First observartion of the ultra rare $K^+ \to \pi^+ \nu\bar{\nu}$ decay by NA62

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Speaker: Radoslav Marchevski
On behalf of the NA62 Collaboration

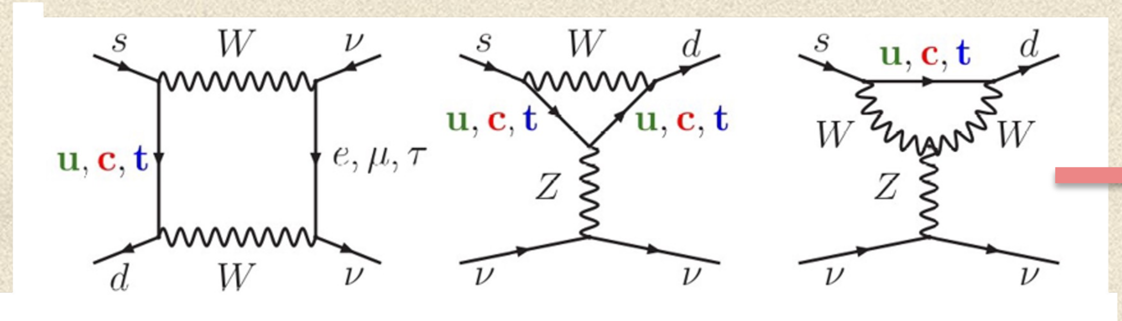
radoslav.marchevski@cern.ch
radoslav.marchevski@epfl.ch

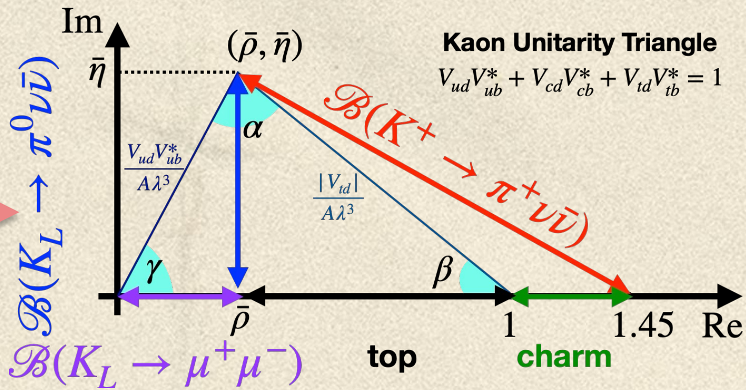
Swiss National Science Foundation

Outline

- The golden $K \to \pi\nu\bar{\nu}$ decay modes: Standard Model and beyond
- NA62: The K^+ factory at the CERN north area
- NA62: Analysis strategy, Detector, Upgrades & Performance
- $K^+ \to \pi^+\nu\bar{\nu}$: Analysis of Run 2 data
- $K^+ \to \pi^+\nu\bar{\nu}$ results: **First observation of the $\boldsymbol{K^+ \to \pi^+\nu\bar{\nu}}$ decay**

$K^+ \to \pi^+\nu\bar{\nu}$: a golden decay mode





- $s \to d$ transition sensitive to the CKM structure of the SM: *loop + CKM suppression*
- Theoretically clean process: *dominated by short-distance physics*
- $K - \pi$ Form Factor (FF) extracted from $K \to \pi l \nu_l$: *sub-% precision*
- Sensitive to new physics in the lepton sector as well: *involves* ν_e, ν_μ, *and* ν_τ

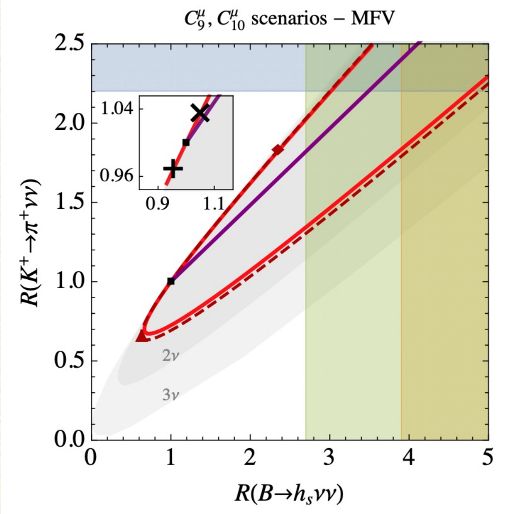
Mode	SM Branching Ratio [1]	SM Branching Ratio [2]	Experimental Status
$K^+ \to \pi^+\nu\bar{\nu}$	$(8.60 \pm 0.42) \times 10^{-11}$	$(7.86 \pm 0.61) \times 10^{-11}$	$(10.6 \pm 4.0) \times 10^{-11}$ NA62 16—18
$K_L \to \pi^0\nu\bar{\nu}$	$(2.94 \pm 0.15) \times 10^{-11}$	$(2.68 \pm 0.30) \times 10^{-11}$	$< 2 \times 10^{-9}$ KOTO (2021 data)

^Recent SM calculations [1:Buras et al. EPJC 82 (2022) 7, 615][2:D'Ambrosio et al. JHEP 09 (2022) 148]
(Differences in SM calculations from choice of CKM parameters: see [Eur.Phys.J.C 84 (2024) 4, 377])

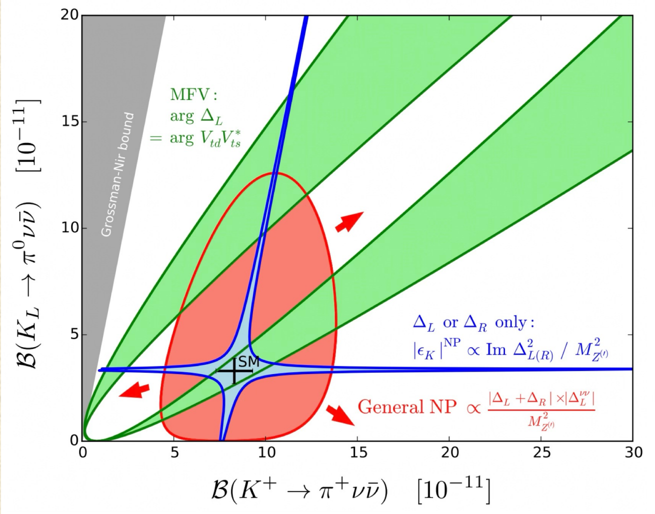
Testing the SM with FCNC: BSM models

- Correlations between BSM contributions to K^+/K_L modes: both need to be measured
- Correlations with other flavour observables (ϵ'/ϵ, ΔM_B, B decays) important
- Leptoquarks [EPJ.C 82 (2022) 4, 320], interplay between CC and FCNC [JHEP 07 (2023) 029], NP in neutrino sector [EPJ. C. 84 (2024) 7, 680], additional scalar/tenson contributions [JHEP 12 (2020) 186], [JHEP 10 (2024) 087]

[Phys. Lett. B 809 (2020) 135769]

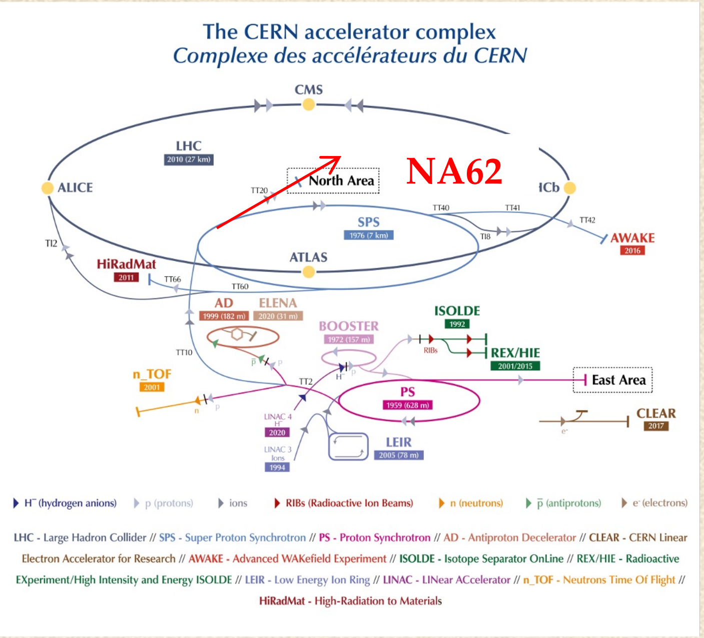


JHEP 11 (2015) 166



The NA62 experiment @ CERN

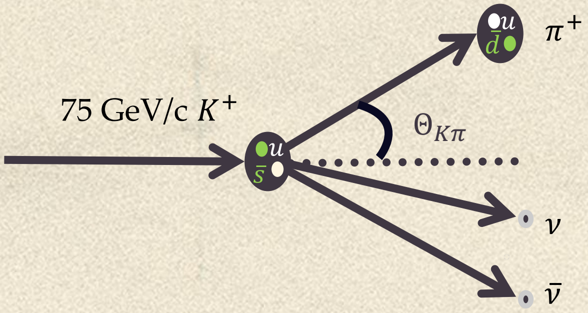
$K_{L,S}$	$K_{L,S}$	K_S	$K^\pm$	K^+	K^+	K^+
NA31	NA48	NA48/1	NA48/2	NA62 – R_K	NA62 Run1	NA62 Run2
1986 – 88	1997 – 2001	2002	2003 – 4	2007 – 8	2016 – 18	2021 –



- Long tradition of kaon experiments at CERN
- NA62 main target: **$K^+ \to \pi^+ \nu\bar{\nu}$ decay measurement**
  [PLB 791 (2019) 156] [JHEP 11 (2020) 042] [JHEP 06 (2021) 093]
- Broad physics program:
  - Rare K^+ decays (e.g. $K^+ \to \pi^+\gamma\gamma$ [PLB 850 (2024) 138513])
  - LFV/LNV searches (e.g. $K^+ \to \pi^-(\pi^0)e^+e^+$ [PLB 830 (2022) 137172])
  - Exotics (e.g. Dark photon [PRL 133 (2024) 11, 111802])
- Data taking
  - 2016-18 Physics run (45 + 160 + 217 days)
  - 2021 Physics run (85 days [10 beam dump])
  - 2022 Physics run (215 days)
  - 2023 Physics run (205 days [10 beam dump])
  - 2024 Physics run (204 days [12 beam dump, 7 low intensity])

200 collaborators from 31 institutions

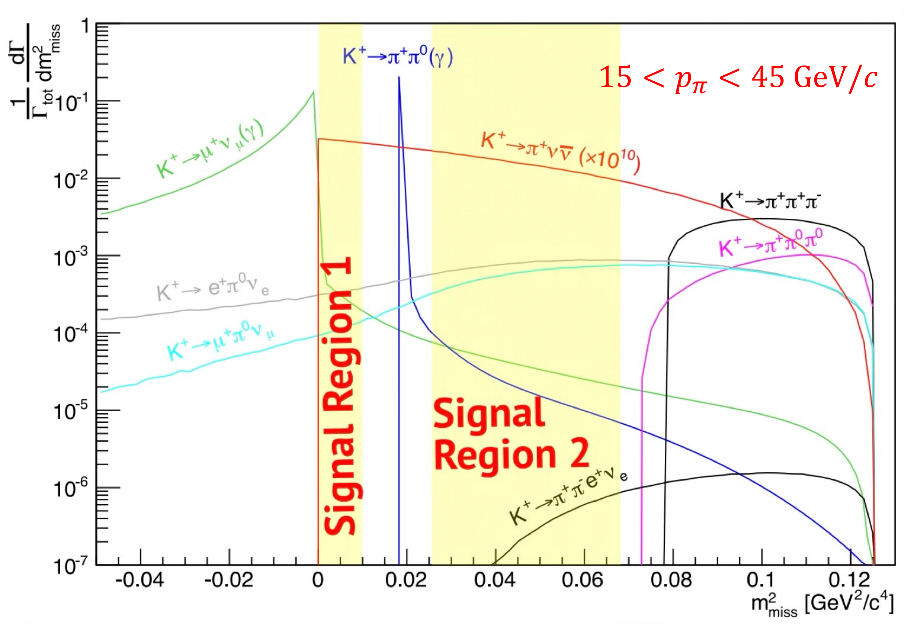
Analysis strategy



Squared missing mass (mass of the $\nu\bar{\nu}$ pair):

