

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$: First Result from the NA62 Experiment

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2018 Vulcano Workshop

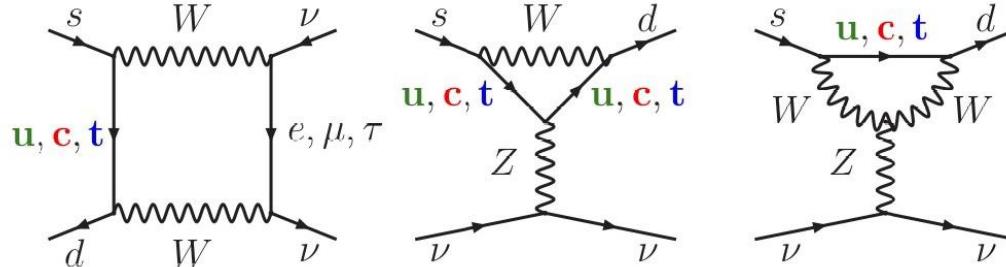
Vulcano, 25/05/2018

Content

- The NA62 Experiment at CERN
- $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

The $K \rightarrow \pi v\bar{v}$ decays: a theoretical clean environment

- FCNC loop processes: $s \rightarrow d$ coupling and highest CKM suppression



- Very clean theoretically: Short distance contribution. No hadronic uncertainties.
- SM predictions [Buras et al. JHEP 1511 (2015) 33]

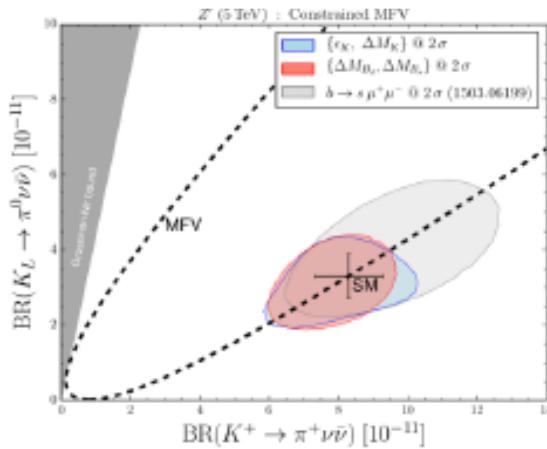
$$\text{BR}(K^+ \rightarrow \pi^+ v\bar{v}) = (8.39 \pm 0.30) \cdot 10^{-11} \left(\frac{|V_{cb}|}{0.0407} \right)^{2.8} \left(\frac{\gamma}{73.2^\circ} \right)^{0.74} = (0.84 \pm 0.10) \cdot 10^{-10}$$

$$\text{BR}(K_L \rightarrow \pi^0 v\bar{v}) = (3.36 \pm 0.05) \cdot 10^{-11} \left(\frac{|V_{ub}|}{0.00388} \right)^2 \left(\frac{|V_{cb}|}{0.0407} \right)^2 \left(\frac{\sin \gamma}{\sin 73.2} \right)^2 = (0.34 \pm 0.06) \cdot 10^{-10}$$

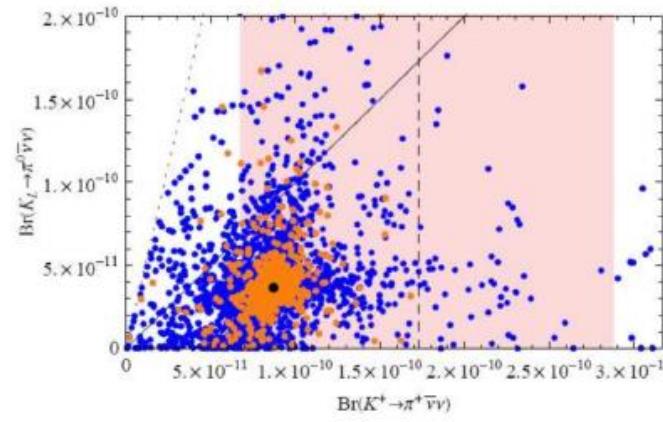
$K \rightarrow \pi\nu\bar{\nu}$ NP Sensitivity

- Simplified Z, Z' models [Buras, Buttazzo,Knegjens, JHEP 1511 (2015) 166]
- Littlest Higgs with T-parity [Blanke, Buras, Recksiegel, EPJ C76 (2016) no.4 182]
- Custodial Randall-Sundrum [Blanke, Buras, Duling, Gemmeler, Gori, JHEP 0903 (2009) 108]
- MSSM non-MFV [Tanimoto, Yamamoto, PTEP 2016 (2016) no.12, 123B02; Blazek, Mata, IntJModPhys.A 29 (2014), 1450162; Isidori et al. JHEP 0608 (2006) 064]
- LFU violation models [Isidori et. al., Eur. Phys. J. C (2017) 77]
- Constraints from existing measurements (correlations model dependent):
 - Kaon mixing and CPV, CKM fit, K,B rare meson decays, NP limits from direct searches

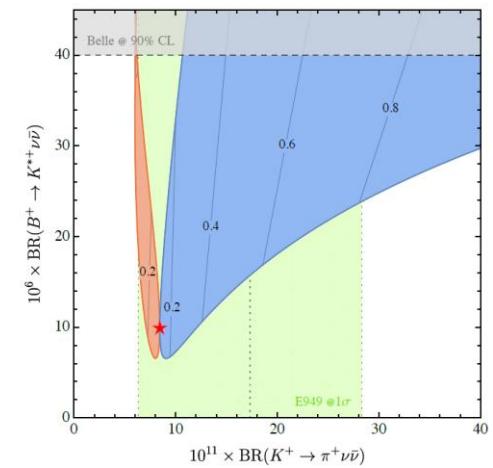
Z' (5 TeV) in constrained MFV



Randall - Sundrum

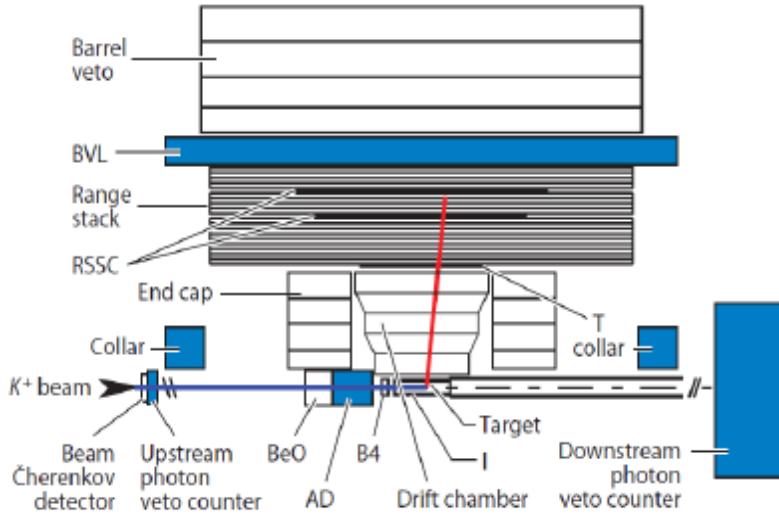


LFU violation

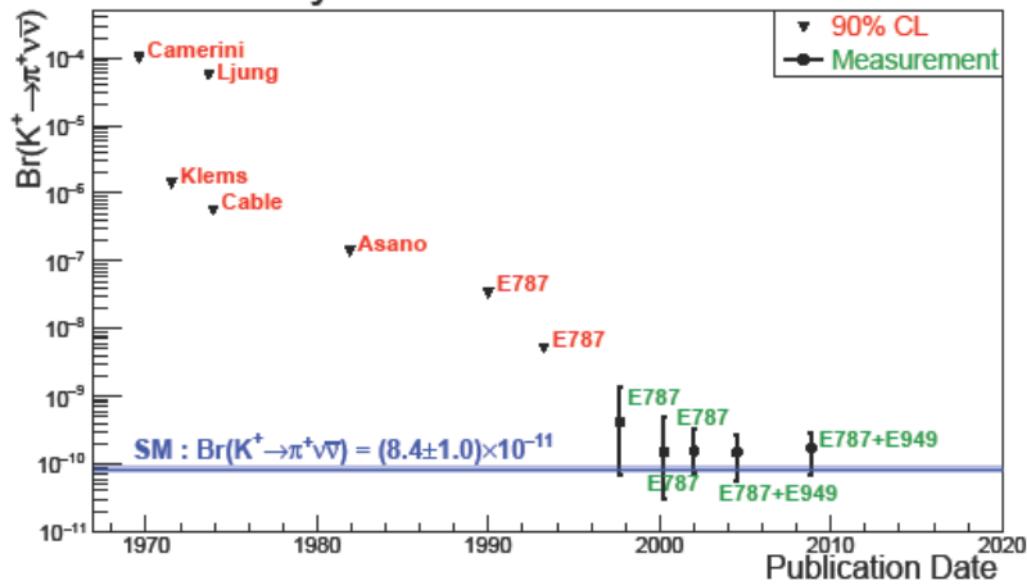


$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ Experimental State of the Art

BNL E787/E949



History of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ Measurement



- «Kaon decay at rest» technique
- E787+E949: K^+ decays: $\sim 3.5 \times 10^{12}$, Single Event Sensitivity: $\sim 0.8 \cdot 10^{-10}$

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

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



NA62 @ CERN - SPS

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



Primary goal:

Measurement of $\text{BR}(\text{K}^+ \rightarrow \pi^+ v\bar{v})$

Technique:

