Future flavour fixed target programme at CERN

110th Plenary ECFA meeting,
22 July 2022, CERN

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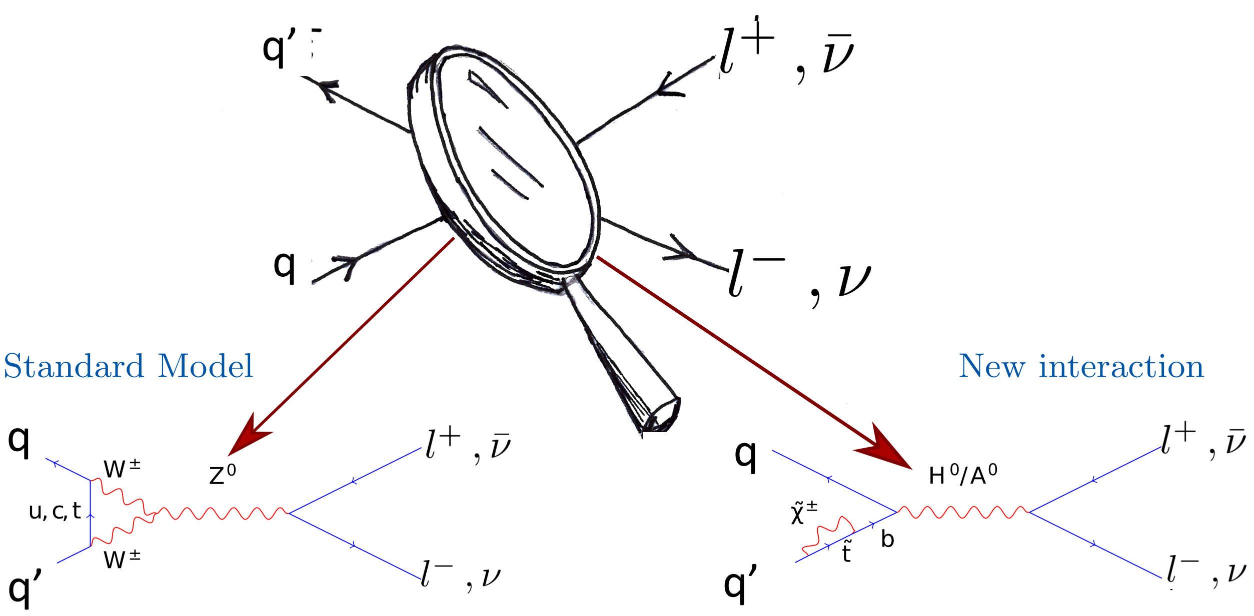
University of Birmingham

Seeking new physics through Flavour



Two strategies:

1) Search for deviations wrt SM predictions

Look for observables:

- (highly) sensitive to contributions of beyond-the-SM physics
- mildly sensitive to hadronic corrections
- accessible experimentally

Specific FCNC processes are examples

2) Search for processes forbidden by (accidental) symmetries of the SM

Very clean probes of new physics

LFV and LNV are examples

Loops are sensitive to the presence of new physics

Rare processes: new interactions can give major contribution

New interactions can have different symmetries than the SM

Over-constraining new interactions and couplings in the entire quark sector – strange, charm, beauty - is crucial to understand their origin

Kaon Experiments in latest European Strategy

Findings of the last European Particle Physics Strategy Group in the deliberation document: **CERN-ESU-014**

“**Rare kaon decays at CERN** and KEK” mentioned in Section 4 as “**Other essential activities for particle physics**”.

Seeking new physics through Kaon decays

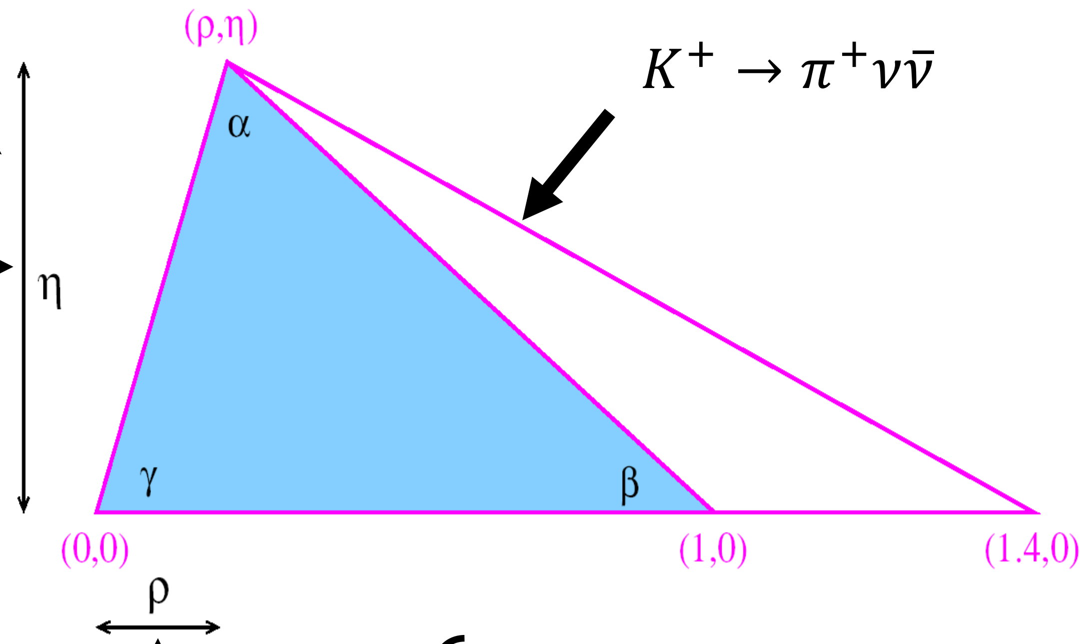
Over-constraining unitary triangle via kaon decays

Crucial compatibility test with B sector

$K_L \to \pi^0 \nu \bar{\nu}$

$$\left.\begin{array}{l} K_S \to \pi^0 l^+ l^- \\ K_L \to \pi^0 \gamma\gamma \\ K_L \to \gamma\gamma l^+ l^- \end{array}\right\} \leftarrow K_L \to \pi^0 l^+ l^-$$