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

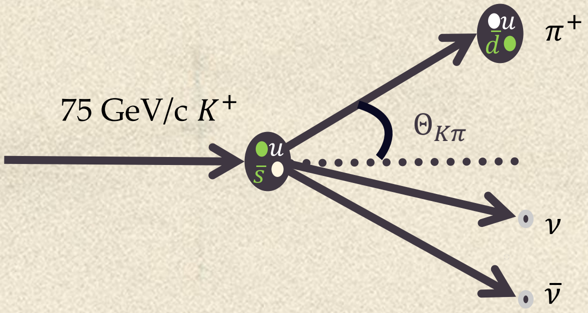
π^+ mass hypothesis



- Highly boosted decay: (75 ± 1) GeV/c K^+ ($\gamma \sim 150$)
- Large undetectable missing energy carried away by the neutrinos
- All energy from visible particles must be detected
- π^+ momentum range 15 – 45 GeV/c ($E_{miss} > 30$ GeV)
- Hermetic detector coverage and O(100%) detector efficiency needed

- **Requirements:**
  - Kinematic suppression – $O(10^4)$
  - μ^+ rejection – $O(10^7)$
  - π^0 rejection – $O(10^7)$
  - Time resolution – $O(100$ ps$)$

Analysis strategy



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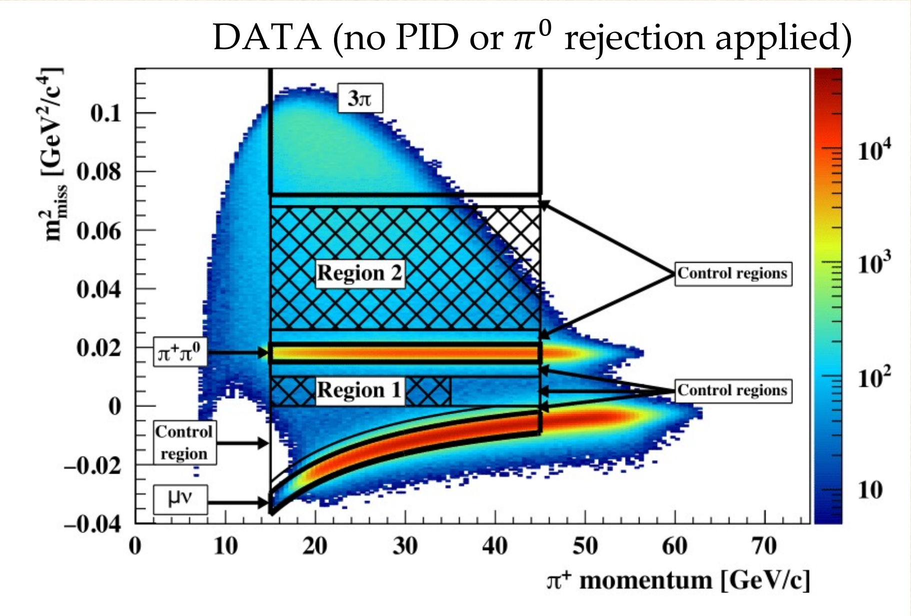

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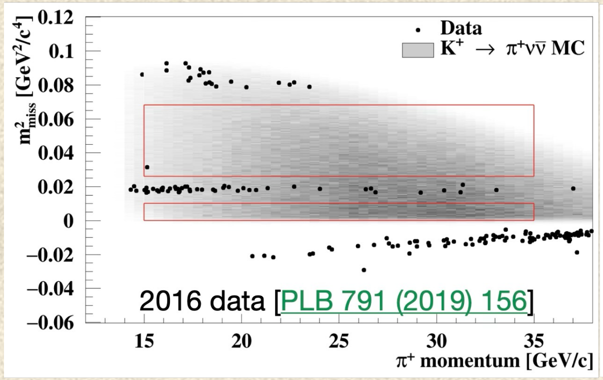
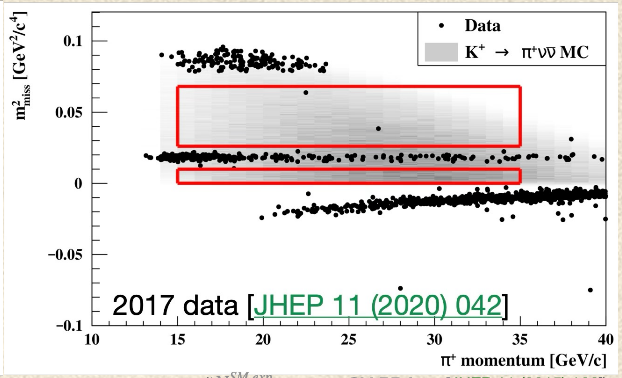
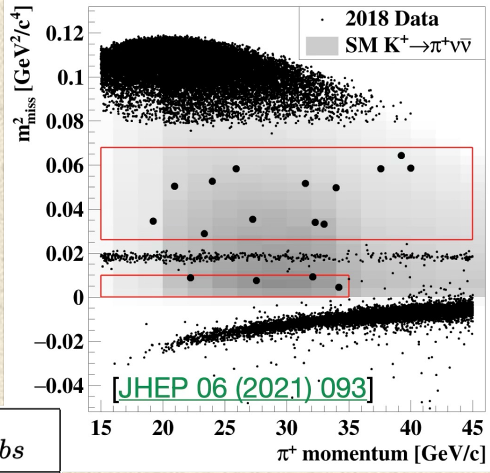
Blast from the past: NA62 Run1 results







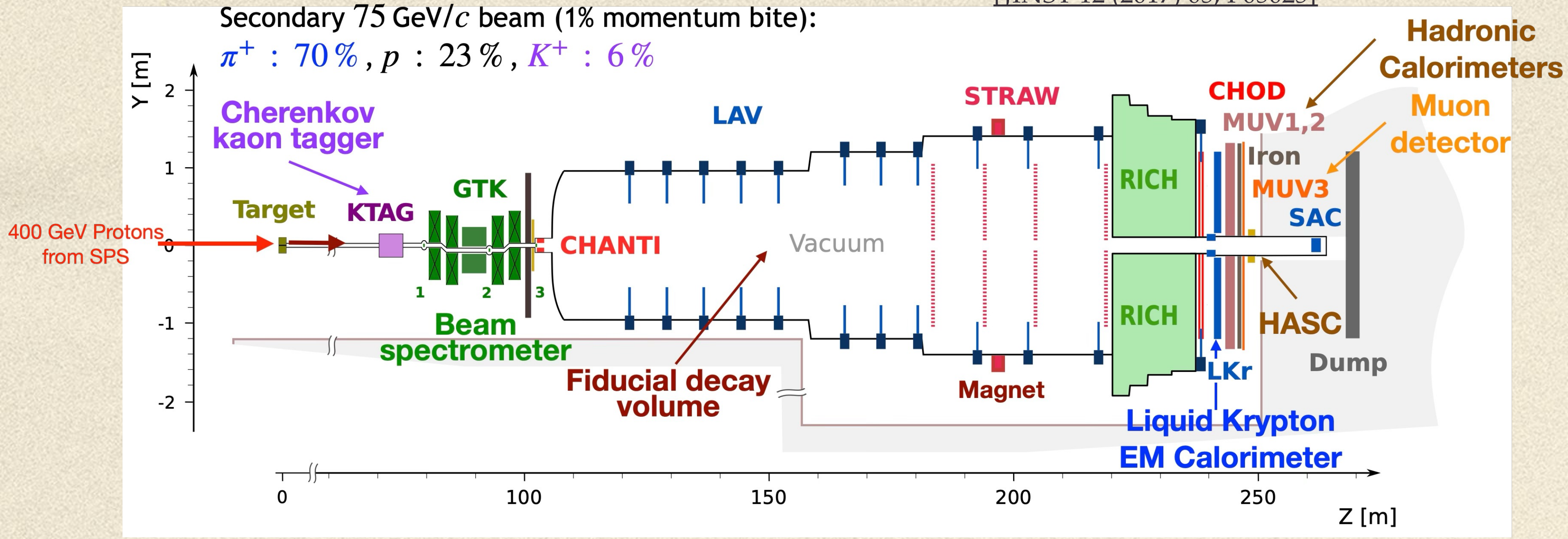
(* $N^{SM,exp}_{\pi\nu\bar{\nu}}$ assumes SM BR from [JHEP 11 (2015) 166])

Data-taking year	[Reference]	N_{bg}	$N^{SM,exp}_{\pi\nu\bar{\nu}}$	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

- $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$ [JHEP 06 (2021) 093]
- Background-only hypothesis $p = 3.4 \times 10^{-4} \Longrightarrow$ significance 3.4σ

The NA62 experimental apparatus

[JINST 12 (2017) 05, P05025]

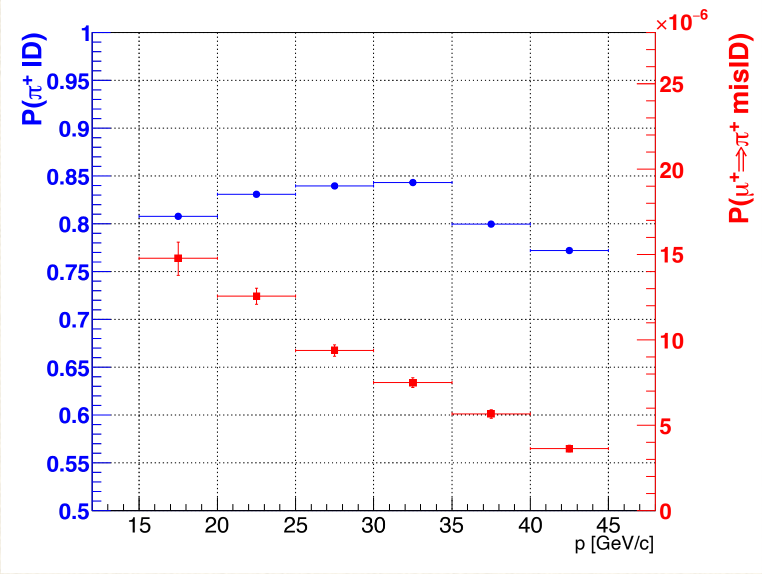


- Designed and optimized to study $K^+ \to \pi^+ \nu \bar{\nu}$ decays
  - **Particle tracking:** beam particle **(GTK)** & downstream tracks **(STRAW)**
  - **PID:** K^+ - **KTAG**, π^+ - **RICH**, Calorimeters (**LKr**, **MUV1/2**), **MUV3** (μ detector)
  - **Hermetic veto systems:** **CHANTI** (beam interactions), **LAV**, **LKr**, **IRC**, **SAC** (γ)