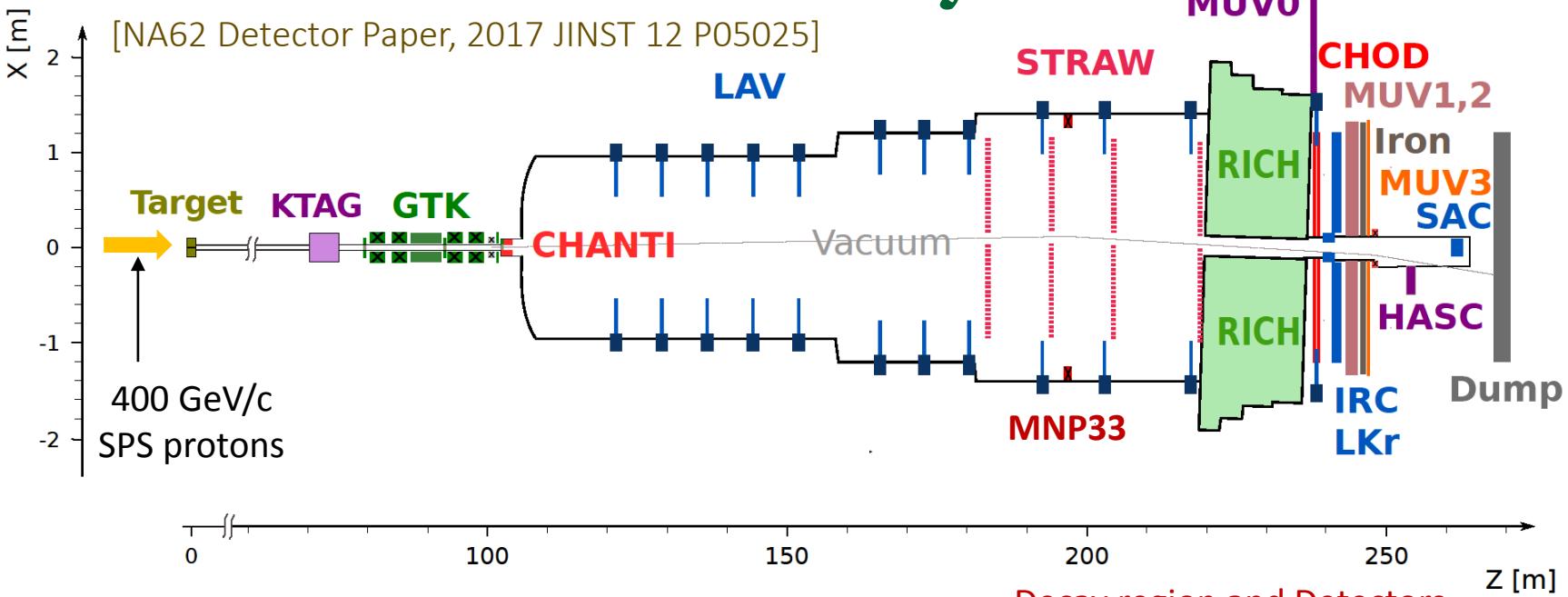
K Decay – in – flight

Requirements:

- K decays 10^{13}
- Signal acceptance $\mathcal{O}(10\%)$
- $\mathcal{O}(10^{12})$ background rejection

Broader Physics program

NA62 Layout



Secondary positive beam

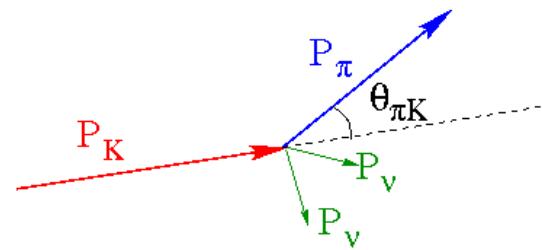
Momentum	$75 \text{ GeV}/c$, 1% bite
Divergence (RMS)	$100 \mu\text{rad}$
Transverse Size	$60 \times 30 \text{ mm}^2$
Composition	$\text{K}^+(6\%)/\pi^+(70\%)/\text{p}(24\%)$
Nominal Intensity	$33 \times 10^{11} \text{ ppp}$ (750 MHz at GTK3)

Decay region and Detectors

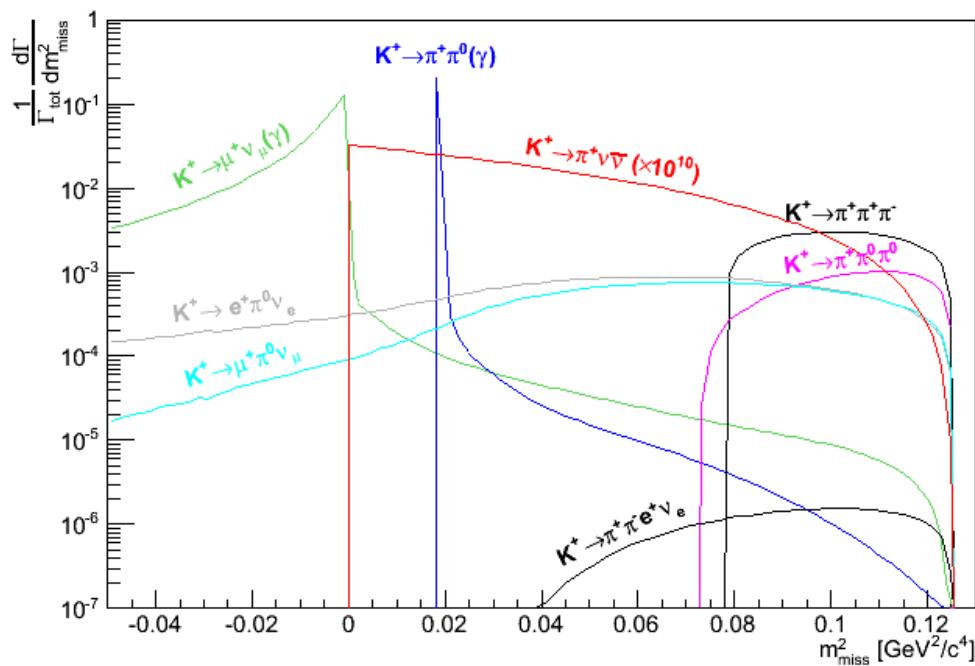
Fiducial region	60 m
K^+ decay rate	$\sim 5 \text{ MHz}$
Vacuum	$\mathcal{O}(10^{-6}) \text{ mbar}$
Si pixel beam tracker + Straw tracker	
LKr Calorimeter from NA48	
Cerenkov counter for K id, RICH for π/μ id	

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ Decay-in-flight @ NA62

$$m_{\text{miss}}^2 = (P_{K^+} - P_{\pi^+})^2$$



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

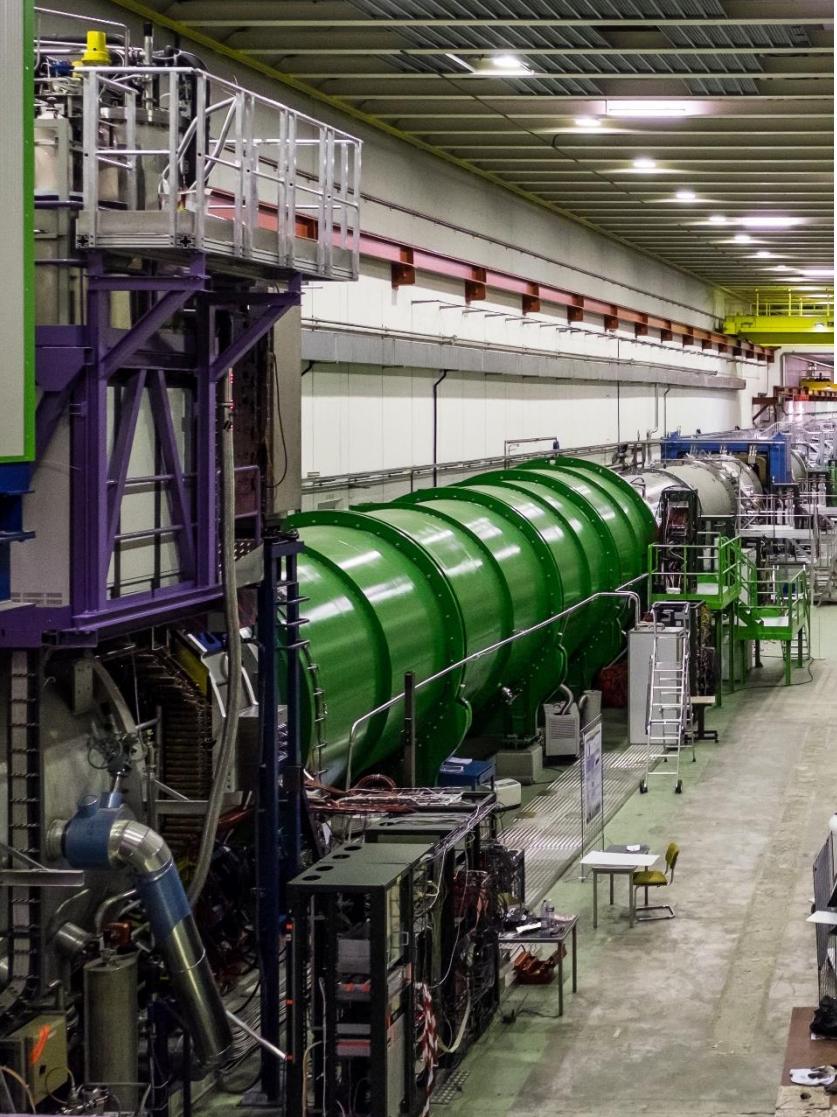


$15 < P_{\pi^+} < 35 \text{ GeV}/c$
 +
 Particle ID (Cherenkov detectors)
 Particle ID (Calorimeters)
 Photon veto

