Search for lepton number violation and lepton flavor violation in K^+ and π^0 decays

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On behalf of the NA62 Collaboration

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Outline

- LNV and LFV in Kaon decays
- The NA62 experiment
- Data analyses:
  - LFV
    - $K^+ \to \pi^+\mu^-e^+$
    - $\pi^0 \to \mu^-e^+$
  - LNV
    - $K^+ \to \pi^-\mu^+e^+$
    - $K^+ \to \pi^-e^+e^+$, $K^+ \to \pi^-\mu^+\mu^+$

NEW: arXiv:2105.06759

Accepted by Phys. Rev. Let.

PLB 797 (2019) 134794

Lepton Number Violation (LNV)

$L = L_e + L_\mu + L_\tau$ **Lepton flavor: L_e, L_μ, L_τ**

- No gauge symmetry imposes the Lepton Number conservation, accidental symmetry in the SM
- No processes with LNV have been observed so far
- In the SM neutrinos are massless, but they do have mass (neutrino oscillations)

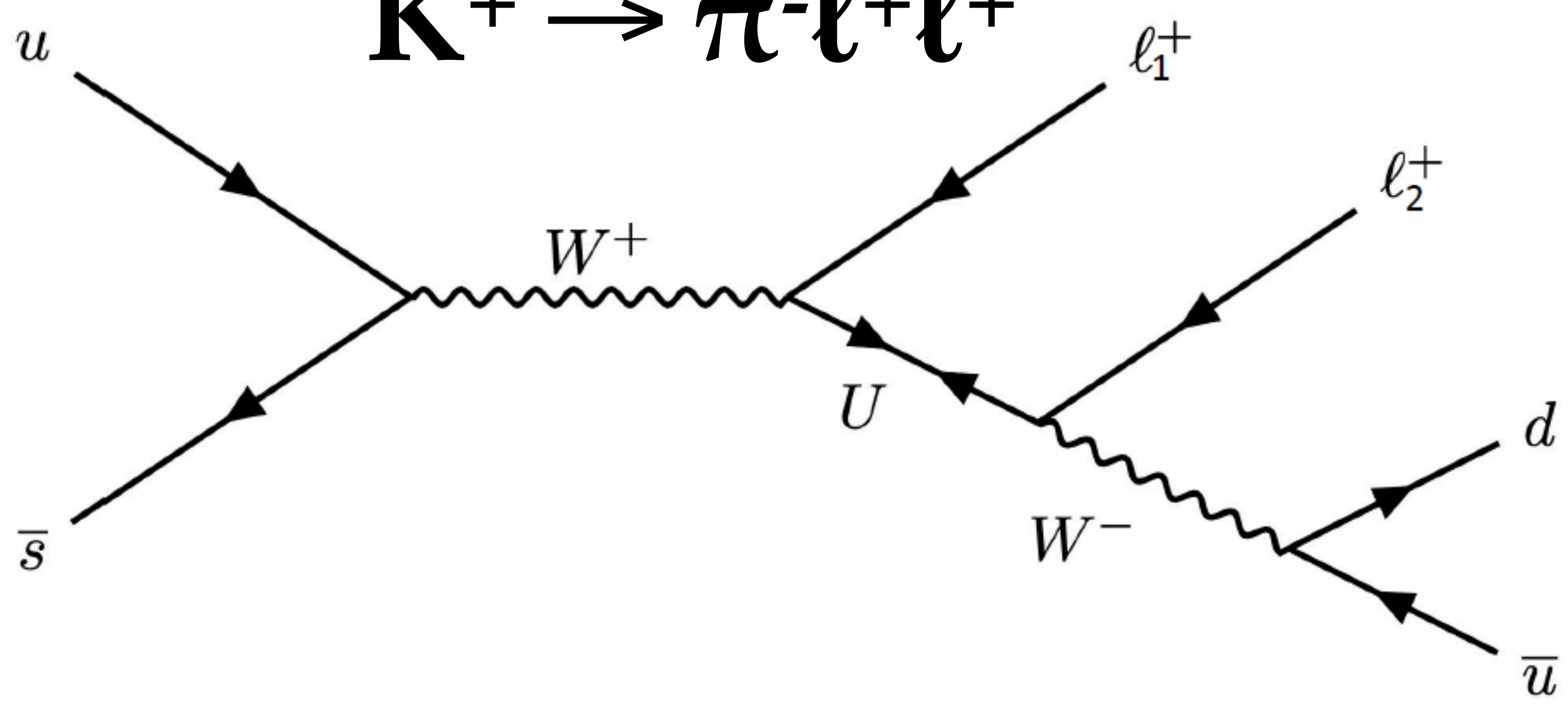
The observation of lepton number violating processes involving charged leptons would verify the Majorana nature of the neutrino.

- Seesaw mechanism:

example:

ΔL=2, via exchange of Majorana neutrinos

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



Atre et al, JHEP05(2009)030

This talk:

$K^+ \to \pi^- \mu^+ e^+$

$K^+ \to \pi^- e^+ e^+$
$K^+ \to \pi^- \mu^+ \mu^+$

- ✦ Probe very high scale
- ✦ Neutrino mass problem

Lepton Flavor Violation (LFV)

Lepton flavor: L_e, L_μ, L_τ

Observation of neutrino oscillations provided the first proof of the non-conservation of LF

But no charged lepton flavor (CLFV) violation has been observed so far

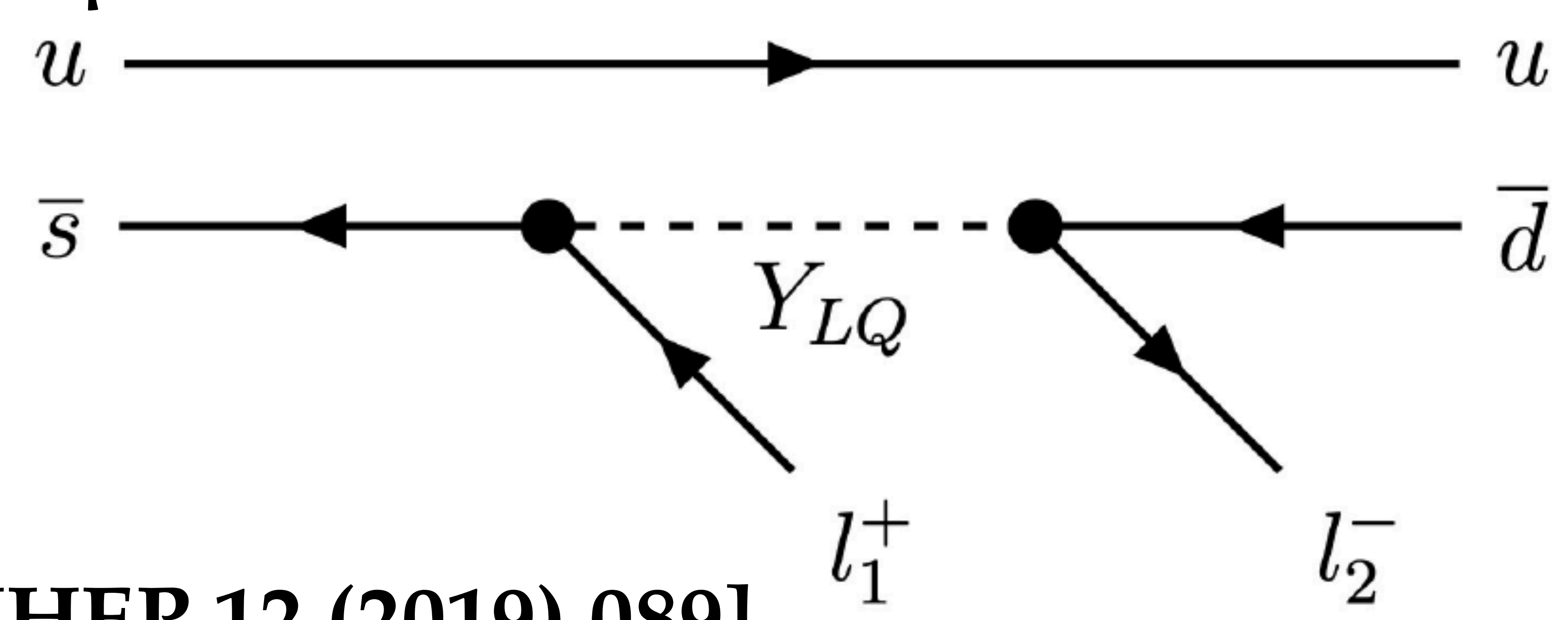
Several BSM scenarios foresee CLFV

example:

$K^+ \to \pi^+\mu^-e^+$ mediated by a **Leptoquark**

$\Delta L_e = 1$

$\Delta L_\mu = 1$



[JHEP 12 (2019) 089],
[Nucl. Phys. B 176 (1980) 135]

Other new physics scenarios:

- Heavy neutrinos
- Heavy Z'
- Anomalous gauge coupling
- SUSY
- ….

This talk:

$K^+ \to \pi^+\mu^-e^+$

$\pi^0 \to \mu^-e^+$

Some of these can explain neutrino oscillations or the possible flavor anomalies in B-physics and foresee LNV or LFV

LNV and LFV experimental status

Searches in K decays are complementary to searches in B-physics and in pure leptonic processes as $\mu \to 3e$, tau or muon decay, or neutrinoless double beta decay

State of the art before NA62 2016-2018 run

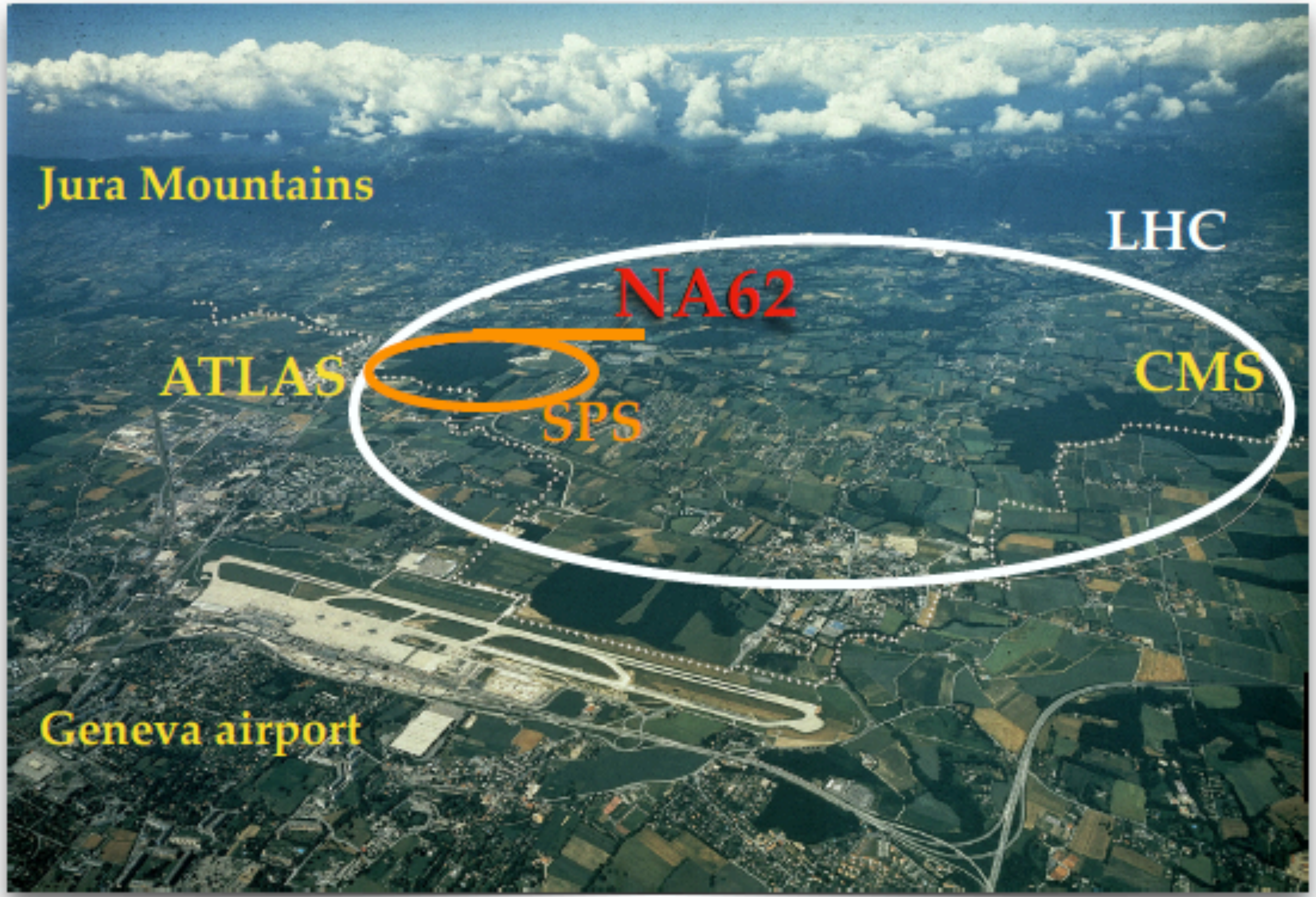
At 90% C.L.

