Attacking the Standard Model with (heavy quark) flavor physics: an experimentalist’s view

Biplab Dey

INFN Milano
Towards the SM - I

- Birth of quantum mechanics in the 1900’s

- Gave rise to Quantum Field Theory

- Particles ↔ fields

- Anti-matter

- Special relativity

$E = mc^2$
Towards the SM - II

- 1950’s Quantum Electrodynamics (renormalization)
- 1960’s Electroweak theory (Higgs, EW unification)
- 1970’s Quantum Chromodynamics (confinement, asymptotic freedom)
The Standard Model

- A remarkably successful theory!
- Fine structure constant \( \alpha = 0.0072973525698(24) \)
- Has withstood experimental tests for over 40 years...
Yet, major difficulties...

- How does gravity fit in?
- Matter-antimatter asymmetry, neutrino oscillations, origin of mass.
- Ordinary matter (SM) accounts for only 4% of universe. What is dark matter/dark energy?

Compelling evidence for beyond the SM physics. But how do we search?
**INDIRECT SEARCHES**

- Historically, indirect observations of “new physics” has often been the portal to infer properties of heavy particles before experiments with sufficient energy to produce them.

- $\beta$ decay: particles of mass $\sim 1$ GeV reveals physics at $\sim 100$ GeV.

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Fermi's 4-point interaction
Theory of beta decay
$\sim 1$ GeV

Exchange of heavy virtual boson
$\sim 80$ GeV

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Biplab Dey
Testing the SM via Flavor Physics
April 13th, 2015
Core principle: precision tests of SM in processes that do not preserve quark flavor.

Heavy \( \{b, c\} \) quarks decaying to lighter \( q \in \{u, d, s\} \) quarks.

\[ A = A_{\text{SM}} + A_{\text{BSM}} \]

\[ A_{\text{BSM}} \propto \frac{C_{\text{BSM}}}{M_{\text{BSM}}^2} \]

involves virtual heavy particles running inside loops.

Carefully choose scenarios where the SM part is well-understood and suppressed (helicity, Cabibbo, FCNC, ...)

Difference in rates or angular distributions wrt SM \( \Rightarrow \) optimally chosen “clean” observables that reduce theory uncertainties.
The LHCb detector

- Dedicated single-arm forward spectrometer with unique pseudo-rapidity range $1.8 < \eta < 4.9$.

- $pp$ collisions in Run 1:
  - 2011: 1/fb at 7 TeV
  - 2012: 2/fb at 8 TeV

- High $b\bar{b}$ and $c\bar{c}$ cross-sections:
  - $\sigma(pp \rightarrow b\bar{b}) = 286 \, \mu$b at 7 TeV
  - $\sigma(pp \rightarrow c\bar{c}) = \times 20$ larger

- Complementary $\eta$ coverage wrt CMS/ATLAS.
The LHCb subsystems and trigger

- Tracking: VeLo + two tracking stations up- and down-stream of the magnet. Resolutions: 20 µm (IP), 0.5% (p) and 45 fs (τ).
- Hadron Id: two RICH detectors with good K/π separation in 2 < p < 100 GeV.
- Calorimetry: HCAL and ECAL for γ, e, π⁰
- Muon detectors: 97% efficiency, < 2.5% π ↔ µ mis-ID
The $b \rightarrow s \ell^+ \ell^-$ “industry” at the LHC

- Everybody’s favorite rare “penguin” decay!
- Flavor-changing-neutral-current (FCNC).
- No tree-level diagram in the SM. Many ways where NP can enter.

Several ways to explore this:

- $B_s \rightarrow \mu^+ \mu^-$ BF @ LHCb/CMS
- $B \rightarrow K^* \gamma_{\text{pol}}$ @ LHCb
- $B_d \rightarrow K(*) \ell^- \ell^+$ @ LHCb
- $B_s \rightarrow \phi \mu^+ \mu^-, \Lambda_b \rightarrow \Lambda \mu^+ \mu^-$ ...
The Operator Product Expansion (OPE)

- Exactly as in the case of Fermi’s 4-point interaction theory of $\beta$-decay.
- Expand $\mathcal{H}_{\text{eff}}$ in a basis of local operators (OPE):

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left( C_i \mathcal{O}_i + C_i' \mathcal{O}'_i \right)_{\text{had. LH}} + \left( C_i \mathcal{O}_i + C_i' \mathcal{O}'_i \right)_{\text{had. RH}}$$

- The Wilson coefficients $C_i^{(i)}(\alpha_s, \mu)$ encode short-distance physics, sensitive to $E \geq M_{EW} \sim M_W, M_Z$. Computed at $\mu \sim m_b$.

