# NA62: First result on $K^+ \to \pi^+ \nu\bar{\nu}$

Riccardo Aliberti

Windows on the Universe

25th Anniversary Rencontres du Vietnam

Quy-Nhon, August 5 – 11, 2018

Bundesministerium
für Bildung
und Forschung

# The NA62 Experiment

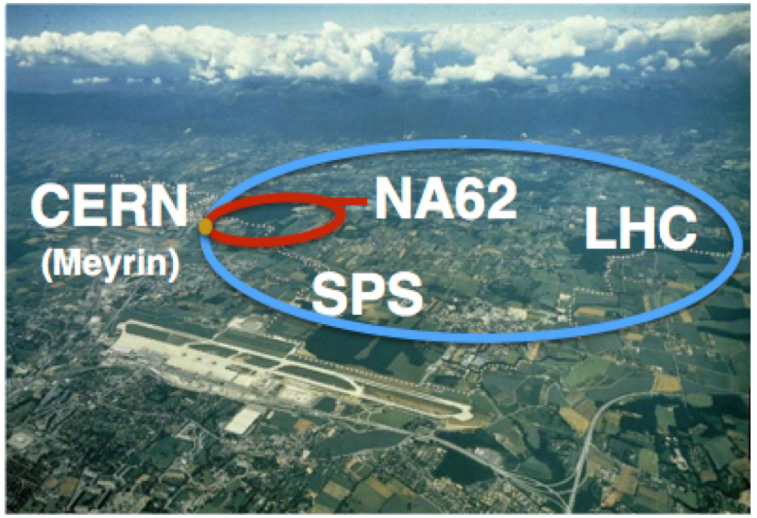
Fixed Target Experiment

Located at the North Area of CERN

75 GeV/c Secondary Hadron Beam

Carry on the tradition of Kaon

experiments at CERN - SPS

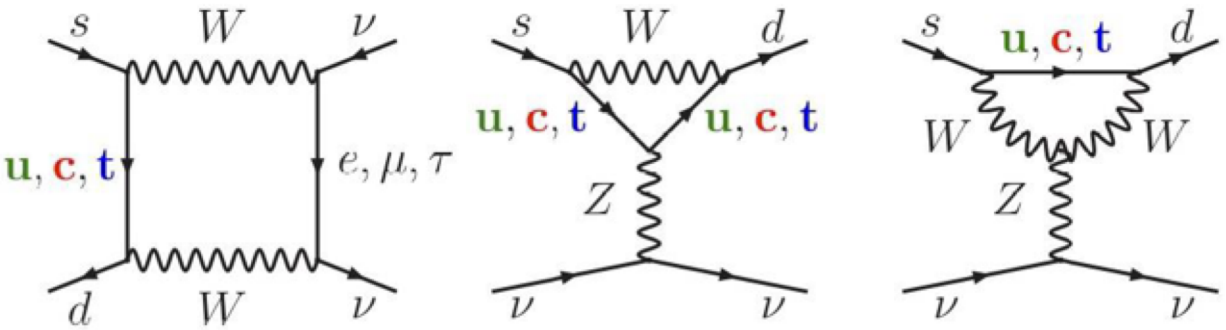


# Kaon @ CERN - SPS

| | | |
|---|---|---|
| ’86 - ‘89 | NA31 | Hint of direct CP violation in Neutral Kaon decays |
| ’97 - ‘01 | NA48 | ε’/ε: Proof of direct CP violation |
| ‘02 | NA48/1 | $K_s$ rare decays |
| ’03 - ‘04 | NA48/2 | CP violation in Charge Kaons decays |
| ’07 - ‘08 | NA62-$R_K$ ( NA48/3 ) | Lepton Universality ($R_k$) |
| ’14 - ’18 | NA62 | $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ decay |

# Theoretical Motivation

FCNC loop process, highly suppressed, theoretically very clean




Well calculated inside the Standard Model [A.J. Buras et al., JHEP 1511 (2015) 033]

$$Br_{SM}(K^+ \to \pi^+ \upsilon\bar{\upsilon}) = (8.4 \pm 1.0)\times 10^{-11}$$

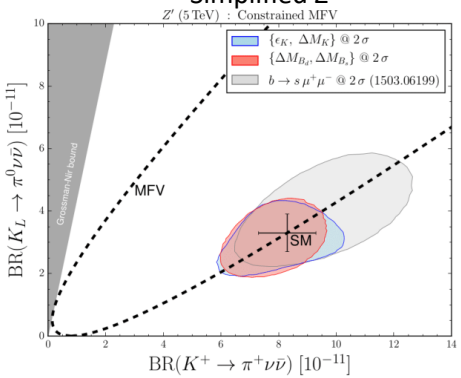
Previous Measurement (only 7 events) [BNL E787/E949: PRL101 (2008) 191802]

$$Br_{Exp}(K^+ \to \pi^+ \upsilon\bar{\upsilon}) = \left(17.3 \pm^{11.5}_{10.5}\right)\times 10^{-11}$$

# Theoretical Motivation

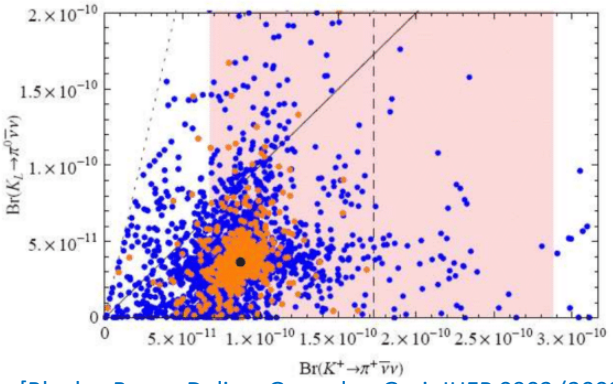
FCNC loop process, highly suppressed, theoretically very clean

Simplified Z’



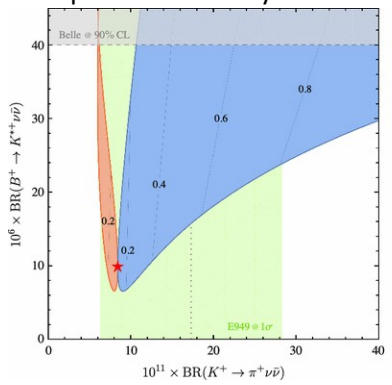

[Buras, Buttazzo,Knegjens, JHEP 1511 (2015) 166]

Custodial Randall-Sundrum




[Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]

Lepton Universality Violation




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

Well calculated inside the Standard Model [A.J. Buras et al., JHEP 1511 (2015) 033]

$$Br_{SM}(K^+ \to \pi^+ \upsilon\bar{\upsilon}) = (8.4 \pm 1.0)\times 10^{-11}$$

Previous Measurement (only 7 events) [BNL E787/E949: PRL101 (2008) 191802]

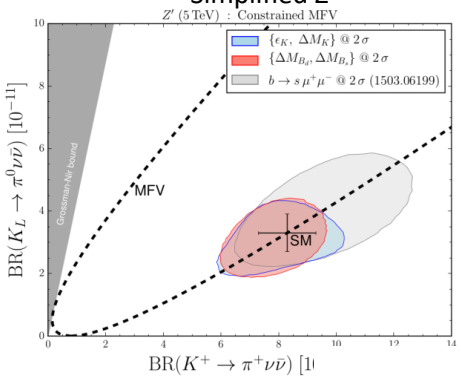
$$Br_{Exp}(K^+ \to \pi^+ \upsilon\bar{\upsilon}) = \left(17.3 \pm^{11.5}_{10.5}\right)\times 10^{-11}$$

**Any deviation from the SM prediction is a hint of new physics**

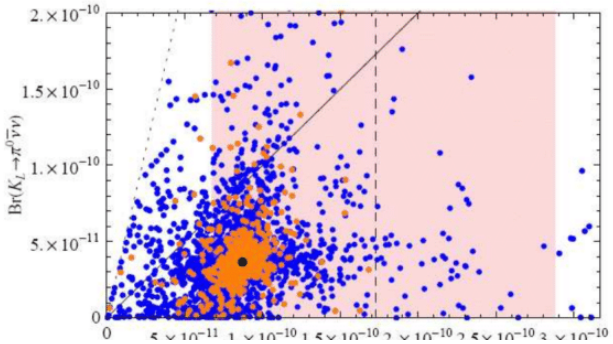
# Theoretical Motivation

FCNC loop process, highly suppressed, theoretically very clean

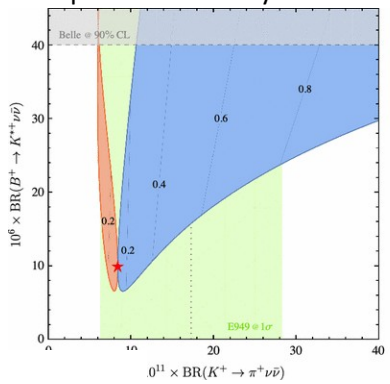
Simplified Z'




Custodial Randall-Sundrum




Lepton Universality Violation




**Expected 10% precision by NA62**

Well calculate 1 (2015) 033]

Previous Measurement (only 7 events) [BNL E787/E949: PRL101 (2008) 191802]

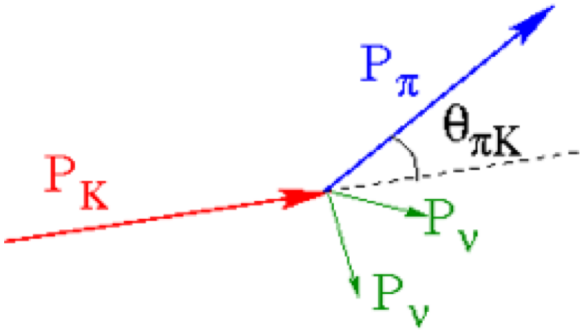
$$Br_{Exp}(K^+ \to \pi^+ \upsilon\bar{\upsilon}) = \left(17.3 \pm^{11.5}_{10.5}\right)\times10^{-11}$$

