Snowmass21 Workshop, LFV & LUV in Meson & Baryon Decays

28th—29th September 2020

NA62 Searches for LNV/LFV in K^+ Decays

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On behalf of the **NA62 Collaboration**

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Overview

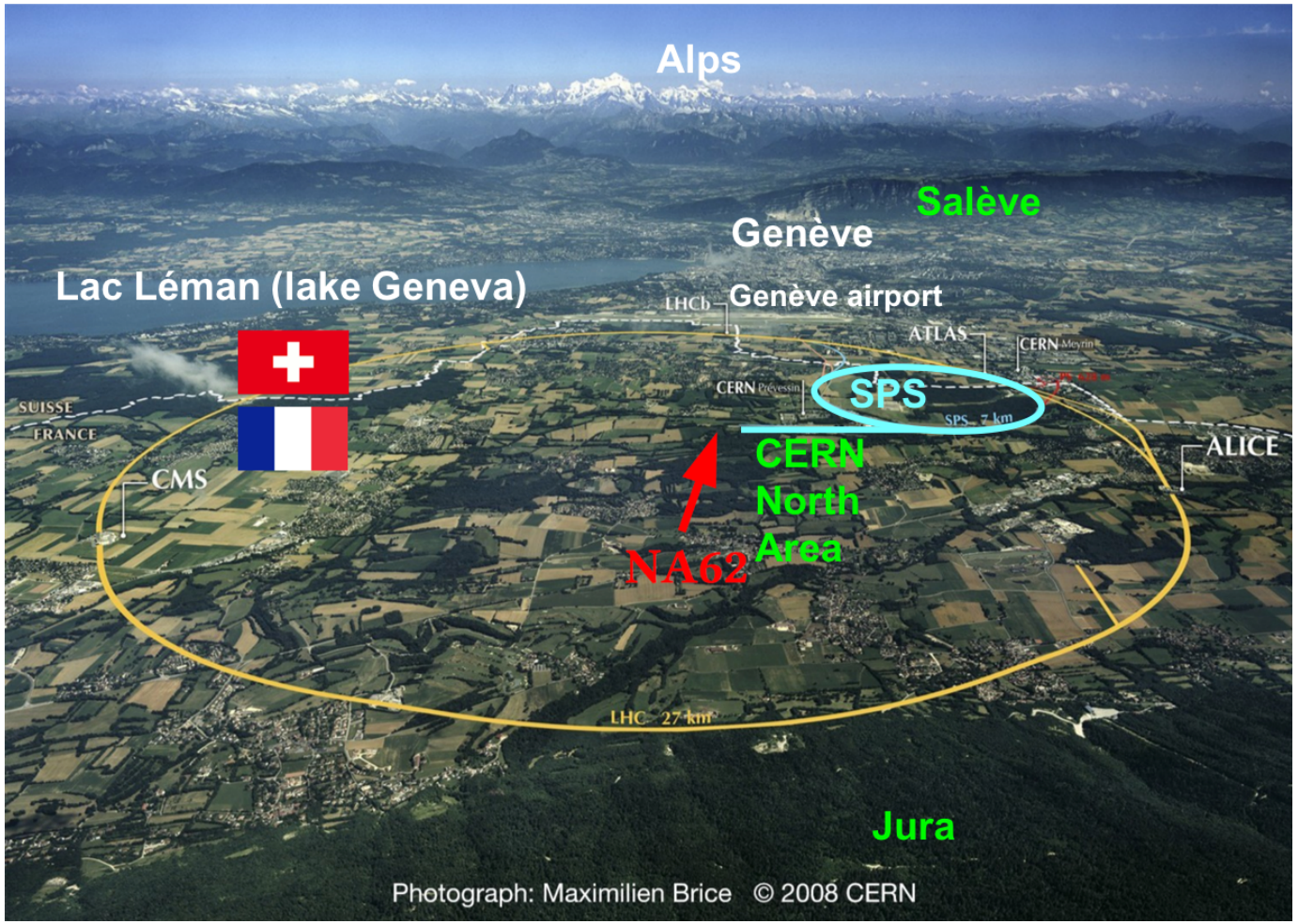
- The NA62 experiment at CERN
- Lepton Number & Lepton Flavour Violation (LNV/LFV)
- Searches for $K^+ \to \pi^- e^+ e^+$ and $K^+ \to \pi^- \mu^+ \mu^+$ [PLB 797 (2019) 134794]
- Searches for $K^+ \to \pi^- \mu^+ e^+$ and $K^+ \to \pi^+ \mu^- e^+$
- Outlook for NA62
  - Stay tuned for more searches e.g. $K^+ \to \mu^- \nu e^+ e^+$, $K^+ \to e^- \nu \mu^+ \mu^+$

Moriond19
ICHEP20

The NA62 Experiment at CERN

~200 collaborators from ~30 institutions :

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



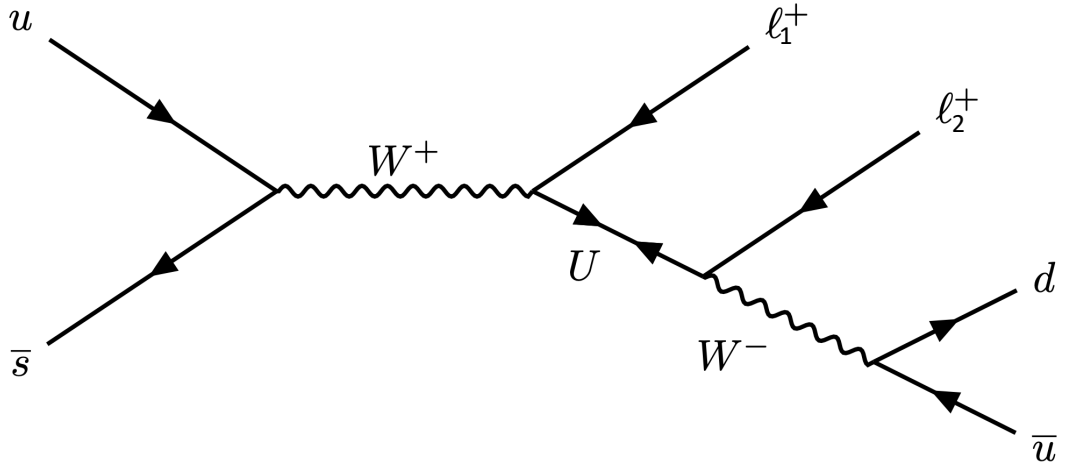
- **Primary goal:** Measurement of $BR(K^+ \to \pi^+ \nu\bar{\nu})$.
- **New Technique:** K decay-in-flight.
- **Requirements:**
  - 10^{13} K^+ decays
  - Signal acceptance $\mathcal{O}(10\%)$
  - $\mathcal{O}(10^{12})$ Background rejection
- $\boldsymbol{\pi\nu\bar{\nu}}$ **results** : [PLB 791 (2019) 156] [arXiv:2007.08218] [ICHEP20]
- **Broader Physics programme** : [SPSC NA62 (2020)]
  - Rare K^+ decays (e.g $K^+ \to \pi^+\mu^+\mu^-$ [ICHEP20]).
  - LNV/LFV K^+ decays (e.g $K^+ \to \pi^\pm l_1^\mp l_2^+$ [ICHEP20]).
  - Exotics (e.g HNL : [PLB 807 (2020) 135599] [ICHEP20]).
- **Data Taking**
  - 2016 Commissioning + Physics run (45 days).
  - 2017 Physics run (160 days).
  - 2018 Physics run (217 days).
  - 2021 resuming data taking.

  This talk

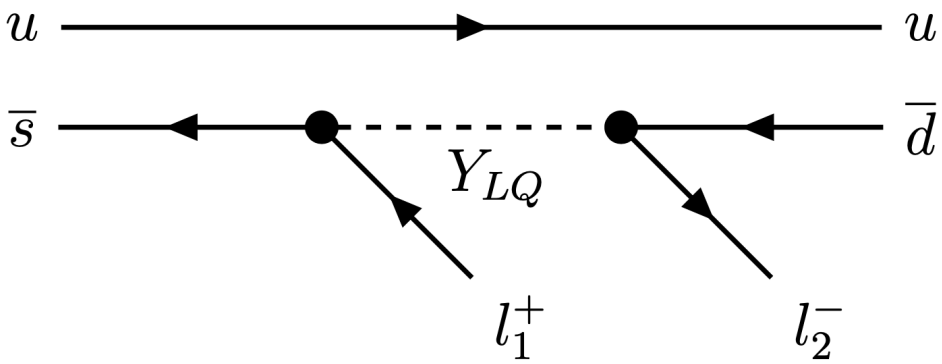
LFV & LNV in Kaon Decays

- Conservation of L and L_e, L_μ, L_τ is an 'emergent' property of SM – not required during construction.
- Violation of these conservation laws is a clear indication of BSM physics:

E.g. $K^+ \to \pi^- \ell_1^+ \ell_2^+$: $\Delta L = 2$ via Majorana neutrinos U (analogue to $0\nu\beta\beta$ decays) [JHEP 0905 (2009) 030], [PLB 491 (2000) 285]

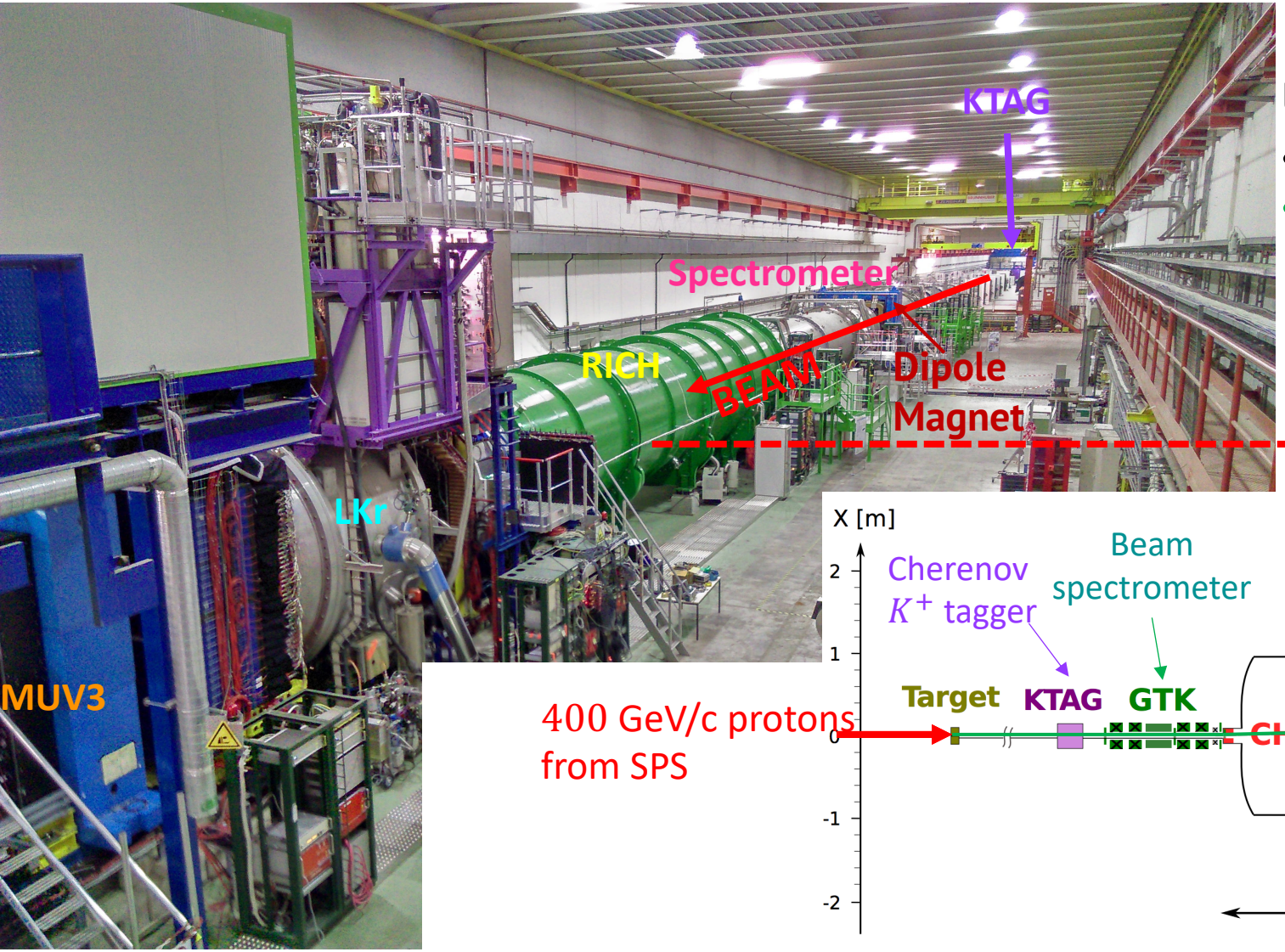


E.g. $K^+ \to \pi^\pm \mu^\mp e^+$ decays ($\Delta L = 2$ if π^- + $\Delta L_e = 1$ and $\Delta L_\mu = 1$) mediated by a leptoquark [JHEP 12 (2019) 089], [NPB 176 (1980) 135]



