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# Rare Decays of K Mesons

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Prague, 05/08/2020

# Stars of Kaon Flavour Physics

$$\varepsilon_K, \Delta M_K$$

$$\varepsilon'/\varepsilon$$

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

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

*A.J. Buras KAON2016*

$$K_L \rightarrow \mu^+ \mu^-$$

$$K_L \rightarrow \pi^0 e^+ e^-$$

$$K_L \rightarrow \pi^0 \mu^+ \mu^-$$

They all can give some information about very short distance scales but to identify new physics, correlations with  $B_{s,d}$  and D observables, EDMs, Lepton physics crucial

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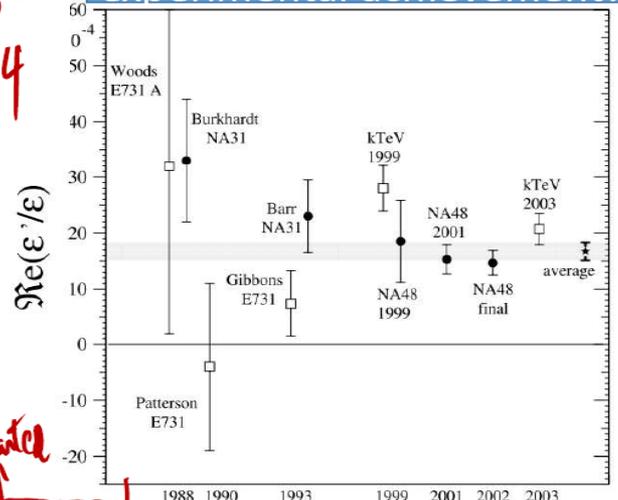
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$16.6(23) \times 10^{-4}$   
PDG 2014

A monumental experimental achievement!



A crucial breakthrough in lattice calculation 2020

A. Soni ICHEP 2020

Quantity	OK Value
$Re(A_0)$	$2.99(0.32)(0.59) \times 10^{-7} \text{ GeV}$
$Im(A_0)$	$-6.98(0.62)(1.44) \times 10^{-11} \text{ GeV}$
$Re(A_0)/Re(A_2)$	$19.9(2.3)(4.4)$
$Re(\varepsilon'/\varepsilon)$	$0.00217(26)(62)(50)$

EXPT  
 $\sim 3.32 \times 10^{-7} \text{ GeV}$

$\rightarrow \sim 22.45$   
 $\rightarrow$  due IB see full page.

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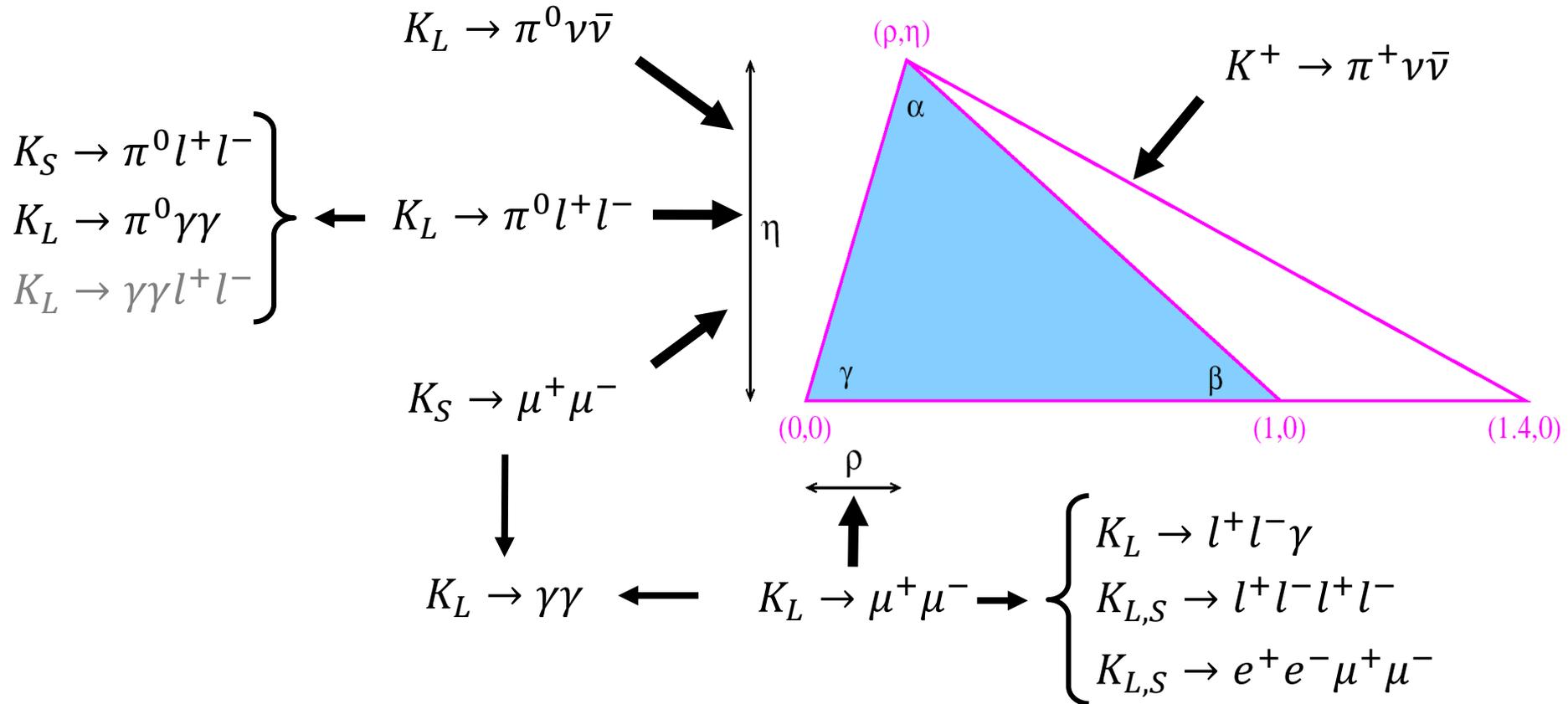
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**this Talk** (an experimental view)

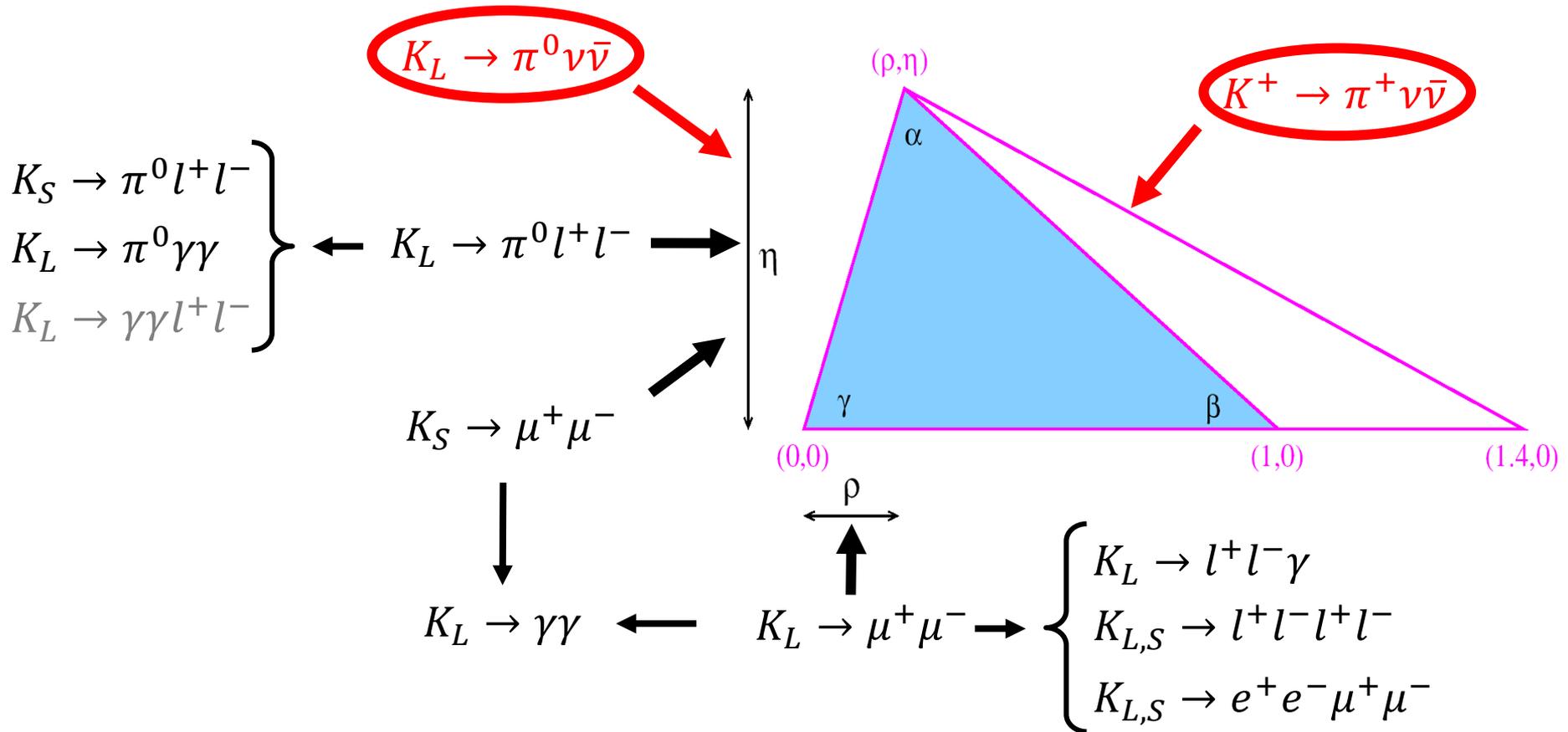
+

K Rare decays & SM violation (LU test, LFV/LNV, exotics)

# Rare Kaon Decays and CKM

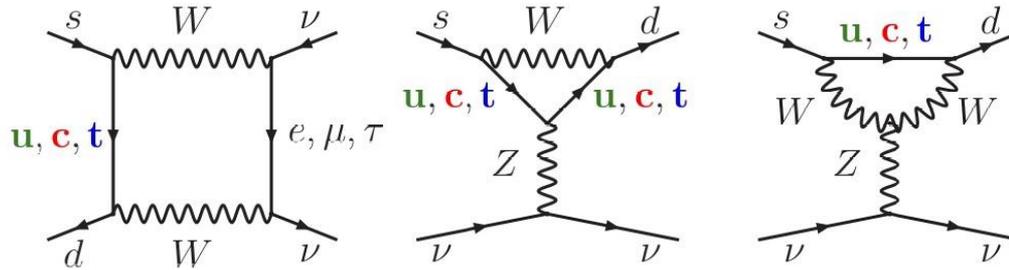


# Rare Kaon Decays and CKM



# $K \rightarrow \pi \nu \bar{\nu}$ : the Subject

- FCNC loop processes:  $s \rightarrow d$  coupling and highest CKM suppression



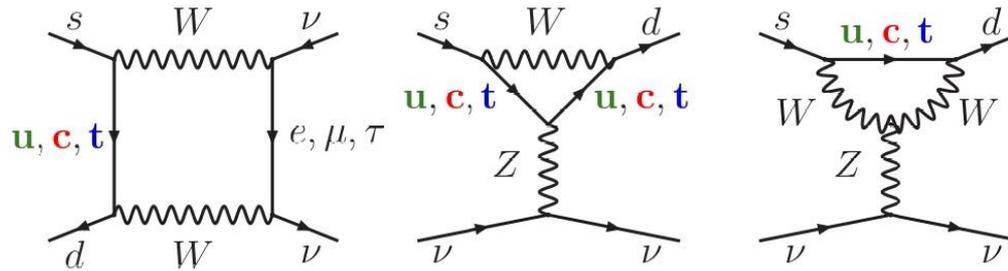
- Very clean theoretically: SD dominated. Hadronic matrix element  $\propto \mathcal{B}(K_{l3})$  (precisely measured)
- [SM predictions](#) [Buras et al. JHEP 11 (2015) 33]

