NA62: kaon physics strikes back!

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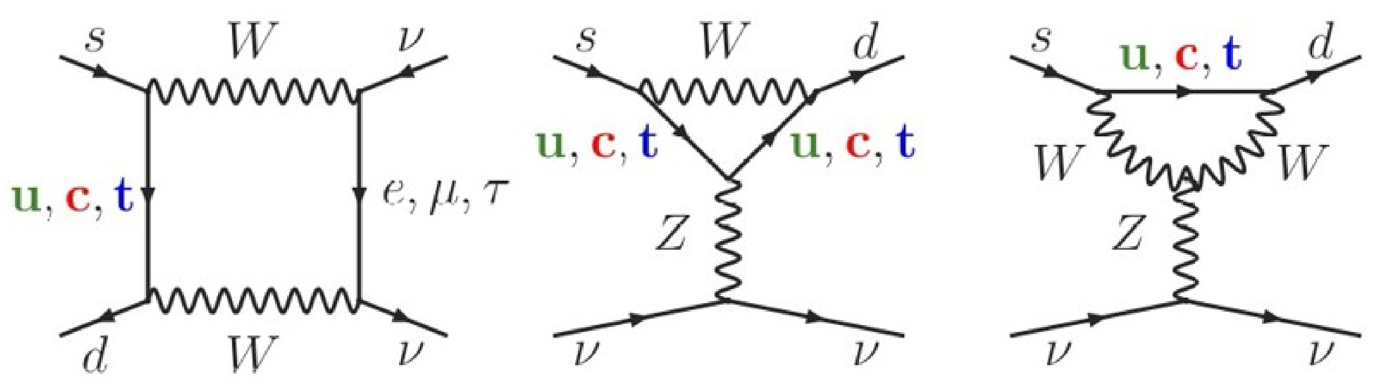
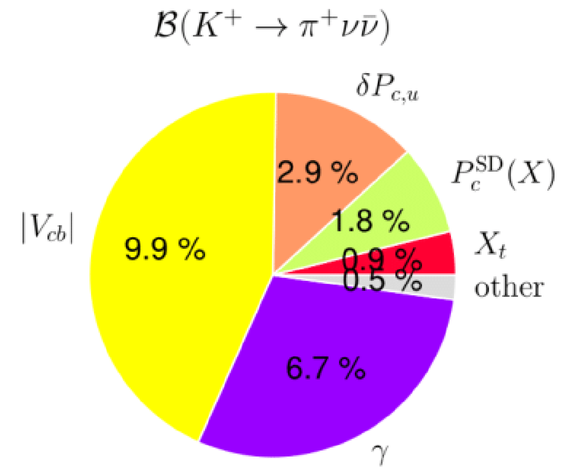
Symmetry Breaking

P326 NA62

The FCNC process $K^+ \to \pi^+ \nu\bar{\nu}$





Theoretical error budget
Buras. et. al., JHEP11(2015)033

- FCNC loop processes: s → d coupling and highest CKM suppression
- Theoretically clean: Short distance contribution dominated.
- Hadronic matrix element measured with K_{l3} decays
- SM predictions:[Brod, Gorbahn, Stamou, Phys. Rev.D 83, 034030 (2011)],[Buras. et. al., JHEP11(2015)033]

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \left(\frac{|V_{cb}|}{0.0407}\right)^{2.8} \left(\frac{\gamma}{73.2^\circ}\right)^{0.74} = (8.4 \pm 1.0) \times 10^{-11}$$

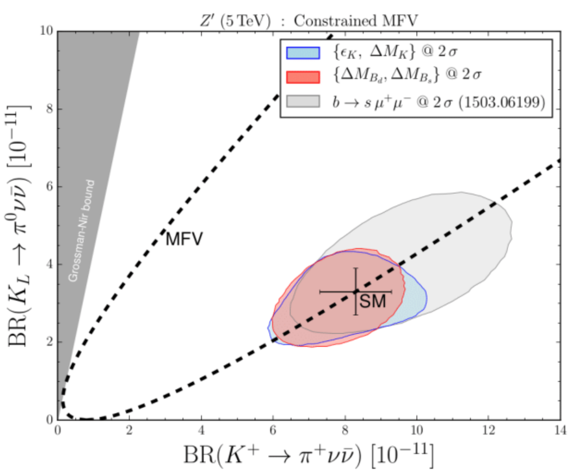
- Experimental result:[Phys. Rev. D 79, 092004 (2009)]

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

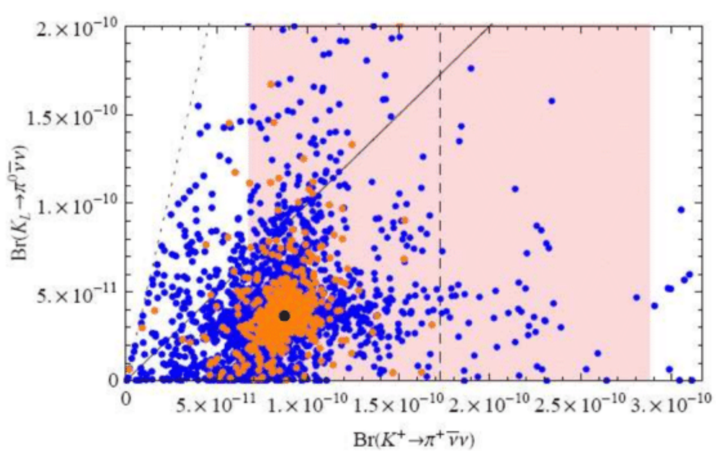
$K^+\to\pi^+\nu\bar{\nu}$ beyond the Standard Model

- 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]
- Leptoquarks [S. Fajfer, N. Košnik, L. Vale Silva, arXiv (2018)]
- Constraints from existing measurements (correlations model dependent)
  - Kaon mixing, CKM elements, K, B rare meson decays, NP limits from direct searches

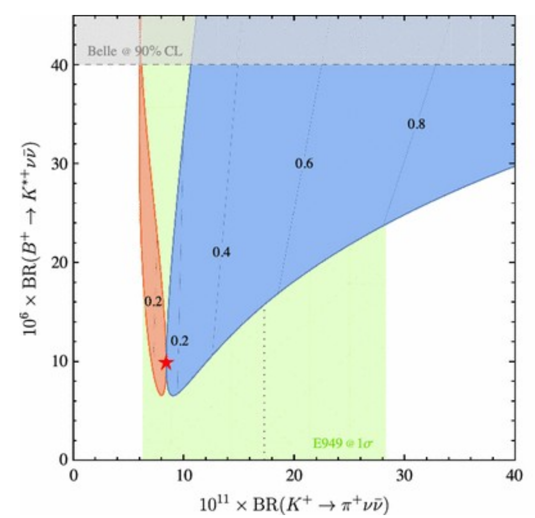
Z'(5 TeV) in Constrained MFV



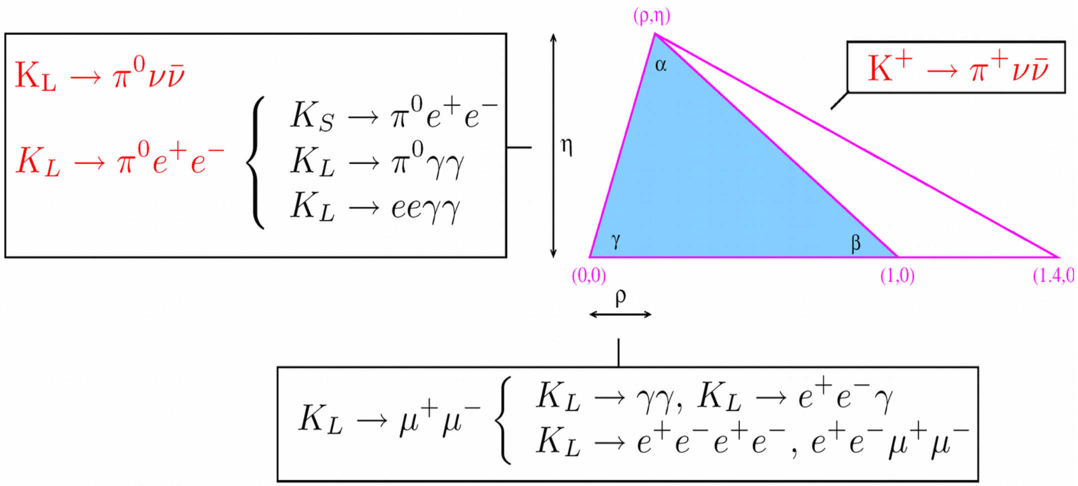
Randall Sundrum

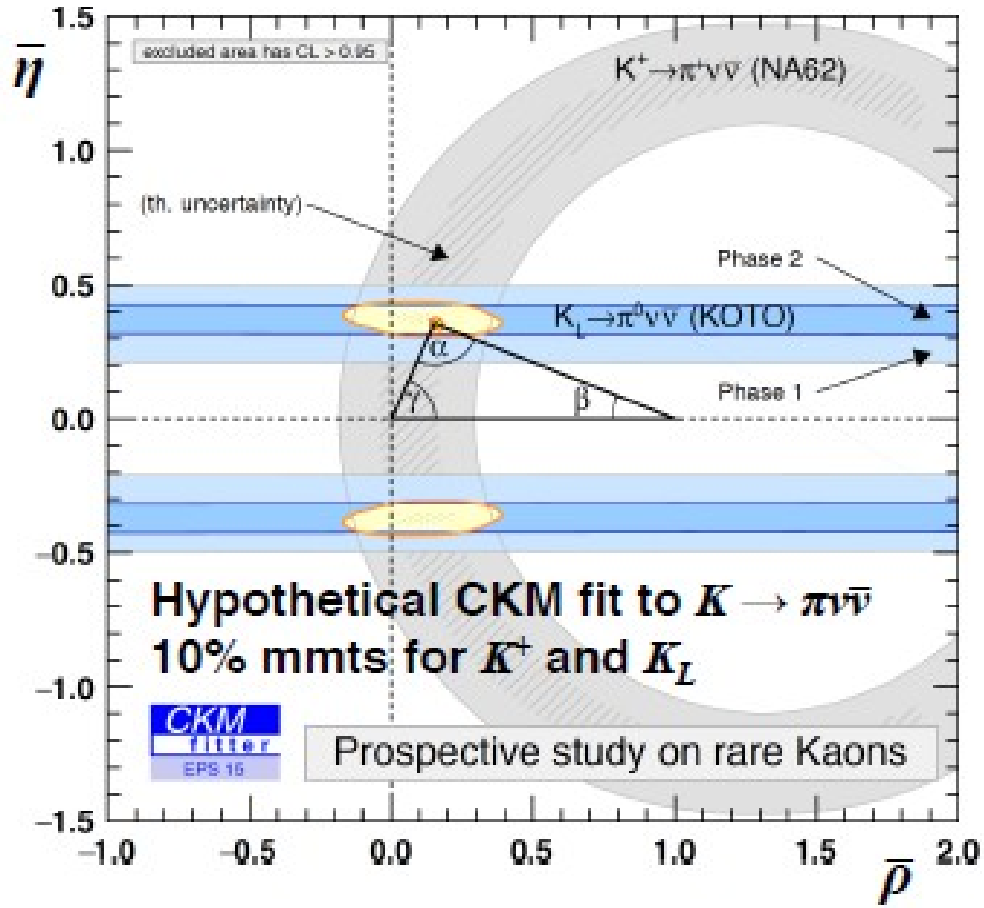


LFU violation



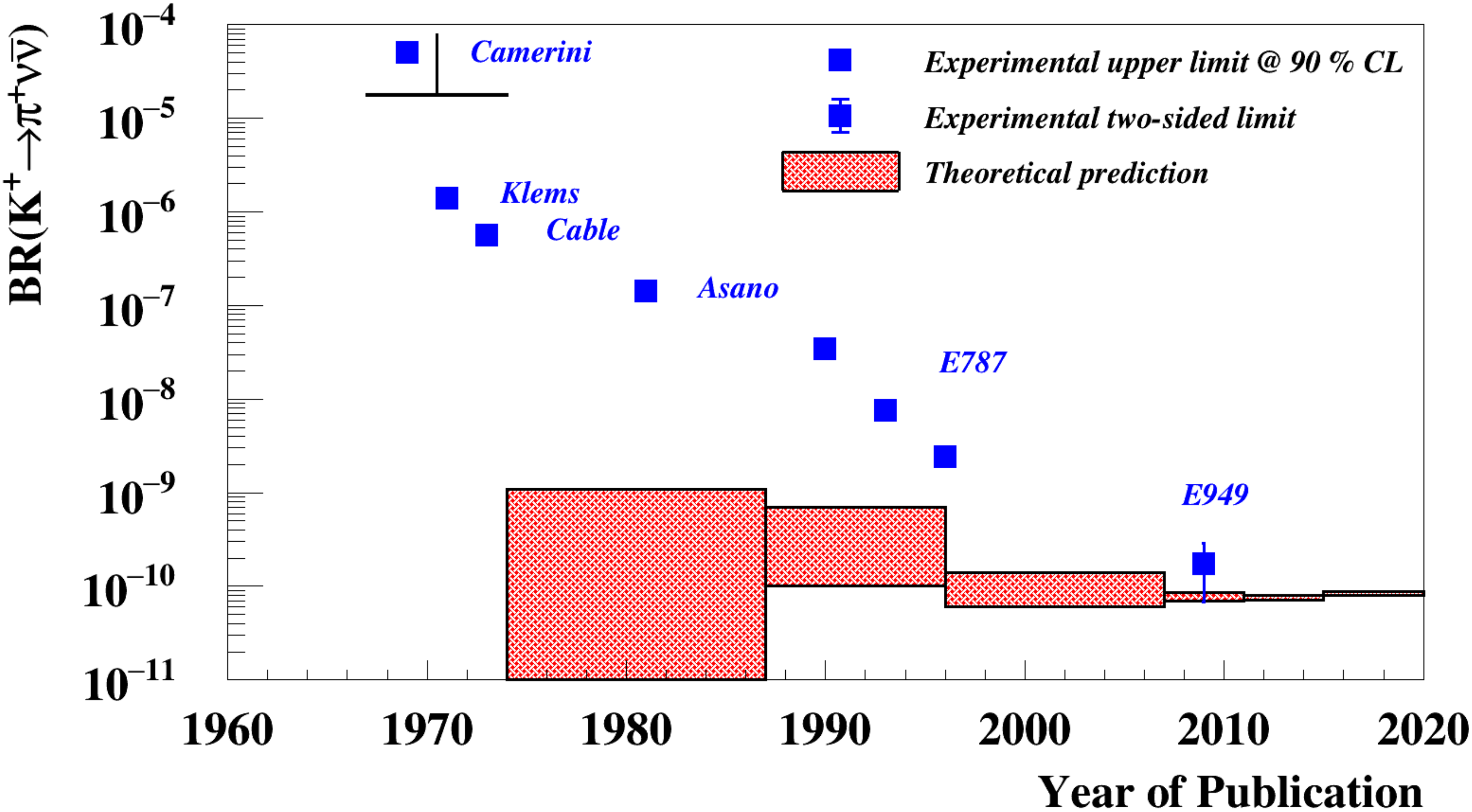
Kaons and the CKM unitarity triangle





- The CKM unitarity triangle can be constrained by kaon physics alone
- Comparison with B physics can provide description of NP flavour dynamics

History of $K^+ \to \pi^+ \nu\bar{\nu}$ progres



Kaon physics @ NA62

- Primary goal
  - Measurement of BR($K^+ \to \pi^+ \nu\bar{\nu}$)
- Kaon decay-in-flight technique
- Requirements
  - 10^{13} kaon decays
  - Signal acceptance O(10%)
  - O(10^{12}) background rejection
- Broad physics program

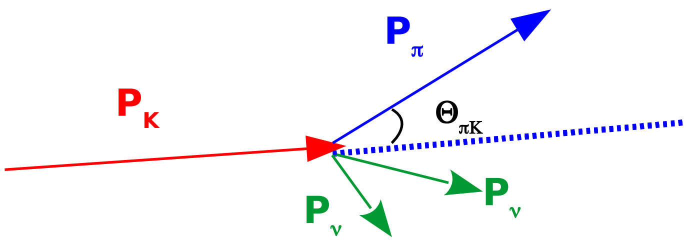
~ 200 participants from: Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, GMU-Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Merced, Moscow, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Sofia, Torino, TRIUMF, Vancouver UBC

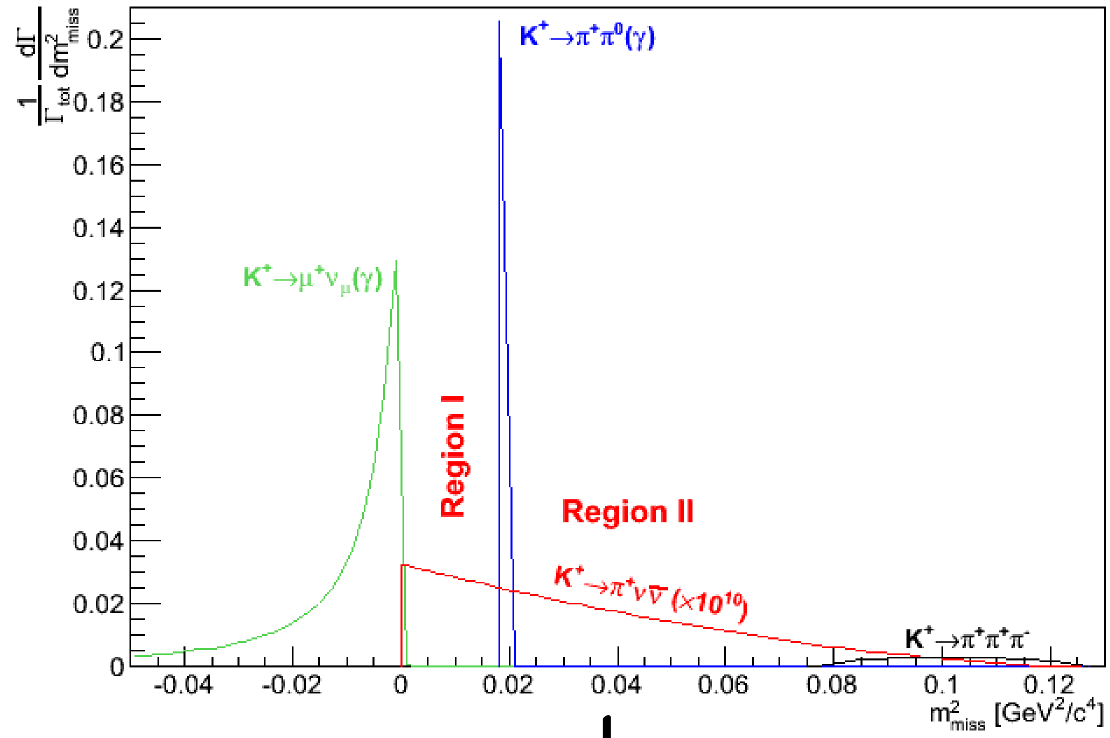
Analysis strategy

NEW

Decay in flight technique

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





Process	Branching ratio
$K^+\to\pi^+\pi^0$	0.2066
$K^+\to\mu^+\nu_\mu$	0.6356
$K^+\to\pi^+\pi^+\pi^-$	0.0558
$K^+\to\pi^+\pi^-e^+\nu_e$	4.25×10^{-5}

+

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

Particle ID(Cherenkov detectors)

Particle ID(Calorimeters)

Photon veto

Multi-charged rejection

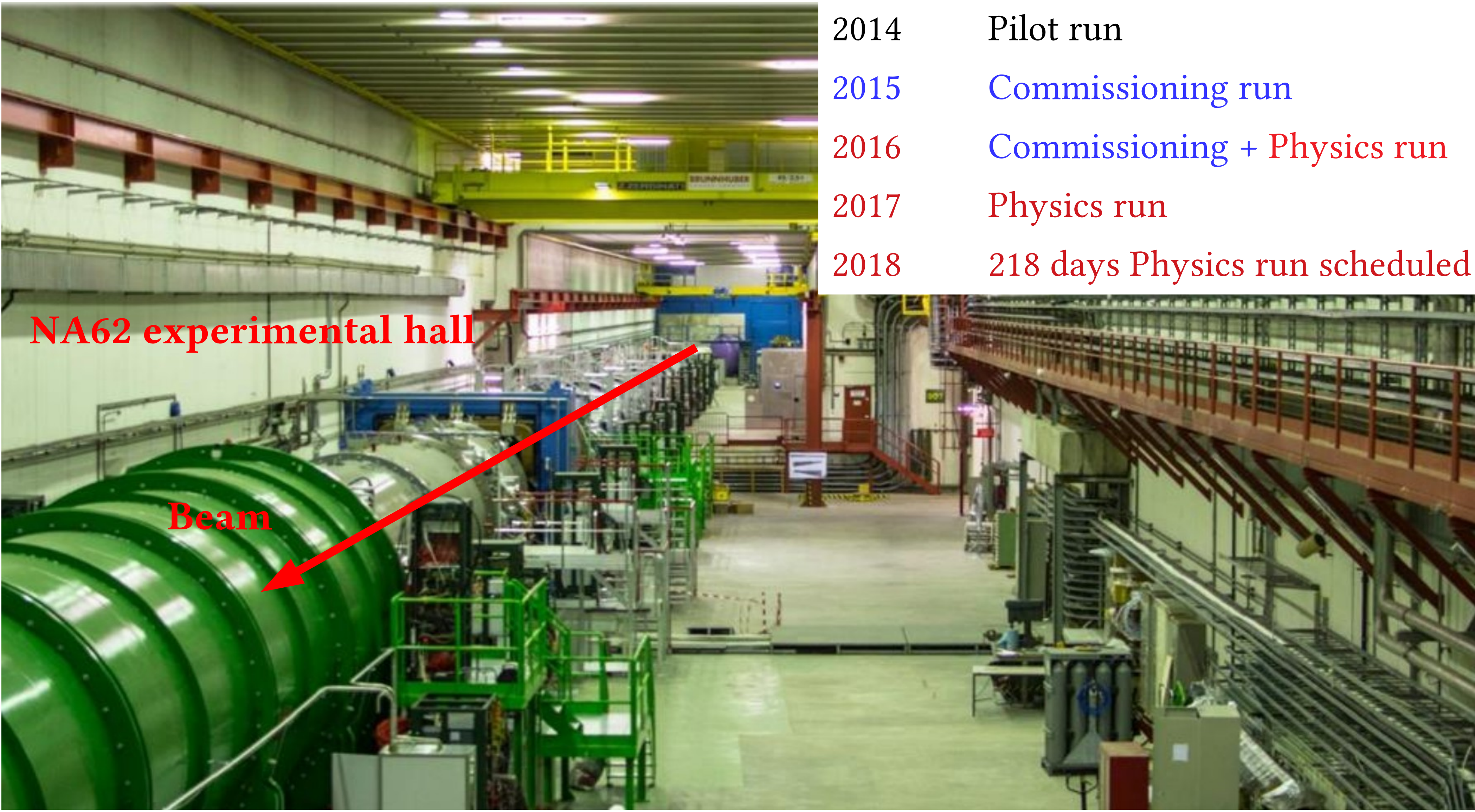
Keystones of the analysis

- Timing between sub-detectors ~ O(100 ps)
- Kinematic suppression ~ O(10^4)
- Muon suppression > 10^7
- π^0 suppression (from $K^+ \to \pi^+\pi^0$) > 10^7

