UNIVERSITY OF BIRMINGHAM

Marie Skłodowska-Curie Actions

First results on the $K^+ \to \pi^+ \nu\bar{\nu}$ decay search from NA62

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University of Birmingham

Outline

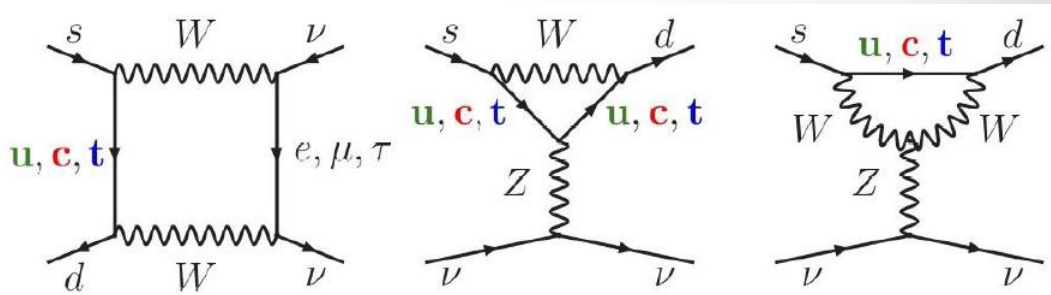
- $K^+ \to \pi^+ \nu\bar{\nu}$ decay
- NA62 experiment
- Analysis principles
- Single event sensitivity
- Background studies
- Final result
- Summary and prospects

K→πνν in SM

2 modes: charged, neutral

- FCNC loop process
- Theoretically clean
- CKM suppression: BR ~ $|V^*_{ts}\ V_{td}|^2$

SM one-loop diagrams: box and penguins



Hadronic matrix element extracted from well-known decay $K^+ \to e^+ \nu \pi^0$

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ \left[\left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2 + \left(\frac{\mathrm{Re}\,\lambda_t}{\lambda^5} X(x_t) + \frac{\mathrm{Re}\,\lambda_c}{\lambda} P_c(X) \right)^2 \right] (1 + \Delta_{EM})$$

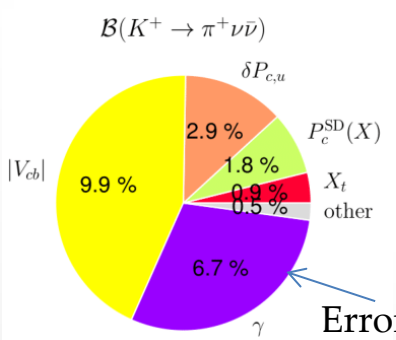
$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}\,\lambda_t}{\lambda^5} X(x_t) \right)^2$$

charm contribution

EM radiative correction

Top contribution (dominant)

$$\lambda = V_{us}$$
$$\lambda_c = V_{cs}^* V_{cd}$$
$$\lambda_t = V_{ts}^* V_{td}$$
$$x_q \equiv m_q^2 / m_W^2$$



Error budget for BR(SM)

[Buras et al. JHEP 1511 (2015) 33]

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

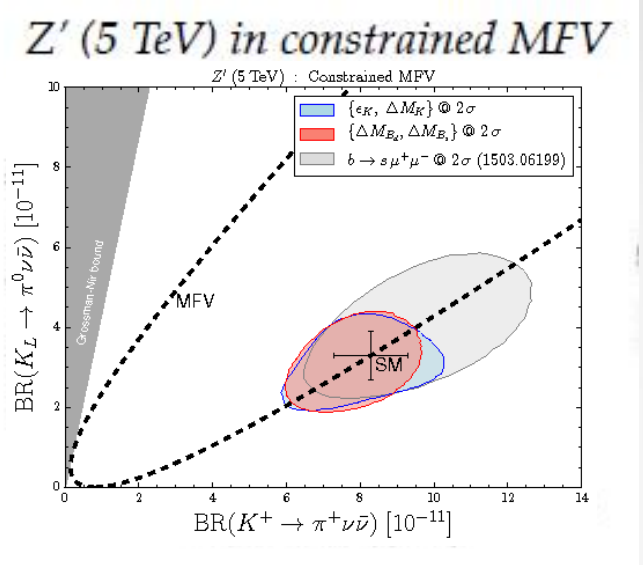
$BR(K^0 \to \pi^0 \nu\nu) = (3.4 \pm 0.6) \times 10^{-11}$

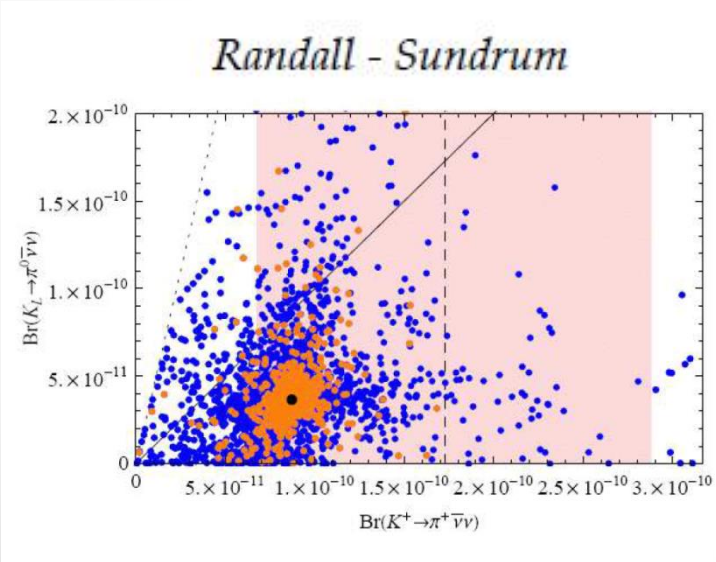
K→πνν in New Physics

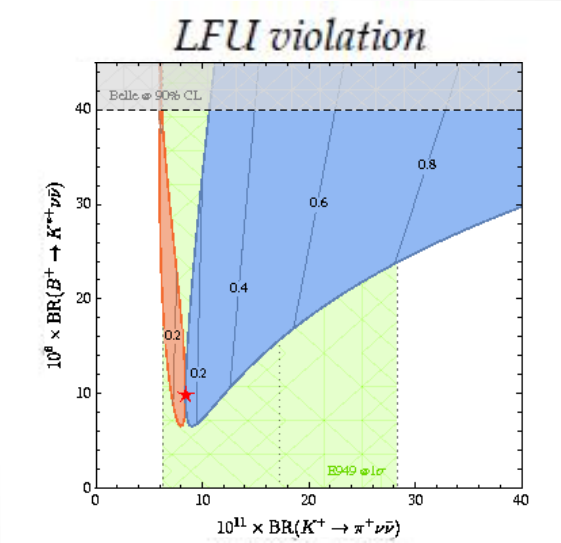
Searches for NP in K→πνν:

- High masses and sizable couplings to SM
- Constraints from existing measurements

- Custodial Randall-Sundrum [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- MSSM analyses [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]



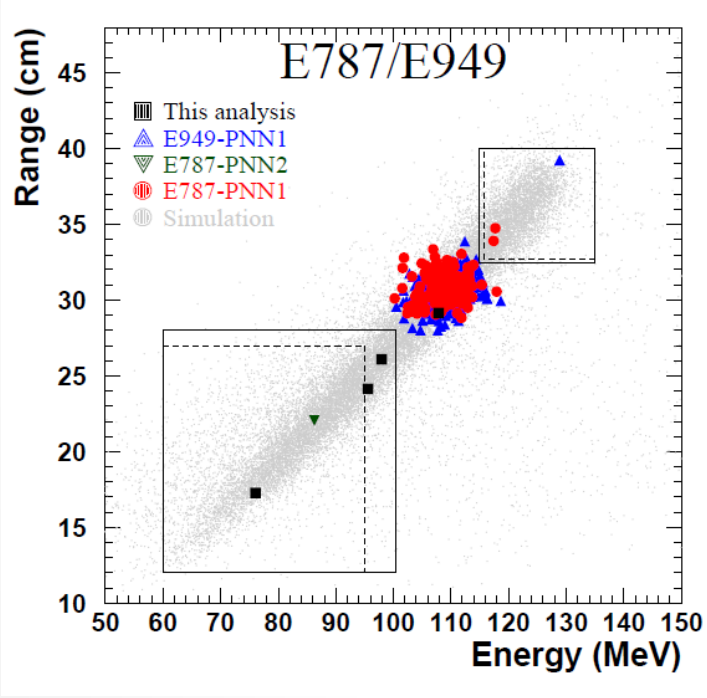




K→πνν in experimental physics

$K^+ \to \pi^+ \nu\nu$
E949 experiment @ BNL

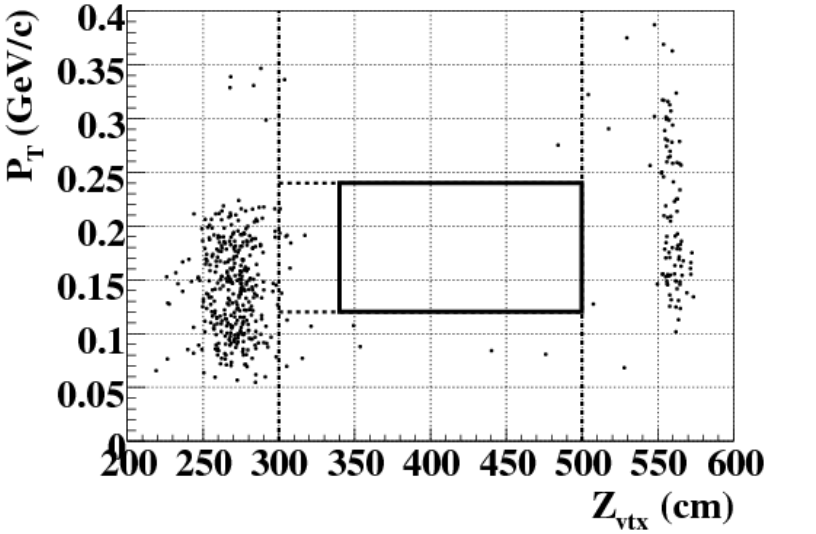
$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = \left(1.73^{+1.15}_{-1.05}\right) \times 10^{-10}$$



