Flavour physics: Lecture 2

Flavour data and New Physics

Amol Dighe

Tata Institute of Fundamental Research, Mumbai

SUSY 2017 pre-school
TIFR Mumbai, Dec 4-8, 2017

Flavor physics: a wall of the SM edifice

Building up the Standard Model

- $\tau - \theta$ puzzle $\Rightarrow$ Parity violation
- Cabibbo angle $\Rightarrow$
  weak coupling universality $\oplus$ quark mixing
- GIM mechanism $\Rightarrow$ no FCNC at tree level, charm
- CKM paradigm $\Rightarrow$ (at least) three quark families
- Large B–$\overline{B}$ mixing $\Rightarrow$ heavy top quark
- Rate of radiative B decay $\Rightarrow$ top quark mass

The standard model looks complete now,
with no confirmed signals of BSM physics at the LHC yet !

Flavor physics: a wall of the SM edifice

Building up the Standard Model

- $\tau - \theta$ puzzle $\Rightarrow$ Parity violation
- Cabibbo angle $\Rightarrow$
  weak coupling universality $\oplus$ quark mixing
- GIM mechanism $\Rightarrow$ no FCNC at tree level, charm
- CKM paradigm $\Rightarrow$ (at least) three quark families
- Large B–$\overline{B}$ mixing $\Rightarrow$ heavy top quark
- Rate of radiative B decay $\Rightarrow$ top quark mass

The standard model looks complete now,
with no confirmed signals of BSM physics at the LHC yet !

Is there just a desert beyond ?

In the light of the high-energy and high-intensity colliders,
We may find some pugmarks
(Need not be of the camel we are seeking)

Is there just a desert beyond ?

In the light of the high-energy and high-intensity colliders,
We may find some pugmarks
(Need not be of the camel we are seeking)

Is there just a desert beyond ?

In the light of the high-energy and high-intensity colliders,
We may find some pugmarks
(Need not be of the camel we are seeking)

Flavour physics: a window of the SM edifice

Precision tests of the Standard Model

- CKM elements: do they explain all CP violation ?
- Rare decays: new particles contribute through loops ?
- Asymmetries: are the predicted SM relations obeyed ?
- What are the features of New Physics (if any) ?

How to look at the multidimentional flavour data ?

- Identify patterns of correlations
- Correlations within a meson system give information on BSM operator structure (V-A, tensor, LR, etc.)
- Correlations among different meson systems tell about underlying flavour symmetries (MFV, universality, etc.)

Flavour physics: a window of the SM edifice

Precision tests of the Standard Model

- CKM elements: do they explain all CP violation ?
- Rare decays: new particles contribute through loops ?
- Asymmetries: are the predicted SM relations obeyed ?
- What are the features of New Physics (if any) ?

How to look at the multidimentional flavour data ?

- Identify patterns of correlations
- Correlations within a meson system give information on BSM operator structure (V-A, tensor, LR, etc.)
- Correlations among different meson systems tell about underlying flavour symmetries (MFV, universality, etc.)

Hints and constraints

1. The hints: from precision measurements
   - CKM matrix elements
   - Mixing and decay in neutral mesons
   - Rare FCNC processes
2. Quantifying constraints on NP
   - Model-independent constraints
   - Constraints on specific new physics models
3. Concluding remarks

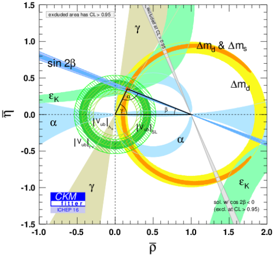
Hints and constraints

Hints and constraints

1. The hints: from precision measurements
   - CKM matrix elements
   - Mixing and decay in neutral mesons
   - Rare FCNC processes
2. Quantifying constraints on NP
   - Model-independent constraints
   - Constraints on specific new physics models
3. Concluding remarks

Global fits to CKM elements

CKMfitter:

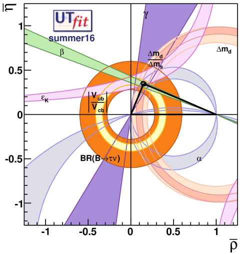


Constraints in the $\bar{\rho}$–$\bar{\eta}$ plane:

- the ratio $|V_{ub}/V_{cb}|$
- ϵ_K from $K \to \pi\pi$
- Mass differences ΔM_d and ΔM_s
- Angles α, β, γ (or ϕ_2, ϕ_1, ϕ_3) of the unitarity triangle

UTfit:

2016-fits



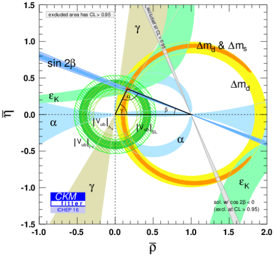
KM paradigm
mostly vindicated !

************** Not so fast ! *************

***** Devil may be in the details ! *****

Global fits to CKM elements

CKMfitter:

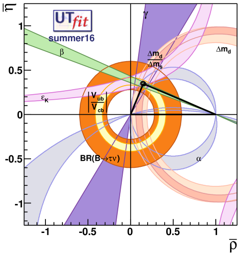


Constraints in the $\bar{\rho}$–$\bar{\eta}$ plane:

- the ratio $|V_{ub}/V_{cb}|$
- ϵ_K from $K \to \pi\pi$
- Mass differences ΔM_d and ΔM_s
- Angles α, β, γ (or ϕ_2, ϕ_1, ϕ_3) of the unitarity triangle

UTfit:

2016-fits



KM paradigm
mostly vindicated !