Particle ID performance: 2021-22 data

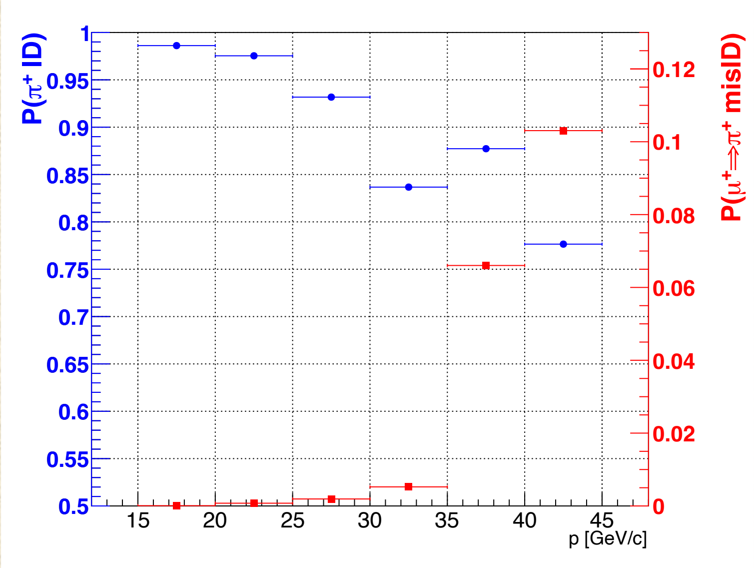
Calorimeters

- BDT classifier for LKr & MUV1/2
- + MUV3 (fast μ detector)



RICH

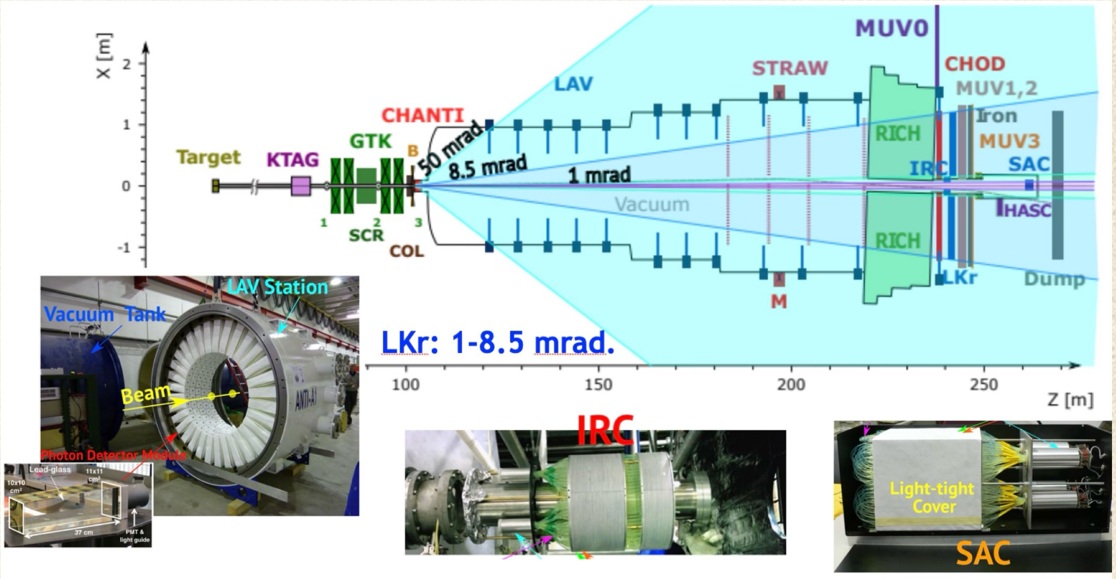
- Designed to distinguish between π^+/μ^+ in the $15-35$ GeV$/c$ momentum range



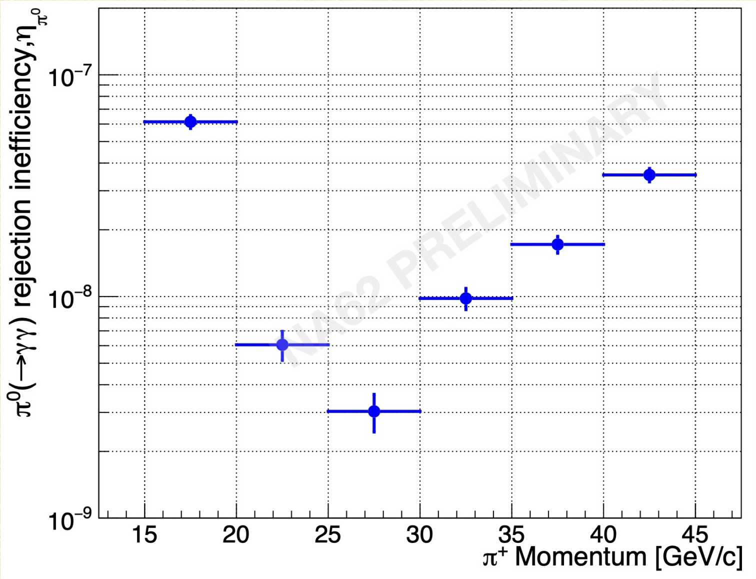
$$\varepsilon(\pi\,\textbf{ID}) = (73.00 \pm 0.01)\,\%$$

$$P(\mu^+\,\textbf{misID as}\,\pi^+) = (1.3 \pm 0.2) \times 10^{-8}$$

Photon veto system: 2021-22



Control sample of $K^+ \to \pi^+\pi^0$



- Probability of $K^+ \to \pi^+\pi^0, \pi^0 \to \gamma\gamma$ event passing all photon veto conditions

$$\eta_{\pi^0} = (1.72 \pm 0.07)\times 10^{-8}$$

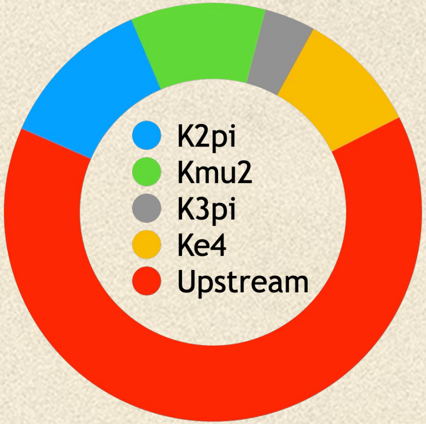
Meets target: combined π^0/γ rejection of $\mathcal{O}(10^8)$

Upgrading NA62

- **2016 – 18 analysis proved NA62 technique**
- **Limitations:** tight cuts to reject background ⟹ reduces signal efficiency
- **To improve:** new tools for background suppression

Background	N(exp) 2018 (S2)
Upstream	$2.76^{+0.90}_{-0.70}$
$K^+ \to \pi^+\pi^0$	0.52 ± 0.05
$K^+ \to \mu^+\nu$	0.45 ± 0.06
$K^+ \to \pi^+\pi^-e^+\nu$	0.41 ± 0.10
$K^+ \to \pi^+\pi^+\pi^-$	0.17 ± 0.08
Total	$4.31^{+0.91}_{-0.72}$

K^+ decays in decay tank



Upstream background

Largest backgrounds:

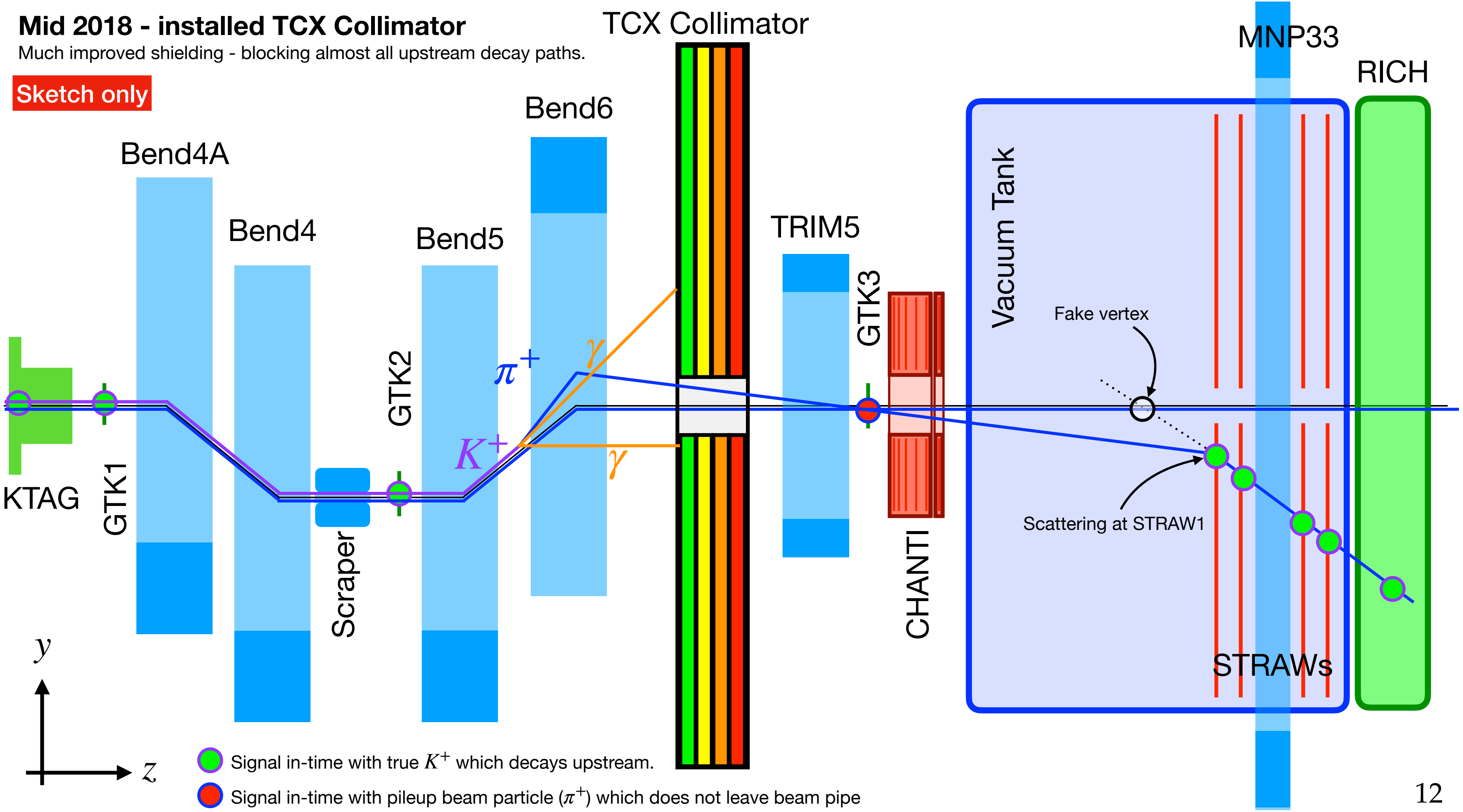
1. Upstream
2. $K^+ \to \pi^+\pi^0$

Veto by detecting previously missed particles …

Mid 2018 - installed TCX Collimator

Much improved shielding - blocking almost all upstream decay paths.

