B-theory: QCD@LHC

CP³ Origins
Cosmology & Particle Physics

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CENTRE FOR THEORETICAL PHYSICS · Higgs

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Overview

- 1. **Summary of essential** 12’

  [A] CKM and flavour **symmetry**

  [B] classification of modes & **dynamics**

  [C] **kinematics** angular distributions

- 2. **Current tensions (anomalies)** SM-status - prospects 16’

  [D] b →sll: angular (P_5’ etc) & lepton flavour violation R_K

  [E] B →$D^{(*)}$lν: l=e,μ vs **τ**

  [F] lV_{ub}l exclusive vs inclusive

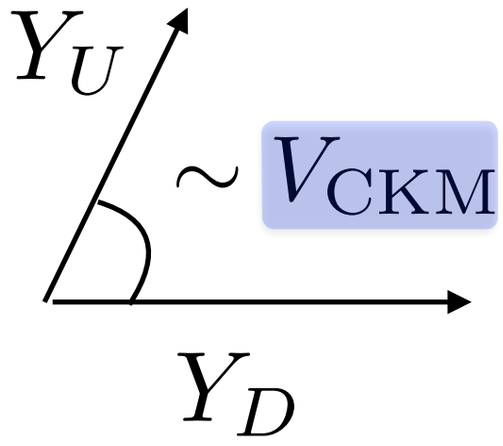
- 3. **Some popular recent BSM proposals** 2’

- **Summary**

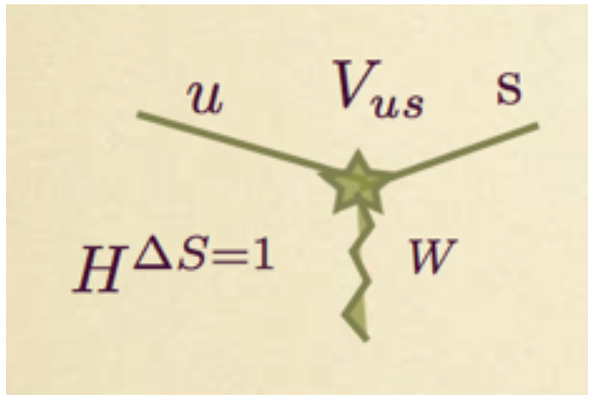
1.A CKM & flavour violation

SM: **Flavour violation** = CKM-mechanism

symbolically

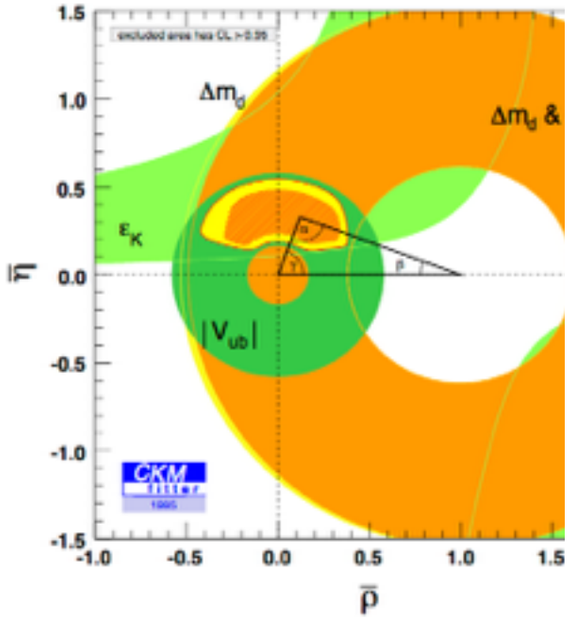


at short distances

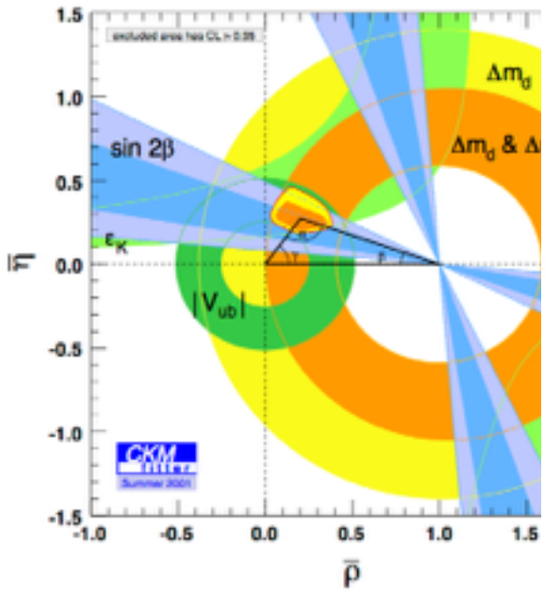


…. originates from misalignment of U,D-Yukawa matrices

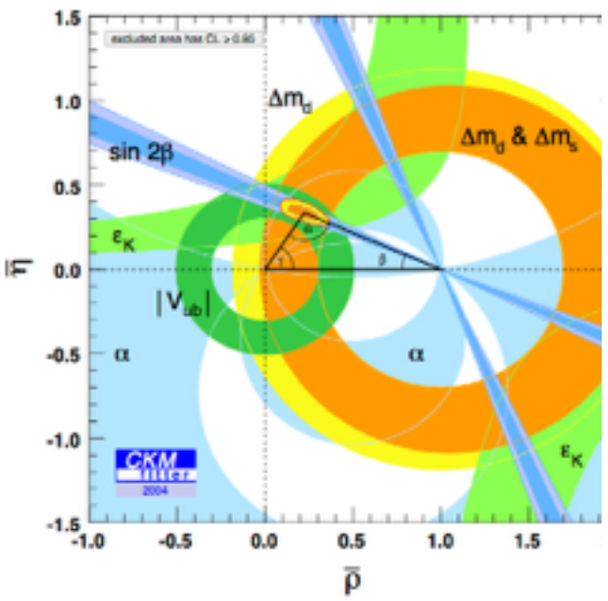
..and the CKM mechanism works better and ever better!



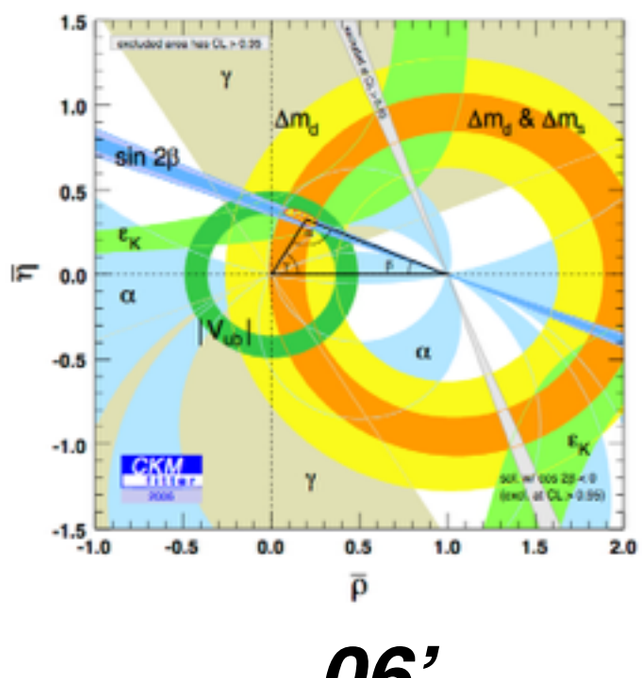
95' pre b-factory



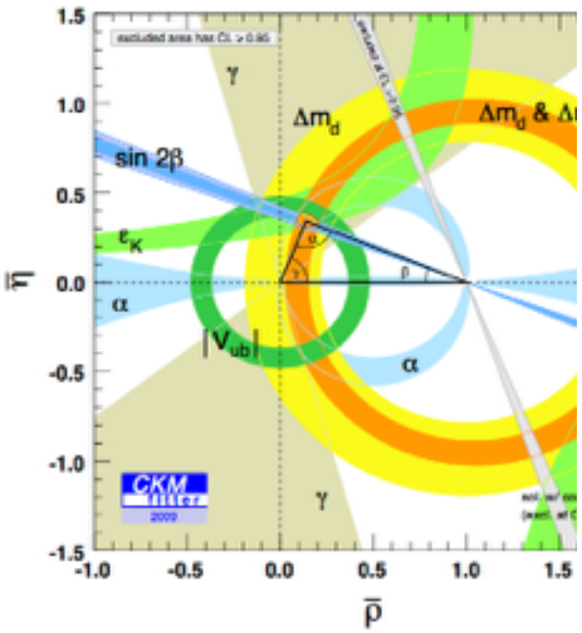
01'



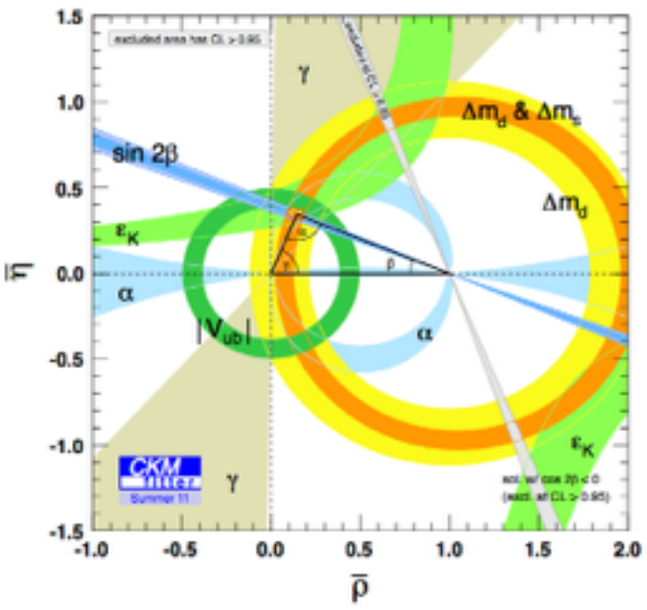
04'