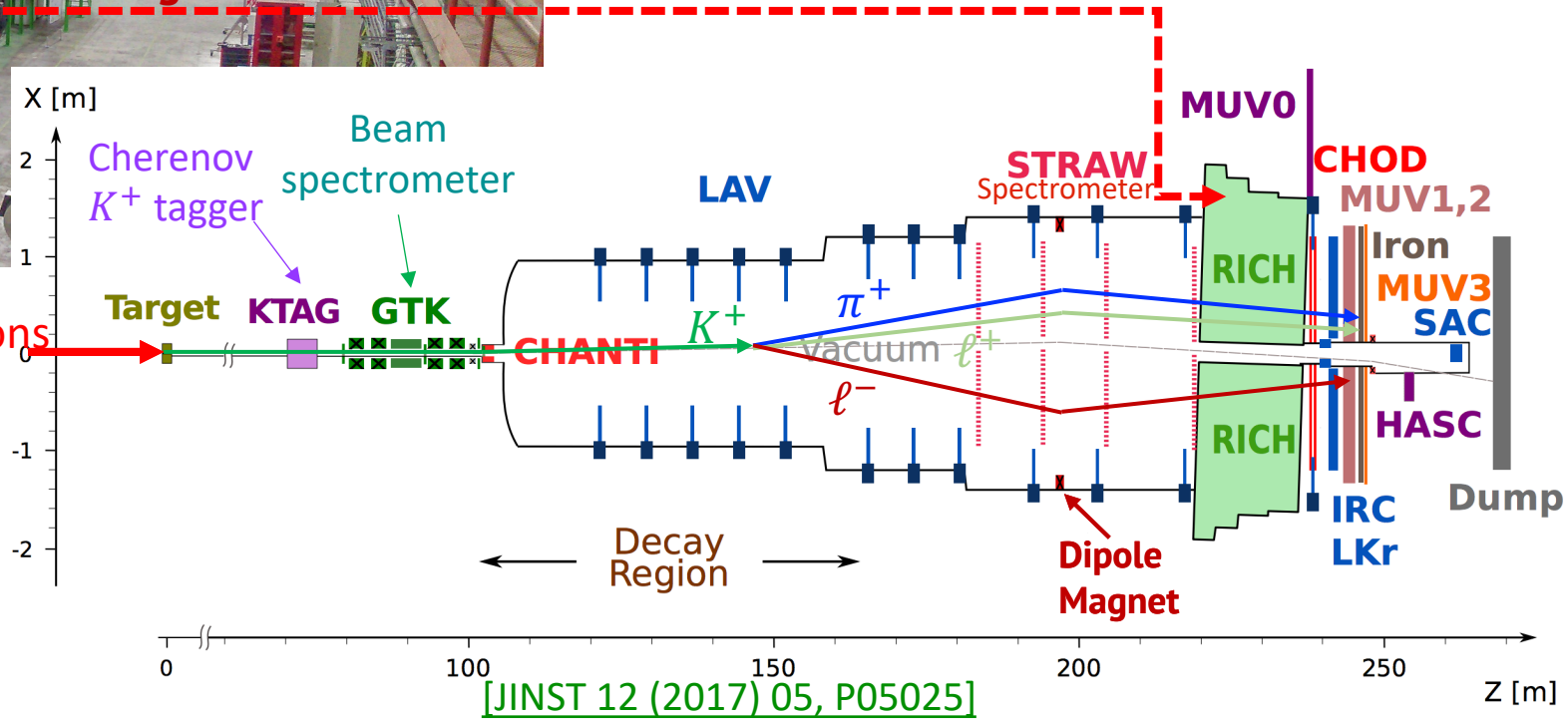
Experimental signature : 3 charged tracks with $\pi^\pm \ell_1^\mp \ell_2^+$ identities, consistent with closed kinematics K^+ decay.

The NA62 Detector



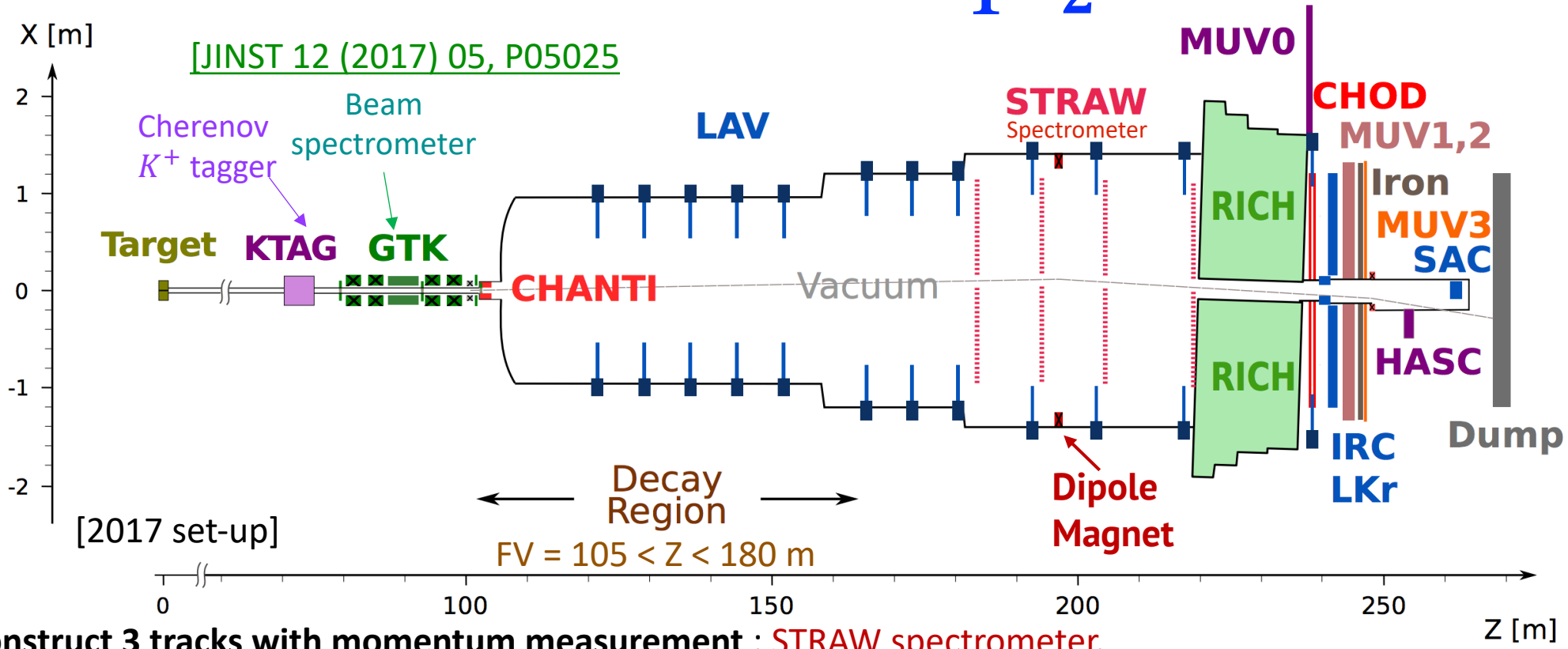
Unseparated secondary hadron beam

- Composition : 70% π^+, 24% p , 6% K^+
- $p_{K^+} = 75$ GeV/c.



[JINST 12 (2017) 05, P05025]

The NA62 Detector & $K^+ \to \pi^\pm \ell_1^\mp \ell_2^+$ Searches



- **Reconstruct 3 tracks with momentum measurement** : STRAW spectrometer.
  - Total momentum consistent with beam K^+, reconstruct decay vertex in FV.
- **PID (1):** Cherenkov detectors: KTAG (K^+), RICH ($\pi/\mu/e$ discrimination) – PID +ve tracks.
- **PID (2) :** use E/p : E = energy deposited in Calorimeter (LKr), p = track momentum **+** MUV3 to ID/veto muons.
- **Photon Vetos** : (hermetic for $0-50$ mrad) 12LAVs, 2SAVs (IRC&SAC), LKr.
- **Tracks are in time :** CHOD.
- **Build invariant mass $M_{\pi\ell\ell}$** with resolution $1.1-1.7\ MeV/c^2$.

LNV/LFV Searches at NA62

- Search in 2017 + 2018 Data [$K^+ \to \pi^- \ell^+ \ell^+$ in 17 only, $K^+ \to \pi^\pm \mu^\mp e^+$ in 17+18]
- Blind analysis strategy
- Triggers : Hardware L0 + software L1.
  - "Rare+Exotics" triggers downscaled (by factor~ 2,~ 8,~ 10, 100) & run simultaneously with $\pi\nu\bar{\nu}$ trigger

Trigger Name	Description	Use in LNV/LFV Searches	
		For $K^+ \to \pi^- \ell^+ \ell^+$	For $K^+ \to \pi^\pm \mu^\mp e^+$
Di-Muon	3 tracks with 2 μ candidates (MUV3)	Signal & normalization	
Multi-Track μ	3 tracks with 10 GeV in LKr and ≥ 1 μ candidate		signal
Multi-Track e	3 tracks with 20 GeV energy deposit in LKr	Signal & normalization	signal
Multi-Track	Minimum bias 3-track trigger		Signal & normalization

- Normalization :
  - For LNV/LFV $K^+ \to \pi^- \ell^+ \ell^+$ use corresponding SM $K^+ \to \pi^+ \ell^+ \ell^-$ decays
  - For LNV/LFV $K^+ \to \pi^\pm \mu^\mp e^+$ use SM $K^+ \to \pi^+ \pi^+ \pi^-$ decay (most common 3-track K^+ decay)

Analysis Procedure

- Evaluate signal acceptance, A_s, with MC.
- Trigger efficiency ε_s measured.
- Study most backgrounds with MC (+ significant data-driven corrections).
- Use normalization channel to determine effective number of K^+ decays in fiducial volume, N_K.
- Evaluate single event sensitivity (SES) for signal $SES = \frac{1}{N_K \varepsilon_s A_s}$
- Use CLs method to set upper limits on BR at 90% CL.
  - $BR < n^{UL} \times SES$

Background Studies

Background Mechanisms:

1. Misidentification (misID)
2. Decays in flight (DIF)

E.g. background from $K^+ \to \pi^+\pi^+\pi^-$ (most common 3-track K^+ decay $BR \sim 5.6\%$):

