Theory Review

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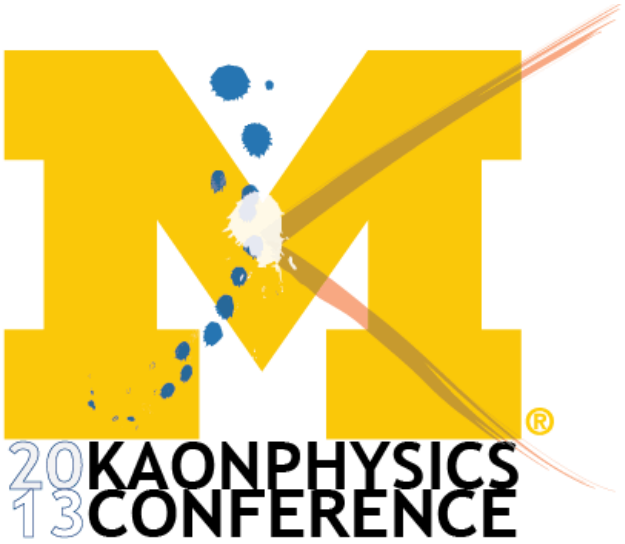
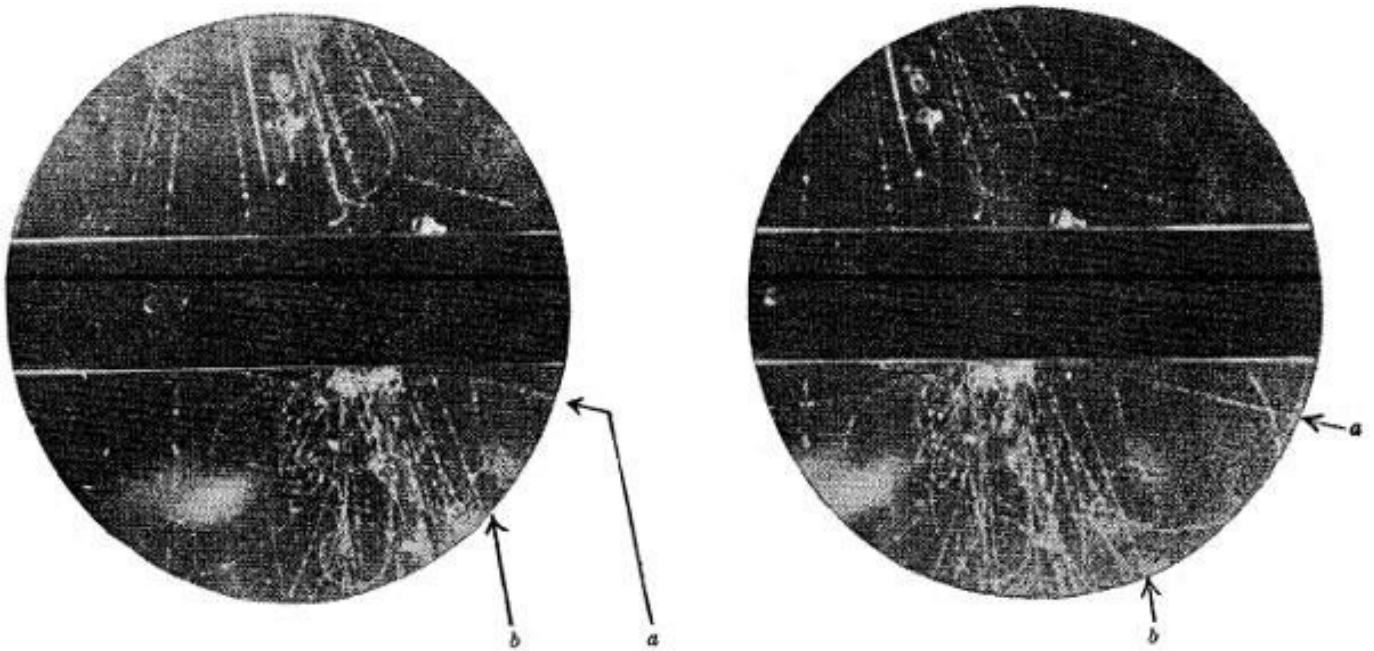
KAON 2013
University of Michigan
Ann Arbor



