Flavour Physics Survey

Roman Zwicky
University of Southampton

HEP Forum Cosoners House May 7-8 2009
From the Tevatron to the LHC

Overview

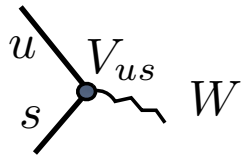
- CKM & CP-violation (4 slides)
- MFV -- theory of flavour (2 slides)
- Flavour tools (1 slide)
- flavour at LHCb & 3 main examples
- 5 current puzzles in flavour physics
- Epilogue

The quark flavour structure

- The standard view: the following term is *part of the SM* or *has been generated*

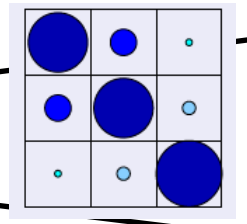
$$L_{yukawa} = v U'_L Y'_U U'_R + (U \leftrightarrow D) \qquad U' = (u', c', t')$$

- Diagonalization with bi-unitary transformation: $M_U = v Y_U = v L_U Y'_U (R_U)^\dagger = \mathrm{diag}(m_u, m_c, m_t)$
- Only effect on physics in SM: $V_{CKM} = (L_U)^\dagger L_D$



- CKM matrix unitary $\Rightarrow$ 9 parameters - $5_{QM\ phases}$ = 4 free parameters

$$|V_{CKM}| \approx \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix}$$



Measured in leptonic/semileptonic tree level decays
Theory input: decay constant/form factor
New physics contamination unlikely, ($D_s \to l\nu$ anomaly later)

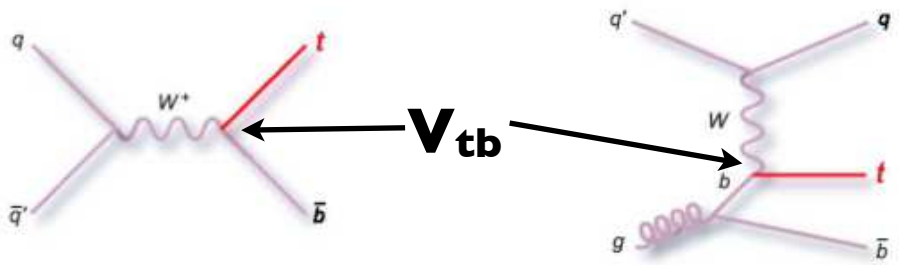
top next slide ...

hierarchical

V_{tb}

- Direct measurement at B factory energetically impossible
- Can do $|V_{tb}V_{ts(d)} \times \text{Form Factor}|^2$ or $|V_{td}/V_{ts}|$
- From measured CKM and unitarity $|V_{tb}| = 0.999100(34)$

Direct production at colliders



V_{tb}

S-channel *T-channel*

	S	T
Tevatron	~30%	~60%
LHC	~3%	~90%

$|V_{tb}| = 0.91(11)_{stat\text{-}sys}(07)_{theor}$ by CDF

$|V_{tb}| = 1.07(12)$ by DØ

@LHC ?

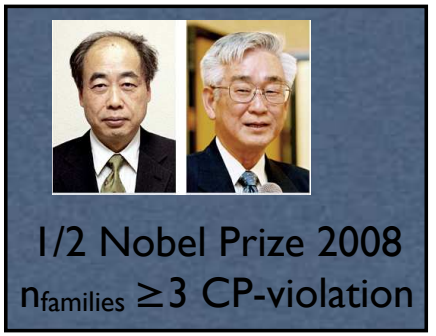
$\delta|V_{tb}| \sim 5\%$ enough statistics & NLO

(NNLO reduce even furhter ...)

CP-violation

(necessary condition for baryon-asymmetry)

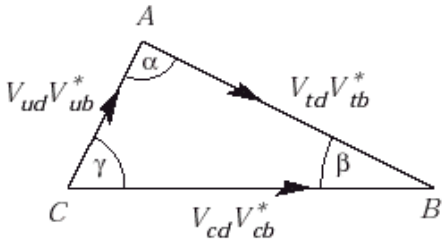
$$(CP)\mathcal{L}^{\text{weak}}(CP)^{\dagger} = \mathcal{L}^{\text{weak}} \;\Leftrightarrow\; V_{\alpha\beta} = V^{*}_{\alpha\beta}$$



