The Role of Flavor in 2016

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The Role of Flavor in ~~2016~~ 2026

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The year of many mood changes...

- Sometimes it feels like being in heaven, sometimes... not quite...

  Key roles of Δm_K and ϵ_K remain — vs. flood of CP viol. data, exploring Higgs flavor, etc.

- The LHC runs amazingly well $\Rightarrow$ many new results soon
  - Some hints of NP come and go ($750\,\mathrm{GeV}$...)
  - 2016 data more than $10\times$ that in 2015

    Big increase in mass scale sensitivity — long time until the next such

  Congratulations to India on becoming an Associate Member State of CERN a week ago!

- Exp.: NA62 data taking, Belle II approaching, LHCb future upgrade discussions

  $+$ improving EDM, CLFV, dark matter, etc., experiments

Guaranteed excitement of probing and understanding the SM much better
(recent discoveries of unexpected hadronic states)

Hope of discovering BSM phenomena

The SM cannot be the full story

- Evidence that the SM is incomplete:
  - Dark matter
  - Baryon asymmetry of the Universe
  - Neutrino mass (lepton number violated?)

  May be connected to the TeV scale: wimp, baryogenesis, but many other options

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- Hierarchy puzzle (Is $126\,\mathrm{GeV}$ scalar $=$ SM Higgs? why so light? why so heavy?)

  In the 90s, most theorists expected NP discoveries well before current sensitivities

  (Many talks on how SUSY cascades would cause problems to understand LHC signals)

  Since then, Dark energy: missing something completely? asking the right questions?

The scale of new physics?

- Theoretical prejudices about new physics did not work as expected 10–20yrs ago

  Arguments quite compelling, eagerly awaiting $13\,\mathrm{TeV}$ LHC results

- Leave no stone unturned searching for NP — but no guarantees after Higgs

- Maybe measures of fine tuning are off, and NP is an order of magnitude heavier?

  Flavor may be even more important (deviation from SM $\to$ upper bound on scale)

- New physics at LHC — MFV probably useful approximation to its flavor structure

  $\Updownarrow$

  New physics at $10^{1-2}\,\mathrm{TeV}$ — less strong flavor suppression (MFV less motivated)

- Discovering deviations from the SM flavor sector is possible in either case (LHC-scale MFV-like, or heavier more generic scenarios)

- Potential for surprises: lepton flavor violation, dark sectors (invisible), etc.

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CP violation itself was a surprise

PROPOSAL FOR K^o_2 DECAY AND INTERACTION EXPERIMENT

J. W. Cronin, V. L. Fitch, R. Turlay

(April 10, 1963)

I. INTRODUCTION

The present proposal was largely stimulated by the recent anomalous results of Adair et al., on the coherent regeneration of K^o_1 mesons. It is the purpose of this experiment to check these results with a precision far transcending that attained in the previous experiment. Other results to be obtained will be a new and much better limit for the partial rate of $K^o_2 \to \pi^+ + \pi^-$, a new limit for the presence (or absence) of neutral currents as observed through $K_2 \to \mu^+ + \mu^-$. In addition, if time permits, the coherent regeneration of K_1's in dense materials can be observed with good accuracy.

II. EXPERIMENTAL APPARATUS

Fortuitously the equipment of this experiment already exists in operating condition. We propose to use the present 30° neutral beam at the A.G.S. along with the di-pion detector and hydrogen target currently being used by Cronin, et al. at the Cosmotron. We further propose that this experiment be done during the forthcoming μ-p scattering experiment on a parasitic basis.

The di-pion apparatus appears ideal for the experiment. The energy resolution is better than 4 Mev in the m^* or the Q value measurement. The origin of the decay can be located to better than 0.1 inches. The 4 Mev resolution is to be compared with the 20 Mev in the Adair bubble chamber. Indeed it is through the greatly improved resolution (coupled with better statistics) that one can expect to get improved limits on the partial decay rates mentioned above.

III. COUNTING RATES

We have made careful Monte Carlo calculations of the counting rates expected. For example, using the 30° beam with the detector 60-ft. from the A.G.S. target we could expect 0.6 decay events per 10^{11} circulating protons if the K_2 went entirely to two pions. This means that one can set a limit of about one in a thousand for the partial rate of $K_2 \to 2\pi$ in one hour of operation. The actual limit is set, of course, by the number of three-body K_2 decays that look like two-body decays. We have not as yet made detailed calculations of this. However, it is certain that the excellent resolution of the apparatus will greatly assist in arriving at a much better limit.

If the experiment of Adair, et al. is correct the rate of coherently regenerated K_1's in hydrogen will be approximately 80/hour. This is to be compared with a total of 20 events in the original experiment. The apparatus has enough angular acceptance to detect incoherently produced K_1's with uniform efficiency to beyond 15°. We emphasize the advantage of being able to remove the regenerating material (e.g., hydrogen) from the neutral beam.

IV. POWER REQUIREMENTS

The power requirements for the experiment are extraordinarily modest. We must power one 18-in. x 36-in. magnet for sweeping the beam of charged particles. The two magnets in the di-pion spectrometer are operated in series and use a total of 20 kw.

⇒ Cronin & Fitch, Nobel Prize, 1980

⇒ 3 generations, Kobayashi & Maskawa, Nobel Prize, 2008

1. **Observation of a broad structure in the $\pi^+\pi^- J/\psi$ mass spectrum around 4.26-GeV/c^2**
BaBar Collaboration (Bernard Aubert (Annecy, LAPP) *et al.*). Jun 2005. 7 pp.
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ADS Abstract Service; BaBar Publications Database; BaBar Password Protected Publications Database; Link to PRESSRELEASE; Phys. Rev. Lett. Server; SLAC Document Server; SLAC Document Server
Detailed record - Cited by 606 records 500+

2. **Study of the $B \to J/\psi K^- \pi^+ \pi^-$ decay and measurement of the $B \to X(3872) K^-$ branching fraction**
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BaBar, 500+ cites

↑ Surprises: “new” QCD states

↓ SM-like: CP violation

1. **Observation of a resonance-like structure in the pi+- psi-prime mass distribution in exclusive B ---> K pi+- psi-prime decays**
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Belle Collaboration (Kazuo Abe (KEK, Tsukuba) *et al.*). Aug 2004. 10 pp.
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Belle, 6 top cited

↑ Surprises: “new” QCD states

↓ SM-like: CP violation

LHCb, top cites

1. **Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays**
LHCb Collaboration (Roel Aaij (CERN) *et al.*). Jul 13, 2015. 15 pp.
Published in **Phys.Rev.Lett. 115 (2015) 072001**
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CERN Document Server; ADS Abstract Service; Interactions.org article; Link to BBC News article; Link to SYMMETRY; Link to Discovery.com news article; Link to Nature News article; Link to PBS website; Link to Scientific American article
Detailed record - Cited by 273 records 250+

2. **Test of lepton universality using $B^+ \to K^+ \ell^+ \ell^-$ decays**
LHCb Collaboration (Roel Aaij (NIKHEF, Amsterdam) *et al.*). Jun 25, 2014. 10 pp.
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3. **Measurement of Form-Factor-Independent Observables in the Decay $B^0 \to K^{*0} \mu^+ \mu^-$**
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4. **Measurement of the $B_s^0 \to \mu^+ \mu^-$ branching fraction and search for $B^0 \to \mu^+ \mu^-$ decays at the LHCb experiment**
LHCb Collaboration (R. Aaij (NIKHEF, Amsterdam) *et al.*). Jul 18, 2013. 9 pp.
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5. **First Evidence for the Decay $B_s^0 \to \mu^+ \mu^-$**
LHCb Collaboration (R Aaij (NIKHEF, Amsterdam) *et al.*). Nov 2012. 9 pp.
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6. **Evidence for CP violation in time-integrated $D^0 \to h^- h^+$ decay rates**
LHCb Collaboration (R. Aaij (NIKHEF, Amsterdam) *et al.*). Dec 2011. 8 pp.
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Hints: lepton flavor violation?
(started @ BaBar & Belle)

Come & gone: D direct CP viol.

Surprises: more "new" QCD

SM-like: $B_s \to \mu^+ \mu^-$
CP violation in B_s

Outline — rest of this talk

- Near future: current tensions with SM — most often talked about

  best chance to become decisive soon (unless fluctuations)

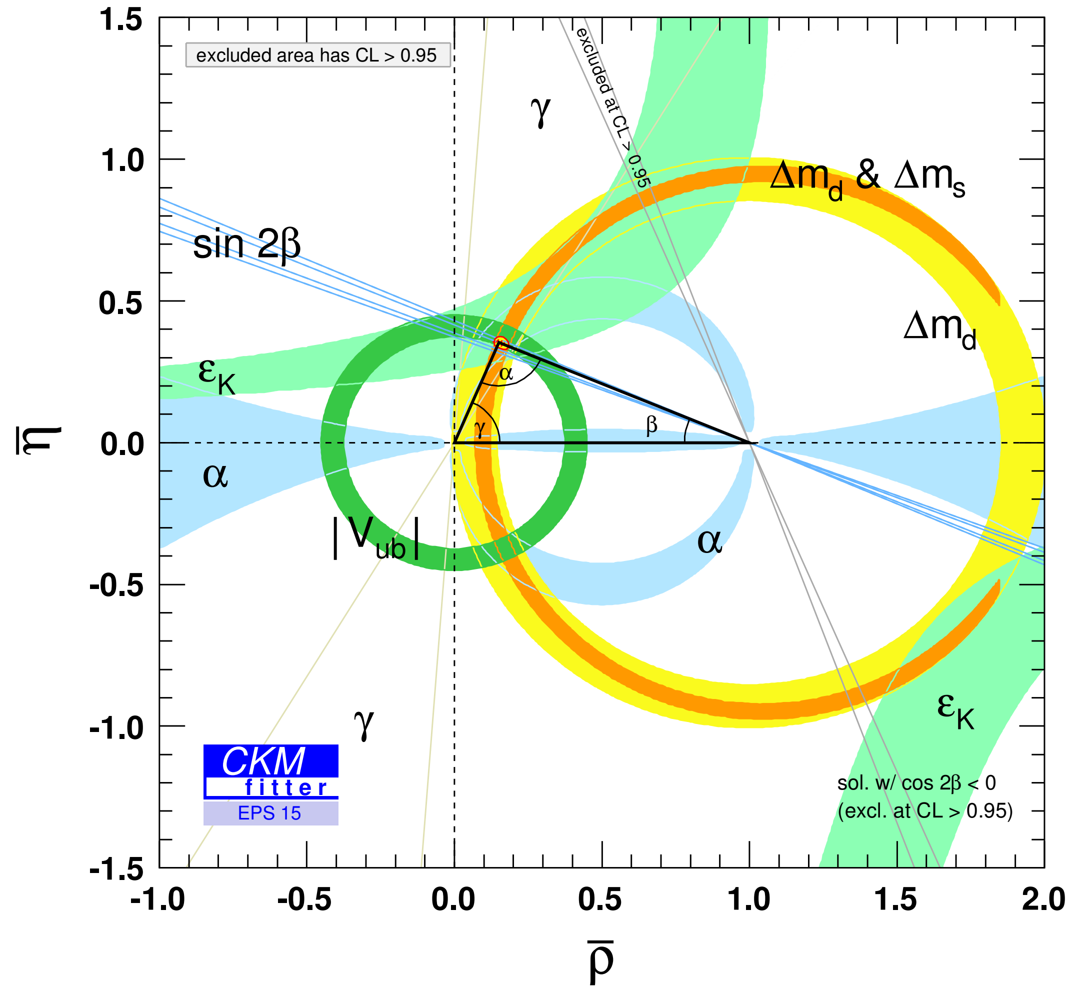
- Far future: large improvements in new physics sensitivity

  two examples: meson mixing & vector-like fermions

- LHC high-p_T flavor: top, higgs, BSM

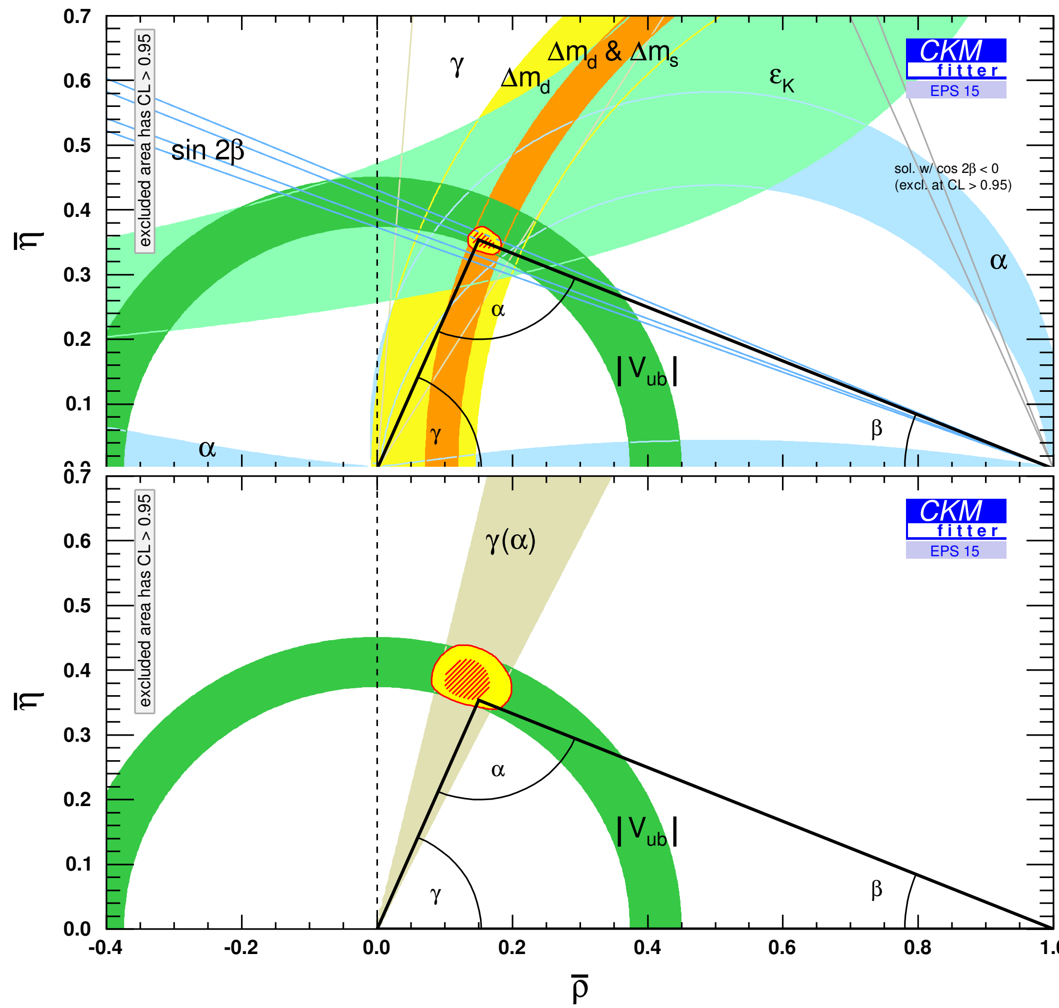
The standard model CKM fit

- SM dominates CP viol. $\Rightarrow$ KM Nobel
- The implications of the consistency often overstated



