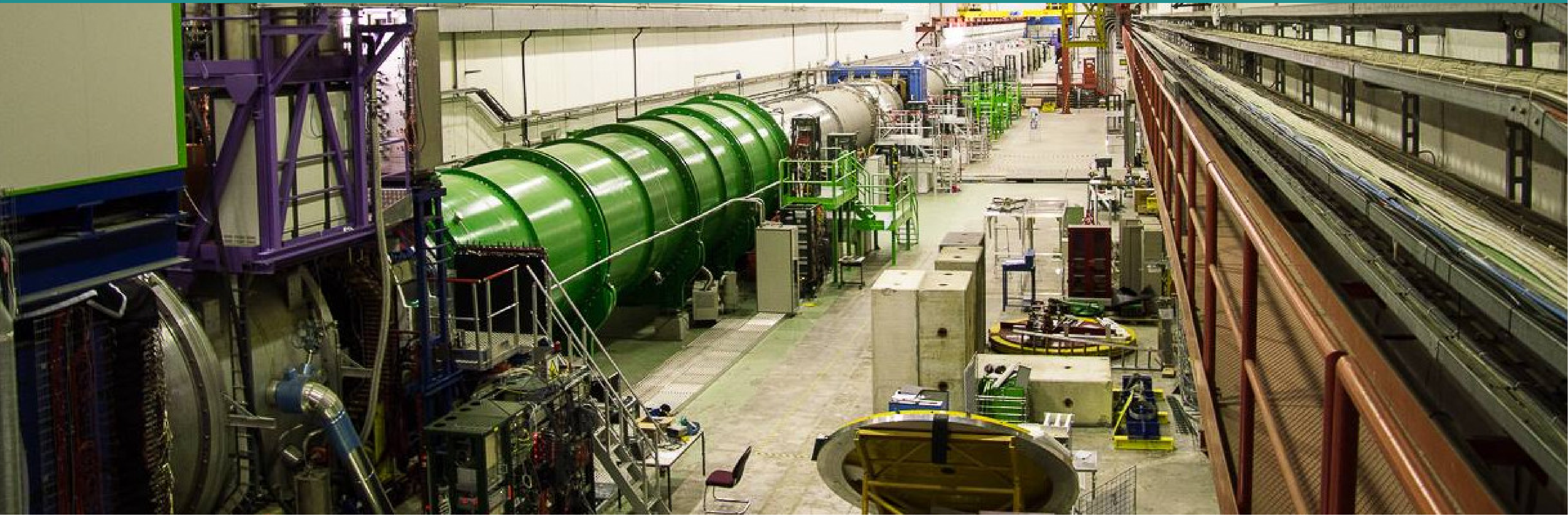
$K^+ \to \pi^+ \nu \bar{\nu}$ from NA62



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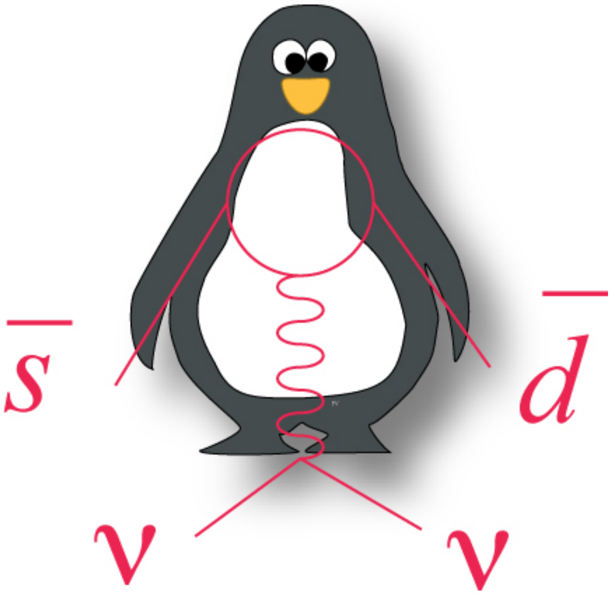
on behalf of the NA62 Collaboration

RKF 2019 - 2nd Forum on Rare Kaon decays – May 2019

Outline

- The NA62 experiment
- Theoretical framework
- Decay in flight technique at NA62
- Signal and control regions
- Signal event sensitivity
- Expected background
- Results (2016 data)
- 2017 data sample
- Conclusions

