Lattice QCD meets BSM

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Lattice QCD Meets Experiment Workshop
Fermilab, Dec 10–11, 2007

- Introduction
- "Straightforward" — doable today?
  One stable initial/final hadron, neither fast
- "More challenging" $\Rightarrow$ need new developments
  Finite width, large velocities, nonlocal matrix elements, more than one hadrons
- Conclusions

USQCD US Lattice Quantum Chromodynamics

How to look for new physics?

- Approach 1: Make overconstraining SM measurements, look for inconsistencies

  + Refining ϵ_K, $\Delta m_{d,s}$, $|V_{ub}|$, etc., is an important way to look for NP

  – Processes uninteresting in the SM can be important (null obs., unrelated to UT)

  – Enhanced sensitivity in less precise measurements (e.g., $B \to D^{(*)} \tau\nu$)

  – NP may yield operators absent in SM (e.g., O_7' giving $S_{K^*\gamma}$)

- Approach 2: Compare specific NP model predictions with data

  – Model dependent (redo when measurements and hadronic inputs improve?)

  – What is the right set of models whose effects we are after?

- This talk: some topics missed if only aiming to improve SM measurements

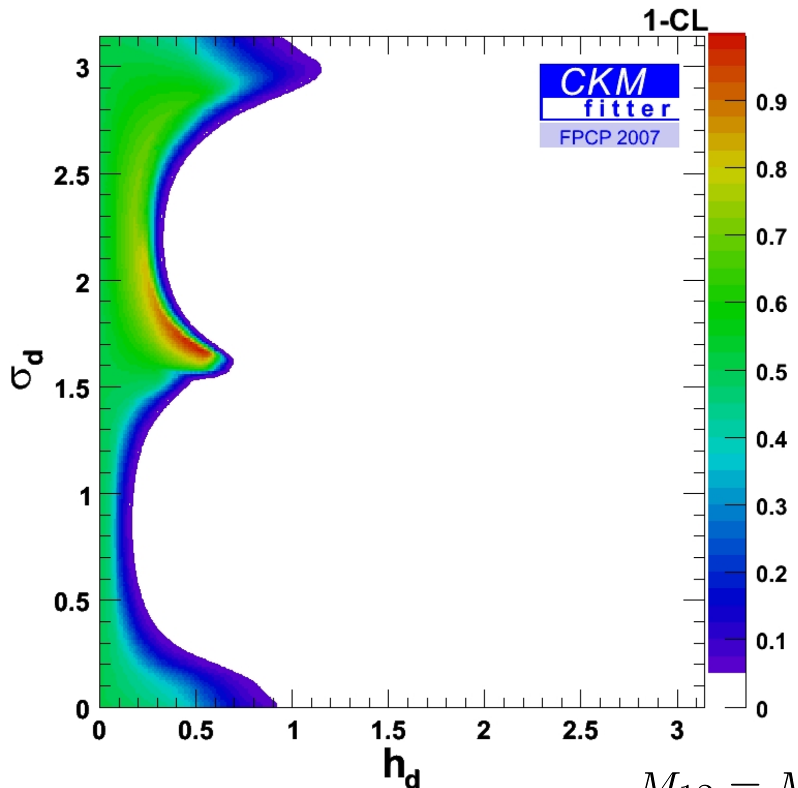
  [$\mathcal{O}(20\%)$ non-SM contributions to most loop-mediated transitions are still allowed]

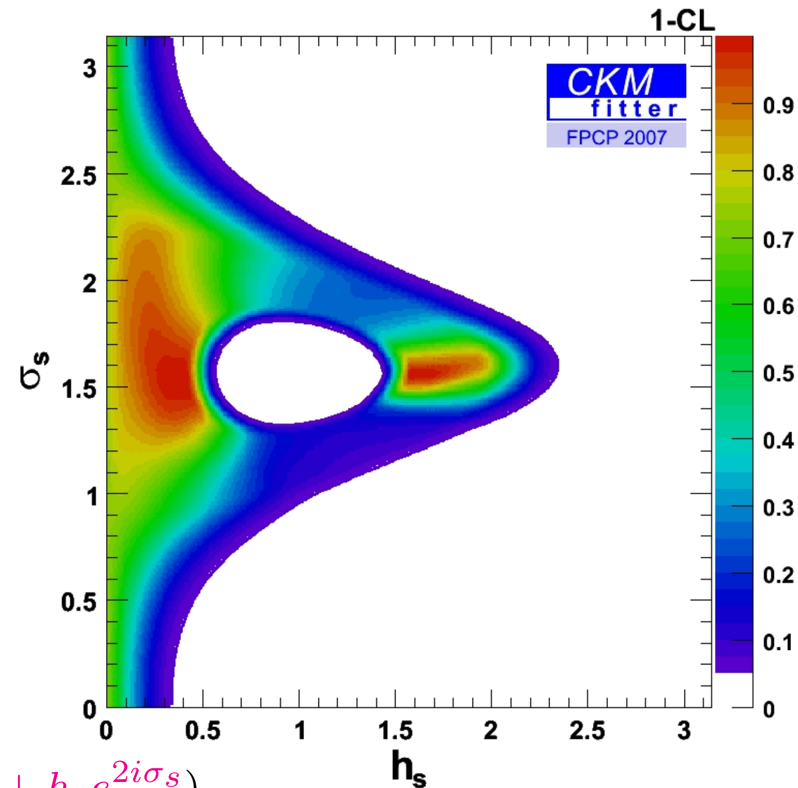
Not included in this talk

- Important, but maybe too far off-shell:
  - Proton decay matrix elements
  - $D^0 - \overline{D}^0$ mixing parameters $(\Delta m_D,\ \Delta\Gamma_D)$
  - Long distance contribution to Δm_K (part not $\propto B_K$)
  - Many nonleptonic decay matrix elements would make huge impact
    E.g., for measurement of γ or α, etc.
- Important model building topics:
  - SUSY and SUSY breaking from the lattice
  - Conformal window in (walking) technicolor
    such regions and S & T in (partly) composite Higgs models, ...
- Disclaimer: may be more glory in making progress on topics skipped than covered

New physics in $B_{d,s}$ mixing — plenty of room

- Many models: (i) 3×3 CKM matrix unitary; (ii) Tree-level decays dominated by SM





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

B_d: NP $\sim$ SM still allowed; approaching NP $\ll$ SM unless $\sigma_d = 0$ (mod $\pi/2$)

B_s: LHCb will probe NP at a level comparable to B_d sector now

Straightforward (?)