************** Not so fast ! *************

***** Devil may be in the details ! *****

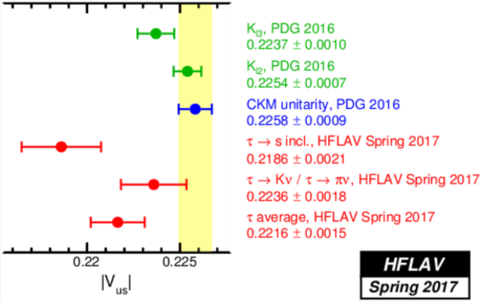
Measurements for determination of CKM elements

V_{ud} $\pi \to \mu\nu$	V_{us} $K \to \pi \ell\nu$ $K \to \mu\nu$	V_{ub} $B \to \pi \ell\nu,\ B_s \to K \ell\nu$ $\Lambda_b \to p \ell\nu$
V_{cd} $D \to \pi \ell\nu$ $D \to \ell\nu$	V_{cs} $D \to K \ell\nu$ $D_s \to \ell\nu$	V_{cb} $B_{(s)} \to D_{(s)}, D^{*}_{(s)} \ell\nu$
V_{td} $B^0 - \overline{B^0}$	V_{ts} $B_s^0 - \overline{B_s^0}$	V_{tb}

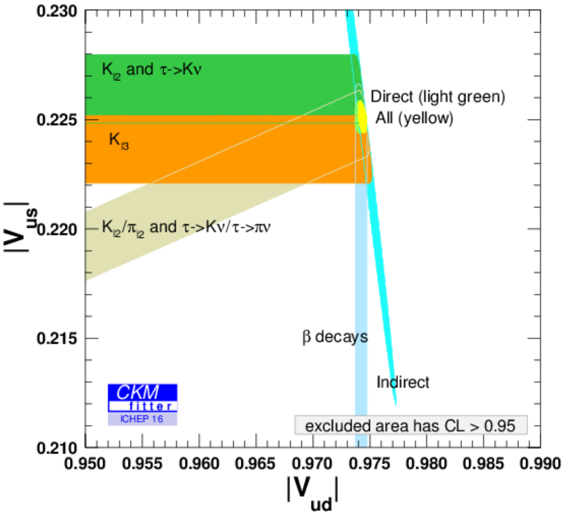
Precision measurements of $|V_{us}|$

Unitarity vs. semileptonic K decays vs. hadronic τ decays

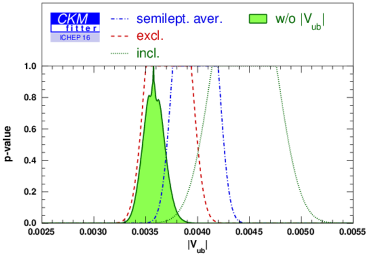
- Semileptonic K decays $\Rightarrow |V_{us}| = 0.2258 \pm 0.0009$
- Strange vs. non-strange hadronic τ decays
  $\Rightarrow |V_{us}| = 0.2216 \pm 0.0015$
- $> 2\sigma$ discrepancy !

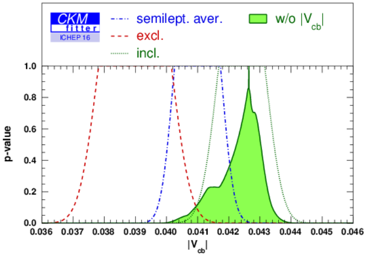


$K_{\ell 2}$ vs. $K_{\ell 3}$ tension in $|V_{us}|$



Inclusive vs exclusive $|V_{cb}|$ and $|V_{ub}|$





$|V_{ub}| \times 10^3$:

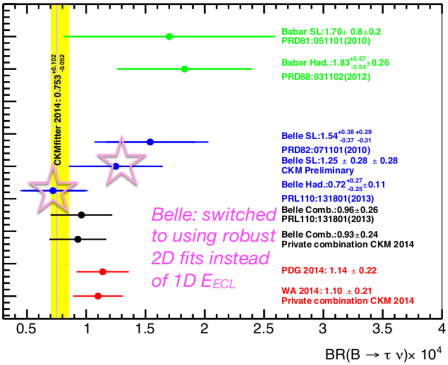
- Excl: (3.72 ± 0.19)
- Incl: $(4.49 \pm 0.16 \pm 0.18)$

$|V_{cb}| \times 10^3$:

- Excl: (39.2 ± 0.7)
- Incl: (42.2 ± 0.8)

CKMFitter

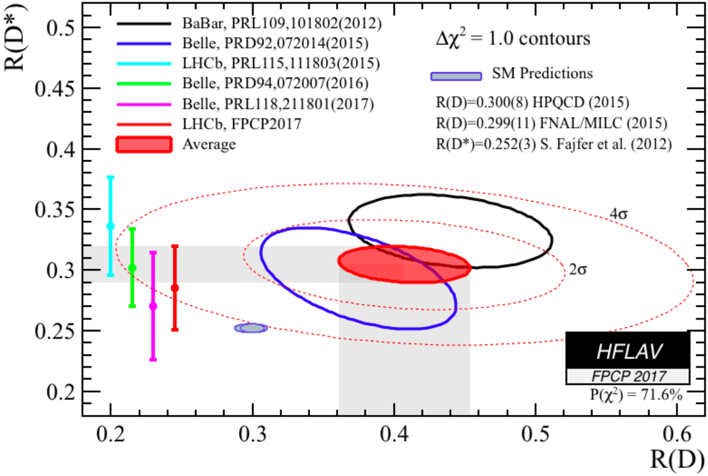
Effective $|V_{ub}|$: through $B(B \to \tau\nu)$



P. Urquio, CKM14

- Apart from the latest Belle measurement, all others indicated excess $B(B \to \tau\nu)$.

Effective $|V_{cb}|$: semileptonic $B \to D\tau\nu$ and $B \to D^*\tau\nu$



- Affect $b \to c\tau\nu$, indicate lepton-universality violation ?

Consolidating observations before going ahead

- Semileptonic decays $s \to u\ell\nu$ as well as $b \to u\ell\nu$ systematically give lower values of $|V_{uq}|$ as compared to those given by the leptonic decays of K and B.
- For semileptonic B decays $b \to u\ell\nu$ and $b \to c\ell\nu$, inclusive decay rates are systematically larger than the exclusive ones.
- Lepton non-universality at play in $b \to c\ell\nu$?
- Lepton non-universality is severely constrained in the first two generations, not so much for the third one. Models with H^+/Z' are natural candidates.
- A single hint may not be sufficient, but overall trends may point the way..

Consolidating observations before going ahead

- Semileptonic decays $s \to u\ell\nu$ as well as $b \to u\ell\nu$ systematically give lower values of $|V_{uq}|$ as compared to those given by the leptonic decays of K and B.
- For semileptonic B decays $b \to u\ell\nu$ and $b \to c\ell\nu$, inclusive decay rates are systematically larger than the exclusive ones.
- Lepton non-universality at play in $b \to c\ell\nu$?
- Lepton non-universality is severely constrained in the first two generations, not so much for the third one. Models with H^+/Z' are natural candidates.
- A single hint may not be sufficient, but overall trends may point the way..