1/2 Nobel Prize 2008

$n_{families} \geq 3$ CP-violation

★ unitary V_{CKM} $(V_{CKM})^{\dagger}=1$) → *useful constraint*



★ Size of triangle measures CP violation $\Delta \sim 3.08(16)10^{-5}$ (N.B. $\Delta_{max} = 1/(6\sqrt{3}) \sim 10^{-1}$)

★ Electroweak Baryogenesis 'fails' by 10 orders of magnitude

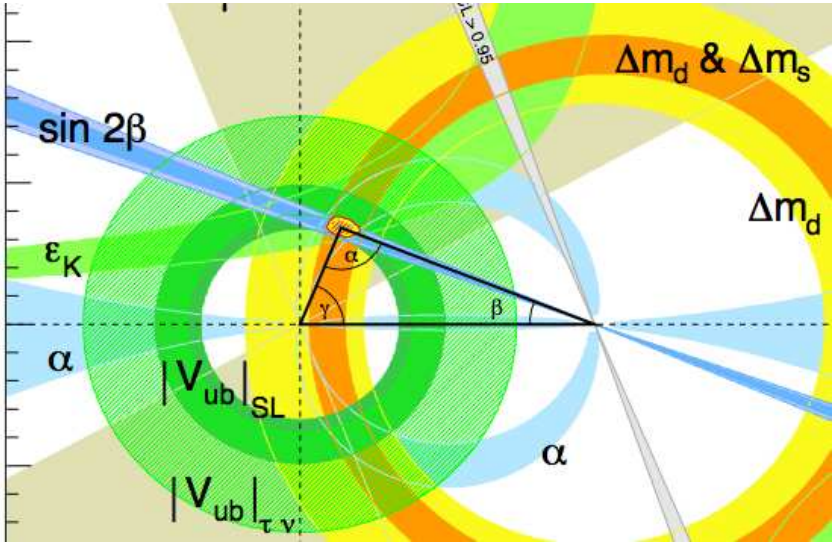
★ Jarlskog condition: Asymmetry must be: $\eta \sim .. \left(\frac{m_s^2 - m_d^2}{\Lambda_{\rm EW}^2}\right) \Delta$ ← *small quark masses (to be blamed)*

★ But: A. CKM only established source of CP-viol. SM → continue search

B. look alternatives e.g. 4th-generation
Leptogenesis CP-viol. neutrino -- $\sin^2\Theta_{13} = 0.02(1)$

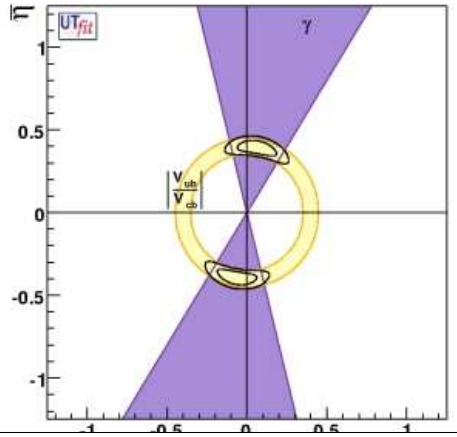
CKM-triangle

(assuming the SM -- .. CLEO,BaBar,Belle, TeVatron)



- CKM describes ~~CP~~ mesons ~10-20%
- bounds on FCNC model building

CKM-triangle from tree-level decays



Unitarity clock .. where will it stop?

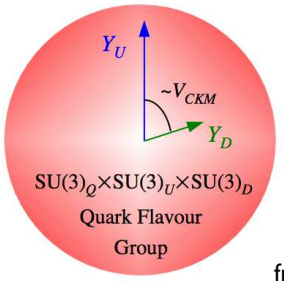
- δ|Vub/Vcb| ~ 7% from B→πlν *(Super-B B→τν)*
- δγ ~ 12° from B→DK & other *(**LHCb** δγ ~ 2.4° 10fb^{-1})*

Principle of Minimal Flavour Violation (MFV)

- Absence of new FCNC so far → systematic?
  Are Yukawa only source of flavour violation?

- N.B. Yukawa → 0 then large global symmetry
  $G_F = SU(3)_Q \otimes SU(3)_U \otimes SU(3)_D \otimes ...$

- Let Yukawa formally transform $Y_D \sim (3^*,1,3)$ ....



from G.Isidori

G_F symmetry restored

MFV effective theory (of higher dimensional operators)
invariant under global G_F and CP with O(1) coefficients.

