Rare decays from NA62

La Thuile 2021

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Outline

- NA62 experiment
- $K^+ \to \pi^+ \nu\nu$
- $K^+ \to \pi^+ X$
- $\pi^0 \to$ invisible
- $K^+ \to \pi^+ \mu^+ \mu^-$
- Conclusions

NA62

NA62: fixed target experiment at CERN SPS

Technique:
Kaon decays in flight

Timeline:
- 2015: commissioning
- 2016-2018: physics runs

- 2021-2024: physics runs

ECN3 hall at CERN

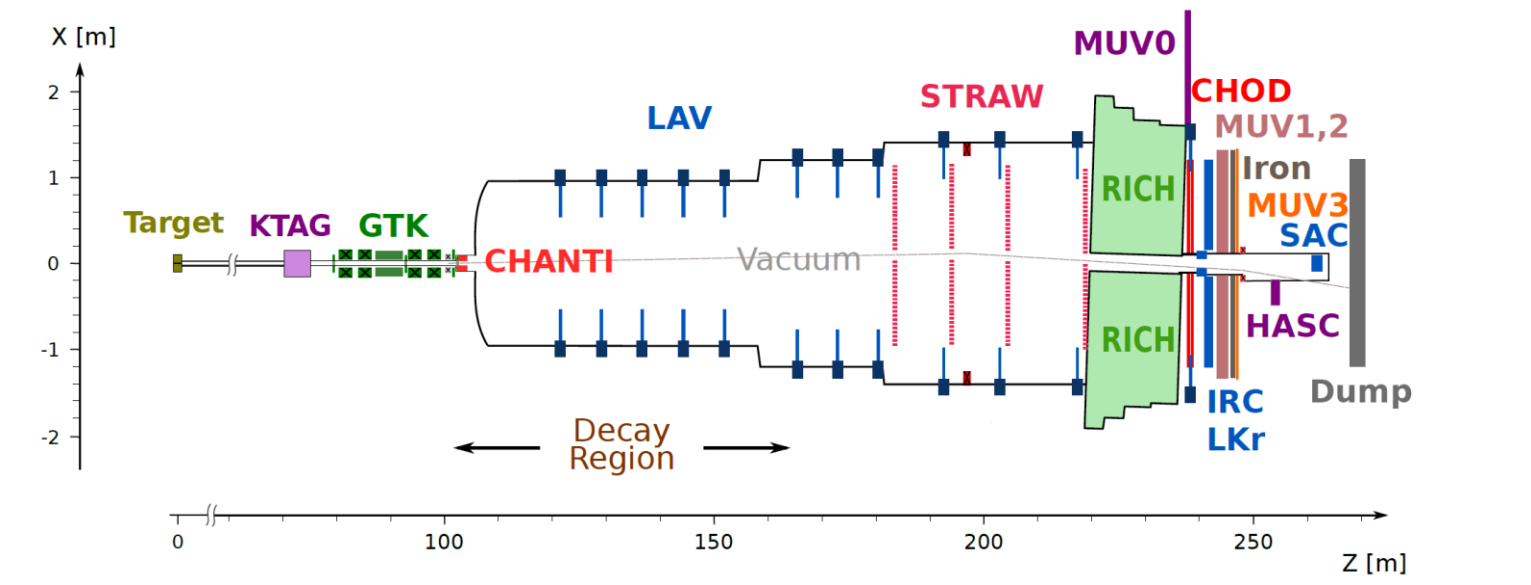
Primary goal:
Measure BR($K^+ \to \pi^+ \nu \bar{\nu}$)

NA62 collaboration: ~200 participants, ~30 institutions

Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, Fairfax GMU, Ferrara, Florence, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Moscow, Naples, Perugia, Pisa, Prague, Protvino, Rome I, Rome II, San Luis Potosi, TRIUMF, Turin, Vancouver UBC

NA62 experimental setup

[NA62 Detector Paper, 2017 JINST 12 P05025]



Primary beam:

- 400 GeV/c protons
- 3×10^{12} protons per spill

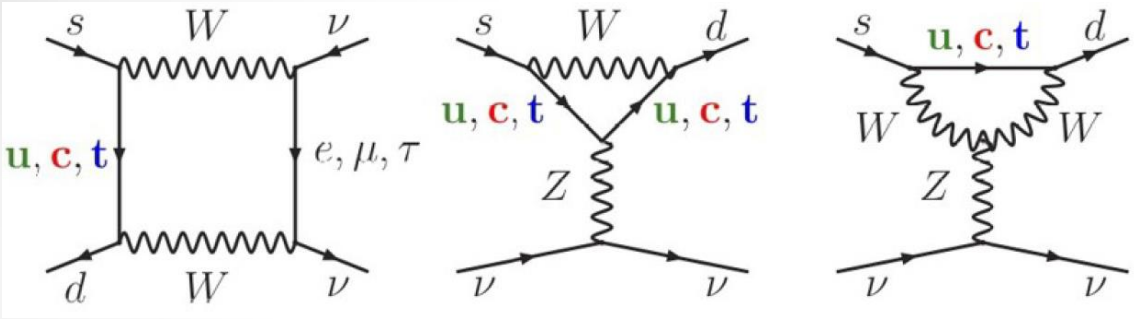
Secondary beam:

- 75 GeV/c (±1%)
- Divergency < 100 μrad
- 70% pions, **6% K^+**, 24% protons

Key detectors:

- PID: KTAG, RICH, LKr, MUV1-2, MUV3
- Momentum: GTK, STRAW
- Time: GTK, KTAG, RICH, CHOD
- Photon veto: LAV, LKr, IRC, SAC

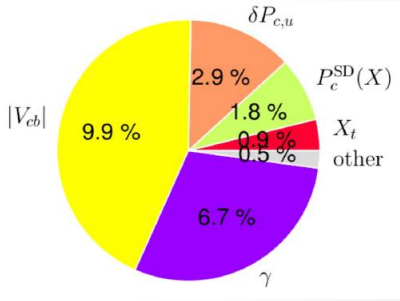
$K^+ \to \pi^+ \nu\nu$ in SM



Theoretical calculation of BR within SM

- FCNC loop process
- Short distance effects: theoretically clean
- Long distance effects: hadronic elements measured with $K \to e\nu\pi^0$ decay
- Parametric uncertainty dominates in δ(BR)

Uncertainty budget for BR($K^+ \to \pi^+\nu\nu$)



$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (0.84 \pm 0.03) \times 10^{-10} \left(\frac{|V_{cb}|}{0.0407}\right)^{2.8} \left(\frac{\gamma}{73.2^\circ}\right)^{0.74} = (0.84 \pm 0.10) \times 10^{-10}$$

$$BR(K_L \to \pi^0 \nu\bar{\nu}) = (0.34 \pm 0.05) \times 10^{-10} \left(\frac{|V_{ub}|}{0.00388}\right)^{2} \left(\frac{|V_{cb}|}{0.0407}\right)^{2} \left(\frac{\sin\gamma}{\sin 73.2^\circ}\right)^{2} = (0.34 \pm 0.06) \times 10^{-10}$$

JHEP 11 (2015) 033

$K^+ \to \pi^+ \nu\nu$ in New Physics

Plenty of models

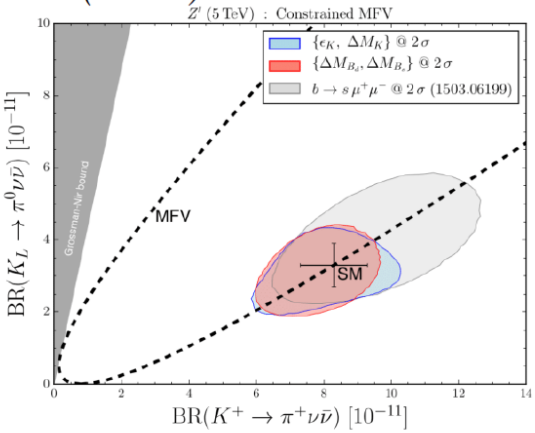
- Littlest Higgs with T-parity
- Simplified Z, Z′ models
- MSSM scenarios
- LFU violation models
- Custodial Randall-Sundrum

NP signatures

- BR(NP)/BR(SM) could reach O(1)
- Deviation from SM both in neutral and charged mode

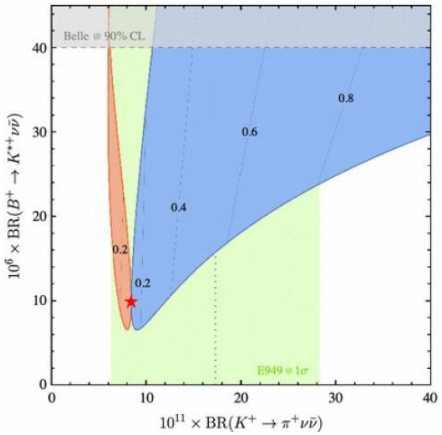
JHEP 11 (2015) 166

Z'(5 TeV) in Constrained MFV



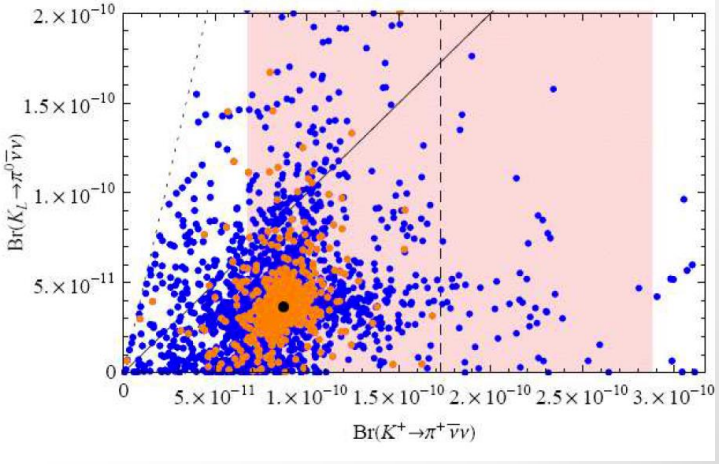
Eur. Phys. J. C (2017) 77:618

LFU violation



JHEP 0903 (2009) 108

Custodial Randall-Sundrum



$K^+ \to \pi^+ \nu\nu$: state of the art

E787/949: $BR(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$

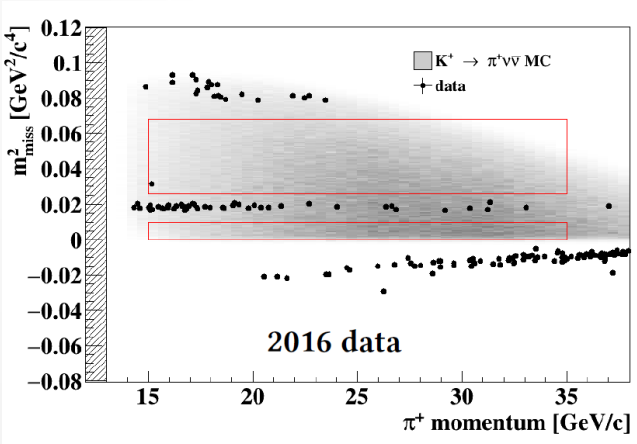
- Kaons decay at rest

Phys. Rev. D 79, 092004 (2009) Phys. Rev. D 77, 052003 (2008)