$K^+ \to \pi^-\mu^+e^+$	$< 5.0 \times 10^{-10}$	**E865 at BNL:** R. Appel et al., Phys. Rev. Lett. 85, 2877 (2000)
$K^+ \to \pi^+\mu^-e^+$	$< 5.2 \times 10^{-10}$	
$K^+ \to \pi^+\mu^+e^-$	$< 1.3 \times 10^{-11}$	**E865 at BNL:** A. Sher et al., Phys. Rev. D 72, 012005 (2005)
$\pi^0 \to \mu^-e^+$	$< 3.4 \times 10^{-9}$	**E865 at BNL:** R. Appel et al., Phys. Rev. Lett. 85, 2877 (2000)
$\pi^0 \to \mu^+e^-$	$< 3.8 \times 10^{-10}$	**E865 at BNL:** A. Sher et al., Phys. Rev. D 72, 012005 (2005)
$\pi^0 \to \mu^\pm e^\mp$	$< 3.6 \times 10^{-10}$	**KTeV at FNAL:** E. Abouzaid et al., Phys. Rev. Lett. 100, 131803 (2008)

NA62 Collaboration

~ 200 participants

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, TRIUMF, Turin, Vancouver (UBC)

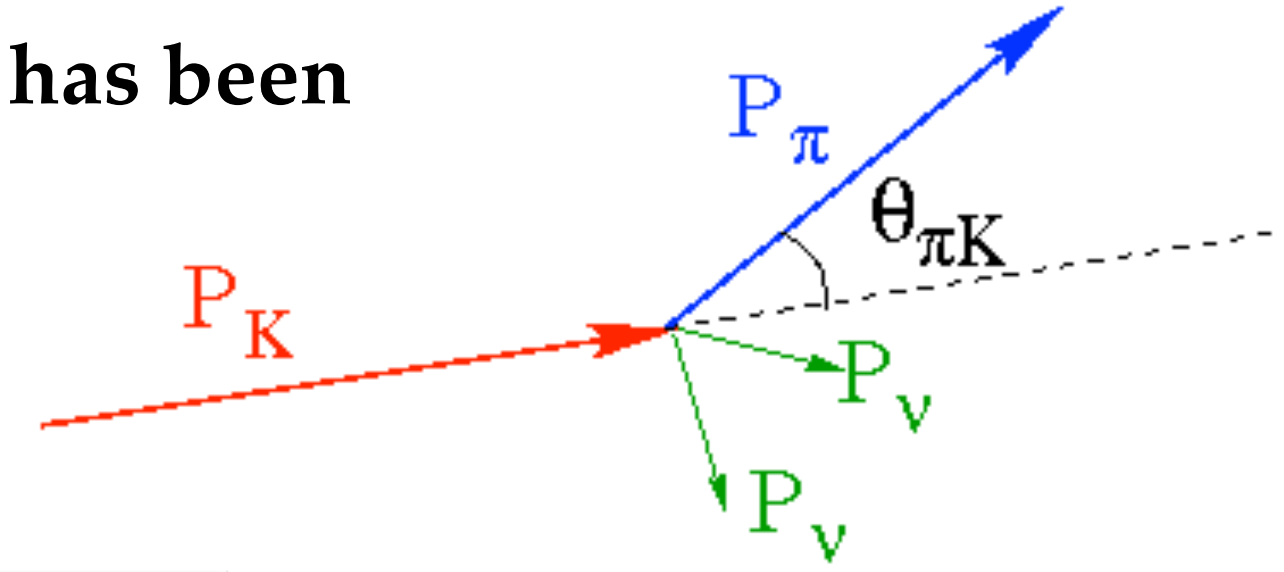


The main aim is the measurement of
BR($K^+ \to \pi^+ \nu\nu$)
with a precision better than 10%

Collected good quality data in 2016-2018

Features required for the BR($K^+ \to \pi^+\nu\nu$)

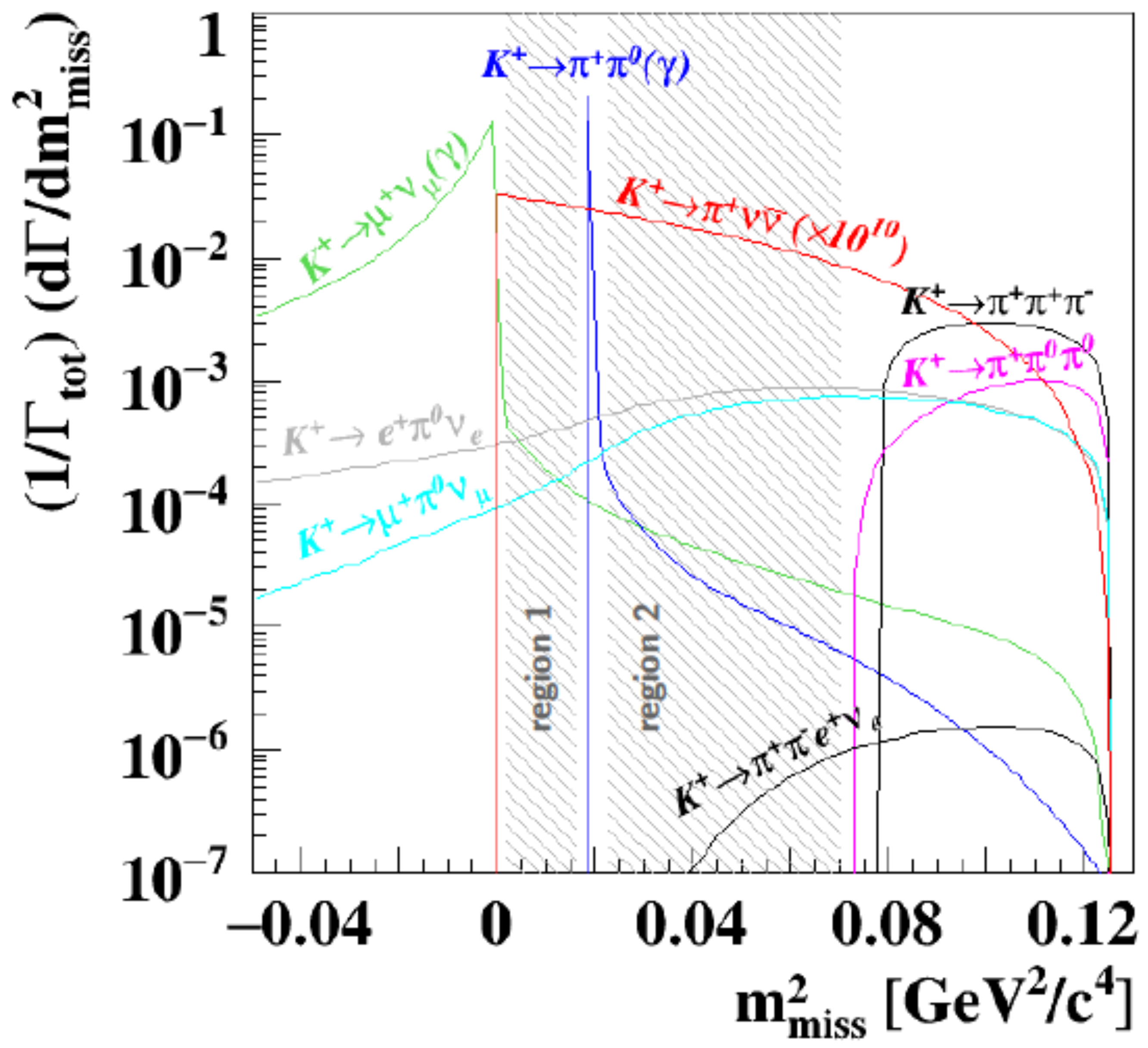
The experimental apparatus has been designed in order to detect:



<u>Decay in flight</u>

$$m^2_{miss} = (p_K - p_\pi)^2$$

Talk by
C. Lazzeroni
in the Flavor session
https://indico.lip.pt/event/592/contributions/3549/



- very good kinematic reconstruction
- time measurements

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

- K,π,μ identification
- Hermetic detection of muons
- Hermetic detection of photons

