Flavor physics &/@ the LHC

Zoltan Ligeti

LHCP, June 2–7, 2014

- Introduction
- Recent hot topics and status
- Future NP sensitivity in B – $\overline{B}$ mixing
- Flavor physics and high-p_T LHC
- Future progress & Conclusions

[Disclaimer: not a review; what I find interesting today]

What is flavor physics?

- Theorist: (quark) flavor physics $\equiv$ what breaks $U(3)_Q \times U(3)_u \times U(3)_d \to U(1)_{\rm Baryon}$
- Experimentalist: rich and sensitive ways to probe the SM and search for NP

- SM flavor problem: hierarchy of masses and mixing angles? why 3 generations?

- 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

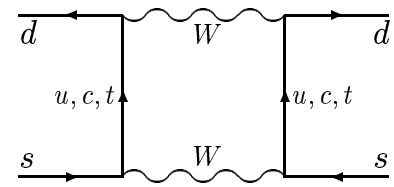
Going from: NP $\lesssim$ (few $\times$ SM) $\to$ NP $\lesssim$ $(0.3 \times$ SM) $\to$ NP $\lesssim$ $(0.05 \times$ SM)

$(-10$ yrs) (now) $(+10$ yrs)

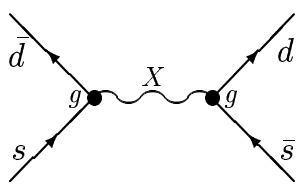
Flavor probes $10^2 - 10^5$ TeV scale

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

  (strong suppressions!)



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



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

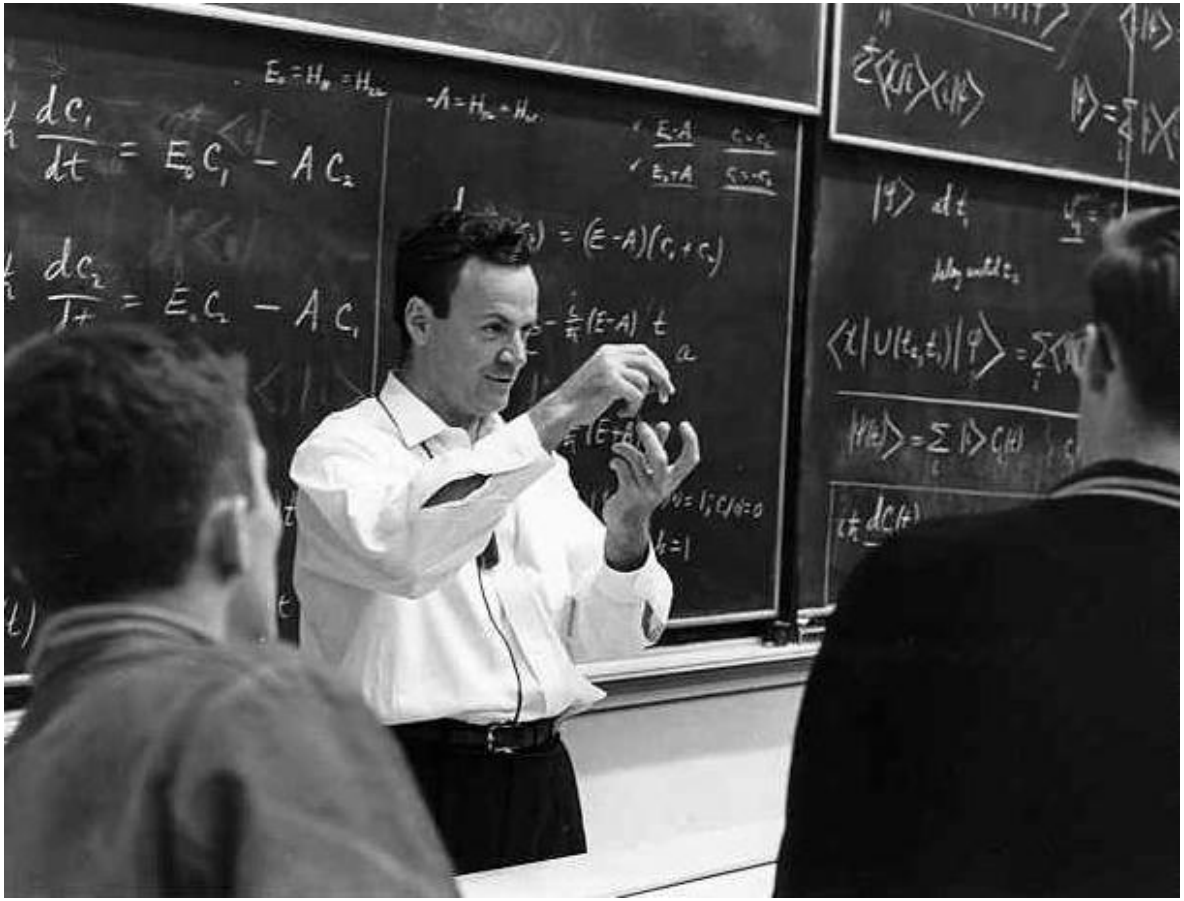
(The bound from ϵ_K is even stronger)

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

- Measurements probe $\begin{cases} \text{TeV-scale physics with SM-like flavor structure} \\ 100\text{–}1000\,\text{TeV physics with generic flavor structure} \end{cases}$

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

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



"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]

Exciting times ahead

- What are the expected deviations from the SM induced by TeV-scale NP?

  Generic flavor structure ruled out, deviations maybe near the bounds, many models predict some

- What to expect in terms of experimental precision?

  Useful data sets will increase by $\sim 10^{2\pm1}$, and will probe fairly generic BSM predictions

- What are the theoretical uncertainties? What will the measurements teach us?

  In many key measurements, theory uncertainty $<$ exp. sensitivity; complementary to high-p_T info

---

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

  Beyond $\sqrt[4]{50} \sim 2.5$ increase in sensitivity to higher mass scales, expect also some yet unknown progress (data motivate theory, recall α, γ)

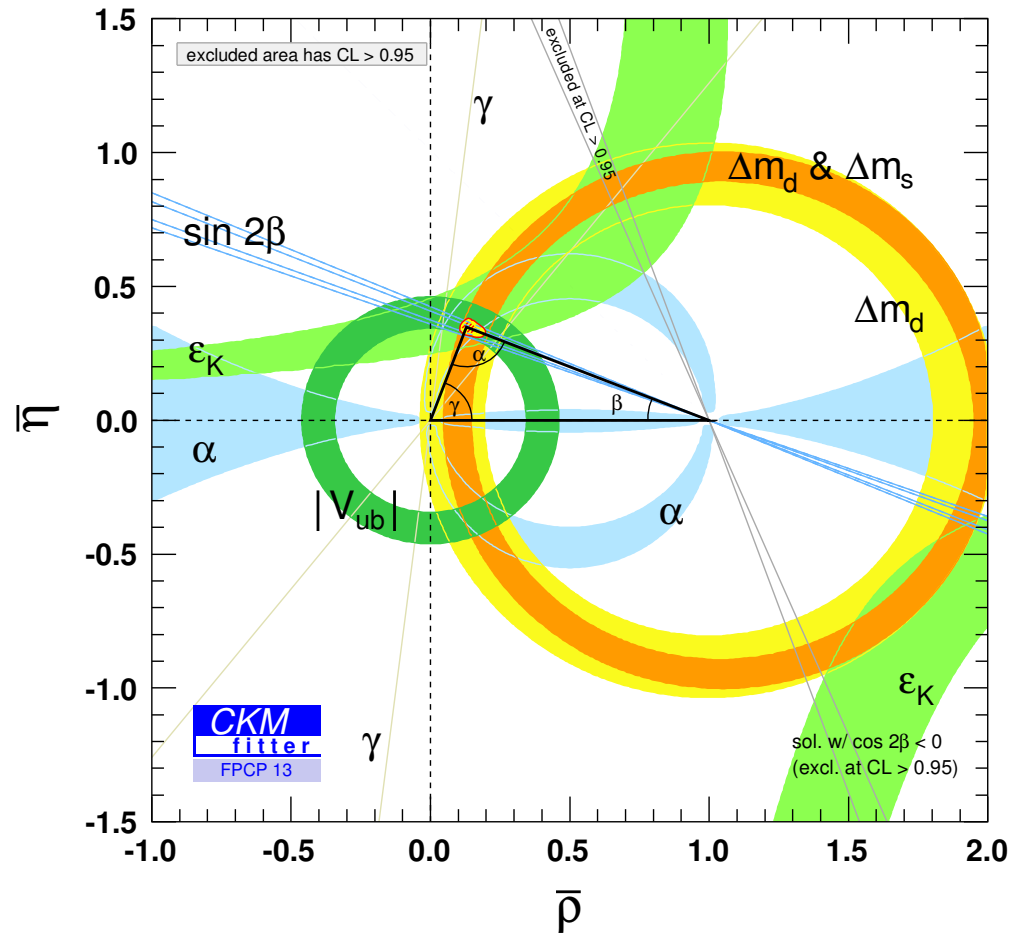
- Comparable increase in reach as going from LHC7–8 $\longrightarrow$ LHC13–14

BERKELEY LAB

Status & recent highlights

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
- To bound NP, compare tree vs. loop measurements $\Rightarrow \gamma$ and $|V_{ub}|$



- Need experimental precision and theoretical cleanliness to increase NP sensitivity

Measuring γ from $B^\pm \to DK^\pm$

- Tree level: interference of $b \to c\bar{u}s$ $(B^- \to D^0 K^-)$ and $b \to u\bar{c}s$ $(B^- \to \overline{D}^0 K^-)$

  Final states that both D^0 and $\overline{D}^0$ can decay into

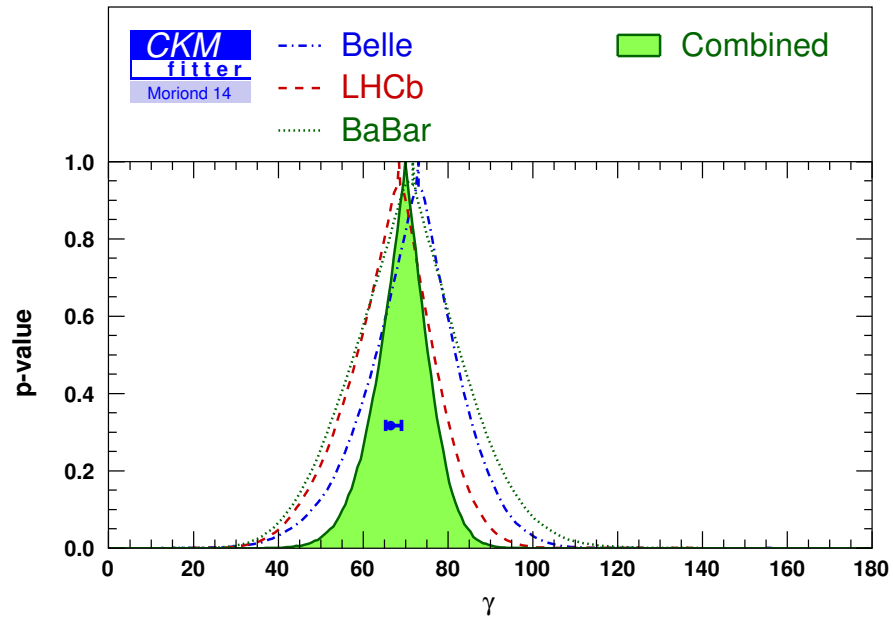
  Measure both B & D decay amplitudes — many variants depending on D decay

- World average: $\gamma = (70 \pm 8)^\circ$

  CKM fit: $\gamma = (67 \pm 2)^\circ$

- Coincidentally, LHCb, BaBar and Belle results are comparable just now

- Future experimental uncertainty: $\sim 1^\circ$



- Crucial for improving sensitivity to BSM (compare tree vs loop)

  Statistics limited with any currently imagined data set / experiment

Mixing and CP violation in B_s

- CDF & LHCb: relative uncertainty of $\Delta m_s <$ that of Δm_d (discovered in 1987)
- Time dependent $B_s \to \psi\phi$ CP asymmetry (analog of $B \to \psi K +$ angular anal.)
- In SM — of order $\lambda^2 \times \beta$