Cornerstones

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

NA62 Runs

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- 2014 Pilot run
 - 2015 Commissioning run
 - 2016 Commissioning + Physics run (30 days)
 - 2017 Physics run (160 days)
 - 2018 217 days Physics run scheduled, on-going

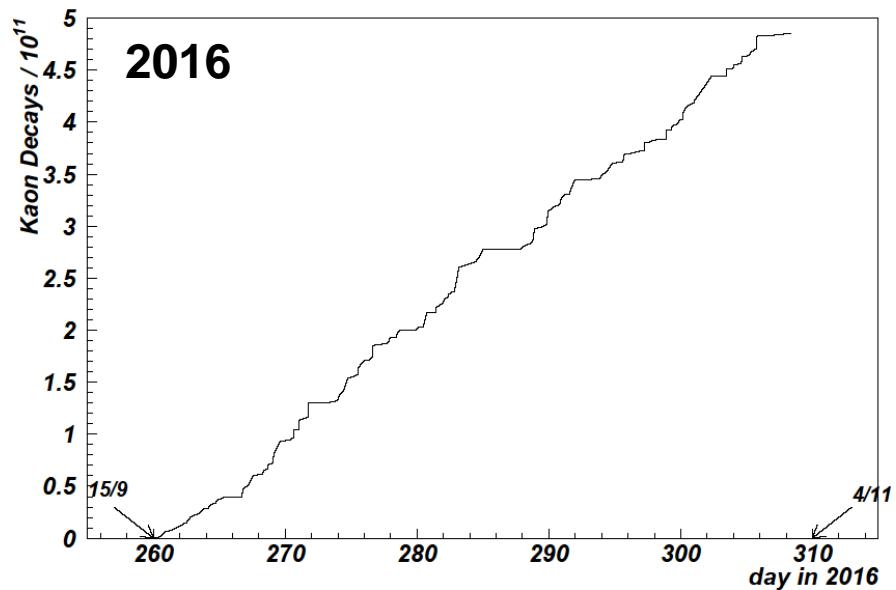
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$: Data Analysed

- 2016 Data
 - 13×10^{11} ppp on target (40% nominal)
 - $\sim 1 \times 10^{11}$ K^+ decays useful for $\pi \nu \bar{\nu}$
 - 35-40% of nominal intensity

- Trigger streams: «PNN», «Control»

- Offline Analysis:

- Data samples: PNN; Control: $K^+ \rightarrow \pi^+ \pi^0$, $K^+ \rightarrow \mu^+ \nu$, $K^+ \rightarrow \pi^+ \pi^+ \pi^-$
- Blind analysis procedure: signal and control regions kept masked for the whole analysis



$K^+ \rightarrow \pi^+ \nu \bar{\nu}$: Analysis Steps

1. Selection
2. Determination of the Single Event Sensitivity (SES)
3. Estimation and validation of the expected background
4. Un-blinding of the signal regions and results

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

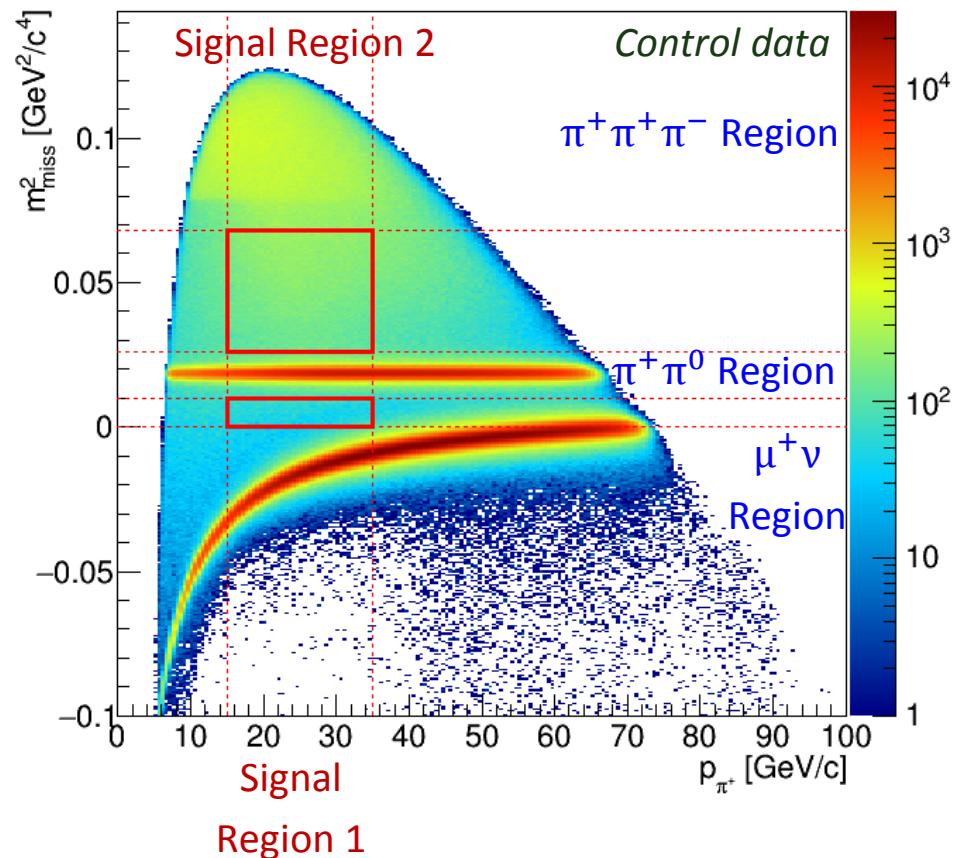
Selection

- K^+ - π^+ matching
- K^+ decays in the decay volume
- π^+ identification
- photon rejection
- Multi track rejection

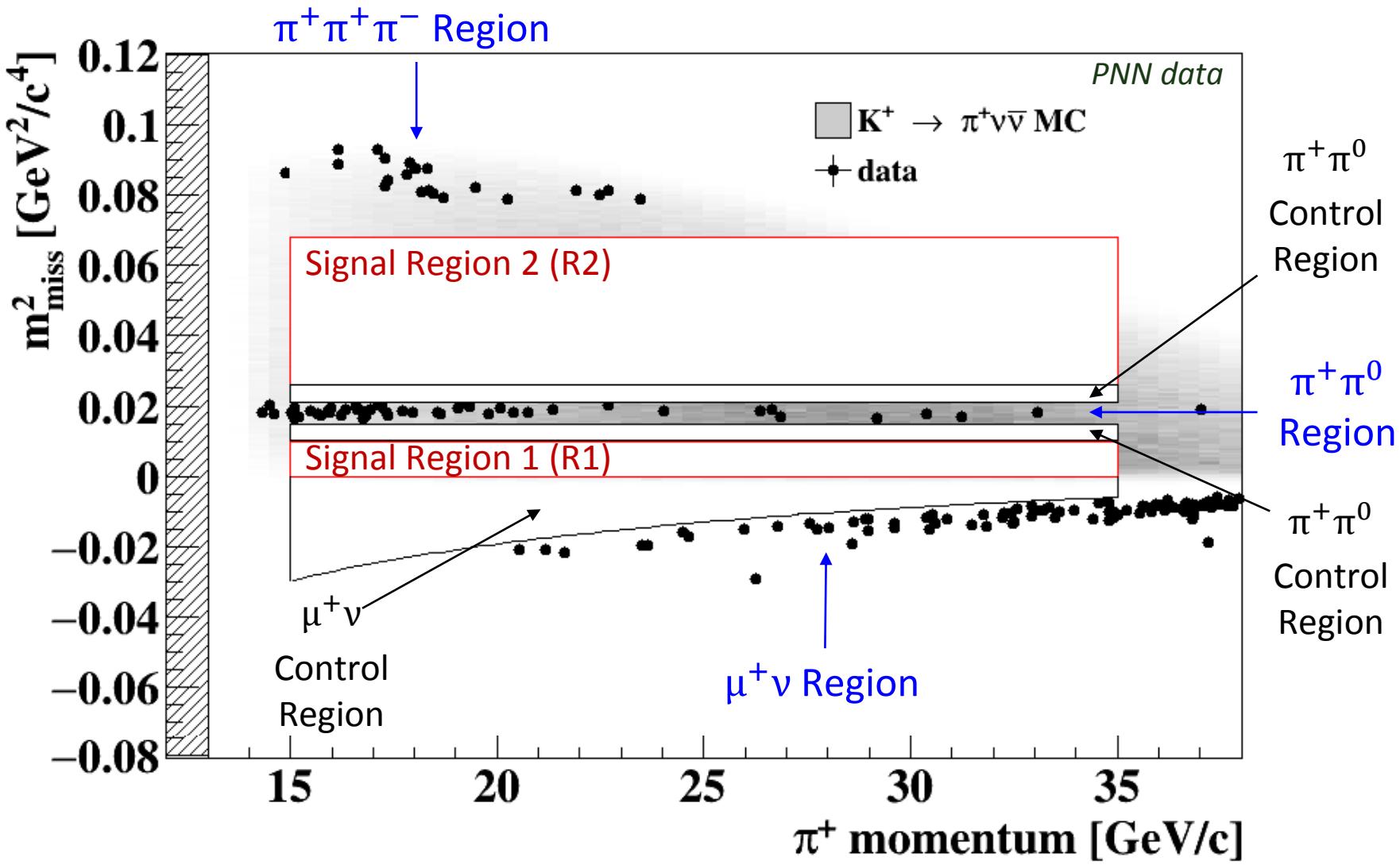
Performances (measured on data)

