Theoretical Outlook

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Clear and well established motivations

Hierarchy problem $\to$ TeV scale?
Dark matter $\to$ WIMP paradigm?
$\Big\}$ $\Leftrightarrow$ no clear BSM signals in FPCP data

– 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)

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

  Hope: verify Kobayashi–Maskawa mechanism $\to$ discover/study BSM

  Increase in sensitivity to high scales $\sqrt[4]{50} \sim 2.5$, similar to LHC 7-8 $\to$ LHC 13-14

  (Minimal estimate, expect “unpredictable” progress, data has always motivated new ideas)

- EDM and CLFV sensitivity will also improve orders of magnitude — very important

Preliminaries

- Experimental outlook: **awesome!** [See: Marconi, Barrett]
- Theoretical outlook: Depends a bit on who you ask [Recall panel discussion w/ Browder]
  Data always motivates theory
  More progress than imagine it now (next breakthroughs?)

- Cannot cover all topics, focus on a few, mainly in the quark sector
- 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`
- Apologies for missing references ["act now, apologize later" ©Ben Grinstein]

New physics: dimension > 4 operators

- Heavy BSM physics generates dimension > 4 operators ("nonrenormalizable")

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

- Unique type of dimension-5 terms: $(L\phi)(L\phi)$
  These were discovered, if m_ν term violates lepton number ("Majorana" $\Rightarrow 0\nu\beta\beta$)

- The presence of no dim-6 term has been established:

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

  Flavor and CP violation: $\dfrac{QQQQ}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^{(3\dots7)}\, \text{GeV}$

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

- Search for (heavy) new physics $=$ search for such new contributions

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 $50/\text{ab}$ 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		$\pm 2^\circ$	$\pm 1^\circ$	
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
$\lvert V_{cb}\rvert$ 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
$S(B \to K_S^0\pi^0\gamma)$	$-0.10 \pm 0.31 \pm 0.07$	± 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 (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}]	$1.11 \pm 0.22 \pm 0.11$	$\pm$(0.11-0.13)	$\pm$(0.05-0.08)	5-8
A_Γ [10^{-2}]	$-0.03 \pm 0.20 \pm 0.08$	± 0.10	$\pm$(0.03-0.05)	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
$\lvert q/p\rvert^{K_S\pi^+\pi^-}$	$0.90 \pm {}^{0.16}_{0.15} \pm {}^{0.08}_{0.06}$	± 0.10	± 0.07	5-6
$\phi^{K_S\pi^+\pi^-}$ [$^\circ$]	$-6 \pm 11 \pm {}^{4}_{5}$	± 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

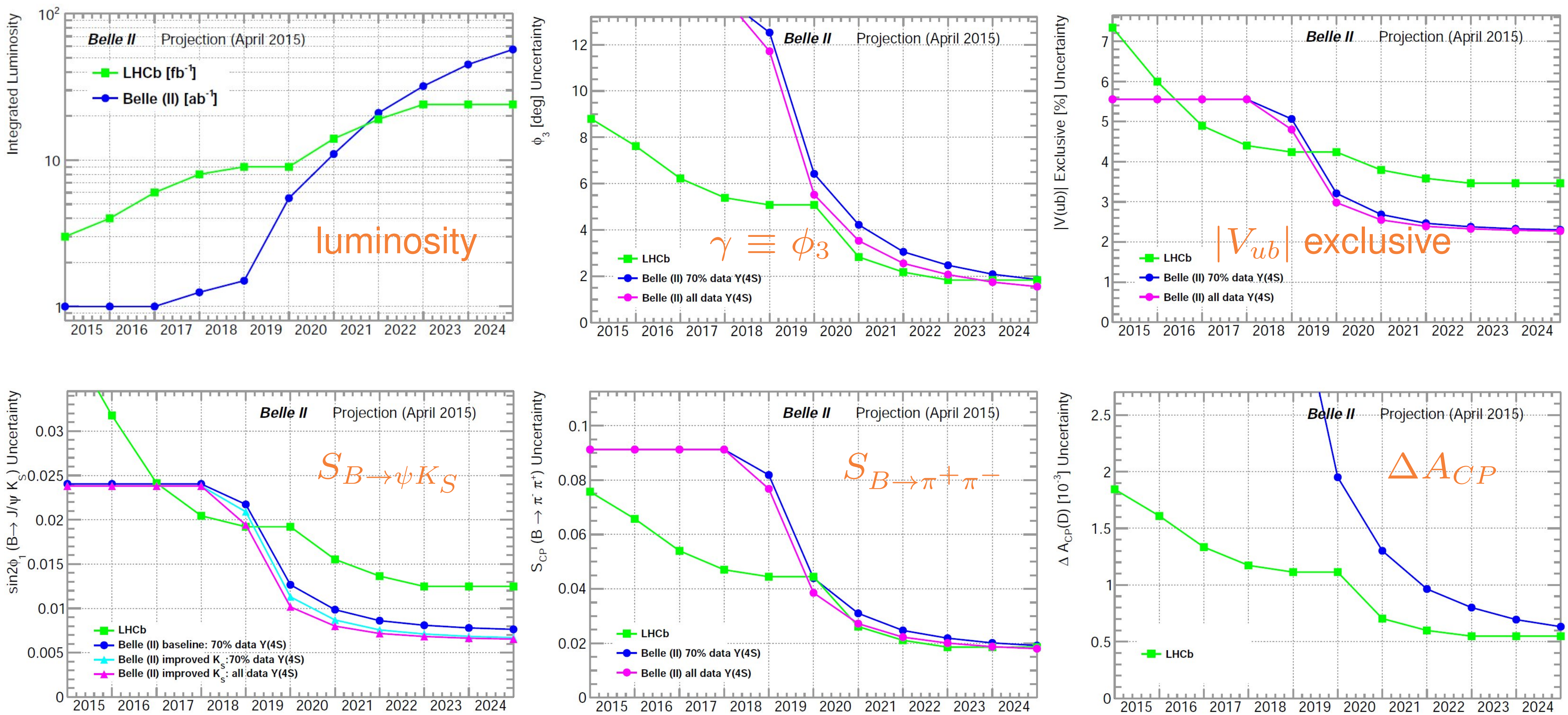
$\mathcal{L}_s$ = luminosity so that $\sigma(\text{stat}) = \sigma(\text{syst})$

Clear physics cases

Broad program, large improvements

I will not go through all...

Belle II — LHCb: complementarity & competition



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

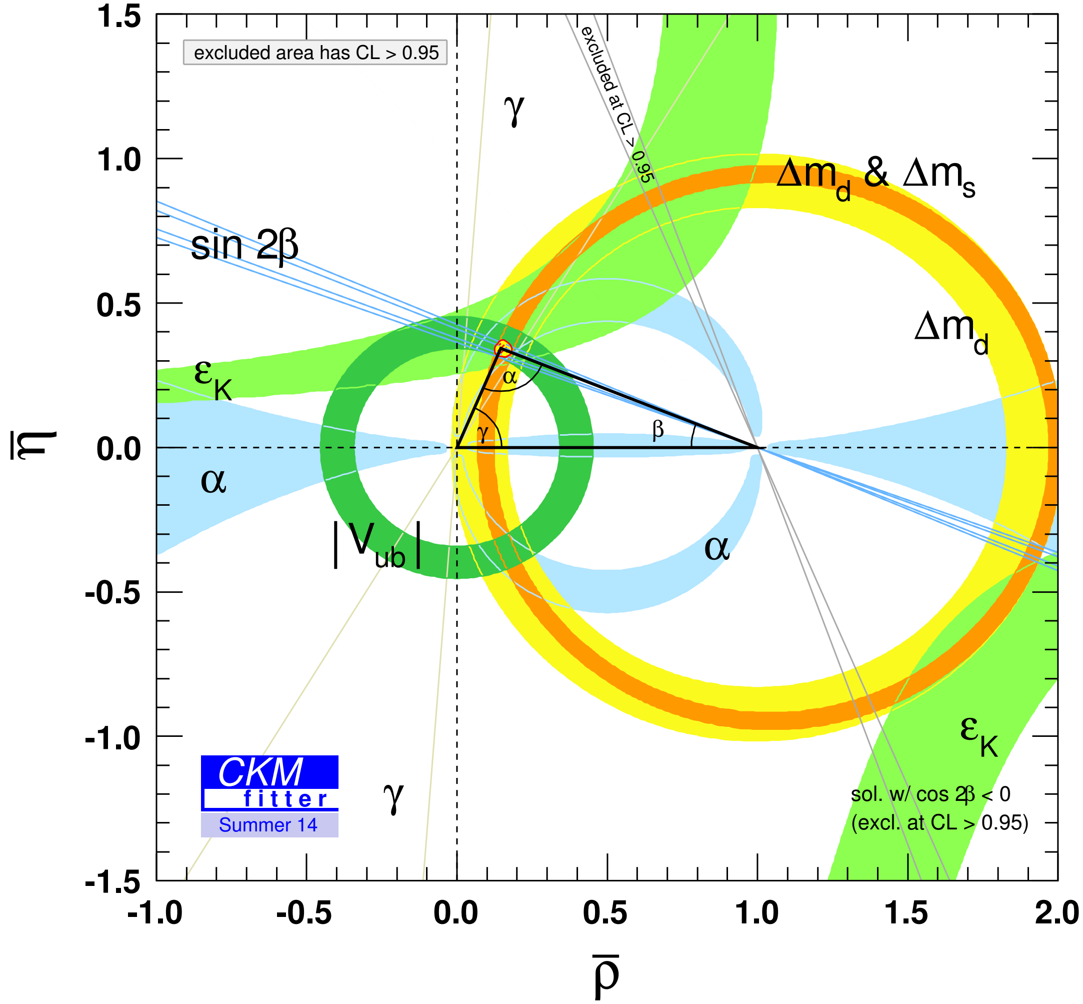
- Details depend on Belle II and LHC LS2–3 schedules [Urquijo, private communications]

