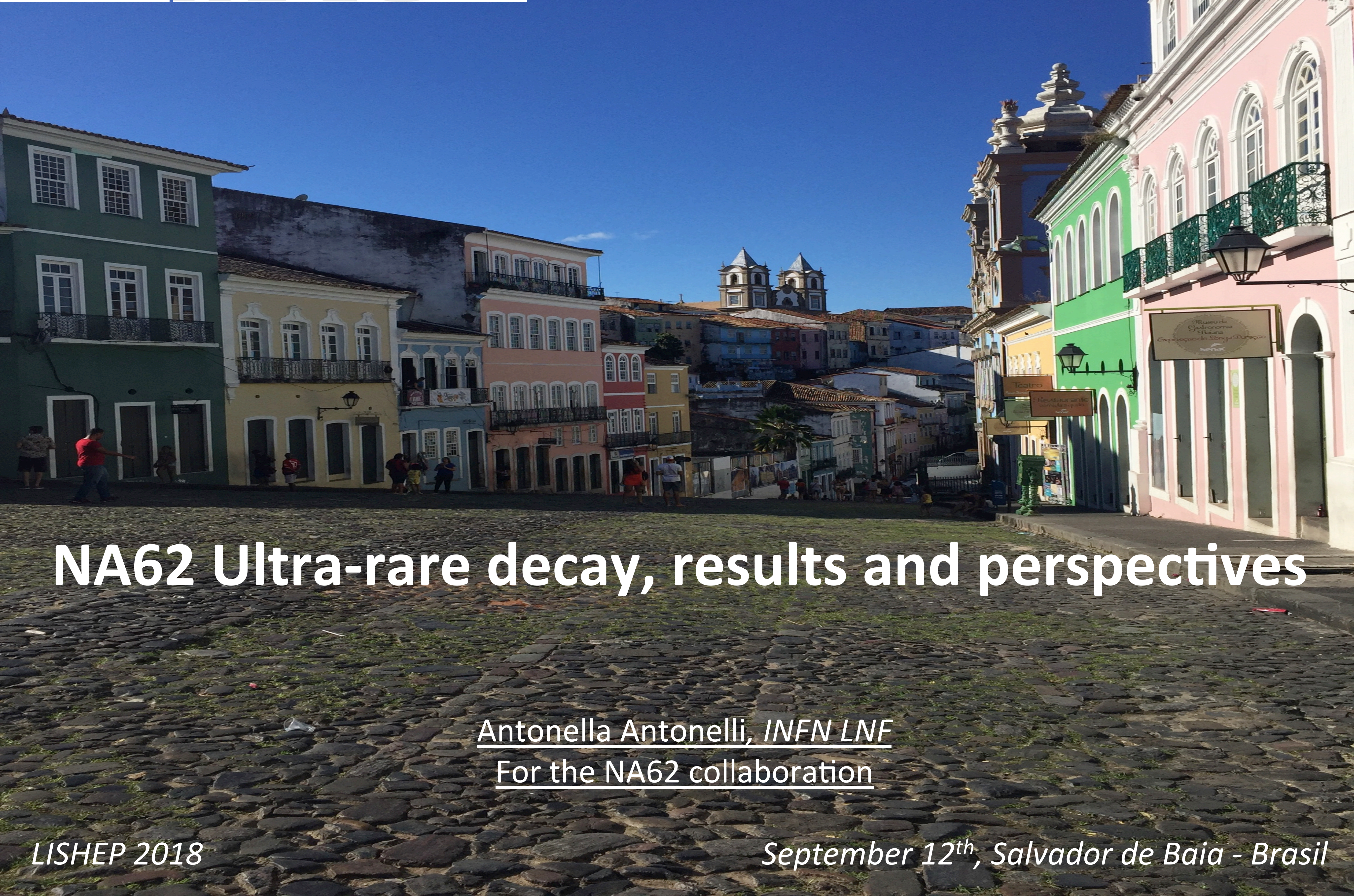


NA62 Ultra-rare decay, results and perspectives

Antonella Antonelli, *INFN LNF*
For the NA62 collaboration

LISHEP 2018

September 12th, Salvador de Baia - Brasil

Outline

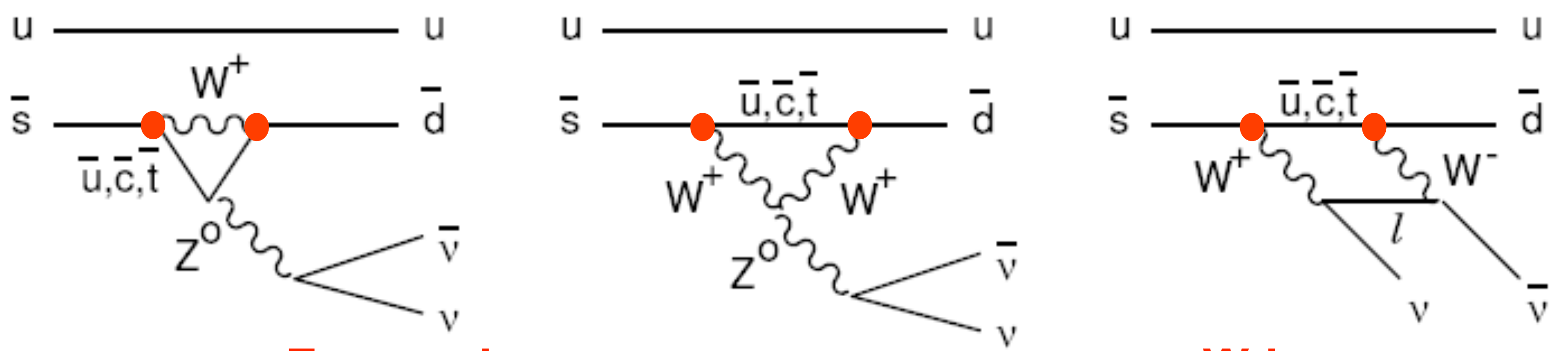
- Aim and strategy for the BR($K^+ \rightarrow \pi^+\nu\nu$) measurement
- Results with 2016 data
- Broader physics program: exotics searches at NA62
- Prospects

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.

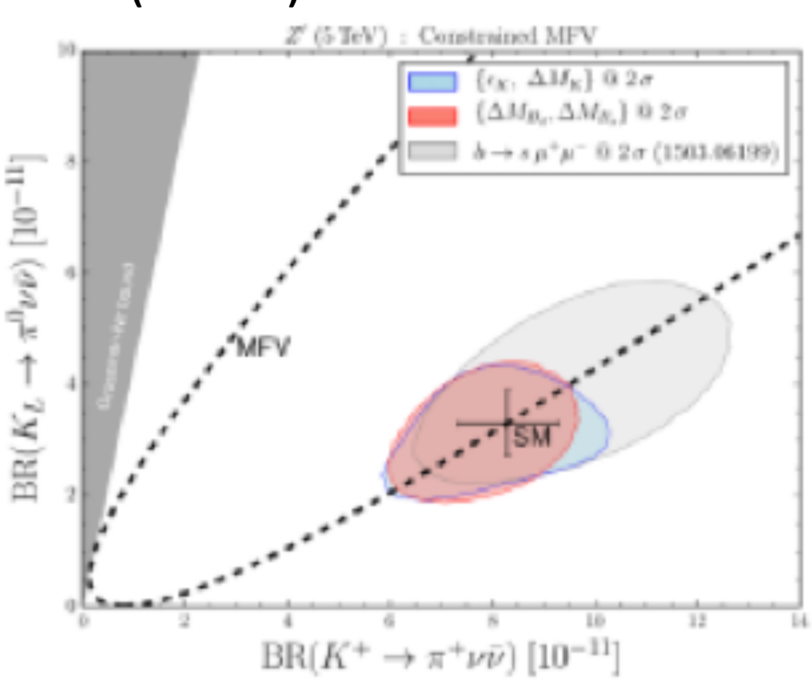
Highly suppressed & Very well predicted ▶ **Excellent laboratory complementary to LHC**

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

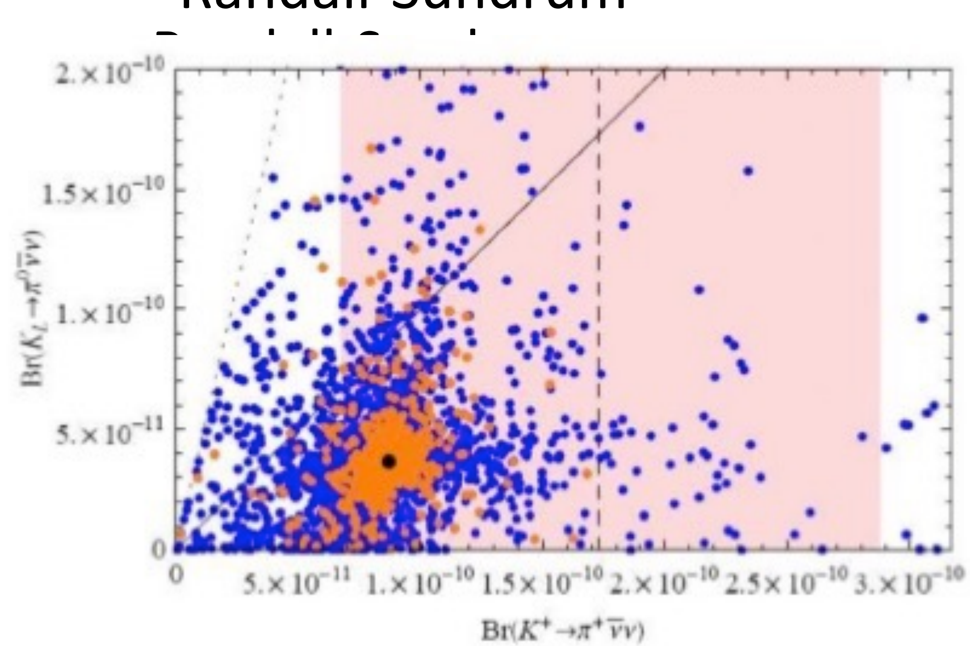
New Physics from K→πνν decays

- **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)

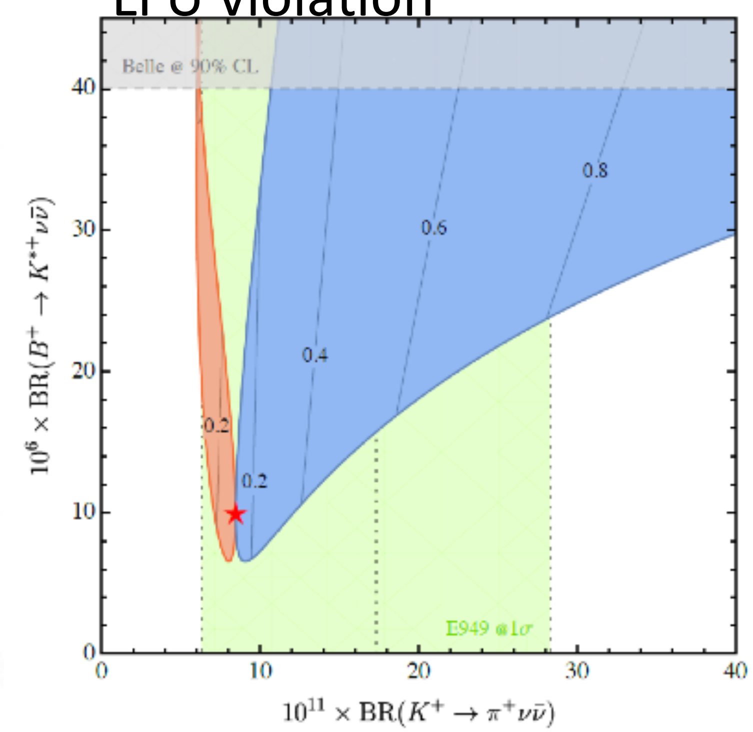
Z' (5 TeV) in constrained MFV



Randall-Sundrum

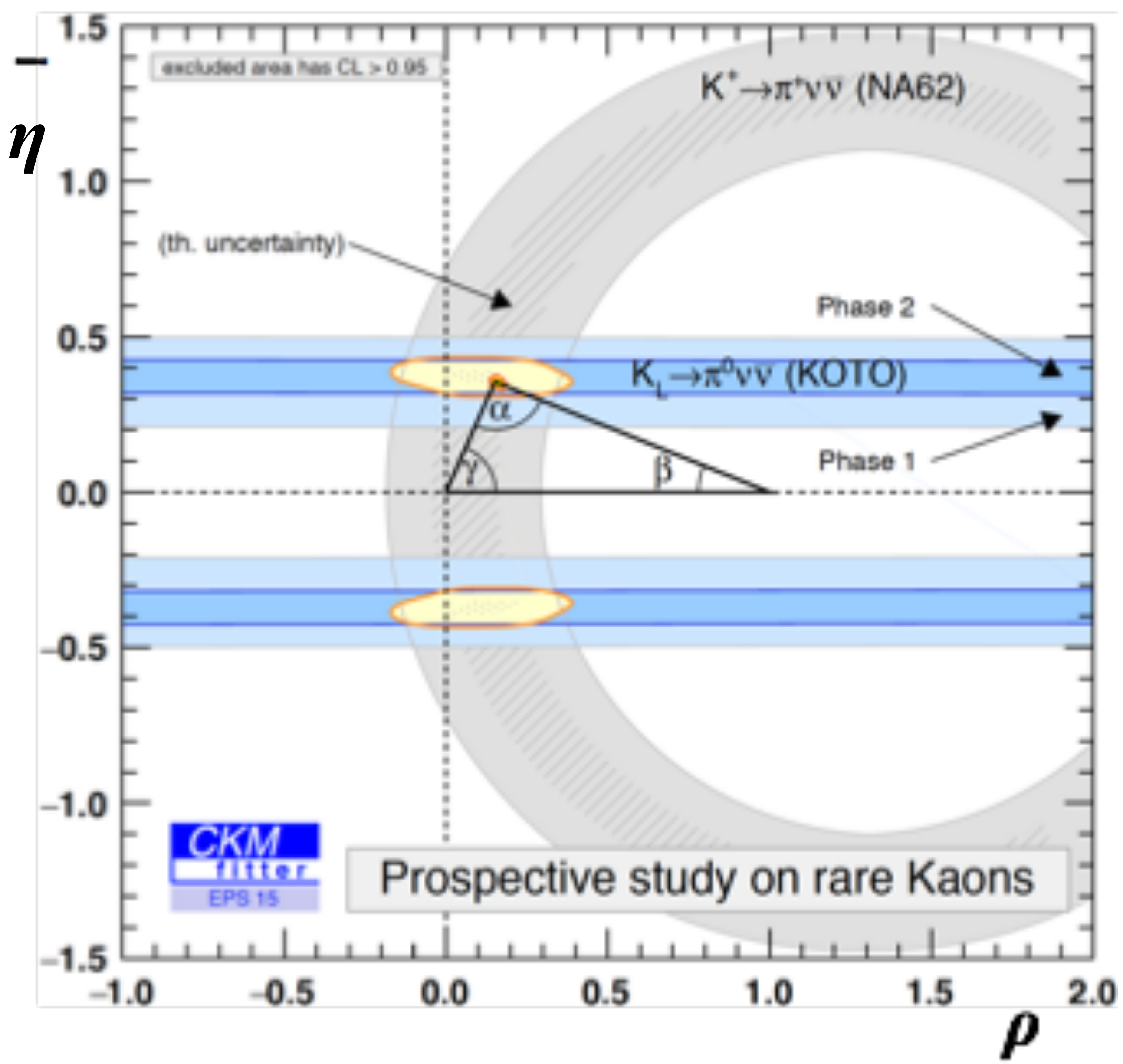


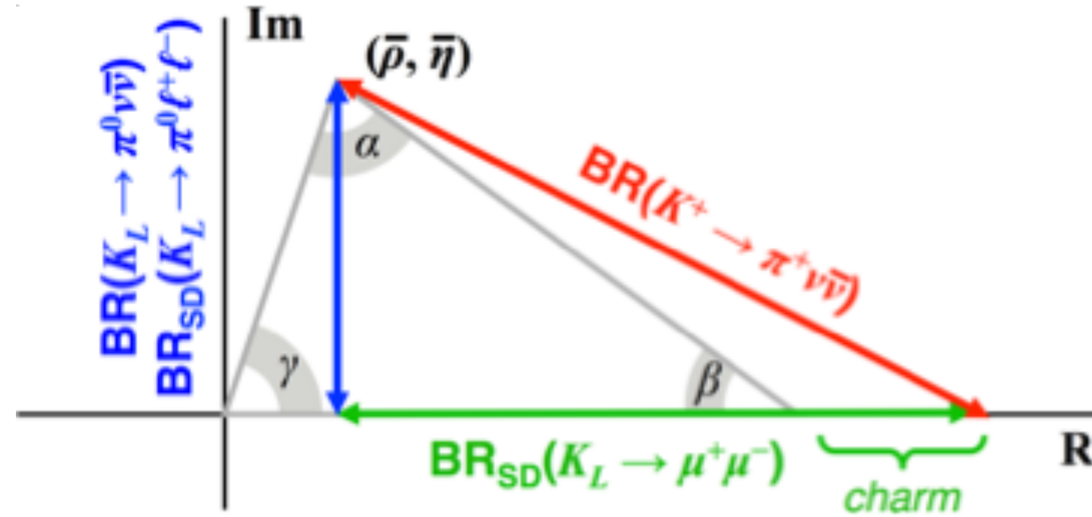
LFU violation



Connection with Flavor Physics

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





Example of CKM constraints:

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

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

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

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.**

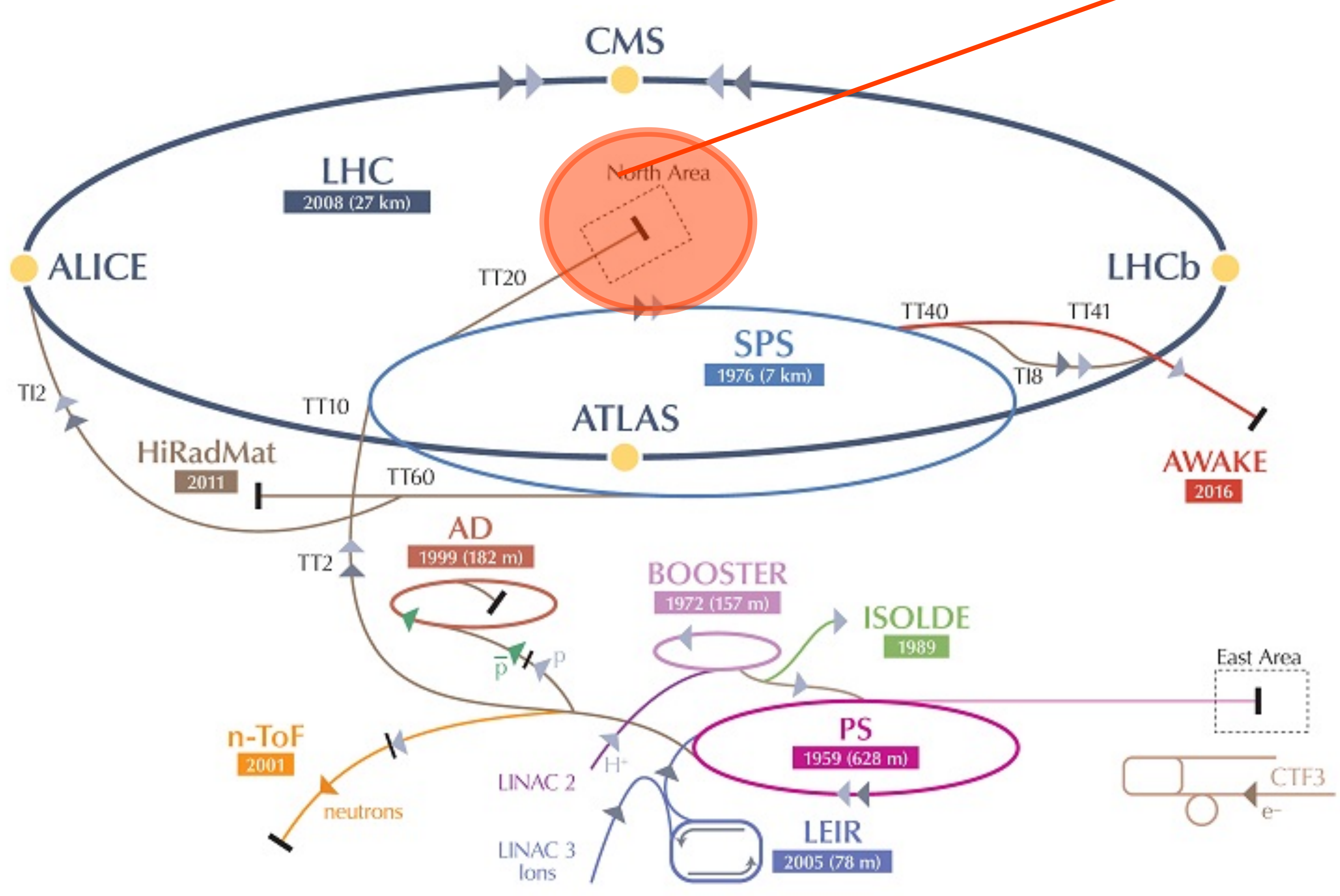
Neutral decay $K_L \to \pi^0 \nu\nu$ has never been measured

