LNF Seminar

$K^+ \rightarrow \pi^+ \nu\nu$: first NA62 results

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(**INFN Laboratori Nazionali di Frascati & CERN*)

Laboratori Nazionali di Frascati. 2018, April 18th.

Outline

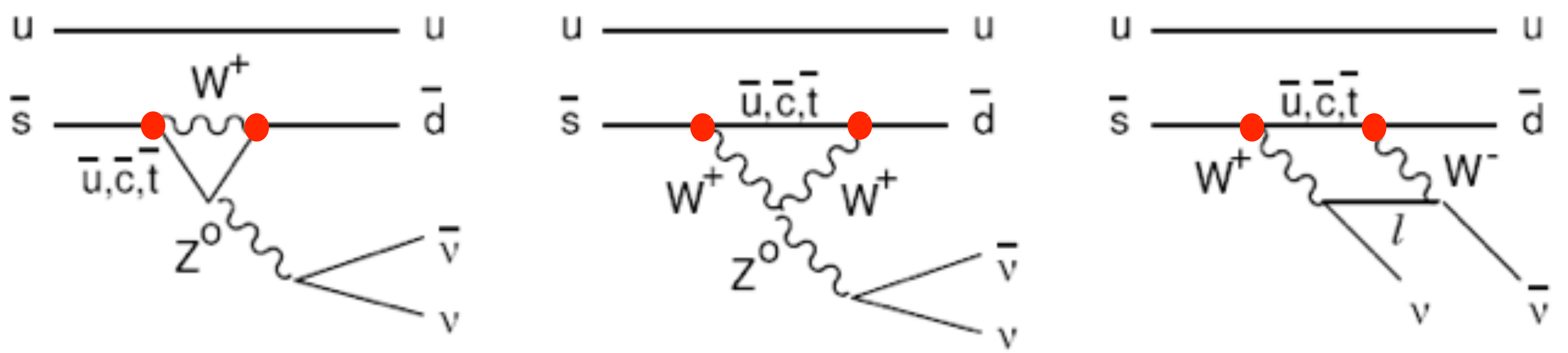
- Theoretical introduction to the $K \longrightarrow \pi\nu\nu$ rare decays
- NA62 experiment at the CERN SpS
  - Aim and strategy for the $BR(K^+ \longrightarrow \pi^+\nu\nu)$ measurement
  - Detector overview
  - Results with 2016 data
  - Prospects

SM theoretical framework

The $K^+ \rightarrow \pi^+\nu\nu$ decay is extremely suppressed

Flavor-changing neutral current quark transition $s \rightarrow d\nu\nu$.

Forbidden at tree level, dominated by short-distance dynamics (GIM mechanism)



Z-penguin   W-box

Is characterized by a theoretical cleanness in the SM prediction of the BR($K^+ \rightarrow \pi^+\nu\nu$): loops and radiative corrections are under control.

Highly suppressed & Very well predicted ▶ **Excellent laboratory complementary to LHC**

Stringent test of the SM and possible **evidence for New Physics**

Past measurement and prediction

Current theoretical prediction:

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

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

A.J. Buras, D.Buttazzo, J. Girrbach-Noe and R.Knegjens arXiv:1503.02693

- Main contribution to the errors comes from the uncertainties on the SM input parameters
- Intrinsic theoretical uncertainties (1-3%) slightly larger for the charged channel because of the corrections from lighter-quark contributions

Experimental status:

$$BR(K^+ \to \pi^+ \nu\bar{\nu})_{exp} = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$$

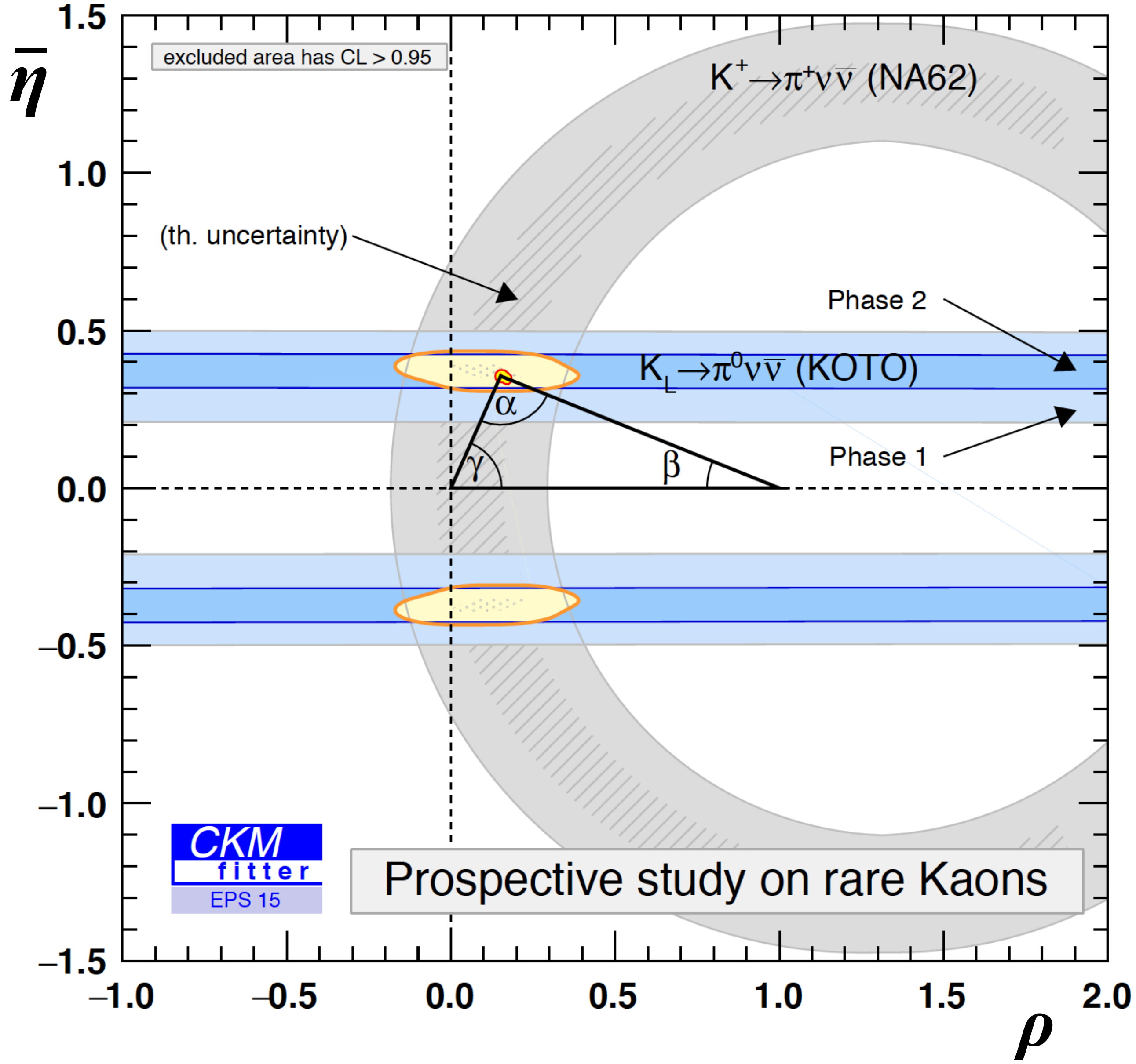
Only measurement obtained by E787 and E949 experiments at BNL with **stopped kaon decays (7 candidates)**

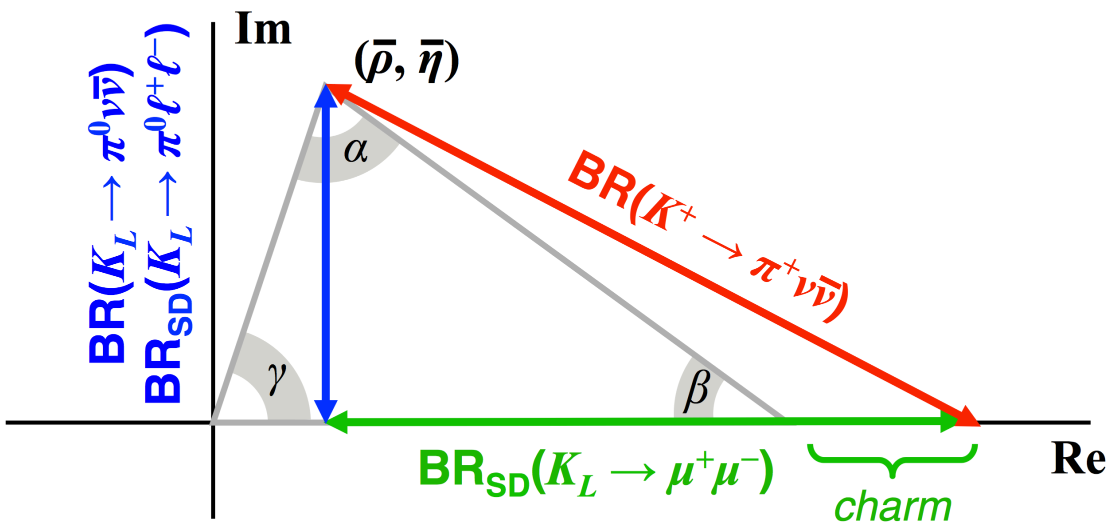
- Gap between theoretical precision and large experimental error motivates a strong experimental effort. **Significant new constraints can be obtained.**

Neutral decay $K_L \to \pi^0 \nu\nu$ has never been measured

Connection with Flavor Physics

Measurement of BR of charged ($K^+ \longrightarrow \pi^+\nu\nu$) and neutral ($K_L \longrightarrow \pi^0\nu\nu$) modes can determine the **unitarity triangle** independently from B inputs





Example of CKM constraints:

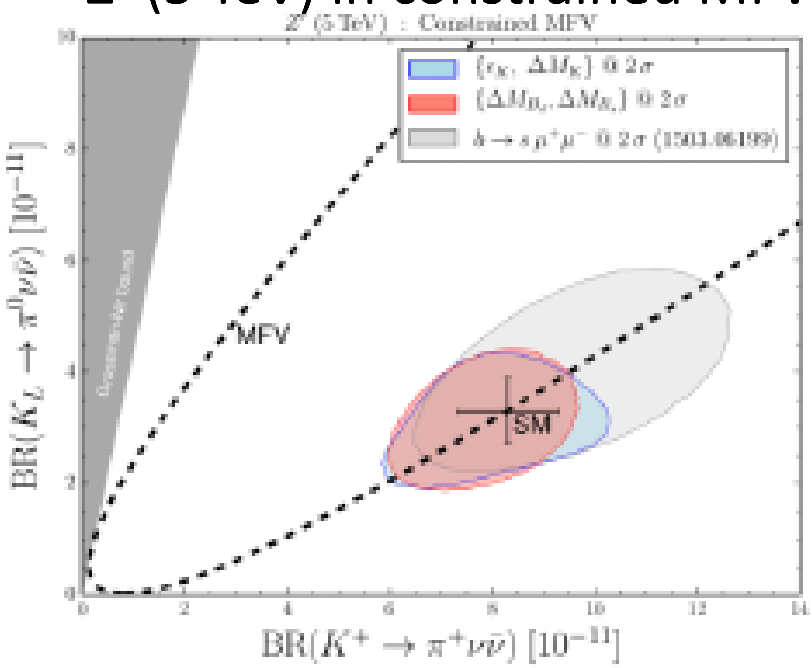
- BR($K^+ \longrightarrow \pi^+ \nu\nu$) to ±10%
- BR($K_L \longrightarrow \pi^0 \nu\nu$) to 15%

δ(BR)/BR = 10% would lead to **δ**($|V_{td}|$)/$|V_{td}|$ = 7%

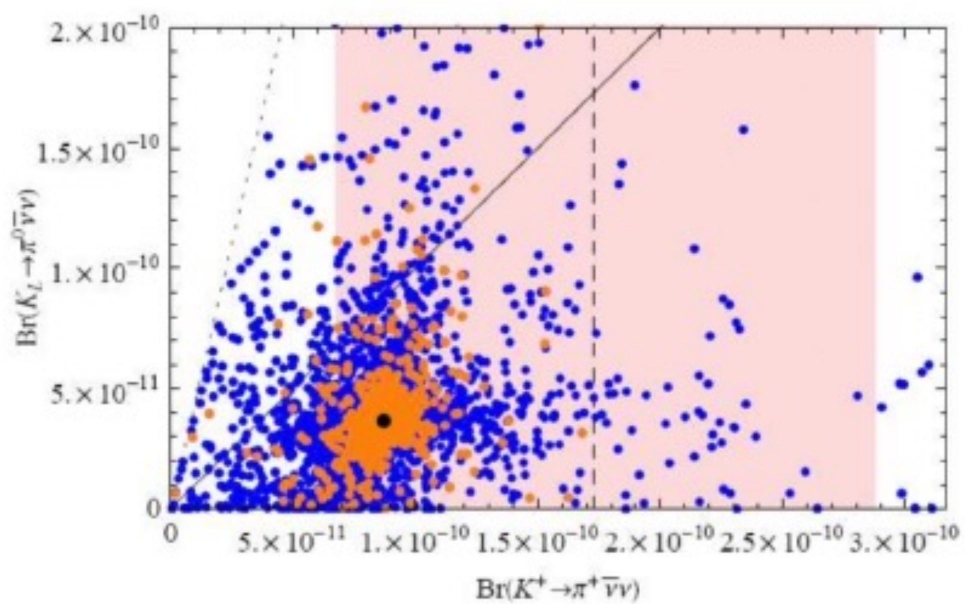
New Physics from K→πνν decays

- **Simplified Z, Z' models** [Buras, Buttazzo,Knegjens, JHEP 1511 (2015) 166]
- **Littlest Higgs with T-parity** [Blanke, Buras, Recksiegel, EPJ C76 (2016) no.4 182]
- **Custodial Randall-Sundrum** [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- **MSSM non-MFV** [Tanimoto, Yamamoto, PTEP 2016 (2016) no.12, 123B02; Blazek, Matak, IntlJModPhys.A 29 (2014), 1450162; Isidori et al. JHEP 0608 (2006) 064]
- **LFU violation models** [Isidori et. al., Eur. Phys. J. C (2017) 77]
- **Constraints from existing measurements** (correlations model dependent)

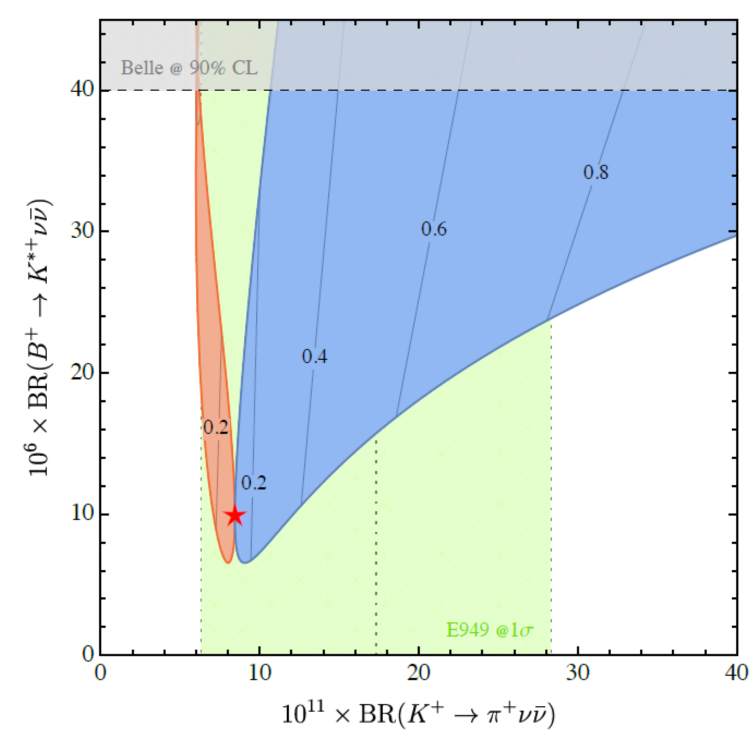
Z' (5 TeV) in constrained MFV



Randall-Sundrum



LFU violation



New Physics from K⟶πνν decays

$K \to \pi\nu\nu$ is uniquely sensitive to high mass scales.

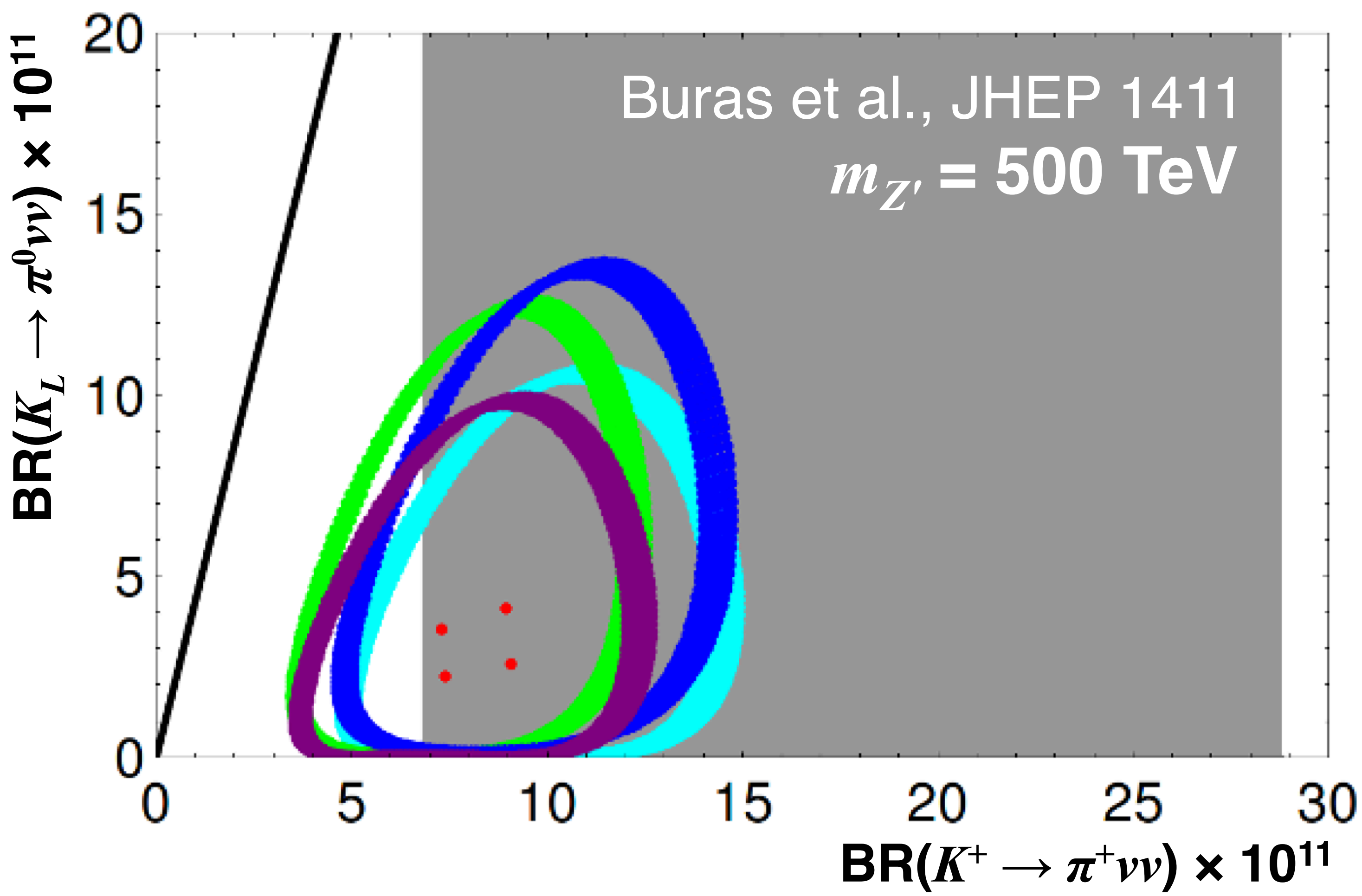
NP may simply occur at a higher mass scale

⟶ Null results from direct searches at LHC so far

Indirect probes to explore high mass scales become very interesting!