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
- If NP couples to quarks and leptons, understanding new flavor parameters will be crucial (recent example: probe SM & BSM Higgs couplings)

The standard model CKM fit

- The level of agreement between the measurements is often mis-interpreted
- Larger allowed region if the SM is not assumed to hold, more fit parameters

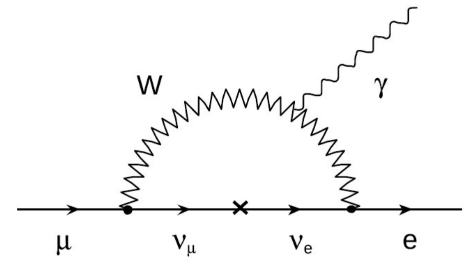


- $\mathcal{O}(20\%)$ NP contributions to most loop-level processes (FCNC) are still allowed

Charged lepton flavor violation

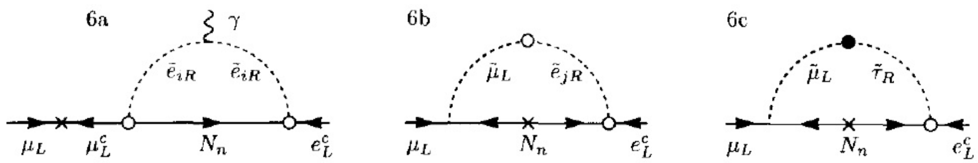
- SM predicted lepton flavor conservation with $m_\nu = 0$

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

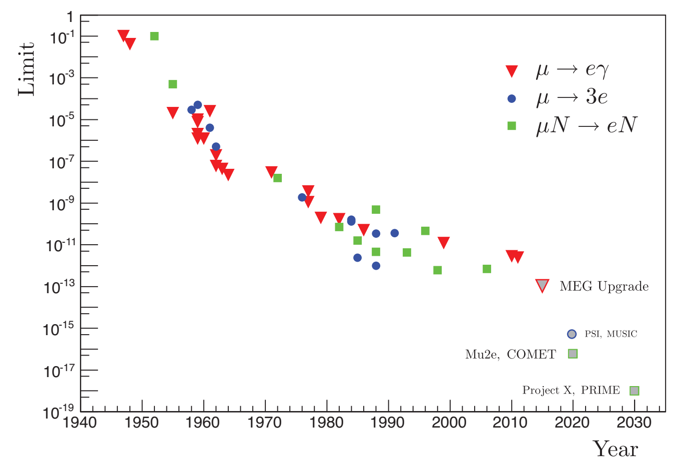


$$\mathcal{B}(\mu \to e\gamma) \sim \alpha \frac{m_\nu^4}{m_W^4} \sim 10^{-52}$$

- If new TeV-scale particles carry lepton number (e.g., sleptons), then they have their own mixing matrices $\Rightarrow$ charged lepton flavor violation [Passemar]



History of $\mu \to e\gamma$, $\mu N \to eN$, and $\mu \to 3e$



- Many interesting processes:

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

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

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

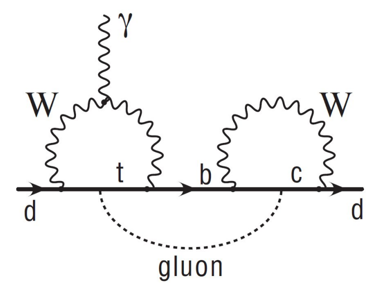
- Next 10–20 years: 10^2–10^5 improvement; any signal would trigger broad program

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 [Jung]

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

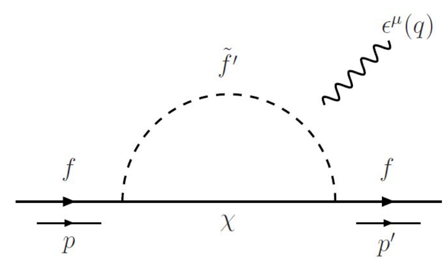
- EDMs from CKM: vanish at one- and two-loop
  large suppression at three-loop level



- In SUSY, both quark and lepton EDMs can be generated at one-loop

  Generic prediction (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



The rest of this talk

- Near future:

  Current anomalies: most often talked about

  best chance to become decisive soon (unless fluctuations)

- Long term future: large improvements in new physics sensitivity

  "Expected" / "predictable": need lots of work and ingenuity still, may encounter surprises while pushing for large improvements

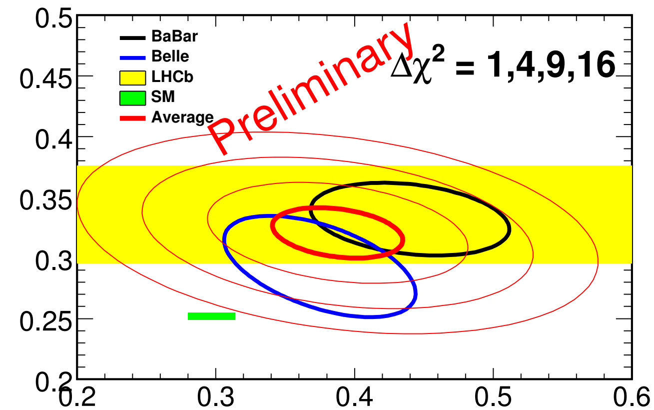
  One example: new physics in meson mixing

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

New results: $B \to D^{(*)}\tau\bar{\nu}$ rates

- New Belle & LHCb results on the anomaly seen by BaBar in $R(X) = \dfrac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X\ell\bar{\nu})}$

	$R(D)$	$R(D^*)$
BaBar	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$
Belle	$0.375^{+0.064}_{-0.063} \pm 0.026$	$0.293^{+0.039}_{-0.037} \pm 0.015$
LHCb		$0.336 \pm 0.027 \pm 0.030$
Average	0.388 ± 0.047	0.321 ± 0.021
SM expectation	0.300 ± 0.010	0.252 ± 0.005
Belle II, 50/ab	± 0.010	± 0.005



[Thanks to M. Rotondo]

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

- An obvious cross-check: precise prediction in SM $R(X_c) = 0.223 \pm 0.004$
  vs. $\mathcal{B}(b \to X\tau^+\nu) = (2.41 \pm 0.23)\%$ (LEP / PDG)
  Neither BaBar nor Belle has measured $\mathcal{B}(B \to X\tau\bar{\nu})$

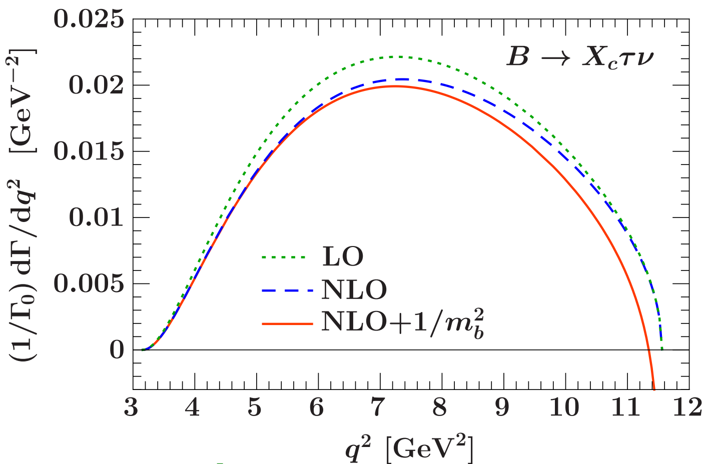
[Freytsis, ZL, Ruderman, to appear, Leptoquarks, W', etc? MFV?]

