New measurement of the $K^+ \to \pi^+ \nu \bar{\nu}$ Branching ratio at the NA62 experiment

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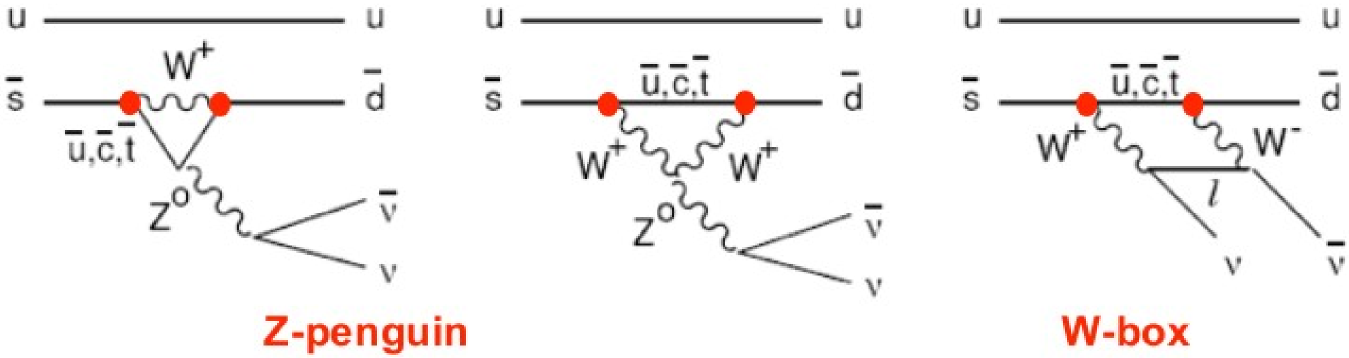
Outline

- ✓ The Golden Channel: $K^+ \to \pi^+ \nu\nu$
- ✓ The NA62 Experiment at CERN
- ✓ NA62: Analysis strategy, Run1 results and upgrades
- ✓ NA62: 2021-2022 analysis
- ✓ NA62: 2021-2022 and 2016-2022 combined Br results
- ✓ Conclusions

$K^+ \to \pi^+ \nu\nu$ in the Standard Model

The $K^+ \to \pi^+ \nu\nu$ process is extremely clean from the theoretical point of view (Matrix Element obtained from the well known Ke3 process): optimal to test the SM

$s \to d\nu\nu$ Flavour-changing neutral current transition (forbidden at tree level) heavily suppressed by GIM.



Current theoretical prediction:

$BR(K^+ \to \pi^+\nu\nu)_{SM} = (8.60 \pm 0.42)\cdot 10^{-11}$ Buras at al. EPJC 82 (2022) 7, 615

$BR(K^+ \to \pi^+\nu\nu)_{SM} = (7.86 \pm 0.61)\cdot 10^{-11}$ D’Ambrosio et al. , JHEP 09 (2022) 148

- Differences between the two predictions come from different choice of CKM parameters: see Eur. Phsy. J. C 84 (2024) 4, 377

Current experimental result (NA62 Run 1):

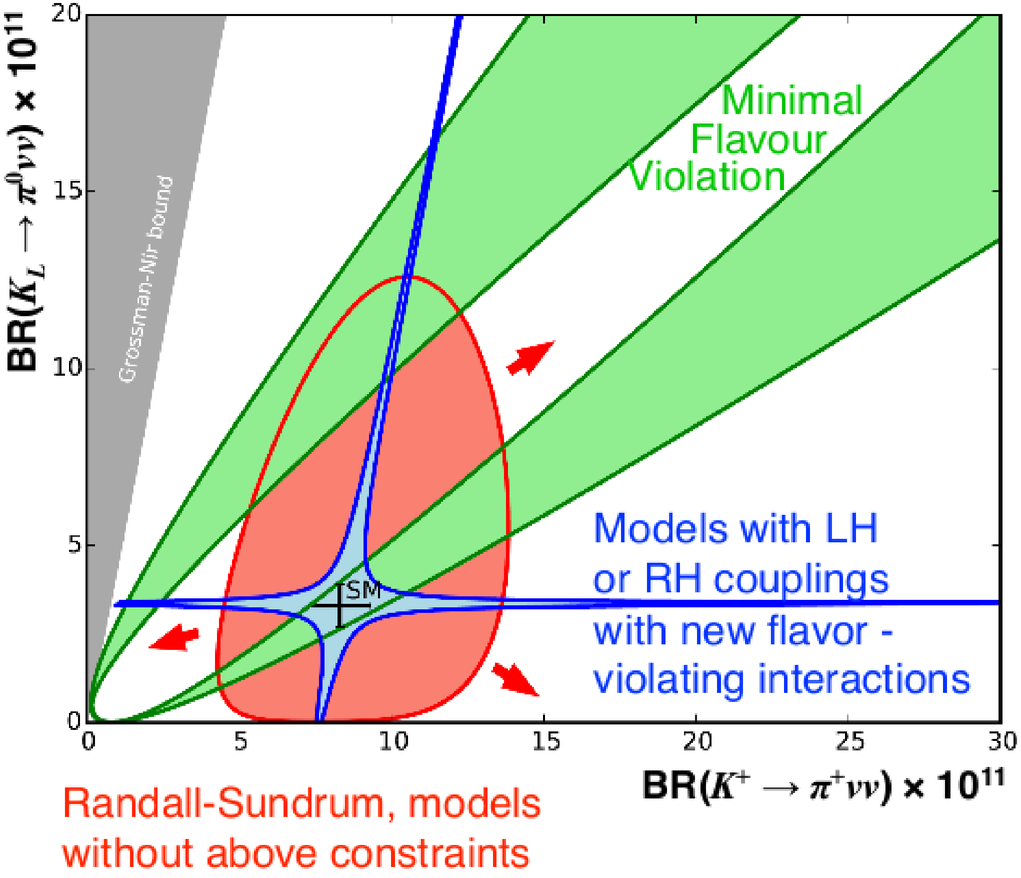
$BR(K^+ \to \pi^+\nu\nu)_{EXP} = (10.6 \pm 4.0)\cdot 10^{-11}$

$K^+ \to \pi^+ \nu\nu$ and NP

- Coorrelation between BR of K^+ and K_L modes within different BSM models JHEP 11 (2015) 166

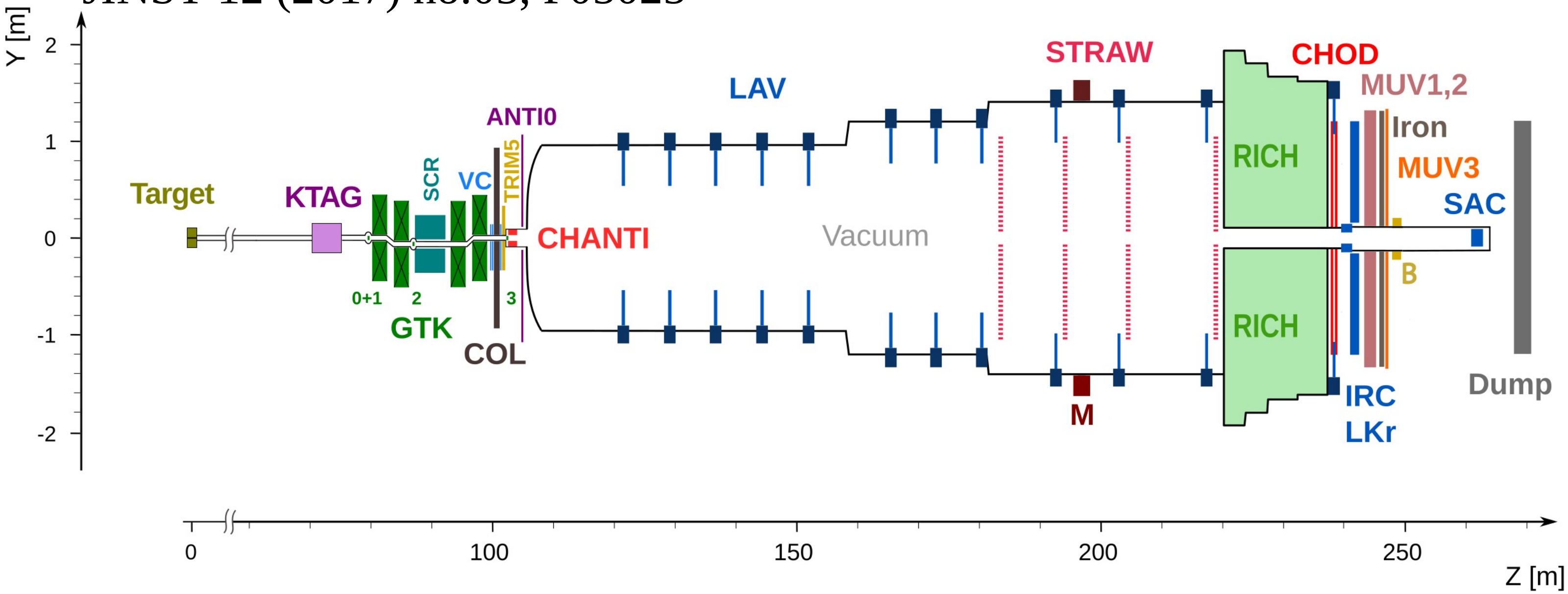
  Both channels needed to be measured
- Correlations with other observables (ε'/ε, ΔM_B, B decays)

JHEP 12 (2020) 097, PLB 809 (2020) 135769



The NA62 Beam and Detector

JINST 12 (2017) no.05, P05025



400 GeV/c protons from the SPS on a beryllium target produce secondary charged beam:

6% are 75 GeV/c K^+ mixed with π^+ (70%) and protons (23%),

1% momentum spread (rms), ~100 μrad divergence.

~10 MHz of raw input data to the L0 trigger (FPGA) from detectors;

~1 MHz of events passing the first trigger level,

L1 and L2 trigger (software) guarantee a maximum of $\mathcal{O}(10)$ kHz of acquisition rate.