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

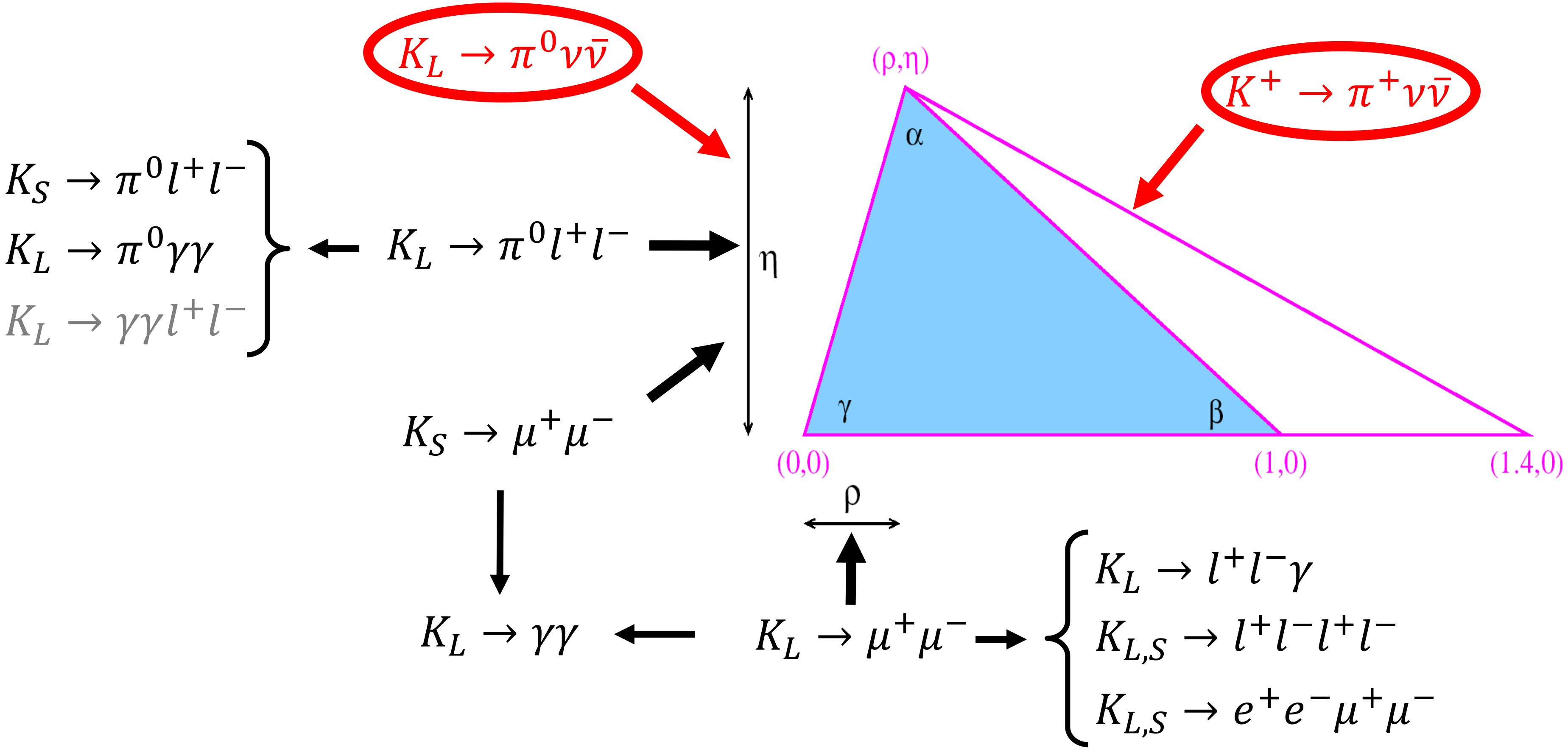


$K^+ \to \pi^+ \nu \bar{\nu}$

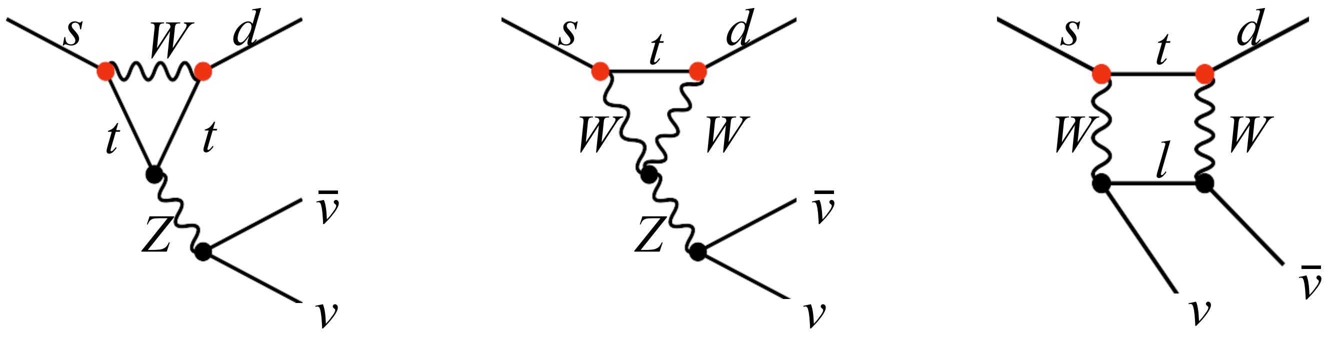
$$K_L \to \gamma\gamma \leftarrow K_L \to \mu^+ \mu^- \to \left\{\begin{array}{l} K_L \to l^+ l^- \gamma \\ K_{L,S} \to l^+ l^- l^+ l^- \\ K_{L,S} \to e^+ e^- \mu^+ \mu^- \end{array}\right.$$

Measuring all charged and neutral rare K decay modes can give clear insight about the new physics flavour structure

The golden channels



Ultra-rare Kaon Decays $K \to \pi \nu \bar{\nu}$



A high-order process with highest CKM suppression:

$A \sim (m_t/m_W)^2 |V_{ts}^* V_{td}| \sim \lambda^5$

Extremely rare decays, rates very precisely predicted in SM

$$\mathrm{BR}(K^+ \to \pi^+ \nu \bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2.8} \cdot \left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$$

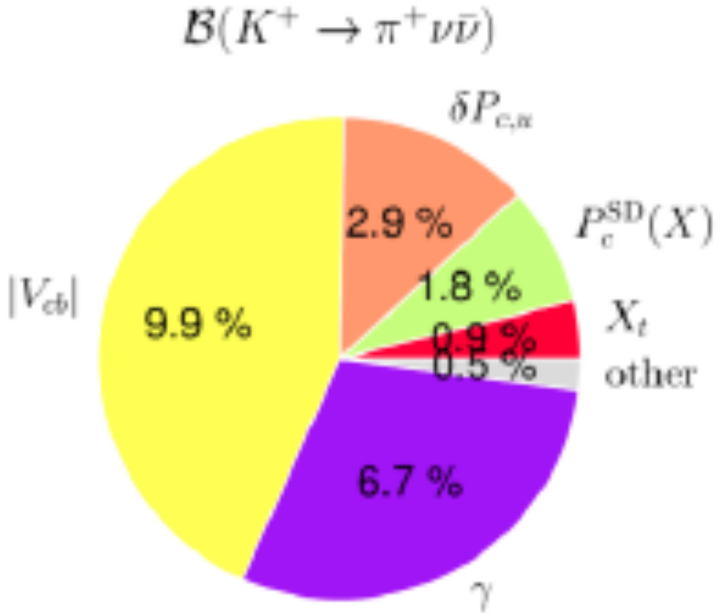
[JHEP 1511 (2015) 033]

$$\mathrm{BR}(K_L \to \pi^0 \nu \bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^2 \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^2 \cdot \left[\frac{\sin\gamma}{\sin 73.2^\circ}\right]^2$$

[arXiv:2203.11960, arXiv:2109.11032]

[arXiv:2105.02868]

“Free” from hadronic uncertainties
Exceptional SM precision



Theoretical error budget

[JHEP 1511 (2015) 033]

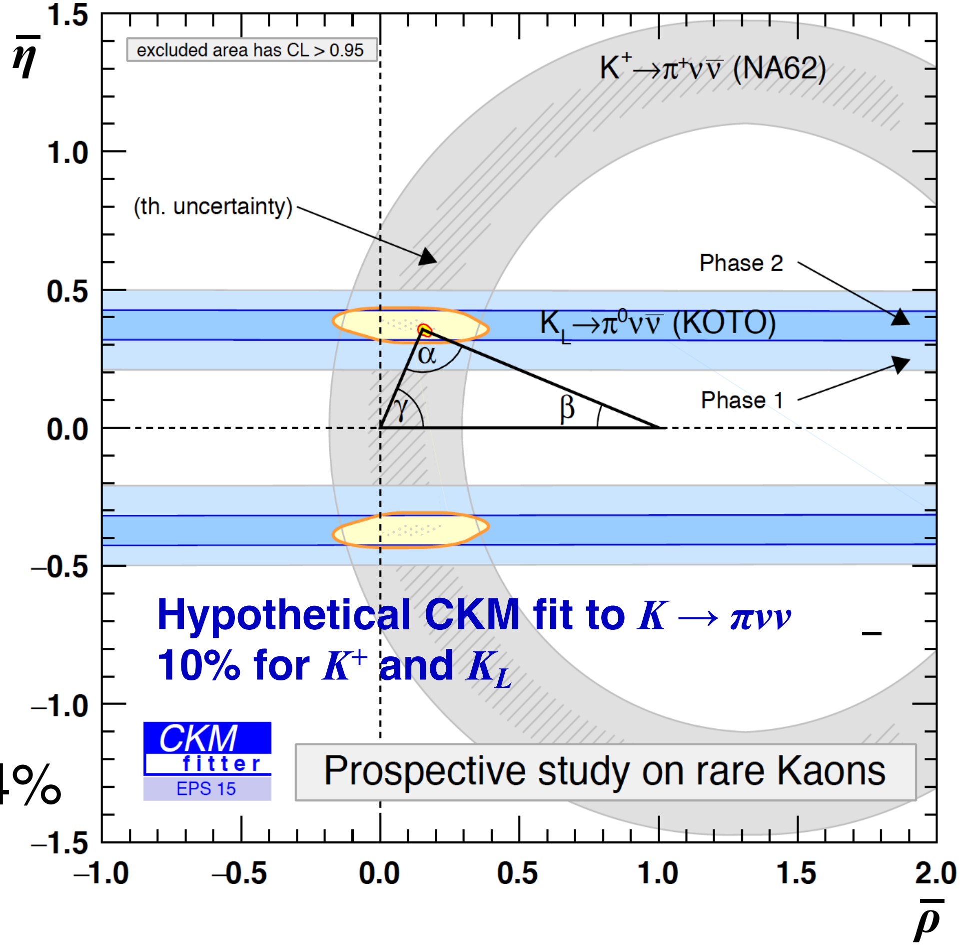
Non-parametric uncertainty: 1.5% for K_L, 3.5% for K^+

$K \to \pi\nu\bar{\nu}$ and flavour

Use measurements in global fit in order to factor out parametric uncertainties.

Or find combination of parameters that are less / not sensitive to New Physics: approach proposed recently to eliminate dependence on V_{cb} and γ leads to 5% precision

[arXiv:2203.11960, arXiv:2109.11032]



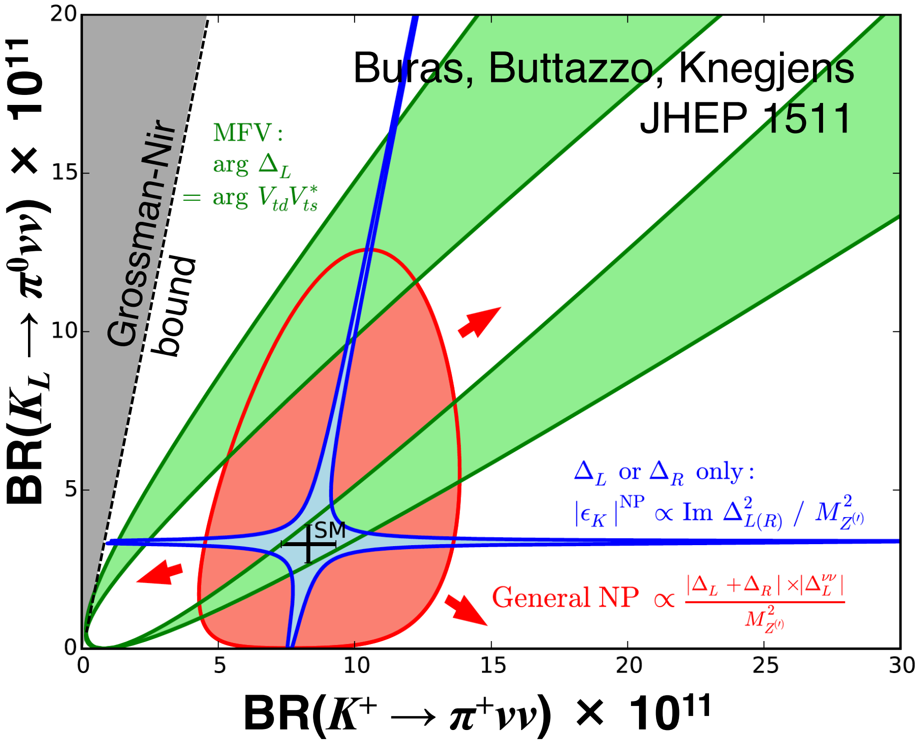
SM predictions accuracy expected to improve to about 3-4% over the next decade, due to lattice QCD progress on the charm contribution [arXiv:1806.11520, arXiv:1910.10644] and reduction of the external parametric uncertainties

