39th International Symposium on Physics in Collision

16–20th September, 2019, Taipei, Taiwan

Latest measurement of $K^+ \rightarrow \pi^+\nu\bar{\nu}$ with the NA62 experiment at CERN

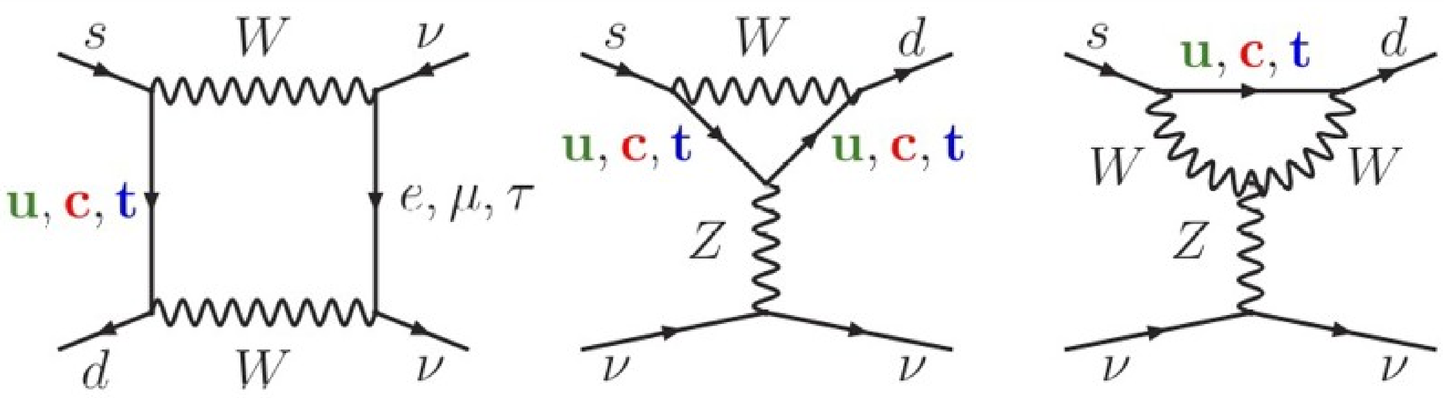
Speaker: Radoslav Marchevski (CERN)

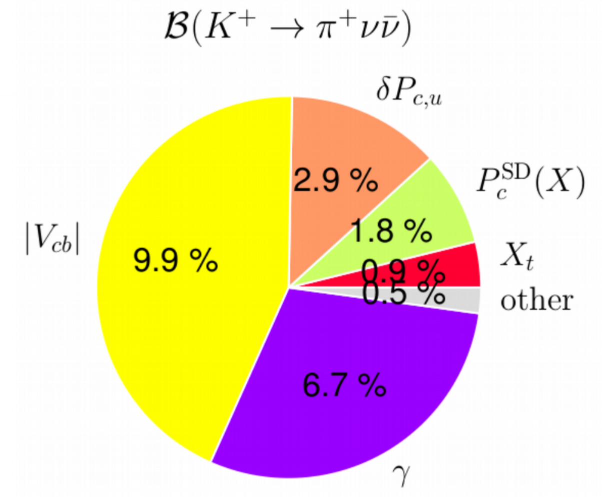
On behalf of the NA62 collaboration

Outline:

- $K^+ \rightarrow \pi^+\nu\nu$ decays in the SM
- The NA62 experiment at CERN
- $K^+ \rightarrow \pi^+\nu\nu$ @ NA62 (2017 data)
- Summary and prospects

The FCNC process K→πνν





Parametric uncertainty dominates

[Buras. et. al., JHEP11(2015)033]

- FCNC loop processes: s ⟶ d coupling and highest CKM suppression
- Theoretically clean: Short distance contribution
- Hadronic matrix element measured with K_{l3} decays
- SM predictions: Buras. et. al., JHEP11(2015)033

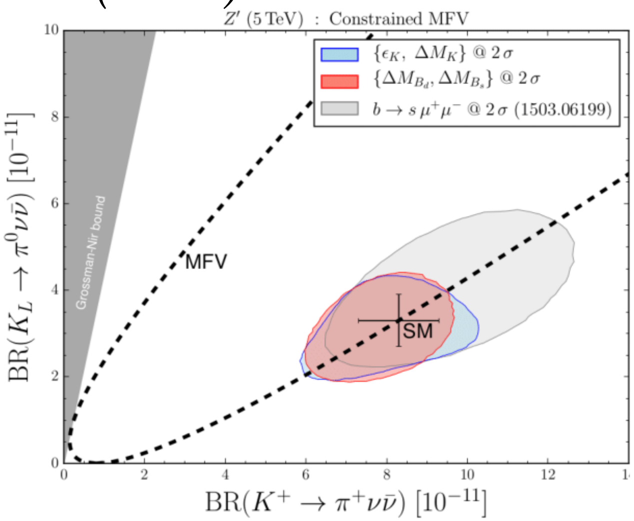
$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (0.84 \pm 0.03) \times 10^{-10} \left(\frac{|V_{cb}|}{0.0407}\right)^{2.8} \left(\frac{\gamma}{73.2^\circ}\right)^{0.74} = (0.84 \pm 0.10) \times 10^{-10}$$

$$BR(K_L \to \pi^0 \nu\bar{\nu}) = (0.34 \pm 0.05) \times 10^{-10} \left(\frac{|V_{ub}|}{0.00388}\right)^{2} \left(\frac{|V_{cb}|}{0.0407}\right)^{2} \left(\frac{\sin\gamma}{\sin 73.2^\circ}\right)^{2} = (0.34 \pm 0.06) \times 10^{-10}$$

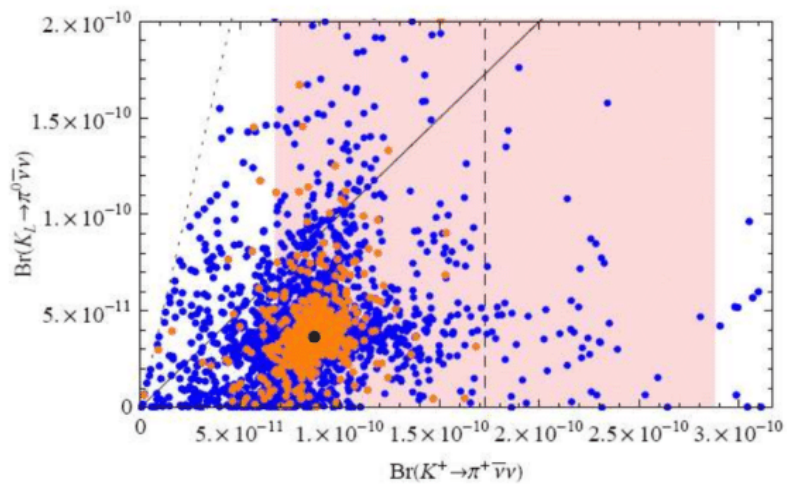
K⟶πνν beyond the Standard Model

- 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:1802.00786v1 (2018)]
- Constraints from existing measurements (correlations model dependent)

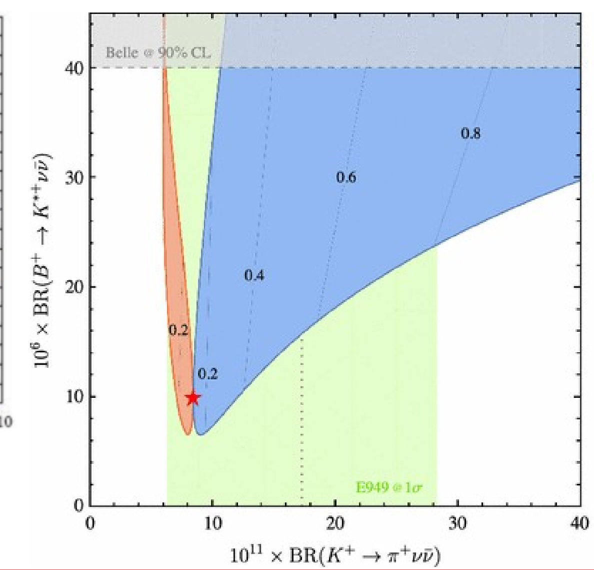
Z'(5 TeV) in Constrained MFV



Randall Sundrum

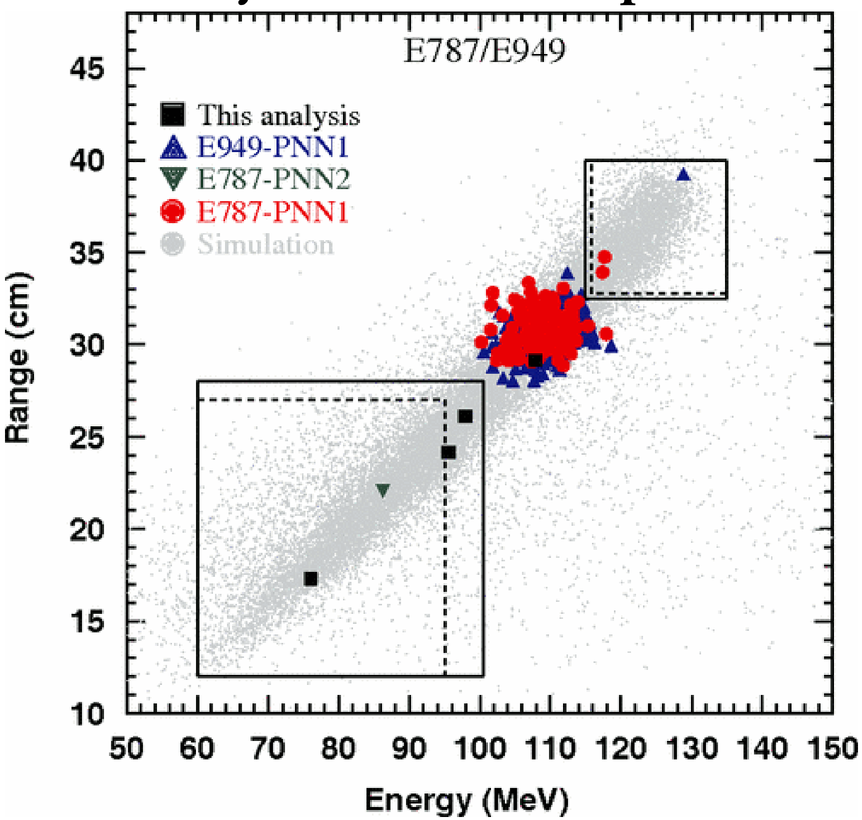


LFU violation

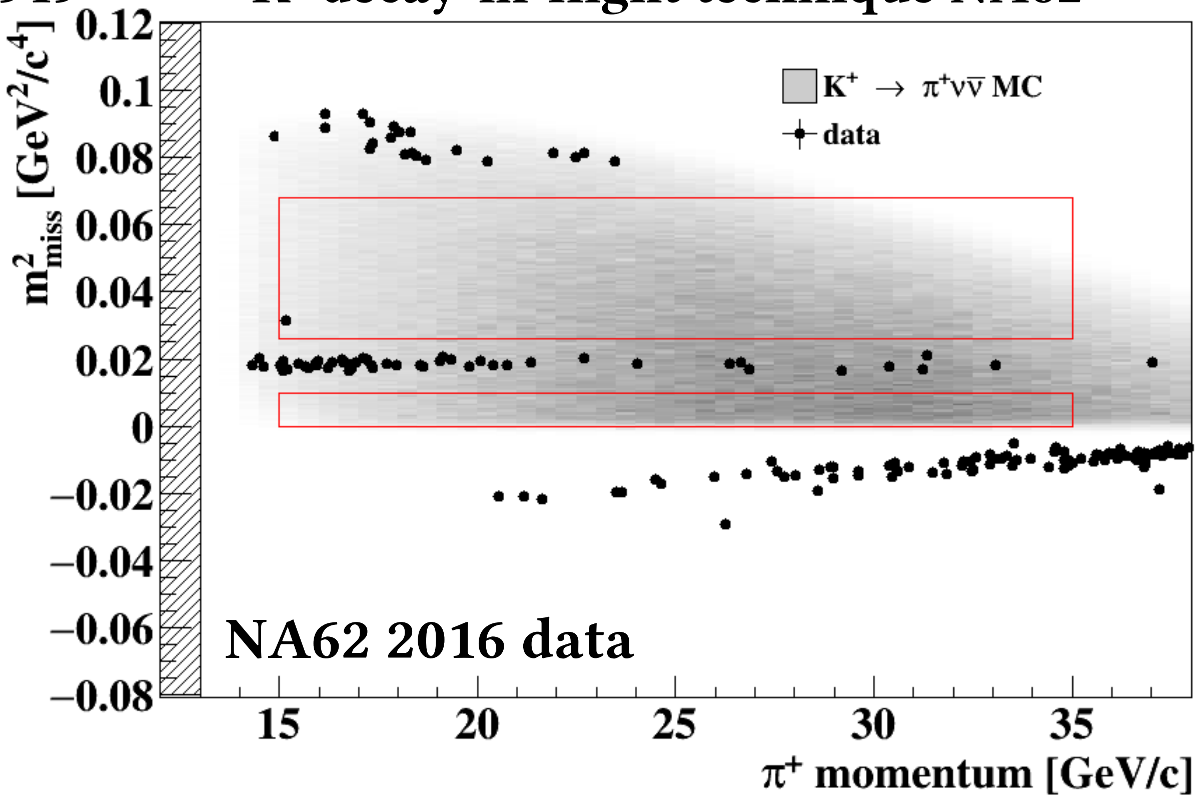


State of the art $K^+ \to \pi^+ \nu\nu$ experiments

K^+ decay-at-rest technique E787/E949



K^+ decay-in-flight technique NA62



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

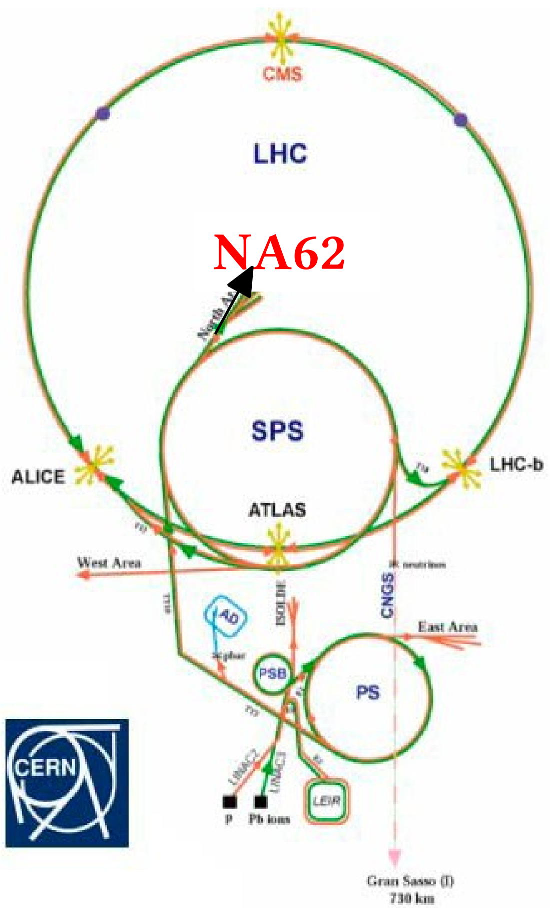
Phys. Rev. D 79, 092004 (2009)

Phys. Rev. D 77, 052003 (2008)

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

Phys. Lett. B 791, 156 (2019)

The NA62 experiment

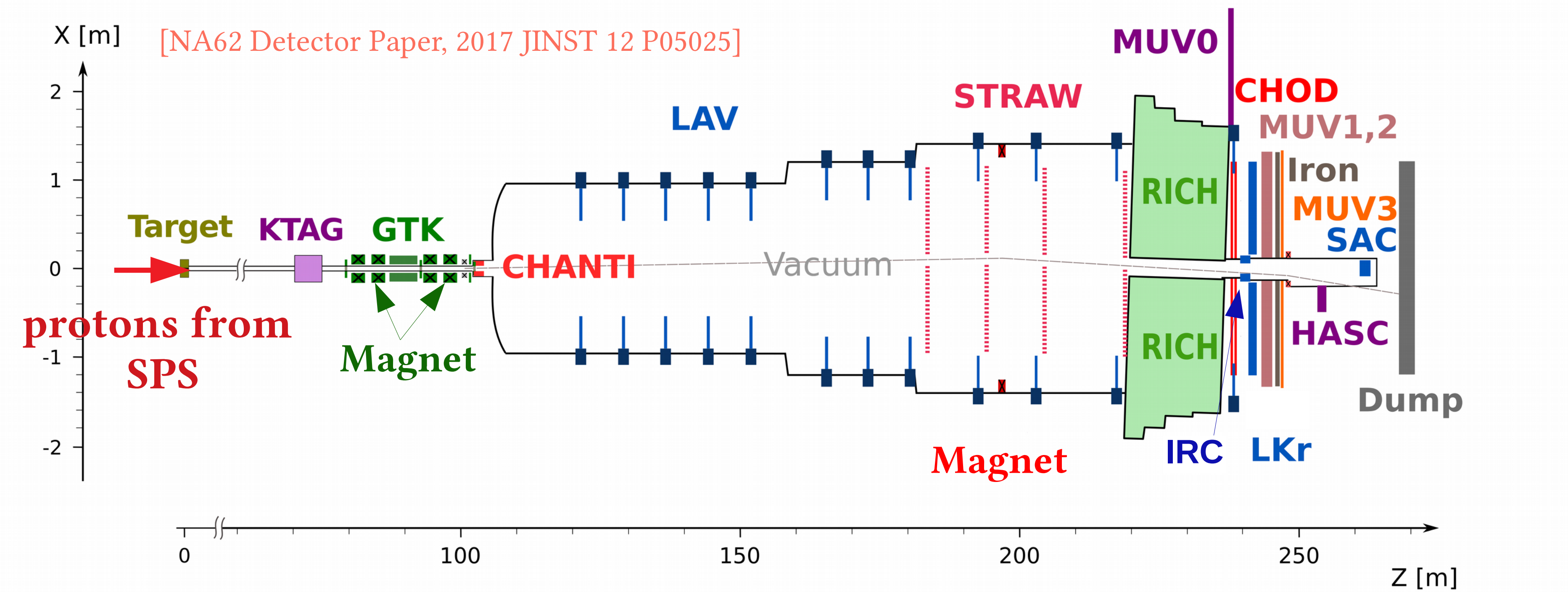


NA62 timeline
Dec 2008: NA62 Approval
2009 – 2014: Detector R&D and installation
2015: Commissioning
2016 – 2018: NA62 Run 1
2021 – 2023: NA62 Run2 (TBA)

NA62 primary goal: measurement of the ultra rare kaon decay $K^+ \rightarrow \pi^+\nu\nu$

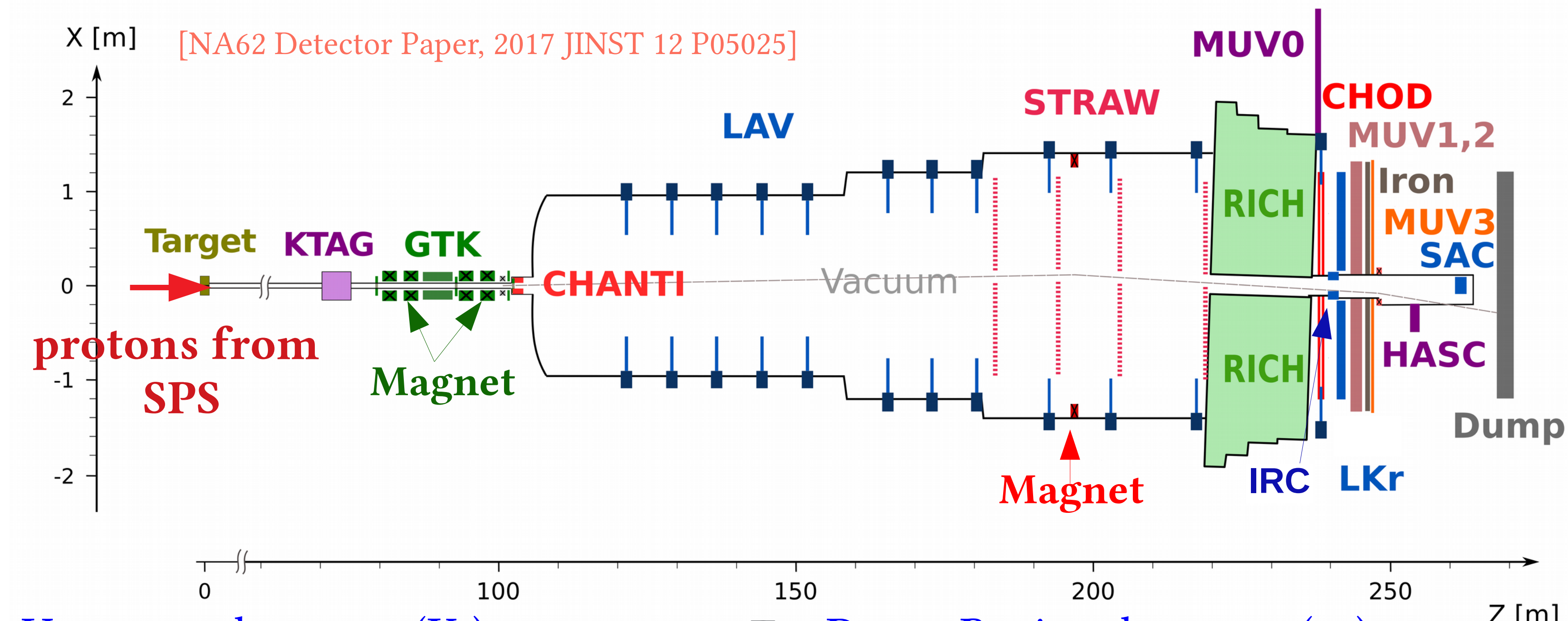
NA62 Collaboration consist of ~ 200 participants from: Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Moskow, Naples, Perugia, Pisa, Prague, Protvino, Rome I, Rome II, San Luis Potosi, Turin, TRIUMF, Vancouver UBC

NA62 detector



- **SPS Beam:**
  - 400 GeV/c protons
  - 2.10^{12} protons/spill
  - 3.5s spill
  - $\sim 10^{18}$ POT/year
- **Secondary positive Beam:**
  - 75 GeV/c momentum, 1% rms
  - 100 μrad divergence (RMS)
  - 60x30 mm^2 transverse size
  - **K^+(6%)**/π^+(70%)/p(24%)
  - ~500 MHz of particles at GTK3
- **Decay Region:**
  - 60 m long fiducial region
  - ~ 3 MHz K^+ decay rate
  - Vacuum ~ $O(10^{-6})$ mbar

NA62 detector



- Upstream detectors (K^+):
  - **KTAG:** Differential Cherenkov counter for K^+ ID
  - **GTK:** Si pixel beam tracker
  - **CHANTI:** Anti-counter for inelastic beam-GTK3 interactions
- Decay Region detectors (π^+):
  - **STRAW:** track momentum spectrometer
  - **CHOD:** Scintillator hodoscopes
  - **LKr/MUV1/MUV2** : Calorimetric system
  - **RICH:** Cherenkov counter for $\pi/\mu/e$ ID
  - **LAV/SAC/IRC:** Photon veto detectors
  - **MUV3:** Muon veto

