CP violation (in b & c decay) in the HL-LHC era

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Thanks to: Greig Cowan, Tim Gershon, Hassan Jawahery, Phill Urquijo

Physics at the High-Luminosity LHC
May 11–13, 2015

Why flavor physics?

- NP flavor problem: TeV scale (hierarchy problem) $\ll$ "naive" flavor & CPV scale
  - Most TeV-scale new physics contain new sources of CP and flavor violation
  - The observed baryon asymmetry of the Universe requires CPV beyond the SM (Not necessarily in flavor changing processes, nor necessarily in quark sector)
- Flavor sector will be tested a lot better, many NP models have observable effects

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- Future: $$\frac{\text{(LHCb upgrade)}}{\text{(LHCb } 1\,\text{fb}^{-1})} \sim \frac{\text{(Belle II data set)}}{\text{(Belle data set)}} \sim \frac{\text{(2009 BaBar data set)}}{\text{(1999 CLEO data set)}} \sim 50$$

  Last 15 yrs: verify Kobayashi–Maskawa mechanism — Next 15 yrs: discover/study BSM signals?

- Increase in sensitivity to high scales $\sqrt[4]{50} \sim 2.5$, similar to LHC7-8 $\to$ LHC13-14

  Minimal estimate, expect "unpredictable" progress, data has always motivated new ideas

Preliminaries

- A large number of reviews & reports w/ large tables of key modes

  LHCb-PUB-2014-040, "Impact of the LHCb upgrade detector design choices on physics and trigger performance" https://cdsweb.cern.ch/record/1748643

  BELLE2-NOTE-0021, "Impact of Belle II on flavour physics"
  https://belle2.cc.kek.jp/~twiki/pub/Public/B2TIP/belle2-note-0021.pdf

- Focus on LHC, apologies to Belle II + Kaons + CLFV

  Apologies for many missing references

LHCb $50/\text{fb}$ 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 direct BSM sensitivity improve by a factor $5 - 10$

Belle II 50/ab summary

Observables	Belle	Belle II		$\mathcal{L}_s$
	(2014)	5 ab^{-1}	50 ab^{-1}	[ab^{-1}]
$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012$	± 0.012	± 0.008	6
α		$\pm 2^\circ$	$\pm 1^\circ$	
γ	$\pm 14^\circ$	$\pm 6^\circ$	$\pm 1.5^\circ$	
$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$	± 0.053	± 0.018	>50
$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$	± 0.028	± 0.011	>50
$S(B \to K_S^0 K_S^0 K_S^0)$	$0.30 \pm 0.32 \pm 0.08$	± 0.100	± 0.033	44
$\|V_{cb}\|$ incl.	$\pm 2.4\%$	$\pm 1.0\%$		< 1
$\|V_{cb}\|$ excl.	$\pm 3.6\%$	$\pm 1.8\%$	$\pm 1.4\%$	< 1
$\|V_{ub}\|$ incl.	$\pm 6.5\%$	$\pm 3.4\%$	$\pm 3.0\%$	2
$\|V_{ub}\|$ excl. (had. tag.)	$\pm 10.8\%$	$\pm 4.7\%$	$\pm 2.4\%$	20
$\|V_{ub}\|$ 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
$\mathcal{B}(B \to K^{*+}\nu\bar{\nu})$ [10^{-6}]	< 40		$\pm 30\%$	>50
$\mathcal{B}(B \to K^{+}\nu\bar{\nu})$ [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
$S(B \to K_S^0 \pi^0 \gamma)$	$-0.10 \pm 0.31 \pm 0.07$	± 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 $(B \to X_s \ell\ell)$	$\sim 20\%$	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	Belle II		$\mathcal{L}_s$
	(2014)	5 ab^{-1}	50 ab^{-1}	[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	$\pm$ 0.06	> 50
$A_{CP}^{\phi\gamma}$ [10^{-2}]	$\pm$ 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
$\|q/p\|^{K_S\pi^+\pi^-}$	$0.90 \pm {}^{0.16}_{0.15} \pm {}^{0.08}_{0.06}$	± 0.10	± 0.07	5-6
$\phi^{K_S\pi^+\pi^-}$ [$^\circ$]	$-6 \pm 11 \pm {}^{4}_{5}$	± 6	± 4	10
$A_{CP}^{\pi^0\pi^0}$ [10^{-2}]	$-0.03 \pm 0.64 \pm 0.10$	± 0.29	± 0.09	> 50
$A_{CP}^{K_S^0\pi^0}$ [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

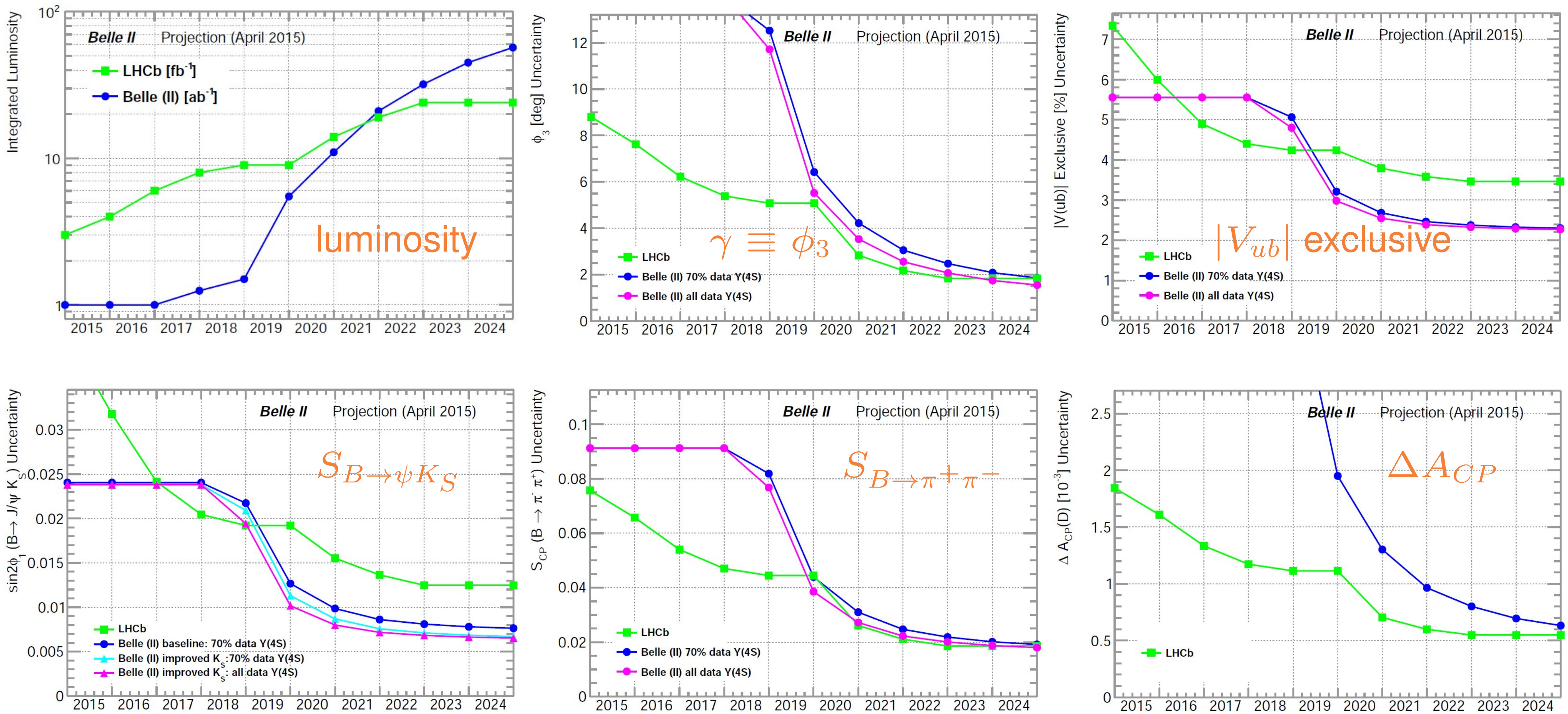
$\mathcal{L}_s =$ luminosity so that $\sigma(\text{stat}) = \sigma(\text{syst})$

Clear physics cases in my opinion!

Broad program, large improvements

I'll try not to simply review these...