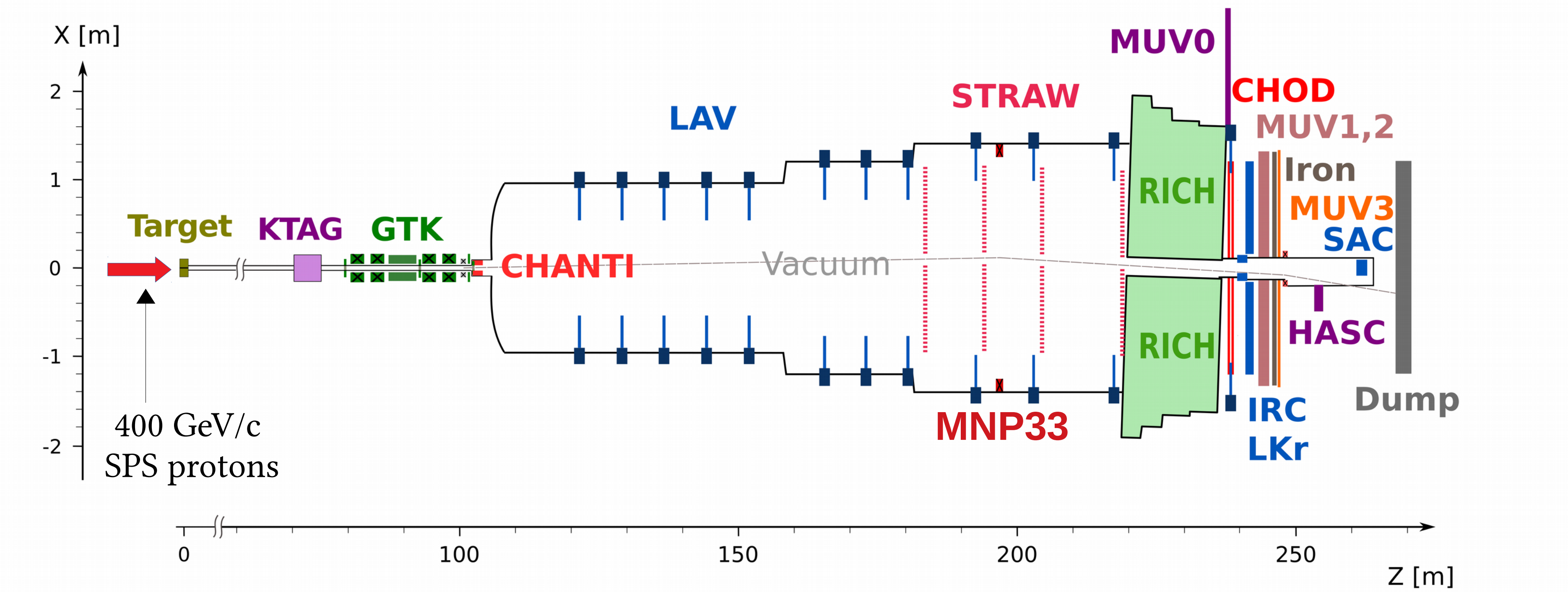
Signal and background control regions are kept blind throughout the analysis

NA62 runs

2014	Pilot run
2015	Commissioning run
2016	Commissioning + Physics run
2017	Physics run
2018	218 days Physics run scheduled

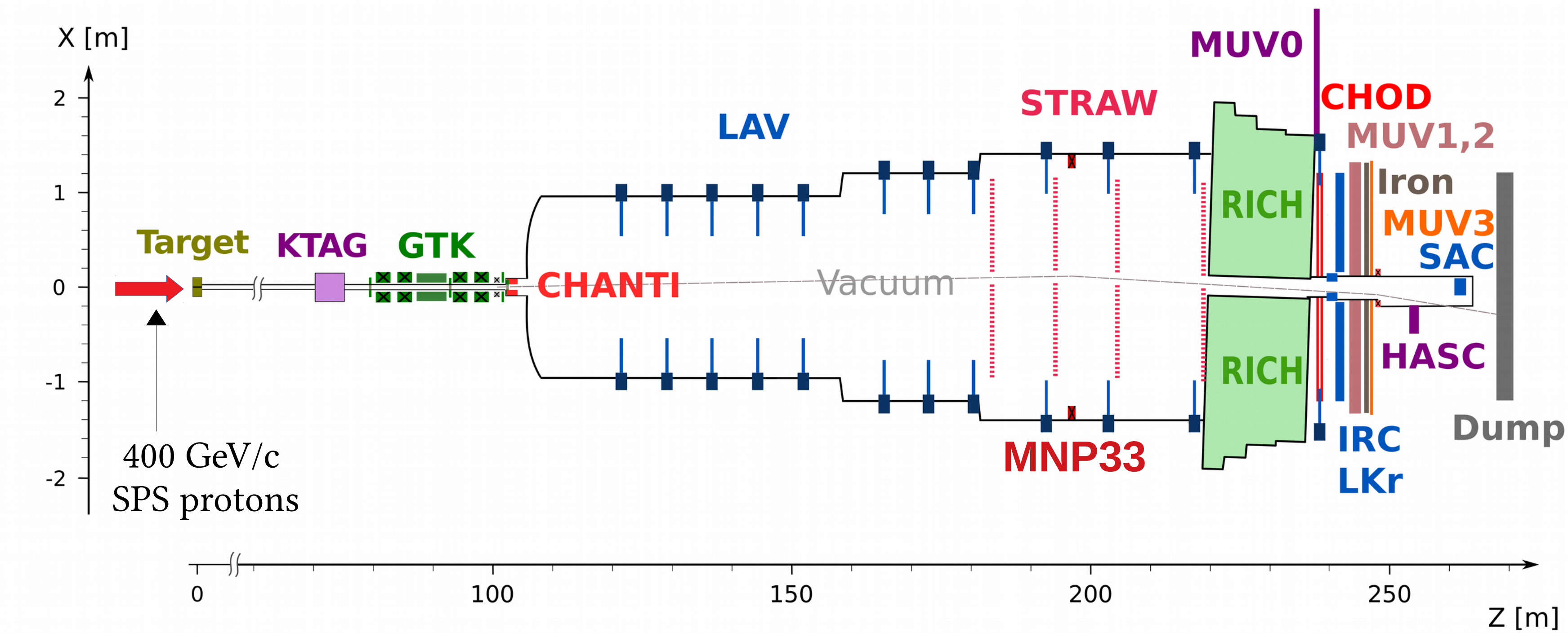


NA62 beam and detector



- **Secondary positive Beam:**
  - 75 GeV/c momentum, 1 % bite
  - 100 μrad divergence (RMS)
  - 60x30 mm^2 transverse size
  - K^+(6%)/π^+(70%)/p(24%)
  - 33×10^{11} ppp on T10 (750 MHz at GTK3)
- **Decay Region:**
  - 60 m long fiducial region
  - ~ 5 MHz K^+ decay rate
  - Vacuum ~ $O(10^{-6})$ mbar

NA62 beam and detector



- **Upstream detectors (K^+):**
  - **KTAG:** Cherenkov counter for K^+ ID
  - **GTK:** Si pixel beam tracker
  - **CHANTI:** Anti-counter for activity induced by inelastic beam-GTK3 interactions

- **Decay Region detectors (π^+):**
  - **STRAW:** Massless straw tracker (1.8% X_0)
  - **CHOD:** Two scintillator hodoscopes to tag the π^+
  - **LKr/MUV1/MUV2 :** Calorimetric system for π^+ ID
  - **RICH:** Cherenkov counter for π/μ ID
  - **LAV/SAC/IRC:** Photon veto detectors
  - **MUV3:** Muon veto
  - **HASC/MUV0:** Off-acceptance vetoes

Data set

- 2016 Data, 4 weeks of data taking
- Trigger streams:
  - "PNN":
    - Hardware (L0): RICH hits, Hodoscope, No muons, < 20 GeV in LKr
    - Software (L1): KTAG in time, No signals in LAV, Momentum in straw < 50 GeV/c
  - "Control (minumum bias, downscaled)":
    - L0: Hodoscope hits
- Offline analysis
  - Bad data based on detector performances identified on a spill-by-spill basis
  - Data samples: **PNN; Control: $K^+ \to \pi^+\pi^0$, $K^+ \to \pi^+\pi^+\pi^-$, $K^+ \to \mu^+\nu_\mu$**
  - Signal selection tuned on MC, 10% PNN data, control data
  - Analysis in four 5 GeV/c wide π^+ momentum bins, from 15 to 35 GeV/c
  - Blind analysis procedure: signal and control regions kept masked for the whole analysis

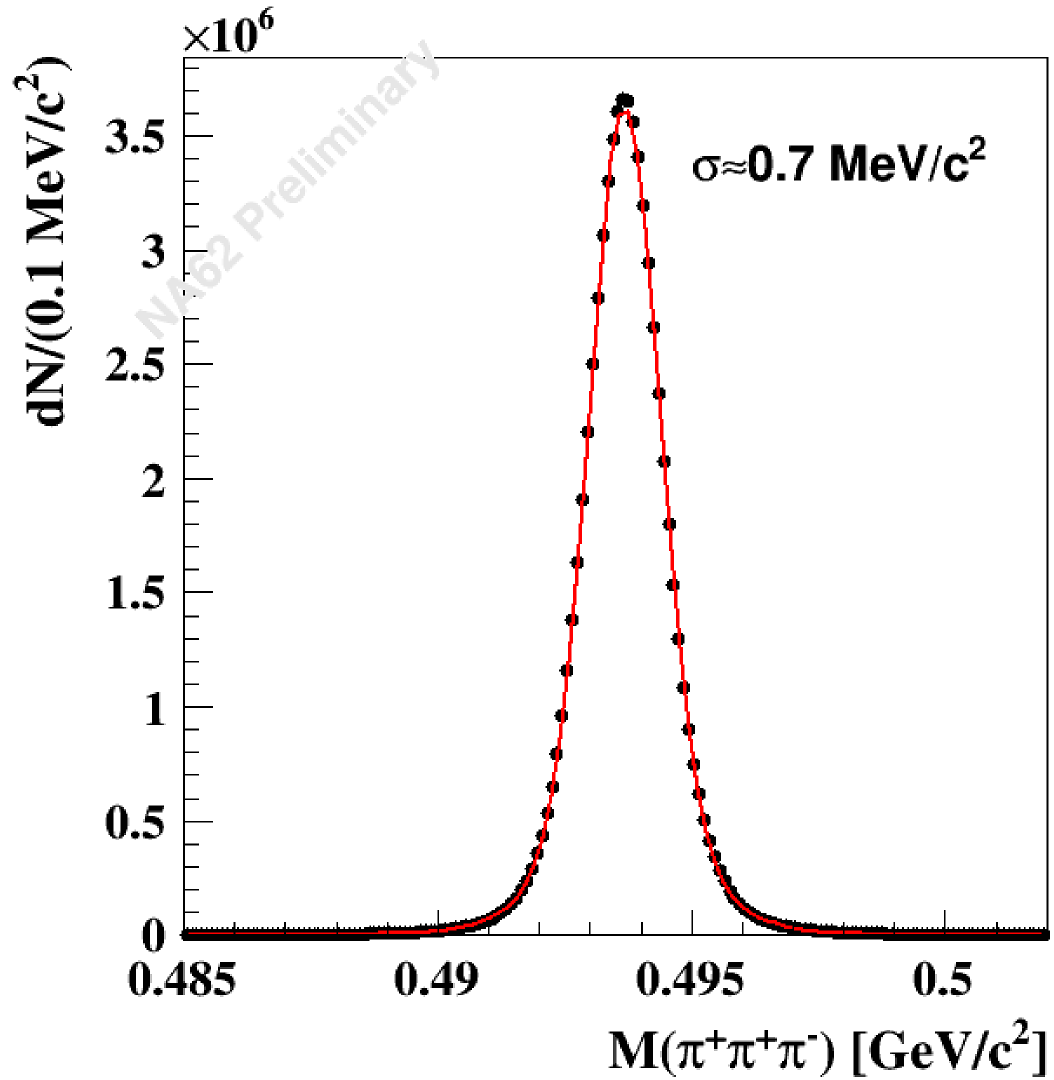
$K^+ \to \pi^+ \nu\bar{\nu}$ analysis

1. Selection
   - K^+ decays with a single charged particles in the final state
   - Particle identification: π^+
   - Photon and multi-charged rejection
   - Kinematic selection of signal regions
2. Determination of the Single Event Sensitivity (SES)
3. Estimation and validation of the expected background
4. Opening of the signal regions and results

1. Selection

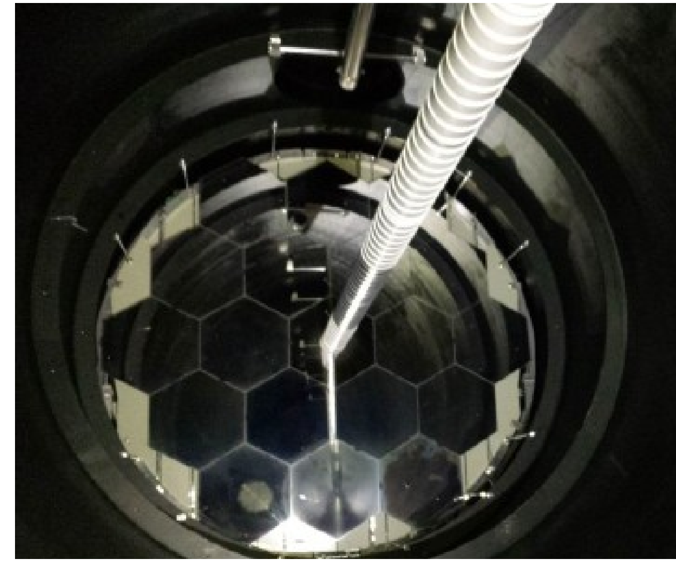
π^+ tracking: Straw spectrometer

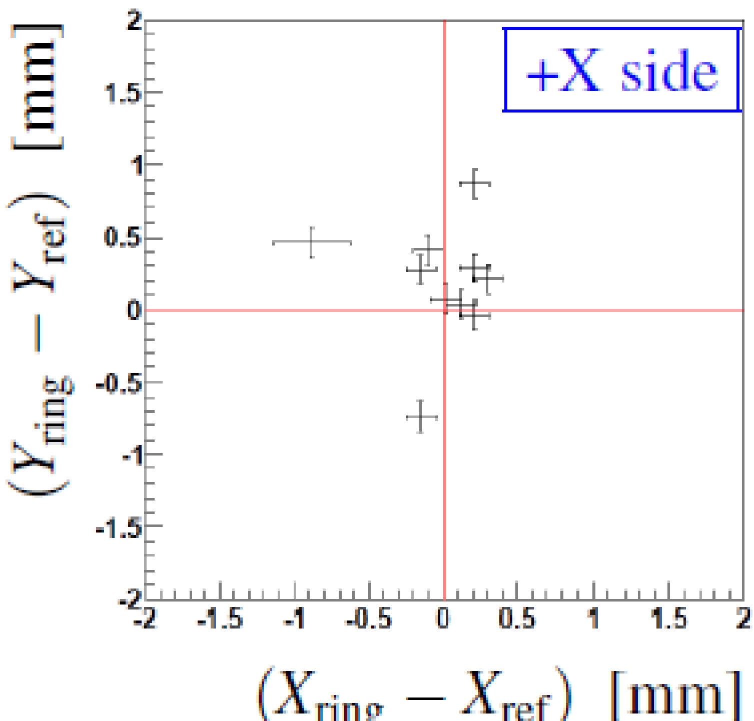
- Straws aligned in time and drift time measured vs trigger time
- Straws aligned geometrically using straight tracks
- Measured 3D B map and stray field included in track reconstruction
- >95% reconstruction efficiency
- Final calibration using: **$K^+ \to \pi^+\pi^+\pi^-$**

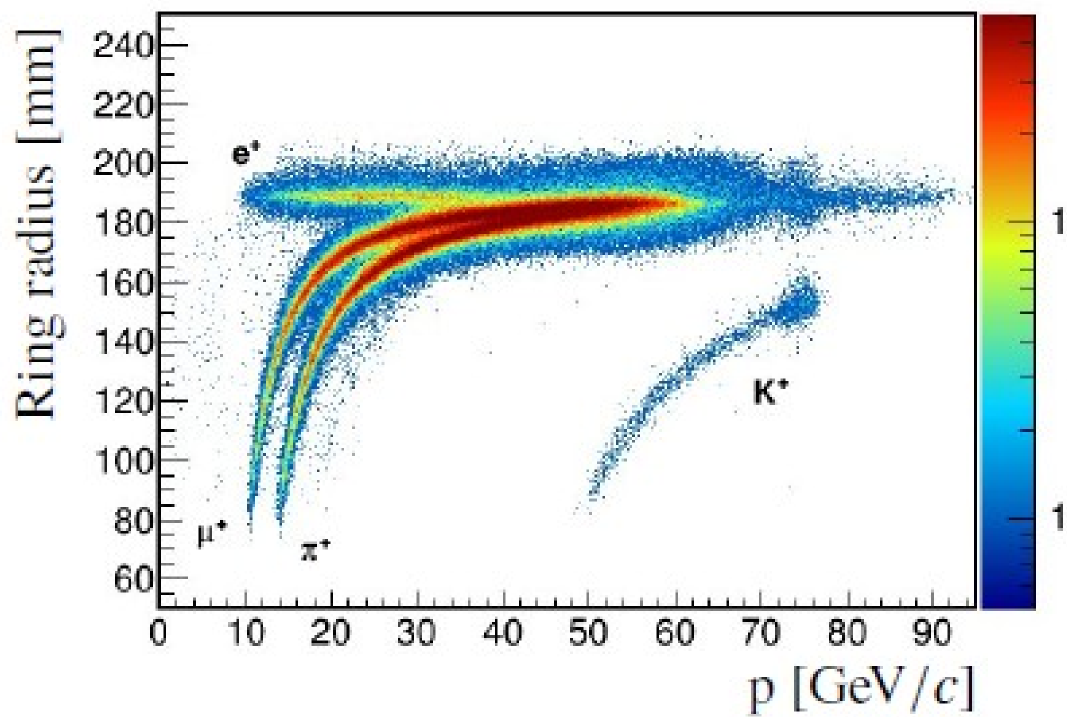


π^+ ID: RICH

- Mirrors aligned using: laser, tracks reconstructed from straw spectrometer
- Monitored using e^+ (~16 hits / e^+ ring)
- PM's aligned vs KTAG time: ring $\sigma(t)$ ~ 80 ps
- Ring - spectrometer track matched comparing ring centre and flight direction

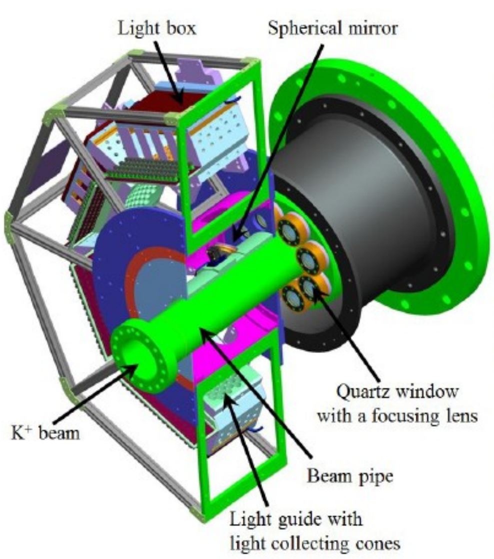


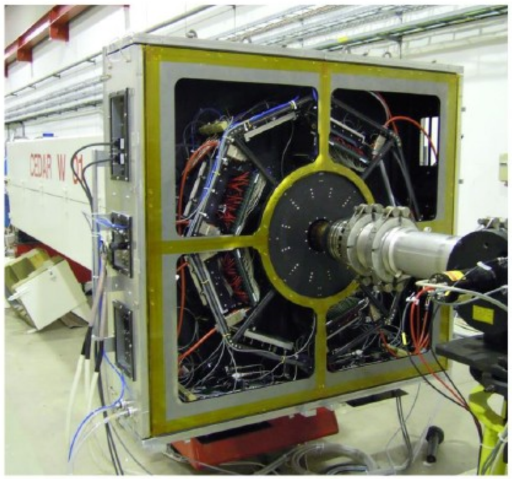


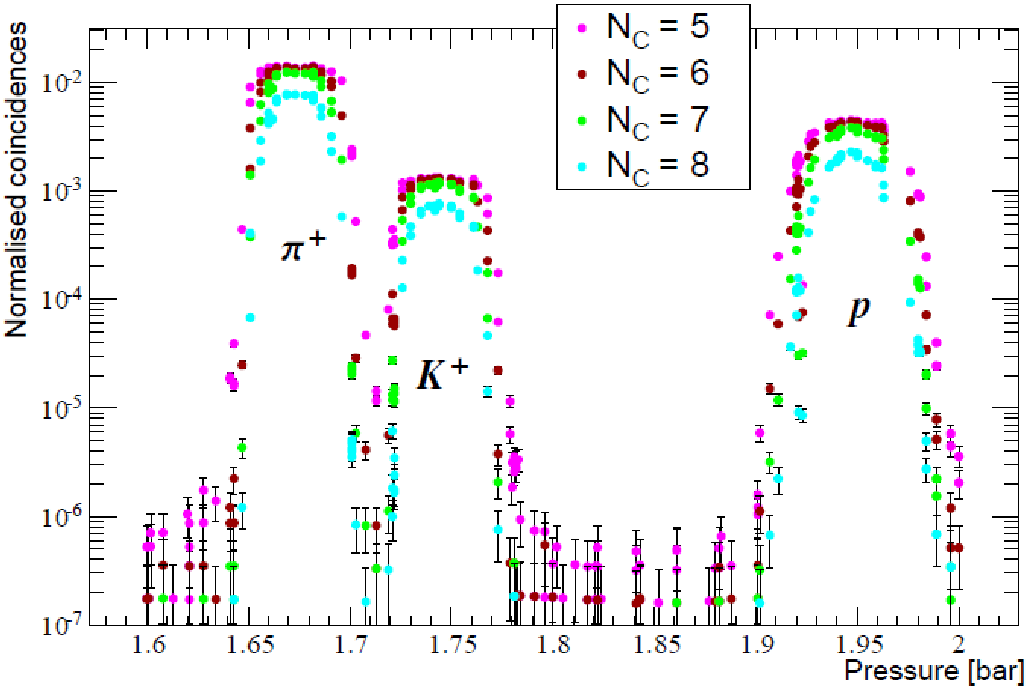


K^+ ID: KTAG

- Geometrically aligned with the beam
- Pressure scan: optimal working point for K^+
- PM's time alignment and time walk corrections: $\sigma(t) \sim 70$ ps
- **K^+** signal from at least 5-fold coincidence (>95% efficiency)

