$B_{d,s}$ mixing & CP violation

Zoltan Ligeti

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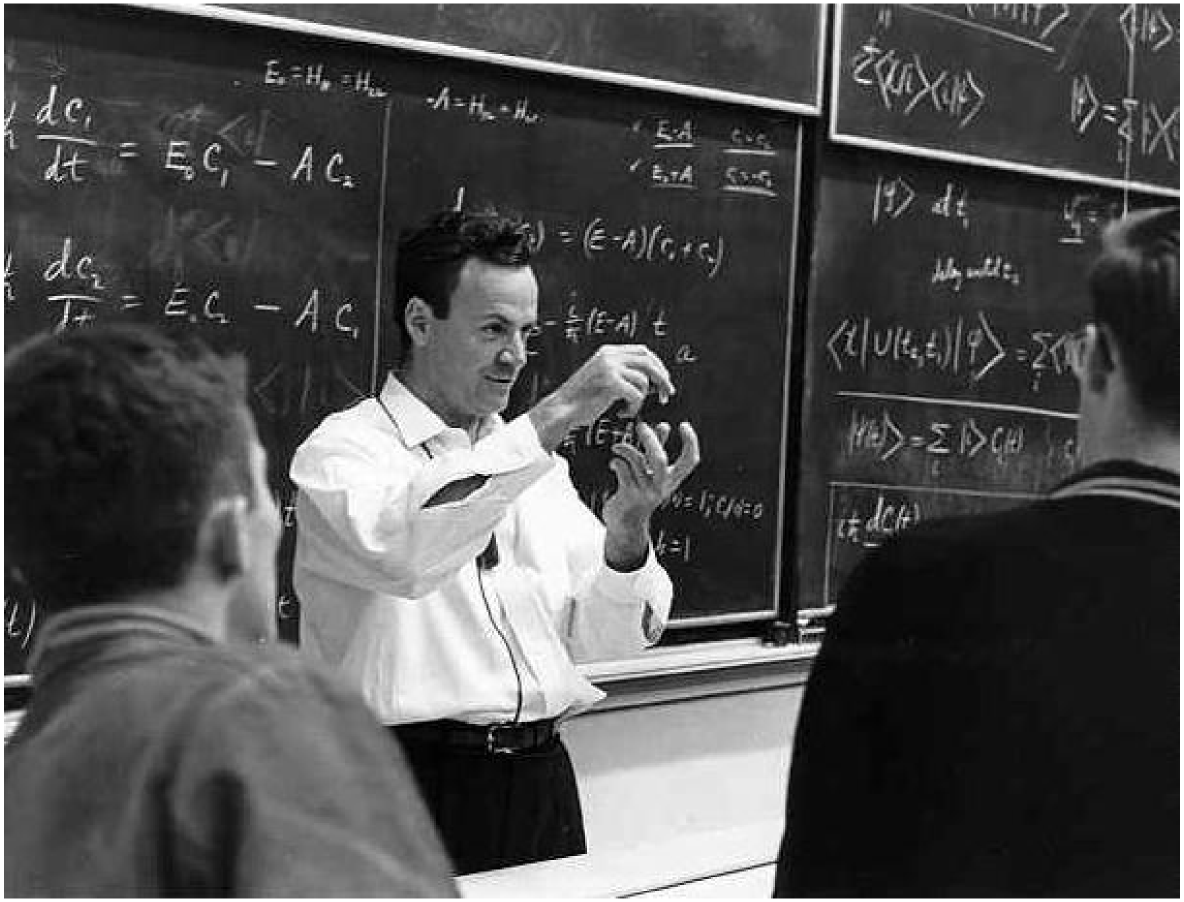
- Future NP sensitivity in B, K mixing [Charles, Descotes-Genon, ZL, Monteil, Papucci, Trabelsi, 1309.2293]
- $|V_{ub}|$, right handed currents in $B \to \rho\ell\bar{\nu}$, etc. [w/ Bernlochner & Turczyk, arXiv:131a.bcde]
- Conclusions

Waited $20+$ years for the LHC

- Conventional views of fine tuning and naturalness in growing tensions with data
- Recent discoveries:
  - SM-like Higgs, no deviations from SM (Large A terms? Extend Higgs sector?)
  - Not even $B_s \to \mu^+\mu^-$ deviates from the SM by $\mathcal{O}(1)$
- If NP is $10-100\,\mathrm{TeV}$ ("split"), flavor especially crucial (less constraints, high reach)
  Flavor can help naturlaness: w/o degeneracy, squark bounds $1.2\,\mathrm{TeV} \to 0.5\,\mathrm{TeV}$

  [Gedalia, Kamenik, ZL, Perez, 1202.5038; Mahbubani, Papucci, Perez, Ruderman, Weiler, 1212.3328; etc.]

- The higher the scale of NP, the less its flavor structure has to be SM-like
- Measurements probe $\begin{cases} \mathrm{TeV}\text{-scale physics with SM-like flavor structure} \\ 100\text{–}1000\,\mathrm{TeV}\text{ physics with generic flavor structure} \end{cases}$
- We do not know where NP will show up $\Rightarrow$ mixing is sensitive to very high scales



"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]

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

- Neutral meson mixings: dimension-6 operators, with coefficients C/Λ^2

Operator	Bounds on Λ [TeV] ($C=1$) Re	Bounds on Λ [TeV] ($C=1$) Im	Bounds on C ($\Lambda = 1$ TeV) Re	Bounds on C ($\Lambda = 1$ TeV) Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\, \epsilon_K$
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\, \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\, \lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\, \lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	$\Delta m_{B_d};\, S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	$\Delta m_{B_d};\, S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	$\Delta m_{B_s};\, S_{\psi\phi}$
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	$\Delta m_{B_s};\, S_{\psi\phi}$

[Isidori, Perez, Nir, 1002.0900; Isidori 1302.0661]

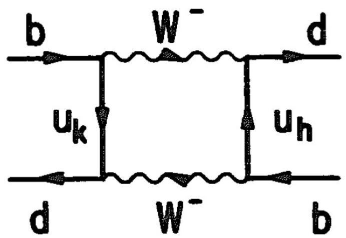
If $\Lambda = \mathcal{O}(1\,\text{TeV})$ then $C \ll 1$ If $C = \mathcal{O}(1)$ then $\Lambda \gg 1\,\text{TeV}$

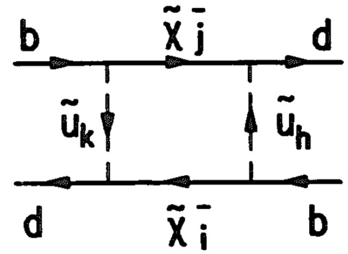
- Flavor physics discoveries would give upper bound on a new energy scale e.g., if NP is $10 - 100\,\text{TeV}$ (split, spread, etc.)