Trigger and data collected

NA62 Run 1
2016: Physics run (45 days*)
2017: Physics run (160 days*)
2018: Physics run (217 days*)

This talk

Collected in 2017
1.9 x 10^{11} proton per spill on target
~2 x 10^{12} K^+ decays

* Includes periods with beam off

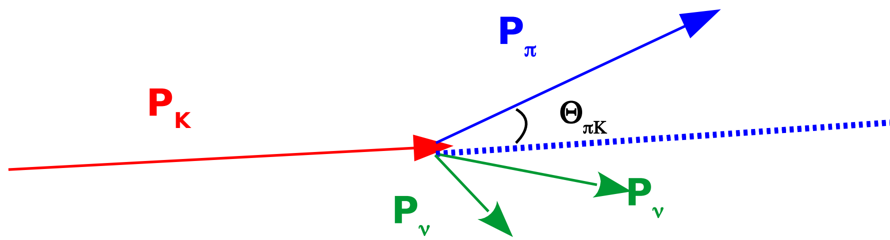
- Trigger streams (hardware L0 + software L1)
  - **"PNN":**
    - L0: presence of a charged particle, photon and muon veto
    - L1: kaon identification, photon veto, STRAW track reconstruction
  - **"Control":** minimum bias
- Offline analysis
  - Data samples: **PNN; Control:** $K^+ \longrightarrow \pi^+\pi^0$, $K^+ \longrightarrow \mu^+\nu$, $K^+ \longrightarrow \pi^+\pi^+\pi^-$
  - Blind analysis procedure: signal/validation regions masked during the analysis

Analysis strategy

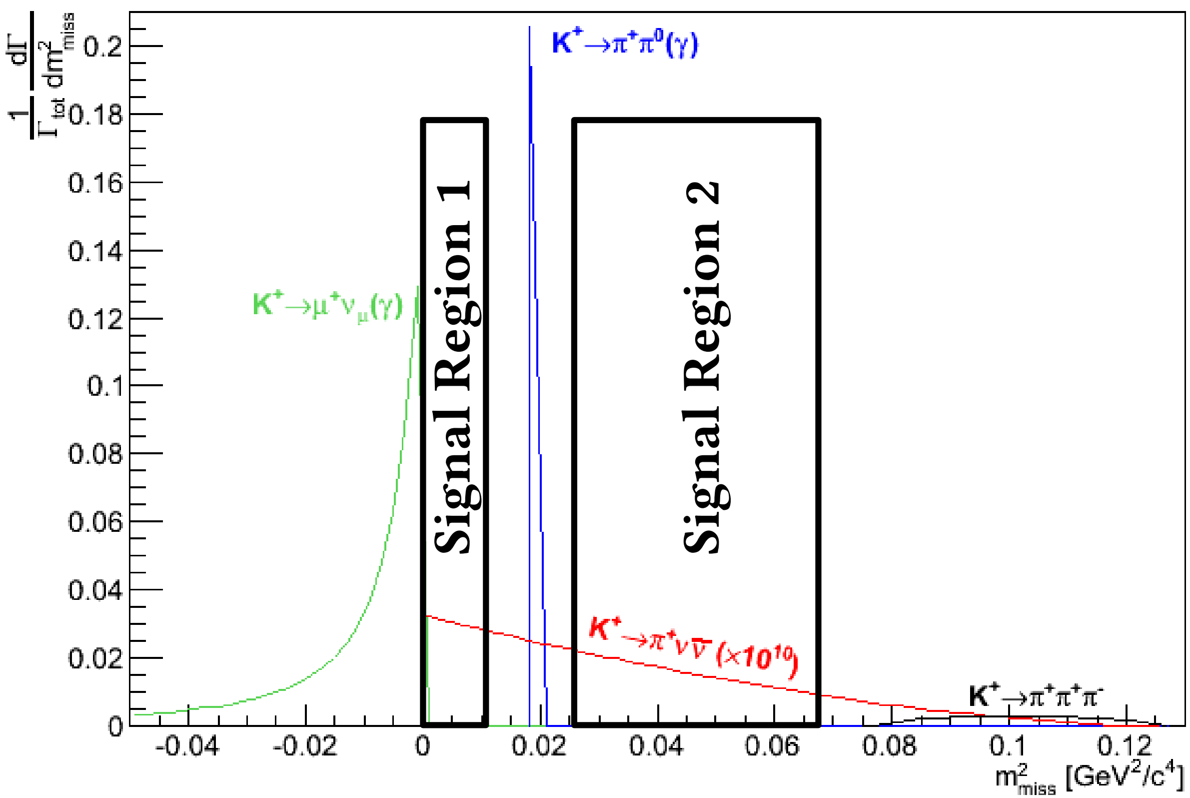
Decay-in-flight technique

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

π^+ mass assumed for the track



- **Muon suppression: > 10^7**
- **π^0 suppression (from $K^+ \to \pi^+\pi^0$): > 10^7**
- **Excellent time resolution: O(100ps)**
- **Kinematic suppression: ~ O(10^4)**



Process	Branching ratio
$K^+ \to \pi^+\pi^0$	0.2066
$K^+ \to \mu^+\nu_\mu$	0.6356
$K^+ \to \pi^+\pi^+\pi^-$	0.0558
$K^+ \to \pi^+\pi^- e\, \nu_e$	4.3×10^{-5}
$K^+ \to \pi^+\nu\nu$ (SM)	**8.4×10^{-11}**

Analysis steps

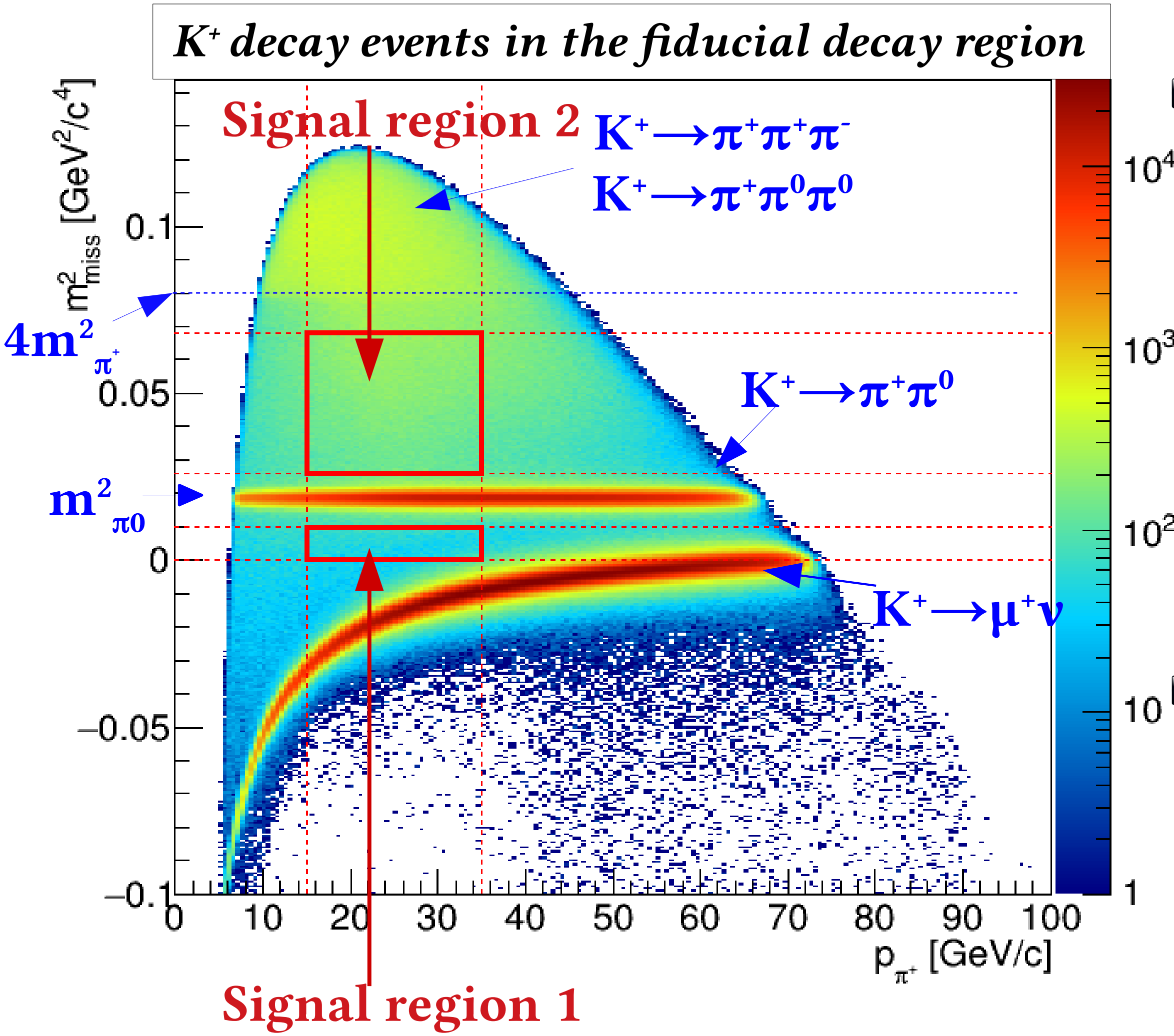
1) Signal selection and Single Event Sensitivity (S.E.S.)

2) Background evaluation

3) Unblinding signal regions and results

1. Signal Selection and Single Event Sensitivity (S.E.S)

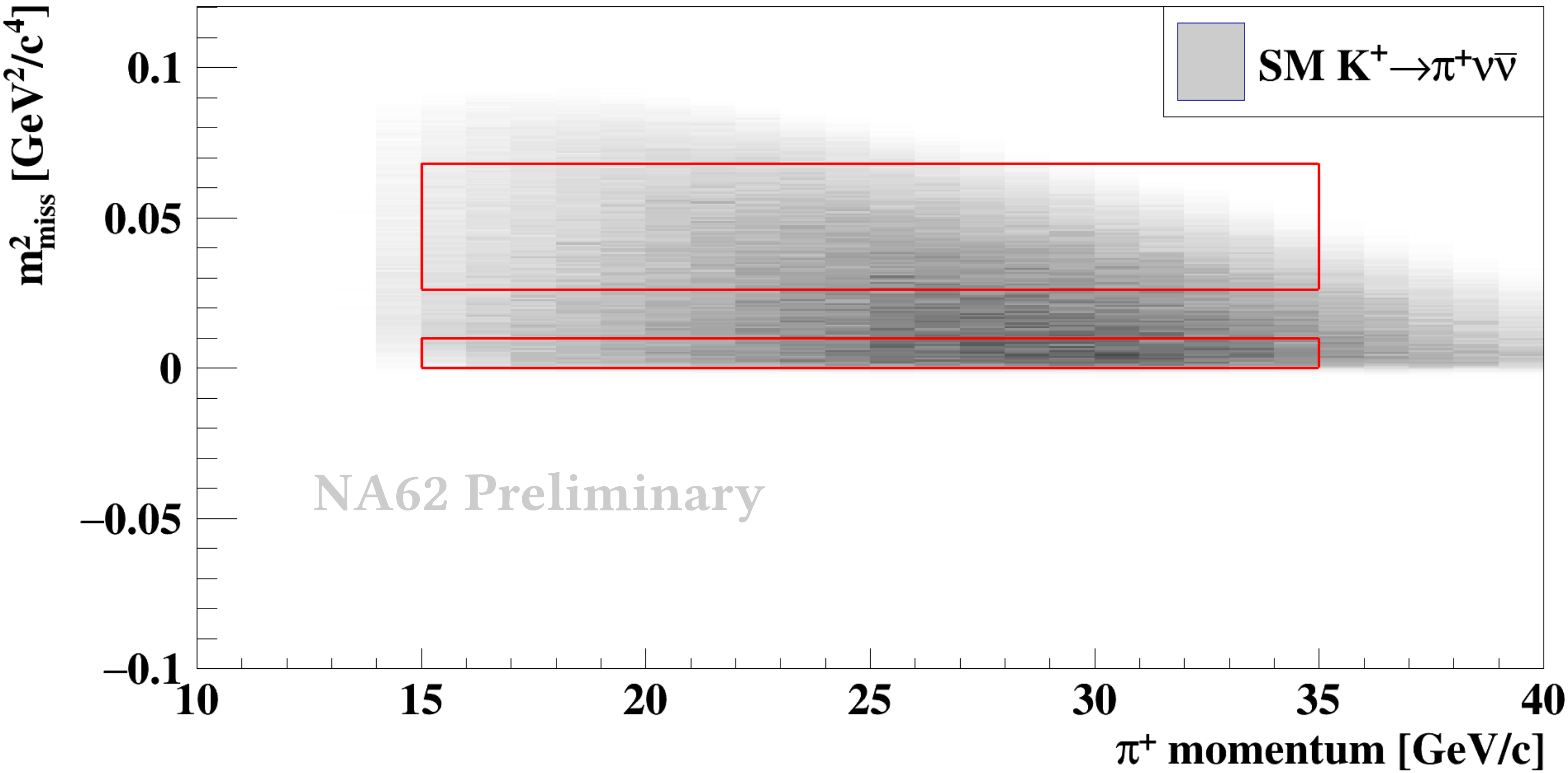
Signal selection



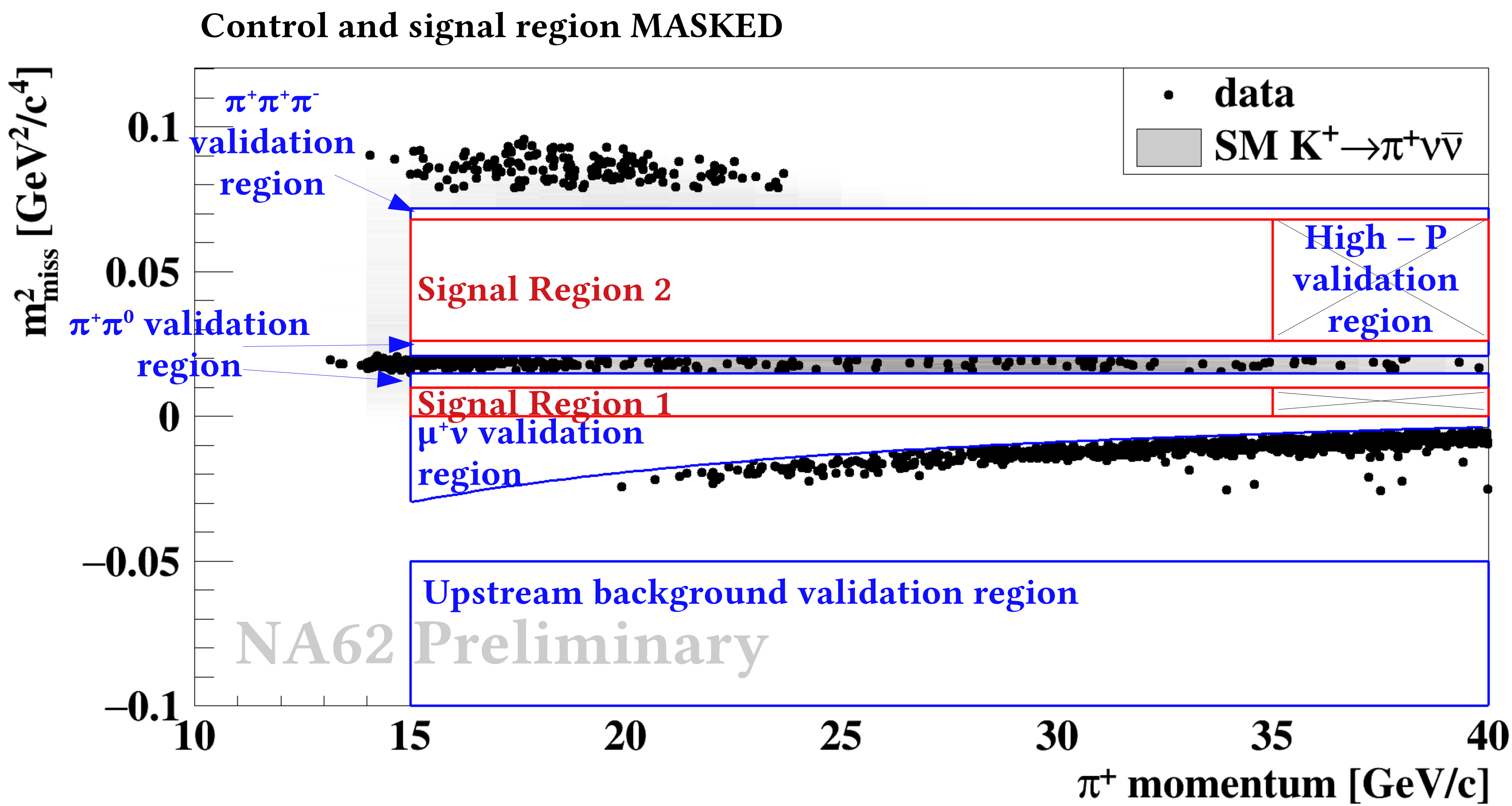
m^2_{miss} computed under π^+ mass hypothesis

- Selection criteria
  - single track decay topology
  - π^+ identification
  - photon rejection
  - multi-track rejection
- Performance summary
  - $\epsilon_{\mu^+} \sim 10^{-8}$ (64% π^+ efficiency)
  - $\epsilon_{\pi^0} = (1.4 \pm 0.1) \cdot 10^{-8}$ (15-35 GeV/c π^+ momentum)
  - $\sigma(m^2_{miss}) = 1 \cdot 10^{-3}$ GeV$^2/c^4$
  - $\sigma_T \sim O(100$ ps$)$

Signal acceptance



Data after signal selection



Single Event Sensitivity: Results

◆ **Integrated over beam intensity and π^+ momentum**

$$\text{S.E.S.} = (0.389 \pm 0.021) \times 10^{-10}$$

$$N^{exp}_{\pi\nu\nu} = 2.16 \pm 0.12 \pm 0.26_{ext}$$

S.E.S error budged ⇨

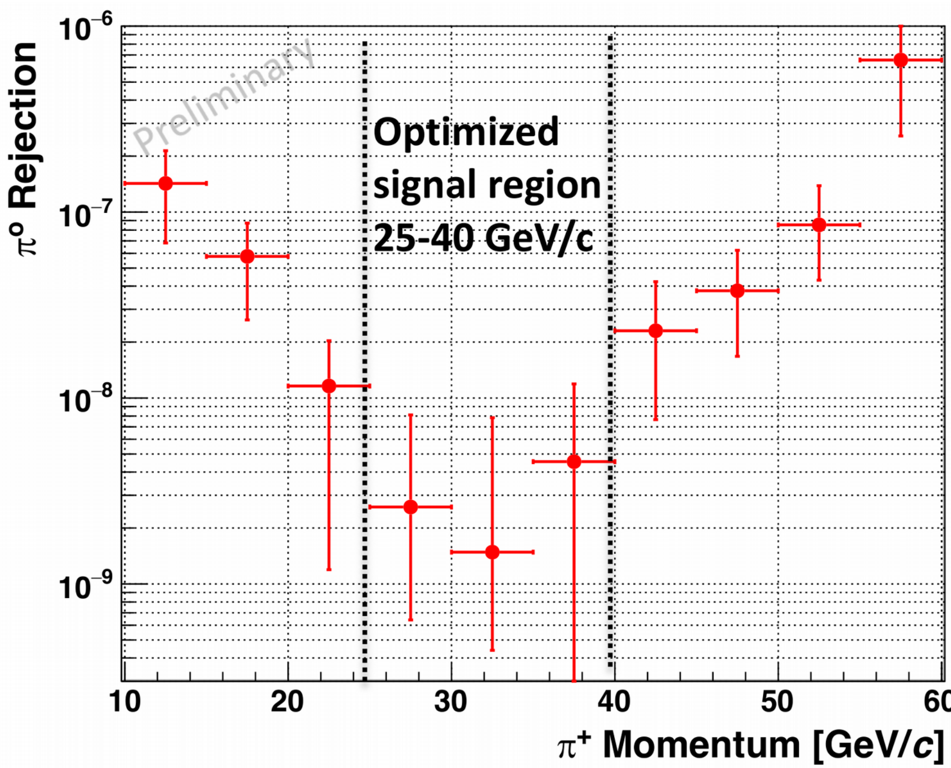
Source	Uncertainty $\times 10^{-10}$
L0 trigger	± 0.015
Acceptance	± 0.012
Random veto	± 0.008
L1 trigger	± 0.003
Normalization background	negligible

◆ **External error on $N^{exp}_{\pi\nu\nu}$ from $Br(\pi\nu\nu) = (0.84 \pm 0.10)\times 10^{-10}$**

2. Background evaluation

π^0 suppression and search for $\pi^0 \rightarrow$ invisible

- A priori evaluation of π^0 suppression of $K^+ \rightarrow \pi^+\pi^0$ decays ($0.015 < m^2_{miss} < 0.021$ GeV^2/c^4)
  - Selection and trigger stream identical to $K^+ \rightarrow \pi^+\nu\nu$ (1/3 of the data set used)
  - Single-γ detection efficiency from control $K^+ \rightarrow \pi^+\pi^0$ data (Tag & Probe)
  - π^0 suppression evaluated from convolution with MC $K^+ \rightarrow \pi^+\pi^0(\gamma)$
  - Validation: side bands with expected rejection O(10^{-7}) where **$\pi^0 \rightarrow$ invisible** excluded [E949, PRD72 (2005)]
- π^0 suppression expected = $(2.8^{+5.9}_{-2.1})\times10^{-9}$ (π^+ momentum region 25-40 GeV/c)



