# Kaon Physics at CERN with the NA62 Experiment

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PP Seminar, University of Chicago

17/05/2021

Istituto Nazionale di Fisica Nucleare
SEZIONE DI FIRENZE

# Stars of Kaon Flavour Physics

***A.J. Buras KAON2016***

$\varepsilon_K, \Delta M_K$ | $\varepsilon'/\varepsilon$ | $K^+ \to \pi^+ \nu\bar{\nu}$ | $K_L \to \pi^0 \nu\bar{\nu}$

$K_L \to \mu^+\mu^-$ | $K_L \to \pi^0 e^+ e^-$ | $K_L \to \pi^0 \mu^+\mu^-$

**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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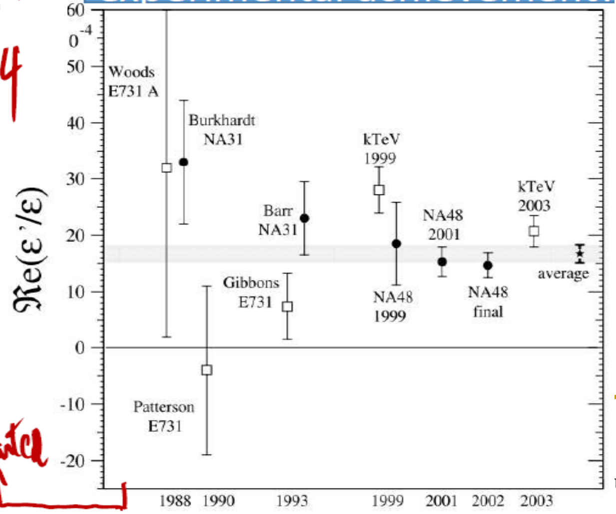
PRD 102 054509 (2020) – RBC-UKQCD

A monumental experimental achievement!

16.6(23)×10⁻⁴ PDG 2014




LATTICE WORK started

**A crucial breakthrough in lattice calculation 2020**

A. Soni, ICHEP 2020

| Quantity | Ours Value | Expt |
|---|---|---|
| $\mathrm{Re}(A_0)$ | $2.99(0.32)(0.59)\times10^{-7}$ GeV | ~ $3.32\times10^{-7}$ GeV |
| $\mathrm{Im}(A_0)$ | $-6.98(0.62)(1.44)\times10^{-11}$ GeV | |
| $\mathrm{Re}(A_0)/\mathrm{Re}(A_2)$ | 19.9(2.3)(4.4) | ~ 22.45 |
| $\mathrm{Re}(\varepsilon'/\varepsilon)$ | 0.00217(26)(62)(50) | |

→ due IB see foll pages

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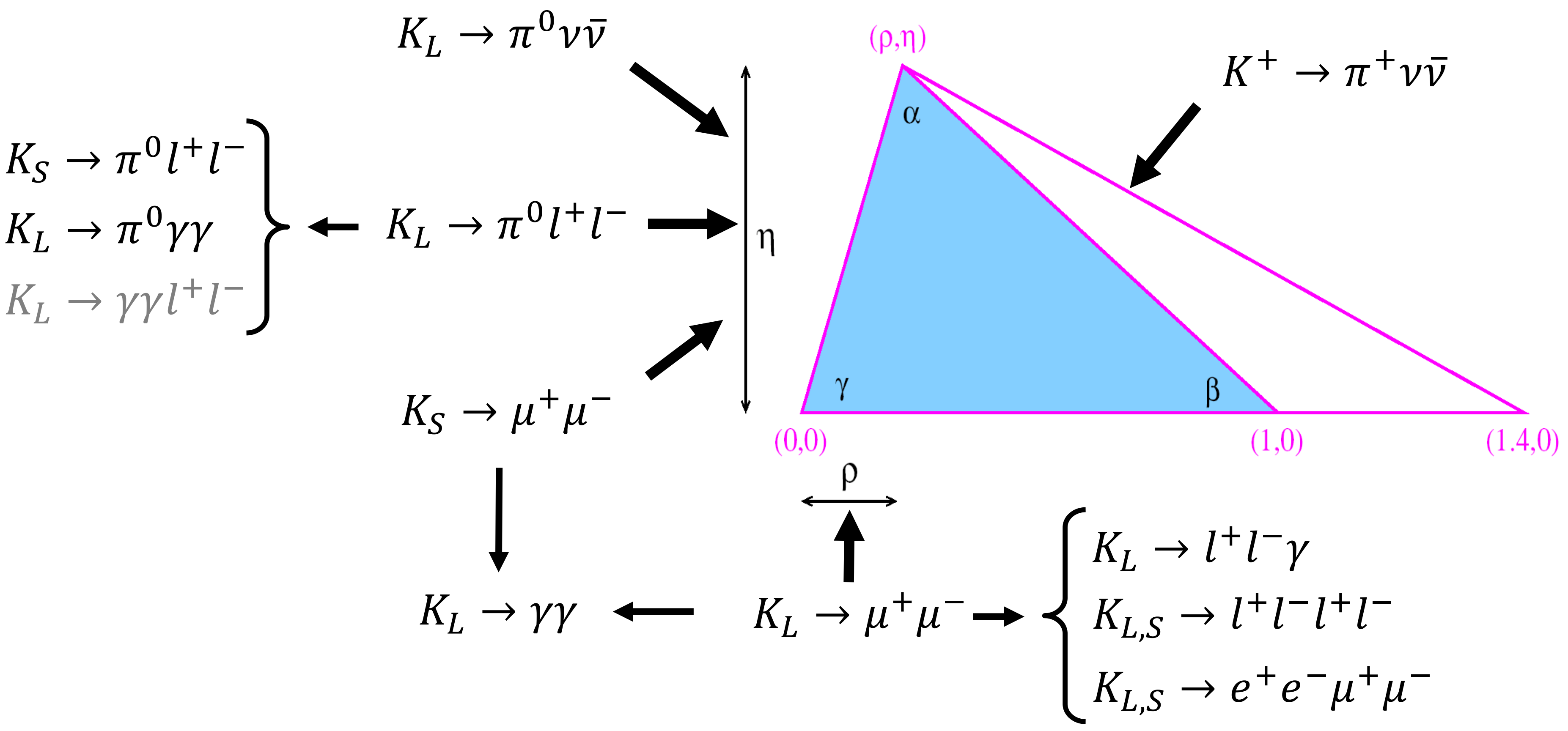
**They all can give some information about very short distance scales but to identify new physics, correlations with $B_{s,d}$ and D observables, EDMs, Lepton physics crucial**

**this Seminar** (an experimental view)

**+**

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

# Rare Kaon Decays and CKM



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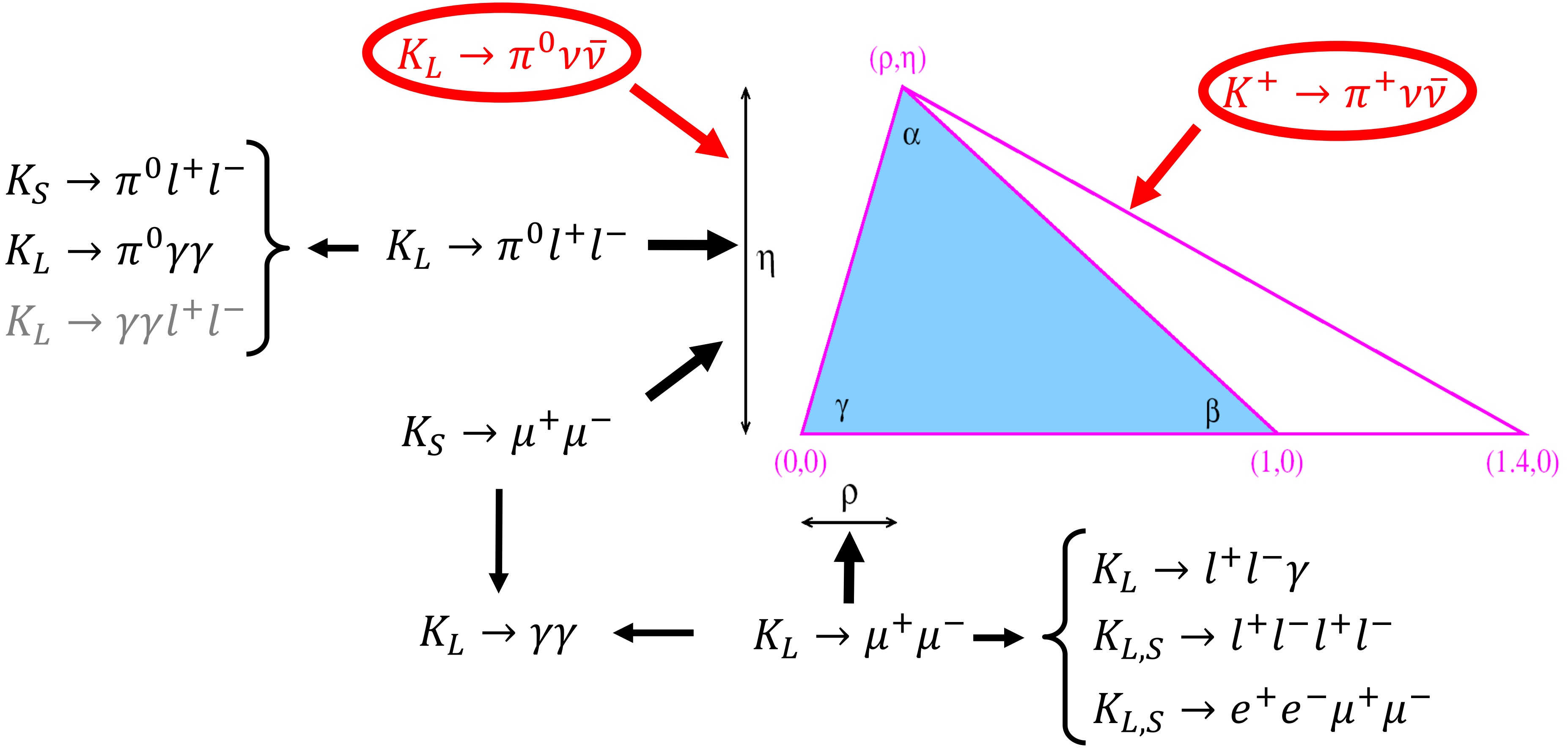
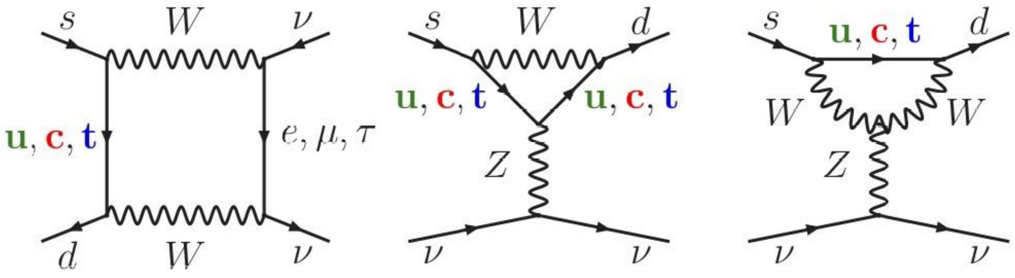


# $K \to \pi\nu\bar{\nu}$: the Subject

- FCNC loop processes: s→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]

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

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

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

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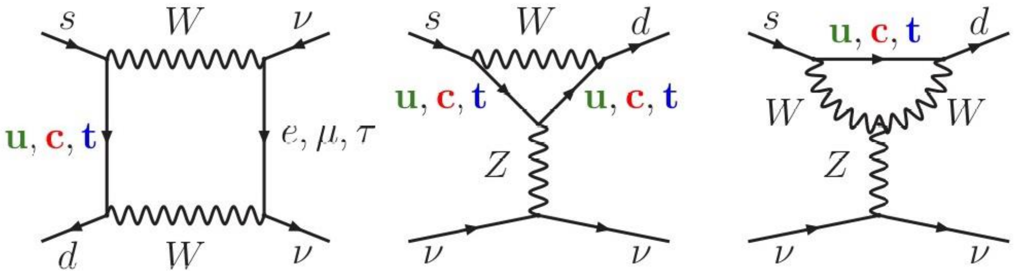



- Very clean theoretically: SD dominated. Hadronic matrix element $\propto \mathcal{B}(K_{l3})$ (precisely measured)

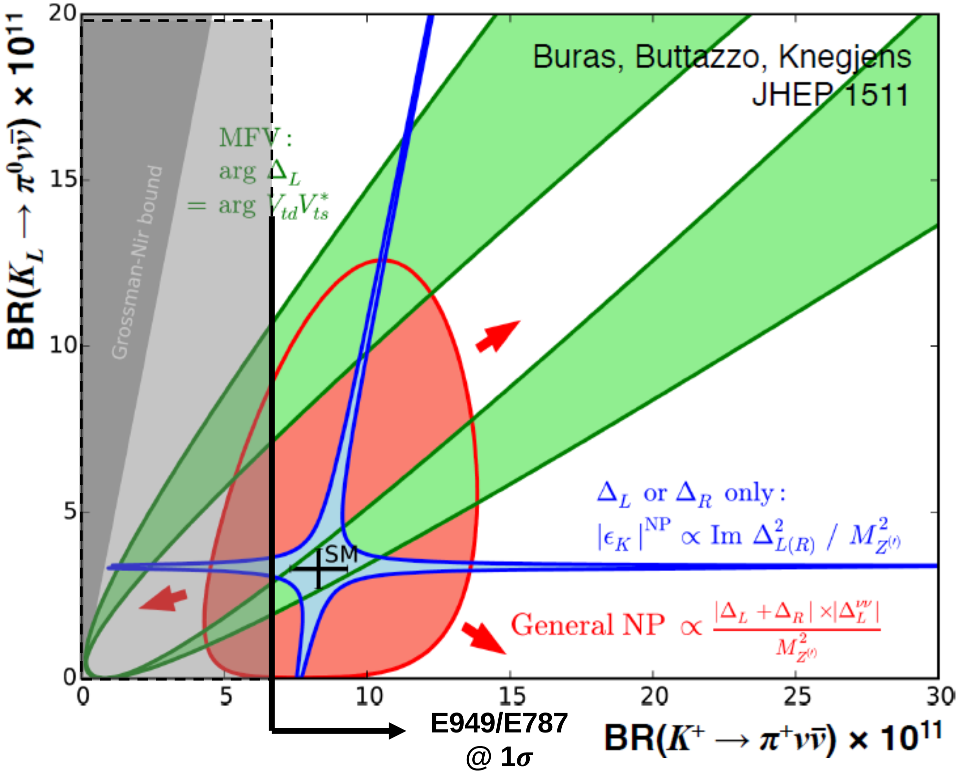
- Experimental status

| | | | |
|---|---|---|---|
| $K^+ \to \pi^+\nu\bar{\nu}$ | BNL E787/E949 (1995-2002) | $\mathcal{B} = \left(1.73^{+1.15}_{-1.05}\right) \times 10^{-10}$ [Final, all data] | PRD 77, 052003 (2008); PRD 79, 092004 (2009) |
| | CERN NA62 (2016 - present) | $\mathcal{B} < 1.78 \times 10^{-10}$ 90% CL [2016-17 data] | PLB 791, 156 (2019); JHEP 11, 042 (2020) |
| | | this seminar [2016-17-18 data] | |
| $K_L \to \pi^0\nu\bar{\nu}$ | KEK E391 (2004-2005) | $\mathcal{B} < 26 \times 10^{-9}$ 90% CL [Final, all data] | PRD 81, 072004 (2010) |
| | JPARC KOTO (2012 - present) | $\mathcal{B} < 3.0 \times 10^{-9}$ 90% CL [2015 data] | PRL 122, 021802 (2018) |
| | | $\mathcal{B} < 4.9 \times 10^{-9}$ 90% CL [2016-17-18 data] | PRL 126, 121801 (2021) |

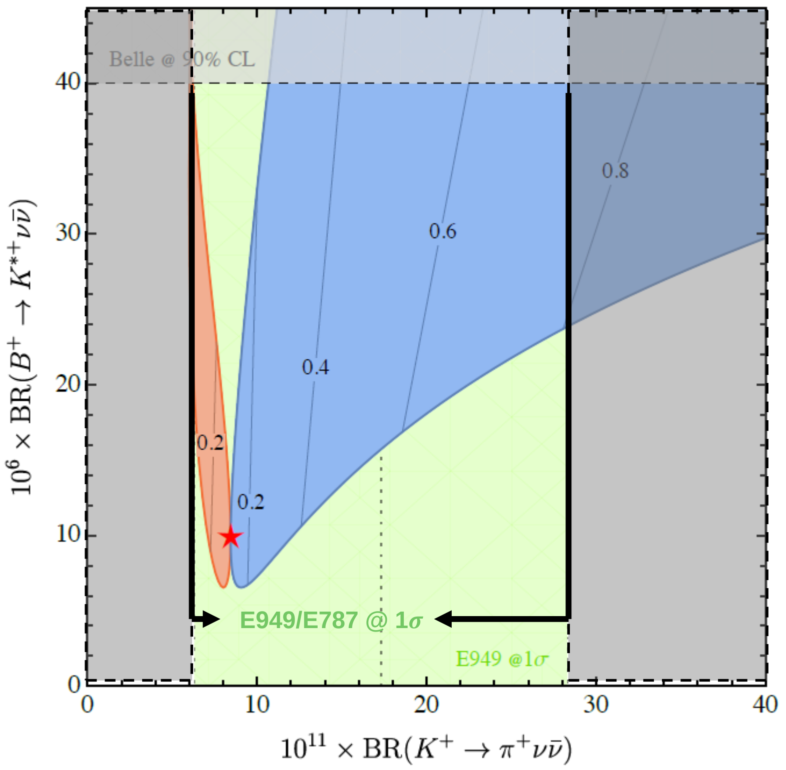
# $K \to \pi\nu\bar{\nu}$: the Plot

- High sensitivity to NP (non MVF): 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* See also arXiv:2006.01138