The standard model CKM fit

- SM dominates CP viol. $\Rightarrow$ KM Nobel
- The implications of the consistency often overstated
- Larger allowed region if the SM is not assumed
- Tree-level (mainly V_{ub} & γ) vs. loop-dominated measurements crucial



- $\mathcal{O}(20\%)$ NP contributions to most loop-level processes (FCNC) are still allowed

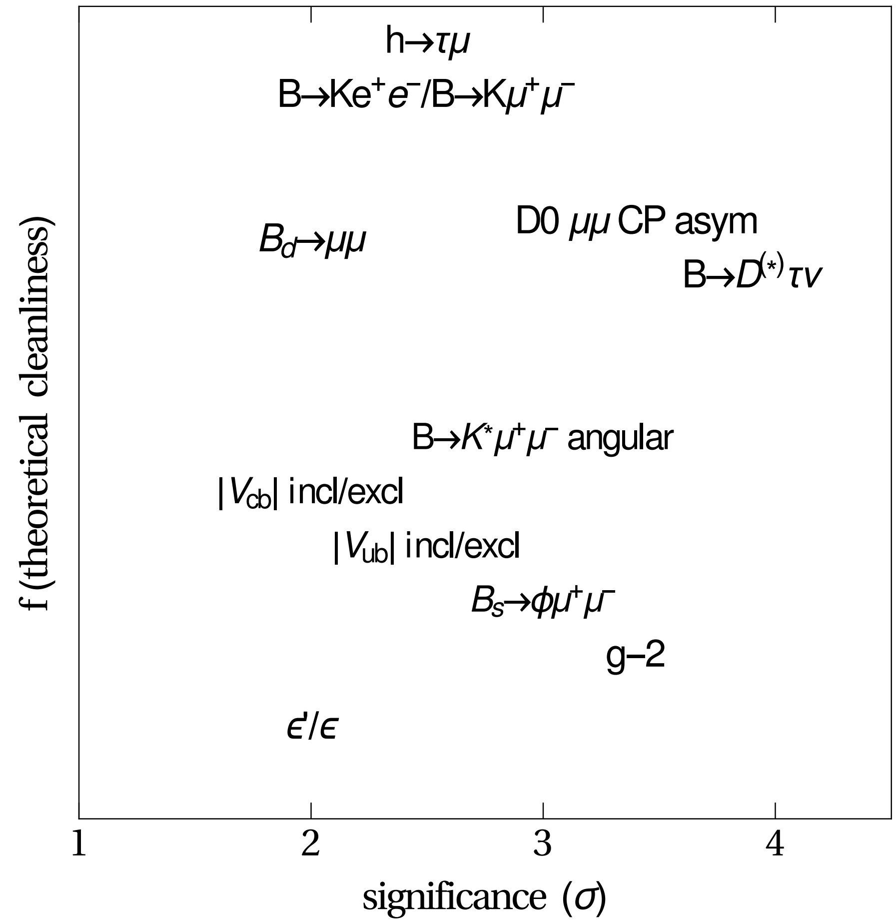
Flavor anomalies: (subjective) status

- Intriguing tensions with the SM predictions
- Some could be unambiguous BSM signals

  Except for theoretically cleanest modes, cross-checks are needed case

  – measurements of related observables

  – independent theory / lattice calculations



- Each could be a whole talk — only a few comments

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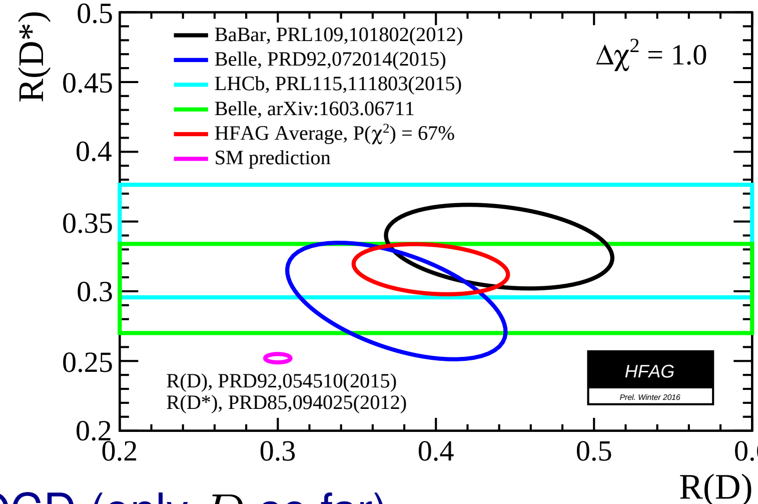
The $B \to D^{(*)}\tau\bar{\nu}$ decay rates

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

  Nearly 4σ from the SM predictions!

	$R(D)$	$R(D^*)$
World average	0.397 ± 0.049	0.316 ± 0.016
SM expectation	0.300 ± 0.010	0.252 ± 0.005
Belle II, 50/ab	± 0.010	± 0.005



Robust SM predictions: heavy quark symmetry + lattice QCD (only D so far)

- Tension: $R(D^{(*)})$ vs. $\mathcal{B}(b \to X\tau^+\nu) = (2.41 \pm 0.23)\%$ (LEP) [Freytsis, ZL, Ruderman]

  SM: $R(X_c) = 0.223 \pm 0.004$ — no $\mathcal{B}(B \to X\tau\bar{\nu})$ measurement since LEP

  Need NP at a fairly low scale (leptoquarks, W', etc.), likely visible at the LHC

  [Fajfer, Kamenik, Nisandzic, Zupan, many others]

- Next: LHCb result with hadronic τ decays, measure $R(D)$, maybe Λ_b decay

- Future experimental precision will match current theory uncertainty (improvable)

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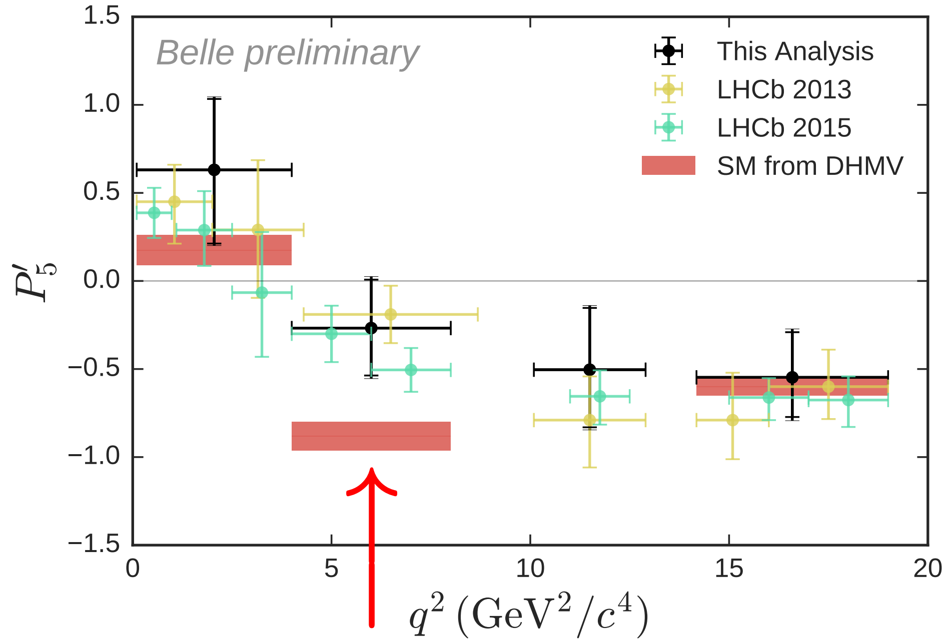
$B \to K^* \mu^+ \mu^-$: the P_5' anomaly

- "Optimized observables" [1202.4266 + long history]
  (some assumptions about what's optimal)

  Global fits: best solution: NP reduces C_9

  [Altmannshofer, Straub; Descotes-Genon, Matias, Virto; Jager, Martin Camalich; Bobet, Hiller, van Dyk; many more]

  Difficult for lattice QCD, large recoil



NP, fluctuation, SM theory?

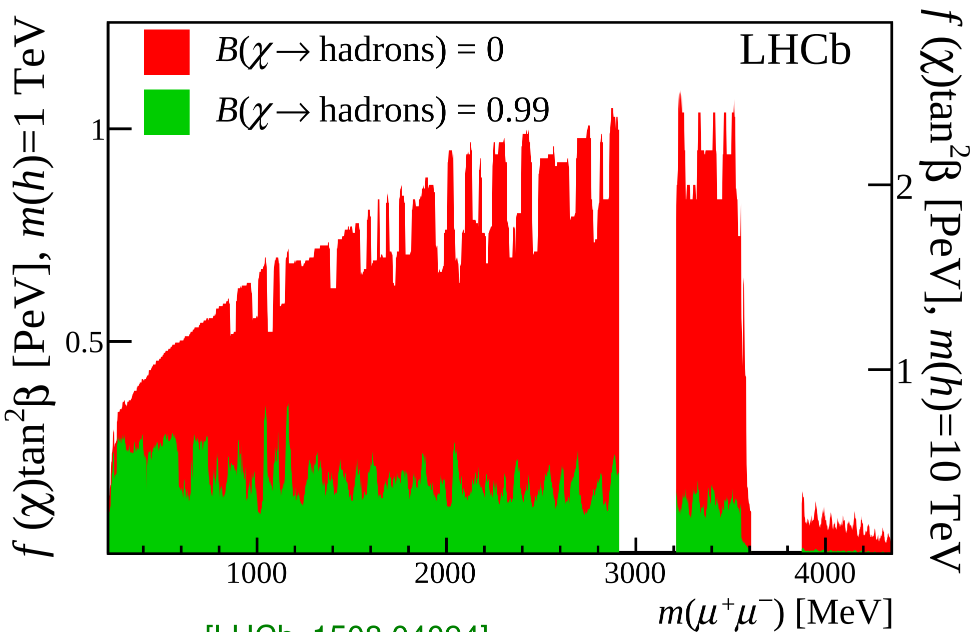
- Tests: other observables, q^2 dependence, B_s and Λ_b decays, other final states

- Connected to many other processes: Is the $c\bar{c}$ loop tractable perturbatively at small q^2? Can one calculate form factors (ratios) reliably at small q^2?
  Impacts many observables: semileptonic & nonleptonic, interpreting CP viol., etc.

