Summary

Zoltan Ligeti

Implications of LHCb Measurements and Future Prospects

CERN, Nov 10–11, 2011

Who needs another Summary ?

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Comments & Perspectives

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Preliminaries

- We all know the importance of: $B_s \to \psi\,\phi$ and $B_s \to \phi\,\phi$

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- If we cannot even agree on spelling FLAVOR vs. FLAVOUR...

- At least, we all agree that today's date is 11.11.11

Every end is a new beginning — transition era

- Past: Ten years ago we did not know that the CKM picture was (essentially) correct

  $\mathcal{O}(1)$ deviations in CP violation were possible

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Photo: Kyodo/Reuters

Makoto Kobayashi

Photo: Kyoto University

Toshihide Maskawa

- End: Nobel Prize in 2008 is formal recognition that the KM phase is the dominant source of CPV in flavor changing transitions of quarks

- Present: No significant deviations from SM

  $\mathcal{O}(1)$ effects in B_s FCNCs less and less viable

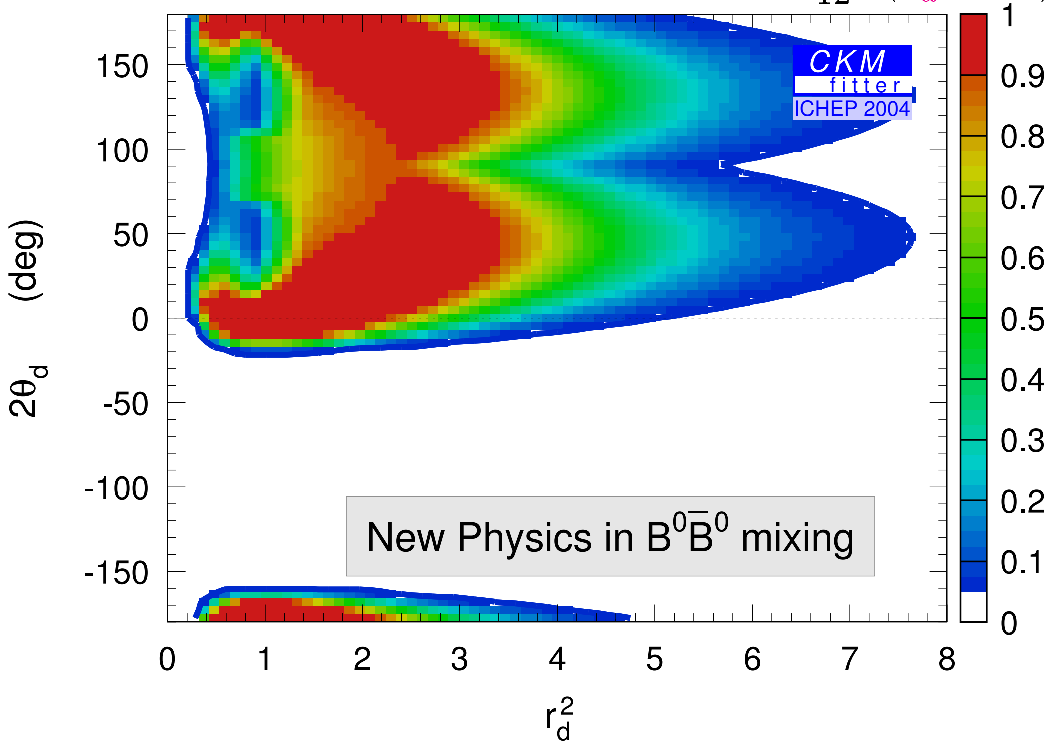
- Begin: Looking for corrections to the SM picture of flavor and CP violation

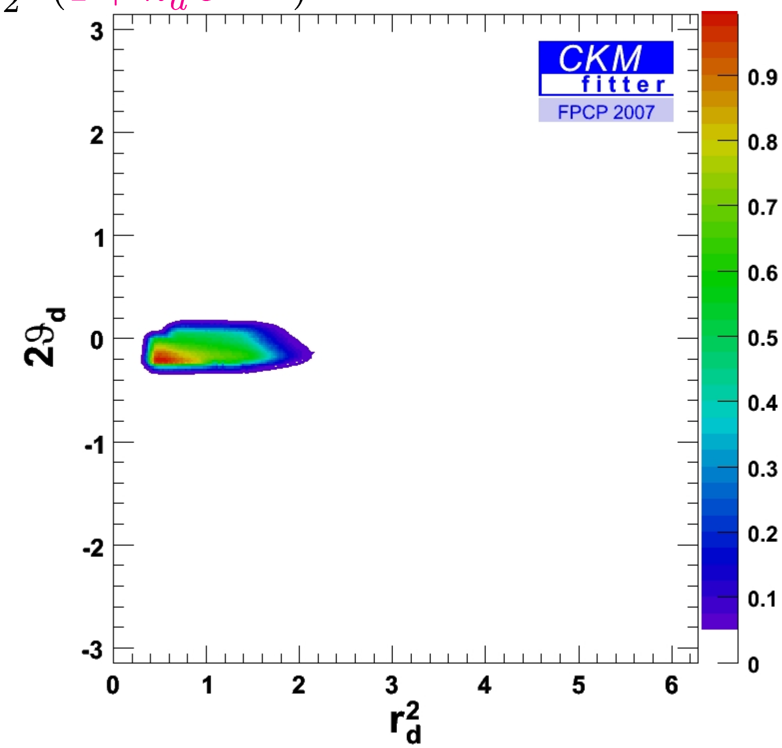
- Future: What can flavor physics teach us about beyond SM physics?

The one-page highlight of BaBar & Belle

- Constrain (NP / SM) in $B^0-\overline{B}^0$ mixing changed from <10 to <1, approaching $\ll 1$

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



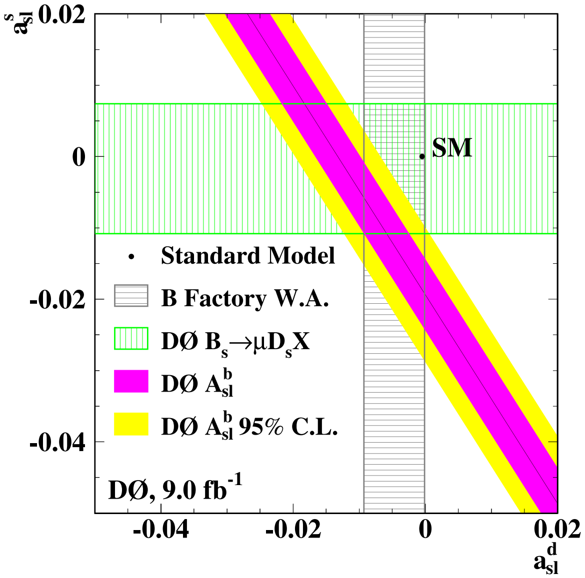


Qualitative change before vs. after 2004 — the main justification for the KM Nobel Prize

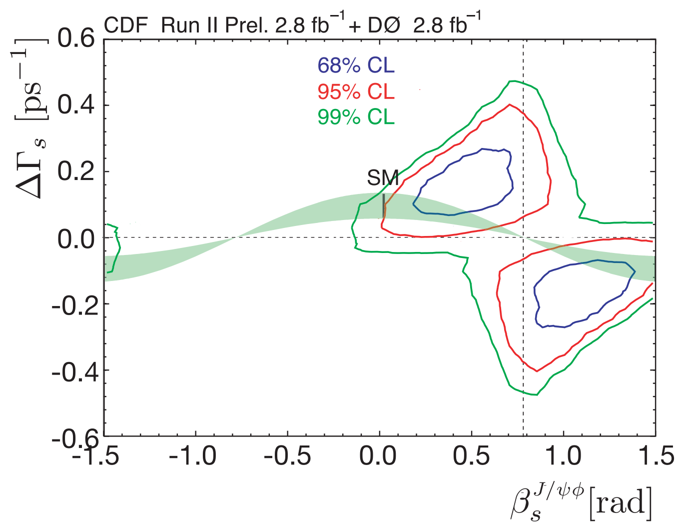
- Strong constraints on new physics in many FCNC amplitudes ($+\, B \to X_s\gamma$, etc.)
- $\mathcal{O}(20\%)$ NP contributions to most loop processes still possible; is $\Lambda_{\rm flavor} \gg \Lambda_{\rm weak}$?