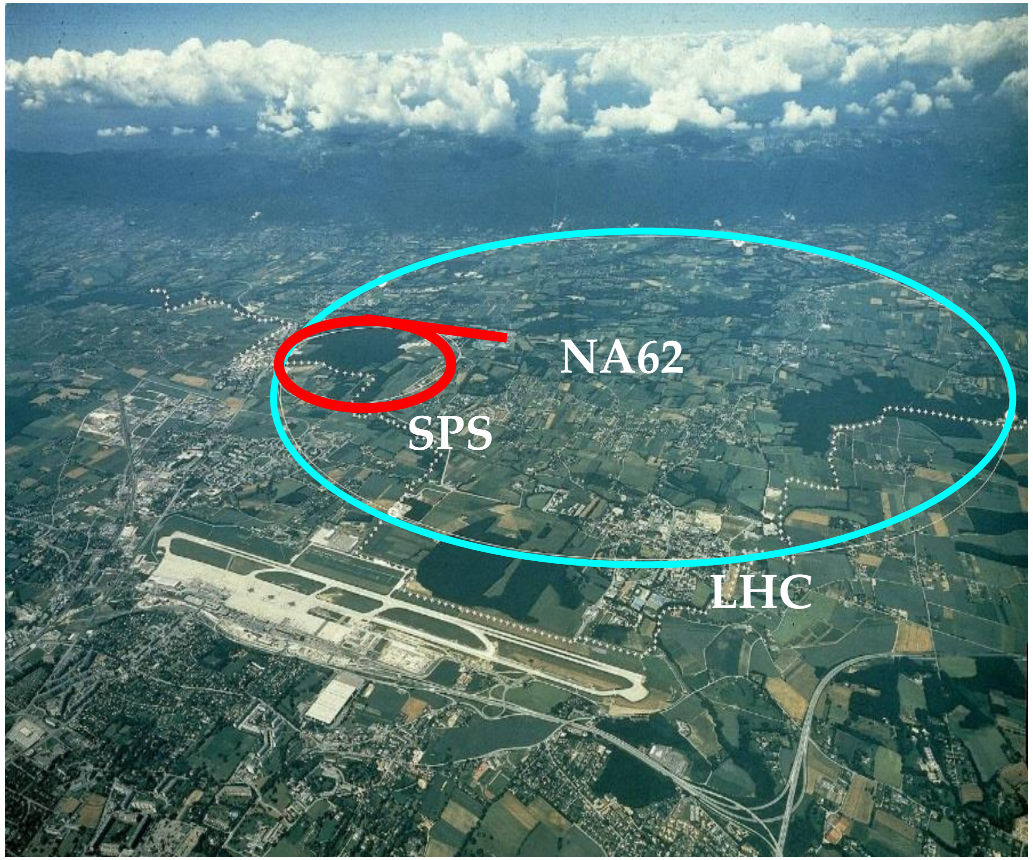


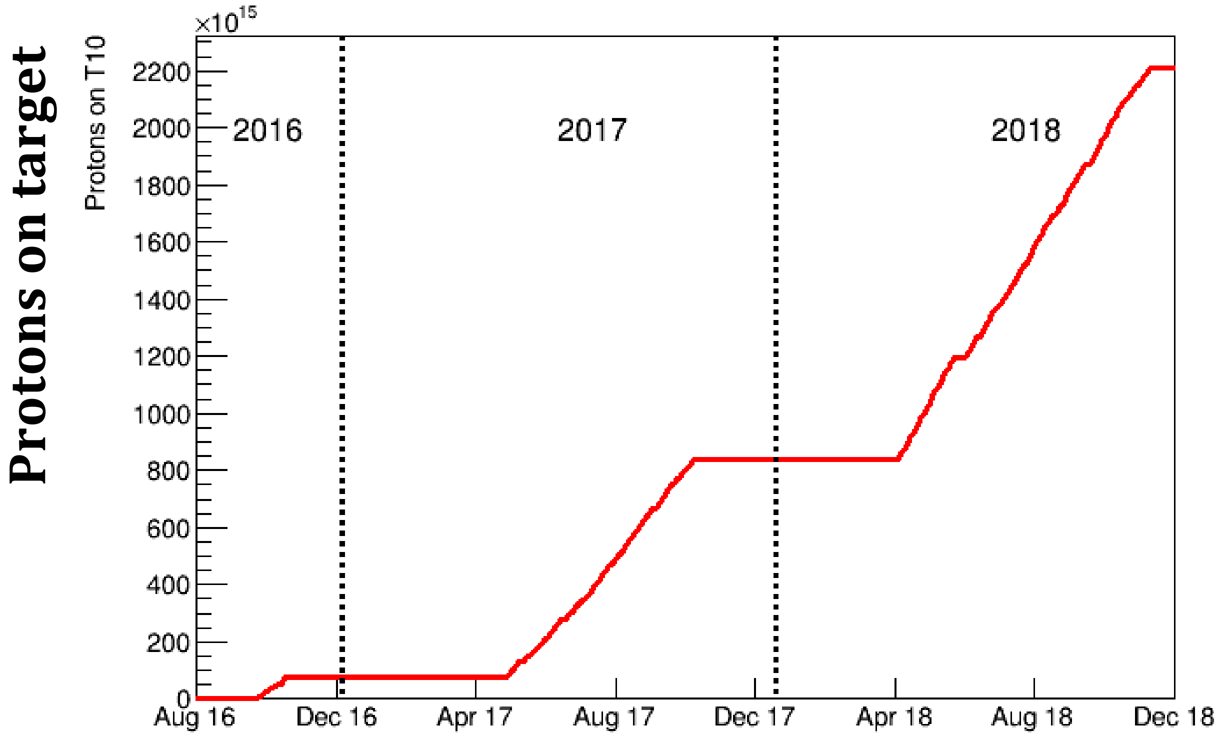

*LFU violation* EPJ C (2017) 77: 618



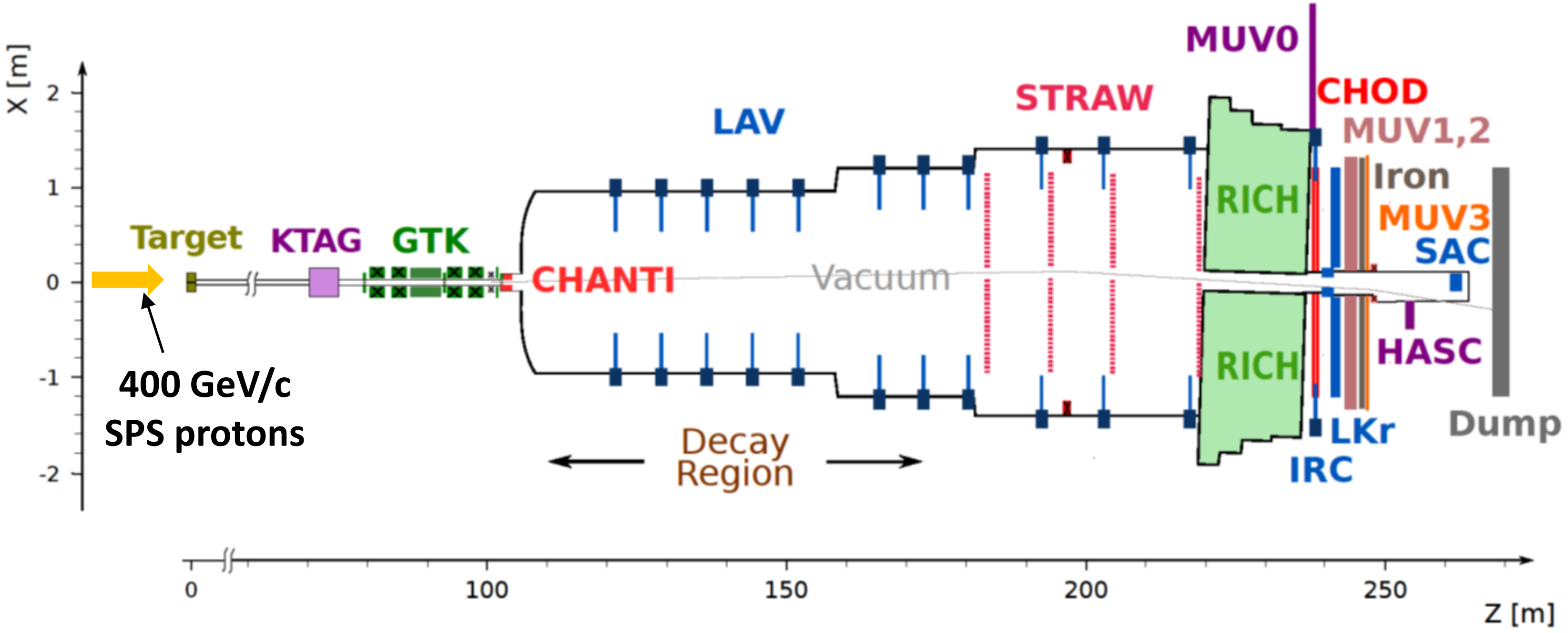
# $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ Today: NA62

~200 participants: Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna (JINR), Fairfax (GMU), Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain-la-Neuve, Mainz, Moscow (INR), Naples, Perugia, Pisa, Prague, Protvino (IHEP) , Rome I, Rome II, San Luis Potosi, Torino, TRIUMF, Vancouver (UBC)



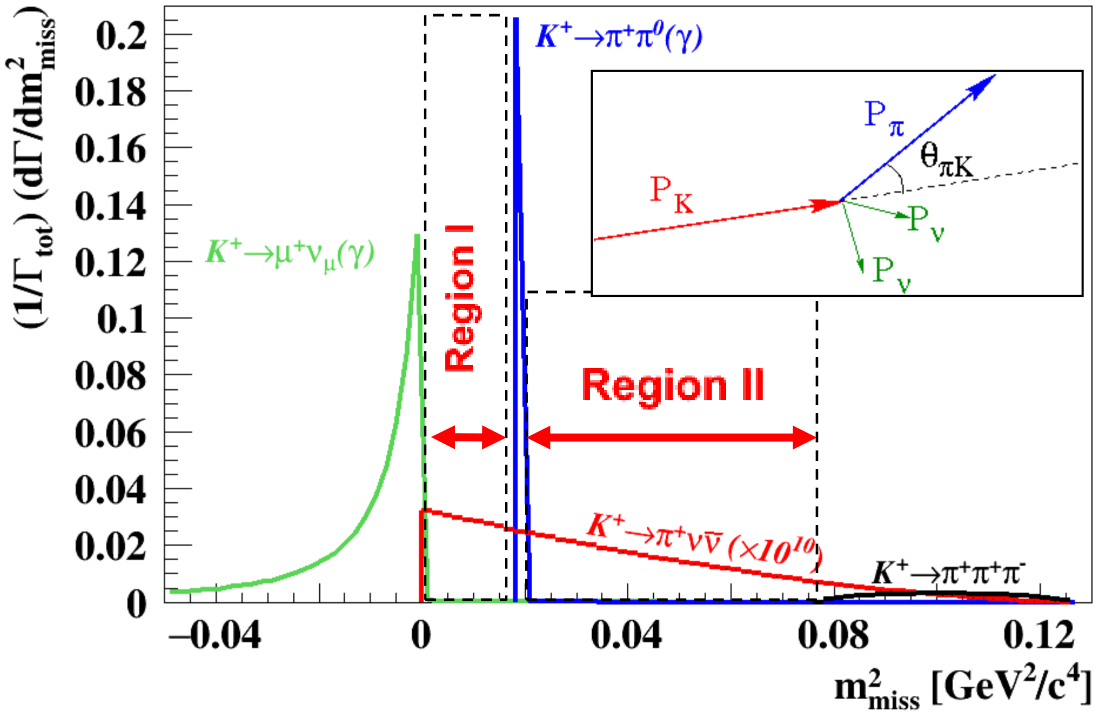
# NA62: the Experiment




| | |
|---|---|
| Beam Intensity | $19 - 22 \times 10^{11}$ ppp (450-550 MHz @ GTK3) |
| Incoming $K^+$, 75 GeV/c, 1% rms | Timing KTAG, GTK ($\sigma_t$~70, 90 ps); momentum by GTK |
| Outing $\pi^+$ | Timing RICH. CHOD ($\sigma_t$~70, 200 ps); momentum by STRAW |
| $\gamma$/multitrack veto | LAV, LKr, IRC, SAC |
| Particle ID | RICH, LKr, MUV1,2,3 |

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

| *Main $K^+$ decays* | *Branching ratio* |
|---|---|
| $K^+ \rightarrow \pi^+\pi^0(\gamma)$ | 0.2067 |
| $K^+ \rightarrow \mu^+\nu(\gamma)$ | 0.6356 |
| $K^+ \rightarrow \pi^+\pi^+\pi^-$ | 0.0558 |
| $K^+ \rightarrow \pi^+\pi^- e^+\nu$ | $4.25 \cdot 10^{-5}$ |




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

**+**

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

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

Photon veto

| | | | |
|---|---|---|---|
| $\mathcal{O}(100\ ps)$ | Timing between sub-detectors | $\Longrightarrow$ | Si – tracker + Cherenkov counters |
| $\geq 10^3$ | Kinematic background suppression | $\Longrightarrow$ | Low – mass spectrometers (0.5% $X_0$) |
| $\geq 10^8$ | Muon suppression | $\Longrightarrow$ | Calorimetric & Cherenkov particle *ID* |
| $\geq 10^8$ | $\pi^0$ (from $K^+ \rightarrow \pi^+\pi^0$) suppression | $\Longrightarrow$ | $\gamma$ detection inefficiency $\lesssim 10^{-5}$ ($E_\gamma$ > 10 GeV)<br>$P_{\pi^+} < 45$ GeV/c $\rightarrow \pi^0$ energy $> 30$ GeV |

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

### Selection

$K^+$- $\pi^+$ matching (Straw – GTK – KTAG - RICH)

$K^+$ decays in the decay region

$\pi^+$ identification (Calorimeters - RICH)

$\gamma$ / multi-track rejection (calorimeters, hodoscope)

### Background in signal regions

$K^+$ decays in decay region: $\pi^+\pi^0$, $\mu^+\nu$, $\pi^+\pi^-e^+\nu$

Accidental $\pi^+$ from the beam line

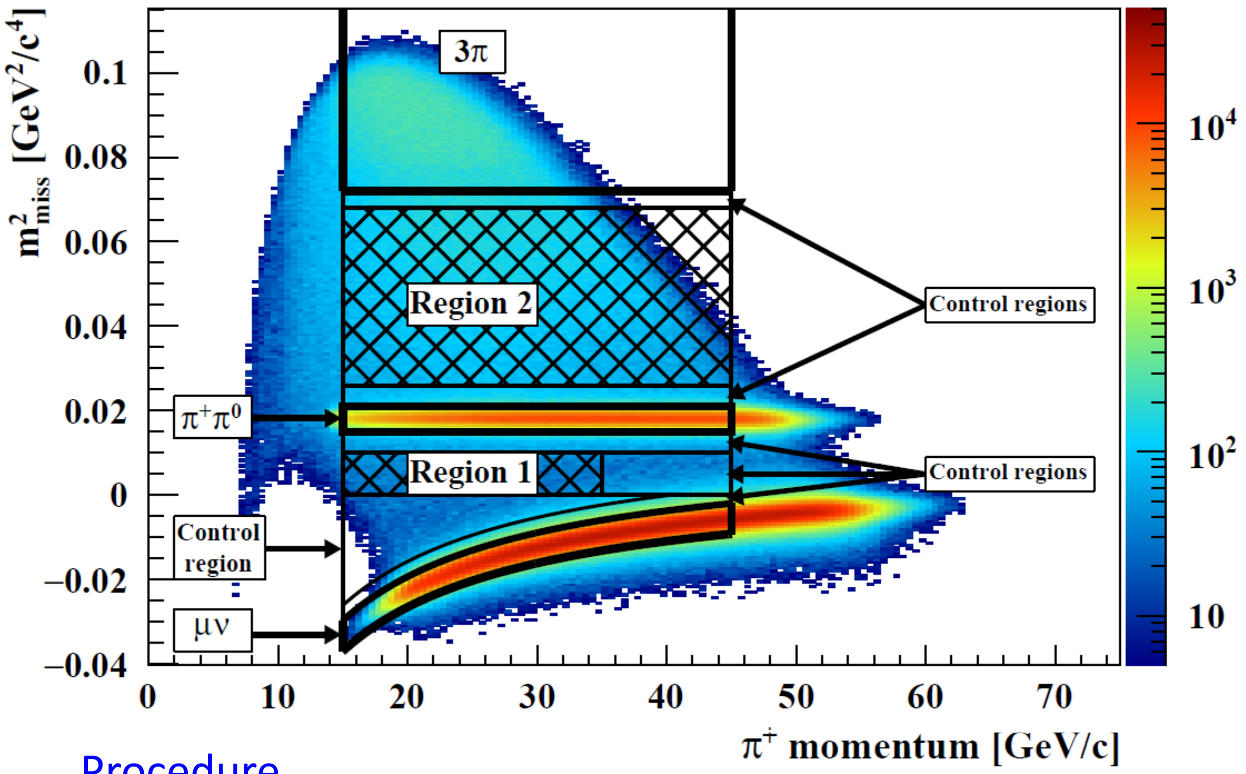
Mostly data – driven predictions, control regions for validation

### Single Event Sensitivity (S.E.S.)

Effective number $K^+$ decays from $K^+ \rightarrow \pi^+\pi^0$

Signal efficiency

- Monte Carlo (acceptance)
- Data (trigger efficiency, random veto)




### Procedure

Analysis in 5 GeV/c wide bins of $\pi^+$ momentum

Counting of the observed events in signal regions

Branching ratio from fit in momentum bins and years of data taking

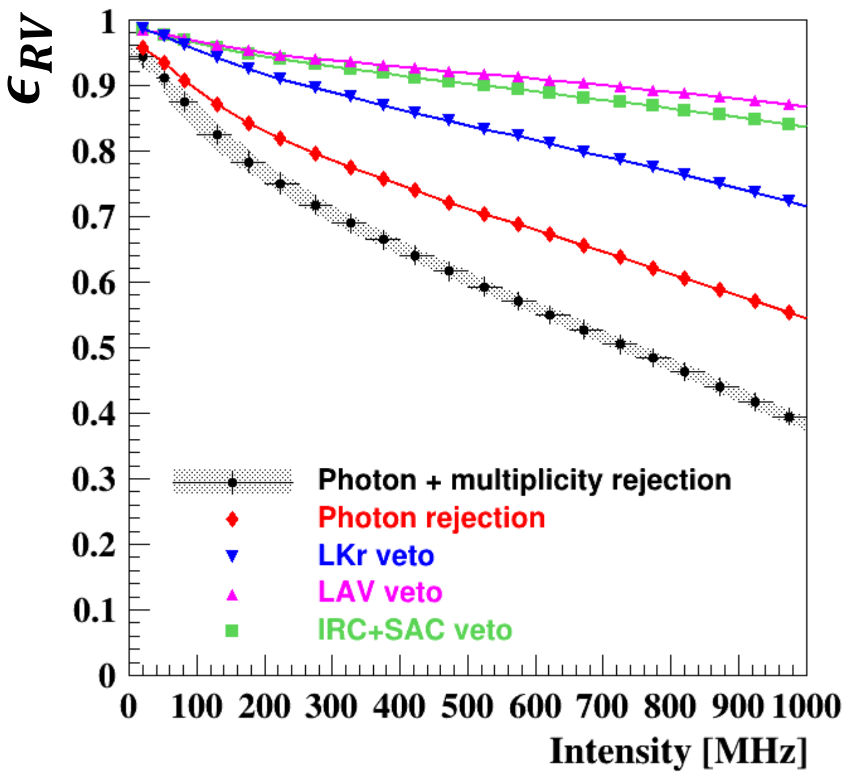
Blind analysis

# $K^+ \to \pi^+\nu\bar{\nu}$ @ NA62: the single event sensitivity (SES)

$$SES = \frac{BR(K^+ \to \pi^+\pi^0) \cdot A_{\pi\pi}}{D \cdot N_{\pi\pi} \cdot \epsilon_{RV} \cdot A_{\pi\nu\bar{\nu}} \cdot \epsilon_{trig}^{PNN}}$$

- $A_{\pi\pi}$: Normalization acceptance
- $D$: Minimum bias trigger downscaling
- $N_{\pi\pi}$: Normalization events from minimum bias
- $A_{\pi\nu\bar{\nu}}$: Signal acceptance ~6.5% (2018)
- $\epsilon_{trig}^{PNN}$: Signal trigger efficiency ~90%
- $\epsilon_{RV}$:

- Signal loss probability resulting from random veto induced by photon rejection/extra particle rejection due to accidental activity
- Estimated from data ($K^+ \to \mu^+\nu$)
- Dependent on the beam intensity; 2018 data: $\langle\epsilon_{RV}\rangle = 0.66 \pm 0.01$