NA62 Data taking

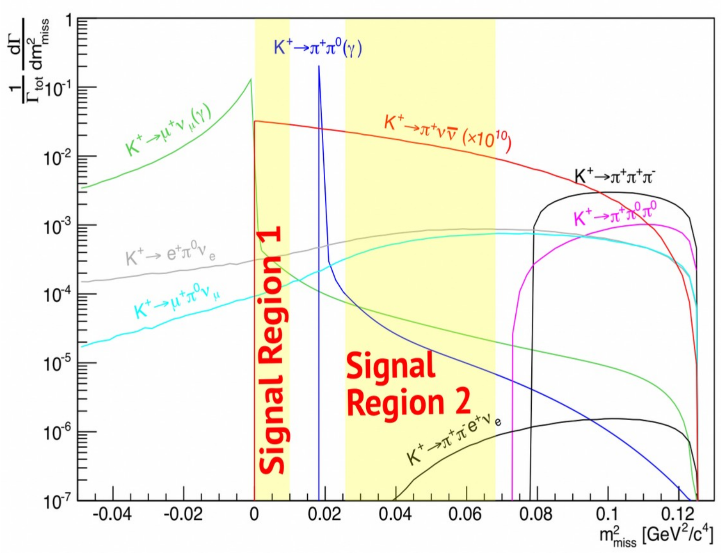
- 2014: Pilot Run
- 2015: Commissioning Run
- 2016: ~ 30 days
- 2017: ~ 160 days
- 2018: ~ 220 days
- 2019 – 2020: LS2, no beam
- 2021: ~ 120 days
- 2022: ~ 200 days
- 2023: ~ 140 days
- 2024: ~ 200 days

Run 1 (2016–2018)

Run 2 (2021–2024)

NA62 Analysis strategy

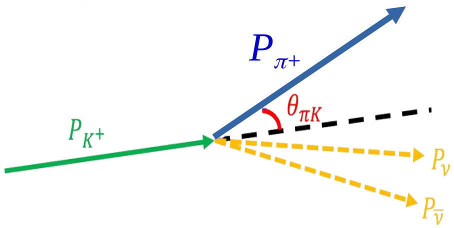
Theoretical distribution



Br of the main SM bkg to [PDG]
$Br(K^+\to\mu^+\nu_\mu) = (63.56 \pm 0.11)\%$
$Br(K^+\to\pi^+\pi^0) = (20.67 \pm 0.08)\%$
$Br(K^+\to\pi^+\pi^-\pi^+) = (5.583 \pm 0.024)\%$
$Br(K^+\to\pi^+\pi^- e^+\nu_e) = (4.247 \pm 0.024)\ 10^{-5}$

Fundamental variable:

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



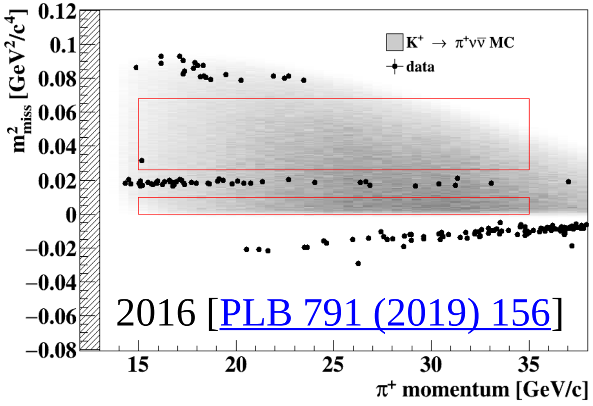
Main bakgrounds entering the two signal regions (SRs) in the distribution:

- $K^+\to\pi^+\pi^0$ and $K^+\to\mu^+\nu$ due to non-Gaussian resolution effects and radiative tails
- $K^+\to\pi^+\pi^-\pi^+$ due to non-Gaussian resolution effects
- Three or four body decays with a neutrino in the final state

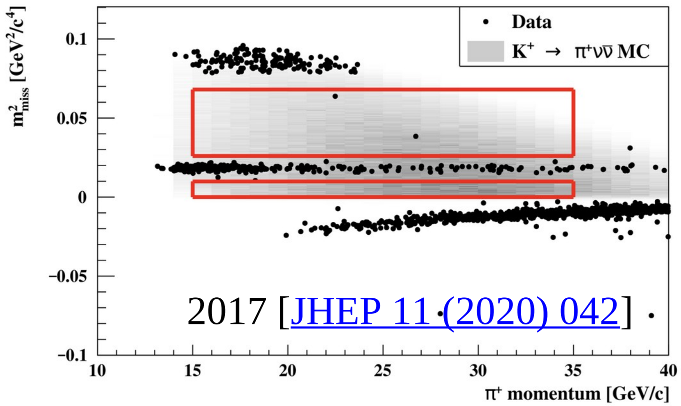
Main experimental requirements:

$\mathcal{O}$(100 ps) timing between sub-detectors
$\mathcal{O}(10^4)$background rejection from kinematics
$\mathcal{O}(10^7)$Muon (from $K^+\to\mu^+\nu$) suppression from PID
$\mathcal{O}(10^7)$ π^0 (from $K^+\to\pi^+\pi^0$) suppression from photon rejection

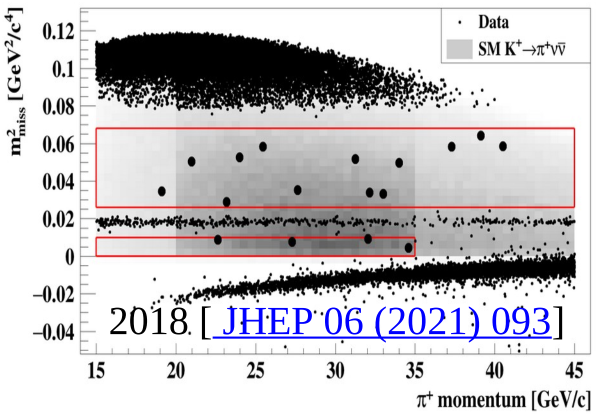
NA62 Run 1 (2016-2018) Results



2016 [PLB 791 (2019) 156]



2017 [JHEP 11 (2020) 042]



2018 [JHEP 06 (2021) 093]

Data-taking year	[Reference]	N_{bg}	$N_{\pi\nu\bar{\nu}}^{SM,exp}$	N_{obs}
2016	[PLB 791 (2019) 156]	$0.152^{+0.093}_{-0.035}$	0.267 ± 0.020	1
2017	[JHEP 11 (2020) 042]	1.46 ± 0.33	2.16 ± 0.13	2
2018	[JHEP 06 (2021) 093]	$5.42^{+0.99}_{-0.75}$	7.58 ± 0.40	17
2016–18	[JHEP 06 (2021) 093]	$7.03^{+1.05}_{-0.82}$	10.01 ± 0.42	20

Assuming:
$BR_{SM} = 8.40 \cdot 10^{-11}$

Statistical combination

$$\mathcal{B}(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}\big|_{stat} \pm 0.9_{syst}) \times 10^{-11} @ 68\%\ CL$$

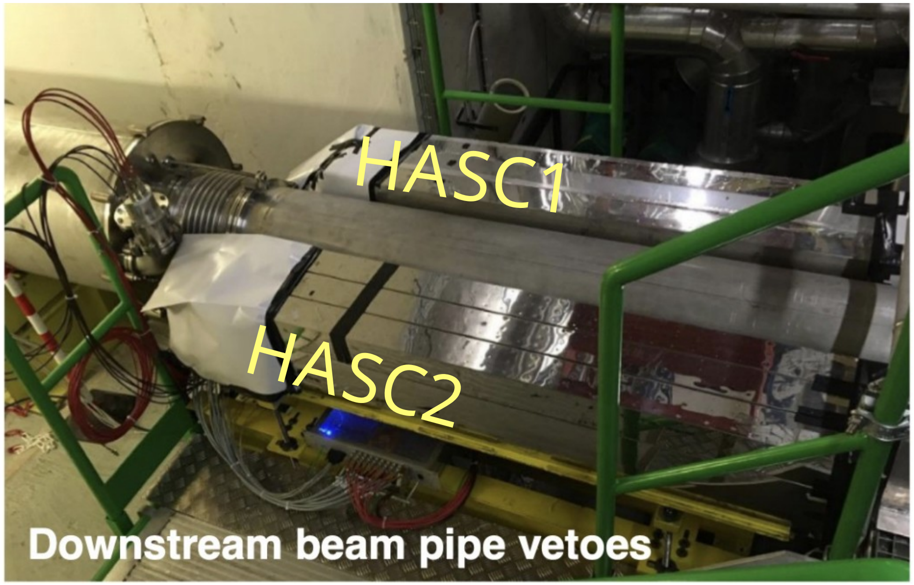
Background-only hypothesis: $p = 3.4 \cdot 10^{-4}$ ⟹ significance = $3.4\ \sigma$