**Any deviation from the SM prediction is a hint of new physics**

# Strategy and Apparatus

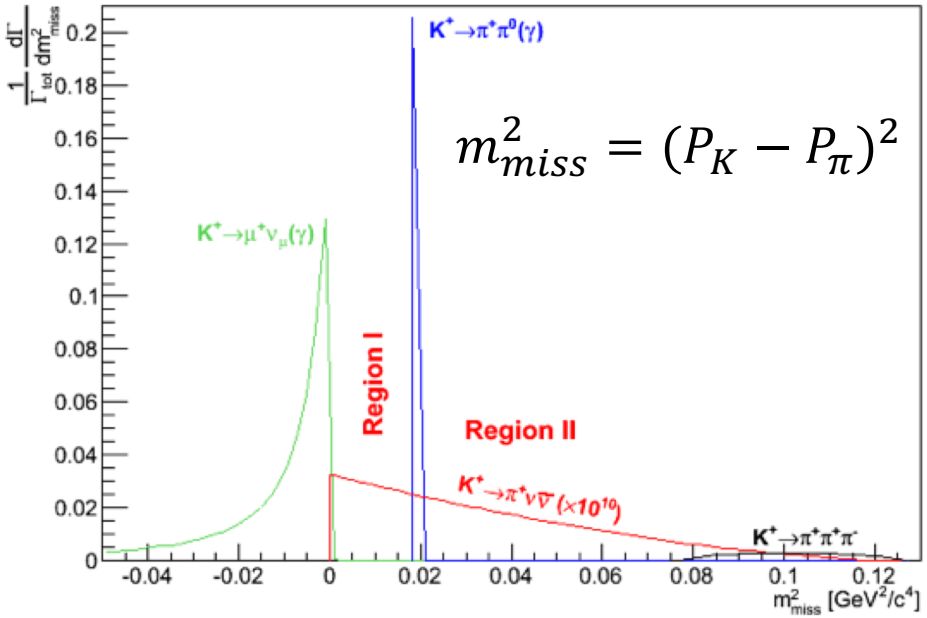
**Signal:**

- ✓ One beam $K^+$
- ✓ One $\pi^+$
- ✓ Nothing else




**Background:**

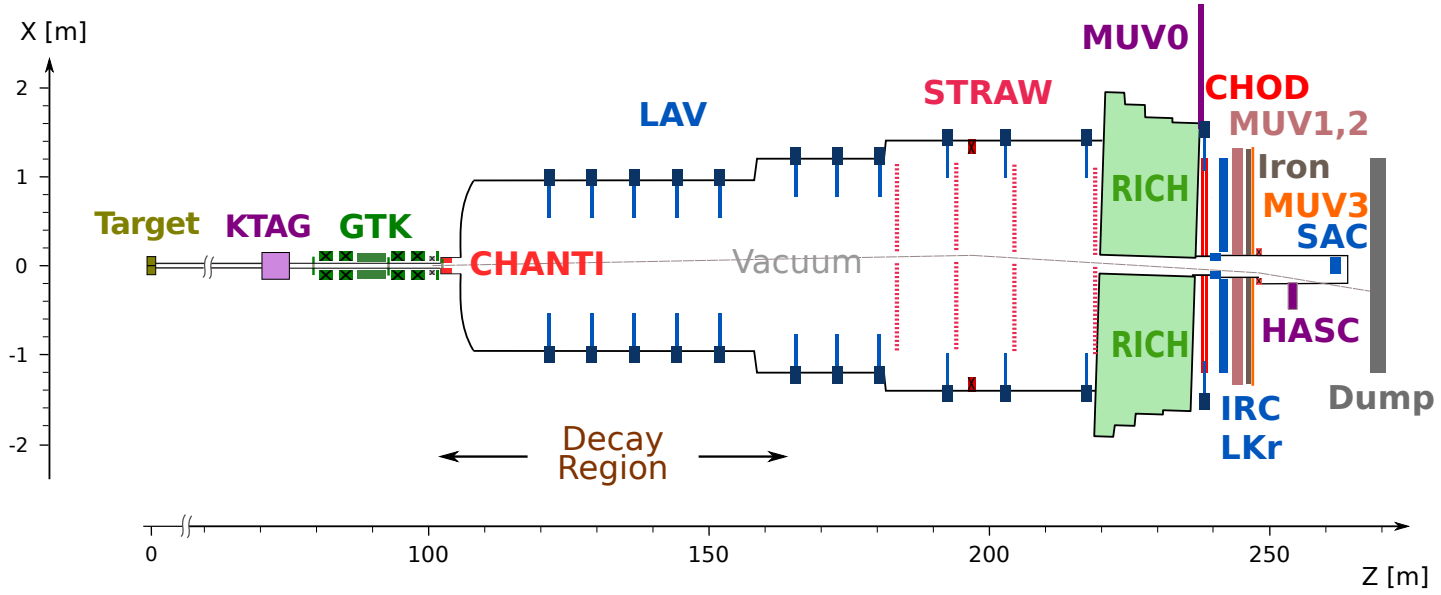
- x Beam activity
- x Other $K^+$ decays




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

- ➢ Precise kinematic reconstruction
- ➢ Hermetic Photon Detection
- ➢ Efficient PID for pion/muon discrimination

# Strategy and Apparatus




**SPS Protons**

400 GeV

$10^{12}$ protons/s

3.5 s spill

Beryllium Target

**Secondary Beam**

75 GeV,

$\Delta p/p \approx 1\%$

K (6%), p (23%), π (70%)

