European Physical Society Conference on High Energy Physics

26 -30 July 2021, Online Conference

Measurement of the very rare $K^+ \to \pi^+ \nu \bar{\nu}$ decay with the NA62 experiment at CERN

Angela Romano*, on behalf of the NA62 Collaboration

Outline:

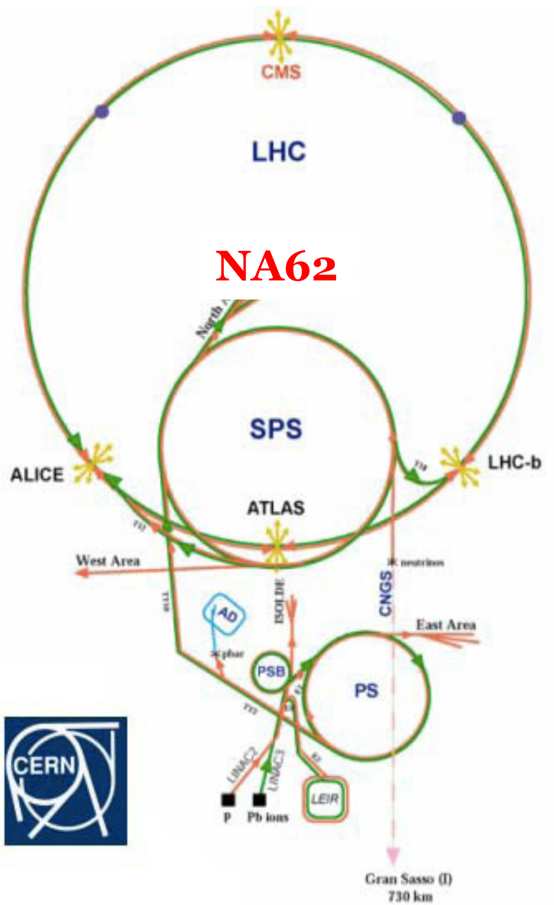
- The NA62 experiment at CERN SPS
- Study of $K^+ \to \pi^+ \nu \bar{\nu}$ decay
- Future

*University of Birmingham

The NA62 experiment

High precision fixed-target Kaon experiment at CERN SPS

Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna (JINR), Fairfax, Ferrara, Florence, Frascati, Glasgow, Lancaster, Liverpool, Louvain-la-Neuve, Mainz, Moscow (INR), Naples, Perugia, Pisa, Prague, Protvino (IHEP), Rome I, Rome II, San Luis Potosí, TRIUMF, Turin, Vancouver UBC.



NA62 Timeline

- **Dec 2008 - NA62 Approval**
- **2009 - 2014: Detector R&D, Installation**
- **2015 Commissioning**
- **2016-2017-2018: Physics Run 1 (this talk)**
- **2021-2023 Physics Run 2** (started in July)

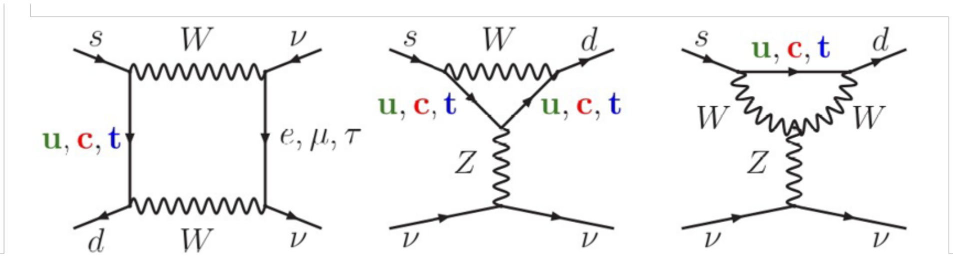
NA62 primary goal: Measure BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$)

New: K^+ decay-in-flight technique

[PLB 791 (2019) 156] [JHEP 11 (2020) 042] [JHEP 06 (2021) 093]

Motivations for $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

Box & Penguin (one-loop) diagrams

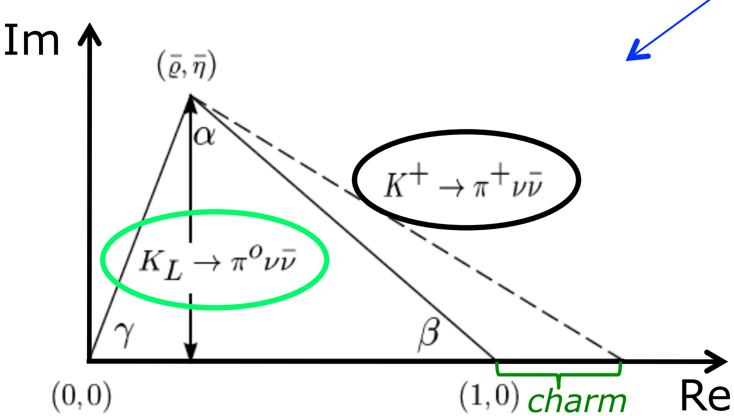


- ✓High sensitivity to New Physics
- ✓FCNC process forbidden at tree level
- ✓ Highly CKM suppressed (BR ~ $|V_{ts}^* V_{td}|^2$)
- ✓Extraction of V_{td} with minimal (few %) non-parametric uncertainty

Theoretically very clean:

- ✓ dominant short-distance contribution
- ✓ hadronic matrix element extracted from precisely measured BR($K^+ \rightarrow \pi^0 e^+ \nu$)

Independent determination of unitary triangle for K meson system (with neutral mode)



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

[Buras et al., JHEP 1511 (2015) 033]

error: CKM parametric, dominated by V_{cb}

Indirect searches of NP with high precision studies of rare K decays

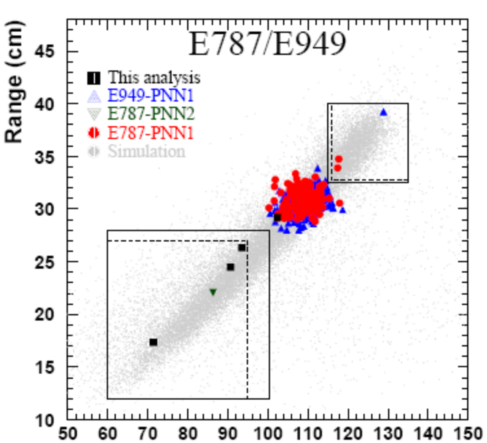
Experimental Status & NP Sensitivity

$BR(K^+ \to \pi^+ \nu\bar{\nu})_{THEORY} = (0.84 \pm 0.10) \times 10^{-10}$

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

[E787/E949, Phys.Rev.Lett.101, 191802, 2008]

- based on 7 candidates
- stopped Kaon technique



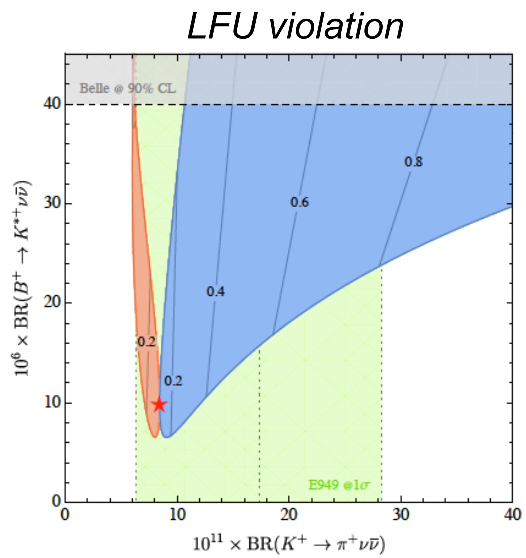
(7 candidates E787+E949)

NA62 result, 2016-2017 data:

$BR(K^+ \to \pi^+ \nu\bar{\nu}) < 1.78 \times 10^{-10}$ @90% CL

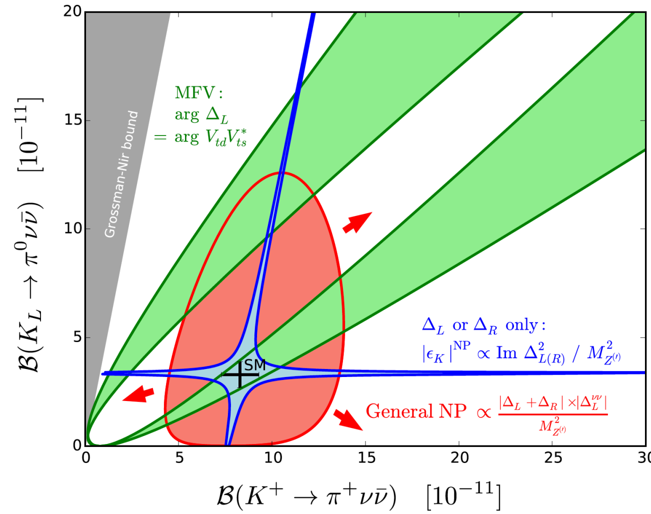
[JHEP 11 (2020) 042]

Discrimination among NP scenarios



[Isidori et al., Eur. Phys. J. C (2017) 77: 618]

[Buras, Buttazzo,Knegjens, JHEP11(2015)166]



Correlations significantly change for different classes of NP models

$K \to \pi\nu\bar{\nu}$ probes of unique sensitivity for NP models among B and K decays

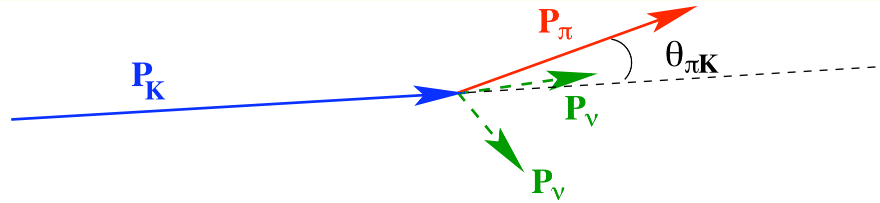
(NP searches complementary/alternative to LHC)

