Observation of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay and measurement of its branching ratio at NA62

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on behalf of the NA62 collaboration

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NA62 P326

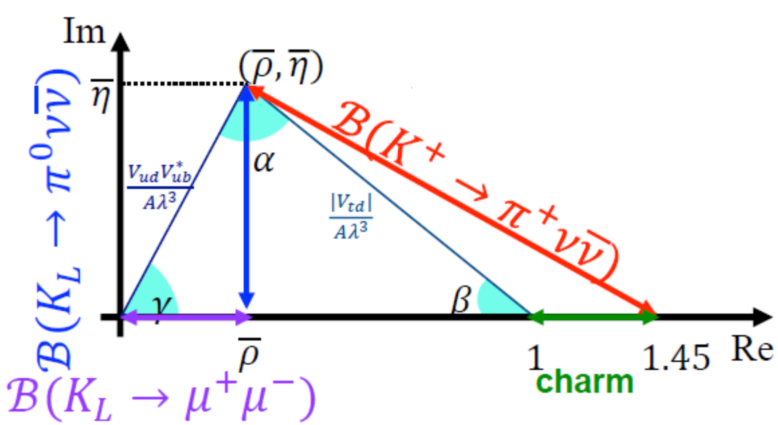
INFN NAPOLI

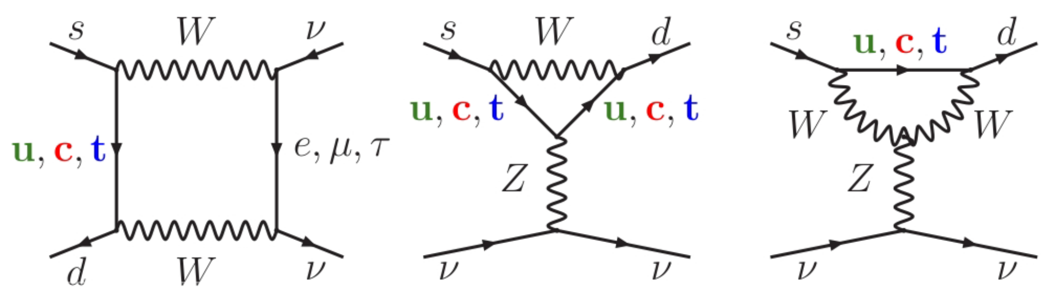
The $K \to \pi\nu\bar{\nu}$ decay

New physics at TeV scale not found (so far): explore higher mass scale via virtual production (ultrarare processes). Over-constraining unitary triangle via kaon decays is a crucial compatibility test of the SM

$K \to \pi\nu\bar{\nu}$ are extremely rare decays with rates very precisely predicted in SM:

- **FCNC processes, no tree-level SM contribution**
- **$\sin^5\theta_C$ suppression (top loop dominance)**
- **Hadronic part from K_{e3} via isospin rotation**





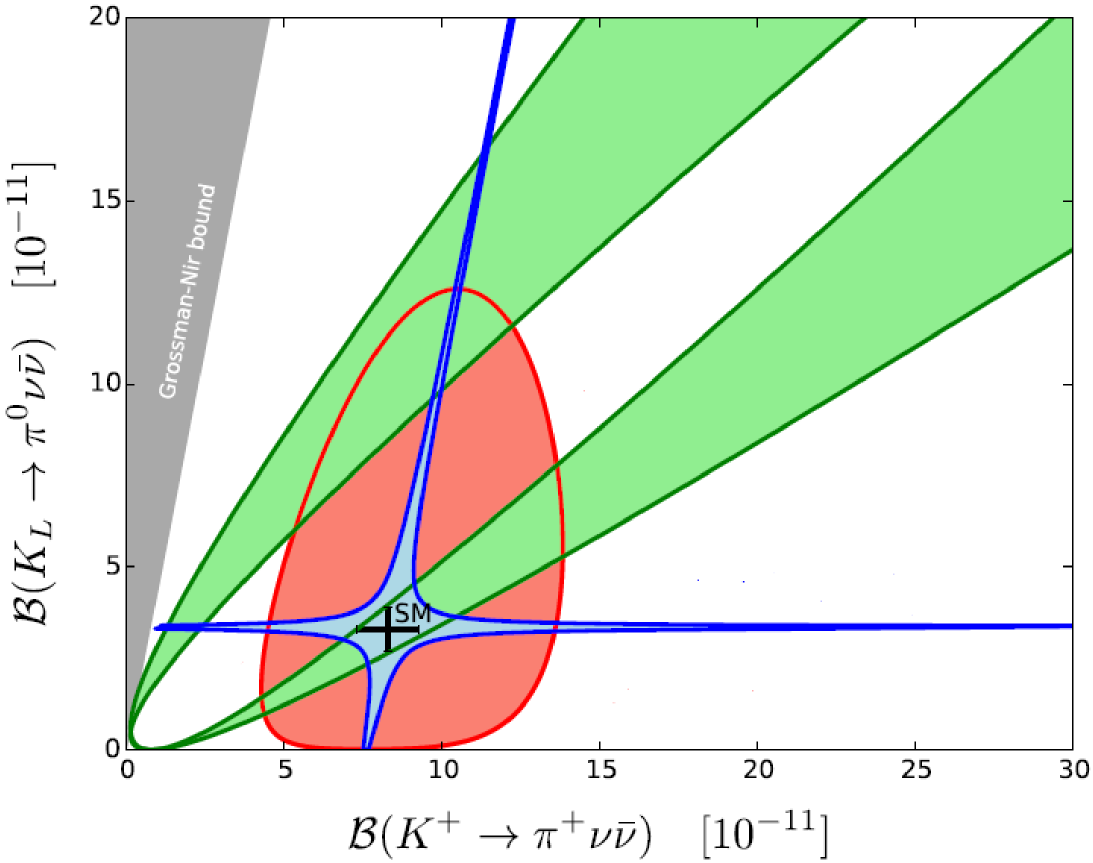
Decay Mode BR	SM [Buras et al. EPJC 82 (2022) 7, 615]	SM [D'Ambrosio et al. JHEP 09 (2022) 148]	Experimental Status
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	$(8.60 \pm 0.42) \times 10^{-11}$	$(7.86 \pm 0.61) \times 10^{-11}$	$(10.6^{+4.1}_{-3.5}) \times 10^{-11}$ (NA62)
$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$	$(2.94 \pm 0.15) \times 10^{-11}$	$(2.68 \pm 0.30) \times 10^{-11}$	$< 2 \times 10^{-9}$ (KOTO)

NA62 (2016–18 data): [JHEP 06 (2021) 093]

KOTO (2021 data): [Eur.Phys.J.C 84 (2024) 4, 377]

Seeking new physics through kaon decays

Correlations between BSM contributions to BRs of K^+ and K_L modes.
Both channels are needed to disentangle NP scenarios involving a new Z' boson:



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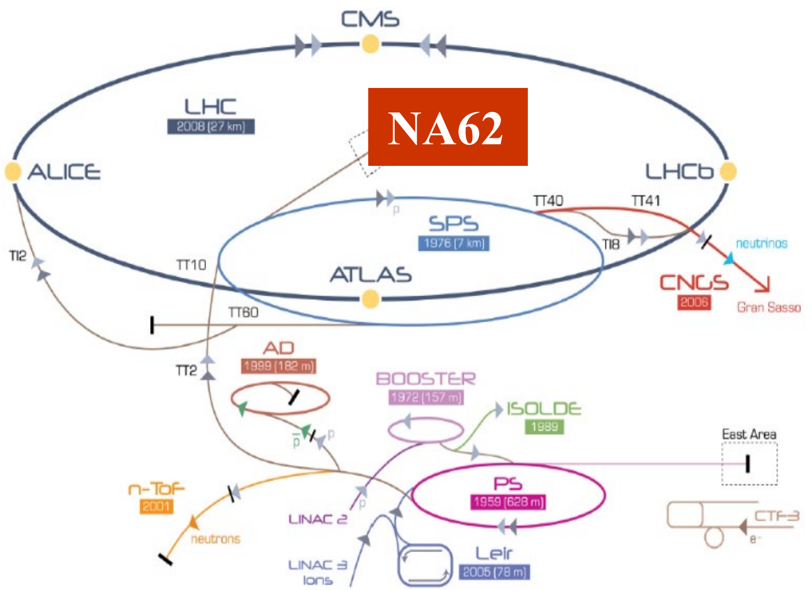
- **Models with a CKM-like structure of flavour interactions (e.g. MFV)**
- **Models with new flavour and CP-violating interactions in which either left or right handed currents fully dominate**
- **Models like Randall-Sundrum**
- **Grossman-Nir Bound:** model-independent relation

$$\frac{\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})}{\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})} \frac{\tau_{K^+}}{\tau_{K_L}} \lesssim 1$$

$$\Rightarrow \mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) \lesssim 4.3 \cdot \mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$$

The NA62 experiment at CERN

A fixed target experiment at the CERN SPS dedicated to the study of rare decays in the kaon sector. Currently in NA62: ~200 physicists, ~ 30 institutions from 11 countries



Main goal: BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$) measurement using the decay-in-flight technique.

Broad physics programme thanks to unprecedented statistics for many decay modes

- ✓ Precision measurements
- ✓ Rare and forbidden decays, LFV and LNV
- ✓ Direct exotic searches, also in dump mode

Commisioning		Run1, Physics Run			LS2		Run2, Physics Run					
2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
		45 days	160 days	217 days	Upgrades		85 days	215 days	150 days	204 days		

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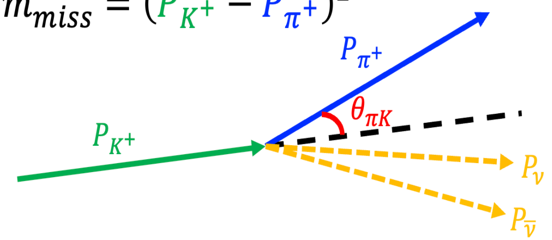
This talk

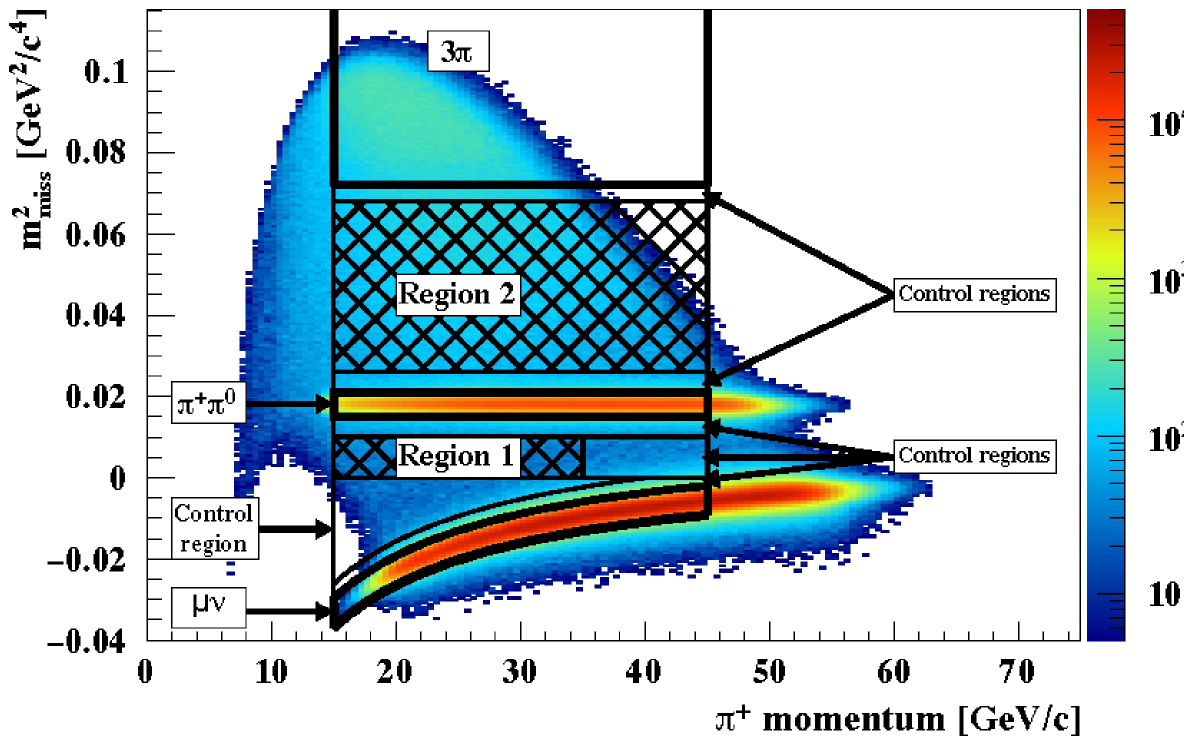
NA62 $K^+ \to \pi^+ \nu\bar{\nu}$ analysis strategy