Comparison / competition



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

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

New physics: dimension > 4 operators

- Heavy BSM physics — higher dimensional ("nonrenormalizable") operators

$$\mathcal{L} = \text{SM} + \sum_i \frac{C_{5i}}{\Lambda} \mathcal{O}_{5i} + \sum_i \frac{C_{6i}}{\Lambda^2} \mathcal{O}_{6i} + \ldots$$

Evidence for dim-5 terms $(L\phi)(L\phi)$ — iff neutrino mass violates lepton number

- Have not established the presence of any dim-6 term:

Precision electroweak: $\dfrac{(\phi D^\mu \phi)^2}{\Lambda^2} \Rightarrow \Lambda > \text{few} \times 10^3\,\text{GeV}$

Flavor and CP violation: $\dfrac{QQQQ}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^{(3\ldots7)}\,\text{GeV}$

Baryon and lepton number violation: $\dfrac{QQQL}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^{16}\,\text{GeV}$

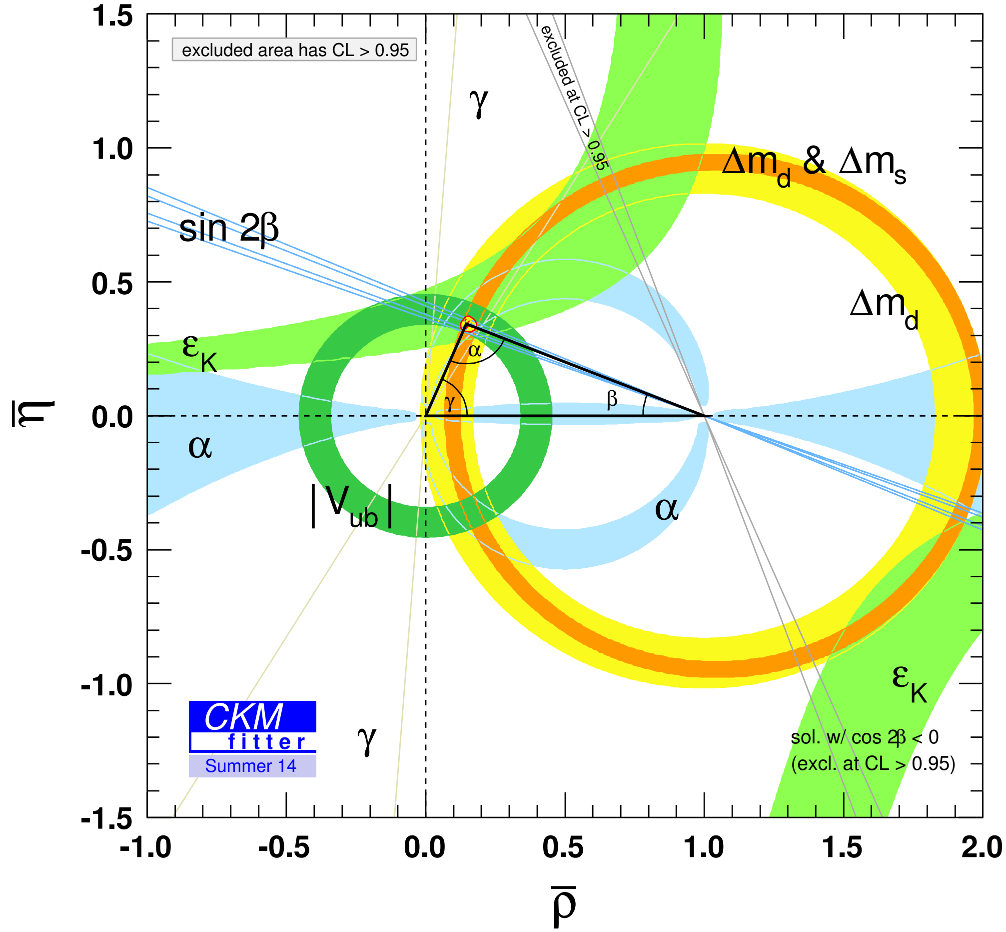
Spectacular track record

- Searching for new physics via virtual effects has been extremely successful
- Flavor physics was crucial to figure out $\mathcal{L}_{\rm SM}$:
  - Absence of $K_L \to \mu\mu$ predicted charm (Glashow, Iliopoulos, Maiani)
  - ϵ_K predicted 3rd generation (Kobayashi & Maskawa)
  - Δm_K predicted m_c (Gaillard & Lee; Vainshtein & Khriplovich)
  - Δm_B predicted large m_t
- Likely to be important to figure out $\mathcal{L}_{\rm BSM}$ as well
- If new physics discovered, want to probe it in as many different ways as possible

[NB: for most accessible-scale NP, whether CP is violated or not is simply Im or Re part...]

The standard model CKM fit

- The level of agreement between the measurements is often misinterpreted
- Much larger allowed region if SM not assumed to hold, more parameters
- $\mathcal{O}(20\%)$ NP contributions to most loop processes (FCNC) are still allowed



The rest of this talk

- Recent anomalies: what most people talk about — highest chance to become decisive soon (if not fluctuations)

- "Expected" / "predictable" progress: may need lots of hard work and ingenuity nevertheless, may encounter surprises while pushing for $\mathcal{O}(10)$ improvements

  Example: NP in neutral meson mixing

- Unexpected developments: Most interesting, but I cannot talk about them...

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- Unexpected developments: Most interesting, but I cannot talk about them...

  Will mention a few recent ones (for me) and some speculations

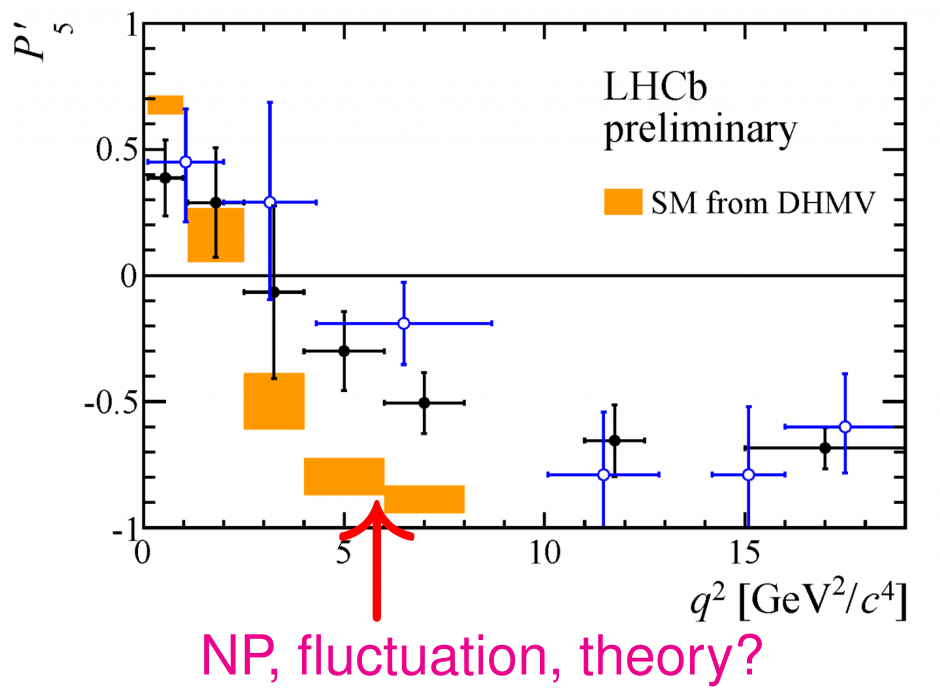
$B \to K^* \ell^+ \ell^-$: the P_5' anomaly

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

  Difficult for lattice QCD, large recoil

  Measuring several other distributions remains important

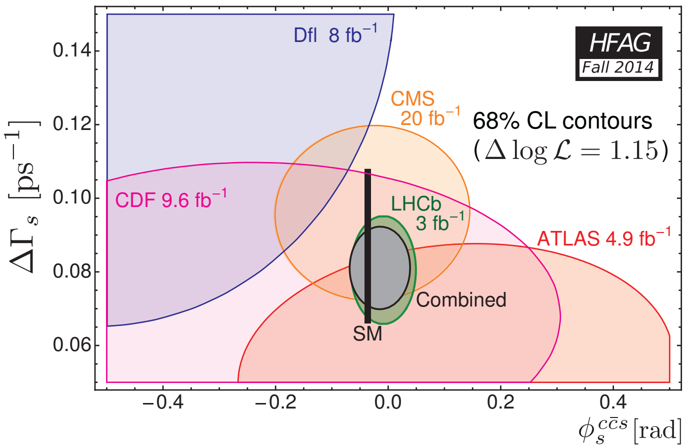
  $\Rightarrow$ See Sebastian Jaeger's talk



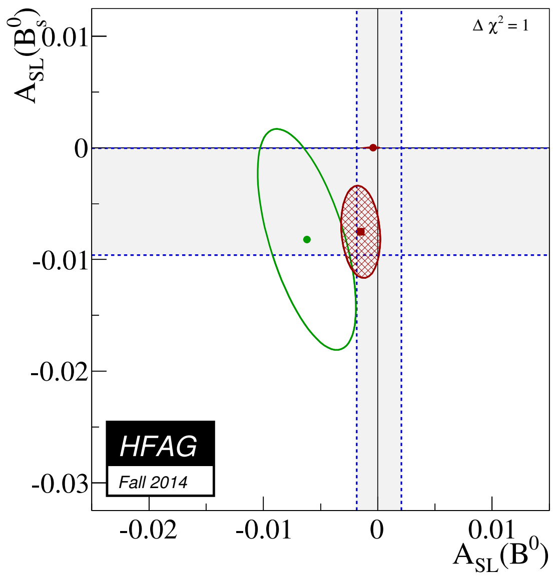
- Cross checks: different regions of phase space, also study in B_s and Λ_b decays?