Features useful also for the LFV and LNV searches

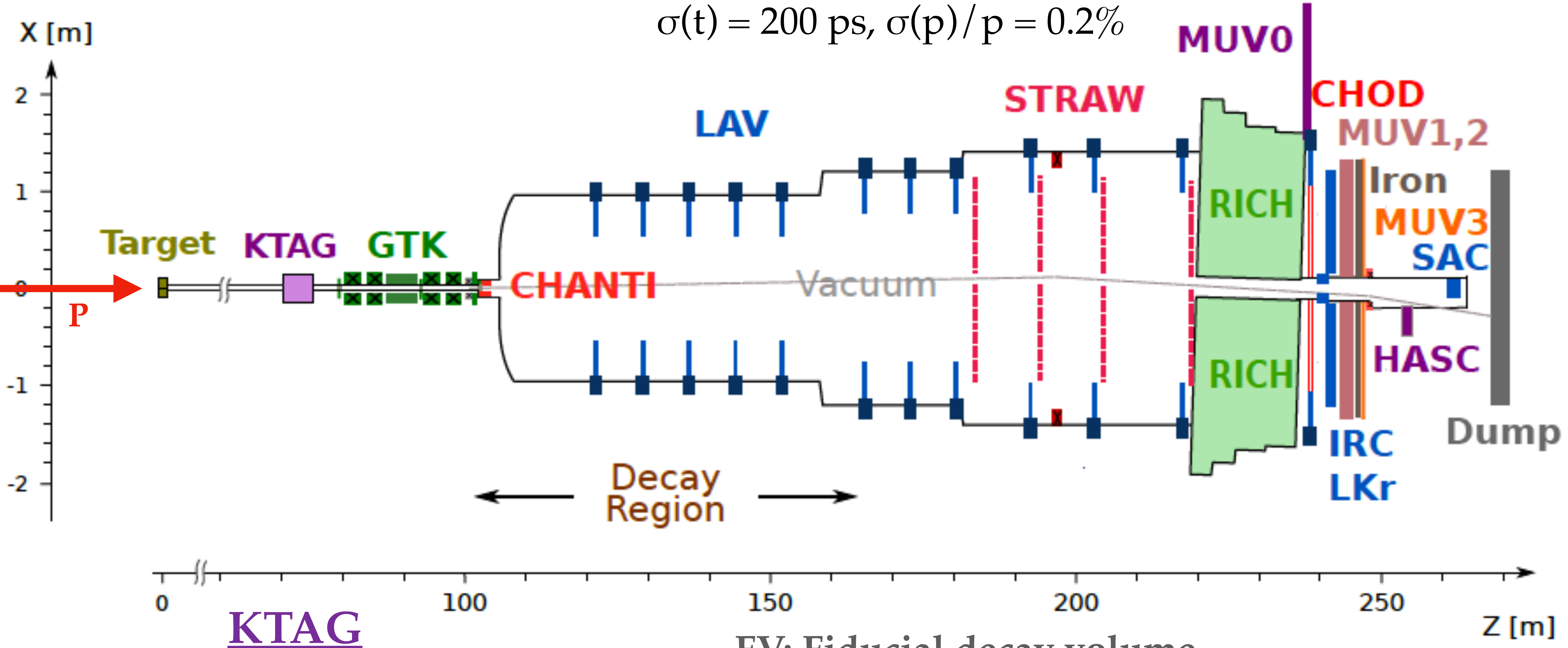
NA62 apparatus: the p and K beam

JINST 12 P05025 (2017), arxiv:1703.08501

33x10[11] ppp on T10 (750 MHz at GTK3)
Secondary beam: 75 GeV/c momentum
K^+ (6%)/π^+ (70%)/p(24%)

Upstream track reconstructed by the GTK

Kaon tracking
Si pixel, 3 stations
$\sigma(t) = 200$ ps, $\sigma(p)/p = 0.2\%$



KTAG

Kaon identification
Differential
Cherenkov detector

FV: Fiducial decay volume
tube evacuated
(500 m^3 at 10^{-6} mbar)

NA62 apparatus: kaon decays reconstruction

JINST 12 P05025 (2017), arxiv:1703.08501

Upstream track reconstructed by the GTK

Kaon tracking

Si pixel, 3 stations

$\sigma(t) = 200$ ps, $\sigma(p)/p = 0.2\%$

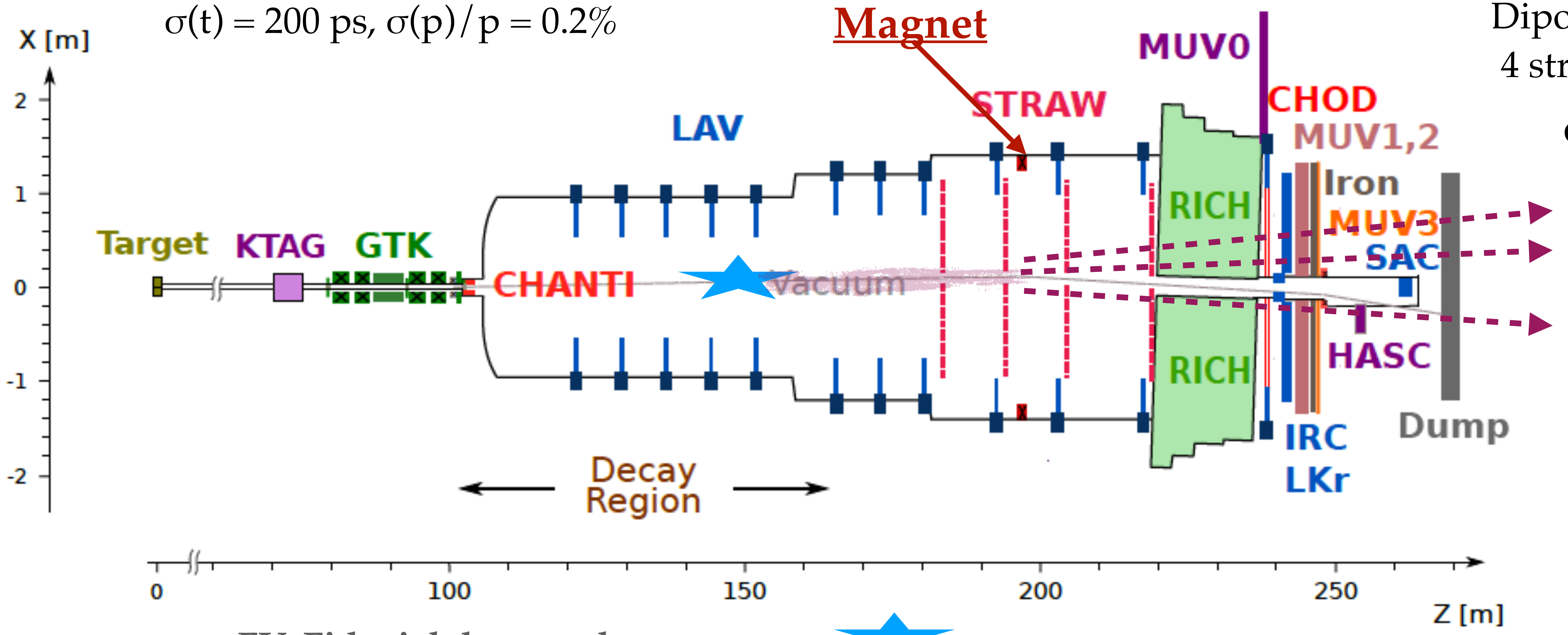
3 tracks reconstructed by the STRAW

Downstream tracking:

Dipole spectrometer

4 straw-tracker stations

$\sigma(p)/p = 0.3\%$



KTAG

Kaon identification

Differential Cherenkov detector

FV: Fiducial decay volume

evacuated tube

(500 m^3 at 10^{-6} mbar)

Vertex fully reconstructed, closed kinematics

3 track invariant mass resolution ~ 1.4 MeV

NA62 apparatus: photon veto system

JINST 12 P05025 (2017), arxiv:1703.08501

Hermetic photon veto system
(LAV,SAV,LKr)

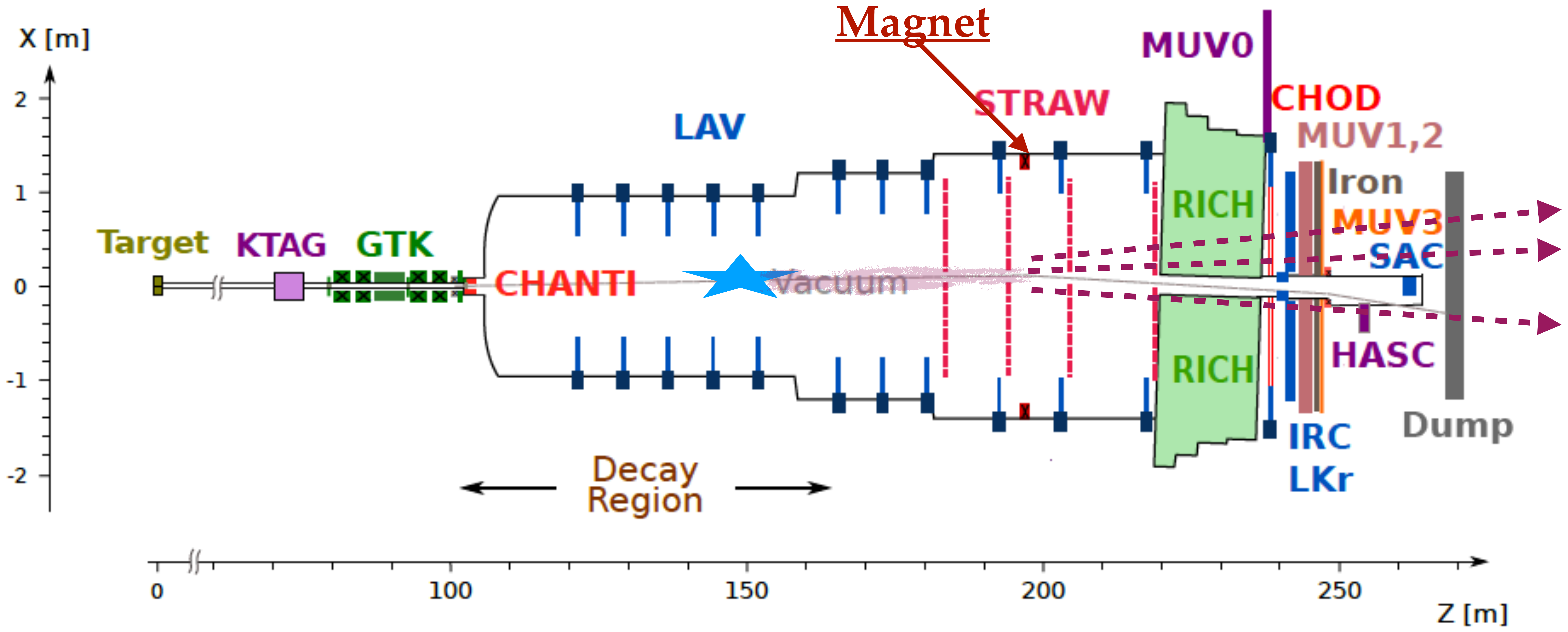
Multiplicity rejection
(LAV,SAV,LKr, CHOD,STRAW)

Large Angle Veto (LAV)

12 stations (lead glass blocks)
Covering angles 8.5 <θ <50 mrad

CHOD

Charged Hodoscope,
plastic scintillator



LKr calorimeter

Photon detection

Covering angles
1<θ<8.5 mrad

πνν background rejection: $K^+ \to \pi^+\pi^0$

☑ $\varepsilon(\pi^0)= 3\ 10^{-8}$

Small Angle Veto (SAV)