D'Ambrosio, Giudice, Isidori & Strumia '02

- Similar to χ-PT where masses $\sim (3^*,3)$ under $SU(3)_L \times SU(3)_R$

- It is testable as it predicts strong correlations $Y_t \gg Y_q$ e.g. ΔM_s and ΔM_d

- If Yukawa are thought of as scalars acquiring a vev what happens Goldstones due to SSB?
  MFV is not (yet) a theory of flavour-- empirically motivated principle to be imposed on models

Theory of flavours ...

Weak gauge sector: $\cos(\theta_W) = M_W/M_Z$
CKM empirically : $\sin(\theta_C)$ $M_\pi/M_K = (m_d/m_s)^{1/2}$ Cabibbo Universality

Can this be extended? more families

The large top mass is a challenge ....

- Higgs fundamental → extend Higgs sector → new FCNC likely (predictive)
  (Weinberg-Glashow'77 conditions: A) $T_{3R/L}(Q) = f_{L/R}(Q)$ ... B) single source for Yukawa terms)

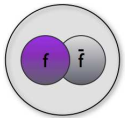
- *Froggat-Nielsen mechanism '77*
  Links mass & CKM hierarchy with (m_t<35GeV)
  $|V_{qq'}| \sim \varepsilon^{f(\text{charges } q \,\&\, q' \text{ under } U_{FN}(1))}$
  $(m_q/m_{q'}) \sim \varepsilon^{g(\text{charges } q \,\&\, q' \text{ under } U_{FN}(1))}$

- *Discrete non-abelain symmetries* e.g. A_4 has 3-representations ∋ $U,D,(H_1,H_2,H_3)$
  (*Wyler'79 predicts $m_t \sim 20$GeV ...*)

- Field revived by PMNS (lepton mixing) matrix (e.g. tri-bi maximal mixing conjecture)
  A_4 is popular in conjunction scalar sector extensions e.g. Ma' et al 01
  Also applied to both quark & lepton sectors (talk by Steve King?)

$$\approx \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & \sim 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

Higgs composite e.g. Extended Technicolor



A) capable generating family hierarchy

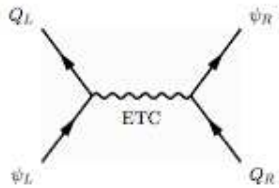
B) doublet mass splitting challenge

(N.B. FCNC and S tamed by waking Technicolor)

$$\mathcal{L}^{\text{eff}} = \alpha_{ab}\frac{\bar{Q}T^aQ\bar{\psi}T^b\psi}{\Lambda^2_{ETC}} + \beta_{ab}\frac{\bar{Q}T^aQ\bar{Q}T^bQ}{\Lambda^2_{ETC}} + \gamma_{ab}\frac{\bar{\psi}T^a\psi\bar{\psi}T^b\psi}{\Lambda^2_{ETC}} + \dots$$

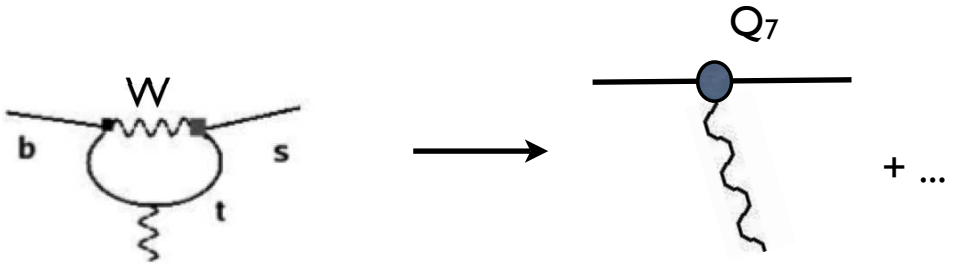
$SM\ fermion\ masses$ $FCNC$

FCNC mass-generation connected new element strong dynamics



The flavour technology

(SM precision)

1. 

$$H_{\text{eff}} = \sum C^i(M_W) O^i(M_W)$$

2. perturbative-RNG $\mu \sim m_b$ (resummation large logs $\ln(M_W)$) $H_{\text{eff}} = \sum C^i(\mu) O^i(\mu)$