<table>
<thead>
<tr>
<th>$i$</th>
<th>Operator</th>
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<tbody>
<tr>
<td>1,2</td>
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<td>3-6,8</td>
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<td>S</td>
<td>Scalar</td>
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<tr>
<td>P</td>
<td>Pseudoscalar</td>
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Relevant operators in $b \rightarrow s\ell^+\ell^-$

- $O^{(′)}(\mu)$ are composite operators depending on hadronic matrix element $\langle K^{(*)}\ell^+\ell^-, \ell^+\ell^-|H_{\text{eff}}|B\rangle$

- Tree-level like with charm fields: $O_1 \sim (\bar{s}_L\gamma_\mu c_L)(\bar{c}_L\gamma^\mu b_L)$

- Radiative penguin: $O_7\gamma \sim (\bar{s}_L\sigma_{\mu\nu} b)F^{\mu\nu}$

- Electroweak: $O_{9V} \sim (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\ell)$, $O_{10A} \sim (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\gamma_5\ell)$

- (pseudo)scalar: $O_S \sim (\bar{s}_L b_L)(\bar{\ell}\ell)$, $O_P \sim (\bar{s}_L b_L)(\bar{\ell}\gamma_5\ell)$

- Many more operators if one includes tensors (leptoquarks), etc...
The Wilson coefficients

- Clues to NP signature hidden in the $C_i$'s.

- SM hierarchy: $C_{7\gamma} \sim -0.331$, $C_{9V} \sim 4.27$, $C_{10A} \sim -4.173$. Everything else small or negligible.

- Lots of complementarity in $C_{NP}$ searches:
  - $\mathcal{B}(B_s \to \ell^+ \ell^-) \sim m_{\ell}^2 (C_{10A} - C'_{10A}) + (C_{S,P} - C'_{S,P})$.
  - $B_d \to X_s \gamma_{pol}$: $C_{7\gamma}$. Photon polarization: $C'_{7\gamma}$.
  - $B_d \to K^{(*)}\mu^+\mu^-$ angular analysis: $C_{7\gamma}$, $C_{9V}$, $C_{10A} + ...$
After 30 years of search, $> 4 \sigma$ in LHCb and CMS for $B_s$.

LHCb and CMS combined results (arXiv:1411.4413, submitted to Nature):
- $\mathcal{B}(B_d) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$, $3.2 \sigma$
- $\mathcal{B}(B_s) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$, $6.2 \sigma$ first observation

Some slight tensions, but mostly compatible with SM.
$B_{d,s} \rightarrow \mu^+ \mu^-$: EFFECT ON NP MODELS

- $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)$ expected to be particularly enhanced ($\sim (\tan \beta)^6$, large $\tan \beta$) in the two-Higgs doublet models.

- LHCb+CMS result has a huge impact on SUSY parameter space.
Photon polarization in $b \to s \gamma$

- Long history of radiative penguin $B \to X_s \gamma$ (inclusive) at CLEO, BABAR, Belle, LHCb.

- Rate: $\mathcal{B}(b \to s \gamma) \propto |C_{7\gamma}|^2 + |C'_{7\gamma}|^2$, with $C'_{7\gamma}$ strongly suppressed in the SM.

