Latest results on $K^+ \to \pi^+ \nu\bar{\nu}$ decay and precision measurements with Kaons at NA62

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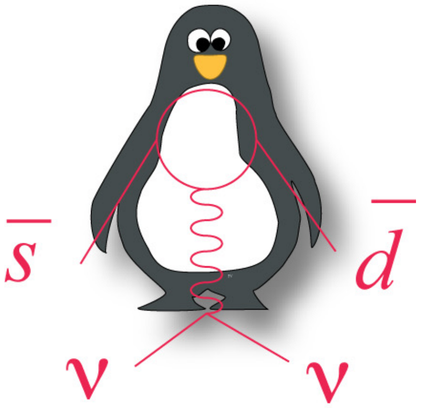
on behalf of the NA62 collaboration

ICNFP2023, Crete

Outline

- The NA62 experiment
- Experimental setup
- NA62 main goal: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
- Precision measurements
    - $K^+ \rightarrow \pi^0 e^+ \nu \gamma$ ($K_{e3\gamma}$)
    - $K^+ \rightarrow \pi^+ \mu^+ \mu^-$
    - $K^+ \rightarrow \pi^+ \gamma \gamma$
- Conclusions



NA62 experiment at CERN

NA62 is located in the North Area at CERN:

- ✓ Fixed target experiment with kaon decay-in-flight
- ✓ Main goal: **BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$) with 10% precision**
  [PLB791 (2019) 156-166, JHEP11 (2020), JHEP06 (2021)]
- ✓ Primary beam: **400 GeV/c protons** from SPS
- ✓ Secondary baem: **75 GeV/c** positive charged particle **(6% K^+)**

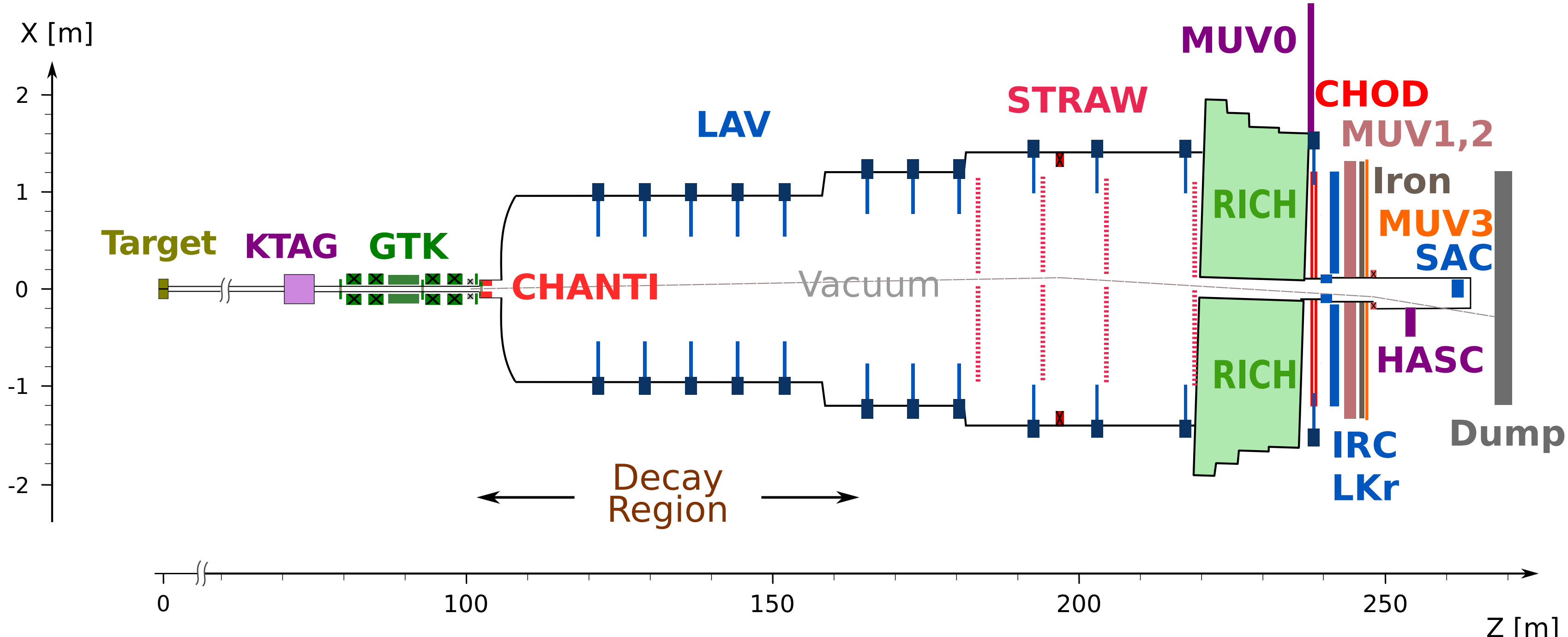
NA62 collaboration: ~ 200 participants from ~ 30 institution:

Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, GMU-Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Moscow, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Sofia, Torino, TRIUMF, Vancouver UBC

Timeline

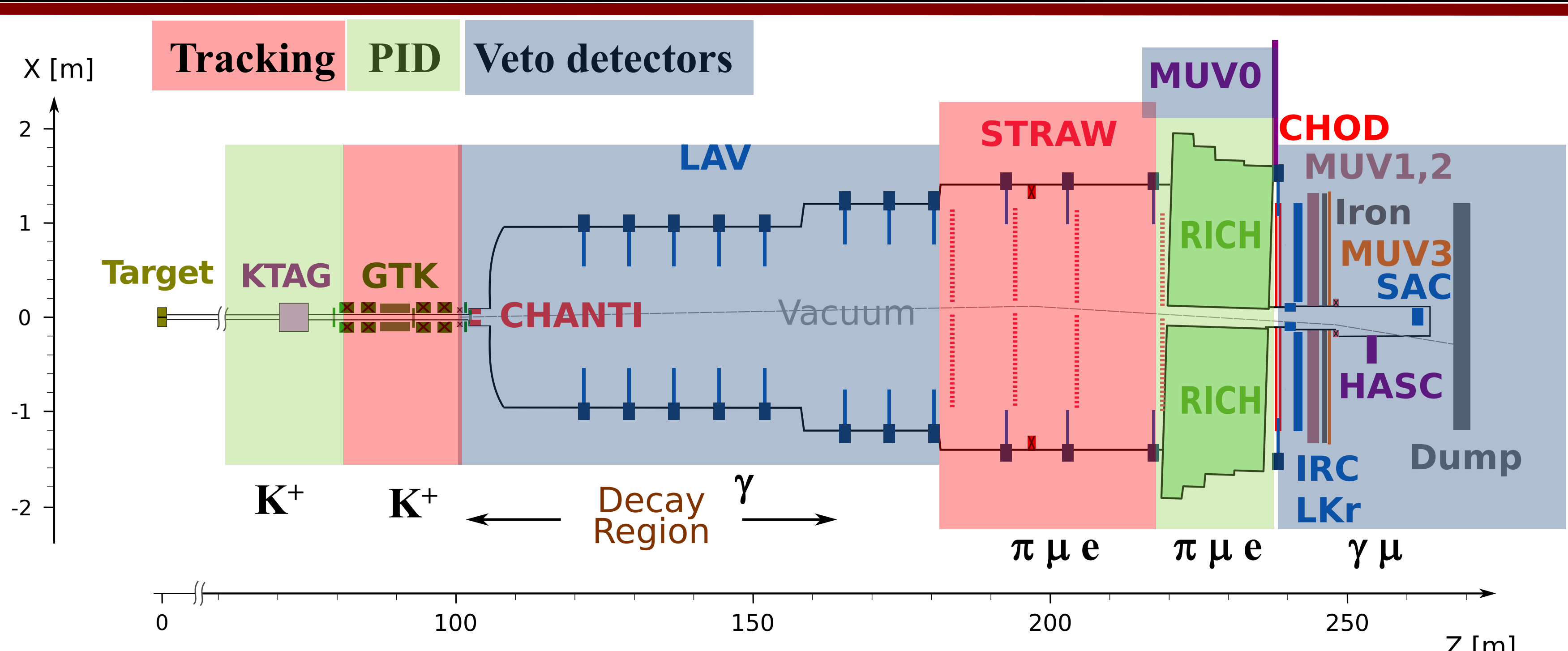
2009 – 2014	2014 – 2015	2016 – 2018	2021 – 2023
Construction and installation	Technical runs	Physics runs	Physics runs

NA62 beam and detector



SPS Beam	Secondary positive beam	Decay Region and Detectors
400 GeV/c protons 3.5s spill	75 GeV/c momentum, 1% bite 100 µrad divergence (RMS) 60x30 mm^2 transverse size K^+(6%)/π^+(70%)/p(24%) 750 MHz at GTK3	Fiducial region 60 m K^+ decay rate ~ 5 MHz Vacuum $\mathcal{O}$ 10^{-6} mbar Si pixel beam tracker + Straw tracker LKr Calorimeter from NA48 Cerenkov counter for K id RICH for π/µ id

NA62 beam and detector



SPS Beam

400 GeV/c protons

3.5s spill

Secondary positive beam

75 GeV/c momentum, 1% bite

100 μrad divergence (RMS)

60x30 mm^2 transverse size

K^+(6%)/π^+(70%)/p(24%)

750 MHz at GTK3

Decay Region and Detectors

Fiducial region 60 m

K^+ decay rate ~ 5 MHz

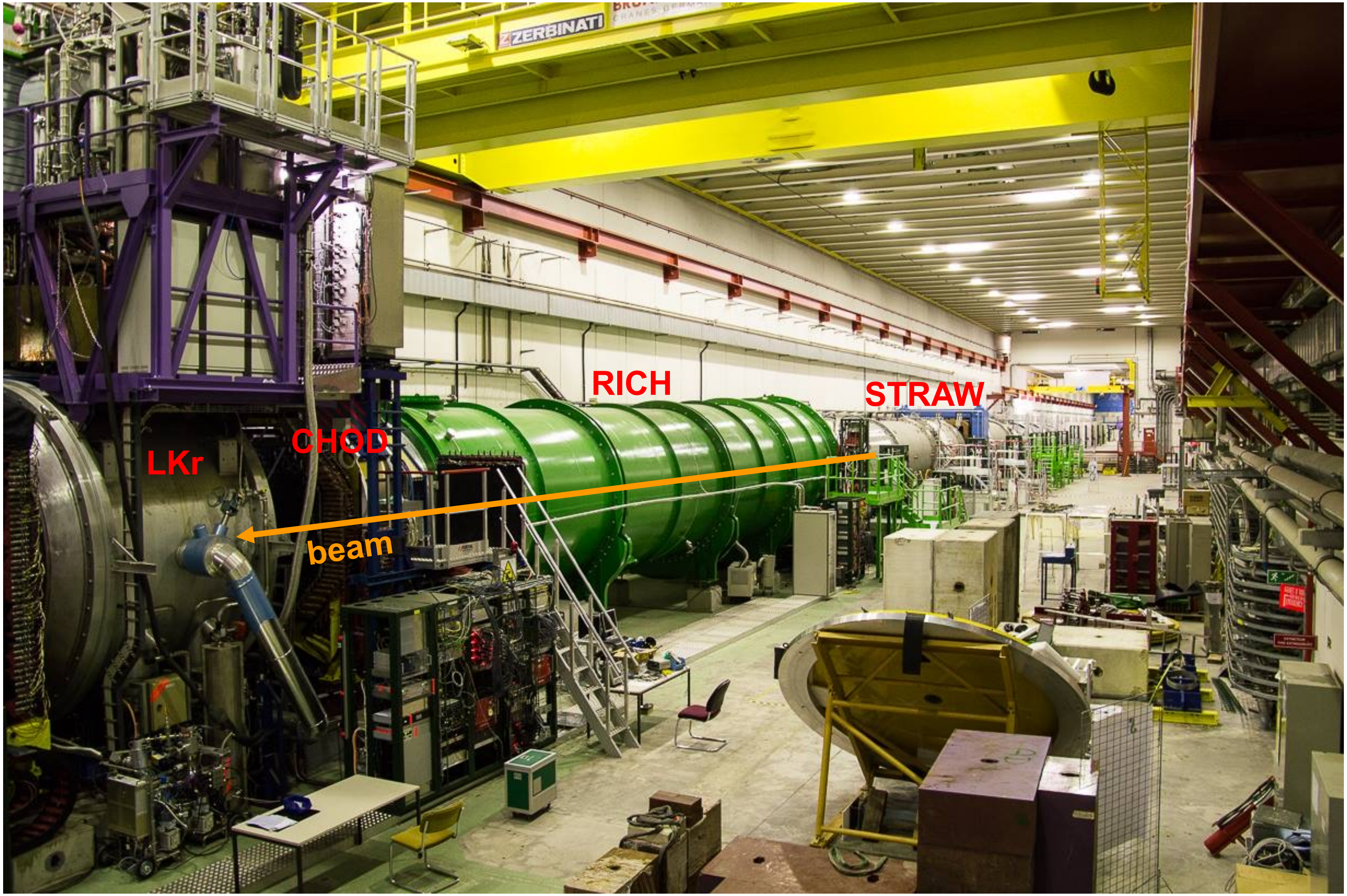
Vacuum $\mathcal{O}\ 10^{-6}$ mbar

Si pixel beam tracker + Straw tracker

LKr Calorimeter from NA48

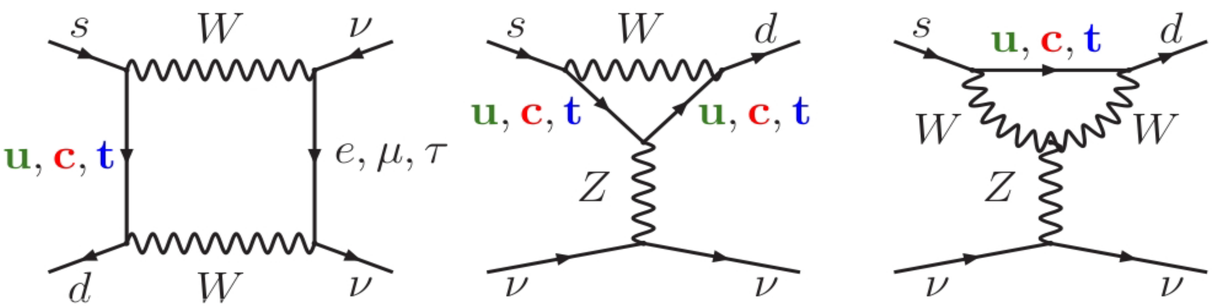
Cerenkov counter for K id RICH for π/μ id