- Connected to many other processes: can one calculate form factors (ratios) reliably at small q^2? (semileptonic & nonleptonic decays, interpreting CP viol., etc.)

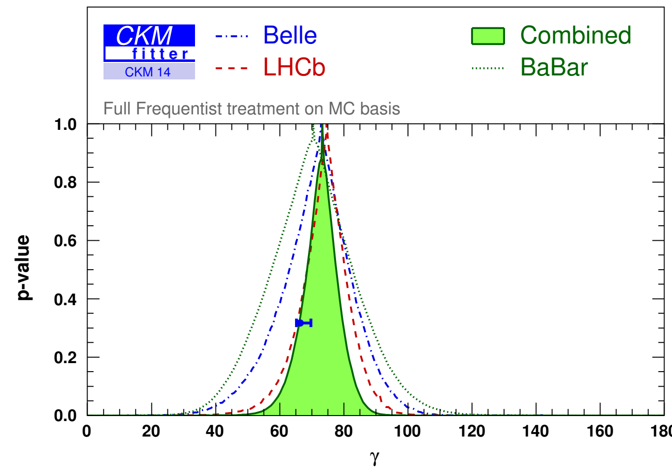
Other recent highlights



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



$A_{\rm SL}$: need more data to settle DØ anomaly



Measurements of γ crucial, LHCb is now the most precise determination

- Uncertainty of SM predictions $\ll$ current experimental error ($\Rightarrow$ much more data)

Charm CP violation

- CP violation in D decay — [many missing refs, incl. to speaker]

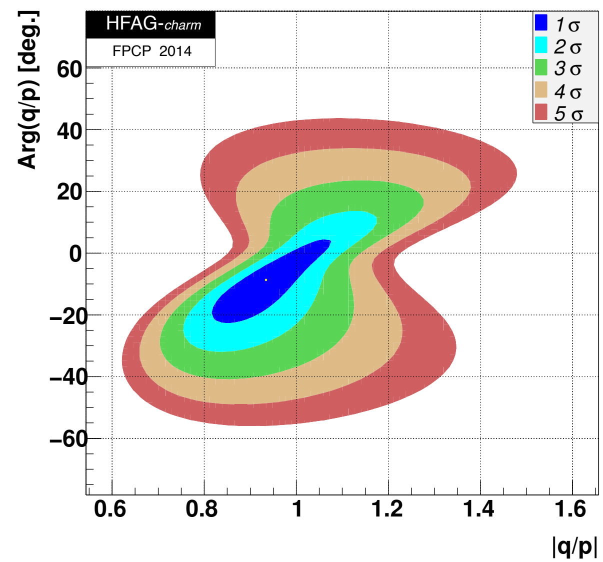
  LHCb, late 2011: $\Delta A_{CP} \equiv A_{K^+K^-} - A_{\pi^+\pi^-} = -(8.2 \pm 2.4) \times 10^{-3}$

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

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

- Only meson mixing generated by down-type quarks or in SUSY by up-type squarks

- $\Delta m \neq 0$ not established at 3σ; bound on CP violation in mixing, $|q/p| \neq 1$, much weaker than in $B_{d,s}$ & K



- Far from being theory limited — more work is needed

  Possible connections to FCNC top decays

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

Hide flavor signals ⇔ hide high-p_T signals

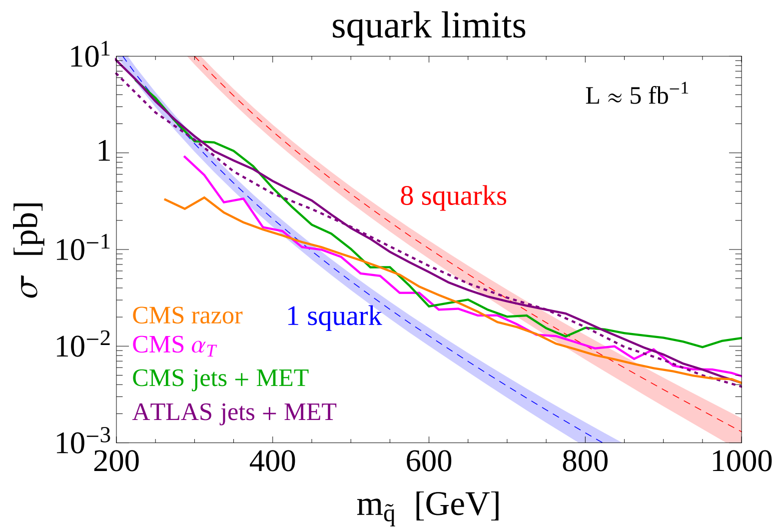
- Squarks need not be as degenerate as often thought or assumed [Gedalia, Kamenik, ZL, Perez, 1202.5038]

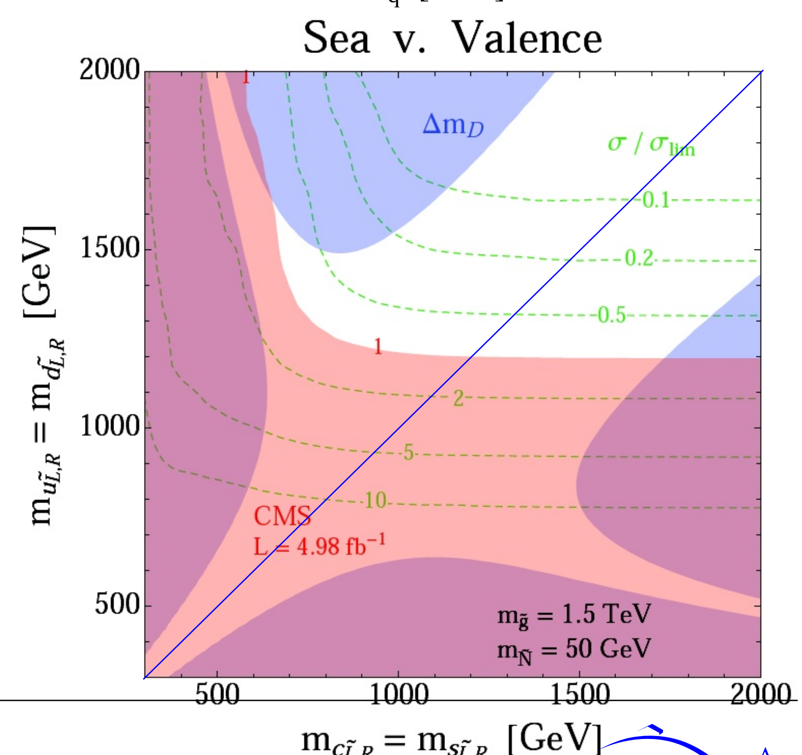
  Top plot: each LHC search becomes weaker [Mahbubani, Papucci, Perez, Ruderman, Weiler, 1212.3328]

  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: can give up many assumptions...





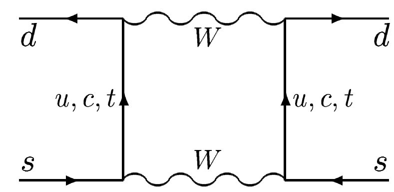
Example: NP in meson mixing

Importance known since the 70s, conservative picture of future progress

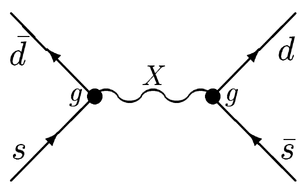
Δm_K — built into all NP models

- E.g., K mixing in SM: $\Delta m_K \sim \alpha_w^2 \, |V_{cs}V_{cd}|^2 \, \frac{m_c^2}{m_W^4} \, f_K^2 \, m_K$

  operator: $(\bar{s}\gamma_\mu P_L d)^2$ (strong suppressions!)



- If exchange of a heavy particle X contributes $\mathcal{O}(1)$ to Δm_K



$$\left|\frac{\Delta m_K^{(X)}}{\Delta m_K}\right| \sim \left|\frac{g^2\,\Lambda_{\rm QCD}^3}{M_X^2\,\Delta m_K}\right| \;\Rightarrow\; M_X \gtrsim g \times 2\cdot 10^3\,\text{TeV}$$

(The bound from ϵ_K is even stronger)

TeV-scale particles with loop-suppressed coupling can still be visible $[g \sim \mathcal{O}(10^{-3})]$

- SM-like Higgs — e.g., SUSY: large A terms? extended Higgs sector? $\to$ flavor?

