INTENSITY FRONTIER

SCIENCE STATUS:

EXPLORING THE UNKNOWN

Jure Zupan
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THE UPSHOT

• baryon asymmetry implies more CP violation than in the SM

• flavor measurements a way to probe such required new CPV sectors
  • high energy scales and/or small couplings

• probes also other puzzles: dark matter, strong CP problem,...
FROM FLAVOR PHYSICS TO NEW PHYSICS

- SM@tree level: no Flavor Changing Neutral Currents
  - all FCNC processes loop suppressed
  - e.g., meson mixing
- can be modified by NP
- NP contribs. scale as
  \[
  \delta C^{NP} \propto \frac{g_{sb}^2}{M_{NP}^2}
  \]
- depends on couplings and NP masses
LARGE SCALES PROBED

dim 6 ops.

midterm future

now

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HEPAP 2019, Nov 22 2019
HIGH ENERGY VS. FLAVOR EXPERIMENTS

• at low energies probe off-shell states

\[ Br(i \rightarrow f) \propto \left( \frac{g_ig_f}{m^2} \right)^2 \]

• at high energies on-shell production
  • s-channel

\[ \sigma(i \rightarrow X) \times Br(X \rightarrow f) \propto \mathcal{L}_i(m) \left( \frac{g_ig_f}{m^2} \right)^2 \frac{1}{\Gamma_{\text{tot}}} \]

• other options: t-channel, pair production, ....

• probe different combinations of couplings and masses*

*small print caveats: at high eng. could also still be off shell; which couplings probed depend on which prod/decay channel, etc
B PHYSICS ANOMALIES

- two quark level transitions show \( \sim 3\sigma \) deviations from the SM*
- lepton flavor universality violating transitions

\[
\mathcal{L}_{\text{SMEFT}} \supset \frac{1}{\Lambda_{Q_{ij}L_{kl}}^2} \left( \bar{Q}_i \gamma^\mu \sigma^A Q_j \right) \left( \bar{L}_k \gamma_\mu \sigma^A L_l \right)
\]

\[b \to c\tau\nu\]
\[b \to s\mu^+\mu^-\]

\[\Lambda_{\text{NP}} \sim 3 \text{ TeV}\]
\[\Lambda_{\text{NP}} \sim 30 \text{ TeV}\]

* there are other interesting deviations, e.g., \( \sim 3\sigma \) deviation in \( \varepsilon'/\varepsilon \), see, e.g., Buras et al, 1507.06345; RBC-UKQCD, 1502.00263

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DIRECT SEARCHES IN ττ

- \( b \to c \tau \nu \) implies a \( 1/V_{cb} \) enhanced \( b \bar{b} \to \tau^+ \tau^- \)
- severe bounds from LHC
- for instance for vector triplet: \( W', Z' \)

**unitarity bound**

\( m_{W'} < 6.5 \text{ TeV} \)

di Luzio, Nardecchia, 1706.01868

for \( b \to c \tau \nu \) need:

Faroughy, Greljo, Kamenik, 1609.07138
DIRECT

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unitarity bound $m_{W'} < 6.5 \text{ TeV}$

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for $b \to c \tau \nu$ need:

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Cerri et al, 1812.07638
PROGRESS

• significant improvements both in theory and experiment
  ● achieved and expected

• for theory just two very recent examples
  ● charm contrib. to $\varepsilon_K$
  ● hadronic light-by-light to $(g-2)_\mu$
CHARM CONTRIB. TO $\varepsilon_K$

- $K-\bar{K}$ mixing parameter $\varepsilon_K$ one of the most sensitive probes of new CPV
- the main th. uncertainty due to charm can be dramatically reduced
  - by using CKM unitarity and re-grouping perturb. corrections
- lattice QCD inputs very important

credit: J. Brod
CHARM CONTRIB. TO $\mathcal{E}_K$

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\[ \Delta \mathcal{E}_K \]

credit: J. Brod

Best fit (CKMfitter 2018)
PDG 2019
SD uncertainty

credit: J. Brod
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$\left( g-2 \right)_\mu$

- first determination of hadronic light-by-light contrib. to $(g-2)_\mu$ from Lattice QCD

Blum et al, 1911.08123
\((g-2)_\mu\)

- first determination of hadronic light-by-light contrib. to \((g-2)_\mu\) from Lattice QCD

Blum et al, 1911.08123

<table>
<thead>
<tr>
<th></th>
<th>(a_\mu \times 10^{10})</th>
<th>Lin@Brookhaven Forum 2019</th>
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<tr>
<td>QED 5-loops</td>
<td>11658471.8853 ± 0.0036</td>
<td>Aoyama, et al, 2012</td>
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<td>Weak 2-loops</td>
<td>15.36 ± 0.10</td>
<td>Gnendiger et al, 2013</td>
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<td>HVP (LO)</td>
<td>692.5 ± 2.7</td>
<td>RBC-UKQCD and FJ17 combined</td>
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<td>693.26 ± 2.46</td>
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<td>693.9 ± 4.0</td>
<td>DHMZ19</td>
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<td>HVP (NLO)</td>
<td>-9.93 ± 0.07</td>
<td>Fred Jegerlehner, 2017</td>
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<td>HVP (NNLO)</td>
<td>1.22 ± 0.01</td>
<td>Fred Jegerlehner, 2017</td>
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<tr>
<td>HLbL</td>
<td>10.3 ± 2.9</td>
<td>Fred Jegerlehner, 2017</td>
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<tr>
<td></td>
<td>10.5 ± 2.6</td>
<td>Glasgow Consensus, 2007</td>
</tr>
</tbody>
</table>

\[7.20(3.98)_{\text{stat}}(1.65)_{\text{sys}}\]