Signal:
BR = (8.60 ± 0.42) × 10^{-11}

K^+ track in, π+ track out
No other particles in final state

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





Main backgrounds

Upstream beam background

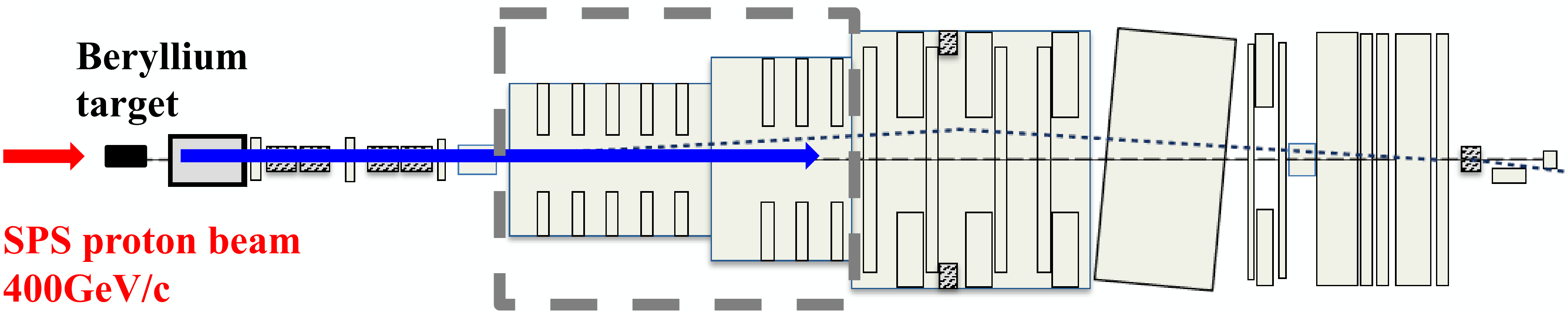
$K^+ \to \mu^+\nu(\gamma)$	**BR = 63.5%**
$K^+ \to \pi^+\pi^0(\gamma)$	**BR = 20.7%**
$K^+ \to \pi^+\pi^+\pi^-$	**BR = 5.58%**

Background rejection relies on **Kinematics** used in conjunction with **Particle ID**, **Veto systems** and **sub-ns timing**

- $O(10^3)$ or better suppression from kinematics for main K decay channels
- $O(10^8)$ muon and π^0 suppression

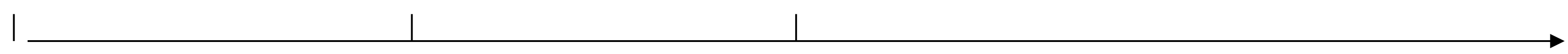
Fiducial volume: 60 m $\mathcal{O}(10^{-6})$ mbar
$\sim$4 MHz of K^+ decays

Beryllium target



SPS proton beam
400GeV/c
3×10^{12} PoT/spill
4.8 sec spill

Secondary beam
75 GeV/c, 1% bite, 60×30 mm^2
K^+(6%)/π^+(70%)/p(24%)
Beam rate: 600 MHz



NA62 layout

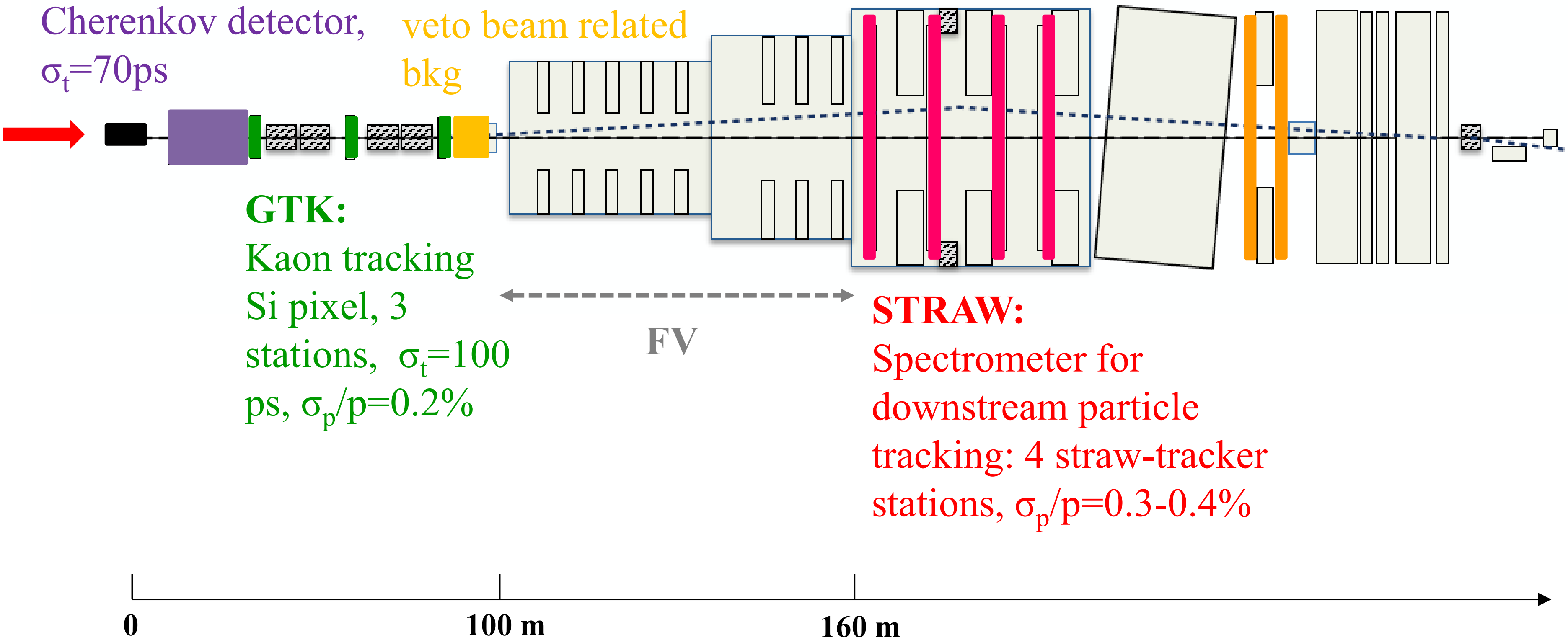
KTAG
Kaon identification Differential Cherenkov detector, σ_t=70ps

CHANTI:
scintillation rings to veto beam related bkg

CHOD:
hodoscope

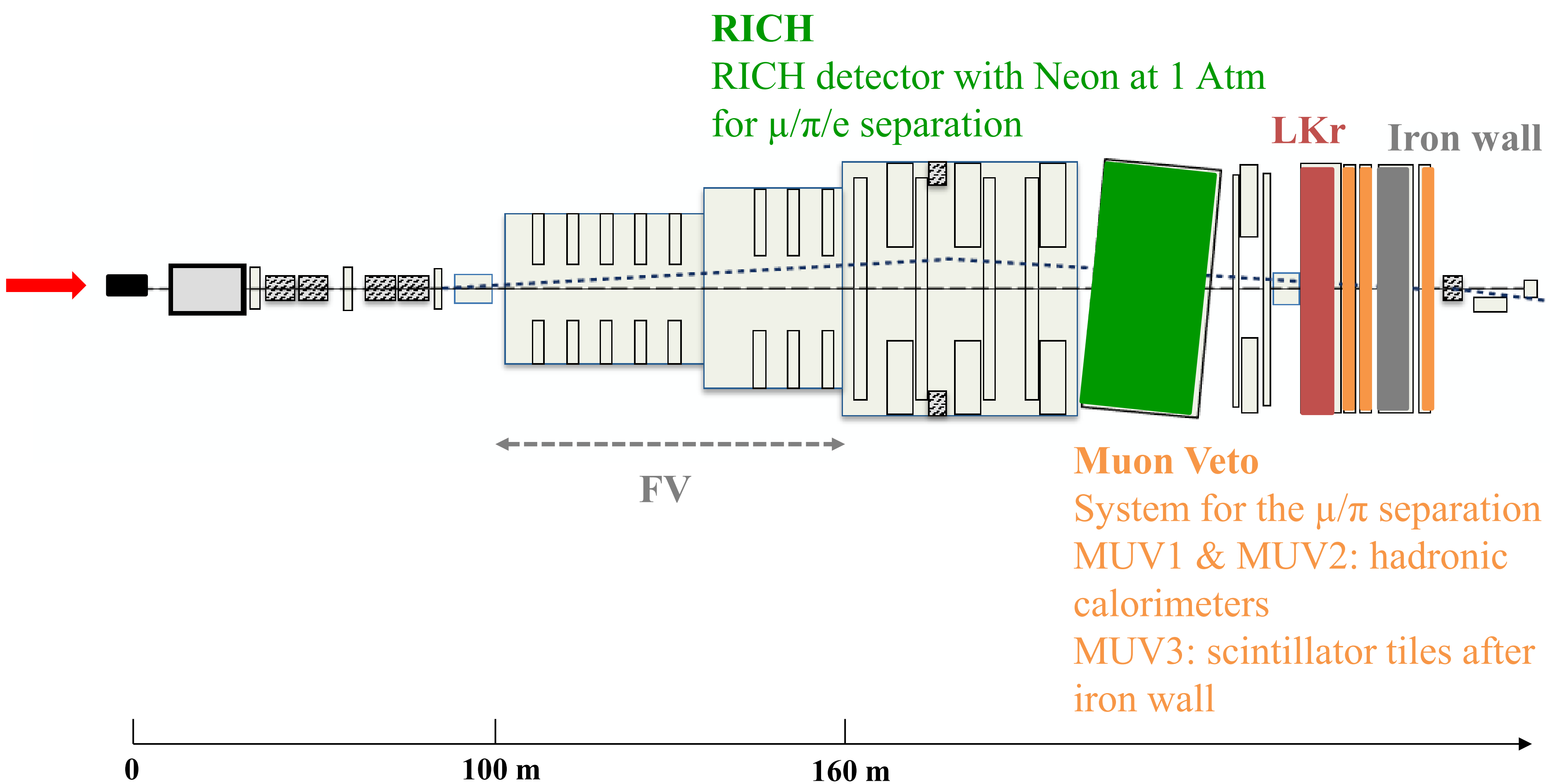
GTK:
Kaon tracking Si pixel, 3 stations, σ_t=100 ps, σ_p/p=0.2%

STRAW:
Spectrometer for downstream particle tracking: 4 straw-tracker stations, σ_p/p=0.3-0.4%



- **Kinematic reconstruction:** $M^2_{miss}=(P_K - P_\pi)^2$, $\sigma_{M^2_{miss}}=10^{-3}$**GeV²/c⁴ at** $K^+ \rightarrow \pi^+\pi^0$
- **Time resolution to match beam and daughter particle information: ~100ps**

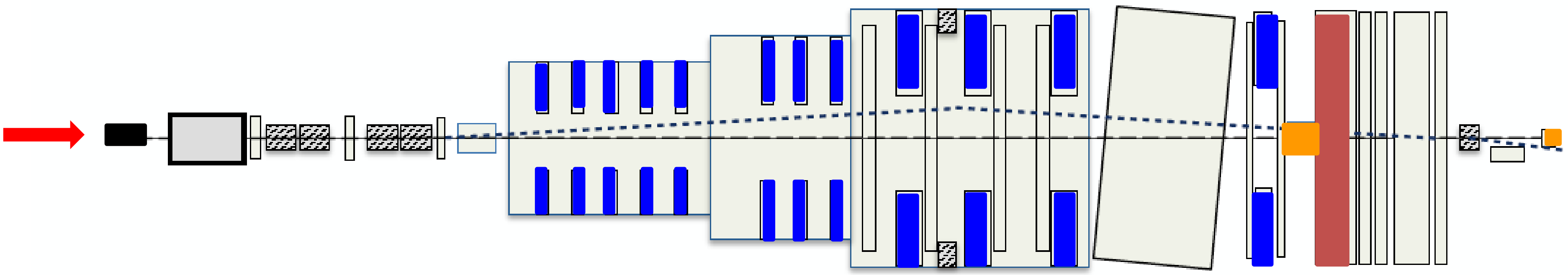
NA62 layout



- **PID detectors to suppress bkg with μ^+or e^+ in the final state for the main analysis: μ vs π rejection of O(10^8) for 15 < p(π^+) < 35 GeV**

Large Angle Veto (LAV)
12 stations with lead glass blocks
Covering angles $10 < \theta < 50$ mrad

Small angle veto (SAV)
Two shashlik calorimeters, IRC and SAC, to cover $\theta < 1$ mrad