NA62 GOAL: measure $BR(K^+ \to \pi^+ \nu\nu)$ 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

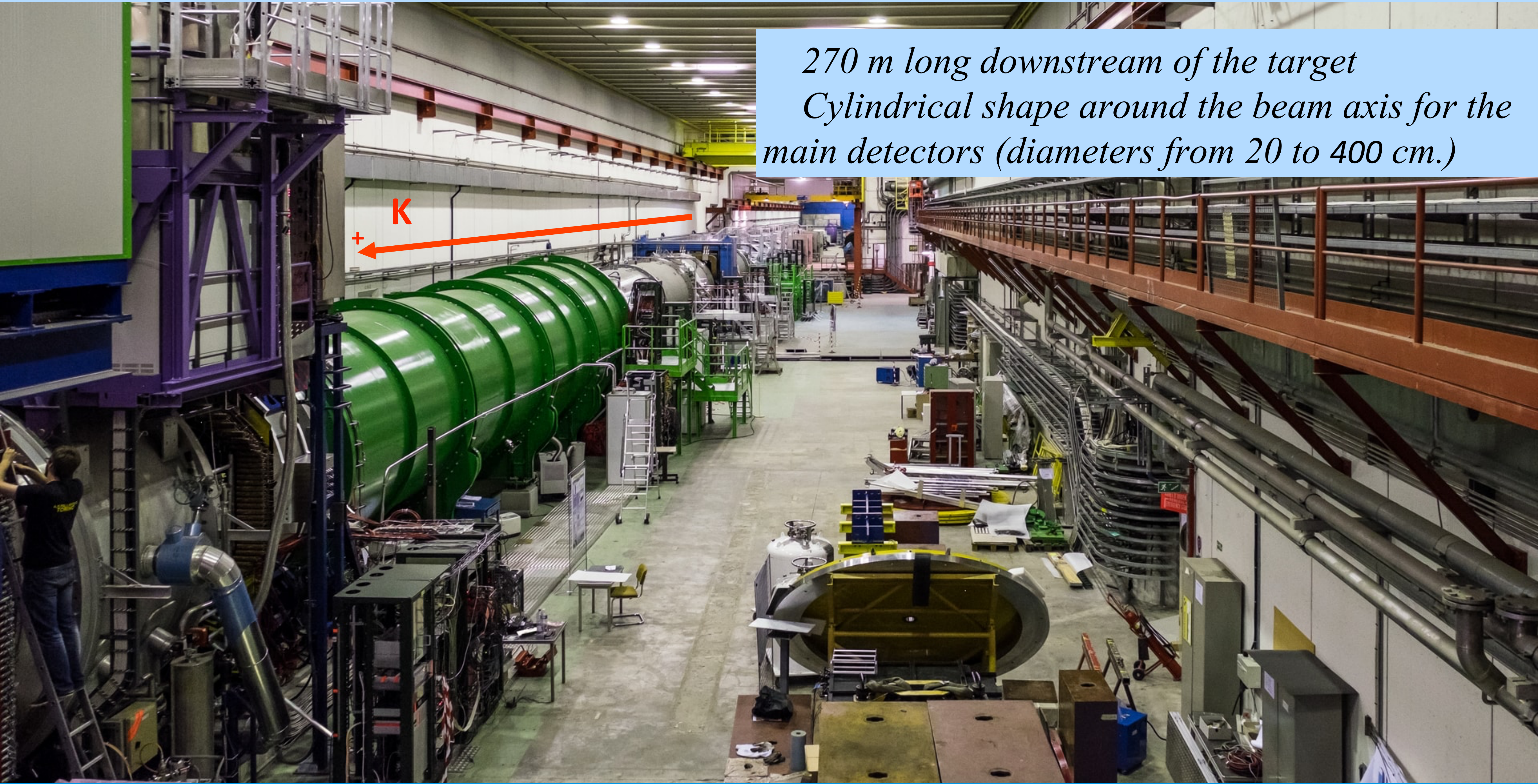
In the North Area the SPS extraction line is providing a secondary charged hadron beam



- 400 GeV/c primary proton beam
- 3 x 10^{12} protons/pulse
- 40 cm beryllium target
- **75 GeV/c** unseparated hadrons beam: $\boldsymbol{\pi^+}$ (70%), **K^+ (6%), protons** (24%) ($\Delta p/p \pm 1\%$)
- 100 mrad divergence (RMS)
- 60x30 mm^2 transverse size
- Intensity: 750 MHz (45 MHz K^+)
- 4.8 x 10^{12} K^+ decays/year

NA62 Experiment

Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna (JINR), Fairfax (GMU), 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)



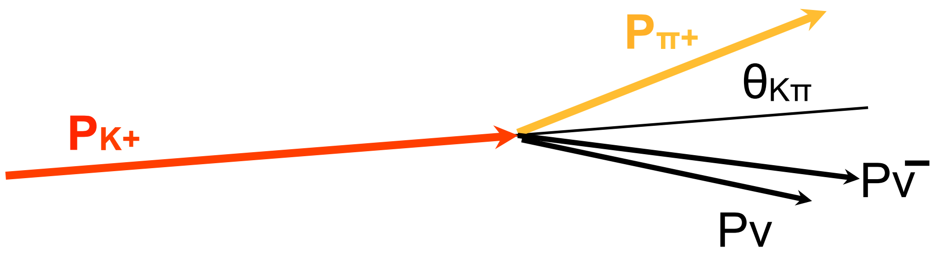
270 m long downstream of the target

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

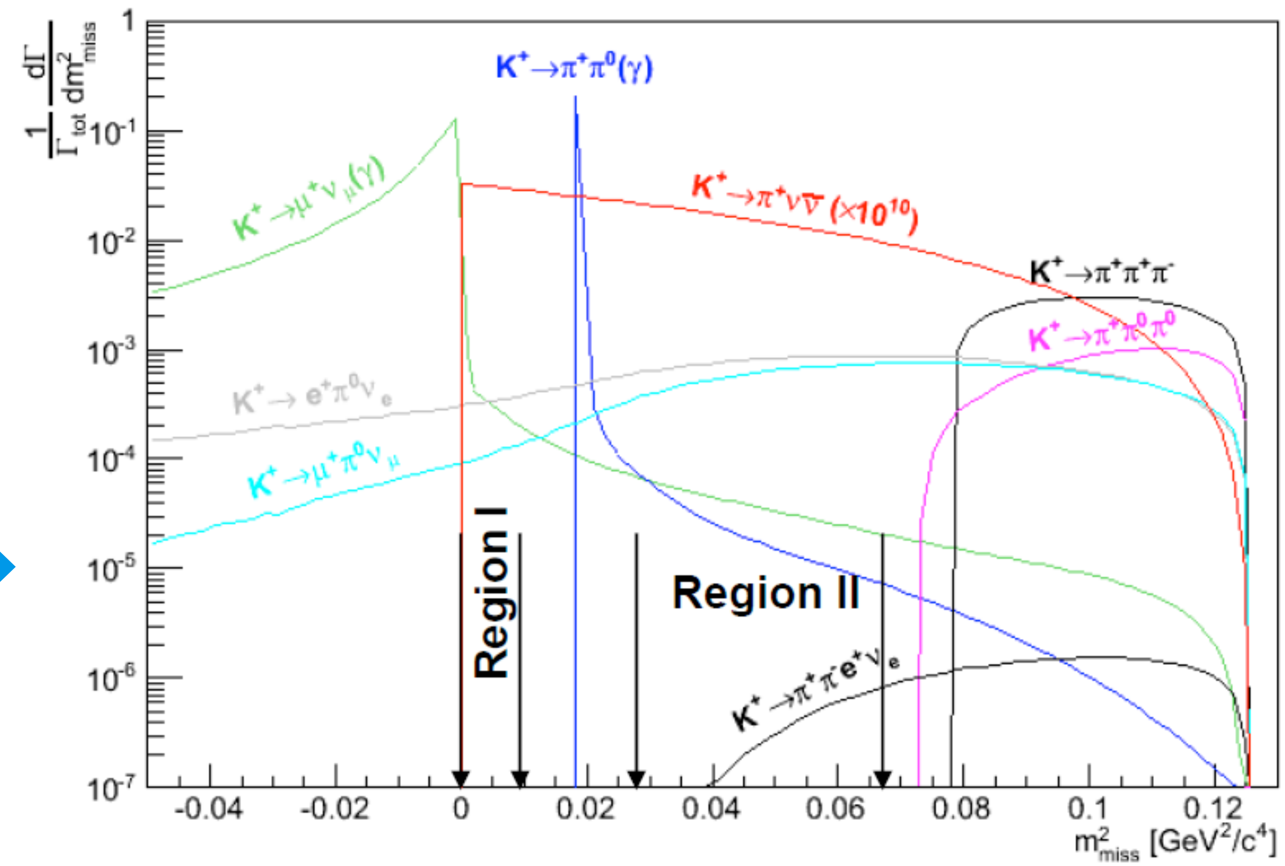
- O(100 ps) Timing between sub-detectors
- O(10^4) Background suppression from kinematics
- O(10^7) μ-suppression ($K^+ \to \mu^+\nu$)
- O(10^7) γ-suppression (from $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\gamma$)

Analysis Strategy

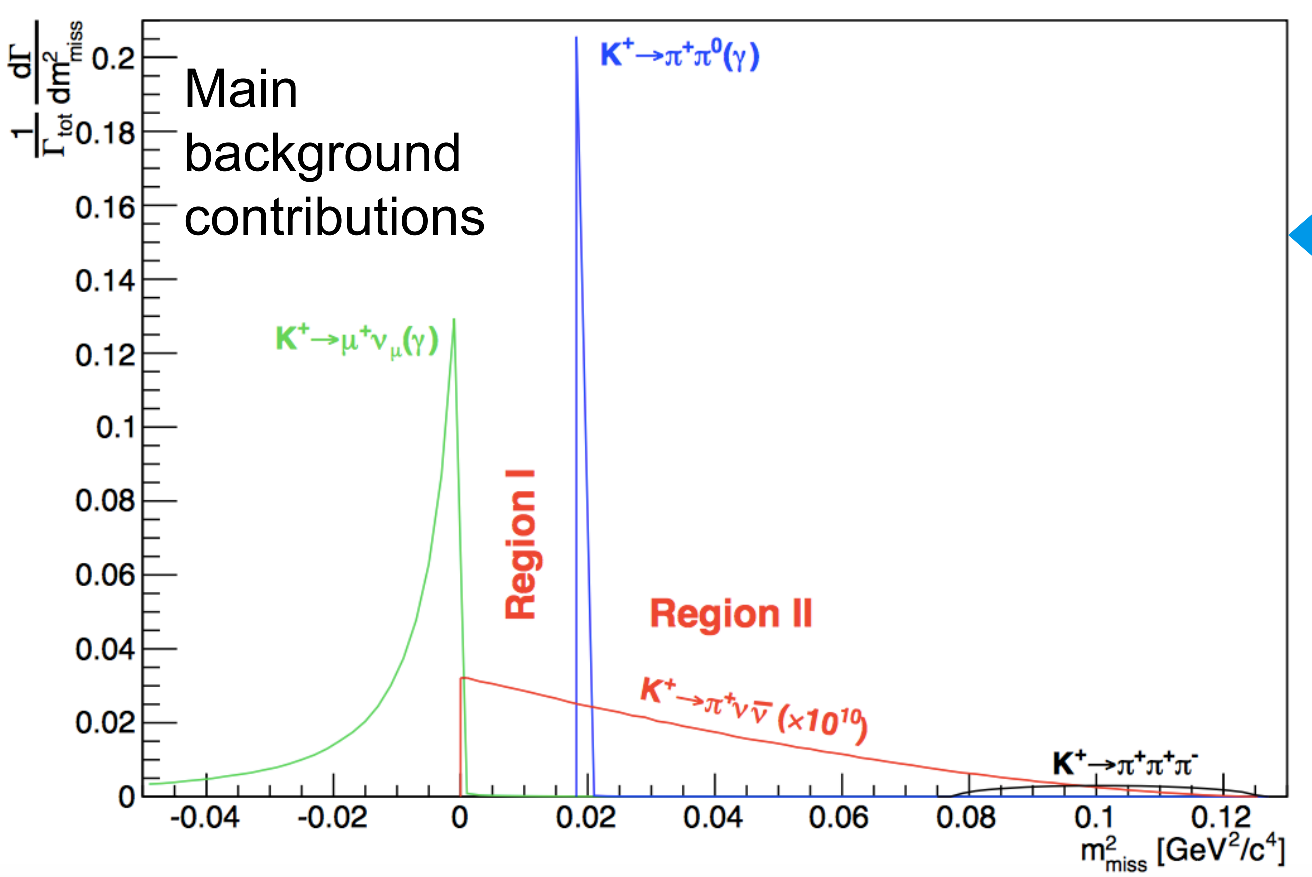
Most discriminating variable:
$m^2_{miss} = (P_{K+} - P_{\pi+})^2$

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:

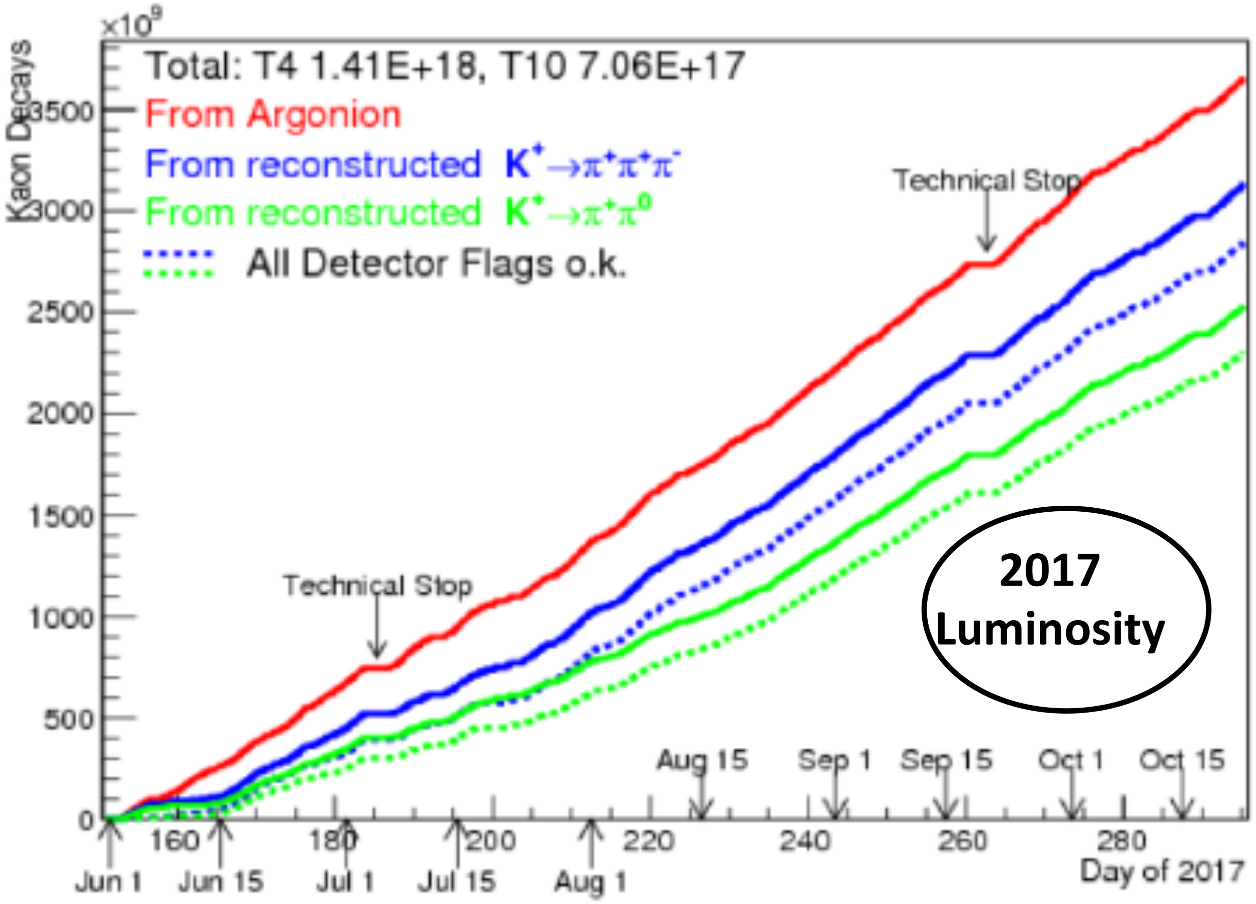
- $K^+ \to \pi^+\pi^0$, $K^+ \to \mu^+\boldsymbol{\nu}$ non gaussian resolution and radiative tails
- $K^+ \to \pi^+\pi^+\pi^-$ non gaussian resolution tails
- decays with neutrino in final state

NA62 Timescale

2014 Pilot Run	2015 Commissioning	2016 Commissioning + Physics Run	2017 Physics Run	2018 Physics Run (ongoing)	2019-2020 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**

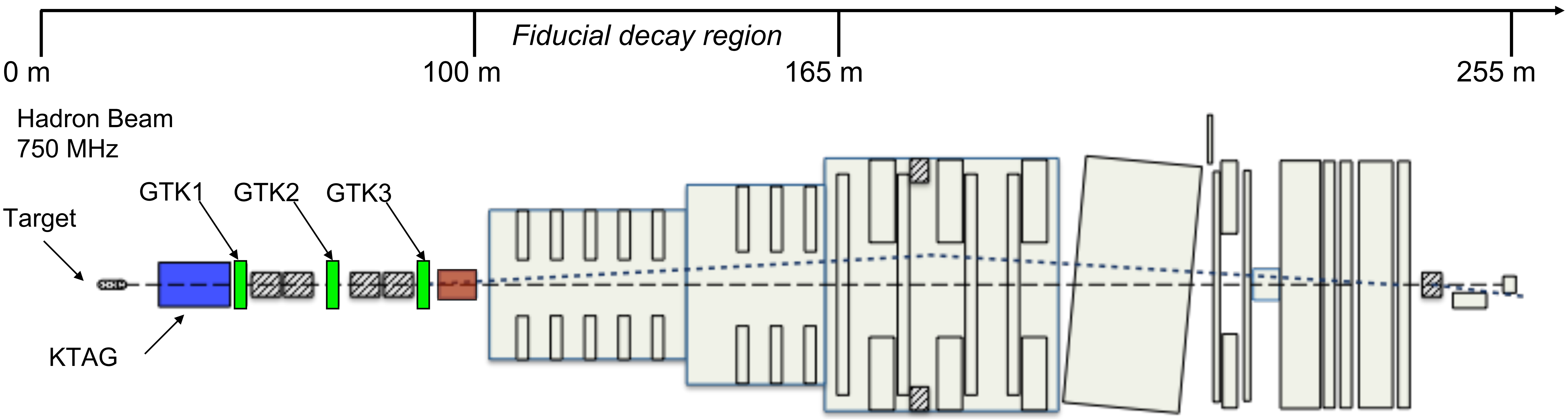
2017: 60% of nominal intensity: 20 x 10^{11} proton on target **> 3 x 10^{12} K^+ decays collected**



beam fluctuations reduced

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

NA62: Beam ID & Tracking

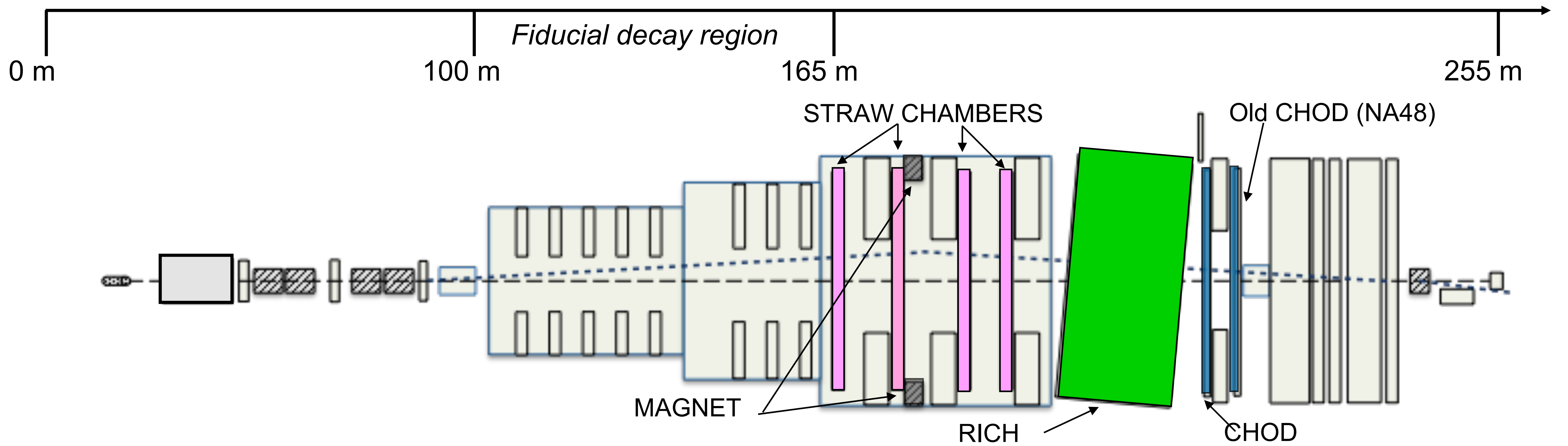


Beam ID & Tracking

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

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

NA62: Secondary ID & Tracking



Beam ID & Tracking

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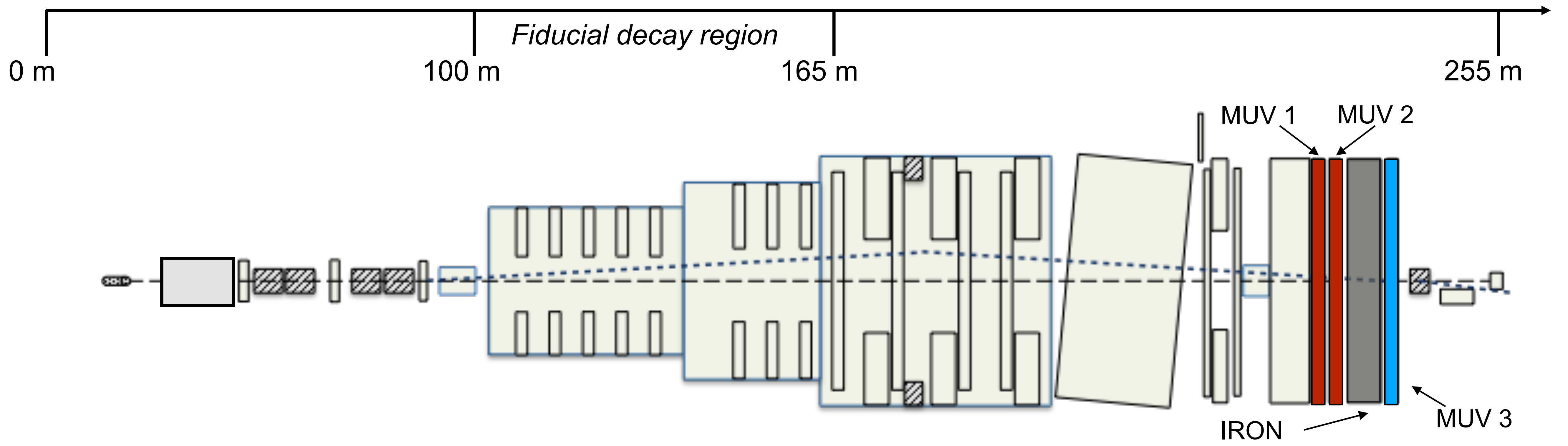
Secondary particle ID & Tracking

