55th Scientific Committee

INFN
Istituto Nazionale
di Fisica Nucleare
Laboratori Nazionali di Frascati

NA62 results and perspectives

Silvia Martellotti
on behalf of the NA62-Frascati group

Frascati 2018, May 14th

Outline

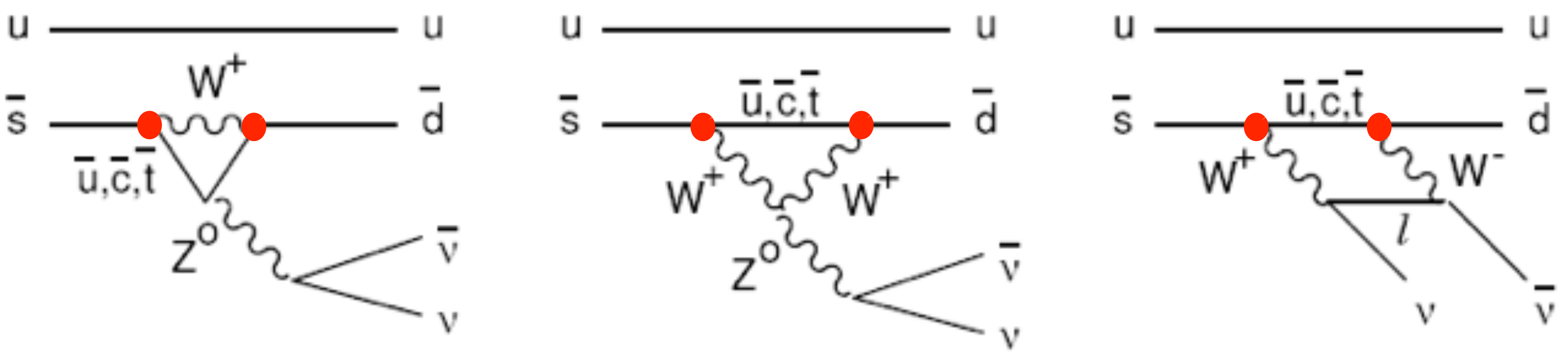
- Theoretical introduction to the K → πνν rare decays
- NA62 experiment at the CERN SPS
    - Aim and strategy for the BR($K^+ \rightarrow \pi^+ \nu\nu$) measurement
    - Results with 2016 data
    - Frascati group activities and responsibilities
    - Broader physics program
    - Prospects

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

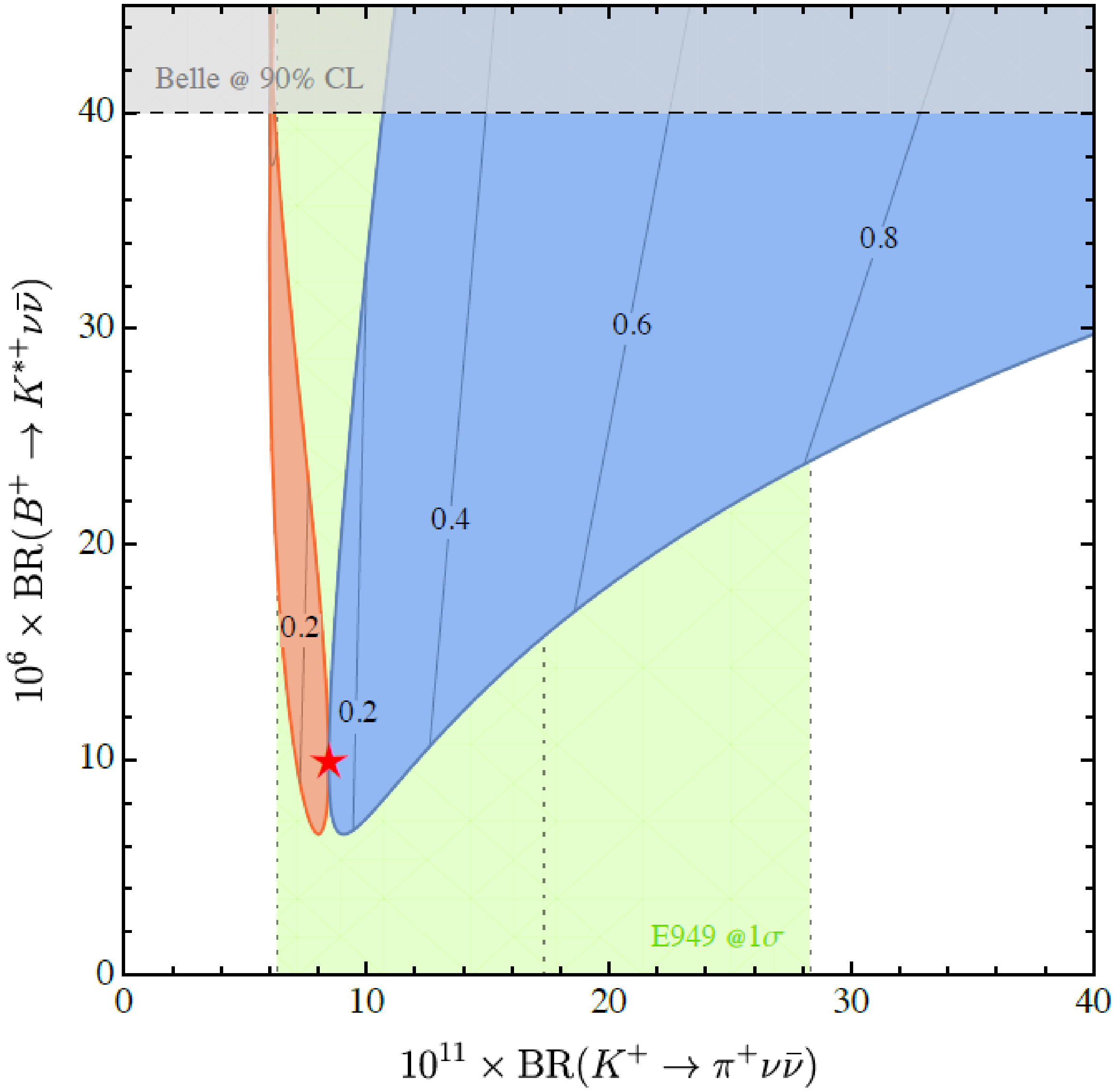
Excellent laboratory
complementary to LHC

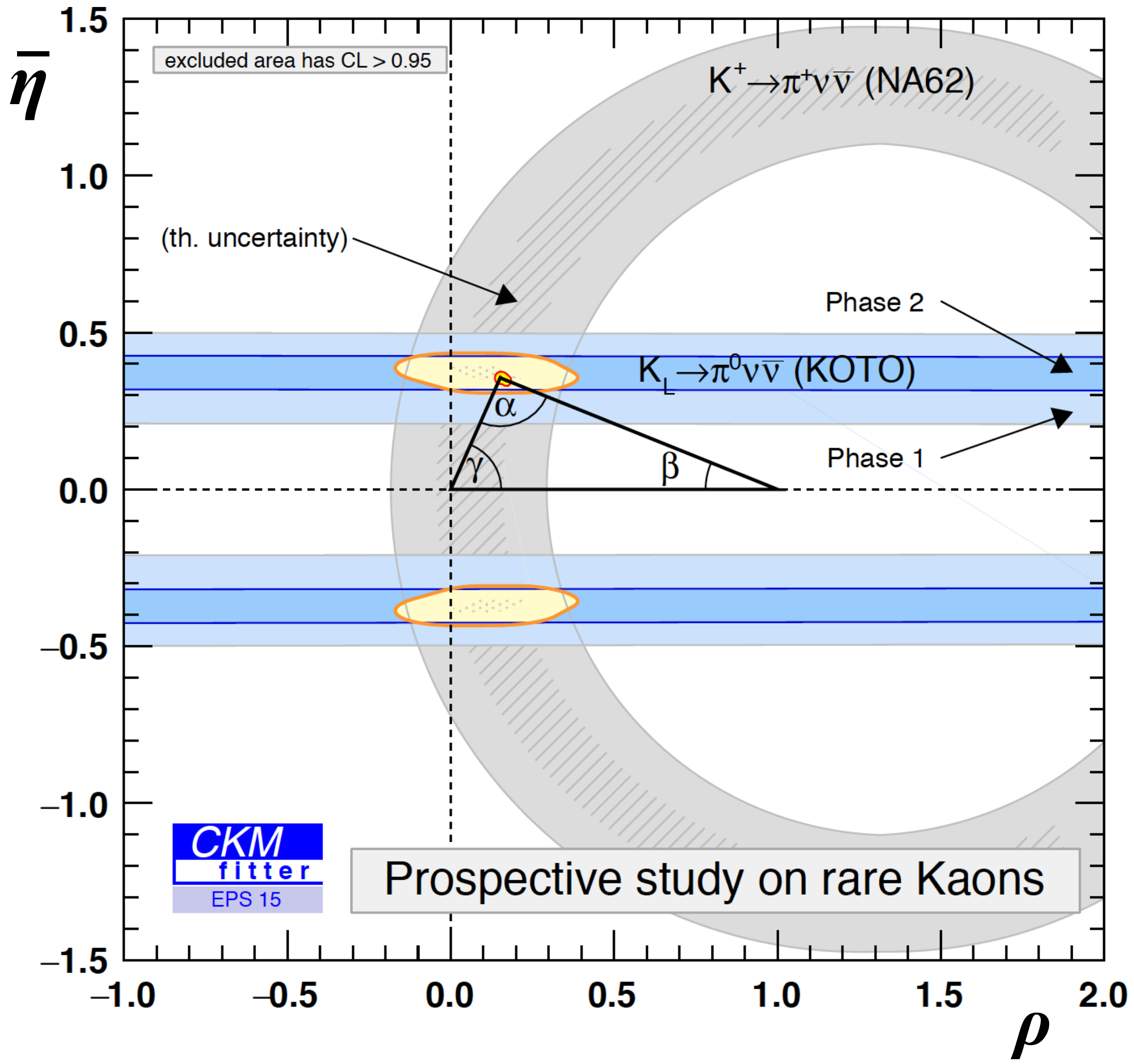
Stringent test of the SM and possible **evidence for New Physics**

New Physics from K⟶πνν decays

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

and can discriminate among NP scenarios:





Prospective study on rare Kaons

LFU violation models

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

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

Past measurement and prediction

Current theoretical prediction:

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

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

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

Experimental status:

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

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

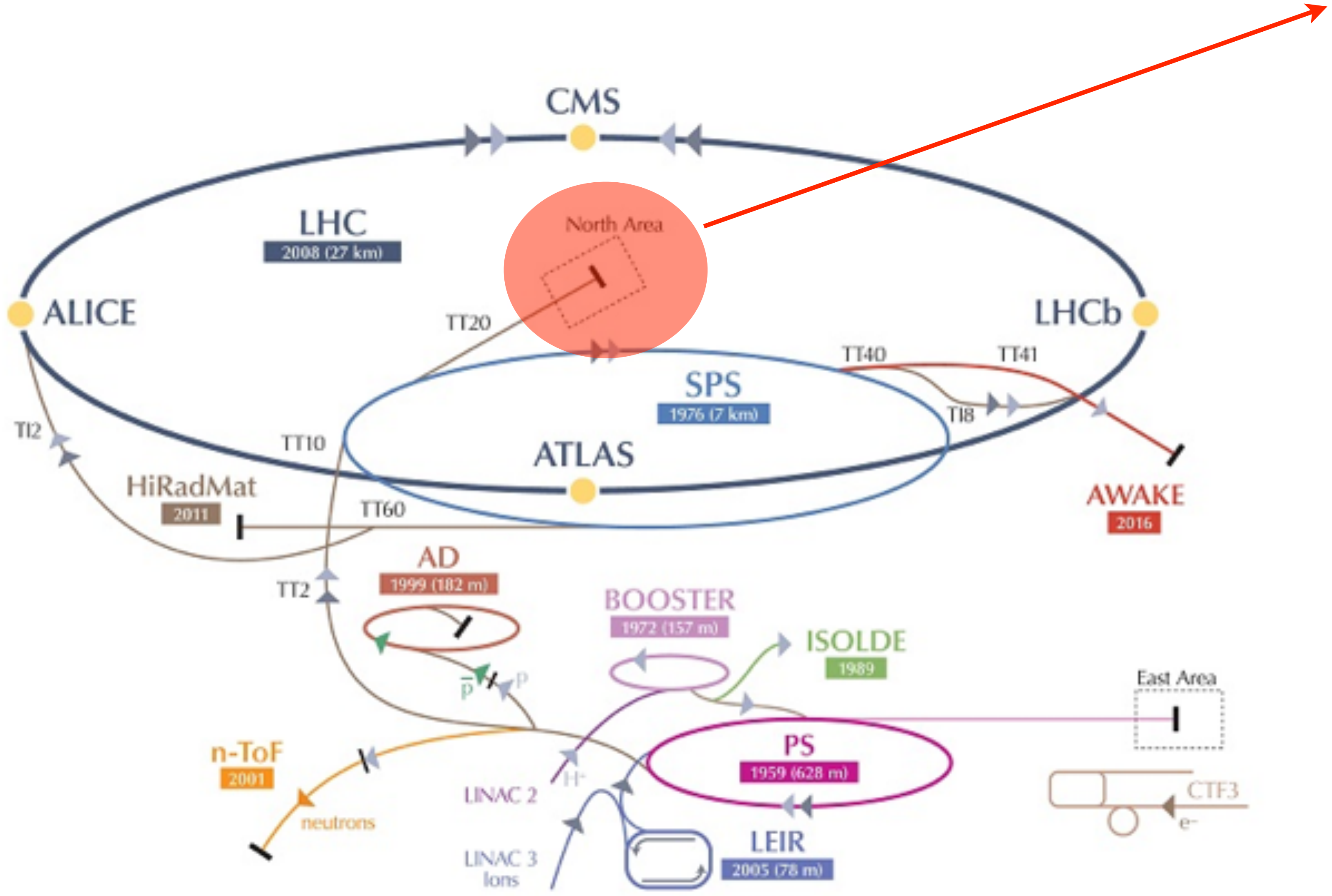
- Gap between theoretical precision and large experimental error motivates a strong experimental effort. **Significant new constraints can be obtained.**

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

NA62 GOAL: measure $BR(K^+ \rightarrow \pi^+ \nu\nu)$ with 10% accuracy
O(100) SM events + control of systematics at % level

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 x 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 x 10^{12} K^+ decays/year

NA62 Experiment

270 m long downstream of the target
Cylindrical shape around the beam axis for the main detectors (diameters from 20 to 400 cm.)