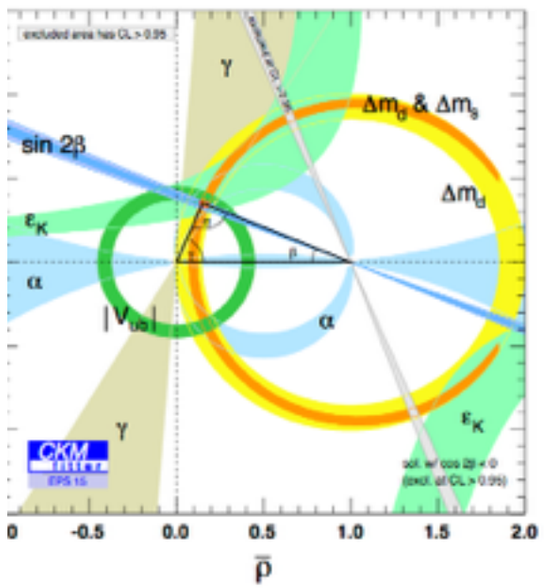
06'



09'



11'



15'

Area triangle = strength CP-violation
NB: ca 10^3 below max.

Note: here CKM-fitter also U-fit group

New flavour physics and generic flavour structure?

- Anarchic flavour O(1) Wilson coefficients
  → most severe **constraints** from **mixing** in Kaon sector

hadron	discovery	dim-6 operator	bound $\Lambda_{FV}/(10^3\text{TeV})$]
K_0	1964	$(\bar{s}d)_{\mathrm{V-A}}(\bar{s}d)_{\mathrm{V-A}}$ $(\Lambda_{FV})^{-2}$	1
B_0	1999	$(\bar{b}d)_{\mathrm{V-A}}(\bar{b}d)_{\mathrm{V-A}}$	0.4
B_s	2006	$(\bar{b}s)_{\mathrm{V-A}}(\bar{b}s)_{\mathrm{V-A}}$	0.07
D_0	2007	$(\bar{c}u)_{\mathrm{V-A}}(\bar{c}u)_{\mathrm{V-A}}$	1

⇒ new flavour better have a structure! (also more likely to explain old one)

Minimal flavour violation = all flavour violation due to Yukawa

Georgi, Chivukula'87

- **Yukawa** = 0 global symmetry: $G_F = U(3)^5 = G_q \times G_l$, $G_q = U(3)_Q \times U(3)_{UR} \times U(3)_{DR}$
  Yukawa ≠0 breaking down: $G_q = U(3)_q^3 \rightarrow U(1)_{Baryon}$

- Let **Yukawa** formally transform as $Y_D \sim (3^*,1,3)_{Gq}$ & $Y_U \sim (3^*,3,1)_{Gq}$

> **MFV** effective theory invariant under global G_F *
> *(criterion of naturalness applied coefficient O(1))*

D'Ambrosio,Giudice, Isidori, Strumia'02

- MFV is proposed principle but **not** a theory of flavour
  e.g. <Yukawa>= VEV ⇒ SSB G_F ⇒ **FC-goldstone bosons** ⇒ constraints

$\Lambda_{flavour} >> \Lambda_{EWSB}$ — ***susy-GUT***

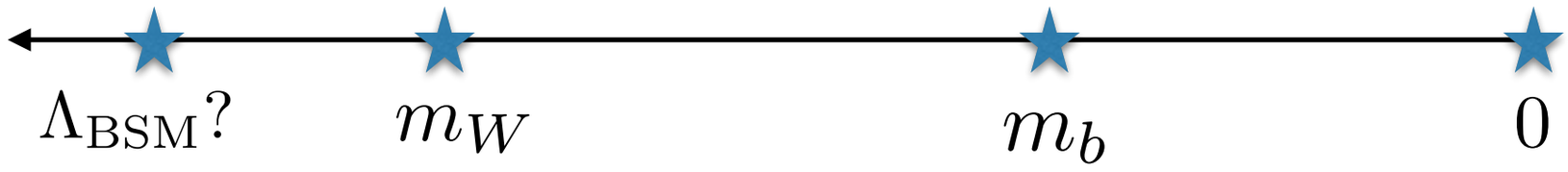
gauge G_F — Albrecht et al'09, Grinstein et al'09

discrete $G_F \subset U(3)^5$ — Fischbacher, RZ

1.B Dynamics

Make use of energy scales (eg. talk T.Becher)

energy

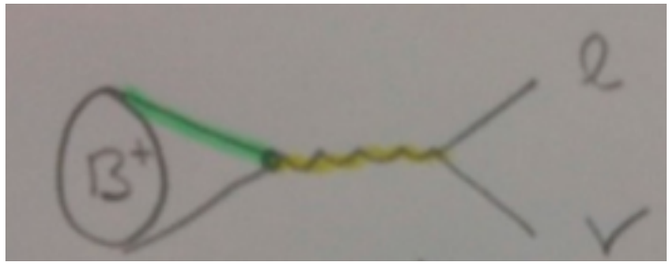
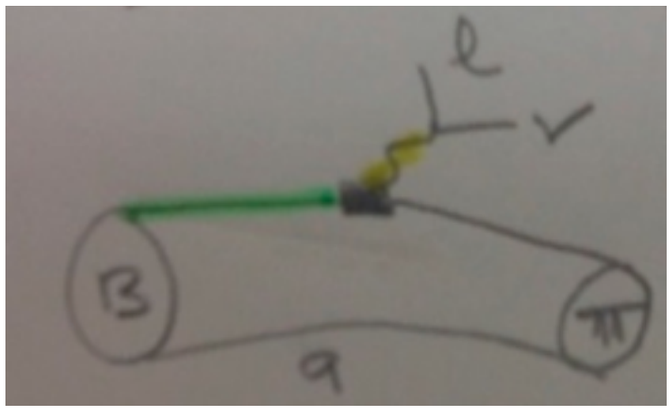
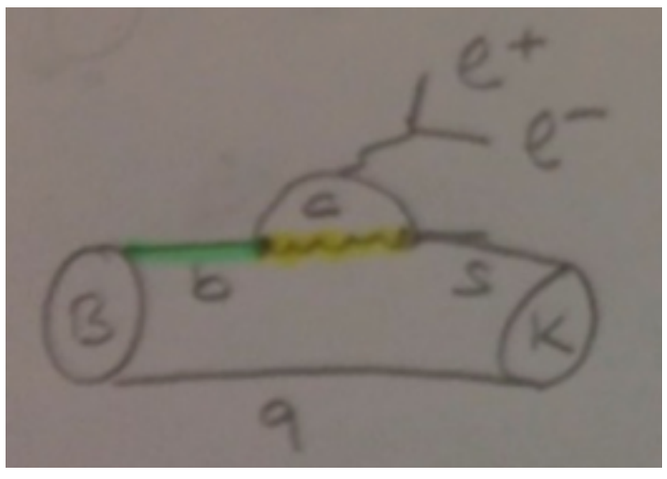
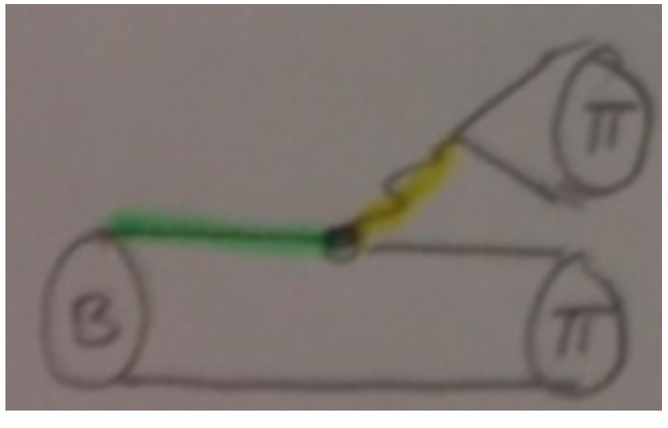


amplitude $\mathcal{A} = \langle XYZ|H_{\rm eff}|B\rangle = \sum_i C_i(m_b)\langle XYZ|\ \underbrace{O_i(m_b)}_{\bar{q}_1\Gamma_1 q_2\,\bar{b}\Gamma_2 q_3}\ |B\rangle$

perturb. calculable
Wilson coefficient
UV physics (BSM?)