NA62 Detector

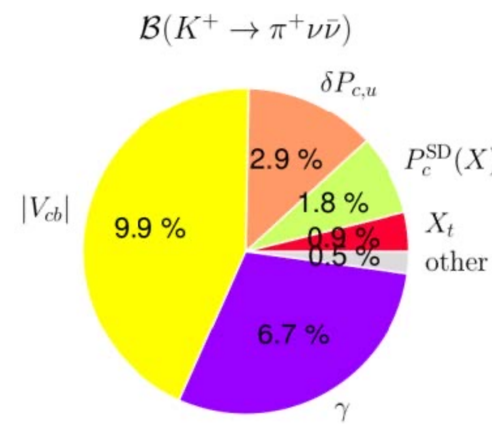


$K^+ \to \pi^+ \nu \bar{\nu}$

$K^+ \to \pi^+ \nu\bar{\nu}$ decay in the SM



Theoretical error budget



- FCNC loop processes: s→d coupling and highest CKM suppression
- Theoretically clean: Short distance contribution
- Hadronic matrix element measured with K_{l3} decays
- Precise SM predictions: [Buras. et. al., JHEP11(2015)033]

$$\mathbf{BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}}$$

$$\mathbf{BR\left(K_L \to \pi^0 \nu\bar{\nu}\right) = (3.4 \pm 0.6) \times 10^{-11}}$$

- Experimental results:

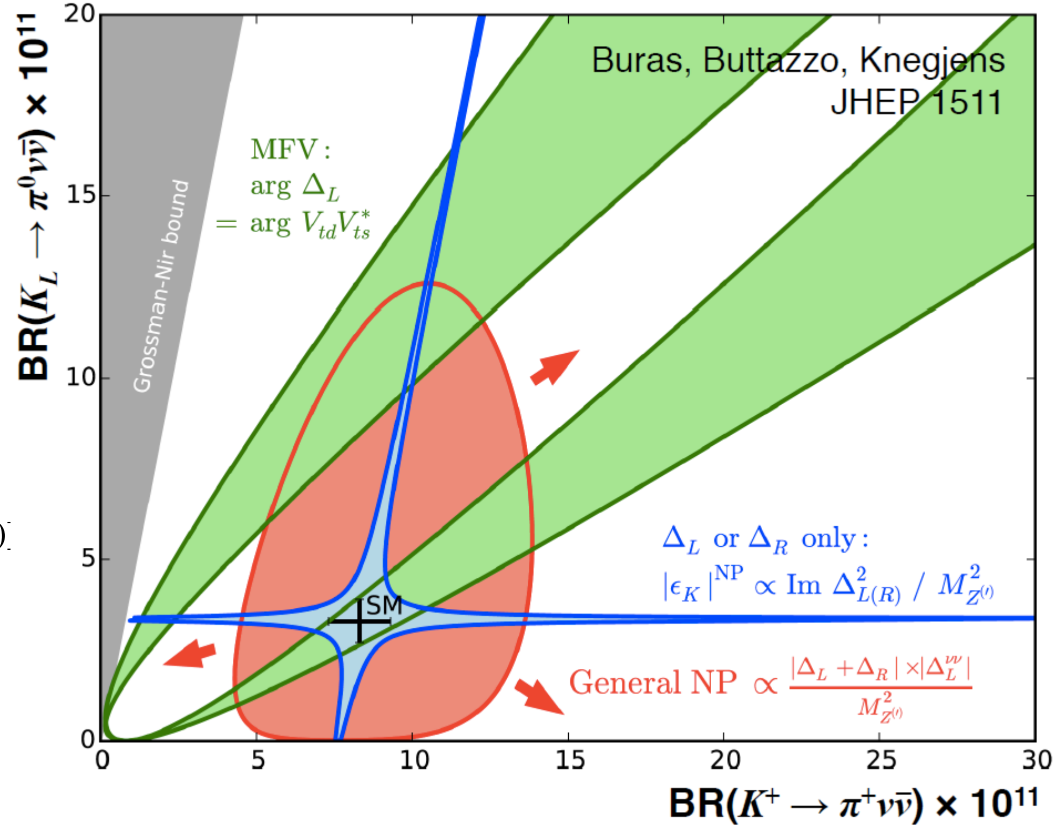
$$\mathbf{BR(K^+ \to \pi^+ \nu\bar{\nu})(E787\ E949) = (17.3\ ^{+11.5}_{-10.5}) \times 10^{-10}}$$ [Phys rev. D 79, 092004 (2009)]

$$\mathbf{BR\left(K_L \to \pi^0 \nu\bar{\nu}\right)(391\ a) < 2.6 \times 10^{-8}\ (90\%\ CL)}$$ [Phys rev. D 81, 072004 (2010)]

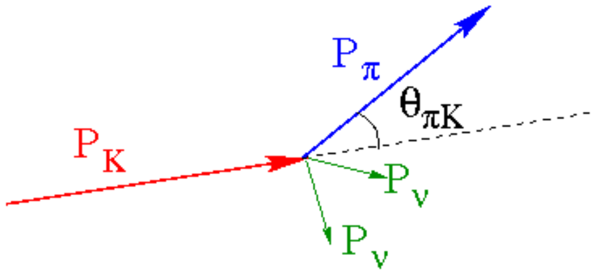
$K^+ \to \pi^+ \nu\bar{\nu}$ Beyond SM

Measurement of charged ($K^+ \to \pi^+ \nu\bar{\nu}$) and neutral ($K_L \to \pi^0 \nu\bar{\nu}$) modes can **discriminate among different NP scenarios**

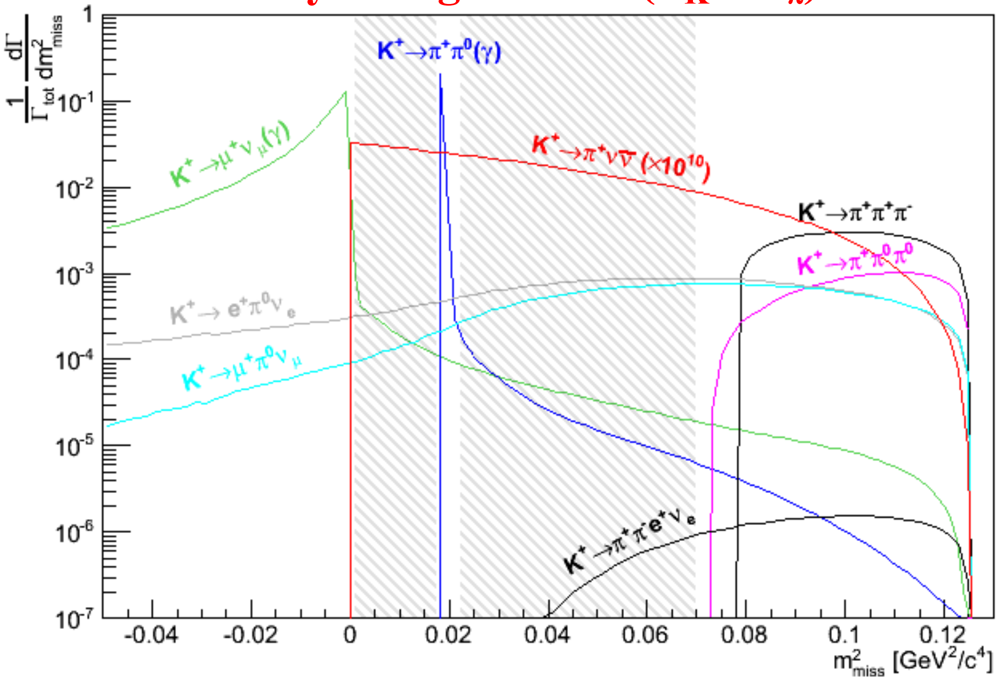
- ✓ **Models with CKM-like flavour structure**
  [Buras , Buttazzo, knegjens, JHEP11(2015) 166]
- ✓ **Custodial Randall-Sundrum**
  [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- ✓ **MSSM analyses**
  [Blazek, Matak, Int.J.Mod.Phys. A29 (2014) no.27],
  [Isidori et al. JHEP 0608 (2006) 064]
- ✓ **LFU violation models**
  [Isidori et al., Eur. Phys. J. C (2017) 77: 618]
- ✓ **Leptoquarks**
  [S. Fajfer, N. Kosnik, L. Vale Silva, arXiv: 1802.00786v1 (2018)]
- ✓ **Simplified Z, Z' models**
  [Buras, Buttazzo,Knegjens, JHEP11(2015)166]
- ✓ **Littlest Higgs with T-parity**
  [Blanke, Buras, Recksiegel, Eur.Phys.J. C76 (2016) 182]



Experimental Strategy



K decay in flight: $m^2 = (P_K - P_\pi)^2$



Performances

- Kinematic suppression $O(10^4)$
- Muon suppression $O(10^7)$
- π^0 suppression $O(10^7)$
- Timing between sub-detectors O(100 ps)

Selection

- K^+, π^+ track reconstruction
- Track matching, vertex reconstruction
- π^+ identification, μ^+ rejection
- Multi-track rejection, photon veto
- Kinematics (m^2_{miss}, p_π)

Analysis

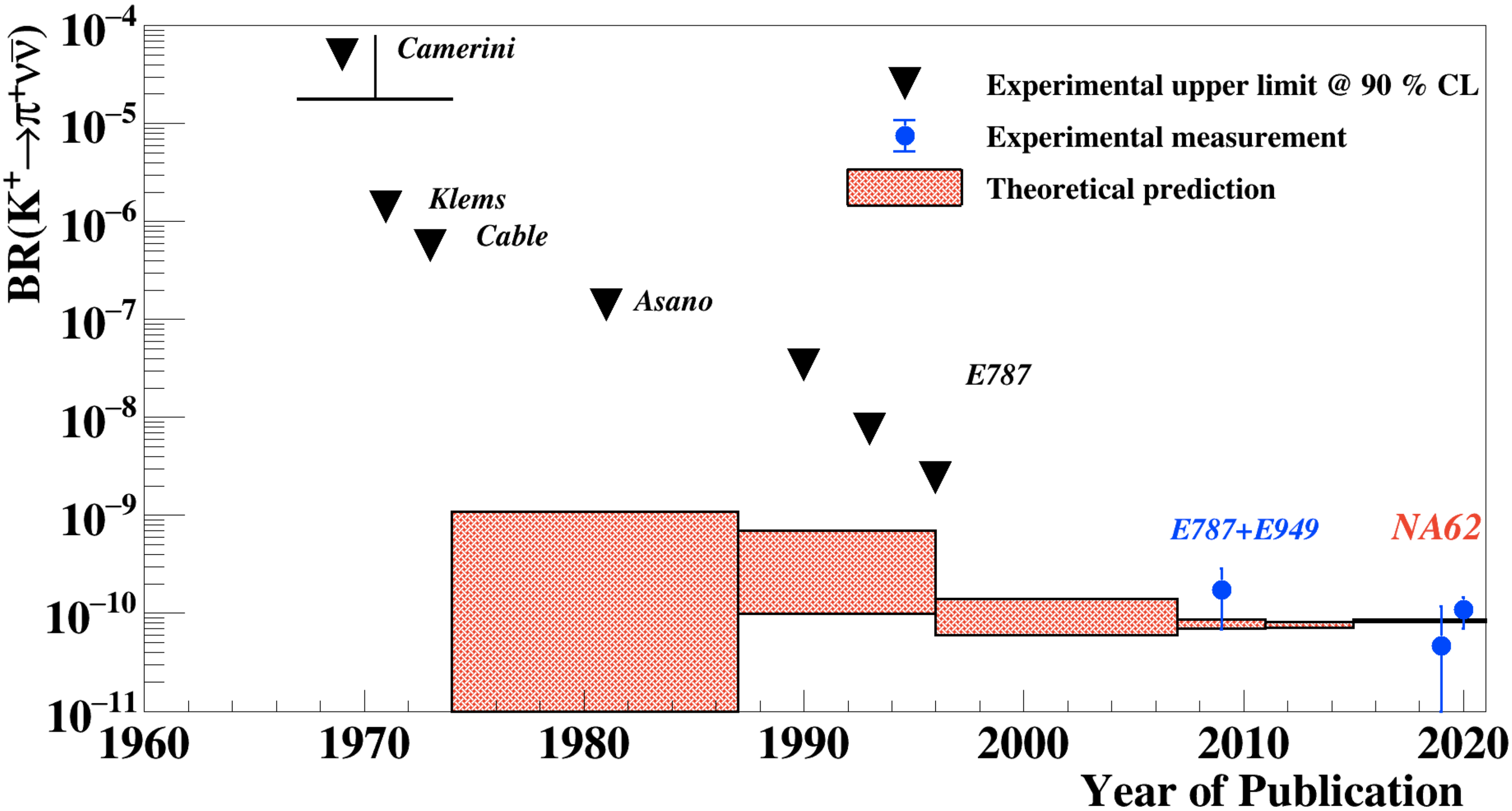
- Momentum range: $15 < p_\pi < 45$ GeV/c
- Signal regions blinded during the analysis
- Data-driven background estimate
- 7 categories depending on hardware and momentum

RUN1 summary

$$N_{\pi\nu\nu}^{exp} \approx N_{\pi\pi}\epsilon_{trigger}\epsilon_{RV}\frac{A_{\pi\nu\nu}}{A_{\pi\pi}}\frac{Br(\pi\nu\nu)}{Br(\pi\pi)} \Rightarrow \text{S.E.S.} = \frac{Br(\pi\nu\nu)}{N_{\pi\nu\nu}^{exp}}$$