- GTK-KTAG-RICH timing: $\mathcal{O}(100 \text{ ps})$
- π^+ ID: $\varepsilon_\mu = 10^{-8}$, $\varepsilon_{\pi^+} \sim 64\%$
- γ/multi rejection: $\varepsilon_{\pi^0} = 2.5 \cdot 10^{-8}$
- $\sigma(m_{\text{miss}}^2) \sim 10^{-3} \text{ GeV}^2/c^4$

Selected K^+ decays, before
 π^+ id and γ/multi rejection



Data After Selection



Single Event Sensitivity (SES)

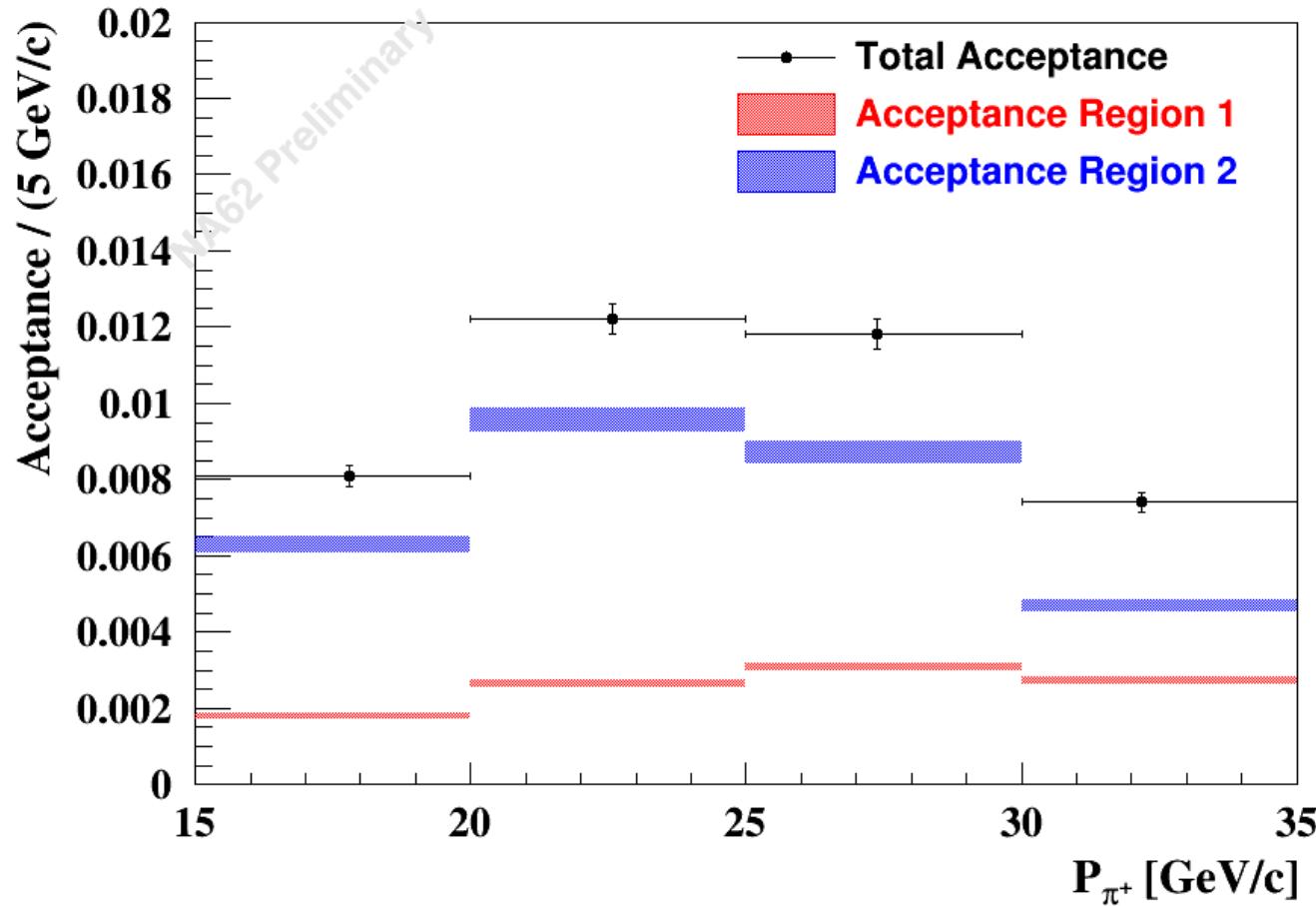
- Nr. of K^+ decays from $K^+ \rightarrow \pi^+\pi^0$ selected on control data (downscaled D=400)
- Same $\pi^+\nu\bar{\nu}$ selection: γ , multiplicity rejection not applied; m_{miss}^2 cuts modified

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

Number of K^+ Decays	$N_K = (1.21 \pm 0.02) \times 10^{11}$
Acceptance $K^+ \rightarrow \pi^+\nu\bar{\nu}$	$A_{\pi\nu\nu} = 0.040 \pm 0.001$
PNN trigger efficiency	$\epsilon_{trig} = 0.87 \pm 0.02$
Random veto	$\epsilon_{RV} = 0.76 \pm 0.04$
SES	$(3.15 \pm 0.01_{stat} \pm 0.24_{syst}) \times 10^{-10}$
Expected SM $K^+ \rightarrow \pi^+\nu\bar{\nu}$	$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$