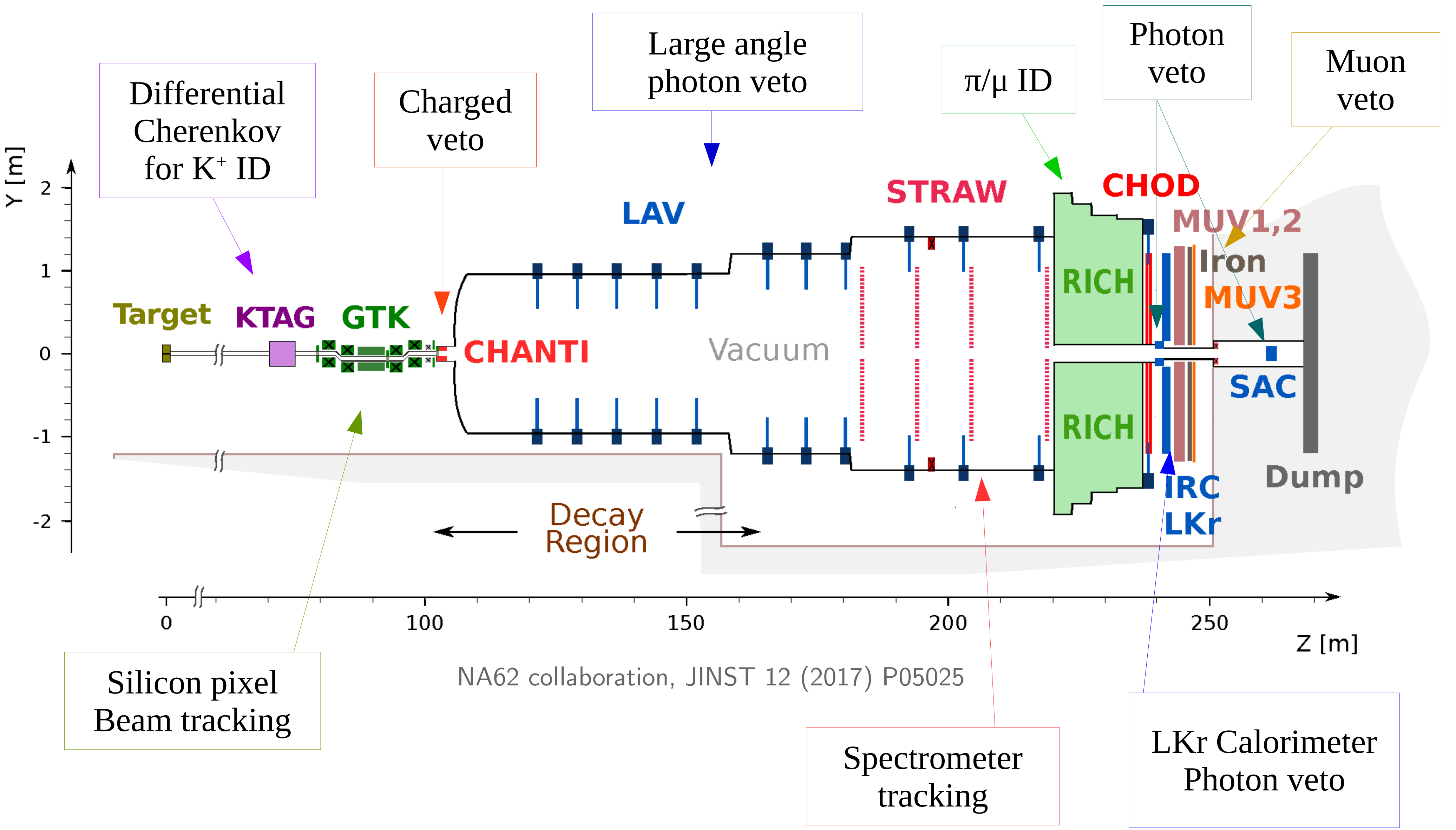


The NA62 experiment

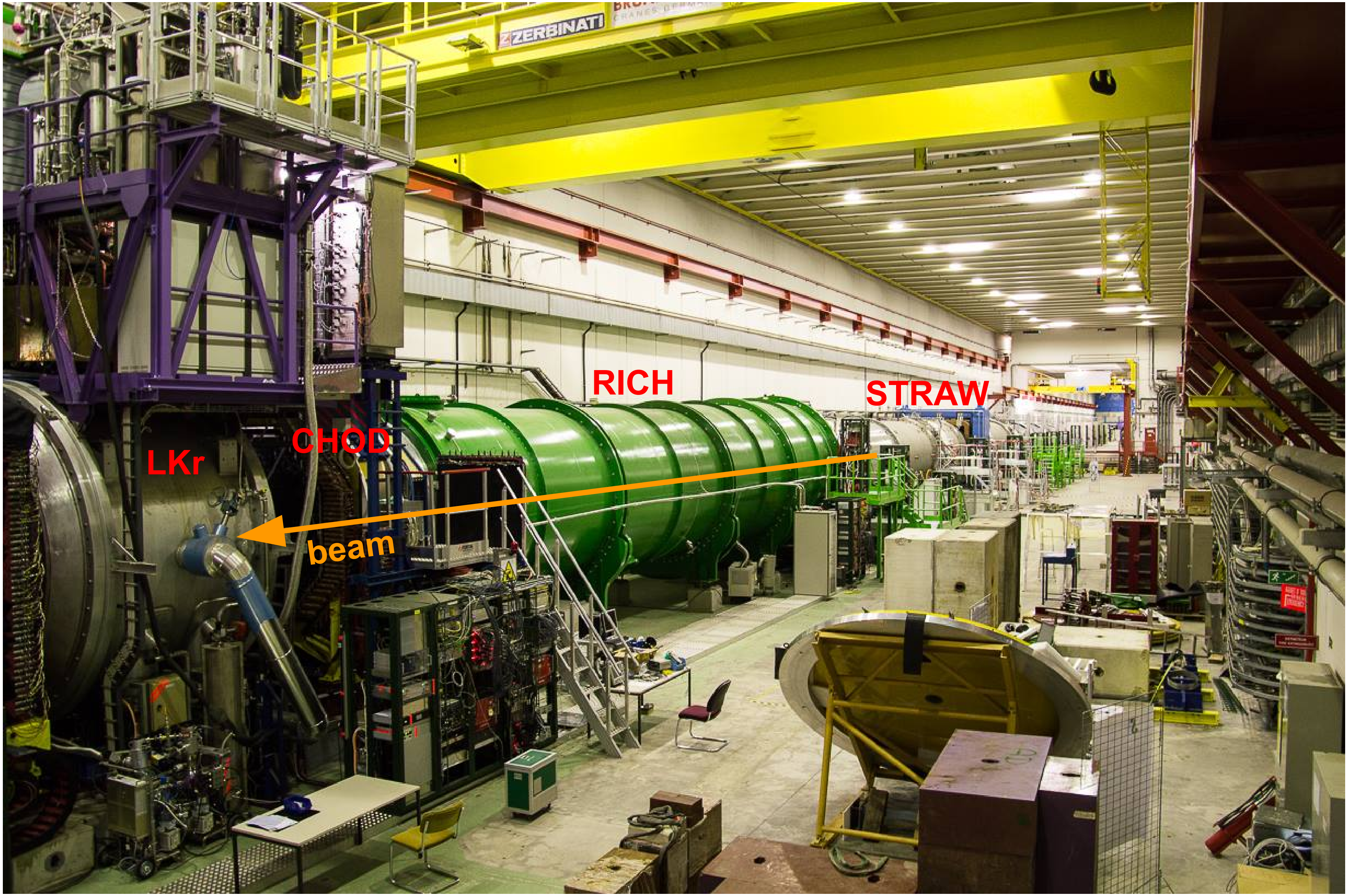
- Main goal: $BR(K^+ \rightarrow \pi^+ \nu\bar{\nu})$ with 10% precision.
- $BR_{th}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$
  [Buras et al., JHEP11(2015)033]
  $BR_{exp}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 17.3^{+11.5}_{-10.5} \times 10^{-11}$
  [Phys. Rev D 79, 092004 (2009)]
- Primary beam: 400 GeV/c protons from SPS.
- Secondary beam: 75 GeV/c positively charged particles, 6% K^+.
- ~200 participants from ~30 insitutes:
  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.

2009-2014	2014	2015	2016-2018
Construction and installation	Technical runs		**Physics runs**

NA62 detector

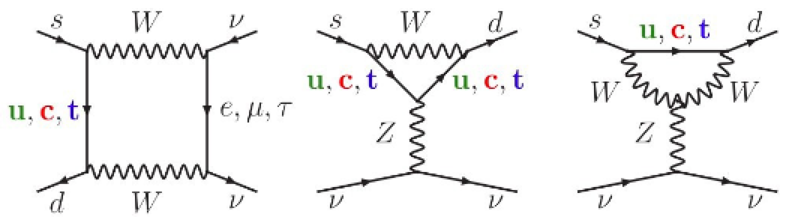


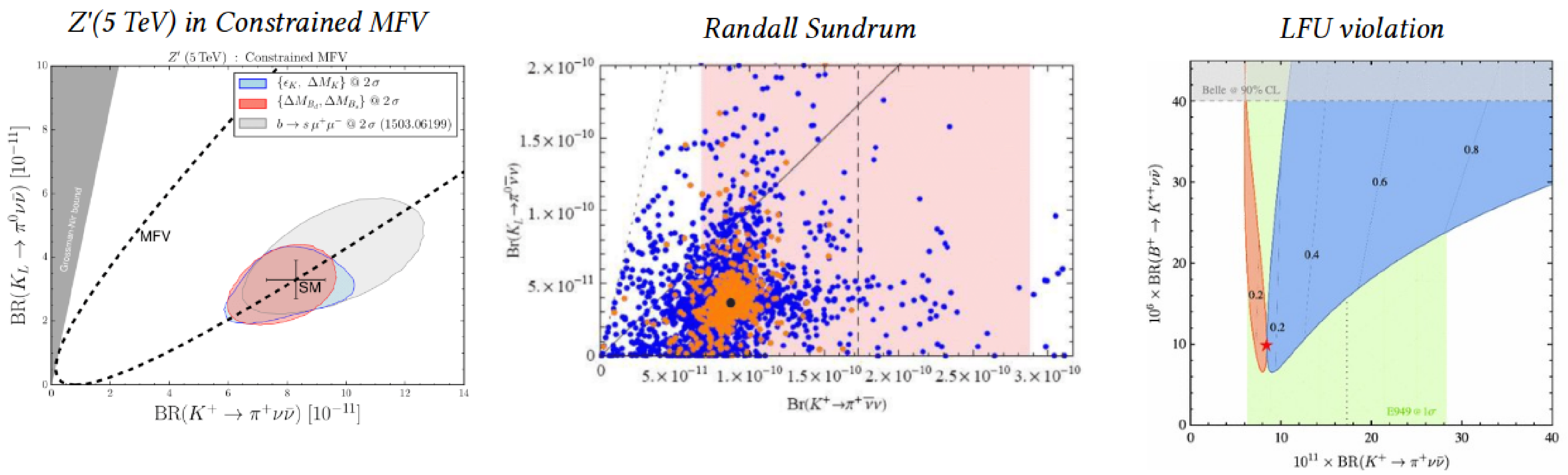
NA62 detector



Theoretical framework

- FCNC loop processes: s→d coupling and highest CKM suppression.
- Theoretically clean.