Dark sectors: bump hunting in $B \to K^* \mu^+ \mu^-$

- Nearly and order of magnitude improvement due to dedicated LHCb analysis

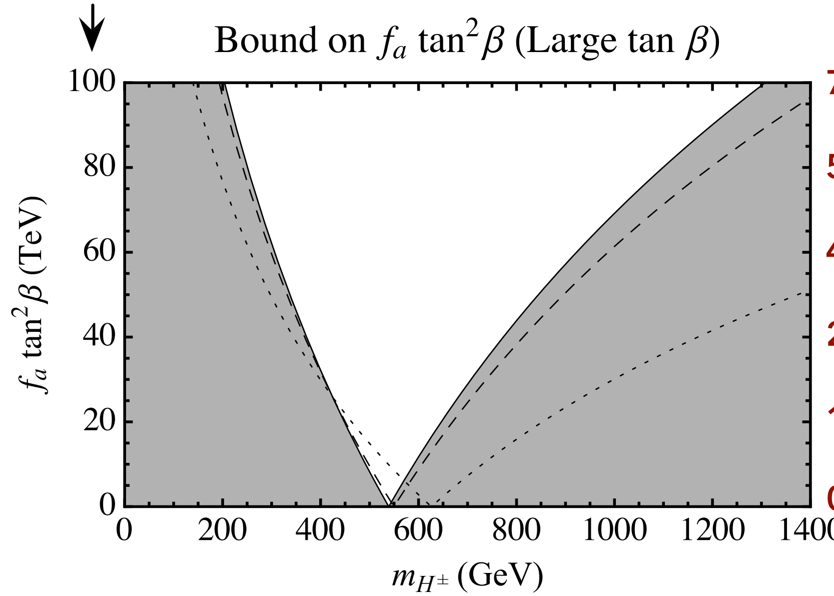
In "axion portal" models, scalar couples as $(m_\psi / f_a)\, \bar\psi \gamma_5 \psi\, a$ (m_t coupling in loops)



[LHCb, 1508.04094]

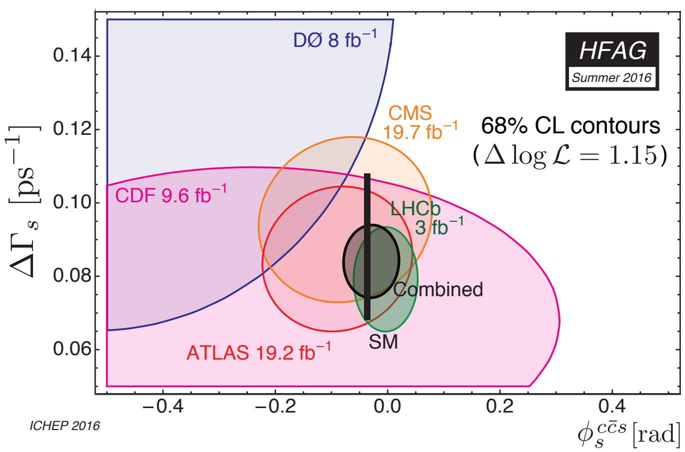
Freytsis, Ligeti, Thaler [0911.5355]

LHCb, m(a) = 600 MeV [1508.04094]

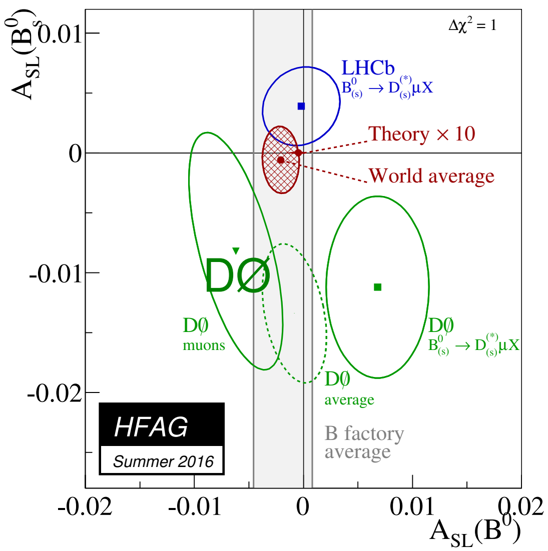


- Several future LHCb dark photon search proposals [Ilten et al., 1603.08926, 1509.06765]

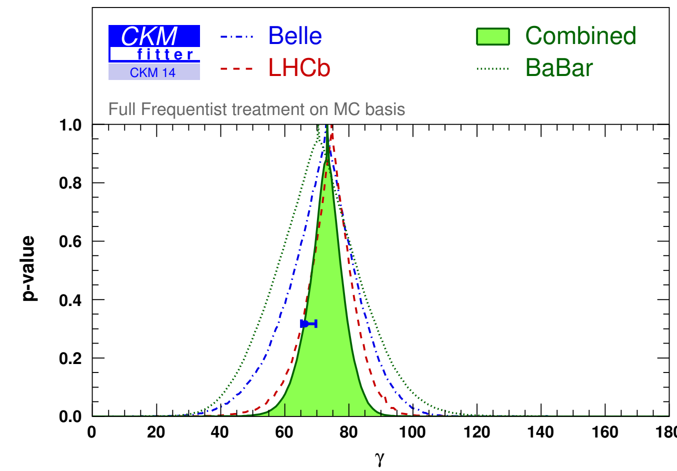
Some other highlights



CP violation in $B_s \to \psi\phi$ now consistent with SM



$A_{\rm SL}$: important, indep. of DØ anomaly



Measurements of γ crucial, LHCb is now most precise

- Uncertainty of predictions $\ll$ current experimental errors ($\Rightarrow$ seek lot more data)
- I have nothing new to add about $h \to \tau\mu$ and hint of violation of lepton universality in $B \to K\mu^+\mu^-$ vs. $B \to Ke^+e^-$ — dramatic implications if established

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Charm CP violation and mixing

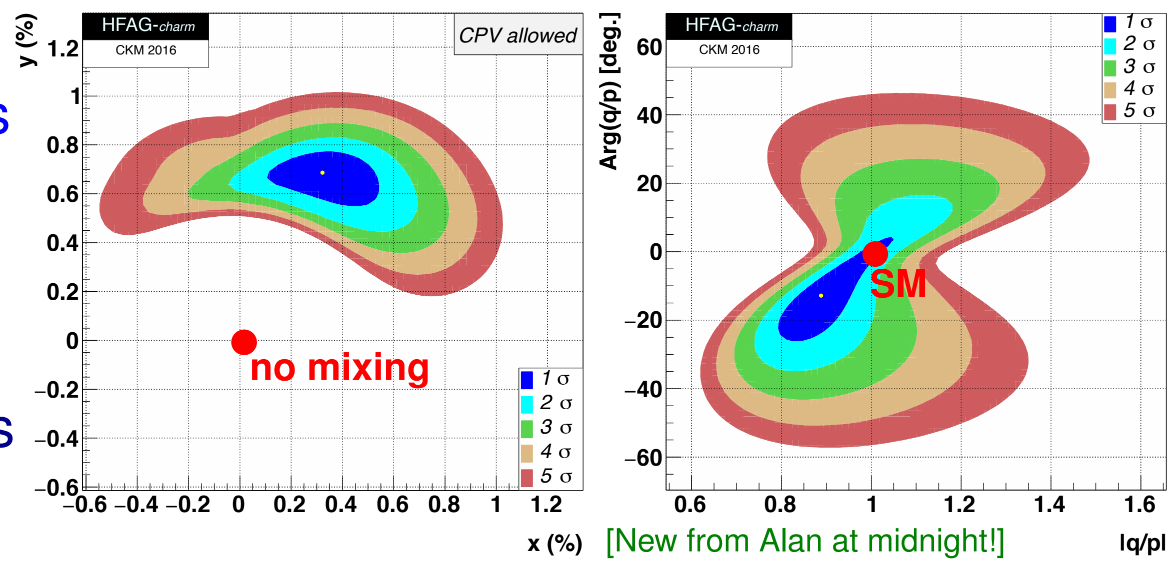
- CP violation in D decay

  LHCb, late 2011: $\Delta A_{CP} \equiv A_{K^+K^-} - A_{\pi^+\pi^-} = -(8.2 \pm 2.4) \times 10^{-3}$

  Current WA: $\Delta A_{CP} = -(2.5 \pm 1.0) \times 10^{-3}$ ↖ (a stretch in the SM, imho)

- I think we still don't know how big an effect could (not) be accommodated in SM

- Mixing generated by down quarks or in SUSY by up-type squarks
- Value of Δm? Not even 2σ yet
- Connections to FCNC top decays



[New from Alan at midnight!]

- SUSY: interplay of D & K bounds: alignment, universality, heavy squarks?

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Future progress samples

Reducing theory uncertainty of $\beta \equiv \phi_1$

- Hadronic uncertainty: $|V_{ub}V_{us}/(V_{cb}V_{cs})| \times (\text{“}P/T\text{”}) \simeq 0.02 \times$ (ratio of matrix elem.)

  Claims of large effects, many proposals, encouraging experimental bounds

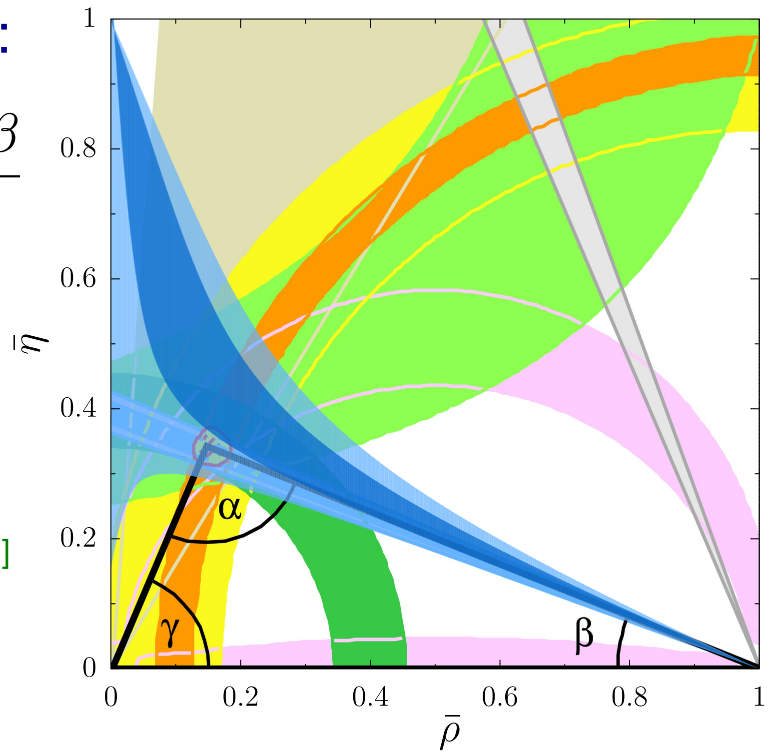
  Complicated literature: diagrammatic assumptions, there is no $SU(3)$ relation between ϕ and ρ

- Can suppress V_{ub} contribution by $SU(3)$ breaking:

$$\sin 2\beta = \frac{S_{K_S} - \lambda^2 S_{\pi^0} - 2(\Delta_K + \lambda^2 \Delta_\pi)\tan\gamma\cos 2\beta}{1+\lambda^2}$$

$$\Delta_K = \frac{\bar\Gamma(B_d \to J/\psi K^0) - \bar\Gamma(B^+ \to J/\psi K^+)}{\bar\Gamma(B_d \to J/\psi K^0) + \bar\Gamma(B^+ \to J/\psi K^+)}$$

$$\Delta_\pi = \frac{2\bar\Gamma(B_d \to J/\psi \pi^0) - \bar\Gamma(B^+ \to J/\psi \pi^+)}{2\bar\Gamma(B_d \to J/\psi \pi^0) + \bar\Gamma(B^+ \to J/\psi \pi^+)}$$



- Control uncertainties with data [ZL & Robinson, 1507.06671]

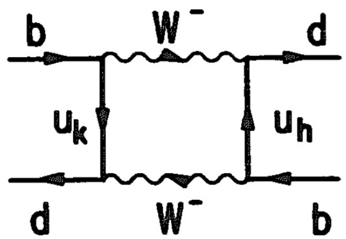
  Get: $\beta = (27.2 \pm 2.6)^\circ$ vs. CKM fit: $(21.9 \pm 0.7)^\circ$

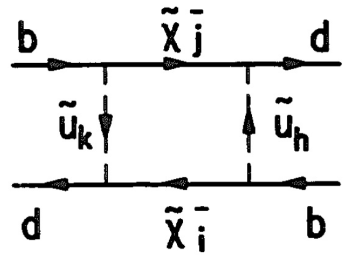
  Isospin asymmetries are difficult [Jung, 1510.03423]

- Mild tension: fluctuation in $\Delta_K = -(4.3 \pm 2.4) \times 10^{-2}$? isospin violation? ...?

New physics in B mixing

- Meson mixing:





General parametrization:

$$M_{12} = M_{12}^{\rm SM} \times (1 + h\, e^{2i\sigma})$$

NP parameters (h, σ)

SM: $\dfrac{C_{\rm SM}}{m_W^2}$ NP: $\dfrac{C_{\rm NP}}{\Lambda^2}$

What is the scale Λ? How different is $C_{\rm NP}$ from $C_{\rm SM}$?

If deviation from SM seen $\Rightarrow$ upper bound on Λ

- Assume: (i) 3×3 CKM matrix is unitary; (ii) tree-level decays dominated by SM

- Modified: loop-mediated (Δm_d, Δm_s, β, β_s, α, ...)

  Unchanged: tree-dominated (γ, $|V_{ub}|$, $|V_{cb}|$, ...)

