Flavor and Precision

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Introduction

Flavor (at least this talk):

$\boxed{\text{Properties of elementary particles that contain strange, charm or bottom quarks, i.e., different } \textit{flavors}}$

Particularly interested in (at least this talk):

$\boxed{\text{Transitions that change flavor}}$

Flavor?: In the absence of weak interactions
(in the SM context: in the limit $g_2 = 0$)
there is a conserved quantum number for each of *u, d, s, c, b, t*

$$U(1)_u \times U(1)_d \times U(1)_s \times U(1)_c \times U(1)_b \times U(1)_t$$

This is a sufficiently good symmetry that we can classify teh spectrum of elementary particles by it – approximately.

It is sufficiently good because the weak interactions are weak.

Weak interactions are weak not because g_2 is small
but because the mediators, W and Z, are heavy compared to $m_u < ... < m_b$

Top is heavy: weak interactions are not weak

Flavor of *top* is still flavor and interesting, but not part of this talk

Weak interaction rates are weak: suppressed by at least

$$\left(g_2 \frac{E}{M_W}\right)^4 \lesssim G_F^2 m_b^4 \sim 10^{-7}$$

Excellent approximation: lowest order perturbation theory in weak interatcions

EFT - Effective Field Theory

Hierarchy of scales $E \ll M_W \ll \Lambda_{NP}$

Assume New Physics (NP) is "heavy" and separates: $\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm NP}$

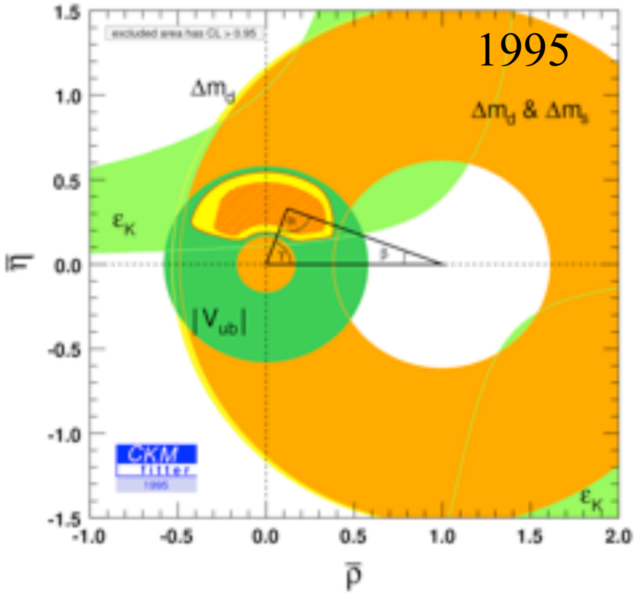
At low energies (m_b or below) $\mathcal{L} = \mathcal{L}_{\rm QCD+EM} + \mathcal{L}_{\rm W}^{\rm eff} + \mathcal{L}_{\rm NP}^{\rm eff}$

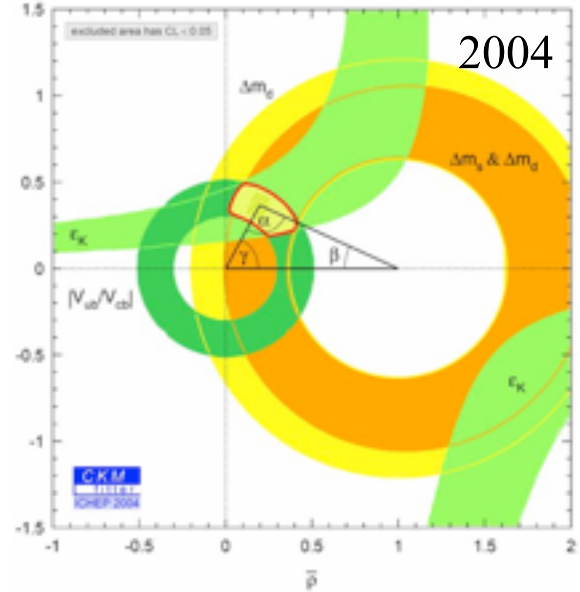
Generically:

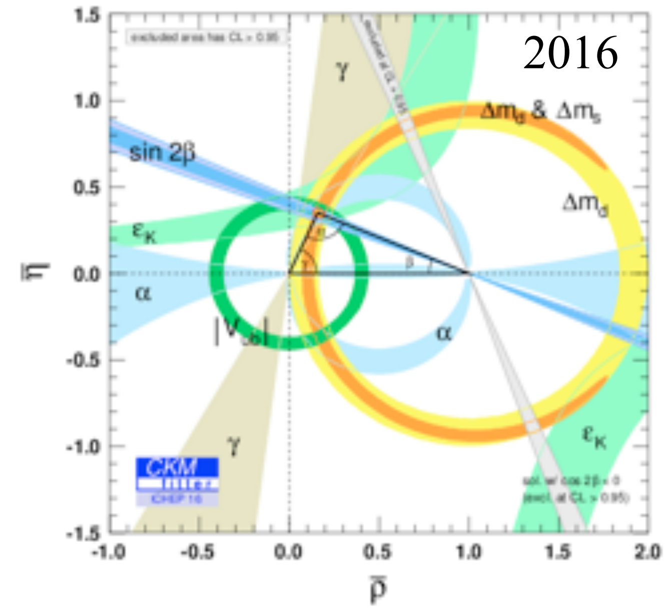
$$\mathcal{L}_{\rm W}^{\rm eff} = \frac{g_2^2}{M_W^2} C O(x) \qquad \mathcal{L}_{\rm NP}^{\rm eff} = \frac{1}{\Lambda_{\rm NP}^2} C O(x)$$

- Heavy degrees of freedom (W/Z, top, NP heavy particles) "integrated out"
- Coefficients C
  - are process independent
  - include short distance QCD effects ("corrections")
  - dominant QCD effect in large logs, eg, $\ln(\mu/M_{\rm W})$, re-summed by RG methods
- Operators *O(x)*
  - organized by dimension; here *dim* = *6*
  - NP may introduce same or new *O*'s
- Caveat: NP with light states

Flavor *and* Precision







Generic amplitude $\mathcal{A} = G_F \times \text{CKMs} \times C \times \langle \text{out}|O(0)|\text{in}\rangle$

- Want G_F, CKMs, C
  - *Disentangle: Need several measurements*
- Compute:
  - Coefficients C: in SM, in terms of other parameters
    - Obtain other parameters elsewhere (eg, m_b, α_s, from ϒ mass)
  - Matrix elements
    - Process dependent
    - Non-perturbative

Interlude:

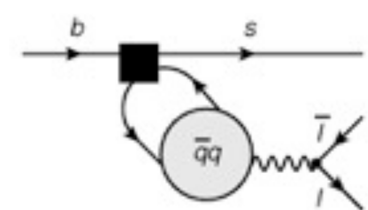
At this point it is standard to say…

*then we use the **lattice** results to get non-perturbative matrix elements*

… and we carry on blindly

2¢:

- Lattice results: often useful, downright of central importance
- Lattice results limited:
  - Few particles (2- and 3-point functions ok, 4-pt barely)
  - Small region of phase space in form factors
  - Difficult: phases
  - Hard to impossible: Non-local operators $\int d^4x\, T(\mathcal{H}(x)\mathcal{H}(0))$
  - Harder(?) to Impossible: inclusive rates
  - ...



End interlude

Precision: strategies I

“Clean” observables

$\boxed{\text{Observable independent of matrix elements}}$

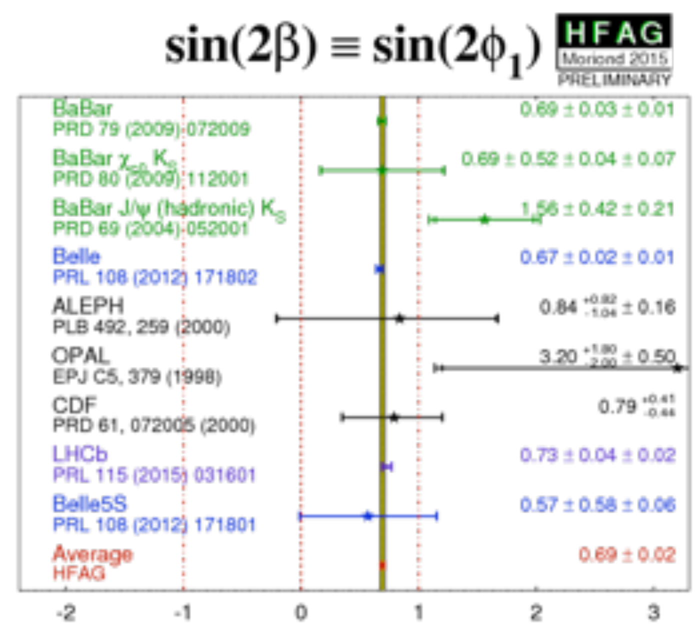
Examples:

1. CP asymmetries in mixing/decay (Bigi+Sanda)

review: $$A_f(t) = \frac{\Gamma(B_{phys}(t)\to f) - \Gamma(\bar{B}_{phys}(t)\to \bar{f})}{\Gamma(B_{phys}(t)\to f) + \Gamma(\bar{B}_{phys}(t)\to \bar{f})}$$ depends on $$\rho_f = \frac{\langle f|\mathscr{H}|\bar{B}^0\rangle}{\langle f|\mathscr{H}|B^0\rangle}.$$

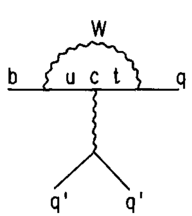
If $\mathcal{H} = \mathcal{H}^{\Delta B=1} + \mathcal{H}^{\Delta B=1\dagger}$ satisfies $(CP)\mathcal{H}^{\Delta B=1}(CP)^\dagger = \exp(-i\alpha)\mathcal{H}^{\Delta B=1\dagger}$

and $f^{CP} = \pm f$ then $$\boxed{\rho_f = \mp\exp(i\alpha)}$$



(BG, London+Peccei)

Caveat: $\mathcal{H} = \xi C_{\rm tree} O_{\rm tree} + \xi' C_{\rm loop} O_{\rm loop} + \text{h.c.}$