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

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

$e^+ e^+$

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

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

$\mu^+ \mu^+$

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

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

$\mu^+ e^+$

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

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

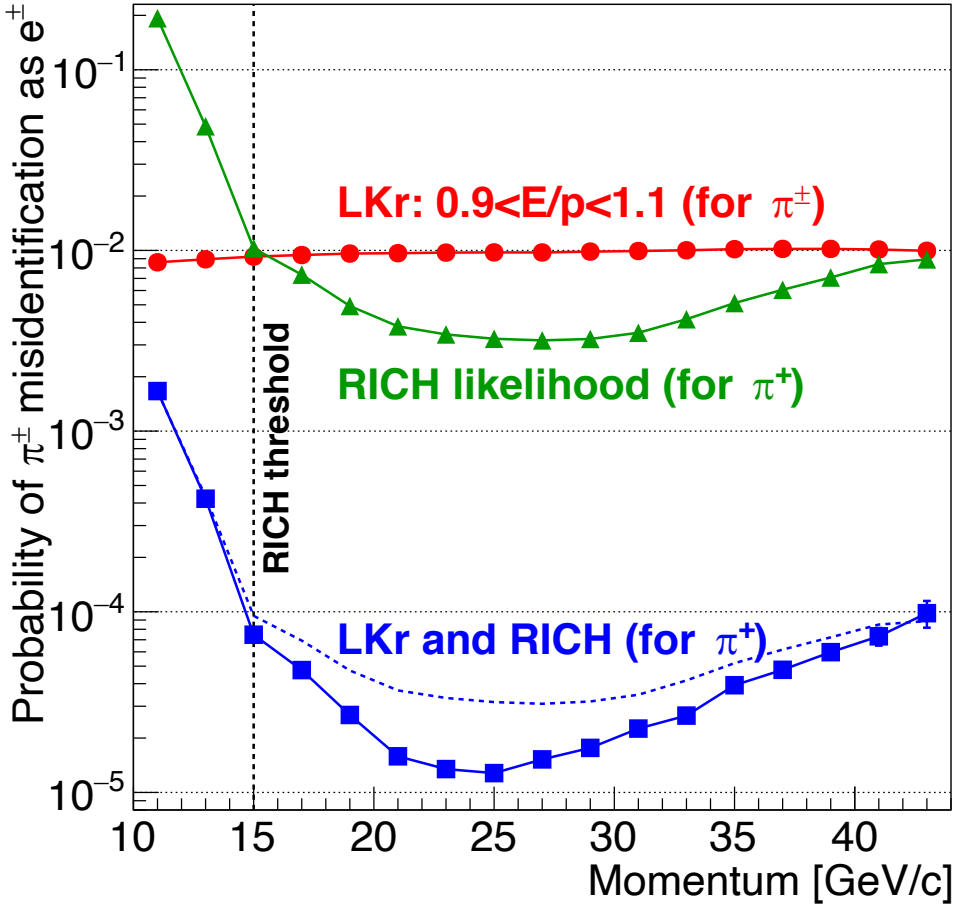
$e^+ \mu^-$

1. Measure misidentification probabilities for: $\pi^\pm \Longrightarrow e^\pm$ but also $e^\pm \Longrightarrow \pi^\pm$, $\pi^\pm \Longrightarrow \mu^\pm$, $\mu^\pm \Longrightarrow e^\pm$
2. Most important DIF: $\boldsymbol{\pi^\pm \to \mu^\pm \nu_\mu}$ OR $\pi^\pm \to e^\pm \nu_e$ with $BR = 99.9\%$ $[1.2\times10^{-4}]$

Background Studies : misID

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

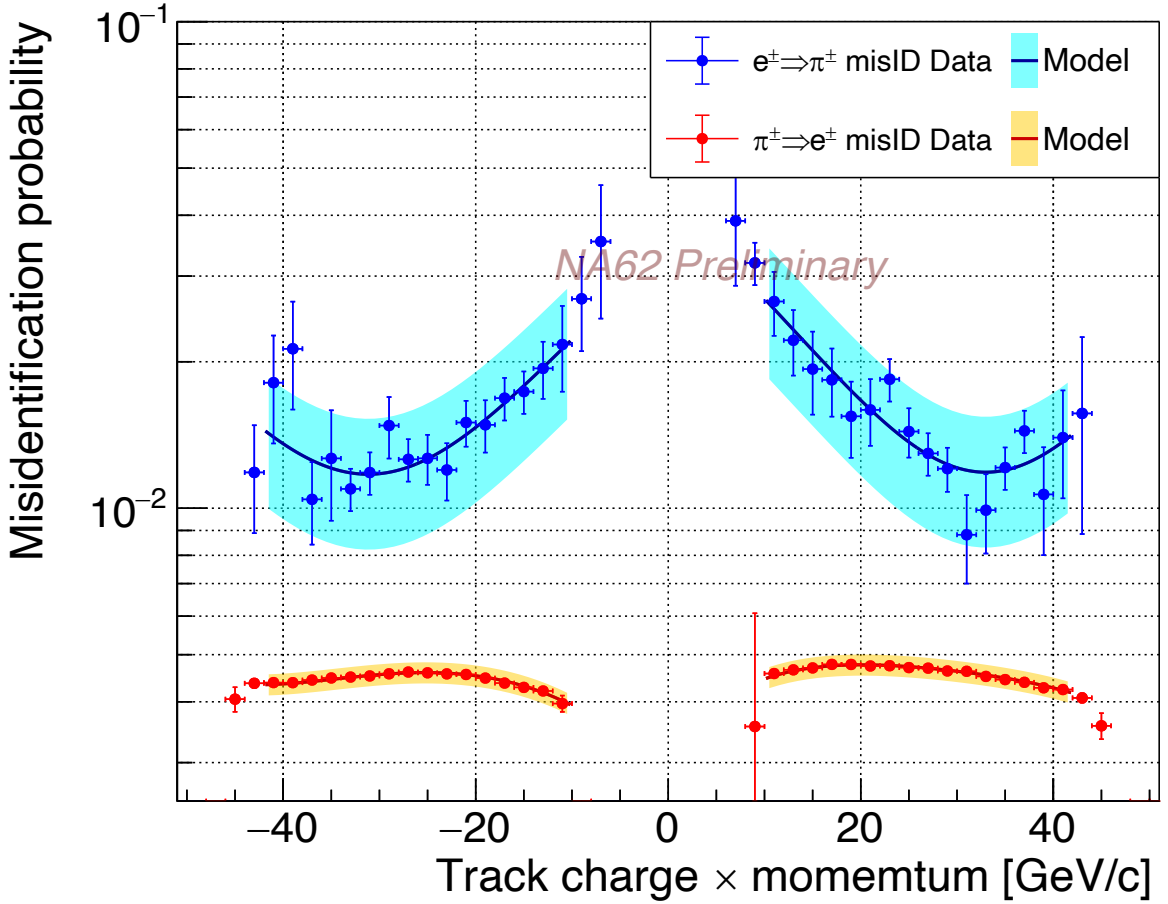
$\pi^\pm \Longrightarrow e^\pm$ **Misidentification Probability**



- $\pi^\pm$: $E/p < 0.9$
- $e^\pm$: $0.90 < E/p < 1.10$

For $K^+ \to \pi^\pm \mu^\mp e^+$ searches

$\pi^\pm \Longrightarrow e^\pm$ and $e^\pm \Longrightarrow \pi^\pm$ **MisID Probabilities**



- $\pi^\pm$: $E/p < 0.9$
- $e^\pm$: $0.95 < E/p < 1.05$

Searches for $K^+ \to \pi^- \ell^+ \ell^+$ $[\ell = \mu, e]$

- Normalise to SM FCNC decay with corresponding particle content [$\pi ee/\pi\mu\mu$].
- Common selection for SM & LNV modes – differentiate only by PID/track charge.

SM : $K^+ \to \pi^+ e^+ e^-$

$BR = (3.00 \pm 0.09)\times10^{-7}$: PDG (NA48/2 [PL B677 (2009) 246] (7253 candidates, $M_{ee} > 140$ MeV)).

LNV : $K^+ \to \pi^- e^+ e^+$

$BR < 6.4\times10^{-10}$ @ 90% CL : E865 [PRL 85 (2000) 2877].

> NA62 : This talk <

SM : $K^+ \to \pi^+ \mu^+ \mu^-$

$BR = (9.4 \pm 0.6)\times10^{-8}$: PDG (NA48/2 [PL B697 (2011) 107] (3120 candidates)).

[dedicated NA62 study of SM $K^+ \to \pi^+ \mu^+ \mu^-$ reported at ICHEP]

LNV : $K^+ \to \pi^- \mu^+ \mu^+$

$BR < 8.6\times10^{-11}$ @ 90% CL : NA62/2 [PL B697 (2011) 107].

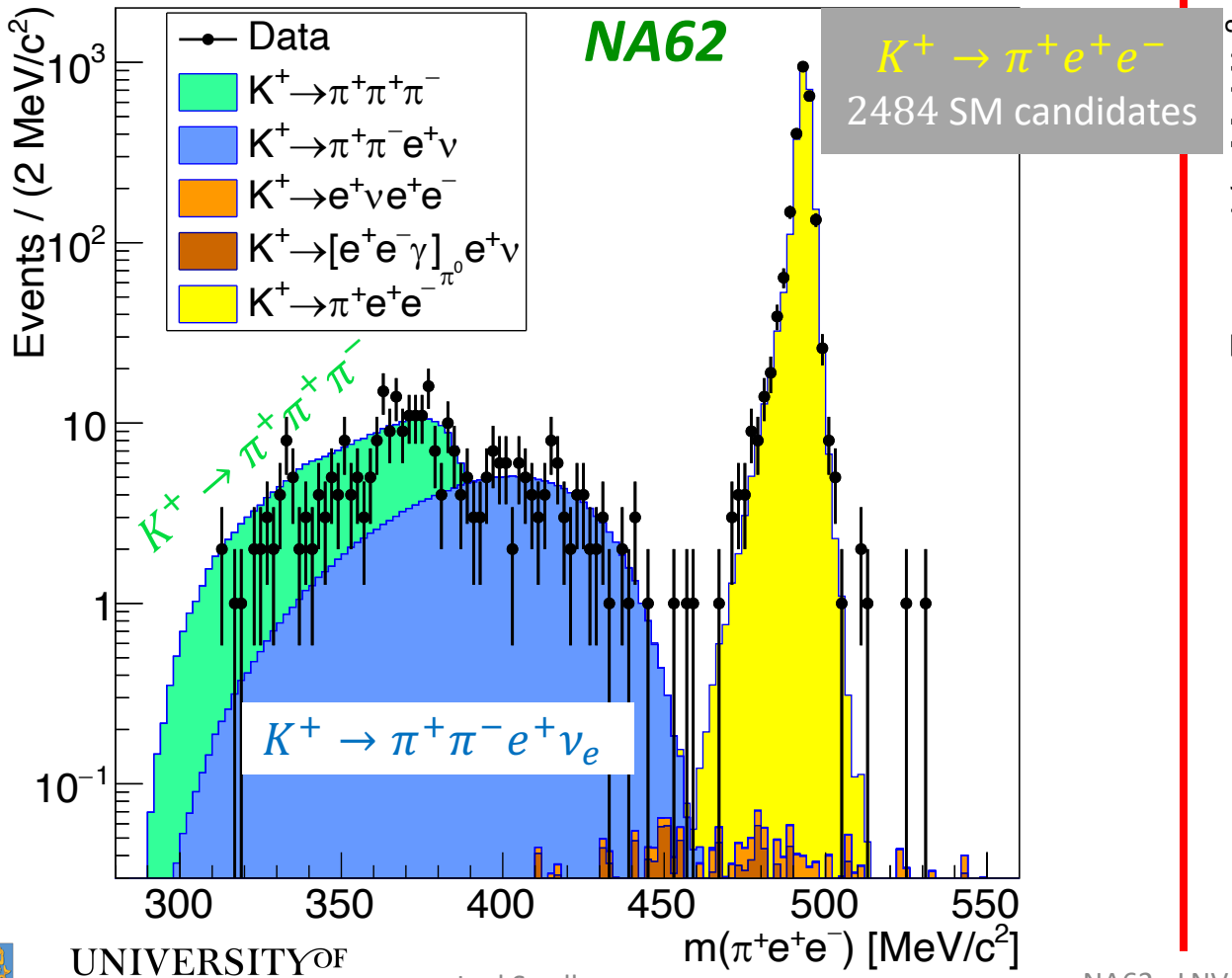
> NA62 : This talk <

2018 PDG $K^\pm$

$K^+ \to \pi^- e^+ e^+ : M_{\pi ee}$ Spectra [With RICH for e^+ ID]

SM : $K^+ \to \pi^+ e^+ e^-$

NA48/2 [PL B677 (2009) 246] : $BR = (3.00 \pm 0.09) \times 10^{-7}$: (7253 candidates, $M_{ee} > 140$ MeV).



