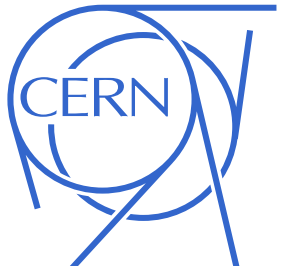


University of Birmingham Particle Physics Seminar

NA62: The (Physics) Story So Far

Joel Swallow

[joel.christopher.swallow@cern.ch]

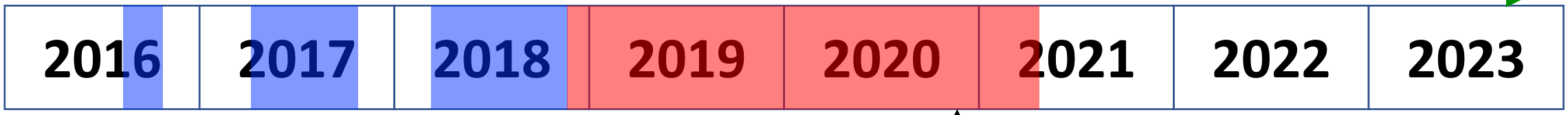
UNIVERSITY OF BIRMINGHAM

commissioning

Run 1 Data-taking

CERN Long shut down 2

Run 2 Data-taking



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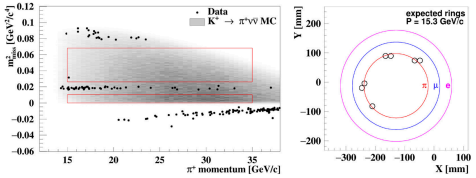
commissioning

Run 1 Data-taking | **CERN Long shut down 2** | **Run 2 Data-taking**

2016	2017	2018	2019	2020	2021	2022	2023

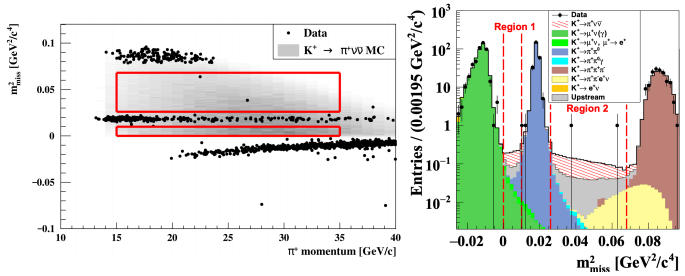
$K^+ \to \pi^+ \nu\bar{\nu}$

Phys. Lett. B 791 (2019) 156-166 (2016 data)



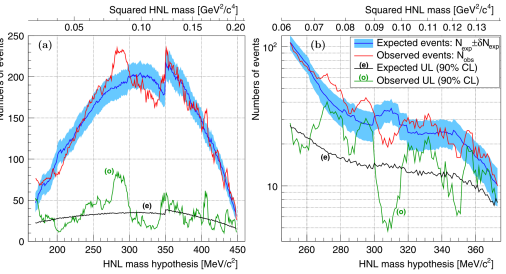
$K^+ \to \pi^+ \nu\bar{\nu}$

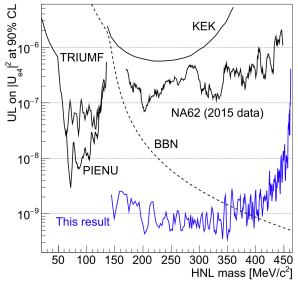
arXiv:2007.08218 (2017 data)



HNL production (2015 data)

Phys. Lett. B 778 (2018) 137-145



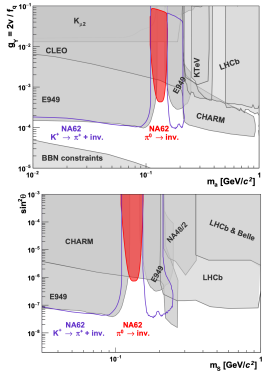


HNL (2017+18 data)

Phys. Lett. B 807 (2020) 135599

$\pi^0 \to invisible$

arXiv:2010.07644

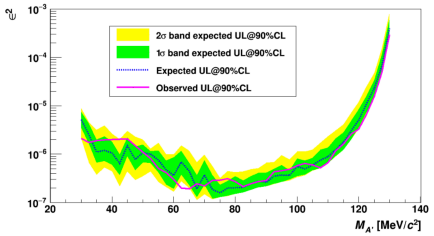


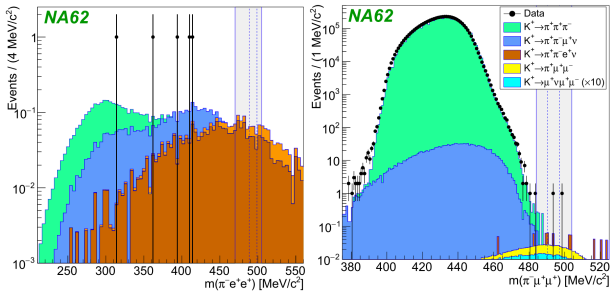
LNV search

Phys. Lett. B 797 (2019) 134794

Dark Photon Search

JHEP 05 (2019) 182





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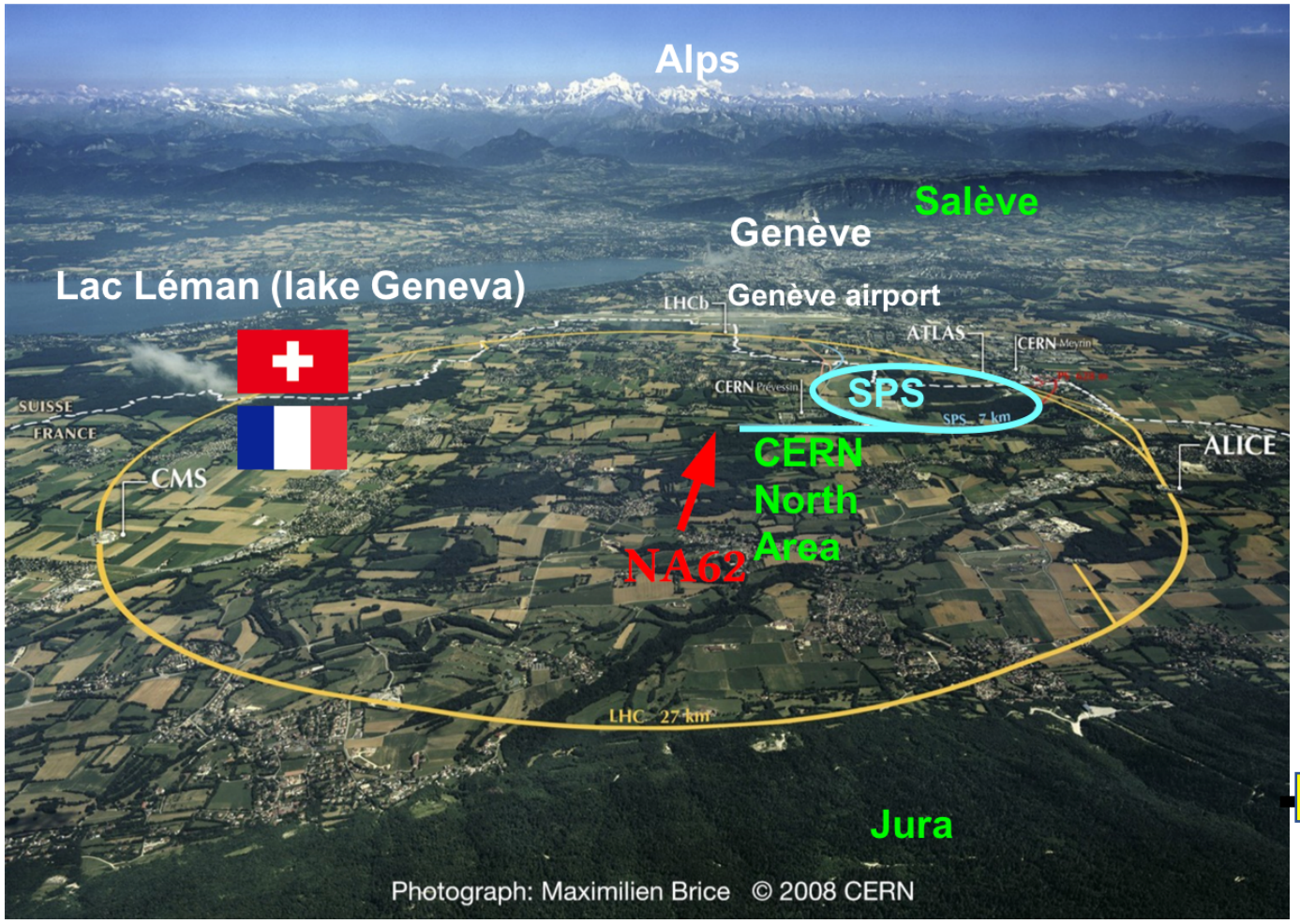
Overview