Phys. Rev. D 77, 052003 (2008), Phys. Rev. D 79, 092004 (2009)

$K^0 \to \pi^0 \nu\nu$
E391 experiment @ KEK

$$BR(K_L \to \pi^0 \nu\bar{\nu}) < 2.6 \times 10^{-8}$$



Phys. Rev. D 81, 072004 (2010)

KOTO experiment @ JPARC:
Better UL (factor ~10) expected from 2015 run, **SES=1.2x10^{-9}**

NA62 goals

Main goal:

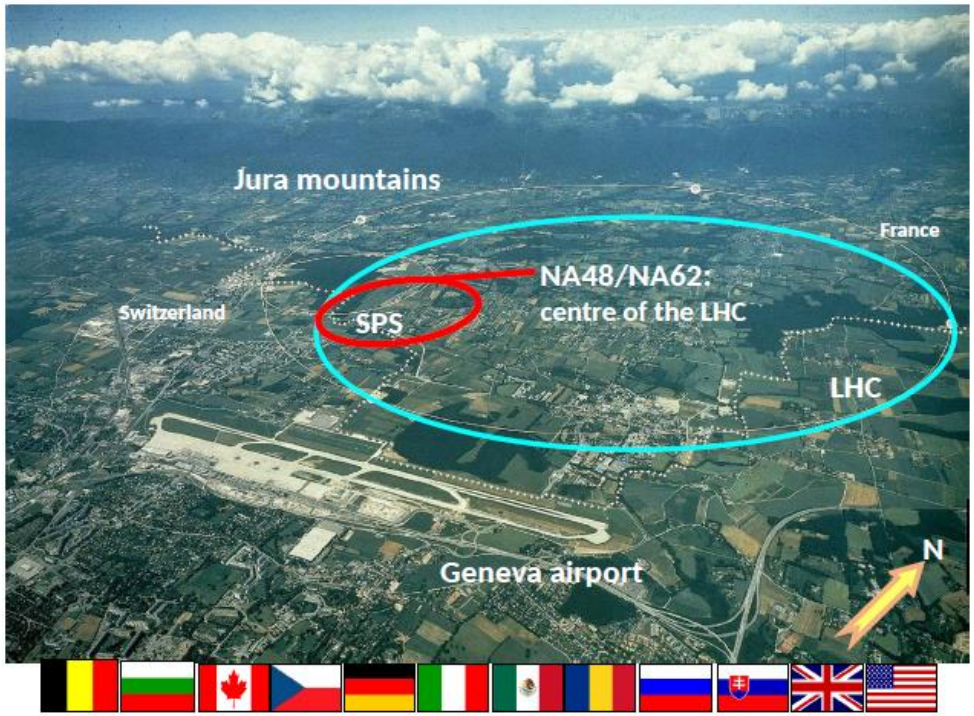
- Measure BR($K^+ \to \pi^+ \nu\nu$) with 10% precision

Requirements:

- O(100) signal events
- ~10^{13} kaon decays
- ~10% signal acceptance
- >10^{12} background suppression

Technique:

- Kaon decay-in-flight



Kaon decay in flight experiments.
NA62: ~200 participants, ~ 30 institutes

Beyond the baseline:

- LFV/LNV in kaon decays
- Heavy neutral lepton searches
- π^0 decays
- Hidden sector particles searches

See talk by A. Shaikhiev 31.05.2018

NA62 runs

NA62 collaboration:

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

This talk: 2016 data, ~1×10^{11} decays useful for $K\to\pi\nu\nu$

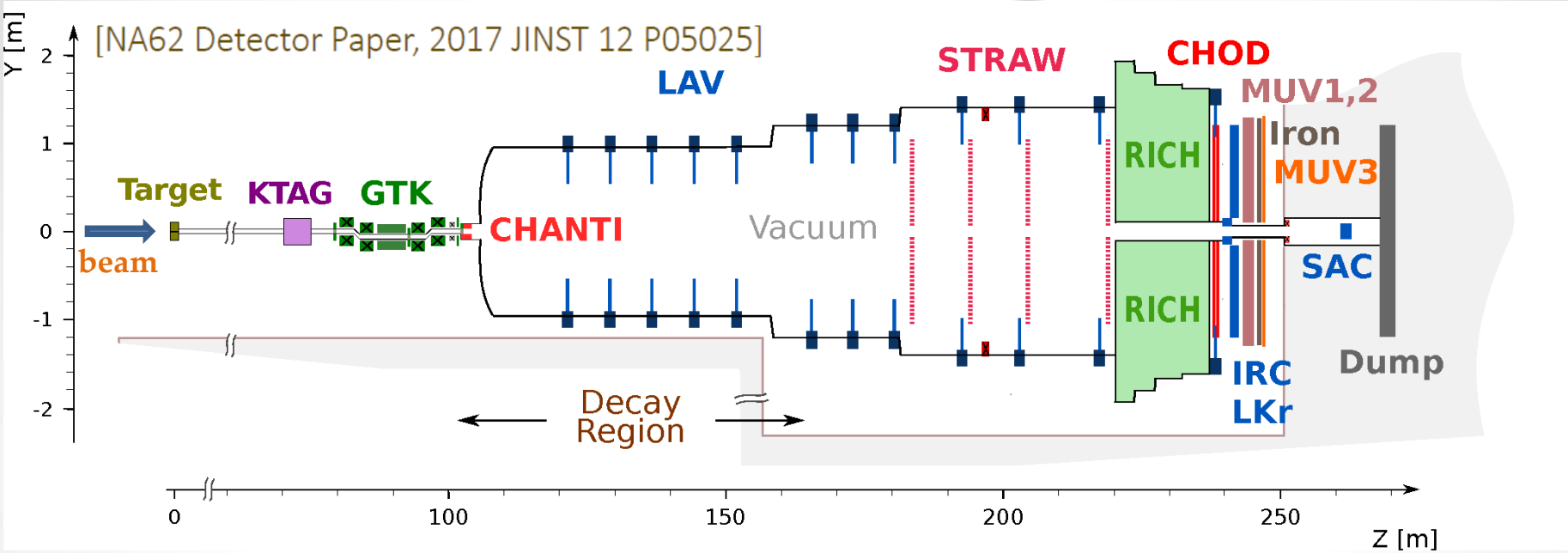
NA62 timeline

- ✓ **2015:** commissioning (1% of the nominal beam intensity I_0)
- ✓ **2016:** commissioning + physics (40% I_0)
- ✓ **2017:** physics (60% I_0)

NA62 present & future

- **2018:** running (60% I_0)
- **2021-2023:** to be approved

NA62 setup



Secondary positive beam	
Momentum	75 GeV/c, 1% bite
Divergence (RMS)	100 μrad
Transverse Size	$60 \times 30\text{mm}^2$
Composition	$K^+(6\%)/\pi^+(70\%)/p(24\%)$
Nominal Intensity	33×10^{11} ppp (750 MHz at GTK3)

Decay region and Detectors	
Fiducial region	60 m
K^+ decay rate	~ 5 MHz
Vacuum	$\mathcal{O}(10^{-6})$ mbar

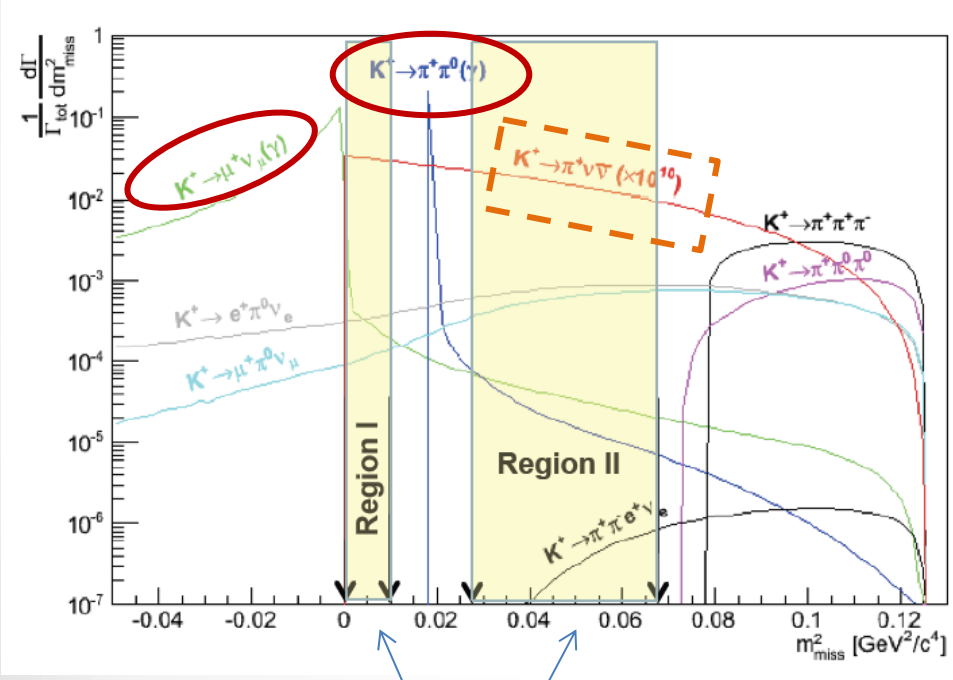
K: GTK, KTAG
π: STRAW, RICH, MUV

Analysis principle

Main kinematical variable for the signal:

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

$$m^2_{miss} \cong m_K^2\left(1-\frac{|P_\pi|}{|P_K|}\right) + m_\pi^2\left(1-\frac{|P_K|}{|P_\pi|}\right) - |P_K||P_\pi|\theta^2_{\pi K}$$



Two signal regions

Background decay modes

Process	Branching ratio
$K^+ \to \pi^+\pi^0(\gamma)$	0.2067
$K^+ \to \mu^+\nu(\gamma)$	0.6356
$K^+ \to \pi^+\pi^+\pi^-$	0.0558
$K^+ \to \pi^+\pi^-e^+\nu$	$4.25 \cdot 10^{-5}$