66 Years of Kaon Physics



$$K_S \to \pi^+ \pi^-$$

Rochester, Butler 1947

cloud chamber, cosmic rays

Grinstein
Kayser

Kaons and the SM

$K_L \to \pi^+ \pi^-$

SU(3)$_F$, quarks, QCD

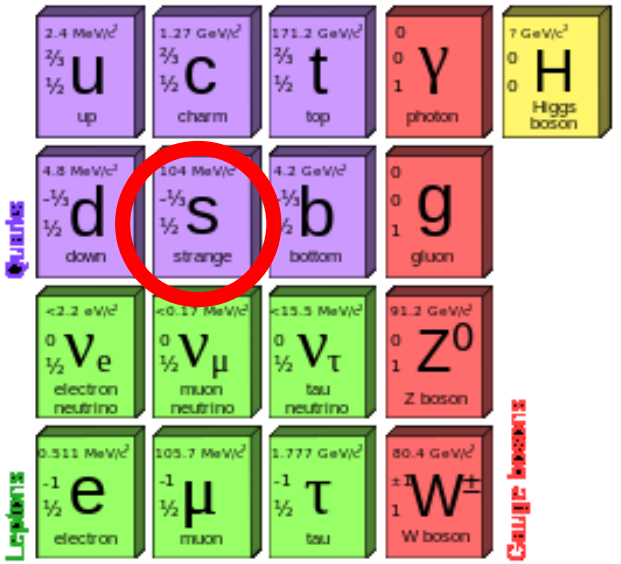
CPV

3 generations

(K_L, B_d, B^+, B_s)

P violation, SU(2)$_L$

$K^+ \to 3\pi, 2\pi$



GIM, FCNC,

$K^0 - \bar{K}^0$, charm

S-quark plays central role

SM as an effective Theory

$$L_{SM,\,eff} = L_{gauge} + L_h + \sum_{d=5,6,\ldots;k} \frac{r_{d,k}}{\Lambda^{d-4}} Q_{d,k}$$