NA62 upgrades in view of Run 2

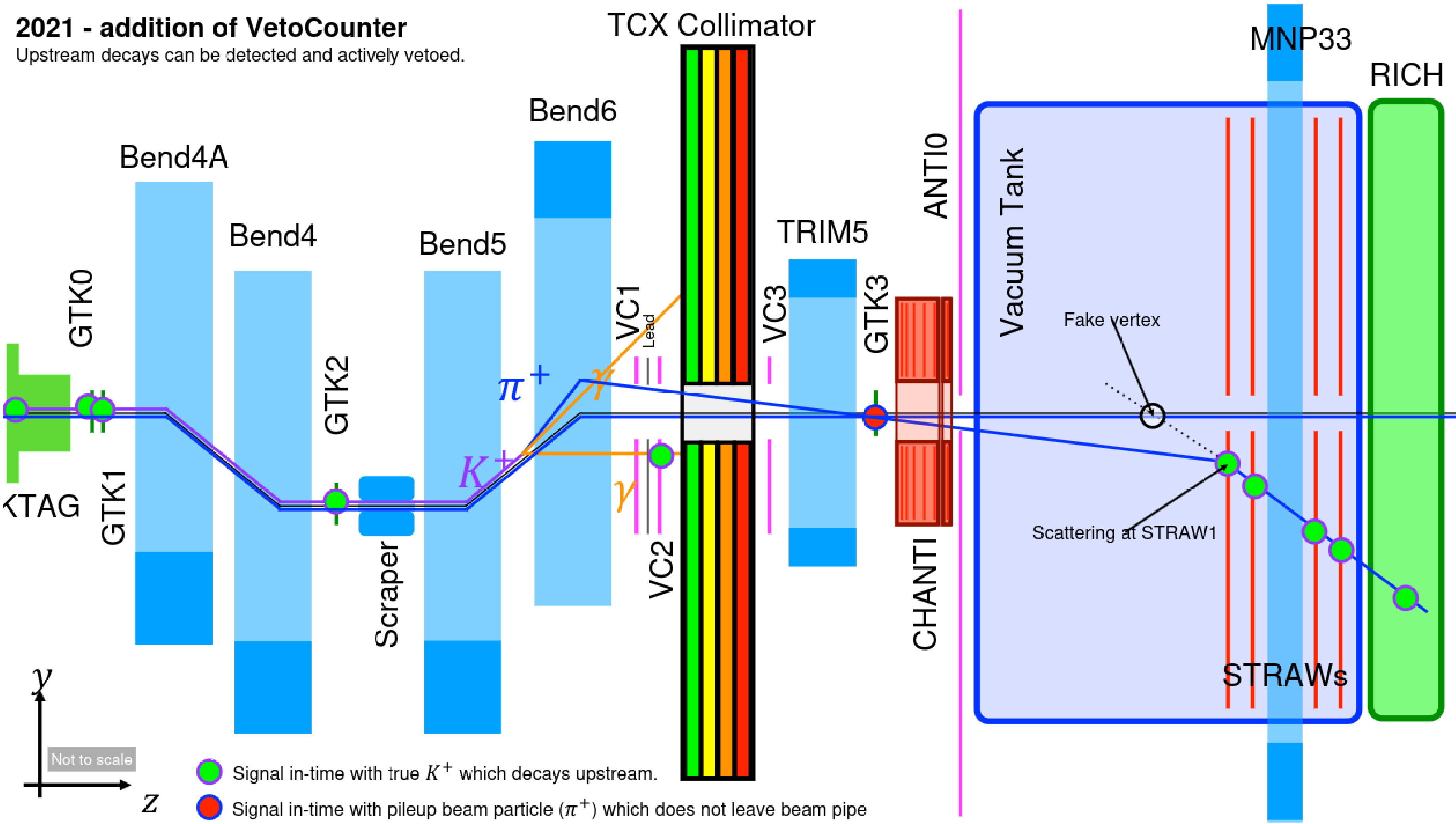
- **New detectors were installed during LS2:**
  - a 4th station in the GTK beam spectrometer; the GTK achromat system was also rearrenged
  - three Veto Counter stations and the ANTI0 hodoscope, both upstream of the decay volume, to improve the upstream decays veto
  - an additional veto detector (HASC2) at end of beam-line

- **The beam intensity was increased by** ~35% with respect to 2018 [450 ➡ 600 MHz].

- **The trigger configuration was improved.**

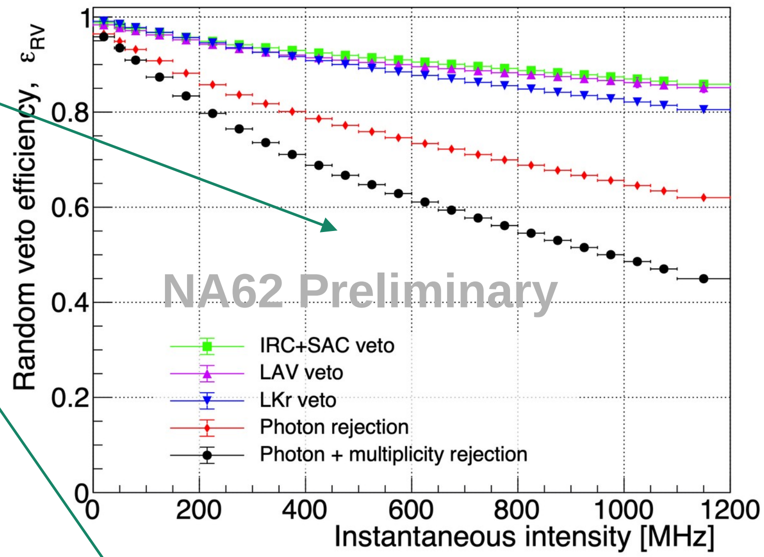


NA62 upgrades (one example)



$K^+ \to \pi^+\nu\nu$ Run 2 (2021-22) analysis

$$N^{exp}_{\pi\nu\bar{\nu}}(p_i) = \frac{\mathcal{B}^{SM}_{\pi\nu\bar{\nu}}}{\mathcal{B}_{SES}(p_i)} = \frac{\mathcal{B}^{SM}_{\pi\nu\bar{\nu}}}{\mathcal{B}_{\pi\pi}} \frac{A_{\pi\nu\bar{\nu}}(p_i)}{A_{\pi\pi}(p_i)} D_0 N_{\pi\pi}(p_i) \varepsilon_{trig}(p_i) \varepsilon_{RV}$$



$K^+ \to \pi^+\pi^0$ used as normalisation channel

$$\varepsilon_{trig} = \frac{\varepsilon_{sig}}{\varepsilon_{norm}}$$

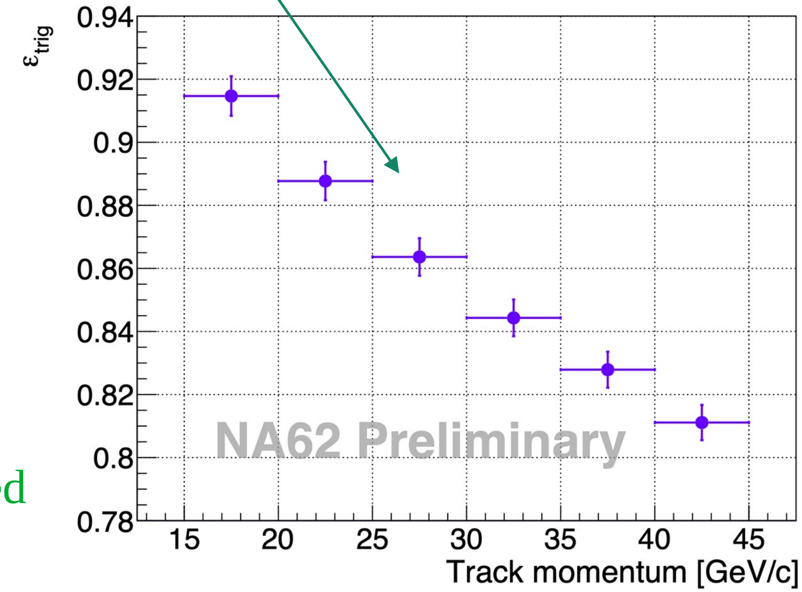
Trigger efficiency ratio:

- 2021-22: new control trigger definition with several conditions overlapping the trigger used for the signal

  → Partial cancellation in the ratio

- 2018: different trigger conditions between signal and normalisation

  → No cancellation



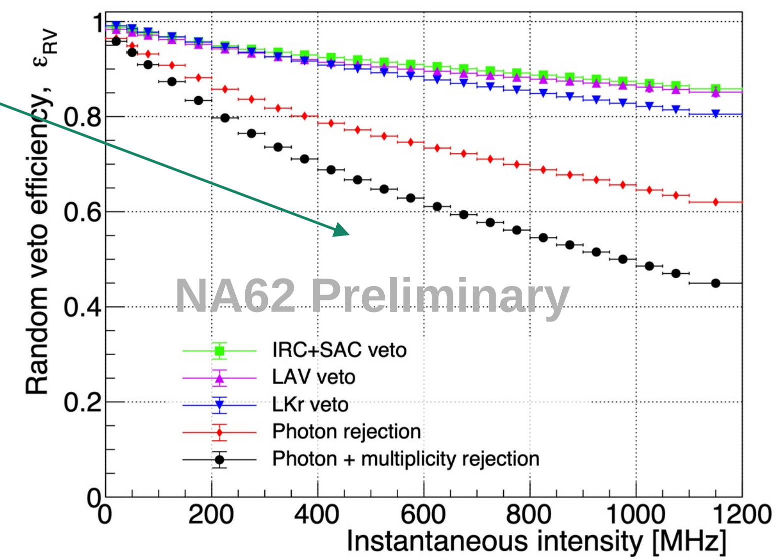
2021-2022: (85.9 ± 1.4)%

2018: (89 ± 5) %

Factor 3 improvement in the precision with reduced sys uncertainty

$K^+ \to \pi^+\nu\nu$ Run 2 (2021-22) analysis

$$N^{exp}_{\pi\nu\bar{\nu}}(p_i) = \frac{\mathcal{B}^{SM}_{\pi\nu\bar{\nu}}}{\mathcal{B}_{SES}(p_i)} = \frac{\mathcal{B}^{SM}_{\pi\nu\bar{\nu}}}{\mathcal{B}_{\pi\pi}} \frac{A_{\pi\nu\bar{\nu}}(p_i)}{A_{\pi\pi}(p_i)} D_0 N_{\pi\pi}(p_i)\, \varepsilon_{trig}(p_i)\, \varepsilon_{RV}$$