One stable hadron in initial and final states with small velocities

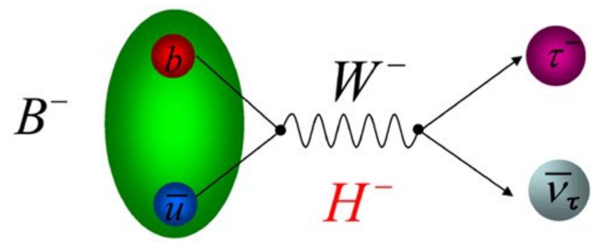
Decay constants

- Leptonic decays: $\Gamma(M^- \to \ell^- \bar{\nu}_\ell) = \frac{G_F^2}{8\pi} |V_{q_u q_d}|^2 f_M^2 \, m_M \, m_\ell^2 \left(1 - \frac{m_\ell^2}{m_M^2}\right)^2$

  Need decay constants: $i p_\mu f_M = \langle 0 | \, \bar{q}_u \, \gamma_\mu \gamma_5 \, q_d \, | M(p) \rangle$

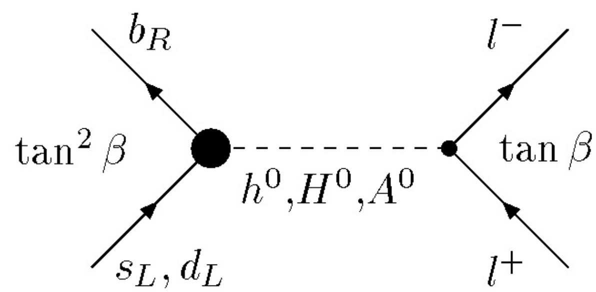
- Charged Higgs contribution: $(\bar{u}_L b_R)(\bar{\ell}_R \nu_L)$

  Using eqm: $\langle 0 | \, \bar{u} \gamma_5 b \, | B^- \rangle = -i f_B \frac{m_B^2}{\overline{m}_b + \overline{m}_u}$



- A recent SUSY favorite: $\mathcal{B}(B_s \to \mu^+ \mu^-) \propto \tan^6 \beta + \ldots$

  ... determined by: $\langle 0 | \, \bar{s}_L \, b_R \, | \bar{B}_s^0 \rangle = -i f_{B_s} \frac{m_{B_s}^2}{\overline{m}_b + \overline{m}_s}$



- Only case where non-SM current matrix elements need not be computed directly?

  (We'll come back to this for light mesons and factorization...)

Tree-level determination of UT: $|V_{ub}|$

- Side opposite to β; precision crucial to be sensitive to NP in $\sin 2\beta$ via mixing

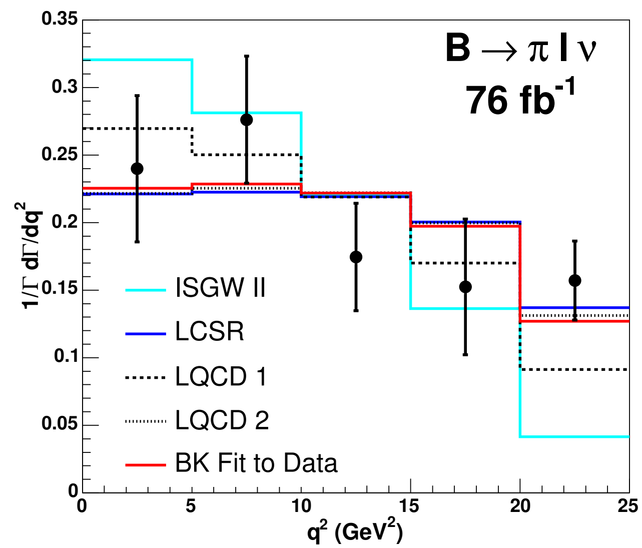
  Lattice appears focused (exclusively?) on exclusive $B \to \pi \ell \bar{\nu}$ mode

  LQCD crucial — less constraints from heavy quark symmetry than in $B \to D^{(*)} \ell \bar{\nu}$

- Exclusive: $$\frac{d\Gamma(\overline{B}^0 \to \pi^+ \ell \bar{\nu})}{dq^2} = \frac{G_F^2 |\vec{p}_\pi|^3}{24\pi^3} |V_{ub}|^2 \, |f_+(q^2)|^2$$

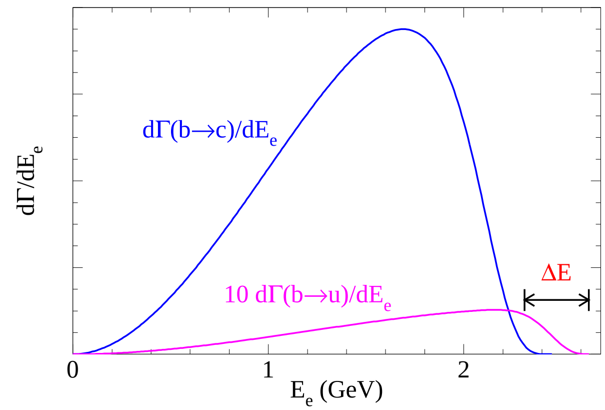
- Lattice QCD crucial to determine $f_+(q^2)$ under better control at large q^2 (small $|\vec{p}_\pi|$)

- Continuum input: analyticity constraint on shape using a few $f_+(q^2)$ values



Tree-level determination of UT: $|V_{ub}|$

- So important, want $|V_{ub}|$ many ways to be sure



- Inclusive: rate known to $\sim 5\%$; cuts to remove $B \to X_c \ell \bar{\nu}$

  Nonperturbative b distribution function ("shape function")

  Related to $\mathrm{d}\Gamma(B \to X_s \gamma)/\mathrm{d}E_\gamma$ — issues at next order

- Weak annihilation is important uncertainty hard to quantify

$$O_{V-A} = (\bar{b}\gamma^\mu P_L u)(\bar{u}\gamma_\mu P_L b), \qquad O_{S-P} = (\bar{b}P_L u)(\bar{u}P_L b)$$

  Need: $\langle B|O_{V-A} - O_{S-P}|B\rangle = B_2 - B_1$ usual assumption: $|B_2 - B_1| < 0.1$

- Any way to control cancellation? (both are $1 +$ small corrections)

- How strong is the suppression of $(B_2 - B_1)_{B_d}$ compared to $(B_2 - B_1)_{B_u}$?

