What can we learn from the NA62 experiment?

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LHCb UK Student meeting, 24th September 2020, Home

Introduction

- Why are Flavour Changing Neutral Currents and kaon physics important ?
- Why does $K^+ \to \pi^+ \nu\bar{\nu}$ is one of the golden channels of flavour physics?
- How can we overcome the experimental challenges and measure such a rare decay?
  - Hint: We need a dedicated experiment with state-of-the-art detectors!
- What can we learn from NA62 Run 1(2016-2018) data?
  - Focus on the 2018 data (preliminary results shown on ICHEP 2020)
- Prospects for the future

Kaon physics, a building block of the SM

- Discovery of strange particles *[Nature 160 4077 (1947) 855]*
- Postulation of neutral meson oscillation *[PR 97 (1955) 1387]*
- $\Theta - \tau$ Puzzle: first hint of P violation *[PR 104 (1956) 254]*
- Discovery of CP violation in the K^0 mixing *[PRL 13 (1964) 138]*
- 3 quark model to describe observed meson/baryon spectra *[PL 8 (1964) 214]*
- *c* quark prediction to explain the observed BR of $K_L \to \mu^+\mu^-$ *[PRD 2 (1970) 1285]*
- Discovery of CP violation in the K^0 decay *[PLB 206 (1988) 169]*

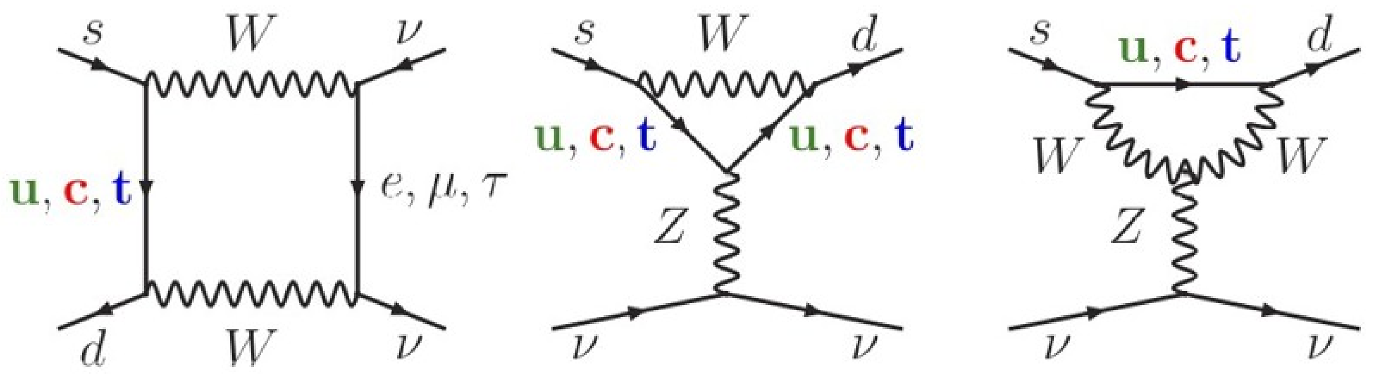
Kaon physics in the last 20 years

- First measurement of direct CP violation
- Test of CPT symmetry invariance
- Low energy QCD (e.g. χPT)
- Precision test of the CKM unitarity
- Test of lepton universality and flavour violation
- Rare K decays: SM and beyond

Kaon factories:

1997-2014	CERN SPS (NA48), CERN LEAR (CPLEAR), FNAL (KTEV), LNF (KLOE, KLOE2), BNL (E787, E865, E949), KEK (E391), Protvino (ISTRA+)
2014-today	CERN SPS (NA48), JPARC (KOTO), CERN LHC (LHCb, K_S rare decay program)

The golden channel $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

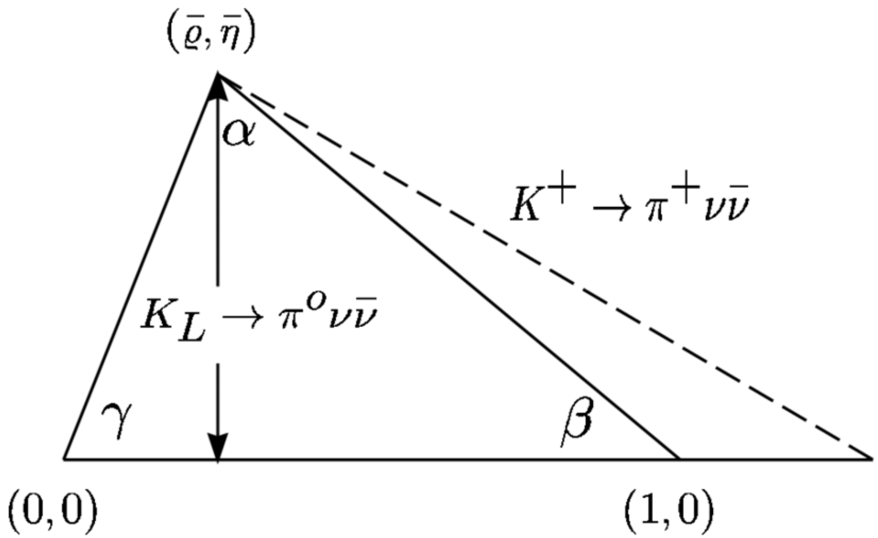


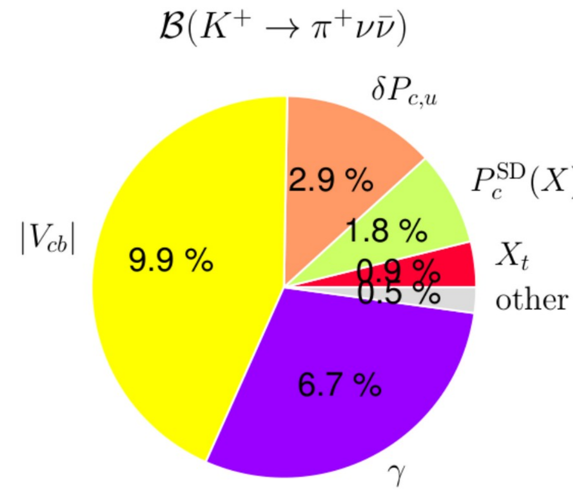
- FCNC loop processes: s ⟶ d coupling and highest CKM suppression
- Theoretically clean: Short distance contribution
- Hadronic matrix element measured with $K^\pm \longrightarrow \pi^0 l^\pm \nu_l$ decays (sub-% precision!)
- SM predictions: Buras. et. al., JHEP11(2015)033

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

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

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





Parametric uncertainty dominates!

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

- Master formula:

EM correction

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

$x_t = m_t^2/M_W^2$, $\lambda = |V_{us}|$, $\lambda_i = V_{is}^* V_{id}$, k_+ – hadronic matrix element

$K - \pi$ transition

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

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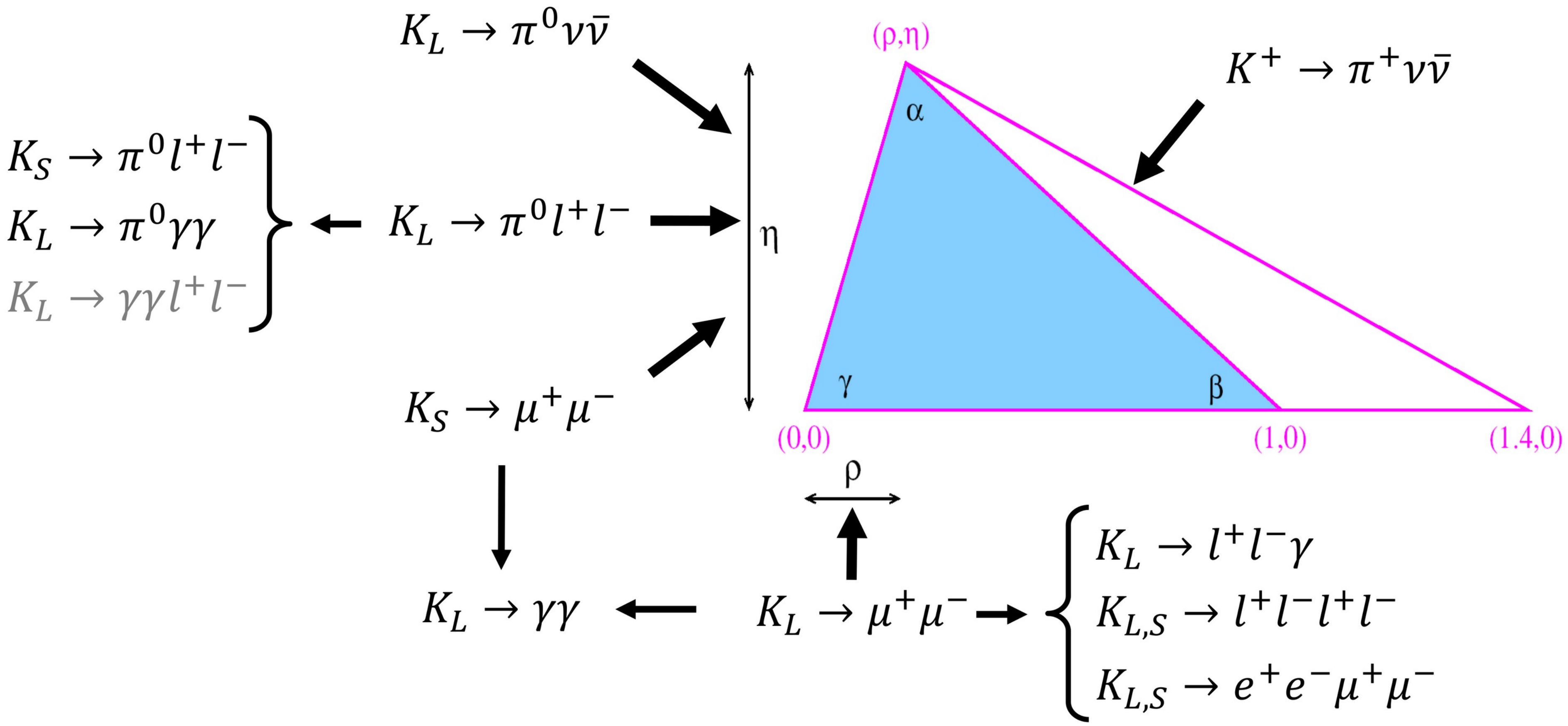
Kaons and the CKM unitarity triangle



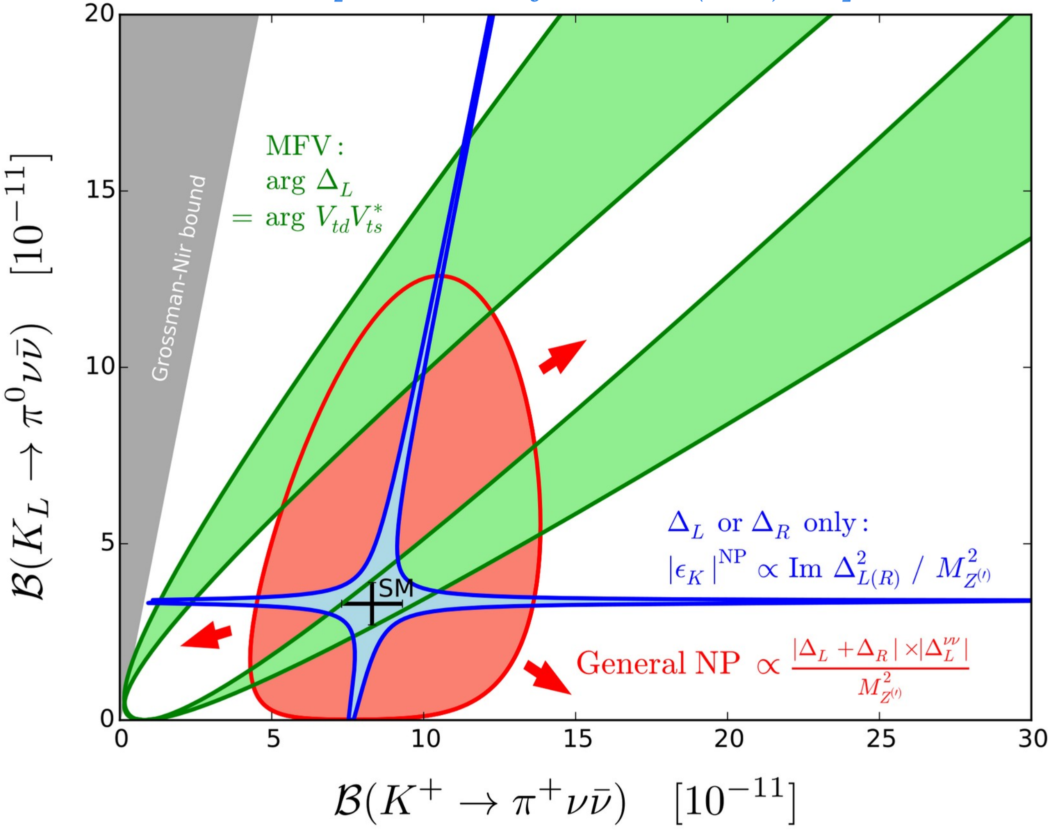
- The CKM unitarity triangle can be constrained by kaon physics alone
- Comparison with B physics can provide description of NP flavour dynamics

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

- High sensitivity to NP (non MFV): significant variations wrt SM possible
- Correlations between rare FCNCs in the kaon and B sectors sensitive to NP flavour structure
  - Correlations model dependent
  - Precise measurement of rare FCNCs can help distinguish between possible NP models!

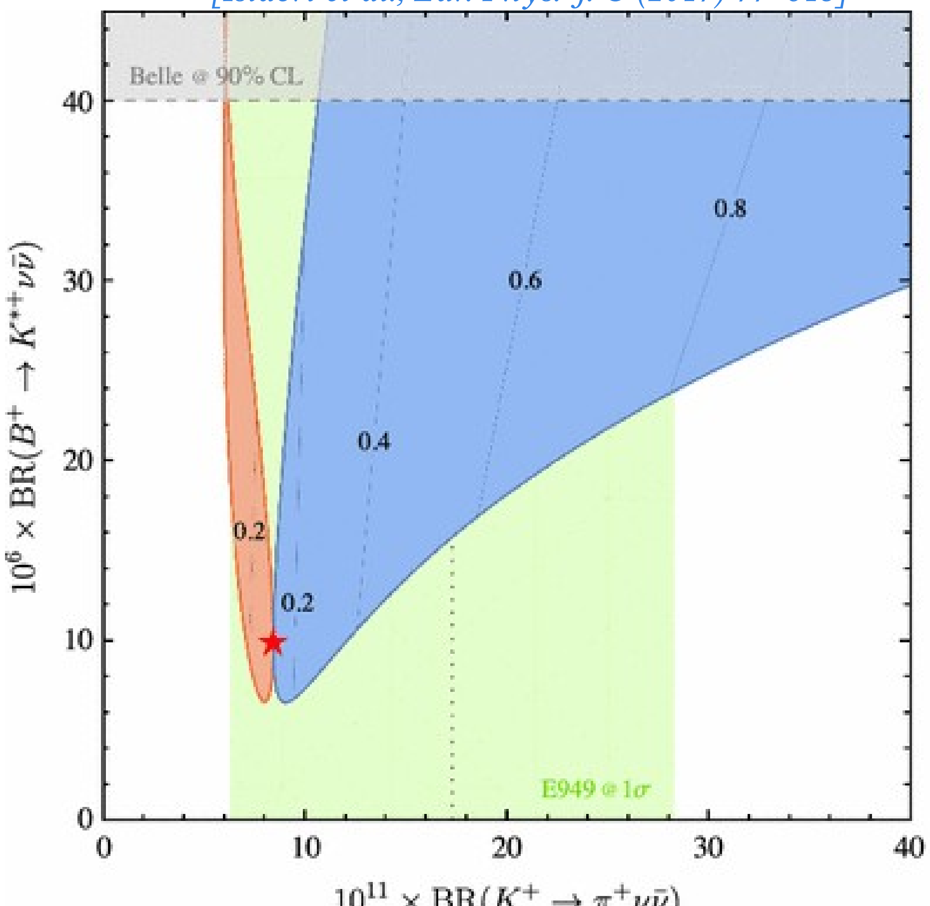
Simplified models

[Buras et al., JHEP 1511 (2015) 166]

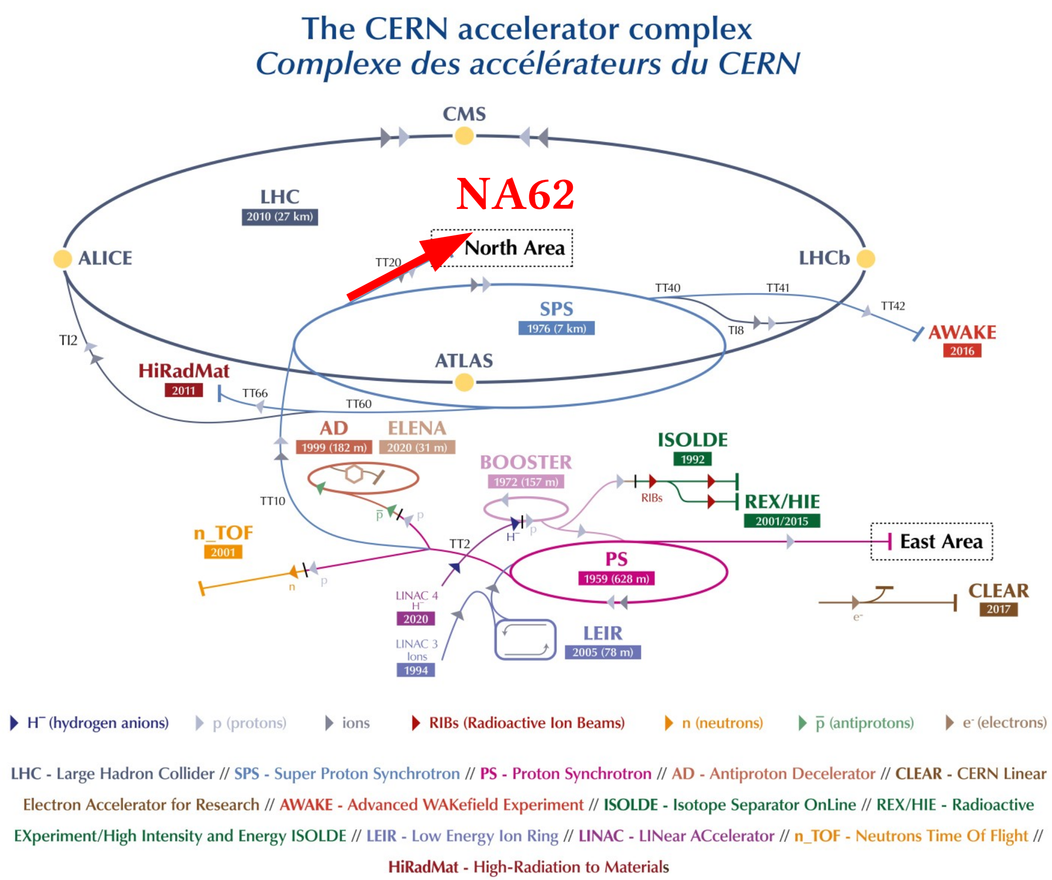


LFU violation

[Isidori et al., Eur. Phys. J. C (2017) 77: 618]



Kaon physics @ NA62



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

NA62 primary goal: measurement of the ultra rare kaon decay $K^+ \to \pi^+ \nu\bar{\nu}$

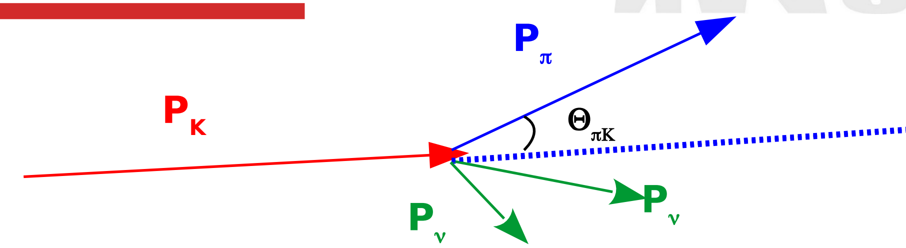
NA62 consists of ~ 200 participants from: Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Moskow, Naples, Perugia, Pisa, Prague, Protvino, Rome I, Rome II, San Luis Potosi, Turin, TRIUMF, Vancouver UBC

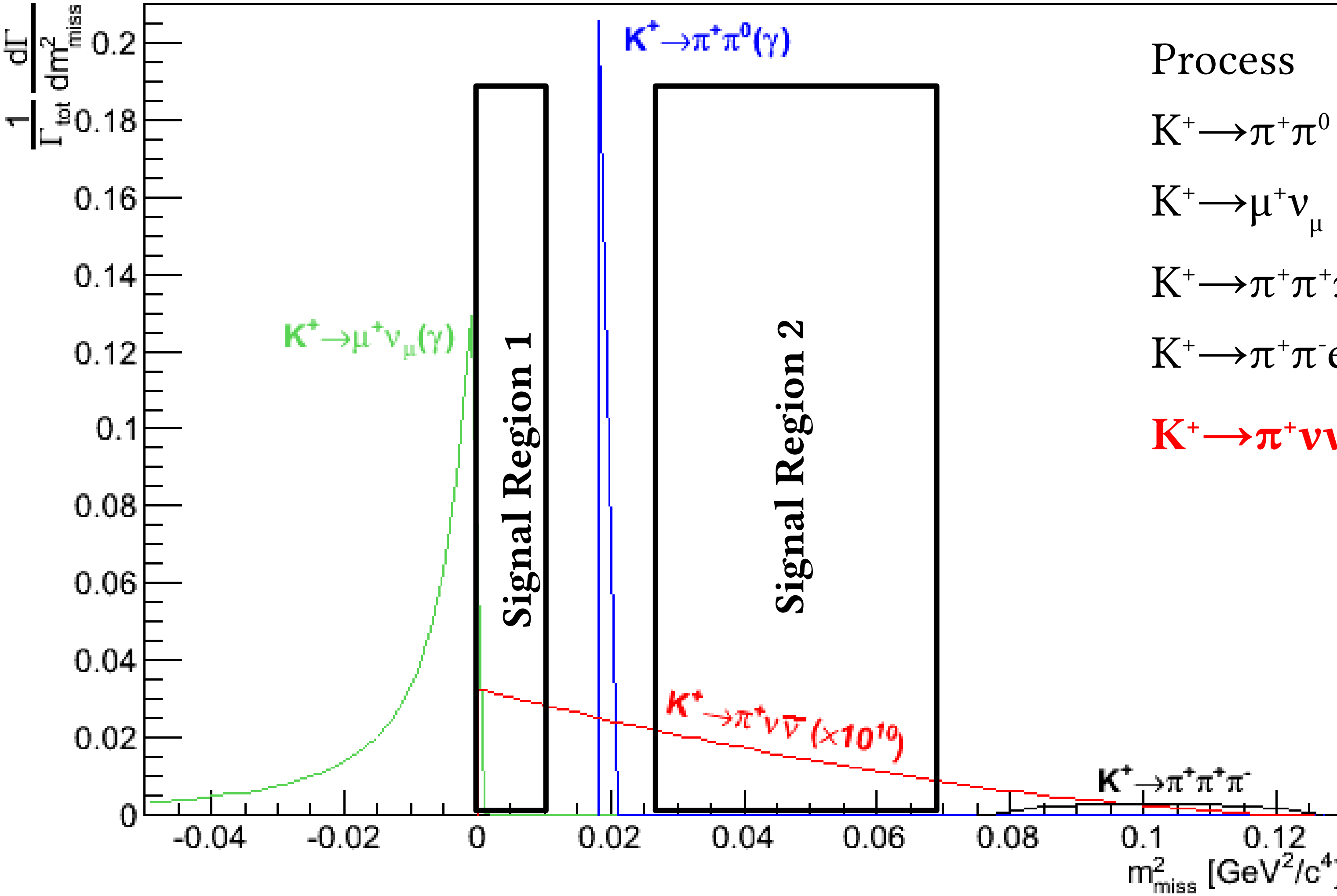
Analysis strategy

Decay-in-flight technique

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

π^+ mass hypothesis

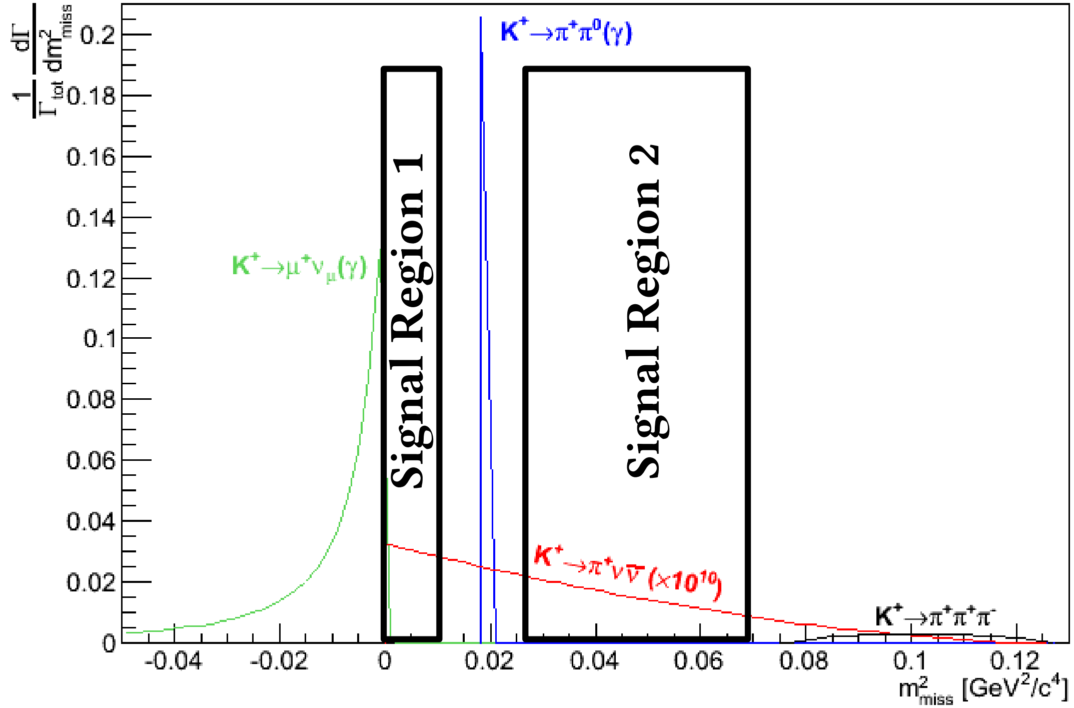




Process	Branching ratio
$K^+ \to \pi^+\pi^0$	0.2066
$K^+ \to \mu^+\nu_\mu$	0.6356
$K^+ \to \pi^+\pi^+\pi^-$	0.0558
$K^+ \to \pi^+\pi^- e^+\nu_e$	4.3×10^{-5}
$K^+ \to \pi^+\nu\nu$ (SM)	**8.4×10^{-11}**