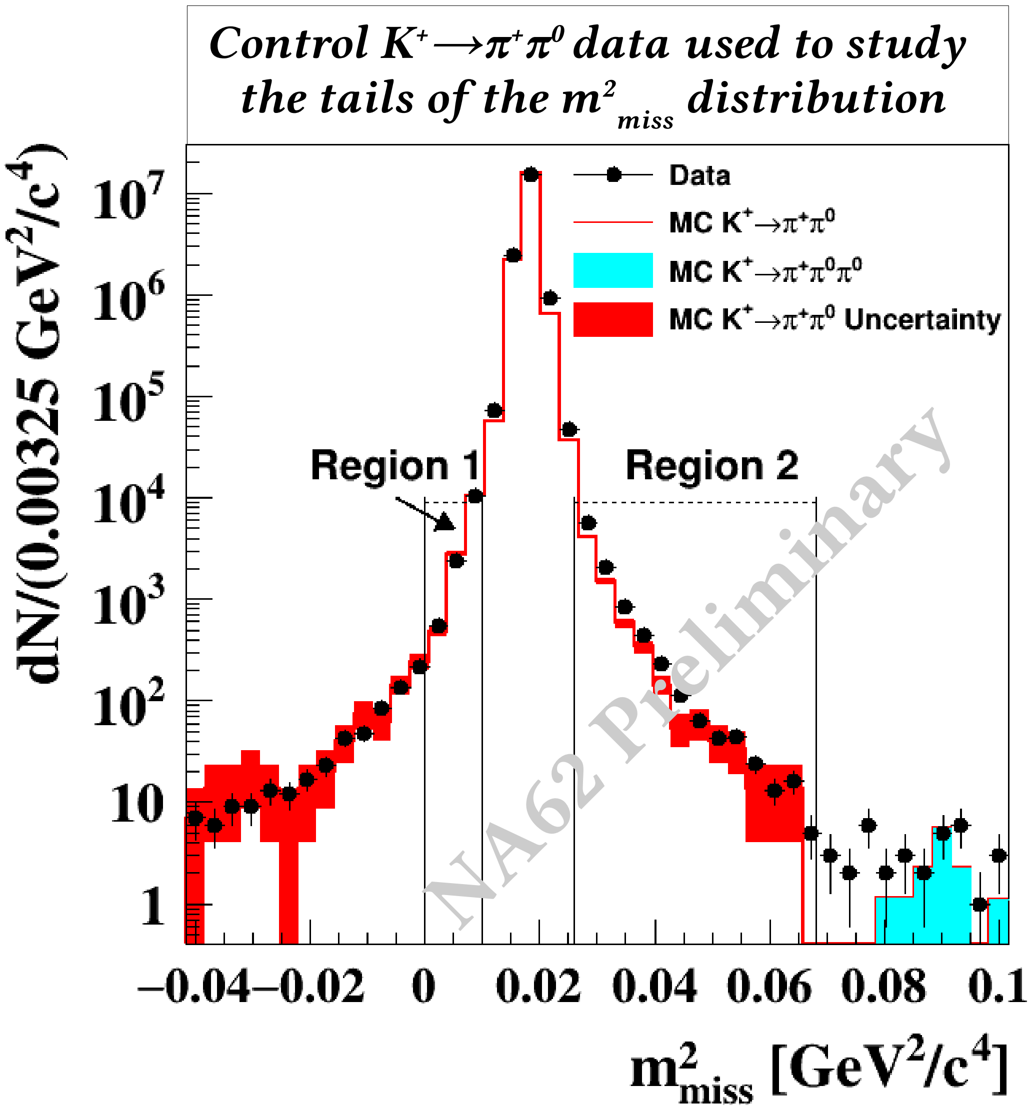
- Results
  - BR($\pi^0 \rightarrow$ invisible) normalized to $\pi^0 \rightarrow \gamma\gamma$
  - Expected background: 10^{+22}_{-8} events
  - Observed: 12 events

BR($\pi^0 \rightarrow$invisible) < 4.4×10^{-9} @ 90% CL

UL 60 times stronger than previous measurements

NA62 Preliminary

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



Data in $\pi^+\pi^0$ region after $\pi\nu\nu$ selection (including π^0 rejection)

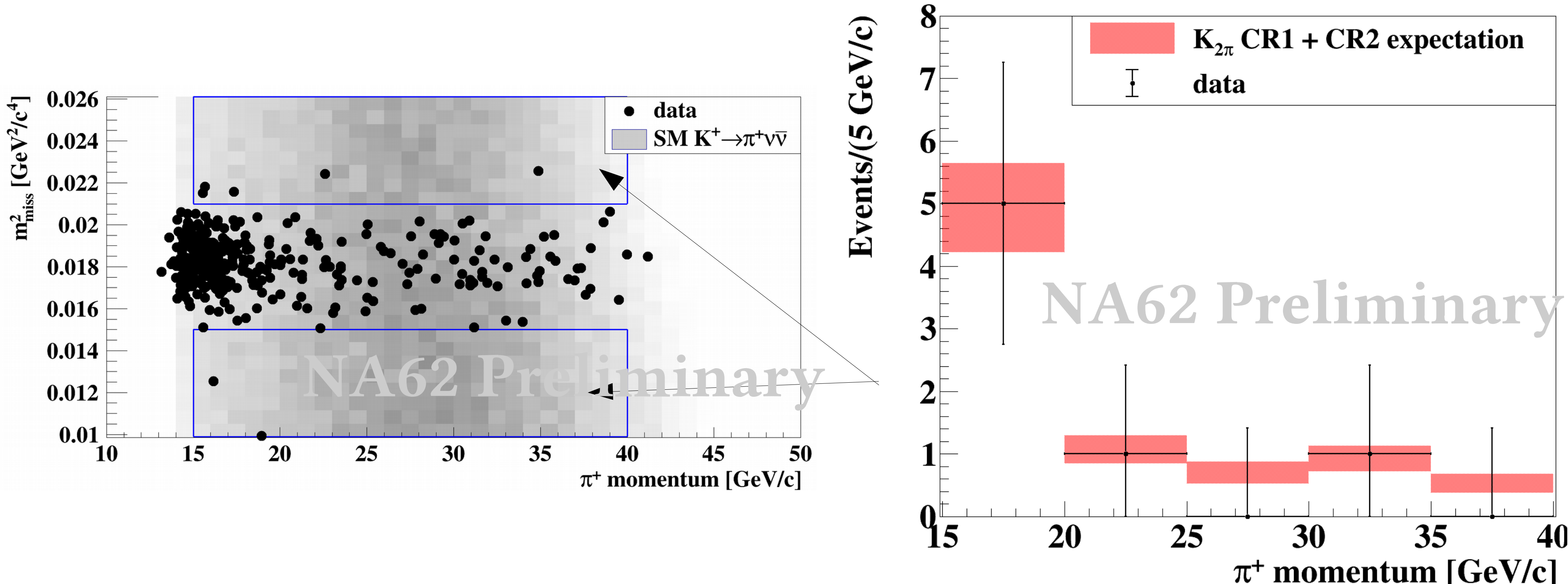
$$N^{exp}_{\pi\pi}(region) = N(\pi^+\pi^0)\cdot f_{kin}(region)$$

Expected $K^+\to\pi^+\pi^0$ in signal regions after the $\pi\nu\nu$ selection

Fraction of $\pi^+\pi^0$ in signal region measured on control data

Background: $K^+ \to \pi^+\pi^0(\gamma)$ IB validation

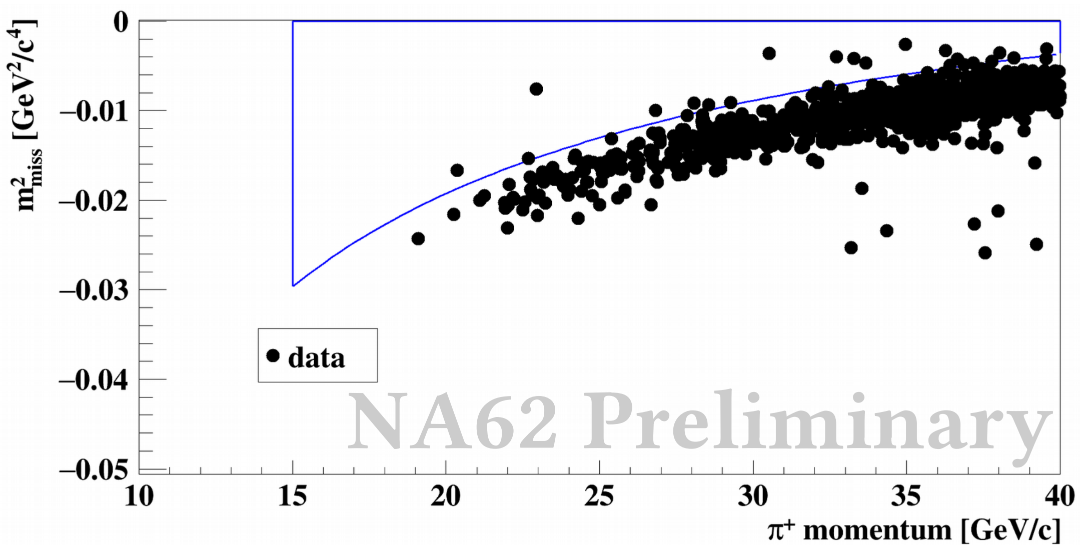
- Agreement between expected and observed kinematic suppression in validation regions

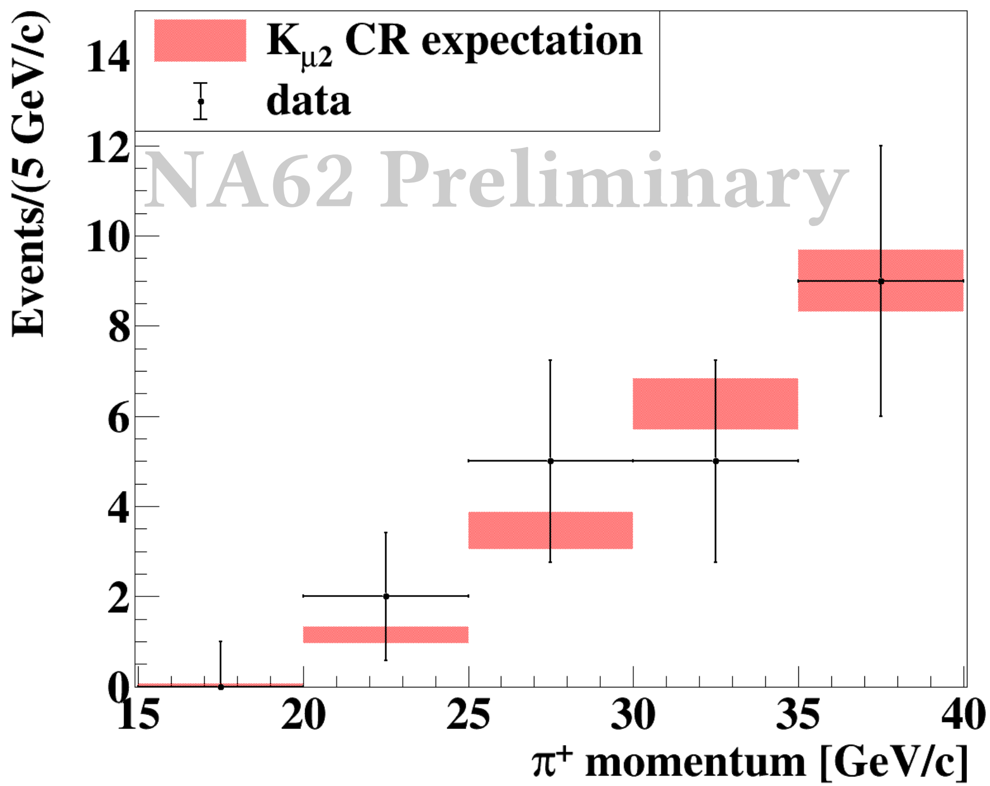


$$N^{bg}_{\pi\pi(\gamma)\mathrm{IB}} = 0.29 \pm 0.03_{stat} \pm 0.03_{syst}$$

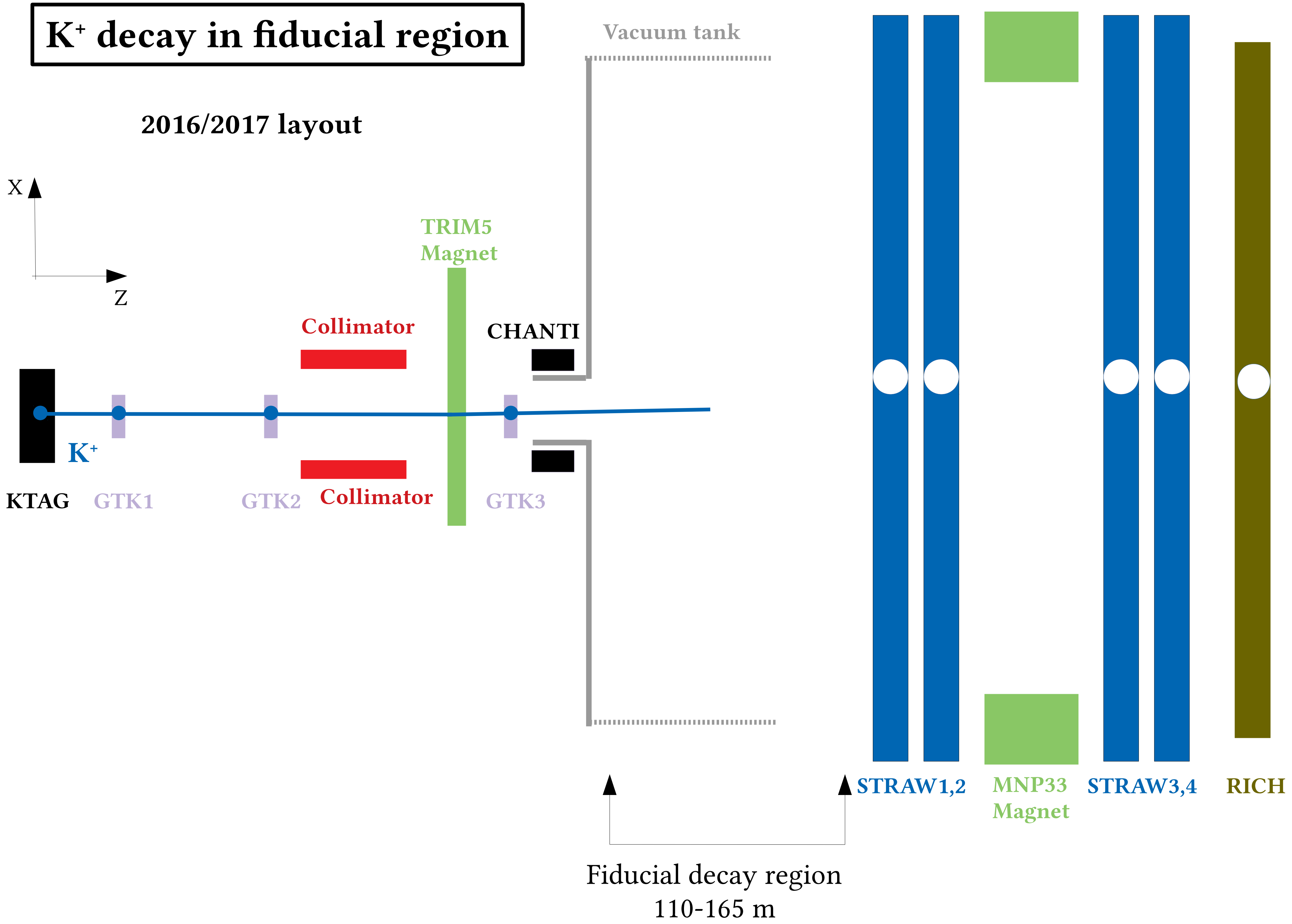
Background: $K^+ \rightarrow \mu^+\nu_\mu(\gamma)$ IB validation

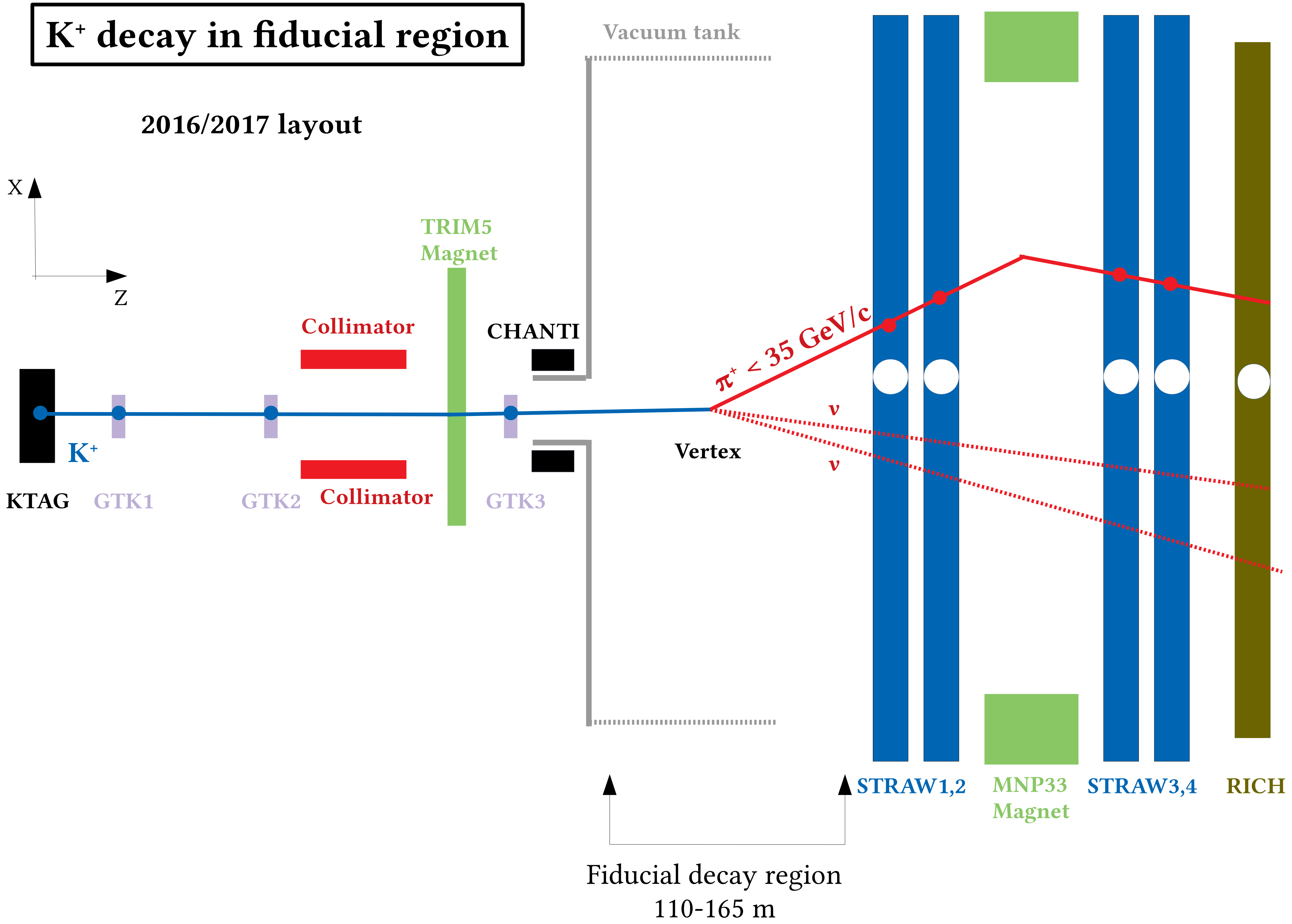
- Agreement between expected and observed kinematic suppression in validation regions



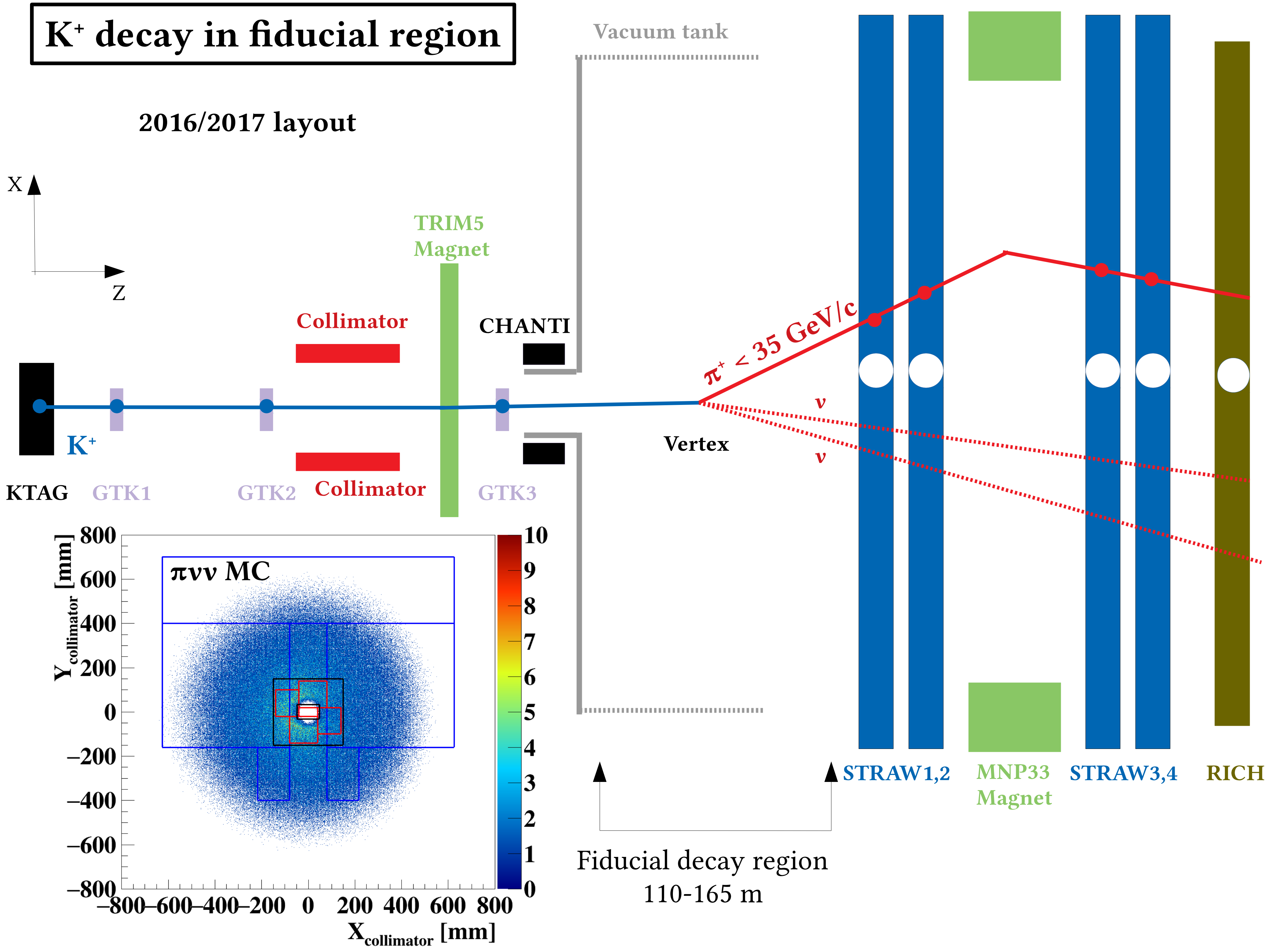


$$N^{bg}_{\mu\nu_\mu(\gamma)\text{IB}} = 0.15 \pm 0.02_{syst} \pm 0.04_{syst}$$

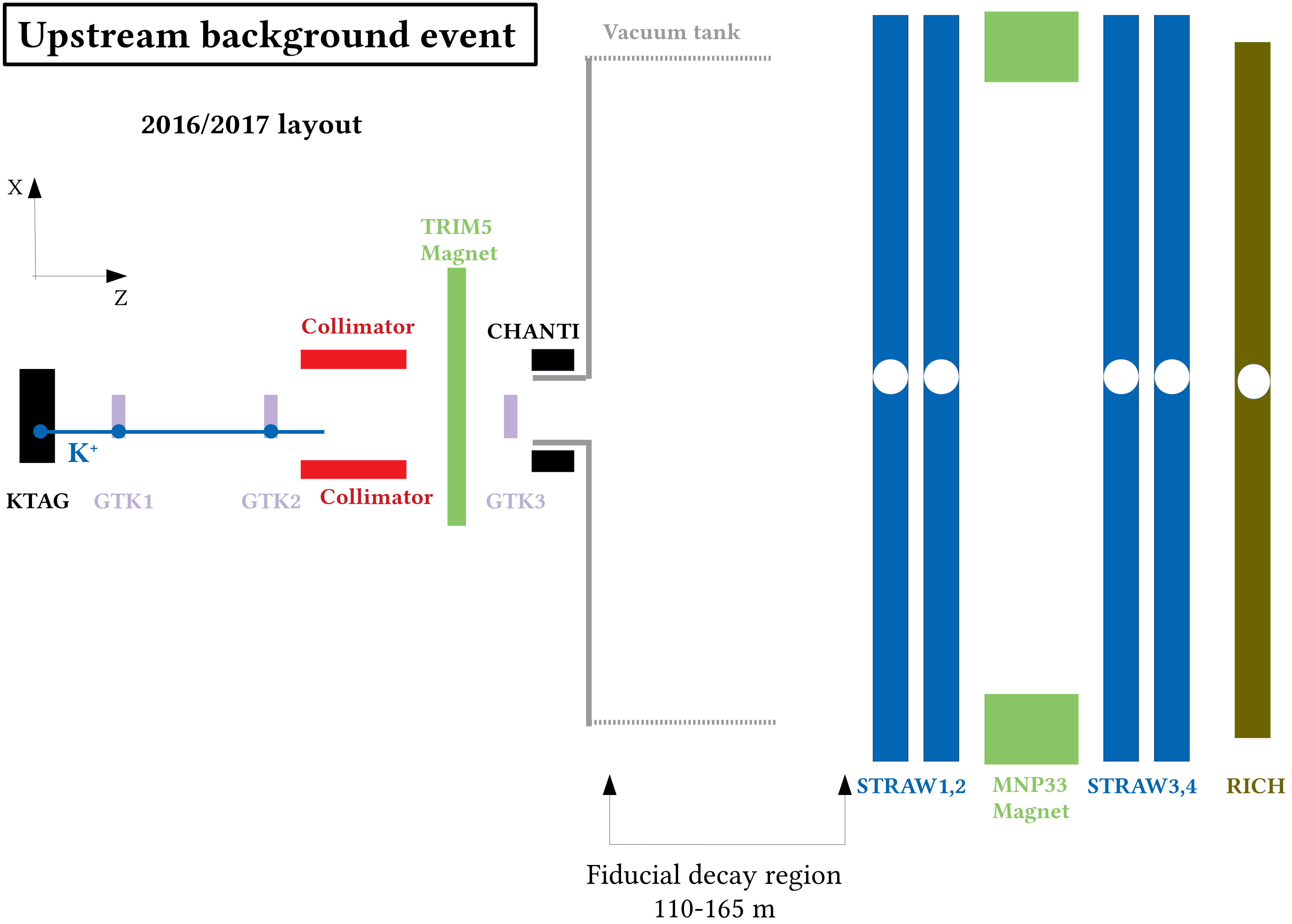

K+ decay in fiducial region
2016/2017 layout
X
Z
Vacuum tank
TRIM5
Magnet
Collimator
CHANTI
K+
KTAG
GTK1
GTK2
Collimator
GTK3
STRAW1,2
MNP33
Magnet
STRAW3,4
RICH
Fiducial decay region
110-165 m