$K^+ \to \pi^+\nu\bar{\nu}$ Signal & Backgrounds

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

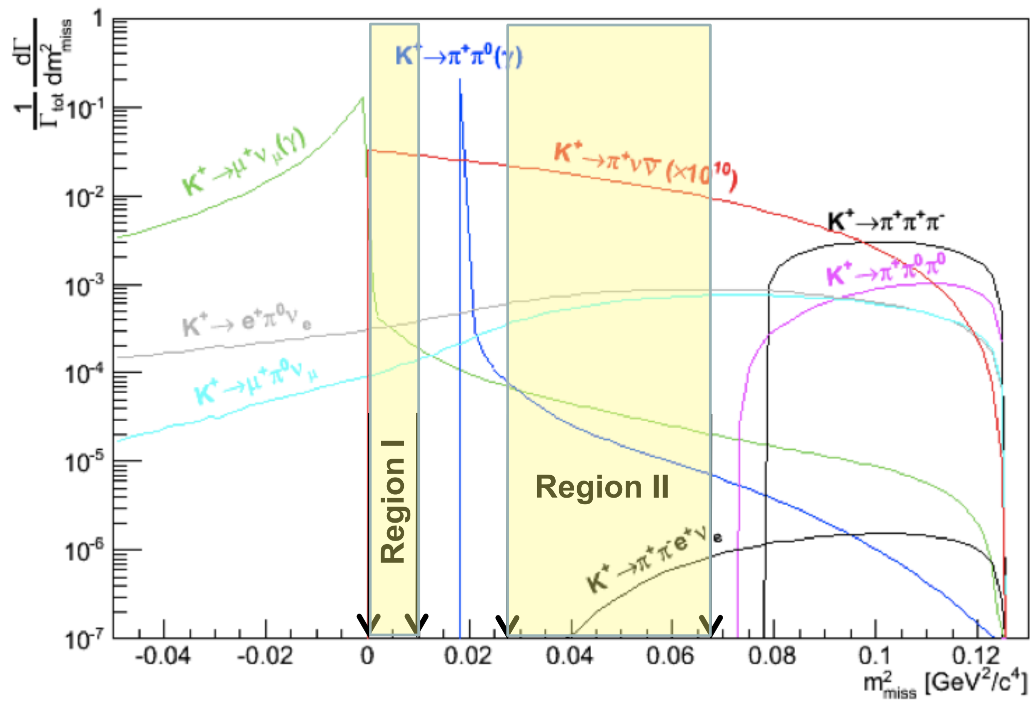
$$m^2_{miss} = (P_K - P_\pi)^2$$

K+ decay-in-flight technique



Main kaon decay backgrounds

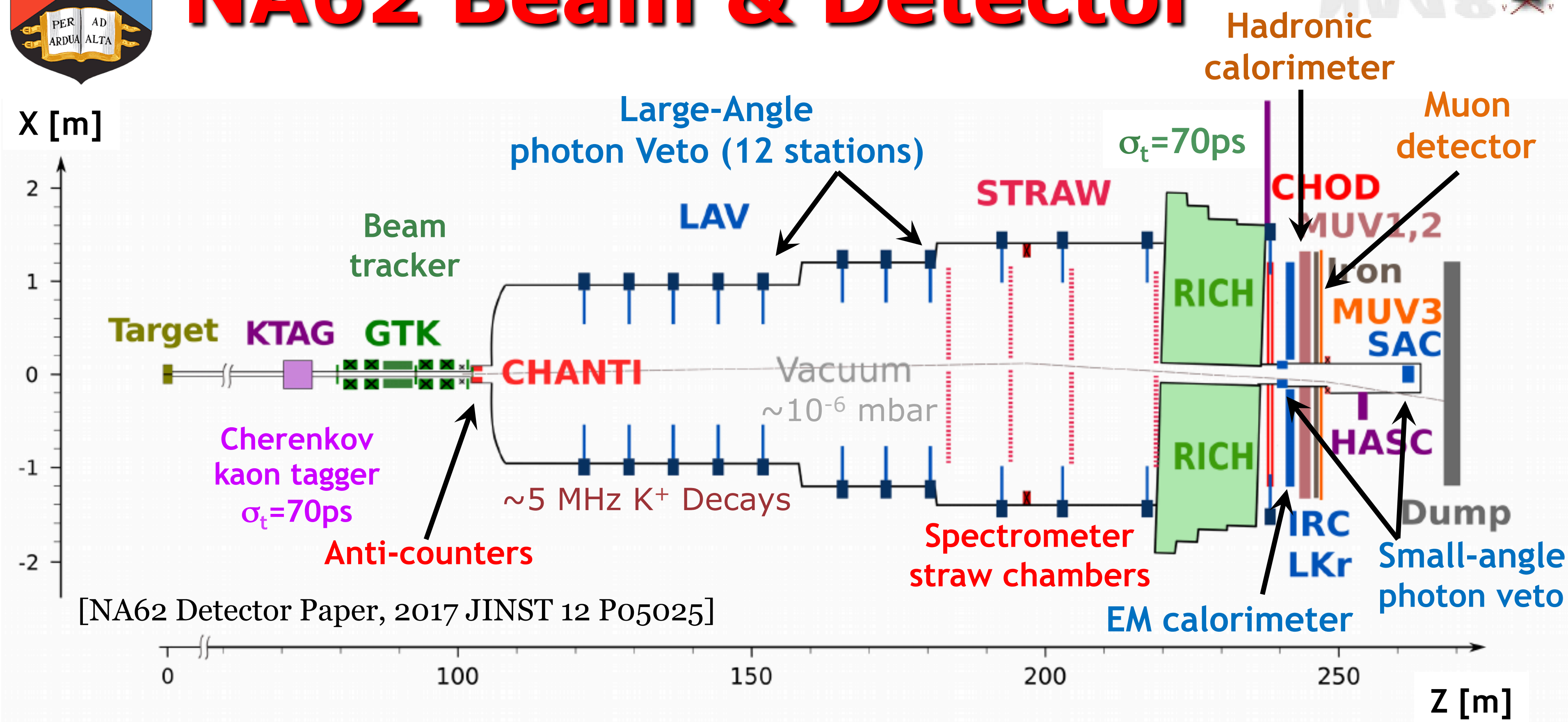
Process	Branching ratio
$K^+ \to \mu^+\nu_\mu(\gamma)$	63.5%
$K^+ \to \pi^+\pi^0(\gamma)$	20.7%
$K^+ \to \pi^+\pi^+\pi^-$	5.6%
$K^+ \to \pi^+\pi^- e^+\nu_e$	4.3×10^{-5}



Sign & Bkg control regions kept blind throughout the analysis

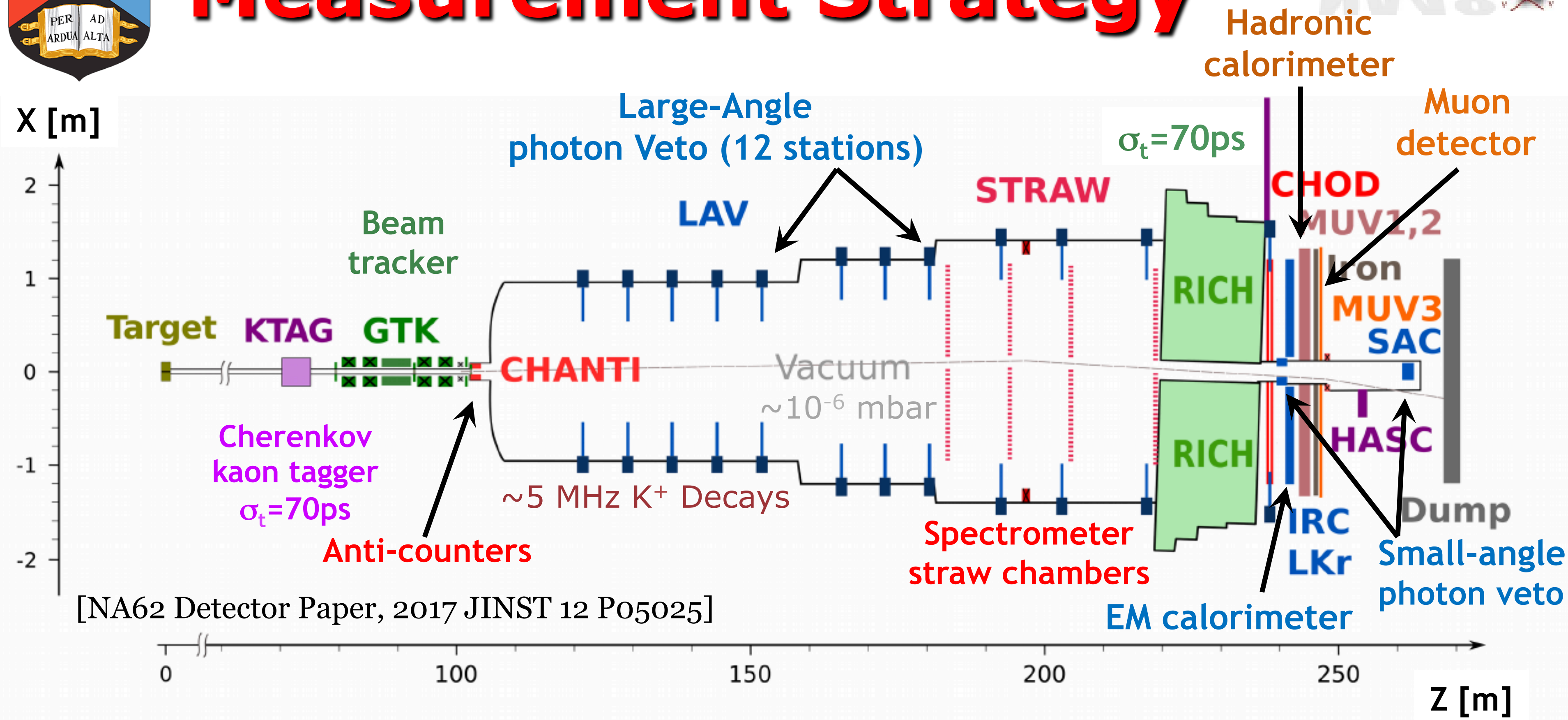
Background rejection relies on **Kinematics** (15GeV/c < P_π < 35GeV/c ; m^2_{miss}) used in conjunction with **Particle ID**, **Veto systems** and **sub-ns timing**