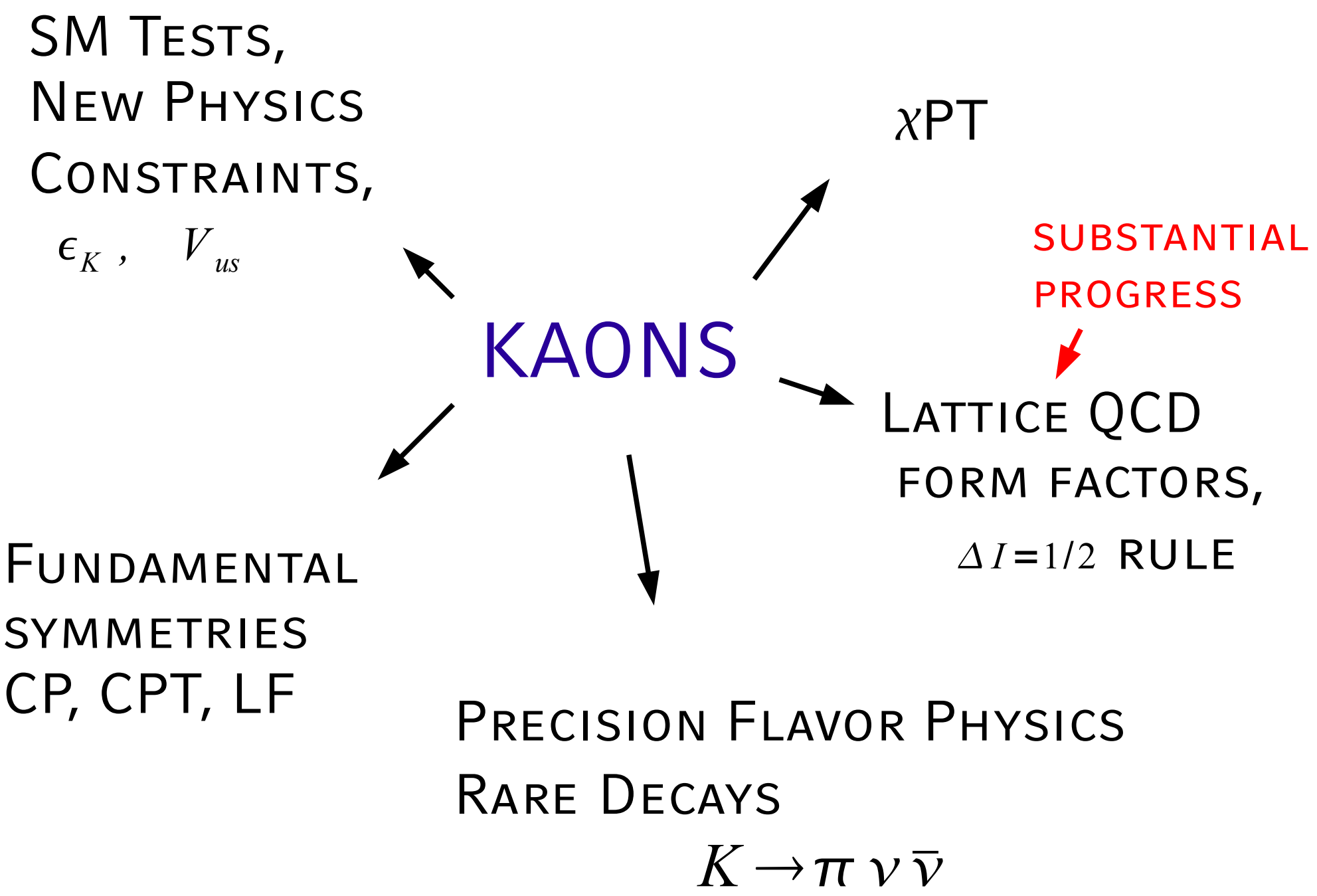
SO FAR

- NO NEW HEAVY PARTICLES
- NO HIGHER-DIM. OPERATORS

NEED HIGH PRECISION $\longrightarrow$ KAONS

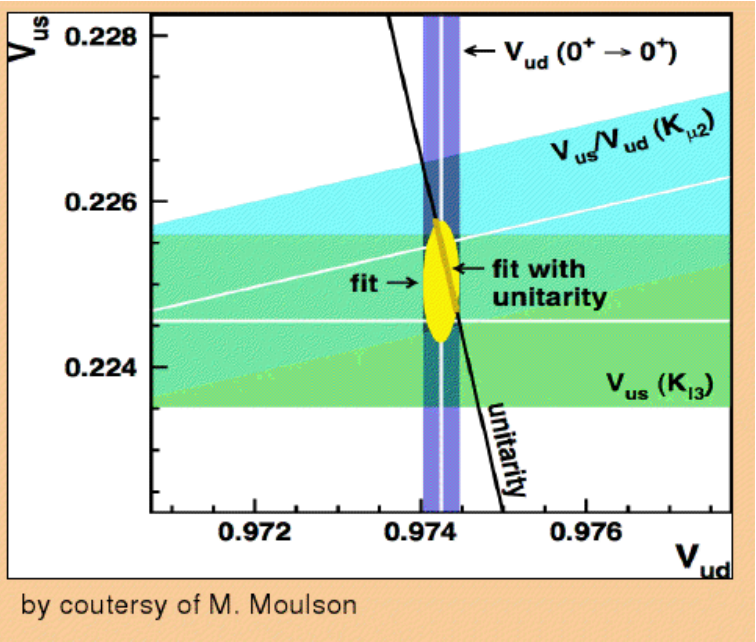
$$\Delta L_{NP} = \frac{c}{\Lambda^2} \bar{d}_L \gamma^\mu s_L \; \bar{d}_L \gamma_\mu s_L \qquad (K - \bar{K})$$

$$\left| M_{12}^{NP} \right| < \left| M_{12}^{SM} \right| \quad \Rightarrow \quad \Lambda > 10^4 \; TeV \; \sqrt{c}$$


SM Tests,
New Physics
Constraints,
ϵ_K , V_{us}
χPT
SUBSTANTIAL
PROGRESS
KAONS
Lattice QCD
form factors,
$\Delta I = 1/2$ rule
Fundamental
symmetries
CP, CPT, LF
Precision Flavor Physics
Rare Decays
$K \to \pi \nu \bar{\nu}$