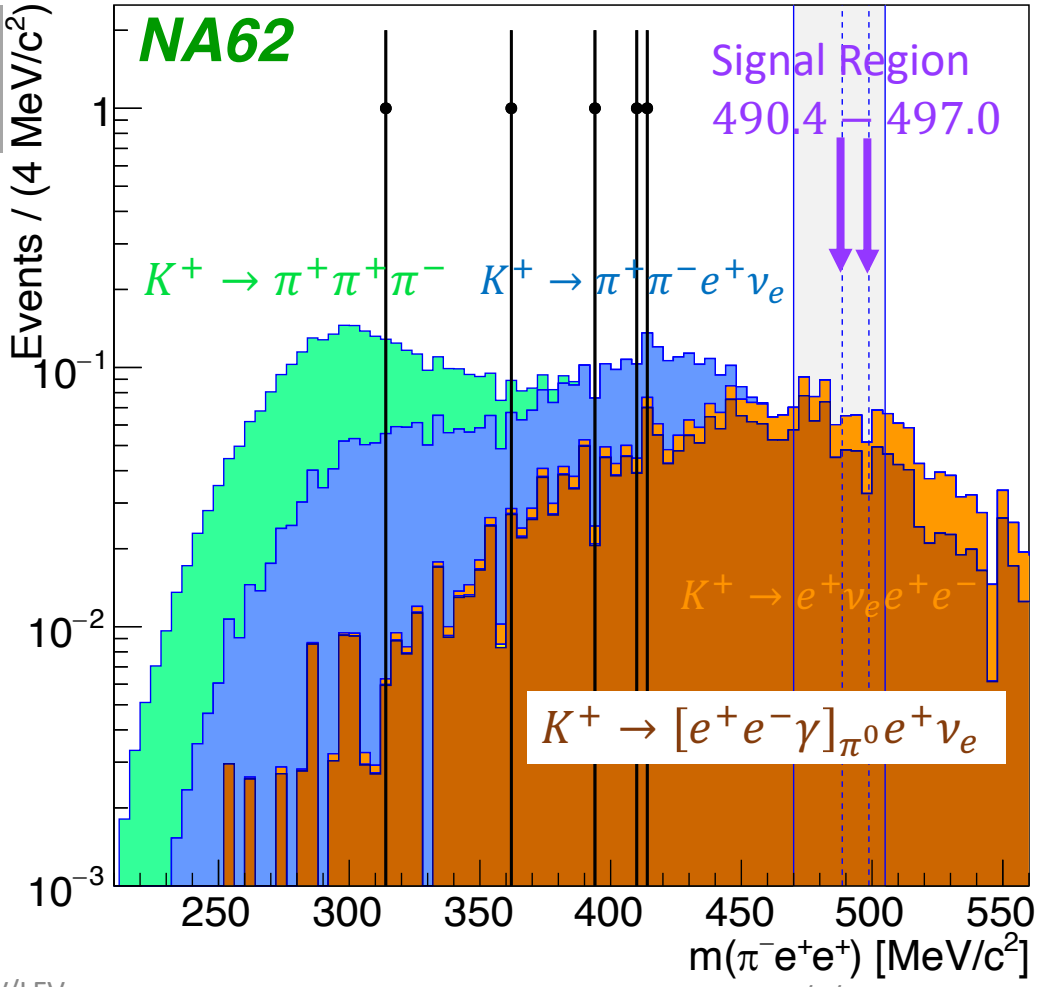
LNV : $K^+ \to \pi^- e^+ e^+$

Predicted Background in Signal Region :

$K^+ \to e^+ \nu_e e^+ e^-$: 0.12 ± 0.02

$K^+ \to [e^+ e^- \gamma]_{\pi^0} e^+ \nu_e$: 0.04

Total = 0.16 ± 0.03



$K^+ \to \pi^- e^+ e^+$: Results [With RICH for e^+ ID]

LNV : $K^+ \to \pi^- e^+ e^+$

Decided to use RICH before unblinding because of better discovery potential for LNV.

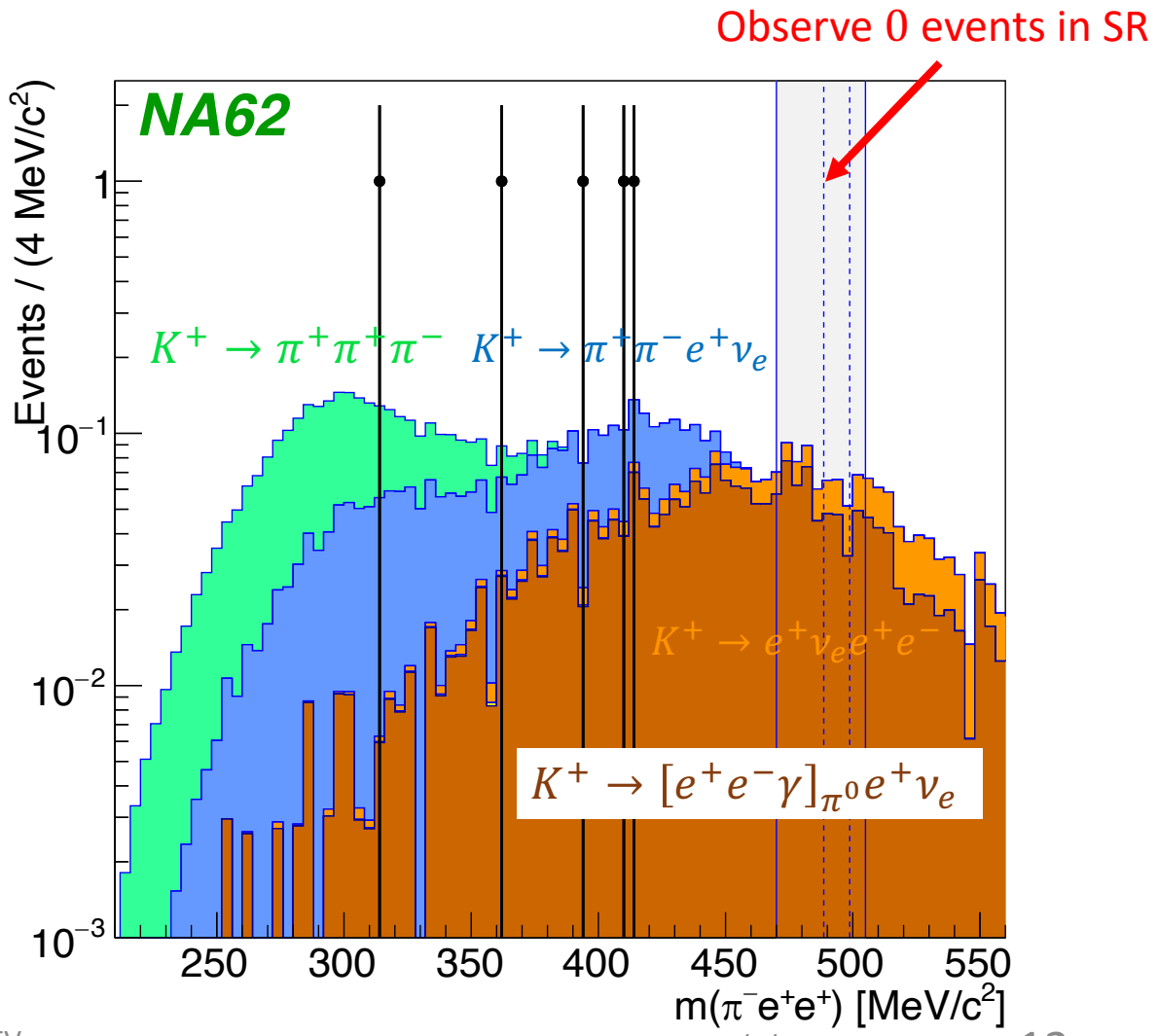
Signal Region

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

Observe : $n_{SR} = 0$

Result

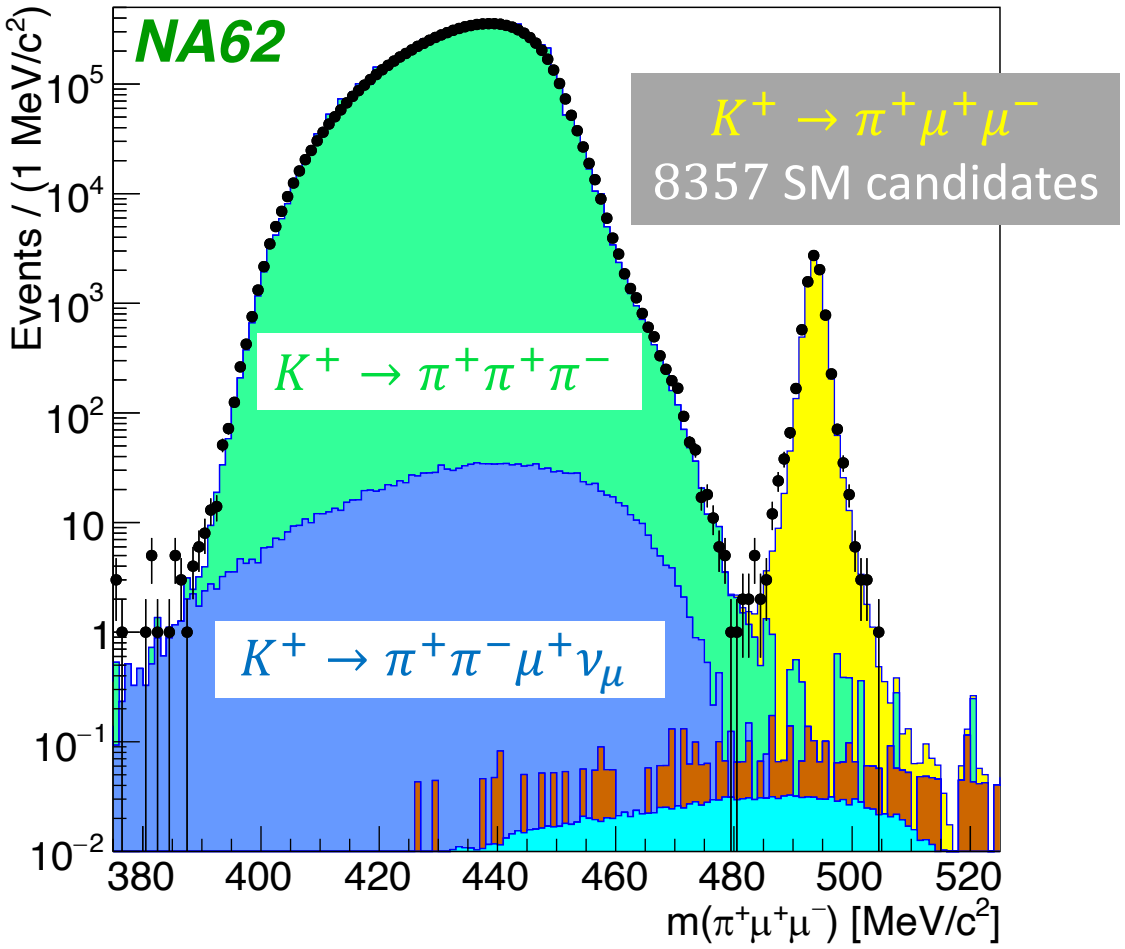
$$\boxed{\boldsymbol{BR(K^+ \to \pi^- e^+ e^+) < 2.2\times10^{-10} \text{ @ } 90\% \ CL}}$$