NA62 Beam & Detector



- SPS protons on Be target (PoT): 400 GeV/c, $\sim 10^{12}$ PoT/sec , 3.5 sec/spill
- Un-separated hadron beam: π^+(70%)/K^+(6%)/p(24%)
- K^+: 75GeV/c (±1%), divergence < 100μrad, (60 x 30) mm² transverse size
- 750MHz nominal beam rate @GTK (~5MHz K^+ decays in 60 m fiducial volume)
- 2016, 2017, 2018 beam rates in Run 1 [MHz]: ~300,~500,~600

Measurement Strategy



NA62 Performance keystones:

- Timing between sub-detectors ~ O(100ps)
- Kinematic rejection ~O(10^4) for $K^+ \to \pi^+\pi^0$, $K^+ \to \mu^+\nu$ bkg channels
- Particle ID: muon suppression (from $K \to \mu^+\nu$) > 10^7
- Photon veto: $\pi^0 \to \gamma\gamma$ suppression (from $K^+ \to \pi^+\pi^0$) > 10^7

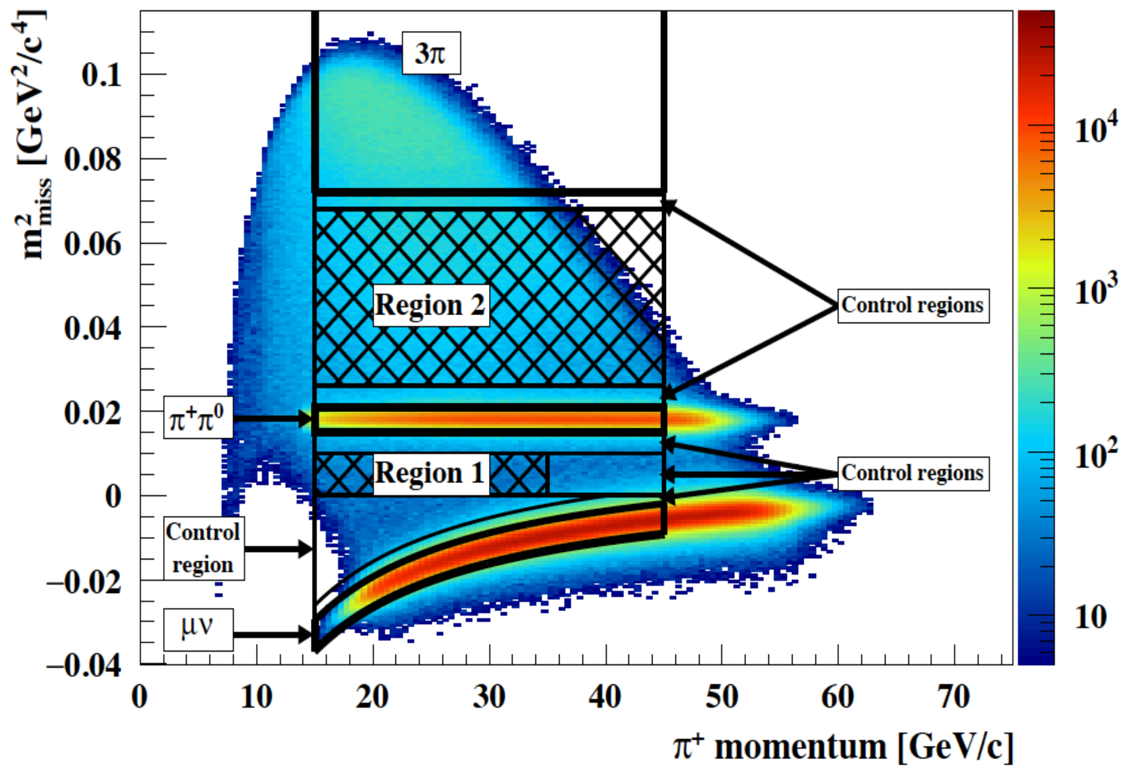
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ Signal Selection

Signal and Control kinematic regions blinded during the analysis

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

Selection steps:

- Reconstruct π^+ and K^+ tracks
- **K-π match & decay vertex**
- **π^+ ID (μ^+ rejection)**
  - RICH (Calorimeters)
  - $\varepsilon(\pi^+) \approx 0.85$ (0.82)
  - $P(\mu^+ \Rightarrow \pi^+) \approx 3\text{x}10^{-3}$ (10^{-5})
- **Photon rejection**
  - $\varepsilon(\pi^0 \rightarrow \gamma\gamma) \approx 2 \cdot 10^{-8}$
- Multi-track rejection
- **Kinematics (m^2_{miss} vs p_π)**
  - $\sigma(m^2_{miss}) = 1 \cdot 10^{-3}$ GeV²/c⁴
  - $\sigma_T \sim O(100\text{ps})$

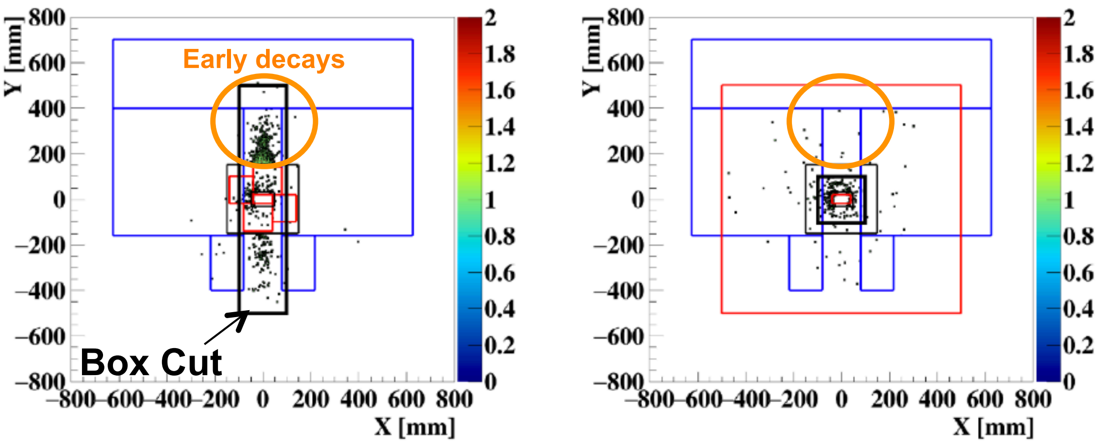


Selection optimized in bins of π^+ momentum

Upstream Background

- Kaon decays in upstream region (e.g. interactions with GTK stations)
- π^+ enters fiducial volume (FV) and scatters in first STRAW chamber
- Beam pileup particle (in GTK) generates a fake decay vertex inside the FV
- In 2018 collimator was replaced to remove early decays mechanism
- Data sample split in subsets S1 (OLD COL) and S2 (NEW COL)

Track extrapolation at collimator in enriched sample of upstream events (data)



OLD COL NEW COL

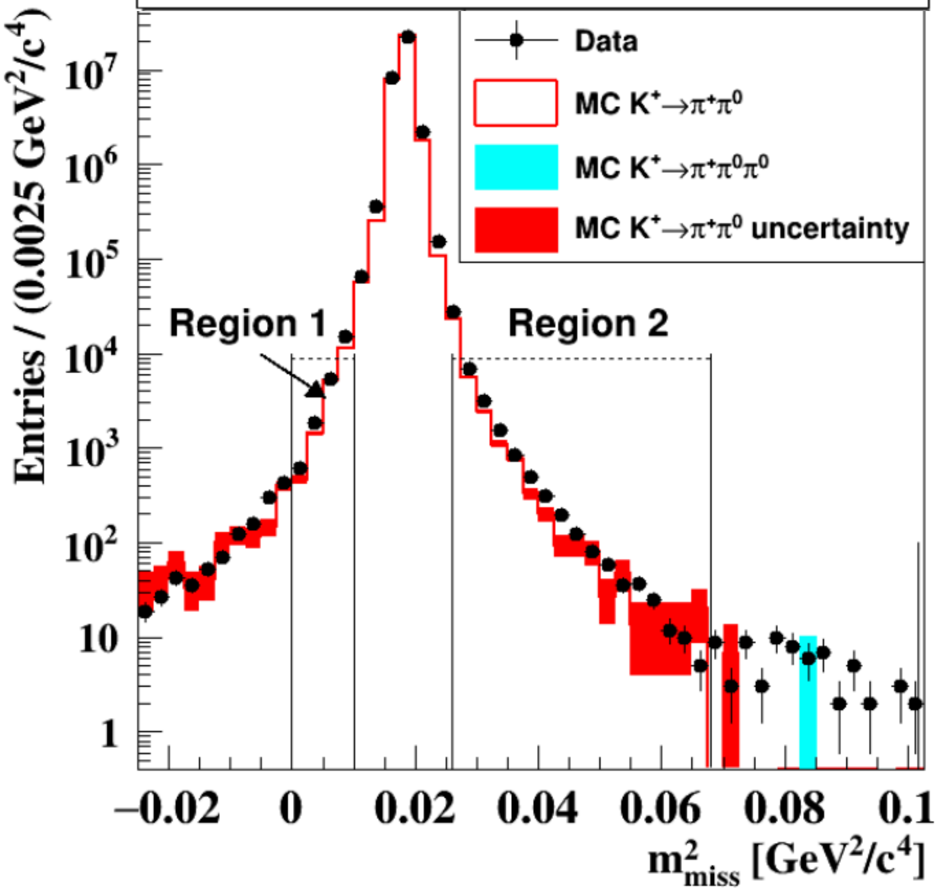
Dipole Magnet
CHANTI acceptance
Collimator

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	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$

Background estimates summed over Region 1 and Region 2

Background from K decays

Control $K^+ \to \pi^+\pi^0$ data used to study the tails of the m^2_{miss} distribution