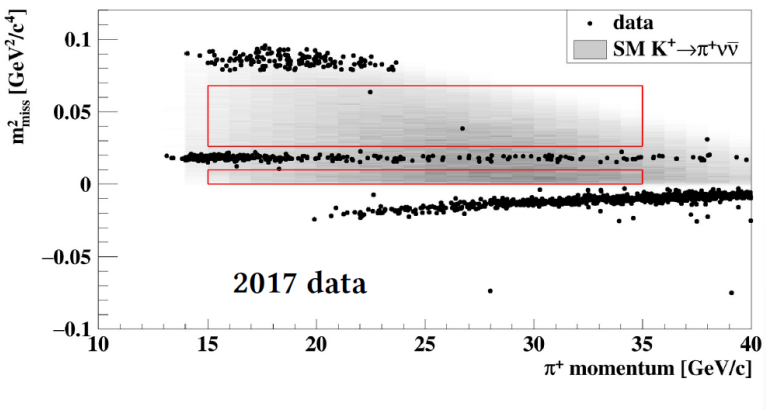
NA62:

- Kaon decays in flight
- 2016 (published), 2017 (published) and 2018 (**this talk**) data available

2016 data



2017 data



- 1 event observed
- **BR($K^+ \to \pi^+\nu\nu$) < 14x10^{-10} @ 90% CL**

Phys. Lett. B 791 (2019) 156-166

- 2 events observed
- **BR($K^+ \to \pi^+\nu\nu$) < 1.78x10^{-10} @ 90% CL**

JHEP 11 (2020) 42

$K^+ \to \pi^+ \nu\nu$: analysis strategy

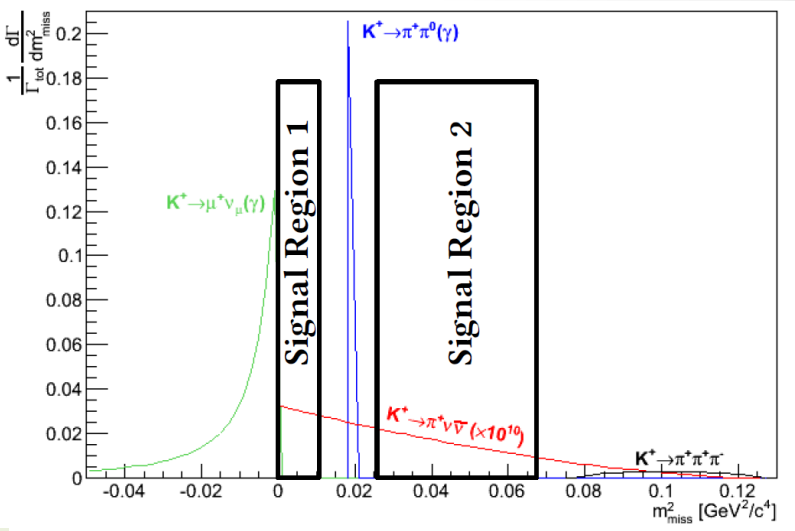
Analysis key stones

- Time resolution: O(100 ps)
- Kinematic suppression O(10^4)
- PID: muon suppression > 10^7
- Photon veto: π^0 suppression > 10^7

Main kinematical variable

$$m^2_{miss} = (p_K - p_\pi)^2$$

2 signal regions



Main backgrounds

Process	Branching ratio
$K^+ \to \pi^+\pi^0$	0.2066
$K^+ \to \mu^+\nu_\mu$	0.6356
$K^+ \to \pi^+\pi^+\pi^-$	0.0558
$K^+ \to \pi^+\pi^- e\, \nu_e$	4.3×10^{-5}
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	**8.4×10^{-11}**

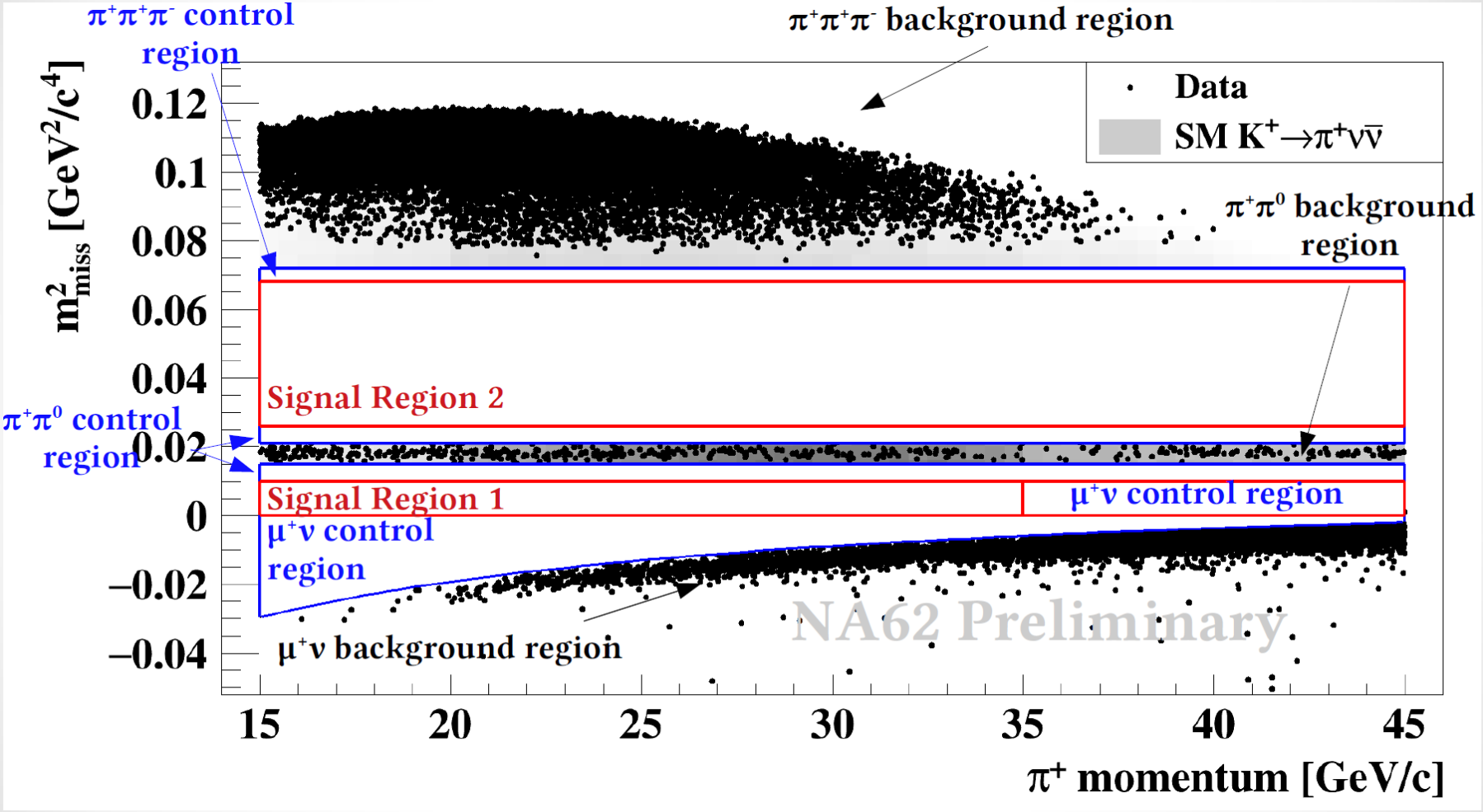
Improvements in analysis wrt 2016-2017:

- 7 categories (hardware configuration, momentum interval)
- Selection optimized for each category
- Increased signal acceptance
- MVA for upstream bkg evaluation

Normalisation:

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

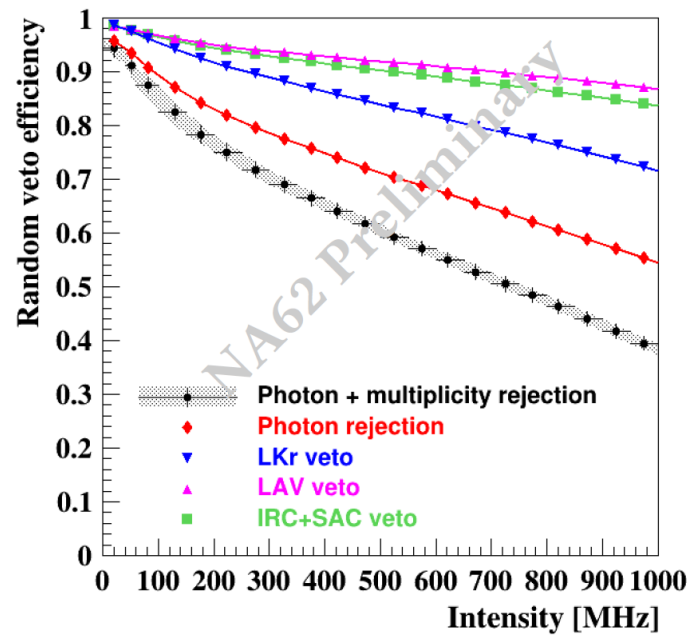
$K^+ \to \pi^+ \nu\nu$: kinematics (2018 data)