Unitarity Triangle

Mescia, Lazzeroni



by coutersy of M. Moulson

$$K_{l3},\quad f_+(0) \quad\to\quad |V_{us}| = 0.2246(10)$$

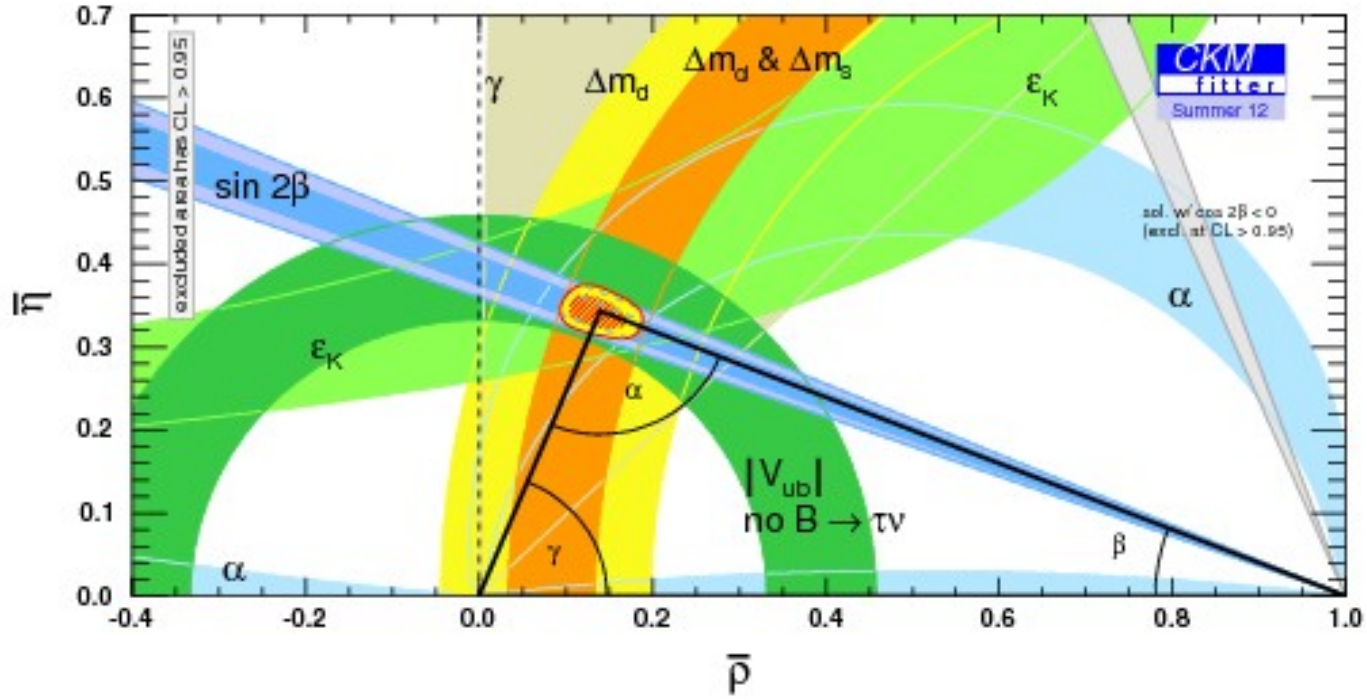
$$K_{l2}/\pi_{l2},\quad f_K/f_\pi \quad\to\quad |V_{us}/V_{ud}| = 0.2315(11)$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.0002\,(6)$$