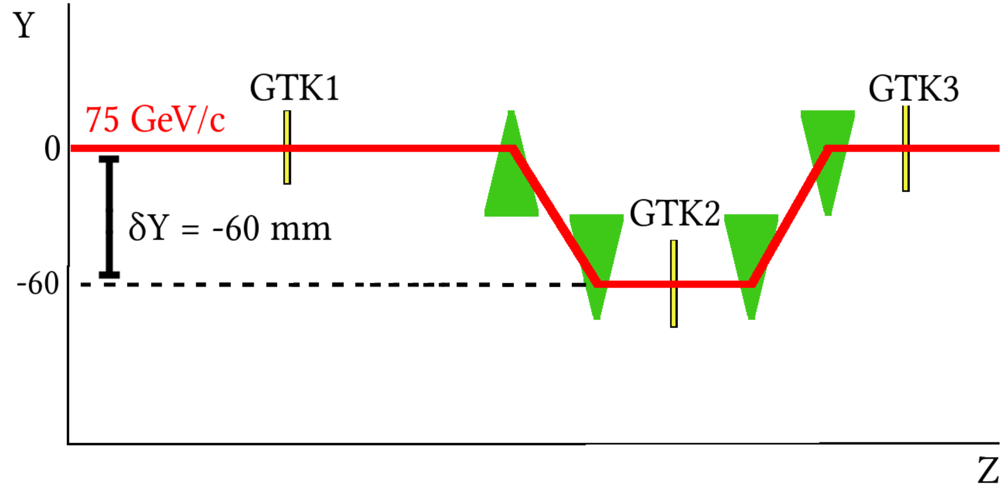


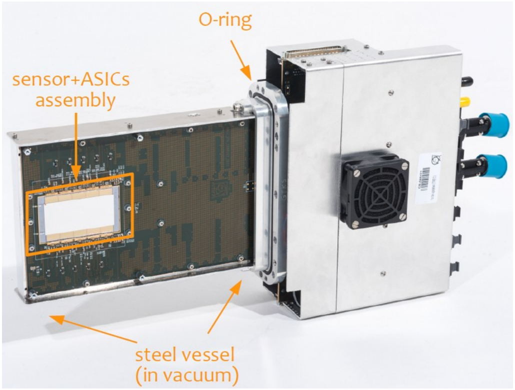


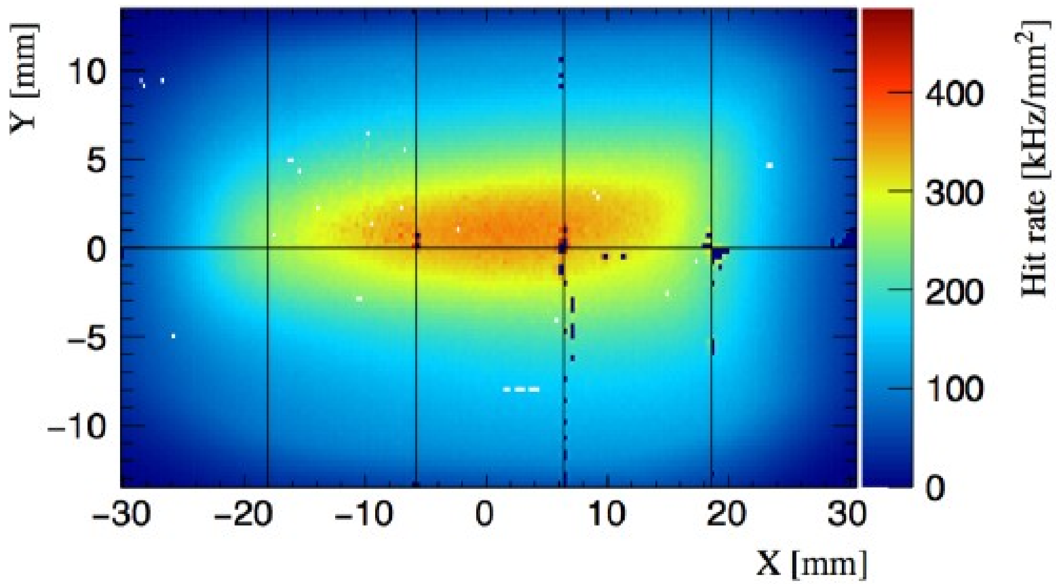


K⁺ tracking: GigaTracker

- 4D kaon track reconstruction using trigger and KTAG as time reference
- Time offset corrections dependent on Station, Chip, Column, Row of the pixel
- Pixel – by – Pixel time walk corrections ($\sigma(t)$ < 150 ps per station)
- Stations aligned with straw Spectrometer and calibrated using $K^+ \to \pi^+\pi^+\pi^-$

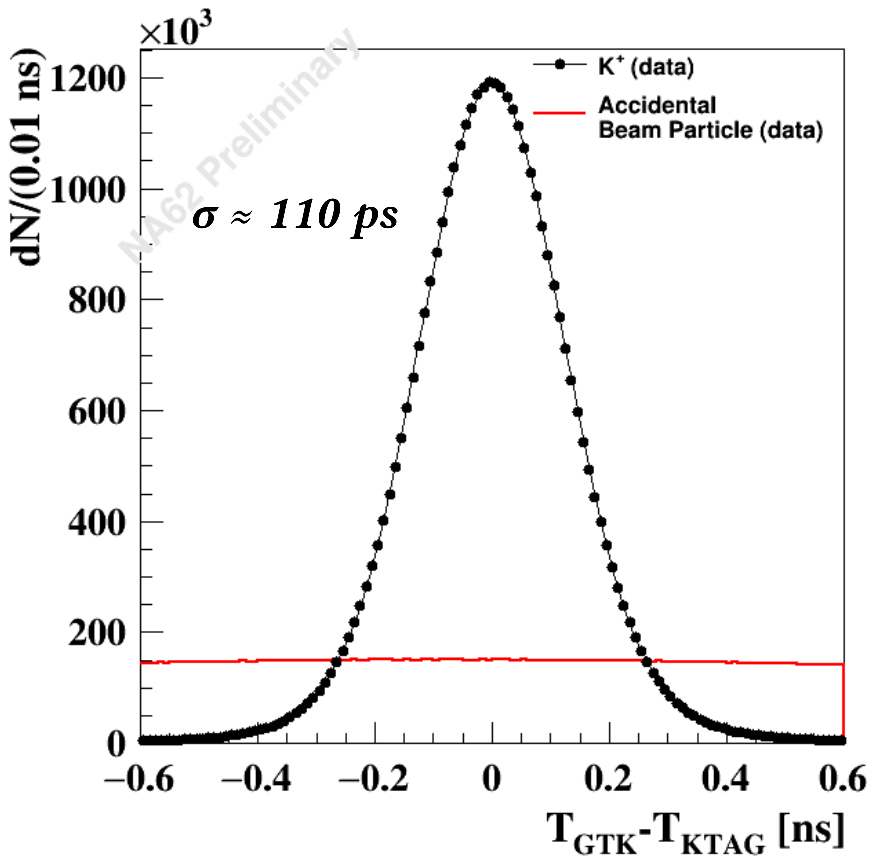


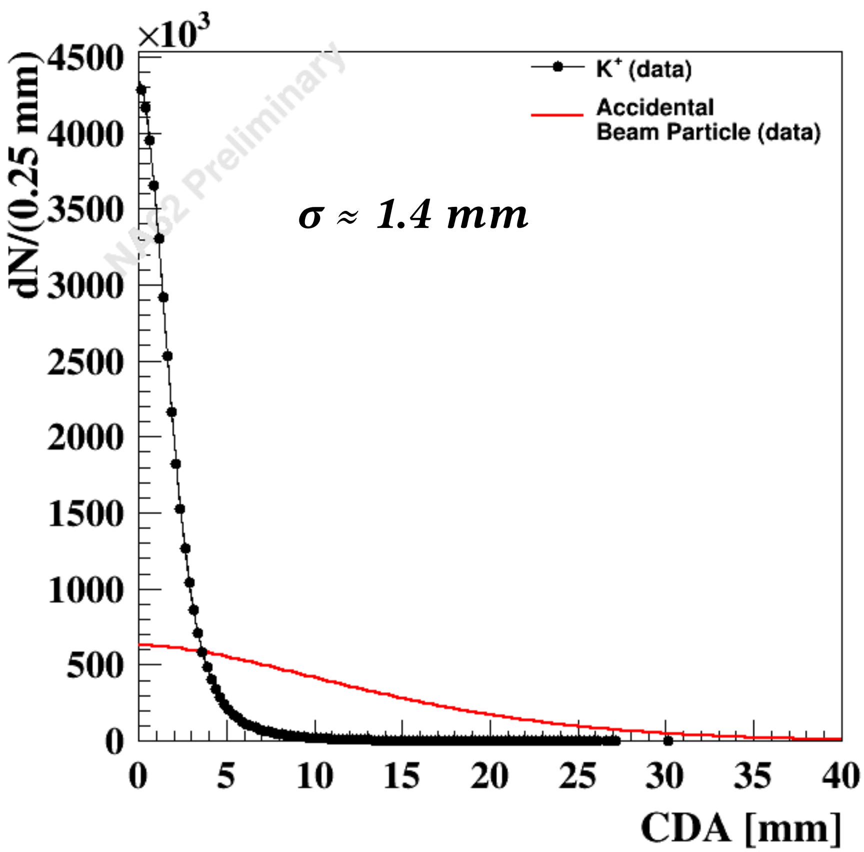




K– π association

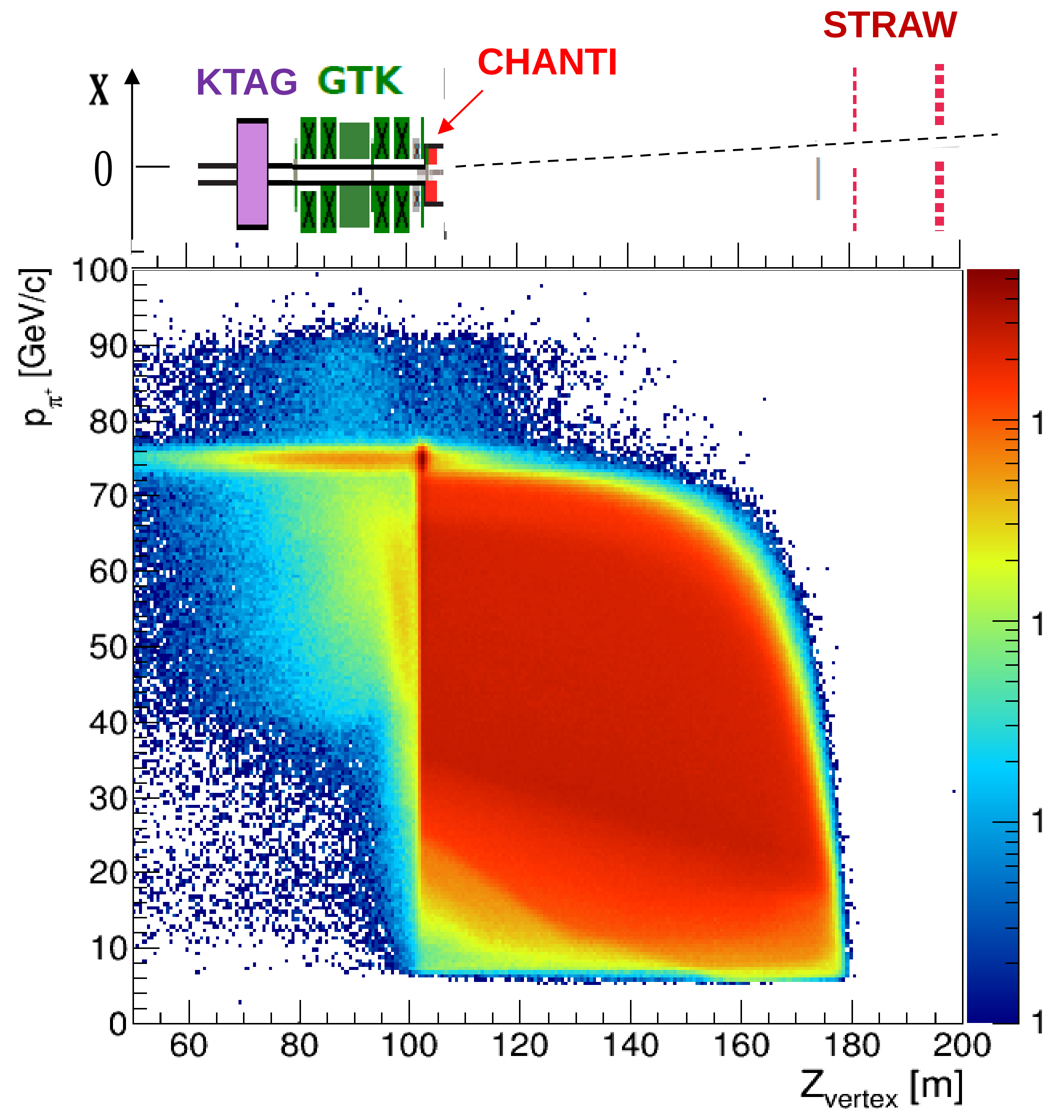
- KTAG – GigaTracker – RICH time matching ⟶ Kaon decay time (t_{decay})
- GigaTracker – Straw Spectrometer spatial matching (CDA)
- 3.5% (<1%) K^+ mis-tag if K^+ track (not) present, dependent on beam intensity
- 75% **K^+** reconstruction and ID efficiency



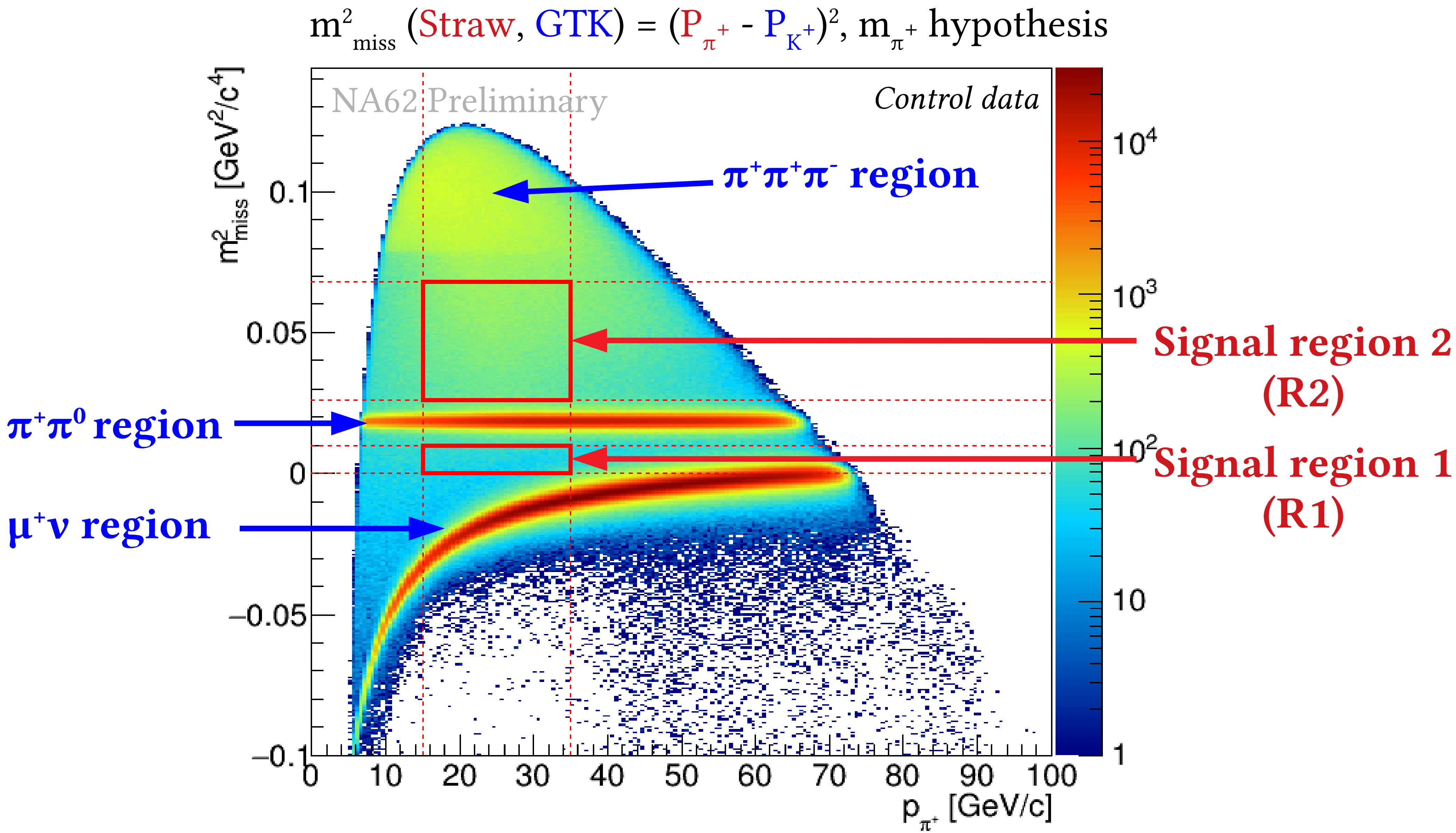


Selection of kaon decays

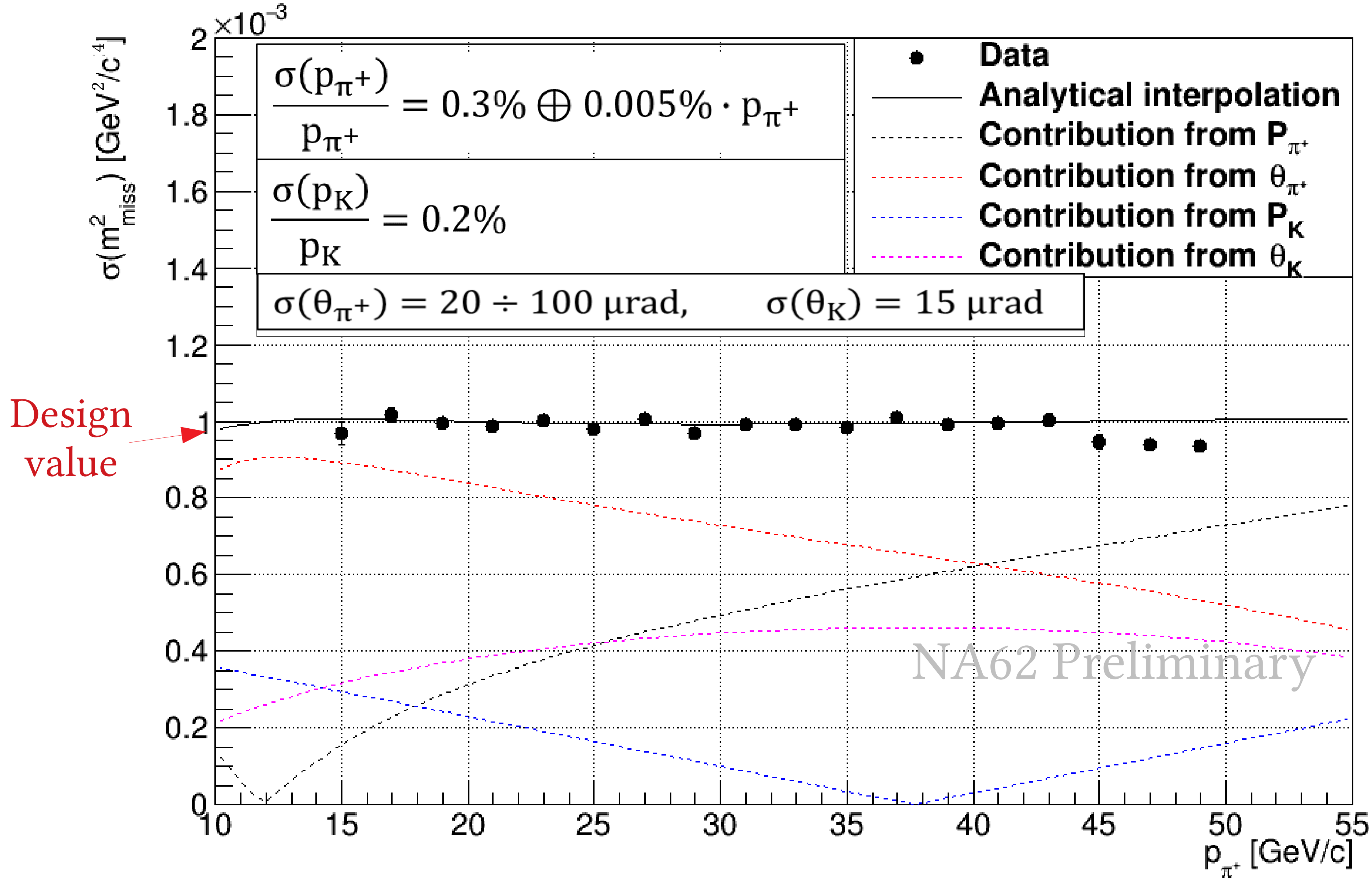
- Selection of K decays
  - K – π association
  - Z vertex (110 and 165 m)
  - Track slope
  - Track projection at collimator
  - No activity in CHANTI
- Tracks from «upstream»
  - mismatching in GTK
  - Decays along the beam line
  - Beam particle interactions in GTK