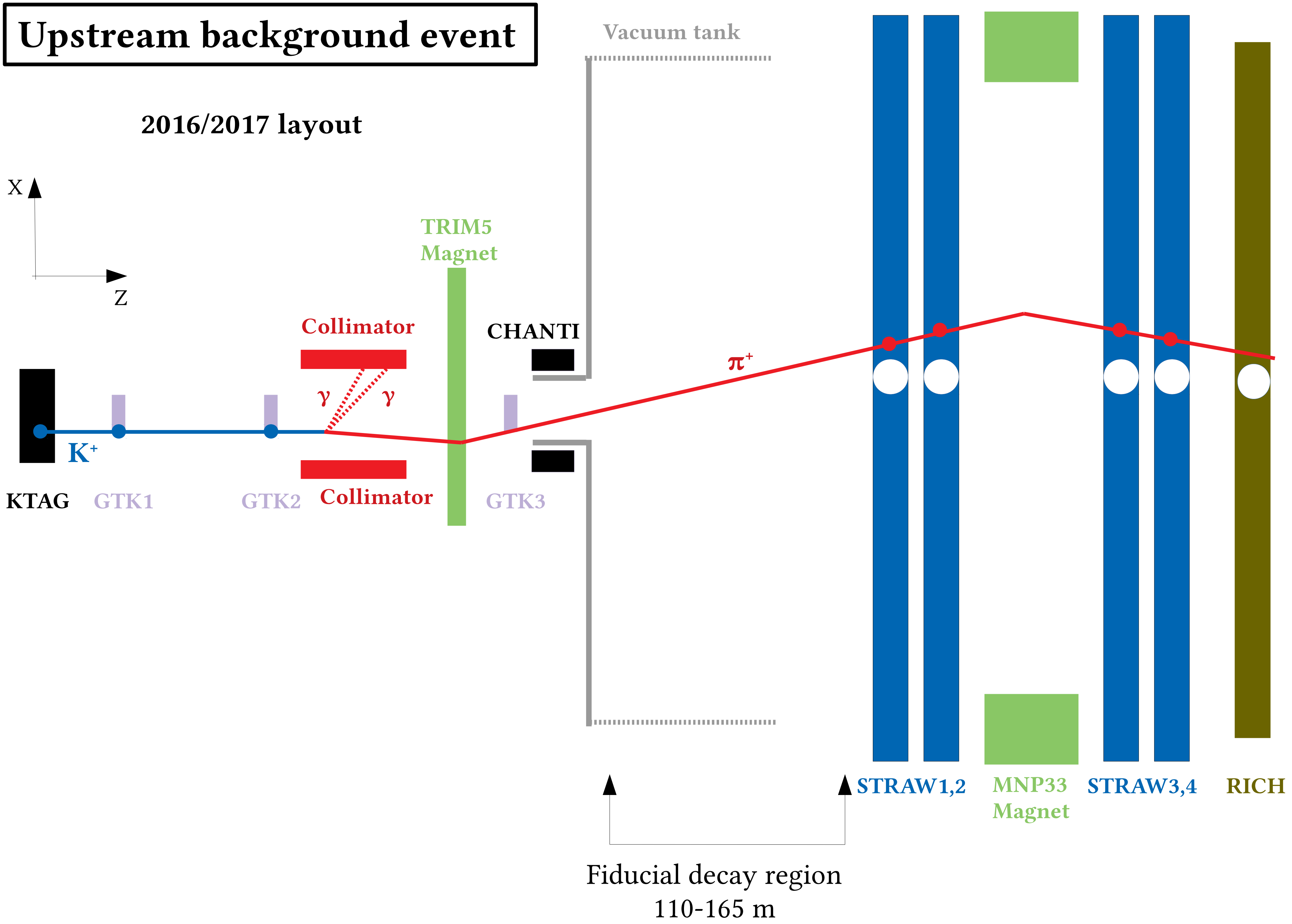
K⁺ decay in fiducial region
2016/2017 layout
X
Z
Vacuum tank
TRIM5
Magnet
Collimator
CHANTI
π⁺ < 35 GeV/c
ν
ν
K⁺
Vertex
KTAG
GTK1
GTK2
Collimator
GTK3
STRAW1,2
MNP33
Magnet
STRAW3,4
RICH
Fiducial decay region
110-165 m

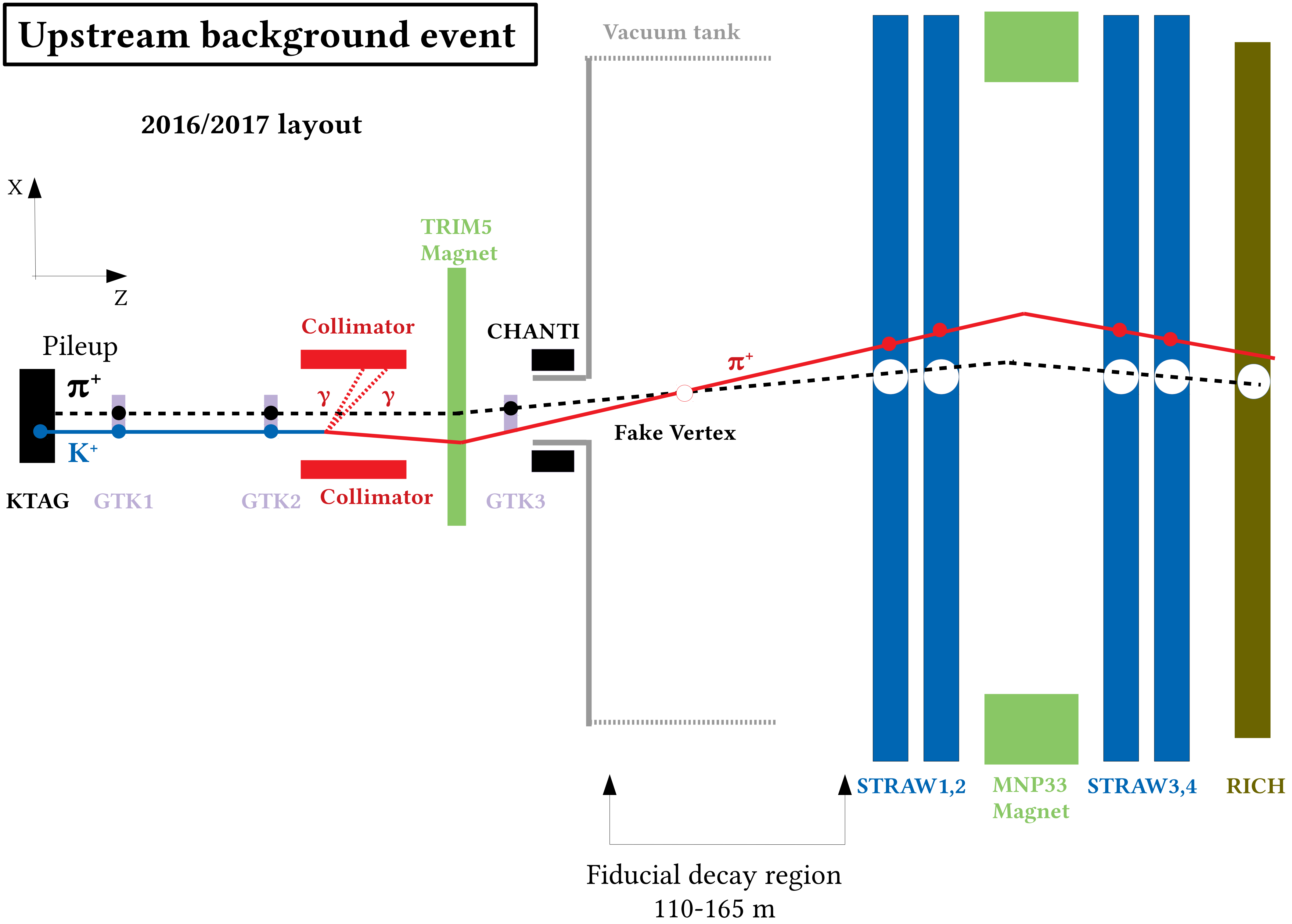


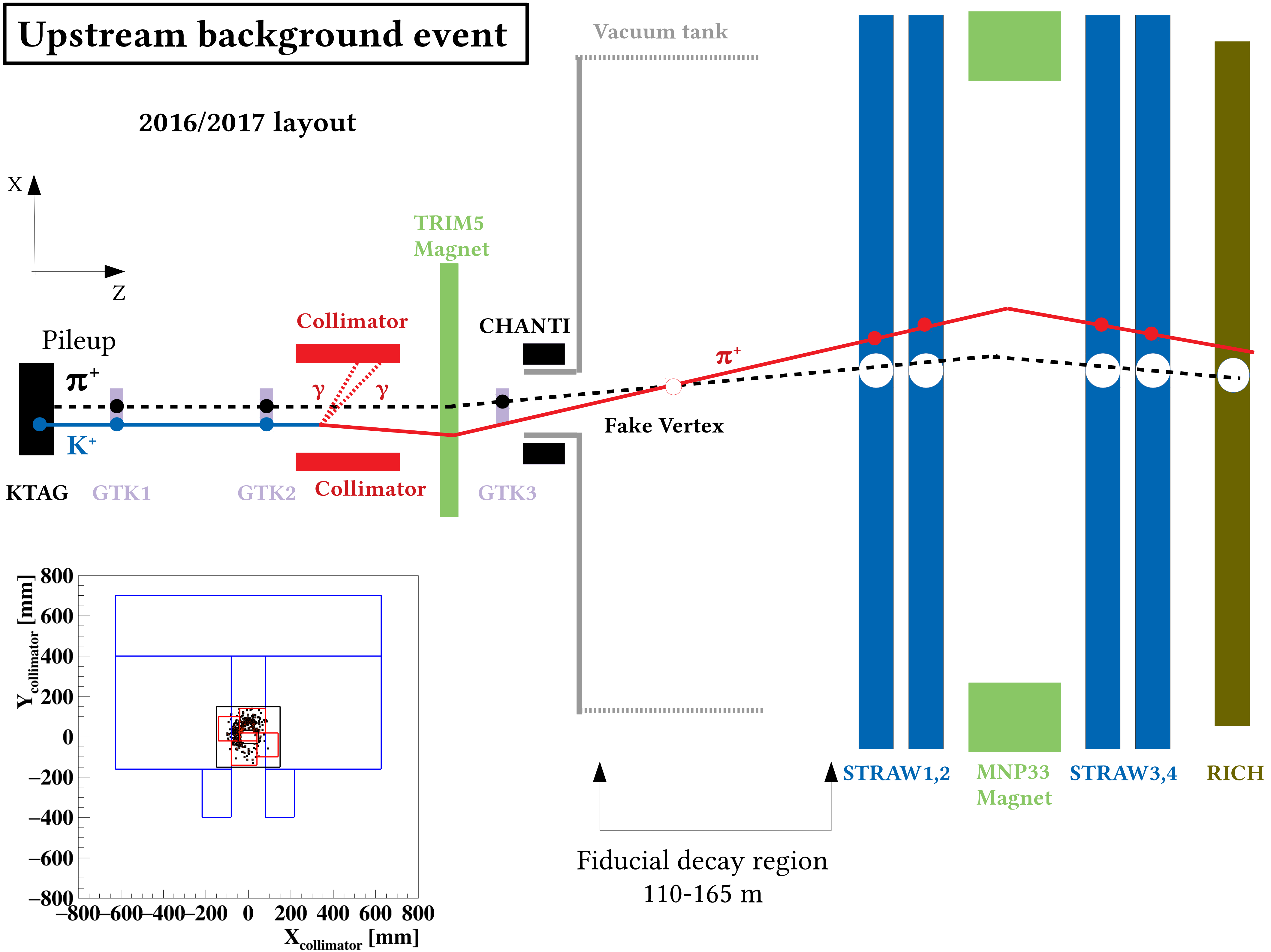
K+ decay in fiducial region
2016/2017 layout
X
Z
Vacuum tank
TRIM5
Magnet
Collimator
CHANTI
KTAG
GTK1
GTK2
Collimator
GTK3
K+
π+ < 35 GeV/c
ν
ν
Vertex
STRAW1,2
MNP33
Magnet
STRAW3,4
RICH
Fiducial decay region
110-165 m
πνν MC
Y_collimator [mm]
X_collimator [mm]



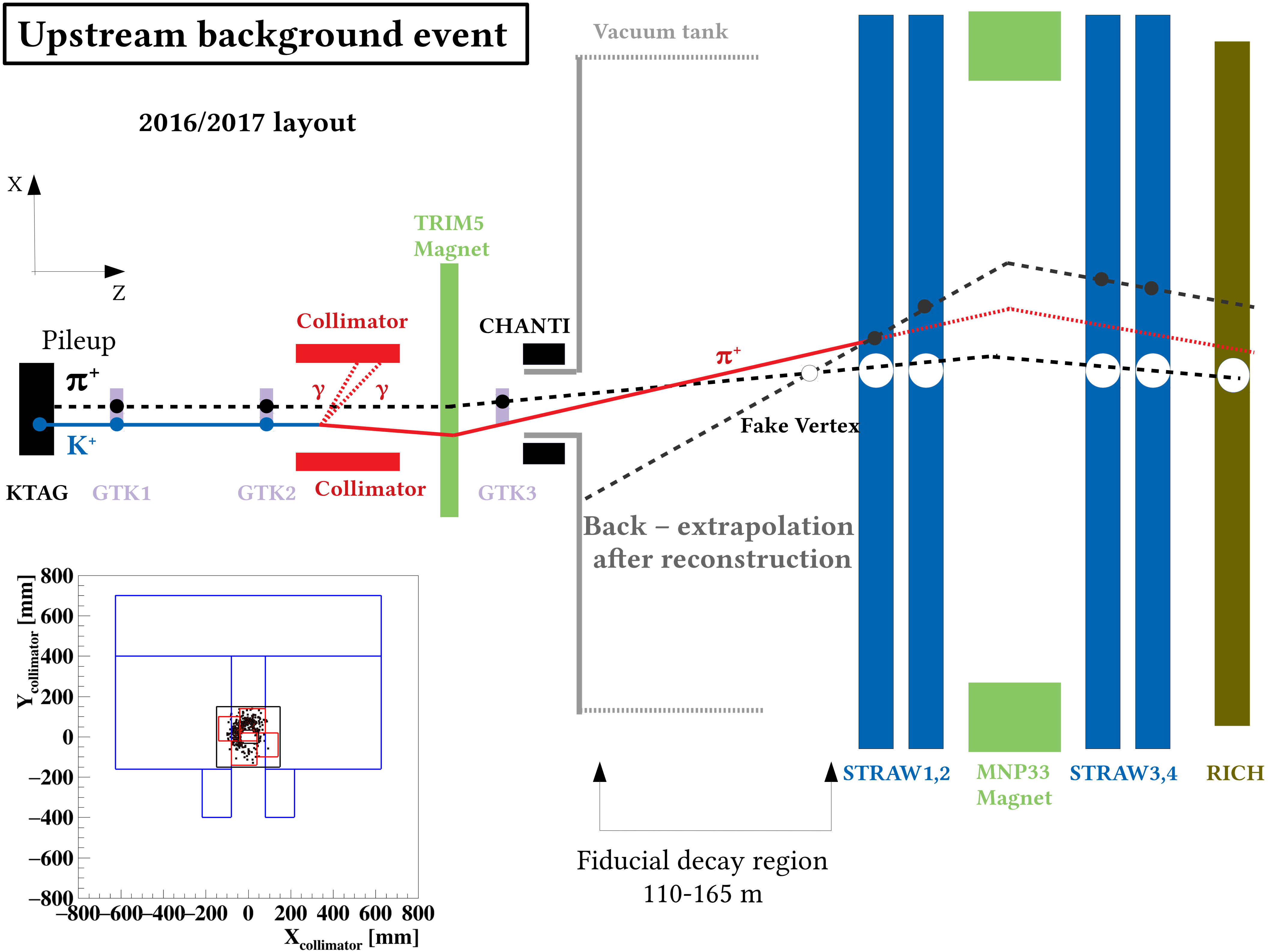
Upstream background event
2016/2017 layout
X
Z
Vacuum tank
TRIM5
Magnet
Collimator
CHANTI
K+
KTAG
GTK1
GTK2
Collimator
GTK3
STRAW1,2
MNP33
Magnet
STRAW3,4
RICH
Fiducial decay region
110-165 m


Upstream background event
2016/2017 layout
X
Z
Vacuum tank
TRIM5
Magnet
Collimator
CHANTI
γ
γ
π^+
K^+
KTAG
GTK1
GTK2
Collimator
GTK3
STRAW1,2
MNP33
Magnet
STRAW3,4
RICH
Fiducial decay region
110-165 m


Upstream background event
2016/2017 layout
Vacuum tank
X
Z
TRIM5
Magnet
Collimator
CHANTI
Pileup
π+
γ
γ
π+
Fake Vertex
K+
KTAG
GTK1
GTK2
Collimator
GTK3
STRAW1,2
MNP33
Magnet
STRAW3,4
RICH
Fiducial decay region
110-165 m



Upstream background event
2016/2017 layout
X
Z
Pileup
π+
K+
KTAG
GTK1
GTK2
Collimator
γ
γ
Collimator
TRIM5
Magnet
CHANTI
GTK3
Vacuum tank
Fake Vertex
π+
STRAW1,2
MNP33
Magnet
STRAW3,4
RICH
Fiducial decay region
110-165 m
Y_collimator [mm]
X_collimator [mm]
800
600
400
200
0
−200
−400
−600
−800
−800 −600 −400 −200 0 200 400 600 800



Upstream background event
2016/2017 layout
X
Z
Pileup
π+
K+
KTAG
GTK1
GTK2
Collimator
γ
γ
Collimator
TRIM5
Magnet
CHANTI
GTK3
Vacuum tank
π+
Fake Vertex
Back – extrapolation
after reconstruction
STRAW1,2
MNP33
Magnet
STRAW3,4
RICH
Fiducial decay region
110-165 m
Y collimator [mm]
X collimator [mm]
800
600
400
200
0
−200
−400
−600
−800

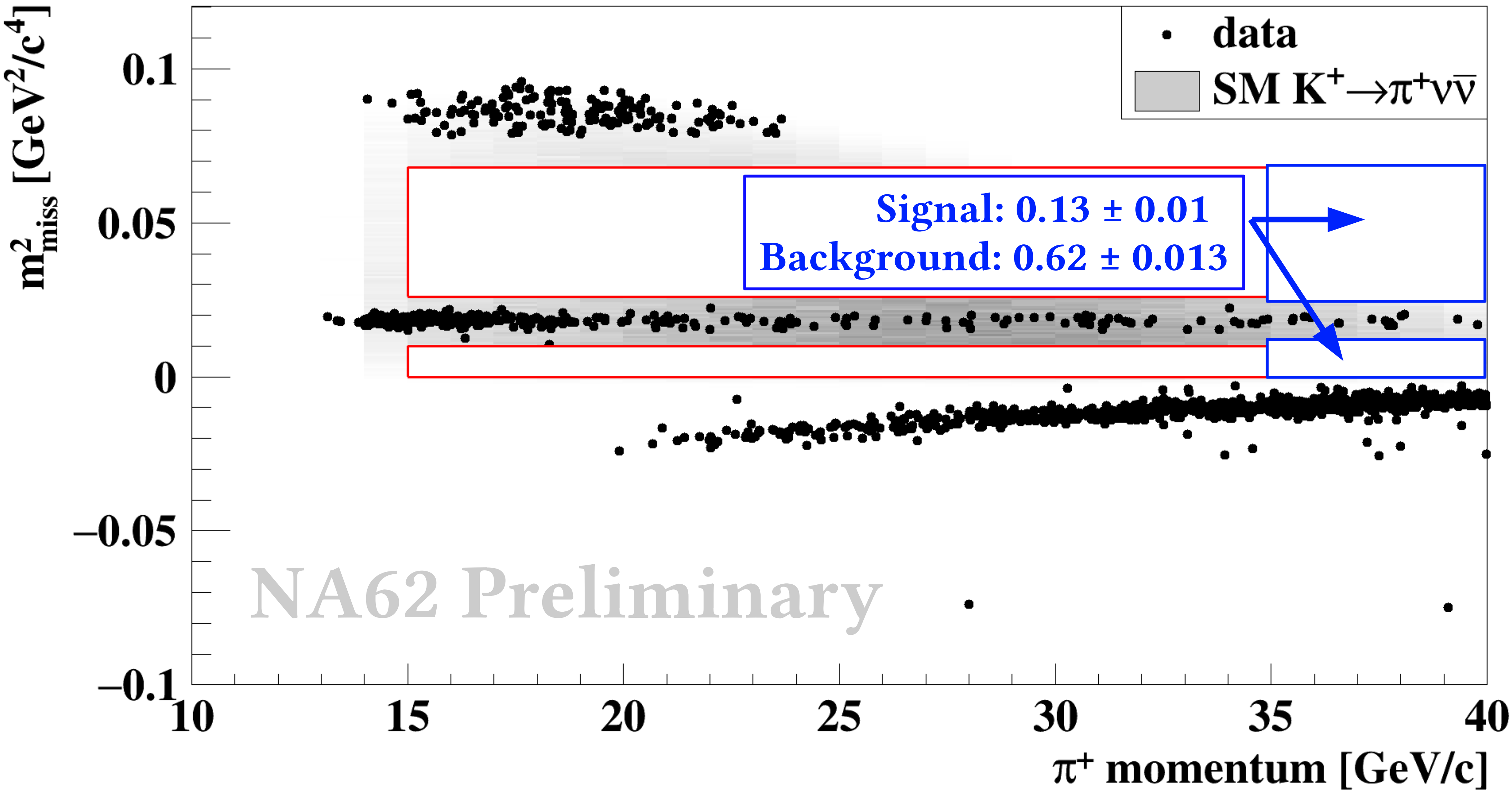
Total expected background

Process	Expected events
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	$2.16 \pm 0.12_{stat} \pm 0.26_{ext}$
$K^+ \to \pi^+\pi^0(\gamma)$ IB	$0.29 \pm 0.03_{stat} \pm 0.03_{syst}$
$K^+ \to \mu^+\nu_\mu(\gamma)$ IB	$0.15 \pm 0.02_{stat} \pm 0.04_{syst}$
$K^+ \to \pi^+\pi^-e^+\nu_e$	$0.12 \pm 0.05_{stat} \pm 0.03_{syst}$
$K^+ \to \pi^+\pi^-\pi^+$	$0.02 \pm 0.02_{syst}$
$K^+ \to \pi^+\gamma\gamma$	$0.005 \pm 0.005_{syst}$
$K^+ \to l^+\pi^0\nu_l$	negligible
Upstream background	$0.9 \pm 0.2_{stat} \pm 0.2_{syst}$
Total background	$1.5 \pm 0.2_{stat} \pm 0.2_{syst}$

