Summary remarks: a theorist's viewpoints

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Second LHCb open semitauonic workshop

LAL, Orsay, Nov 13–15, 2017

Disclaimers — plagiarizing Ben Grinstein

- I am not sure of the point of summarizing a two-day workshop, will express my opinions instead — “act now, apologize later”

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              Once in a while,
              I’m standing here, doing something.
Rumsfeld:     And I think,
              "What in the world am I doing here?"
              It’s a big surprise.
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- Let’s make this a discussion, please interrupt any time

[Sorry for missing & inconsistent referencing]

Prevalent evidence for new flavor physics...

Some key questions — now and in 10 yrs

- Can it be a theory issue? — not at the current level
- Can it be an experimental issue? — that's Vincenzo's job
- Are there [reasonable] models that fit the data? — yes [depends on you definition]

- Not a binary question: smallest effect in $R(D^{(*)})$ that can be established as NP?
  TBD: we know how to make progress
- Which channels are most interesting? (To establish deviation from SM / understand NP?)
  $B_{(s)} \to D_{(s)}^{(*,**)}\ell\bar{\nu}$, $\Lambda_b \to \Lambda_c^{(*)}\ell\bar{\nu}$, $B_c \to \psi\ell\bar{\nu}$, $B \to X_c\ell\bar{\nu}$, etc.
- Which calculations can be made most robust (both continuum and LQCD)?
- Status of $|V_{cb}|$?

my notation: $\ell = e, \mu, \tau$ and $l = e, \mu$

On theory uncertainties

- No clearly right way how to assign theory uncertainties (maybe except LQCD stat.)
- [strong interaction] model independent

  $\equiv$ theor. uncertainty suppressed by small parameters

  ... so theorists argue about $\mathcal{O}(1)\times$(small numbers) instead of $\mathcal{O}(1)$ effects

  Well defined starting point is crucial to claim a deviation from SM
- Most progress have come from expanding in $\Lambda_{\rm QCD}/m_Q$ and $\alpha_s(m_Q)$
  - Estimating higher orders in α_s by scale variation is not fail-safe
  - Can get unlucky (e.g., in some cases $\Lambda_{\rm QCD}/m_c$ expansion might not work well)

  Need experimental guidance: $f_\pi \sim 140\,{\rm MeV},\ m_\rho \sim 770\,{\rm MeV},\ m_K^2/m_s \sim 2\,{\rm GeV}$
- Consequently: pdf interpretation of theory uncertainties are fraught with peril

Reasons (not) to take the tension seriously

- Measurements with τ leptons are difficult
- Need a large tree-level contribution, SM suppression only by m_τ

  NP expected to show up in FCNCs — need fairly light NP to fit the data
- Strong constraints on concrete models from flavor physics, as well as high-p_T

- Results from BaBar, Belle, LHCb are consistent
- Often when BaBar and Belle disagreed in the past, averages were still meaningful
- If Nature were as most theorist imagined (until a few years ago), then the LHC (Tevatron, LEP, DM searches) should have discovered new physics already

My current view of B anomalies

- Lepton non-universality would be clear evidence for NP

  1) R_K and R_{K^*} $\sim 20\%$ correction to SM loop diagram $(B \to X\mu^+\mu^-)/(B \to Xe^+e^-)$

  2) $R(D)$ and $R(D^*)$ $\sim 20\%$ correction to SM tree diagram $(B \to X\tau\bar\nu)/(B \to X(e,\mu)\bar\nu)$

- Scales: $R_{K^{(*)}} <$ few $\times\, 10^1\,\mathrm{TeV}$, $R(D^{(*)}) <$ few $\times\, 10^0\,\mathrm{TeV}$ Bounds on NP scale!

  3) P_5' angular distribution (in $B \to K^*\mu^+\mu^-$) 4) $B_s \to \phi\mu^+\mu^-$ rate

- Theoretically cleanest: 1) and 2)

  Can fit 1), 3), 4) with one operator: $C_{9,\mu}^{(\mathrm{NP})}/C_{9,\mu}^{(\mathrm{SM})} \sim -0.2\,,\ C_{9,\mu} = (\bar s\gamma_\alpha P_L b)(\bar\mu\gamma^\alpha\mu)$

- Viable BSM models to fit all... Leptoquarks? (Fairly wild scenarios remain viable)

  No immediate connection to DM & hierarchy puzzle

  Is the hierarchy problem or the flavor problem more pressing for Nature?