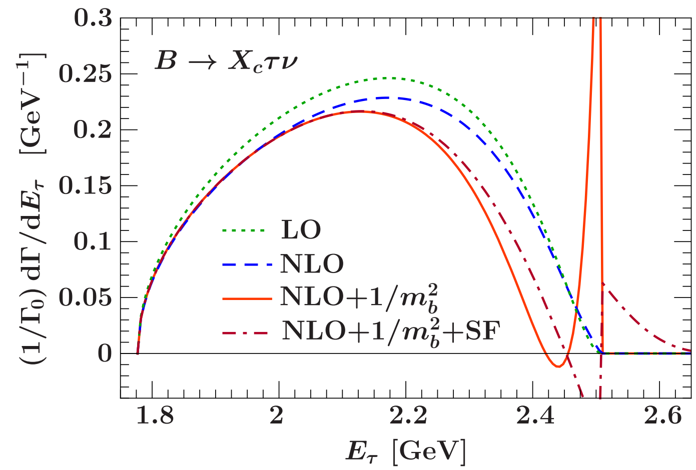
- Next steps: LHCb result with hadronic τ decays, measure $R(D)$, maybe Λ_b decay

Aside: precision $B \to X_c \tau \bar{\nu}$ predictions

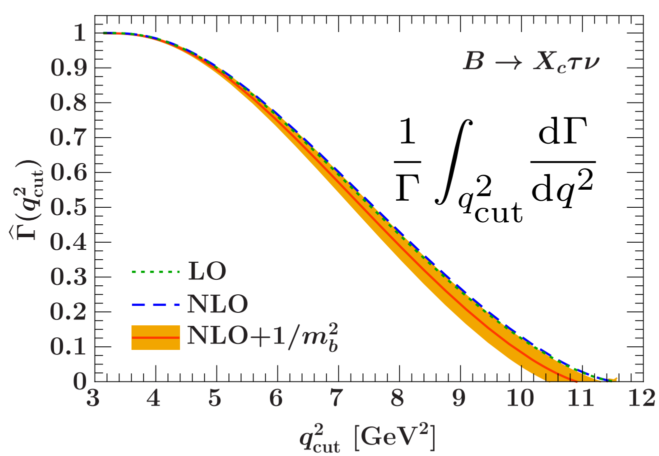
- No measurements since LEP (work in progress?) (No theory work in ~ 15 yrs)

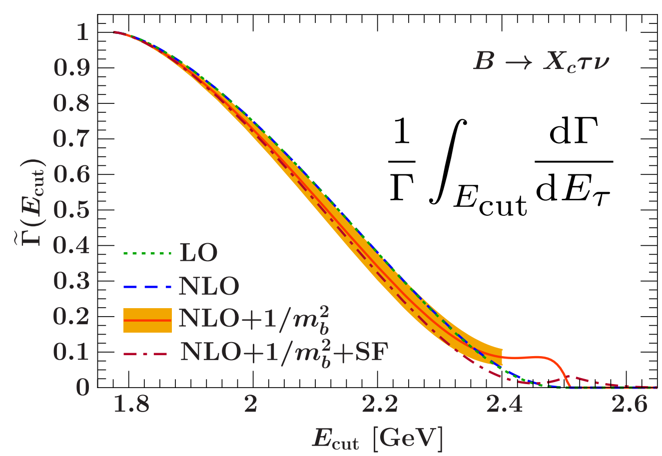
Papers in '90s used pole mass, no predictions for spectra — interesting theory issues





[ZL & Tackmann, 1406.7013]





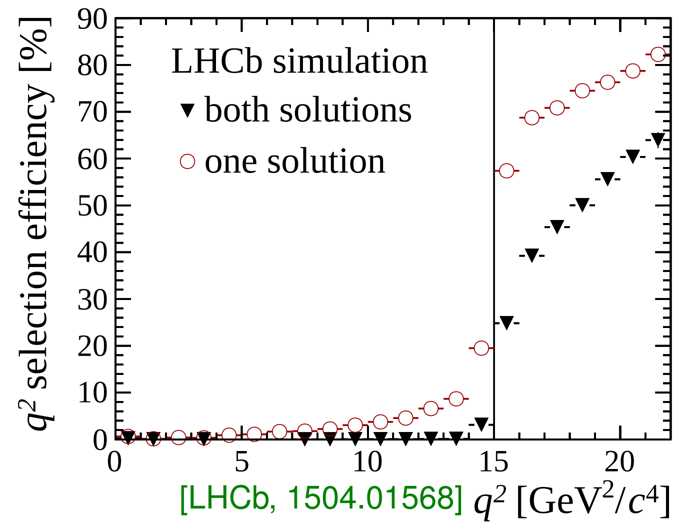
$|V_{ub}|$ from $\Lambda_b \to p\mu\bar{\nu}$

- $|V_{ub}|$ 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%

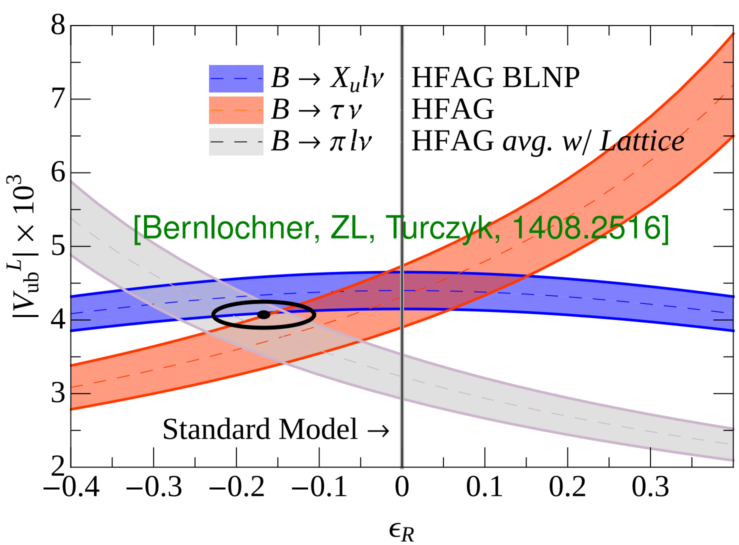
  BES III result soon; did you look carefully at the posters?

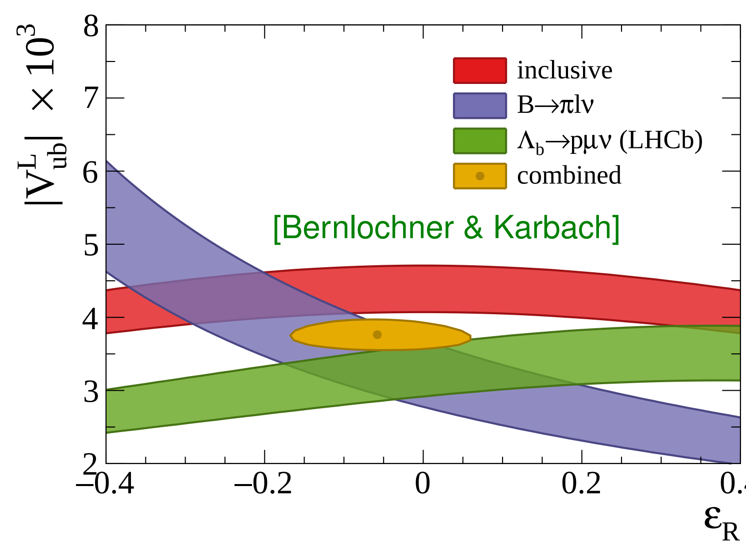


- $\sim 3\,\sigma$ tension among $|V_{ub}|$ measurements

  Too early to conclude, measurements and theory will improve

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





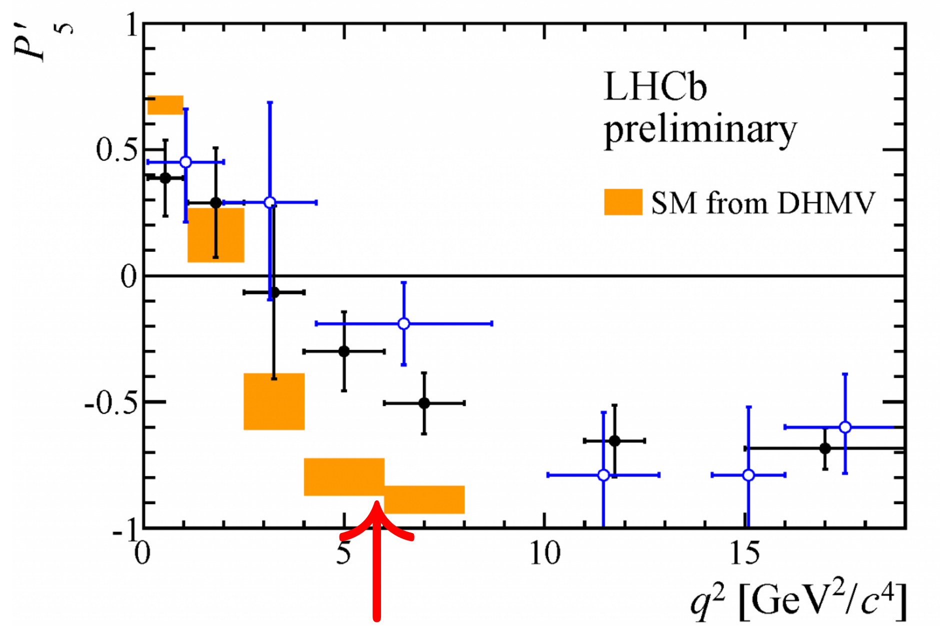
$B \to K^* \ell^+ \ell^-$: the P_5' anomaly