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Data Driven estimation

Number of events in $\pi^+\pi^0$ regions after $\pi\nu\nu$ selection

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

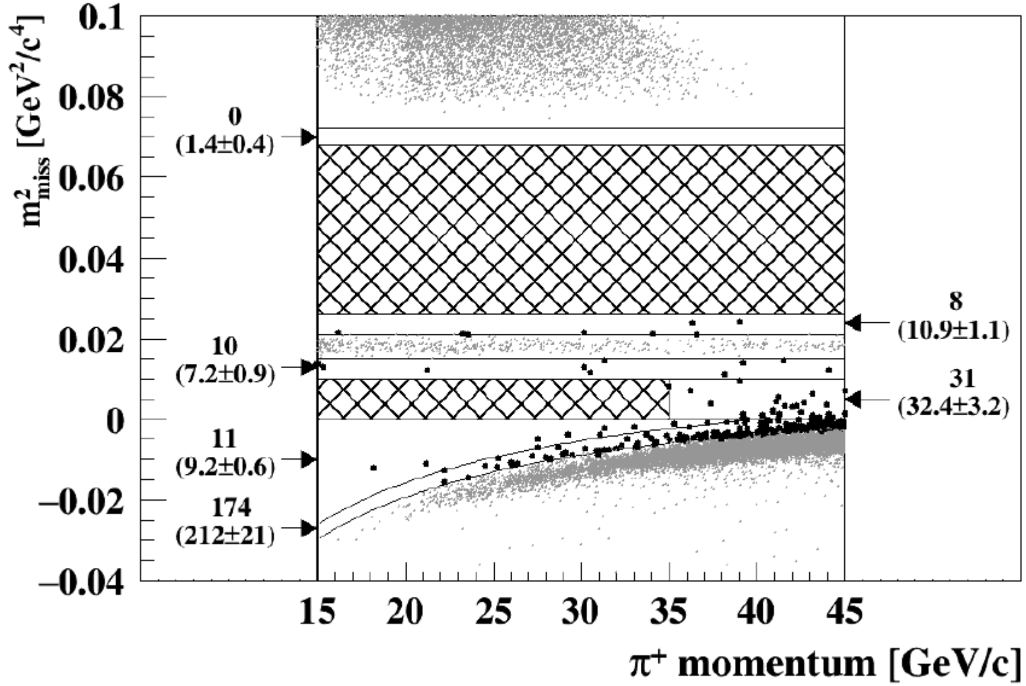
Expected number of $\pi^+\pi^0$ events in signal region after $\pi\nu\nu$ selection

Fraction of $\pi^+\pi^0$ events in signal region measured from control data

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

Background expectations validated using control regions

Observed (expected) events in control regions



Background	Subset S1	Subset S2
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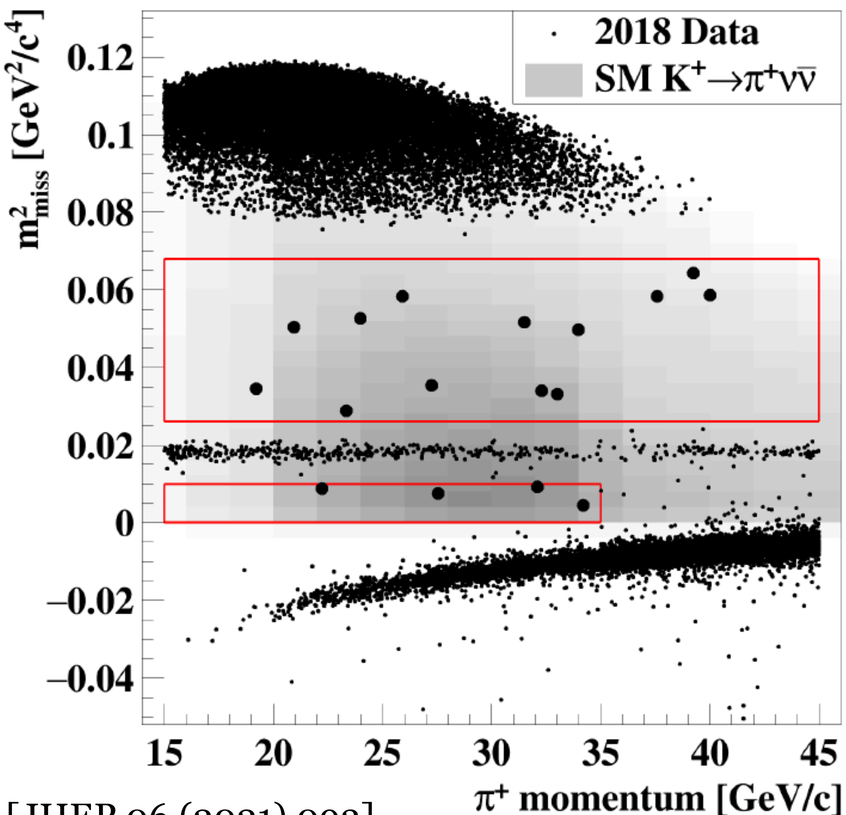
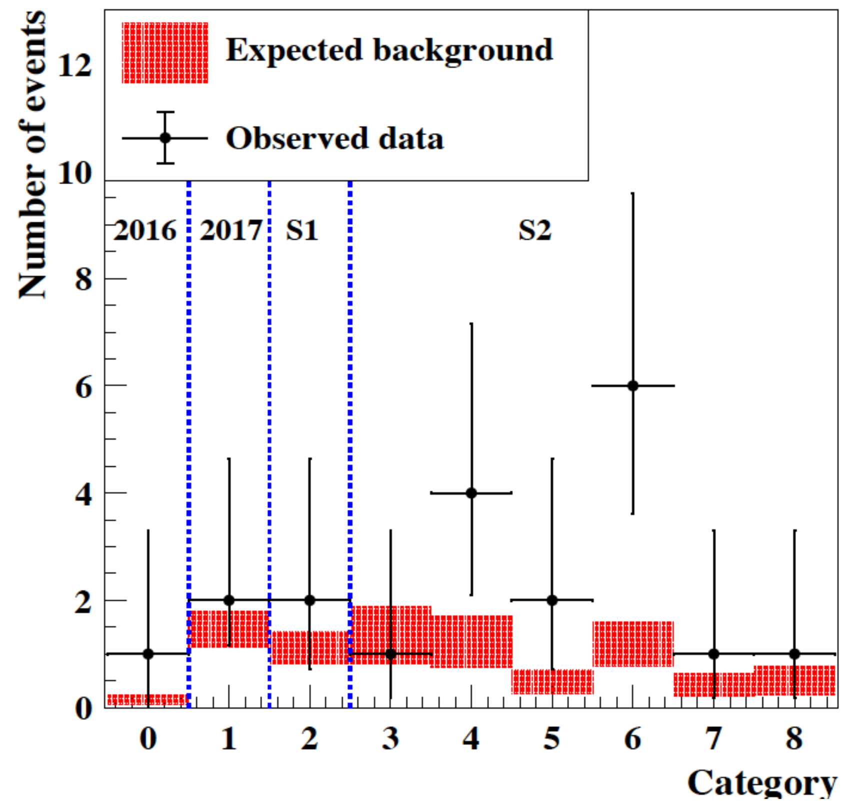
Background estimates summed over Region 1 and Region 2

Validation: expected vs observed background events in control regions in bins of π^+ momentum

Signal Regions are blinded!

Result: 2016+2017+2018





[JHEP 06 (2021) 093]

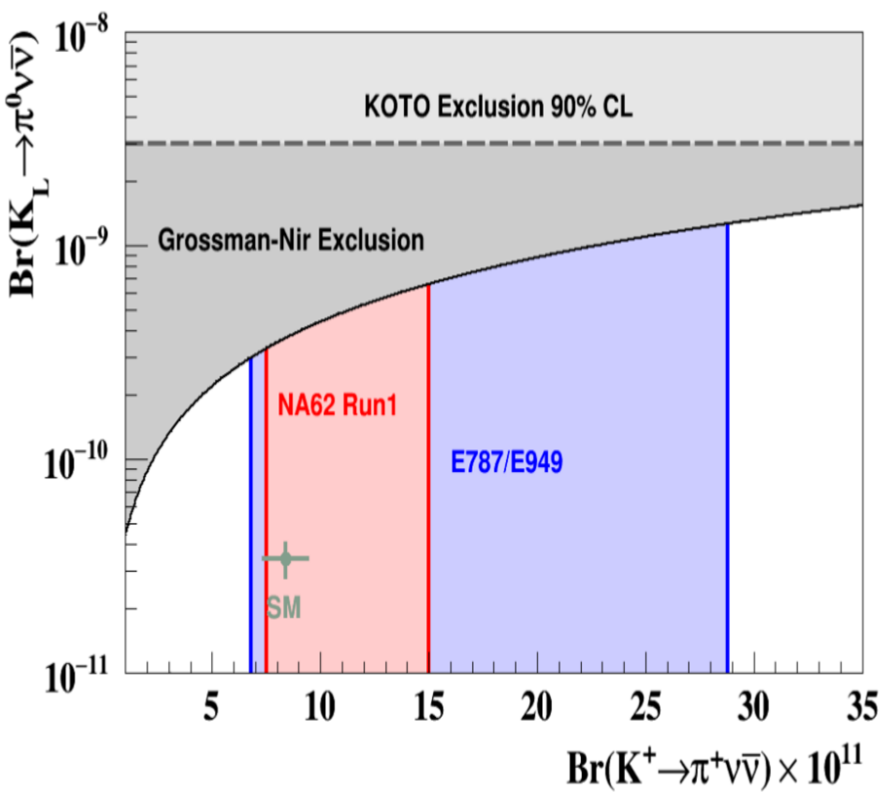
- 20 events observed in signal regions
- P(only bkg) = 3.4 x 10^{-4}
- corresponding to 3.4σ significance

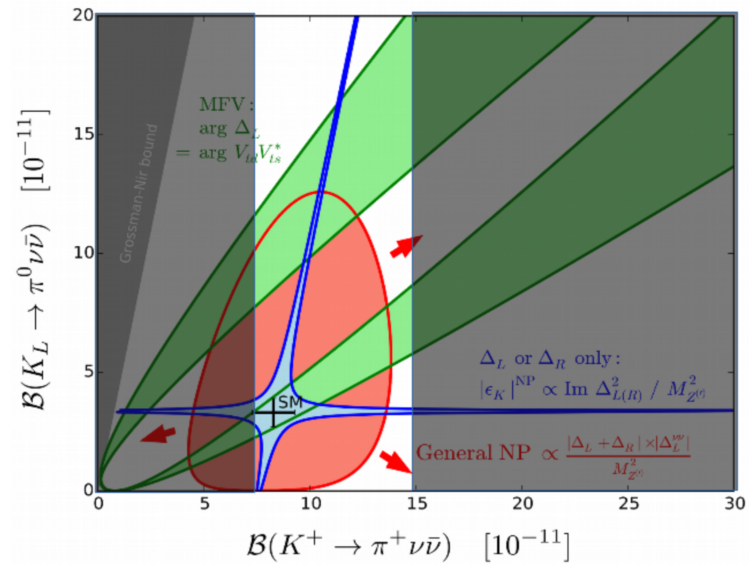
$$SES = (0.839 \pm 0.053_{\mathrm{syst}}) \times 10^{-11},$$
$$N^{\mathrm{exp}}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42_{\mathrm{syst}} \pm 1.19_{\mathrm{ext}},$$
$$N^{\mathrm{exp}}_{\mathrm{background}} = 7.03^{+1.05}_{-0.82}.$$