STRAW: Spectrometer with STRAW tubes. **σ_t ~ 6 ns, $\sigma_{dx,dy}$ ~130 μm,$\sigma p/p$~(0.300+0.005p)% (GeV/c)**

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

NA62: Muon Veto System



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, $\Delta P/P < 0.4\%$.**

Secondary particle ID & Tracking

STRAW: Spectrometer with STRAW tubes. **σ_t ~ 6 ns, $\sigma_{dx,dy}$ ~130 µm. $\sigma p/p$~(0.300+0.005p)% (GeV/c)**

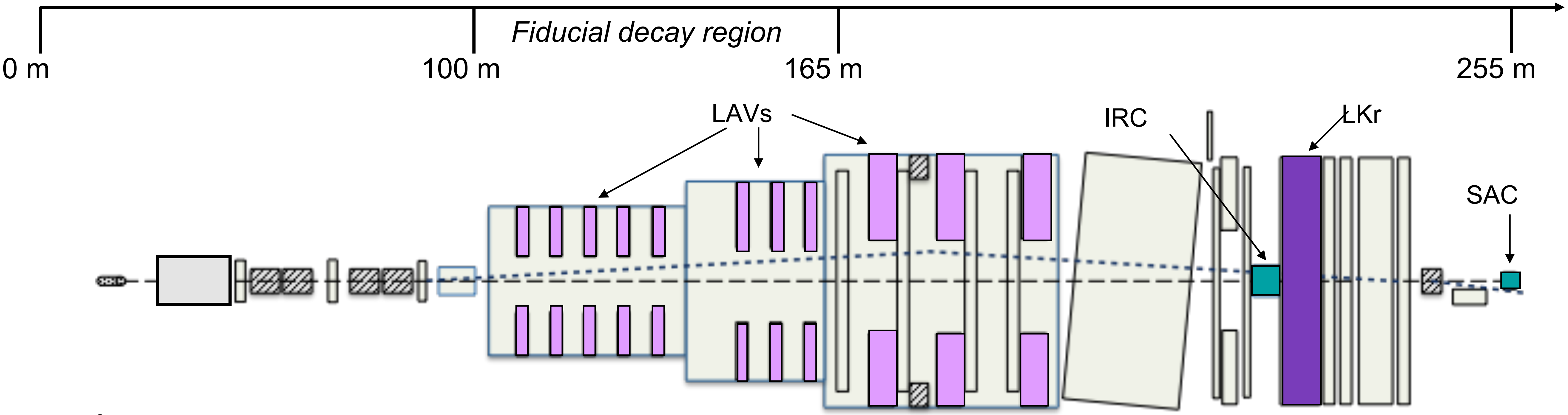
RICH: Ring Imaging Cherenkov detector. **µ/π separation ~ 10^{-2}, σ_t of a ring < 100 ps.**

Muon Veto

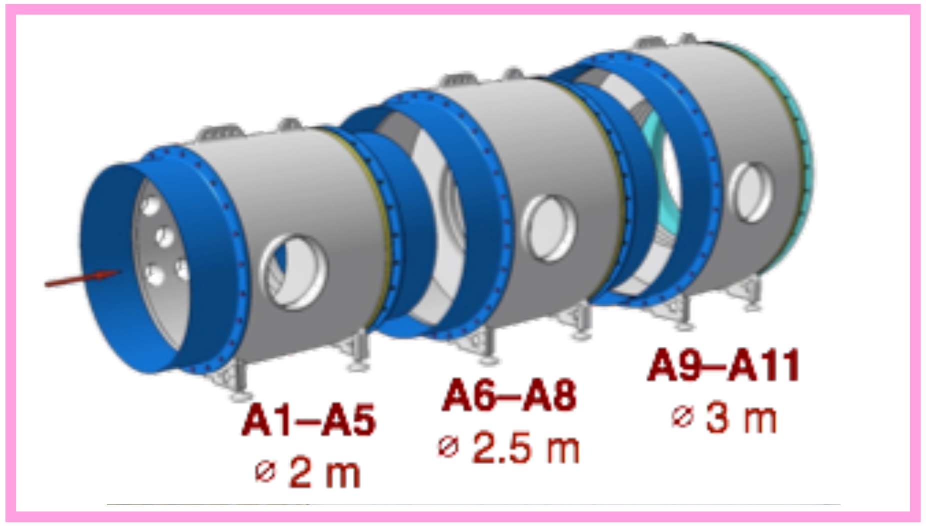
MUV3: Scintillator hodoscope. **σ_t ~500 ps, efficiency ~99.5%.**

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

NA62: Photon Veto System



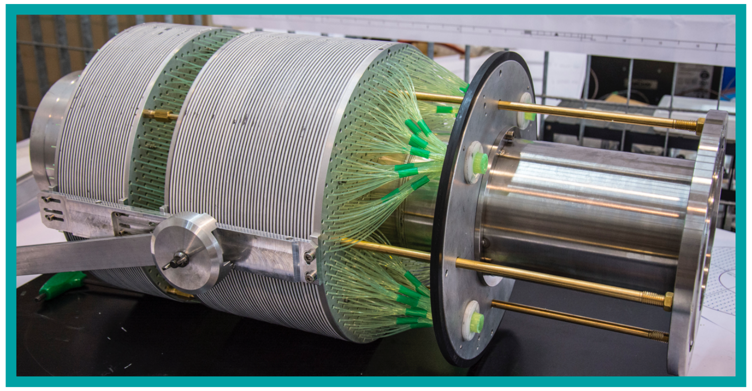
Photon Veto



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.**



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

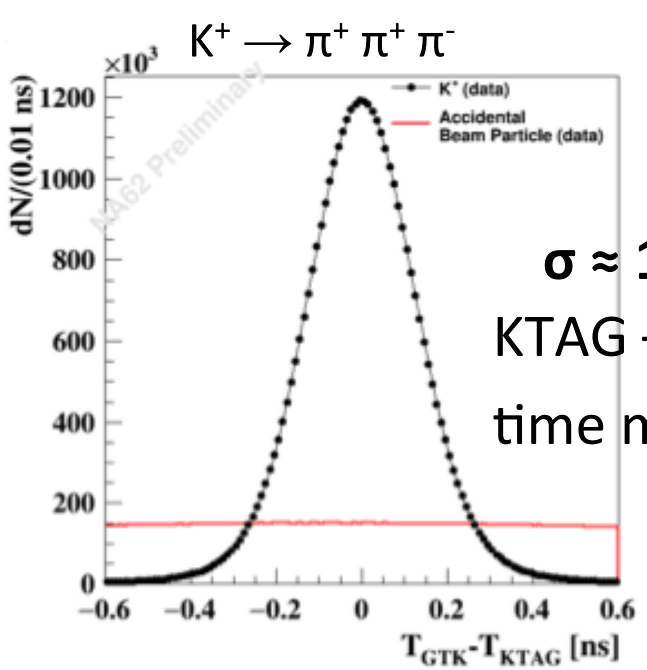
$K^+ \to \pi^+\pi^0$, $K^+ \to \mu^+\nu$, $K^+ \to \pi^+\pi^+\pi^-$ samples for background estimation

- 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

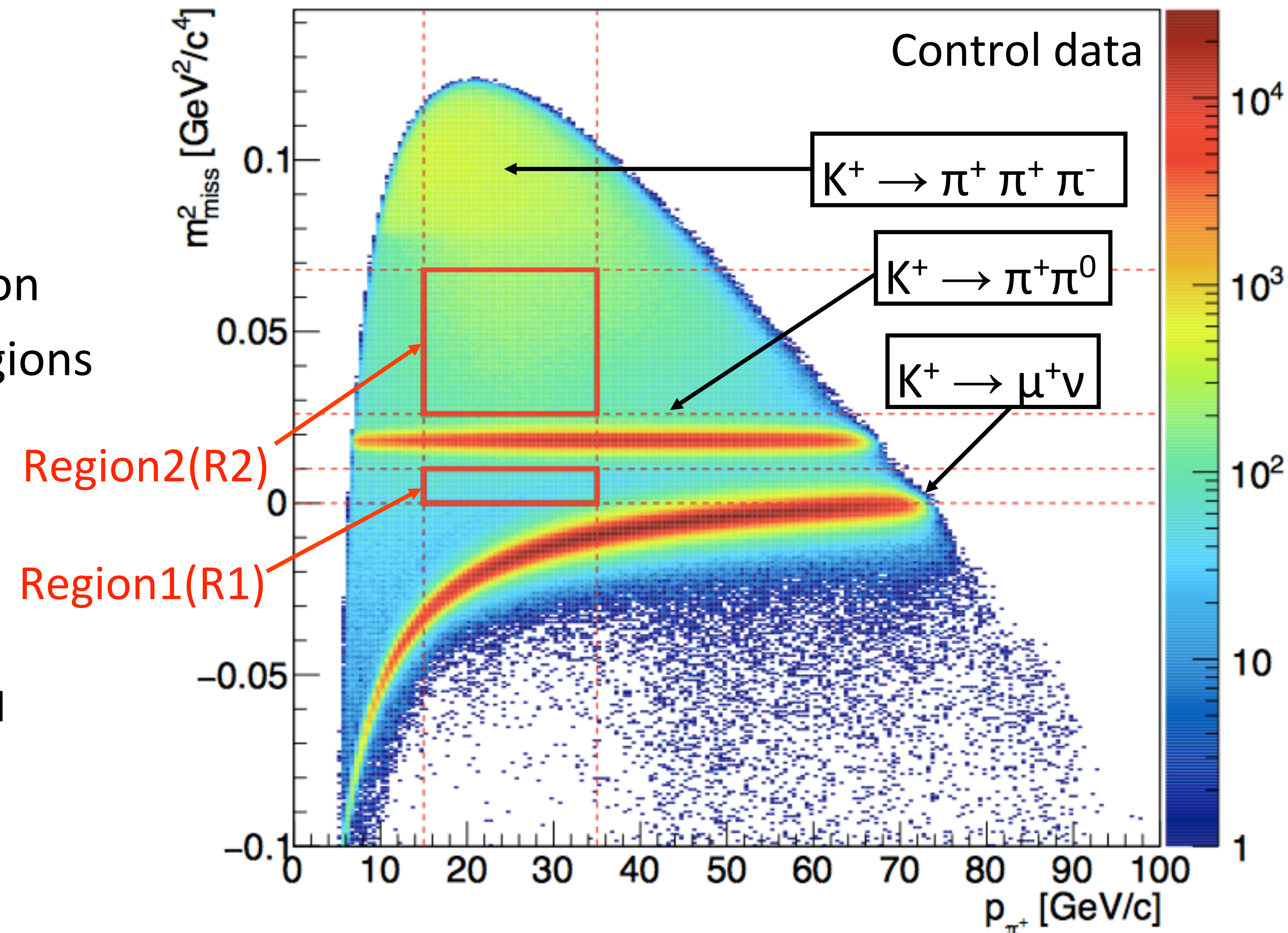
- K^+ decays with a single charged particle in final state
- Particle ID: π^+
- Multiple charged particle rejection
- Kinematic Selection of Signal Regions



σ ≈ 110 ps

KTAG –GTK –RICH

time matching



- $110 < Z_{vertex} < 165$ m
- $15 < P_{\pi+} < 35$ GeV/c

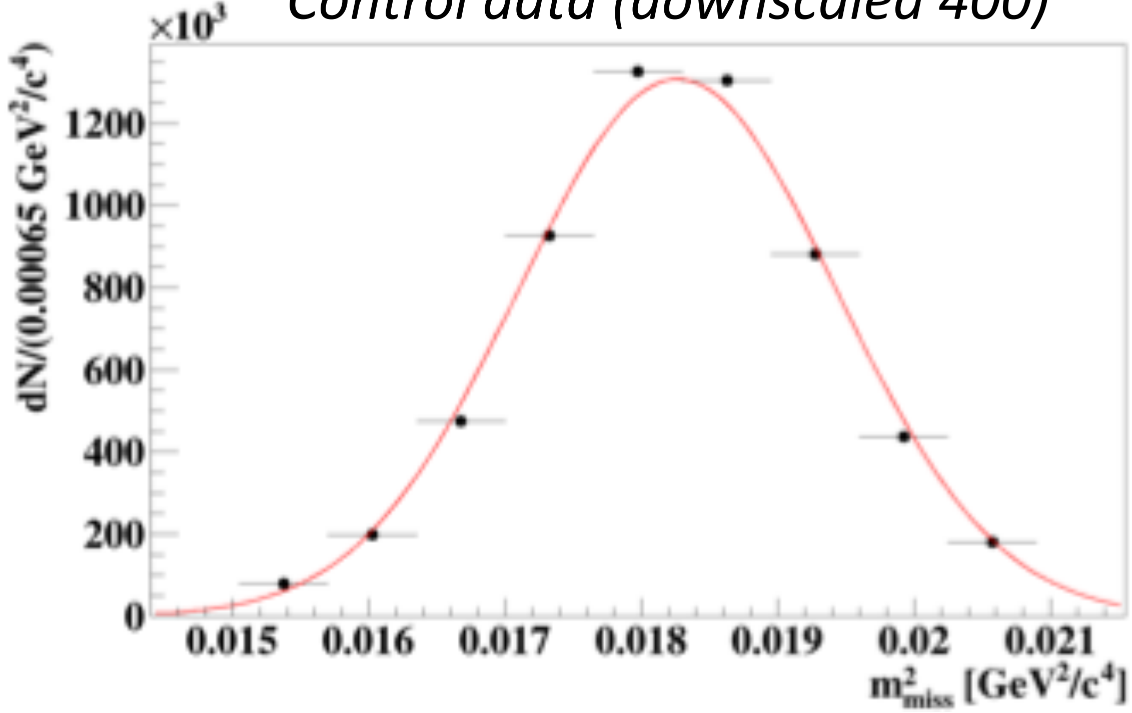
(to leave at least 40 GeV of E_{mis})

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

Photon rejection

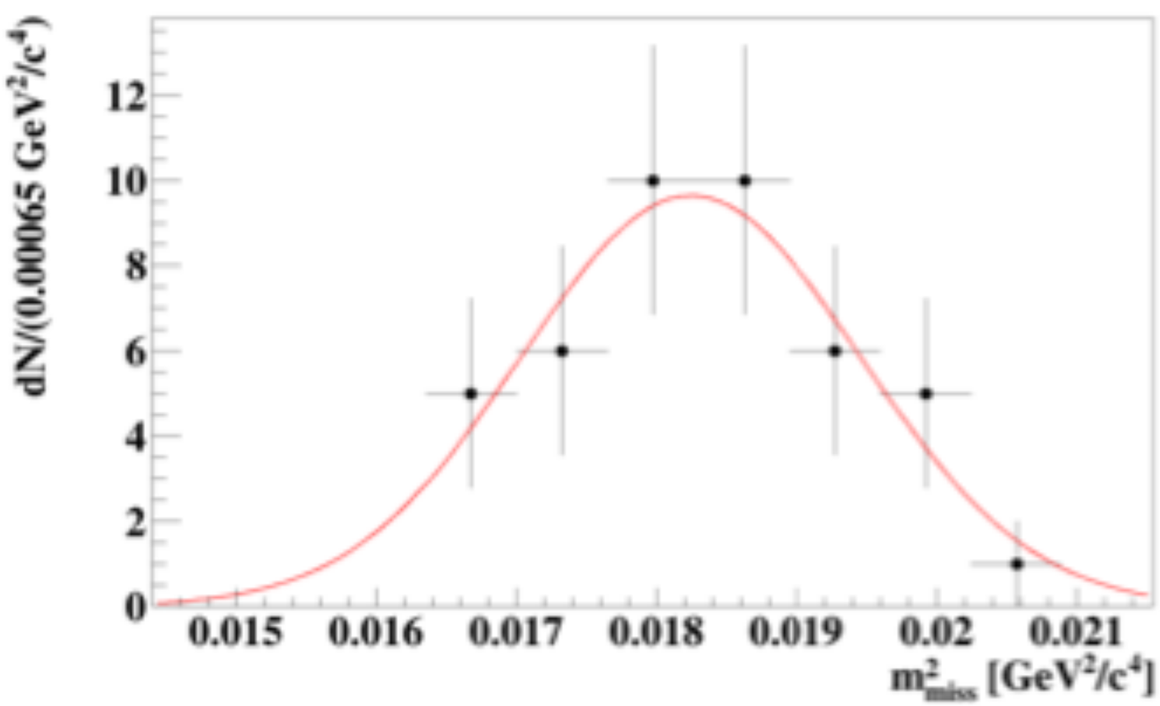
Events are rejected in case of coincidence between decay time and signals (±3-5 ns) in the LKr, LAV, SAC, IRC or hodoscope not associated to the π^+