3. evaluation of matrix elements → non-perturbative methods $\langle B|O^i(\mu \sim m_b)|X\rangle$

- ★ In flavour physics look for deviations
  - A. in SM Wilson coefficients
  - B. new operators O^i_{BSM}
- ★ When SM was built, people knew about $O_{4-fermi} = \frac{1}{M_W^2} \bar{u}\gamma_\mu d_L \, \bar{l}\gamma^\mu \nu_L$

Flavour physics at LHCb

- B factories Belle, BaBar designed mass produce B_d mesons -- *(charm possible large statistics)*
- At TeVatron B_s study began -- *(some SM results & some open issues ϕ_s later ...)*
- LHCb collider experiment with:
  (~ 10^{12} bb/ year)

1. producing 'all' mesons B_d, B_s, D_0, D_s
2. large statistics
3. detector: can't afford ν, good μ, improvable (upgrade) γ

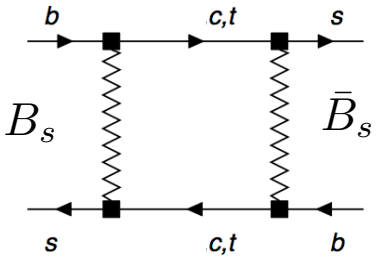
	Channel	Yield	B/S	Precision
γ	$B_s \to D_s^{-+} K^{+-}$	5.4k	< 1.0	σ(γ) ~ 14°
	$B_d \to \pi^+\pi^-$	36k	0.46	σ(γ) ~ 4°
	$B_s \to K^+K^-$	36k	< 0.06	
	$B_d \to D^0$ (Kπ,KK) K^{*0}	3.4 k, 0.5 k, 0.6 k	<0.3, <1.7, < 1.4	σ(γ) ~ 7° - 10°
	$B^- \to D^0$ ($K^-\pi^+$,$K^+\pi^-$) K^-	28k, 0.5k	0.6, 1.5	σ(γ) ~ 5° - 15°
	$B^- \to D^0$ (K^+K^-,$\pi^+\pi^-$) K^-	4.3 k	1.0	
	$B^- \to D^0$ ($K_S\pi^+\pi^-$) K^-	1.5 - 5k	< 0.7	σ(γ) ~ 8° - 16°
α	$B_d \to \pi^+\pi^-\pi^0$	14k	< 0.8	σ(α) ~ 10°
	$B \to \rho^+\rho^0$,$\rho^+\rho^-$,$\rho^0\rho^0$	9k, 2k, 1k	1, <5, < 4	

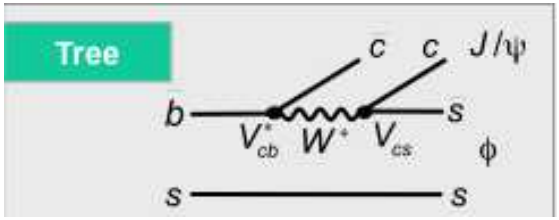
from F.Muheim talk HEP forum '07 for $2fb^{-1}$ (~1yr) and 14TeV

β	$B_d \to J/\psi(\mu\mu)K_S$	216k	0.8	σ(sin2β) ~ 0.022
	$B_d \to \phi K_S$	0.8k	<2.4	σ(sin2β) ~ 0.32
Δm_s	$B_s \to D_s^- \pi^+$	80k	0.3	$\sigma(\Delta m_s) \sim 0.01\ ps^{-1}$
ϕ_s	$B_s \to J/\psi(\mu\mu)\phi$	131k	0.12	$\sigma(\phi_s) \sim 0.023$
	$B_s \to \phi\phi$	4k	<0.8	$\sigma(\phi_s) \sim 0.10$
Rare decays	$B_s \to \mu^+\mu^-$	20	< 5.7	
	$B_d \to K^{*0}\mu^+\mu^-$	4.4 k	< 2.6	$\sigma(C_7^{eff}/C_9^{eff}) \sim 0.13$
	$B_d \to K^{*0}\gamma$	35k	< 0.7	$\sigma(A_{CP}) \sim 0.01$
	$B_s \to \phi\gamma$	9.3 k	< 2.4	
charm	$D^{*+} \to D^0$ ($K^-\pi^+$) π^+	50 M		