- The NA62 experiment
- The story so far: physics results from Run 1
- Preparations and prospects for future data-taking

The NA62 Experiment at CERN

~200 collaborators from ~30 institutions :

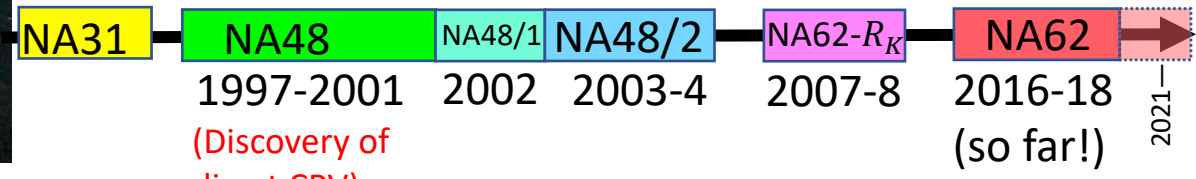
Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna (JINR), Fairfax, Ferrara, Florence, Frascati, Glasgow, Lancaster, Liverpool, Louvain-la-Neuve, Mainz, Moscow (INR), Naples, Perugia, Pisa, Prague, Protvino (IHEP) , Rome I, Rome II, San Luis Potosi, TRIUMF, Turin, Vancouver (UBC) .



- **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
- **+ Broader Physics programme**

- **Data Taking**
  - 2016 Commissioning + Physics run (45 days).
  - 2017 Physics run (160 days).
  - 2018 Physics run (217 days).
  - 2021 resuming data taking.

Continues long history of Kaon physics at CERN:



NA62 Physics

[Credit : Silvia Martellotti @RKF19]

Flavour Physics

Search for New Physics at the EW scale with sizeable coupling to SM particles via indirect effects in loops:

Main goal:
$BR(K^+ \to \pi^+ \nu\nu)$

Search for lepton flavour and number violation, rare and forbidden decays:

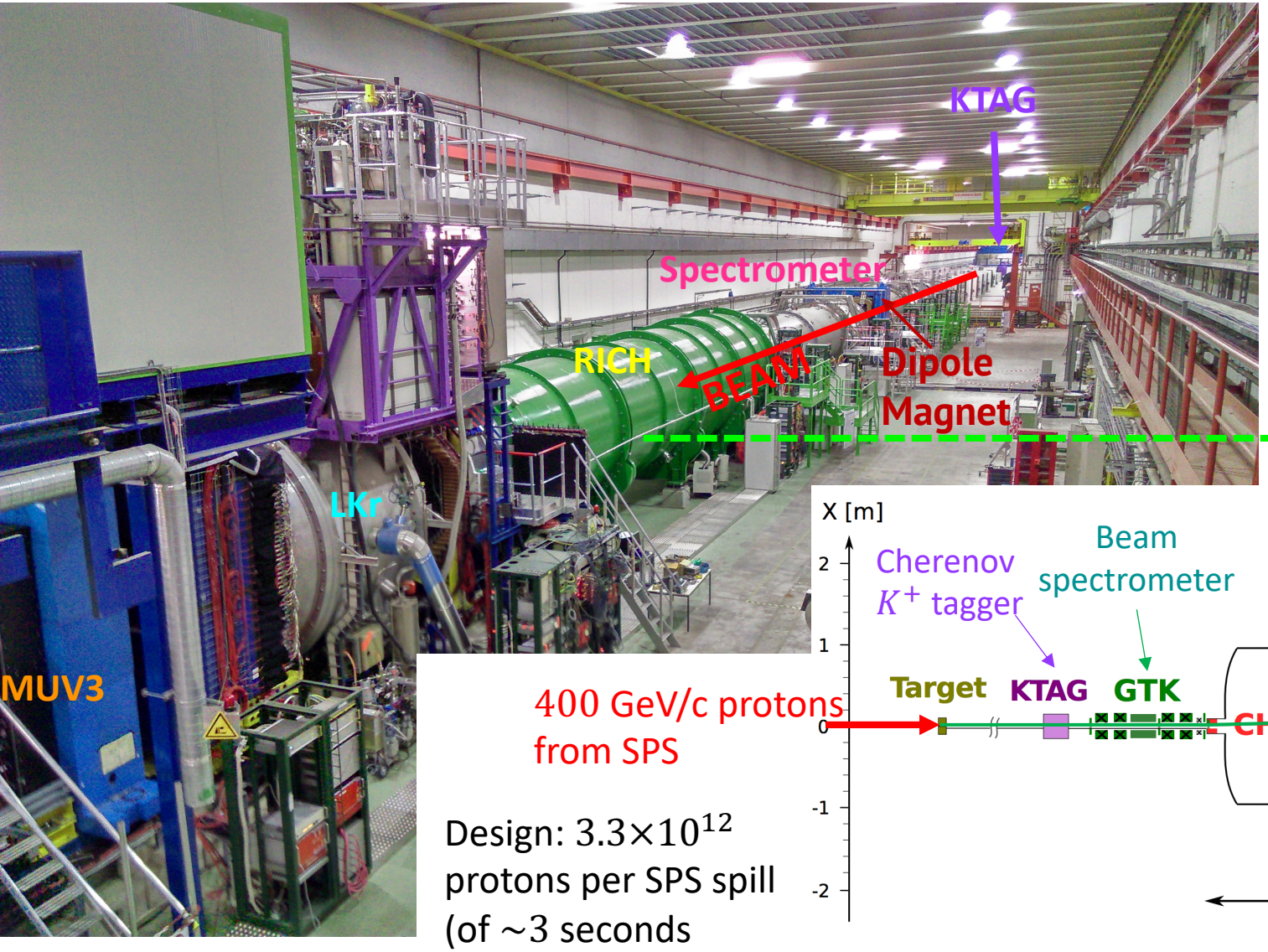
LFV, LNV,
$K^+ \to \pi^+ \mu^+ \mu^-$

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**), Axion Like Particle (**ALPs**), Dark Scalar (**S**)

The NA62 Detector

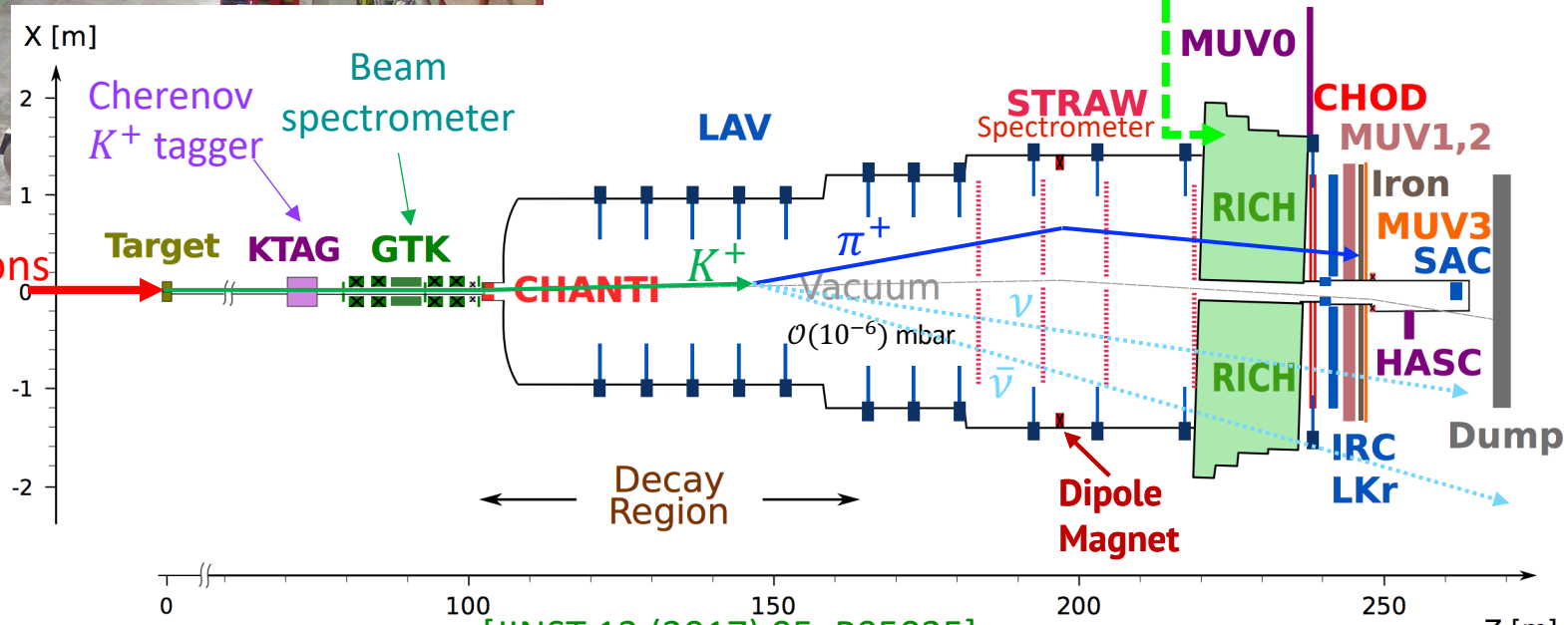


Unseparated secondary hadron beam

- Composition : 70% π^+, 24% p , 6% K^+
- $p_{K^+} = 75$ GeV/c.
- Average instantaneous beam Intensity [MHz]: ~300,~500, ~600 (in 2016,17,18).
  - At 750 MHz get ~5 MHz K^+ decays in ~60 m decay region.