- We do not know where NP will show up $\Rightarrow$ sensitivity to higher scales is crucial

Inputs: many measurements & calculations

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

- Need many measurements listed earlier, and lattice QCD improvements

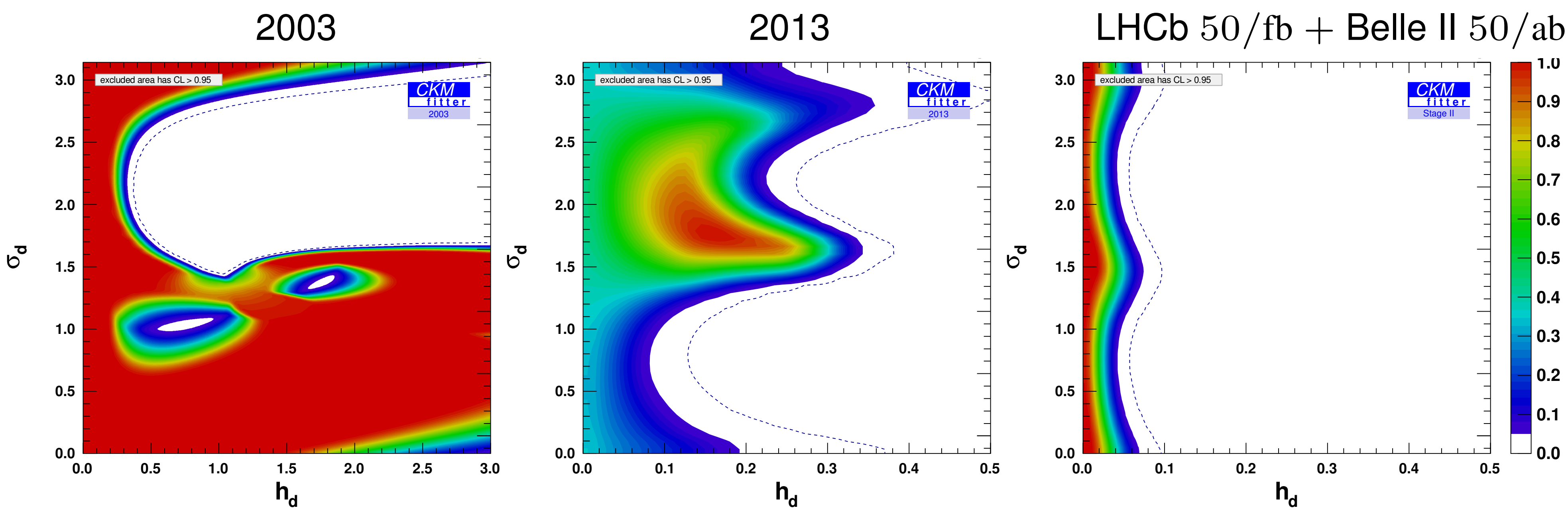
[Charles et al., 1309.2293]

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

	2003	2013	Stage I		Stage II	
$\lvert V_{ud}\rvert$	0.9738 ± 0.0004	$0.97425 \pm 0 \pm 0.00022$	id		id	
$\lvert V_{us}\rvert\ (K_{\ell 3})$	$0.2228 \pm 0.0039 \pm 0.0018$	$0.2258 \pm 0.0008 \pm 0.0012$	0.22494 ± 0.0006		id	
$\lvert\epsilon_K\rvert$	$(2.282 \pm 0.017) \times 10^{-3}$	$(2.228 \pm 0.011) \times 10^{-3}$	id		id	
$\Delta m_d\ [\text{ps}^{-1}]$	0.502 ± 0.006	0.507 ± 0.004	id		id	
$\Delta m_s\ [\text{ps}^{-1}]$	> 14.5 [95% CL]	17.768 ± 0.024	id		id	
$\lvert V_{cb}\rvert \times 10^3\ (b \to c\ell\bar{\nu})$	$41.6 \pm 0.58 \pm 0.8$	$41.15 \pm 0.33 \pm 0.59$	42.3 ± 0.4	[17]	42.3 ± 0.3	[17]
$\lvert V_{ub}\rvert \times 10^3\ (b \to u\ell\bar{\nu})$	$3.90 \pm 0.08 \pm 0.68$	$3.75 \pm 0.14 \pm 0.26$	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]
$\alpha\ (\text{mod}\ \pi)$	—	$(85.4^{+4.0}_{-3.8})^\circ$	$(91.5 \pm 2)^\circ$	[17]	$(91.5 \pm 1)^\circ$	[17]
$\gamma\ (\text{mod}\ \pi)$	—	$(68.0^{+8.0}_{-8.5})^\circ$	$(67.1 \pm 4)^\circ$	[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]
$A^d_{\text{SL}} \times 10^4$	10 ± 140	23 ± 26	-7 ± 15	[17]	-7 ± 10	[17]
$A^s_{\text{SL}} \times 10^4$	—	-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 $\lvert V_{ub}\rvert$ are crucial (tree / reference UT): hope that $2-3\%$ $\lvert V_{ub}\rvert$ uncertainty can be obtained from several measurements: $B \to \tau\nu$, $B \to \mu\nu$, $B \to \pi\ell\nu$, $\Lambda_b \to p\mu\nu$

New physics in B_d^0 mixing



$$M_{12}^{(d)} = M_{12}^{\rm SM} \times (1 + h_d\, e^{2i\sigma_d})$$

[1309.2293]

- 95% CL: NP $\lesssim$ (many $\times$ SM) $\rightarrow$ NP $\lesssim (0.3 \times$ SM) $\rightarrow$ NP $\lesssim (0.05 \times$ SM)

$$h \simeq \frac{|C_{ij}|^2}{|V_{ti}^* V_{tj}|^2} \left(\frac{4.5\,\mathrm{TeV}}{\Lambda}\right)^2$$ — will reach: $\Lambda \sim 20\,\mathrm{TeV}$ (tree), $\Lambda \sim 2\,\mathrm{TeV}$ (loop)

- Right sensitivity to be in the ballpark of gluino masses explored at LHC14

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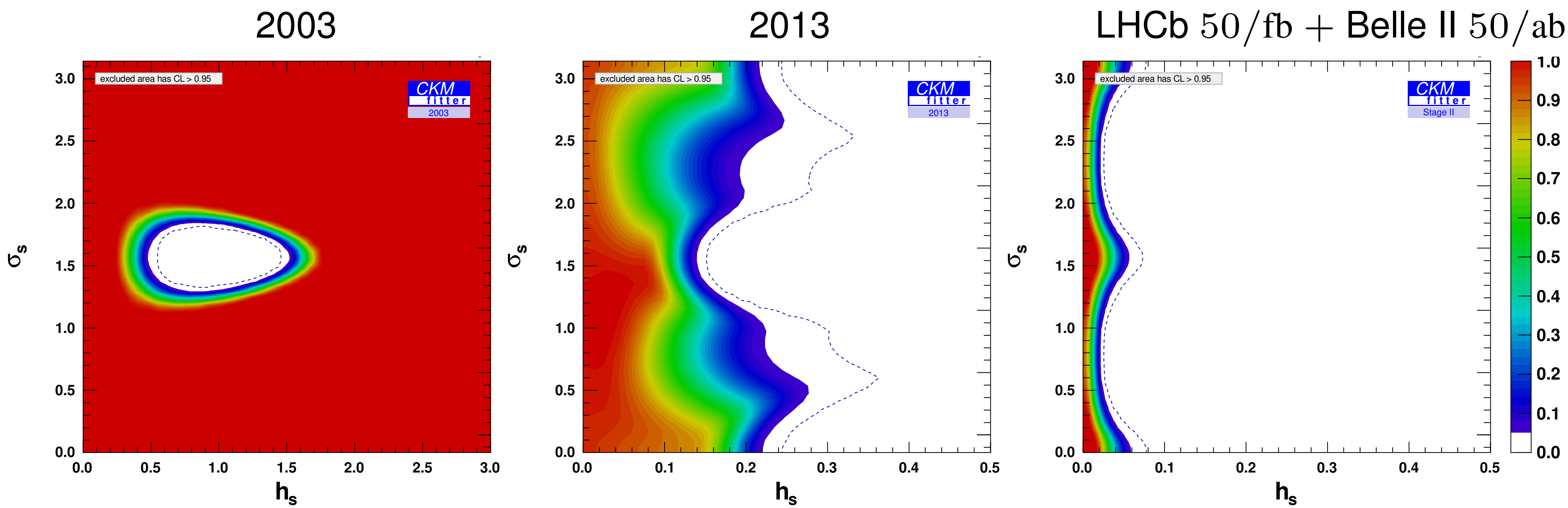
New physics in B_s^0 mixing



$$M_{12}^{(s)} = M_{12}^{\mathrm{SM}} \times (1 + h_s\, e^{2i\sigma_s})$$

[1309.2293]

- 95% CL: NP $\lesssim$ (many $\times$ SM) $\rightarrow$ NP $\lesssim (0.3 \times$ SM) $\rightarrow$ NP $< (0.05 \times$ SM)
- Sensitivity caught up with that in B_d mixing, and will improve comparably

  Slightly better sensitivity in B_s, due to less “background” in SM expectation

Future mixing sensitivity

- Mixing of neutral mesons will remain a special process to search for new physics, sensitive to some of the highest scales
- Summary of expected sensitivities to $(C_q^2/\Lambda^2)\,(\bar{b}_L \gamma^\mu q_L)^2$ [Charles et al., 1309.2293]