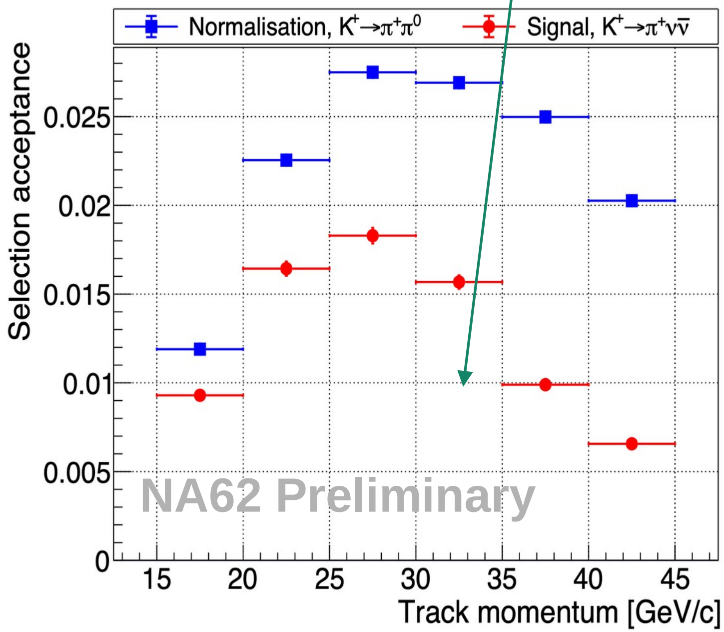


$K^+ \to \pi^+\pi^0$ used as normalisation channel

Case	OLD 2018 (S2)	NEW 2021-22
Norm.	11.8%	13.4%
Signal	(6.37±0.64)%	(7.61±0.18)%

+15%

+20%



- New K^+-π^+ matching
- Re-tuned vertex condition
- Relaxation of some vetoes
- Improved precision and better sys evaluation

Acceptances evaluation made at 0 intensity

Intensity effects taken into account with the random veto correction

$K^+ \to \pi^+ \nu\nu$ sensitivity

$$N_K = \frac{N_{\pi\pi} D_0}{\mathcal{B}_{\pi\pi} A_{\pi\pi}}$$

$$\mathcal{B}_{SES} = \frac{1}{N_K \varepsilon_{RV} \varepsilon_{trig} A_{\pi\nu\bar{\nu}}}$$

$N_{\pi\pi}^{\text{eff}}$	Effective number of normalisation events	$(1.953 \pm 0.005) \times 10^8$
$A_{\pi\pi}$	Normalisation acceptance	$(13.410 \pm 0.005)\%$
N_K	Effective number of K^+ decays	$(2.85 \pm 0.01) \times 10^{12}$
$A_{\pi\nu\bar{\nu}}$	Signal acceptance	$(7.62 \pm 0.22)\%$
$\varepsilon_{\text{trig}}$	Trigger efficiency ratio	$(85.9 \pm 1.4)\%$
ε_{RV}	Random veto efficiency	$(63.2 \pm 0.6)\%$
$\mathcal{B}_{\text{SES}}$	Single event sensitivity	$(8.48 \pm 0.29) \times 10^{-12}$
$N_{\pi\nu\bar{\nu}}^{\text{SM}}$	Number of expected SM $K^+ \to \pi^+\nu\bar{\nu}$ events	9.91 ± 0.34

Uncertainty significantly improved: 6.3% → 3.5%

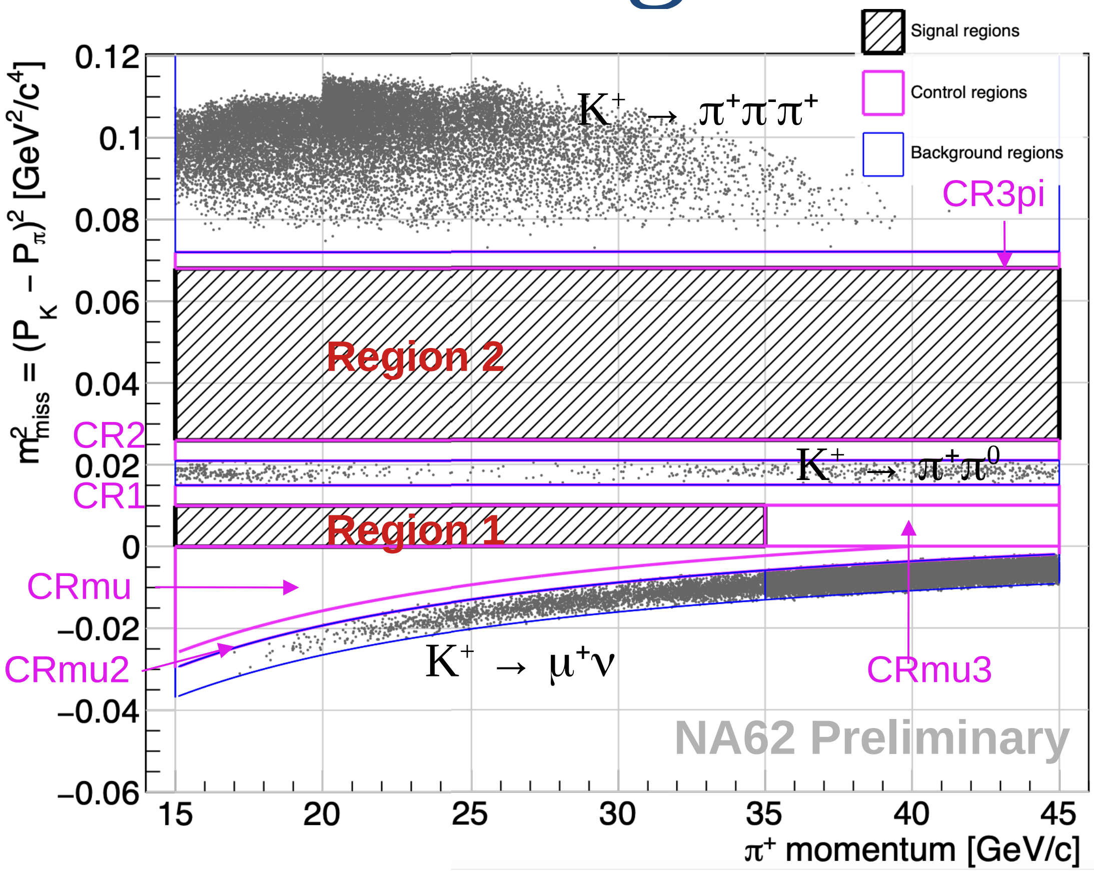
- trigger efficiency cancellation
- improved acceptances and ε_{RV} evaluation

Assuming $BR_{SM} = 8.4 \cdot 10^{-11}$:

$N_{\pi\nu\nu}$ (2021-2022): 9.91 ± 0.34

$N_{\pi\nu\nu}$ (2016-2018): 10.01 ± 0.42

Background evaluation



Number of event passing the signal selection in the background region

Control sample events in signal regions

$$N_{bg} = N_{bkgR} \cdot f_{tail} = N_{bkgR} \cdot \frac{N^{CS}_{SR}}{N^{CS}_{bkgR}}$$

Kinematic tail fraction: measured in control sample

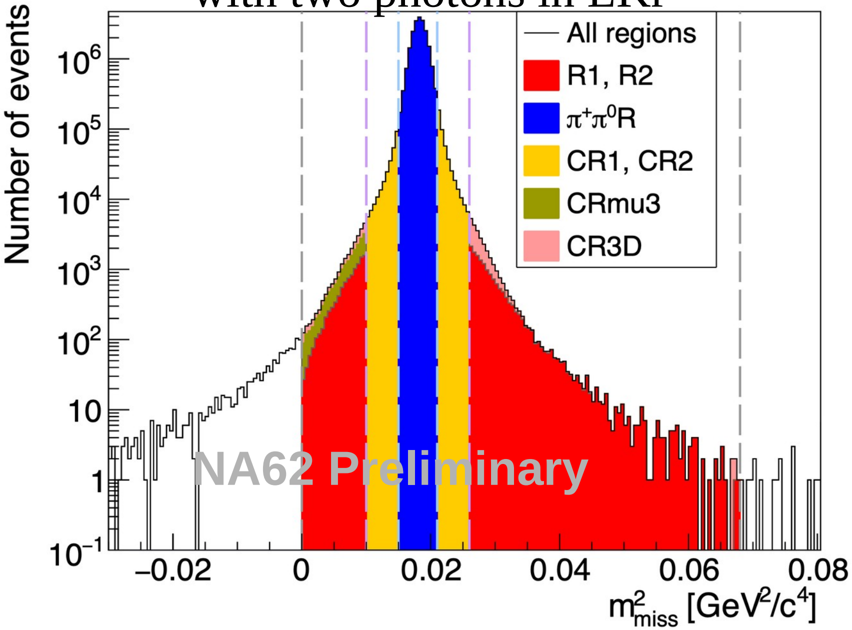
Control sample events in background regions