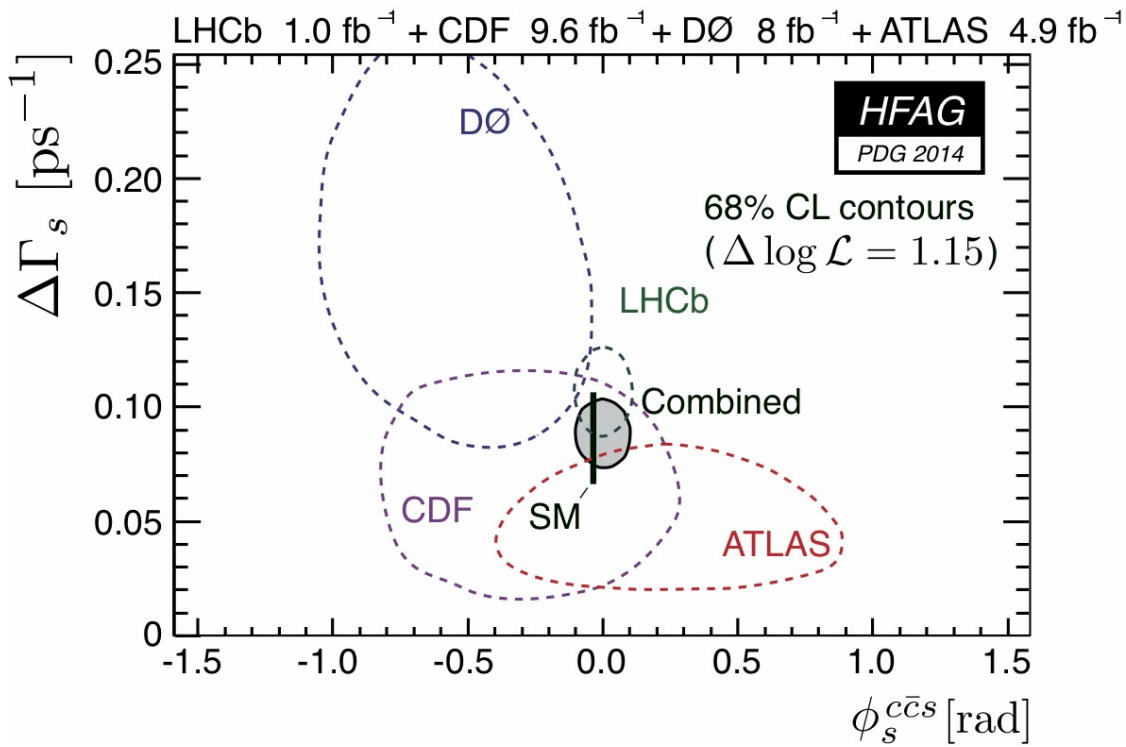
  $2\beta_s \equiv -\phi_s \simeq 0.037 \pm 0.00?$

  Past hints of tensions gone

- Unofficial LHCb average, incl. not shown recent result [Artuso, FPCP]

  $\phi_s = 0.07 \pm 0.05\,[= (4.0 \pm 3.1)^\circ]$

  Expect w/ LHCb upgrade: ± 0.008



- Uncertainty of the SM prediction $\ll$ current experimental error ($\Rightarrow$ LHCb upgrade)

Dilepton asymmetry

- Nearly 4σ significance of DØ measurement

$$A_{\rm SL} = \frac{\Gamma[\overline{B}^0(t) \to \ell^+ X] - \Gamma[B^0(t) \to \ell^- X]}{\Gamma[\overline{B}^0(t) \to \ell^+ X] + \Gamma[B^0(t) \to \ell^- X]}$$

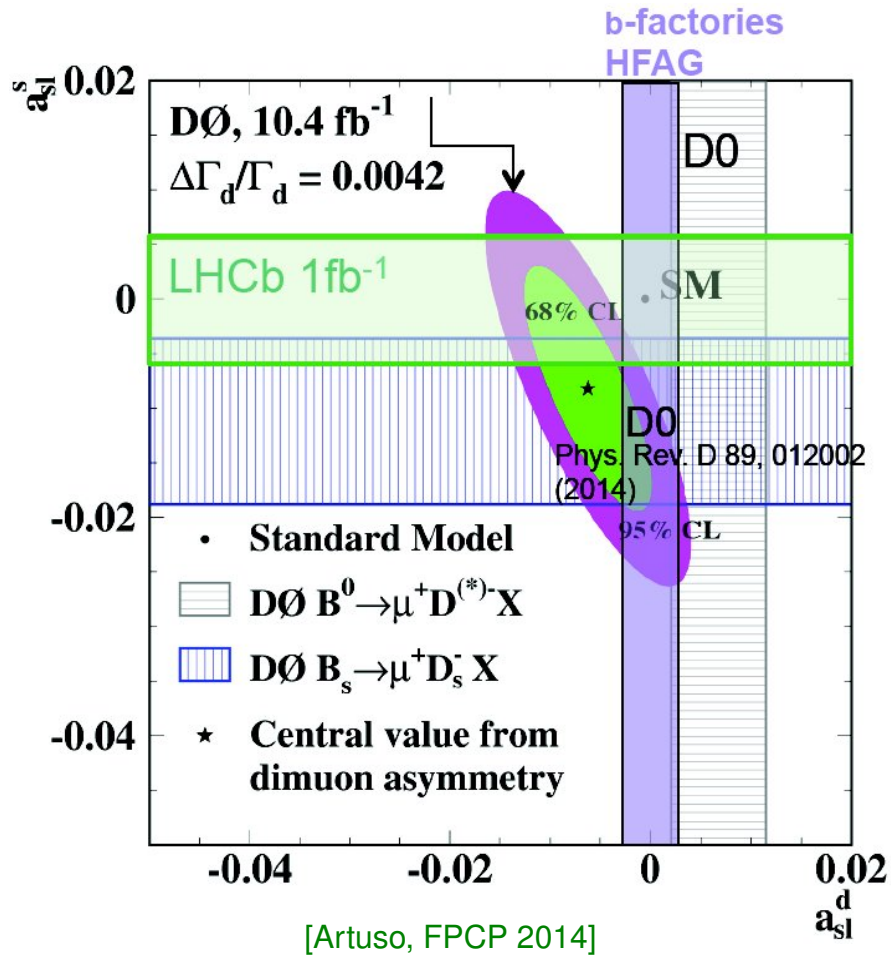
At hadron colliders, time dipendence can be integrated over:

$$A_{\rm SL}^{\rm D\emptyset} = \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)}$$

Would be a clear sign of NP

SM $\sim 4 \times 10^{-4}$ in B_d (2×10^{-5} in B_s)

(The absolute uncertainty of the SM prediction is not particularly small, but its magnitude is much smaller than claimed signal)



[Artuso, FPCP 2014]

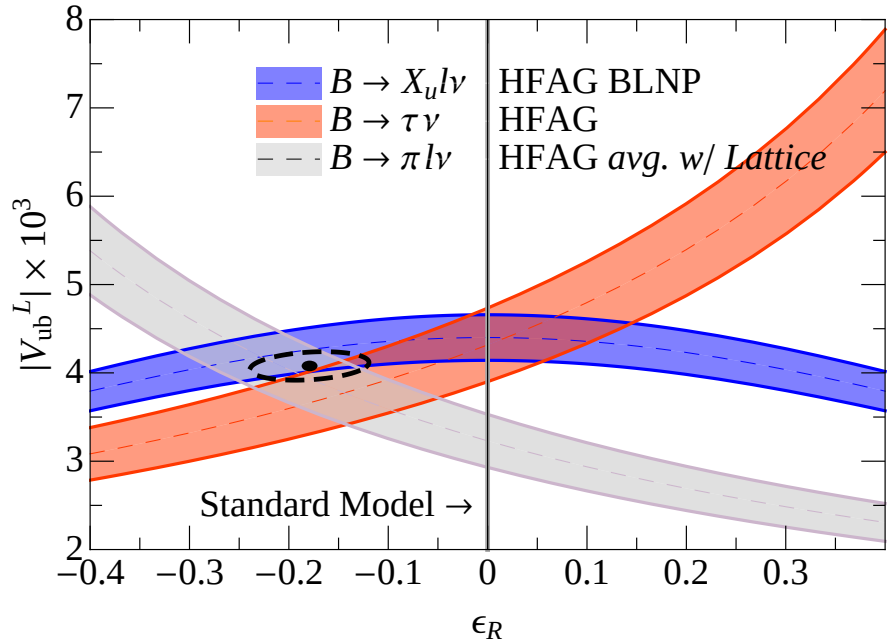
- More (maybe much more) data is needed to unambiguously understand this

The $|V_{ub}|$ saga continues...

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

  Gershon @ FPCP 2014: "Understanding this will involve a great deal of effort, but is essential for continued progress in the field"

- Too early to conclude:
  - Inclusive determination can improve
  - Exclusive measured better with full reco
  - Lattice QCD results will improve



[Bernlochner, ZL, Turczyk, to appear]

- A BSM possibility:

$$\mathcal{L} = -\frac{4G_F}{\sqrt{2}} V_{ub}^L \left(\bar{u}\gamma_\mu P_L b + \epsilon_R\, \bar{u}\gamma_\mu P_R b\right)\left(\bar{\nu}_\ell \gamma^\mu P_L \ell\right)$$

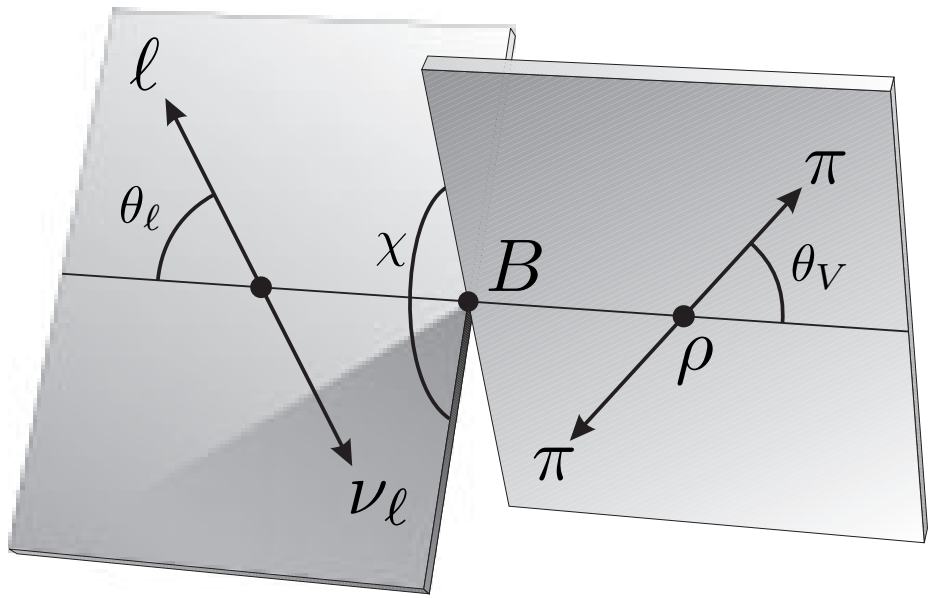
Can we construct observables which give "more vertical" constraints?

Decay	$\lvert V_{ub}\rvert \times 10^4$	adm.
$B \to \pi\, \ell\, \bar{\nu}_\ell$	3.23 ± 0.30	$(1+\epsilon_R)$
$B \to X_u\, \ell\, \bar{\nu}_\ell$	4.39 ± 0.21	$\left(1+\epsilon_R^2\right)$
$B \to \tau\, \bar{\nu}_\tau$	4.32 ± 0.42	$(1-\epsilon_R)$

- NB: Cleanest $|V_{ub}|$ I know, only isospin, $\mathcal{B}(B_u \to \ell\bar{\nu})/\mathcal{B}(B_d \to \mu^+\mu^-)$ — run LHCb @ 33 TeV

Decay distributions: $B \to \rho \ell \bar{\nu}$, $K^* \ell^+ \ell^-$

- Important for complementary reasons, similar 4-body final states (so is $B \to VV$)



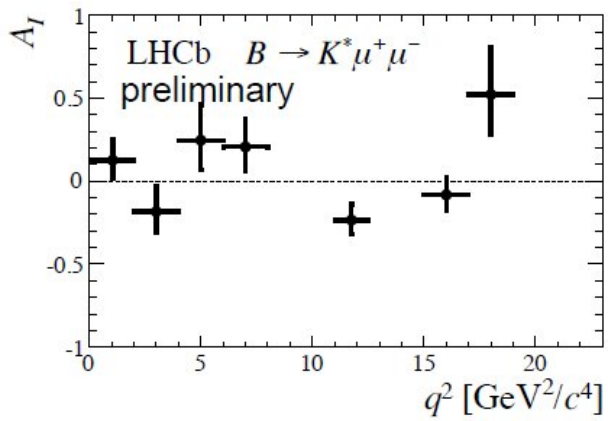
Large q^2: some relations from heavy quark symmetry, easier for lattice QCD

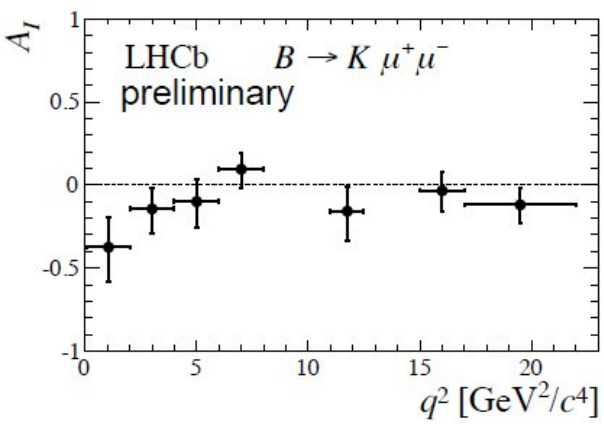
Small q^2: some relations from soft-collinear effective theory, light-cone sum rules