Couplings	NP loop order	Scales (TeV) probed by B_d mixing	Scales (TeV) probed by B_s mixing
$\lvert C_q\rvert = \lvert V_{tb} V_{tq}^*\rvert$ (CKM-like)	tree level	17	19
	one loop	1.4	1.5
$\lvert C_q\rvert = 1$ (anarchic)	tree level	2×10^3	5×10^2
	one loop	2×10^2	40

- Scales probed: $\Lambda \sim$ LHC (SM-like flavor)

  $\Lambda \gg$ LHC (anarchic flavor)

Recent surprises (to me)

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

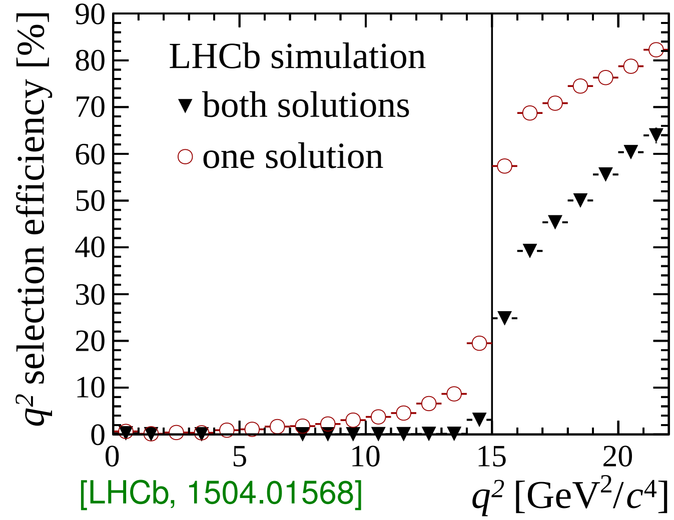
- $|V_{ub}|$ is crucial for future progress

  The q^2 resolution is surprising

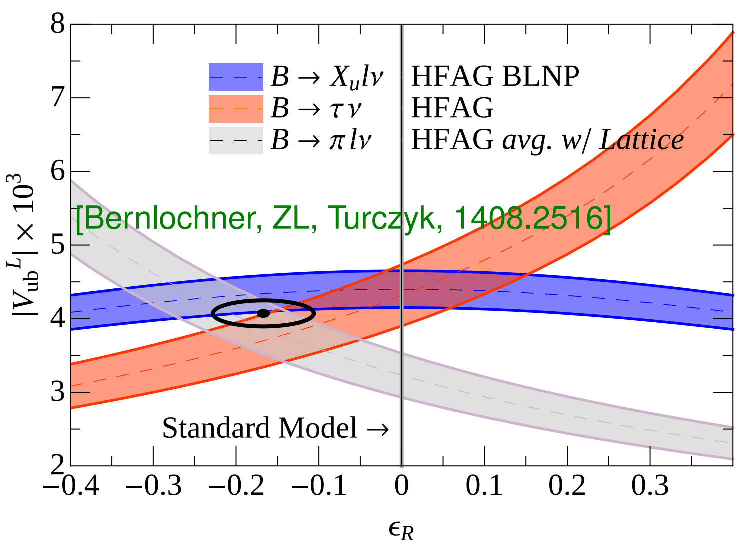
  $|V_{ub}| = (3.27 \pm 0.15 \pm 0.17 \pm 0.06) \times 10^{-3}$

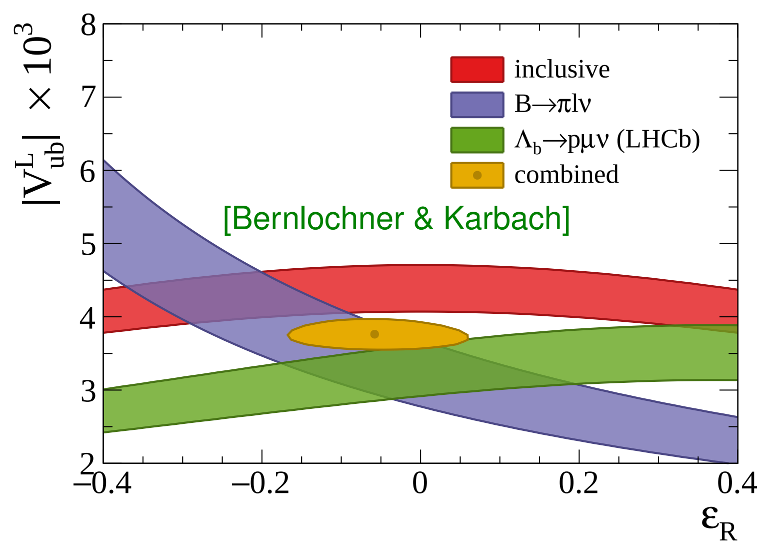
- $\sim 3\,\sigma$ tension among $|V_{ub}|$ measurements

  Too early to conclude, all measurements and theory will improve, simplest BSM possibility less good fit



[LHCb, 1504.01568]





The $B \to D^{(*)}\tau\bar{\nu}$ anomaly and LHCb

- BaBar reported 3.4σ deviation from SM in analysis of

$$R(X) = \frac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X\ell\bar{\nu})}$$

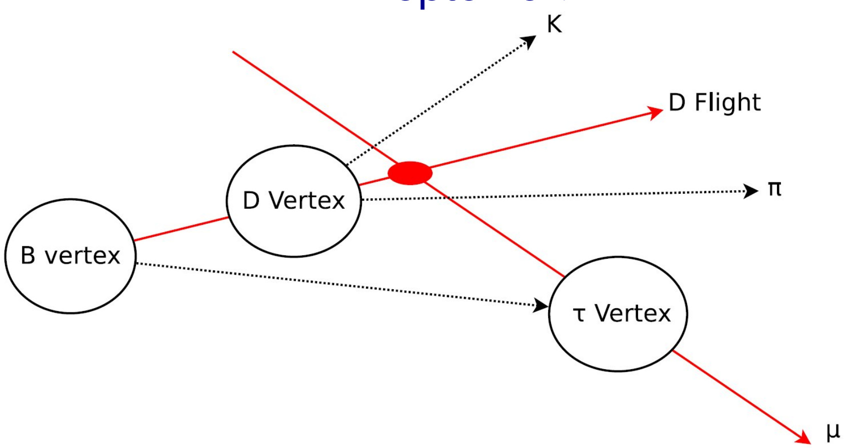
	Belle	BABAR	SM
$R(D)$	0.430 ± 0.091	$0.440 \pm 0.058 \pm 0.042$	0.297 ± 0.017
$R(D^*)$	0.405 ± 0.047	$0.332 \pm 0.024 \pm 0.018$	0.252 ± 0.003
correlation	neglected	-0.27	-

[Watanabe, FPCP 2014 — BaBar 1205.5442 + Belle private combination]

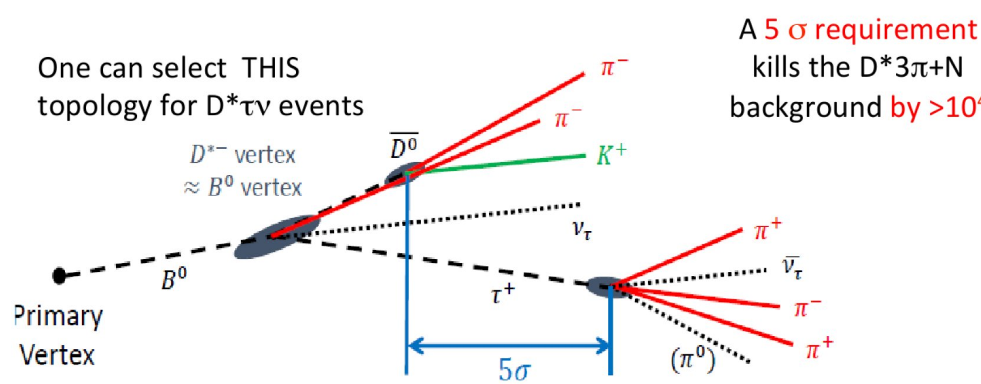
SM predictions fairly robust: heavy quark symmetry + lattice QCD

- Range of possible LHCb measurements keeps growing!

leptonic τ



hadronic τ



[G. Ciezarek @ https://indico.mitp.uni-mainz.de/conferenceDisplay.py?confId=30]

$B^+ \to K^+\pi^0$ at LHCb

- Observe 3.7σ mass peak in decay w/ photons and no reconstructed decay vertex

http://cds.cern.ch/record/1988475 [LHCb-CONF-2015-001]

At LHCb, this study also serves as a prototype for analyses with similar topologies, such as $B^0 \to K^0\pi^0$, $\Lambda_b \to \Lambda\gamma$, and $B^0 \to K^0\pi^0\gamma$

Important modes to study, yet very challenging at LHCb

- No secondary vertex, photons in final state

Analysis of $B^+ \to K^+\pi^0$ is a critical first step, and a proof-of-concept

Encouraged by the outcome of this analysis, a dedicated software trigger is being developed for use in Run II

[Andrews, Moriond EW 2015]

- Large set of “new” processes for LHCb to explore!