  Also important for $B \to X_s \ell^+ \ell^-$ (see later)

Other ways to get $|V_{ub}|$

- $\mathcal{B}(B \to \ell\bar\nu)$ measures $f_B \times |V_{ub}|$ — need f_B from lattice
- "Grinstein-type double ratio" inspired ideas (HQS / chiral symmetry suppressions)
  - $\dfrac{f_B}{f_{B_s}} \times \dfrac{f_{D_s}}{f_D}$ — lattice: double ratio $= 1$ within few $\%$ [Grinstein '93]
  - $\dfrac{f^{(B\to\rho\ell\bar\nu)}}{f^{(B\to K^*\ell^+\ell^-)}} \times \dfrac{f^{(D\to K^*\ell\bar\nu)}}{f^{(D\to\rho\ell\bar\nu)}}$ or q^2 spectra — accessible soon? [ZL, Wise; Grinstein, Pirjol]

    CLEO-C $D \to \rho\ell\bar\nu$ data still consistent with no $SU(3)$ breaking in form factors [ZL, Stewart, Wise]

    Could lattice do more to pin down the corrections?

    Worth looking at similar ratio with K, π — role of B^* pole...?
  - $\dfrac{\mathcal{B}(B \to \ell\bar\nu)}{\mathcal{B}(B_s \to \ell^+\ell^-)} \times \dfrac{\mathcal{B}(D_s \to \ell\bar\nu)}{\mathcal{B}(D \to \ell\bar\nu)}$ — very clean... after 2015? [Ringberg workshop, '03]
  - $\dfrac{\mathcal{B}(B_u \to \ell\bar\nu)}{\mathcal{B}(B_d \to \mu^+\mu^-)}$ — even cleaner... ever possible? [Grinstein, CKM'06]

$B \to D^{(*)}\tau\bar{\nu}$: massive leptons

- $\mathcal{B}(B \to D^*\tau\bar{\nu}) = \begin{cases} (2.02^{+0.40}_{-0.37} \pm 0.37)\% & \text{[Belle, arXiv:0706.4429]} \\ (1.62 \pm 0.31 \pm 0.10 \pm 0.05)\% & \text{[BaBar arXiv:0709.1698]} \end{cases}$

  $\mathcal{B}(B \to D\tau\bar{\nu}) = (0.86 \pm 0.24 \pm 0.11 \pm 0.06)\%$ [BaBar arXiv:0709.1698]

  For each decay, there is a form factor $\propto q_\mu$ which does not contribute for $\ell = e,\ \mu$

- HQS $\Rightarrow$ relations between all form factors

  Much smaller efficiency due to τ's $\Rightarrow$ want to use full rate, not just zero recoil limit

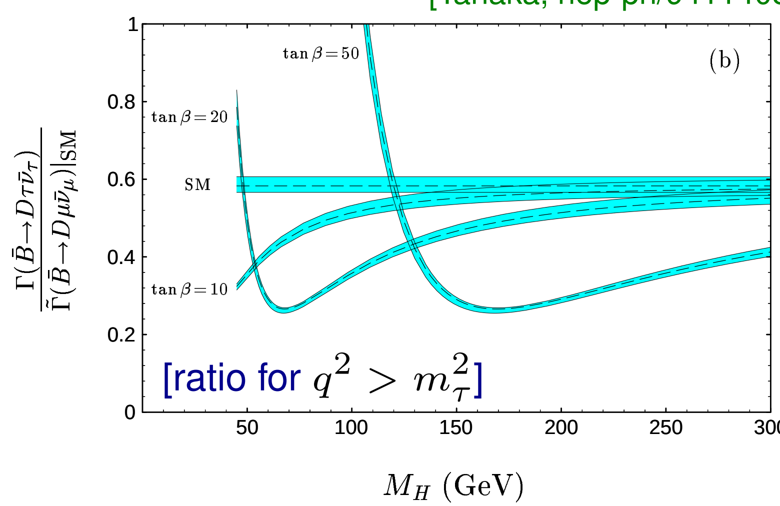
  Lattice: want as much info on form factors as possible, besides $w = 1$, slope ($w_{\max} = 1.43$)

  (I would not directly simulate non-SM currents)

- Obvious need to recast analyticity constraints for $B \to D\tau\bar{\nu}$ rate (both form factors)

$H^\pm$ does not contribute to transverse D^*, so $D\tau\nu$ more sensitive

[Tanaka, hep-ph/9411405]

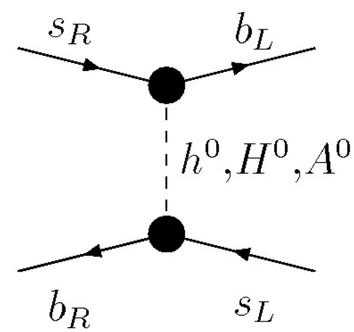


Sensitive to $\tan\beta/m_{H^\pm} \gtrsim 0.1$ or less

Bag parameters: Δm_B, $\Delta\Gamma_B$, $A_{\rm SL}^{s,d}$, lifetimes

- $|M_{12}|$ is short distance dominated; OPE for $|\Gamma_{12}|$, $\mathrm{Im}(\Gamma_{12}/M_{12})$, and lifetimes
- Δm_B: need $\langle \overline{B}|(\bar b d)_{V-A}(\bar b d)_{V-A}|B\rangle = \frac{8}{3} m_B^2 f_B^2 B_B$