Keystones of the analysis

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



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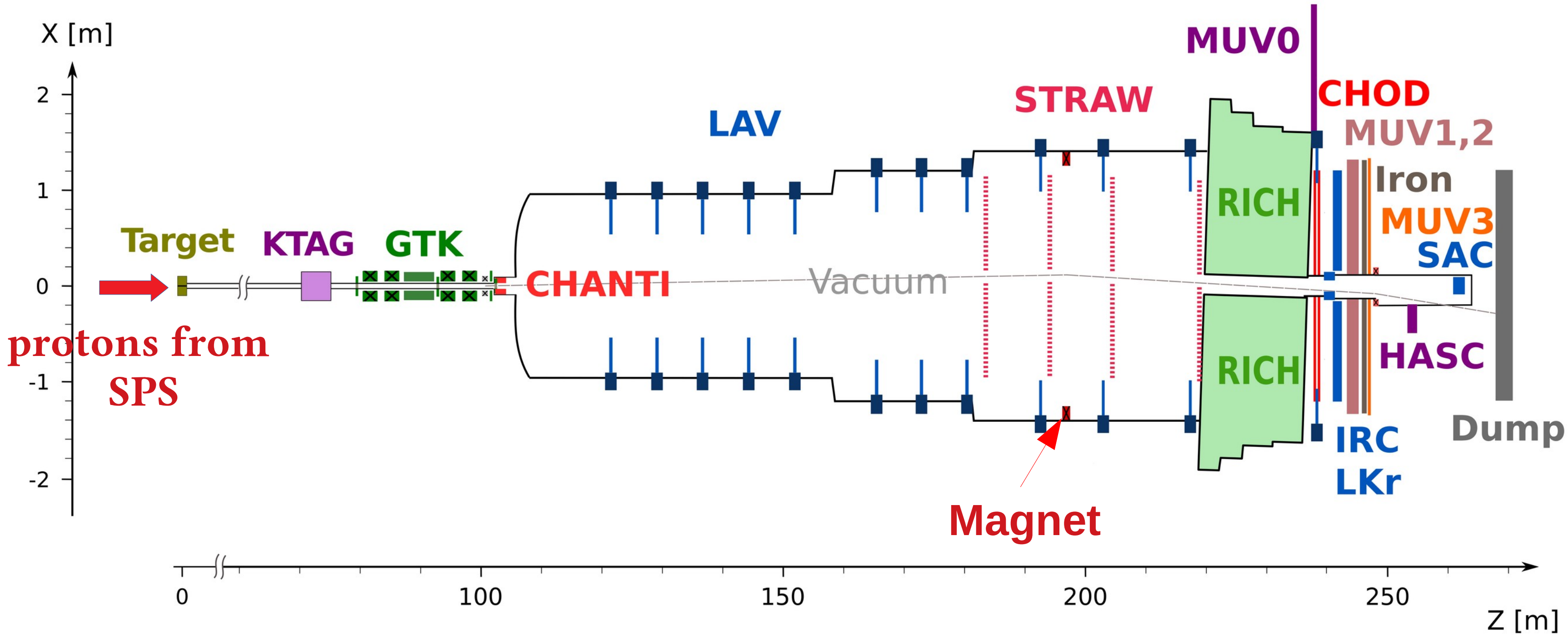
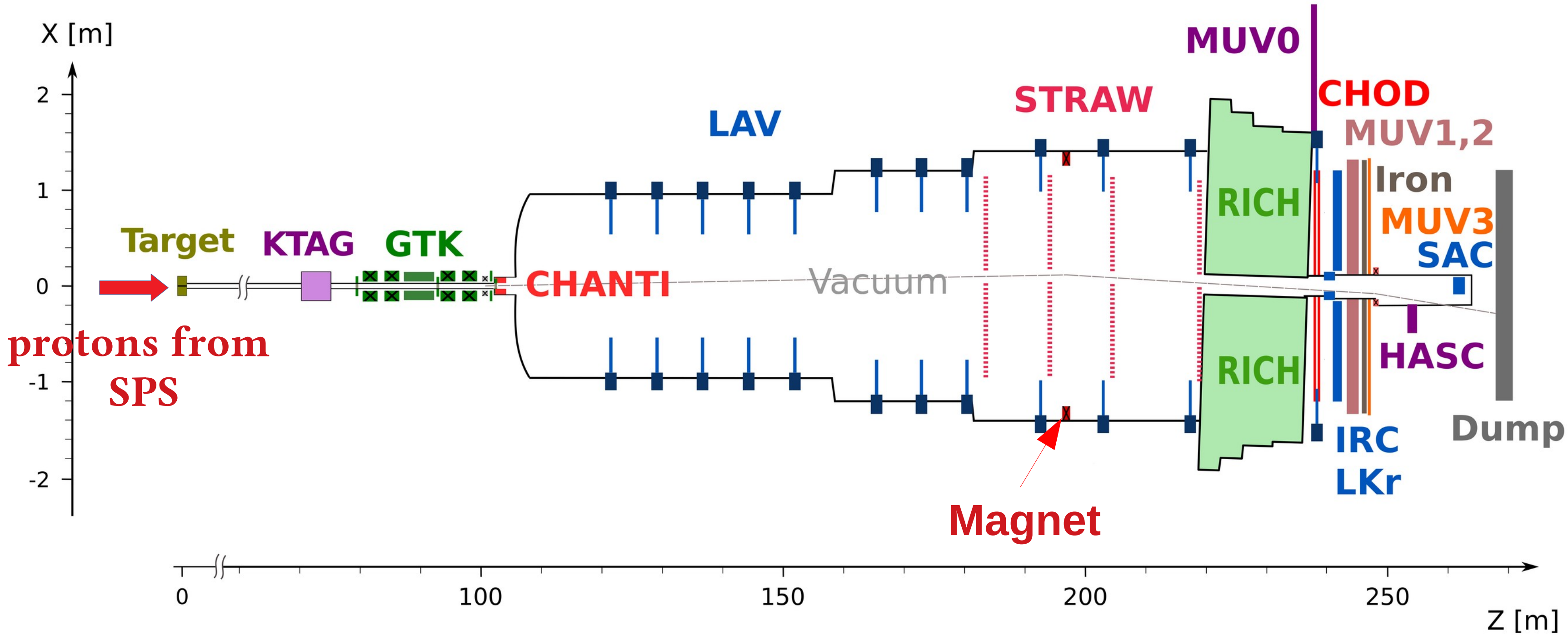
NA62 beam and detector



- **SPS Beam:**
  - 400 GeV/c protons
  - 1.9×10^{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%)
  - 450 MHz of particles at GTK3
- **Decay Region:**
  - 60 m long fiducial region
  - ~ 3 MHz K^+ decay rate
  - Vacuum ~ O(10^{-6}) mbar

NA62 beam and detector

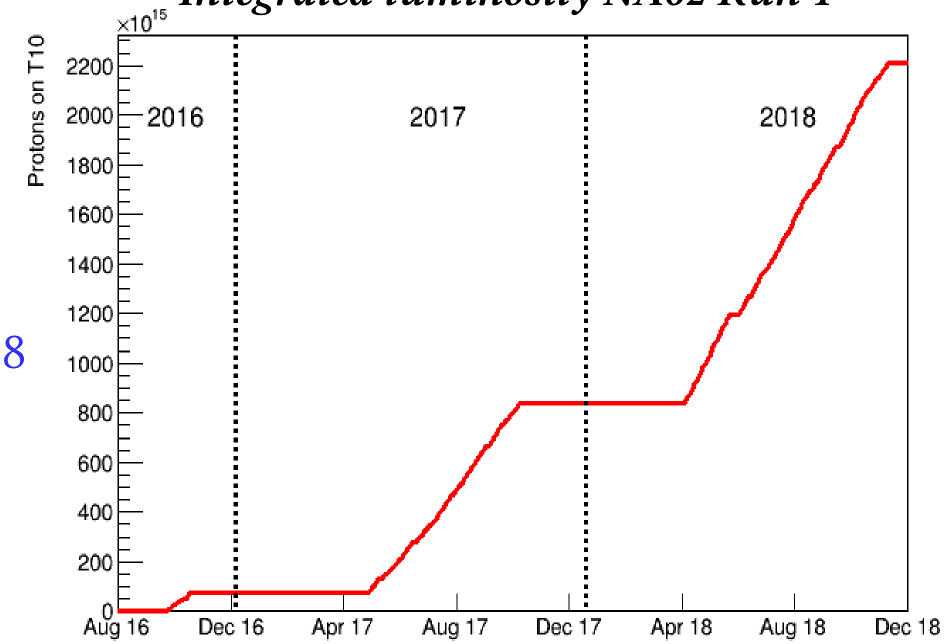


- Upstream detectors (K^+):
  - **KTAG:** Differential Cherenkov counter for K^+ ID
  - **GTK:** Si pixel beam tracker
  - **CHANTI:** Anti-counter for inelastic beam-GTK3 interactions
- Decay Region detectors (π^+):
  - **STRAW:** track momentum spectrometer
  - **CHOD:** Scintillator hodoscopes
  -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

Data set and trigger

Run 1 statistics
1.9 x 10^{12} proton per spill on target
~ 2.2 x 10^{18} POT collected in Run 1

Integrated luminosity NA62 Run 1



- Two different hardware configurations in 2018
  - 2018_S1 ~ 20% of the 2018 data
  - 2018_S2 ~ 80% of the 2018 data
- 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, presence of a charged particle downscaled by 400
- Offline analysis
  - Data samples: **PNN; Control:** $K^+ \to \pi^+\pi^0$, $K^+ \to \mu^+\nu$, $K^+ \to \pi^+\pi^+\pi^-$, $K^+ \to \pi^+\pi^- e^+\nu$

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

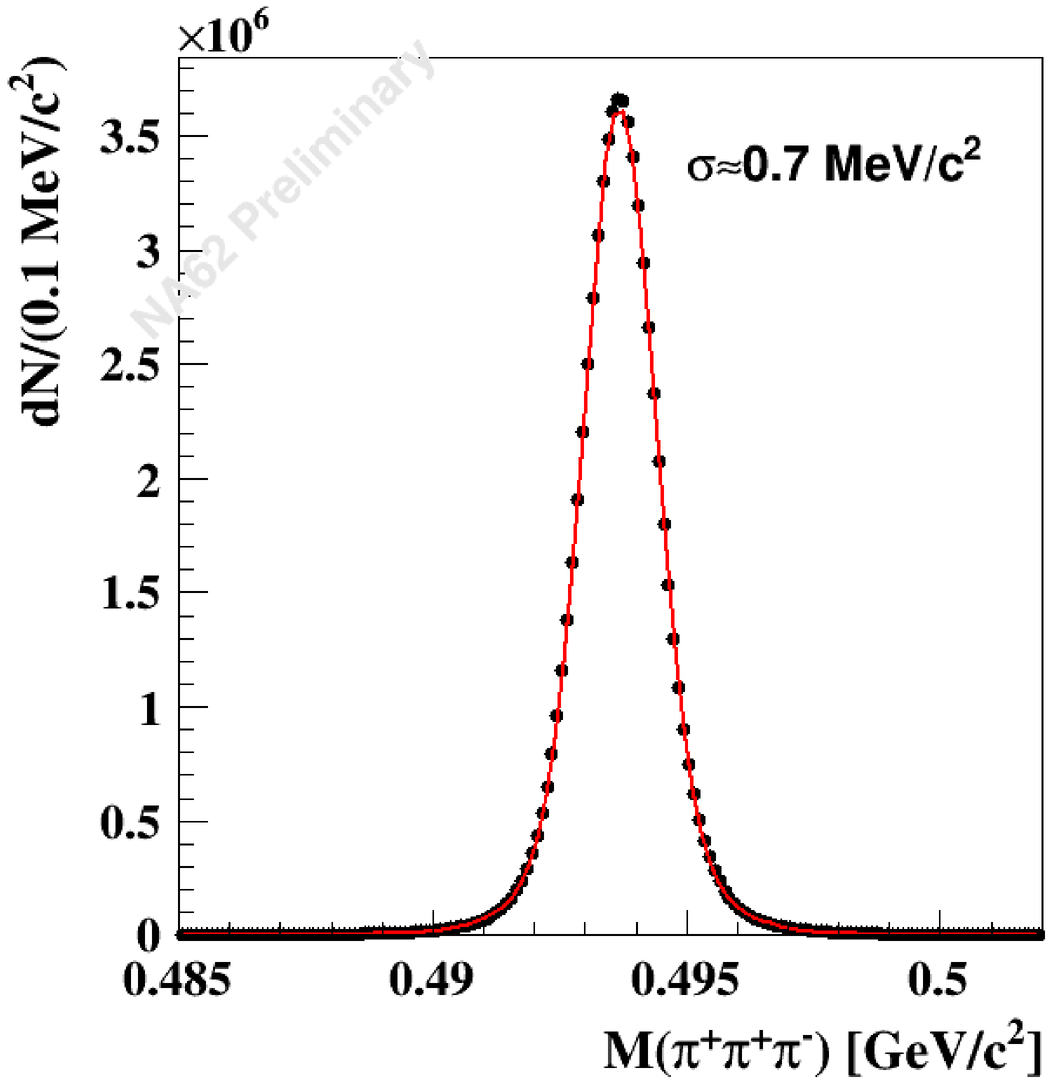
1. Selection
   - K^+ decays with a single charged particle in the final state
   - Particle identification: π^+
   - Photon and multi-charged rejection
   - Kinematic selection of signal regions
2. Determination of the Single Event Sensitivity (SES)
3. Estimation and validation of the expected background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

Signal and background control regions are kept blind throughout the analysis

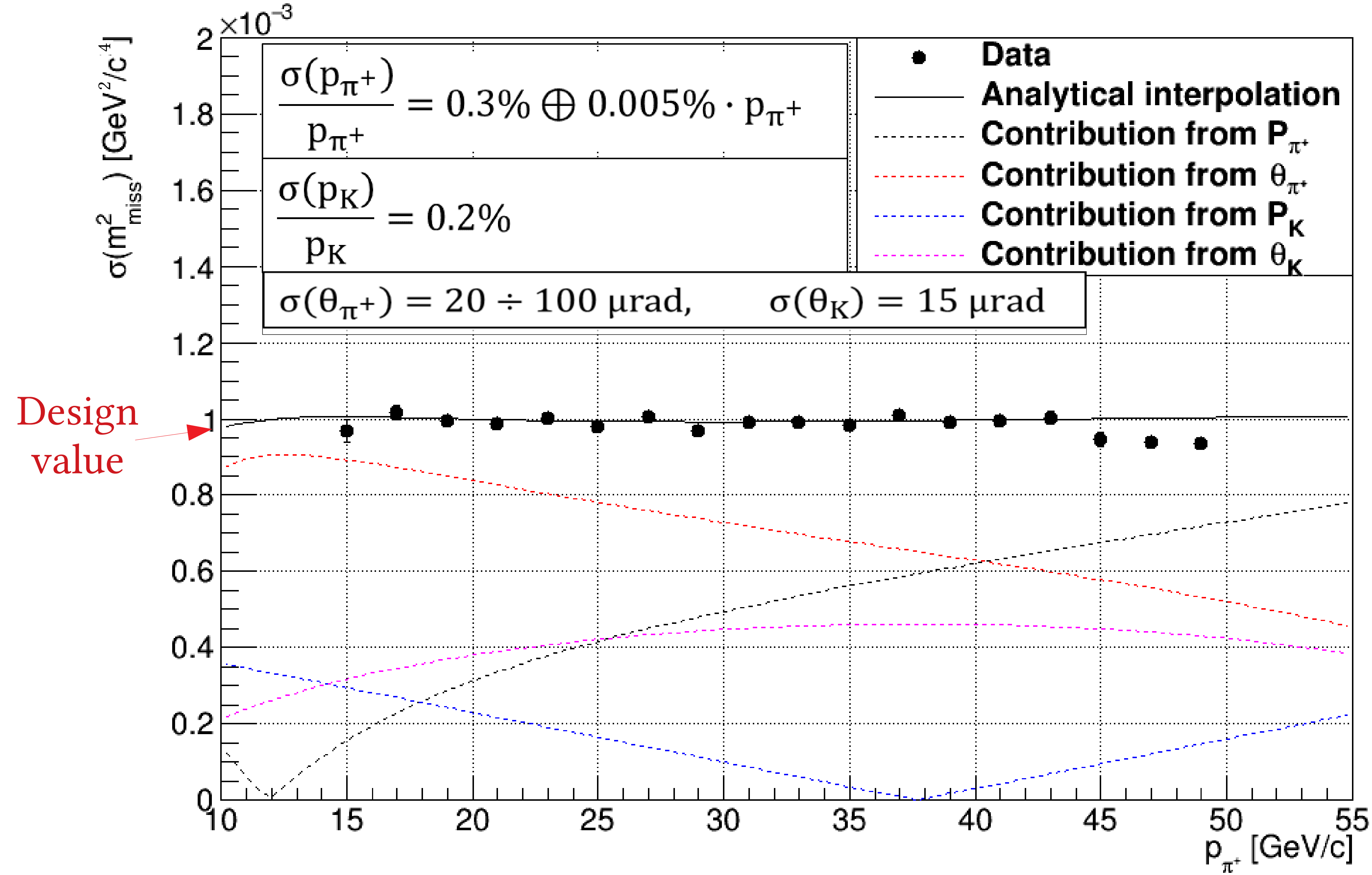
1. Selection

π^+ tracking: Straw spectrometer

- "Massless" tracker in vacuum to reduce multiple scattering
  - ➢ Total tracker mass: 1.8% X_0
  - ➢ Excellent mass resolution ~ O(10^{-3})
- 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 $K^+ \to \pi^+\pi^+\pi^-$



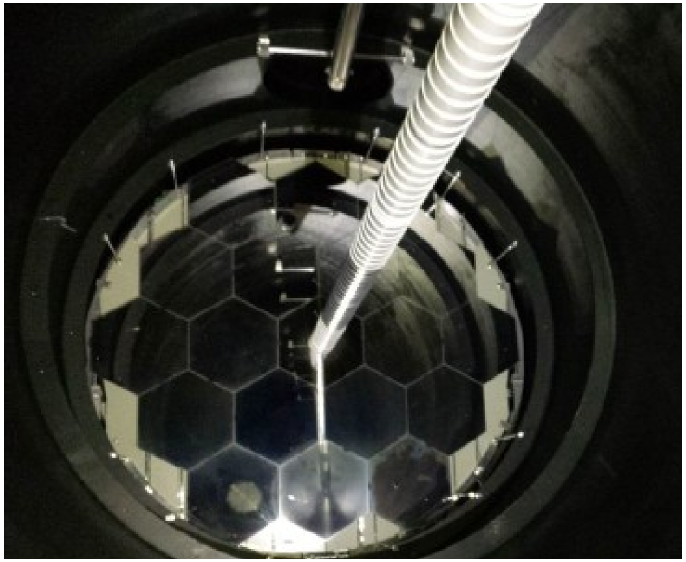
Kinematic resolution @ $\pi^+\pi^0$ mass peak

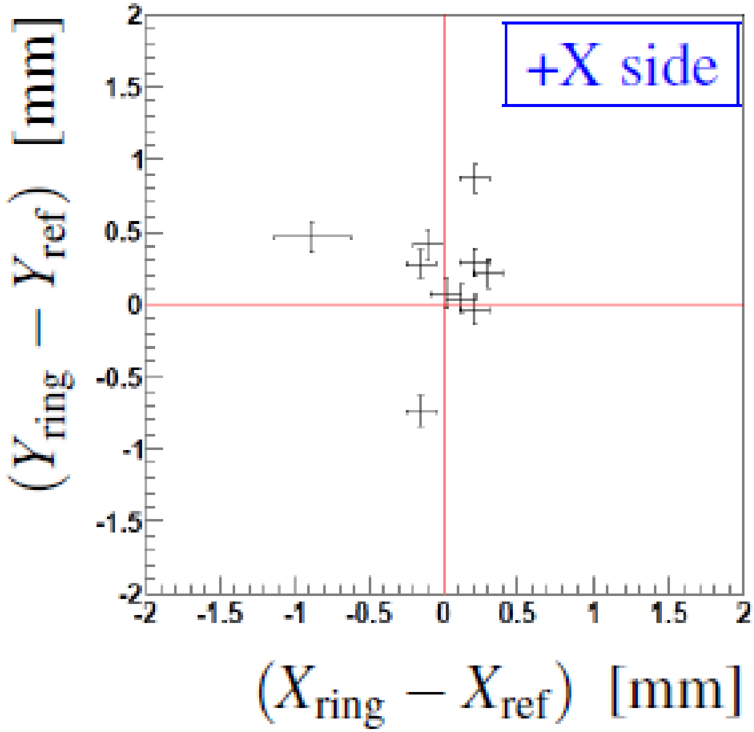


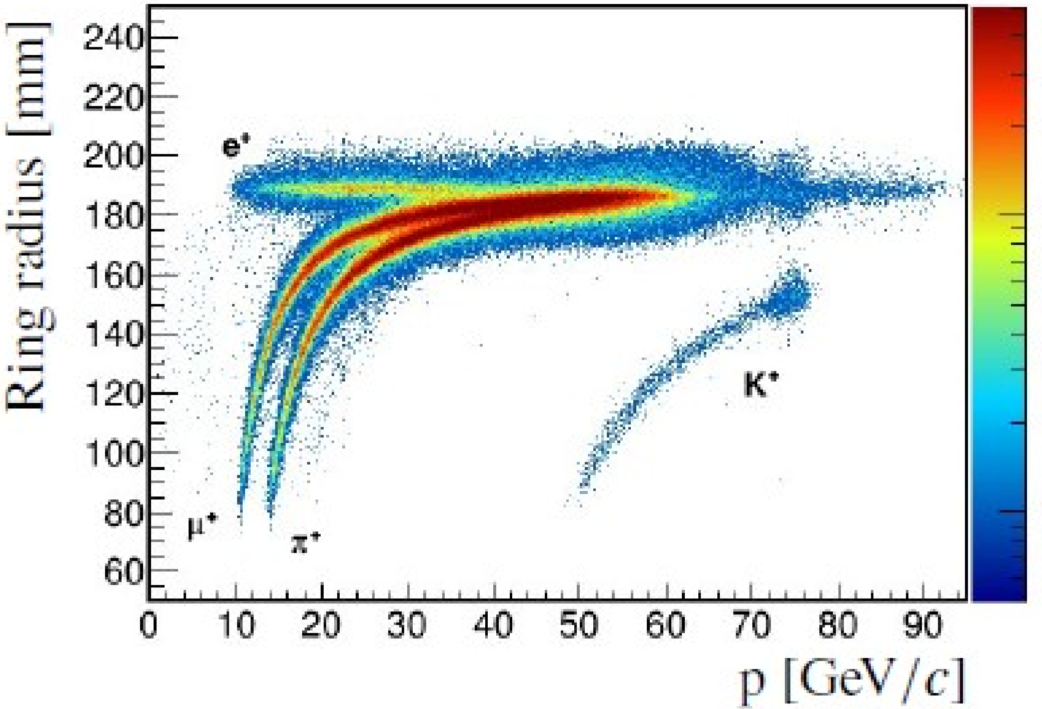
π^+ tagging: RICH

RICH calibration

- 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

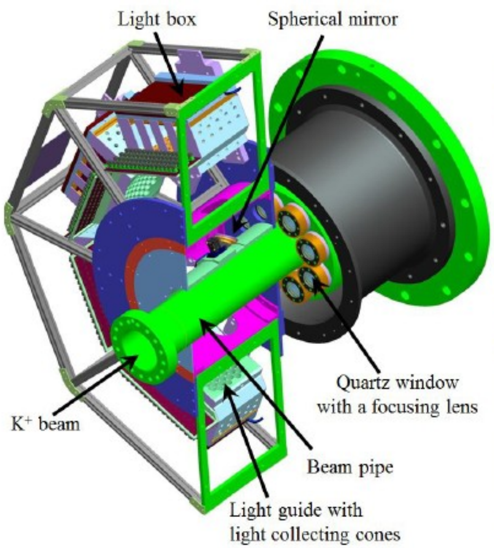


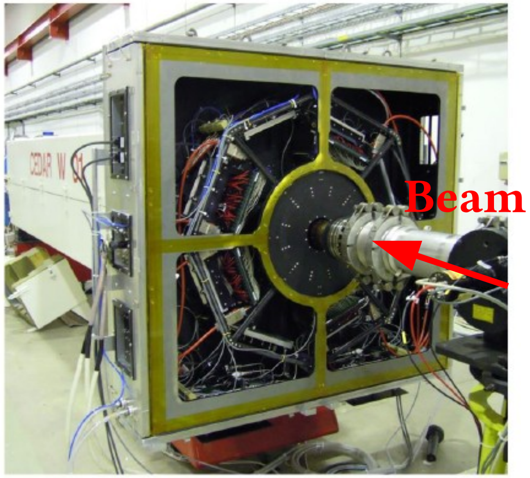


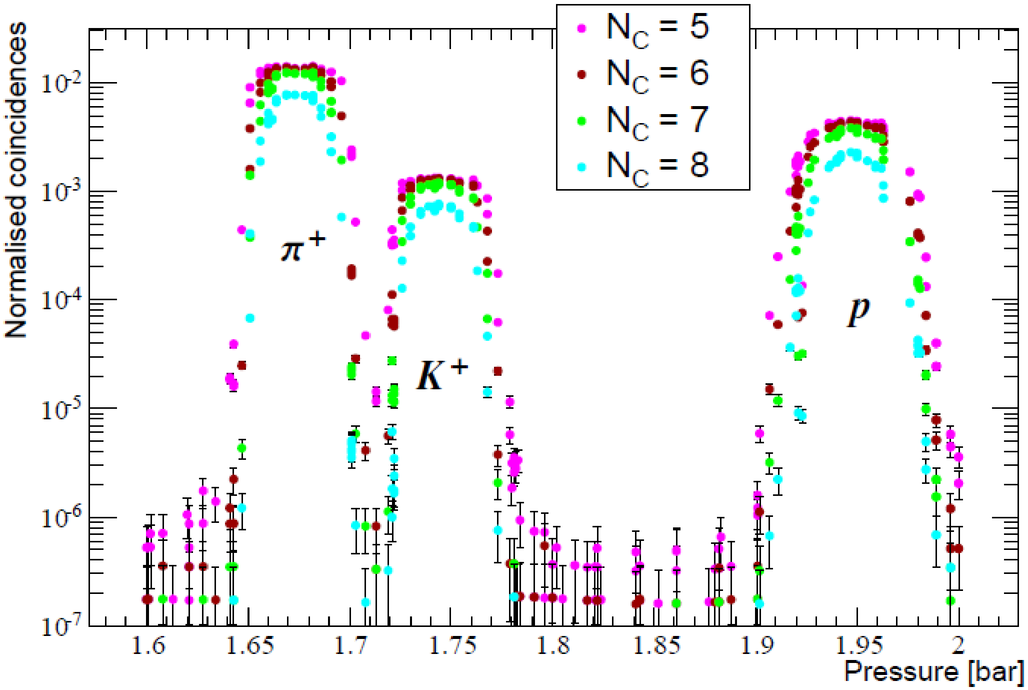


K⁺ tagging: KTAG

- Differential Cherenkov Counter, 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)