Backgrounds due to mis-reconstruction in the m^2_{miss} tails

Backgrounds from kinematic tails

Control sample of $K^+ \to \pi^+\pi^0(\gamma)$

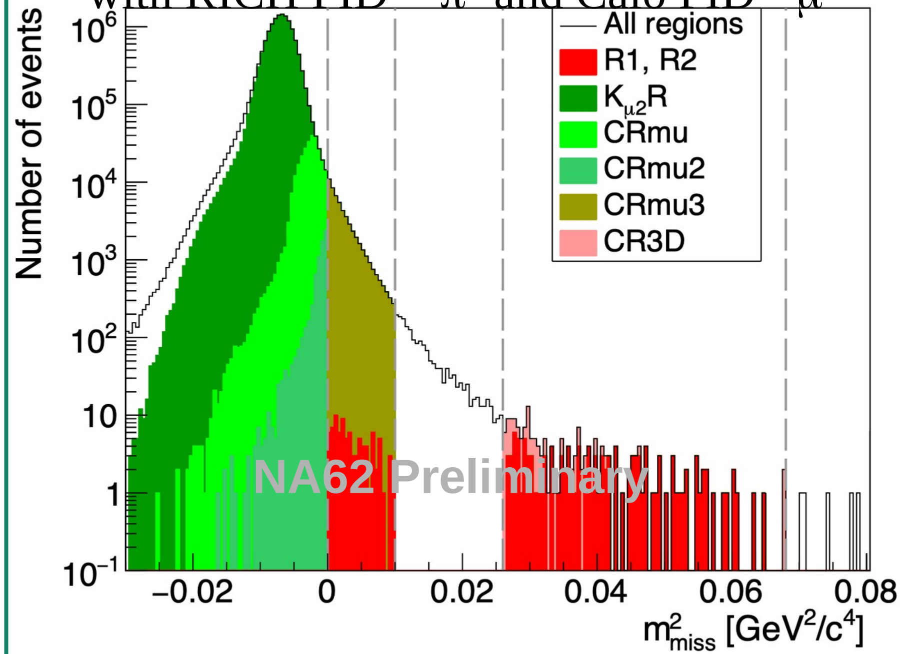
with two photons in LKr



N_{bg} ($K^+ \to \pi^+\pi^0(\gamma)$) = 0.83 ± 0.05

Control sample of $K^+ \to \mu^+\nu$

with RICH PID = π^+ and Calo PID= μ^+

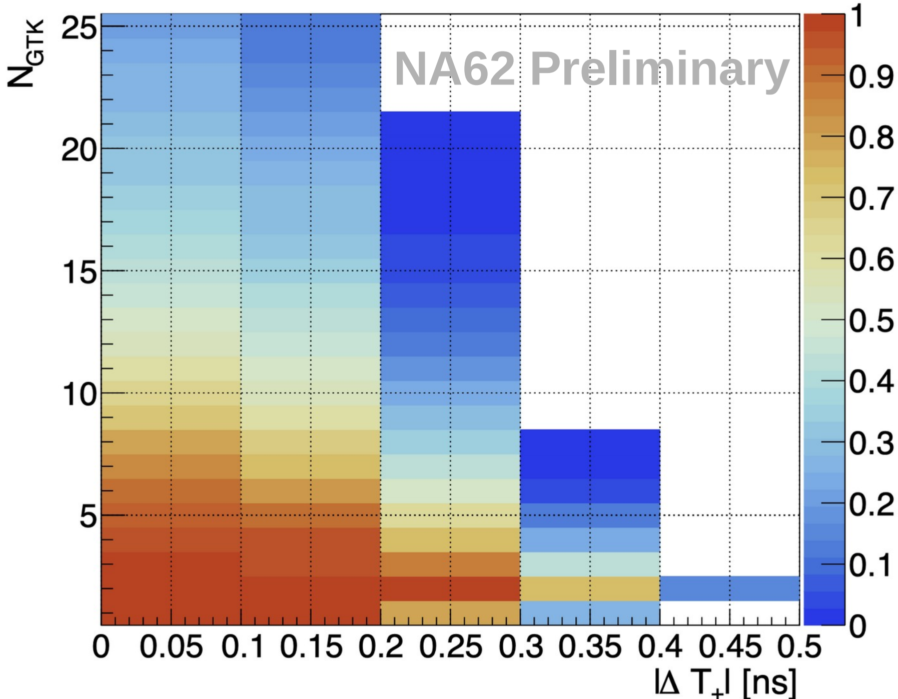


N_{bg} ($K^+ \to \mu^+\nu$) = 0.9 ± 0.2

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

Used MC to evaluate f_{tail} N_{bg} ($K^+ \to \pi^+\pi^-\pi^+$) = 0.11 ± 0.03

Upstream background



$$N_{bg} = N_i \cdot f_{cda} \cdot P_i^{match}$$

N_i Upstream reference sample (CDA > 4 mm)

→ Contains all known ups mechanisms and provides normalization

f_{cda} Scaling factor: bad CDA → good CDA

→ Depends only on geometry

P_i^{match} Probability to pass K^+ - π^+ matching

→ Depends on (ΔT, N_{GTK})

$\Sigma N_i = 51$

$f_{cda} = 0.20 \pm 0.03$

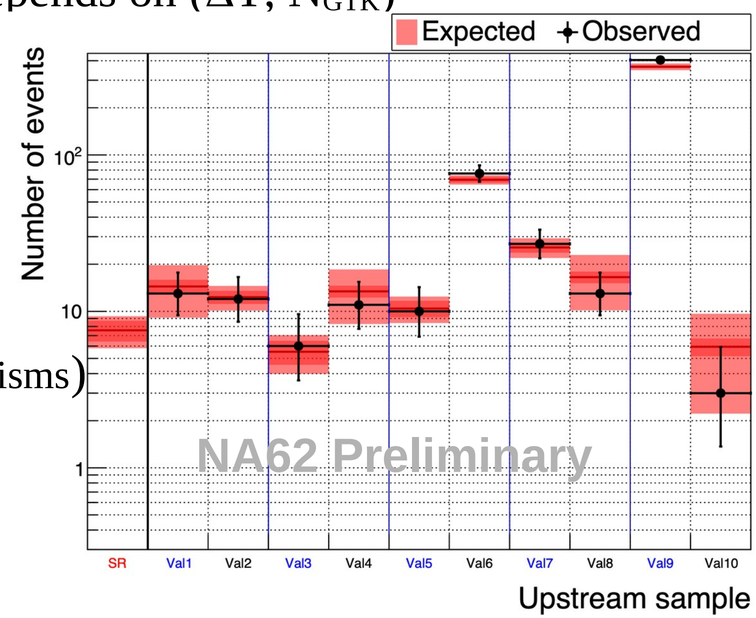
$<P_i^{match}> = 73\%$

$N_{bg} = 7.4^{+2.1}_{-1.8}$

Validation samples:

invert & loosen ups vetoes

(enriched with different mechanisms)



Summary of expectations

Backgrounds

$K^+ \to \pi^+\pi^0(\gamma)$	0.83 ± 0.05
$K^+ \to \pi^+\pi^0$	0.76 ± 0.04
$K^+ \to \pi^+\pi^0\gamma$	0.07 ± 0.01
$K^+ \to \mu^+\nu(\gamma)$	1.70 ± 0.47
$K^+ \to \mu^+\nu$	0.87 ± 0.19
$K^+ \to \mu^+\nu\gamma$	0.82 ± 0.43
$K^+ \to \pi^+\pi^+\pi^-$	0.11 ± 0.03
$K^+ \to \pi^+\pi^-e^+\nu$	$0.89^{+0.34}_{-0.28}$
$K^+ \to \pi^0\ell^+\nu$	< 0.001
$K^+ \to \pi^+\gamma\gamma$	0.01 ± 0.01
Upstream	$7.4^{+2.1}_{-1.8}$
Total	$11.0^{+2.1}_{-1.9}$

Sensitivity

$\mathcal{B}_{SES} = (8.48 \pm 0.29)\cdot 10^{-12}$

Assuming $BR_{SM} = 8.4\cdot 10^{-11}$:

$N_{\pi\nu\nu}$ (2021-2022): 9.91 ± 0.34

$N_{\pi\nu\nu}$ (2016-2018): 10.01 ± 0.42

- $N^{SM}_{\pi\nu\nu}$ per SPS spill = $2.5 \cdot 10^{-5}$ in 2022

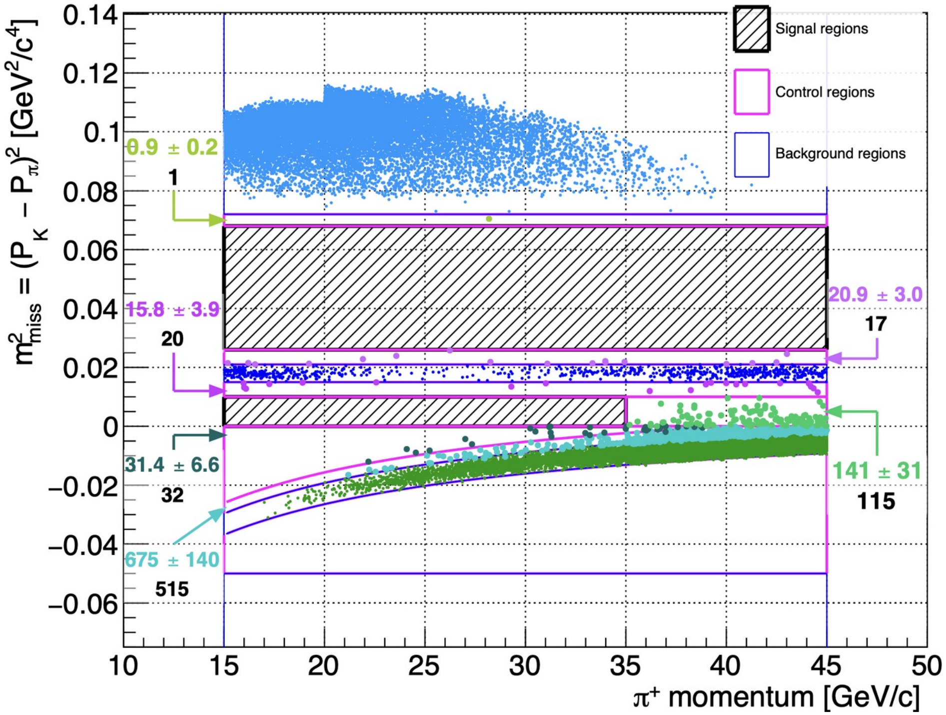
  It was $1.7 \cdot 10^{-5}$ in 2018 ➡ **signal yield increased by 50%**

