$K^+ \to \pi^+ \nu\nu$ and New Physics searches @ NA62 experiment

In Pursuit of New Particles and Paradigms

Dario Soldi *on behalf of NA62 collaboration*

A general purpose experiment

Flavour Physics

Search for **New Physics** at the EW scale with sizeable coupling to SM particles **via indirect effects in loops** → **BR($K^+ \to \pi^+ \nu\nu$)**

Search for **lepton flavour and number violation**, rare and forbidden decays → **LFV, LNV**

Hidden sector Physics → Search for **New Physics below the EW scale** (MeV-GeV) feebly-coupled to SM particles via direct detection of long-lived particles → **Heavy Neutral Lepton(HNL) Dark Photon(DP), ALPs**

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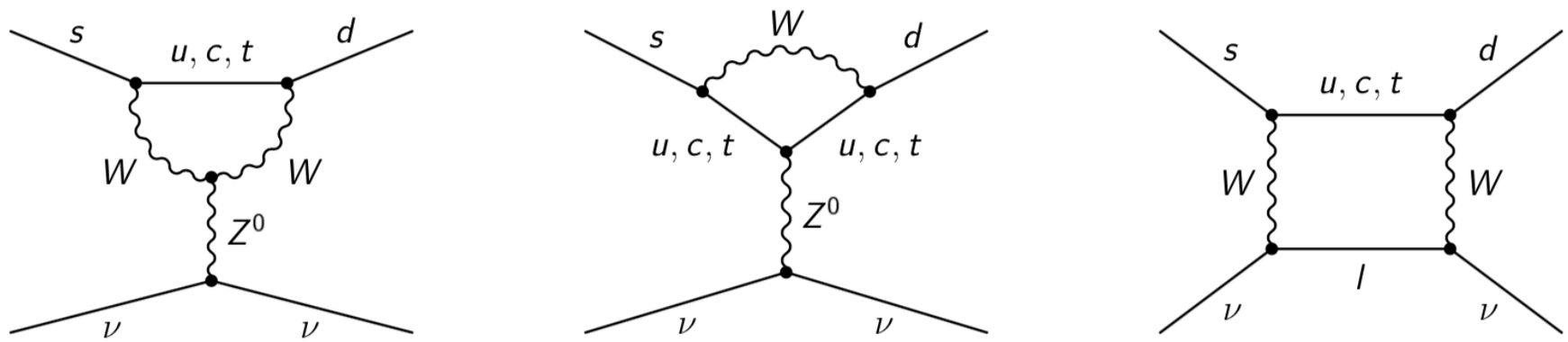
NA62 Main Goal



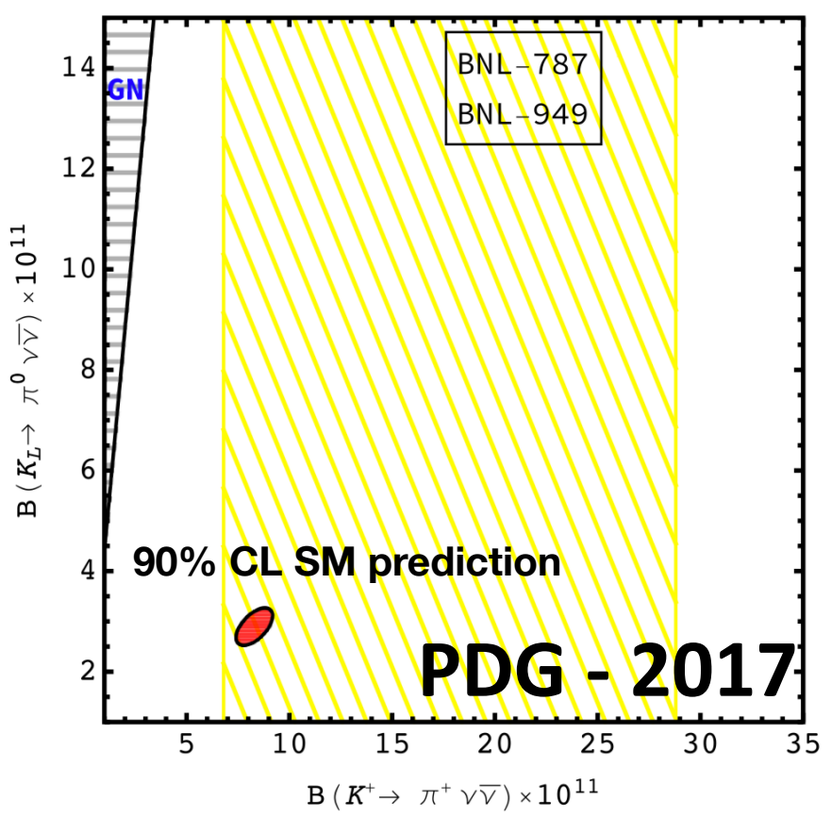
The **$K^+ \rightarrow \pi^+\nu\nu$** decay is extremely suppressed

flavor-changing neutral current quark transition s→dνν forbidden at tree level

BUT

Clean theoretical prediction: QCD corrections, electroweak corrections, hadronic matrix element related to $K^+ \rightarrow \pi^0 e^+ \nu_e$ decay.

A.J. Buras, et al. arXiv:1503.02693



SM theoretical prediction:

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

Previous measurement: E787 and E949 @ BNL (7 events)

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

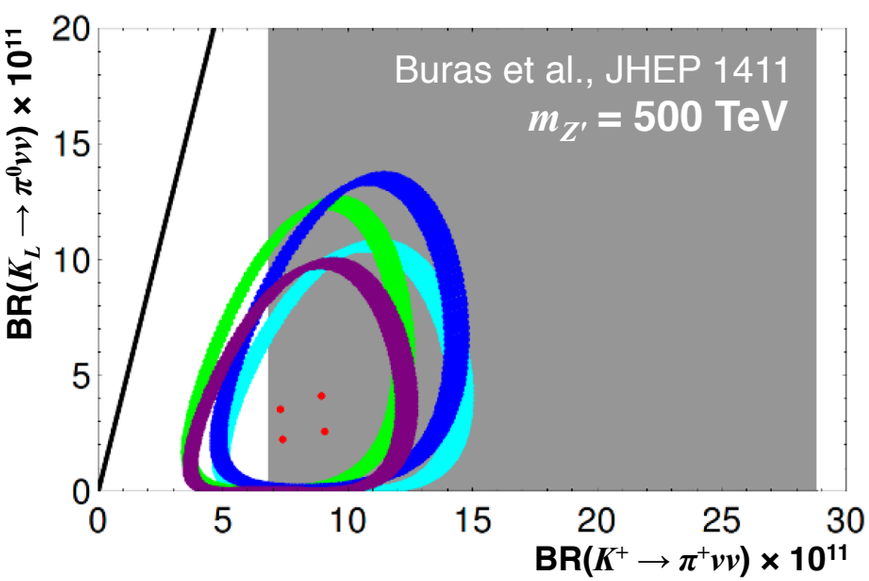
Gap between theoretical precision and large experimental error motivates a strong experimental effort. Significant new constraints can be obtained.

New Physics from K→πνν

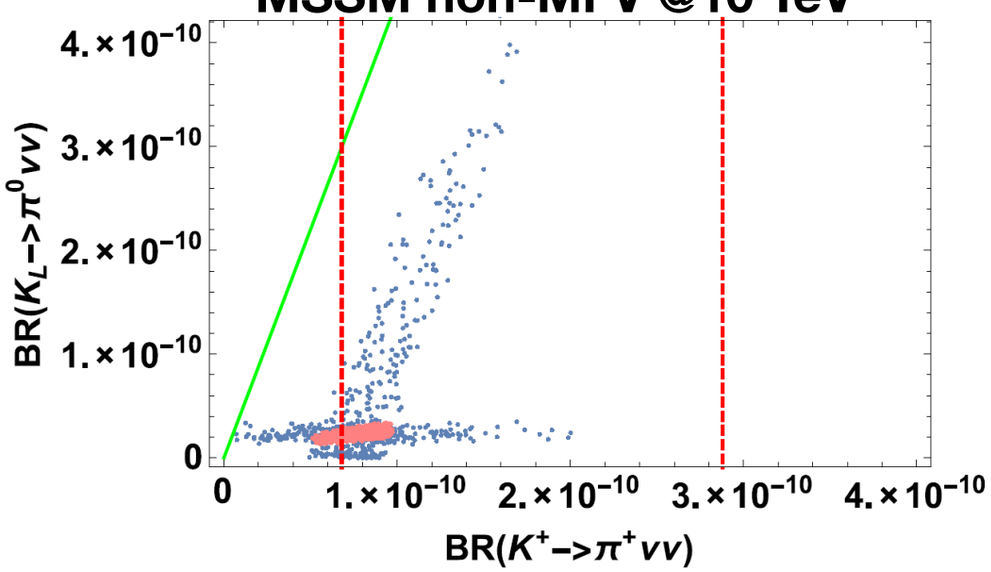
many BSM scenarios:

- **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]

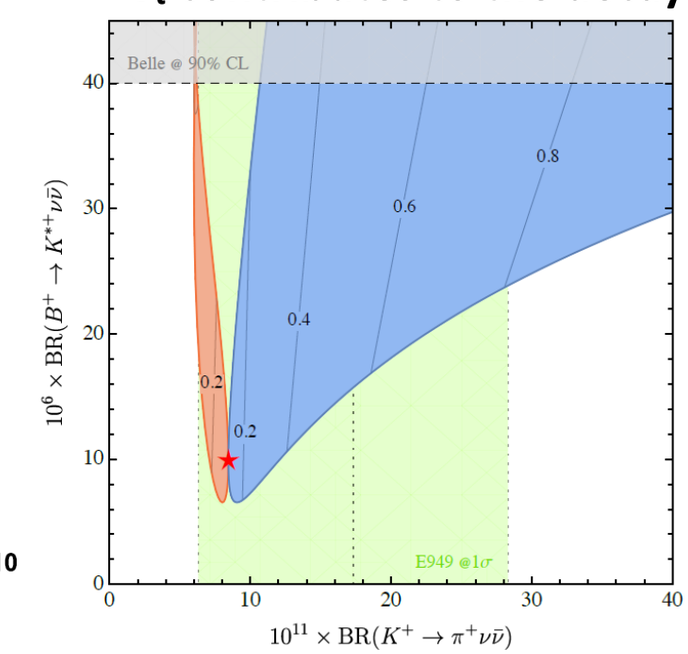
Tree-level flavour changing Z′, LH+RH couplings



MSSM non-MFV @10 TeV



LFU violation
ν_τ contributes to the decay

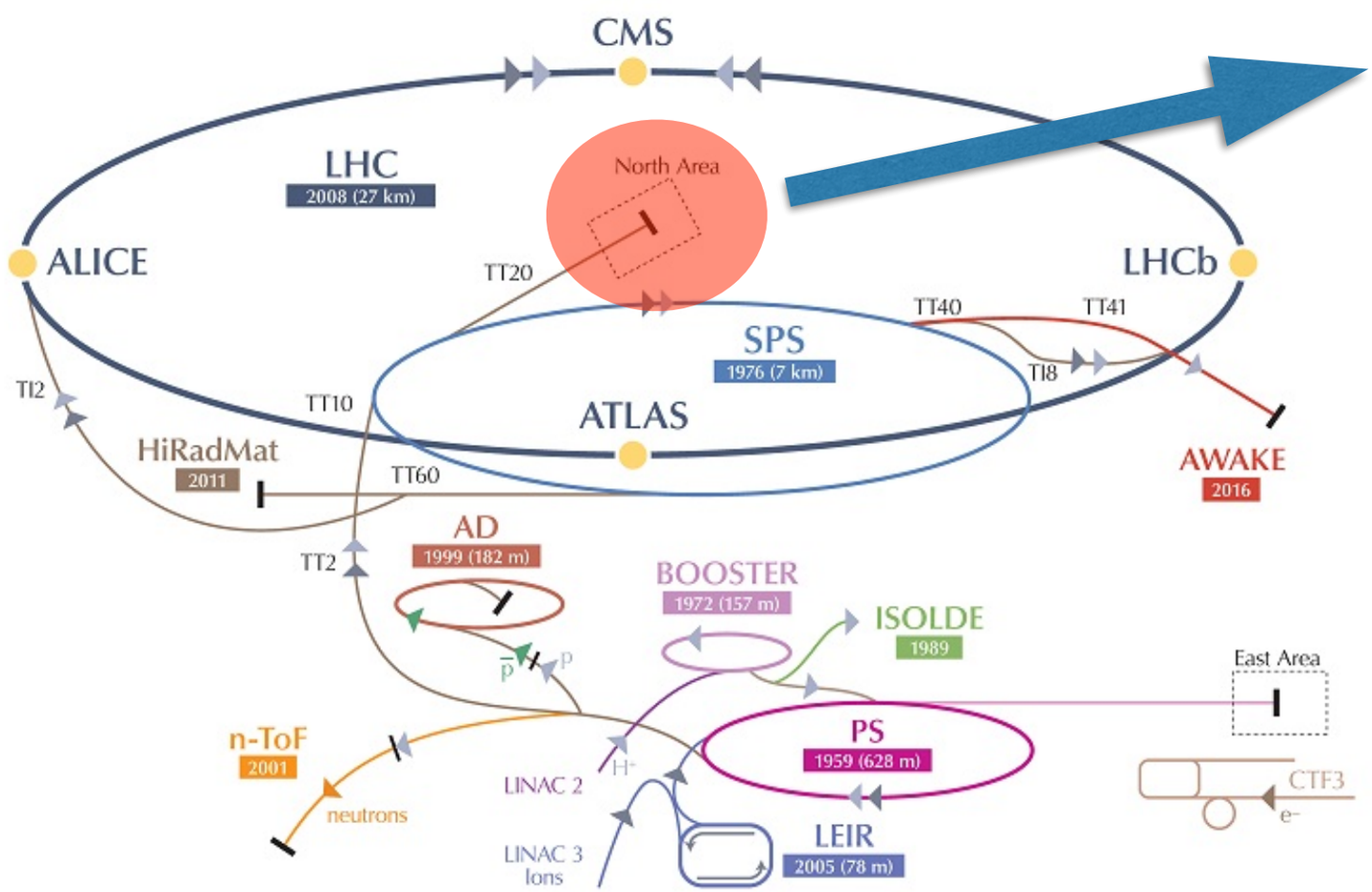


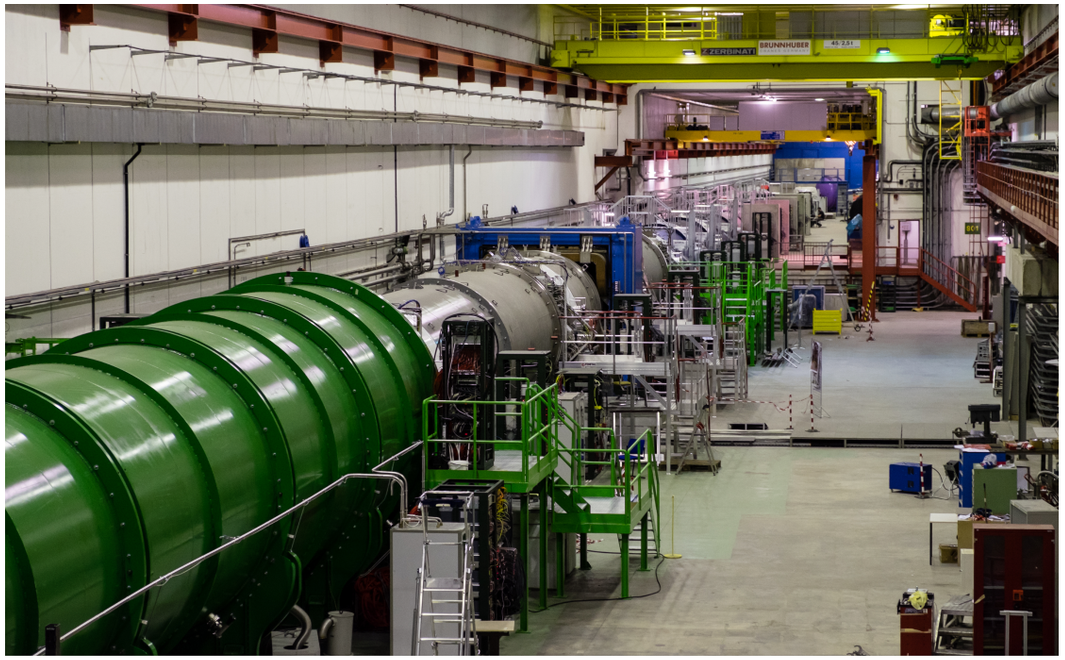
***K → πνν* is uniquely sensitive to high mass scales, up to 2000 TeV: NA62 complementary to the LHC experiments and the B factories**

A Kaon Factory at CERN SPS

High intensity beam: least 10^{13} K^+ decays are required to measure πνν with 10% statistical error

the North Area the SpS extraction line is delivers the charged hadron beam with the required K^+ intensity.