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.39 \pm 0.30) \cdot 10^{-11} \left( \frac{|V_{cb}|}{0.0407} \right)^{2.8} \left( \frac{\gamma}{73.2^\circ} \right)^{0.74} = (8.4 \pm 1.0) \cdot 10^{-11}$$

$$\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = (3.36 \pm 0.05) \cdot 10^{-11} \left( \frac{|V_{ub}|}{0.00388} \right)^2 \left( \frac{|V_{cb}|}{0.0407} \right)^2 \left( \frac{\sin \gamma}{\sin 73.2^\circ} \right)^2 = (3.4 \pm 0.6) \cdot 10^{-11}$$

# $K \rightarrow \pi \nu \bar{\nu}$ : the Actors

- FCNC loop processes:  $s \rightarrow d$  coupling and highest CKM suppression



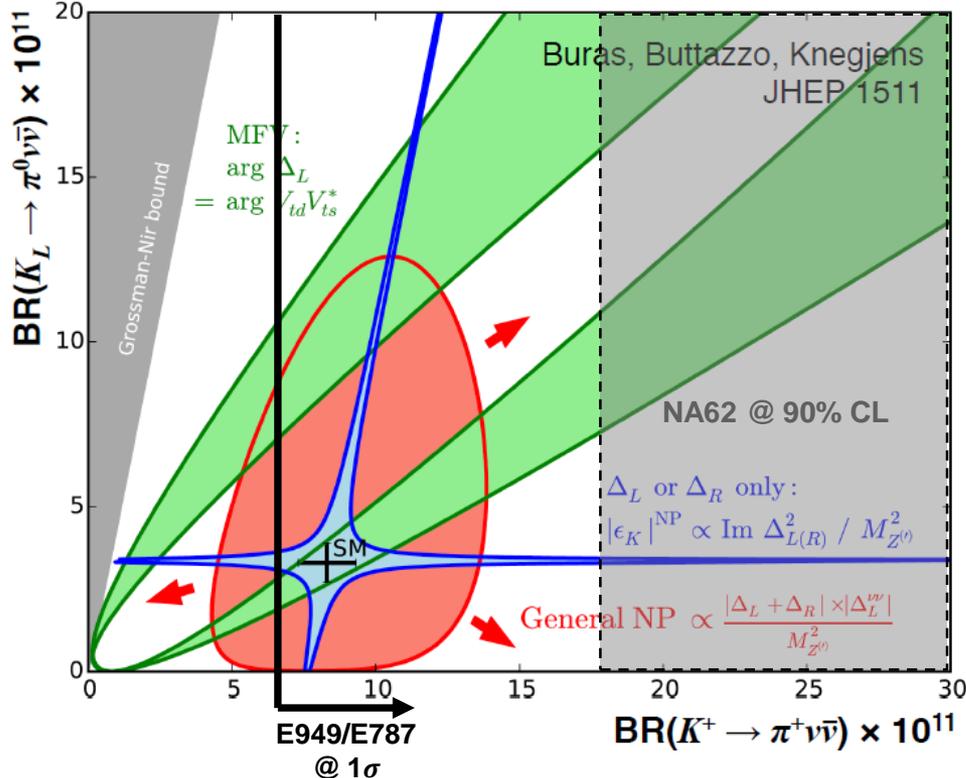
- Very clean theoretically: SD dominated. Hadronic matrix element  $\propto \mathcal{B}(K_{l3})$  (precisely measured)
- Experimental status (before ICHEP 2020):

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	BNL E787/E949 (1995-2002)	$\mathcal{B} = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ [Final, all data] PRD 77, 052003 (2008); PRD 79, 092004 (2009)
	CERN NA62 (2016 - present)	$\mathcal{B} < 1.78 \times 10^{-10}$ 90% [2016-17 data] PLB 791, 156 (2019); arXiv.2007.08218 (subm. JHEP)
$K_L \rightarrow \pi^0 \nu \bar{\nu}$	KEK E391 (2004-2005)	$\mathcal{B} < 26 \times 10^{-9}$ 90% [Final, all data] PRD 81, 072004 (2010)
	JPARC KOTO (2012 - present)	$\mathcal{B} < 3.0 \times 10^{-9}$ 90% [2015 data] PRL 122, 021802 (2018)

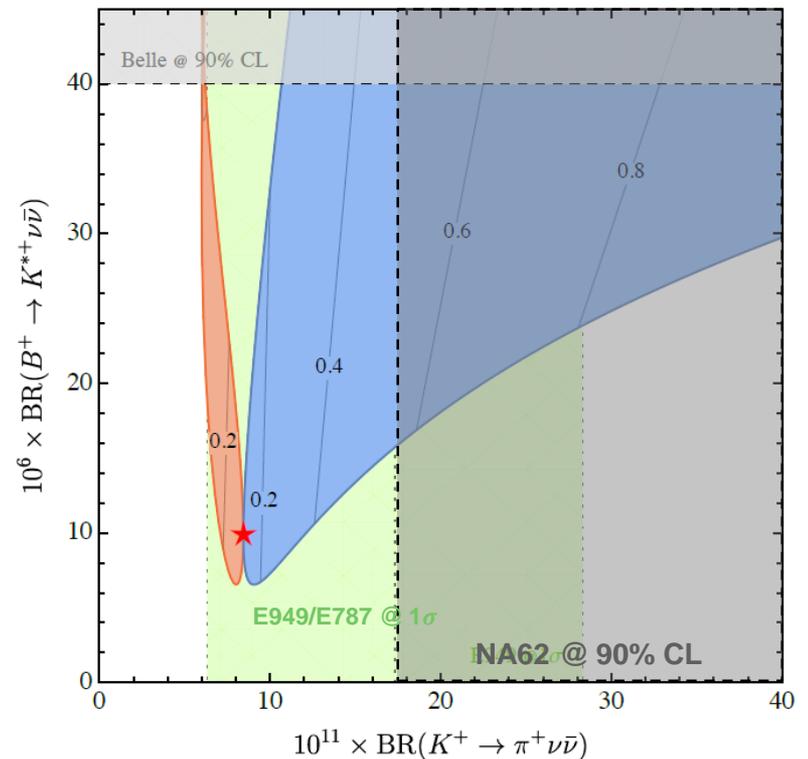
# $K \rightarrow \pi \nu \bar{\nu}$ : the Plot

- High sensitivity to NP (non MFV): significant variations wrt SM possible
- Model-dependent correlations of possible variations of  $K^+$  and  $K_L$  BR
- Weak constraints from other flavour observables

*Not-SUSY models\**



*LFU violation\*\**

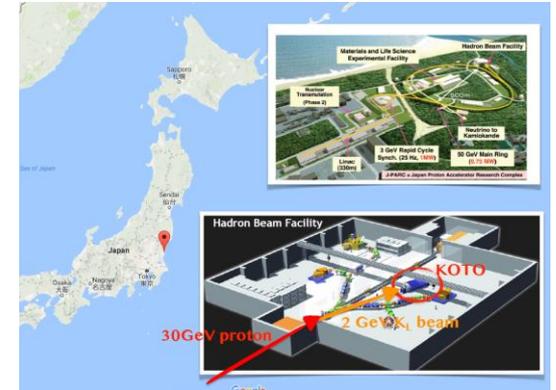
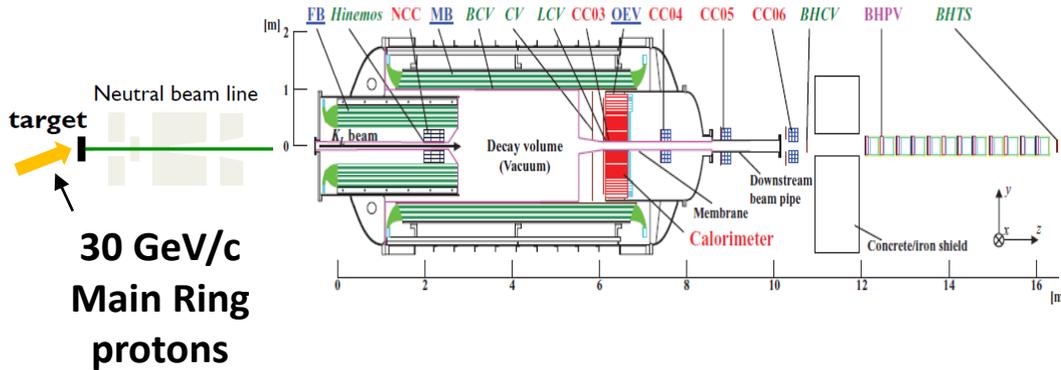


\*See also arXiv:2006.01138

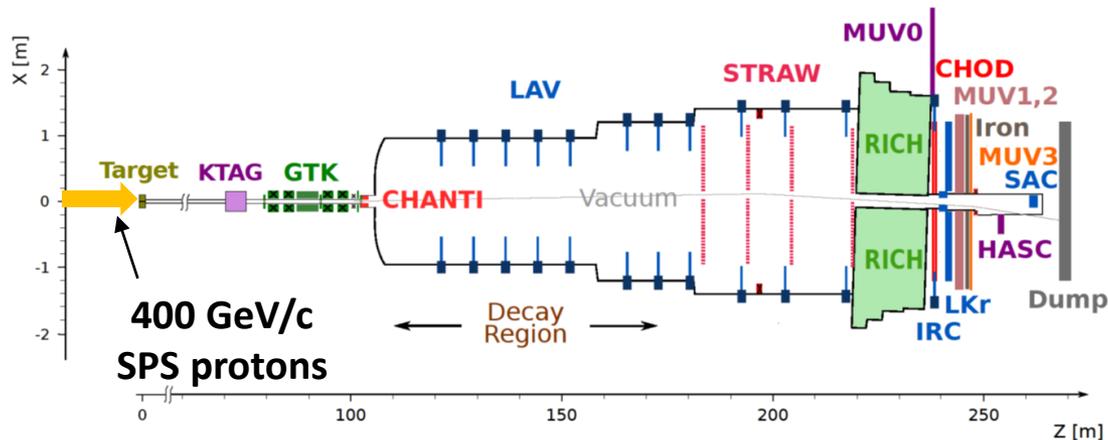
\*\*EPJ C (2017) 77: 618

# $K \rightarrow \pi \nu \bar{\nu}$ Today

- 
 experiment at JPARC:  $K_L \rightarrow \pi^0 \nu \bar{\nu}$

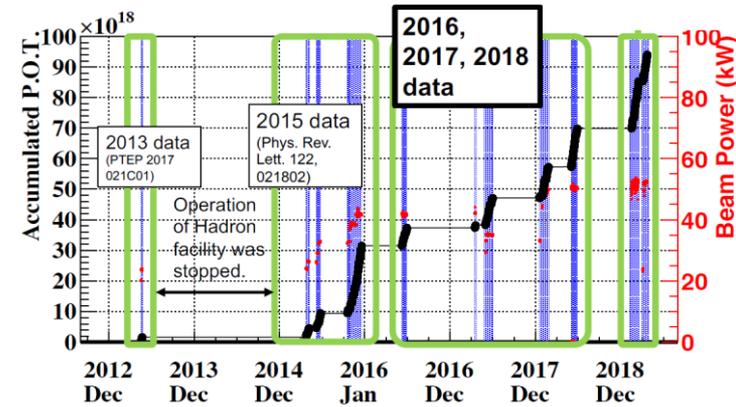
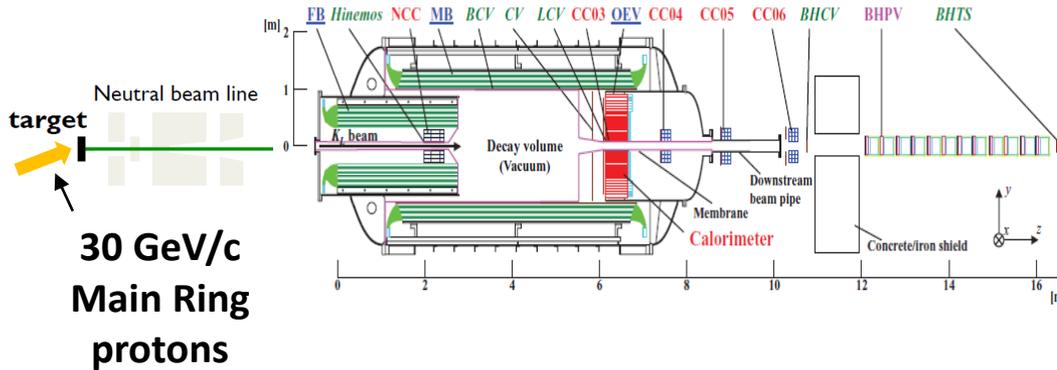