- Need (lots of) data to understand reliability of predictions, size of corrections

$B \to K^{(*)}\ell^+\ell^-$ decay distributions

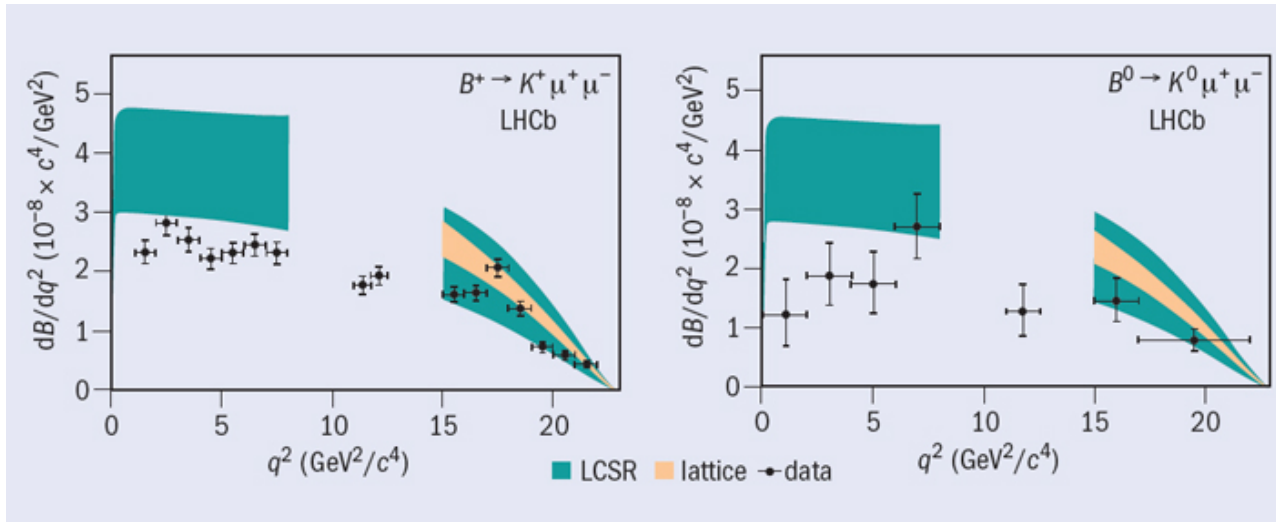
- Isospin asymmetry: SM is close to zero, past signals at small q^2 — going away?





Predictions for the rate at small q^2 are a bit off

(fluctuations? uncertainty in light-cone sum rules?)



Interesting in its own right + form factors at small q^2 enter nonleptonic decays (factorization) — impact on CPV program

And then the question whether $c\bar{c}$ loops are tractable

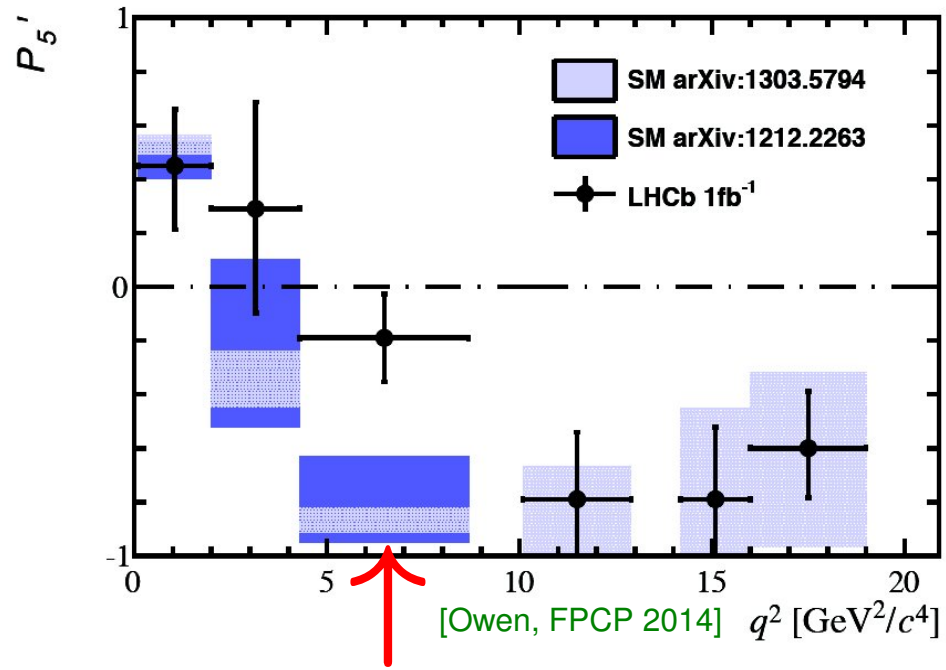
$B \to K^{(*)}\ell^+\ell^-$: the P_5' anomaly

- It's all connected — can one calculate the form factor ratios reliably at small q^2?

  (more difficult for lattice QCD, large recoil)

  "Optimized observables" defined using a particular approach to factorization (suppression of "factorizable" terms) [1202.4266]

  Global fits: a plausible explanation is NP reducing C_9 [1307.5683, 1308.1501, 1310.2478, etc.]



[Owen, FPCP 2014]

NP, fluctuation, theory?

- What set of measurements can check / firm up / refine uncertainty estimates?

- Form factors at small q^2 also enter nonleptonic decays and interpreting CP viol.

Recall: the $B \to K\pi$ puzzle

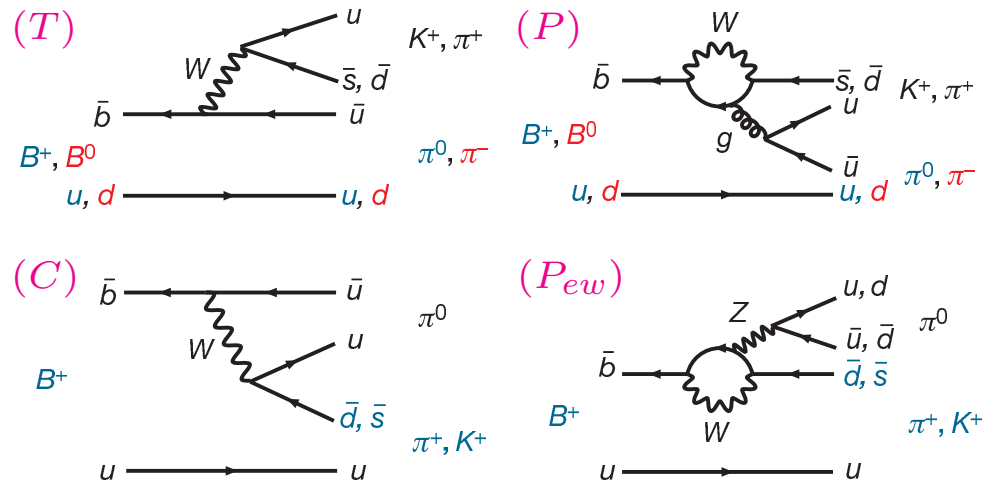
- Have we seen new physics in CPV?

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

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

- 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?

CP asymmetries in $B_{(s)} \to PP$ and PV

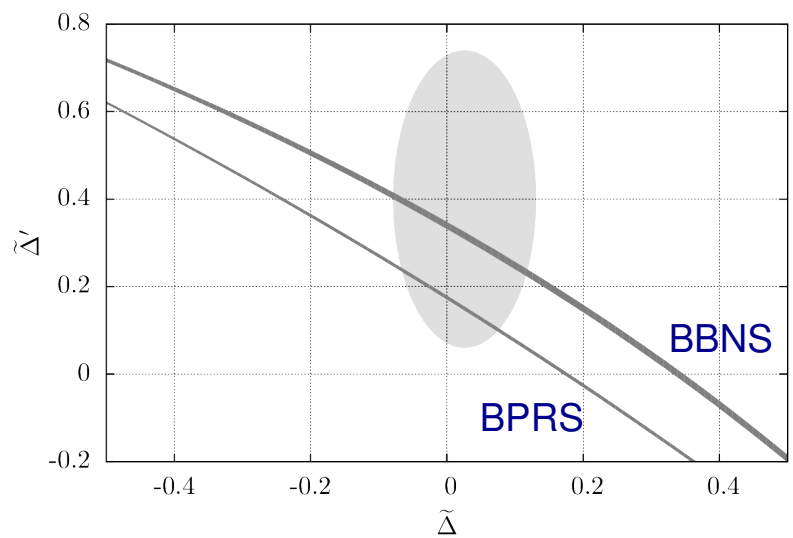
- Largest direct CPV (2-body): $A_{CP}(B_s \to K^-\pi^+) = 0.27 \pm 0.04$ [LHCb: 1304.6173]

  Study $SU(3)$ breaking for (suitably defined) relations [Grossman, ZL, Robinson, 1308.4143]

$$\widetilde{\Delta} \equiv \frac{\Delta_{CP}[B_d \to K^+\pi^-] + \Delta_{CP}[B_s \to K^-\pi^+]}{\Delta_{CP}[B_d \to K^+\pi^-] - \Delta_{CP}[B_s \to K^-\pi^+]} = 0.026 \pm 0.106$$

- Derived complete set of isospin, U-spin, $SU(3)$ relations among CP asymmetries
- $SU(3)$ viol' in different factorization approaches:

  BBNS $\alpha_1 \hat{\alpha}_4^c$ flavor indep / BPRS $A_{c\bar{c}}$ flavor indep



- Correlations between $B_s \to K^-\pi^+$ vs $B_d \to K^+\pi^-$

  $B_s \to K^+K^-$ vs $B_d \to \pi^+\pi^-$

  $B_s \to \pi^+\pi^-$ vs $B_d \to K^+K^-$

  will teach us a lot about $SU(3)$ & large m_b limits

- A huge number of possible tests to improve understanding of strong interaction

Other interesting topics

- BaBar reported 3.4σ deviation from SM in correlated 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

- Little SM suppression: need fairly light NP, constraints from flavor & LHC searches

---

- CP violation in D decay

[many missing refs, incl. to speaker]

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

Current WA: $\Delta A_{CP} = -(2.5 \pm 1.0) \times 10^{-3}$

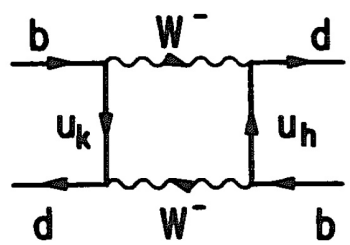
(unlikely in the SM, imho)

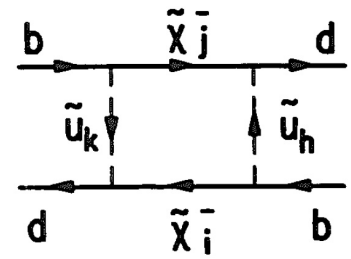
- I think we still do not know how big an effect could (not) be accommodated in SM

New physics in meson mixing

What are we after?