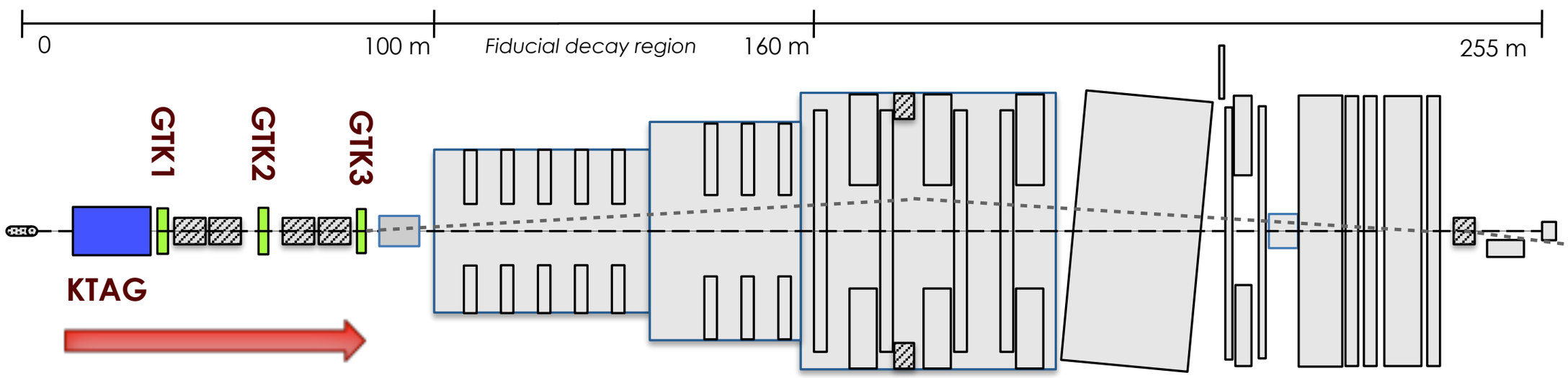




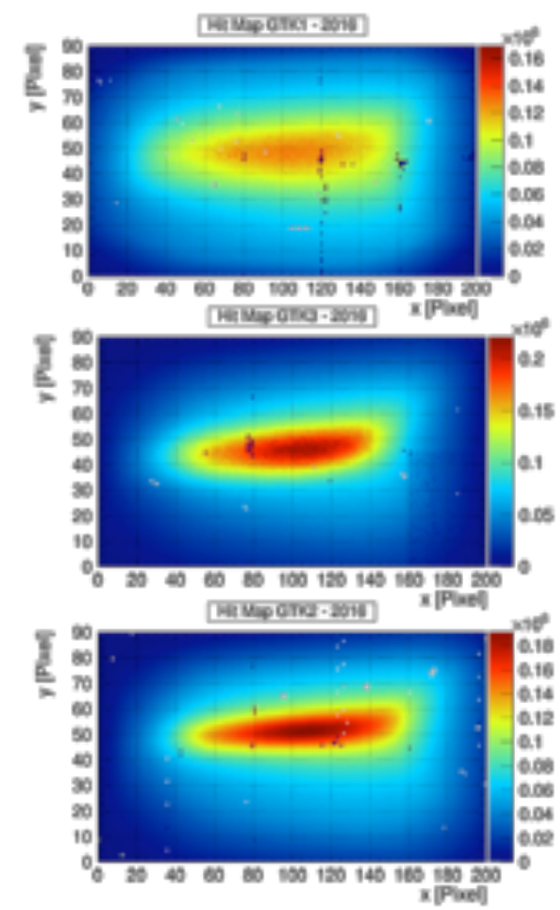
- 400 GeV/c primary proton beam
- 3 x 10^{12} protons/pulse
- 40 cm beryllium target
- 75 GeV/c unseparated hadrons beam: π^+, K^+ (6%), protons ($\Delta p/p \pm 1\%$)
- 4.8 x 10^{12} K^+ decays/year

NA62 Apparatus

270 m long region starting about 100 m downstream of the beryllium target
Detector diameters go from 20 to 400 cm



Beam particles identification and tracking



Kaon Tag (KTAG):

- Differential Cherenkov detecting Kaons;

Beam Spectrometer (GigaTracker - GTK):

- 3 stations of Silicon pixel detectors inside an achromat;

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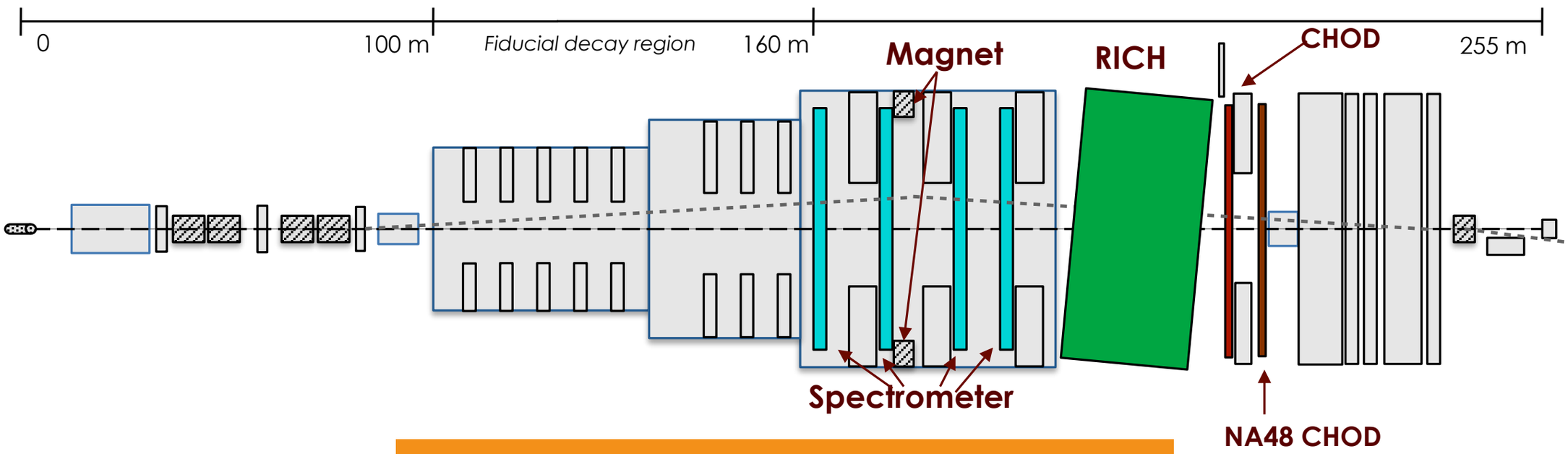

Downstream tracks - Kinematics

Straw Spectormeter:
- 4 straw chambers in vacuum;

RICH:
- Cherenkov detector filled with Neon;
- distinguis π/μ/e

NA48 CHOD
- Plastic scintillators;
- Control Trigger

CHOD:
- Plastic tile scintillators;
- Decay topology detection;

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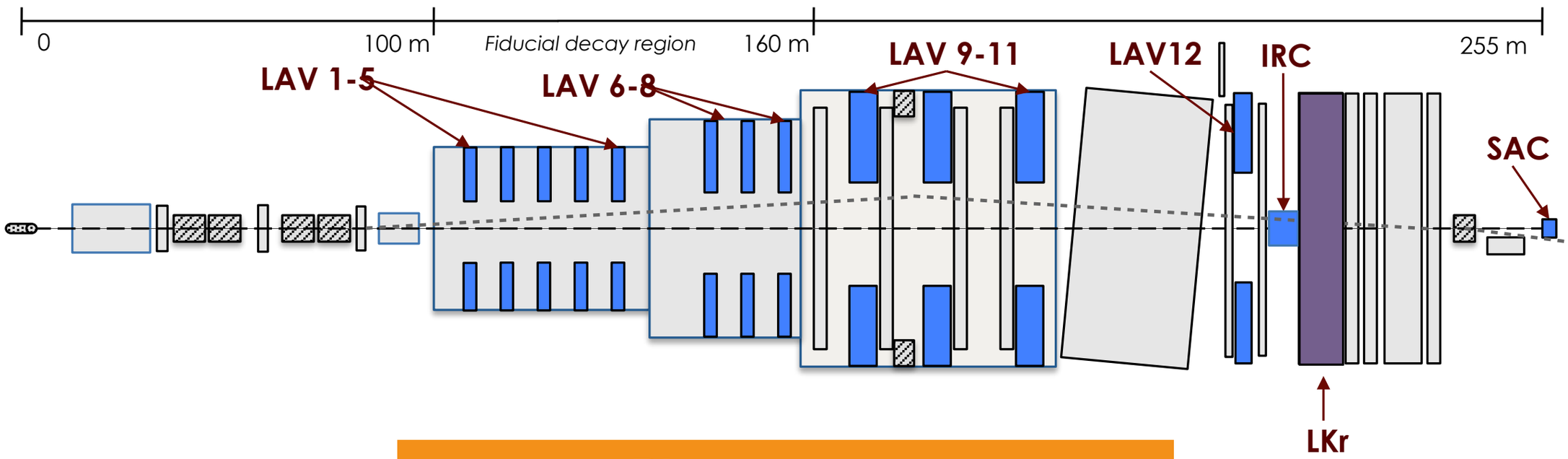

Photon vetoes

Large Angle Vetoes (LAV):
- 8.5 – 50 mrad
- 12 stations along the vacuum tank;

Liquid Krypton Calorimeter (LKr):
- Electromagnetic calorimeter
- photon veto coverage 1÷8.5 mrad;

Small Angle Vetoes (SAV):
- very small angle <1 mrad;

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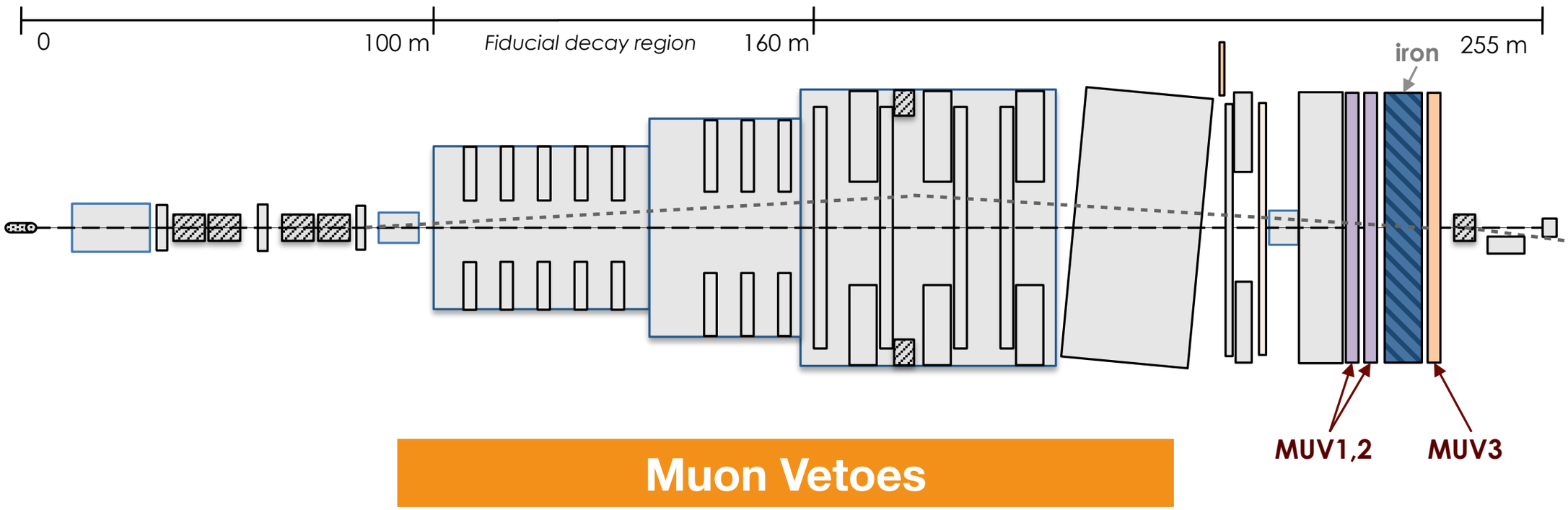


Muon Veto 1,2

- hadron calorimeter to complete the LKr-electromagnetic calorimeter information;

Muon Veto 3

- Placed after an iron wall;

NA62 Timescale

2016: 40% of nominal intensity: 13 x 10^{11} proton on target: **~5 x 10^{11} K^+** decays recorded
2017 + 2018: 60% of nominal intensity: **> 8 x 10^{12} K^+** decays on tape
- better data quality assessment
- higher data taking efficiency

Measurement of BR($K^+ \to \pi^+ \nu\nu$) with 2016 Data Analysis (4 weeks of data taking) will be here presented

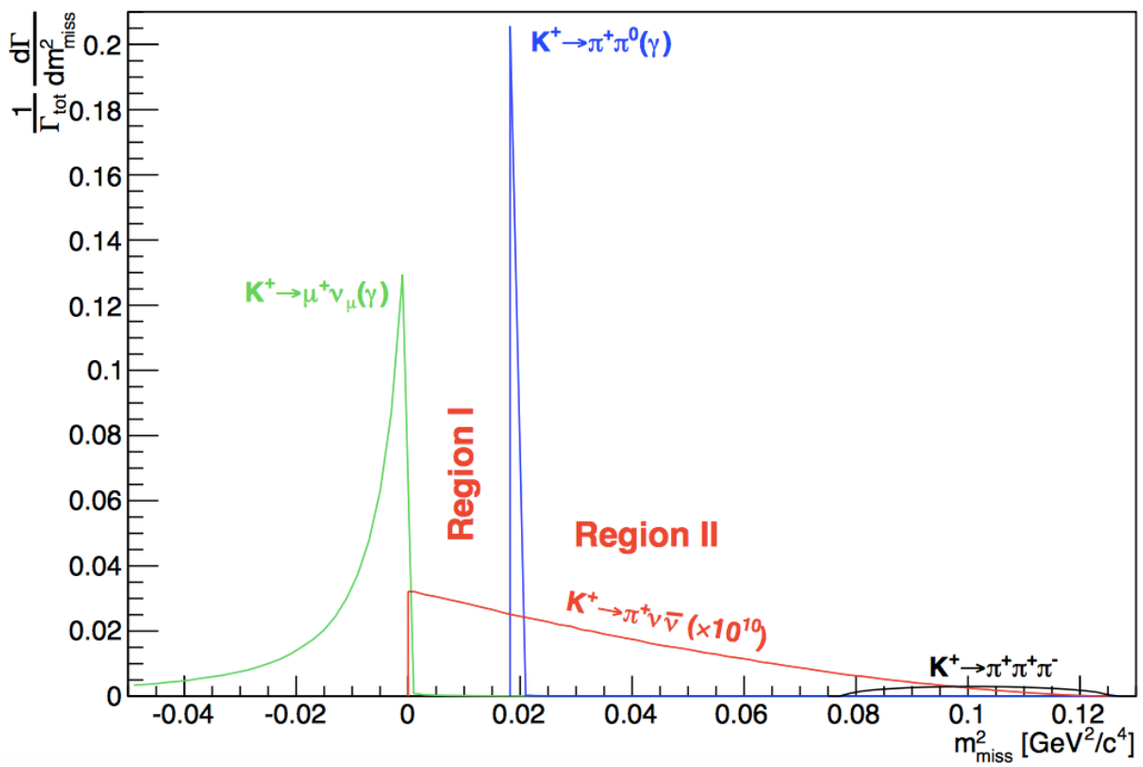
New Strategy:
Kaons with high momentum.
Decay in flight technique.
Signal signature: K^+ track + π^+ track