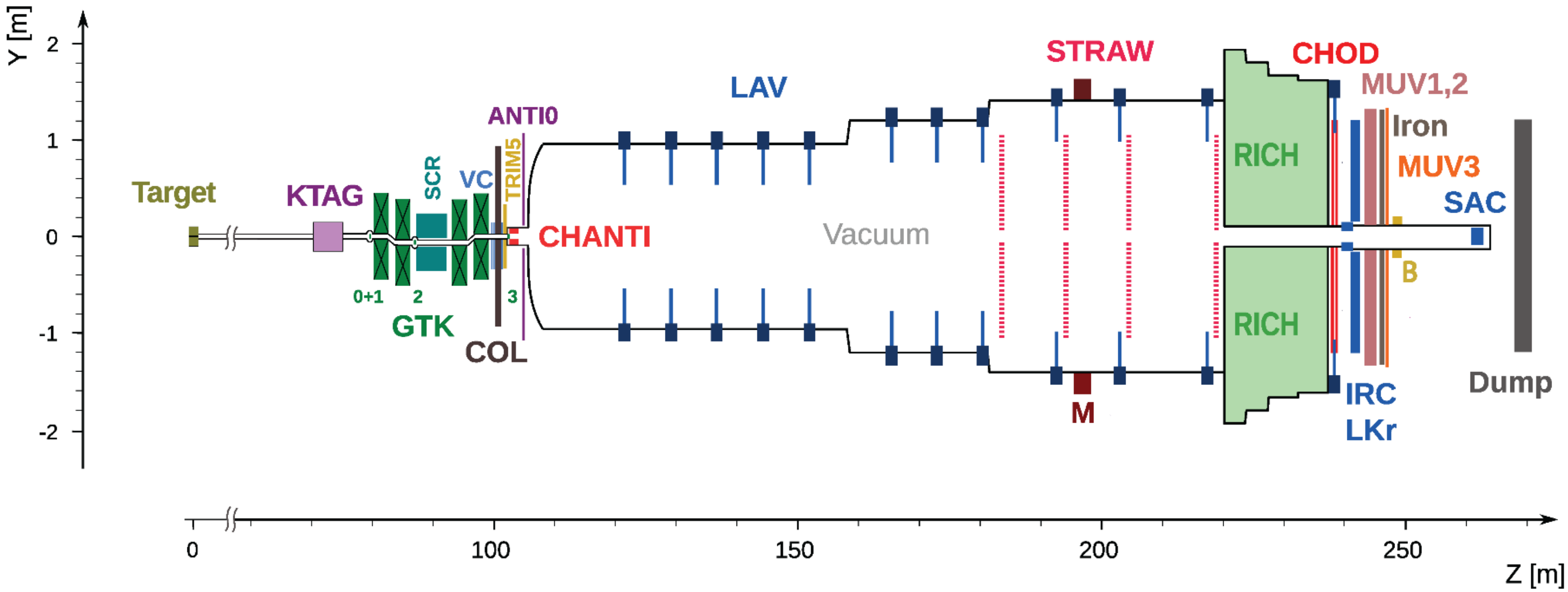
FV

LKr calorimeter
27 X_0 thick quasi-homogeneous LKr electromagnetic calorimeter detects photons in $1 < \theta < 10$ mrad

0 100 m 160 m

- **Photon vetoes to suppress bkg with π^0 in the final state for the main analysis: 10^8 rejection of π^0 for $E(\pi^0) > 40$ GeV**

NA62 layout



Performances

- ✓ **Excellent time resolution $\mathcal{O}$(100 ps)** to match beam and daughter particle information
- ✓ **Kinematics:** rejection of main K modes 10^4 via kinematics reconstruction
- ✓ **PID capability:** μ vs π rejection of O(10^8) for $15 < p(\pi^+) < 35$ GeV
- ✓ **High-efficiency veto:** 10^8 rejection of π^0 for $E(\pi^0) > 40$ GeV

The beam and detector of the NA62 experiment at CERN, 2017 JINST 12 P0502

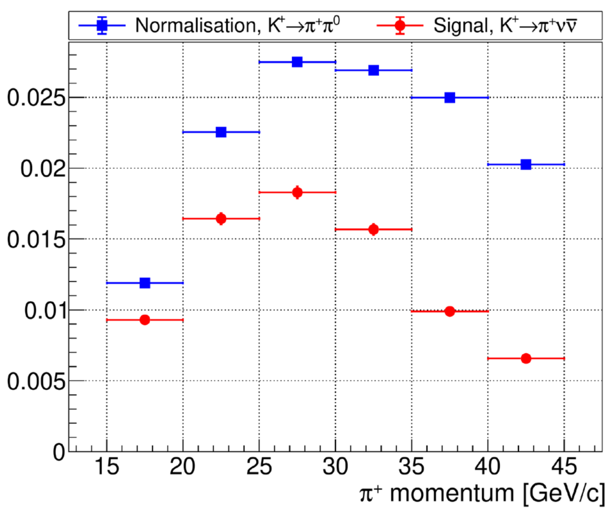
Signal expectation

- Normalisation channel $K^+ \to \pi^+\pi^0$
- Analysis performed in π^+ momentum bins p_i

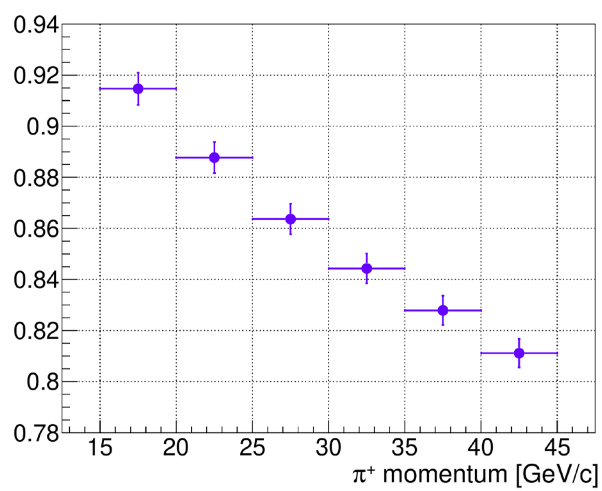
Expected SM signal events **Selected $\pi^+\pi^0$** **Trigger downscaling**

$$\underline{N^{SM}_{\pi\nu\nu}(p_i)} = \underline{N_{\pi^+\pi^0}(p_i)} \frac{BR(\pi^+\nu\nu, SM)}{BR(\pi^+\pi^0, PDG)} \frac{\mathcal{A}(\pi^+\nu\nu)}{\underline{\mathcal{A}(\pi^+\pi^0)}} \underline{D}\, \underline{\varepsilon_{trig}(p_i)}\, \underline{\varepsilon_{RV}}$$

Acceptances at 0 intensity

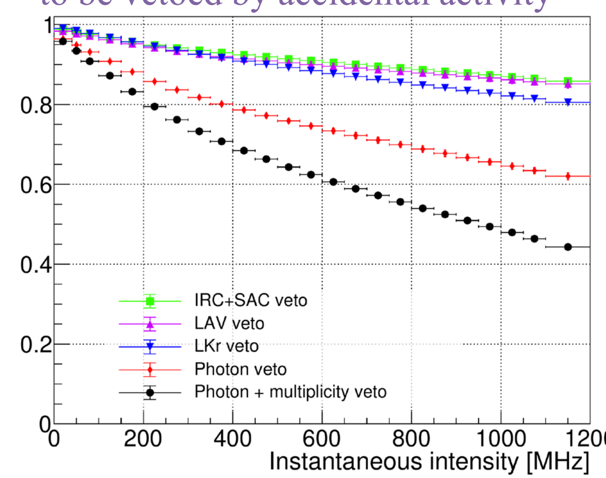


Trigger efficiency ratio



Random veto efficiency

$1 - \varepsilon_{RV}$= probability of a signal event to be vetoed by accidental activity



Signal expectation

$$N^{SM}_{\pi\nu\nu}(p_i) = N_{\pi^+\pi^0}(p_i)\frac{BR(\pi^+\nu\nu, SM)}{BR(\pi^+\pi^0, PDG)}\frac{\mathcal{A}(\pi^+\nu\nu)}{\mathcal{A}(\pi^+\pi^0)}\, D\, \varepsilon_{trig}(p_i)\varepsilon_{RV}$$

$N_{\pi\pi}$	$(1.953 \pm 0.005) \times 10^8$
$A_{\pi\pi}$	13.4%
$A_{\pi\nu\nu}$	$(7.62 \pm 0.2)\%$
ε_{trig}	$(85.9 \pm 1.4)\%$
ε_{RV}	$(63.2 \pm 0.6)\%$

$$N^{exp}_{\pi\nu\nu} = 9.91 \pm 0.34$$

2016 – 2018: 10.01 ± 0.42

Double expected signal by including 2021-22 data

Single Event Sensitivity

$$SES = \frac{BR(\pi\nu\nu)}{N^{exp}_{\pi\nu\nu}} = (8.48 \pm 0.29) \times 10^{-12}$$

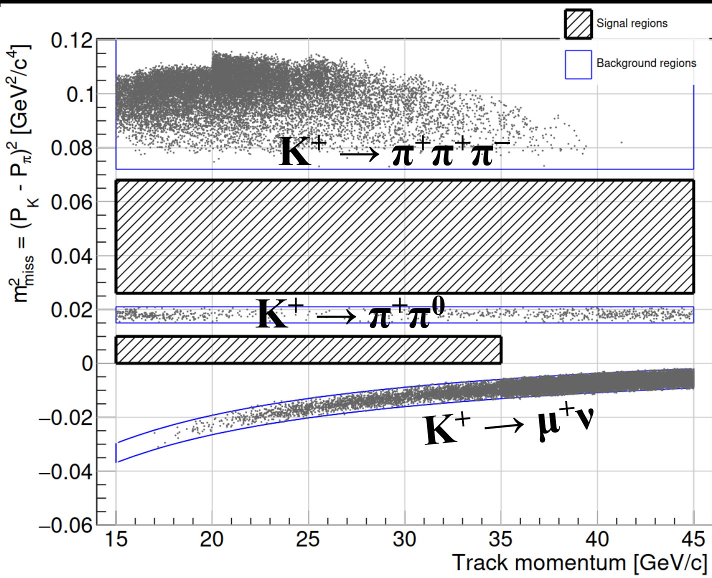
2016 – 2018: $(8.39 \pm 0.54) \times 10^{-12}$

Improvements wrt 2018:

- **New detectors installed during LS2 (additional kaon beam tracker station, new veto hodoscopes upstream FV, additional veto counters around beam pipe**
- **Beam intensity increased by ~35%**
- **Retuned selection and reconstruction**
- **New trigger configuration (common conditions lead to cancellation of systematics)**

⇒ signal yield per SPS spill increased by 50%, ×2 better SES precision

Backgrounds from K^+ decays



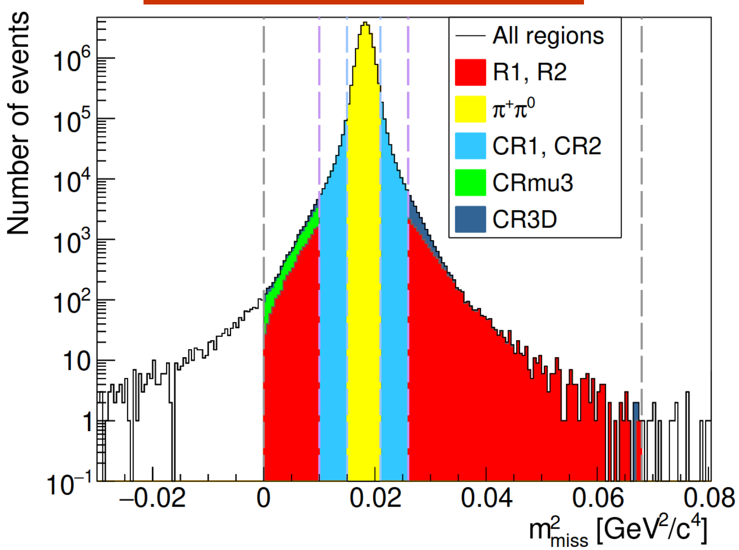
Estimation data-driven for all main K channels using Control Regions

$K^+ \to \pi^+\pi^0(\gamma)$	0.83 ± 0.05
$K^+ \to \mu^+\nu(\gamma)$	1.70 ± 0.47
$K^+ \to \pi^+\pi^+\pi^-$	0.11 ± 0.03
$K^+ \to \pi^+\pi^-e^+\nu$	$0.89\ ^{+0.33}_{-0.27}$
$K^+ \to \pi^+\gamma\gamma$	0.01 ± 0.01
$K^+ \to \pi^0\ell^+\nu$	< 0.001

$\underbrace{K^+ \to \pi^+\pi^0(\gamma),\ K^+ \to \mu^+\nu(\gamma),\ K^+ \to \pi^+\pi^+\pi^-}_{\text{data-driven}}$

$\underbrace{K^+ \to \pi^+\pi^-e^+\nu,\ K^+ \to \pi^+\gamma\gamma,\ K^+ \to \pi^0\ell^+\nu}_{\text{estimated with MC}}$