(Importance of these constraints is known since the 70s, conservative picture of future progress)

Future sensitivity to new physics in B mixing

- At 95% CL: NP $\lesssim (0.3 \times$ SM)

  $\Rightarrow$ NP $< (0.05 \times$ SM)

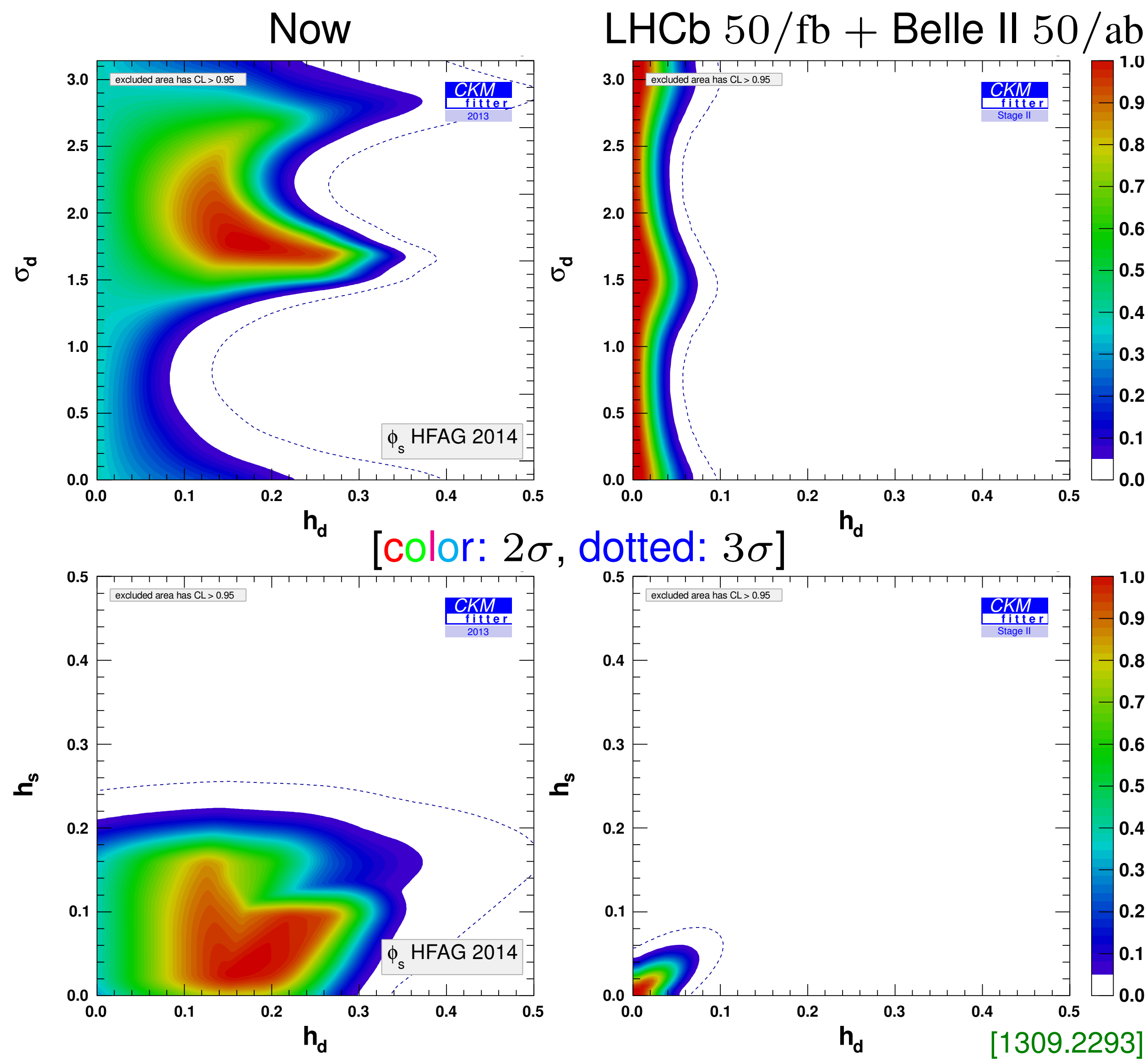
Use: $M_{12}^{(q)} = M_{12}^{\rm SM}(1 + h_q e^{2i\sigma_q})$

- Scale: $h \simeq \dfrac{|C_{ij}|^2}{|V_{ti}^* V_{tj}|^2} \left(\dfrac{4.5\,\text{TeV}}{\Lambda}\right)^2$

$$\Rightarrow \Lambda \sim \begin{cases} 2.3 \times 10^3\ \text{TeV} \\ 20\ \text{TeV (tree + CKM)} \\ 2\ \text{TeV (loop + CKM)} \end{cases}$$

- Similar to LHC $m_{\tilde g}$ reach

- B_d vs. B_s, MFV vs. non-MFV will have comparable constraints (unlike in the past)



[1309.2293]

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Sensitivity to vector-like fermions

- Do not make hierarchy problem worse; vector-like fermions can Yukawa couple to the SM fermions via the Higgs in 11 models ($\Rightarrow$ FCNC Z couplings)

Model	Quantum numbers	Bounds on M/TeV and $\lambda_i\lambda_j$ for each ij pair					
		$ij = 12$		$ij = 13$		$ij = 23$	
II	$(1, 3, -1)$	220[a]		4.9[b]		5.2[c]	
		1400[a]		13[b]		15[c]	
III	$(1, 2, -1/2)$	310[a]		7.0[b]		7.4[c]	
		2000[a]		19[b]		21[c]	
		$\Delta F = 1$	$\Delta F = 2$	$\Delta F = 1$	$\Delta F = 2$	$\Delta F = 1$	$\Delta F = 2$
V	$(3, 1, -1/3)$	66[d] [100][e]	{42, 670}[f]	30[g]	25[h]	21[i]	6.4[j]
		280[d]	{100, 1000}[f]	60[l]	61[h]	39[k]	14[j]
VII	$(3, 3, -1/3)$	47[d] [71][e]	{47, 750}[f]	21[g]	28[h]	15[i]	7.2[j]
		200[d]	{110, 1100}[f]	42[l]	68[h]	28[k]	16[j]
XI	$(3, 2, -5/6)$	66[d] [100][e]	{42, 670}[f]	30[g]	25[h]	18[k]	6.4[j]
		280[d]	{100, 1000}[f]	60[l]	61[h]	39[k]	14[j]

Upper (lower) rows are current (future) sensitivities for 5 models [Ishiwata, ZL, Wise, 1506.03484; Bobeth et al., 1609.04783]

Strongest bounds from many processes, nominally 1-2 generation is most sensitive, many options in concrete models

- Planned experiments increase mass scale sensitivity by factor $2.5 - 7$

Semileptonic decays and time travel

- I am working on several topics that could have been done 10–20 years ago
  ... motivated by $R(D^{(*)})$ and inclusive/exclusive $|V_{xb}|$ issues

- SIMBA [F. Bernlochner, H. Lacker, ZL, I. Stewart, F. Tackmann, K. Tackmann] $\Rightarrow$ Frank's talk
  Optimally combine all information on $B \to X_u \ell \bar\nu$ & $B \to X_s \gamma$
  Consistently treat uncertainties and correlations (exp, theo, param's)

- HAMMER [F. Bernlochner, S. Duell, ZL, M. Papucci, D. Robinson] See: 1610.02045 + in progress
  Analytic treatment of fully differential rates of the visible final states in $B \to X \ell \bar\nu$ + efficient MC to reweight simulations to any NP model
  Helicity Amplitude Module for Matrix Element Reweighting

- $B \to D^{**} \ell \bar\nu$ [Bernlochner & ZL, 1606.09300] + in progress
  A large systematic uncertainty in $R(D^{(*)})$ and some $|V_{xb}|$ measurements
  Measuring $R(D^{**})$: additional discriminating power between models

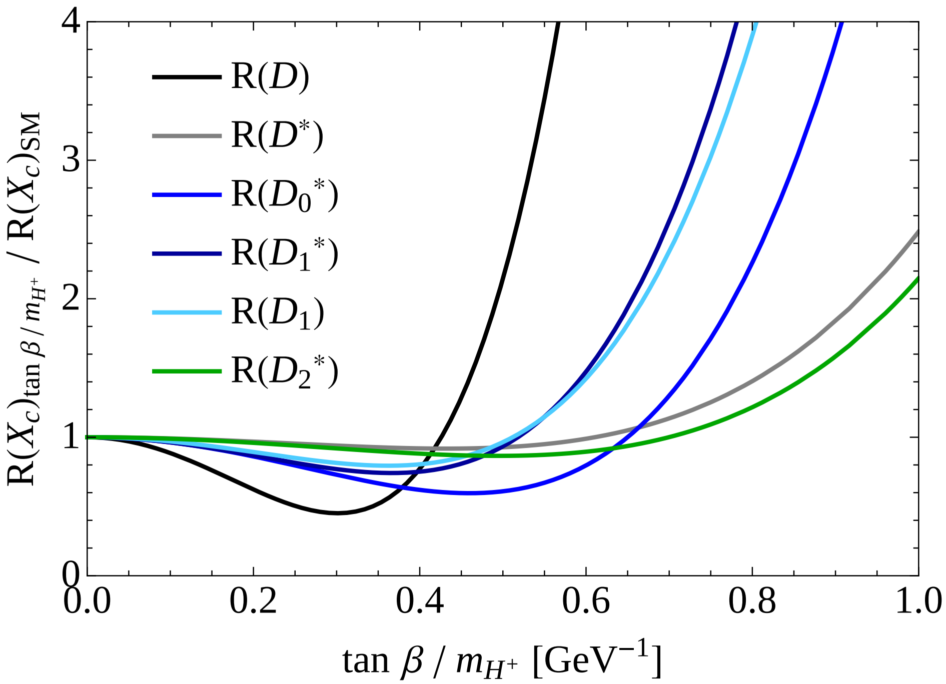
Amusingly, few days ago was just looking at Cho, Wise, Trivedi, hep-ph/9408352, "Gluon fragmentation into polarized charmonium"

Couple of $B \to D^{**}\tau\bar{\nu}$ plots

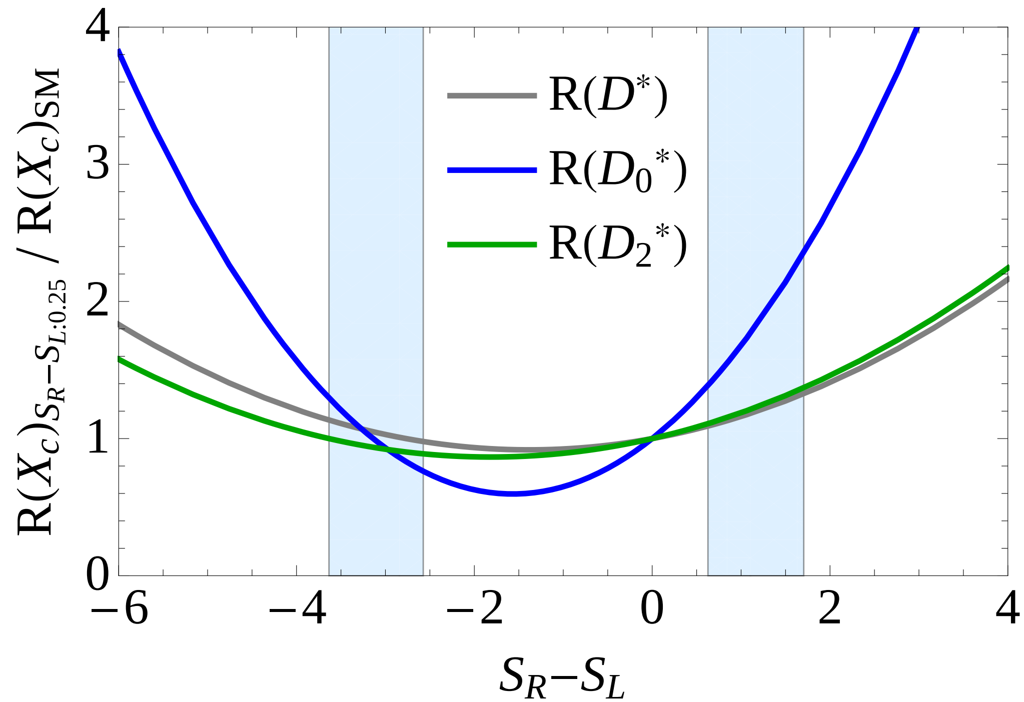
- Complementary sensitivities

[Bernlochner & ZL, 1606.09300v2]

Type II 2HDM



For fixed $S_R + S_L = 0.25$, favored by BaBar



Different patterns in two blue bands

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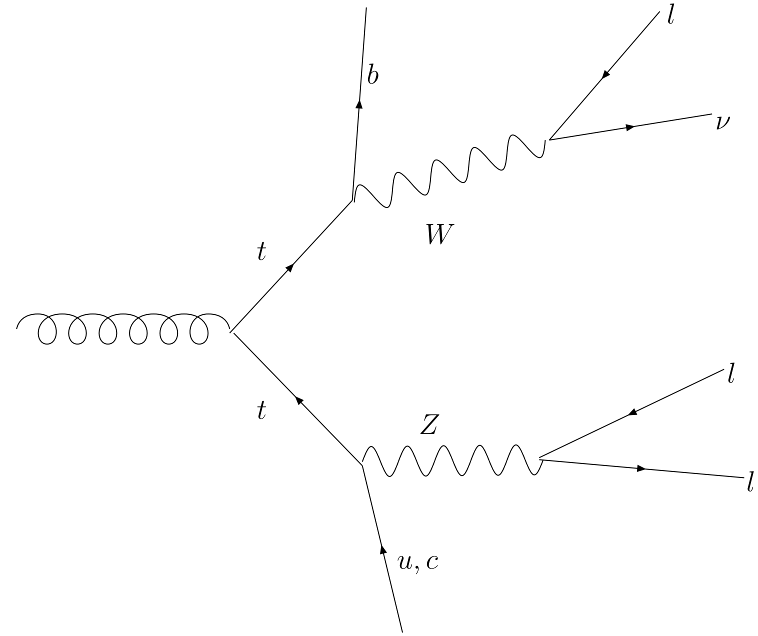
top / higgs / BSM flavor