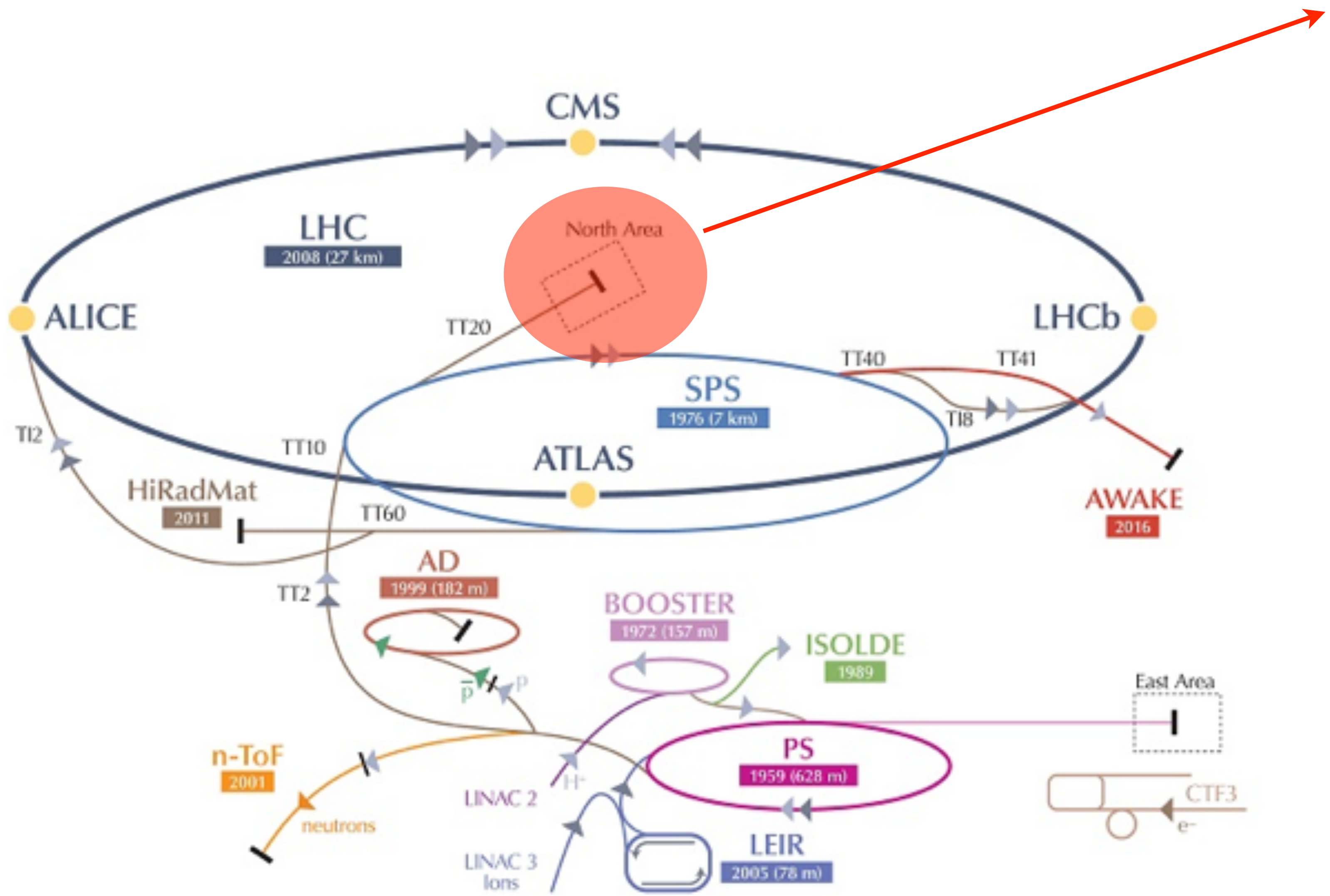
Es: Tree-level flavor changing Z′ LH+RH couplings

- Some fine-tuning around constraint from ε_K
- K ⟶ πνν sensitive to mass scales up to 2000 TeV (up to tens of TeV even if LH couplings only)
- Order of magnitude higher than for B decays



Kaon at CERN SPS

The **CERN-SPS secondary beam line** already used for the NA48 experiment can deliver the required K^+ intensity



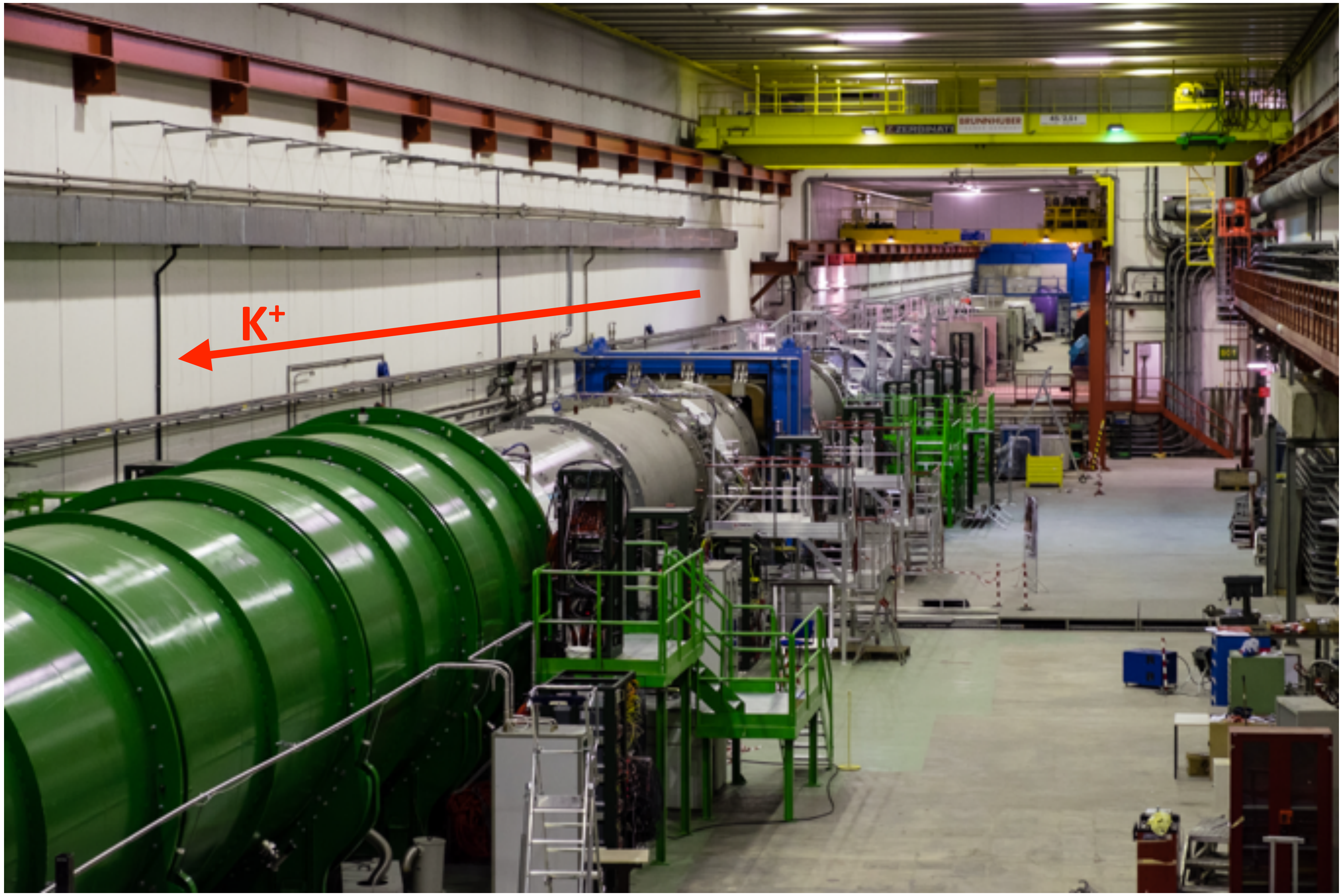
In the North Area the SpS extraction line is providing a secondary charged hadron beam

- 400 GeV/c primary proton beam
- 3×10^{12} protons/pulse
- 40 cm beryllium target
- **75 GeV/c** unseparated hadrons beam: **π^+, K^+ (6%), protons** ($\Delta p/p \pm 1\%$)
- 4.8×10^{12} K^+ decays/year

NA62 Experiment

NA62 Apparatus

270 m long downstream of the beryllium target.
Useful K^+ decays are detected in a **65 m long fiducial volume**.



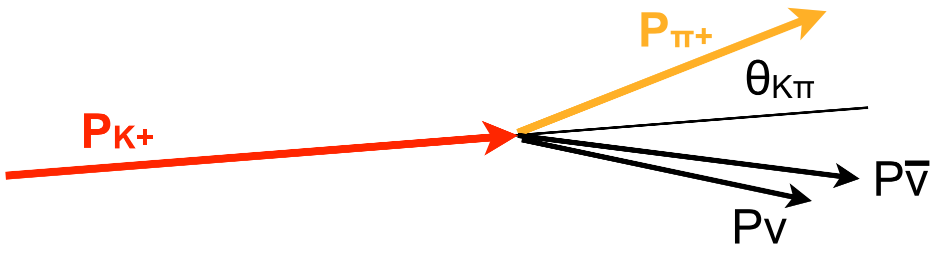
Approximately cylindrical shape around the beam axis for the main detectors.
Diameter varies from 20 to 400 cm.

Each detector sends ~ 10 MHz of raw input data to the Level 0 trigger (FPGA) that selects 1 MHz of events. L1 and L2 triggers (software) guarantee a maximum of 10 kHz of acquisition rate.

NA62 Goal

Design criteria: **kaon intensity, signal acceptance, background suppression**

Kaons with high momentum.
Decay in flight technique.
Signal signature: **K^+ track** + **π^+ track**



Backgrounds

Decay	BR	Main Rejection Tools
$K^+ \to \mu^+\nu_\mu(\gamma)$	63%	μ-ID + kinematics
$K^+ \to \pi^+\pi^0(\gamma)$	21%	γ-veto + kinematics
$K^+ \to \pi^+\pi^+\pi^-$	6%	multi-track + kinematics
$K^+ \to \pi^+\pi^0\pi^0$	2%	γ-veto + kinematics
$K^+ \to \pi^0 e^+\nu_e$	5%	e-ID + γ-veto
$K^+ \to \pi^0\mu^+\nu_\mu$	3%	μ-ID + γ-veto

Keystones

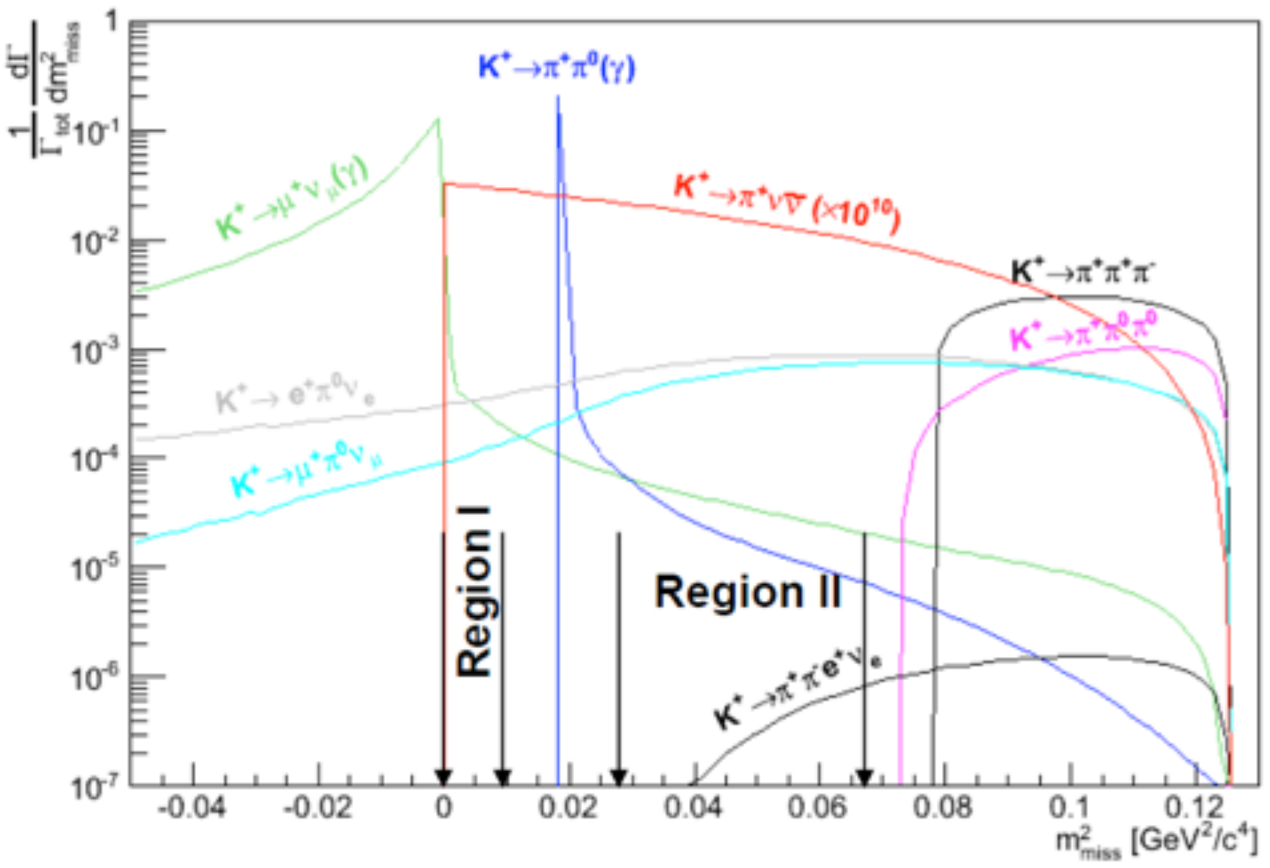
- O(100 ps) Timing between sub-detectors
- O(10^4) Background suppression from kinematics
- O(10^7) μ-suppression ($K^+ \to \mu^+\nu$)
- O(10^7) γ-suppression (from $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\gamma$)

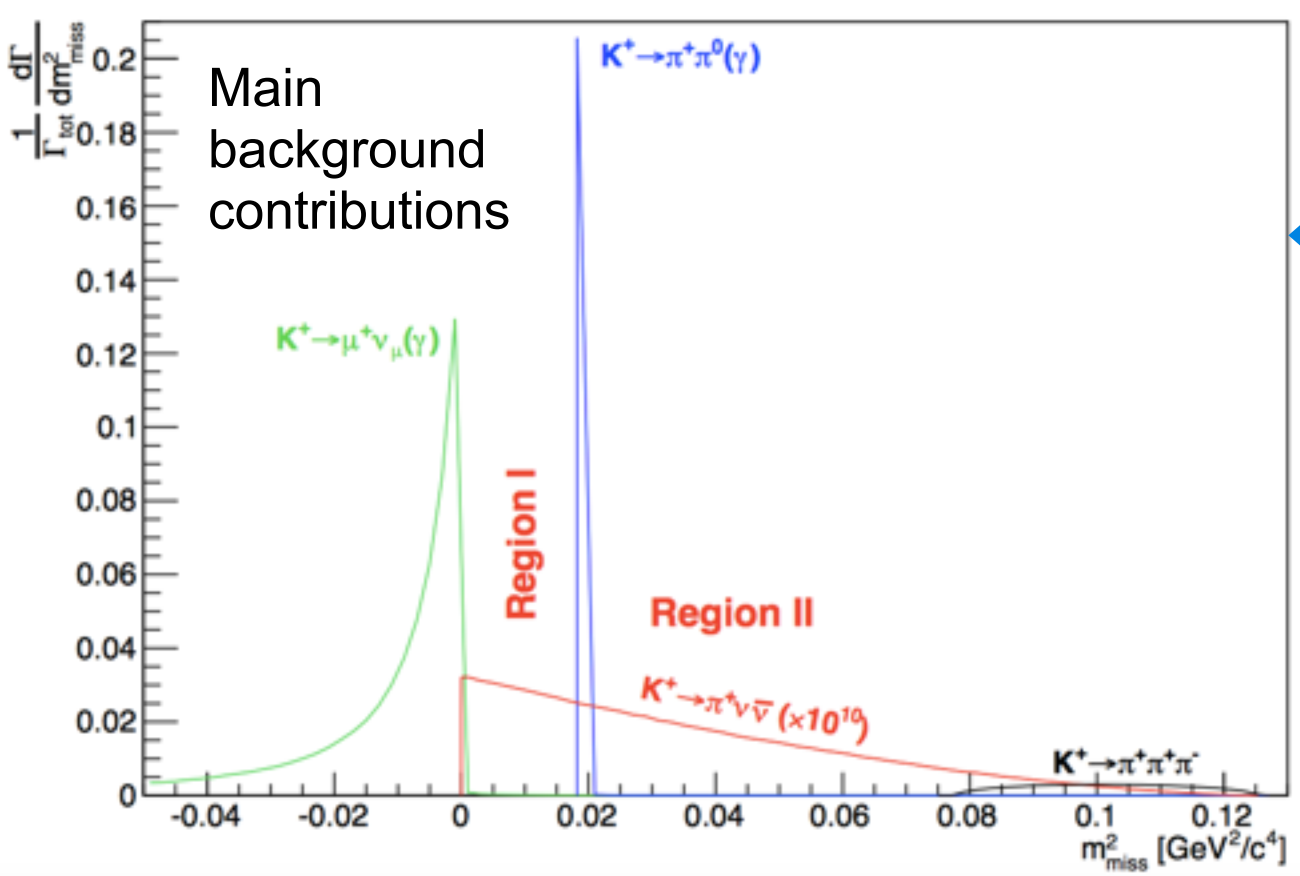
Analysis Strategy

Most discriminating variable:
$\mathbf{m^2_{miss} = (P_{K+} - P_{\pi+})^2}$

Where the daughter charged particle is assumed to be a pion

Theoretical m^2_{miss} distribution for signal and backgrounds of the main K^+ decay modes: (signal is multiplied by a factor 10^{10}).





2 signal regions, on each side of the $K^+ \to \pi^+\pi^0$ peak (to eliminate 92% of the K^+ width)

Main background sources:

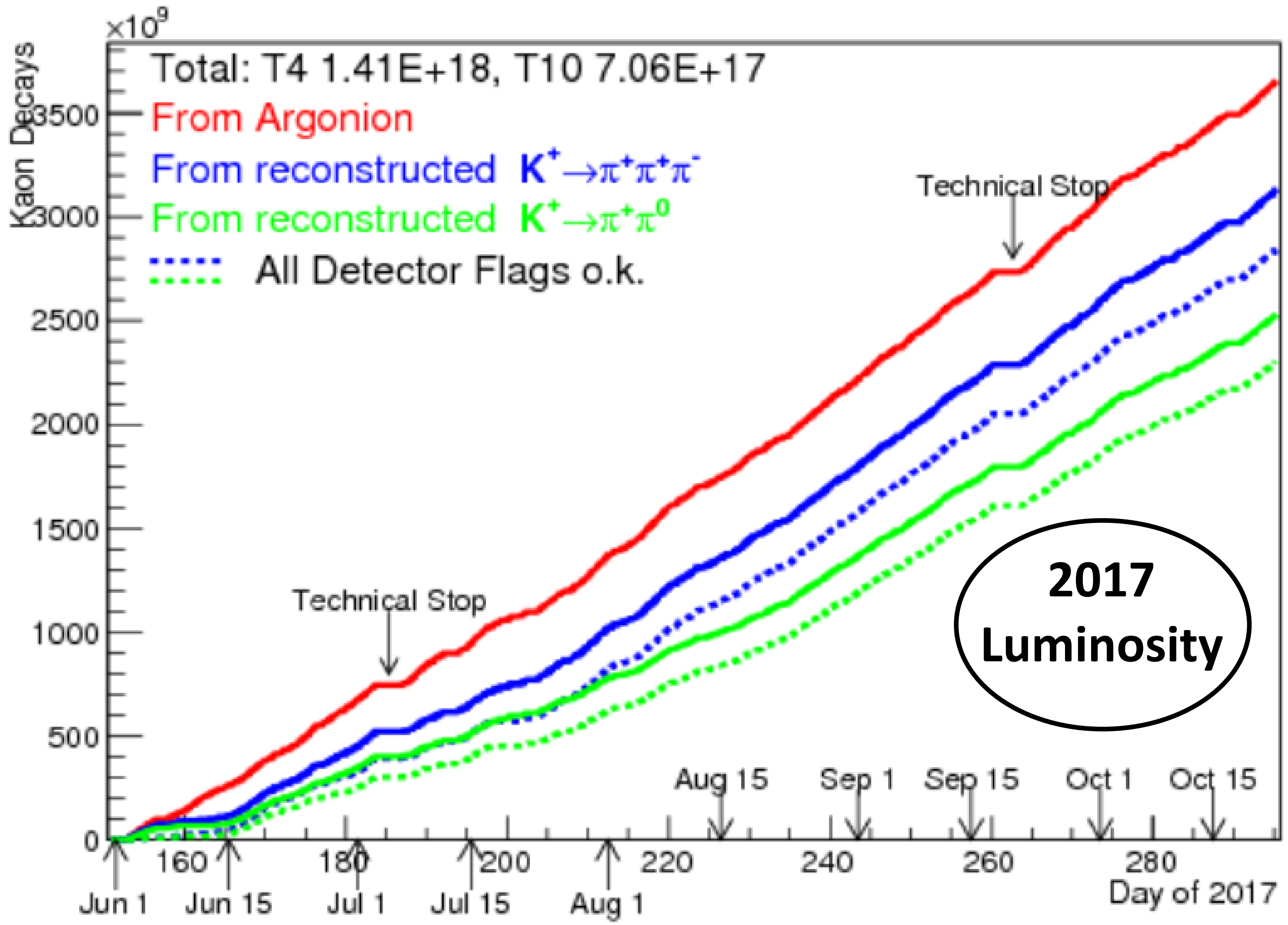
- $K^+ \to \pi^+\pi^0$, $K^+ \to \mu^+\nu$ non gaussian resolution and radiative tails
- $K^+ \to \pi^+\pi^+\pi^-$ non gaussian resolution tails
- decays with neutrino in final state

NA62 Timescale

2014	2015	2016	2017	2018	2019-2020
Pilot Run	Commissioning	Commissioning + Physics Run	Physics Run	Physics Run (ongoing)	LS2 Long shutdown 2