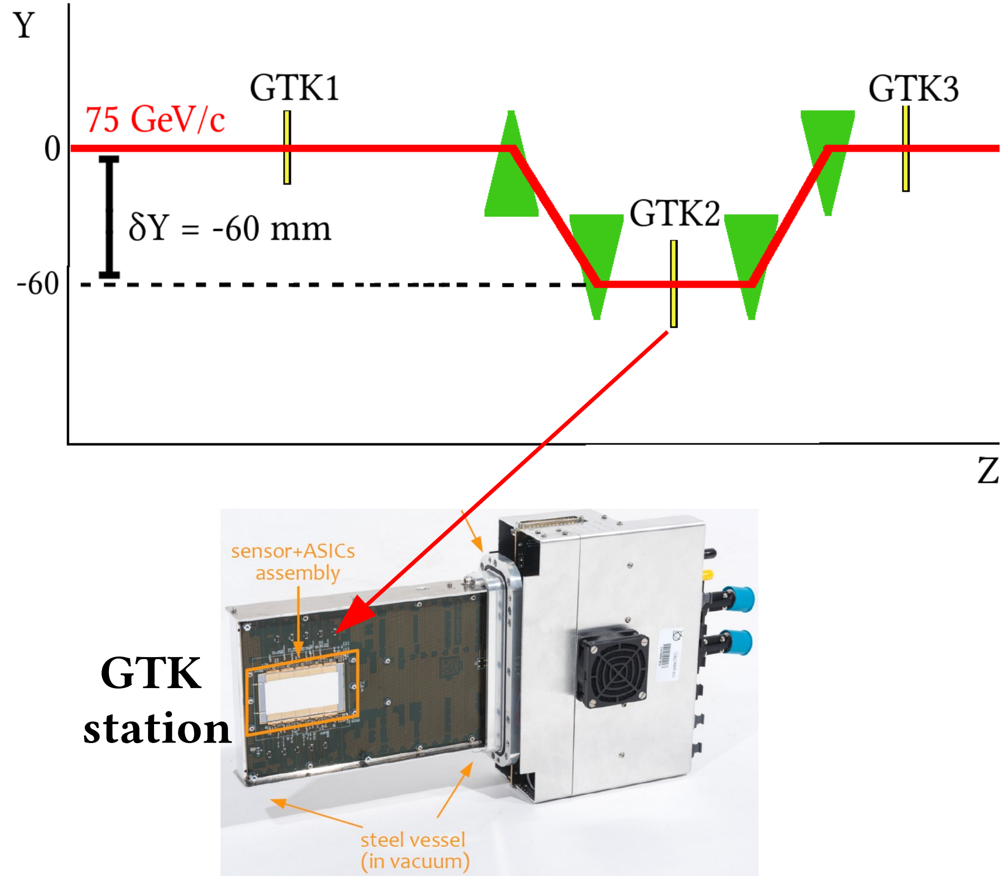


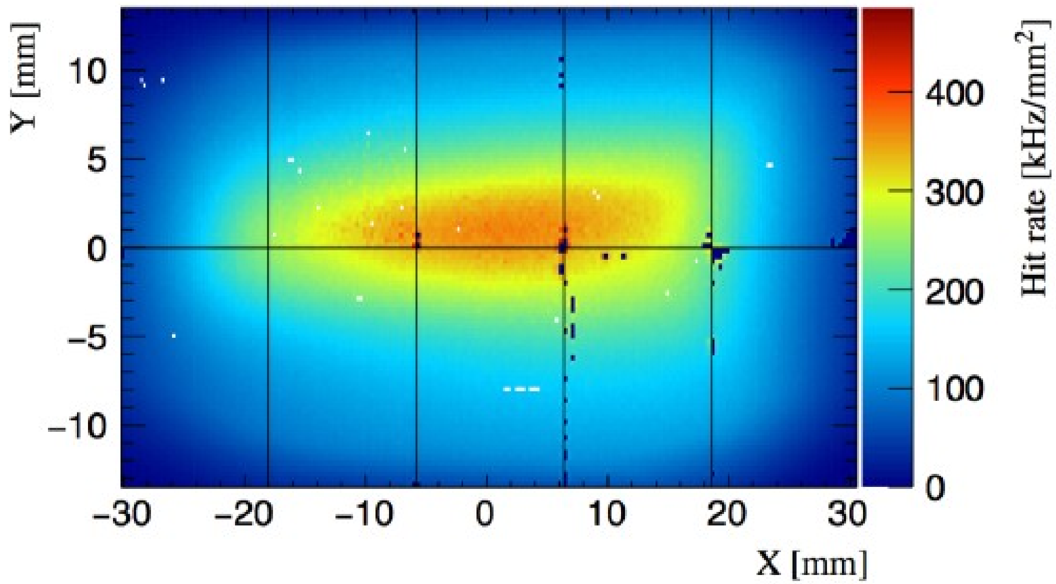


K^+ tracking: GigaTracker

First time

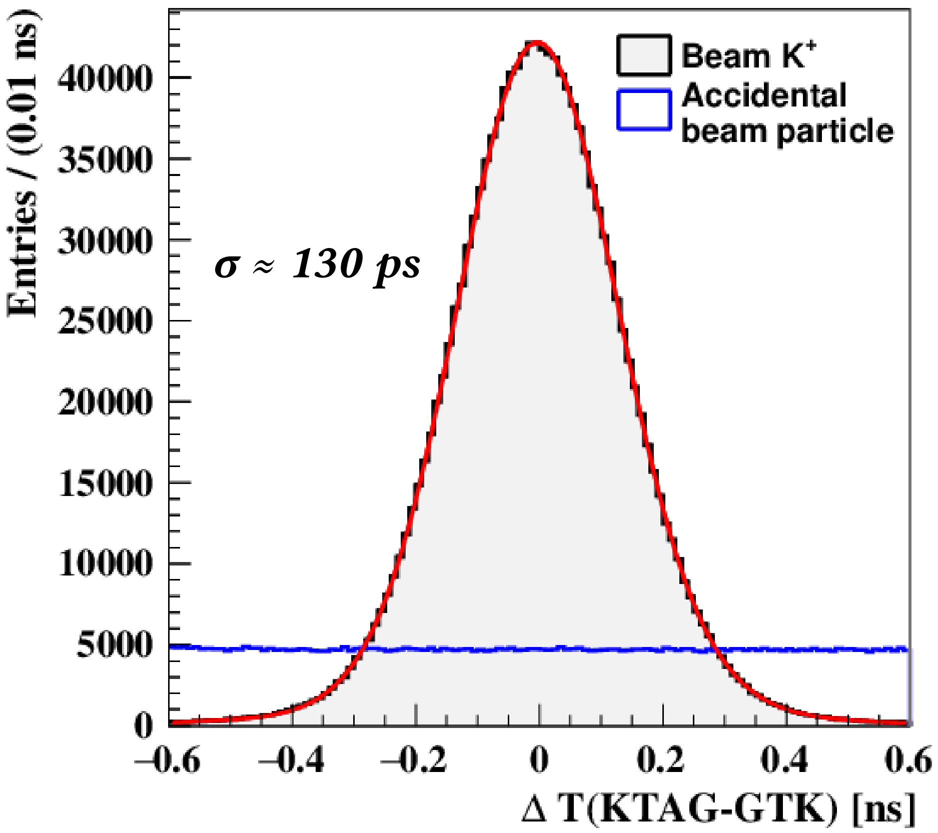
- 4D track reconstruction using trigger and KTAG as time reference
- Time offset corrections dependent on Station, Chip, Column, Row of the pixel
- Pixel – by – pixel time walk corrections ($\sigma(t) < 150$ ps per station)
- Stations aligned with straw Spectrometer and calibrated using $K^+ \to \pi^+\pi^+\pi^-$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

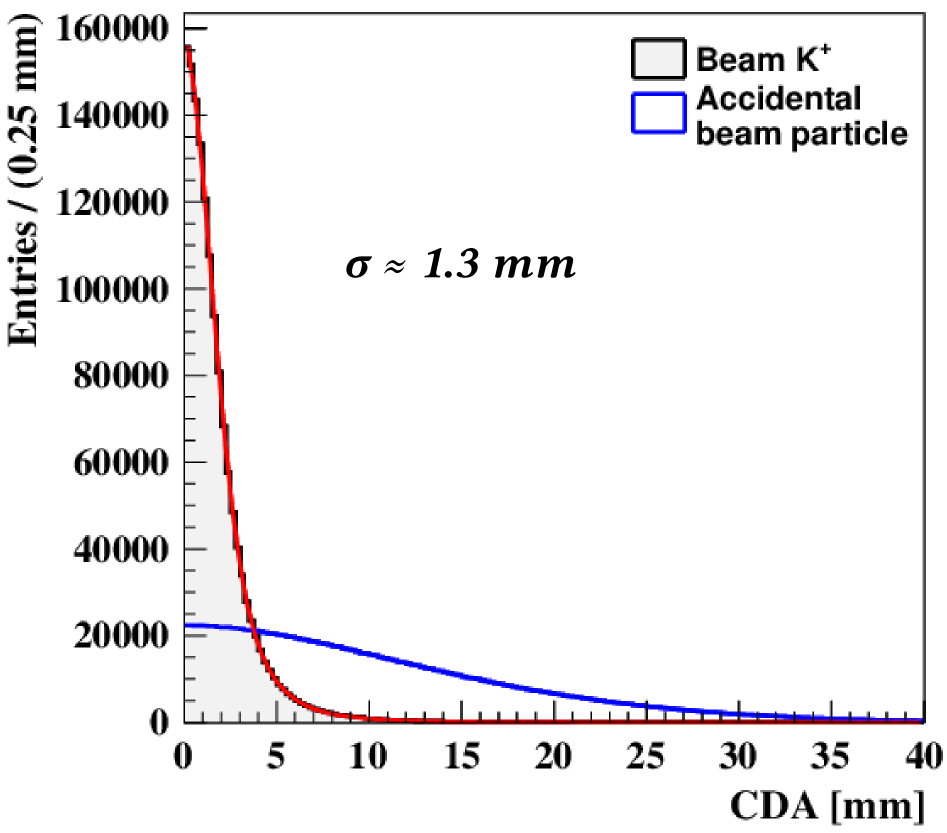




K– π association

- KTAG – GigaTracker – RICH time matching ⟶ Kaon decay time (t_{decay})
- GigaTracker – Straw Spectrometer spatial matching (CDA)
- 3.5% (1.3%) K^+ mis-tag if K^+ track (not) present, dependent on beam intensity
- ~ 75% K^+ reconstruction and ID efficiency, depends on intensity

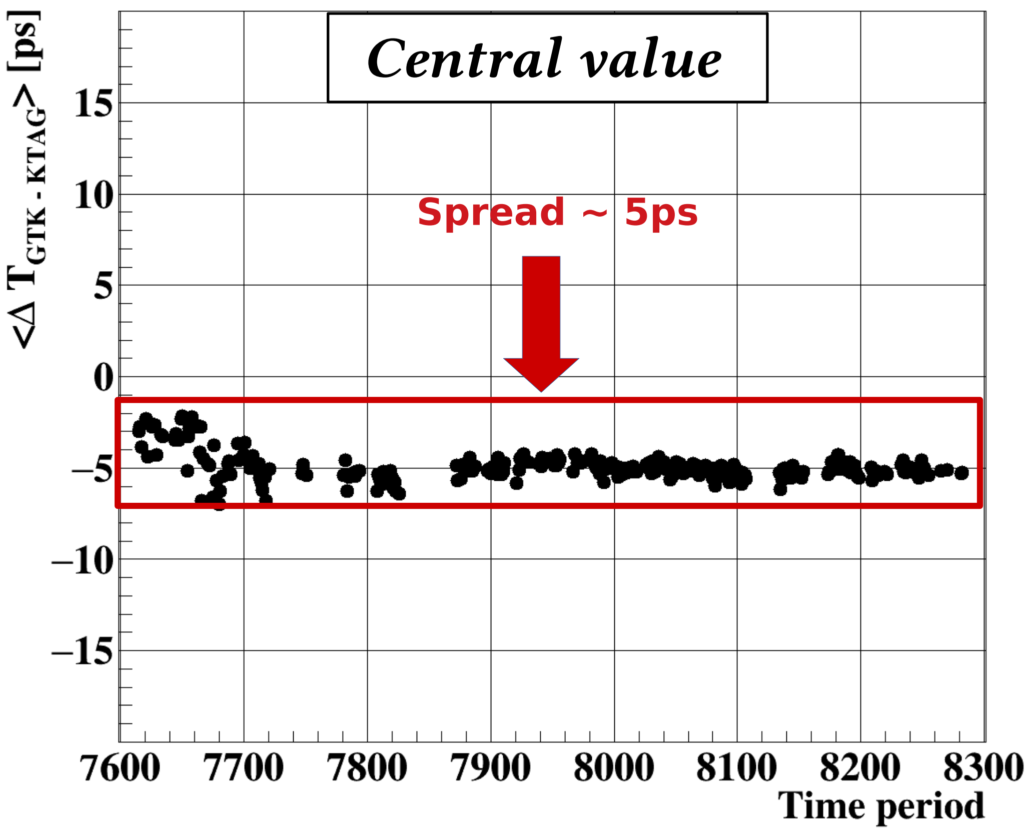


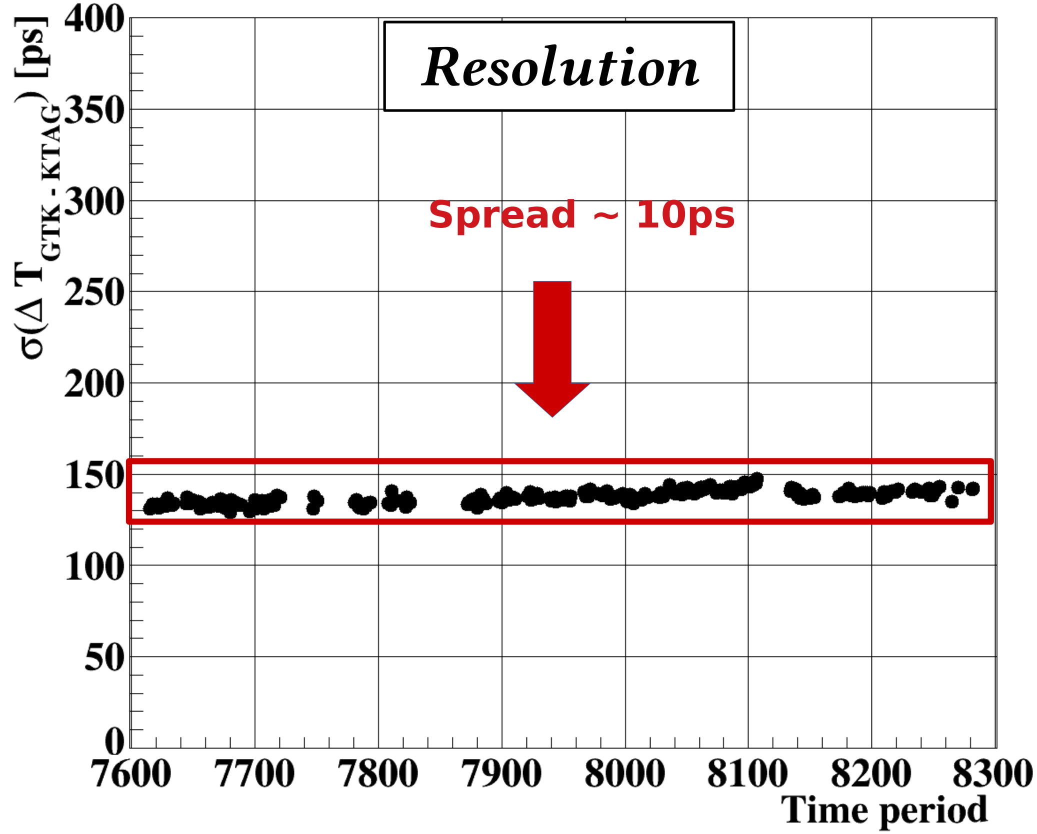


Time resolution

Time calibration stability

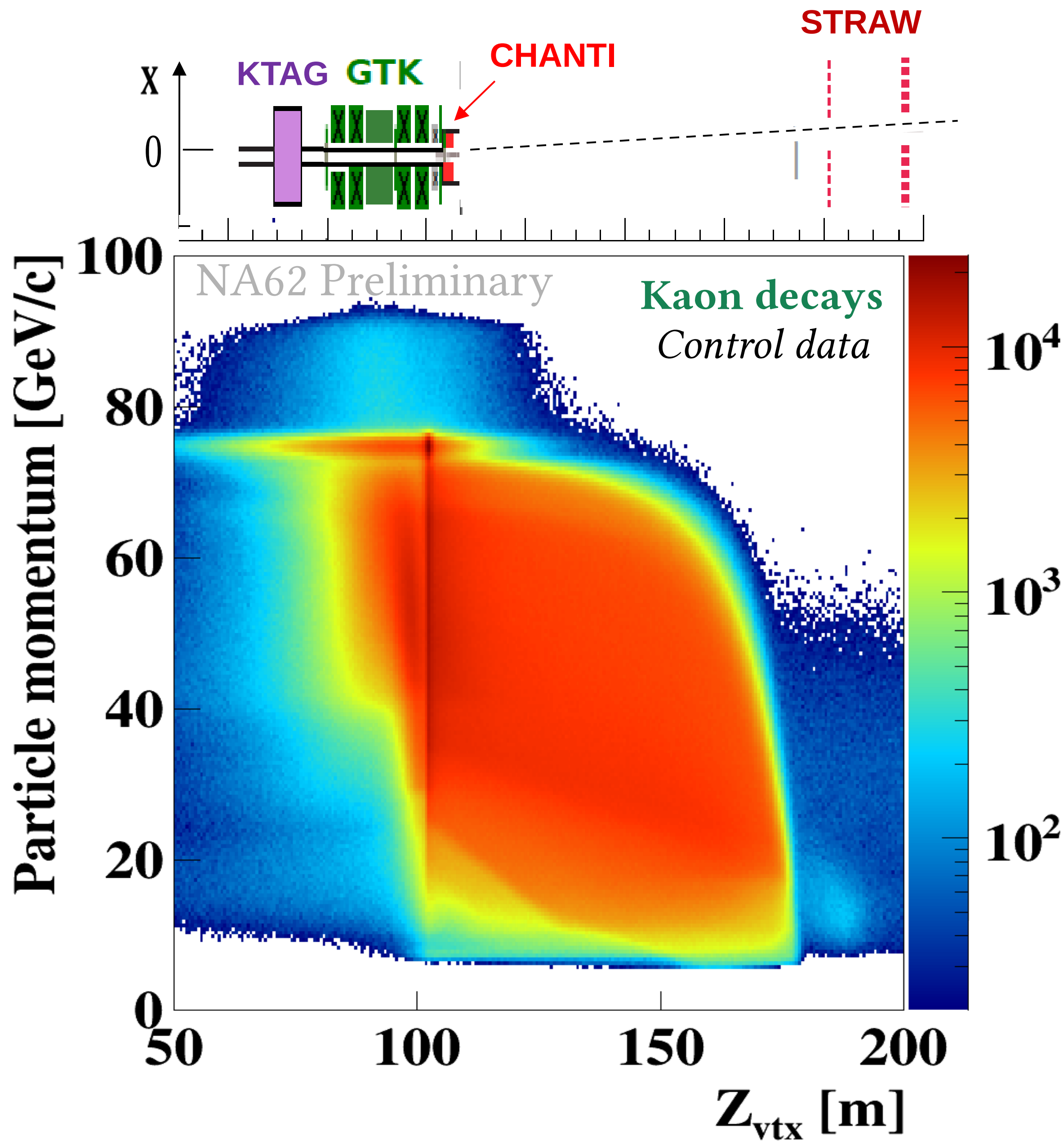
- Excellent calibration at the processing level in Run 1
- Stable central value and time resolution
- Single-detector time resolution ~ 90ps



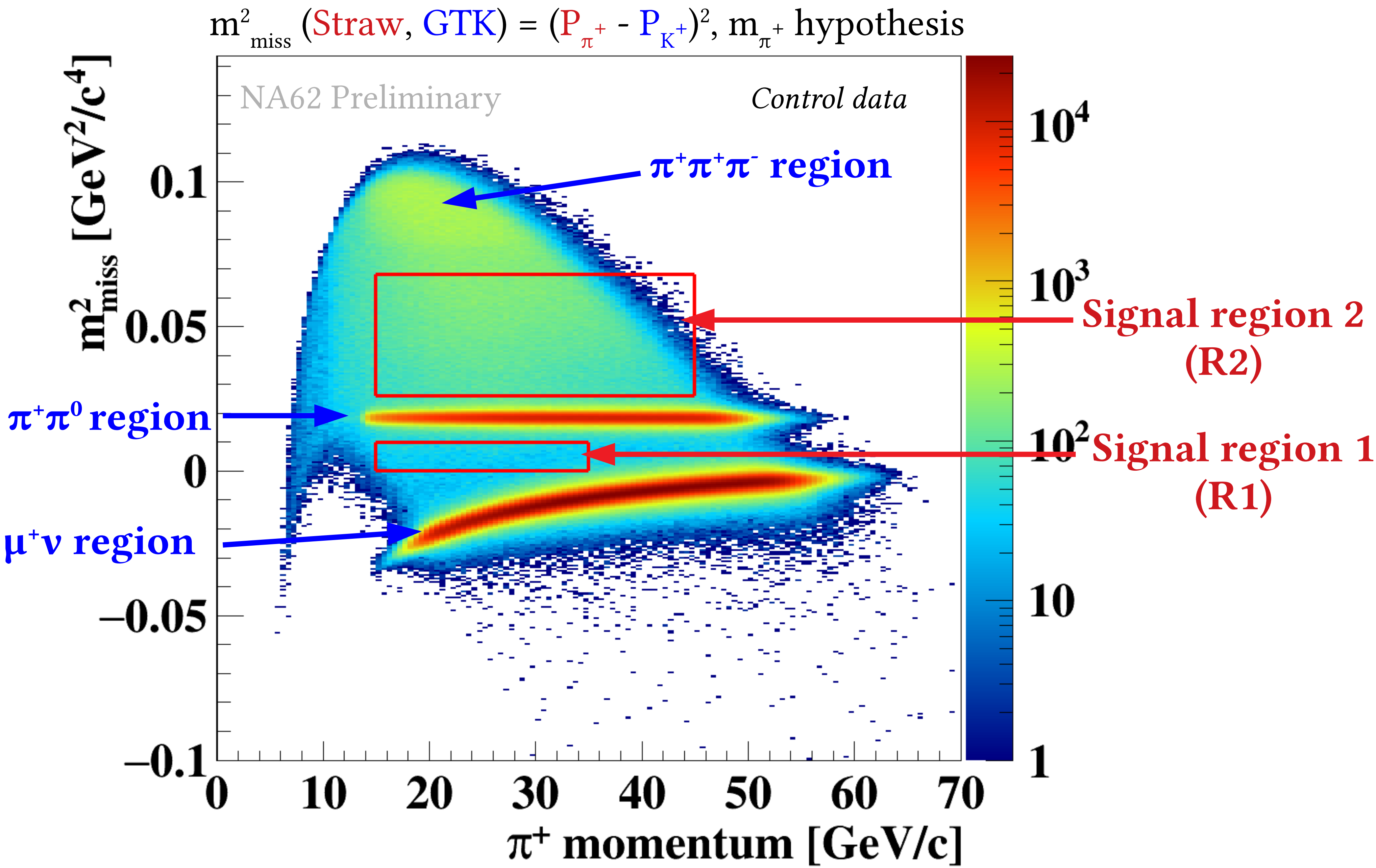


Selection of kaon decays

- K – π association
- No activity in CHANTI
- 2018_S1 geometrical constraints
  - Z vertex 110 – 165 m
  - Track slope
  - Track projection at collimator
- 2018_S2 geometrical constraints
  - BDT algorithm used
- Momentum 15 – 45 GeV/c in 2018
  - Analysis divided into 6 5GeV/c-wide categories (if enough statistics)
- Tracks from «upstream»
  - mismatching in GTK
  - Decays along the beam line
  - Beam particle interactions in GTK

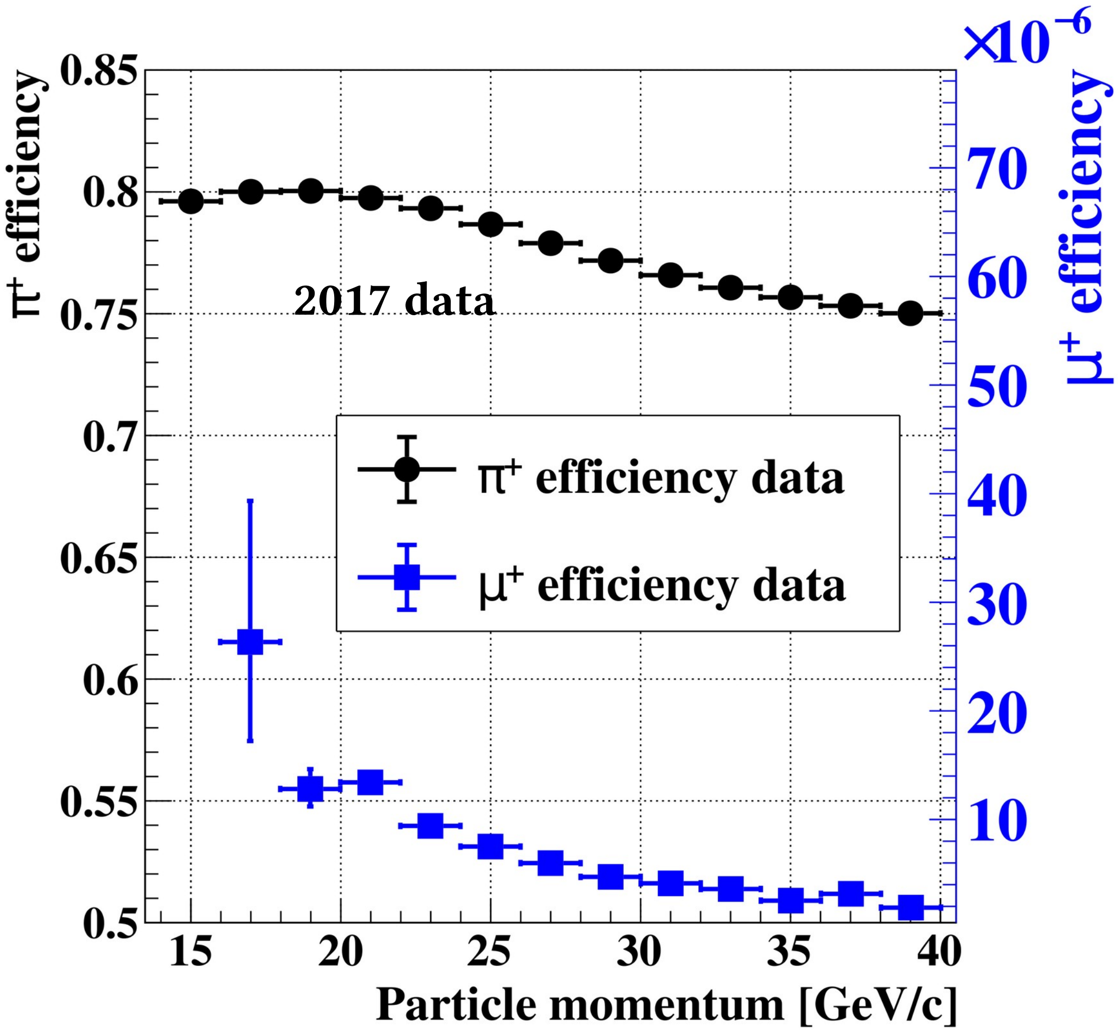


Kaon-decay kinematics



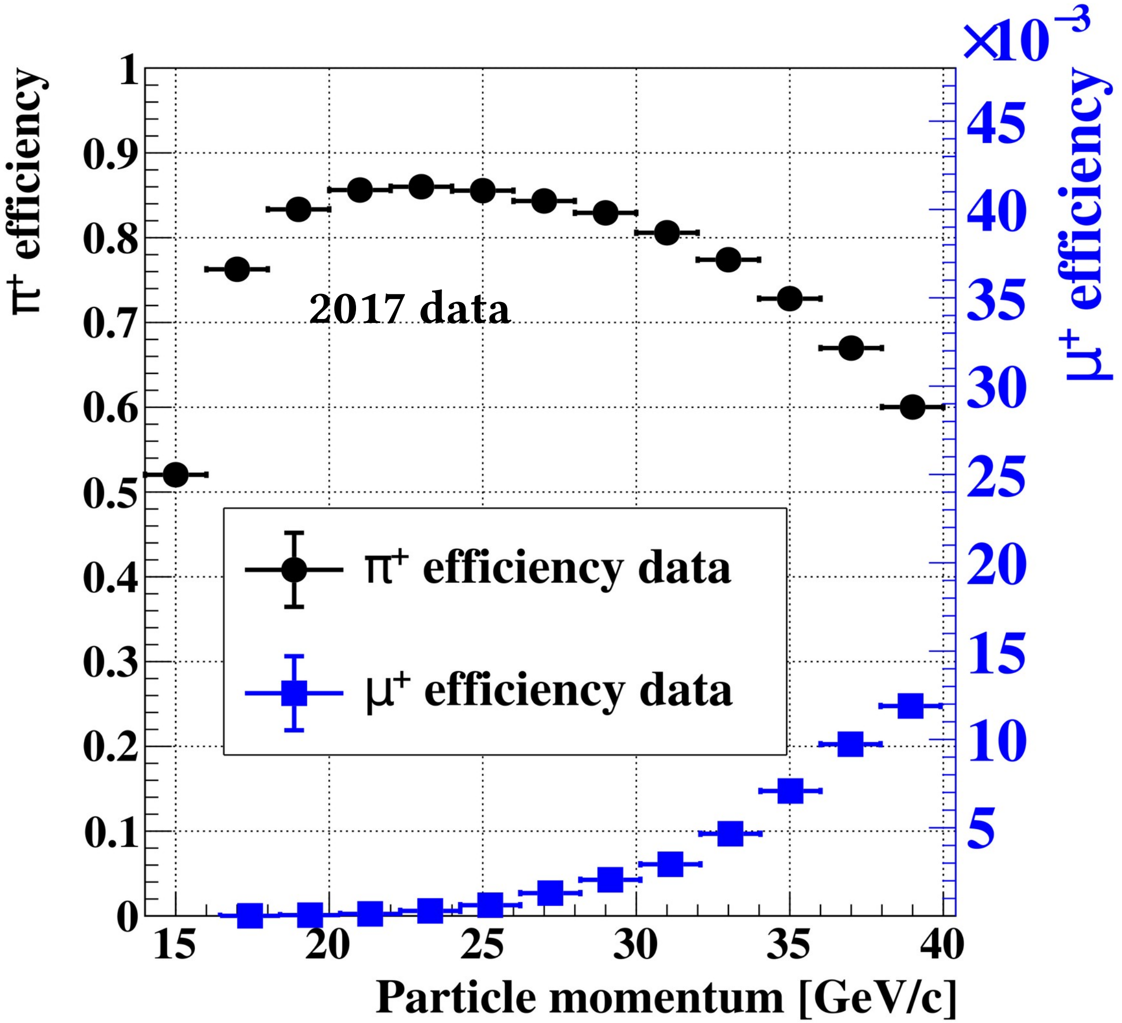
Particle ID with calorimeters

- Electromagnetic calo (LKr), Hadronic calo (MUV1, 2), scintillator blocks (MUV3)
- Machine learning approach (BDT) + MUV3 veto
  - Energy deposition + Energy sharing + Shower shape profiles