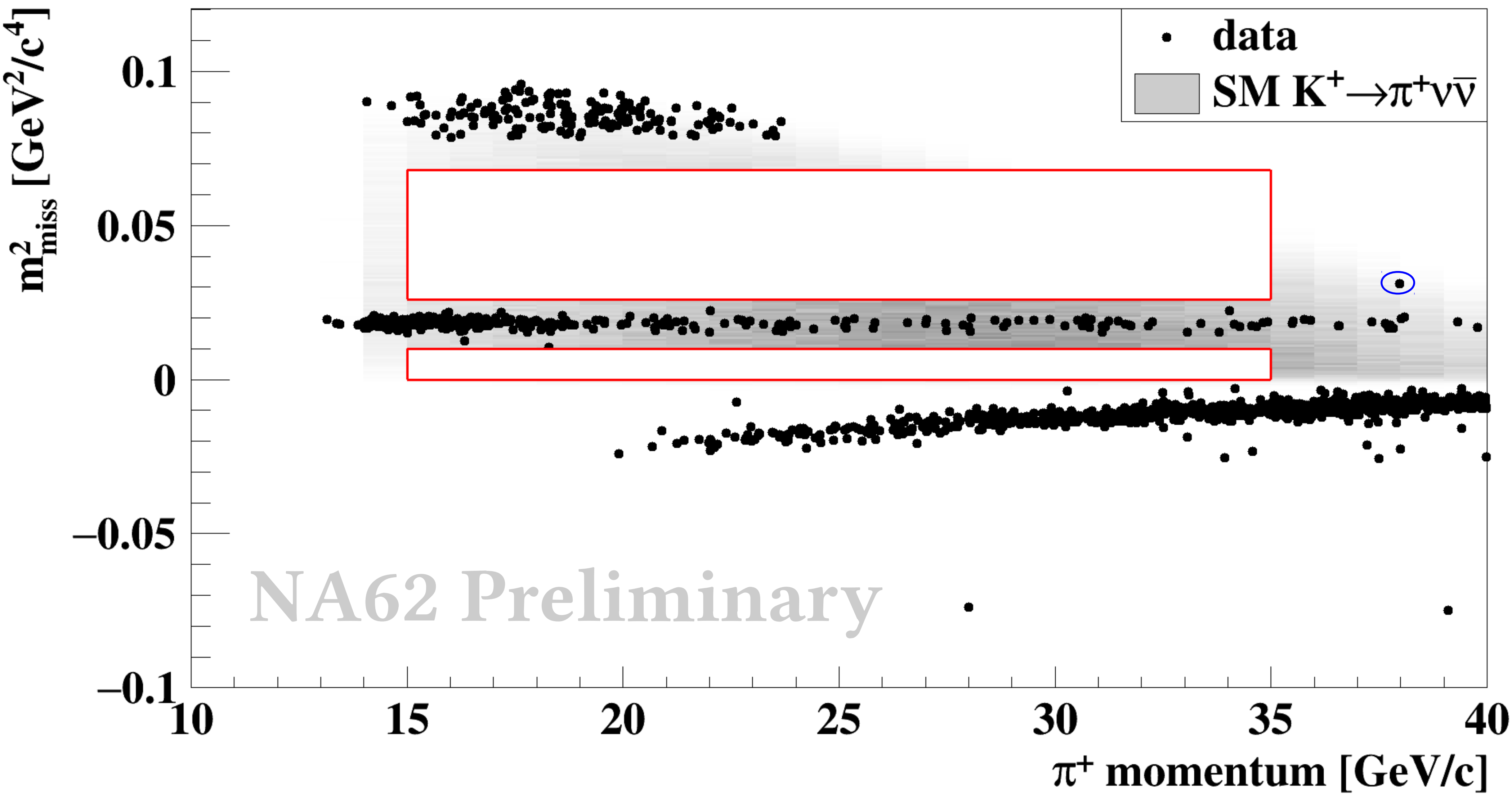
3. Unblinding signal region and results

Final background validation

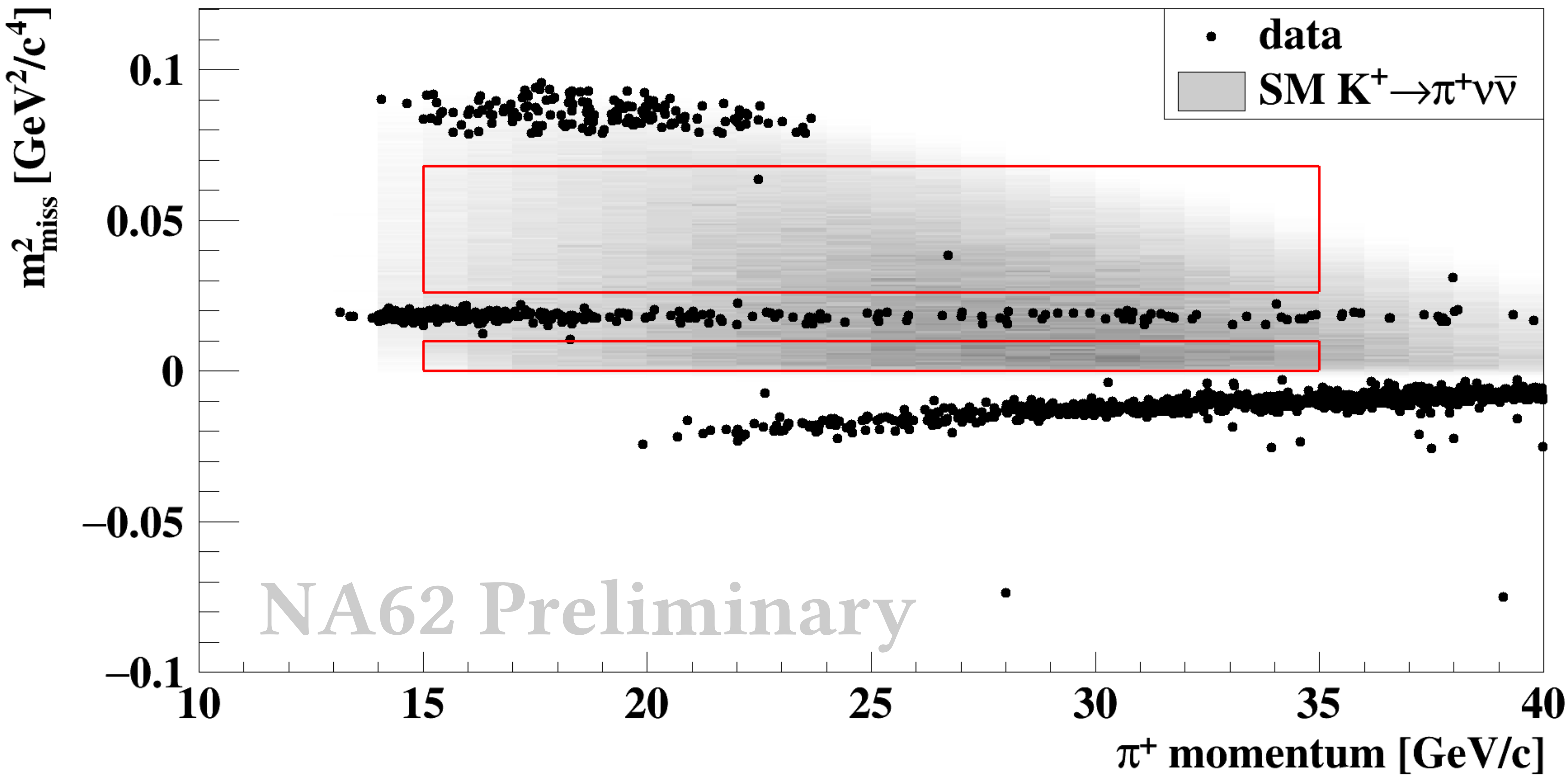
Signal and background evaluated in the 35-40 GeV/c signal-like region



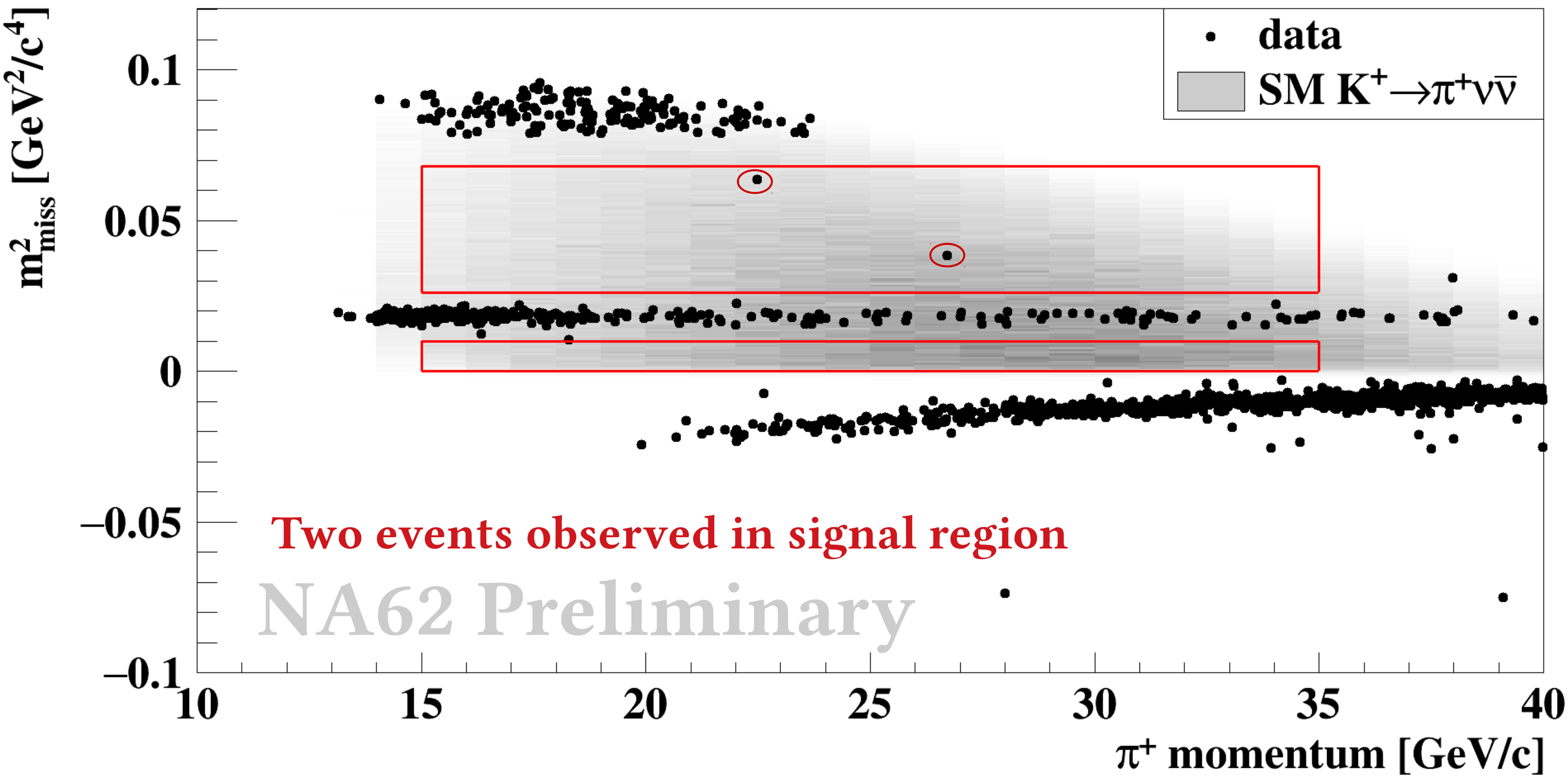
Final background validation



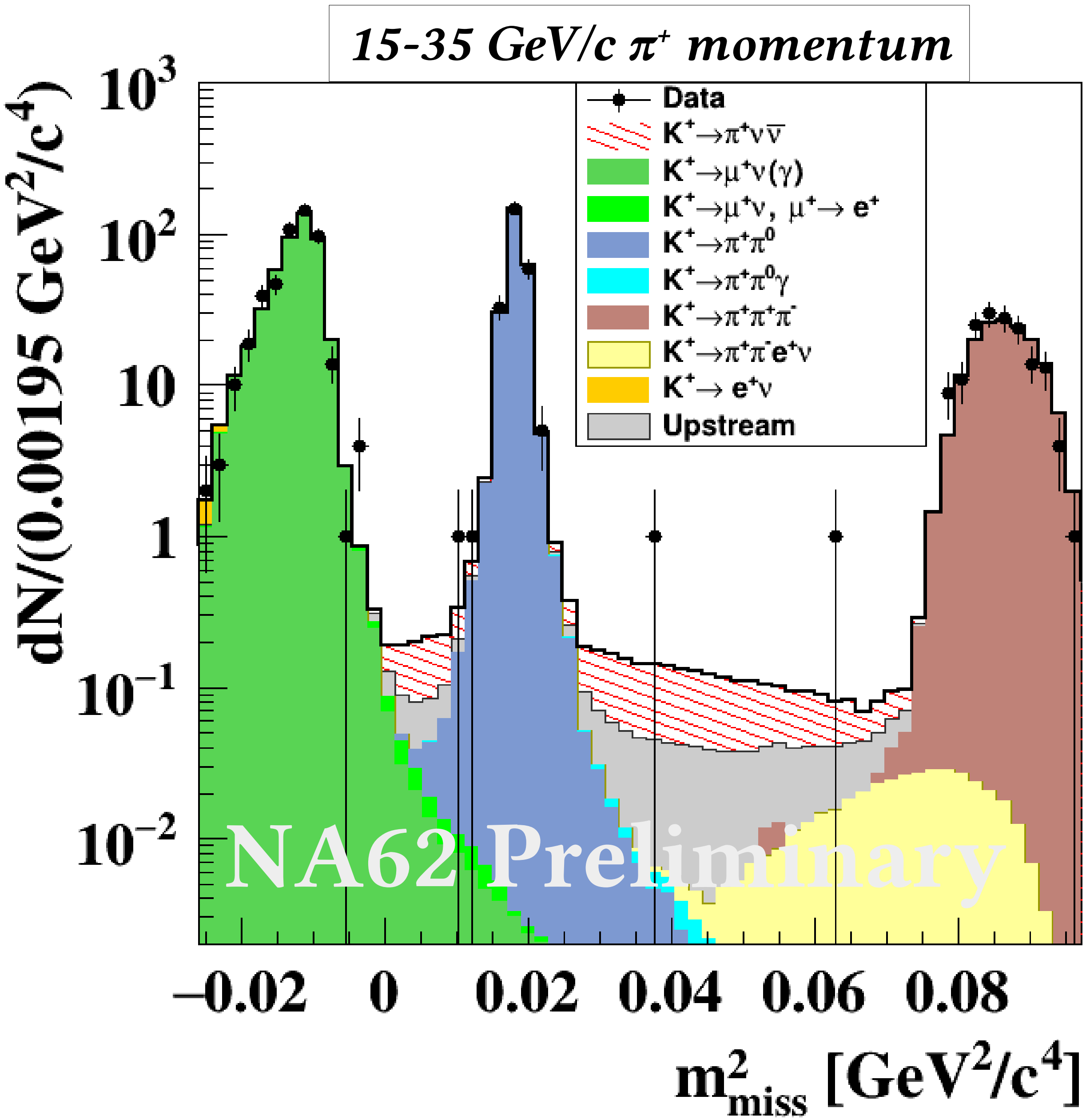
Opening the box



Opening the box



m^2_{miss} signal and background 2017



2016+2017 result

- Counting experiment

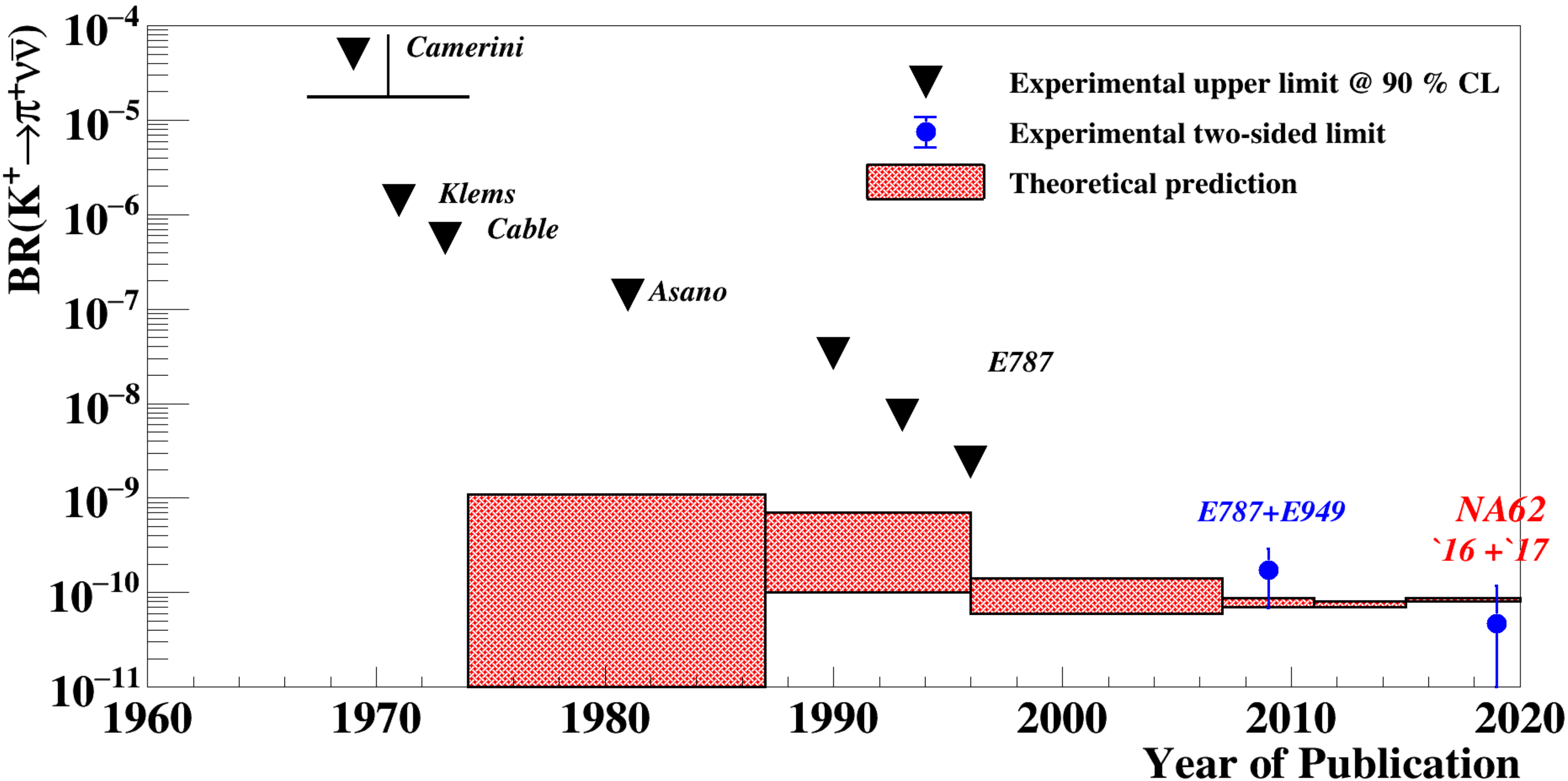
Events observed	**3**
Single event sensitivity	**$(0.346 \pm 0.017) \times 10^{-10}$**
Expected background	**1.65 ± 0.31**

- Upper limits (CLs method)