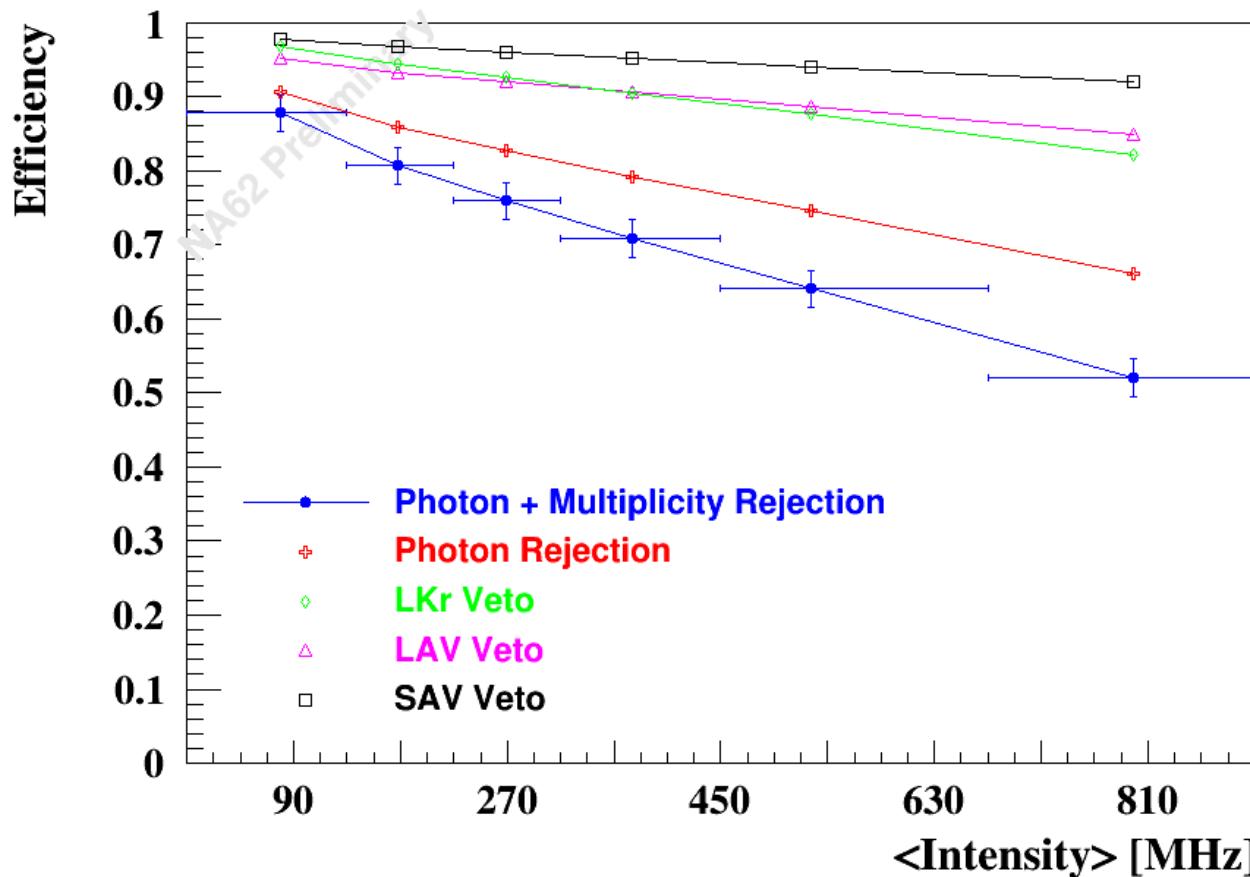
SES: Signal Acceptance

- Computed with MC
- Particle ID, losses due to π^+ interaction included

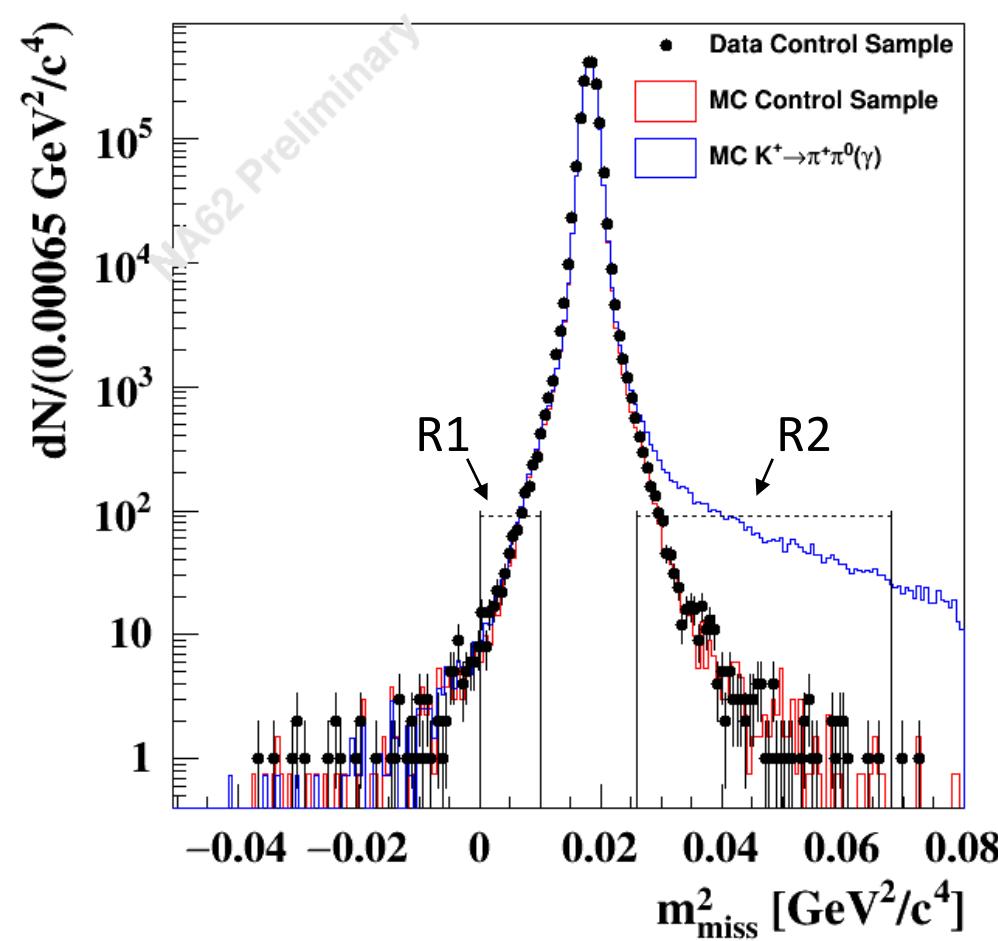


SES: Random Veto

- Random signal losses due to $\gamma +$ multiplicity rejection measured with $K^+ \rightarrow \mu^+ \nu$
- $\langle \epsilon_{RV} \rangle = 0.76 \pm 0.04$ independent from P_{π^+} , dependent on instantaneous intensity



$K^+ \rightarrow \pi^+ \pi^0(\gamma)$ Background

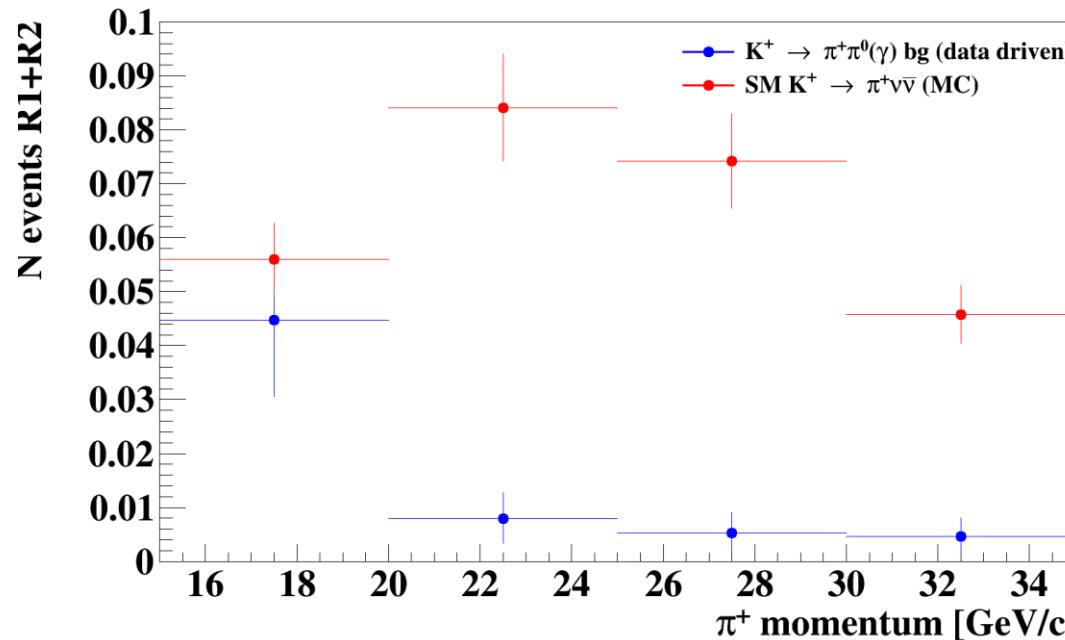


$$N_{\pi\pi}^{\text{exp}}(\text{region}) = N(\pi^+ \pi^0) \cdot f^{\text{kin}}(\text{region})$$

- Kinematic rejection independent from photon rejection
- $N(\pi^+ \pi^0)$: events (data) in $\pi^+ \pi^0$ region after $\pi^+ \nu \bar{\nu}$ selection
- f^{kin} : tails, from $\pi^+ \pi^0$ control sample selected on data tagging the π^0
- $f^{\text{kin}}(R1 + R2) \sim 10^{-3}$ [not radiative]
- Radiative: $\pi^0 + \gamma \rightarrow \times 30 \pi^0$ rejection in R2

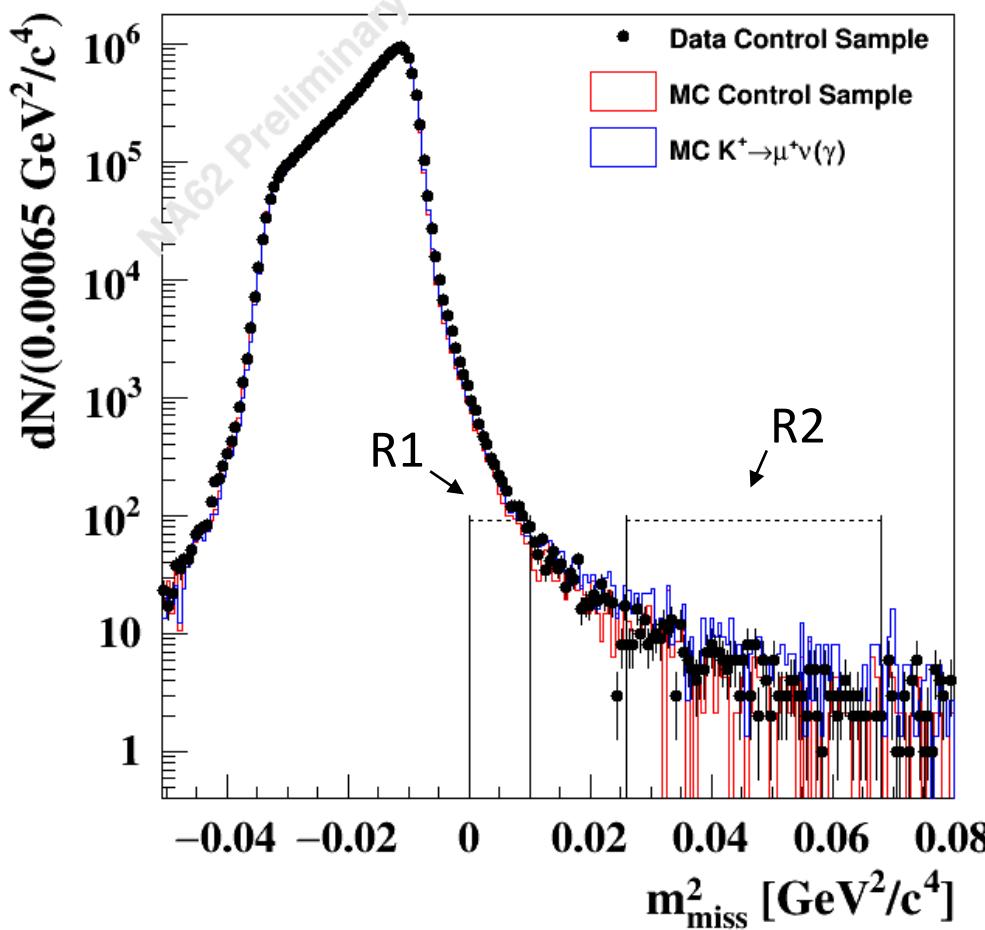
$K^+ \rightarrow \pi^+\pi^0(\gamma)$ Background: Result

$$N_{\pi\pi(\gamma)}^{expected} = 0.064 \pm 0.007_{stat} \pm 0.006_{syst} \quad (< 10\% \text{ Radiative})$$