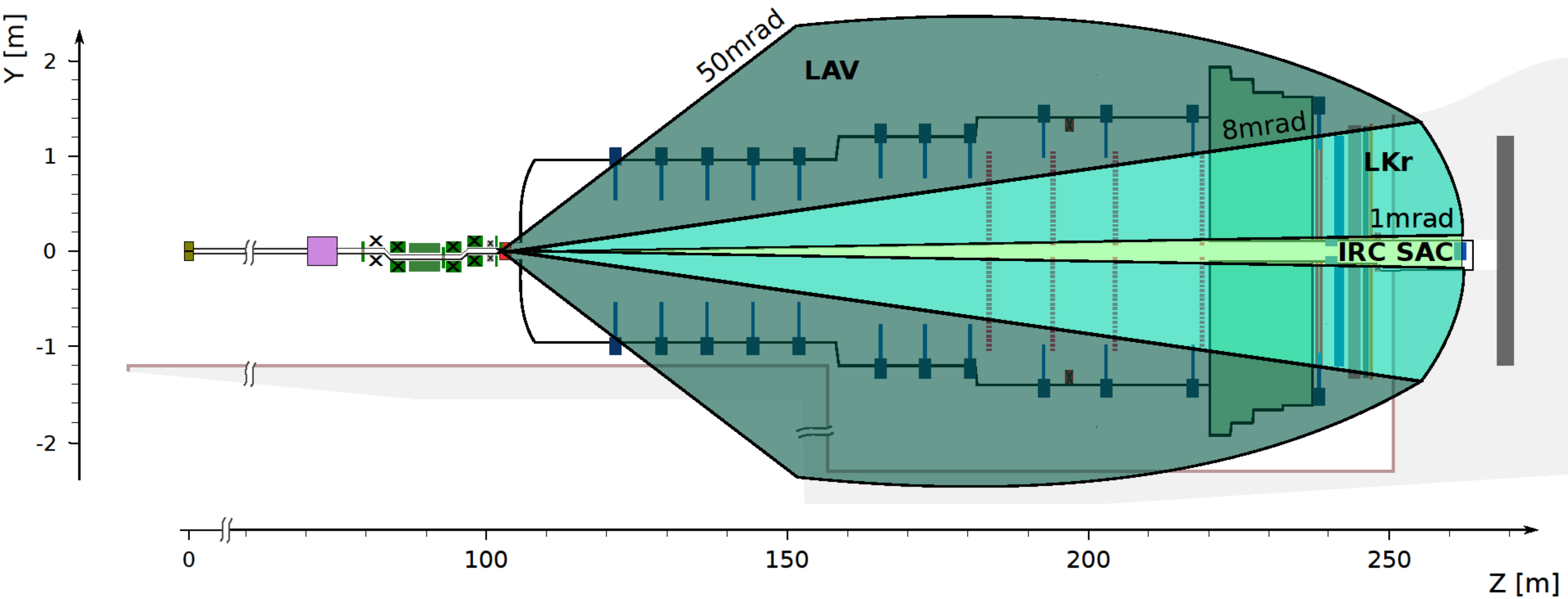


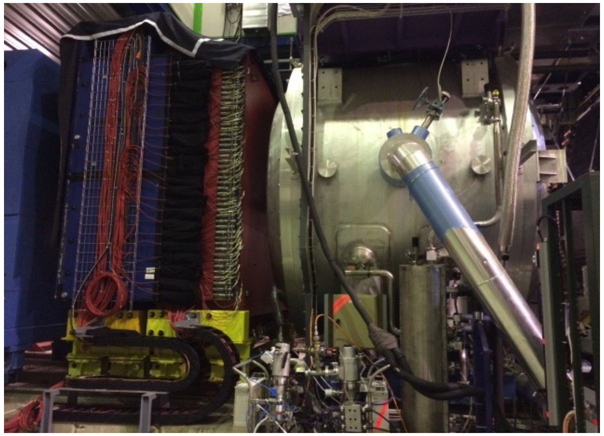
Particle ID with RICH

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



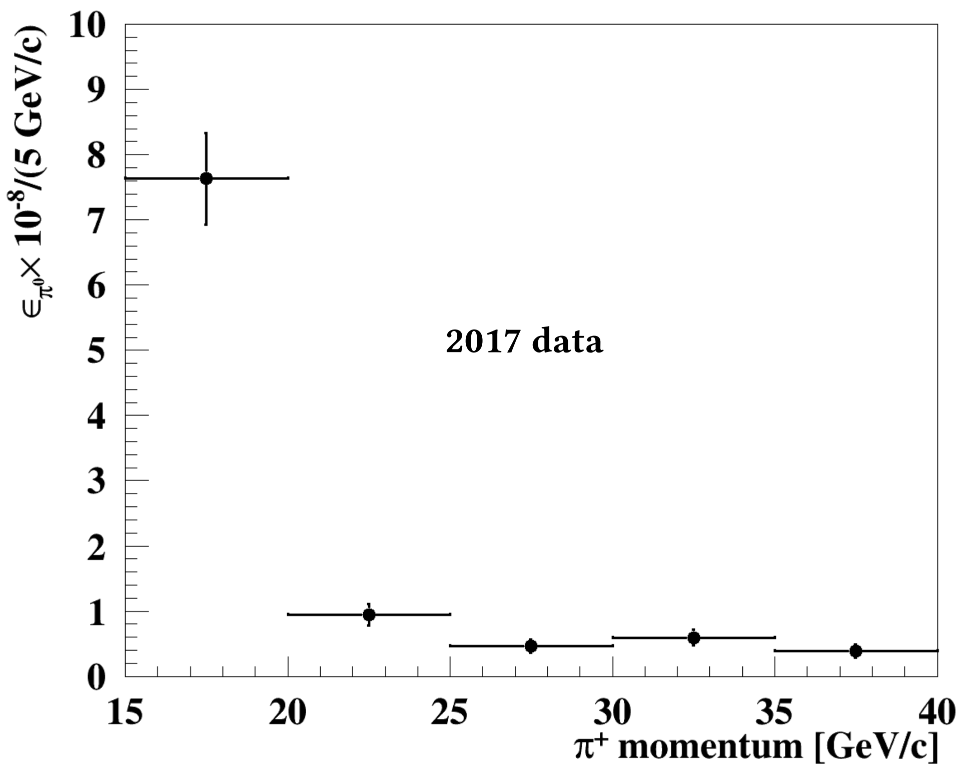
Photon rejection



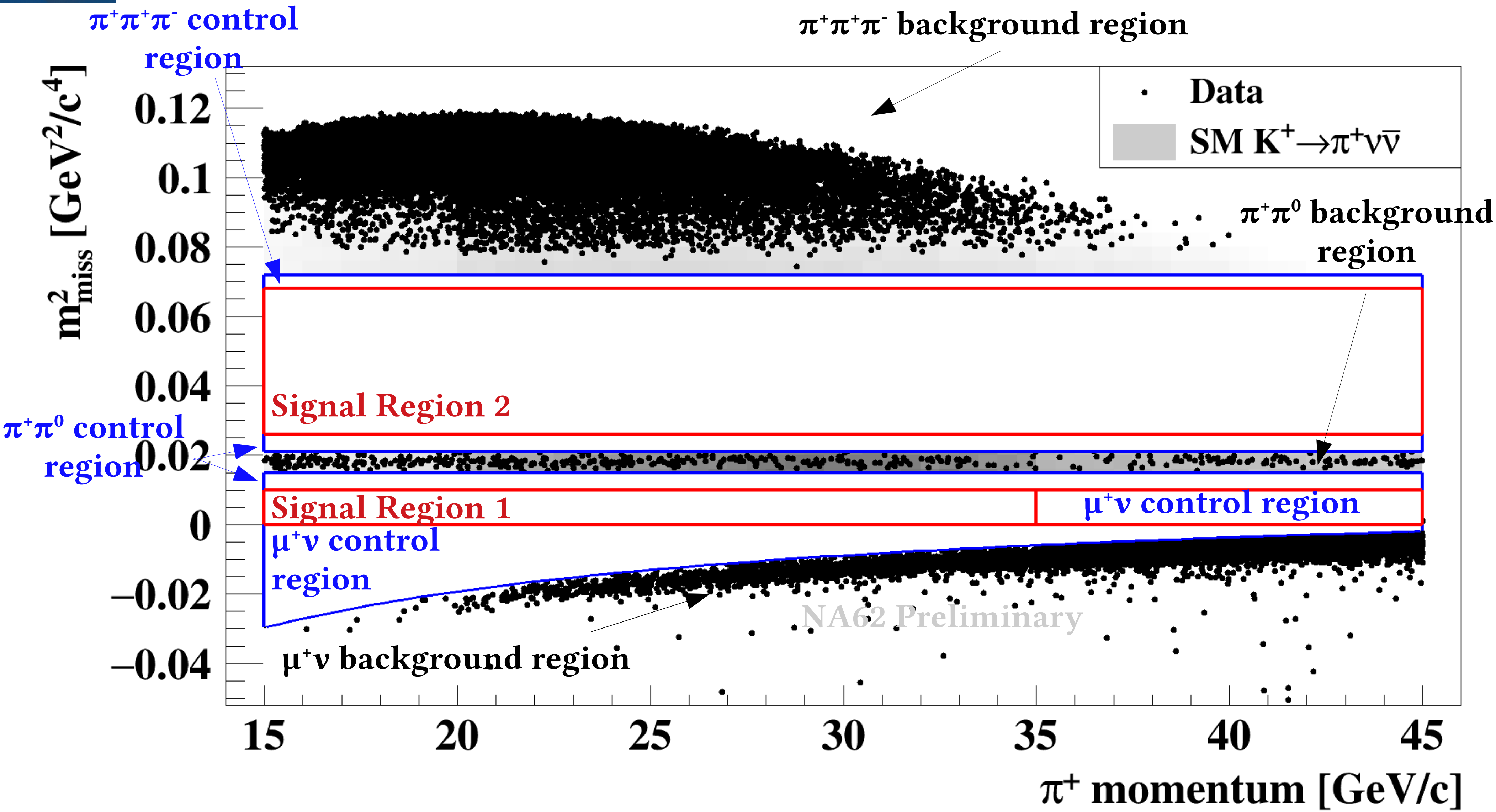


Photon and multi-charged rejection

- 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 ±7 ns; energy dependent time cuts in Lkr
- Fraction of surviving $K^+ \rightarrow \pi^+\pi^0$ (15 – 45 momentum range) : **~ 2 x 10^{-8}**
- High suppression of $K^+ \rightarrow \pi^+\pi^+\pi^-$, $K^+ \rightarrow \pi^+\pi^- e^+ \nu_e$



2018 data after signal selection



2. Single Event Sensitivity (S.E.S.)

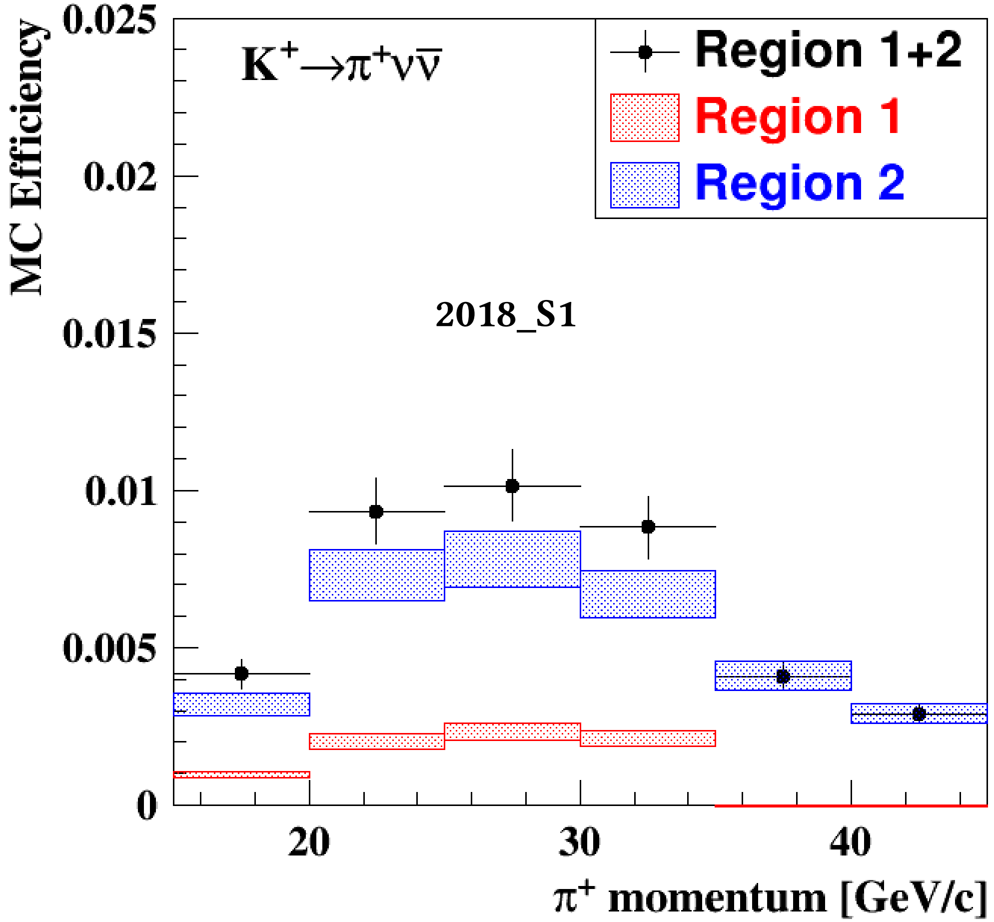
Signal Event Sensitivity (S.E.S.)

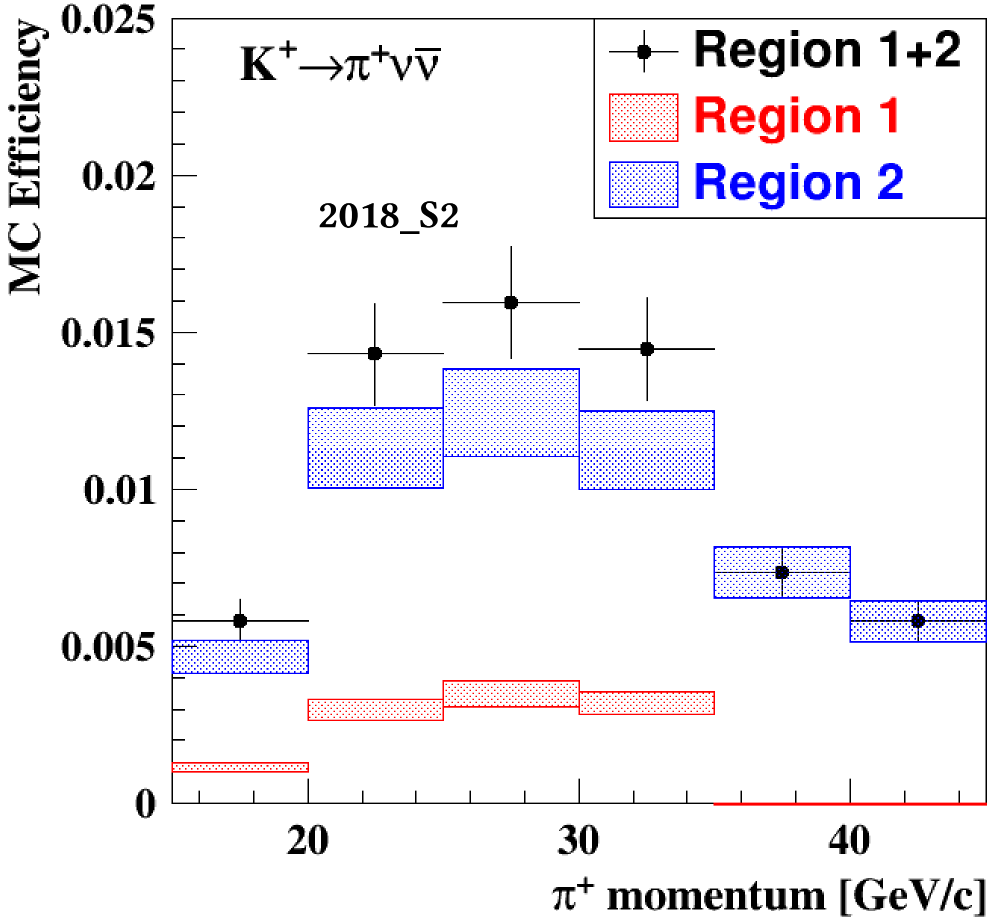
- Normalization: $K^+ \longrightarrow \pi^+\pi^0$ from control data
- Same $\pi^+\nu\bar{\nu}$ selection: γ, multi-charged rejection not applied; $\mathbf{m^2_{miss}}$ cuts modified

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

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

Signal acceptance

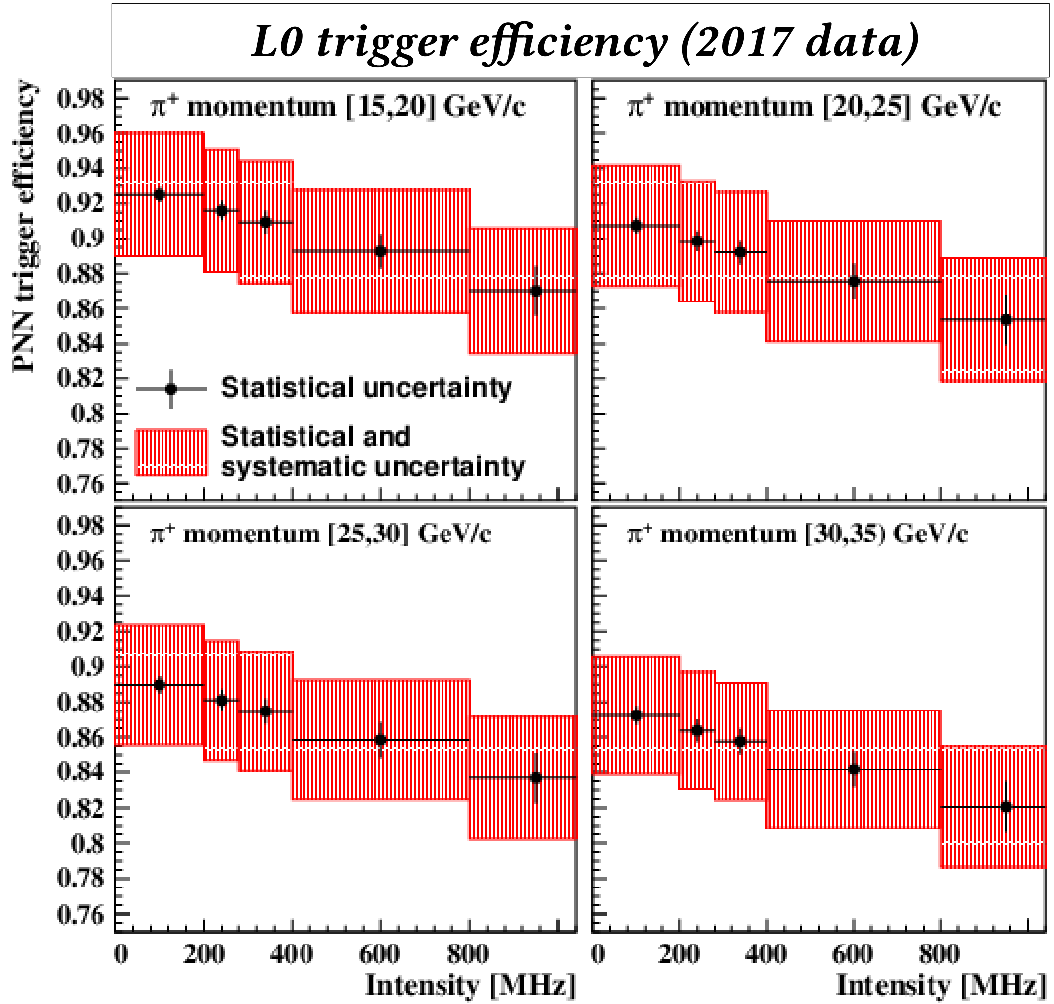




- Significant acceptance improvement after the installation of a new collimator in 2018_S2
- Region 20-35 GeV/c the most sensitive in both samples
- Normalization acceptance ~ 7.6% (2018_S1) and 11.8% (2018_S2)

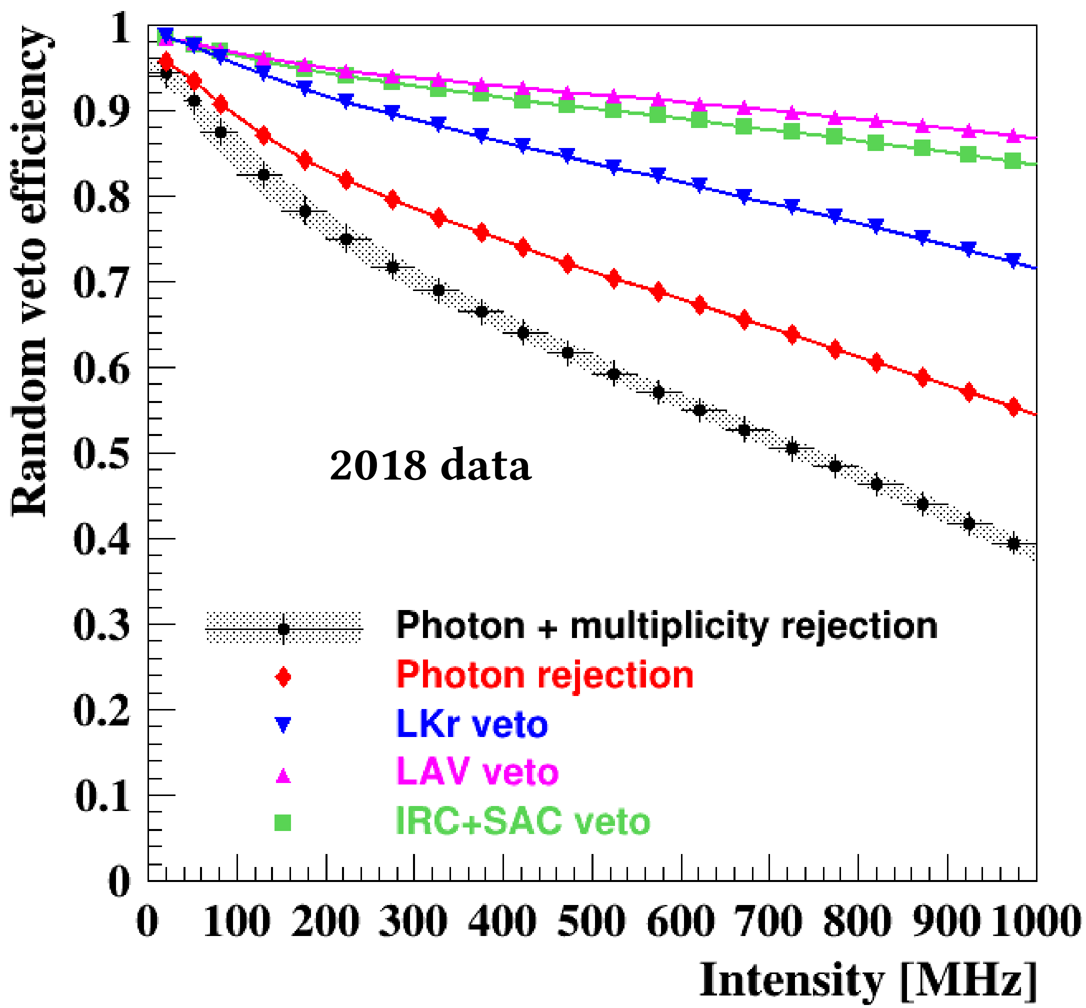
Trigger efficiency

- Measured on data using $K^+ \to \pi^+\pi^0$ selected from control triggers
- Losses mainly from L0 , L1 efficiency ~ 0.97
- Performance similar in 2018 within 1% (extended to 45 GeV/c)

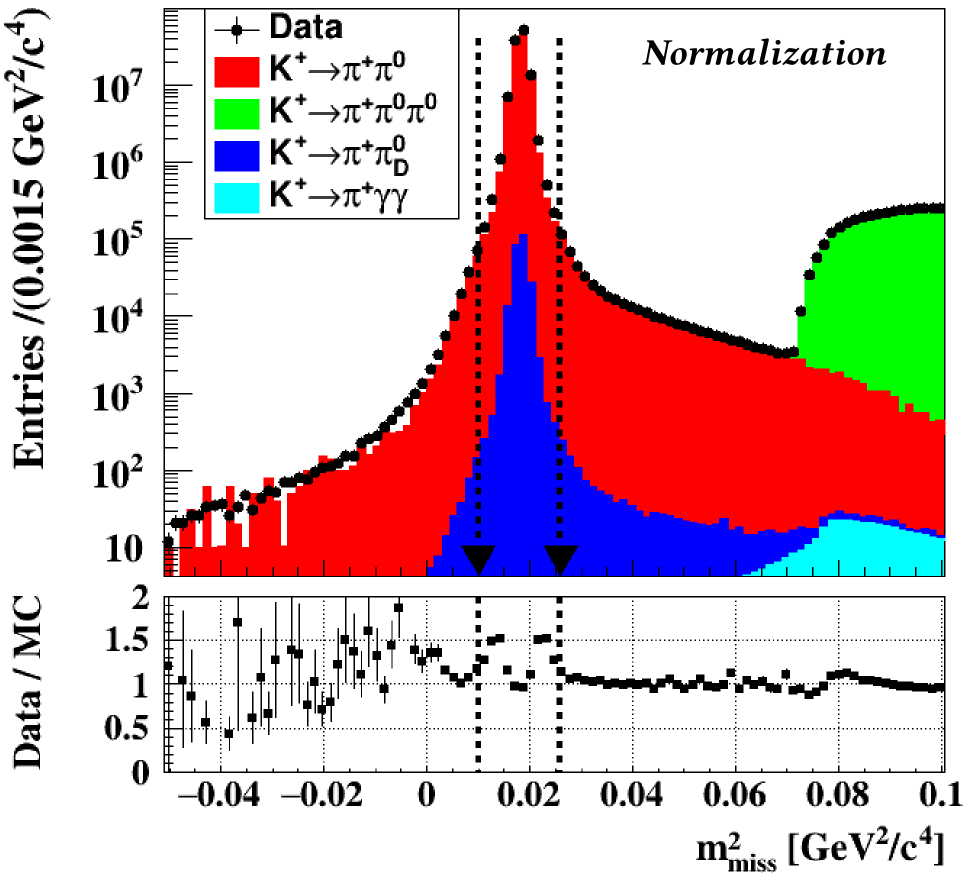


Random veto

- Random signal losses due to γ+ multi-charged rejection measured with $K^+ \to \mu^+ \nu_\mu$
- $\varepsilon_{RV} \approx 0.66$ independent of $P_{\pi+}$, but depends on instantaneous intensity
- No difference between 2018_S1 and 2018_S2



Single event sensitivity 2018



	Error budget S.E.S.
Trigger efficiency	5%
MC acceptance	3.5%
Random Veto	2%
Background(normalization)	0.7%
Instantaneous intensity	0.7%
Total	**6.5%**