NP in 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

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

In K system introduce h_K in "tt" contribution

- Mature topic, conservative picture of future progress

Inputs: many measurements & calculations

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

- Lattice QCD is essential

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

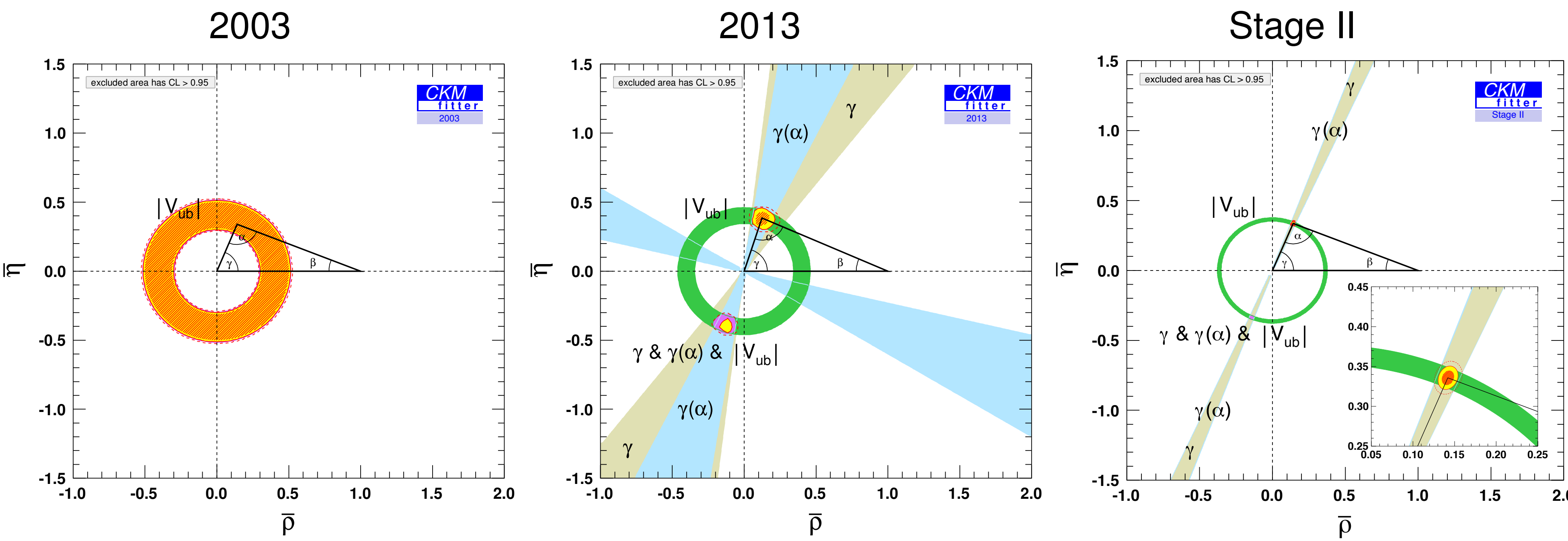
	2003	2013	Stage I		Stage II	
$\lvert V_{ud}\rvert$	0.9738 ± 0.0004	$0.97425 \pm 0 \pm 0.00022$	id		id	
$\lvert V_{us}\rvert$ ($K_{\ell 3}$)	$0.2228 \pm 0.0039 \pm 0.0018$	$0.2258 \pm 0.0008 \pm 0.0012$	0.22494 ± 0.0006		id	
$\lvert \epsilon_K\rvert$	$(2.282 \pm 0.017) \times 10^{-3}$	$(2.228 \pm 0.011) \times 10^{-3}$	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): reassuring that $2-3\%$ uncertainty in $|V_{ub}|$ seems obtainable from several measurements: $B \to \tau\nu$, $B \to \mu\nu$, $B \to \pi\ell\nu$

  (NB: I don't see how inclusive $|V_{ub}|$ can compete, but still think it's important to push it to the limit)

The CKM fit with NP allowed in mixing

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

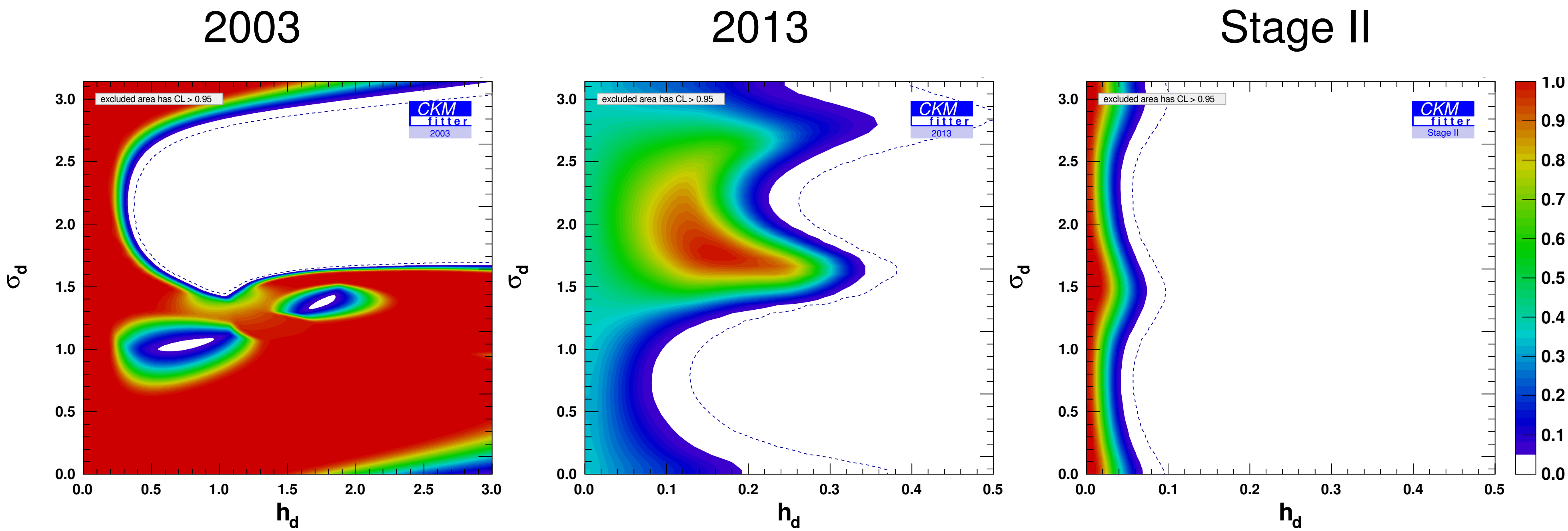


Qualitative change after 2003: first constraints on γ and α

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

- Stage II: Belle II $50\,{\rm ab}^{-1}$ + LHCb $50\,{\rm fb}^{-1}$ Stage I: Belle II $5\,{\rm ab}^{-1}$ + LHCb $7\,{\rm fb}^{-1}$