Intriguing anomalies — early 2011

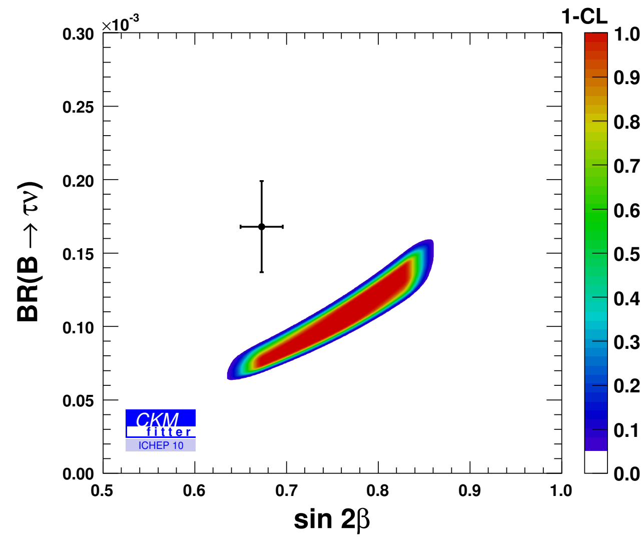
- $A_{\rm SL}$ — CP violation in $B_{d,s}$ mixing: $\sim 4\sigma$



β_s — analog of β, measured in $B_s \to \psi\phi$: $\sim 2\sigma$

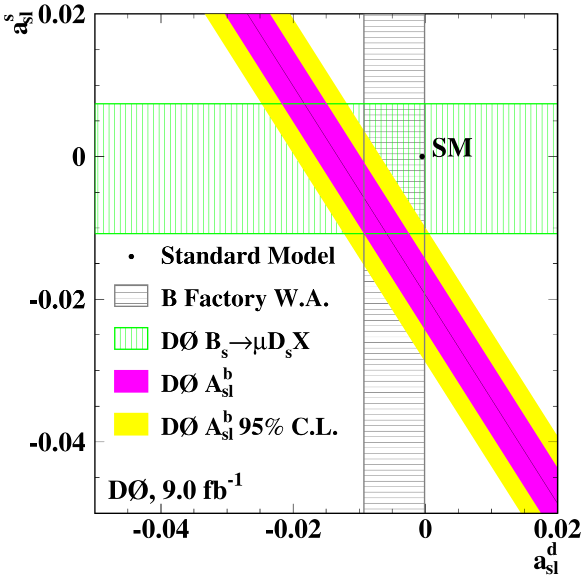


$\mathcal{B}(B \to \tau\nu)$ — above the SM prediction: $\sim 2.5\sigma$



Intriguing anomalies — late 2011

- $A_{\rm SL}$ — CP violation in $B_{d,s}$ mixing: $\sim 4\sigma$



β_s — analog of β, measured in $B_s \to \psi\phi$: $\sim 2\sigma$

LHCb consistent with SM

Most importantly, theory uncertainty $\ll$ measurement uncertainty

$\Rightarrow$ remains very important

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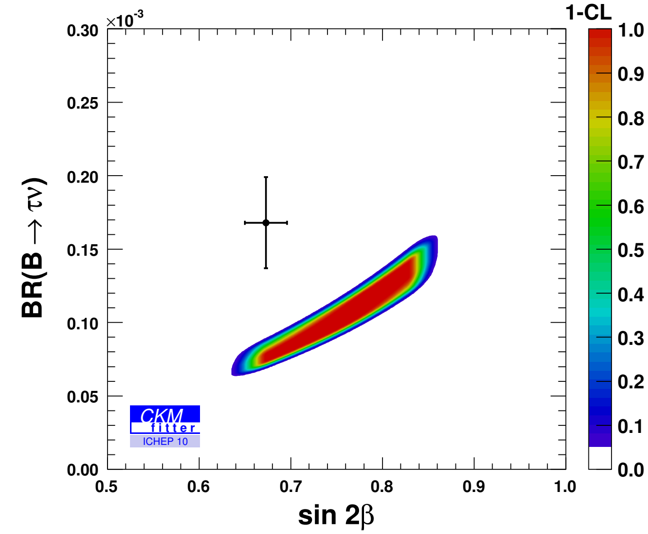


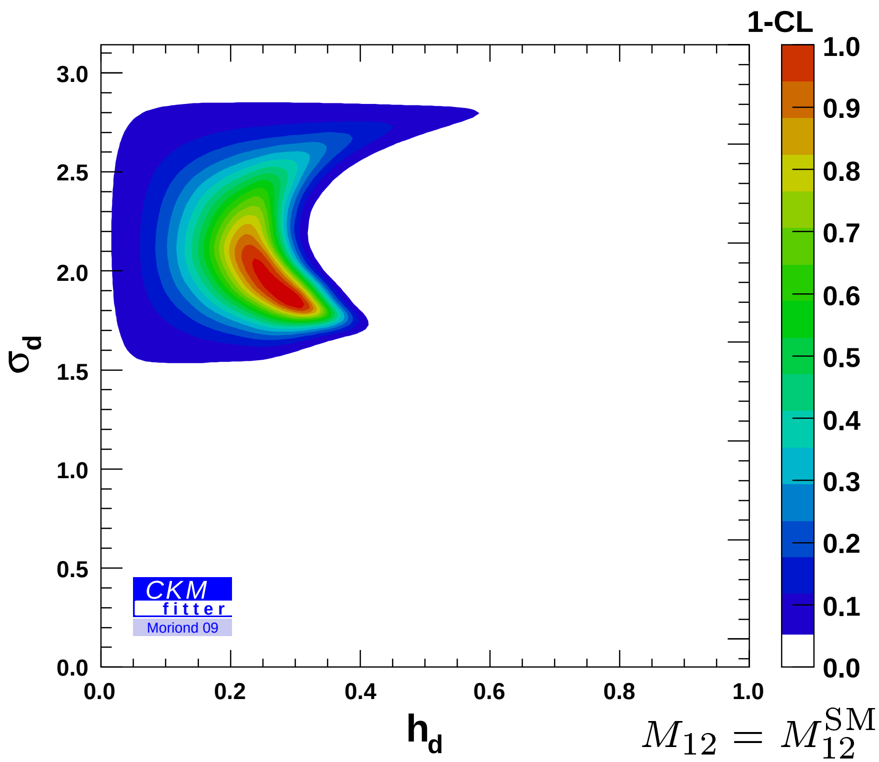
- $B \to K\pi$ CP asymmetries: theoretically less clean, but very puzzling (many "σ")

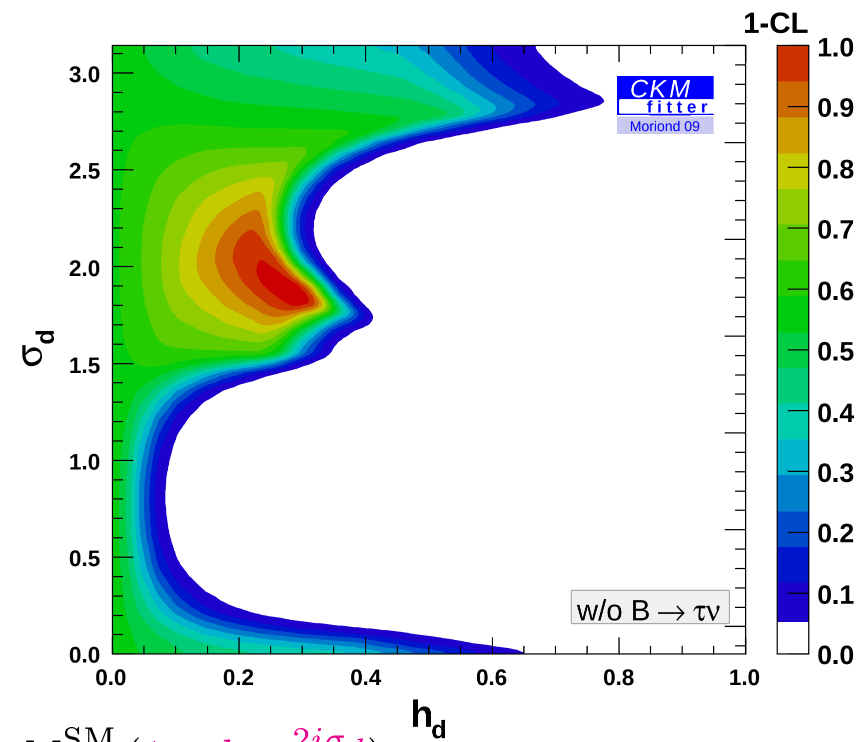
- Improved sensitivity can establish BSM physics in many other observables

As for Tevatron $t\bar t$ and Wjj anomalies, flavor properties will be important to understand what does (and what does not!) explain the high-p_T data

B_d: does $B \to \tau\nu$ hint at BSM?

- Some $2-3\sigma$ tensions (I don't think ϵ_K); many future measurements can show NP





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

- Tree-level measurements are crucial: $|V_{xb}|$ and γ

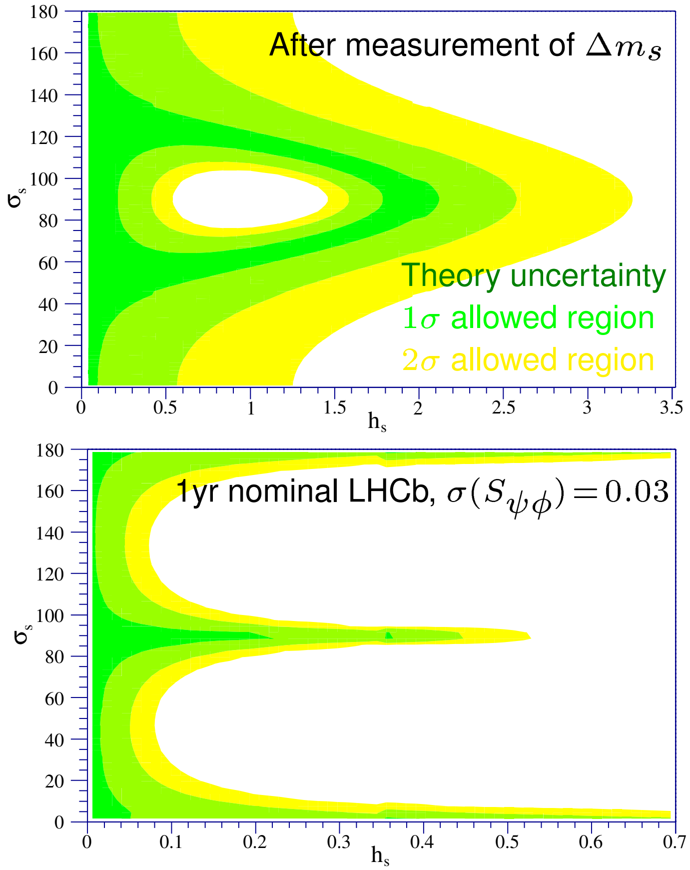
- Need precise γ measurement in order to substantially improve constraint on BSM