Hints and constraints

1. The hints: from precision measurements
   - CKM matrix elements
   - Mixing and decay in neutral mesons
   - Rare FCNC processes
2. Quantifying constraints on NP
   - Model-independent constraints
   - Constraints on specific new physics models
3. Concluding remarks

Mass and width differences: theory and experiment

ΔM Measurements

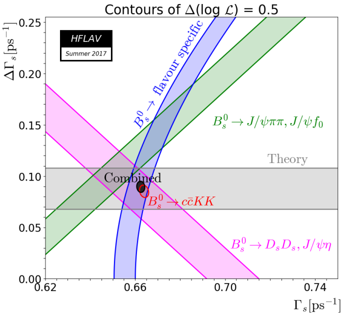
- $\Delta M_d/\Gamma_d = 0.769 \pm 0.003 \Rightarrow |V_{td}|$
- $\Delta M_s/\Gamma_s = 26.80 \pm 0.08 \Rightarrow |V_{ts}|$

$\Delta\Gamma_d$ and $\Delta\Gamma_s$: predictions and measurements

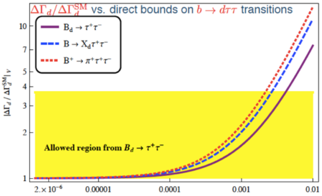
- In SM, $\Delta\Gamma_d/\Gamma_d = (42 \pm 8) \times 10^{-4}$
- Measurement: $\Delta\Gamma_d/\Gamma_d = (20 \pm 100) \times 10^{-4}$ (HFAG)

- In SM, $\Delta\Gamma_s/\Gamma_s = 0.137 \pm 0.027$
- Measurement: $\Delta\Gamma_s/\Gamma_s = 0.135 \pm 0.008$
  (mainly from $B_s \to J/\psi\phi$ at LHCb)

Lifetime difference in B_s and B_d decays



- $\Delta\Gamma$ measured through B_s to flavor-specific modes, $B_s \to K^+K^-, J/\psi f_0$, $B_s \to J/\psi\phi$.
- Some enhancement possible, has to be through $b \to s\tau\tau$ transitions.

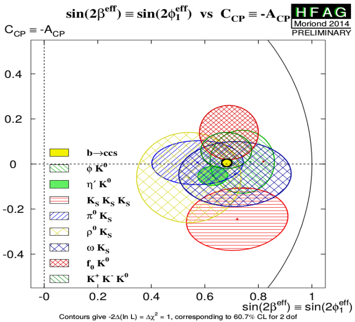


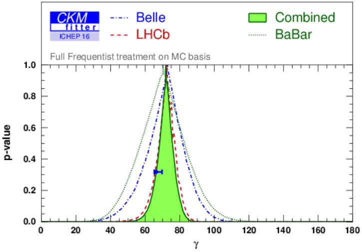
- $\Delta\Gamma_d$ should also be controlled by new physics $b \to d\tau\tau$ transitions

Lenz, CKM2014

$\Delta\Gamma$'s are sensitive to models with Z'

The angles of the unitarity triangle





- The value of β consistent across multiple modes
- The value of γ consistent across experiments
- $\alpha = \pi - \beta - \gamma$ by definition. True test of unitarity:

$$\sin\beta_s = \left|\frac{V_{us}}{V_{ud}}\right|^2 \frac{\sin\beta\ \sin(\gamma+\beta_s)}{\sin(\beta+\gamma)}\ [1+\mathcal{O}(\lambda^4)]$$

Aleksan et al, 1994

- Measurements of β_s needed

The tale of two betas in B_s-$\bar{B}_s$ mixing

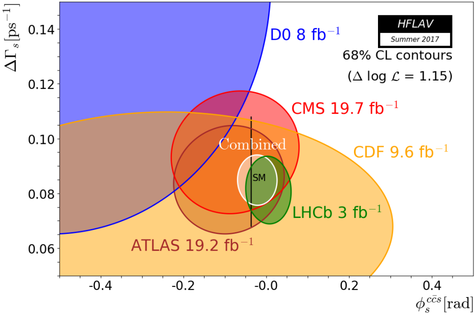
$\beta_s^{J/\psi\phi}$ from $B_s \to J/\psi\phi$

- $\beta_s^{J/\psi\phi} \approx \frac{1}{2}\mathrm{Arg}\left(-\frac{(V_{cb}V_{cs}^*)^2}{M_{12s}}\right)$
- $\beta_s^{J/\psi}(SM) = 0.019 \pm 0.001$

β_s^{sl} from a_{sl}

- $a_{sl} = (\Delta\Gamma_s/\Delta M_s)\ \tan\phi_s^{sl}$
- $\phi_s^{sl} = \mathrm{Arg}(-M_{12s}/\Gamma_{12s})$
- $\mathrm{Arg}(\Gamma_{12}) \neq \mathrm{Arg}(V_{cb}V_{cs}^*)^2$ since the (c-u) and (u-u) intermediate states contribute to Γ_{12}.
- $\phi_s^{sl}(SM) = 0.0041 \pm 0.0007$
- $\beta_s^{sl}(SM) = -0.0020 \pm 0.0003$

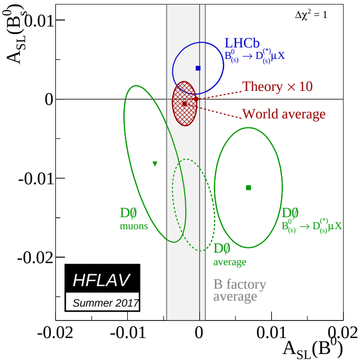
$\phi_s^{J/\psi\phi}$: Angular analysis of $B_s \to J/\psi\phi$



$$\phi_s = -2\beta_s^{J/\psi\phi}$$

- Results for $\Delta\Gamma_s$ very close to SM now: enhancement by only a few tens of per cent possible.
- $\phi_s = -0.021 \pm 0.031$ rad
  Large (relative) enhancement in $\beta_s^{J/\psi\phi}$ is possible, also detectable since the SM value is small and precisely known.