400 GeV/c protons from SPS

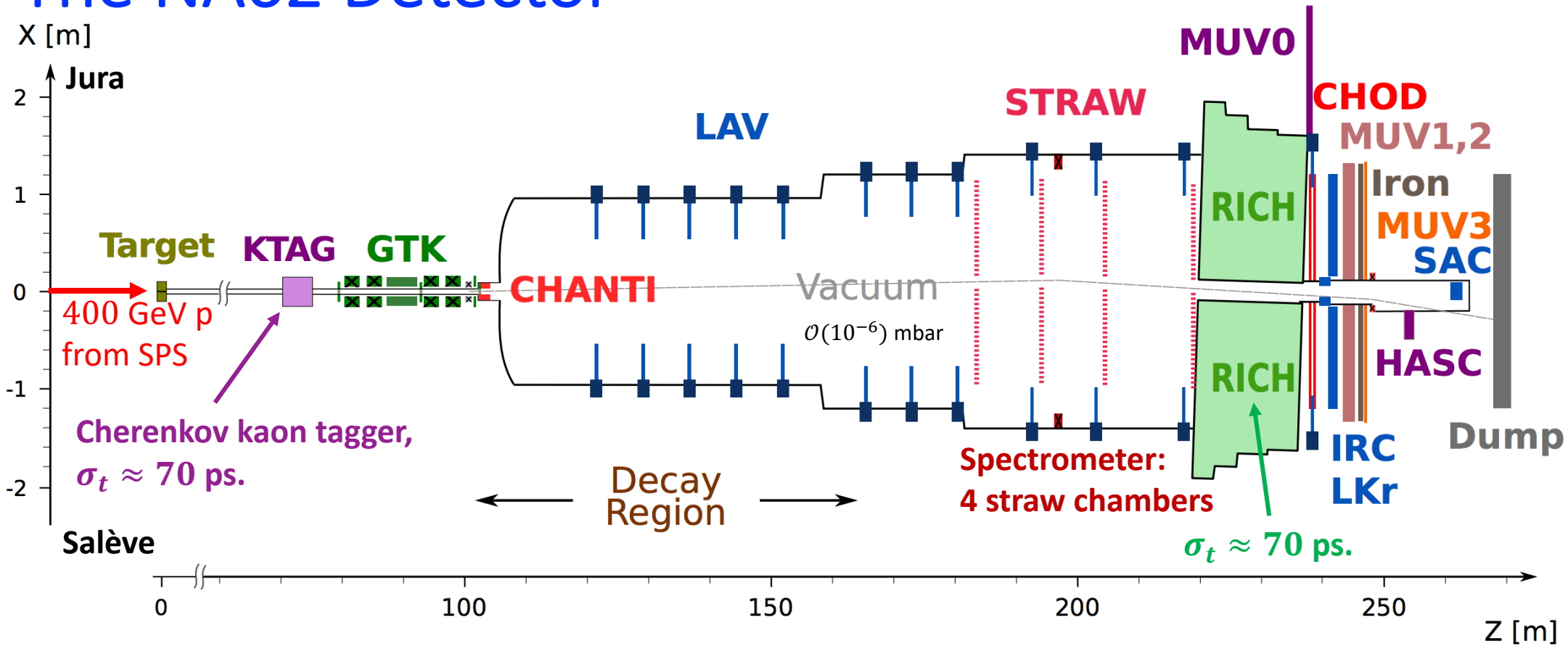
Design: 3.3×10^{12} protons per SPS spill (of ~3 seconds effective length)



[JINST 12 (2017) 05, P05025]

The NA62 Detector

[NA62 Detector Paper, 2017 JINST 12 P05025]



Detector Systems

- **Spectrometers:** GTK (upstream) and STRAWs (downstream).
- **PID (1):** Cherenkov detectors: KTAG (K^+), RICH (π/μ separation).
- **PID (2):** Calorimeters (ECAL = LKr , HCALs = MUV1&2).
- **Photon vetos:** (hermetic for $0 - 50$ mrad) 12LAVs, 2SAVs (IRC&SAC), LKr.
- **Muon veto:** MUV3.
- **Additional detectors:** NA48-CHOD, CHOD, CHANTI, MUV0, HASC.

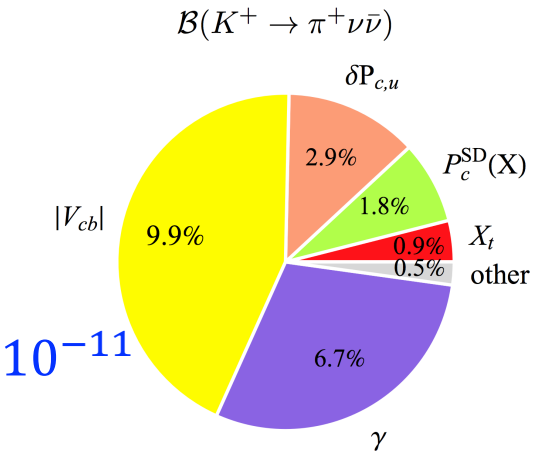
Part 1 : $K^+ \to \pi^+ \nu\bar{\nu}$

$K^+ \to \pi^+ \nu\bar{\nu}$: Precision test of the SM

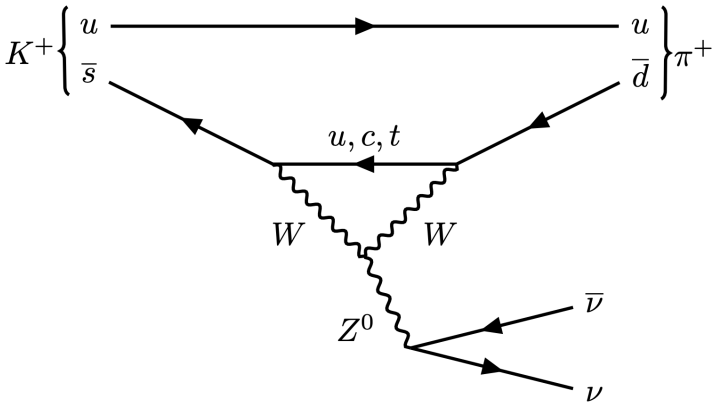
- **SM BR highly suppressed:** $BR(K^+ \to \pi^+ \nu\bar{\nu})_{SM} = (8.4 \pm 1.0) \times 10^{-11}$
  - Precise theoretical prediction: [Buras et al. : JHEP 1511 (2015) 033]
- **FCNC loop process:** $\bar{s} \to \bar{d}$ transition, dramatic CKM & GIM suppression.

$$\therefore BR(K^+ \to \pi^+ \nu\bar{\nu})_{SM} = (8.38 \pm 0.30) \times 10^{-11} \left[\frac{|V_{cb}|}{40.7 \times 10^{-3}}\right]^{2.8} \left[\frac{\gamma}{73.2°}\right]^{0.74} = (8.4 \pm 1.0) \times 10^{-11}$$

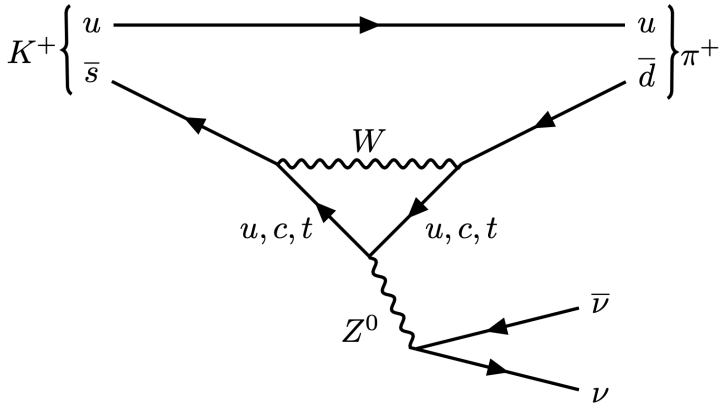
- **Intrinsic theory uncertainty ~2%**
  - NLO (NNLO) QCD corrections to top (charm) contributions, NLO EW corrections.
  - Hadronic matrix elements precisely measured from $BR(K^+ \to \pi^0 e^+ \nu_e)$ decay.