- 
 experiment at CERN:  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

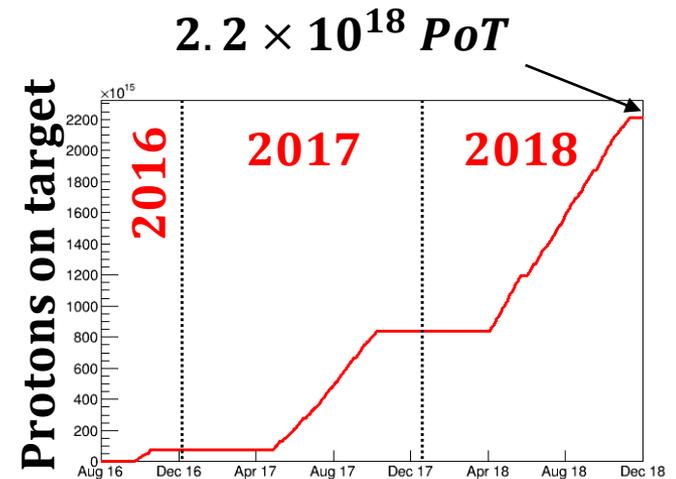
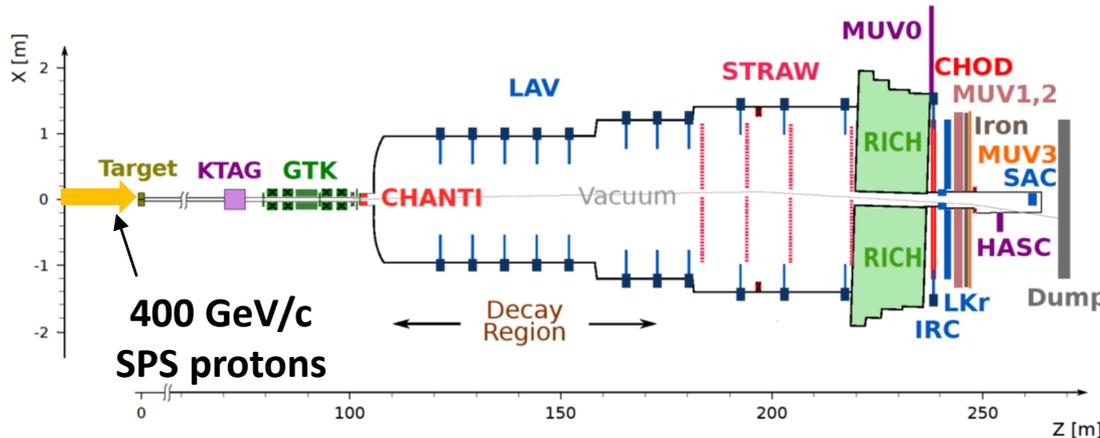


# $K \rightarrow \pi \nu \bar{\nu}$ Today

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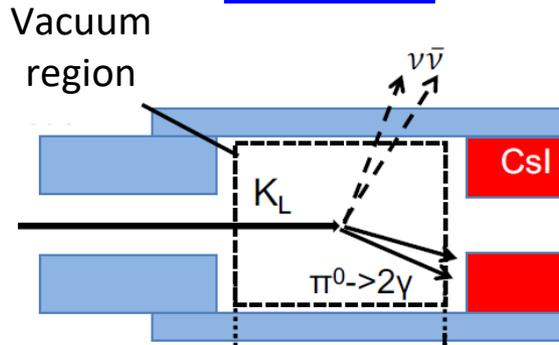
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 experiment at CERN:  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$



# $K_L \rightarrow \pi^0 \nu \bar{\nu}$ @ KOTO: the Method

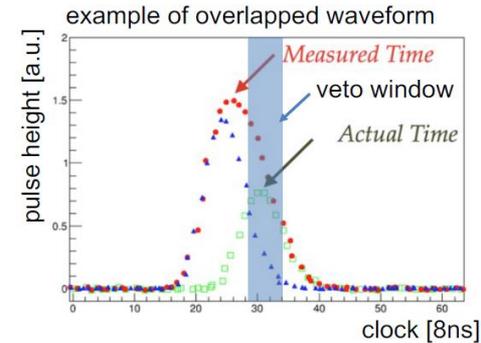
Signal

Backgrounds (some of...)



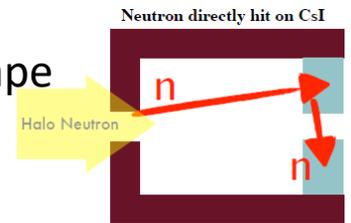
## $K_L$ - decays

- ~Hermeticity
- Efficient photon detection
- Overlapping pulses ID



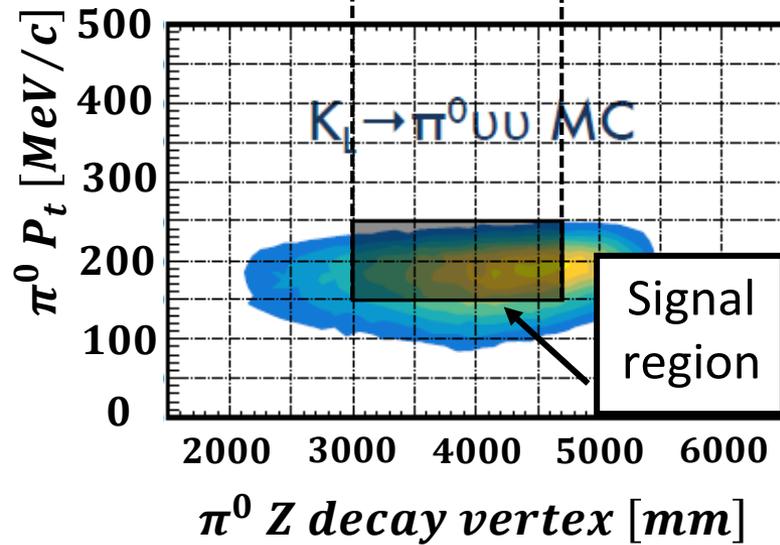
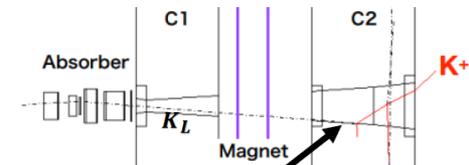
## Neutron - induced

- Calorimetric pulse /cluster shape
- Double-sided crystal readout
- Special neutron runs



## $K^+$ - induced:

- $K_L$  interaction in the inner wall of collimators



# $K_L \rightarrow \pi^0 \nu \bar{\nu}$ @ KOTO: Status

Outcome from 2016-17-18 data:  $SES = 6.9 \times 10^{-10}$

- 4 (3) events found in signal region: marginally consistent with the expected background
- $K^+$  background found: now the largest one
- Dedicated run 2020: estimation of the  $K^+$  background
- Upgrade: New charged veto detector to reduce the  $K^+$  background

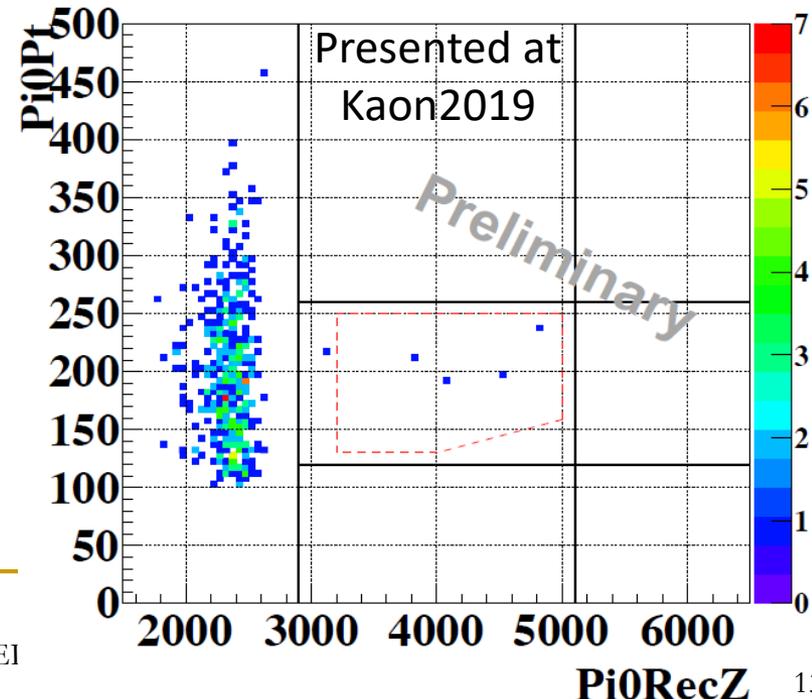
Background from 2016-17-18 data: **Total =  $1.05 \pm 0.28$**



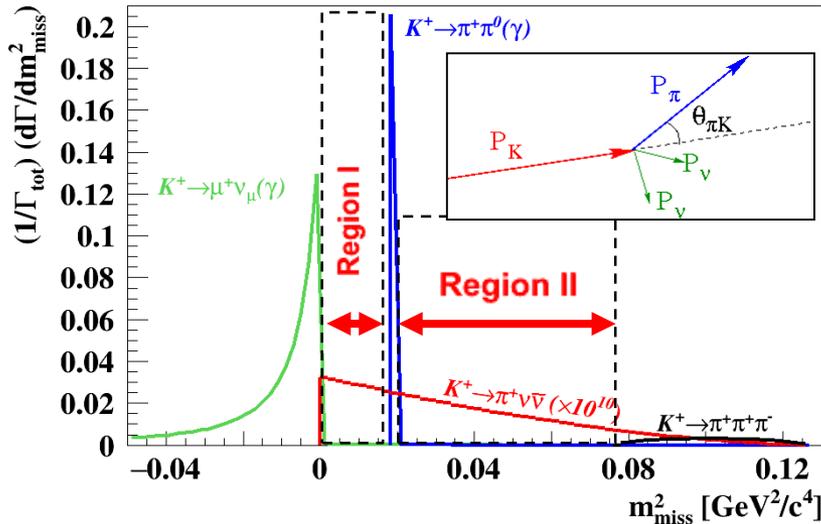
- $K_L$ : negligible
- $K^\pm$  / neutron:

Preliminary

source		#BG (90% C.L.)	#BG (68% C.L.)
K+/-	$K^\pm \rightarrow \pi^0 \pi^\pm$	$0.09 \pm 0.09$	$0.09 \pm 0.09$
	$K^\pm \rightarrow \pi^0 e^\pm \nu$	$0.90 \pm 0.27$	$0.90 \pm 0.27$
	$K^\pm \rightarrow \pi^0 \mu^\pm \nu$	$<0.21$	$<0.12$
Neutron	Upstream $\pi^0$	$0.001 \pm 0.001$	$0.001 \pm 0.001$
	Hadron cluster	$0.02 \pm 0.00$	$0.02 \pm 0.00$
	CV-pi0	$<0.10$	$<0.05$
	CV-eta	$0.03 \pm 0.01$	$0.03 \pm 0.01$



# $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ @ NA62: the Method



$$m_{\text{miss}}^2 = (P_{K^+} - P_{\pi^+})^2: \text{Kinematic suppression}$$

+

$$15 < P_{\pi^+} < (35)45 \text{ GeV}/c$$

Particle ID ( $\mu - \pi$  separation)

Photon veto

- $\mathcal{O}(100 \text{ ps})$  Timing between sub-detectors
- $\geq 10^3$  Kinematic background suppression
- $\geq 10^8$  Muon suppression
- $\geq 10^8$   $\pi^0$  (from  $K^+ \rightarrow \pi^+ \pi^0$ ) suppression

Si – tracker + Cherenkov counters

Low – mass spectrometers (0.5%  $X_0$ )

Calorimetric & Cherenkov particle ID

$\gamma$  detection inefficiency  $\lesssim 10^{-5}$  ( $E_\gamma > 10 \text{ GeV}$ )