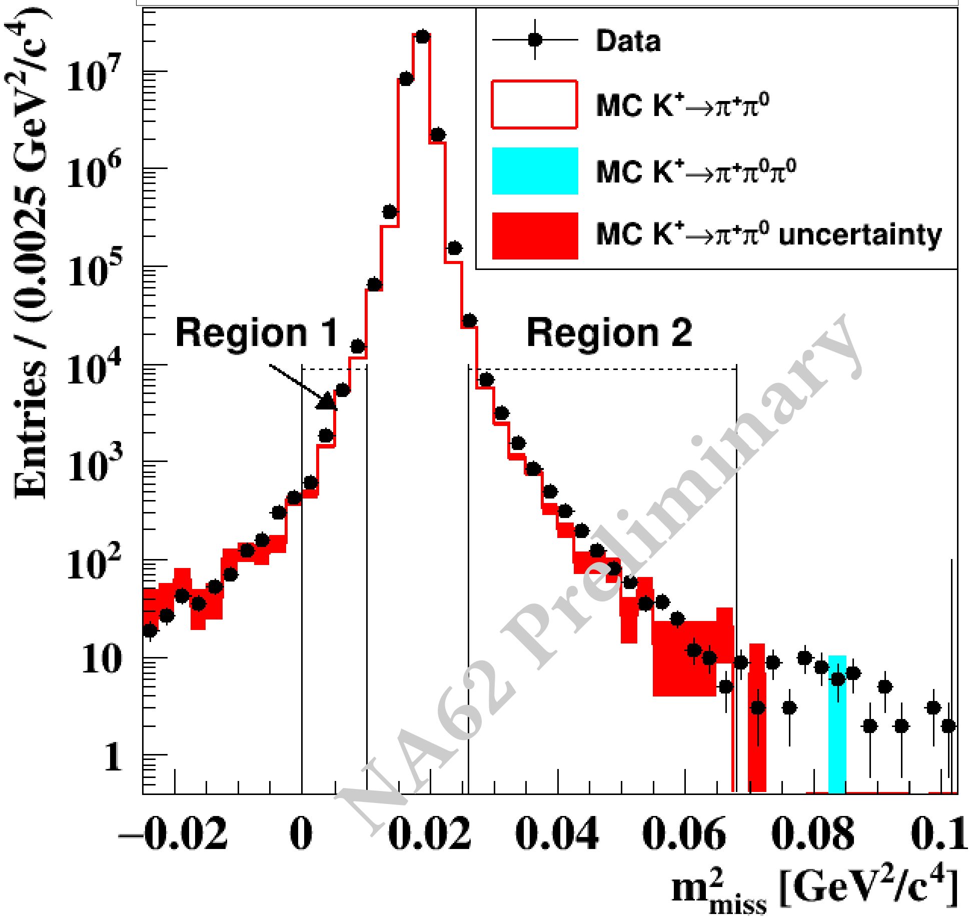
- $K^+ \to \pi^+\pi^0$ decay used for normalization
- Cancellation of systematic effects to first order (PID, Detector efficiencies, kaon ID and beam-related acceptance loss)

$$S.E.S. = (1.11 \pm 0.07_{syst.}) \times 10^{-11}$$

3. Background estimation

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

Control $K^+ \to \pi^+\pi^0$ data used to study the tails of the m^2_{miss} distribution



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

- Same procedure used for $K^+ \to \pi^+\pi^+\pi^-$ background estimation
- Radiative $K^+ \to \pi^+\pi^0\gamma$ decays estimated with MC combined with single photon efficiency measurement on data

Background: $K^+ \to \mu^+ \nu_\mu(\gamma)$

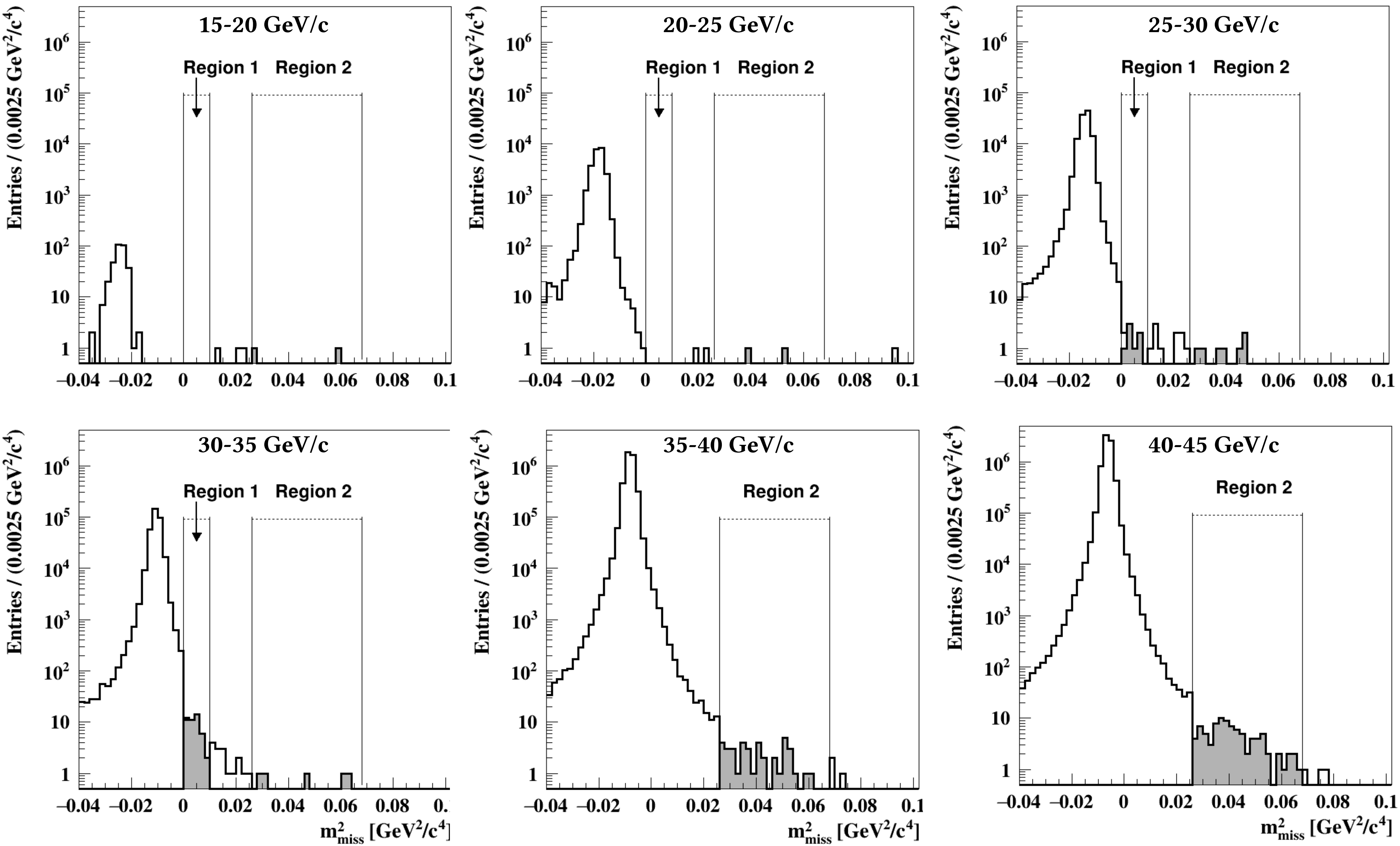
$$N^{bg}_{\mu\nu} = \sum^{N_{cat}} f_{kin+RICH} \cdot N_{\mu\nu}(\mu\nu)$$

Number of μν events in the μν background region

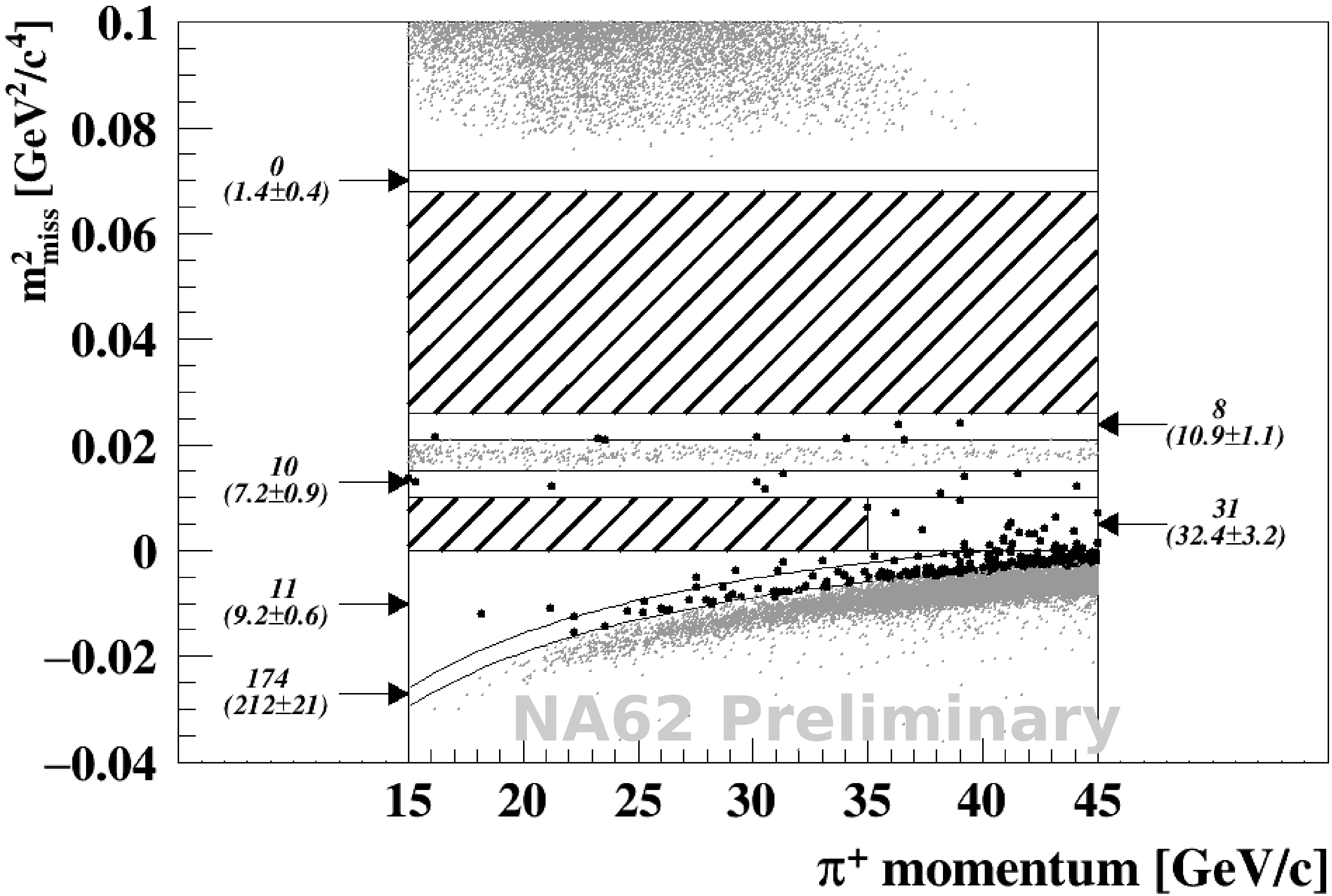
Kinematic tails x RICH muon rejection

- PNN-like $K^+ \to \mu^+ \nu_\mu$ selection with inverted Calo PID
- Tails are measured together with the RICH muon rejection applied on data
- Correlation between kinematics and RICH PID are properly handled in this case

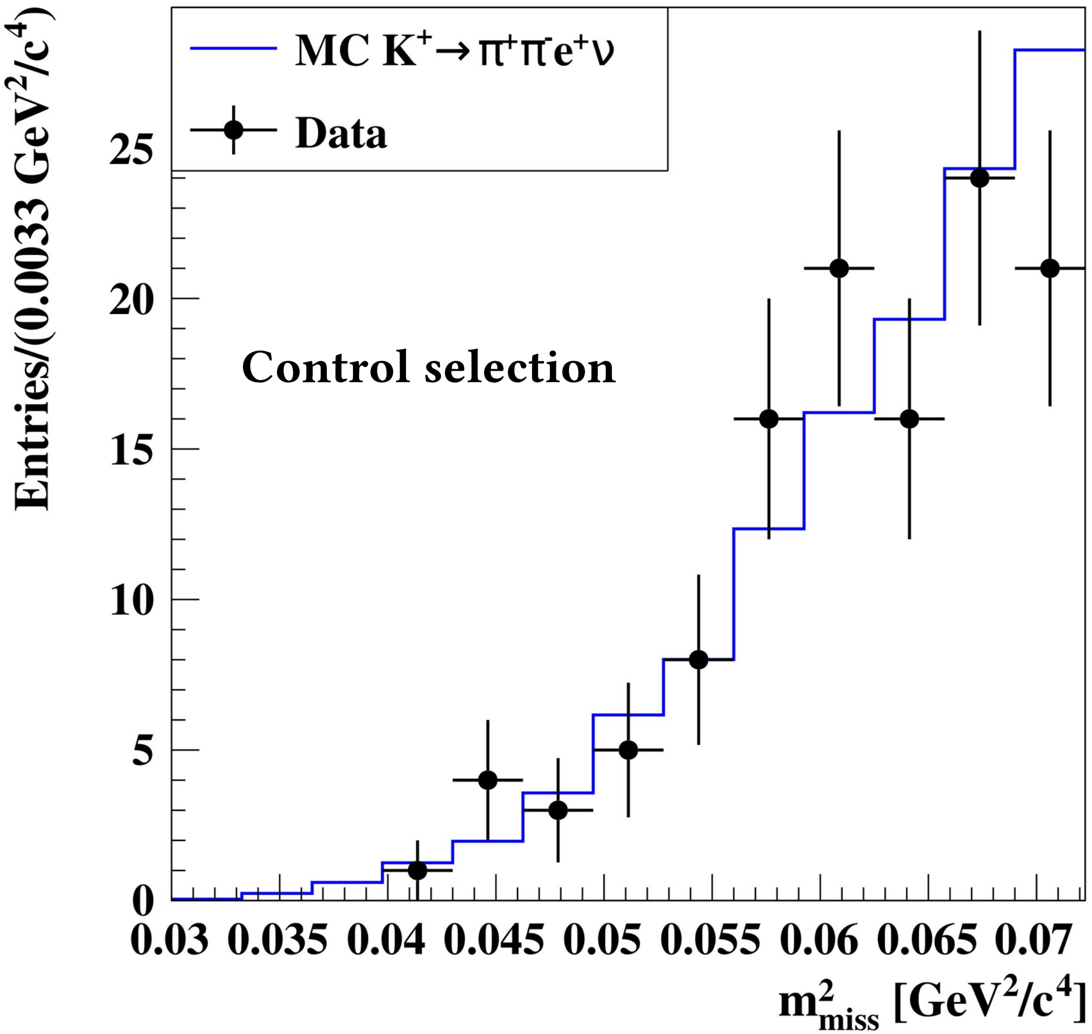
Background: $K^+ \to \mu^+ \nu_\mu(\gamma)$



Control regions: $K^+ \to \pi^+\pi^0$, $\mu^+\nu_\mu$ and $\pi^+\pi^+\pi^-$

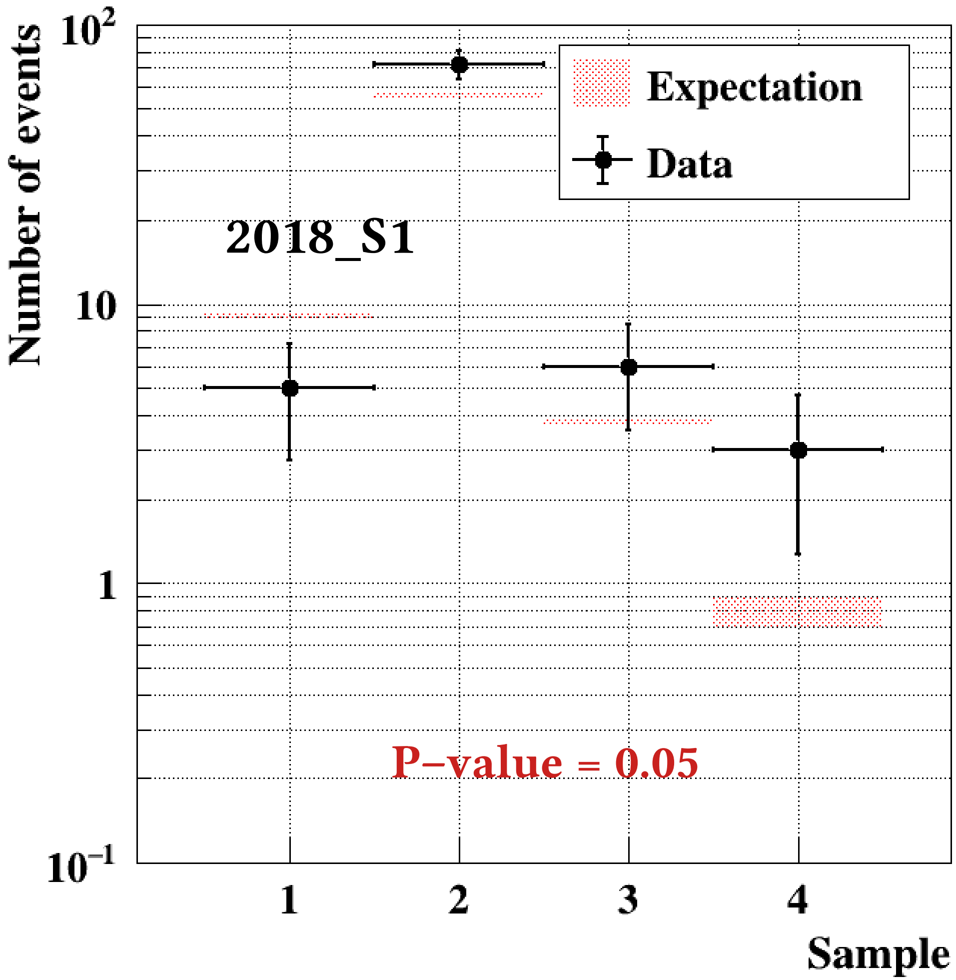


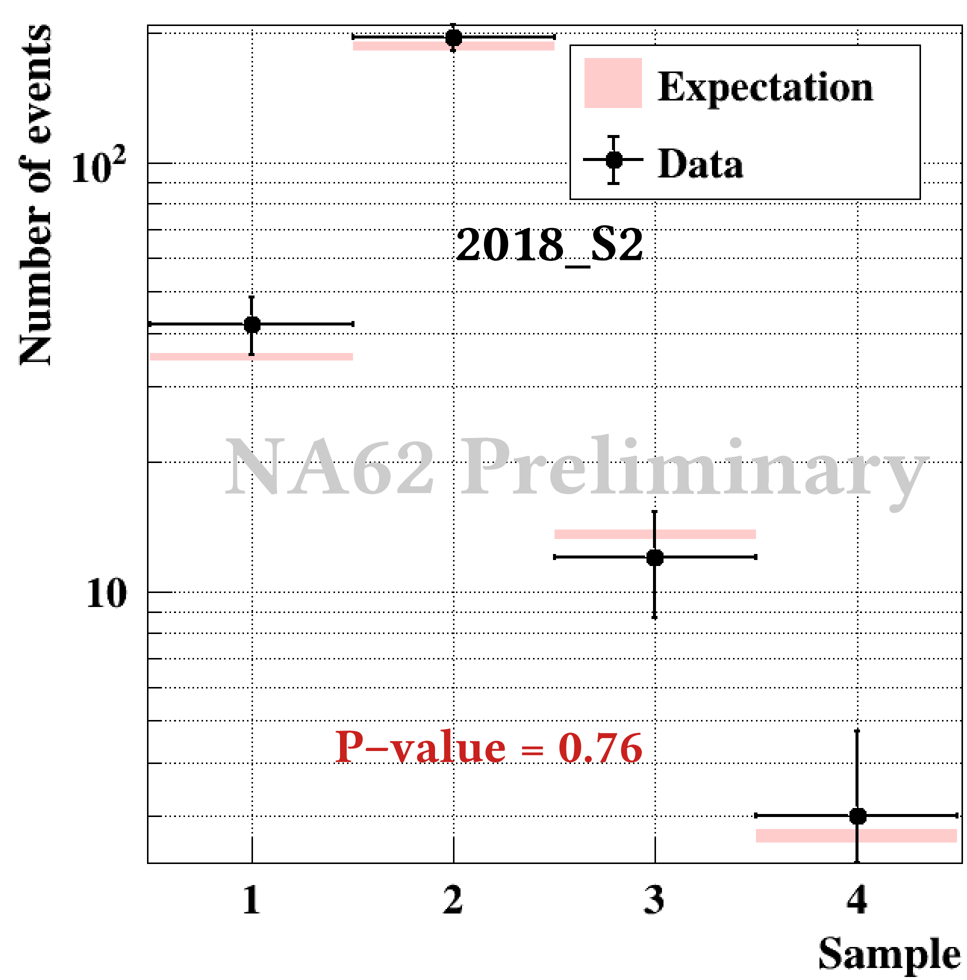
Background: $K^+ \rightarrow \pi^+\pi^- e^+\nu_e (K_{e4})$



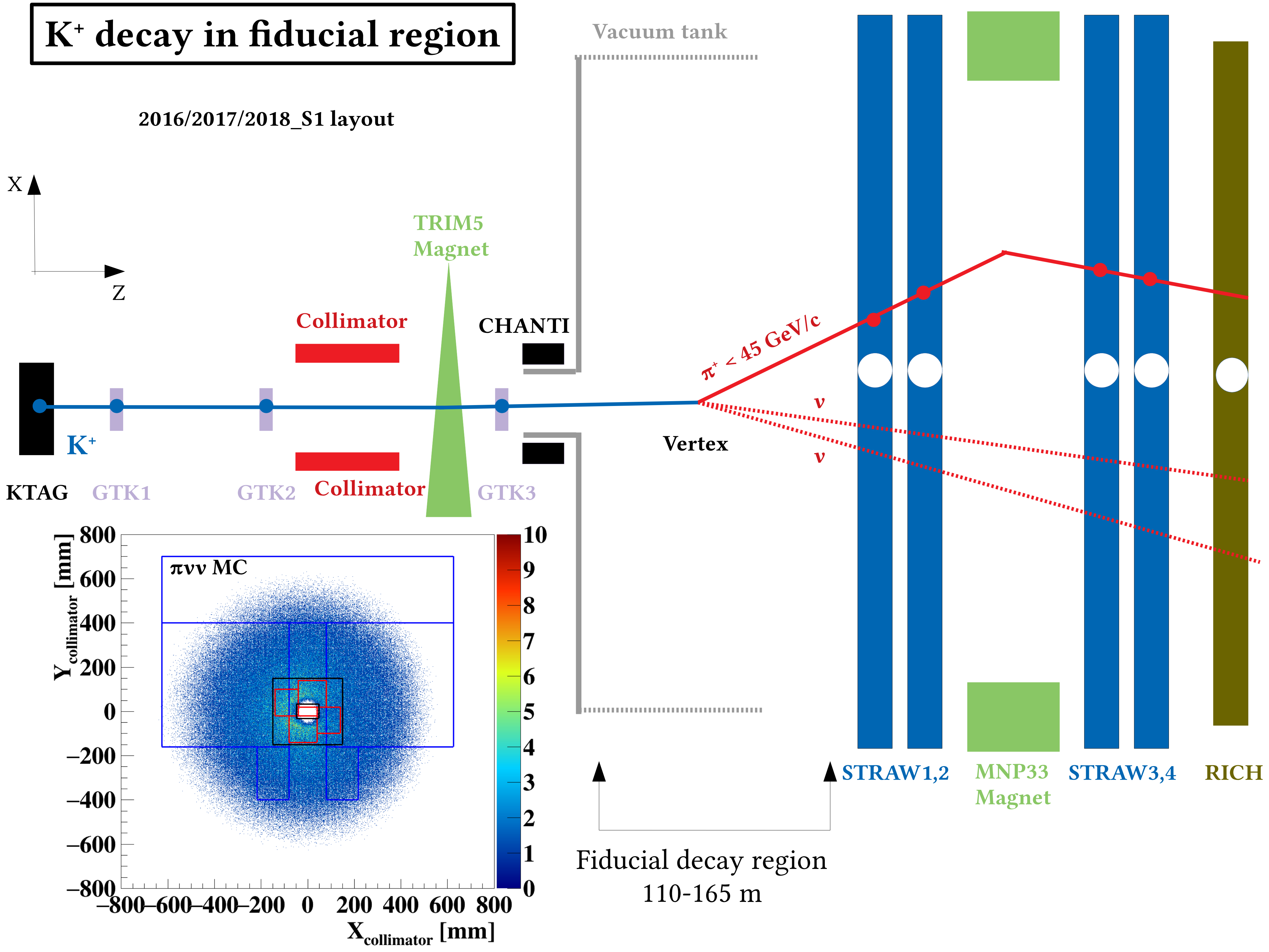
- Background estimated using MC normalized to SES (2x10⁹ events generated)
- Predictions validated using several control selections orthogonal to the signal
- MC normalized to $K^+ \rightarrow \pi^+\pi^0$ decays