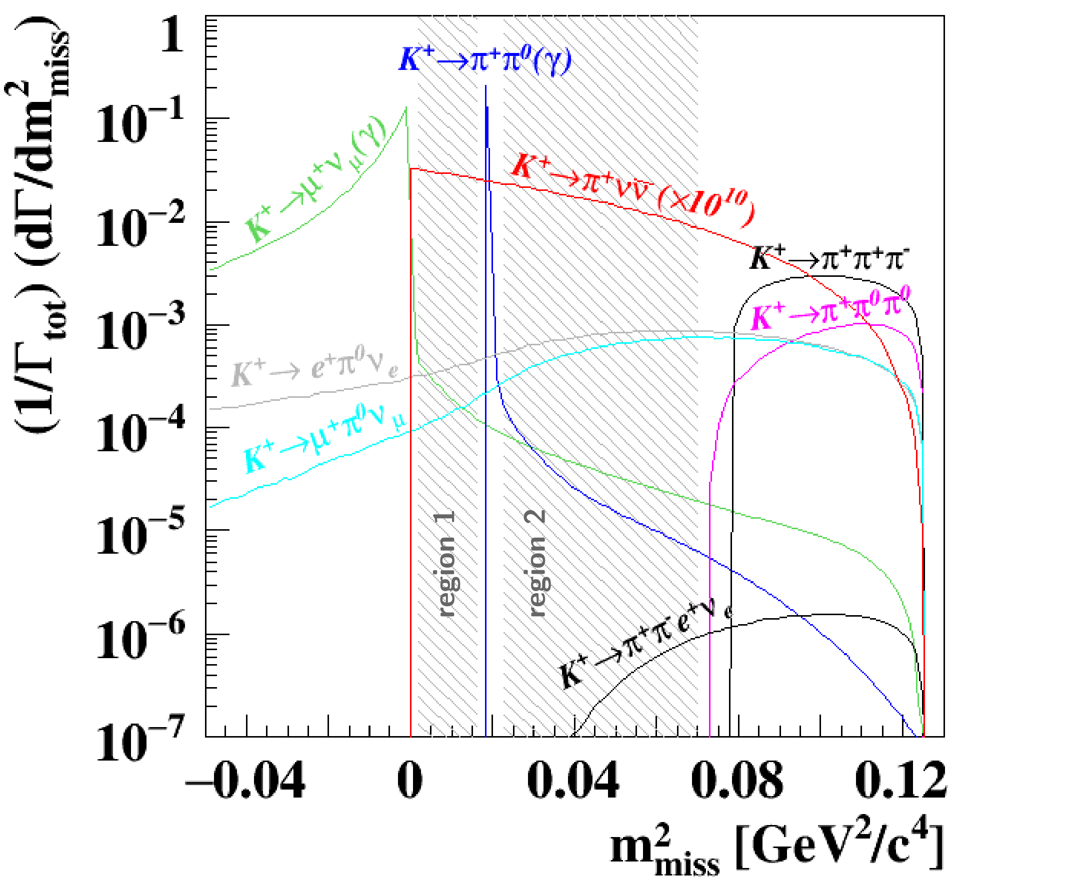




- Custodial Randall-Sundrum [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- MSSM Analysis [Blazek, Matak, Int.J.Mod.Phys. A29 (2014) no.27], [Isidori et al. JHEP 0608 (2006) 064]
- Simplified Z, Z' models [Buras, Buttazzo,Knegjens, JHEP11(2015)166]
- Littlest Higgs with T-parity [Blanke, Buras, Recksiegel, Eur.Phys.J. C76 (2016) 182]
- LFU violation models [Isidori et al., Eur. Phys. J. C (2017) 77: 618]

Decay in flight technique at NA62

Main background sources



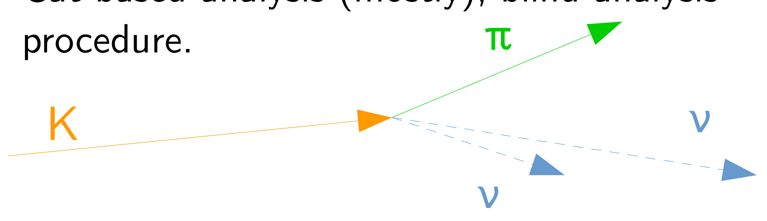
Decay mode	BR	Main rejection tools
$K^+ \to \mu^+\nu(\gamma)$	63%	μ–ID + kinematics
$K^+ \to \pi^+\pi^0(\gamma)$	21%	γ-veto + kinematics
$K^+ \to \pi^+\pi^+\pi^-$	6%	multi + kinematics
$K^+ \to \pi^+\pi^0\pi^0$	2%	γ-veto + kinematics
$K^+ \to \pi^0 e^+\nu_e$	5%	e–ID + γ-veto
$K^+ \to \pi^0\mu^+\nu_\mu$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

- The squared missing mass is the main variable used to kinematically separate signal from background:

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

$$15\ \text{GeV/c} < P_{\pi^+} < 35\ \text{GeV/c}$$

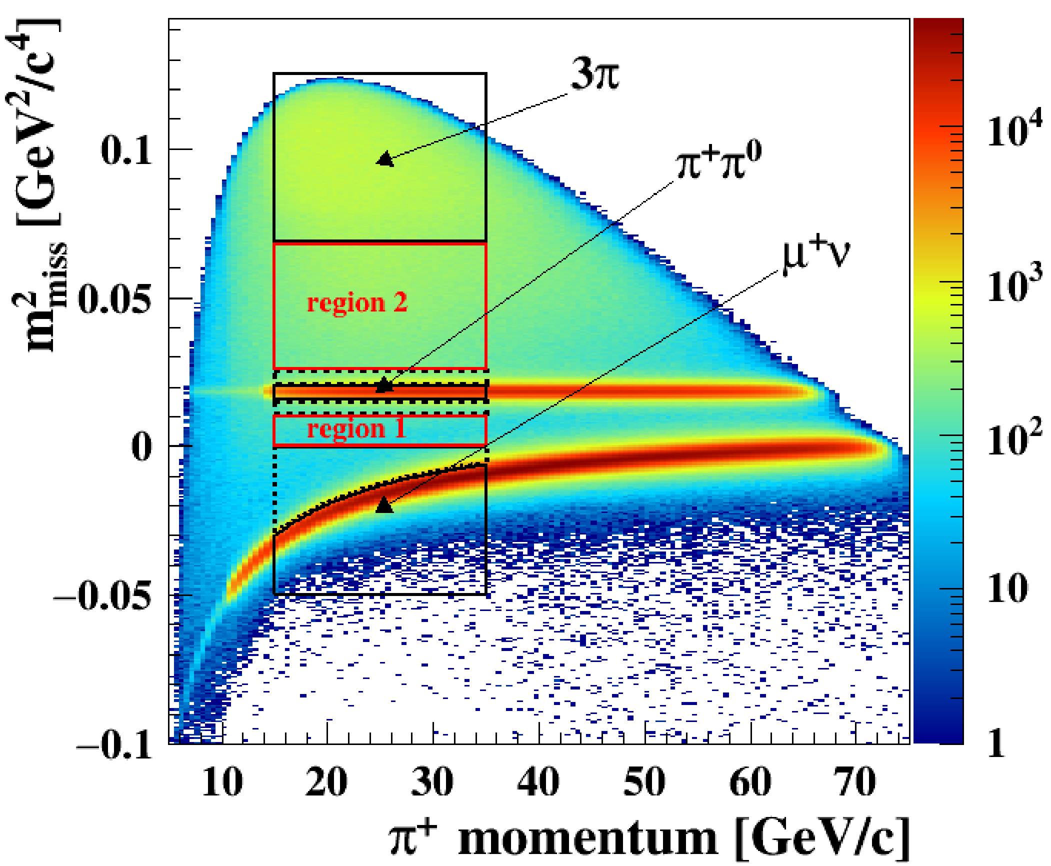
- Two signal region on each side of the K→π+π0 peak.
- Cut based analysis (mostly), blind analysis procedure.



- Requirements:
  - O(100 ps) timing between sub-detectors
  - O(10^4) background suppression with kinematics
  - O(10^7) background muon suppression ($K^+ \to \mu^+\nu_\mu$)
  - O(10^7) photon suppression ($K^+ \to \pi^+\pi^0$)

Signal and control regions

- Two signal regions kept blinded
- Kaon decays can enter the signal regions via m^2_{miss} mis-reconstruction.
- The control regions are kept blinded too, to validate the procedure.