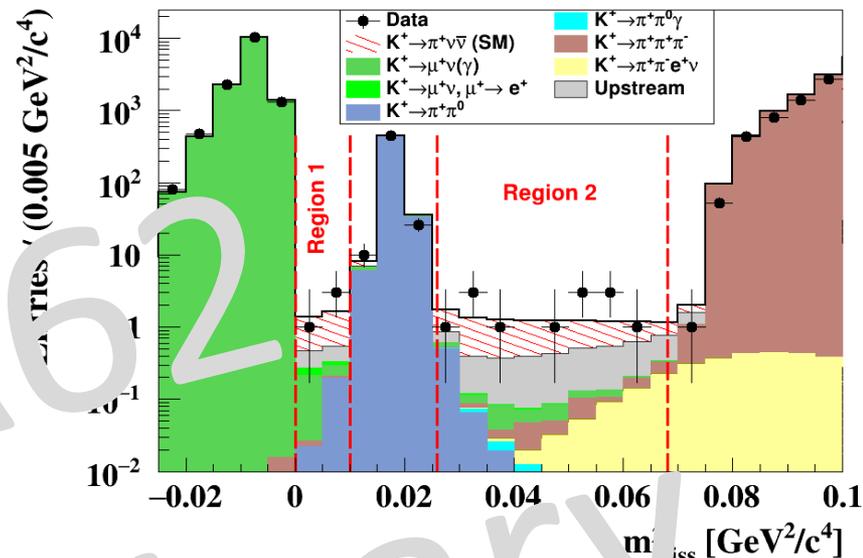
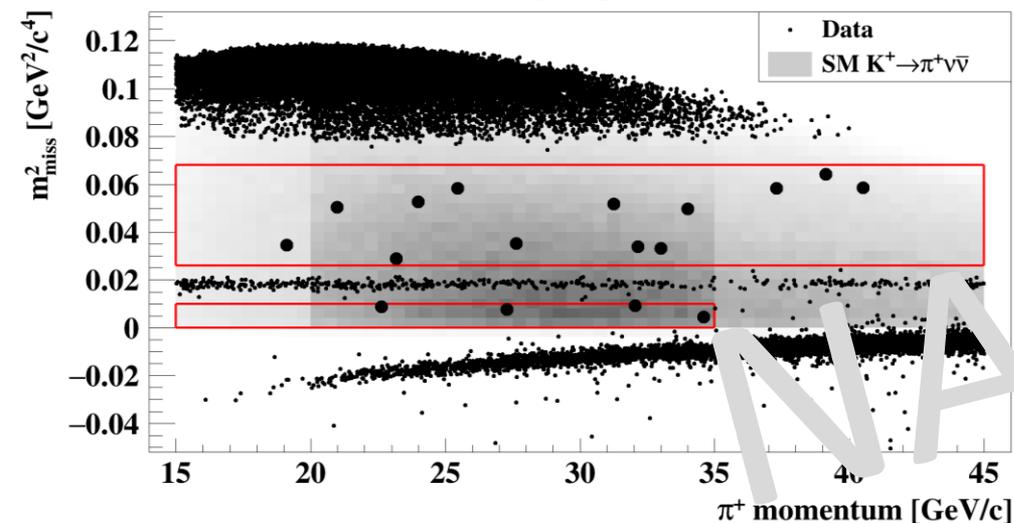
$P_{\pi^+} < 45 \text{ GeV}/c \rightarrow \pi^0 \text{ energy} > 30 \text{ GeV}$

- Data – driven evaluation of the most important backgrounds
- Largest background from accidental  $\pi^+$  coming from the beam line
- Blind analysis procedure

# $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ @ NA62: Results



2018



$$SES = (0.111 \pm 0.07) \times 10^{-10}$$

Expected SM signal:  $\sim 7.6$

Expected background:  $5.28^{+0.99}_{-0.74}$

Observed events: **17 (3.5 $\sigma$  evidence of  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ )**

**Combined 2016,17,18 (Run1)**

Expected background:  $\sim 7$

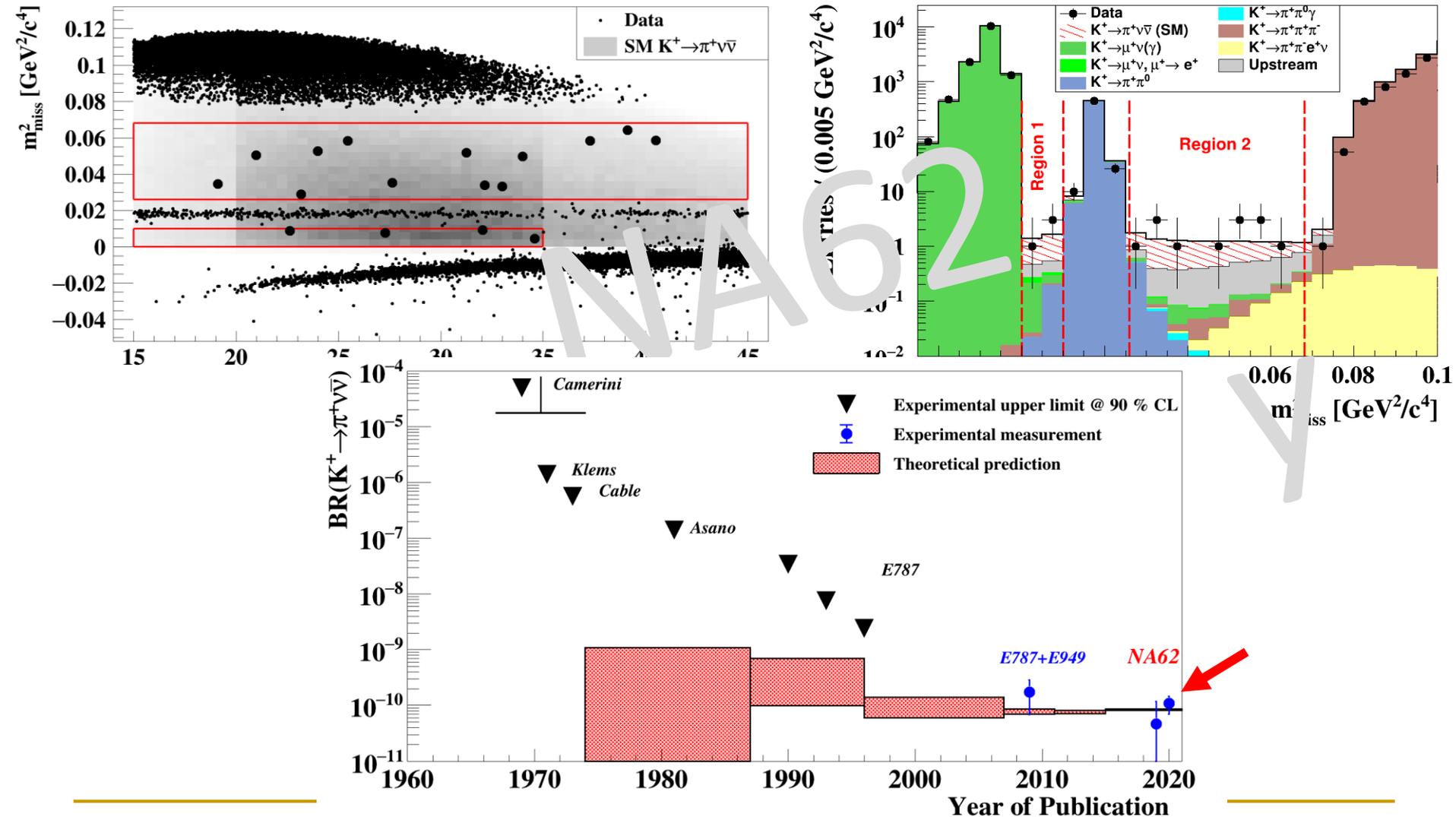
Observed events: 20 (1 [2016], 2 [2017], 17 [2018])

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = \left( 11.0^{+4.0}_{-3.5} \Big|_{stat} \pm 0.3_{syst} \right) \times 10^{-11}$$

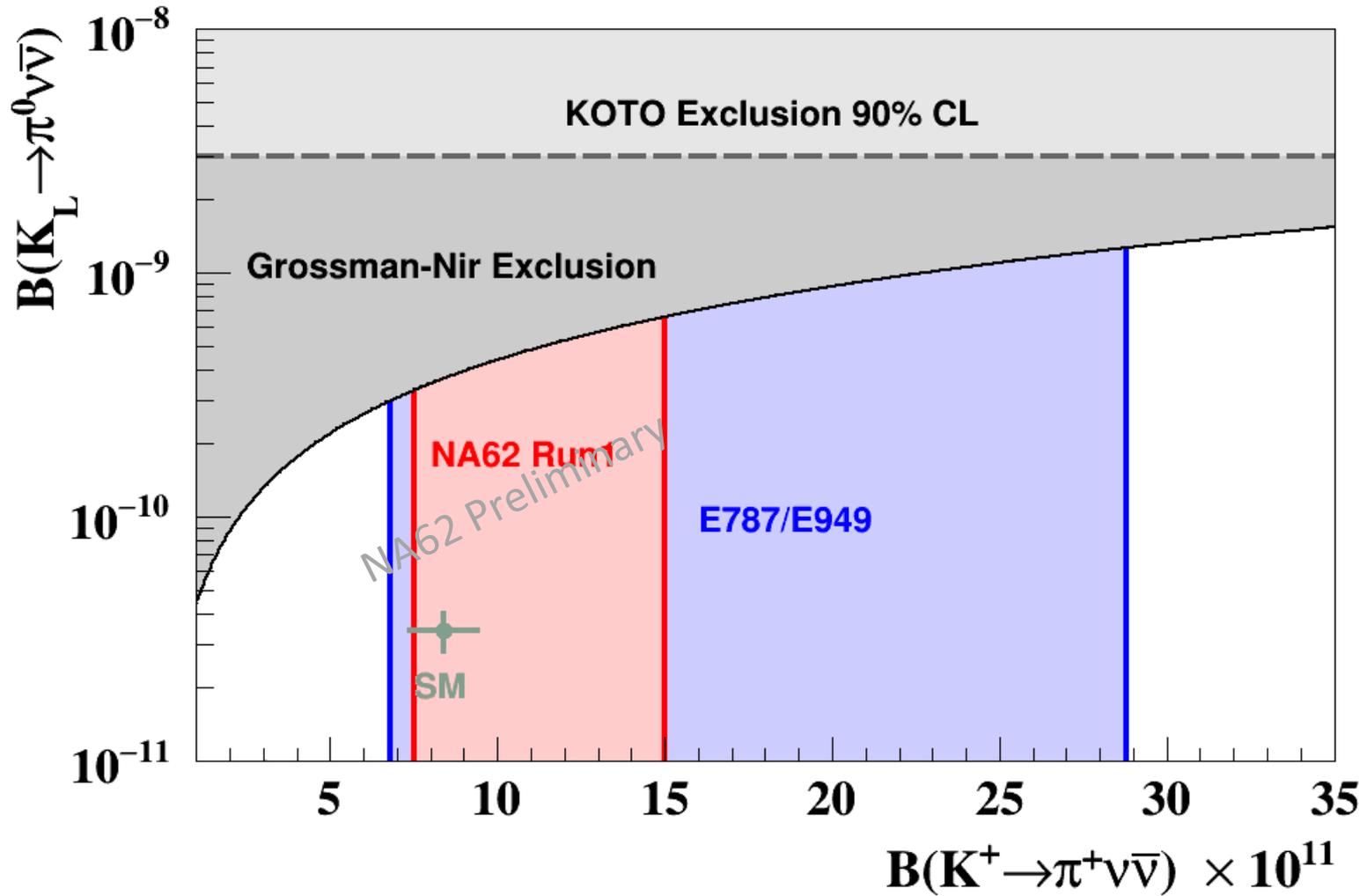
# $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ @ NA62: Results