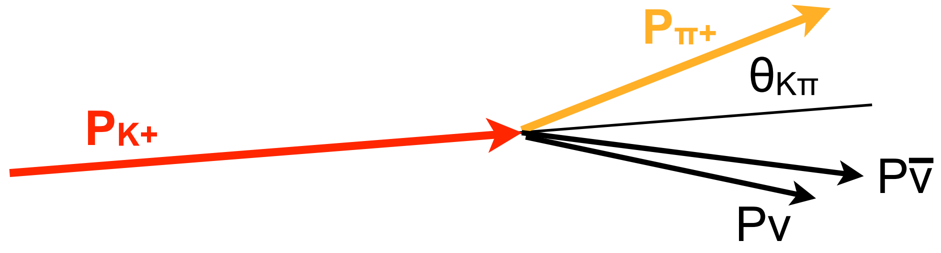
NA62 Goal

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

Key features

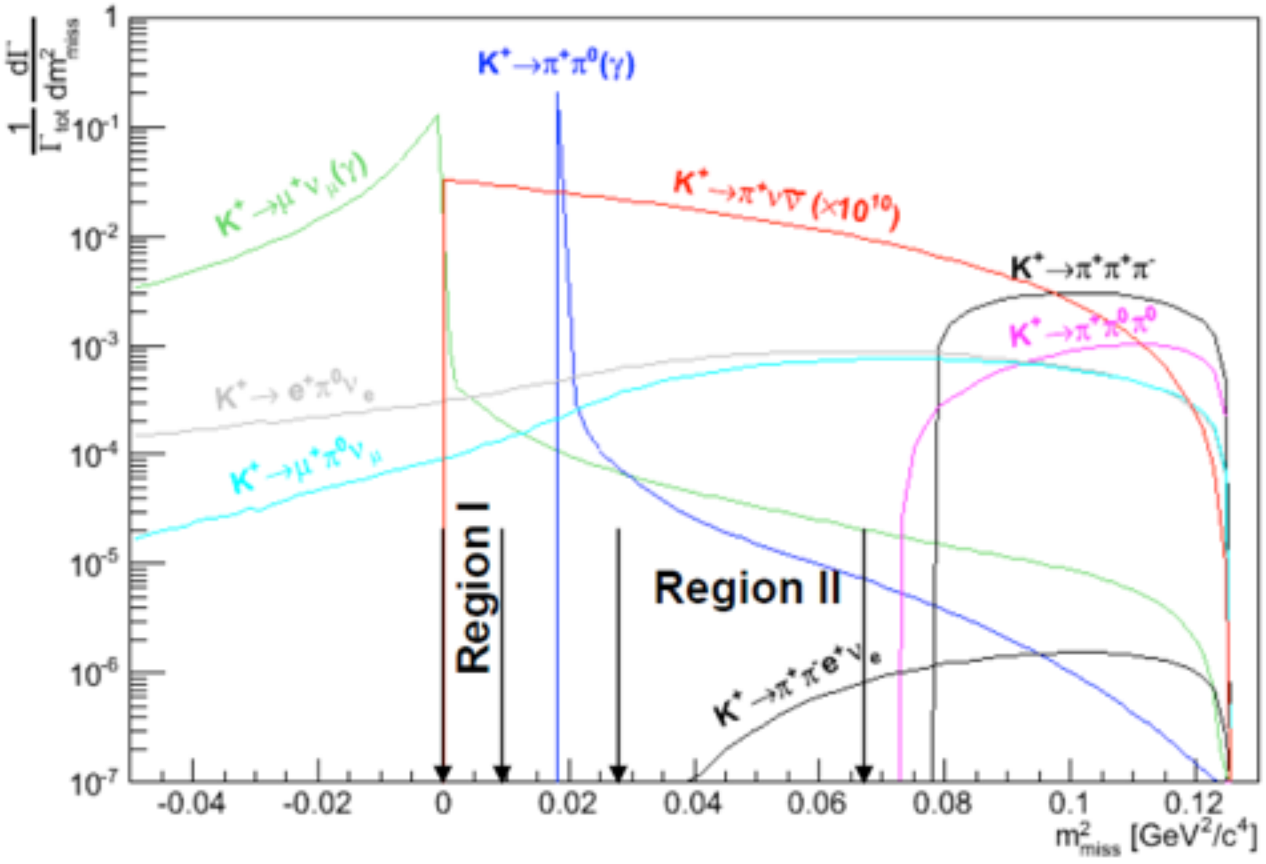
- O(100 ps) Timing between sub-detectors
- O(10^4) Background suppression from kinematics
- O(10^7) μ-suppression ($K^+ \to \mu^+\nu$)
- O(10^7) γ-suppression (from $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\gamma$)

Analysis Strategy

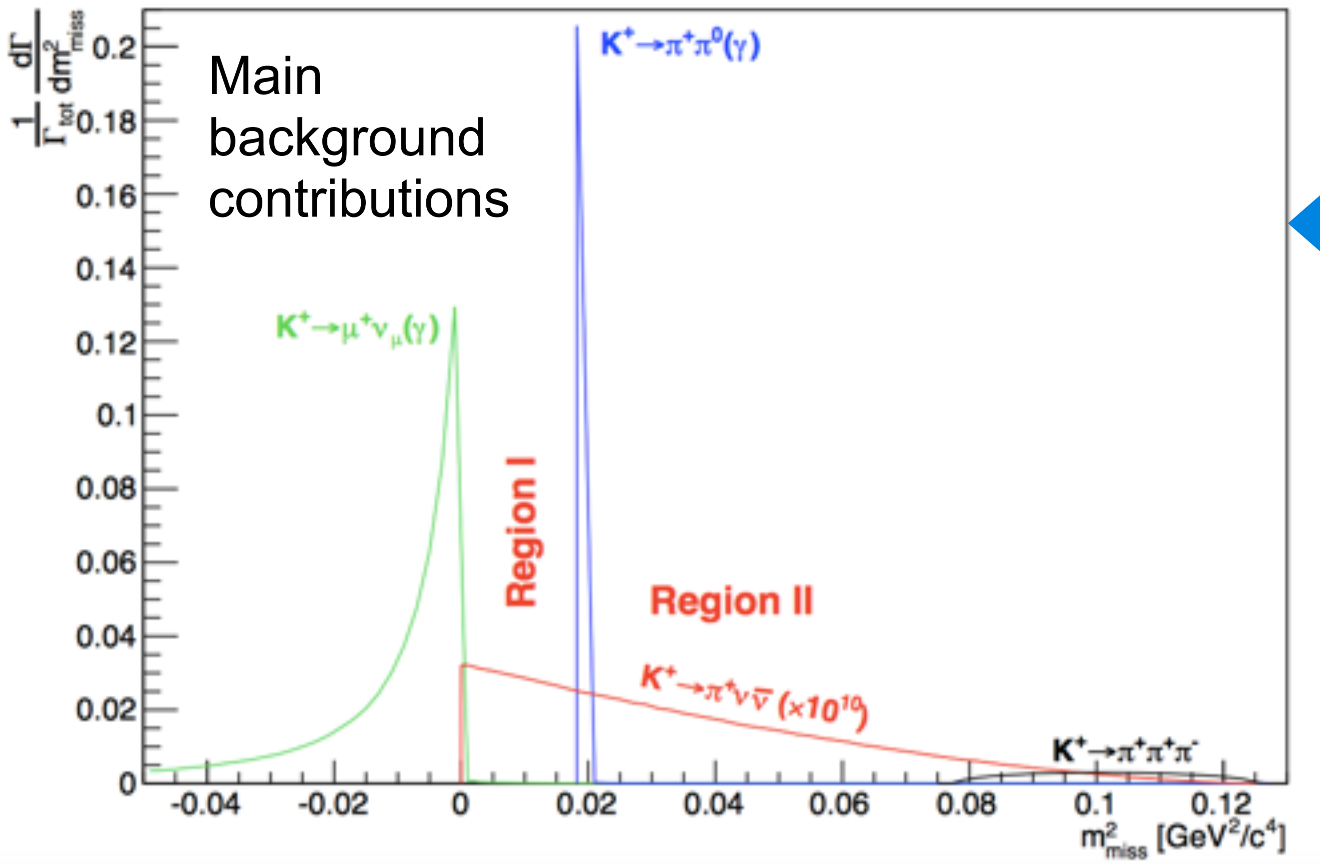
Most discriminating variable:
$m^2_{miss} = (P_{K+} - P_{\pi+})^2$

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:

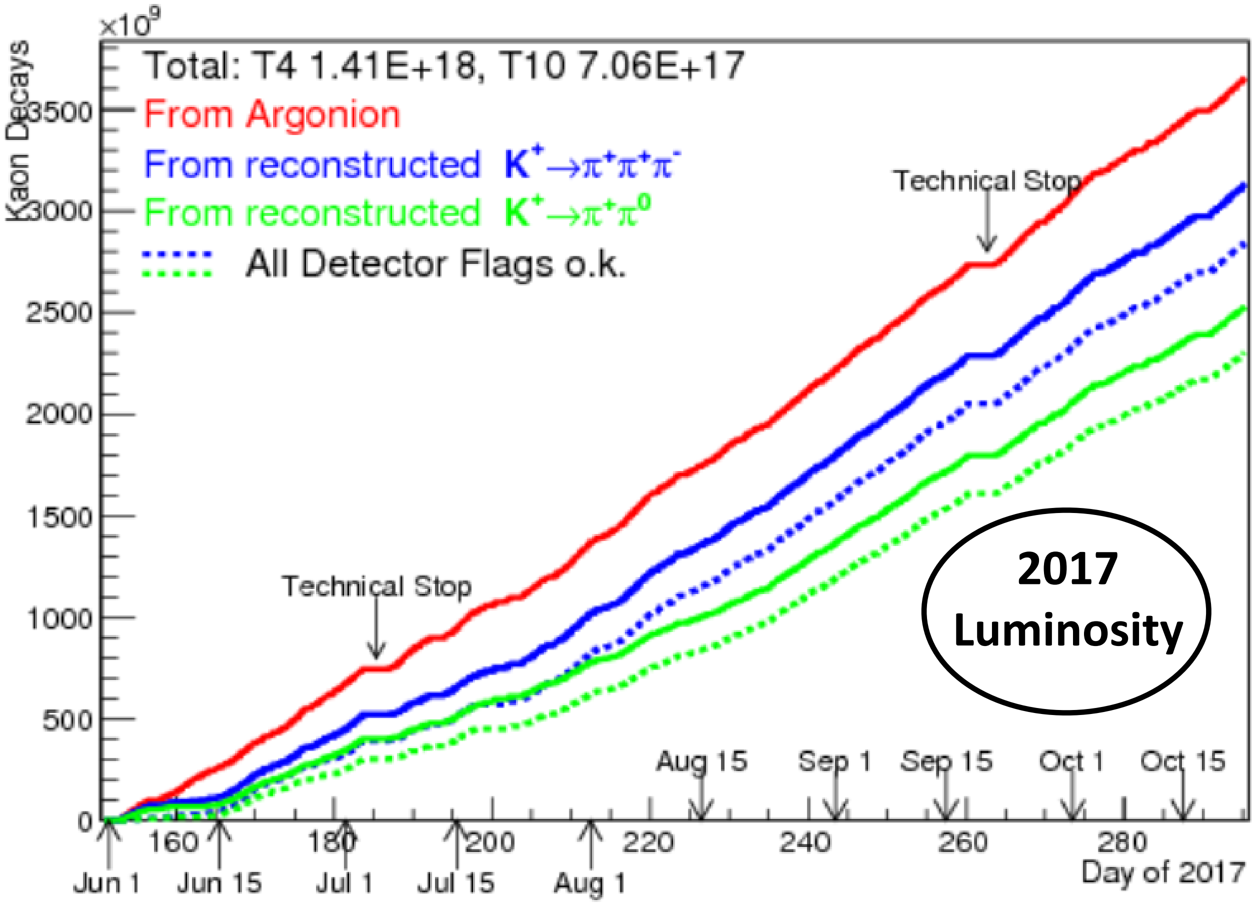
- $K^+ \to\pi^+\pi^0$, $K^+ \to\mu^+\boldsymbol{\nu}$ non gaussian resolution and radiative tails
- $K^+ \to\pi^+\pi^+\pi^-$ non gaussian resolution tails
- decays with neutrino in final state