- Selection:
  - single track in final state
  - π^+ identification
  - photon rejection
  - 110 m < z_{vertex} < 165 m
  - 15 GeV/c < $p_{\pi+}$ < 35 GeV/c, in order to have at least E_{miss} = 40 GeV and have an optimal π/μ separation in the RICH.
- Performances:
  - $\varepsilon(\mu^+) = 10^{-8}$ (64% π^+ efficiency)
  - $\varepsilon(\pi^0) = 3 \cdot 10^{-8}$
  - $\sigma(m^2_{miss}) = 10^{-3}$ GeV^2/c^4
  - σ_t = O(100 ps)

Single Event Sensitivity

- N_K from $K^+ \to \pi^+\pi^0$ control trigger: $(1.21 \pm 0.02) \times 10^{11}$

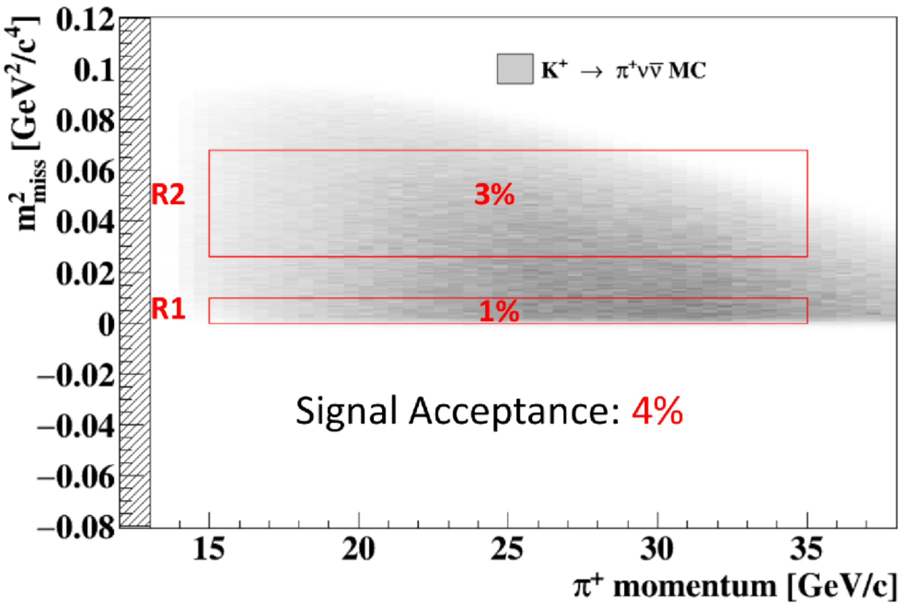
$$N_K = \frac{N_{\pi\pi} \cdot R}{A_{\pi\pi} \cdot BR_{\pi\pi}}$$ (R: reduction factor applied to CTRL trigger)

- $K^+ \to \pi^+\nu\bar{\nu}$ acceptance: $(4.0 \pm 0.1) \times 10^{-2}$
- Random veto efficiency: 0.76 ± 0.04
- Trigger efficiency: 0.87 ± 0.2

$$SES = \frac{1}{N_K \cdot \sum_j \left(A^j_{\pi\nu\nu} \cdot \epsilon^j_{\mathrm{trig}} \cdot \epsilon^j_{\mathrm{RV}} \right)}$$

$$N^{\mathrm{expected}}_{\pi\nu\nu}(\mathrm{SM}) = \frac{BR_{\pi\nu\nu}(\mathrm{SM})}{SES}$$

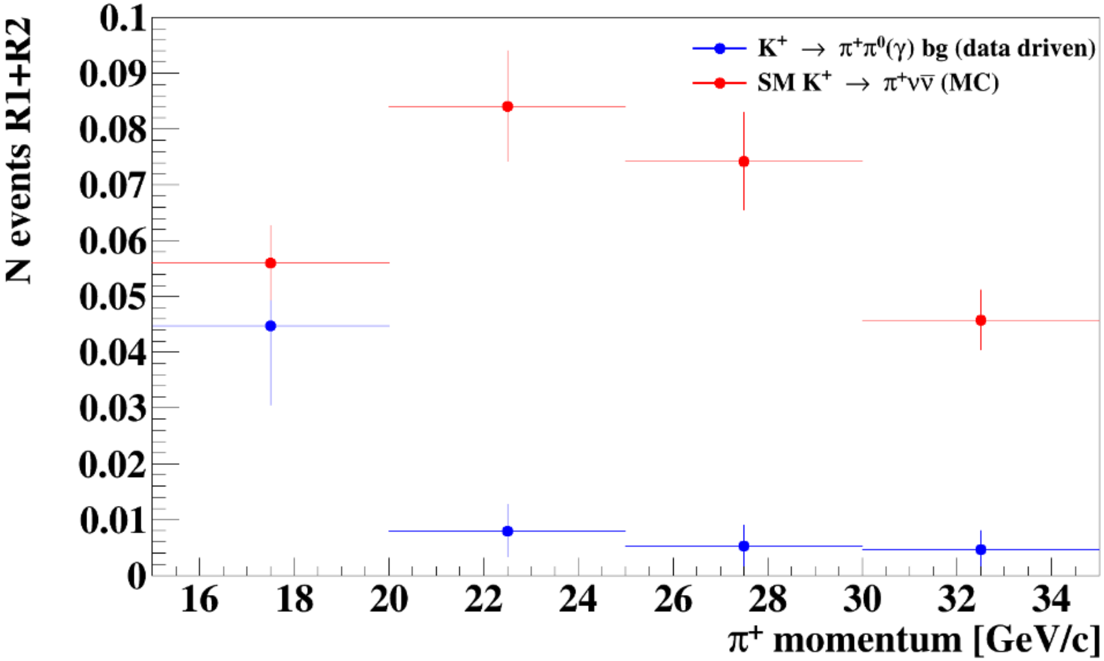
Source	δ SES (10^{-10})
Random veto	± 0.17
Definition of $\pi^+\pi^0$ region	± 0.10
Simulation of π^+ interactions	± 0.09
N_K	± 0.05
Trigger efficiency	± 0.04
Extra activity	± 0.02
GTK pileup simulation	± 0.02
Momentum spectrum	± 0.01
Total	± 0.24

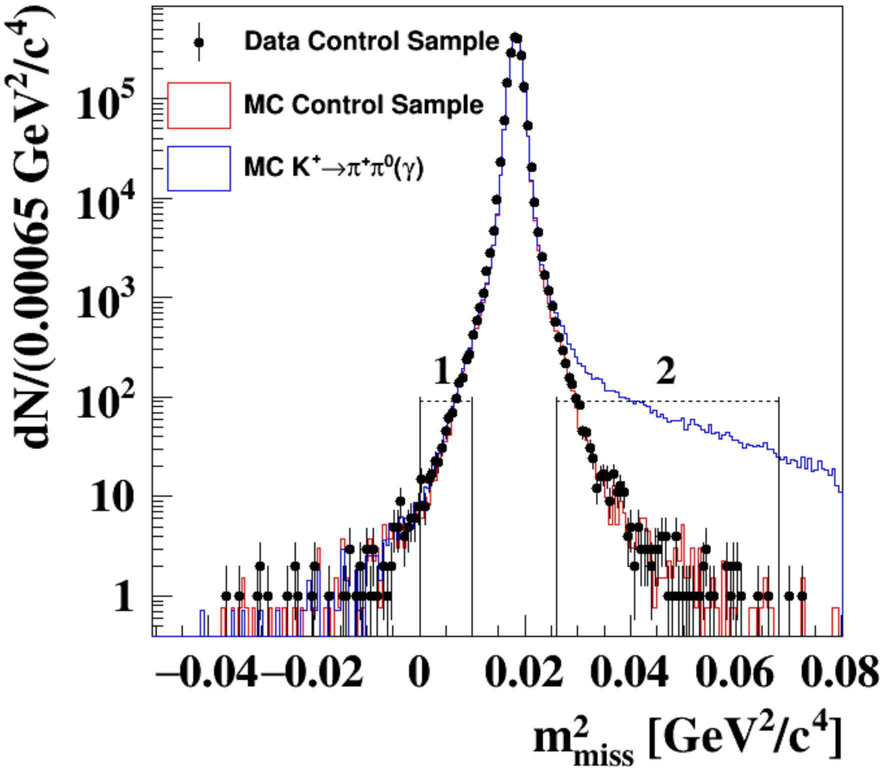


$$SES = (3.15 \pm 0.01_{\mathrm{stat}} \pm 0.24_{\mathrm{syst}}) \cdot 10^{-10}$$

$$N^{\mathrm{expected}}_{\pi\nu\nu}(\mathrm{SM}) = 0.267 \pm 0.001_{\mathrm{stat}} \pm 0.020_{\mathrm{syst}} \pm 0.032_{\mathrm{extr}}$$