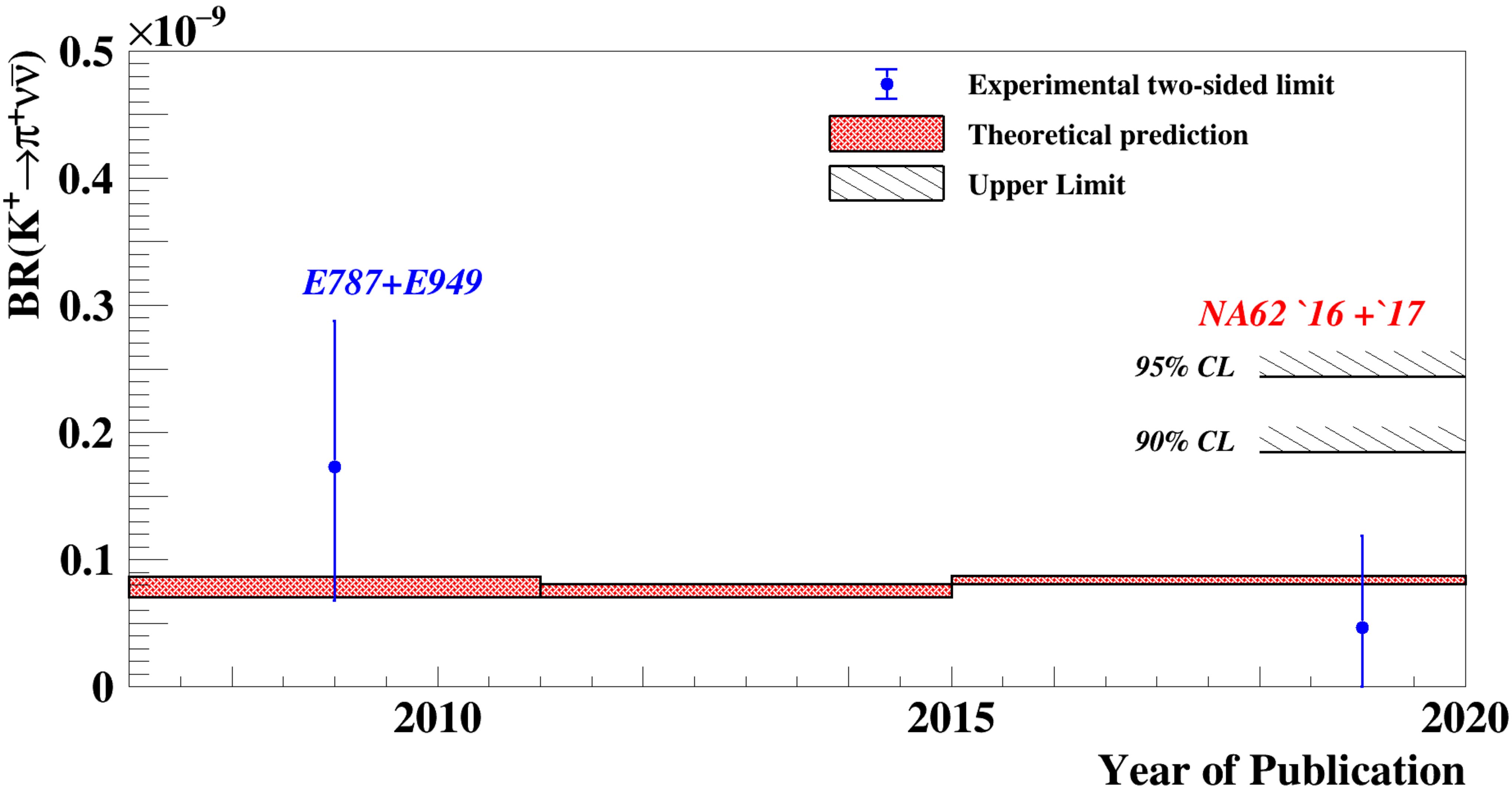
Observed	**Expected (background only)**	**CL**
$Br(K^+ \to \pi^+ \nu\nu) < 1.85 \times 10^{-10}$	**$Br(K^+ \to \pi^+ \nu\nu) < 1.32 \times 10^{-10}$**	**90%**
$Br(K^+ \to \pi^+ \nu\nu) < 2.44 \times 10^{-10}$	**$Br(K^+ \to \pi^+ \nu\nu) < 1.62 \times 10^{-10}$**	**95%**

- Two-sided 68% band: **$Br(K^+ \to \pi^+ \nu\nu) = (0.47^{+0.72}_{-0.47}) \times 10^{-10}$**
- Grossman – Nir limit: **$Br(K_L \to \pi^0 \nu\nu) < 8.14 \times 10^{-10}$ @ 90% CL**

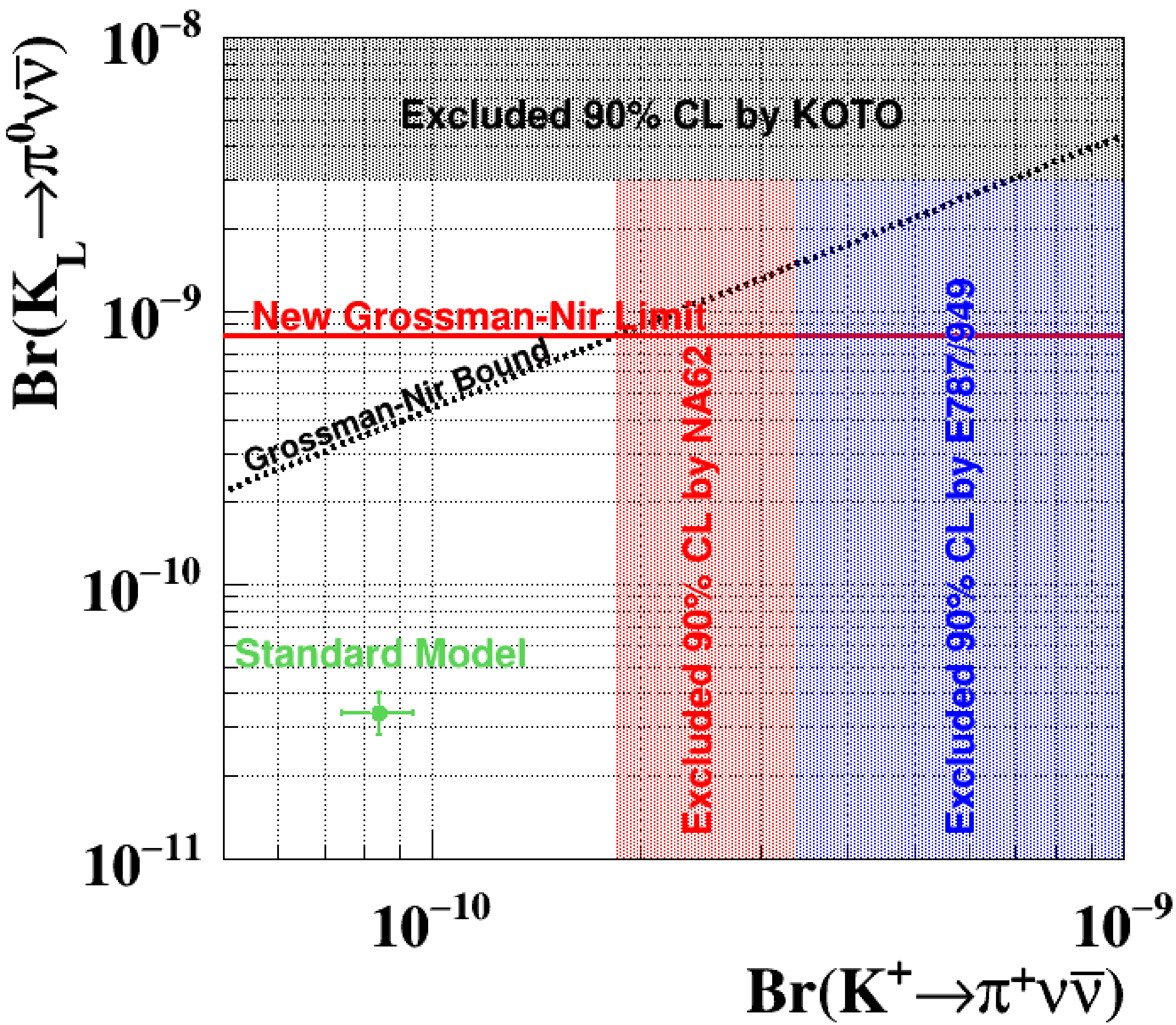
$K^+ \rightarrow \pi^+\upsilon\upsilon$: historical perspective



$K^+ \rightarrow \pi^+\nu\nu$: historical perspective



$K^+ \to \pi^+\nu\nu$: Grossman – Nir limits



Summary and prospects

- Two events in signal region observed in 2017 data
- 2016+2017 NA62 result

$$BR(K^+ \to \pi^+\nu\nu) < 1.85 \times 10^{-10} \text{ @ } 90\ \%\ \text{CL}$$

$$BR(K^+ \to \pi^+\nu\nu) = 0.47^{+0.72}_{-0.47} \times 10^{-10}$$

- Constraints on the largest enhancements allowed by NP models

- 2018 data analysis in progress (factor 2 more data)
  - On-going studies to increase signal efficiency
- Hardware improvements foreseen from 2021 to mitigate the upstream background

SPARES

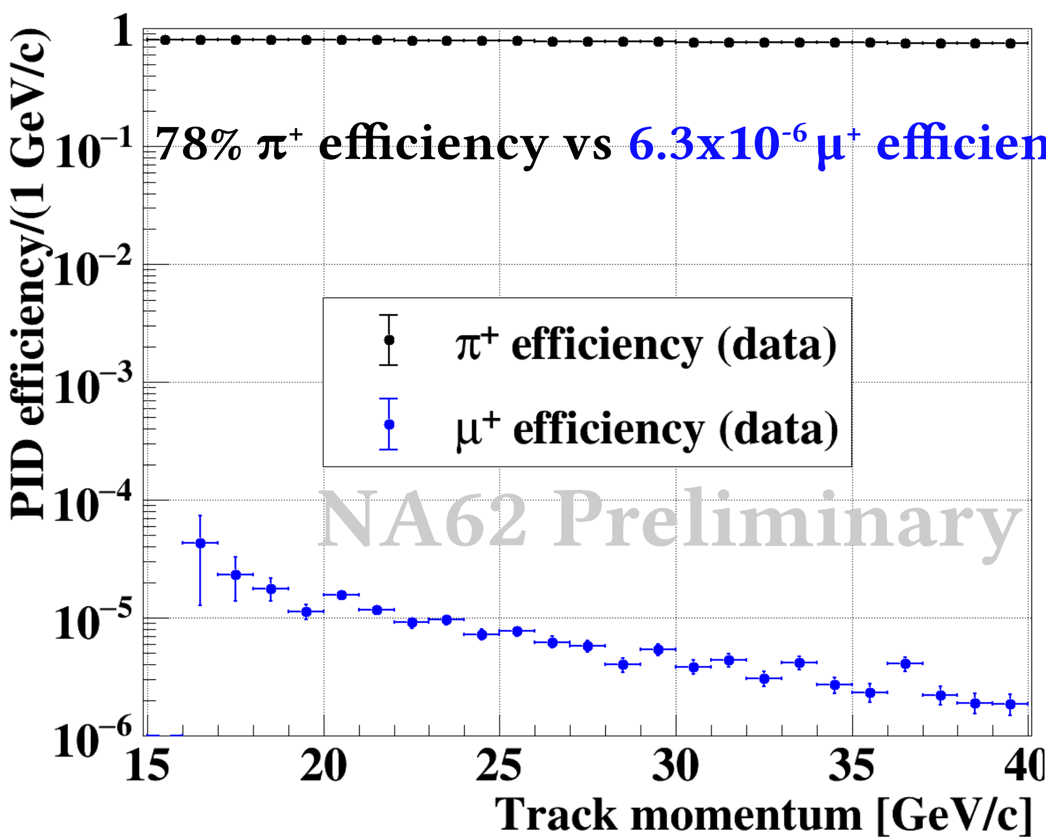
Keystones of the analysis: Particle identification

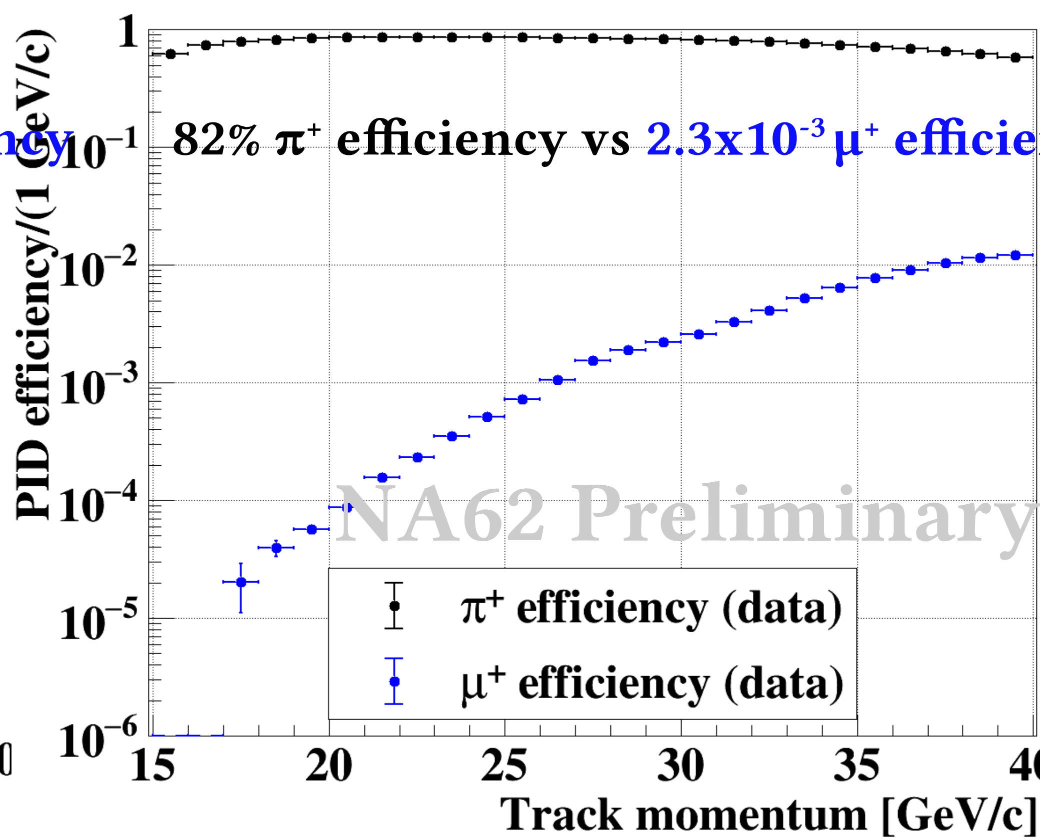
Calorimetric PID

- Machine learning approach (BDT)
  - Energy deposition
  - Energy sharing
  - Shower shape profiles

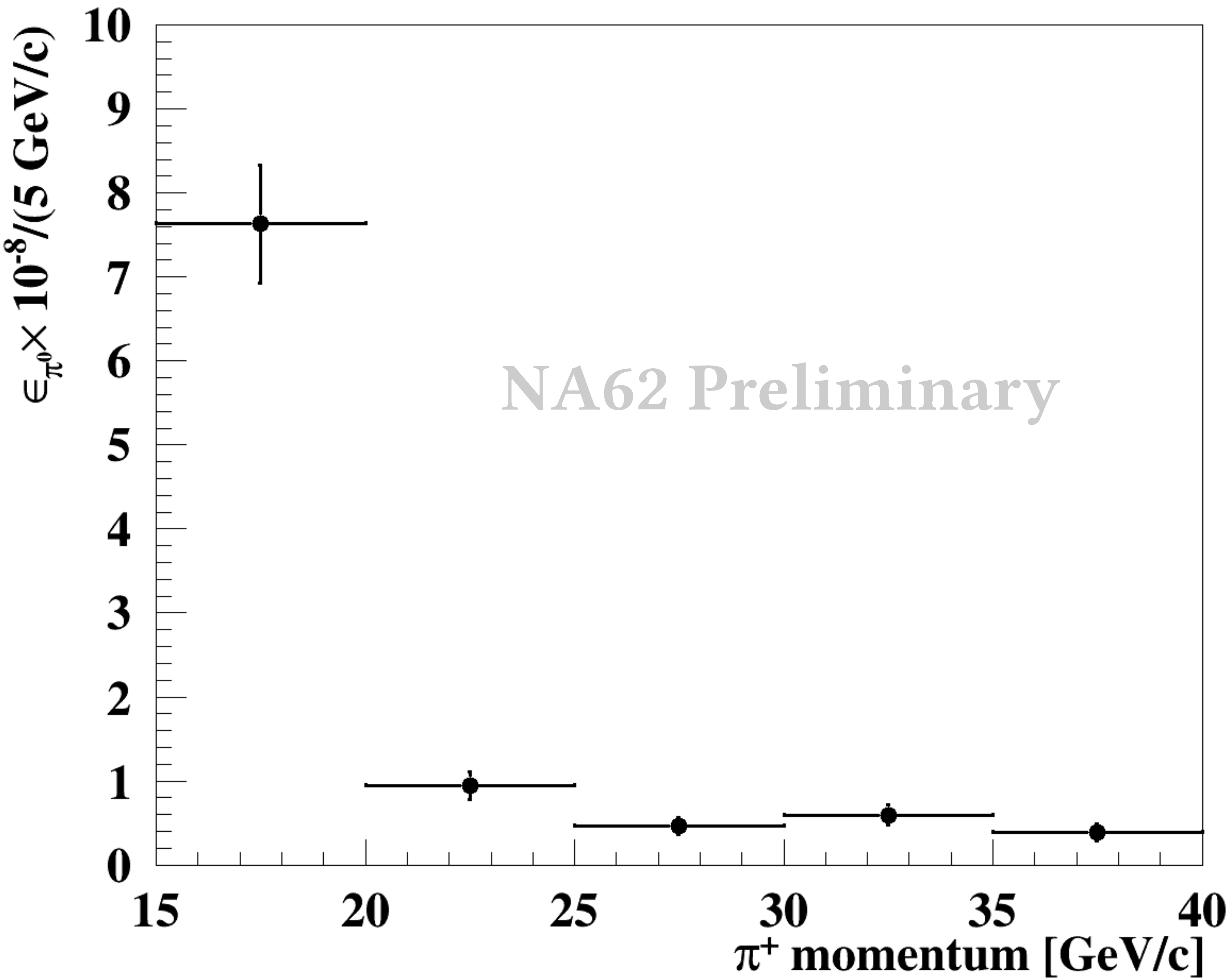
RICH PID

- Track driven likelihoods discriminant for π/μ/e separation
- Particle mass using track momentum
- Momentum measurement under mass hypothesis (velocity spectrometer)





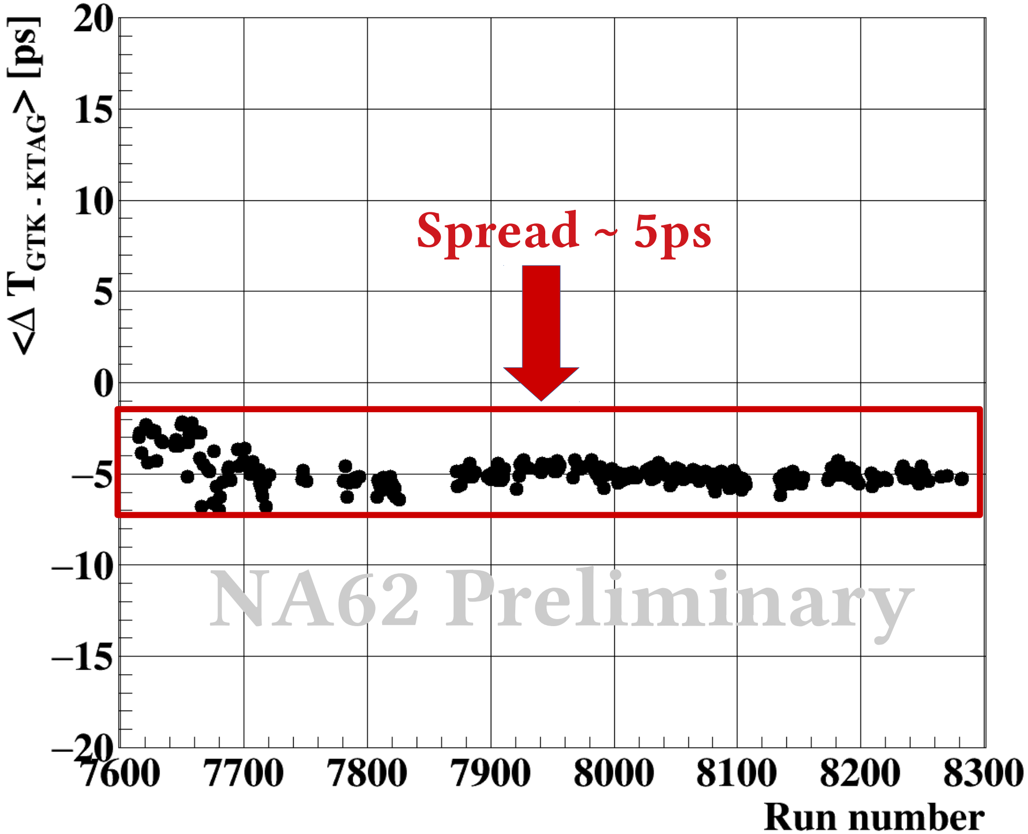
Keystones of the analysis: π^0 suppression

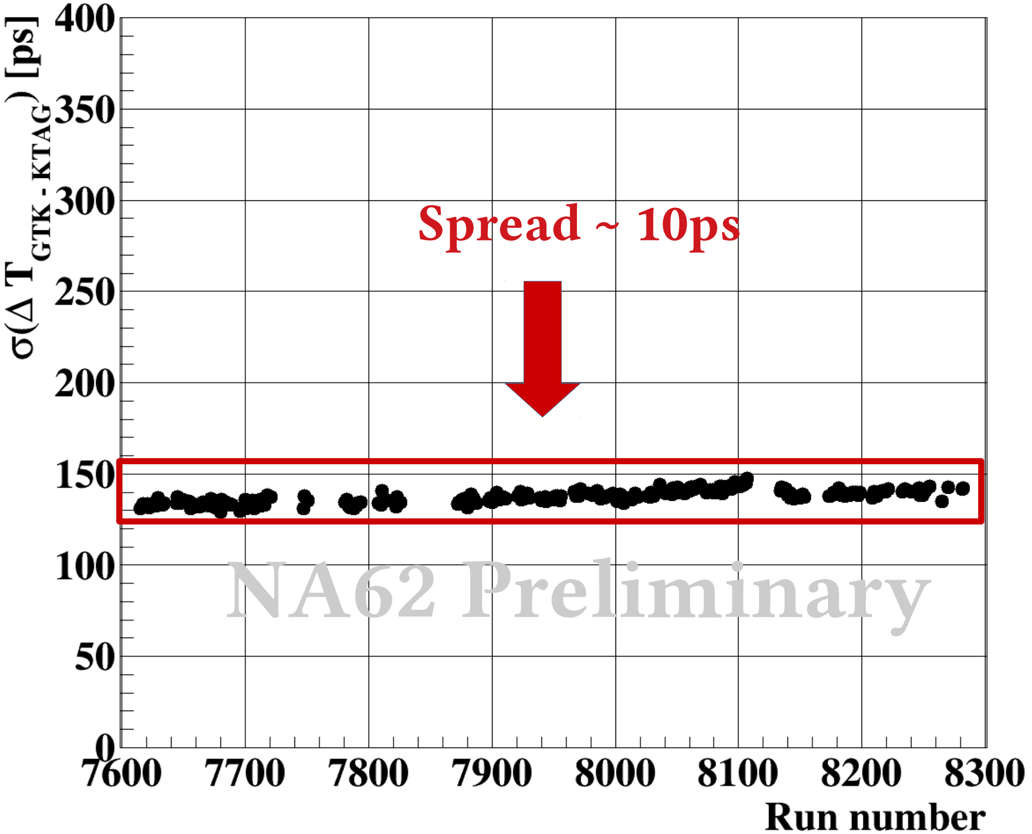


Keystones of the analysis: Time resolution

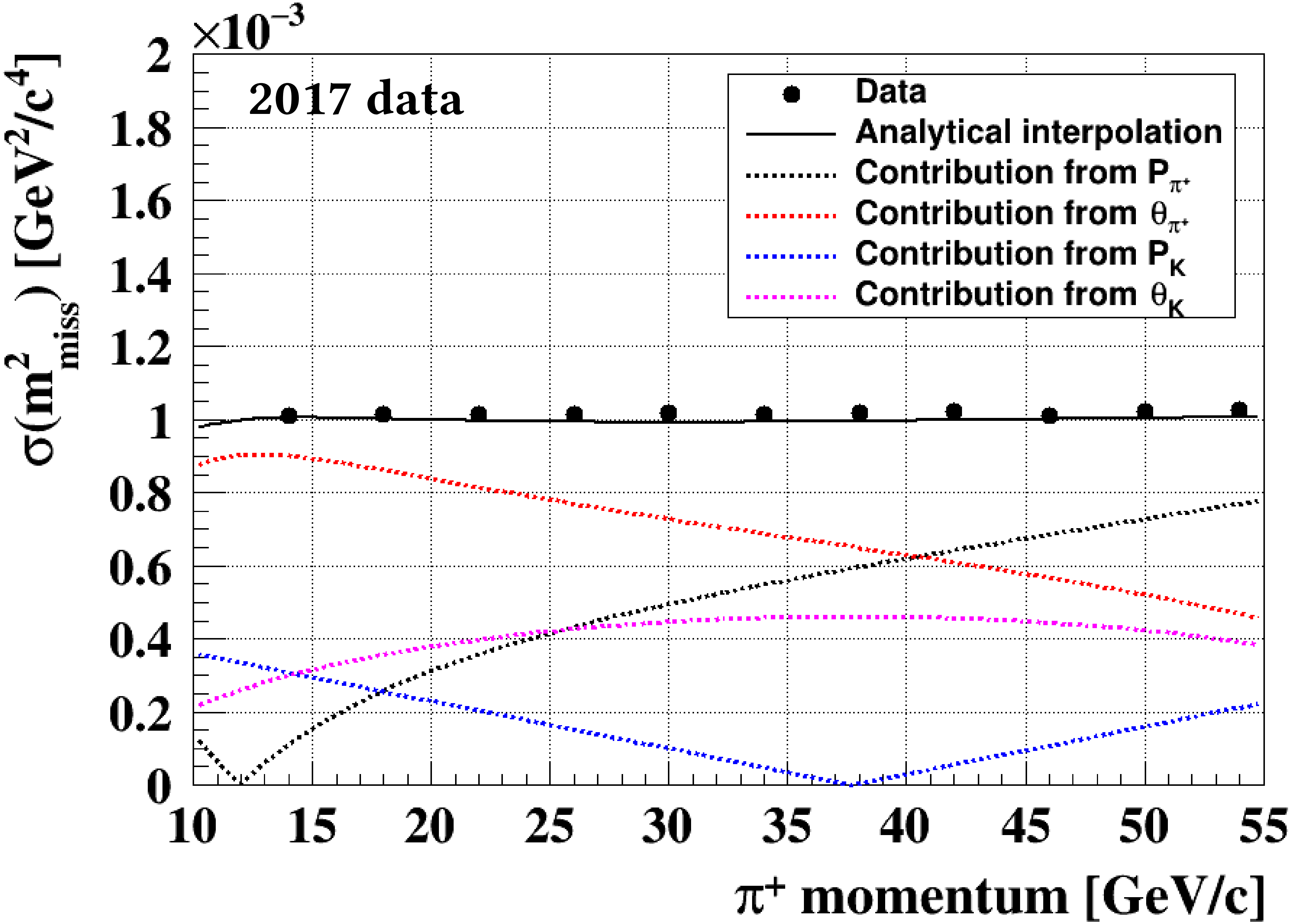
Time calibration stability

- Excellent calibration at the processing level in 2017
- Stable time resolution and central value
- Single-detector time resolution ~ 90ps