$K^+ \to \pi^-\mu^+\mu^+ : M_{\pi\mu\mu}$ Spectra

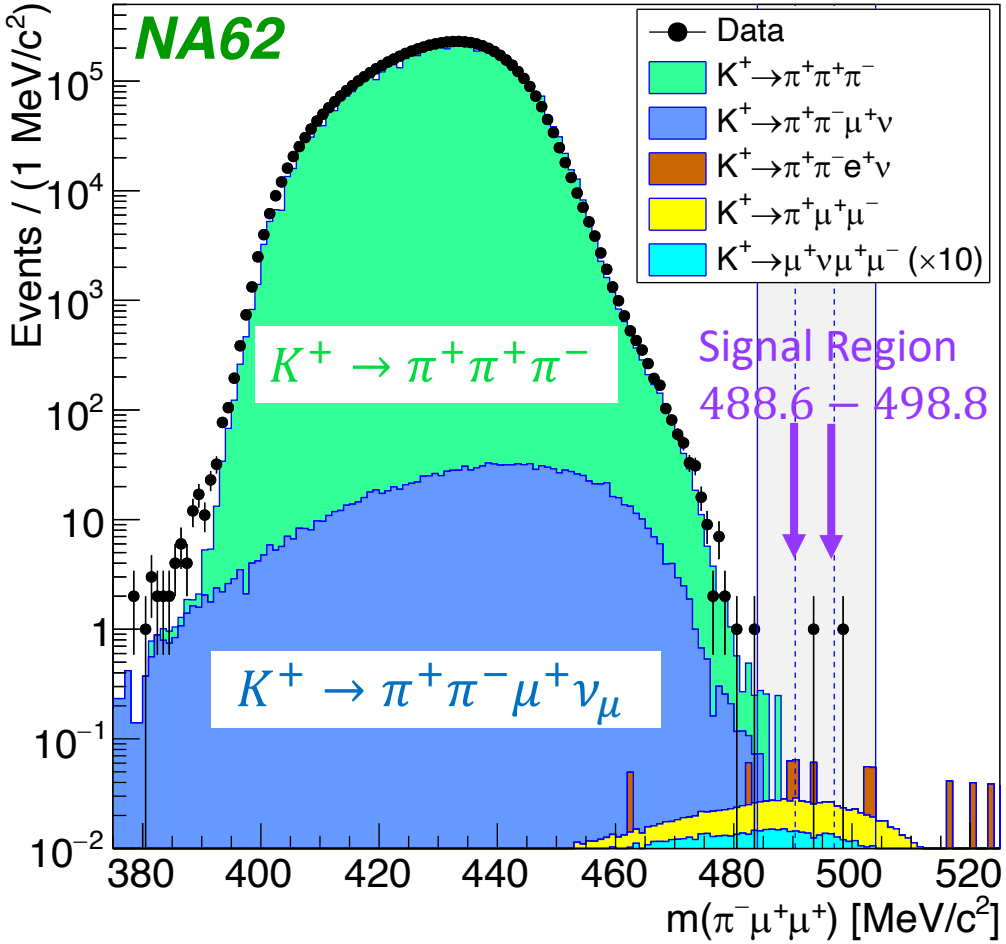
SM : $K^+ \to \pi^+\mu^+\mu^-$

$BR = (9.4 \pm 0.6)\times10^{-8}$: PDG (NA48/2 [PL B697 (2011) 107] (3120 candidates)).



LNV : $K^+ \to \pi^-\mu^+\mu^+$

Predicted Background in Signal Region



0.70 ± 0.40
0.05 ± 0.05
0.07 ± 0.05
0.08 ± 0.02
0.01

Total = 0.91 ± 0.41

[dedicated study of SM $K^+ \to \pi^+\mu^+\mu^-$ reported at ICHEP]

$K^+ \to \pi^- \mu^+ \mu^+$: Results

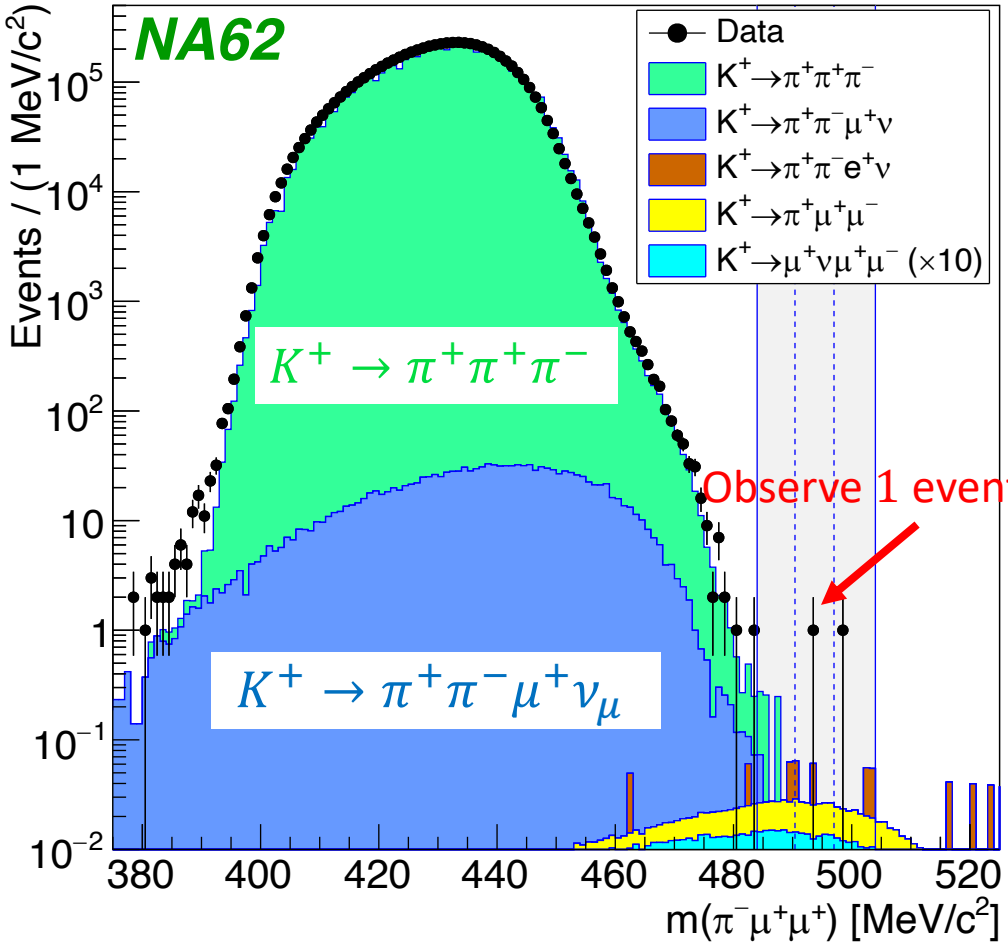
LNV : $K^+ \to \pi^- \mu^+ \mu^+$

Signal Region

- Bkg. Prediction: $N_{SR}^{tot} = 0.91 \pm 0.41$
- Observe : $n_{SR} = 1$

Result

$$\boxed{BR(K^+ \to \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11} \text{ @ } 90\% \ CL}$$



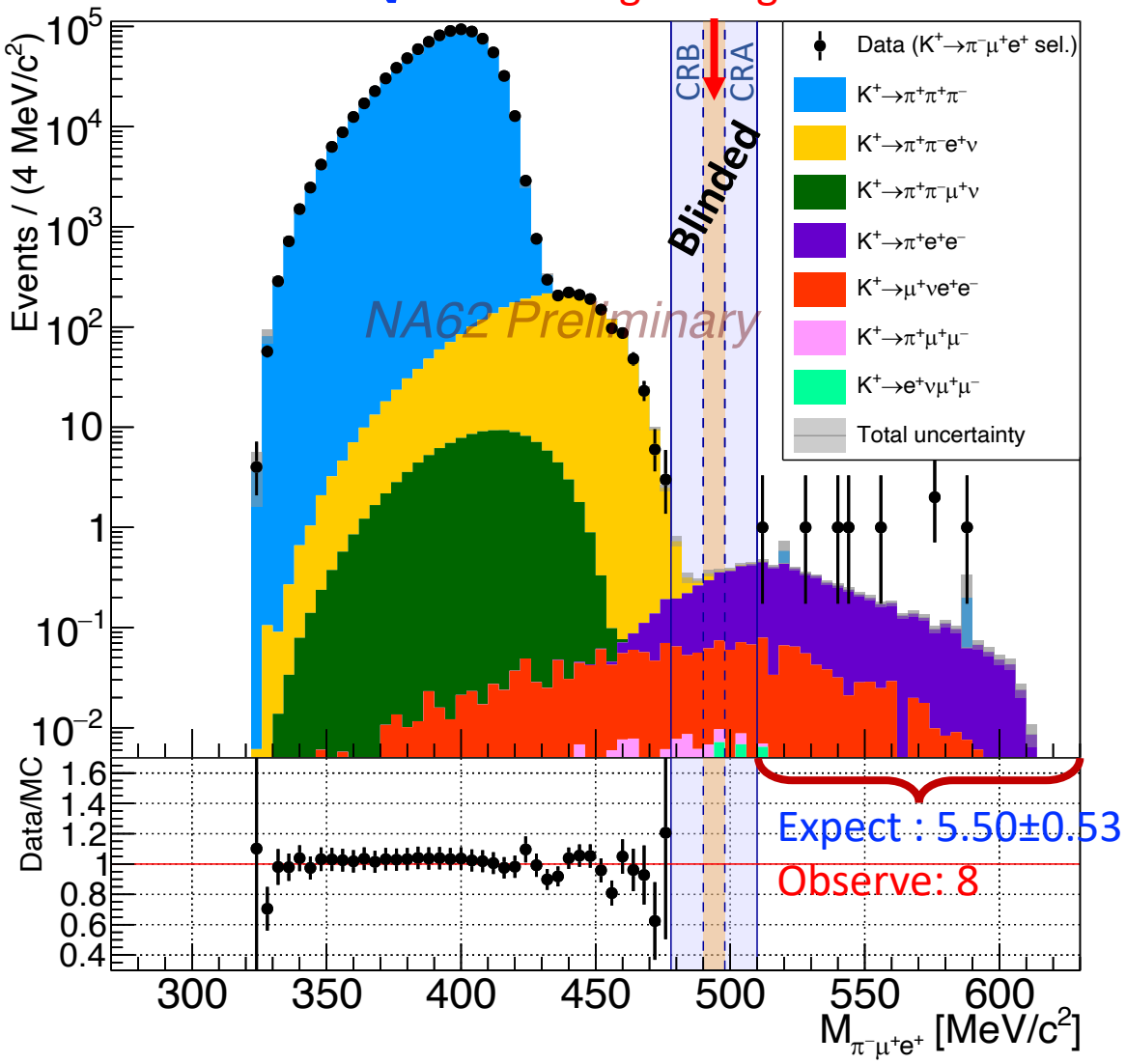
Predicted Background in Signal Region

$K^+ \to \pi^+\pi^+\pi^-$	0.70 ± 0.40
$K^+ \to \pi^+\pi^-\mu^+\nu$	0.05 ± 0.05
$K^+ \to \pi^+\pi^-e^+\nu$	0.07 ± 0.05
$K^+ \to \pi^+\mu^+\mu^-$	0.08 ± 0.02
$K^+ \to \mu^+\nu\mu^+\mu^-$ (×10)	0.01