$K^+ \to \pi^+ \pi^0$ background





- Expected in Control Region:

$$N^{\text{expected}}_{\pi+\pi 0(\gamma)}(\text{CR1}) = 0.52 \pm 0.08_{\text{stat}} \pm 0.03_{\text{syst}}$$

$$N^{\text{expected}}_{\pi+\pi 0(\gamma)}(\text{CR2}) = 0.94 \pm 0.14_{\text{stat}} \pm 0.05_{\text{syst}}$$

- Observed in Control Region:

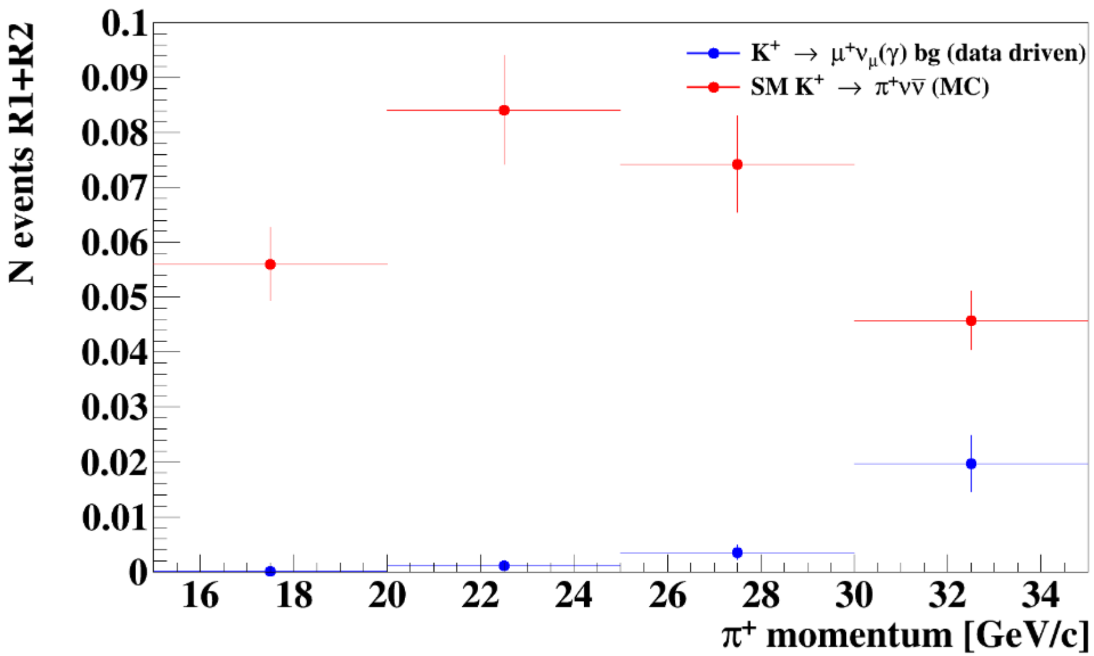
$$N^{\text{observed}}_{\pi+\pi 0(\gamma)}(\text{CR1}) = 0$$

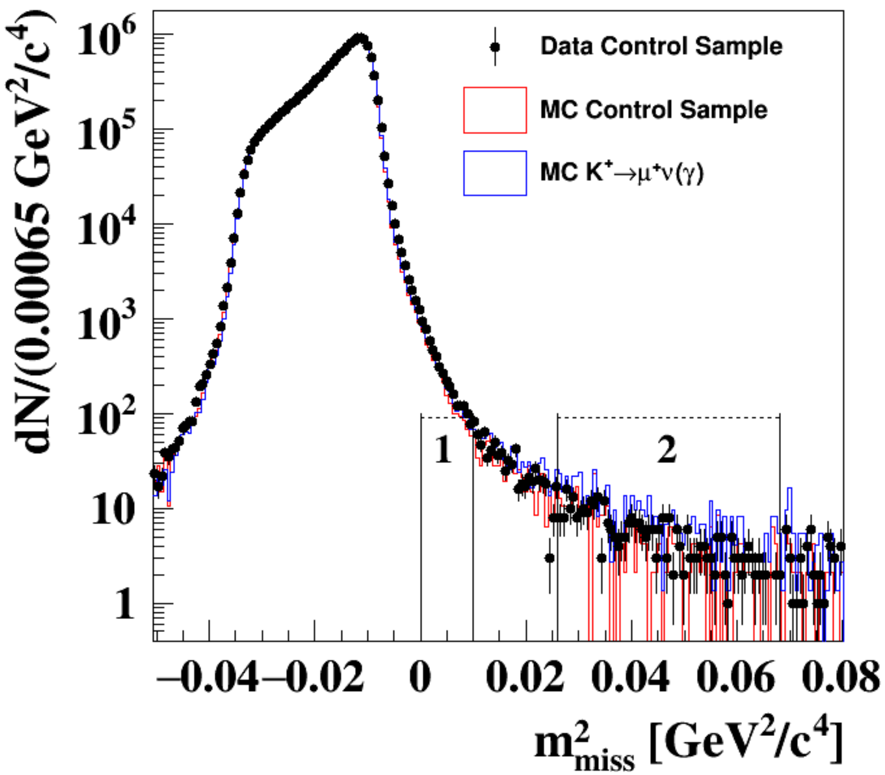
$$N^{\text{observed}}_{\pi+\pi 0(\gamma)}(\text{CR2}) = 1$$

Background expected in Signal Regions:

$$N^{\text{expected}}_{\pi+\pi 0(\gamma)}(\text{R1+R2}) = 0.064 \pm 0.007_{\text{stat}} \pm 0.006_{\text{syst}}$$

$K^+ \to \mu^+ \nu$ background





- Expected in Control Region:

$$N^{\mathrm{expected}}_{\mu+\nu(\gamma)}(\mathrm{CR}) = 1.02 \pm 0.16_{\mathrm{stat}}$$

- Observed in Control Region:

$$N^{\mathrm{observed}}_{\mu+\nu(\gamma)}(\mathrm{CR}) = 2$$

Background expected in Signal Regions:

$$N^{\mathrm{expected}}_{\mu+\nu(\gamma)}(\mathrm{R1+R2}) = 0.020 \pm 0.003_{\mathrm{stat}} \pm 0.003_{\mathrm{syst}}$$