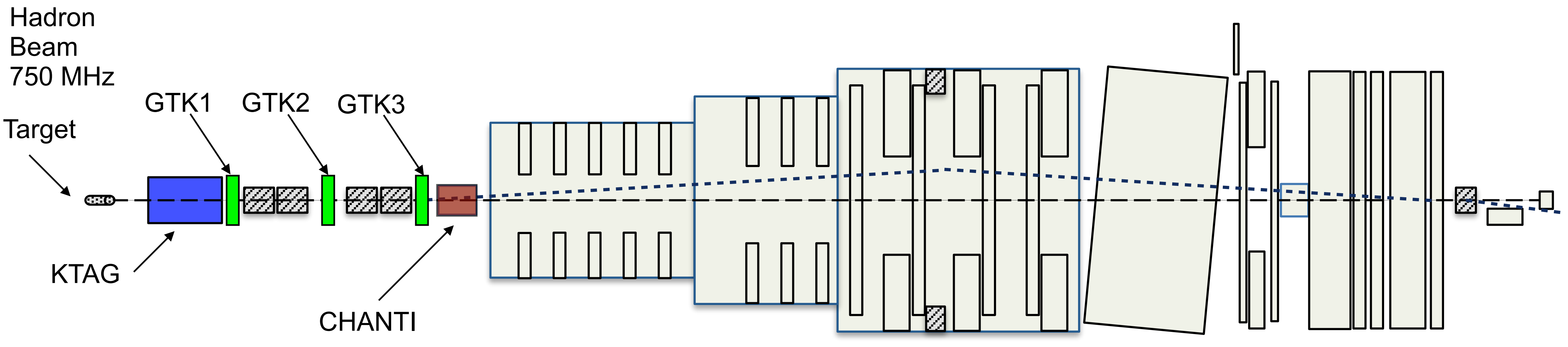
2016: 40% of nominal intensity: 13 x 10^{11} proton on target ~ **1 x 10^{11} K^+ decays useful for πνν**

2017: 60% of nominal intensity: 20 x 10^{11} proton on target **> 3 x 10^{12} K^+ decays collected**



beam fluctuations reduced

NA62: Beam ID & Tracking



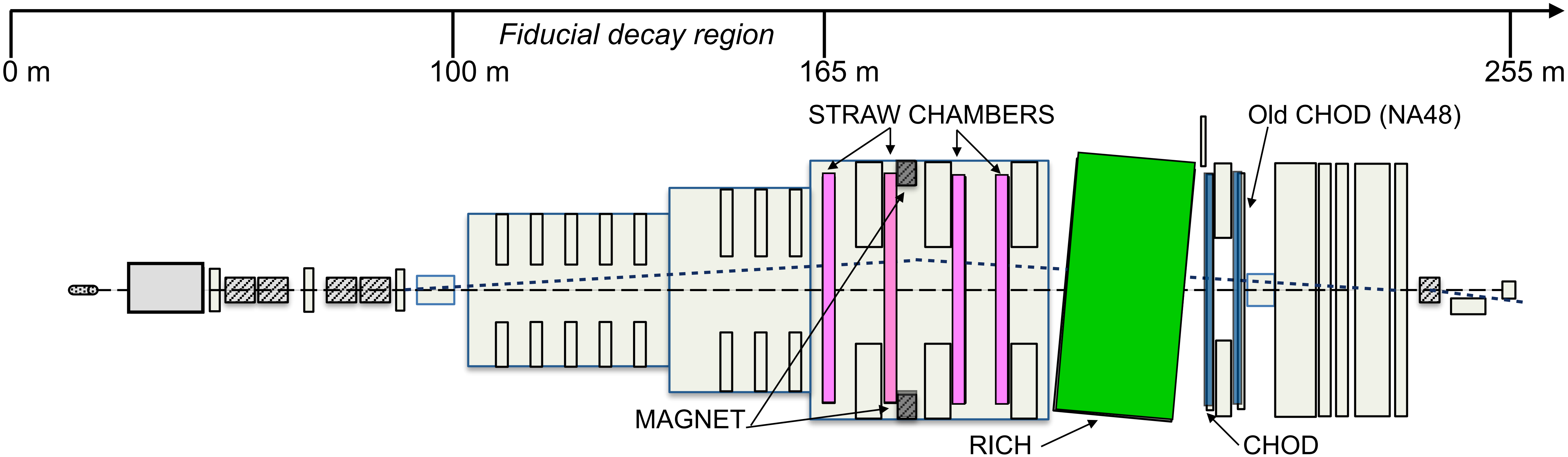
Beam ID & Tracking

KTAG: Differential Čerenkov counter blind to all particles but kaons of appropriate momentum (75 GeV, K+ rate:~45MHz). **σ_t ~70 ps, efficiency > 99%.**
Steel vessel, 4.5 m long, filled with compressed nitrogen.

GTK: GigaTracKer Spectrometer for K^+ momentum and timing measurement.
σ_t ~100 ps, $\sigma_{dx,dy} \approx 0.016$ mrad, $\Delta P/P < 0.4\%$.
750 MHz beam environment. 3 stations of 18000 silicon pixels (140 KHz/pixel).

CHANTI: Charged particle veto to reduce the background induced by inelastic interactions.
6 stations of X-Y plastic scintillator bars coupled with optical fibers. **Efficiency > 99%.**

NA62: Secondary ID & Tracking



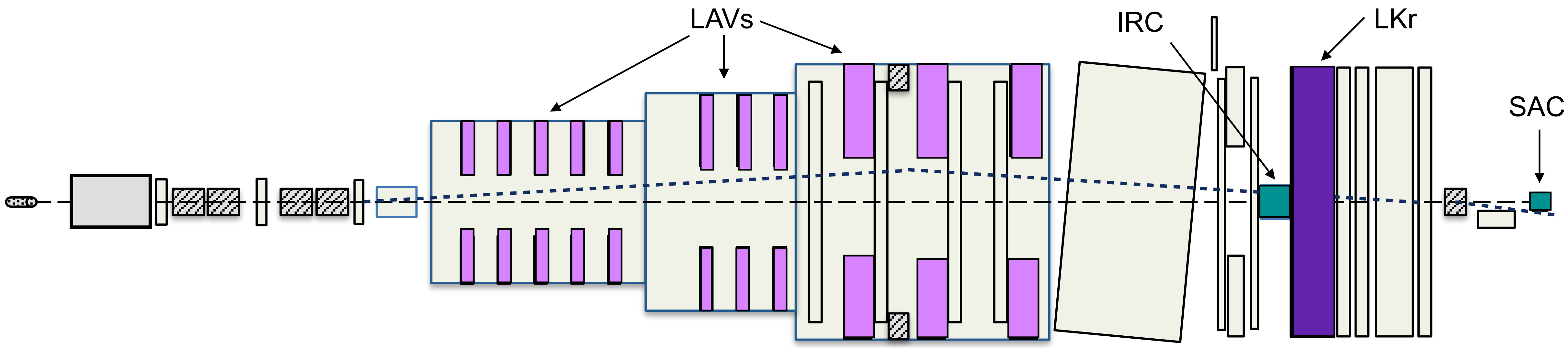
Secondary particle ID & Tracking

STRAW: Spectrometer with STRAW tubes for secondary particle momentum measurement. *4 chambers (4 layers < 0.5 X_0) in vacuum, 7168 STRAW tubes. Magnet provides a 270 MeV/c momentum kick in the horizontal plane.* **σ_t ~ 6 ns, $\sigma_{dx,dy}$ ~130 μm.**

CHOD: Charged Hodoscope of *plastic scintillator* to provide fast signal of the beam. **Old CHOD σ_t ~ 250 ns, CHOD σ_t ~ 1 ns**

RICH: Ring Imaging Cherenkov detector for the secondary particle identification. *17 m long tank. Neon gas (1 atm). Downstream: mosaic of 20 spherical mirrors. Upstream: ~2000 PMTs.* ***μ/π separation ~ 10^{-2}, σ_t of a ring < 100 ps***

NA62: Photon Veto System



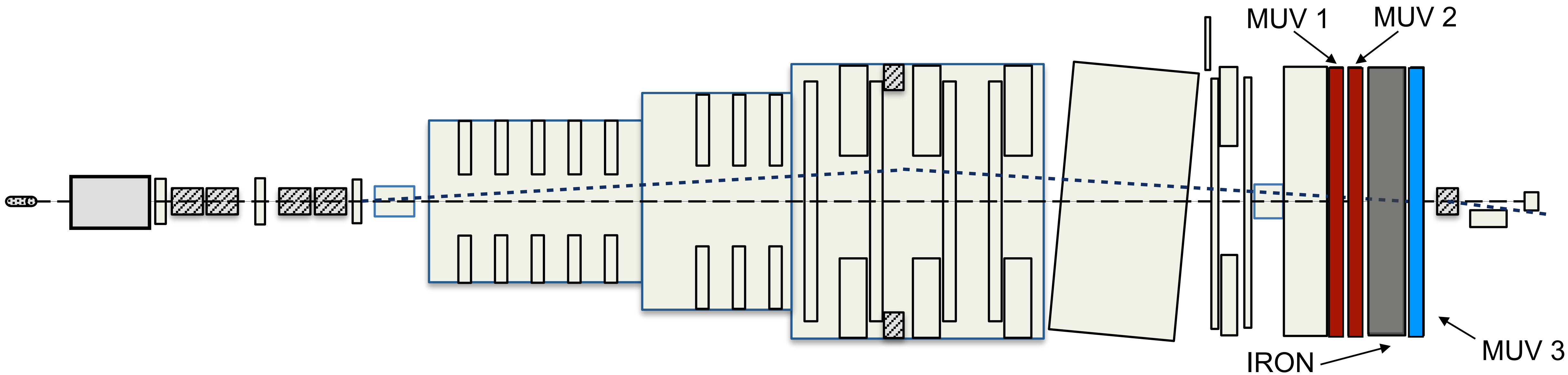
Photon Veto

LAV: Large Angle Veto. 12 stations to veto γ with angles 8.5 <θ <50 mrad.
4 or 5 rings of lead glass crystals read out by PMTs. First 11 stations are in vacuum.
σ_t ~ 1 ns, 10^{-3} to 10^{-5} inefficiency (on γ down to 150 MeV).

IRC/SAC: Inner Ring Calorimeter and Small Angle Calorimeter. To veto γ with angles <1 mrad.
Shashlik calorimeters. Lead and plastic scintillator plates. **σ_t < 1 ns, 10^{-4} inefficiency.**

LKr: NA48 LKr Calorimeter: to veto γ with angles 1 <θ <8.5 mrad and for PID.
Ionization chamber + liquid Krypton, 2x2 cm2 cells. **σ_t~500 ps ($E_{clusters}$ > 3 GeV), σ_t~1 ns (hadronic and MIP clusters), $\sigma_{dx,dy}$ ~1 mm, 10^{-5} inefficiency ($E\gamma$ > 10 GeV).**

NA62: Muon Veto System



Muon Veto

MUV3: Efficient fast Muon Veto (reduction factor > 10) used in the hardware trigger level.
Placed after an iron wall. 1 plane of 148 5cm thick scintillator tiles. Muon Rate: 10 MHz.
σ_t ~500 ps, efficiency ~99.5%

MUV1/2: Hadronic calorimeters for the μ/π separation.
2 modules of iron-scintillator plate sandwiches. Readout with LKr electronics.
Cluster reco at ~20 ns from T_{track}, and at ±150 mm from the expected impact point

2016 Data

First data declared good for πνν. 4 weeks of Data taking. < **60'000 good spills**

Trigger streams

PNN Trigger

Hardware L0: RICH, CHOD, MUV3 (Veto), LKr (E < 20 GeV).

Software L1: KTAG, LAV (Veto), STRAW (momentum < 50 GeV/c).

Control Trigger

Hardware L0: CHOD

Offline Analysis

Data Sample

$K^+ \rightarrow \pi^+\pi^0$, $K^+ \rightarrow \mu^+\nu$, $K^+ \rightarrow \pi^+\pi^+\pi^-$ samples for background estimation

- Bad data based on detector performances identified on spill by spill basis
- Signal selection tuned on MC, 10% PNN data, control data
- The analysis is mostly cut based

Blind analysis procedure: signal and control regions kept masked for the whole analysis

Analysis steps

- Selection
- Evaluation of the single event sensitivity
- Background estimation and validation
- Un-blinding of signal regions and interpretation of the results

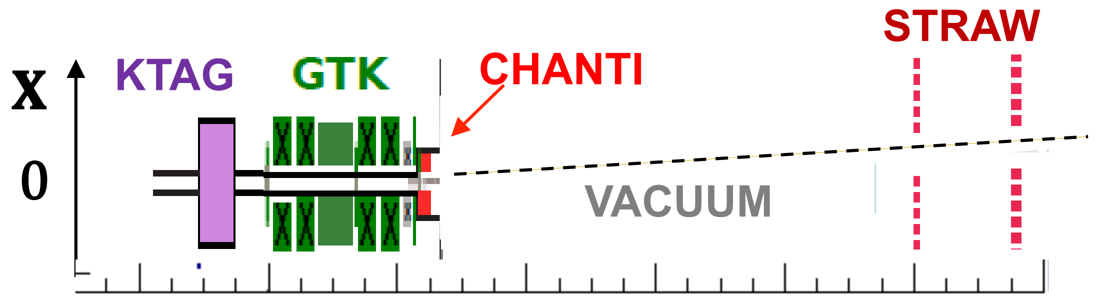
Analysis steps

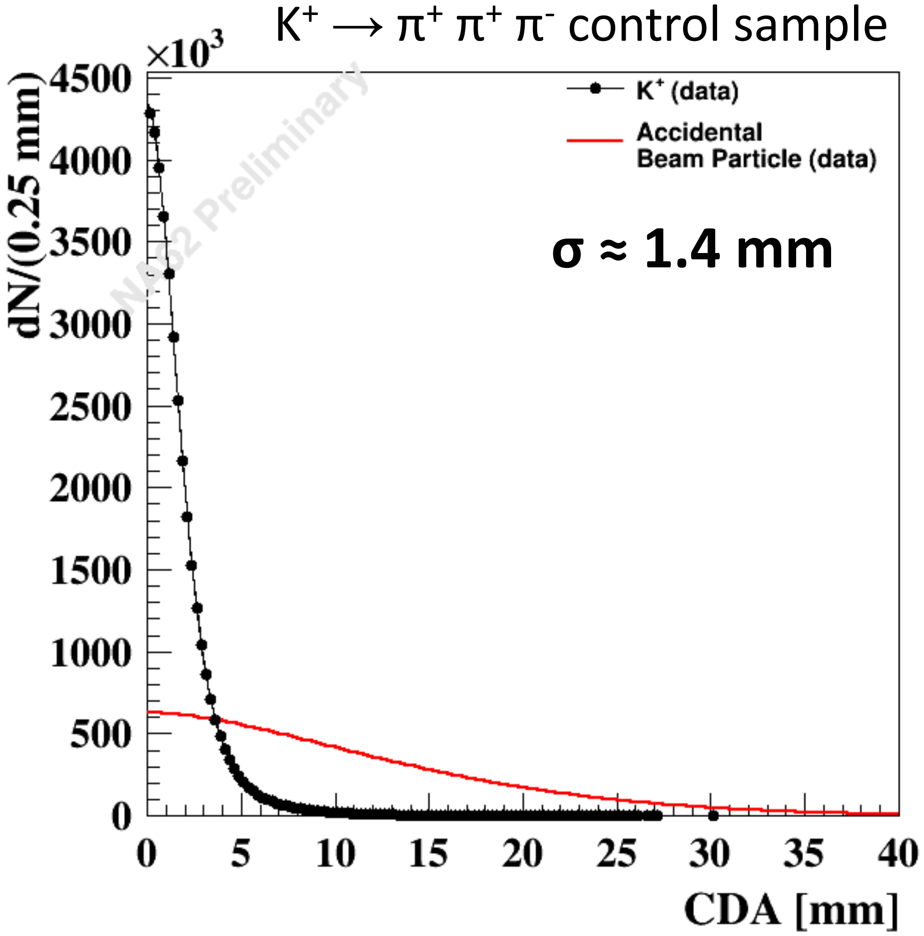
- Selection

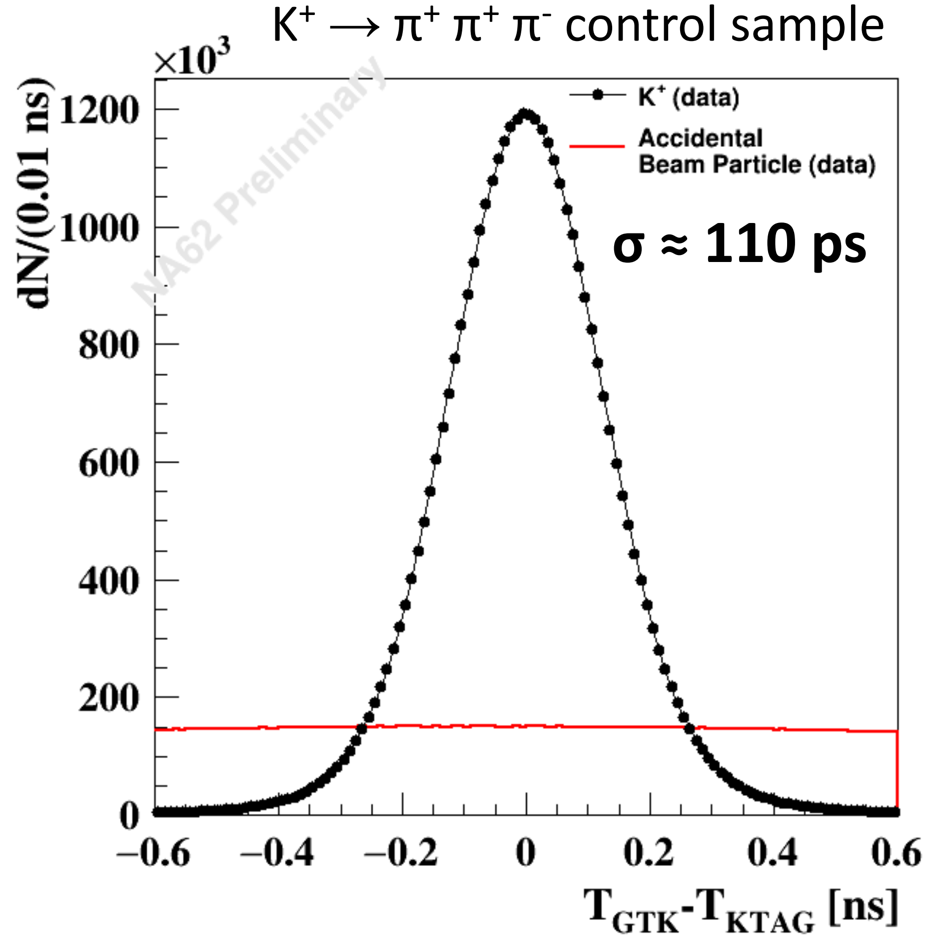
  - K^+ decays with a single charged particle in final state
  - Particle ID: π^+
  - Photon & Multiple charged particle rejection
  - Kinematic Selection of Signal Regions

K^+-π^+ matching

- KTAG –GTK –RICH time matching:
  Kaon decay time (t_{decay})
- GTK –STRAW Spectrometer spatial matching (CDA)
- 75% K^+ reconstruction and ID efficiency
- <1% K^+ mis-tag if K^+ track present, dependent on beam intensity