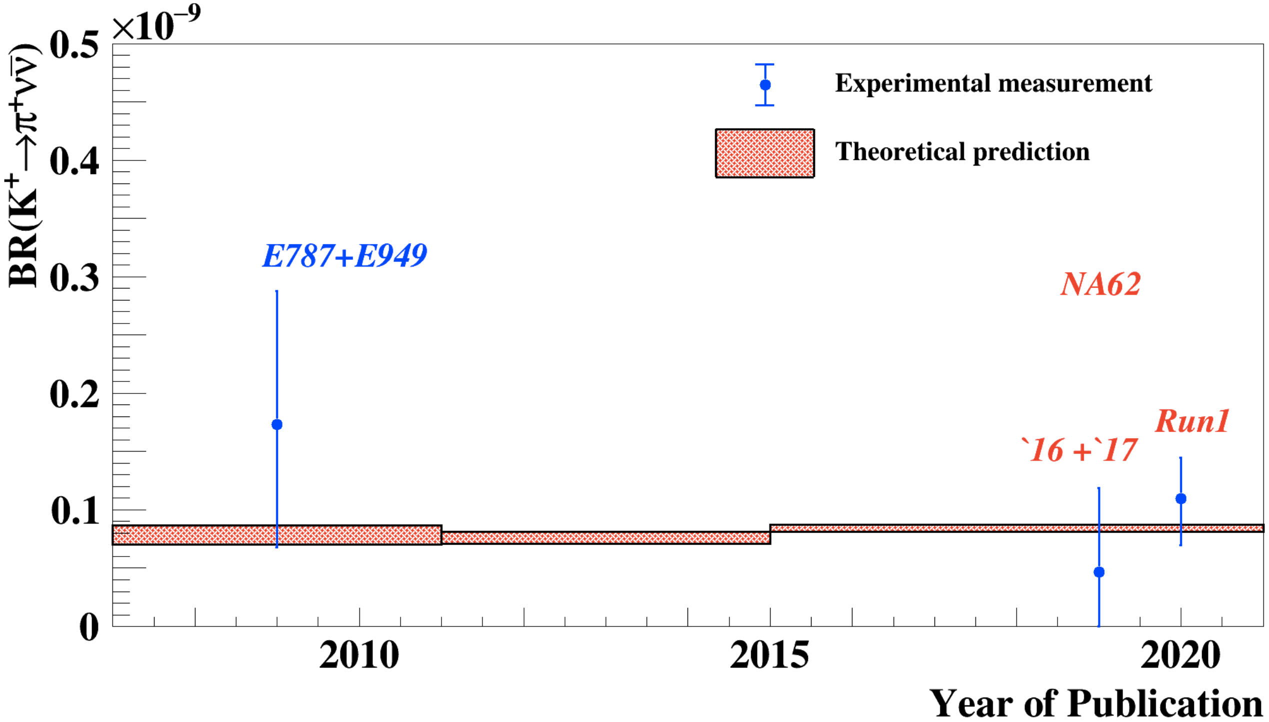
	2016 data	2017 data	2018 S1 data	2018 S2 data
$SES \times 10^{10}$	3.15 ± 0.24	0.39 ± 0.02	0.54 ± 0.04	0.14 ± 0.01
$A_{\pi\nu\nu} \times 10^{2}$	4 ± 0.4	3 ± 0.3	4 ± 0.4	6.4 ± 0.6
Expected SM signal	0.27 ± 0.04	2.16 ± 0.13	1.56 ± 0.10	6.02 ± 0.39
Expected background	0.15 ± 0.090	1.46 ± 0.30	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$
Observed events	1	2	2	15
	[PLB 791 (2019) 156-166]	[JHEP 11 (2020) 042]	[JHEP 06 (2021) 093]	

RUN1 summary



$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.5}\,_{stat} \pm 0.9\,_{syst}) \cdot 10^{-11}\ (3.4\ \sigma\ \text{significance})$$

RUN1 summary



Single Event Sensitivity: $(0.839 \pm 0.053_{syst}) \times 10^{-11}$

Expected SM signal events: $10.01 \pm 0.42_{syst} \pm 1.19_{ext}$

Expected background events: $7.03^{+1.05}_{-0.82}$

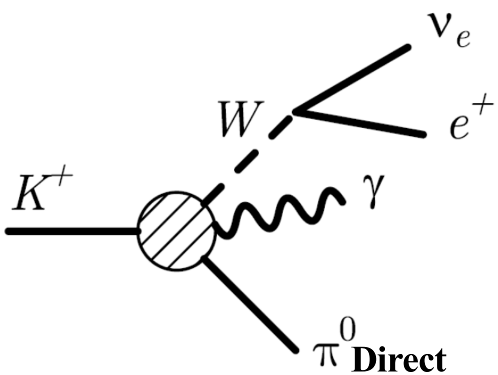
Observed events: 20

Significance: 3.4σ

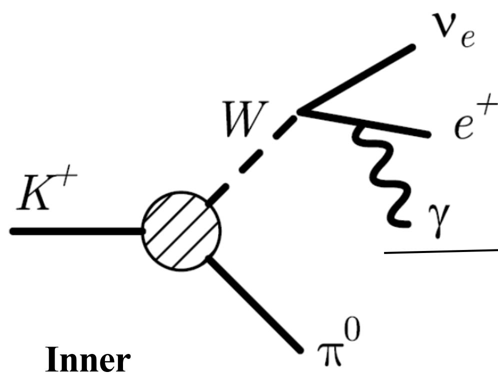
$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.5}\,{}_{stat} \pm 0.9\,{}_{syst}) \cdot 10^{-11}$ (3.4 σ significance)

$$K^+ \rightarrow \pi^0 e^+ \bar{\nu} \gamma$$

$K^+ \to \pi^0 e^+ \nu\gamma$ theoretical view



Direct Emission



Inner Brehmsstrahlung

divergent for E_γ and $\theta_{e,\gamma} \to 0$

Eur. Phys. J. C 50 (2007)

$$R_j = \frac{BR(\pi^0 e^+ \nu\gamma \mid j\text{–th phase space region})}{BR(\pi^0 e^+ \nu(\gamma))}$$

	$E_\gamma^j,\ \theta_{e\gamma}^j$	ChPT
$R_1 \times 10^2$	$E_\gamma > 10$ MeV, $\theta_{e\gamma} > 10°$	1.804 ± 0.021
$R_2 \times 10^2$	$E_\gamma > 30$ MeV, $\theta_{e\gamma} > 20°$	0.640 ± 0.008
$R_3 \times 10^2$	$E_\gamma > 10$ MeV, $0.6 < \cos\theta_{e\gamma} < 0.9$	0.559 ± 0.006

T-odd observable

$$\xi = \frac{\vec{p_\gamma} \cdot \vec{p_e} \times \vec{p_\pi}}{m_K^3}$$

Test of T-asymmetry

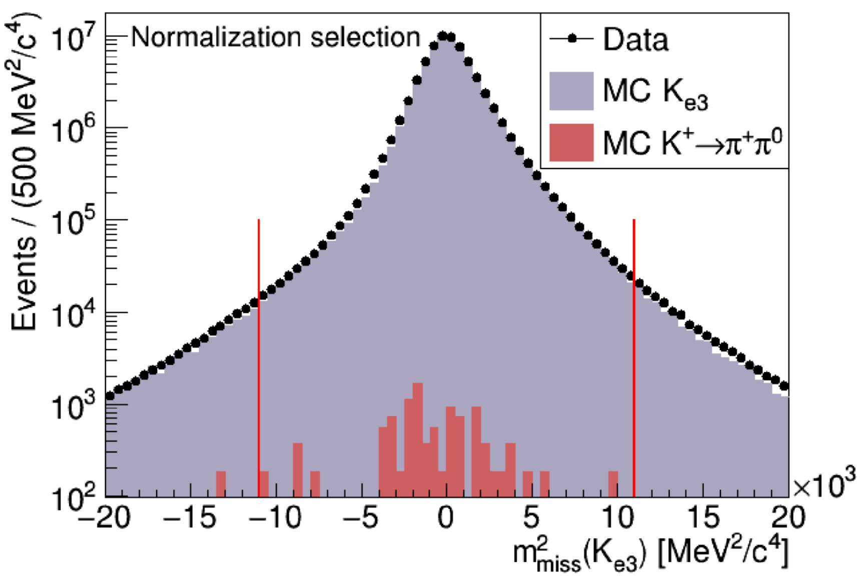
$$A_\xi = \frac{N_+ - N_-}{N_+ + N_-}$$

-10^{-4} to -10^{-5} (SM and beyond)

$K^+ \to \pi^0 e^+ \nu \gamma$ experimental selection

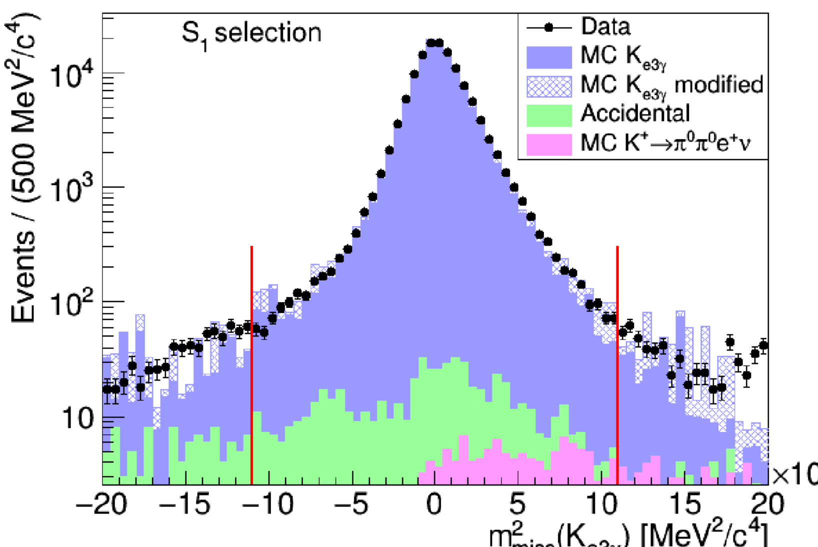
Normalization

- One downstream track with e^+ PID
- Vertex with a K^+ upstream track
- 2γ in LKr with $m(\gamma\gamma)$ compatible with π^0
- Veto on additional photons
- Cut on $m^2_{miss}(K_{e3}) = (P_K - P_{\pi 0} - P_e)^2$



Signal

- One downstream track with e^+ PID
- Vertex with a K^+ upstream track
- 2γ in LKr with $m(\gamma\gamma)$ compatible with π^0 **+ radiative γ**
- Veto on additional photons
- Cut on $m^2_{miss}(K_{e3\gamma}) = (P_K - P_{\pi 0} - P_e - P_\gamma)^2$ **and $m^2_{miss}(K_{e3})$**

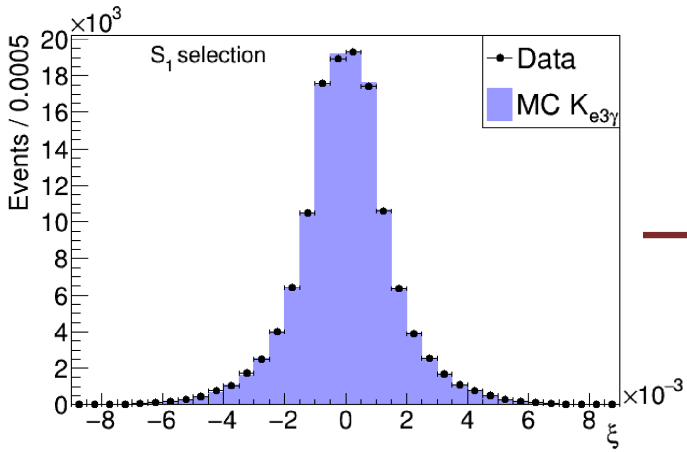


$K^+ \to \pi^0 e^+ \nu \gamma$ analysis

	Normalization	S_1	S_2	S_3
Selected candidates	6.6420×10^7	1.2966×10^5	0.5359×10^5	0.3909×10^5
Acceptance	$(3.842 \pm 0.002)\%$	$(0.444 \pm 0.001)\%$	$(0.514 \pm 0.002)\%$	$(0.432 \pm 0.002)\%$
Accidental	—	$(4.9 \pm 0.2 \pm 1.3) \times 10^2$	$(2.3 \pm 0.2 \pm 0.3) \times 10^2$	$(1.1 \pm 0.1 \pm 0.5) \times 10^2$
$K^+ \to \pi^0 \pi^0 e^+ \nu$	—	$(1.1 \pm 1.1) \times 10^2$	$(1.1 \pm 1.1) \times 10^2$	$(0.1 \pm 0.1) \times 10^2$
$K^+ \to \pi^+ \pi^0 \pi^0$	—	< 20	< 20	< 20
$K^+ \to \pi^+ \pi^0$	$(1.0 \pm 1.0) \times 10^4$	—	—	—
Total background	$(1.0 \pm 1.0) \times 10^4$	$(6.0 \pm 1.8) \times 10^2$	$(3.4 \pm 1.2) \times 10^2$	$(1.2 \pm 0.6) \times 10^2$
Fractional background	1.6×10^{-4}	0.46×10^{-2}	0.64×10^{-2}	0.29×10^{-2}

$$R_j = \frac{\mathcal{B}(K_{e3\gamma^j})}{\mathcal{B}(K_{e3})} = \frac{N^{\text{obs}}_{Ke3\gamma^j} - N^{\text{bkg}}_{Ke3\gamma^j}}{N^{\text{obs}}_{Ke3} - N^{\text{bkg}}_{Ke3}} \cdot \frac{A_{Ke3}}{A_{Ke3\gamma^j}} \cdot \frac{\epsilon^{\text{trig}}_{Ke3}}{\epsilon^{\text{trig}}_{Ke3\gamma^j}}$$

- Bkg from accidental activity in LKr: data-driven estimation with timing sidebands
- Bkg from e^+ mis-ID / undetected γ: estimated from MC
- Systematics: LKr response correction, bkg estimation, veto of additional radiative γ, theory, MC sample size



$$A_\xi^{\text{NA62}} = A_\xi^{\text{Data}} - A_\xi^{\text{MC}}$$

- A_ξ^{MC}: contribution due to detector + selection
- Systematics: MC sample size