  Recently: SUSY at large $\tan\beta$: suppression of $\Delta m_s \propto \tan^4\beta$



- In general, many operators:

  [Buras, Jager, Urban hep-ph/0102316]

  [Becirevic *et al.*, hep-lat/0110091]

$$\begin{aligned}
O_1 &= \bar b^i \gamma_\mu (1-\gamma_5) q^i\, \bar b^j \gamma_\mu (1-\gamma_5) q^j\,, \\
O_2 &= \bar b^i (1-\gamma_5) q^i\, \bar b^j (1-\gamma_5) q^j\,, \\
O_3 &= \bar b^i (1-\gamma_5) q^j\, \bar b^j (1-\gamma_5) q^i\,, \\
O_4 &= \bar b^i (1-\gamma_5) q^i\, \bar b^j (1+\gamma_5) q^j\,, \\
O_5 &= \bar b^i (1-\gamma_5) q^j\, \bar b^j (1+\gamma_5) q^i\,,
\end{aligned}$$

- $\Delta\Gamma$ & $A_{\rm SL}$: In addition to B_B, need $\langle \overline{B}|(\bar b d)_{S-P}(\bar b d)_{S-P}|B\rangle = -\frac{5}{3} m_B^2 \frac{m_B^2}{(m_b+m_d)^2} f_B^2 B_S$

  At order $1/m$, additional operators involving $\overleftarrow{D}_\alpha D^\alpha$ [Beneke, Buchalla, Dunietz, hep-ph/9605259]

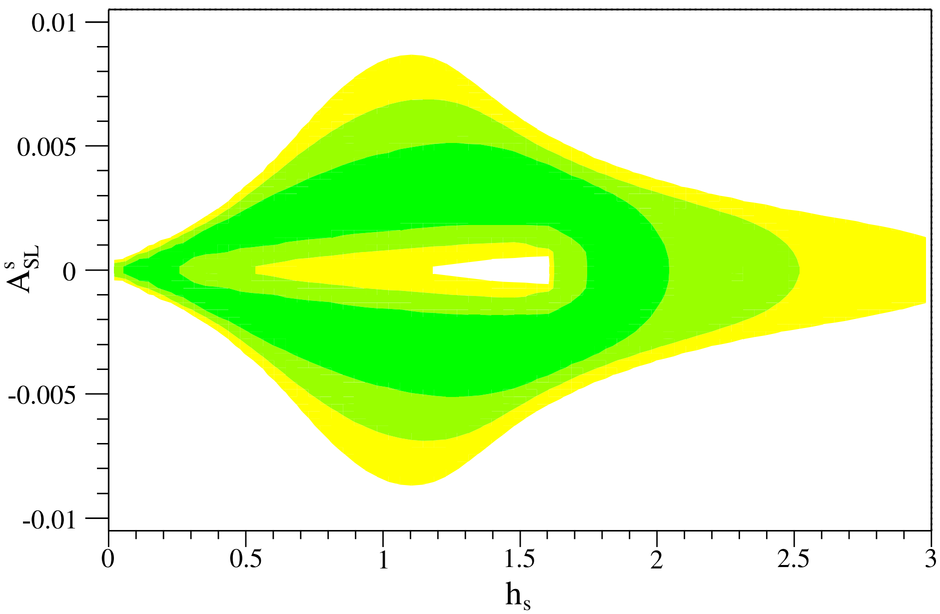
  Not sure if any groups tried to compute them — vacuum saturation is used

- Lifetimes: same theory as $\Delta\Gamma_B$ & $A_{\rm SL}^{s,d}$, except $\langle B|\ldots|B\rangle$ vs. $\langle \overline{B}|\ldots|B\rangle$ $(\tau_{\Lambda_b}?)$

CPV in B_s mixing: correlation of $S_{\psi\phi}$ and A_{SL}^s

- In SM: $A_{\mathrm{SL}}^s \sim 3\times10^{-5}$ is not observable

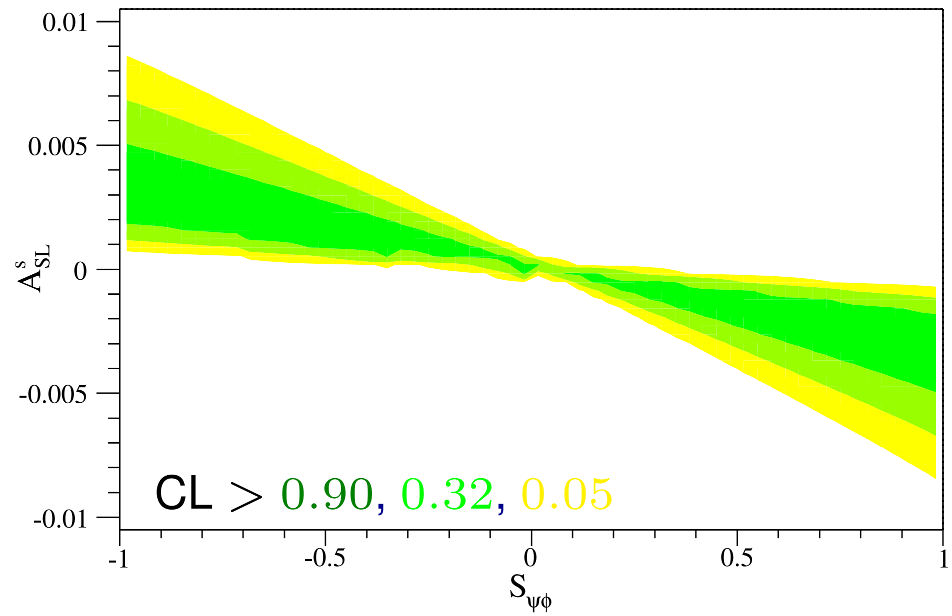
$$\frac{\Gamma[\overline{B}^0(t) \to \ell^+ X] - \Gamma[B^0(t) \to \ell^- X]}{\Gamma[\overline{B}^0(t) \to \ell^+ X] + \Gamma[B^0(t) \to \ell^- X]} = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$