750 MHz

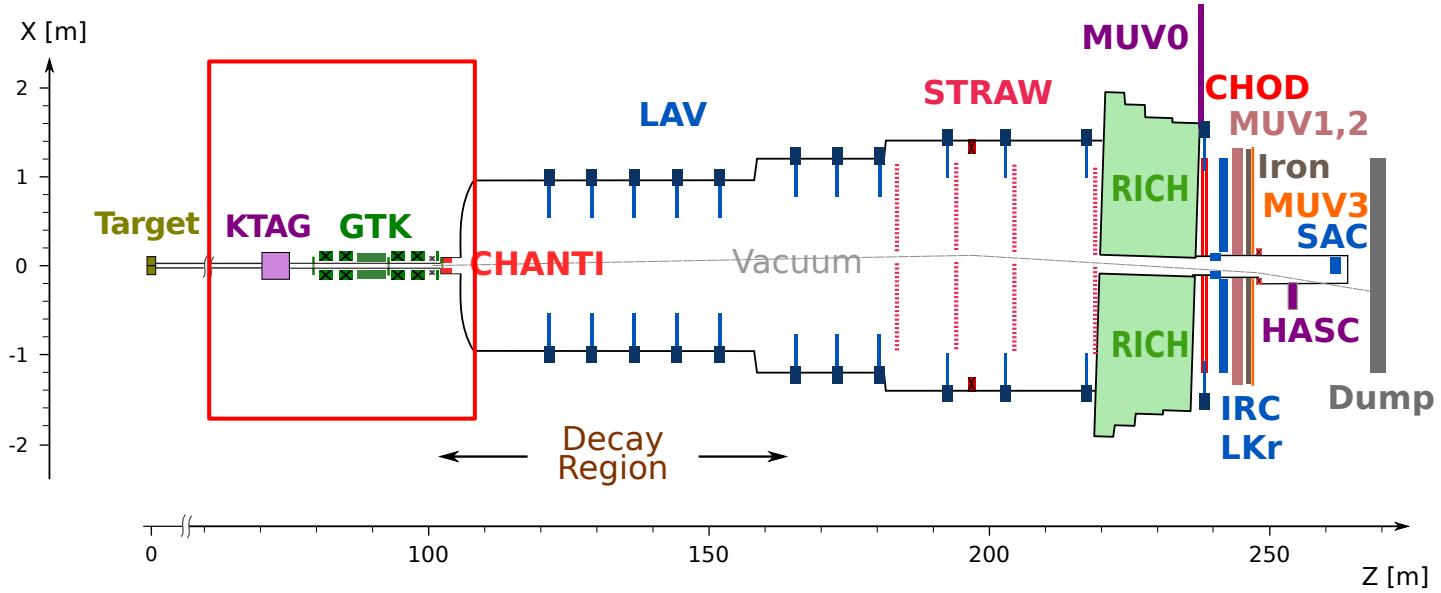
**Kaon Decays**

≈ 5 MHz

4.5 x $10^{12}$ per year

$10^{-6}$ mbar vacuum

# Strategy and Apparatus




## Kaon Tagging – CEDAR

45 MHz rate

time: 100 ps

## Kaon Tracking – GTK

time: ≈ 150 ps

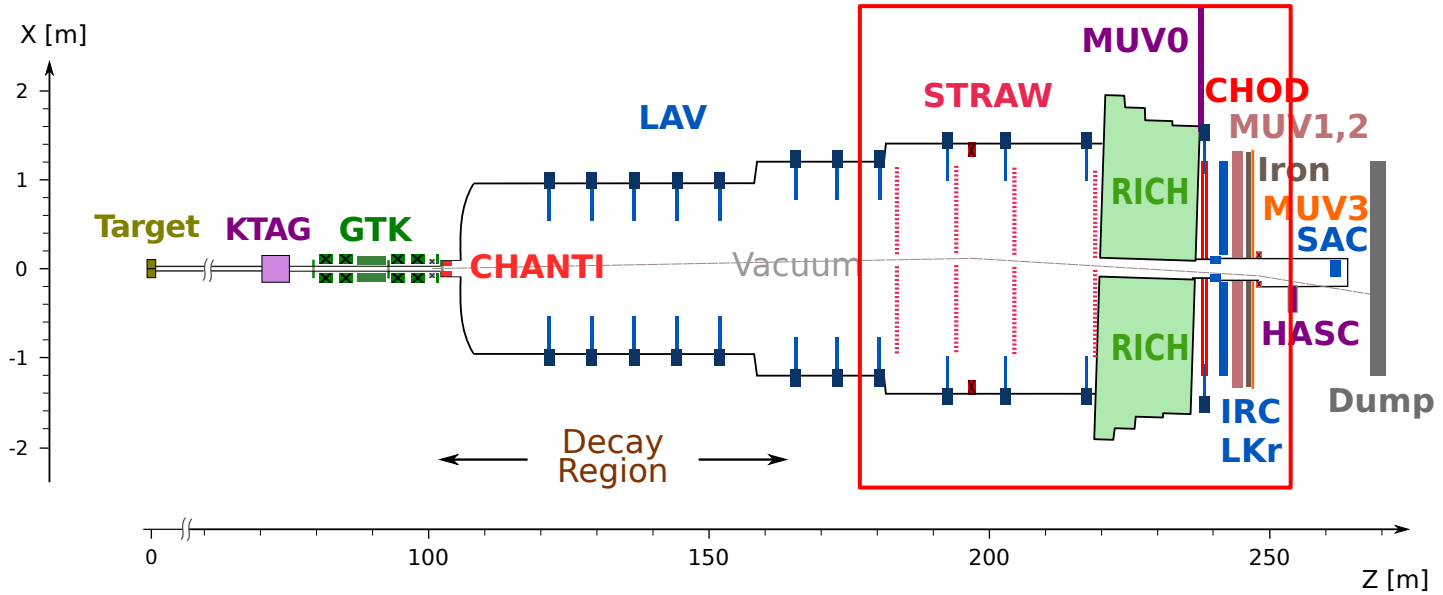
momentum: dp/p < 0.4%

direction : ≈ 0.016 mrad

## Beam Veto – CHANTI

time: ≈ 1 ns

# Strategy and Apparatus




## Spectrometer – STRAW

momentum: dp/p < 0.33%

direction : ≈ 10 mrad

extracted vertex: ≈ 1 mm

## RICH

time: < 100 ps

muon rejection: 100

## Calorimeters – LKr, HAC

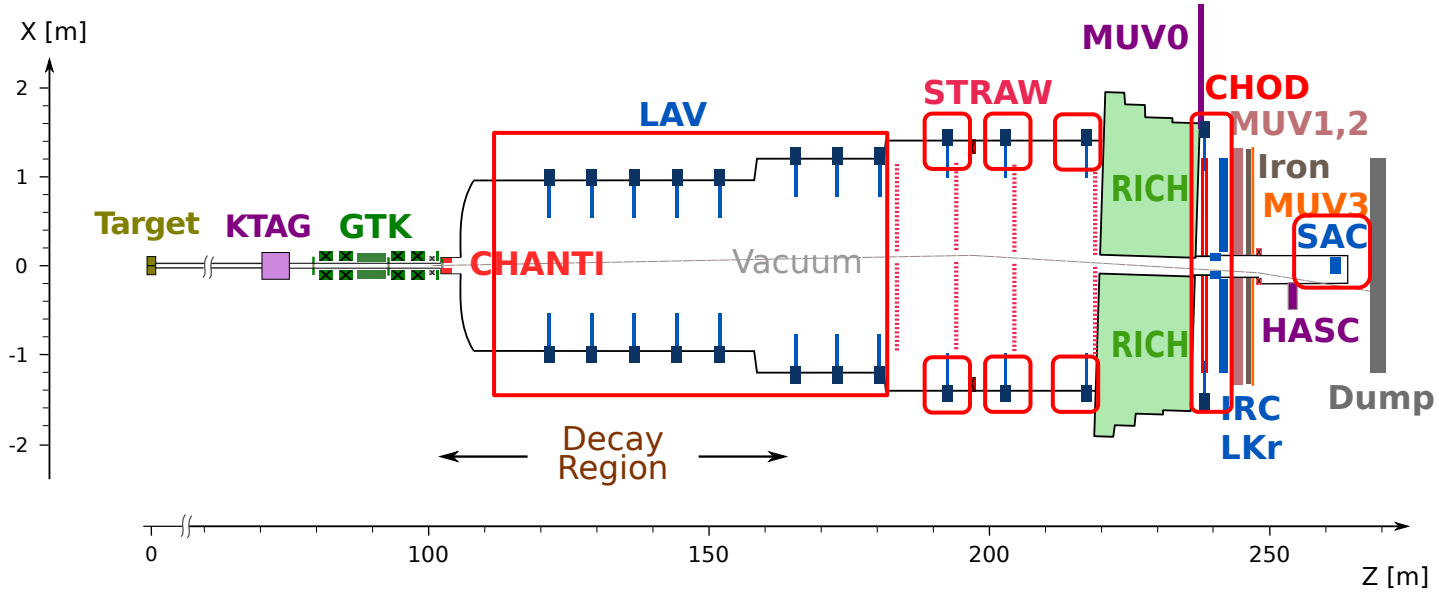
Hadronic Shower Reconstruction

muon rejection: $10^5$

## Fast Muon Veto

time: ≈ 300 ps

# Strategy and Apparatus




## Small Angle – IRC, SAC

coverage: < 1 mrad

## Large Angle – LAV

coverage: 8.5 – 50 mrad

time: ≈ 1 ns

## EM Calorimeter – LKr

coverage: 1 – 8.5 mrad

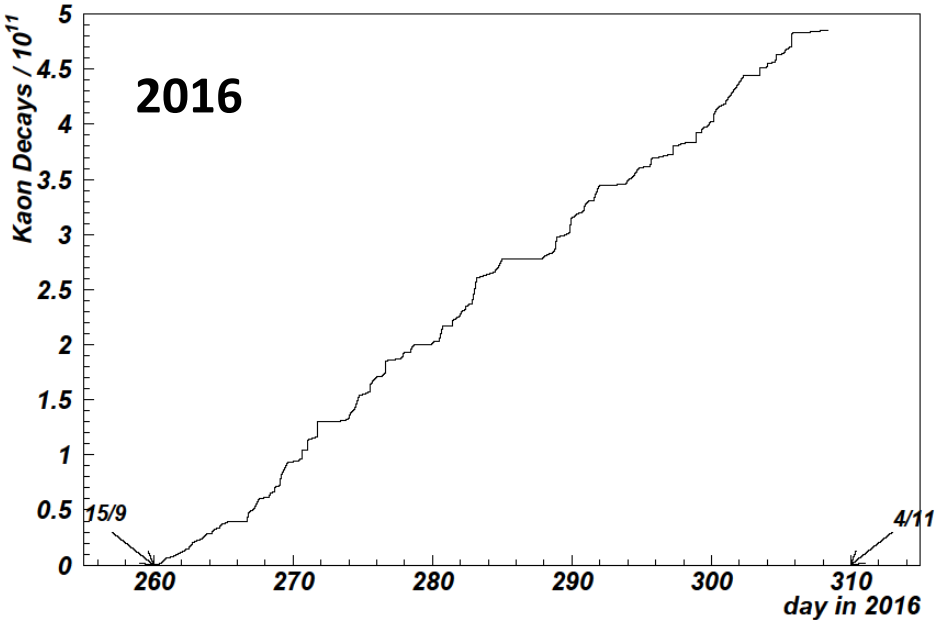
time: ≈ 300 ps

resolution: $\frac{\sigma_E}{E}(20\ GeV) < 1\%$

# $K^+ \rightarrow \pi^+ \nu\bar{\nu}$: Analyzed Data

2016 Data Taking:

- Final commissioning of the apparatus
- About 50 days for physics
- 35 – 40 % of nominal intensity
- About 1 x $10^{11}$ $K^+$ decays for the analysis




In 2017 and 2018 more the 20x larger statistics (per year)

Trigger Streams:

- "PNN": Online K-ID, μ and γ rejection
- "Control": Minimum Bias

Analysis:

Data Samples:

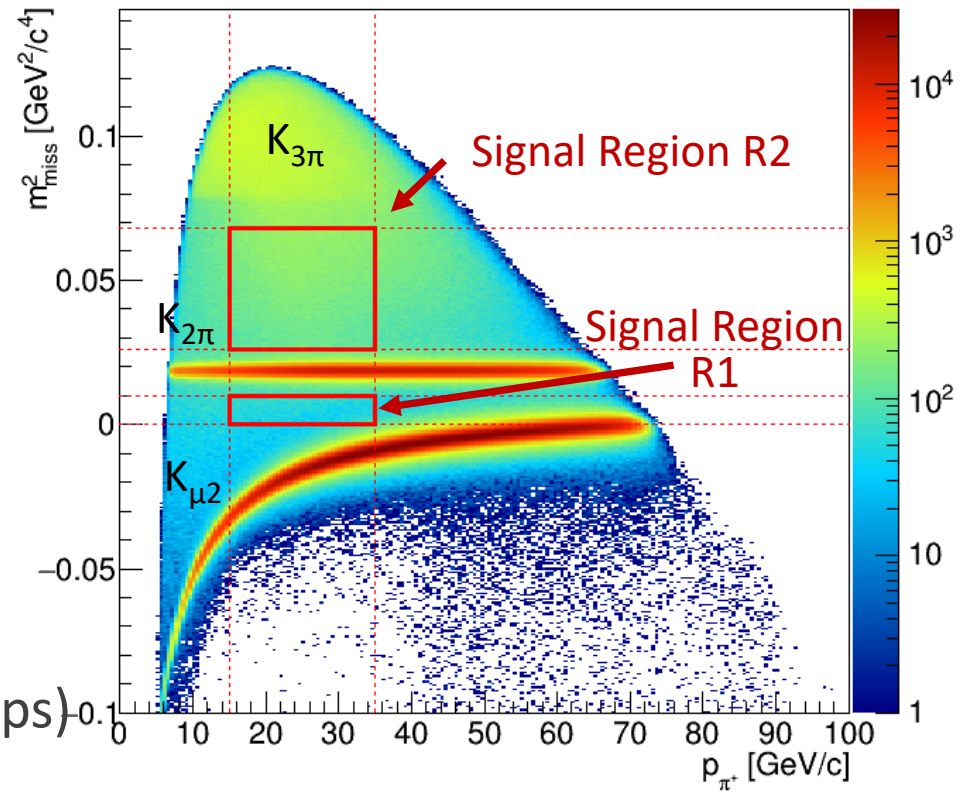
- PNN: $K^+ \rightarrow \pi^+ \nu\nu$
- Control: $K^+ \rightarrow \pi^+\pi^o$ ($K_{2\pi}$), $K^+ \rightarrow \mu^+\nu$ ($K_{\mu 2}$), $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ ($K_{3\pi}$)