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) : ~$2.5 \cdot 10^{-8}$

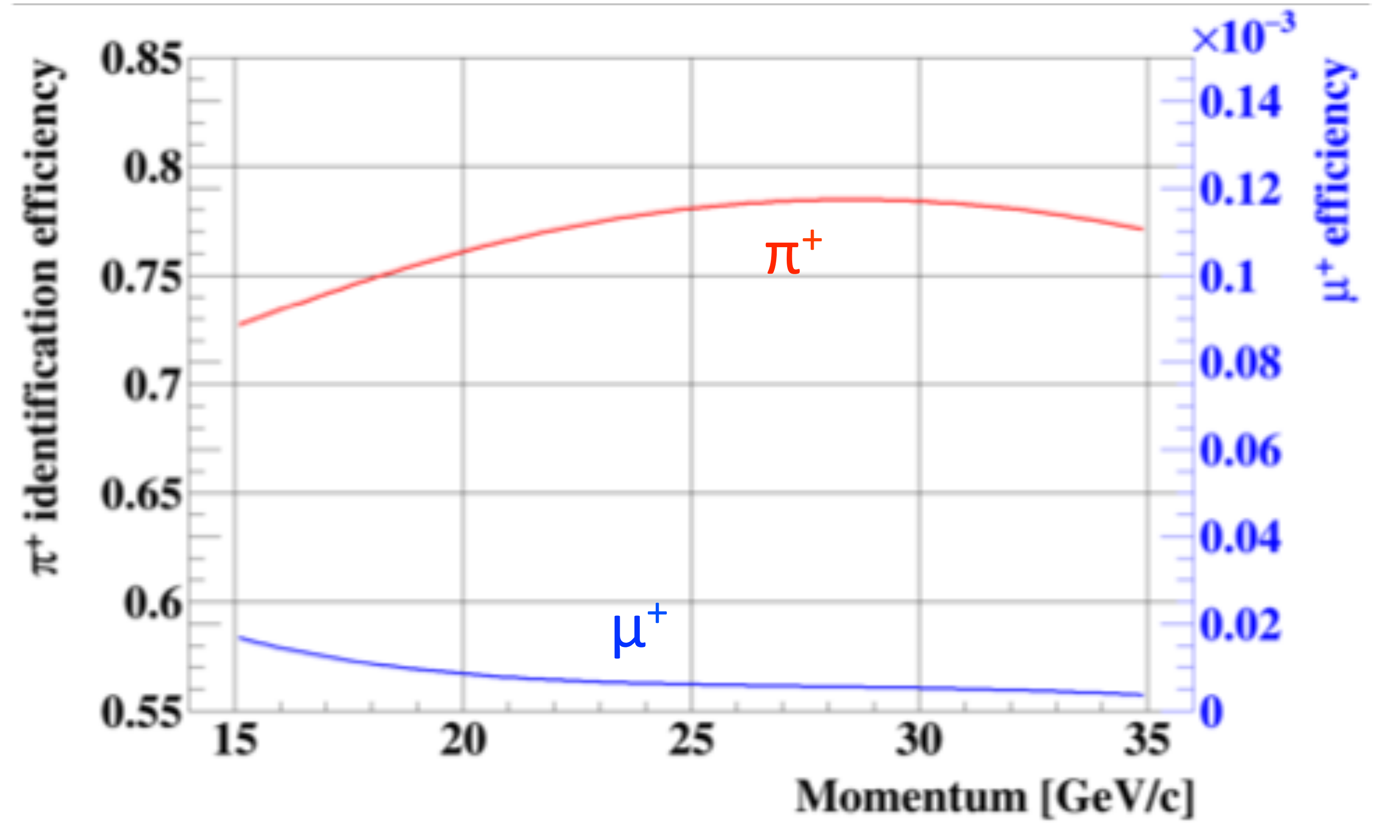
π^+ Particle identification

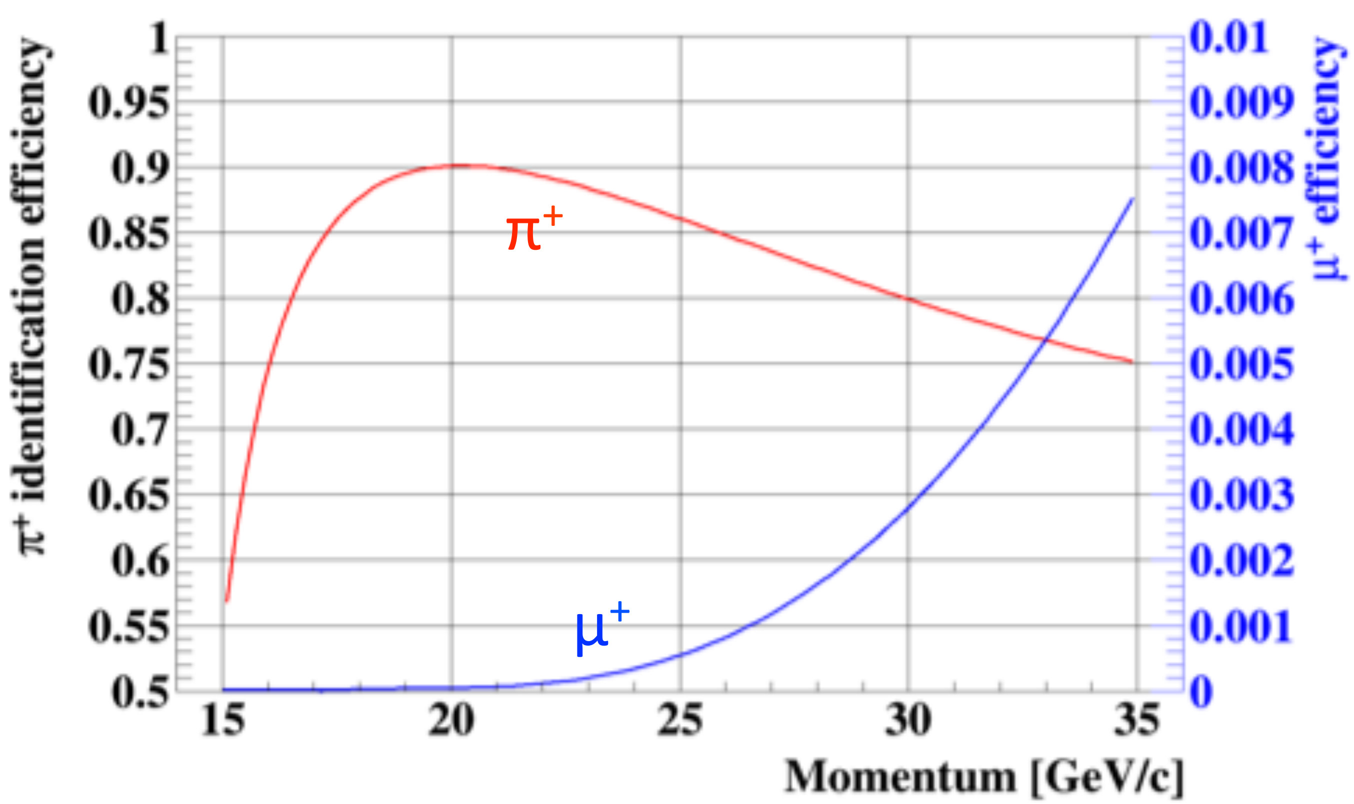
in Calorimeters

- 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**



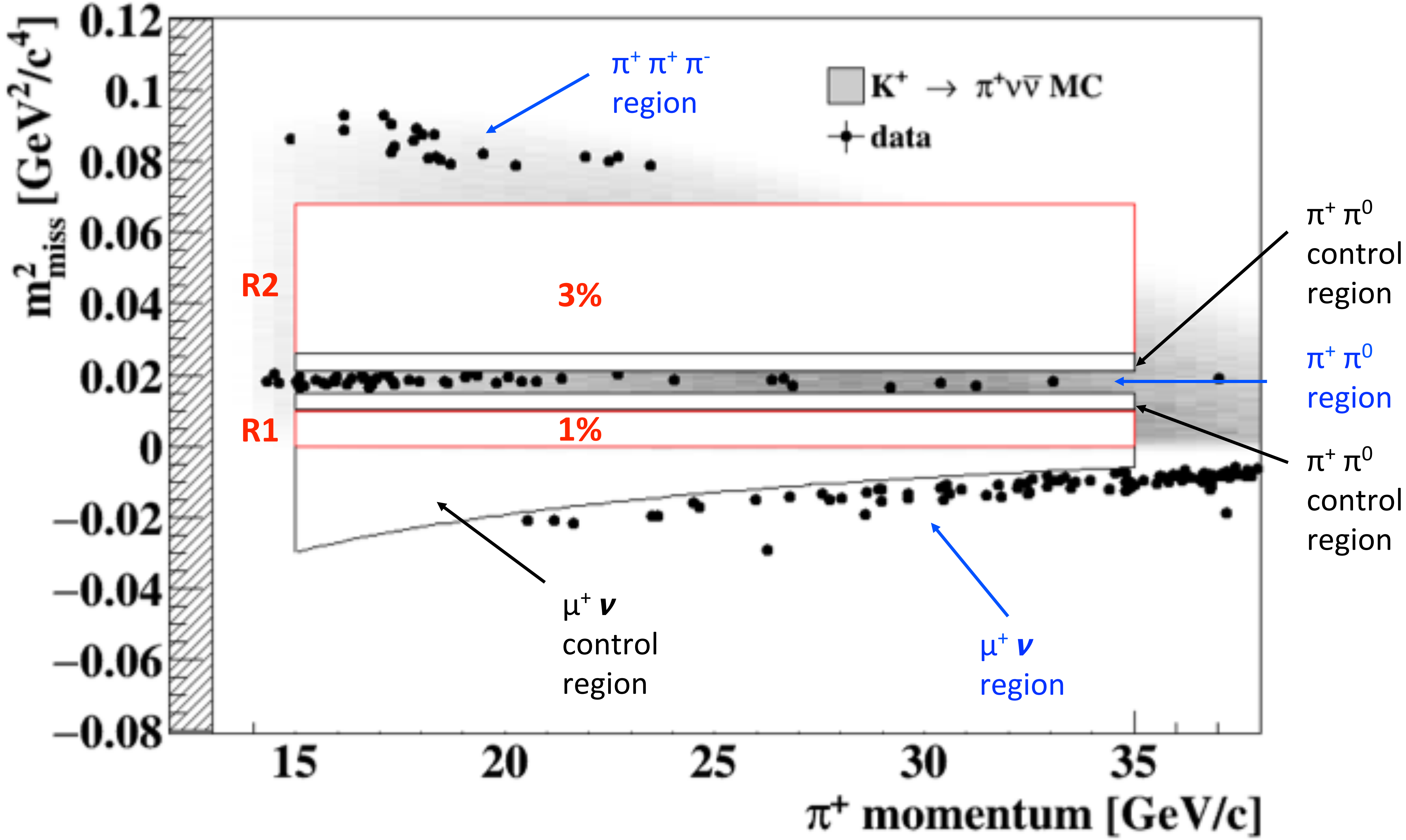


in RICH

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**

Data after selection

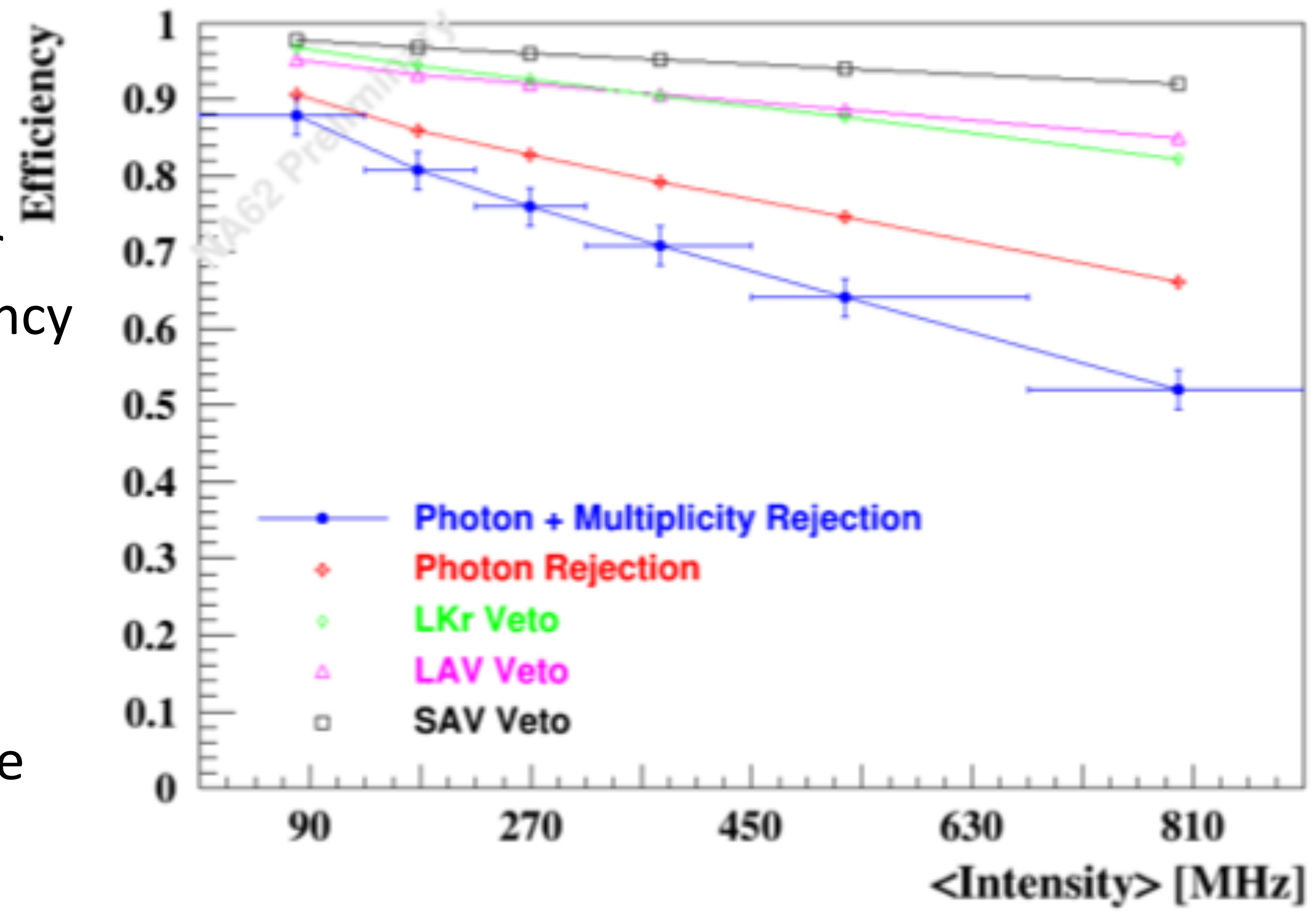


Single Event Sensitivity (SES)

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

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



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

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

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

f_j^{kin}

- 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

Calculated for the main background decays :

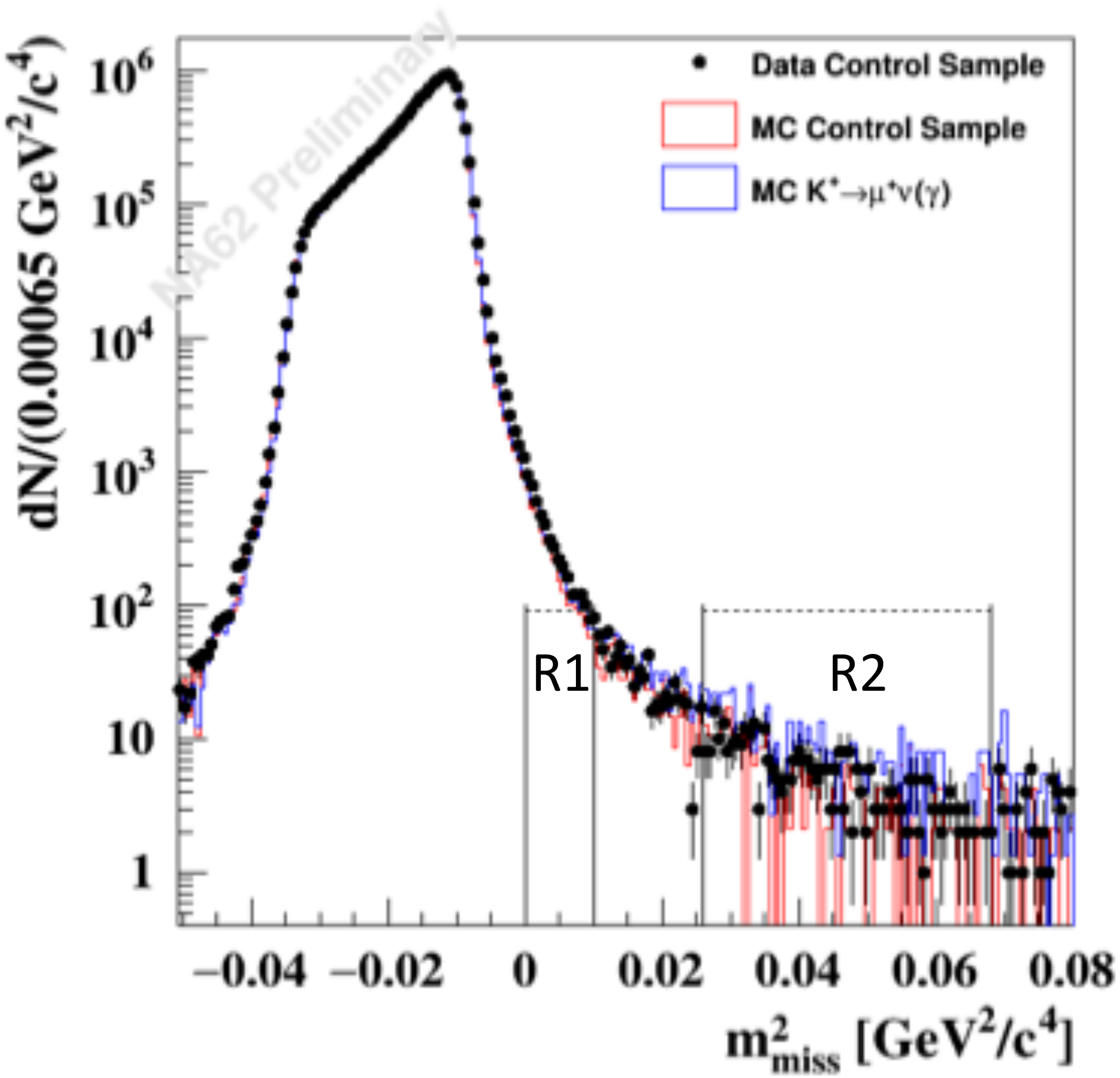
$K^+ \to \pi^+\pi^0(\gamma)$, $K^+ \to \mu^+\nu(\gamma)$, $K^+ \to \pi^+\pi^+\pi^-$, $K^+ \to \pi^+\pi^- e^+\nu$