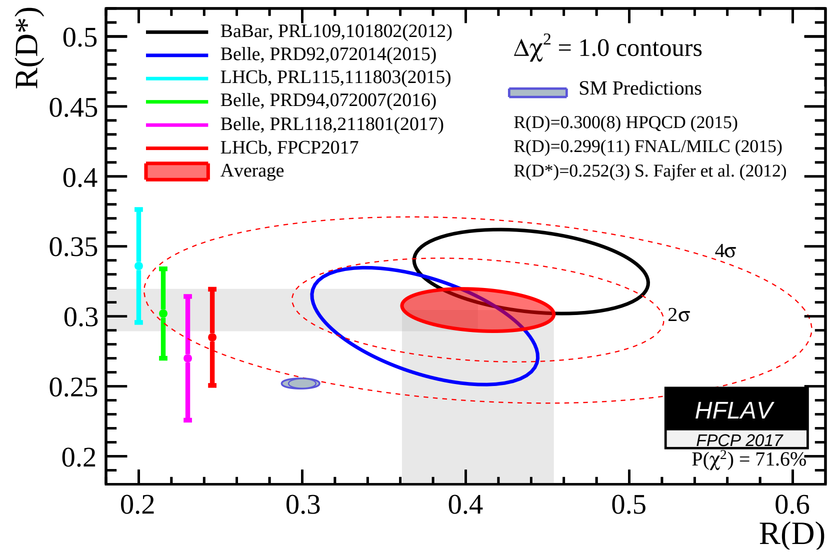
The data vs. the SM

- BaBar, Belle, LHCb: $R(X) = \dfrac{\Gamma(B \to X\tau\bar\nu)}{\Gamma(B \to X(e/\mu)\bar\nu)}$

  4.1σ from SM predictions — robust due to heavy quark symmetry $+$ lattice QCD (only D so far)

  more than statistics: $R(D^*)$ with $\tau \to \nu 3\pi$ [1708.08856]

  $B_c \to J/\psi\,\tau\bar\nu$ [LHCb @ LHCC]



- Imply NP at a fairly low scale (leptoquarks, W', etc.), likely visible at ATLAS / CMS

  Some of the models Fierz (mostly) to the same (SM) operator: distributions, τ polarization $=$ SM

- Tree level: three ways to insert mediator: $(b\nu)(c\tau)$, $(b\tau)(c\nu)$, $(bc)(\tau\nu)$

  overlap with ATLAS & CMS searches for $\tilde b$, leptoquark, $H^\pm$

$B \to D^{(*)}\ell\bar\nu$ and HQET

- Only Lorentz invariance: 6 functions of q^2, only 4 measurable with $e,\ \mu$ final states

$$\begin{aligned}
\langle D|\,\bar c\gamma^\mu b\,|\overline{B}\rangle &= f_+(q^2)(p_B+p_D)^\mu + \Big[f_0(q^2) - f_+(q^2)\Big]\frac{m_B^2-m_D^2}{q^2}\,q^\mu \\
\langle D^*|\,\bar c\gamma^\mu b\,|\overline{B}\rangle &= -ig(q^2)\,\epsilon^{\mu\nu\rho\sigma}\,\varepsilon^*_\nu\,(p_B+p_{D^*})_\rho\, q_\sigma \\
\langle D^*|\,\bar c\gamma^\mu\gamma^5 b\,|\overline{B}\rangle &= \varepsilon^{*\mu} f(q^2) + a_+(q^2)\,(\varepsilon^*\cdot p_B)\,(p_B+p_{D^*})^\mu + a_-(q^2)\,(\varepsilon^*\cdot p_B)\,q^\mu
\end{aligned}$$

  The a_- and $f_0 - f_+$, involving $q^\mu = p_B^\mu - p_{D^{(*)}}^\mu$, do not contribute for $m_l = 0$

- HQET: 1 Isgur-Wise function in $m_{c,b} \gg \Lambda_{\rm QCD}$ limit $+\,3$ more at $\mathcal{O}(\Lambda_{\rm QCD}/m_{c,b})$

- Measurable for e,μ : $B \to Dl\bar\nu$: $\mathrm{d}\Gamma/\mathrm{d}w$ (Only Belle published fully corrected distributions)
  $B \to D^*l\bar\nu$: $\mathrm{d}\Gamma/\mathrm{d}w + R_{1,2}(w)$ form factor ratios

- Can constrain all 4 functions from data $\Rightarrow$ $\mathcal{O}(\Lambda_{\rm QCD}^2/m_{c,b}^2\,,\ \alpha_s^2)$ uncertainties

- Difficult to estimate $\mathcal{O}(\Lambda_{\rm QCD}^2/m_{c,b}^2)$ terms $\Rightarrow$ check χ^2, dim. anal., LQCD

Assumptions and concerns

- Measurements based on CLN: $R_{1,2}(w) = \underbrace{R_{1,2}(1)}_{\text{fit}} + \underbrace{R'_{1,2}(1)}_{\text{fixed}}(w-1) + \underbrace{R''_{1,2}(1)}_{\text{fixed}}(w-1)^2/2$

HQET: $R_{1,2}(1) = 1 + \mathcal{O}(\Lambda_{\rm QCD}/m_{c,b}\,,\alpha_s)$ $\qquad R^{(n)}_{1,2}(1) = 0 + \mathcal{O}(\Lambda_{\rm QCD}/m_{c,b}\,,\alpha_s)$