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 $\pi\nu\nu$**

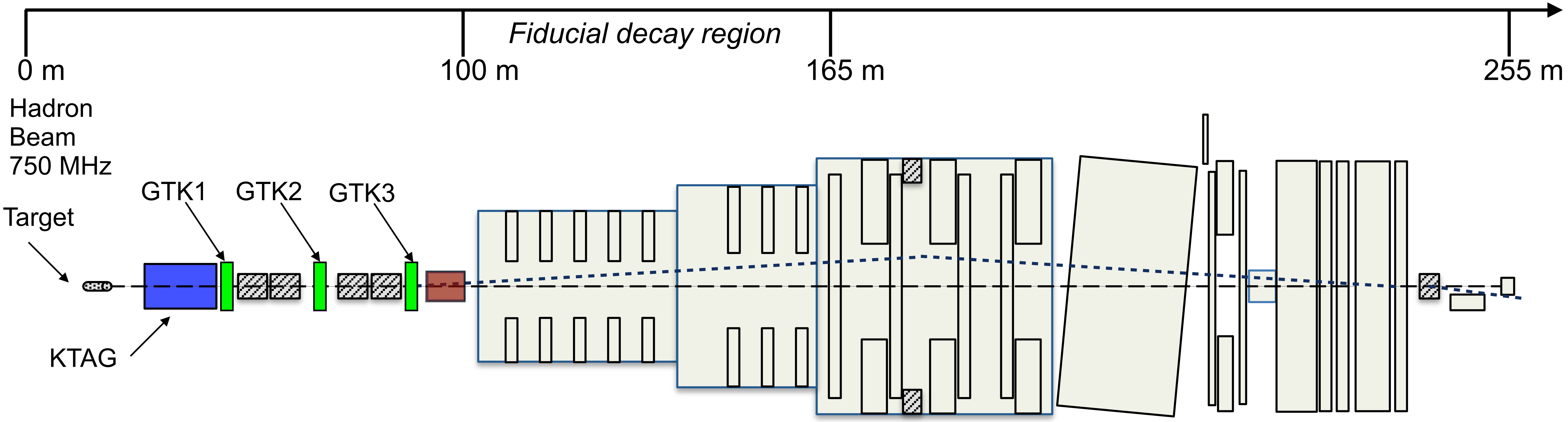
2017: 60% of nominal intensity: 20 x 10^{11} proton on target **> 3 x 10^{12} K^+ decays collected**



beam fluctuations reduced

2018 data taking started in the same conditions of 2017 with optimized data quality monitoring

NA62: Beam ID & Tracking

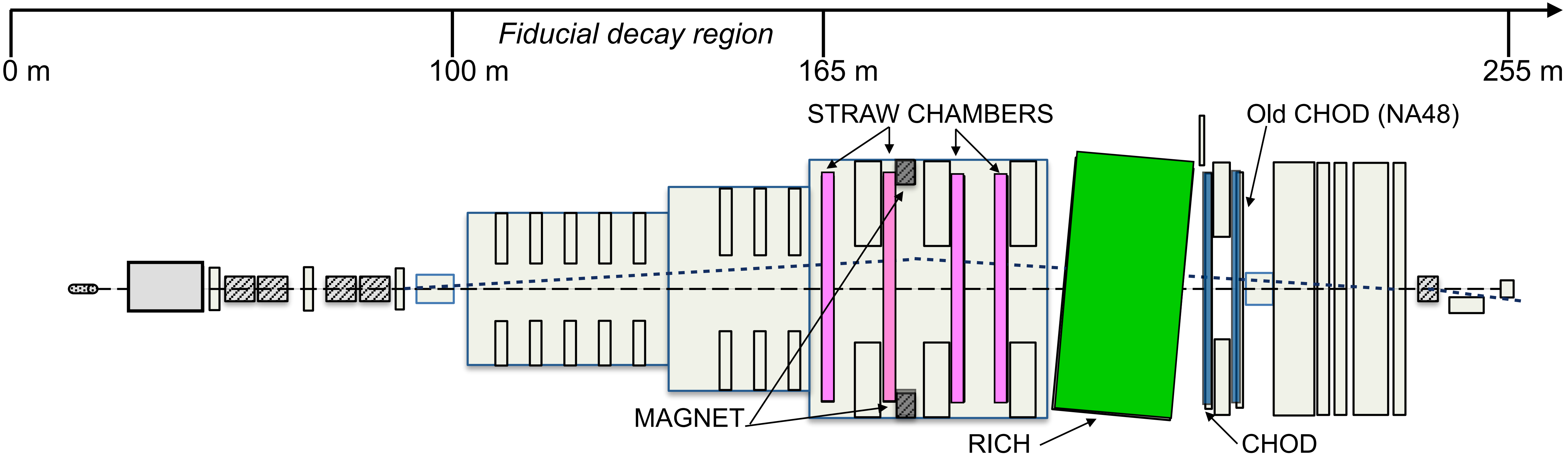


Beam ID & Tracking

KTAG: Differential Čerenkov counter. **σ_t ~70 ps, efficiency > 99%.**

GTK: GigaTracKer Spectrometer. **σ_t ~100 ps, $\sigma_{dx,dy} \approx 0.016$ mrad, $\Delta P/P < 0.4\%$.**

NA62: Secondary ID & Tracking



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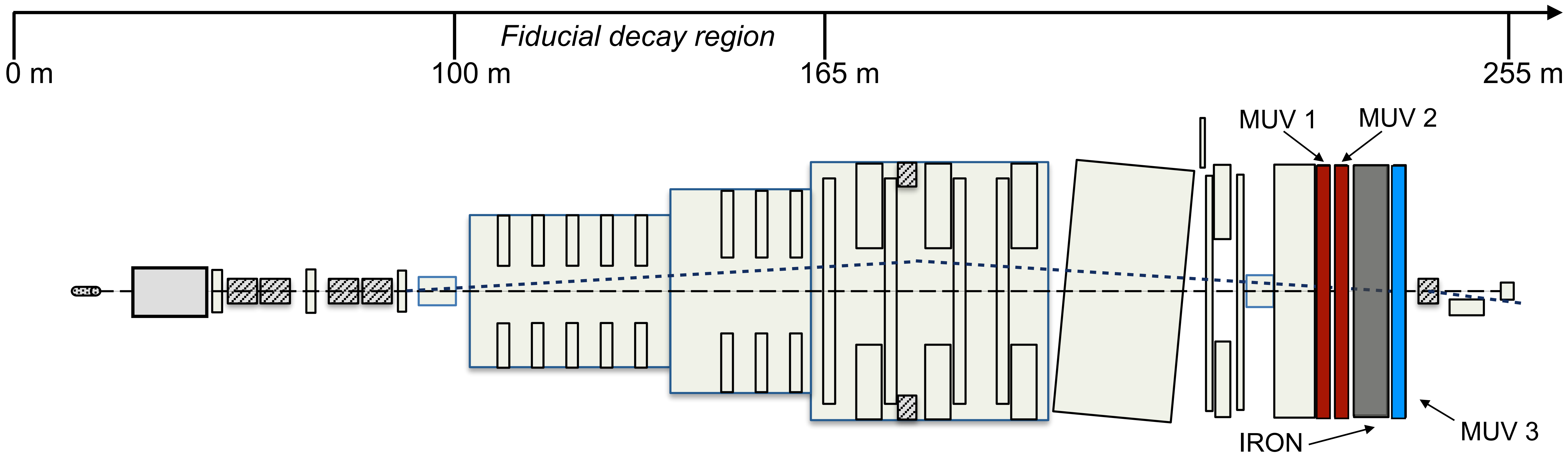
Secondary particle ID & Tracking

STRAW: Spectrometer with STRAW tubes. **σ_t ~ 6 ns, $\sigma_{dx,dy}$ ~130 µm.**

RICH: Ring Imaging Cherenkov detector. **µ/π separation ~ 10^{-2}, σ_t of a ring < 100 ps.**

NA62: Muon Veto System



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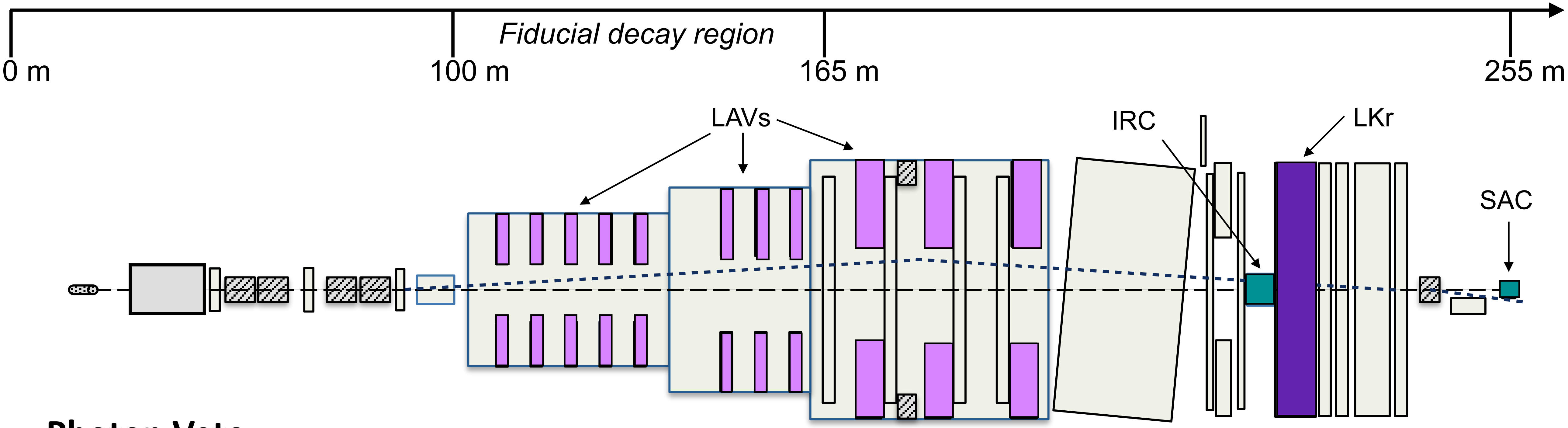
Muon Veto

MUV3: Scintillator hodoscope. **σ_t ~500 ps, efficiency ~99.5%.**

MUV1/2: Hadronic calorimeters for the µ/π separation. **Cluster reco at ~20 ns from T_{track}.**

NA62: Photon Veto System

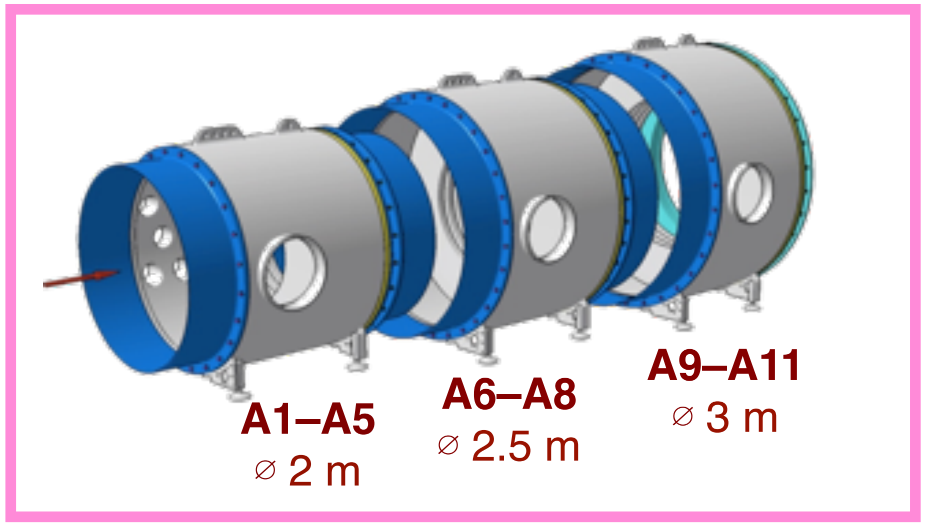


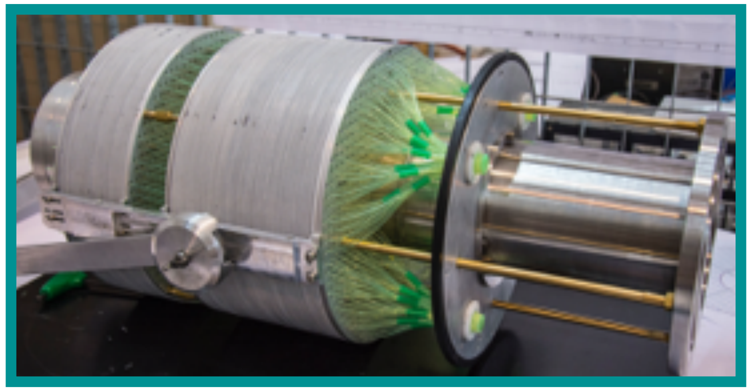
Photon Veto

LKr: NA48 LKr Calorimeter (1 <$\theta\gamma$<8.5 mrad) also for PID.
σ_t~500 ps (E > 3 GeV), σ_t~1 ns (hadronic and MIP clusters), $\sigma_{dx,dy}$ ~1 mm

LAV: Large Angle Veto. 12 stations (8.5 <$\theta\gamma$ <50 mrad).
4 or 5 rings of lead glass crystals read out by PMTs.
σ_t ~ 1 ns, 10^{-3} to 10^{-5} inefficiency (down to 150 MeV).