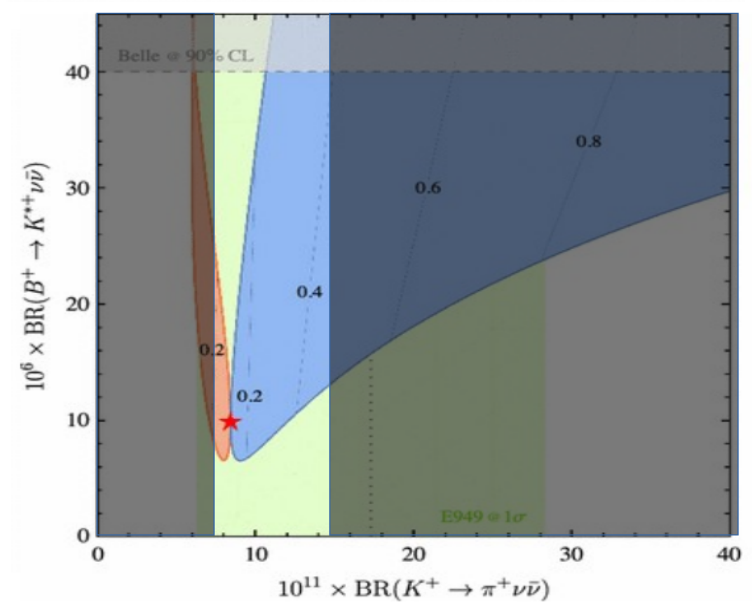
$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11} \text{ at } 68\% \text{ CL}$$

Interpretation of Result

Large BR($K^+ \to \pi^+ \nu\bar{\nu}$) deviations SM are excluded
→ high precision measurement needed

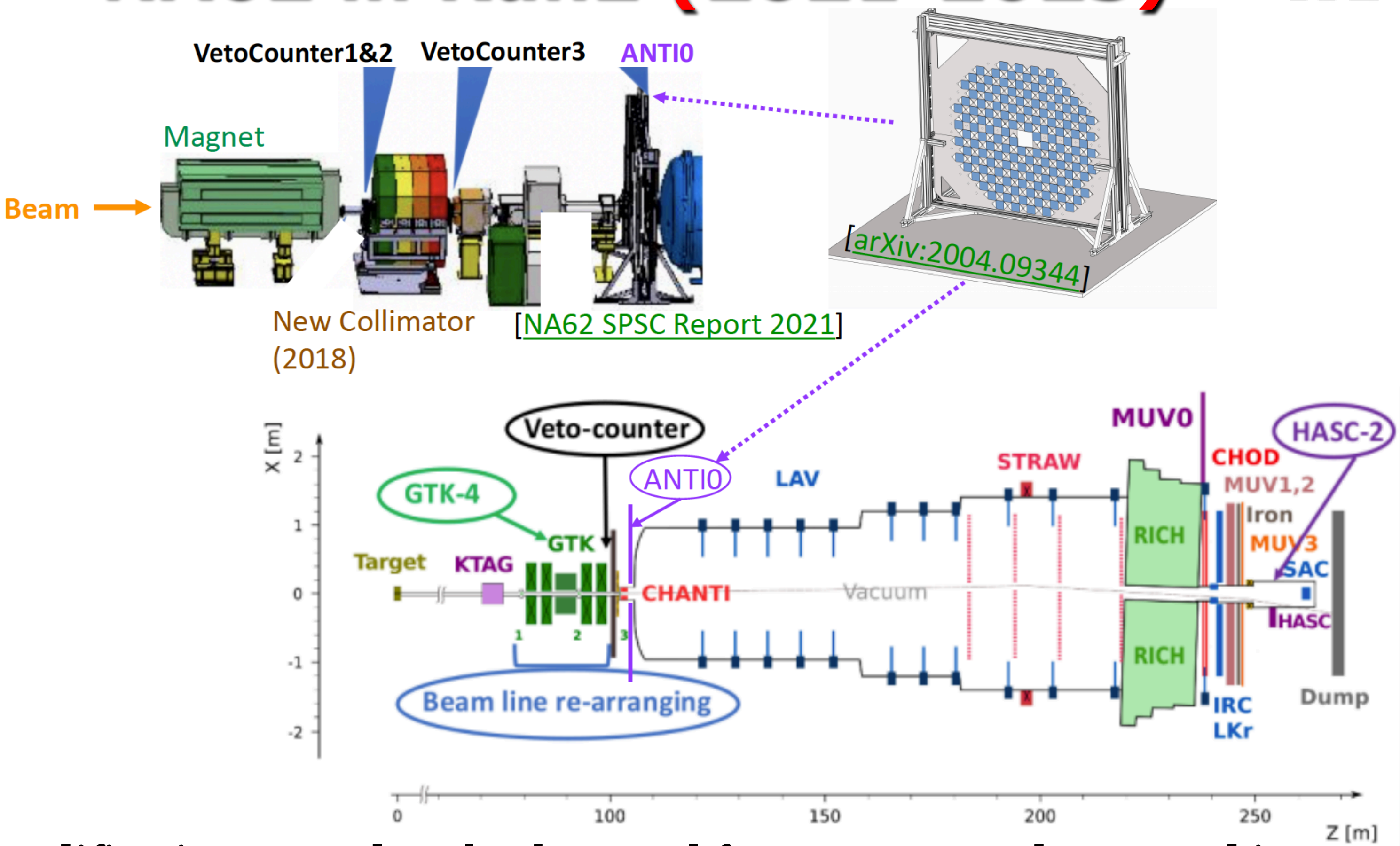






Grossman-Nir limit: $Br(K_L \to \pi^0 \nu\bar{\nu}) < 4.3 \cdot Br(K^+ \to \pi^+ \nu\bar{\nu})$

NA62 in Run2 (2021-2023)



- Key modifications to reduce background from upstream decays and interactions:
  - Add 4th station to GTK beam tracker
  - New veto hodoscope upstream of decay volume and additional veto counters around downstream beam pipe

- Run at higher beam intensity (70% → 100%)
- **Expect to measure BR($K^+ \to \pi^+ \nu\bar{\nu}$) to O(10%) by LS3**

Conclusions

- NA62 result with data collected in 2016-2018 (Run 1)

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11} \text{ at } 68\% \text{ CL}$$

- **The most precise measurement of $K^+ \to \pi^+ \nu\bar{\nu}$ to date**
- Starting constrain NP scenarios: need high precision measurement $+K_L \to \pi^0 \nu\bar{\nu}$
- Same data set used to search for $K^+ \to \pi^+ X$, where X is e.g. a Dark Scalar

- **NA62 restarted taking data in July 2021**
  - upgraded detector & beam line modifications
  - aim at further improving upstream rejection
  - run at higher intensities
  - allow for improved signal sensitivity

- NA62 2021-2023 (Run 2) will improve the current knowledge of BR($K^+ \to \pi^+ \nu\bar{\nu}$), **ultimately reaching O(10%) precision**

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SPARES

Angela Romano*, on behalf of the NA62 Collaboration

*University of Birmingham

NA62: a general purpose experiment

- **NA62**
  - **Flavour Physics**
    - Search for NP at the EW scale with sizeable coupling to SM particles via indirect effects in loops:
      Golden mode: $K^+ \to \pi^+ \nu\nu$;
      → **THIS TALK**
    - χPT and Lepton Universality tests - Precision measurements of K^+ decays
      → Talk by F. Brizioli TF8 on 29/07
    - Searches for lepton flavour and number violation (LFV, LNV) - Rare and forbidden decay analysis
      → Talk by E. Minucci TF8 on 26/07
  - **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..
      → Talk by C. Parkinson TF10 on 27/07