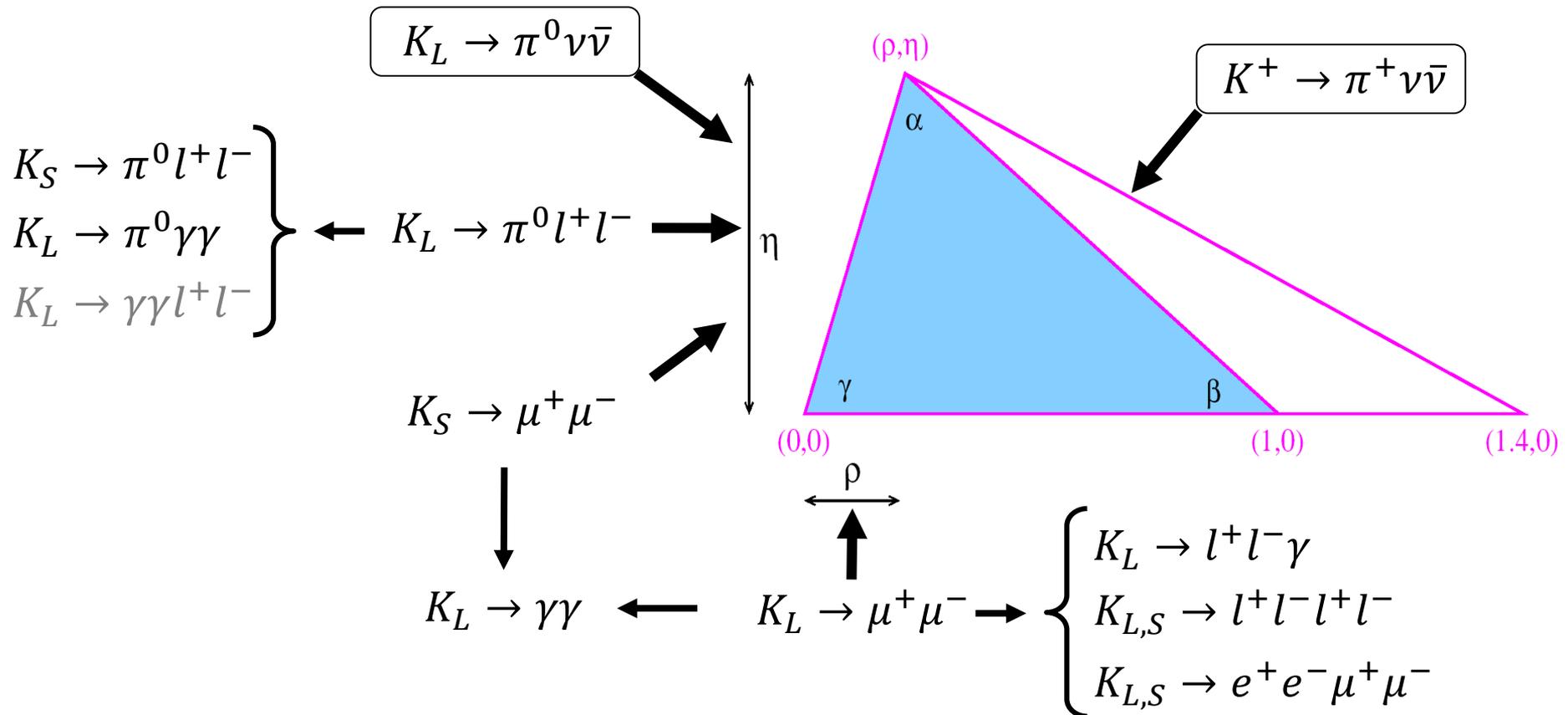
2018



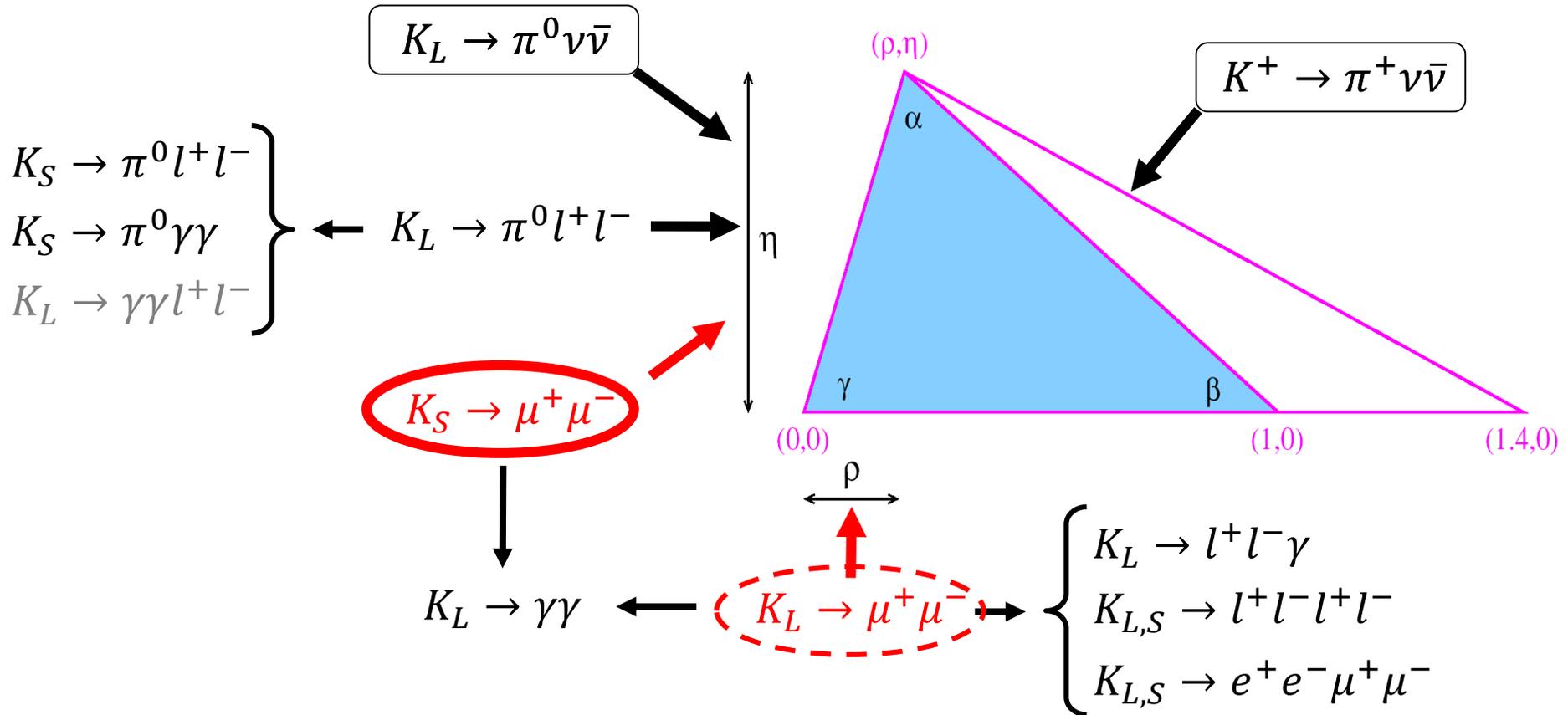
# $K \rightarrow \pi \nu \bar{\nu}$ : the present Plot



# Rare Kaon Decays and CKM

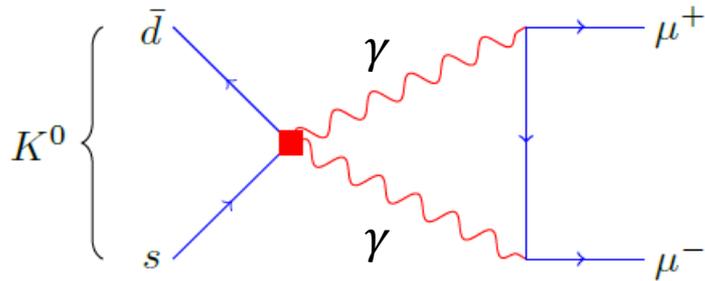


# Rare Kaon Decays and CKM

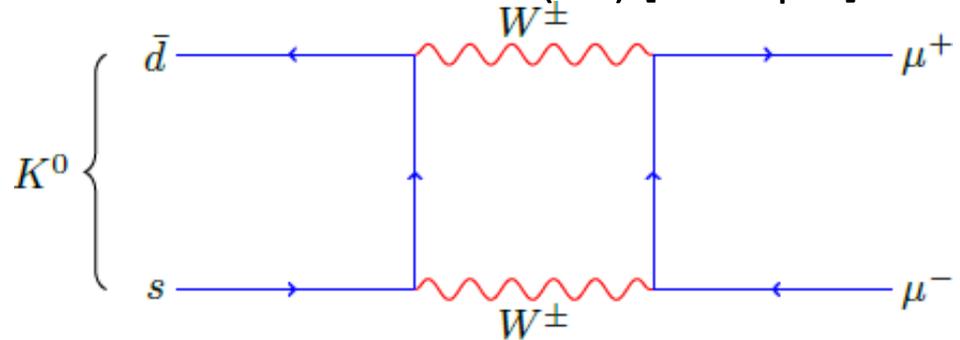


# $K^0 \rightarrow \mu^+ \mu^-$

Long distance (LD)



Short distance (SD) [example]



$$\mathcal{B}(K_L \rightarrow \mu^+ \mu^-)_{SM} \propto |A_L^{LD} + A_L^{SD}|^2, \quad |A_L^{SD}|^2 \propto |1 - \bar{\rho}|^2 \quad \text{Buras, and Fleisher, Adv. Ser. Direct. High Energy Phys. 15, 65 (1998),}$$

- $\mathcal{B}(K_L \rightarrow \mu^+ \mu^-)_{meas} = (6.84 \pm 0.11) \times 10^{-9} \sim |A_L^{LD}|^2$  PRL 84, 1389 (2000) [B871]
- Prediction depends on the sign of the  $K_L \rightarrow \gamma\gamma$  amplitude that determines the effect of the SD – LD interference contribution

$$\mathcal{B}(K_S \rightarrow \mu^+ \mu^-)_{SM} = (5.0 \pm 1.5) \times 10^{-12} \propto |A_S^{LD} + A_S^{SD}|^2, \quad |A_S^{SD}|^2 \propto |\bar{\eta}|^2 \sim \mathcal{O}(10^{-13})$$

- NP:  $\mathcal{B}(K_S \rightarrow \mu^+ \mu^-)_{NP} \leq 10^{-11}$  Isidori and Unterdorfer. JHEP01 (2004) 009
- $K_S - K_L$  interference  $\rightarrow \mu^+ \mu^-$ : higher sensitivity to NP and to the sign of  $K_L \rightarrow \gamma\gamma$  amplitude entering  $K_L \rightarrow \mu^+ \mu^-$  D'Ambrosio et al. PRL 119, 20, 201802 (2017), JHEP 05 024 (2018)

# Kaons @ LHCb

LHCb: 1 strange hadron / event produced at 13 TeV ( $\mathcal{O}(10^3) > B_S^0$ )

Production rate compensates low trigger efficiency and long lifetime

Vast  $K$  program [mainly for Run3]

$$K_{S,L} \rightarrow \mu^+ \mu^-$$

$$K_S \rightarrow \pi^0 \mu^+ \mu^-$$

$$K_S \rightarrow \mu^+ \mu^- \mu^+ \mu^- (e^+ e^-)$$

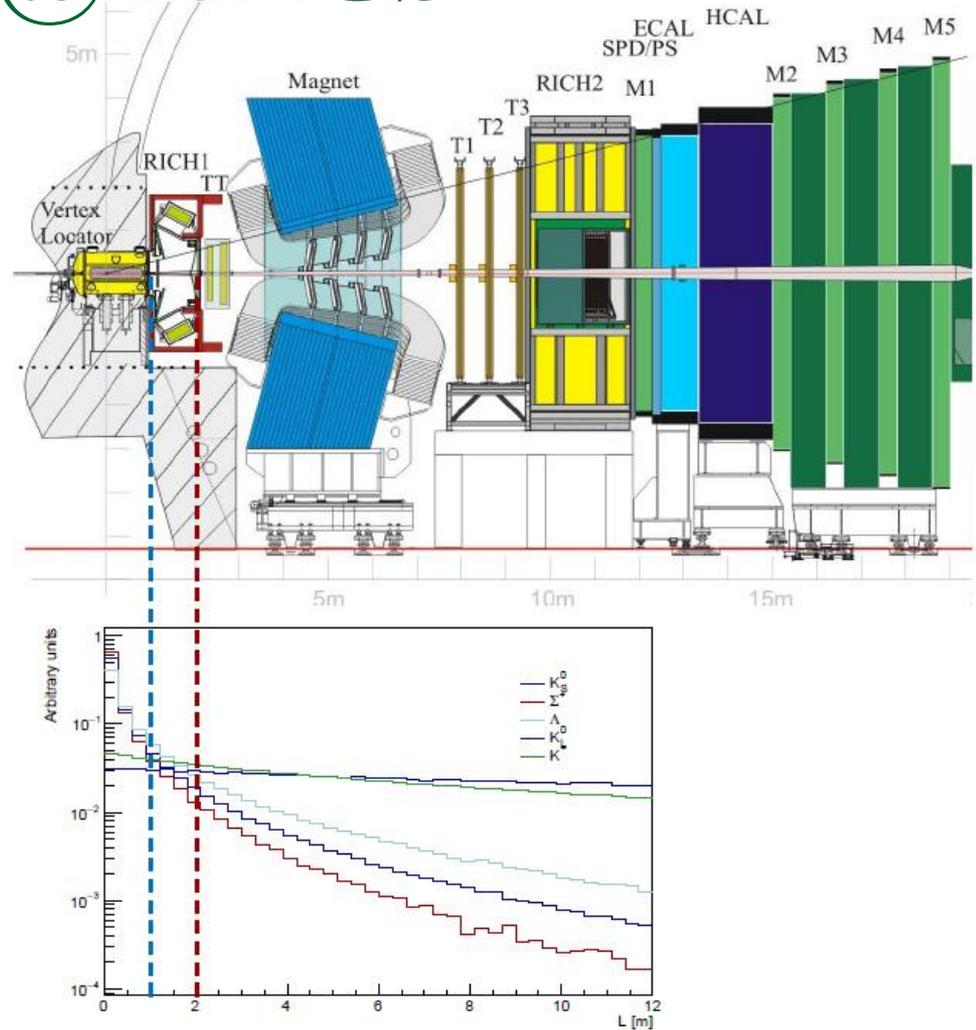
$$K_S \rightarrow \pi^+ \pi^- e^+ e^-$$

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

...