Expected control regions: 1.46 ± 0.17 → Observed 1

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

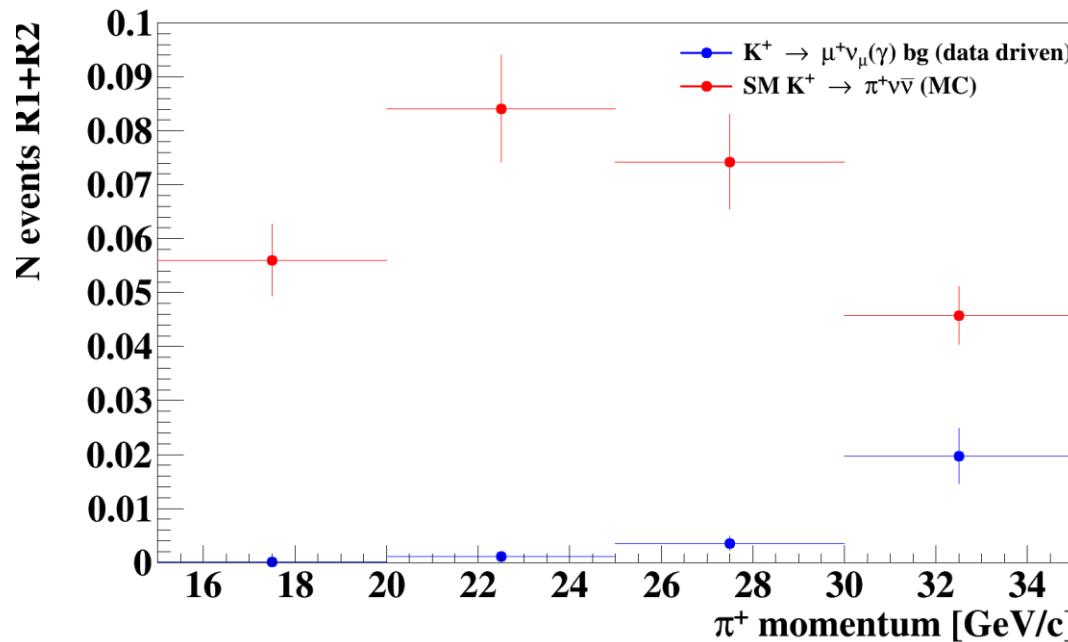


$$N_{\mu\nu}^{\text{exp}}(\text{region}) = N(\mu^+\nu) \cdot f^{\text{kin}}(\text{region})$$

- Kinematic rejection independent from particle identification
- $N(\mu^+\nu)$: events (data) in $\mu^+\nu$ region after $\pi^+\bar{\nu}\nu$ selection
- f^{kin} : tails, from $\mu^+\nu$ control sample selected on data with μ^+ – ID in calo
- $f^{\text{kin}}(R1) \sim 10^{-5}, 10^{-3} [15, 35] \text{ GeV}/c$
- $f^{\text{kin}}(R2) \sim \mathcal{O}(10^{-5})$
- Radiative included in f^{kin}

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

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

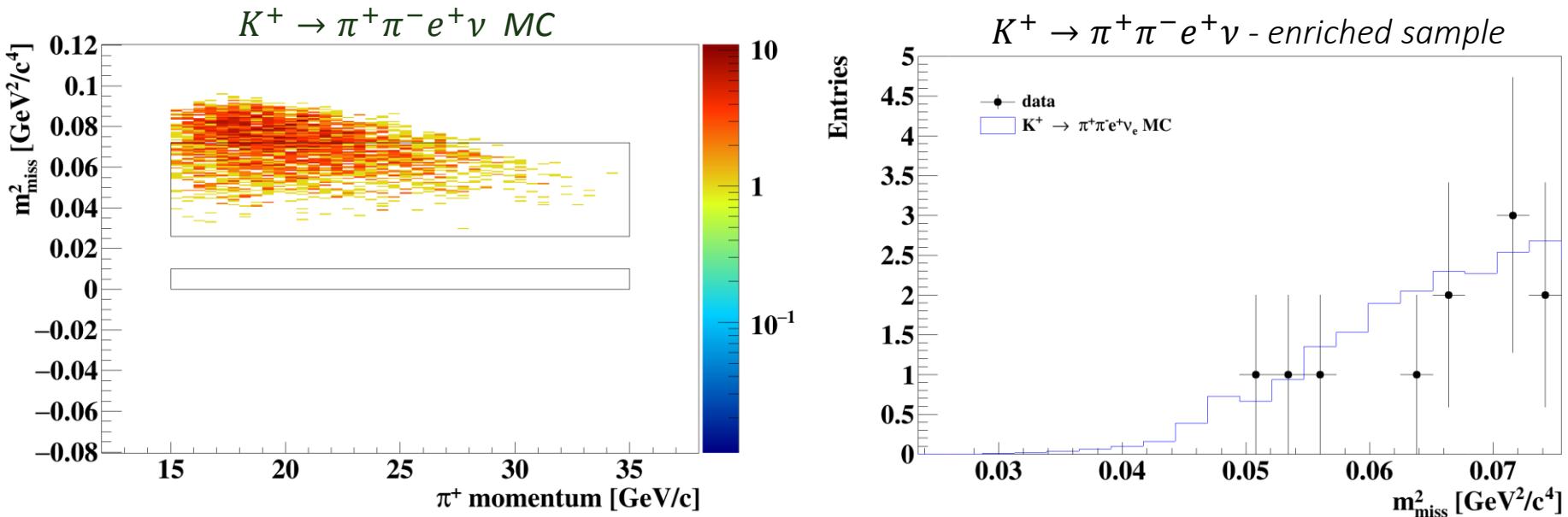


Expected control regions: $1.02 \pm 0.16 \rightarrow$ Observed 2

$K^+ \rightarrow \pi^+\pi^-e^+\nu$ Background

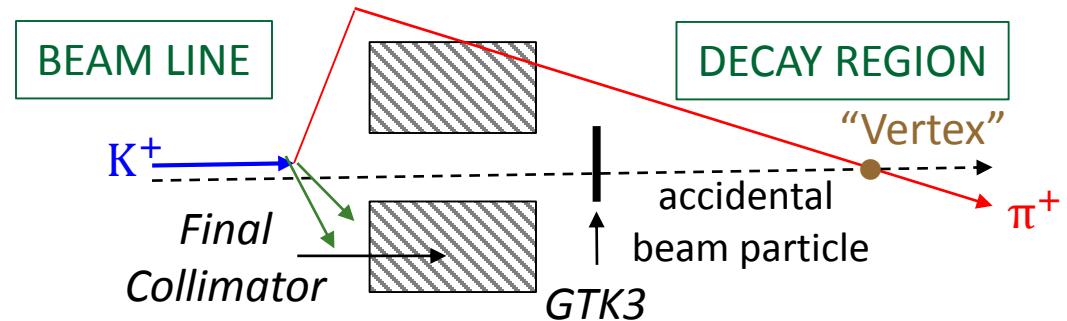
- Measured branching ratio $4.247(24) \times 10^{-5}$
- Kinematics spanning R2, correlated with topology
- Background estimated using MC ($\sim 4 \times 10^8$ events generated)
- MC validated on data using control samples $K^+ \rightarrow \pi^+\pi^-e^+\nu$ - enriched

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

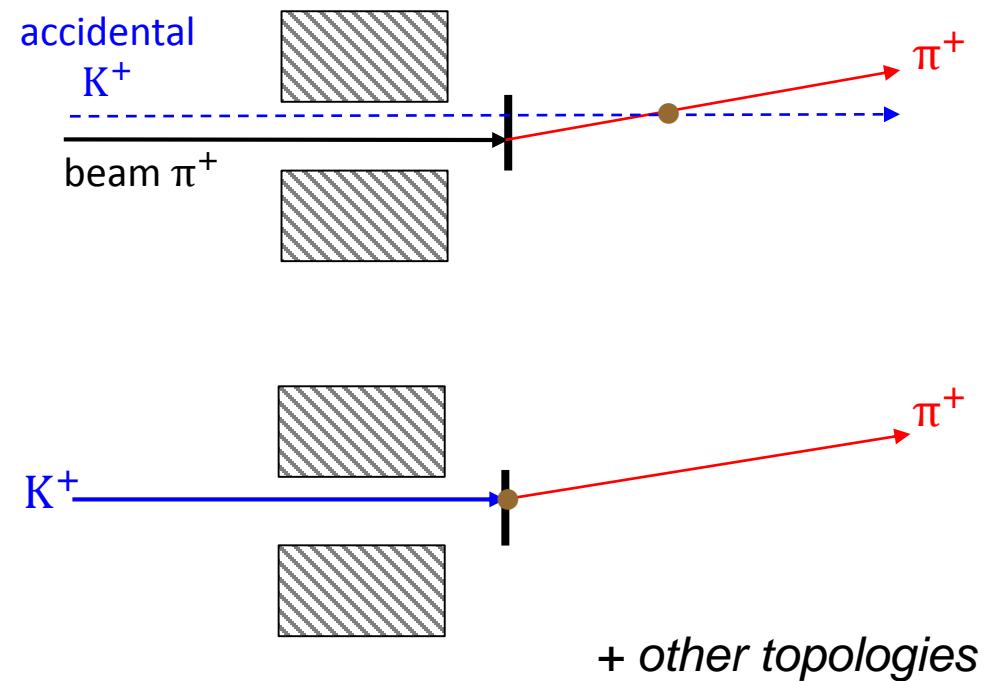


Upstream Background

- K^+ decays along the beam line
- Extra particles (e.g. π^0) stopped
- π^+ in decay region depending on:
beam material - magnetic fields
- Accidental beam particle matched