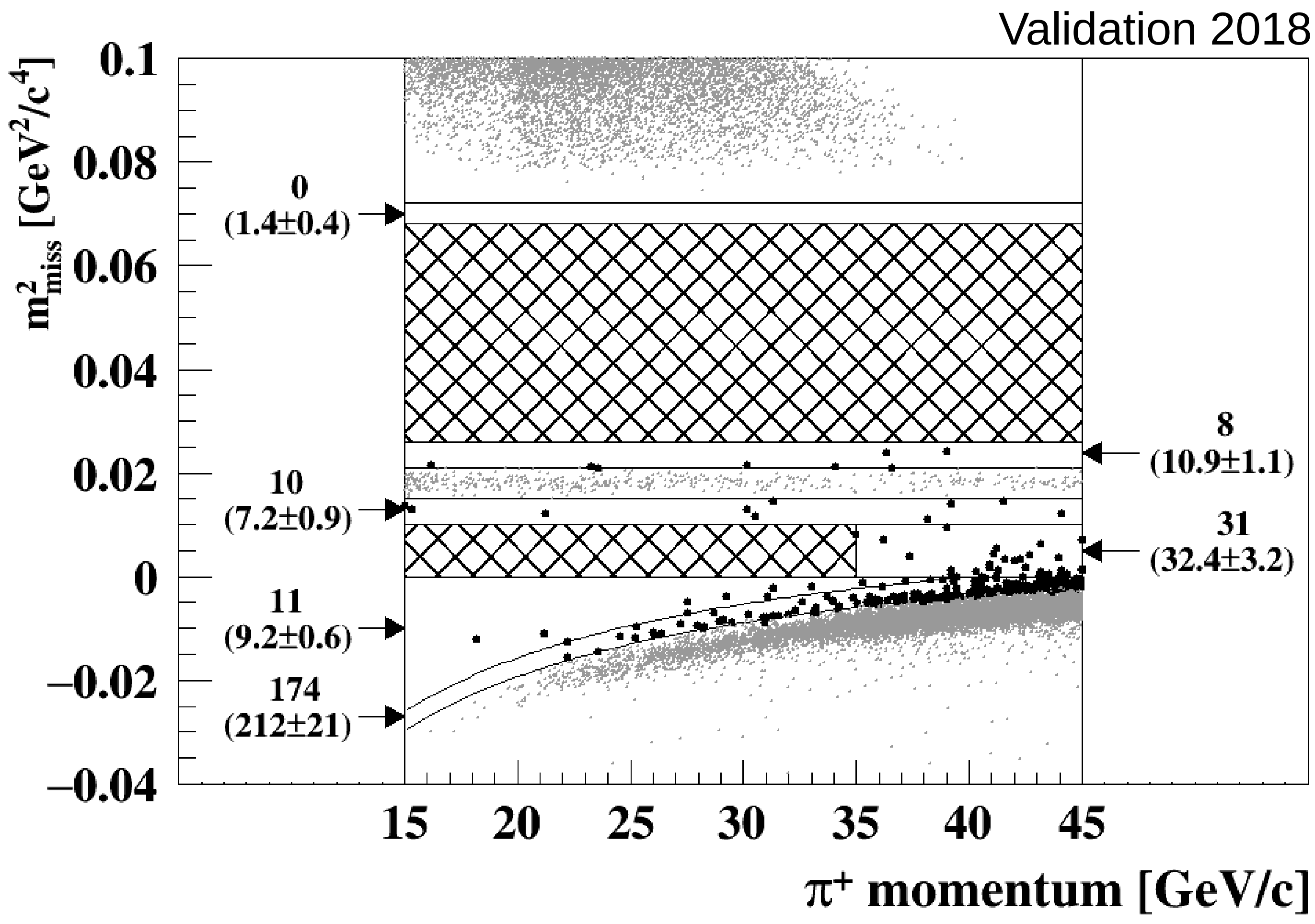



$$SES\ (2018) = (1.1 \pm 0.1) \times 10^{-11} \Rightarrow N_{\pi\nu\nu}^{exp}\ (2018) \sim 7.6$$

$$\mathbf{SES\ (2016+17+18) = (0.84 \pm 0.05) \times 10^{-11} \Rightarrow N_{\pi\nu\nu}^{exp}\ (2016+17+18) \sim 10}$$

# $K^+ \to \pi^+ \nu\bar{\nu}$ @ NA62: the Background (2018 data)

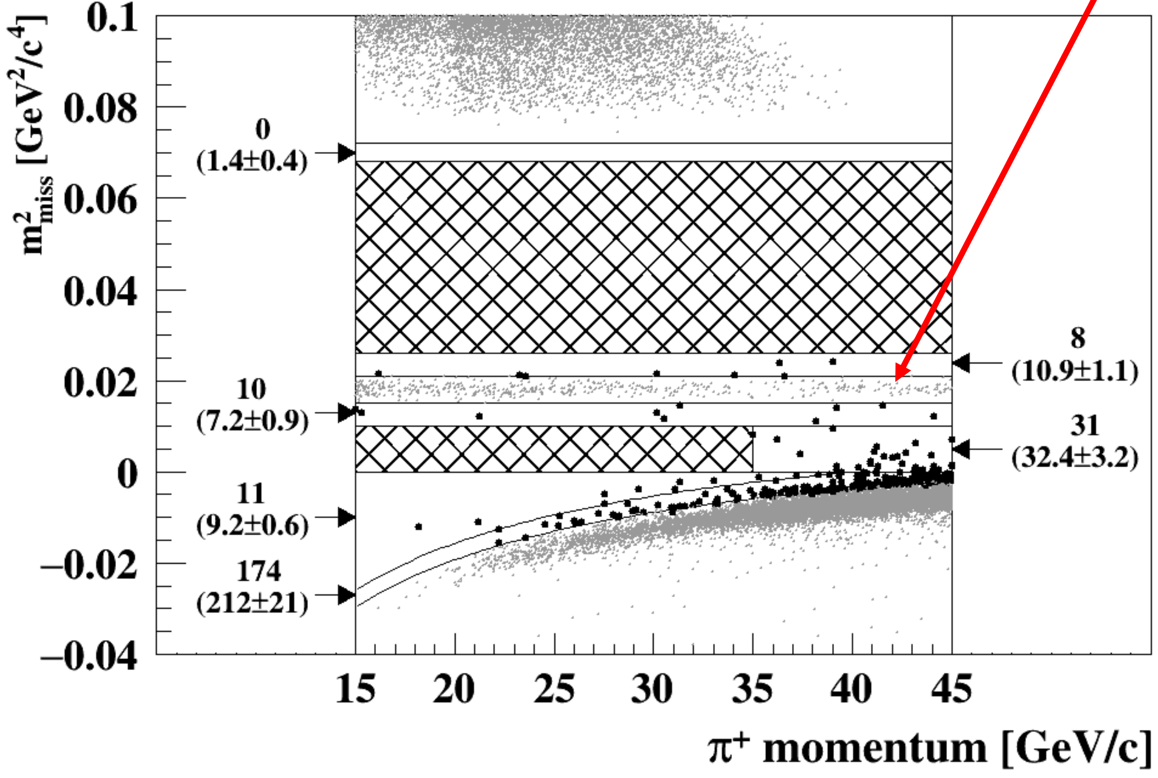
| Channel | Background |
|---|---|
| $\pi^+\pi^0$ | $0.75 \pm 0.05$ |
| $\mu^+\nu$ | $0.64 \pm 0.08$ |
| $\pi^+\pi^-e^+\nu$ | $0.51 \pm 0.10$ |
| $\pi^+\pi^+\pi^-$ | $0.22 \pm 0.10$ |
| $\pi^+\gamma\gamma$ | $< 0.01$ |
| $\pi^0 l^+\nu$ | $< 0.001$ |
| Upstream | $3.30^{+1.00}_{-0.75}$ |
| Total (2018) | $5.42^{+1.00}_{-0.75}$ |
| **Total (2016+17+18)** | $\mathbf{7.03^{+1.05}_{-0.82}}$ |

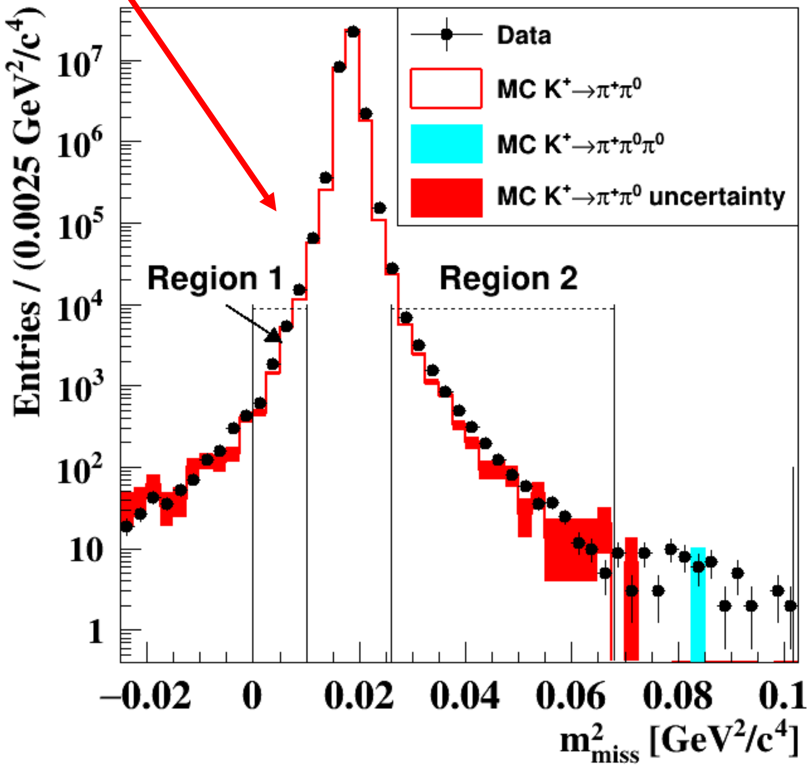


# $K^+ \to \pi^+ \nu\bar{\nu}$ @ NA62: $\pi^+\pi^0$ Background

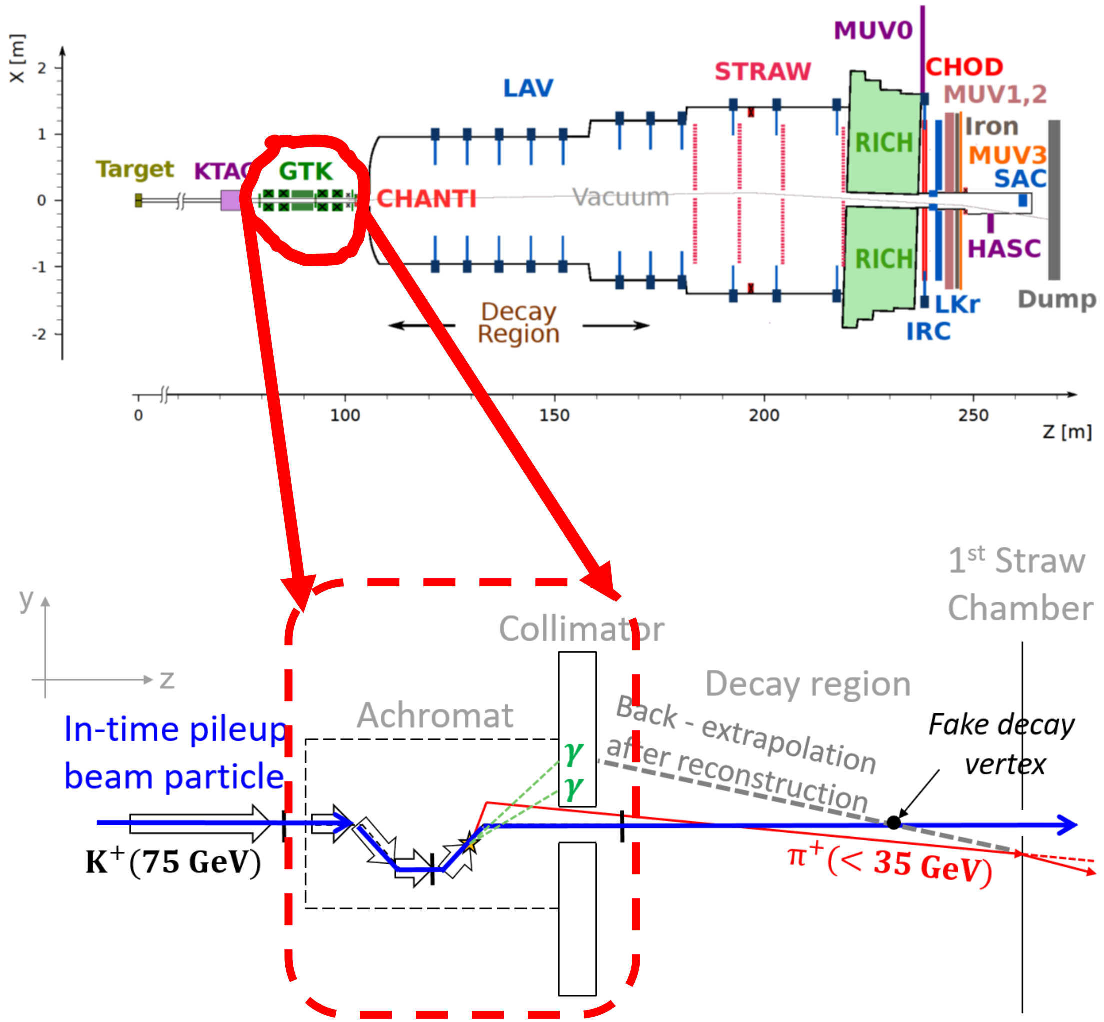
$$N^{exp}_{\pi\pi}(region) = N(\pi^+\pi^0) \cdot f^{kin}(region)$$

Minimum bias $K^+ \to \pi^+\pi^0$ data to study the tails of the $m^2_{miss}$



# $K^+ \to \pi^+\nu\bar{\nu}$ @ NA62: Upstream Background



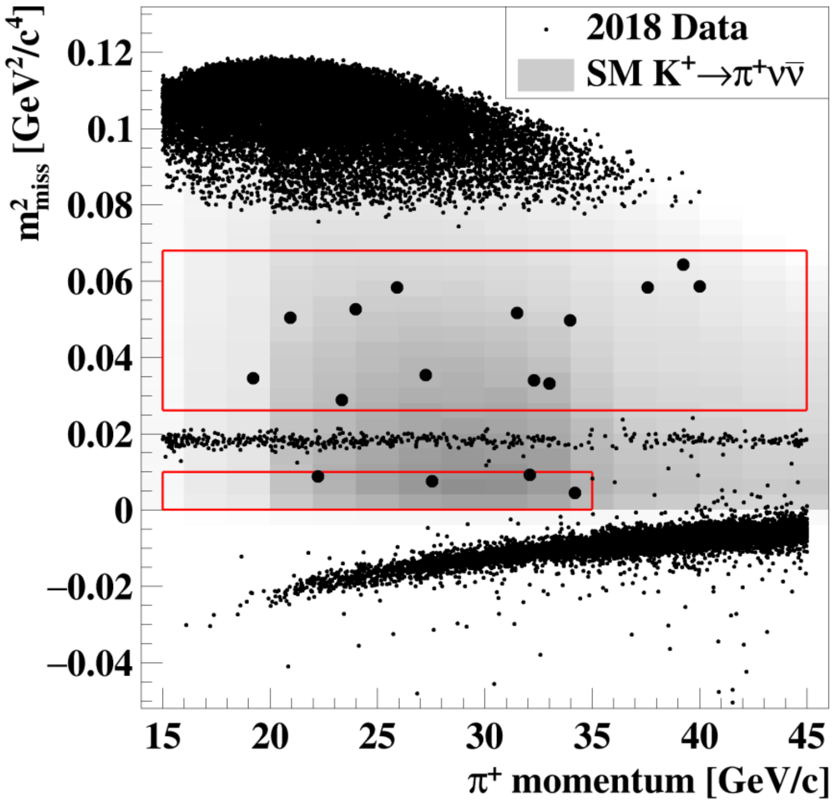

- $K^+$ decays/interacts along the beam line
- Secondary $\pi^+$ downstream
- Beam elements block additional particles
- $\pi^+$ scattering in straw chamber 1
- Pileup beam particle tagged as $K^+$

Count events on data with inverted $K-\pi$ matching × Estimate the probability to occur from data/simulation

Estimated events in signal regions

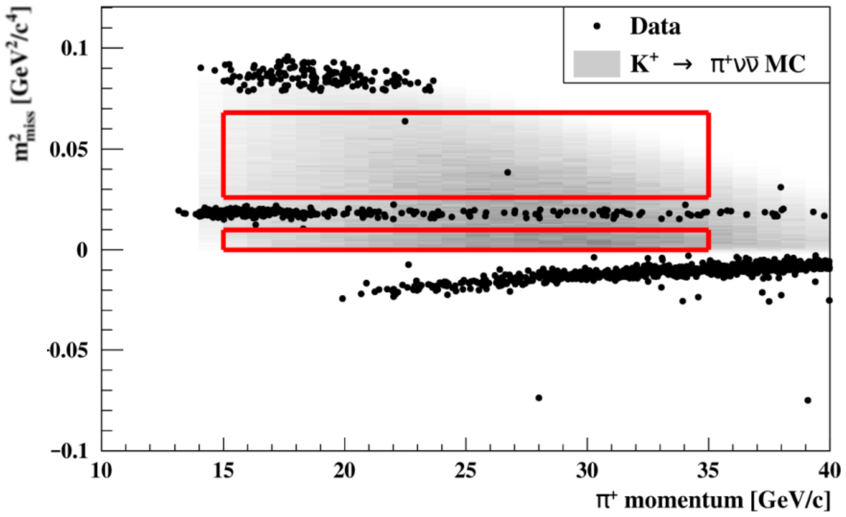
# $K^+ \to \pi^+\nu\bar{\nu}$ @ NA62: the Result

**2018 data:**
**17 candidates observed**



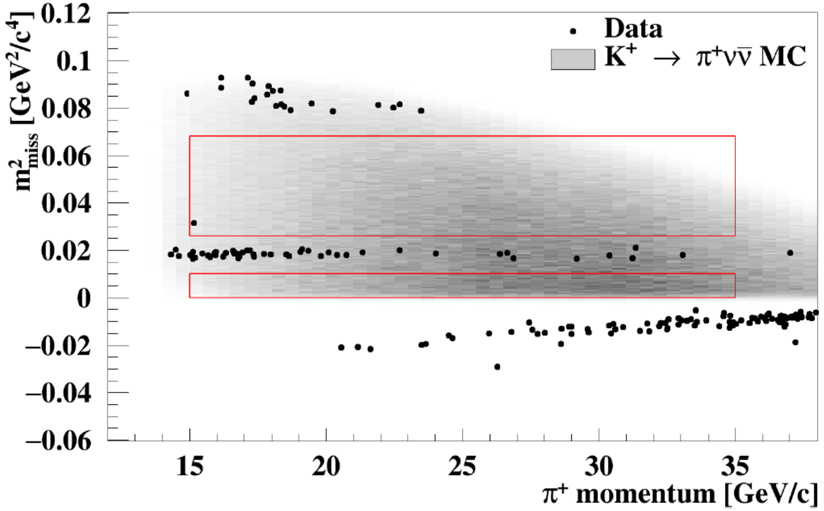

**2017 data:**
**2 candidates observed**

JHEP 11, 042 (2020)




**2016 data:**
**1 candidates observed**

PLB 791, 156 (2019)