- Novel feature: outgoing photon is almost fully left-chiral for $b$ quark.

\[
\begin{align*}
\mathcal{A}_{\text{SM}} &\propto m_b \bar{s}_L \sigma_{\mu\nu} q^\nu b_R + m_s \bar{s}_R \sigma_{\mu\nu} q^\nu b_L \\
C'_{7\gamma} / C_{7\gamma} &\sim m_s / m_b \approx 0.02 \ll 1 \\
\lambda_\gamma &= \frac{|C'_{7\gamma}|^2 - |C_{7\gamma}|}{|C'_{7\gamma}|^2 + |C_{7\gamma}|} = -1 \begin{pmatrix} b \\ \bar{b} \end{pmatrix} \left( +1 \right)
\end{align*}
\]

- NP can enhance $C'_{7\gamma}$: left-right symmetric models (w/ a heavy $W_R$).
Measurement of $\lambda_\gamma$ at LHCb

- Parity-odd triple product $\vec{p}_\gamma \cdot (\vec{p}_\pi \times \vec{p}_\pi)$ in $B^\pm \to K^{\pm} \pi^\mp \pi^\pm \gamma$ decays is sensitive to $\lambda_\gamma$.

- Complicated Dalitz structures in $K\pi\pi$ system pushed into $C_{K\pi\pi} \sim 0.1$ (for $B^{\pm}$).

- Up-down asymmetry (arXiv:0205065):

$$A_{UD} \equiv \frac{N_{\cos \theta > 0} - N_{\cos \theta < 0}}{N_{\cos \theta > 0} + N_{\cos \theta < 0}} = C_{K\pi\pi} \lambda_\gamma$$
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First observation of photon polarization in $b \rightarrow s\gamma$

- Further theory input needed on $C_{K\pi\pi}$ to extract $\lambda_\gamma$.
Angular analyses of $\bar{B} \rightarrow X \ell_1 \ell_2$

- So far so good. No spectacular deviations from SM.
- As we will see, the “interesting” anomalies involve $\bar{B} \rightarrow X \ell_1 \ell_2$.
  - Electroweak Penguins (EWP): $\ell^- \ell^+$, $\ell \in \{e, \mu\}$
  - Semileptonic (SL): $\ell^- \bar{\nu}_\ell$, $\ell \in \{e, \mu, \tau\}$
  - $X$ is a mesonic system $\in \{\pi, K, \pi\pi, K\pi, KK, D, D\pi\}$
- Four kinematic variables: $\phi \in \{q^2, \theta_l, \theta_V, \chi\}$

![Diagram of angular variables](image-url)
THE HELICITY AMPLITUDES

- Three helicity amplitudes for the spin-1 dilepton \{W^*, Z^*, \gamma(*)\}:

\[
H^{L,R}_{\pm} \bigg|_{J \geq 1} = \beta_{J} \left( \frac{k}{m_{X}} \right)^{J-1} \left\{ \mathcal{C}^{L,R} (m_{B} + m_{X}) A_{1}(q^{2}) + \frac{2m_{B}}{q^{2}} (m_{B}^{2} - m_{X}^{2}) \mathcal{C}_{7} T_{2}(q^{2}) \right. \\
\left. \quad + 2m_{B} k \left[ \mathcal{C}^{L,R} \left( \frac{V(q^{2})}{m_{B} + m_{X}} \right) + \mathcal{C}_{7} \frac{2m_{B}}{q^{2}} T_{1}(q^{2}) \right] \right\} \\
H^{L,R}_{0} \bigg|_{J \geq 1} = \frac{\alpha_{J}}{2m_{X} \sqrt{q^{2}}} \left( \frac{k}{m_{X}} \right)^{J-1} \left\{ \mathcal{C}^{L,R} \left[ (m_{B}^{2} - m_{X}^{2} - q^{2})(m_{B} + m_{X}) A_{1}(q^{2}) - \frac{4m_{B}^{2}k^{2}}{m_{B} + m_{X}} A_{2}(q^{2}) \right] \\
+ 2m_{B} \mathcal{C}_{7} \left[ (m_{B}^{2} + 3m_{X}^{2} - q^{2}) T_{2}(q^{2}) - \frac{4m_{B}^{2}k}{m_{B}^{2} - m_{X}^{2}} T_{3}(q^{2}) \right] \right\}
\]

- QCD form-factors are the largest source of systematic uncertainties.
The “clean” observables