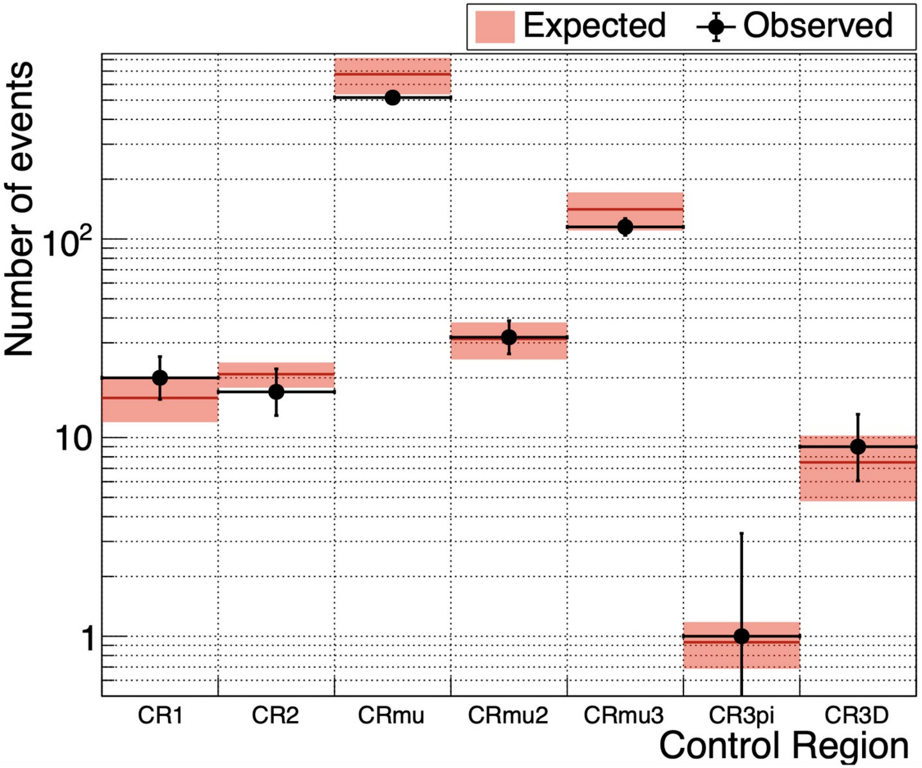
- Sensitivity for BR $\sim \sqrt{S+B}/S = 0.5$

  Similar but improved with respect 2018 analysis for the same amount of data

Control regions opening

2021-2022 Data

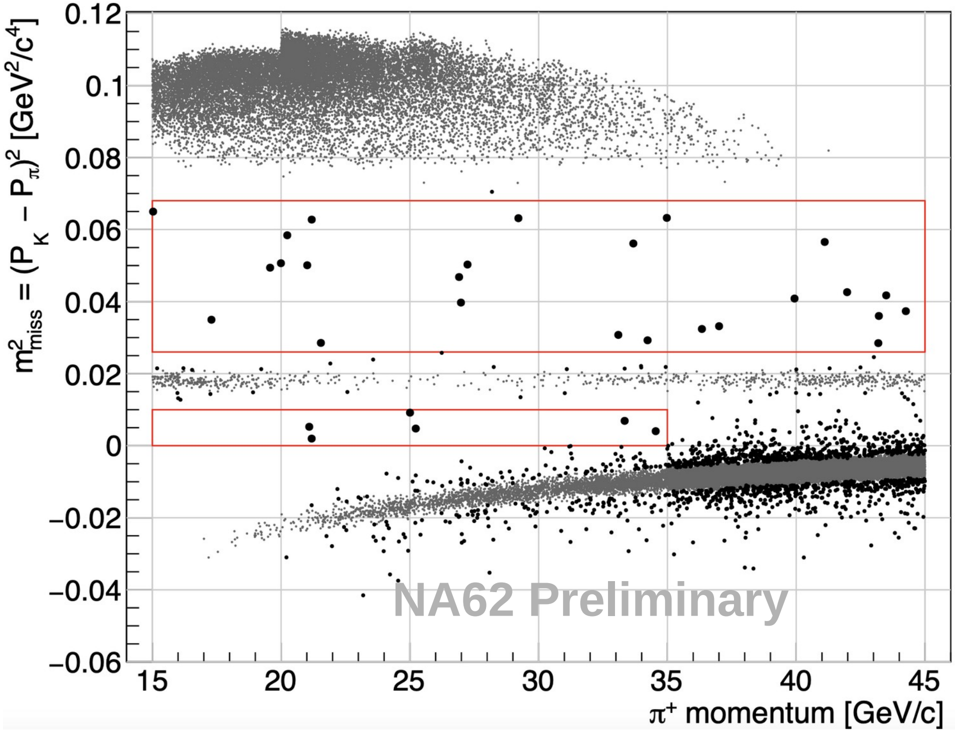




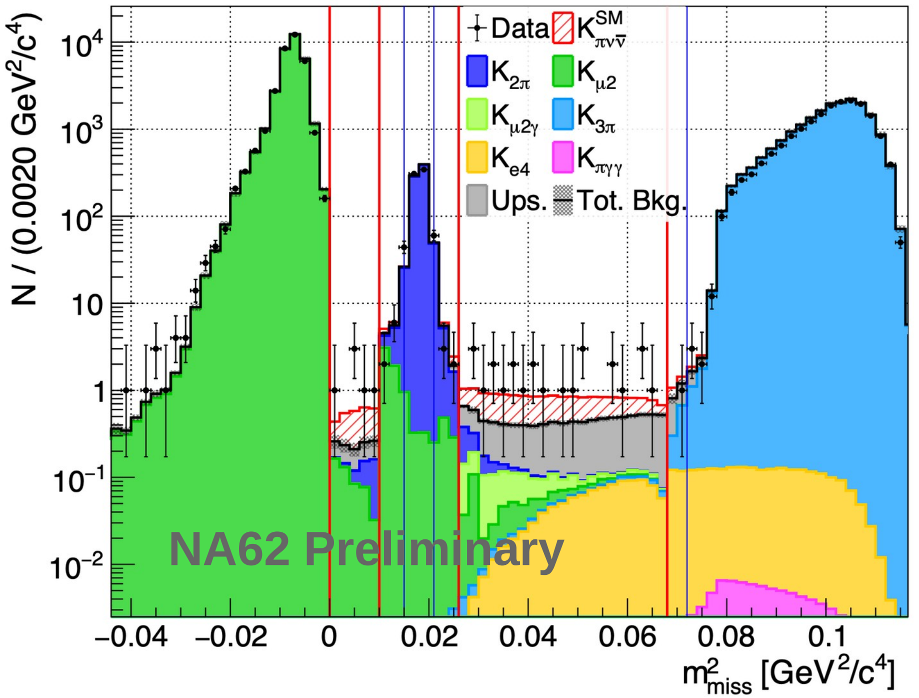
Good agreement between the expectations and the observed number of background events in the CRs → the background evaluation is validated

Signal regions opening

2021-2022 Data



1-d projection with different background Predictions & SM expectation [not a fit]



Expected SM events:10

Expected backgrounds: $11^{+2.1}_{-1.9}$

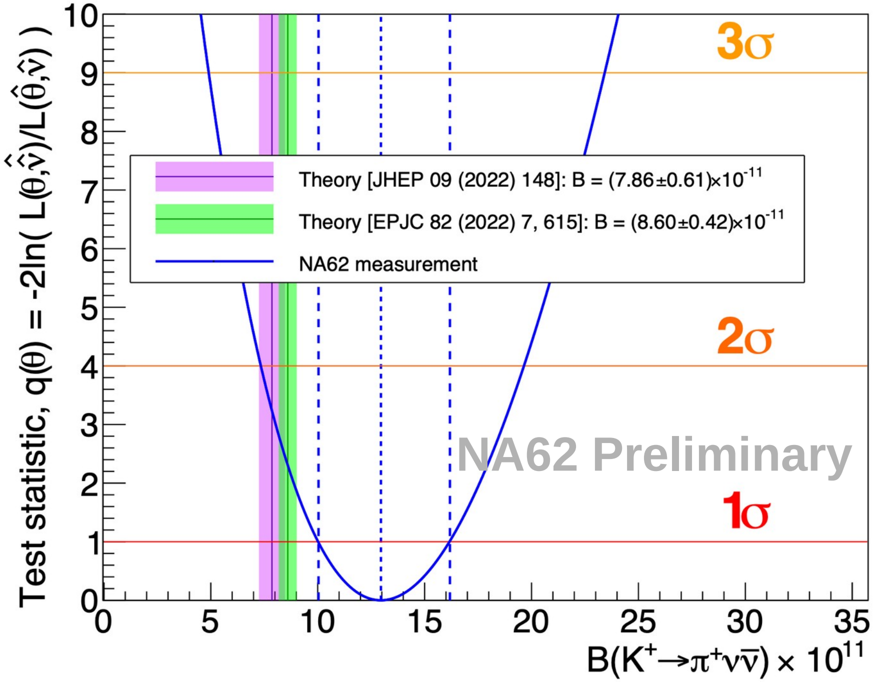
Observed events: 31

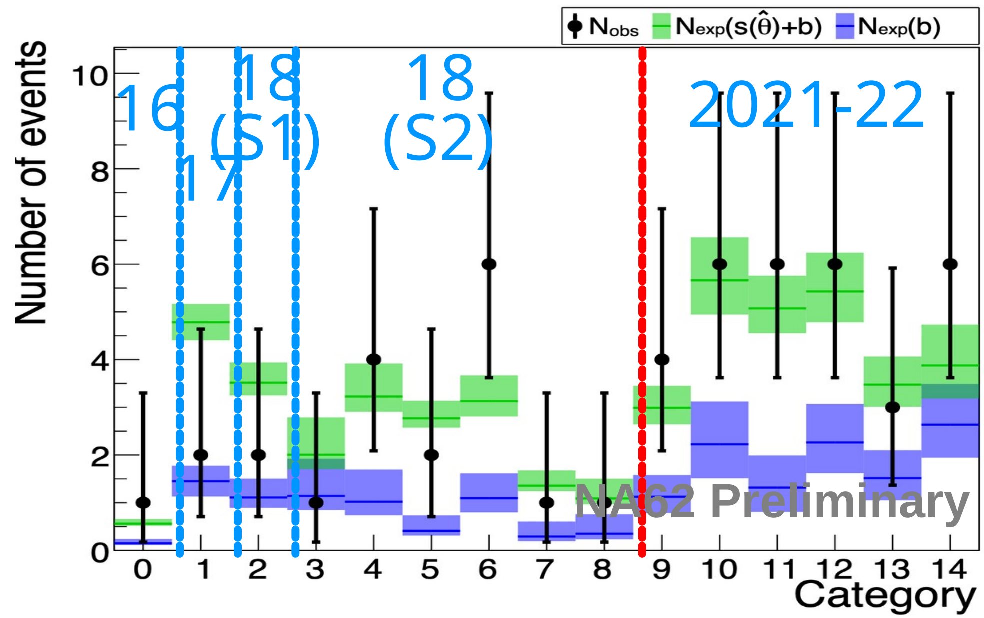
arXiv:2412.12015

Combined result Run1 + 2021-2022

Integrating 2016-2022 Data: $N_{bg} = 18^{+3}_{-2}$ $N_{obs} = 51$

arXiv:2412.12015





Background-only hypothesis p = 2·10⁻⁷ significance > 5 σ

$$Br_{16-22}(K^+ \to \pi^+ \nu\nu) = (13.0(^{+3.0}_{-2.7})_{stat}\,(^{+1.3}_{-1.3})_{syst})\cdot 10^{-11} = (13.0^{+3.3}_{-3.0})\cdot 10^{-11}$$