IRC: Inner Ring Calorimeter
Small Angle Calorimeter, Covering angles <1 mrad

NA62 apparatus: particle identification

JINST 12 P05025 (2017), arxiv:1703.08501

RICH
Ring Imaging Cherenkov detector

Neon 1 Atm

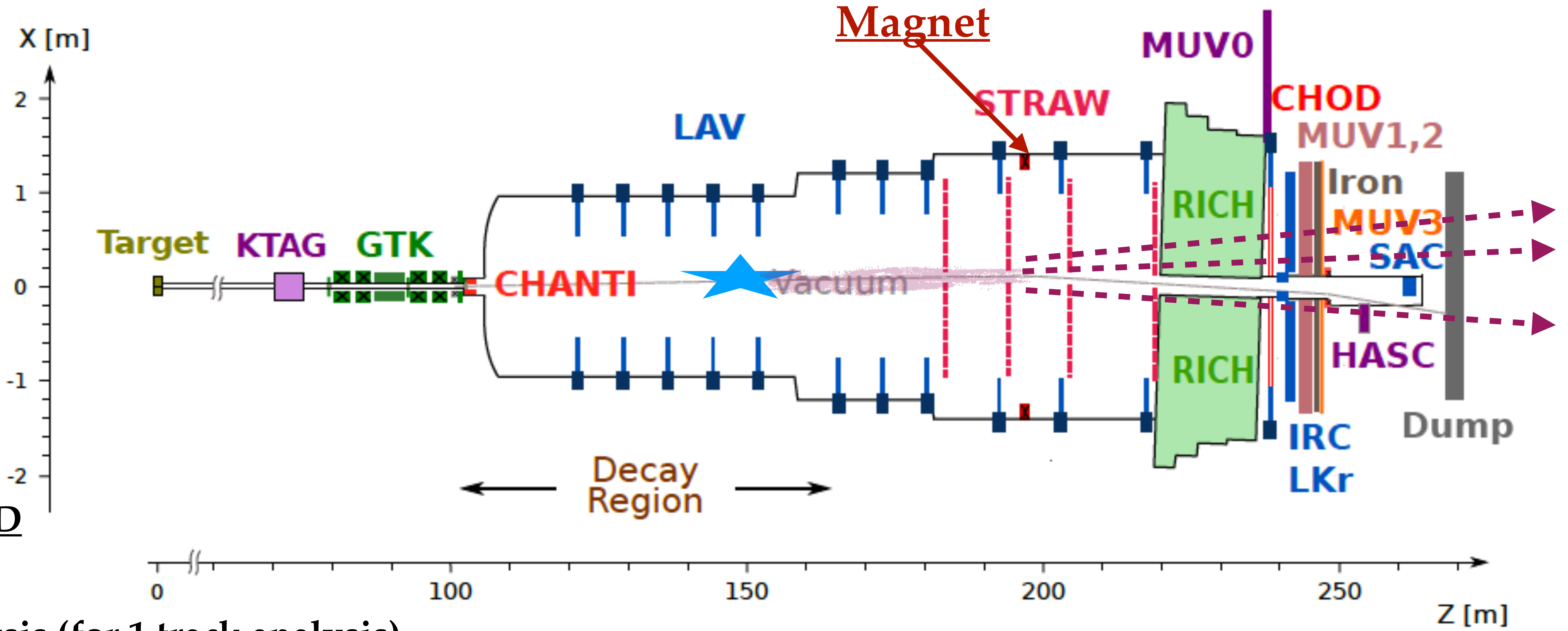
π/μ/e separation
Reference event time

The RICH is used also to obtain an independent p momentum measurement

MUV **Muon veto system**

MUV1 & MUV2: Hadronic calorimeters for the μ/π separation

E/p variable
E = energy deposited in LKr
p = track momentum



MUV3: Efficient fast Muon Veto used in the hardware trigger level.

Other available PID tools in NA62:

Multivariate analysis (for 1 track analysis) with MUV1, MUV2 and LKr info

2 algorithms for the RICH variables

- very good kinematic reconstruction
- Precise time measurements by the CHOD, RICH, KTAG

Data taking timeline

NA62 Data Taking

- ☑ 2015 Commissioning run
- ☑ 2016 Commissioning + Physics run (45 days)
- ☑ 2017 Physics run (160 days)
- ☑ 2018 Physics run (217 days)
- ☐ 2021 Physics run ongoing

Till the next LHC Long Shutdown

results on K->πνν and K->πX$_{inv}$:
[PLB 791 (2019) 156]
[JHEP 11 (2020) 042]
[JHEP 06 (2021) 093]
https://indico.lip.pt/event/592/contributions/3549/

Much broader physics program
eg at PANIC2021:
HNL searches: https://indico.lip.pt/event/592/contributions/3546/
Radiative decay: https://indico.lip.pt/event/592/contributions/3206/

$K^+ \rightarrow \pi^{+/-}\mu^{-/+}e^+$ and $\pi^0 \rightarrow \mu^- e^+$

Analysis strategy:

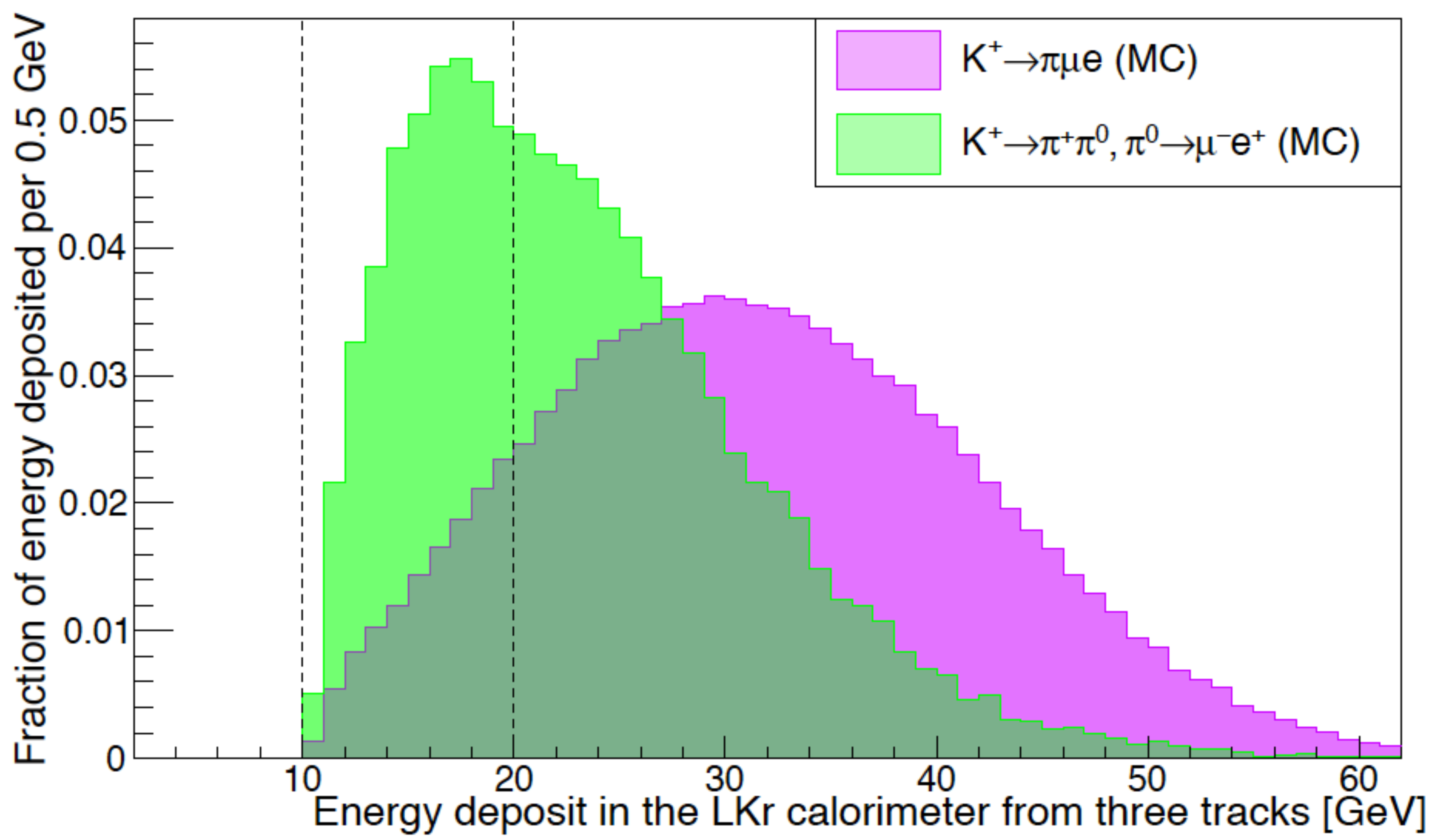
- Search in 2017 + 2018 Data
- Blind analysis strategy: unblind control regions, then unblind the signal regions
- 2 independent analyses cross-checked
- Normalization to $K \to \pi^+\pi^+\pi^-$
- Triggers :
  - Dedicated triggers downscaled recorded simultaneously with $\pi\nu\bar{\nu}$ trigger
- Event selection:
  - Reconstruct 3 tracks with momentum measurement by the STRAW spectrometer
  - Total momentum consistent with beam K^+ , reconstruct decay vertex in FV: z in 107(111)-180 m
  - PID : use E/p and MUV3 to ID/veto muons
  - Photon Vetos : LAV, IRC, SAC, LKr
  - Tracks in time, measured with the CHOD
  - Build invariant mass $M(\pi\mu e)$
- Signal region defined in $M(\pi\mu e)$ around the Kaon mass (resolution ≈ 1.4 MeV)
  - For $K \to \pi^-\mu^+e^+$: additional cut to reduce the π^0 Dalitz decays
- Additional request for $\pi^0 \rightarrow \mu^- e^+$: $M(\mu e)$ around π^0 mass

- $K \to \pi^-\mu^+e^+$
- $K \to \pi^+\mu^-e^+$
- $K \to \pi^+\pi^0$
  $\pi^0 \rightarrow \mu^- e^+$

Trigger Efficiency

Normalization: multi-track (MT)

Signal: 3 trigger streams in OR logic with different downscaling factors



Trigger ε measured with minimum bias data

The downscaling factors can vary during the data taking
Here **D** is a typical value

Trigger stream	Description	D	$\varepsilon(K^+\to\pi^-\mu^+e^+)$ [%]	$\varepsilon(K^+\to\pi^+\mu^-e^+)$ [%]	$\varepsilon(\pi^0\to\mu^-e^+)$ [%]
Multi-track (MT)	3 tracks	100	**93.5 ± 0.5**	**93.5 ± 0.5**	**93.5 ± 0.5**
Multi-track μ	3 tracks, E(LKr)>10GeV, at least 1 μ	8	**97.5 ± 1.3**	**97.5 ± 1.3**	**92.9 ± 1.2**
Multi-track e	3 tracks, E(LKr)>20GeV	8	**74.1 ± 1.6**	**73.3 ± 1.6**	**45.3 ± 1.0**

Single event sensitivity

Signal processes are normalized to the $K^+ \to \pi^+\pi^+\pi^-$ channel, $B(K_{3\pi}) = (5.583 \pm 0.024)\%$

Number of Kaon decays in the FV:

$$N_K = \sum_i N_K^i = \frac{1}{\mathcal{B}(K_{3\pi}) A_n \varepsilon_n} \cdot \sum_i \left(N_{3\pi}^i \frac{D_{MT}^i}{D_{eff}^i} \right)$$

i: data taking period

Normalization efficiencies

Downscaling factor of the multi-track trigger (used for the normalization channel)

Downscaling factor of the signal trigger

$$\sum_i N_{3\pi}^i = 2.73 \times 10^8$$

$N_K = (1.32 \pm 0.01) \times 10^{12}$

$$\mathcal{B}_{SES}^i = \frac{1}{N_K^i A_s \varepsilon_s^i} = \mathcal{B}(K_{3\pi}) \frac{A_n D_{eff}^i}{A_s N_{3\pi}^i D_{MT}^i} \frac{\varepsilon_n}{\varepsilon_s^i}$$