Kaon-decay kinematics

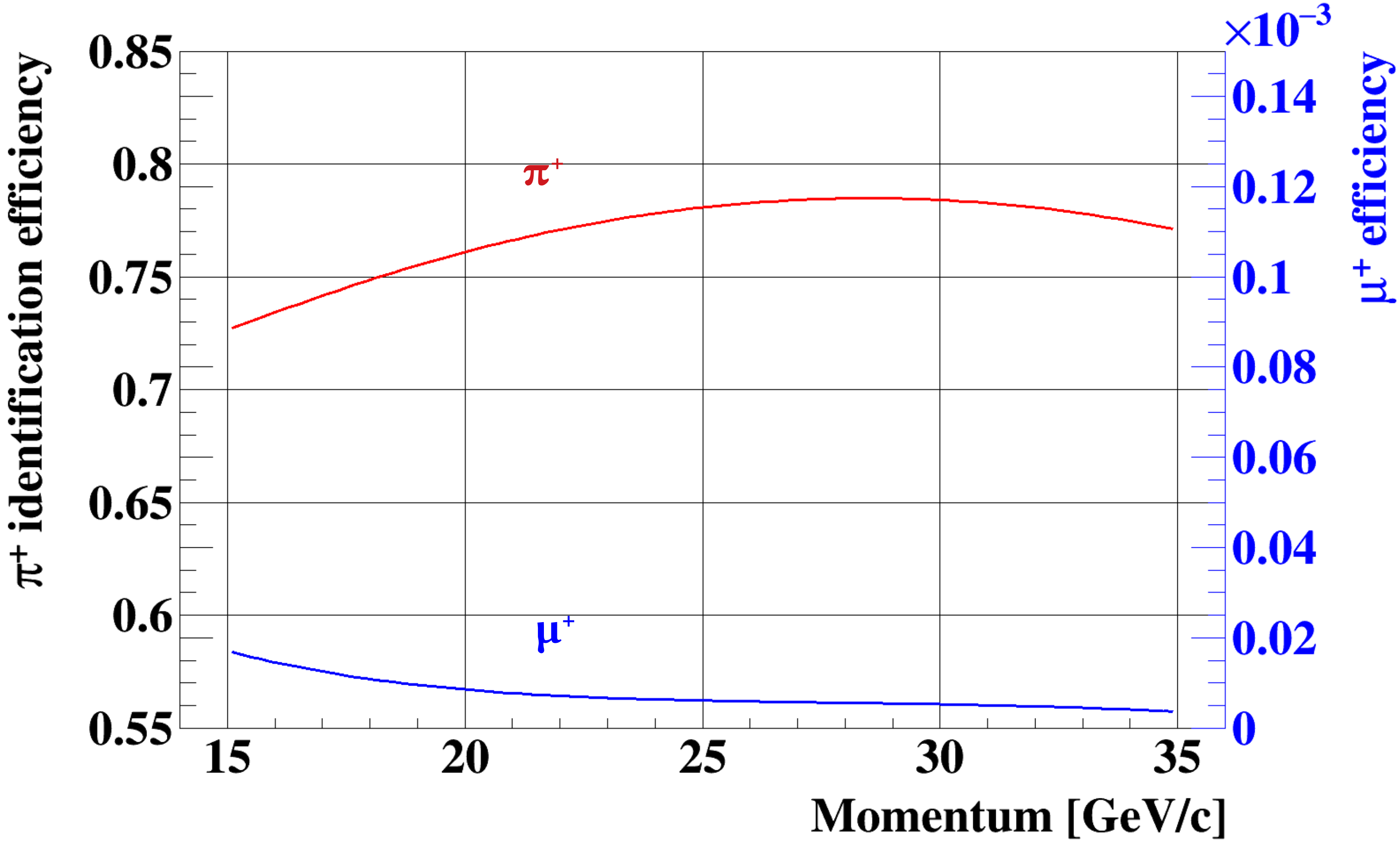


Kinematic resolution



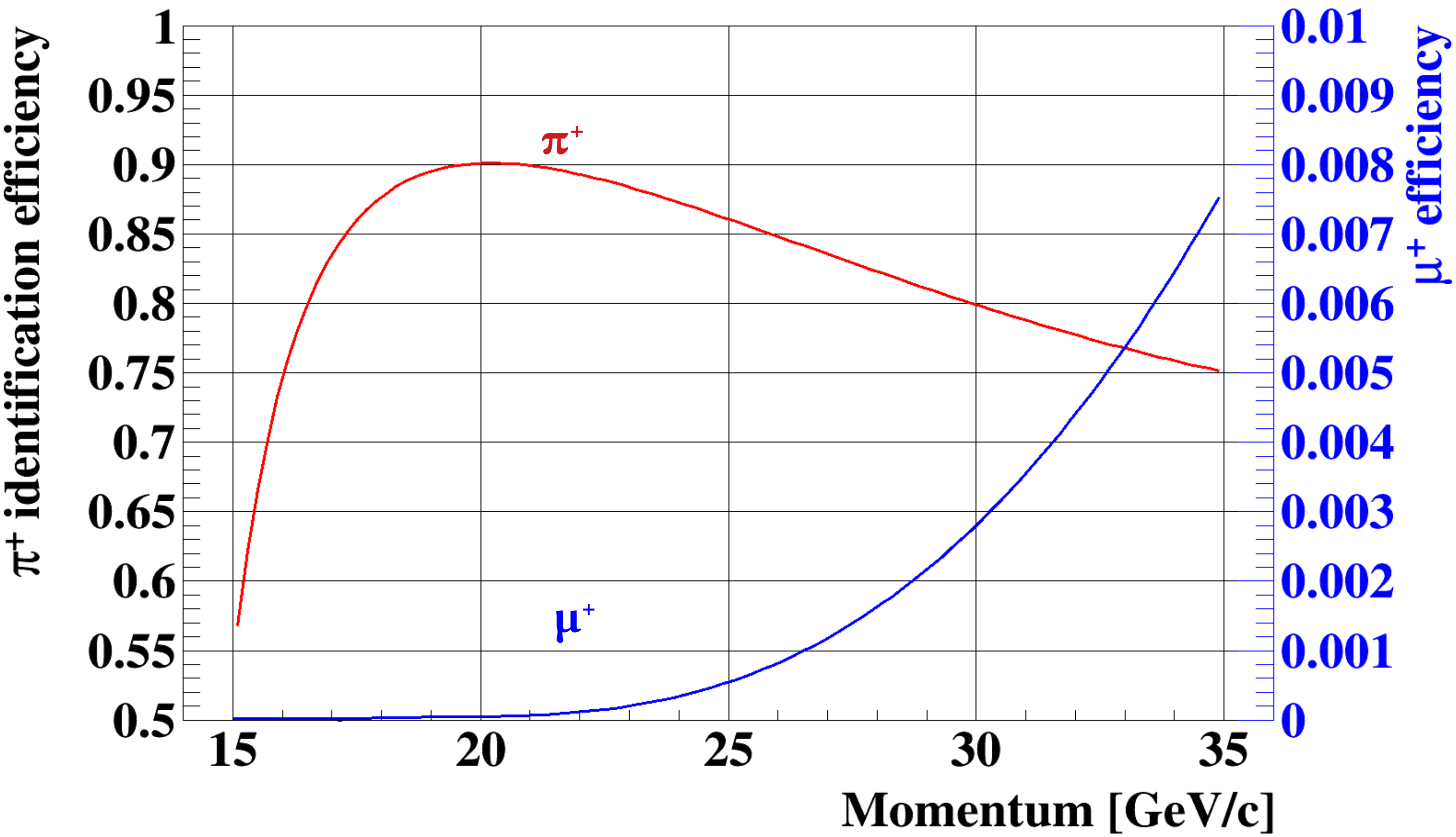
Particle ID with calorimeters

- Electromagnetic calo (LKr), Hadronic calo (MUV1, 2), scintillator blocks (MUV3)
- MUV3+BDT classifier using: energy, energy sharing, clusters shape
- 0.6×10^{-5} μ^+ efficiency vs 77% π^+ efficiency

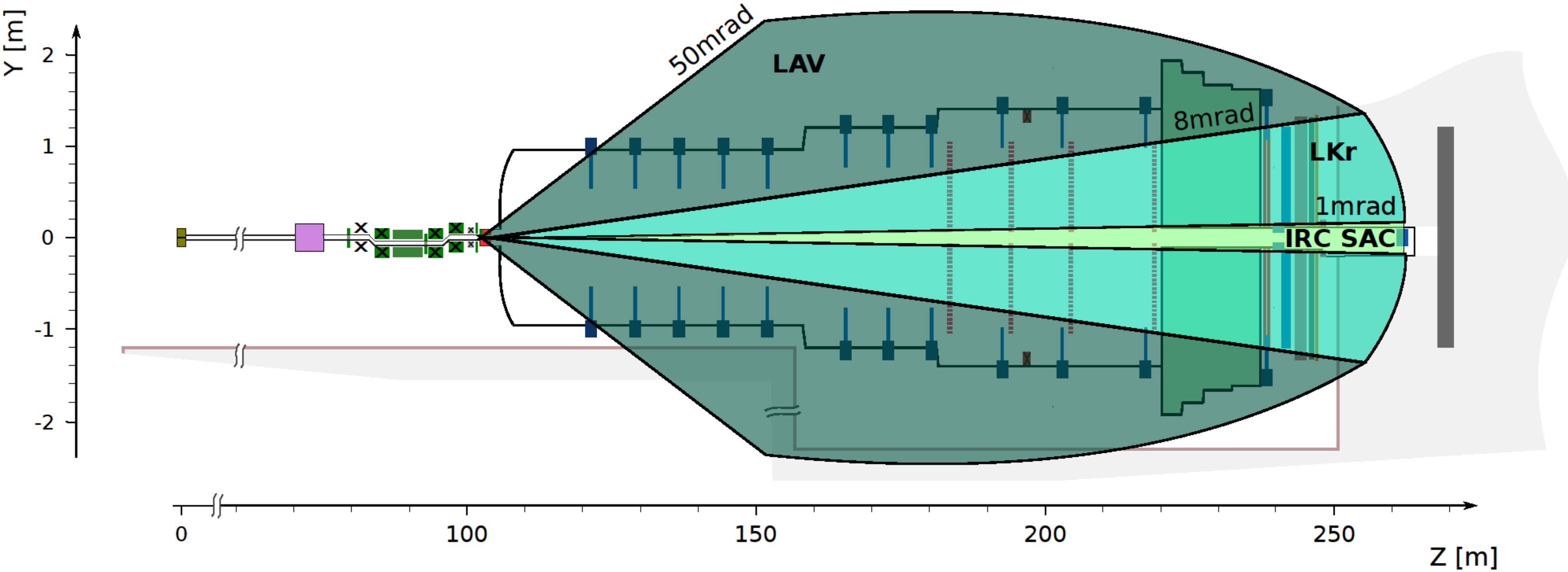


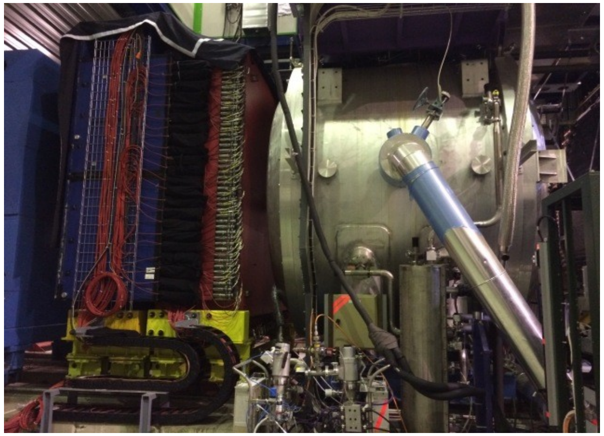
Particle ID with RICH

- Track driven Likelihood particle ID discriminant
- Particle mass using track momentum
- Momentum measurement under mass hypothesis (velocity - spectrometer)
- 2.5×10^{-3} μ^+ efficiency vs 82% π^+ efficiency



Photon rejection

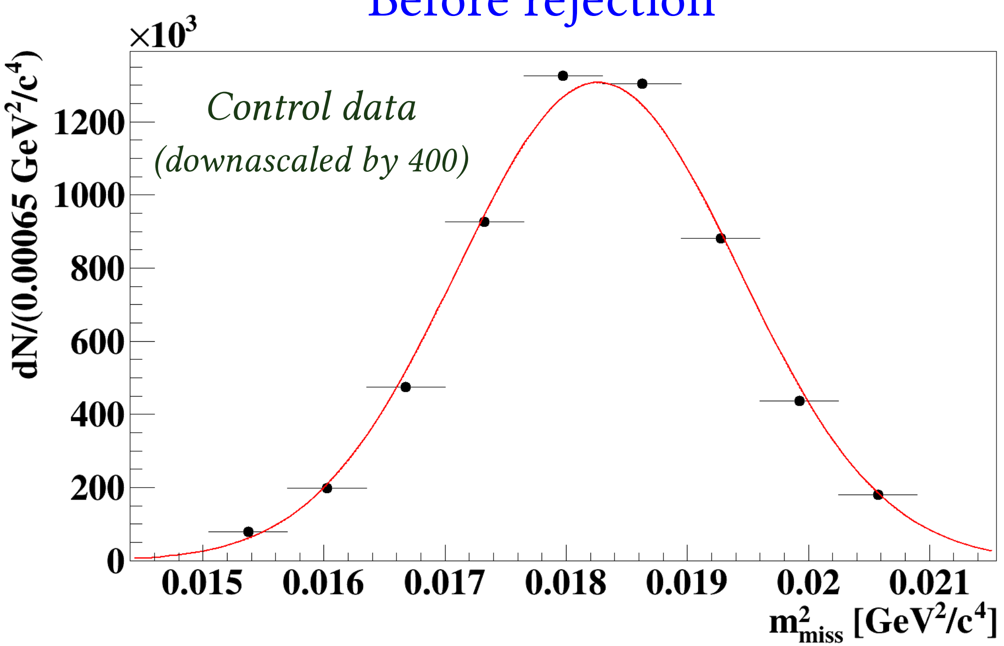




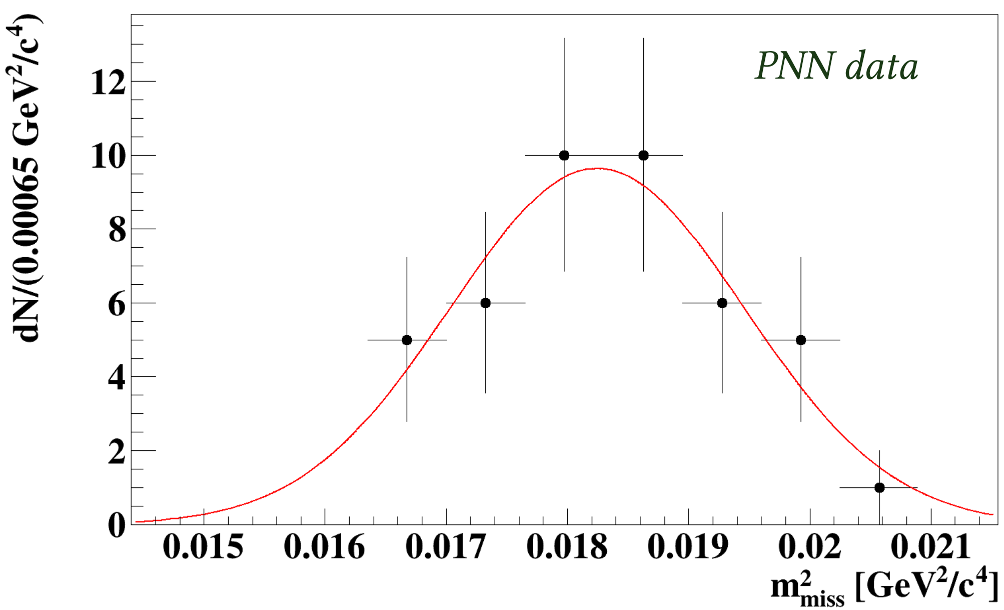
Photon and multi-charged rejection

- Timing coincidence of signals in LKr, LAV, SAV not associated to π^+ and t_{decay}
- Coincidences of signals in LKr and hodoscopes not associated to π^+, in time with t_{decay}
- No hits in time in HASC and MUV0 (off-acceptance veto); segments rejection in Straw
- Typical timing coincidences: ±3 to ±5 ns; energy dependent time cuts in LKr
- Fraction of surviving $K^+ \to \pi^+\pi^0$ (15 – 35 momentum range) : **~ 2.5 x 10^{-8}**
- High suppression of $K^+ \to \pi^+\pi^+\pi^-$, $K^+ \to \pi^+\pi^-e^+\nu_e$

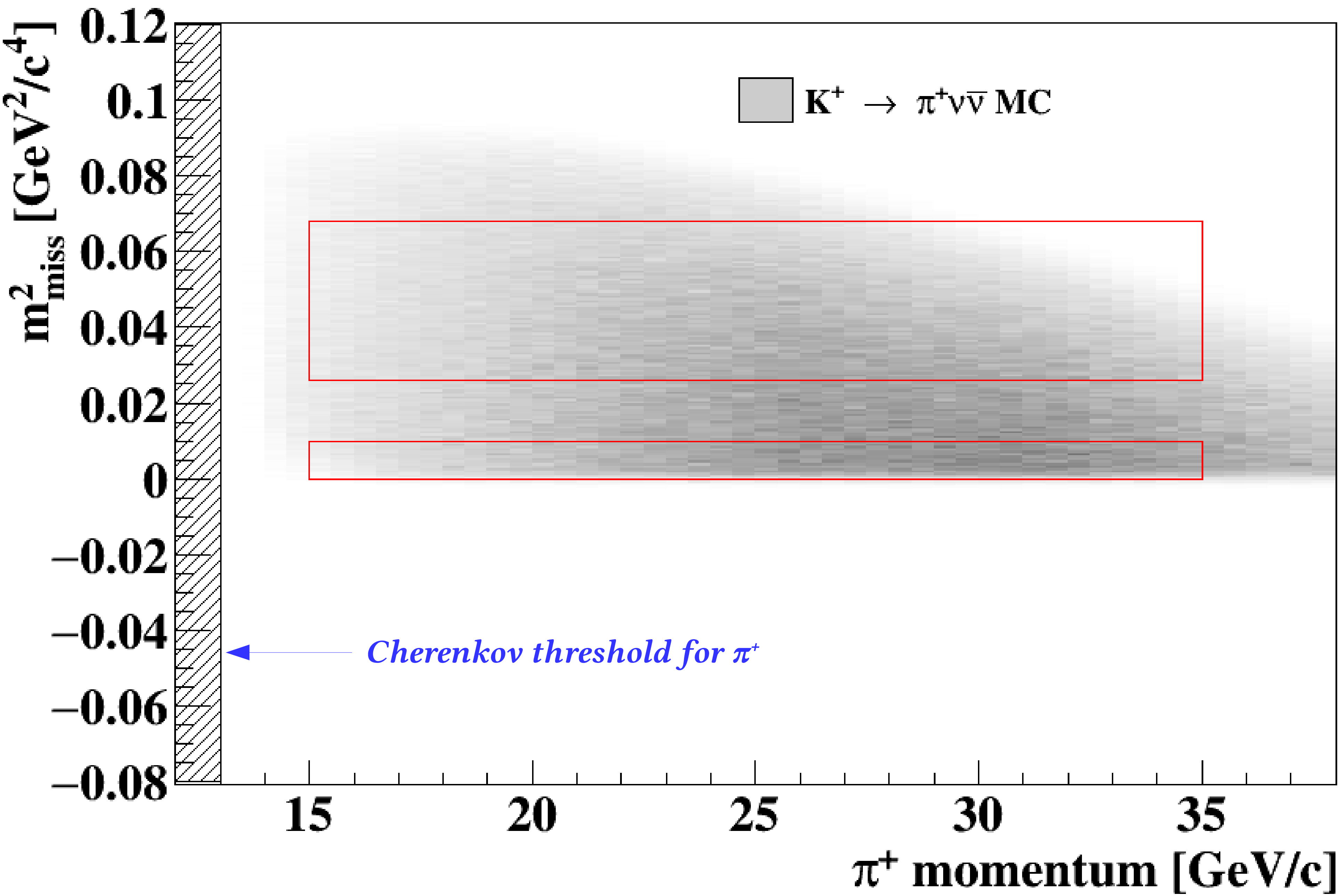
Before rejection



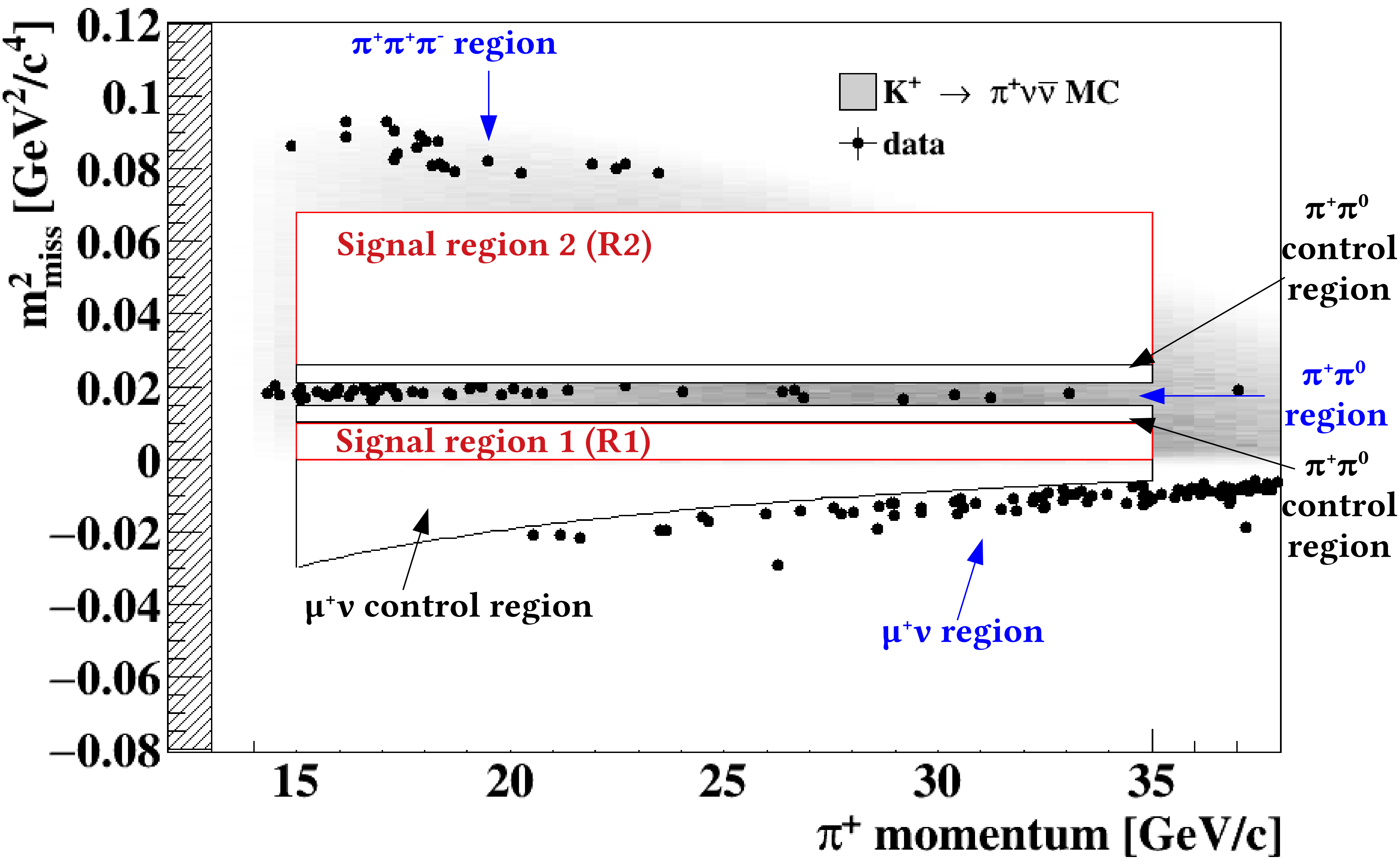
After rejection



Signal MC after selection



Data after selection



2. Single Event Sensitivity (SES)

Signal Event Sensitivity (SES) definition

- Normalization: $K^+ \rightarrow \pi^+\pi^0$ from control data
- Same $\pi^+\nu\bar{\nu}$ selection: γ, multiplicity rejection not applied; $\mathbf{m^2_{miss}}$ cuts modified