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



- Background suppression based on kinematics and photon vetoes
- Fraction of kinematic tails in SR region estimated on data on a sample selected tagging positively the π^0, via photons detected in the calorimeter
- $K^+ \to \pi^+\pi^0$ events in signal region:

$$N_{\pi^+\pi^0}(SR) = N_{\pi^+\pi^0}\, f_{\pi^+\pi^0}(SR)$$

Events in $\pi^+\pi^0$ region after selection

Ratio of events in $\pi^+\pi^0$ region to SR, measured on control sample

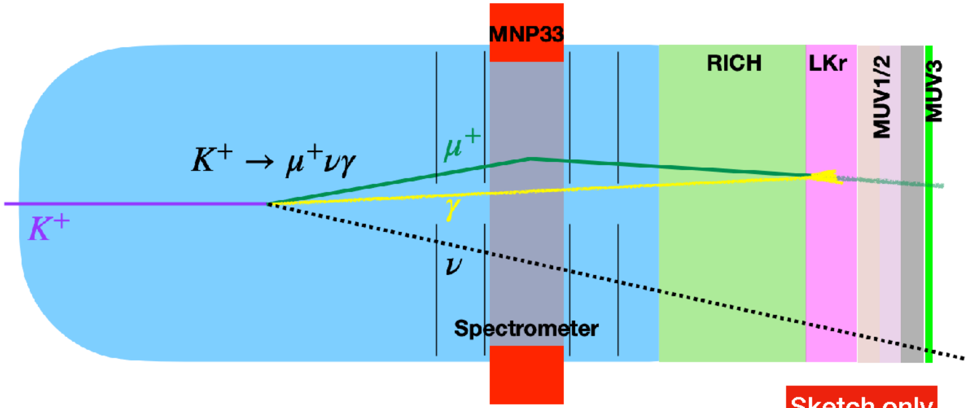
Backgrounds from K^+ radiative decays

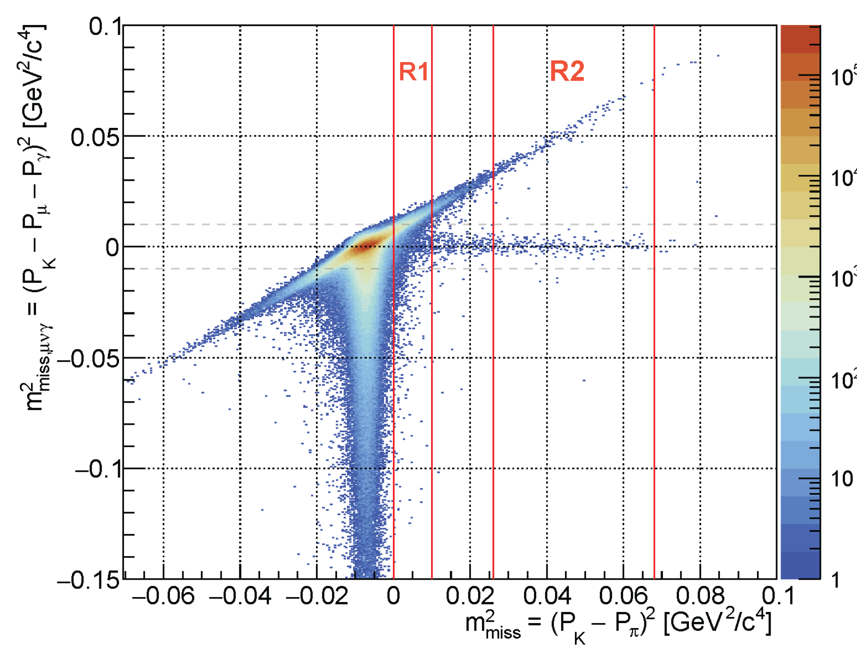
$K^+ \to \pi^+\pi^0\gamma$: not contained in the kinematic tails procedure (2γ in Calo, no additional γ).

- **Photon vetos rejection with extra γ is 30x stronger**
- **Estimation using MC + measured single γ rejection: $N(K^+ \to \pi^+\pi^0\gamma) = 0.07 \pm 0.01$**

$K^+ \to \mu^+\nu\gamma$: not included in the kinematic tails estimation if the γ overlaps a high-momentum μ^+ at LKr leading to misID as a π^+

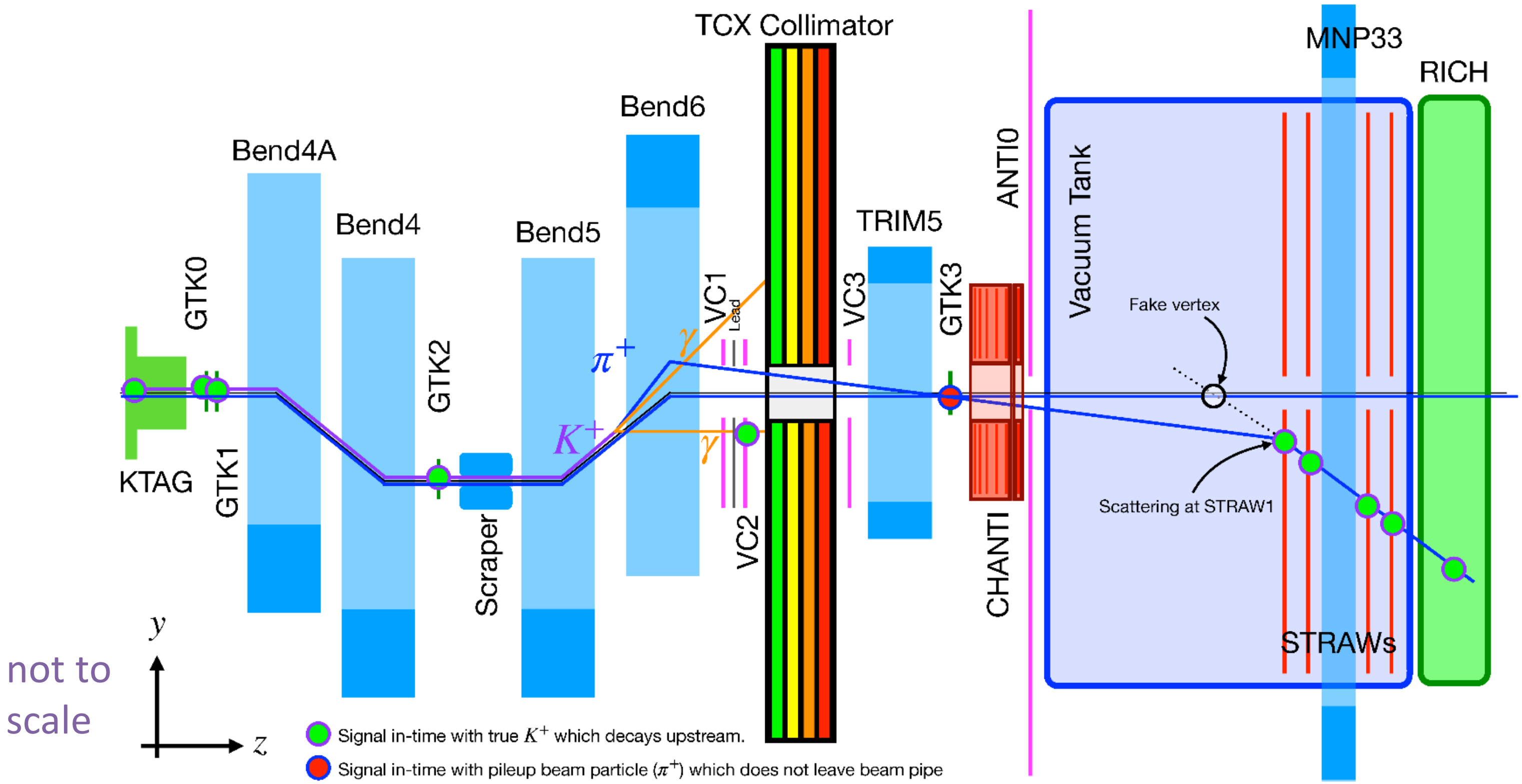
- **Veto based on $(P_K - P_\mu - P_\gamma)^2$ and E_γ with γ = LKr cluster (mis)associated to muon (*Necessary for 2021-22 data, since Calorimetric PID degraded at higher intensities*)**
- **Estimation using control sample with signal in MUV3 : $N(K^+ \to \mu^+\nu\gamma) = 0.82 \pm 0.43$**





- **Before veto, found excess of events in Region 2 wrt Run1 data**
- **$K^+ \to \mu^+\nu\gamma$ identified as bkg and studied with control samples and MC**
- **Veto added to selection for final analysis**

Upstream background



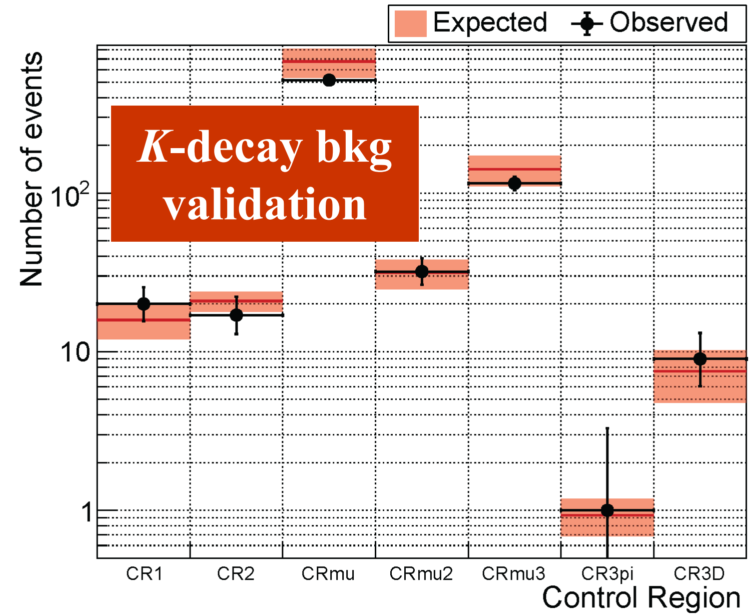
- **Suppression: Δt (K⁺ and π⁺), upstream vetoes (VC, CHANTI, ANTI0), BDT using spatial infos of K+ and π+**
- **Estimation: Fully data-driven, "Upstream Reference Sample" contains all known generation mechanisms, bkg-to-signal probability estimated with data driven technique**

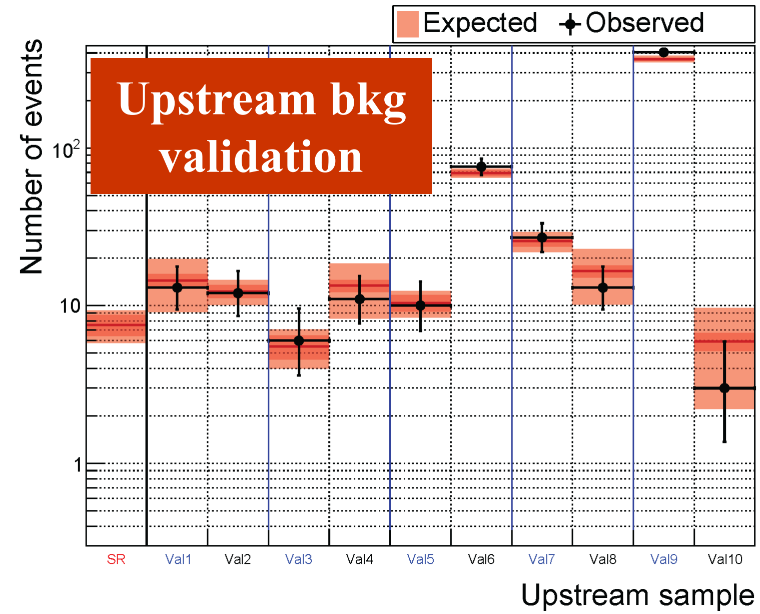
$$N(\text{Upstream}) = 7.4^{+2.1}_{-1.8}$$

- **Validation: 10 independent samples enriched with different mechanisms.**

Background validation

$K^+ \to \pi^+\pi^0(\gamma)$	0.83 ± 0.05
$K^+ \to \mu^+\nu(\gamma)$	1.70 ± 0.47
$K^+ \to \pi^+\pi^+\pi^-$	0.11 ± 0.03
$K^+ \to \pi^+\pi^- e^+\nu$	$0.89\,^{+0.33}_{-0.27}$
$K^+ \to \pi^+\gamma\gamma$	0.01 ± 0.01
$K^+ \to \pi^0\ell^+\nu$	< 0.001
Upstream	$7.4\,^{+2.1}_{-1.8}$
Total background	$11.0\,^{+2.1}_{-1.9}$
SM signal	9.91 ± 0.34