Data Sample:
$\pi\nu\nu$ Trigger
- 1 track
- γ/μ veto

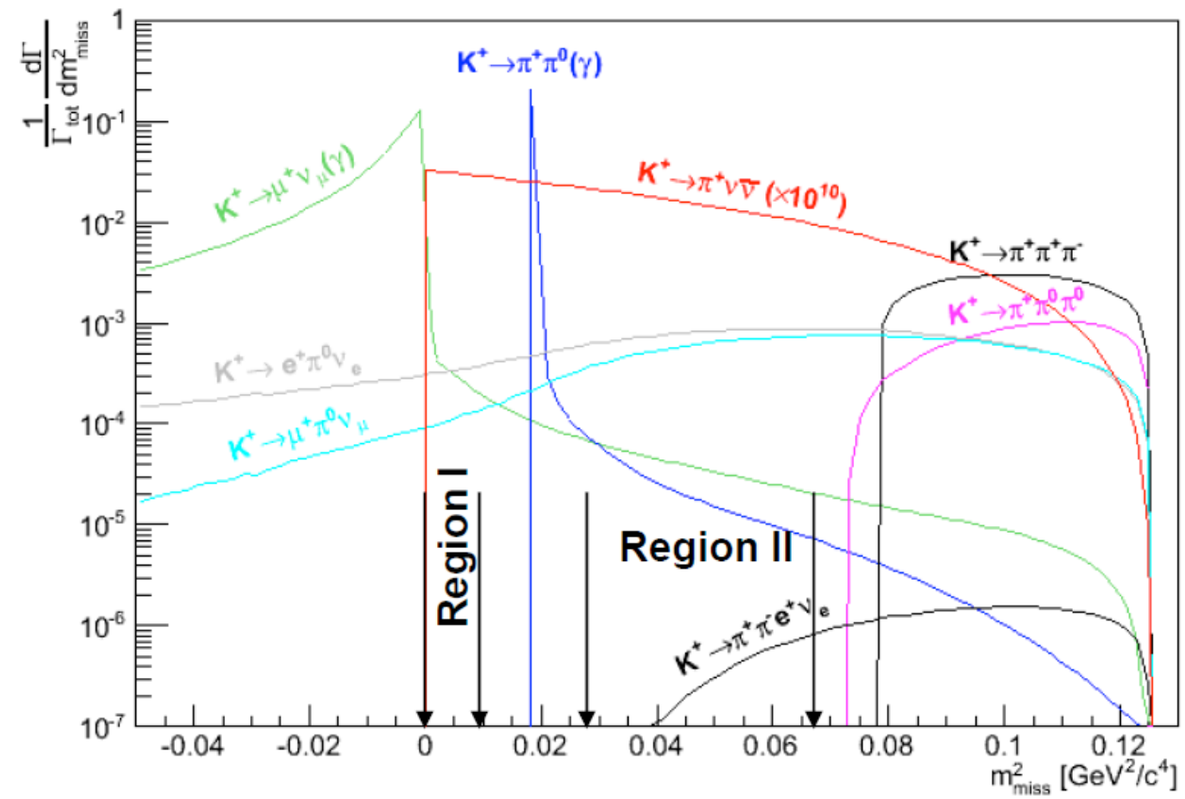
Control Trigger:
$K^+ \to \pi^+\pi^0$, $K^+ \to \mu^+\nu$, $K^+ \to \pi^+\pi^+\pi^-$ samples for background estimation

NA62 Strategy

2 signal regions, on each side of the $K^+ \to \pi^+\pi^0$ peak



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



Main background sources:

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

requirements

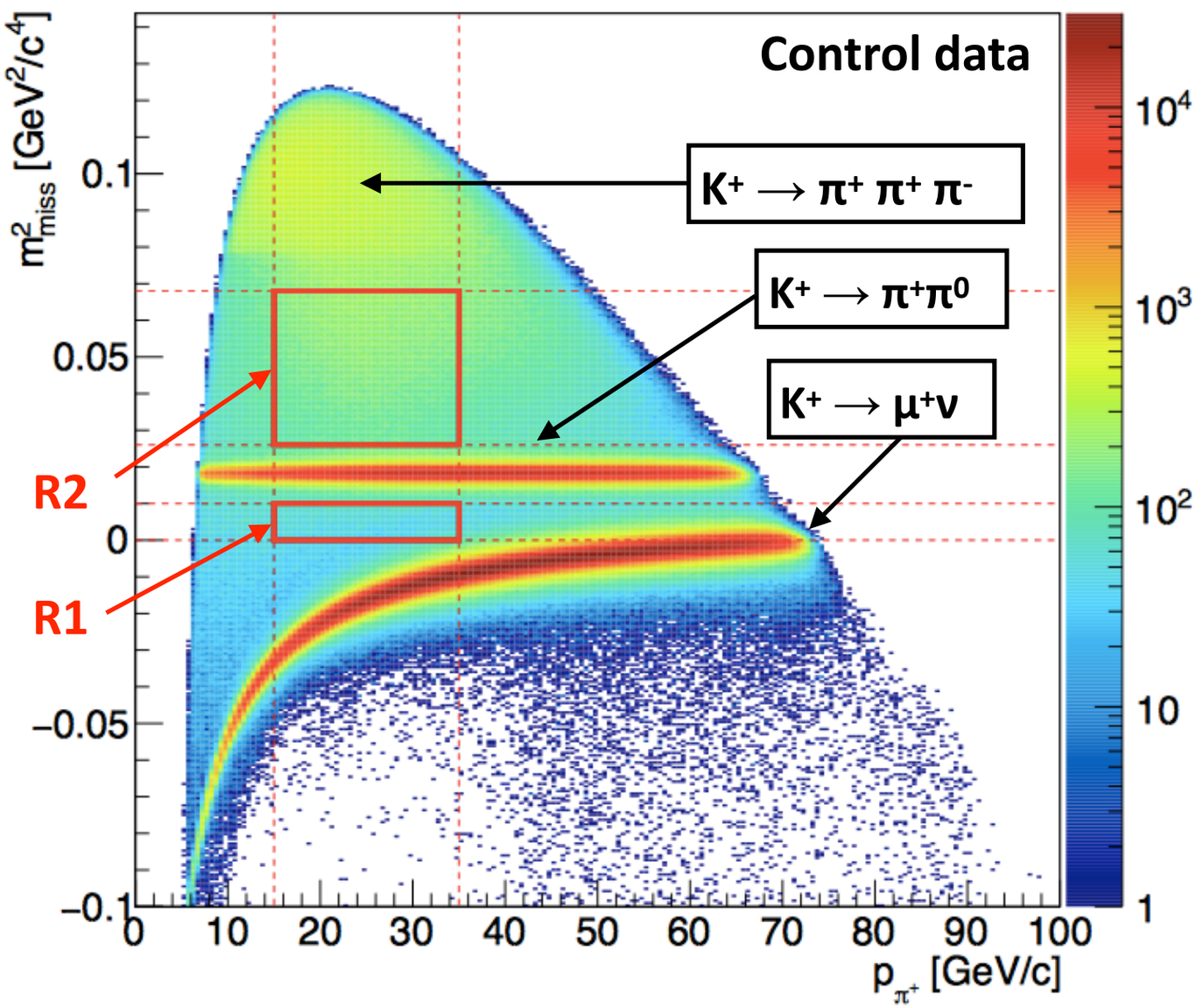
- O(100 ps) **timing** between sub-detectors
- O(10^4) background suppression with **kinematics**
- O(10^7) **μ-suppression** ($K^+\to\mu^+\nu$)
- O(10^7) **γ-suppression** (from $K^+\to\pi^+\pi^0$, $\pi^0\to\gamma\gamma$)

- **The analysis is mostly cut based**
- **Blind analysis procedure: signal and control regions kept masked for the whole analysis**

Kinematic selection of signal regions

K^+ decays with a single charged particle in final state and vertex between tracks reconstructed in the fiducial region

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



Selection:

- Single track in final state topology
- π^+ identification
- Photon rejection
- $110 < Z_{vertex} < 165$ m
- $15 < P_{\pi+} < 35$ GeV/c (to leave at least 40 GeV of E_{mis})

Performances:

- $\varepsilon(\mu^+) = 1 \cdot 10^{-8}$ (64% π^+ efficiency)
- $\varepsilon(\pi^0) = 3 \cdot 10^{-8}$
- $\sigma(m^2_{miss}) = 1 \cdot 10^{-3}$ GeV^2/c^4
- $\sigma T \sim O(100ps)$

Single Event Sensitivity

Kabala:

- **Nk** from $K^+ \to \pi^+\pi^0$ control trigger: (1.21 ± 0.02) x 10^{11}
- $K^+ \to \pi^+\nu\nu$ **acceptance**: (4.0 ± 0.1) x 10^{-2}
- **Random Veto** Efficiency: 0.76 ± 0.04
- **Trigger** Efficiency: 0.87 ± 0.2

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

j = π^+ momentum bin

number of K^+ decays

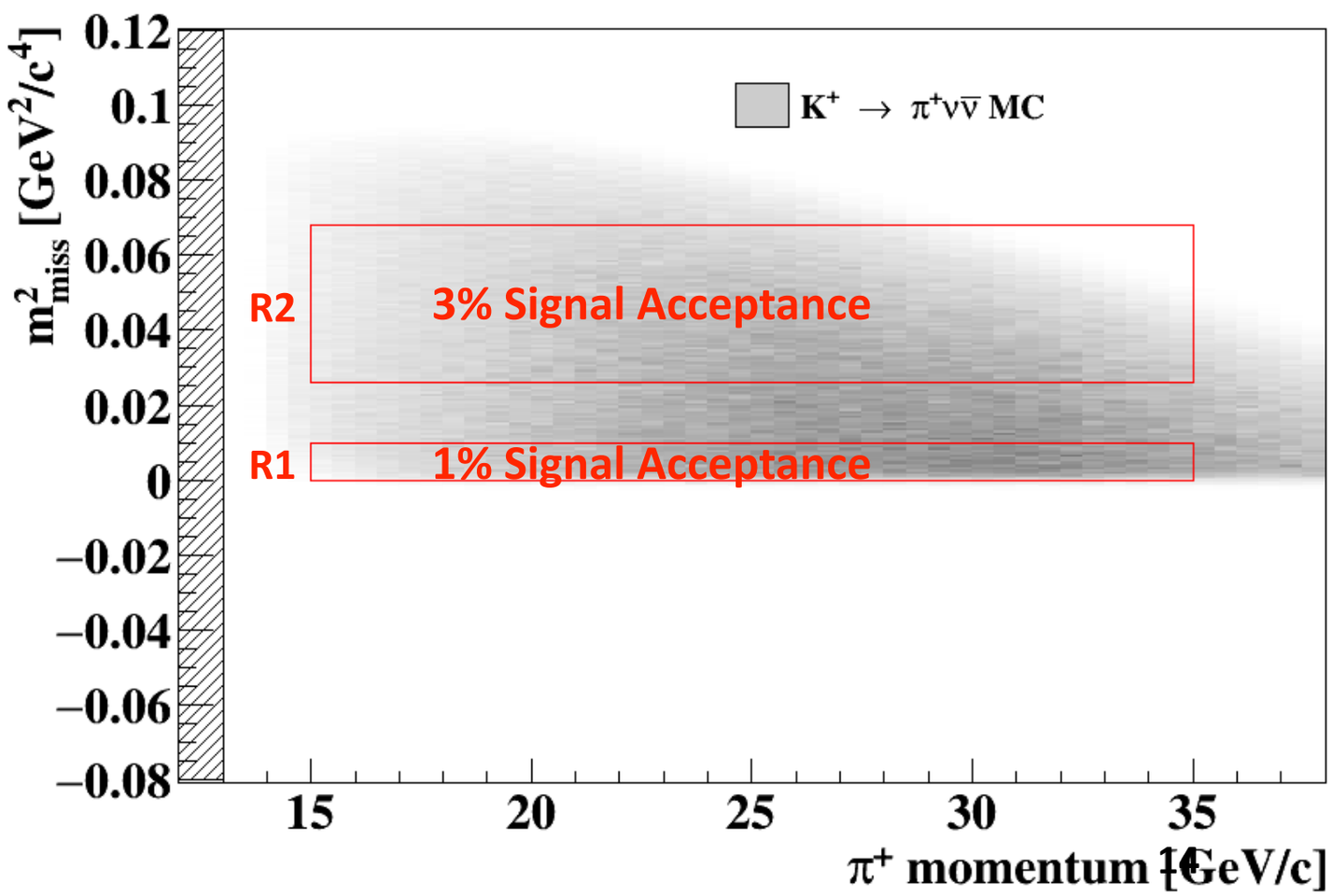
signal acceptance

random veto efficiency

trigger efficiency

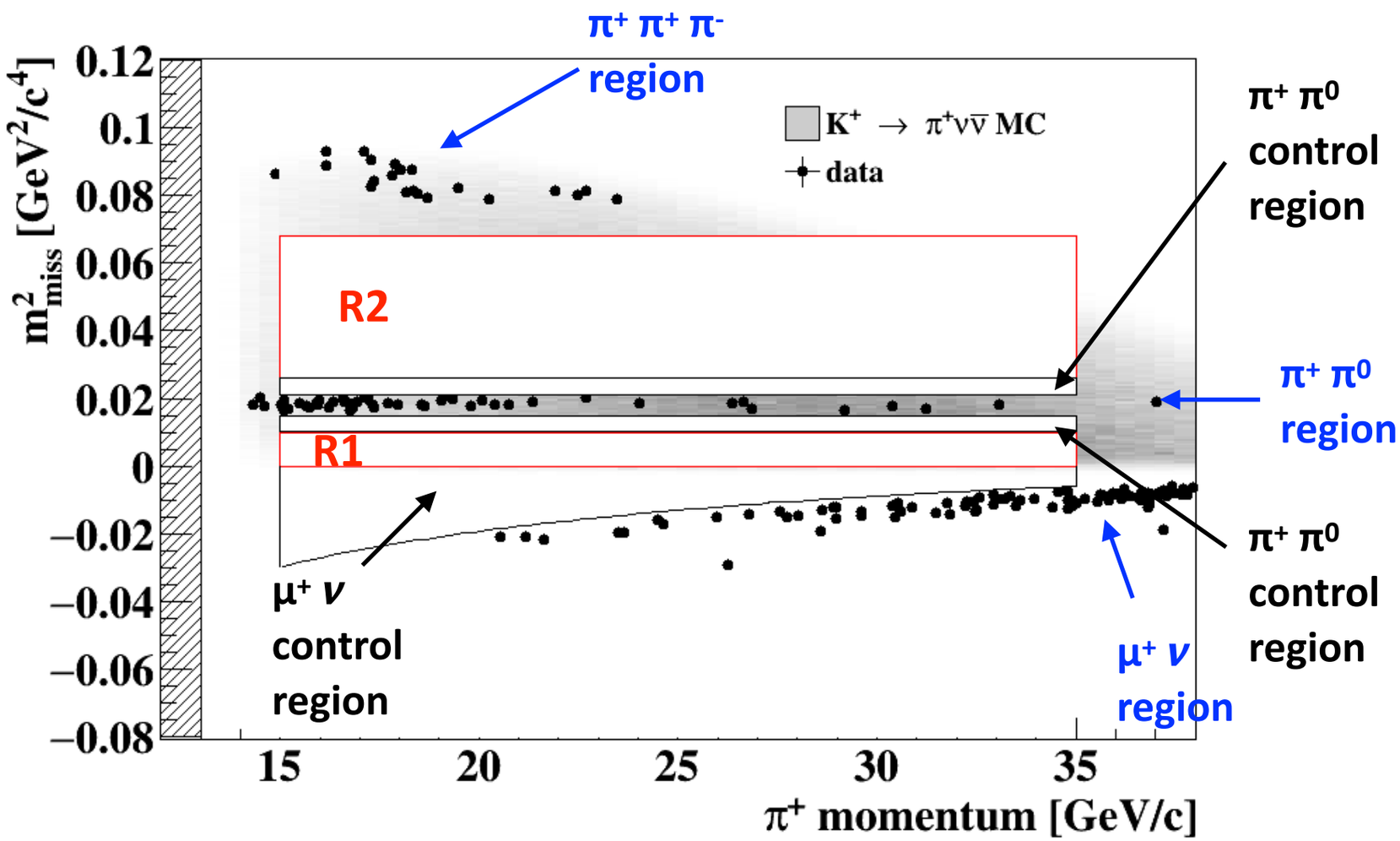
SES	$(3.15 \pm 0.01_{stat} \pm 0.24_{syst}) \cdot 10^{-10}$
Expected SM $K^+ \to \pi^+\nu\bar{\nu}$	$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$