One secondary track

+

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

Particle ID (Cherenkov detectors)

Particle ID (Calorimeters)

Photon veto

Analysis keystones

$\mathcal{O}(100\ \mathrm{ps})$	Timing between sub-detectors
$\mathcal{O}(10^4)$	Background suppression from kinematics
$> 10^7$	Muon suppression
$> 10^7$	π^0 (from $K^+ \to \pi^+\pi^0$) suppression

Blind analysis procedure:

- Signal regions are masked
- Control regions for background estimation are masked

Analysis steps

- **Selection:**
  - K+ decays with a single charged particle in the final state
  - Particle ID (pion)
  - Photon and multiple charged particle rejection
  - Kinematic selection of Signal Regions
- **Determination of the Single Event Sensitivity (SES)**
- **Background estimation**
- **Unblinding Signal Regions**

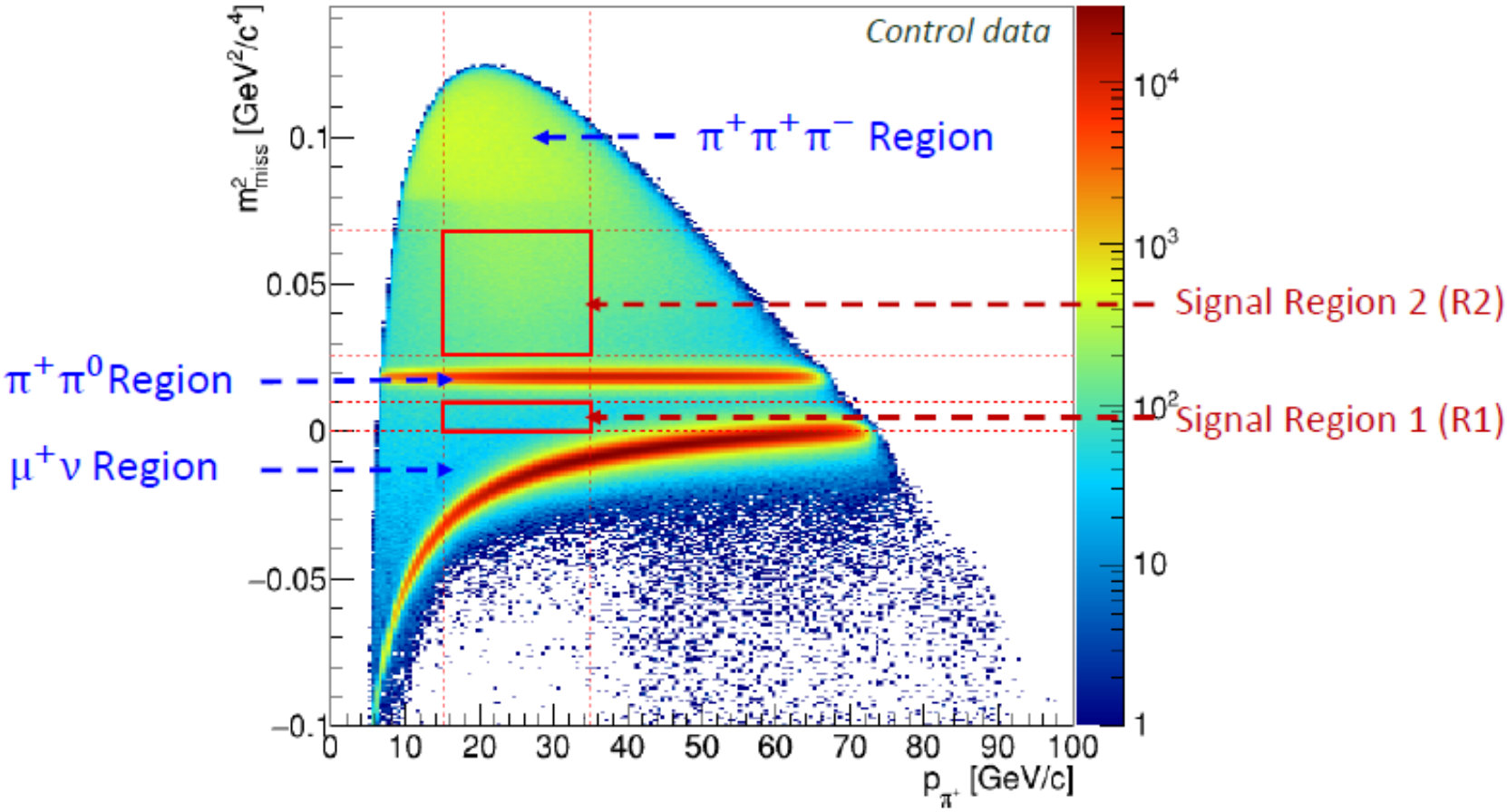
Trigger streams:

PNN: {RICH hits} x {hodoscope hits} x (no muons} x {<20 GeV in LKr}

Minimum bias: {hodoscope hits}

Signal and background regions

$$m^2_{miss} \equiv m^2_{miss}(\text{Straw}, \text{GTK}) = (P_{\pi^+} - P_{K^+})^2, \ \ m_{\pi^+} \text{ hypothesis}$$



Performance

kinematics

Fraction of events in signal regions

- $K^+ \to \pi^+\pi^0 \sim 1 \cdot 10^{-3}$ (resolution tails)
- $K^+ \to \mu^+\nu_\mu \sim 3 \cdot 10^{-4}$

Particle identification (PID)

PID	π^+ efficiency	μ^+ efficiency
Calorimeters	77%	$0.6 \cdot 10^{-5}$
RICH	80%	$2.5 \cdot 10^{-3}$

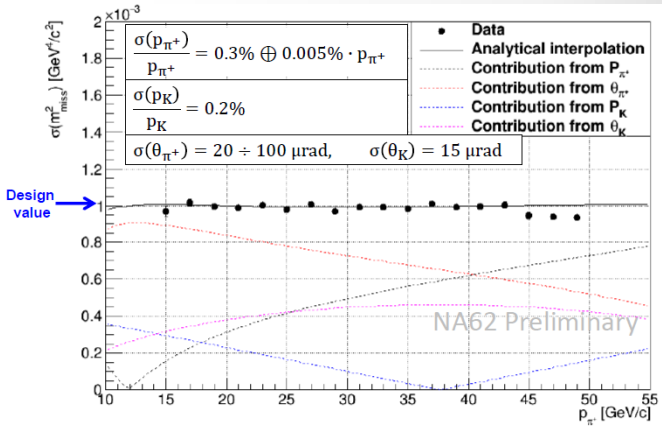
π^0 suppression

Fraction of surviving $K^+ \to \pi^+\pi^0$ (15 – 35 momentum range) : $\sim 2.5 \cdot 10^{-8}$

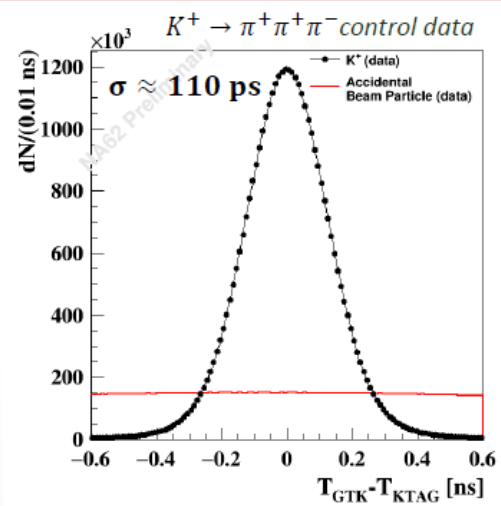
Performance requirements (recap)

$\mathcal{O}(100\ \mathrm{ps})$	Timing between sub-detectors
$\mathcal{O}(10^4)$	Background suppression from kinematics
$> 10^7$	Muon suppression
$> 10^7$	π^0 (from $K^+ \to \pi^+\pi^0$) suppression

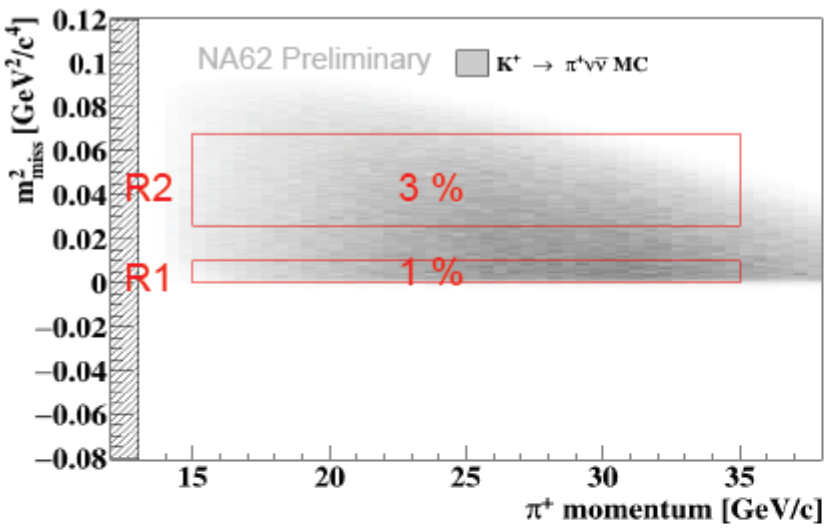
Kinematic resolution



Timing between detectors



Single event sensitivity (SES)



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

- Signal acceptance : 4 %
- Normalization acceptance : 10 %
- Control triggered $K^+ \to \pi^+\pi^0$ used for normalization
- Number of kaon decays in the fiducial volume : N_K = 1.21(2) x 10^{11}