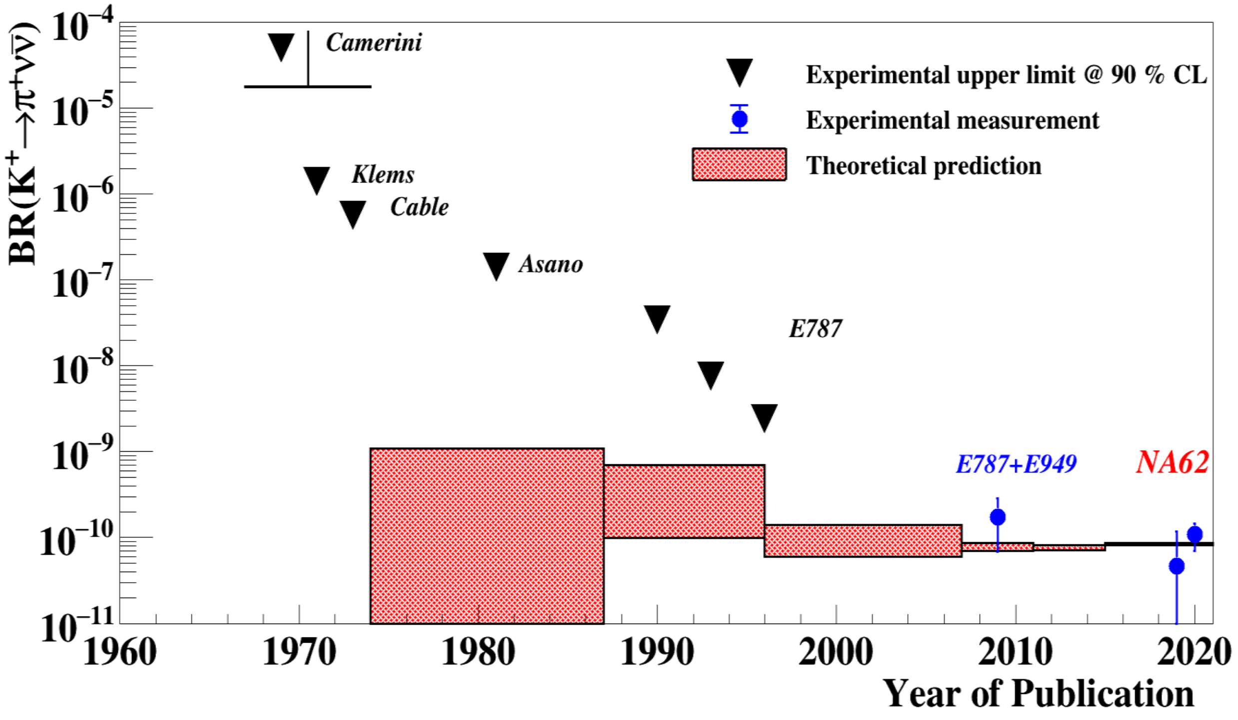

$$SES = (0.839 \pm 0.053_{\text{syst}}) \times 10^{-11} \quad N^{\text{exp}}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42_{\text{syst}} \pm 1.19_{\text{ext}}, \quad N^{\text{exp}}_{\text{background}} = 7.03^{+1.05}_{-0.82}.$$

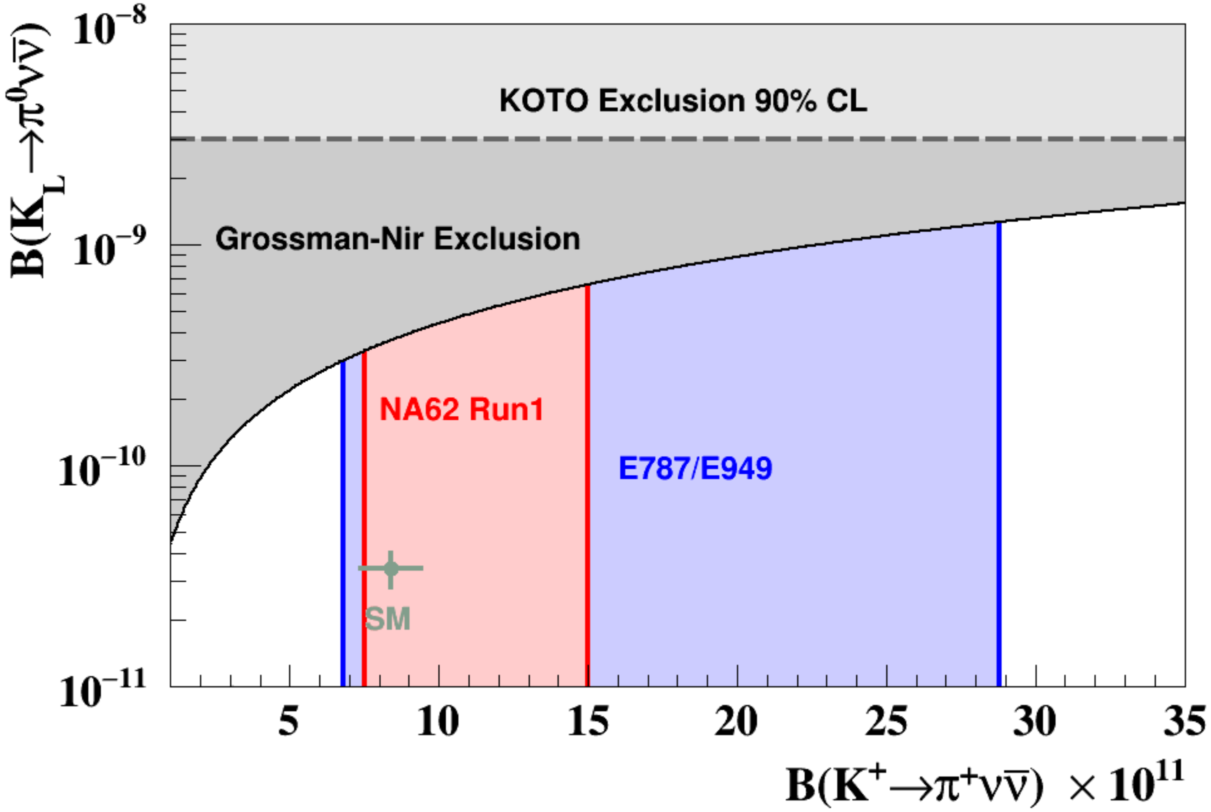
# $K^+ \to \pi^+\nu\bar{\nu}$ @ NA62: the Result

3.4$\sigma$ evidence for $K^+ \to \pi^+\nu\bar{\nu}$

$$BR(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11} \text{ at } 68\% \text{ CL}$$

arXiv: 2103.15389, accepted by JHEP



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

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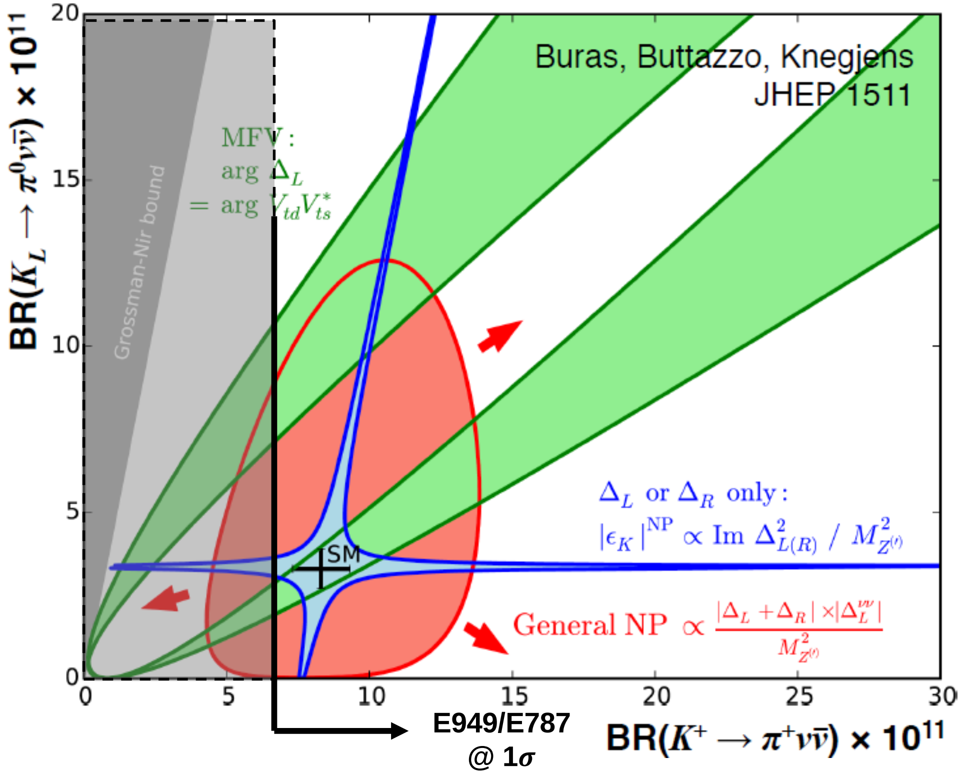
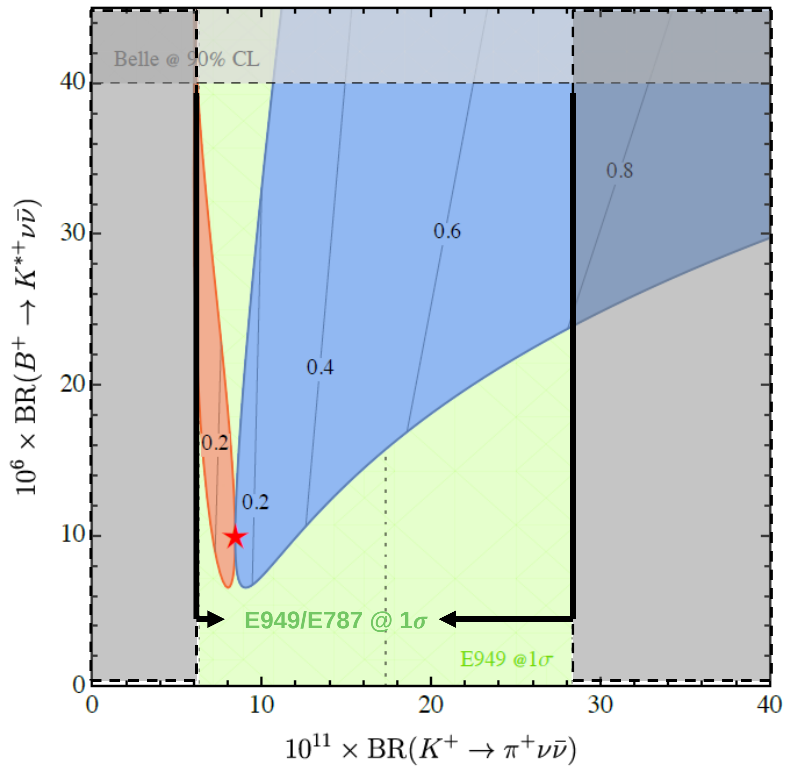
*Not-SUSY models* See also arXiv:2006.01138




*LFU violation* EPJ C (2017) 77: 618



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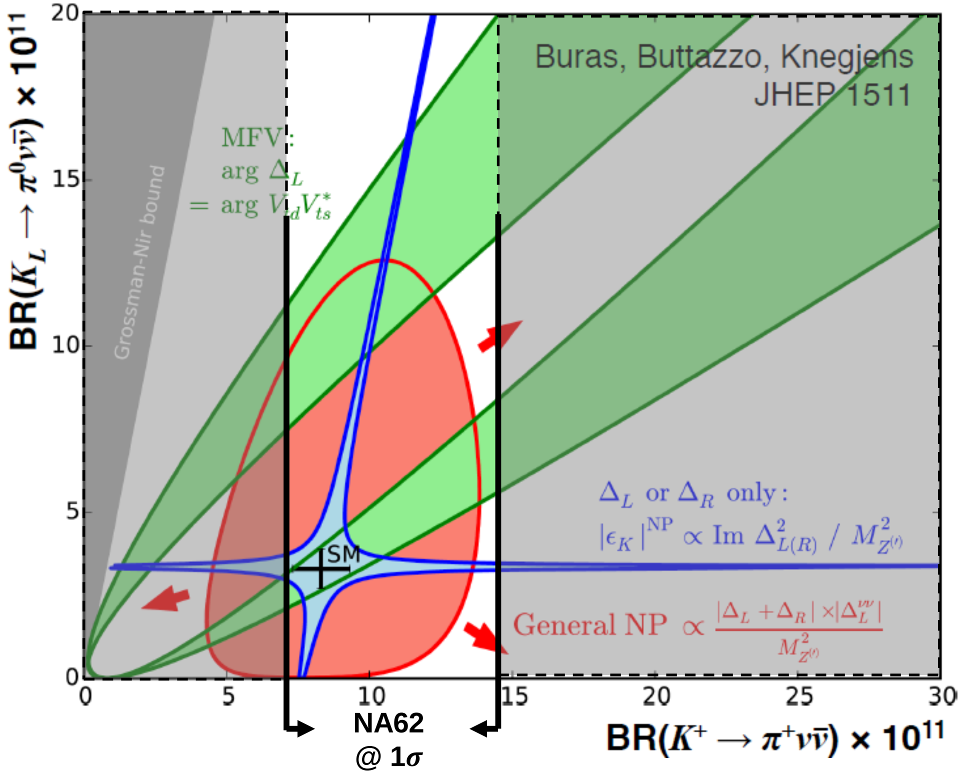


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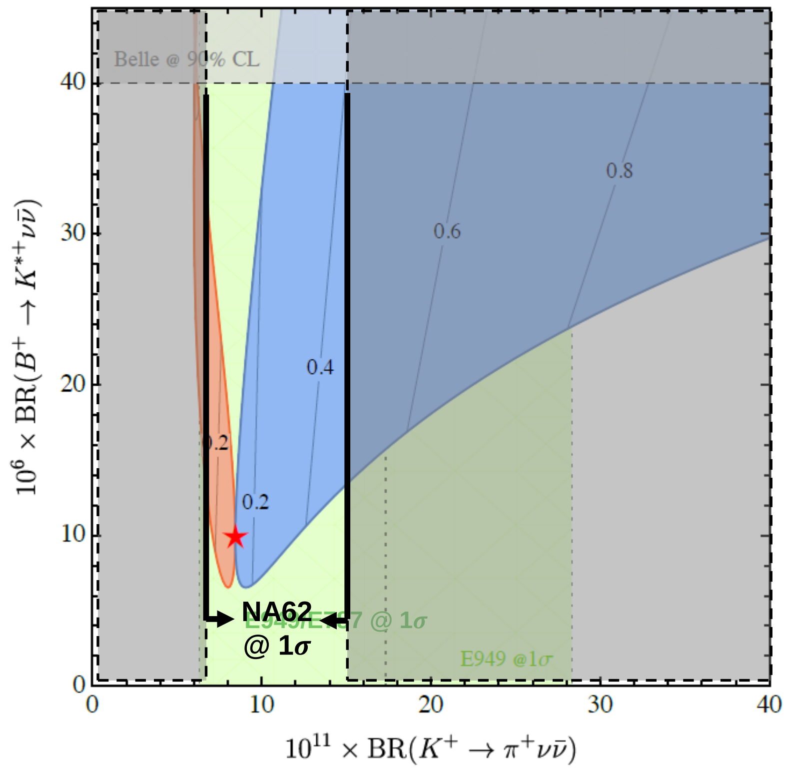

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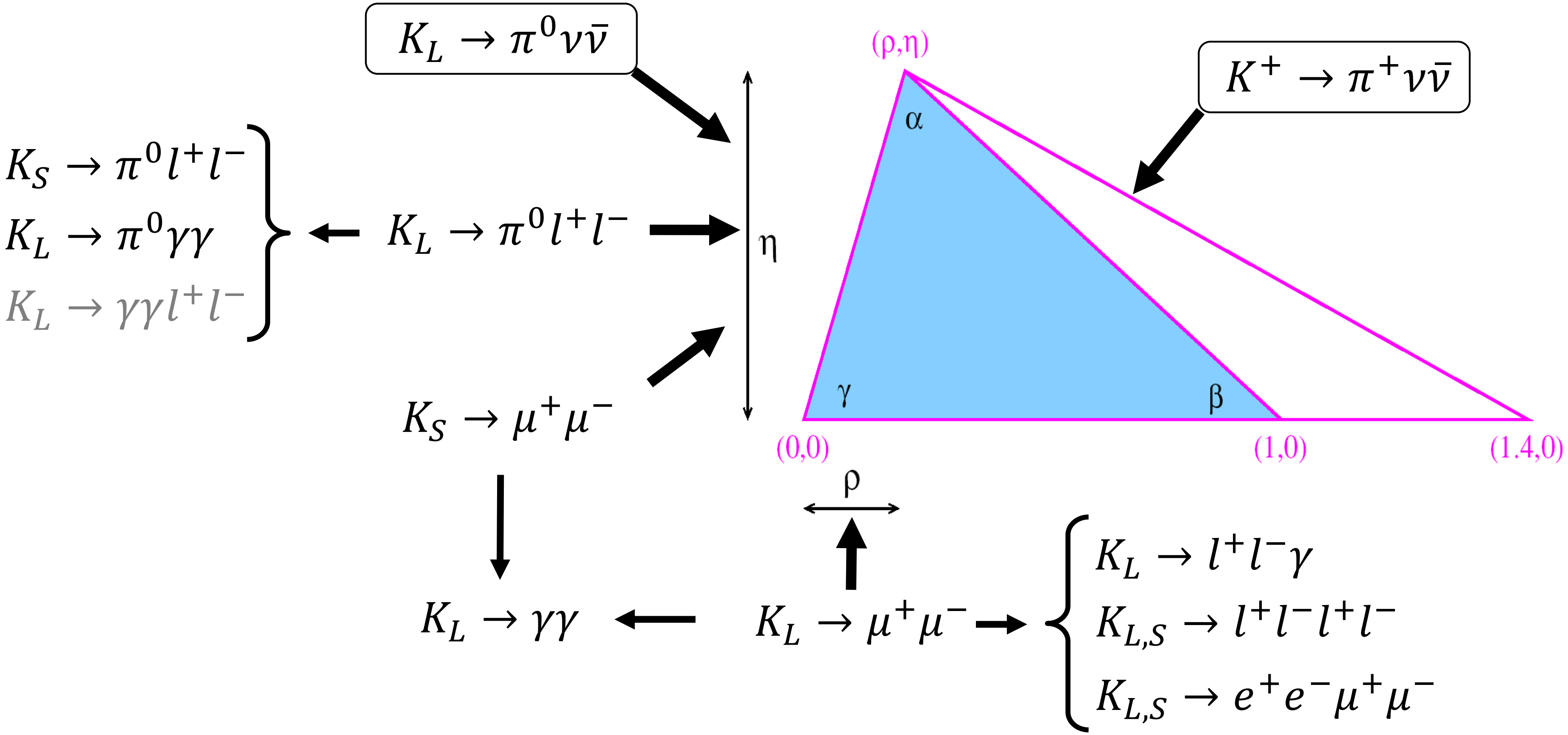