- If the $X$ system is in spin-$J$, the amplitude squared reads:

$$|\mathcal{M}|^2 = \sum_{L,R} \sum_{\lambda \in \{0, \pm 1\}} \frac{\sqrt{2J + 1}}{\sqrt{2J + 1}} \mathcal{H}_\lambda^{\{L,R\},J} d^J_{\lambda,0}(\theta_V) d^1_{\lambda,\eta}(\theta_\ell) e^{i\lambda\chi} \left| \sum_{J} \right|^2$$

$$= \sum_i \Gamma_i(q^2) f_i(\theta_\ell, \theta_V, \chi)$$

- Matias et al. (arXiv:1303,5794): carefully constructed ratios of the $\Gamma_i$ observables.

- Leading order FF uncertainties cancel in the $q^2 \leq 6$ GeV$^2$ regime.

- Forward-backward zero crossing point long known to be theoretically clean.

- New observable $P'_5$ turns out to be particularly sensitive.
$B^0 \to K^{*0} \mu^+ \mu^-$ STATUS WITH 1/ FB DATA

- Good agreement with the SM (JHEP 07 (2011) 067)
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ STATUS WITH 1/FB DATA

- Good agreement with the SM (JHEP 07 (2011) 067)

![Diff. rate](image1)

- Except $3.7\sigma$ local deviation in $P'_5$ from SM (JHEP 05 (2013) 137):

![P'_5](image2)
3/FB: ANOMALOUS TRENDS NOW SEEN IN $B$

- Isospin channels: $B$ tend to lie below SM (PRL 112 212003, arXiv:1411.3161)
3/FB: ANOMALOUS TRENDS NOW SEEN IN $B$

- **Isospin channels**: $B$ tend to lie below SM ([PRL 112 212003, arXiv:1411.3161](https://arxiv.org/abs/1411.3161))

- Updated lattice calculations at high $q^2$ reflect this as well
Effect on Wilson coefficients

- With 2013 data, $C_9$ and $C_7$ seen as main players.
- All theory groups find $C_9^{NP} < 0$
  
- Different bins, observables, statistical approaches...
- Contentions whether $C_9' \sim -C_9^{NP}$ or $C_9' \to 0$ (Matias et al.)
Another unexpected development: $R_K$

- Other than a tiny effect from mass difference, $e/\mu$ behaves the same in SM

\[ R_K \equiv \frac{\mathcal{B}(B \to K\mu\mu)}{\mathcal{B}(B \to Kee)} = 1.0 \pm \mathcal{O}(10^{-4}) \]

- $R_{K_{LHCb}} = 0.745^{+0.090}_{-0.074} \pm 0.036$

Hints towards lepton universality violation in 1st and 2nd generations for the first time
Angular analysis of $B^0 \rightarrow K^* e^+ e^-$ at low $q^2$

- Since $q_{\text{min}}^2 \geq 4m_\ell^2$, ee mode allows to explore the very low $q^2$ region.

- Sensitivity to $C_7^{(')}$ competitive with rad. penguins.

- New LHCb results: angular analysis in $q^2 \in [0.002, 1.120]$ GeV$^2$.

- Results consistent with SM.

- $R_{K^*}$ could be very interesting

- Experimentally much more challenging than $\mu\mu$: trigger and modeling of bremsstrahlung inside detector material.
$B^0 \rightarrow K^* \mu^+ \mu^-$ update from Moriond 2015
The anomaly persists!

Excellent consistency between 2011 and 2012 results.
And if we are aggressive...

- Moves closer to $C_9^{NP} < 0$ as well.
Slightly lower than SM. ZCP: $q_0^2 \sim 3.7 \text{ GeV}^2$. 
**Heavy $Z'$ with non-universal flavor couplings?**

- Numerous theory papers combining all $b \to s\ell\ell$ measurements
  Descotes-Genon et al [1307.5683], Beaujean et al [1310.2478], Gauld et al [1308.1959], Hurth et al [1312.5267], Straub et al [1308.1501], Horgan et al [1310.3887], Altmannshofer et al [1403.1269], Biancofore et al [1403.2944]...

- Simplest explanation of $C_9^{\text{NP}} \sim -1.5$ is a $Z'$ boson with specific flavor couplings.