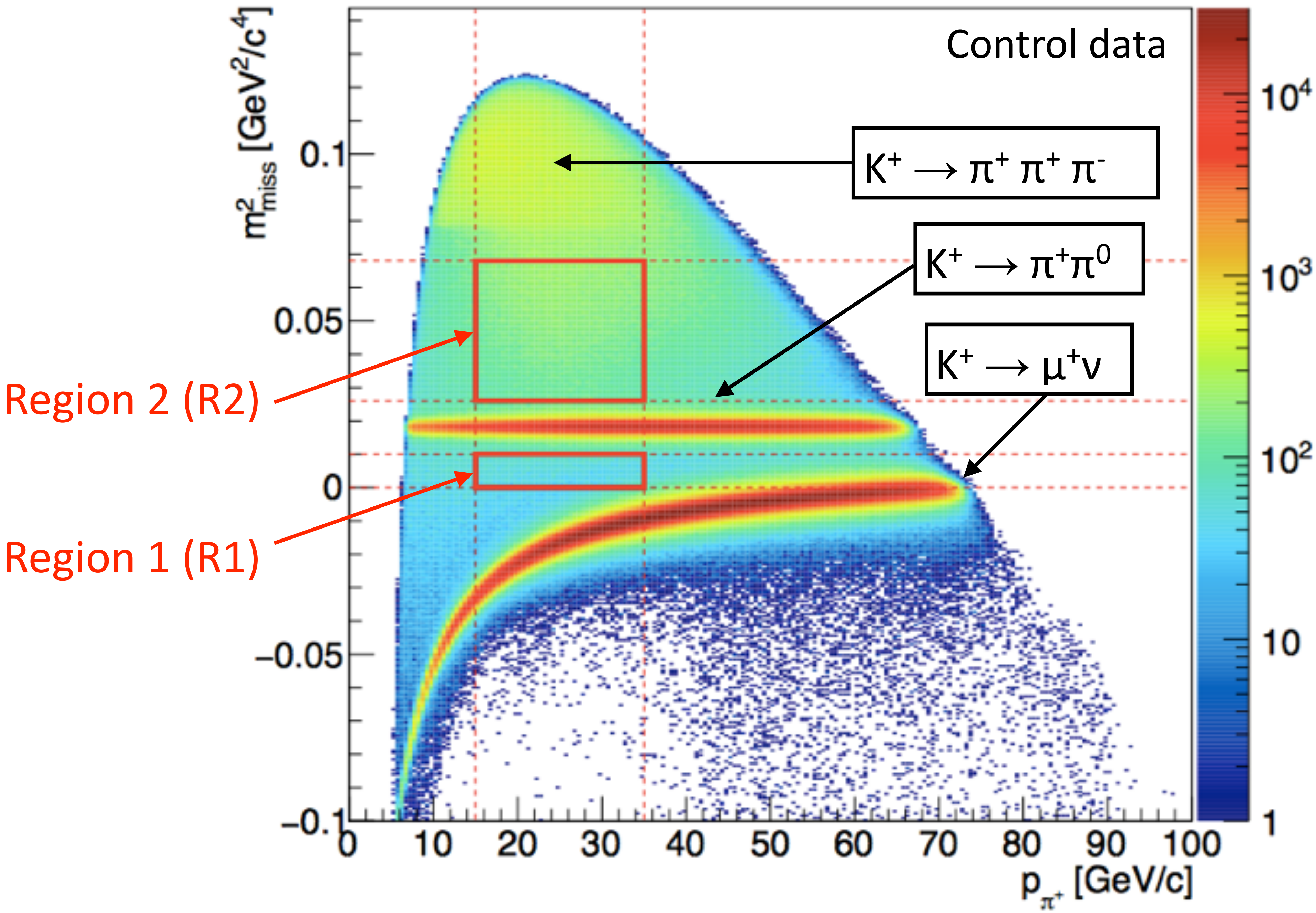




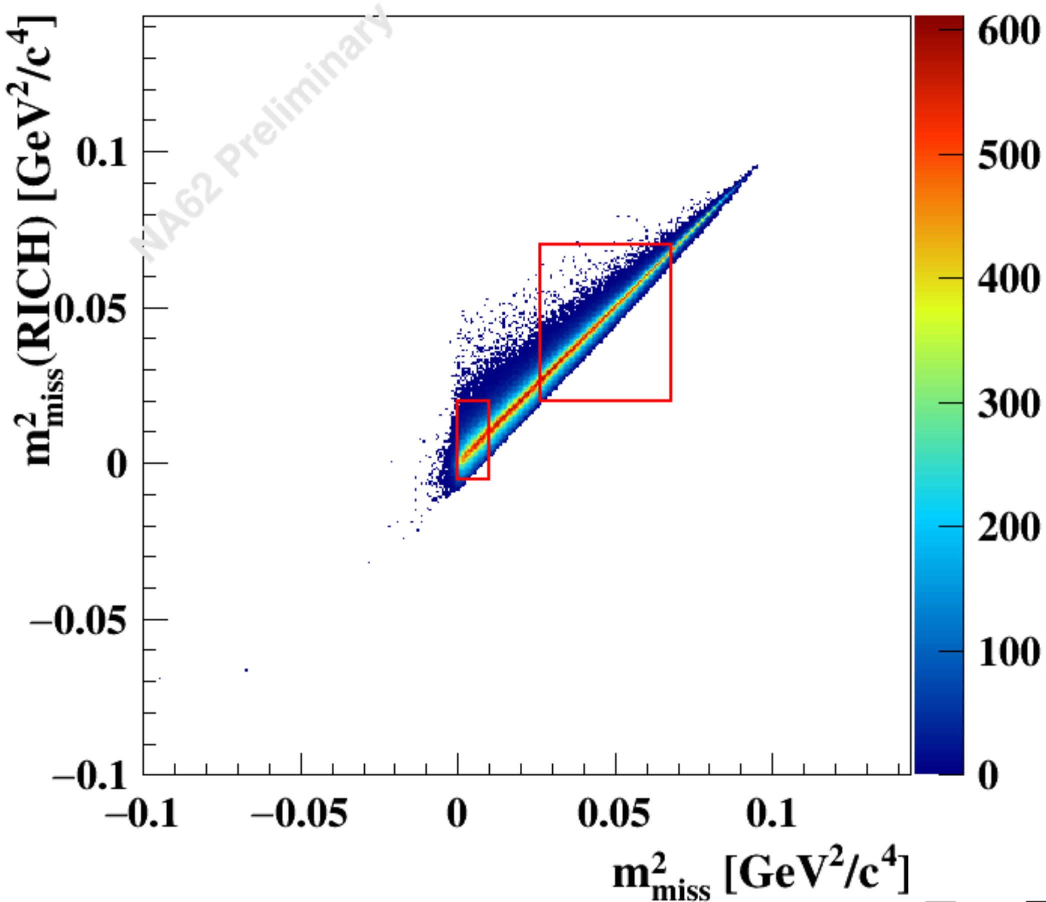
- No activity in CHANTI
- 110 < Z_{vertex} < 165 m
- 15 < $P_{\pi+}$ < 35 GeV/c
(to leave at least 40 GeV of missing energy)

Kinematics

$m^2_{miss} \equiv m^2_{miss}(GTK, STRAW) = (P_K - P_\pi)^2$ with m_π hypothesis



Signal regions



3 different ways to compute $m^2_{miss} = (P_K - P_\pi)^2$:

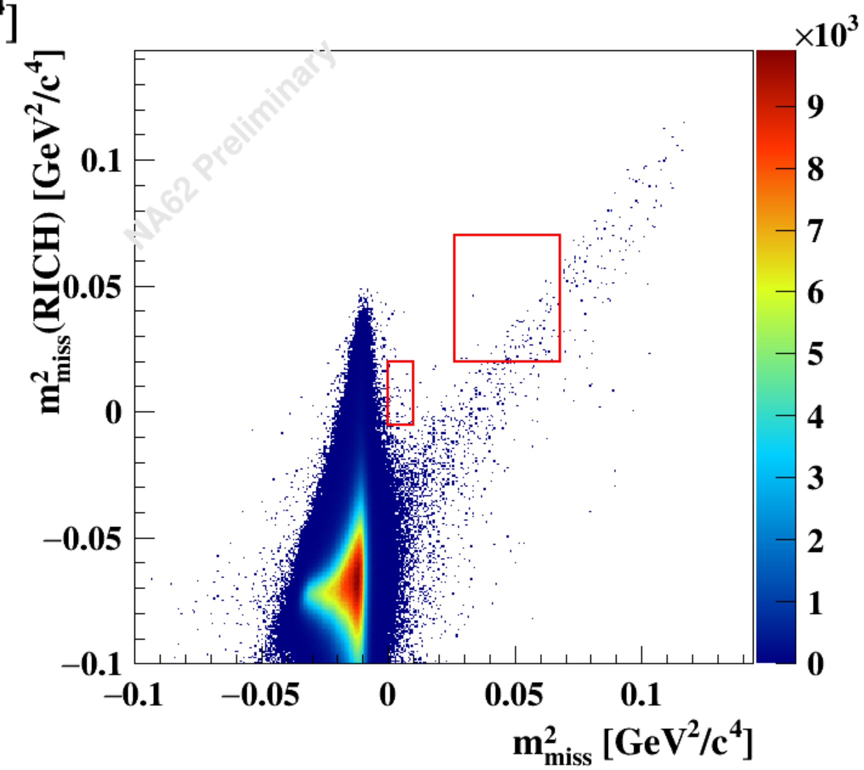
- $m^2_{miss} \equiv m^2_{miss}$(GTK, STRAW)
- m^2_{miss} (RICH) $\equiv m^2_{miss}$ (GTK, RICH)
- m^2_{miss} (beam) $\equiv m^2_{miss}$ (beam, STRAW)

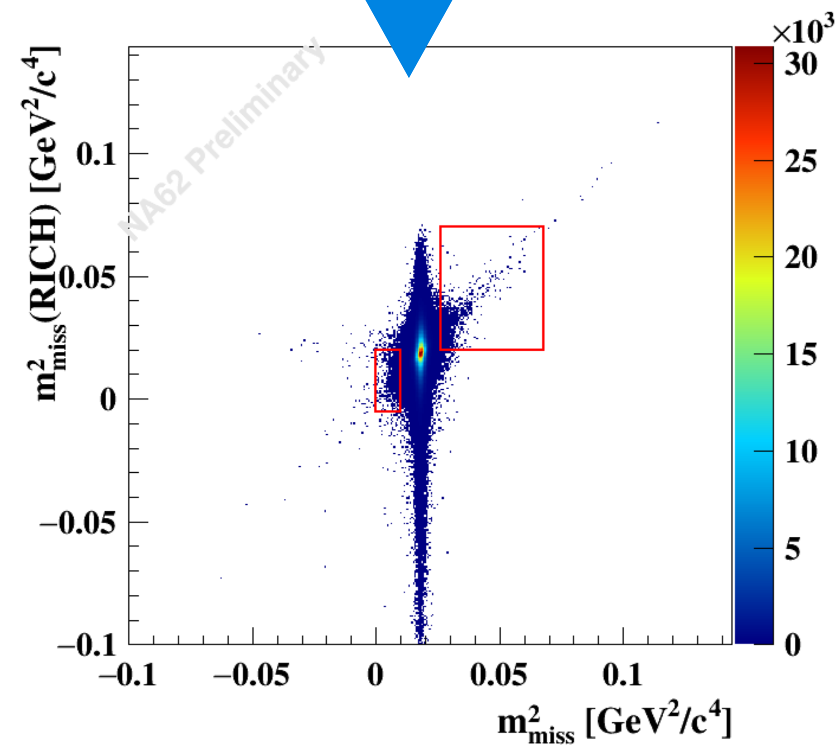
Additional power for background suppression

$K^+ \to \pi^+ \nu \nu$ MC

$K^+ \to \pi^+ \pi^0$ control data

$K^+ \to \mu^+ \nu$ control data





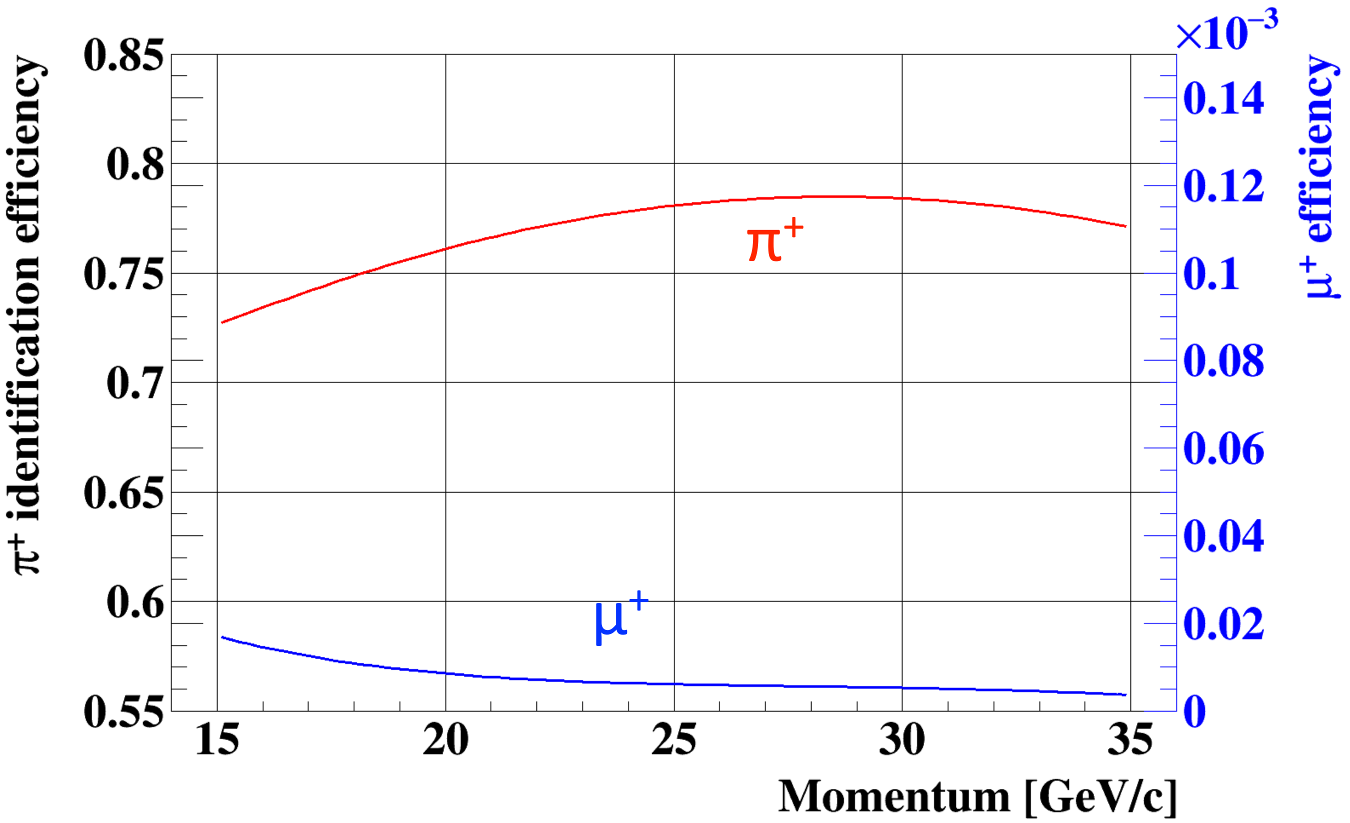
π^+ Particle identification

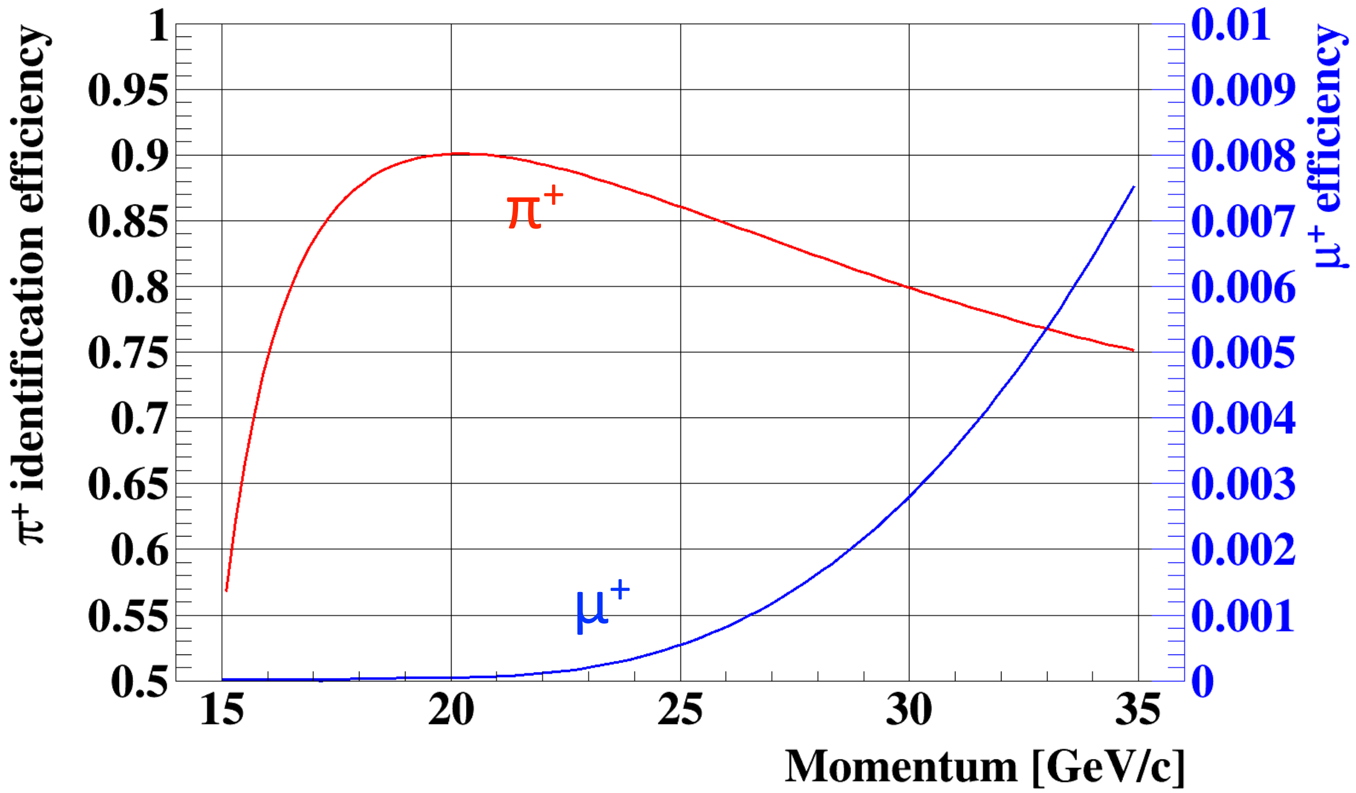
in Calorimeters

- Electromagnetic calo (LKr),
- Hadronic calo (MUV1,2)
- Scintillator pads (MUV3)

MUV3+BDT classifier using: energy, energy sharing, clusters shape

$0.6 \cdot 10^{-5}$ μ^+ efficiency vs **77% π^+ efficiency**





in RICH

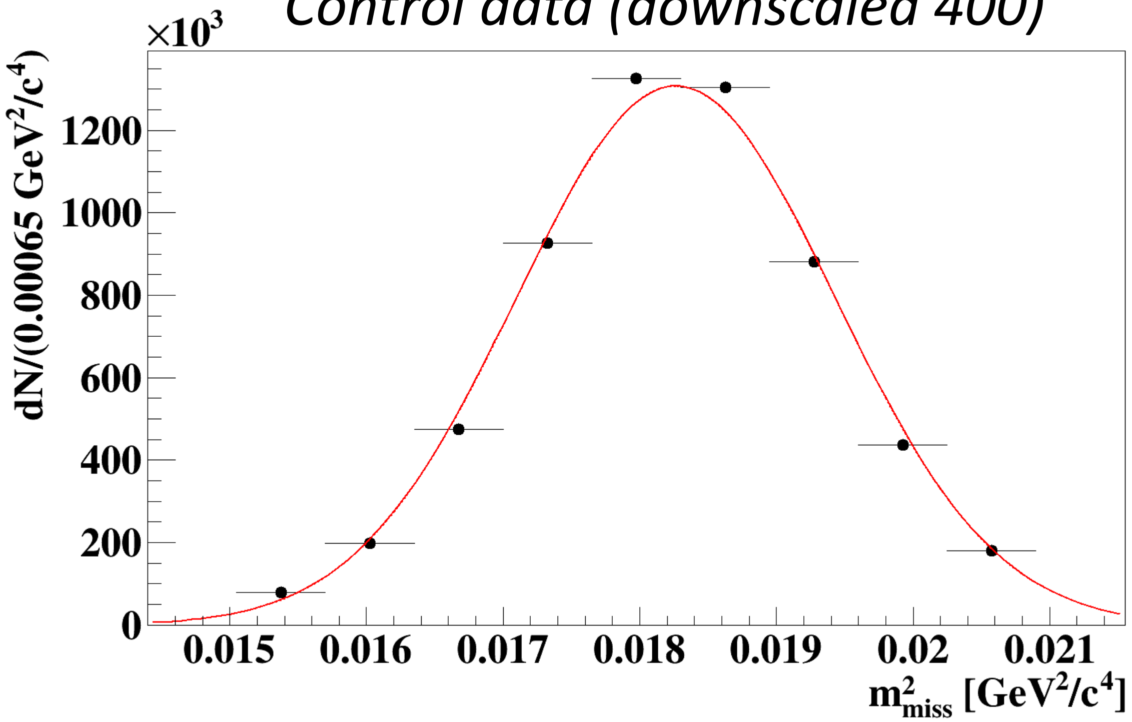
Track driven Likelihood particle ID discriminant
Particle mass using track momentum
Momentum measurement under mass hypothesis (velocity - spectrometer)

$2.5 \cdot 10^{-3}$ μ^+ efficiency vs **75% π^+ efficiency**

Photon rejection

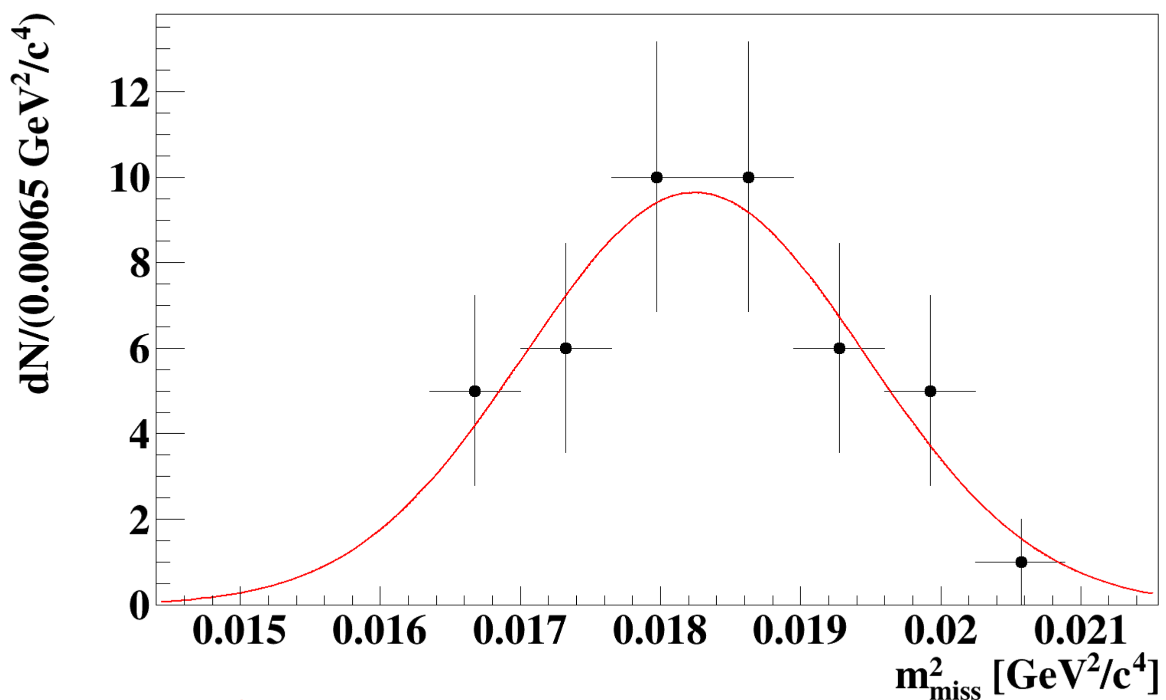
- Timing coincidence of signals in LKr, LAV, SAV not associated to π^+ and t_{decay}
- Not coincidences of signals in LKr and hodoscopes not associated to π^+, in time with t_{decay}
- Typical timing coincidences: ±3 ÷ ±5 ns; energy dependent time cut in LKr