Present result from Run1 + 2

$$B(K_S \rightarrow \mu^+ \mu^-) < 2.1(2.4) \times 10^{-10} @ 90 (95)\% CL \quad \text{arXiv:2001.10354 subm. PRL}$$



# Rare/Forbidden K Decays: Test of Lepton Universality and Explicit SM Violation

Test of lepton universality:  $K^+ \rightarrow \pi^+ \mu^+ \mu^-$  vs  $K^+ \rightarrow \pi^+ e^+ e^-$ ,  $R_K \equiv \Gamma(K^+ \rightarrow e^+ \nu) / \Gamma(K^+ \rightarrow \mu^+ \nu)$

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

PDG '20

LFV mode	90% CL upper limit	Experiment	Yr./Ref.	Type
$K^+ \rightarrow \pi^+ e^- \mu^+$	$1.3 \times 10^{-11}$	BNL-865	2005/Ref. [15]	LFV
$K^+ \rightarrow \pi^+ e^+ \mu^-$	$5.2 \times 10^{-10}$	BNL-865	2000/Ref. [16]	LFV
$K_L \rightarrow \mu e$	$4.7 \times 10^{-12}$	BNL-871	1998/Ref. [17]	LFV
$K_L \rightarrow \pi^0 e \mu$	$7.6 \times 10^{-11}$	KTeV	2008/Ref. [18]	LFV
$K_L \rightarrow \pi^0 \pi^0 e \mu$	$1.7 \times 10^{-10}$	KTeV	2008/Ref. [18]	LFV
$K^+ \rightarrow \pi^- e^+ e^+$	$2.2 \times 10^{-10}$	NA-62	2019/Ref. [19]	LNV
$K^+ \rightarrow \pi^- \mu^+ \mu^+$	$4.2 \times 10^{-11}$	NA-62	2019/Ref. [19]	LNV
$K^\pm \rightarrow \pi^\mp \mu^\pm \mu^\pm$	$8.6 \times 10^{-11}$	NA48/2	2017/Ref. [20]	LNV
$K_L \rightarrow e^\pm e^\pm \mu^\mp \mu^\mp$	$4.12 \times 10^{-11}$	KTeV	2003/Ref. [21]	LNV
$K^+ \rightarrow \pi^- \mu^+ e^+$	$5.0 \times 10^{-10}$	BNL-865	2000/Ref. [16]	LNFV

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



Form factors (FF)  $K_{3\pi}$  loop term  
(non pert. QCD)

LD dominated, mediated by  $K^+ \rightarrow \pi^+ \gamma^*$ :  $d\Gamma/dz \propto G_F M_K^2 (a + bz) + W^{\pi\pi}(z)$   
 $z = m(l^+ l^-)^2 / M_K^2$

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

Difference correlated to possible anomalies in B physics

Crivellin et al. PRD **93** 074038 (2016)  
 D'Ambrosio et al. JHEP **02** 049 (2019)

$K^+ \rightarrow \pi^+ \mu^+ \mu^-$  FF and B measured by NA62 using data from 2017+2018



Experimental key feature: precise track reconstruction

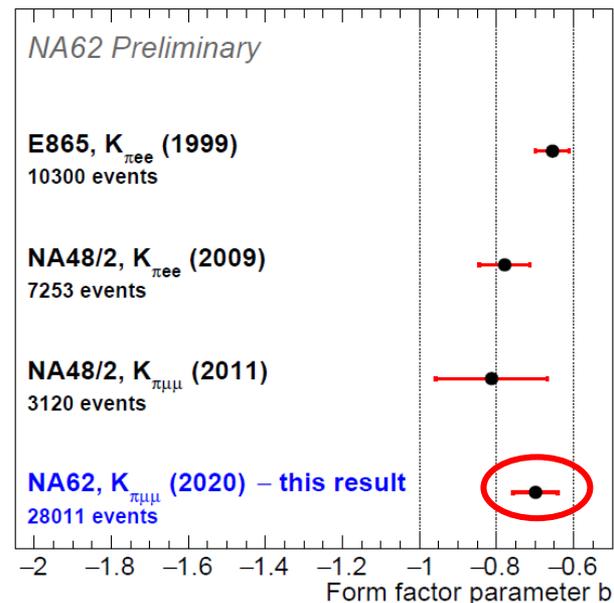
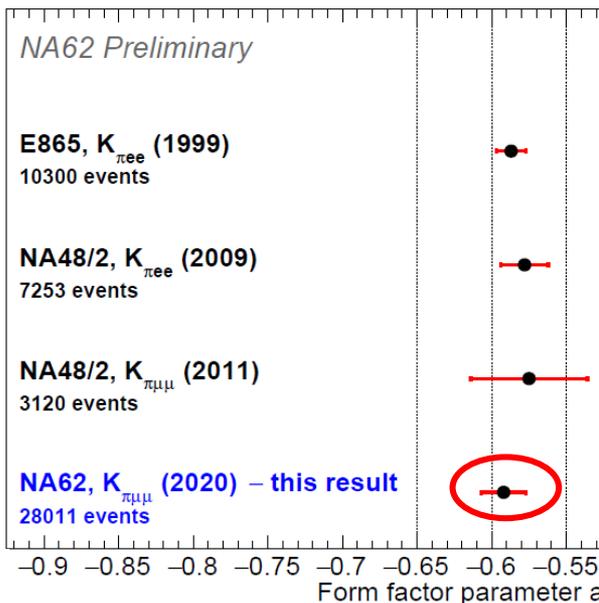
Analysis strategy: Normalization to  $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ , fit to  $z$  spectrum to extract FF

### Signal and background

- $N(\pi^+ \mu^+ \mu^-) \sim 28 \times 10^3$
- Background  $< 0.1\%$

### Result

- $a$ : 2% precision
- $b$ : 8% precision

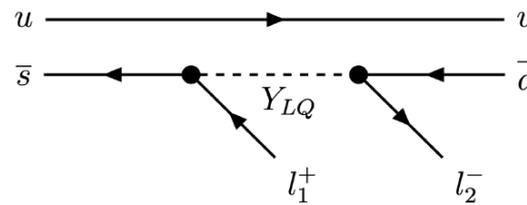


(\*) L. Bician 28/07 flavor session

# LFV & LNV @ NA62: $K^+ \rightarrow \pi\mu e$

E.g. mediated by leptoquark

[JHEP 12(2019) 089], [NPB 176 (1980) 135]



Experimental key-features: particle ID (calorimeters), precise track reconstruction

Background: mis-ID  $e^\pm \leftrightarrow \pi^\pm$  ( $\mathcal{O}(\%)$  data-driven estimation),  $\pi^\pm$  decay in flight

Normalization:  $K^+ \rightarrow \pi^+\pi^+\pi^-$

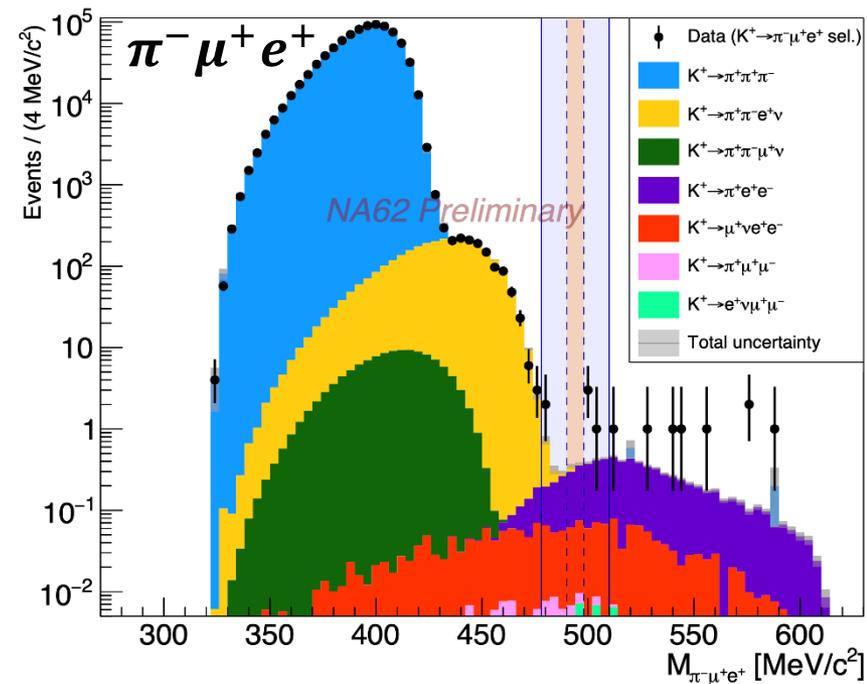
Results (90% CL):

$\pi^-\mu^+e^+$ : background expected  $1.06 \pm 0.20$   
events observed 0

$$B(K^+ \rightarrow \pi^-\mu^+e^+) < 4.2 \times 10^{-11}$$

$\pi^+\mu^-e^+$ : background expected  $0.92 \pm 0.34$   
events observed 2

$$B(K^+ \rightarrow \pi^+\mu^-e^+) < 6.6 \times 10^{-11}$$

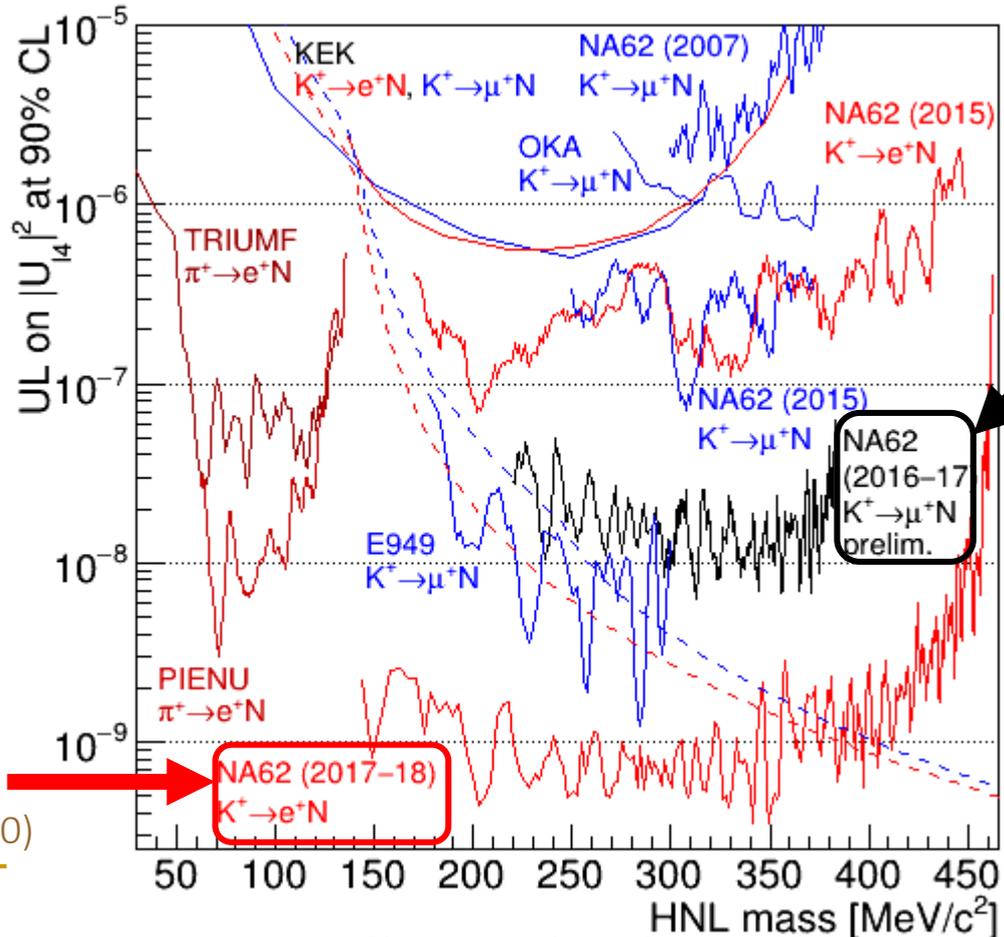


# K decays & exotic particles @ NA62

Heavy Neutral Lepton production:  $K^+ \rightarrow l^+ N, l = e, \mu$

Experimental key features: precise track reconstruction,  $\gamma$  veto, particle ID