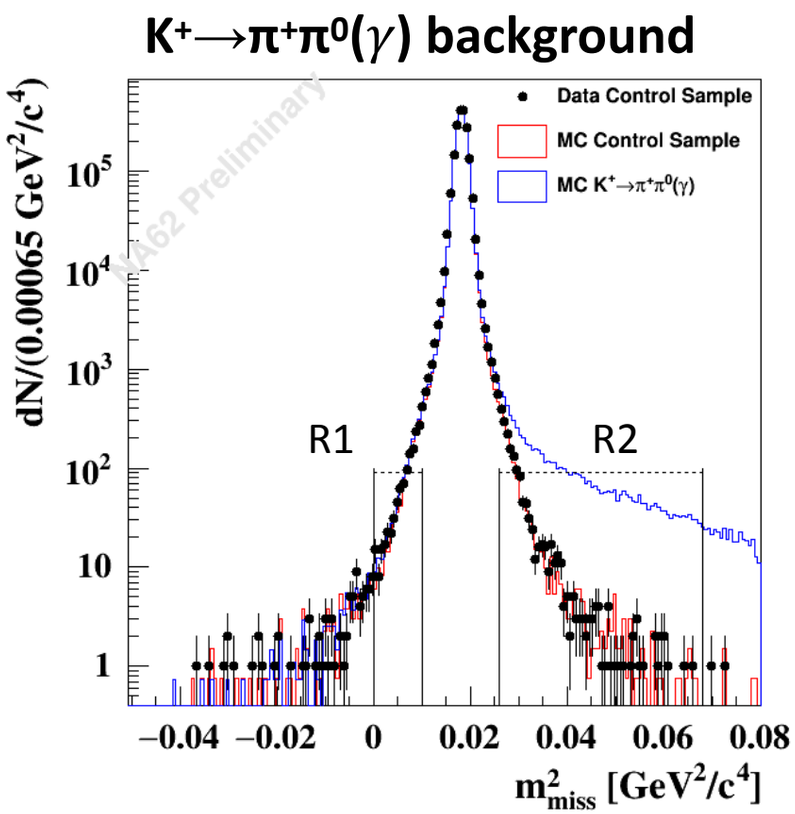
Error on the SM BR

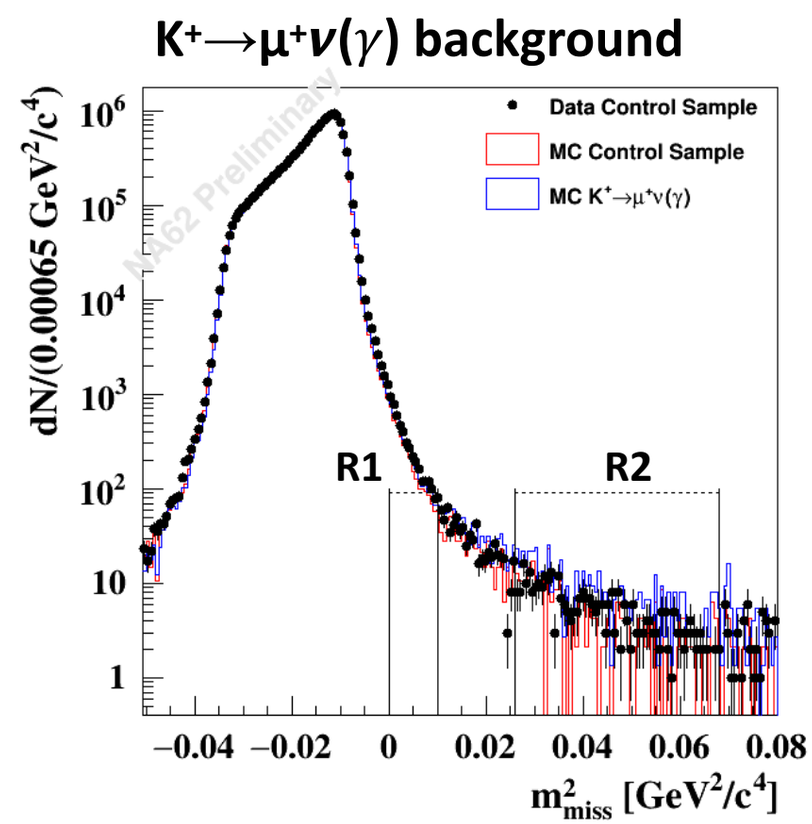


Source	δ SES (10^{-10})
Random veto	±0.17
Definition of $\pi^+\pi^0$ region	±0.10
Simulation of π^+ interactions	±0.09
N_K	±0.05
Trigger efficiency	±0.04
Extra activity	±0.02
GTK pileup simulation	±0.02
Momentum spectrum	±0.01
Total	±0.24

Data after selection:

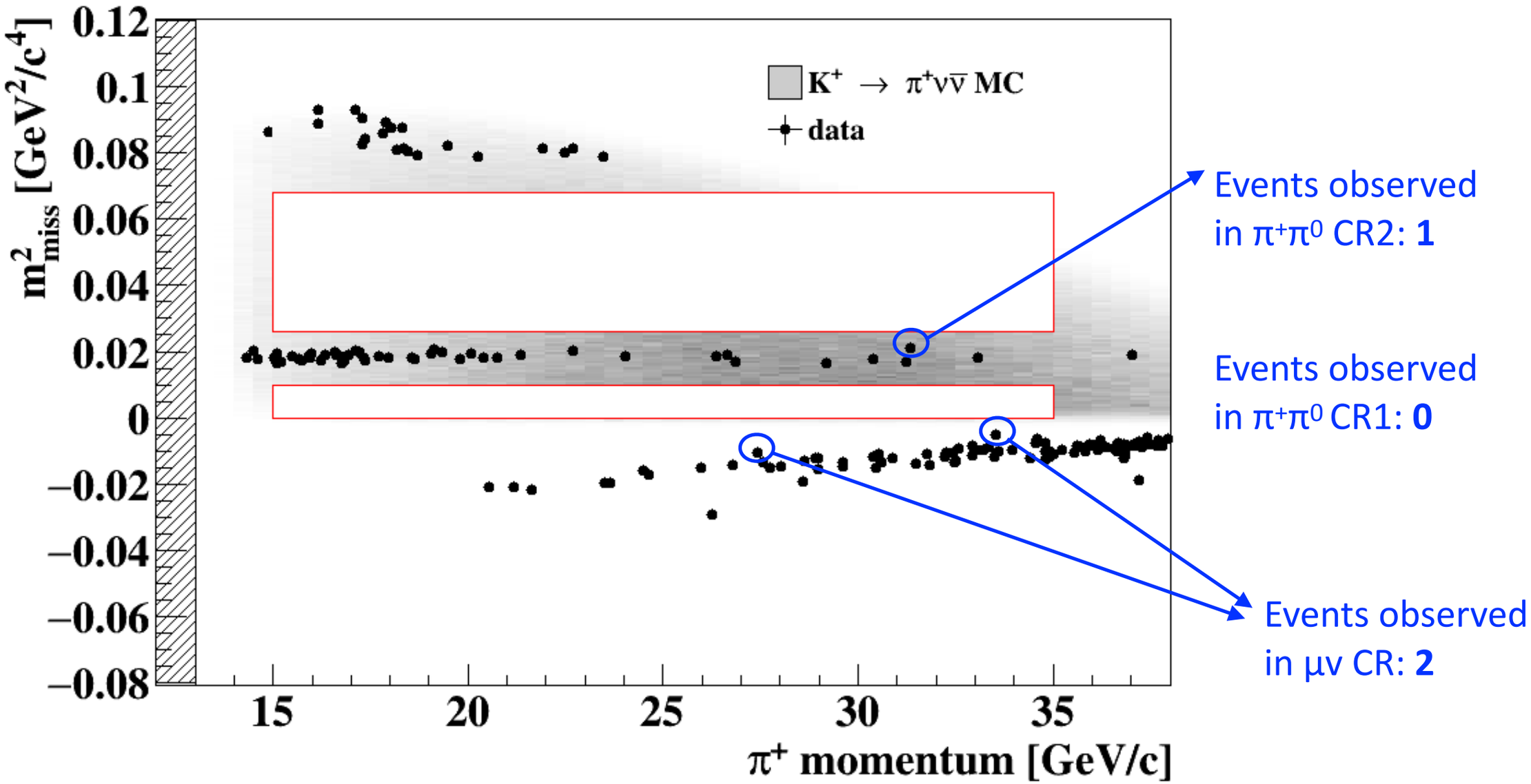






Process	Expected events in R1+R2
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$
Total Background	$0.15 \pm 0.09_{\mathrm{stat}} \pm 0.01_{\mathrm{syst}}$
$K^+ \to \pi^+\pi^0(\gamma)$ IB	$0.064 \pm 0.007_{stat} \pm 0.006_{syst}$
$K^+ \to \mu^+\nu(\gamma)$ IB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