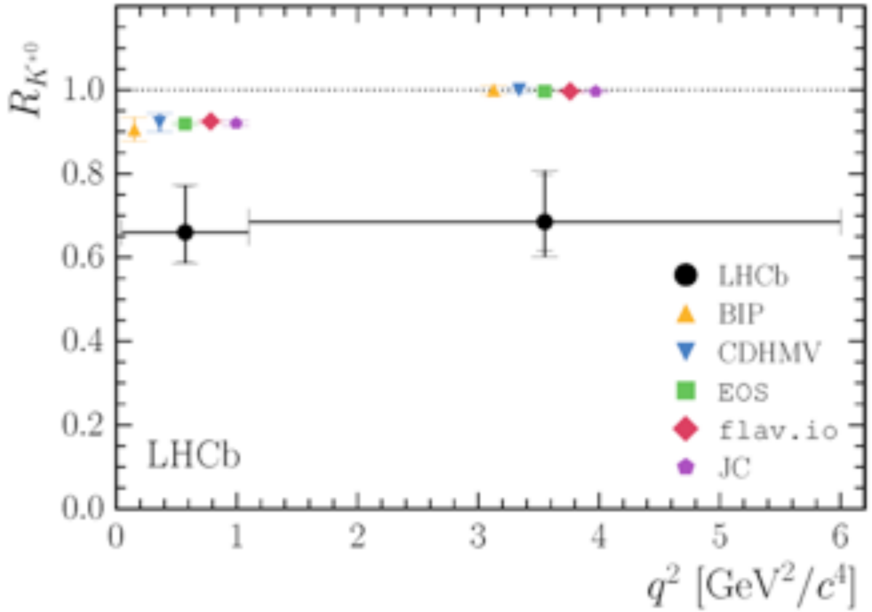


$$\rho_f = \frac{\xi}{\xi^*}\left(1 + 2i\mathrm{Im}\left(\frac{\xi'}{\xi}\right)\frac{\langle f|C_{\rm loop}O_{\rm loop}|B\rangle}{\langle f|C_{\rm tree}O_{\rm tree}|B\rangle}\right)$$

Moral: Still need matrix elements
(if only to bound errors)

2. Lepton Universality Violation

$$R_{K^*} = \frac{\mathrm{Br}(B \to K^* \mu\mu)}{\mathrm{Br}(B \to K^* ee)}$$



In SM: $R_{K^*} = 1$ for $m_e = m_\mu$

Caveat: Actually $m_e \neq m_\mu$

Corrections: phase space $\to$ near endpoint

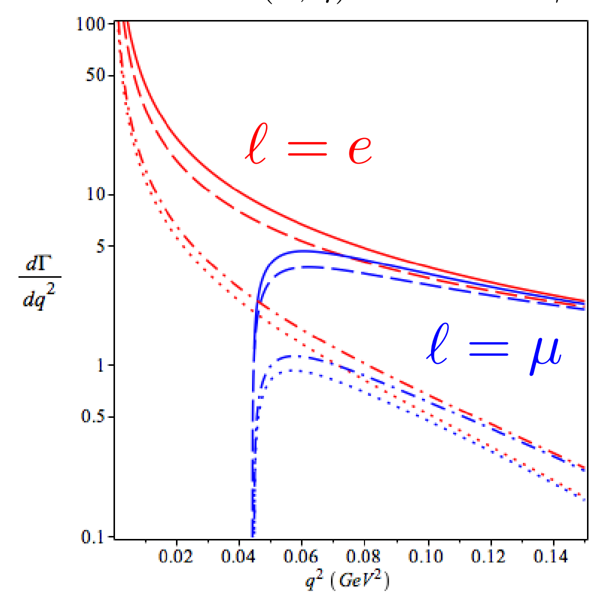
Figure of merit $\dfrac{m_\mu - m_e}{E_{\ell\ell}}$ Bordone et al 1605.07633

Colinear/soft $\dfrac{\alpha}{\pi} \ln^2(m_\mu/m_e) \approx 7\%$ need re-summing

Caveat redux: Hadronic contributions important near endpoint

e.g., $B \to K^* \pi \to K^* e^+ e^- \gamma$

$B \to K^*(\pi, \eta) \to K^* \ell^+ \ell^- \gamma$



Lesson #1: “Clean” observables require cleaning up after them

Precision: strategies II

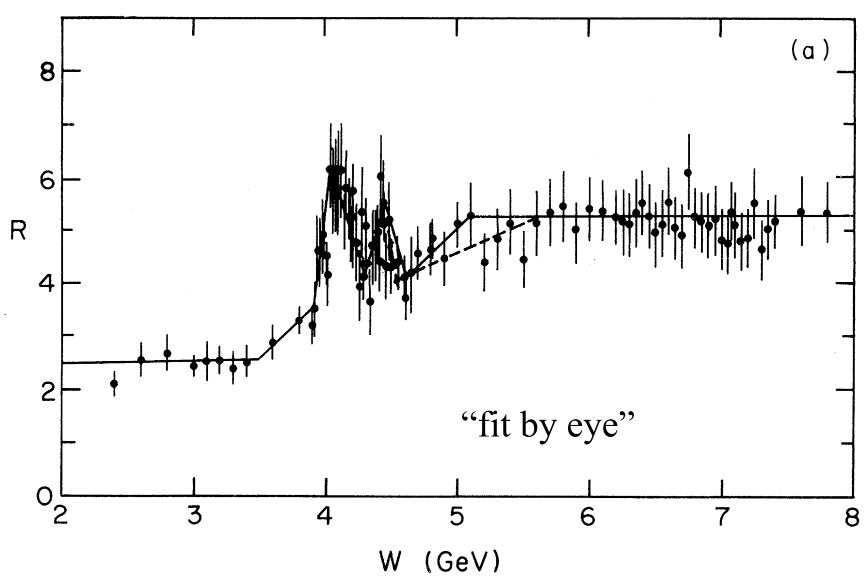
Inclusive observables

If sufficiently inclusive, perturbation theory (unconfined quarks) can be used

(aka, quark-hadron duality — a la Blook-Gilman, PQW)

1. Textbook example: $R = \dfrac{\sigma(e^+e^- \to \text{all})}{\sigma(e^+e^- \to \mu^+\mu^-)}$

PQW, PRD13(1976)1958



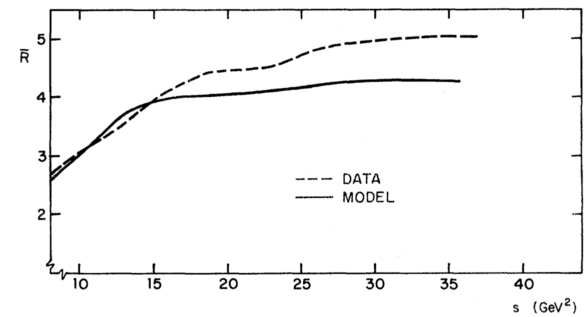


FIG. 10. Model with five quark flavors, charge $\frac{1}{3}$ for additional quark, and nondegenerate fourth and fifth flavors.

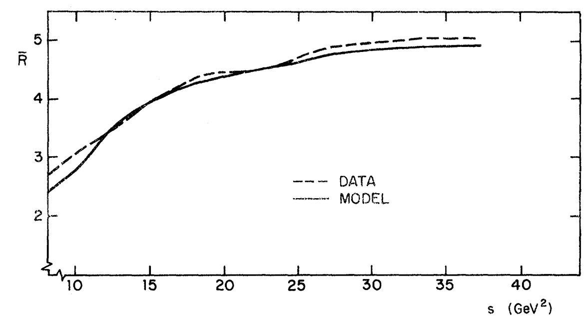
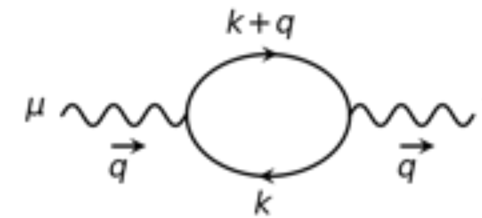


FIG. 14. The model of Fig. 10 with an additional heavy lepton, $m_l = 1.7$ GeV.

We understand why this works:

"Smearing" $$\bar{R}(s,\Delta) = \frac{\Delta}{\pi}\int_0^\infty ds' \, \frac{R(s')}{(s'-s)^2+\Delta^2}$$



Dispersion relation $$\Pi(z) = \frac{1}{\pi}\int_0^\infty ds \, \frac{R(s)}{z-s}$$

$$\Rightarrow \qquad 2i\bar{R}(s,\Delta) = \Pi(s+i\Delta) - \Pi(s-i\Delta)$$

That the self-energy can be computed is understood from OPE

$$\int d^4x \, e^{iqx} \, T(J(x)J(0)) = \sum q^{-n} c_n O_n$$

valid in the "Deep Euclidean" region and $O_1 = \mathbf{1}$ dominates

Caveats:

- Finite order in perturbative coefficients (with RG re-sumation
- Integral over *s* goes to infinity
- "Deep Euclidean" is $s \pm i\Delta$ with $\Delta \to \infty$
  but we take Δ large enough that it smears resonances
- Sub-leading operators

Chay, BG, Georgi, PLB247(1990)399
Bigi *et al,* PRL71(1993)496
Bigi *et al,* PLB323(1994)408
Manohar+Wise, PRD49(1994)1310
Trott, PRD70(2004)073003
Bauer *et al,* PRD70(2004) 094017

Closer to home examples:

2. Inclusive semileptonic decays: $\Gamma(B \to X_c \ell\nu)$

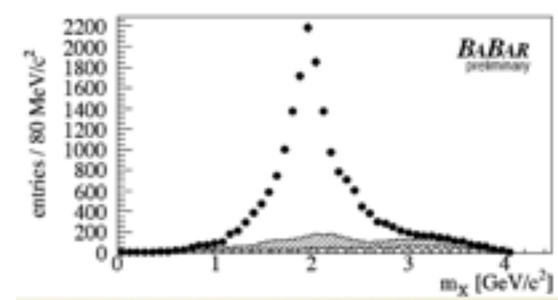
- Rate proportional to $|V_{cb}|^2$, used in CKM determination
- Dispersion relation, need >1 integrated kinematic variable: $d\Gamma/dE_{\ell\nu}$
- Moments of kinematic distributions: more inclusive
- Expansion in Λ/m_b; corrections first at $(\Lambda/m_b)^2$
- Coefficients of OPE: perturbative in α_s . Double expansion:

$$\Gamma = \Gamma_0^{(0)} + \frac{\alpha_s}{\pi}\Gamma_0^{(1)} + \left(\frac{\alpha_s}{\pi}\right)^2 \Gamma_0^{(2)} + \left(\Gamma_\pi^{(0)} + \frac{\alpha_s}{\pi}\Gamma_\pi^{(1)}\right)\frac{\mu_\pi^2}{m_b^2} + \left(\Gamma_G^{(0)} + \frac{\alpha_s}{\pi}\Gamma_G^{(1)}\right)\frac{\mu_G^2}{m_b^2} + \Gamma_D^{(0)}\frac{\rho_D^3}{m_b^3} + \Gamma_{LS}^{(0)}\frac{\rho_{LS}^3}{m_b^3} + \cdots$$

$$\mu_\pi^2 = -\langle B|\bar{b}(iD_\perp)^2 b|B\rangle$$
$$\mu_G^2 = -\langle B|\bar{b}(iD_\perp^\mu)(iD_\perp^\nu)\sigma_{\mu\nu} b|B\rangle$$

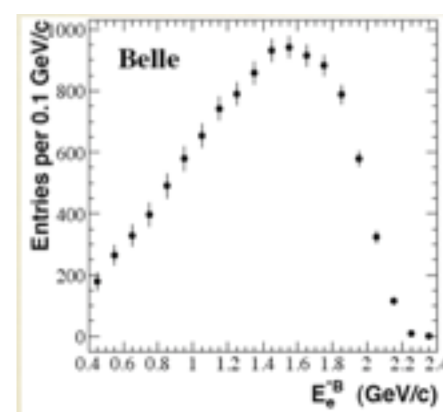
Recent fits:

- Six parameters: $m_{b,c}, \mu^2_{\pi,G}, \rho^3_{D,LS}$
- Includes corrections:
  - At order $(m_b)^0$: α_s^2
  - At order $(m_b)^{-2}$: α_s



Alberti *et al*, PRL114(2015)061802

m_b^{kin}	$\overline{m}_c(3\,\mathrm{GeV})$	μ_π^2	ρ_D^3	μ_G^2	ρ_{LS}^3	$\mathrm{BR}_{c\ell\nu}$	$10^3\lvert V_{cb}\rvert$
4.553	0.987	0.465	0.170	0.332	-0.150	10.65	42.21
0.020	0.013	0.068	0.038	0.062	0.096	0.16	0.78



Gambino+Schwanda, PRD89 (2014) 014022

m_b^{kin}	m_c	μ_π^2	ρ_D^3	μ_G^2	ρ_{LS}^3	$\mathrm{BR}_{c\ell\nu}(\%)$	$10^3\lvert V_{cb}\rvert$
4.541	0.987	0.414	0.154	0.340	-0.147	10.65	42.42
0.023	0.013	0.078	0.045	0.066	0.098	0.16	0.86

3. Inclusive semileptonic decays: $\Gamma(B \to X_u \ell \nu)$

Problem: u hides under c ($V_{ub} \ll V_{cb}$)
Experimental Solution: kinematic region (phase space) inaccessible to charm
New problem: not sufficiently inclusive, non-perturbative effects: “shape function”

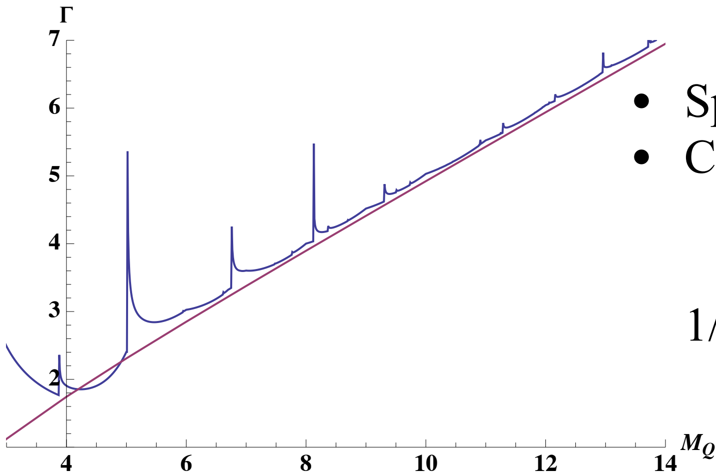
QCD Calculation	Phase Space Region	$\Delta\Gamma_{\text{theory}}$ (ps^{-1})	$\lvert V_{ub}\rvert(10^{-3})$
	$M_X \le 1.55$ GeV	$39.3^{+4.7}_{-4.3}$	$4.17 \pm 0.15 \pm 0.12^{+0.24}_{-0.24}$
	$M_X \le 1.70$ GeV	$46.1^{+5.0}_{-4.4}$	$3.97 \pm 0.17 \pm 0.14^{+0.20}_{-0.20}$
	$P_+ \le 0.66$ GeV	$38.3^{+4.7}_{-4.3}$	$4.02 \pm 0.18 \pm 0.16^{+0.24}_{-0.23}$
BLNP	$M_X \le 1.70$ GeV, $q^2 \ge 8$ GeV^2	$23.8^{+3.0}_{-2.4}$	$4.25 \pm 0.19 \pm 0.13^{+0.23}_{-0.25}$
	$M_X - q^2$, $p^*_\ell > 1.0$ GeV	$62.0^{+6.2}_{-5.0}$	$4.28 \pm 0.15 \pm 0.18^{+0.18}_{-0.20}$
	$p^*_\ell > 1.0$ GeV	$62.0^{+6.2}_{-5.0}$	$4.30 \pm 0.18 \pm 0.21^{+0.18}_{-0.20}$
	$p^*_\ell > 1.3$ GeV	$52.8^{+5.3}_{-4.3}$	$4.29 \pm 0.18 \pm 0.20^{+0.19}_{-0.20}$
	$M_X \le 1.55$ GeV	$35.3^{+3.3}_{-3.5}$	$4.40 \pm 0.16 \pm 0.12^{+0.24}_{-0.19}$
	$M_X \le 1.70$ GeV	$42.0^{+4.8}_{-4.8}$	$4.16 \pm 0.18 \pm 0.14^{+0.26}_{-0.22}$
	$P_+ \le 0.66$ GeV	$36.9^{+5.5}_{-5.8}$	$4.10 \pm 0.19 \pm 0.17^{+0.37}_{-0.28}$
DGE	$M_X \le 1.70$ GeV, $q^2 \ge 8$ GeV^2	$24.4^{+2.4}_{-2.0}$	$4.19 \pm 0.19 \pm 0.12^{+0.18}_{-0.19}$
	$M_X - q^2$, $p^*_\ell > 1.0$ GeV	$58.7^{+3.5}_{-3.2}$	$4.40 \pm 0.16 \pm 0.18^{+0.12}_{-0.13}$
	$p^*_\ell > 1.0$ GeV	$58.7^{+3.5}_{-3.2}$	$4.42 \pm 0.19 \pm 0.23^{+0.13}_{-0.13}$
	$p^*_\ell > 1.3$GeV	$50.4^{+3.3}_{-3.0}$	$4.39 \pm 0.19 \pm 0.20^{+0.15}_{-0.14}$
	$M_X \le 1.55$ GeV	$41.0^{+4.6}_{-3.8}$	$4.08 \pm 0.15 \pm 0.11^{+0.20}_{-0.21}$
	$M_X \le 1.70$ GeV	$46.8^{+4.2}_{-3.6}$	$3.94 \pm 0.17 \pm 0.14^{+0.16}_{-0.17}$
	$P_+ \le 0.66$ GeV	$44.0^{+8.6}_{-6.3}$	$3.75 \pm 0.17 \pm 0.15^{+0.30}_{-0.32}$
GGOU	$M_X \le 1.70$ GeV, $q^2 \ge 8$ GeV^2	$24.7^{+3.2}_{-2.4}$	$4.17 \pm 0.18 \pm 0.12^{+0.22}_{-0.25}$
	$M_X - q^2$, $p^*_\ell > 1.0$ GeV	$60.2^{+3.0}_{-2.5}$	$4.35 \pm 0.16 \pm 0.18^{+0.09}_{-0.10}$
	$p^*_\ell > 1.0$ GeV	$60.2^{+3.0}_{-2.5}$	$4.36 \pm 0.19 \pm 0.23^{+0.09}_{-0.10}$
	$p^*_\ell > 1.3$ GeV	$51.8^{+2.8}_{-2.3}$	$4.33 \pm 0.18 \pm 0.20^{+0.10}_{-0.11}$
	$M_X \le 1.55$ GeV	$47.1^{+5.2}_{-4.3}$	$3.81 \pm 0.14 \pm 0.11^{+0.18}_{-0.20}$
	$M_X \le 1.70$ GeV	$52.3^{+5.4}_{-4.5}$	$3.73 \pm 0.16 \pm 0.13^{+0.17}_{-0.18}$
	$P_+ \le 0.66$ GeV	$48.9^{+5.6}_{-4.6}$	$3.56 \pm 0.16 \pm 0.15^{+0.18}_{-0.19}$
ADFR	$M_X \le 1.70$ GeV, $q^2 \ge 8$ GeV^2	$30.9^{+3.0}_{-2.5}$	$3.74 \pm 0.16 \pm 0.11^{+0.16}_{-0.17}$
	$M_X - q^2$, $p^*_\ell > 1.0$ GeV	$62.0^{+5.7}_{-5.0}$	$4.29 \pm 0.15 \pm 0.18^{+0.18}_{-0.19}$
	$p^*_\ell > 1.0$ GeV	$62.0^{+5.7}_{-5.0}$	$4.30 \pm 0.19 \pm 0.23^{+0.18}_{-0.19}$
	$p^*_\ell > 1.3$ GeV	$53.3^{+5.1}_{-4.4}$	$4.27 \pm 0.18 \pm 0.19^{+0.18}_{-0.19}$

BLNP: Bosch, *et al,* PRD 72 (2005)073006
DGE: “dressed gluon exponentiation” Andersen, Gardi, JHEP 0601 (2006)097
ADFR: Aglietti, *et al*, Eur. Phys. J. C 59(2009)831
GGOU: Gambino, *et al*, JHEP 0710 (2007)058

4. Total width

Lifetimes, $\Delta\Gamma$, ...

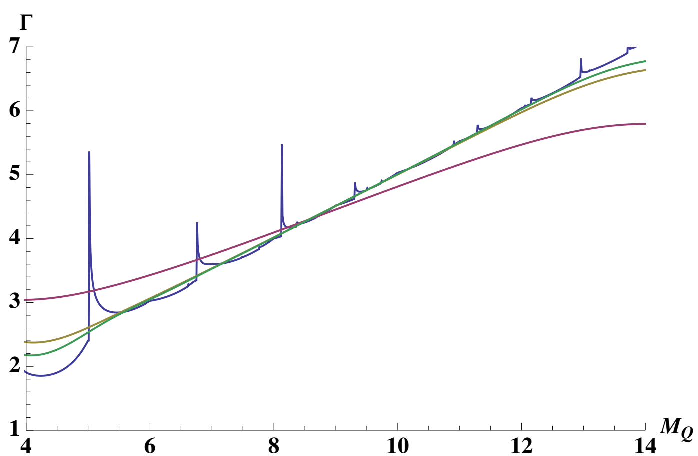
- For B decay we cannot smear (integrate) over quark masses
- Neither can we compute for “deep euclidean” mass
- Maybe duality works if mass is large enough (large number of decay channels)?
- Test the idea by applying it to soluble model: QCD in 2-dims at large N_c (the ‘t Hooft model)



- Spikes from phase space at thresholds
- Constant difference between “exact”– perturbative: $O(1/M_Q)^0$

$$\Gamma(B) = \Gamma(Q)(1 + 0.14/M_Q)$$

$1/M_Q$ rather than $1/M_Q^2$!!



- In toy model: smear over mass
- Lorentzian-power smearing

$$\frac{1}{((x - M_Q)^2 + 1)^n}$$

- Justified by OPE provided $n \geq 2$
- Corrections to OPE: order $1/M_Q^2$
- I conclude: Cannot trust OPE for total width unless asymptotically heavy quark

Lesson #2: Expansions must be systematic (justified)

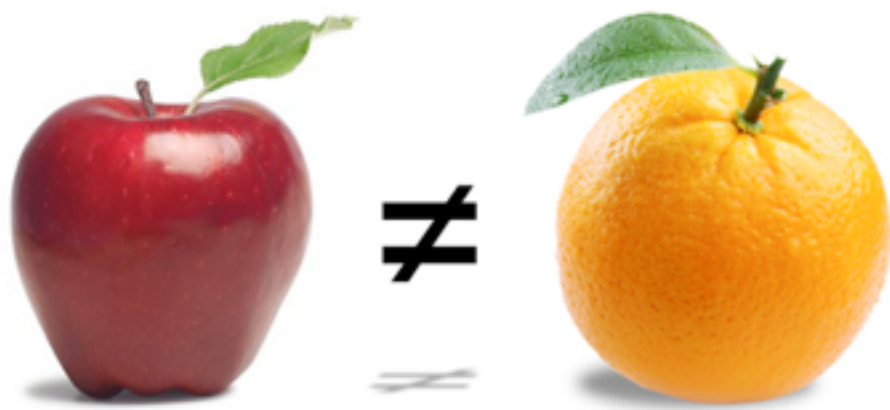
You may want to pull a rabbit out of the hat and ...