$K^+ \to \pi^0 e^+ \nu \gamma$ results

	Eur. Phys. J. C 50 (2007) 557 Eur. Phys. J. C 48 (2006) 427	Phys. Atom. Nucl. 70 (2007) 702	Eur. Phys. J. C 81.2 (2021) 161 JETP Lett. 116 (2022) 608	arXiv:2304.12271, submitted to JHEP
	ChPT O(p^6)	**ISTRA+**	**OKA**	**NA62**
$R_1 \times 10^2$	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$	$1.715 \pm 0.005 \pm 0.010$
$R_2 \times 10^2$	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$	$0.609 \pm 0.003 \pm 0.006$
$R_3 \times 10^2$	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$	$0.533 \pm 0.003 \pm 0.004$
$A_\xi (S_1) \times 10^3$			$-0.1 \pm 3.9 \pm 1.7$	$-1.2 \pm 2.8 \pm 1.9$
$A_\xi (S_2) \times 10^3$	-0.059		$7.0 \pm 8.1 \pm 1.5$	$-3.4 \pm 4.3 \pm 3.0$
$A_\xi (S_3) \times 10^3$		0.015 ± 0.021	$-4.4 \pm 7.9 \pm 1.9$	$-9.1 \pm 5.1 \pm 3.5$

Decay rates

- Factor > 2 more precise wrt previous measurements
- Relative uncertainty < 1%
- 5% smaller than ChPT prediction O(3σ)

T-asymmetry

- Compatible with no asymmetry
- Improved precision
- Uncertainty still O(10^2) larger wrt predictions

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

$K^+ \to \pi^+ \mu^+ \mu^-$ theoretical view

- FCNC, long distance dominated, mediated by $K^+ \to \pi^+ \gamma^*$ **JHEP 02 (2019) 049**
- Test of LFU by comparing $K^+ \to \pi^+ e^+ e^-$
- One-photon-inclusive differential decay width:

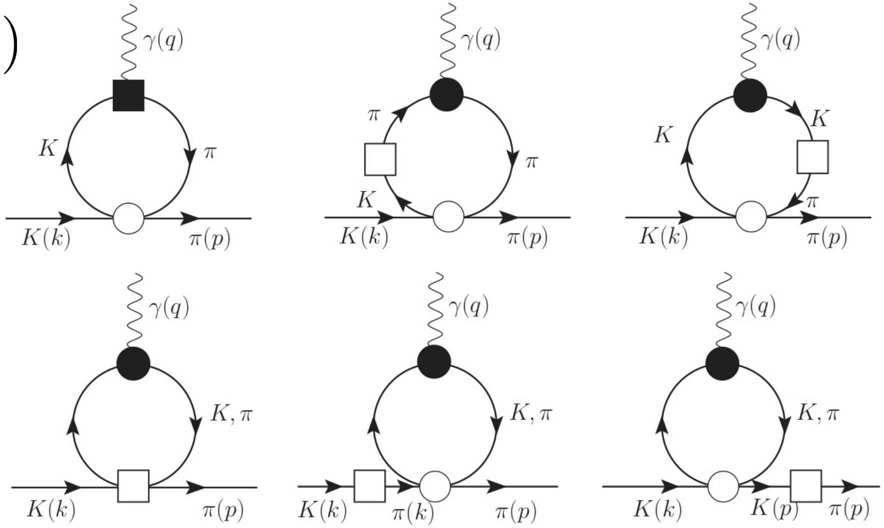
$$\frac{d\Gamma(z)}{dz} = g(z) \cdot |W(z)|^2 + \frac{d\Gamma_{\text{4-body}}(z)}{dz}$$

where $$z = m(\mu^+\mu^-)^2 / m_K^2$$

- Form factor parametrized by ChPT at $O(p^6)$ **JHEP 08 (1998) 004**

$$W(z) = G_F m_K^2 (a_+ + b_+ z) + W^{\pi\pi}(z)$$

- Measurements:
  - a_+, b_+
  - Model-independent BR
  - Forward-backward asymmetry



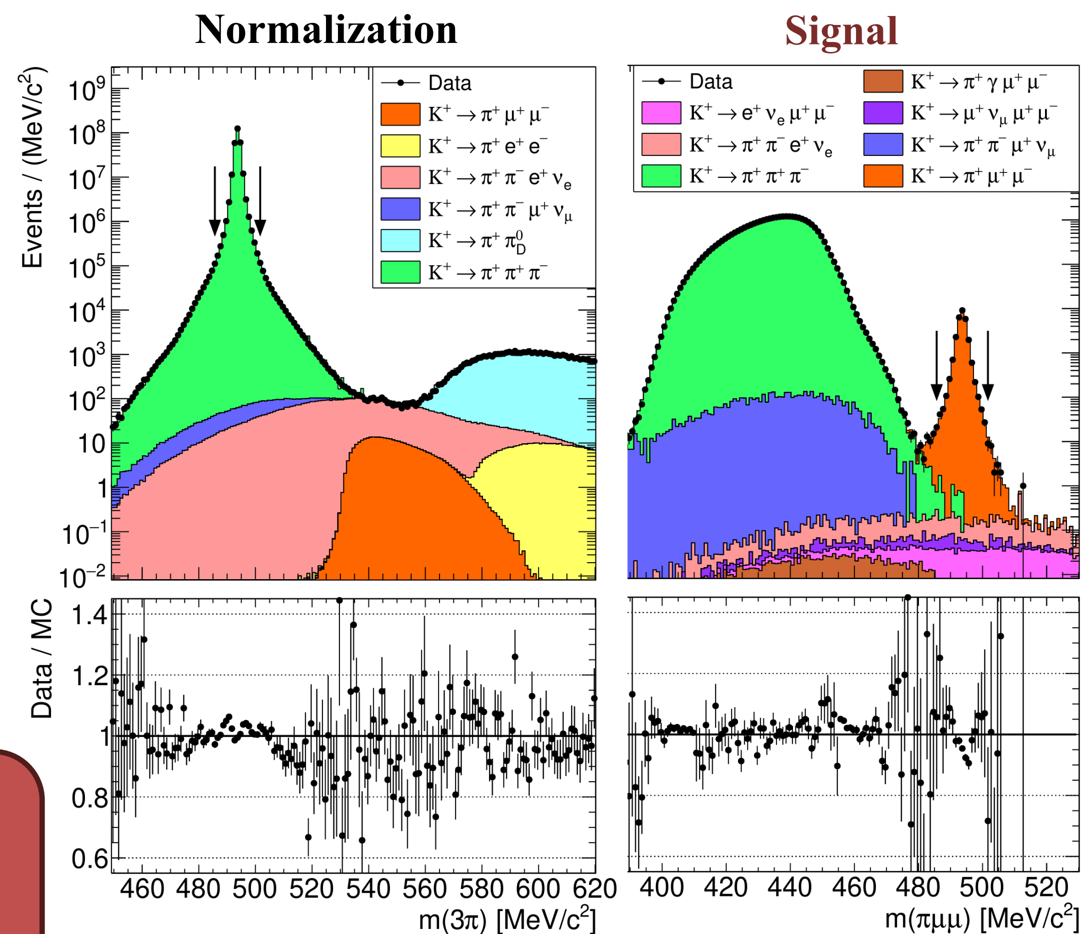
$K^+ \to \pi^+\mu^+\mu^-$ selection

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

- Abundant (BR ~ 5.6%)
- Kinematically similar
- Cancellation of systematics

Selection

- 3-track vertex topology
- Event in time with KTAG
- π^+ calorimetric PID
- μ calorimetric PID
- $m(\pi\mu\mu)$, $m(3\pi)$ requirements



Effective kaon decays:
$(3.48 \pm 0.09_{syst} \pm 0.02_{ext}) \times 10^{12}$
Selected events: 27679
Expected background events: 7.8 ± 5.6

$K^+ \to \pi^+ \mu^+ \mu^-$ Form Factor and BR

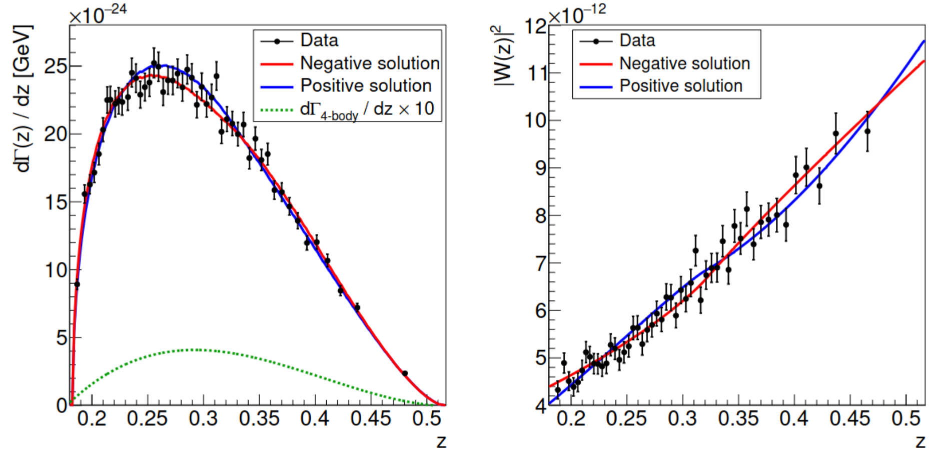
50 equipopulated bins of z:

$$\left(\frac{d\Gamma(z)}{dz}\right)_i = \frac{N_{\pi\mu\mu,i}}{A_{\pi\mu\mu,i}} \cdot \frac{1}{\Delta z_i} \cdot \frac{1}{N_K} \cdot \frac{\hbar}{\tau_K}$$

$\chi^2(a_+, b_+)$ fit

- Theoretically preferred negative solution
- Additional χ^2 minimum: positive solution

Model-independent BR from integration of $d\Gamma/dz$



$a_+ = -0.575 \pm 0.013, \quad b_+ = -0.722 \pm 0.043$

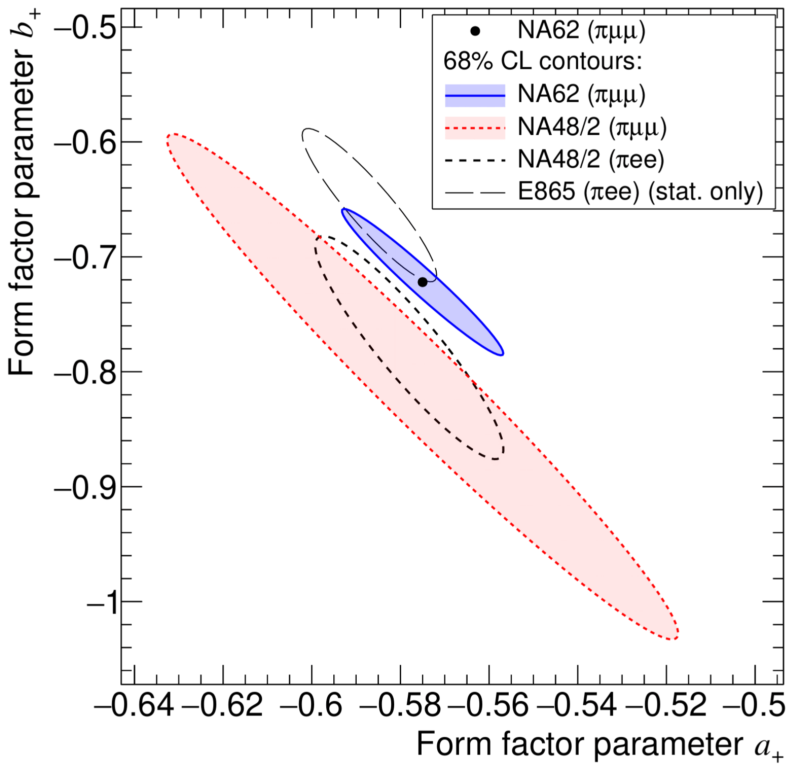
$\chi^2 / \mathrm{ndf} = 45.1 / 48, \qquad \rho(a_+, b_+) = -0.972$

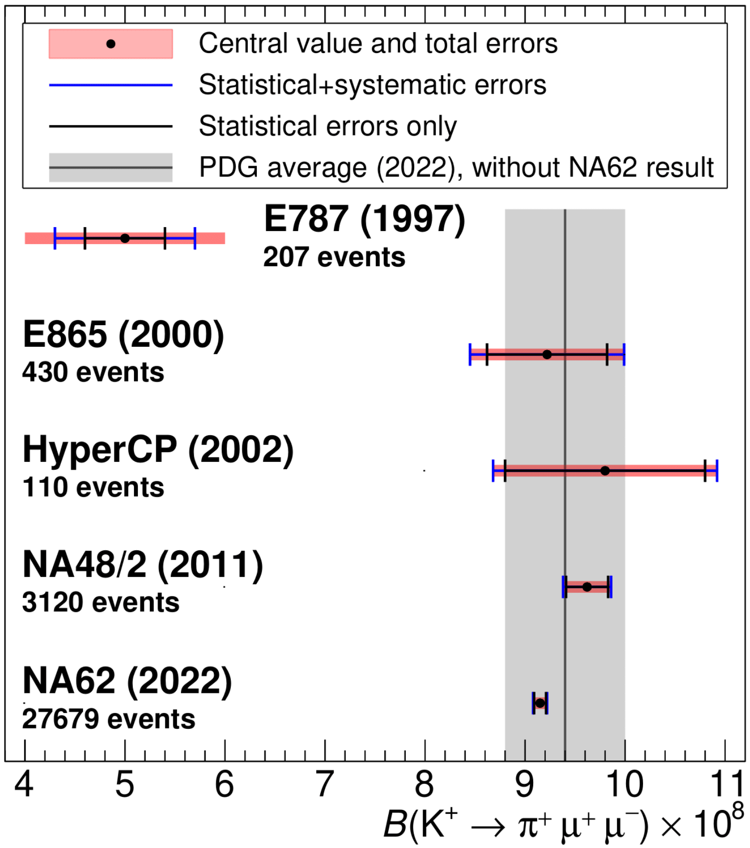
$\mathrm{BR}(K^+ \to \pi^+ \mu^+ \mu^-) = (9.15 \pm 0.08) \times 10^{-8}$