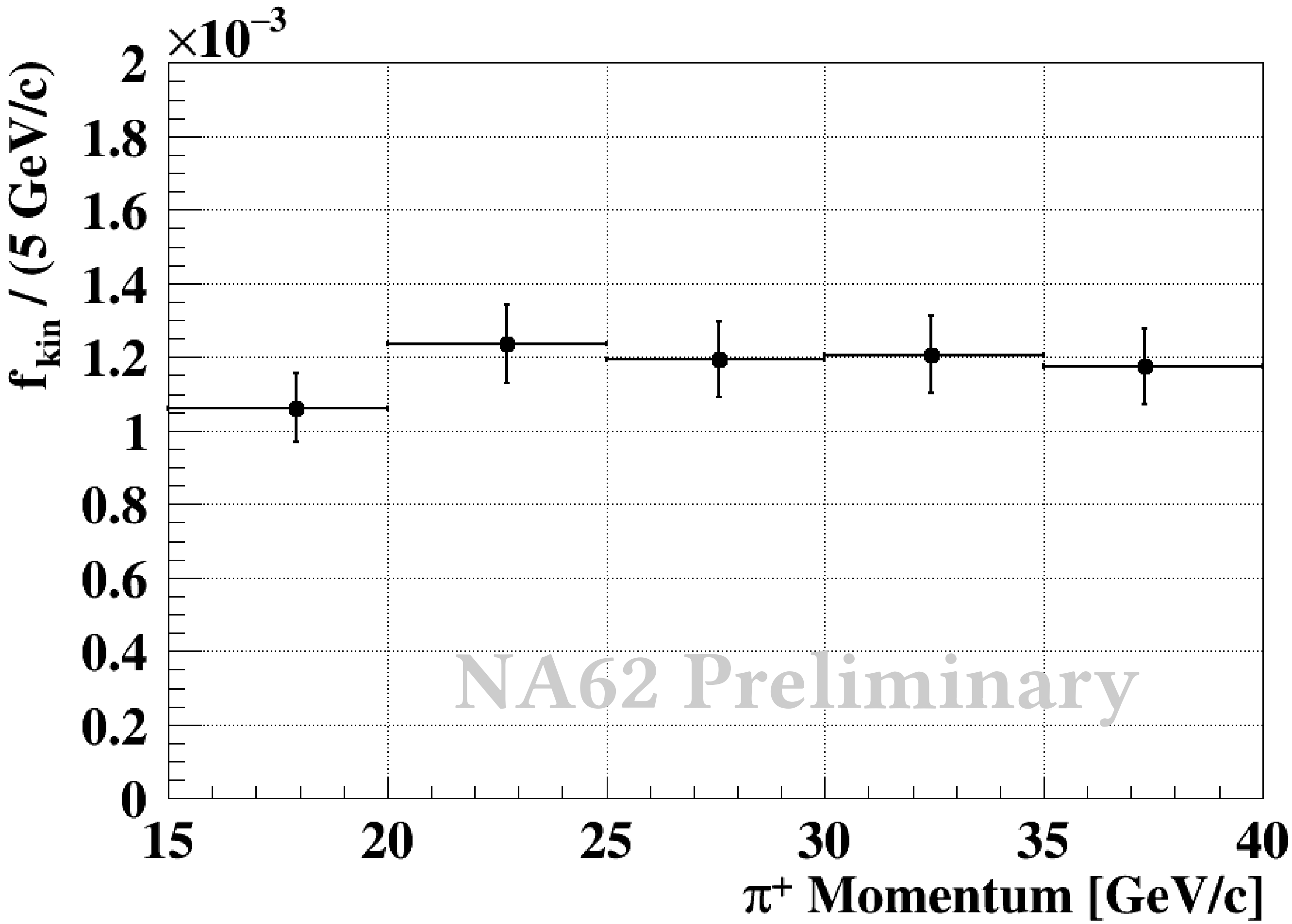
Keystones of the analysis: Kinematic resolution



Keystones of the analysis: Kinematic suppression

$K^+ \longrightarrow \pi^+\pi^0$

- Kinematic suppression measured on $K^+ \longrightarrow \pi^+\pi^0$ decays in data
- Fraction of events $\pi^+\pi^0$ entering m^2_{miss} signal region



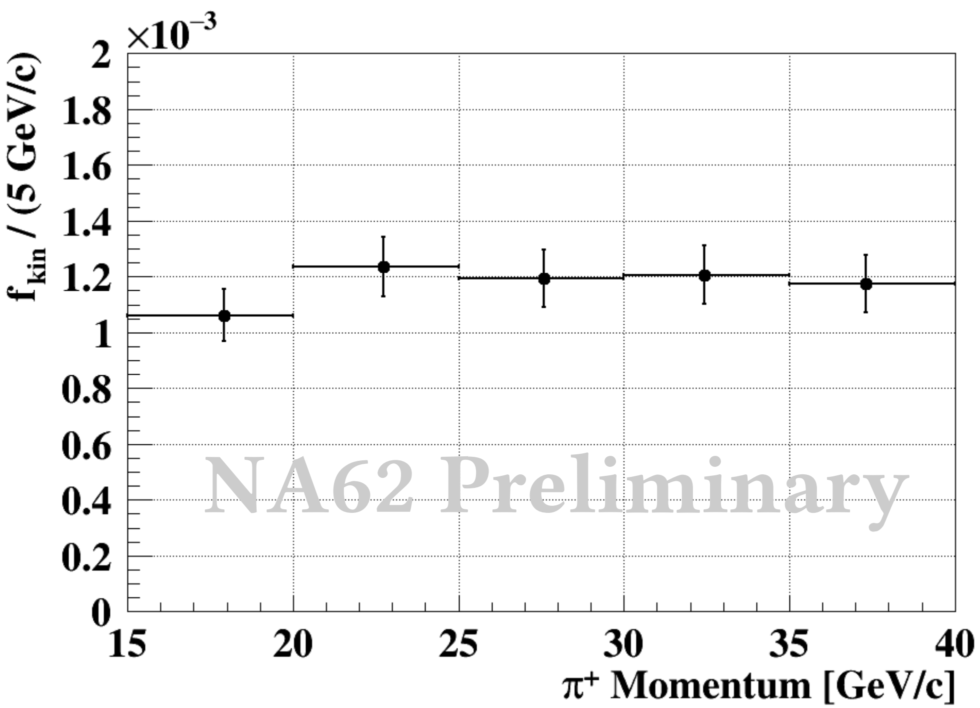
Keystones of the analysis: Kinematic suppression

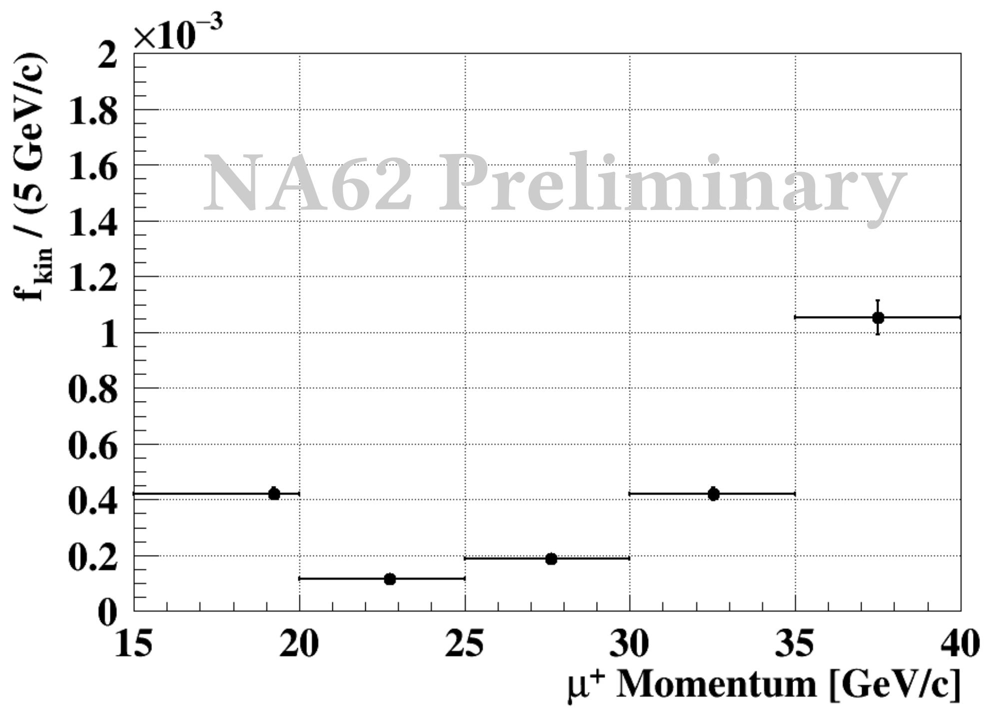
$K^+ \longrightarrow \pi^+\pi^0$

- Kinematic suppression measured on $K^+ \longrightarrow \pi^+\pi^0$ decays in data
- Total kinematic suppression in signal region ~ 10^{-3}

$K^+ \longrightarrow \mu^+\nu$

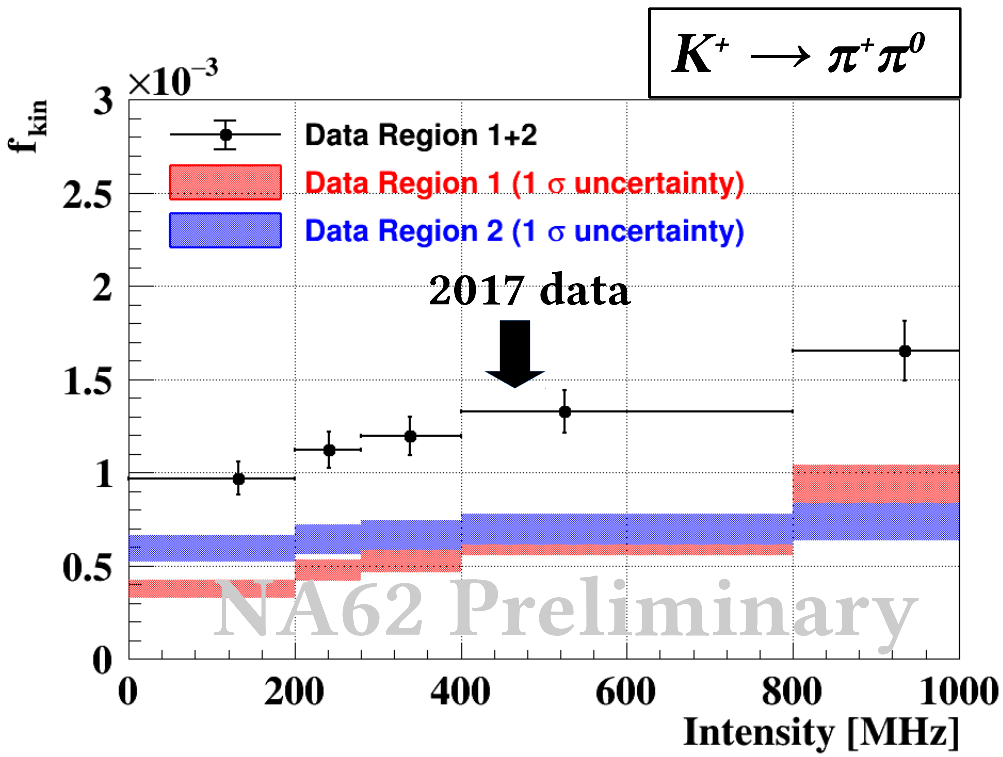
- Kinematic suppression measured on $K^+ \longrightarrow \mu^+\nu$ decays in data
- Total kinematic suppression in signal region ~ $5\text{x}10^{-4}$

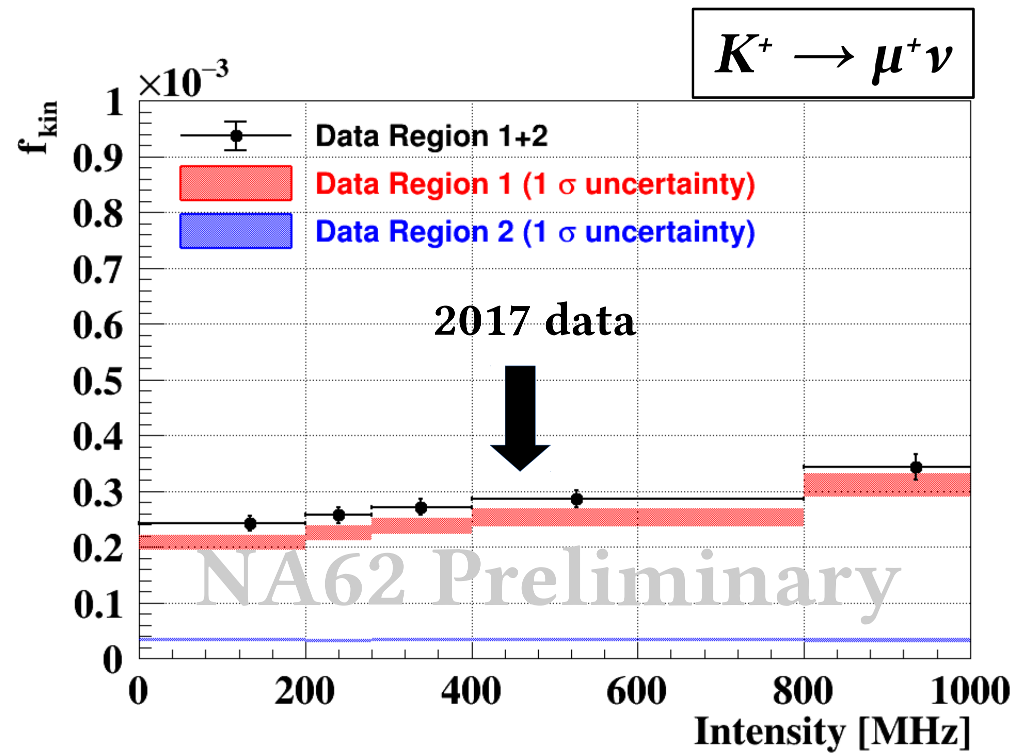




Keystones of the analysis: Kinematic suppression

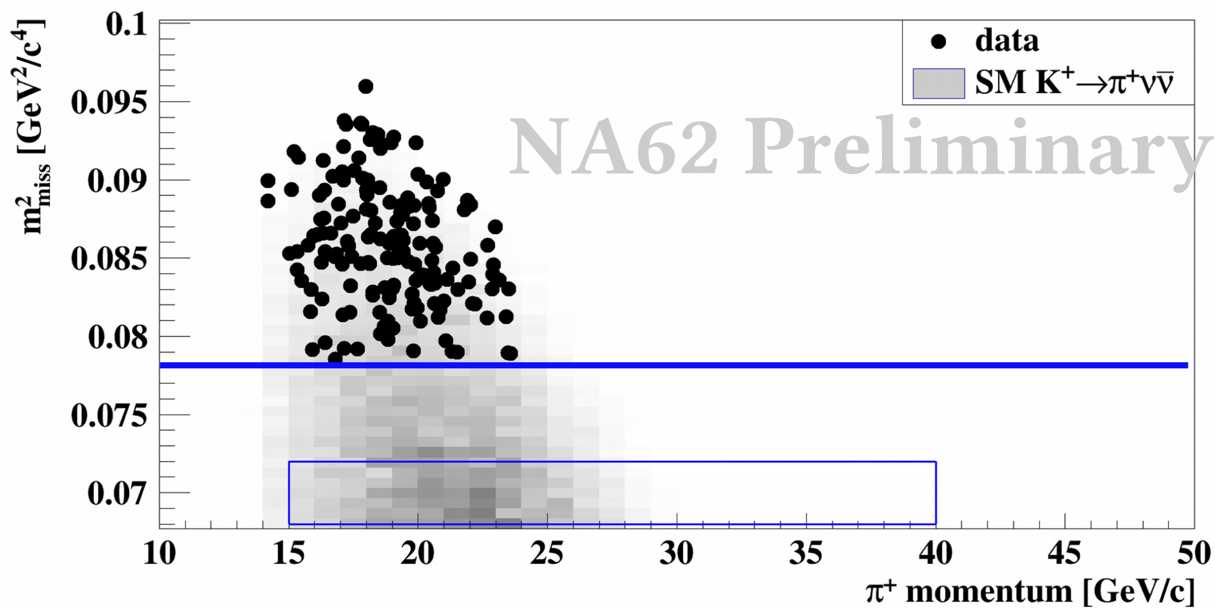
- Low intensity dependence of the kinematic suppression
- More pronounced in Region 1
- Kinematic misreconstruction dominated by mistagging in GTK





Background: $K^+ \rightarrow \pi^+\pi^+\pi^-$ validation

- < 0.5 events expected in validation region (observed 0)
- Indications from simulation that the background might be up to 2 times lower