Control data (downscaled 400)



Before rejection

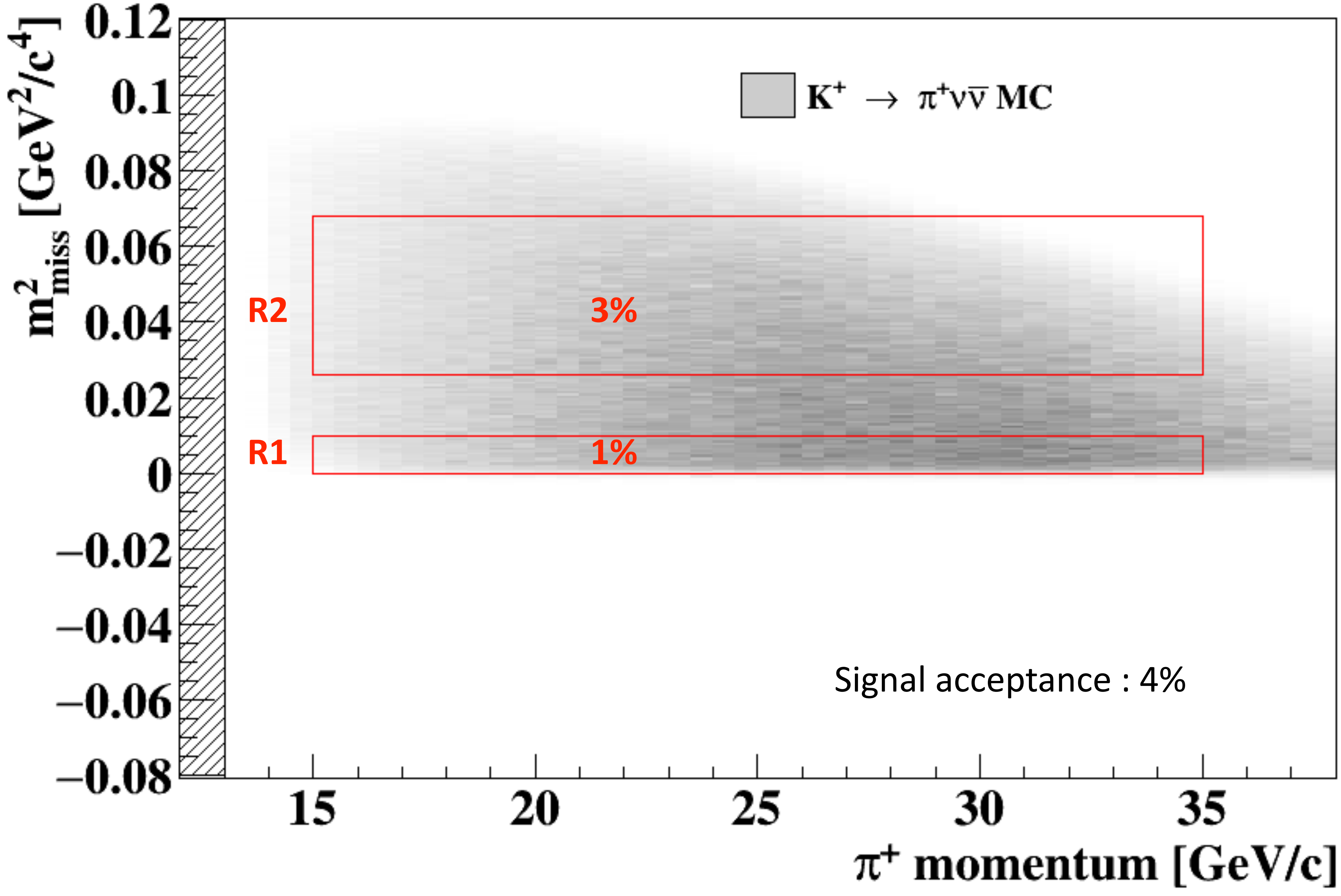
PNN data



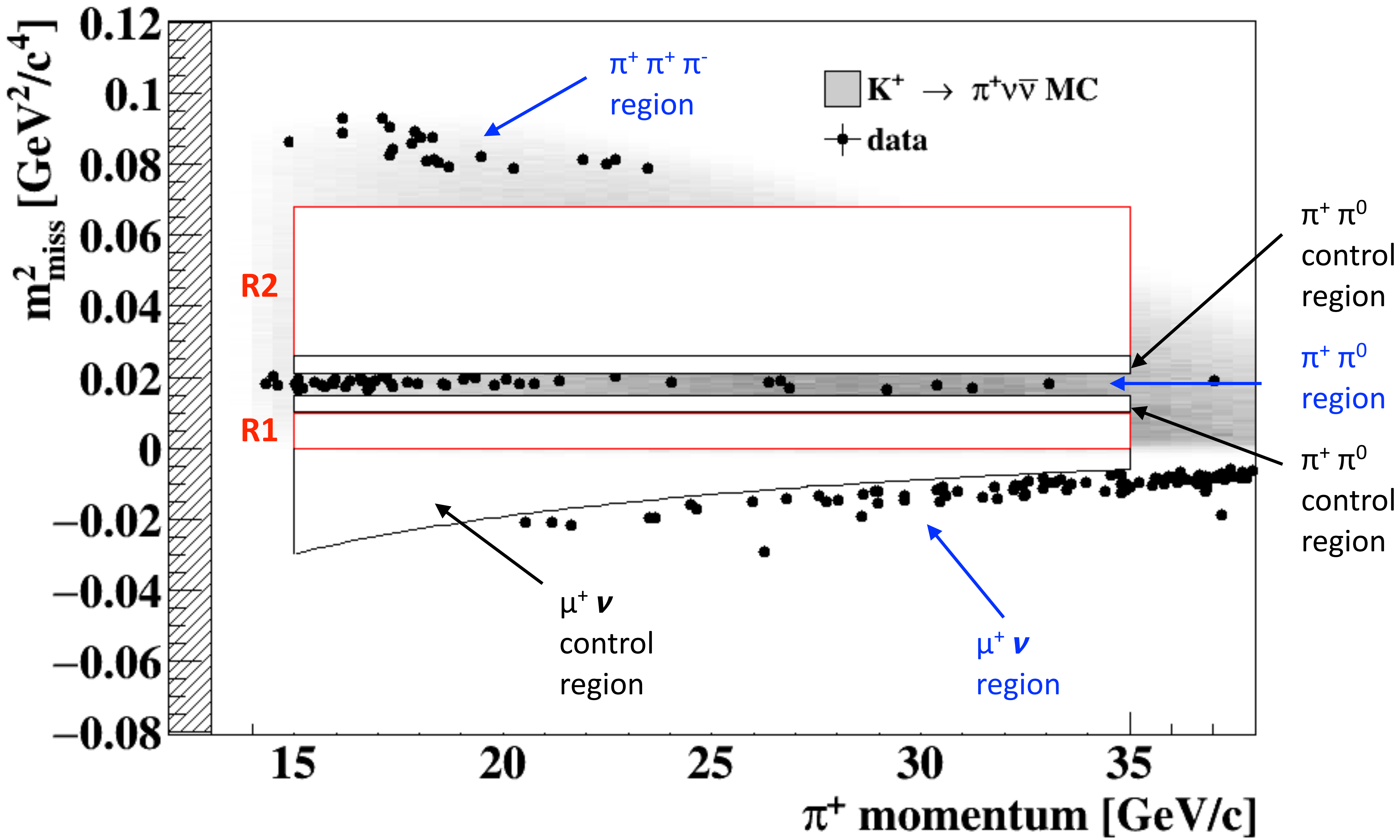
After rejection

- Fraction of surviving $K^+ \rightarrow \pi^+\pi^0$ (15 – 35 GeV momentum range) : ~$2.5 \cdot 10^{-8}$
- High suppression of $K^+ \rightarrow \pi^+\pi^+\pi^-$, $K^+ \rightarrow \pi^+\pi^-e^+\nu$ with Multi-Charge cuts

MC Signal after selection



Data after selection



Analysis steps

- Selection
- Evaluation of the single event sensitivity
- Background estimation and validation
- Un-blinding of signal regions and interpretation of the results

Single Event Sensitivity (SES)

$$SES = \frac{1}{N_K \sum_j (A^j_{\pi\nu\nu} \cdot \epsilon^J_{RV} \cdot \epsilon^j_{trig})}$$

j = π^+ momentum bin

- N_K: number of K^+ decays
- $A^j_{\pi\nu\nu}$: signal acceptance
- ϵ^J_{RV}: random veto efficiency
- ϵ^j_{trig}: trigger efficiency

Normalization: **$K^+ \rightarrow \pi^+\pi^0$ from control data.**

Same $\pi^+\nu\nu$ selection with γ, multiplicity rejection not applied; m_{miss}^2 cuts modified

$$N_K = \frac{N_{\pi\pi} \cdot D}{A_{\pi\pi} \cdot BR_{\pi\pi}}$$

$N_{\pi\pi}$ = number of $K^+ \rightarrow \pi^+\pi^0$ (~6 x 10^6)

D = control trigger downscaling (400)

$A_{\pi\pi}$ = normalization acceptance (~0.1 from MC)

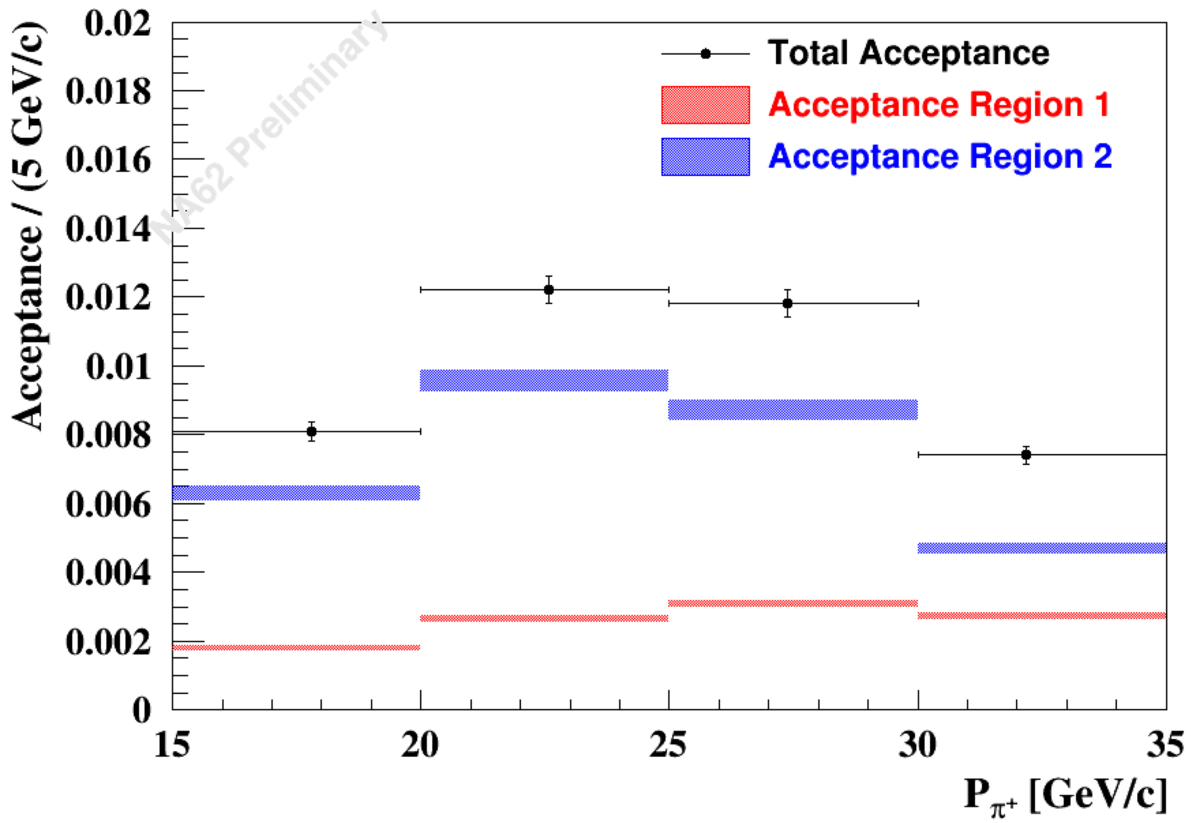
$$N_K = (1.21 \pm 0.02_{syst}) \times 10^{11}$$

systematic uncertainty:

- discrepancies in data/MC

- variation of the measured K^+ flux as a function of $P_{\pi+}$

Signal Acceptance & Trigger Efficiency



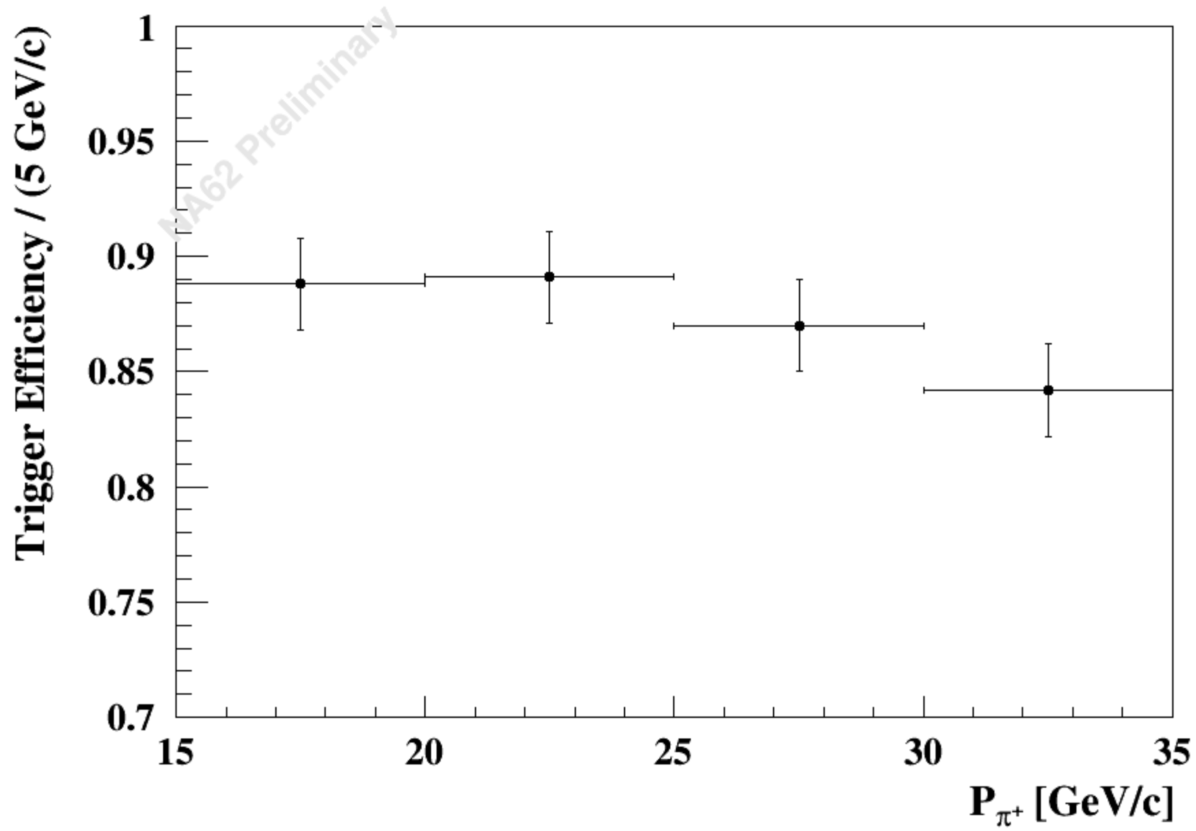
Everything is computed separately in 4 bins of $P_{\pi+}$, 5 GeV/c wide

Signal acceptance (~ **4%**)

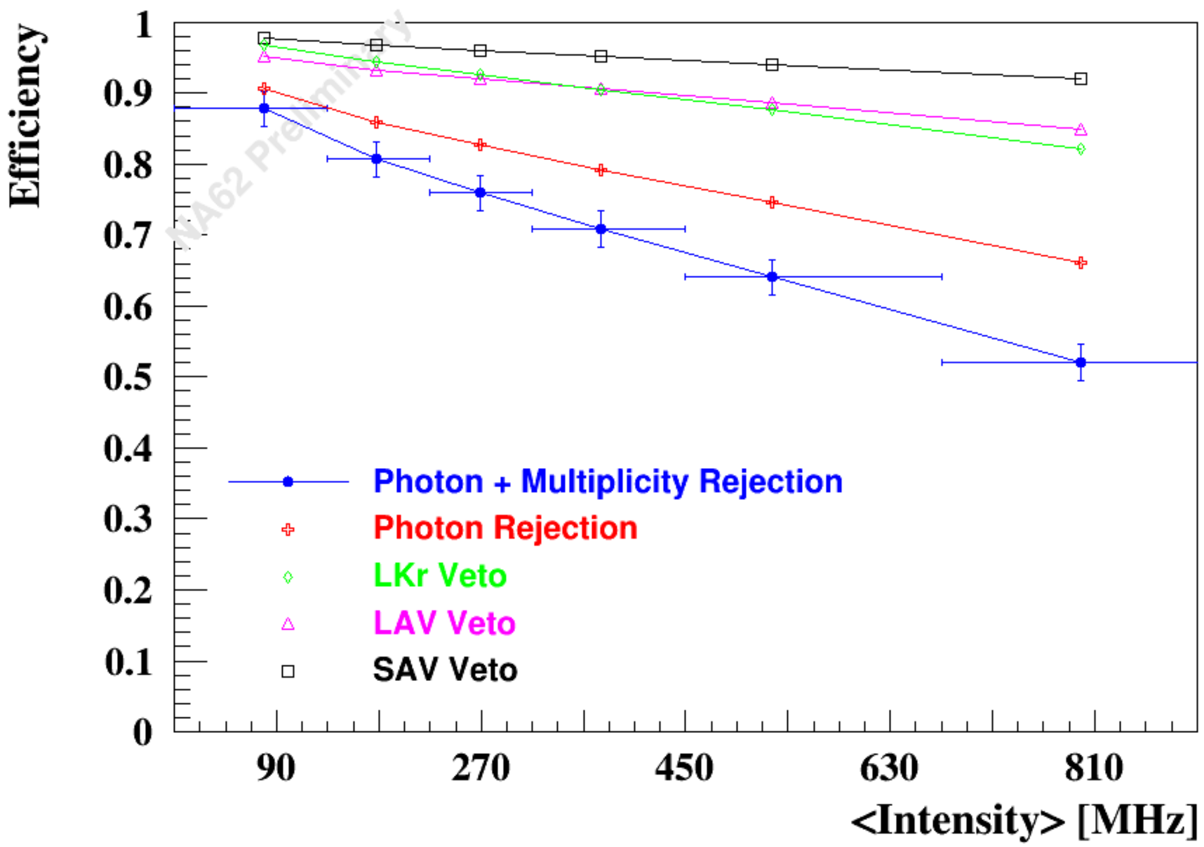
- Computed with MC
- Particle ID and losses due to π^+ interaction in the detector material included (main sources of systematic error)

PNN Trigger efficiency

- Computed using control data and $K^+ \rightarrow \pi^+\pi^0$ control sample
- L0 efficiency ~ **90%**, weakly dependent on $P_{\pi+}$, losses due mainly to LKr and MUV3 veto conditions
- L1 efficiency > **97%**



Single Event Sensitivity (SES)



Random veto

- Signal efficiency losses due to random activity in the veto detectors
- Estimated on data using a $K^+ \to \mu^+ \nu$ sample (ratio of events selected before and after the γ and multiplicity cuts)
- is flat as a function of $P_{\pi+}$, but depends on the instantaneous intensity

Single event sensitivity

Number of K^+ decays	$N_K = (1.21 \pm 0.02) \times 10^{10}$
Acceptance $K^+ \to \pi^+ \nu \bar{\nu}$	$A_{\pi\nu\nu} = 4.0 \pm 0.1$
PNN trigger efficiency	$\epsilon_{trig} = 0.87 \pm 0.2$
Random Veto	$\epsilon_{RV} = 0.76 \pm 0.04$
SES	$(3.15 \pm 0.01_{stat} \pm 0.24_{syst}) \cdot 10^{-10}$
Expected SM $K^+ \to \pi^+ \nu \bar{\nu}$	$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$

Error on the SM BR

Analysis steps

- Selection
- Evaluation of the single event sensitivity
- Background estimation and validation
- Un-blinding of signal regions and interpretation of the results

Background estimation

$$N^{exp}_{bkg}(R1/R2) = \sum_j \left[N(bkg)_j \cdot f^{kin}_j(R1/R2)\right]$$

- $N^{exp}_{bkg}(R1/R2)$: Expected background events in region 1/2
- j: π^+ momentum bin
- $N(bkg)_j$: bkg events after $\pi\nu\nu$ selection
- $f^{kin}_j(R1/R2)$: Fraction of events in region 1/2