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

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

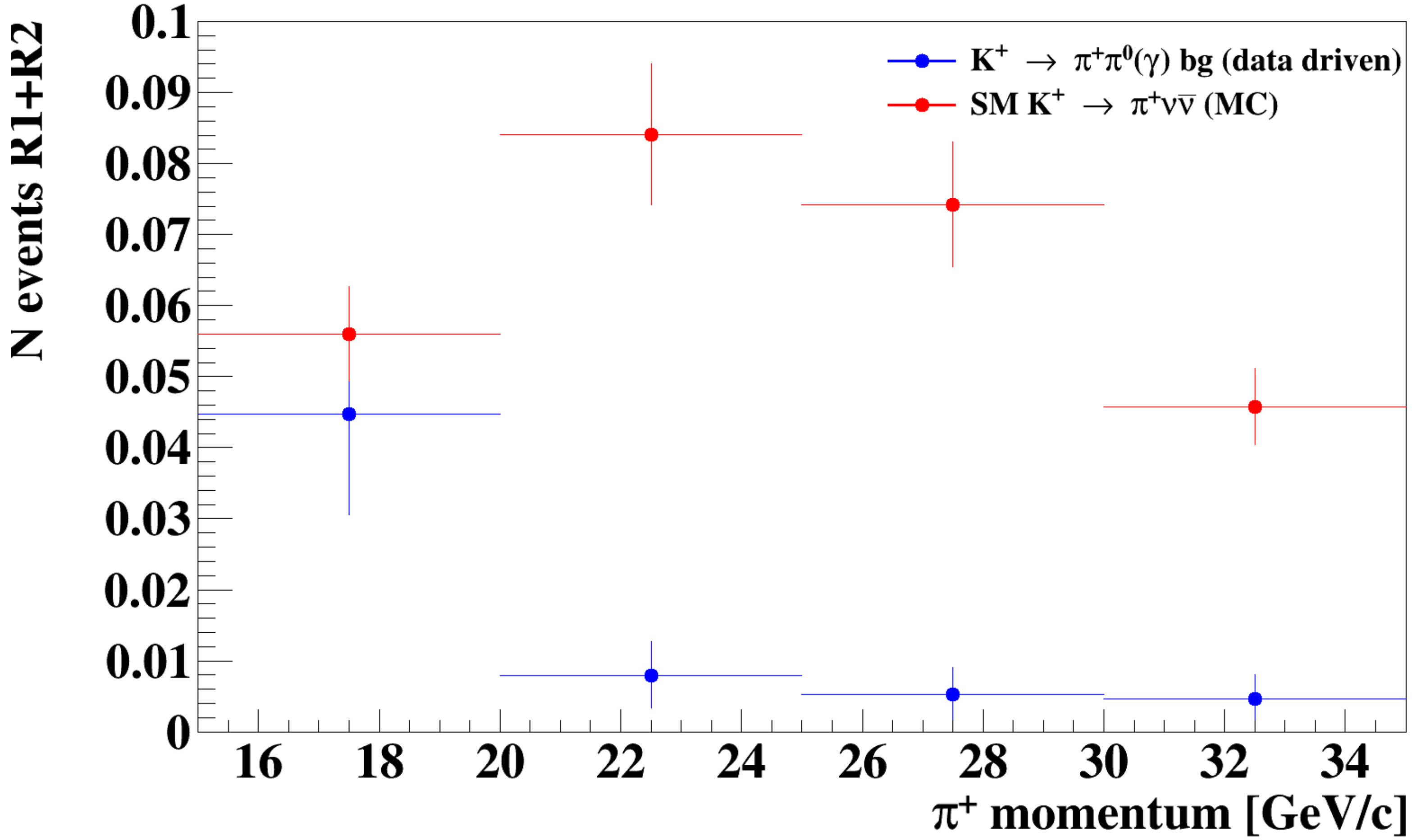


$K^+ \rightarrow \mu^+\nu(\gamma)$ background estimation

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

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

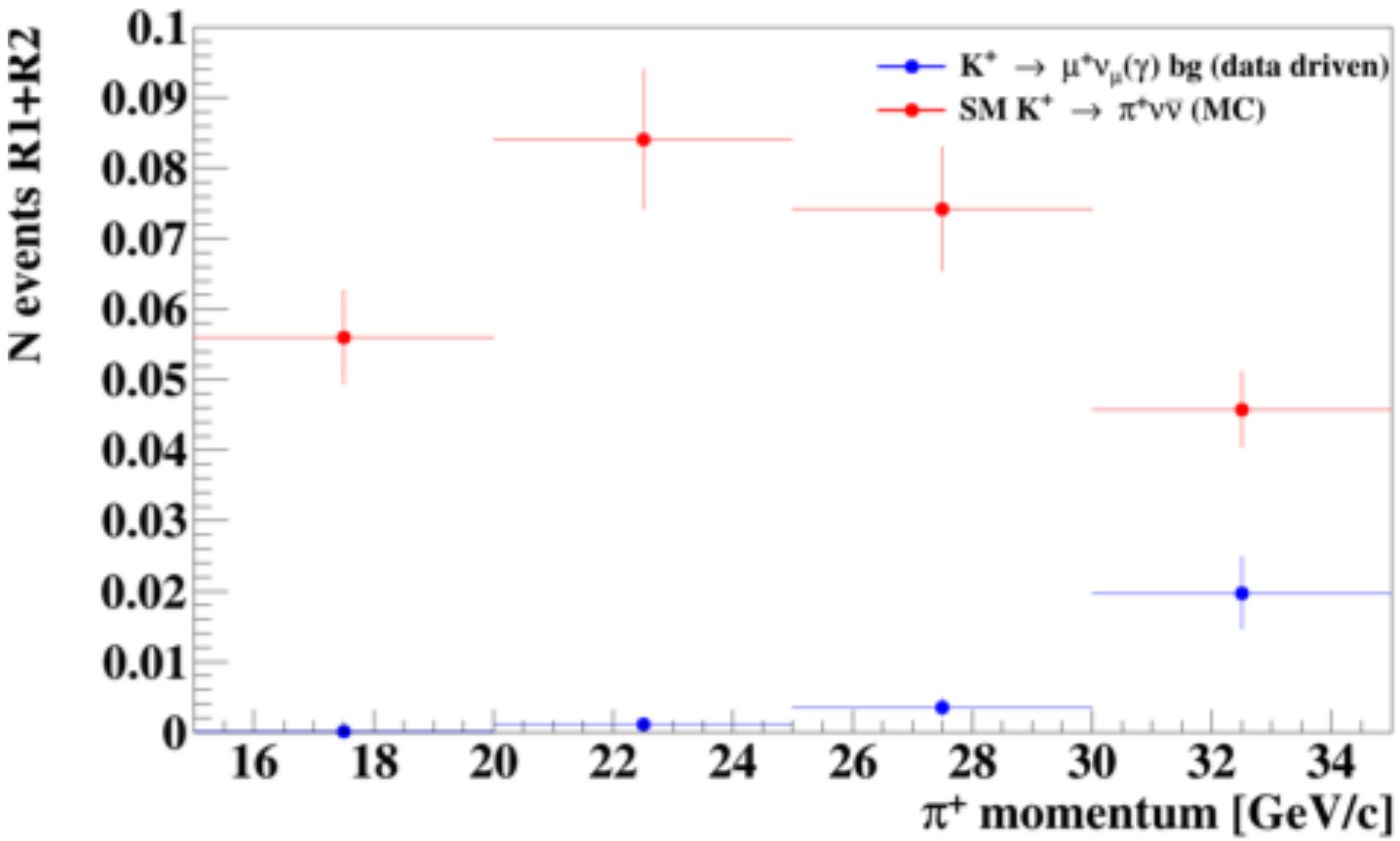
Residual PNN trigger $\pi^+\pi^0$ events gather at low $P_{\pi+}$

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

Control region validation: 1 event observed (1.5 expected)

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

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



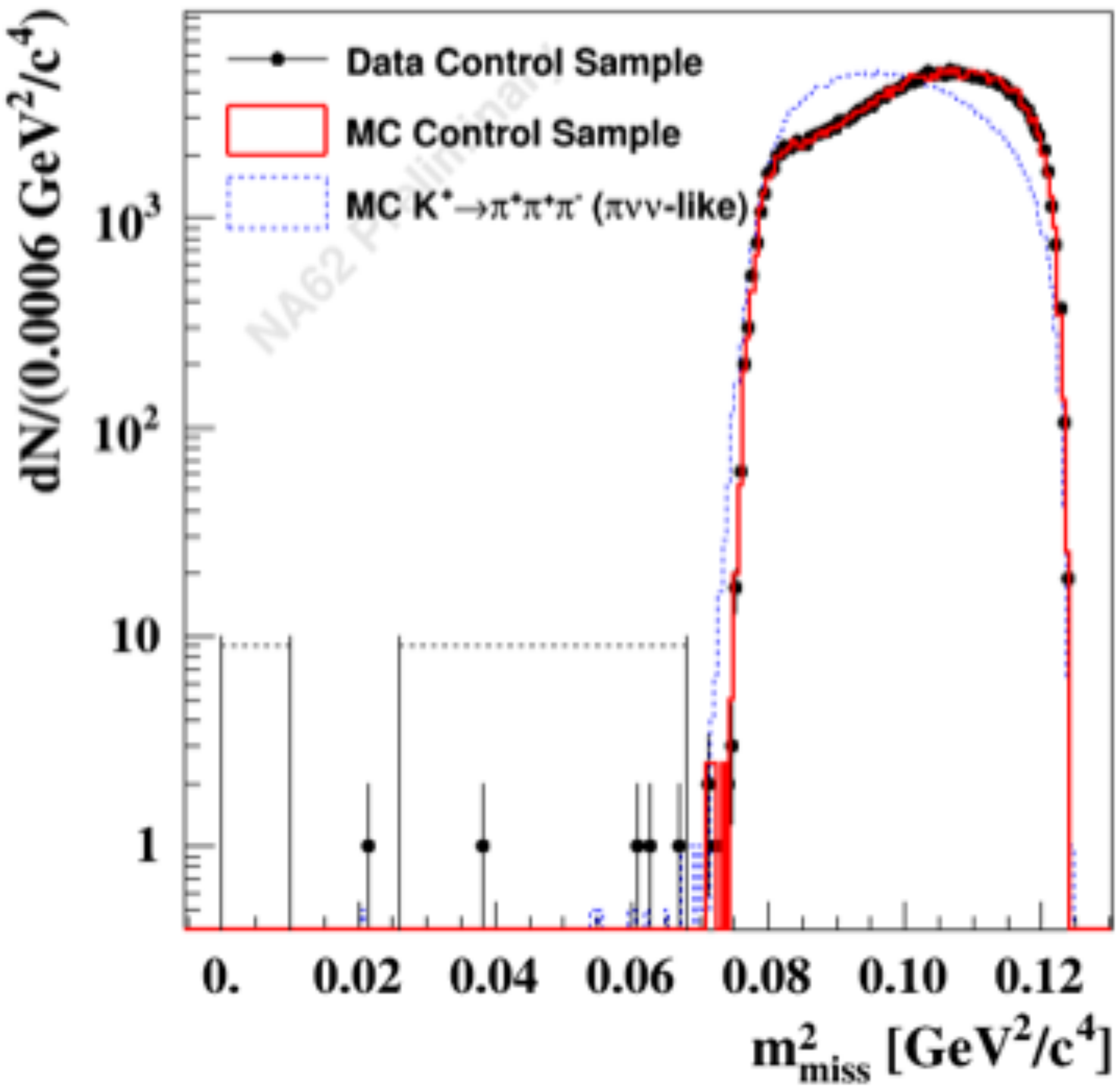
Expected $K^+ \rightarrow \mu^+\nu(\gamma)$ background in $P_{\pi+}$ bins compared to the expected number of SM $K^+ \rightarrow \pi^+\nu\nu$ events

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

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

Control region validation: 2 events observed (1.1 expected)

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



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

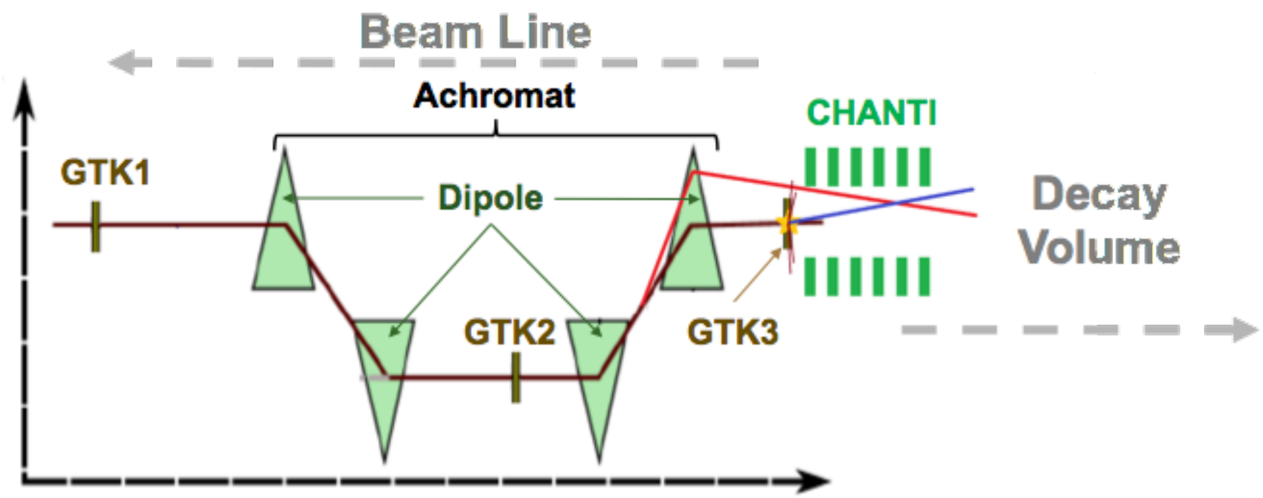
Multiplicity rejection and kinematics cuts turn out to be very effective against $K^+ \rightarrow \pi^+\pi^+\pi^-$ decays (one order of magnitude lower than the other two)

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

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

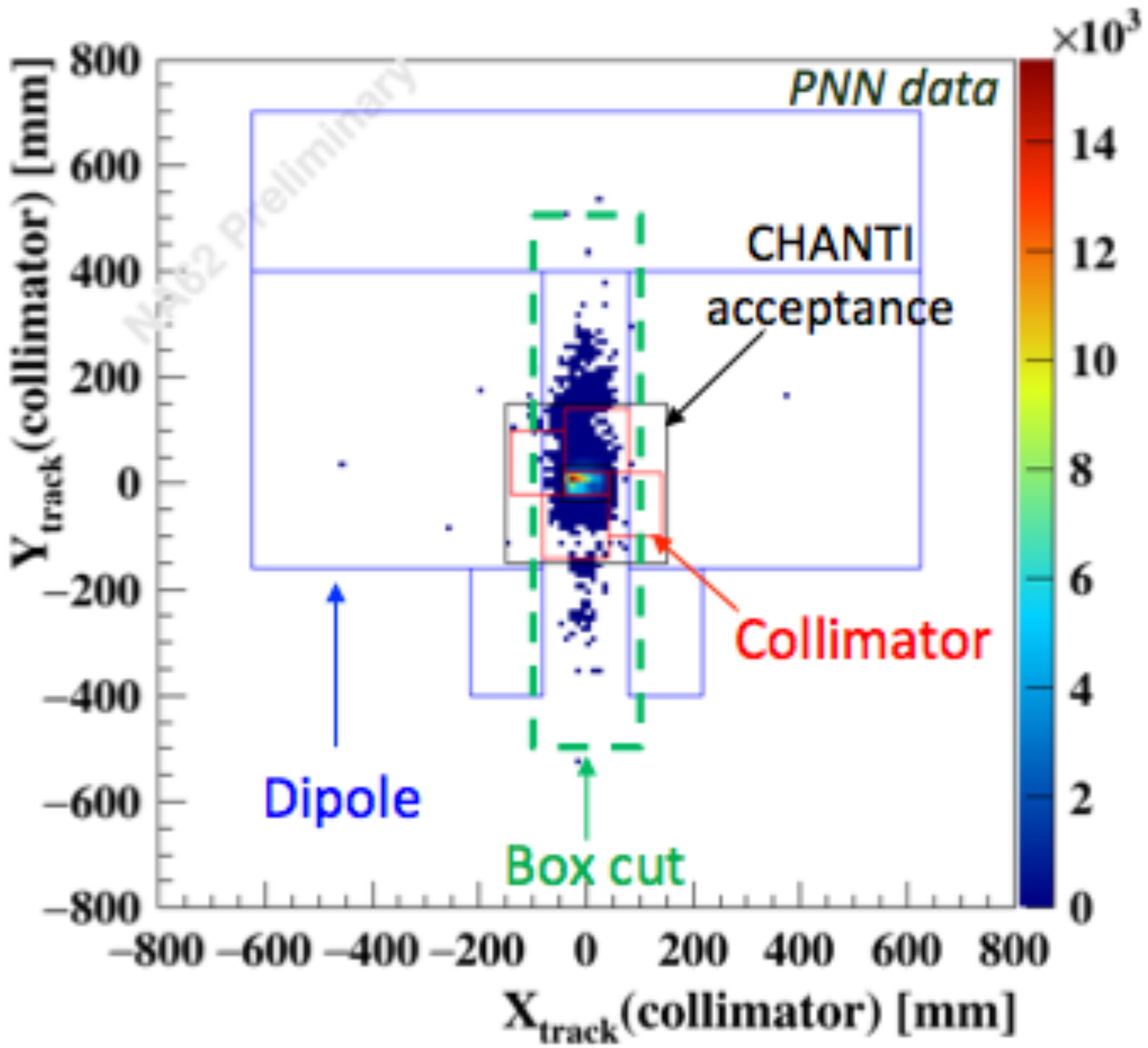
$$N^{expected}_{\pi\pi\pi} = 0.002 \pm 0.001_{stat} \pm 0.002_{syst}$$

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**

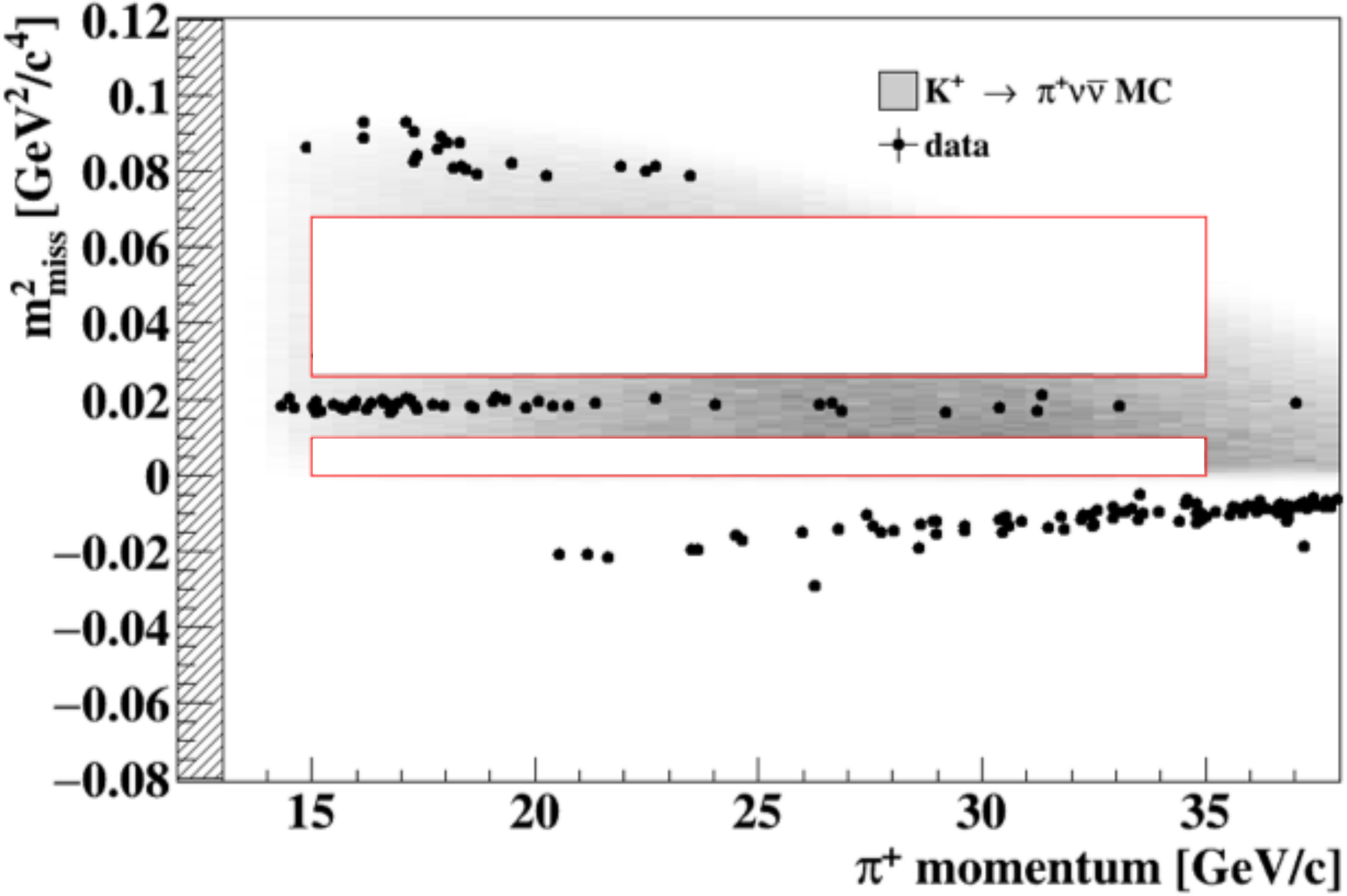
$$|X_{track}| > 100\text{mm}, \quad |Y_{track}| > 500\text{mm}$$

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	$0.020 \pm 0.003_{stat} \pm 0.003_{syst}$
$K^+ \to \pi^+\pi^-e^+\nu$	$0.018^{+0.024}_{-0.017}\vert_{stat} \pm 0.009_{syst}$
$K^+ \to \pi^+\pi^+\pi^-$	$0.002 \pm 0.001_{stat} \pm 0.002_{syst}$
Upstream Background	$0.050^{+0.090}_{-0.030}\vert_{stat}$

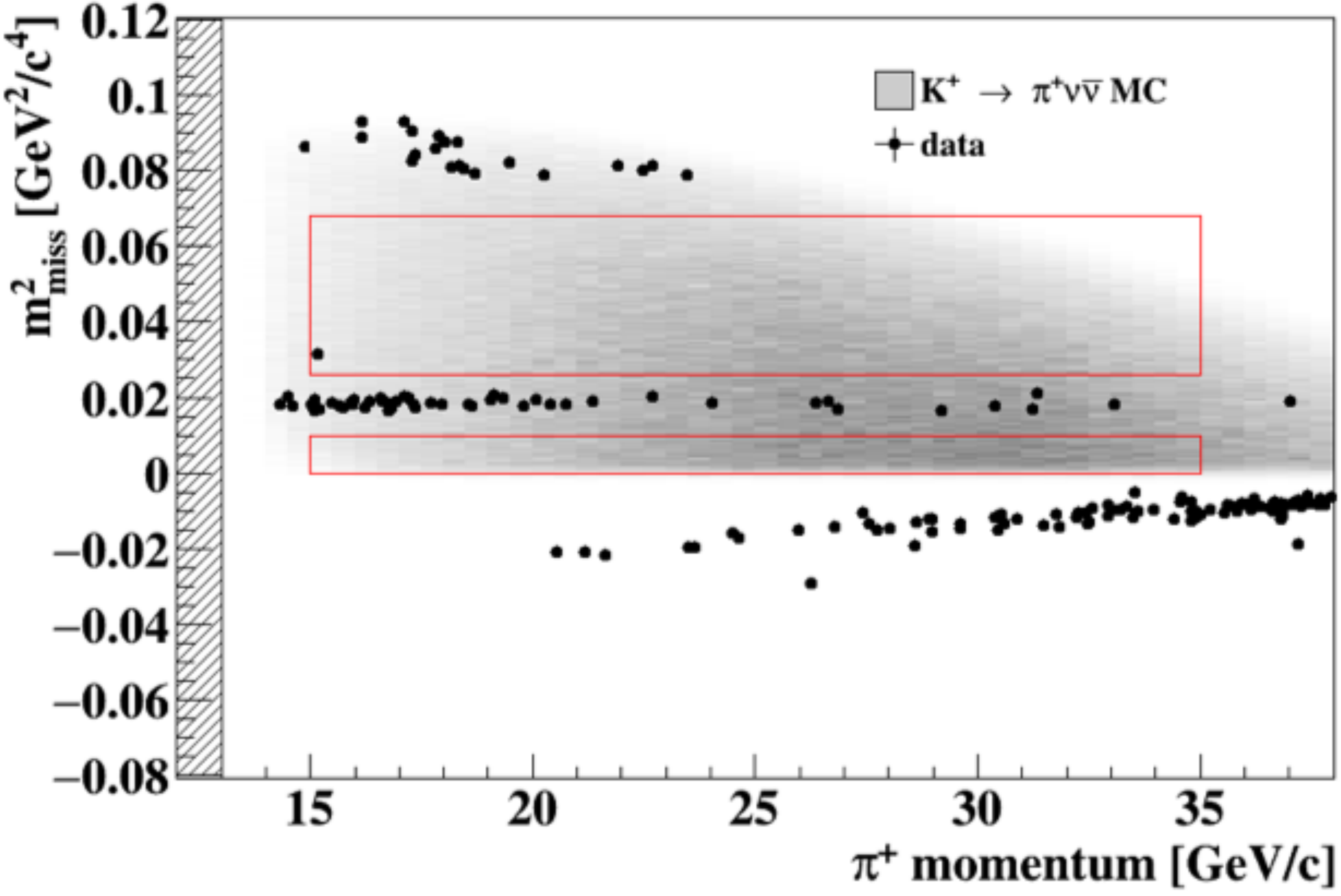
- In the final part of 2017 data-taking a copper plug was inserted in to the last dipole to mitigate this issue
- Upstream background has been further reduced by a ew final collimator that covers a much larger area in the transverse plane installed in mid-June 2018.