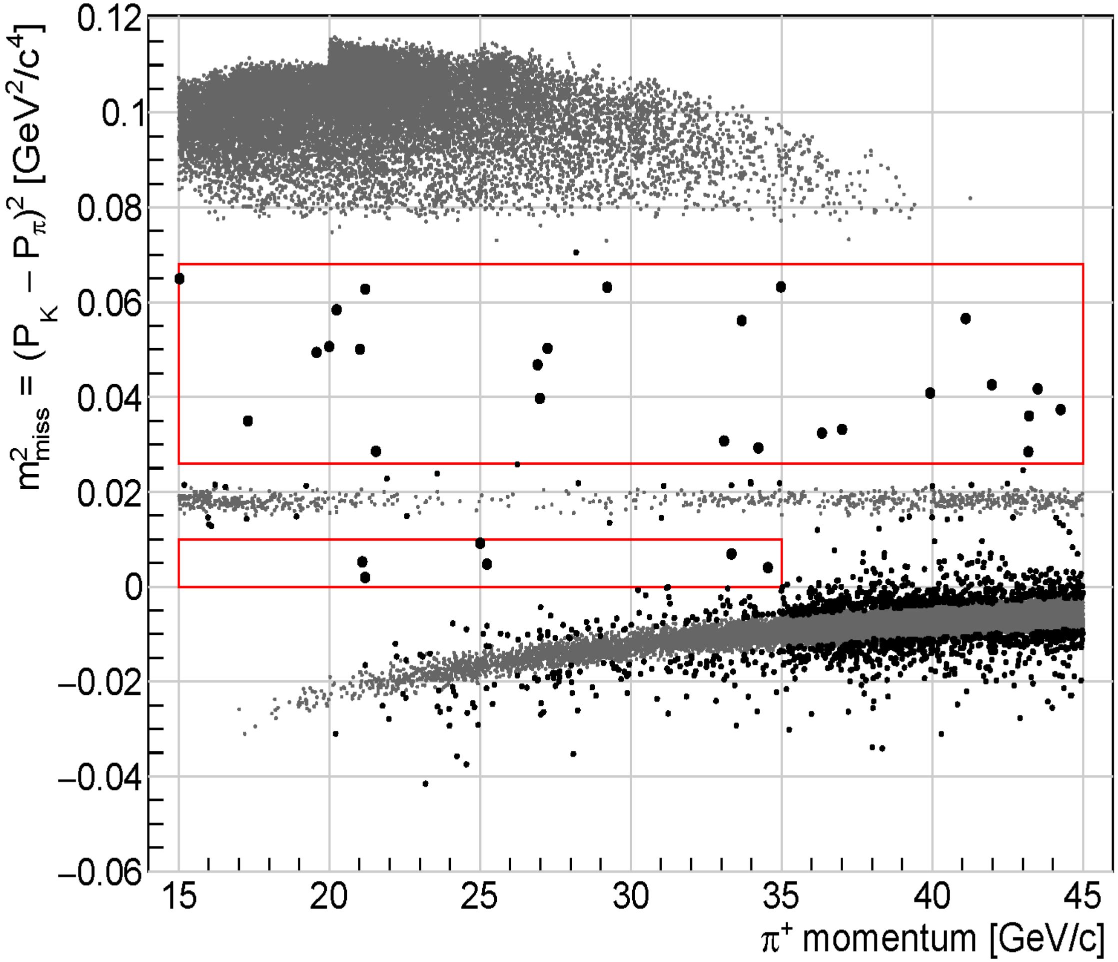




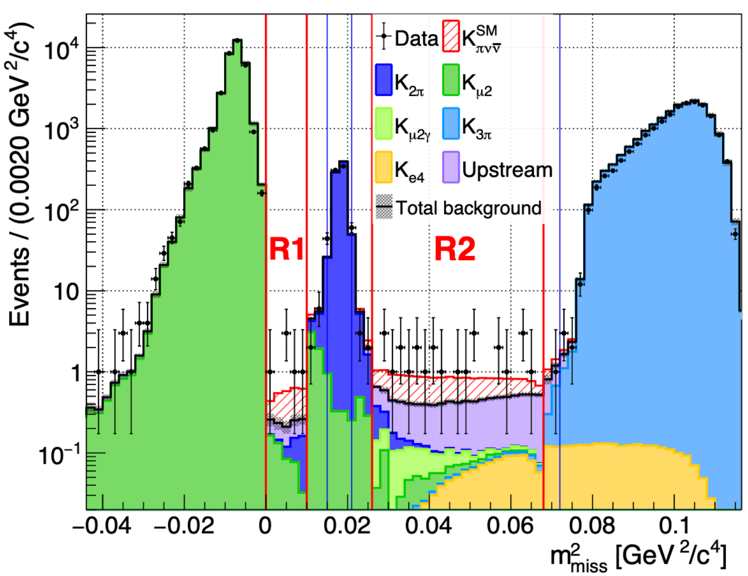
Validation consistent across all samples

Signal regions

- Expected SM signal: 9.91 ± 0.34
- Estimated background: 11.0 $^{+2.1}_{-1.9}$
- Observed: 31

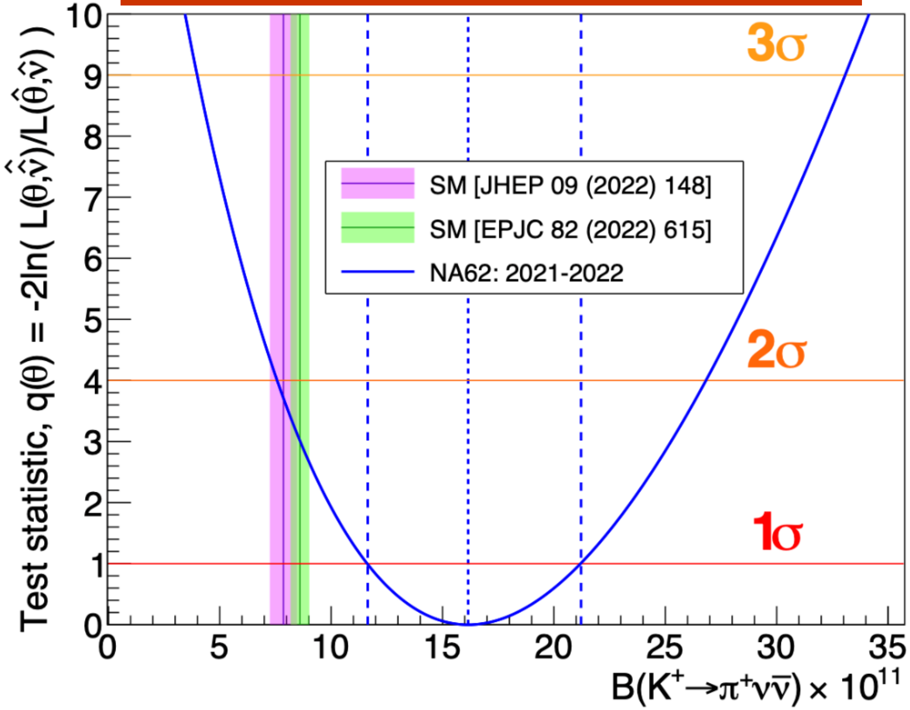


1D projection with differential background predictions & SM signal expectation [not a fit]

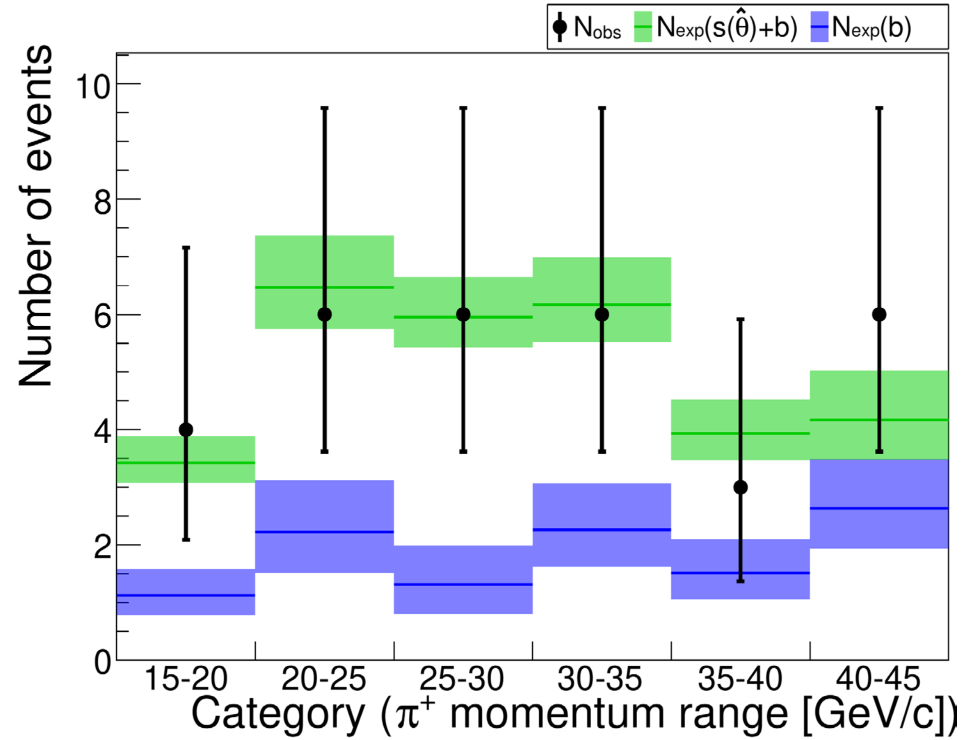


Results for BR($K^+ \to \pi^+ \nu\bar{\nu}$) : 2021 - 2022

Measure BR($K^+ \to \pi^+ \nu\bar{\nu}$) and 1σ confidence interval using a profile likelihood ratio test statistic



Number of expected and observed events in 6 momentum bin categories



$$BR_{2021-2022}(K^+ \to \pi^+ \nu\bar{\nu}) = (16.2\ ^{+5.1}_{-4.5}) \times 10^{-11} = (16.2\ ^{+4.9}_{-4.3}|_{stat}\ ^{+1.4}_{-1.4}|_{syst}) \times 10^{-11}$$

$N_{bkg} = 11.0\ ^{+2.1}_{-1.9}$, $N_{obs} = 31$ ⇒ **Significance: 3.6σ**

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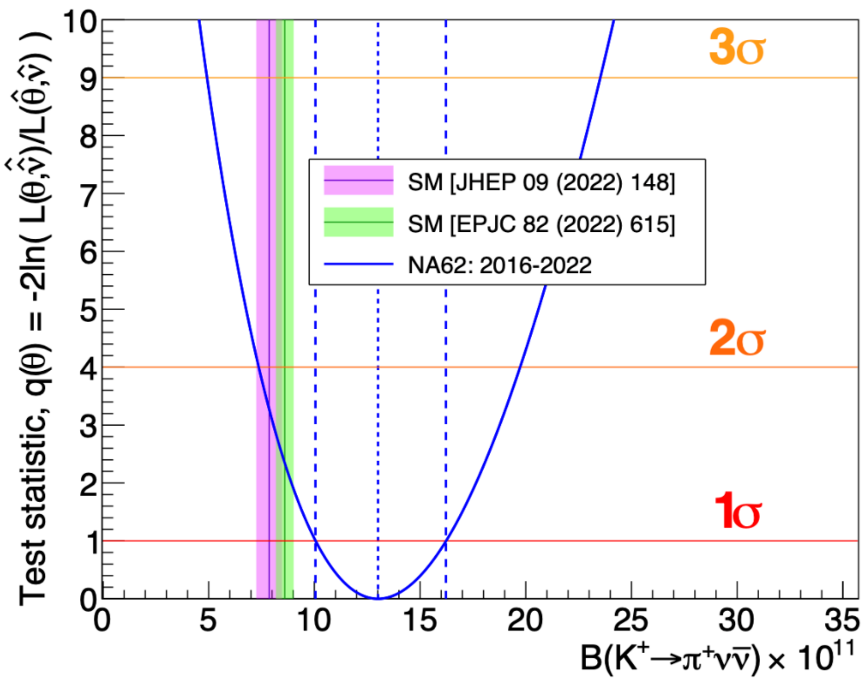
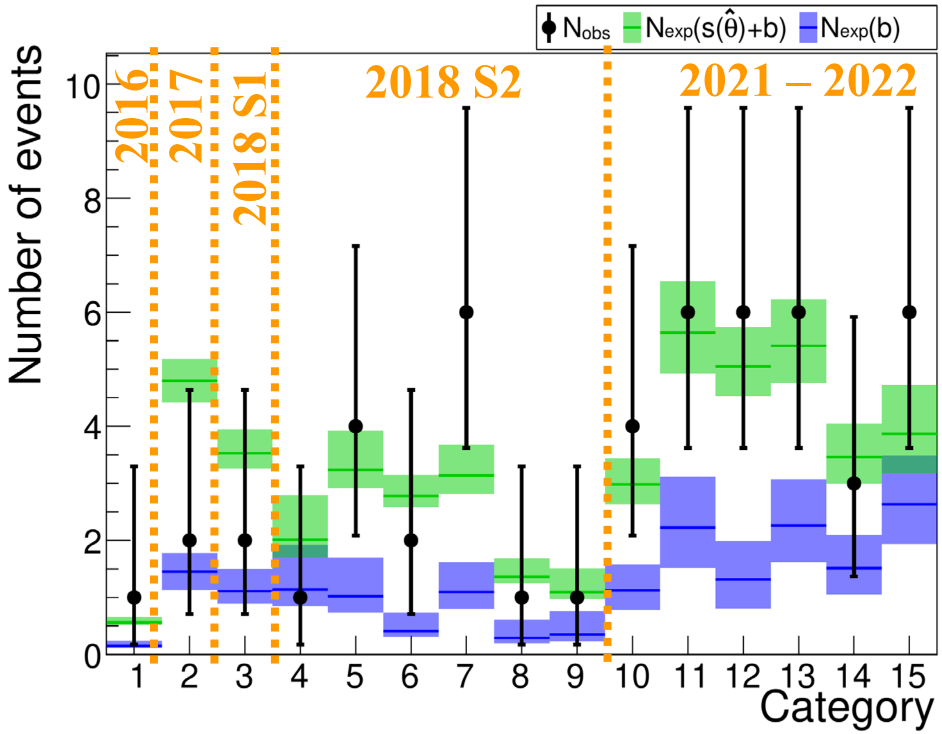
NA62 Combined Result 2016 - 2022