– Can be $\mathcal{O}(10^3)$ times SM

– $|A_{\mathrm{SL}}^s| > |A_{\mathrm{SL}}^d|$ possible (unlike SM)

If large NP in B_s mixing $\Rightarrow$ A_{SL}^s and $S_{\psi\phi}$ are strongly correlated [ZL, Papucci, Perez]



$$A_{\mathrm{SL}}^s = -\left|\frac{\Gamma_{12}^s}{M_{12}^s}\right|^{\mathrm{SM}} S_{\psi\phi} + \mathcal{O}\left(h_s^2,\, \frac{m_c^2}{m_b^2}\right)$$

Lattice can help reduce uncertainties

Getting tougher...

Hadrons with non-negligible widths (ρ, K^*)

Heavy-to-light at small q^2

$B \to \rho\gamma$ and $K^*\gamma$

- First not fully hadronic FCNC $b \to d$ decay (B^0 ratio cleaner than $B^\pm$):

$$\frac{\Gamma(B^+ \to \rho^+\gamma) + 2\Gamma(B^0 \to \rho^0\gamma)}{\Gamma(B^+ \to K^{*+}\gamma) + \Gamma(B^0 \to K^{*0}\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{1}{\xi_\gamma^2} = (2.96 \pm 0.57)\% \quad \text{(exp)}$$

In SM just another way to get $|V_{td}/V_{ts}|$; different sensitivity to NP than $\Delta m_d/\Delta m_s$

Sizable uncertainties: using $\xi_\gamma = 1.2 \pm 0.2$ (made up...) $\Rightarrow |V_{td}/V_{ts}| = 0.21 \pm 0.04$

…sometimes smaller errors are quoted from QCD sum rules

- Can LQCD address some of the uncertainties?

– $SU(3)$-breaking in form factors at $q^2 = 0$?

– How about annihilation? (Saw in inclusive: OPE, given by local matrix elements)

Would need matrix elements of the form: $\langle\rho\gamma|\, T\{[(\bar b u)(\bar u d)]\, J_{\rm em}\}\, |B_{u,d}\rangle$

$B \to K^{(*)}\ell^+\ell^-$ and $X_s\ell^+\ell^-$

- Sensitive besides O_7 to $O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$ and $O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5 \ell)$
  H_{eff} and inclusive rate calculated to NNLO [Many authors: Bobeth, Misiak, Urban, Munz, Gambino, Gorbahn, Haisch, Asatryan, Asatrian, Bieri, Hovhannisyan, Greub, Walker, Ghinculov, Hurth, Isidori, Yao, etc.]

- At LHCb, exclusive $B \to K^{(*)}\ell^+\ell^-$, $\pi\ell^+\ell^-$, $\rho\ell^+\ell^-$ may give best sensitivity... if form factors are known precisely enough

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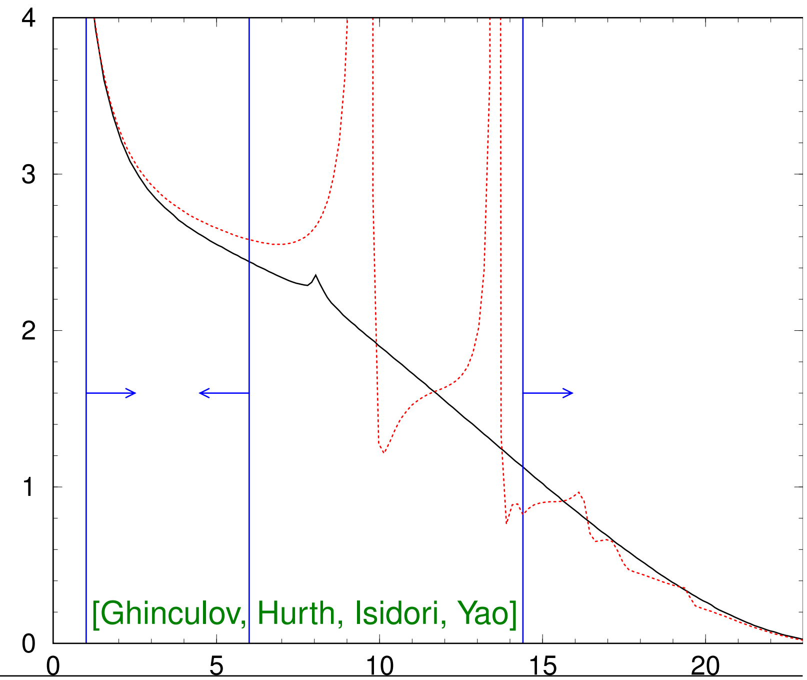
- Inclusive: high precision only if ∃ super-b

  Not inconceivable that large q^2 region is measurable at LHCb semi-inclusively

- Large q^2: rate becomes precise by taking ratio with $B \to X_u \ell\bar{\nu}$; weak annihilation (B_s vs. B_u matrix element) may become a dominant uncertainty [ZL & Tackmann, arXiv:0707.1694]

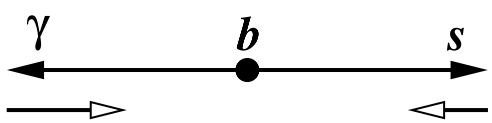


Left vs. right

- SM: $O_7 = \bar{s}\,\sigma_{\mu\nu}F^{\mu\nu}(\overline{m}_b P_R + \overline{m}_s P_L)\,b$ NP: $O_7' = \bar{s}\,\sigma_{\mu\nu}F^{\mu\nu}(\overline{m}_b P_L + \overline{m}_s P_R)\,b$