M-element
IR physics (**non-perturbative**)

→ decays classified according to final state XYZ

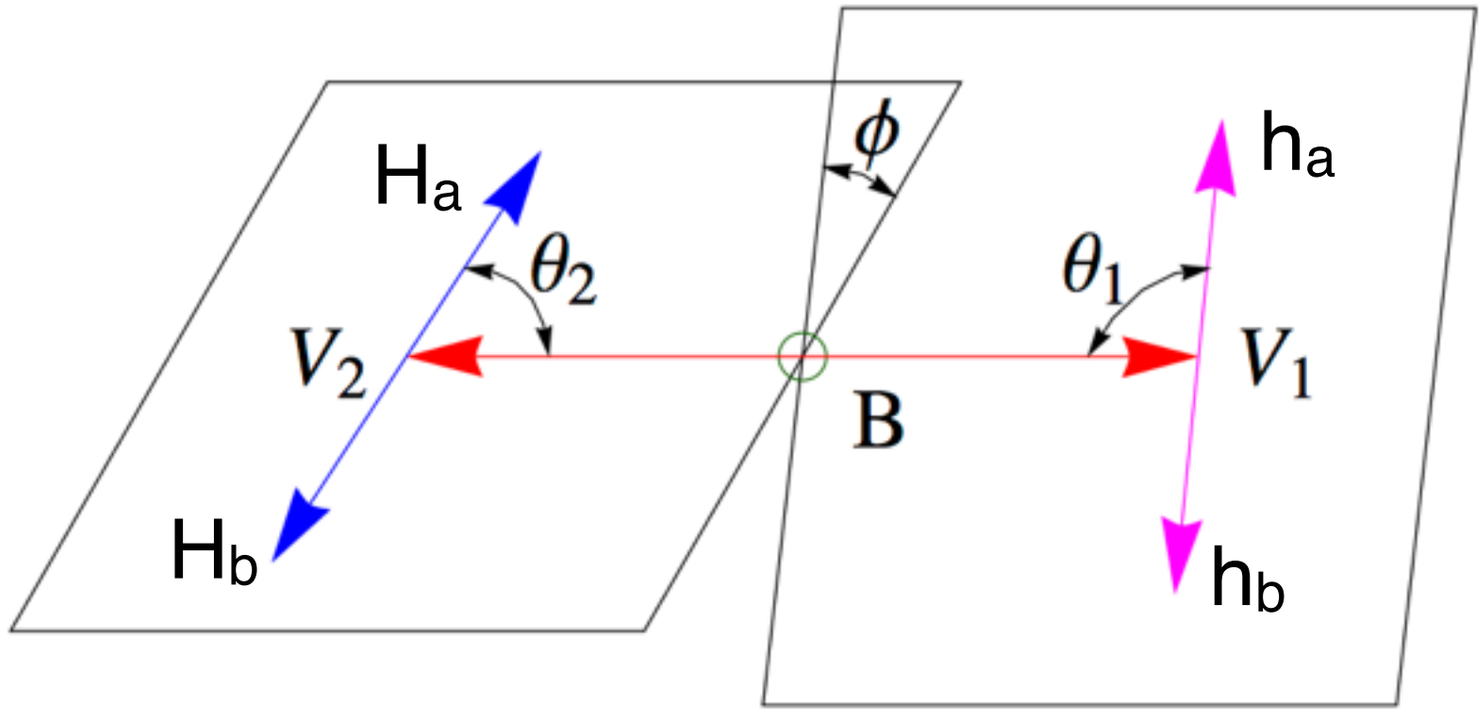
final hadrons	type	topology (example)	theory	methods
0	**leptonic**		decay constant f_B	lattice sum rules (SR)
1	**semi-leptonic**		form factors $f_{+,0}(q^2)$	lattice, slow π LCSR, fast π
	radiative FCNC		form factors LD multi-hadrons resonance	***duality*** QCDF LCSR Breit-Wigner
≥2	**non-leptonic**		factorisation (fast pions) pb: FSI size of Λ/m_b	QCDF: $1/m_b$ SCET: $1/m_b$ LCSR

difficulty theory

1.C Angular kinematics

angular distributions give information on spin of particles and interactions

- Any B →$H_aH_bh_ah_b$ (1 →4) decay described by 3 helicity-angles*



high degree of complexity

- decay sequential simplifies e.g. H → Z(→ll) Z^*(→ll)
  Use Jacob-Wick formalism [Wigner matrices] few partial waves contribute to decay distribution e.g. Bolognesi et al'12

few terms

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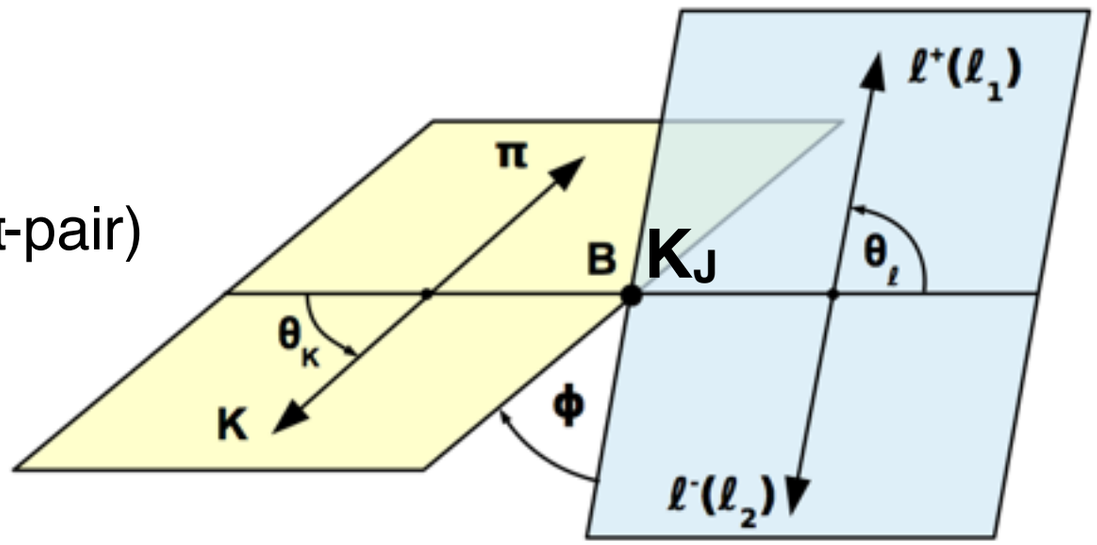
*3 angles simply complete set (of fcts)

Jacob-Wick formalism for effective theories

Gratrex. Hopfer, RZ'15

- $B \to K_J(\to K\pi)ll$ somewhere in between *(later for anomalies)*



- Heff of dim=6 with 10 operators

$$H^{\rm eff} = -\frac{4G_F}{\sqrt{2}}\frac{\alpha}{4\pi}V_{ts}V_{tb}^*\sum_{i=V,A,S,P,\mathcal{T}}(C_iO_i + C_i'O_i')\,.$$

$$O_{S(P)} = \bar{s}_L b\;\bar{\ell}(\gamma_5)\ell\,, \qquad O_{V(A)} = \bar{s}_L\gamma^\mu b\;\bar{\ell}\gamma_\mu(\gamma_5)\ell$$

$$O_{\mathcal{T}} = \bar{s}_L\sigma^{\mu\nu}b\;\bar{\ell}\sigma_{\mu\nu}\ell\,, \qquad O' = O|_{s_L\to s_R}$$

S- and **P-wave**

$$\frac{d^4\Gamma}{dq^2\,d\cos\theta_\ell\,d\cos\theta_K\,d\phi} = \sum_{m,l_l=0..2,l_K=0..J_K}\underbrace{G_m^{l_k,l_l}}_{|\mathcal{A}_{S,P}|^2}Y_{l_k}(\theta_K,\phi)Y_{l_l,m}(\theta_l,0)$$

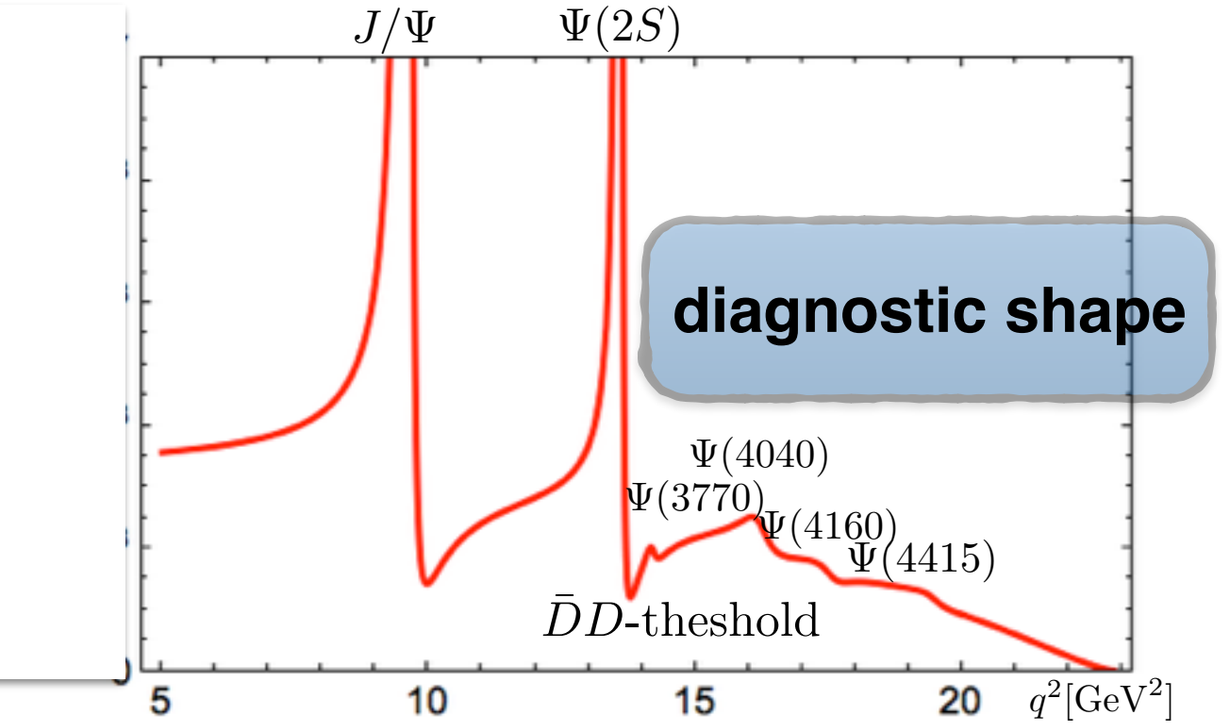
12-terms known for some time

2 Current tensions (anomalies) in B-physics with the SM

2.1 Basics $B \to K^*(\to K\pi)$ & P_5'

Recall

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \sum_{m,l_l=0..2,l_K=0..J_K} \underbrace{G_m^{l_k,l_l}}_{|\mathcal{A}_{S,P}|^2} Y_{l_k}(\theta_K,\phi) Y_{l_l,m}(\theta_l,0)$$