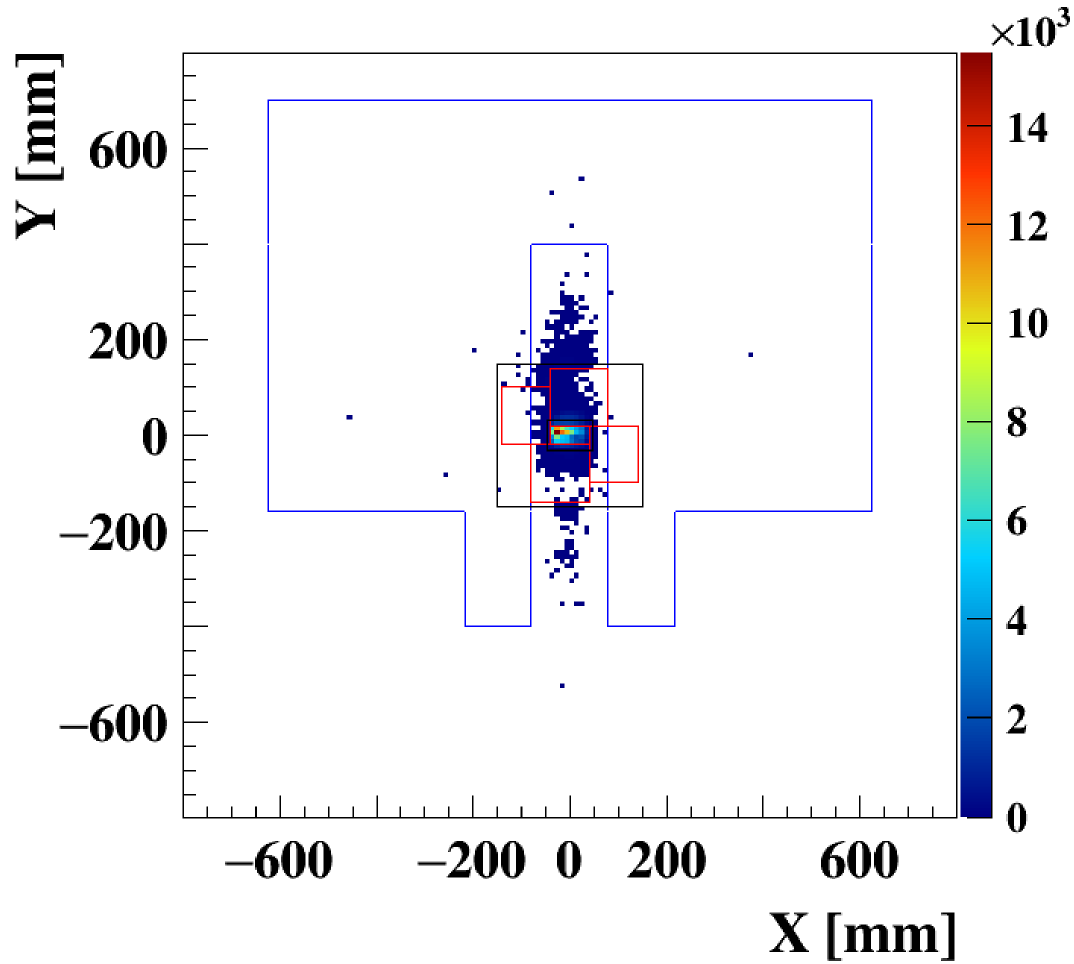
Upstream background

Upstream event: any particle not originated from K dacays in the FV. They can be produced in many different ways:

- K^+ decays before the GTK3, matched with a pile-up π^+ in the GTK;
- π^+ interactions in GTK2 or GTK3 with a pile-up K^+ in the GTK;
- K^+ interactions in GTK2 or GTK3.

Expected in Signal Region:

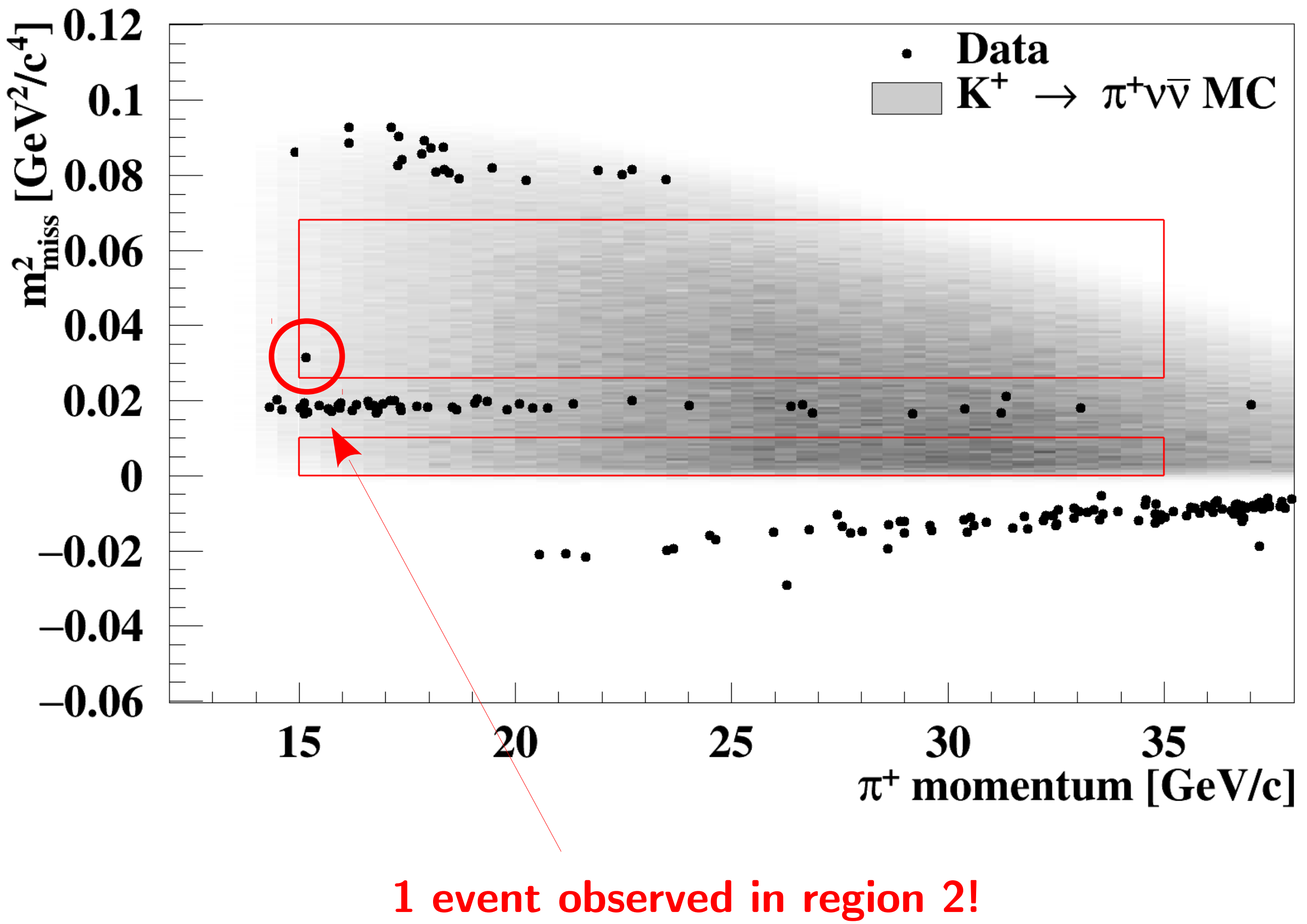
$$N_{\mathrm{UB}}^{\mathrm{expected}}(\mathrm{R1{+}R2}) = 0.050^{+0.090}_{-0.030}$$



Expected background

Process	Expected events in R1+R2
$K^+ \to \pi^+ \nu \bar{\nu}$	$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$
Total Background	$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$
$K^+ \to \pi^+ \pi^0 (\gamma)$ IB	$0.064 \pm 0.007_{stat} \pm 0.006_{syst}$
$K^+ \to \mu^+ \nu (\gamma)$ IB	$0.020 \pm 0.003_{stat} \pm 0.003_{syst}$
$K^+ \to \pi^+ \pi^- e^+ \nu$	$0.018^{+0.024}_{-0.017}\vert_{stat} \pm 0.009_{syst}$
$K^+ \to \pi^+ \pi^+ \pi^-$	$0.002 \pm 0.001_{stat} \pm 0.002_{syst}$
Upstream background	$0.050^{+0.090}_{-0.030}\vert_{stat}$

Results (2016 data)