Clear opportunity in the kaon sector

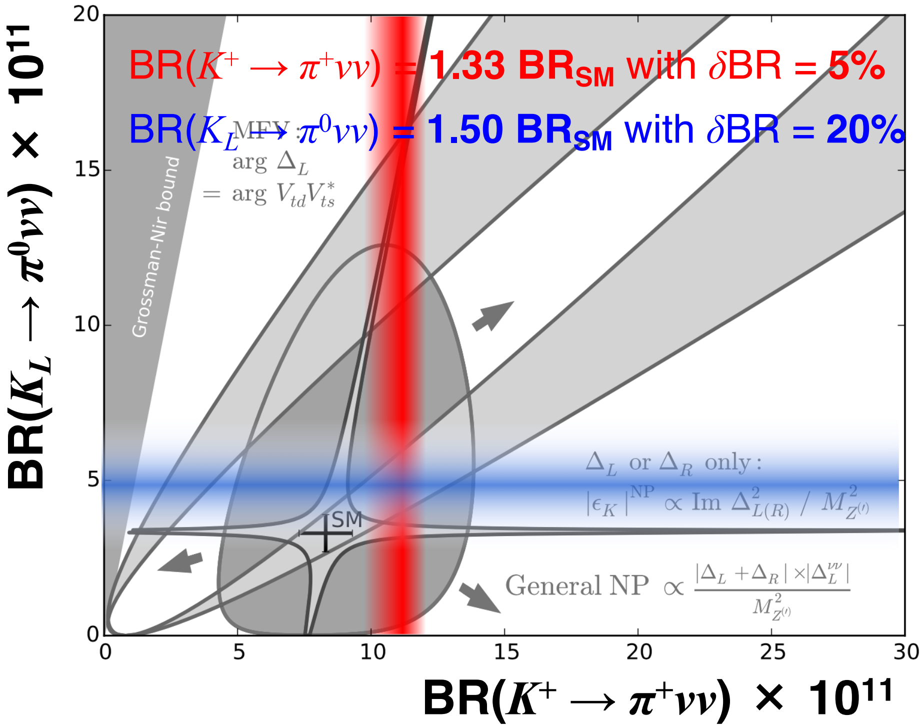
NA62 will measure $K^+ \to \pi^+ \nu\nu$ with O(10%) precision with Run1&2 data

After LS3, experiments to approach theory error and show possible evidence of deviation from SM

High sensitivity to NP (non-MFV): significant variations wrt SM
New physics affects K^+ and K_L BRs differently
Measurements of both can discriminate among NP scenarios
Weak constraints from other observables



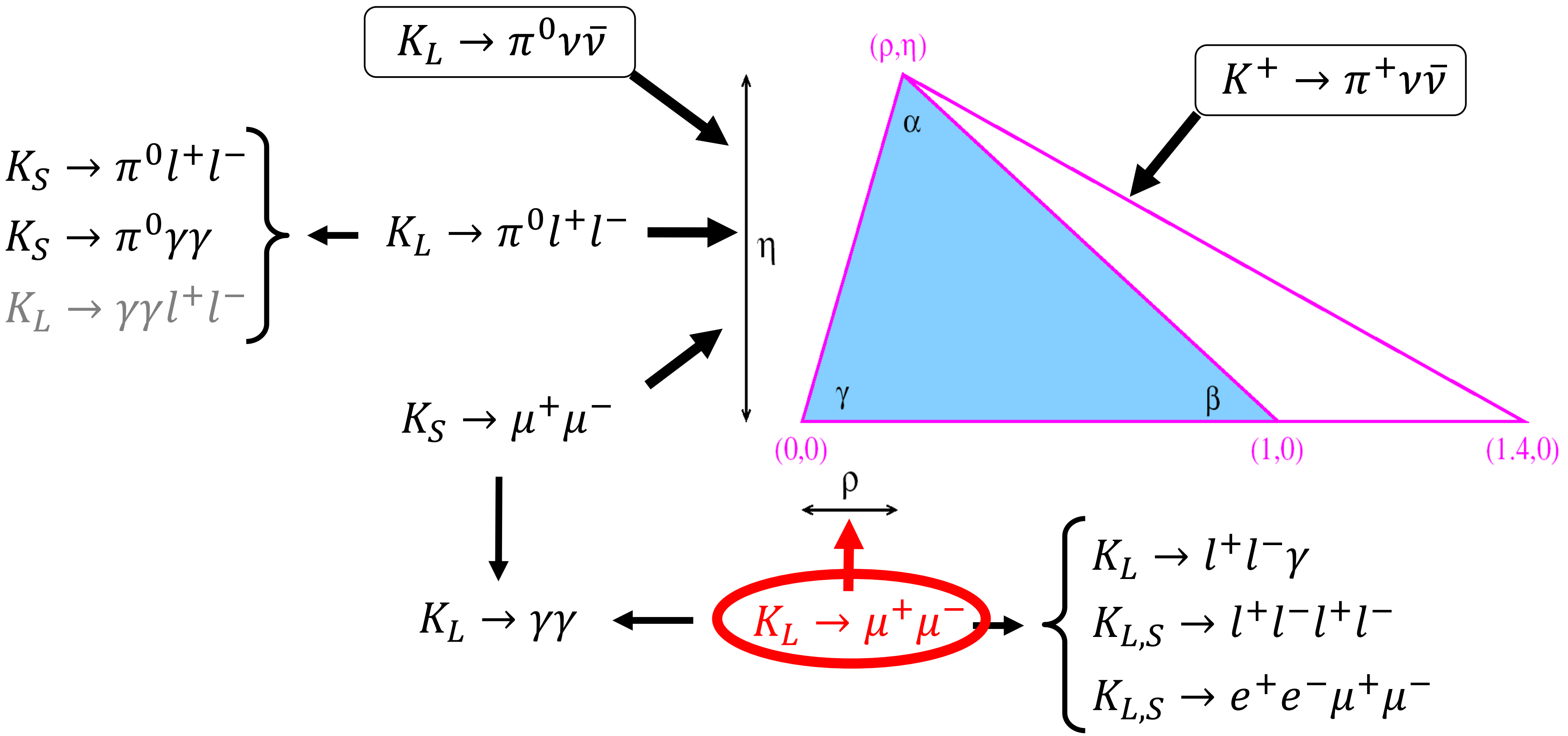
- Models with CKM-like flavor structure
  - Models with MFV
- Models with new flavor-violating interactions in which either LH or RH couplings dominate
  - Z/Z' models with pure LH/RH couplings
  - Littlest Higgs with T parity
- Models without above constraints
  - Randall-Sundrum



Going beyond 10% measurement on $K \to \pi+\nu\nu$
Precision measurements of $K \to \pi\nu\nu$ BRs provide model-independent tests for NP with sensitivity to **O(100) TeV scale**

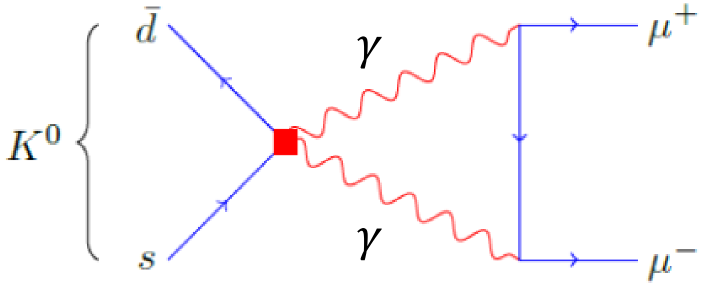
[JHEP 1511 (2015) 166, EPJ C76 (2016) 182, JHEP 0903 (2009) 108, PEPT 2016 123802, JHEP 0608 (2006) 064, EPJ C77 (2017) 618, arXiv:1705.10729, arXiv:2207.00018, arXiv:2203.09524]