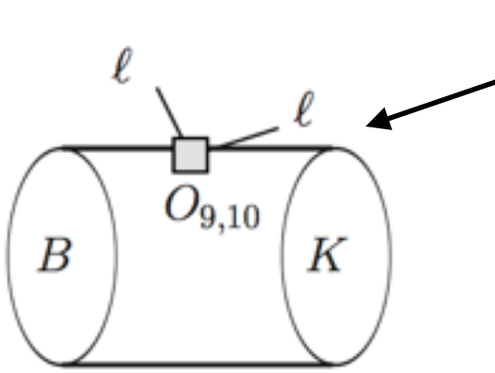


diagnostic shape

K **fast**:
- **light-cone** methods
LCSR, QCDF/SCET

K **slow**:
- high-q² **"OPE"**
-**endpoint relations**

Dynamics: interference of

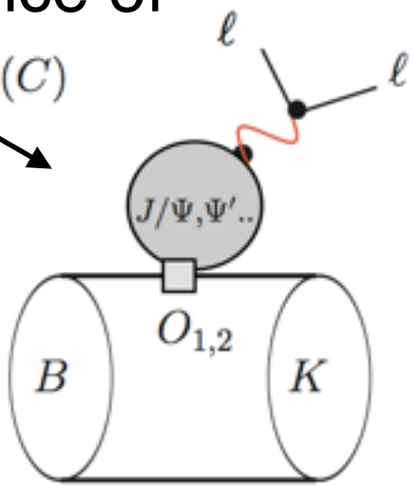


short-distance
form factor

$$\langle K^{(*)}|(\bar{b}s)_{V-A}|B\rangle = \sum_{pol} P_{pol}\, f_{pol}(q^2)$$

relatively well-known
LCSR, SCET,
Large energy limit

(C)



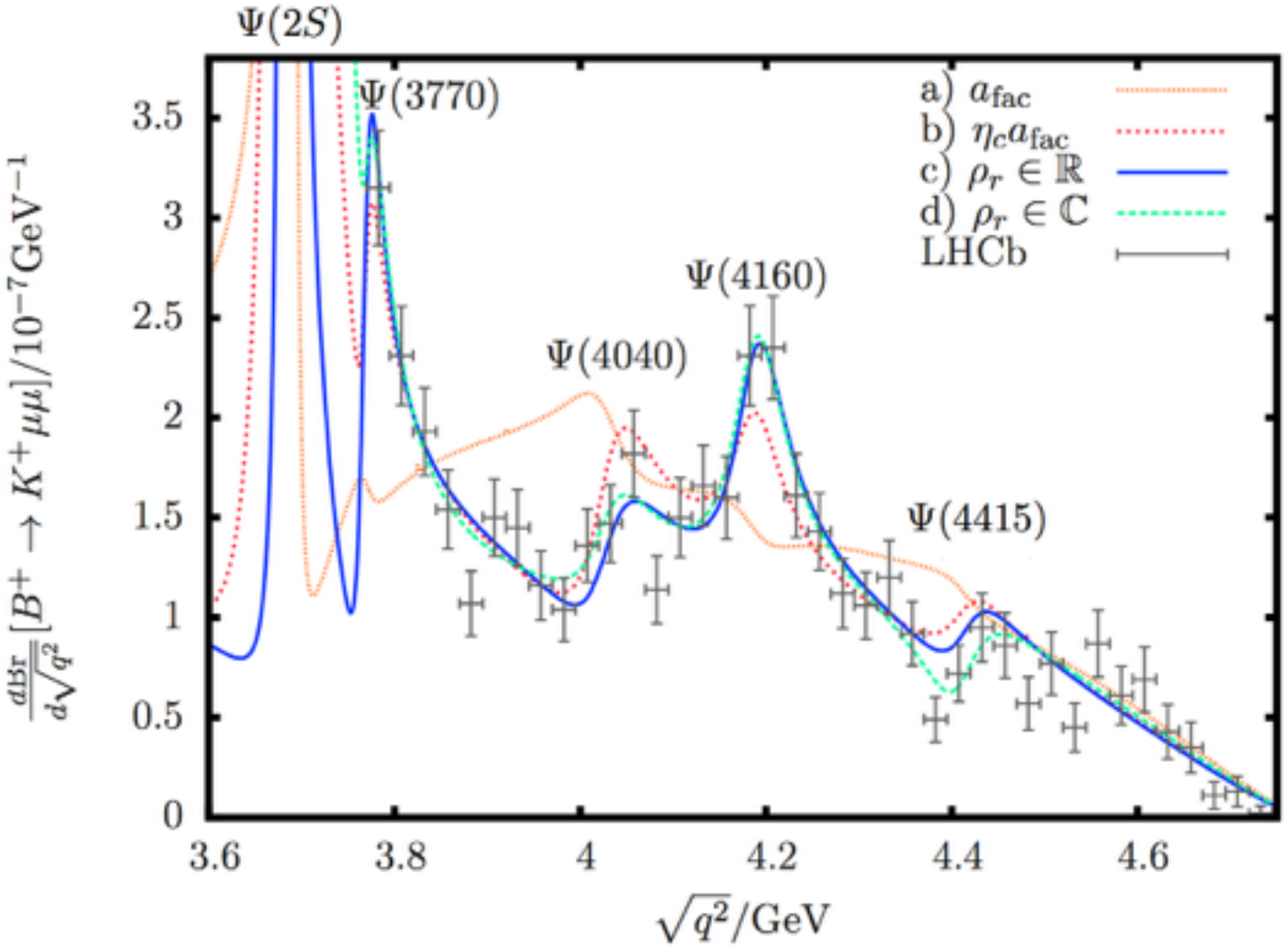
long-distance
e.g. charmonium
resonances
non-local effects

model
Breit-Wigner
good if fits spectrum

- first principles: Breit-Wigner **residues** related to amplitudes

$$\mathcal{A}(B \to K\ell\ell)|_{q^2 \simeq m_\Psi^2} = \frac{\mathcal{A}(B \to \Psi K)\mathcal{A}^*(\Psi \to \ell\ell)}{q^2 - m_\Psi^2 + i m_\Psi \Gamma_\Psi} + ..$$

Lyon, RZ '14 fit to LHCb data **broad** charmonium resonances



results:

- residues large and opposite in phase to what people used to use for estimates (pQCD or e^+e^- -> hadrons)

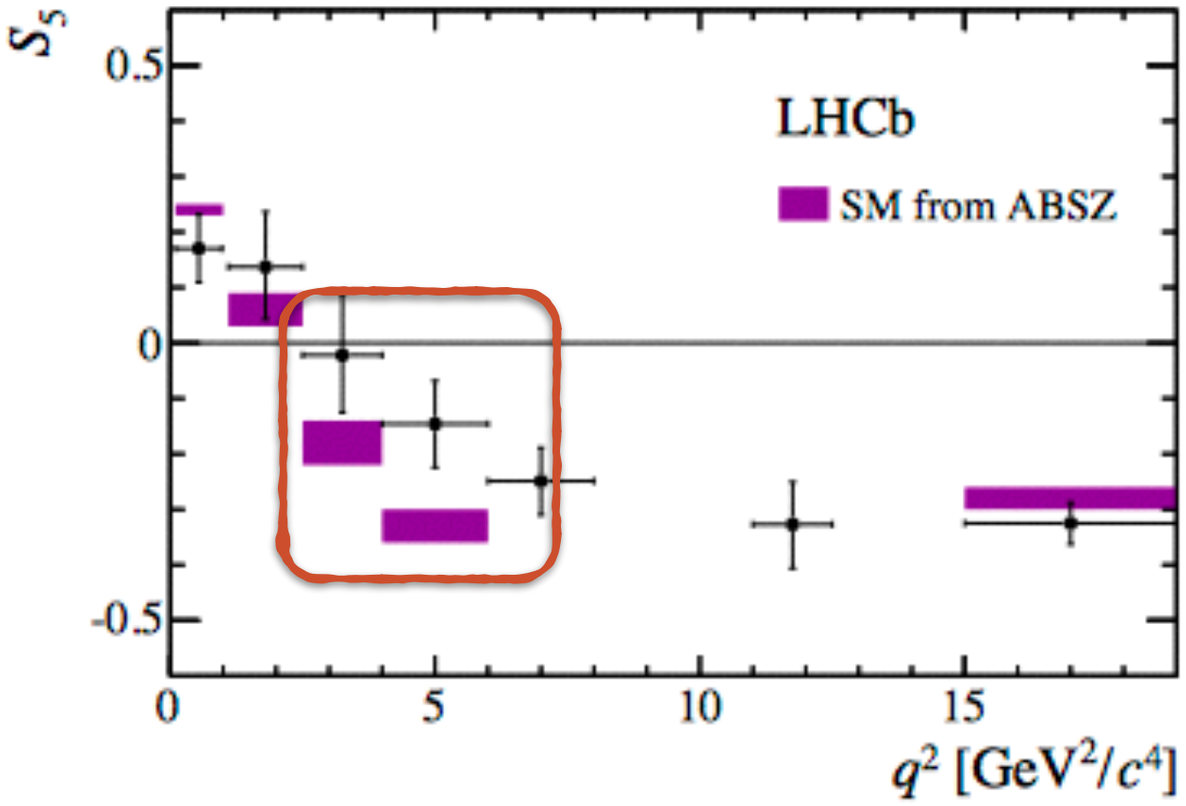
- need to measure phase of narrow J/Ψ, Ψ(2S)-resonance since most important for low q^2-spectrum [⇒ ongoing LHCb-analysis]