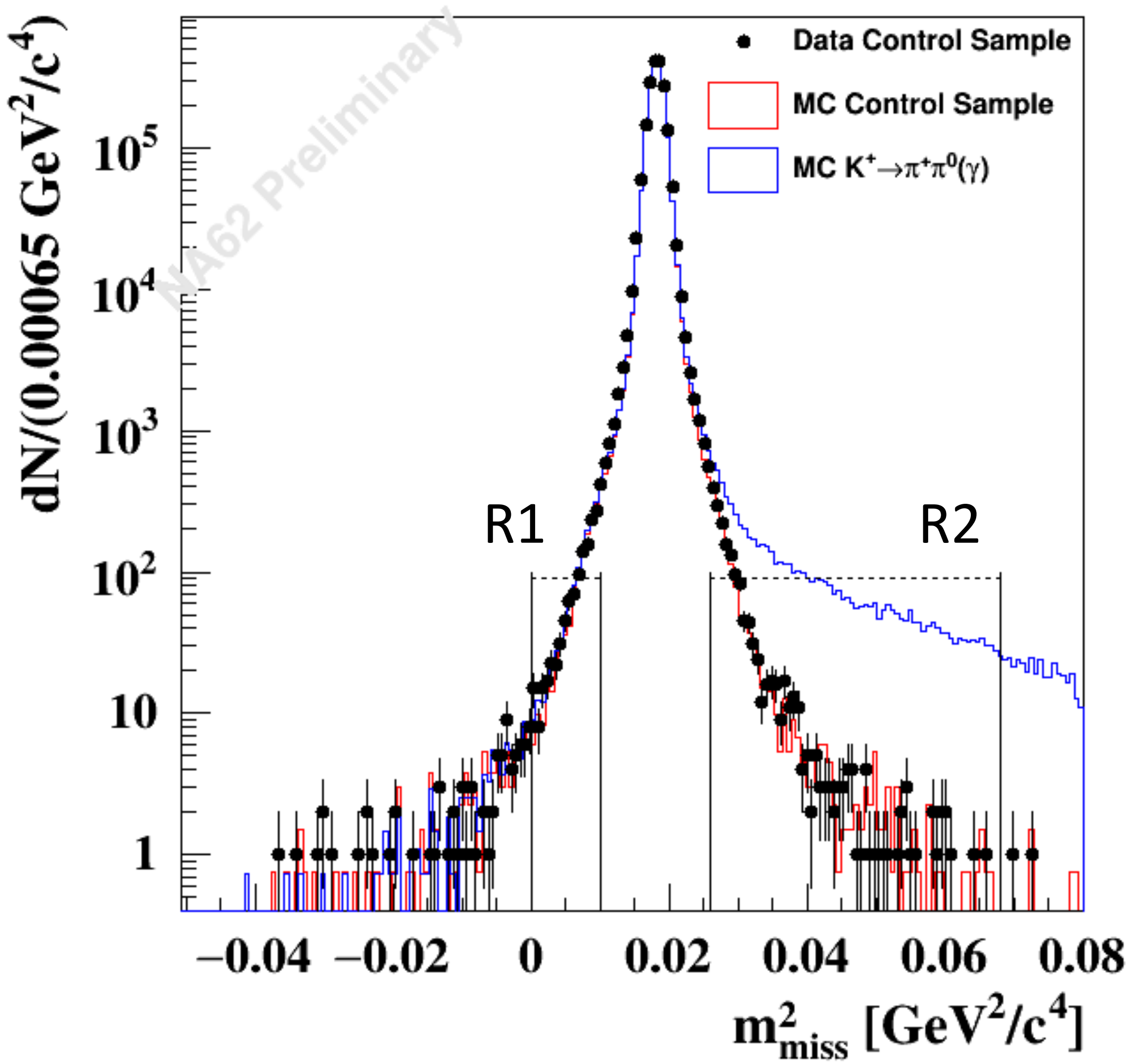
Calculated for the main background decays:

$K^+ \to \pi^+\pi^0(\gamma)$, $K^+ \to \mu^+\nu(\gamma)$, $K^+ \to \pi^+\pi^+\pi^-$, $K^+ \to \pi^+\pi^- e^+\nu$

under the assumption that particle identification, γ and multiplicity rejection are independent from the cuts on m^2_{miss}

f^{kin}_j

- Fraction of background events entering signal regions through the reconstructed tails of the corresponding m^2_{miss} peak
- is modeled on control samples selected on data and eventually corrected for biases induced by selection criteria using MC simulation



- **Data control sample of $K^+ \to \pi^+\pi^0$ selected tagging the π^0 with the two γ's in the LKr**
- **MC sample of $K^+ \to \pi^+\pi^0(\gamma)$ selected as in data**

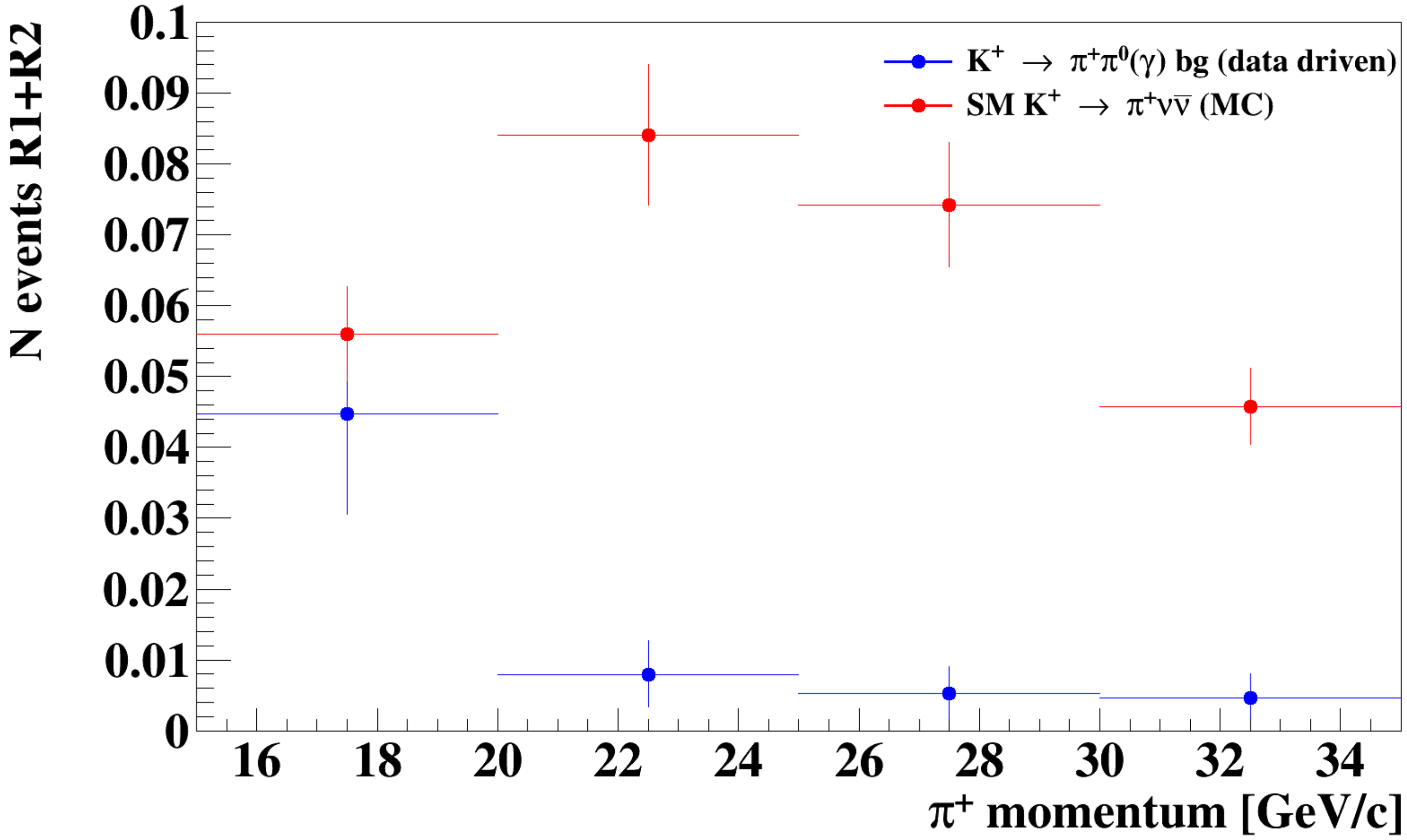
  The π^0 tagging suppresses almost completely the radiative part

- **MC sample of $K^+ \to \pi^+\pi^0(\gamma)$ selected as $\pi\nu\nu$ without applying γ and multiplicity rejection**

- $\pi^0\,\gamma$ rejection of the radiative tail in R2 estimated from MC:
  single photon detection efficiency applied to each of the 3 photons in the final state
  × 30 than single π^0 rejection
- The radiative part accounts for about 13% of the total background and dominates the systematic uncertainty

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

	$\pi^+\pi^0$	$\pi^+\pi^0(\gamma)$
R1	$0.022 \pm 0.004_{stat} \pm 0.002_{syst}$	0
R2	$0.037 \pm 0.006_{stat} \pm 0.003_{syst}$	$0.005 \pm 0.005_{syst}$

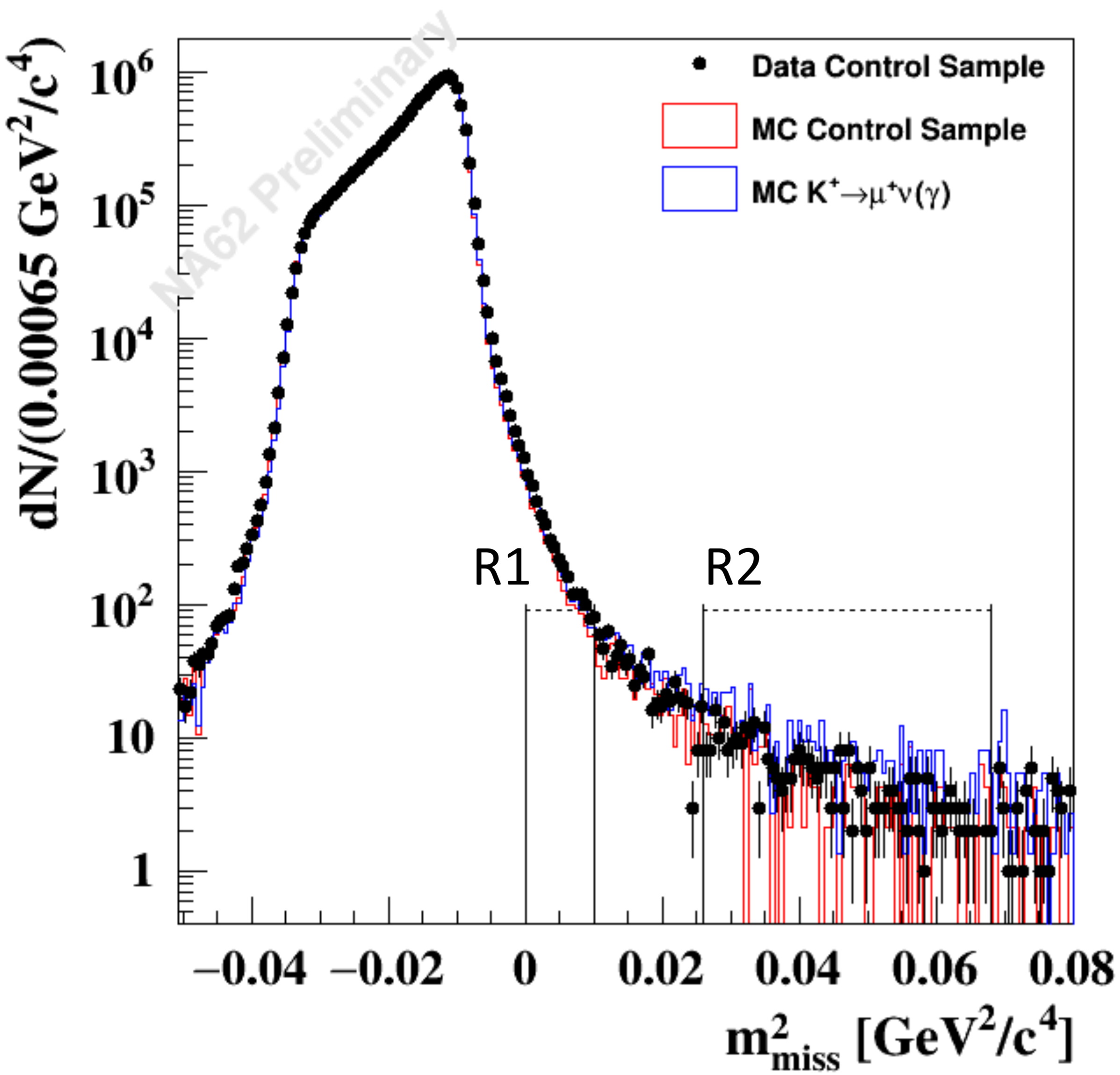


Expected $K^+ \to \pi^+\pi^0(\gamma)$ background in $P_{\pi+}$ bins compared to the expected number of SM $K^+ \to \pi^+\nu\nu$ events

Residual PNN trigger $\pi^+\pi^0$ events gather at low $P_{\pi+}$

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

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



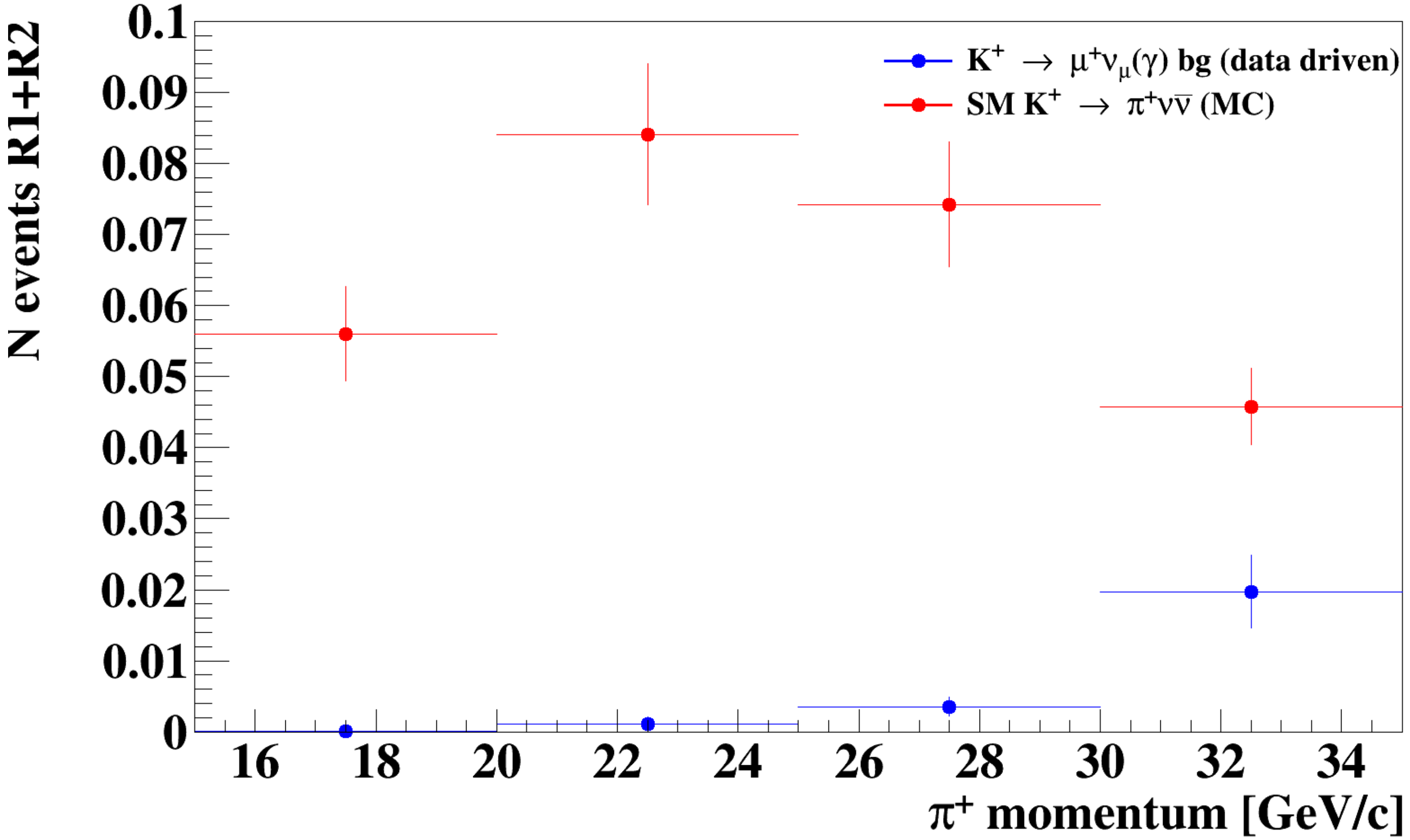
- **Data control sample of $K^+ \to \mu^+\nu(\gamma)$ selected tagging μ^+ in MUV3**
- **MC sample of $K^+ \to \mu^+\nu(\gamma)$ selected as in data**
- **MC sample of $K^+ \to \mu^+\nu(\gamma)$ selected as $\pi\nu\nu$ (γ veto, multiplicity rejection) without muon-ID (to test the effect of the μ-ID on the tails)**

The radiative contribution is included in the measured tails

- RICH potentially correlates particle ID and kinematics if events enter in signal region because of momentum mis-measurement is STRAW
- The effect on background is estimated on data comparing RICH performances measured on $K^+ \to \mu^+\nu(\gamma)$ events in $\mu^+\nu$ peak and signal region

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

	$\mu^+\nu$
R1	$0.019 \pm 0.003_{stat} \pm 0.003_{syst}$
R2	$0.0012 \pm 0.0002_{stat} \pm 0.0006_{syst}$



Expected $K^+ \to \mu^+\nu(\gamma)$ background in $P_{\pi+}$ bins compared to the expected number of SM $K^+ \to \pi^+\nu\nu$ events

The background depends on $P_{\pi+}$ as both tails and particle ID steeply increase at higher momentum because of kinematics and RICH performances

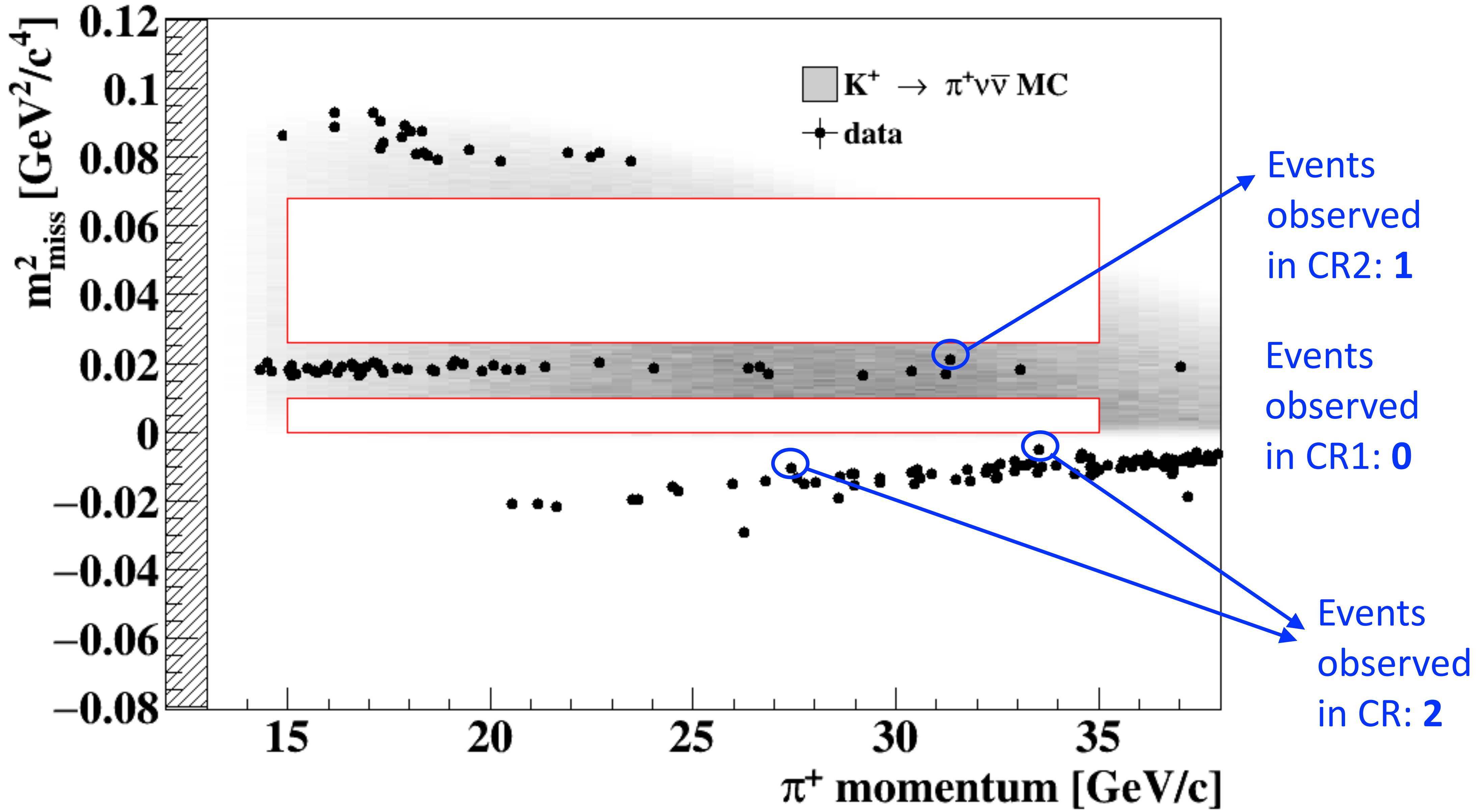
$$N^{expected}_{\mu\nu(\gamma)} = 0.020 \pm 0.003_{stat} \pm 0.003_{syst}$$