A_S: Signal acceptance

ε_S: Signal trigger efficiency

	$K^+ \to \pi^- \mu^+ e^+$	$K^+ \to \pi^+ \mu^- e^+$	$\pi^0 \to \mu^- e^+$
$A_s \times 10^2$	4.90 ± 0.02	6.21 ± 0.02	3.11 ± 0.02
$\mathcal{B}_{SES} \times 10^{11}$	1.82 ± 0.08	1.44 ± 0.05	13.9 ± 0.9

Single Event Sensitivity of the order of 10^{-11} -10^{-10}

Background estimation

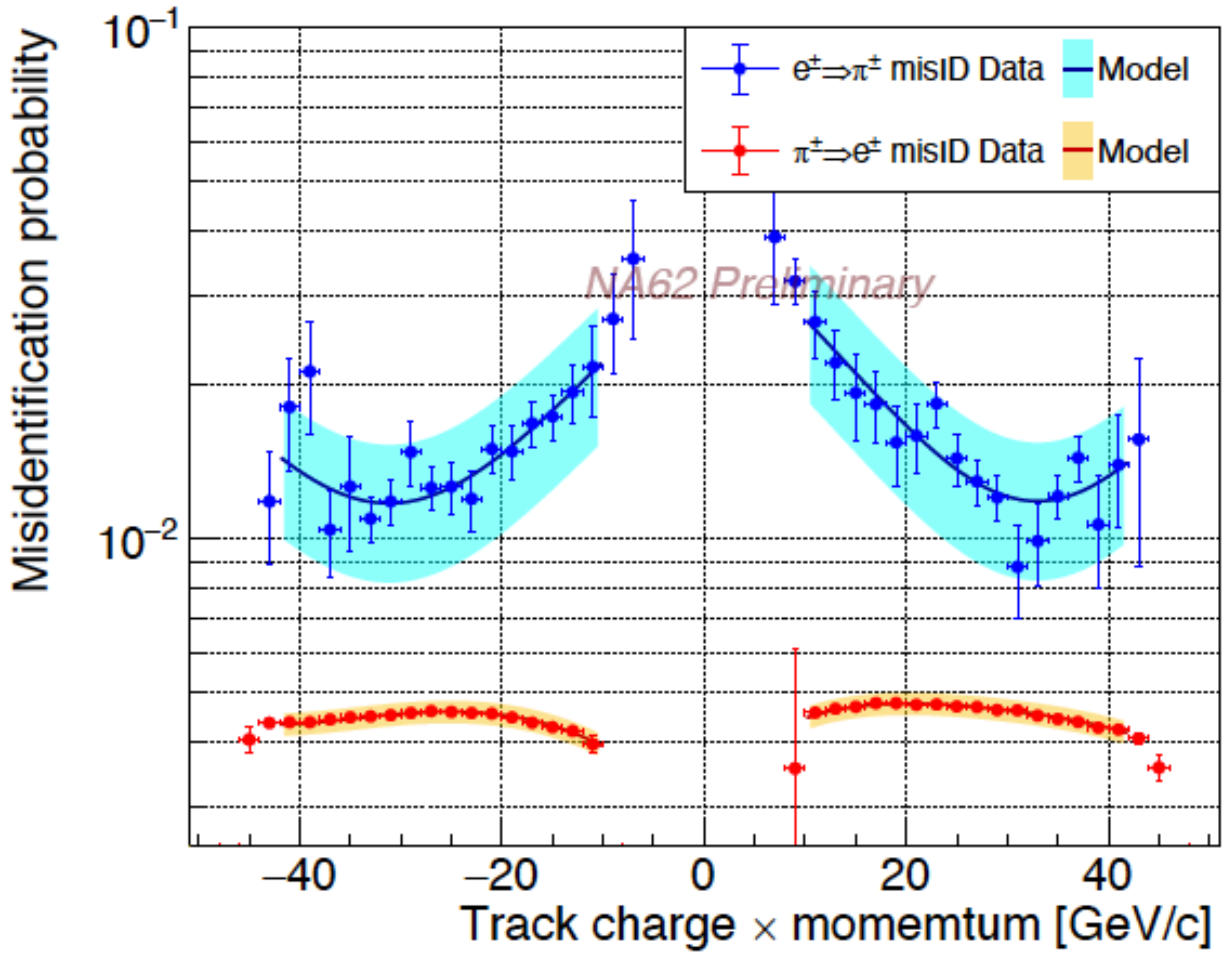
Background mechanisms:

- **Mis-ID**
  - **Estimated with data samples:**

$e^{\pm} \Rightarrow \pi^{\pm}$ measured with $K^{+} \rightarrow \pi^{+}\pi^{0}$, $\pi^{0} \rightarrow e^{+}e^{-}\gamma$

$\pi^{\pm} \Rightarrow e^{\pm}$ measured with $K^{+} \rightarrow \pi^{+/-}\pi^{-/+}\pi^{+}$

$\pi^{\pm} \Rightarrow \mu^{\pm}$ and $\mu^{\pm} \Rightarrow e^{\pm}$ Measured with sample of MUV3 signals in time sidebands depends on track p and position at MUV3

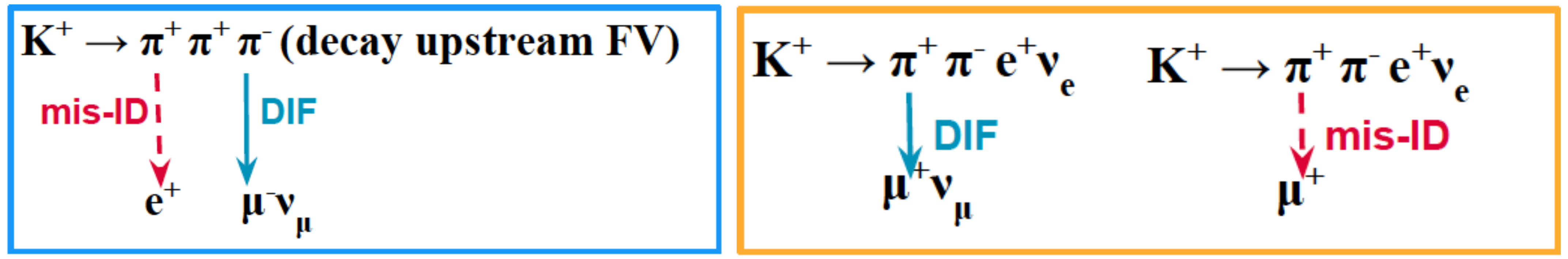


- **Decay in flight (DIF)**
  - **$\pi^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}$ or $\mu^{\pm} \rightarrow e^{\pm}\nu_{e}$**
  - **Dalitz decay : $\pi^{0} \rightarrow e^{+}e^{-}\gamma$**

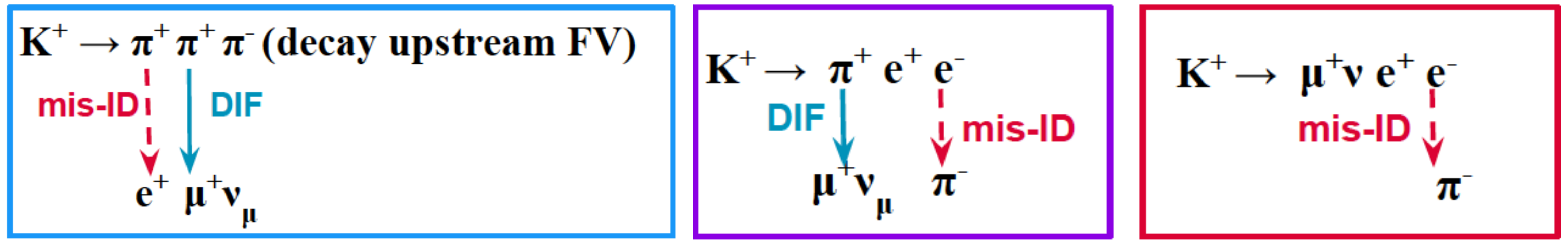
measured with simulation

Dedicated cut in π^{-} channel, reduces acceptance wrt the μ^{-} channel

$K^{+} \rightarrow \pi^{+}\mu^{-}e^{+}$

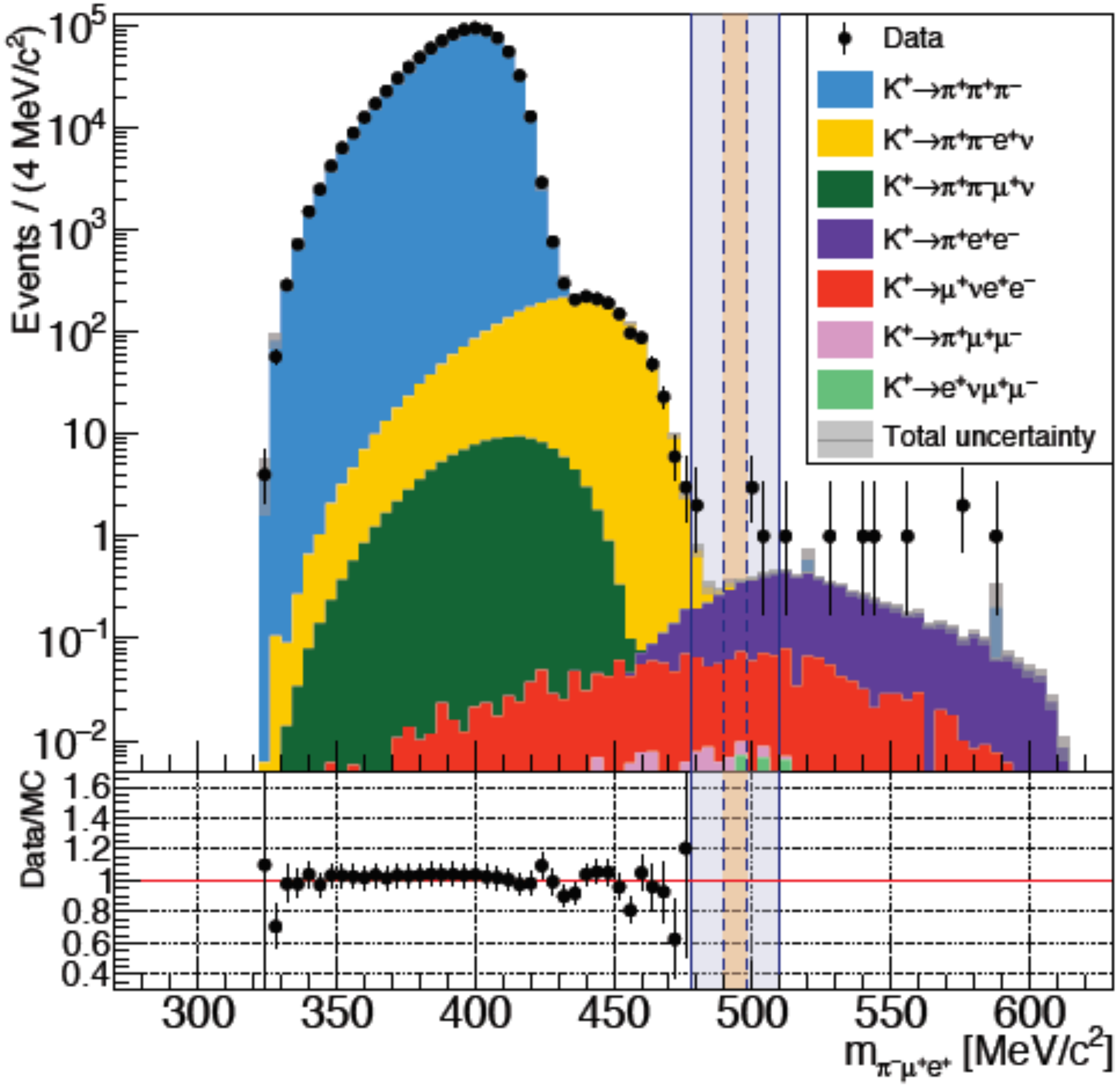


$K^{+} \rightarrow \pi^{-}\mu^{+}e^{+}$



$K^+ \to \pi^- \mu^+ e^+$ results

Control Regions (CR1, CR2)