Sketch only

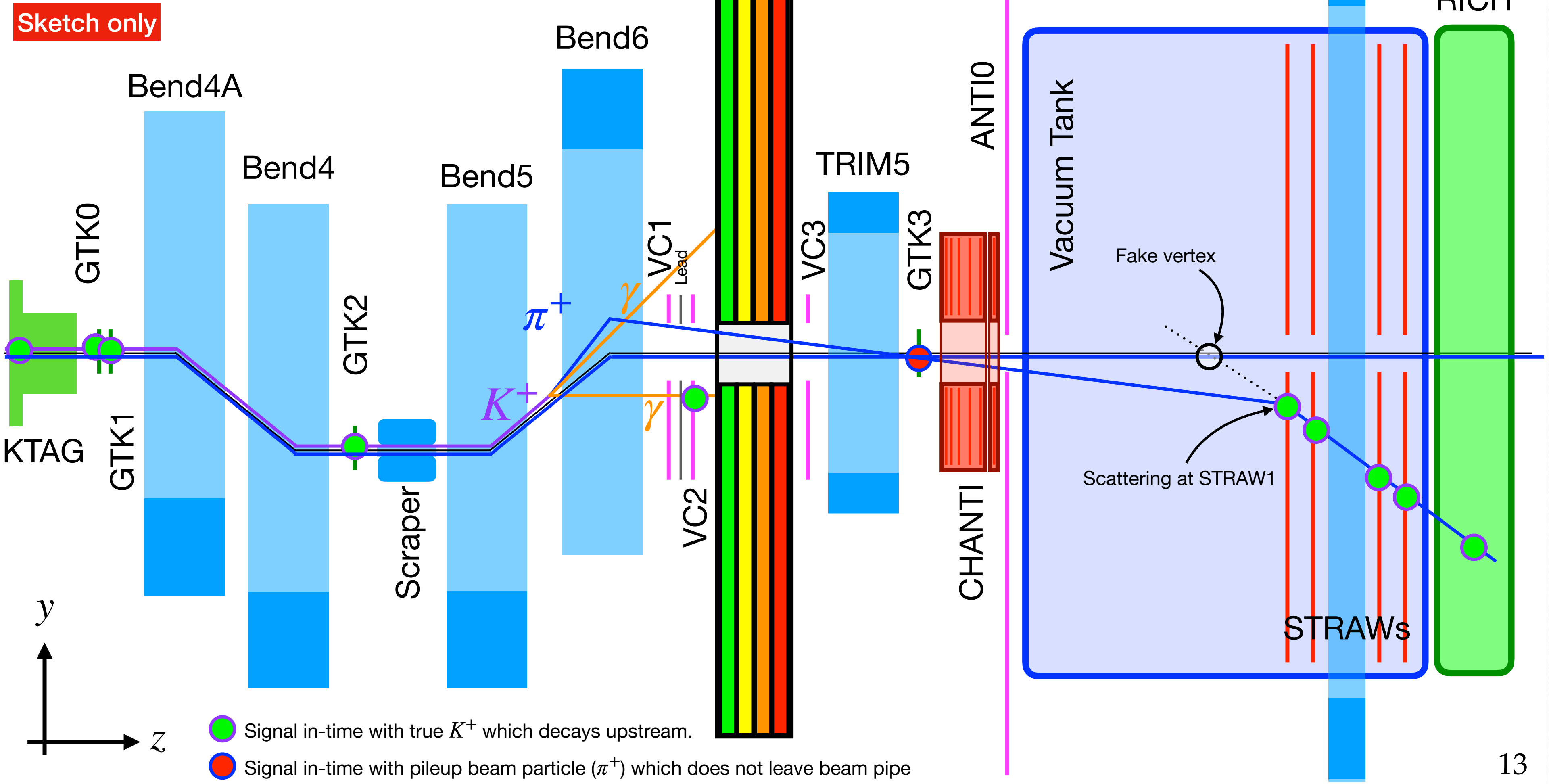


Signal in-time with true K^+ which decays upstream.

Signal in-time with pileup beam particle (π^+) which does not leave beam pipe

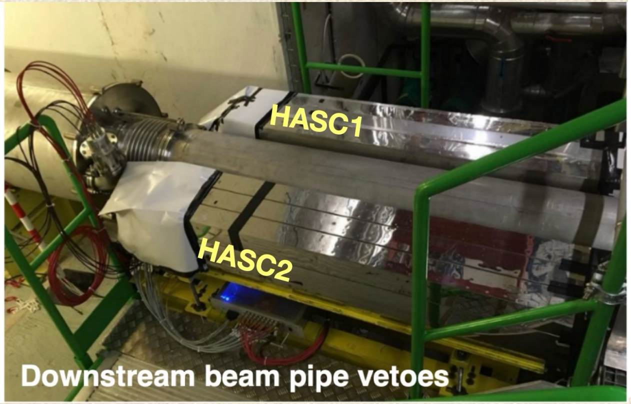
2021 - addition of VetoCounter

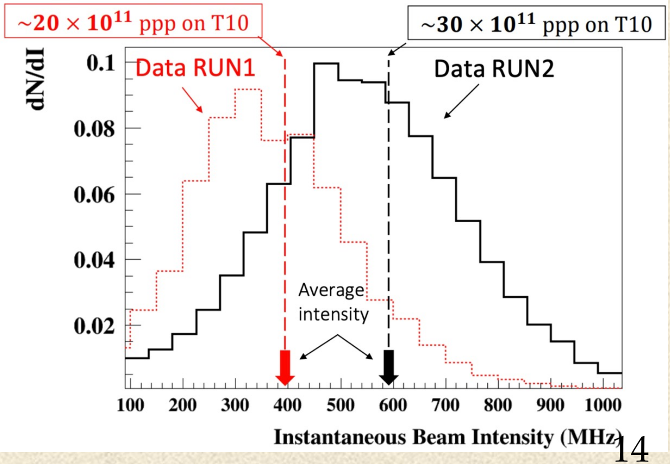
Upstream decays can be detected and actively vetoed.



Summary of NA62 upgrades

- New detectors installed during LS2
- 4^{th} GTK station & rearranging the beam elements in the upstream section of NA62
- New upstream veto (VetoCounter) & veto hodoscope (ANTI0) upstream of decay volume
- Additional veto detector (HASC2) at the end of the beam-line
- Intensity increased by ~35% with respect to 2018 [450 → 600 MHz]
- Improvements to the trigger configuration

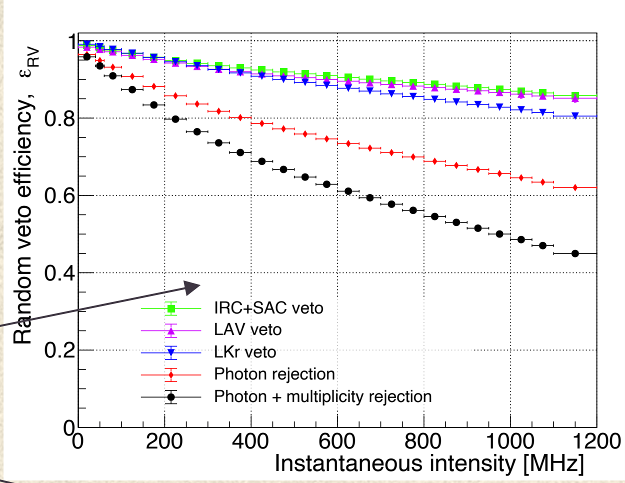




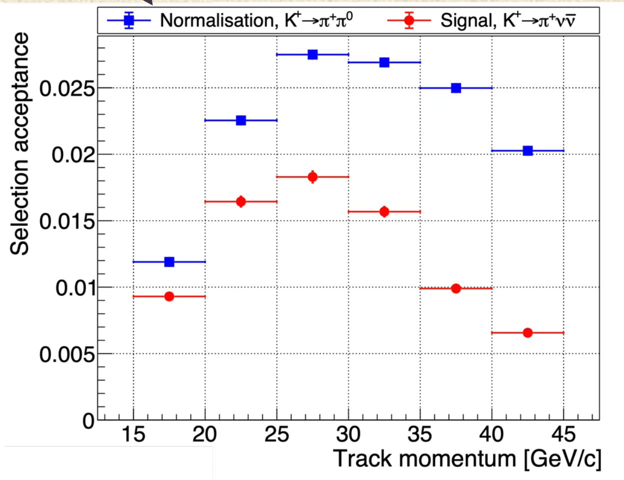
$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ in Run 2 (2021-22)

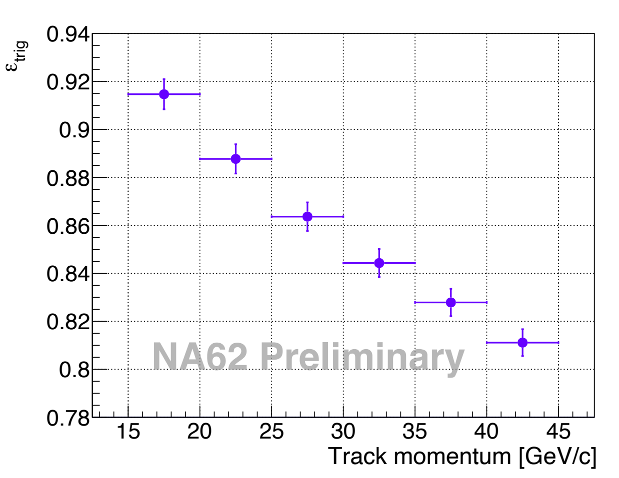
- $K^+ \rightarrow \pi^+\pi^0$ used as a normalization decay

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



Case	OLD 2018 (S2)	NEW 2021–22	
Norm.	11.8%	13.4%	+15%
Signal	(6.37±0.64)%	(7.61±0.18)%	+20%





$K^+ \to \pi^+ \nu\bar{\nu}$ in Run 2 (2021-22)

$N_{\pi\pi}$	Normalisation $K^+ \to \pi^+\pi^0$	2.0×10^8
$A_{\pi\pi}$	Normalisation acceptance	$(13.410 \pm 0.005)\%$
N_K	Effective K^+ decays	2.9×10^{12}
$A_{\pi\nu\bar{\nu}}$	Signal acceptance	$(7.6 \pm 0.2)\%$
ε_{trig}	Trigger efficiency	$(85.9 \pm 1.4)\%$
ε_{RV}	Random veto efficiency	$(63.6 \pm 0.6)\%$
$\mathcal{B}_{SES}$	Single event sensitivity	$(0.84 \pm 0.03) \times 10^{-11}$

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

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

- Acceptances evaluated at 0 intensity
- Significant improvements in SES uncertainty: **6.5% → 3.5%**
    - trigger efficiency cancellations
    - improved procedures for evaluation of acceptances and ϵ_{RV}

Signal and background 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	$11.0^{+2.1}_{-1.9}$

Signal Sensitivity

$$\mathcal{B}_{SES} = (0.84 \pm 0.03)\times10^{-11}$$

$$N^{SM,exp}_{\pi\nu\bar{\nu}} = \frac{\mathcal{B}^{SM}_{\pi\nu\bar{\nu}}}{\mathcal{B}_{SES}}$$

Assuming $\mathcal{B}^{SM}_{\pi\nu\bar{\nu}} = 8.4 \times10^{-11}$:

2021 – 22: $N_{\pi\nu\bar{\nu}} = 10.00 \pm 0.34$

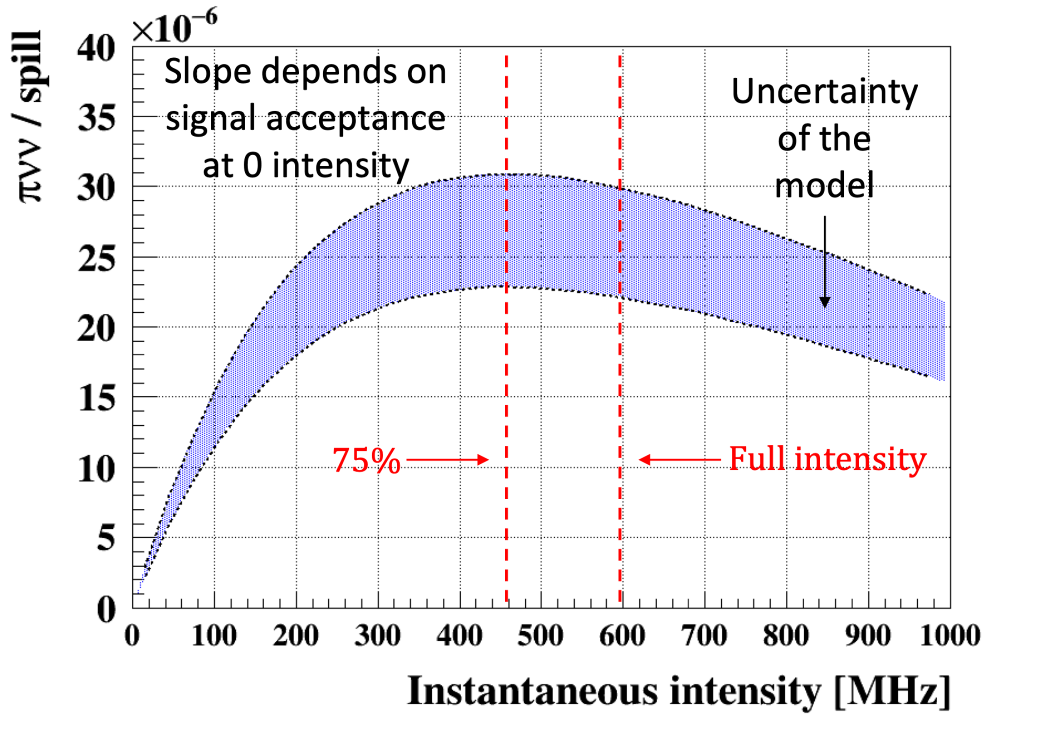
c.f. 2016 – 18: $N_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42$

Expected signal doubled by including 2021 – 22

- $N^{SM}_{\pi\nu\bar{\nu}}$ per SPS spill: 2.5×10^{-5} in 2022
  - c.f. 1.7×10^{-5} in 2018 $\Rightarrow$ **signal yield increased by 50%**
- BR sensitivity $\sim\sqrt{S+B}/S = 0.5$
  - similar but improved wrt 2018 analysis for the same amount of data

Optimal NA62 intensity

Selected signal yield vs intensity

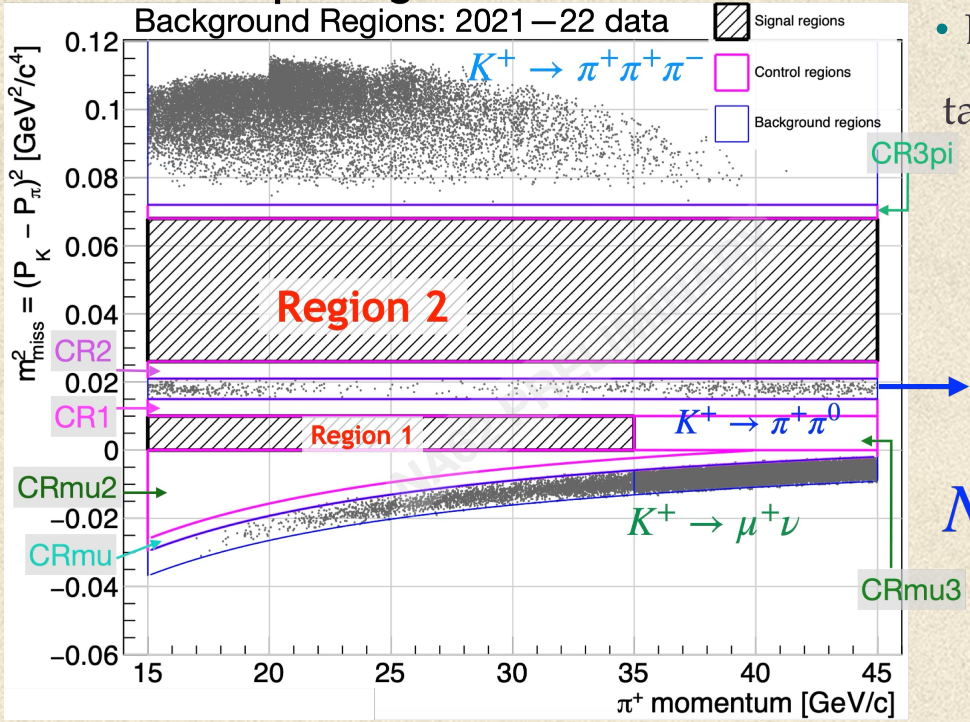


- Saturation of expected signal yield with intensity:
  - paralyzable effect due to TDAQ dead time
  - offline selection, due to veto conditions
- Main sources of uncertainty of the model
  - online time—dependent mis-calibration
  - fit uncertainty
- **Operating at optimal intensity (75% of full) to maximise $\pi\nu\bar{\nu}$ sensitivity**
  - Better yield
  - Lower expected background
  - Higher DAQ efficiency

Studies of 2021—22 data at high intensity were crucial to establish optimal intensity

Background regions and & estimations

Events passing $\pi\nu\nu$ selection



- Background from kinematic misreconstruction tails in m^2_{miss}

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

Number of events passing signal selection in background region (N_{bkgR})

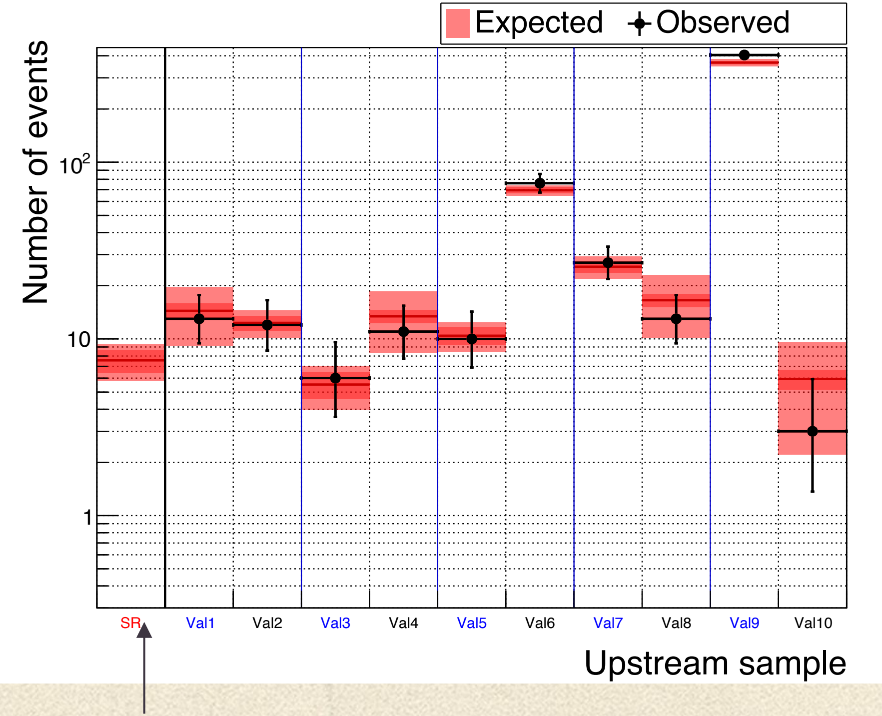
Kinematic tail fraction: measured in control sample (f_{tail})

Control sample events in Signal Regions (N^{CS}_{SR})

Control sample events in Background Region (N^{CS}_{bkgR})

Upstream background validation

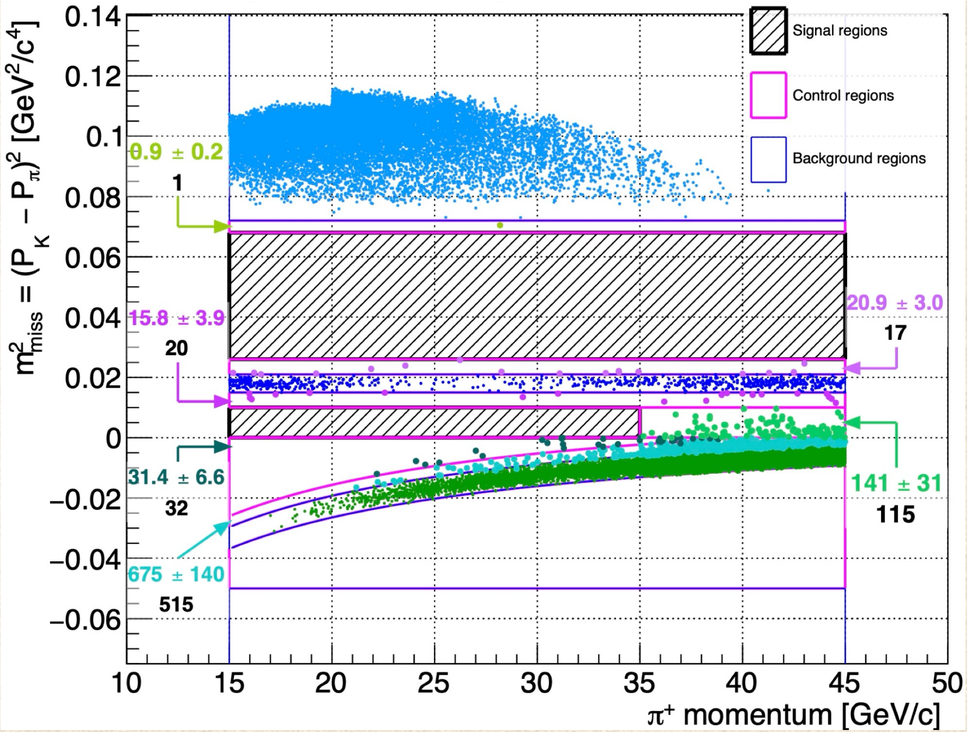
- Invert and loosen upstream vetoes to enrich with different mechanisms
  - **Interaction-enriched: Val1, 2, 7, 8**
  - **Accidental-enriched: Val3, 4, 5, 6, 9, 10**
  - **All samples independent**
- Good agreement between expectation and observation across validation samples
- Number of events rejected by VetoCounter (i.e. events in signal region with associated VC signal):
  - $N_{exp}^{VC\,rej.} = 6.9 \pm 1.4, N_{obs}^{VC\,rej.} = 9$
- **VetoCounter essential to control background!**