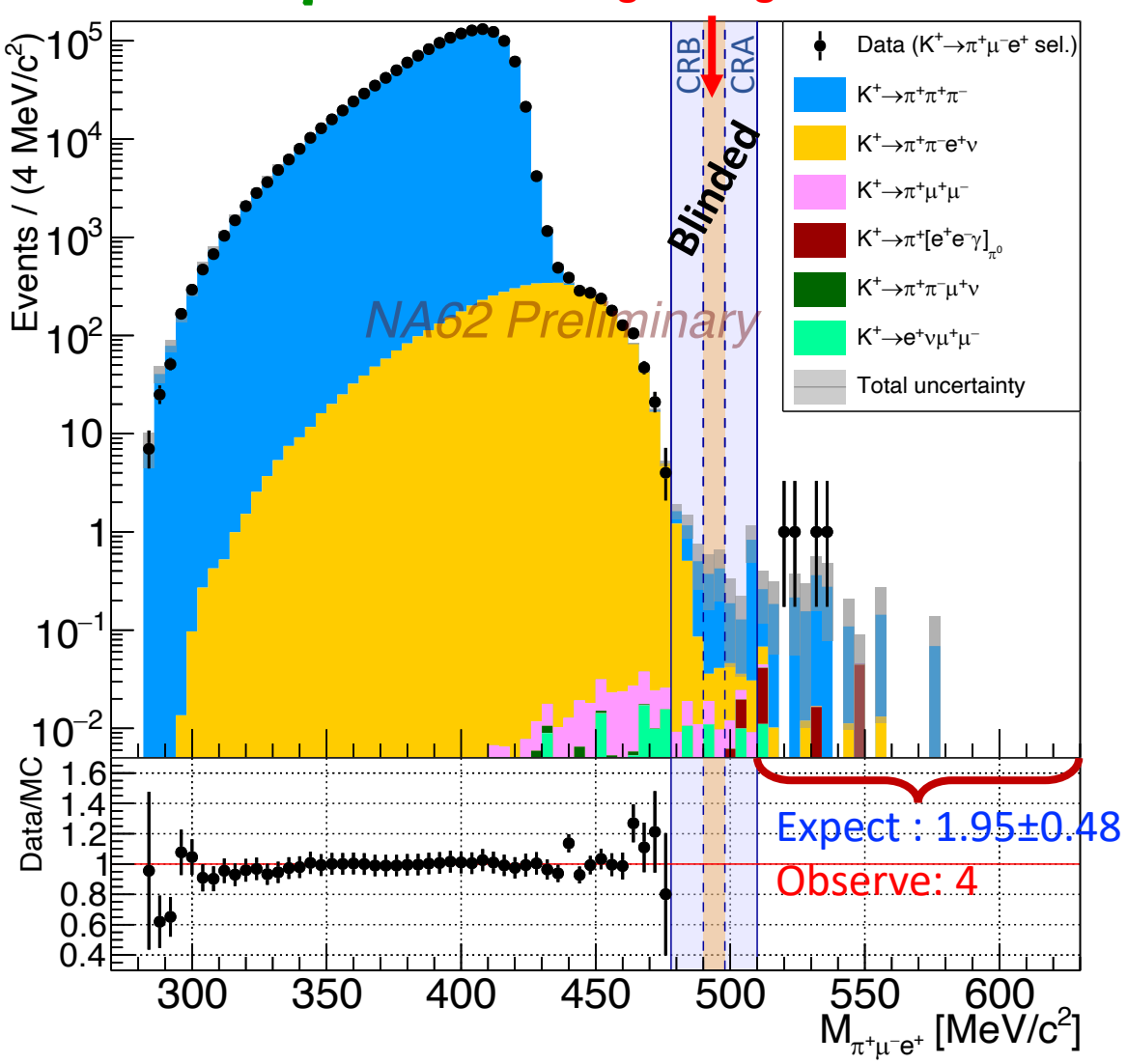
Total = 0.91 ± 0.41

Searches for $K^+ \to \pi^\pm \mu^\mp e^+$

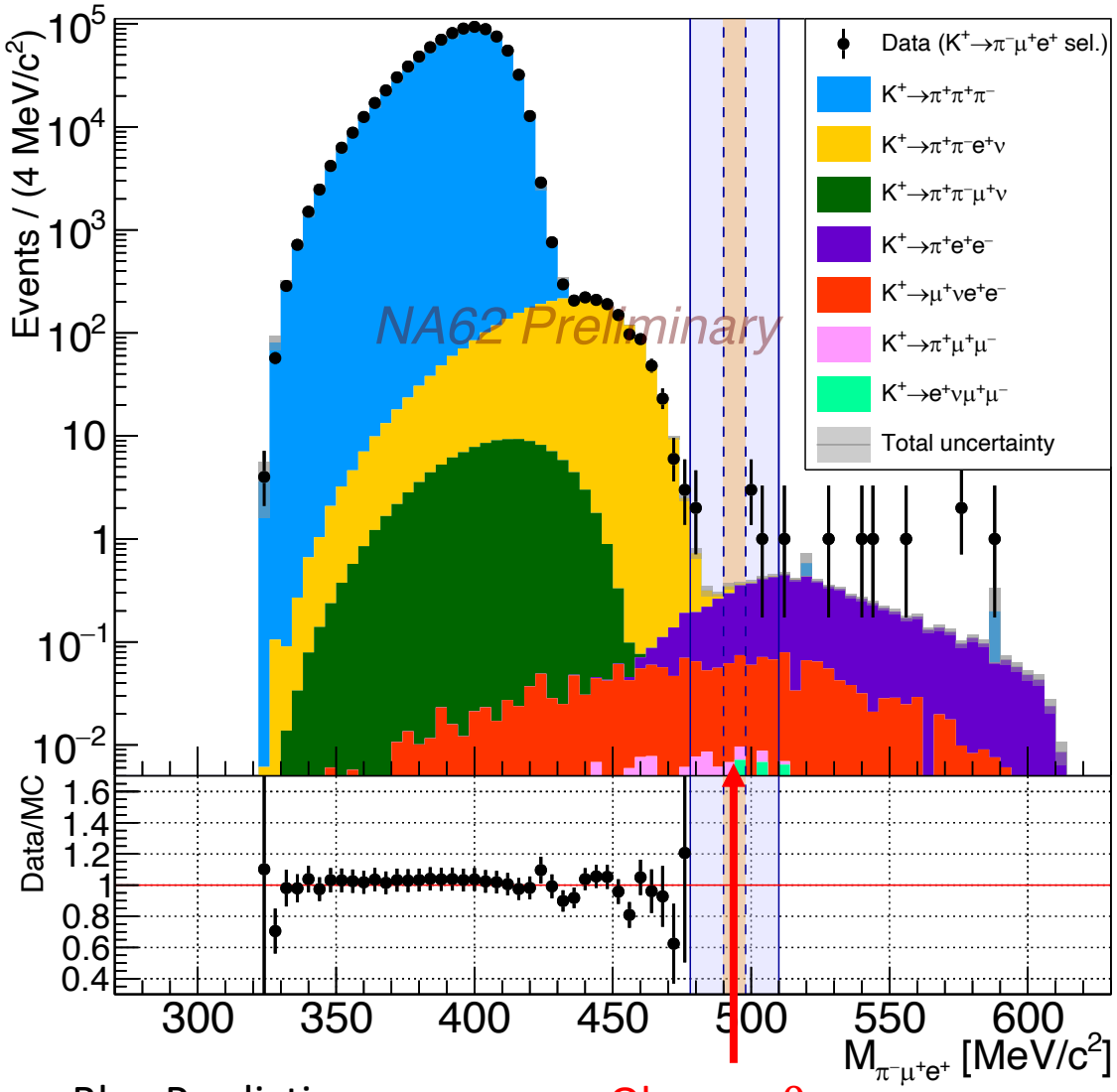
$K^+ \to \pi^- \mu^+ e^+$



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



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



Signal Region

- Bkg. Prediction: $N_{SR}^{tot} = 1.06 \pm 0.20$
- Observe : $n_{SR} = 0$

Result

$$\boldsymbol{BR(K^+ \to \pi^- \mu^+ e^+) < 4.2 \times 10^{-11} \text{ @ } 90\% \ CL}$$

Bkg. Prediction:
$N_{SR}^{tot} = 1.06 \pm 0.20$

Observe 0 events in SR

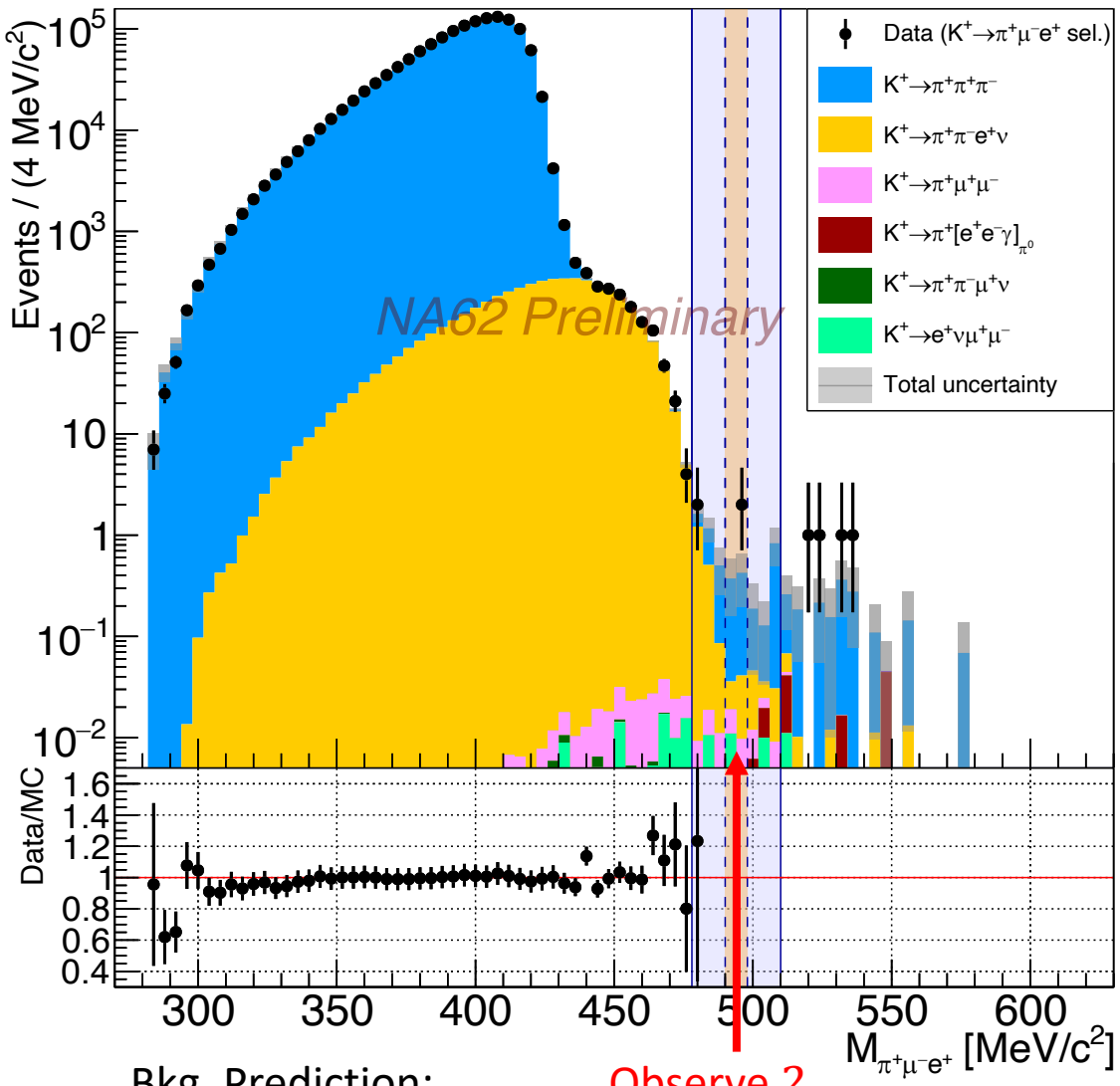
$K^+ \to \pi^+\mu^-e^+$: Results

Signal Region

- Bkg. Prediction: $N_{SR}^{tot} = 0.92 \pm 0.34$
- Observe : $n_{SR} = 2$

Result

$$\boxed{BR(K^+ \to \pi^+\mu^-e^+) < 6.6\times10^{-11} \text{ @ } 90\%\ CL}$$



Bkg. Prediction: $N_{SR}^{tot} = 0.92 \pm 0.34$

Observe 2 events in SR

Results: Summary

- Observations consistent with background expectation therefore set upper limit on branching ratios.

	2017 data[PLB 797 (2019) 134794]		2017+2018 data	
	$K^+ \to \pi^- e^+ e^+$	$K^+ \to \pi^- \mu^+ \mu^+$	$K^+ \to \pi^- \mu^+ e^+$	$K^+ \to \pi^+ \mu^- e^+$
Signal acceptance*	4.98%	9.81%	$(4.90 \pm 0.02)\%$	$(6.21 \pm 0.02)\%$
Single event sensitivity [$\times 10^{-11}$]	9.4 ± 0.3	1.28 ± 0.04	1.82 ± 0.08	1.44 ± 0.05
Bkg. exp. in signal region	$\mathbf{0.16 \pm 0.03}$	$\mathbf{0.91 \pm 0.41}$	$\mathbf{1.06 \pm 0.20}$	$\mathbf{0.92 \pm 0.34}$
Events observed	**0**	**1**	**0**	**2**
BR* upper limit @ 90% CL	$\mathbf{2.2 \times 10^{-10}}$	$\mathbf{4.2 \times 10^{-11}}$	$\mathbf{4.2 \times 10^{-11}}$	$\mathbf{6.6 \times 10^{-11}}$
Previous world-best limits : [PRL 85 (2000) 2877, PL B697 (2011) 107, PRL 85 (2000) 2877]	6.4×10^{-10}	8.6×10^{-11}	5.0×10^{-10}	5.2×10^{-10}

- Improve limits by factors 3, 2, 12 and 8.