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

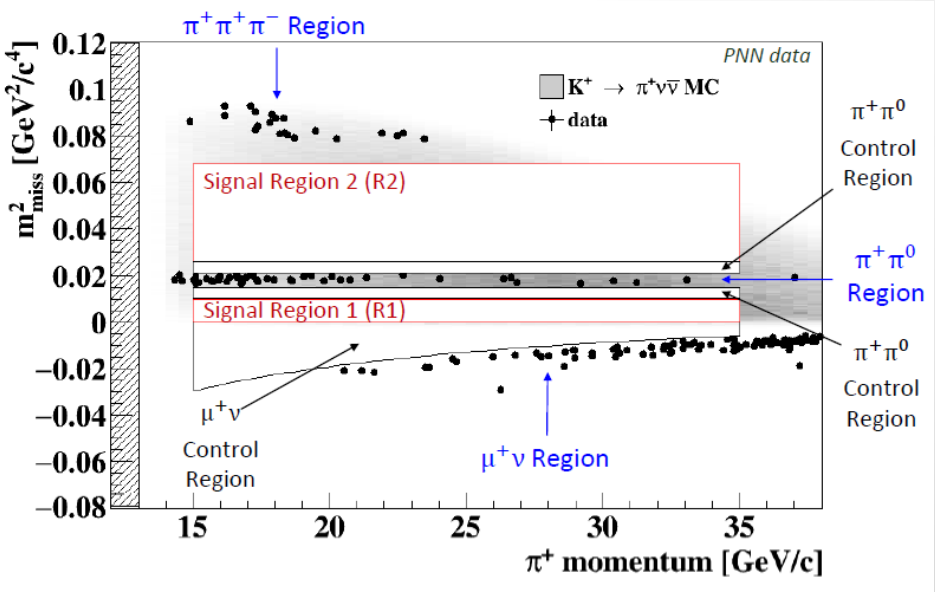
$$SES = (3.15 \pm 0.01_{stat} \pm 0.24_{syst}) \cdot 10^{-10}$$

E949 (for comparison):
N_K ~3.5x10^{12}
SES ~0.8x10^{-10}

Background studies

General approach:

- Define a background region (BkgR), measure N(BkgR)
- Define control region(s) (CR) for validation
- Data driven background estimation:
  - assume cut independence (e.g. kinematics, PID, π^0 rejection)
  - invert one of cuts (e.g. PID, π^0 rejection)
  - estimate N(CR)/N(BkgR) and N(SR)/N(BkgR) with the inverted cut
  - Calculate N(CR) and N(SR)
- Open CR and validate the estimation

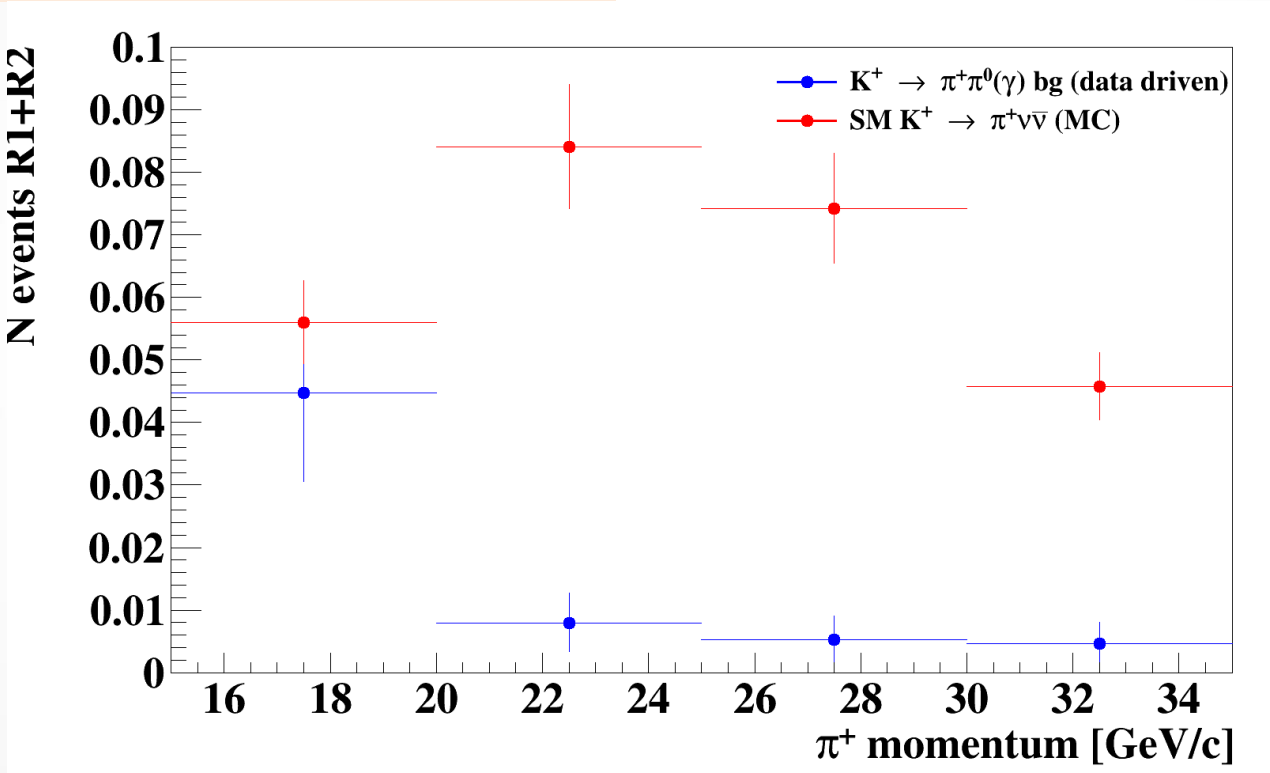


In addition:

- ✓ Split into momentum bins if necessary
- ✓ MC samples
- ✓ Bifurcation analysis (if >1 cut inverted)

$K^+ \to \pi^+\pi^0$ (K2π) background

- π^0 rejection inverted
- $N_{K2\pi}$(SR) estimated from K2π
- 4 momentum bins (5 GeV/c each)