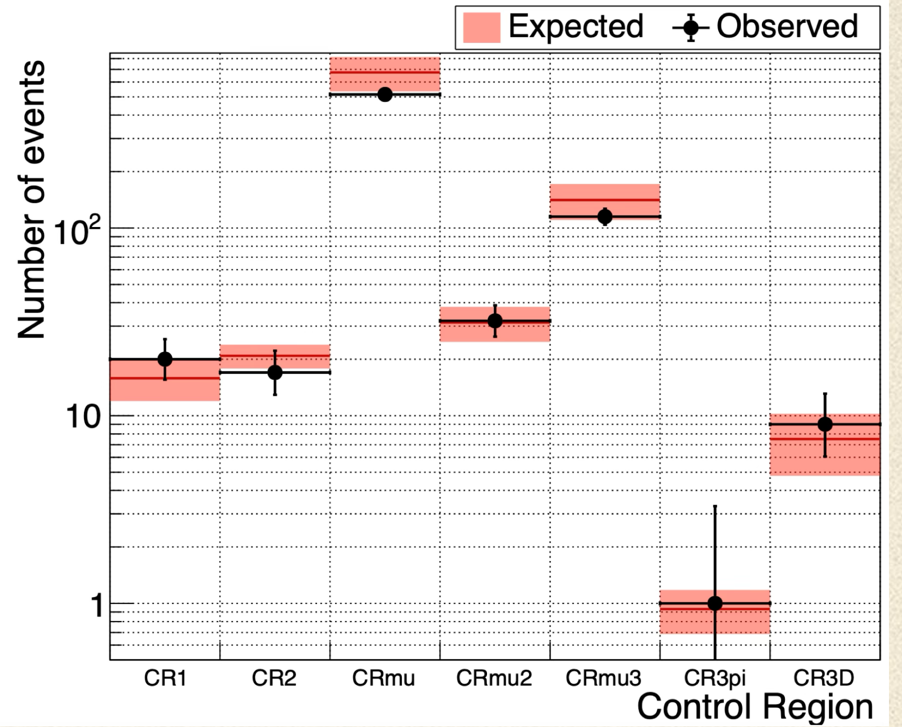


Signal region masked

Control regions

2021 – 22 data





Good agreement across all control regions validates background expectations

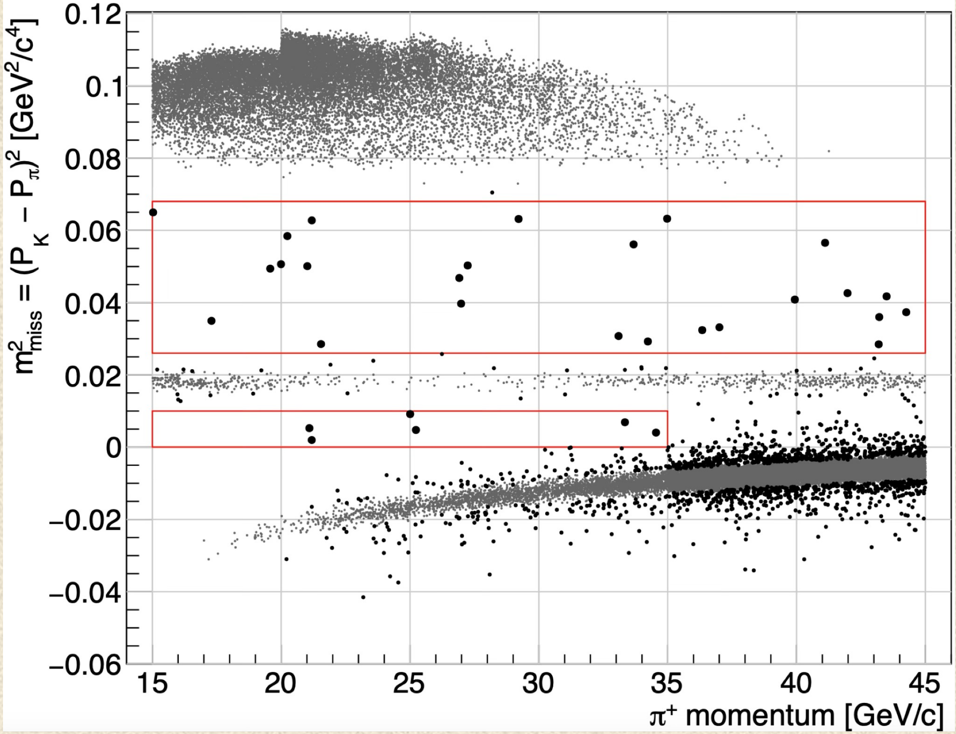
Signal regions

Expected SM signal: $N_{\pi\nu\bar{\nu}}^{SM} \approx 10$

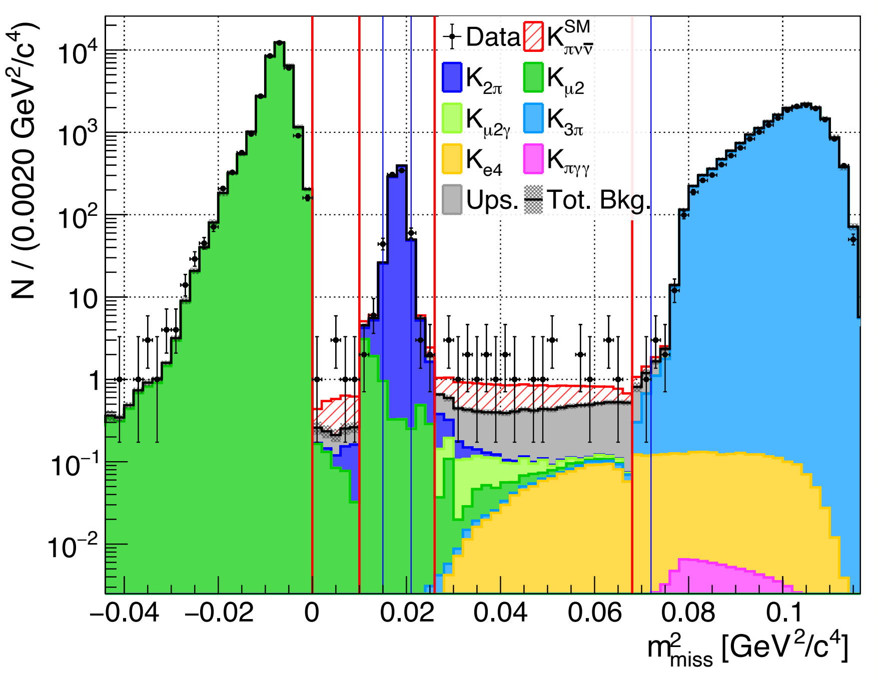
Expected background: $N_{bg} = 11.0^{+2.1}_{-1.9}$

Observed: $N_{obs} = 31$

2021 – 22 data

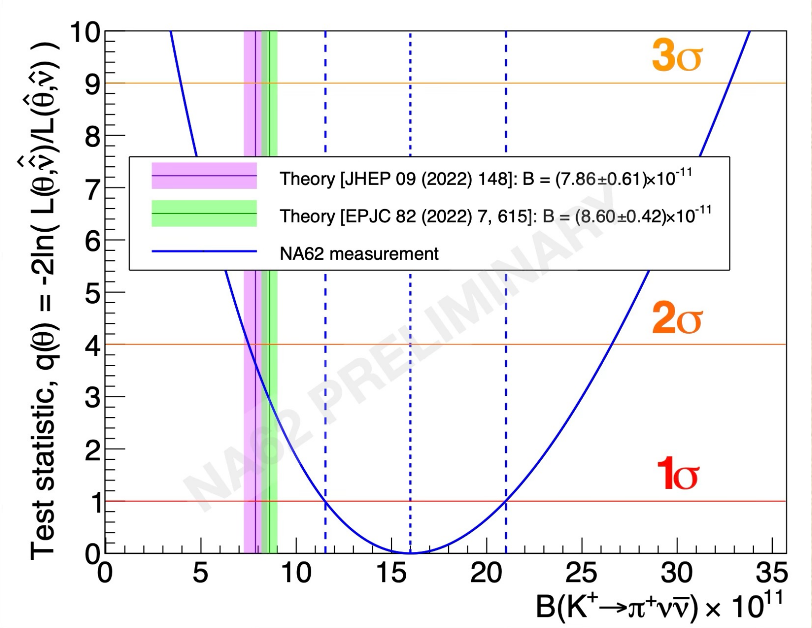


1D projection with differential background predictions & SM signal expectation [not a fit]:

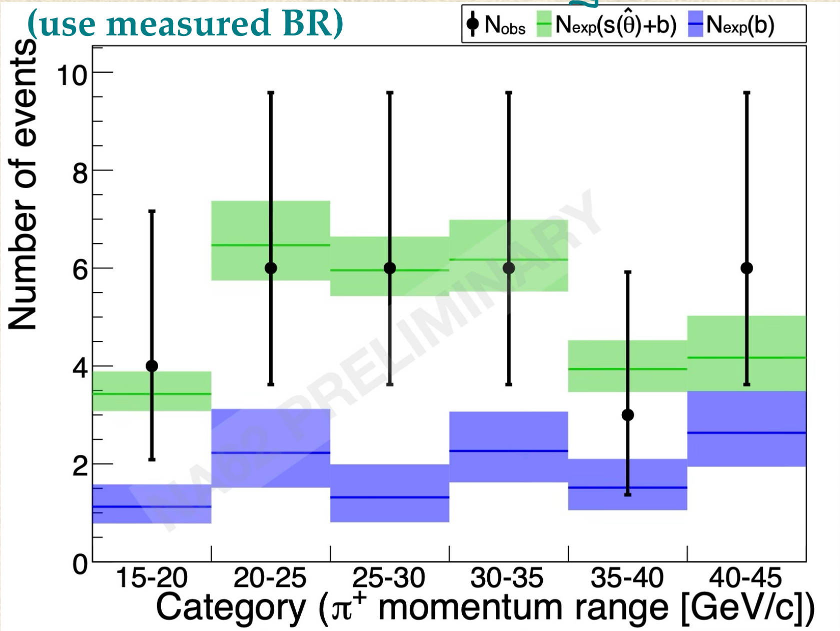


$K^+ \to \pi^+\nu\bar{\nu}$ results: 2021-22 data

- Measure $\mathcal{B}_{\pi\nu\bar{\nu}}$ and 68% (1σ) confidence interval using a profile likelihood ratio test statistics $q(\theta)$
- Use 6 (momentum bins) categories



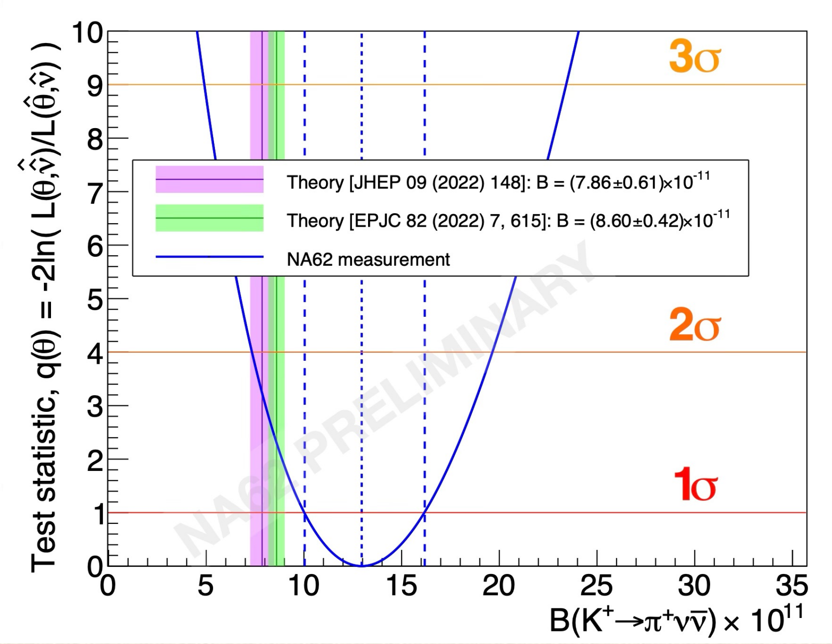
After fit (use measured BR)