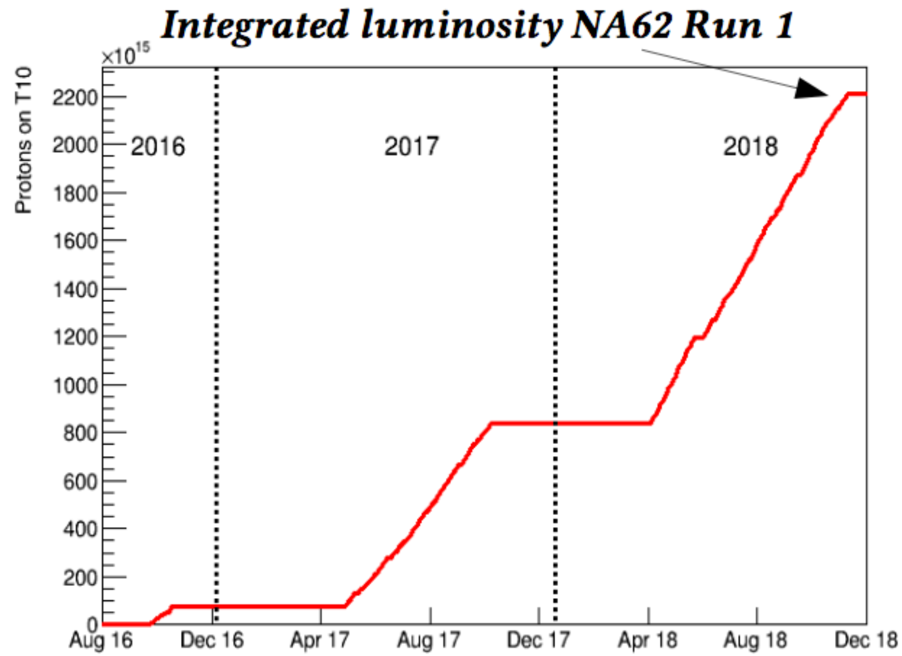
NA62 2016-2017 Results

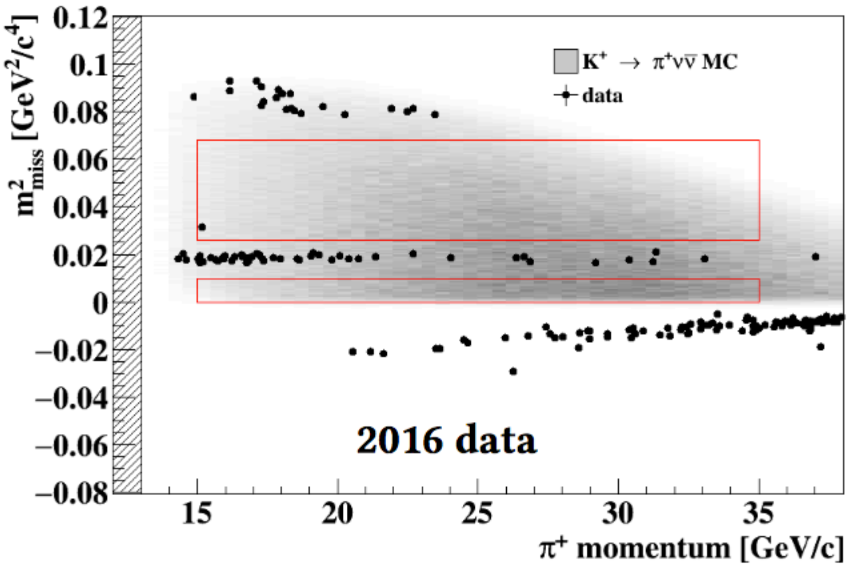
2016 40% of nominal intensity
0.12×10^{12} K^+ decays in FV

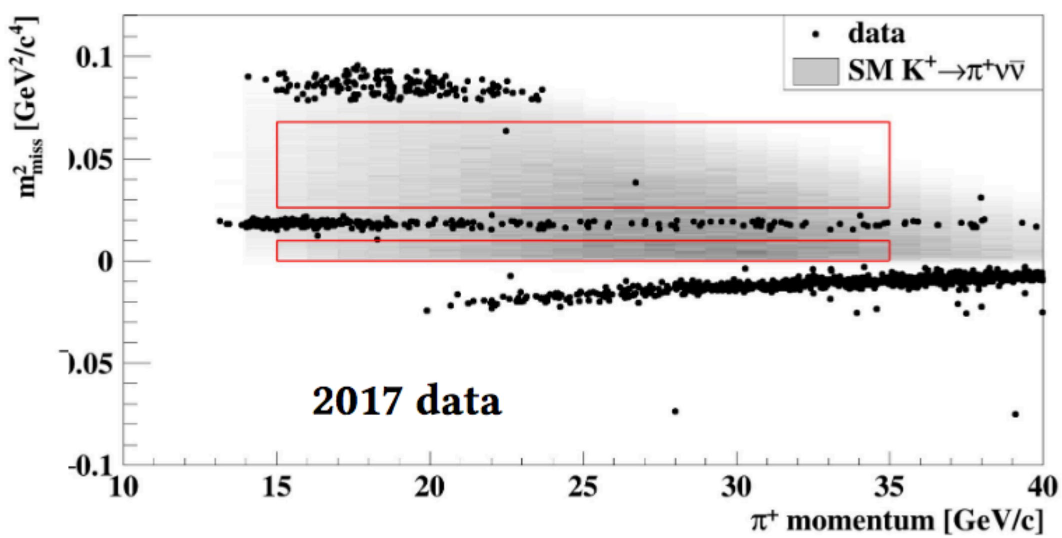
Result, 2016 data:
$BR(K^+ \rightarrow \pi^+ \nu\nu) < 14\times10^{-10}$ @ 95% CL
[PL B791 (2019) 156–166]

2017 60% of nominal intensity
1.5×10^{12} K^+ decays in FV

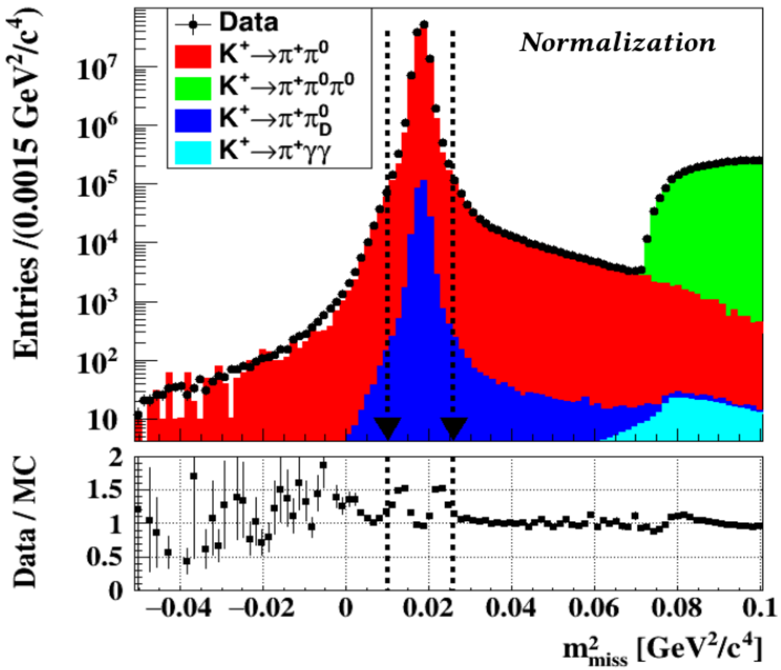
Combined result, 2016-2017 data:
$BR(K^+ \rightarrow \pi^+ \nu\nu) < 1.78\times10^{-10}$ @ 90% CL
[JHEP 11 (2020) 042]







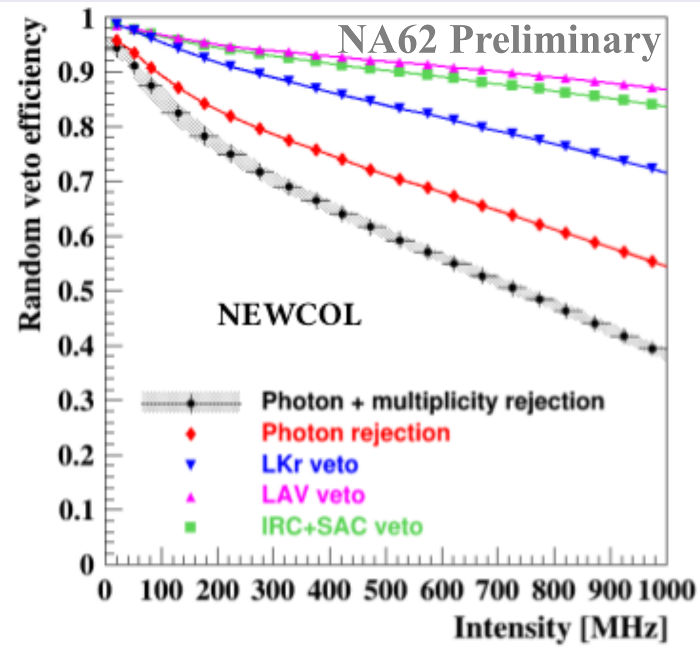
Normalisation and Single Event Sensitivity



SES error budget:

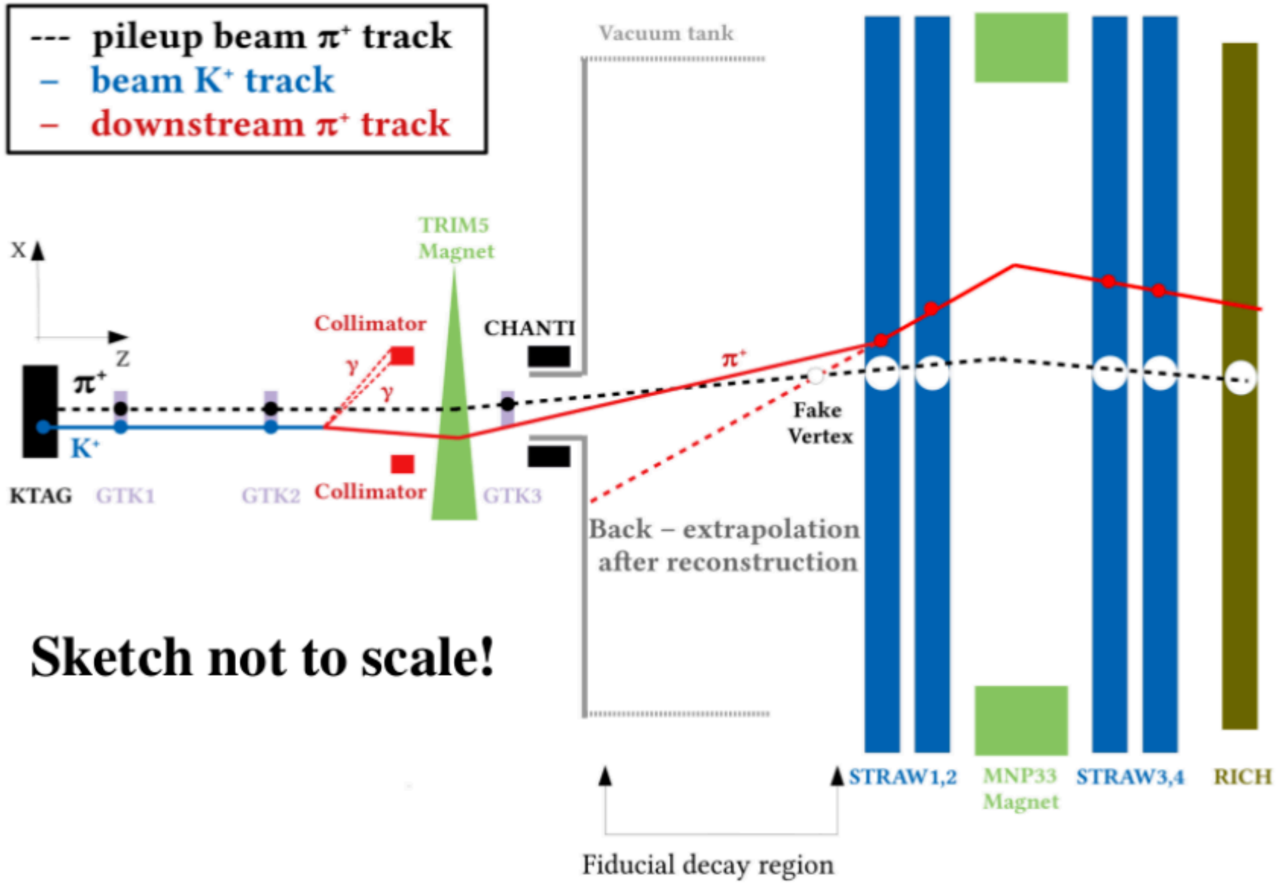
Source	Relative uncertainty
trigger efficiency	5%
MC acceptance	3.5%
random veto efficiency	2%
normalization background	0.7%
instantaneous intensity	0.7%
Total	6.5%