$$B \to \tau\,\nu,\quad |V_{ub}|$$

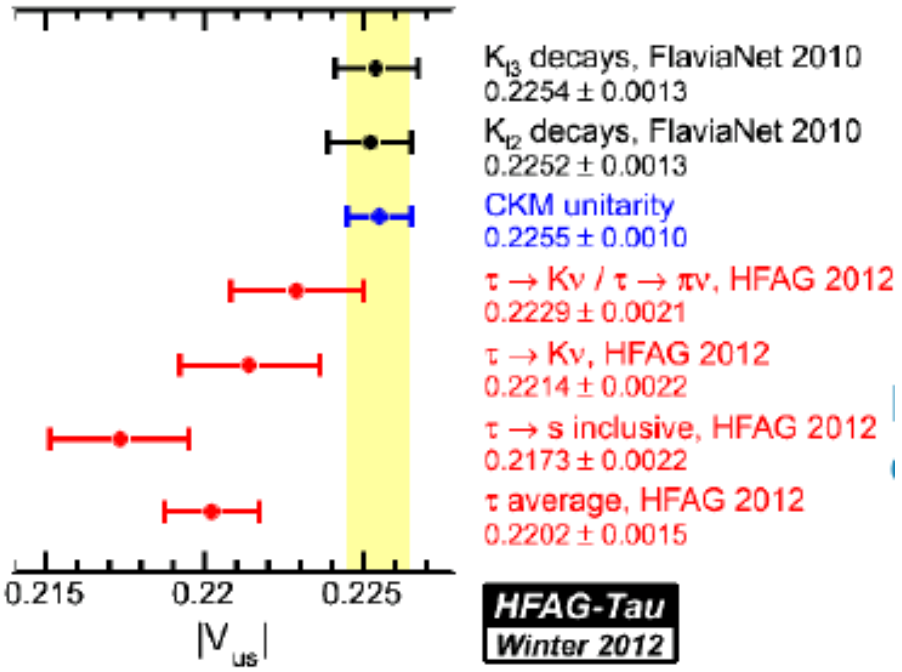
$$\epsilon_K,\quad \sin 2\beta$$

$$B \to D^*\,\tau\,\nu$$



V_{us} from Kaon and Tau Decays

Nugent
Passemar
Raggi
Lubicz



$K\pi$ form factors from $\tau \to K\pi\nu_\tau$, K_{l3} using dispersion relations

Passemar

→ V_{us}

The Golden Modes — SM Theory

$K^+ \to \pi^+ \nu \bar{\nu}$ — top and charm

$BR/10^{-11} = 8.22 \pm 0.69\ (par)\ \pm 0.29$ — Gorbahn

- isospin — Marciano, Parsa; Mescia, Smith
- long distance — hagelin, Littenberg, Lu, Wise; isidori et al.
- NLO QCD — GB, Buras; Misiak, Urban
- NNLO QCD (charm) — Buras, Gorbahn, Haisch, Nierste; Mondejar, Rittinger
- 2-loop electroweak — GB, Buras; Brod, Gorbahn, Stamou

$K_L \to \pi^0 \nu \bar{\nu}$ — direct CPV, top

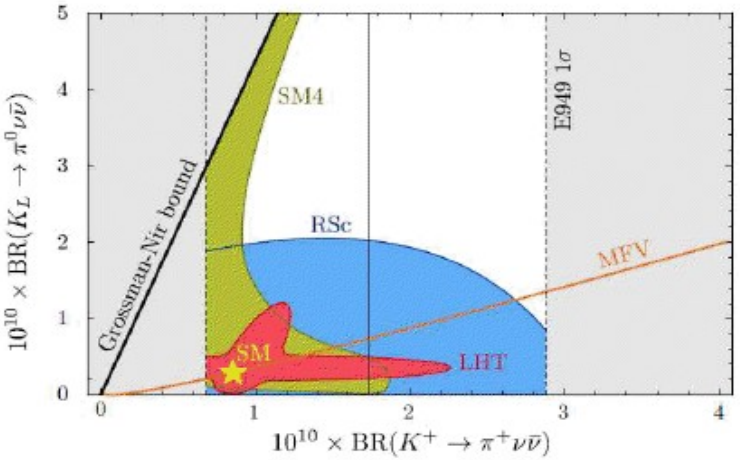
$BR/10^{-11} = 2.43 \pm 0.39\ (par)\ \pm 0.06$

Kaon Physics Beyond the SM

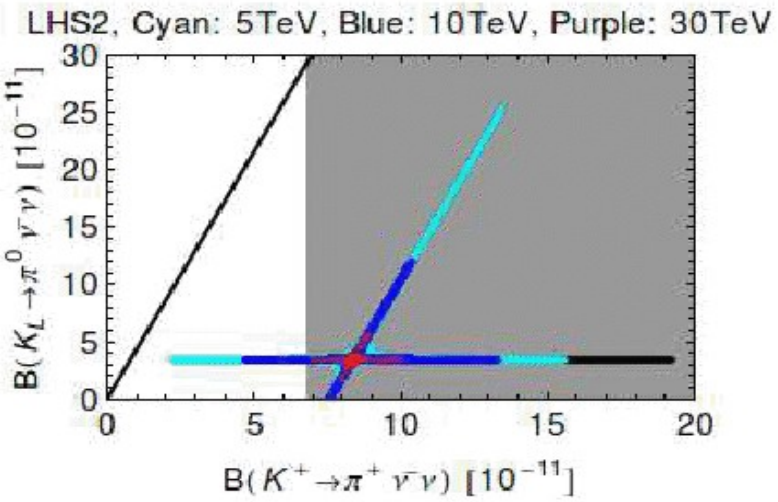
Blanke

- high NP sensitivity $K \to \pi \nu \bar{\nu}$

Blanke et al. (2006,2008), Buras et al. (2010)
figure taken from Straub (2010)