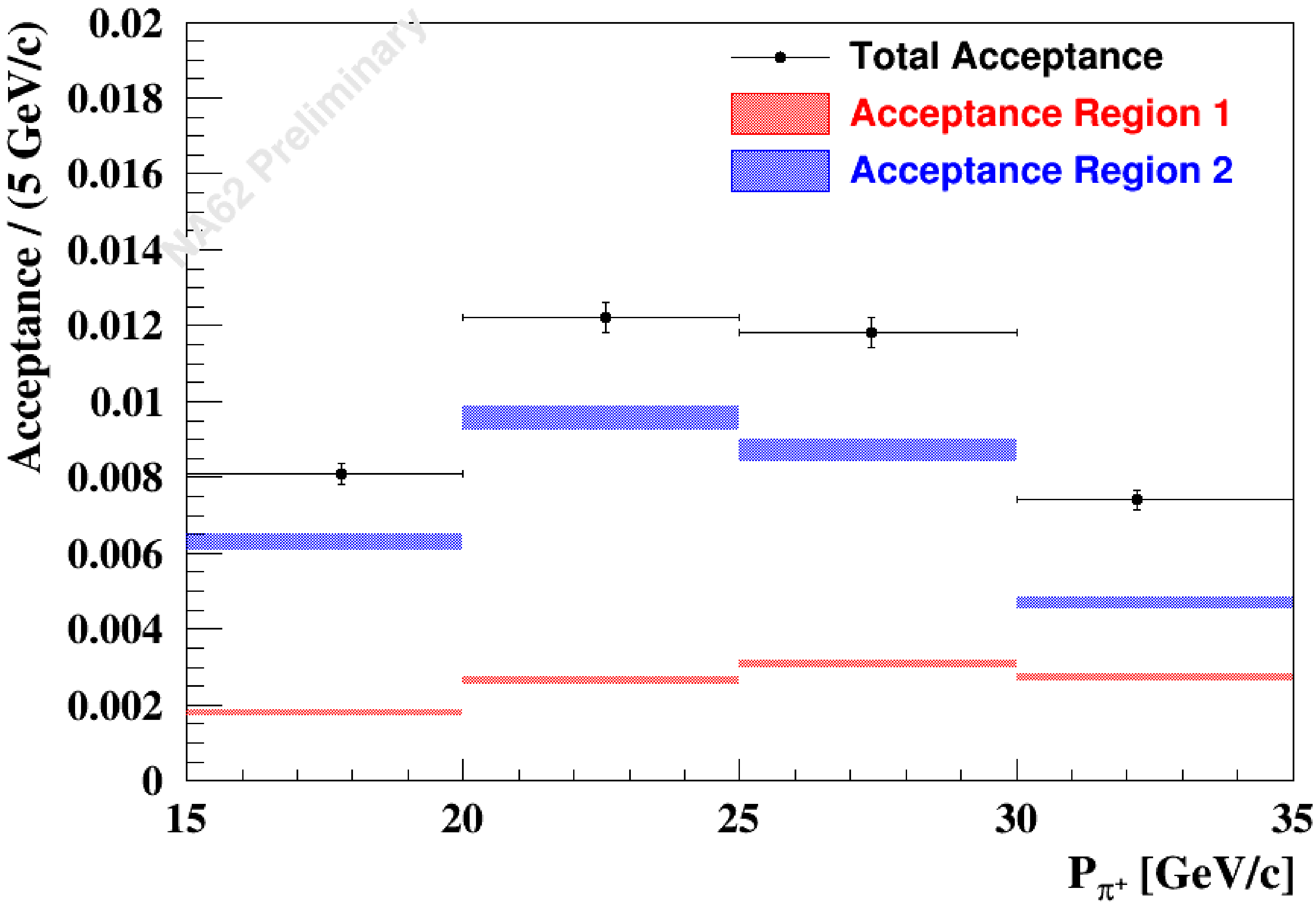
$$N_K = \frac{N_{\pi\pi} \cdot D}{A_{\pi\pi} \cdot BR_{\pi\pi}} \qquad SES = \frac{1}{N_K \sum_j \left(A^j_{\pi\nu} \cdot \epsilon^j_{RV} \epsilon^j_{trig} \right)}$$

N_K	Number of K^+ decays	ϵ_{RV}	Random veto efficiency
$N_{\pi\pi} \sim 6 \cdot 10^6$	Number of $K^+ \rightarrow \pi^+\pi^0$	ϵ_{trig}	Trigger efficiency
$A_{\pi\pi} \sim 0.1$	Normalization acceptance	$A_{\pi\nu\nu}$	Signal acceptance
$D = 400$	Control-trigger downscaling	j	π^+ momentum bin

$$N_{K^+} = (1.21 \pm 0.02) \times 10^{11}$$

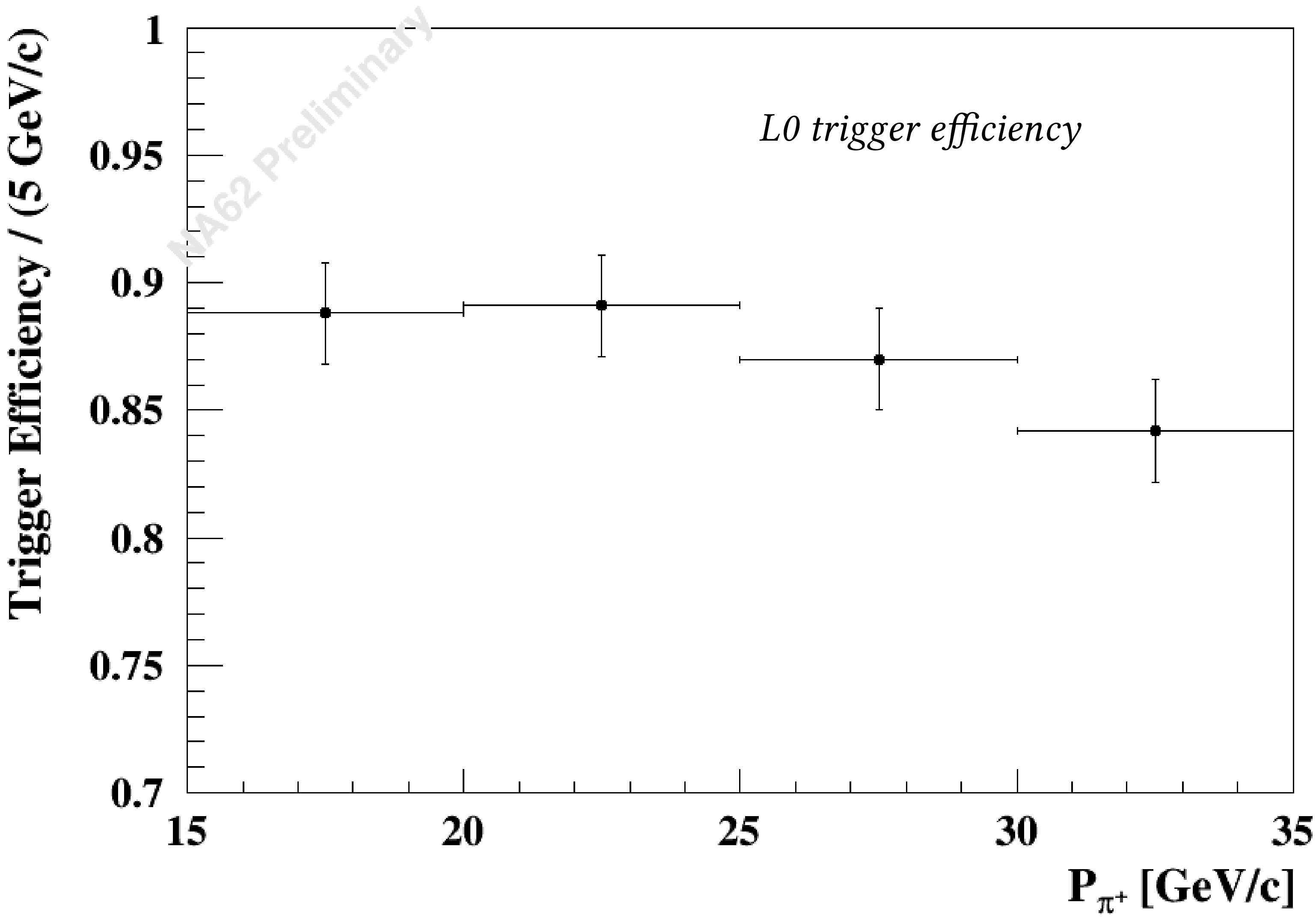
Signal acceptance

- Computed with MC
- Particle ID, losses due to interactions included



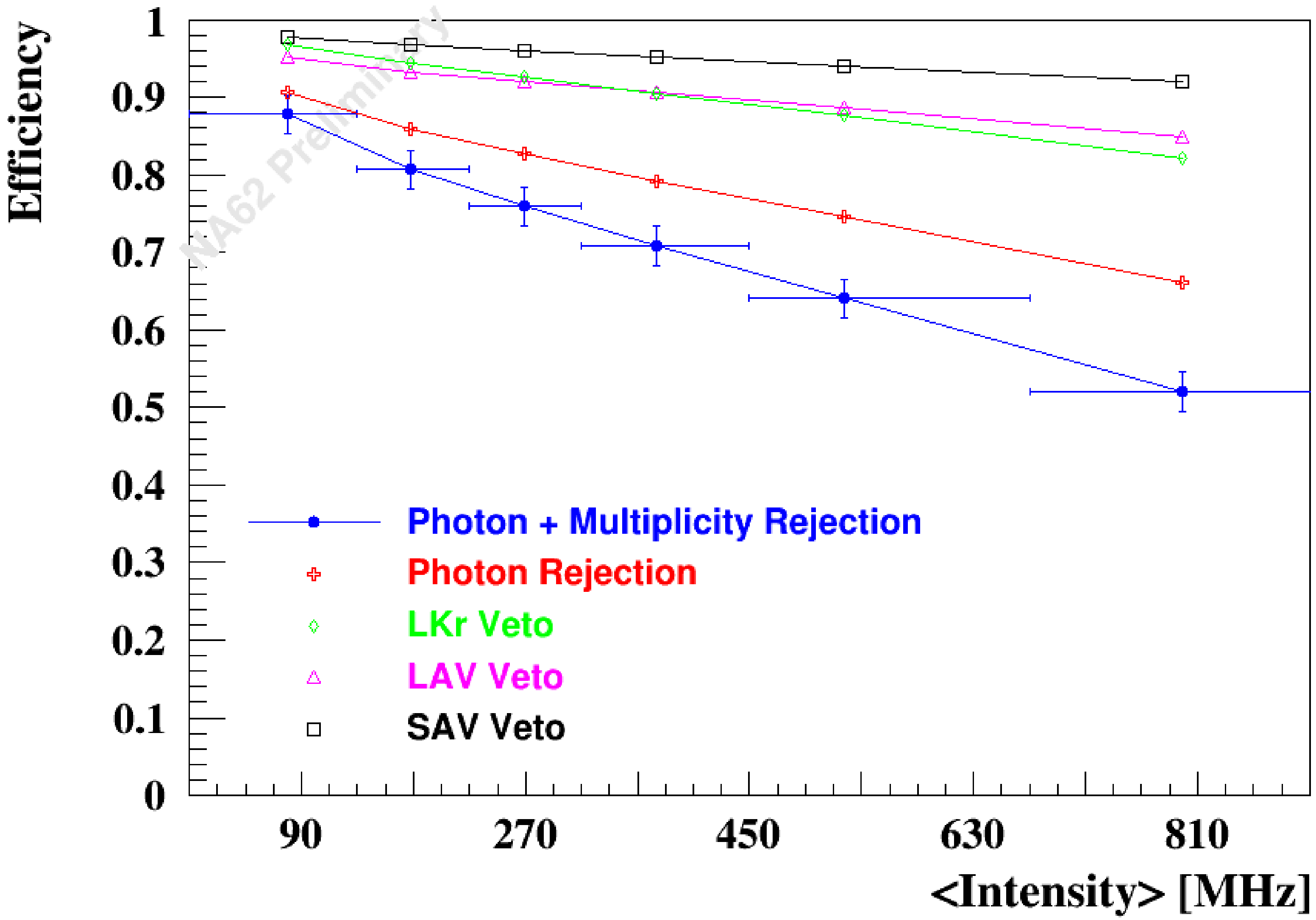
Trigger efficiency

- Measured on data using $K^+ \to \pi^+\pi^0$ selected from control triggers
- Losses mainly from L0, L1 efficiency ~ 0.97



Random veto

- Random signal losses due to γ+ multi-charged rejection measured with $K^+ \to \mu^+ \nu_\mu$
- $\varepsilon_{RV} \approx 0.76$ independent of $P_{\pi+}$, but depends on instantaneous intensity



Single event sensitivity results

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

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

Acceptance $K^+ \to \pi^+\nu\bar{\nu}$	(4.0 ± 0.1) %
PNN trigger efficiency	0.87 ± 0.2
Random veto	0.76 ± 0.04

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 π+ interactions	± 0.09
Extra activity	± 0.02
GTK Pileup simulation	± 0.02
Total	± 0.24

3. Background estimation

$K^+\to\pi^+\pi^0(\gamma)$ background

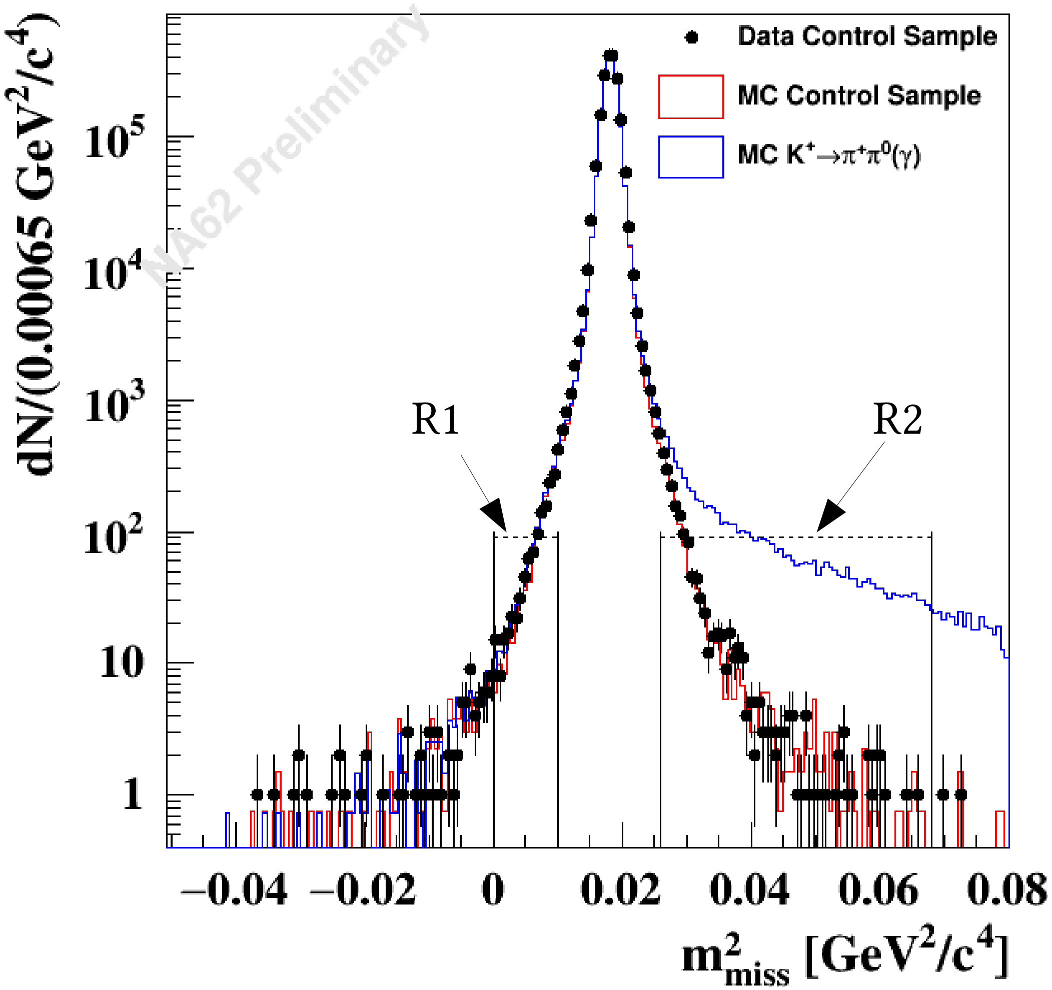
Events in $\pi^+\pi^0$ region after $\pi^+\nu\bar{\nu}$ selection

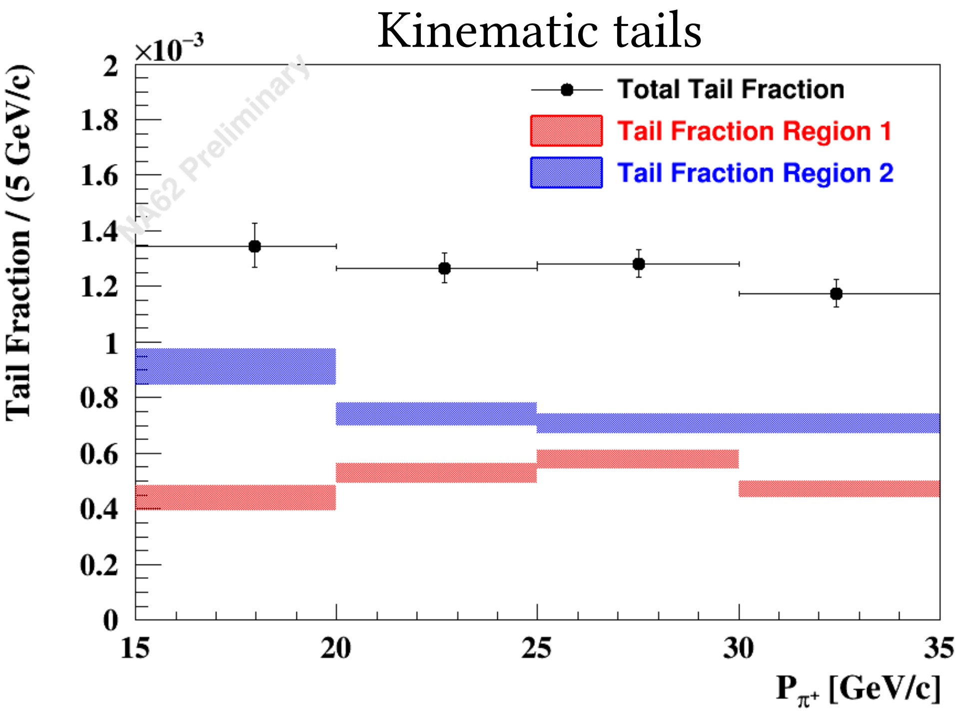
$$\underbrace{N^{exp}_{\pi\pi}(region)}_{\text{Expected events}} = \sum_{j} \left[\overbrace{N_{\pi\pi}(\pi^+\pi^0)_j}^{} \cdot \underbrace{f^{kin}_j(region)}_{\text{Fraction of events in } region} \right]$$

j: π^+ momentum bin

- f_j^{kin} (region) measured: $\pi^+\pi^0$ sample selected tagging the π^0 with 2 γ's in Lkr
- MC studies with and without π^0 tagging
- π^0 and kinematic rejection assumed independent

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

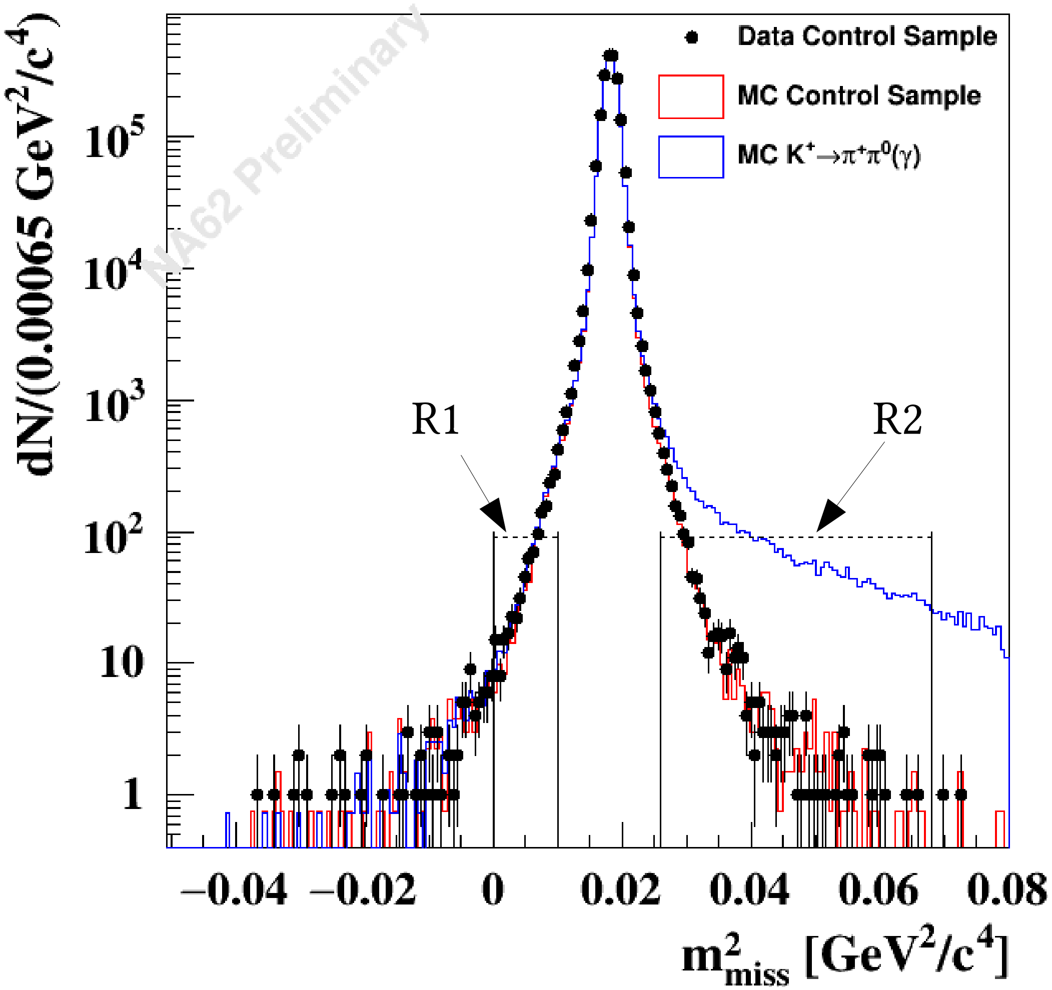




Number of expected events

Region	$\pi^+\pi^0$
R1	$0.022 \pm 0.004_{stat} \pm 0.002_{syst}$
R2	$0.037 \pm 0.006_{stat} \pm 0.003_{syst}$