IRC/SAC: Inner Ring Calorimeter and Small Angle Calorimeter ($\theta\gamma$ <1 mrad). Shashlik calorimeters. Lead and plastic scintillator plates. **σ_t < 1 ns, 10^{-4} inefficiency.**





LNF responsibilities in NA62

Large Angle (LAV) and Small Angle (SAV) photon veto detectors

- Coordination of the photon veto system (fully constructed at LNF, calibrated and commissioned by Frascati group)
- Data quality monitoring and performance evaluation
- Experts support during data taking

L1 Trigger streams

- Development and optimization of algorithms; performance monitoring
- Experts support during data taking

Run coordination

Coordination of hidden sector analysis

PHYSICISTS: Antonella Antonelli, Gaia Lanfranchi, Gianpaolo Mannocchi, Silvia Martellotti, Matteo Martini, Matthew Moulson, Tommaso Spadaro.
Associates: Georgi Georgiev, Venelin Kozhuharov (Sofia).
TECHNICIANS: Rosario Lenci, Vincenzo Russo, Sauro Valeri, Tania Vassilieva, Giovanni Corradi, Diego Tagnani, Cesidio Capoccia, Emilio Capitolo.

2016 Data

First data declared good for $\pi\nu\nu$. 4 weeks of data taking. ~55000 good spills

Trigger streams

PNN Trigger

Hardware L0: RICH, CHOD, MUV3 (Veto), LKr ($E < 20$ GeV) **(~400 kHz)**

Software L1: KTAG, LAV (Veto), STRAW (momentum < 50 GeV/c). **(~20 kHz)**

Control Trigger Downscaling 400 (~32 KHz)

Hardware L0: CHOD

Offline Analysis

Data Sample

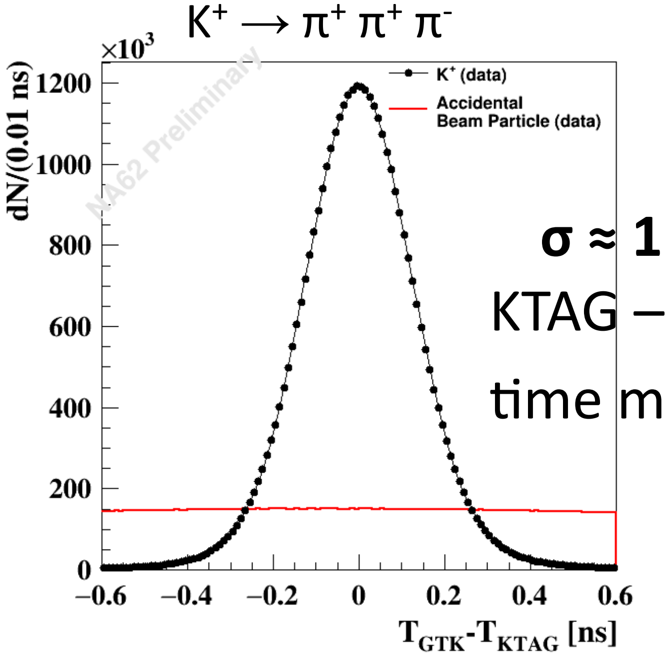
$K^+ \rightarrow \pi^+\pi^0$, $K^+ \rightarrow \mu^+\nu$, $K^+ \rightarrow \pi^+\pi^+\pi^-$ samples for background estimation

- 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 masked throughout the analysis

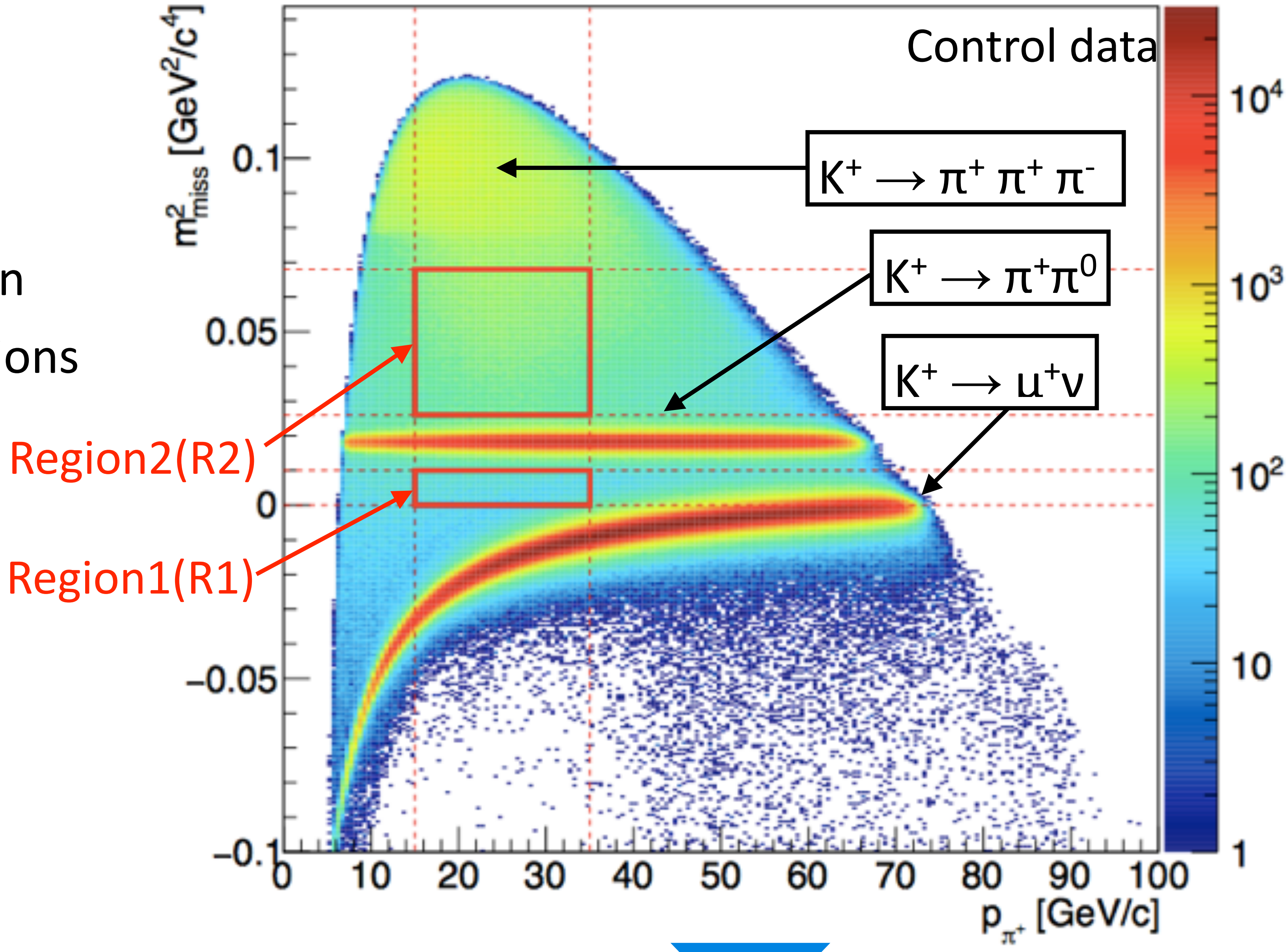
Kinematic selection of signal regions

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



$\sigma \approx 110$ ps

KTAG –GTK –RICH time matching



- 110 < Z_{vertex} < 165 m

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

(to leave at least 40 GeV of E_{mis})

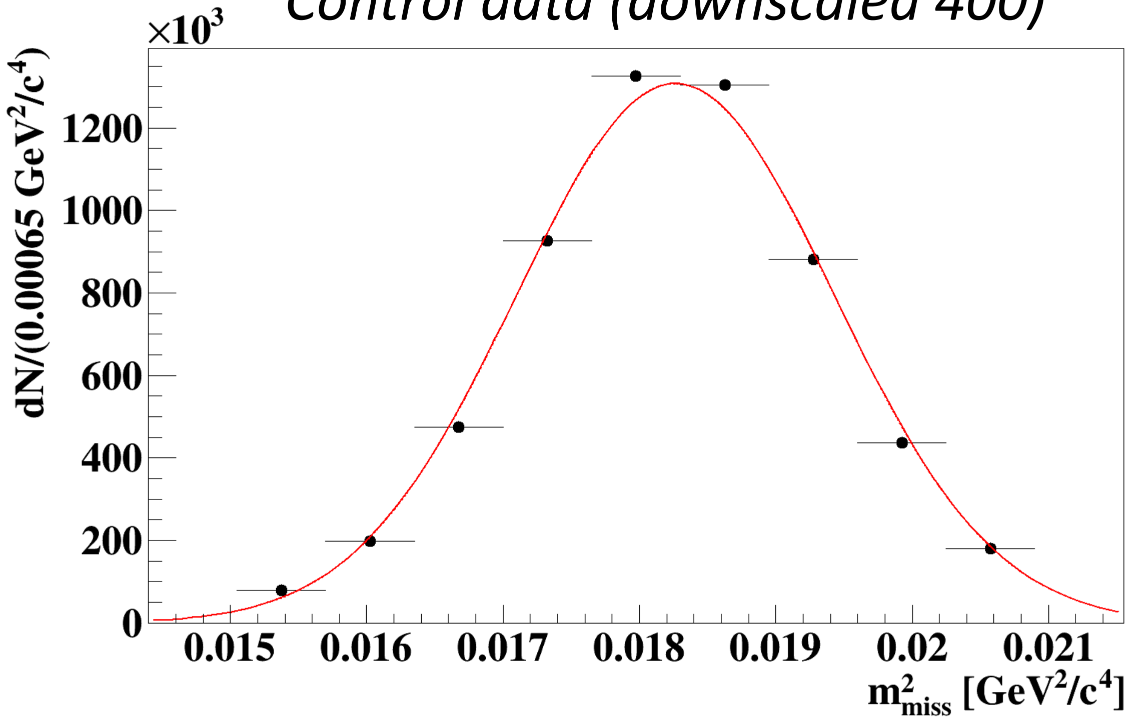
$m^2_{miss} \equiv m^2_{miss}$ (GTK, STRAW) = $(P_K - P_\pi)^2$

with m_π hypothesis

Photon rejection

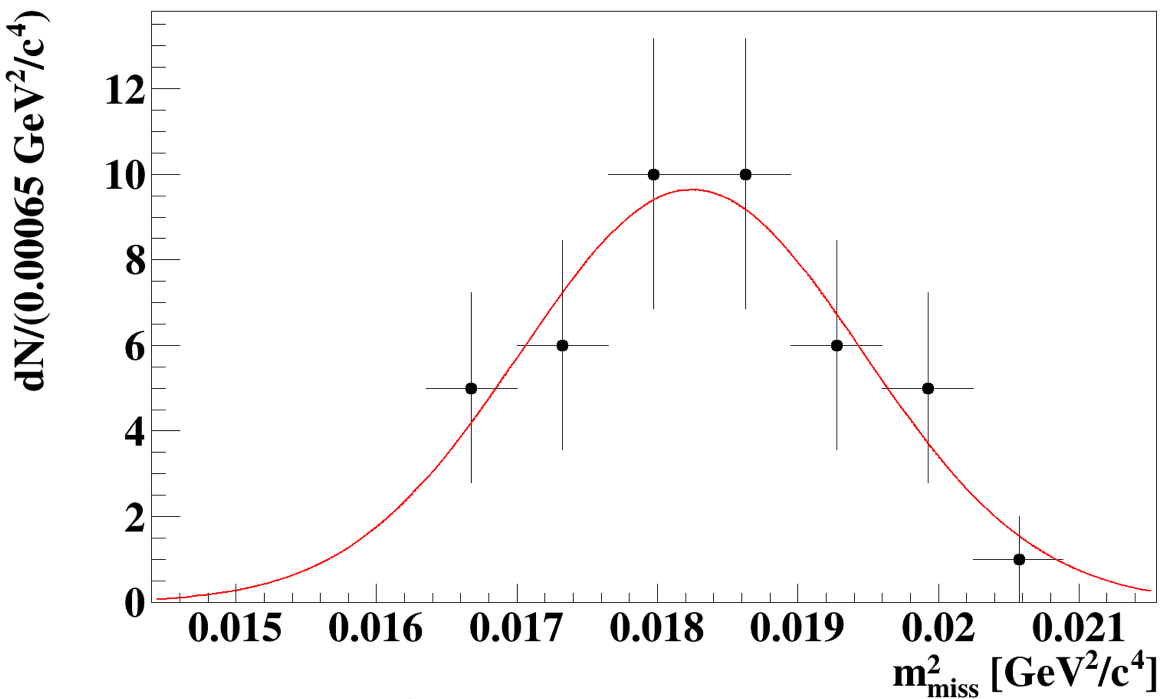
Events are rejected in case of coincidence between decay time and signals (±3-5 ns) in the LKr, LAV, SAC, IRC or hodoscope not associated to the π^+