Rare Kaon decays and the CKM

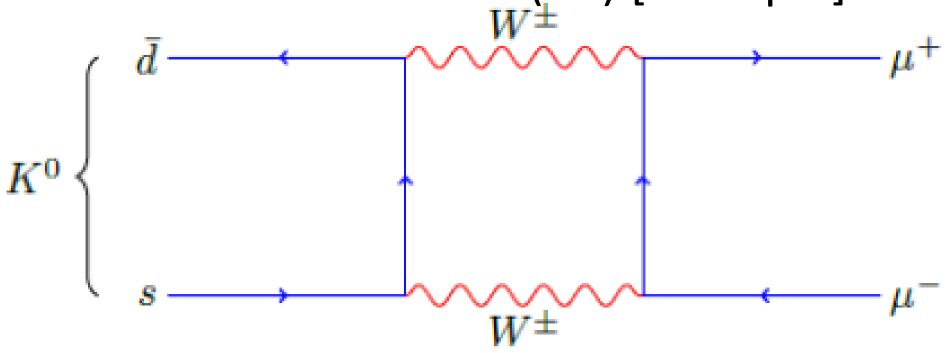


$K^0 \to \mu^+\mu^-$

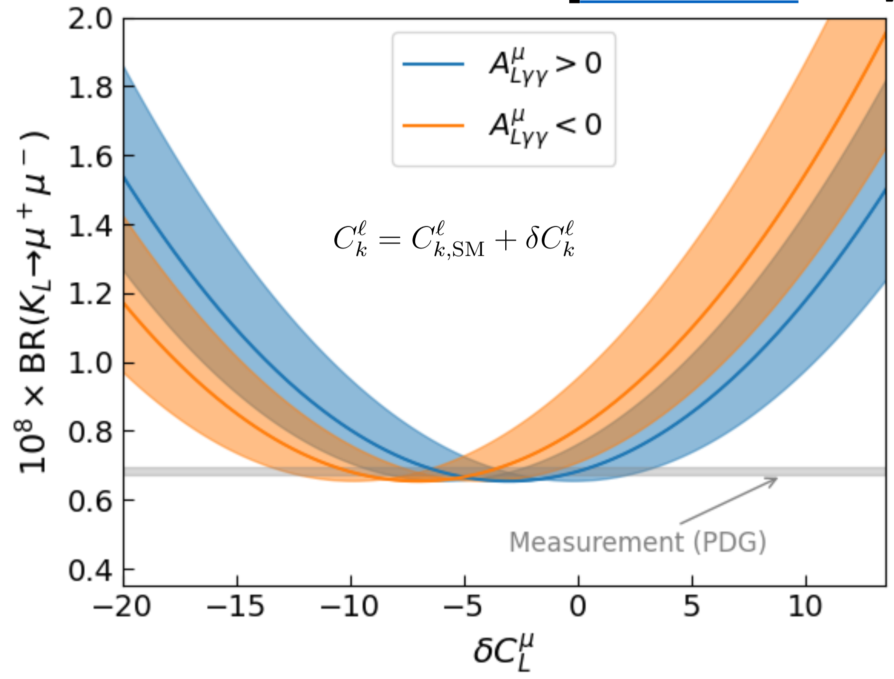
Long distance (LD)



Short distance (SD) [example]



[arXiv:2206.14748]



$\mathcal{B}(K_L \to \mu^+\mu^-)_{SM} \propto \left|A_L^{LD} + A_L^{SD}\right|^2, \left|A_L^{SD}\right|^2 \propto |1-\bar{\rho}|^2$

[Buras, and Fleisher,
Adv. Ser. Direct. High Energy Phys. 15, 65 (1998)]

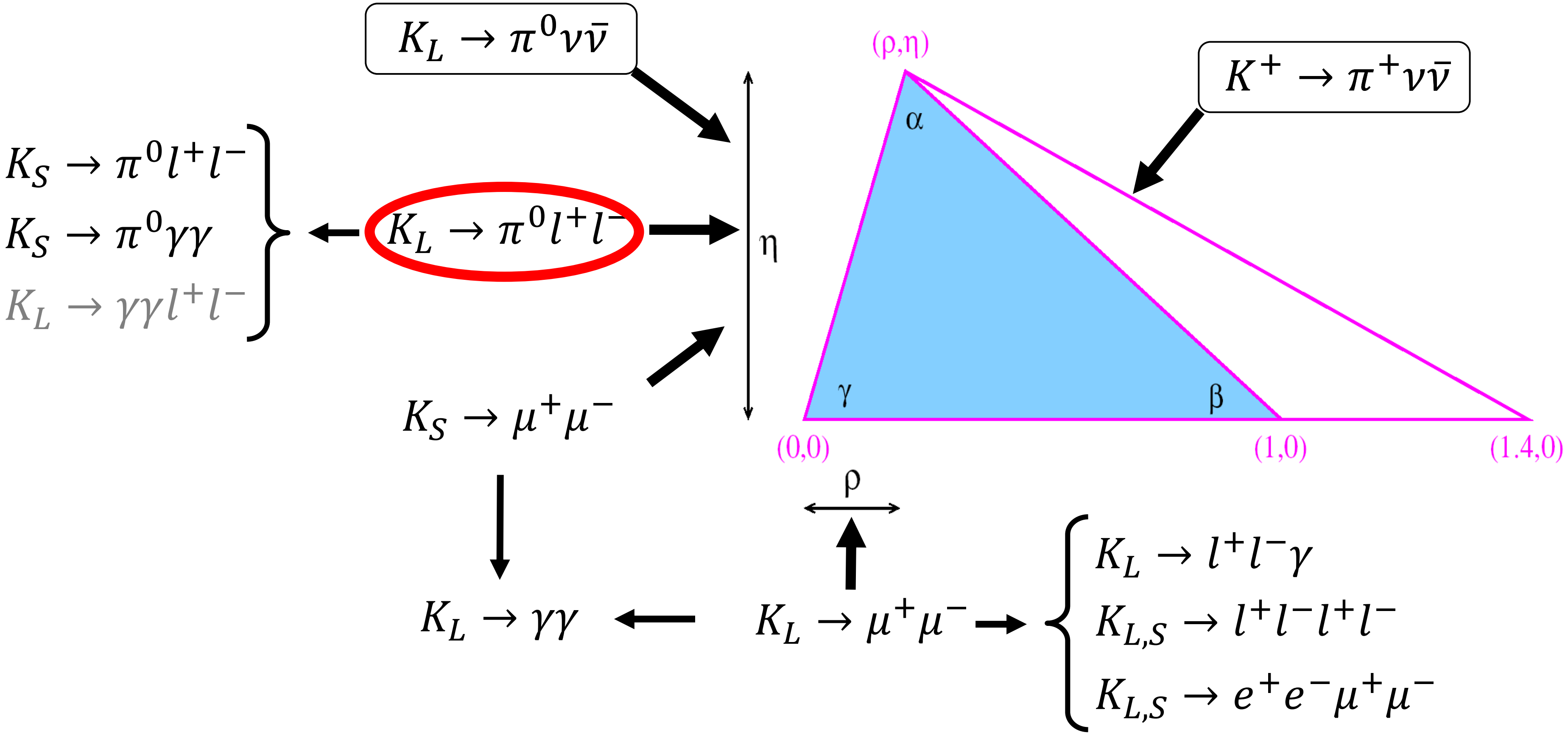
- $\mathcal{B}(K_L \to \mu^+\mu^-)_{meas} = (6.84 \pm 0.11)\times 10^{-9} \sim \left|A_L^{LD}\right|^2$

[PRL 84, 1389 (2000) [B871]

- Prediction depends on the sign of the $K_L \to \gamma\gamma$ amplitude

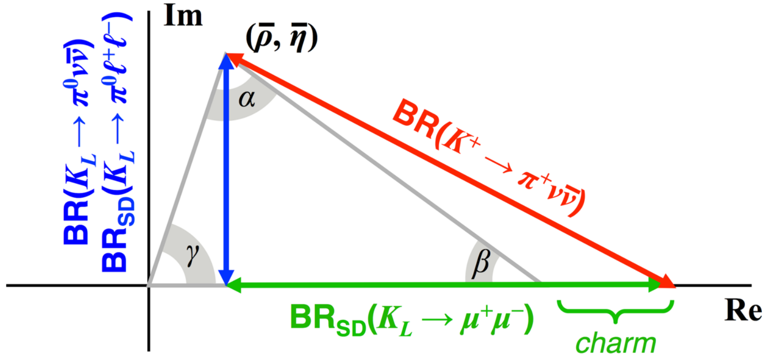
that determines the effect of the SD – LD interference contribution

Rare Kaon decays and the CKM



$K_L \to \pi^0 \ell^+ \ell^-$

- Contributions from long-distance physics
  - SD CPV amplitude: γ/Z exchange
  - LD CPC amplitude from 2γ exchange
  - LD indirect CPV amplitude: $K_L \to K_S$
- $K_S \to \pi^0 \ell^+ \ell^-$ will help reducing theoretical uncertainties
  - measured NA48/1 with limited statistics
  - planned by LHCb Upgrade
- $K_L \to \pi^0 \ell^+ \ell^-$ can be used to explore helicity suppression in FCNC decays



$K_L \to \pi^0 \ell^+ \ell^-$ CPV amplitude constrains UT in same way as BR$(K_L \to \pi^0 \nu\nu)$

Experimental status:
BR$(K_L \to \pi^0 e^+ e^-) < 28 \times 10^{-11}$
BR$(K_L \to \pi^0 \mu^+ \mu^-) < 38 \times 10^{-11}$

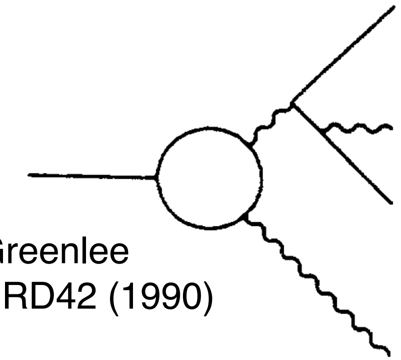
Phys. Rev. Lett. 93 (2004) 021805
Phys. Rev. Lett. 84 (2000) 5279–5282