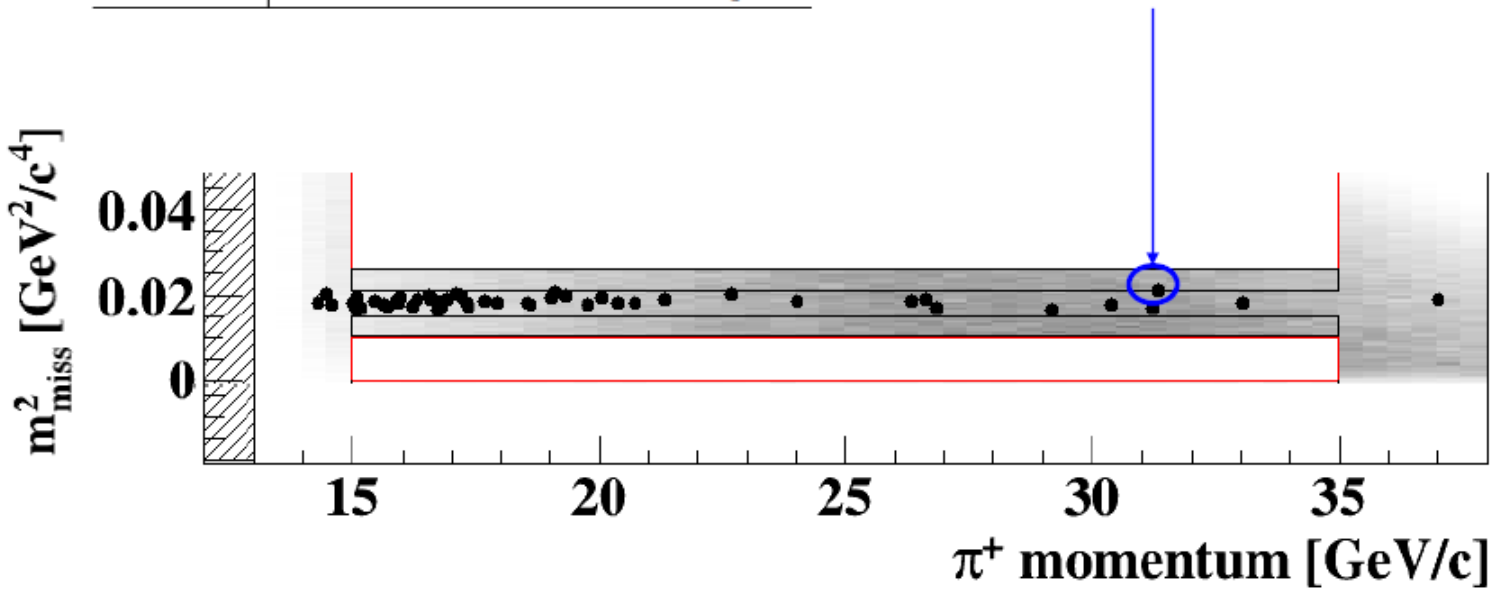


$$N^{expected}_{\pi\pi(\gamma)} = 0.064 \pm 0.007_{stat} \pm 0.006_{syst}$$

K2π background: validation

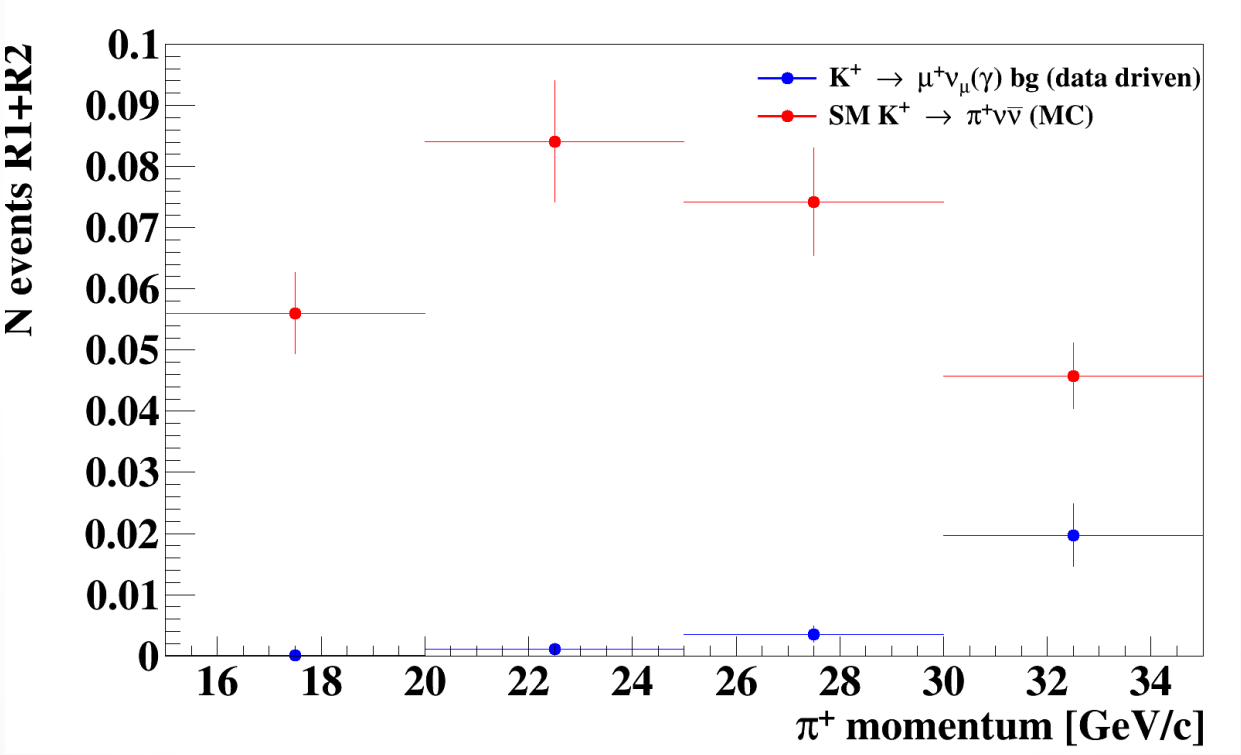
Region	$\pi^+\pi^0$
CR1	$0.52 \pm 0.08_{stat} \pm 0.03_{syst}$
CR2	$0.94 \pm 0.14_{stat} \pm 0.05_{syst}$

Events observed CR1: **0**
Events observed CR2: **1**



$K^+ \to \mu^+ \nu_\mu$ (Kμ2) background

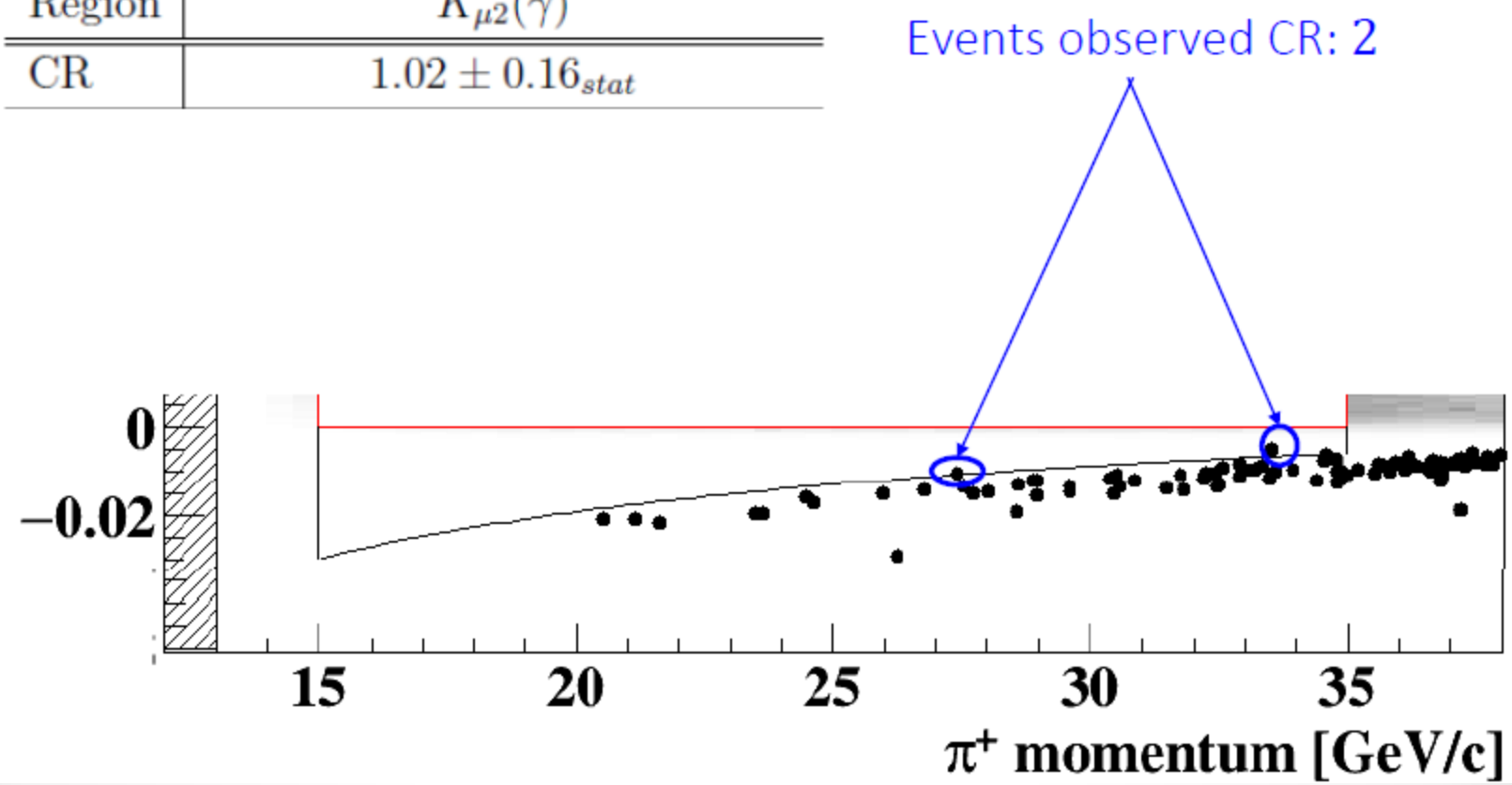
- PID inverted
- $N_{K\mu2}$(SR) estimated from Kμ2
- 4 momentum bins (5 GeV/c each)



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

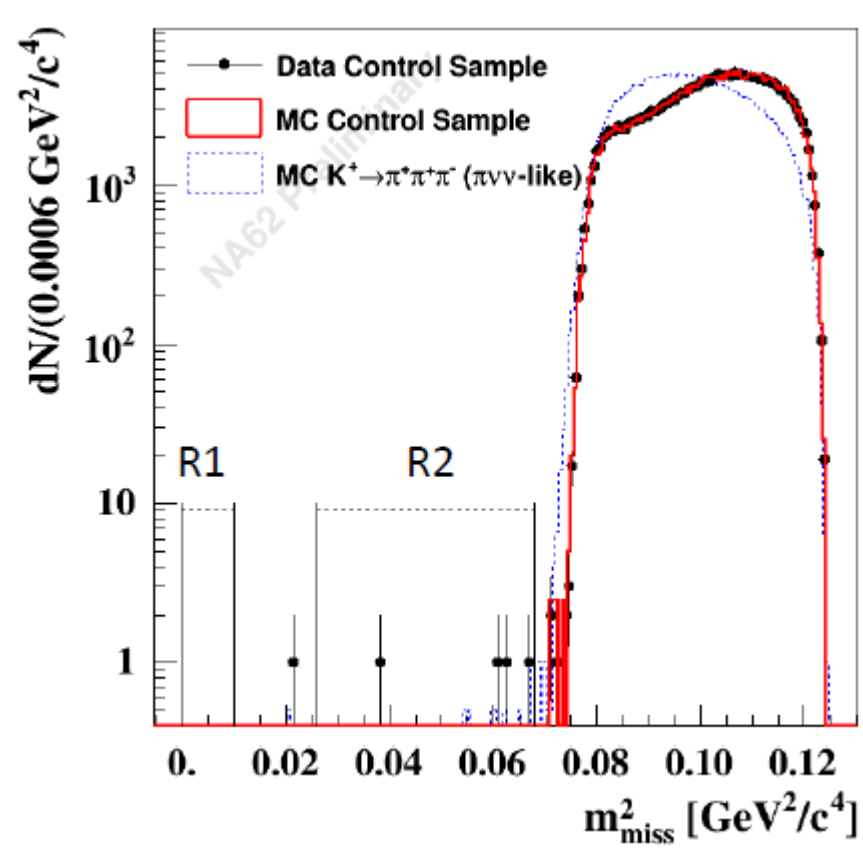
Kμ2 background: validation

Region	$K_{\mu 2}(\gamma)$
CR	$1.02 \pm 0.16_{stat}$



$K^+ \to \pi^+\pi^+\pi^-$ (K3π) background

- 1-track selection inverted
- $N_{K3\pi}$(SR) estimated from K3π with ($\pi^+\pi^-$) tagging