B_s: implication of $B_s \to \psi\phi$ for BSM

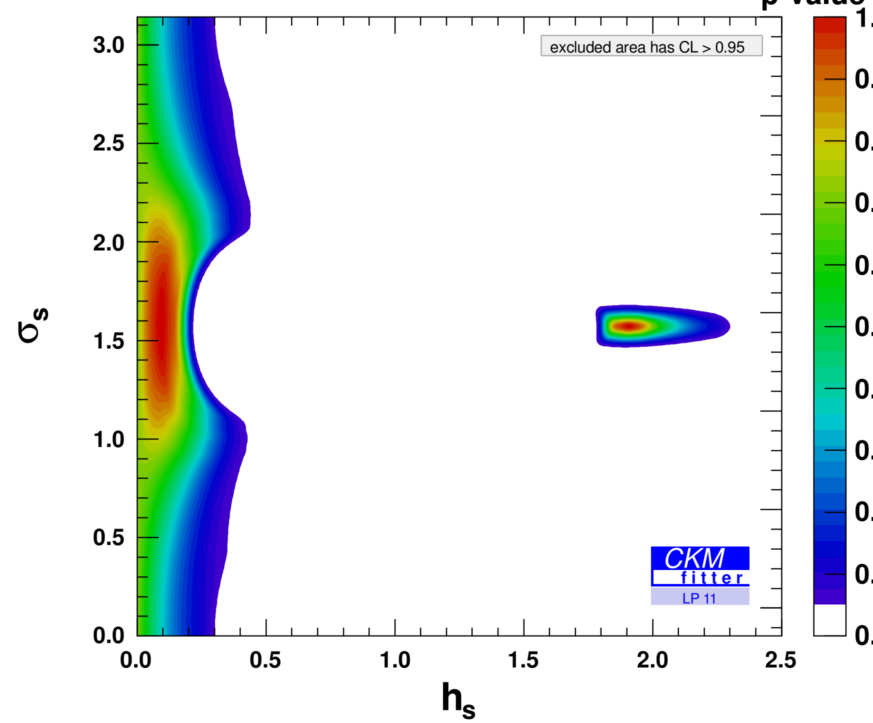
- Is B_s mixing different from B_d? We may approach the "BSM $\ll$ SM limit" faster

[ZL, Papucci, Perez, hep-ph/0604112]

Since the SM prediction of β_s is much better known (suppressed by λ^2) than that of β



Current CKMfitter result



BERKELEY LAB

D^0 mixing — what's different?

- General solution for q/p:

$$\frac{q^2}{p^2} = \frac{2M_{12}^* - i\Gamma_{12}^*}{2M_{12} - i\Gamma_{12}}$$

- $B_{d,s}^0$: $|\Gamma_{12}| \ll |M_{12}|$, so $q/p = e^{iX}$ to a good approximation

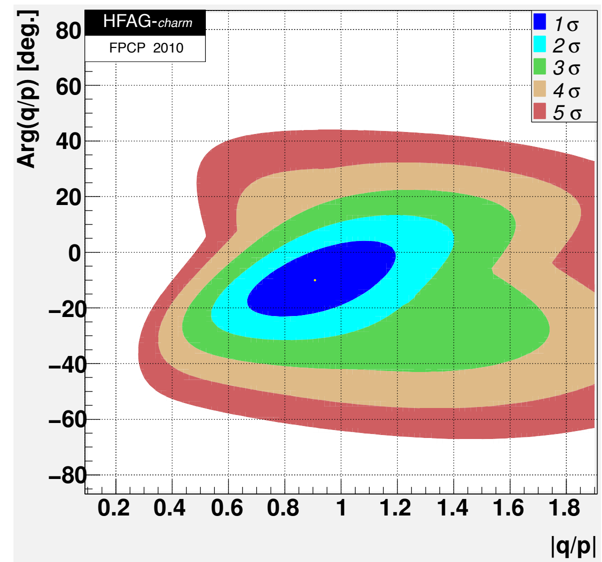
  X determined by M_{12} (+ phase conventions) $\Rightarrow$ sensitive to NP

- D^0: $|\Gamma_{12}/M_{12}| = \mathcal{O}(1)$, so q/p depends on both Γ_{12} and M_{12}

  Bounds on most CP violating effects in D^0 decays are $\lesssim 1\,\%$, however, $|q/p| - 1$ is much less constrained

D^0: mixing in up sector

- Complementary to K, B: CPV, FCNC both GIM & CKM suppressed $\Rightarrow$ tiny in SM
  - 2007: observation of mixing, now $\gtrsim 10\sigma$ [HFAG combination]
  - Only meson mixing generated by down-type quarks (SUSY: up-type squarks)
  - SM suppression: $\Delta m_D,\, \Delta\Gamma_D \lesssim 10^{-2}\,\Gamma$, since doubly-Cabibbo-suppressed and vanish in flavor $SU(3)$ limit
  - Direct CPV bounds are approaching the 10^{-3} level
  - How small CPV would still unambiguously establish new physics? [Kagan, Bobrowski]



Don't known if $|q/p|$ is near 1!

- Particularly interesting for SUSY: Δm_D and $\Delta m_K \Rightarrow$ if first two squark doublets are within LHC reach, they must be quasi-degenerate (alignment alone not viable)

Where do we go from here?

Rich experimental future

- LHCb collects $2\,\mathrm{fb}^{-1}$/yr until $\sim 10\,\mathrm{fb}^{-1}$; plan upgrade for ~ 10 times the rate
- KEK-B / Belle upgrade in progress in Japan, Super-B approved in Italy
- $\mu \to e\gamma$: MEG (PSI) sensitivity to 10^{-13}, maybe 10^{-14} later

  $\mu N \to eN$: Fermilab mu2e sensitivity 2×10^{-17}, maybe 10^{-18} later

  J-PARC: COMET sensitivity to 10^{-16}, later PRISM/PRIME to 10^{-18}

  EDM experiments
- $K \to \pi\nu\bar{\nu}$: CERN NA62: about 60 $K^+ \to \pi^+\nu\bar{\nu}$ events / yr in 2012–2014

  plans for $K_L \to \pi^0\nu\bar{\nu}$ mode later

  J-PARC E14 KOTO 10^{-11} $K_L \to \pi^0\nu\bar{\nu}$ sensitivity, later 100 events

  FNAL: proposals for $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ at ~ 1000 events
- Neutrino experiments

Very broad LHCb physics program

- B_s, B, D, baryons, plethora of observables, probe large fraction of terms in $\mathcal{H}_{\rm weak}^{(5,6)}$

  Cannot overestimate the value of the breadth of the physics program

  E.g.: Best α & γ measurements at BaBar/Belle not in previously expected modes

  Not to mention "new" $Q\overline{Q}$ and $D_s(2317, etc.)$ narrow states

- I hope there will be surprises and some "key" measurements are not yet known

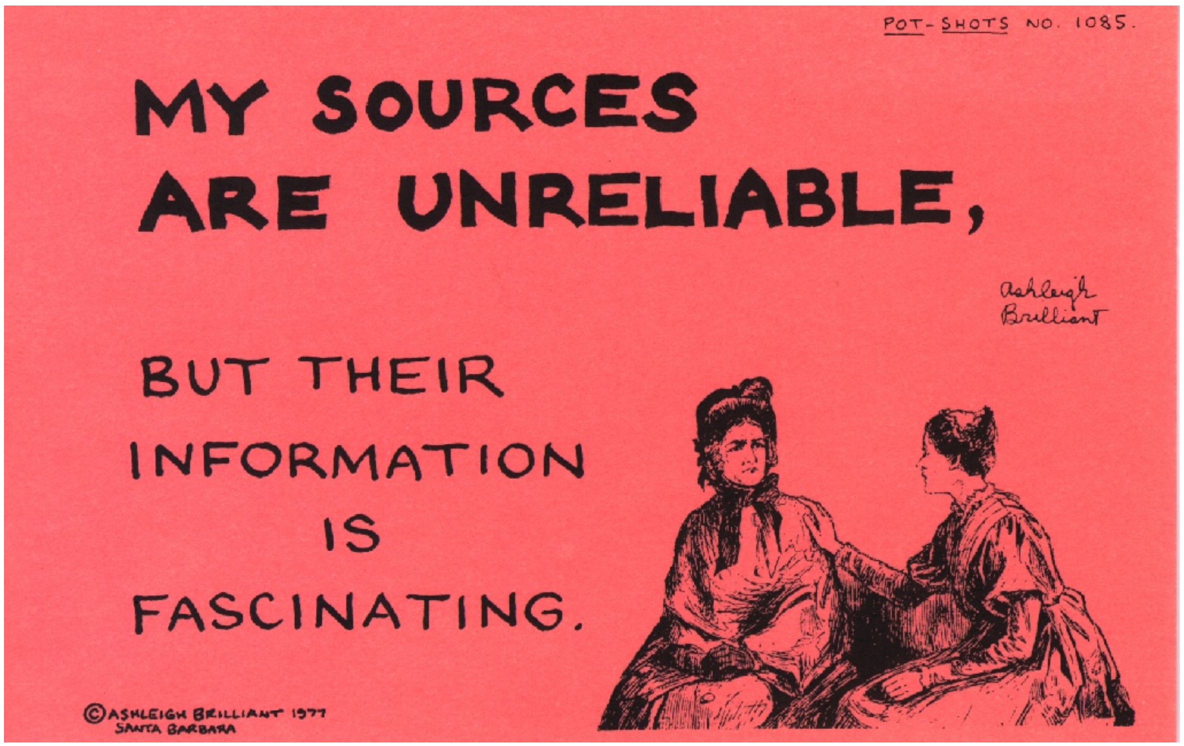
- Keep an open mind about what may be possible — good to challenge each other!