The LHC is a top factory: top flavor physics

- FCNC top decays not too strongly constrained

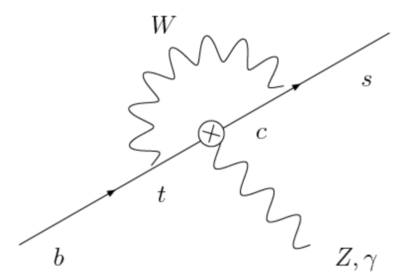
  SM predictions: $< 10^{-12}$

  Best current bound: $\lesssim$ few $\times\ 10^{-4}$ [ATLAS, CMS]



- Sensitivity will improve ~ 2 orders of magnitude

- Indirect constraints: $t_L \leftrightarrow b_L \Rightarrow$ tight bounds from B decays
  - Strong bounds on operators with left-handed fields
  - Right-handed operators could give rise to LHC signals



- If top FCNC is seen, LHC & B factories will both probe the NP responsible for it

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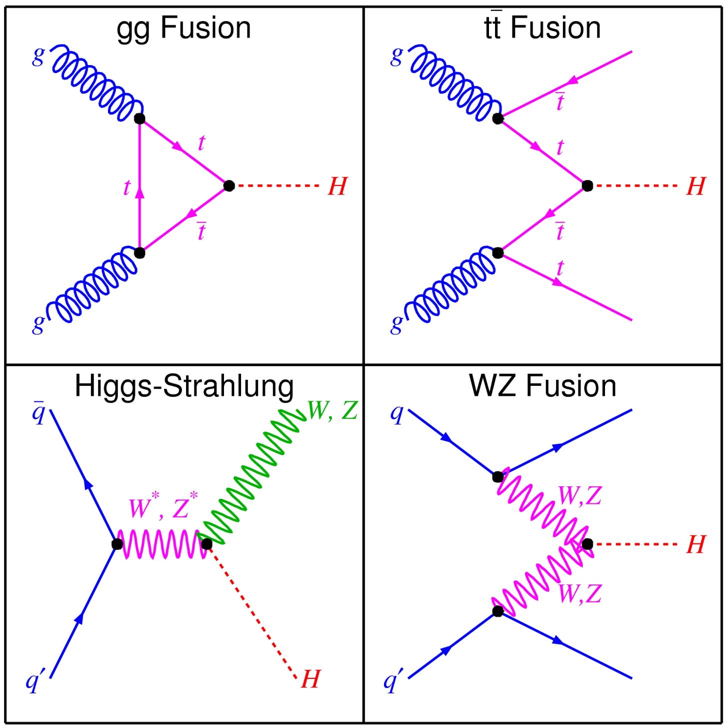
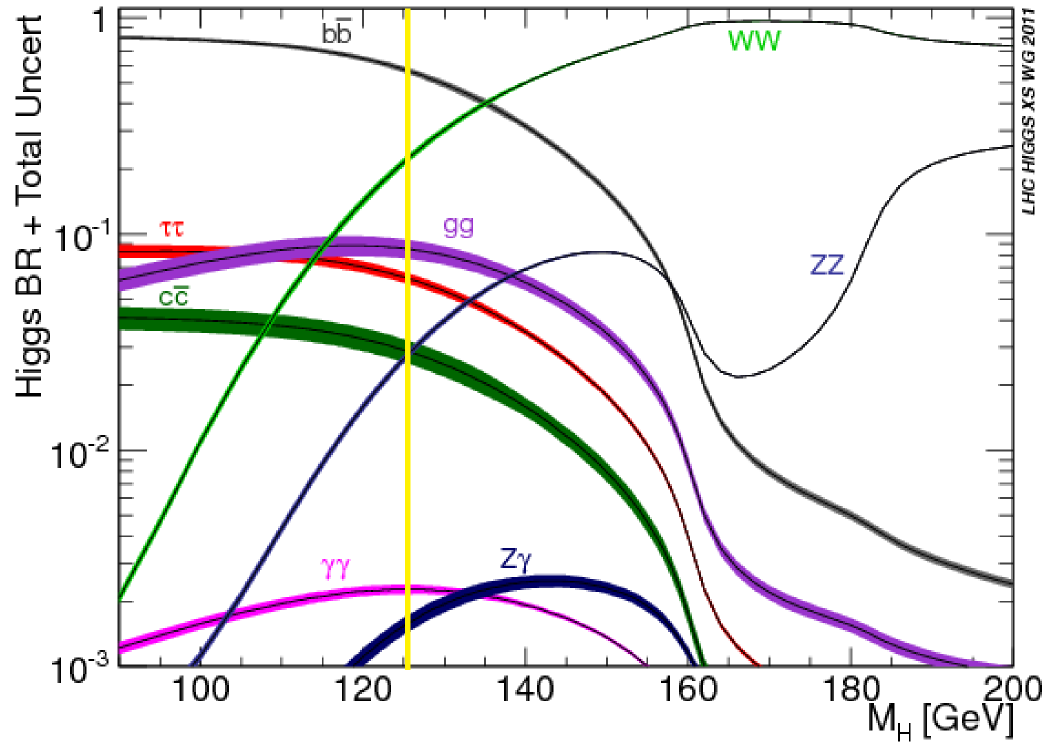
The LHC is a Higgs factory

- Richness due to Yukawa couplings: same as origin of "GeV-scale flavor physics"

  Many production and decay channels, fermion couplings crucial





- Higgs flavor param's: 3rd gen: $\kappa_t, \kappa_b, \kappa_\tau$ 2nd gen: κ_c, κ_μ Do $\kappa_{tc}, \kappa_{\tau\mu}$ vanish?

New particles, e.g., SUSY

- Any new particle that couples to quarks or leptons $\Rightarrow$ new flavor parameters

  (Squark & slepton couplings may modify FCNCs and CP violation, e.g., $B \to \ell^+\ell^-$, $\mu \to e\gamma$, ...)

  CP violation also possible in flavor diagonal processes (EDMs), neutral currents

  Couplings of new particles to quarks and leptons will be important (e.g.: Higgs)

- New physics flavor structure can be: new physics mass scale:
  - (Near) minimally flavor violating (mimic SM) ↑↓ can be "light"
  - Related but not identical to SM
  - Unrelated to the SM, or completely anarchic — must be heavy

- The heavier the new particles are, the less the flavor structure need to be SM-like

Hide flavor ⇔ high-p_T signals (Run 1 plots)

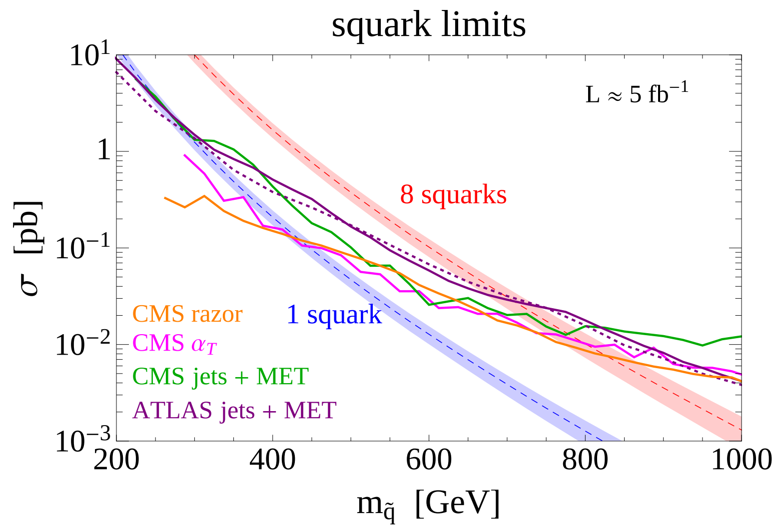
- Despite lore, squarks need not be as degenerate as often thought / assumed (triggered by studying charm CPV) [Gedalia, Kamenik, ZL, Perez]

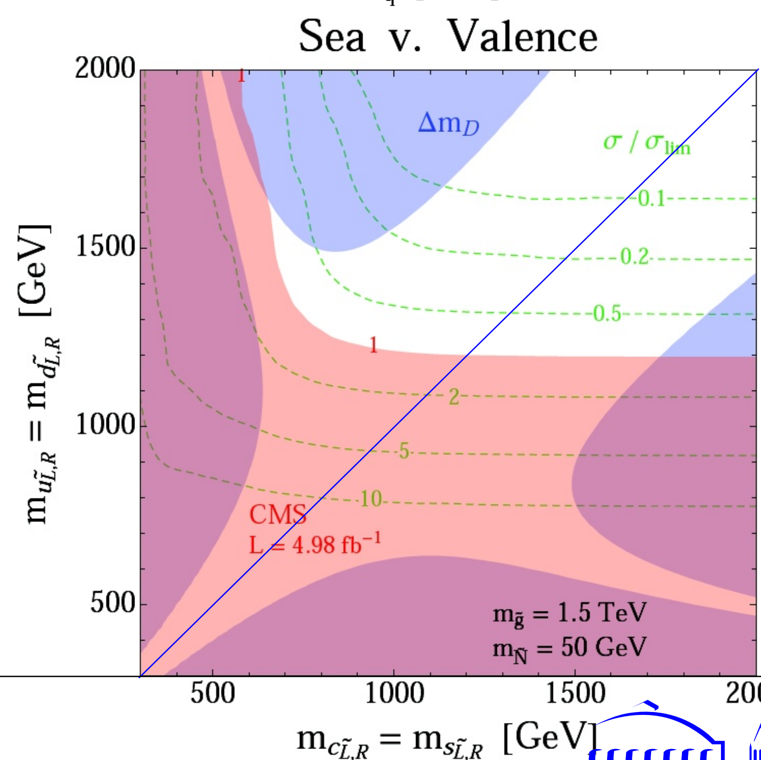
  Top plot: each LHC search becomes weaker [Mahbubani, Papucci, Perez, Ruderman, Weiler]

  Bottom plot: unshaded region still allowed if 4–4 squarks (but not all 8) are degenerate

- If 4 pairs of u, d, s, c squarks not degenerate, lot weaker LHC bounds: $1.2\,\mathrm{TeV} \;\Rightarrow\; 600\,\mathrm{GeV}$

- Ways for naturalness to survive...





Final remarks

What are the largest useful data sets?

- Which measurements will remain far from being limited by theory uncertainties?
  - For $\gamma \equiv \phi_3$, theory uncertainty only from higher order EW
  - $B_{s,d} \to \mu\mu$, $B \to \mu\nu$ and other leptonic decays (lattice QCD, [double] ratios)
  - $A_{\rm SL}^{d,s}$ — new ideas to get around exp. syst. limits?
  - Probably CP violation in D mixing (firm up theory)
  - CLFV, EDM, etc.

  [I guess until $\sim 10^2 \times$ Belle II & LHCb upgrade data, sensitivity to higher scales would improve]

- In some decay modes, even in 2030 we'll have: (exp. bound)/SM $\gtrsim 10^3$

  E.g., $B_{d,s} \to \tau^+\tau^-,\ e^+e^-$ — can build models... I hope to be wrong!

- Precision of f_s/f_d? 0.259 ± 0.015 appears near the $\sim 5\%$ systematic limit [LHCb-CONF-2013-011]

  Ultimately normalize to semileptonic, e.g., $\dfrac{\mathcal{B}(B_s \to \mu^+\mu^-)}{\mathcal{B}(B_s \to D_s^- \mu^+\nu)} \times \dfrac{\mathcal{B}(B_d \to D\mu\nu)}{\mathcal{B}(B_d \to \mu^+\mu^-)}$?