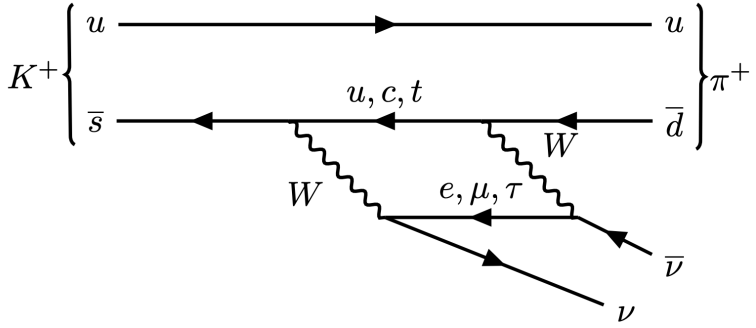
Uncertainty budget



$K^+ \to \pi^+ \nu\bar{\nu}$ SM Z^0 penguin diagram.



$K^+ \to \pi^+ \nu\bar{\nu}$ SM Z^0 penguin diagram.

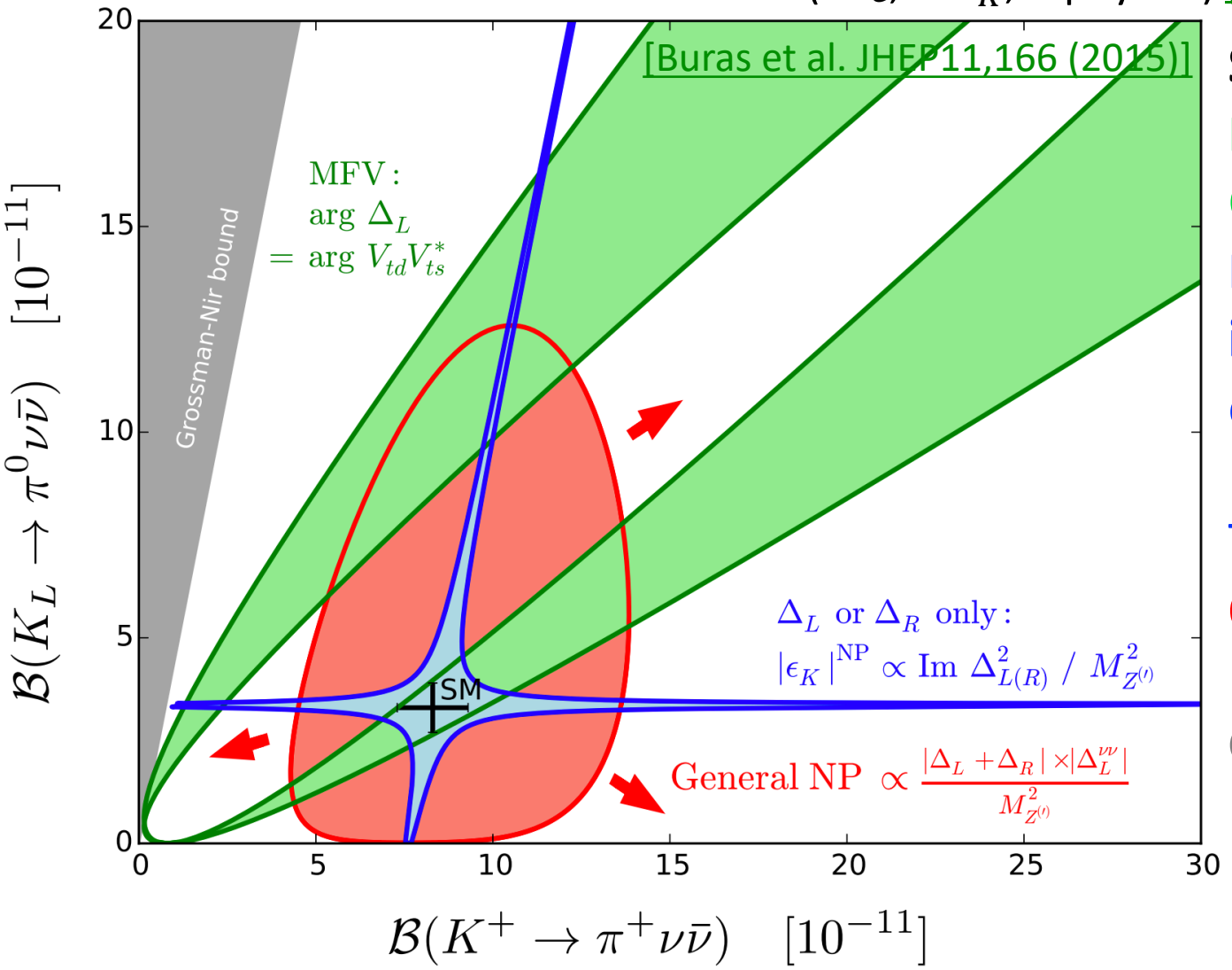


$K^+ \to \pi^+ \nu\bar{\nu}$ SM W box diagram.

NP Prospects for $K^+ \to \pi^+ \nu\bar{\nu}$

[see M. Moulson RKF19]

- Spot NP in deviation from SM prediction in $Br(K \to \pi\nu\nu)$ – very sensitive.
- Correlations between BSM contributions to K^+& K_L BRs [JHEP 1511 (2015) 166].
- Correlations with other observables (ε'/ε, ΔM_K, B physics) [arXiv:2006.01138]



SM

Minimal Flavour Violation – models with CKM-like flavor structure

Models with new flavour violating interactions in which either LH or RH couplings dominate (e.g. Z/Z' models with pure LH/RH couplings or Littlest Higgs with T-parity)

Other NP without flavour constraints (e.g. Randall-Sundrum)

Grossman-Nir bound: model-independent

$$\frac{BR(K_L \to \pi^0\nu\bar{\nu})}{BR(K^+ \to \pi^+\nu\bar{\nu})} = \frac{\tau_{K_L}}{\tau_{K^+}} \frac{\sin^2\theta}{r_{is}} \leq 4.3$$

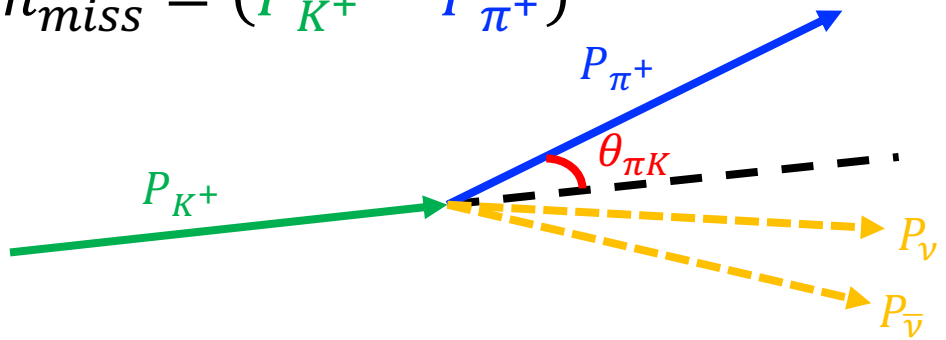
$K^+ \to \pi^+ \nu\bar{\nu}$ Analysis Strategy at NA62

