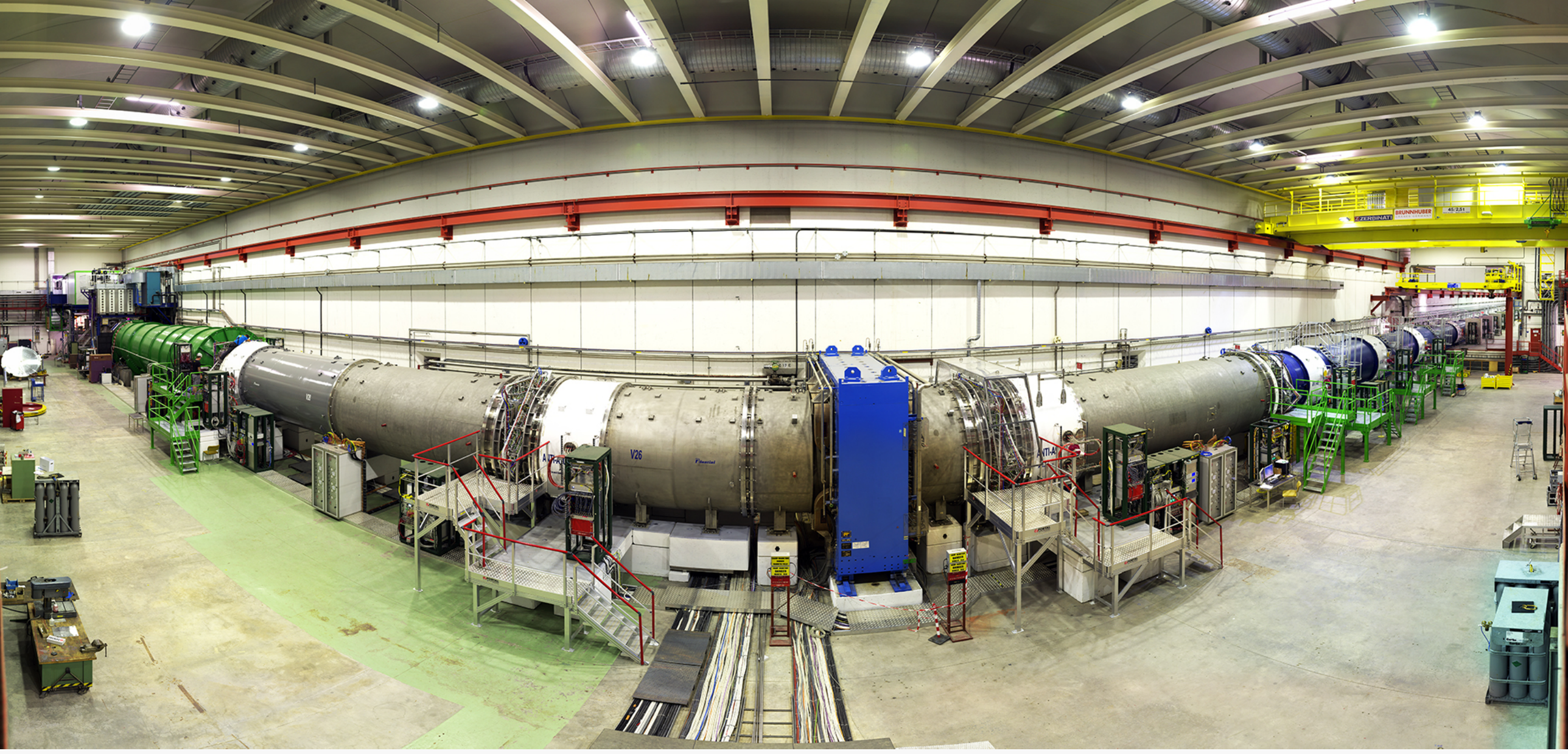

Rare strangeness-changing processes from lattice QCD

Antonin Portelli (RBC-UKQCD)

2nd of October 2020

Snowmass RF2 town-hall meeting

Photo credit: M Brice/CERN-PHOTO-201509-239-1

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Letters of interests

https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF2_RF0-TF5_TF0-CompF2_CompF0_Antonin_Portelli-055.pdf

https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF2_RF0-TF5_TF6-CompF2_CompF0_Norman_Christ-066.pdf

Semi-leptonic rare kaon decays

FCNC $s \to d$ decays

- $K^+ \to \pi^+ \ell^+ \ell^-$
  Long-distance dominated, “easy” to see experimentally.

- $K^0_{L/S} \to \pi^0 \ell^+ \ell^-$
  Long-distance dominated, interesting CP violations.

- $K^+ \to \pi^+ \bar{\nu} \nu$
  Mainly short-distance (top loop), **NA62 Run 1**.
  Long-distance charm effects?