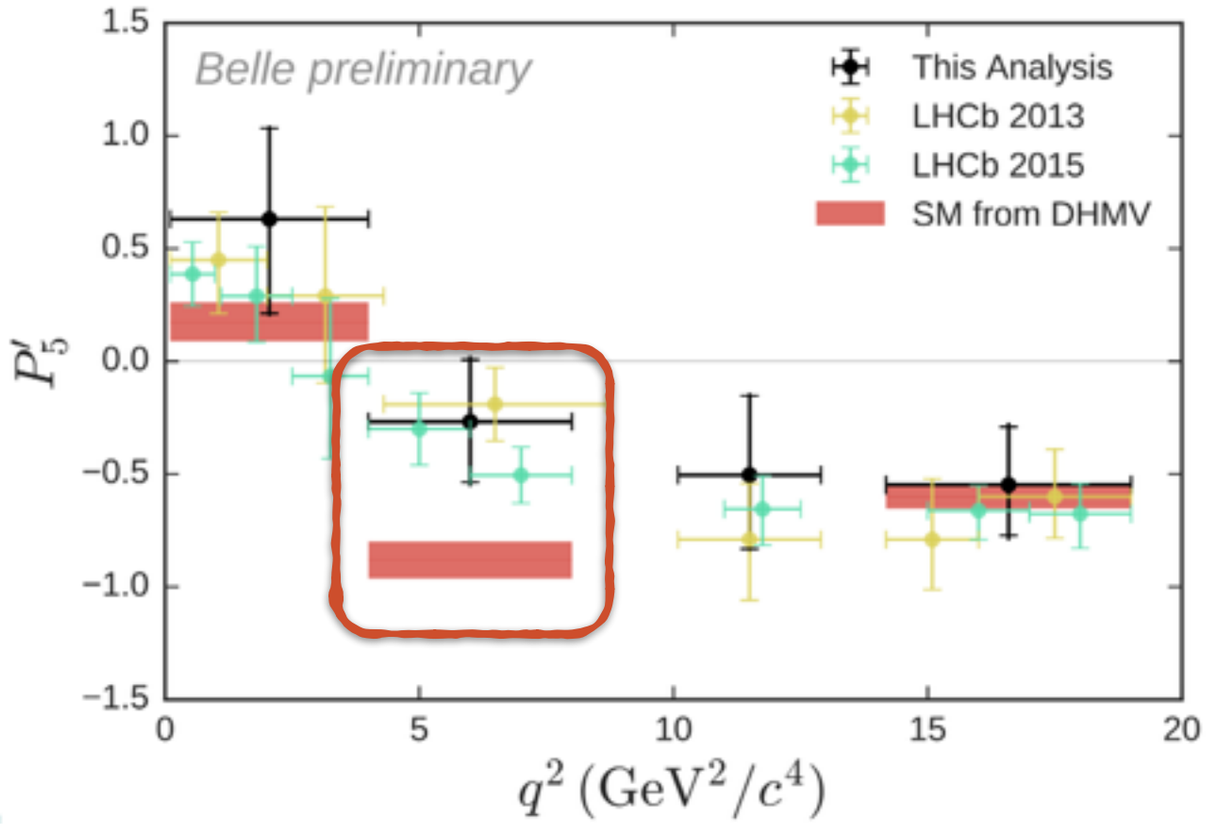
global fits

Several groups Altmanshofer, Straub || Descotes et al || Bobeth et al || Hurth et al doing **global fits** to 12 angular observables in B->K*ll and other modes finding **3-5σ deviations** to the SM. Shifts in the amplitudes with charm quantum numbers can accommodate anomaly

- Some people think its new physics some not - personally I would like to see:
  a) more of the **q^2-spectrum** (fine binning)
  b)measurement of charmonium phases

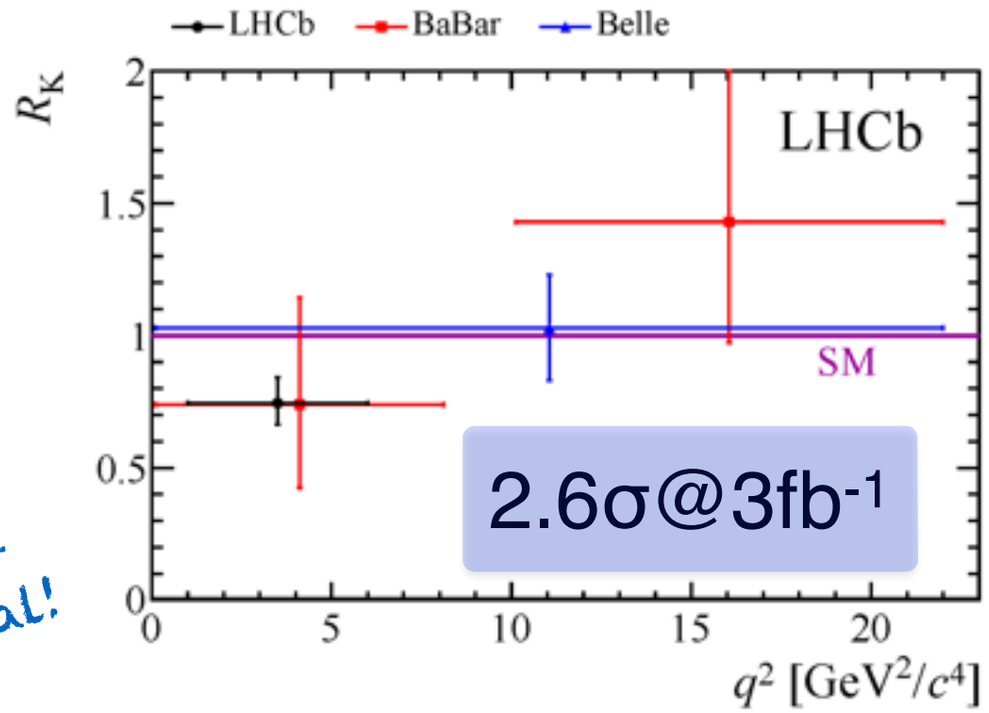
- Note added: $P_{5'} \sim \mathrm{Re}[G_1^{21}]$ one angular observable which makes deviation apparent. Designed to minimise form factor impact. Yet with correlations of of form factors this does not (really) matter anymore





R_K Lepton-flavour universality

$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} \qquad R_K|_{\rm SM} \simeq 1$$



- hadronic effects cancel
- BSM? more sbee than sbμμ *would be sensational!*
- SM-corrections: - phase space (tiny)
  - QED $\sim \alpha \ln^2\left(\frac{m_e}{m_\mu}\right)$ O(few%) - unknown at time

QED no factorisation → all partial waves!
estimate QED effect from D,F,..-waves

Gratrex. Hopfer, RZ'15 [ongoing LHCb analysis]

computation largest logs
effect up to 10% in principle
but with **cuts** & **PHOTOS**
net effect: **1%**