Main background: $K_L \to \ell^+ \ell^- \gamma\gamma$

- Like $K_L \to \ell^+ \ell^- \gamma$ with hard bremsstrahlung

BR$(K_L \to e^+ e^- \gamma\gamma) = (6.0 \pm 0.3) \times 10^{-7}$ $\quad E_\gamma^* > 5$ MeV

BR$(K_L \to \mu^+ \mu^- \gamma\gamma) = 10^{+8}_{-6} \times 10^{-9}$ $\quad m_{\gamma\gamma} > 1$ MeV



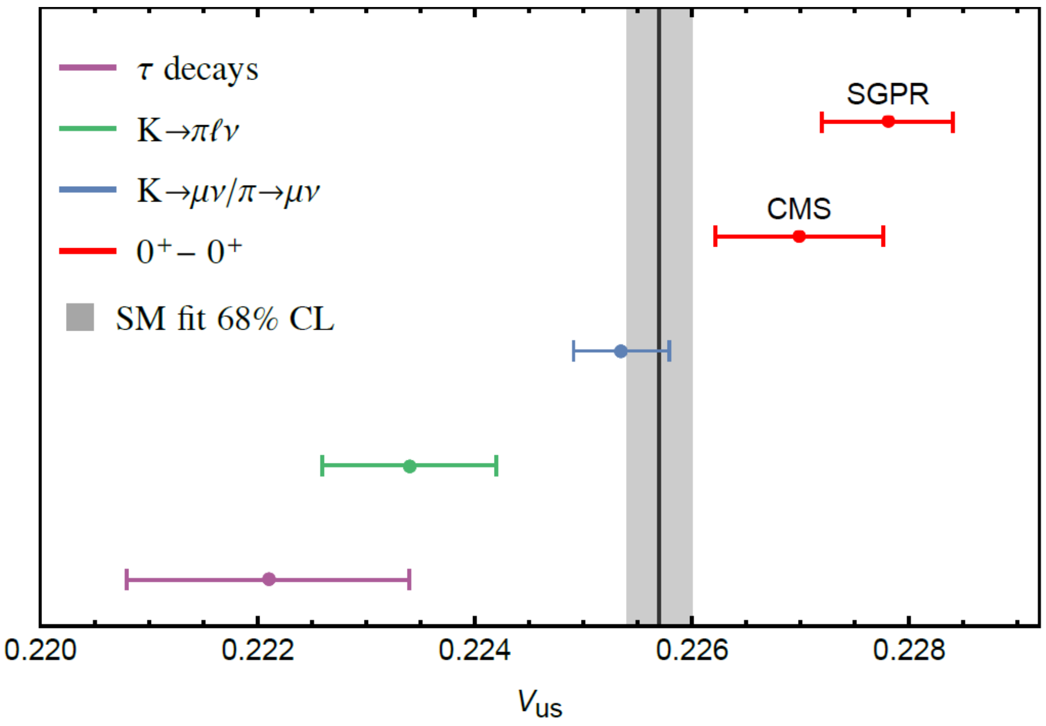
Greenlee
PRD42 (1990)

Cabibbo Angle Anomaly

Slide from talk by
Andreas Crivellin
La Thuille 2022

Cabibbo Angle Anomaly

- V_{ud} from super-allowed beta decays
- V_{us} from Kaon and tau decays
- Disagreement leads to a (apparent) violation of CKM unitarity



CMS, SGPR: radiative corrections

$$\left|V_{ud}^2\right|+\left|V_{us}^2\right|+\left|V_{ub}^2\right|=0.9985\pm0.0005,\ \left|V_{ud}^2\right|+\left|V_{cd}^2\right|+\left|V_{td}^2\right|=0.9970\pm0.0018$$

Deficits in 1th row and column CKM unitarity

Test of Lepton Universality and Explicit SM Violation

Search for LFV and/or LNV (before ICHEP 2020):

$K^+ \to \pi^+\mu^+\mu^-$ vs $K^+ \to \pi^+e^+e^-$, $R_K \equiv \Gamma(K^+ \to e^+\nu)/\Gamma(K^+ \to \mu^+\nu)$

PDG 2022

LFV mode	90% CL upper limit	Experiment	Yr./Ref.	Type
$K^+ \to \pi^+ e^- \mu^+$	1.3×10^{-11}	BNL-865	2005/ [16]	LFV
$K^+ \to \pi^+ e^+ \mu^-$	6.6×10^{-11}	NA62	2021/ [17]	LFV
$K_L \to \mu e$	4.7×10^{-12}	BNL-871	1998/ [18]	LFV
$K_L \to \pi^0 e\mu$	7.6×10^{-11}	KTeV	2008/ [19]	LFV
$K_L \to \pi^0\pi^0 e\mu$	1.7×10^{-10}	KTeV	2008/ [19]	LFV
$K^+ \to \pi^- e^+ e^+$	5.3×10^{-11}	NA62	2022/ [20]	LNV
$K^+ \to \pi^-\pi^0 e^+ e^+$	8.5×10^{-10}	NA62	2022/ [20]	LNV
$K^+ \to \pi^- \mu^+ \mu^+$	4.2×10^{-11}	NA62	2019/ [21]	LNV
$K_L \to e^\pm e^\pm \mu^\mp \mu^\mp$	4.12×10^{-11}	KTeV	2003/ [22]	LNV
$K^+ \to \pi^- \mu^+ e^+$	4.2×10^{-11}	NA62	2021/ [17]	LNFV

Search for feably interacting particle production: $K^+ \to l^+N$, $K^+ \to \pi^+X$, ...

$K^+ \to \pi^+ l^+ l^-$

[arXiv:2206.14748]

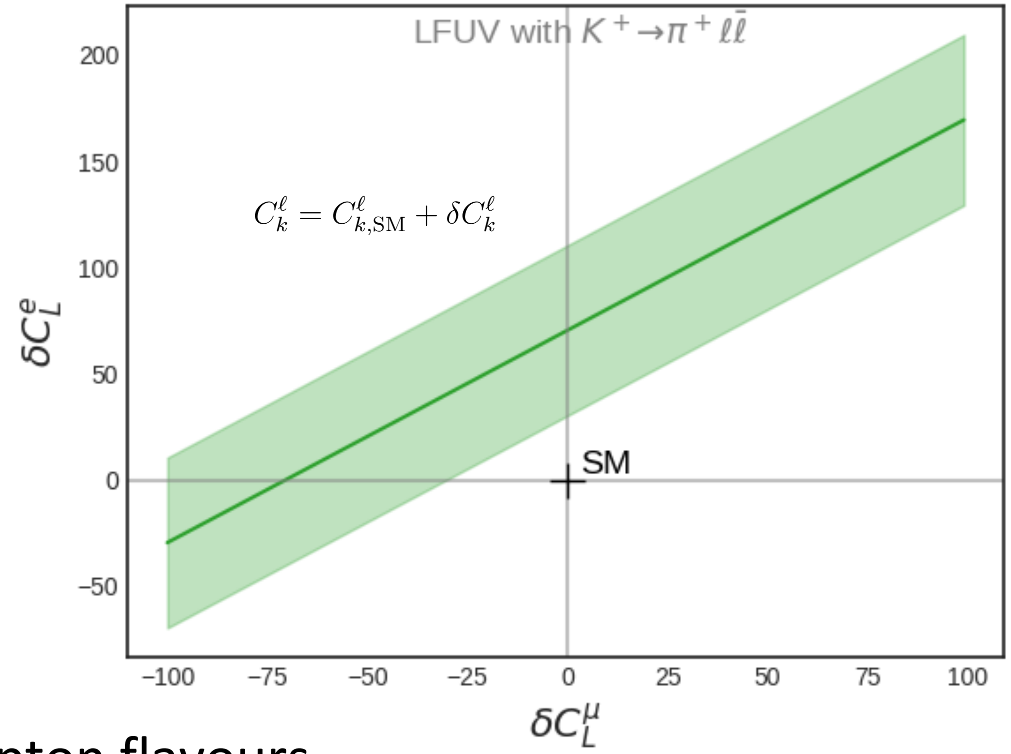
LD dominated, mediated by $K^+ \to \pi^+ \gamma^*$

$$d\Gamma/dz \propto G_F M_K^2 (a + bz) + W^{\pi\pi}(z)$$

$z = m(l^+ l^-)^2 / M_K^2$

Form factors (FF)
(non pert. QCD)

$K_{3\pi}$ loop term



Long-distance effects are purely universal and same for all lepton flavours

Lepton universitality (LU) predicts same a, b for $l = e, \mu$

$$a_+^{\mu\mu} - a_+^{ee} = -\sqrt{2}\,\mathrm{Re}\left[V_{td}V_{ts}^*(C_9^\mu - C_9^e)\right]$$

Long-distance contribution to the difference cancels out and is sensitive only to short-distance effects

Difference correlated to possible anomalies in B physics

[JHEP 02 049 (2019), PRD 93 074038 (2016)]