NA62 Performance Keystones

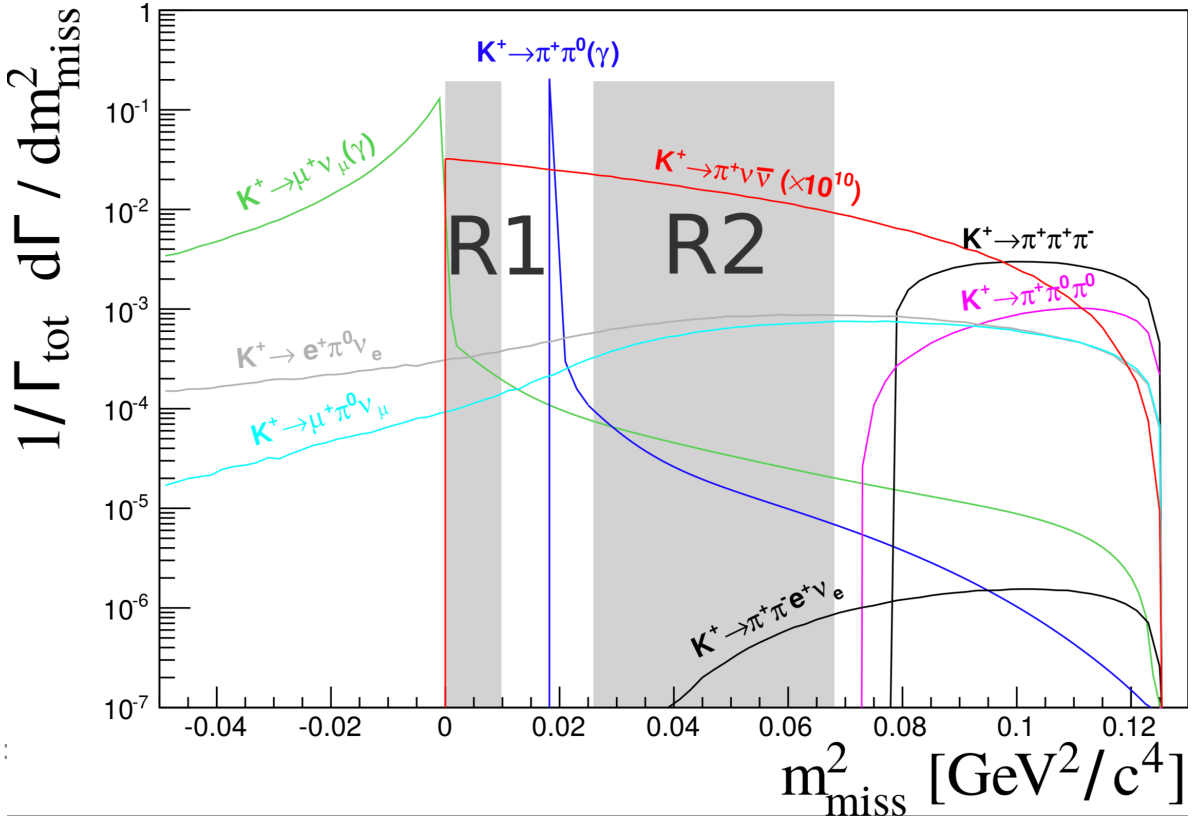
- $\mathcal{O}(100)$ ps timing between sub-detectors.
- $\mathcal{O}(10^4)$ background suppression from kinematics.
- $> 10^7$ muon rejection.
- $> 10^7$ rejection of π^0 from $K^+ \to \pi^+\pi^0$.

Process	Branching Ratio [PDG]
$K^+ \to \mu^+\nu_\mu$	0.6356 ± 0.0011
$K^+ \to \pi^+\pi^0$	0.2067 ± 0.0008
$K^+ \to \pi^+\pi^+\pi^-$	0.05583 ± 0.00024
$K^+ \to \pi^+\pi^- e^+\nu_e$	$(4.247 \pm 0.024)\times10^{-5}$
$\boldsymbol{K^+ \to \pi^+\nu\bar{\nu}}$	[SM] $\boldsymbol{(8.4 \pm 1.0)\times10^{-11}}$

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



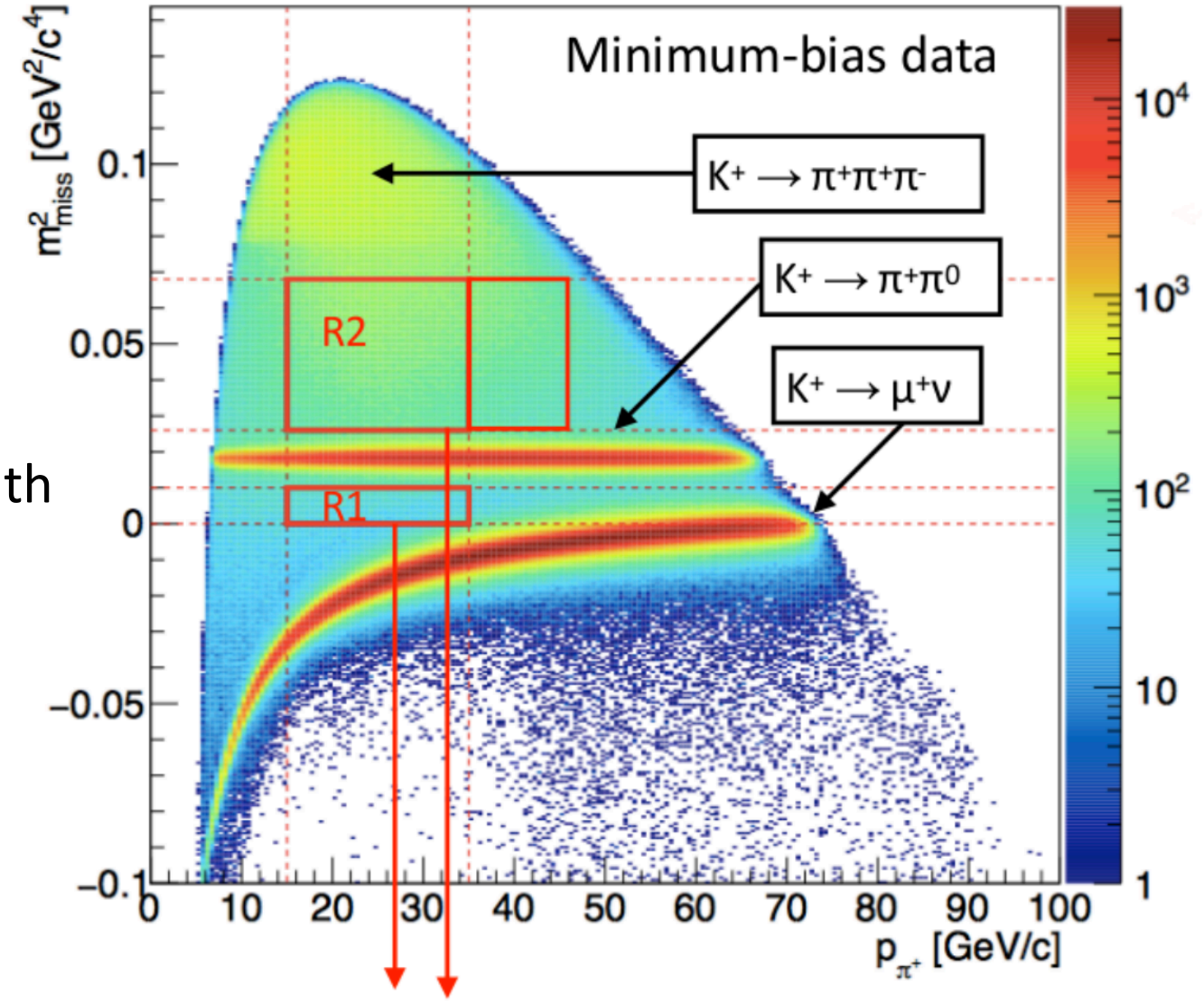
- **Kinematic suppression:** restrict to R1 & R2 with $15 < p_{\pi^+} < 45$ GeV.
- **Muon rejection:** PID (Cherenkov detectors + Calorimeters)
- $\boldsymbol{\pi^0}$ **rejection:** photon vetos.



Signal Selection

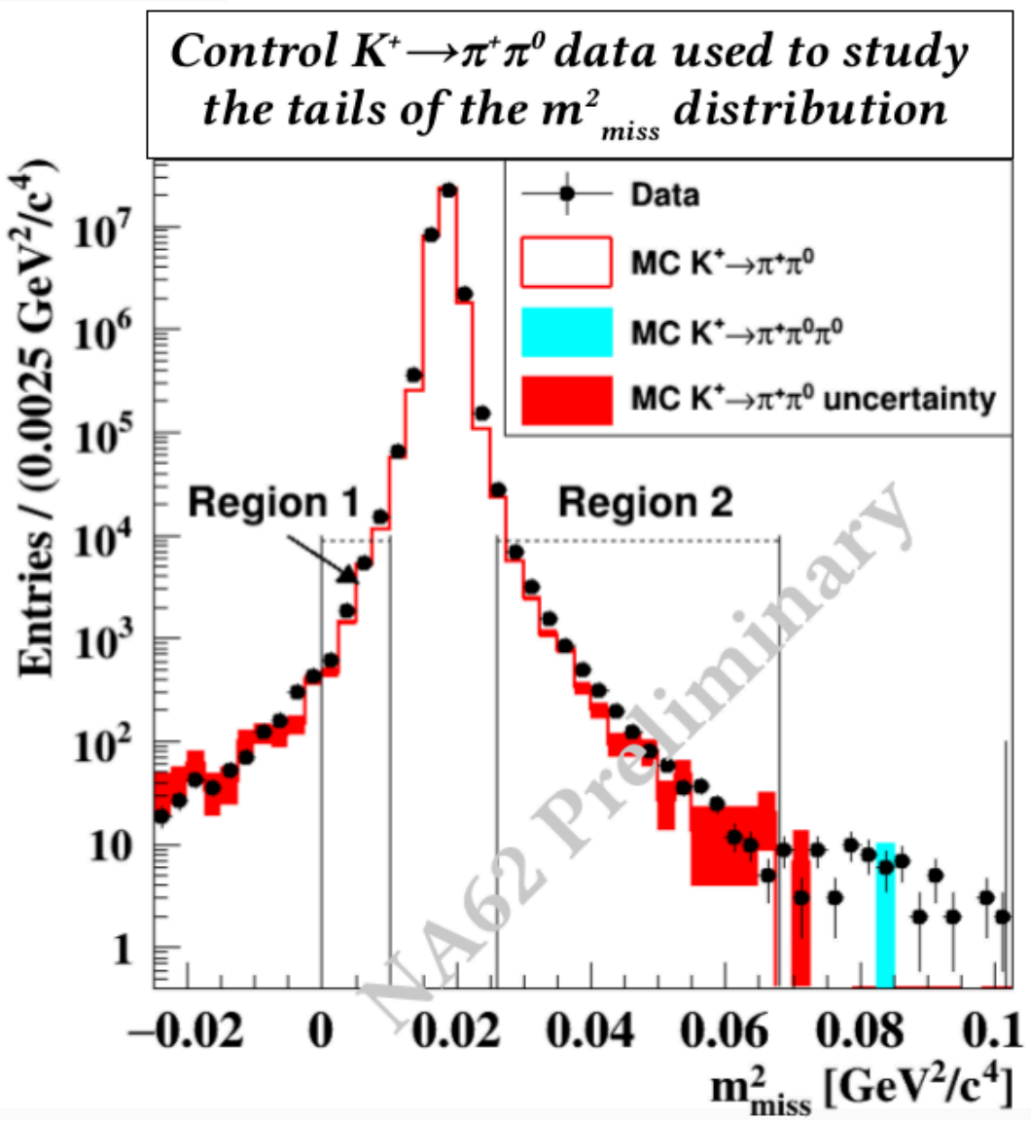
[see CERN Seminar F. Brizioli]