- Heavy (TeV range) $Z'$ boson with FCNC at tree-level

- Couples only to LH quarks.

- Couples equally with $\ell_{R,H}$, but differently to $e/\mu$

- CPV in $B_s-\bar{B}_s$ places strong limits on the couplings.

- Difficult to accommodate within MSSM.
Charm-loop effects: potential show-stopper?

- Lyon-Zwicky (1406.0566): non-factorizable $c\bar{c}$ loops are large and can accommodate the $P'_5$ anomaly.

- OPE breaks down. Very hard to calculate.

- Can we disentangle $b \rightarrow s\ell\ell$ from $b \rightarrow s\bar{c}\bar{c}$?

- What can we do experimentally in the $b \rightarrow s\mu^+\mu^-$ sector?
  - Go closer to $q^2 = m^2_\psi$ by improving $\psi$ vetoes.
  - Look at higher $K^{*J}$ states, especially around the $K_2^*(1430)$. 
$|V_{ub}|$ and $|V_{cb}|$
**Importance of $|V_{ub}|/|V_{cb}|$**

$V_{CKM} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$

- In SM, unitary CKM matrix $\Rightarrow$ flavor-mixing
- Fantastic success of the CKM paradigm thru’ the years...

**1995:**

**2014:**
Importance of $|V_{ub}|/|V_{cb}|$

- Side opposite to $\beta$ proportional to $|V_{ub}|/|V_{cb}|$. Both $\beta$ and $|V_{cb}|$ known better than 3%.

- Closure test of UT mainly limited by $|V_{ub}|$. 

![Diagram showing the correlation between $|V_{ub}|$ and $|V_{cb}|$ and other parameters such as $\sin 2\beta$, $\Delta m_d$, $\Delta m_s$, $\varepsilon_K$, $\alpha$, $\beta$, and $\rho$. The excluded area has CL > 0.95.](image-url)
Inclusive and exclusive $|V_{ub}|$

- Exclusive $\bar{B} \rightarrow \pi \ell^- \bar{\nu}_\ell$. Need QCD form-factors.

- Inclusive $\bar{B} \rightarrow X_u \ell^- \bar{\nu}_\ell$. No form-factors (sum of states), but kinematics cuts to reduce $\times 50$ large charm background.

- Different experiment/theory techniques. Persistent $\sim 3\sigma$ tension!
$|V_{ub}|$ AT LHCb VIA $\Lambda_b \to p\mu\nu$

$|V_{ub}|/|V_{cb}|$ long thought to be impossible at a hadron collider

- LHCb probes $b \to u$ in exclusive baryonic $\Lambda_b \to p\mu\nu$ decay.
- High statistics ($\mathcal{O}(10^4)$) even for a rare decay!
- Critical role played by latest lattice calculations at high $q^2$.

![Graph showing signal and normalization for $\Lambda_b \to p\mu\nu$ and $\Lambda_b \to \Lambda_c (\to pK\pi)\mu\nu$]

Detmold et al. (1503.01421)
**Two experimental challenges**

- Dominant charm backgrounds have additional tracks close to the $p\mu$ vertex.
- Multivariate classifier trained to discriminate between red and blue tracks.
- 90% rejection with 10% efficiency.

**Two-fold ambiguity in $q^2$:**

- Sign of $p_\parallel$ unknown
- Require both $q^2$ solns. $\geq 15$ GeV$^2$:
Fit the corrected mass: $M_{\text{corr}} = \sqrt{p_{\perp}^2 + M_{p\mu}^2} + p_{\perp}$.

$N_{\text{norm}} = 34255 \pm 571$

$N_{\text{sig}} = 17687 \pm 733$
**What can LHCb say about $|V_{ub}|$?**

1. $|V_{ub}|_{LHCb} = (3.27 \pm 0.15^{\text{exp}} \pm 0.17^{\text{theory}} \pm 0.06(|V_{cb}|)) \times 10^{-3}$

2. Total uncertainty is 7.2%. World’s best exclusive measurement.

3. Consistent with WA of sin(2$\beta$).

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**Large tension between inclusive and exclusive $|V_{ub}|$ persists**
Right-handed currents in the SL sector

- In the SM, weak interaction is purely LH. Add a small RH admixture \( \epsilon_R \) (connected to \( C' \) variables).