Background estimation validation

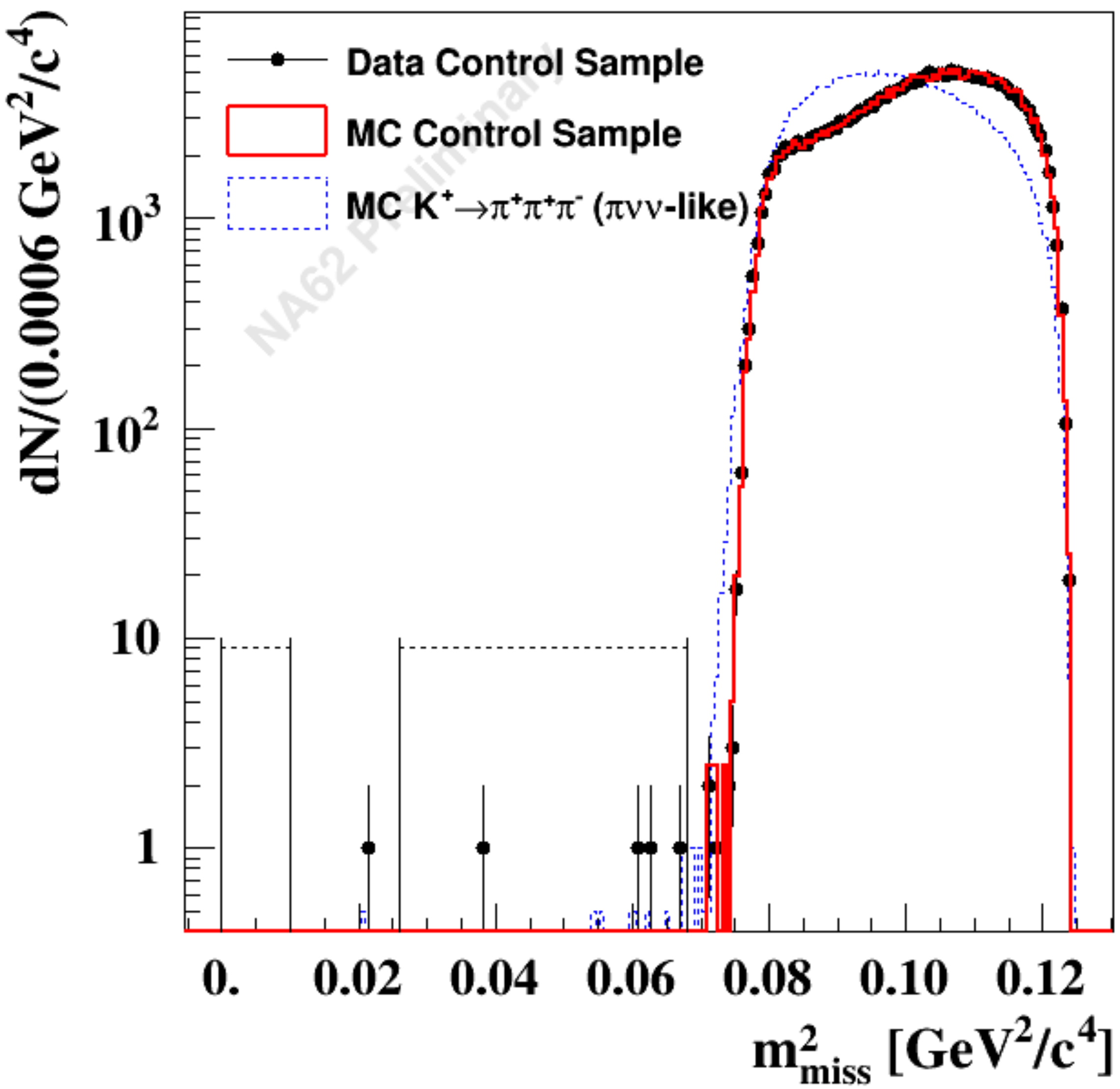
Validation: event expected in the control regions

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

	$\mu^+\nu$
CR	$1.02 \pm 0.16_{stat}$



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



- **Data control sample of $K^+ \to \pi^+\pi^+\pi^-$ selected tagging $\pi^+\pi^-$ pair**
- MC sample of $K^+ \to \pi^+\pi^+\pi^-$ selected as in data

Multiplicity rejection and kinematics cuts turn out to be very effective against $K^+ \to \pi^+\pi^+\pi^-$ decays (one order of magnitude lower than the other two)

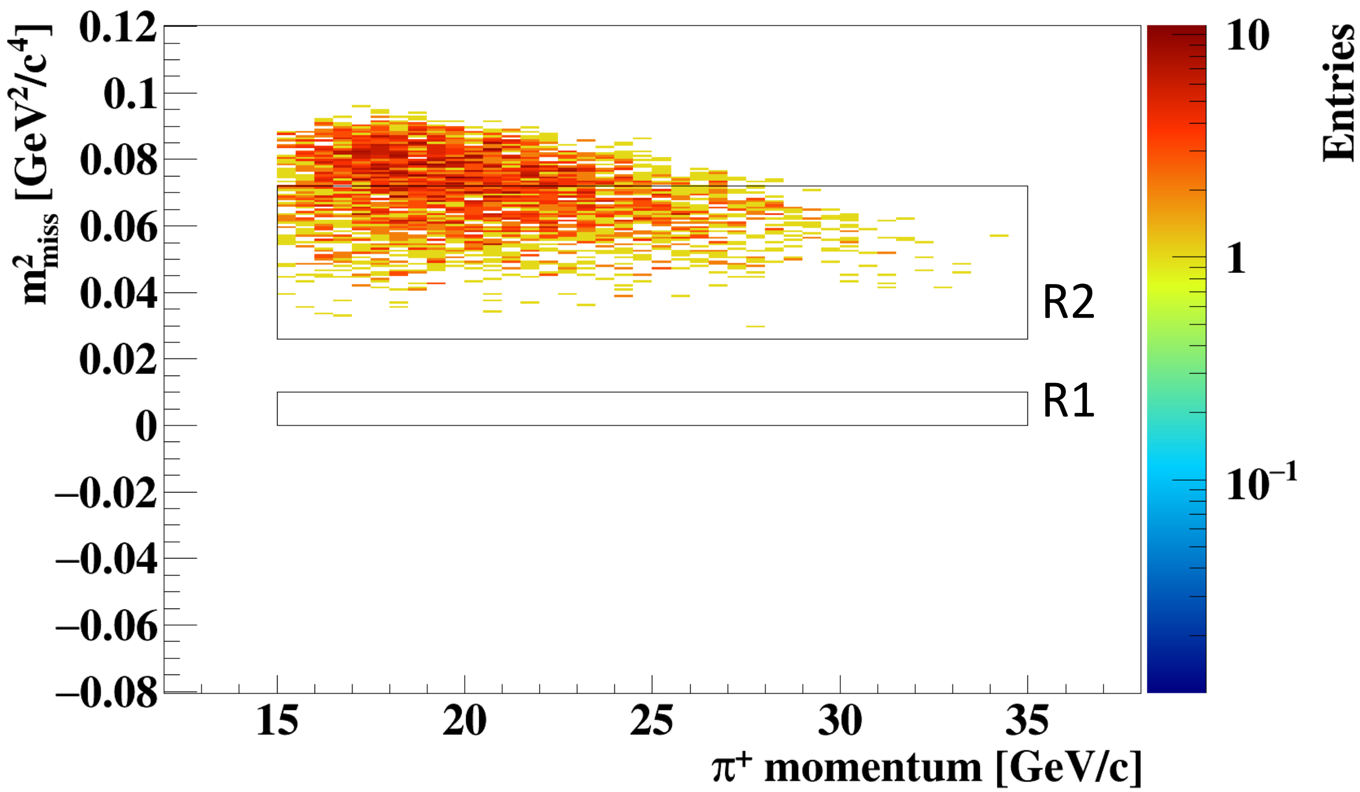
$$f^{kin}(R2) \leq 10^{-4}$$

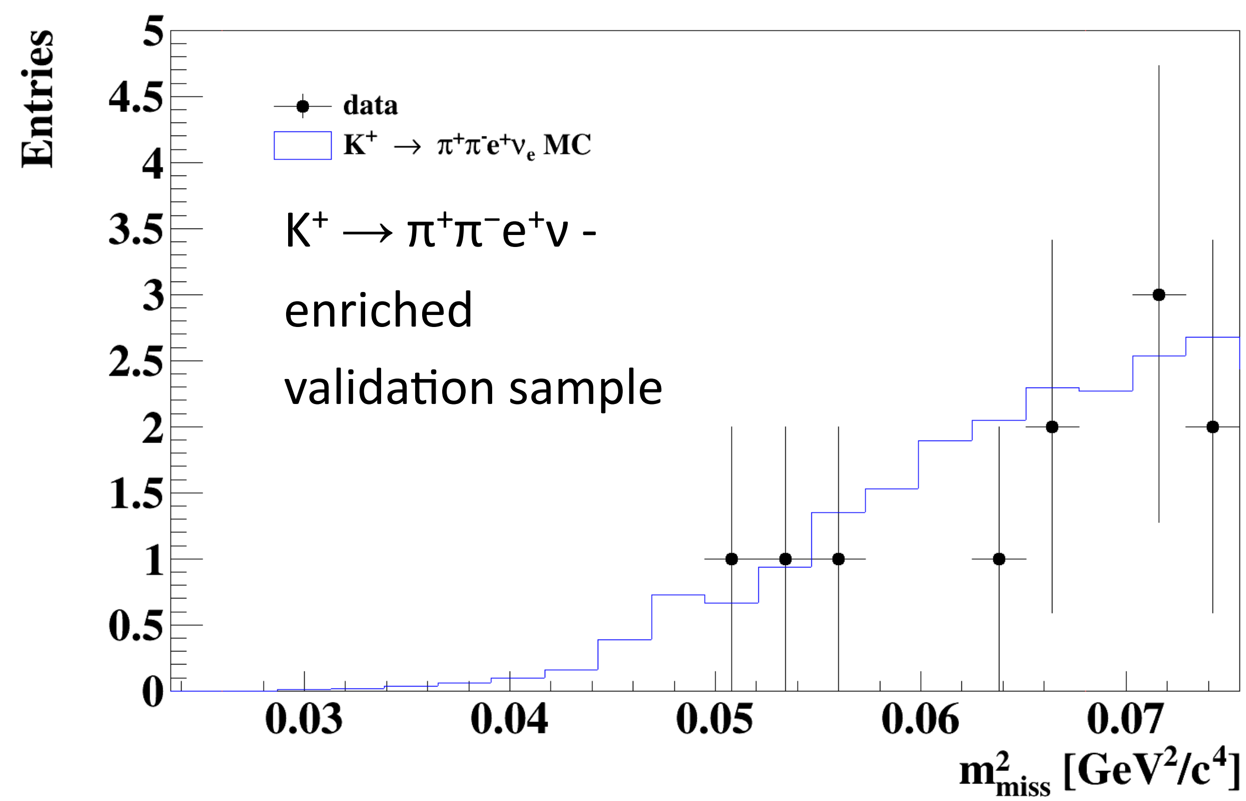
- Kinematic rejection factor corrected for biases induced by the control sample selection using MC

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

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

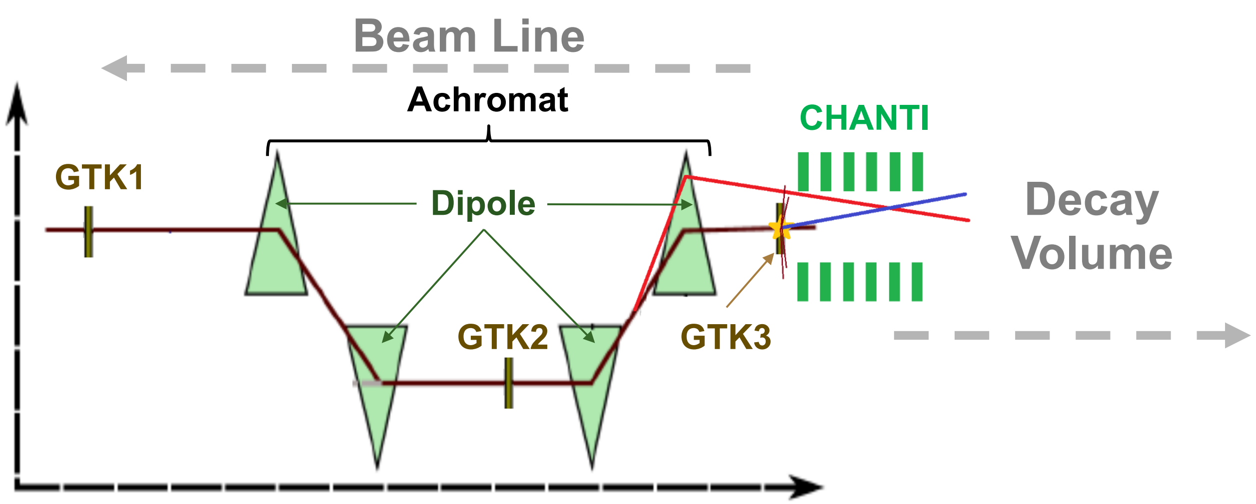
- Expected in signal region 2
- Branching ratio 4.25×10^{-5}
- Kinematics is strongly correlated with topology: different method
- Background estimated using MC (~4×10^8 events generated)
- Validated using different control samples $K^+ \to \pi^+\pi^- e^+\nu$ - enriched
- The statistics of the MC sample is the limiting factor of the final estimation





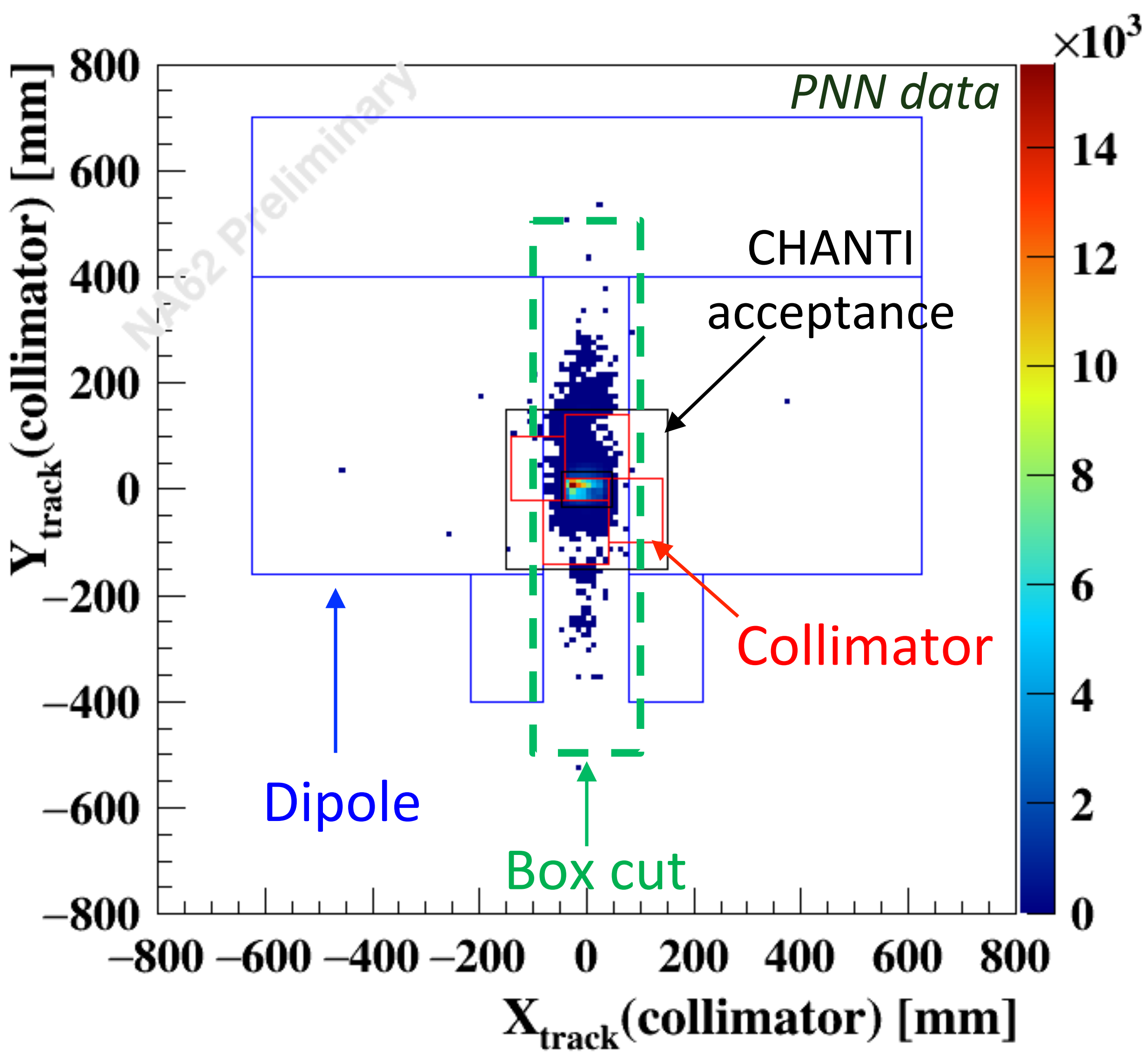
$$N^{expected}_{\pi\pi e\nu} = 0.018^{+0.024}_{-0.017}\,|_{stat} \pm 0.009_{syst}$$

Upstream background



- π^+ from a decay upstream of the decay region matching a π^+ from the beam
- π^+ from beam particle interactions in GTK matching a K^+
- π^+ from interaction of a K^+ with material in the beam (prompt particle or decay product)

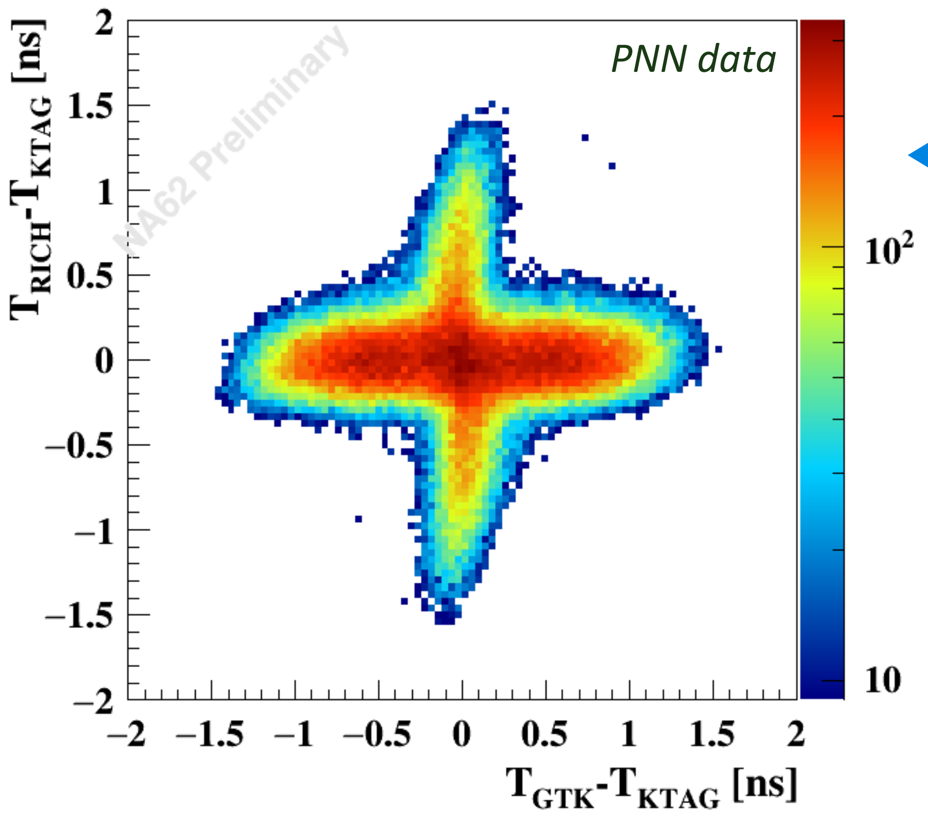
$\pi\nu\nu$-like data sample enriched for upstream events: position of π^+ at the entrance of the decay region