Corollary:

Should not use

- Lattice
- Sum rules
- SCET, QCDfac, pQCD
- Quark model
- AdS/QCD
- ...

on the same footing

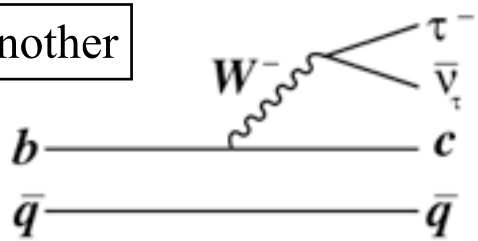


Precision: strategies III

BGL: Boyd *et al,* PLB353 (1995) 306;
Nuovo Cim. A109 (1996) 863;
NPB 461 (1996) 493;
PRD56 (1997) 6895-6911
CLN: Caprini *et al*, PLB380 (1996) 376;
NPB530 (1998) 153
FNAL/MILC: PRD89 (2014) 114504

Complementarity

Combine methods: Fill gaps in one methods and another



Examples:

1. Lattice + z-expansion + data, exclusive semileptonic decays, $B \to D\ell\nu$

form factors: $\langle D(p')|V^\mu|B(p)\rangle = f_+(p+p')^\mu + (f_0 - f_+)\frac{m_B^2 - m_D^2}{q^2}q^\mu, \quad q = p - p', f = f(q^2)$

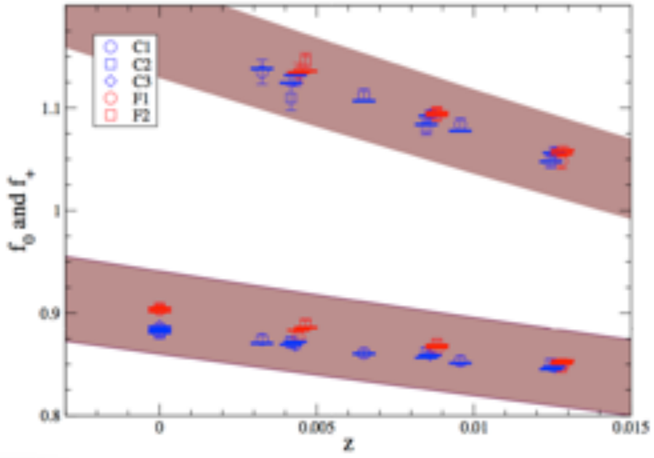
rate: $$\frac{d\Gamma}{dw} = \frac{G_F^2 m_B^5}{48\pi^3}|V_{cb}|^2(m_B + m_D)^2 m_D^3(\sqrt{w^2-1})^3(\eta_{\mathrm{ew}}\mathcal{G}(w))^2$$

z-expansion:

$$f(w) = \mathcal{P}(z)\sum_{n=0}^{\infty} a_n z^n, \quad \sum_{n=0}^{\infty} a_n^2 \le 1, \qquad z = \frac{\sqrt{w+1}-\sqrt{2}}{\sqrt{w+1}+\sqrt{2}}$$

- Ingredients: Analyticity, crossing symmetry, unitarity
- $\mathcal{P}(z)$: computable (Blaschke, QCD)
- Physical region: $0 \le z \le 0.056$
- Not just a "parametrization": $n \ge 2$ terms give no more than 1%

Story in pictures:



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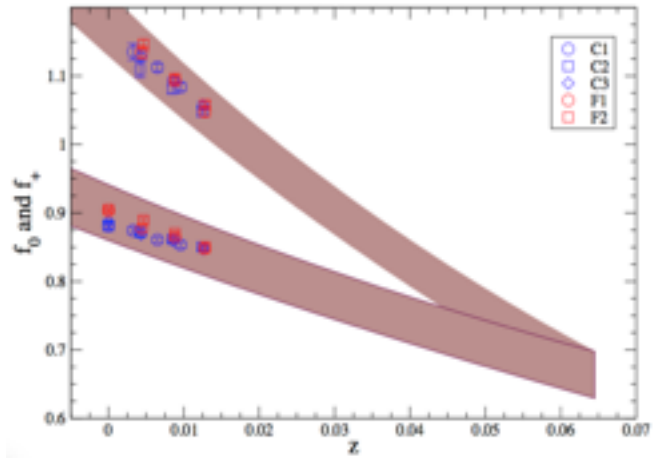

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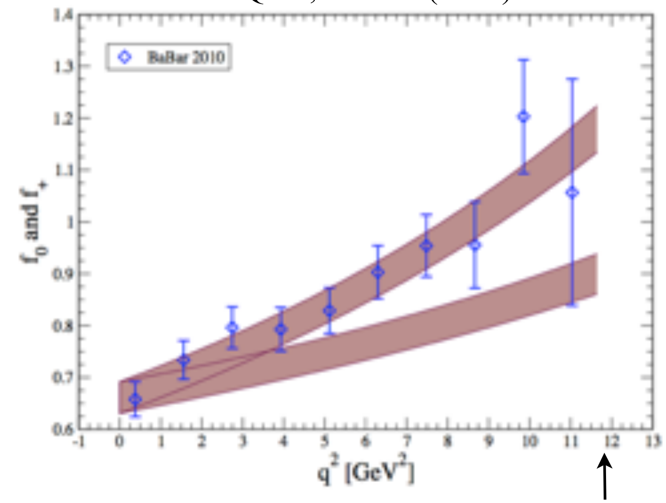
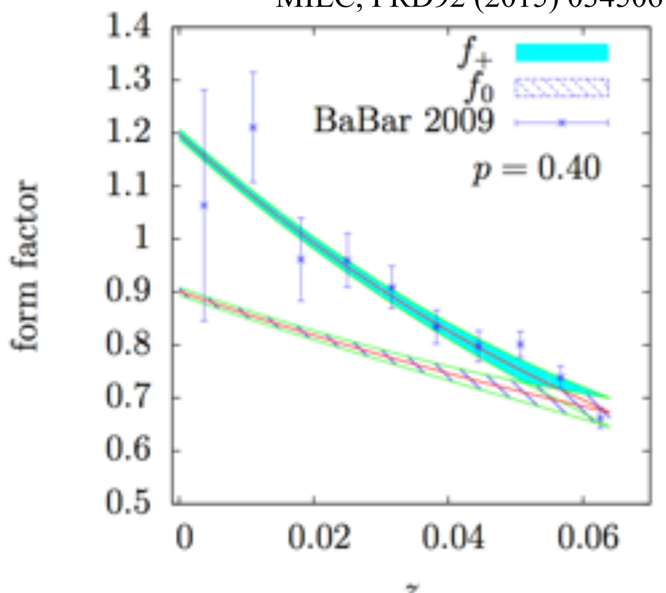
HPQCD, PRD92 (2015) 054510



$z = 0$

Complementarity!

MILC, PRD92 (2015) 034506



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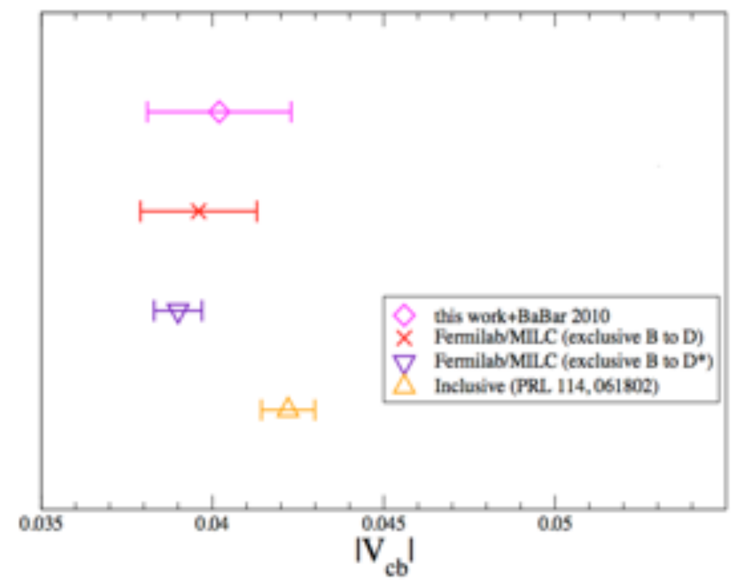
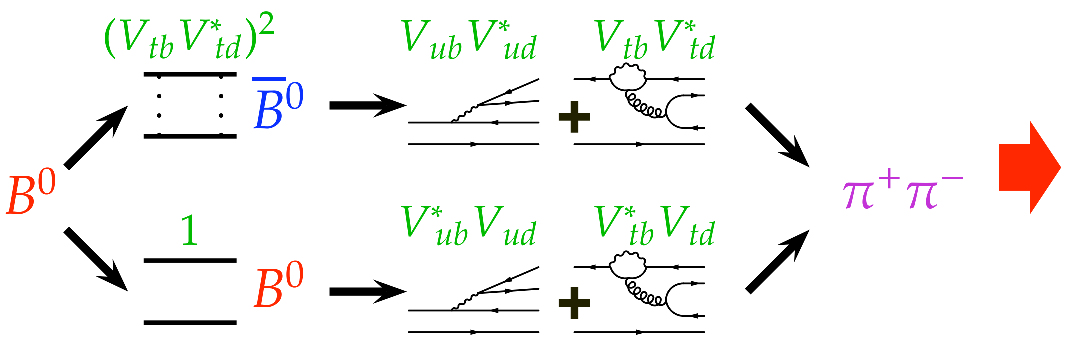


Caveat:

As good as the worst.

eg, MILC uses BGL for fit, else no control of theoretical errors.