With O_7 only, photon must be left-handed to conserve J_z along decay axis

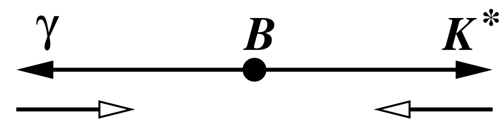
Inclusive $B \to X_s\gamma$



Assumption: 2-body decay

Does not apply for $b \to s\gamma g$

Exclusive $B \to K^*\gamma$



... quark model (s_L implies $J_z^{K^*} = -1$)

... higher K^* Fock states

[Atwood, Gronau, Soni; Grinstein, Grossman, ZL, Pirjol]

$$S_{K^*\gamma} = -2\,(\overline{m}_s/\overline{m}_b + C_7'/C_7)\,\sin 2\beta + \mathcal{O}(\Lambda_{\rm QCD}/m_b) = -0.19 \pm 0.23$$ (exp)

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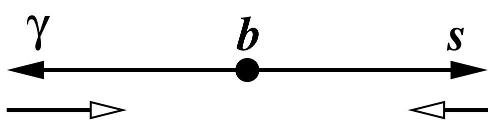

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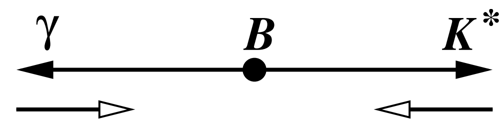

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Now... what does this have to do with LQCD...?

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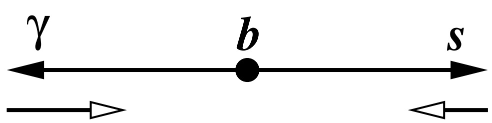
  Inclusive $B \to X_s\gamma$



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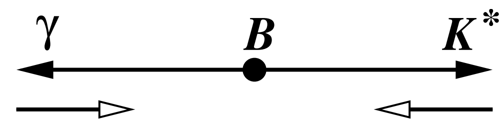

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- At LHCb $S_{K^*\gamma}$ impossible $\Rightarrow$ study $B \to K^*\ell^+\ell^-$ angular distributions ($K\ell^+\ell^-$ no good) at small q^2 — precise form factors are necessary for good sensitivity

Nonleptonic decays

- SCET provides an effective theory framework to analyze many decays of interest

  More work & data needed to understand the expansions

  Why some predictions work at $\lesssim 10\%$ level, while others receive $\gtrsim 30\%$ corrections

- LQCD can help even without addressing hardest questions:

  – Light quark masses: "chirally (non-)enhanced" $\mathcal{O}(\Lambda_{\rm QCD}/m_b)$ terms

  $$\langle 0|\, \bar u \gamma_5 d \,|\pi^-\rangle = -i f_\pi \frac{m_\pi^2}{\overline{m}_d + \overline{m}_u} \quad \text{or try} \quad \frac{\langle 0|\, \bar u \gamma_\mu \gamma_5 d \,|\pi^-\rangle}{\langle 0|\, \bar u \gamma_5 d \,|\pi^-\rangle} = -\frac{p_\mu}{f_\pi} \frac{\overline{m}_d + \overline{m}_u}{m_\pi^2} \;?$$

  – Semileptonic form factors (precision, include ρ and K^*, larger recoil)

  – Light cone distribution functions of heavy and light mesons

  – $SU(3)$ breaking in form factors and distribution functions

  – Moments, e.g., SCET can accomodate $\mathcal{B}(B \to \pi^0\pi^0)$ via $\langle k_+^{-1}\rangle_B = \int \frac{\mathrm{d}k_+}{k_+}\, \phi_B(k_+)$

Final comments

Need sensible averages (e.g., PDG CKM review)

- Need to be conservative: what are the uncertainties such that if predictions and data disagree by $5(3)\sigma$ statistical errors, people would believe it's new physics?

  Need systematic and statistical uncertainties separately

  "I'll believe a 3% lattice theory error when the lattice has produced one successful prediction and several 3% postdictions" (Ben Grinstein, CKM 2006 plenary)

- Particularly important at present:

  $|V_{us}|$: $f^{K\to\pi}$, f_K/f_π

  $|V_{cs}|$, $|V_{cd}|$: $f_{D_{(s)}}$, $f^{D\to K,\pi}$

  $|V_{td}|$, $|V_{ts}|$: $f^2_{B_{(s)}} B_{B_{(s)}}$ and ξ

  ϵ_K: $\hat{B}_K$, $|V_{ub}|$: $f^{B\to\pi}$, etc.

Scenarios:

Reasonable combination $f_K/f_\pi = 1.198(10)\Big|^{\rm Lattice'07}_{\rm Juttner}$

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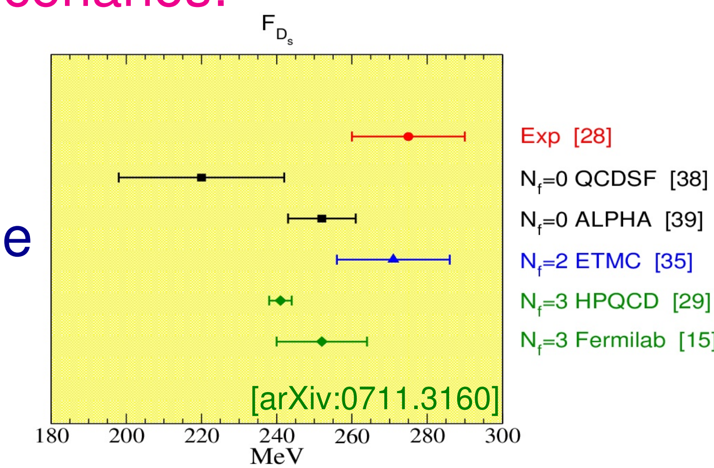
  ϵ_K: $\hat{B}_K$, $|V_{ub}|$: $f^{B\to\pi}$, etc.

Scenarios:

No average available



arXiv:0712.1175 today: $f_{D_s} = (274 \pm 10 \pm 5)$ MeV vs. $241(3)$ MeV?