Kaon Global Fit

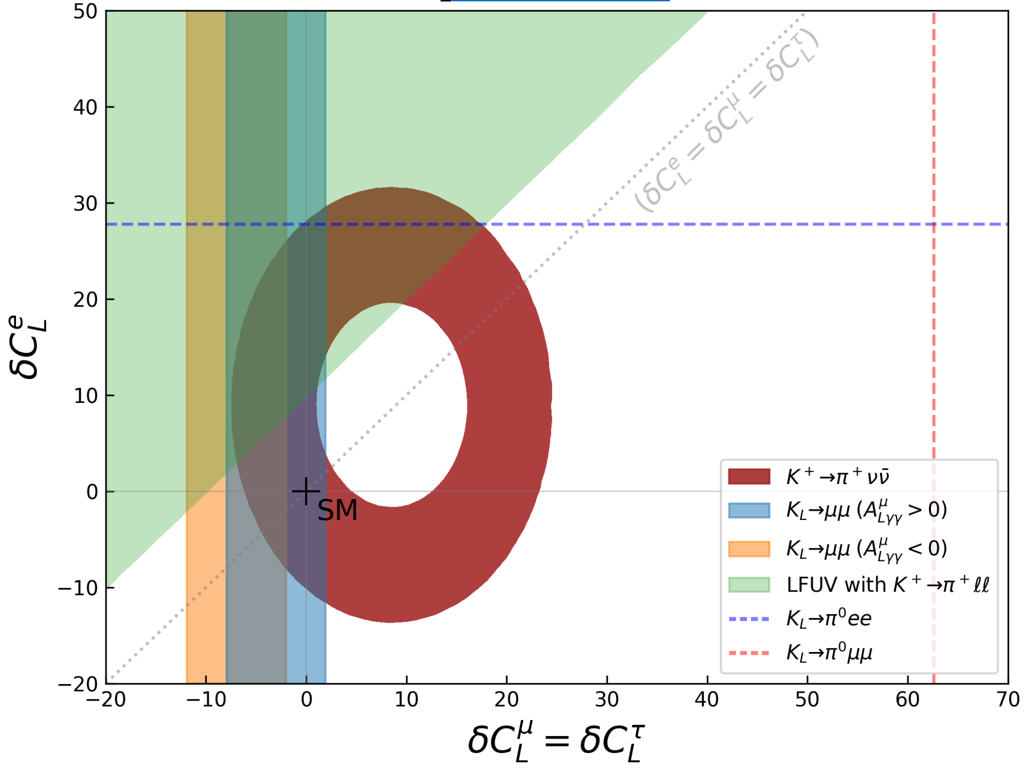
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}\lambda_t^{sd}\frac{\alpha_e}{4\pi}\sum_k C_k^\ell O_k^\ell$$

$$O_L^\ell = (\bar{s}\gamma_\mu P_L d)\,(\bar{\nu}_\ell\,\gamma^\mu(1-\gamma_5)\,\nu_\ell)$$

$$C_k^\ell = C_{k,\rm SM}^\ell + \delta C_k^\ell$$

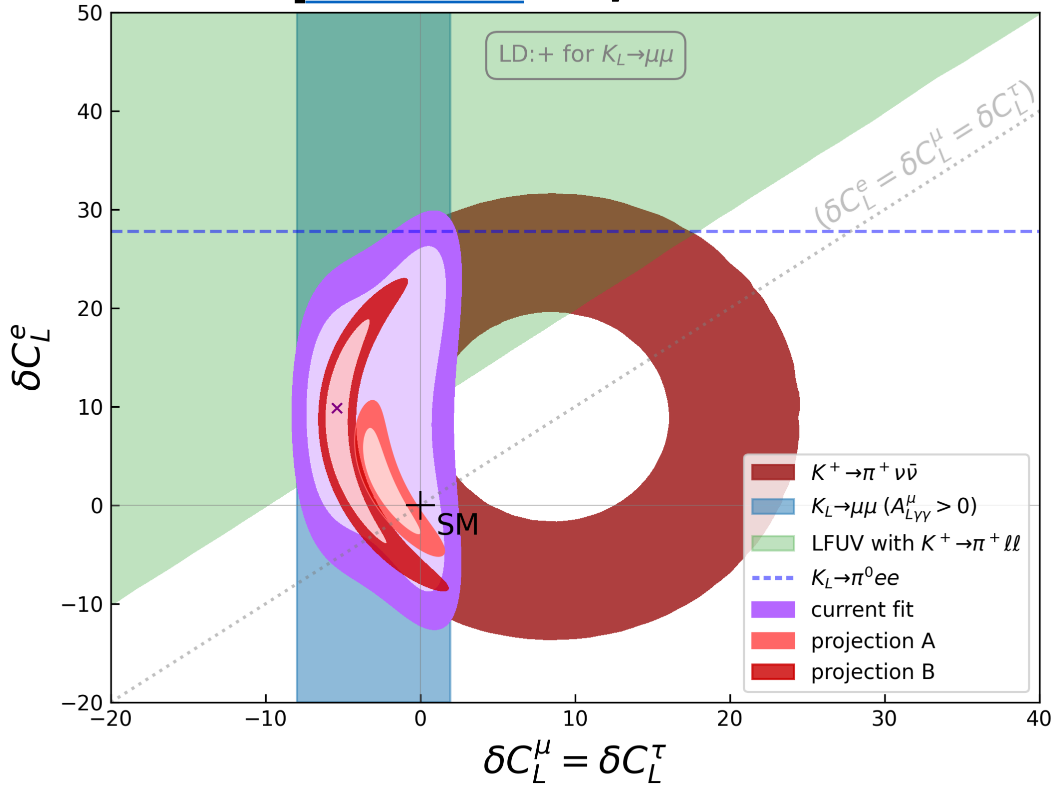
For example, recent paper with global fits to set of kaon measurements
Deviation of Wilson coefficients from SM, for NP scenarios with only left-handed quark currents.

[arXiv:2206.14748]



Bounds from individual observables.
Coloured regions are 68%CL measurements
Dashed lines are 90%CL upper limits

[arXiv:2206.14748]

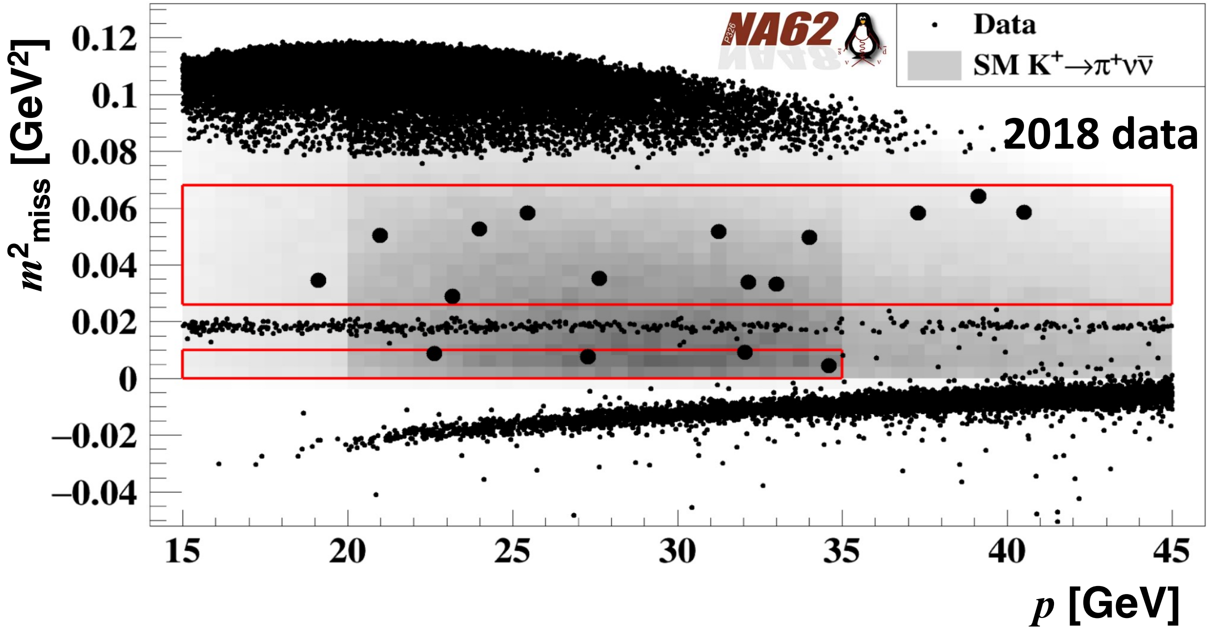


With projections: central value for existing measurements kept the same, A upper bounds extrapolated to central value consistent with SM, B central value of all observables is projected to the best-fit points obtained from fits to existing data

NA62 through LS3

Summary of NA62 Run 1 (2016-2018):

- **Expected signal (SM): 10 events**
- **Expected background: 7 events**
- **Total observed: 20 events**
    - 3.5σ signal significance
    - Most precise measurement to date



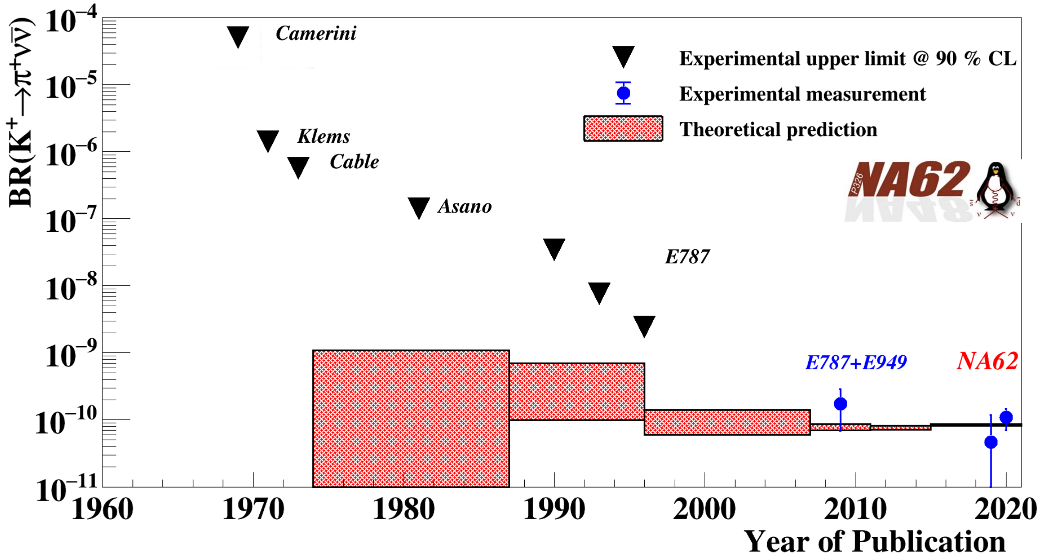
$\mathrm{BR}(K^+ \to \pi^+ \nu\nu) = (11.0\ ^{+4.0}_{-3.5\ \mathrm{stat}} \pm 0.3_{\mathrm{syst}}) \times 10^{-11}$ [JHEP 06 (2021) 093]