Result



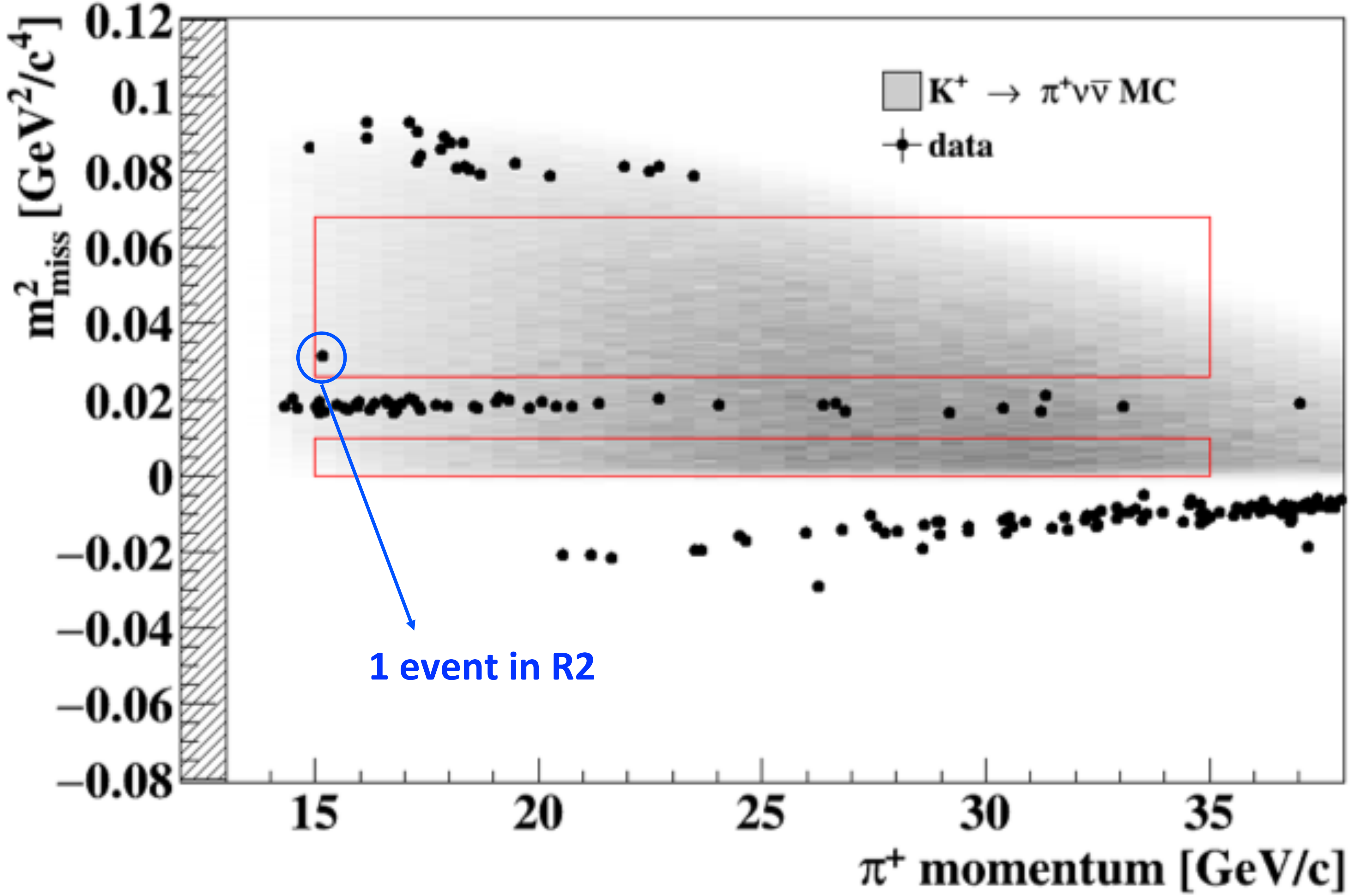
m^2_{miss} [GeV^2/c^4]
0.12
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
15
20
25
30
35
π^+ momentum [GeV/c]
$K^+ \rightarrow \pi^+\nu\bar{\nu}$ MC
data

Result



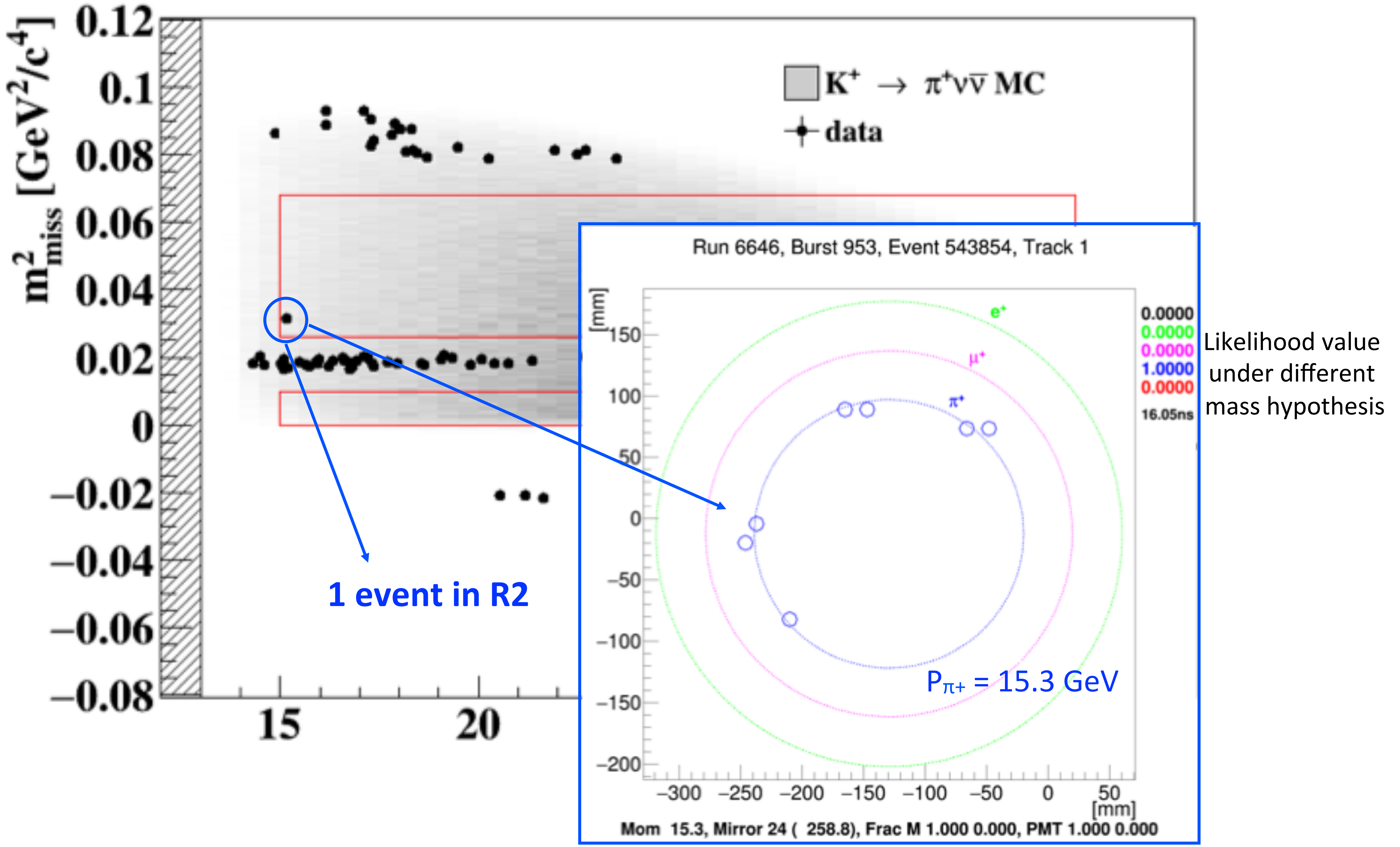
$K^+ \rightarrow \pi^+\nu\bar{\nu}$ MC
data
m^2_{miss} [GeV^2/c^4]
0.12
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
15
20
25
30
35
π^+ momentum [GeV/c]

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
$K^+ \to \pi^+ \nu \bar{\nu}$ 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 1

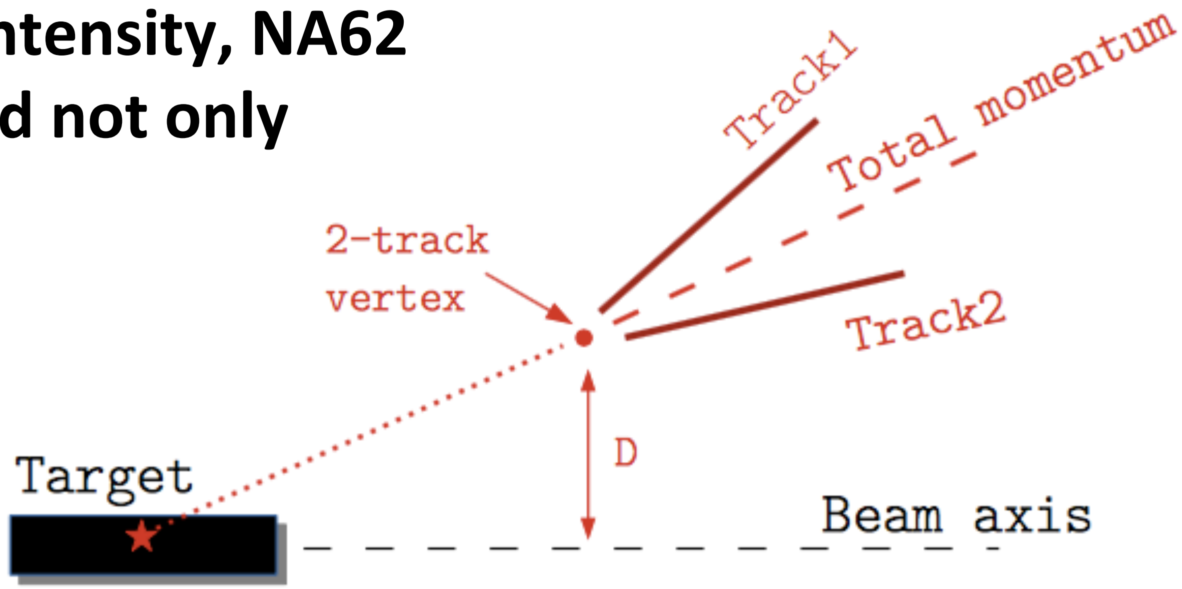
- **The new NA62 decay in flight technique to measure BR($K^+ \rightarrow \pi^+\nu\nu$) works!**
  - 1 event observed in 2016 data
  - BR($K^+ \rightarrow \pi^+\nu\nu$) < 14 x 10^{-10} @ 95% CL
- **Processing of the 2017 data is ongoing**
  - 20 times more than the present statistics
  - upstream background 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

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'$\rightarrow \pi e$, HN'$\rightarrow \pi\mu$**

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

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

Why search for exotic particles?

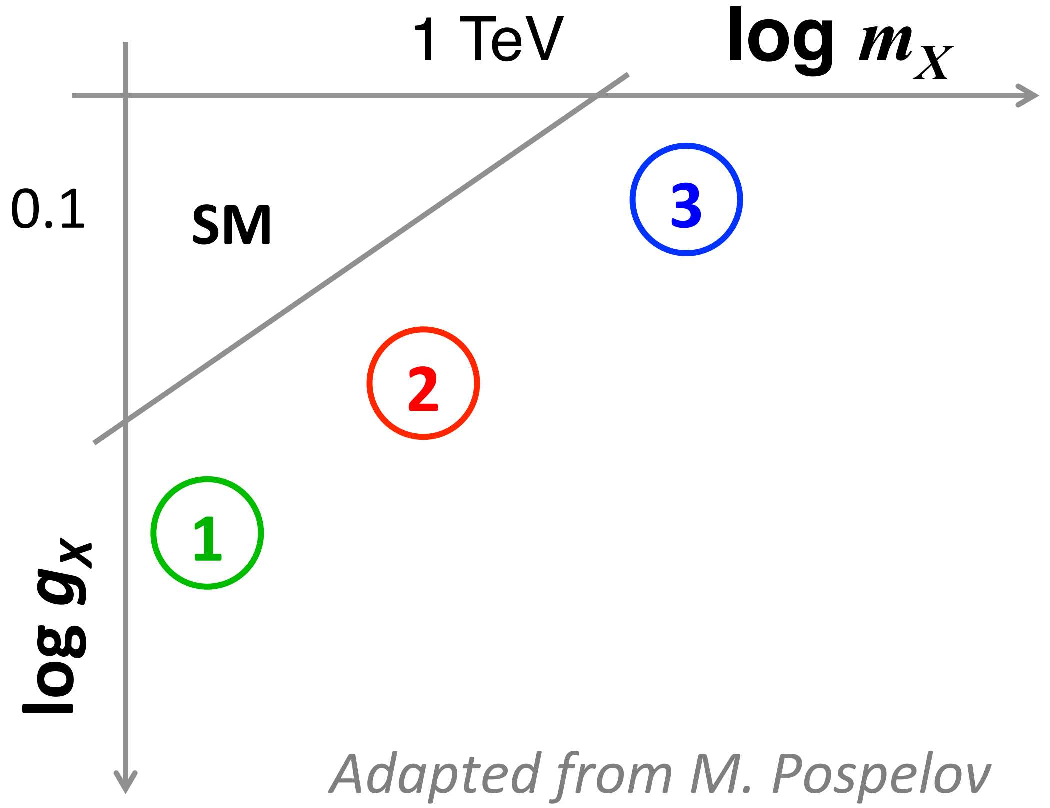
No hints of new physics at high energy so far?

- Strong constraints on SUSY, extra dimensions, technicolor, etc.
- Constraints on new *Z′* bosons push new gauge groups into multi-TeV territory

Yet, SM is obviously incomplete:

- **Neutrino masses and oscillations**
  - See-saw mechanism with RH neutrinos with masses from 10^{-9} to 10^{15} GeV, with Yukawa couplings to the Higgs and SM leptons?
- **Matter-antimatter asymmetry**
  - Requires violation of baryon number, *C*, and *CP* in the early universe. Not enough non-equilibrium *CP* violation in the SM to explain it.
- **Dark Matter**
  - SM particles alone cannot account for the observed matter in the universe
  - Masses for viable DM candidates: 10^{-31} GeV (ultralight scalars) to 10^{20} GeV (black holes) (10 keV to 100 TeV if from thermal origin)
- **Strong CP problem**
  - Apparent conservation of *CP* in QCD requires fine tuning
  - Axion (pseudo-Goldstone boson of spontaneously broken Peccei-Quinn symmetry) may resolve strong *CP* problem while providing DM candidate

Searches for exotic particles



Distinguish searches by mass scale:

1. **Sub-eV:** Search for axions or axion-like particles (ALPs) via EDMs or in direct laboratory searches
2. **MeV-GeV:** Search for heavy neutrinos, ALPs, light DM particles and mediators (dark photons, dark scalars) in fixed-target or collider experiments
3. **10-1000 TeV:** Search for NP in clean and very rare flavor processes or in EDMs

Much attention has been dedicated to TeV-scale models and ideas

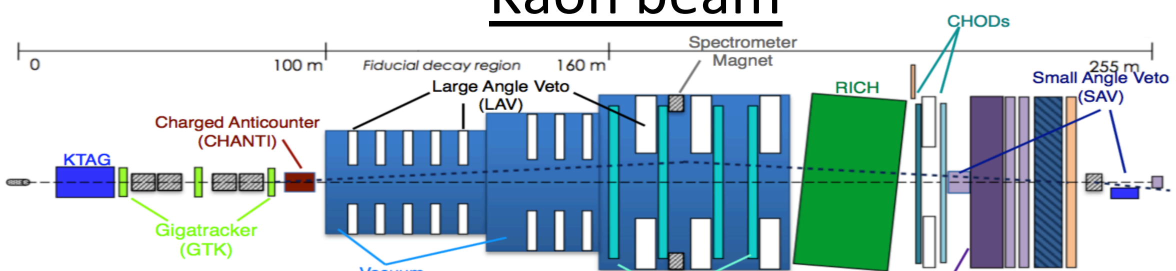
Need a systematic approach for NP at the intensity frontier

Portal	Coupling
Dark photon	$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Scalar	$(\mu S + \lambda S^2) H^\dagger H$
Axion	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}, \frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}, \frac{\partial_\mu a}{f_a} \bar{\psi}\gamma^\mu\gamma^5\psi$
Neutrino/HNL	$y_N L H N$

NA62 designed to be sensitive to *K*$^+$ BRs of order 10^{-12}
Well suited to explore new physics portals in the MeV-GeV scale

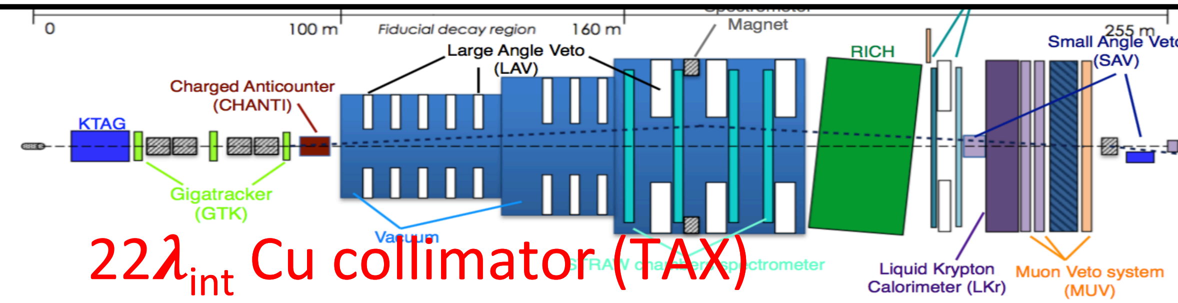
Exotic searches at NA62

Kaon beam



Be $1\lambda_{int}$ target

Dedicated beam dump mode



$22\lambda_{int}$ Cu collimator (TAX)

- Missing mass from K^+ decays
  - $K^+ \rightarrow \pi^+ \nu\nu$ parasitic mode

$K^+ \rightarrow \pi^+ X$ (dark photon, dark scalar, axion)
$K^+ \rightarrow \ell^+ N$ (Heavy Neutral Lepton)

- B/D/K decays in the target and reconstructed daughter particles in fiducial volume,parasitic dump mode
  - dedicated trigger stream
  - O(10^{17}) POT already collected in 2016-2017

- B/D/K mesons produced by 400GeV/c protons in the TAX collimator and visible decays reconstructed in the fiducial volume
  - dedicated data taking with target lifted and tax closed (15 minutes)
  - expected 10^{18} POT / nominal year
  - O(10^{15}) POT already collected in 2016-2017 (few hours)

Dark scalar, dark photon, axion, HNL decaying in 2-particles final state originated at target/TAX

Dark photons

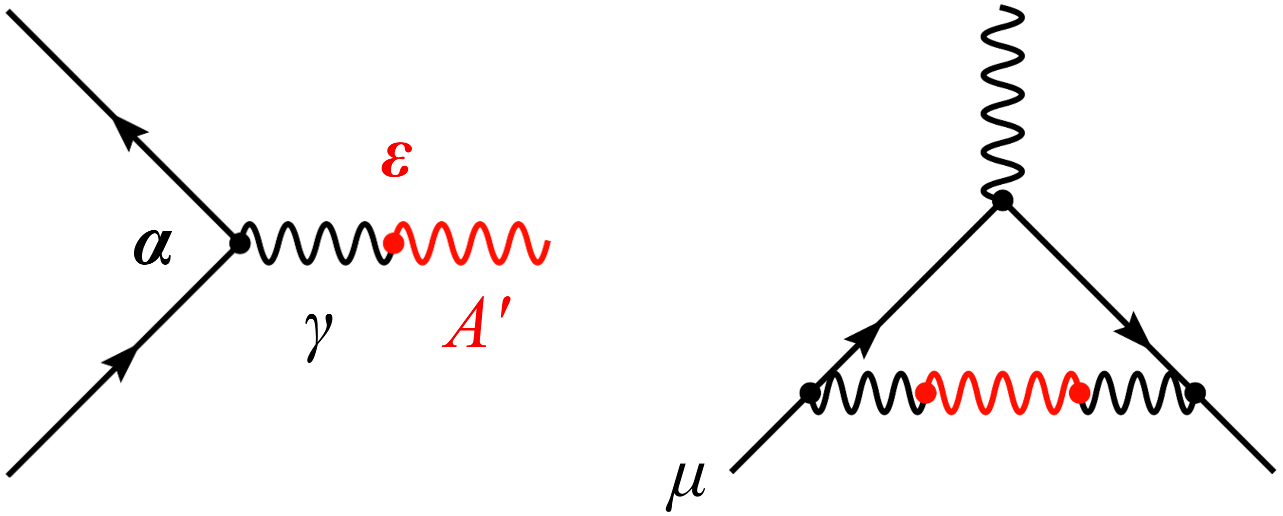
Simplest hidden sector model introduces a new U(1) gauge symmetry with one extra gauge boson: the dark photon *A′*

$$\mathcal{L}_{\text{vector}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - \frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B_{\mu\nu}$$

$$\mathcal{L}_{\text{DS}} = -\frac{1}{4}(F'_{\mu\nu})^2 + \frac{1}{2} m^2_{A'} (A'_\mu)^2 + |(\partial_\mu + i g_D A'_\mu)\chi|^2 + \ldots$$