- If experts cannot agree, it's unlikely the rest of the community would believe a claim of new physics (same for measurements using continuum methods)

Summary

- The SM flavor sector has been tested with impressive & increasing precision
  KM phase is the dominant source of CP violation in flavor changing processes

- Deviations from SM in $B_{d,s}$ mixing, $b \to s$ and even $b \to d$ decays are constrained
  NP in loops not yet bound to be $\ll$ SM contribution (sensitive to scales $\gg$ LHC)

- The non-observation of NP at $E_{\rm exp} \sim m_B$ is a problem for NP at $\Lambda_{\rm NP} \sim \rm TeV$

- Tests of 3-2 generation transitions will approach precision of 3-1, approaching 2-1
  Many important matrix elements, $SU(3)$ & HQS breaking, often useful separately

- If NP seen at LHC, flavor may provide important clues to model building
  If NP is seen in flavor sector: study it in as many different operators as possible
  If NP is not seen in flavor sector: achieve what is theoretically possible
  In either case, LQCD will play important roles

Backup slides

Neutral meson mixings

- Identities, neglecting CPV in mixing (not too important, surprisingly poorly known)

K: long-lived $=$ CP-odd $=$ heavy

D: long-lived $=$ CP-odd (3.5σ) $=$ light (2σ)

B_s: long-lived $=$ CP-odd (1.5σ) $=$ heavy in the SM

B_d: yet unknown, same as B_s in SM for $m_b \gg \Lambda_{\rm QCD}$

Before 2006, we only knew experimentally the kaon line above

- We have learned a lot about meson mixings — good consistency with SM

	$x = \Delta m/\Gamma$ SM theory	$x = \Delta m/\Gamma$ data	$y = \Delta\Gamma/(2\Gamma)$ SM theory	$y = \Delta\Gamma/(2\Gamma)$ data	$A = 1 - \lvert q/p\rvert^2$ SM theory	$A = 1 - \lvert q/p\rvert^2$ data
B_d	$\mathcal{O}(1)$	0.78	$y_s\, \lvert V_{td}/V_{ts}\rvert^2$	-0.005 ± 0.019	$-(5.5 \pm 1.5)10^{-4}$	$(-4.7 \pm 4.6)10^{-3}$
B_s	$x_d\, \lvert V_{ts}/V_{td}\rvert^2$	25.8	$\mathcal{O}(-0.1)$	-0.05 ± 0.04	$-A_d\, \lvert V_{td}/V_{ts}\rvert^2$	$(0.3 \pm 9.3)10^{-3}$
K	$\mathcal{O}(1)$	0.948	-1	-0.998	$4\,\mathrm{Re}\,\epsilon$	$(6.6 \pm 1.6)10^{-3}$
D	< 0.01	< 0.016	$\mathcal{O}(0.01)$	$y_{CP} = 0.011 \pm 0.003$	$< 10^{-4}$	$\mathcal{O}(1)$ bound only

Parameterization of NP in mixing

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

  NP in mixing — two new param's for each neutral meson:

$$M_{12} = \underbrace{M_{12}^{\rm SM}\, r_q^2\, e^{2i\theta_q}}_{\text{easy to relate to data}} \equiv \underbrace{M_{12}^{\rm SM}(1 + h_q\, e^{2i\sigma_q})}_{\text{easy to relate to models}}$$

- Observables sensitive to $\Delta F = 2$ new physics:

$$\Delta m_{B_q} = r_q^2\, \Delta m_{B_q}^{\rm SM} = |1 + h_q e^{2i\sigma_q}| \Delta m_q^{\rm SM}$$

$$S_{\psi K} = \sin(2\beta + 2\theta_d) = \sin[2\beta + \arg(1 + h_d e^{2i\sigma_d})]$$

$$S_{\rho\rho} = \sin(2\alpha - 2\theta_d)$$

$$S_{B_s \to \psi\phi} = \sin(2\beta_s - 2\theta_s) = \sin[2\beta_s - \arg(1 + h_s e^{2i\sigma_s})]$$

$$A_{\rm SL}^q = {\rm Im}\left(\frac{\Gamma_{12}^q}{M_{12}^q r_q^2\, e^{2i\theta_q}}\right) = {\rm Im}\left[\frac{\Gamma_{12}^q}{M_{12}^q(1 + h_q e^{2i\sigma_q})}\right]$$

$$\Delta\Gamma_s^{CP} = \Delta\Gamma_s^{\rm SM} \cos^2(2\theta_s) = \Delta\Gamma_s^{\rm SM} \cos^2[\arg(1 + h_s e^{2i\sigma_s})]$$

- Tree-level constraints unaffected: $|V_{ub}/V_{cb}|$ and γ (or $\pi - \beta - \alpha$)

Next milestone in B_s: $S_{B_s \to \psi\phi,\, \psi\eta^{(\prime)}}$

- $S_{\psi\phi}$ ($\sin 2\beta_s$ for CP-even) analog of $S_{\psi K}$
  CKM fit predicts: $\sin 2\beta_s = 0.0368^{+0.0017}_{-0.0018}$

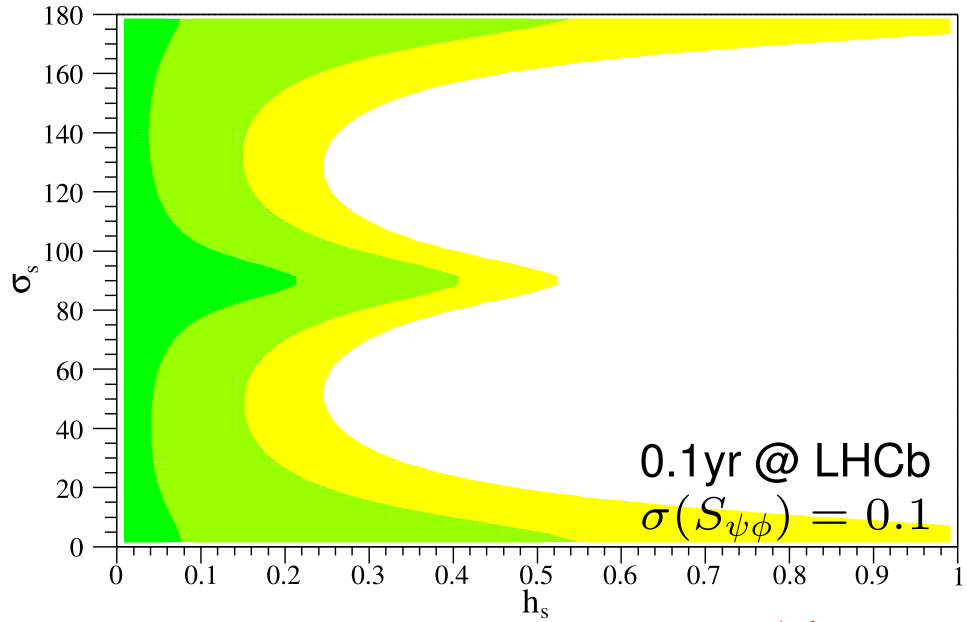
- 2000: Is $\sin 2\beta$ consistent with ϵ_K, $|V_{ub}|$
  Δm_B and other constraints?
  2009: Is $\sin 2\beta_s$ consistent with ...?