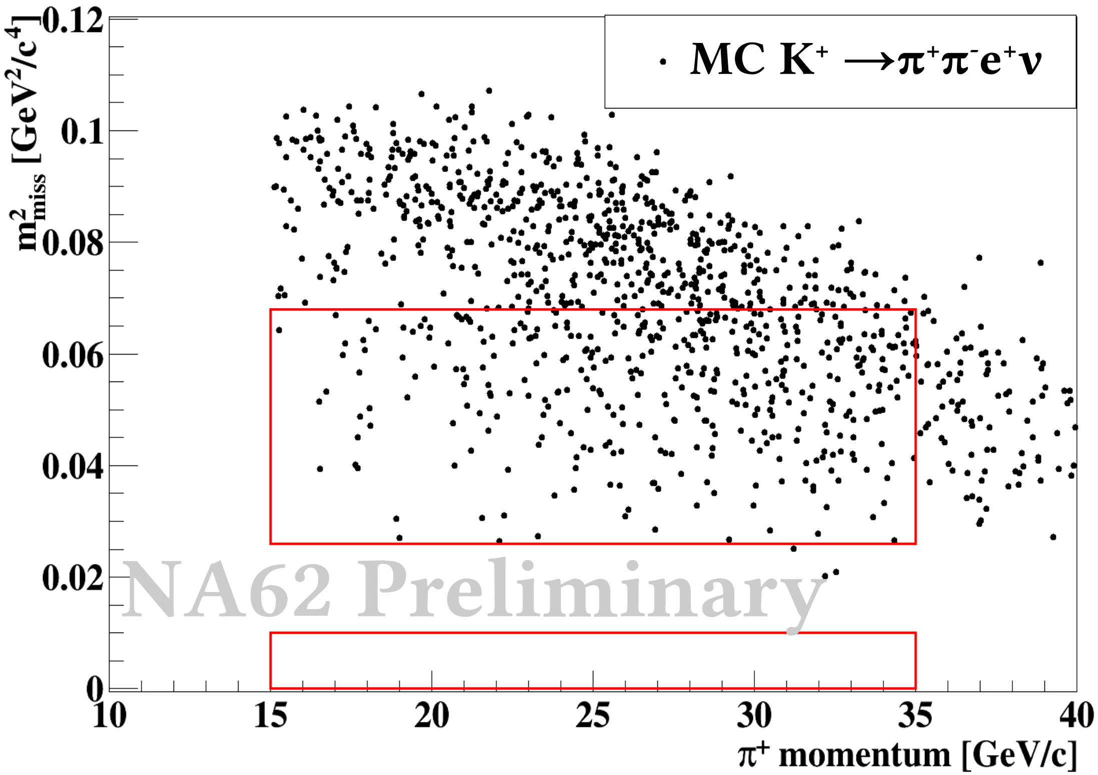


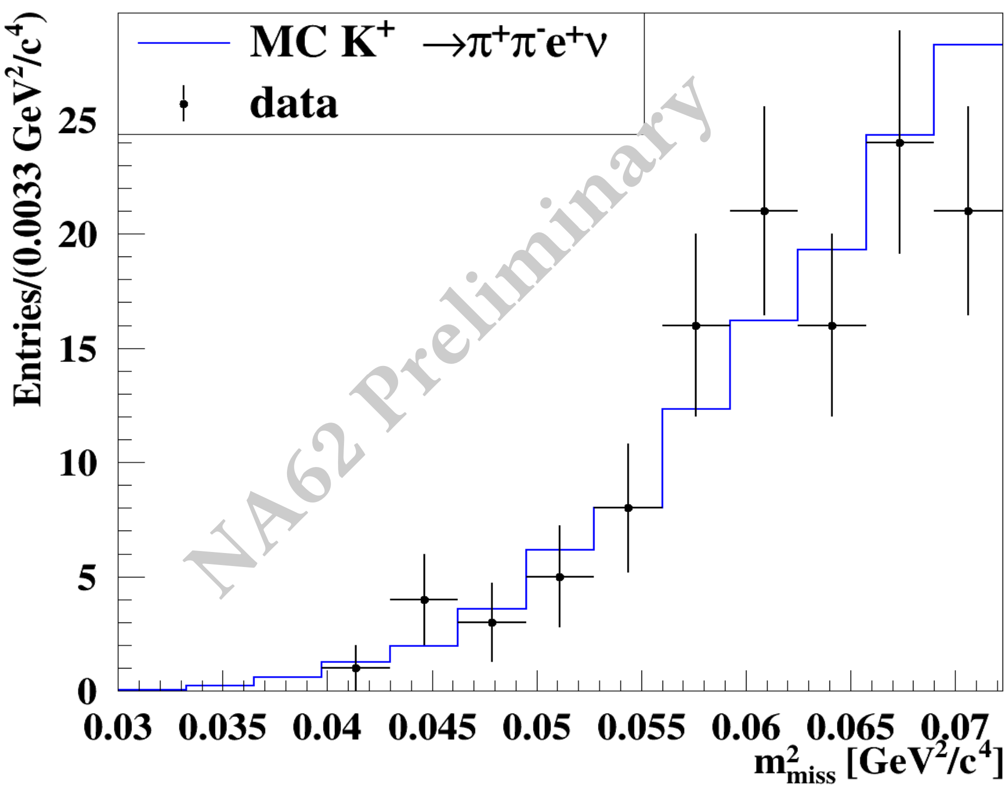
4m²π+ kinematic boundary

$$N^{bg}_{\pi\pi\pi} = 0.016 \pm 0.016_{syst}$$

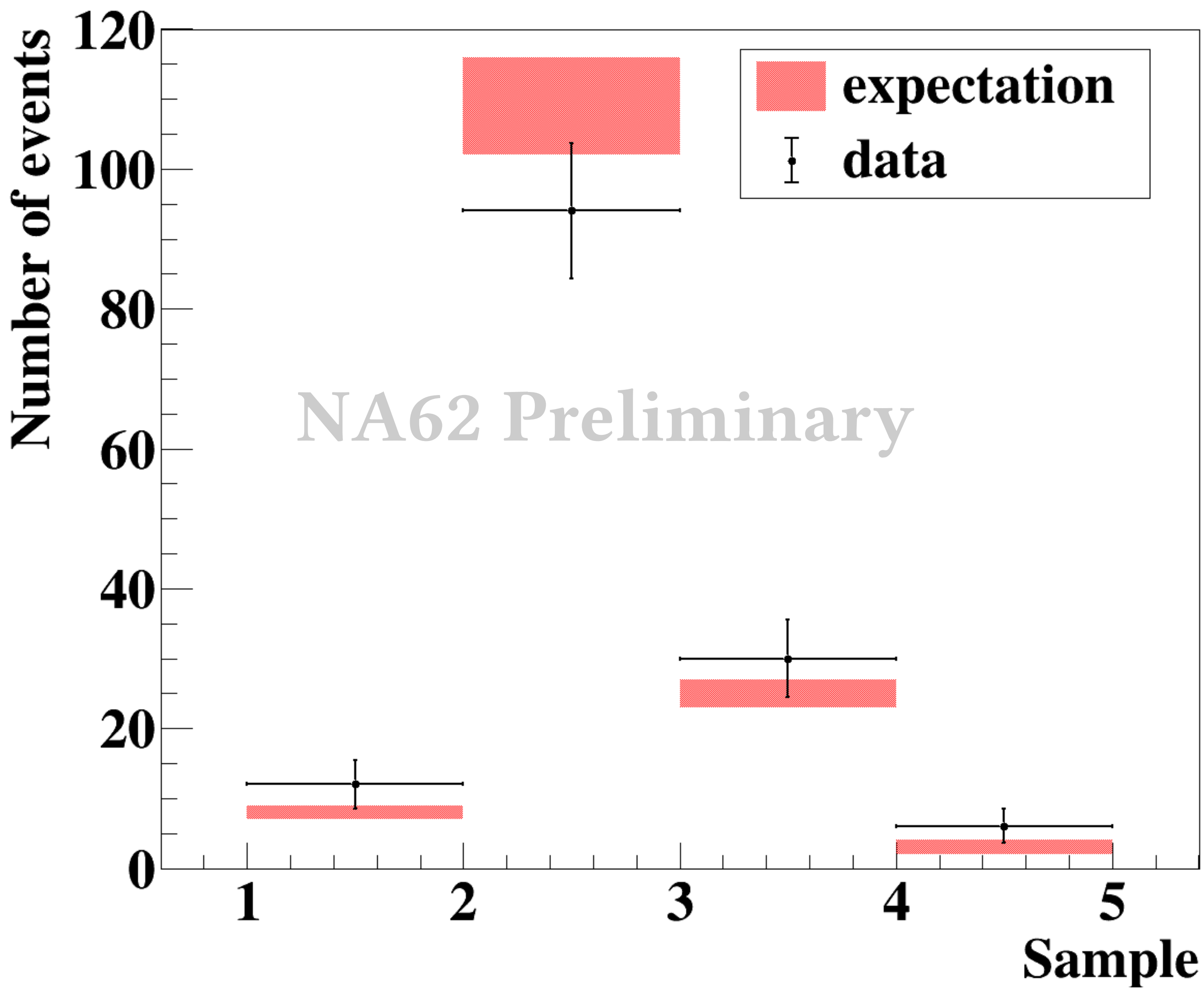
Background: $K^+ \rightarrow \pi^+\pi^-e^+\nu$

- Sample of $2\text{x}10^9$ MC generated $K^+ \rightarrow \pi^+\pi^-e^+\nu$ decays used for background estimation
  - Correlation between m^2_{miss}, kinematics and multi-track rejection
- MC simulation validated using data
- $K^+ \rightarrow \pi^+\pi^-e^+\nu$ expectation normalized to S.E.S. (m^2_{miss} shape well reproduced)





Background: $K^+ \to \pi^+\pi^-e^+\nu$ validation



$$N_{Ke4}^{bg} = 0.12 \pm 0.05_{stat} \pm 0.03_{syst}$$

Background: Upstream decays

$$N^{bg}_{upstream} = N^{upstream}_{\pi^+} \cdot P^{reco}_{pileup} \cdot P^{matching}_{K-\pi}$$

$N^{upstream}_{\pi^+}$ $\Longrightarrow$ Events with a downstream 15-35 GeV/c π^+ originating upstream of GTK3

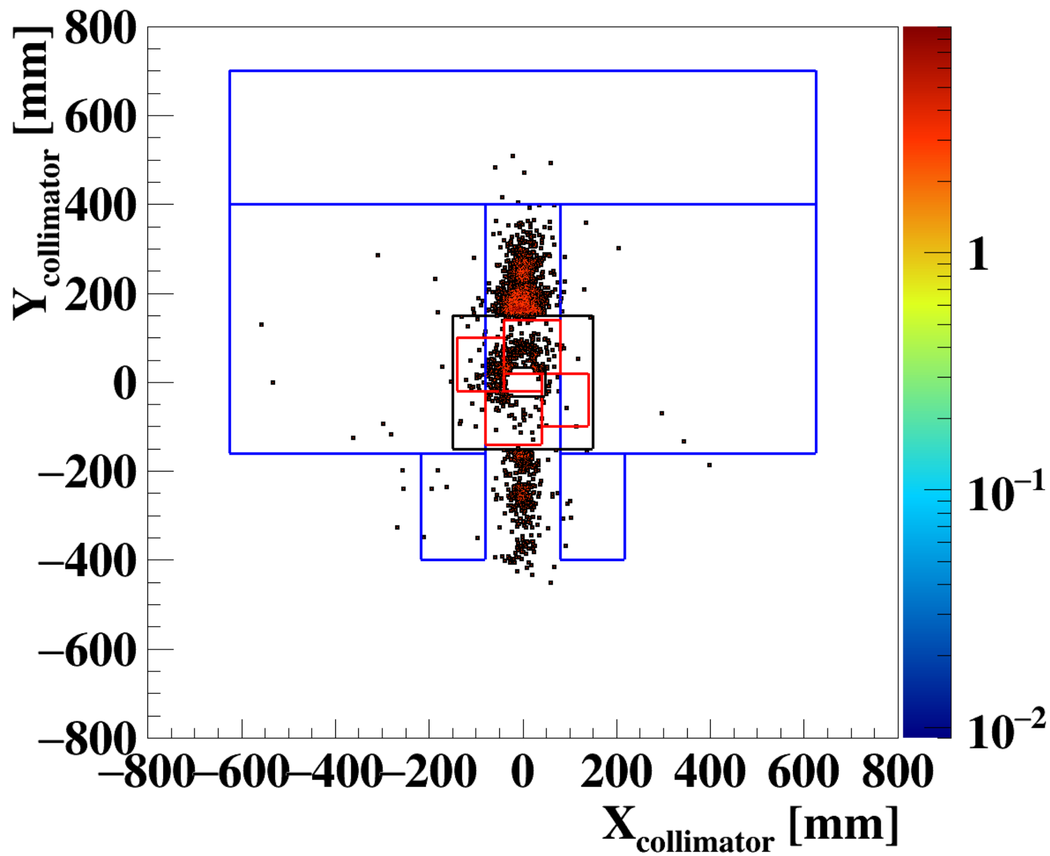
P^{reco}_{pileup} $\Longrightarrow$ Probability that the source of upstream π^+ is reconstructed in the GTK

$P^{matching}_{K-\pi}$ $\Longrightarrow$ Probability the downstream π^+ to be matched to a GTK track

Background: Upstream decays

$$N^{bg}_{upstream} = N^{upstream}_{\pi^+} \cdot P^{reco}_{pileup} \cdot P^{matching}_{K-\pi}$$

Count events in an upstream enriched sample

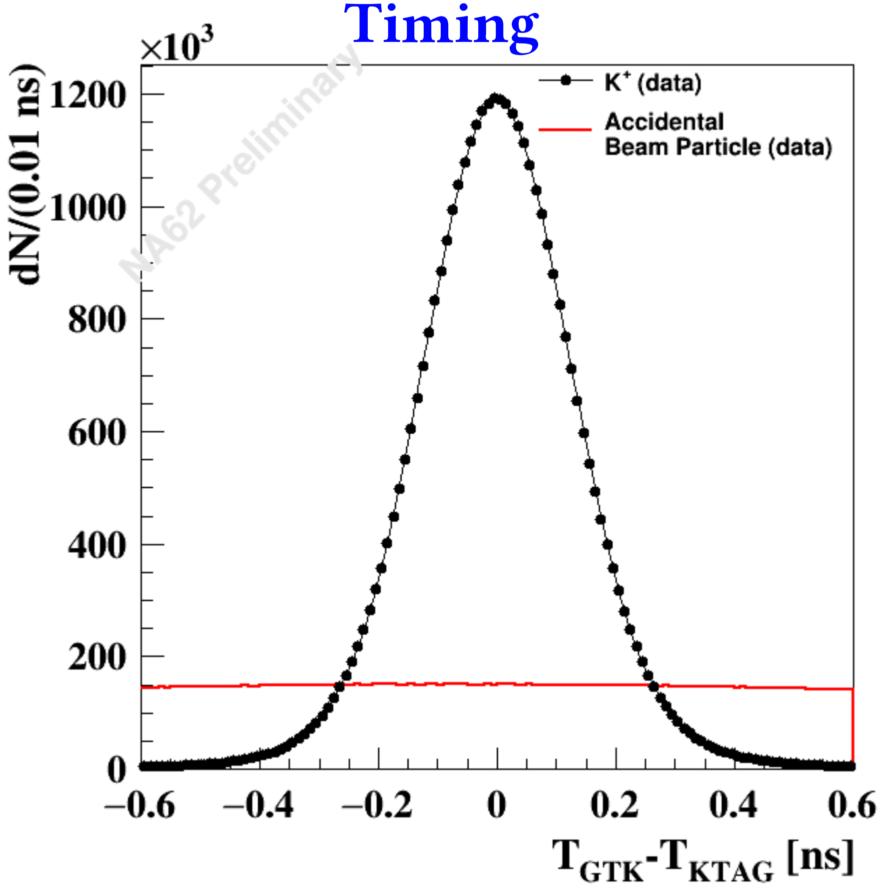


Background: Upstream decays

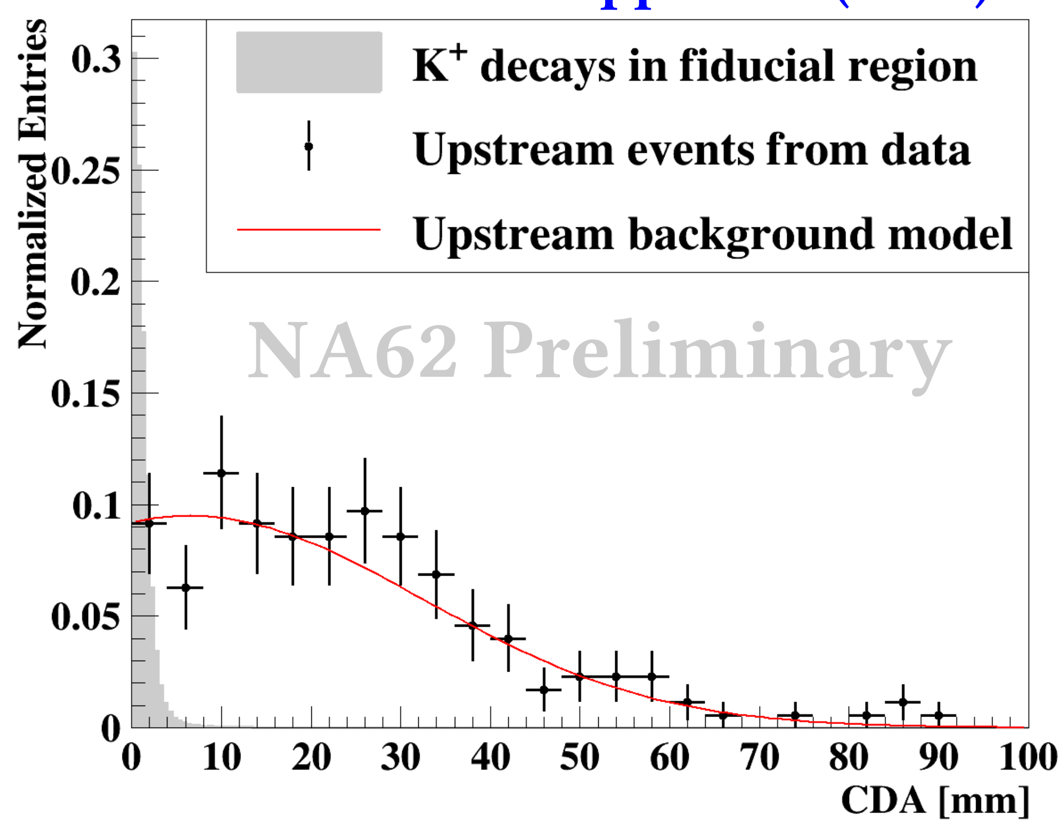
$$N^{bg}_{upstream} = N^{upstream}_{\pi^+} \cdot P^{reco}_{pileup} \cdot P^{matching}_{K-\pi}$$

Measured

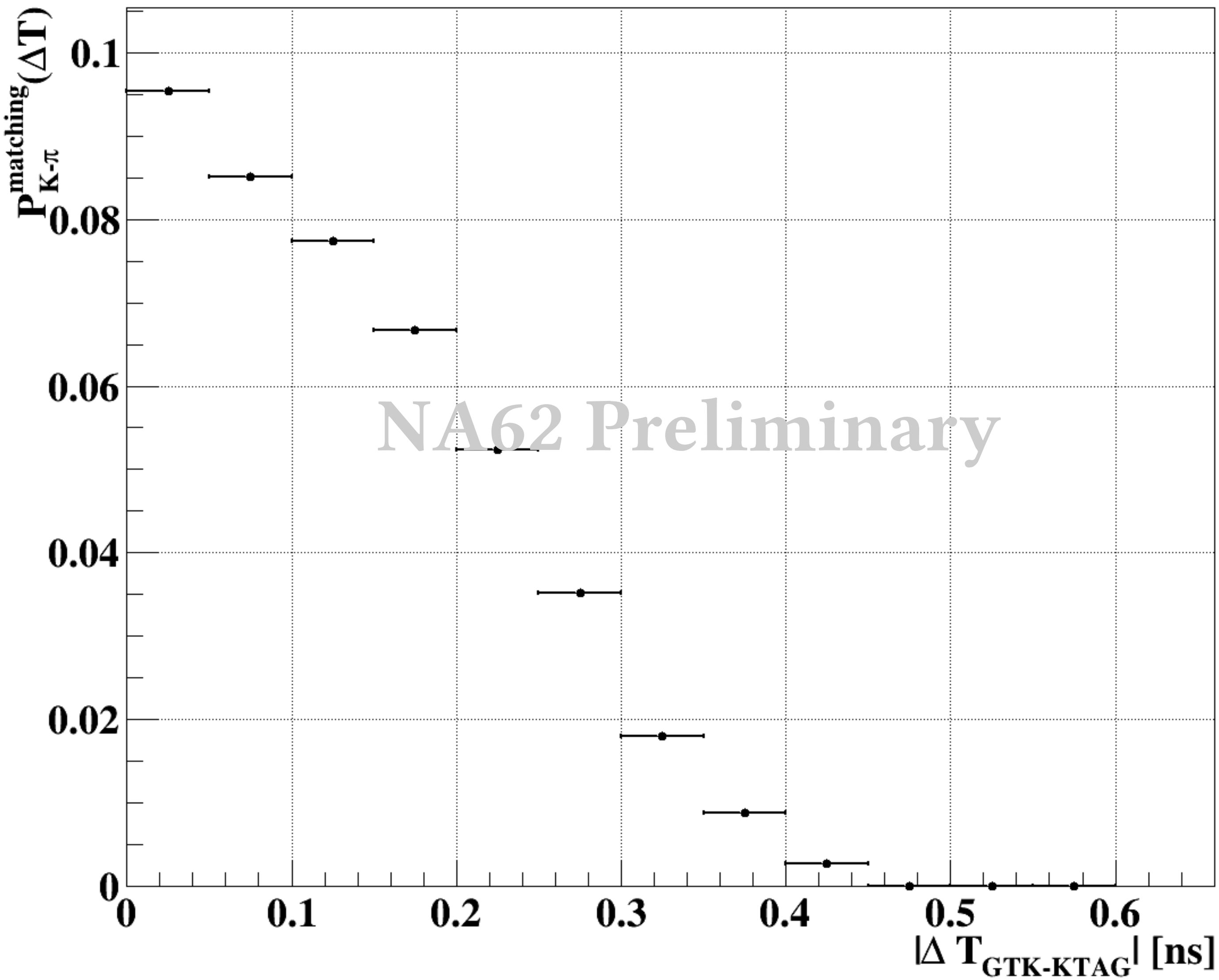
Timing



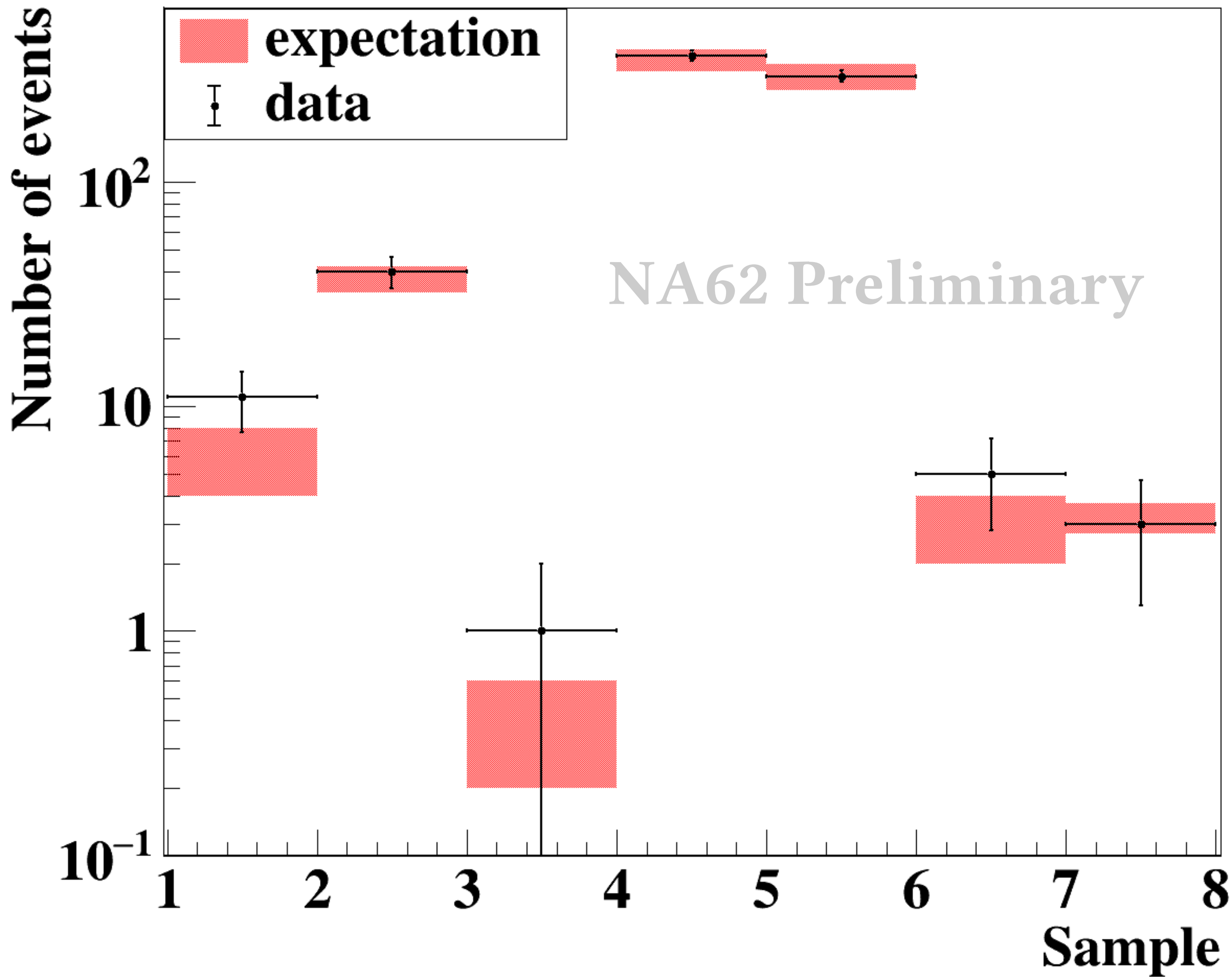
Closest distance of approach (CDA)



Background: $P^{matching}_{K-\pi}$ measurement



Background: Upstream decays validation



m^2_{miss} signal and background 2017