What are ultimate uncertainties? Increase in overlap between LHCb and Belle II

Crazy (?) questions

What are the largest useful data sets?

- What are the theory uncertainties that limit sensitivity to higher mass scales?
  - Known that $\gamma \equiv \phi_3$ can in principle be improved; theory limit: higher order EW
  - $A_{\rm SL}^{d,s}$ (can get around exp. syst. limits?)
  - $B_{s,d} \to \mu\mu$, $B \to \mu\nu$ and other leptonic decays (lattice QCD, [double] ratios)
  - Possibly CP violation in D mixing (firm up theory)

  [Should think more about this!]

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

  E.g.: $B_{(s)} \to \tau^+\tau^-$, e^+e^-, can build models...

  I hope to be proven wrong!

- Ultimate precision of f_s/f_d and other production ratios? Any new ideas?

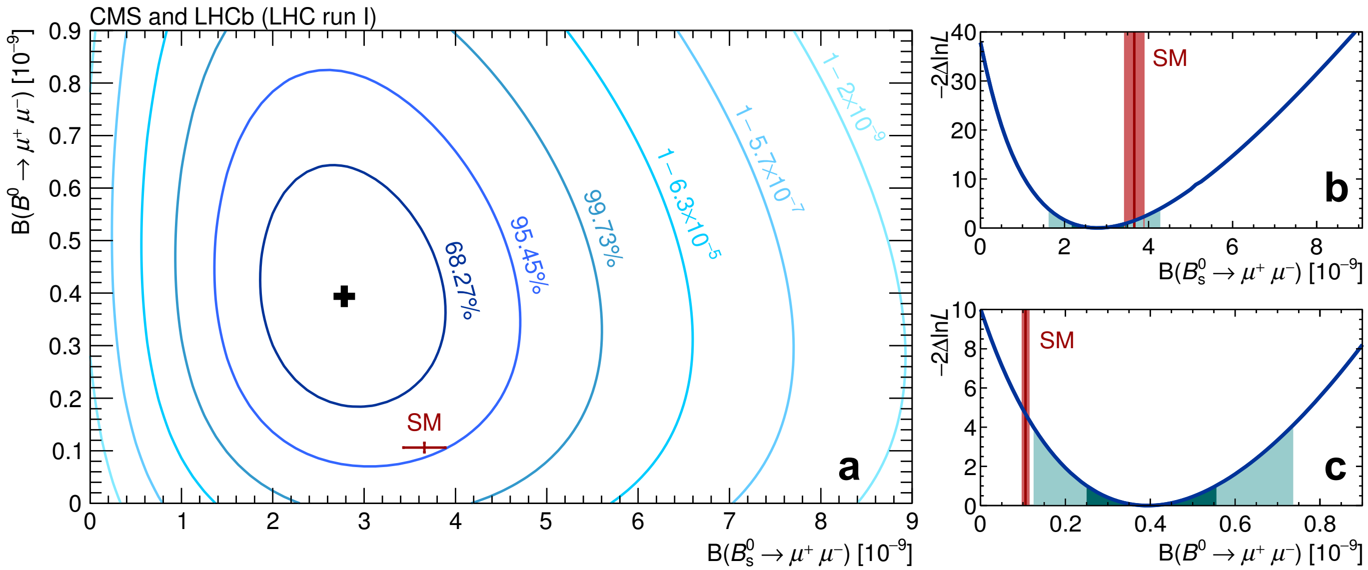
  Latest $f_s/f_d = 0.259 \pm 0.015$ appears not too far from systematics limited [LHCb-CONF-2013-011]

- New experimental analysis ideas?

Push $B_d \to \mu^+\mu^-$ to theory limit

- LHCb with $50/\text{fb}$ expects 40% precision at SM level — theory good to few $\%$!

  Would need ~ 100 times anticipated $50/\text{fb}$ data — will CMS win on this?



[LHCb & CMS, 1411.4413]

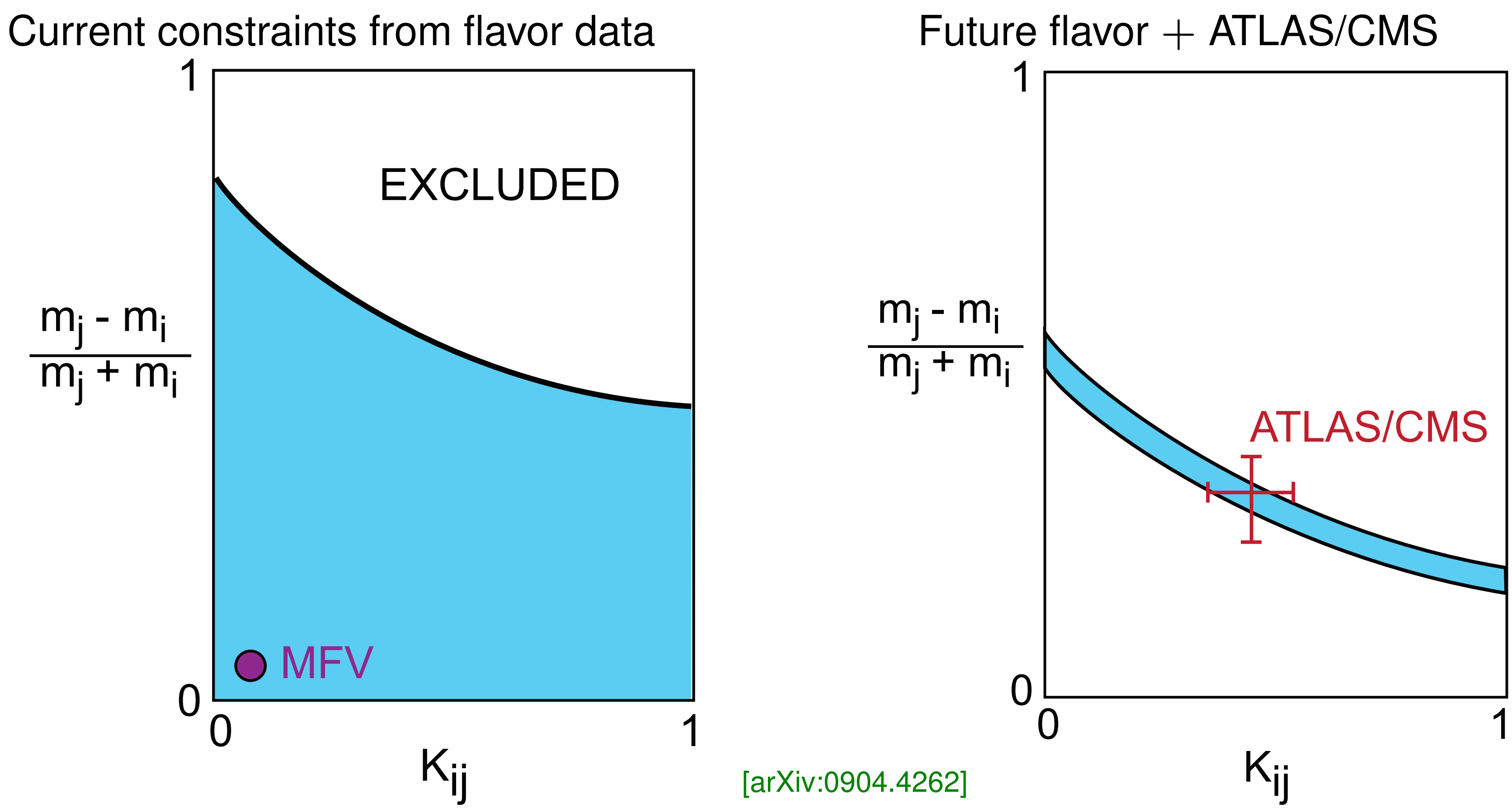
- Theoretically cleanest $|V_{ub}|$ I know, only isospin: $\mathcal{B}(B_u \to \ell\bar\nu)/\mathcal{B}(B_d \to \mu^+\mu^-)$

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

Final remarks

Flavor / LHC complementarity

- Combination of LHC and flavor data can be very powerful to discriminate models



- Let’s hope we’ll be in such a situation...

(Part of) a wish-list for theory

- New methods: recall that the best α and γ measurements are in modes proposed in light of the BaBar & Belle 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)
  - Variations on factorization, tractability of charm loops
  - Can direct CP asymmetries in nonleptonic modes be understood enough to make them “discovery modes”? [$SU(3)$ vs the heavy quark limit, etc...]