* Assuming uniform phase space distribution.

Prospects:

PDG entry for K^+

Lepton family number (*LF*), Lepton number (*L*), $\Delta S = \Delta Q$ (*SQ*) violating modes, or $\Delta S = 1$ weak neutral current (*S1*) modes

$\pi^+\pi^+e^-\overline{\nu}_e$	*SQ*		$<$ 1.3		$\times 10^{-8}$	CL=90%	203
$\pi^+\pi^+\mu^-\overline{\nu}_\mu$	*SQ*		$<$ 3.0		$\times 10^{-6}$	CL=95%	151
$\pi^+e^+e^-$	*S1*		(3.00	± 0.09)	$\times 10^{-7}$		227
$\pi^+\mu^+\mu^-$	*S1*		(9.4	± 0.6)	$\times 10^{-8}$	S=2.6	172
$\pi^+\nu\overline{\nu}$	*S1*		(1.7	± 1.1)	$\times 10^{-10}$		227
$\pi^+\pi^0\nu\overline{\nu}$	*S1*		$<$ 4.3		$\times 10^{-5}$	CL=90%	205
$\mu^-\nu e^+e^+$	*LF*		$<$ 2.1		$\times 10^{-8}$	CL=90%	236
$\mu^+\nu_e$	*LF*	[*j*]	$<$ 4		$\times 10^{-3}$	CL=90%	236
$\pi^+\mu^+e^-$	*LF*		$<$ 1.3		$\times 10^{-11}$	CL=90%	214
$\pi^+\mu^-e^+$	*LF*		$<$ 5.2	(0.66)	$\times 10^{-10}$	CL=90%	214
$\pi^-\mu^+e^+$	*L*		$<$ 5.0	(0.42)	$\times 10^{-10}$	CL=90%	214
$\pi^-e^+e^+$	*L*		$<$ 2.2	(NA62)	$\times 10^{-10}$	CL=90%	227
$\pi^-\mu^+\mu^+$	*L*		$<$ 4.2	(NA62)	$\times 10^{-11}$	CL=90%	172
$\mu^+\overline{\nu}_e$	*L*	[*j*]	$<$ 3.3		$\times 10^{-3}$	CL=90%	236
$\pi^0e^+\overline{\nu}_e$	*L*		$<$ 3		$\times 10^{-3}$	CL=90%	228
$\pi^+\gamma$		[*k*]	$<$ 2.3		$\times 10^{-9}$	CL=90%	227

LNV & LFV decays

Highlighted cases = new results from NA62 most not yet in PDG

(Rare decays) NA62 preliminary results reported at ICHEP

Future targets for NA62…
+ $K^+ \to e^-\nu\mu^+\mu^+$ **(no limit in PDG)**

NA62 preliminary result in this talk : $K^+ \to \pi^\pm\mu^\mp e^+$ **searches**

NA62 result as in this talk:
$K^+ \to \pi^-\ell^+\ell^+$ **searches**

With new data improvements expected in all decays studied at NA62 so far + prospects for new searches…

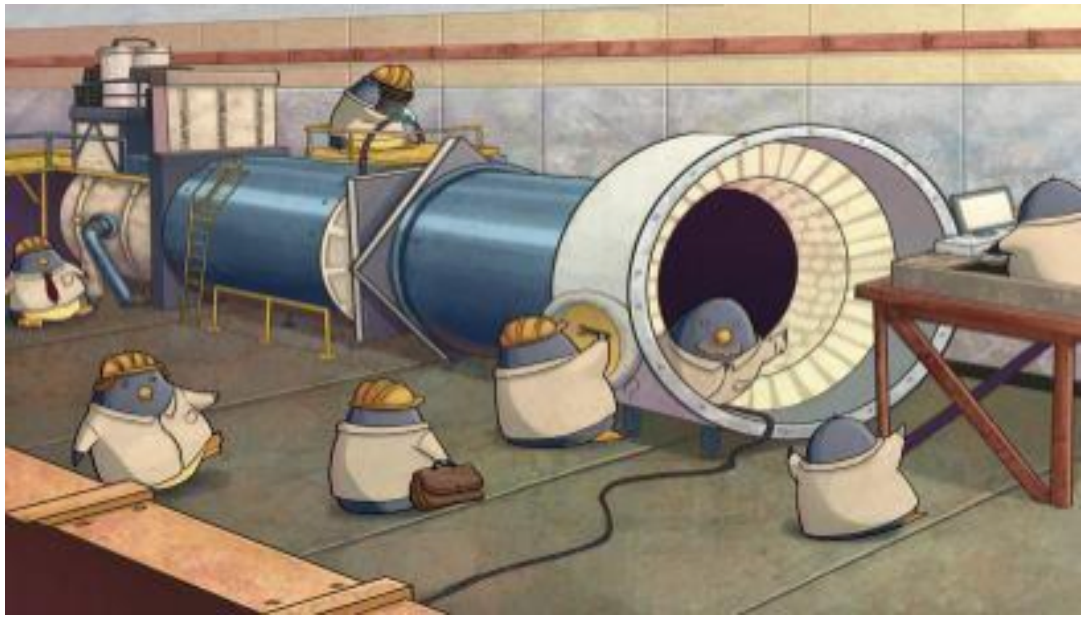
Conclusions And Outlook

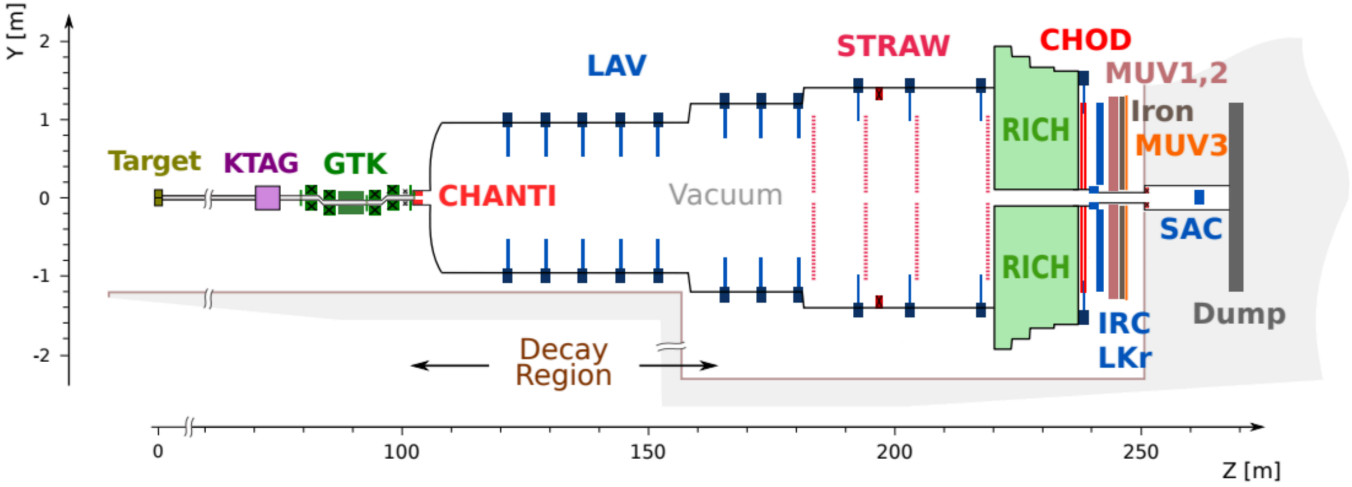
- Alongside 'headline' $K^+ \to \pi^+ \nu\bar{\nu}$ studies NA62 has a broad physics program with world-leading sensitivities to rare and forbidden K^+ decays.
- Set new limits on LNV/LFV decays $K^+ \to \pi^- e^+ e^+$, $K^+ \to \pi^- \mu^+ \mu^+$ $K^+ \to \pi^- \mu^+ e^+$ and $K^+ \to \pi^+ \mu^- e^+$, improved limits by factors 3, 2, 12 and 8.
- Also under consideration:

Decay	Previous BR upper limit @ 90% CL [PDG]	NA62 prospects
$K^+ \to \mu^- \nu e^+ e^+$	2.1×10^{-8}	$SES\sim1\times10^{-10}$ [17 data]
$K^+ \to e^- \nu \mu^+ \mu^+$	No previous limit…	$SES\sim5\times10^{-11}$ [17 data](first search)

- NA62 resumes data-taking in 2021.
  - Background is not limiting – expect improvements in sensitivity.
- Stay tuned for more LNV/LFV searches…