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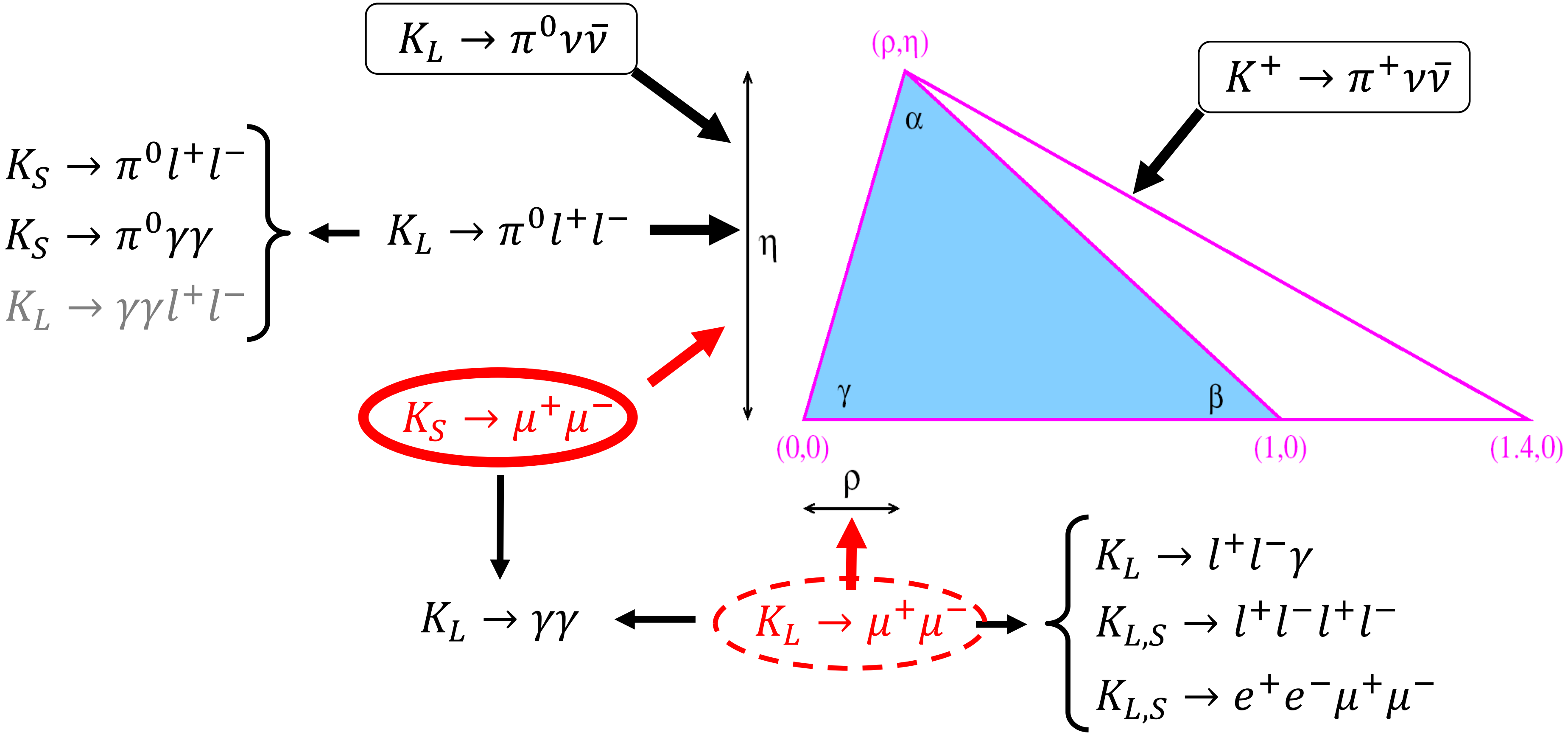
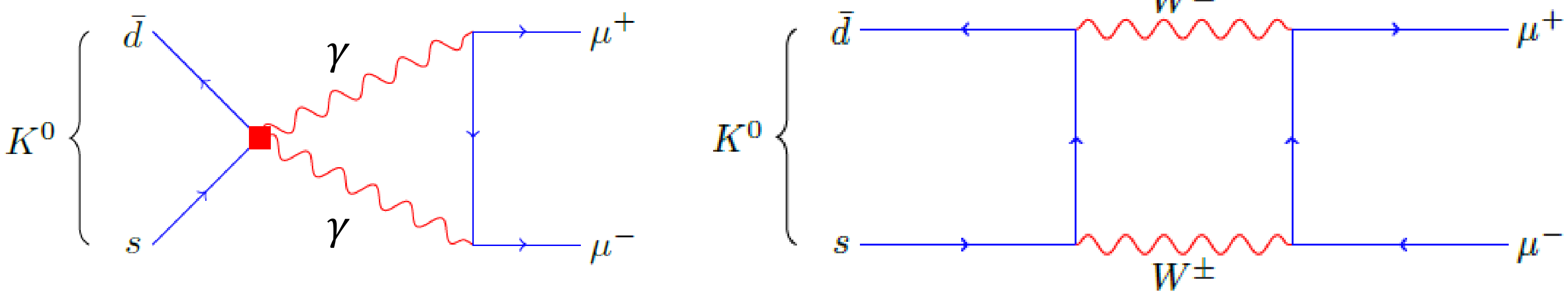


# $K^0 \to \mu^+\mu^-$

Long distance (LD) Short distance (SD) [example]




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

$\mathcal{B}(K_S \to \mu^+\mu^-)_{SM} = (5.0 \pm 1.5) \times 10^{-12} \propto \left|A_S^{LD} + A_S^{SD}\right|^2$, $\left|A_S^{SD}\right|^2 \propto |\bar{\eta}|^2 \sim \mathcal{O}(10^{-13})$, 1% theory error

- $K_S - K_L$ interference $\to \mu^+\mu^-$ : allows the measurement of $\left|A_S^{SD}\right|^2$ D'Ambrosio et al. PRL 119, 20, 201802 (2017), JHEP **05** 024 (2018) Dery, Ghosh, Grossman, Schacht, arXiv 2104.06427
  - $\mathcal{B}(K_L \to \mu^+\mu^-)$, $\mathcal{B}(K_S \to \mu^+\mu^-)$ + time dependent rate measurement

# Kaons @ LHCb

LHCb: 1 strange hadron / event produced at 13 TeV

Production rate compensates low trigger efficiency and long lifetime

Vast $K$ program [mainly for Run3]

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

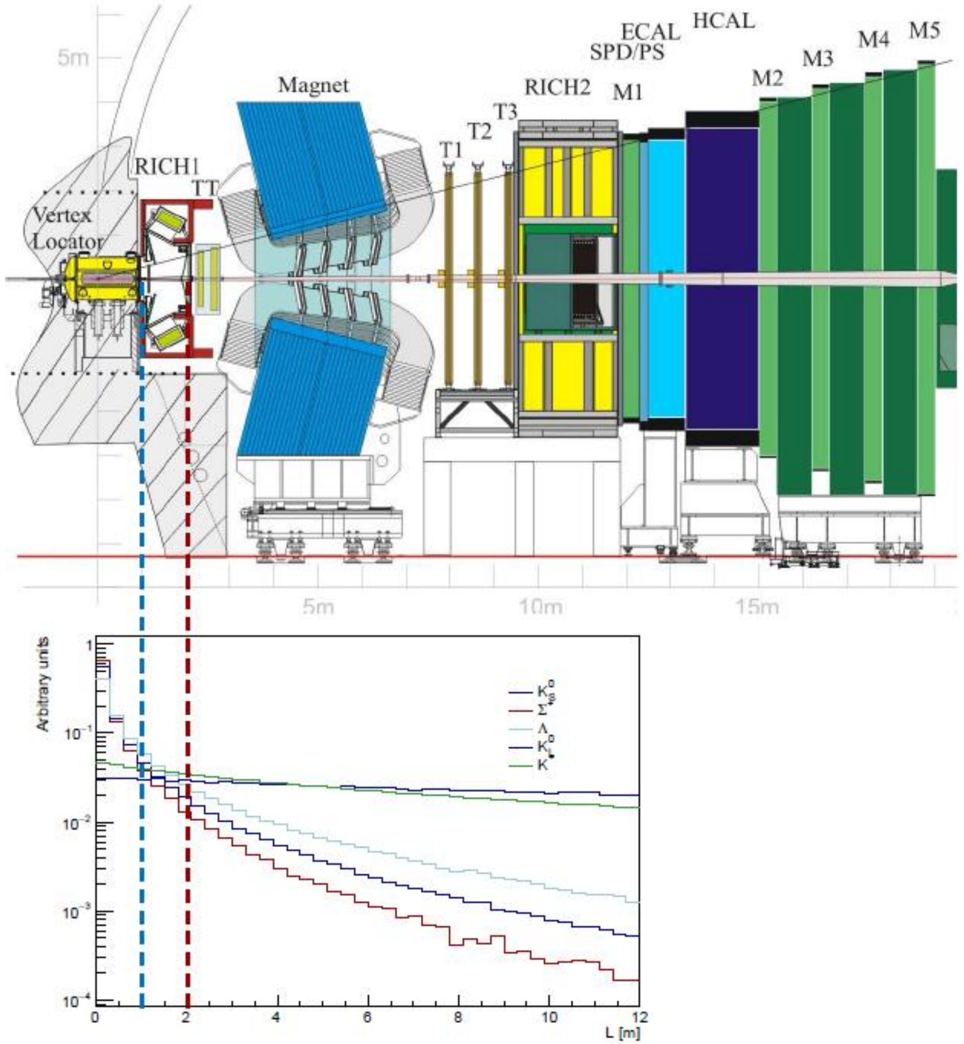
$K_S \to \pi^0\mu^+\mu^-$

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

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

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

…




Present result from Run1 + 2

$B(K_S \to \mu^+\mu^-) < 2.1(2.4) \times 10^{-10}$@ 90 (95)% CL PRL 125, 231801 (2020)

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

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

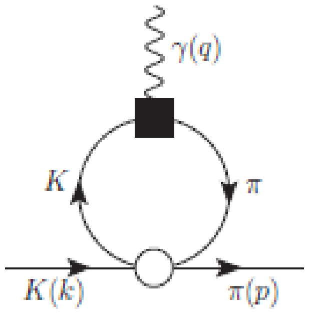
Search for LFV and/or LNV (before ICHEP 2020)

PDG '20

| LFV mode | 90% CL upper limit | Experiment | Yr./Ref. | Type |
|---|---|---|---|---|
| $K^+ \to \pi^+ e^- \mu^+$ | $1.3\times10^{-11}$ | BNL-865 | 2005/Ref. [15] | LFV |
| $K^+ \to \pi^+ e^+ \mu^-$ | $5.2\times10^{-10}$ | BNL-865 | 2000/Ref. [16] | LFV |
| $K_L \to \mu e$ | $4.7\times10^{-12}$ | BNL-871 | 1998/Ref. [17] | LFV |
| $K_L \to \pi^0 e \mu$ | $7.6\times10^{-11}$ | KTeV | 2008/Ref. [18] | LFV |
| $K_L \to \pi^0 \pi^0 e \mu$ | $1.7\times10^{-10}$ | KTeV | 2008/Ref. [18] | LFV |
| $K^+ \to \pi^- e^+ e^+$ | $2.2\times10^{-10}$ | NA-62 | 2019/Ref. [19] | LNV |
| $K^+ \to \pi^- \mu^+ \mu^+$ | $4.2\times10^{-11}$ | NA-62 | 2019/Ref. [19] | LNV |
| $K^\pm \to \pi^\mp \mu^\pm \mu^\pm$ | $8.6\times10^{-11}$ | NA48/2 | 2017/Ref. [20] | LNV |
| $K_L \to e^\pm e^\pm \mu^\mp \mu^\mp$ | $4.12\times10^{-11}$ | KTeV | 2003/Ref. [21] | LNV |
| $K^+ \to \pi^- \mu^+ e^+$ | $5.0\times10^{-10}$ | BNL-865 | 2000/Ref. [16] | LNFV |

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

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




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

- Differential decay rate: $d\Gamma/dz \propto G_F M_K^2(a + bz) + W^{\pi\pi}(z)$ $z = m(\mu^+,\mu^+)^2/M_K^2$

Form factors (FF) (non pert. QCD) — $a$, $b$

$K_{3\pi}$ loop term — $W^{\pi\pi}(z)$

- Lepton Flavour universitality (LFU) predicts same $a, b$ for $l = e, \mu$
- Difference correlated to possible LFU in B sector

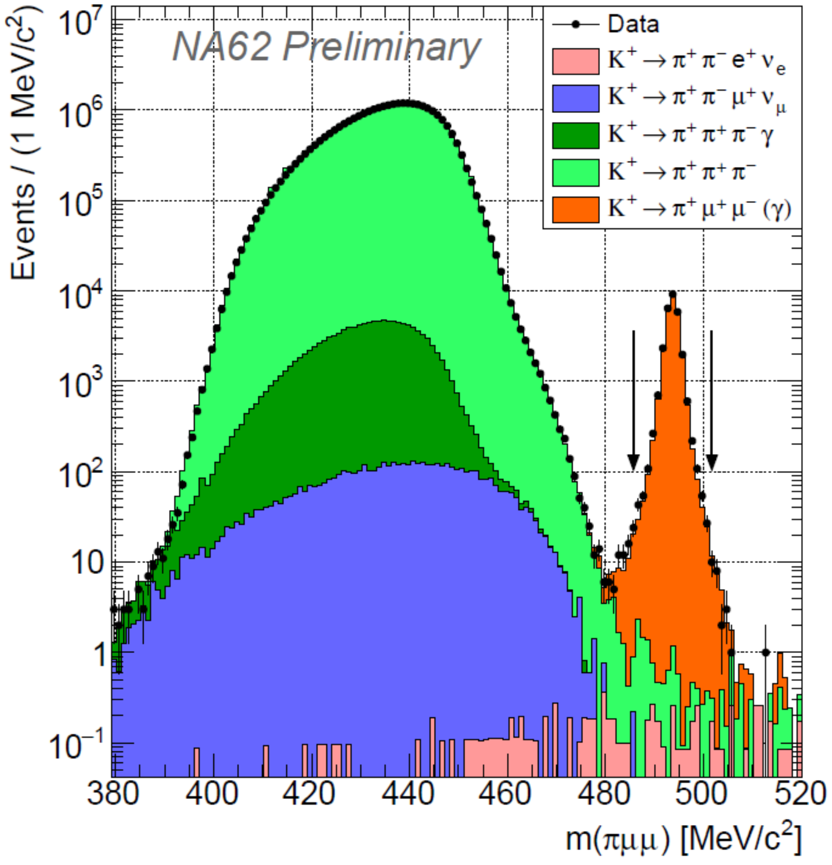
Crivellin et al. PRD **93** 074038 (2016) D'Ambrosio et al. JHEP **02** 049 (2019)

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

# $K^+ \to \pi^+\mu^+\mu^-$@ NA62

## Key feature:

- precise track reconstruction




## Analysis strategy

- Normalization to $K^+ \to \pi^+\pi^+\pi^-$
- Fit to $z$ spectrum to extract FF

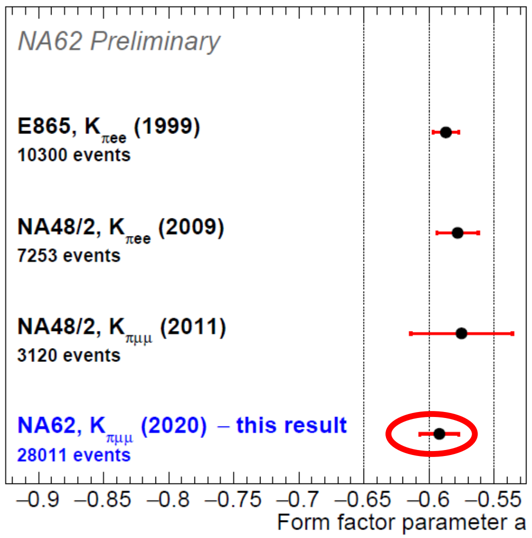
## Signal and background

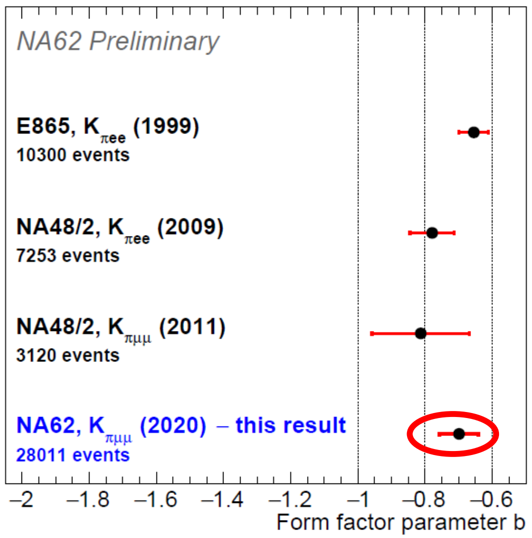
- $N(\pi^+\mu^+\mu^-) \sim 28 \times 10^3$
- Background $< 0.1\%$

## Result (preliminary):

PoS(ICHEP2020) 364

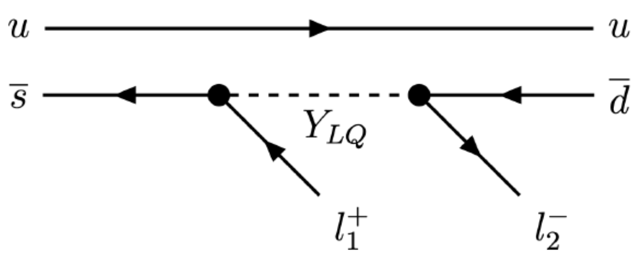
$$a = -0.592 \pm 0.013_{stat} \pm 0.007_{syst} \pm 0.001_{ext}$$
$$b = -0.699 \pm 0.046_{stat} \pm 0.035_{syst} \pm 0.003_{ext}$$
$$\mathcal{B} = (9.27 \pm 0.07_{stat} \pm 0.08_{syst} \pm 0.04_{exr}) \times 10^{-8}$$



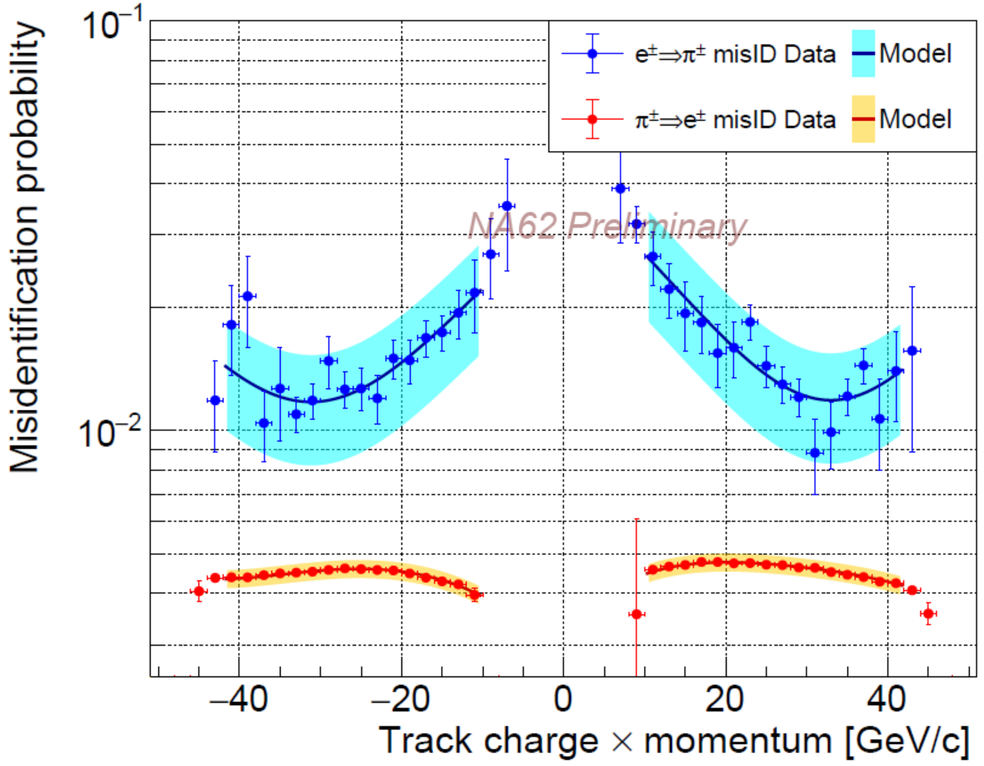
# LFV & LNV @ NA62: $K^+ \to \pi\mu e$

Forbidden SM, possible in NP scenario




E.g. mediated by leptoquark
[JHEP 12(2019) 089], [NPB 176 (1980) 135]

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




Background:

$K^+ \to$ 3 charged particles +

mis-ID $e^\pm \leftrightarrow \pi^\pm$ ($\mathcal{O}(\%)$ data-driven estimation) +