$B_s \rightarrow J/\Psi\, \phi$

- Cousin (≠ final state spin) of gold platted $B_d \rightarrow J/\Psi\, K_s$ sin(2β)
  - Single dominant tree amplitude → no direct ~~CP~~
  - Indirect/time-dep. ~~CP~~ in B_s-mixing





$(\phi_s)_{SM} \cong -2\lambda^2\eta \cong -2^\circ$ (N_g^{eff}=2)

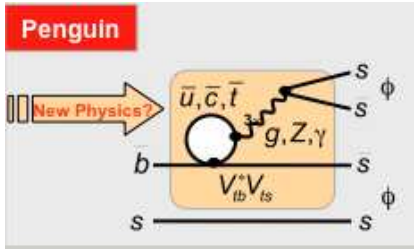
- Rate absence of strong phases (sake of simplicity) and for mixing parameters $|p/q|_s$=1

$$\Gamma(B_s(\bar{B}_s) \rightarrow f) \sim \cosh(\frac{\Delta\Gamma_s t}{2}) - \cos(\phi_s)\sinh(\frac{\Delta\Gamma_s t}{2}) \pm \sin(\phi_s)\sin(\Delta M_s t)\,,$$

Extract mixing phase (SM small) ϕ_s
Large phase unambiguous signal for new ~~CP~~ → 'rules out MFV'

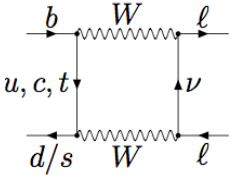
TeVatron results in puzzle section

- Alternatively: ϕ_s also be extracted from $B_s \rightarrow \phi\phi$
  Penguin affected by new physics

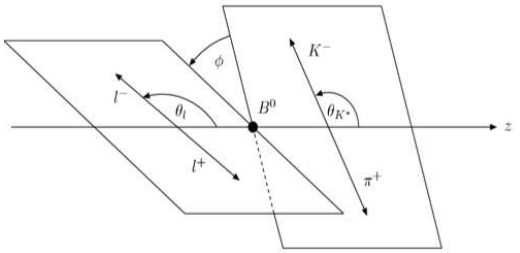


$B_d \rightarrow K^* \mu\mu$ Br ~ 3.5 10^{-9}

- The rate of $B \rightarrow K^* \gamma$ ($b \rightarrow s\gamma$) (prototype of FCNC) not show deviations from SM at B-factories Constrains penguin coefficient C_{7L}. *What about other Wilson coefficients?*
- $B \rightarrow K^* \mu\mu = B \rightarrow K^* (\gamma^* \rightarrow \mu\mu)$ +