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

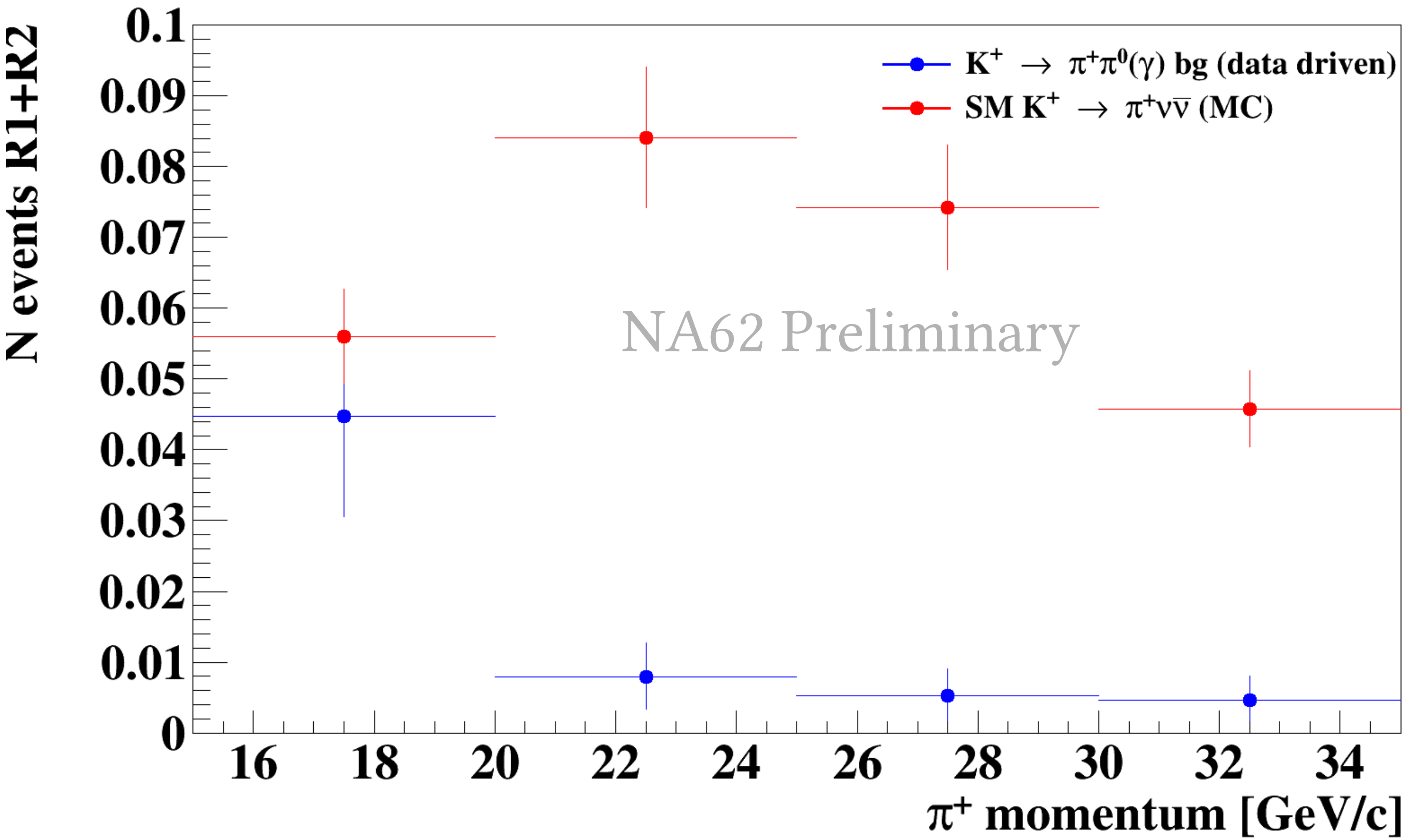


- Radiative tail in R2 estimated from MC:
  - x6 higher than kinematic tails
- Single-γ veto efficiency measured on data
- Measured π^0 rejection reproduced on MC
- $\pi^0\gamma$ rejection of the radiative tail in R2 estimated from MC:
  - x30 better than single π^0 rejection

Number of expected events

Region	$\pi^+\pi^0\gamma$
R1	0
R2	$0.005 \pm 0.005_{syst}$

$K^+ \to \pi^+\pi^0(\gamma)$ background estimation



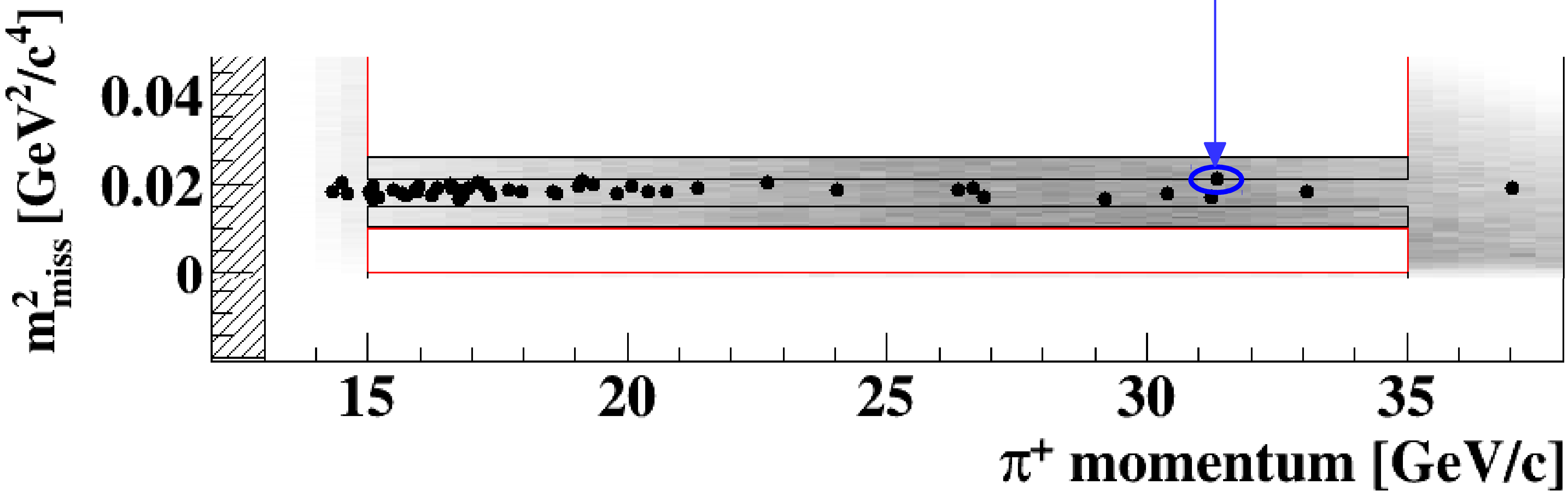
$$N^{bg}_{\pi\pi(\gamma)} = 0.064 \pm 0.007_{stat} \pm 0.006_{syst}$$

$K^+ \to \pi^+\pi^0(\gamma)$ 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



41

$K^+ \rightarrow \mu^+ \nu_\mu (\gamma)$ background

Events in $\mu^+\nu$ region after $\pi^+\nu\bar{\nu}$ selection

$$N_{\mu\nu}^{exp}(region) = \sum_j \left[N(\mu^+\nu)_j \cdot f_j^{kin}(region) \right]$$

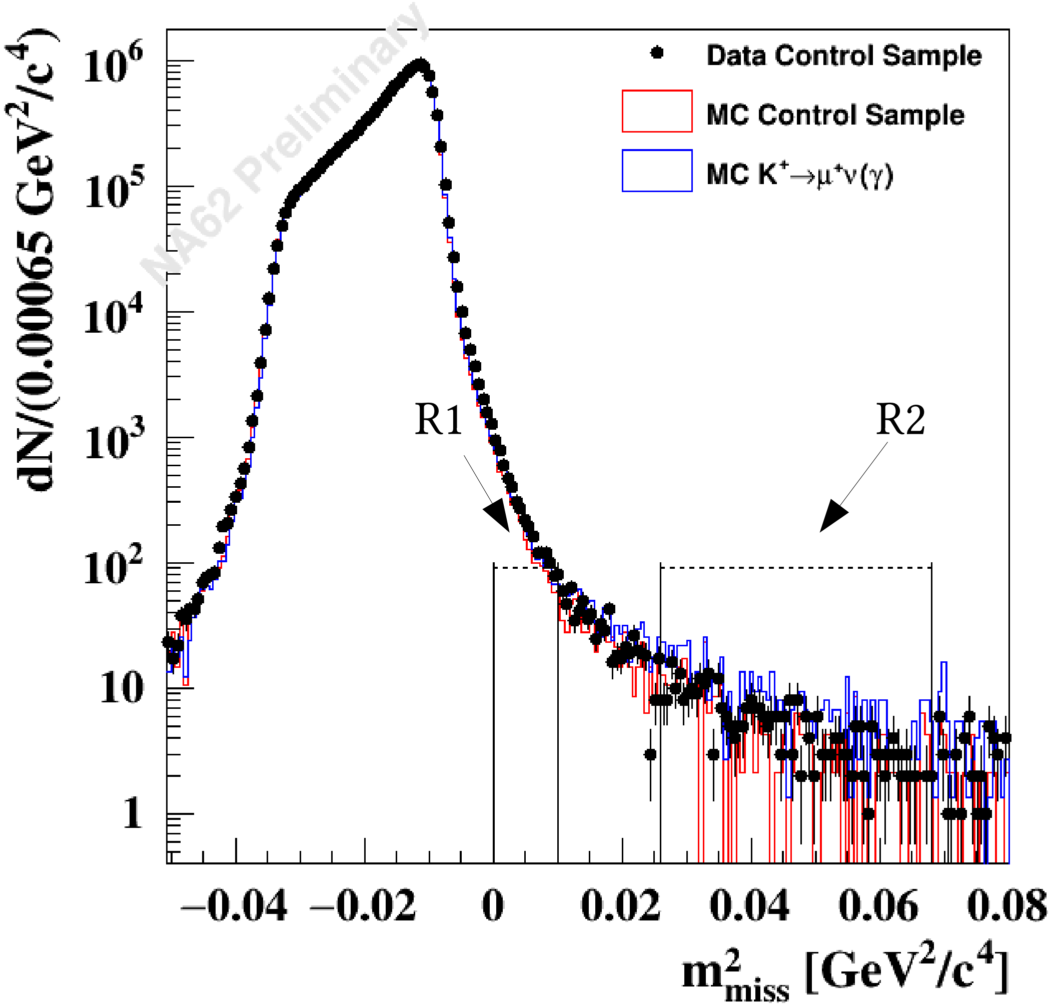
Expected events

Fraction of events in region *region*

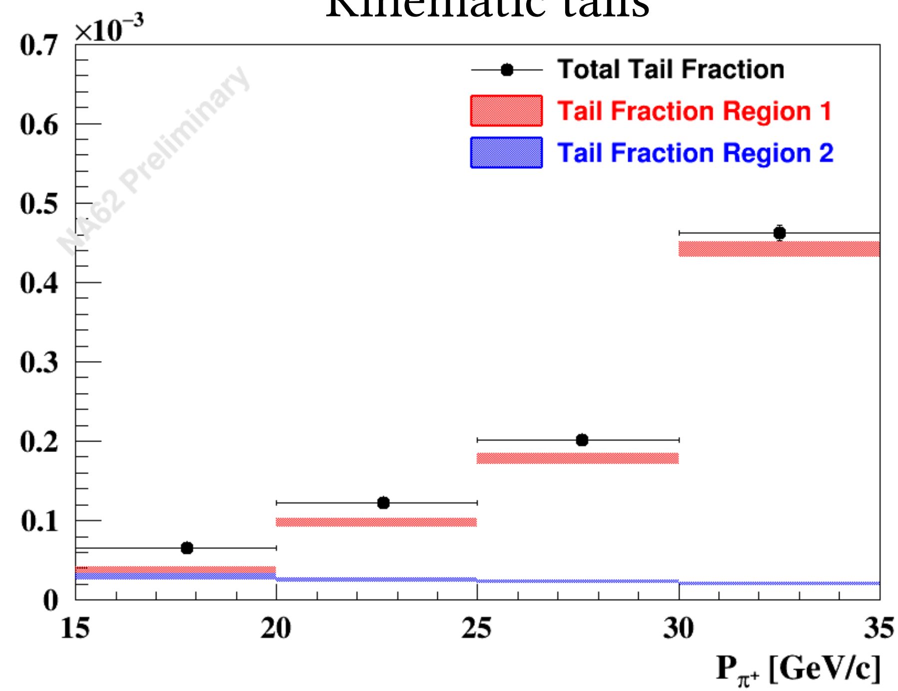
π^+ momentum bin

- f_j^{kin} (region) measured: $\mu^+\nu$ sample selected tagging the μ^+ and applying γ rejection
- Same method applied to MC
- PID and kinematic rejection assumed independent
  - Independence tested measuring muon PID with RICH directly on tails.

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



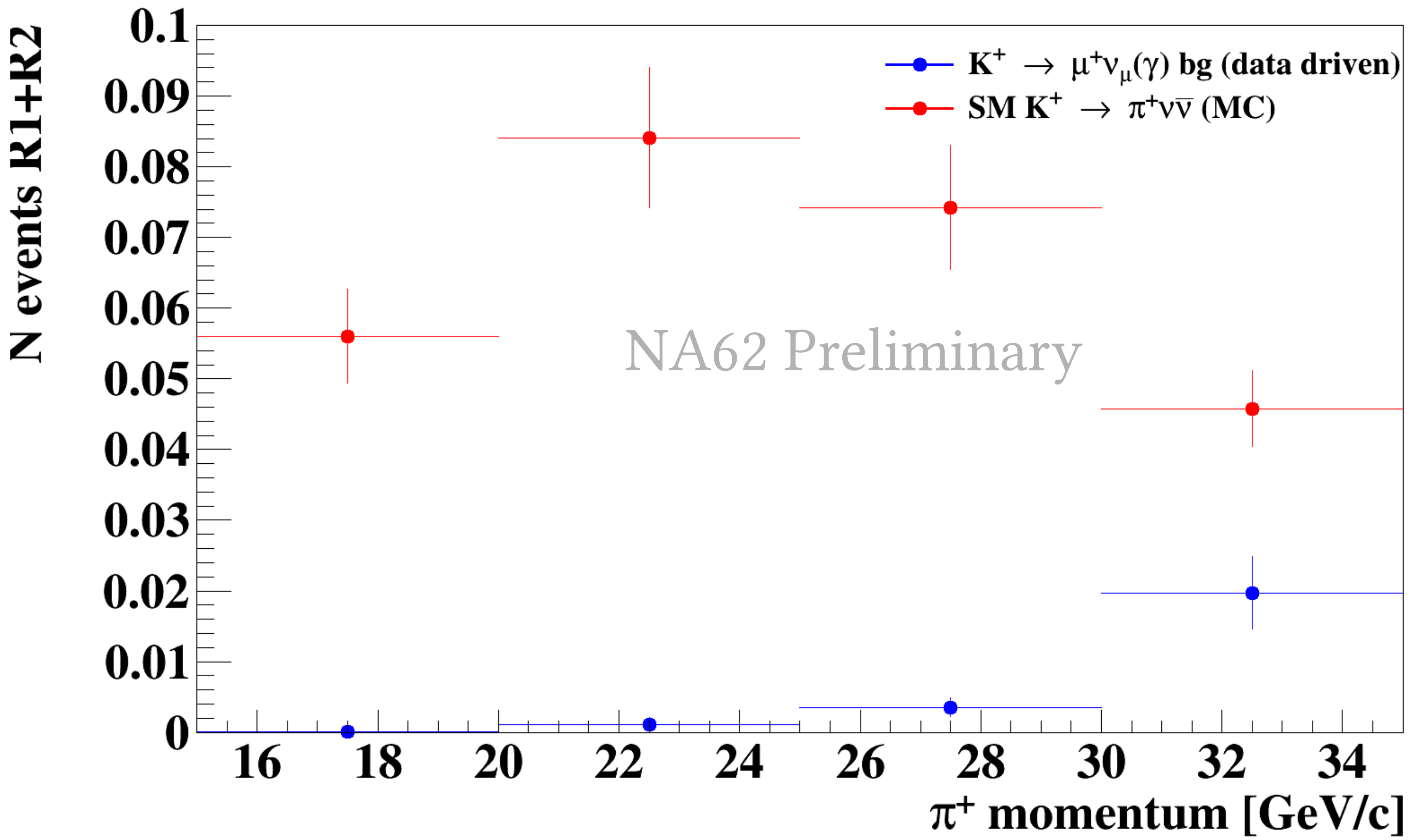
Kinematic tails



Number of expected events

Region	$K_{\mu2}(\gamma)$
R1	$0.019 \pm 0.03_{stat} \pm 0.03_{syst}$
R2	$0.0012 \pm 0.0002_{stat} \pm 0.0006_{syst}$

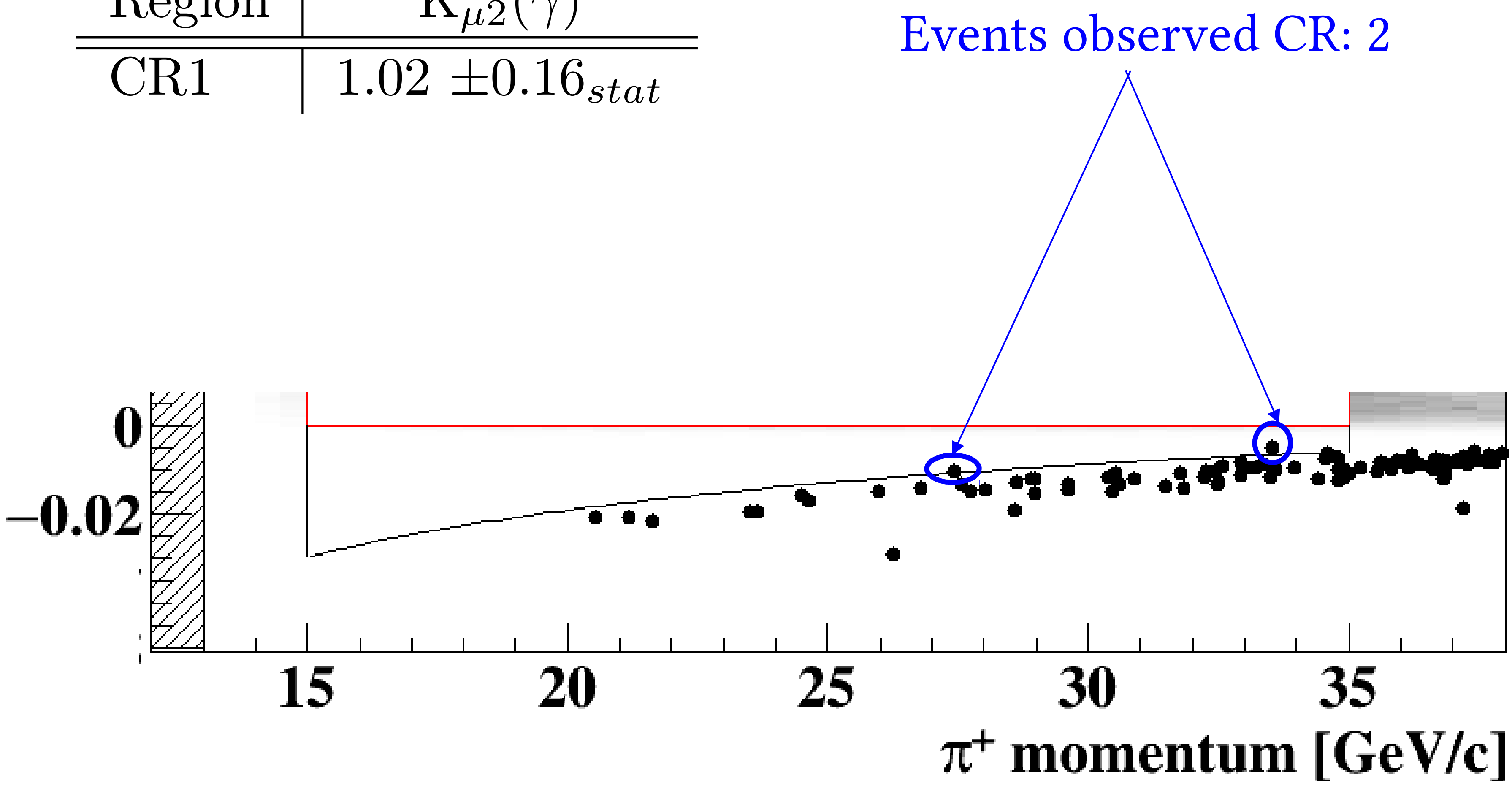
$K^+ \to \mu^+\nu_\mu(\gamma)$ background estimation



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

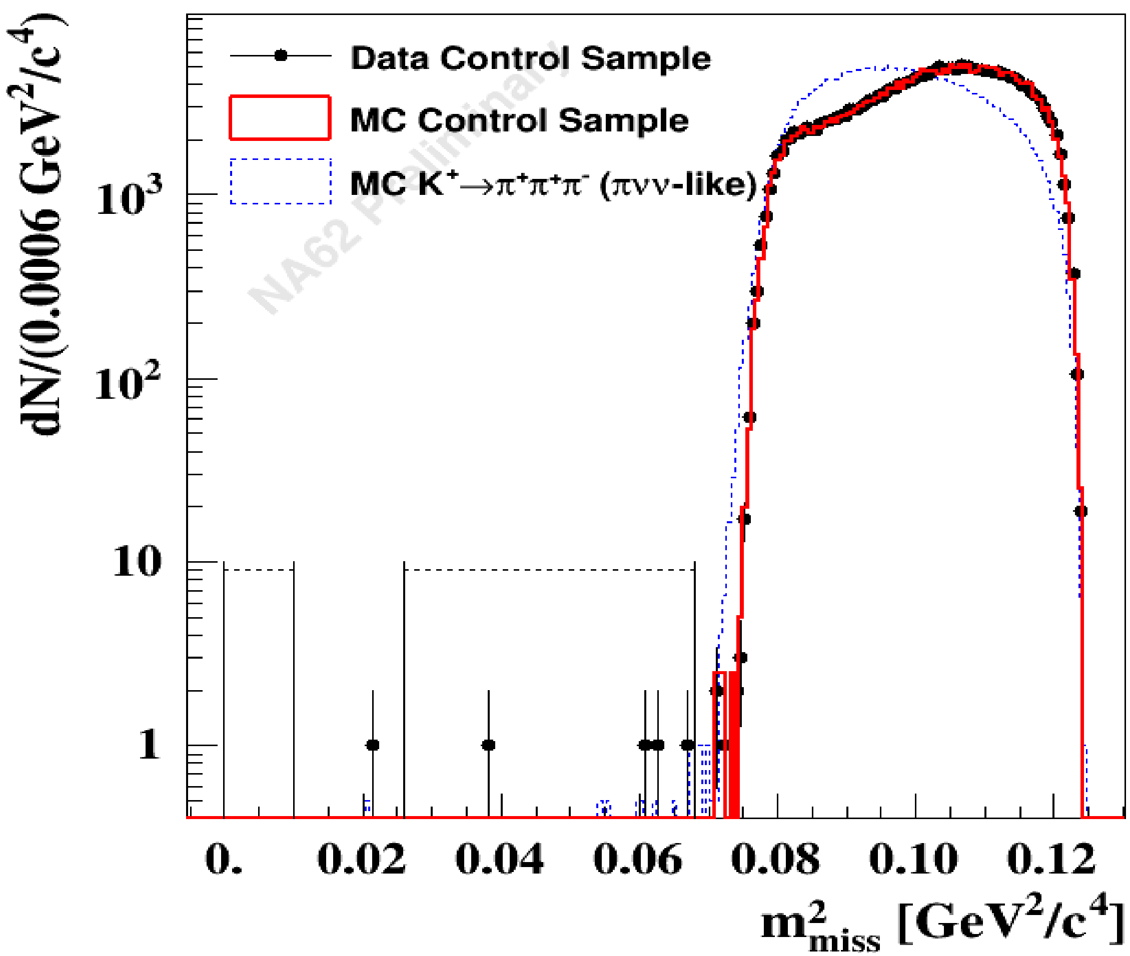
$K^+ \to \mu^+ \nu_\mu(\gamma)$ background validation