2. CP asymmetries in mixing/decay: Penguin pollution revisited

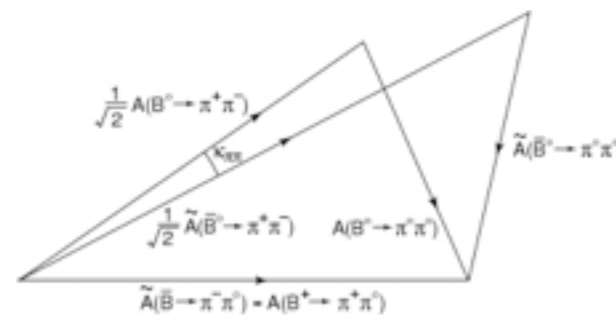


$$\Gamma(B^0) \propto e^{-t/\tau}\,(1+\mathcal{S}_{\pi\pi}\sin\Delta mt + \mathcal{A}_{\pi\pi}\cos\Delta mt)$$

$$\Gamma(\overline{B}^0) \propto e^{-t/\tau}\,(1-\mathcal{S}_{\pi\pi}\sin\Delta mt + \mathcal{A}_{\pi\pi}\cos\Delta mt)$$

$\mathcal{S}_{\pi\pi} = \sqrt{1-\mathcal{A}^2_{\pi\pi}}\,\sin 2\phi_2^{\rm eff}$, **where** $\phi_2^{\rm eff} = (\phi_2+\kappa)$ **is not** ϕ_2

Gronau-London PRL65,3381(1990)

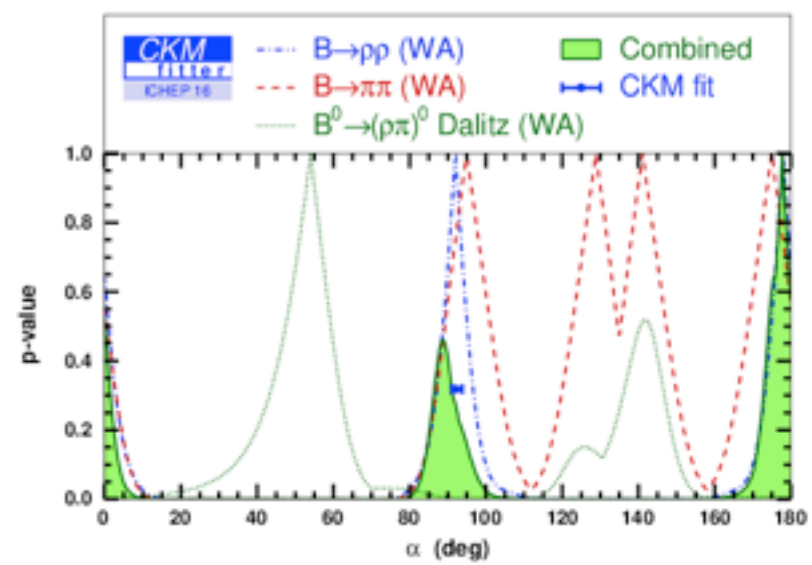


- Isospin analysis combines methods:
  - Relations with $B\to\pi^+\pi^0$ and $B^0\to\pi^0\pi^0$ (same for $B\to\rho\rho$ after resolving polarization)
  - Isospin breaking effects are small

Alternative

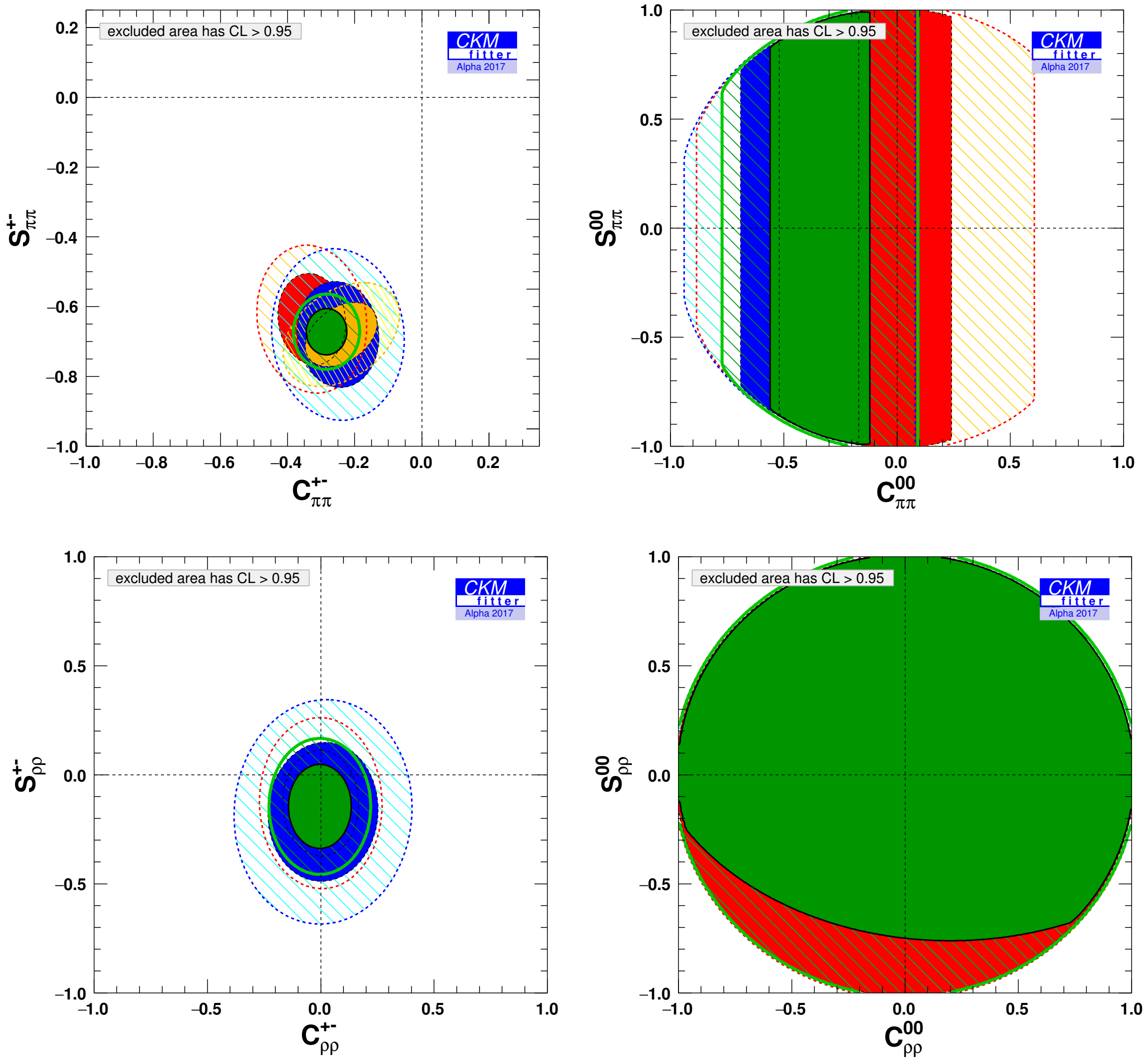
Snyder-Quinn PRD48,2139(1993)

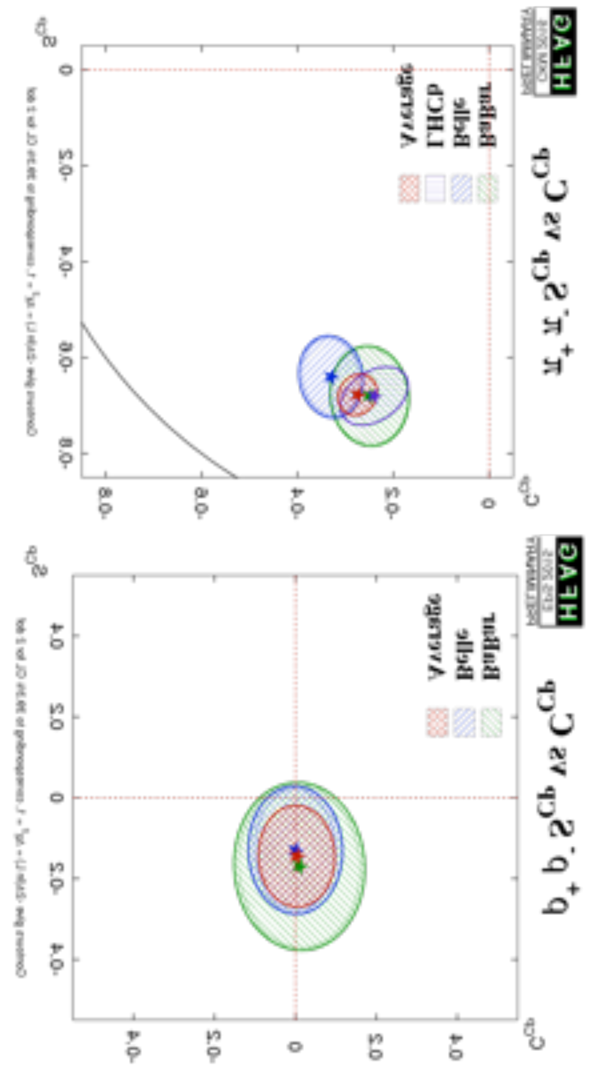
- Time-dependent Dalitz analysis
  - $B^0\to\pi^+\pi^-\pi^0$ contains $\rho^+\pi^-$, $\rho^-\pi^+$, $\rho^0\pi^0$ and cross terms (interference)
  - α/φ_2 directly determined, $\rho^\pm\pi^0$ and $\rho^0\pi^\pm$ may improve further (future)



Latest

Charles *et al,* arXiv:1705.02981



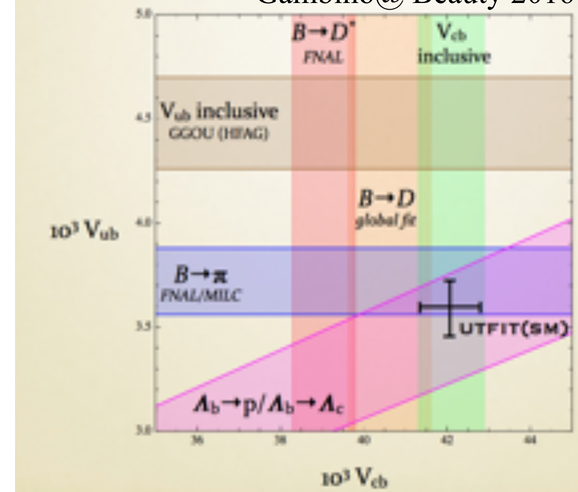


$$
\begin{array}{llll}
\alpha_{\rm dir} & (\text{BaBar}) & : & (86.6^{+5.9}_{-8.3})^\circ \quad \cup \quad (174.8^{+3.6}_{-3.8})^\circ\,, \\
 & (\text{Belle}) & : & (172.7^{+6.5}_{-6.1})^\circ\,.
\end{array}
$$

Anomalies I

Is there NP in Inclusive vs Exclusive semileptonic B decays?

Gambino@ Beauty 2016



- Longstanding tension in exclusive vs inclusive determination

$$|V_{cb}| = (39.18 \pm 0.99)\times 10^{-3} \qquad (\bar{B}\to D\ell\overline{\nu})$$

$$|V_{cb}| = (38.71 \pm 0.75)\times 10^{-3} \qquad (\bar{B}\to D^*\ell\overline{\nu})$$

$$|V_{cb}| = (42.19 \pm 0.78)\times 10^{-3} \qquad (\bar{B}\to X_c\ell\overline{\nu},\ \text{kinetic scheme})$$

$$|V_{cb}| = (41.98 \pm 0.45)\times 10^{-3} \qquad (\bar{B}\to X_c\ell\overline{\nu},\ \text{1S scheme})$$

- CLN used for exclusives
- CLN: $\Lambda_{\rm QCD}/m_Q$ in relations between form factors $\Rightarrow$ uncertainties in $|V_{cb}|$ underestimated

  Bernlochner *et al*, 1703.05330
- CLN not a good fit to data in $B\to D\,l\,\nu$ Bigi+Gambino, PRD 94(2016)094008
- Can NP accomodate?
  - No Crivellin-Pokorski, PRL114(2015)011802
  - Maybe Colangelo-De Fazio, PRD95(2017)011701
  - not in SV limit, for any EFT operators Voloshin+Shifman, SJNP47('88)511; BGM, PRD54('96)2081; BG unpub

example: RH currents with strength ϵ

$$|V_{cb}|_{\rm incl} = |V_{cb}|(1+\tfrac{1}{2}\epsilon^2)$$

$$|V_{cb}|_{D^*} = |V_{cb}|(1+\epsilon)$$

$$|V_{cb}|_{D} = |V_{cb}|(1-\epsilon)$$

- Is tension from CLN? (Precision!)