Blind Analysis: Signal and Control regions masked

# Selection

**Event Selection:**

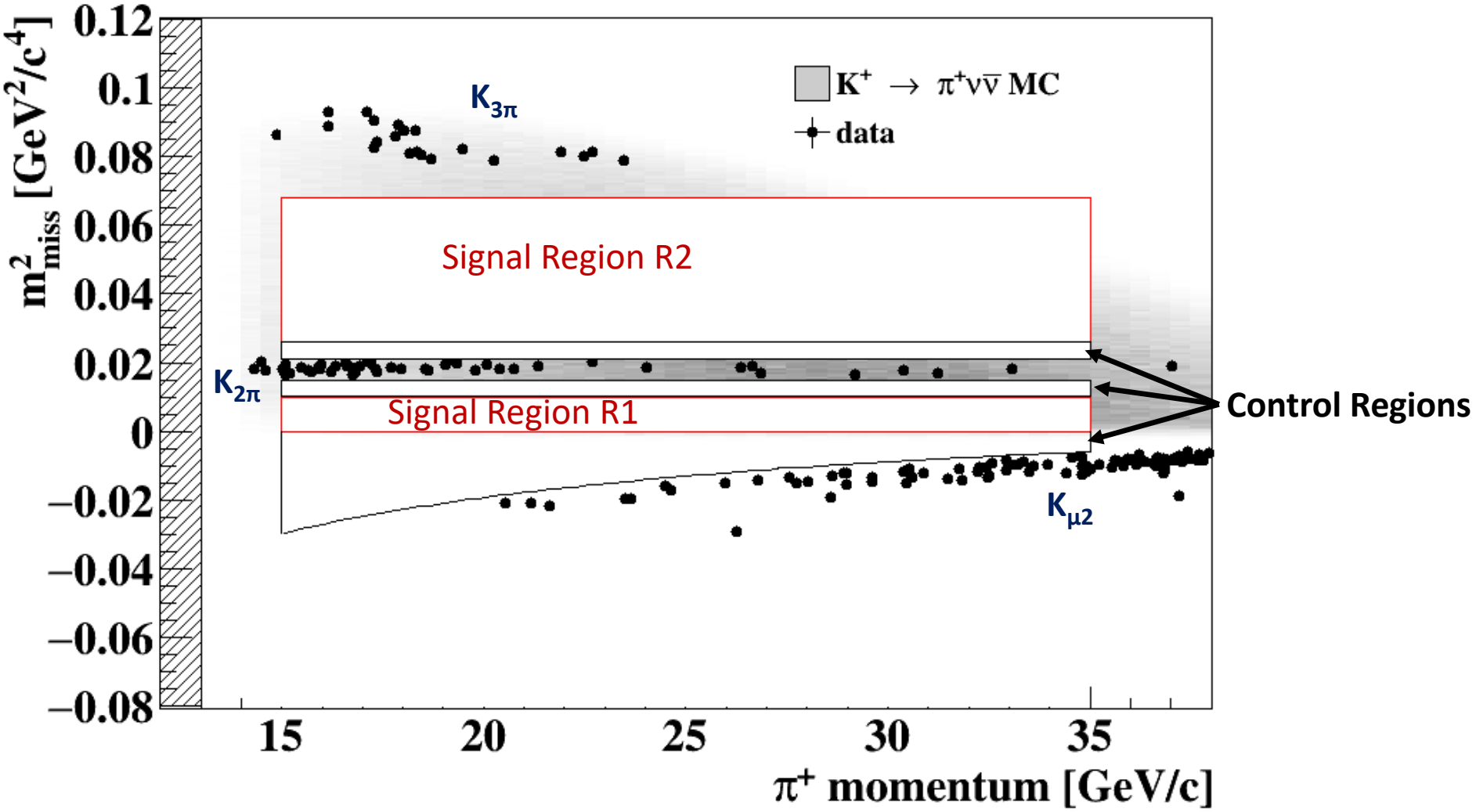
- One track final state
- $K^+$ - $\pi^+$ Matching
- $K^+$ decay in fiducial volume
- Pion Identification
- Photon Rejection
- Multi-Track Rejection




**Performance:**

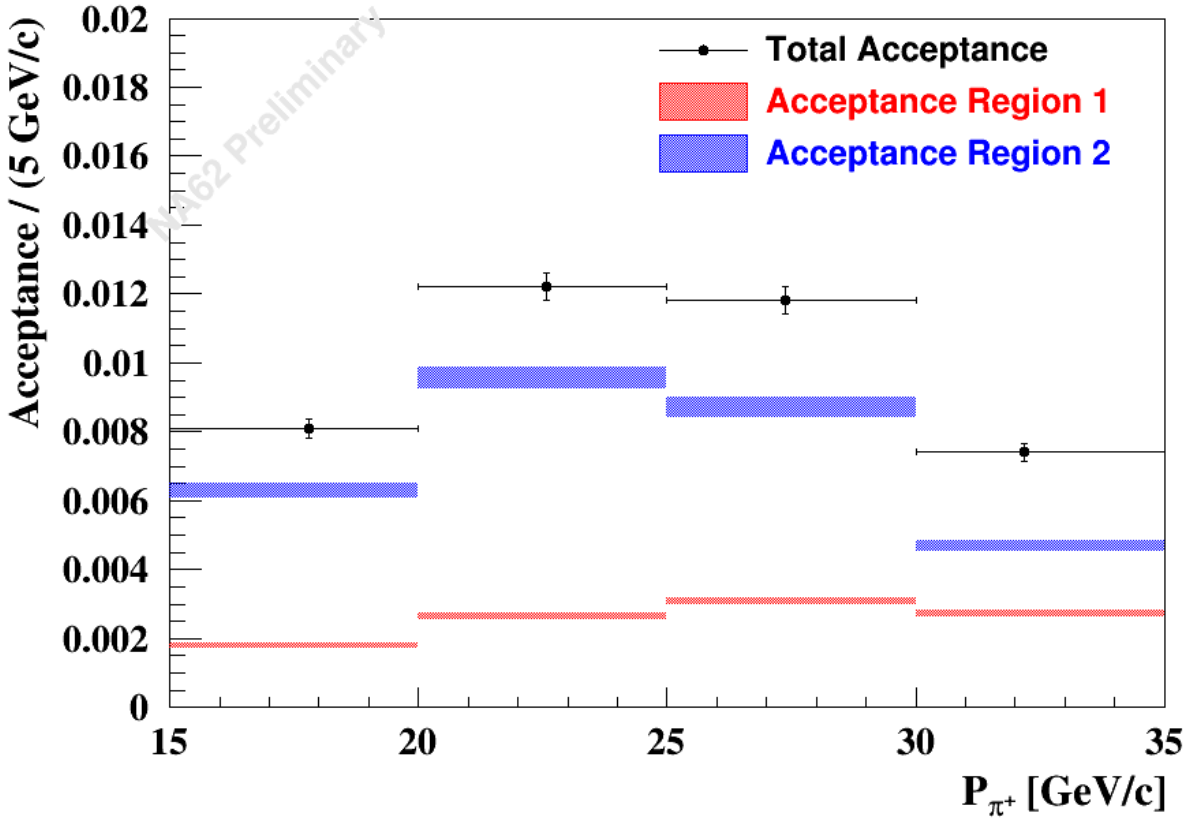
- ✓ GTK – KTAG – RICH Timing: O(100 ps)
- ✓ $\pi^+$ ID: $\varepsilon_{\mu^+} = 10^{-8}$ vs $\varepsilon_{\pi^+} \approx 64\%$
- ✓ Photon rejection: $\varepsilon_{\pi^0} = 2.5 \times 10^{-8}$
- ✓ $\sigma_{m^2_{miss}} \approx 10^{-3}$ GeV$^2$/c$^4$

# Selected Events



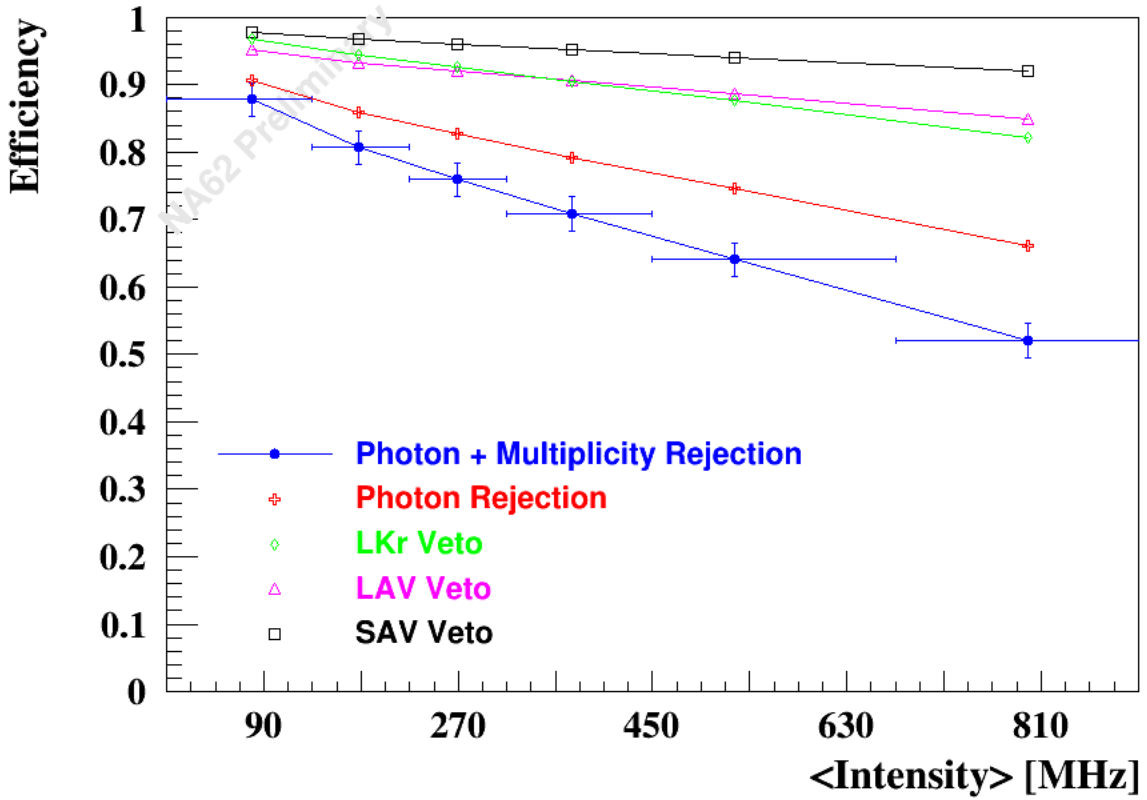
# Signal Acceptance

- Evaluated from MC simulations: $A_{\pi\nu\nu} = (4.0 \pm 0.1)\%$
- Includes PID inefficiency and losses due to $\pi^+$ interactions