New physics in B_d^0 mixing

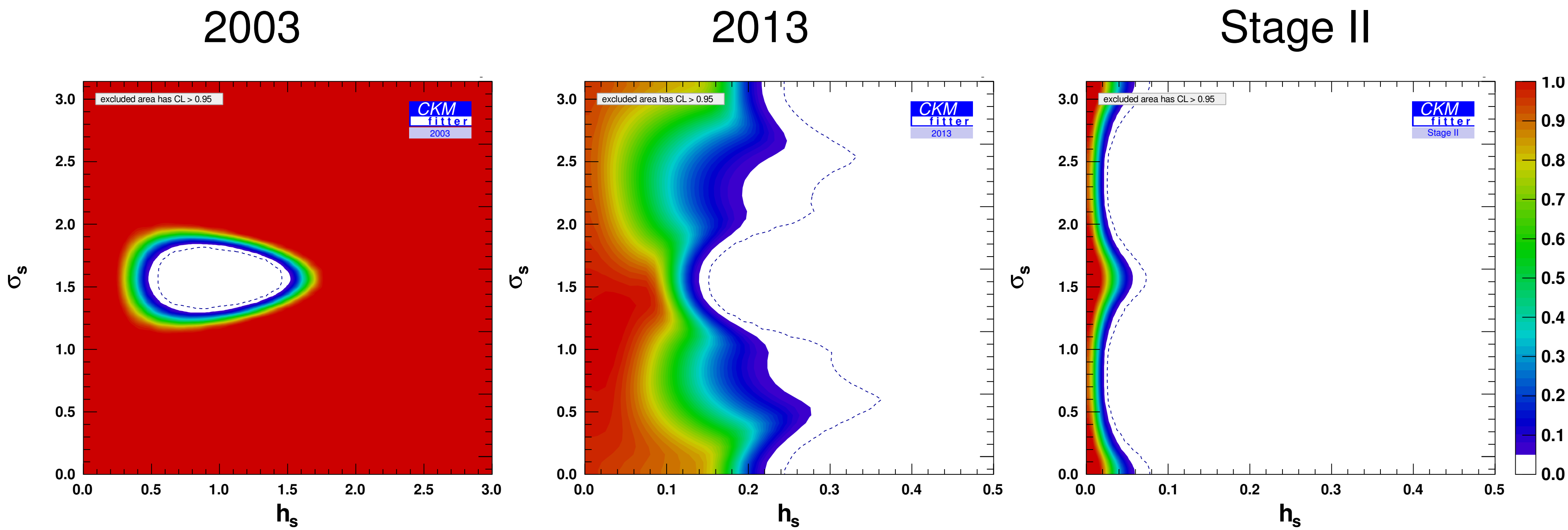


- 95% CL: NP $\lesssim$ (many $\times$ SM) $\rightarrow$ NP $\lesssim$ $(0.3 \times$ SM) $\rightarrow$ NP $\lesssim$ $(0.05 \times$ SM)

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

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

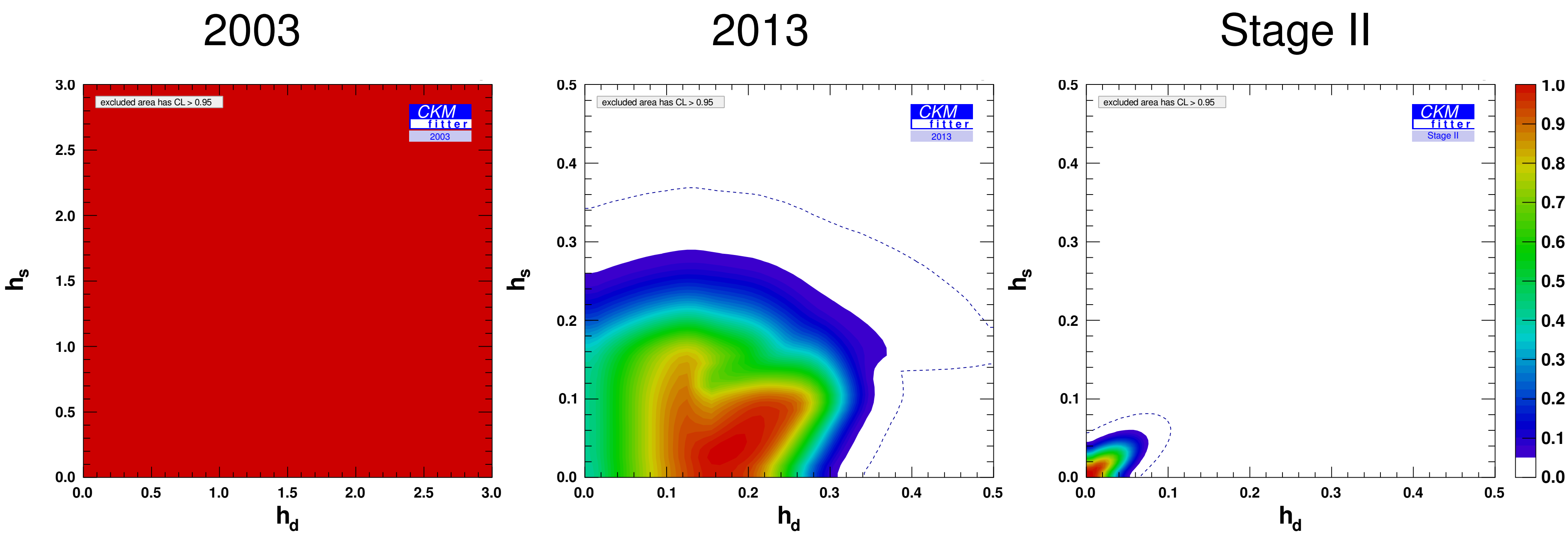
New physics in B_s^0 mixing



- 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 (at least)
- Sensitivity in the future will remain comparable; slightly better in B_s do to less SM "background" in SM expectations

New physics in $B_{d,s}$ mixing

- Looking at $B_{d,s}$ mixing simultaneously   (Connections to K mixing in $U(2)^3$ flavor models)