- New Belle analysis released
  - Unfolded data, full correlation matrix
  - Large dataset, energy and angular distributions
  - CLN: $|V_{cb}| = (37.4 \pm 1.3)\times 10^{-3}$
- Two independent analyses using BGL:
  - Very consistent fits:

$$|V_{cb}| = (41.7\ ^{+2.0}_{-2.1}) \times 10^{-3}$$

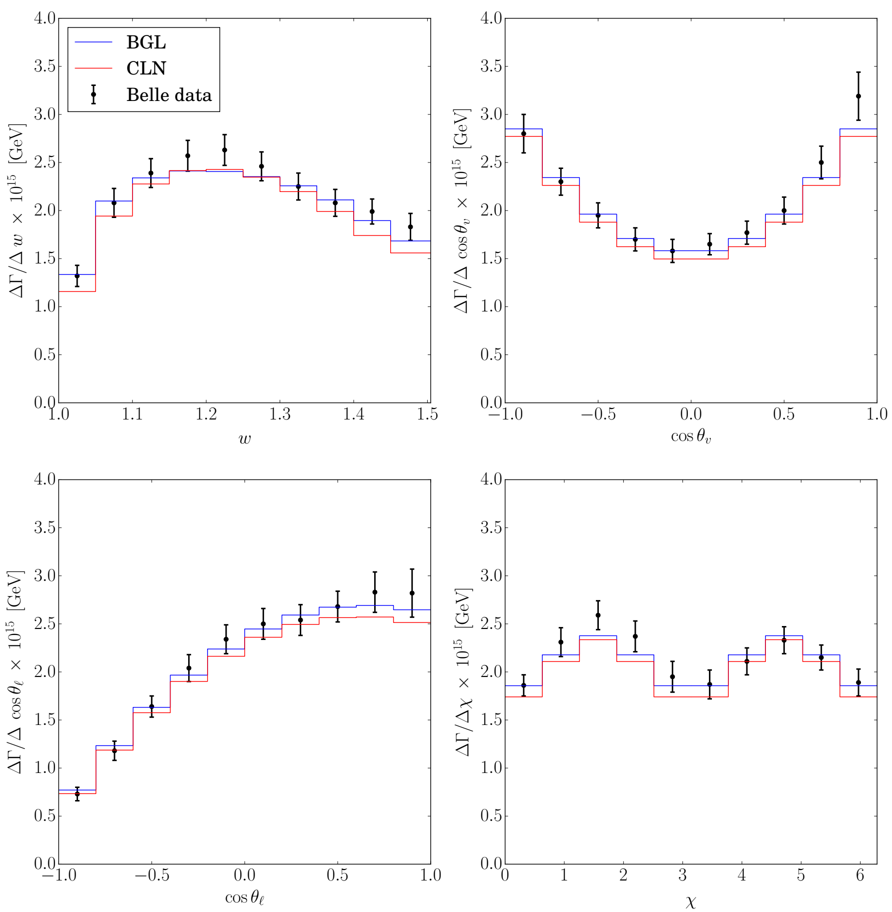
$$|V_{cb}| = (41.9\ ^{+2.0}_{-1.9}) \times 10^{-3}$$

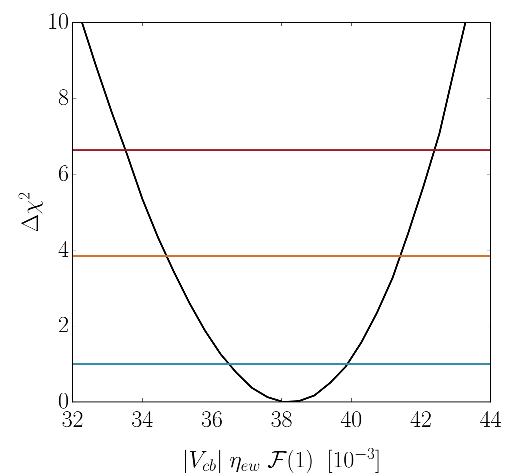
  - Robust: different numerical inputs

Abdesselam *et al,* (Belle) 1702.01521

Bigi *et al*, PLB769 (2017) 441-445

BG+Kobach, PLB771 (2017) 359-364





Notes:

Fitted coefficients in ff expansion far from unitary bounds

Use $\eta_{ew} = 1.0066$ Sirlin, NPB196(1982)83

$\mathcal{F}(1) = 0.906 \pm 0.013$ FNAL/MILC PRD89(2014)114504

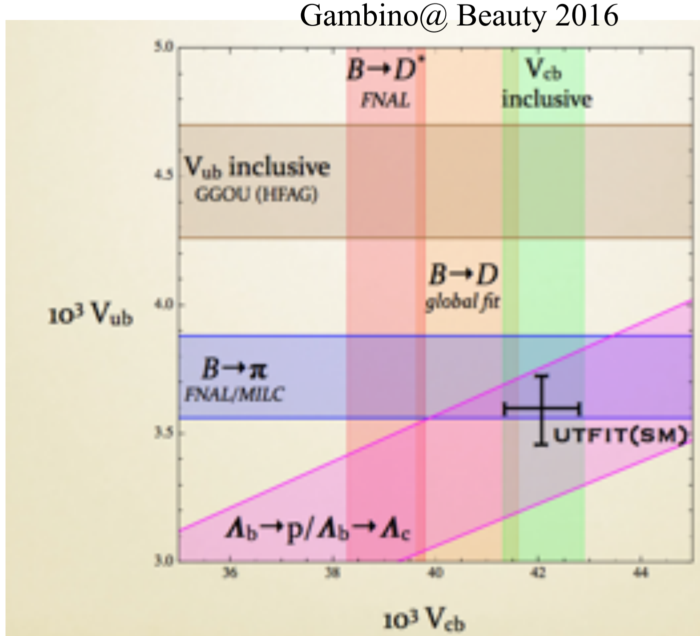
$\boxed{\text{20 year tension no more}}$

Anomalies I.5

Is there NP in Inclusive vs Exclusive <u>non-charm</u> semileptonic B decays?

Gambino@ Beauty 2016

Again:



My guess: Systematics in $|V_{ub}|$ from inclusive determination ***badly*** underestimated

I already explained why

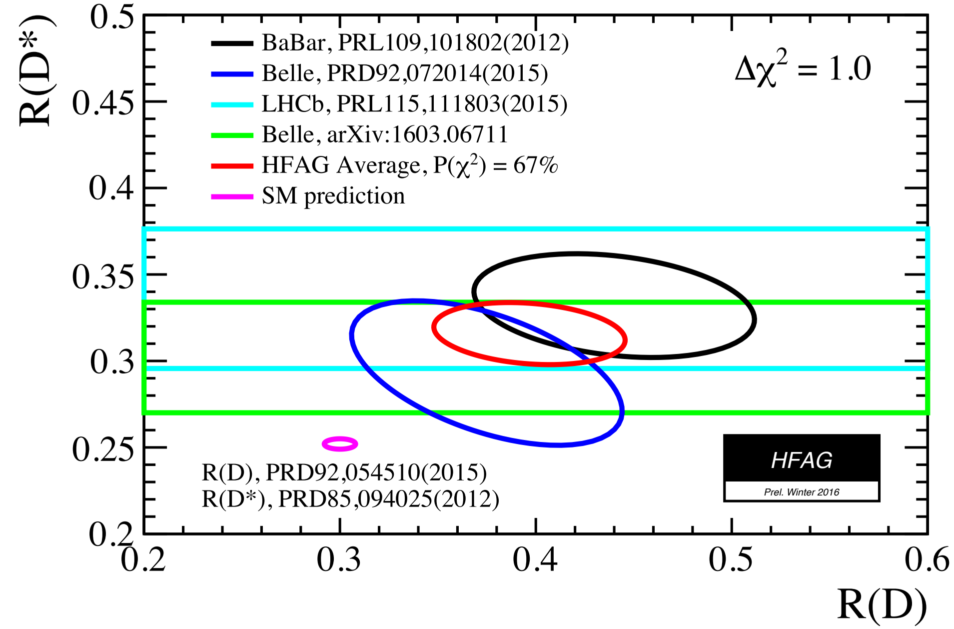
Anomalies II

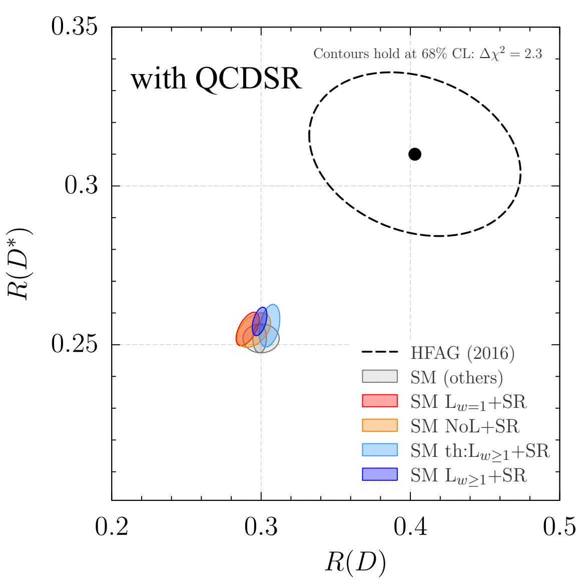
Is there NP in B decays to τ?

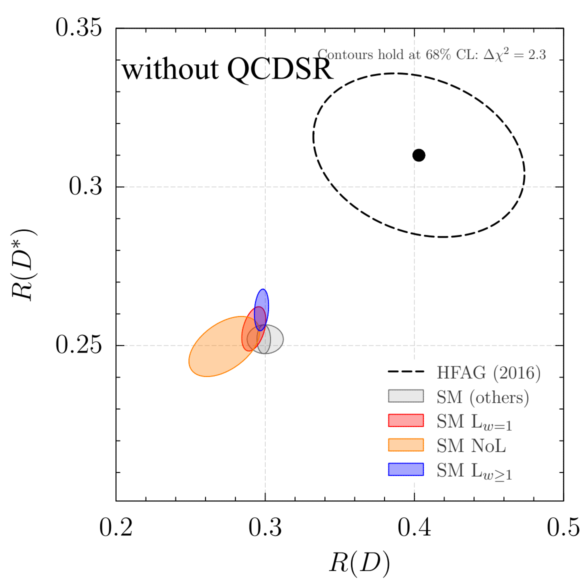
"$R_{D^{(*)}}$ anomaly"

$$R_{D^{(*)}} = \frac{\mathrm{Br}(B \to D^{(*)}\tau\nu)}{\mathrm{Br}(B \to D^{(*)}\ell\nu)}$$

Excesses observed at more than 4σ







New: analysis of theory uncertainty

Bernlochner *et al*, 1703.05330

NP? Compete with SM-tree level!