- Meson mixing:





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

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
- Define: $M_{12} = M_{12}^{\rm SM} \times \left(1 + h\, e^{2i\sigma}\right)$ (In K system introduce h_K in "tt" contribution)
- Importance known since the 70s, conservative picture of future progress

Inputs: many measurements & calculations

- Any future projection has uncertainties; sources of experimental and theoretical (lattice) inputs shown

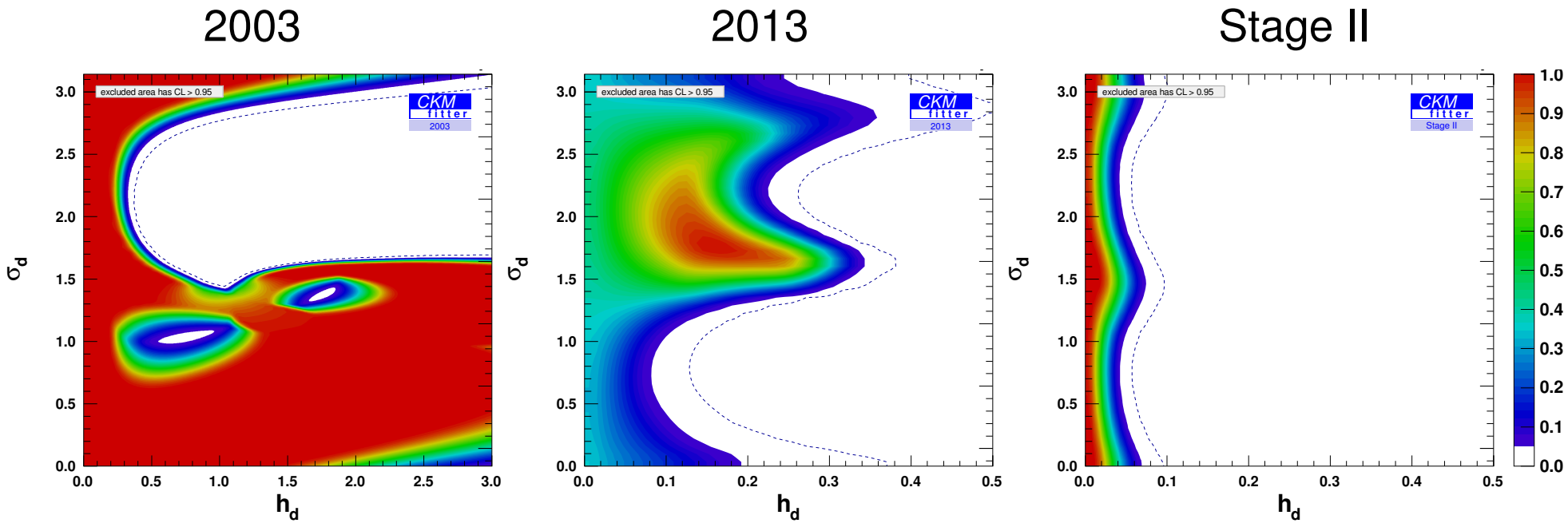
  [Charles et al., 1309.2293]

- Lattice QCD is essential
- 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 $|V_{ub}|$ are crucial (tree / reference UT): the hope is that $2-3\%$ uncertainty in $|V_{ub}|$ can be obtained from several measurements: $B \to \tau\nu$, $B \to \mu\nu$, $B \to \pi\ell\nu$

New physics in B_d^0 mixing



[1309.2293]

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

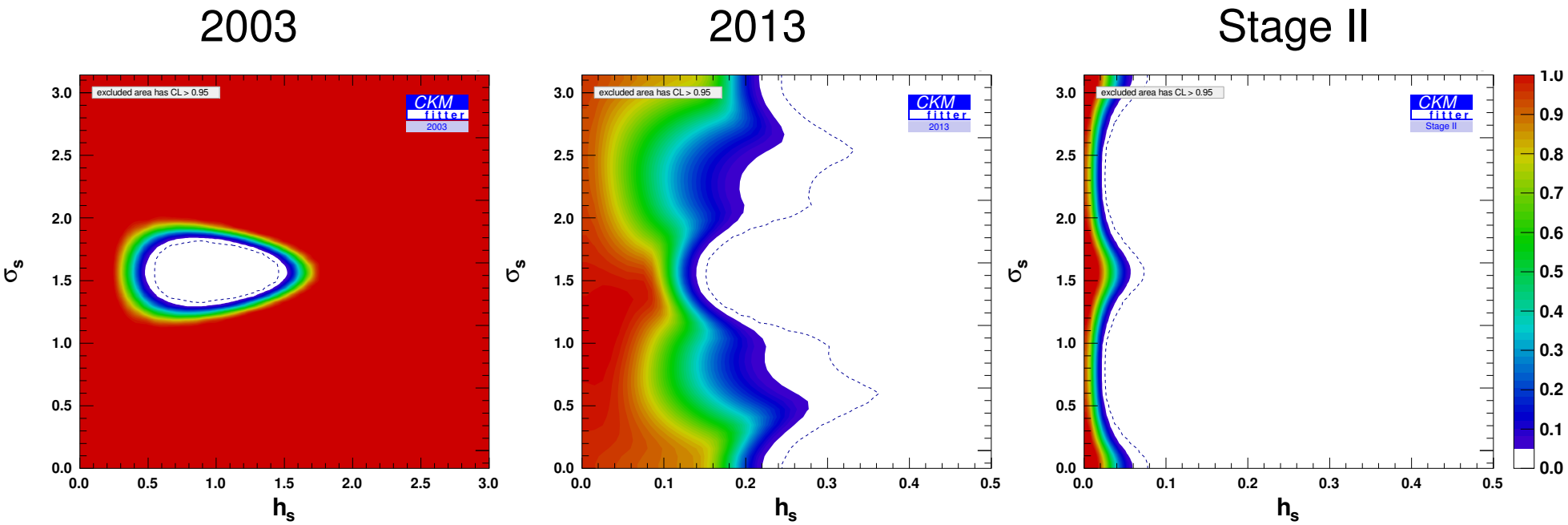
$$h \simeq \frac{|C_{ij}|^2}{|V_{ti}^* V_{tj}|^2} \left(\frac{4.5\,\mathrm{TeV}}{\Lambda}\right)^2$$

— by Stage II: $\Lambda \sim 20\,\mathrm{TeV}$ (tree), $\Lambda \sim 2\,\mathrm{TeV}$ (loop)

Belle II $50\,\mathrm{ab}^{-1}$ + LHCb $50\,\mathrm{fb}^{-1}$

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

New physics in 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)
- Sensitivity caught up with that in B_d mixing
- Sensitivities in the future will improve comparably

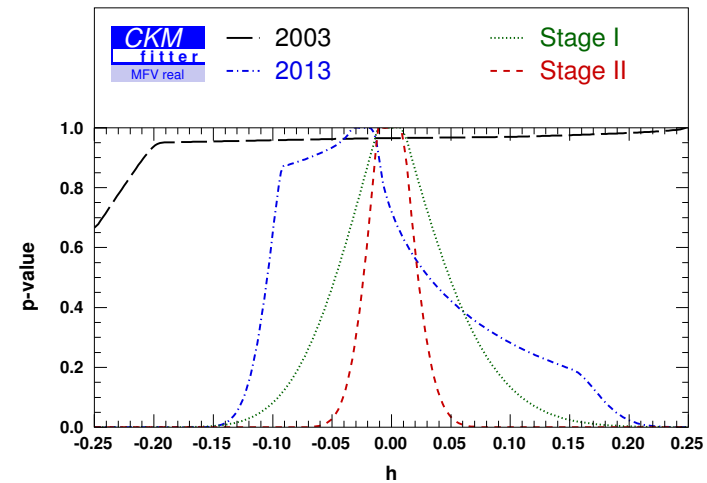
  Slightly better in B_s due to less "background" in SM expectation

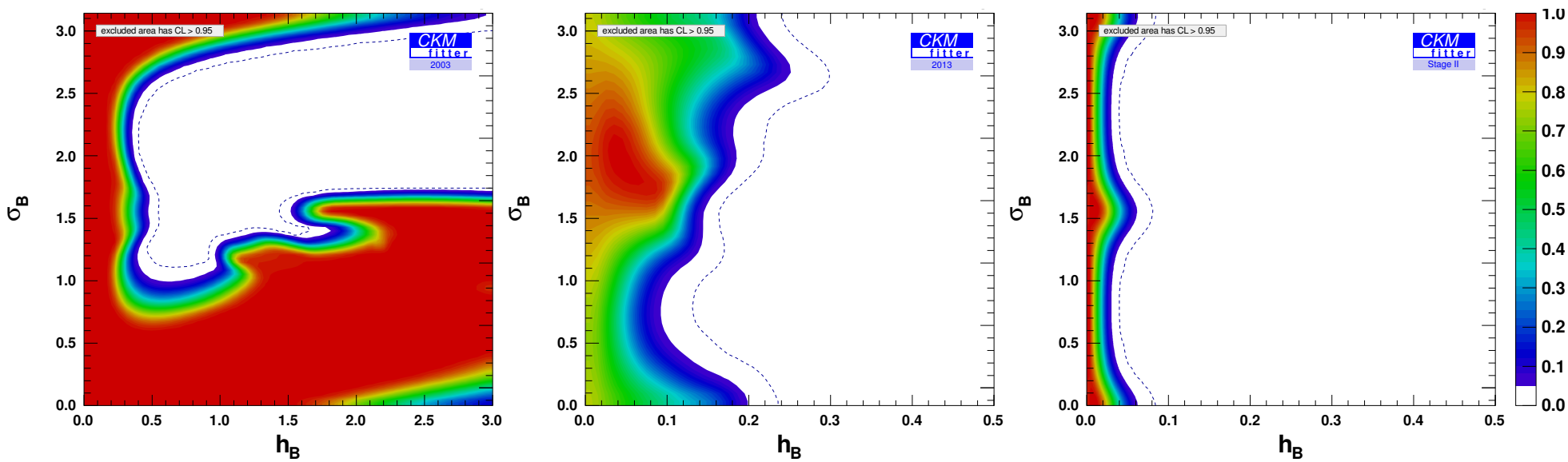
Constraining MFV and $U(2)^3$ flavor structures

- MFV: $h \equiv h_d\, e^{2i\sigma_d} = h_s\, e^{2i\sigma_s} = h_K\, e^{2i\sigma_K}$

  $\sigma_d = \sigma_s = \sigma_K = 0 \ \ (\text{mod } \pi/2)$

- $U(2)^3$: $h_B \equiv h_d = h_s, \ \ \sigma_B \equiv \sigma_d = \sigma_s$ [1309.2293]





Forecasting mixing sensitivity

- Mixing of neutral mesons will remain a special process to search for new physics, sensitive to some of the highest scales

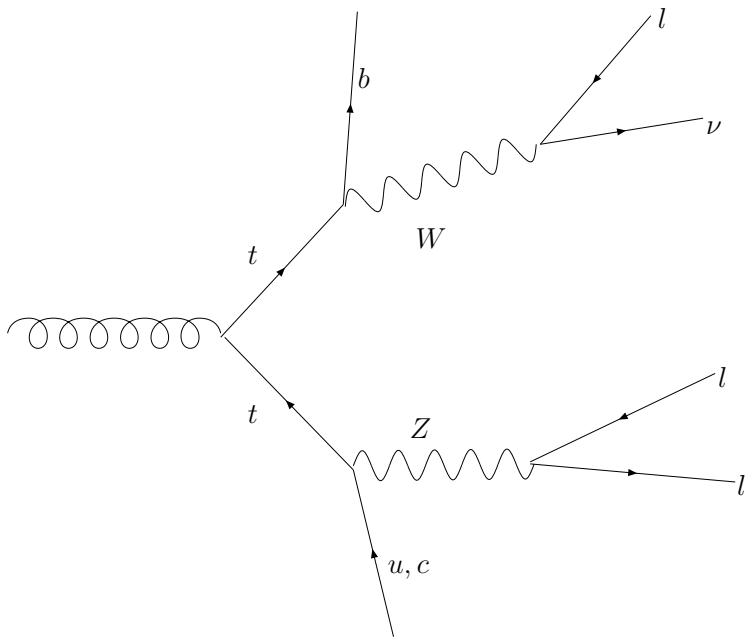
- Summary of expected sensitivities to $(C_{ij}^2/\Lambda^2)\,(\bar{q}_{i,L}\gamma^\mu q_{j,L})^2$ [Charles et al., 1309.2293]

Couplings	NP loop order	Scales (TeV) probed by B_d mixing	Scales (TeV) probed by B_s mixing
$\lvert C_{ij}\rvert = \lvert V_{ti}V_{tj}^*\rvert$ (CKM-like)	tree level	17	19
	one loop	1.4	1.5
$\lvert C_{ij}\rvert = 1$ (no hierarchy)	tree level	2×10^3	5×10^2
	one loop	2×10^2	40

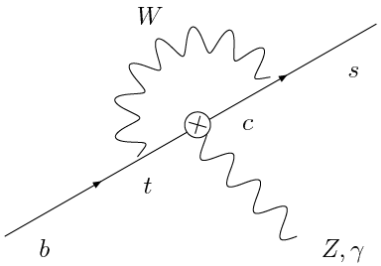
Flavor and the LHC

The LHC is a top factory: top flavor physics

- $A_{\rm FB}^{t\bar{t}}$ signals and models seem to be going away
- Flavor violation in top decays not well explored
  SM $\sim 10^{-13}$, current bound $\sim 10^{-3}$
- LHC14: $\sigma_{t\bar{t}} \sim 850\,$pb $\Rightarrow$ sensitivity $\lesssim 10^{-5}$
- Observable top FCNC possible in extensions of the SM and still allowed by B-factory constraints
  [e.g., 0704.1482]