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

  Difficult for lattice QCD, large recoil

  Measuring all the other distributions remains important

  Global fits: simplest solution may be that NP reduces C_9 [Altmannshofer, Bobeth, Martin Camalich]

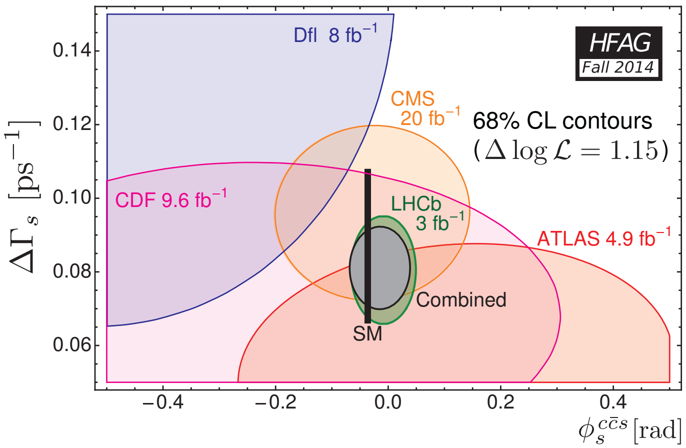


NP, fluctuation, theory?

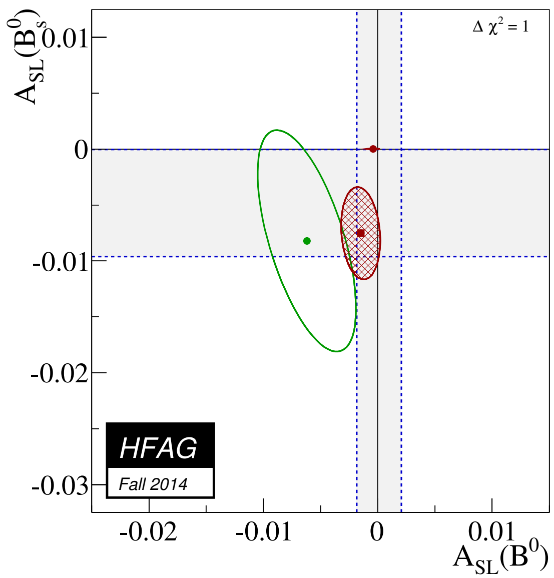
- Cross checks: different regions of phase space, also study in B_s and Λ_b decays?

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

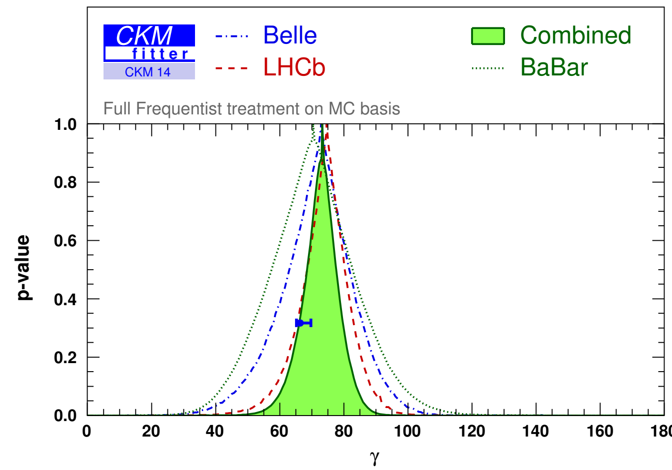
Other recent highlights



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 predictions $\ll$ current experimental errors ($\Rightarrow$ much more data)
- I have nothing new to say 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 clearly established

Charm CP violation

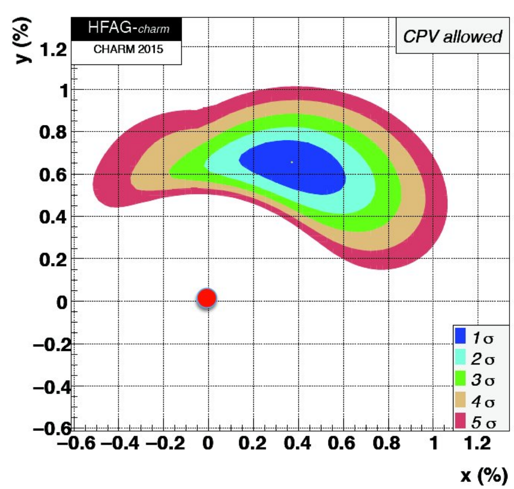
- CP violation in D decay

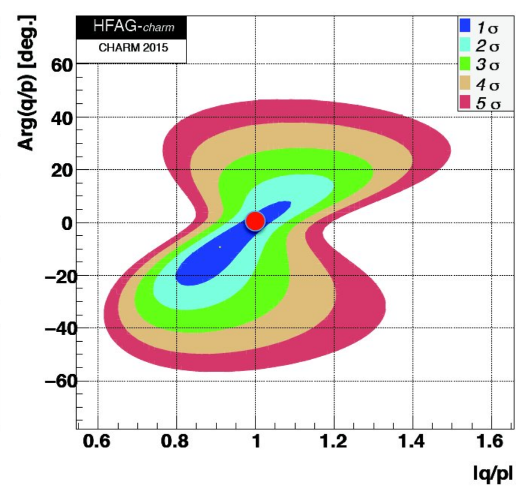
  LHCb, late 2011: $\Delta A_{CP} \equiv A_{K^+K^-} - A_{\pi^+\pi^-} = -(8.2 \pm 2.4) \times 10^{-3}$

  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-type quarks or in SUSY by up-type squarks
- How large is Δm? Not even 2σ now! Bound on $|q/p| - 1$ remains weak
- Not theory limited, more work needed Connections to FCNC top decays





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

Hide flavor signals ⇔ hide high-p_T signals

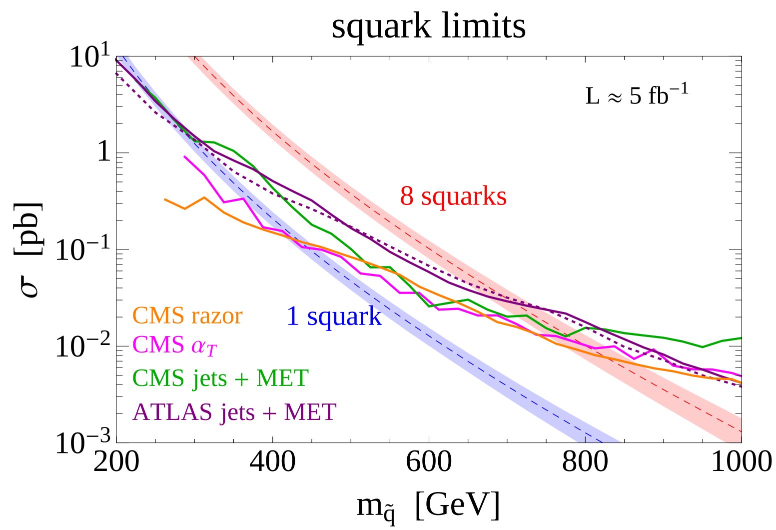
- Squarks need not be as degenerate as often thought or assumed [Gedalia, Kamenik, ZL, Perez, 1202.5038]