Use EFT to characterize any model with heavy mediators:

$$\mathcal{L}_{\text{eff}} = -\frac{4G_F V_{cb}}{\sqrt{2}} \Big[\Big(1+\epsilon_L\Big) \bar{\tau}\gamma_\mu P_L \nu_\tau \cdot \bar{c}\gamma^\mu P_L b + \epsilon_R \bar{\tau}\gamma_\mu P_L \nu_\tau \cdot \bar{c}\gamma^\mu P_R b$$

$$+ \epsilon_T\, \bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau \cdot \bar{c}\sigma^{\mu\nu} P_L b + \epsilon_{S_L} \bar{\tau} P_L \nu_\tau \cdot \bar{c} P_L b + \epsilon_{S_R} \bar{\tau} P_L \nu_\tau \cdot \bar{c} P_R b \Big] + \text{h.c.}$$

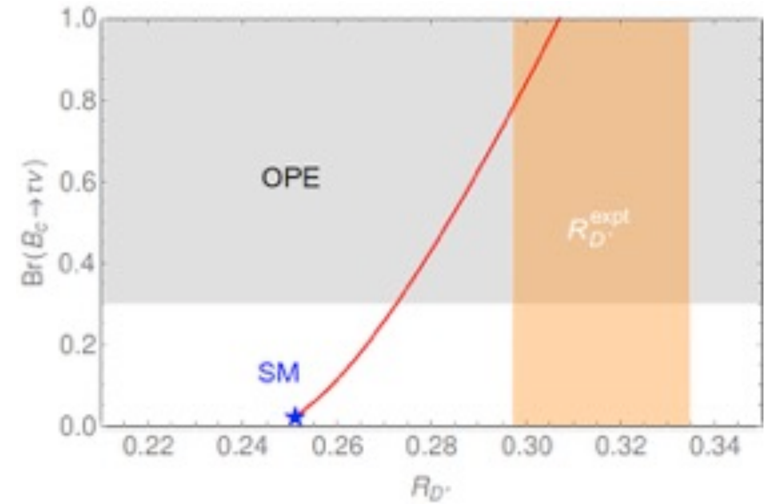
Narrow it down:

Alonso *et al*, PRL118 (2017) no.8, 081802

1. SM-EFT: no ϵ_R $\quad \mathcal{L}^{\text{eff,NP}} = \frac{1}{\Lambda^2}\left(C^{(1)}_{leu} Q^{(1)}_{lequ} + C^{(3)}_{leu} Q^{(3)}_{leu} + C^{(3)}_{\ell q} Q^{(3)}_{\ell q} + C_{\ell edu} Q_{\ell edq}\right)$

$$Q^{(1)}_{lequ} = (\bar{\ell} e_R)(\bar{q}_L u_R) + \text{h.c.} \qquad Q^{(3)}_{lequ} = (\bar{\ell}\sigma_{\mu\nu} e_R)(\bar{q}_L \sigma^{\mu\nu} u_R) + \text{h.c.}$$

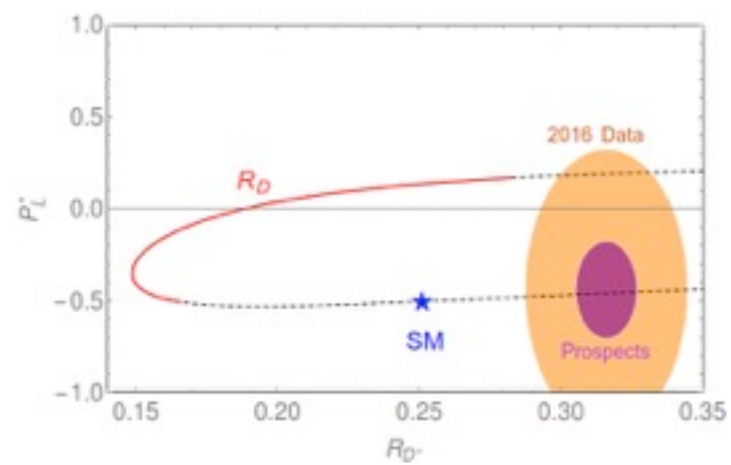
$$Q^{(3)}_{\ell q} = (\bar{q}\vec{\tau}\gamma^\mu q_L)\cdot(\bar{\ell}\vec{\tau}\gamma_\mu \ell_L) \qquad Q_{\ell edq} = (\bar{\ell}_L e_R)(\bar{d}_R q) + \text{h.c.}$$



2. B_c width: no $\epsilon_P = \epsilon_{S_R} - \epsilon_{S_L}$

Vector-current chirally suppressed by $(m_\tau/m_b)^2$ (as in $\pi \to \mu\nu$) relative to scalar operator

Pseudoscalar needed for $R_{D^{(*)}}$ anomaly overwhelms total width



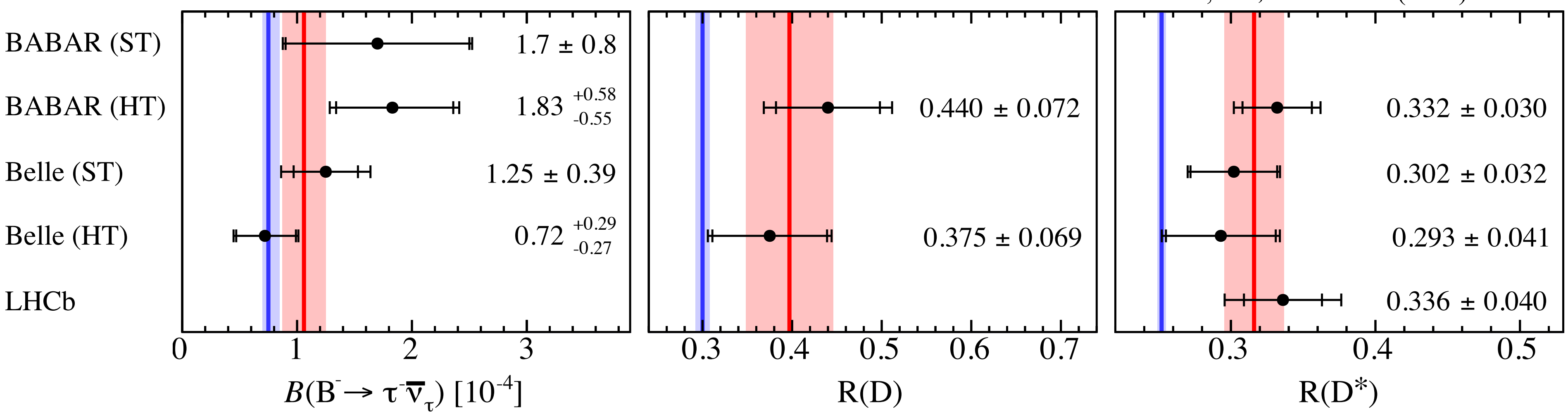
3. Angular distribution: constrains ϵ_T

To me: this suggests ϵ_L, i.e., V–A

Anomalies II.5

Is there NP in B decay to $\tau\nu$?

Plot from Ciezarek,*et al,* Nature 546 (2017) 227-233



Since WIN 2015, new Belle measurements have made significance go away.

... which is really interesting! because:

not only effects of (*putative*) NP differentiate tau's from electrons and muons

it differentiates between charm and up

And in both cases in the direction of amplifying effects for heavier fermions.

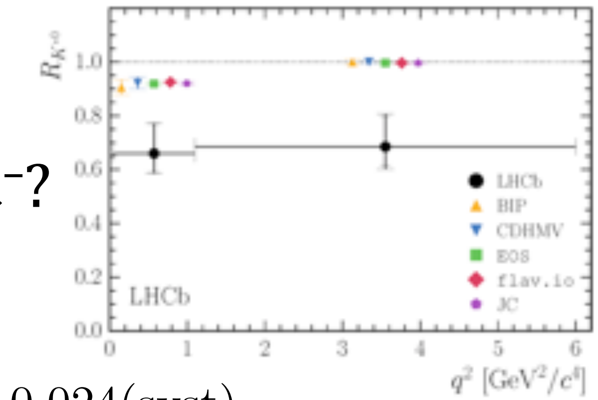
If so:

- The NP is tied to flavor!!
- Amplification ~ mass?
  Smells like MFV+MLFV
  (Minimal Flavor Violation + Minimal Lepton Flavor Violation)
- Scale of NP cannot be arbitrarily high; naively:

$$\frac{1}{\Lambda^2} \gtrsim 0.4 \times \frac{|V_{cb}|}{v^2} \quad \Rightarrow \quad \Lambda \lesssim 2\ \text{TeV}$$

Anomalies III

Is there NP in B decays to $K^{(*)}\mu^+\mu^-$?



$$R_{K^*} = \frac{\mathrm{Br}(B \to K^*\mu\mu)}{\mathrm{Br}(B \to K^*ee)}$$

$$\langle R_{K^*}\rangle_{[0.045,1.1]} = 0.660^{+0.110}_{-0.070}(\mathrm{stat}) \pm 0.024(\mathrm{syst})$$

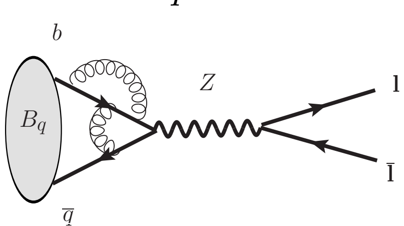
$$\langle R_{K^*}\rangle_{[1.1,6]} = 0.685^{+0.113}_{-0.069}(\mathrm{stat}) \pm 0.047(\mathrm{syst})$$

$$R_K = \left.\frac{\mathrm{Br}(B \to K\mu\mu)}{\mathrm{Br}(B \to Kee)}\right|_{[1,6]}$$

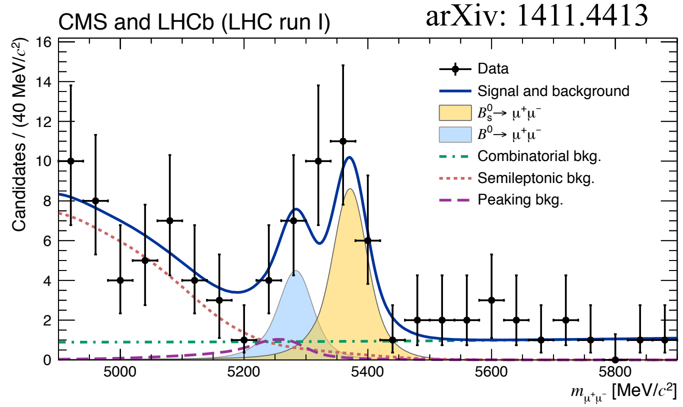
$$\langle R_K\rangle_{[1,6]} = 0.745^{+0.090}_{-0.074}(\mathrm{stat}) \pm 0.036(\mathrm{syst})$$