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

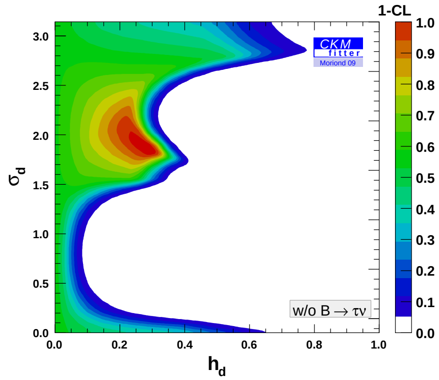
Constraining MFV-like scenarios

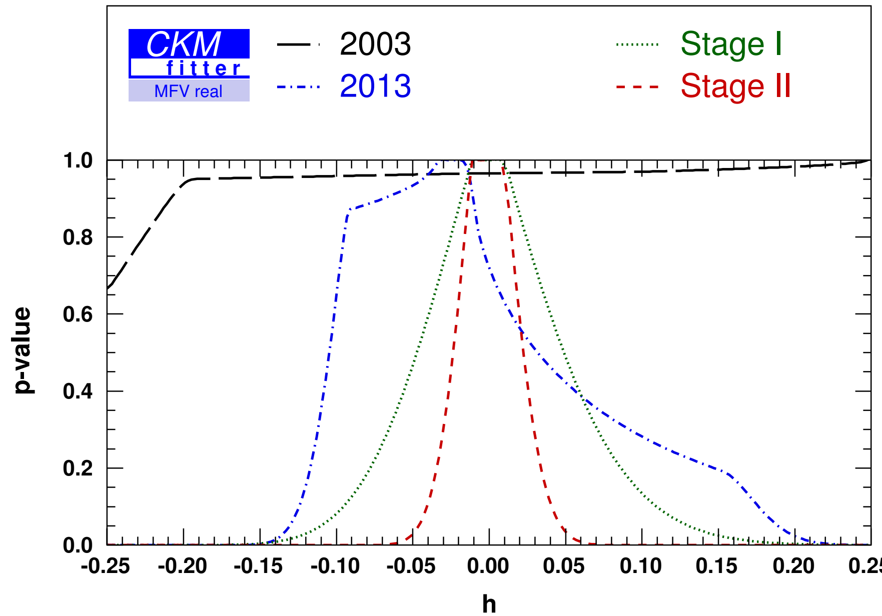
- MFV: $h \equiv h_d\, e^{2i\sigma_d} = h_s\, e^{2i\sigma_s} = h_K\, e^{2i\sigma_K}$

  $\sigma_d = \sigma_s = \sigma_K = 0 \pmod{\pi/2}$

- Lattice QCD progress has improved bounds on MFV substantially

  2009 $\Rightarrow$

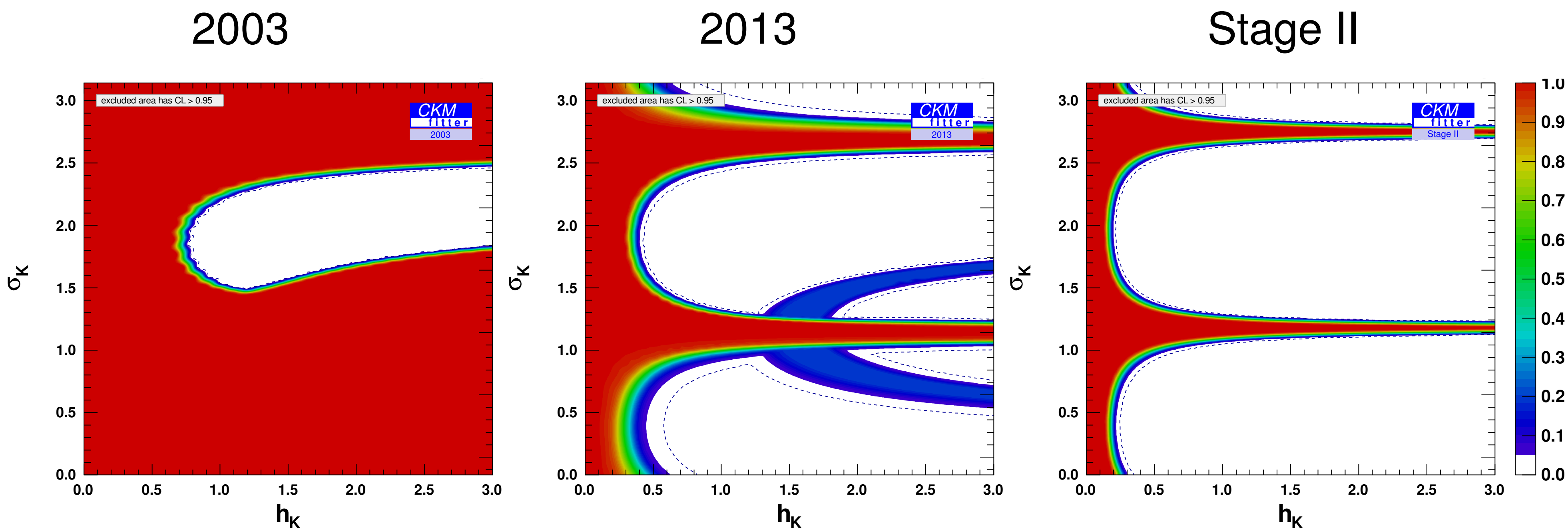




  Lattice also essential for future progress

- Plateau at Stage II: treated future lattice QCD uncertainties as Gaussians, but used Rfit for non-lattice theoretical inputs: m_t, $\eta_{cc,ct,tt}$, η_B

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 $K_L \to \pi^0 \nu \bar{\nu}$

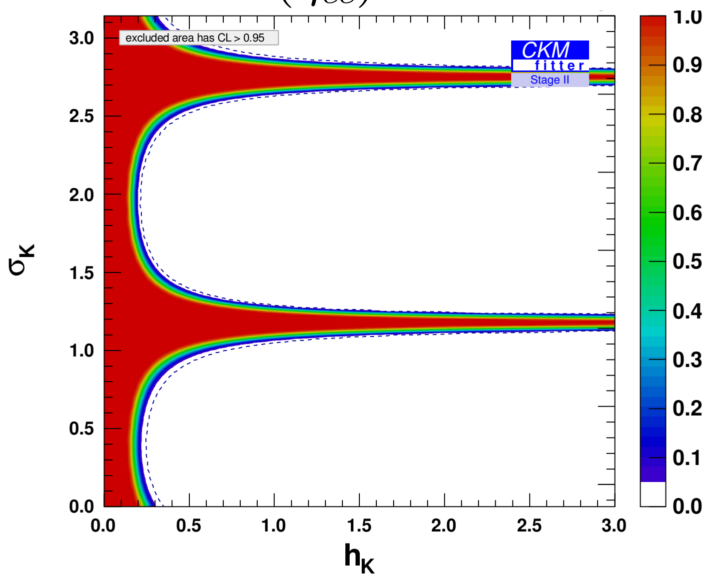
K^0 mixing, lattice QCD, other prospects

- 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]

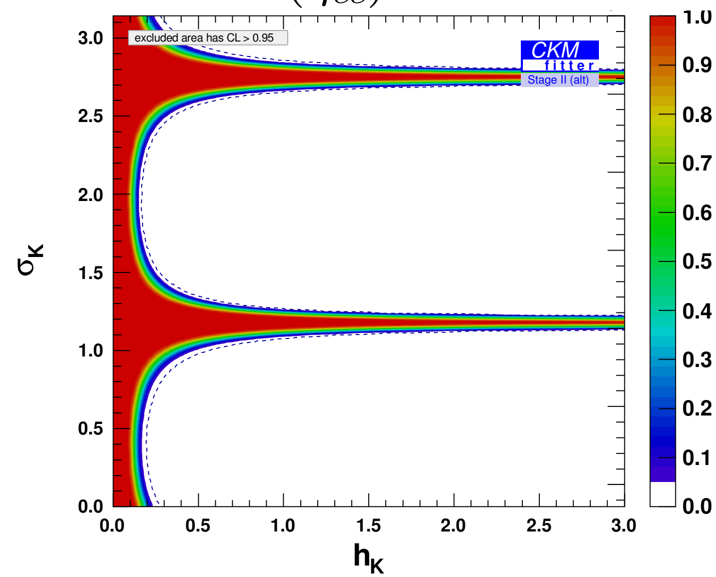
Hard to connect lattice QCD to SD/LD separation in dim.reg. (remove λ_c vs. λ_u)