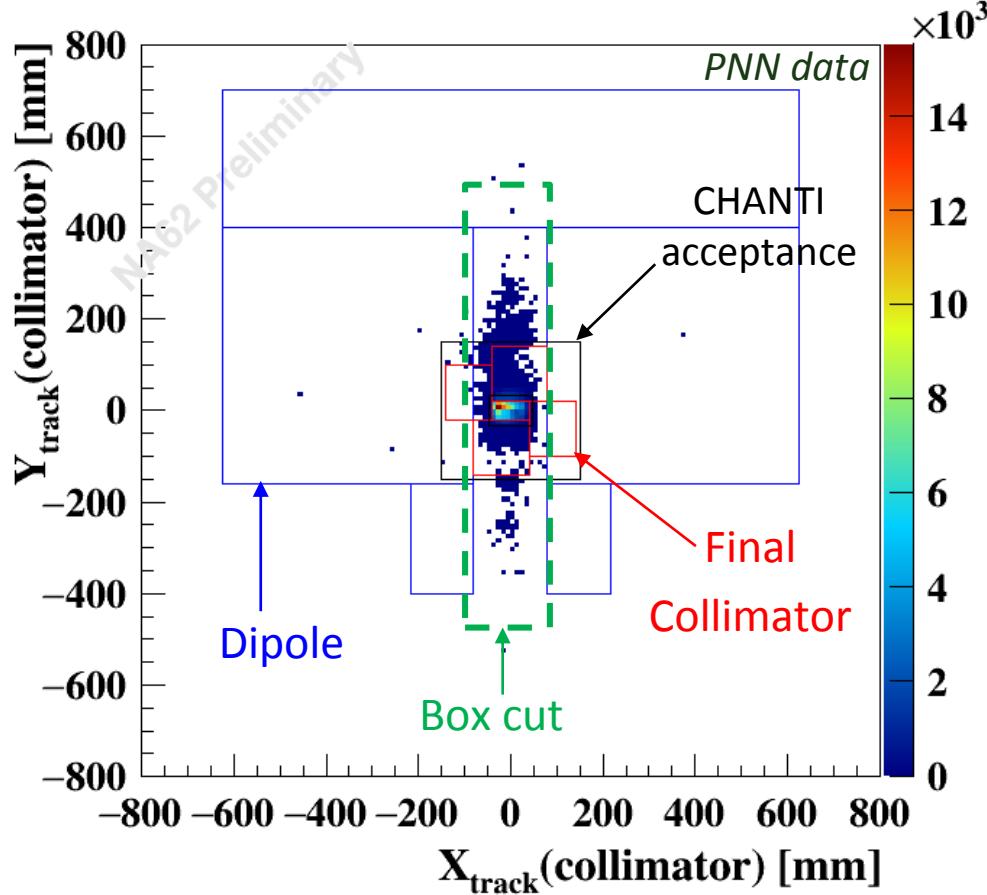


- Beam π^+ interactions in GTK station
 - π^+ produced in interaction
 - Accidental K^+ matched
-
- K^+ interactions in GTK station
 - π^+ produced in interaction
 - Vertex mis-reconstructed



Upstream Background

π^+ at collimator with $K^+ - \pi^+$ matching inverted



Against upstream background

- $K^+ - \pi^+$ matching
- Geometrical cut around π^+ position at collimator (Box cut)
- Z_{vertex} , CHANTI

Upstream background estimation

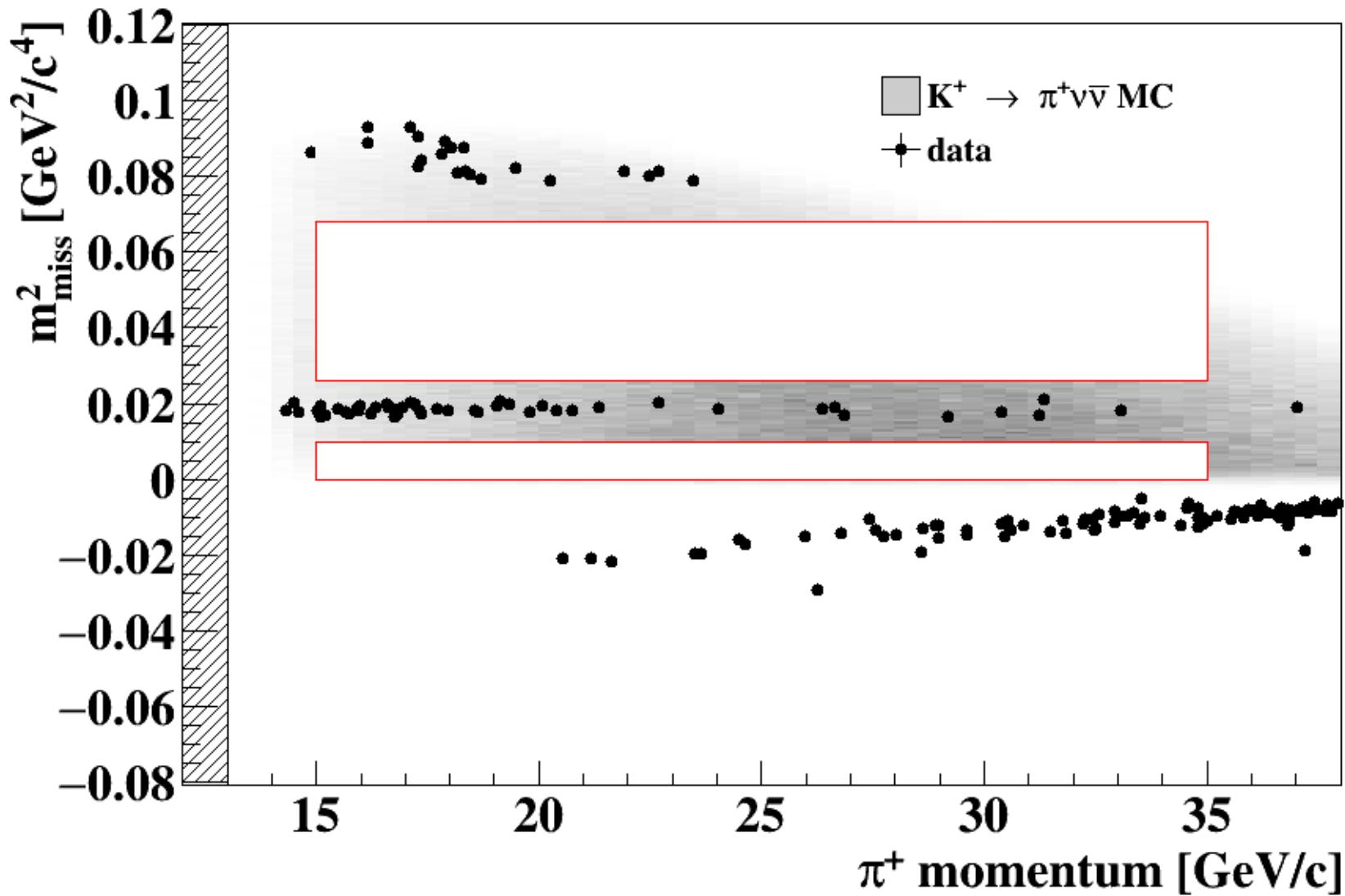
- Fully data driven
- Cuts inversion
- Limited statistics in 2016