Analysis technique: mass peak search



$K^+ \rightarrow \mu^+ N$  Preliminary



$K^+ \rightarrow e^+ N$  Final\*

PLB 807, 135599 (2020)

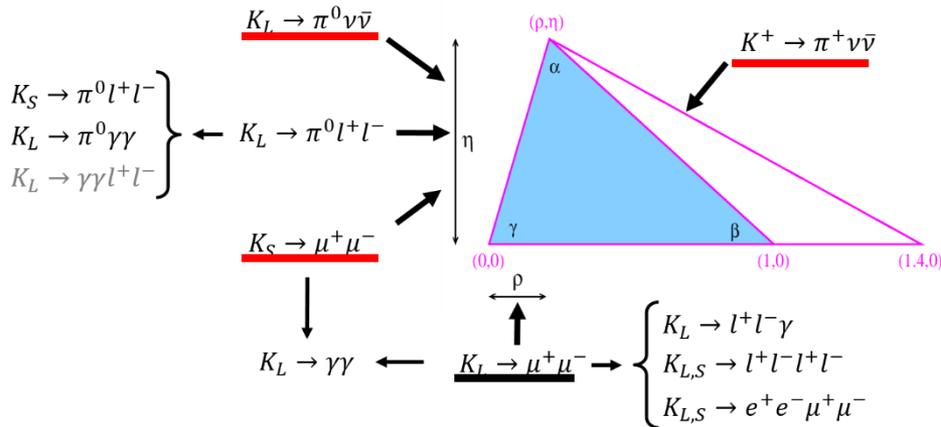
# Present

LHCb (Run1+2)

NA62 (Run1 Preliminary)

KOTO ( $\leq 2020$  data)

## Flavour & NP



$K_L \rightarrow \pi^0 \nu \bar{\nu}$ : Sensitivity  $\mathcal{O}(10^{-9} \div 10^{-10})$  (KOTO)

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ : 30% measurement (NA62)

$K_S \rightarrow \mu^+ \mu^-$ : Sensitivity  $\mathcal{O}(10^{-10})$  (LHCb)

$K_S \rightarrow \pi^0 l^+ l^-$ : 40% meas. (NA48/1)

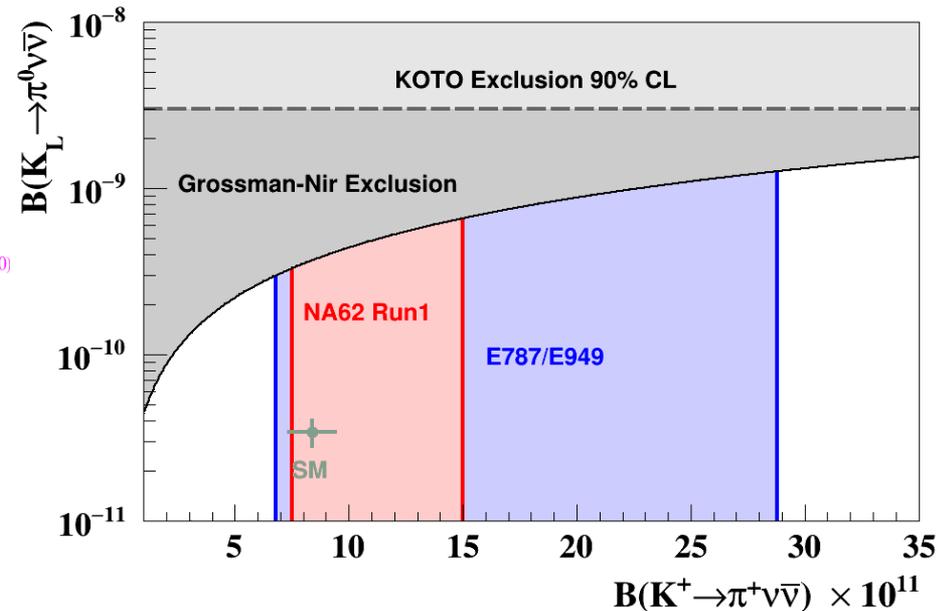
$K_L \rightarrow \pi^0 \gamma \gamma$ : 40% meas. (NA48, KTeV)

$K_L \rightarrow \gamma \gamma l^+ l^-$ : 10% meas./SM sensitivity ( $\mu$ ) (KTeV)

$K_L \rightarrow \gamma \gamma$ : precise meas. (NA48, KLOE)

$K_L \rightarrow \mu^+ \mu^-, l^+ l^- \gamma$ : precise meas. (B871, KTeV, NA48, E799)

$K_L \rightarrow l^+ l^- l^+ l^-$ : precise meas. (KTeV, NA48)



## LU Test and Explicit violation of SM

$K^+ \rightarrow \pi^+ l^+ l^-$ : LU conservation test  $\mathcal{O}(\%)$

$K \rightarrow LNV/LFV$ : Single event sensitivity  $\mathcal{O}(10^{-11})$

$K \rightarrow Exotics$ : Single event sensitivity  $\mathcal{O}(10^{-8} \div 10^{-11})$

# Future (< 2025)

## LHCb (Upgrade phase I)

- new trigger

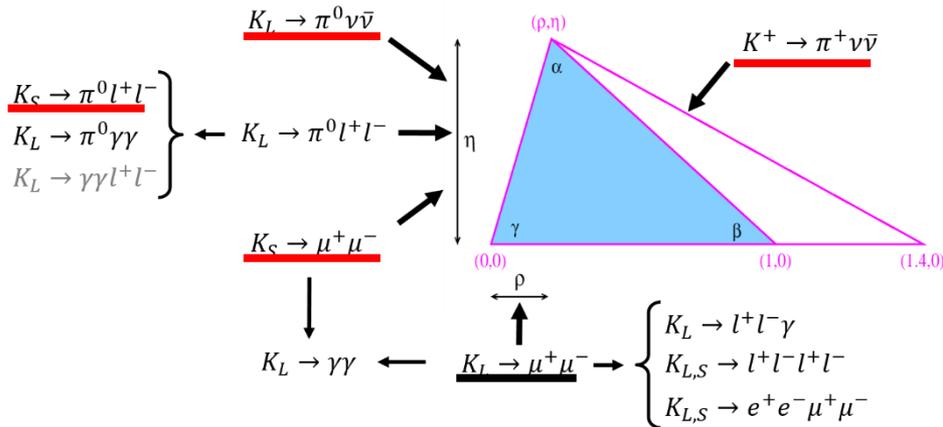
## NA62 (Run2)

- hwd improvements

## KOTO (Step - 1)

- Main ring power increase
- hwd improvements

## Flavour & NP



$K_L \rightarrow \pi^0 \nu \bar{\nu}$ : SM Sensitivity (KOTO)

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ :  $\mathcal{O}(10\%)$  measurement (NA62)

$K_S \rightarrow \mu^+ \mu^-$ : Sensitivity  $\mathcal{O}(10^{-11})$  (LHCb)

$K_S \rightarrow \pi^0 l^+ l^-$ : 20% meas. (LHCb, NA48/1)

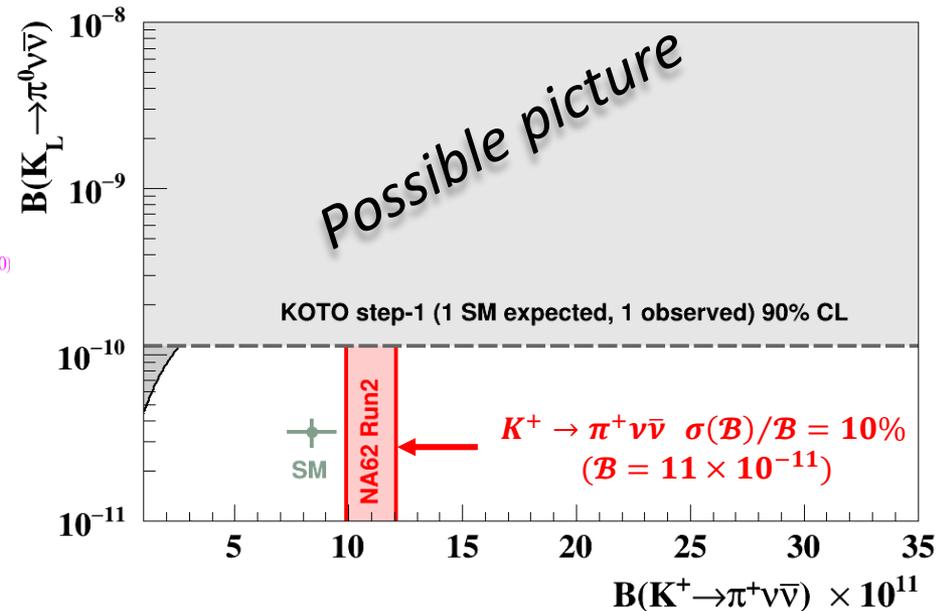
$K_L \rightarrow \pi^0 \gamma \gamma$ : 40% meas. (NA48, KTeV)

$K_L \rightarrow \gamma \gamma l^+ l^-$ : 10% meas./SM sensitivity ( $\mu$ ) (KTeV)

$K_L \rightarrow \gamma \gamma$ : precise meas. (NA48, KLOE)

$K_L \rightarrow \mu^+ \mu^-, l^+ l^- \gamma$ : precise meas. (B871, KTeV, NA48, E799)

$K_L \rightarrow l^+ l^- l^+ l^-$ : precise meas. (KTeV, NA48)



## LU Test and Explicit violation of SM

$R_K$ :  $\mathcal{O}(0.1\%)$  measurement

$K^+ \rightarrow \pi^+ l^+ l^-$ : LU conservation test  $\mathcal{O}(< \%)$

$K \rightarrow LNV/LFV$ : Single event sensitivity  $\mathcal{O}(10^{-12})$

$K \rightarrow Exotics$ : Single event sensitivity  $\mathcal{O}(10^{-8} \div 10^{-11})$