The name of the game

- SM shows impressive consistency — room for large deviations decrease rapidly

Only robust deviations from model independent theory are likely to be interesting

To avoid...



(2σ: 50 theory papers 3σ: 200 theory papers 5σ: strong sign of effect)

The name of the game

- SM shows impressive consistency — room for large deviations decrease rapidly

  Only robust deviations from model independent theory are likely to be interesting

- [strong interaction] model independent $\equiv$ theoretical uncertainty suppressed by small parameters

  ... so theorists argue about $\mathcal{O}(1)\times$(small numbers) instead of $\mathcal{O}(1)$ effects

- Most of the progress have come from expanding in powers of Λ/m_Q, $\alpha_s(m_Q)$

  ... a priori not known whether $\Lambda \sim 200\,\mathrm{MeV}$ or $\sim 2\,\mathrm{GeV}$ $(f_\pi, m_\rho, m_K^2/m_s)$

  ... need experimental guidance to see how well the theory works

"When you have to descend into the brown muck, you abandon all pretense of doing elegant, pristine, first-principles calculations. You have to get your hands dirty with uncontrolled approximations and models. When you are finished with the brown muck you should wash your hands." [H. Georgi, TASI lecture notes, 1991]

The news of the week (year?): LHCb $\to$ LHCc

- The 0.8% direct CPV (even 0.4%) is beyond all sensible SM estimates I know

  What is "sensible"? When the $\Delta I = \frac{1}{2}$ rule is at play, we include the measured ~ 20 enhancement, but only a factor of a few in general (lore, like μ variation)

  It would be "more conservative" to say that we can get arbitrary enhancement, but it's not practical, and even misleading, because it would make many important measurements look uninteresting

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- There will be a flood of model building papers: RPV, flavor off-diagonal Z's, etc.

- The important question is:
  How do we convince ourselves that we do not see a "fluke" like the $\Delta I = \frac{1}{2}$ rule?

- How do we get from: "New physics could show up" $\Longleftrightarrow$ "Must be a sign of NP"

  [We heard these and similar expressions in several talks]

Small and large penguins

Galapagos: 45 cm, 2 kg

Gentoo: 80 cm, 6 kg

Emperor: 1.2 m, 40 kg

Small and large trees

Juniper: 0.1 m, 0.1 kg

Cherry: 10 m, 300 kg

Giant Sequoia: 100 m, 10^6 kg

Can LHCb help to pin down $|V_{ub}|$?

- Gino suggested measuring: $B_s \to K^+\mu^-\nu$ and / or $B_d \to \pi^+\mu^-\nu$

  Definitely interesting — will have to rely on LQCD

  How good can the q^2 resolution get in such decays?

- The theoretically most precise $|V_{ub}|$ determinations I know of:

  use: $\dfrac{f_B}{f_{B_s}} \times \dfrac{f_{D_s}}{f_D}$ — two suppressions; LQCD: 1 within few $\%$ [Grinstein, '93]
  [Constrain SUSY — Nazila]

  $\dfrac{\mathcal{B}(B \to \ell\bar\nu)}{\mathcal{B}(B_s \to \ell^+\ell^-)} \times \dfrac{\mathcal{B}(D_s \to \ell\bar\nu)}{\mathcal{B}(D \to \ell\bar\nu)}$ — may get precise by ~ 2020? [ZL, Ringberg workshop, '03]

  $\dfrac{\mathcal{B}(B_u \to \ell\bar\nu)}{\mathcal{B}(B_d \to \mu^+\mu^-)}$ — only uses isospin [Grinstein, CKM'06]

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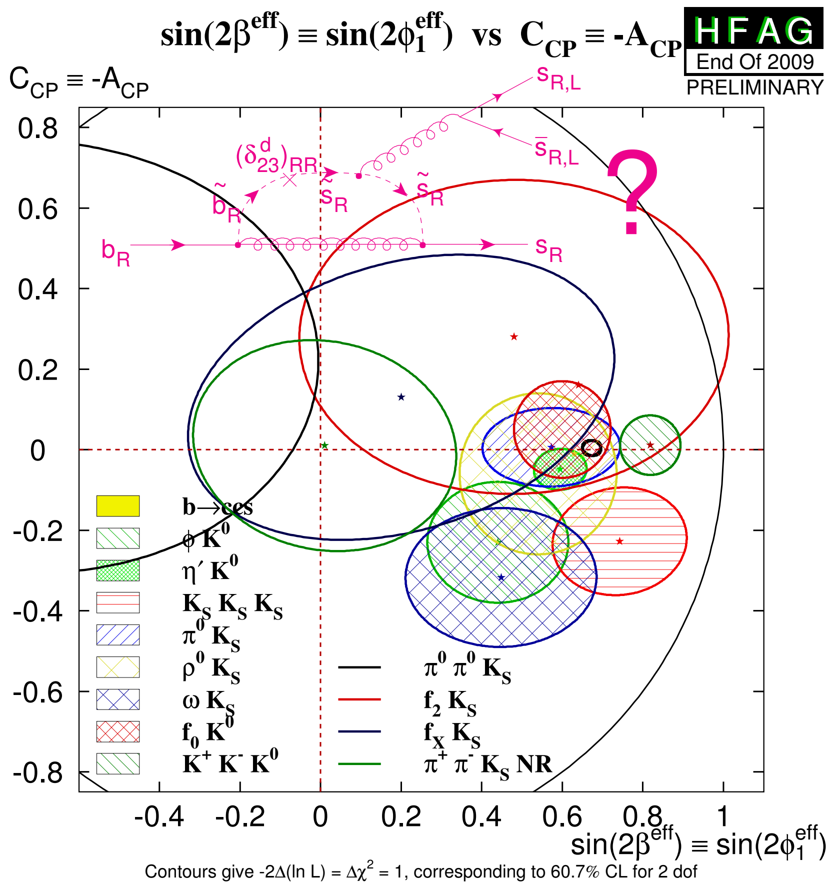
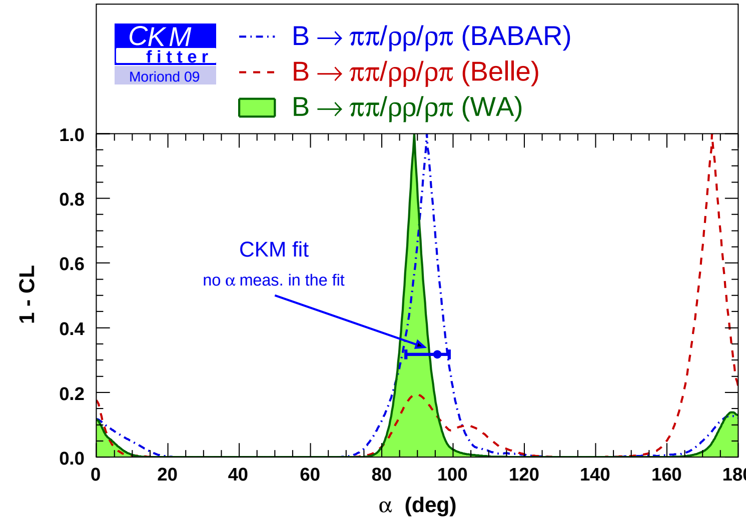
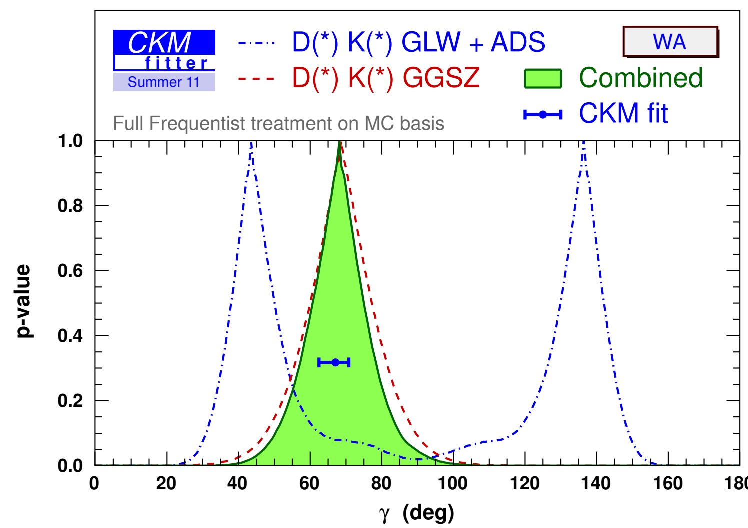
- Need both LHCb and Super-B... keep collecting data during the $28\,\mathrm{TeV}$ run...?