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

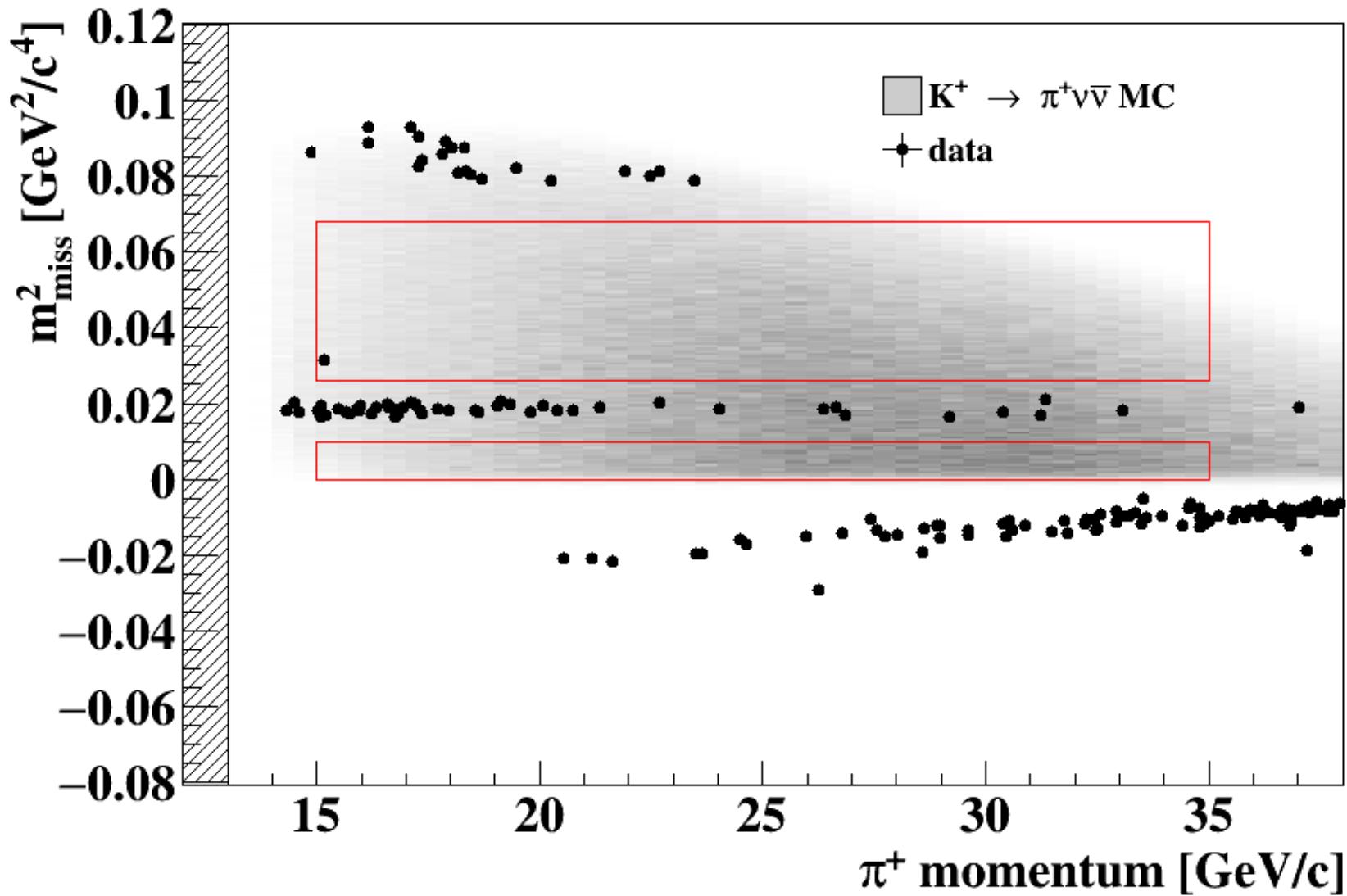
Background Summary

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

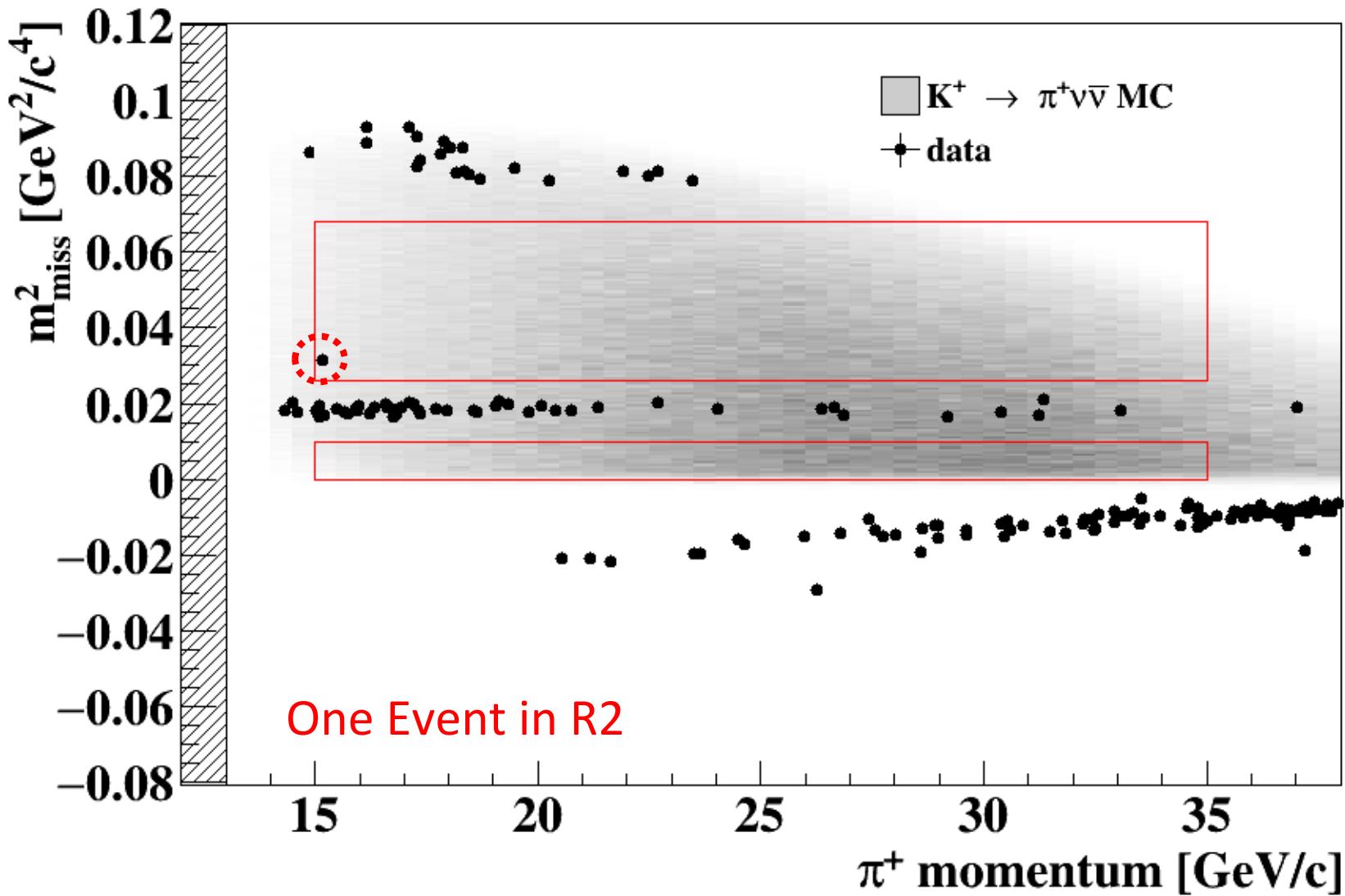
Result



Result

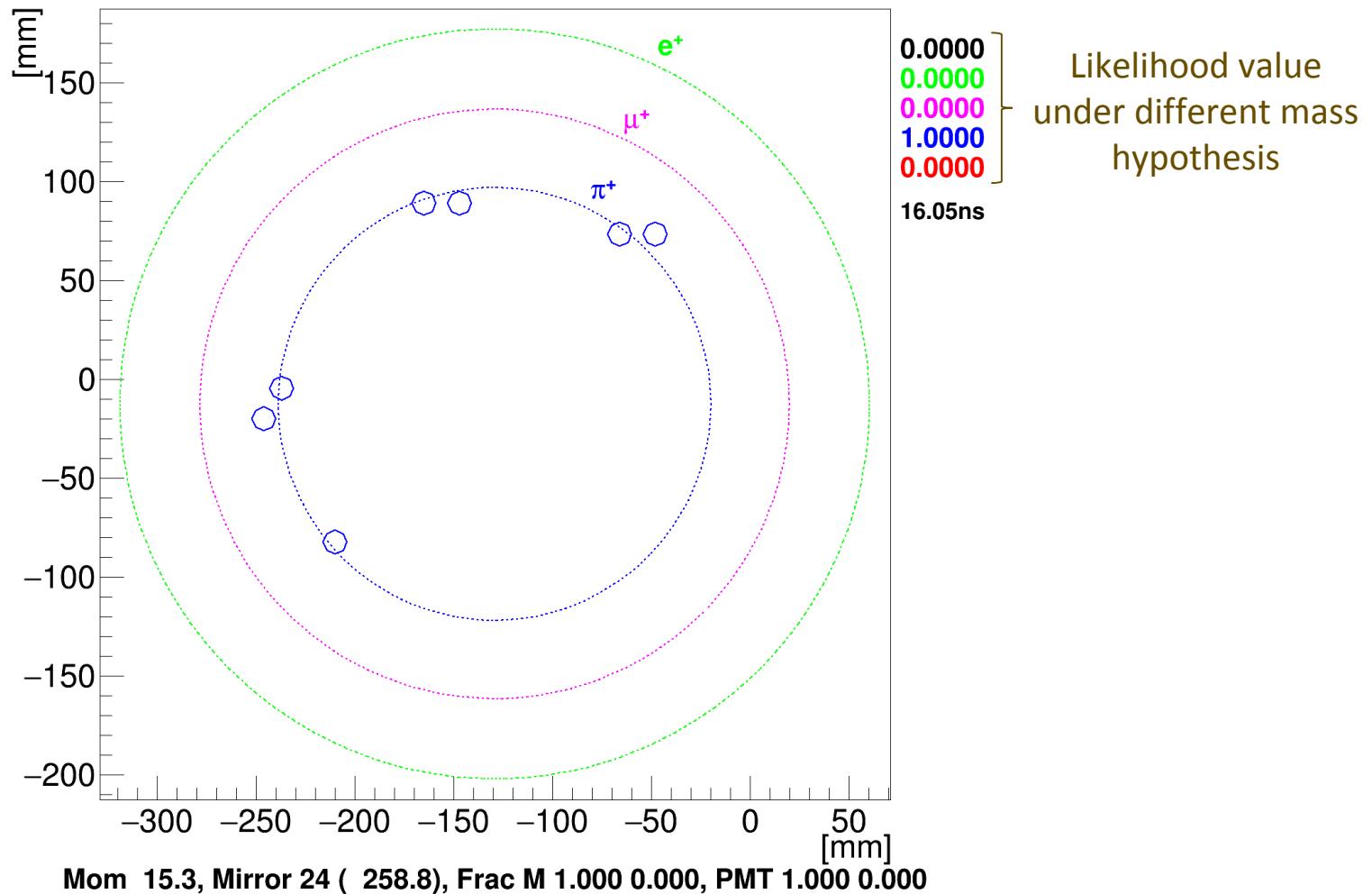


Result



The Candidate in the RICH

Run 6646, Burst 953, Event 543854, Track 1



$K^+ \rightarrow \pi^+ \nu \bar{\nu}$: Preliminary Results

Events Observed	1
SES	$(3.15 \pm 0.01_{\text{stat}} \pm 0.24_{\text{syst}}) \cdot 10^{-10}$
Expected Background	$0.15 \pm 0.09_{\text{stat}} \pm 0.01_{\text{syst}}$

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

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

- Expected limit: $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 10 \times 10^{-10} \text{ @ 95\% CL}$
 - For comparison $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 2.8^{+4.4}_{-2.3} \times 10^{-10} \text{ @ 68\% CL}$
- $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{SM} = (0.84 \pm 0.10) \times 10^{-10}$ SM prediction
- $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ BNL E949/E787 Kaon Decay at Rest

NA62 Prospects on $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

- Processing of 2017 data ongoing
 - 20 more than the presented statistic
 - Upstream background reduction expected
 - Methods to improve signal efficiency under study
- 2018 data
 - Run on – going smoothly
 - Further mitigation of the upstream background is expected
- Expected about 20 SM events from the 2017+2018 data sample

Conclusions

- The new NA62 decay in flight technique to study $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ works
- One event observed in 2016 data
- $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) < 14 \times 10^{-10}$ @ 95% CL
- O(20) events expected from 2017+2018 data
- Cutting – edge physics in K sector and beyond