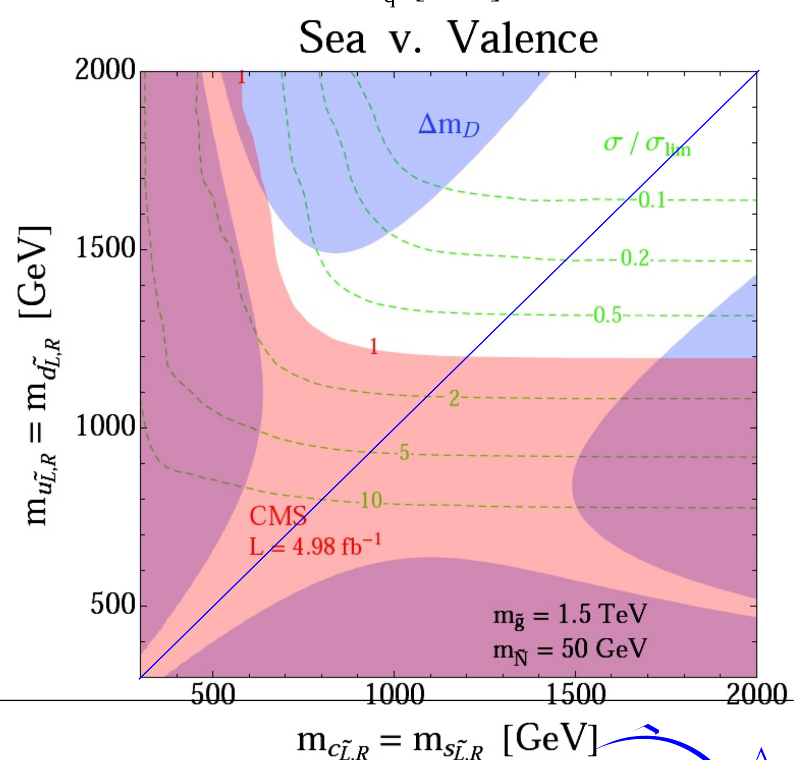
  Top plot: each LHC search becomes weaker [Mahbubani, Papucci, Perez, Ruderman, Weiler, 1212.3328]

  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: $1.2\,\text{TeV} \;\Rightarrow\; 600\,\text{GeV}$

- Ways for naturalness to survive: can give up many assumptions...





A surprise (for me): $B^+ \to K^+\pi^0$ at LHCb

- Observed 3.7σ mass peak in decay w/ photons and no reconstructed decay vertex [LHCb-CONF-2015-001]

  http://cds.cern.ch/record/1988475

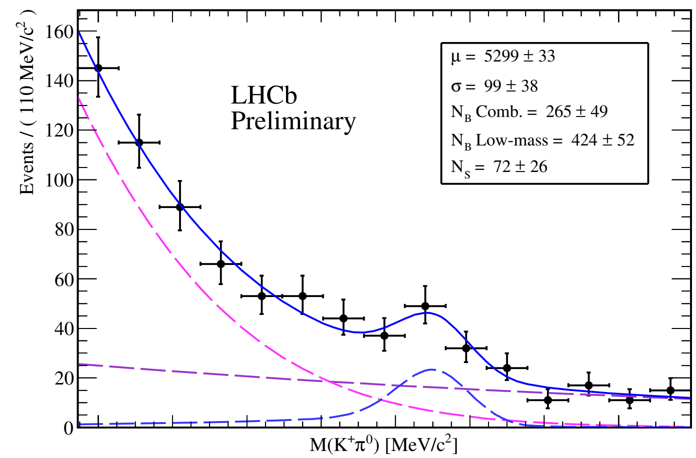
  At LHCb, this study also serves as a prototype for analyses with similar topologies, such as $B^0 \to K^0\pi^0$, $\Lambda_b \to \Lambda\gamma$, and $B^0 \to K^0\pi^0\gamma$

  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

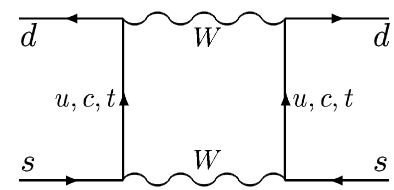
Far future: e.g., meson mixing

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

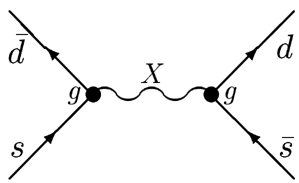
Δm_K — built into all NP models

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

  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



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

(The bound from ϵ_K is even stronger)

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

- Mechanisms devised to suppress this in all TeV-scale NP models (SUSY, etc.)
- SM-like Higgs — e.g., SUSY: large A terms? extended Higgs sector? $\to$ flavor?
- Sensitivity to higher scales is crucial, as we do not know where NP will show up

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

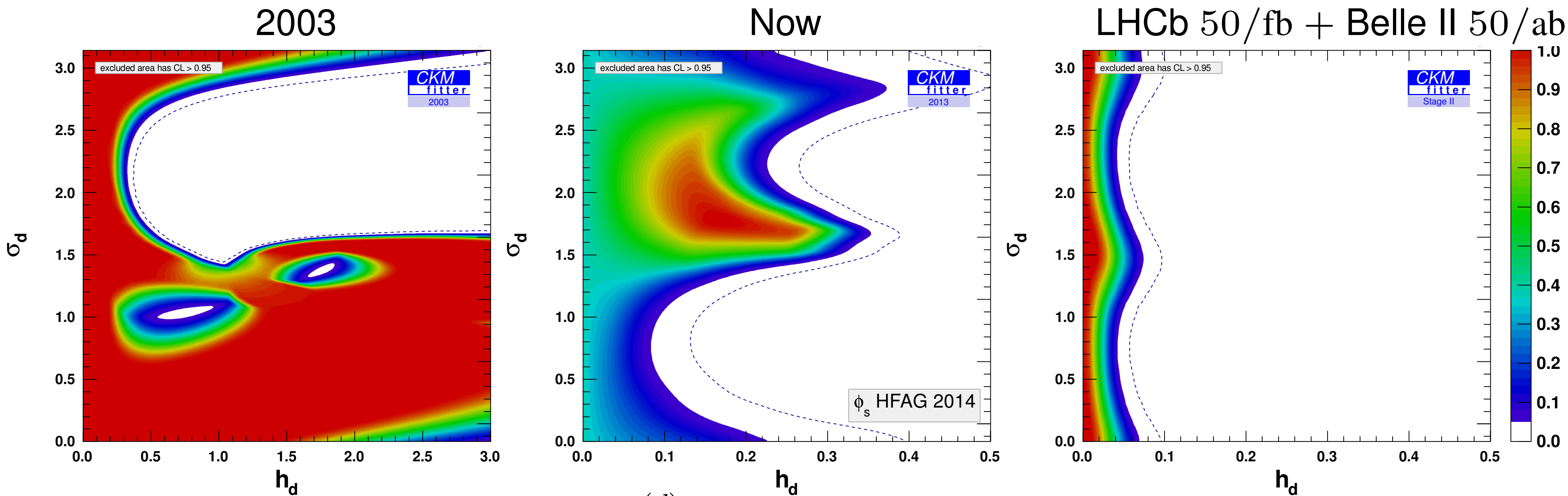
[Charles et al., 1309.2293]

- 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	
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	
$\lvert V_{cb}\rvert \times 10^3$ $(b \to c\ell\bar\nu)$	$41.6 \pm 0.58 \pm 0.8$	$41.15 \pm 0.33 \pm 0.59$	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]
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]
$A^d_{\rm SL} \times 10^4$	10 ± 140	23 ± 26	-7 ± 15	[17]	-7 ± 10	[17]
$A^s_{\rm SL} \times 10^4$	—	-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



[color: 2σ, dotted: 3σ]