$K^+ \to \pi^+ \nu\nu$: SES (2018 data)

$$\text{S.E.S.} = \frac{Br(\pi\nu\nu)}{N^{exp}_{\pi\nu\nu}}$$

$$N^{exp}_{\pi\nu\nu} \approx N_{\pi\pi} \epsilon_{trigger} \epsilon_{RV} \frac{A_{\pi\nu\nu}}{A_{\pi\pi}} \frac{Br(\pi\nu\nu)}{Br(\pi\pi)}$$

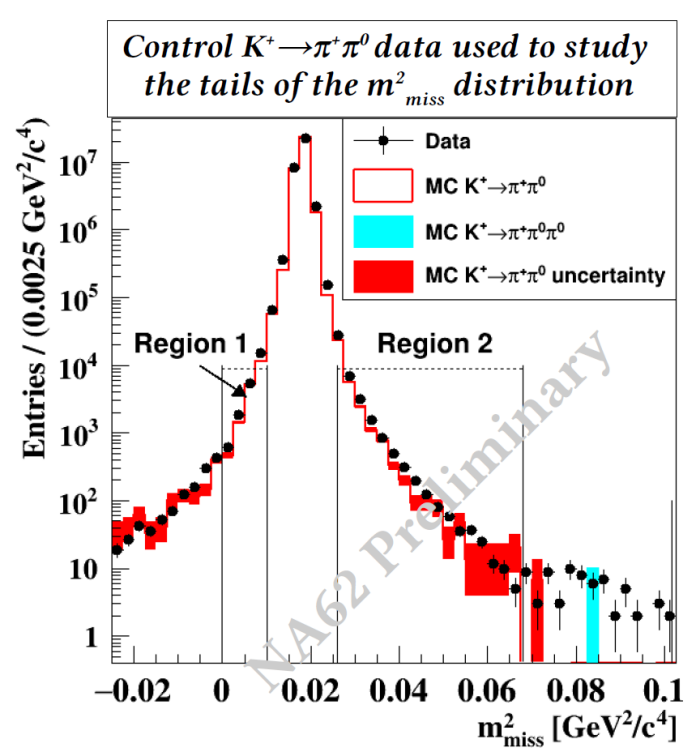


Contribution to SES	δ(SES)
$\varepsilon_{trigger}$	5%
Acceptance	3.5%
ε_{RV}	2%
Normalisation	0.7%
Instantaneous intensity	0.7%
Total	**6.5%**

SES = (1.11 ± 0.07) x 10^{-11}

$K^+ \to \pi^+ \nu\nu$: background from kaon decays

$K^+ \to \pi^+ \pi^0$ evaluation



Event fraction in $K^+ \to \pi^+\pi^0$ region, measured on control data

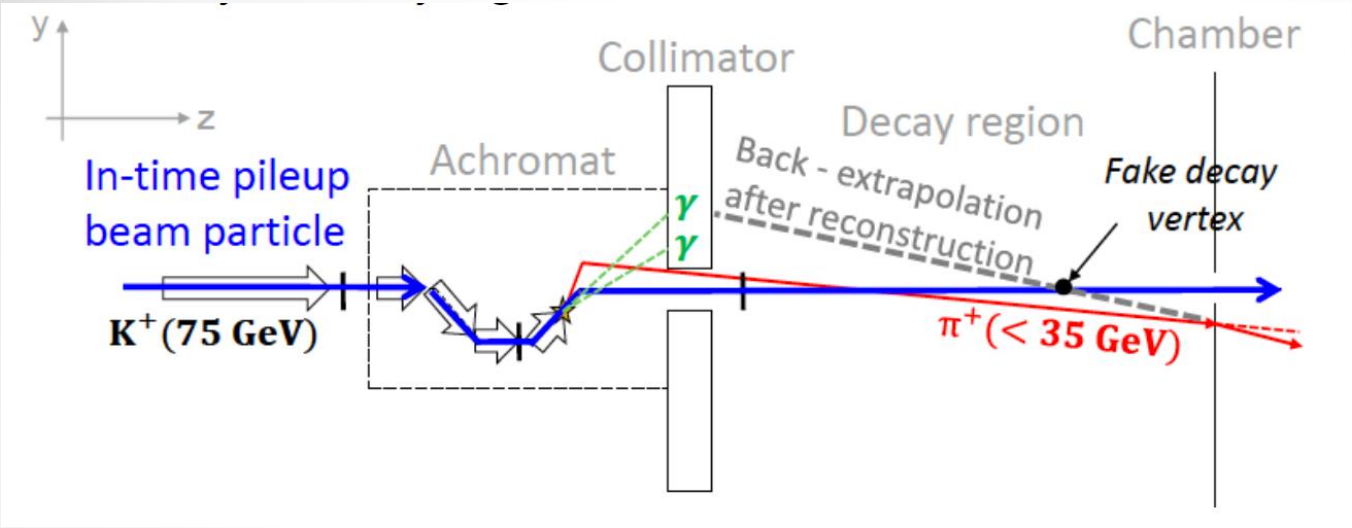
$$N^{exp}_{\pi\pi}(region) = N(\pi^+\pi^0) \times f_{kin}(region)$$

Expected bkg in signal region

Data in $K^+ \to \pi^+\pi^0$ region

- Similar procedure for $K^+ \to \mu^+ \nu$ and $K^+ \to \pi^+ \pi^+ \pi^-$
- $K^+ \to \pi^+ \pi^- e^+ \nu$ estimated from MC

$K^+ \to \pi^+ \nu\nu$: upstream background



Kaon:

- Intime pileup K^+

Pion:

- Early K^+ decay + scattering in the 1st spectrometer chamber
- Interactions of beam particles in the beam spectrometer

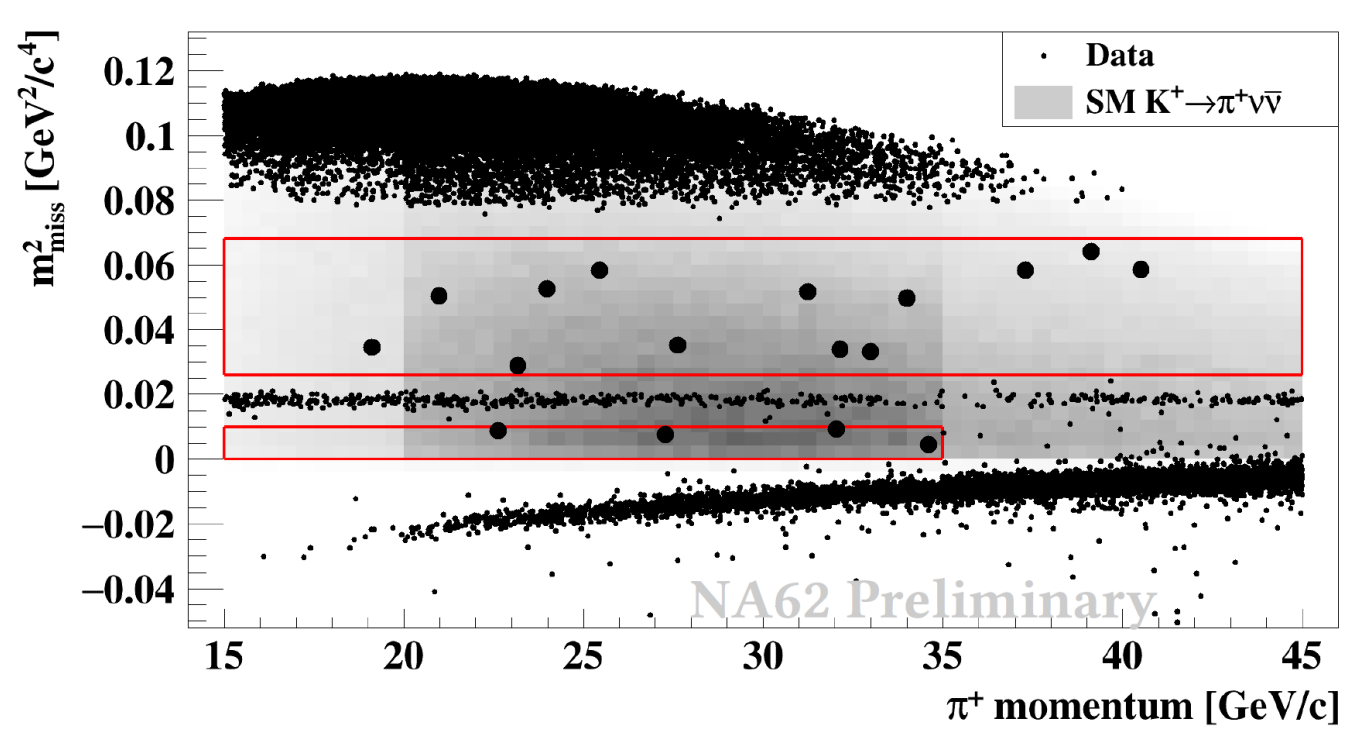
Upstream bkg estimation:

- Data driven approach
- Use the geometric origin to define samples for the validation

$K^+ \to \pi^+ \nu\nu$: expected bkg (2018 data)