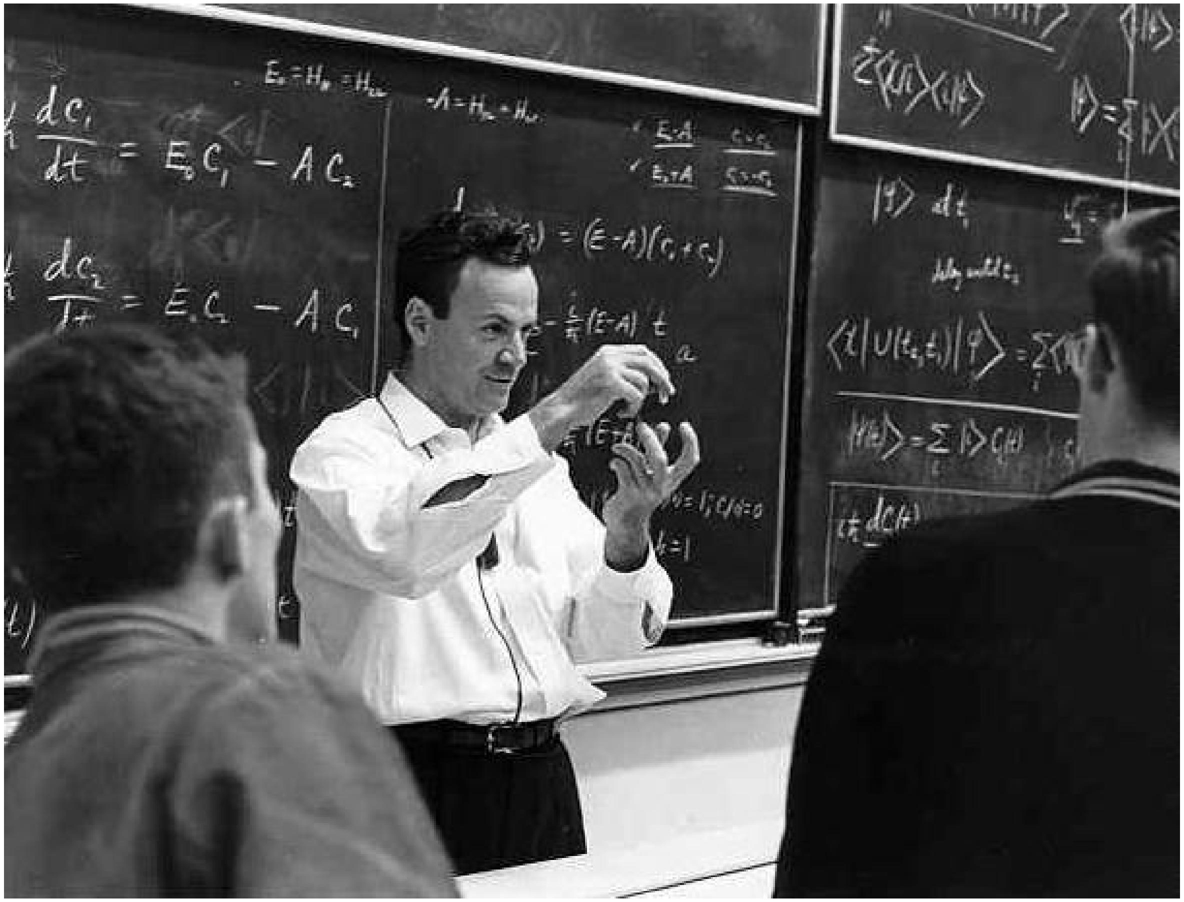
Conclusions

- Flavor physics probes scales $\gg 1\,\mathrm{TeV}$; sensitivity limited by statistics, not theory
- New physics in most FCNC processes may still be $\gtrsim 20\%$ of the SM or more
- Few discrepancies in SM fit; some of these (or others) may become decisive
- Precision tests of SM will improve by $10^1 - 10^4$ in some channels (CLFV)
- Flavor physics data will tell us a lot, whether NP is found or not

Evidence for BSM?		FLAVOR: yes	FLAVOR: no
ATLAS & CMS	yes	complementary information	distinguish models
ATLAS & CMS	no	tells us where to look next	flavor is the best microscope

- If new physics is discovered, many new questions about its structure and origin

  E.g., possible convergence between (s)quark and (s)lepton flavor physics



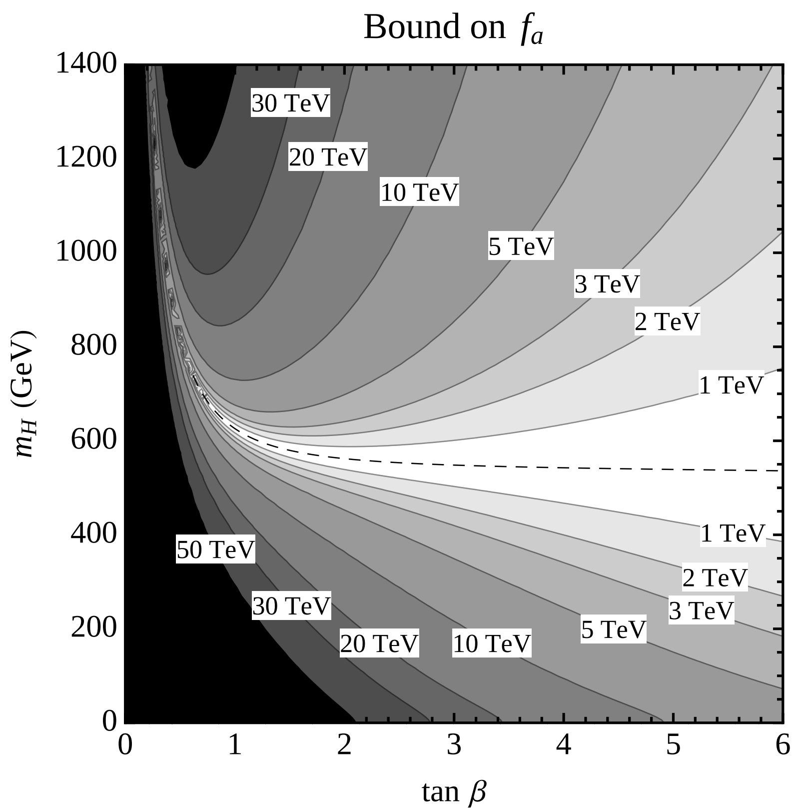
"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong." [Feynman]

Backup slides

Dark sectors: bumps in $B \to K^{(*)}\ell^+\ell^-$?

- Can probe certain DM models with B decays

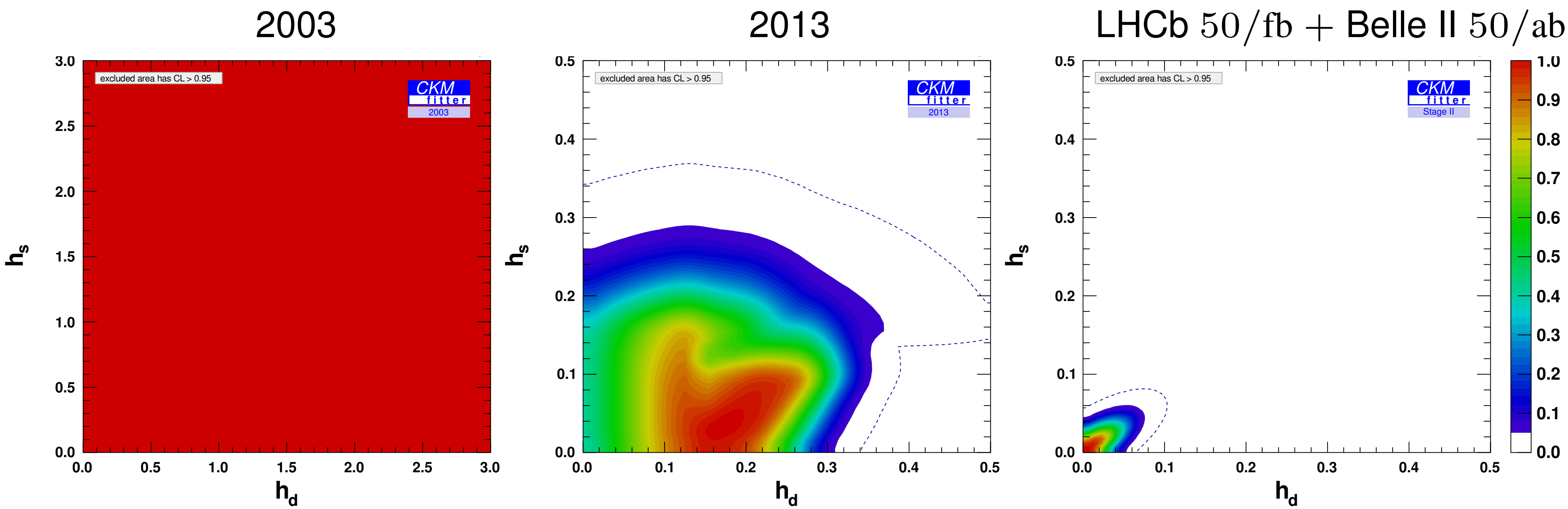
  E.g., "axion portal": light ($\lesssim 1\,\mathrm{GeV}$) scalar particle coupling as $(m_\psi/f_a)\,\bar{\psi}\gamma_5\psi\,a$



[Freytsis, ZL, Thaler, arXiv:0911.5355]