+ angular variables

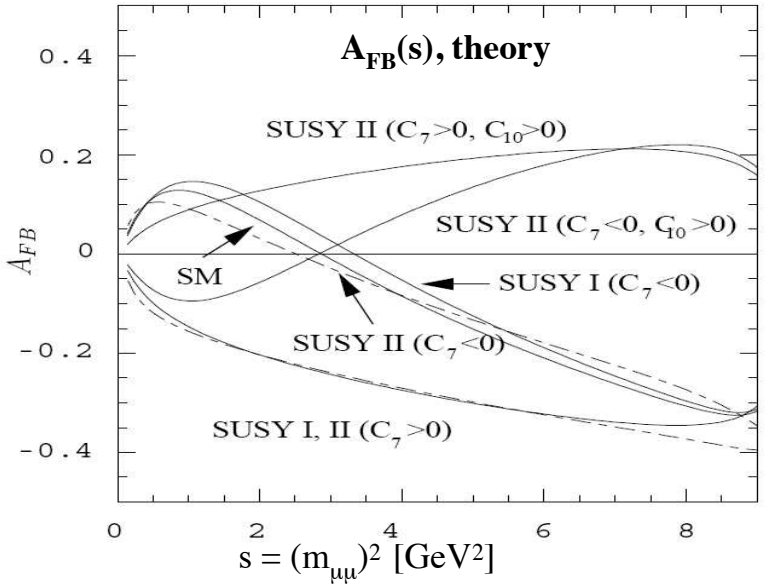


→ s,p,d-wave 1+3+5=9 angular amplitudes → many observables

a) Forward backward asymmetry

b) Angular distributions/ combine CP etc

c) Isospin

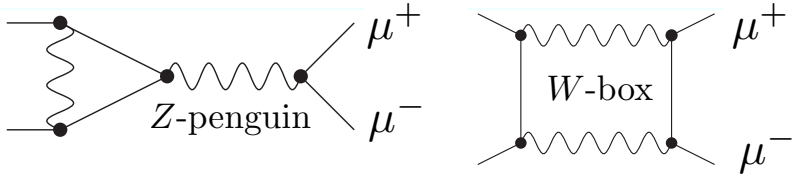


- Recall 4.4k per nominal year

$B_s \rightarrow \mu\mu$

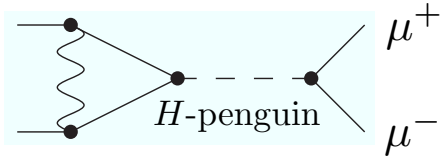
- Flavour changing neutral current Br ~ 3.5 10^{-9} -- TeVatron bound Br < 4.7 10^{-8}

  - The SM (Inami-Lim diagrams) rate is helicity suppressed



$$\sim \left(\frac{2m_\mu}{m_B}\right)^2$$

  - Can be relived in BSM e.g. MSSM $tg\beta^6$ Higgs-penguin

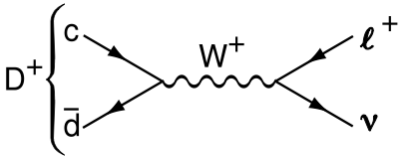


  - SM rate will be measured <2fb^{-1} **@LHCb**

  - Flavour brother $B_d \rightarrow \mu\mu$ double Cabibbo suppressed 1/25 (upgrade?)

The puzzles (not *(yet:)* at 5σ-significance)

$$\Gamma(D_s \to l\nu) \sim f_{D_s}^2 |G_F V_{cs} m_l|^2 \left(1 - \frac{m_l^2}{m_{D_s}^2}\right)^2$$

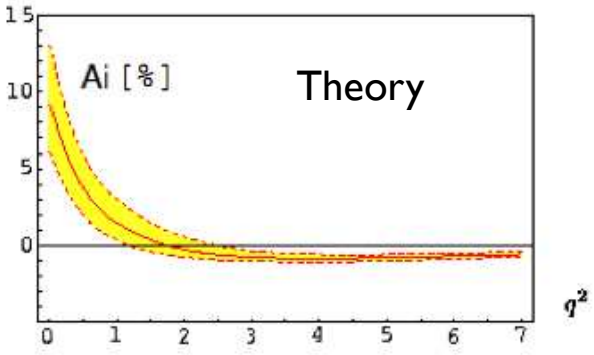


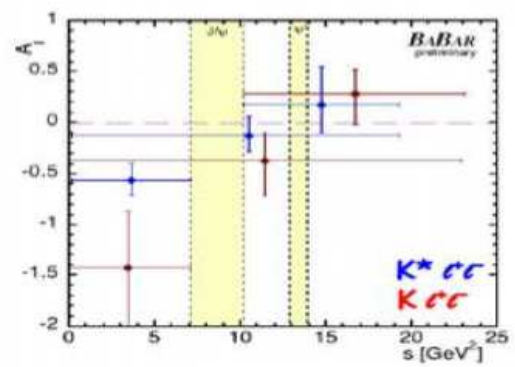
$|V_{cs}|_{CKM}$ & Cleo-BaBar-Belle rate average → $(f_{Ds})_{ex}$ vs $(f_{Ds})_{theory}$
New physics?: tree-level SM but helicity suppressed
could be relieved in BSM

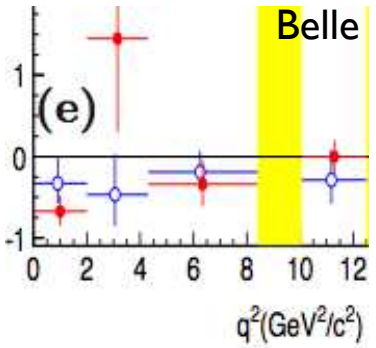
(f_{Ds} (New Belle-Cleo average'09) 270(8) still 3σ .....)

f_{Ds}	who
241(3)	HPQCD'08
249(11)	MILC'08
248(9)	ETMC'09
277(9)	Exp. Average

Isospin asymmetry in $B \to K^* ll$ in pictures .....
(@ **LHCb** 'moderate' improvement. .. neutral states in K^{*+} channel)