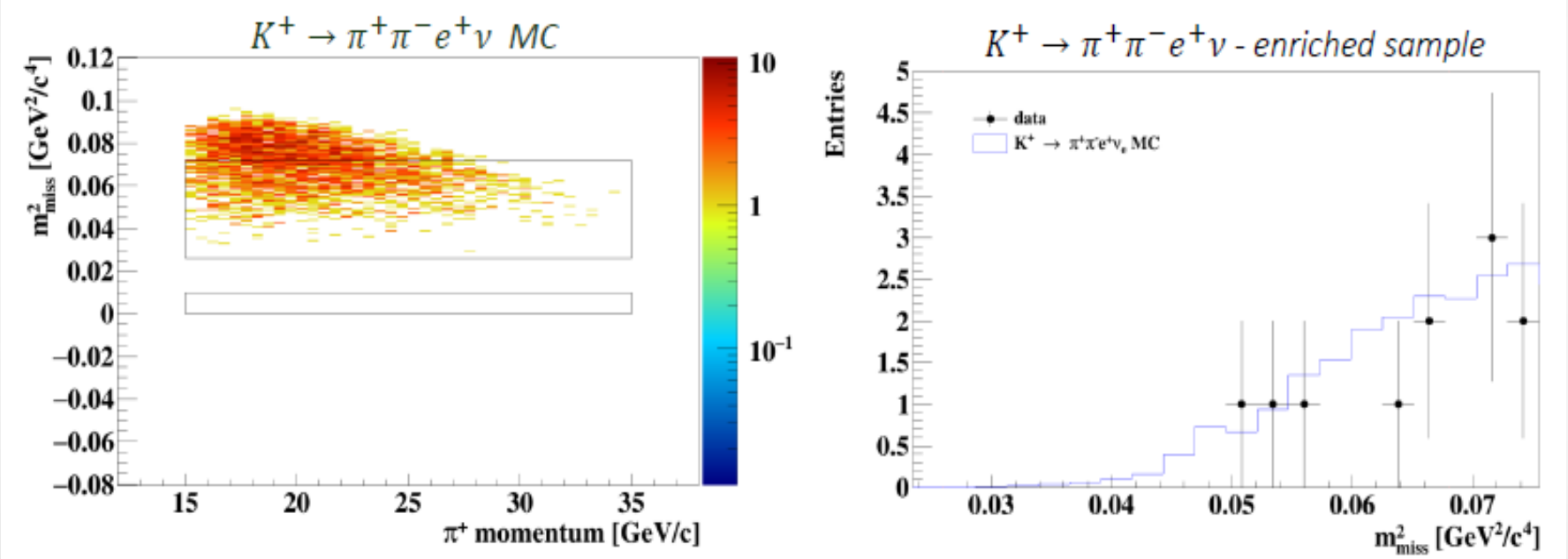


Number of expected events

$$N^{exp}_{\pi\pi\pi} = 0.002 \pm 0.001_{stat} \pm 0.002_{syst}$$

$K^+ \to e^+ \nu_e \pi^+ \pi^-$ (Ke4) background

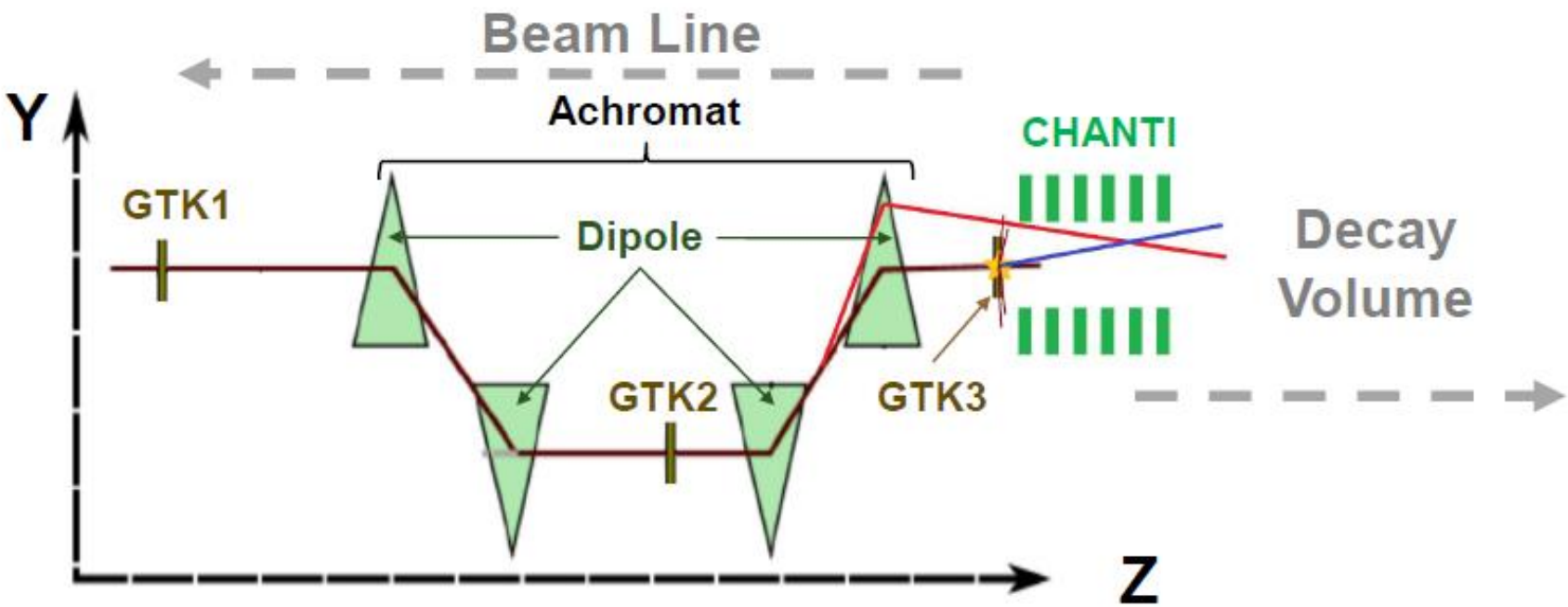
- Track charge inverted (single π^- events): for validation only
- N_{Ke4}(SR) estimated from MC
- Control region for MC validation: $0.026 < m^2_{miss} < 0.072$ GeV^2/c^4



$$N^{expected}_{\pi\pi e\nu} = 0.018^{+0.024}_{-0.017}|_{stat} \pm 0.009_{syst}$$

Upstream background

- Decays along the beam line; beam particle interactions in GTK
- Random track matched in GTK and/or possible additional energy not detected



- Specific cuts against upstream background

1) $K - \pi$ matching 2) Z_{vertex} 3) CHANTI veto

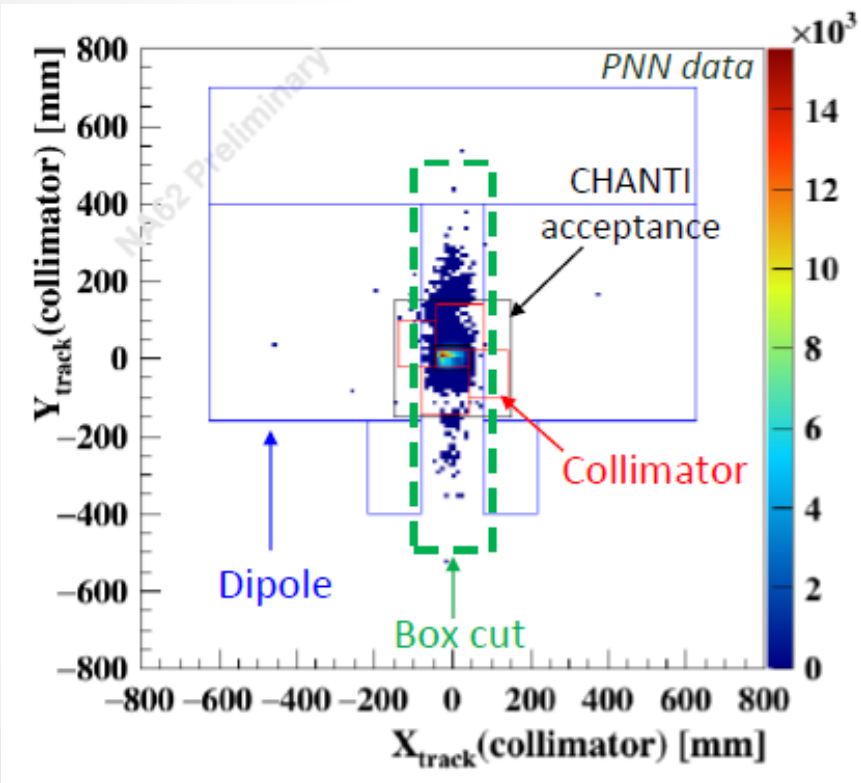
4) Cut on X,Y π^+ at the entrance of the decay volume («Box cut»)

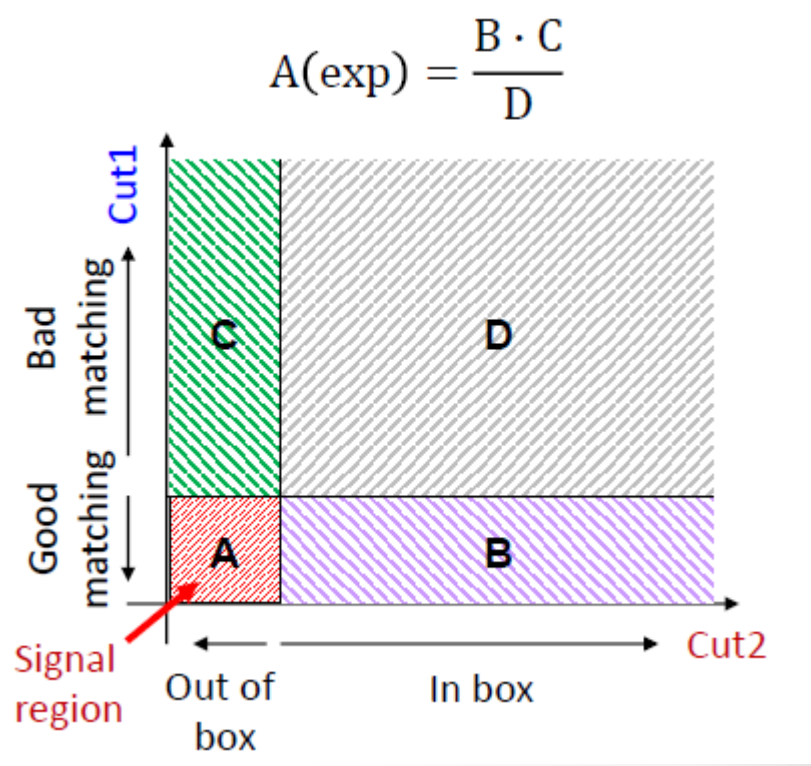
Upstream background

- 2 cuts inverted: K-π matching, Box cut
- Cuts on Z_{vertex} and CHANTI not applied
- $N_{upstream}$(SR) estimated from bifurcation method

Bifurcation on PNN triggered data inverting:

K – π matching (cut1); Cut box (cut2)