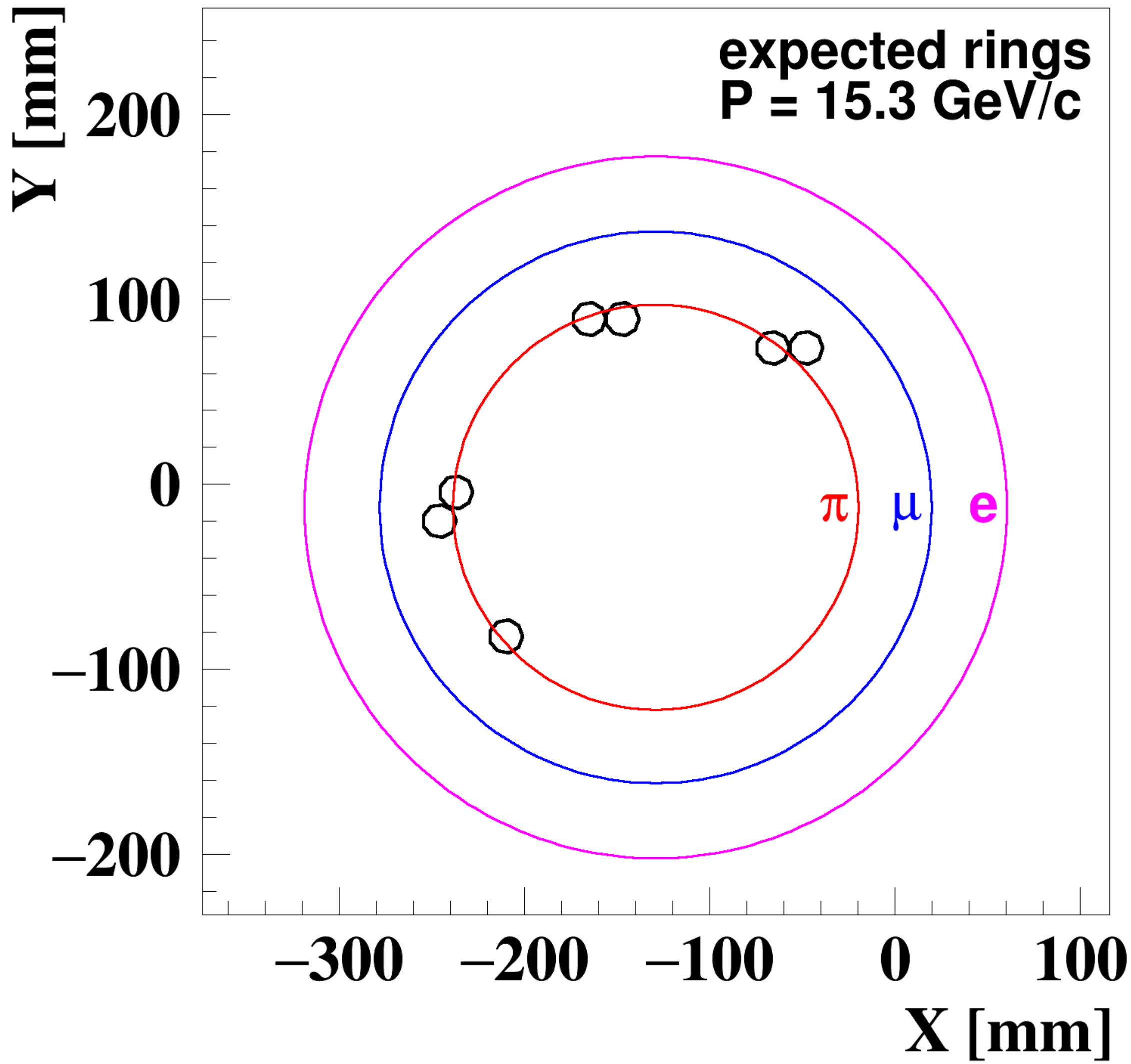
Signal events expected in signal region (SM)

$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{extr}$

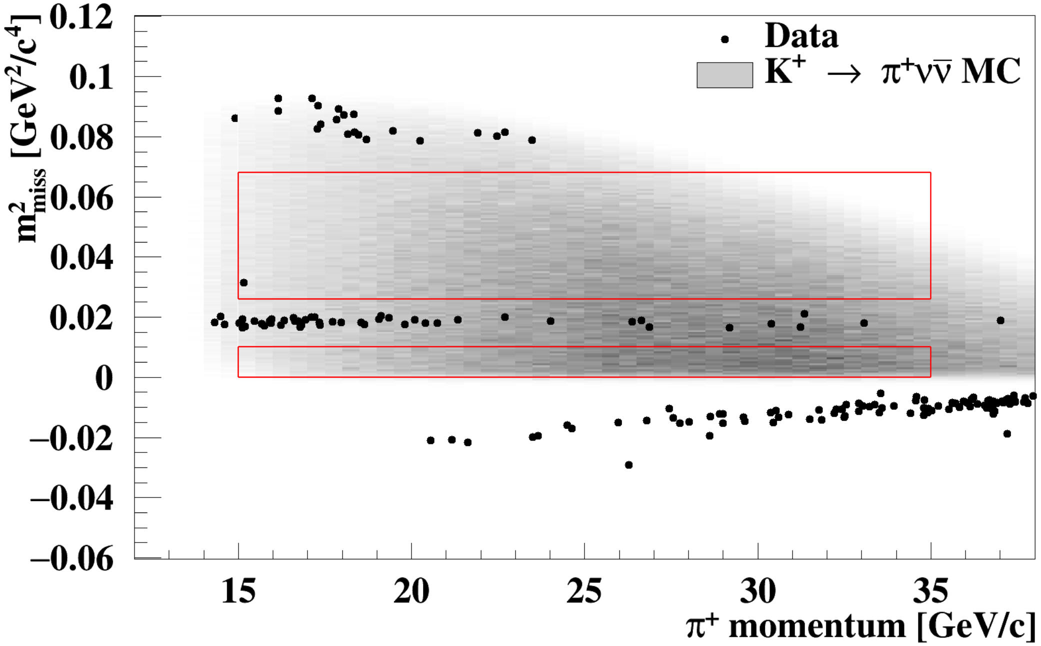
Background events expected in signal region

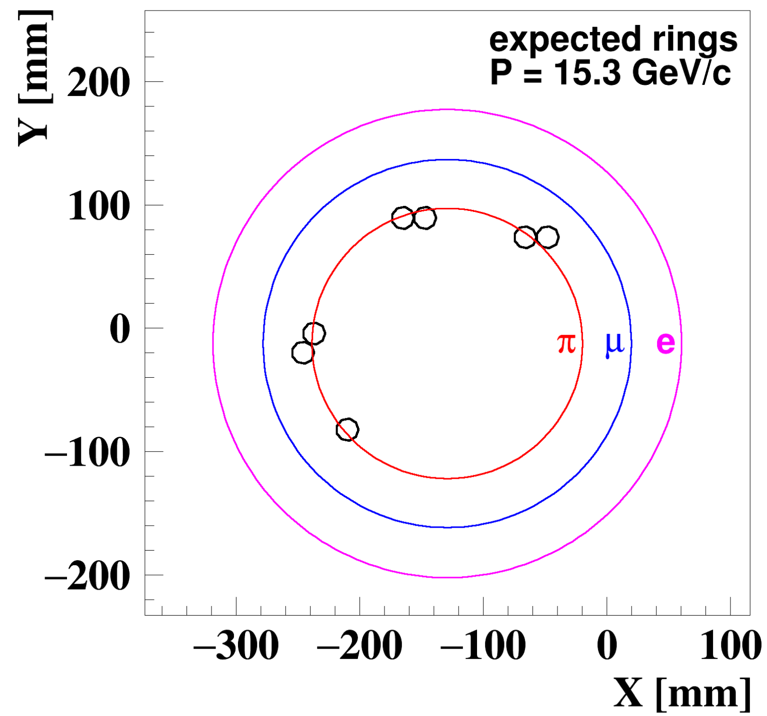
$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$

Results (2016 data)



The Cherenkov ring as seen by the RICH detector, with three different ring radii for the three different particle hypothesis at p = 15.3 GeV/c.