# Future ( $\geq 2025$ )

## LHCb (Upgrade phase II)

- hwd upgrade

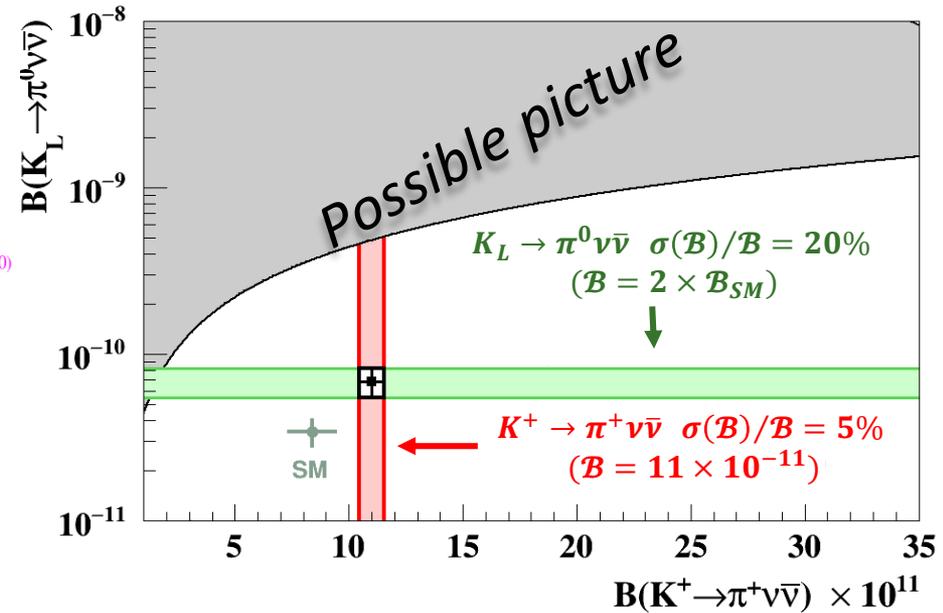
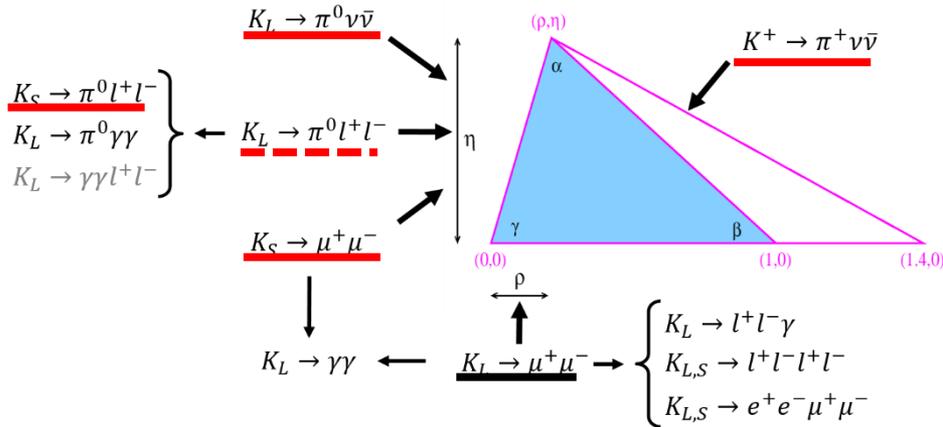
## K Facility at CERN

- $K^+ / K^0$
- NA62-like, Klever

## KOTO (Step - 2)

- hwd upgrade

## Flavour & NP



$K_L \rightarrow \pi^0 \nu \bar{\nu}$ :  $\mathcal{O}(20\%)$  measurement (KOTO / Klever)

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ :  $\mathcal{O}(5\%)$  measurement (NA62-like)

$K_S \rightarrow \mu^+ \mu^-$ : SM Sensitivity (LHCb)

$K_S \rightarrow \pi^0 l^+ l^-$ : precision meas. (LHCb, NA48/1)

$K_L \rightarrow \pi^0 l^+ l^-$ : (K Facility at CERN)

$K_L \rightarrow \pi^0 \gamma \gamma$ : 40% meas. (NA48, KTeV)

$K_L \rightarrow \gamma \gamma l^+ l^-$ : 10% meas./SM sensitivity ( $\mu$ ) (KTeV)

$K_L \rightarrow \gamma \gamma$ : precise meas. (NA48, KLOE)

$K_L \rightarrow \mu^+ \mu^-, l^+ l^- \gamma$ : precise meas. (B871, KTeV, NA48, E799)

$K_L \rightarrow l^+ l^- l^+ l^-$ : precise meas. (KTeV, NA48)

## LU Test and Explicit violation of SM

$R_K$ :  $\mathcal{O}(0.1\%)$  measurement

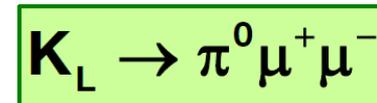
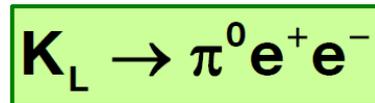
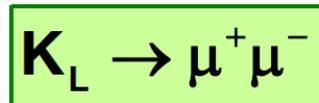
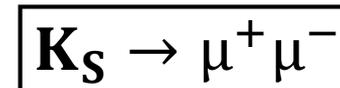
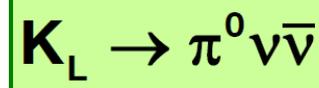
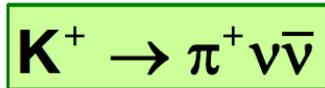
$K^+ \rightarrow \pi^+ l^+ l^-$ : LU conservation test  $\mathcal{O}(< \%)$

$K \rightarrow LNV/LFV$ : Single event sensitivity  $\mathcal{O}(10^{-12})$

$K \rightarrow Exotics$ : Single event sensitivity  $\mathcal{O}(10^{-8} \div 10^{-11})$

# Conclusions

- **Rare kaon decays** are among the more sensitive probe of NP at the highest mass scale, complimentary to B and D physics

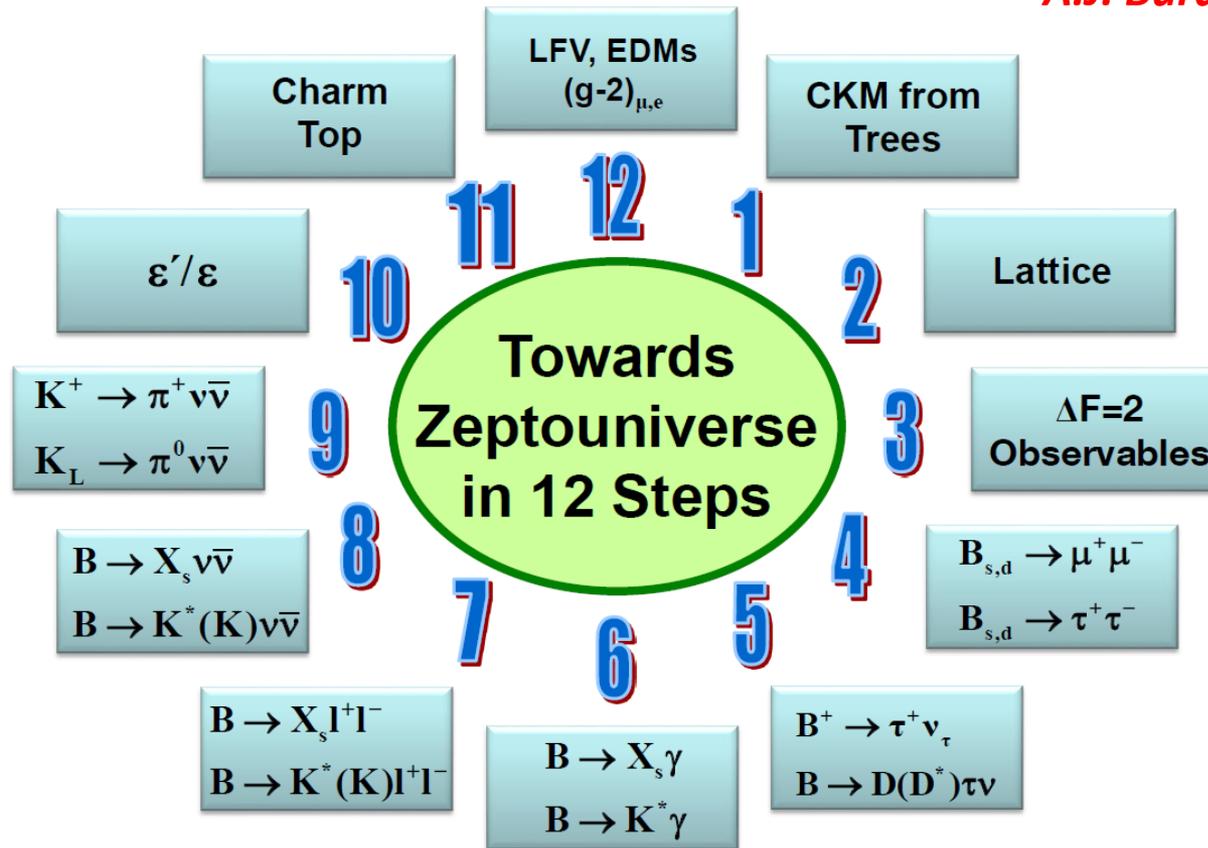


- **$K \rightarrow \pi \nu \nu$  experiments are successfully striking back, and  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  is entering the era of the branching ratio measurement**
- **Kaons decays** can probe NP through: **test of lepton universality**, search for LFV/LNV processes

# Conclusions

- Rare kaon decays are crucial in the quest for the smallest distances

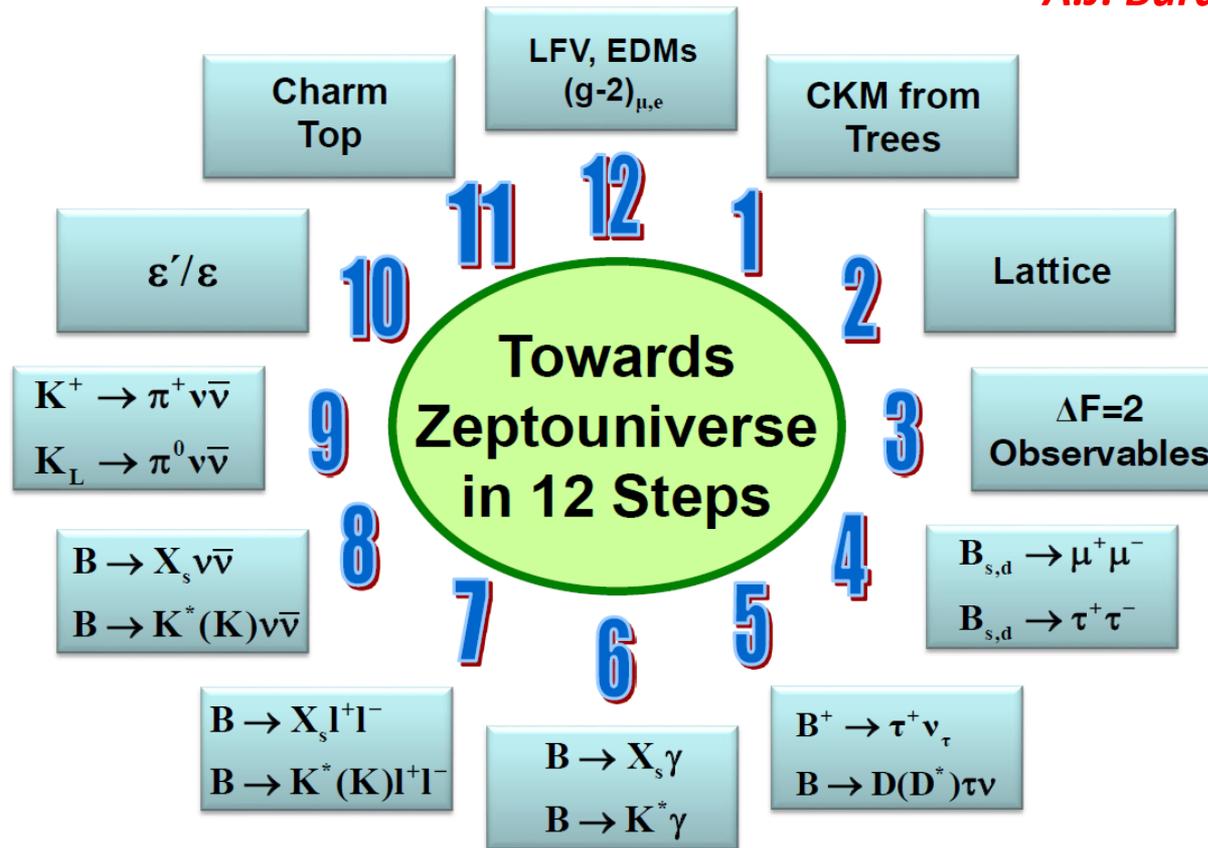
*A.J. Buras KAON2016*



# Conclusions

- Rare kaon decays are crucial in the quest for the smallest distances

*A.J. Buras KAON2016*



- but if the NP paradigm at high mass does not work...

# Conclusions

- We can look into the dark sector



- **Rare kaon decays** experiments are also a laboratory to test the production of **feably interacting particles** (HNL, ALP, dark scalars, ...)