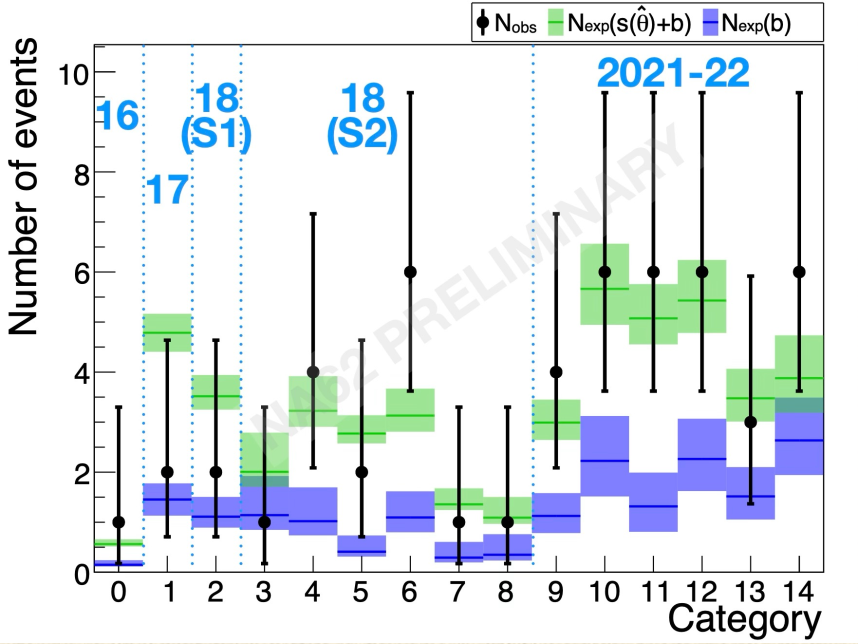


$$\mathcal{B}_{21-22}(K^+ \to \pi^+\bar{\nu}\nu) = \left(16.0^{+5.0}_{-4.5}\right)\times 10^{-11} = \left(16.0^{+4.8}_{-4.2}\Big|_{\text{stat}}\ {}^{+1.4}_{-1.3}\Big|_{\text{syst}}\right)\times 10^{-11}$$

Combining NA62 results: 2016-2022

- Integrating 2016-2022 data: $N_{bg} = 18^{+3}_{-2}, N_{obs} = 51$
- Background only hypothesis: $\boldsymbol{p - \text{value} = 2\times10^{-7} \Longrightarrow \text{significance } Z > 5}$





$$\mathcal{B}_{16-22}(K^+ \to \pi^+\bar{\nu}\nu) = (13.0^{+3.3}_{-2.9})\times10^{-11} = \left(13.0^{+3.0}_{-2.7}\Big|_{stat}{}^{+1.3}_{-1.2}\Big|_{syst}\right)\times10^{-11}$$

Results in context

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

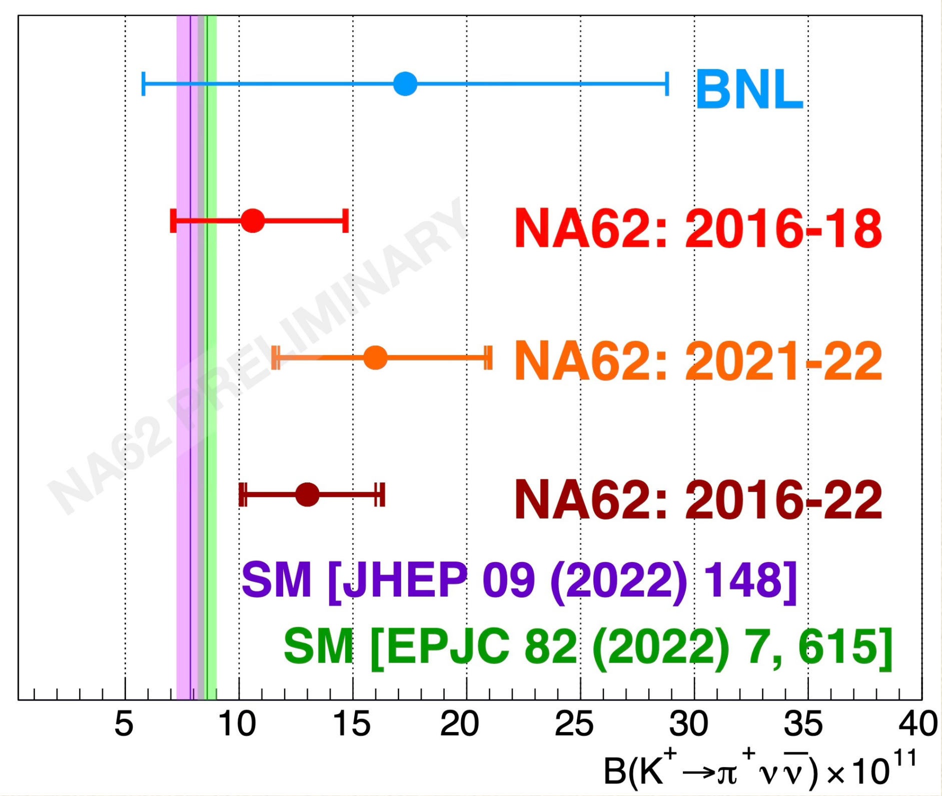
- $\mathcal{B}_{\pi\nu\bar{\nu}}^{16-18} = \left(10.6^{+4.1}_{-3.5}\right)\times 10^{-11}$

  [JHEP 06 (2021) 093]

- $\mathcal{B}_{\pi\nu\bar{\nu}}^{21-22} = \left(16.0^{+5.0}_{-4.5}\right)\times 10^{-11}$

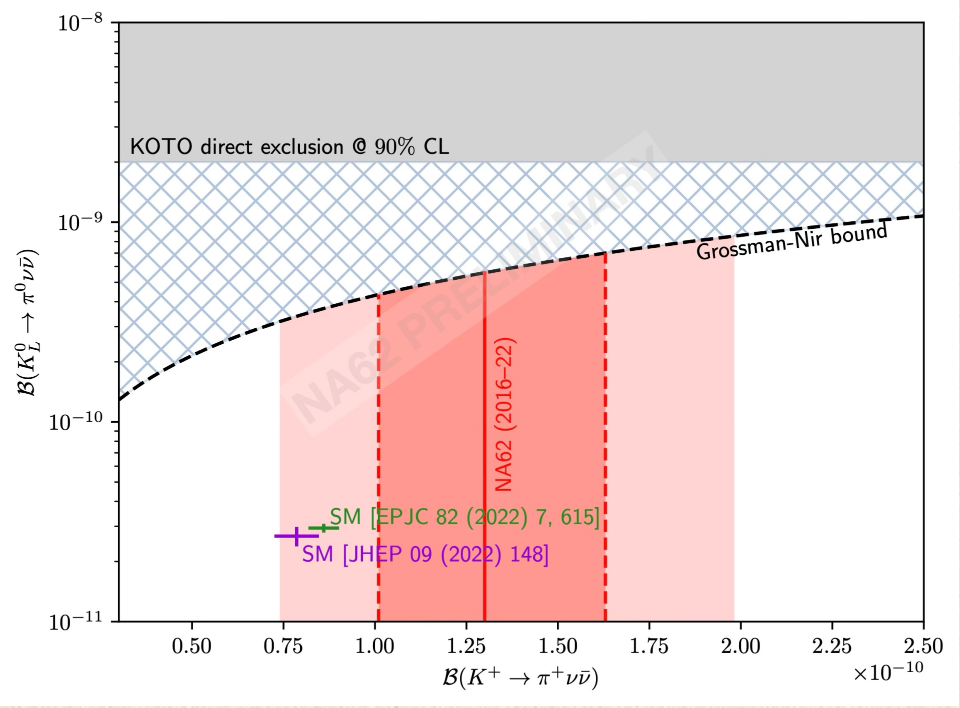
- $\mathcal{B}_{\pi\nu\bar{\nu}}^{16-22} = \left(13.0^{+3.3}_{-2.9}\right)\times 10^{-11}$

- NA62 results are consistent
- Central value moved up ($1.5 - 1.7\sigma$ above SM)
- Fractional uncertainty decreased: **40% → 25%**
- Bkg-only hypothesis rejected with significance $\boldsymbol{Z > 5}$



Results in context

- Fractional uncertainty: 25%
- Bkg-only hypothesis rejected with significance $Z > 5$
- **Observation of the $K^+ \to \pi^+\bar{\nu}\nu$ decay with BR consistent with the SM within 1.7σ**
- **Need full NA62 data set to clarify SM agreement or tension**



$$\mathcal{B}^{16-22}_{\pi\nu\bar{\nu}} = \left(13.0^{+3.3}_{-2.9}\right)\times10^{-11}$$

KOTO preliminary: [Eur.Phys.J.C 84 (2024) 4, 377]