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

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

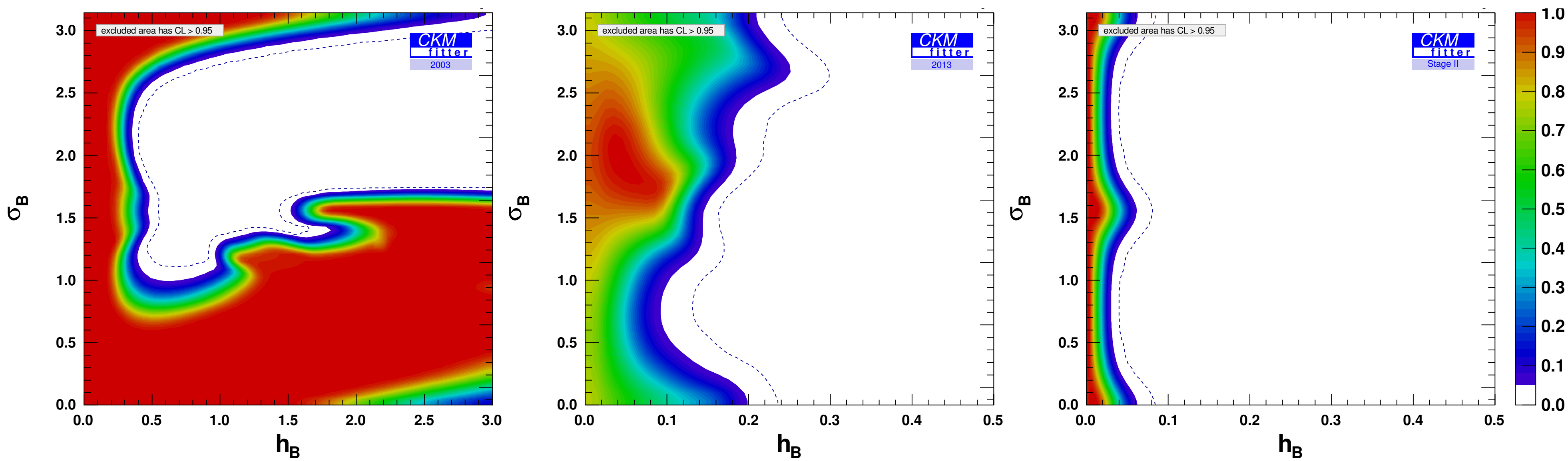


$\sigma(\eta_{cc}) = 0.2$



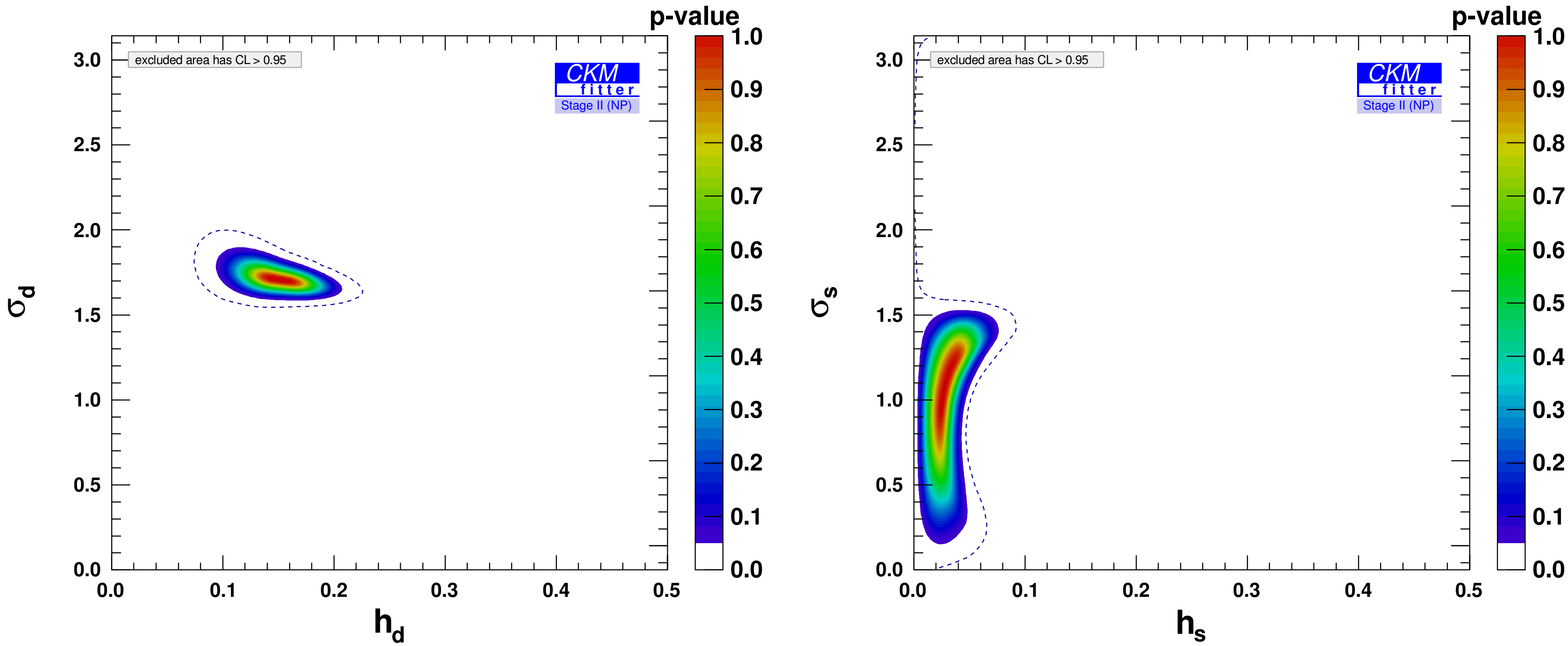
$U(2)^3$ flavor models

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



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 $\bar{\rho}$, $\bar{\eta}$, $h_{d,s}$, $\sigma_{d,s}$

$|V_{ub}|$, $B \to \rho \ell \bar{\nu}$, right-handed currents

The $|V_{ub}|$ saga continues... (?)