- If \( \epsilon_R \) real and negative, can help resolve the \( |V_{ub}| \) tension:
  - \( |V_{ub}|_{incl.} \sim 1 + \epsilon_R^2 \)
  - \( |V_{ub}|_{excl.} \sim 1 + \epsilon_R \)

- Several authors have looked at this (1408.2516, 1411.1177, 1407.1320 etc.) but no clear picture.

- \( \epsilon_R \) difficult to decouple from the FF normalizations.

- Similar 3\( \sigma \) tensions seen in the \( |V_{cb}| \) sector as well.
The BR eco technique at $B$-factories

- In $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B_{\text{sig}}B_{\text{tag}}$, full hadronic reconstruction of $B_{\text{tag}}$

- A single missing $\nu$: reconstructed as $p_{\text{miss}}$ via kinematic fit.

- $\bar{B} \rightarrow X\mu^-\mu^+$ (LHCb) and $\bar{B} \rightarrow X\ell^-\bar{\nu}_\ell$ (BABAR) on a completely equal footing now (resolutions).

- Low efficiency, but de facto method in Belle II era for neutrinos.
$\bar{B} \to D^* \ell^- \bar{\nu}_\ell$ AT BABAR

- Remarkably clean dataset!
  $\sim 6000$ events w/ $\sim 2\%$ bkgd.

- Pure $P$-wave. Best known FF’s from HQET.

- Entire suite of “clean” observables accessible here.

- Any $\sin \chi$ term (absent in SM) sensitive to $\text{Im}(\epsilon_R)$.

- Cleanest/simplest possible situation $\implies$ very important testbed.
**THE \( \tau \) CASE IS SPECIAL**

- For massive \( \tau \), chirality \( \neq \) helicity. The \( W^* \) can have spin-0.
- Charged-Higgs enters at tree-level.
- Type 2 two-Higgs doublet model: amplitude scales as \( m_\tau \left( \frac{\tan \beta}{m_{H^\pm}} \right)^2 \).
- Additional form-factor: \( A_0(q^2) \). Different phase-space constraints:
**THE BaBar R(D(∗)) ANOMALY (1205.5442)**

- Measured the ratios:
  \[ R(D(∗)) \equiv \frac{\mathcal{B}(B \to D(∗)τν)}{\mathcal{B}(B \to D(∗)ℓν)}, \quad τ \to ℓ\bar{ν}_ℓν_τ. \]

- Same final state in numerator and denominator. Many uncertainties cancel.

- \[ R(D(∗)) > 3 \sigma \] tension with SM:

  **Combined: 3.4σ**

2-d fit in \( p_{miss}^2 \) and \( p_ℓ^* \):

![2-d fit graph](image)
2HDM models confronting $BaBar$ data

- **type II 2HDM**: the two Higgs doublets couple to up- and down-type quarks separately.
- Favored scenario in MSSM.
- However, can’t explain $R(D)$ and $R(D^*)$ simultaneously.

- Can be accommodated in **type III 2HDM** (both doublets couple to up and down-type quarks). Crivellin et al. (1206.2634v2).
Connection of $R(D^{(*)})$ models to $\epsilon_R$

- Effective Lagrangian approach with generic 4-quark operators (Datta et al., 1206.3760) includes $g_V, g_A, g_S, g_P$...

- But $\frac{g_V}{g_A} \sim \frac{1 + \epsilon_R}{1 - \epsilon_R}$, so this should affect $\ell \in \{e, \mu\}$ cases as well.

Angular analysis of $\bar{B} \rightarrow D^* \ell^- \bar{\nu}_\ell$ should place constraints on these models.
\( R(D^{(*)}) \) from Belle and LHCb

- We (still) eagerly await results from the full Belle I dataset.
- “Trends” indicate \( BABAR + \) Belle I might be close to 5 \( \sigma \)!
- LHCb has also entered the game.
We are in a unique situation where several very interesting tensions exist with the SM in the heavy quark flavor sector.