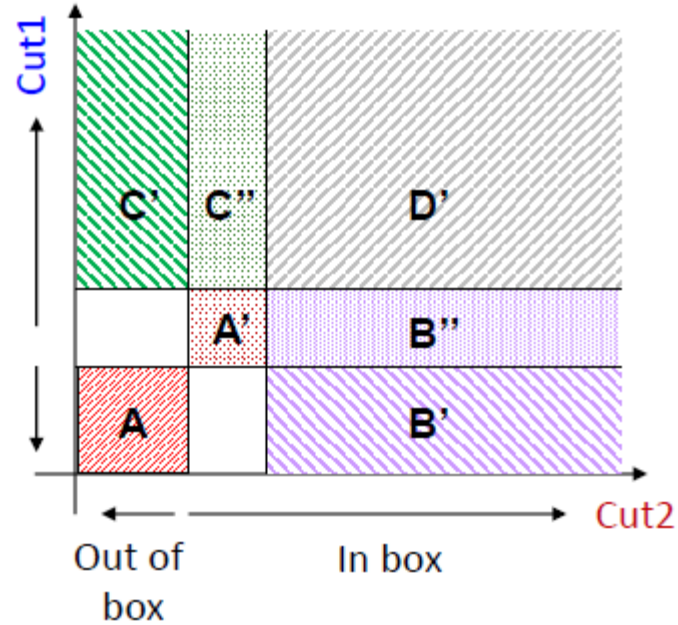
$$N^{exp}_{upstream} = 0.050^{+0.090}_{-0.030}|_{stat}$$

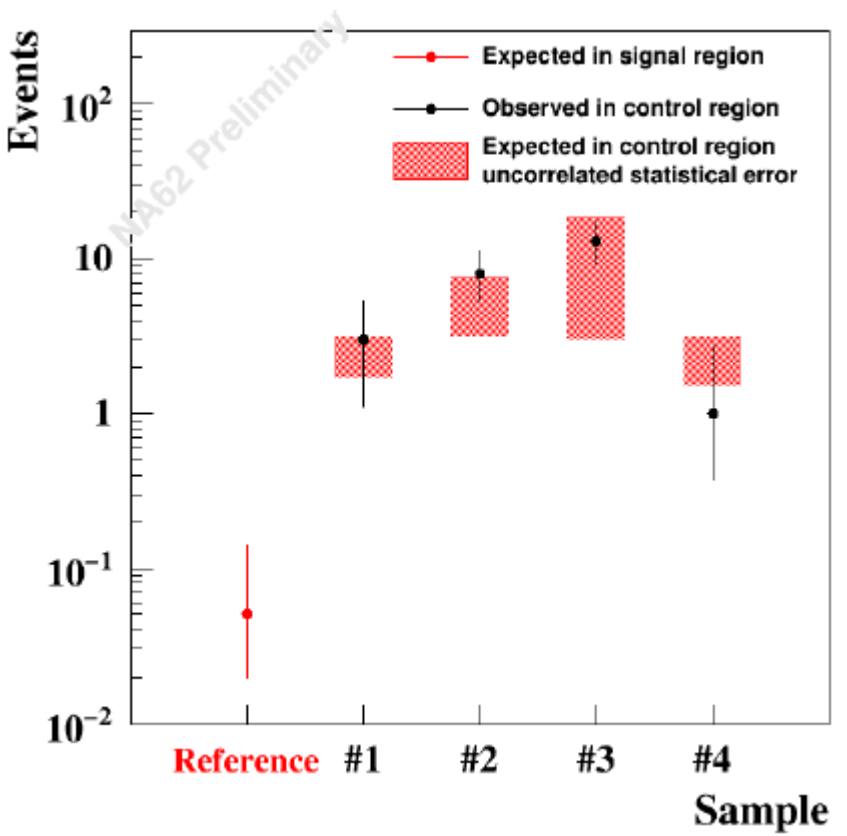
Upstream background: validation

A': control region

B'C'D'B''C'': control samples

$$A(\exp) = \frac{B' \cdot C'}{D'} \qquad A'(\exp) = \frac{B'' \cdot C''}{D'}$$

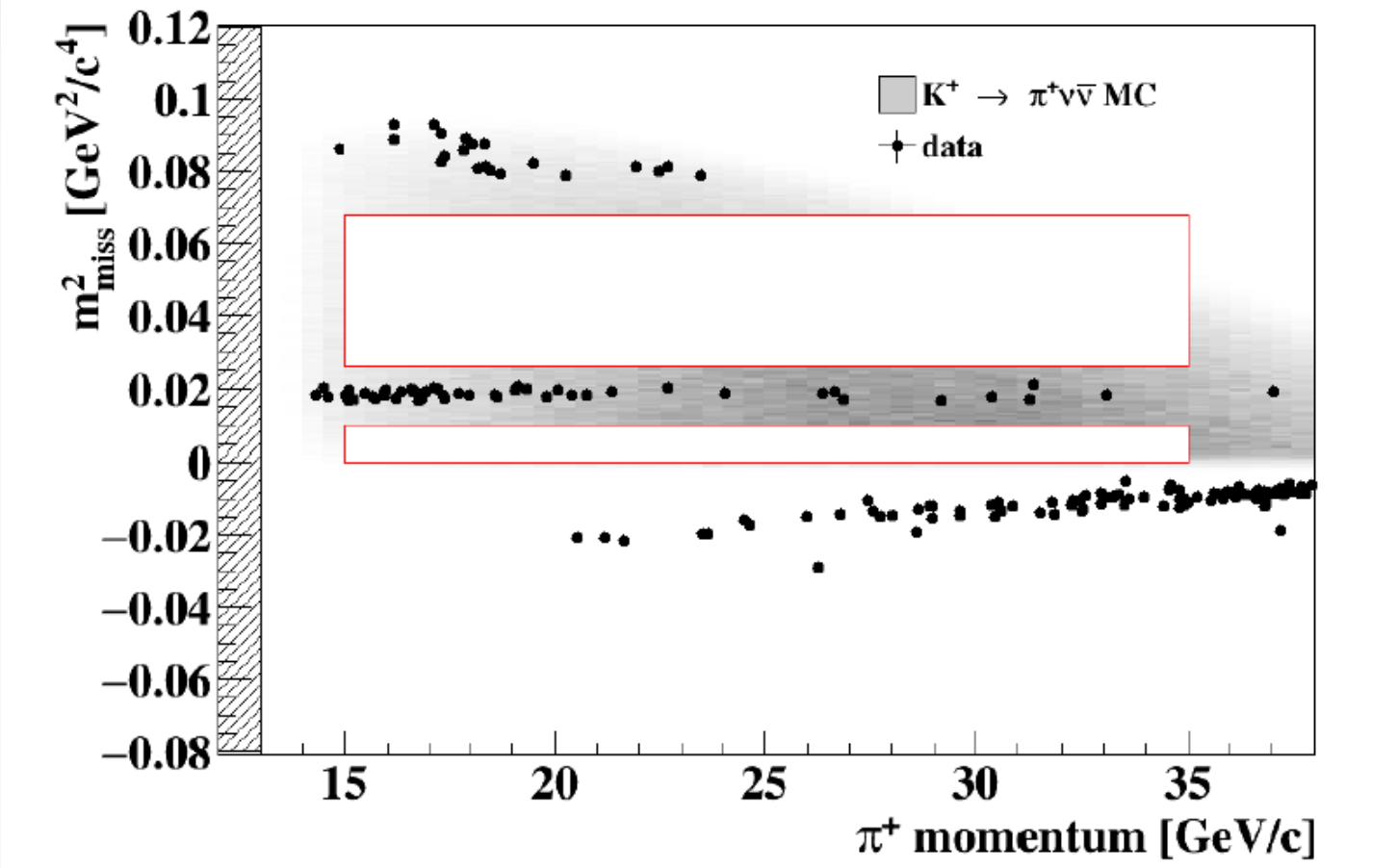




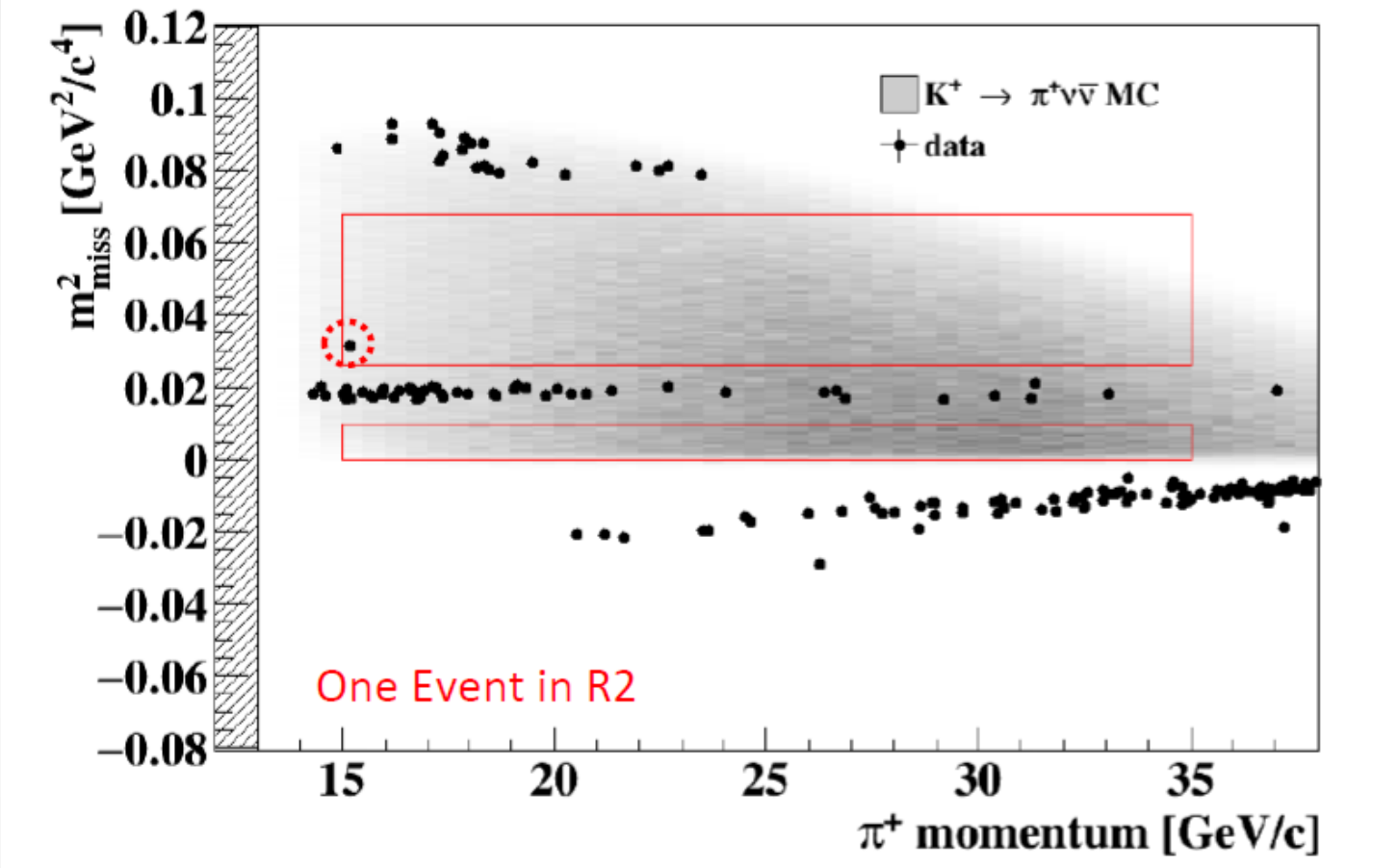
Background summary

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

Unblinding Signal Regions



Unblinding Signal Regions



Upper limit setting (Rolke-Lopez method):