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

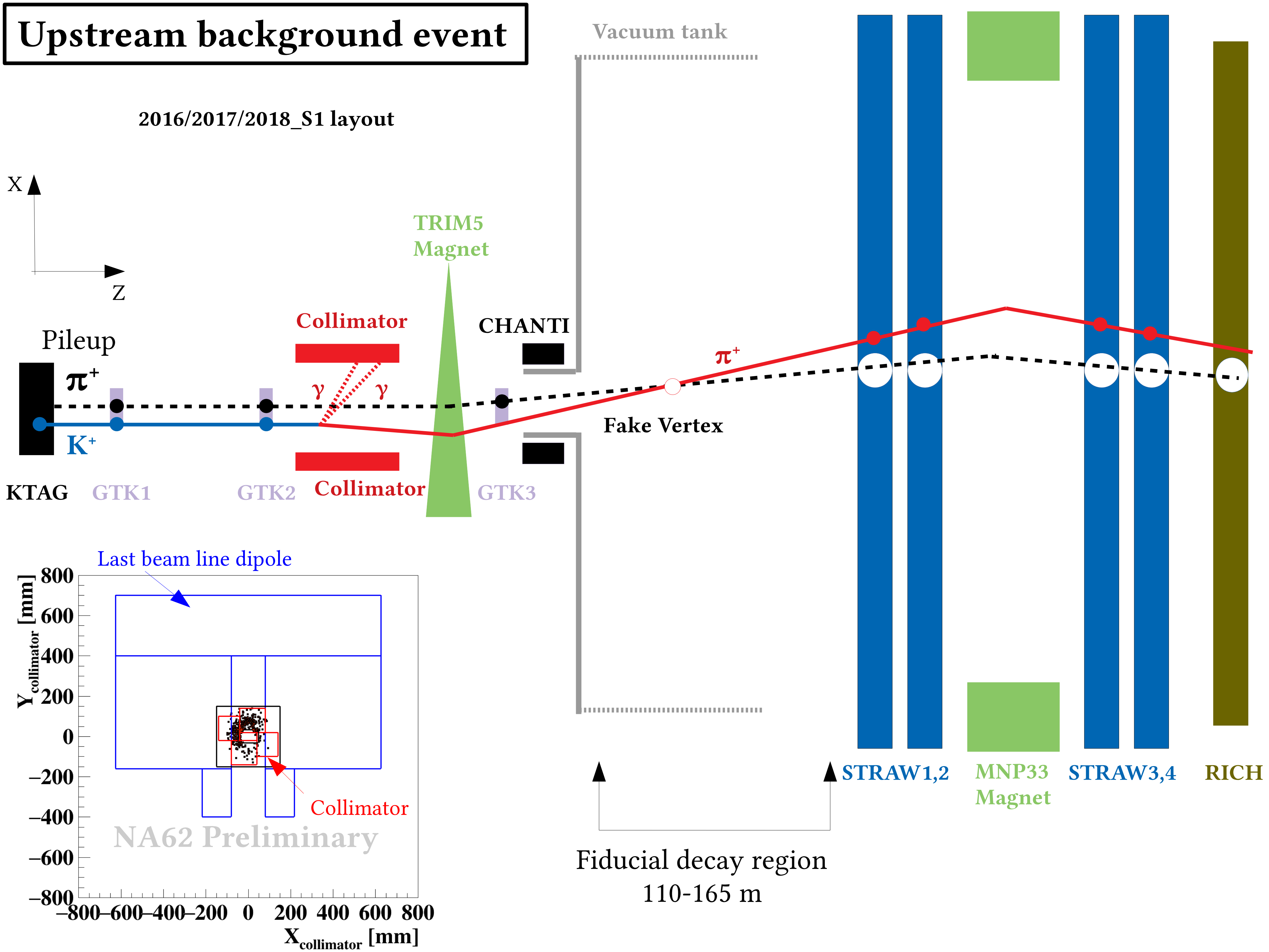




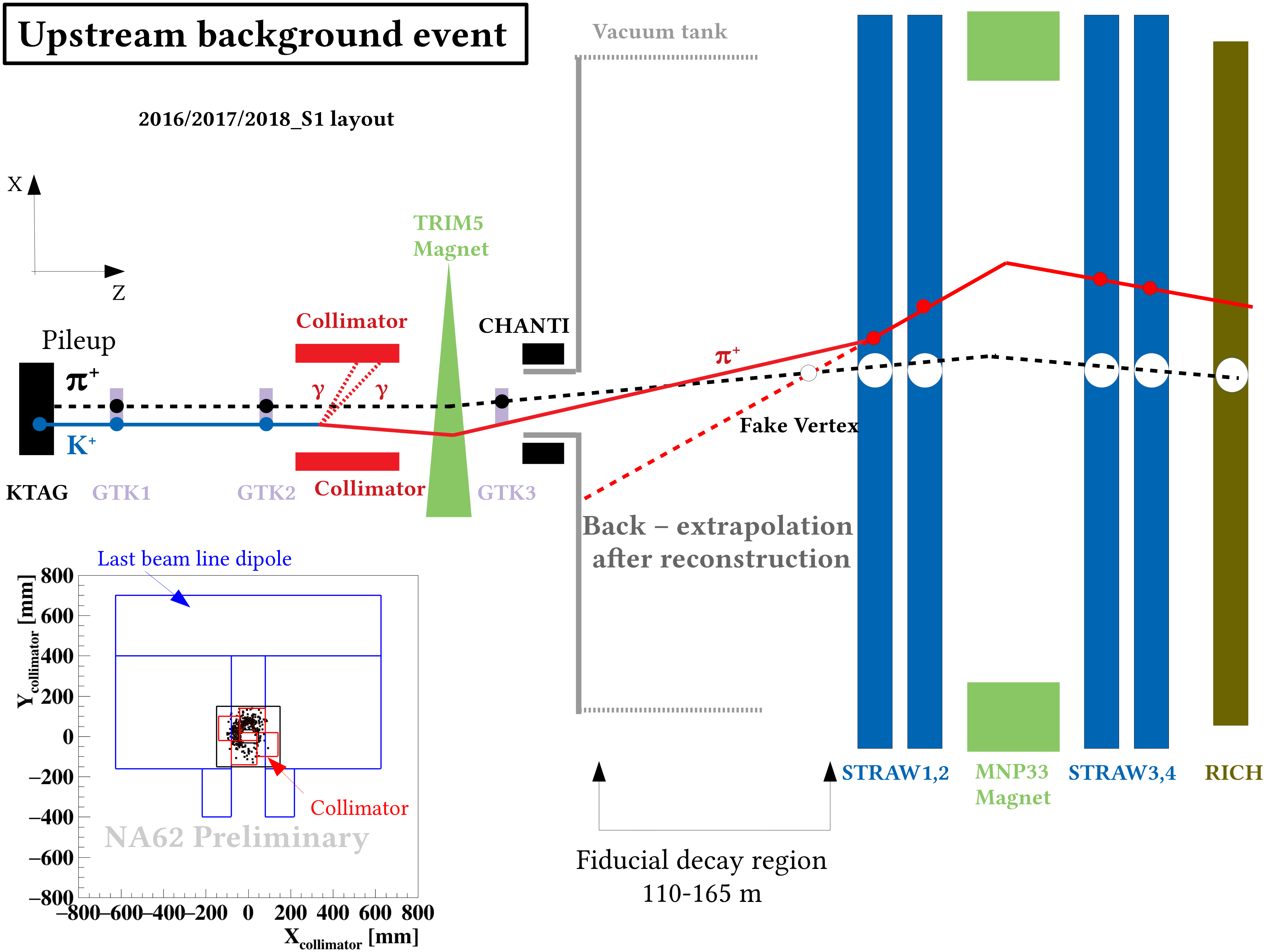
- Sensitivity of the validation samples spans 2 orders of magnitude (Acc ~ $10^{-6} - 10^{-8}$)
- Samples 3 and 4 of particular importance
  - Sensitivity similar or even lower than the signal



K+ decay in fiducial region
2016/2017/2018_S1 layout
Vacuum tank
X
Z
TRIM5
Magnet
Collimator
CHANTI
π+ < 45 GeV/c
ν
ν
Vertex
K+
KTAG
GTK1
GTK2
Collimator
GTK3
πνν MC
Y_collimator [mm]
X_collimator [mm]
STRAW1,2
MNP33
Magnet
STRAW3,4
RICH
Fiducial decay region
110-165 m

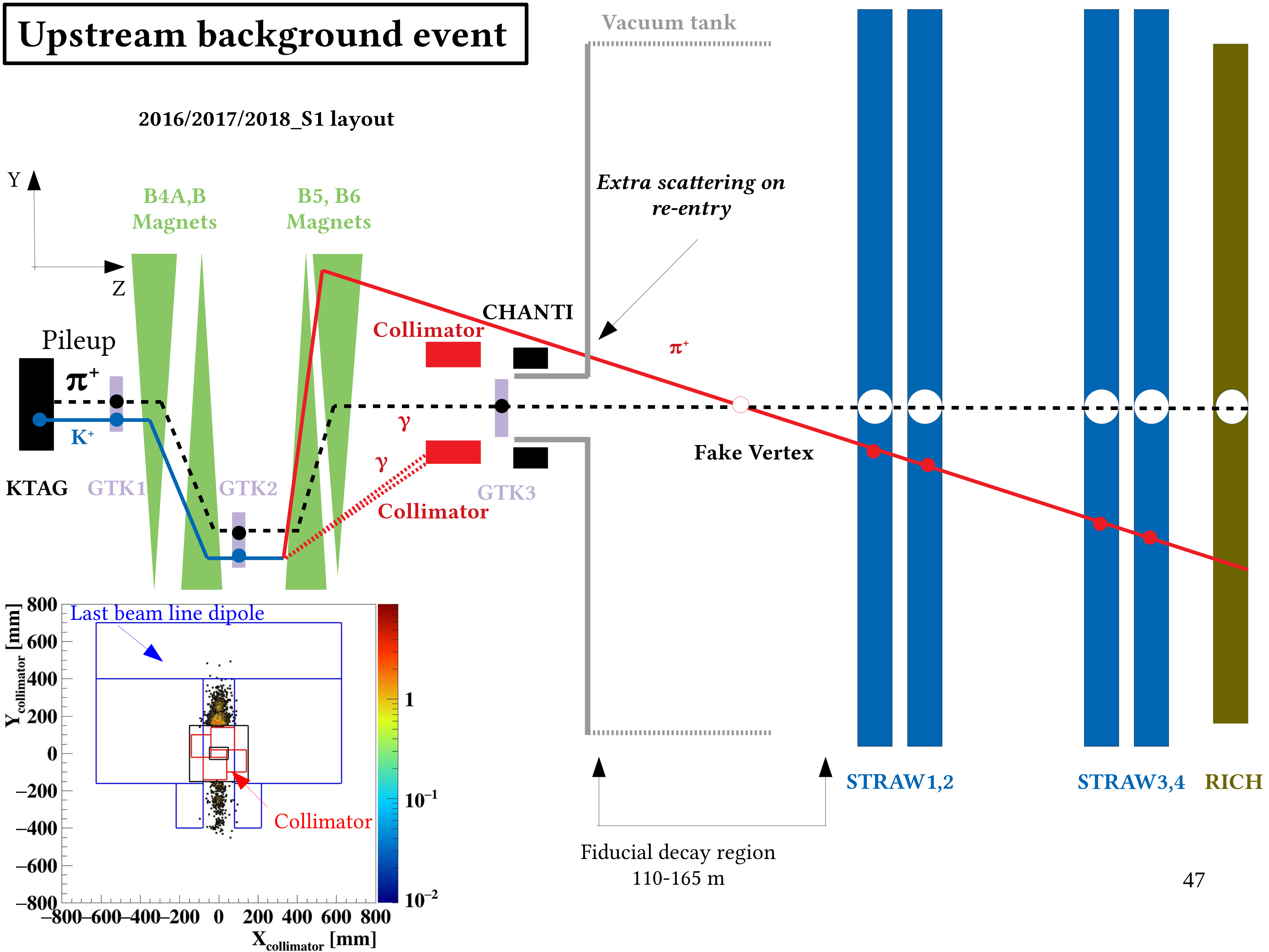


Upstream background event
2016/2017/2018_S1 layout
X
Z
Vacuum tank
TRIM5
Magnet
Collimator
CHANTI
Pileup
π+
γ
γ
π+
K+
Fake Vertex
KTAG
GTK1
GTK2
Collimator
GTK3
Last beam line dipole
Ycollimator [mm]
Xcollimator [mm]
Collimator
NA62 Preliminary
STRAW1,2
MNP33
Magnet
STRAW3,4
RICH
Fiducial decay region
110-165 m

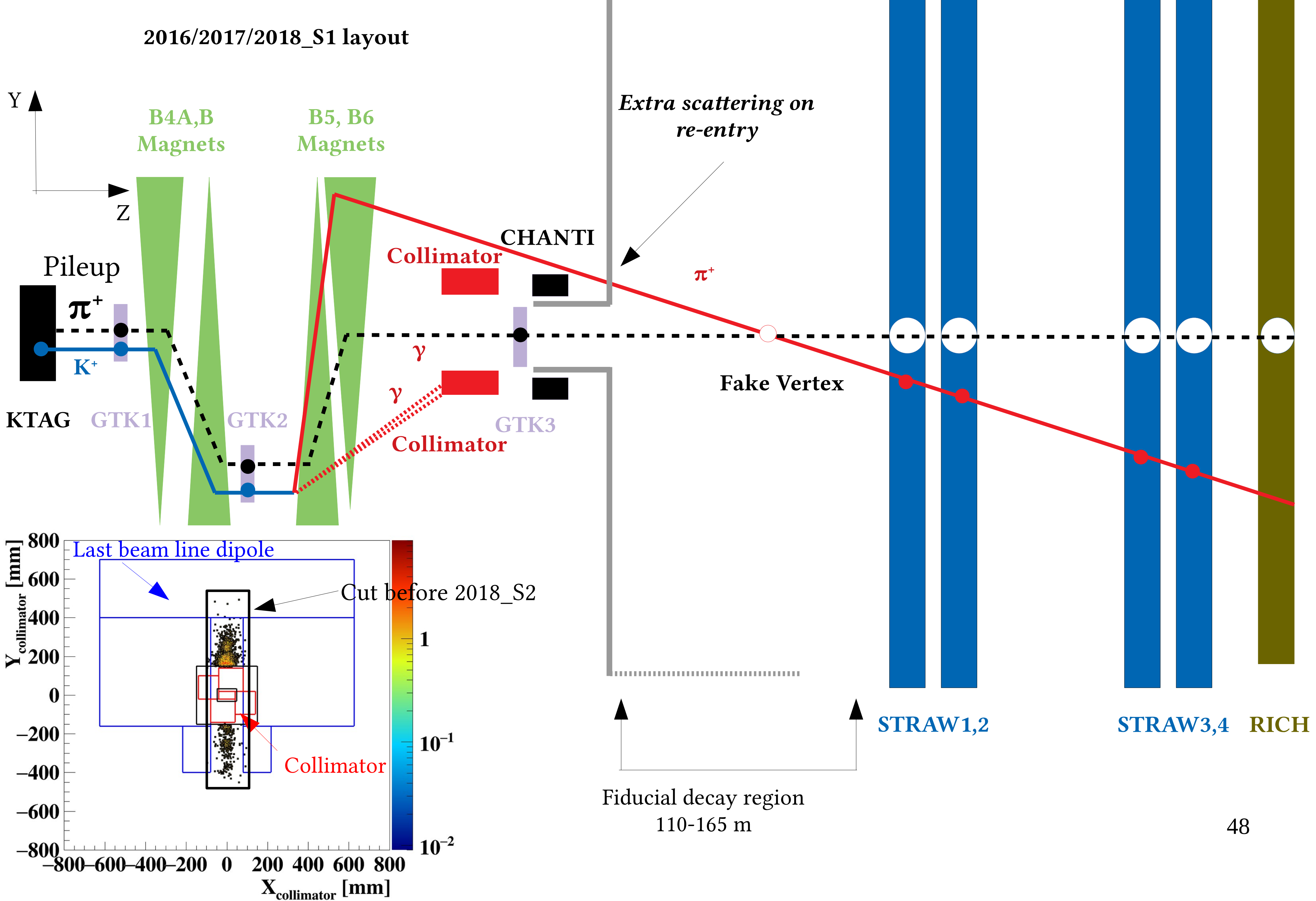


Upstream background event
2016/2017/2018_S1 layout
X
Z
Vacuum tank
TRIM5
Magnet
Collimator
CHANTI
Pileup
π+
γ
γ
K+
π+
Fake Vertex
KTAG
GTK1
GTK2
Collimator
GTK3
Back – extrapolation
after reconstruction
Last beam line dipole
Collimator
NA62 Preliminary
Ycollimator [mm]
Xcollimator [mm]
800
600
400
200
0
−200
−400
−600
−800
−800 −600 −400 −200 0 200 400 600 800
STRAW1,2
MNP33
Magnet
STRAW3,4
RICH
Fiducial decay region
110-165 m

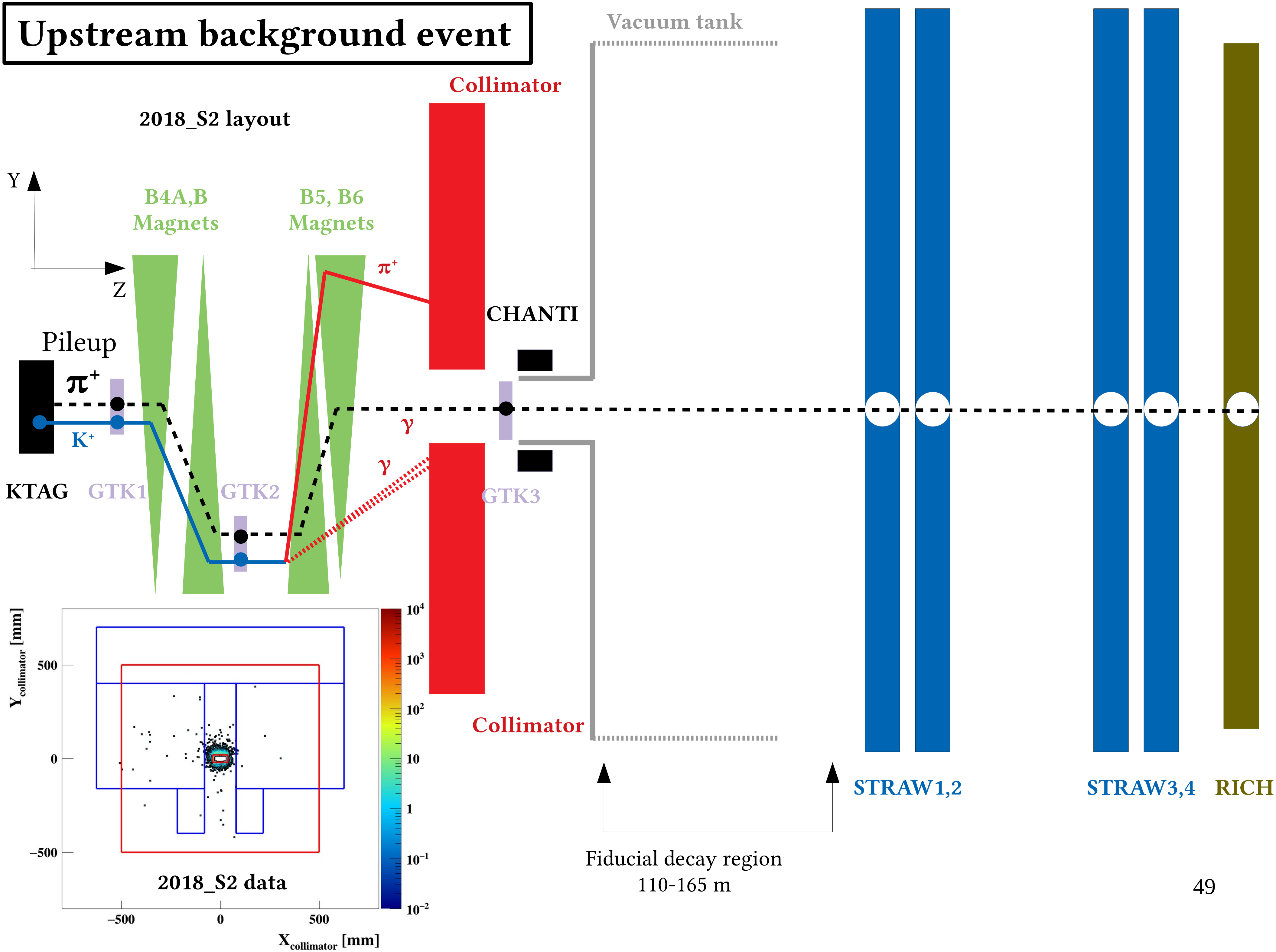
Upstream background event



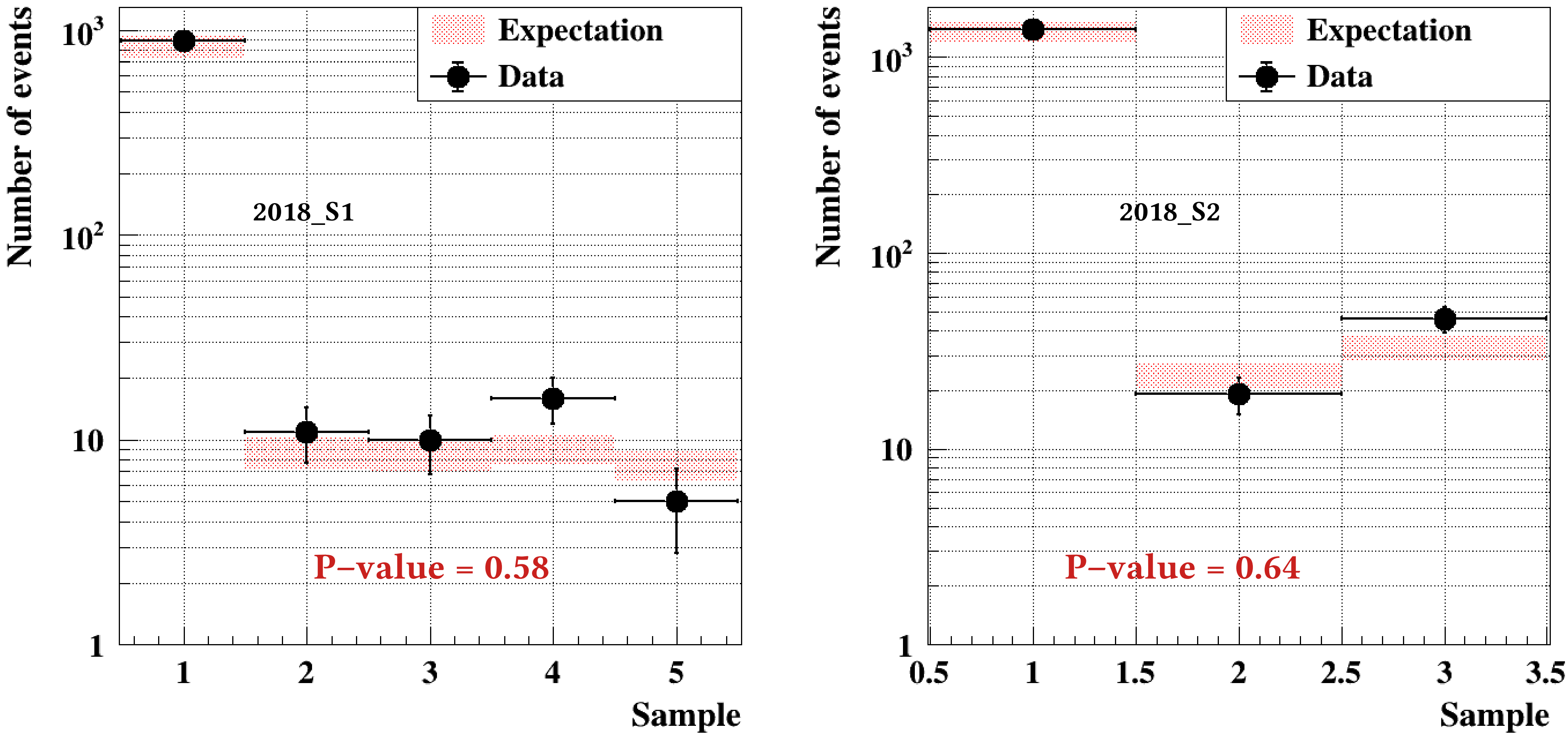
Upstream background event



Upstream background event



Upstream background validation



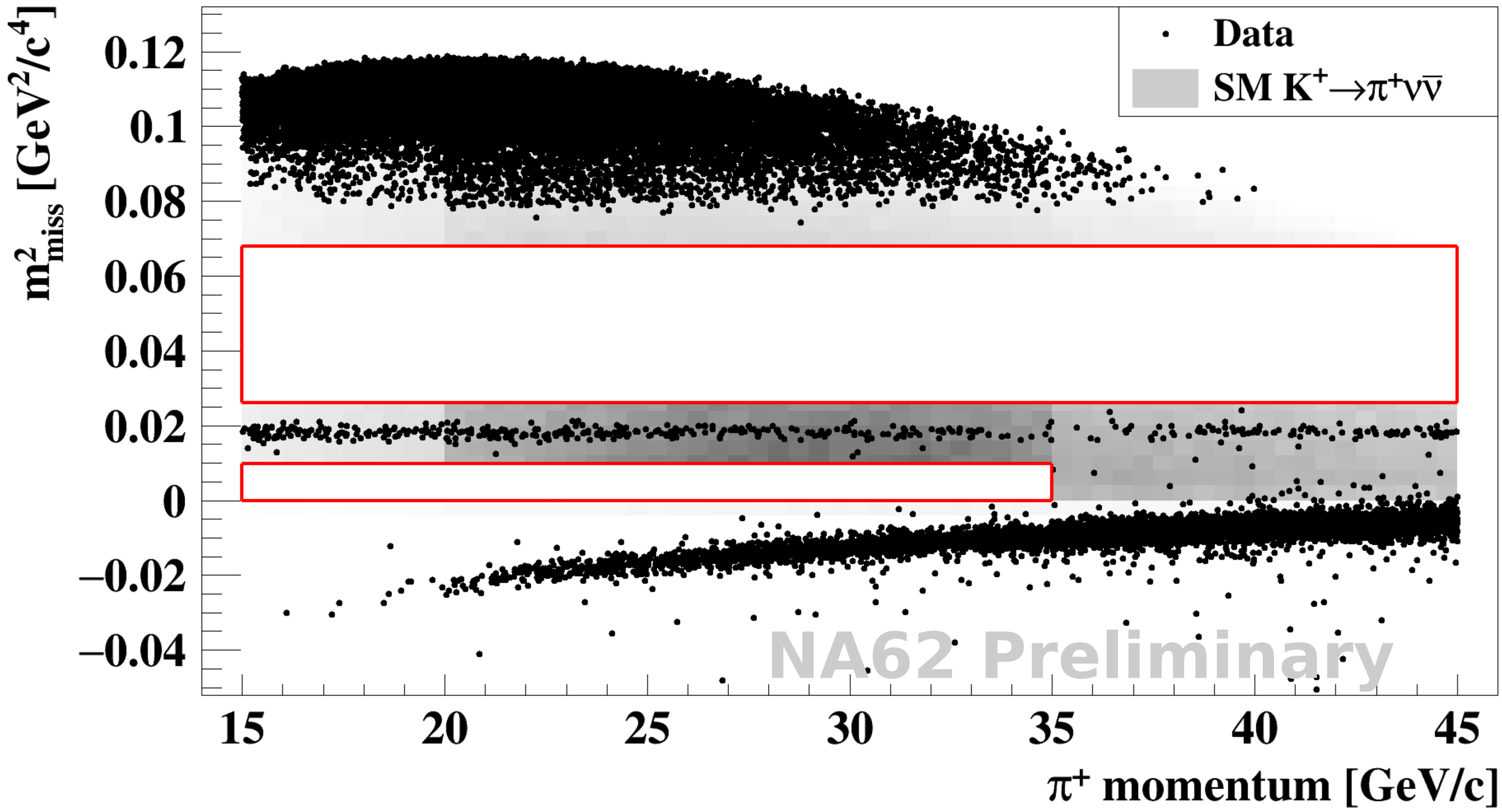
- CDA distributions of each validation sample is extracted separately from data
- Good agreement across all samples
  - Sensitivity of the validation samples spans 2 orders of magnitude

Background summary

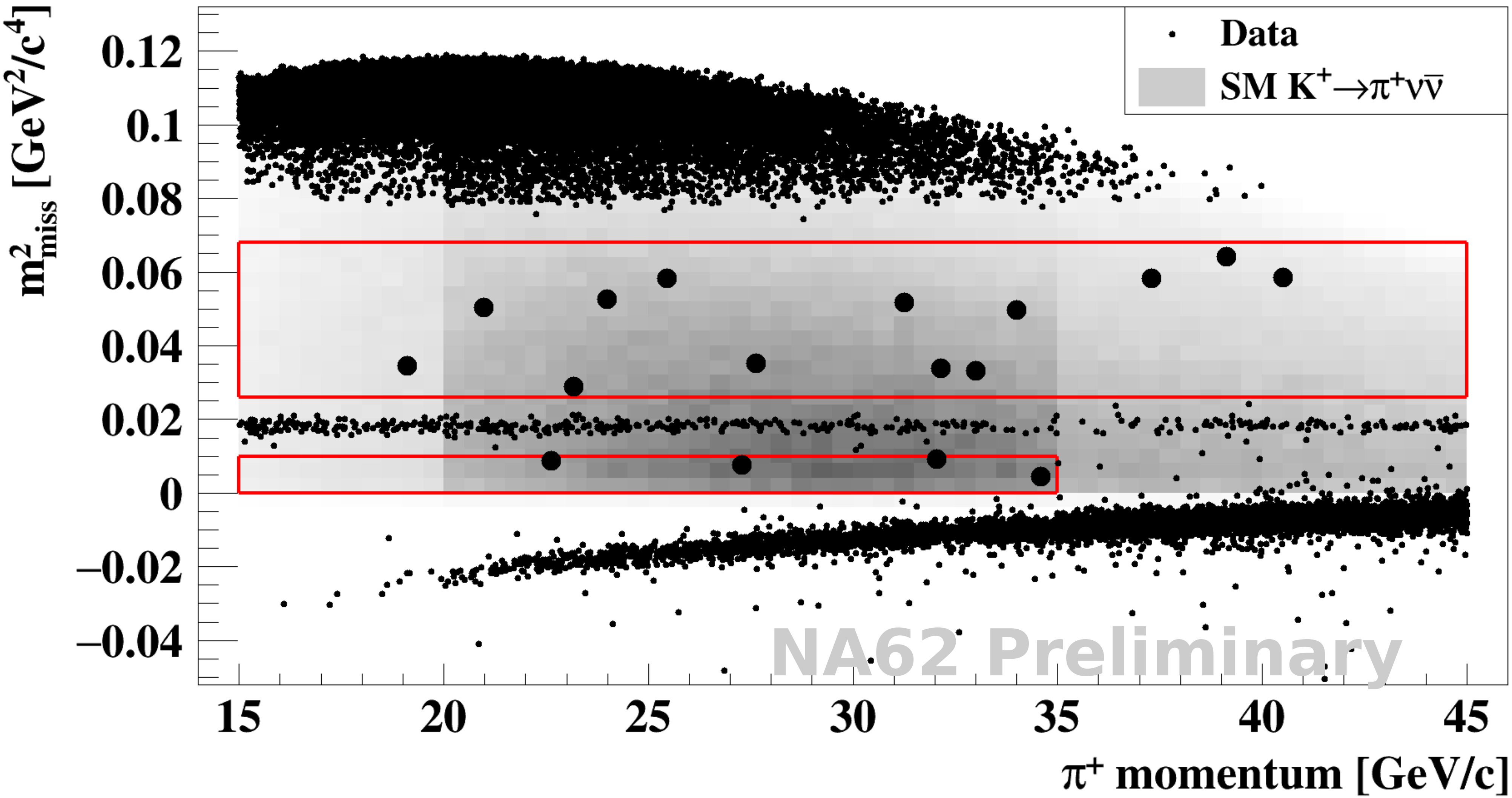
	2018 data
Expected SM signal	**$7.58(40)_{syst}(75)_{ext}$**
$K^+ \longrightarrow \pi^+\pi^0(\gamma)$	0.75(4)
$K^+ \longrightarrow \mu^+\nu(\gamma)$	0.49(5)
$K^+ \longrightarrow \pi^+\pi^-e^+\nu$	0.50(11)
$K^+ \longrightarrow \pi^+\pi^+\pi^-$	0.24(8)
$K^+ \longrightarrow \pi^+\gamma\gamma$	< 0.01
$K^+ \longrightarrow \pi^0 l^+\nu$	< 0.001
Upstream	$3.30^{+0.98}_{-0.73}$
Total background	$\mathbf{5.28^{+0.99}_{-0.74}}$