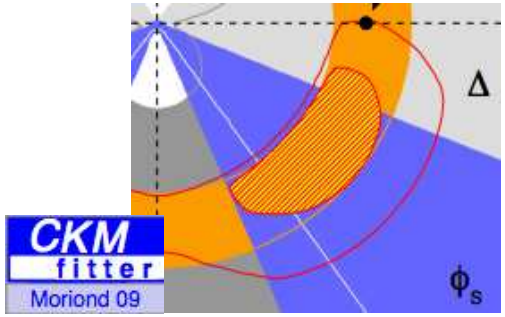






★ B_s-mixing: TeVatron $\phi_s = (\phi_s^{SM} \approx 2°) + 2\phi_{Bs}$

A. new source CP-violatn
B. $\delta\phi_s =$ *1° 2fb^{-1} @* ***LHCb***



	UT-fit (Bayesian)	CKM-fit (frequency)
ϕ_{Bs}	-19(8)° 2.1σ	picture 2.1σ

★ Revival of a B →Kπ puzzle

large difference

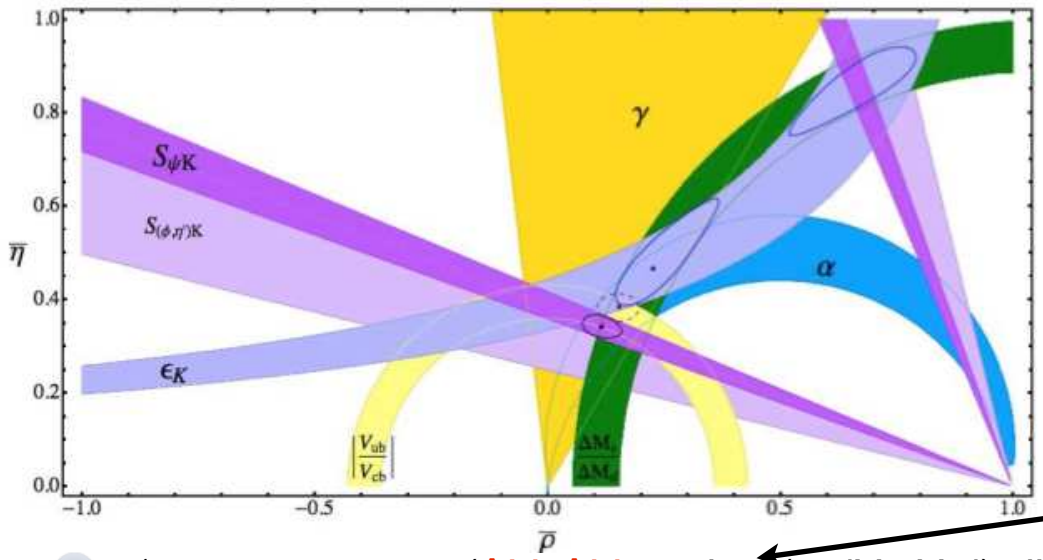
$$A_{\rm CP}(B^0 \to K^+\pi^-) = -0.097(12) \qquad A_{\rm CP}(B^+ \to K^+\pi^0) = 0.050(25)$$

- At first: Analysis of topologies (penguin, tree....) & information from BBNS factorization hints at something .... (Belle & BaBar have articles in Nature'08)
- Alternatively: Adjust strong phases (generally difficult to predict) to fit A_{CP} then time dependent CP $S_{K_S\pi^0}$ still shows 2σ discrepancy

Fleischer, Jager, Pirjol, Zupan

- Also within the CKM triangle there is tension

advocated by Lunghi & Soni



new lattice determination
RBC/UKQCD'07

- 4 parameters α ,γ, ($\Delta M_s/\Delta M_d$) and ε_K (or $|V_{ub}/V_{cb}|$) allow us to rebuild CKM triangle
  → compare with sin(2β) from 'gold-platted' B →J/Ψ K_s

Epilogue

- Did not talk about: a) helicity test in $B_s \to \phi\gamma$ (right handed currents)
  b) Small $\not{CP}$ D-decays GIM & Cabibbo^4 & loop suppressed - small CP-background - use "CPT filter"

- LHC(b) eagerly awaited for -- ϕ_s-puzzle

- The CKM and PMNS matrix are (so) non-random that
  it is hard to conceive that there is no theory of flavour.