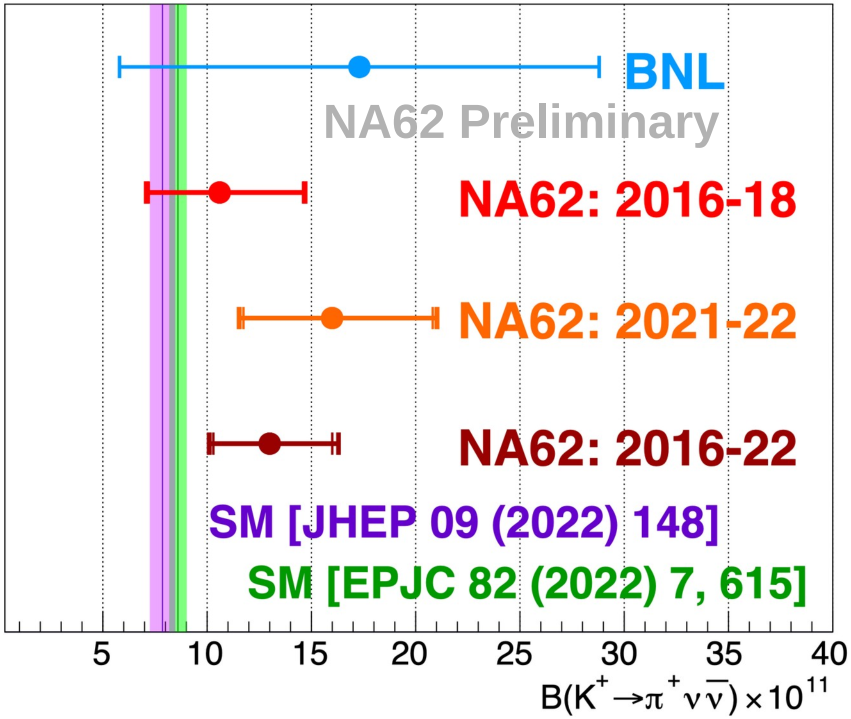
World data and SM predictions

BNL E787/E949 experiment
Phys.Rev.D 79 (2009) 092004

NA62 2016-2018
JHEP 06 (2021) 093

NA62 2021-2022
this talk: $(16.0^{+5.0}_{-4.5})\cdot 10^{-11}$

NA62 2016-2022
this talk: $(13.0^{+3.3}_{-3.0})\cdot 10^{-11}$



- The NA62 results are consistent within the years
- The fraction uncertainty decreased from 40% to 25%
- The background-only hypothesis is rejected with a significance > 5 σ
- Central value moved up: now 1.5-1.7 σ above SM

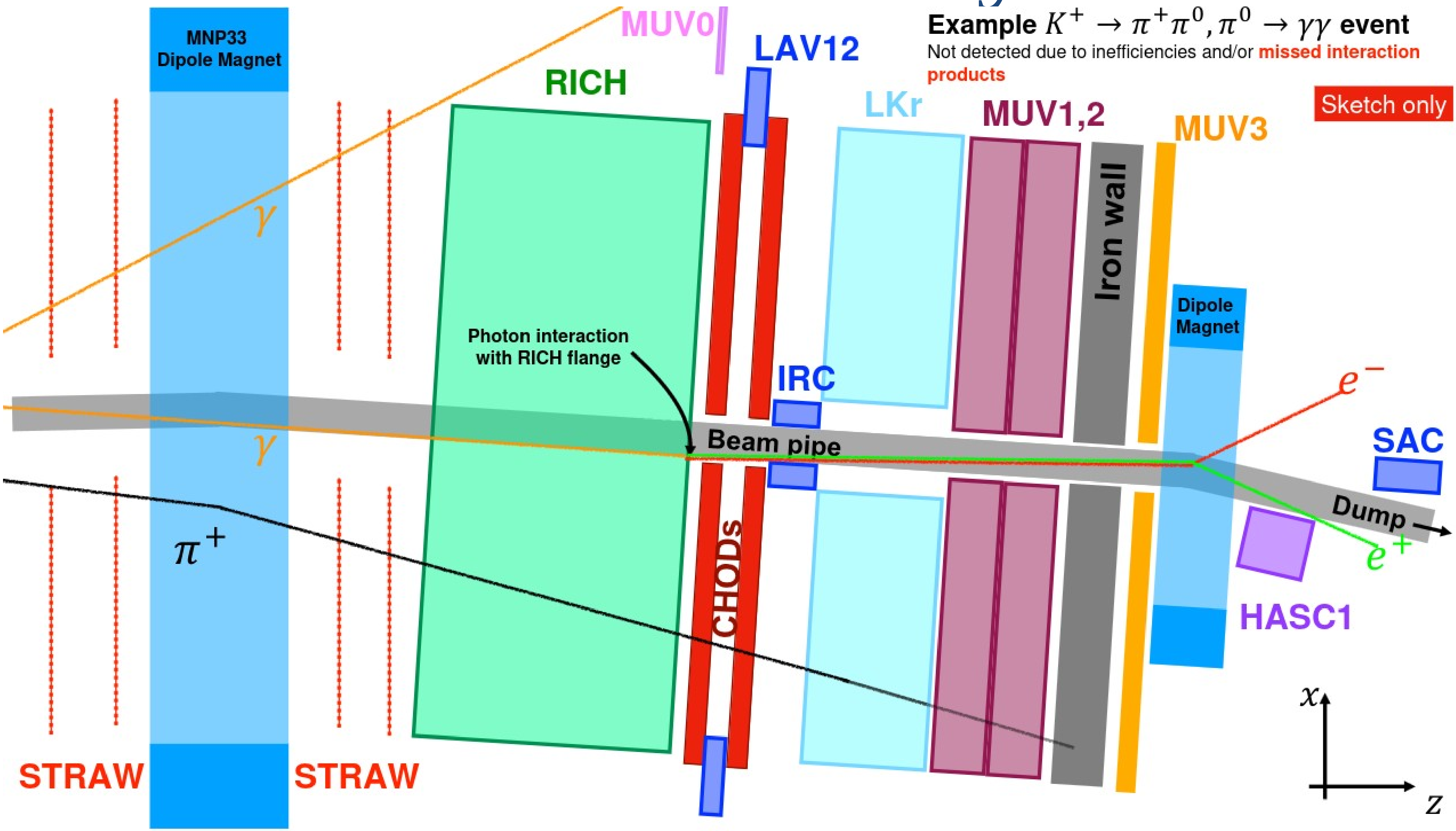
➡ **Need full NA62 data-set to clarify SM agreement or tension**