Region	$K_{\mu 2}(\gamma)$
CR1	$1.02 \pm 0.16_{stat}$



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

$$N_{\pi\pi\pi}^{exp} = N(\pi^+\pi^+\pi^-) \cdot f^{kin}(R2)$$

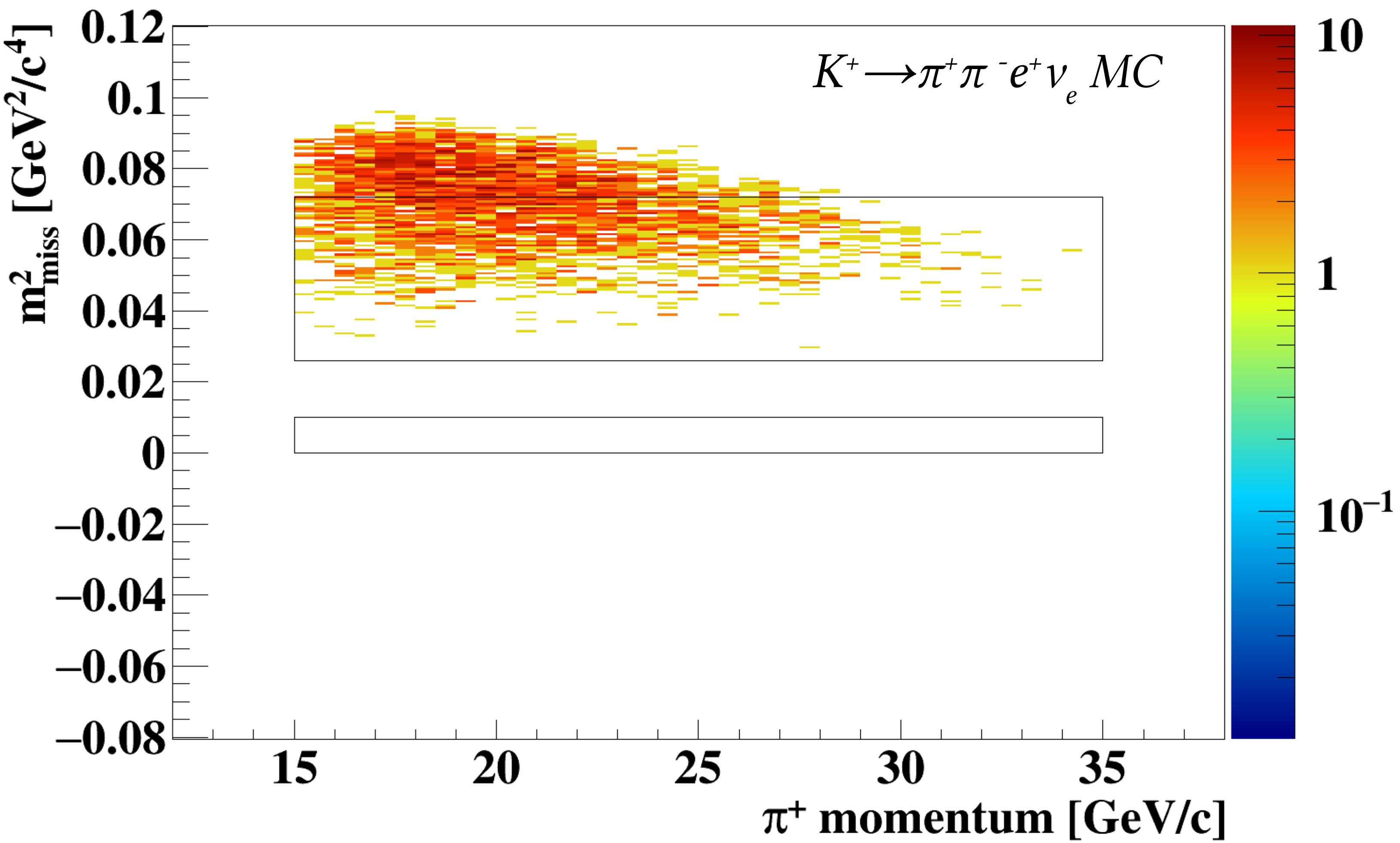


- $N(\pi^+\pi^+\pi^-)$: Event in $\pi^+\pi^+\pi^-$ region after $\pi^+\nu\bar{\nu}$ selection
- f^{kin} measured on a $\pi^+\pi^+\pi^-$ control sample selected tagging the $\pi^+\pi^-$ pair
- Kinematic rejection factor corrected for biases induced by the control sample selection using MC
- f^{kin} (R2) $\leq 10^{-4}$

Number of expected events

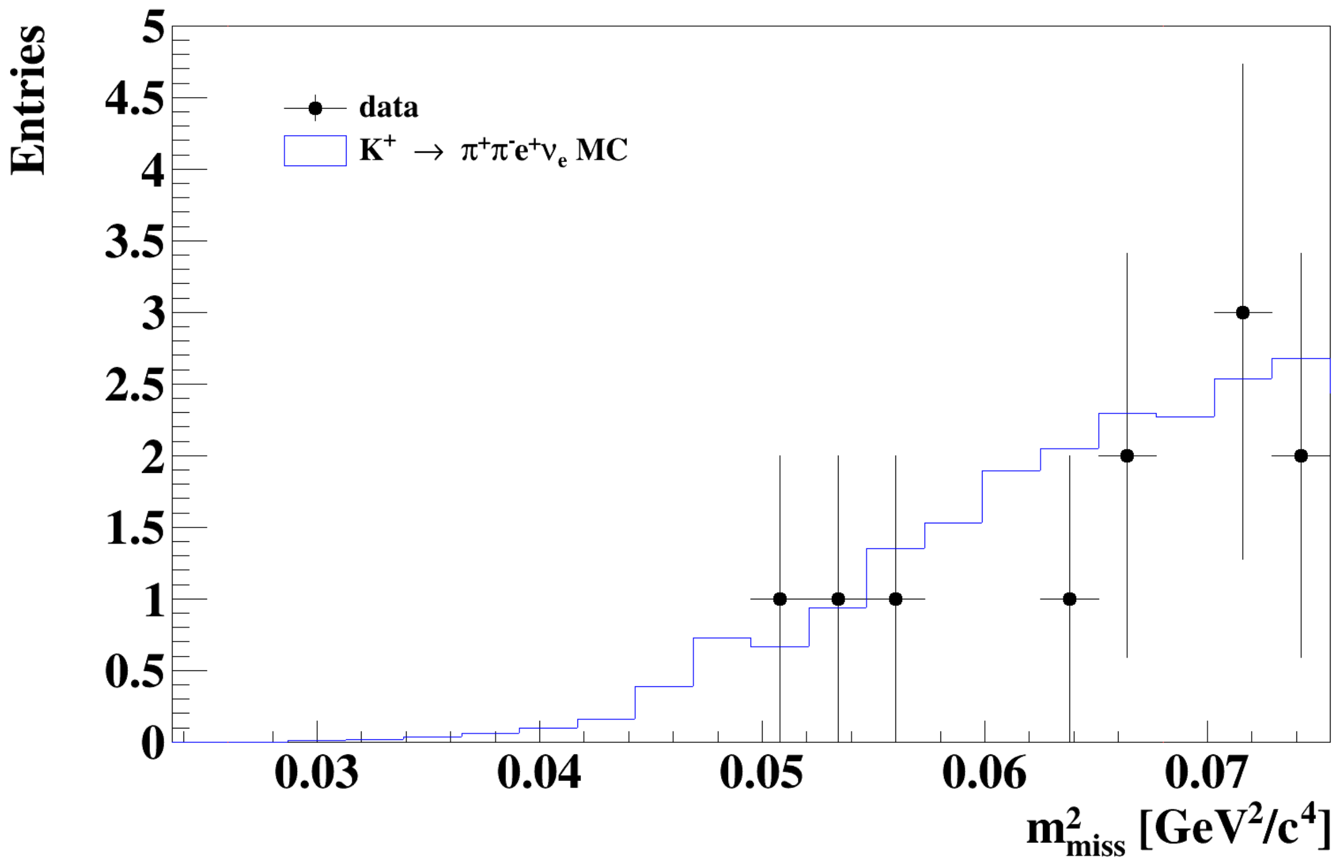
$$N_{\pi\pi\pi}^{exp} = 0.002 \pm 0.001_{stat} \pm 0.002_{syst}$$

$K^+ \to \pi^+\pi^- e^+\nu_e (K_{e4})$ background



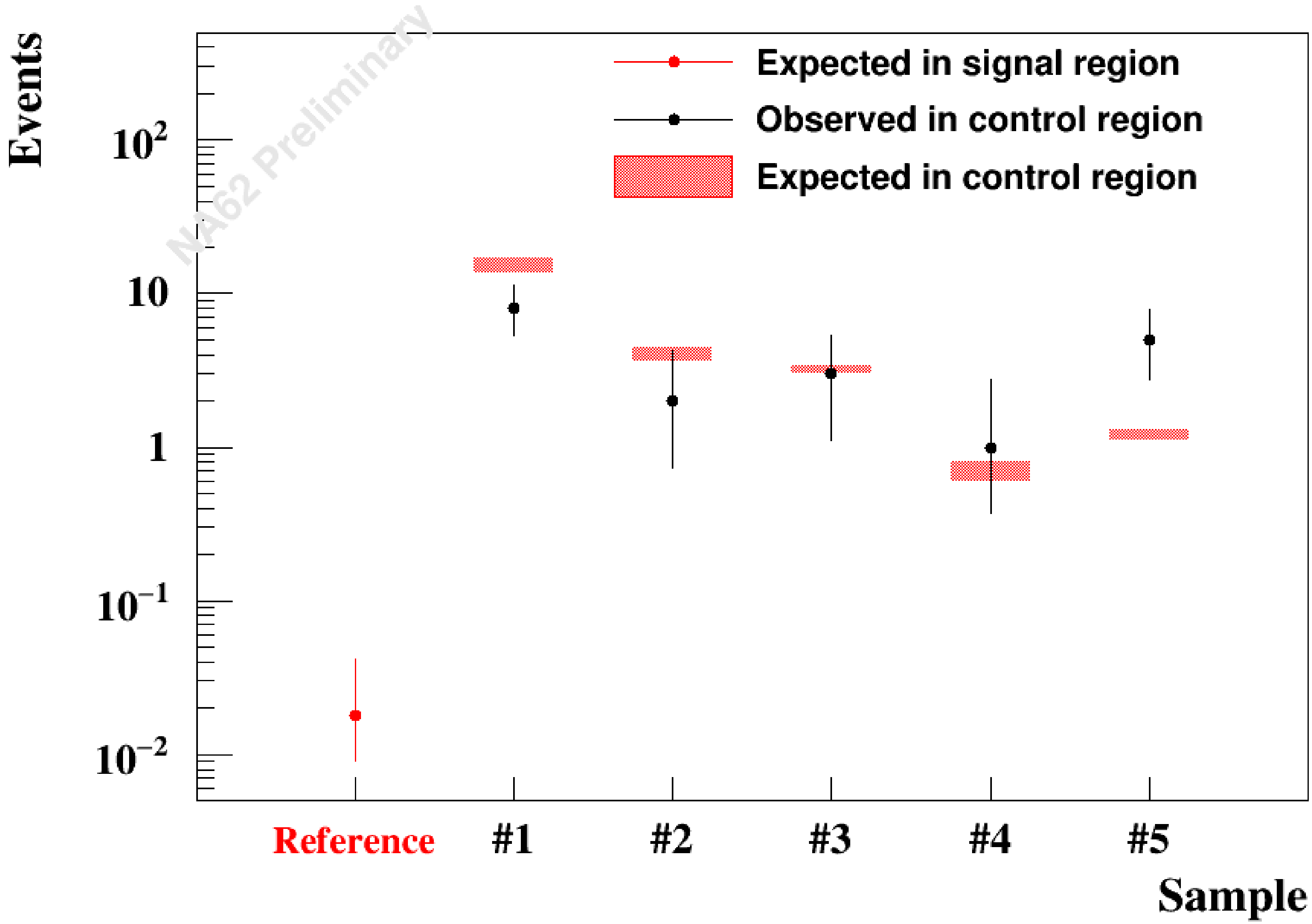
- Background estimated using MC
  - ~4 x 10^8 million events generated
- Validate using 5 different control samples enriched with $K^+ \to \pi^+\pi^- e^+\nu_e$ decays

$K^+ \to \pi^+\pi^- e^+\nu_e (K_{e4})$ background



- Single-π^- events, full $\pi\nu\nu$ selection, straw - multiplicity cuts inverted
- Control region: $0.026 < m^2_{miss} < 0.072$ GeV^2/c^4

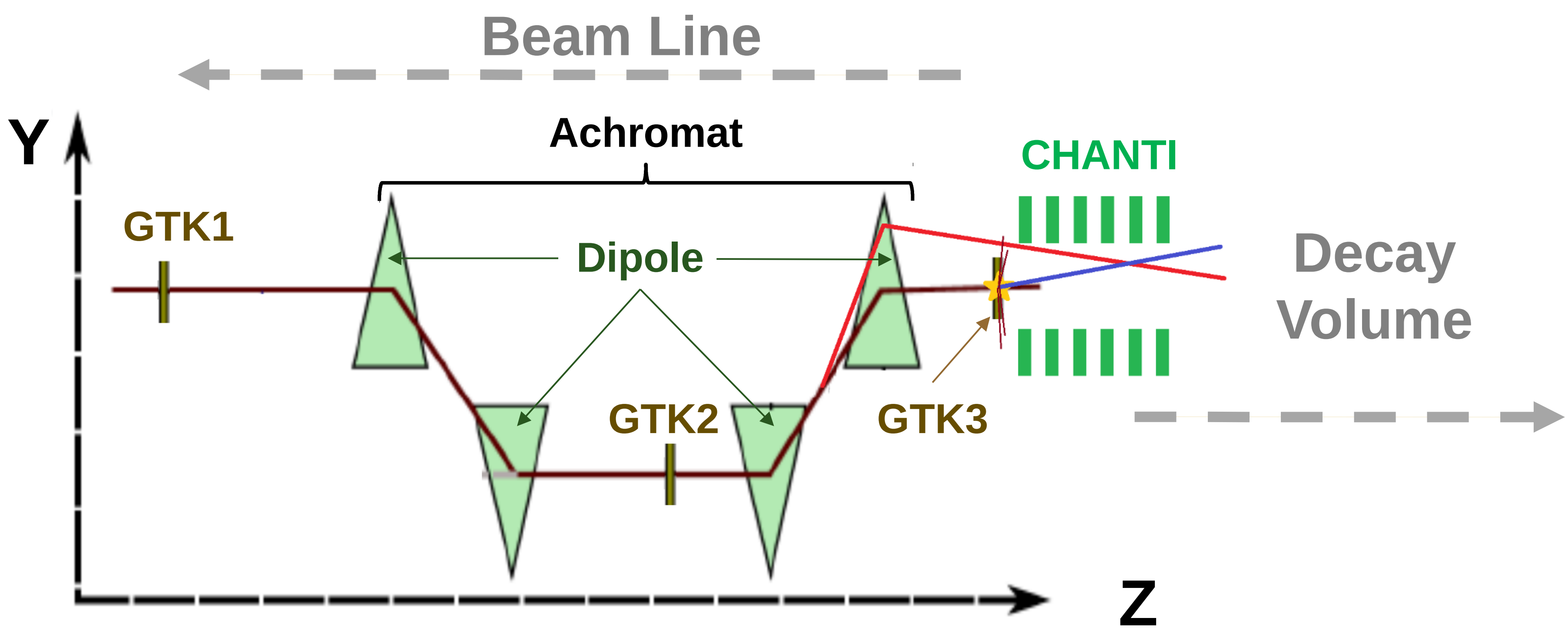
$K^+ \to \pi^+\pi^- e^+\nu_e (K_{e4})$ background estimation



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

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

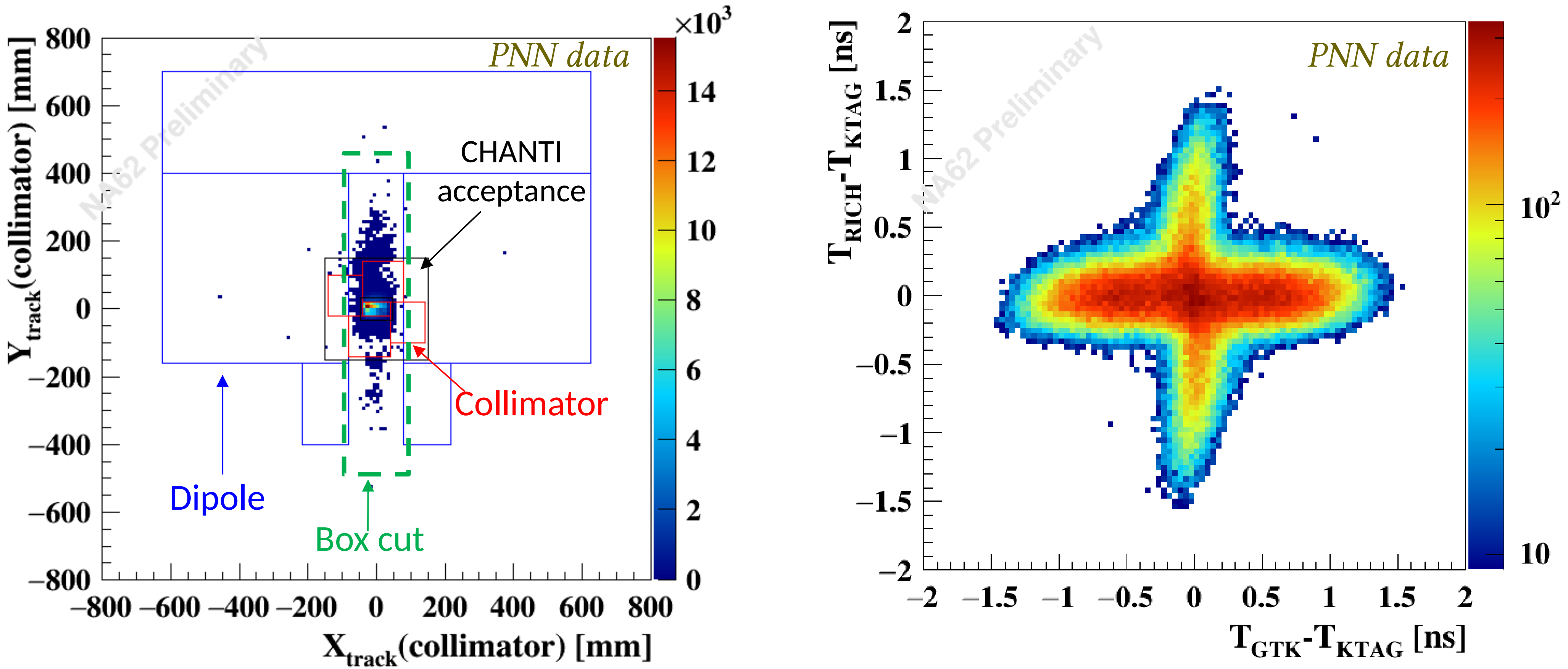
  1) K-π matching 2) Z_{vertex} 3) CHANTI veto

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

Upstream background

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

PNN data: $\pi\nu\nu$ selection, K-π matching inverted, Z_{vertex}, Box cut and CHANTI not applied

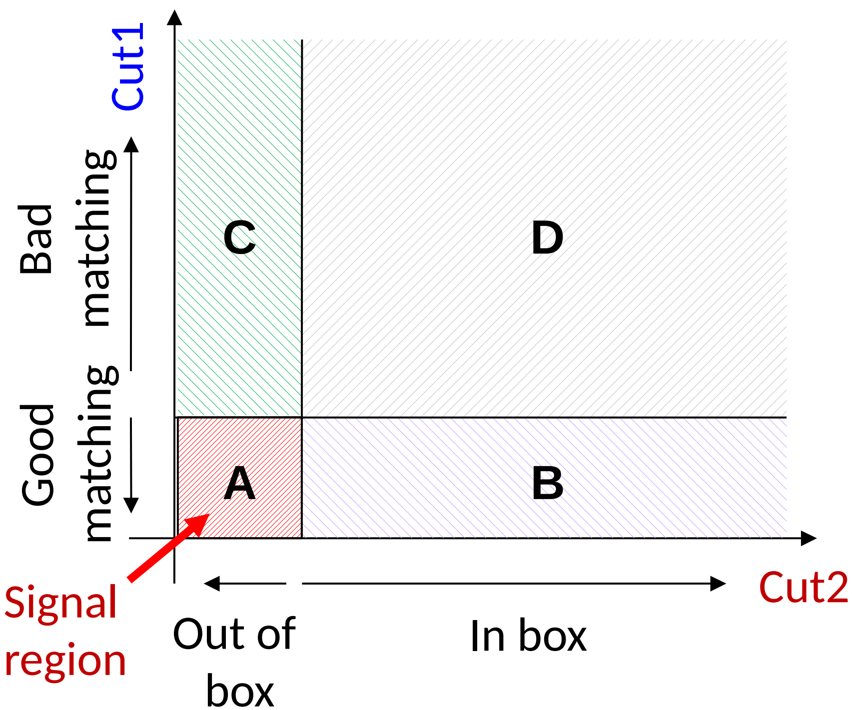


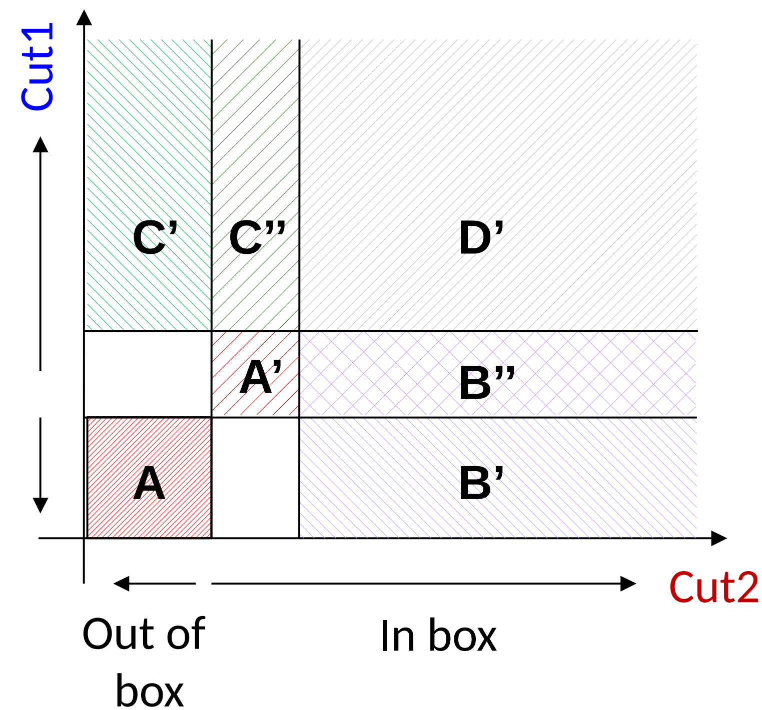
Upstream background

- Bifurcation on PNN triggered data inverting: matching (cut1); Cut box (cut2)
- BCD: reference sample; B’ C’ D’ B’’ C’’: control samples → *4 control samples studied*
- A: signal region; A’: control region