- In most of parameter space best bound is from $B \to K\ell^+\ell^-$

Magnitudes on NP in B_d^0 and B_s^0 mixing

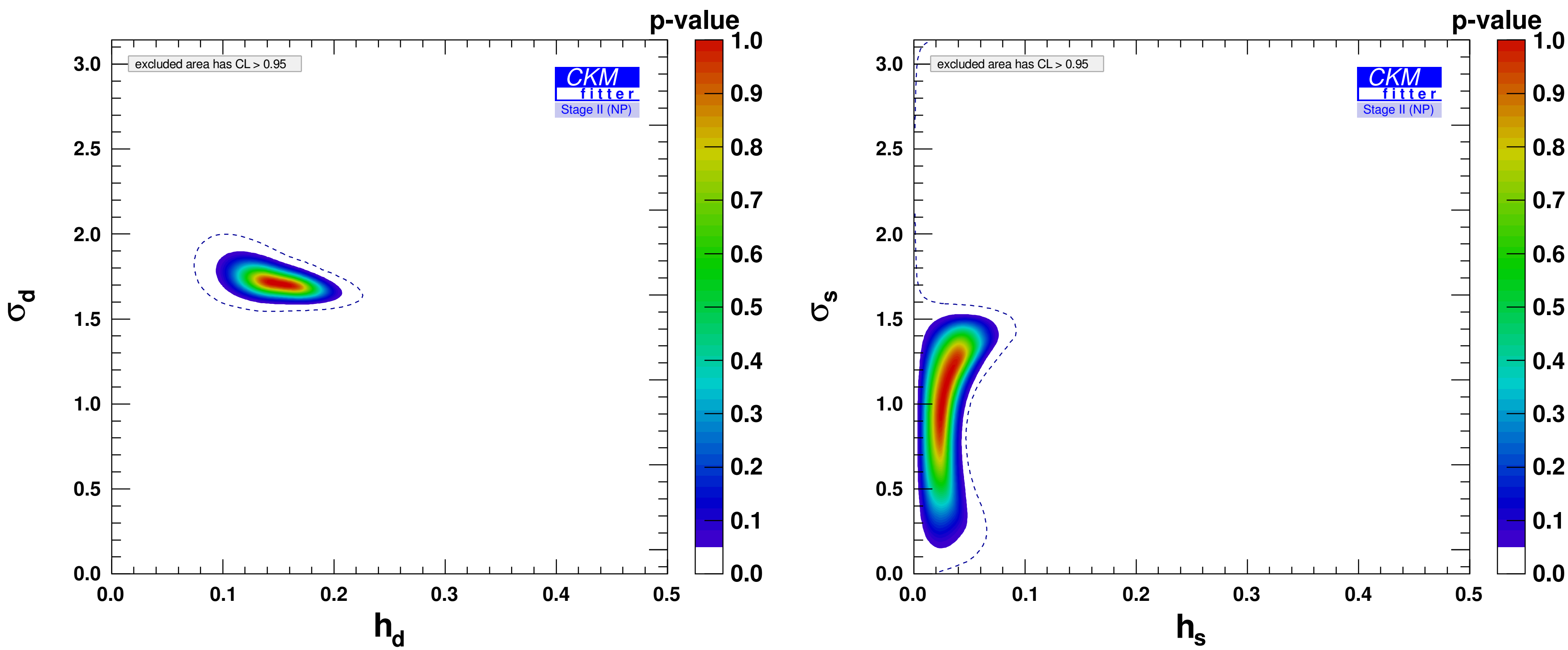


[1309.2293]

- 95% CL: NP $\lesssim$ (many $\times$ SM) $\rightarrow$ NP $\lesssim$ $(0.3\times$ SM) $\rightarrow$ NP $<$ $(0.05\times$ SM)
- Looking at $B_{d,s}$ mixing simultaneously (Connections to K mixing in $U(2)^3$ flavor models)

Can such fits discover NP?

- Interesting to see if NP can be discovered and not only constrained



Any assumption about future NP signals is ad hoc — simplest scenario: assume all future (Stage II) experimental results correspond to the current best-fit values of $\bar{\rho}$, $\bar{\eta}$, $h_{d,s}$, $\sigma_{d,s}$

The MSSM parameters and flavor

- Superpotential: [Haber, hep-ph/9709450]

$$W = \sum_{i,j} \left(Y^u_{ij} H_u\, Q_{Li} \bar{U}_{Lj} + Y^d_{ij} H_d\, Q_{Li} \bar{D}_{Lj} + Y^\ell_{ij} H_d\, L_{Li} \bar{E}_{Lj} \right) + \mu H_u H_d$$

- Soft SUSY breaking terms: $(S = \tilde{Q}_L, \tilde{\bar{D}}_L, \tilde{\bar{U}}_L, \tilde{L}_L, \tilde{\bar{E}}_L)$

$$\mathcal{L}_{\rm soft} = -\left(A^u_{ij} H_u \tilde{Q}_{Li} \tilde{\bar{U}}_{Lj} + A^d_{ij} H_d \tilde{Q}_{Li} \tilde{\bar{D}}_{Lj} + A^\ell_{ij} H_d \tilde{L}_{Li} \tilde{\bar{E}}_{Lj} + B H_u H_d \right)$$
$$- \sum_{\rm scalars} (m_S^2)_{ij}\, S_i \bar{S}_j - \frac{1}{2} \left(M_1 \tilde{B} \tilde{B} + M_2 \tilde{W} \tilde{W} + M_3 \tilde{g} \tilde{g} \right)$$

$3\ Y^f$ Yukawa and $3\ A^f$ matrices — $6\times$(9 real $+\ 9$ imaginary) parameters

$5\ m_S^2$ hermitian sfermion mass-squared matrices — $5\times$(6 real $+\ 3$ imag.) param's

Gauge and Higgs sectors: $g_{1,2,3},\, \theta_{\rm QCD},\, M_{1,2,3},\, m^2_{h_{u,d}},\, \mu,\, B$ — 11 real $+\ 5$ imag.

Parameters: $(95 + 74) - (15 + 30)$ from $U(3)^5 \times U(1)_{\rm PQ} \times U(1)_R \to U(1)_B \times U(1)_L$

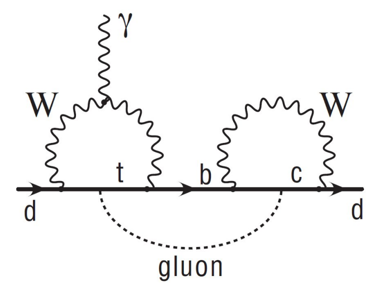
- 44 CPV phases: CKM $+\ 3$ in M_1, M_2, μ (set $\mu B^*, M_3$ real) $+\ 40$ in mixing matrices of fermion-sfermion-gaugino couplings ($+80$ real param's)

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

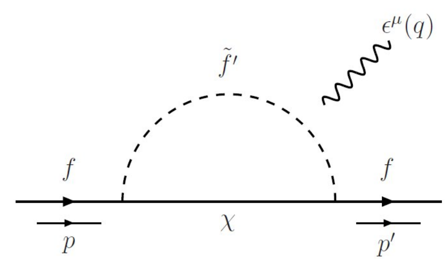
- Neutron EDM bound: "The strong CP problem:" $\theta_{\rm QCD} < 10^{-10}$ — axion?
  $\theta_{\rm QCD}$ is negligible for CPV in flavor-changing processes

- EDMs from CKM: vanish at one- and two-loop
  large suppression of this diagram



- In SUSY, both 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

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

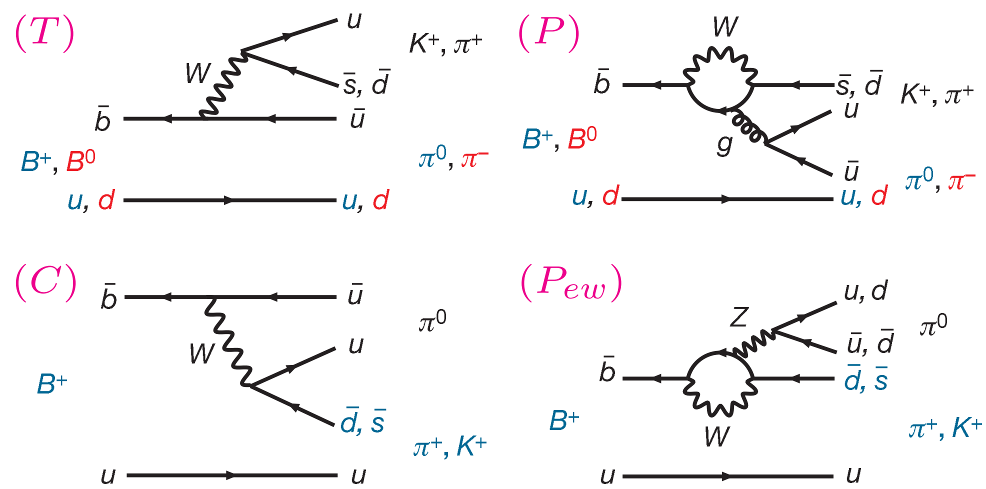
- Have we seen new physics in CPV?

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

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

- 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 (Lipkin) and $SU(3)$ relations

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