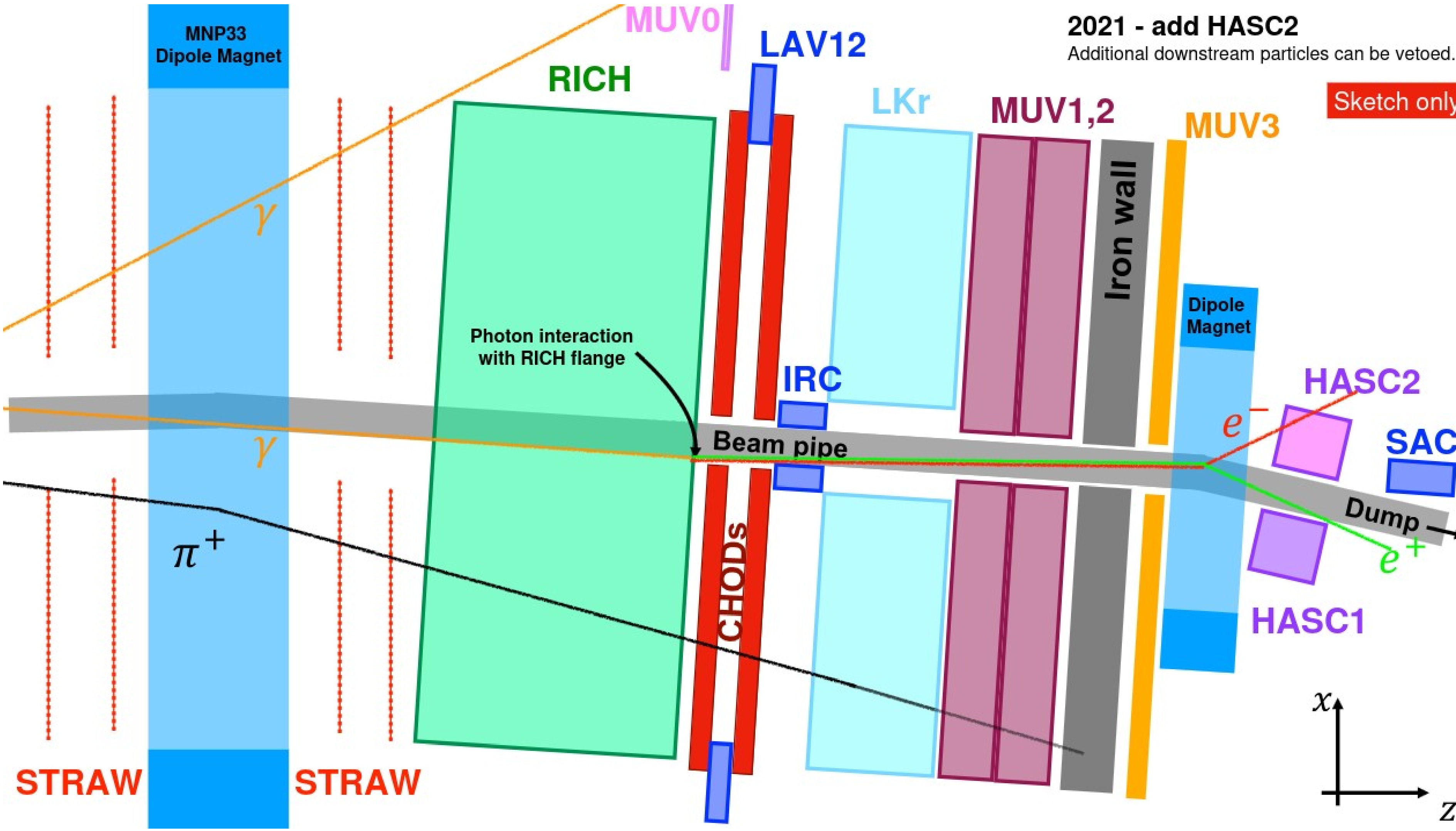
Conclusions

- New study of $K^+ \to \pi^+ \nu\nu$ using NA62 20201-2022 data presented:
  - Improved signal yield per SPS spill by 50%
  - $N_{bg} = 11.0^{+2.1}_{-1.9}$ N_{obs}=31
  - $Br_{21\text{-}22}(K^+ \to \pi^+ \nu\nu) = (16.2(^{+4.9}_{-4.3})_{stat}\,(^{+1.4}_{-1.4})_{syst})\cdot 10^{-11}$
- Combining 2016-2018 with 2021-2022
  - $N_{bg} = 18^{+3}_{-2}$ N_{obs}=51 (9+6 categories to extract the Br)
  - $Br_{16\text{-}22}(K^+ \to \pi^+ \nu\nu) = (13.0(^{+3.0}_{-2.7})_{stat}\,(^{+1.3}_{-1.3})_{syst})\cdot 10^{-11}$
  - Background-only hypothesis excluded with significance > 5σ
- First observation of $K^+ \to \pi^+ \nu\nu$ decay: Br in agreement with SM prediction within 1.7σ
- Needed the full Run1-Run2 data-set to confirm SM agreement or tension
- 2023 – LS3 data-set collection & analysis ongoing

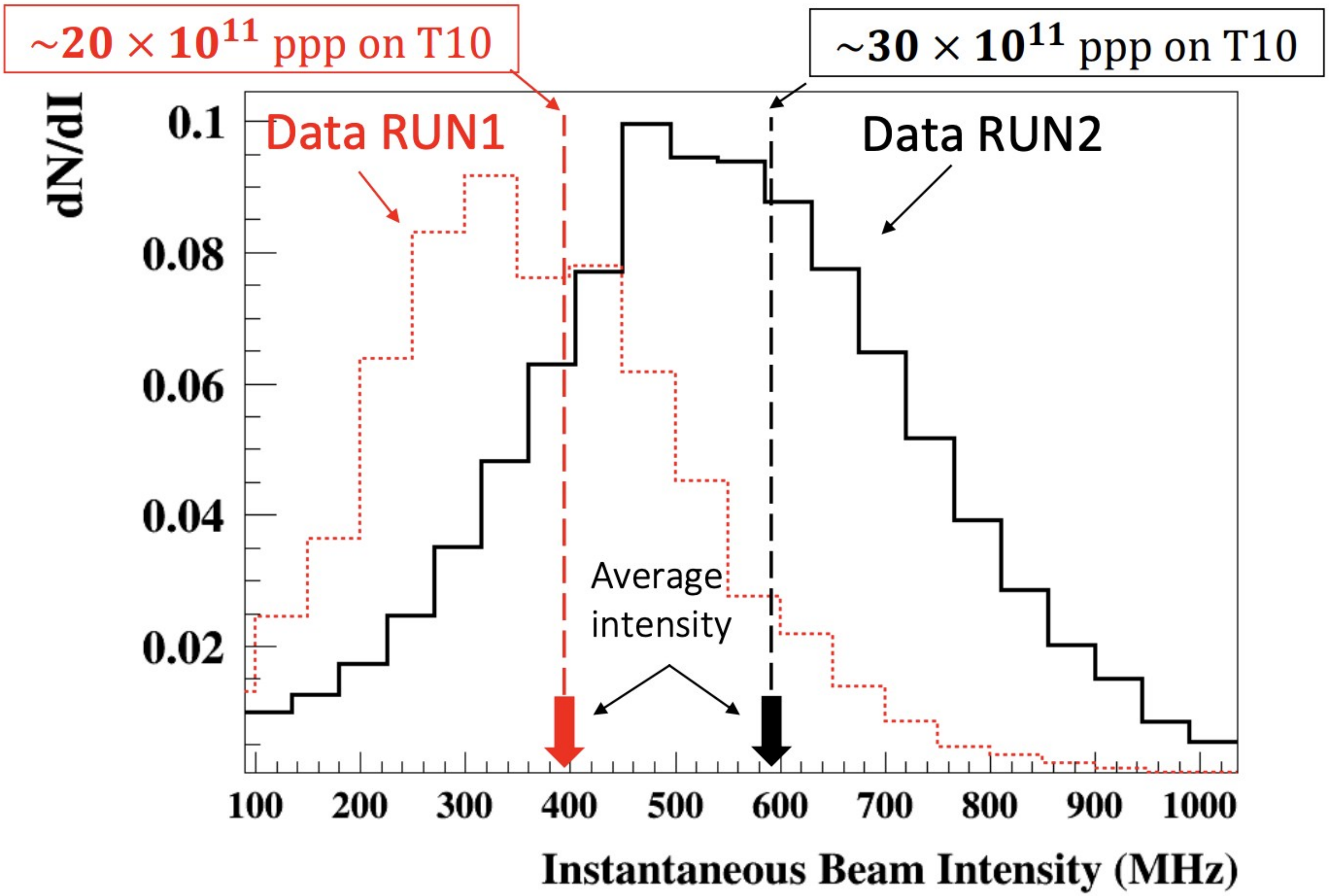
Spares

Beam Intesity



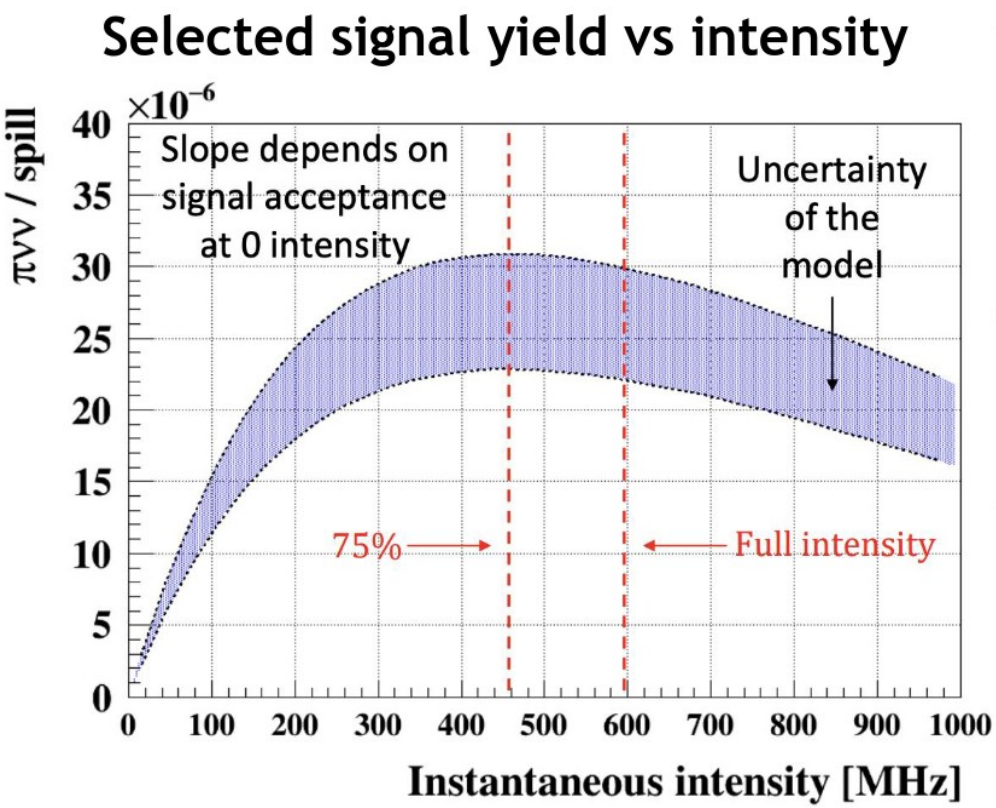

MNP33
Dipole Magnet
MUV0
LAV12
RICH
2021 - add HASC2
Additional downstream particles can be vetoed.
Sketch only
LKr
MUV1,2
MUV3
Iron wall
Dipole
Magnet
γ
Photon interaction
with RICH flange
IRC
HASC2
Beam pipe
γ
e−
SAC
Dump
π+
CHODs
e+
HASC1
x
STRAW
STRAW
z

Beam Intensity



- Avarage beam intensity increased
- NA62 "Full intensity" with 4.8 spill length = 600 MHz

Optimum NA62 Beam Intensity



- Saturation of expected signal yield with intensity. Mainly due to:
  - Paralyzable effects from TDAQ dead time and trigger veto windows.
  - Offline selection, due to veto conditions.
- Main sources of uncertainty for model:
  - Online time-dependent mis-calibrations.
  - Fit uncertainty.
- **From August 2023 operate at optimal intensity** (~75% of full) to maximise $\pi\nu\nu$ sensitivity
  - Maximise signal yield
  - lower expected background
  - Higher DAQ efficiency

Studies of 2021-2022 data at high intensity were crucial to define the optimal beam intensity

Results in context