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

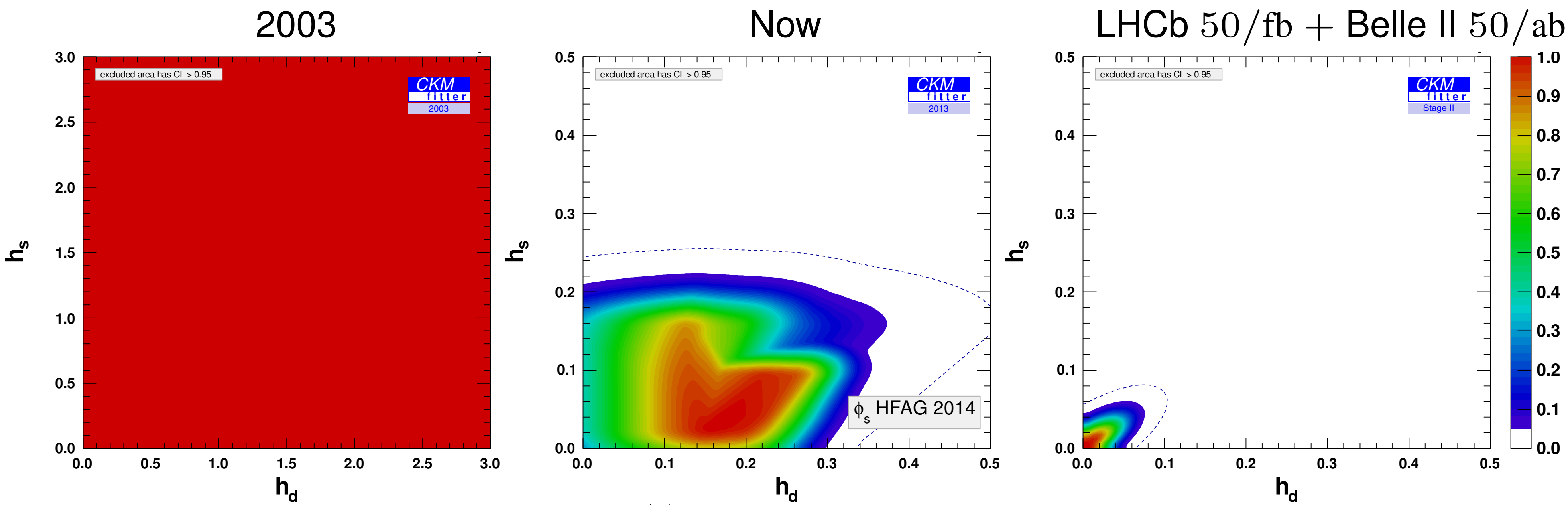
[1309.2293]

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

$$h \simeq \frac{|C_{ij}|^2}{|V_{ti}^* V_{tj}|^2} \left(\frac{4.5\,\text{TeV}}{\Lambda}\right)^2$$ — Will reach: $\Lambda \sim \begin{cases} 2.3 \times 10^3\,\text{TeV} \\ 20\,\text{TeV (tree + CKM)} \\ 2\,\text{TeV (loop + CKM)} \end{cases}$

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

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



[color: 2σ, dotted: 3σ]

$$M_{12}^{(q)} = M_{12}^{\mathrm{SM}} \times (1 + h_q\, e^{2i\sigma_q})$$

[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 — less “background” in SM expectation

Future mixing sensitivity

- Neutral meson mixing will remain a special process to search for new physics, sensitive to some of the highest scales

- Sensitivity to $(C_q^2/\Lambda^2)\,(\bar{b}_L\gamma^\mu q_L)^2$ with Belle II $50/\mathrm{ab}$ + LHCb $50/\mathrm{fb}$ [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: CKM & loop suppression)

  $\Lambda\sim 10^3\,\mathrm{TeV}$ (anarchic flavor)

- MFV and non-MFV regions will have comparable constraints (unlike to date)

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
  - $B_{s,d} \to \mu\mu$, $B \to \mu\nu$ and other leptonic decays (lattice QCD, [double] ratios)
  - Possibly CP violation in D mixing (firm up theory)
  - $A_{\rm SL}^{d,s}$ (can get around exp. syst. limits?)

  [Worth thinking about: I guess 10^2 – $10^3\times$ Belle II & LHCb upgrade?]

- 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]

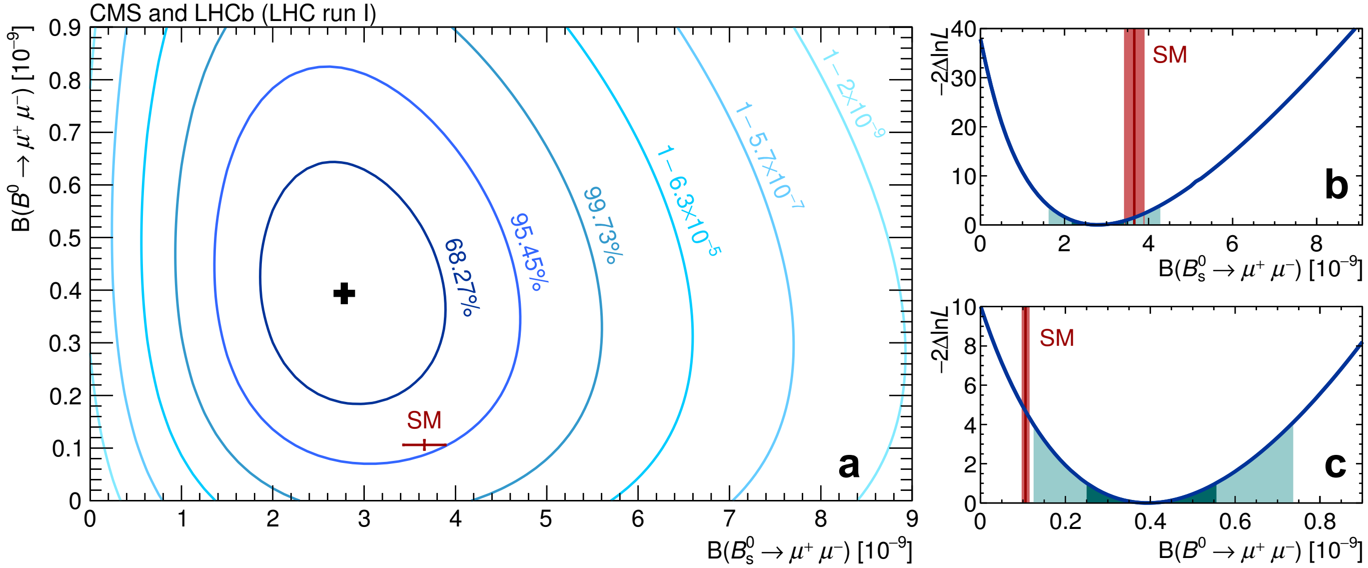
  Ultimately normalize to semileptonic, such as $\mathcal{B}(B_s \to \mu^+\mu^-)/\mathcal{B}(B_s \to D_s^-\mu^+\nu)$?

- New experimental analysis ideas?

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 $\simeq (2\%) \oplus f_{B_q}^2 \oplus \mathrm{CKM}$ [Bobeth]



[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

(Part of) a wish-list for theory

- 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, 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 many channels (CLFV)
- Flavor physics data will tell us a lot, whether NP is discovered or not

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

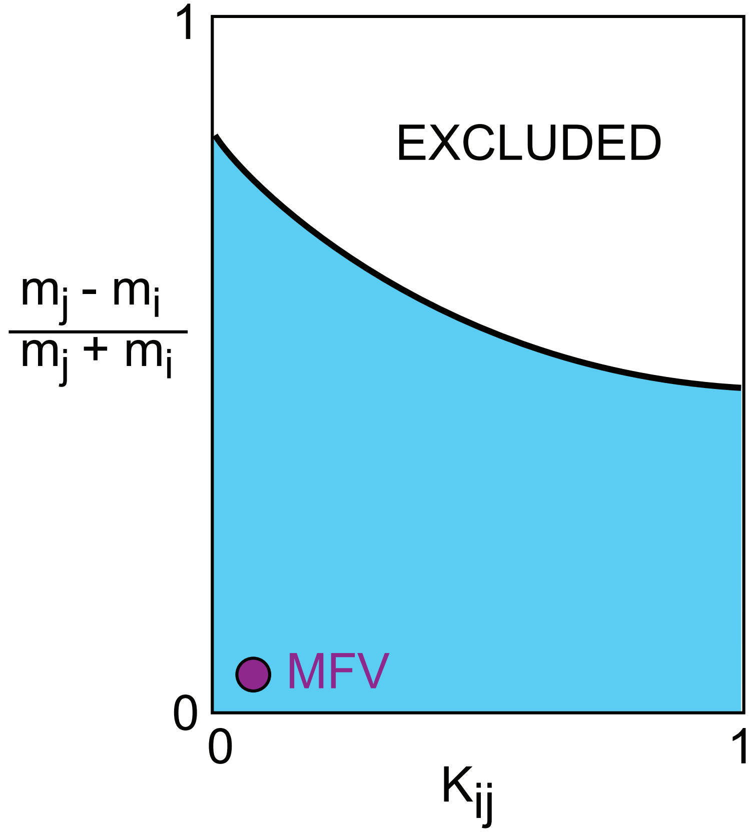
- If new physics is discovered, many new questions about its structure and origin