Control data (downscaled 400)



$K^+ \rightarrow \pi^+\pi^0$ events before the γ rejection (minimum bias trigger)

PNN data

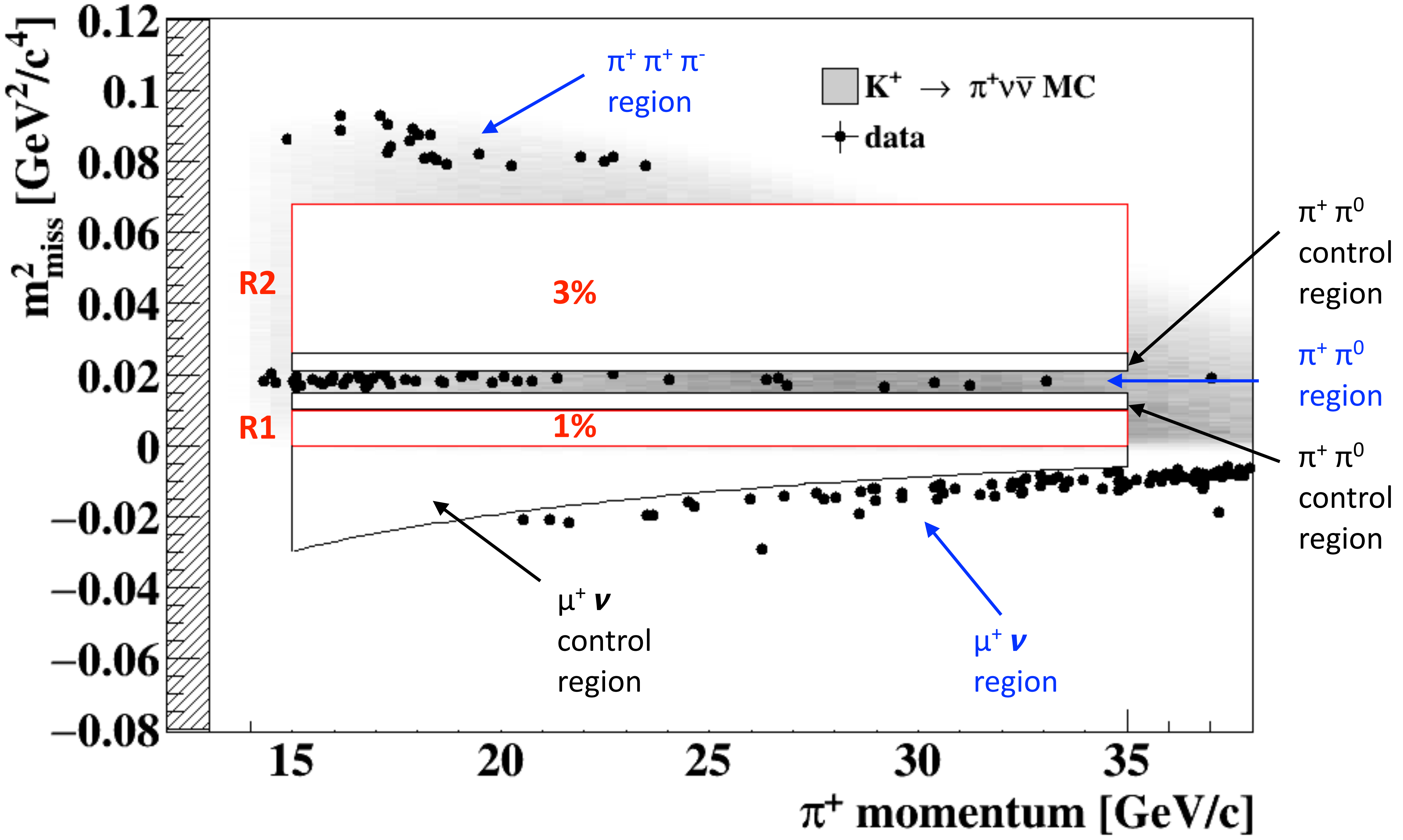


$K^+ \rightarrow \pi^+\pi^0$ events after γ rejection (PNN trigger):

The expected rejection is obtained with an estimate based on single-photon efficiencies

Fraction of surviving $K^+ \rightarrow \pi^+\pi^0$ (15 – 35 GeV momentum range) : ~$2.5 \cdot 10^{-8}$

Data after selection



Single Event Sensitivity (SES)

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

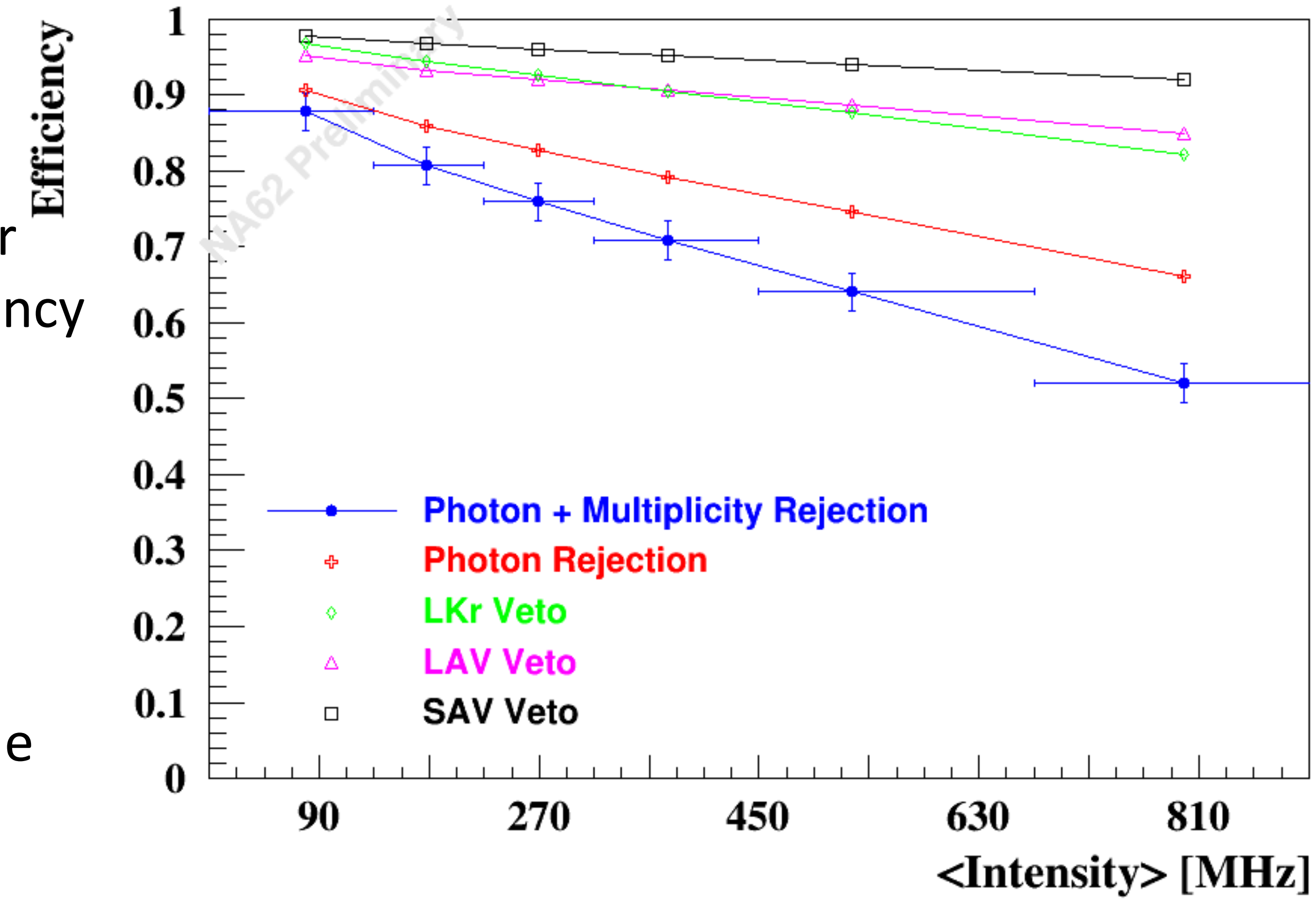
j = π^+ momentum bin

number of K^+ decays

signal acceptance

random veto efficiency

trigger efficiency



Random veto

- Signal efficiency losses due to random activity in the veto detectors
- Estimated on data using a $K^+ \rightarrow \mu^+\nu$ sample (ratio of events selected before and after the γ and multiplicity cuts)

Number of K^+ decays	$N_K = (1.21 \pm 0.02) \times 10^{10}$
Acceptance $K^+ \rightarrow \pi^+\nu\bar{\nu}$	$A_{\pi\nu\nu} = 4.0 \pm 0.1$
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 $K^+ \rightarrow \pi^+\nu\bar{\nu}$	$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$

Error on the SM BR

Background estimation

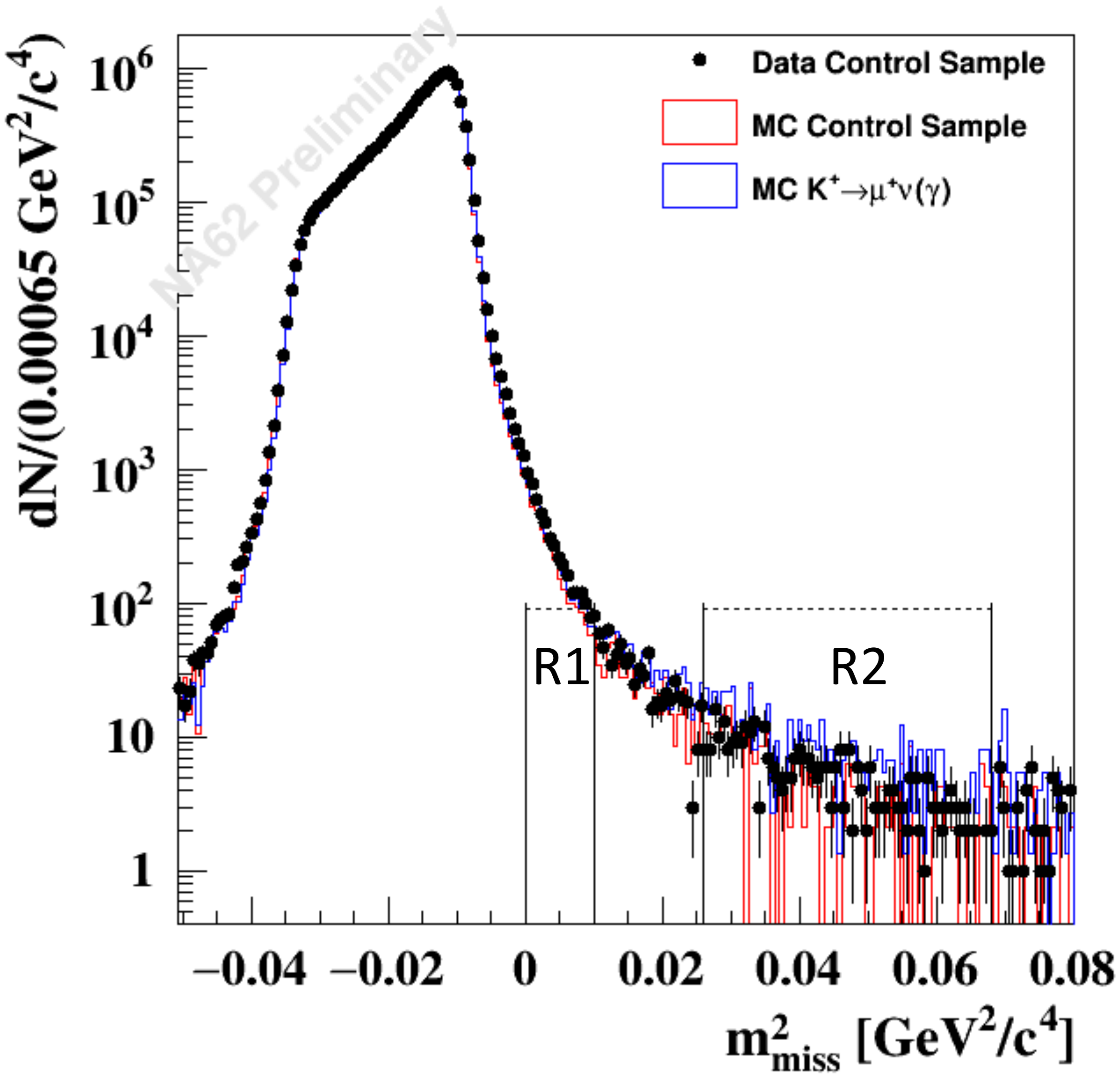
$$\underbrace{N_{bkg}^{exp}(R1/R2)}_{\text{Expected background events in region 1/2}} = \sum_{j} \left[\underbrace{N(bkg)_j}_{\text{bkg events after } \pi\nu\nu \text{ selection}} \cdot \underbrace{f_j^{kin}(R1/R2)}_{\text{Fraction of events in region 1/2}} \right]$$