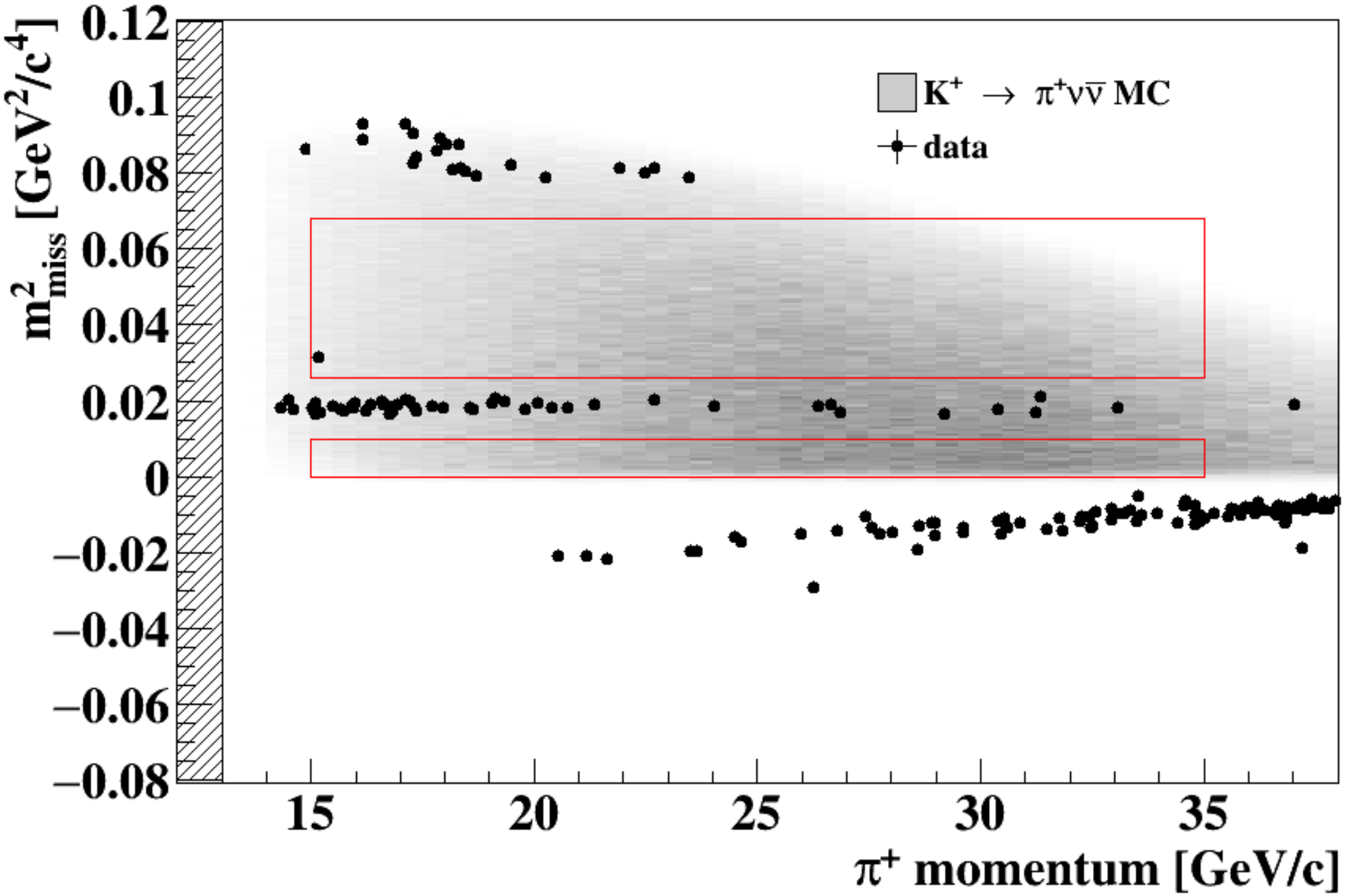
Validation



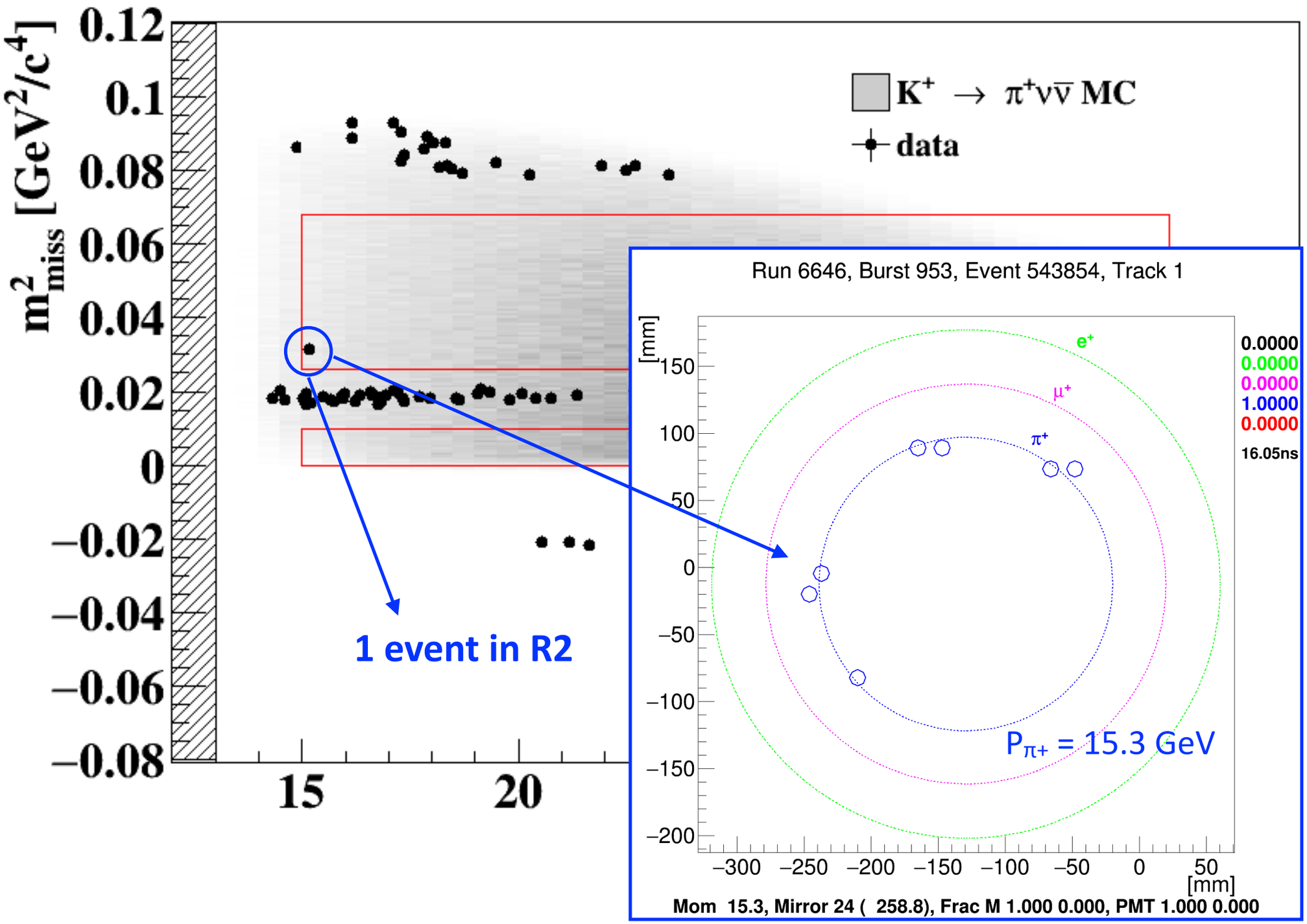
	$\pi^+\pi^0$
CR1	$0.52 \pm 0.08_{stat} \pm 0.03_{syst}$
CR2	$0.94 \pm 0.14_{stat} \pm 0.05_{syst}$

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

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]
$K^+ \to \pi^+\nu\bar{\nu}$ MC
data

Result



Likelihood value under different mass hypothesis

Conclusions from $K \rightarrow \pi\nu\nu$ 2016 data taking

- *The NA62 decay-in-flight technique works*
- SM sensitivity for $K^+ \rightarrow \pi^+\nu\nu$ reached with the 2016 data analysis
- **One** event observed in 2016 data compatible with SM prediction

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

NA62 collaboration arXiv:1811.08508 (submitted to PLB)

- **~8.5×10^{12} K^+** decays collected in the whole NA62 Run1 (2016-2018).

  Analysis in progress…
- Focus on improvements:
  - increased signal acceptance
  - better reconstruction efficiency
  - higher background suppression
  - probability based analysis

Data taking after LS2 (2021-2023) in approval stage

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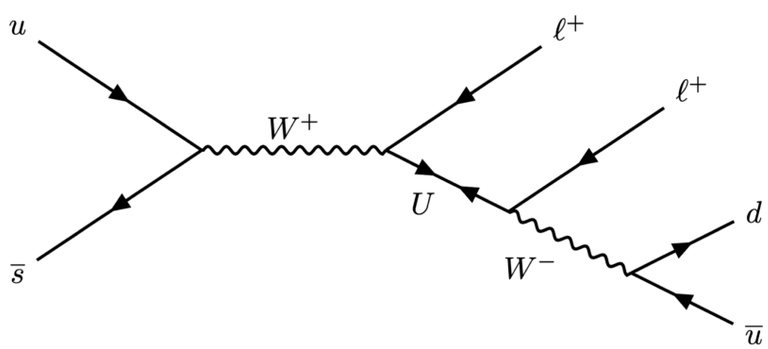
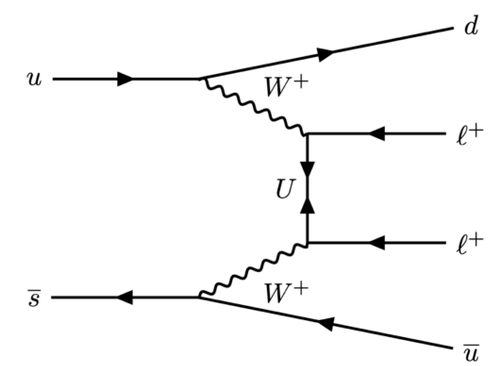
Lepton Flavour Violation

Conservation of **L** and **Le** , **Lμ** , **Lt** is an 'emergent' property of SM – not required during construction.

• Violation of these conservation laws predicted in BSM models:

• E.g. $K^+ \to \pi^- l^+ l^+$: ΔL = 2 and ΔLμ =2 or ΔLe =2 via **Majorana neutrinos** U (analogue to v0$\beta\beta$ decays) [JHEP 0905 (2009) 030], [Phys.Lett. B491 (2000) 285-290]





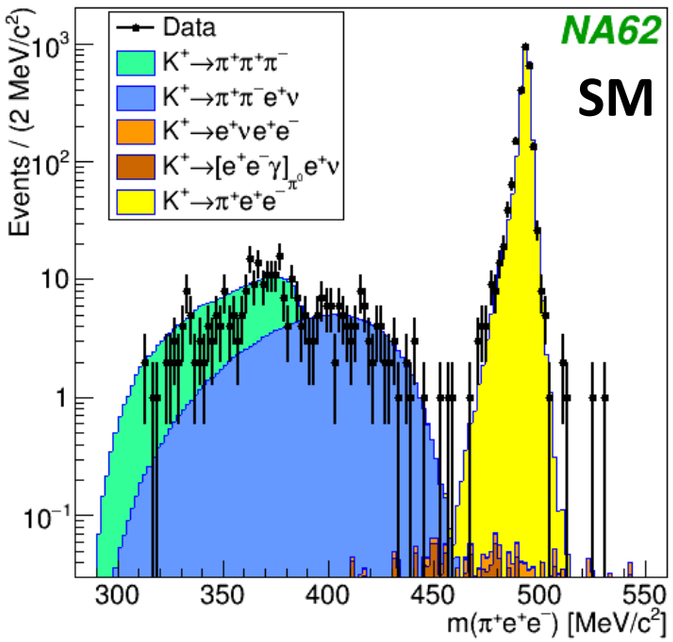
Trigger Name	Description	Use in LNV/LFV Searches
Di-Muon	3 tracks with 2 μ candidates (MUV3)	Collect SM $K^+ \to \pi^+\mu^+\mu^-$ & LNV $K^+ \to \pi^-\mu^+\mu^+$
Multi-Track e	3 tracks with 20 GeV energy deposit in LKr	Collect SM $K^+ \to \pi^+e^+e^-$ & LNV $K^+ \to \pi^-e^+e^+$
Multi-Track	Minimum bias 3-track trigger	Control samples for background studies

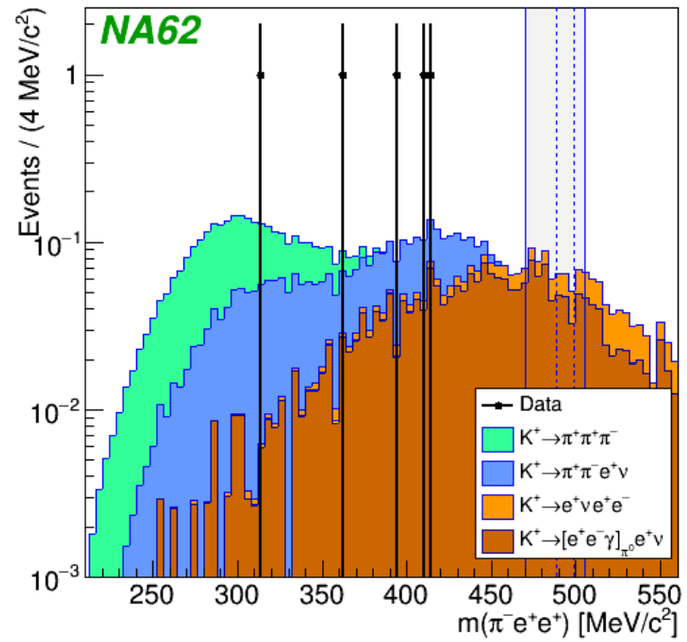
Previous Experimental results :

$BR(K^+ \to \pi^-e^+e^+) < 6.4\times10^{-10}$ @ 90% CL (BNL E865 : PRL 85 2877 (2000))

$BR(K^+ \to \pi^-\mu^+\mu^+) < 8.6\times10^{-11}$ @ 90% CL (CERN NA48/2 : PL B769 67 (2017))

Lepton Flavour Violation



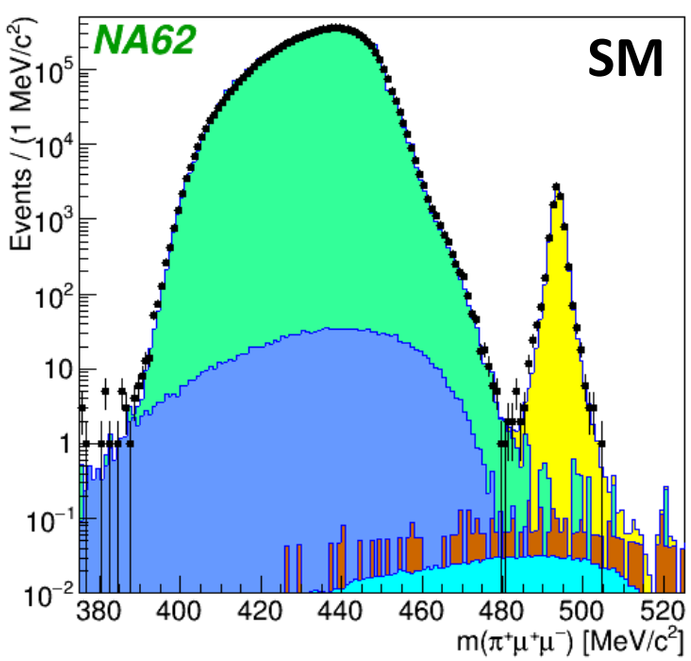


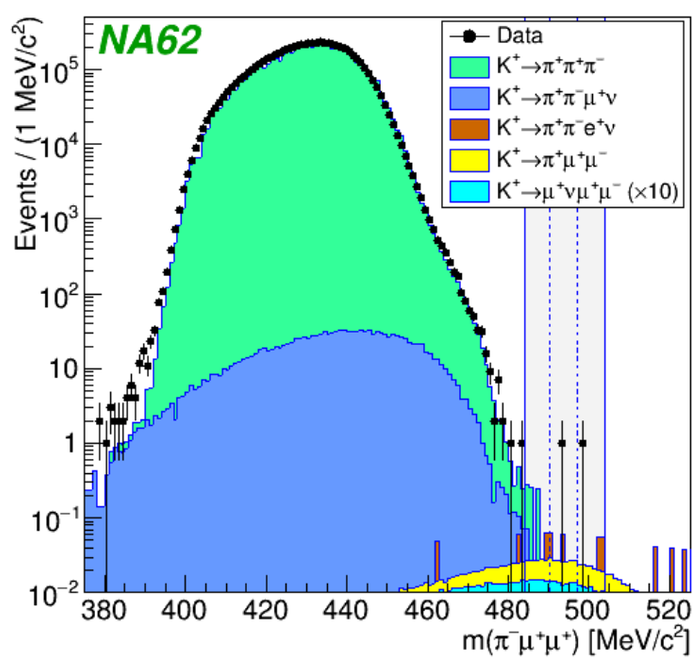
Signal Region

Bkg. Prediction: $N_{SR}^{tot} = 0.16 \pm 0.03$

Observe : $n_{SR} = 0$

- $N_K = (2.14 \pm 0.07)\times10^{11}$
- $SES = (0.94 \pm 0.03)\times10^{-10}$





Signal Region

Bkg. Prediction: $N_{SR}^{tot} = 0.91 \pm 0.41$

Observe : $n_{SR} = 1$

- $N_K = (7.94 \pm 0.23)\times10^{11}$
- $SES = (1.28 \pm 0.03)\times10^{-11}$

New NA62 upper limits: 3 months of data taking in 2017! ~3 times more data still to analyse

Decay	BR UL @ 90% CL	PDG UL @ 90% CL
$K^+ \to \pi^- e^+ e^+$	2.2×10^{-10}	6.4×10^{-10}
$K^+ \to \pi^- \mu^+ \mu^+$	4.2×10^{-11}	8.6×10^{-11}

Dark Photons

New *U(1)* gauge-symmetry sector, with a vector mediator field A';
In a simple realization of such a scenario, A' would interact with the SM photon through a "kinetic mixing" lagrangian:

$$\mathcal{L} = \epsilon A'^{\mu\nu} F_{\mu\nu}$$

L. Okun, Sov.Phys.JETP 56 (1982) 502;
B. Holdom, Phys.Lett. B166 (1986) 196.

The lagrangian might be accompanied by further interactions, both with SM matter and with a secluded, hidden sector of possible dark-matter candidates.

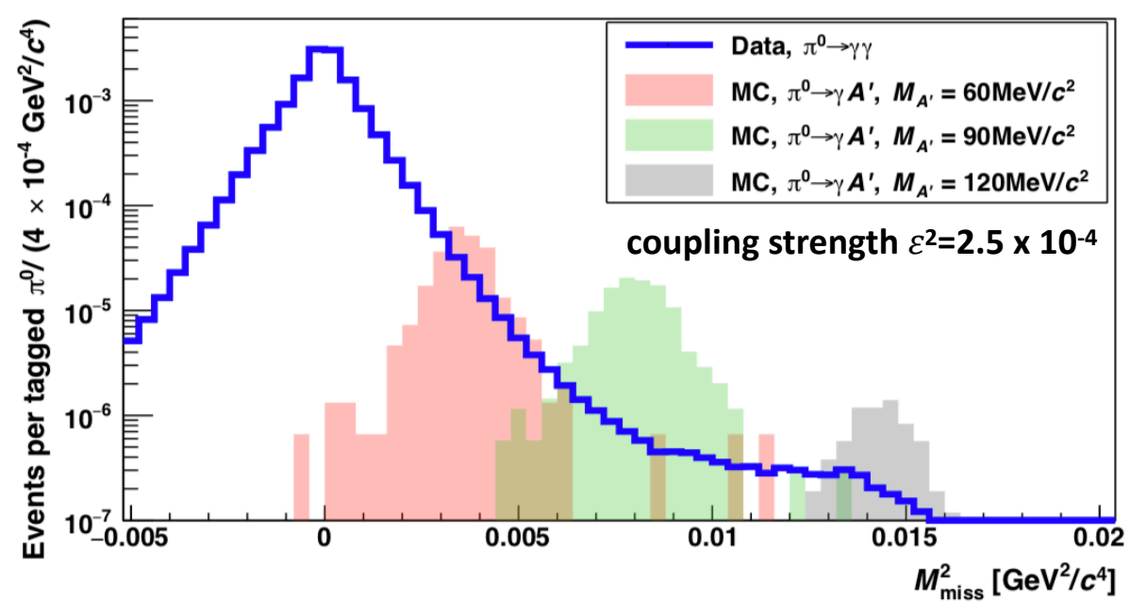
Missing-energy signature might reveal its presence.