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

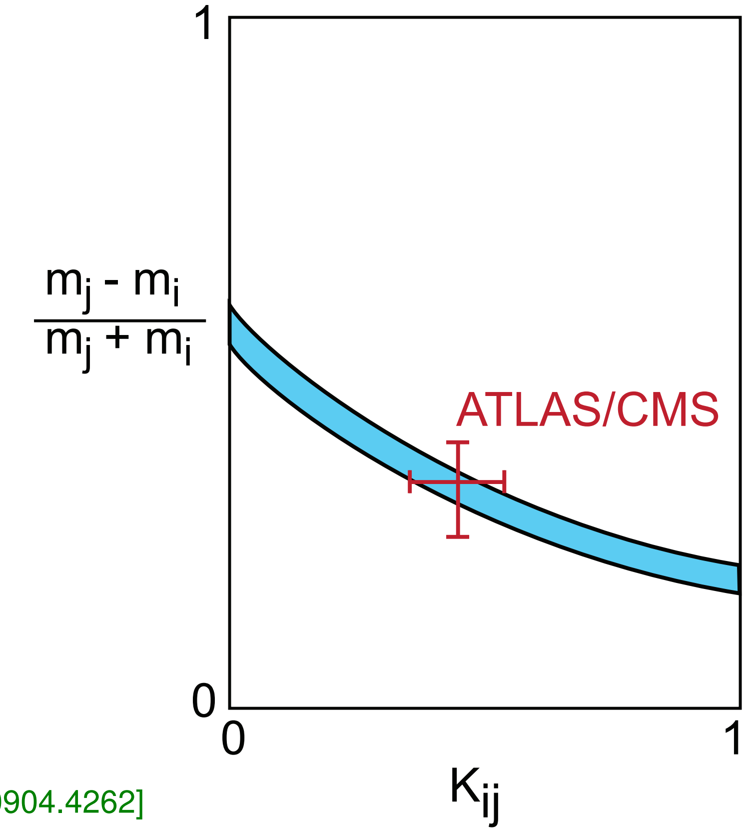
Flavor / high-p_T complementarity

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

Current constraints from flavor data



Future flavor + ATLAS/CMS



[arXiv:0904.4262]

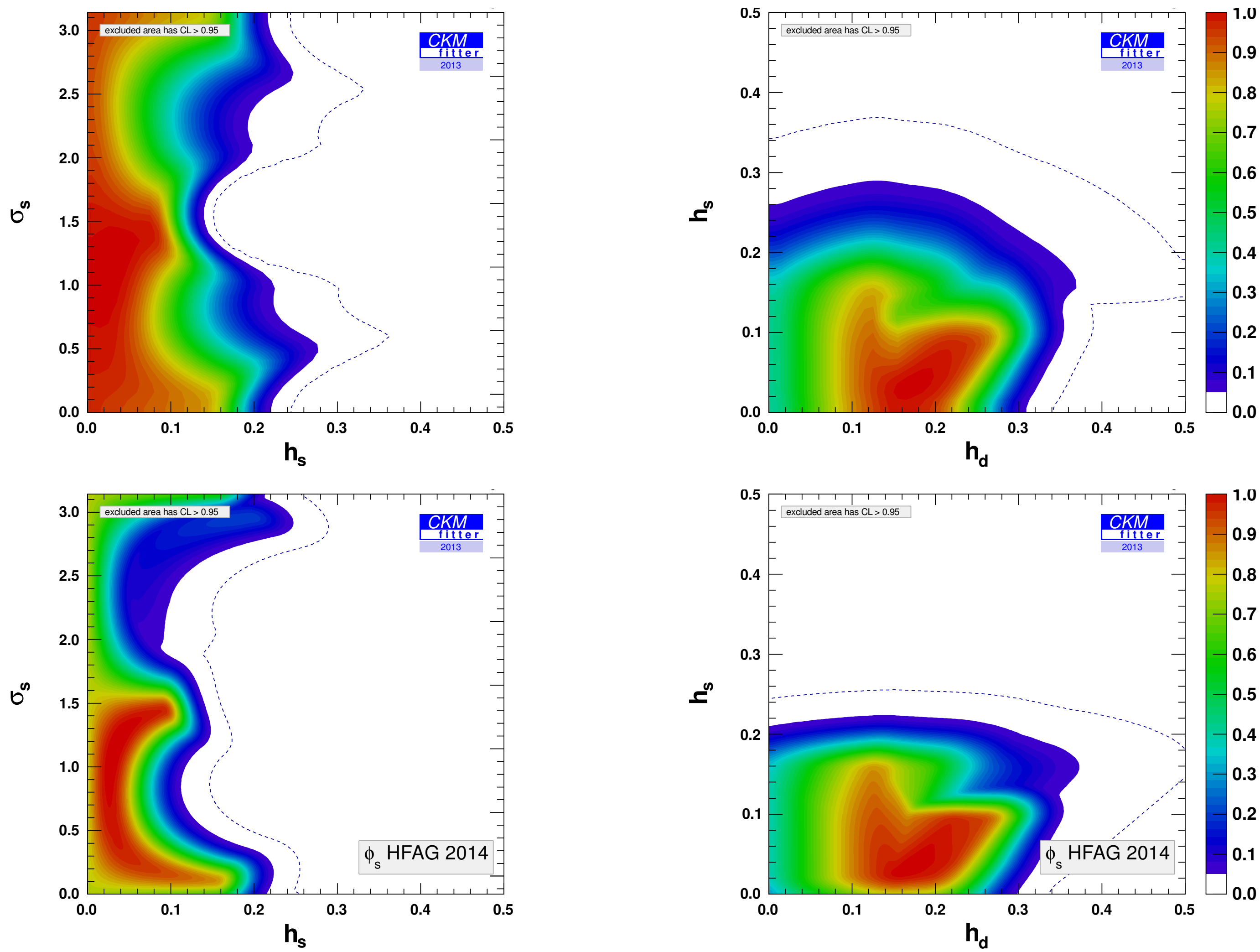
- Let's hope we'll be in such a situation...

Backup slides

2013 → 2015: impact of β_s with $1 \to 3/$ fb

2013:

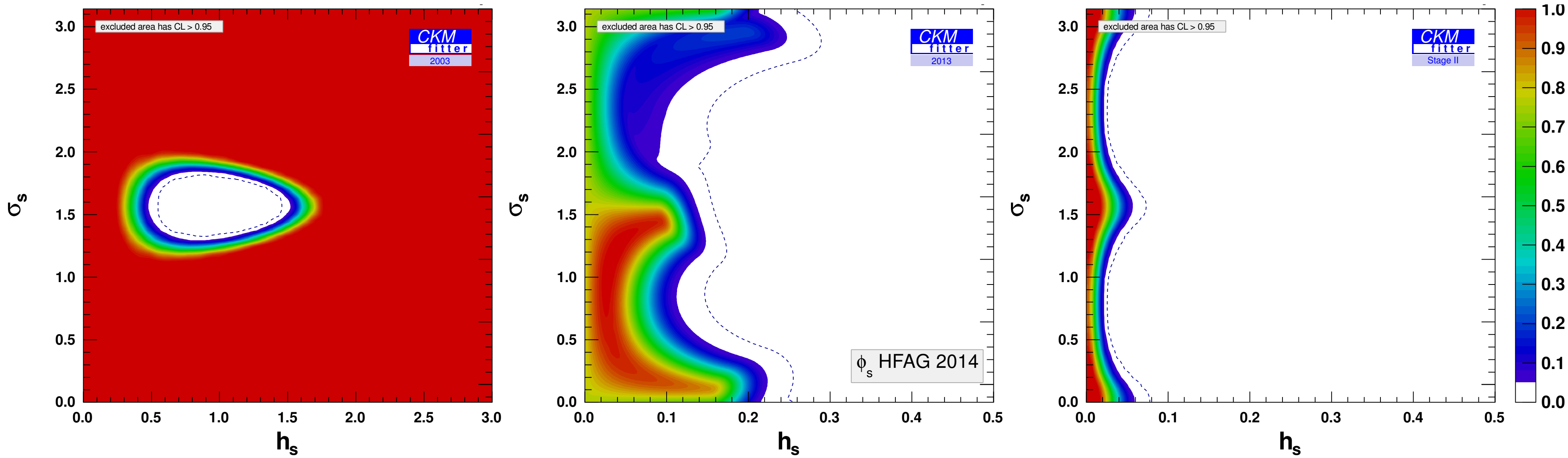
2015:



- Improvement mainly in h_s as expected

New physics in B_s^0 mixing

2003 | Now | LHCb $50/\mathrm{fb}$ + Belle II $50/\mathrm{ab}$



[color: 2σ, dotted: 3σ]