- The connection between CKM and PMNS matrix with the Higgs mechanism makes
  it seem plausible that the theory(ies) behind it are connected with what is underneath the Higgs

- Where we are (reasonably) convinced that the LHC will uncover what unitarizes
  W_L-W_L scattering, we are not sure which experiments gets the first clue of BSM ...
  Hopefully both types will see something and benefit from each other ...

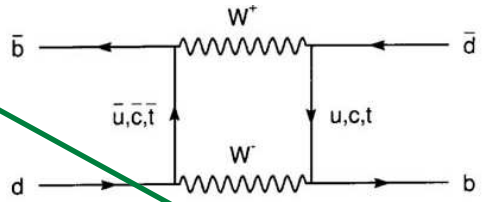
Thanks for you attention!

Backup Slides

Minimal Flavour Violation (MFV)

"flavour problem"

$$\Delta M_{B_d} \sim \frac{(V_{\rm tb}^* V_{\rm td})^2}{16\pi^2 M_W^2} + \frac{c_{NP}^{flavour}}{\Lambda_{NP}^2}$$



loop	MFV	$c_{NP}^{flavour} \sim$	Λ_{NP}	from
		1	$2 \cdot 10^4$ TeV	K_0
+		$\frac{1}{16\pi^2}$	$2 \cdot 10^3$ TeV	K_0
	+	$V_{\rm ti}^* V_{\rm tj}$	5 TeV	$K_0 + B_d$
+	+	$\frac{V_{\rm ti}^* V_{\rm tj}}{16\pi^2}$	0.5 TeV	$K_0 + B_d$

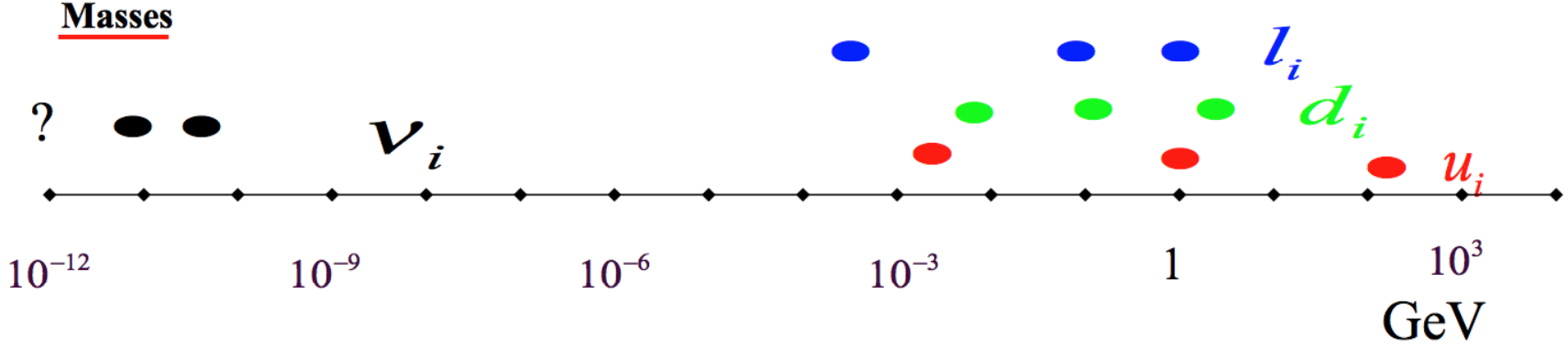
- cannot disentangle $c_{NP}^{flavour}$ from Λ_{NP}
- $\Lambda_{NP}^{natural} \sim 1$ TeV

$\Rightarrow$ MFV 'natural'

from G.Ross

DATA :

Masses



Mixing

Quarks

$$V_{CKM} \approx \begin{pmatrix} 1 & 0.218-0.224 & 0.002-0.005 \\ 0.218-0.224 & 1 & 0.032-0.048 \\ 0.004-0.015 & 0.03-0.048 & 1 \end{pmatrix}$$

Leptons

$$V_{MNS} = \begin{pmatrix} 0.79-0.88 & 0.48-0.61 & <0.2 \\ 0.27-0.49 & 0.45-0.71 & 0.52-0.82 \\ 0.28-0.5 & 0.51-0.65 & 0.57-0.81 \end{pmatrix}$$