4. Result

2018 data before unblinding

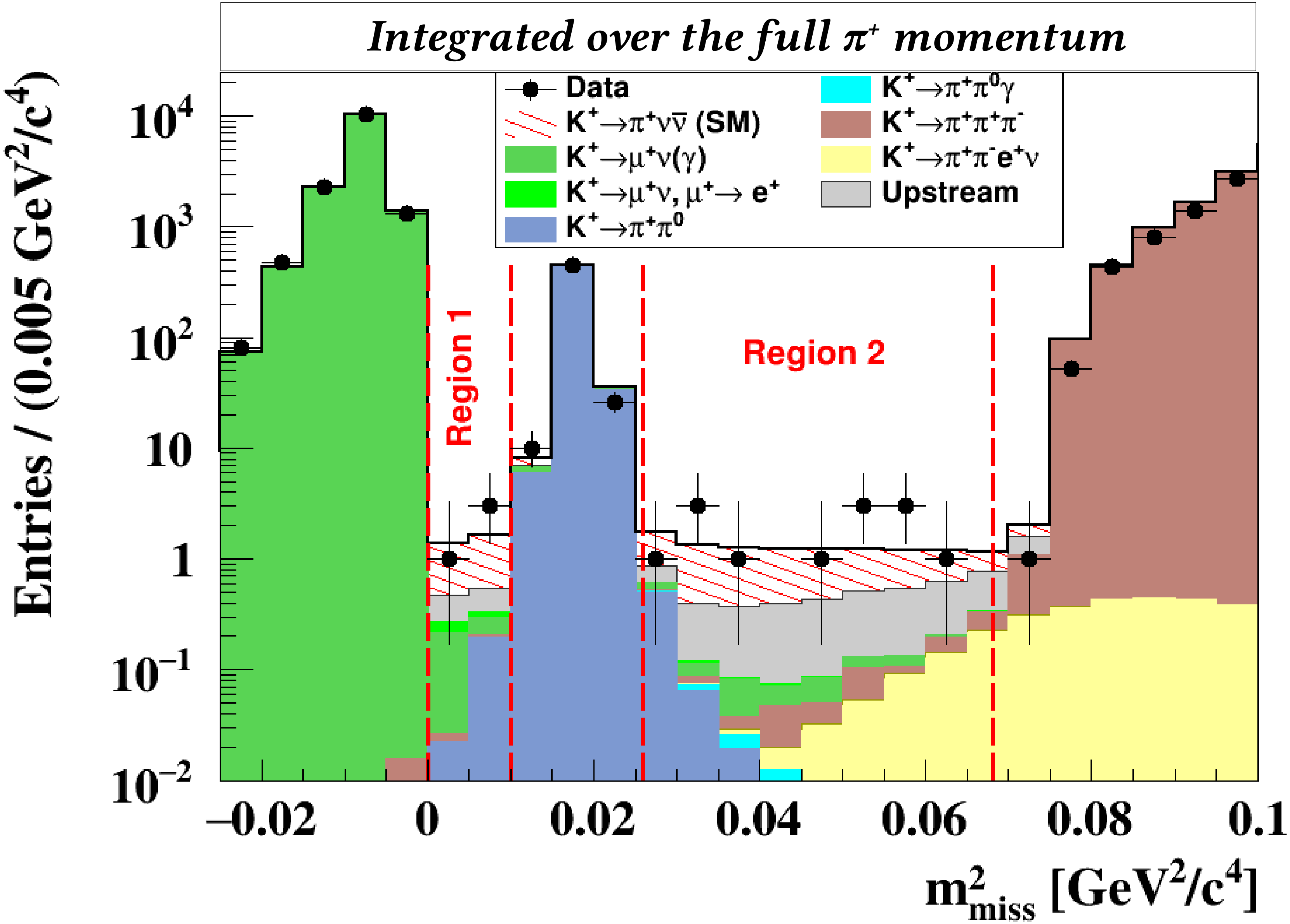


Opening the box in the 2018 data

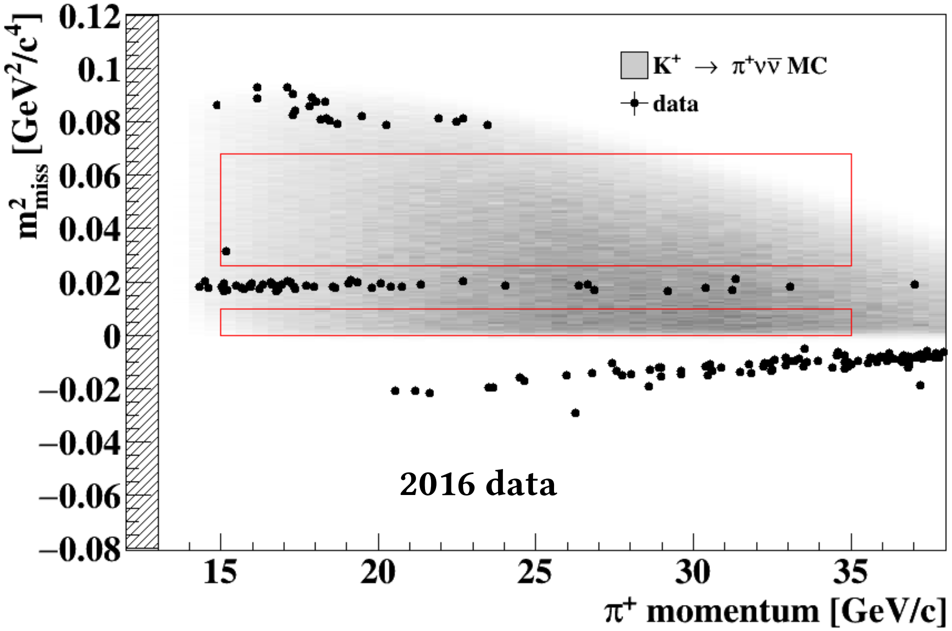


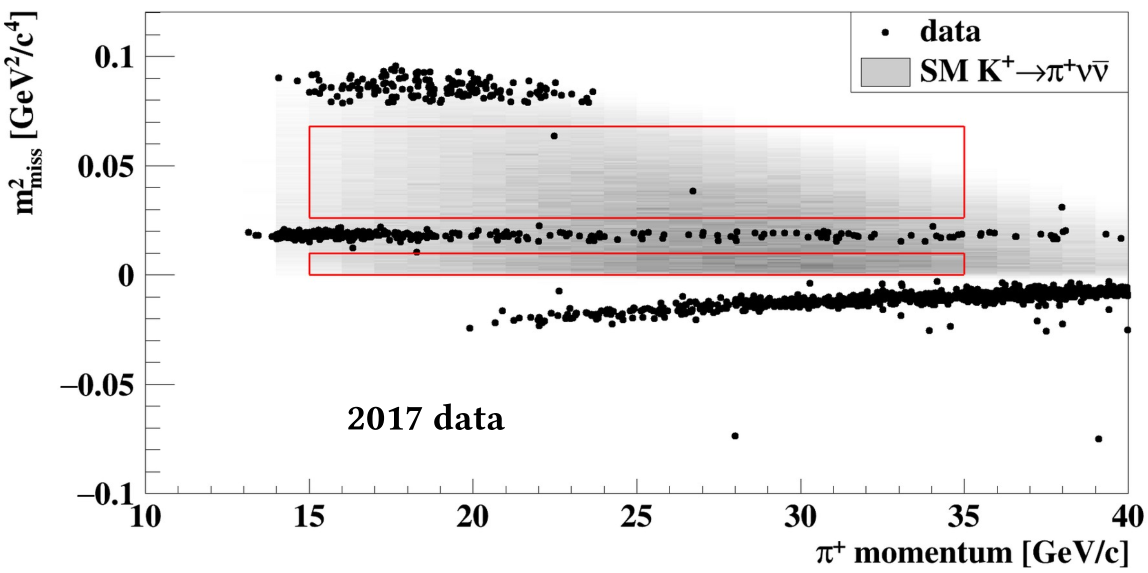
5.3 background + 7.6 SM signal events expected, 17 events observed

m^2_{miss} signal and background (2018 data)



Combine with the 2016 and 2017 results

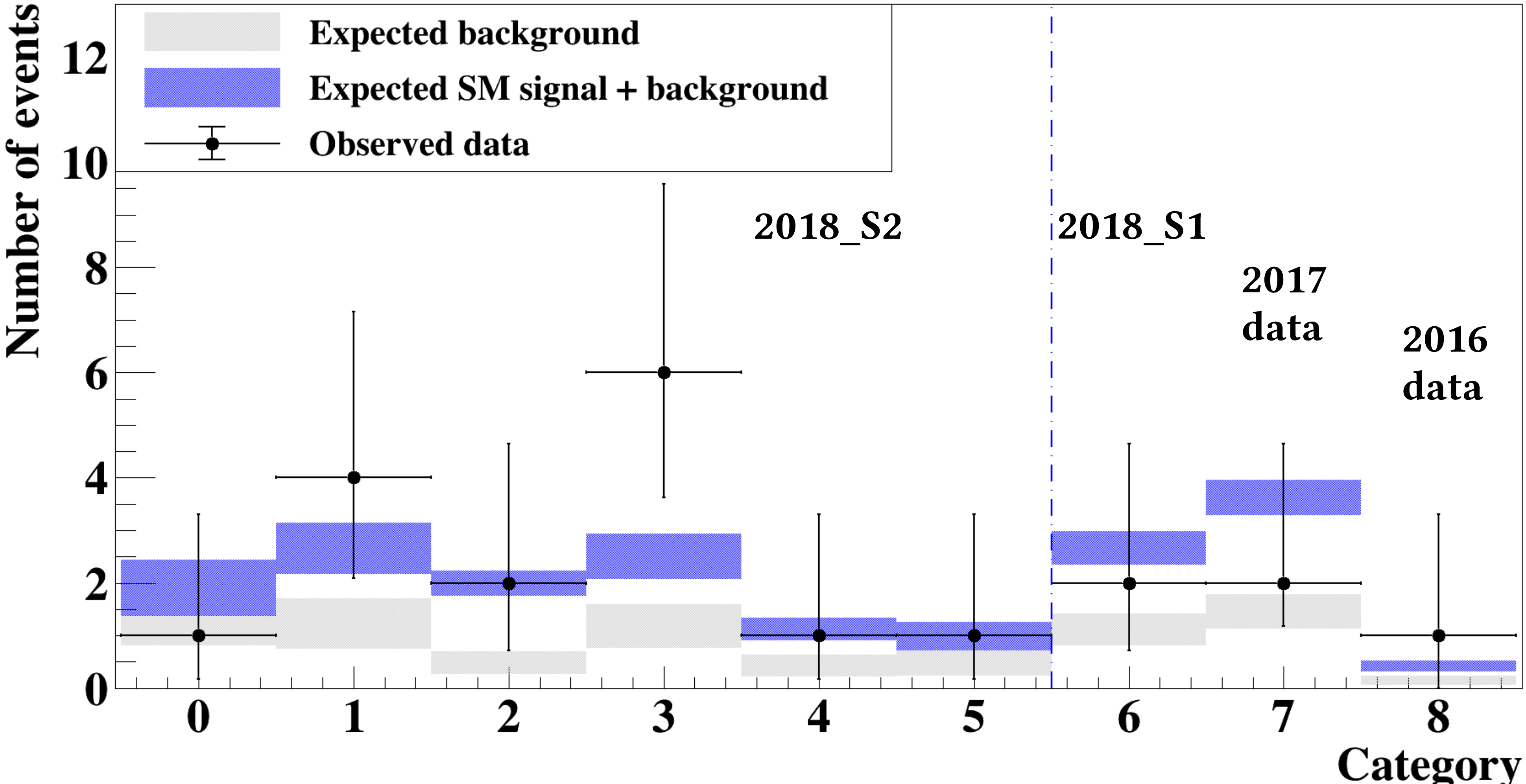




- 1 events observed
- Br($K^+ \to \pi^+\nu\nu$) < 14x10^{-10} @ 90% CL
  Phys. Lett. B 791 (2019) 156-166

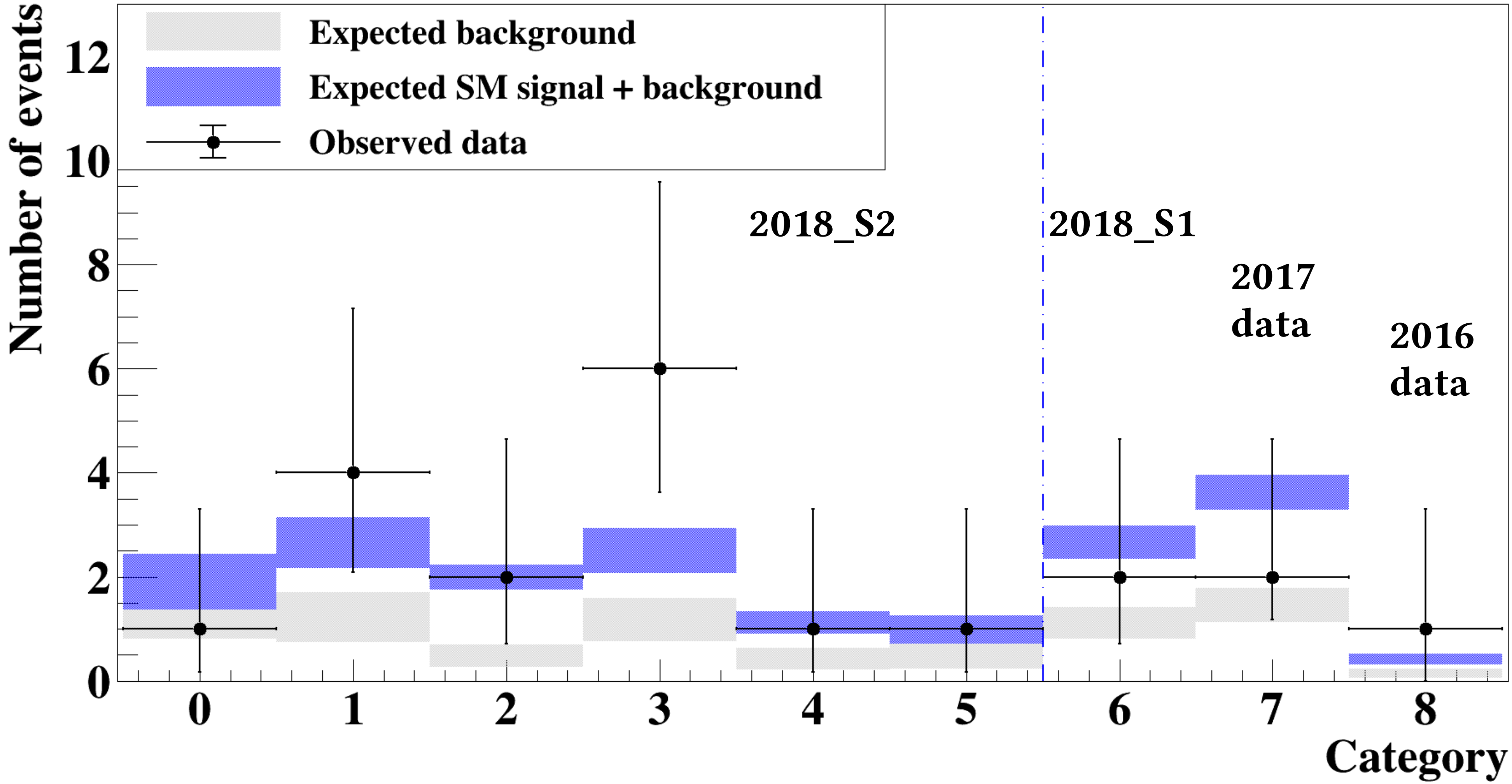
- 2 events observed
- Br($K^+ \to \pi^+\nu\nu$) < 1.78x10^{-10} @ 90% CL
  [arXiv:2007.08218 [hep-ex]](submitted to JHEP)

Branching ratio extraction



- Maximum likelihood fit using signal and background expectation in each category
- Two samples with different hardware configurations in 2018
  - 2018_S1 ~ 20% of the 2018 dataset, integrated over momentum
  - 2018_S2 ~ 80% of the 2018 dataset, 5 GeV/c wide bins from 15-45 GeV/c
  - 2016 and 2017 datasets, integrated over momentum added as separate categories

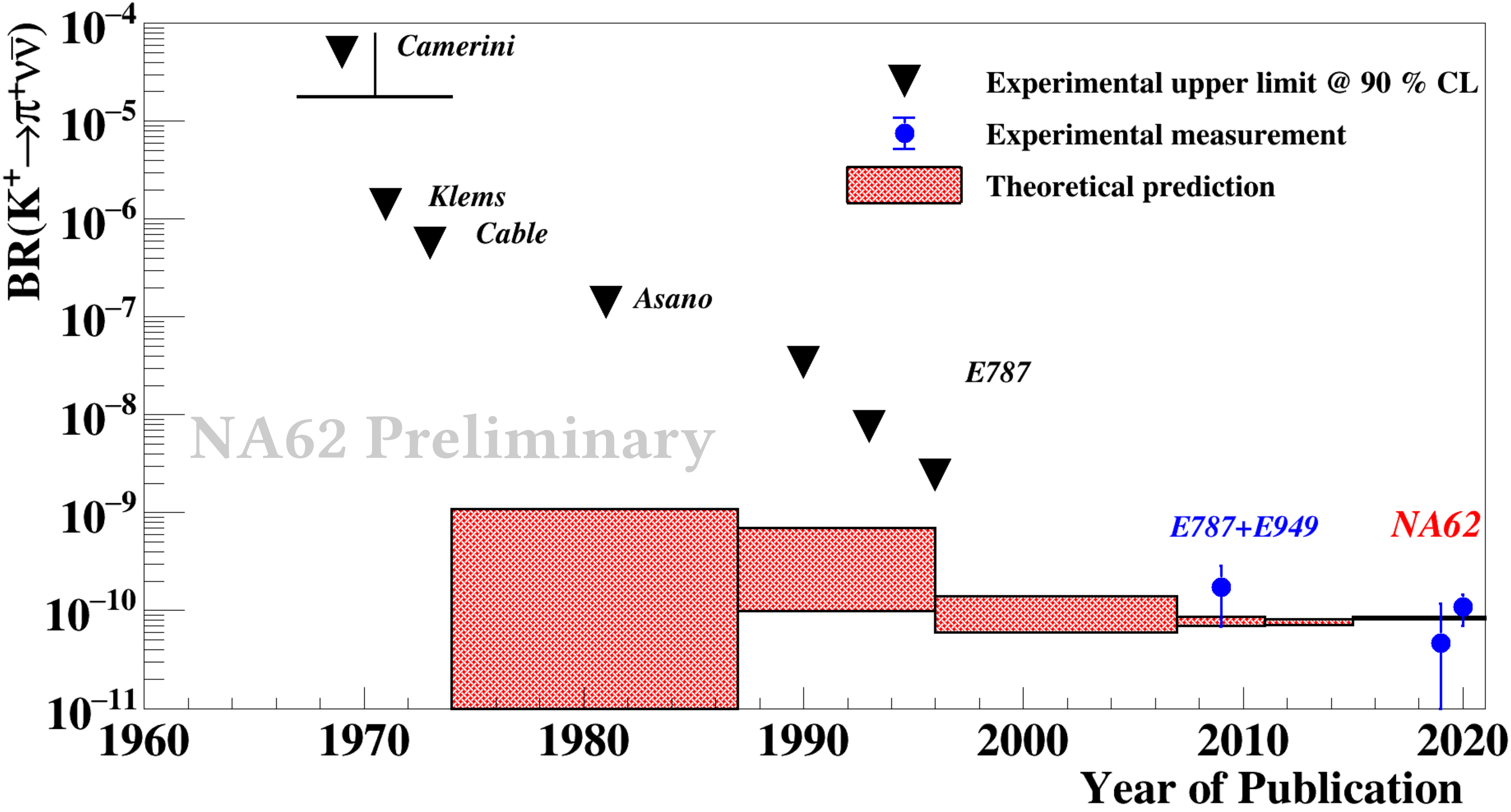
Branching ratio result



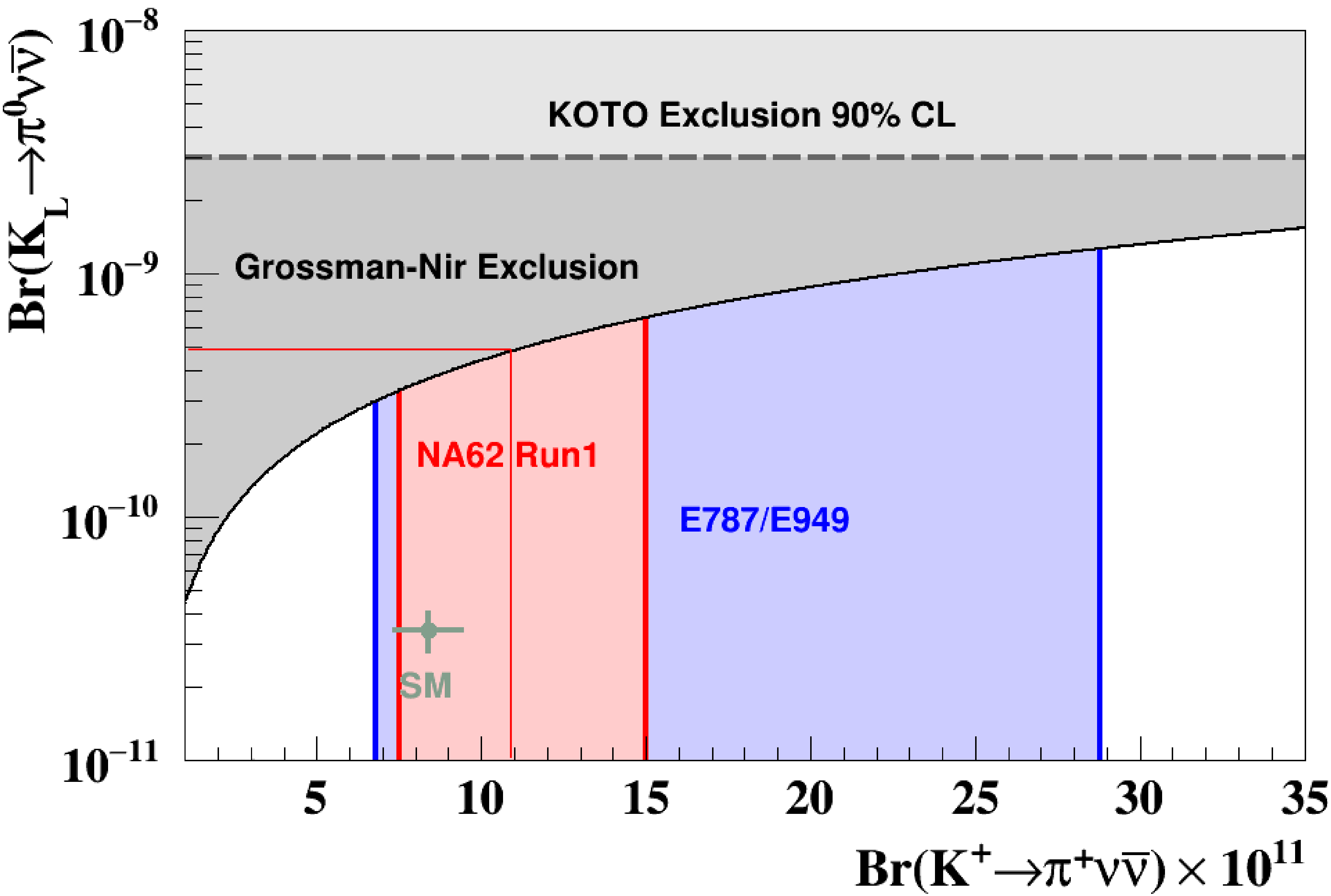
NA62 Run1(2016 + 2017 + 2018) result:

- $Br(K^+ \to \pi^+ \nu\bar{\nu}) = (11.0^{+4.0}_{-3.5}{}_{stat.} \pm 0.3_{syst.}) \times 10^{-11} (3.5\sigma \text{ significance})$

$K^+ \to \pi^+ \nu\nu$ decay: Historical context



Grossman-Nir limit

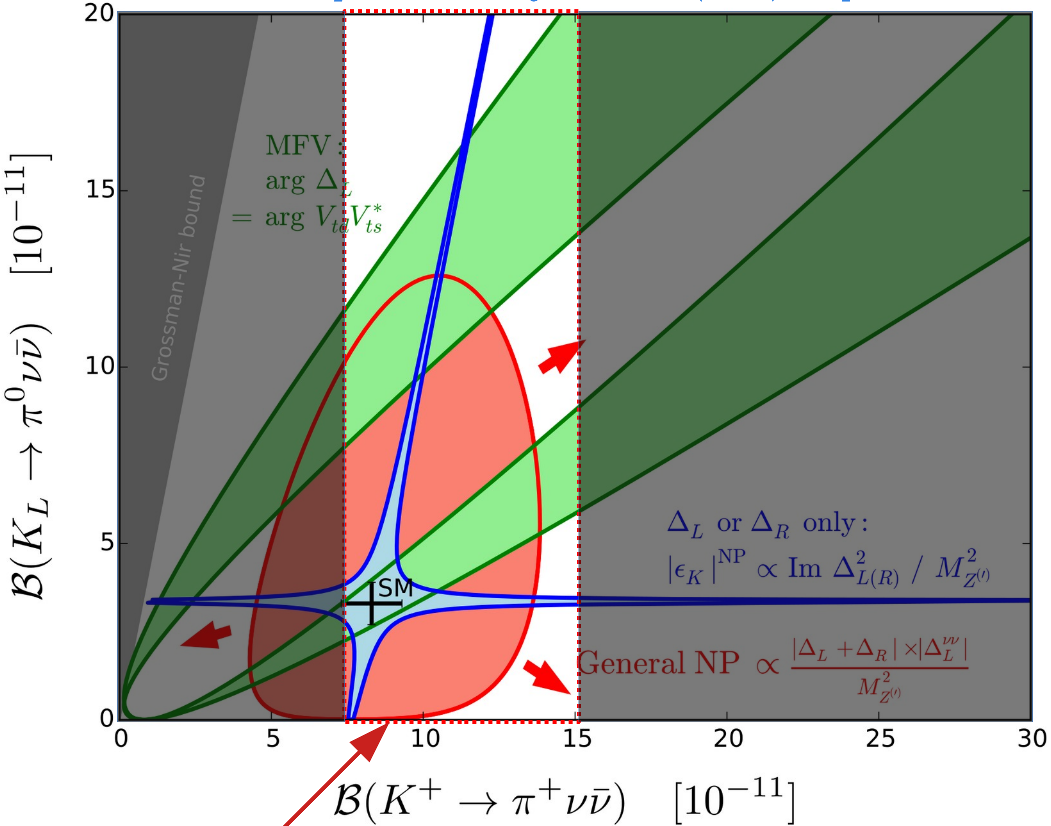


Impact in the context of BSM models

- A 30% measurement can already shrink significantly the parameter space of some NP models
- In combination with K_L and B physics will be a powerful probe of NP in the near future