- **Reconstruct K^+ and π^+**
- **$K^+ - \pi^+$ matching & reconstruct vertex**
  - CDA & timing, vertex in FV: 105-170m
- **π^+ identification (μ^+ rejection)**
  - RICH (Calorimeters) 2018 analysis performance: $\varepsilon(\pi^+ \text{ ID}) \approx 0.85(0.82)$ with $P(\mu^+ \Rightarrow \pi^+ \text{ misID}) \approx 3\times10^{-3}(10^{-5})$
- **Photon vetos**
  - $\pi^0(\rightarrow \gamma\gamma)$ rejection inefficiency $\sim 10^{-8}$
- **Multi-track rejection**
- **Kinematics (m^2_{miss} vs p_{π^+})**
  - Selection optimized in bins of p_{π^+} momentum.

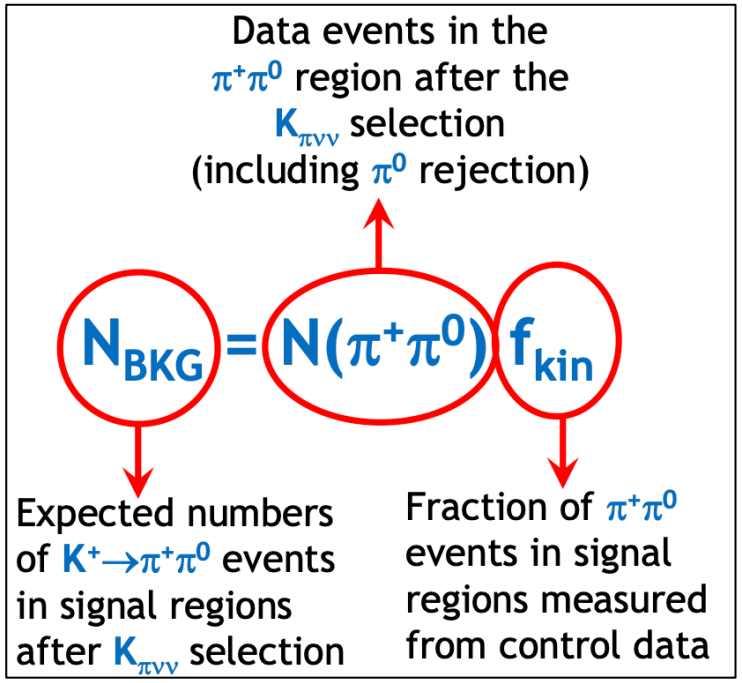


Kinematic cuts to define signal regions R1 and R2

Background Studies: K^+ decays in the FV

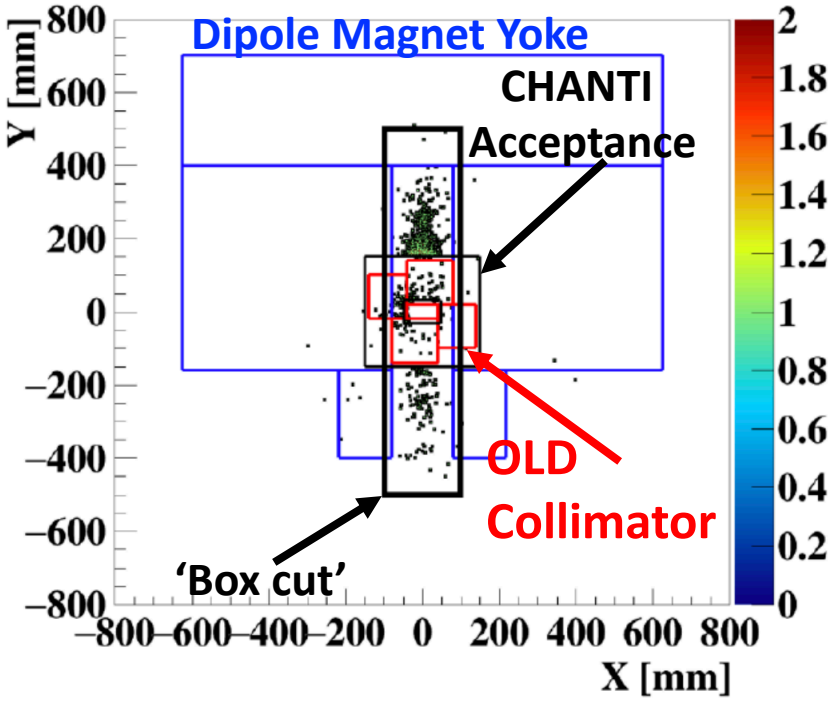


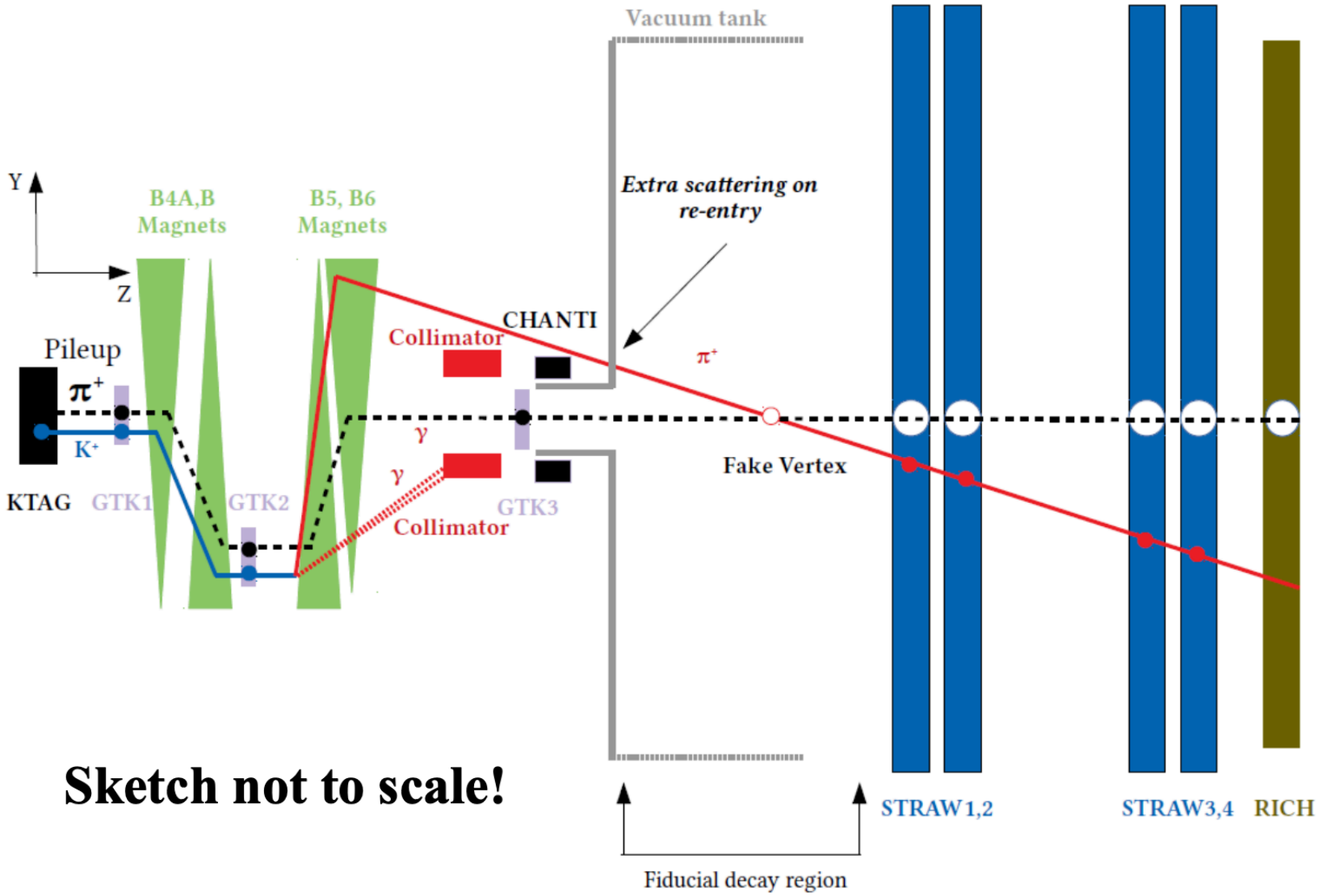
- Background from $K^+ \to \pi^+\pi^0$, $K^+ \to \mu^+\nu_\mu$ and $K^+ \to \pi^+ \pi^+ \pi^-$ enter through tails of the reconstructed m^2_{miss}.
- Data-driven estimation:



- Background from $K^+ \to \pi^+\pi^- e^+\nu_e$ decay studied with simulations.
- All validated using control regions.

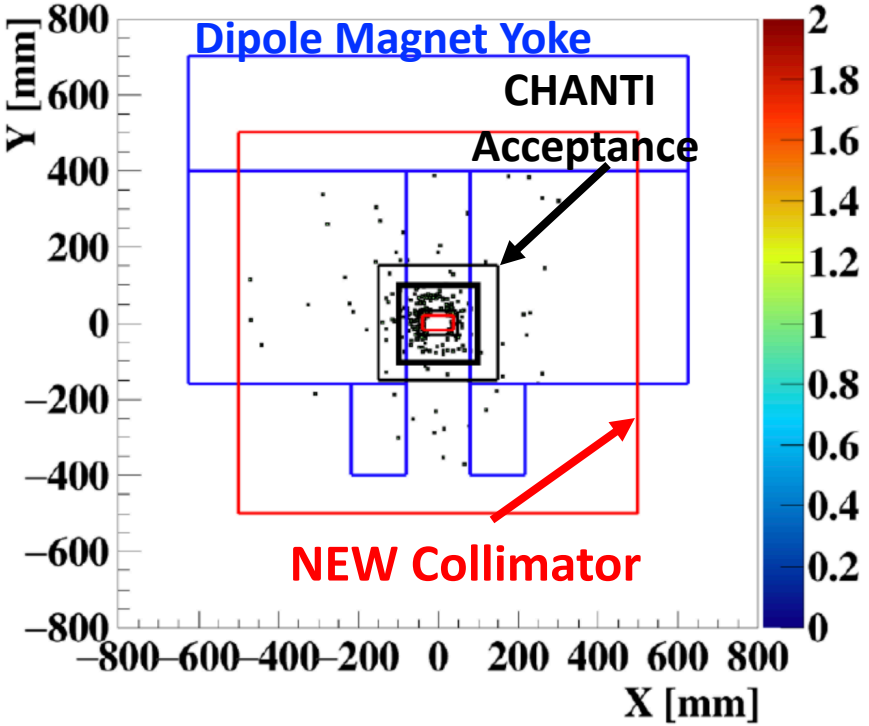
Upstream background [Old Collimator: up to June 2018]

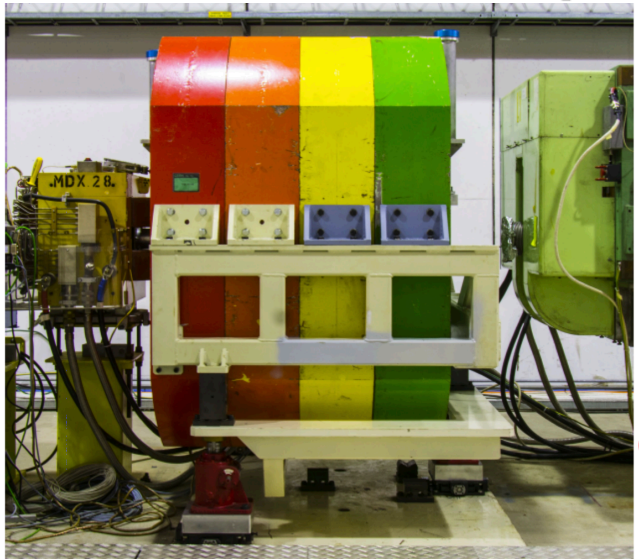


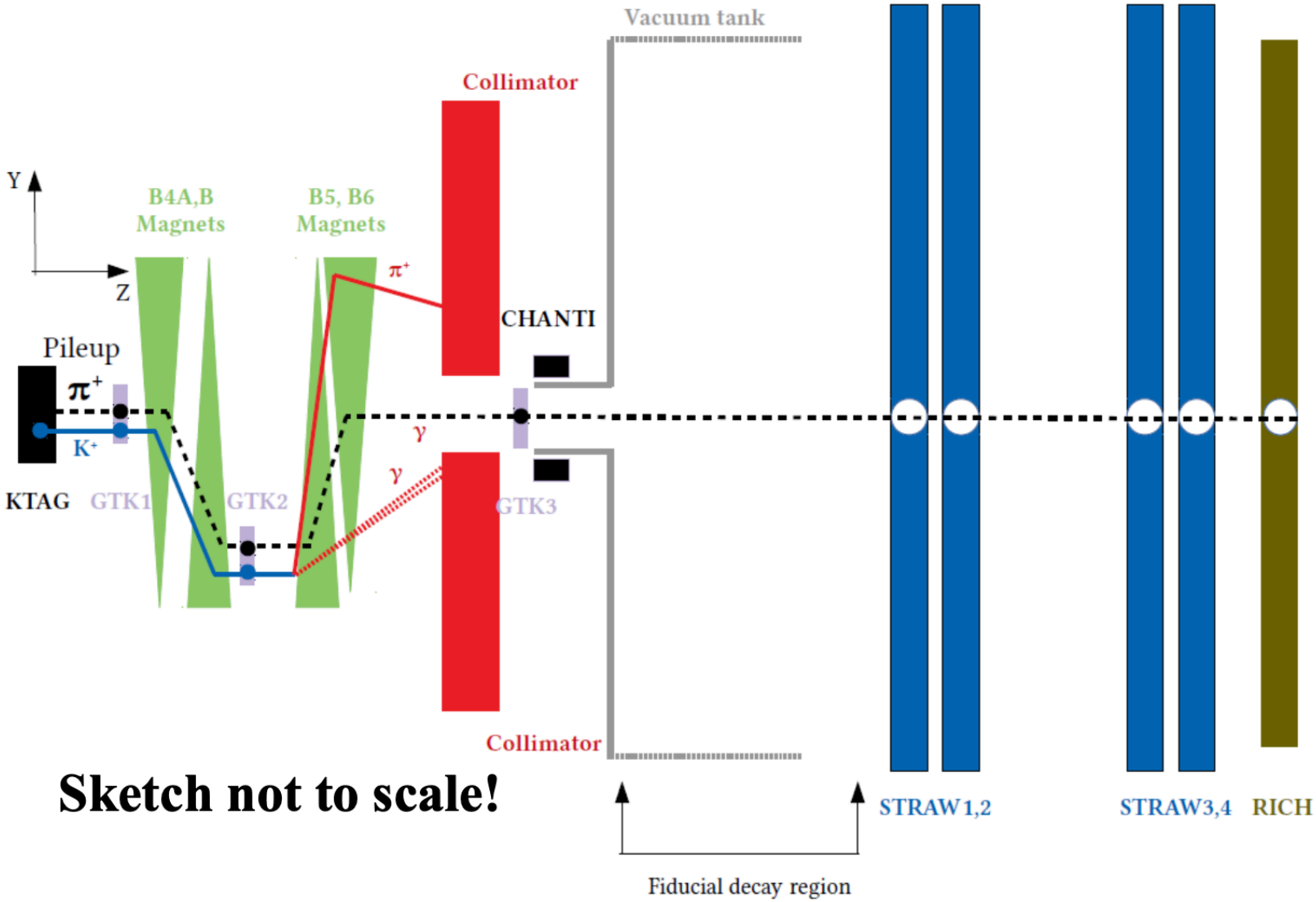


Upstream background [New Collimator: from June 2018]