HLbL from Lattice QCD

leaves little room for this notoriously difficult hadronic contribution to explain the difference between the Standard Model and the BNL experiment. Blum et al, 1911.08123
EXPERIMENTAL PROGRESS - UPHSHOT

• LHCb Upgrade 2+Belle II: a factor of 2x - 3x improvement in reach for NP scale
  • ~ like going from LHC (13 TeV) to HE-LHC (27 TeV)
  • more precise measurements + expected theory advance: lattice QCD improvements
• many other experiments also significant improvements in the reach
  • Mu3e, Mu2e, MEG II, eEDM, rare kaon decays,...
EXPERIMENTAL PROGRESS

- example: mini-split SUSY
- $O(1-10\text{TeV})$ gauginos at LHC or future collider; PeV sfermions from low energy precision probes

$|m_{\tilde{B}}| = |m_{\tilde{W}}| = 3\text{ TeV}$, $|m_{\tilde{g}}| = 10\text{ TeV}$

2013

$m_{\tilde{q}} = m_{\tilde{\ell}} = |\mu|$ (TeV)

Altmannshofer, Harnik, JZ, 1308.3653
and will improve dramatically in the future
• further orders of magnitude experimental progress expected in CLFV transitions
LFUV OBSERVABLES

- example: LHCb after Upgrade II

\[
R_K = \frac{Br(B \to K\mu\mu)}{Br(B \to K\mu\mu)} \quad [1,6] \text{GeV}^2
\]

Akar et al., 1812.07638
LFUV observables

- example: only inclusive $b \rightarrow sll$

Belle–2 Projections: Inclusive $b \rightarrow sll$

Huber, Ishikawa, Virto '2016

Contours: SM Pull with 50/ab: BR & AFB

Red: Exclusive Fit (arXiv:1510.04239 [hep-ph])
LFUV observables

- example: LHCb+ATLAS+CMS, from $B_s \rightarrow \mu^+\mu^-$, $B^0 \rightarrow K^{*0}\mu^+\mu^-$
RARE KAON DECAYS

- $\text{Br}(K\rightarrow\pi\nu\bar{\nu})$ theoretically very clean

![Diagram showing the dependence of $B(K_L \rightarrow \pi^0 \nu\bar{\nu})$ and $B(K^+ \rightarrow \pi^+ \nu\bar{\nu})$ on $\Delta_L$ or $\Delta_R$]
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![Graph showing $\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})$ and $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$]
RARE KAON DECAYS

\[ \mathcal{B}(K_L \to \pi^0 \nu \bar{\nu}) \]

\[ \mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) \]

NA62

KOTO

MFV:
\[ \text{arg} \, \Delta_L = \text{arg} \, V_{td} V_{ts}^* \]

\[ \Delta_L \text{ or } \Delta_R \text{ only: } \]
\[ |\epsilon_K|_{NP}^{\text{NP}} \propto \text{Im} \, \frac{\Delta_L^2}{M_{\rho}^2} \]

General NP:
\[ \propto \frac{|\Delta_L + \Delta_R| \times |\Delta_L^\mu|}{M_{\rho}^2} \]
Rare kaon decays

- $\beta(K_L \rightarrow \pi^0 \nu\bar{\nu})$ is theoretically very clean

**KOTO Step 2**

**KLEVER**

**NA62 Step 2?**

- $\Delta_L$ or $\Delta_R$ only:
  - $|\epsilon_K|^{NP} \propto \text{Im} \left( \frac{\Delta_L^2}{M_{Z^0}^2} \right)$
- General NP:
  - $\Delta_L + \Delta_R \propto \frac{|\Delta_L^\nu|}{M_{Z^0}^2}$
LIGHT NEW PHYSICS

• flavor observables also probe light NP
  • example: $(g-2)_\mu$ NP models of two types

• chirality flip on SM fermion leg
  • NP need to be light, example: $Z'$

• chirality flip can be on the NP fermion leg
  • NP can be much heavier
  • example: minimal models with DM
**Light New Physics**

- Flavor observables also probe light NP.
  - Example: $(g-2)_\mu$ New Physics
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Heeck, 1602.03810
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DARK MATTER IN RARE DECAYS

- DM could be produced at tree level, if FV couplings
- for flavor diagonal couplings DM can be produced at 1 loop
- X can be (pseudo-)scalar, (axial-) vector mediator
  - can decay to DM or visible

see, e.g., Bird et al, hep-ph/0401195; Kamenik, Smith, 1111.6402
DARK PHOTON

- $U(1)_D$ can have kinetic mixing with hypercharge

$$\mathcal{L}_{\text{vector}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - \frac{\epsilon}{2 \cos \theta_W} F'_{\mu \nu} B_{\mu \nu},$$

- induces couplings of dark photon to the SM, prop.to charge
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CONCLUSIONS

• flavor program expected to significantly improve new physics reach
• probes both high scales and weakly coupled light sectors
BACKUP SLIDES