Integrating 2016-22 data: $N_{bkg}=18\ ^{+3}_{-2}$, $N_{obs}=51$

Background-only hypothesis p-value = $2\times10^{-7} \Rightarrow$ significance $Z>5$





$$BR_{2016-2022}(K^+ \to \pi^+\nu\bar{\nu}) = (13.0\ ^{+3.3}_{-3.0}) \times10^{-11} = (13.0\ ^{+3.0}_{-2.7}|_{stat}\ ^{+1.3}_{-1.3}|_{syst}) \times10^{-11}$$

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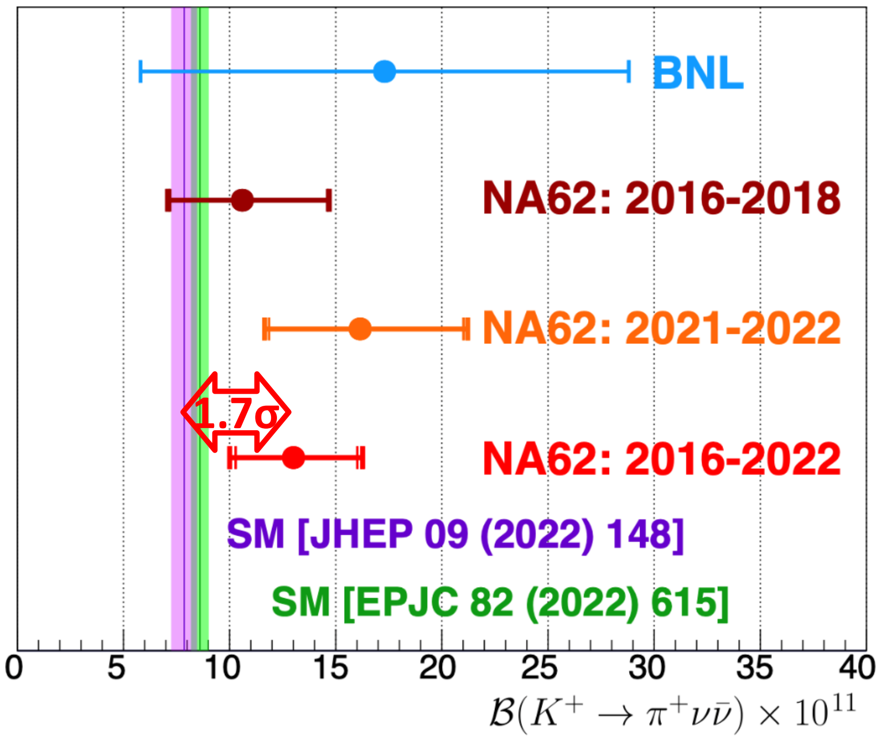
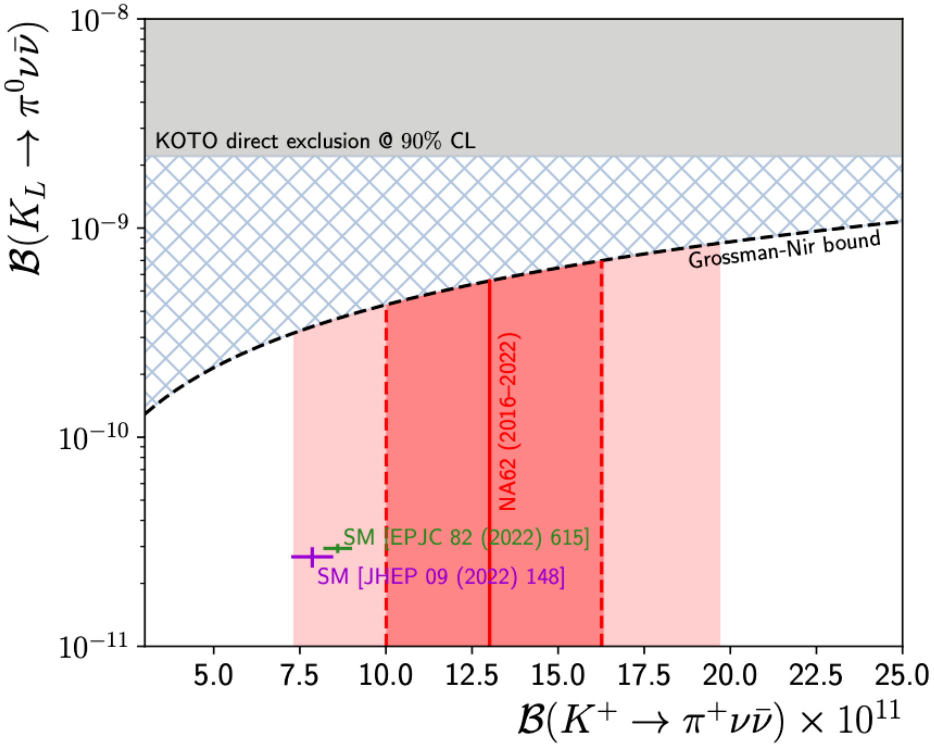
NA62 result in a global perspective





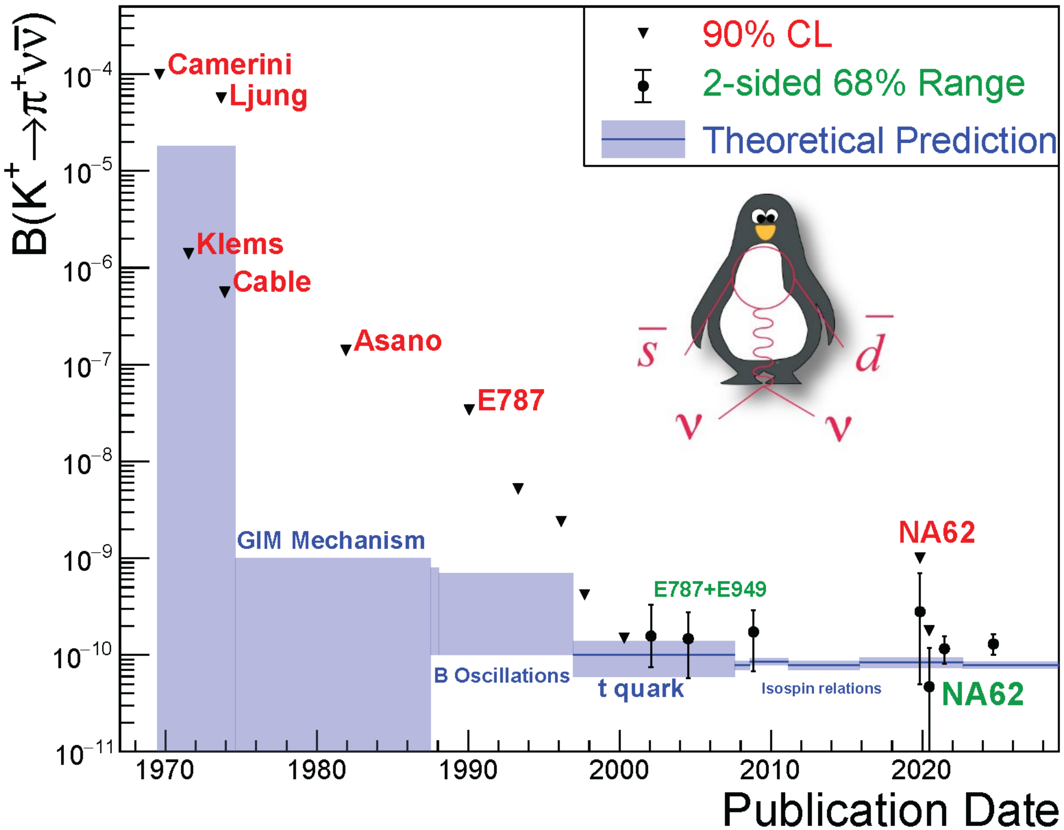
- **NA62 results are consistent**
- **Central value moved up (now 1.7 above SM)**
- **Fractional uncertainty decreased: 40% to 25%**
- **Bkg-only hypothesis rejected with significance Z>5**

Conclusions

NA62 result on $K^+ \to \pi^+ \nu\bar{\nu}$ decay using 2021-22 dataset, combined with 2016-18

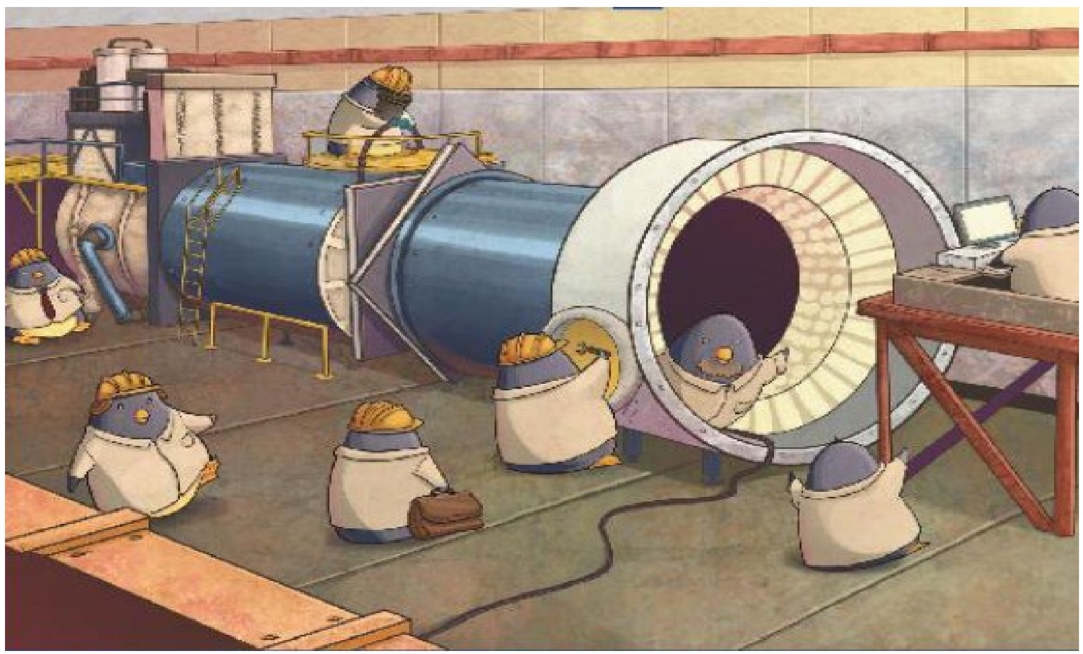
$$\mathrm{BR}_{2016\text{-}2022} = (13.0\,^{+3.3}_{-3.0}) \times 10^{-11}$$, *JHEP 02 (2025) 191*

BR consistent with SM prediction within 1.7σ



- ✓ **The long quest for $K^+ \to \pi^+ \nu\bar{\nu}$ has reached a very important step: the observation of the decay!**
- ✓ **The rarest particle decay ever observed at 5 sigma level**
- ✓ **NA62 2023-24 dataset of comparable size to 2016-22 one**
- ✓ **Analysis is ongoing**
- ✓ **NA62 will take data until LS3 (summer 2026)**

Additional materials



NA62 physics programme

NA62

Flavour Physics

Search for NP at the EW scale with sizeable coupling to SM particles via indirect effects in loops:

Golden mode: $K^+ \to \pi^+ \nu\nu$;

χPT and Lepton Universality tests - Precision measurements of K^+ decays

Searches for lepton flavour and number violation (LFV, LNV) - Rare and forbidden decay analysis

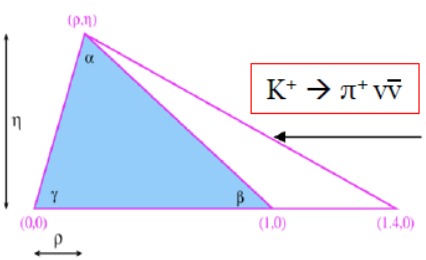
Hidden Sector

Search for NP below the EW scale (MeV-GeV range) feebly-coupled to SM particles via direct detection of long-lived particles:

HNL, Dark Photon, ALP..