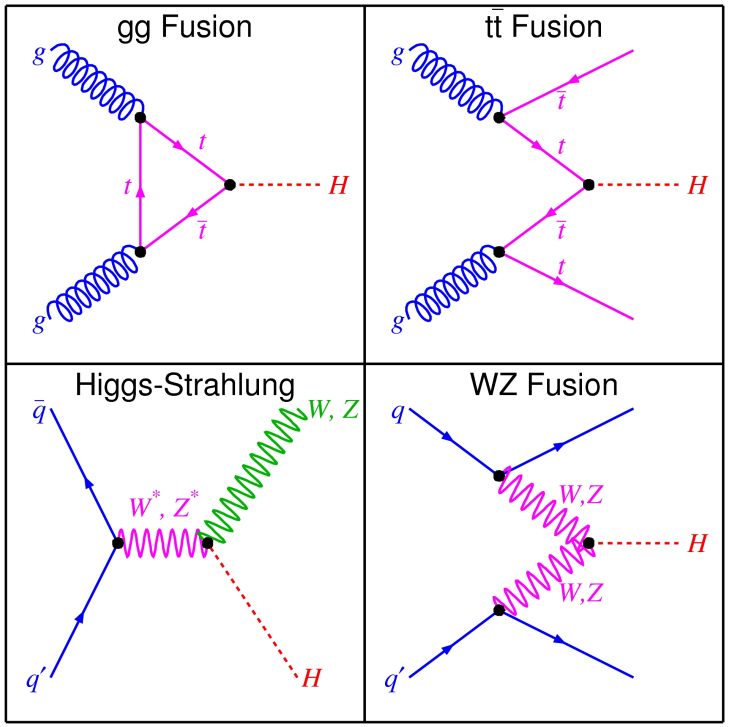
- Indirect constraints: $t_L \leftrightarrow b_L \Rightarrow$ tight bounds from B decays
  - Strong bounds on operators with left-handed fields
  - Right-handed operators could give rise to LHC signals

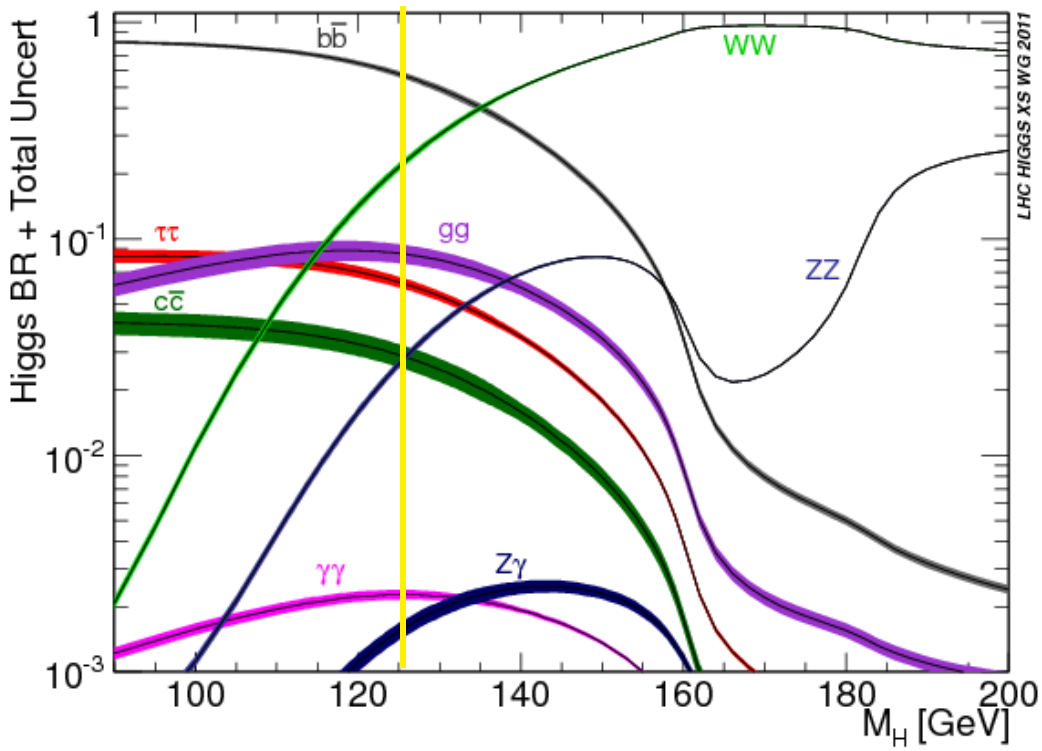


- If top FCNC is seen, LHC & B factories will both probe the NP responsible for it

The LHC is a Higgs factory

- Rich physics: many production and decay channels (fermion couplings crucial)





- Richness due to Yukawa couplings: same as origin of "GeV-scale flavor physics"
- Higgs flavor param's: 3rd gen: κ_t, κ_b, κ_τ 2nd gen: κ_c, κ_μ Do κ_{tc}, $\kappa_{\tau\mu}$ vanish?

New particles, e.g., supersymmetry

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

  The LHC will measure: masses, production rates, decay modes (some), etc.

  Details of interactions of new particles with quarks and leptons will be important

- New physics flavor structure can be: — new physics mass scale:
  - Minimally flavor violating (mimic the SM) — can be "light"
  - Related but not identical to the SM $\uparrow\downarrow$
  - Unrelated to the SM, or even completely anarchical — must be heavy

  Some aspects will be understood from ATLAS & CMS data (masses, decays, etc.)

- New sources of CP violation: squark & slepton couplings, flavor diagonal processes (e, n EDM), neutral currents; may enhance FCNCs ($B_{(s)} \to \ell^+\ell^-$, $\mu \to e\gamma$)

Example: SUSY in $K^0 - \overline{K}^0$ mixing

- $\dfrac{(\Delta m_K)^{\rm SUSY}}{(\Delta m_K)^{\rm exp}} \sim 10^4 \left(\dfrac{1\,{\rm TeV}}{\tilde{m}}\right)^2 \left(\dfrac{\Delta\tilde{m}^2_{12}}{\tilde{m}^2}\right)^2 {\rm Re}\left[(K^d_L)_{12}(K^d_R)_{12}\right]$ (oversimplified)

  $K^d_{L(R)}$: mixing in gluino couplings to left-(right-)handed down quarks and squarks

- Constraint from ϵ_K: replace $10^4\,{\rm Re}\left[(K^d_L)_{12}(K^d_R)_{12}\right]$ with $\sim 10^6\,{\rm Im}\left[(K^d_L)_{12}(K^d_R)_{12}\right]$

  (44 CPV phases: CKM $+$ 3 flavor diagonal $+$ 40 in mixing of fermion-sfermion-gaugino couplings)

- Classes of models to suppress each terms (structures imposed to satisfy bounds)

  (i) Heavy squarks: $\tilde{m} \gg 1\,{\rm TeV}$ (e.g., split SUSY)

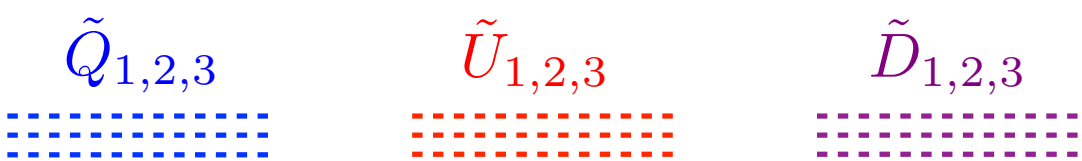
  (ii) Universality: $\Delta m^2_{\tilde{Q},\tilde{D}} \ll \tilde{m}^2$ (e.g., gauge mediation)

  (iii) Alignment: $|(K^d_{L,R})_{12}| \ll 1$ (e.g., horizontal symmetry)

- All models incorporate some of the above — known since the '70s

Squark spectra, LHC, flavor

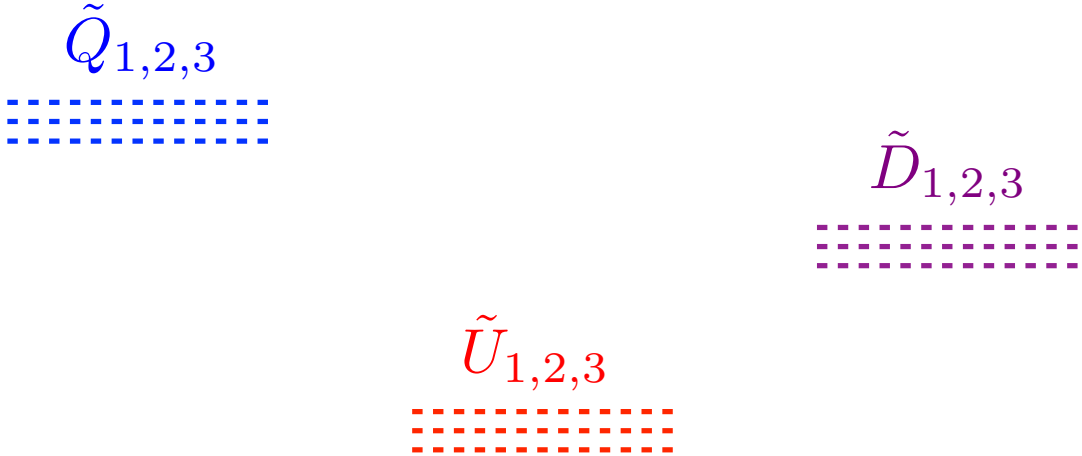
- Exploring more general spectra is motivated by both LHC and flavor bounds
- All squarks degenerate:



Simplest models — strongest LHC bounds from non-observation of new particles

Squark spectra, LHC, flavor

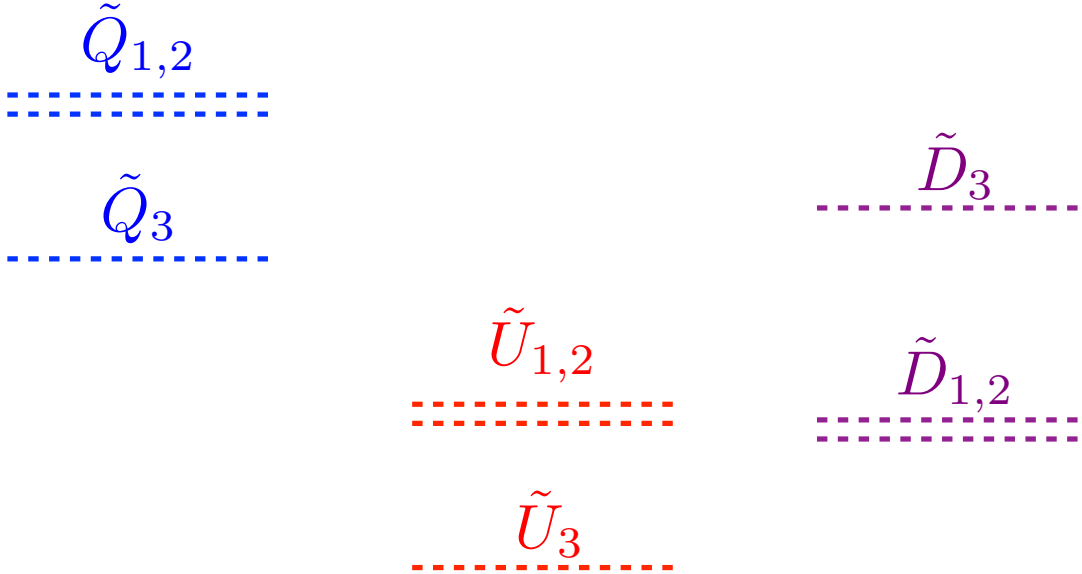
- Exploring more general spectra is motivated by both LHC and flavor bounds
- Gauge split



Can have (almost) completely SM-like flavor structure

Squark spectra, LHC, flavor

- Exploring more general spectra is motivated by both LHC and flavor bounds
- Minimal flavor violation

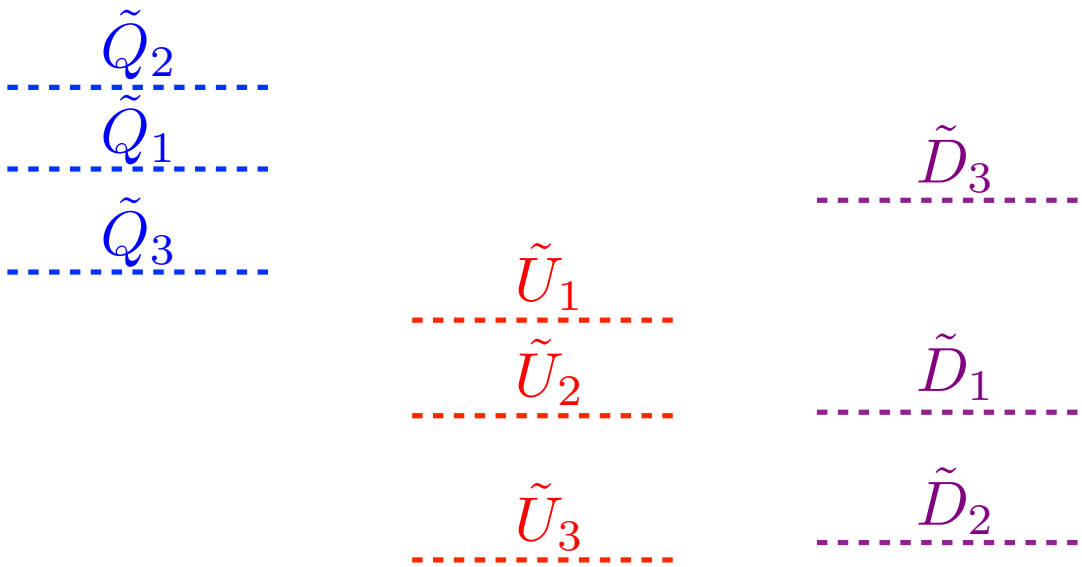


$$m^2_{\tilde{U}} = (1 + Y_u^\dagger Y_u + \ldots)$$

Can evade flavor bounds — LHC search limits get somewhat weaker

Squark spectra, LHC, flavor

- Exploring more general spectra is motivated by both LHC and flavor bounds
- Quark-squark alignment:



May come from horizontal symmetries

- We do not know which is right — need broad set of searches (both LHC & flavor)

Hide flavor signals ⇔ hide LHC signals

- Despite lore, squarks need not be as degenerate as thought earlier (triggered by studying charm CPV) [Gedalia, Kamenik, ZL, Perez, 1202.5038]

  Top plot: each LHC search becomes weaker

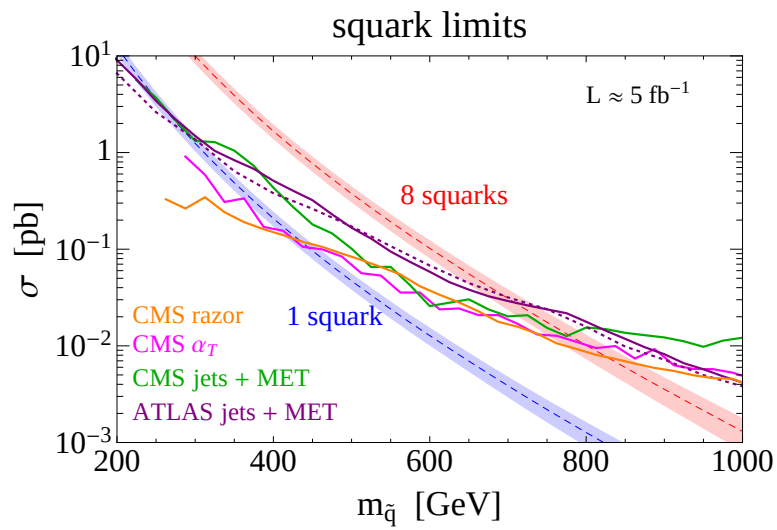
  Bottom plot: unshaded region still allowed if 4–4 squarks (but not all 8) are degenerate

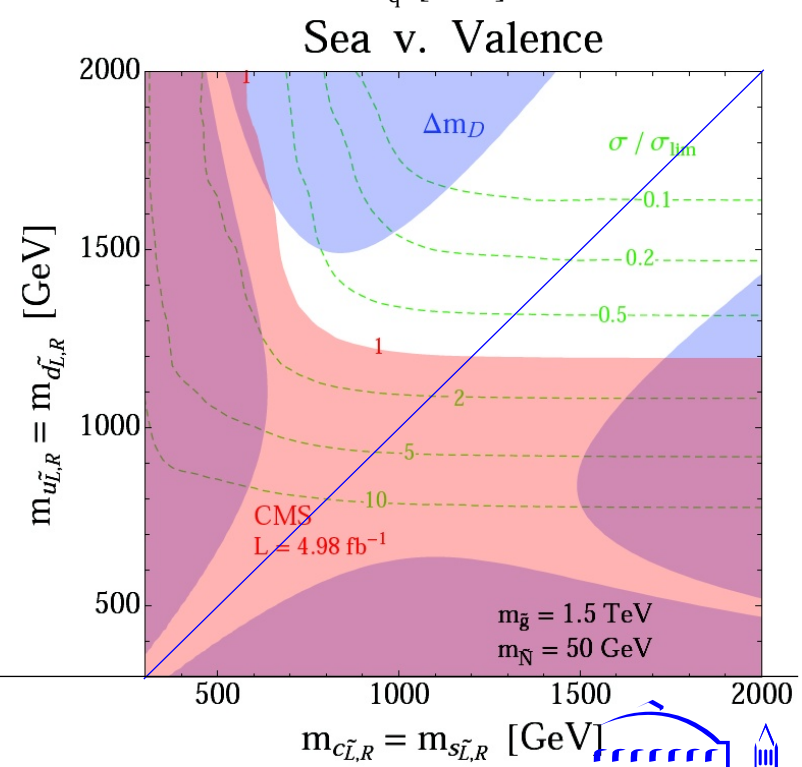
  [Mahbubani, Papucci, Perez, Ruderman, Weiler, 1212.3328]

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

- Modify search strategies to improve coverage

- Ways for naturalness to survive: we can give up many assumptions before giving up principles

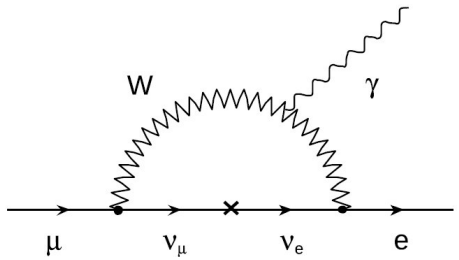




Charged lepton flavor violation

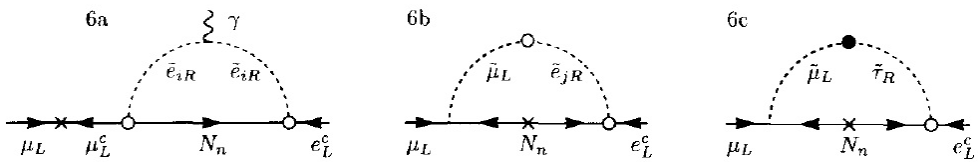
- SM predicted lepton flavor conservation with $m_\nu = 0$

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

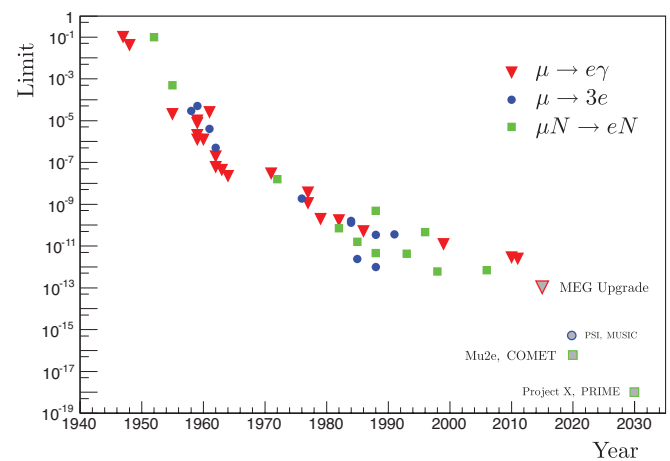


$$\mathcal{B}(\mu \to e\gamma) \sim \alpha \frac{m_\nu^4}{m_W^4} \sim 10^{-52}$$

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



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



- Many interesting processes:

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

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

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

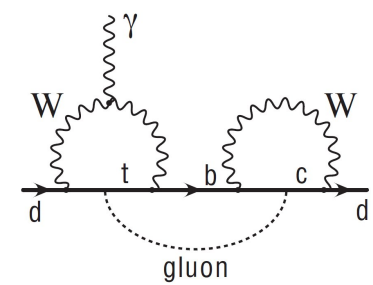
- Next 10–20 years: 10^2–10^5 improvement; any signal would trigger broad program

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

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

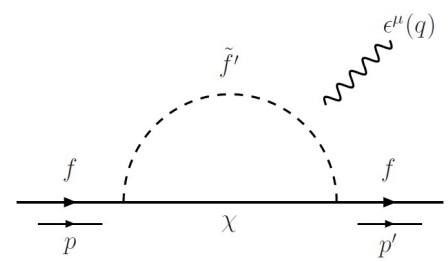
- EDMs from CKM: vanish at one- and two-loop
  large suppression of this diagram



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

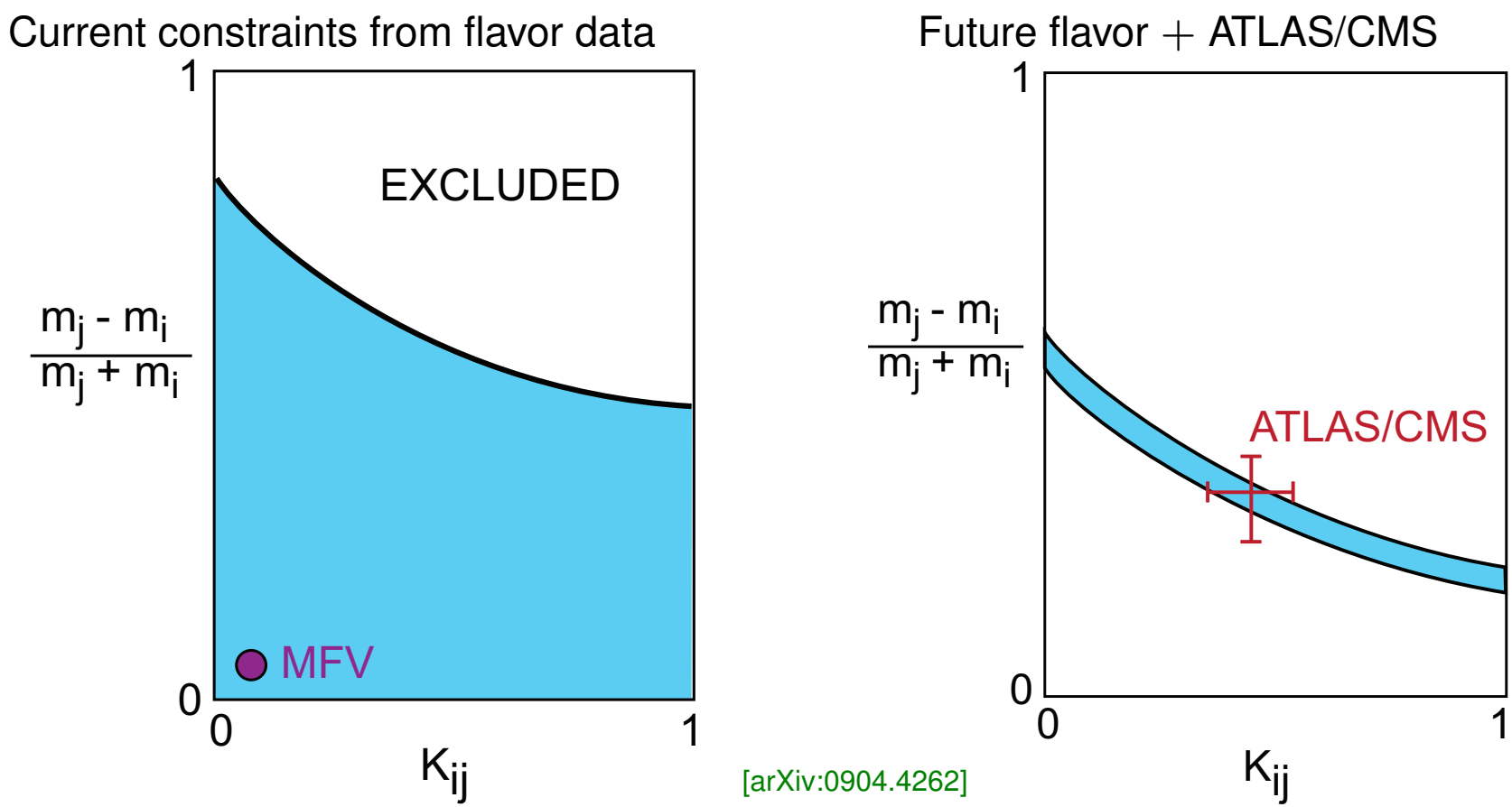
  Generic prediction ($\rm TeV$-scale, no small param's) above current bounds; if $m_{\rm SUSY} \sim \mathcal{O}(10\,{\rm TeV})$, may still discover EDMs

- Expected 10^2–10^3 improvements: complementary to LHC



Flavor / LHC complementarity

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



[arXiv:0904.4262]

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

Final remarks & Future

(Part of) a SM "to-do list" for theory

- New ideas: recall that the best α and γ measurements are in modes influenced by BaBar & Belle data (not thought about before ~ 2003)
  - How big can CP violation be in $D^0 - \overline{D}^0$ mixing in the SM?
  - How big can direct CP violation be in D decays in the SM?
  - 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)
  - What is the SM upper bound on $S_{K_S \pi^0 \gamma}$?
  - What is the "ultimate" uncertainty of $|V_{ub}|$?
  - Can direct CP asymmetries in nonleptonic modes be understood enough to make them "discovery modes"? [$SU(3)$, heavy quark limit, SCET, etc.]