$\pi^\pm$ decay in flight

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

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

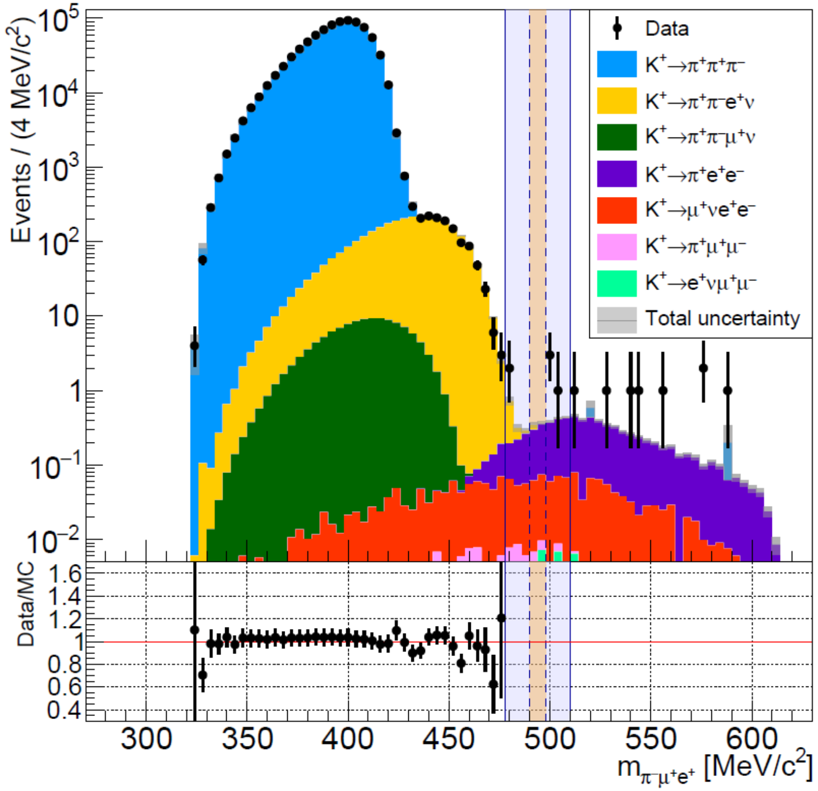
**Signal and Backgrounds:**

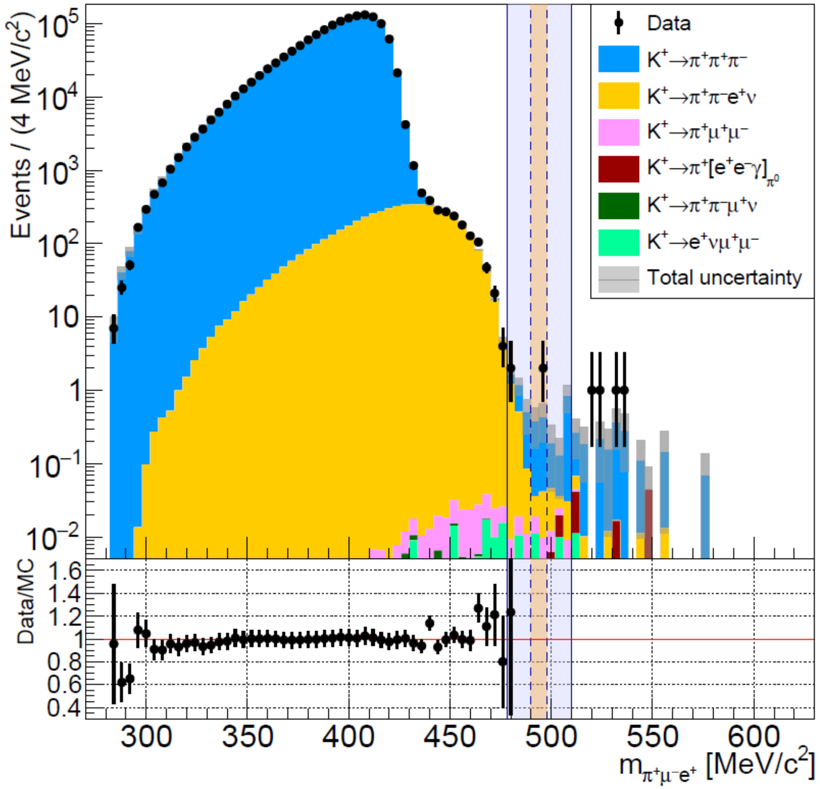
$$K^+ \to \pi^-\mu^+e^+ \;:\quad n_{\rm bg} = 1.07 \pm 0.20\,,\quad n_{\rm obs} = 0;$$
$$K^+ \to \pi^+\mu^-e^+ \;:\quad n_{\rm bg} = 0.92 \pm 0.34\,,\quad n_{\rm obs} = 2;$$
$$\pi^0 \to \mu^-e^+ \;:\quad n_{\rm bg} = 0.23 \pm 0.15\,,\quad n_{\rm obs} = 0.$$

**Results (90% CL):**

$$\mathcal{B}(K^+ \to \pi^-\mu^+e^+) < 4.2\times10^{-11};$$
$$\mathcal{B}(K^+ \to \pi^+\mu^-e^+) < 6.6\times10^{-11};$$
$$\mathcal{B}(\pi^0 \to \mu^-e^+) < 3.2\times10^{-10}.$$

arXiv: 2105.06759, subm. to PRL



# K decays & exotic particles @ NA62

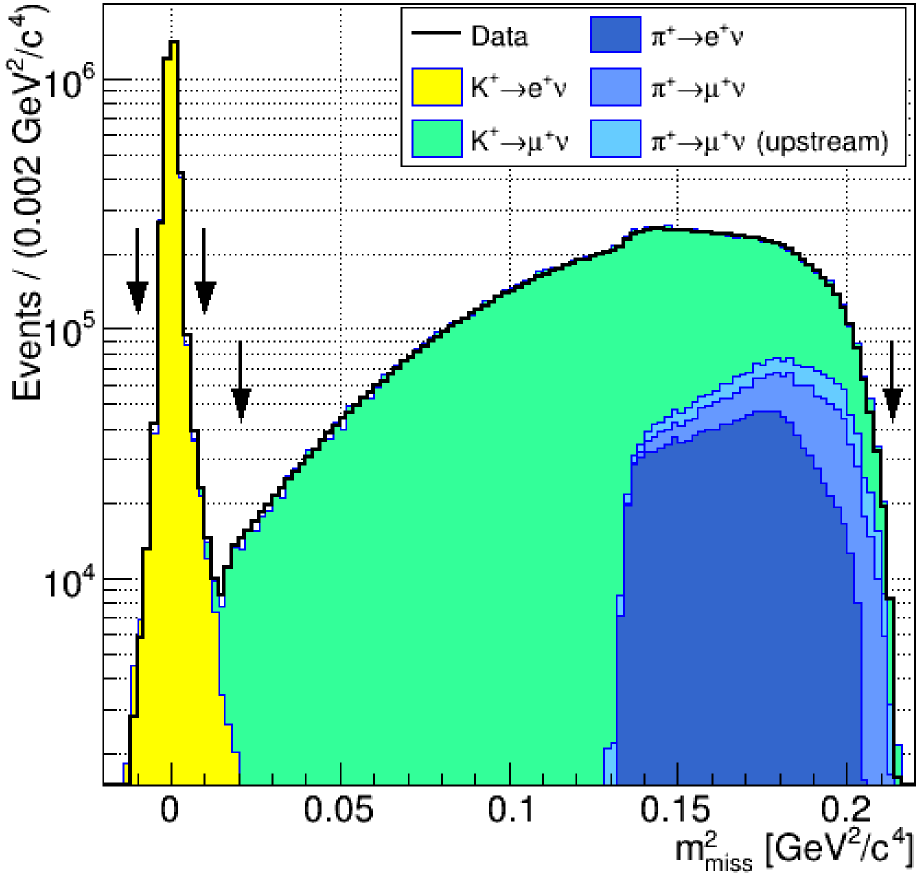
Heavy Neutral Lepton production: $K^+ \to l^+ N, l = e, \mu$

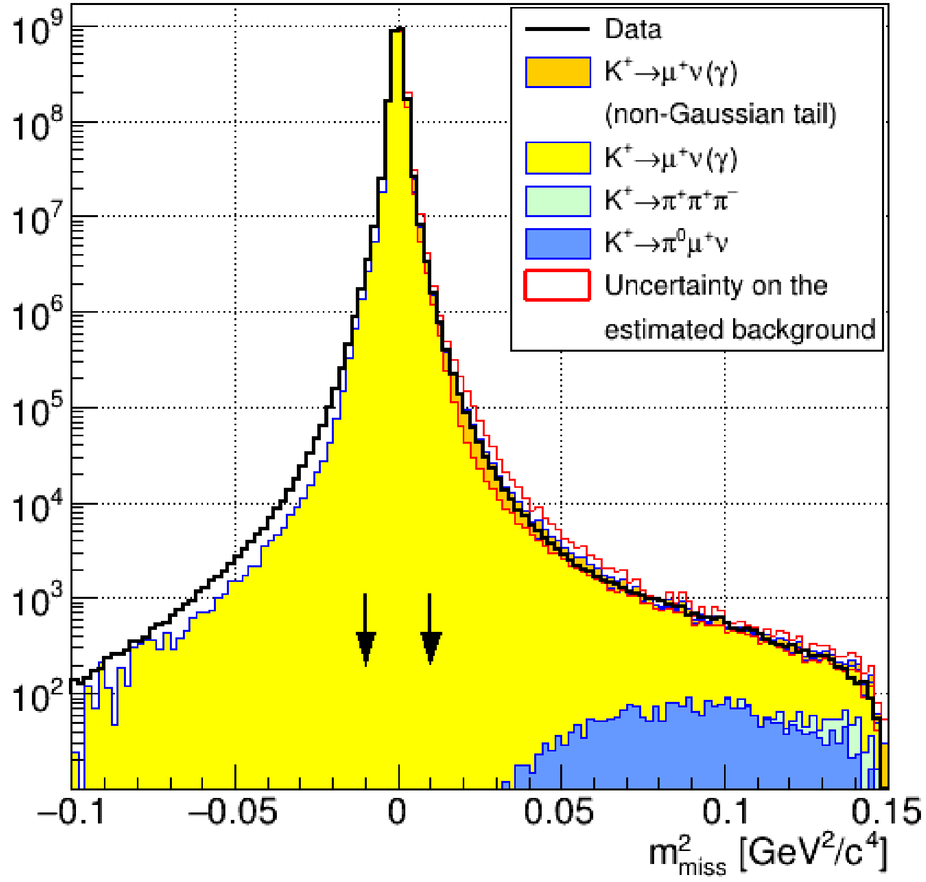
Experimental key features: precise track reconstruction, $\gamma$ veto, particle ID

Analysis technique: peak search over the reconstructed $N$ mass spectrum, scanning several $N$ mass hyptoheses

Background: data-driven evaluation from the mass spectrum exptrapolated in the search window

Normalization: acceptance from simulation, kaon flux from $K_{l2}$ peak



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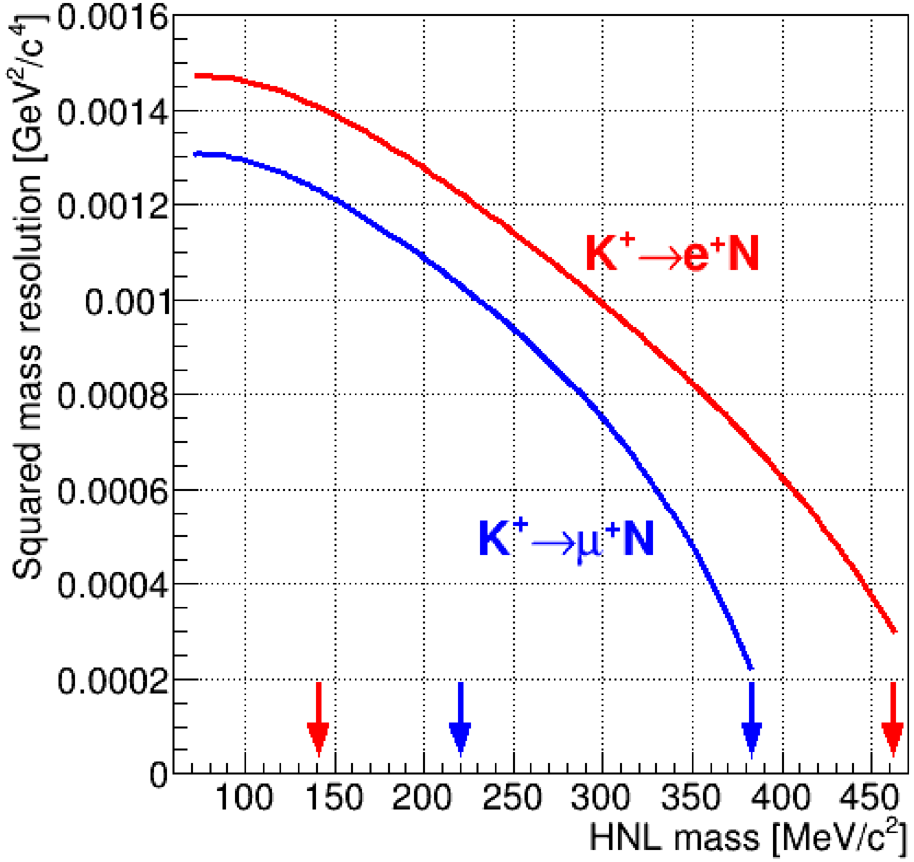
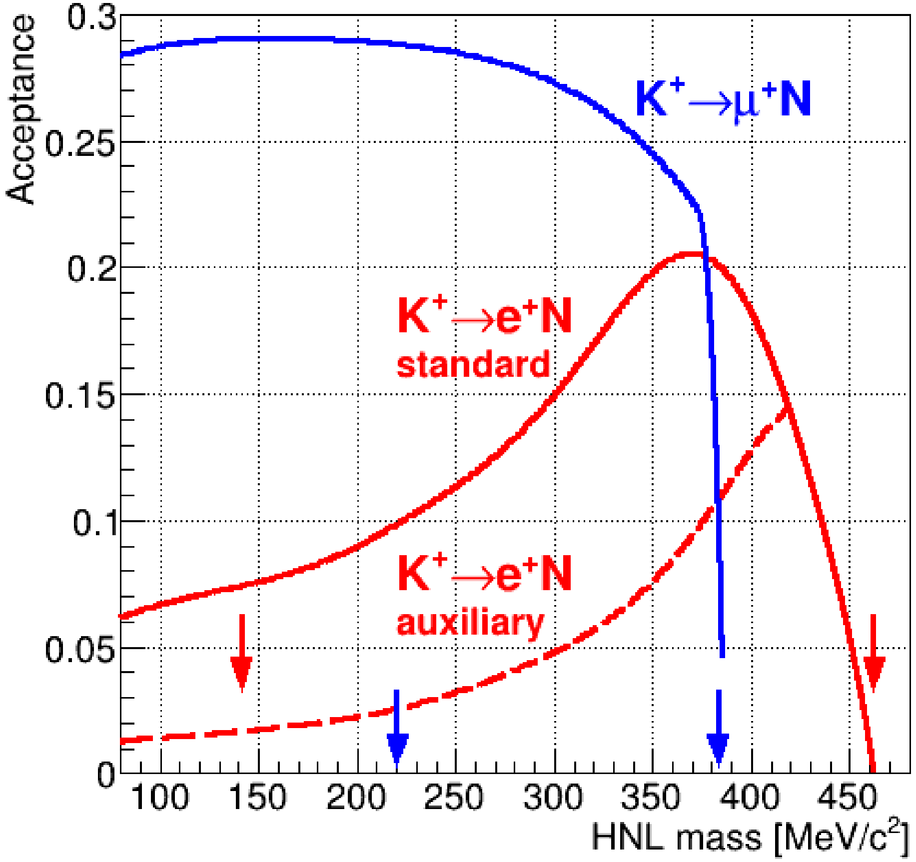
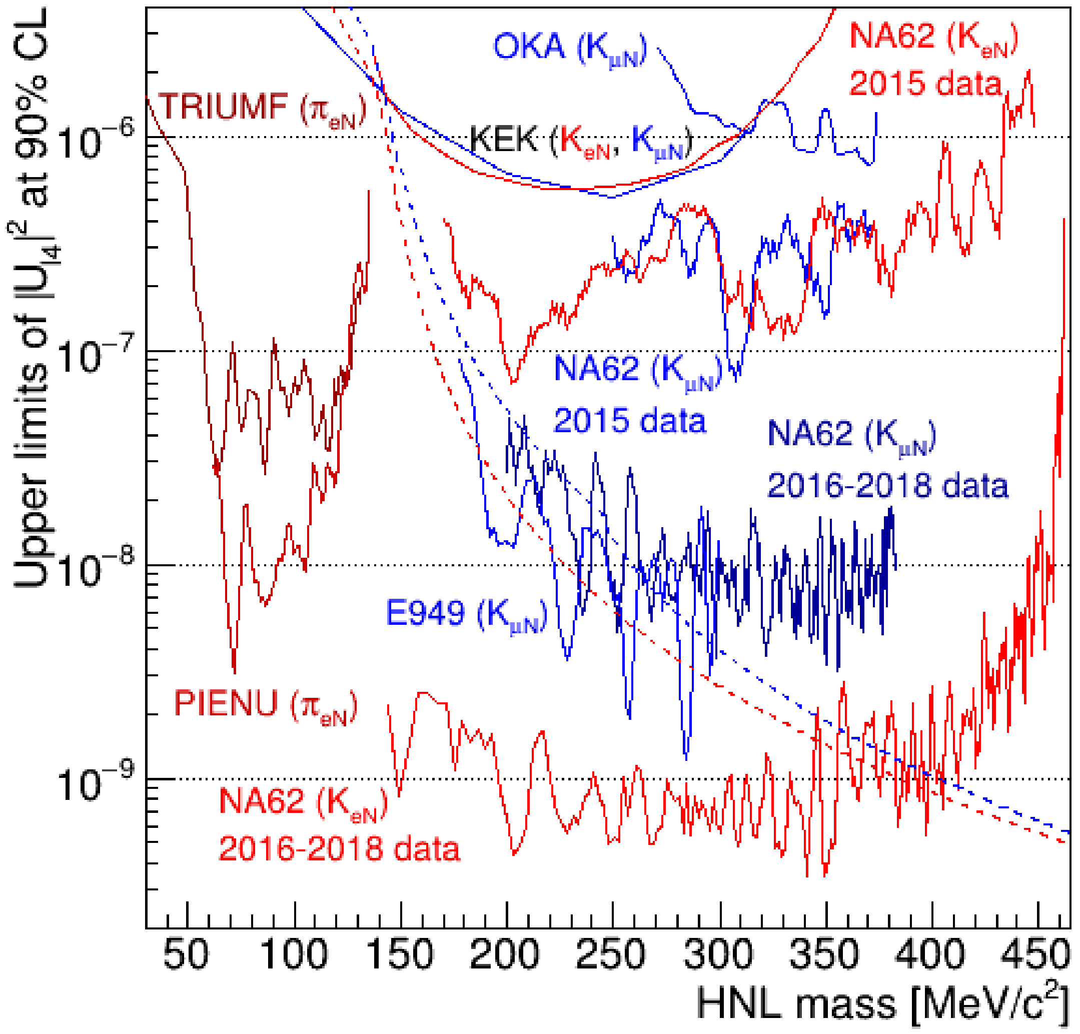