- $K^0_{L/S} \to \pi^0 \bar{\nu} \nu$
  Short-distance (top loop) dominated. KOTO experiment.

Semi-leptonic rare kaon decays

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Lattice

- $K^+ \to \pi^+ \bar{\nu} \nu$

  Mainly short-distance (top loop), **NA62 Run 1**.

  Long-distance charm effects?

- $K^0_{L/S} \to \pi^0 \bar{\nu} \nu$

  Short-distance (top loop) dominated. KOTO experiment.

$K^+ \to \pi^+ \nu\bar{\nu}$ decays

$$\mathrm{Br}(K^+ \to \pi^+ \bar{\nu}\nu) = \kappa \left\{ \left[\frac{\Im\lambda_t}{\lambda^5} X_t \left(\frac{m_t^2}{M_W^2} \right) \right]^2 + \left[\frac{\Re\lambda_c}{\lambda} P_c + \frac{\Re\lambda_t}{\lambda^5} X_t \left(\frac{m_t^2}{M_W^2} \right) \right]^2 \right\}$$

Top loops: short-distance ~68%

Charm loops: short-distance ~29% / long-distance ~3%

- Mainly short-distance through top loops, but potentially up to ~5% long-distance charm effects. **One of the dominant systematics**.

- Lattice aim: precision calculation through direct determination of long-distance effects.

[RBC-UKQCD, PRD 100(11), 114506, 2019] [RBC-UKQCD, PRL 118(25), 252001, 2017]

- **LoI goal: physical lattice calculation of the LD part with uncertainties lower than 30%**

$K \to \pi \ell^+ \ell^-$ decays

- Single form factor, **virtual part poorly known**.

$$V_c(z) = a_c + b_c z + V_c^{\pi\pi}(z) \qquad z = q^2/M_K^2$$

[RBC-UKQCD, PRD 92(9), 094512, 2015]
[RBC-UKQCD, PRD 94(1), 114516, 2016]

- a_c and b_c possibly related to other rare decays in MFV models. [Crivellin et al., PRD 93(7) 074038, 2016]

- **LoI goal:** SM values of a_+, b_+, a_S, and b_S **with 10% precision in the next 5-10 years**.

Precision direct CP violations in kaon decays

- The SM origin of the $\Delta I = 1/2$ rule in $K \to \pi\pi$ decays demonstrated from lattice QCD.
  ε' predicted with 40% accuracy.
  Achievement of decades of lattice QCD research.
  [RBC-UKQCD, arXiv:2004.09440]

- Going forward, the main systematics are **radiative corrections** and **non-perturbative charm effects**.

- $\mathcal{O}(\alpha)$ corrections enhanced 20x by the $\Delta I = 1/2$ rule. Requires important new theoretical developments (radiative corrections to scattering states).

Precision indirect CP violations in kaon decays

- B_K , computed with sub-percent accuracy, gives the short-distance part to ε.

- Main uncertainties are CKM V_{cb} and the long-distance part from $K^0 - \bar{K}^0$ mixing.

- **LoI goal: ~10% accuracy on the long-distance part** achievable within the next decade.

- General formalism similar to semi-leptonic rare kaon decays.

$K_L - K_S$ mass difference

- Well measured $\mathcal{O}(10^{-12})$ MeV energy difference.
- **Sensitive to PeV** scales, but SM values **only known with 36% accuracy**.
- Natural side-product of the $K^0 - \bar{K}^0$ mixing project.
- **LoI goal: 5% accuracy within the next decade.**

[RBC-UKQCD, PRL 113(11), 112003, 2014]

Leptonic rare kaon decays

- $K_L \to \mu^+\mu^-$: **FCNC** $s \to d$ **decays** with significant SM $K_L \to \gamma^*\gamma^* \to \mu^+\mu^-$ long-distance background.

- **LoI goal:**
  ~10% accurate SM amplitude within 5 years

- Significant theoretical progress needed for understanding **multi-local matrix elements**

- First steps ongoing: $K_L \to \gamma\gamma$ and $\pi^0 \to e^+e^-$
  [Christ *et al.*, arXiv:2001.05642]

$\Sigma^+ \to p\ell^+\ell^-$ rare hyperon decays

- "Baryonic version" of $K^+ \to \pi^+\ell^+\ell^-$.
  Never studied on the lattice.

- Poorly know SM contribution because of **challenging baryonic dynamics**.
  [He *et al.*, PRD 72(7), 074003, 2005]

- Observed at HyperCP and LHCb.
  [HyperCP, PRL 94(2), 021801, 2005] [LHCb, PRL 120(22), 221803, 2018]

- 4 unknown form factors.

- **LoI goal:** at least the $q^2 = 0$ values of the 4 form factors **with 10% precision within the next decade**.

Thank you!