	Expected N_{evt}
SM signal	$7.58 \pm 0.40(\text{syst}) \pm 0.75(\text{ext})$
Total background	$5.28\ ^{+0.99}_{-0.74}$
$K^+ \to \pi^+ \pi^0(\gamma)$	0.75 ± 0.04
$K^+ \to \mu^+ \nu(\gamma)$	0.49 ± 0.05
$K^+ \to \pi^+ \pi^- e^+ \nu$	0.50 ± 0.11
$K^+ \to \pi^+ \pi^+ \pi^-$	0.24 ± 0.08
$K^+ \to \pi^+ \gamma \gamma$	< 0.01
$K^+ \to l^+ \nu \pi^0$	< 0.001
upstream	$3.30\ ^{+0.98}_{-0.73}$

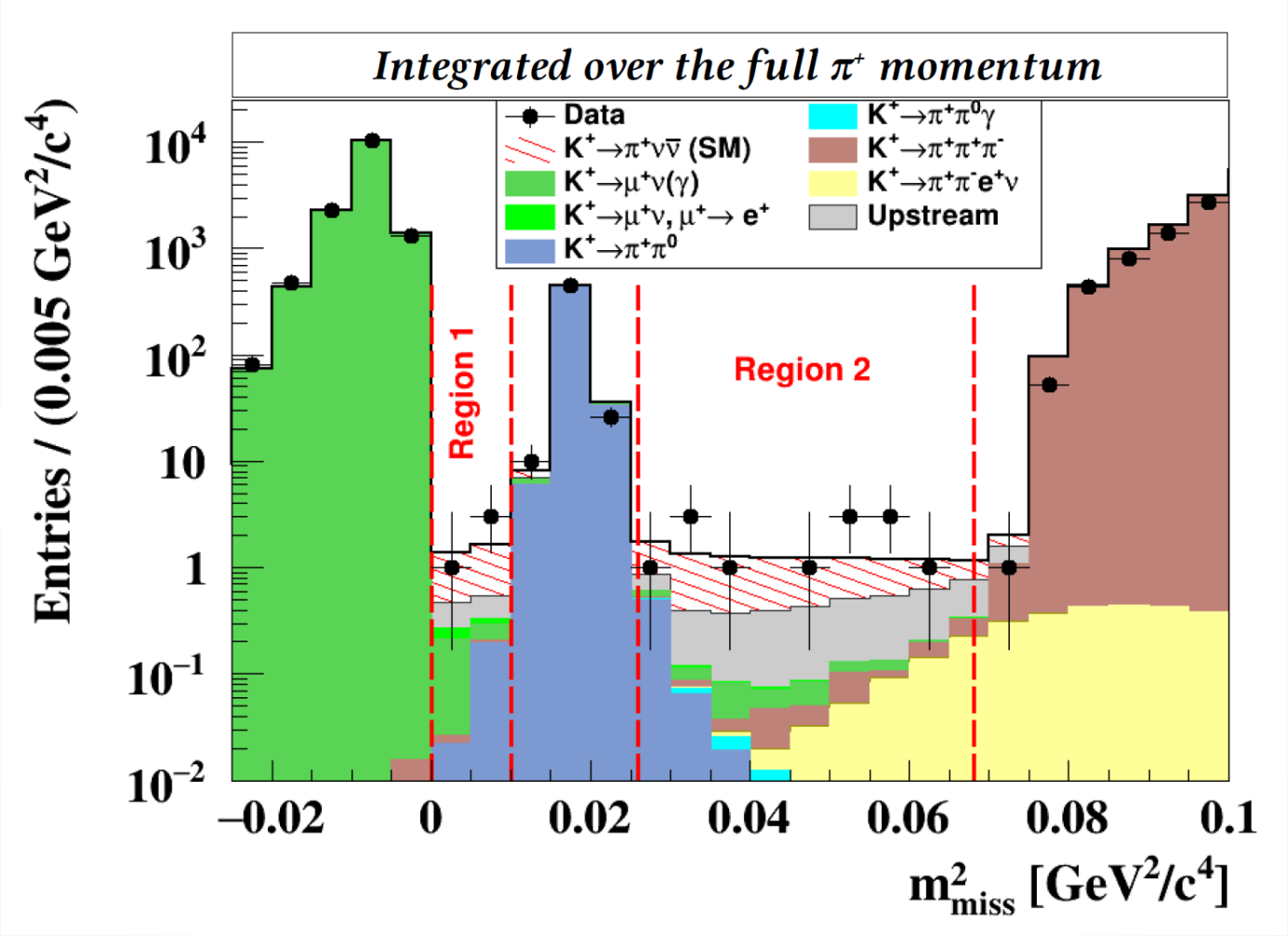
$K^+ \to \pi^+ \nu\nu$: opening the box (2018 data)



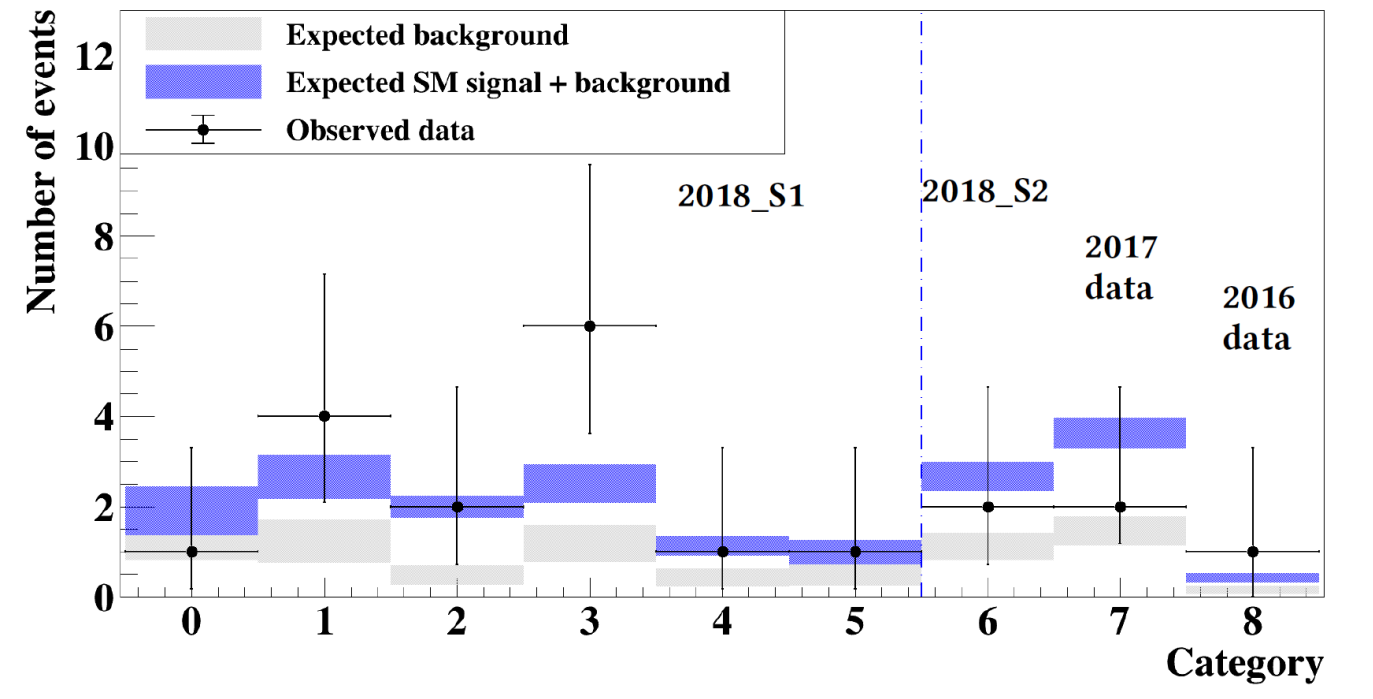
17 events observed

Expected SM signal: 7.6
Expected background: 5.3

$K^+ \to \pi^+ \nu\nu$: missing mass spectrum (2018 data)