Expected background events in region 1/2

π^+ momentum bin

bkg events after $\pi\nu\nu$ selection

Fraction of events in region 1/2



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

- **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)**

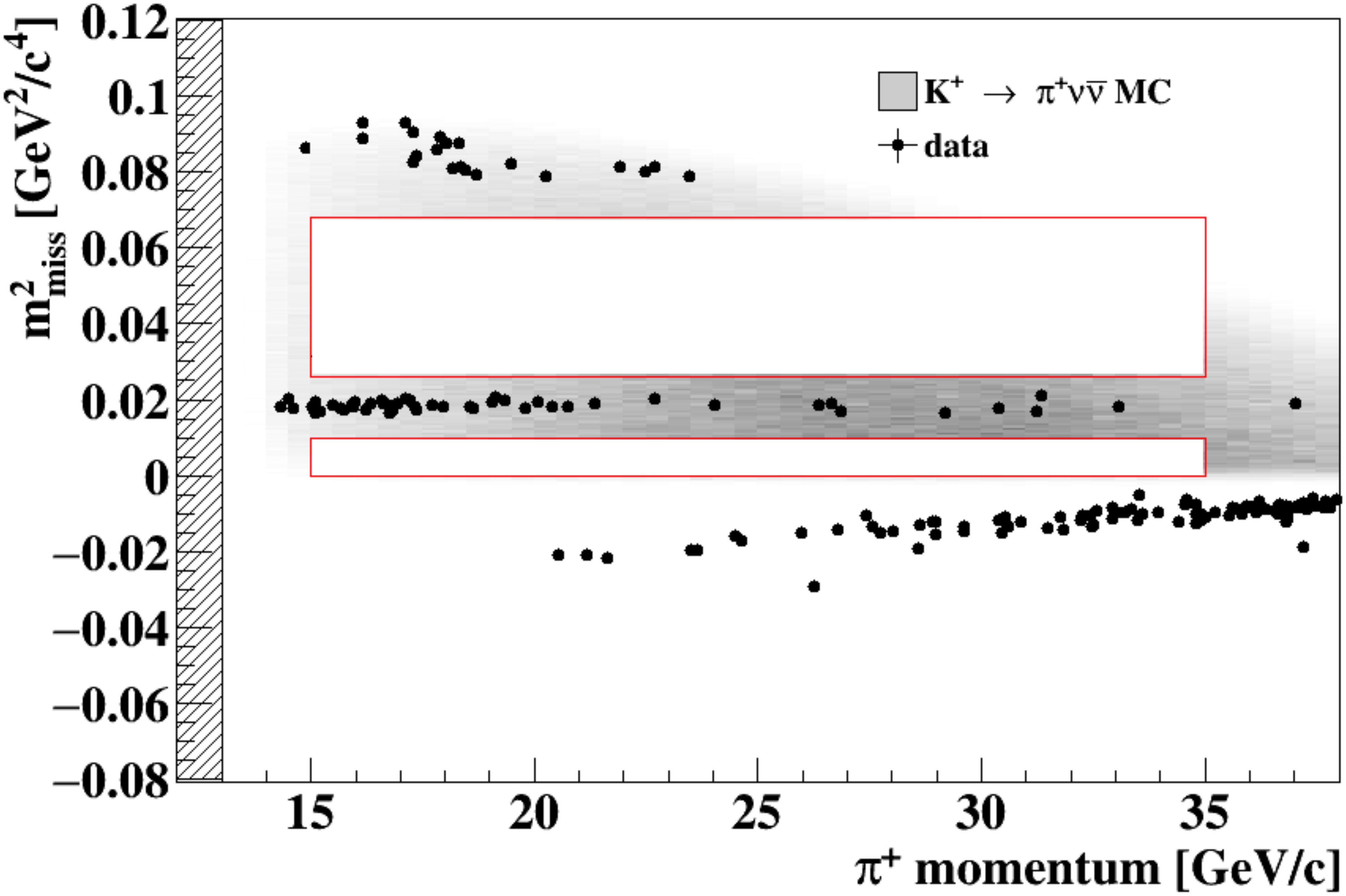
Summary of expected events

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

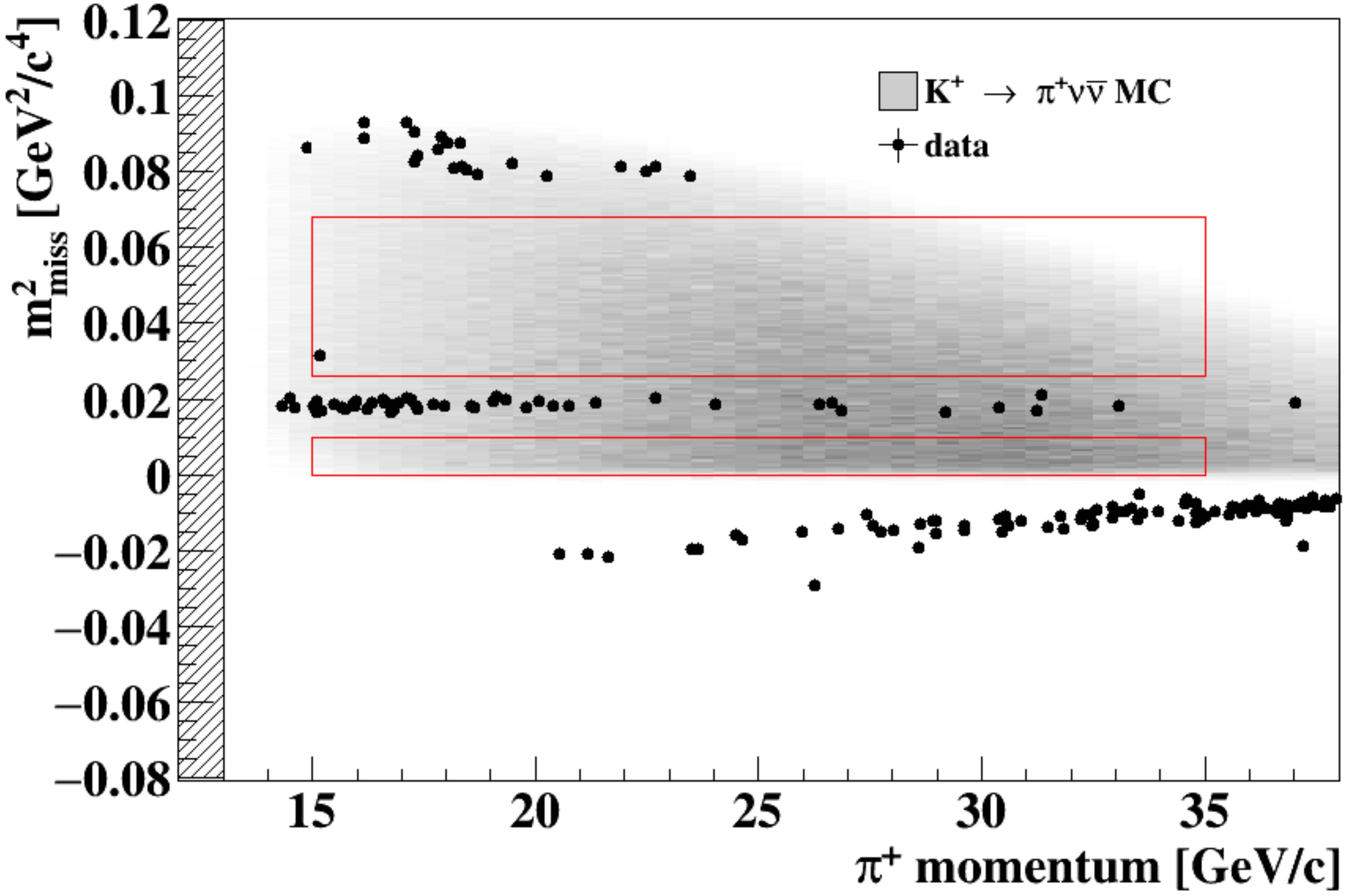
* The upstream background (π^+ from a upstream decays or beam particle interactions in GTK) might be relevant. In 2016 data analysis tight geometrical cuts are employed to keep it under control causing up to 30-40% signal acceptance reduction

- In the final part of 2017 data-taking a copper plug was inserted in to the last dipole to mitigate this issue
- Upstream background will be further reduced when a new final collimator that covers a much larger area in the transverse plane is installed in mid-June 2018.