2σ range : $[7.4 - 19.7] \times 10^{-11}$

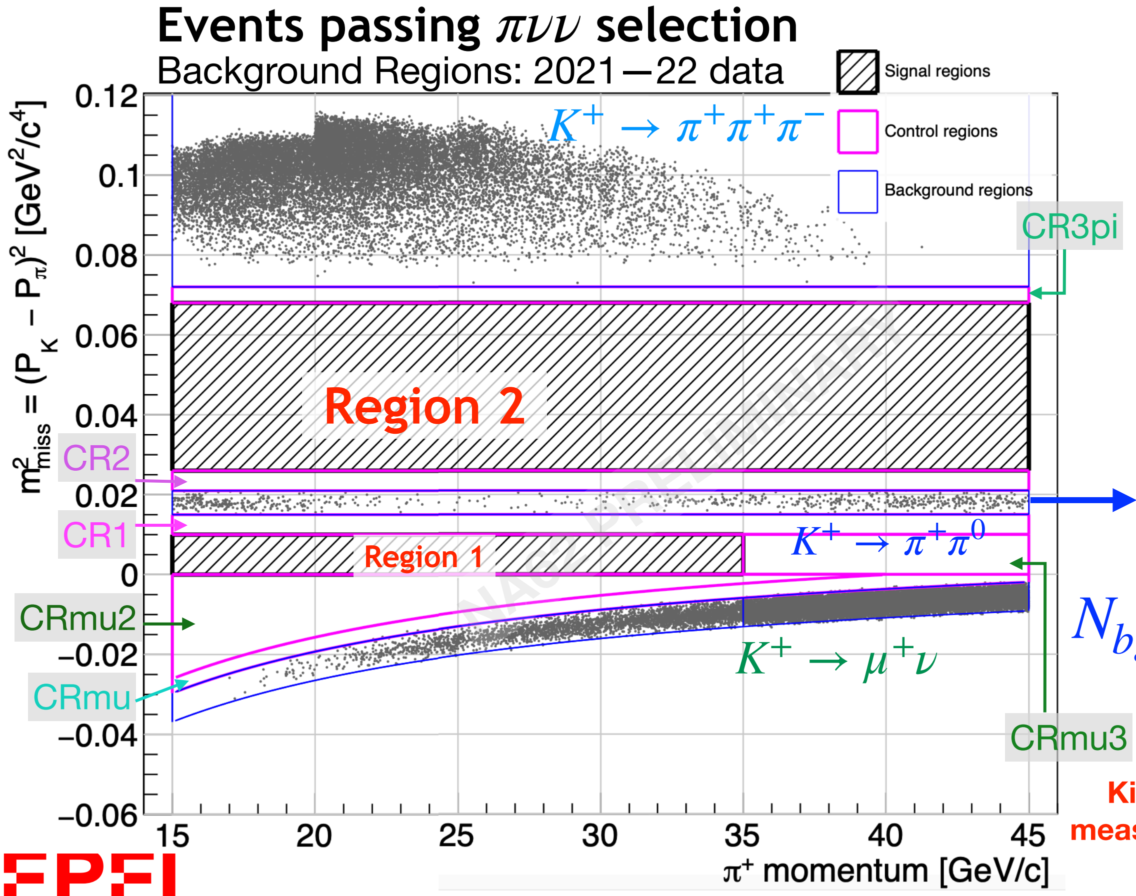
Conclusions

- New study of $K^+ \to \pi^+ \nu\bar{\nu}$ decay using $2021-22$ dataset
  - Improved signal yield per SPS spill by 50%
  - $N_{bg} = 11.0^{+2.1}_{-1.9}, N_{obs} = 31$
  - $\boldsymbol{\mathcal{B}_{21-22}(K^+ \to \pi^+ \bar{\nu}\nu) = \left(16.0^{+5.0}_{-4.5}\right)\times 10^{-11} = \left(16.0^{+4.8}_{-4.2}|_{stat}{}^{+1.4}_{-1.3}|_{syst}\right)\times 10^{-11}}$
- Combining with $2016-18$ data we get the full $2016-22$ result
  - $N_{bg} = 18^{+3}_{-2}, N_{obs} = 51$ (using 9+6 categories for BR extraction)
  - $\boldsymbol{\mathcal{B}_{16-22}(K^+ \to \pi^+ \bar{\nu}\nu) = \left(13.0^{+3.3}_{-2.9}\right)\times 10^{-11} = \left(13.0^{+3.0}_{-2.7}|_{stat}{}^{+1.3}_{-1.2}|_{syst}\right)\times 10^{-11}}$
  - Bkg-only hypothesis rejected with significance $\boldsymbol{Z > 5}$
- **First observation of the $K^+ \to \pi^+ \bar{\nu}\nu$ decay: BR consistent with the SM within 1.7σ**
  - **Need full NA62 data set to clarify SM agreement or tension**

$2023-$ LS3 data set collection and analysis in progress …

Backup slides

Background regions & background estimations



- Backgrounds from kinematic misconstruction tails in m^2_{miss}

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

Number of events passing signal selection in background region

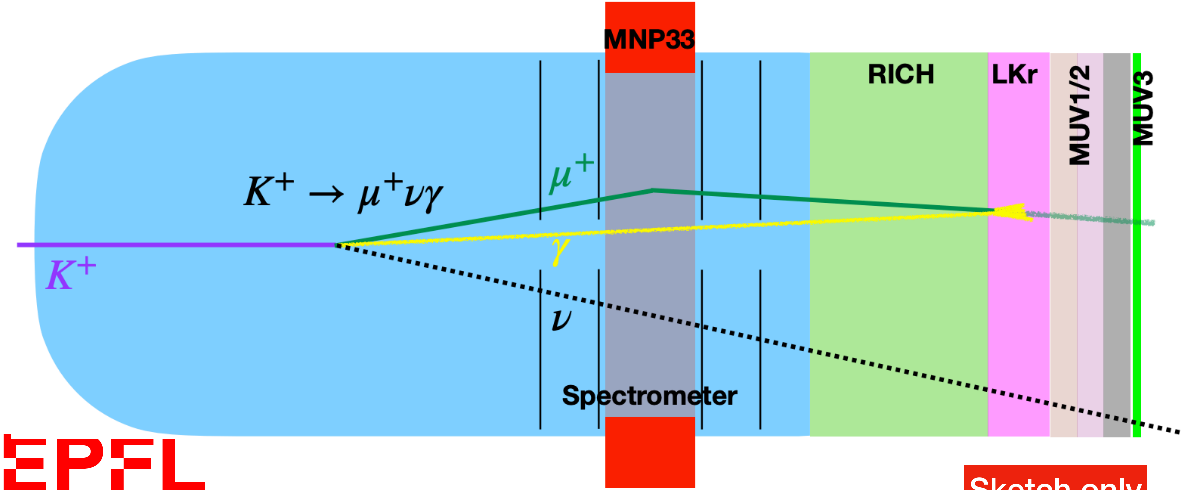
Kinematic tail fraction: measured in control sample

Control sample events in Signal Regions

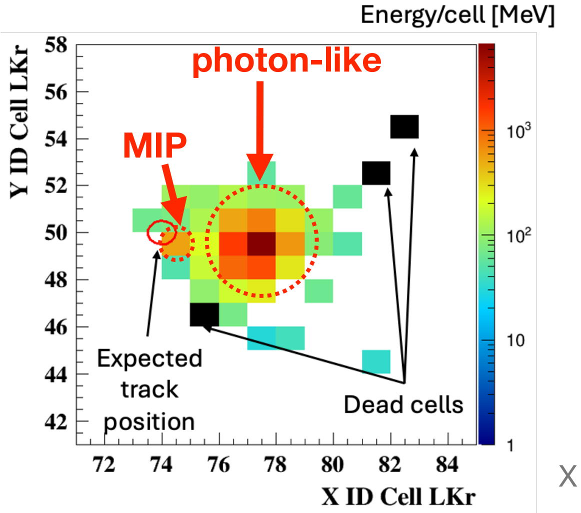
Control sample events in Background Region

Radiative decays: $K^+ \to \pi^+\pi^0\gamma$ & $K^+ \to \mu^+\nu\gamma$

- $K^+ \to \pi^+\pi^0\gamma$: **included with "kinematic tails" estimation.**
  - Suppression: photon vetos, rejection with additional γ is 30x stronger.
  - Estimation: MC + measured single photon rejection efficiency : $N_{bg}(K^+ \to \pi^+\pi^0\gamma) = 0.07 \pm 0.01$
  - Validation: m^2_{miss} control regions (CR1,2 - see later)
- $K^+ \to \mu^+\nu\gamma$: **not included in "kinematic tails" estimation if γ overlaps μ^+ at LKr (leading to misID as π^+)**
  - Suppression: based on $(P_K - P_\mu - P_\gamma)^2$ and E_γ with γ = LKr cluster (mis)associated to muon.
    - Necessary for 2021—22 data, since Calorimetric PID degraded at higher intensities.
  - Estimation: min. Bias data control sample with signal in MUV3 : $N_{bg}(K^+ \to \mu^+\nu\gamma) = 0.8 \pm 0.4$
  - Validation: data sample without $K^+ \to \mu^+\nu\gamma$ veto and PID = "less pion-like" (Calo BDT bins below π^+ bin).



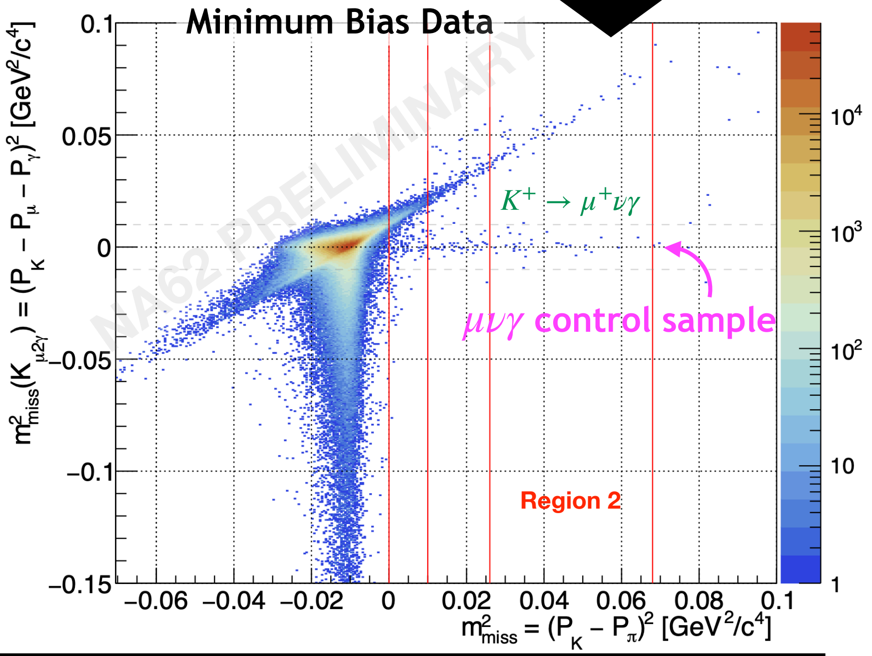
Sketch only



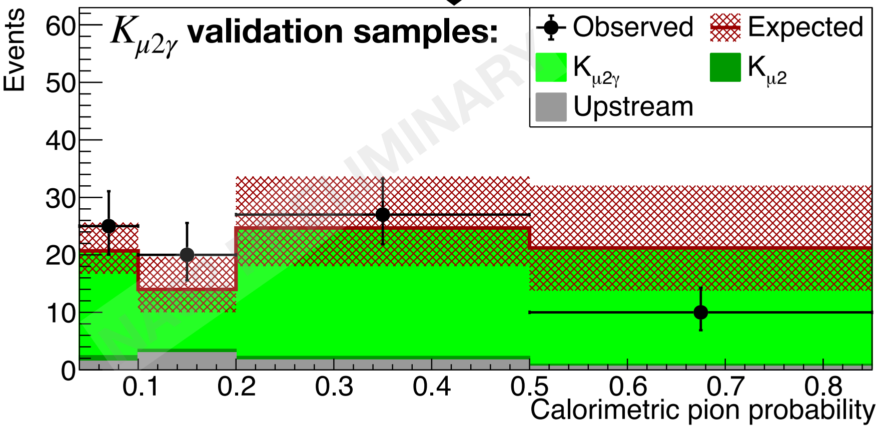
$K^+ \to \mu^+\nu\gamma$ Background

- Kinematically select $K^+ \to \mu^+\nu\gamma$ events:
  $m^2_{miss}(K_{\mu 2\gamma}) = (P_K - P_\mu - P_\gamma)^2$
  - P_K : 4-momentum of K^+ from GTK (as normal)
  - P_μ : 4-momentum of track with μ^+ mass hypothesis.
  - P_γ : reconstructed from energy and position of LKr cluster (and position of K^+-μ^+ vertex).

Evaluate background expectation using $\mu\nu\gamma$ control sample from MinimumBias trigger, not applying Calorimetric BDT classifier and MUV3 signal:



Validation: data sample with PID = "less pion-like" (Calo BDT bins below π^+ bin).



- Before $K^+ \to \mu^+\nu\gamma$ veto: found excess of events at $p > 35$ GeV/c in Region 2 relative to 2016–18 data.
- Additional background identified and studied in data control samples & MC.
- $K^+ \to \mu^+\nu\gamma$ veto added to selection criteria for final analysis.

Upstream background evaluation

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

N Upstream Reference Sample: signal selection but invert CDA cut (CDA>4mm)

f_{cda} Scaling factor : bad cda —> good cda

P_{match} Probability to pass $K^+ - \pi^+$ matching

Calculate using bins (i) of $(\Delta T_+, N_{GTK})$

[Updated to fully data-driven procedure]

$N = 51$ $f_{CDA} = 0.20 \pm 0.03$ $< P_{match} > = 73\,\%$

$$N_{bg}(\text{Upstream}) = 7.4^{+2.1}_{-1.8}$$

- **Upstream reference sample contains all known upstream mechanisms.**
  - N provides normalisation.
- f_{CDA} **depends only on geometry.**
- P_{match} **depends on** $(\Delta T_+, N_{GTK})$.