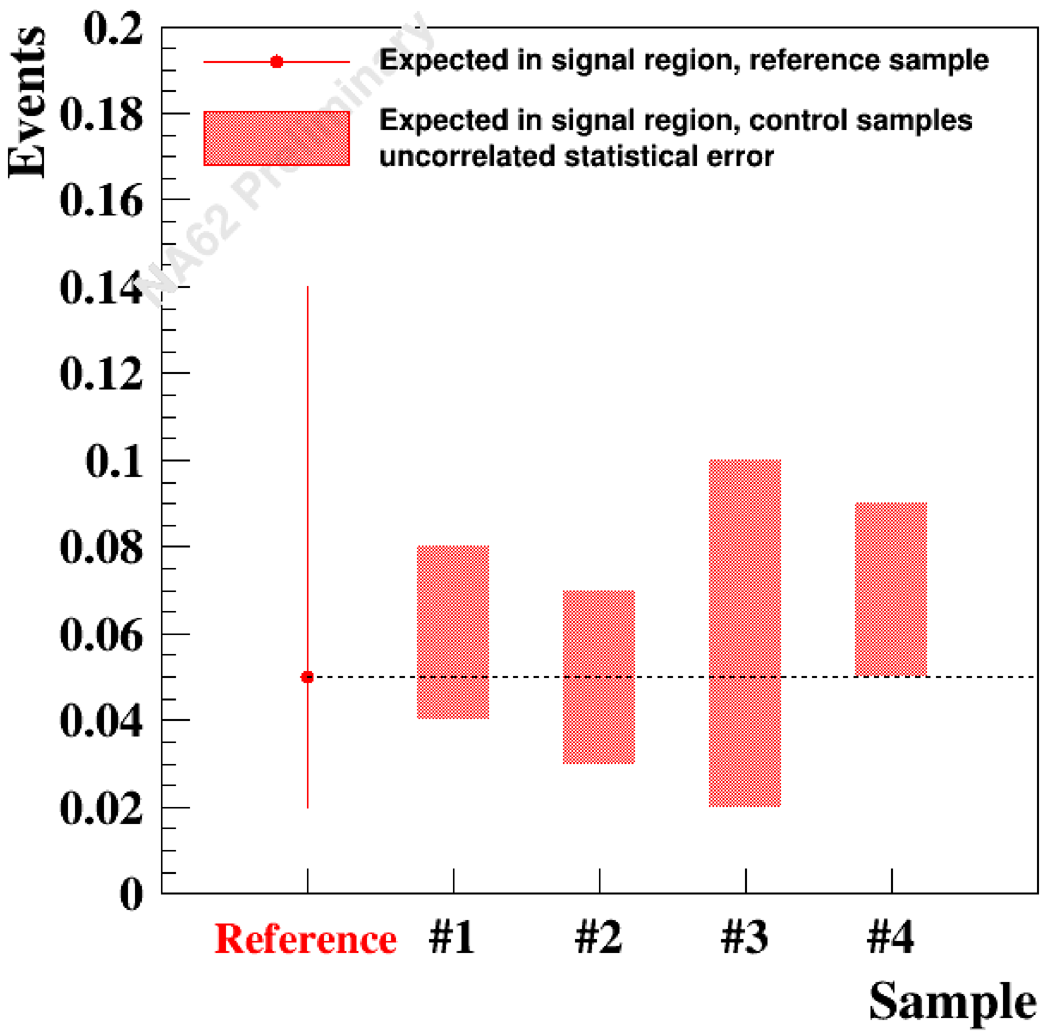
$$A(exp) = \frac{B \cdot C}{D}$$

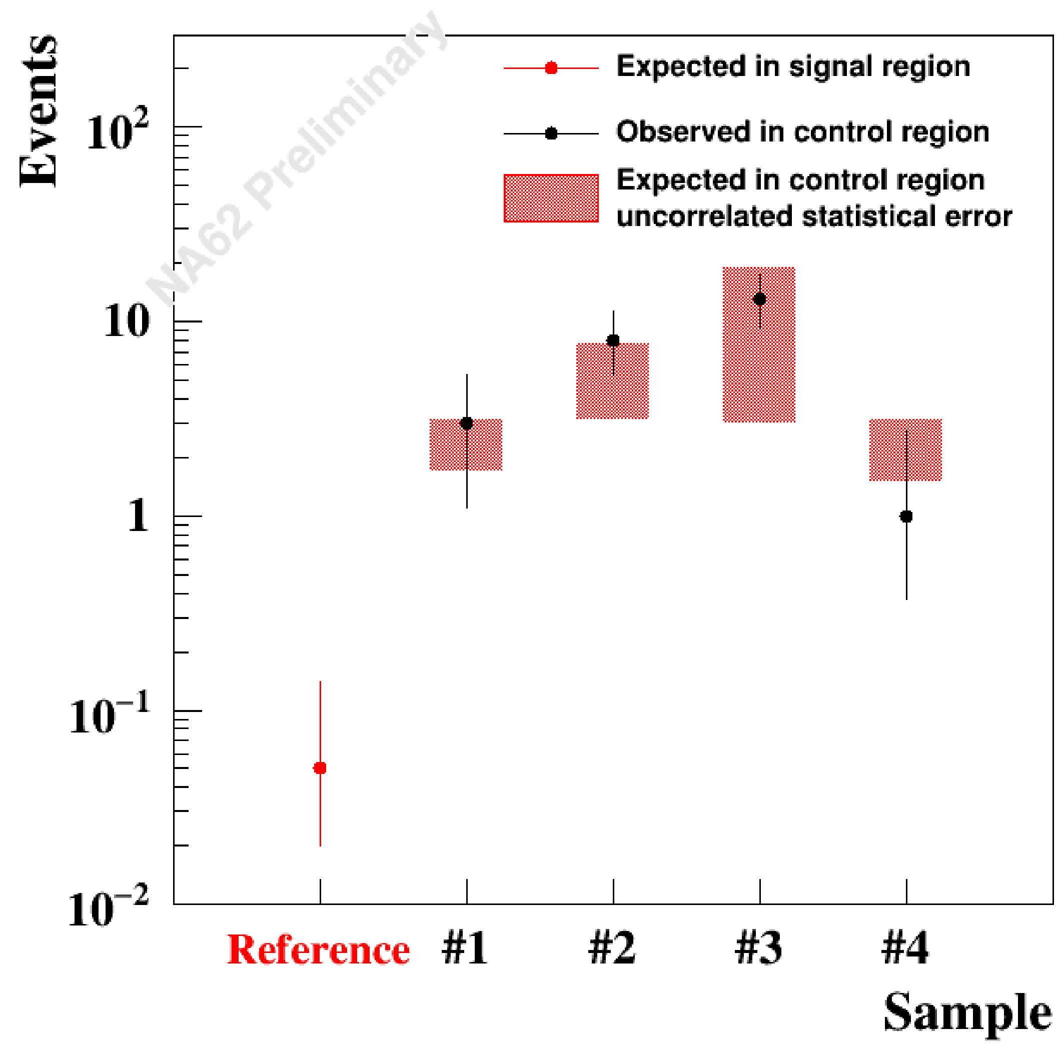
$$A(exp) = \frac{B' \cdot C'}{D'} \quad A'(exp) = \frac{B'' \cdot C''}{D'}$$





Upstream background





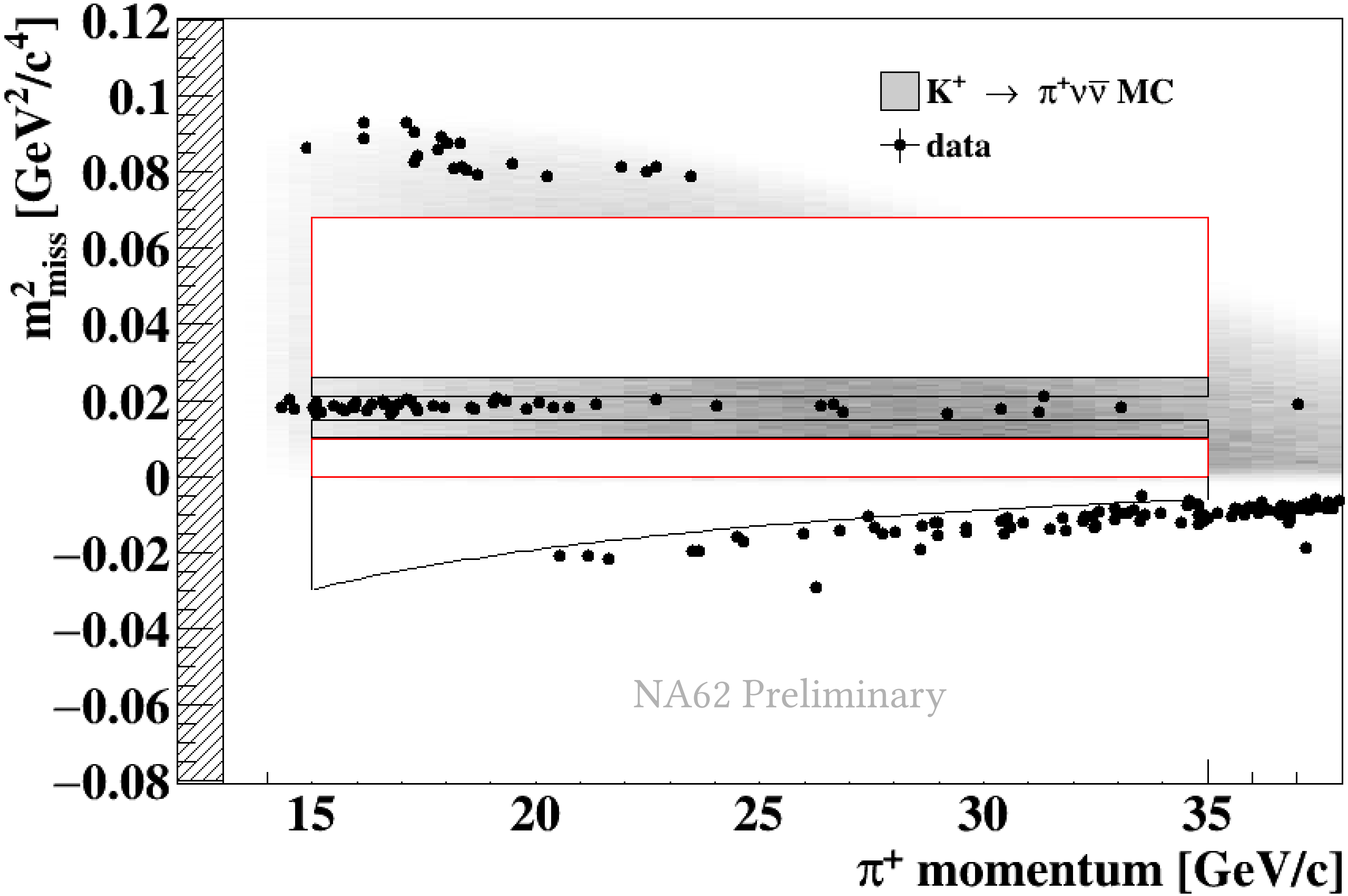
$$N^{exp}_{upstream} = 0.050^{+0.090}_{-0.030}\Big|_{stat}$$

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	$0.15 \pm 0.09_{\mathrm{stat}} \pm 0.01_{\mathrm{syst}}$
$K^+ \to \pi^+\pi^0(\gamma)$ 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	$0.050^{+0.090}_{-0.030}\|_{stat}$

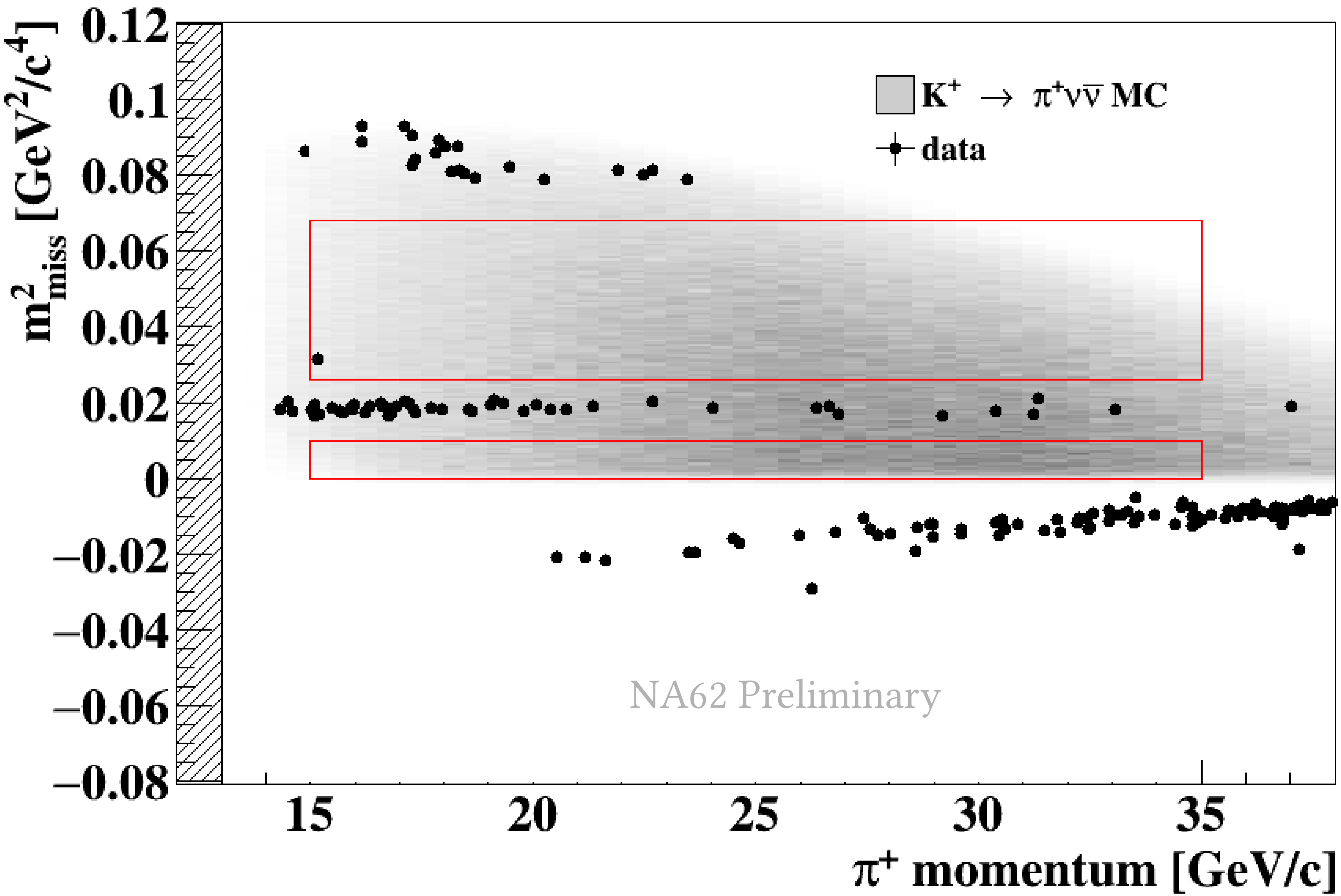
4. Result

Result



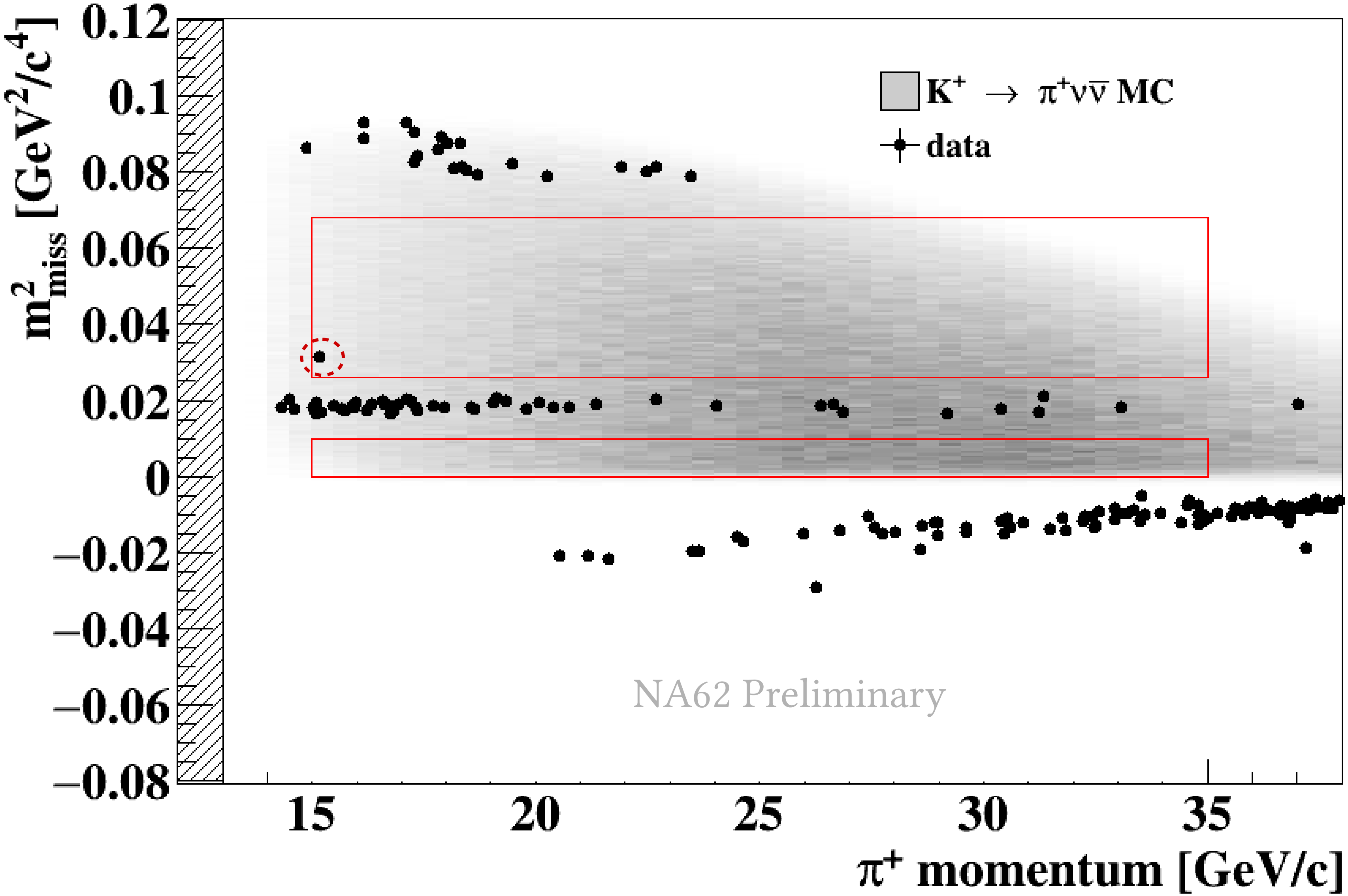
m^2_{miss} [GeV^2/c^4]
0.12
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
15
20
25
30
35
π^+ momentum [GeV/c]
$K^+ \rightarrow \pi^+\nu\bar{\nu}$ MC
data
NA62 Preliminary

Result



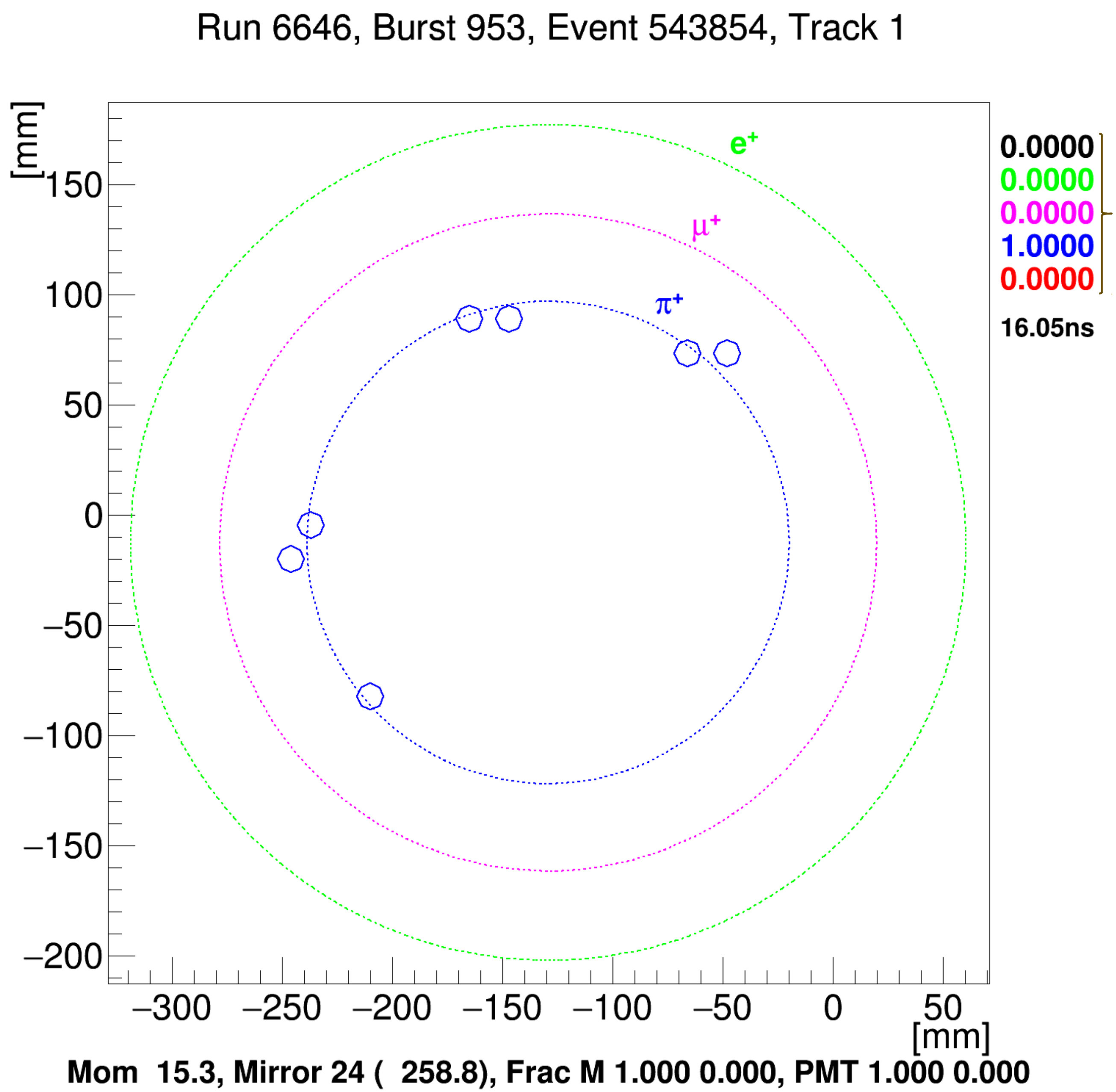
One event observed in R2

Result



One event observed in R2

Result: RICH ring for the event



Likelihood value under different mass hypothesis

Result

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

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

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

Preliminary

- Expected limit: $BR(K^+ \to \pi^+ \nu\overline{\nu}) < 10 \times 10^{-10}$ @ 95% CL
- For comparison: $BR(K^+ \to \pi^+ \nu\overline{\nu}) = 28^{+44}_{-23} \times 10^{-11}$ @ 68% CL

Preliminary

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

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

Prospects

- Processing of 2017 data is ongoing
  - ~ 20 times more data than the presented statistics
  - expected reduction of upstream background
  - improvements of the reconstruction efficiency
- Preparing 2018 data taking
  - 218 days including stops
  - ongoing studies to improve the signal acceptance
- ~ 20 SM events expected before LS2
- Running after 2018 to be approved
  - Conditions for ultimate sensitivity under evaluation

Summary

- The new NA62 decay in flight technique works
- One event observed in the 2016 data
- $BR(K^+ \to \pi^+\nu\bar{\nu}) < 14 \times 10^{-10}$ @ $95\%\ CL$

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