$\sin 2\beta_{\rm eff}$, α, γ — large improvements possible







- Key masurements will benefit from ~ 100 times more data $\Rightarrow$ 10 times smaller error
- Will improve bounds on NP substantially [need both LHCb and super-(KEK-)B]

Only LHCb: γ from $B_s \to D_s^\pm K^\mp$

- Same weak phase in each $B_s, \overline{B}_s \to D_s^\pm K^\mp$ decay $\Rightarrow$ the 4 time dependent rates determine 2 amplitudes, a strong, and a weak phase (clean, although $|f\rangle \neq |f_{CP}\rangle$)

Four amplitudes: $\overline{B}_s \stackrel{A_1}{\to} D_s^+ K^- \quad (b \to c\bar{u}s)\,, \qquad \overline{B}_s \stackrel{A_2}{\to} K^+ D_s^- \quad (b \to u\bar{c}s)$

$$B_s \stackrel{A_1}{\to} D_s^- K^+ \quad (\bar{b} \to \bar{c}u\bar{s})\,, \qquad B_s \stackrel{A_2}{\to} K^- D_s^+ \quad (\bar{b} \to \bar{u}c\bar{s})$$

$$\frac{\overline{A}_{D_s^+ K^-}}{A_{D_s^+ K^-}} = \frac{A_1}{A_2}\left(\frac{V_{cb}V_{us}^*}{V_{ub}^* V_{cs}}\right), \qquad \frac{\overline{A}_{D_s^- K^+}}{A_{D_s^- K^+}} = \frac{A_2}{A_1}\left(\frac{V_{ub}V_{cs}^*}{V_{cb}^* V_{us}}\right)$$

Magnitudes and relative strong phase of A_1 and A_2 drop out if four time dependent rates are measured $\Rightarrow$ no hadronic uncertainty:

$$\lambda_{D_s^+ K^-}\, \lambda_{D_s^- K^+} = \left(\frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*}\right)^2 \left(\frac{V_{cb}V_{us}^*}{V_{ub}^* V_{cs}}\right)\left(\frac{V_{ub}V_{cs}^*}{V_{cb}^* V_{us}}\right) = e^{-2i(\gamma - 2\beta_s - \beta_K)}$$

- Similarly, $B_d \to D^{(*)\pm}\pi^\mp$ determines $\gamma + 2\beta$, since $\lambda_{D^+\pi^-}\, \lambda_{D^-\pi^+} = e^{-2i(\gamma+2\beta)}$
... ratio of amplitudes $\mathcal{O}(\lambda^2)$ $\Rightarrow$ small asymmetries (tag side interference)

Substantial discovery potential in many modes

- Some of the theoretically cleanest modes (ν, τ, inclusive) only possible at e^+e^-
- Many modes first seen at LHCb or super-(KEK-)B
- In some decay modes, even in 2025:

  (Exp. bound)/SM $\gtrsim 10^3$

  (E.g.: $B_{(s)} \to \tau^+\tau^-$ "unlimited" muddle building)

[Grossman, ZL, Nir, arXiv:0904.4262]

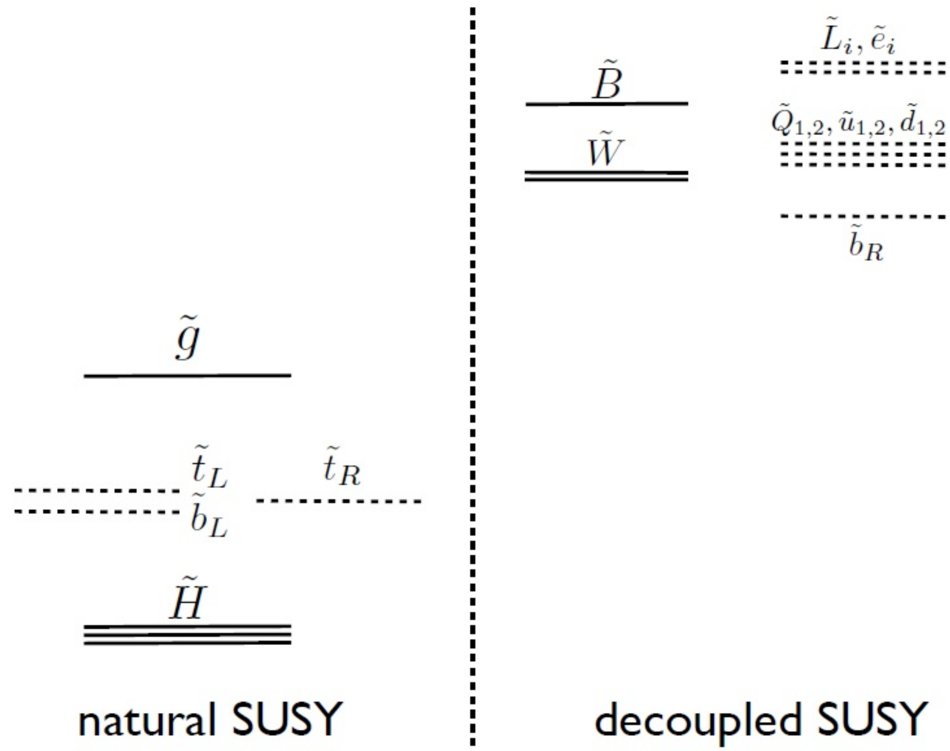
Observable	Approximate SM prediction	Present status	Uncertainty / number of events Super-B (50 ab^{-1})	LHCb (10 fb^{-1})
$S_{\psi K}$	input	0.671 ± 0.024	0.005	0.01
$S_{\phi K}$	$S_{\psi K}$	0.44 ± 0.18	0.03	0.1
$S_{\eta' K}$	$S_{\psi K}$	0.59 ± 0.07	0.02	not studied
$\alpha(\pi\pi, \rho\rho, \rho\pi)$	α	$(89 \pm 4)^\circ$	2°	4°
$\gamma(DK)$	γ	$(70^{+27}_{-30})^\circ$	2°	3°
$S_{K^*\gamma}$	few $\times$ 0.01	-0.16 ± 0.22	0.03	—
$S_{B_s \to \phi\gamma}$	few $\times$ 0.01	—	—	0.05
$\beta_s(B_s \to \psi\phi)$	1°	$(22^{+10}_{-8})^\circ$	—	0.3°
$\beta_s(B_s \to \phi\phi)$	1°	—	—	1.5°
$A_{\rm SL}^d$	-5×10^{-4}	$-(5.8 \pm 3.4) \times 10^{-3}$	10^{-3}	10^{-3}
$A_{\rm SL}^s$	2×10^{-5}	$(1.6 \pm 8.5) \times 10^{-3}$	$\Upsilon(5S)$ run?	10^{-3}
$A_{CP}(b \to s\gamma)$	< 0.01	-0.012 ± 0.028	0.005	—
$\|V_{cb}\|$	input	$(41.2 \pm 1.1) \times 10^{-3}$	1%	—
$\|V_{ub}\|$	input	$(3.93 \pm 0.36) \times 10^{-3}$	4%	—
$B \to X_s\gamma$	3.2×10^{-4}	$(3.52 \pm 0.25) \times 10^{-4}$	4%	—
$B \to \tau\nu$	1×10^{-4}	$(1.73 \pm 0.35) \times 10^{-4}$	5%	—
$B \to X_s\nu\bar\nu$	3×10^{-5}	$< 6.4 \times 10^{-4}$	only $K\nu\bar\nu$?	—
$B \to X_s\ell^+\ell^-$	6×10^{-6}	$(4.5 \pm 1.0) \times 10^{-6}$	6%	not studied
$B_s \to \tau^+\tau^-$	1×10^{-6}	$<$ few %	$\Upsilon(5S)$ run?	—
$B \to X_s\tau^+\tau^-$	5×10^{-7}	$<$ few %	not studied	—
$B \to \mu\nu$	4×10^{-7}	$< 1.3 \times 10^{-6}$	6%	—
$B \to \tau^+\tau^-$	5×10^{-8}	$< 4.1 \times 10^{-3}$	$\mathcal{O}(10^{-4})$	—
$B_s \to \mu^+\mu^-$	3×10^{-9}	$< 5 \times 10^{-8}$	—	$> 5\sigma$ in SM
$B \to \mu^+\mu^-$	1×10^{-10}	$< 1.5 \times 10^{-8}$	$< 7 \times 10^{-9}$	not studied
$B \to K^*\ell^+\ell^-$	1×10^{-6}	$(1 \pm 0.1) \times 10^{-6}$	15k	36k
$B \to K\nu\bar\nu$	4×10^{-6}	$< 1.4 \times 10^{-5}$	20%	—

Flavor information useful in all scenarios

- Simplest bottom-up approach to keep SUSY as natural as possible, in light of ATLAS & CMS constraints

  [Papucci, Ruderman, Weiler, 1110.6926; Brust, Katz, Lawrence, Sundrum, 1110.6670; Kats, Meade, Reece, Shih, 1110.6444; Essig, Izaguirre, Kaplan, Wacker, 1110.6443]

  Can use approximate MFV, GIM, etc., but as first two generations are pushed heavier, typically expect larger breaking, and increasing flavor signals



- Another scenario: LHC sees what looks like GMSB — will want lots of precision tests to understand, at a detailed level, what the underlying theory really is

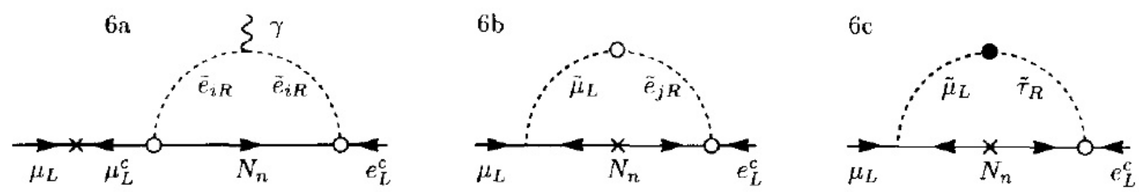
  (As in SM: CPV + absence of $K_L \to \mu\mu \Rightarrow$ GIM & CKM, but decades to establish it with precision)

Charged LFV, search for $\tau \to 3\mu$, etc.