LHCb PRL113(2014)151601

$$B_q^0 \to \mu\mu$$



arXiv: 1411.4413

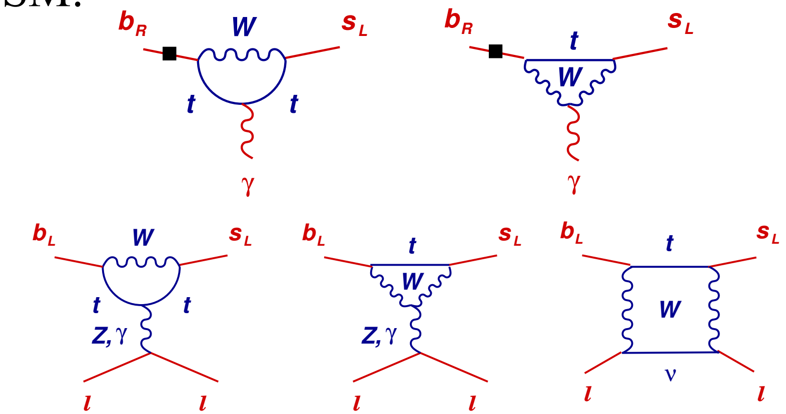


Bobeth *et al*, PRL112(2014)101801

$$\overline{\mathcal{B}}^{\mathrm{SM}}_{s\mu} = 3.65(23) \times 10^{-9}$$

$$\overline{\mathcal{B}}^{\mathrm{expt}}_{s\mu} = 2.9(7) \times 10^{-9}$$

SM:



$$\mathcal{L}^{\text{eff}}_{\text{SM}} = \frac{e}{4\pi^2} G_F V_{tb} V_{ts}^* m_b C_7 O_7, \quad O_7 = \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$$

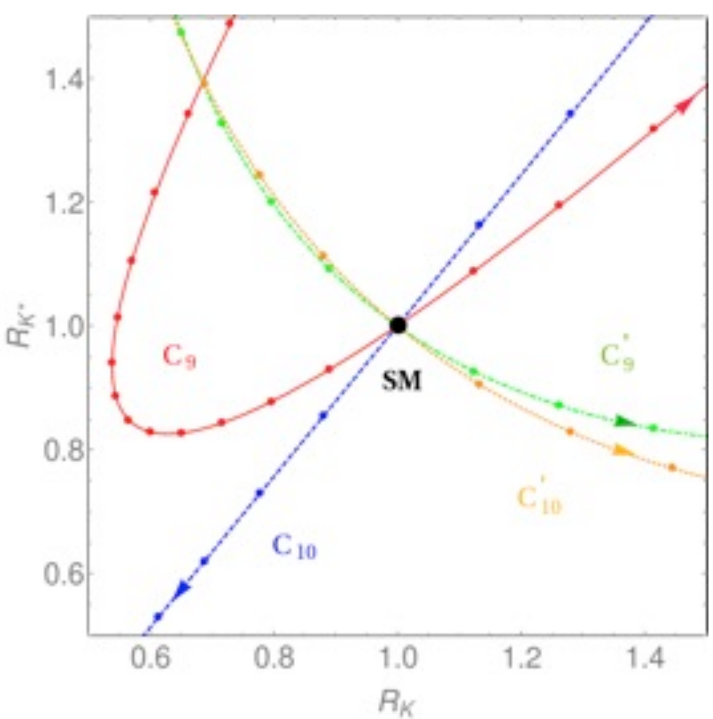
$$+ G_F V_{tb} V_{ts}^* \frac{\alpha}{4\pi} C_{9(10)} O_{9(10)}, \quad O_{9(10)} = \bar{s}_L \gamma^\mu b_L \bar{\ell} \gamma_\mu (\gamma_5) \ell$$

(Reference: in SM $C_9 \approx -C_{10} \approx 4.5$)

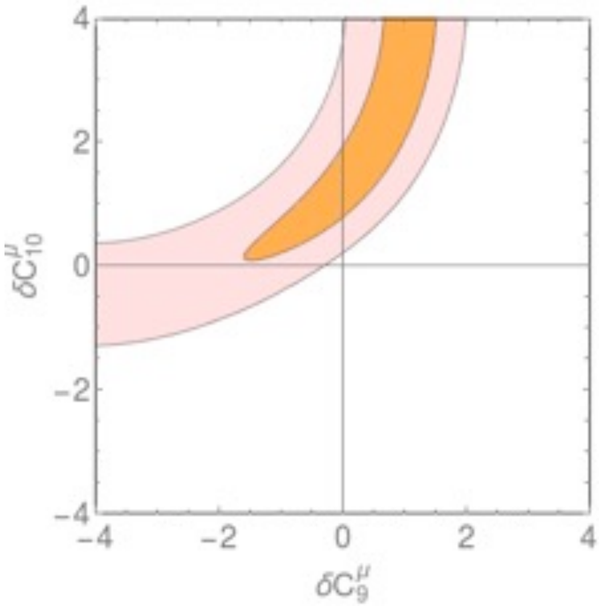
NP: SM-EFT plus constraints from $B_s \to \mu\mu$ $\Rightarrow$ no scalar or tensor operators Alonso, *et al*, PRL113(2014)241802

Left with vector operators: $C_{9(10)} \to C_{9(10)} + \delta C_{9(10)}$; additionally

$$+ G_F V_{tb} V_{ts}^* \frac{\alpha}{4\pi} C'_{9(10)} O'_{9(10)}, \quad O'_{9(10)} = \bar{s}_R \gamma^\mu b_R \bar{\ell} \gamma_\mu (\gamma_5) \ell$$

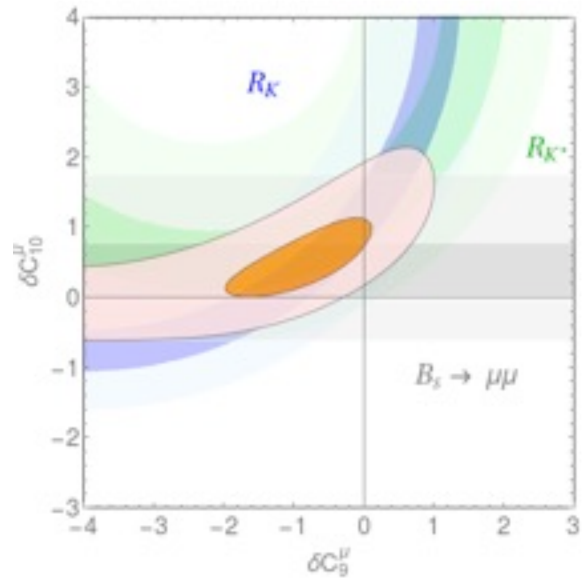


- These are $\delta C_i = C_i^{\text{NP}}$
- Arrows: increasing δC
- Dots: intervals of $\Delta(\delta C) = 0.5$
- Central Value (R_K, R_{K^*}) on blue line
- Not C'_9, C'_{10}, *i.e.*, not V+A
- As with tau anomalies: V–A !!



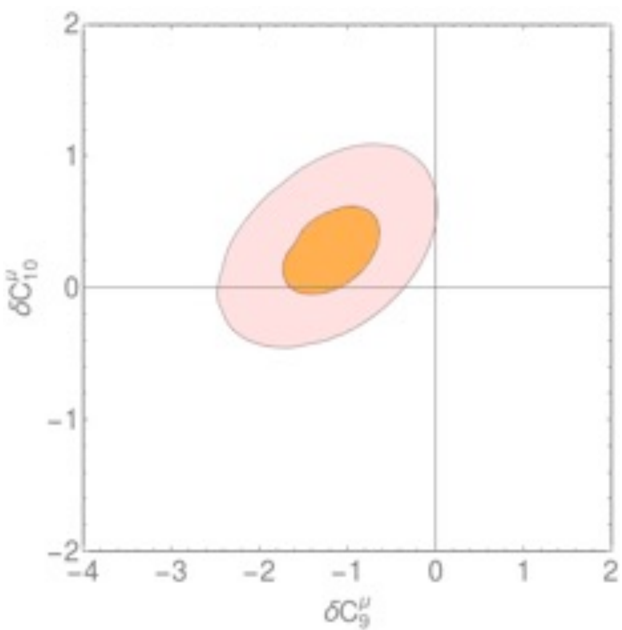
Fit to (R_K, R_{K^*})

Capdevila, *et al*, 1704.05340
Altmannshofer, *et al*, 1704.05435
D'Amico, *et al*, 1704.05438
Hiller, *et al*, 1704.05444
Ciuchini, *et al*, 1704.05447
Celis, *et al*, 1704.05672
Li-Sheng Geng, *et al*, 1704.05446



Fit to (R_K, R_{K^*}) plus $B_s \to \mu\mu$

Dirty observables, mostly from angular distribution in $B \to K^*\mu\mu$ (e.g., P'_5), had already suggested $\delta C_9 \approx -1$. So combine **all** $b \to s$ observables:



The shape of NP:
An attractive scenario

$$\boxed{\delta C_9 = -\delta C_{10} = -0.5}$$

My next slide is very busy

But it is the last

and not as bad as

this

NP Models?

Large and growing literature. Approaches for $b \to s$ anomalies:

- Long distance, lighter than EW — Sala+Straub, 1704.06188; Bishara *et al*, 1705.03465
- Non-decoupling, EW scale
  - SM-EFT analysis does not necessarily apply
  - Loop mediators — Arnan et al, 1608.07832; Gripaios et al, JHEP1606(2016)083; Kamenik et al, 1704.06005
  - Composites, partial composites — *e.g.,* Gripaios et al, JHEP1505(2015)006
- Short distance (most popular) — unapologetic avoidance of references
  - Z':
    - LUV: couple (typically) to $L_\mu - L_\tau$, strength $g_{\mu\mu}$
    - FCNC: non-diag coupling to $\bar{s}b$, strength g_{bs}; B_s-mixing $\Rightarrow g_{bs}/M_{Z'} < 5 \times 10^{-3}$ TeV^{-1}
    - B-anomalies: $g_{\mu\mu}/M_{Z'} > 1/(3.7$ TeV$)$, or $M_{Z'} < 13$ TeV for $g_{\mu\mu} < \sqrt{(4\pi)}$
    - Need to address LFV (*e.g.*, $\mu \to e\gamma$) and other quark FCNC
  - Leptoquarks
    - Scalars: no $SU(3)_c$-triplet, $SU(2)_w$-singlet ($Y = 7/6, 1/6, -1/3, -4/3$) works (either $\delta C_9 = +\delta C_{10}$ or give $C'_{9(10)}$)
    - Scalars: Unique $SU(2)_w$-triplet ($SU(3)_c$-triplet), $Y = -1/3$, gives right pattern
    - Vectors: $SU(3)_c$-triplets, $SU(2)_w$-singlets with $Y = 5/6, -1/6, -5/3$, don't work either
    - Vectors: both $SU(2)_w$ singlet and triplet (color triplets) with $Y = 2/3$ give right pattern
- Some short distance models address also tau anomalies

Is quark and lepton flavor fundamental to the NP?

- ⋆ No, small numbers look fine tuned just as in CKM model
- ⋆ Yes, this is a window to flavodynamics, e.g., gauged flavor — Crivellin et al, PRD91(2015)075006

No need for conclusions

The End