NA62 Run 2 (from 2021 to LS3):

Key modifications to reduce background:

- Rearrangement of beamline elements around GTK achromat
- 4th station to GTK beam tracker
- New veto hodoscope upstream of decay volume and veto counters around downstream beam pipe

Higher beam intensity (70% → 100%), control random veto



Measure $\mathrm{BR}(K^+ \to \pi^+ \nu\nu)$ to O(10%) by LS3

High-Intensity Kaon Experiments (HIKE) at the SPS

Broad programme with multiple phases, K^+ + K_L beams and dump mode.
Exceptional sensitivity to discovery new physics:
Rare K decays, precision measurements , exotic particles in K/dump
FCNC in K are complementary to B in testing LFUV with comparable sensitivity

Long-term Kaon Physics Programme in NA-ECN3 from end of LS3
High-rate beam of 1.5-2 10^{13} protons on target over 4.8 sec spill.
Best possible duty cycle. Good spill quality. Unseparated secondary hadron beam.
1.3 10^{19} POT/year

Compatible with a diverse program in the North Area

HIKE timeline

Step 1, from the end of LS3: K^+
Approach ultimate theory error in $K^+ \rightarrow \pi^+ \nu\nu$ decays, flavour physics with K^+ , + dump.
New and upgraded detectors
Step 2: switch to neutral mode
Transition: K_L rare decays with tracking & PID. Periodic dump mode.
Step 3: neutral mode
$K_L \rightarrow \pi^0 \nu\nu$ decays with specific modifications for background rejection (K_LEVER)

HIKE Physics Program

$K^+ \to \pi^+ \nu\bar{\nu}$	$\sigma(BR) \sim 5\%$	New physics (also LFUV)
$K^+ \to \pi^+ l^+ l^-$	$<$ % precision form factors	LFUV
$K^+ \to \pi\mu e, \pi ee$	Sensitivity $O(10^{-12})$	LFV / LNV
K^+ semileptonics, main decay modes	$\sigma(BR) \sim 0.1\%$	V_{us} - unitarity
$R^K_{e\mu} = \Gamma(K^+ \to e\nu)/\Gamma(K^+ \to \mu\nu)$	$\sigma(R^K_{e\mu}) \sim 0.1\%$	LFUV
ancillary K^+ decays **($K^+ \to \pi^+\gamma\gamma, \pi^+\pi^0\gamma, \pi^+\pi^0 ee$, …)**	as good as possible	Chiral parameters (LECs)
$K_L \to \pi^0 l^+ l^-$	Observation	New physics (also LFUV)
$K_L \to \mu^+\mu^-$	$\sigma(BR) \sim 1\%$	Ancillary for $K \to \mu\mu$ physics
$K_L \to \mu e$	Sensitivity $\mathrm{O}(10^{-12})$	LFV
K_L semileptonics, main decay modes	$\sigma(BR) \sim 1\%$	V_{us} - unitarity
ancillary K_L decays **($K_L \to \gamma\gamma, \pi^0\gamma\gamma$, …)**	as best as possible	Chiral parameters (LECs)
$K_L \to \pi^0 \nu\bar{\nu}$ $(KLEVER)$	$\sigma(BR) \sim 20\%$	New physics (also LFUV)

Feebly interacting particles (dump phase)

Physics goals for operation in dump mode:

Search for visible decays feebly-interacting new-physics particles

x10 statistics improvement expected with respect to samples available by LS3

If no signal and negligible background → **x10 sensitivity improvement in a unique region**

Dump mode is most sensitive to forward processes, complimentary to off-axis experiments

Advantages of Kaon experiments:

Long decay volume and detector characteristics/performances suitable to search for **feebly-interacting long-lived particles**

Extend Dark Particle mass range > M(K) (D, B associated production)

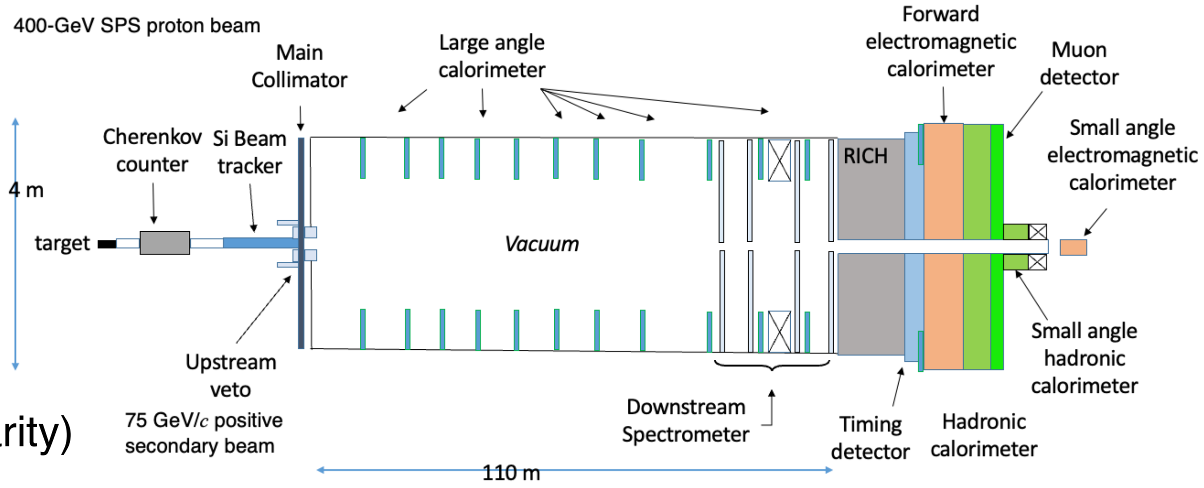
Low rate in detector allows for potentially much higher beam intensity

HIKE design

K^+ : phase 1

- Decay in flight technique, experience from NA62 and similar layout
- Essential K^+ ID, momentum, space and time
- High-rate, precision tracking of pion
- Minimize material
- Highly efficient PID for photons, pions, electrons and muon vetoes
- Highly efficient and hermetic photon vetoes
- High-performance EM calorimeter (energy resolution, time, granularity)

***HIKE-K+* Conceptual sketch**



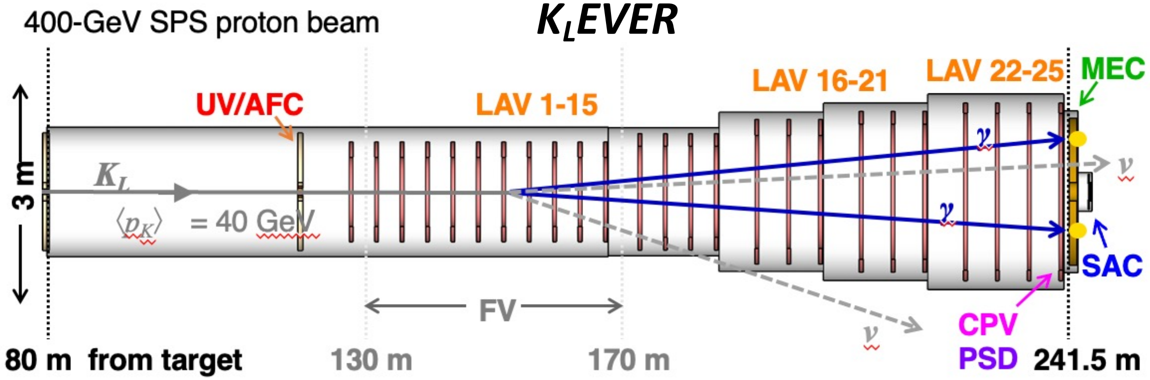
K_L + tracking: phase 2

- using detectors of previous phase, with some detectors removed
- minor modifications to make left/right symmetric and optimize geometrical acceptance

K_L without tracking: phase 3 (K_LEVER)