- $\mu \to e\gamma, eee$ vs. $\tau \to \mu\gamma, \mu\mu\mu$

  Very large model dependence

  $\mathcal{B}(\tau \to \mu\gamma)/\mathcal{B}(\mu \to e\gamma) \sim 10^{4\pm3}$



  If a positive signal is seen, it's the tip of an iceberg $\Rightarrow$ trigger broad program

- $\tau^- \to \ell_1^- \ell_2^- \ell_3^+$ (few $\times 10^{-10}$) vs. $\tau \to \mu\gamma$?

  Consider operators: $\bar{\tau}_R \sigma_{\alpha\beta} F^{\alpha\beta} \mu_L, \; (\bar{\tau}_L \gamma^\alpha \mu_L)(\bar{\mu}_L \gamma_\alpha \mu_L)$

  Suppression of $\mu\gamma$ and $\mu\mu\mu$ final states by $\alpha_{\rm em}$ opposite for these two operators $\Rightarrow$ winner is model dependent

sensitivity with $75\,\mathrm{ab}^{-1}$ e^+e^- data

Process	Sensitivity
$\mathcal{B}(\tau \to \mu\,\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to e\,\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to \mu\,\mu\,\mu)$	2×10^{-10}
$\mathcal{B}(\tau \to eee)$	2×10^{-10}

- $\mu \to e\gamma$ and $(g-2)_\mu$ operators are very similar: $\dfrac{m_\mu}{\Lambda^2}\,\bar{\mu}\sigma_{\alpha\beta}F^{\alpha\beta}e\,, \quad \dfrac{m_\mu}{\Lambda^2}\,\bar{\mu}\sigma_{\alpha\beta}F^{\alpha\beta}\mu$

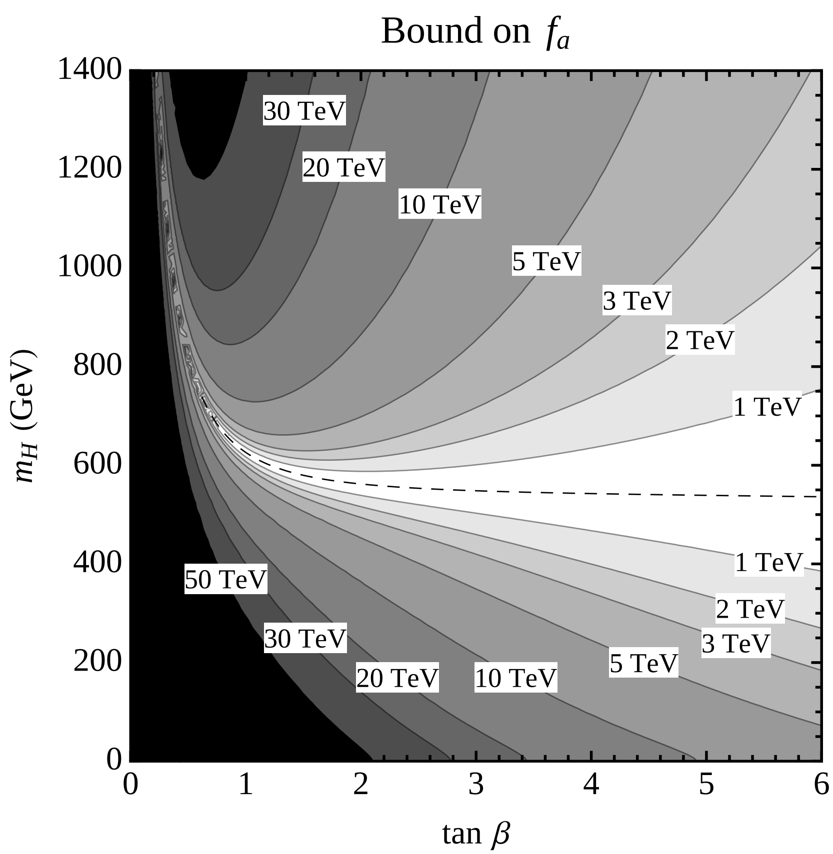
  If coefficients are comparable, $\mu \to e\gamma$ gives much stronger bound already

  If $(g-2)_\mu$ is due to NP, large hierarchy of coefficients ($\Rightarrow$ model building lessons)

"Odd" searches: probe DM models with B decays

- Observations of cosmic ray excesses lead to flurry of DM model building

  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, 0911.5355]

- Best bound in most of parameter space is from $B \to K\ell^+\ell^-$ — can be improved

Interesting hadronic physics

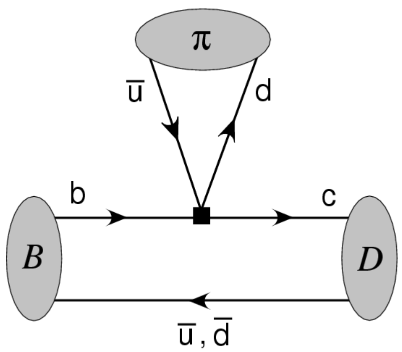
I do care about τ_{Λ_b} — affects how much we trust $\Delta\Gamma_{B_s}$ calculation, etc.

[Will be very brief]

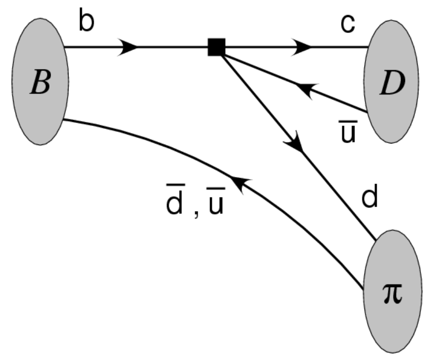
$B \to D^{(*)}\pi$ decays in SCET

- Decays to $\pi^\pm$: proven that leading order prediction is $A \propto \mathcal{F}^{B\to D} f_\pi$ (also large N_c)

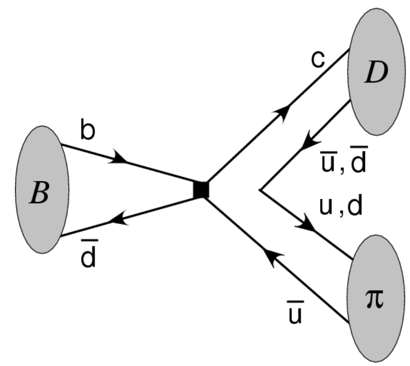
$\overline{B}^0 \to D^+\pi^-$
$B^- \to D^0\pi^-$



$B^- \to D^0\pi^-$
$\overline{B}^0 \to D^0\pi^0$



$\overline{B}^0 \to D^+\pi^-$
$\overline{B}^0 \to D^0\pi^0$



SCET: $\mathcal{O}(1)$ $\qquad$ $\mathcal{O}(\Lambda_{\rm QCD}/Q)$ $\qquad$ $\mathcal{O}(\Lambda_{\rm QCD}/Q)$ $\qquad$ $Q = \{E_\pi, m_{b,c}\}$

- Predictions: $$\frac{\mathcal{B}(B^- \to D^{(*)0}\pi^-)}{\mathcal{B}(\overline{B}^0 \to D^{(*)+}\pi^-)} = 1 + \mathcal{O}(\Lambda_{\rm QCD}/Q)\,,$$

data: $\sim 1.8 \pm 0.2$ (also for ρ)
$\Rightarrow$ $\mathcal{O}(30\%)$ power corrections

[Beneke, Buchalla, Neubert, Sachrajda; Bauer, Pirjol, Stewart]

- Unforeseen: $$\frac{\mathcal{B}(\overline{B}^0 \to D^0\pi^0)}{\mathcal{B}(\overline{B}^0 \to D^{*0}\pi^0)} = 1 + \mathcal{O}(\Lambda_{\rm QCD}/Q)\,,$$

data: $\sim 1.1 \pm 0.25$

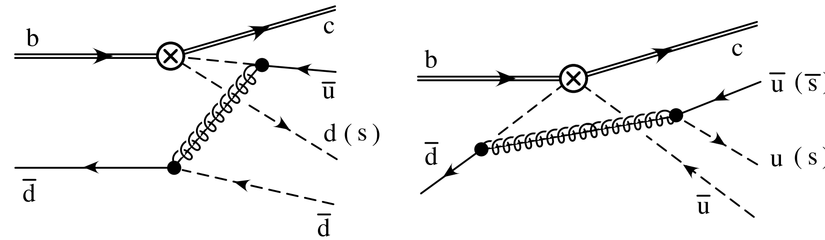
Not even guessed before SCET!