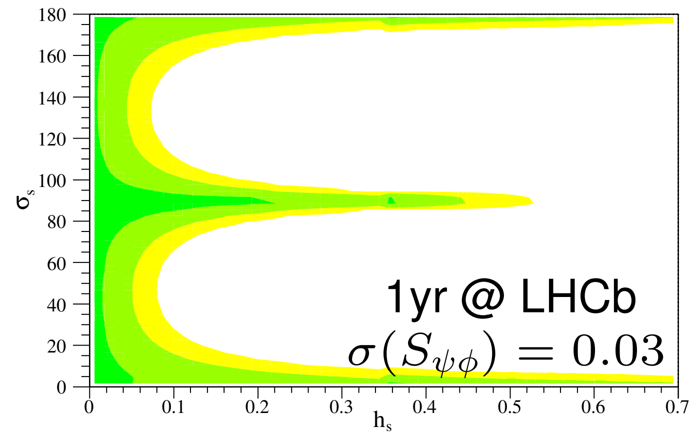
  Plot $S_{\psi\phi}$ = SM value ± 0.10 / $\pm\, 0.03$

  $0.1/1$ yr of nominal LHCb data ⇒

- With modest data sets, huge impact on our understanding; one of the most interesting early measurements

- Many important LHCb measurements





Notice scales!

Minimal flavor violation (MFV)

- How strongly can effects of NP at scale $\Lambda_{\rm NP}$ be (sensibly) suppressed?

- SM global flavor symmetry $U(3)_Q \times U(3)_u \times U(3)_d$ broken by nonzero Yukawa's

$$\mathcal{L}_Y = -Y_u^{ij}\, \overline{Q_{Li}^I}\, \widetilde\phi\, u_{Rj}^I - Y_d^{ij}\, \overline{Q_{Li}^I}\, \phi\, d_{Rj}^I \qquad \widetilde\phi = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \phi^*$$

- MFV: Assume Y's are the only source of flavor and CP violation (cannot demand all higher dimension operators to be flavor invariant and contain only SM fields)

[Chivukula & Georgi '87; Hall & Randall '90; D'Ambrosio, Giudice, Isidori, Strumia '02]

- CKM and GIM (m_q) suppressions similar to SM; allows EFT-like analyses

  Sizable corrections possible to some observables, even imposing MFV:
  $B \to X_s\gamma,\ B \to \tau\nu,\ B_s \to \mu^+\mu^-,\ \Delta m_{B_s},\ \Omega h^2,\ g-2$, precision electroweak

- In some scenarios high-p_T LHC data may rule out MFV or make it more plausible

Many interesting rare B decays

- Important probes of new physics
  - $B \to K^*\gamma$ or $X_s\gamma$: Best $m_{H^\pm}$ limits in 2HDM — in SUSY many param's
  - $B \to K^{(*)}\ell^+\ell^-$ or $X_s\ell^+\ell^-$: bsZ penguins, SUSY, right handed couplings

A crude guide ($\ell = e$ or μ)

Decay	$\sim$ SM rate	physics examples
$B \to s\gamma$	3×10^{-4}	$\lvert V_{ts}\rvert$, $H^\pm$, SUSY
$B \to \tau\nu$	1×10^{-4}	$f_B \lvert V_{ub}\rvert$, $H^\pm$
$B \to s\nu\nu$	4×10^{-5}	new physics
$B \to s\ell^+\ell^-$	5×10^{-6}	new physics
$B_s \to \tau^+\tau^-$	1×10^{-6}	
$B \to s\tau^+\tau^-$	5×10^{-7}	⋮
$B \to \mu\nu$	5×10^{-7}	
$B_s \to \mu^+\mu^-$	4×10^{-9}	
$B \to \mu^+\mu^-$	2×10^{-10}	

Replacing $b \to s$ by $b \to d$ costs a factor ~ 20 (in SM); interesting to test in both: rates, CP asymmetries, etc.

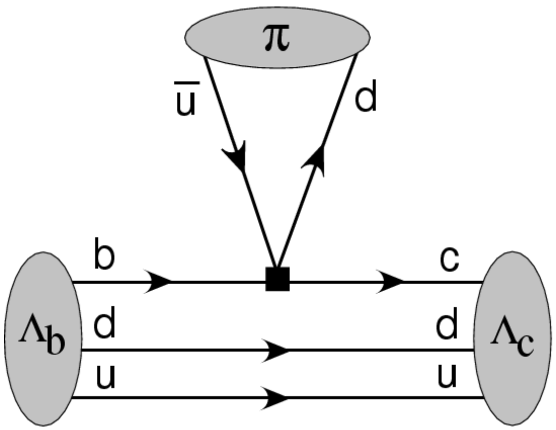
In $B \to q\, l_1\, l_2$ decays expect 10–20% K^*/ρ, and 5–10% K/π (model dept)

LHC: $B \to K^*\ell^+\ell^-$ and $B_s \to \mu^+\mu^-$

Inclusive modes impossible

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