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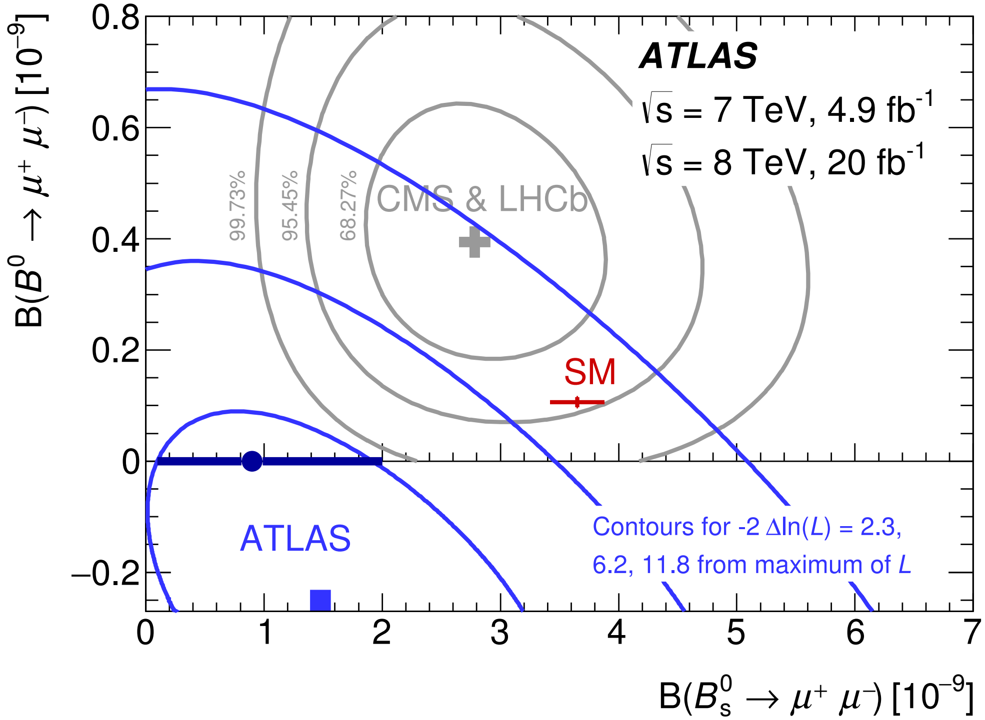
Push $B_{s,d} \to \mu^+\mu^-$ to theory limit

- For B_d, CMS (LHCb) expect ultimately 15–20% (30–40%) precision at SM level

  SM uncertainty $\simeq (2\%) \oplus f_{B_q}^2 \oplus \text{CKM}$ [Bobeth, FPCP'15]



- Theoretically cleanest $|V_{ub}|$ I know, only isospin: $\mathcal{B}(B_u \to \ell\bar\nu)/\mathcal{B}(B_d \to \mu^+\mu^-)$

- A decay with mass-scale sensitivity (dim.-6 operator) that competes w/ $K \to \pi\nu\bar\nu$

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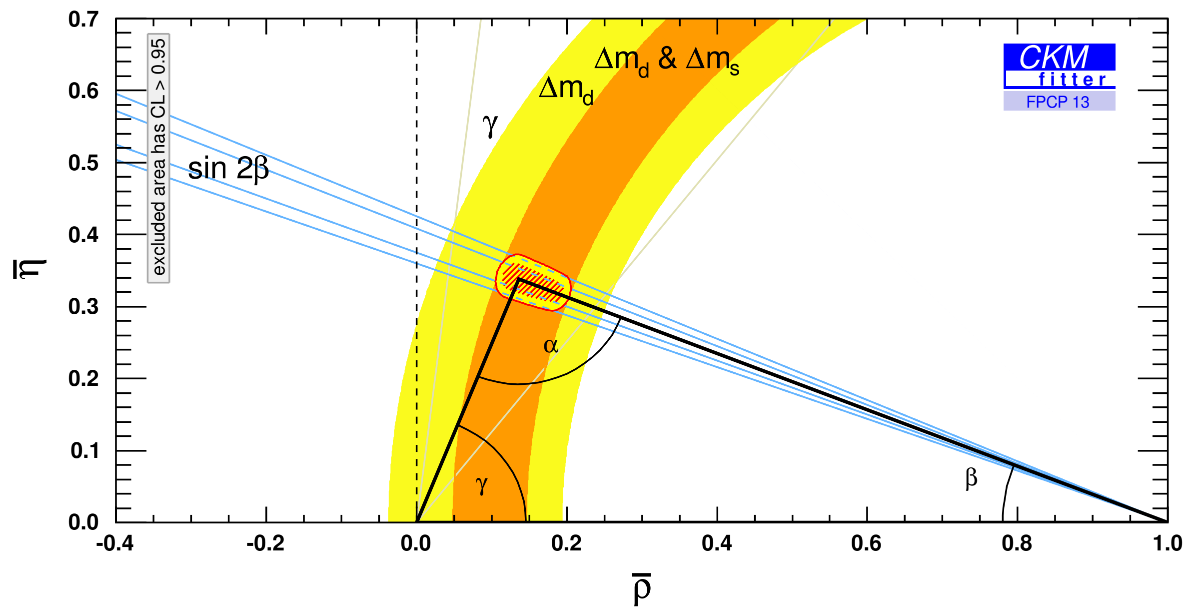
A test that can improve $\times 10$

- Order of magnitude improvement in this comparison is possible



- More data will directly translate to improved sensitivity to new physics
- Ultimate reach does depend on theory progress (uncertainty of β and $\Delta m_{d,s}$)

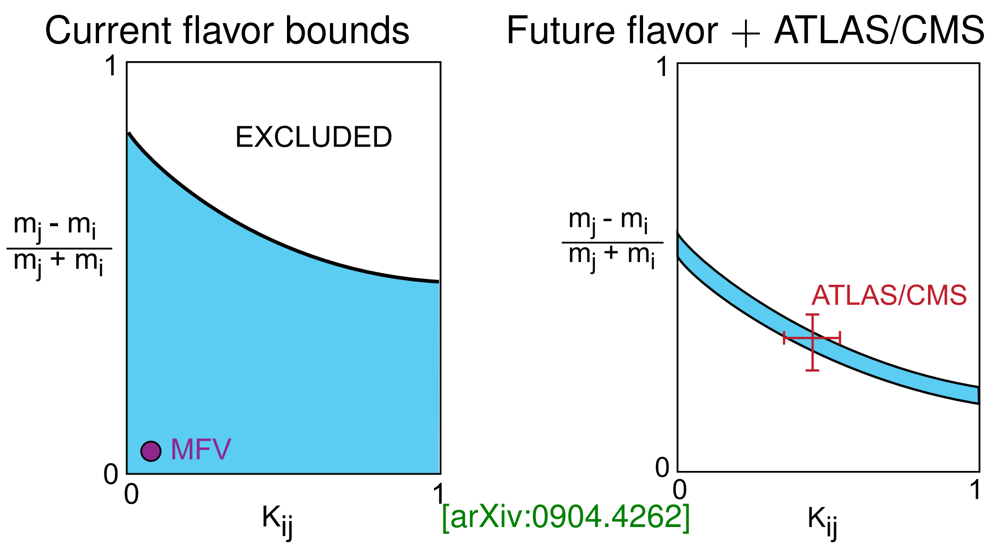
Some theory challenges

- New methods & ideas: recall that the best α and γ measurements are in modes proposed in light of Belle & BaBar data (i.e., not in the BaBar Physics Book)
  - Better SM upper bounds on $S_{\eta' K_S} - S_{\psi K_S}$, $S_{\phi K_S} - S_{\psi K_S}$, and $S_{\pi^0 K_S} - S_{\psi K_S}$ (and similarly in B_s decays)
  - How big can CP violation be in $D^0 - \overline{D}^0$ mixing (and in D decays) in the SM?
  - Better understanding of semileptonic form factors; bound on $S_{K_S \pi^0 \gamma}$ in SM?
  - Inclusive & exclusive semileptonic decays
  - Many lattice QCD calculations (operators within and beyond SM)
  - Factorization at subleading order (different approaches), charm loops
  - Can direct CP asymmetries in nonleptonic modes be understood enough to make them “discovery modes”? [$SU(3)$, the heavy quark limit, etc.]
- We know how to make progress on some $+$ discover new frameworks / methods?

Conclusions

- Flavor physics probes scales $\gg 1\,\mathrm{TeV}$; sensitivity limited by statistics
- New physics in FCNCs may still be $\gtrsim 20\%$ of the SM
- Few tensions with the SM; some of these (or others) may become decisive
- Large future improvements in many channels (+ CLFV + EDM)
- Many open theoretical questions which are important for experimental sensitivity
- Let's hope there is NP within reach to be discovered and understood

  Flavor & high-p_T info complementary

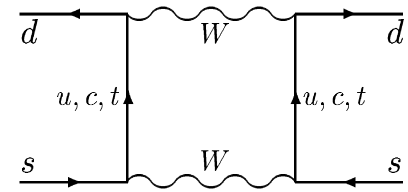


[arXiv:0904.4262]

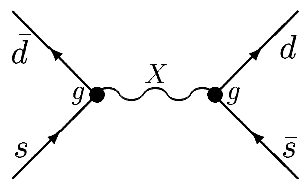
Extra slides

Flavor: very high scale sensitivity

- E.g.: $\Delta m_K/m_K \simeq 7\times10^{-15}$ — huge suppressions
- In SM: $\Delta m_K/m_K \sim \alpha_W^2\, |V_{cs}V_{cd}|^2\, \dfrac{m_c^2}{m_W^4}\, f_K^2$ (several small factors)



- Hypothetical particle:



$$\left|\frac{\Delta m_K^{(X)}}{\Delta m_K}\right| \sim \left|\frac{g^2\,\Lambda_{\rm QCD}^3}{M_X^2\,\Delta m_K}\right| \;\Rightarrow\; \frac{M_X}{g} \gtrsim 2\times10^3\ {\rm TeV}$$

(The bound from ϵ_K is even stronger)

- Measurements probe $\begin{cases} \text{TeV scale with SM-like CKM and loop suppressions} \\ \sim 10^3\ \text{TeV scale with generic flavor structure} \end{cases}$

Kaon bounds on NP are often the strongest, since so are the SM suppressions

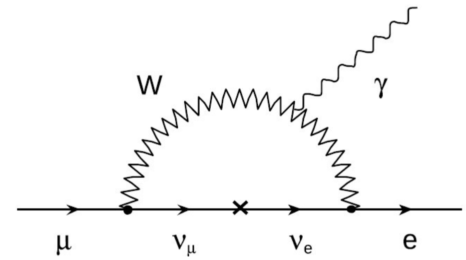
This has been an input to (and not output from) model building — suppression mechanisms devised to be viable

- We do not know where NP will show up ⇒ sensitivity to highest scales is crucial

Aside: Charged lepton flavor violation

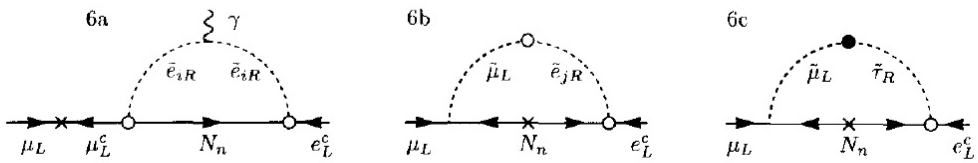
- SM predicted lepton flavor conservation with $m_\nu = 0$

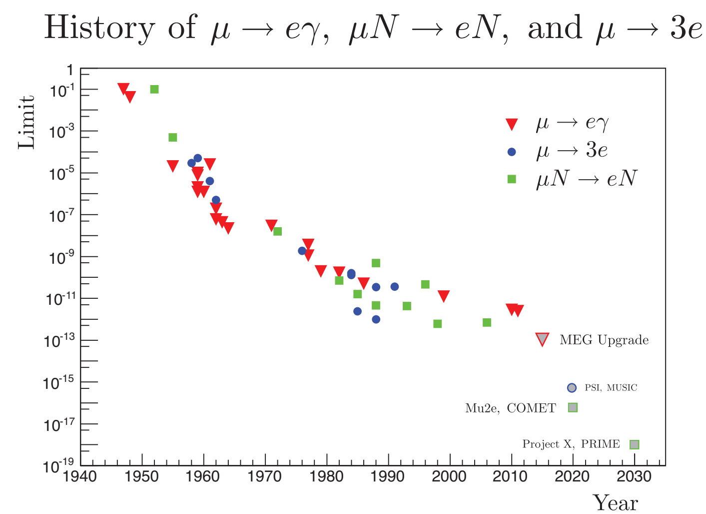
  Given $m_\nu \neq 0$, no reason to impose it as a symmetry



$$\mathcal{B}(\mu \to e\gamma) \sim \alpha \, \frac{m_\nu^4}{m_W^4} \sim 10^{-52}$$

- If new TeV-scale particles carry lepton number (e.g., sleptons), then they have their own mixing matrices ⇒ charged lepton flavor violation





- Many interesting processes:

  $\mu \to e\gamma$, $\mu \to eee$, $\mu + N \to e + N^{(\prime)}$, $\mu^+ e^- \to \mu^- e^+$

  $\tau \to \mu\gamma$, $\tau \to e\gamma$, $\tau \to \mu\mu\mu$, $\tau \to eee$, $\tau \to \mu\mu e$

  $\tau \to \mu ee$, $\tau \to \mu\pi$, $\tau \to e\pi$, $\tau \to \mu K_S$, $eN \to \tau N$

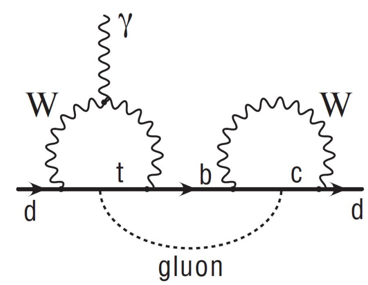
- Next 10–20 years: 10^2–10^5 improvement; any signal would trigger broad program

Aside: Electric dipole moments and SUSY

- SM $+ m_\nu$: CPV can occur in: (i) quark mixing; (ii) lepton mixing; and (iii) $\theta_{\rm QCD}$
  Only observed $\delta_{\rm KM} \neq 0$, baryogenesis implies there must be more

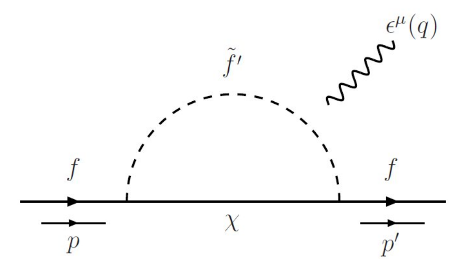
- Neutron EDM bound: “The strong CP problem”, $\theta_{\rm QCD} < 10^{-10}$ — axion?
  $\theta_{\rm QCD}$ is negligible for CPV in flavor-changing processes

- EDMs from CKM: vanish at one- and two-loop
  large suppression at three-loop level