[Mantry, Pirjol, Stewart]

Color suppressed $B \to D^{(*)0}\pi^0$ — cool stuff

- Single class of power suppressed $\mathrm{SCET_I}$ operators: $T\{\mathcal{O}^{(0)}, \mathcal{L}_{\xi q}^{(1)}, \mathcal{L}_{\xi q}^{(1)}\}$

[Mantry, Pirjol, Stewart]



$$A(D^{(*)0}M^0) = N_0^M \int \mathrm{d}z\, \mathrm{d}x\, \mathrm{d}k_1^+ \mathrm{d}k_2^+\, T^{(i)}(z)\, J^{(i)}(z, x, k_1^+, k_2^+)\, \underbrace{S^{(i)}(k_1^+, k_2^+)}_{\text{complex} - \text{nonpert. strong phase}}\, \phi_M(x) + \ldots$$

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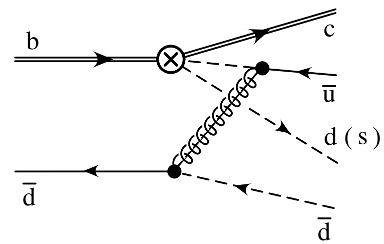
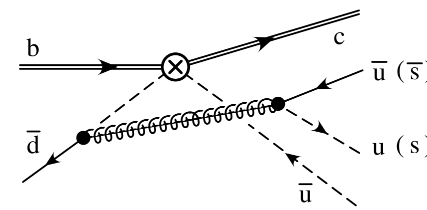
[Mantry, Pirjol, Stewart]





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- Not your garden variety factorization formula... $S^{(i)}(k_1^+, k_2^+)$ know about n

$$S^{(0)}(k_1^+, k_2^+) = \frac{\langle D^0(v')|(\bar h_{v'}^{(c)} S)\, \not{n} P_L (S^\dagger h_v^{(b)})(\bar d S)_{k_1^+}\, \not{n} P_L (S^\dagger u)_{k_2^+} |\bar B^0(v)\rangle}{\sqrt{m_B m_D}}$$

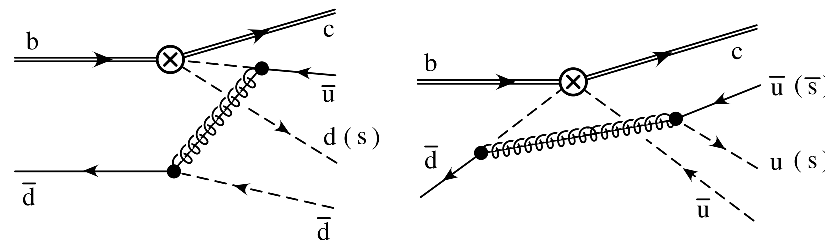
Separates scales, allows to use HQS without $E_\pi/m_c = \mathcal{O}(1)$ corrections

($i = 0, 8$ above)

Color suppressed $B \to D^{(*)0}\pi^0$ — cool stuff

- Single class of power suppressed SCET$_\mathrm{I}$ operators: $T\{\mathcal{O}^{(0)}, \mathcal{L}^{(1)}_{\xi q}, \mathcal{L}^{(1)}_{\xi q}\}$

[Mantry, Pirjol, Stewart]



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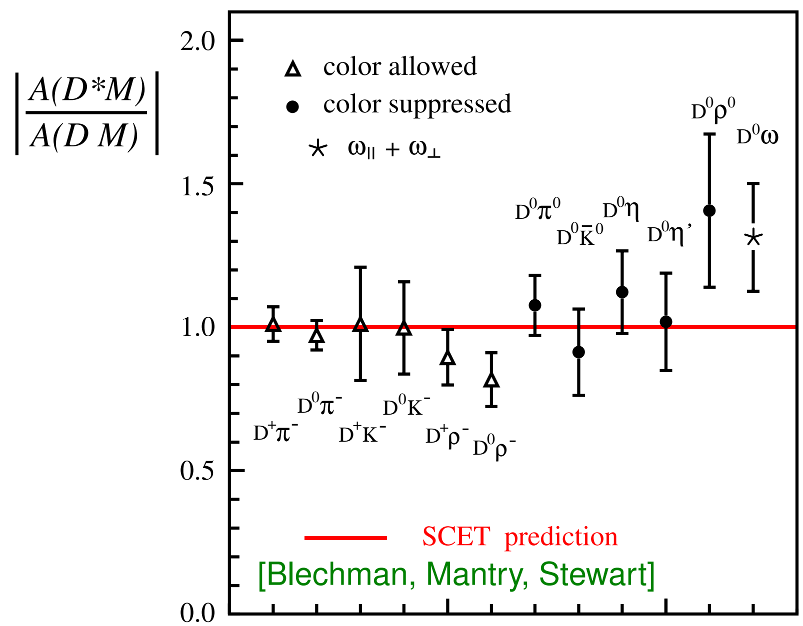
- Ratios: the $\triangle = 1$ relations follow from naive factorization and heavy quark symmetry

The $\bullet = 1$ relations do not — a prediction of SCET not foreseen by model calculations

Also predict equal strong phases between amplitudes to $D^{(*)}\pi$ in $I = 1/2$ and $3/2$

Data: $\delta(D\pi) = (30 \pm 5)^\circ, \;\; \delta(D^*\pi) = (31 \pm 5)^\circ$



Color suppressed $B \to D^{(*)0}\pi^0$ — cool stuff

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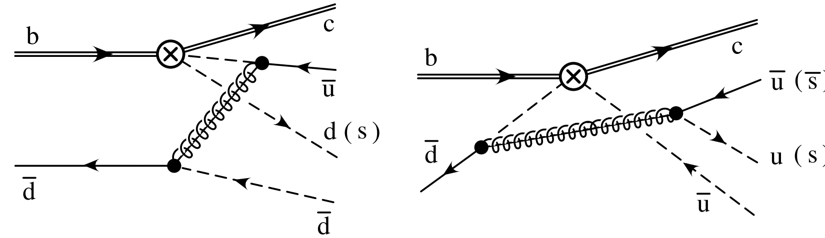
[Mantry, Pirjol, Stewart]



$$A(D^{(*)0}M^0) = N_0^M \int \mathrm{d}z\, \mathrm{d}x\, \mathrm{d}k_1^+ \mathrm{d}k_2^+\, T^{(i)}(z)\, J^{(i)}(z, x, k_1^+, k_2^+)\, \underbrace{S^{(i)}(k_1^+, k_2^+)}_{\text{complex}\,-\,\text{nonpert. strong phase}}\, \phi_M(x) + \ldots$$

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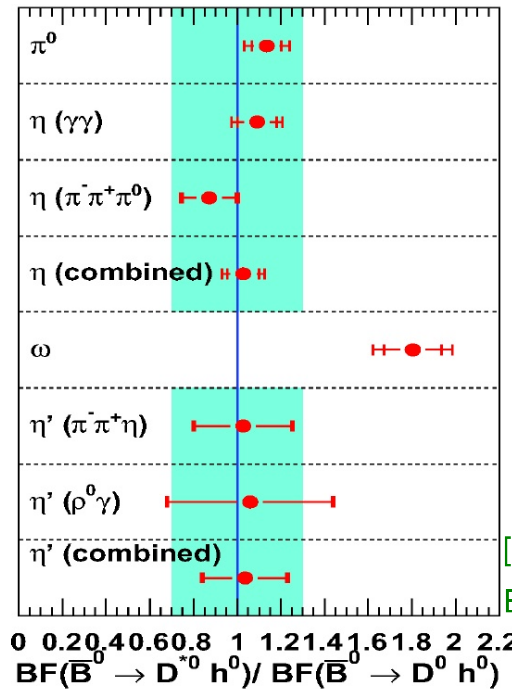
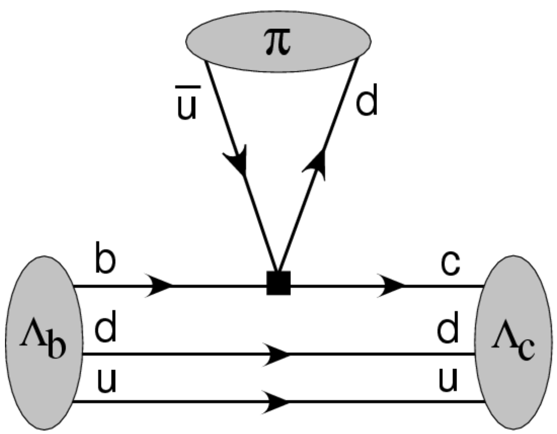


(understood)

[A. Gaz, BaBar, EPS-HEP 2011]

Λ_b and B_s decays

- CDF measured in 2003: $\Gamma(\Lambda_b \to \Lambda_c^+ \pi^-)/\Gamma(\overline{B}^0 \to D^+\pi^-) \approx 2$



Factorization does not follow from large N_c, but holds at leading order in $\Lambda_{\rm QCD}/Q$

$$\frac{\Gamma(\Lambda_b \to \Lambda_c \pi^-)}{\Gamma(\overline{B}^0 \to D^{(*)+}\pi^-)} \simeq 1.8 \left(\frac{\zeta(w_{\rm max}^{\Lambda})}{\xi(w_{\rm max}^{D^{(*)}})} \right)^2$$

[Leibovich, ZL, Stewart, Wise]

Isgur-Wise functions may be expected to be comparable

Lattice could nail this

- $B_s \to D_s \pi$ is pure tree, can help to determine relative size of E vs. C

[CDF '03: $\mathcal{B}(B_s \to D_s^- \pi^+)/\mathcal{B}(B^0 \to D^-\pi^+) \simeq 1.35 \pm 0.43$ (using $f_s/f_d = 0.26 \pm 0.03$)]

Lattice could help: Factorization relates tree amplitudes, need $SU(3)$ breaking in $B_s \to D_s \ell \bar\nu$ vs. $B \to D\ell\bar\nu$ form factors from exp. or lattice

More complicated: $\Lambda_b \to \Sigma_c \pi$

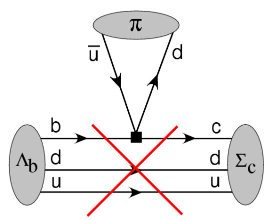
- Recall quantum numbers:

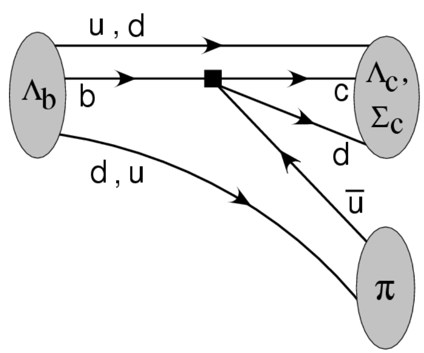
multiplets	s_l	$I(J^P)$
Λ_c	0	$0(\frac{1}{2}^+)$
$\Sigma_c,\ \Sigma_c^*$	1	$1(\frac{1}{2}^+),\ 1(\frac{3}{2}^+)$

$$\Sigma_c = \Sigma_c(2455),\ \Sigma_c^* = \Sigma_c(2520)$$

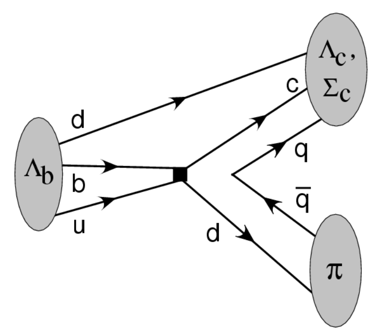
[Leibovich, ZL, Stewart, Wise, hep-ph/0312319]

- Can't address in naive factorization, since $\Lambda_b \to \Sigma_c$ form factor vanishes by isospin





$\mathcal{O}(\Lambda_{\rm QCD}/Q)$



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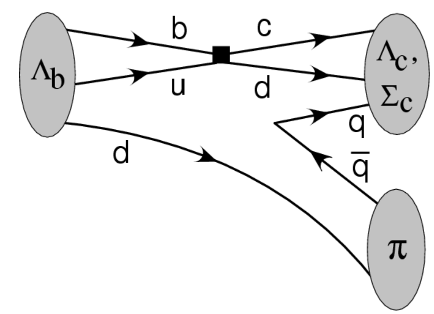


$\mathcal{O}(\Lambda_{\rm QCD}^2/Q^2)$

- Prediction: $$\frac{\Gamma(\Lambda_b \to \Sigma_c^* \pi)}{\Gamma(\Lambda_b \to \Sigma_c \pi)} = 2 + \mathcal{O}\big[\Lambda_{\rm QCD}/Q\,,\ \alpha_s(Q)\big] = \frac{\Gamma(\Lambda_b \to \Sigma_c^{*0} \rho^0)}{\Gamma(\Lambda_b \to \Sigma_c^0 \rho^0)}$$

Only charged particles in ratio on r.h.s. — measurable? $(\Sigma_c^{(*)0} \to \Lambda_c \pi^-,\ \rho^0 \to \pi^- \pi^+)$

Final comments

A personal concern

- As the possibilities of large deviations from SM are being cornered, understanding systematic effects will become important to be able to claim BSM discovery

  Clear history of constructive competitions: BaBar – Belle, LEP experiments, CLEO – Argus

  In many cases cross-checks are possible (with super-B for some angles, penguins, etc., and maybe ATLAS/CMS for $B_s \to \mu\mu$)

- In many key B_s measurements, LHCb will be without cross-checks

Conclusions

- Consistency of precision flavor measurements with SM is a problem for NP @ TeV
  However, new physics in most FCNC processes may still be $\gtrsim 20\%$ of the SM
- Few hints of discrepancies — hopefully LHCb will confirm some and find new ones (theoretical uncertainties won't be limiting in many cases)
- Low energy tests will improve a lot in next decade, by 10–1000 in some channels
  Exploring influence of NP requires LHCb, super-B, K, lepton flavor violation
- If LHC discovers "only" the Higgs, precision measurements are the only possibility to show the way ahead (sensitive to $\gg \mathrm{TeV}$), and point to the next energy scale
- If new particles are discovered, their flavor properties will be important to understand the underlying physics in all scenarios
- We shall learn an incredible amount in the next decade!

Let’s thank

Fredric, Gilad, Guy, John, Tim

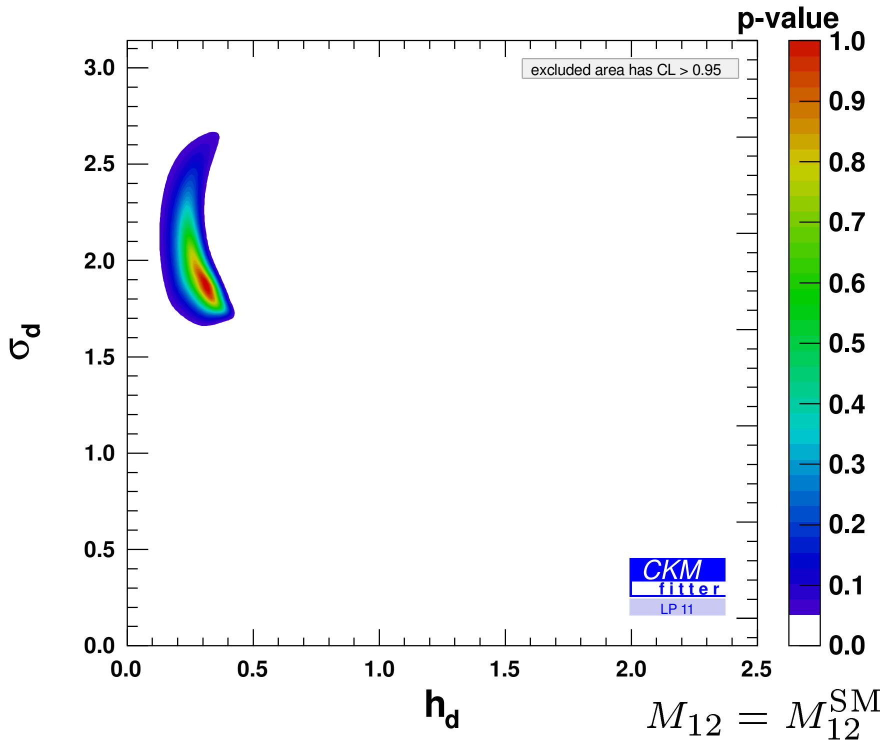
for organizing a very

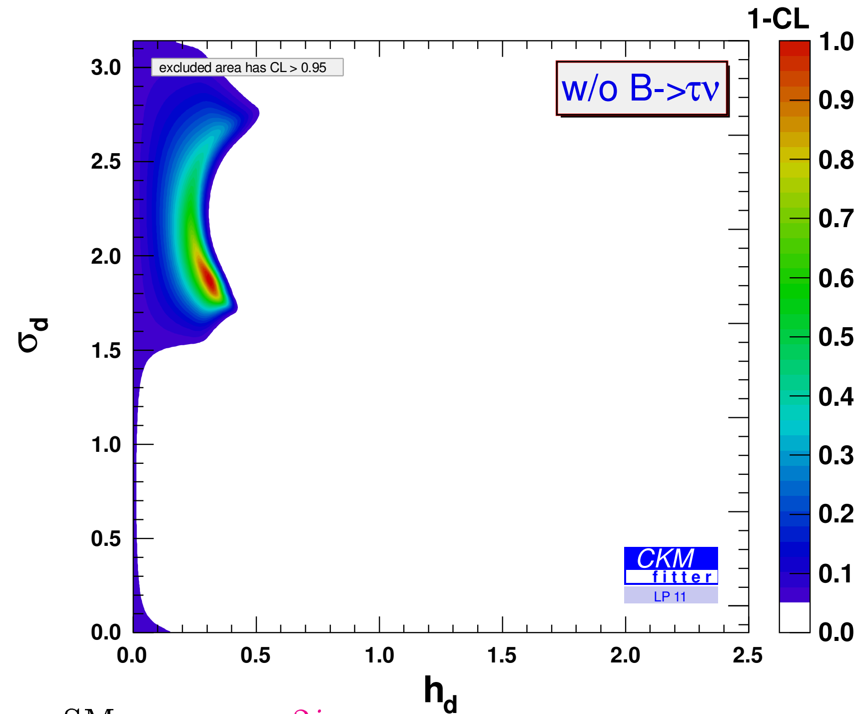
enjoyable workshop!

Backup slides

B_d: does $B \to \tau\nu$ hint at BSM?

- The 2011 update (note the different scales!); change mostly due to $A^b_{\rm SL}$ from DØ





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

(From a 4-parameter fit with NP in both $B_{d,s}$, projected on 2-d)

A super-(KEK-)B best buy list

- Include observables: (i) sensitive to different NP, (ii) measurements can improve order of magnitude, (iii) not limited by hadronic uncertainties
  - Difference of CP asymmetries, $S_{\psi K_S} - S_{\phi K_S}$
  - γ from CP asymmetries in tree-level decays vs. γ from $S_{\psi K_S}$ and $\Delta m_d / \Delta m_s$
  - Search for charged lepton flavor violation, $\tau \to \mu\gamma$, $\tau \to 3\mu$, and similar modes
  - Search for CP violation in $D^0 - \overline{D}^0$ mixing
  - CP asymmetry in semileptonic decay (dilepton asymmetry), $A_{\rm SL}$
  - CP asymmetry in the radiative decay, $S_{K^*\gamma}$
  - Rare decay searches and refinements: $b \to s\nu\bar{\nu}$, $B \to \tau\bar{\nu}$, etc.
- Complementary to LHCb
- Any one of these measurements has the potential to establish new physics