# Random Veto

- Random Veto induced by photon and multiplicity/multi-track rejection
- Measured with $K^+ \rightarrow \mu^+ \nu$ events
- $< \varepsilon_{RV} > = 0.76 \pm 0.04$: independent from p, but dependent on the instantaneous intensity



# Single Event Sensitivity (SES)

- Number of Kaon decays: $K_{2\pi}$ events selected in Control trigger (Downscaling D = 400)
- Same selection as for $K^+ \to \pi^+ \nu\nu$, but no photon rejection, different $m^2_{miss}$ region

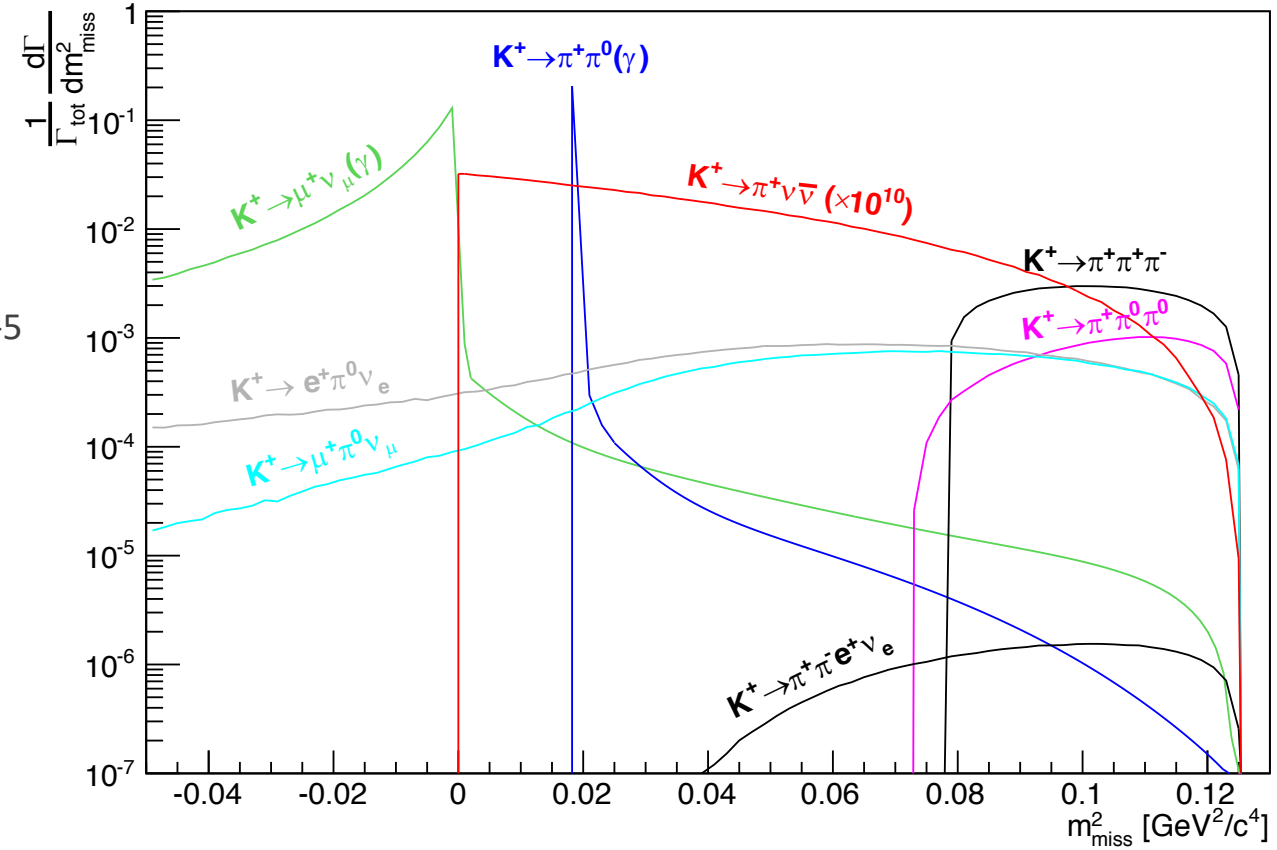
$$SES = \frac{1}{N_K \times (A_{\pi\nu\nu} \times \epsilon_{RV} \times \epsilon_{trigger})} \qquad N_K = \frac{N_{\pi\pi} \times D}{A_{\pi\pi} \times BR_{\pi\pi}}$$

| | |
|---|---|
| Number of Kaon Decays | $N_K = (1.21 \pm 0.02)\ 10^{11}$ |
| Acceptance $K^+ \to \pi^+ \nu\nu$ | $A_{\pi\nu\nu} = 0.040 \pm 0.001$ |
| Trigger Efficiency | $\varepsilon_{trigger} = 0.87 \pm 0.02$ |
| Random Veto | $\varepsilon_{RV} = 0.76 \pm 0.04$ |
| **SES** | $\mathbf{(3.15 \pm 0.01_{stat} \pm 0.24_{syst})\ 10^{-10}}$ |
| **Expected SM Events** | $\mathbf{0.267 \pm 0.01_{stat} \pm 0.020_{sys} \pm 0.032_{ext}}$ |

# Backgrounds

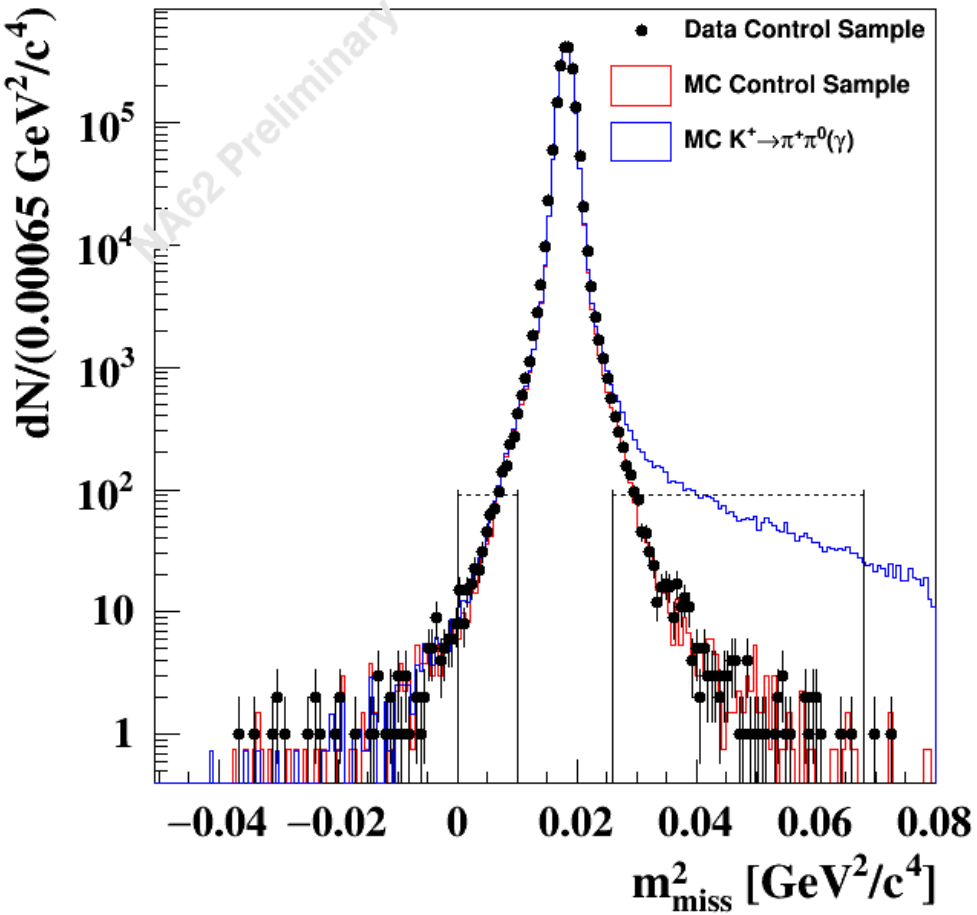
Main background sources:

1. $K_{2\pi}$: BR = 20.67%
2. $K_{\mu 2}$: BR = 63.56%
3. $K_{e4}$: BR = $4.25 \cdot 10^{-5}$
4. Beam Induced



# $K^+ \rightarrow \pi^+\pi^o(\gamma)$ Background

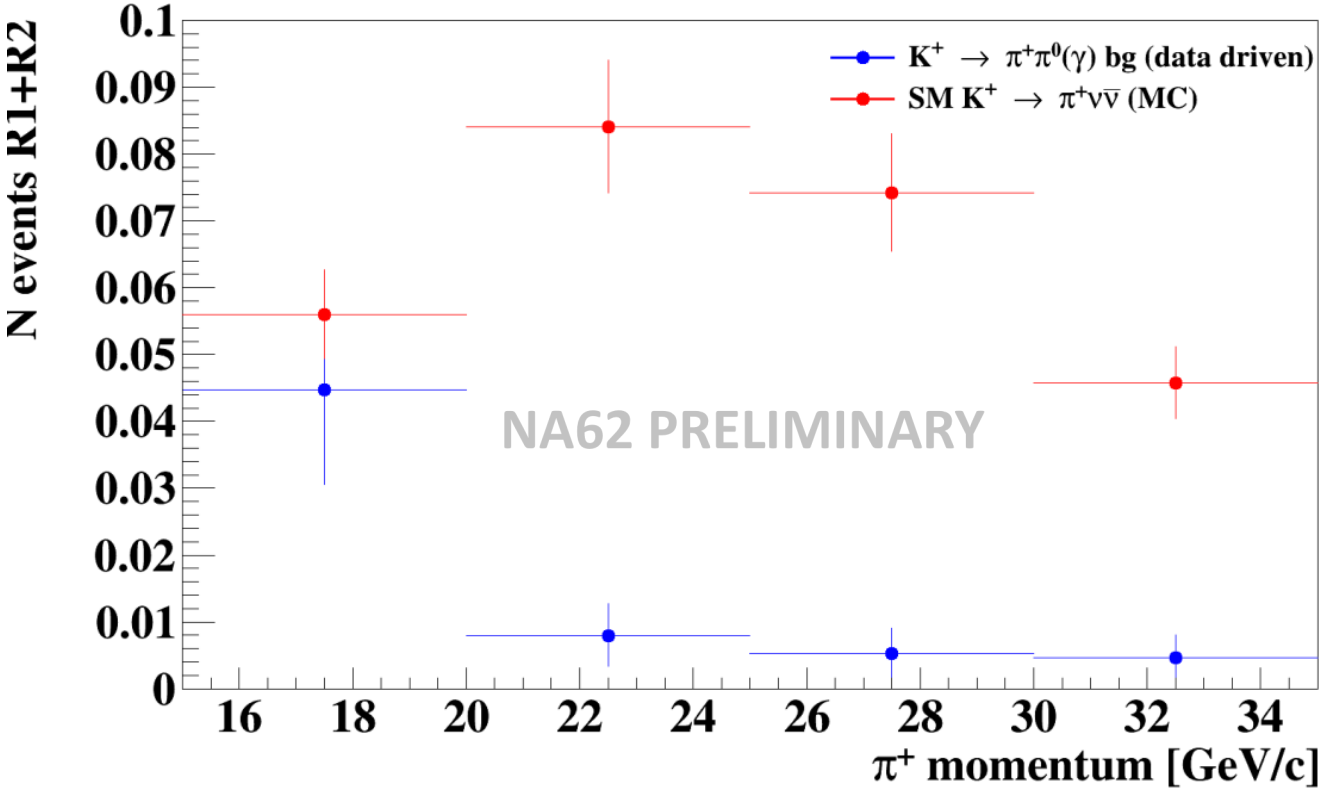
$$N_{\pi\pi}(Region) = N(\pi^+\pi^o) \times f^{kin}(Region)$$