NA62 is looking for:

$$K^+ \to \pi^+\pi^0 \; with \; \pi^0 \to A'\gamma$$

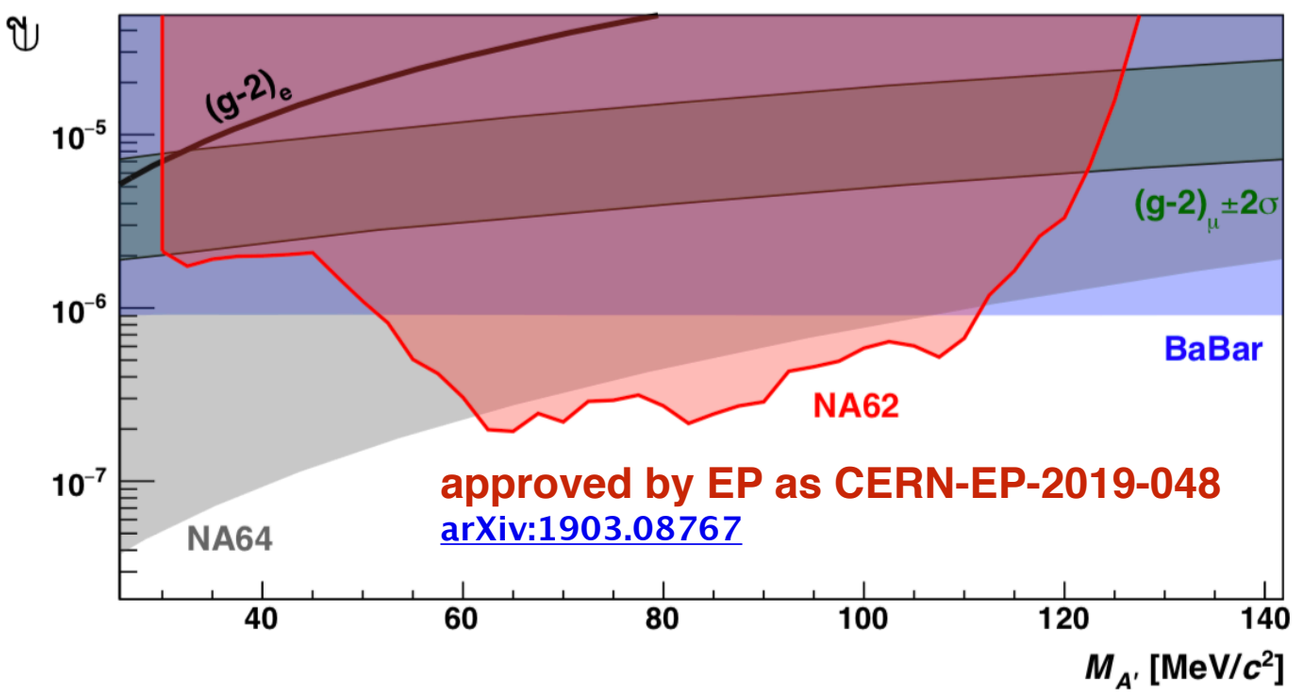
$$A' \to \; invisible$$

$$M^2_{miss} = (P_K - P_\pi - P_\gamma)^2$$



Exploiting extreme photon-veto capability and high resolution tracking while sustaining a high-rate environment makes the dark photon analysis synergic with and parasitic to the $K^+ \to \pi^+\nu\nu$ measurement.

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



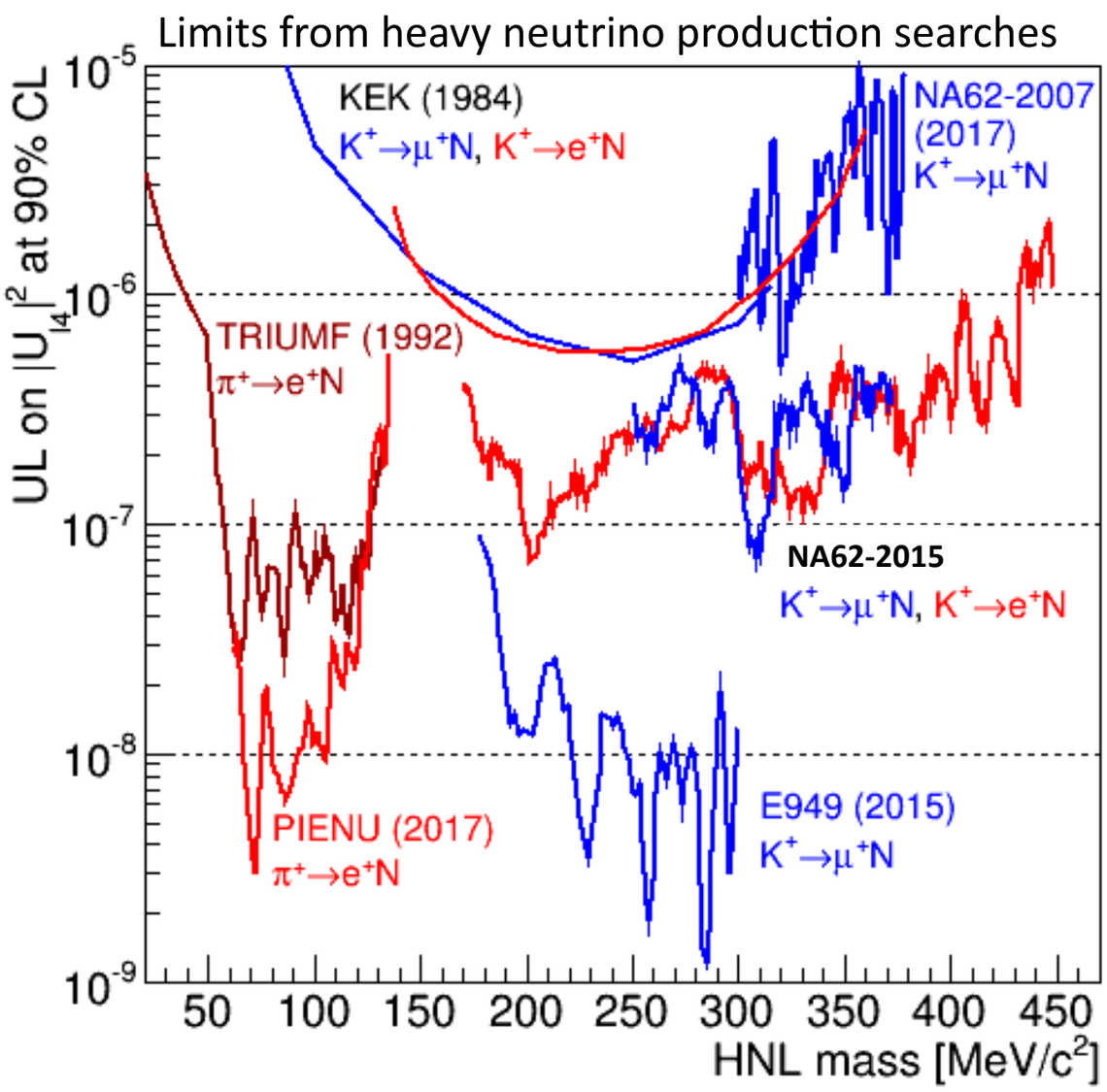
- Search **parasitic to πνν-trigger**
  - ("1 track" + small forward energy)
- **Signal signature: 1 track, 1 γ + E_{mis}**
- **Data driven background estimation.**
- Dominant background:
  - $\pi^0 \to \gamma\gamma$ with 1 γ missing

Analysis with data from 2016:
~1.5 10^{10} K^+ (~5% of 2016 statistics)

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

HNL from K decays

Search for HNL produced in $K^+ \to e^+ \nu_H$ and $K^+ \to \mu^+ \nu_H$ decays: peaks m^2_{miss} spectra



Range mass from π-mass to K-mass

→ NA62 **2007 data**

Extends the mass range for upper limits on $|U_{\mu 4}|^2$

[Phys. Lett. B772 (2017) 712]

→ NA62 2015 data with minimum bias trigger @ 1% intensity, 5 days, i.e., K^+ decays in FV:
$N_K = (3.01 \pm 0.11) \times 10^8$ for $K^+ \to e^+ \nu_H$
$N_K = (1.06 \pm 0.12) \times 10^8$ for $K^+ \to \mu^+ \nu_H$

Reached 10^{-6}-10^{-7} limits for $|U_{l4}|^2$ in HNL (170,448) MeV/c^2 mass range

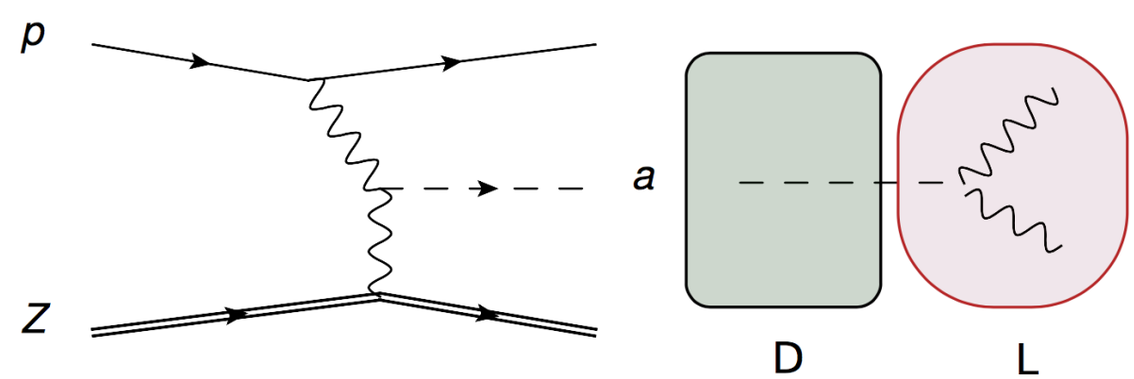
[Phys. Lett. B778 (2018) 137]
Best world limit above 300 MeV/c2

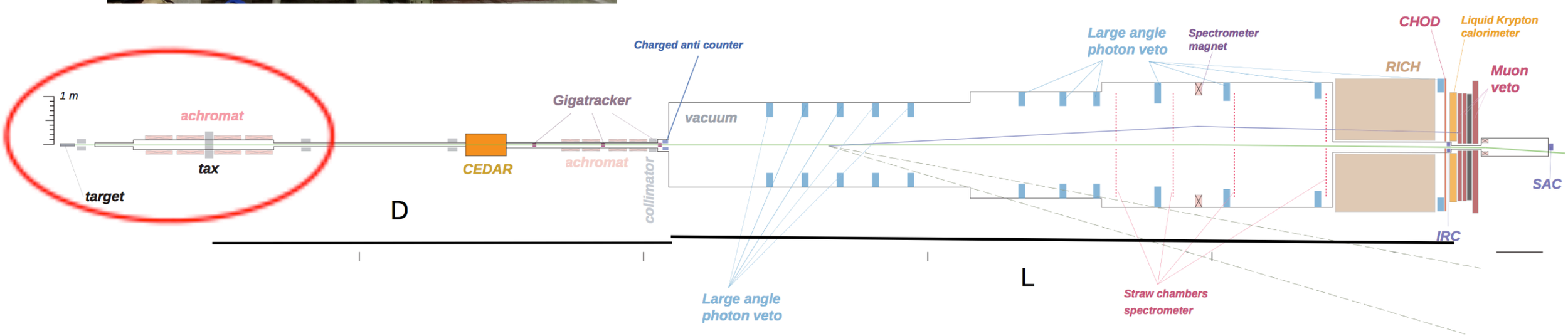
Full 2016-2018 data set analysis will explore $|U_{l4}|^2 \lesssim 10^{-8}$ range

NA62 as a dump experiment

- NA62 has the possibility to **dump the entire beam** by closing TAX (~10^{12} p/s) and removing target;
- Copper TAX → coherent Z^2 enhancement with charge;

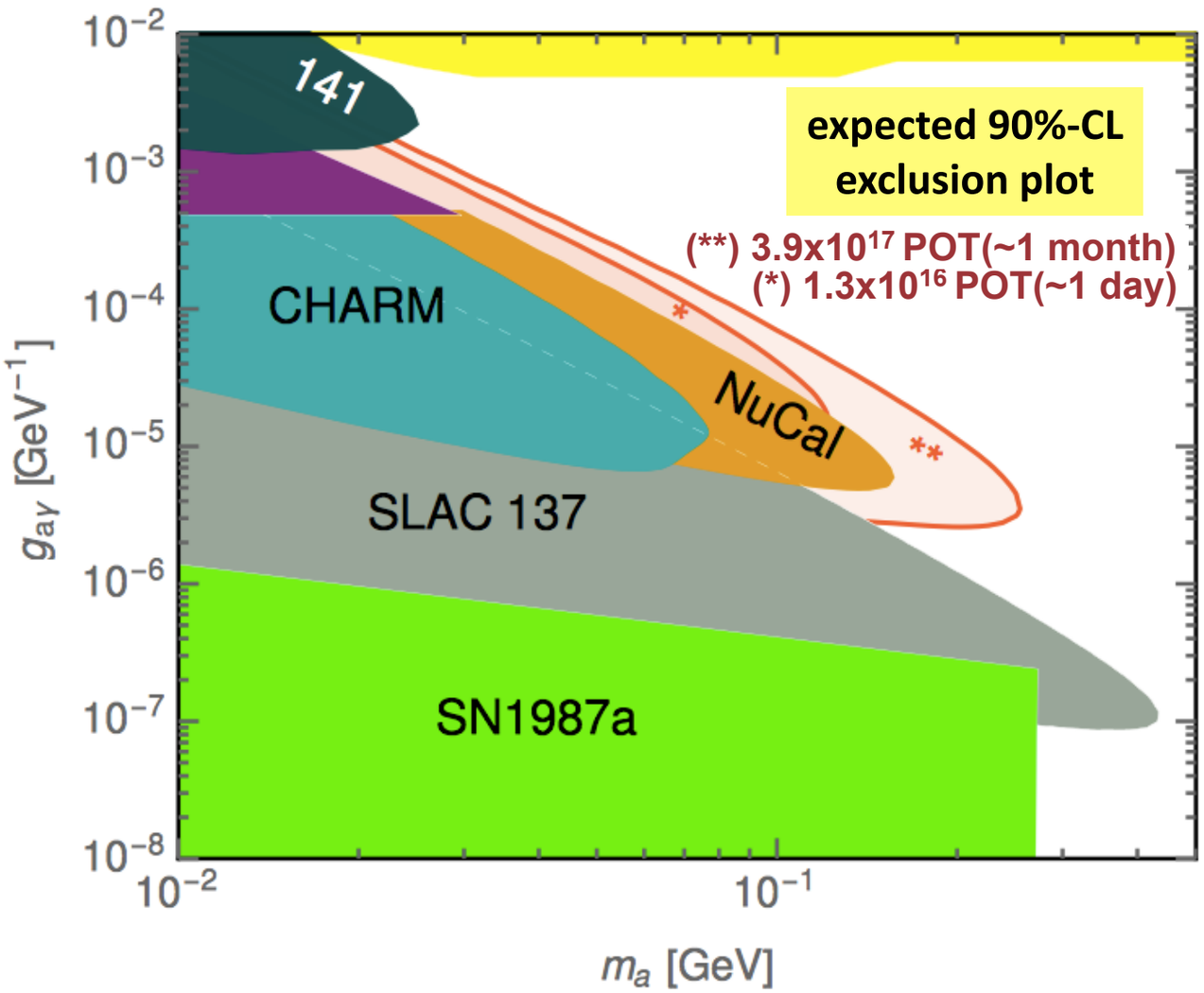
NA62 looking for
- → **Axion Like Particles (ALPs)**
- → **Heavy Neutral Leptons (HNLs)**





NA62 potential for Axion Like Particles

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



Search for $\gamma\gamma$ fusion via Primakoff effect [JHEP 1602 (2016) 018] for ALP production and **subsequent decay to $\gamma\gamma$ in NA62 fiducial volume**