- Tensions among $|V_{ub}|$ measurements

  Old story, still don't know the resolution

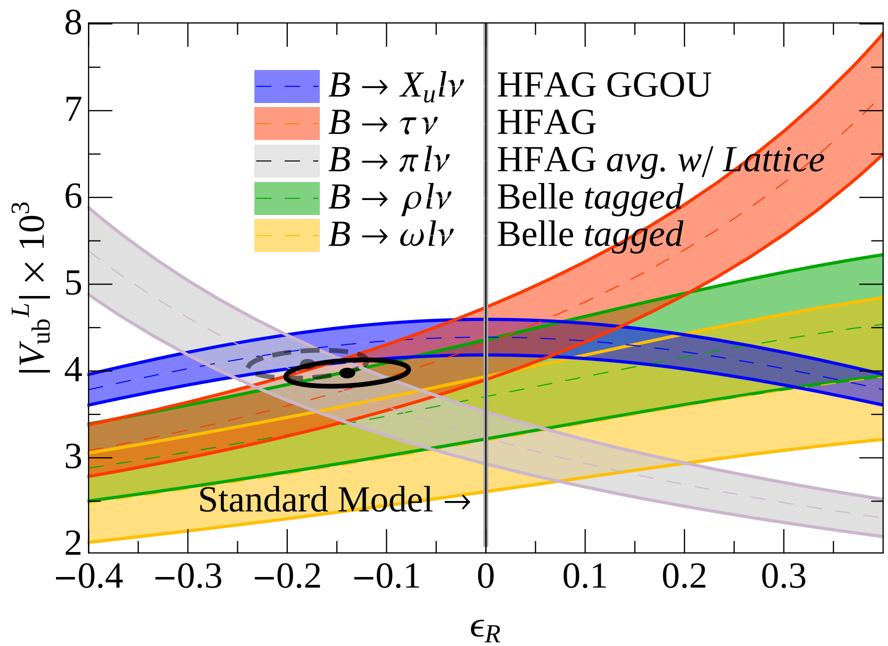
- Too early to conclude:
  - Inclusive measuerment can improve a lot
  - Exclusive done better with full reco
  - Will have more robust lattice QCD results

- 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	$(1 + \epsilon_R^2)$
$B \to \tau\, \bar{\nu}_\tau$	4.32 ± 0.42	$(1 - \epsilon_R)$



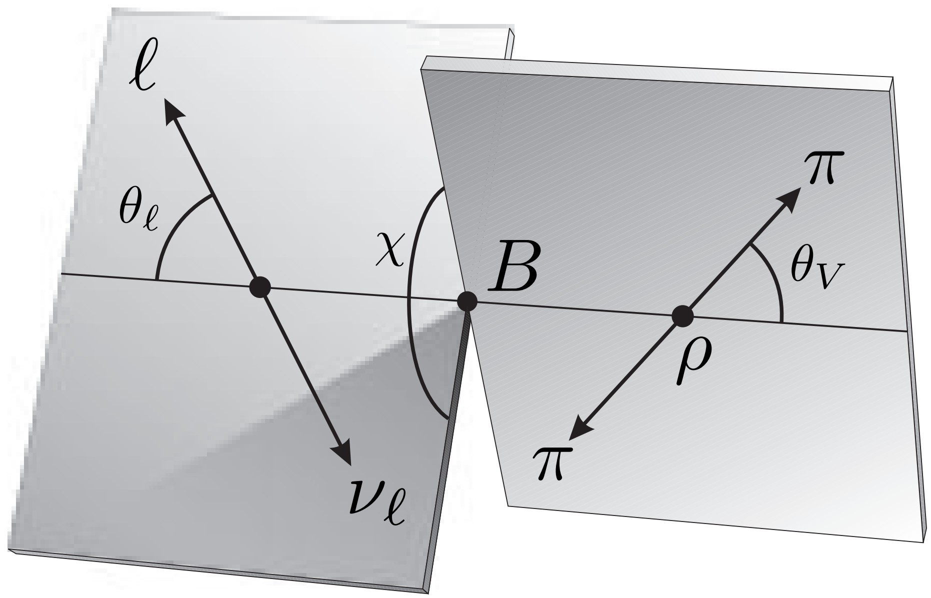
- NB: Cleanest $|V_{ub}|$ I know, only isospin, $\mathcal{B}(B_u \to \ell\bar{\nu})/\mathcal{B}(B_d \to \mu^+\mu^-)$ — run LHCb @ 33 TeV

SIMBA — advantages of a global fit

- Optimally combine all information, $B \to X_u \ell \bar{\nu}$, $B \to X_s \gamma$, etc.
  Consistently treat uncertainties and their correlations (exp, theo, parameters)
- Simultaneously determine:
  - Overall normalization: $\mathcal{B}(B \to X_s \gamma)$, $|V_{ub}|$
  - Parameters: m_b, shape function(s)
- Utilize all measurements:
  - Different $B \to X_s \gamma$ spectra, or partial rates
  - Different $B \to X_u \ell \bar{\nu}$ spectra, or partial rates
  - Include other constraints on m_b, λ_1, etc.
  - Eventually use or predict $B \to X_s \ell^+ \ell^-$
- Same strategy as for $|V_{cb}|$, just a lot more complicated...

$B \to \rho\ell\bar{\nu}$ kinematics

- Same description as in familiar $B \to VV$ or $B \to K^*\ell^+\ell^-$ decays

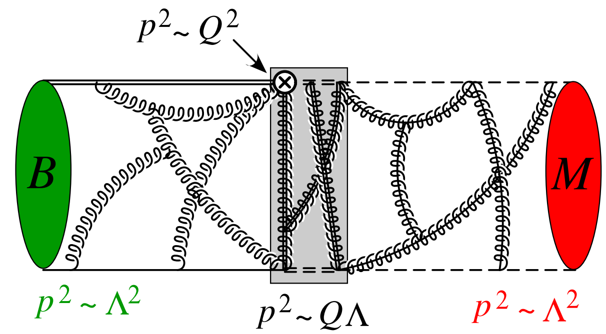


Integrate over χ and some q^2 range, study many variables, incl. those in $K^*\ell^+\ell^-$