- Kinematic rejection uncorrelated wrt photon rejection
- $N(\pi^+\pi^o)$: remaining events under $K_{2\pi}$ peak after full selection
- $f^{kin}$ from $K_{2\pi}$ control sample with tagged $\pi^o$
- $\boldsymbol{f^{kin}(R1+R2) \approx 10^{-3}}$
- **Radiative: $\pi^o$ + γ 30x stronger photon rejection**

# $K^+ \rightarrow \pi^+\pi^o(\gamma)$ Background

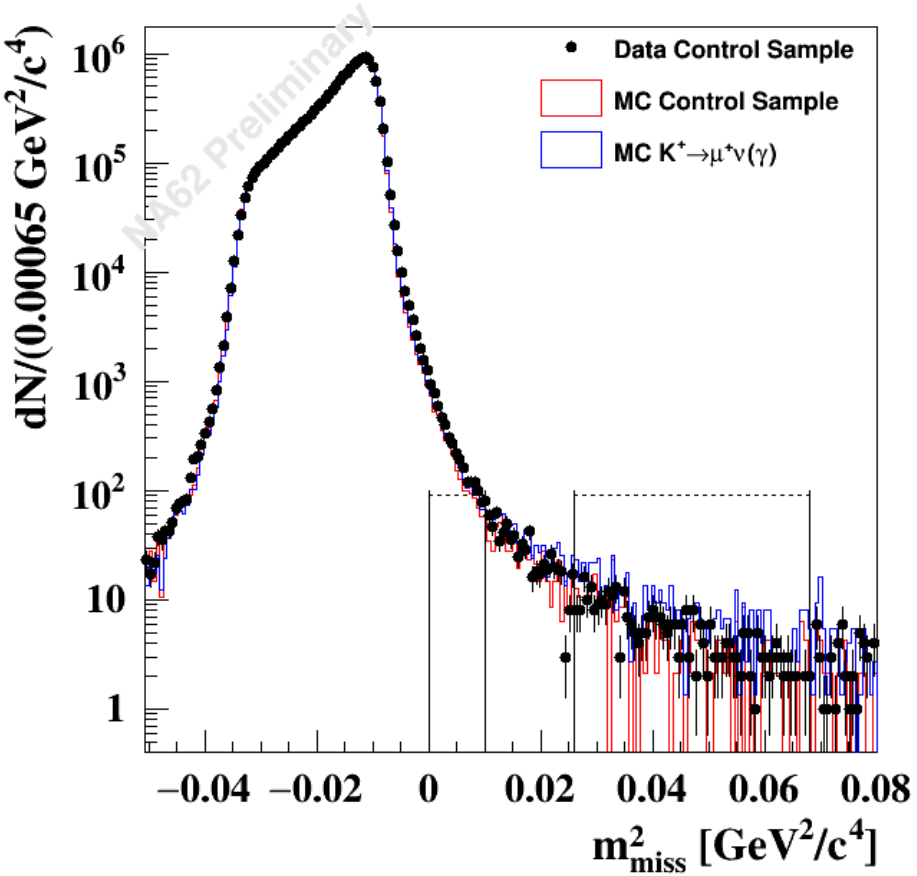
$$N_{\pi\pi}(R1 + R2) = 0.064 \pm 0.007_{stat} \pm 0.006_{syst}$$




**Expected control regions: 1.46 ± 0.17 ⇒ Observed 1**

# $K^+ \rightarrow \mu^+\nu(\gamma)$ Background

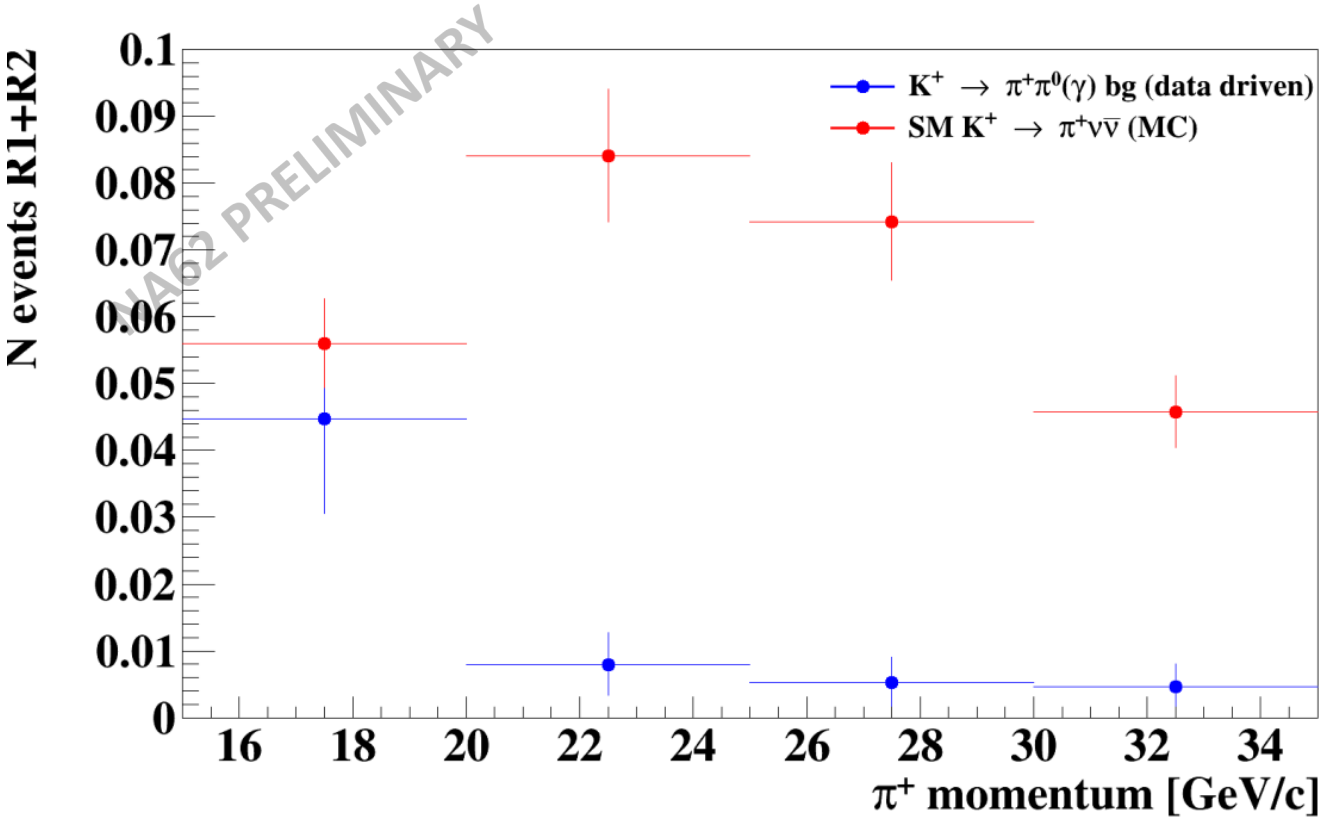
$$N_{\mu\nu}(Region) = N(\mu^+\nu) \times f^{kin}(Region)$$




- Kinematic rejection uncorrelated wrt PID
- $N(\mu^+\nu)$: remaining events in $K_{\mu 2}$ region after full selection
- $f^{kin}$ from $K_{\mu 2}$ control sample with μ-ID
- $\boldsymbol{f^{kin}(R1) \approx 10^{-5} \div 10^{-3}}$
- $\boldsymbol{f^{kin}(R2) \approx 10^{-5}}$

# $K^+ \rightarrow \mu^+\nu(\gamma)$ Background

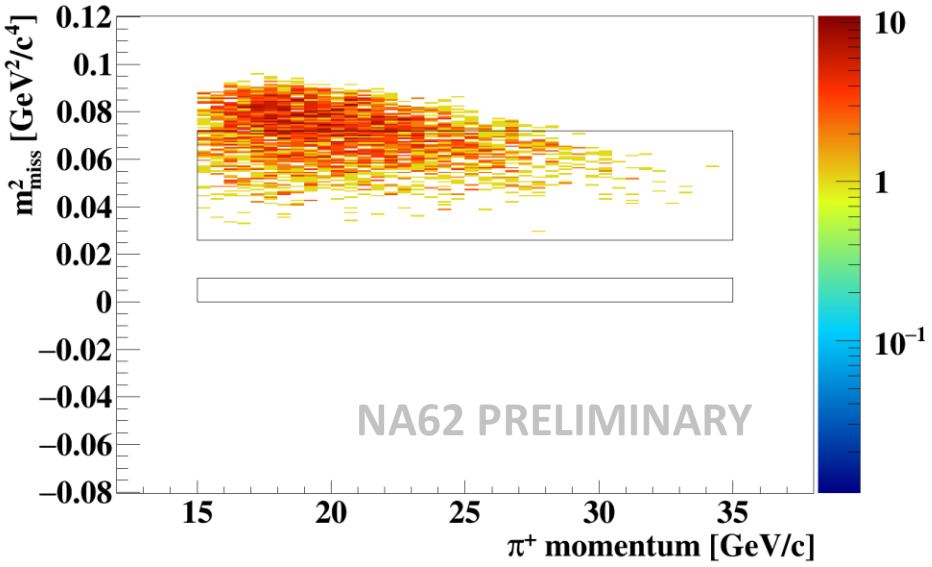
$$N_{\mu\nu}(R1 + R2) = 0.020 \pm 0.003_{stat} \pm 0.003_{syst}$$