# K decays & exotic particles @ NA62



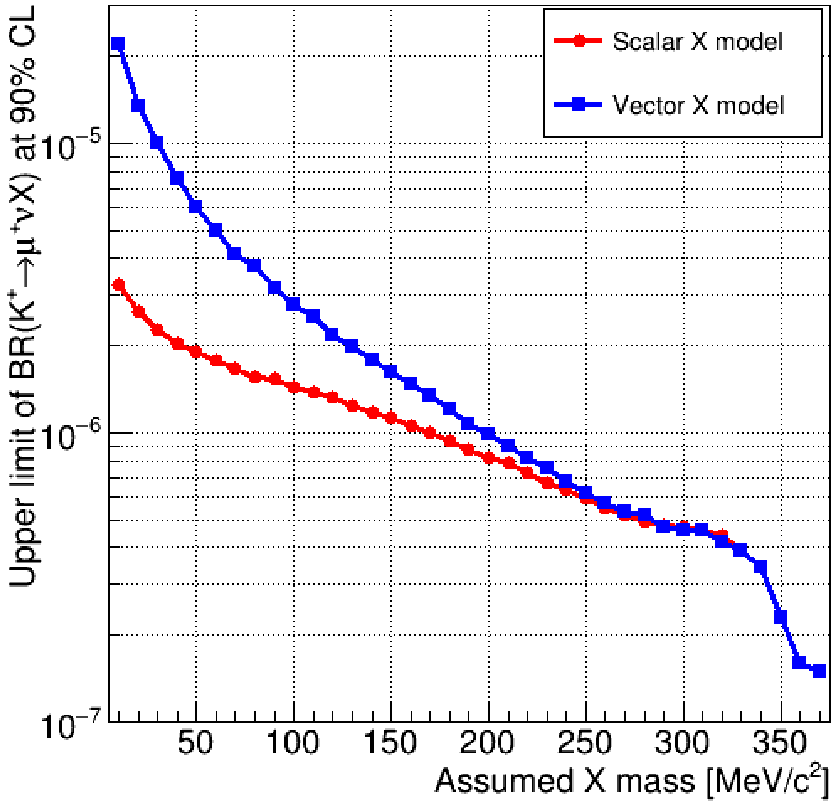

Production of $X$ in $K^+ \to \mu^+ \nu X$

Search of data excess in a broad off-peak mass region

Background from simulation

PLB 807 (2020) 135599

PLB 816 (2021) 136259



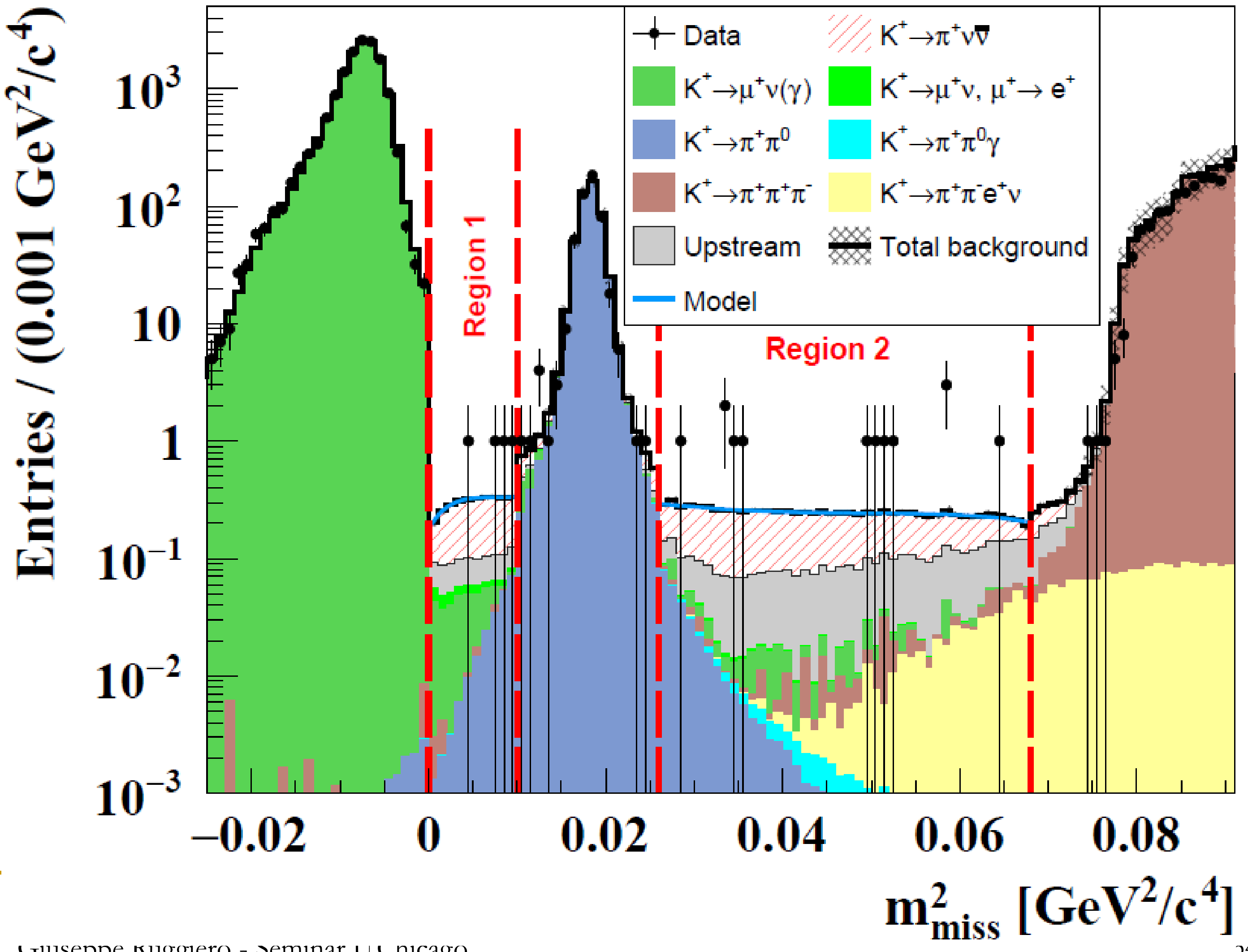
# K decays & exotic particles @ NA62

$X$ particle production in $K^+ \to \pi^+ X$

**Analysis technique:** peak search using $m^2_{miss} = (p_K - p_l)^2$ as observable, for several $X$ mass hyptoheses

**Background:** from $K^+ \to \pi^+ \nu\bar{\nu}$ analysis with modelling of the $m^2_{miss}$ + $K^+ \to \pi^+ \nu\bar{\nu}$ itself from simulation

**Experimental key features:** spin-off analysis of $K^+ \to \pi^+ \nu\bar{\nu}$



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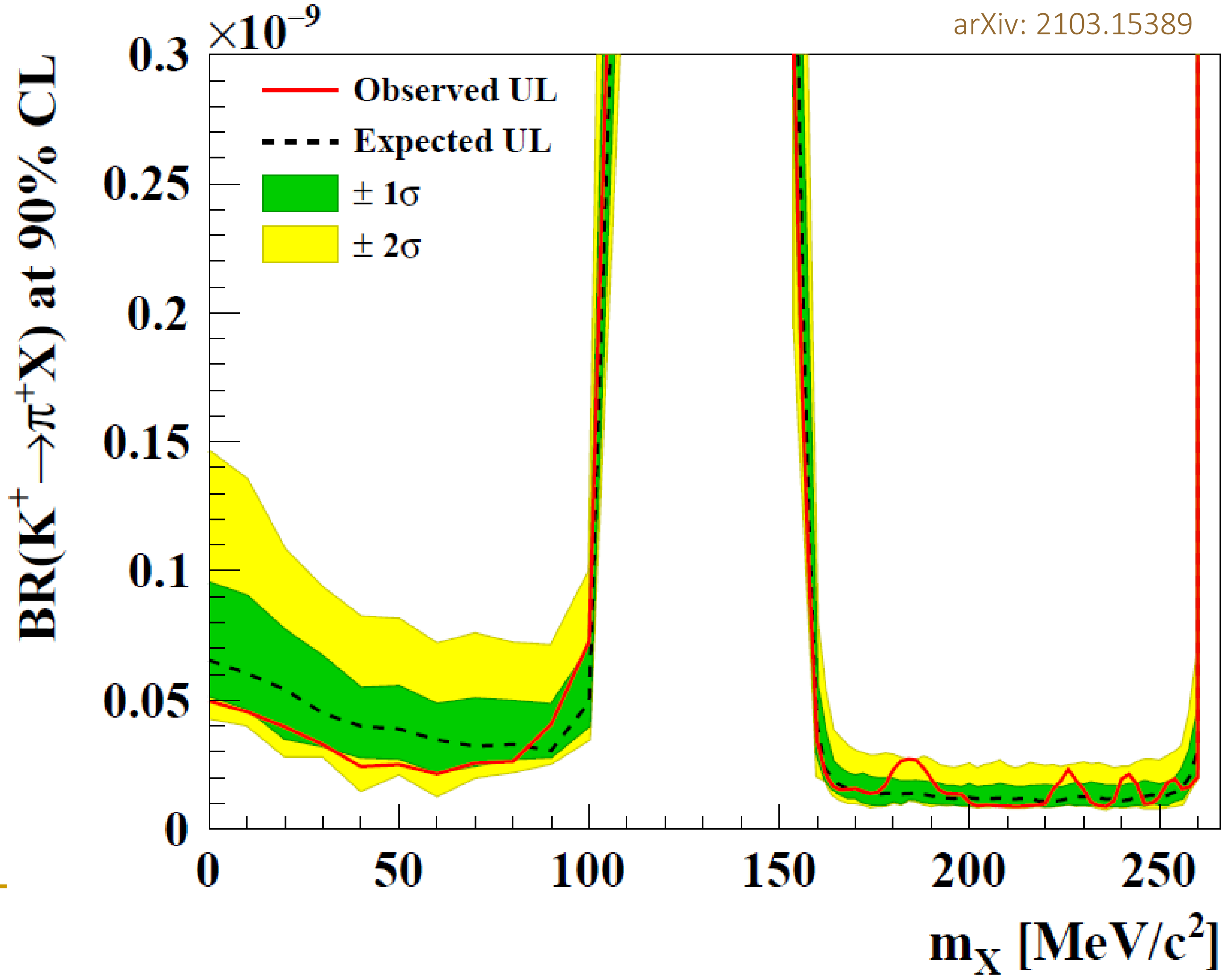
arXiv: 2103.15389



# K decays & exotic particles @ NA62

$X$ particle production in $K^+ \to \pi^+ X$

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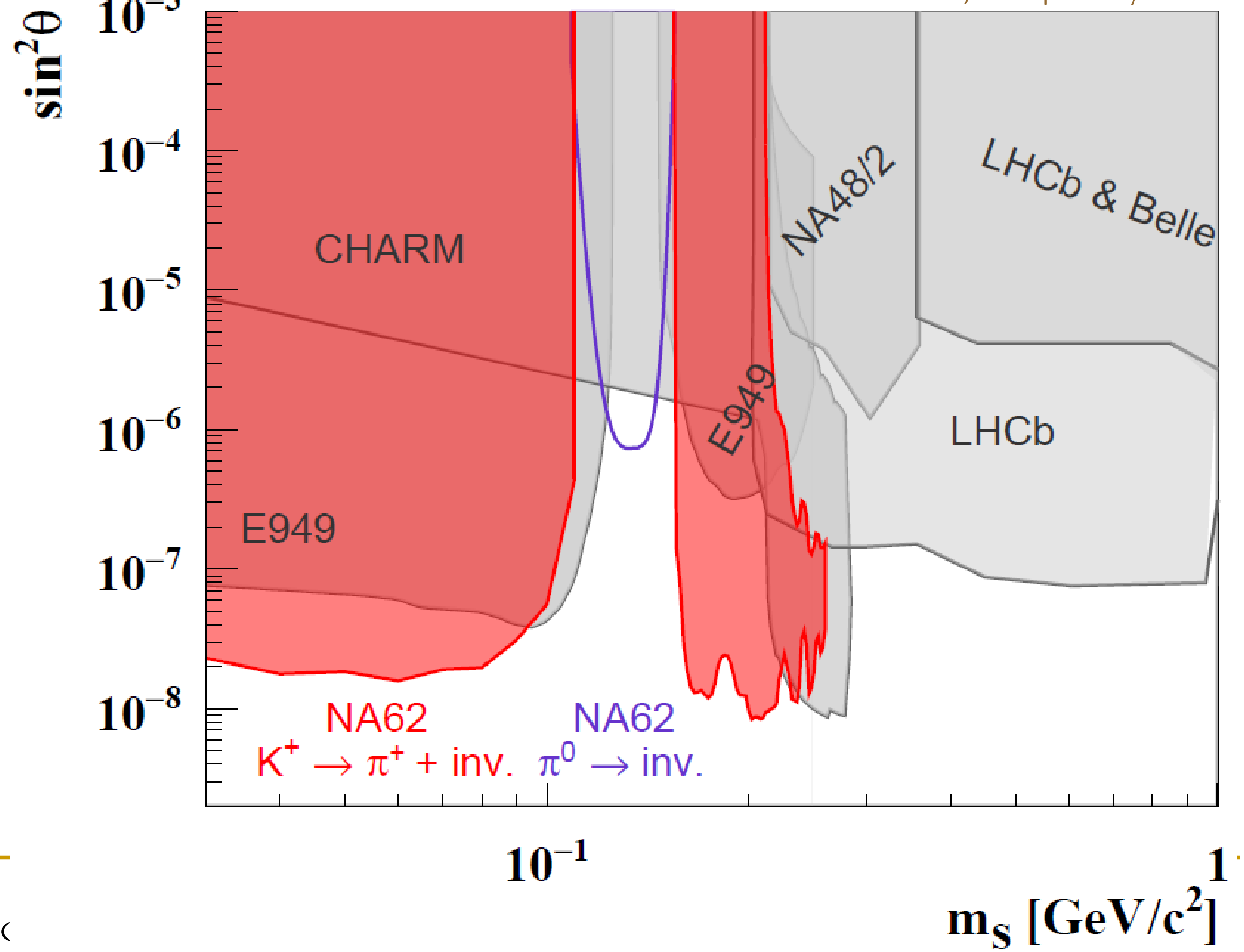
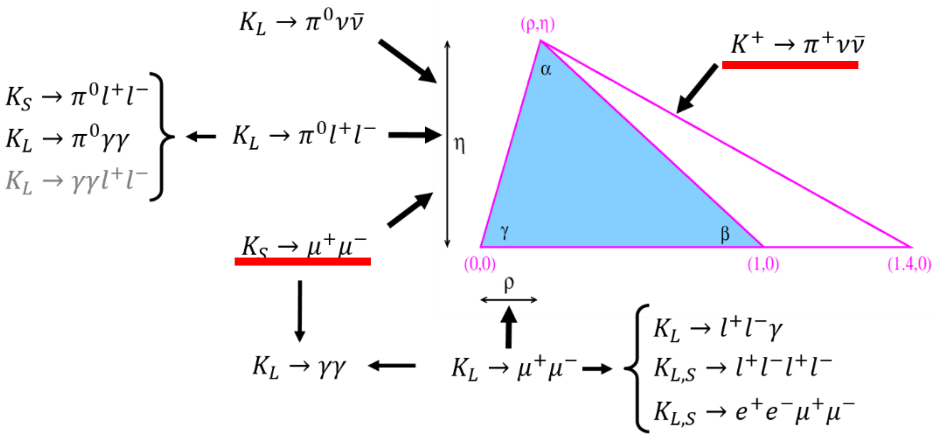
arXiv: 2103.15389, accepted by JHEP

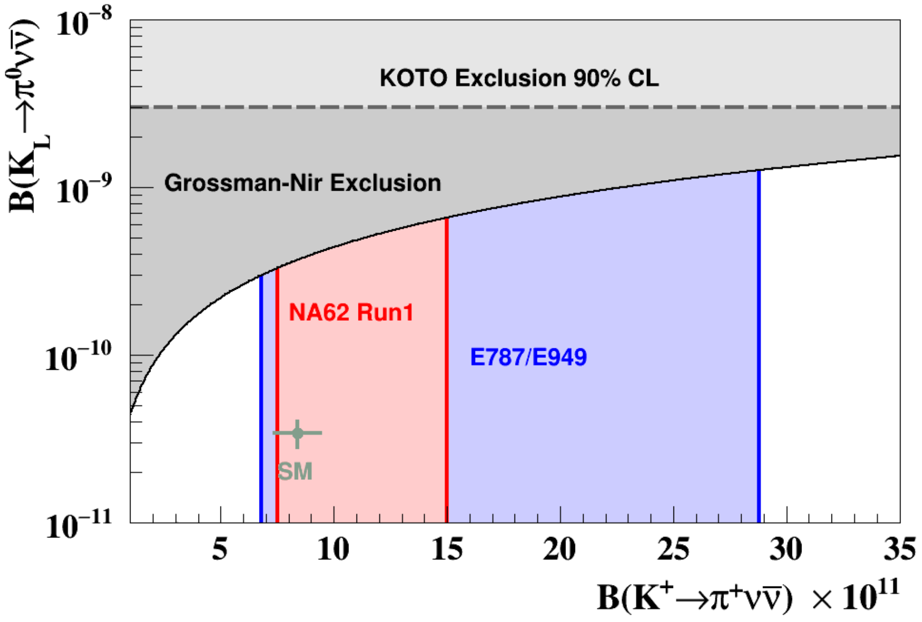


# Present @ CERN

NA62 (Run1) LHCb (Run1-2)

**Flavour & NP**




$K^+ \to \pi^+ \nu\bar{\nu}$:
$\mathcal{O}(40\%)$ measurement (NA62)

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

**LU Test and Explicit violation of SM**

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

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

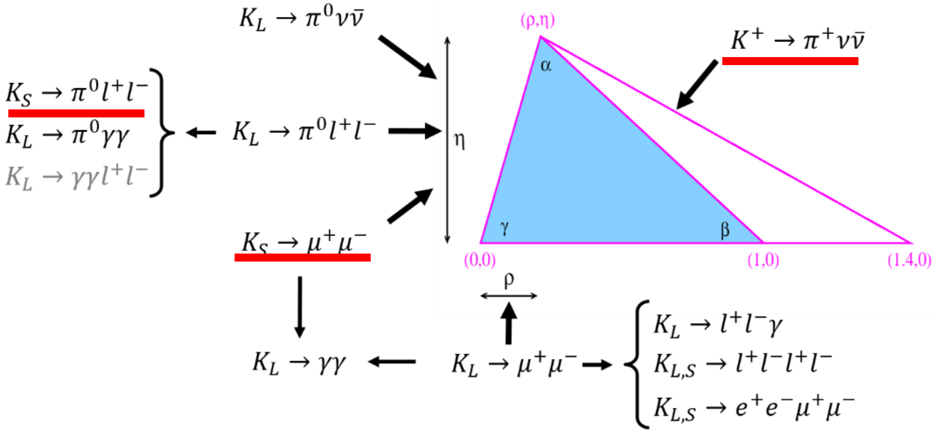
$K \to Exotics$: Single event sensitivity $\mathcal{O}(10^{-8} \div 10^{-11})$

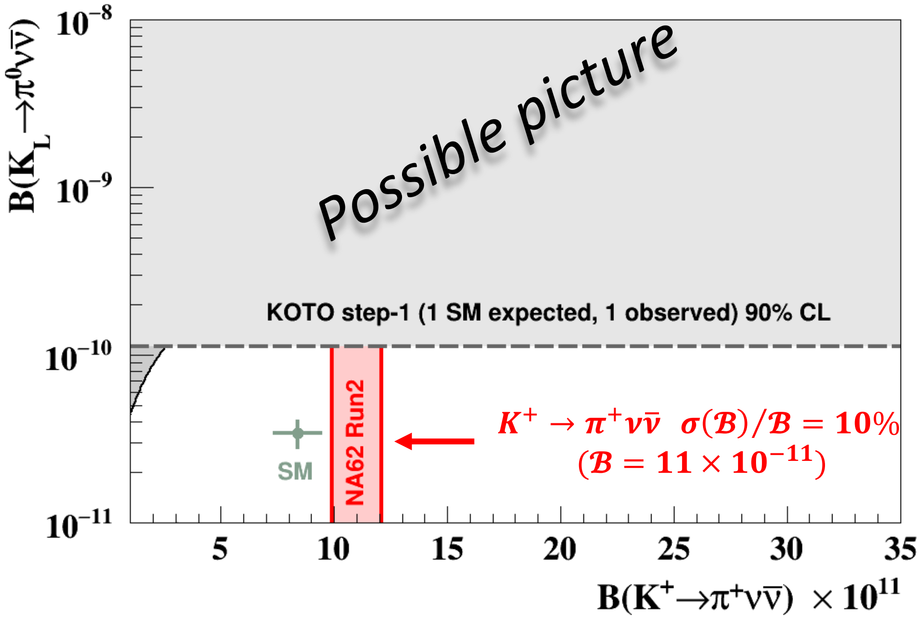
# Future (<2025) @ CERN

**NA62 (Run2)**
- Hwd improvements

**LHCb (Upgrade phase 1)**
- New trigger

## Flavour & NP




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

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

$K_S \to \pi^0 l^+ l^-$:
$\mathcal{O}(20\%)$ measurement (LHCb)