- The q^2 range is affected by limitations of our knowledge of the form factors

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

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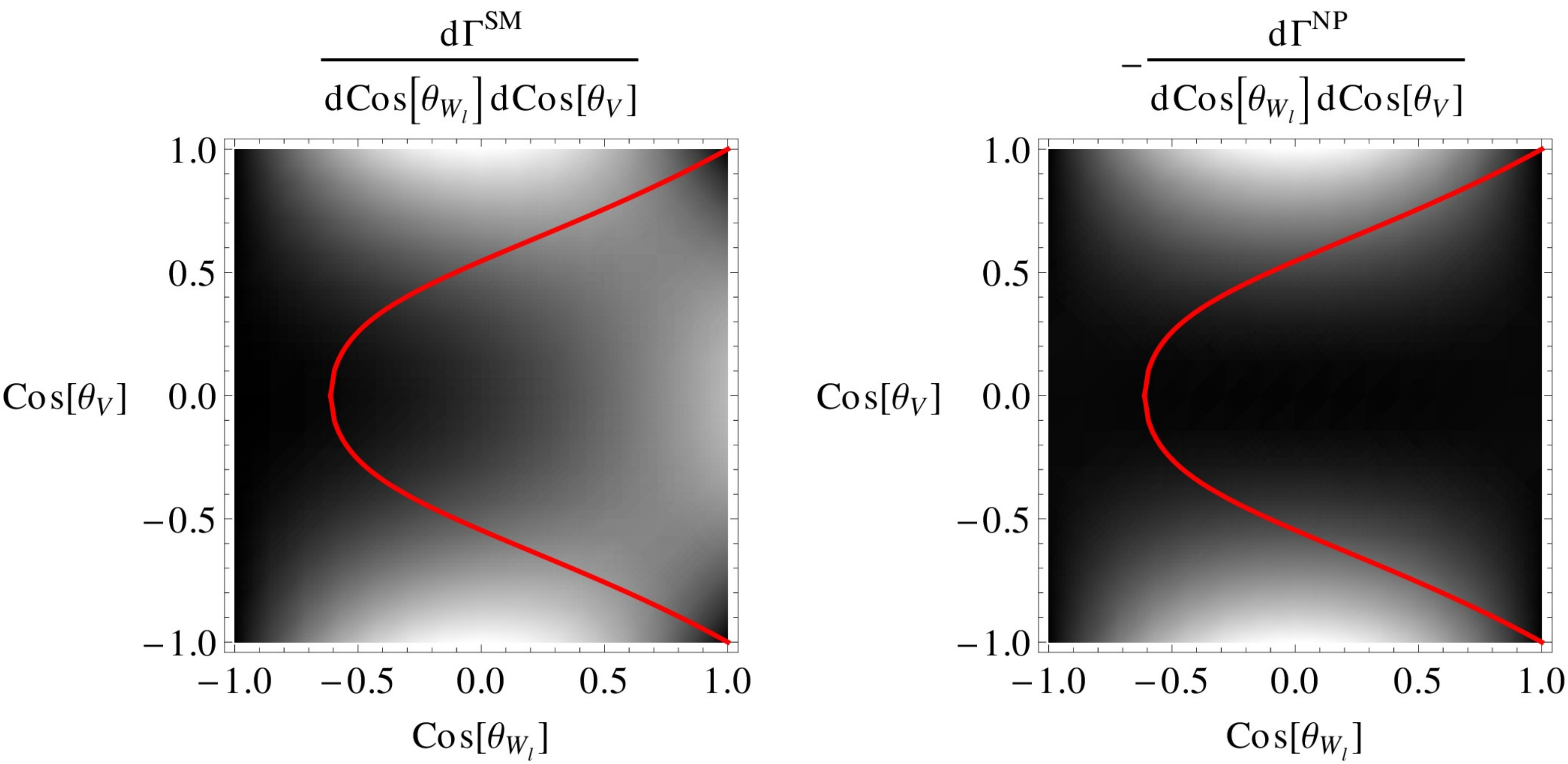
- Relative size? QCDF: 2nd $\sim \alpha_s \times$(1st) SCET: 1st $\sim$ 2nd

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

SM and NP distributions

- Very different distributions for left- and right-handed interactions (white > black)



- Choose contour (red curve) to maximize sensitivity to ϵ_R in $S = (A - B)/(A + B)$

$B \to \rho$ form factors

- Unfortunately not much available from lattice QCD yet (harder than $B \to \pi$)

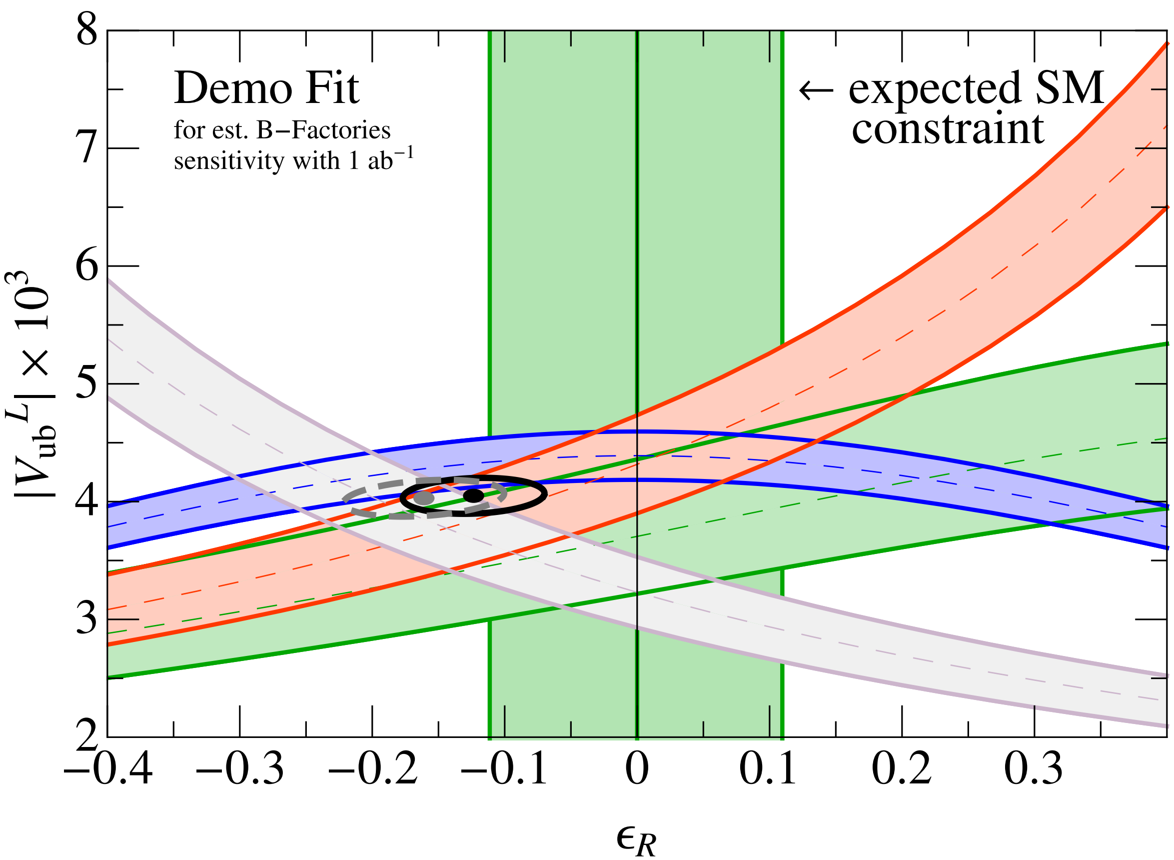
- Use analyticity constraints / parameterization [Bharucha, Feldmann, Wick, arXiv:1004.3249]
  Same issues for $B \to K^*$ form factors... [Hambrock, Hiller, Schacht, Zwicky, arXiv:1308.4379]

  More assumptions / complications than for $B \to \pi$ case
  (Γ_ρ, sub-threshold resonances in scattering channel, etc.)