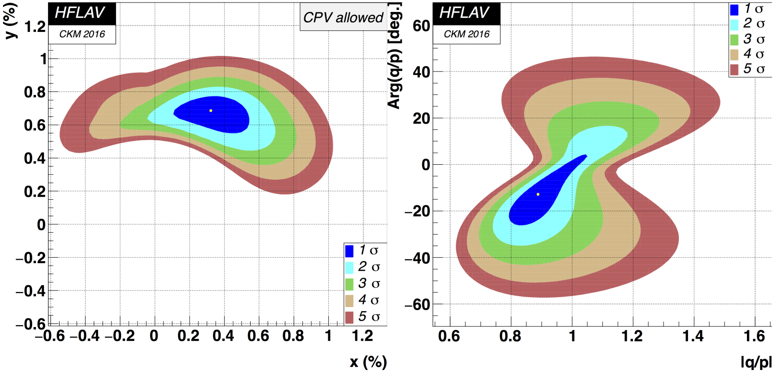
β_s^{sl}: Like-sign dimuon asymmetry



- SM ⇒ $A^b_{sl} = (-0.023^{+0.005}_{-0.006})\%$
- $A^b_{sl} = (-0.787 \pm 0.172 \pm 0.093)\%$
  ⇒ 3.9σ deviation
  (original D0 result)

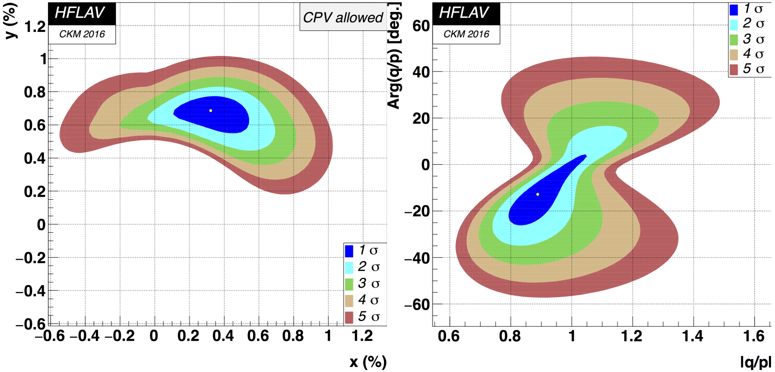
- $A_{\rm CP}(B^0_s) \equiv a^s_{sl} = \frac{\Delta\Gamma_s}{\Delta M_s} \tan\phi^{sl}_s$
- Large $\Delta\Gamma_s$ and/or large ϕ_s !

D–$\bar{D}$ mixing



- Both $\Delta m/\Gamma$ and $\Delta\Gamma/\Gamma$ significantly nonzero
- D–$\bar{D}$ mixing detected.
- Cannot be sure that it is all SM, long-distance contributions hard to calculate
- It is possible that $|q/p|$ is significantly non-unity.
- CP violation through mixing possible, not detected yet

D–$\bar{D}$ mixing



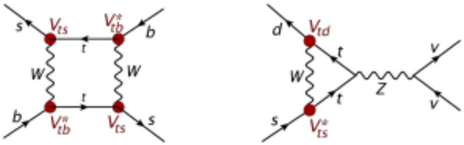
- Both $\Delta m/\Gamma$ and $\Delta\Gamma/\Gamma$ significantly nonzero
- D–$\bar{D}$ mixing detected.
- Cannot be sure that it is all SM, long-distance contributions hard to calculate
- It is possible that $|q/p|$ is significantly non-unity.
- CP violation through mixing possible, not detected yet

Hints and constraints

1. The hints: from precision measurements
   - CKM matrix elements
   - Mixing and decay in neutral mesons
   - Rare FCNC processes
2. Quantifying constraints on NP
   - Model-independent constraints
   - Constraints on specific new physics models
3. Concluding remarks

Flavour changing neutral current processes

- Suppressed in the SM due to the loop factor, CKM hierarchy, chiral structure and GIM mechanism.



CKM hierarchy predicts specific pattern of effects in the SM

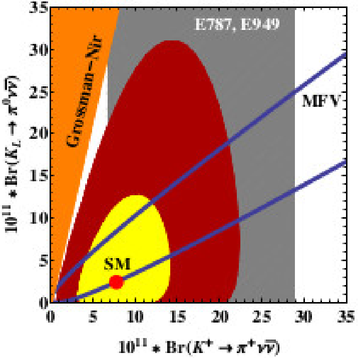
$$\underbrace{V_{ts}^*V_{td}}_{K\text{ system}} \sim 5\cdot 10^{-4} \ll \underbrace{V_{tb}^*V_{td}}_{B_d\text{ system}} \sim 10^{-2} < \underbrace{V_{tb}^*V_{ts}}_{B_s\text{ system}} \sim 4\cdot 10^{-2}$$

➢ K decays in general most sensitive to BSM physics

(Slide from M. Blanke)

The rare but clean decay $K \to \pi\nu\bar{\nu}$ ***

Not yet observed, but...



- $C_{NP} \leq 0.5|\lambda_t C_{SM}|$
- $C_{NP} \leq |\lambda_t C_{SM}|$

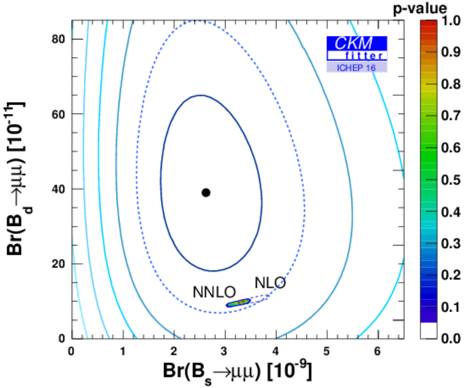
Minimal flavor violation:

- $C_{NP} \propto \lambda_t C_{SM}$

J. Brod, CKM14

- Models can change the relative BRs of $K_L \to \pi^0\nu\bar{\nu}$ and $K^+ \to \pi^+\nu\bar{\nu}$ to a large extent

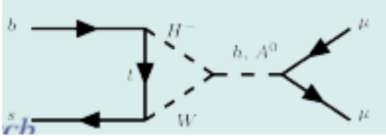
Branching ratios of $B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$



- $B(B_s \to \mu\mu) = (3.145^{+0.150}_{-0.069}) \times 10^{-9}$
- $B(B_d \to \mu\mu) = (9.55^{+0.25}_{-0.44}) \times 10^{-11}$

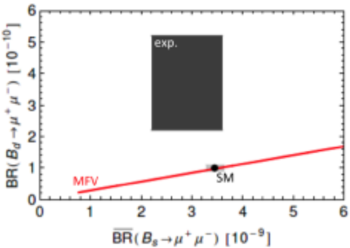
What NP can affect $B(B_{s/d} \to \mu\mu)$?