All $\Lambda_{\rm QCD}/m_{c,b}$ terms depend on the same subleading Isgur-Wise fn-s

Sometimes calculations using QCD sum rule predictions for $\Lambda_{\rm QCD}/m_{c,b}$ corrections are called the HQET predictions

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- Calculations of $\mathcal{O}(\Lambda_{\rm QCD}/m_{c,b})$ terms are model dependent
  ... except LQCD, or fitting them from $B \to D^{(*)} l\bar\nu$ data
- Fitted values of $R_{1,2}(1)$ change a lot if slope & curvature not fixed
- Can be compared / cross checked with LQCD calculations soon
- Revisit to fit different theor. param. inside the experimental analysis frameworks?
- Exemplifies: result with the smallest uncertainty need not be the best one

SM predictions for $R(D^{(*)})$

- Small variations: heavy quark symmetry & phase space leave little wiggle room

Reference (Scenario)	$R(D)$	$R(D^*)$	Correlation
Data [HFAG]	0.403 ± 0.047	0.310 ± 0.017	-23%
Lattice [FLAG]	0.300 ± 0.008	—	—
Fajfer et al. '12	—	0.252 ± 0.003	—
Bernlochner *et al.* '17 ($L_{w\geq1}$)	0.298 ± 0.003	0.261 ± 0.004	19%
Bernlochner *et al.* '17 ($L_{w\geq1}$+SR)	0.299 ± 0.003	0.257 ± 0.003	44%
Bigi, Gambino '16	0.299 ± 0.003	—	—
Bigi, Gambino, Schacht '17	—	0.260 ± 0.008	—
Jaiswal, Nandi, Patra '17 (case-3)	0.302 ± 0.003	0.262 ± 0.006	14%
Jaiswal, Nandi, Patra '17 (case-2)	0.302 ± 0.003	0.257 ± 0.005	13%

- All 2017 prediction for $R(D^*)$ higher than Fajfer et al., shown in the HFAG plots

Light-cone QCD SR & HQET QCD SR inputs are model dependent

None of these are "ultimate" results — can be improved in coming years

Inclusive / exclusive $|V_{cb}|$ resolved?

- Two other fits (few days later), only to the Belle $B \to D^* l\bar{\nu}$ data:

Bigi, Gambino, Schacht, 1703.06124, $|V_{cb}|_{\rm BGL} = (41.7^{+2.0}_{-2.1}) \times 10^{-3}$

Grinstein & Kobach, 1703.08170, $|V_{cb}|_{\rm BGL} = (41.9^{+2.0}_{-1.9}) \times 10^{-3}$

Belle, 1702.01521, $|V_{cb}|_{\rm CLN} = (38.2 \pm 1.5) \times 10^{-3}$

- Fitting the same data: if correlation near 100%, substantial inconsistency

- Fits getting "large" $|V_{cb}|$ w/o QCDSR input $\Rightarrow R_1(w)$ in tension w/ HQET & LQCD

- Phill: m_l^2/q^2 effects, important near $q^2 = 0$, exclude maximal w bin?
Not easy with unfolded data (correlation mx) $\Rightarrow$ fit multiple theory param in expt?

- It is usually easy to tell when theorists agree, and when they don't...
(No arguments about well understood phenomena)

D^{**} and higher excited states

- Puzzles remain concerning $\sum$ exclusive $=$ inclusive
- The $B \to D_0^*\pi$ rate remains very puzzling, it is $\ll B \to D_2^*\pi$ and $B \to D_1\pi$

  Only use small fraction of BaBar & Belle data $+$ LHCb

  Any measurements / improvements / clarifications are eagerly awaited
- $D_{s0}^*(2317)$: orbitally excited state or "molecule"?

  If D_{s0}^* is excited $c\bar{s}$ state, predict $\mathcal{B}(D_{s0}^* \to D_s^*\gamma)/\mathcal{B}(D_{s0}^* \to D_s\pi)$ above CLEO bound, < 0.059 [Mehen & Springer, hep-ph/0407181; Colangelo & De Fazio, hep-ph/0305140; Godfrey, hep-ph/0305122]

  CLEO used 13.5/fb, the Belle bound < 0.18 used $87/\text{fb}$, the BaBar bound < 0.16 used $232/\text{fb}$
- As in $B \to D^{(*)}\ell\bar{\nu}$, HQS relates form factors $\propto q_\mu$ to those measurable for $m_l = 0$