- E.g., SUSY: quark and lepton EDMs can be generated at one-loop

  Generic prediction ($\rm TeV$-scale, no small param’s) above current bounds; if $m_{\rm SUSY} \sim \mathcal{O}(10\,{\rm TeV})$, may still discover EDMs



- Expected 10^2–10^3 improvements: complementary to LHC
  Discovery would give (rough) upper bound on NP scale

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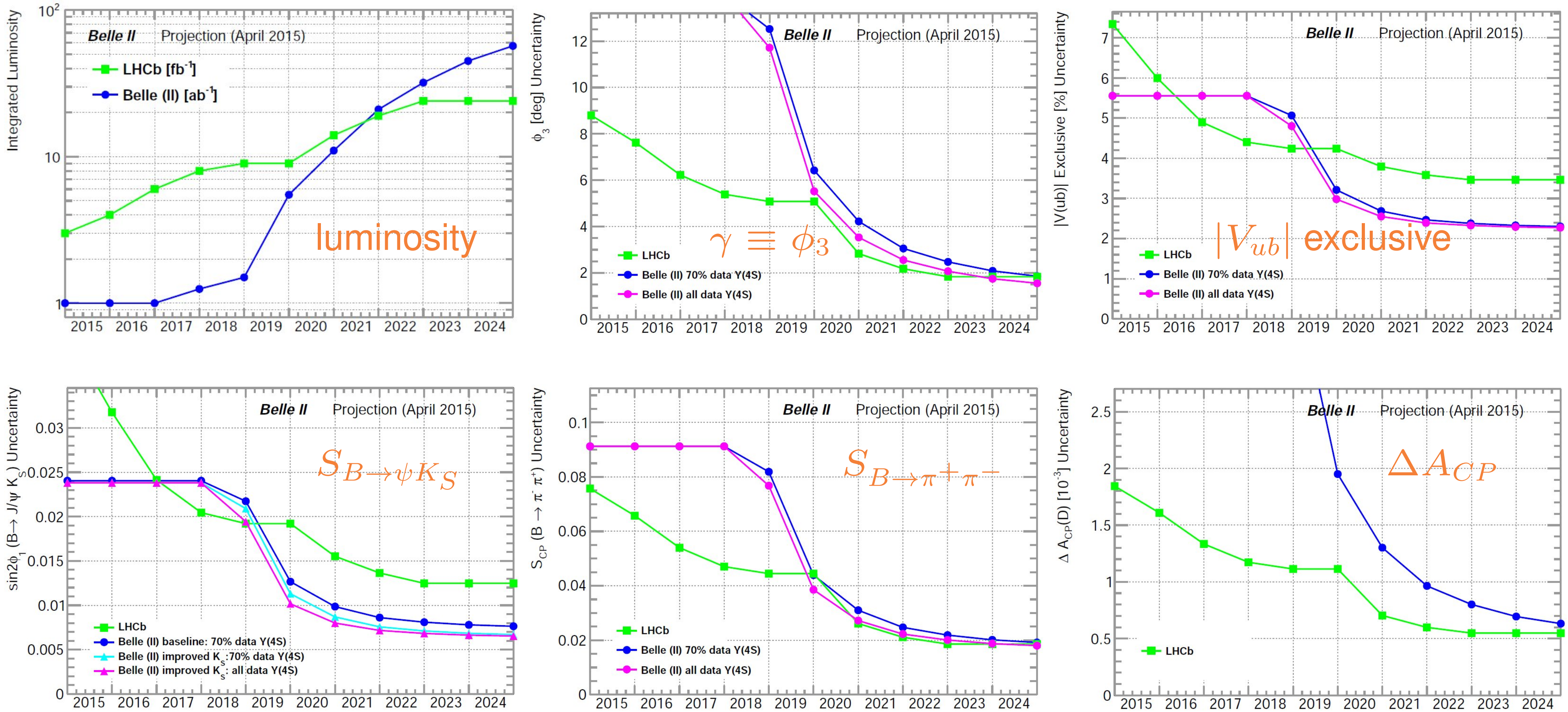
Belle II — LHCb: complementarity & competition



NB: these plots show statistical errors only, important issues swept under the rug

- Details depend on Belle II and LHC LS2–3 schedules [Urquijo, private communications]

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LHCb 50/fb summary

Type	Observable	LHC Run 1	LHCb 2018	LHCb upgrade	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.018**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.036**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**0.9°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.0°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm CP violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.4**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–

- Many measurements with BSM sensitivity improve a lot — 50/fb not enough

Belle II $50/\text{ab}$ summary

Observables	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	$\mathcal{L}_s$ [ab^{-1}]
$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012$	± 0.012	± 0.008	6
α		$\pm 2°$	$\pm 1°$	
γ	$\pm 14°$	$\pm 6°$	$\pm 1.5°$	
$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$	± 0.053	± 0.018	>50
$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$	± 0.028	± 0.011	>50
$S(B \to K^0_S K^0_S K^0_S)$	$0.30 \pm 0.32 \pm 0.08$	± 0.100	± 0.033	44
$\lvert V_{cb}\rvert$ incl.	$\pm 2.4\%$	$\pm 1.0\%$		< 1
$\lvert V_{cb}\rvert$ excl.	$\pm 3.6\%$	$\pm 1.8\%$	$\pm 1.4\%$	< 1
$\lvert V_{ub}\rvert$ incl.	$\pm 6.5\%$	$\pm 3.4\%$	$\pm 3.0\%$	2
$\lvert V_{ub}\rvert$ excl. (had. tag.)	$\pm 10.8\%$	$\pm 4.7\%$	$\pm 2.4\%$	20
$\lvert V_{ub}\rvert$ excl. (untag.)	$\pm 9.4\%$	$\pm 4.2\%$	$\pm 2.2\%$	3
$\mathcal{B}(B \to \tau\nu)$ [10^{-6}]	96 ± 26	$\pm 10\%$	$\pm 5\%$	46
$\mathcal{B}(B \to \mu\nu)$ [10^{-6}]	< 1.7	5σ	$>> 5\sigma$	>50
$R(B \to D\tau\nu)$	$\pm 16.5\%$	$\pm 5.6\%$	$\pm 3.4\%$	4
$R(B \to D^*\tau\nu)$	$\pm 9.0\%$	$\pm 3.2\%$	$\pm 2.1\%$	3
$\mathcal{B}(B \to K^{*+}\nu\overline{\nu})$ [10^{-6}]	< 40		$\pm 30\%$	>50
$\mathcal{B}(B \to K^{+}\nu\overline{\nu})$ [10^{-6}]	< 55		$\pm 30\%$	>50
$\mathcal{B}(B \to X_s\gamma)$ [10^{-6}]	$\pm 13\%$	$\pm 7\%$	$\pm 6\%$	< 1
$A_{CP}(B \to X_s\gamma)$		± 0.01	± 0.005	8
$S(B \to K^0_S \pi^0 \gamma)$	$-0.10 \pm 0.31 \pm 0.07$	± 0.11	± 0.035	> 50
$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$	± 0.23	± 0.07	> 50
C_7/C_9 $(B \to X_s \ell\ell)$	~20%	10%	5%	
$\mathcal{B}(B_s \to \gamma\gamma)$ [10^{-6}]	< 8.7	± 0.3		
$\mathcal{B}(B_s \to \tau^+\tau^-)$ [10^{-3}]		< 2		

Observables	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	$\mathcal{L}_s$ [ab^{-1}]
$\mathcal{B}(D_s \to \mu\nu)$	$5.31 \times 10^{-3}(1 \pm 0.053 \pm 0.038)$	$\pm 2.9\%$	$\pm(0.9\%\text{-}1.3\%)$	> 50
$\mathcal{B}(D_s \to \tau\nu)$	$5.70 \times 10^{-3}(1 \pm 0.037 \pm 0.054)$	$\pm(3.5\%\text{-}4.3\%)$	$\pm(2.3\%\text{-}3.6\%)$	3-5
y_{CP} [10^{-2}]	$1.11 \pm 0.22 \pm 0.11$	$\pm(0.11\text{-}0.13)$	$\pm(0.05\text{-}0.08)$	5-8
A_Γ [10^{-2}]	$-0.03 \pm 0.20 \pm 0.08$	± 0.10	$\pm(0.03\text{-}0.05)$	7 - 9
$A_{CP}^{K^+K^-}$ [10^{-2}]	$-0.32 \pm 0.21 \pm 0.09$	± 0.11	± 0.06	15
$A_{CP}^{\pi^+\pi^-}$ [10^{-2}]	$0.55 \pm 0.36 \pm 0.09$	± 0.17	± 0.06	> 50
$A_{CP}^{\phi\gamma}$ [10^{-2}]	± 5.6	± 2.5	± 0.8	> 50
$x^{K_S\pi^+\pi^-}$ [10^{-2}]	$0.56 \pm 0.19 \pm {}^{0.07}_{0.13}$	± 0.14	± 0.11	3
$y^{K_S\pi^+\pi^-}$ [10^{-2}]	$0.30 \pm 0.15 \pm {}^{0.05}_{0.08}$	± 0.08	± 0.05	15
$\lvert q/p\rvert^{K_S\pi^+\pi^-}$	$0.90 \pm {}^{0.16}_{0.15} \pm {}^{0.08}_{0.06}$	± 0.10	± 0.07	5-6
$\phi^{K_S\pi^+\pi^-}$ [°]	$-6 \pm 11 \pm {}^{4}_{5}$	± 6	± 4	10
$A_{CP}^{\pi^0\pi^0}$ [10^{-2}]	$-0.03 \pm 0.64 \pm 0.10$	± 0.29	± 0.09	> 50
$A_{CP}^{K^0_S\pi^0}$ [10^{-2}]	$-0.10 \pm 0.16 \pm 0.09$	± 0.08	± 0.03	> 50
$Br(D^0 \to \gamma\gamma)$ [10^{-6}]	< 1.5	$\pm 30\%$	$\pm 25\%$	2
	$\tau \to \mu\gamma$ [10^{-9}]	< 45	< 14.7	< 4.7
	$\tau \to e\gamma$ [10^{-9}]	< 120	< 39	< 12
	$\tau \to \mu\mu\mu$ [10^{-9}]	< 21.0	< 3.0	< 0.3

$\mathcal{L}_s$ = luminosity so that $\sigma(\text{stat}) = \sigma(\text{syst})$

Clear physics cases

Broad program, large improvements

I will not go through all...

Not understood: the $B \to K\pi$ puzzle

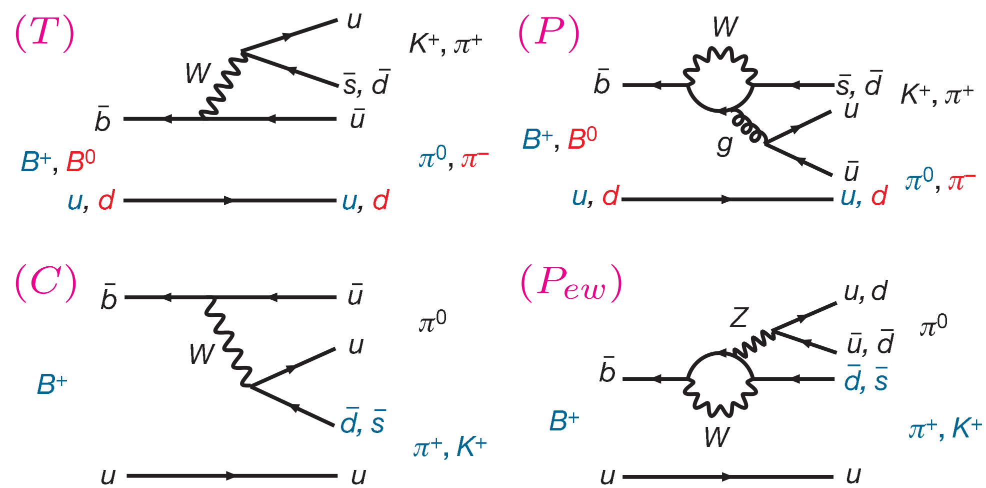
- Have we seen new physics in CPV?

$$A_{K^+\pi^-} = -0.082 \pm 0.006 \quad (P+T)$$

$$A_{K^+\pi^0} = 0.040 \pm 0.021 \quad (P+T+C+A+P_{ew})$$

- Large difference — small SM sources?

$$A_{K^+\pi^0} - A_{K^+\pi^-} = 0.122 \pm 0.022$$



(Annihilation not shown)

[Belle, Nature 452, 332 (2008)]

SCET / factorization predicts: $\arg(C/T) = \mathcal{O}(\Lambda_{\rm QCD}/m_b)$ and $A + P_{ew}$ small

- Large fluctuations? Breakdown of $1/m$ exp.? Missing something subtle? BSM?

No similar tension in branching ratio sum rules and $SU(3)$ relations

- Can we unambiguously understand theory, so that such data could disprove SM?