- Sensitive to minimal SUSY model parameters:



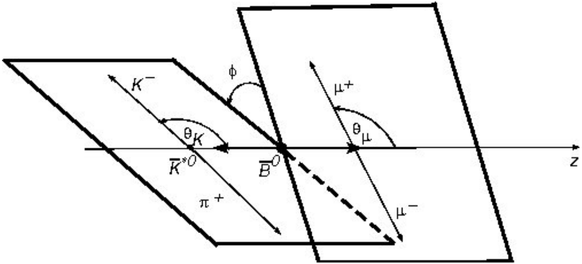
$$B(B_q \to \mu\mu) \propto |V_{tb}^* V_{tq}| \frac{m_b^2 m_\ell^2 \tan^6\beta}{m_A^4}$$

- Severely restricts large $\tan\beta$



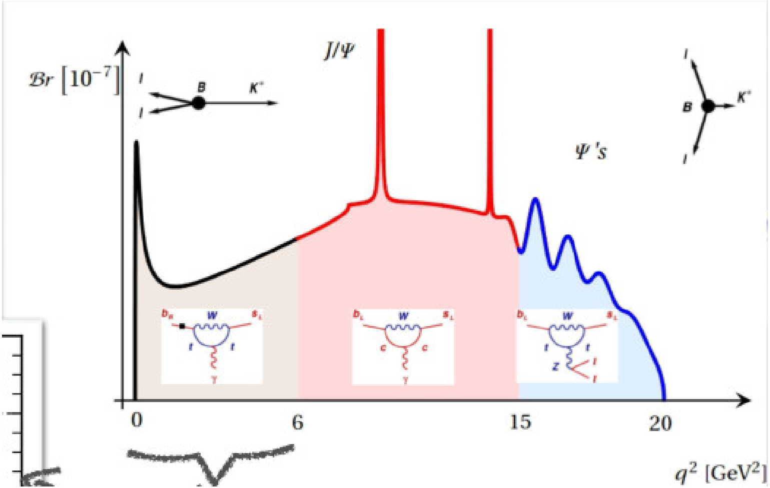
- MFV models cannot account for the observed values Buras 2014
- Role for Z' ?

Angular distribution in $B \to K^* \mu^+ \mu^-$

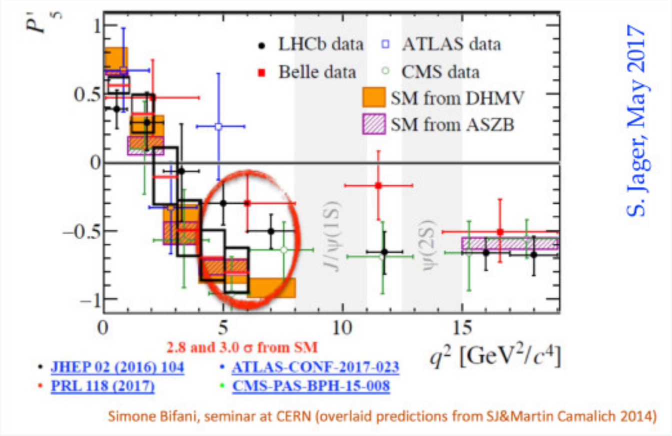


$$\frac{1}{\Gamma}\frac{d^4\Gamma}{d\cos\theta_\ell\, d\cos\theta_K\, d\hat{\phi}\, dq^2} = \frac{9}{16\pi}\Big[F_L\cos^2\theta_K + \frac{3}{4}(1-F_L)(1-\cos^2\theta_K) + F_L\cos^2\theta_K(2\cos^2\theta_\ell - 1) + \frac{1}{4}(1-F_L)(1-\cos^2\theta_K)(2\cos^2\theta_\ell - 1) + S_3(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\cos 2\hat{\phi} + \frac{4}{3}A_{FB}(1-\cos^2\theta_K)\cos\theta_\ell + A_{Im}(1-\cos^2\theta_K)(1-\cos^2\theta_\ell)\sin 2\hat{\phi} \Big]$$

q^2 distribution of $B \to K^* \mu^+ \mu^-$

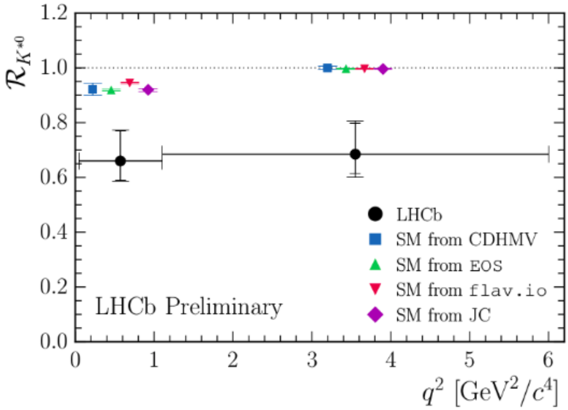


The P_5' anomaly



- $P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$, largely free from formfactor uncertainties
- Local discrepancy of 3.7σ in P_5'.

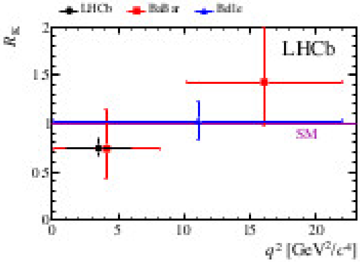
Lepton non-universality in $B \to K^* \ell\ell$



- The ratio $R_K(q^2) \equiv B(B^+ \to K^* \mu^+ \mu^-)/B(B^+ \to K^* e^+ e^-)$
- 2.2 – 2.5 σ deviation in each bin

Lepton non-universality in $B \to K\ell\ell$

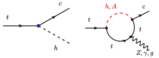
- The ratio $R_K \equiv B(B^+ \to K^+\mu^+\mu^-)/B(B^+ \to K^+e^+e^-)$ expected to be 1.00 in SM



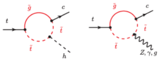
- Measured value for $1 < q^2 < 9$ GeV^2:
  $R_K = 0.745^{+0.090}_{-0.074} \pm 0.035 \Rightarrow \sim 2.6\sigma$ deviation from SM
- Non-universality from Higgs not enough since Higgs contribution is m_ℓ-suppressed.
- Models with Z' that does not couple to electrons can explain this anomaly.