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



$$\text{S.E.S.} = \frac{Br(\pi\nu\nu)}{N_{\pi\nu\nu}^{exp}} = (1.11 \pm 0.07_{syst.}) \times 10^{-11}$$

Upstream Background



Kaon decays upstream the FV

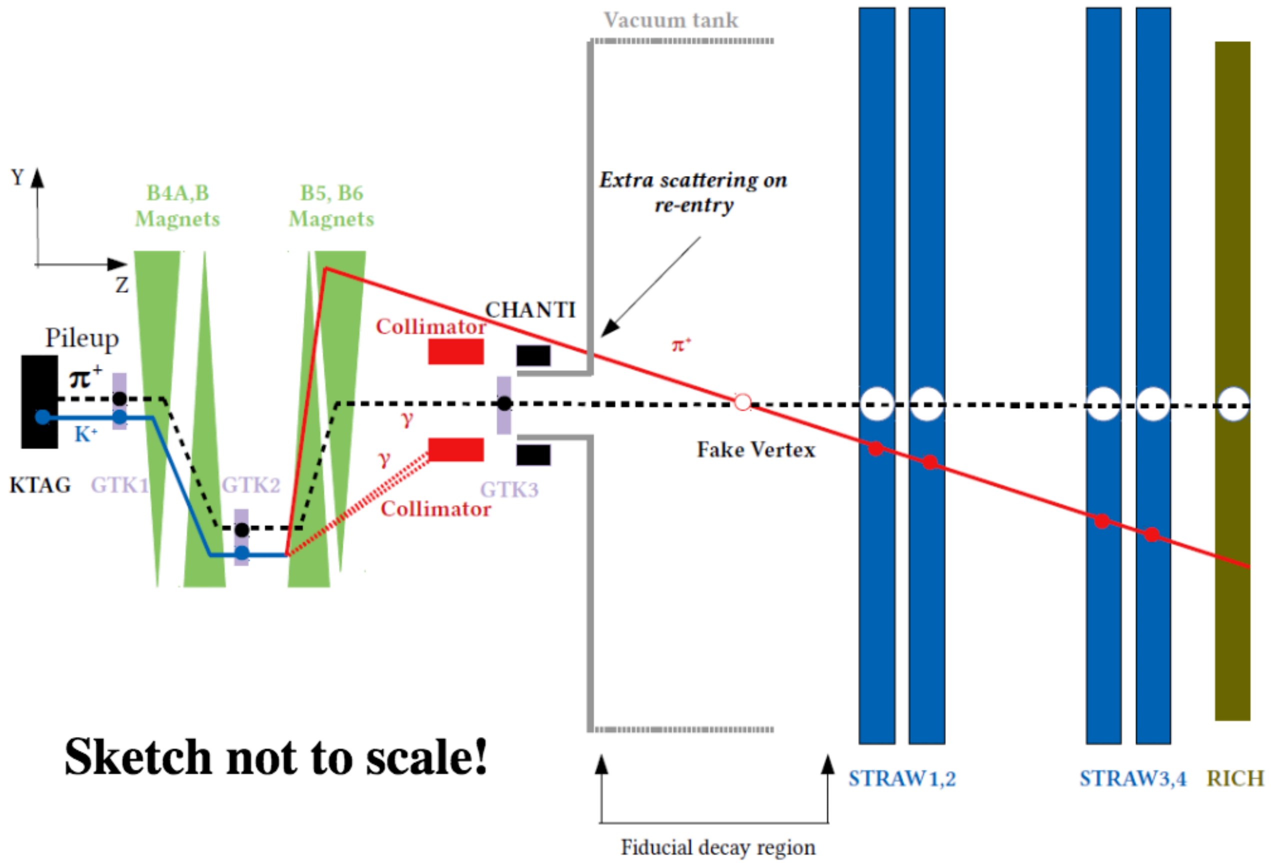
→ only π^+ enters FV and scatters in first STRAW chamber

In-time pileup beam particle (in GTK) generates a fake decay vertex inside the FV

Upstream Background

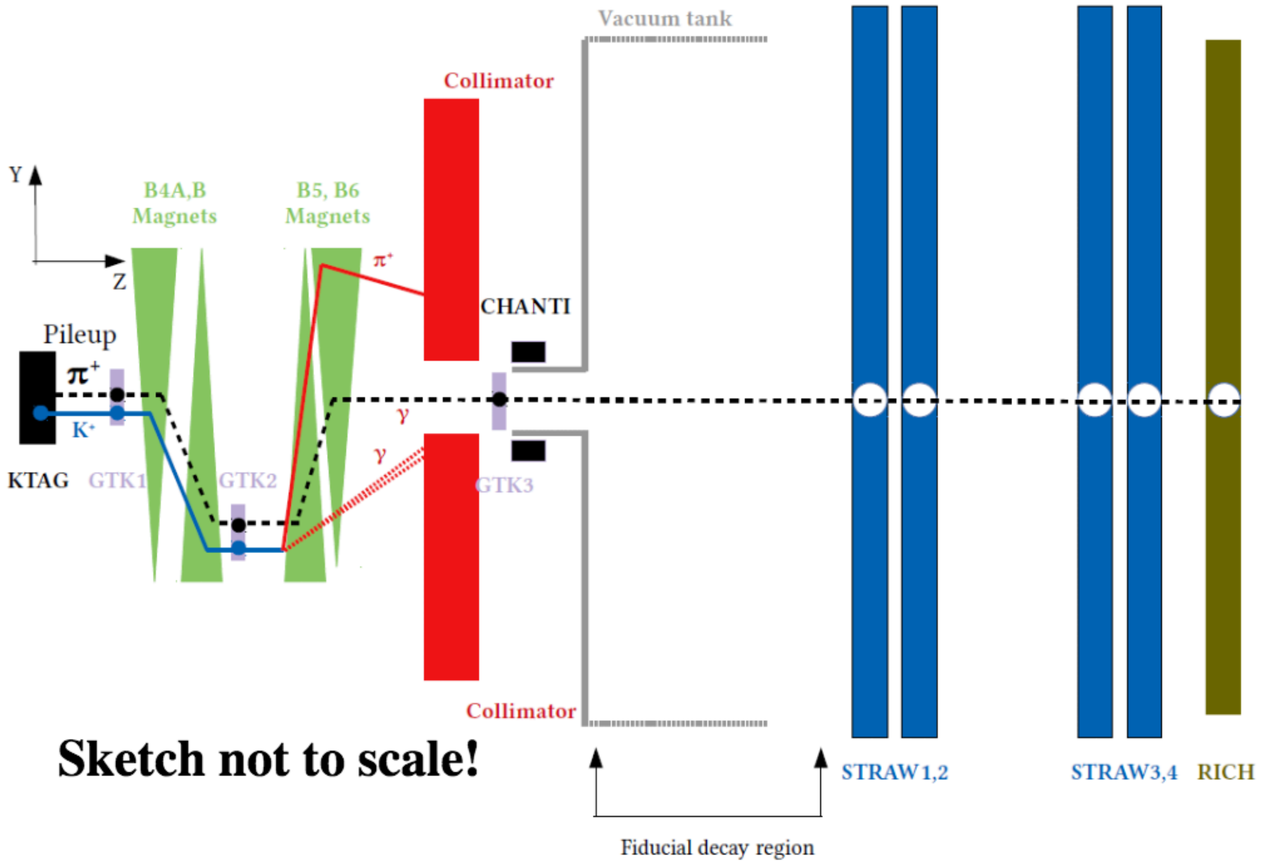
Replacement of the final collimator against Upstream events (June 2018)

Upstream Background



A particular upstream event in the OLD COL configuration

Upstream Background



Sketch not to scale!

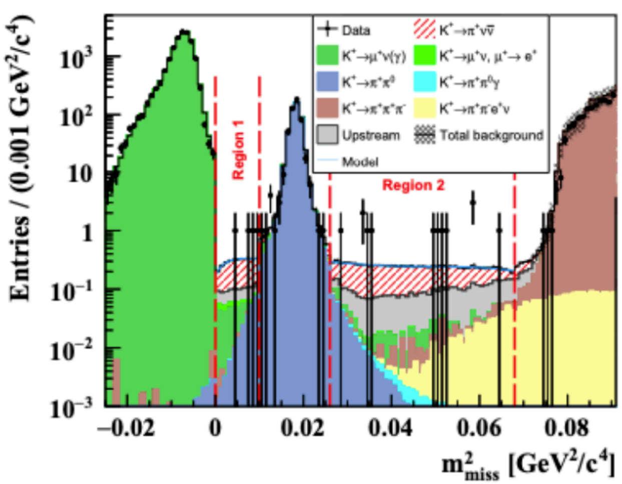
The same upstream event in the NEW COL configuration

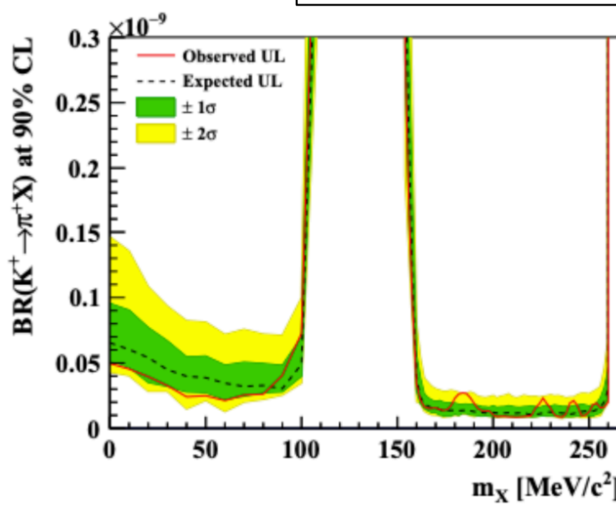
Interpretation of Result: Search for $K^+ \to \pi^+ X$