Lots of "other" searches

- Cast a wide net — broad program is critical:

$B \to (\gamma +)\,\text{invisible}$ [Belle, 1206.5948; BaBar, 1206.2543]

$B \to X_s + \text{invisible}$

$\Upsilon(1S) \to \text{invisible}$ [Belle, hep-ex/0611041; BaBar, 0908.2840]

$\Upsilon(nS) \to \gamma + \text{invisible}$ [e.g., for $1S$ and $3S$: BaBar, 0808.0017, 1007.4646]

$e^+e^- \to (\gamma +)\,\text{invisible}$

- Also include "invisible" replaced by $\ell^+\ell^-$
- τ and μ lepton flavor violation
- Searches for violations of conservation laws
- Obvious! most cited Belle paper: $X(3872)$, most cited BaBar paper: $D_{s0}^*(2317)$

[You may say it's "QCD stuff", but $\Gamma/m < 3 \times 10^{-4}$ and $\Gamma/m < 1.6 \times 10^{-3}$, respectively...]

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 in the next decade by 10–10^4 in some channels
- Flavor physics data in next decade will tell us a lot, whether NP is found 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 telescope

- 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

Backup slides

$B_{s,d} \to \mu^+\mu^-$ and other rare decays

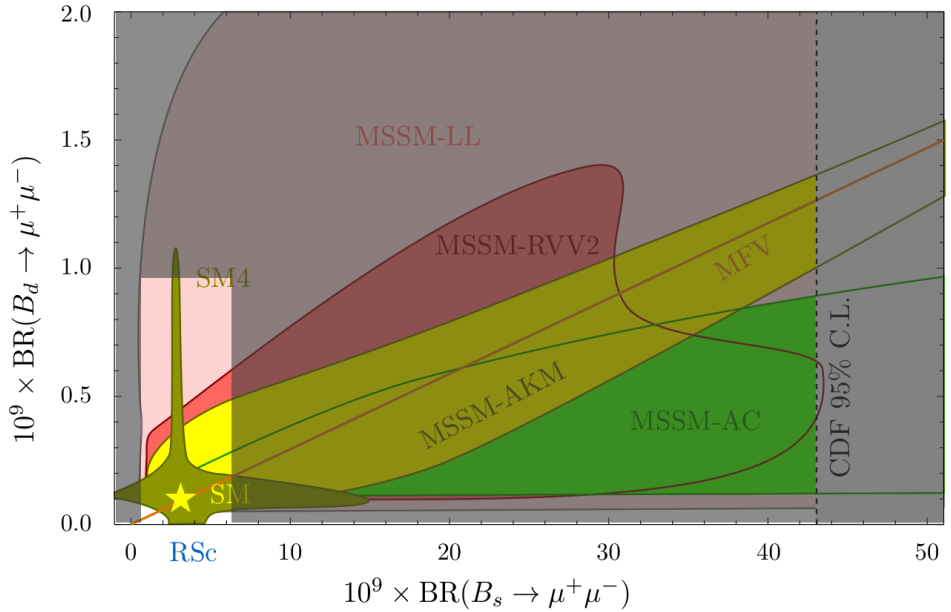
- Shrinking room for NP comparable to SM

  LHCb – CMS combination:

  $$\mathcal{B}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

  $$\mathcal{B}(B_d \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$

- Experimental uncertainty will decrease a lot, interpretation not theory limited



- Many other rare decays, $b \to q\ell^+\ell^-$, $b \to q\nu\bar{\nu}$, with much improved sensitivity

  [LHCb @ EPS: $\sim 4\sigma$ difference from a SM expectation in $B \to K^*\mu^+\mu^-$ angular distribution]

- In some decay modes, even in 2025 we'll have (Exp. bound)/SM $\gtrsim 10^3$

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

D mixing and CPV in up sector

- Mass eigenstates: $|D_{H,L}\rangle = p|D^0\rangle \mp q|\overline{D}^0\rangle$ — CP is conserved iff $|q/p| = 1$

  CPV iff: (mass eigenstates) $\neq$ (CP eigenstates)

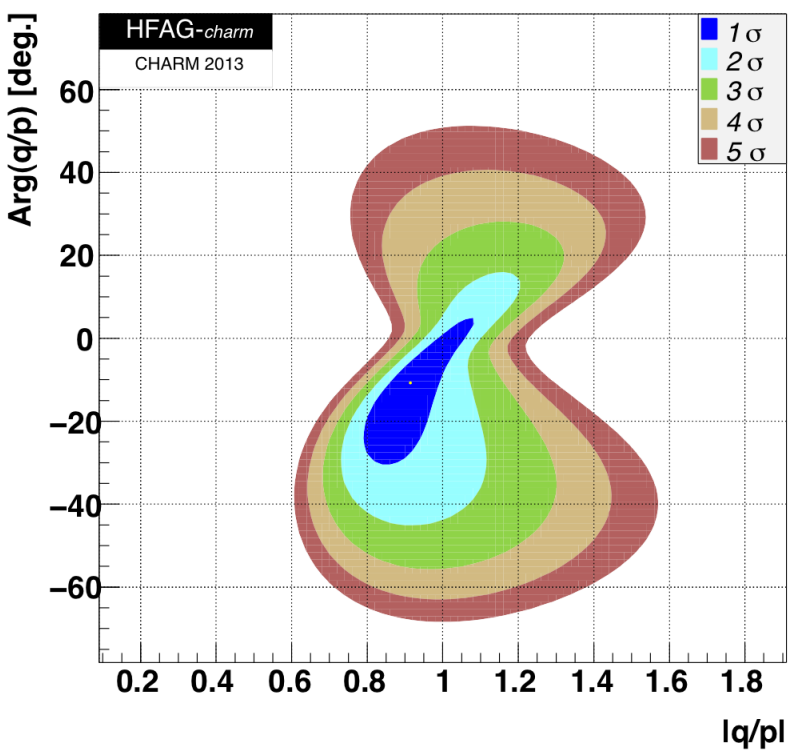
- Only meson mixing generated by down-type quarks — in SUSY by up-type squarks

  Mixing observed only in 2007

  Bound on CPV in mixing is 1–2 orders of magnitude weaker than in $B_{d,s}$ and K mixing

- Far from hitting the "theory wall"

- Possible connections to FCNC top decays



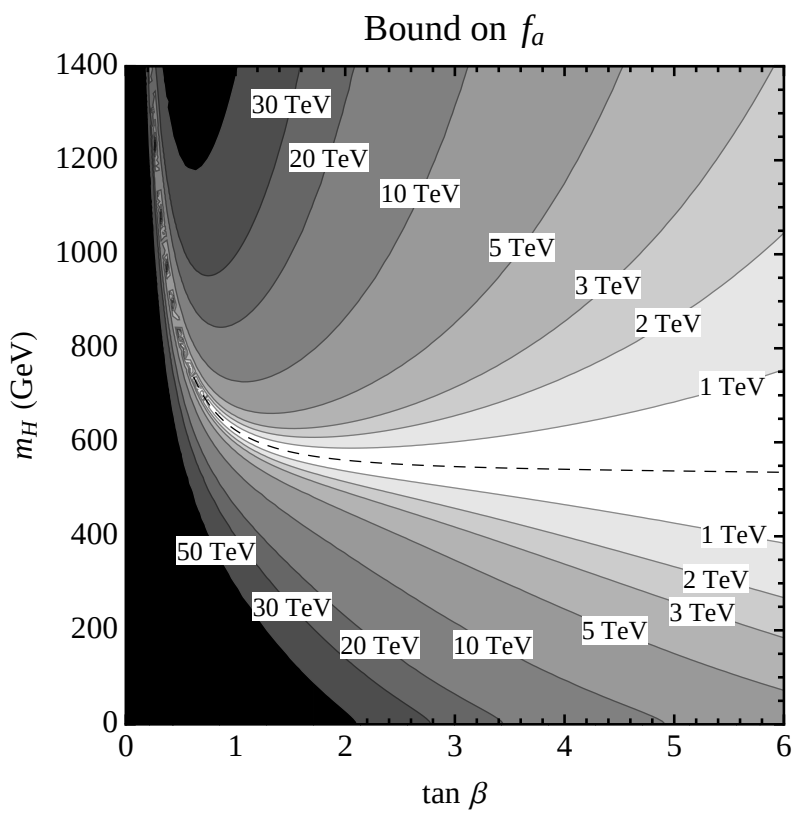
Uncertainty of $|q/p|$ is ~ 0.2 !

- Complementary to K, B — interplay in SUSY between Δm_D & Δm_K constraints

Example: bump searches in $B \to K^{(*)}\ell^+\ell^-$

- Can probe certain DM models with B decays

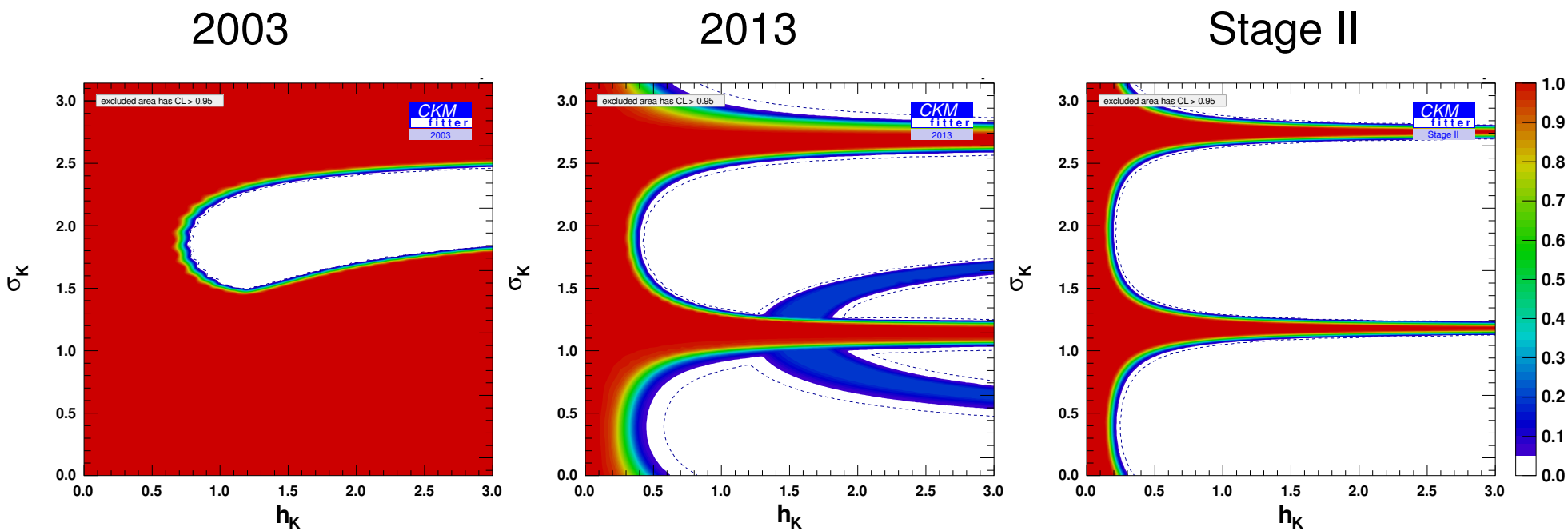
  E.g., "axion portal": light ($\lesssim 1\,\mathrm{GeV}$) scalar particle coupling as $(m_\psi/f_a)\,\bar{\psi}\gamma_5\psi\,a$



[Freytsis, ZL, Thaler, arXiv:0911.5355]

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

New physics in K^0 mixing



- Only ϵ_K constraint — two "chimneys"
- Precision lattice QCD calculation of Δm_K would cut those off
- In some classes of models can combine with $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$

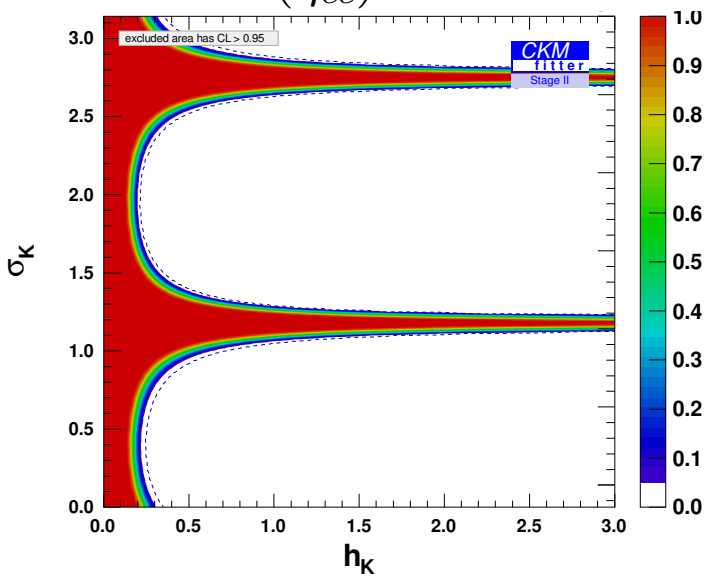
K^0 mixing, lattice QCD, other prospects

- How to best use anticipated precise lattice QCD calculation of Δm_K in the SM?
  - Directly constrain $|h_K|$ [what we did]
  - Constrain η_{cc}, which is the largest uncertainty in ϵ_K [Buras and Girrbach, 1304.6835]