$K^+ \to \pi^+ \nu\nu$: combined result

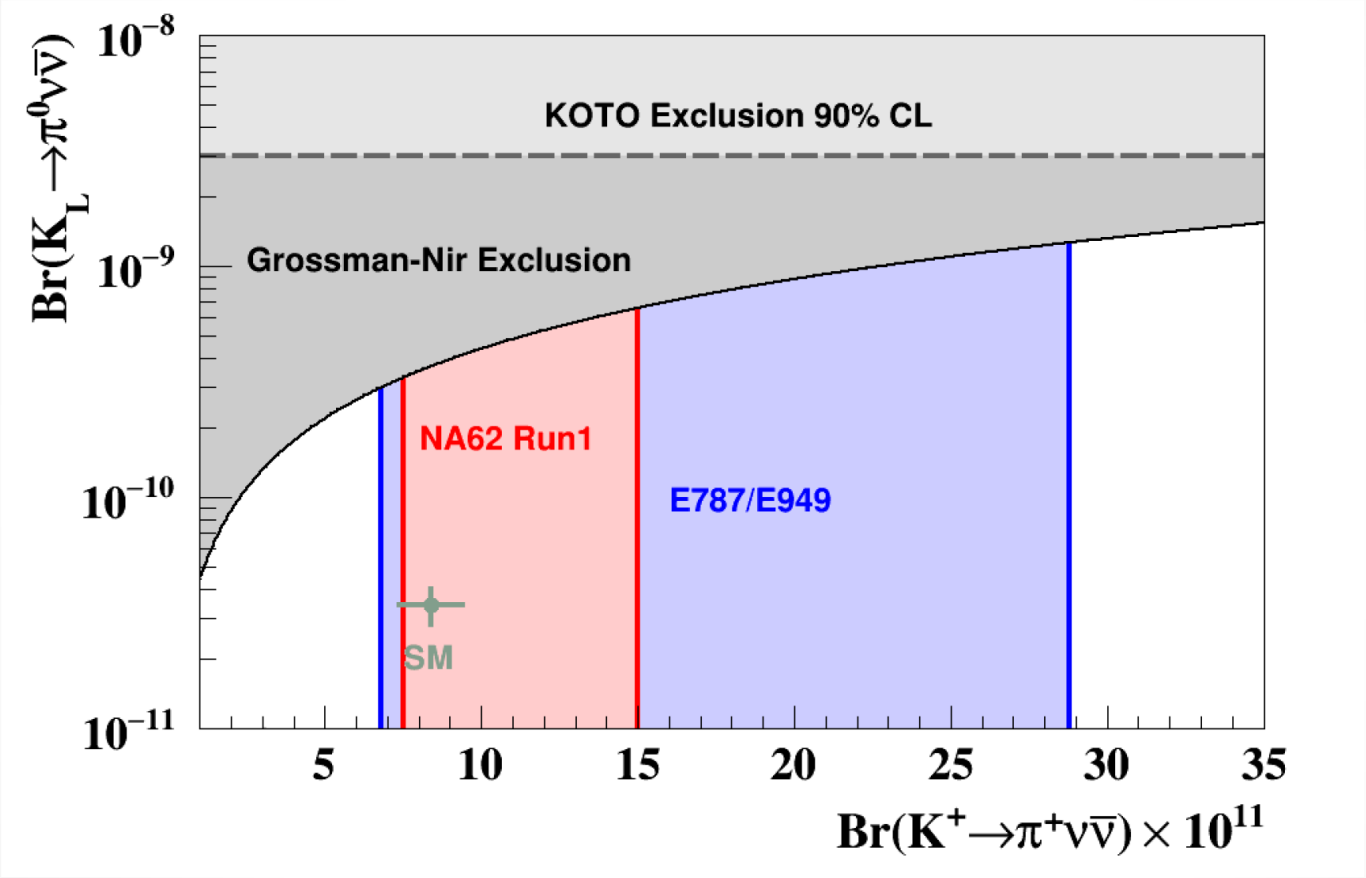


- Categories 0-5: 2018 data, 5 GeV/c momentum bins in the range 15-45 GeV/c
- Categories 6-8: integrated over momentum
- S1, S2: different hardware configurations
- Maximum likelihood fit to combine all categories

Combined result:

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (11.0^{+4.0}_{-3.5 stat.} \pm 0.3_{syst.}) \times 10^{-11} (3.5\sigma \text{ significance})$$

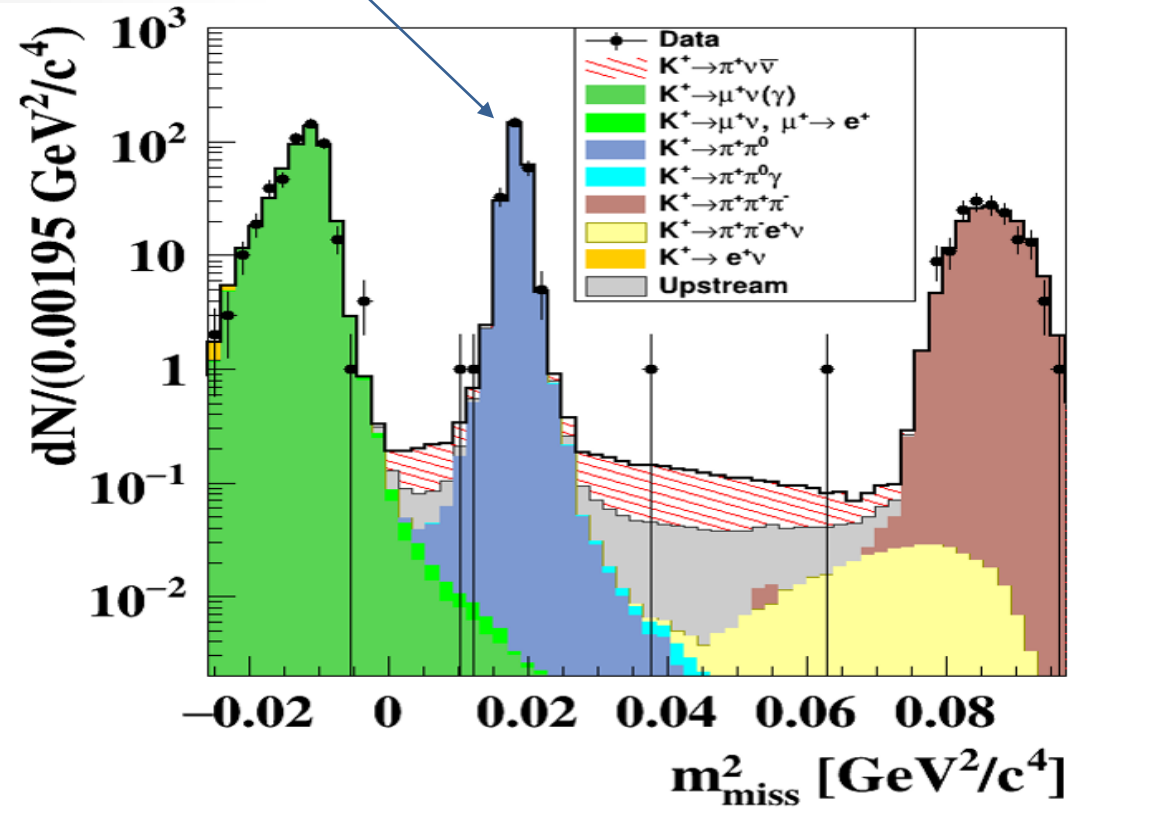
$K^+ \to \pi^+ \nu\nu$: correlation with $K_L \to \pi^0 \nu\nu$



$K^+ \to \pi^+ \nu\nu$ analysis: beyond BR measurement

Hidden sector searches with 2017 data:

- $K^+ \to \pi^+$ X, X invisible
- $K^+ \to \pi^+\pi^0$ region: $K^+ \to \pi^+\pi^0$, $\pi^0 \to$ invisible



$K^+ \to \pi^+ X$

Motivation:

- X could be a feebly interacting particle (FIP)

Scalar (Higgs portal)

$$\mathcal{L}_{\text{scalar}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - (\mu S + \lambda S^2) H^\dagger H$$
$$\mu = \sin\theta \quad \lambda = 0$$

JHEP 05 (2010) 010

JHEP 02 (2014) 123

Pseudoscalar (ALP)

$$\mathcal{L}_{\text{SM}} = \frac{\partial_\mu a}{f_\ell} \sum_\alpha \bar{\ell}_\alpha \gamma_\mu \gamma_5 \ell_\alpha + \frac{\partial_\mu a}{f_q} \sum_\beta \bar{q}_\beta \gamma_\mu \gamma_5 q_\beta$$

JHEP 03 (2015) 171

Phys. Rev. D16 (1977) 1791-1797

Phys. Rev. D95 (2017) 095009

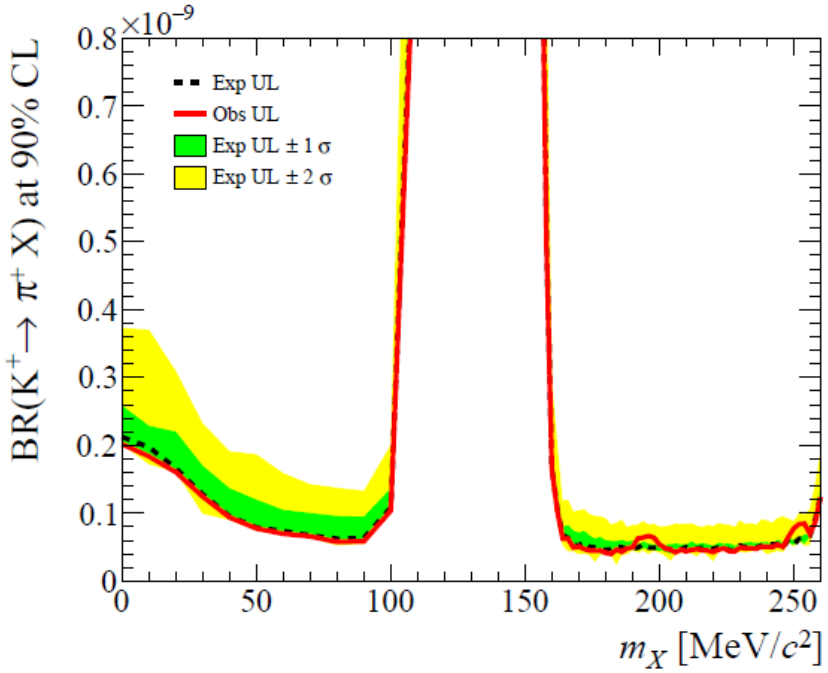
Analysis strategy:

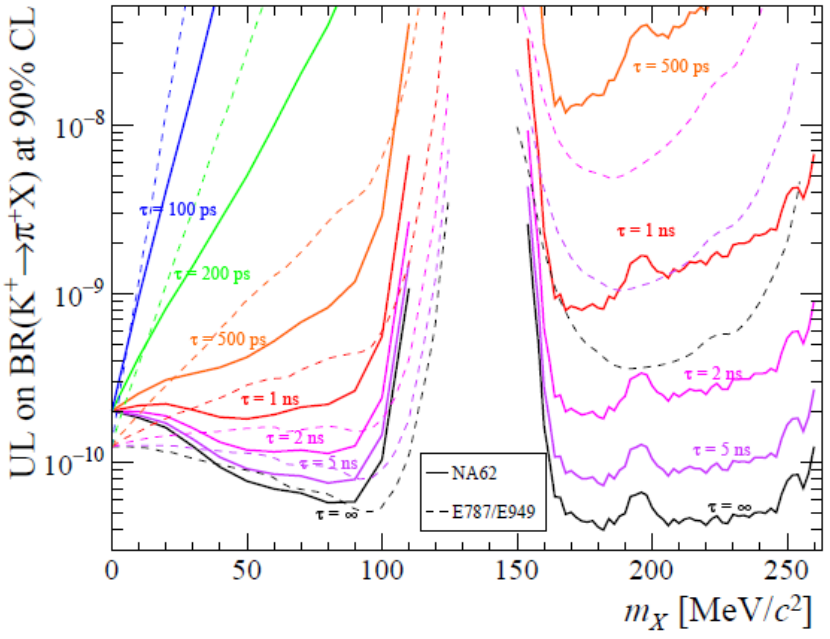
- Selection, normalisation and bkg evaluation from the $\pi\nu\nu$ analysis
- Signal acceptance: generate MC samples for 200 mass hypotheses
- Shape analysis of the m_{miss}^2 distribution to search for a signal peak