Interaction of *A′* with visible sector through kinetic mixing with SM hypercharge

- QED-like interactions with SM fermions
- Free parameters: ε and $m_{A'}$



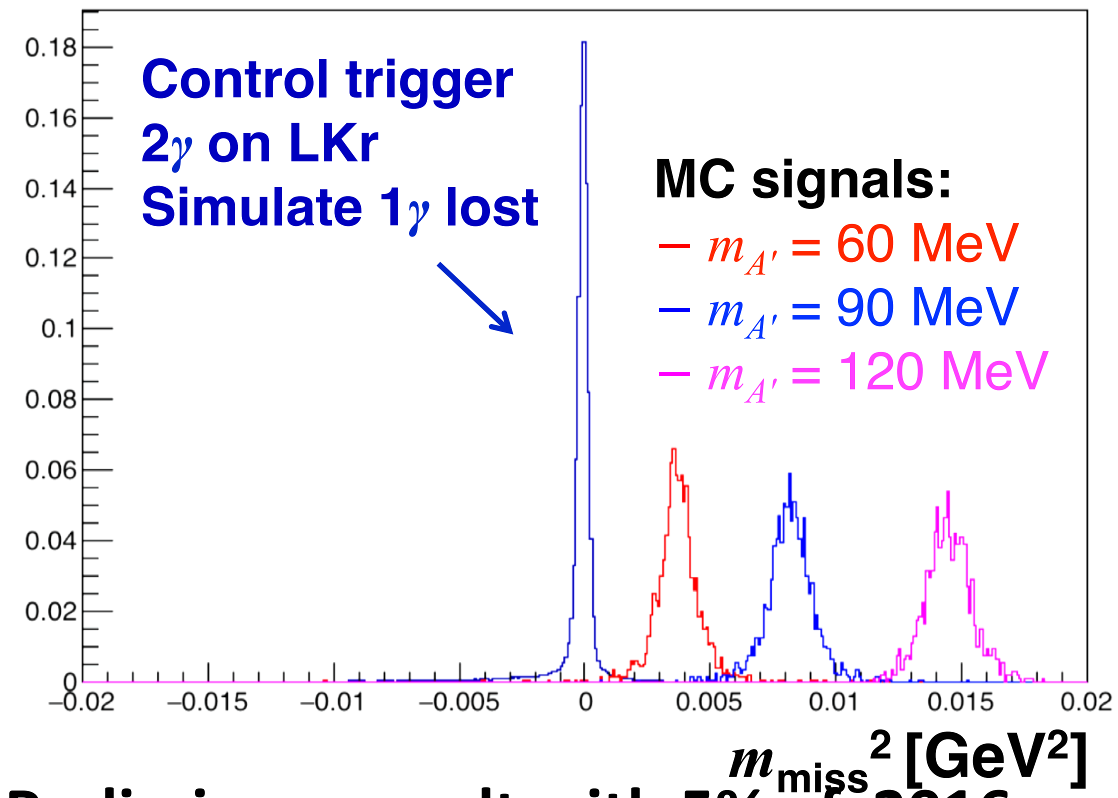
NA62 can search for dark photons:

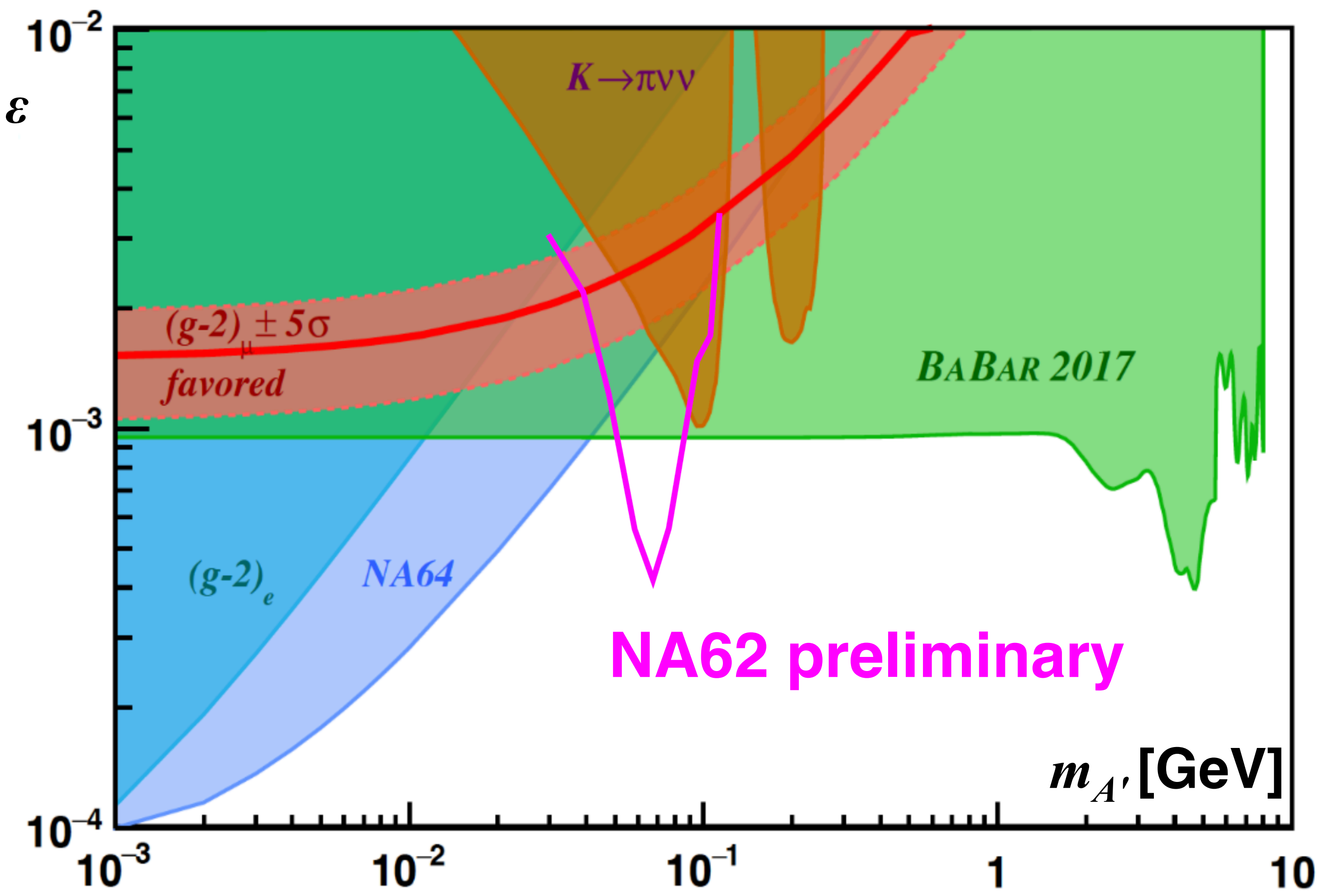
- With no decays to SM particles, in $K^+ \to \pi^+ X$ or $K^+ \to \pi^+\pi^0$ with $\pi^0 \to \gamma X$
- With dedicated trigger for decays such as $A' \to e^+e^-$ or $A' \to \mu^+\mu^-$

Dark photons with invisible decays

Search for $K^+ \rightarrow \pi^+\pi^0$ with $\pi^0 \rightarrow \gamma A'$ and A' invisible

- Sensitivity for $m_{A'} < m_{\pi 0}$
- Signal: 1 track + 1 γ + missing energy
- Search for missing mass peak corresponding to A'
- Main background: $\pi^0 \rightarrow \gamma\gamma$ with 1 γ lost





Preliminary result with 5% of 2016 data sample

- **1.5×10^{10} K^+ decays**
- Background from negative m_{miss} resolution tail from control data
- No significant excess observed
  90% CL UL within expected statistical uncertainty band
- Analysis with full 2016 data set in progress

Dark photons with visible decays

Search for A' produced in target or dump with decay to e^+e^- or $\mu^+\mu^-$ in FV

- Meson decays: From primary beam secondaries, e.g., $pN \to X\pi^0$, $\pi^0 \to \gamma A'$
- Bremsstrahlung from primary beam: $pN \to XA'$

Sensitivity estimate assumes:

- **10^{18} pot on Be target**
- Production in meson decays and bremsstrahlung
- Reconstruction of both e^+e^- and $\mu^+\mu^-$ channels
- 90% CL exclusion in zero-background assumption

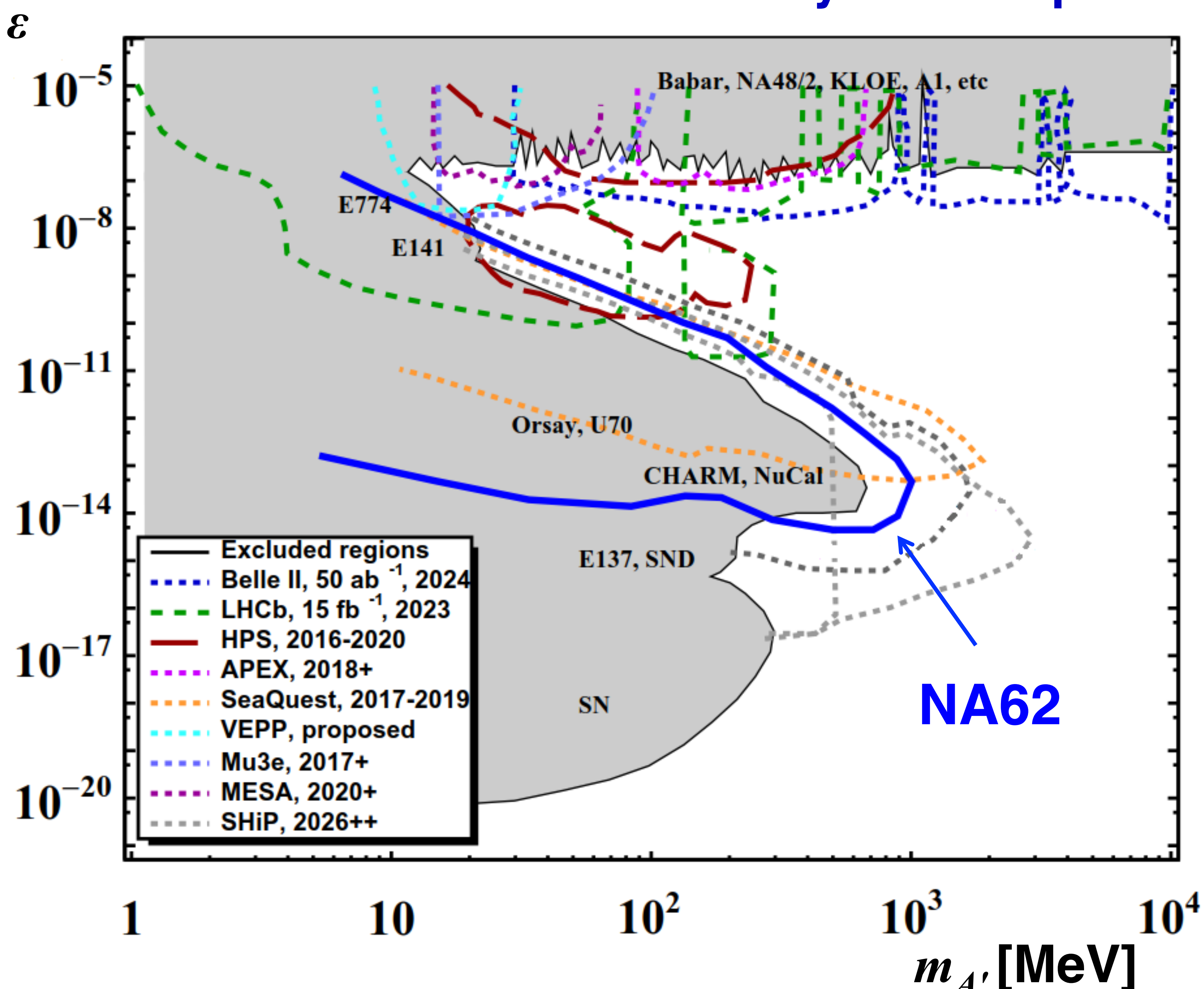
Sensitivity estimate does not include contributions from:

- A' from QCD processes
- A' produced in TAX

Data from 2016-2017 runs

- 3×10^{17} pot with $\mu\mu$ trigger
- 5×10^{16} pot with ee trigger

NA62 estimated sensitivity for 10^{18} pot



Dark scalar particles

Dark sector coupled to Higgs by new singlet scalar field *S*

ϑ mixing angle S-Higgs

$$\mathcal{L}_{\text{scalar}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - (\mu S + \lambda S^2) H^\dagger H$$

$$\mathcal{L}_{\text{DS}} = S\bar{\chi}\chi + \ldots \qquad \theta = \frac{\mu v}{m_h^2 - m_S^2}$$

S produced most efficiently by decays of *B*-mesons from interactions in TAX

Reconstruction of 2-track final states (*ee*, *μμ*, *ππ*, *KK*) with vertex pointing back to TAX:

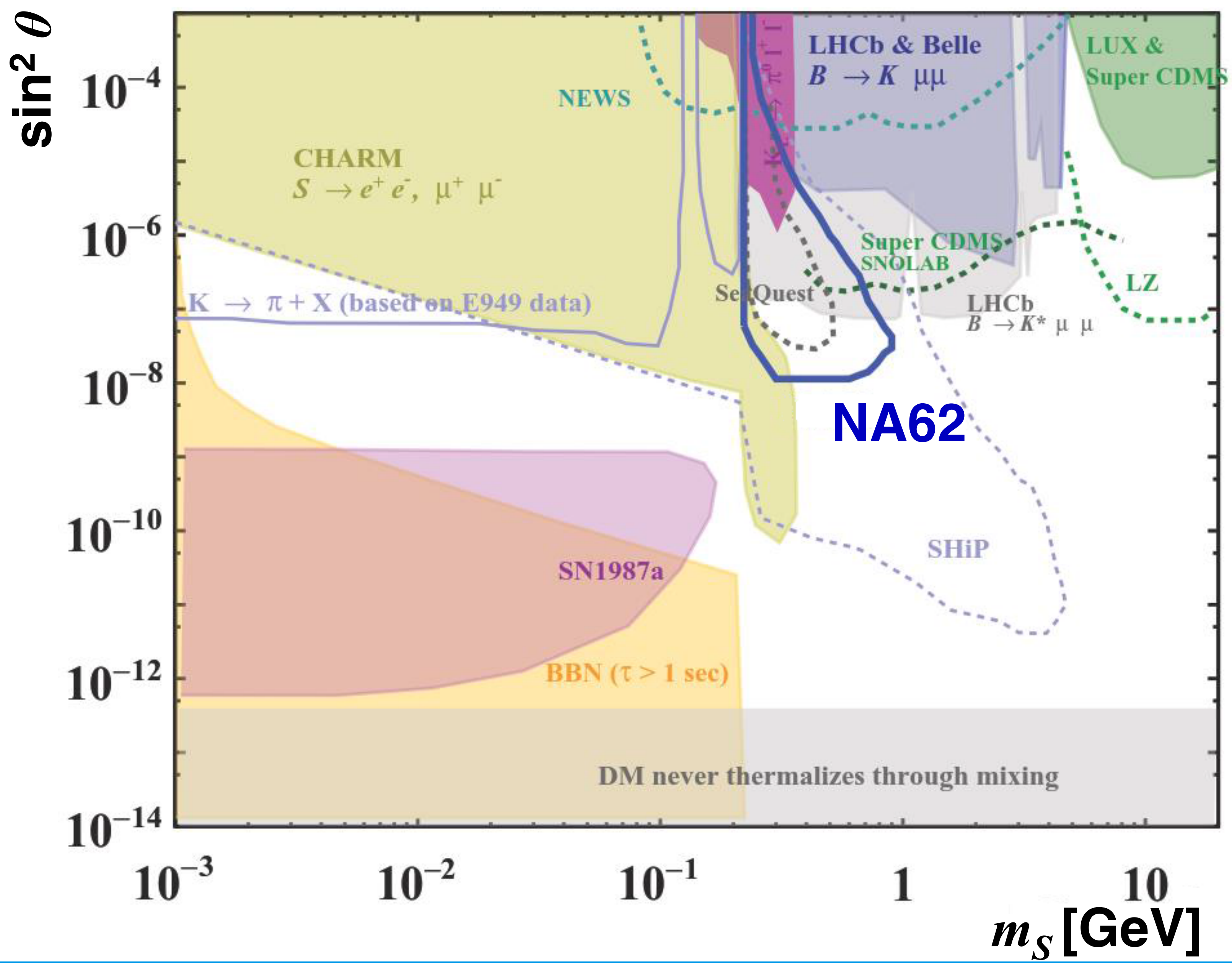
Sensitivity estimate assumes:

- **10^{18} pot on Be target**
- 90% CL exclusion in zero-background assumption

Data from 2016-2017 runs

- 3×10^{17} pot with *μμ* trigger
- 5×10^{16} pot with *ee* trigger

NA62 estimated sensitivity for 10^{18} pot



Axion-like particles

Light pseudoscalar ALP may act as a mediator between SM and dark matter

$$\mathcal{L}_{\text{axion}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \frac{a}{4f_\gamma} F_{\mu\nu}\tilde{F}_{\mu\nu} + \frac{a}{4f_G} \text{Tr} G_{\mu\nu}\tilde{G}_{\mu\nu} + \frac{\partial_\mu a}{f_l} \sum_\alpha \bar{l}_\alpha \gamma_\mu \gamma_5 l_\alpha + \frac{\partial_\mu a}{f_q} \sum_\beta \bar{q}_\beta \gamma_\mu \gamma_5 q_\beta$$

NA62 can explore ALP masses in the MeV-GeV range

Focus on pseudoscalar ALPs whose dominant interaction is with photons:

- Dedicated running in beam dump mode (TAX closed)
- Primakoff ($\gamma\gamma$ fusion) production from interaction in TAX with $a \to \gamma\gamma$ decay
- ALP produced at low $p_\perp$ → good acceptance even if detector far from production point

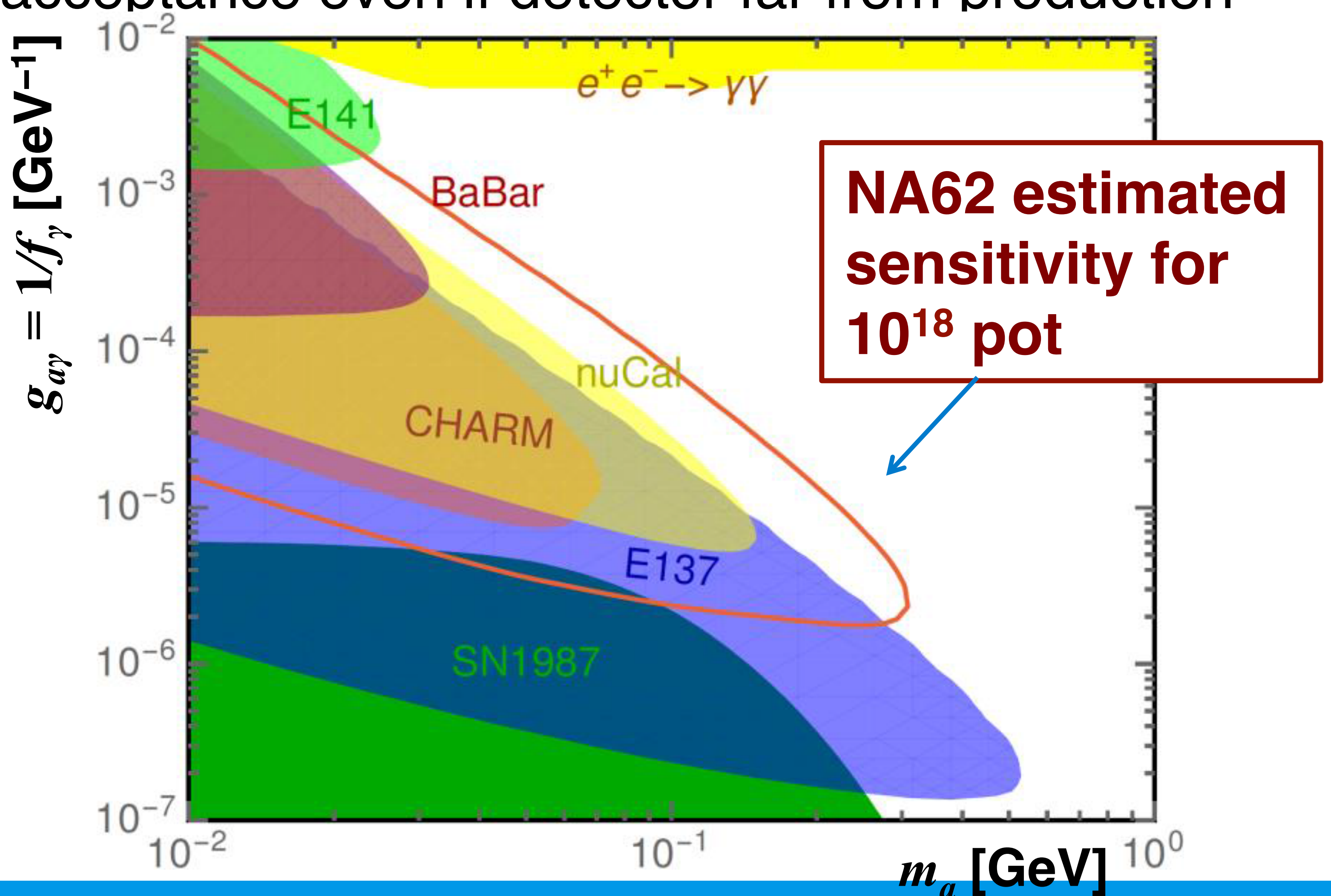
Sensitivity estimate assumes:

- **10^{18} pot on closed TAX**
- 90% CL exclusion in zero-background assumption

Significant results obtainable with only 1 day of data taking (1.3×10^{16} pot)

- Analysis of 2017 data in progress:

  5×10^{15} pot in dump mode



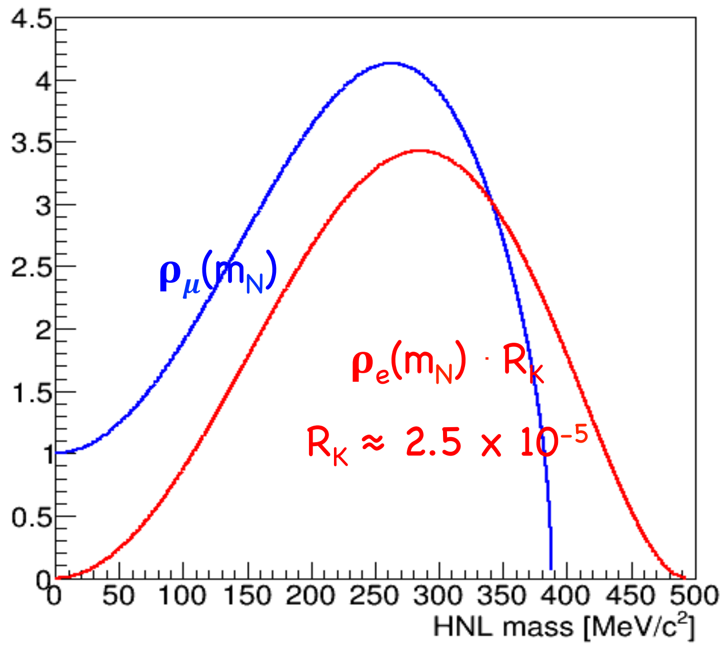
HNLs

Various extensions to SM to accommodate massive sterile neutrino (HNLs) (see A. De Roeck talk)

Neutrino Minimal Standard Model ($\boldsymbol{\nu}$MSM)

- 3 right-handed massive neutrino N_i added to SM
  - N_1 mass O(10 KeV) : Dark Matter candidate
  - $N_{2,3}$ mass O(100 MeV) : mass to SM neutrinos via see-saw mechanism
- 18 new parameters in the Lagrangian that can explain Dark Matter, Baryon Asymmetry of the Universe and neutrino oscillation

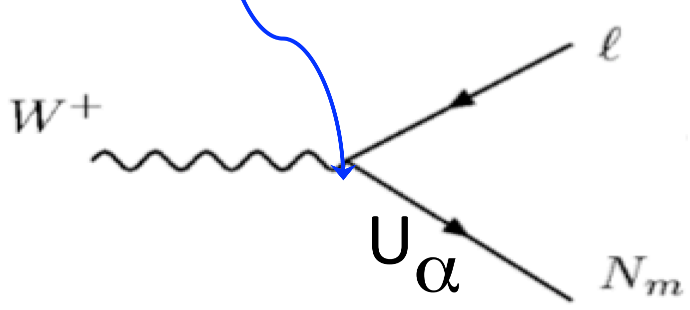
- HNL production in Kaon decays ($m_N < m_K$): $K^+ \rightarrow \ell^+ N$ ($\ell = \boldsymbol{\mu}$,e)



[R. Shrock PLB96 (1980) 159]

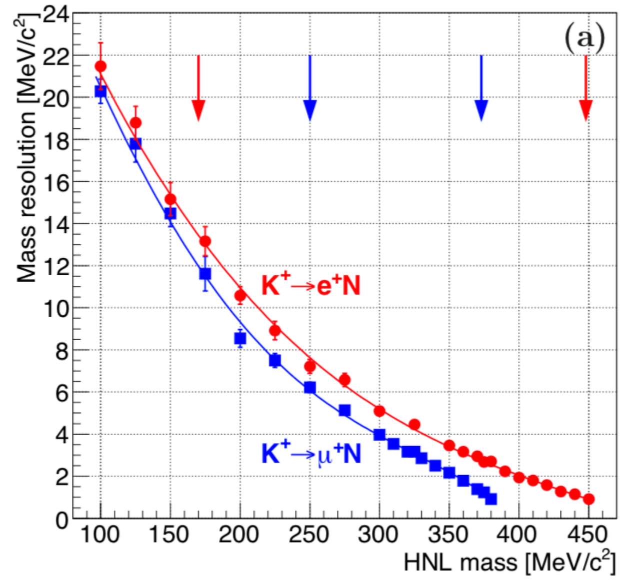
$$\Gamma(K \rightarrow \ell N) = \Gamma(K \rightarrow \ell \nu_\ell) \cdot \rho_\ell(m_N) \cdot |U_{\ell 4}|^2$$

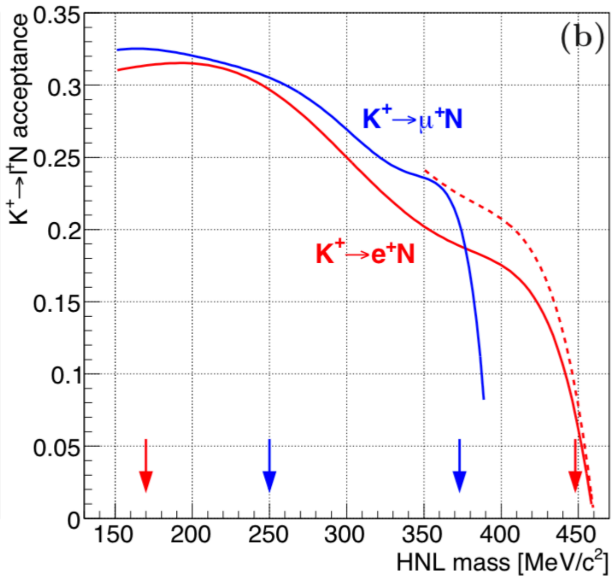
kinematic factor accounts for the phase space and the helicity suppression

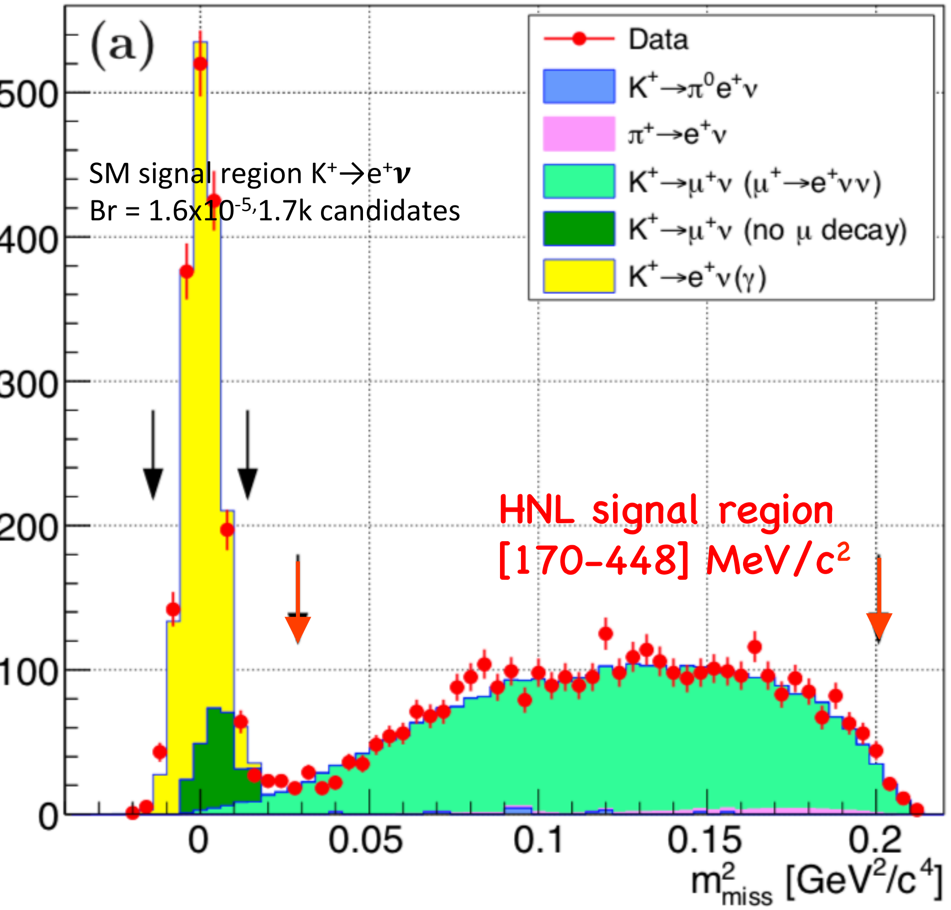


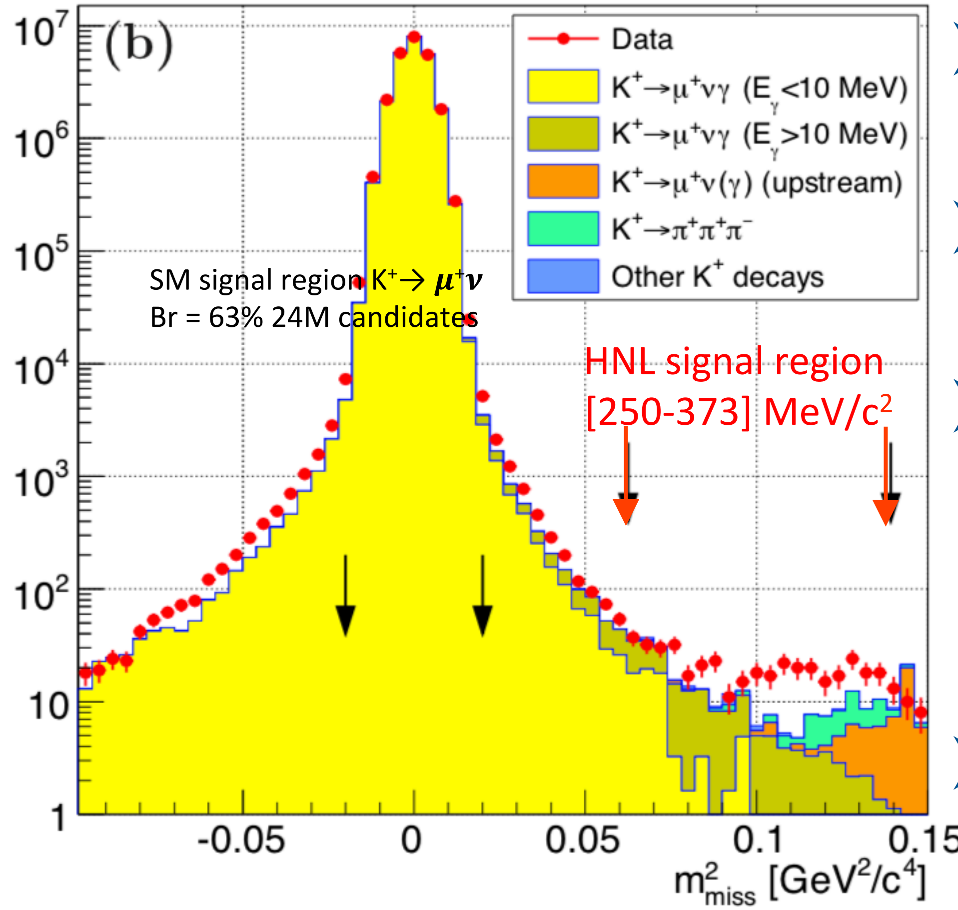
HNLs SEARCH IN KAON DECAYS

- Looking for peak in $M^2_{miss.} = (P_K - P_\ell)^2$ (HNL decay length> 10 Km)
- 2015 minimum bias data (5 days @ 1% nominal intensity)
- No beam tracker available
- K decays in FV 3×10^8 electron mode & 1×10^8 muon mode





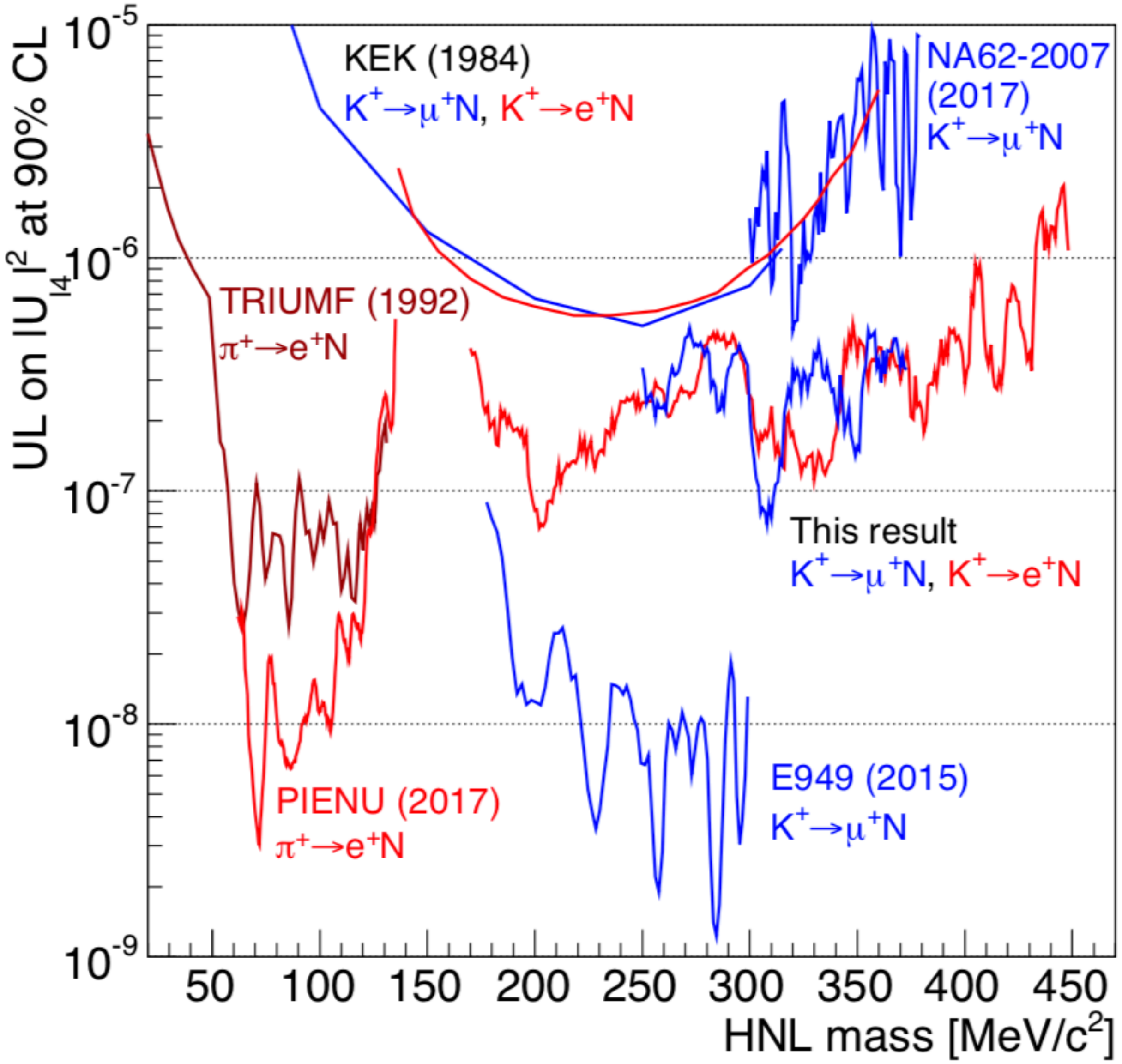




- Scan of HNL mass
- $\pm1.5\sigma_m$ mass window
- Mass resolution & acceptance evaluated with MC
- No signal observed only upper limit set

HNLs SEARCH IN KAON DECAYS

- Published results:
  NA62 Coll. PL B778 137 (2018)
  10^{-6}-10^{-7} limits for $|U_{\ell 4}|^2$
  in the mass range 170-448 MeV/c^2

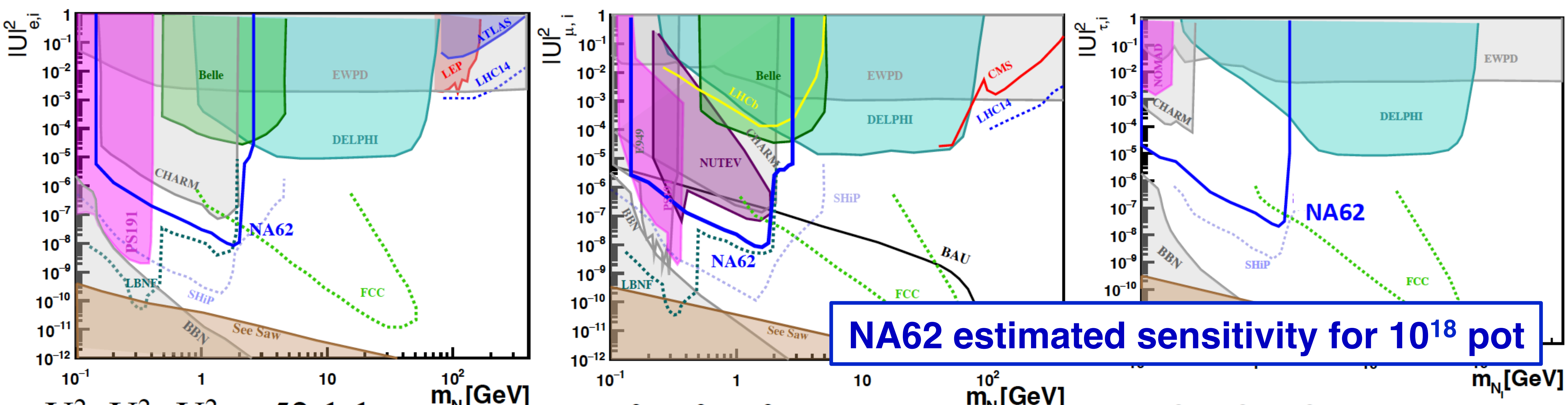


- Analysis with 2016-2018 collected data on-going, 2 order of magnitude improvement expected on $U_{\ell 4}$
  - more statistics
  - GTK in
  - lower background

HNLs with visible decays

Search for *N* produced in TAX with decays to two-track final states:

- Assume 10^{18} pot on closed TAX
- Reconstruct two-track final states HNL -> $\pi\mu/\pi e$, including open channels
- 90% CL exclusion in zero-background assumption
- Derive sensitivity for coupling scenarios in Shaposhnikov & Gorbunov 0705.1729v2



$U^2_e:U^2_\mu:U^2_\tau = 52:1:1$
Normal hierarchy of active ν masses

$U^2_e:U^2_\mu:U^2_\tau = 1:16:3.8$
Normal hierarchy of active ν masses

$U^2_e:U^2_\mu:U^2_\tau = 0.061:1:4.3$
Normal hierarchy of active ν masses

Data from 2016-2017 runs: 10^{17} pot with $\pi\mu$ trigger; few 10^{16} pot with πe trigger

Summary and outlook

Main goal of NA62 is to measure BR($K^+ \rightarrow \pi^+\nu\nu$) with 10% accuracy

- Physics runs in 2016, 2017, and 2018 − data taking in progress!
- Data taking after LS2 under consideration

Hidden-sector physics program before LS2:

- Dedicated triggers compatible with $\pi\nu\nu$ program to search for dark photons, dark scalars, and HNLs
- Short, dedicated beam-dump runs to search for ALP decays to $\gamma\gamma$

After LS2, collection of 10^{18} pot in beam-dump mode will provide sensivity to various hidden-sector models

- Expected sensitivity beyond that of other initiatives with same time scale