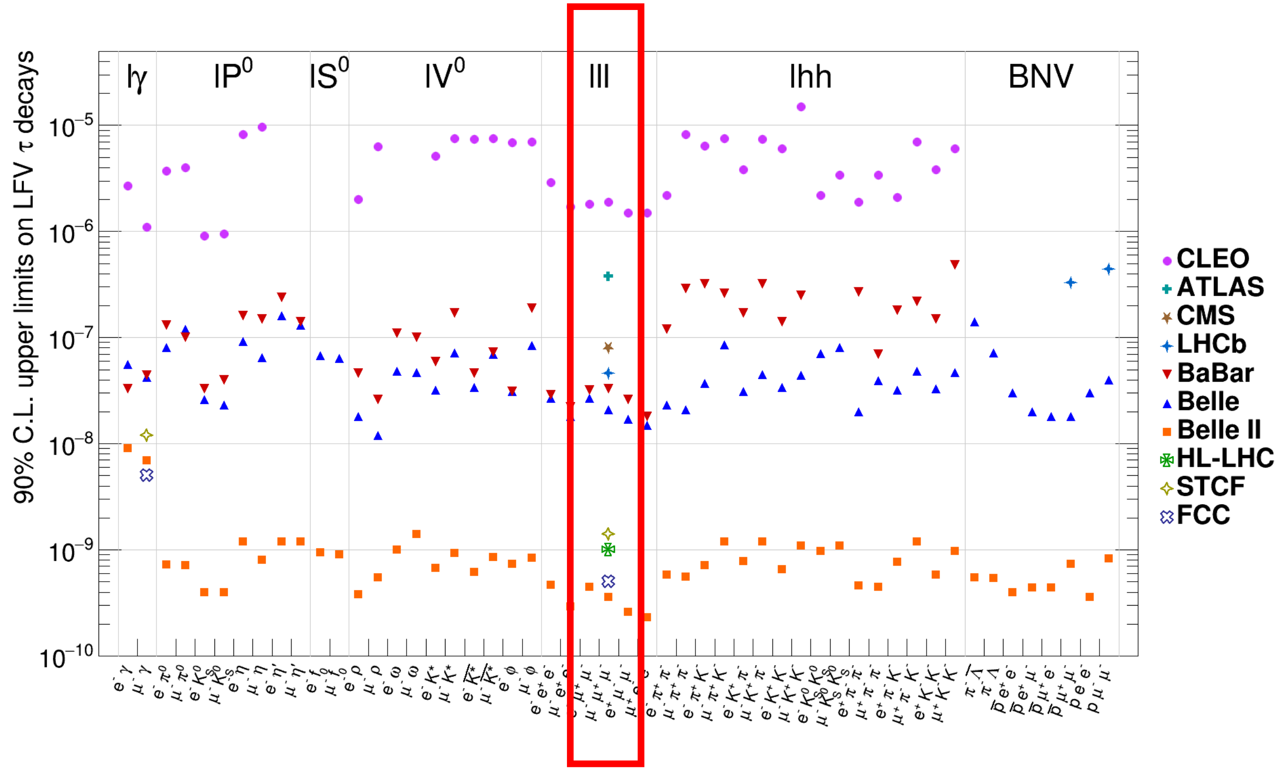
- 2γ with unbalanced p_T + nothing else
- K_L momentum generally not known
- Background rejection from Λ and neutrons, and K decays
- Background rejection mainly by vetoes
- Time-resolved particle flow
- Neutron rejection

K_LEVER



Technological solutions exist for all detectors, thanks also to the synergy with HL-LHC

Charged lepton flavour violation in tau decays at SPS



Large τ production rate in SPS beam from $D_s \to \tau\nu$

Assuming 4 10^{18} POT in 5 years, get 8 10^{13} $D_s \to \tau\nu$ decays:

~ 10^2 x produced in LHCb in Run1&2

~ 10^5 x produced in Belle

Assuming 10% total efficiency for $\tau \to 3\mu$ in TauFV, get for Br ~10^{-10} :

$\tau \to 3\mu$

Observed Limits			Expected Limits		
Experiment	Luminosity	UL (obs)	Experiment	Luminosity	UL (exp)
Belle	782 fb^{-1}	2.1×10^{-8}	Belle II	50 ab^{-1}	3.6×10^{-10}
BaBar	468 fb^{-1}	3.3×10^{-8}			
LHCb	3 fb^{-1}	4.6×10^{-8}	LHCb	300 fb^{-1}	$\mathcal{O}(10^{-9})$
CMS	33 fb^{-1}	8.0×10^{-8}	CMS	3 ab^{-1}	3.7×10^{-9}
ATLAS	20 fb^{-1}	3.8×10^{-7}	ATLAS	3 ab^{-1}	1.0×10^{-9}
			STCF	1 ab^{-1}	1.4×10^{-9}
			FCC-ee	150 ab^{-1}	$\mathcal{O}(10^{-10})$

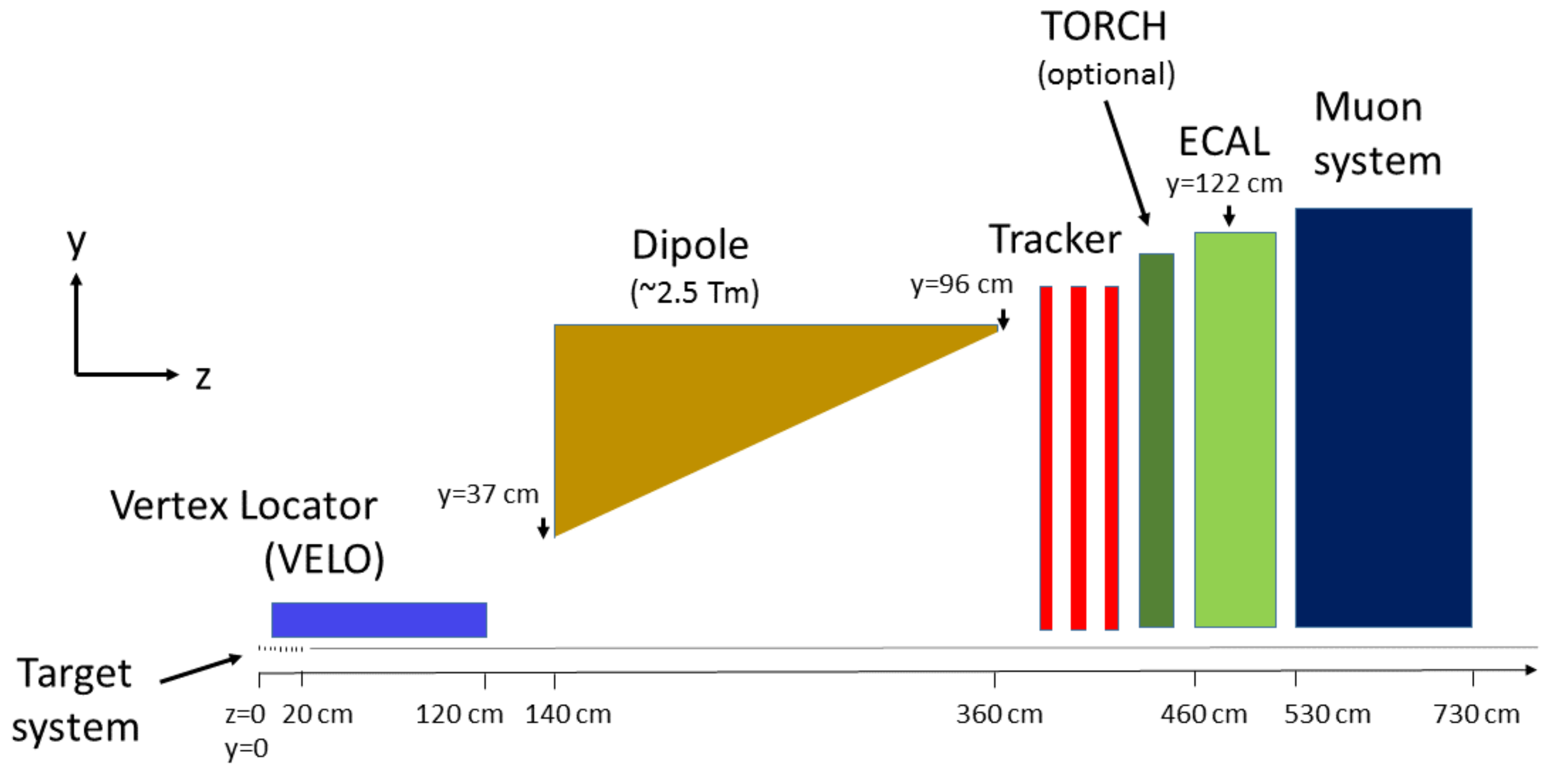
Experiment	Luminosity/PoT	Yield	UL (exp)
TauFV	4×10^{18}	800	$\mathcal{O}(10^{-10})$
Belle II	50 ab^{-1}	1	3.6×10^{-10}
LHCb Upgrade I	50 fb^{-1}	14	$\mathcal{O}(10^{-8})$
LHCb Upgrade II	300 fb^{-1}	84	$\mathcal{O}(10^{-9})$

TauFV: LFV τ decays at the SPS

Design dedicated experiment upstream of any fixed target experiment

Use thin, distributed targets to bleed off ~2% of the beam into 2 mm of tungsten

Half-view schematic of a *possible* TauFV configuration (non bending plane).



Angular acceptance: 20→260 mrad   (geometrical efficiency ~40% for $\tau \to \mu\mu\mu$).

Relies on technologies developed for LHCb Upgrade II and pushed them further

Synergetic with downstream fixed target operation

High-radiation environment (rad hard) and very high event rates (granularity, timing, front-end)

Hadronic environment:
must contend with combinatoric and specific charm background

High-performance vertex detector,
Good mass resolution, PID

Essential is role of *fast timing* provided
Precision timing gives *powerful discrimination* between random associations.

Summary

Fixed target experiments offer excellent sensitivity for new physics at high mass scales

Unique opportunity to address a strong motivated physics case at CERN NA facility

High intensity frontier is synergetic with main LHC program: in search for new physics, and in detector challenges

Next generation high-intensity kaon experiments HIKE will provide a powerful tool to search for physics beyond the Standard Model in flavour physics and beyond

Combination of ultra-rare decay measurements , precision measurements and searches

TauFV offers a possibility to study an unprecedented sample of tau decays and complements HL-LHC and SPS programmes