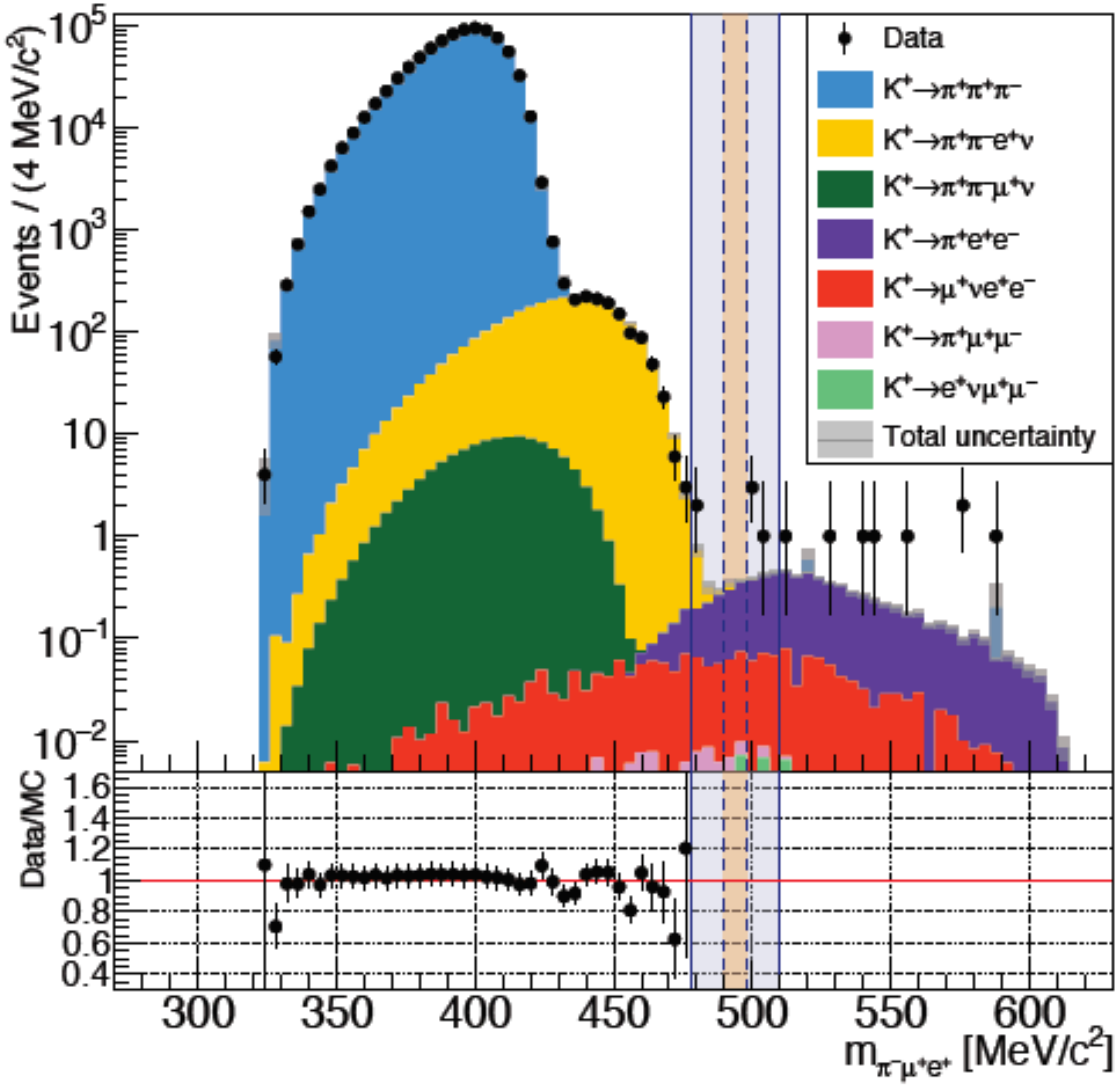


- Misidentification rate measured in data applied to the MC samples
- Open the control regions:

	$K^+ \to \pi^- \mu^+ e^+$	
	CR1	CR2
Predicted	1.68 ± 0.20	1.66 ± 0.26
Observed	2	4

$K^+ \to \pi^-\mu^+e^+$ results

Control Regions (CR1, CR2) Signal Region: 490–498 MeV



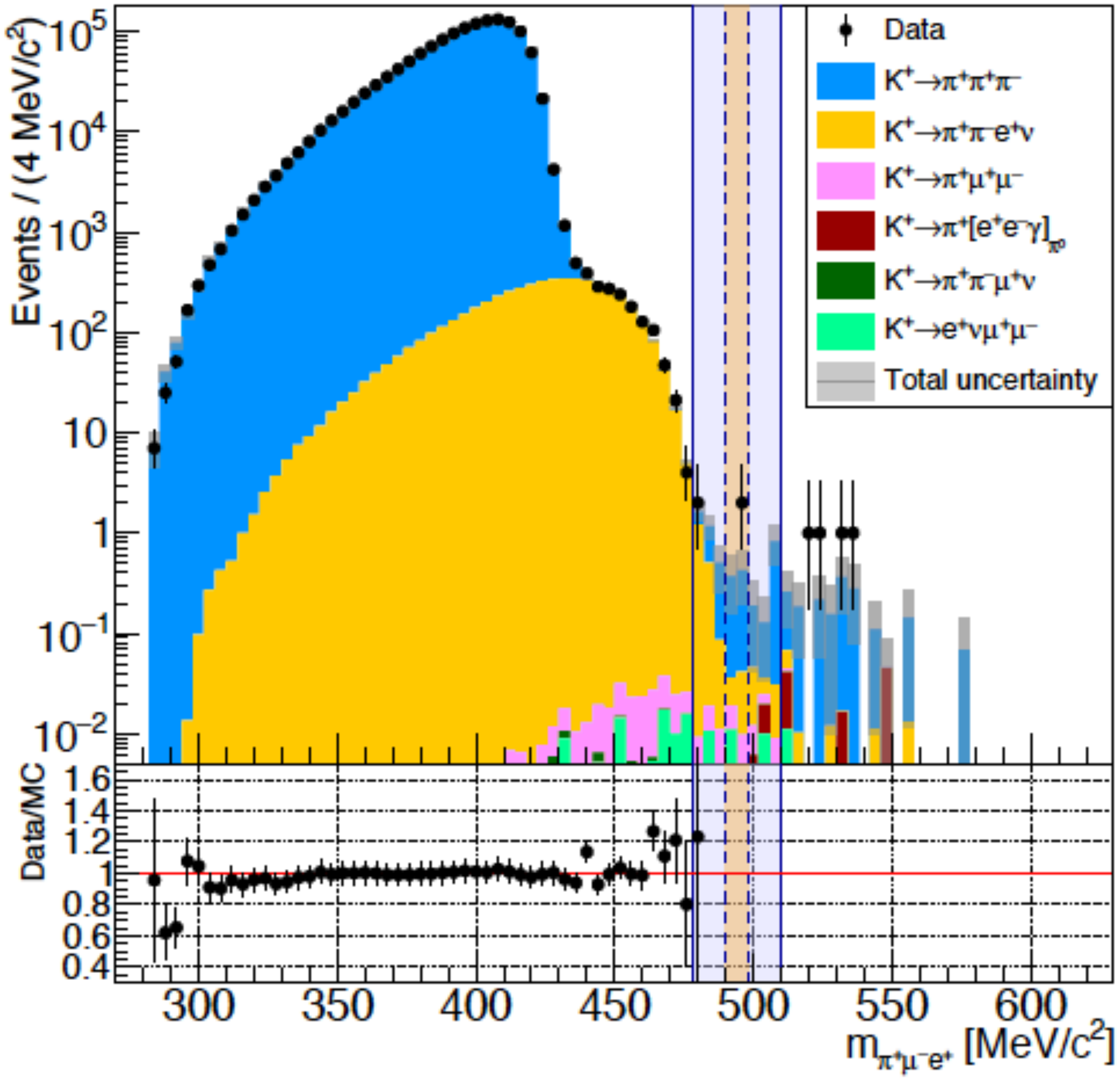
Open the signal region

Source	$K^+ \to \pi^-\mu^+e^+$
$K^+ \to \pi^+\pi^+\pi^-$	0.22 ± 0.15
$K^+ \to \pi^+e^+e^-$	0.63 ± 0.13
$K^+ \to \mu^+\nu_\mu e^+e^-$	0.13 ± 0.02
$K^+ \to \pi^+\pi^-e^+\nu_e$	0.07 ± 0.02
$K^+ \to \pi^+\mu^+\mu^-$	0.01 ± 0.01
$K^+ \to e^+\nu_e\mu^+\mu^-$	0.01 ± 0.01
Total	1.07 ± 0.20

Number of observed events	**0**

$K^+ \to \pi^+\mu^-e^+$ results

Control Regions (CR1, CR2)