The position of the π^+ indicates their origin upstream or via interactions in GTK stations and drive the choice of a **geometrical cut covering the central aperture of the dipole**

$$|X_{track}| > 100 \text{ mm}, \quad |Y_{track}| > 500 \text{ mm}$$

Upstream background

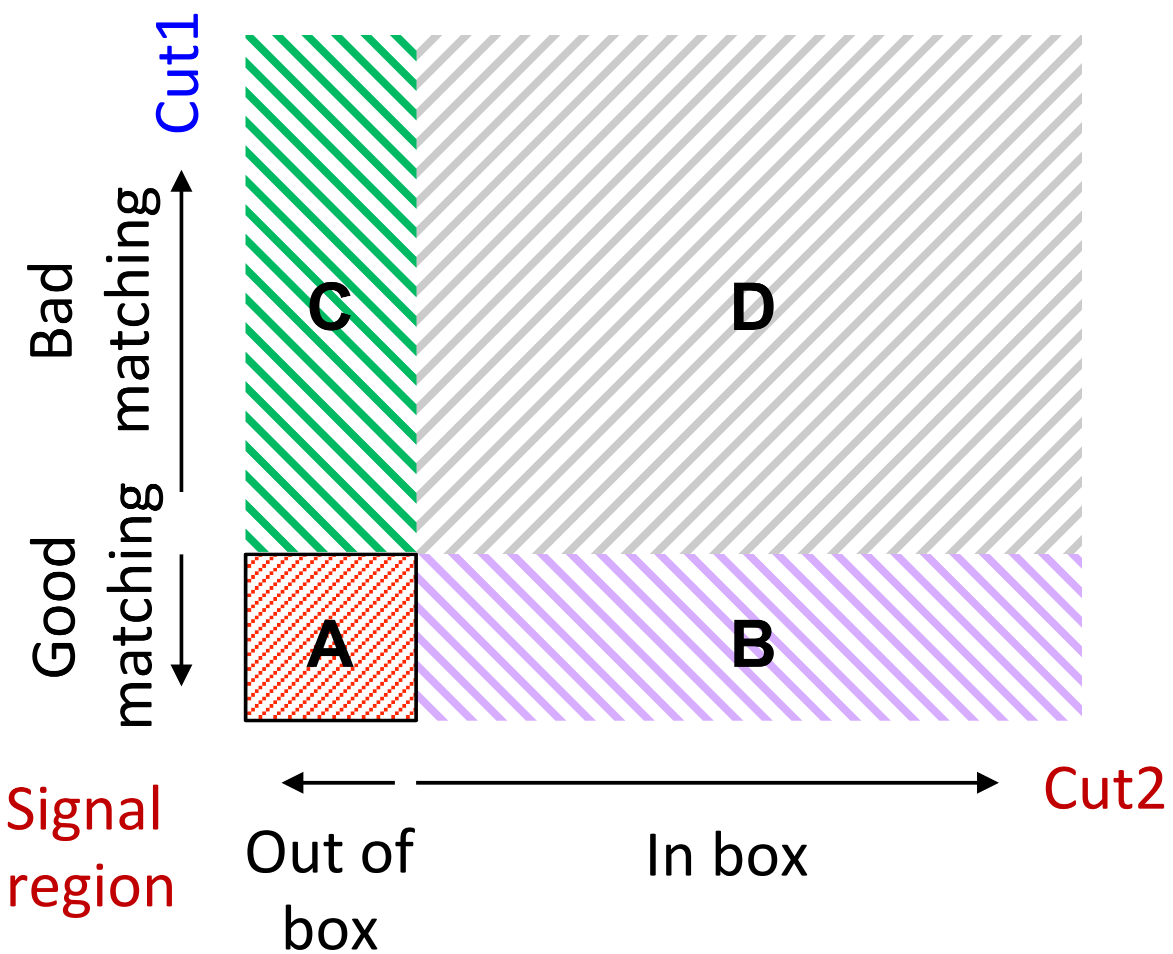


Distribution of the time coincidence between KTAG-RICH and GTK-KTAG.
Suggest an accidental source for these events

- Cut 1: K^+ - π^+ matching
- Cut 2: box cut

Bifurcation technique is adopted

The combinations of Cut1 and Cut2 defines 4 samples:



If all the samples contain the same type of events and Cut1 and Cut2 are independent:

$$A_{exp} = B \cdot C/D$$

Procedure validated using different sets of values for Cut1 – Cut2

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

(statistics limit the accuracy)

Expected events summary

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

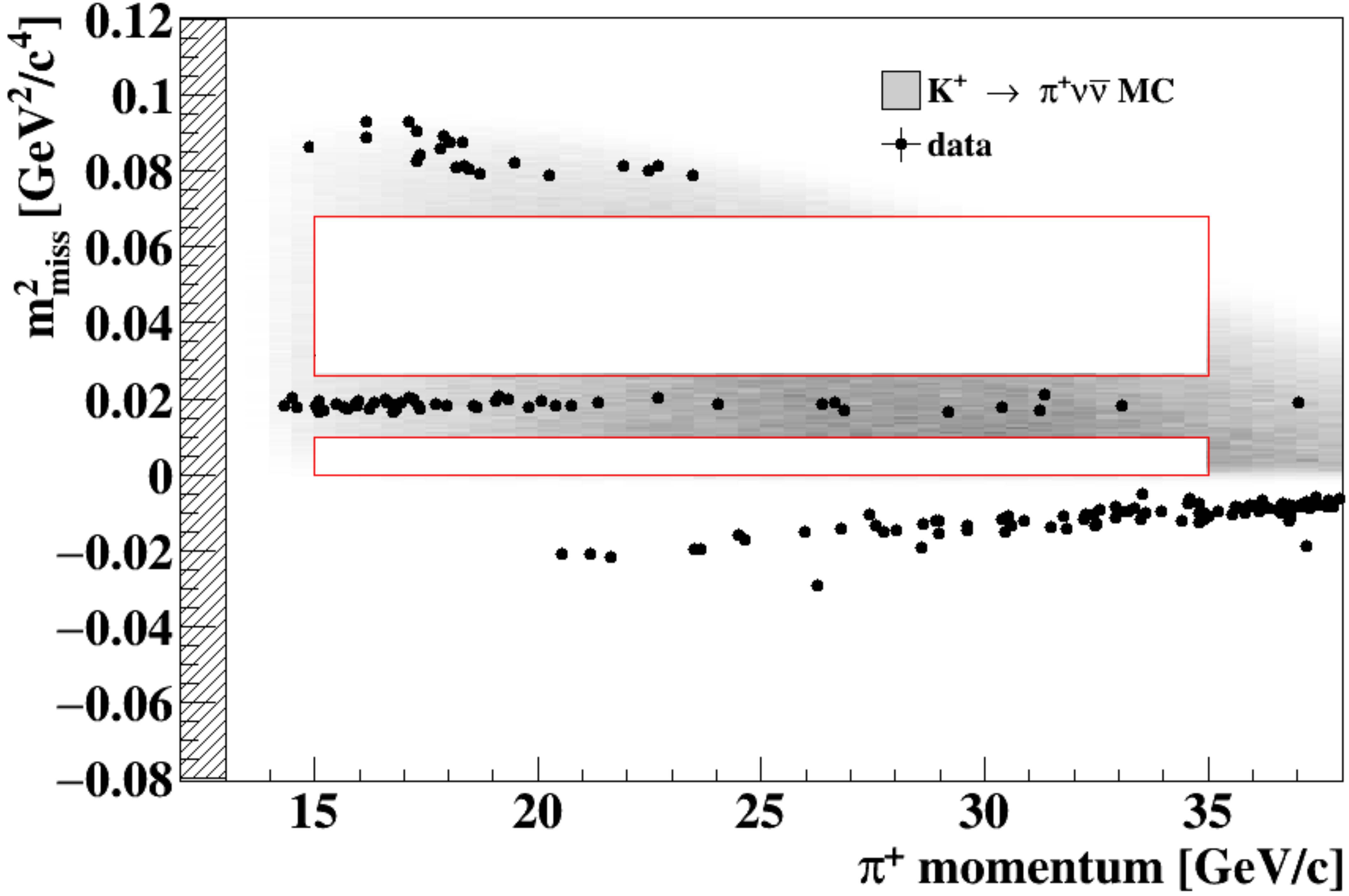
* The upstream background is relevant. In 2016 data analysis tight geometrical cuts are employed to keep it under control causing up to 30-40% signal acceptance reduction

- In the final part of 2017 data-taking a copper plug was inserted in to the last dipole (corresponding to the aperture of the final collimator) to mitigate this issue
- The installation of a new final collimator which extends further transversally that will improve our immunity to upstream interaction is foreseen in mid June 2018

Analysis steps

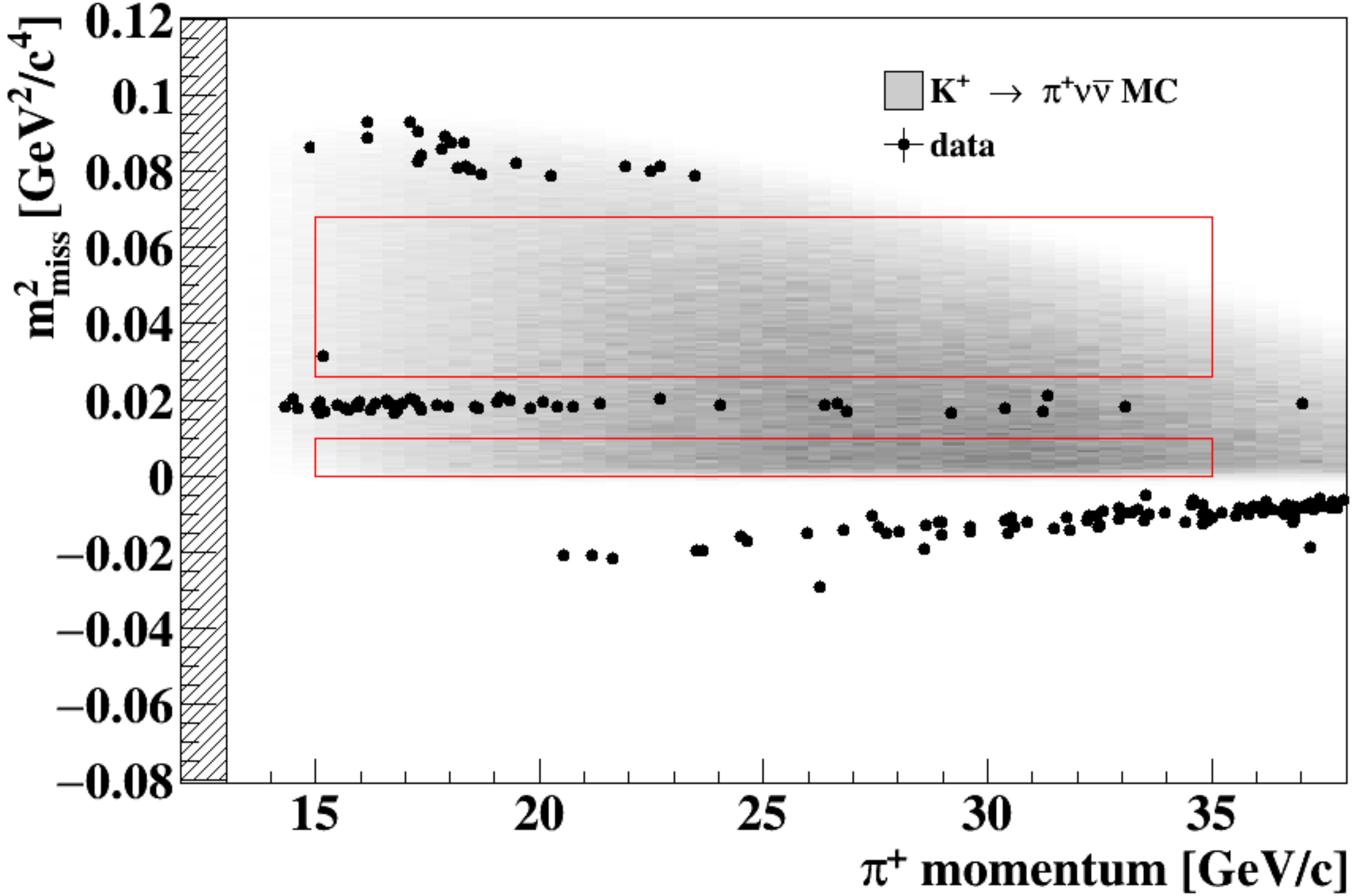
- Selection
- Evaluation of the single event sensitivity
- Background estimation and validation
- Un-blinding of signal regions and interpretation of the results

Result

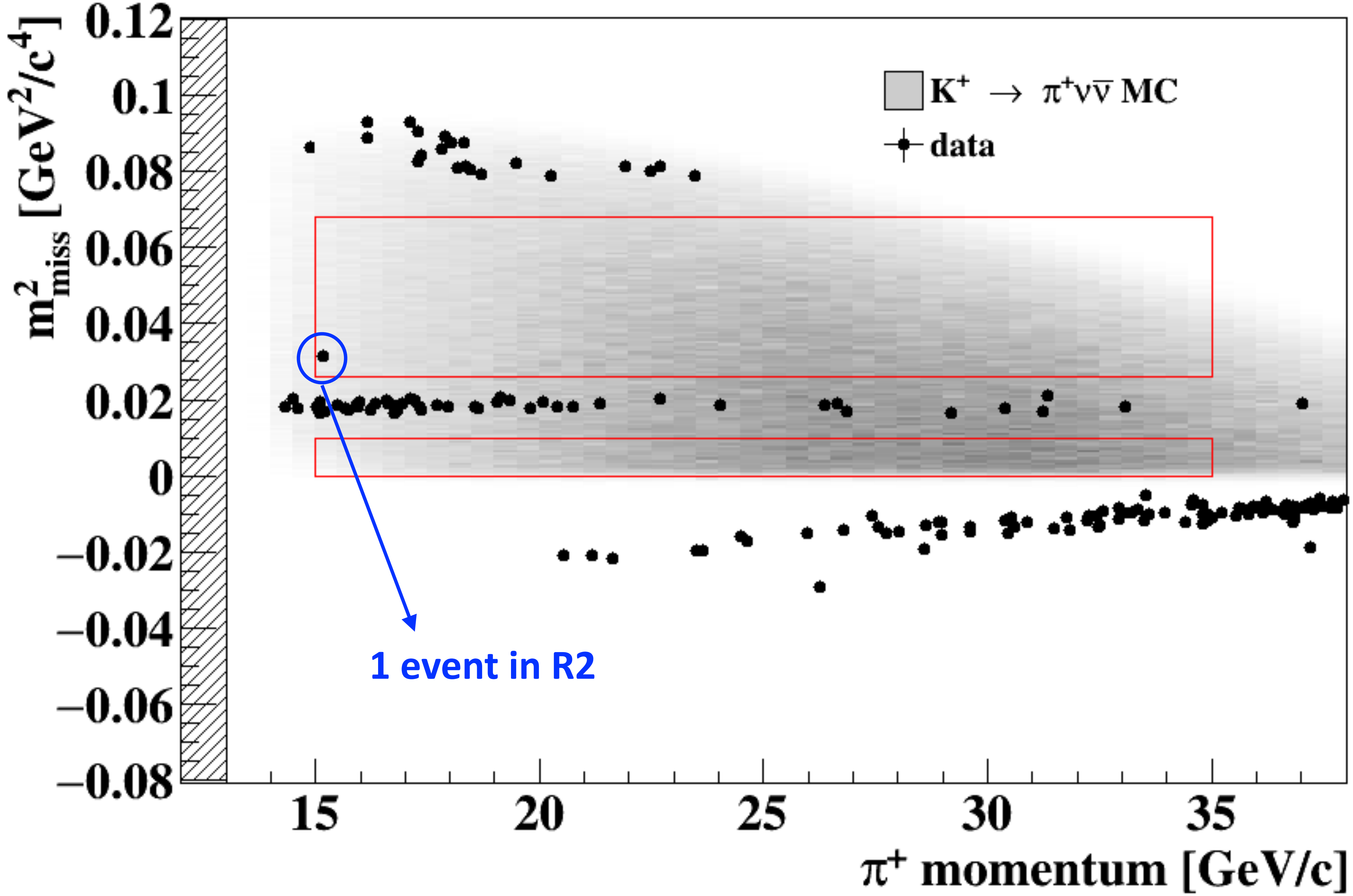


$K^+ \rightarrow \pi^+\nu\bar{\nu}$ MC
data
m^2_{miss} [GeV^2/c^4]
0.12
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
15
20
25
30
35
π^+ momentum [GeV/c]

Result

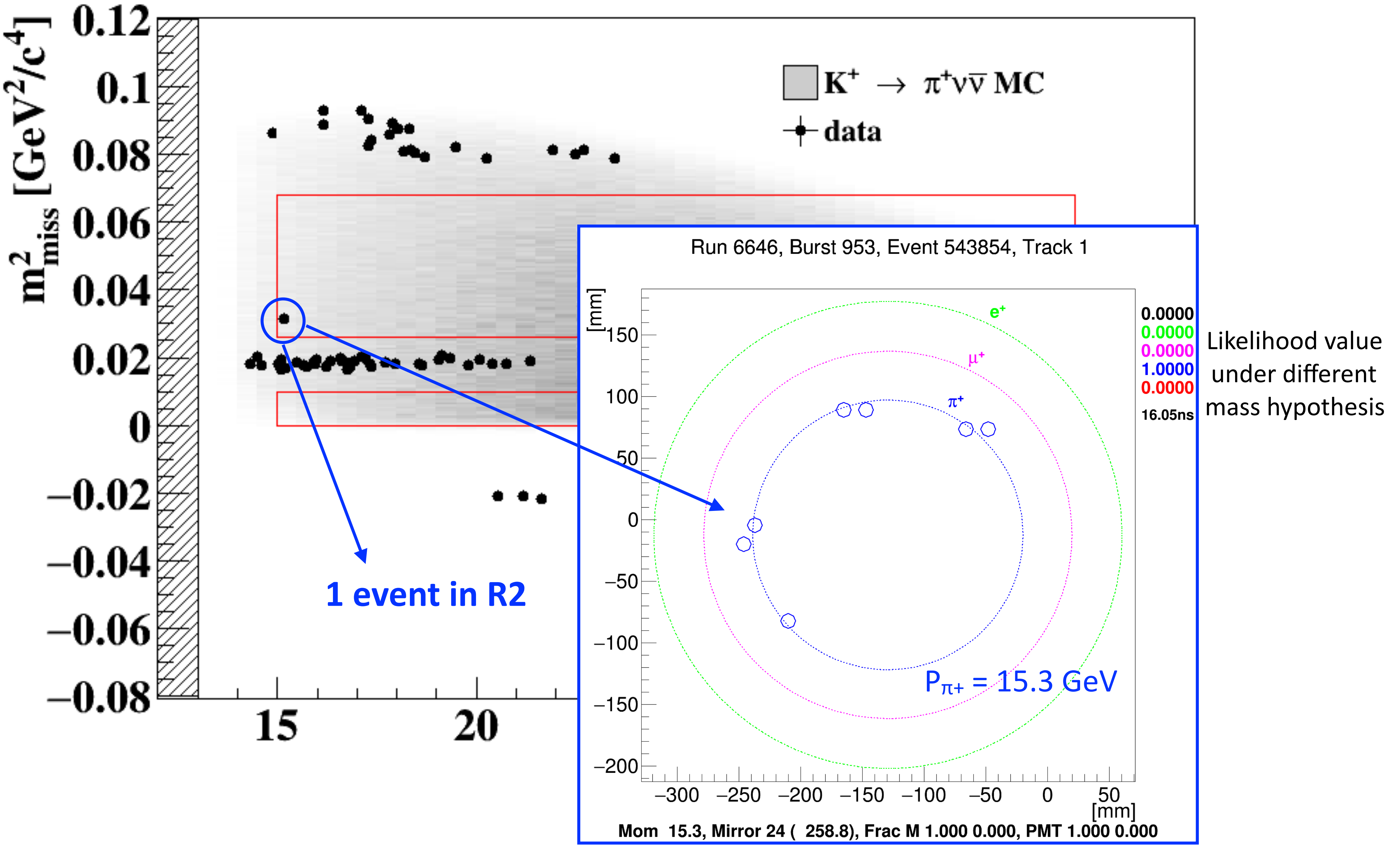

$K^+ \rightarrow \pi^+\nu\bar{\nu}$ MC
data
m^2_{miss} [GeV^2/c^4]
0.12
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
15
20
25
30
35
π^+ momentum [GeV/c]

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
1 event in R2

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
$K^+ \rightarrow \pi^+\nu\bar{\nu}$ MC
data
1 event in R2
Run 6646, Burst 953, Event 543854, Track 1
[mm]
150
100
50
0
−50
−100
−150
−200
−300 −250 −200 −150 −100 −50 0 50
[mm]
e^+
μ^+
π^+
0.0000
0.0000
0.0000
1.0000
0.0000
16.05ns
$P_{\pi+}$ = 15.3 GeV
Mom 15.3, Mirror 24 (258.8), Frac M 1.000 0.000, PMT 1.000 0.000
Likelihood value under different mass hypothesis

Preliminary Results

Event Observed	1
SES	$(3.15 \pm 0.01_{stat} \pm 0.24_{syst} \cdot 10^{-10})$
Expected Background	$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$
Expected SM $K^+ \to \pi^+ \nu\bar{\nu}$	$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$

Preliminary

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

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

$$BR(K^+ \to \pi^+ \nu\bar{\nu})_{SM} = (0.84 \pm 0.10) \times 10^{-10}$$

$$BR(K^+ \to \pi^+ \nu\bar{\nu})_{exp} = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$ BNL E949/E787 Kaon Decay at Rest

- Present result is from cut based analysis
- Full probability based analysis is under development

Conclusions

- **The new NA62 decay in flight technique to measure BR($K^+ \to \pi^+\nu\nu$) works!**
  - 1 event observed in 2016 data
  - BR($K^+ \to \pi^+\nu\nu$) < 14 x 10^{-10} @ 95% CL
- **Processing of the 2017 data is on-going**
  - 20 times more than the present statistics
  - upstream background reduction expected
  - improvements on reconstruction efficiency
- **2018 data taking on going**
  - 218 days including stops
  - studies to improve signal acceptance on going (MVA approach)

20 SM events expected before LS2

- **Running after 2018 to be approved**
  - condition for ultimate sensitivity under evaluation

Thank you for the attention from the NA62 Collaboration!

28 institutions, ~200 participants,

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