  Precise measurements of $B \to D^{(*)}l\bar{\nu}$ will be important

$B \to D^{**}\ell\bar{\nu}$: consequences of HQET

- Schematic form of $B \to D^{(*,**)}\ell\bar{\nu}$ rates: $[\varepsilon^n \sim (\Lambda_{\rm QCD}/m_Q)^n]$

$$\frac{\mathrm{d}\Gamma_{D^*}}{\mathrm{d}w} \sim \sqrt{w^2-1}\,\Big[\big(1_{\rm (HQS)} + 0_{\rm (Luke)}\,\varepsilon + \varepsilon^2 + \ldots\big) + (w-1)\,(1+\varepsilon+\ldots) + \ldots\Big]$$

$$\frac{\mathrm{d}\Gamma_{D,\,D_0^*}}{\mathrm{d}w} \sim (w^2-1)^{3/2} \text{ in the SM and for } m_\ell = 0$$

$\sqrt{w^2-1}$ terms for D (D_0^*) have the same structure as D^* above (D_1, D_1^* below)

$$\frac{\mathrm{d}\Gamma_{D_1,\,D_1^*}}{\mathrm{d}w} \sim \sqrt{w^2-1}\,\Big[\big(0_{\rm (HQS)} + 0_{\rm (HQS)}\,\varepsilon + \varepsilon^2 + \ldots\big) + (w-1)\,(1+\varepsilon+\ldots) + \ldots\Big]$$

$$\frac{\mathrm{d}\Gamma_{D_2^*}}{\mathrm{d}w} \sim (w^2-1)^{3/2} \quad \text{for all terms} \Rightarrow \text{no constraints}$$

- For $B \to D^{**}\ell\bar{\nu}$, the $\mathcal{O}(\Lambda_{\rm QCD}/m_Q)$ corrections can be very important, due to suppression at $w=1$ in heavy quark limit

- $(w-1)^0\,\varepsilon^2$ terms determined by hadron masses and leading Isgur-Wise fn [LLSW]

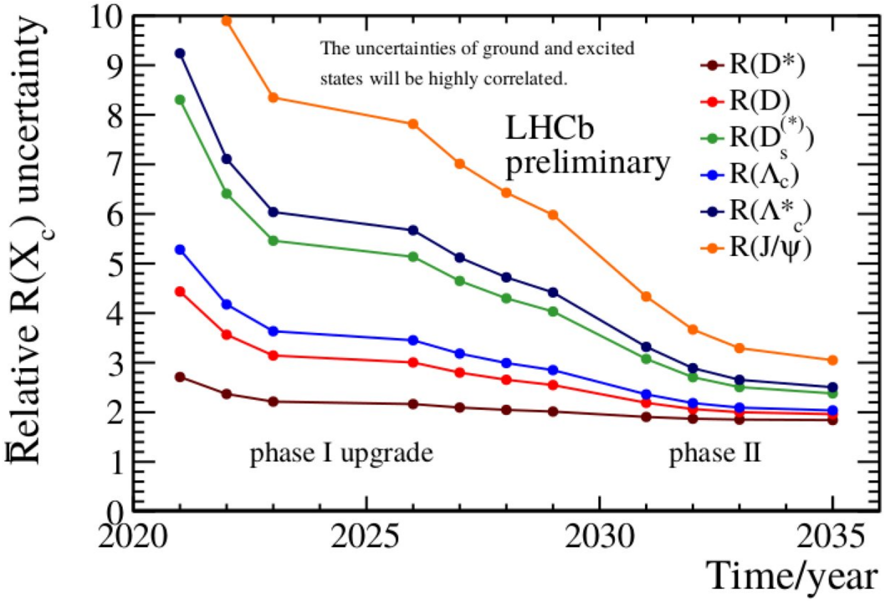
A few more comments

- Better constraints on (in)equality of e and μ modes — what are the ultimate limits?
- Measure inclusive $B \to X_c \tau \bar{\nu}$ (not since LEP 1)
- Largely different theoretical methods: $B_{(s)} \to D_{(s)}^{(*,**)} \ell\bar{\nu}$, $B_c \to \psi\ell\bar{\nu}$, $B \to X_c\ell\bar{\nu}$
- One LQCD collaboration dominates each calc. — need independent confirmation

Final remarks

Exciting future

- LHCb:



Belle II ($50/$ab, at SM level):

$\delta R(D) \sim 0.005$ (2%)

$\delta R(D^*) \sim 0.010$ (3%)

Measurements will improve by a lot!

(Even if central values change, plenty of room for establishing deviation from SM)

- Competition, complementarity, cross-checks between LHCb and Belle II will be crucial to make a convincing case

- Maximal useful B physics data $\gg$ LHCb & Belle II (Belle II / ARGUS $\sim 10^6$)

Lepton universality $\to$ lepton flavor violation

- Connection to LFV: "any departure from lepton universality is necessarily associated with the violation of lepton flavor conservation. No known symmetry principle can protect the one in the absence of the other." [Glashow, Guadagnoli, Lane, 1411.0565]