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

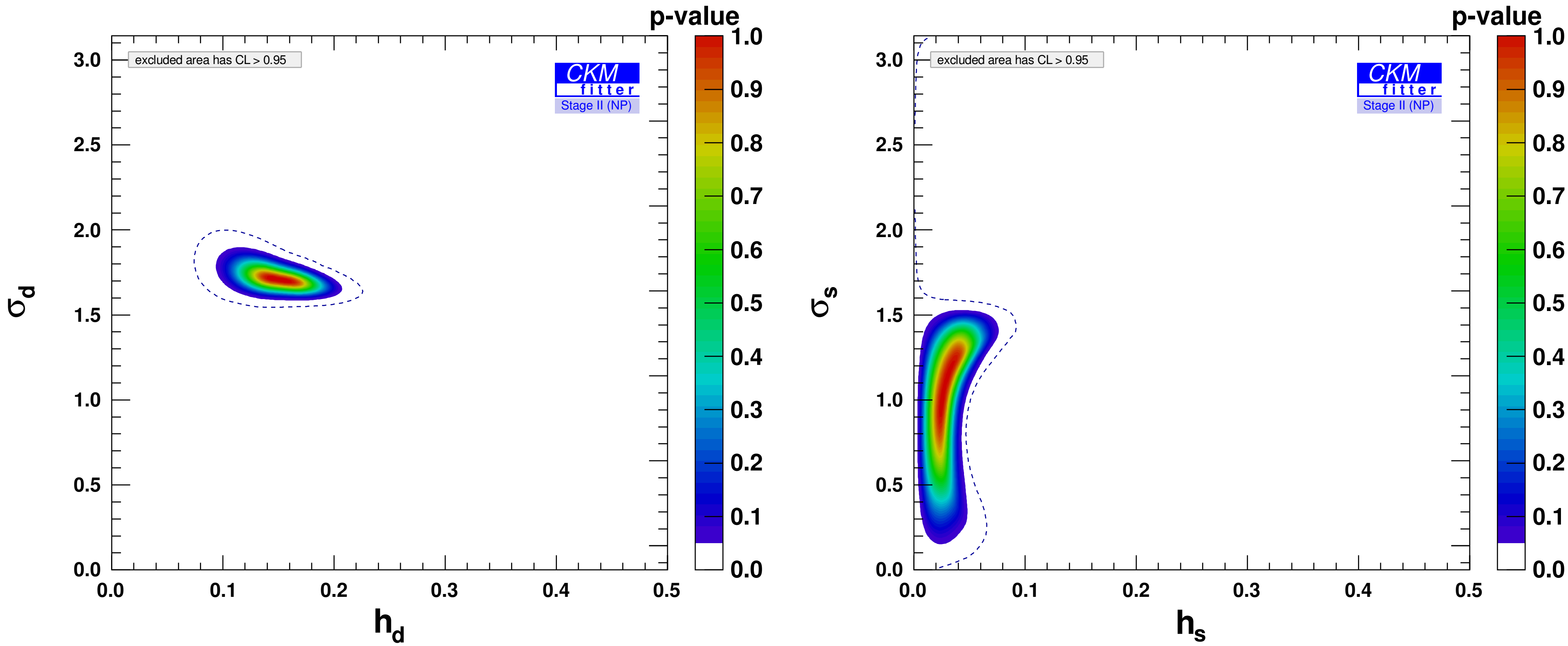
[1309.2293]

- Sensitivity caught up with that in B_d mixing, and will improve comparably

  Slightly better sensitivity in B_s — less “background” in SM expectation

Can such fits discover NP?

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

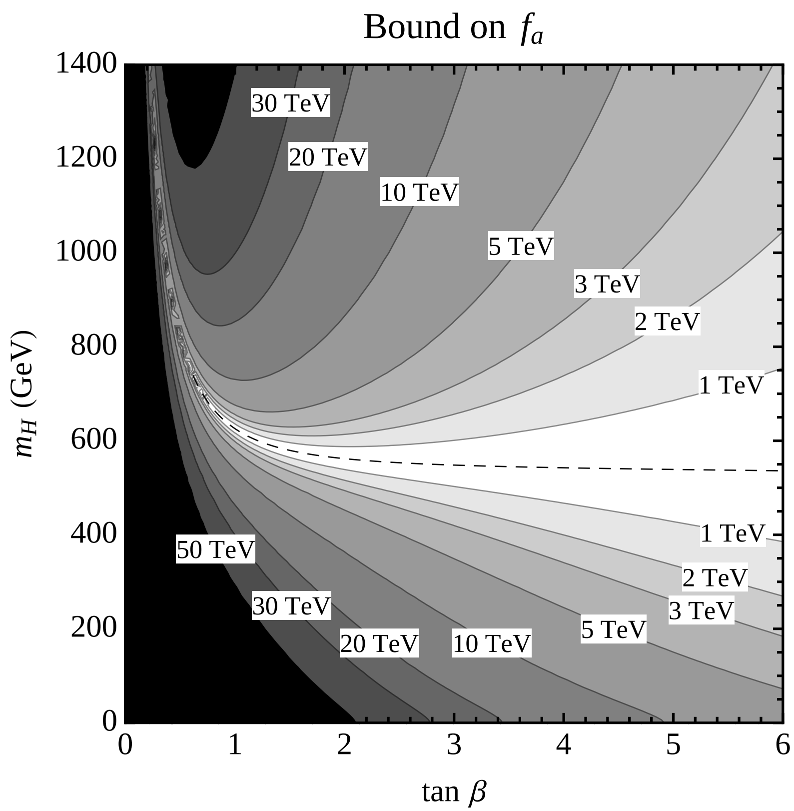


Any assumption about future NP signals is ad hoc — simplest scenario: assume all future (Stage II) experimental results correspond to the current best-fit values of $\bar{\rho}$, $\bar{\eta}$, $h_{d,s}$, $\sigma_{d,s}$

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

- Can probe certain DM models with B decays

  E.g., "axion portal": light ($\lesssim 1\,\text{GeV}$) 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 $B \to K\ell^+\ell^-$

FLAVOR PHYSICS & CP VIOLATION FPCP 2015 NAGOYA, JAPAN, 25–29 MAY 2015

Berkeley Lab

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

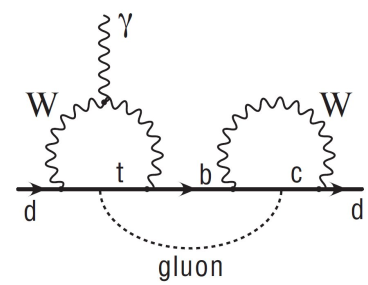
Gauge and Higgs sectors: $g_{1,2,3}, \theta_{\rm QCD}, M_{1,2,3}, m^2_{h_{u,d}}, \mu, B$ — 11 real $+$ 5 imag.

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)

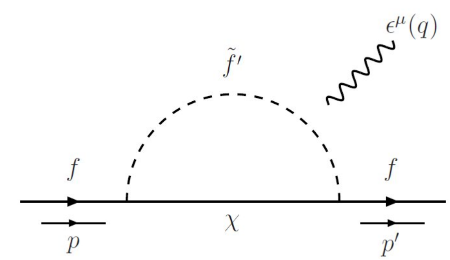
Electric dipole moments and SUSY

- 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 (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

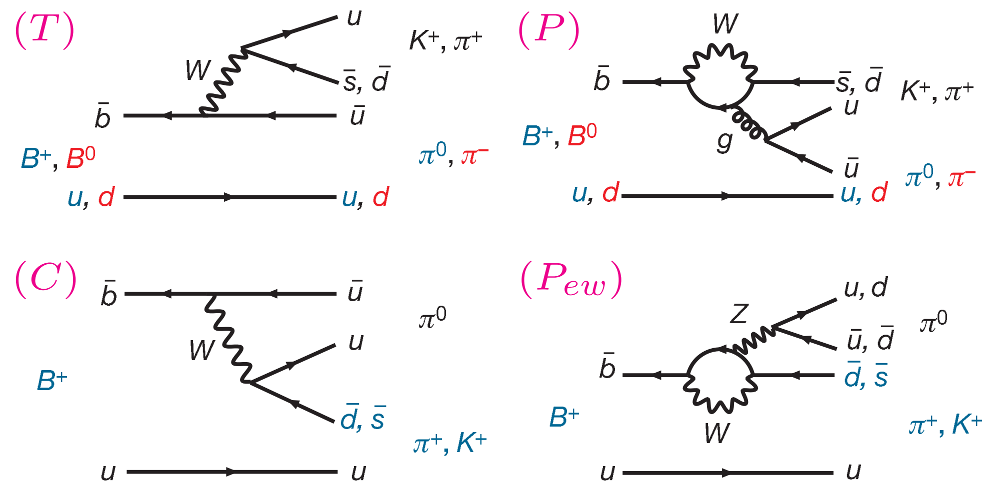
- Have we seen new physics in CPV?

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

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

- 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 and $SU(3)$ relations

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