Neutrino Physics

Experimental proof of principle of Neutrino Tagging technique using NA62 layout



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

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

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

$K^+ \to \pi^\pm \mu^\mp e^+$

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

$K^+ \to \mu^- \nu e^+ e^+$

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

$\cdots$

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

$K^+ \to l^+ N$

$K^+ \to \pi^+ aa, a \to e^+ e^-$

$A' \to l^+ l^-$

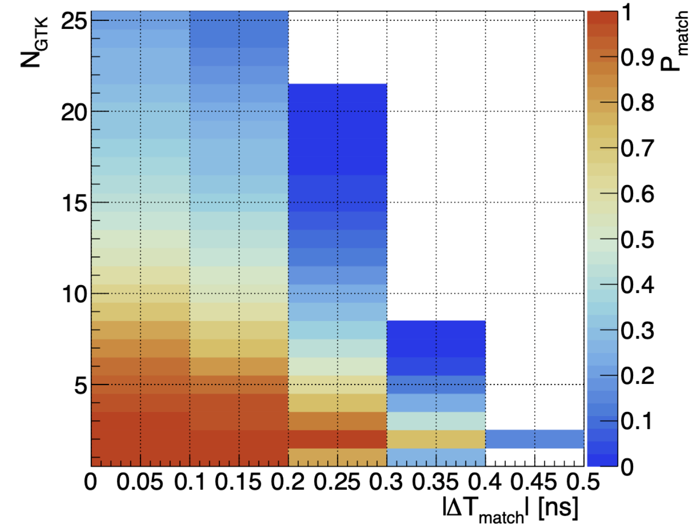
$N \to \pi^\pm l^\mp$

$\cdots$

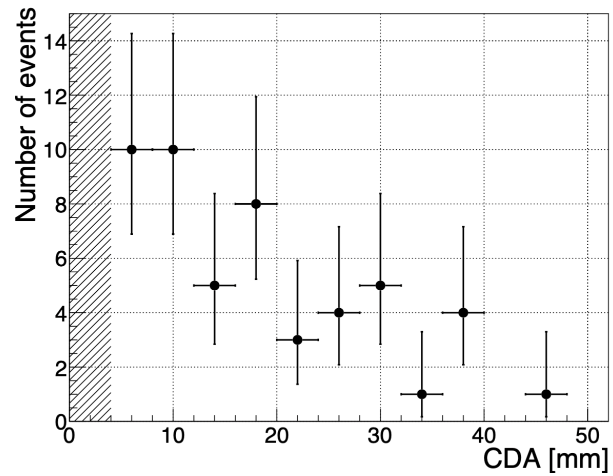
$K^+ \to \mu^+ \nu_\mu$

Upstream background estimation

$N(\text{Upstream}) = \sum_i N_{URS}(i)\, f_{CDA}\, P_{match}(i)$



- **i: bins of (ΔT, N_{GTK})**
- **Upstream Reference Sample: signal selection but bad CDA**
  - **Contains all known upstream background mechanisms**
  - **Provides normalization**
- **f_{CDA}: ratio of bad CDA events to good CDA events**
  - **Extracted from the URS**
  - **Depends on geometry only**
- **P_{match}: probability of passing K-π matching criteria**
  - **Extracted from normalization data**

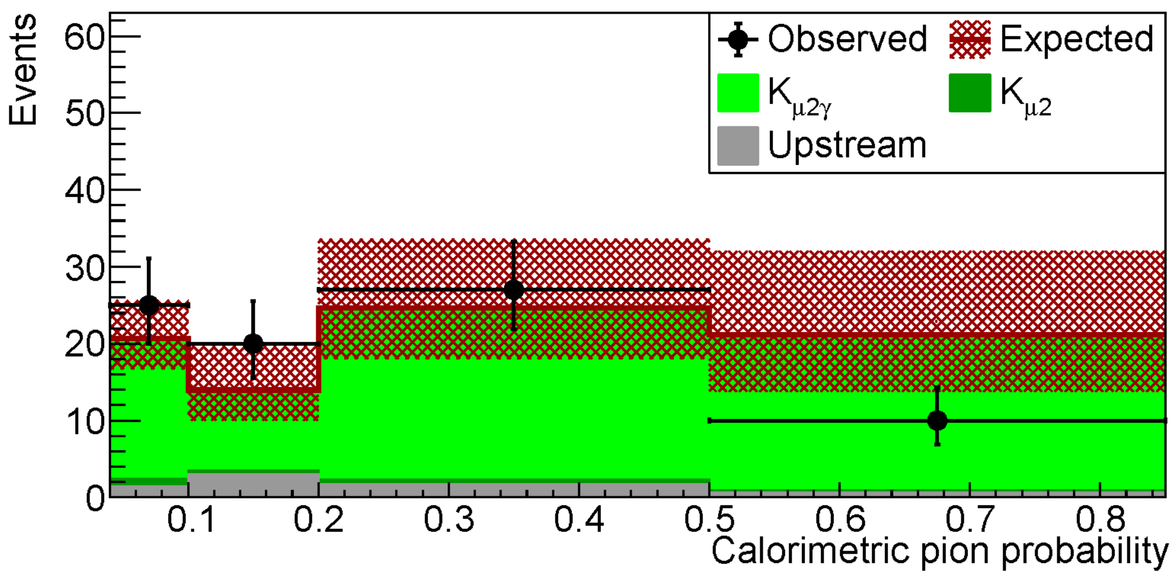


$N_{URS} = 51$, $f_{CDA} = 0.20 \pm 0.03$, $\langle P_{match} \rangle = 73\%$

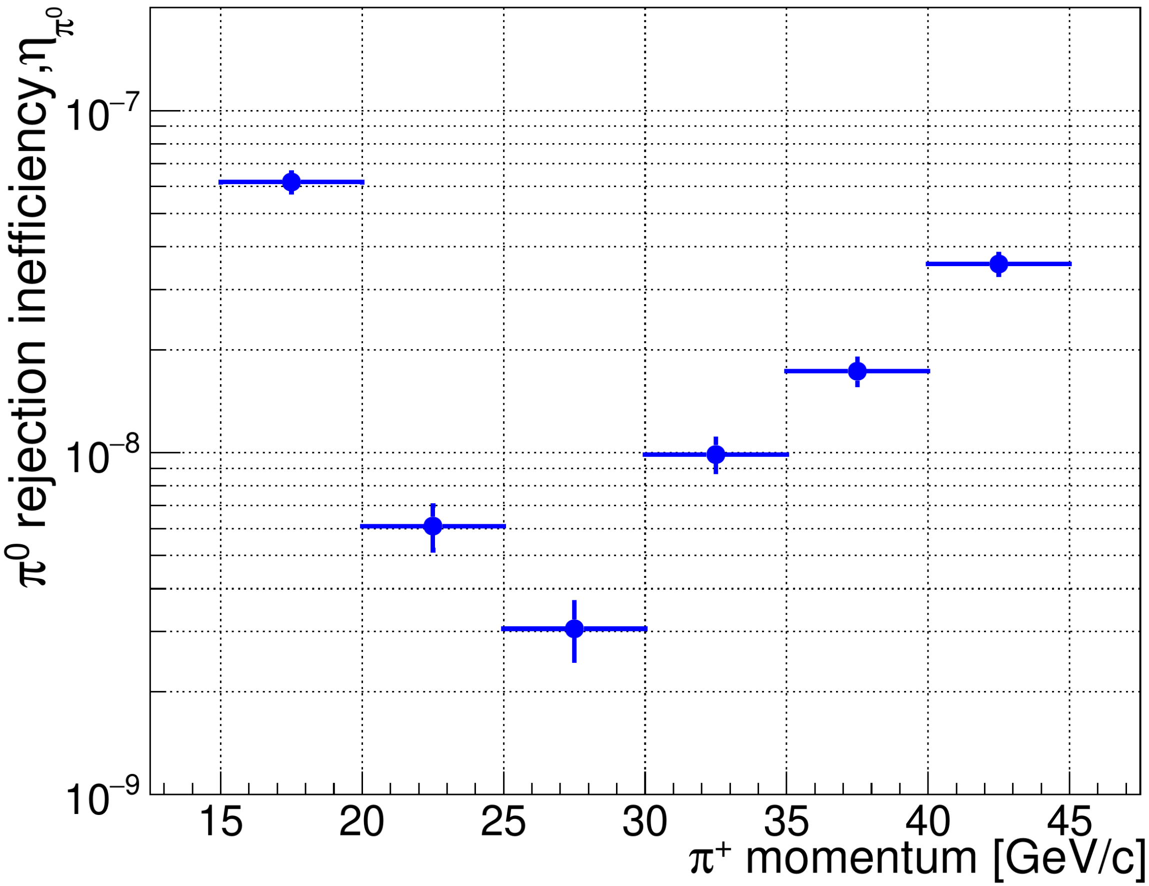
$N(\text{Upstream}) = 7.4^{+2.1}_{-1.8}$

$K^+ \to \mu^+ \nu \gamma$ background estimation and validation

- Estimation and validation of background using dedicated control samples
  - Minimum Bias trigger + MUV3 positive muon ID
  - Positively identify $\mu\gamma\,\nu$ events using $|(P_K - P_\mu - P_\gamma)^2| < 0{,}01\ \mathrm{GeV}^2/c^4$
- Probability of calo mis-ID estimated using events passing calorimetric BDT pion selection (in a muon enriched sample with relaxed RICH selection)
- Use calo mis-ID probability and appropriate trigger rescaling to estimate bkg
- Bkg checked in the sidebands of the calorimetric BDT pion probability (with standard RICH selection)



Photon veto performance

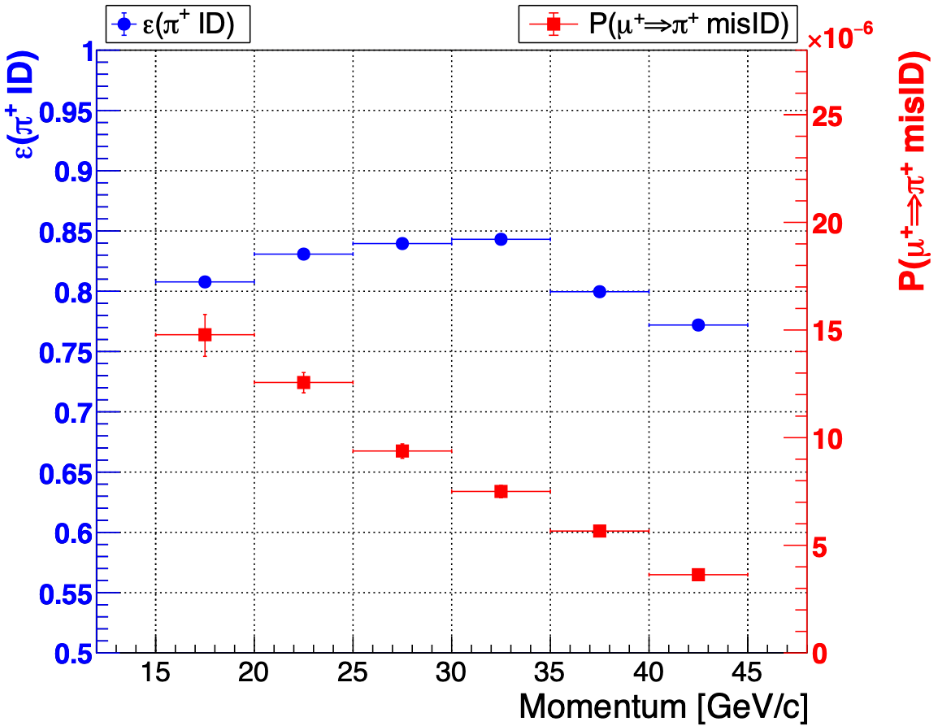


Probability of $K^+ \to \pi^+\pi^0$ events with $\pi^0 \to \gamma\gamma$ passing full photon vetos:

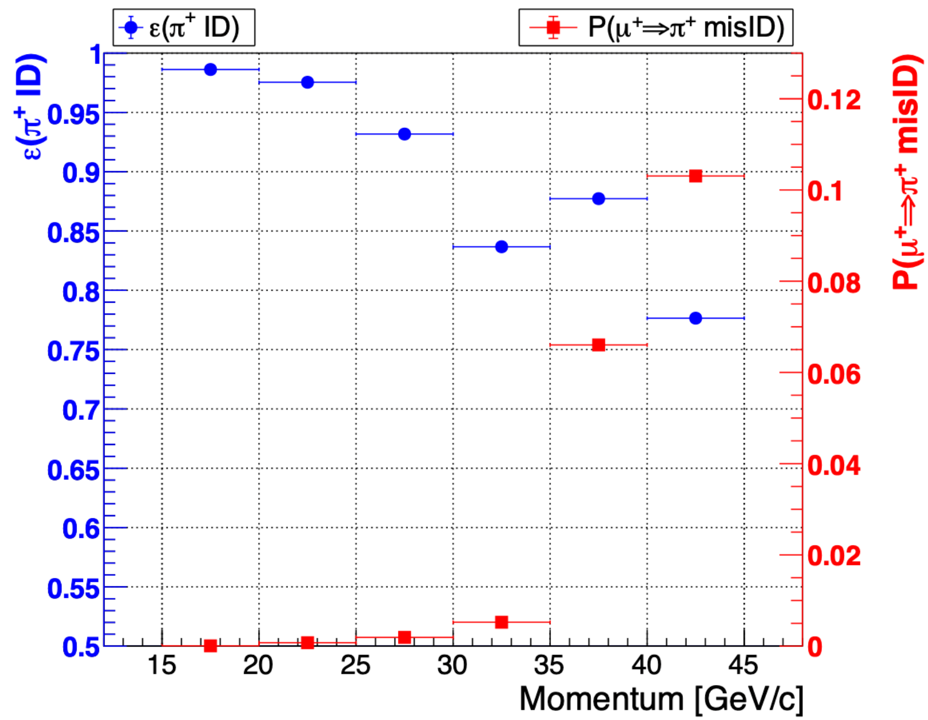
$$\eta_{\pi 0} = (1.72 \pm 0.07) \times 10^{-8}$$