JHEP 11 (2022) 011

	δa_+	δb_+	$\delta \mathcal{B}_{\pi\mu\mu} \times 10^8$
Statistical uncertainty	0.012	0.040	0.06
Trigger efficiency	0.002	0.008	0.02
Reconstruction and particle identification	0.002	0.007	0.02
Size of the simulated $K_{\pi\mu\mu}$ sample	0.002	0.007	0.01
Beam and accidental activity simulation	0.001	0.002	0.01
Background	0.001	0.001	—
Total systematic uncertainty	0.003	0.013	0.03
$K_{3\pi}$ branching fraction	0.001	0.003	0.04
$K_{\pi\mu\mu}$ radiative corrections	0.003	0.009	0.01
Parameters α_+ and β_+	0.001	0.006	—
Total external uncertainty	0.003	0.011	0.04

$K^+ \to \pi^+\mu^+\mu^-$ Comparison with previous results

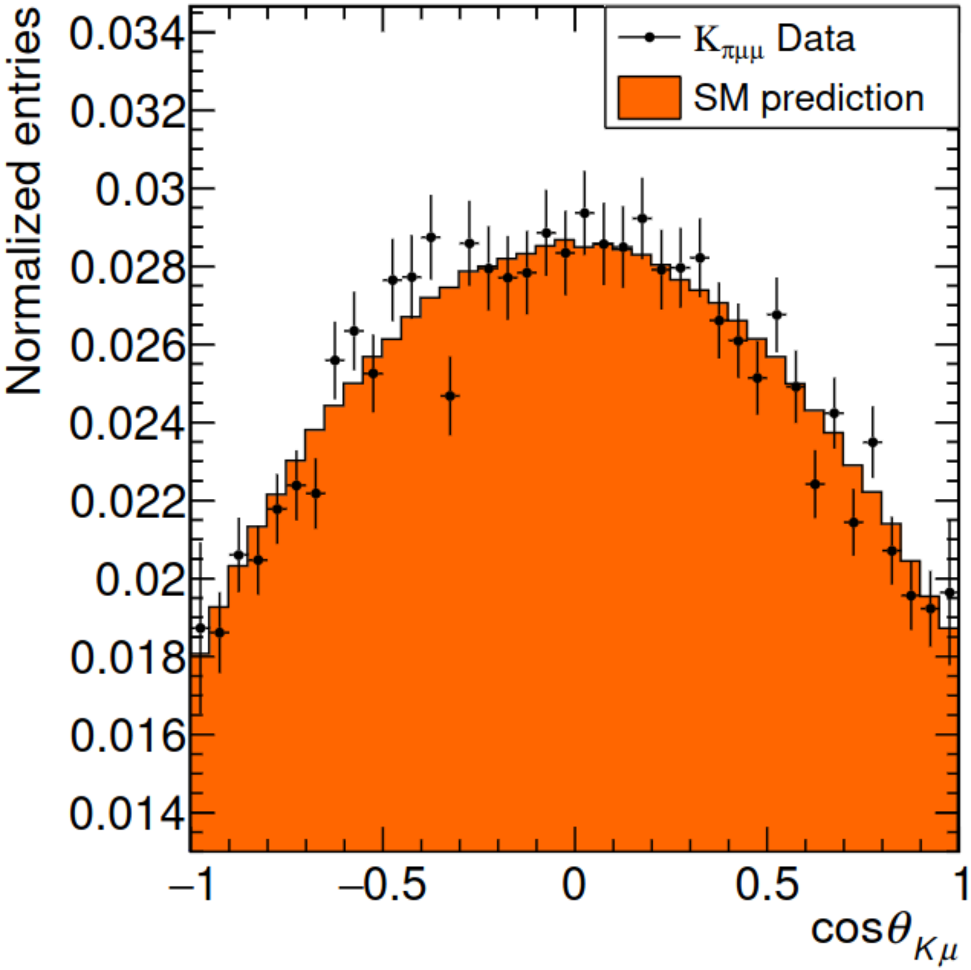




JHEP 11 (2022) 011

- Much improved precision
- Sample size ~9x larger than NA48/2

$K^+ \to \pi^+\mu^+\mu^-$ Forward-Backward asymmetry



angle between K^+ and μ^- in $\mu\mu$ rest frame

$$A_{FB} = \frac{\mathcal{N}(\cos\theta_{K\mu} > 0) - \mathcal{N}(\cos\theta_{K\mu} < 0)}{\mathcal{N}(\cos\theta_{K\mu} > 0) + \mathcal{N}(\cos\theta_{K\mu} < 0)}$$

$A_{FB} = (0.0 \pm 0.7_{stat} \pm 0.2_{syst} \pm 0.2_{ext}) \times 10^{-2}$ @ 68% CL

$|A_{FB}| < 0.9 \times 10^{-2}$ @ 90% CL

JHEP 11 (2022) 011, JHEP 06 (2023) 040

$$K^{+} \rightarrow \pi^{+}\gamma\gamma^{-}$$

$K^+ \to \pi^+\gamma\gamma$ theoretical view

- Long distance dominated: crucial ChPT test
- Kinematic variables

$$z = \frac{(q_1+q_2)^2}{m_K^2} = \left(\frac{m_{\gamma\gamma}}{m_K}\right)^2, \quad y = \frac{p(q_1-q_2)}{m_K^2}$$

p: K^+ 4-momentum
$q_{1,2}$: γ 4-momenta
m_K: K^+ mass
$m_{\gamma\gamma}$: di-photon invariant mass

- Decay width parametrized by a real parameter $\hat{c}$

$$\frac{\partial\Gamma}{\partial y \partial z}(\hat{c}, y, z) = \frac{m_K}{2^9\pi^3}\left[z^2\left(\left|A(\hat{c}, z, y^2) + B(z)\right|^2 + |C(z)|^2\right) + \left(y^2 - \frac{1}{4}\lambda(1, r_\pi^2, z)\right)^2 |B(z)|^2\right]$$

nonzero at $O(p^6)$

- Goals:
  - Measure $\hat{c}_6$
  - Extrapolate model-dependent BR

Phys. Lett. B 386 (1996) 403

$K^+ \to \pi^+\gamma\gamma$ analysis

Selection

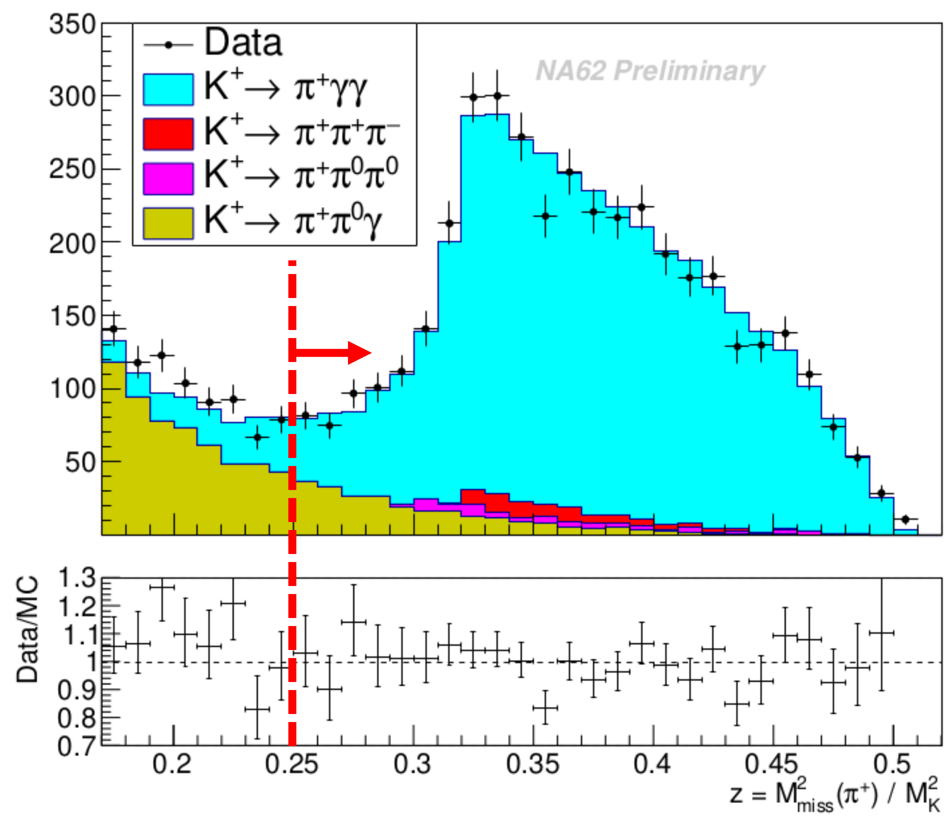
- K^+, π^+ matching tracks + 2 clusters in LKr
- $z = (P_K - P_\pi)^2 / M_K^2$
- 4039 events observed
- 393 ± 20 background events expected

Background

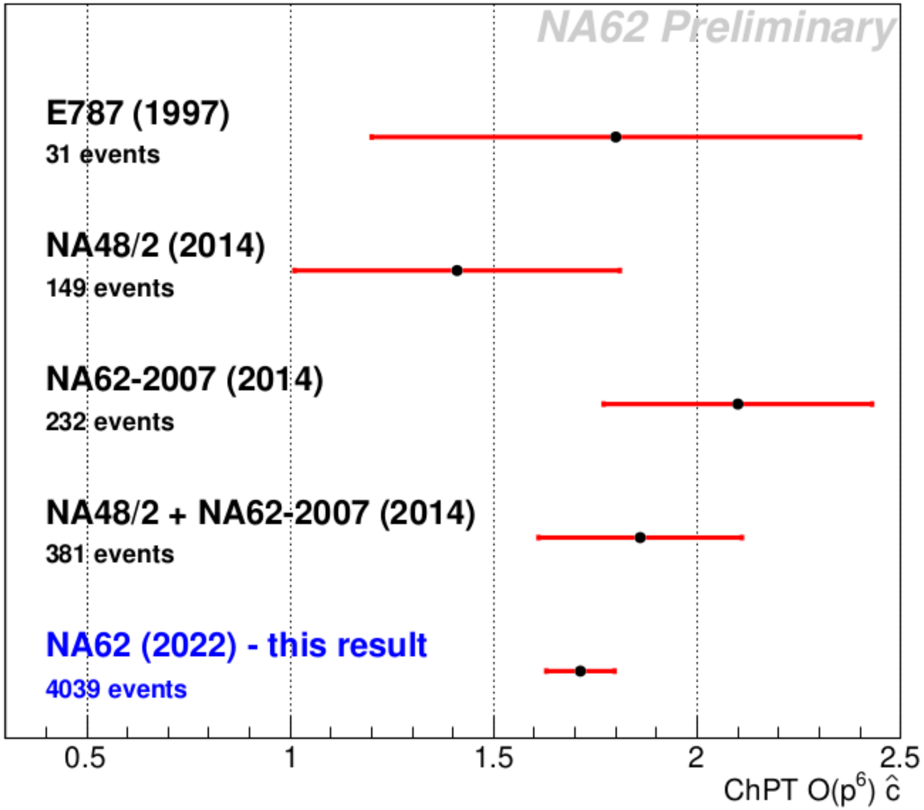
- Cluster merging: $K^+ \to \pi^+\pi^0\gamma$, $K^+ \to \pi^+\pi^0\pi^0$
- Missing tracks: $K^+ \to \pi^+\pi^+\pi^-$
- Estimated with MC, validated with control regions

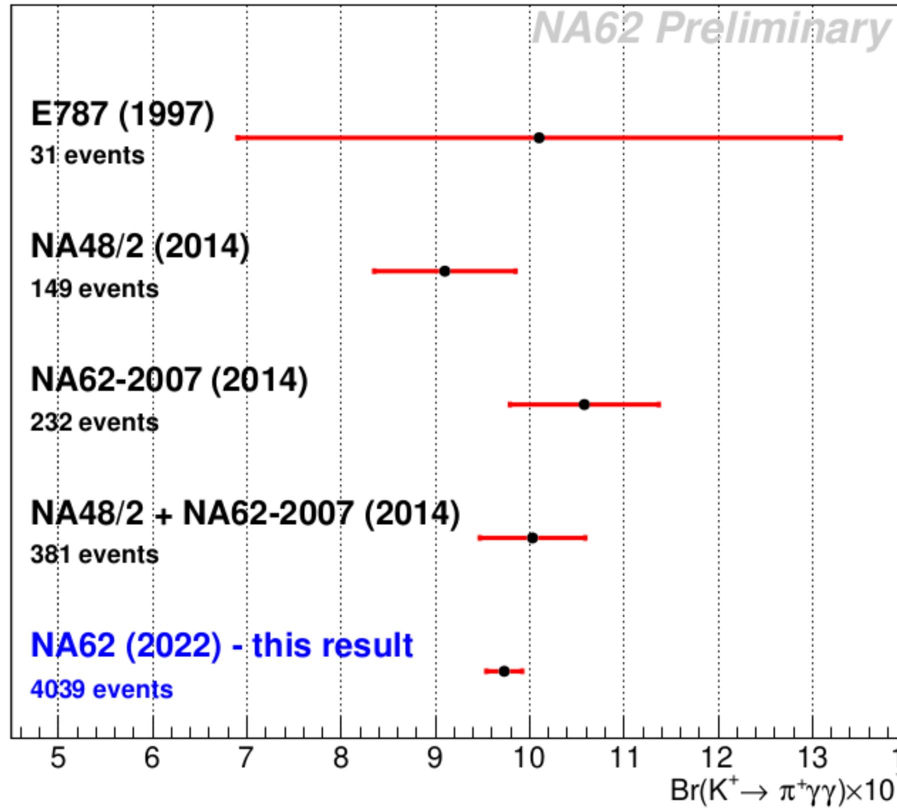
Fit procedure

- MC reweighted for different values of $\hat{c}$
- Scan of $\hat{c}$ to find maximum likelihood
- External parameters fixed:
  Rev. Mod. Phys. 84 399 (2012),
  Science 368 (2020) 6490,
  Nucl.Phys. B648 (2003) 317
  (to be updated to use arXiv:2209.02143)