Bordone, Isidori, Pattori'16

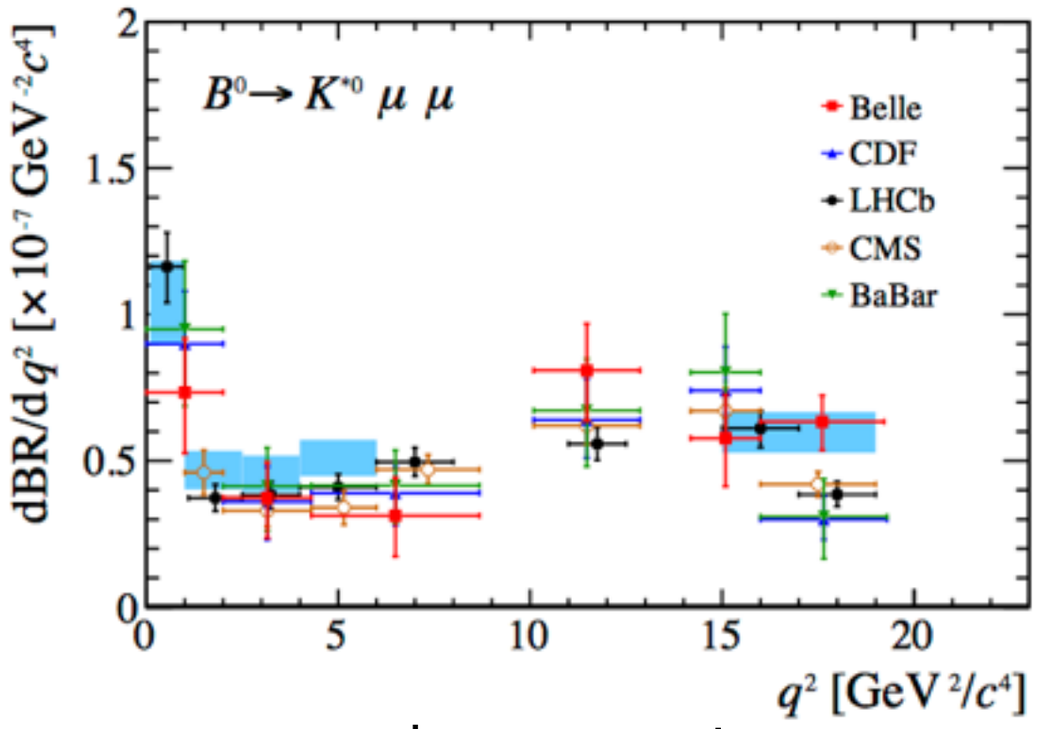
$B_s \to \phi$ vs $B \to K^*$ tension

- at $q^2=0$ to photons

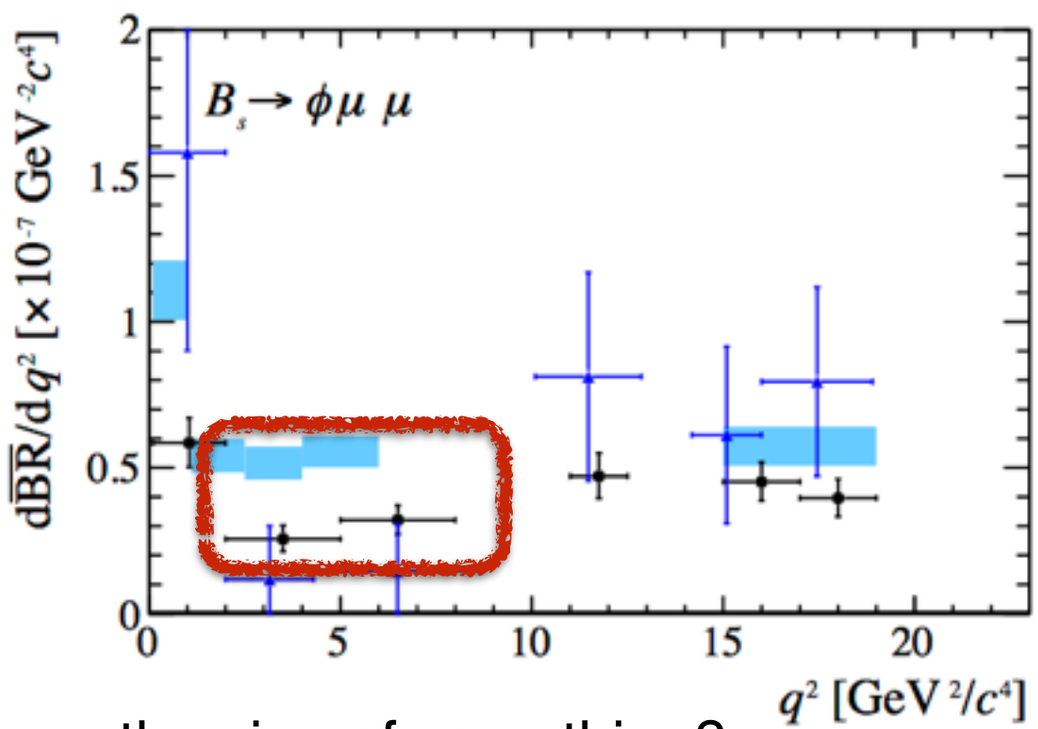
$$R^{(\gamma)}_{K^*\phi} \equiv \frac{\mathrm{BR}(B^0 \to K^{*0}\gamma)}{\mathrm{BR}(B_s \to \phi\gamma)}$$

Lyon, RZ '13 $0.78(18)$ LHCb '12 1202.6267 $1.23(32)$

- $B \to V ll$ look at q^2-spectrum

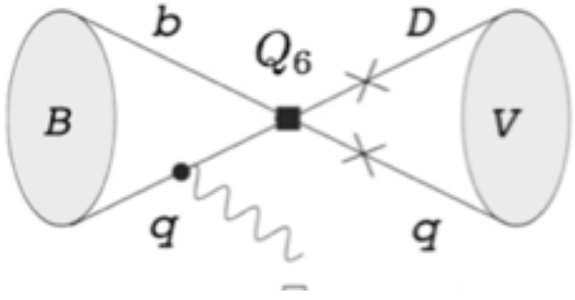


good agreement



the sign of something?

origin of differences?



- lifetimes (effect small)
- weak annihilation taken from Lyon, RZ '13
- form factors Bharucha,Straub,RZ '15
  normalisation experimental decay constants..

Tensions in tree-level decays!
(no sizeable long distance contamination!)

2.B $|V_{ub}|$ exclusive vs inclusive/ B→V form factors test

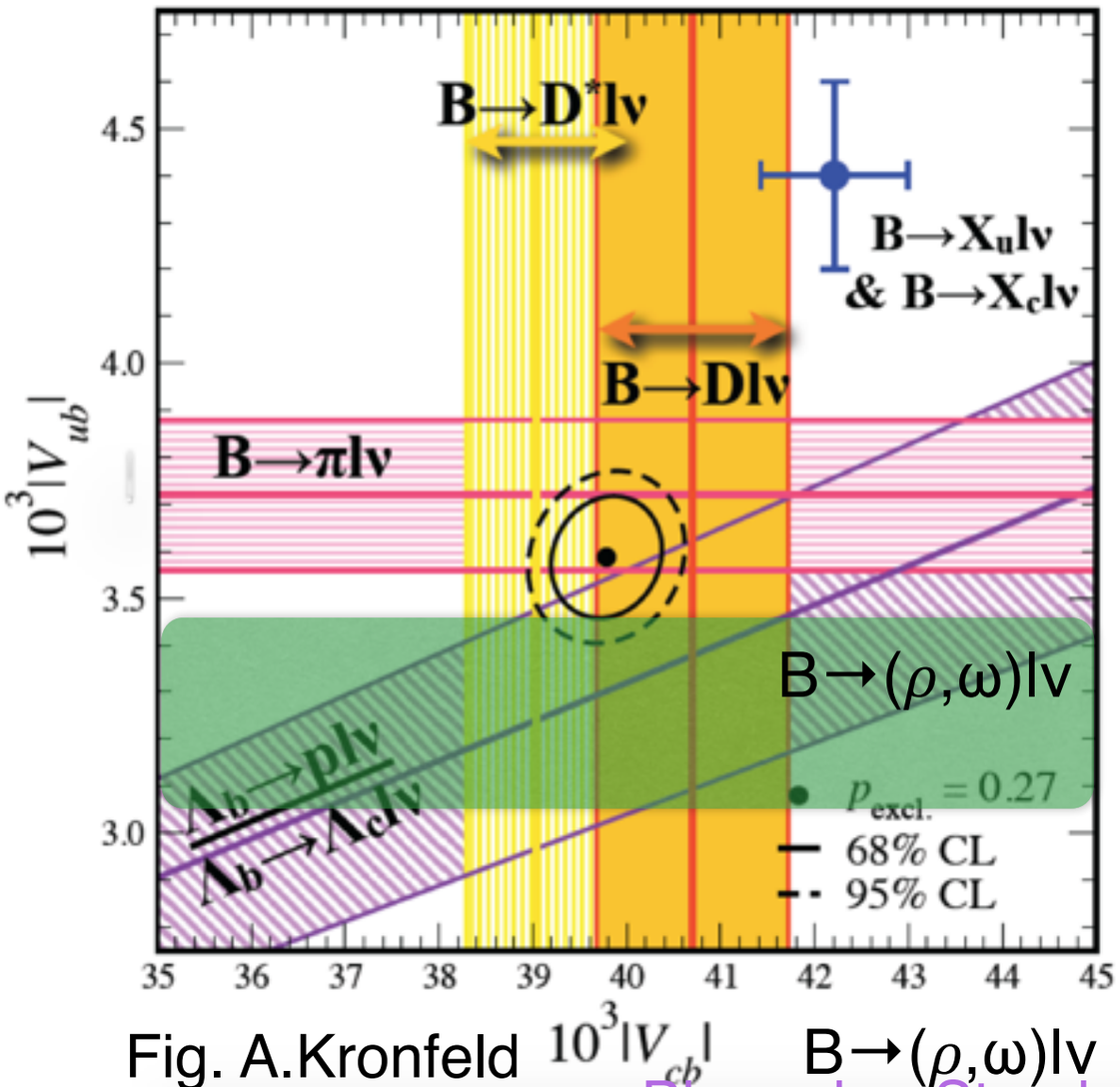


Fig. A.Kronfeld B→(ρ,ω)lν

Bharucha, Straub, RZ '15

global CKM-fits

$$|V_{ub}|_{\text{CKMfitter}} = \left(3.44^{+0.25}_{-0.08}\right) \times 10^{-3}$$