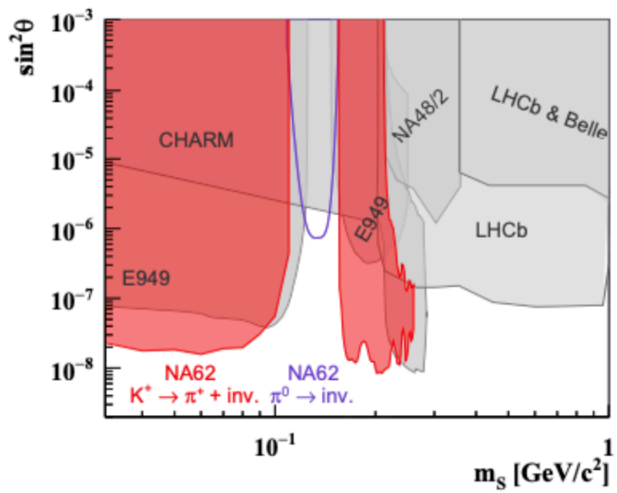
- Search for e.g. Dark Scalar (X = S), production & decay driven by mixing with Higgs boson (mixing parameter $\sin^2\theta$)
- Perform a peak search considering $K^+ \to \pi^+ \nu\bar{\nu}$ as a background
- Improve on recent NA62 limits from 2017 analysis by factor ~4

[JHEP 03 (2021) 058]

Assume X decays to visible (SM) particles





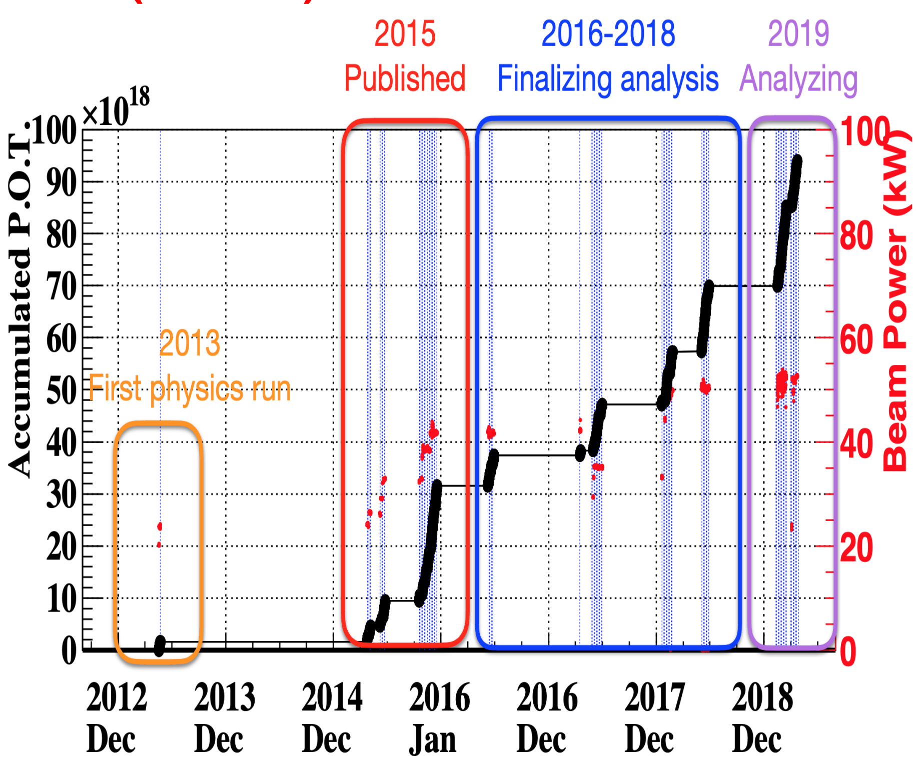


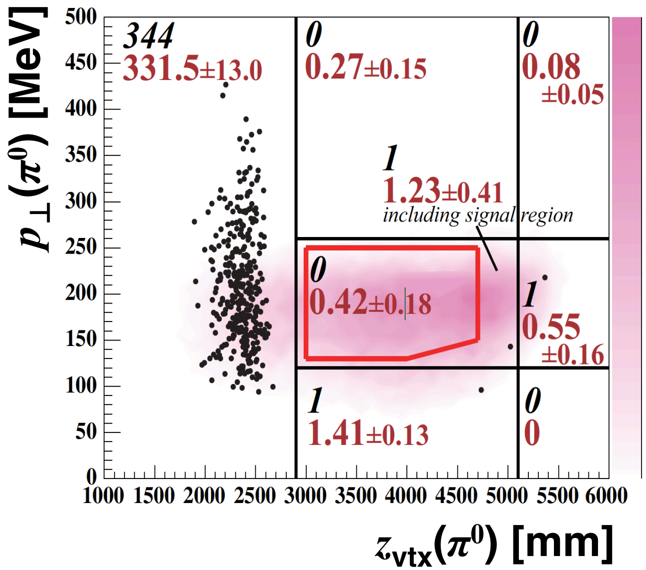
[JHEP 06 (2021) 093]

KOTO status and timeline

2015 run

- Reached **40 kW** slow-extracted beam power
- 3×10^{19} pot collected
- **BR($K_L \to \pi^0 \nu\nu$) < 5.1×10^{-8} (90%CL)**





2016-2018 runs

- Reached **50 kW beam power**
- 4×10^{19} pot collected
- Preliminary results at KAON19

2019 run

- Analysis in progress

Preliminary results: 2016-2018 data

Several important detector upgrades and analysis improvements compared to 2015 data

KOTO preliminary (KAON, Sep 2019)

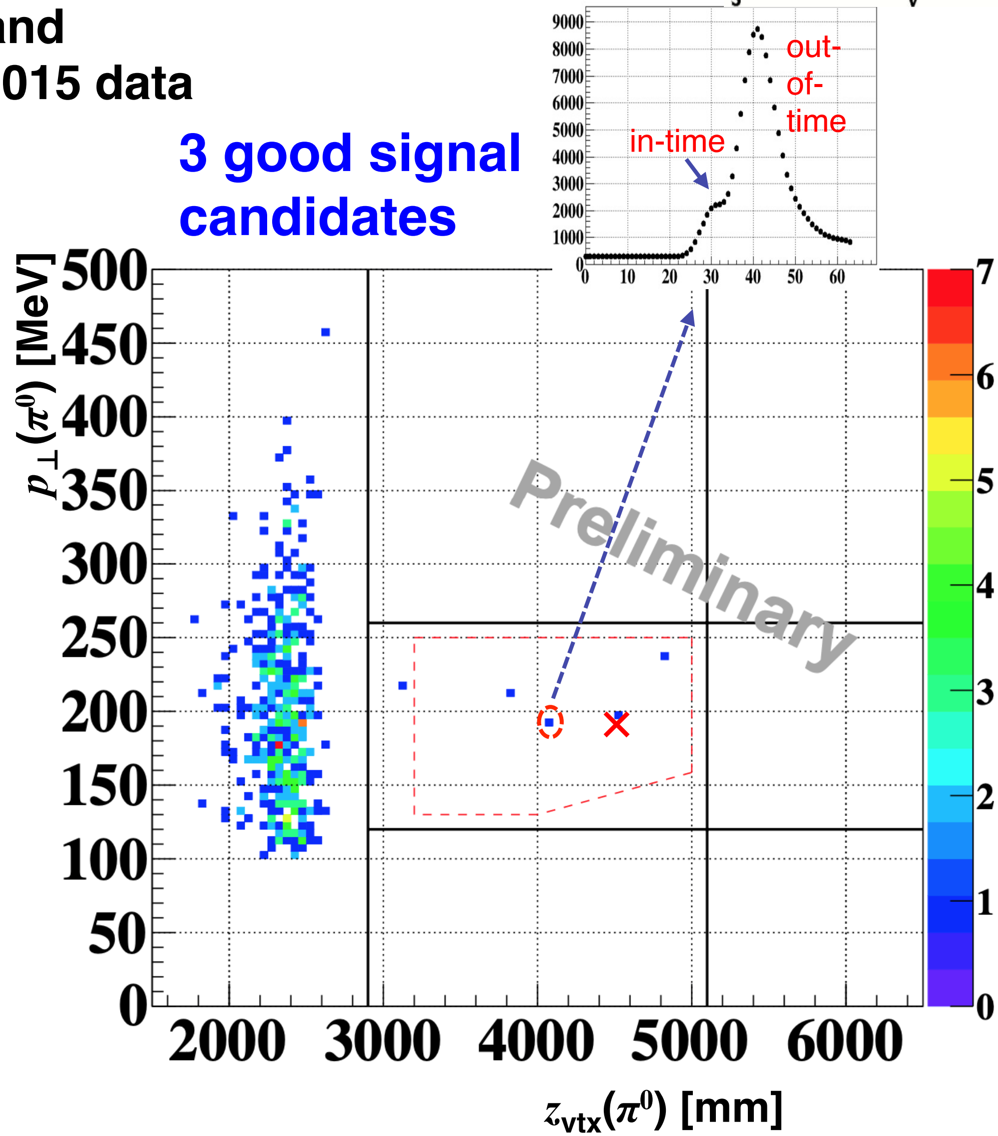
SES: 6.9×10^{-10} (0.05 SM evts)

Expected bkg: 0.05 ± 0.02 evts

3 good signal candidates

Background estimates (ICHEP 2020)

Source	**Expected (68%CL)**
$K_L \to \pi^0\pi^0$	< 0.05
$K_L \to \pi e \nu$ overlap pulse	< 0.05
$K_L \to ee\gamma$	< 0.05
$K_L \to \gamma\gamma$ core	< 0.06
$K_L \to \gamma\gamma$ halo	< 0.10
$K^+ \to \pi^0 e^+ \nu$	0.90 ± 0.27
$K^+ \to \pi^+ \pi^0$	0.09 ± 0.09
$K^+ \to \pi^0 \mu^+ \nu$	< 0.12
π^0 from n in CV	< 0.05
Total	**1.05 ± 0.28**



KOTO will reach SM SES by mid-decade: Step-2 required for BR