## LU Test and Explicit violation of SM

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

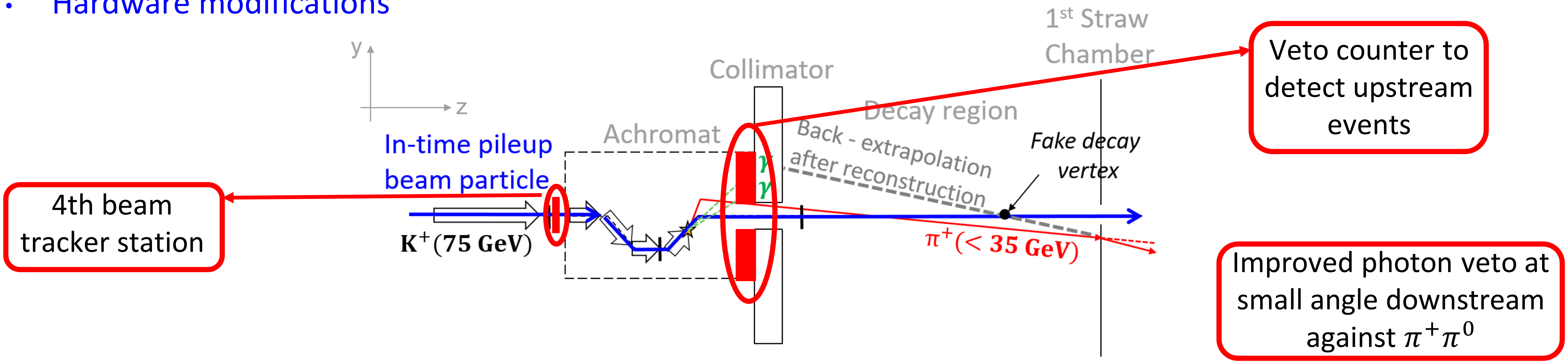
$K \to LNV/LFV$: Single event sensitivity $\mathcal{O}(10^{-12})$

$K \to Exotics$: Single event sensitivity $\mathcal{O}(10^{-8} \div 10^{-12})$

$R_K$: $\mathcal{O}(0.1\%)$ measurement (NA62)

# Future (< 2025): NA62

- SPSC approved the NA62 run until LS3 [$\mathcal{O}$(2024)]
- 2021 NA62 run scheduled mid-July – mid-November
  - Warm-up run to commission new hardware
  - Scan of the intensity
  - Find the optimal run working point, hopefully 30% higher than in Run1 («nominal intensity»)
- Hardware modifications




  - Expected upstream background reduction × 5

# Future (>2025) @ CERN

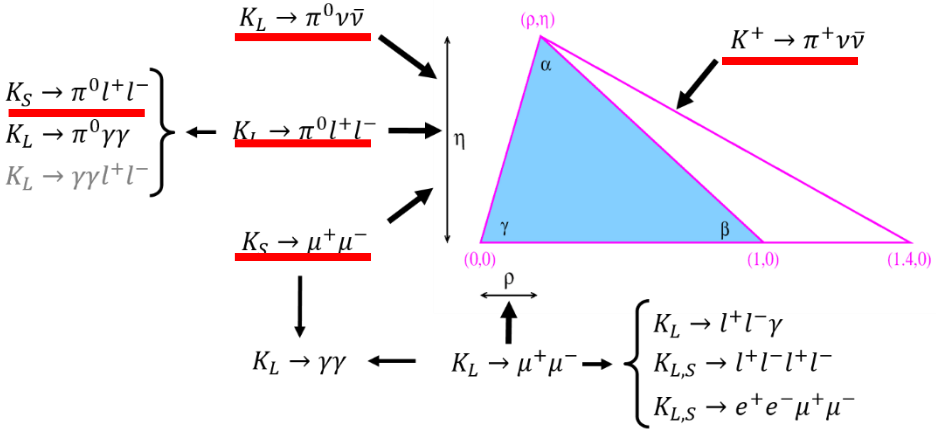
**Kaon facility**

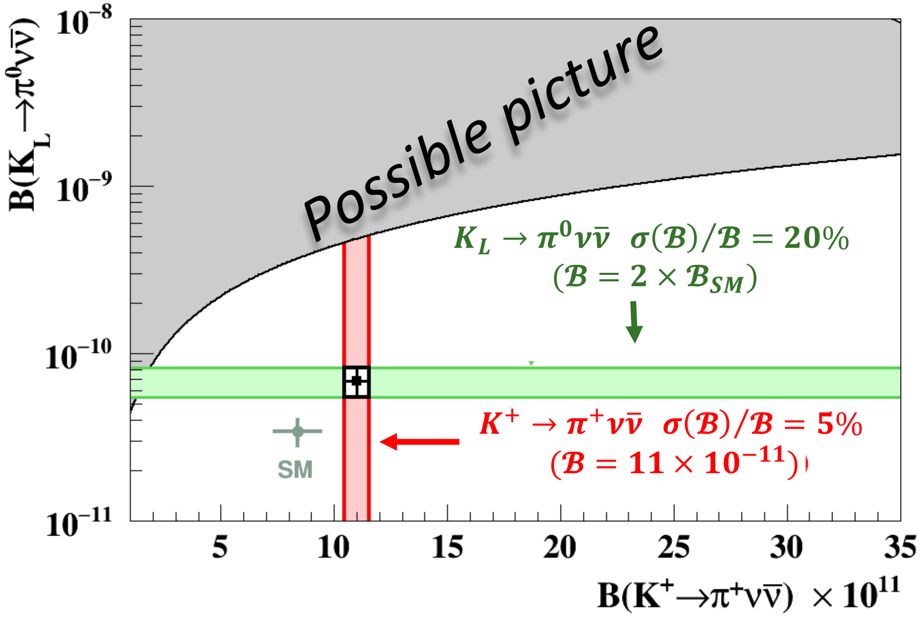
- $K^+/K^0$

**LHCb (Upgrade phase 2)**

- Hwd upgrade

**<u>Flavour & NP</u>**




$K^+ \to \pi^+ \nu\bar{\nu}$: (K facility)
$\mathcal{O}(5\%)$ measurement

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

$K_S \to \pi^0 l^+ l^-$: (LHCb)
precision measurement

$K_L \to \pi^0 \nu\bar{\nu}$: (KOTO+K facility)
$\mathcal{O}(20\%)$ measurement

$K_L \to \pi^0 l^+ l^-$: (K facility)
SM Sensitivity at least

**<u>LU Test and Explicit violation of SM</u>**

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

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

$K \to Exotics$: Single event sensitivity $\mathcal{O}(10^{-8} \div 10^{-12})$

$R_K$: $\mathcal{O}(0.1\%)$ measurement (NA62)

# Future (> 2025) @ CERN: K - facility

- $K^+ - K_L$ integrated «high intensity» beam in North Area (SPS)
  - New targets; beam line elements and shielding upgrade

- NA62-like experiment at $\times$ 4 intensity (at least) for $K^+ \rightarrow \pi^+ \nu\bar{\nu}$
  - Improved time resolution ($\mathcal{O}(25\ ps)$) to reduce random veto
  - Mantain key performance at high rate: space-time reconstruction, low material-budget, photon-rejection
  - Synergies for detectors with collider projects (e.g. New generation silicon pixels for beam tracker)

- KLEVER for $K_L \rightarrow \pi^0 \nu\bar{\nu}$
  - $10^{13}$ $K_L$ decays / year @ $10^{19}$ proton on target / year (100 effective days)
  - New / refurbished e.m. Calorimeters
  - No tracking

- Experiment for $K_L \rightarrow \pi^0 l^+ l^-$, $K_L/K_S \rightarrow \mu^+\mu^-$, Lepton – flavour violation in $K_L$ decays
  - Tracking and PID of $K^+$ experiment, KLEVER-like calorimeters

# Conclusions

- **Rare kaon decays** are among the most sensitive probe of NP at the highest mass scale, and are addressed at CERN with the NA62 and LHCb experiment

$K^+ \to \pi^+ \nu\bar{\nu}$ | $K_L \to \pi^0 \nu\bar{\nu}$ | $K_S \to \mu^+\mu^-$

$K_L \to \mu^+\mu^-$ | $K_L \to \pi^0 e^+ e^-$ | $K_L \to \pi^0 \mu^+\mu^-$

  - $K^+ \to \pi^+ \nu\bar{\nu}$ is entering the era of the precise branching ratio measurement with the NA62 experiment

- **Kaons decays** can probe NP through: test of lepton universality, search for LFV/LNV processes, search for exotic low-mass particles

- **Kaon physics** at CERN is officially scheduled up to 2025

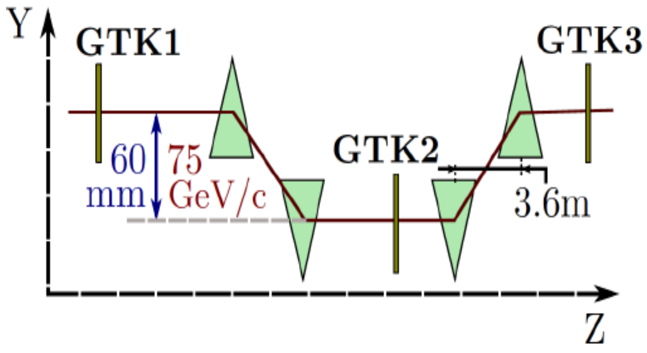
- A **Kaon facility** for $K^+$ and $K_L$ at SPS is under study [PBC workshop 01/03/2021, Snowmass 2021 RF0-010]

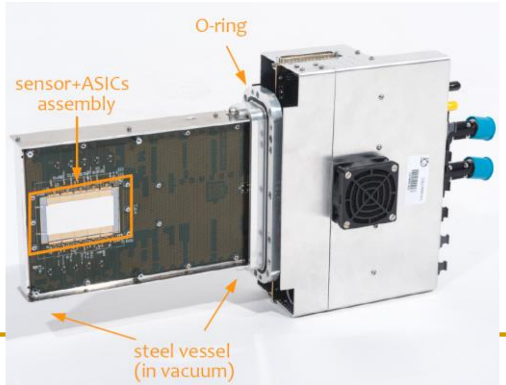
# SPARE

# Tracking @ NA62

«kaon» [Gigatracker]

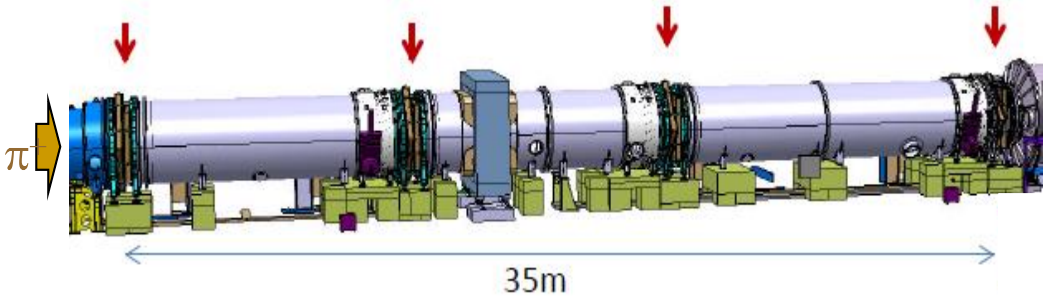
- 3 stations Silicon pixel $300 \times 300 \mu m^2$
- Time resolution $\sigma(t)$ < 150 ps / station
- «4D» track reconstruction
- Rate (2017) $\sim 400$ MHz hadrons

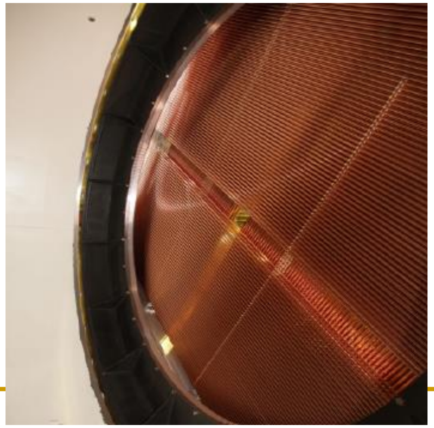



«pion» [STRAW]

- 4 Stations, 7000 straws, ∅ 10 mm
- Total radiation length 0.5% $X_0$
- Spatial resolution $\sim 80$ $\mu$m
- Rate (2017) $\sim 5$ MHz (mostly $\mu$)

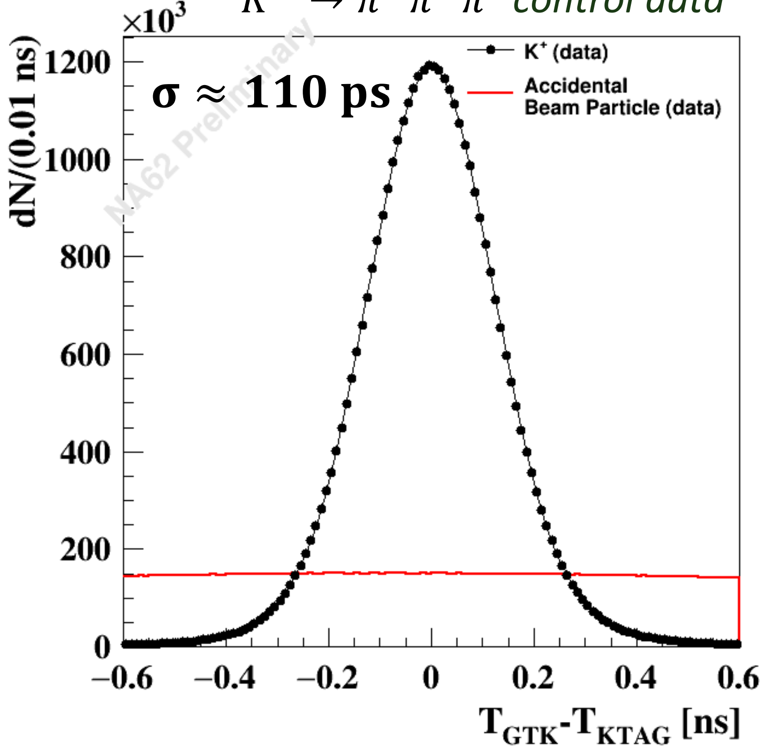


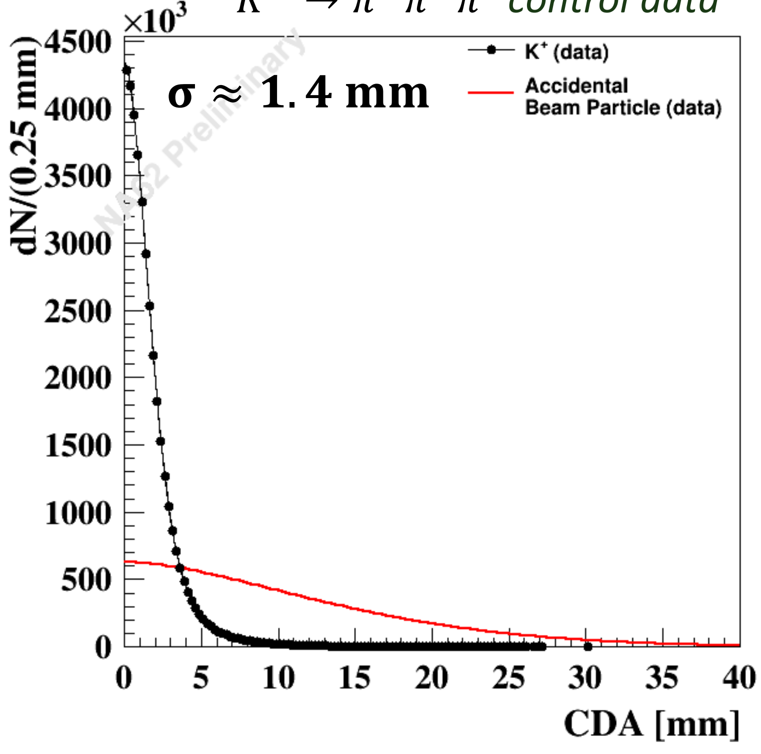
# K - π Matching @ NA62

- KTAG – Gigatracker – RICH Time matching
- Gigatracker – Straw tracks closest distance of approach (CDA)
- O(%) $K^+$ mis – identification (pileup beam track associated to $\pi^+$
- 75% $K^+ \to \pi^+$ efficiency

$K^+ \to \pi^+\pi^+\pi^-$ *control data*




$K^+ \to \pi^+\pi^+\pi^-$ *control data*



# RICH @ NA62

17 m long, Ne Radiator, sealed

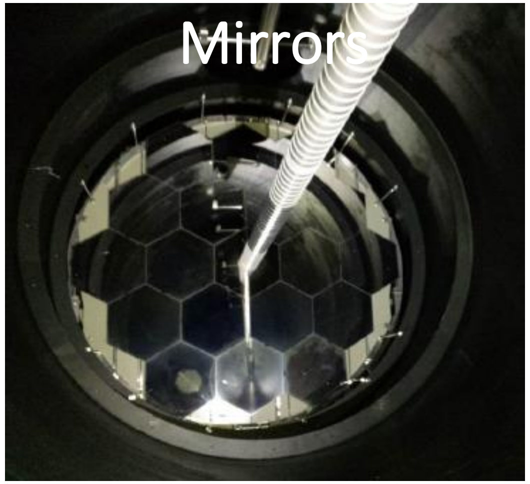
2000 PMs' in 2 spots

Array of exagonal mirrors

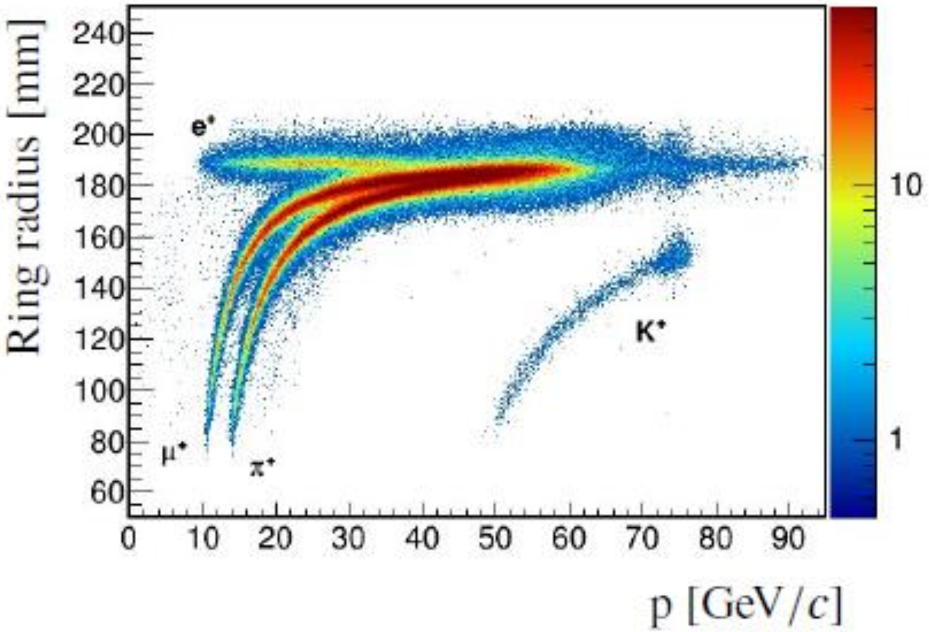
$\theta_c$ resolution $\sim 100\ \mu rad$

Particle ID: pi – mu separation

Timing





# Photon Vetoes @ NA62