Possible enhancement of rare top FCNC decays

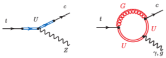
2HDM



MSSM



RS flavor



	SM	2HDM	MSSM	RS
$t \to cZ$	$\sim 10^{-14}$	$\lesssim 10^{-6}$	$\lesssim 10^{-7}$	$\lesssim 10^{-5}$
$t \to c\gamma$	$\sim 10^{-13}$	$\lesssim 10^{-7}$	$\lesssim 10^{-8}$	$\lesssim 10^{-9}$
$t \to cg$	$\sim 10^{-11}$	$\lesssim 10^{-5}$	$\lesssim 10^{-7}$	$\lesssim 10^{-10}$
$t \to ch$	$\sim 10^{-15}$	$\lesssim 10^{-2}$	$\lesssim 10^{-5}$	$\lesssim 10^{-4}$

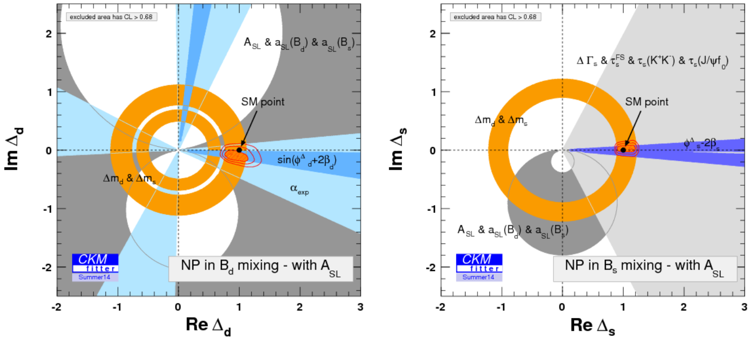
Atwood-Reina-Soni 1996, Cao et al 2009, Agashe-Contino 2009

Azatov et al 2009, Casagrande et al 2010

Hints and constraints

Hints and constraints

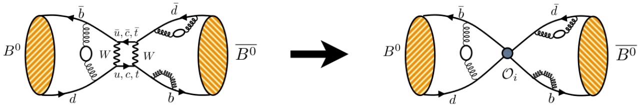
NP contributions to B–$\overline{B}$ mixing



- $\Delta_d = \dfrac{M_{12d}}{M_{12d}(SM)}$, $\Delta_s = \dfrac{M_{12s}}{M_{12s}(SM)}$,
- $\Gamma_{12d/s}(NP) = 0$ assumed (not true in general)

Effective operators for meson mixing

Standard Model



In general :

$$\mathcal{H}_{\text{eff}} = \sum_{i=1}^{5} c_i(\mu)\mathcal{O}_i(\mu)$$

SM:

$$\mathcal{O}_1 = (\bar{b}^\alpha \gamma_\mu L q^\alpha)\,(\bar{b}^\beta \gamma_\mu L q^\beta)$$

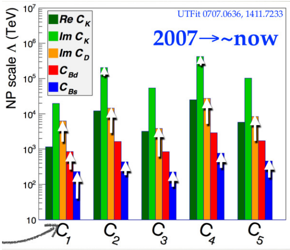
$$\mathcal{O}_2 = (\bar{b}^\alpha L q^\alpha)\,(\bar{b}^\beta L q^\beta)$$

$$\mathcal{O}_3 = (\bar{b}^\alpha L q^\beta)\,(\bar{b}^\beta L q^\alpha)$$

BSM:

$$\mathcal{O}_4 = (\bar{b}^\alpha L q^\alpha)\,(\bar{b}^\beta R q^\beta)$$

$$\mathcal{O}_5 = (\bar{b}^\alpha L q^\beta)\,(\bar{b}^\beta R q^\alpha)$$



- Meson mixing measurements give limits on $c_i^{\text{NP}} \equiv 1/\Lambda^2$

Lorentz structure of NP operators in $b \to s\mu\mu$

$$\mathcal{H}_{\rm eff}(b \to s\mu^+\mu^-) = \mathcal{H}_{\rm eff}^{SM} + \mathcal{H}_{\rm eff}^{VA} + \mathcal{H}_{\rm eff}^{SP} + \mathcal{H}_{\rm eff}^{T} \,,$$

$$\begin{aligned}
\mathcal{H}_{\rm eff}^{SM} &= -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \Big\{ \sum_{i=1}^{6} C_i(\mu)\mathcal{O}_i(\mu) + C_7 \frac{e}{16\pi^2} (\bar{s}\sigma_{\mu\nu}(m_s P_L + m_b P_R) b) F^{\mu\nu} \\
&\quad + C_9 \frac{\alpha_{em}}{4\pi} (\bar{s}\gamma_\mu P_L b)\, \bar{\mu}\gamma_\mu \mu + C_{10} \frac{\alpha_{em}}{4\pi} (\bar{s}\gamma_\mu P_L b)\, \bar{\mu}\gamma_\mu\gamma_5 \mu \Big\} \\
\mathcal{H}_{\rm eff}^{VA} &= \frac{\alpha G_F}{\sqrt{2}\pi} V_{tb}^* V_{ts} \Big\{ R_V\, \bar{s}\gamma_\mu P_L b\, \bar{\mu}\gamma_\mu \mu + R_A\, \bar{s}\gamma_\mu P_L b\, \bar{\mu}\gamma_\mu\gamma_5 \mu \\
&\quad + R_V'\, \bar{s}\gamma_\mu P_R b\, \bar{\mu}\gamma_\mu \mu + R_A'\, \bar{s}\gamma_\mu P_R b\, \bar{\mu}\gamma_\mu\gamma_5 \mu \Big\} \,, \\
\mathcal{H}_{\rm eff}^{SP} &= \frac{\alpha G_F}{\sqrt{2}\pi} V_{tb}^* V_{ts} \Big\{ R_S\, \bar{s} P_R b\, \bar{\mu}\mu + R_P\, \bar{s} P_R b\, \bar{\mu}\gamma_5 \mu \\
&\quad + R_S'\, \bar{s} P_L b\, \bar{\mu}\mu + R_P'\, \bar{s} P_L b\, \bar{\mu}\gamma_5 \mu \Big\} \,, \\
\mathcal{H}_{\rm eff}^{T} &= \frac{\alpha G_F}{\sqrt{2}\pi} V_{tb}^* V_{ts} \Big\{ C_T\, \bar{s}\sigma_{\mu\nu} b\, \bar{\mu}\sigma^{\mu\nu} \mu + i C_{TE}\, \bar{s}\sigma_{\mu\nu} b\, \bar{\mu}\sigma_{\alpha\beta} \mu\, \epsilon^{\mu\nu\alpha\beta} \Big\}
\end{aligned}$$