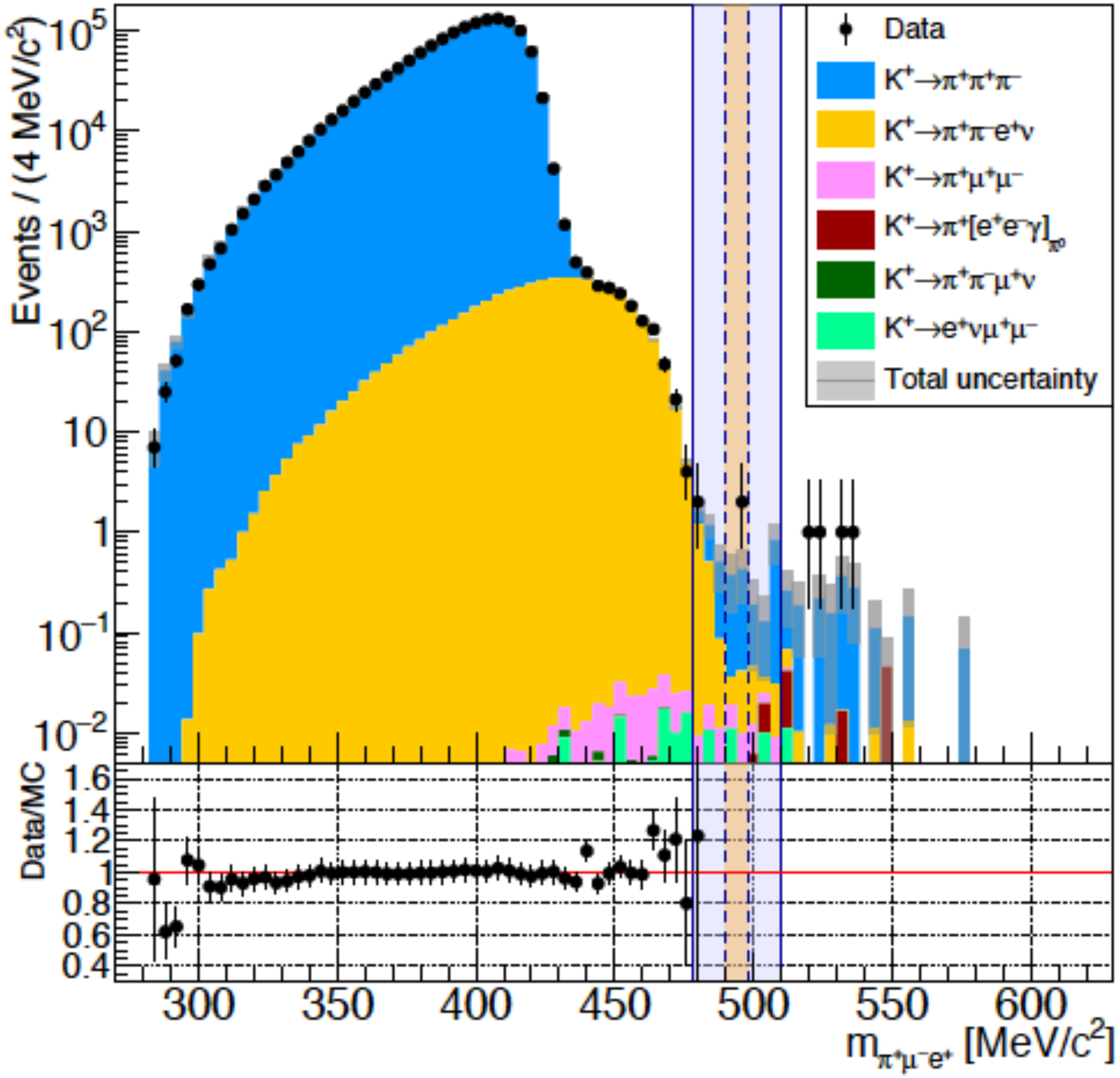


- Misidentification rate measured in data applied to the MC samples
- Open the control regions:

	$K^+ \to \pi^+\mu^-e^+$ CR1	CR2
Predicted	3.41 ± 0.54	1.27 ± 0.40
Observed	2	0

$K^+ \to \pi^+\mu^-e^+$ results

Control Regions (CR1, CR2)   Signal Region: 490–498 MeV



Open the signal region

Source	$K^+ \to \pi^+\mu^-e^+$	$\pi^0 \to \mu^-e^+$
$K^+ \to \pi^+\pi^+\pi^-$	0.84 ± 0.34	0.22 ± 0.15
$K^+ \to \pi^+e^+e^-$	negl.	negl.
$K^+ \to \mu^+\nu_\mu e^+e^-$	negl.	negl.
$K^+ \to \pi^+\pi^-e^+\nu_e$	0.05 ± 0.03	0.01 ± 0.01
$K^+ \to \pi^+\mu^+\mu^-$	0.02 ± 0.01	negl.
$K^+ \to e^+\nu_e\mu^+\mu^-$	0.01 ± 0.01	negl.
Total	0.92 ± 0.34	0.23 ± 0.15

Number of observed events	**2**	**0**

$K^+ \to \pi^{+/-}\mu^{-/+}e^+$ and $\pi^0 \to \mu^- e^+$ results

Counting experiment

CLs treatment

Upper limit at 90% C.L.:

$$K^+ \to \pi^-\mu^+e^+ \; : \quad n_{\rm bg} = 1.07 \pm 0.20\,, \quad n_{\rm obs} = 0$$
$$K^+ \to \pi^+\mu^-e^+ \; : \quad n_{\rm bg} = 0.92 \pm 0.34\,, \quad n_{\rm obs} = 2$$
$$\pi^0 \to \mu^-e^+ \; : \quad n_{\rm bg} = 0.23 \pm 0.15\,, \quad n_{\rm obs} = 0$$

$$\mathcal{B}(K^+ \to \pi^-\mu^+e^+) < 4.2 \times 10^{-11}$$
$$\mathcal{B}(K^+ \to \pi^+\mu^-e^+) < 6.6 \times 10^{-11}$$
$$\mathcal{B}(\pi^0 \to \mu^-e^+) < 3.2 \times 10^{-10}$$

improve on previous searches by ~ one order of magnitude

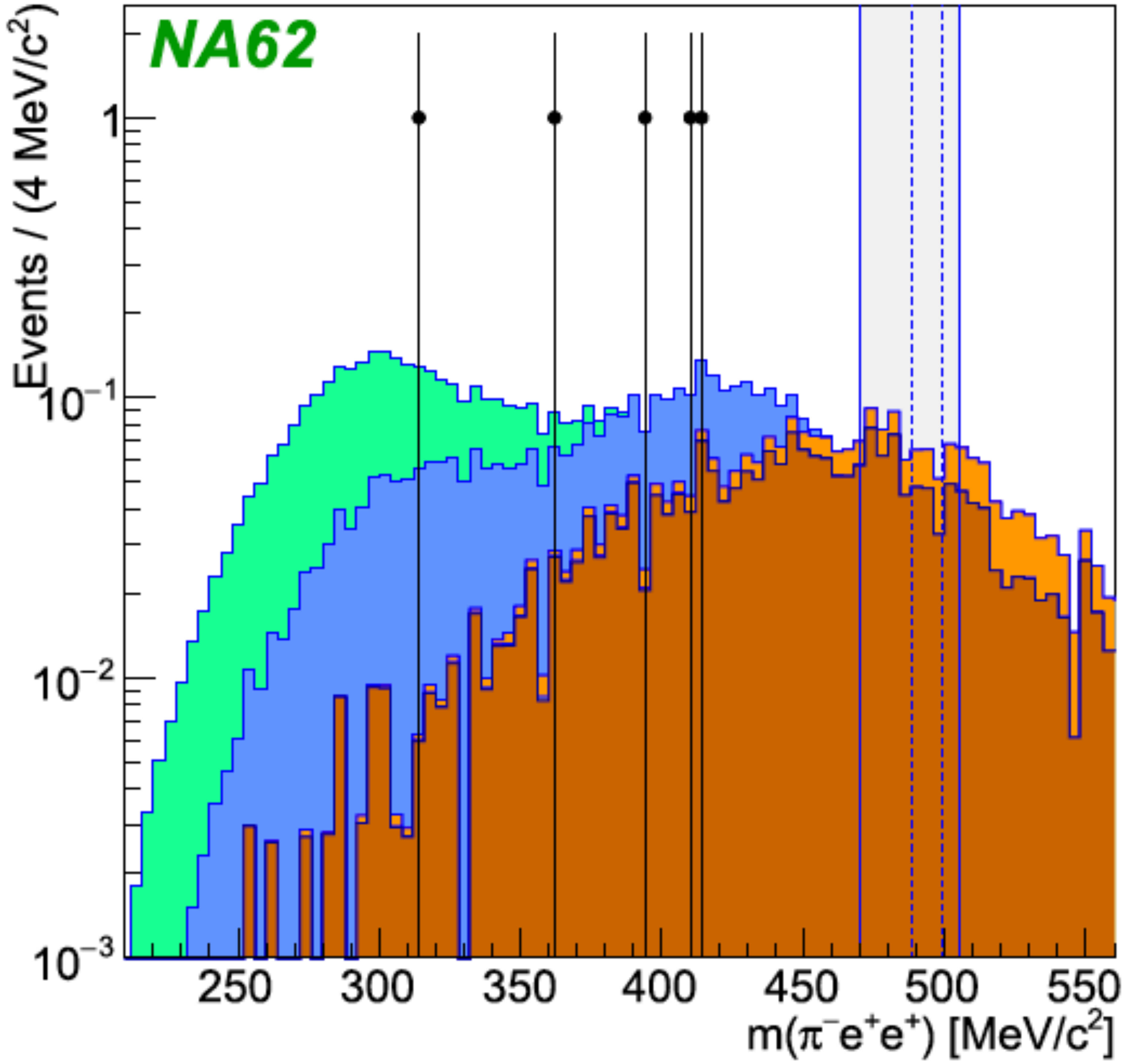
E865 at BNL: R. Appel et al.,
Phys. Rev. Lett. 85, 2877 (2000)