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

Result


$K^+ \rightarrow \pi^+\nu\bar{\nu}$ MC
data
0.12
0.1
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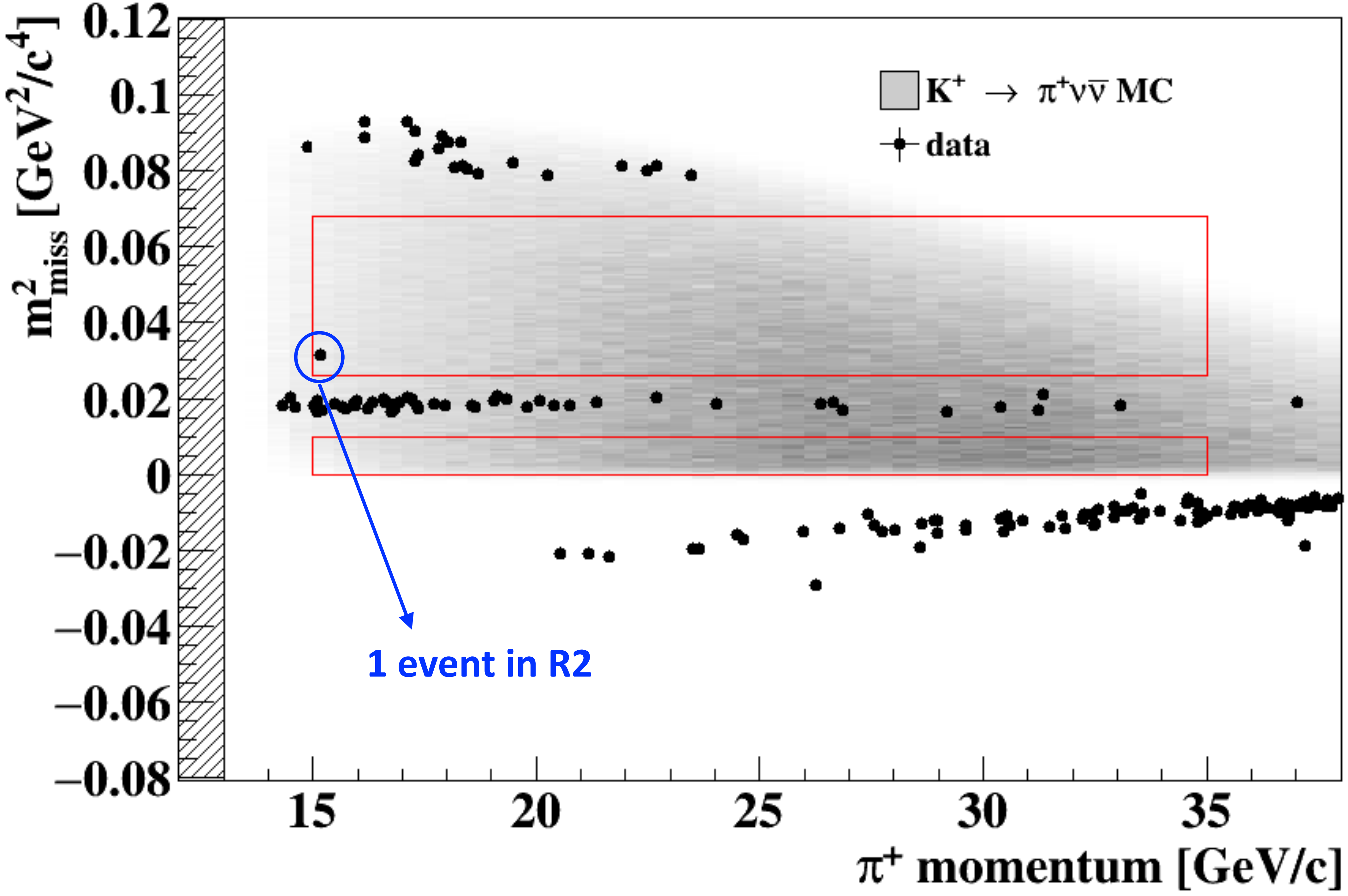
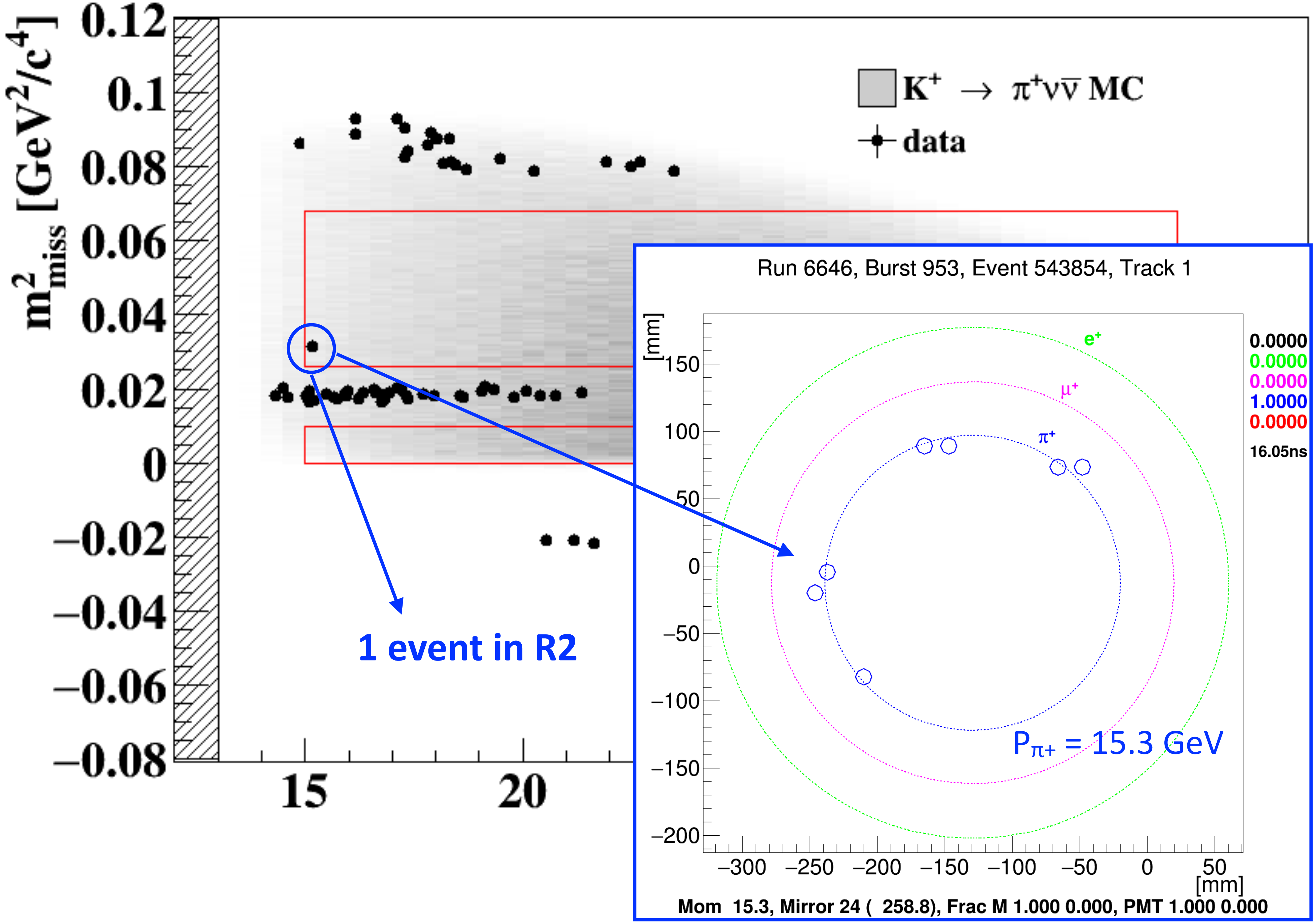
Result



1 event in R2

Result



1 event in R2

$P_{\pi+}$ = 15.3 GeV

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($K^+ \rightarrow \pi^+ \nu\nu$) works!

- 1 event observed in 2016 data
- BR($K^+ \rightarrow \pi^+ \nu\nu$) < 14×10^{-10} @ 95% CL

Processing of the 2017 data is ongoing

- 20 times more than the present statistics
- upstream background reduction expected
- improvements on reconstruction efficiency

2018 data taking ongoing

- studies to improve signal acceptance ongoing (MVA approach)

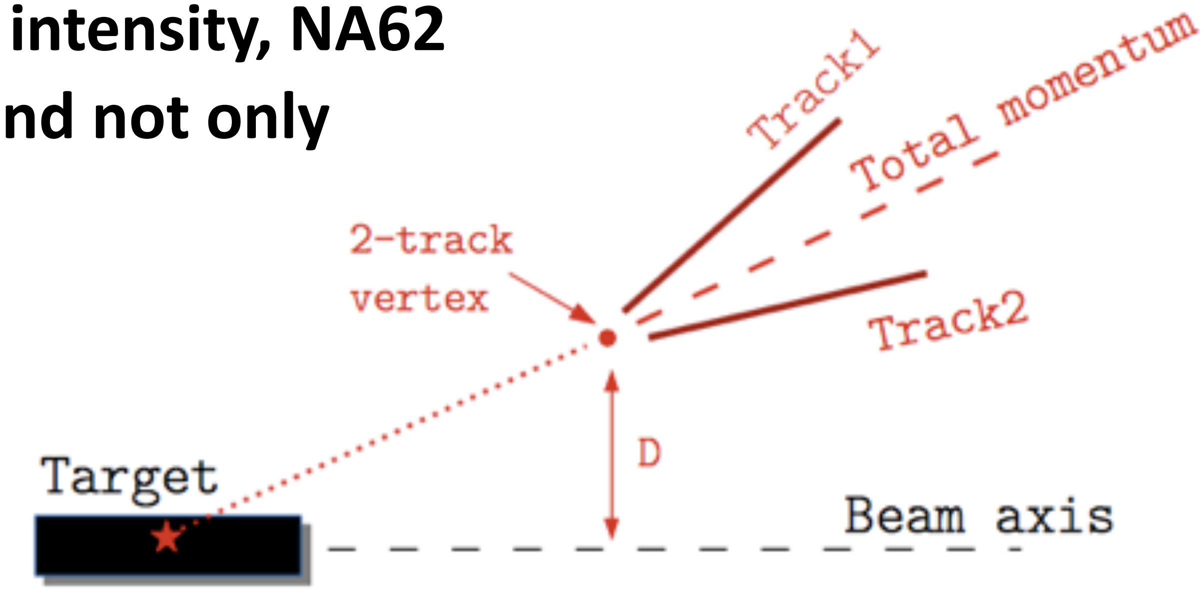
~ 20 SM **$K^+ \rightarrow \pi^+ \nu\nu$** events expected before LS2

A compelling broader physics program will be addressed.

Exotic searches at NA62

Beside $K^+ \rightarrow \pi^+ \nu\nu$, thanks to the high beam intensity, NA62 can do further searches for other K decays and not only

Long-lived exotic particles from Hidden Sector (DM candidates) may be created in the proton-target interaction and reach the NA62 decay volume. We can be sensitive to:



Heavy Neutrinos (Neutrino portal HN') with mass up to the D meson

- **HN'→ πe, HN'→ πμ**

Dark Photon (Vector Mediator A') with mass below (above) 600 MeV

- **$A' \rightarrow e^+e^-$, $A' \rightarrow \mu^+\mu^-$**

Trigger bandwidth for final states other than "$\pi^+ + E_{miss}$" limited.
Requiring 1 track, muon veto, and Emiss ≠ 0 at L0 reduces event rate from 15 MHz to **750 kHz,** including calibration and control triggers, little free bandwidth.
Parallel trigger masks have been developed: high efficiency & negligible efficiency reduction for the main stream

NA62 potential for A' visible decays

~3 10^{17} POT acquired in 2016/17 with di-muon parasitic trigger, 5 10^{16} POT with ee trigger

Assume 10^{18} 400-GeV POT :

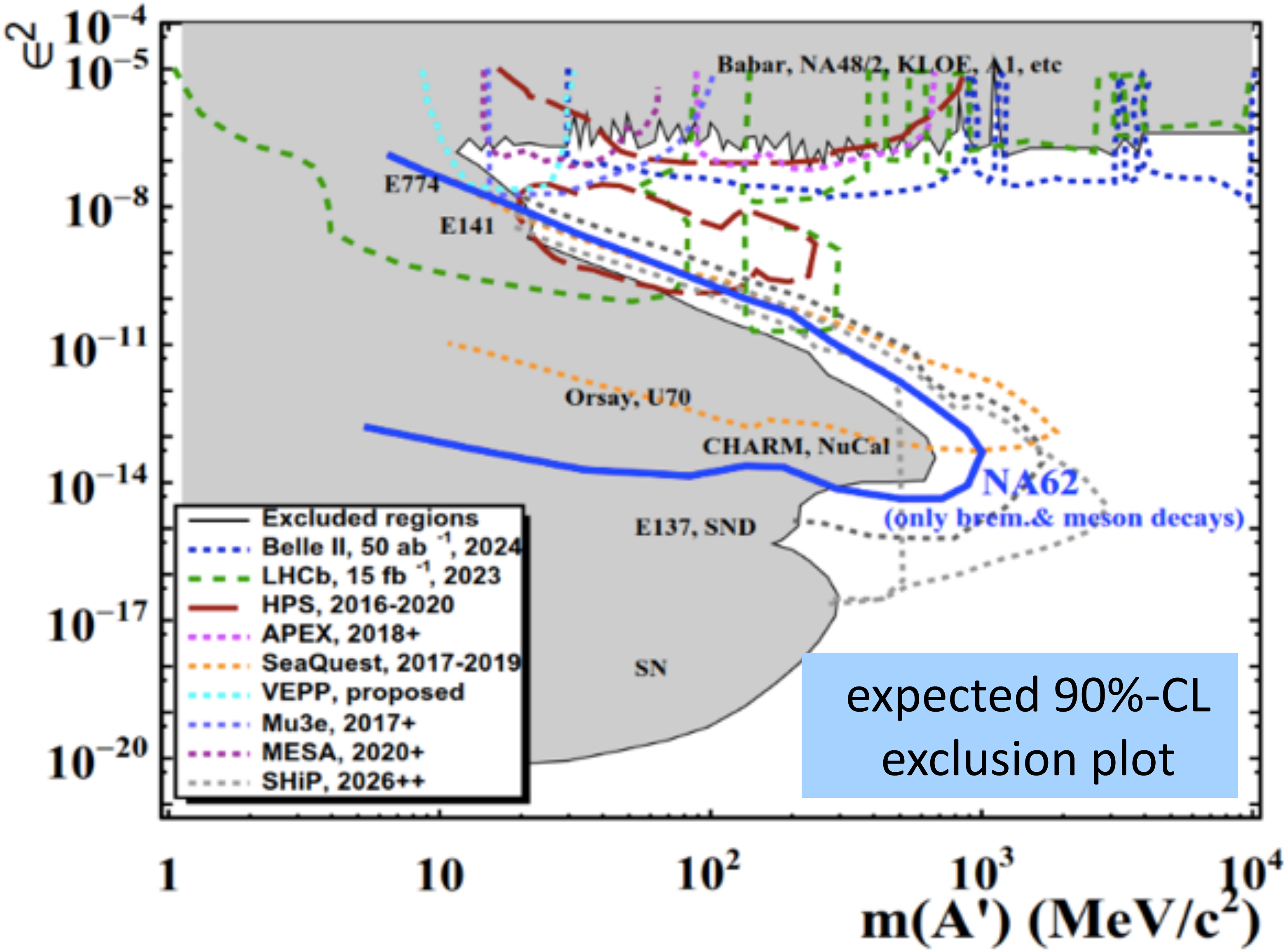
Study DP production from interaction onto target search for decay to ee, μμ in NA62 fiducial volume, account for geometrical acceptance and trigger efficiency, assume zero-background.