$K^+ \to \pi^+ X$

X invisible

X decays to SM particles





$m_X = 0 - 100$ MeV: $BR(K^+ \to \pi^+ X) < (0.5 - 2.0) \times 10^{-10}$ @ 90% CL

$m_X = 160 - 260$ MeV: $BR(K^+ \to \pi^+ X) < (0.4 - 1.4) \times 10^{-10}$ @ 90% CL

Region I: small improvement in 40-80 MeV

Region II: factor of 10 improvement

JHEP 03 (2021) 058

$\pi^0 \to$ invisible

Motivation:
- BR($\pi^0 \to \nu\nu$) = O(10^{-24})
- Any observation means New Physics

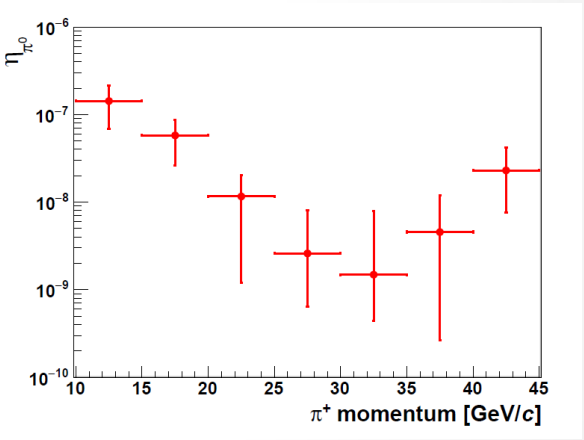
Current limit (BNL):
BR($\pi^0 \to \nu\nu$) < 2.7×10^{-7} @ 90% CL

Phys. Rev. D 72 (2005) 091102

Analysis strategy:
- Select $K^+ \to \pi^+ \pi^0$ events
- Normalize on $\pi^0 \to \gamma\gamma$
- Main bkg: $\pi^0 \to \gamma\gamma$ with 2 lost photons
- $25 < p_\pi < 40$ GeV/c
- $0.015 < (P_K - P_\pi)^2 < 0.021$ GeV^2/c^4

Search for a FIP in $K^+ \to \pi^+ X$ for $m_X \sim m(\pi^0)$

Expected veto inefficiency

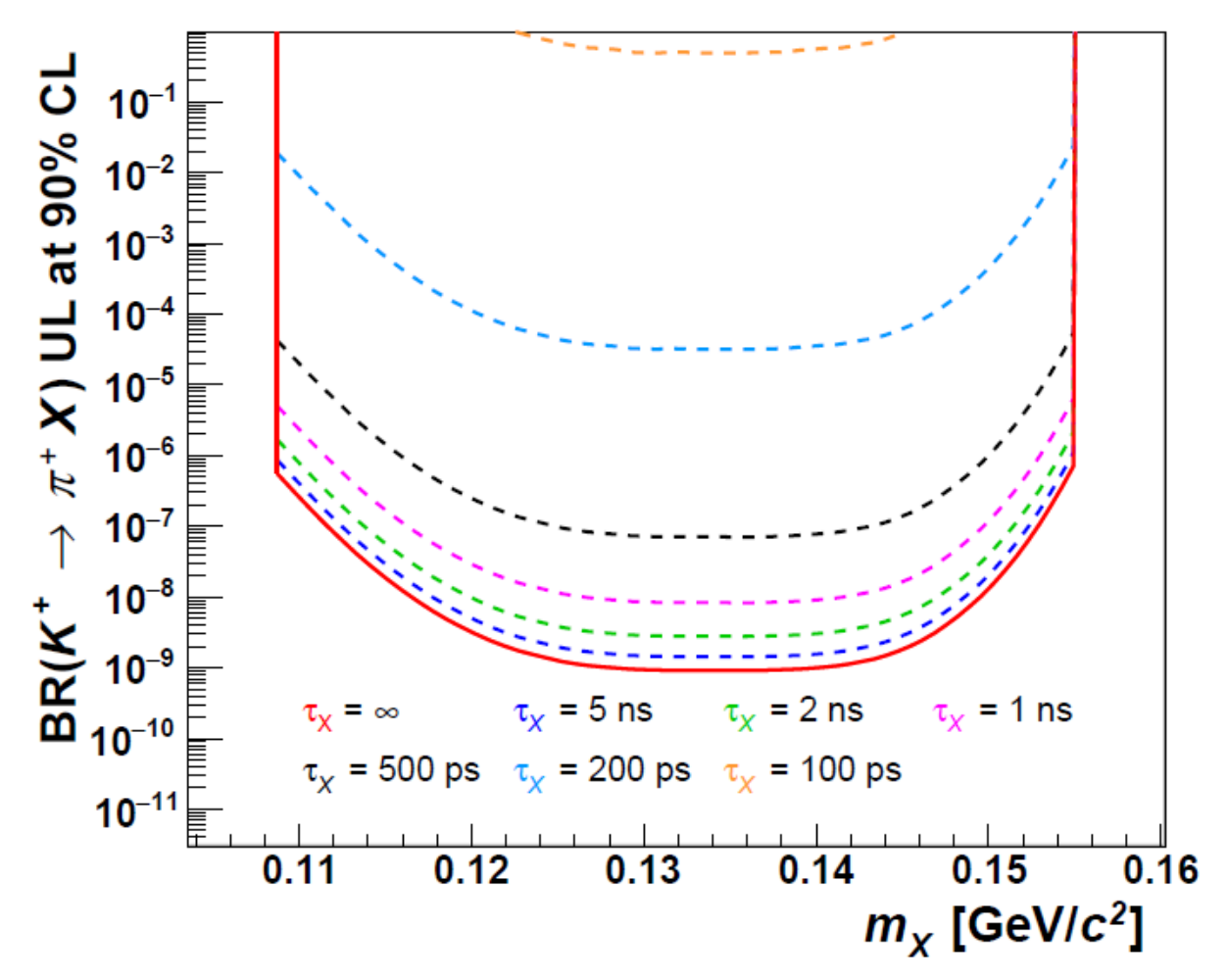


Final result: $\mathrm{BR}(\pi^0 \to \text{invisible}) \leq 4.4 \times 10^{-9}$ at 90% C.L.

JHEP 02 (2021) 201

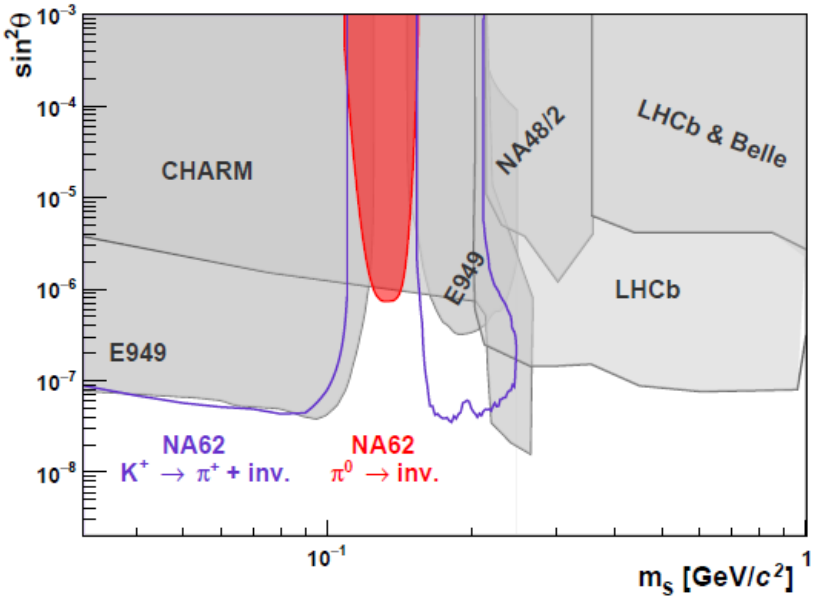
Factor of 60 improvement wrt the previous result