Simplified models

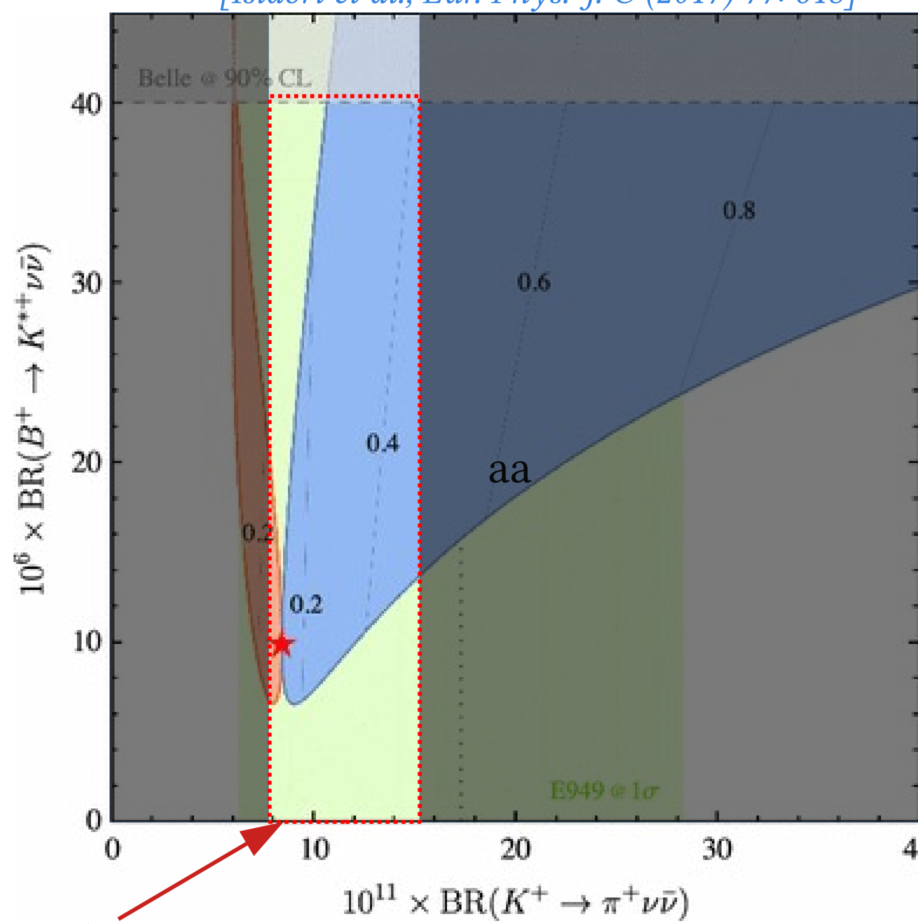
[Buras et al., JHEP 1511 (2015) 166]



NA62 measurement

LFU violation

[Isidori et al., Eur. Phys. J. C (2017) 77: 618]



NA62 measurement

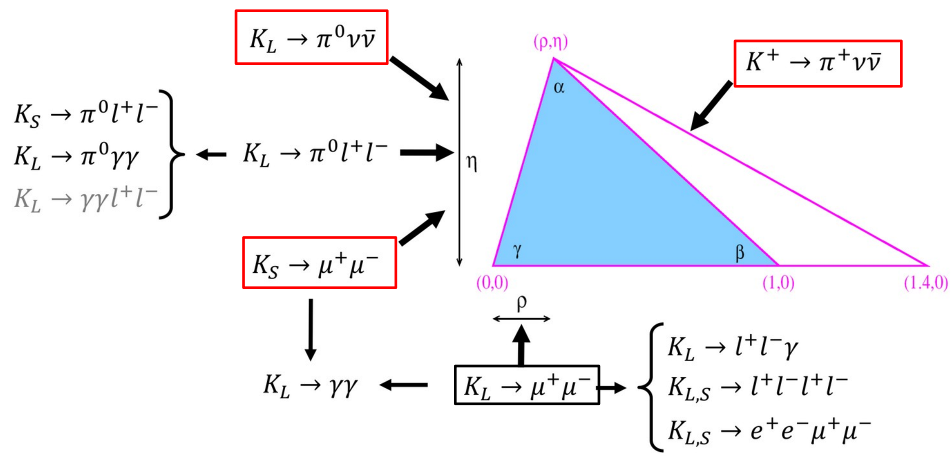
Summary and conclusions

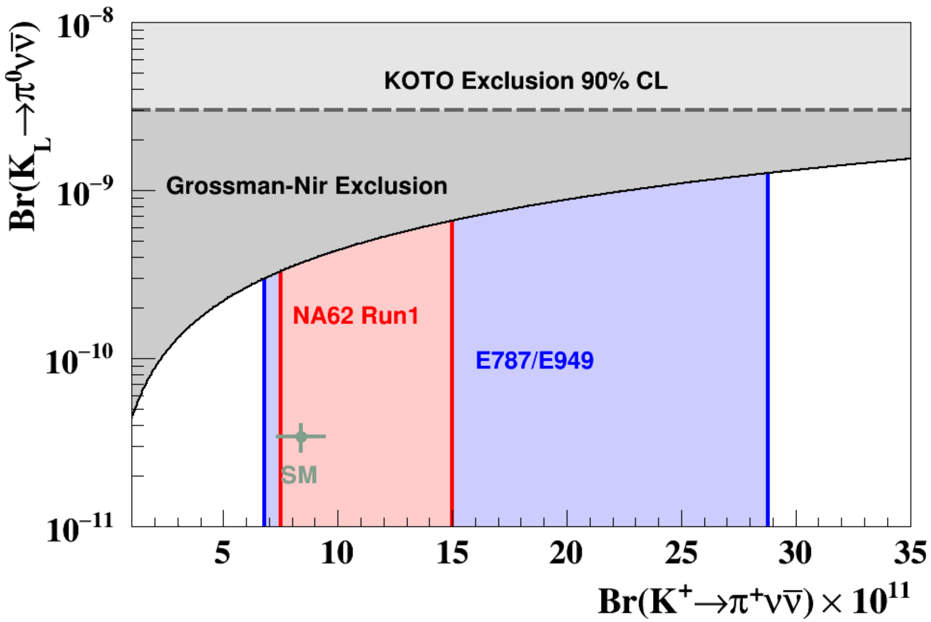
- NA62 result from the complete Run 1(2016 + 2017 + 2018)
  - Observed events: 1 (2016) + 2 (2017) + 17(2018) = 20 (Run 1)
  - Expected background ~ 0.2(2016) + 1.5(2017) + 5.3(2018) = 7 (Run 1)
  - $Br(K^+ \to \pi^+ \nu\bar{\nu}) = (11.0^{+4.0}_{-3.5}{}_{stat.} \pm 0.3_{syst.}) \times 10^{-11}$ (3.5σ significance)
  - The most precise measurement of the BR obtained so far
- The result is compatible with the SM prediction within one standard deviation

- Towards the 2021 run
  - NA62 will resume data-taking in 2021
  - Modifications of the NA62 beam line, installation of an additional beam spectrometer station and a veto counter to reduce upstream background
  - New calorimeter downstream of MUV and upstream of the beam dump to further suppress kaon decay background
  - More information can be found in the NA62 SPSC addendum

Status of the CKM matrix with kaons

- Main players: NA62 (Run 1 Preliminary), LHCb (Run1+2), KOTO (< 2020 data)





$K_L \to \pi^0 \nu\bar{\nu}$: Sensitivity $\mathcal{O}(10^{-9} \div 10^{-10})$ (KOTO)

$K^+ \to \pi^+ \nu\bar{\nu}$: 30% measurement (NA62)

$K_S \to \mu^+\mu^-$: Sensitivity $\mathcal{O}(10^{-10})$ (LHCb)

$K_S \to \pi^0 l^+ l^-$: 40% meas. (NA48/1)

$K_L \to \pi^0 \gamma\gamma$: 40% meas. (NA48, KTeV)

$K_L \to \gamma\gamma l^+ l^-$: 10% meas./SM sensitivity (μ) (KTeV)

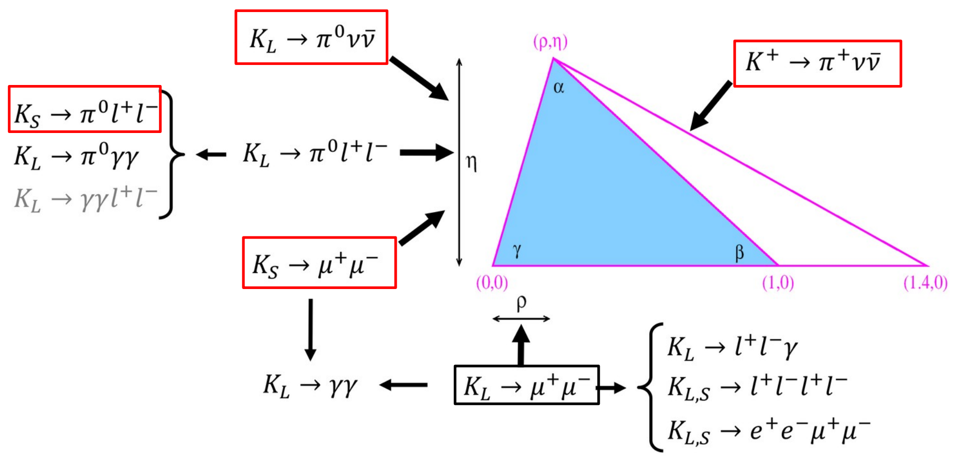
$K_L \to \gamma\gamma$: precise meas. (NA48, KLOE)

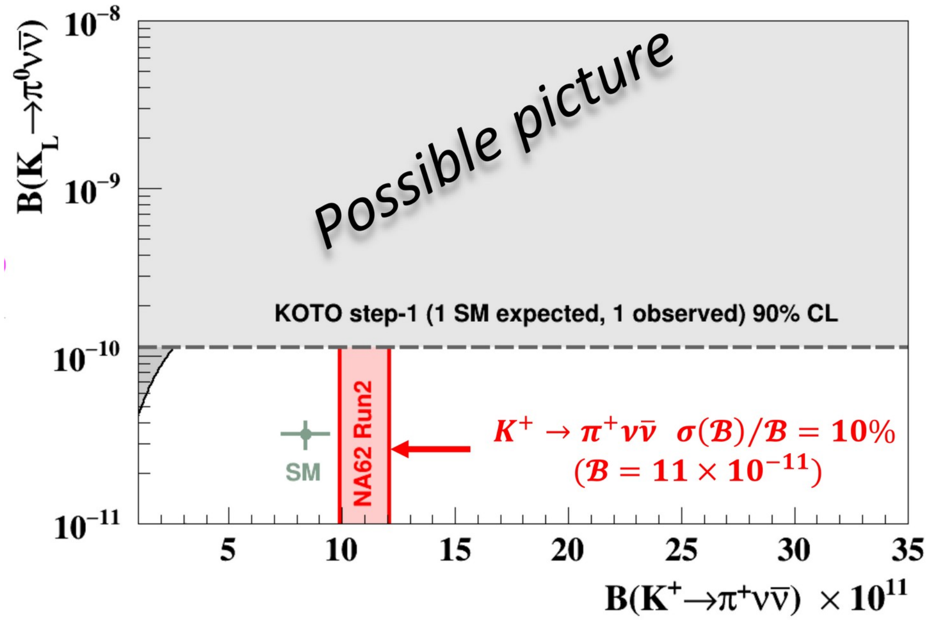
$K_L \to \mu^+\mu^-, l^+ l^- \gamma$: precise meas. (B871,KTeV,NA48,E799)

$K_L \to l^+ l^- l^+ l^-$: precise meas. (KTeV, NA48)

Future (< 2025)

- Main players: NA62 (Run 2), LHCb (Upgrade I), KOTO (Step – 1)

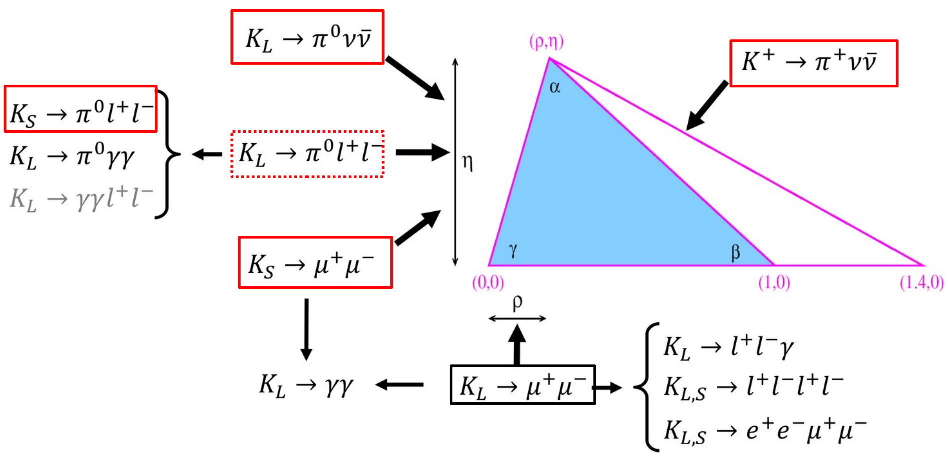


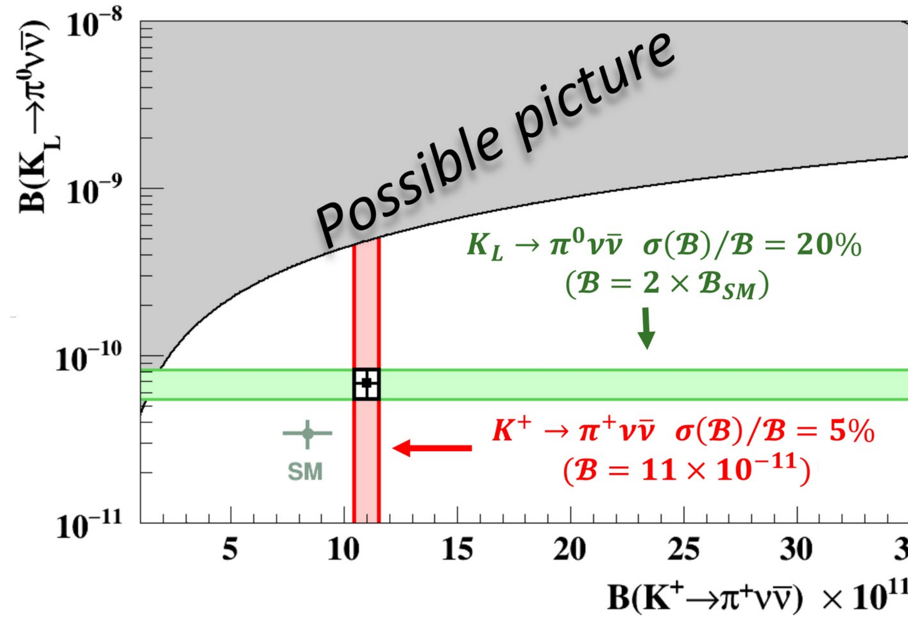


$K_L \to \pi^0 \nu\bar{\nu}$: SM Sensitivity (KOTO)
$K^+ \to \pi^+ \nu\bar{\nu}$: $\mathcal{O}(10\%)$ measurement (NA62)
$K_S \to \mu^+ \mu^-$: Sensitivity $\mathcal{O}(10^{-11})$ (LHCb)
$K_S \to \pi^0 l^+ l^-$: 20% meas. (LHCb, NA48/1)
$K_L \to \pi^0 \gamma\gamma$: 40% meas. (NA48, KTeV)
$K_L \to \gamma\gamma l^+ l^-$: 10% meas./SM sensitivity (μ) (KTeV)
$K_L \to \gamma\gamma$: precise meas. (NA48, KLOE)
$K_L \to \mu^+ \mu^-, l^+ l^- \gamma$: precise meas. (B871,KTeV,NA48,E799)
$K_L \to l^+ l^- l^+ l^-$: precise meas. (KTeV, NA48)

Future (> 2025)

- Main players: K facility @ CERN (K^+/K^0, NA62-like, Klever), LHCb (Upgrade II), KOTO (Step – 2)





- $K_L \to \pi^0 \nu\bar{\nu}$: $\mathcal{O}(20\%)$ measurement (KOTO / Klever)
- $K^+ \to \pi^+ \nu\bar{\nu}$: $\mathcal{O}(5\%)$ measurement (NA62-like)
- $K_S \to \mu^+\mu^-$: SM Sensitivity (LHCb)
- $K_S \to \pi^0 l^+ l^-$: precision meas. (LHCb, NA48/1)
- $K_L \to \pi^0 l^+ l^-$: (K Facility at CERN)
- $K_L \to \pi^0 \gamma\gamma$: 40% meas. (NA48, KTeV)
- $K_L \to \gamma\gamma l^+ l^-$: 10% meas./SM sensitivity (μ) (KTeV)
- $K_L \to \gamma\gamma$: precise meas. (NA48, KLOE)
- $K_L \to \mu^+\mu^-, l^+ l^- \gamma$: precise meas. (B871,KTeV,NA48,E799)
- $K_L \to l^+ l^- l^+ l^-$: precise meas. (KTeV, NA48)

Final remarks

- Rare kaon FCNCs are among the most sensitive probes of NP at the highest mass scales
- We see very important progress in the last years
  - NA62 reaching the 3σ evidence for $K^+ \to \pi^+ \nu\nu$
  - KOTO and LHCb pushing closer to SM sensitivity for $K_L \to \pi^0 \nu\nu$ and $K_S \to \mu^+\mu^-$
- If NP is close we may see first hints in the kaon sector within the next 5-10 years

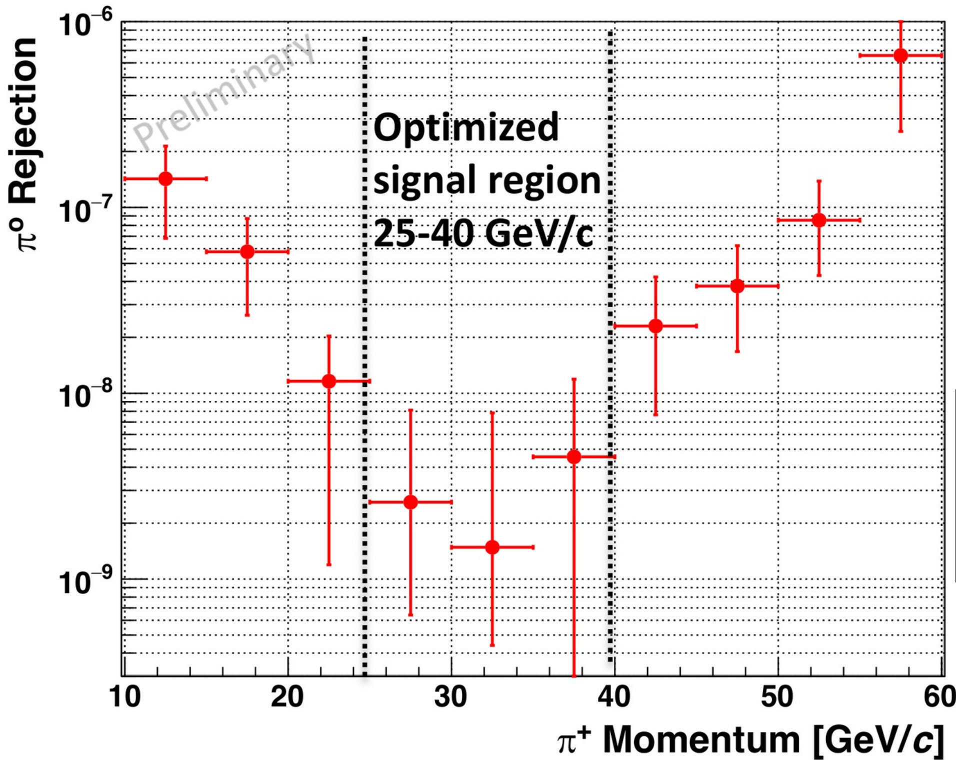
One of the most interesting decade for kaon physics is ahead of us!!!

Thank You for Your attention!

SPARE

Search for $\pi^0 \to$ invisible

- A priori evaluation of π^0 suppression of $K^+ \to \pi^+\pi^0$ decays ($0.015 < m^2_{miss} < 0.021$ GeV^2/c^4)
  - Selection and trigger stream identical to $K^+ \to \pi^+\nu\nu$ (1/3 of the 2017 data set used)
  - Single-γ detection efficiency from control $K^+ \to \pi^+\pi^0$ data (Tag & Probe)
  - π^0 suppression evaluated from convolution with MC $K^+ \to \pi^+\pi^0(\gamma)$
  - Validation: side bands with expected rejection $O(10^{-7})$ where **$\pi^0 \to$ 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($\pi^0 \to$invisible) normalized to $\pi^0 \to \gamma\gamma$
  - Expected background: 10^{+22}_{-8} events
  - Observed: 12 events

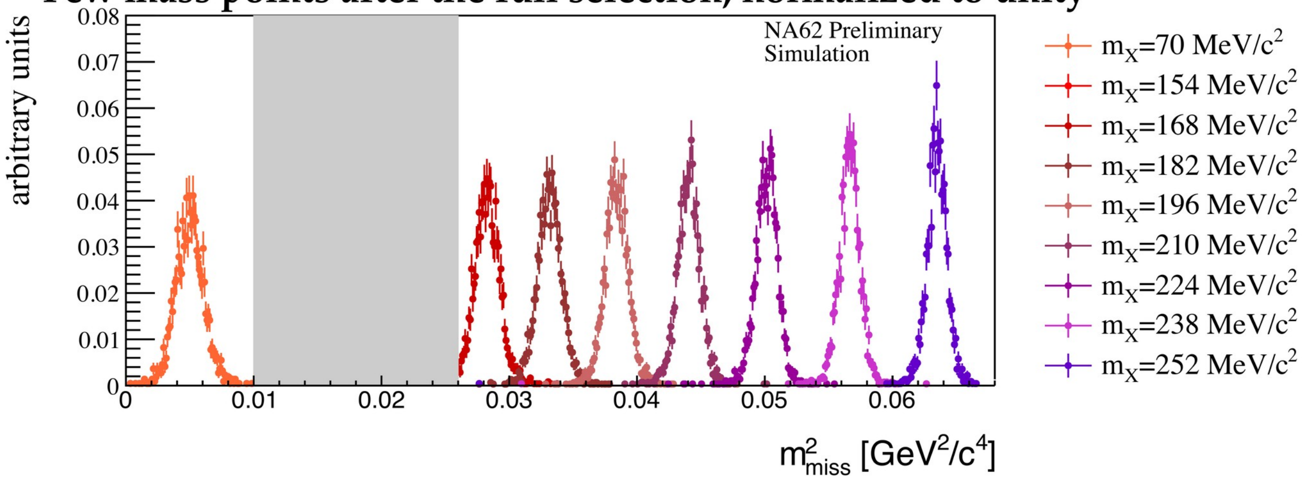
BR($\pi^0 \to$invisible) < 4.4×10^{-9} @ 90% CL

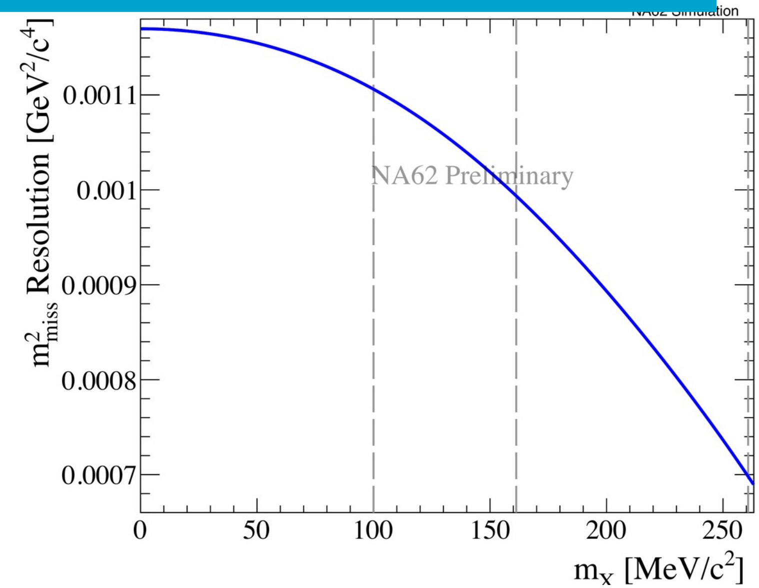
UL 60 times stronger than previous measurements
(Paper is in final stages preparation)

$K^+ \to \pi^+ X$, X invisible

- Feebly interacting new particles foreseen in several models
  - Axion-like particles (ALPs)
  - QCD axion, Axiflavon (m~0)
- By-product of the $K^+ \to \pi^+ \nu\nu$ analysis
  - Same selection, normalization and backgrounds
  - Exception: SM $K^+ \to \pi^+ \nu\nu$ decay is a background for this search
- Peak search with a sliding mass window proportional to the m^2_{miss} resolution
  - Performed inside the $K^+ \to \pi^+ \nu\nu$ signal regions
  - Gaussian shape for X

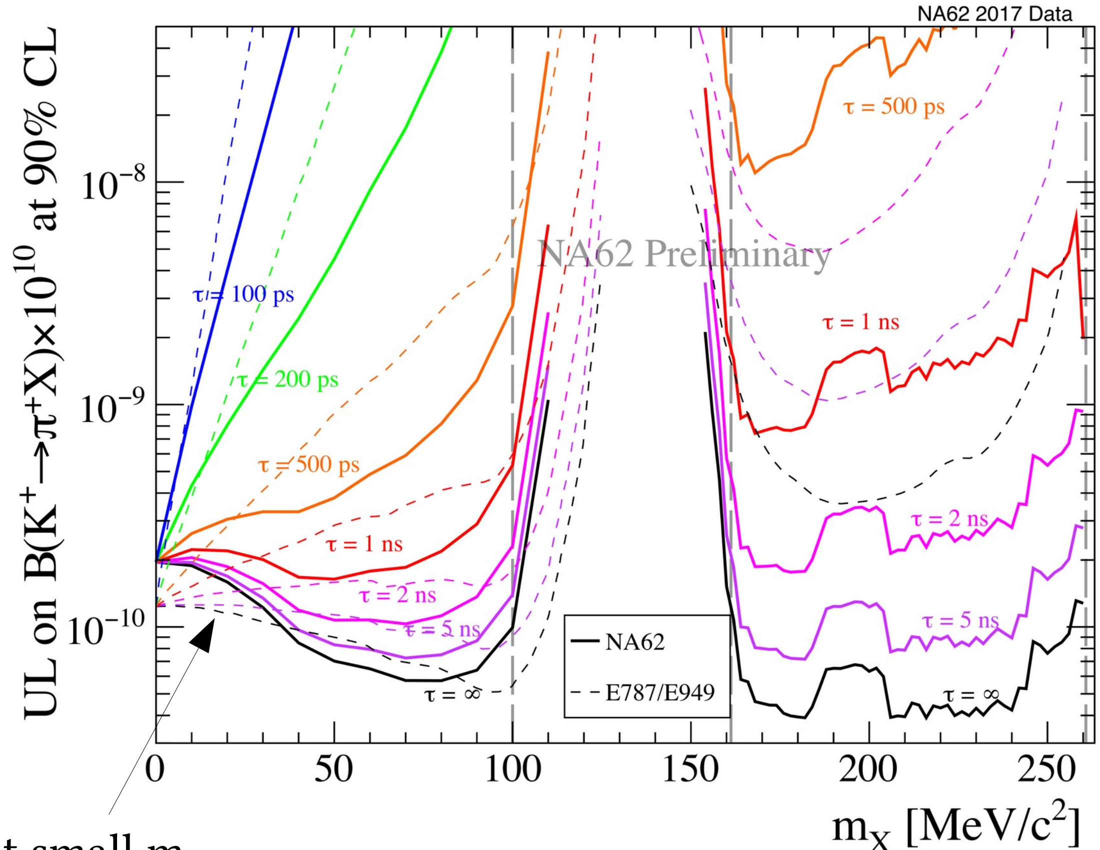
Few mass points after the full selection, normalized to unity





$K^+ \to \pi^+ X$, X decaying to SM

- X can decay to visible particles
- Comparison between NA62 and the previous best limit [E949 Collaboration, PRD 79 092004]
  - ~ Factor 10 improvement in Region 2
- Prospects with 2018 data: Improvements by ~ factor 2 expected from a dedicated analysis



Degraded sensitivity at small m_X because of resolution effects