$$|V_{ub}|_{\text{UTfit}} = (3.61 \pm 0.12) \times 10^{-3}$$

fit LCSR,lattice to Belle,Babar

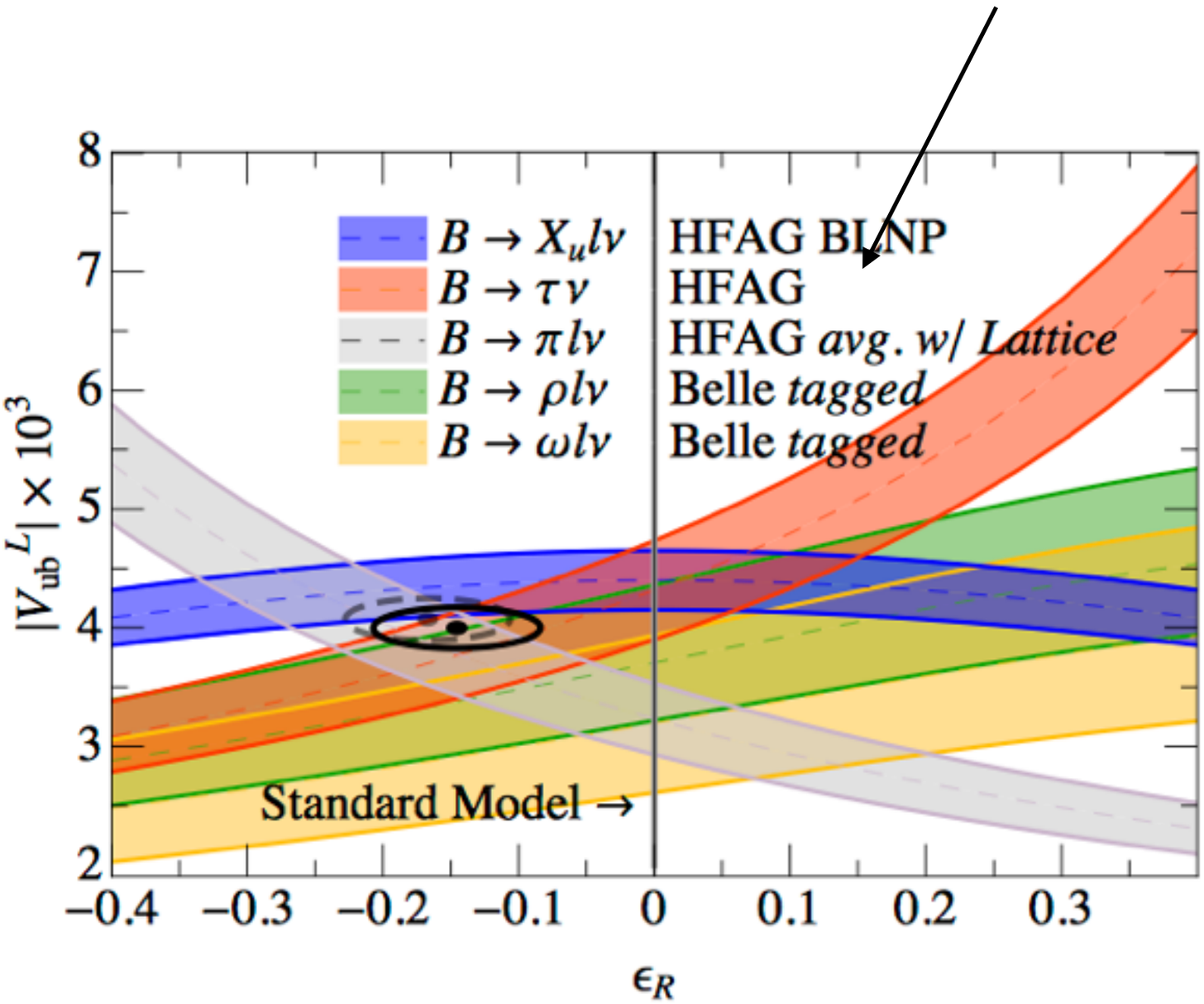
$$|V_{ub}|^{B\to\pi\ell\nu} = (3.41 \pm 0.22) \times 10^{-3}$$

inclusive

$$|V_{ub}|^{\text{incl.}} = \left(4.41 \pm 15^{+15}_{-17}\right) \times 10^{-3}$$

- roughly: 3 exclusive channels around 3.5(2)x10^{-3} vs inclusive 4.4(2) x10^{-3}
- 3 channels put pressure on inclusive result (theory? experiment?)
- B→(ρ,ω) form factors look ok B_s→ϕ vs B→K* tension

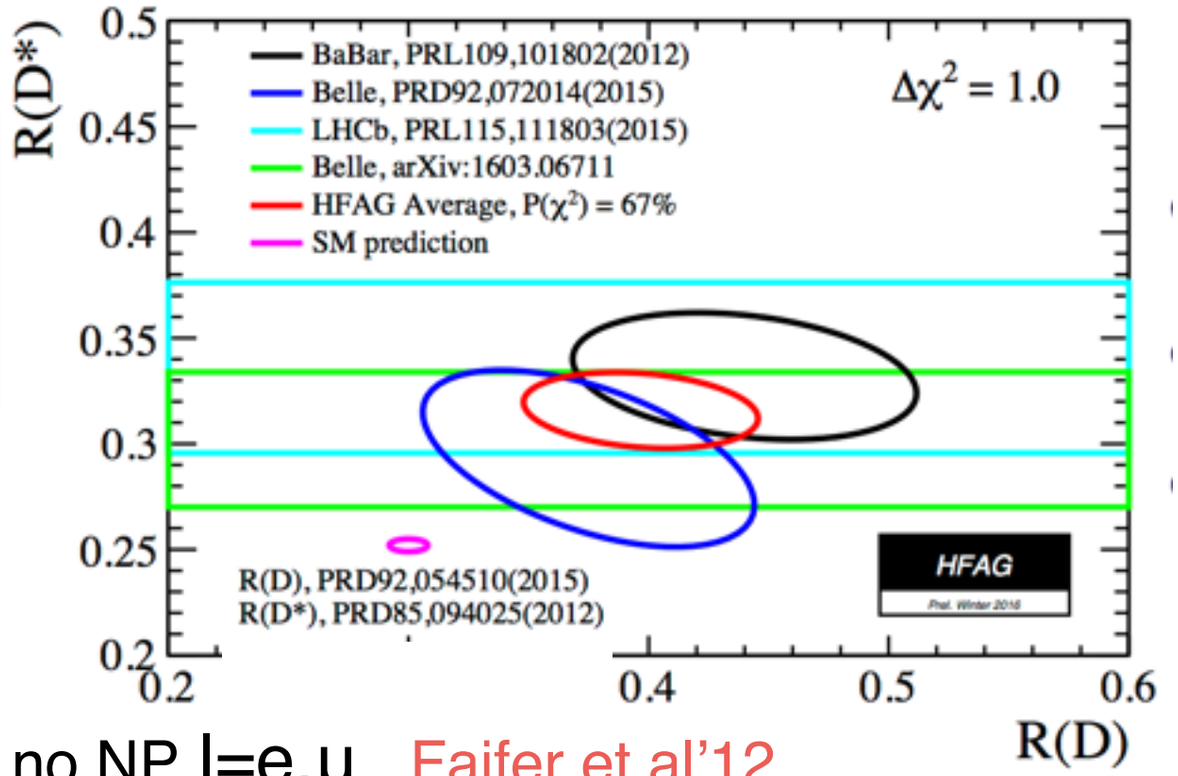
- BSM: right-handed currents Crivellin'09
- Diagnosing better via angular distribution Bernlocher,Ligeti, Turczek'14



- Word of caution:
  $\Lambda_b \to$ plv from LHCb from '15 does not support right handed currents
  (not exclude them either)

2.C Tensions in B→D$^{(*)}$lν in lepton universality

$$R_{D^{(*)}} = \frac{BF(B \to D^{(*)}\tau\nu)}{BF(B \to D^{(*)}\ell\nu)}$$
$$\ell = e, \mu$$



- SM: S,P wave form factors
  R_D lattice HPQCD Na el'15
  R_{D^*} using Caprini et al'97 assume no NP l=e,μ Fajfer et al'12
- Good: BelleII@50/ab competitive with theory error
- Yet: **τ** difficult particle …

$$BF(B \to X_c\tau\nu) = \begin{cases} 2.42(06) \cdot 10^{-2} & \text{Ligeti, Tackman(theory)} \\ 2.41(23) \cdot 10^{-2} & \text{LEP(experiment)} \end{cases}$$

$$BF(B \to D\tau\nu) + BF(B \to D^*\tau\nu) = \begin{cases} Kamenik, Fajfer'12 & BaBar'12, LHCb'15 & Belle'15 \\ 2.01(7) \cdot 10^{-2} & 2.78(25) \cdot 10^{-2} & 2.39(32) \cdot 10^{-2} \end{cases}$$

looks like two modes experimentally saturate inclusive rate …

3. BSM-activity

Crivellin, d'Ambrosio, Jung, Gauld, Haisch, Cellis, Martin, Hofer, Straub, Gori, Altmanshofer, Hiller, Kamenik, Becirevic, Fajifer, Buras, Neubert, Bauer, Isidori, Buttazzo, Greillo, …

some activity at explaining several anomalies within one model ….