$K^+ \to \pi^+ X$, $m_X \sim m(\pi^0)$

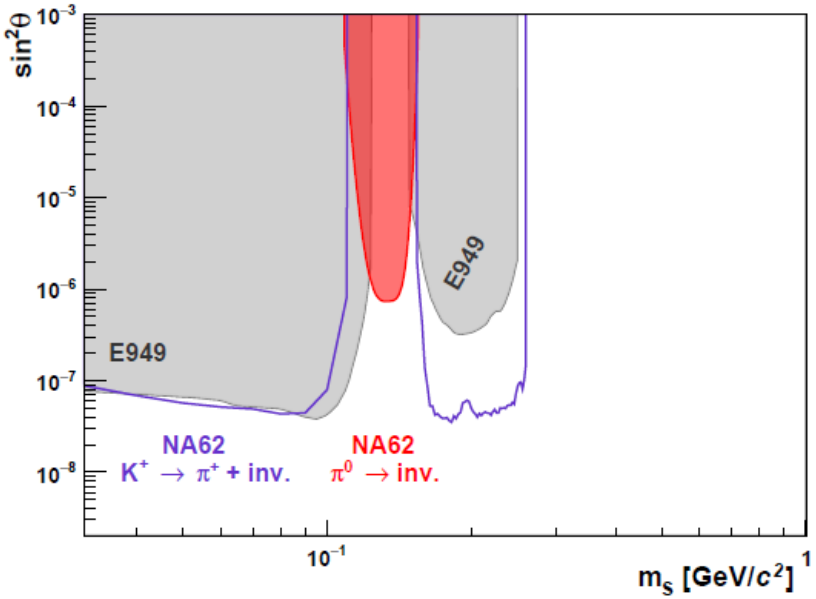


$K^+ \to \pi^+ X$, dark scalar interpretation

X decays to SM particles



X invisible

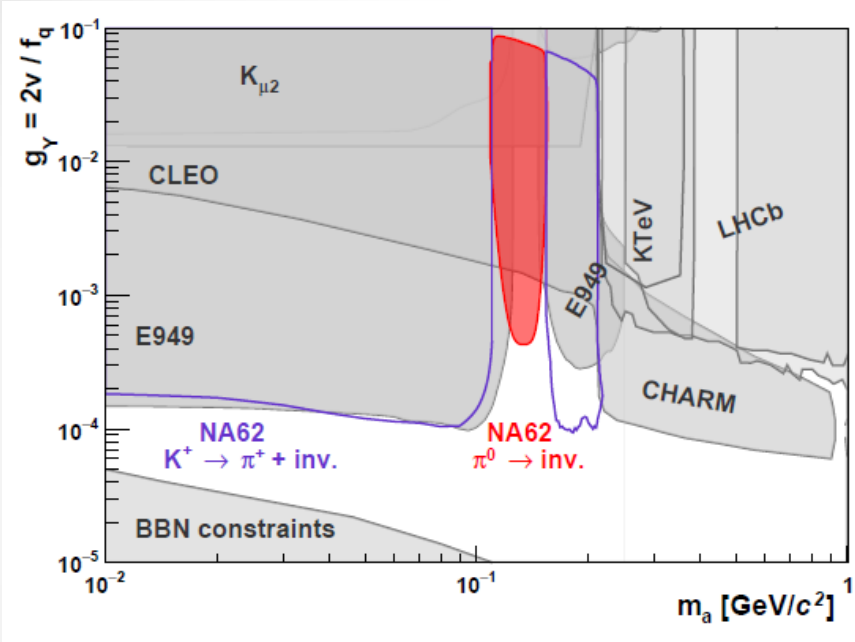


Small improvement

Filled the gap between 2 exclusion regions

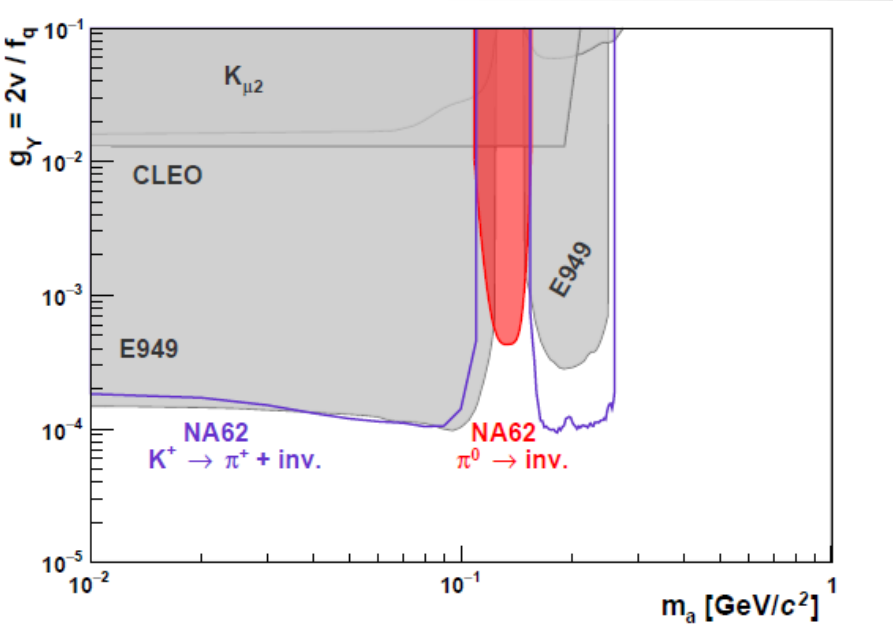
$K^+ \to \pi^+ X$, ALP interpretation

X decays to SM particles



Significant improvement

X invisible



Significant improvement

$K^+ \to \pi^+ \mu^+ \mu^-$ ($K\pi\mu\mu$)

Main interest:
- Search for anomalies in s→dll similar to b→sll
- LFU test together with K→πee (Kπee)

Kπμμ in SM: Nucl. Phys. B291 (1987) 692-719 Phys. Part. Nucl. Lett. 5 (2008) 76-84
- FCNC decay
- Decay rate calculated within ChPT: $K^+ \to \pi^+ \gamma^*$

Kinematical variables: $x = m(\pi^+\mu^+)^2/M_K^2, \quad z = m(\mu^+\mu^-)^2/M_K^2$

Differential decay width:

$$\frac{d^2\Gamma(x,z)}{dx\,dz} = \frac{d^2\Gamma_0(x,z)}{dx\,dz} \times (1+\delta(x,z))$$

Radiative corrections
Eur. Phys. J. C70 (2010) 219-231

$$\frac{d^2\Gamma_0(x,z)}{dx\,dz} = \frac{\alpha^2 M_K}{8\pi(4\pi)^4}\left[(2x+z-2-2r_\mu^2)(-2x-z+2r_\pi^2+2r_\mu^2)+z(z-2-2r_\pi^2)\right]|W(z)|^2$$

Formfactor W(z): JHEP 08 (1998) 004

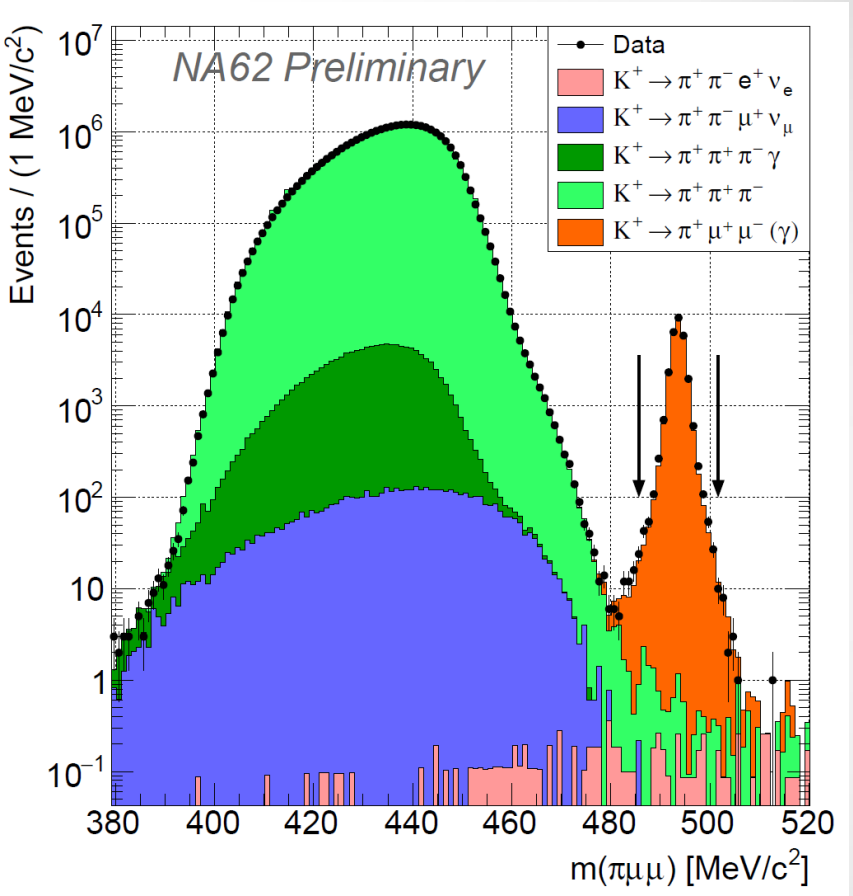
$$W(z) = G_F M_K^2 (a+bz) + W^{\pi\pi}(z)$$

FF parameters

Pion loop term from $K^+ \to \pi^+\pi^+\pi^-$

Kπμμ: event selection

- 2017+2018 data
- FF parameter measurement
- BR(Kπμμ) measurement
- Normalisation: $K^+ \to \pi^+ \pi^+ \pi^-$



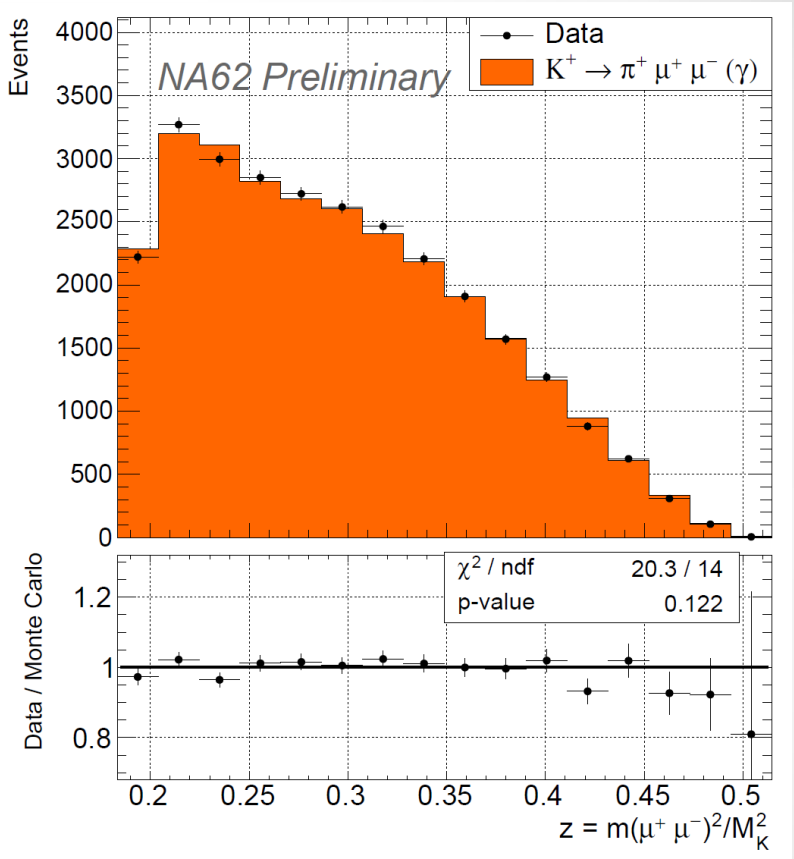
Event selection:

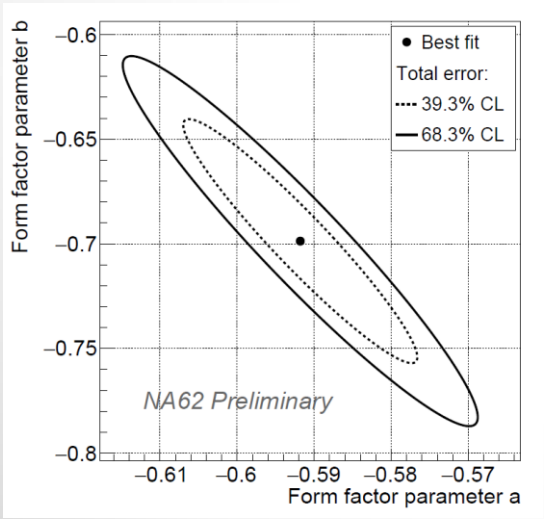
- Generic 3-track selection
- Pion PID: E/p < 0.9, !MUV3
- Muon PID: E/p < 0.2, MUV3
- $|m(\pi\mu\mu) - M_K| < 8$ MeV/c^2
- **28011 events selected**
- Expected bkg:
  N(bkg) = 12.5 ± 1.7(stat) ± 12.5 (syst)

Kπμμ: fit of formfactors

FF parameter measurement from the fit of z distributions:

- Reweight MC for various (a, b)
- **a = -0.592 ± 0.015**
- **b = -0.699 ± 0.058**
- $\chi 2/ndf = 20.3/14$
- P-value = 0.122
- Correlation coefficient $\varrho(a,b) = -0.973$

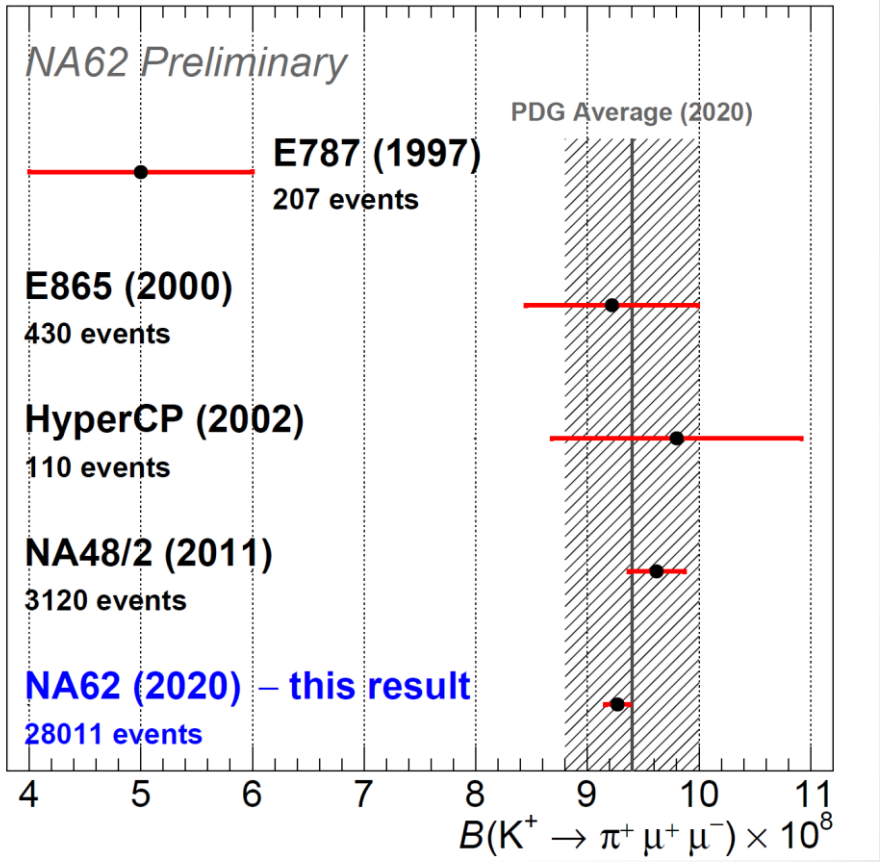




parameter	value	Stat. error	Syst. error	Ext . error	Total error
a	-0.592	0.013	0.007	0.001	0.015
b	-0.699	0.046	0.035	0.003	0.058

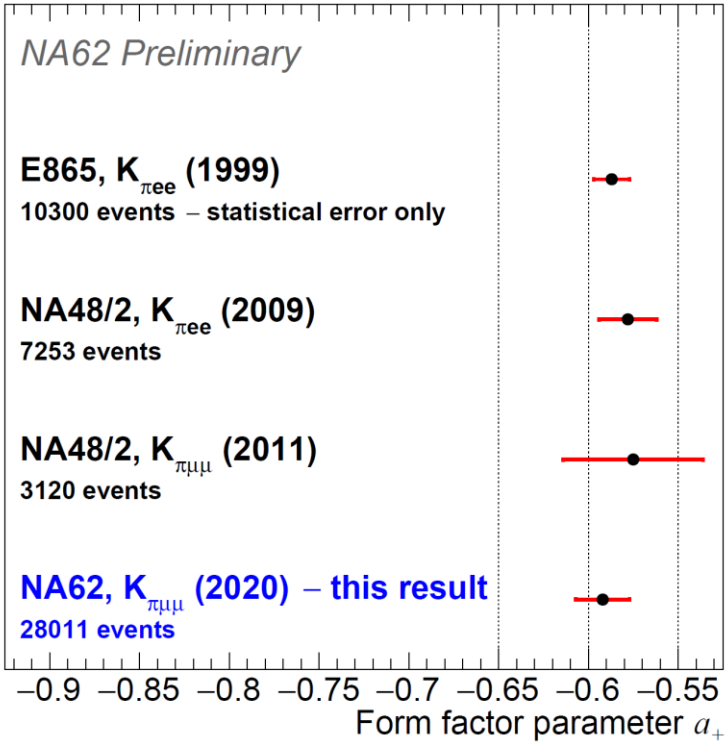
Kπμμ BR

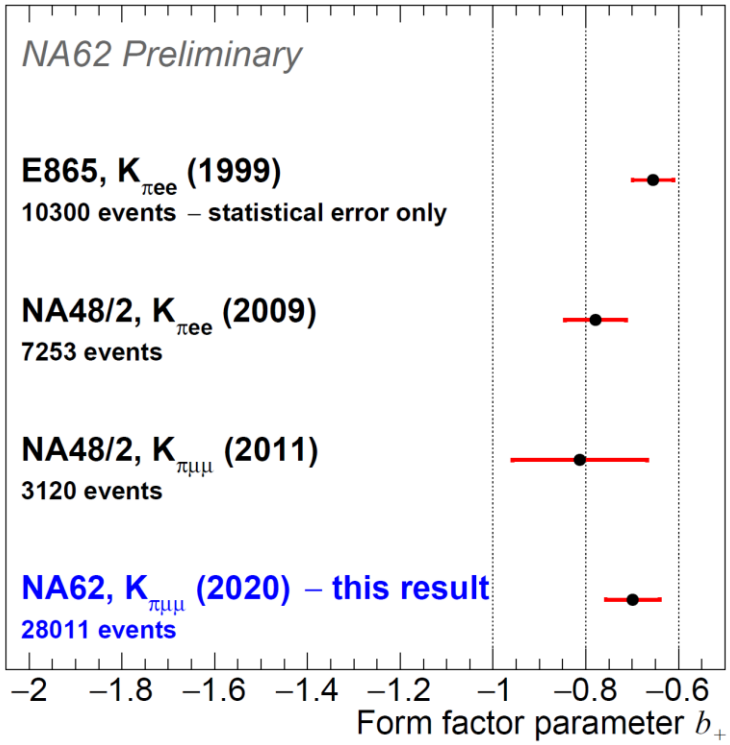
Model-dependent BR(Kπμμ):
BR(Kπμμ) = (9.27 ± 0.11) x 10^{-8}



parameter	value	Stat. error	Syst. error	Ext. error	Total error
BR x 10^8	9.27	0.07	0.08	0.04	0.11

Kπμμ and LFU





E865: Kπee Phys. Rev. Lett. 83 (1999) 4482-4485

NA48/2: Kπee Phys. Lett. B 677 (2009) 246-254

NA48/2: Kπμμ Phys. Lett. B 697 (2011) 107-115

No tension between (a, b) from Kπμμ and Kπee

Conclusions

- $K^+ \to \pi^+ \nu\nu$ (2016+2017+2018 data) — paper in preparation
  - 20 events observed in 2016(1) + 2017(2) + 2018(17)
  - **BR($K^+ \to \pi^+ \nu\nu$) = 11(4) x 10^{-11} , 3.5σ significance**
  - BR compatible with SM within 1σ

- $\pi^0 \to$ invisible (2017 data) — JHEP 02 (2021) 201
  - BR($\pi^0 \to$ invisible) < 4.4 x 10^{-10} @ 90% CL
  - Factor of 60 improvement

- $K^+ \to \pi^+ X$ (2017 data) — JHEP 03 (2021) 058
  - BR($K^+ \to \pi^+ X$) < O(10^{-10})
  - UL improved for m_X in 40-80 MeV and 160-260 MeV

- $K^+ \to \pi^+ \mu^+ \mu^-$ (2017+2018 data) — Paper in preparation
  - BR($K^+ \to \pi^+ \mu^+ \mu^-$) = 9.27(11) x 10^{-8}
  - FF parameters: a = -0.592(13) , b = -0.699(58)
  - (a, b) compatible with measurements from $K^+ \to \pi^+ e^+ e^-$

Prospects

- Data taking in 2021-2024
- New detectors against upstream bkg (beam spectrometer station, veto counter)
- New calorimeter downstream MUV against K decay bkg

spare