- Upper limits on the Branching Ratio: $\mathrm{BR}\left(K^+ \to \pi^+ \nu \bar{\nu}\right) < 11 \cdot 10^{-10}$ @90%CL

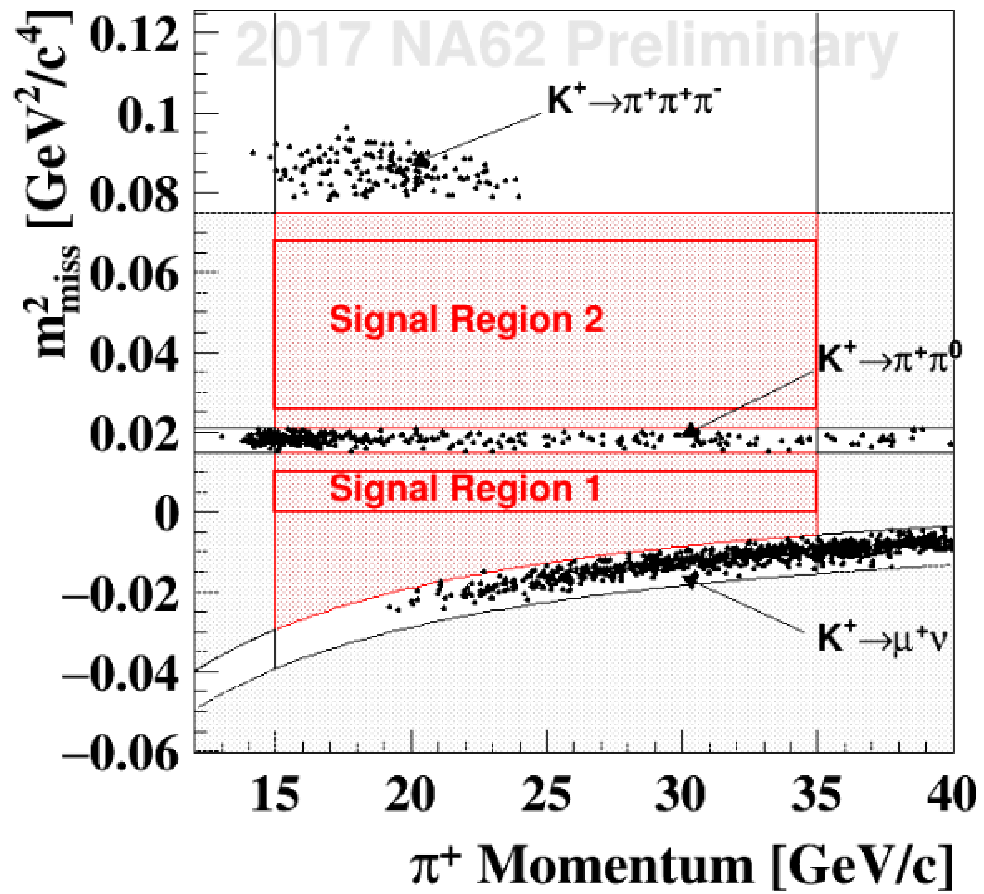
  $\mathrm{BR}\left(K^+ \to \pi^+ \nu \bar{\nu}\right) < 14 \cdot 10^{-10}$ @95%CL

- Standard Model prediction on the Branching Ratio:

$$\mathrm{BR}\left(K^+ \to \pi^+ \nu \bar{\nu}\right) = (0.84 \pm 0.10) \cdot 10^{-10}$$

2017 data sample

- Higher beam intensity
- 2016-like selection
- Performances are comparable to 2016
  - Better pile-up treatment in IRC/SAC
  - 40% better π^0 rejection (does not depend on intensity)
  - Slightly improved usage of RICH variables.
- 2 signal regions, like in 2016
- 3 control regions used to evaluate the background
- Signal and control regions kept masked, as well as the region below the K→μν used to validate the upstream background.



Single Event Sensitivity

$N_K = (1.3 \pm 0.1) \cdot 10^{12}$ (~10 × 2016)

$SES = (0.34 \pm 0.04) \cdot 10^{-10}$ (scales linearly with intensity)

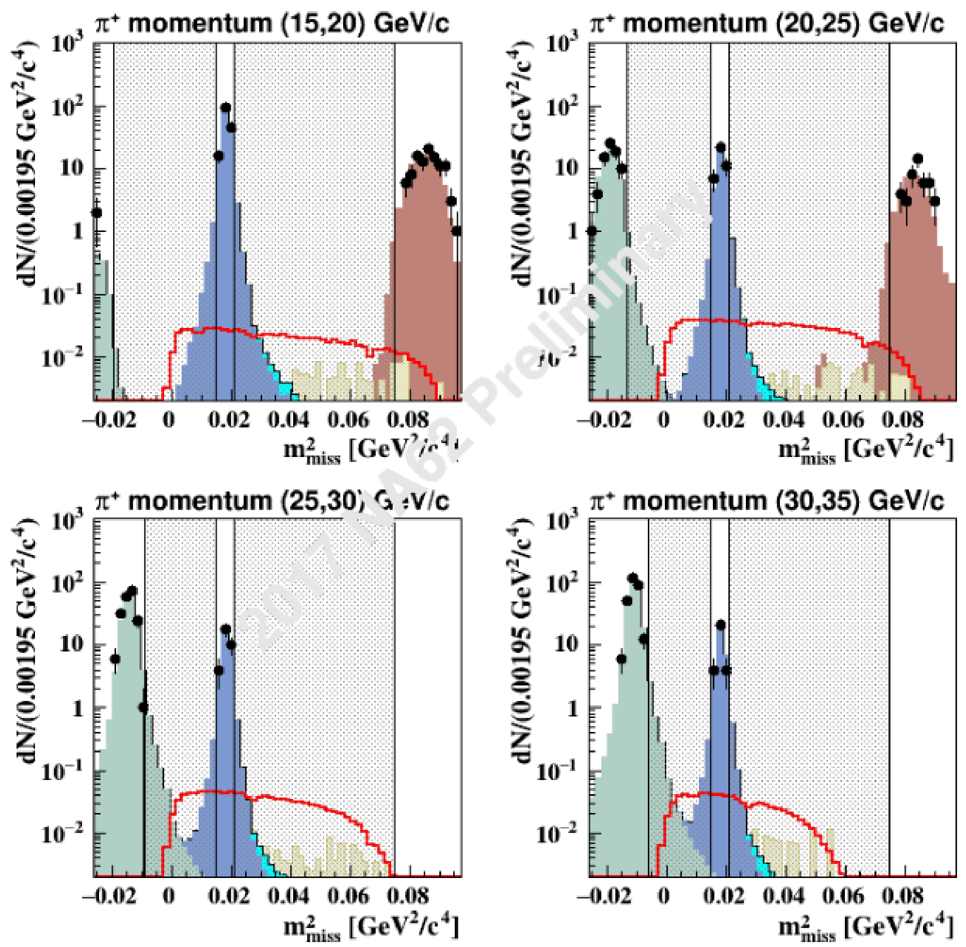
$N^{\text{expected}}_{\pi\nu\nu}(\text{SM}) = 2.5 \pm 0.4$

2017 data sample

Expected background

Process	Expected events in signal regions
$K^+ \to \pi^+\pi^0(\gamma)$ IB	$0.35 \pm 0.02_{stat} \pm 0.03_{syst}$
$K^+ \to \mu^+\nu(\gamma)$ IB	$0.16 \pm 0.01_{stat} \pm 0.05_{syst}$
$K^+ \to \pi^+\pi^-e^+\nu$	$0.22 \pm 0.08_{stat}$
$K^+ \to \pi^+\pi^+\pi^-$	$0.015 \pm 0.008_{stat} \pm 0.015_{syst}$
$K^+ \to \pi^+\gamma\gamma$	$0.005 \pm 0.005_{syst}$
$K^+ \to l^+\pi^0\nu_l$	$0.012 \pm 0.012_{syst}$
Upstream Background	Analysis on–going

Excellent agreement between modeled background distributions and data in the same regions: validity of background evaluation from kaon decays in the fiducial region.



Conclusions

- One event observed in region 2 in 2016
- This result is compatible with the Standard Model:

  $$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 14 \cdot 10^{-10} \quad @95\%CL$$

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

- The analysis of 2017 data is ongoing and results are expected very soon.
  - SES improved by a factor 10 with respect to 2016.
  - Signal over background ratio does not degrade with intensity
  - Strong effort to improve the analysis

- Branching ratio measurement expected in the next few years.

THANK YOU!