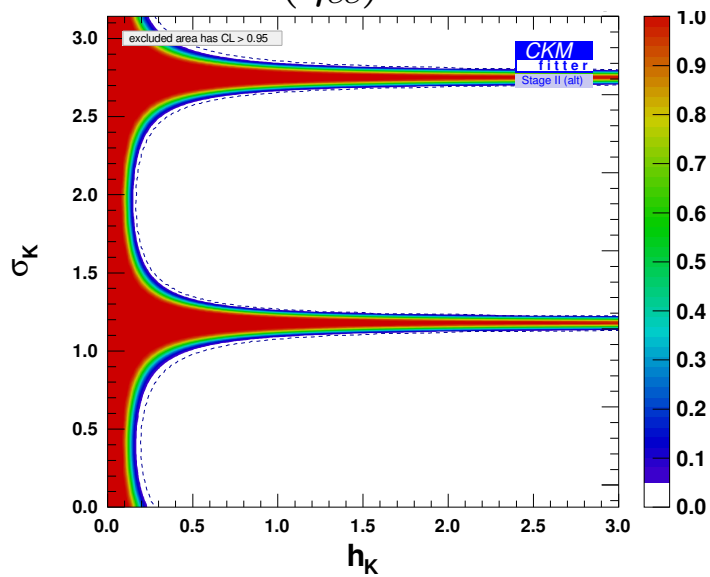
Hard to connect lattice QCD to SD/LD separation in dim.reg. (remove λ_c vs. λ_u)

[Christ, Izubuchi, Sachrajda, Soni, Yu, 1212.5931]

$\sigma(\eta_{cc}) = 0.76$

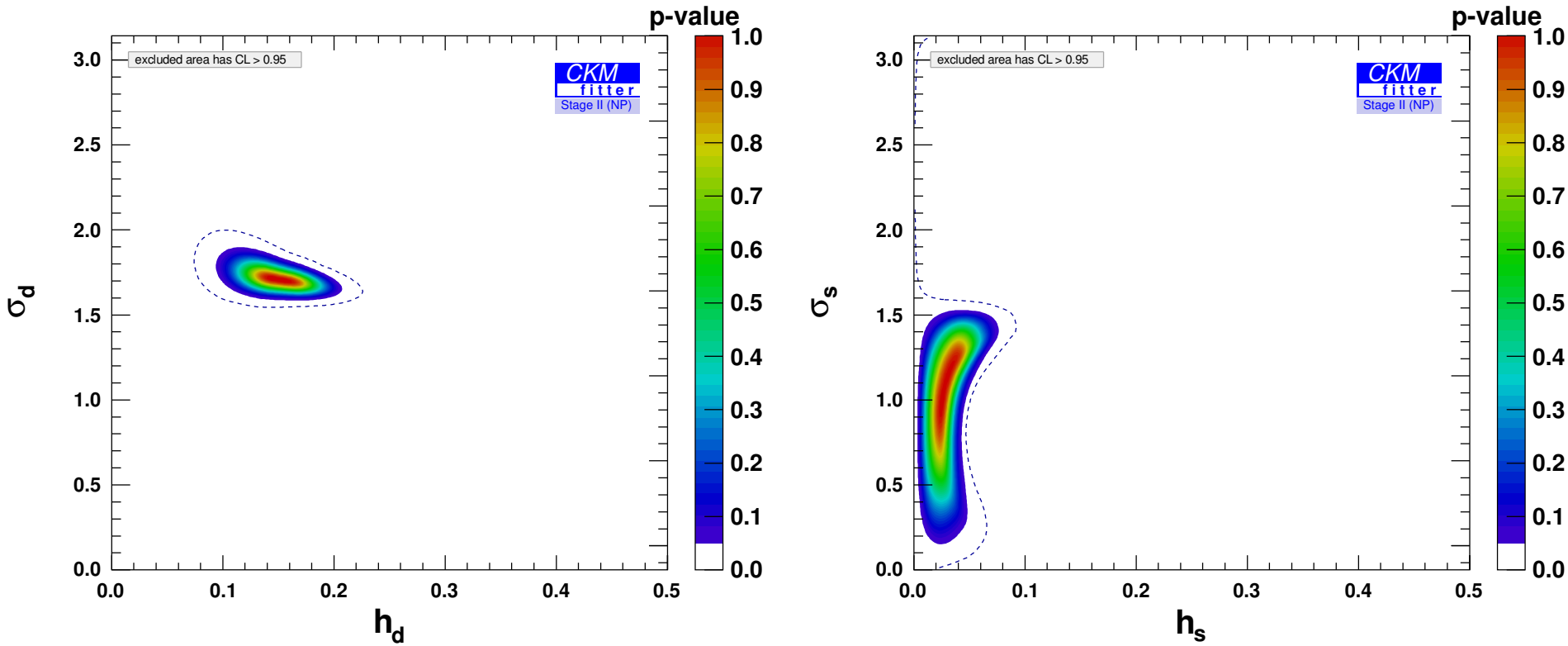


$\sigma(\eta_{cc}) = 0.2$



Can such fits discover NP?

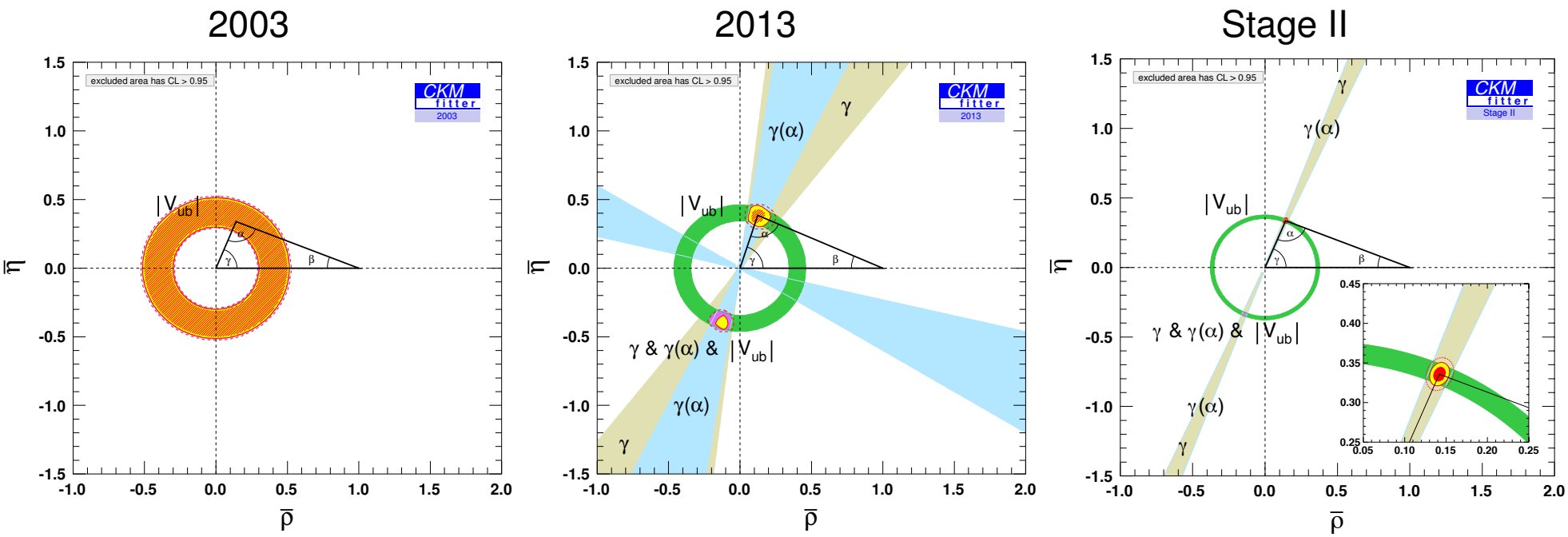
- Interesting to see if NP can be discovered and not only constrained



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 CKM fit with NP allowed in mixing

- Much larger allowed regions when fitting more (NP) free parameters

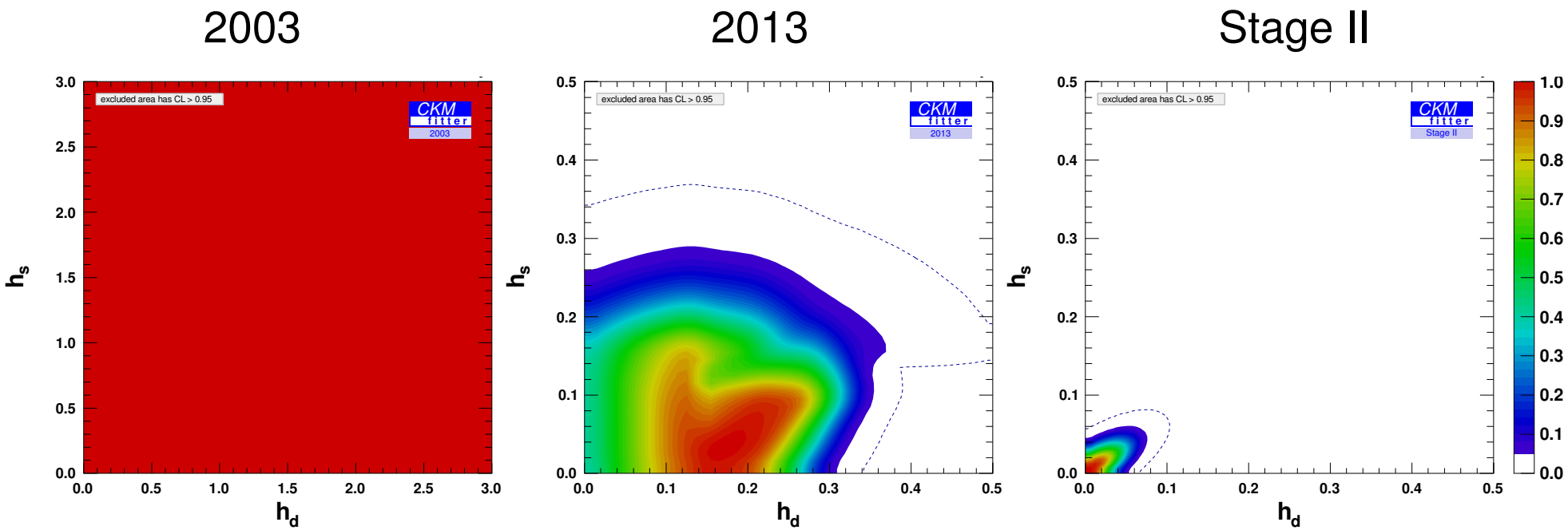


Qualitative change after 2003: first constraints on γ (and α)

- Define "Stage II": Belle II $50\,\mathrm{ab}^{-1}$ + LHCb $50\,\mathrm{fb}^{-1}$ [Charles et al., 1309.2293]

- At 95% CL, $\bar{\rho} < 0$ & $\bar{\eta} < 0$ is still allowed now (importance of future A_{SL}^{d})

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



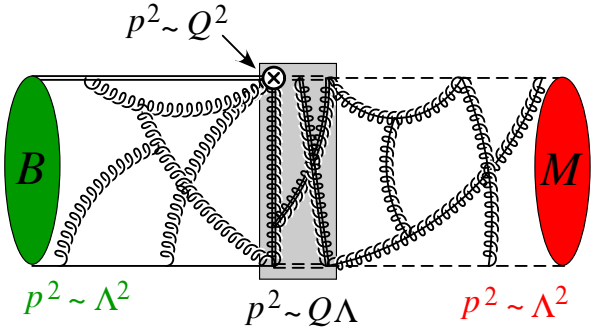
[1309.2293]

- 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)

Semileptonic $B \to \pi, \rho$ form factors

- At leading order in Λ/Q, to all orders in α_s, two contributions at $q^2 \ll m_B^2$: soft form factor & hard scattering (Separation scheme dependent; $Q = E, m_b$, omit μ's)

  [Beneke & Feldmann; Bauer, Pirjol, Stewart; Becher, Hill, Lange, Neubert]



$$F(Q) = C_i(Q)\,\zeta_i(Q) + \frac{m_B f_B f_M}{4E^2}\int \mathrm{d}z\mathrm{d}x\mathrm{d}k_+\, T(z,Q)\, J(z,x,k_+,Q)\,\phi_M(x)\phi_B(k_+)$$

- Symmetries $\Rightarrow$ nonfactorizable (1st) term obey form factor relations [Charles *et al.*]

  $3\ B \to P$ and $7\ B \to V$ form factors related to 3 universal functions

---

- Relative size? QCDF: 2nd $\sim \alpha_s \times$(1st) SCET: 1st $\sim$ 2nd

- Whether first term factorizes (involves $\alpha_s(\mu_i)$, as 2nd term does) involves same physics issues as hard scattering, annihilation, etc., contributions to $B \to M_1 M_2$

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: $(S = \tilde{Q}_L, \tilde{\bar{D}}_L, \tilde{\bar{U}}_L, \tilde{L}_L, \tilde{\bar{E}}_L)$

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

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

$5\ m^2_S$ 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)