Happening times – both Run II at LHC and Belle II. Much more data expected soon.
**Summary and outlook**

- We are in a unique situation where several very interesting tensions exist with the SM in the heavy quark flavor sector.
- Happening times – both Run II at LHC and Belle II. *Much* more data expected soon.
- The higher $\Lambda_{NP}$ is, the more unexpected non-CKM type flavor violations. *Measure everything!*

\[ \text{Naturaness Loss} = \text{Flavor Gain} \]

*CAST A WIDE NET*

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*Nima Arkani Hamed*

*Intensity Frontier Workshop 2011*
Higher track multiplicities, ghost rates, interactions/crossing, vertices...

Replace current hardware L0 trigger (1MHz) to more flexible software trigger

Read out everything (40 MHz) and HLT output 20 kHz

VeLo and tracking (new Upstream Tracker, Fiber Tracker)

RICH system: new photo-detectors, upgraded optics
# LHCb upgrade

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>Current precision</th>
<th>LHCb 2018</th>
<th>Upgrade (50 fb⁻¹)</th>
<th>Theory uncertainty</th>
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<td>$B_s^0$ mixing</td>
<td>$2\beta_s (B_s^0 \rightarrow J/\psi \phi)$, $2\beta_s (B_s^0 \rightarrow J/\psi f_0(980))$, $A_{fs}(B_s^0)$</td>
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<td>$6.4 \times 10^{-3}$ [18]</td>
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<td>Gluonic penguin</td>
<td>$2\beta_s^{\text{eff}} (B_s^0 \rightarrow \phi \phi)$, $2\beta_s^{\text{eff}} (B_s^0 \rightarrow K^{*0} \bar{K}^{*0})$, $2\beta_s^{\text{eff}} (B^0 \rightarrow \phi K^0_S)$</td>
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<td>0.02</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5%</td>
<td>1%</td>
<td>0.2%</td>
<td></td>
</tr>
<tr>
<td>Electroweak penguin</td>
<td>$S_2(B^0 \rightarrow K^{*0} \mu^+ \mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4)$, $s_0 A_{FB}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)$, $A_1(K \mu^+ \mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4)$, $\mathcal{B}(B^+ \rightarrow \pi^+ \mu^+ \mu^-)/\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)$</td>
<td>0.08 [14]</td>
<td>0.025</td>
<td>0.008</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25% [14]</td>
<td>6%</td>
<td>2%</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.25 [15]</td>
<td>0.08</td>
<td>0.025</td>
<td>~ 0.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25% [16]</td>
<td>8%</td>
<td>2.5%</td>
<td>~ 10%</td>
</tr>
<tr>
<td>Higgs penguin</td>
<td>$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$, $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)/\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$</td>
<td>$1.5 \times 10^{-9}$ [2]</td>
<td>0.5 $\times 10^{-9}$</td>
<td>0.15 $\times 10^{-9}$</td>
<td>0.3 $\times 10^{-9}$</td>
</tr>
<tr>
<td>Unitarity triangle</td>
<td>$\gamma (B \rightarrow D^{(<em>)} K^{(</em>)})$</td>
<td>~ 10–12° [19, 20]</td>
<td>4°</td>
<td>0.9°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\gamma (B_s^0 \rightarrow D_s K)$</td>
<td>–</td>
<td>11°</td>
<td>2.0°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\beta (B^0 \rightarrow J/\psi K^0_S)$</td>
<td>0.8° [18]</td>
<td>0.6°</td>
<td>0.2°</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>$A_T$</td>
<td>$2.3 \times 10^{-3}$ [18]</td>
<td>0.40 $\times 10^{-3}$</td>
<td>0.07 $\times 10^{-3}$</td>
<td>–</td>
</tr>
<tr>
<td>CP violation</td>
<td>$\Delta A_{CP}$</td>
<td>$2.1 \times 10^{-3}$ [5]</td>
<td>0.65 $\times 10^{-3}$</td>
<td>0.12 $\times 10^{-3}$</td>
<td>–</td>
</tr>
</tbody>
</table>