$K^+ \to \pi^+\gamma\gamma$ results





$\hat{c}_6 = 1.713 \pm 0.075_{stat} \pm 0.037_{syst}$

$BR(K^+ \to \pi^+\gamma\gamma) = (9.73 \pm 0.17_{stat} \pm 0.08_{syst}) \times 10^{-7}$

Conclusions

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

- ✓ Run1 measurement compatible with the SM within one standard deviation
- ✓ **Br($K^+ \to \pi^+ \nu\bar{\nu}$) = $(10.6^{+4.0}_{-3.5}\,_{stat} \pm 0.9\,_{syst}) \cdot 10^{-11}$ (3.4 σ significance)**
- ✓ The most precise measurement of the BR obtained so far

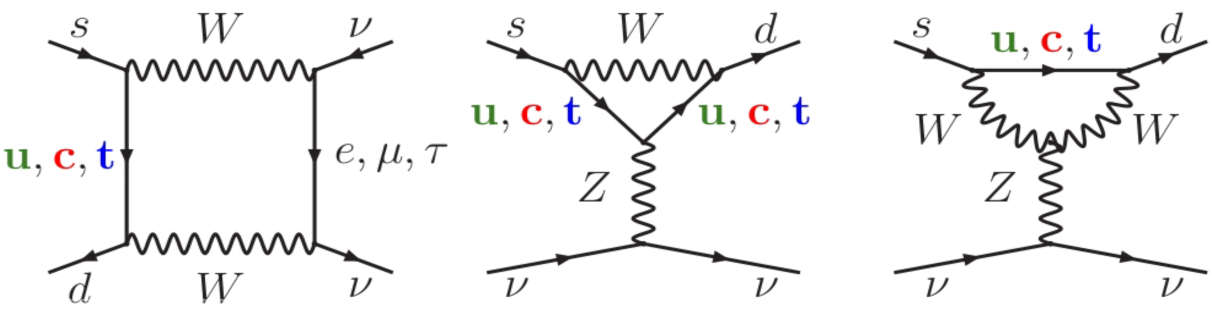
Precision Measurements

- ✓ $K^+ \to \pi^0 e^+ \nu\gamma$ **arXiv:2304.12271, submitted to JHEP**
- ✓ $K^+ \to \pi^+ \mu^+ \mu^-$ **JHEP 11 (2022) 011**
- ✓ $K^+ \to \pi^+ \gamma\gamma$ **preliminary, final results in progress**

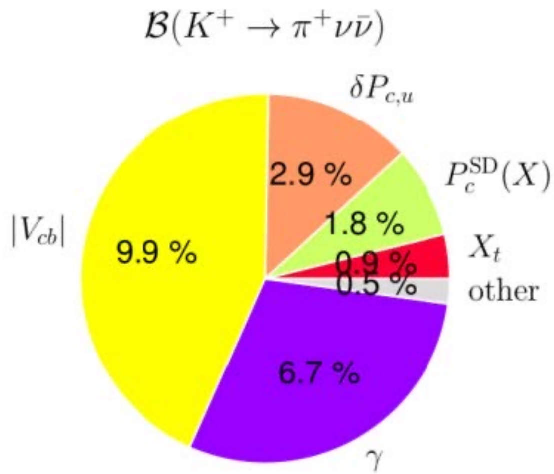
NA62 will take data until LS3

SPARE

$K^+ \to \pi^+ \nu\bar{\nu}$ decay in the SM



Theoretical error budget
Buras. et. al., JHEP11(2015)033



- FCNC loop processes: s→d coupling and highest CKM suppression
- Theoretically clean: Short distance contribution
- Hadronic matrix element measured with K_{l3} decays
- SM predictions: [Buras. et. al., JHEP11(2015)033]

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

- Experimental result collecting 7 events: [Phys. Rev. D 79, 092004 (2009)]

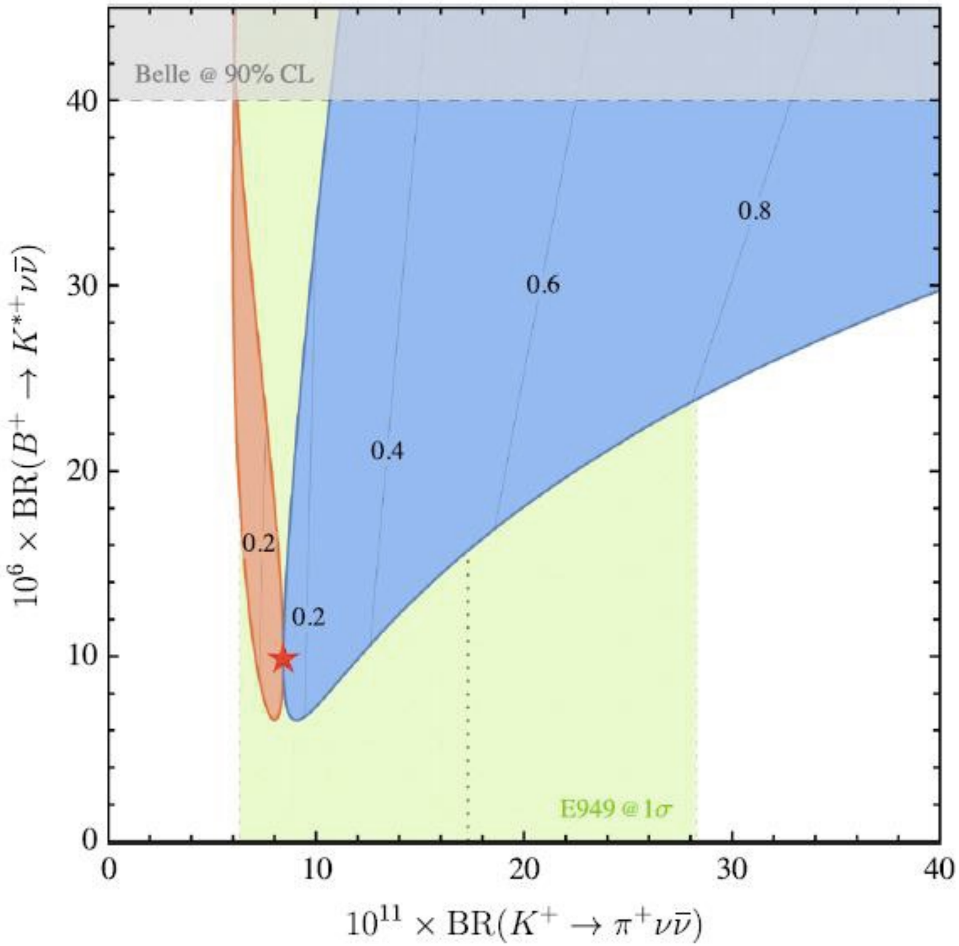
$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$$

(BNL “kaon decays at rest)

$K^+ \to \pi^+ \nu\bar{\nu}$ and the LFU violation

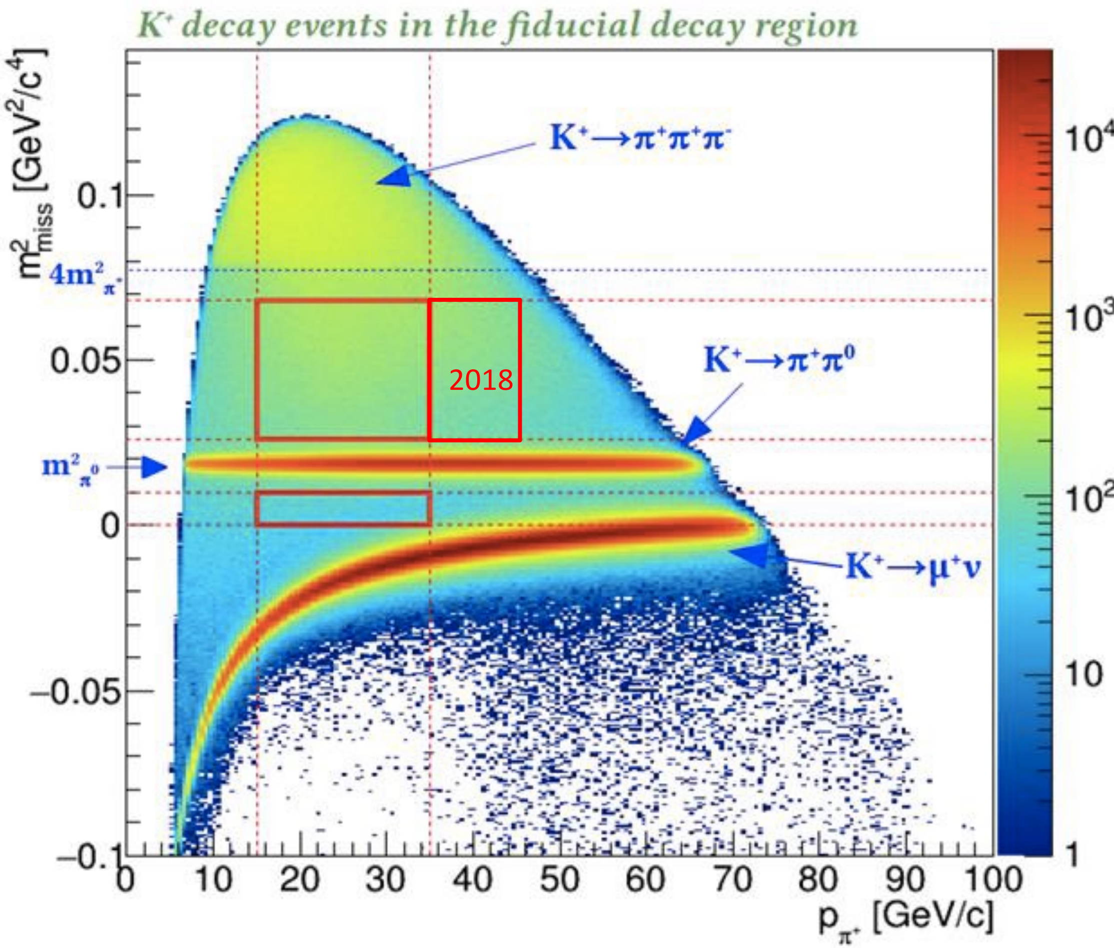
Measurement of **$K^+ \to \pi^+\nu\bar{\nu}$** together with **$B^+ \to K^{*+}\nu\bar{\nu}$** can probe the **Lepton-Flavour Universality**

- ✓ An interactions responsible for LFU violations can couple mainly to the third generation of left-handed fermions;
- ✓ **$K^+ \to \pi^+\nu\bar{\nu}$** is the only kaon decays with third-generation leptons (the τ neutrinos) in the final state;
- ✓ A deviations from the Standard Model predictions in **$K^+ \to \pi^+\nu\bar{\nu}$** branching ratios should be closely correlated to similar effects in **$B^+ \to K^{*+}\nu\bar{\nu}$** .



Signal Selection

- Two signal regions kept blinded
- In order to evaluate the background from K decays, the tails of the distribution are extrapolated into the signal regions.
- The control regions are kept blinded too, to validate the procedure.



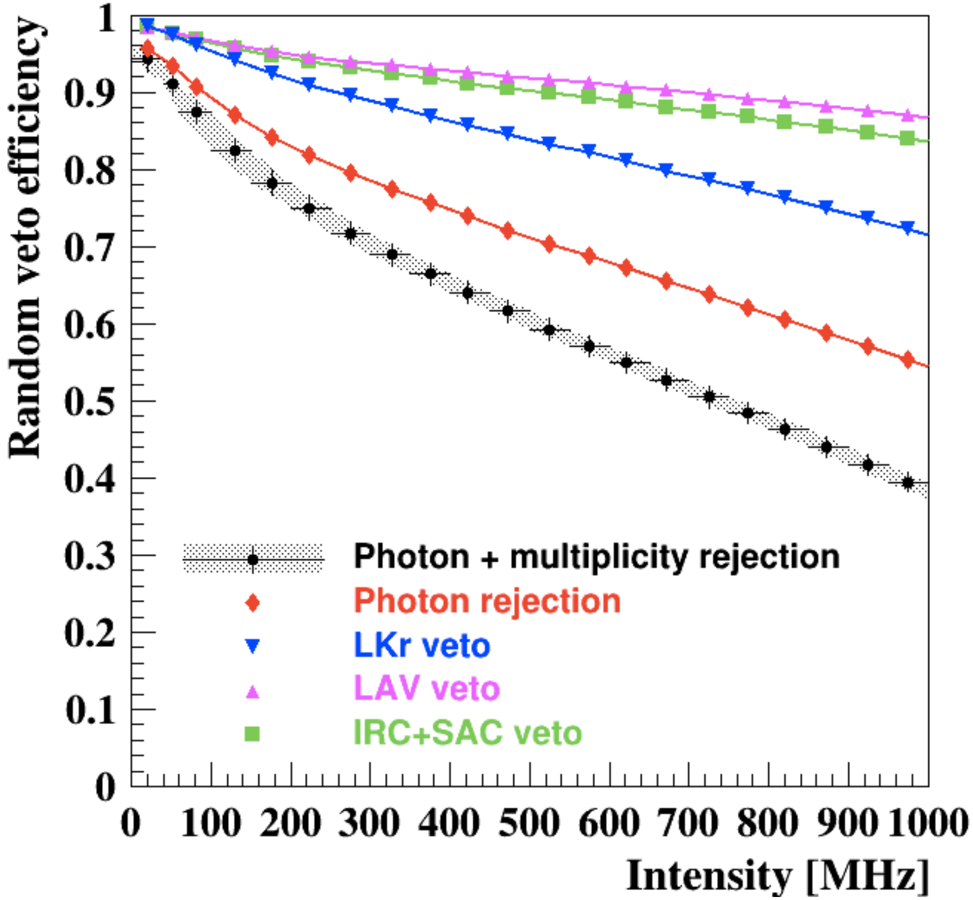
Selection criteria

- single track decay topology
- π^+ identification
- photon rejection
- multi-track rejection