- account for geometrical acceptance
- zero-background assumption
- evaluate expected 90% C.L. exclusion contours

1 day of run in real beam-dump mode :~ 1.3 10^{16} POT's

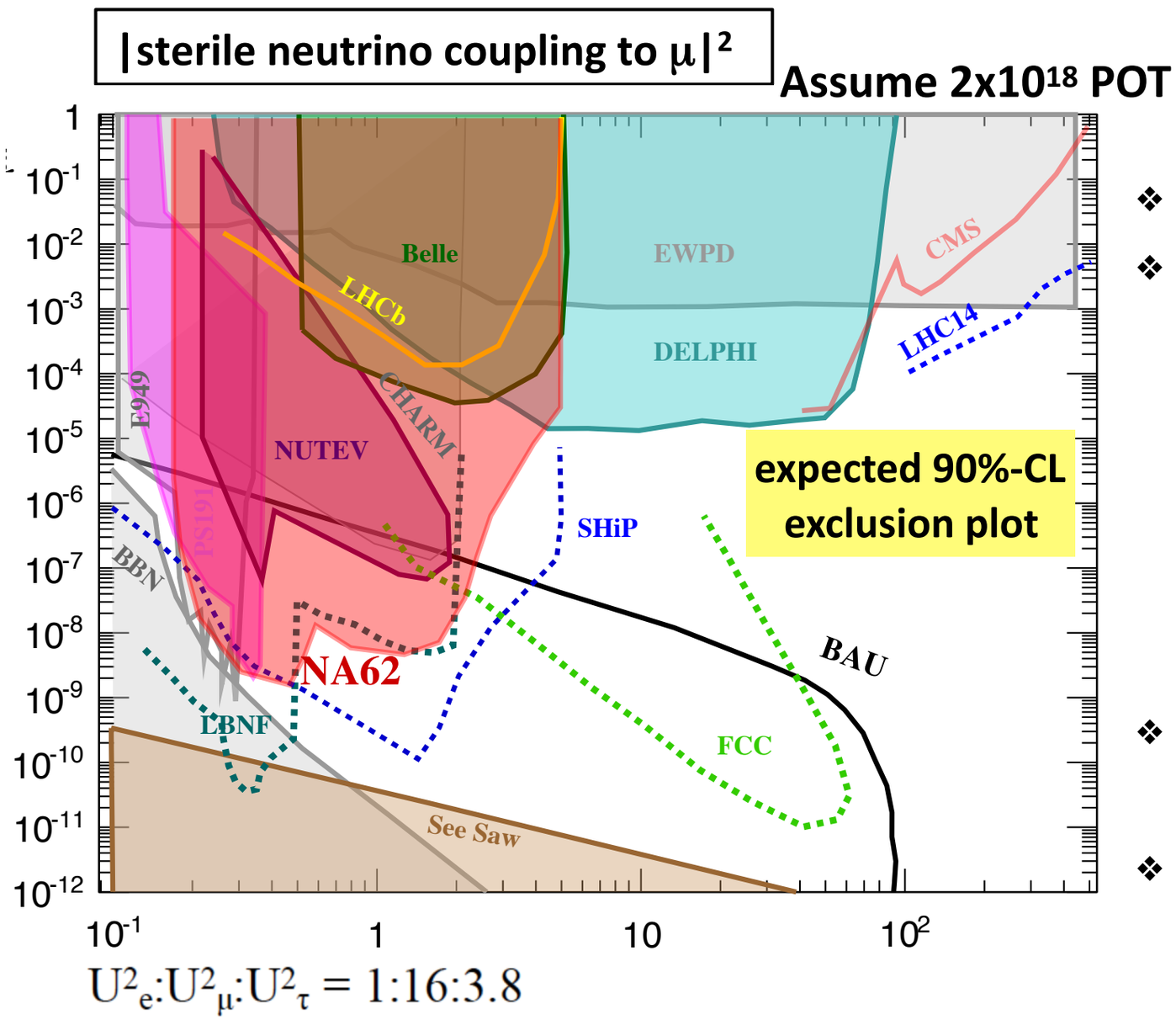
NA62 → small D, large E: one day runtime as 'dump' is sensitive to new physics (90% confidence at 0 background)

Analysis of 2x10^{16} POT collected in dump mode in 2017-2018 in progress….

Potential for HNL from beam dump

The HNLs may be also produced in beam dump mode:

From leptonic decays **D(D$_s$)** → $l^+\nu_H$ soon after production in the target (mass up to ~ 1.7 GeV)



- ν_H → πe, ν_H → πμ:
- 2 oppositely-charged, in-time, tracks reconstructed as originating from the 60-m long fiducial volume, 1-lepton final states

Invariant mass should reconstruct HNL mass

- include trigger/acceptance/selection efficiency
- assume zero-background.

Analysis of 2x10¹⁶ POT collected in dump mode in 2017-2018 in progress….

Conclusions

The 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

First results on Dark Photons and HNL searches

First results on LFV physics

NA62 potential has been shown

Running after LS2 (2021-2023) will allow to fully exploit the physics reach with the current NA62 setup, with minimally upgraded detector and modified beam line

THANK YOU
for your
ATTENTION!

K→πνν and the Unitary Triangle

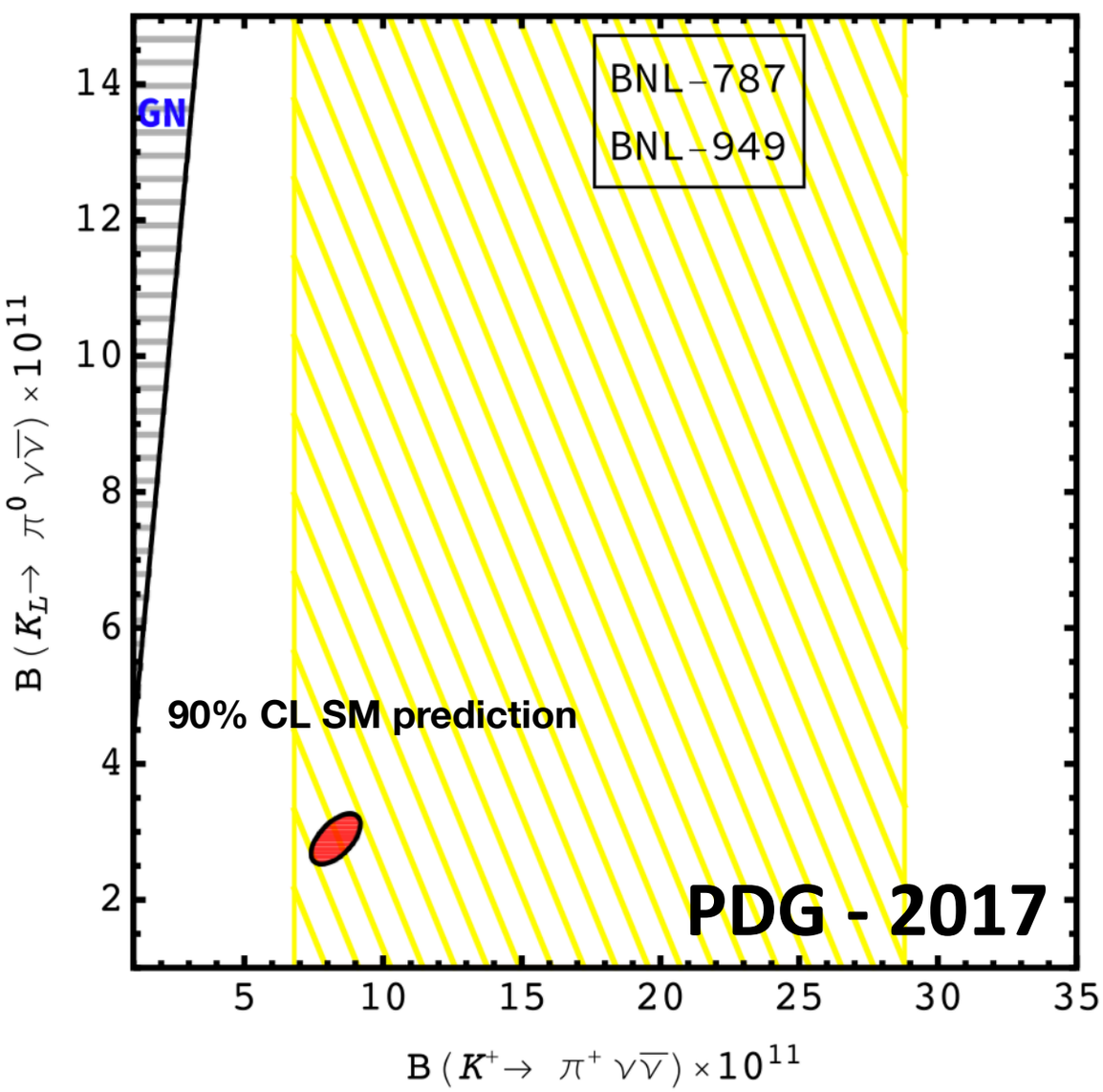
Highly suppressed
Very well predicted

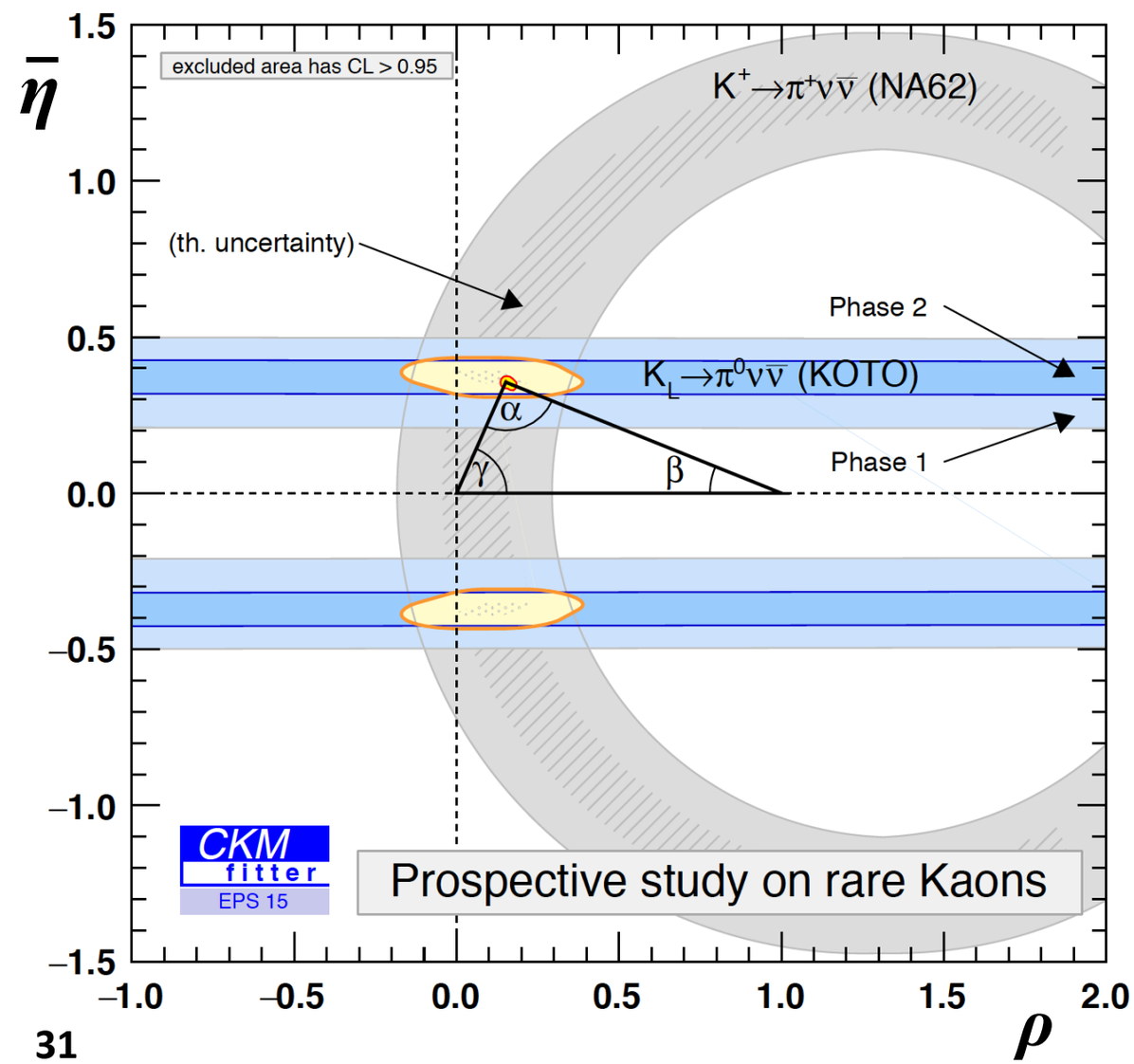
Stringent test of the SM and possible evidence for New Physics
—> complementary to LHC!

Overconstrain CKM matrix
→ reveal New Physics?

Example of CKM constraints:

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





A General purpose experiment

The high-intensity setup, **trigger system flexibility**, and **detector performance as**

high - frequency tracking of beam particles;
redundant PID;
ultra-high-efficiency photon vetoes;

make NA62 particularly suitable for searching for new-physics effect from different scenarios:

Standard Kaon Physics

- **Measurements of the BR of all the main** K^+ **decay modes**
- **ChPT studies:** $K^+ \to \pi^+\gamma\gamma$, $K^+ \to \pi^+\pi^0 e^+e^-$, $K^+ \to \pi^{0(+)}\pi^{0(-)}l^+\nu$
- **Precision measurement of** R_K **=** $\Gamma(K^+ \to e^+\nu_e)/\Gamma(K^+ \to \mu^+\nu_\mu)$

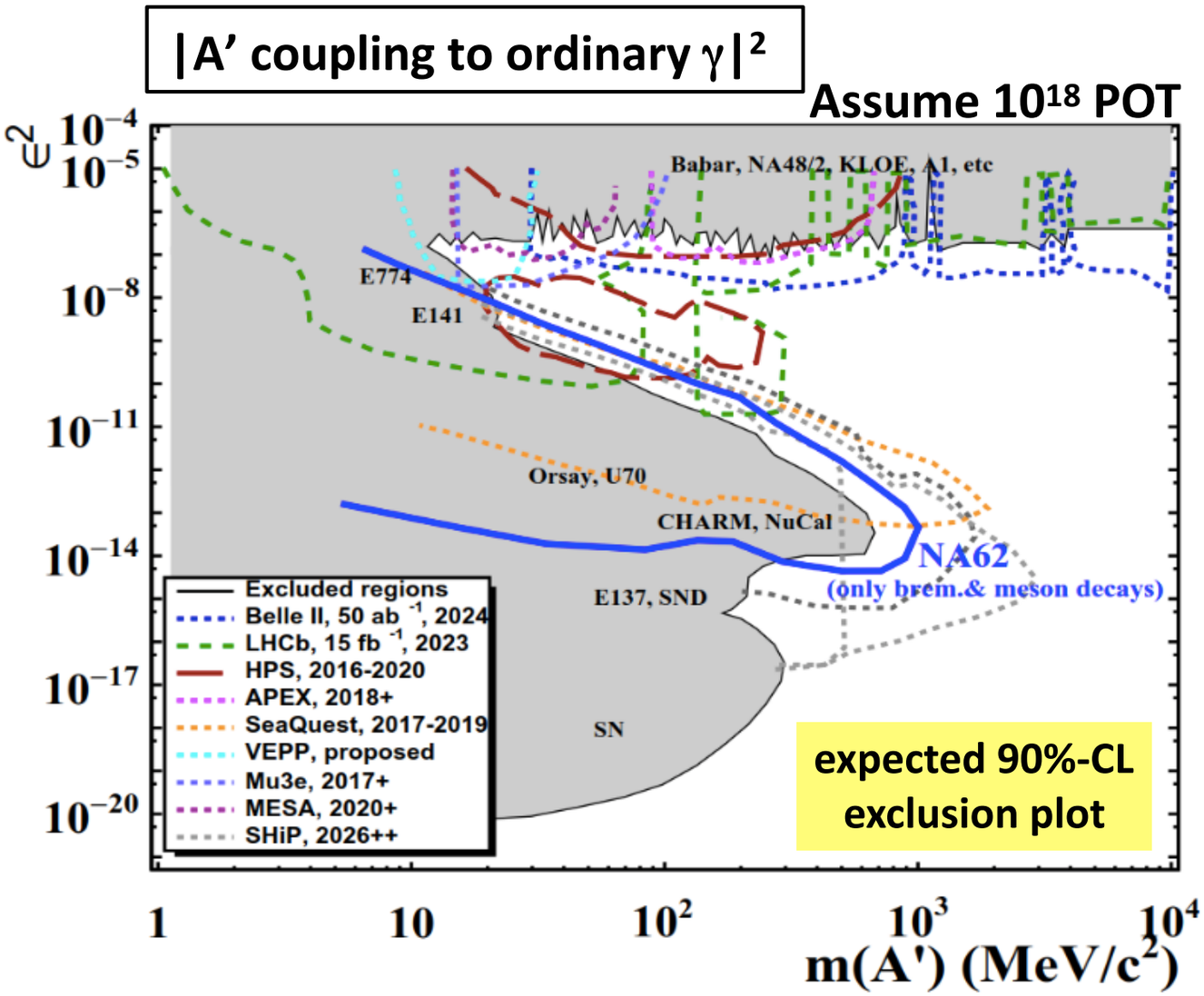
Rare/forbidden K+ and π^0 decays at SES ~10^{-12}