$K^+ \to \pi^- e^+ e^+$, $K^+ \to \pi^- \mu^+ \mu^+$

PLB 797 (2019) 134794

2017 Data

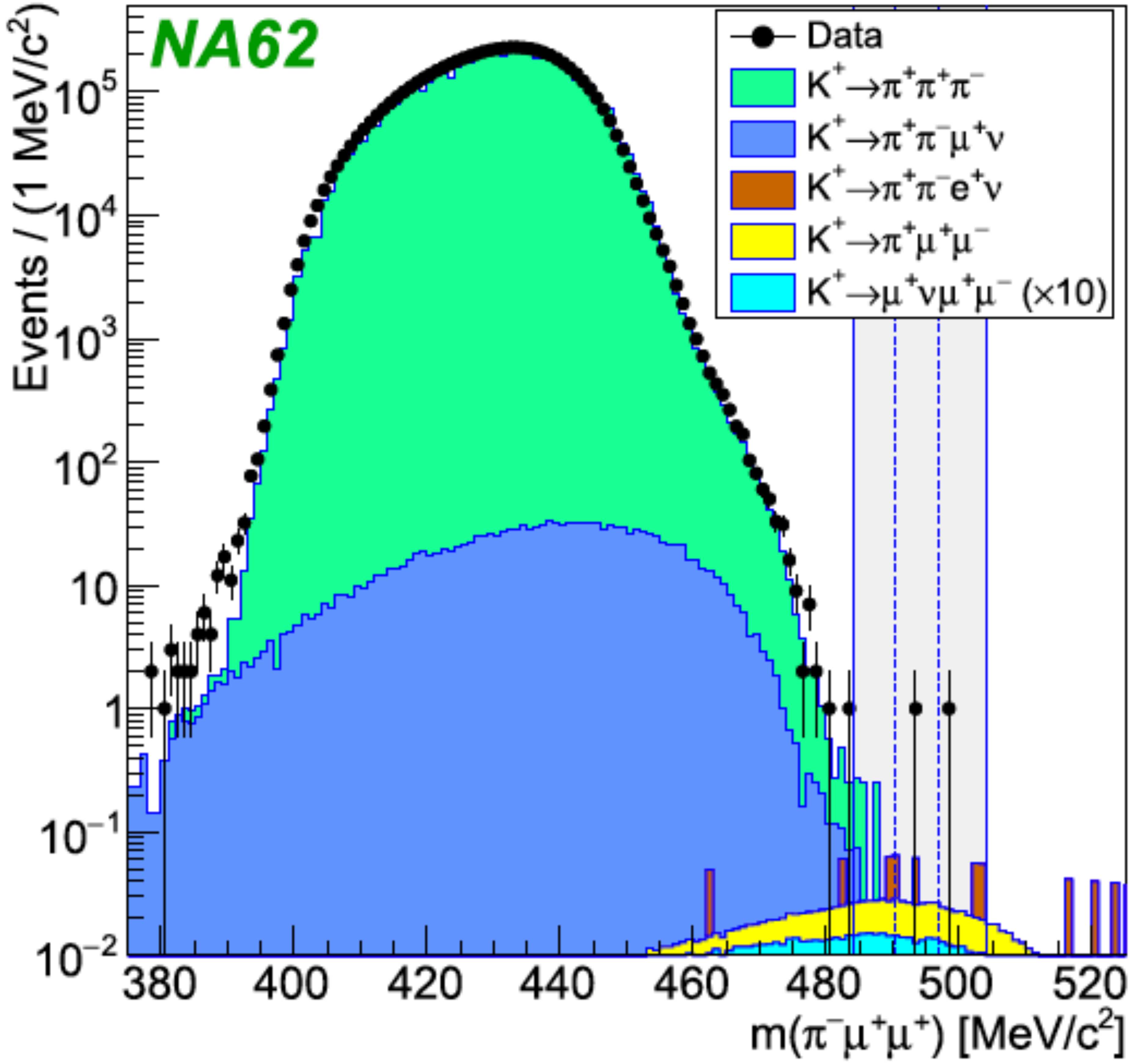
$N_B = 0.16 \pm 0.03$



Limit at 90% CL

$\mathcal{B}(K^+ \to \pi^- e^+ e^+) < 2.2 \times 10^{-10}$

$N_B = 0.91 \pm 0.41$



Limit at 90% CL

$\mathcal{B}(K^+ \to \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11}$

Conclusions

Improved on previous searches by ~ one order of magnitude

	Limit at 90% CL
$K^+ \to \pi^- \mu^+ \mu^+$	$< 4.2 \times 10^{-11}$ (NA62 at CERN [10])
$K^+ \to \pi^- e^+ e^+$	$< 2.2 \times 10^{-10}$ (NA62 at CERN [10])
$K^+ \to \pi^- \mu^+ e^+$	$< 5.0 \times 10^{-10}$ (E865 at BNL [11])
$K^+ \to \pi^+ \mu^- e^+$	$< 5.2 \times 10^{-10}$ (E865 at BNL [11])
$K^+ \to \pi^+ \mu^+ e^-$	$< 1.3 \times 10^{-11}$ (E865 at BNL [12])
$\pi^0 \to \mu^- e^+$	$< 3.4 \times 10^{-9}$ (E865 at BNL [11])
$\pi^0 \to \mu^+ e^-$	$< 3.8 \times 10^{-10}$ (E865 at BNL [12])
$\pi^0 \to \mu^\pm e^\mp$	$< 3.6 \times 10^{-10}$ (KTeV at FNAL [13])

Limit at 90% CL

$$\mathcal{B}(K^+ \to \pi^- \mu^+ e^+) < 4.2 \times 10^{-11}$$

$$\mathcal{B}(K^+ \to \pi^+ \mu^- e^+) < 6.6 \times 10^{-11}$$

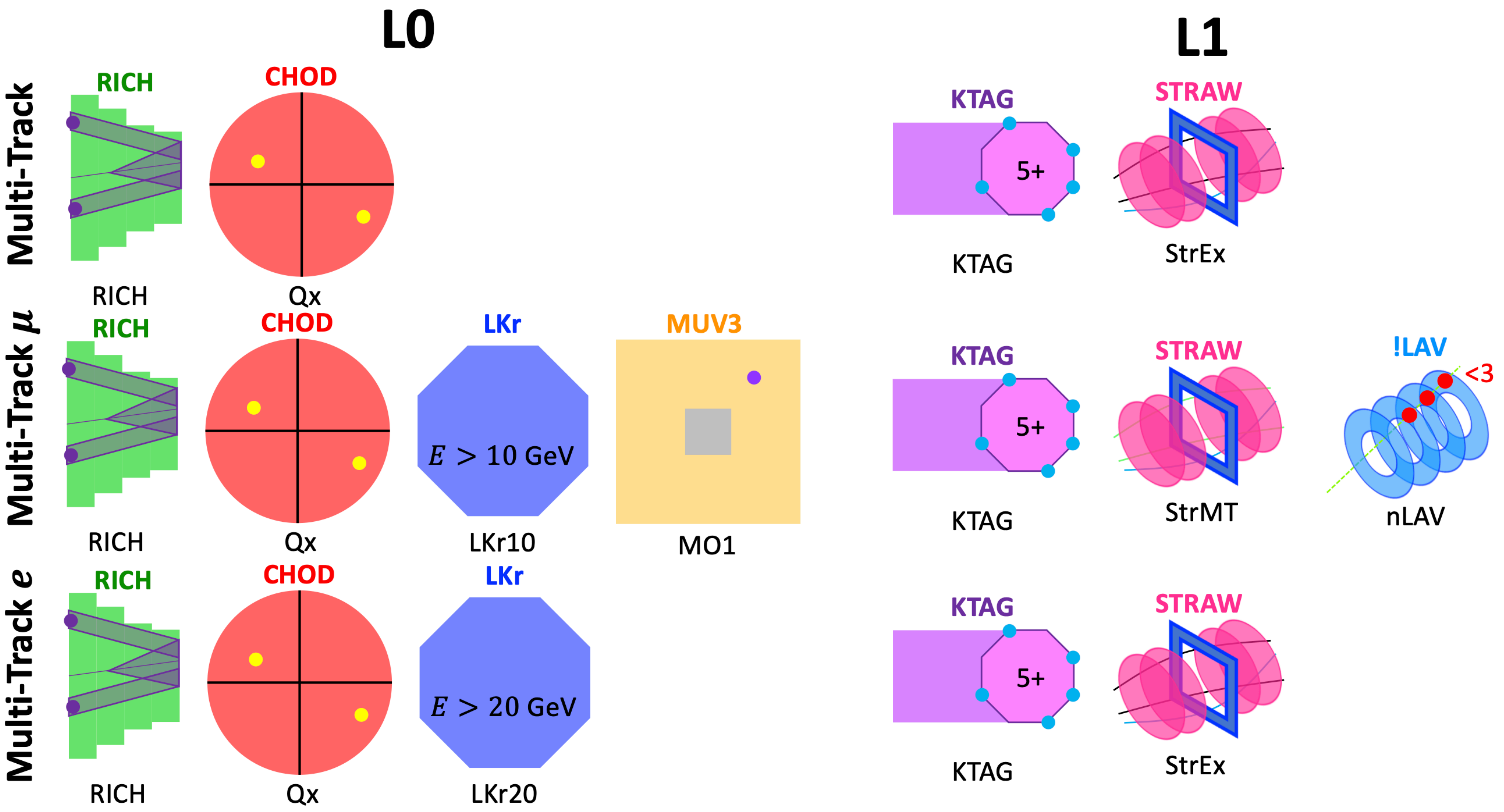
$$\mathcal{B}(\pi^0 \to \mu^- e^+) < 3.2 \times 10^{-10}$$

NA62 has started the new data taking and will run till 2024

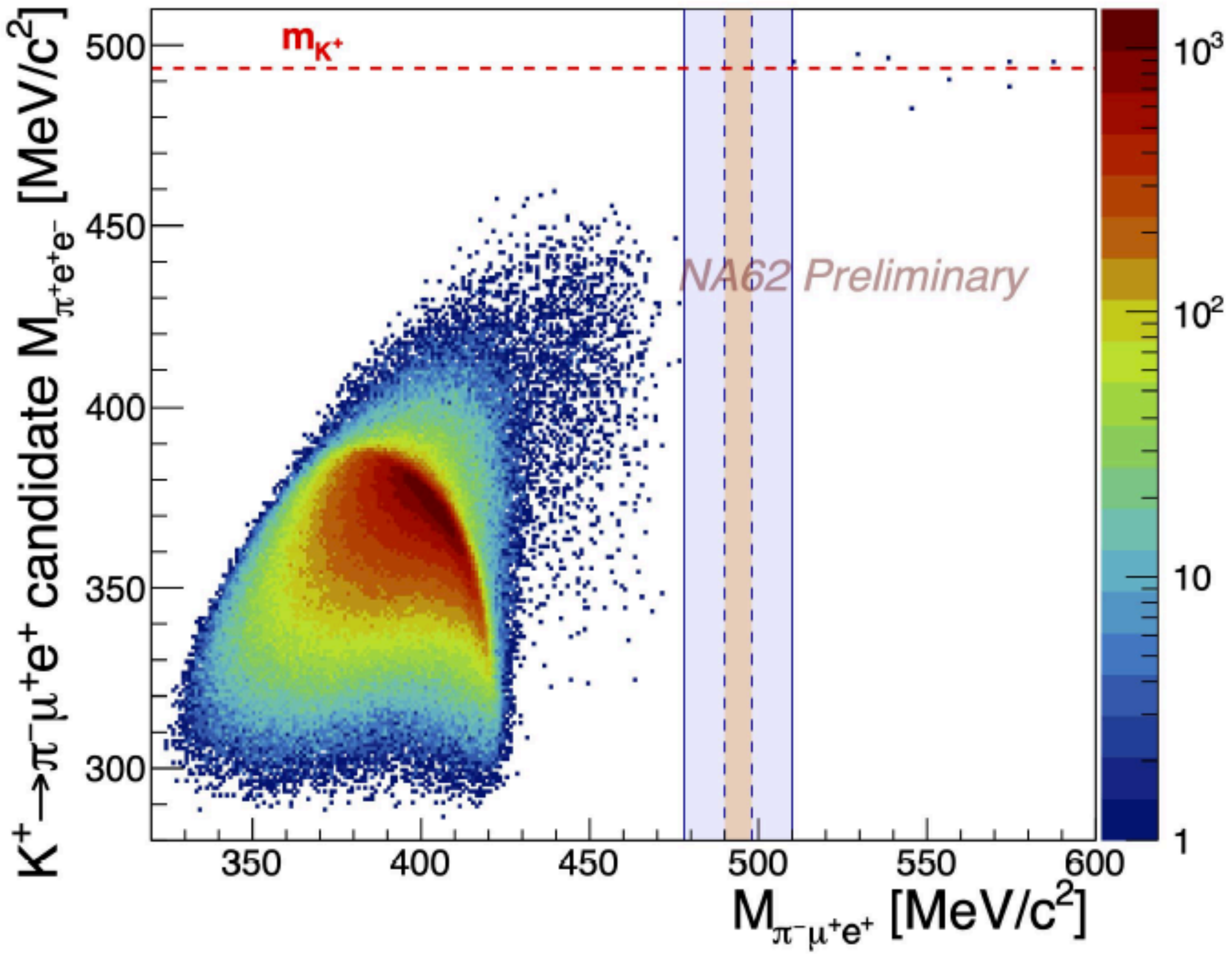
Stay tuned for new results

Thank you

Trigger


L0
L1
Multi-Track
RICH
CHOD
RICH
Qx
KTAG
STRAW
5+
KTAG
StrEx
Multi-Track μ
RICH
CHOD
LKr
MUV3
$E > 10$ GeV
RICH
Qx
LKr10
MO1
KTAG
STRAW
!LAV
<3
5+
KTAG
StrMT
nLAV
Multi-Track e
RICH
CHOD
LKr
$E > 20$ GeV
RICH
Qx
LKr20
KTAG
STRAW
5+
KTAG
StrEx

Other background contributions



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

$\pi^- e^+$ pair calculated under the $e^- e^+$ mass hypothesis is required to exceed 140 MeV.