- Same issue as generic new physics altering FCNCs in the quark sector

- With a given leptoquark model and patterns of couplings, can make predictions:

$$\mathcal{B}(B \to K\mu^\pm e^\mp) \simeq 3 \cdot 10^{-8}\,\kappa^2 \left(\frac{1-R_K}{0.23}\right)^2, \qquad \mathcal{B}(\mu \to e\gamma) \simeq 2 \cdot 10^{-12}\,\frac{\kappa^2}{\rho^2} \left(\frac{1-R_K}{0.23}\right)^2,$$

$$\mathcal{B}(B \to K e^\pm \tau^\mp) \simeq 2 \cdot 10^{-8}\,\kappa^2 \left(\frac{1-R_K}{0.23}\right)^2, \qquad \mathcal{B}(\tau \to e\gamma) \simeq 4 \cdot 10^{-14}\,\frac{\kappa^2}{\rho^2} \left(\frac{1-R_K}{0.23}\right)^2,$$

$$\mathcal{B}(B \to K\mu^\pm \tau^\mp) \simeq 2 \cdot 10^{-8} \left(\frac{1-R_K}{0.23}\right)^2, \qquad \mathcal{B}(\tau \to \mu\gamma) \simeq 3 \cdot 10^{-14}\,\frac{1}{\rho^2} \left(\frac{1-R_K}{0.23}\right)^2,$$

[de Medeiros Varzielas, Hiller, 1503.01084]

Congratulations to Helen Quinn!

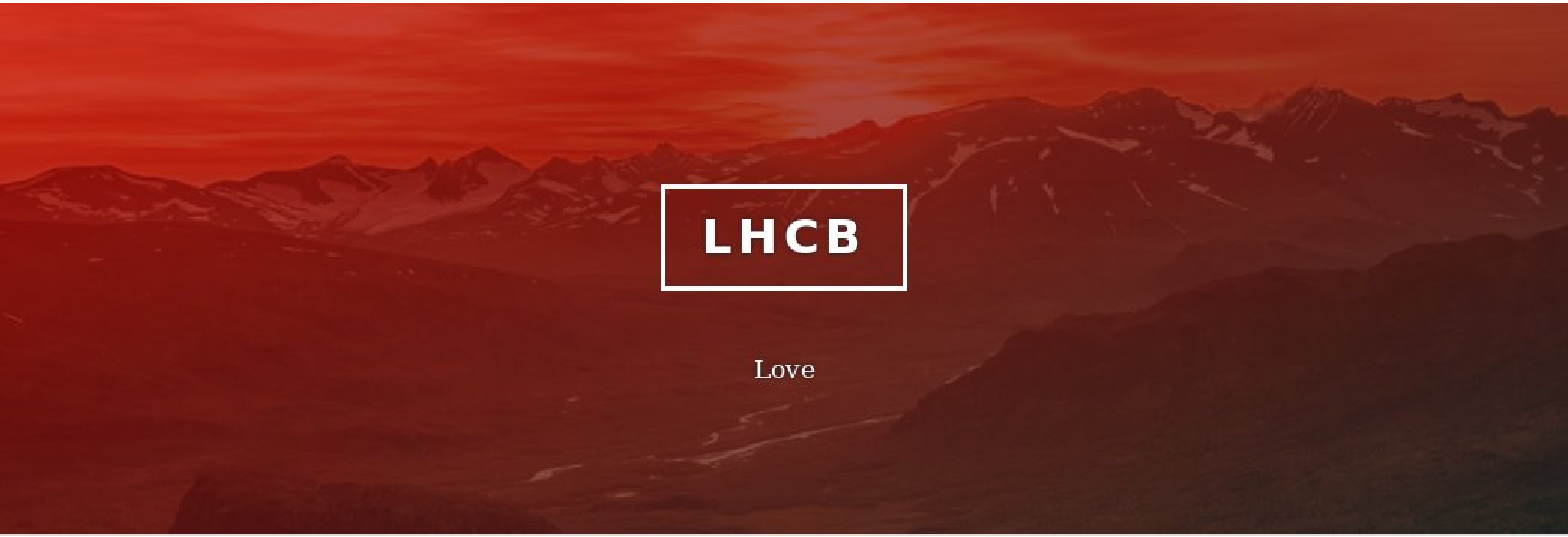
2018 Benjamin Franklin Medal in Physics

Helen Rhoda Quinn, Ph.D.
Stanford University
SLAC National Accelerator Laboratory
Stanford, California

For her pioneering contributions to the long-term quest for a unified theory of the strong, weak, and electromagnetic interactions of fundamental particles.