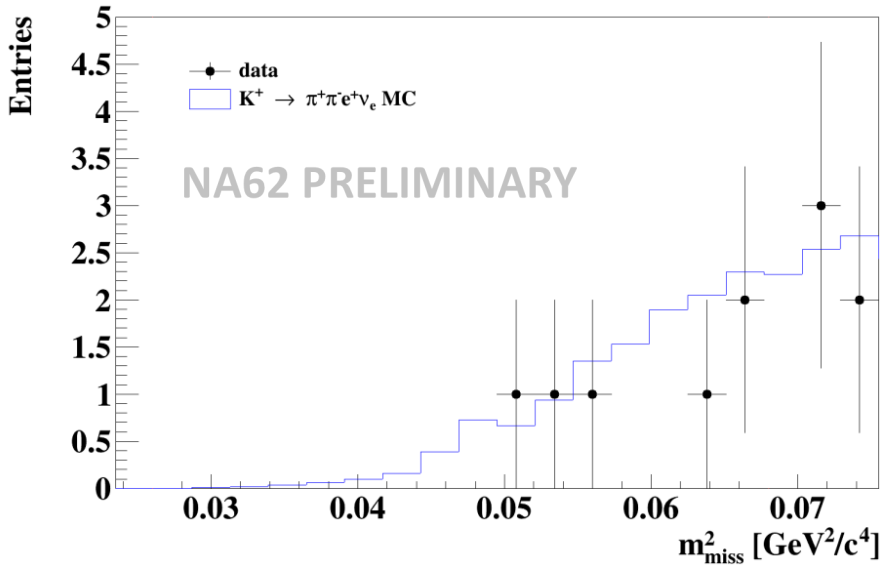



**Expected control regions: 1.02 ± 0.16 ⇒ Observed 2**

# $K^+ \rightarrow \pi^+\pi^o e^+\nu$ Background

- Kinematics spanning over R2, correlated to topology
- Evaluated with about 4 x $10^8$ MC events
- **Validated with enriched data sample**



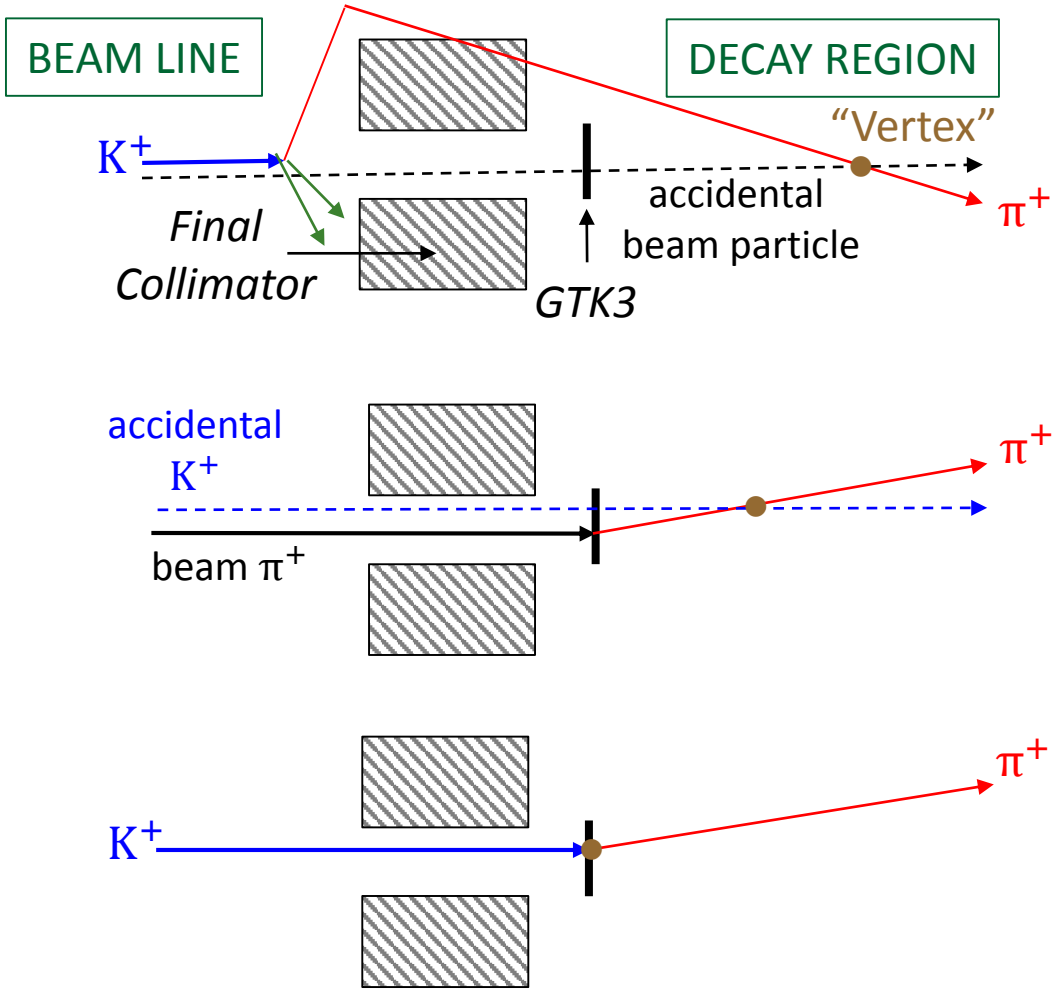




$$N_{e4}(R2) = 0.018^{+0.024}_{-0.017}|_{stat} \pm 0.009_{syst}$$

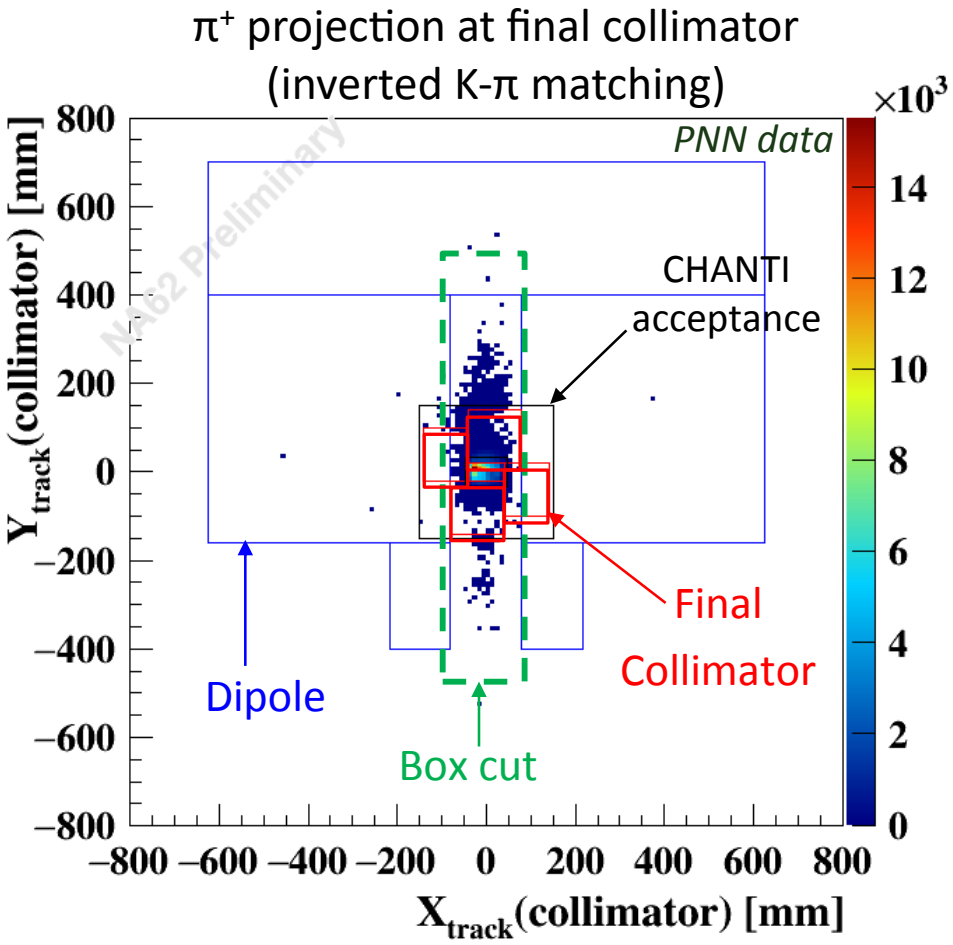
# Beam Related Background

Related to accidentals and/or interactions

1. $K^+$ decay along beam line
2. $\pi^+$ interactions
3. $K^+$ Interactions
4. Other similar topologies



# Beam Related Background




Against Beam Background:

- K – π Matching
- Geometrical cut on back-projection
- $Z_{vertex}$ and CHANTI

Background Estimation:

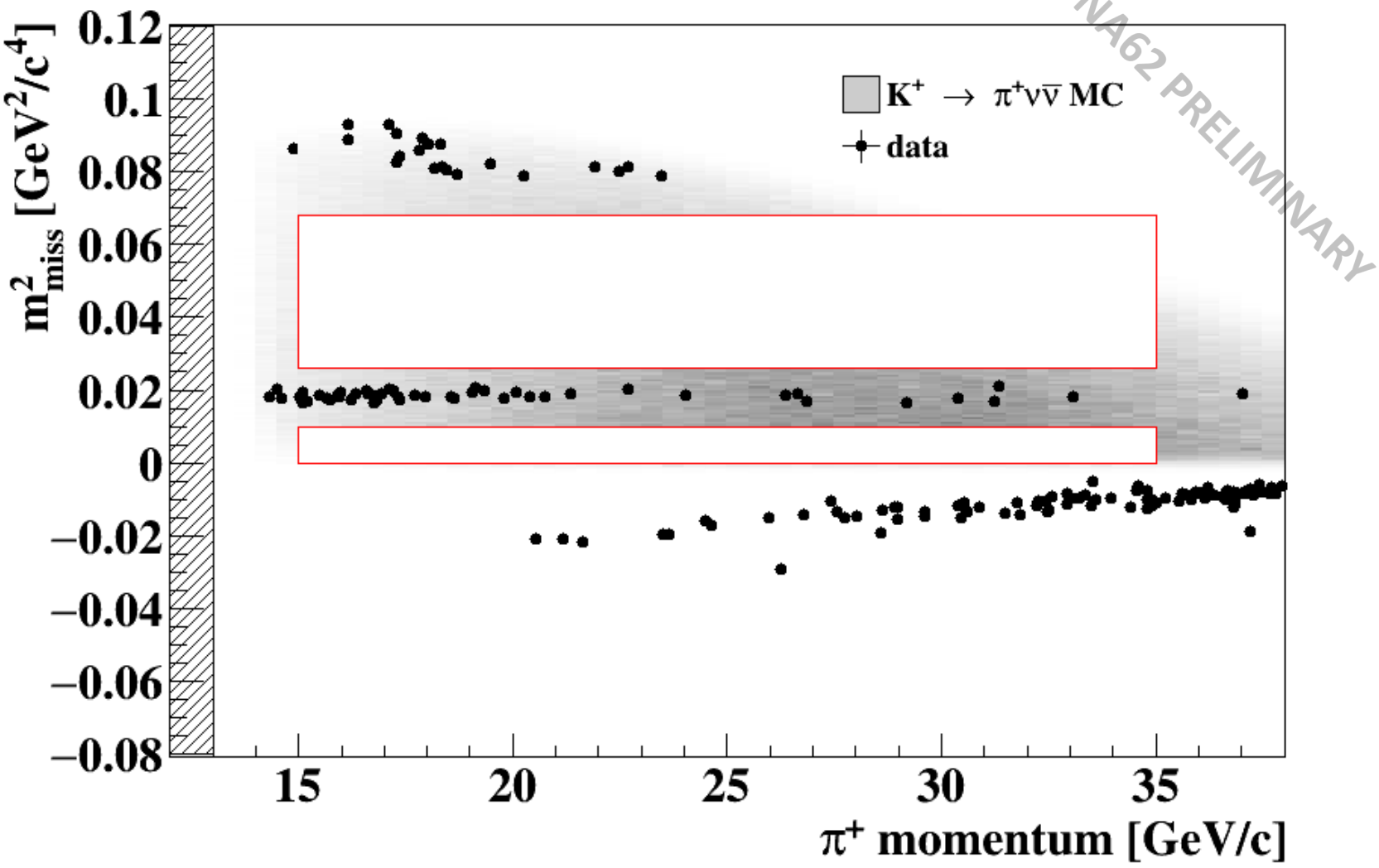
- Fully data driven
- Cut inversion
- Limited Statistics in 2016

$$N_{beam}(R1 + R2) = 0.050^{+0.090}_{-0.030}|_{stat}$$

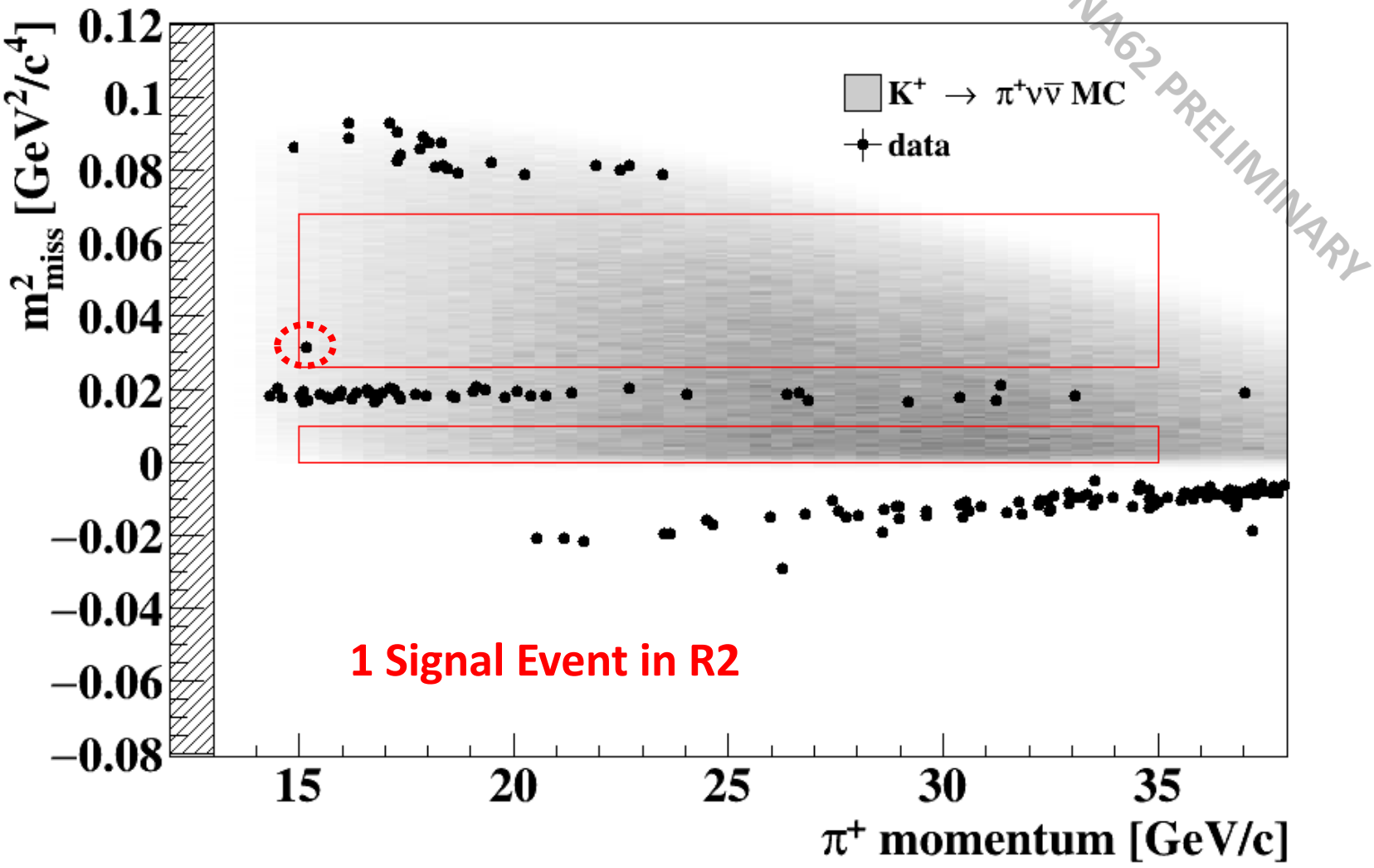
# Background Summary

| Process | Expected Events (R1+R2) |
|---|---|
| **$K^+ \to \pi^+ \nu\bar{\nu}$ (SM)** | **$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$** |
| **Total Background** | **$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$** |
| $K^+ \to \pi^+\pi^o(\gamma)$ IB | $0.064 \pm 0.007_{syst} \pm 0.006_{syst}$ |
| $K^+ \to \mu^+\nu(\gamma)$ IB | $0.020 \pm 0.003_{syst} \pm 0.003_{syst}$ |
| $K^+ \to \pi^+\pi^o e^+\nu$ | $0.018\ ^{+0.024}_{-0.017}\vert_{stat} \pm 0.009_{syst}$ |
| $K^+ \to \pi^+\pi^+\pi^-$ | $0.002 \pm 0.001_{syst} \pm 0.002_{syst}$ |
| Beam Related | $0.050\ ^{+0.09}_{-0.03}\vert_{stat}$ |

# Result


NA62 PRELIMINARY
$K^+ \to \pi^+\nu\bar{\nu}$ MC
data
$m^2_{miss}$ [GeV$^2$/c$^4$]
0.12
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
15
20
25
30
35
$\pi^+$ momentum [GeV/c]

# Result


NA62 PRELIMINARY
$K^+ \to \pi^+\nu\bar{\nu}$ MC
data
1 Signal Event in R2
$m^2_{miss}$ [GeV$^2$/c$^4$]
0.12
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
15
20
25
30
35
$\pi^+$ momentum [GeV/c]

# Preliminary Results

| **Observed Events** | **1** |
|---|---|
| SES | $3.15 \pm 0.01_{stat} \pm 0.24_{syst}$ |
| Expected Backgrounds | $0.15 \pm 0.09_{stat} \pm 0.01_{syst}$ |
| Expected Signals (SM) | $0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$ |

$$\boldsymbol{Br(K^+ \to \pi^+ \nu\bar{\nu}) < 11 \times 10^{-10} \ @90\% \ CL}$$

$$\boldsymbol{Br(K^+ \to \pi^+ \nu\bar{\nu}) < 14 \times 10^{-10} \ @95\% \ CL}$$

NA62 PRELIMINARY

- ✓ Expected Limit: $Br(K^+ \to \pi^+ \nu\bar{\nu}) < 10 \times 10^{-10} \ @95\% \ CL$
- ✓ For comparison: $Br(K^+ \to \pi^+ \nu\bar{\nu}) = (2.8\,^{+4.4}_{-2.3}) \times 10^{-10} \ @68\% \ CL$

SM prediction: $Br(K^+ \to \pi^+ \nu\bar{\nu}) = (0.84 \pm 0.10) \times 10^{-10}$

BNL E747/E949: $Br(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73\,^{+1.15}_{-1.05}) \times 10^{-10}$

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

- **Data collection still on-going!**
  - In 2017 collected about 20x more data: currently processing and analyzing.
  - 2018 data taking expected to provide at least same statistics as 2017.
- **Selection efficiency improvements:**
  - Refine the analysis
  - Study of better handling of beam background (thanks to larger statistics)
  - Hardware mitigation of beam background (new collimator installed)
- **Expected about 20 SM events from the 2017-18 data sample**

# Conclusions

- **NA62 Decay-in-Flight Technique works!**
- Analysis of 2016 data sample completed: 1 event observed
- $\boldsymbol{Br(K^+ \to \pi^+ \nu\bar{\nu}) < 11 \times 10^{-10}}$ **@90% CL**

NA62 PRELIMINARY

- O(20) events expected from (2017+2018) data