Decay mode	BR	Main rejection tools
$K^+\to\mu^+\nu(\gamma)$	63%	μ–ID + kinematics
$K^+\to\pi^+\pi^0(\gamma)$	21%	γ-veto + kinematics
$K^+\to\pi^+\pi^+\pi^-$	6%	multi + kinematics
$K^+\to\pi^+\pi^0\pi^0$	2%	γ-veto + kinematics
$K^+\to\pi^0e^+\nu_e$	5%	e–ID + γ-veto
$K^+\to\pi^0\mu^+\nu_\mu$	3%	μ–ID + γ-veto

Single Event Sensitivity (SES)

$$N^{exp}_{\pi\nu\nu} \approx N_{\pi\pi}\epsilon_{trigger}\epsilon_{RV}\frac{A_{\pi\nu\nu}}{A_{\pi\pi}}\frac{Br(\pi\nu\nu)}{Br(\pi\pi)} \Rightarrow \text{S.E.S.} = \frac{Br(\pi\nu\nu)}{N^{exp}_{\pi\nu\nu}}$$



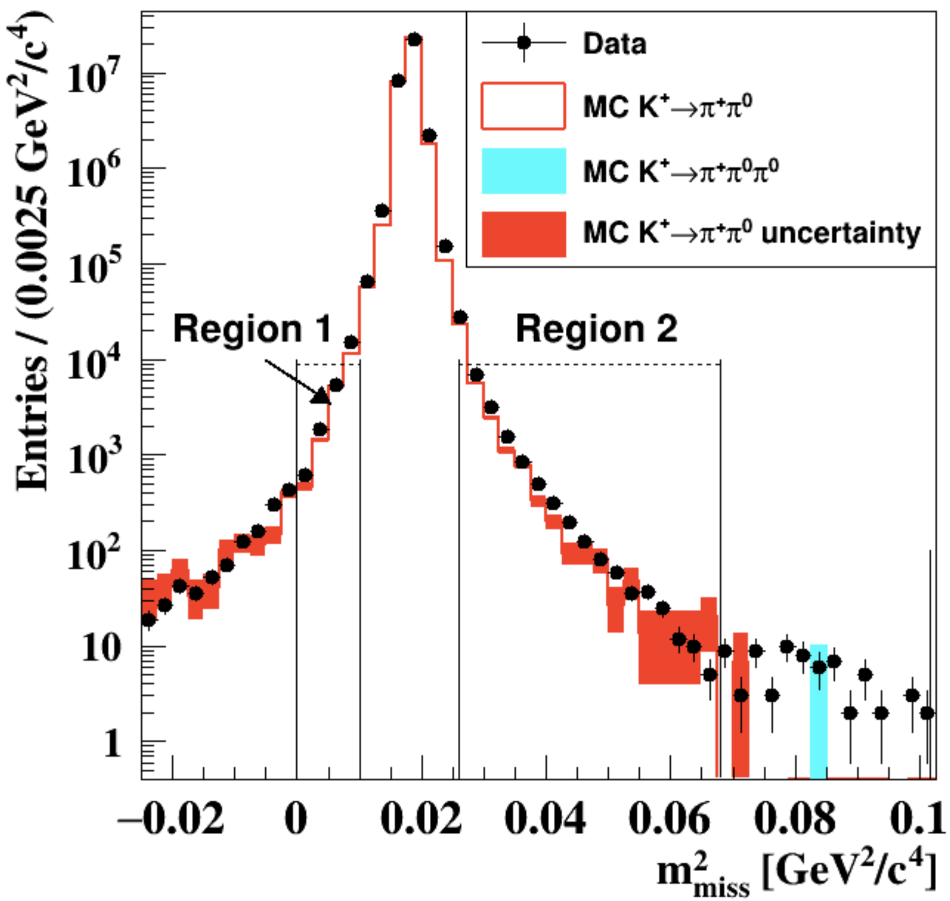
	Subset S1	Subset S2
$N_{\pi\pi} \times 10^{-7}$	3.14	11.6
$A_{\pi\pi} \times 10^{2}$	7.62 ± 0.77	11.77 ± 1.18
$A_{\pi\nu\bar{\nu}} \times 10^{2}$	3.95 ± 0.40	6.37 ± 0.64
$\epsilon^{\mathrm{PNN}}_{\mathrm{trig}}$	0.89 ± 0.05	0.89 ± 0.05
ϵ_{RV}	0.66 ± 0.01	0.66 ± 0.01
$SES \times 10^{10}$	0.54 ± 0.04	0.14 ± 0.01
$N^{\mathrm{exp}}_{\pi\nu\bar{\nu}}$	$1.56 \pm 0.10 \pm 0.19_{\mathrm{ext}}$	$6.02 \pm 0.39 \pm 0.72_{\mathrm{ext}}$

- ✓ $K^+ \rightarrow \pi^+\pi^0$ normalization signal
- ✓ Cancellation of systematic effects
- ✓ Random Veto: efficiency loss due to beam activity

$SES_{Run1} = (0.839 \pm 0.054) \times 10^{-11}$

Background from Kaon Decay

Control $\pi^+ \pi^0$ data to study m^2_{miss} distribution



Expected $K^+ \to \pi^+\pi^0$ events in signal region

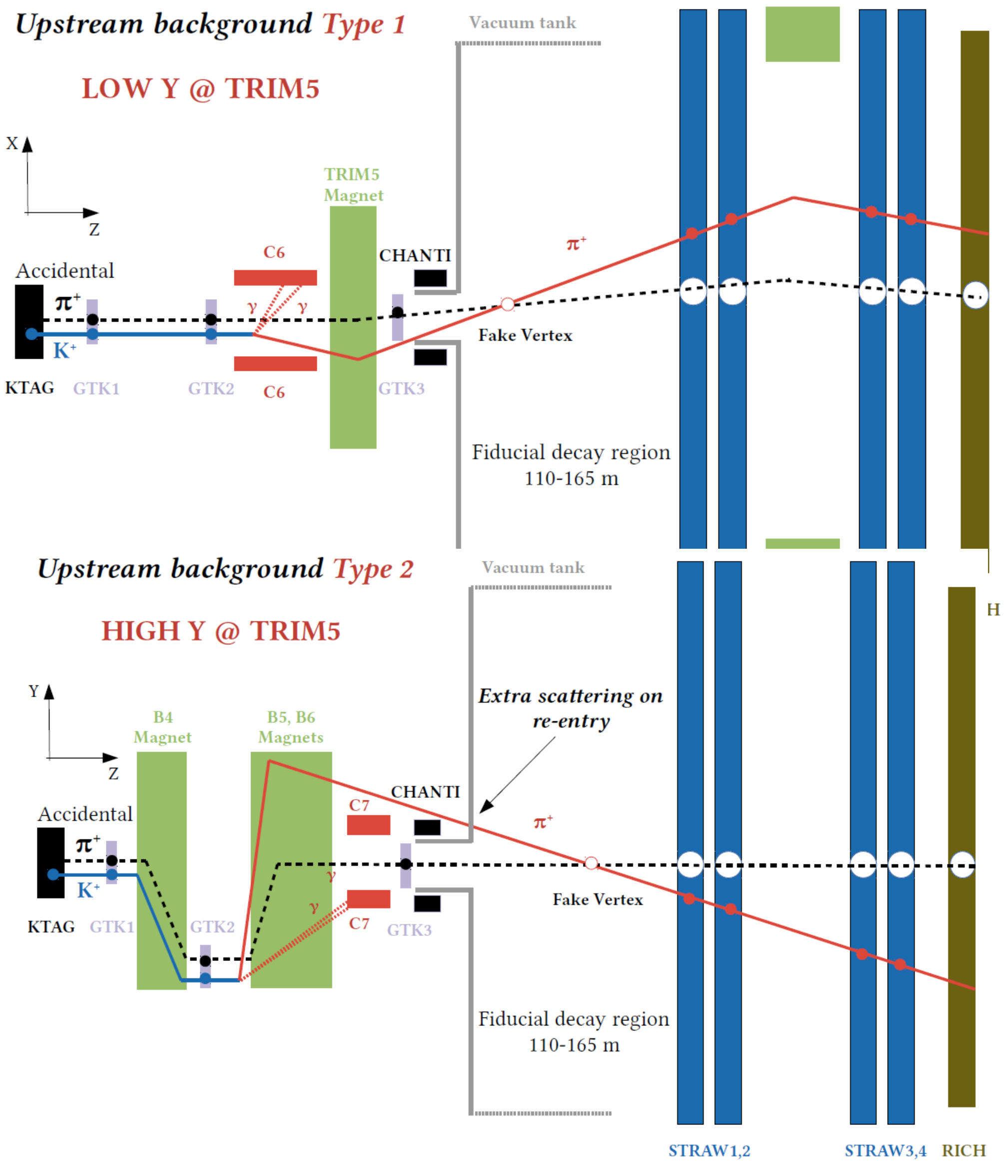
$$N^{exp}_{\pi\pi}(SR) = N_{\pi\pi}\, f_{kin}(SR)$$

Data in $\pi^+\pi^0$ region after $\pi^+\nu\bar{\nu}$ selection

Fraction of $\pi^+\pi^0$ in signal region, measured on control data

- $K^+ \to \mu^+ \nu_\mu$ and $K^+ \to \pi^+ \pi^+ \pi^-$ backgrounds: similar procedure
- $K^+ \to \pi^+\pi^- e^+ \nu_e$ evaluated with MC simulations

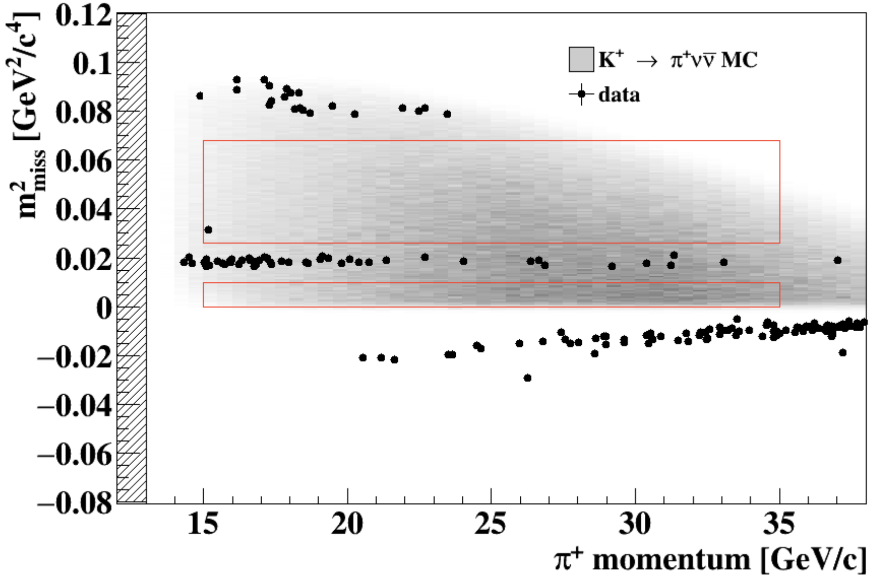
Upstream background

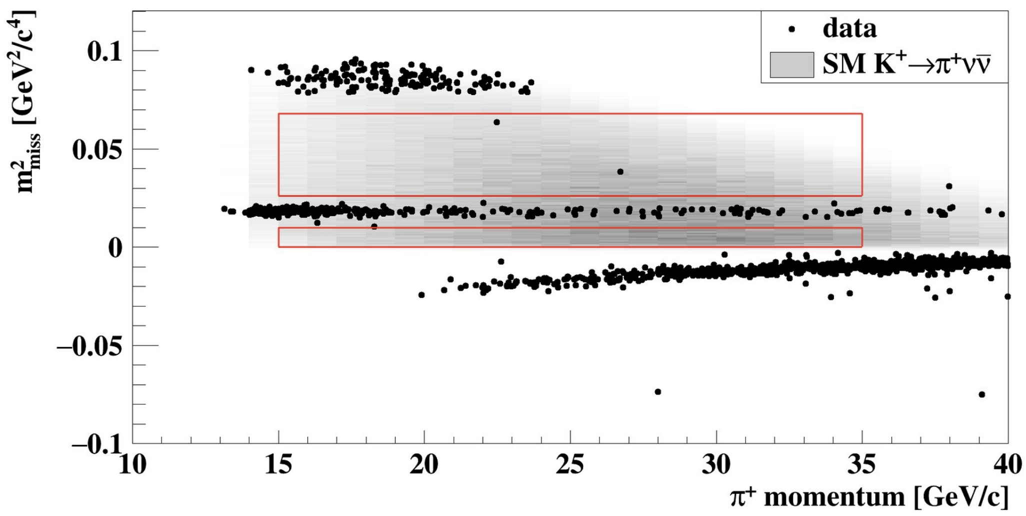


- Pions produced upstream the fiducial volume
  - ✓ Early K^+decay or interaction with the beam spectrometer material
  - ✓ only a π^+ enters the fiducial decay region
  - ✓ there is an in-time pileup beam particle (in GTK)
  - ✓ the upstream π^+ is scattered in the first STRAW chamber.