Huge impact on B physics, both with orignal papers & the BaBar Physics Book

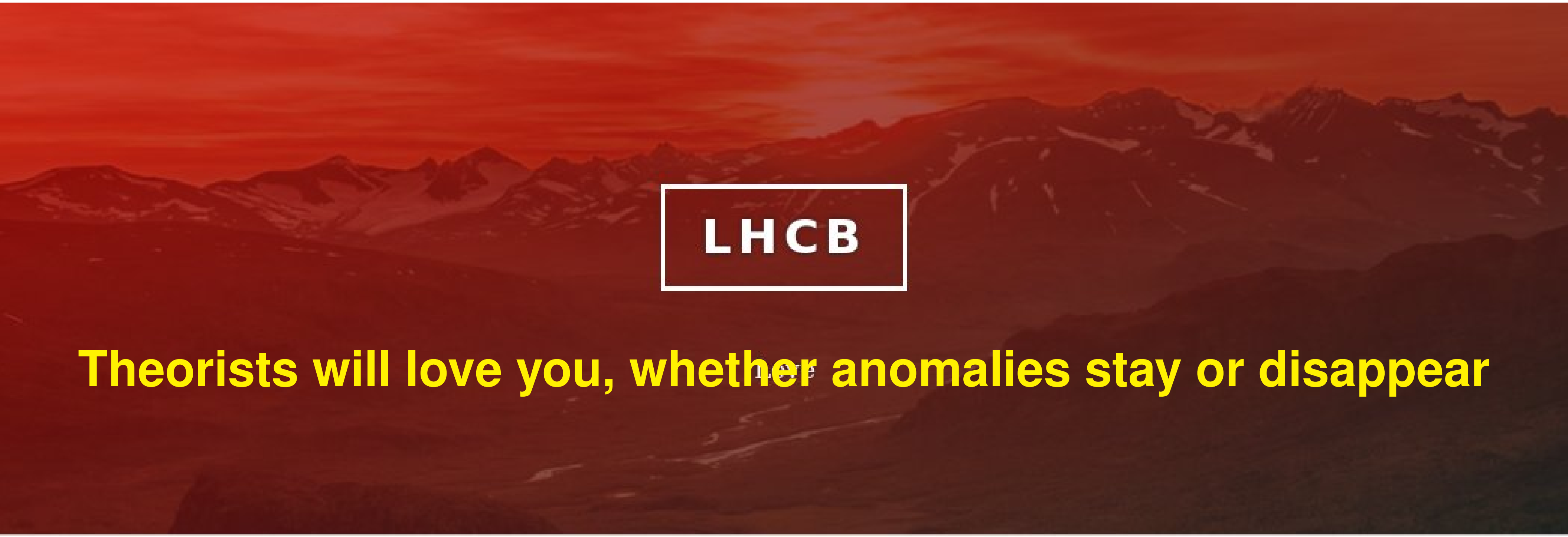
(20 years ago, workshops right here, soon after CLEO saw $B \to K\pi \Rightarrow$ large penguins)



Today’s lhcb.org Topic: Love and Forgiveness

adminlhcb | October 6, 2017

It’s sometimes difficult to feel love when someone has hurt you. And sometimes it’s even harder to feel forgiving towards them. So, today at lhcb.org, I want to just touch on this topic.



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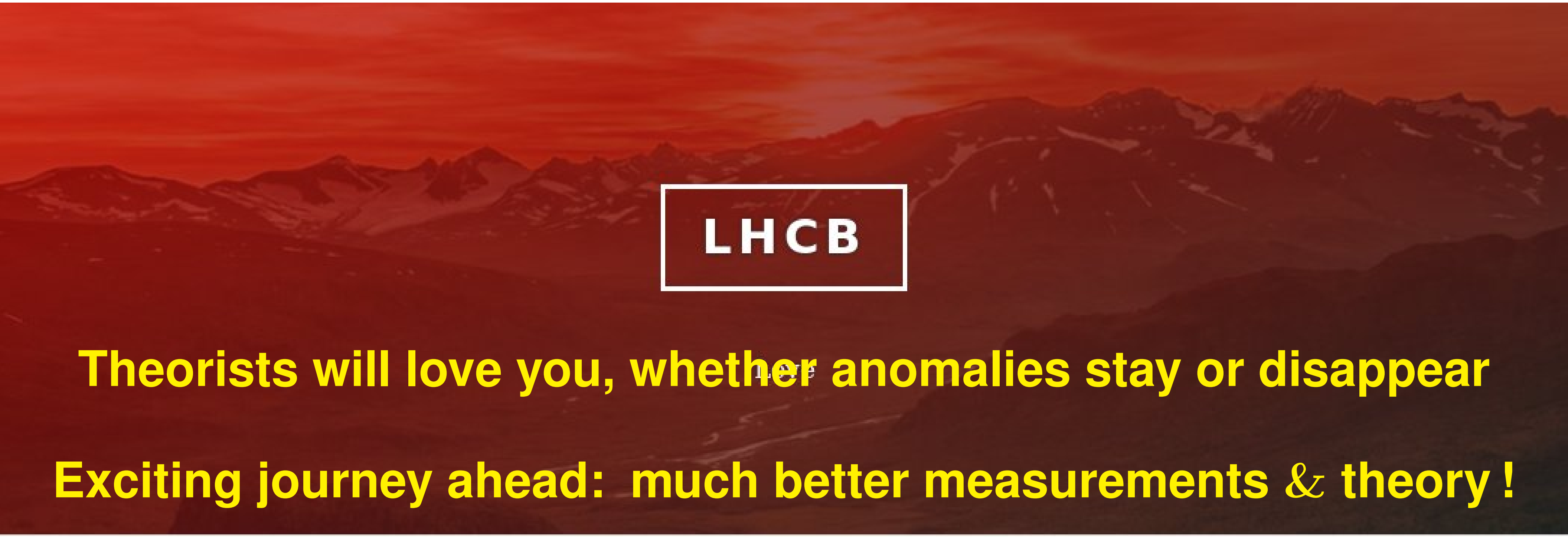