- Use light-cone sum rule predictions, assessing correlations is tricky

Demo fit for Belle II

- VERY preliminary



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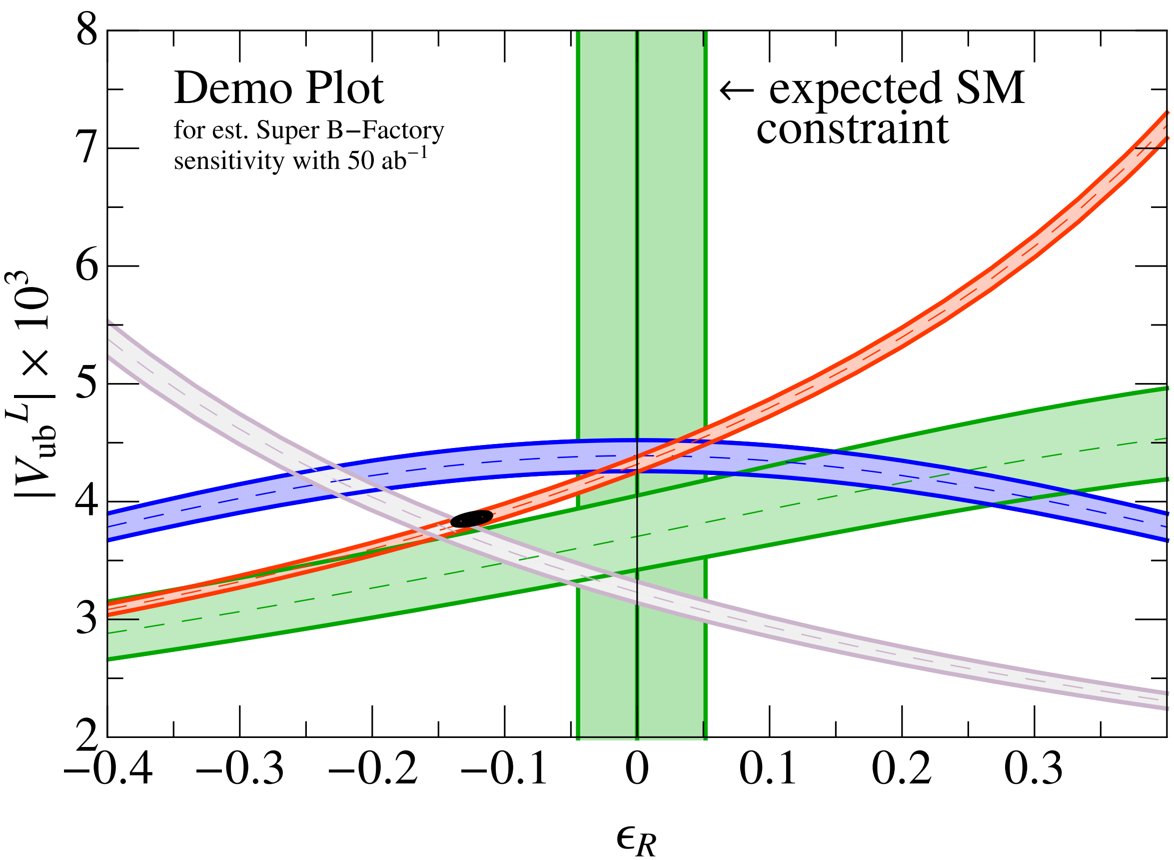


Conclusions

- New physics in most FCNC transitions may still be $\sim 20\%$ of the SM or more
- Neutral meson mixings will remain special, sensitive to some of the highest scales

Couplings	NP loop order	Scales (in TeV) probed by B_d mixing	Scales (in 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

- Progress in $b \to u$ will be important to constrain NP (expect significant progress)
- There must be new and unexpected ways to utilize:

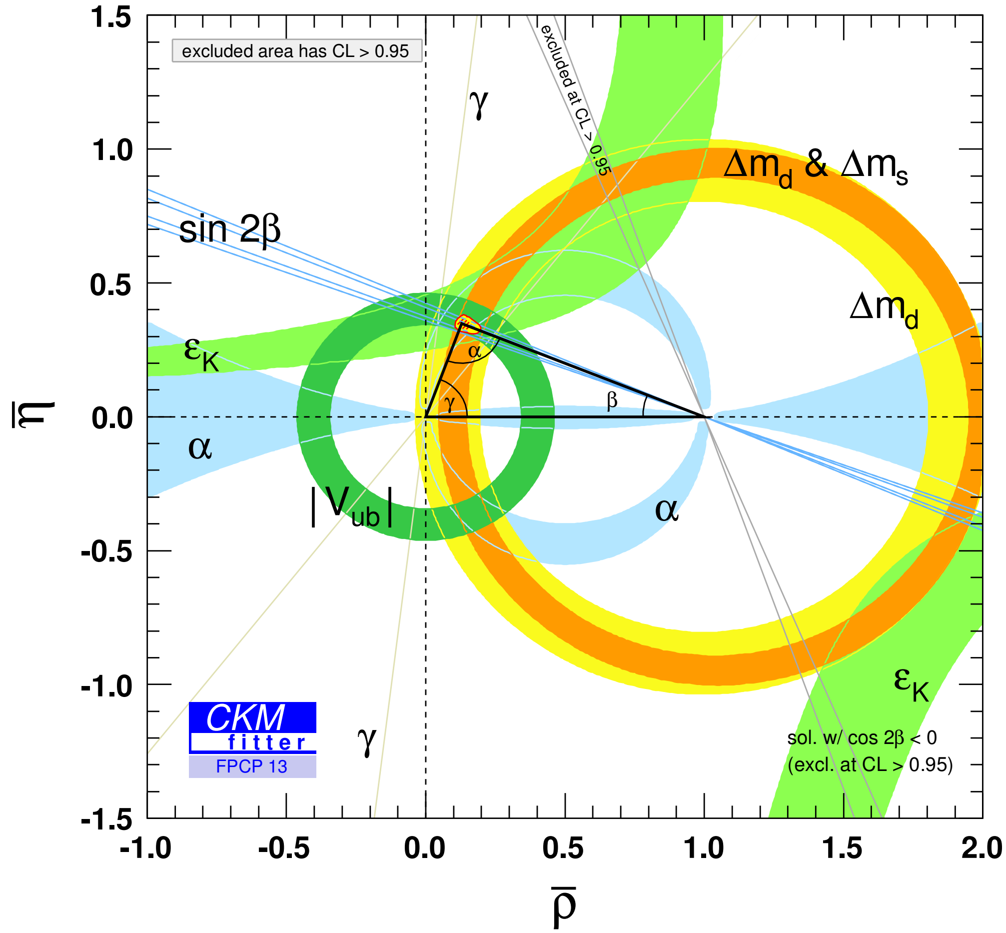
$$\frac{\text{(LHCb upgrade)}}{\text{(LHCb } 1\,\text{fb}^{-1})} \sim \frac{\text{(Belle II data set)}}{\text{(Belle data set)}} \sim \frac{\text{(2009 BaBar data set)}}{\text{(1999 CLEO data set)}} \sim 50$$

... beyond $\sqrt[4]{50} \sim 2.5$ increase in sensitivity to higher mass scales

Backup slides

Status of the CKM fit

- The level of agreement between the measurements is often misinterpreted
- Allowed region is much larger if NP is included in the fit, more parameters, which changes the fit completely
- $\mathcal{O}(20\%)$ NP contributions to most loop processes (FCNS) are still allowed



- Need experimental precision and theoretical cleanliness to increase NP sensitivity