- K^+ **physics:** $K^+ \to \pi^- e^+e^+(\gamma)$, $K^+ \to \pi^-\mu^+\mu^+(\gamma)$, $K^+ \to \gamma l^+\nu$
  (sensitivity x 100 wrt the past results)
- π^0 **physics:** $\pi^0 \to e^+e^-$, $\pi^0 \to e^+e^-e^+e^-$, $\pi^0 \to \gamma\gamma\gamma$, $\pi^0 \to \gamma\gamma\gamma\gamma$, $\pi^0 \to \nu\nu$, **…**
- **LFV-LNV searches:** $K^+ \to \pi^+\mu^\pm e^\mp(\gamma)$, $K^+ \to \pi^-\mu^+e^+(\gamma)$, $K^+ \to \pi^- l^+l^+$, **…**

Searches for exotic particles from hidden sector

NA62 potential for A' visible decays

Study Dark Photon production from interaction onto target



- search for di-lepton decays **A'→e⁺e⁻, A'→μ⁺μ⁻** in NA62 fiducial volume
- account for **acceptance/trigger/ selection efficiency**
- Assume **zero-background**

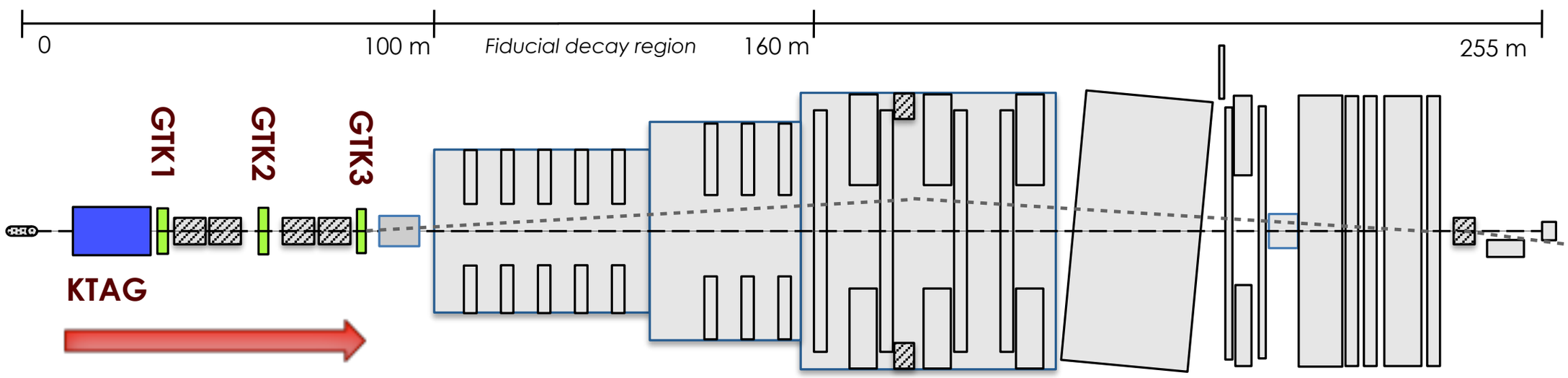
Sensitivity expected to be higher than shown:

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

Acquired in 2016-2018:
~ 10¹⁸ POT with μμ-parasitic trigger,
~5 10¹⁶ POT with ee-parasitic trigger
… to be analyzed

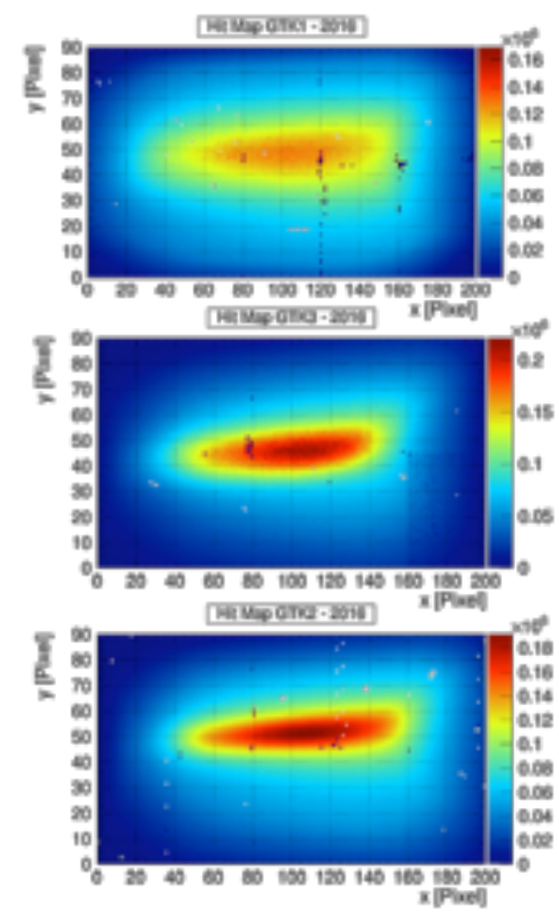
NA62 Apparatus

270 m long region starting about 100 m downstream of the beryllium target
Detector diameters go from 20 to 400 cm



Beam particles identification and tracking

Kaon detection



Kaon Tag (KTAG):

- Differential Cherenkov detecting Kaons;
- ~80 ps time precision;

Beam Spectrometer (GigaTracker - GTK):

- 3 stations of Silicon pixel detectors inside an achromat;
- Time : $\sigma \approx 130$ ps per station;
- Direction: $\sigma_{dx,dy} \approx 0.016$ mrad, Momentum: $\Delta P/P < 0.4\%$;

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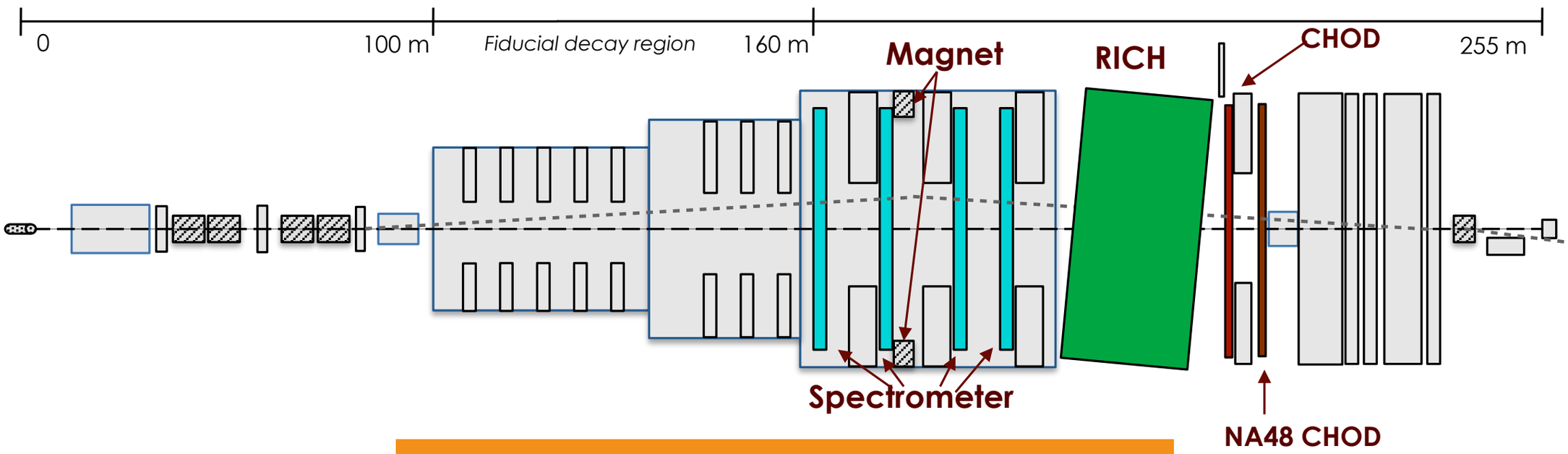
270 m long region starting about 100 m downstream of the beryllium target
Detector diameters go from 20 to 400 cm



Downstream tracks - Kinematics

Straw Spectormeter:
- 4 straw chambers in vacuum;
- Each chamber measuring 4 coordinates (views);
- High accuracy: 130 μm/view;

RICH:
- Cherenkov detector filled with Neon;
- 70 ps of time resolution;

NA48 CHOD
- Plastic scintillator hodoscope;
- ~200 ps time resolution;

CHOD:
- Plastic tile scintillator;
- <1 ns time resolution;
- Decay topology detection;

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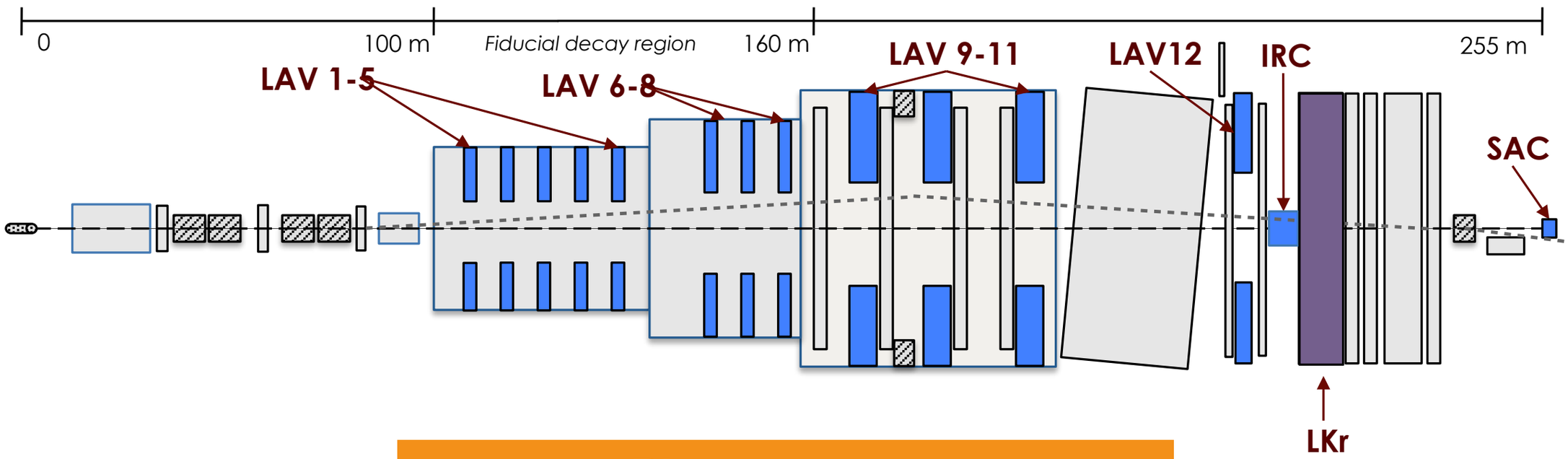
Detector diameters go from 20 to 400 cm



Photon vetoes

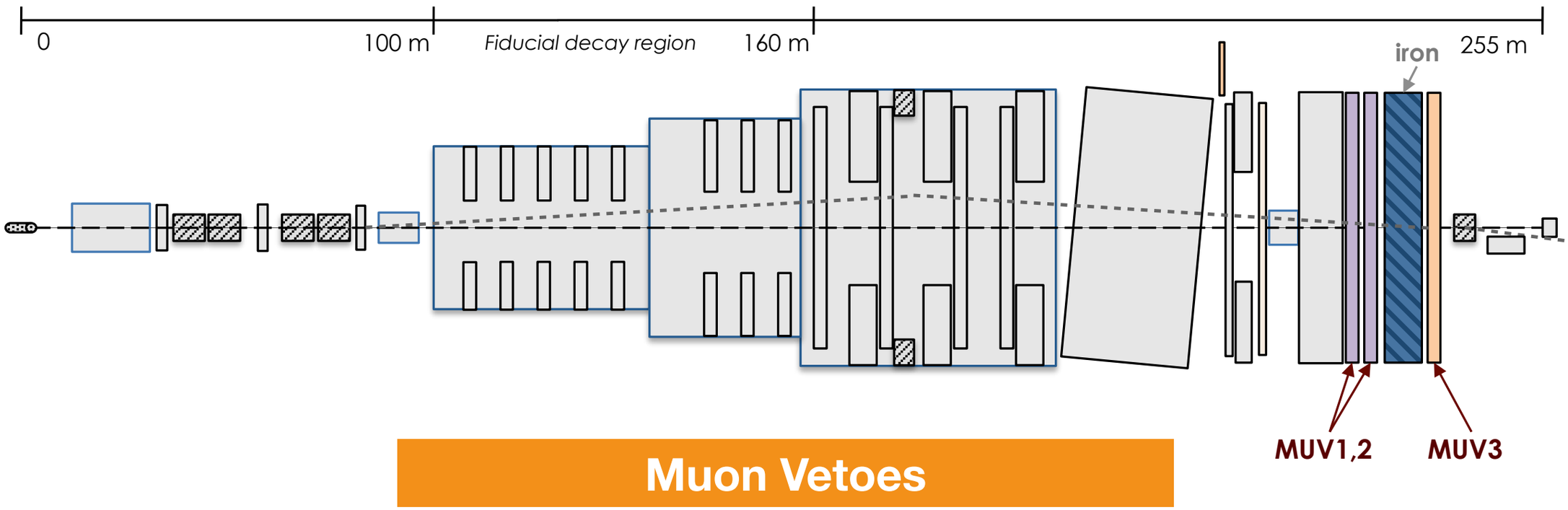
Large Angle Vetoes (LAV):
- 8.5 – 50 mrad
- 12 stations along the vacuum tank;

Liquid Krypton Calorimeter (LKr):
- Electromagnetic calorimeter
- photon veto coverage 1÷8.5 mrad;

Small Angle Vetoes (SAV):
- very small angle <1 mrad;

NA62 Apparatus

270 m long region starting about 100 m downstream of the beryllium target
Detector diameters go from 20 to 400 cm



Muon Veto 1,2

- Readout with LKr electronics;
- Can be used in level-0 as hadron trigger to complete the LKr-electromagnetic calorimeter information;

Muon Veto 3

- Placed after an iron wall;
- Rate: > 10 MHz muons.
- Used in level-0 trigger to veto muons;