Alok et al, 2011

Characteristics of NP Lorentz structures

New SP operators: affect $B(B_s \to \mu^+\mu^-)$

$$B(\bar{B}_s \to \mu^+\mu^-) = \frac{G_F^2 \alpha_{em}^2 m_{B_s}^5 f_{B_s}^2 \tau_{B_s}}{64\pi^3} |V_{tb} V_{ts}^*|^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}} \times$$

$$\left\{ \left(1 - \frac{4m_\mu^2}{m_{B_s}^2}\right) \left| \frac{R_S - R_S'}{m_b + m_s} \right|^2 + \left| \frac{R_P - R_P'}{m_b + m_s} + \frac{2m_\mu}{m_{B_s}^2} (C_{10} + R_A - R_A') \right|^2 \right\}.$$

$\Rightarrow$ Strong bounds on Scalar and pseudoscalar operators

A typical B-decay rate calculation ($b \to s\mu\mu$)

The effective Hamiltonian: Operator Product Expansion

$$
\begin{aligned}
\mathcal{H}_{\rm eff}^{SM} &= -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \Big\{ \sum_{i=1}^{6} C_i(\mu)\mathcal{O}_i(\mu) \\
&\quad + C_7 \frac{e}{16\pi^2} (\bar{s}\sigma_{\mu\nu}(m_s P_L + m_b P_R)b)\, F^{\mu\nu} \\
&\quad + C_9 \frac{\alpha_{em}}{4\pi} (\bar{s}\gamma_\mu P_L b)\, \bar{\mu}\gamma_\mu \mu + C_{10} \frac{\alpha_{em}}{4\pi} (\bar{s}\gamma_\mu P_L b)\, \bar{\mu}\gamma_\mu \gamma_5 \mu \Big\}
\end{aligned}
$$

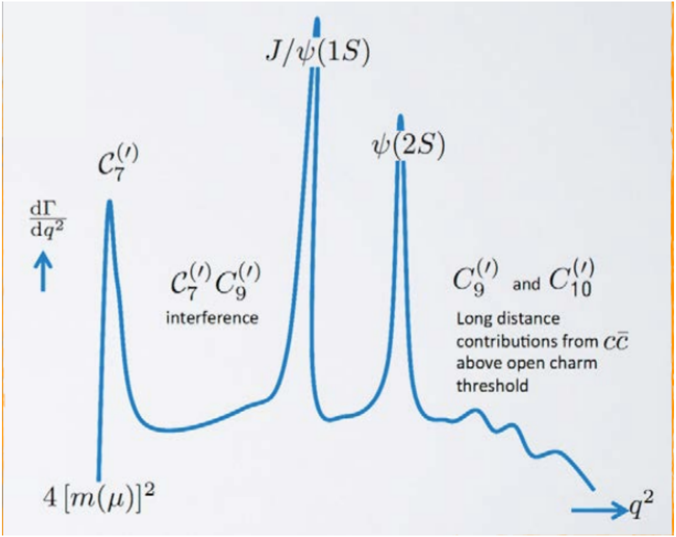
Decay rate:

$$\Gamma(B \to f) = [phase\ space)] |\langle f | H_{\rm eff}^{SM} | B \rangle|^2$$

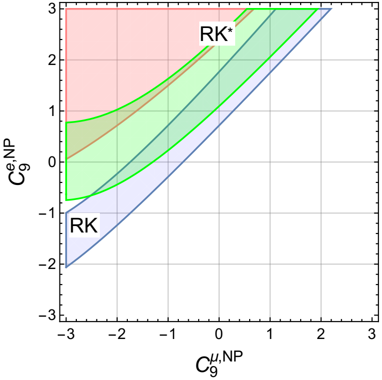
Quantities involved:

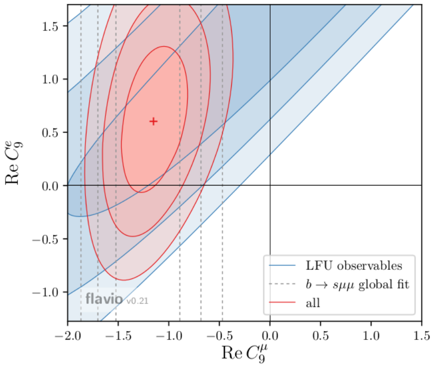
• Masses, • Decay constants, • Bag parameters,
• Wilson coefficients, • Hadronic matrix elements (form factors),
• CKM elements

Wilson coefficients in $B \to K^* \mu\mu$



Constraints on $C_9^{\mathrm{NP},\mu}$ and $C_9^{\mathrm{NP},e}$





Bhatia, AD, et al.

Altmannshofer et al.

Rare top decays

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i$$

Operators that are only weakly constrained by indirect probes

	$t \to c$	$t \to u$
SU(2) dipole $\mathcal{O}_{LR}^{W}$	$\Lambda \gtrsim 0.75$ TeV	$\Lambda \gtrsim 0.75$ TeV
SU(3) dipole $\mathcal{O}_{RL}^{G}$	$\Lambda \gtrsim 4.0$ TeV	$\Lambda \gtrsim 5.8$ TeV
Higgs penguin $\mathcal{O}_{RL}^{h}$	$\Lambda \gtrsim 0.73$ TeV	$\Lambda \gtrsim 0.73$ TeV

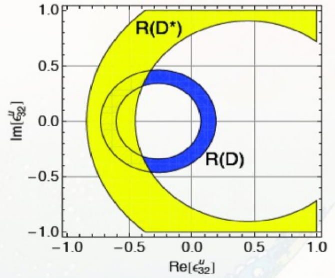
J. Brod

- TeV scales are already being probed here.

Hints and constraints

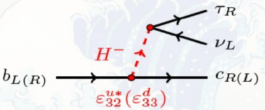
Two-Higgs Doublet Model (Type-III) for R_D and R_{D^*}

$$\mathcal{L}_Y = \overline{Q}^a_{fL}[Y^d_{fi}\epsilon_{ab}H^{b*}_d - \varepsilon^d_{fi}H^a_u]d_{iR} - \overline{Q}^a_{fL}[Y^u_{fi}\epsilon_{ab}H^{b*}_u + \varepsilon^u_{fi}H^a_u]u_{iR} + \text{h.c.}$$



Allowed 1σ regions for $\tan\beta = 50$ and $M_H = 500$ GeV

[Crivellin at al.('12), arXiv:1206.2634]