one may distinguish 3 different level of approaches

effective Lagrangian
write down operators
and **fit**

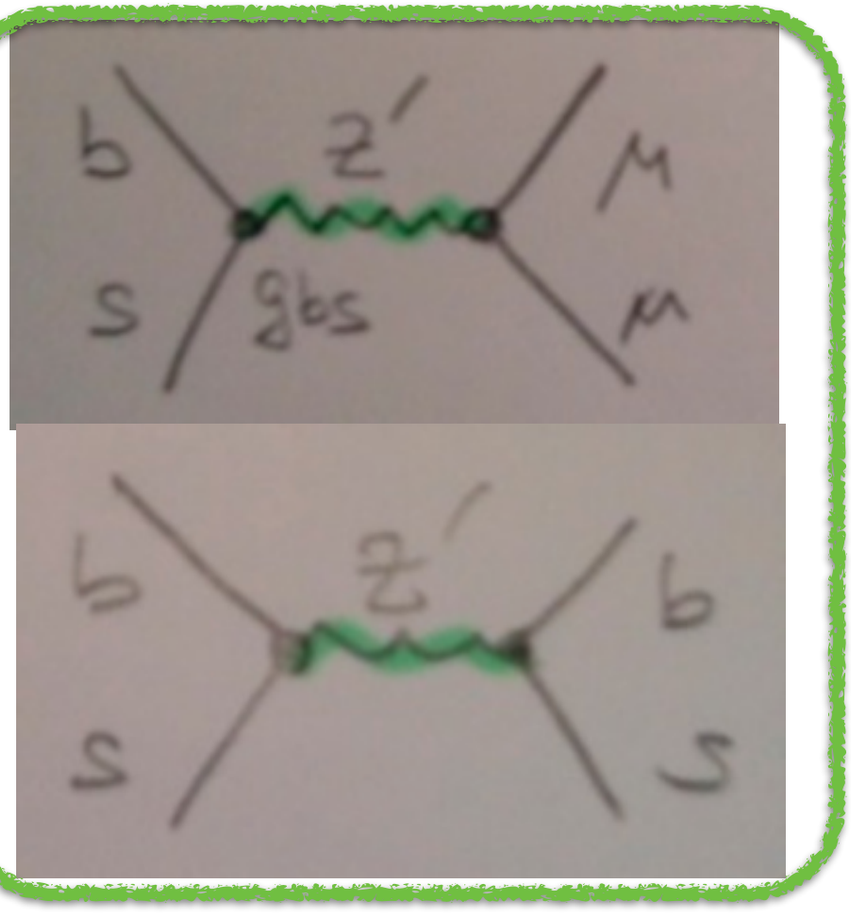
new mediator
=new particle

UV-complete models

specific operator

new mediators (model prototypes)

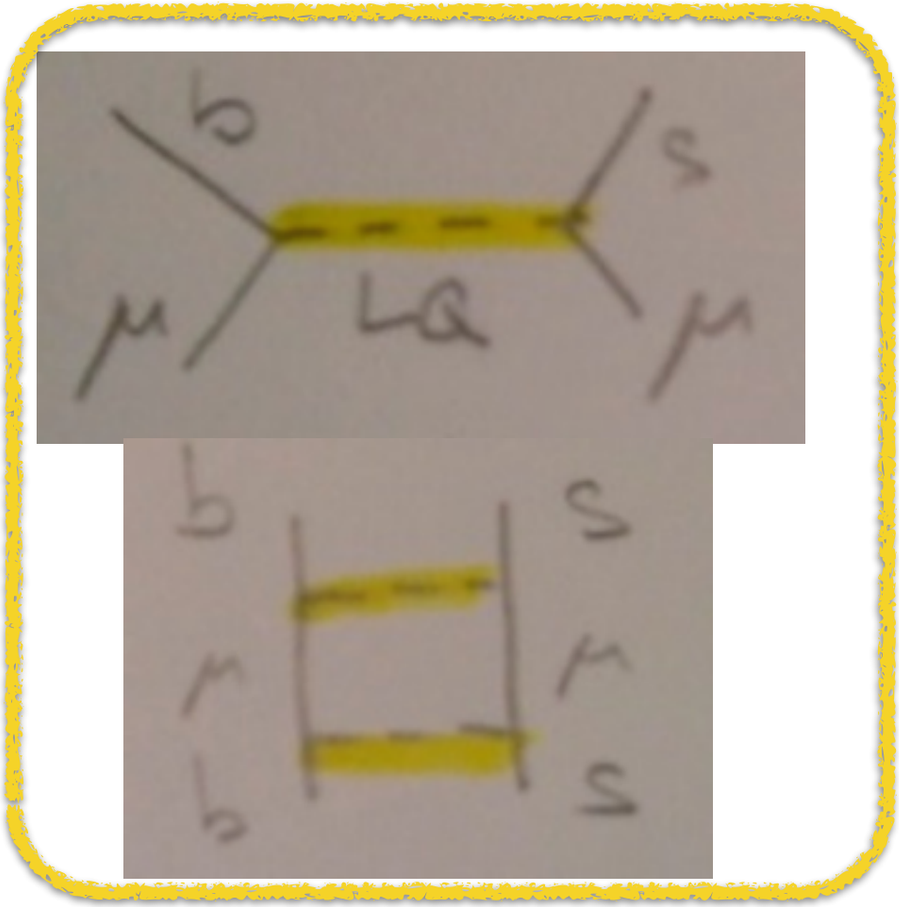
Z': e.g. 3-3-1 model

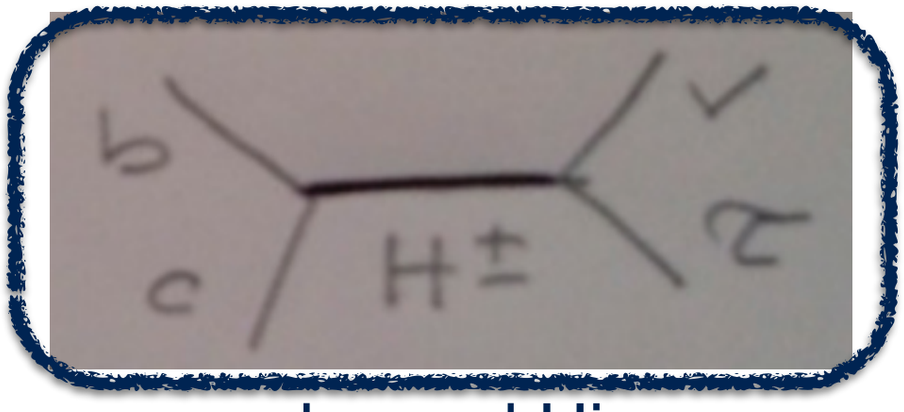


$\frac{g_{bs}g'}{m^2_{Z'}}$ b→sll more bsμμ

$\frac{g^2_{bs}}{m^2_{Z'}}$ B_s-mixing

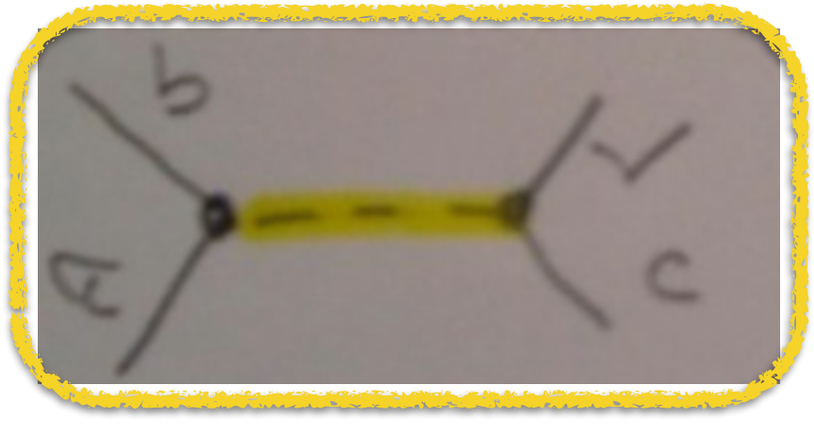
Leptoquarks





charged Higgs

R_{D^*}: b→cτν



- b→u no LFV - right-handed currents can make modes agree (if necessary)

discussion & conclusions

interesting anomalies 2-4σ anomalies
good news: will know more in the foreseeable future

- **Lepton flavour violation**:
  1) R_K: R_{K^*} LHCb (Oct), R_Λ?
     ultimately R_K etc BelleII (better suited FS-electrons)
  2) $R_D^{(*)}$: theory: more lattice B→D form factors
     exp. BelleII (competitive with theory error)

- **Angular anomalies b->sll**:
  1) more q^2-bins also in fast recoil
  2) need to know residues of charmonium resonances
     [awaiting LHCb-analysis]
  3) close interaction between experiment and theory needed

- **b->ulv** redo inclusive analyse at BelleII

some of my personal impressions

apologies for all topics not covered –