Buras, De Fazio, Girrbach (2012)



- complementary constraints from

$$K \to \pi \nu \bar{\nu}, \quad K_L \to \pi^0 l^+ l^-, \quad \epsilon_K, \quad \epsilon'/\epsilon, \quad \ldots$$

- lepton universality

$$R_K = \Gamma(K \to e\nu)/\Gamma(K \to \mu\nu) \qquad SM: 2.472(1)\cdot 10^{-5} \quad NA62: 2.488(10)\cdot 10^{-5}$$

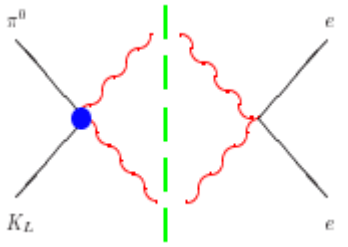
Rare and Radiative Decays

Sachrajda
D'Ambrosio

$K_L \to \mu^+ \mu^-$ $\qquad$ $K_S \to \mu^+ \mu^-$

$K_L \to \pi^0 e^+ e^-$ $\qquad$ $BR_{KTeV} < 2.8 \cdot 10^{-10}$

$$BR_{CPV} = \left[15.3\ a_S^2 - 6.8 \frac{Im\lambda_t}{10^{-4}}\ a_S + 2.8 \left(\frac{Im\lambda_t}{10^{-4}} \right)^2 \right] \cdot 10^{-12}$$



$BR_{CPC} < 3 \cdot 10^{-12}$ $\qquad \leftarrow \qquad$ $K_L \to \pi^0 \gamma \gamma$

$K^+ \to \pi^+ \pi^0 e^+ e^-$

SD info from Dalitz plot distribution

CP asymmetry

Nonleptonic Decays and Chiral PT

ππ scattering phase shifts
isospin breaking matters

Descotes-Genon

Catà
Christ
Dürr

$K \to 2\pi$

(i) $\mathrm{Re}(\epsilon'/\epsilon)$: experiment ahead of theory.

(ii) Silver lining: remarkable progress in the quantitative understanding of the $\Delta I = 1/2$ rule (RBC-UKQCD). Determination of $\mathrm{Re}(\epsilon'/\epsilon)$ in coming years feasible.

(iii) ϵ_K: with inclusion of nonperturbative effects and NNLO perturbative corrections, $|\epsilon_K|_{exp} > |\epsilon_K|_{th}$.

$K \to 3\pi$

T, CPT Violation and forbidden Decays

De Santis
Di Domenico
Moulson

entangled kaons at KLOE
→ improved T and CPT tests

$K_L \to \mu e \qquad LFV$

$K \to \pi \mu e \qquad LFV$

$K^+ \to \pi^- \mu^+ \mu^+ \qquad LNV$

$K \to \mu \nu_h$

$\pi^0 \to invisible$

Kaon Physics: Outlook

Impressive impact on fundamental physics

Rich and diverse field
progress in experiment, theory, lattice

Exciting opportunities with rare decays
in the era of LHC and precision flavor studies

KOTO, NA62, ORKA, Project X, TREK, ...

Gaillard and Lee, March 1974
Rare decay modes of the K mesons in gauge theories

„Owing to the extreme experimental difficulties in carrying out the necessary precision, the predictions ... are well within the presently available experimental upper bounds ...“

$$K^+ \to \pi^+ \nu \bar{\nu} \qquad BR \sim 10^{-10} \qquad BR_{\text{exp}} < 5.6 \times 10^{-7}$$

$$E787/E949 \qquad BR = 1.73^{+1.15}_{-1.05} \times 10^{-10} \qquad (2008)$$

▶ Getting ready for 2014