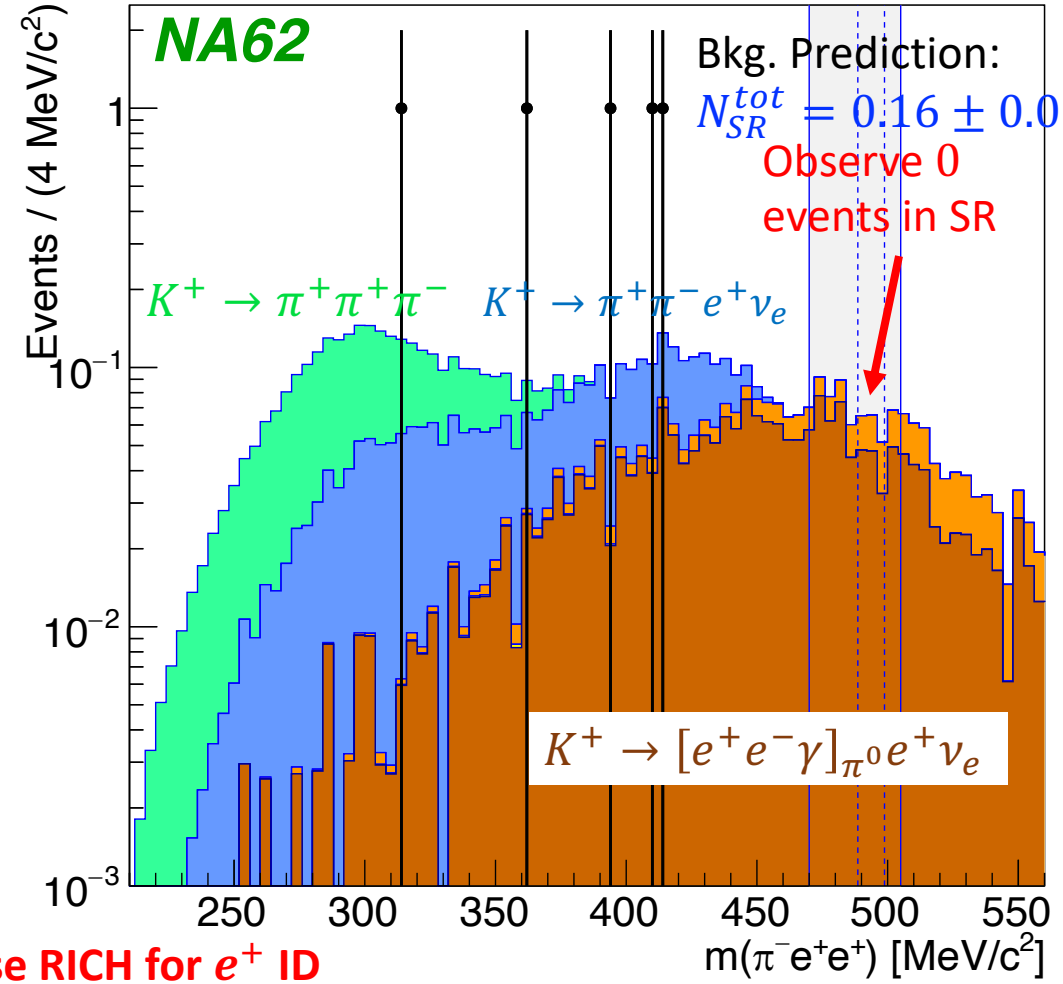
Supplemental

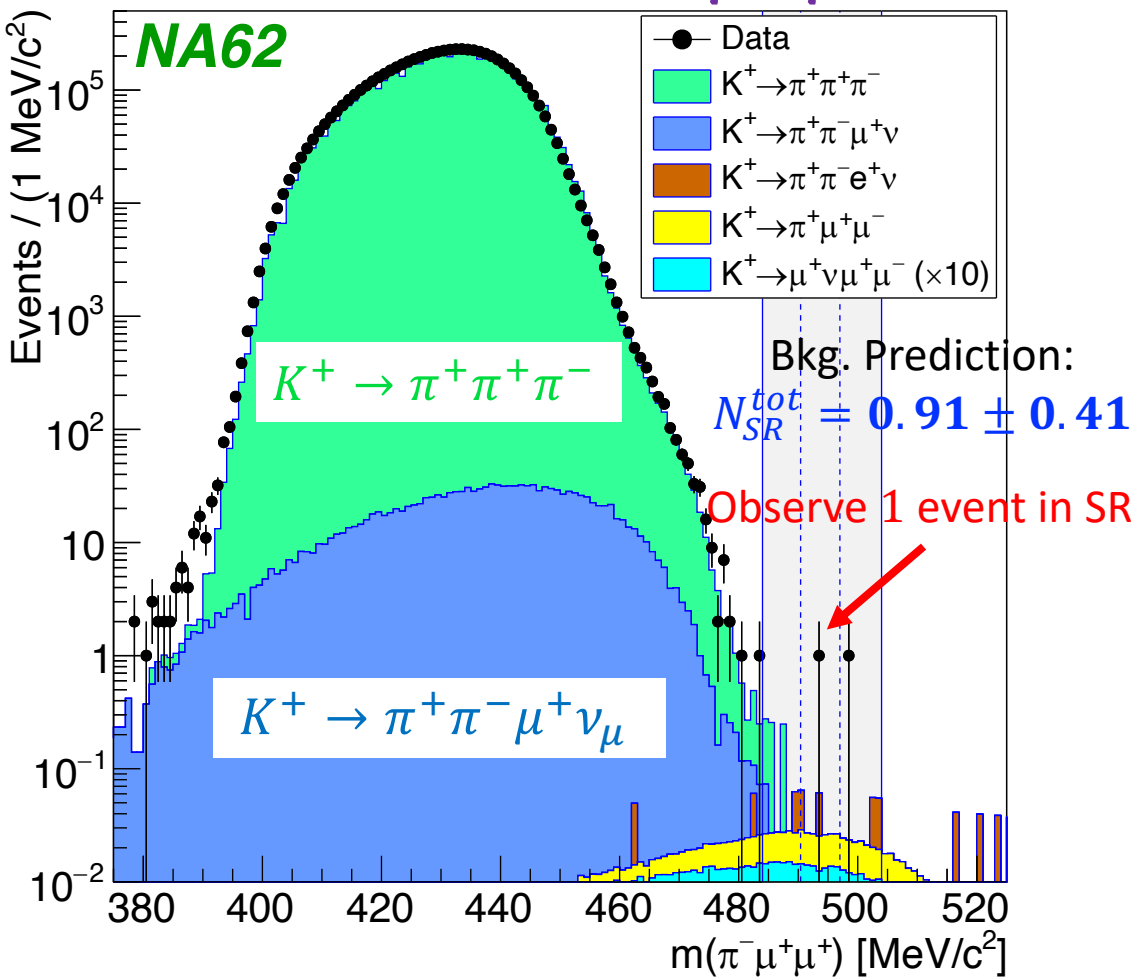




NA62 searches for $K^+ \to \pi^- \ell^+ \ell^+ \; [\ell = \mu, e]$

$K^+ \to \pi^- e^+ e^+$ **PLB 797 (2019) 134794** $K^+ \to \pi^- \mu^+ \mu^+$





Use RICH for e^+ ID

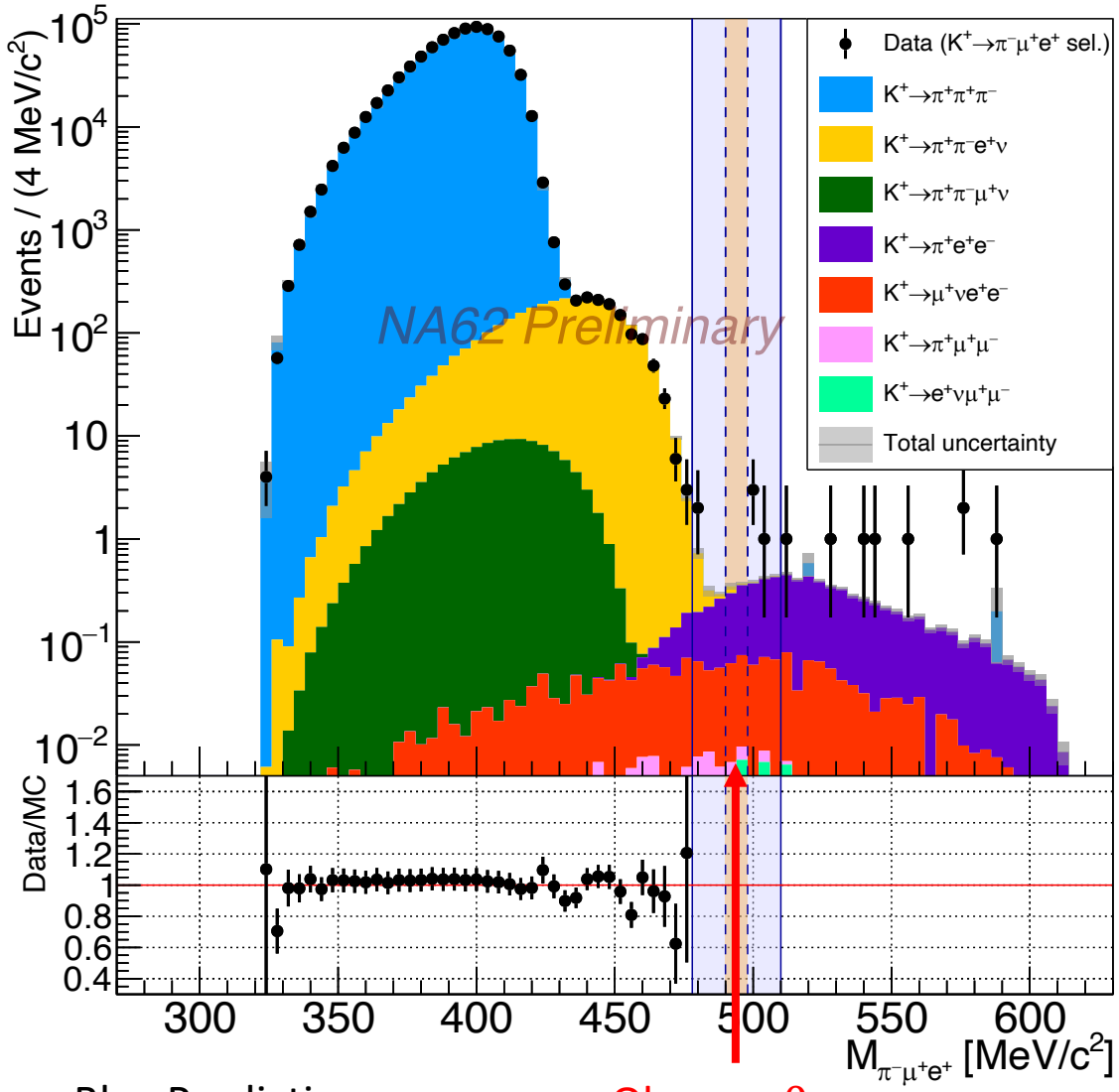
$$BR(K^+ \to \pi^- e^+ e^+) < 2.2 \times 10^{-10} \text{ @ } 90\% \; CL$$

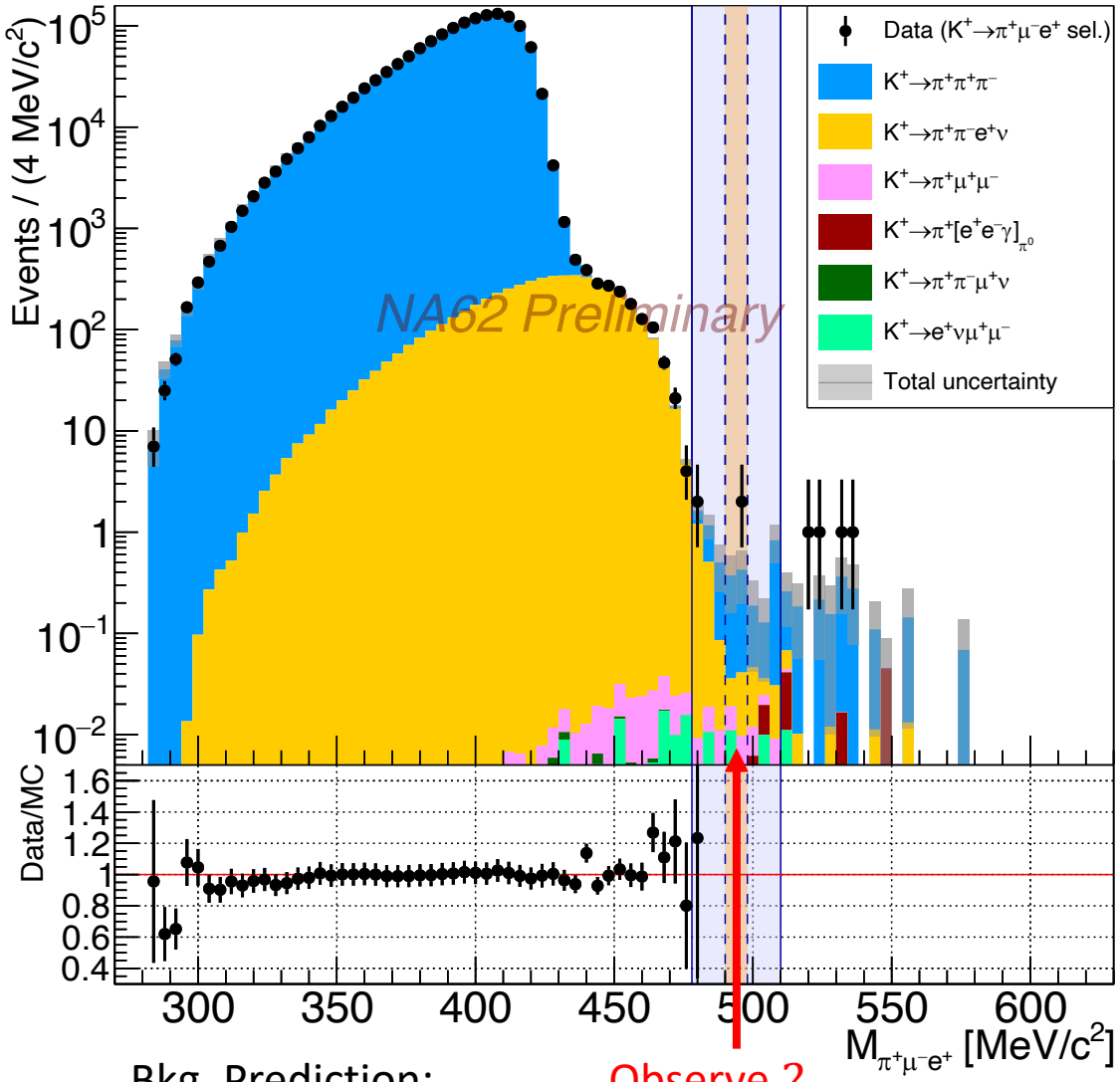
$$BR(K^+ \to \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11} \text{ @ } 90\% \; CL$$

NA62 searches for $K^+ \to \pi^\pm \mu^\mp e^+$

$BR(K^+ \to \pi^- \mu^+ e^+) < 4.2 \times 10^{-11}$ @ 90% CL

$BR(K^+ \to \pi^+ \mu^- e^+) < 6.6 \times 10^{-11}$ @ 90% CL





Bkg. Prediction:
$N_{SR}^{tot} = 1.06 \pm 0.20$

Observe 0 events in SR

Bkg. Prediction:
$N_{SR}^{tot} = 0.92 \pm 0.34$

Observe 2 events in SR