Theorists will love you, whether anomalies stay or disappear

Exciting journey ahead: much better measurements & theory !

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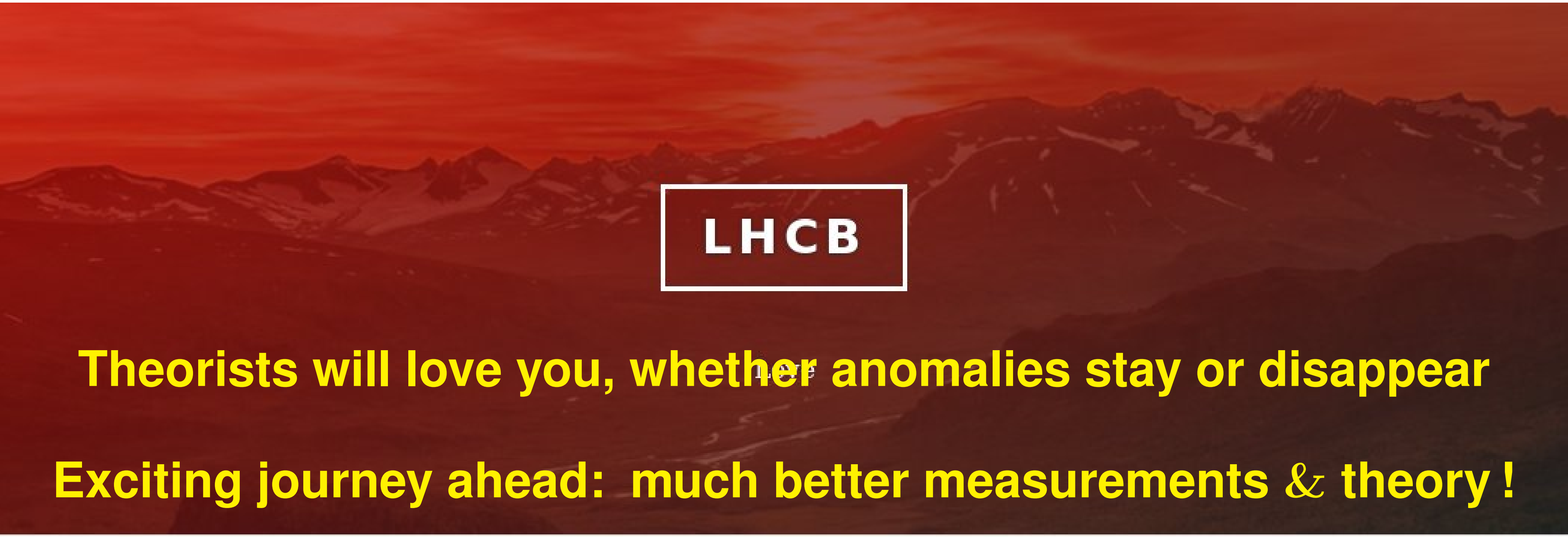

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Exciting journey ahead: much better measurements & theory !