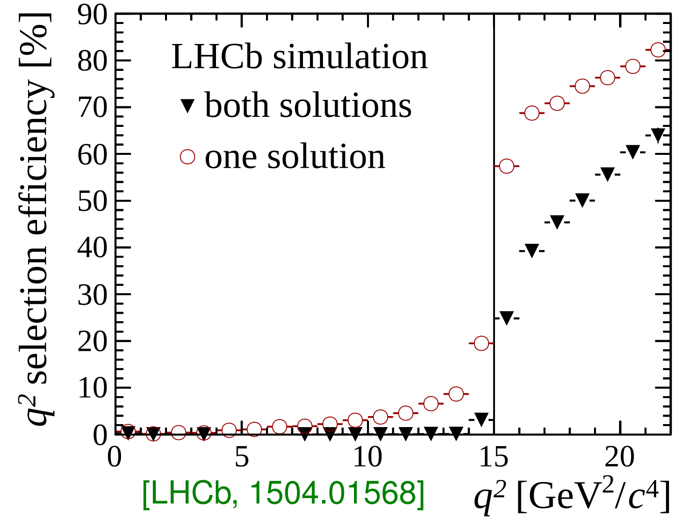
LHCb: $|V_{ub}|$ from $\Lambda_b \to p\mu\bar\nu$

- $|V_{ub}|$ crucial for improving constraints on NP

  $|V_{ub}|_{\rm LHCb} = (3.27 \pm 0.15 \pm 0.17 \pm 0.06) \times 10^{-3}$

  $|V_{ub}|^2_{\rm LHCb} \propto \mathcal{B}(\Lambda_c \to pK\pi)$ PDG: $25\% \to$ Belle: 5%

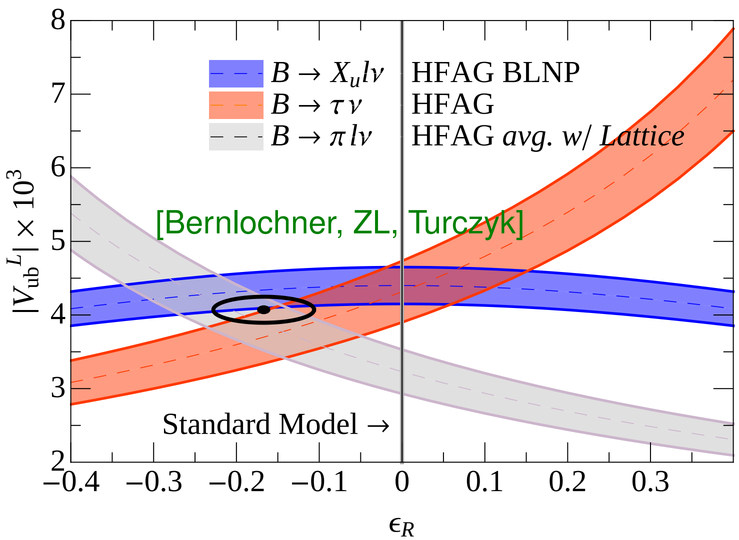
  (BES III result soon)

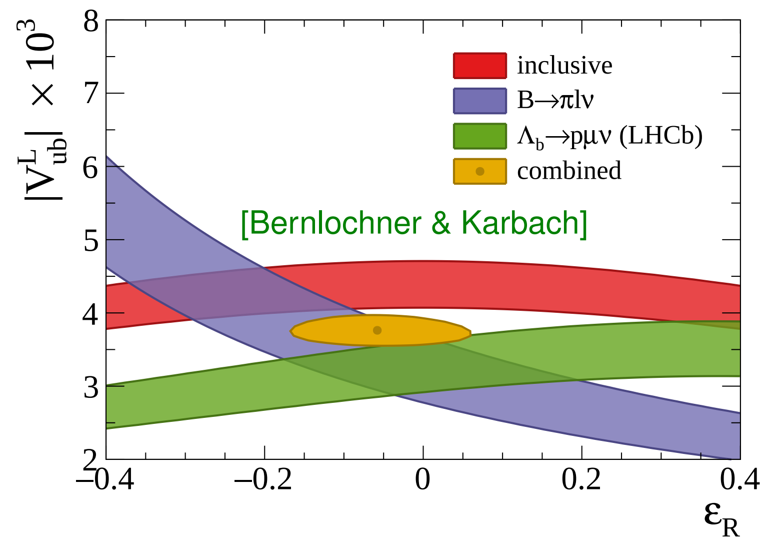


- $\sim 3\,\sigma$ tension among $|V_{ub}|$ measurements

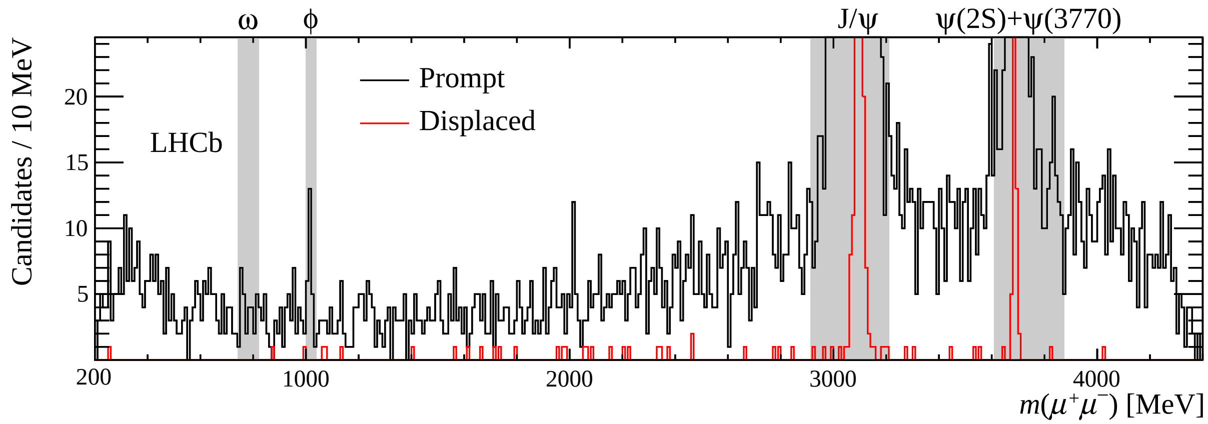
  Too early to conclude, measurements and theory will improve

- A BSM option: right-handed current — less good fit now



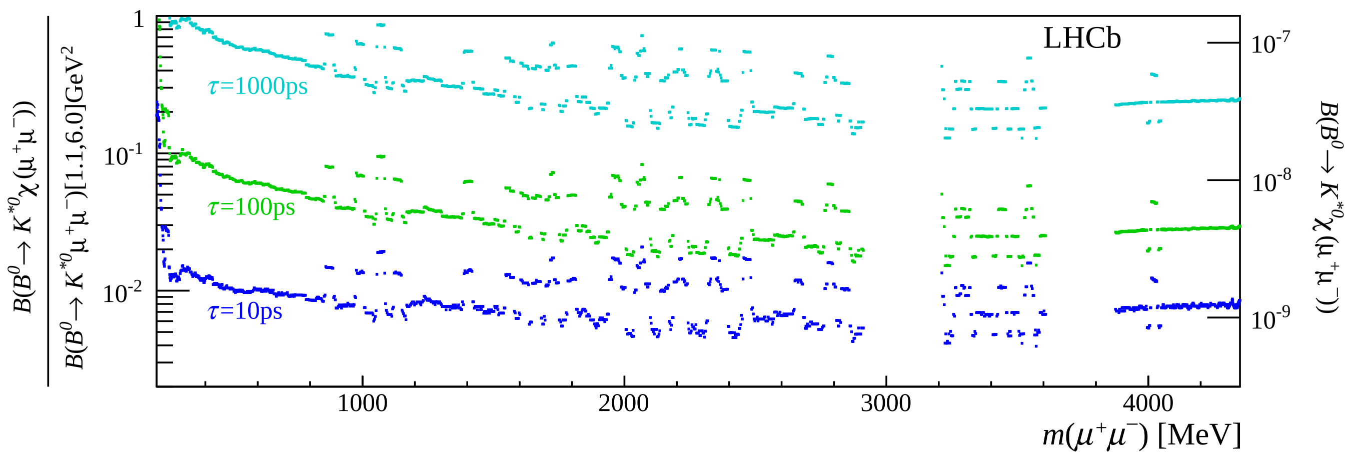


LHCb results on $B^0 \to K^{*0}\chi(\mu^+\mu^-)$



[LHCb, 1508.04094]

Distribution of $m(\mu^+\mu^-)$ in the (black) prompt and (red) displaced regions. The shaded bands denote regions where no search is performed due to (possible) resonance contributions.



Upper limits at 95% CL. The sparseness of the data leads to rapid fluctuations in the limits.

Example 1: NP in mixing

- Assume: (i) 3×3 CKM matrix is unitary; (ii) tree-level decays dominated by SM
- Simple & general description:

$$M_{12} = M_{12}^{\rm SM} \times (1 + h\, e^{2i\sigma})$$

NP parameters (h, σ)

Need many measurements and lattice QCD progress

- If NP discovery hinges on one ingredient, will need cross-checks (e.g., lattice w/ different formulations)

	2003	2013	Stage I		Stage II	
$\|V_{ud}\|$	0.9738 ± 0.0004	$0.97425 \pm 0 \pm 0.00022$	id		id	
$\|V_{us}\|$ $(K_{\ell 3})$	$0.2228 \pm 0.0039 \pm 0.0018$	$0.2258 \pm 0.0008 \pm 0.0012$	0.22494 ± 0.0006		id	
$\|\epsilon_K\|$	$(2.282 \pm 0.017) \times 10^{-3}$	$(2.228 \pm 0.011) \times 10^{-3}$	id		id	
Δm_d [ps^{-1}]	0.502 ± 0.006	0.507 ± 0.004	id		id	
Δm_s [ps^{-1}]	> 14.5 [95% CL]	17.768 ± 0.024	id		id	
$\|V_{cb}\| \times 10^3$ $(b \to c\ell\bar\nu)$	$41.6 \pm 0.58 \pm 0.8$	$41.15 \pm 0.33 \pm 0.59$	42.3 ± 0.4	[17]	42.3 ± 0.3	[17]
$\|V_{ub}\| \times 10^3$ $(b \to u\ell\bar\nu)$	$3.90 \pm 0.08 \pm 0.68$	$3.75 \pm 0.14 \pm 0.26$	3.56 ± 0.10	[17]	3.56 ± 0.08	[17]
$\sin 2\beta$	0.726 ± 0.037	0.679 ± 0.020	0.679 ± 0.016	[17]	0.679 ± 0.008	[17]
α (mod π)	—	$(85.4^{+4.0}_{-3.8})^\circ$	$(91.5 \pm 2)^\circ$	[17]	$(91.5 \pm 1)^\circ$	[17]
γ (mod π)	—	$(68.0^{+8.0}_{-8.5})^\circ$	$(67.1 \pm 4)^\circ$	[17, 18]	$(67.1 \pm 1)^\circ$	[17, 18]
β_s	—	$0.0065^{+0.0450}_{-0.0415}$	0.0178 ± 0.012	[18]	0.0178 ± 0.004	[18]
$\mathcal{B}(B \to \tau\nu) \times 10^4$	—	1.15 ± 0.23	0.83 ± 0.10	[17]	0.83 ± 0.05	[17]
$\mathcal{B}(B \to \mu\nu) \times 10^7$	—	—	3.7 ± 0.9	[17]	3.7 ± 0.2	[17]
$A_{\rm SL}^d \times 10^4$	10 ± 140	23 ± 26	-7 ± 15	[17]	-7 ± 10	[17]
$A_{\rm SL}^s \times 10^4$	—	-22 ± 52	0.3 ± 6.0	[18]	0.3 ± 2.0	[18]
$\bar m_c$	$1.2 \pm 0 \pm 0.2$	$1.286 \pm 0.013 \pm 0.040$	1.286 ± 0.020		1.286 ± 0.010	
$\bar m_t$	167.0 ± 5.0	$165.8 \pm 0.54 \pm 0.72$	id		id	
$\alpha_s(m_Z)$	$0.1172 \pm 0 \pm 0.0020$	$0.1184 \pm 0 \pm 0.0007$	id		id	
B_K	$0.86 \pm 0.06 \pm 0.14$	$0.7615 \pm 0.0026 \pm 0.0137$	0.774 ± 0.007	[19, 20]	0.774 ± 0.004	[19, 20]
f_{B_s} [GeV]	$0.217 \pm 0.012 \pm 0.011$	$0.2256 \pm 0.0012 \pm 0.0054$	0.232 ± 0.002	[19, 20]	0.232 ± 0.001	[19, 20]
B_{B_s}	1.37 ± 0.14	$1.326 \pm 0.016 \pm 0.040$	1.214 ± 0.060	[19, 20]	1.214 ± 0.010	[19, 20]
f_{B_s}/f_{B_d}	$1.21 \pm 0.05 \pm 0.01$	$1.198 \pm 0.008 \pm 0.025$	1.205 ± 0.010	[19, 20]	1.205 ± 0.005	[19, 20]
B_{B_s}/B_{B_d}	1.00 ± 0.02	$1.036 \pm 0.013 \pm 0.023$	1.055 ± 0.010	[19, 20]	1.055 ± 0.005	[19, 20]
$\tilde B_{B_s}/\tilde B_{B_d}$	—	$1.01 \pm 0 \pm 0.03$	1.03 ± 0.02		id	
$\tilde B_{B_s}$	—	$0.91 \pm 0.03 \pm 0.12$	0.87 ± 0.06		id	

- γ and $|V_{ub}|$ are crucial (tree / reference UT): hope that $2-3\%$ $|V_{ub}|$ uncertainty can be obtained from several measurements: $B \to \tau\nu$, $B \to \mu\nu$, $B \to \pi\ell\nu$, $\Lambda_b \to p\mu\nu$