- Kaon-pion association and geometrical variables
- Data driven background estimation

2016 – 2017 data tacking results





2016

1 events observed

SES = 3.15 x 10^{-10}

Br($K^+ \rightarrow \pi^+\nu\bar{\nu}$) < 14x$10^{-10}$@ 90% CL

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

2017

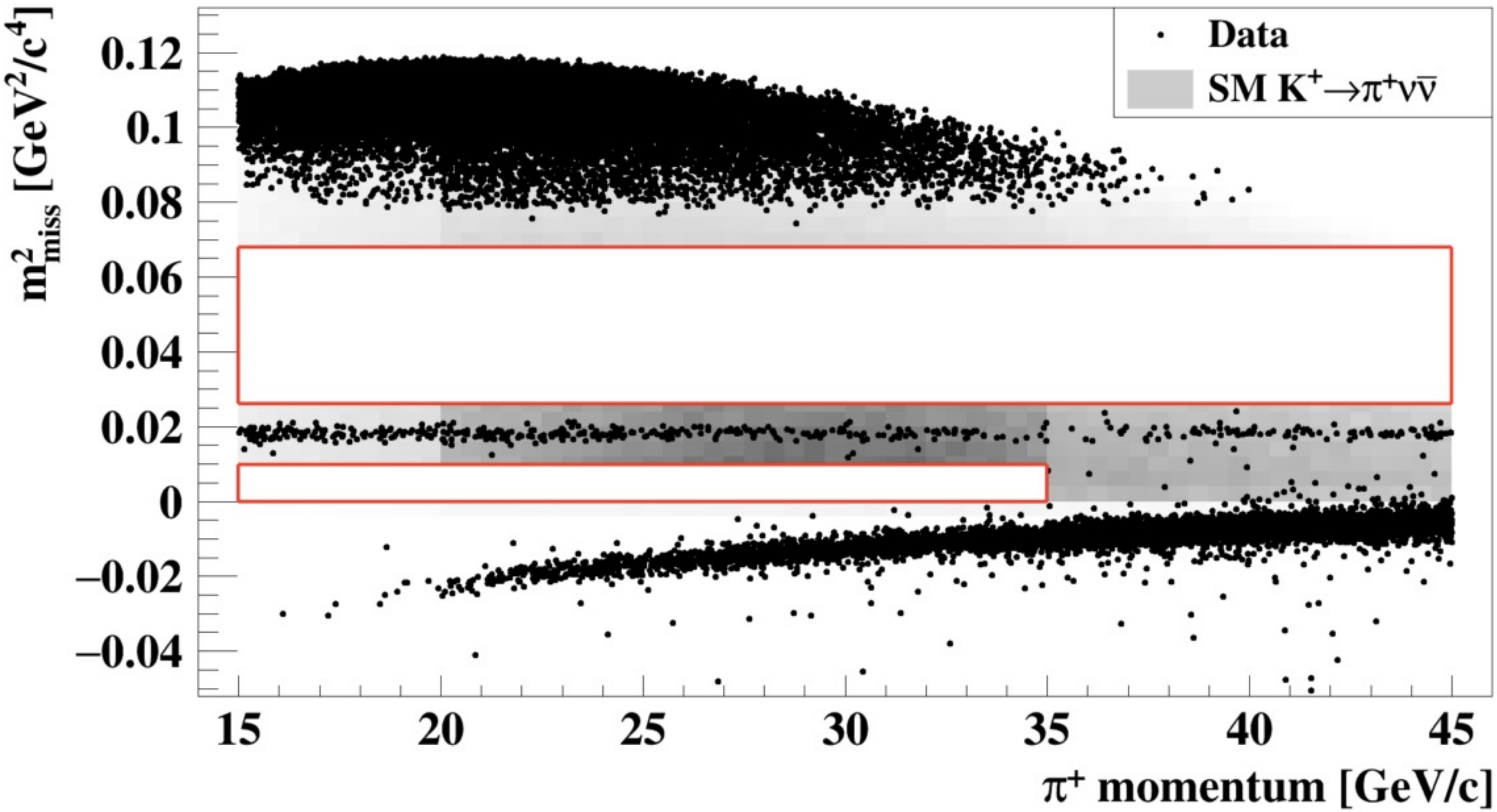
2 events observed

SES = 0.389 x 10^{-10}

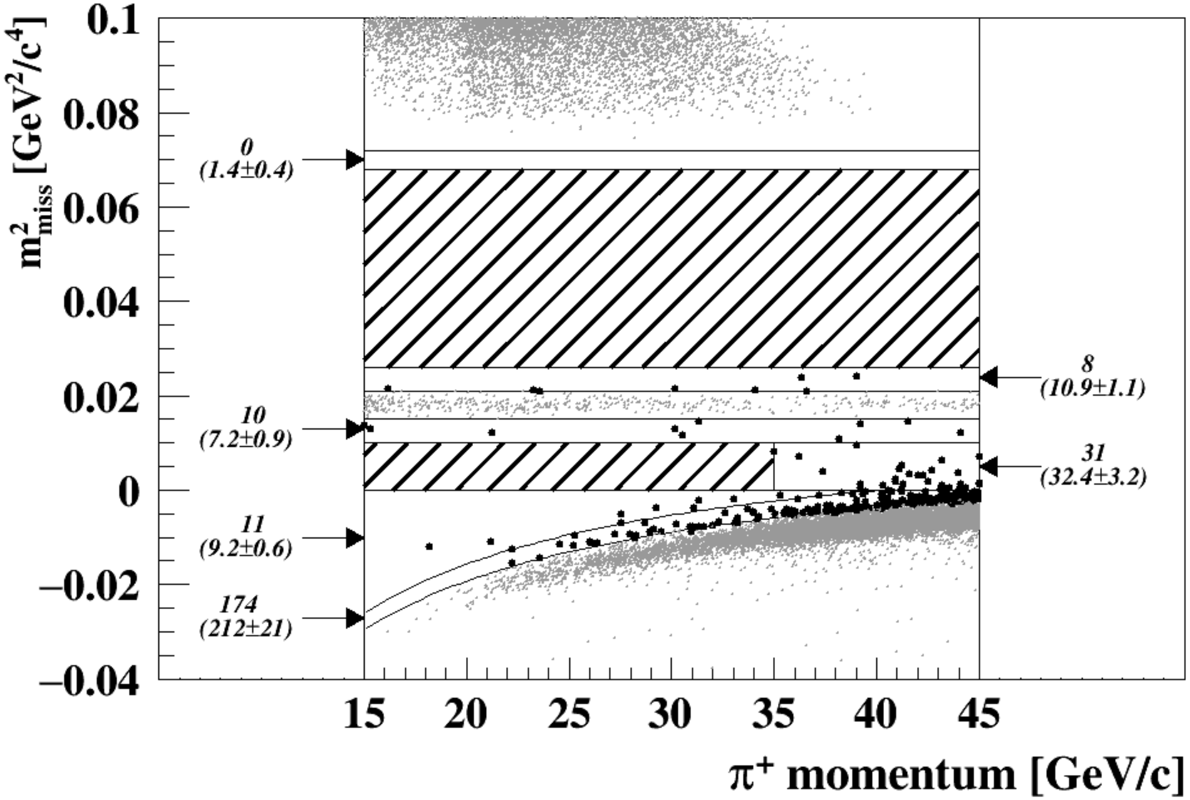
Br($K^+ \rightarrow \pi^+\nu\bar{\nu}$) < 1,7x$10^{-10}$@ 90% CL

[J. High Energ. Phys. 2020, 42 (2020)]

2018 data tacking results

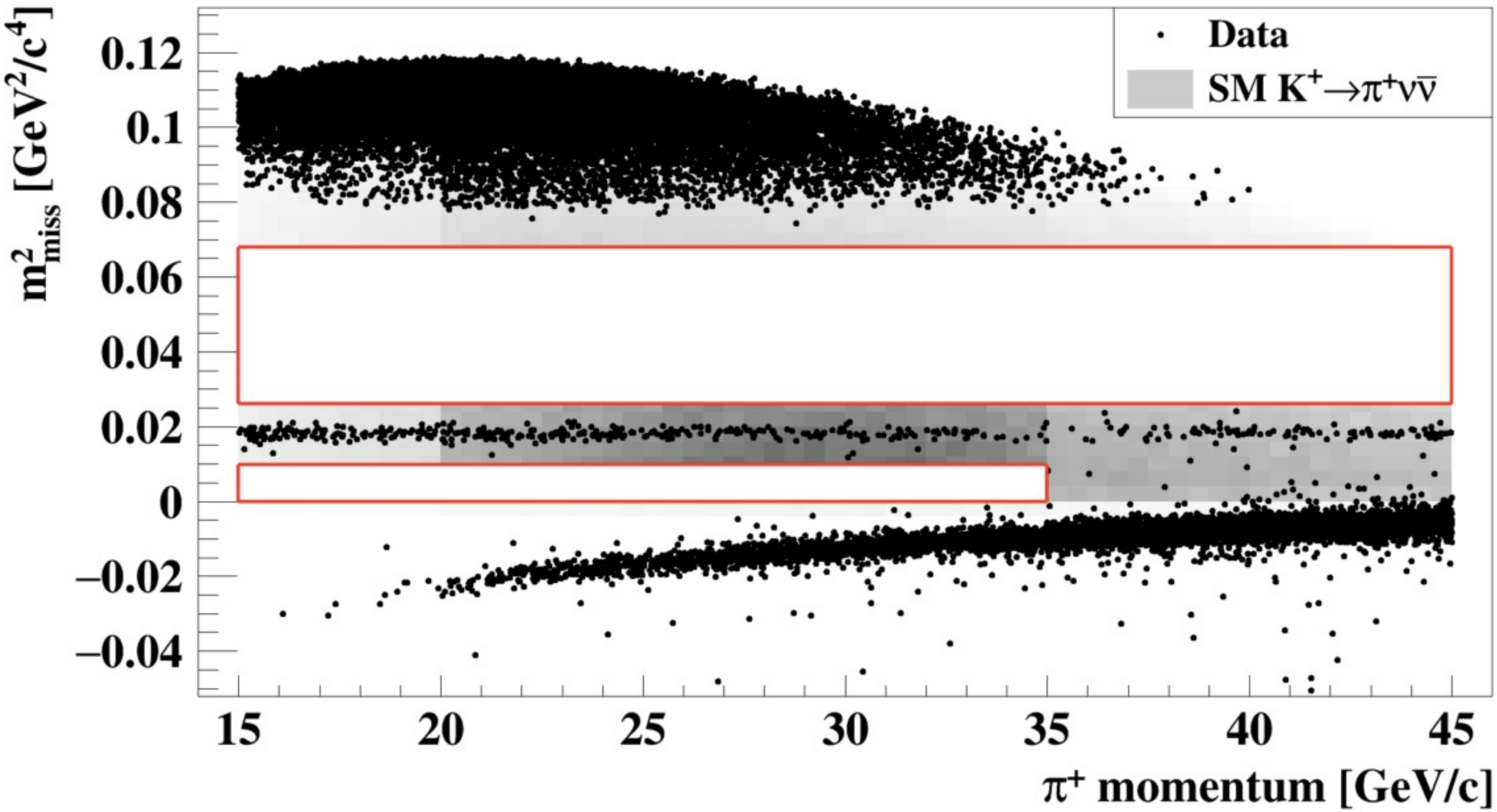


Control regions: main decays



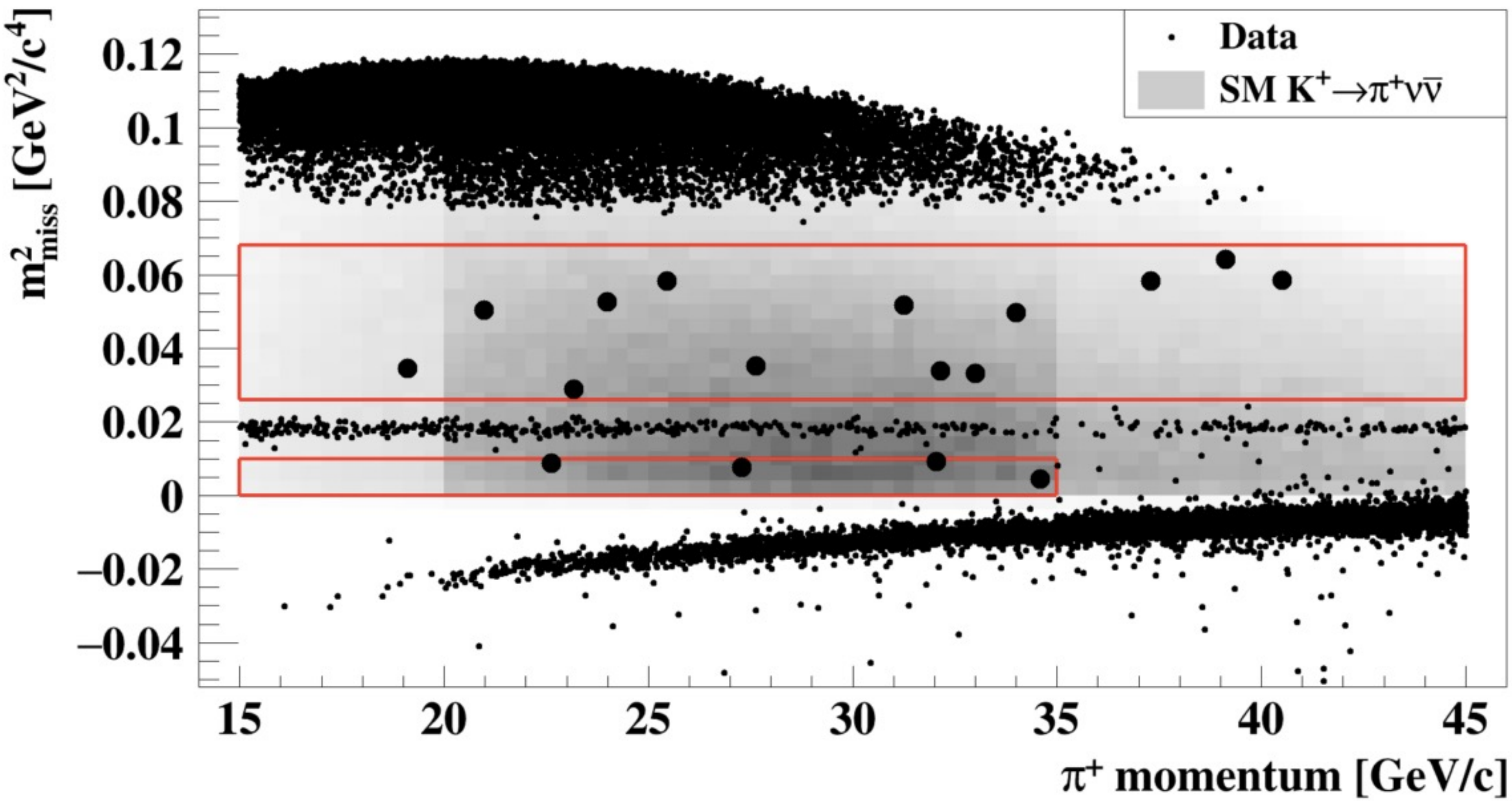
Background	Subset S1	Subset S2
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^-e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$
Total	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$

2018 data tacking results



5.3 background + 7.6 SM signal events expected

2018 data tacking results



5.3 background + 7.6 SM signal events expected, **17 events** observed