Thank you for inviting theorists, and ensuring a very informal workshop

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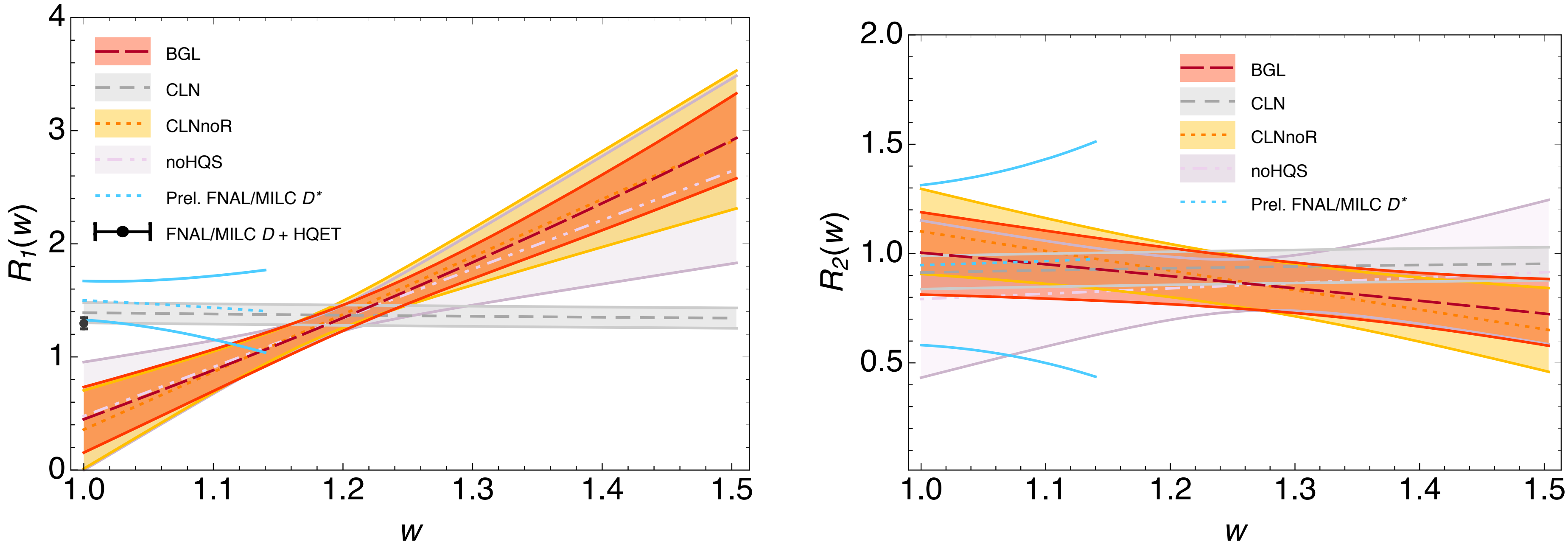
Extra slides

Tensions remain...

- Larger values of $|V_{cb}| \longleftrightarrow R_1$ far from heavy quark symmetry



This would be a spectacular breakdown of heavy quark symmetry

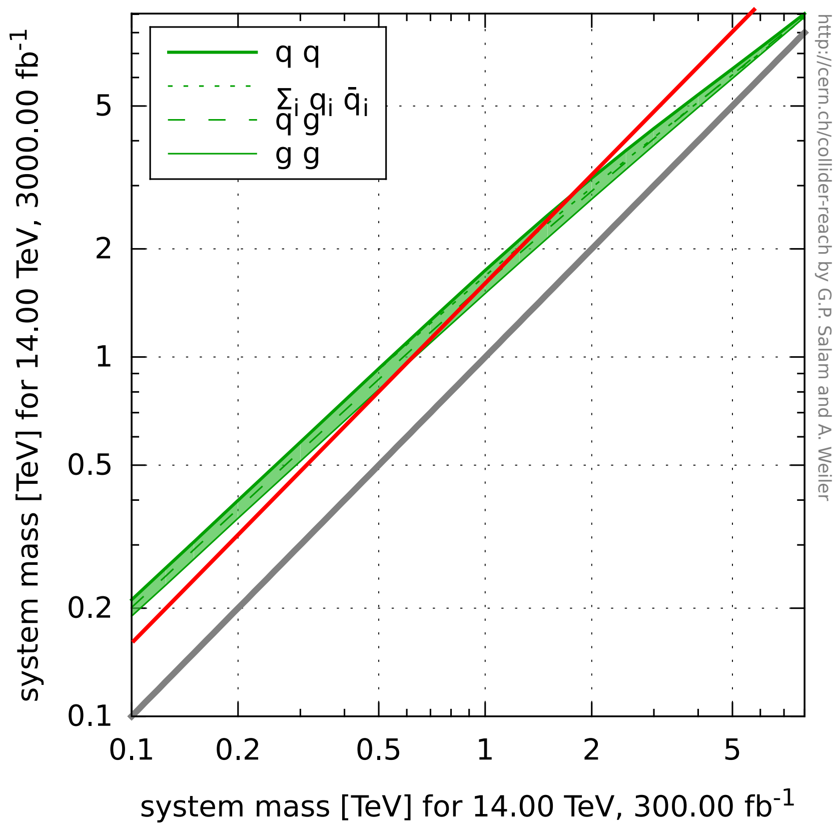
Tension w/ prelim. lattice QCD results for R_1 — same calculation determines $F(1)$

- If issues with lattice $\Rightarrow$ cannot trust $|V_{cb}|$

  If issues with data $\Rightarrow$ cannot trust $|V_{cb}|$

ATLAS/CMS 300→3000/fb vs. LHCb 50→300/fb

- $\sqrt[4]{6} \sim 1.6$ vs. mass-scale increase at $14\,\mathrm{TeV}$, 300 → 3000/fb [http://collider-reach.web.cern.ch/]



- Increase in mass limit > 1.6, iff limit with 300/fb at 14TeV is below $\sim 1\,\mathrm{TeV}$

  Weakly produced particles and/or difficult decays — not your typical Z', $\tilde{q}$, $\tilde{g}$