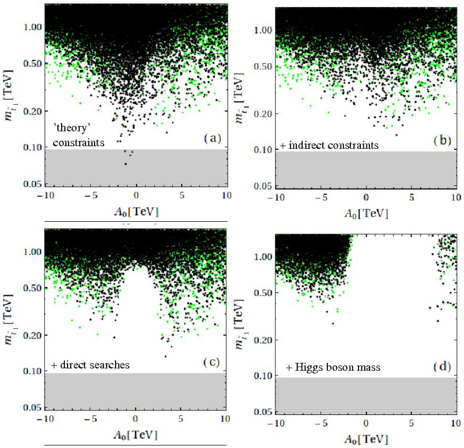
$$C_{S_1} \simeq \frac{1}{2\sqrt{2}G_F}\frac{m_\tau}{v}\varepsilon^d_{33}\frac{\sin\beta\tan^2\beta}{M^2_{H^\pm}}$$

-disfavoured by *BABAR*!

$$C_{S_2} \simeq \frac{1}{2\sqrt{2}G_F V_{cb}}\frac{m_\tau}{v}\varepsilon^{u*}_{32}\frac{\sin\beta\tan\beta}{M^2_{H^\pm}}$$

- $R(D)$ and $R(D^*)$ may be accounted with a single parameter ϵ^u_{32}.
- Not possible for Type-I or Type-II models

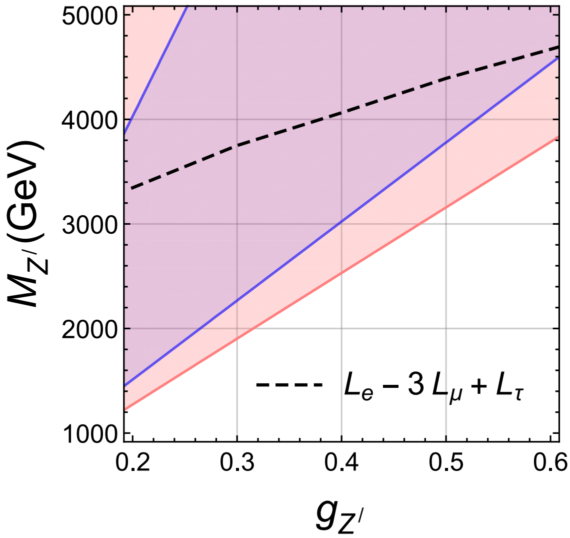
Constraints on CMSSM with light stop ($m_{\tilde{t}} < 1.5$ TeV)



AD, Ghosh, Patel, Raychaudhuri 2013

- Higgs mass constraints are dominant, at least at low tan β
- At high tan β, flavour constraints come into play again.

Constraints on specific Z' models



Bhatia, Chakraborty, AD, 2017

Hints and constraints

1. The hints: from precision measurements
   - CKM matrix elements
   - Mixing and decay in neutral mesons
   - Rare FCNC processes
2. Quantifying constraints on NP
   - Model-independent constraints
   - Constraints on specific new physics models
3. Concluding remarks

Concluding remarks

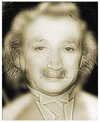
- B physics: a magnifying glass for testing SM
  Thanks to the lattice colleagues for the precision.
- Rare decays and precision measurements constrain specific NP models as well as indicate what classes of NP may be present
- While rare K decays have the largest precision reach, the large number of rare B decays offer probing power into the flavour structure.
- SUSY, multiple Higgses, Z', extra qyarks, leptoquarks, ... many possibilities
- Only data will tell, one has to look closely, though...

A closer look can take you

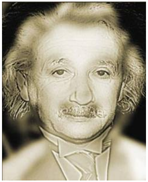
From beauty...

A closer look can take you

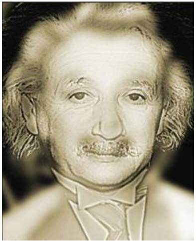
From beauty...



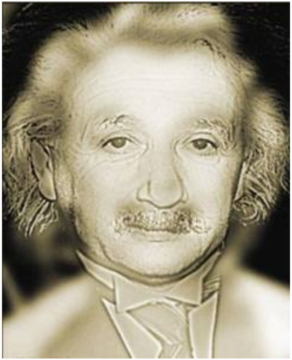
A closer look can take you



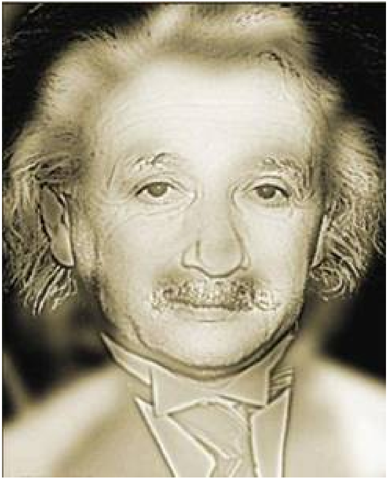
A closer look can take you



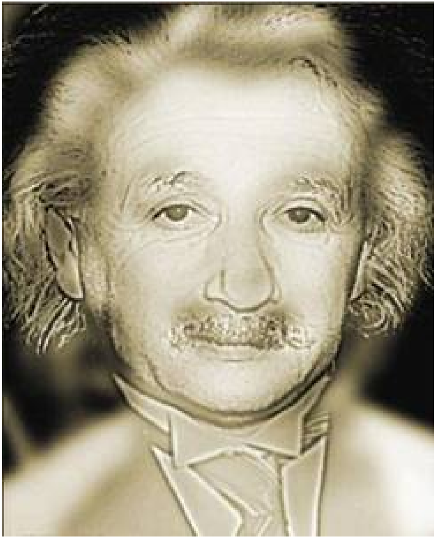
A closer look can take you



A closer look can take you

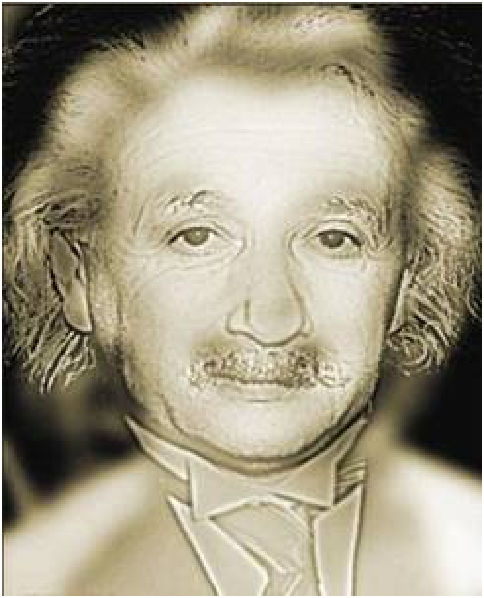


A closer look can take you



A closer look can take you

... to relativity !



So simply....

Follow the pugmarks.....