Sensitivity expected to be higher than shown:

- including direct QCD production of A'
- Including A' production in the dump (here, only target)

Cross-checked with full MC.

|A' coupling to ordinary γ|²



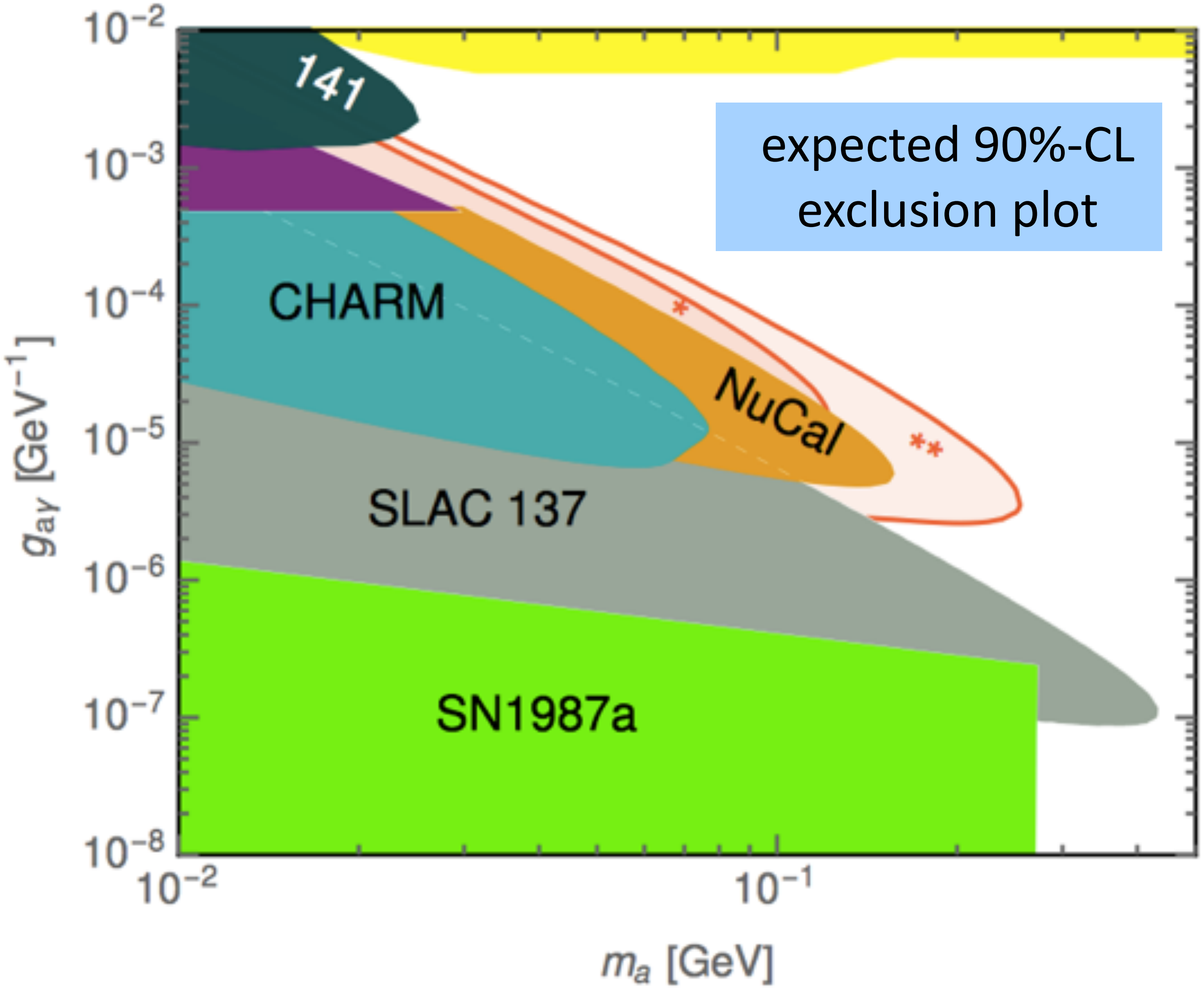
expected 90%-CL exclusion plot

NA62 potential ALP visible decays

Can act as a compact beam dump if ~11 λ_I Cu-based beam-defining collimator (TAX) is closed

- Study Axion Like Particle (ALP) production from interaction onto TAX, search must be performed in real beam-dump mode

Assume 10^{18} 400-GeV POT : search for ALP-decay to $\gamma\gamma$ in NA62 fiducial volume, account for geometrical acceptance assume zero-background.



expected 90%-CL exclusion plot

Analysis of 2017 data for ~5x10^{15} POT's taken in "dump mode" in progress….
1 day of run in real beam-dump mode (~ 1.3 10^{16} POT's) is enough for improvements

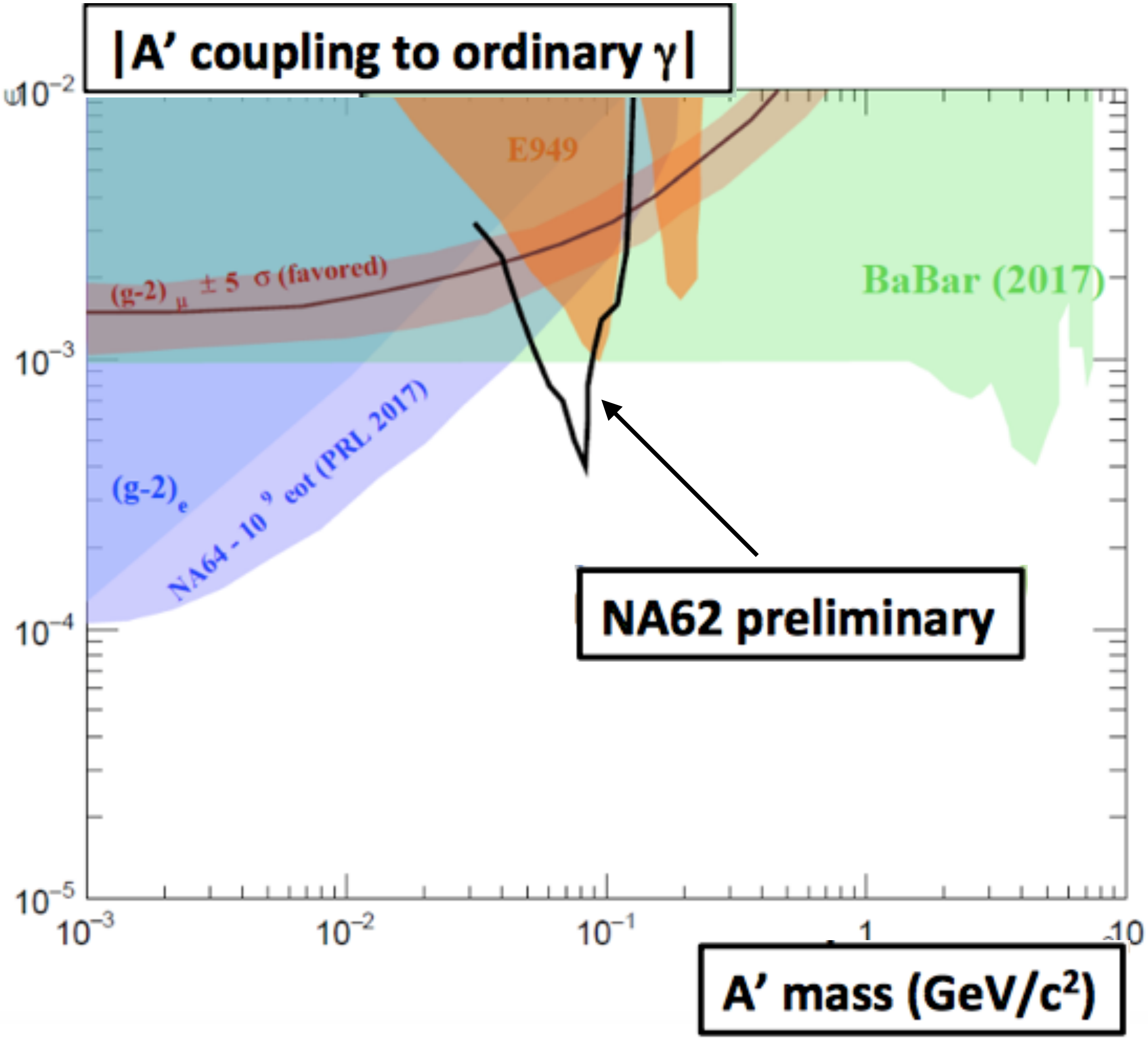
Search for $\pi^0 \to \gamma A'$, $A' \to$ invisible

Search for an invariant mass peak around A' mass

Data from 2016:~1.5 10^{10} K^+
(4% of statistics)

- Sensitivity for masses below the π^0 mass
- Signal signature: 1 track, 1 photon + missing energy
- Search parasitic to $\pi\nu\nu$, trigger based on "1 track" + small forward energy
- Dominant background from $\pi^0 \to \gamma\gamma$ with 1 photon missing

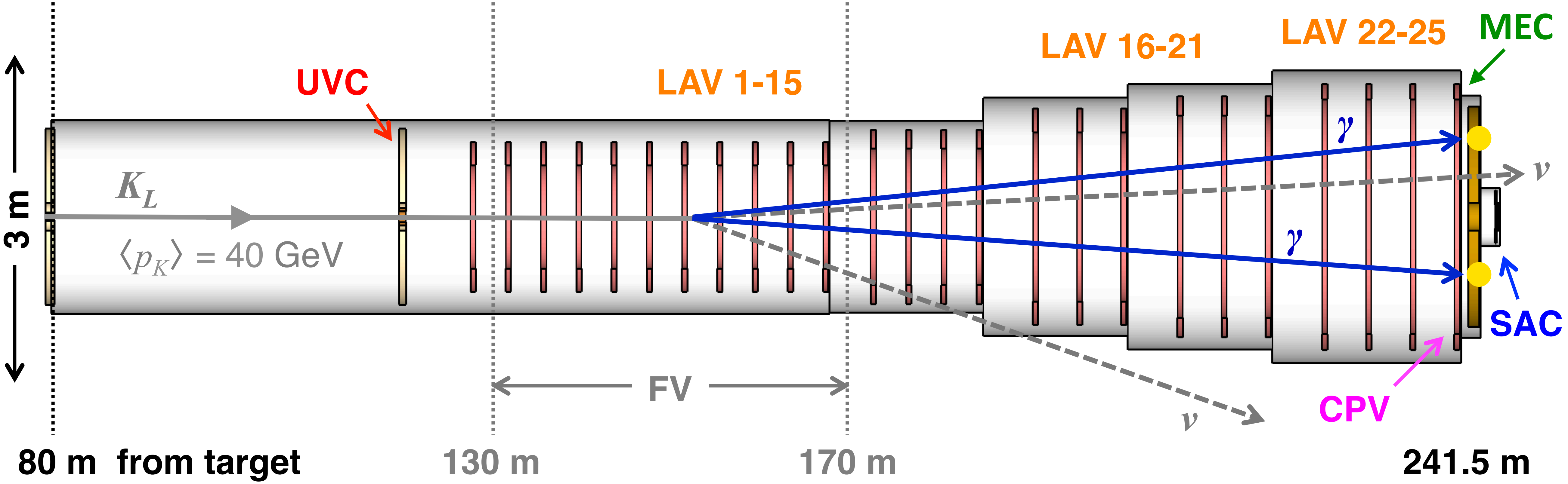
No signal observed, 90% CL UL within expected statistical uncertainty band



KLEVER experiment

Feasibility study of an experiment to measure BR($K_L \to \pi^0 \nu\nu$) at the SPS

400-GeV SPS proton beam incident on Be target, beam intensity of 2×10^{13} pot/16.8 s.
Intensity 6x higher than NA62: Target area and transfer lines will require upgrades.



Main detector /veto systems:

- **UVC** Upstream veto calorimeter
- **LAV 1-25** Large angle vetoes (25 stations)
- **MEC** Main electromagnetic calorimeter
- **SAC** Small angle calorimeter
- **CPV** Charged particle veto

Target sensitivity:
5 years starting in Run 4
60 SM $K_L \to \pi^0 \nu\nu$ with S/B ~ 1
δBR/BR(π0νν) ~ 20%

Conclusion and What Next

A compelling broader physics program will be addressed.

- Data from 2016-17 runs being analyzed, feasibility studies / first results
- Closed-TAX mode, present statistic ~6 x 10^{15} POT's
- Background estimate for future operation in beam-dump mode
- Low-bandwidth triggers parasitic to $\pi\nu\nu$

Running after 2018 to be approved

- condition for ultimate sensitivity under evaluation

▶ **<u>LNF is playing an important role:</u>**

- in the 2018 ongoing data taking
- in the analysis of 2017 and 2018 data
- in the future plans beyond NA62

Perspectives from NA62 and beyond for exotic searches and KLEVER project studies are part of discussion in CERN Physics Beyond Collider Working Groups