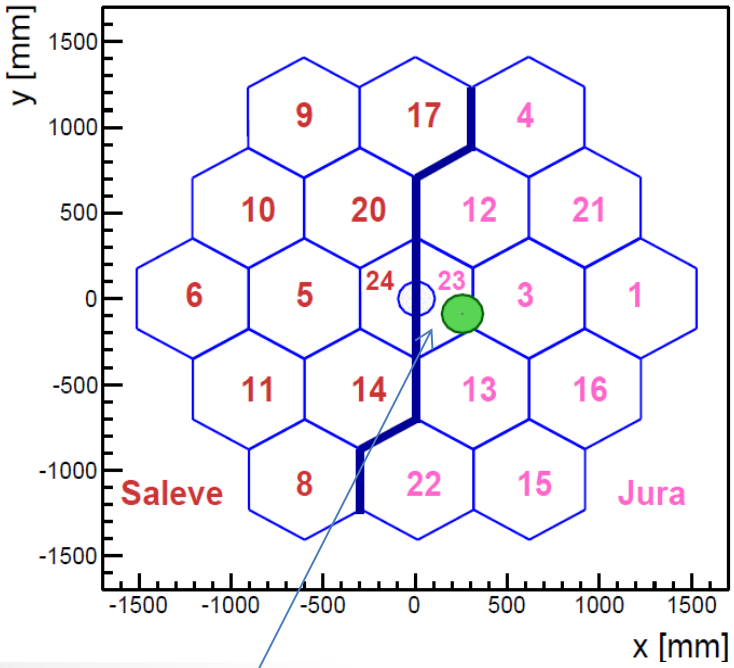
- Poissonian signal
- Gaussian background

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

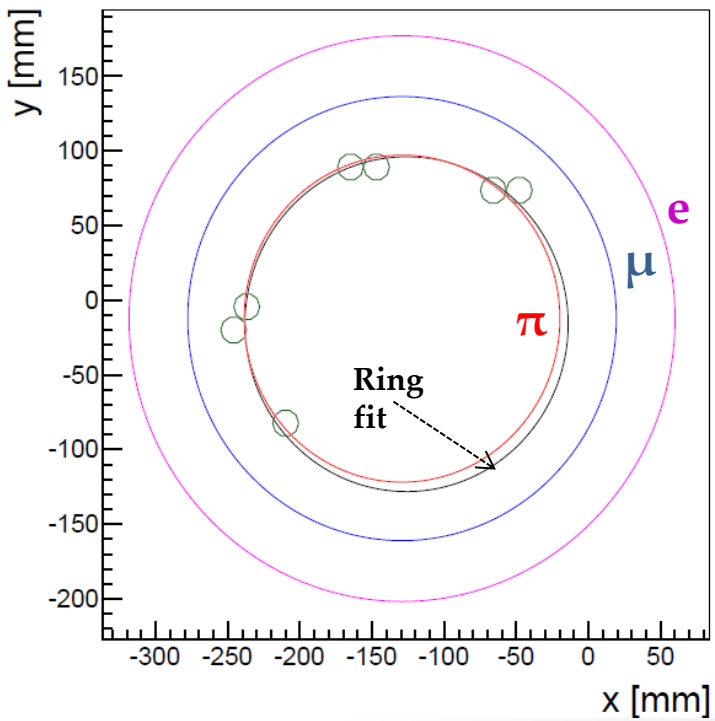
$$BR(K^+ \to \pi^+\nu\bar{\nu}) < 14 \times 10^{-10} \text{ @ } 95\% \; CL$$

The Event in the RICH

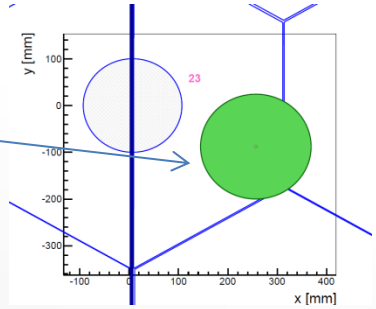
Pion track at the RICH mirror plane



Ring reconstruction at the PM plane



Area illuminated by
the Cherenkov light



Summary

$K^+ \to \pi^+ \nu\nu$ search at NA62 with 2016 data:

- SES = 3.15(01)(24) x 10^{-10}
- One event observed in Region 2
- Results are compatible with SM
- Upper limits (Rolke-Lopez method):

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

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

For comparison:

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

$$BR(K^+ \to \pi^+ \nu\bar{\nu})_{exp} = (17.3^{+11.5}_{-10.5}) \times 10^{-11} \text{ (BNL, "kaon decays at rest")}$$

Prospects

2017 data: processing ongoing

- Statistics: 20 times more than in 2016
- Better upstream background reduction expected
- Methods to improve signal efficiency under investigation

2018 data: data taking ongoing

- Further mitigation of the upstream background expected
- Processing parallel to data taking for monitoring the data quality
- Expected final reprocessing: early 2019

2017+2018 data sample:

- **Expected 20 SM events**
- Input to the European Strategy for Particle Physics
- Extrapolation to the NA62 sensitivity in 2021-2023

Spare

Correlations with flavor physics

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

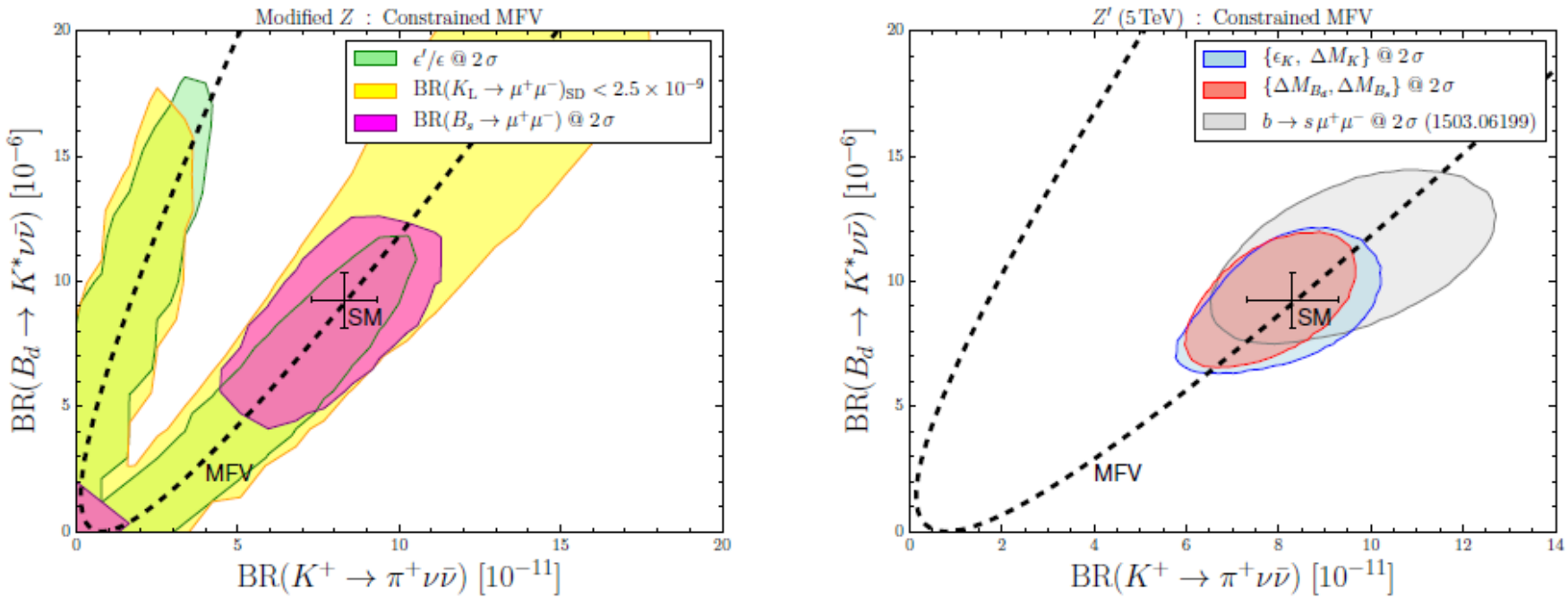


Figure 4: *Allowed ranges for $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ versus $\mathcal{B}(B_d \to K^*\nu\bar{\nu})$ in a simplified Z model (left panel) and a 5 TeV Z' model (right panel) obeying CMFV. In the left panel the 2σ confidence regions shown correspond to constraints from ϵ'/ϵ (green), $K_L \to \mu^+\mu^-$ (yellow) and $B_s \to \mu^+\mu^-$ (magenta), while in the right panel they correspond to constraints from kaon mixing (blue), B mixing (red) and $b \to s\mu^+\mu^-$ transitions (grey) (from [68]).*