Particle ID performance

Calorimetric
(LKr + MUV12 + MUV3)

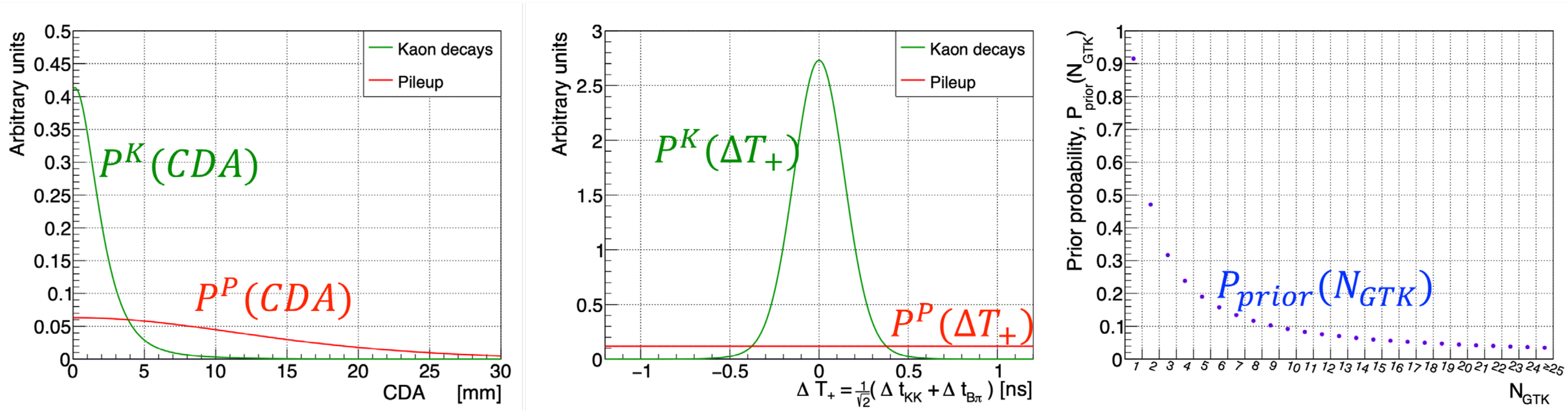


RICH



Bayesian $K - \pi$ matching

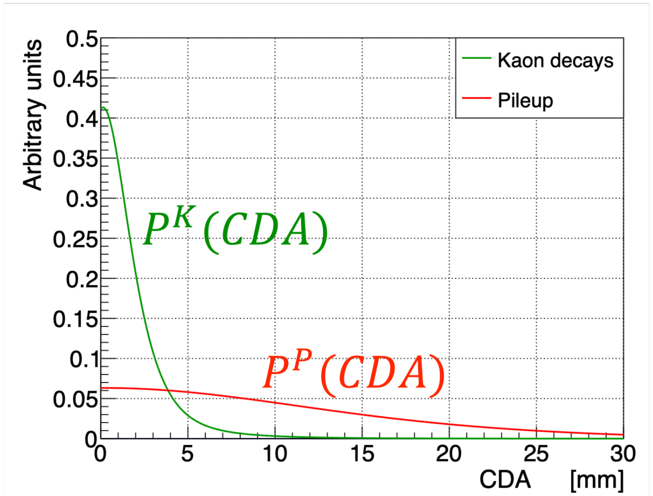
- **Inputs:** spatial (CDA) & time (ΔT_+) matching, intensity/pileup (N_{GTK}) [prior]
  - Models for PDFs/Prior from $K^+ \to \pi^+\pi^+\pi^-$ data.



- **Output:** posterior probability of GTK track = true K^+
  - Use likelihoods of kaons (K) and pileup (P)
  - Likelihood ratio used to select true match when $N_{GTK} > 1$
- Efficiency improved (+10%) and mistagging probability maintained.

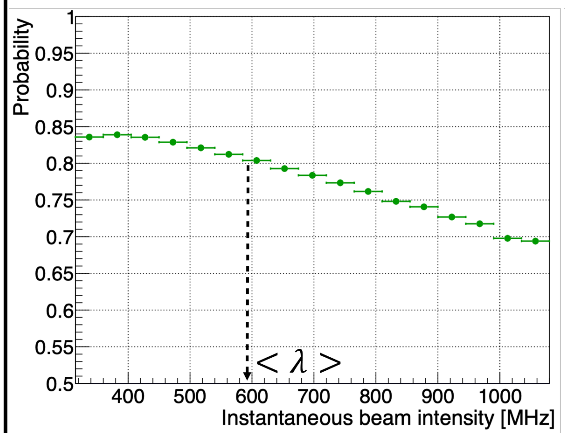
Bayesian $K - \pi$ matching

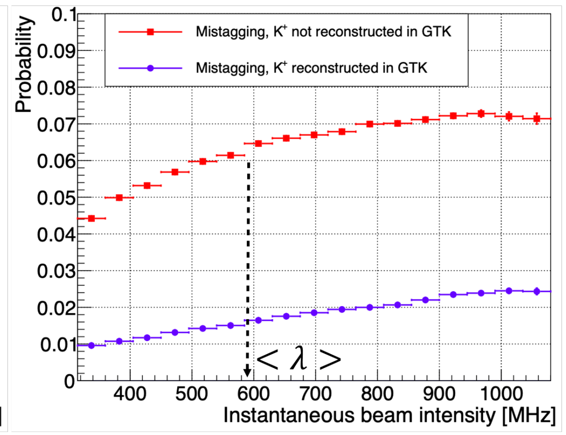
- **Inputs:** matching in space (CDA) & time (ΔT)
  Prior: pileup (N_{GTK})
  - Models for PDFs/Prior from $K^+ \to \pi^+\pi^+\pi^-$ data



- **Output:** posterior probability of GTK track = true K^+
  - Use likelihoods of kaons (K) and pileup (P)
  - Likelihood ratio used to select true match when $N_{GTK} > 1$

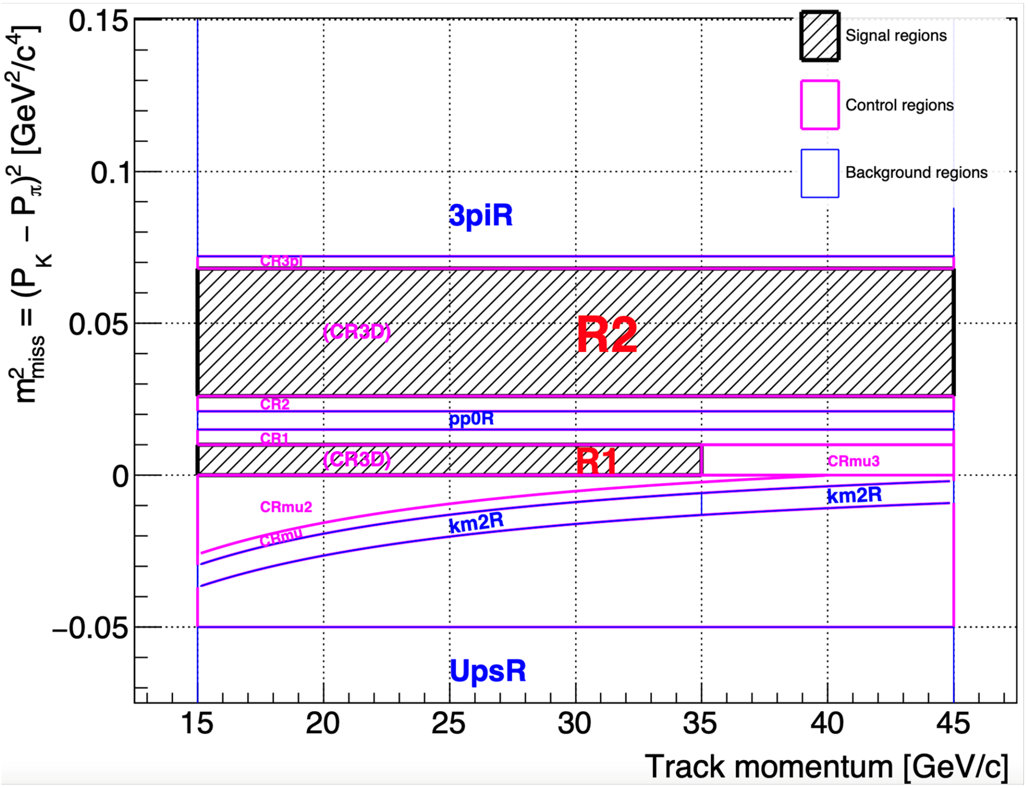
$\varepsilon = 80\%$ $P^P_{mistag} = 6\%$ $P^K_{mistag} = 2\%$





- Efficiency improved (+10%) and mistagging probability maintained.

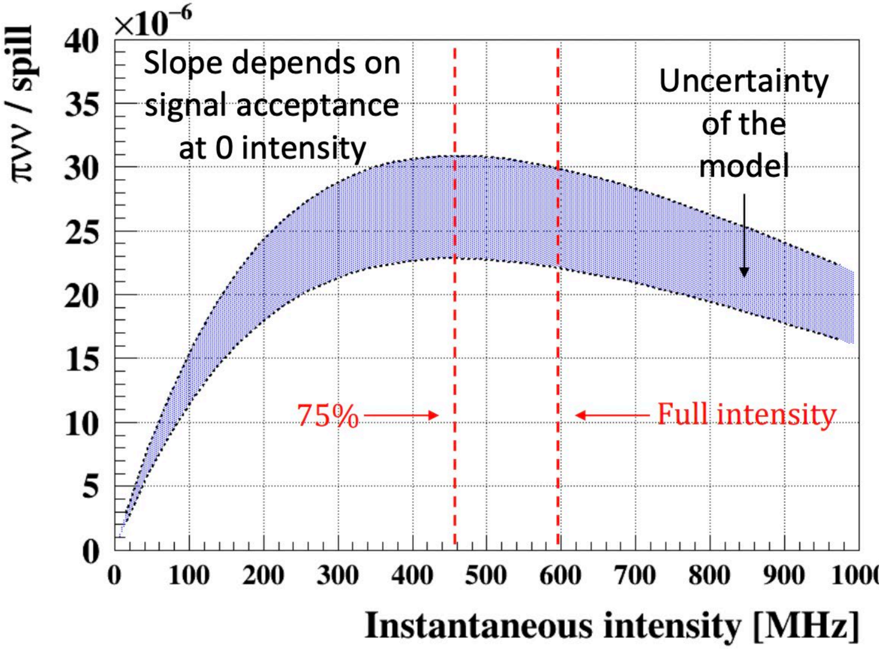
Kinematic regions

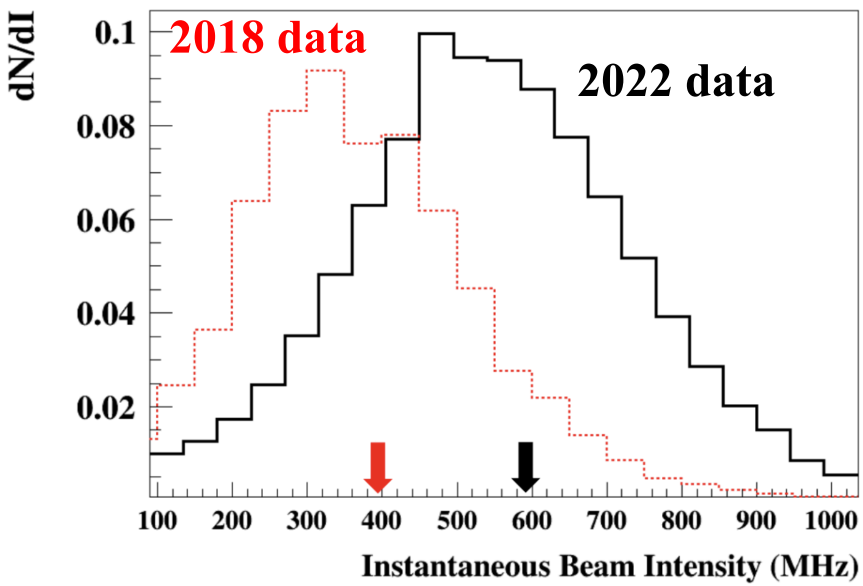


- **Signal regions:**
- **Control regions:**
  - Used to validate background predictions.
- **Background regions:**
  - Used as "reference samples" for some background estimates.

Beam intensity

Optimum NA62 intensity





- Saturation due to paralyzable dead time
  - TDAQ dead time
  - Trigger veto
  - Offline veto
- Operated at 75% intensity (450 MHz) since August 2023