[~70% of 2018 data taken with new collimator]







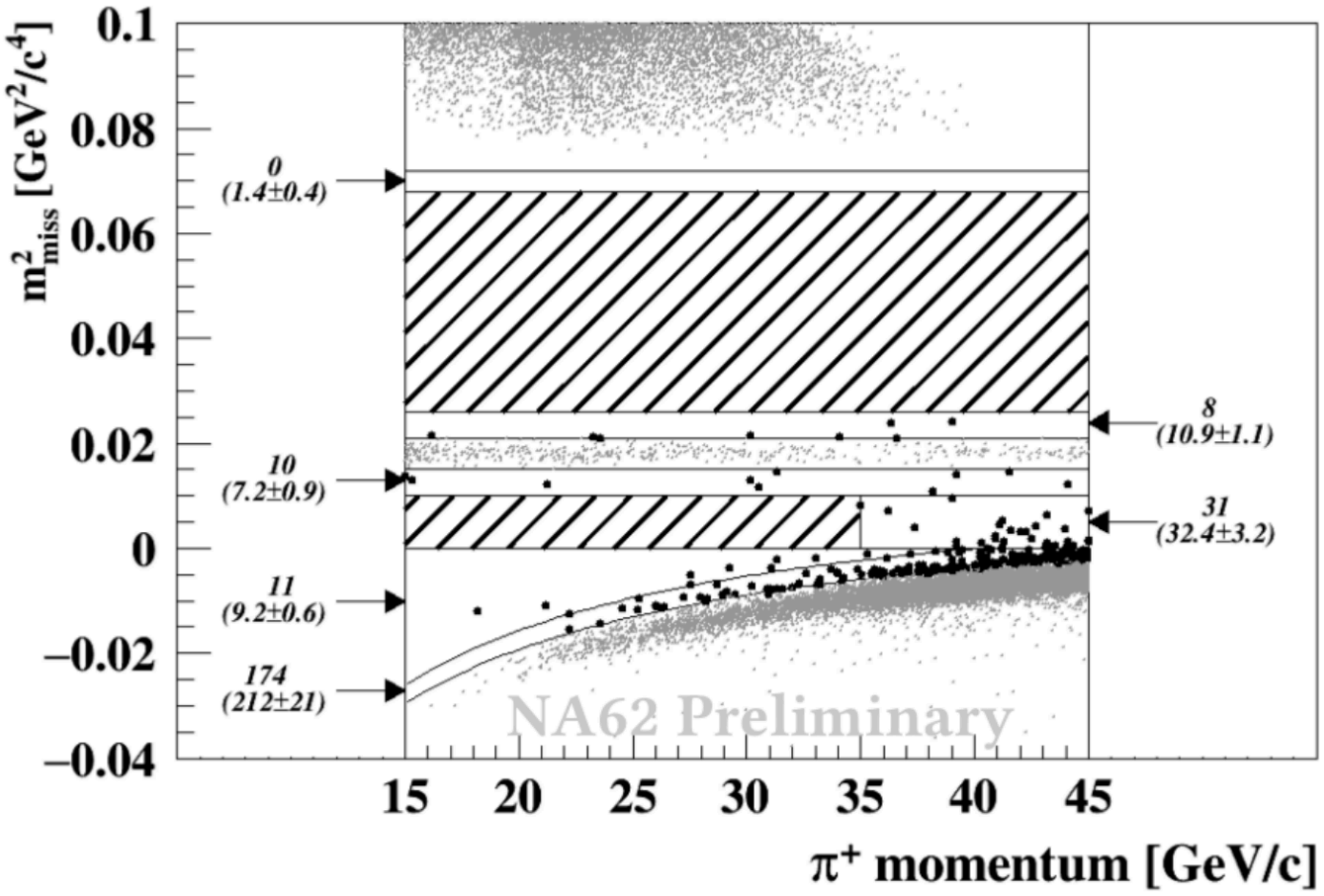
Can relax 'box cut' and gain signal acceptance $(4.0\% \rightarrow 6.4\%)$ keeping S/B to same level.

Preliminary Results : 2018 Data analysis

Process	Expected events in $\pi\nu\nu$ signal regions
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	$7.58 \pm 0.40_{syst} \pm 0.75_{ext}$
$K^+ \to \pi^+\pi^0(\gamma)$	0.75 ± 0.04
$K^+ \to \mu^+\nu(\gamma)$	0.49 ± 0.05
$K^+ \to \pi^+\pi^-e^+\nu$	0.50 ± 0.11
$K^+ \to \pi^+\pi^+\pi^-$	0.24 ± 0.08
$K^+ \to \pi^+\gamma\gamma$	< 0.01
$K^+ \to l^+\pi^0\nu_l$	< 0.001
Upstream background	$3.30^{+0.98}_{-0.73}$
Total background	$5.28^{+0.99}_{-0.74}$

K^+ decays in the FV

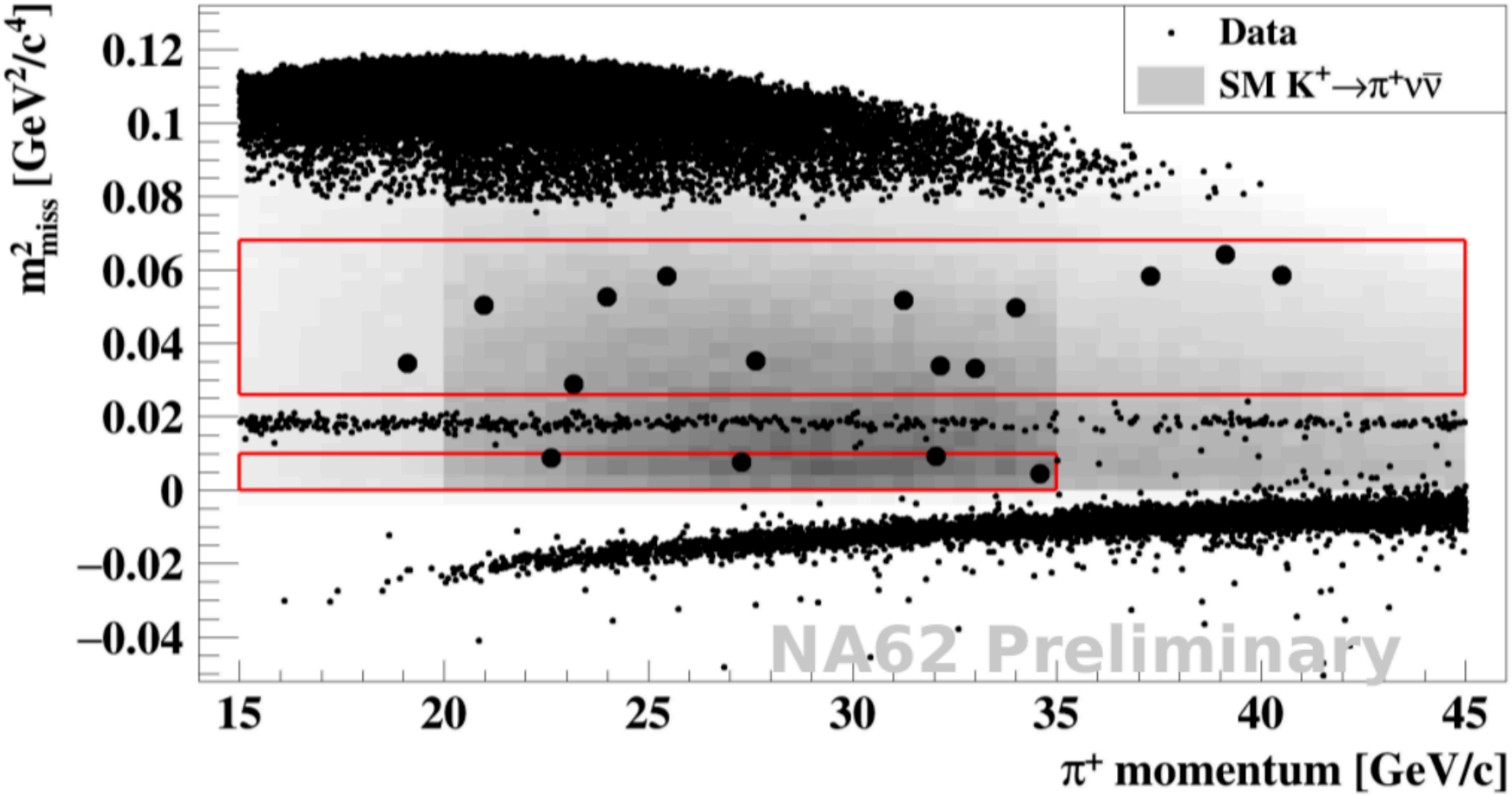
Signal regions blinded



Background expectations validated using control regions.

Preliminary Results : 2018 Data analysis

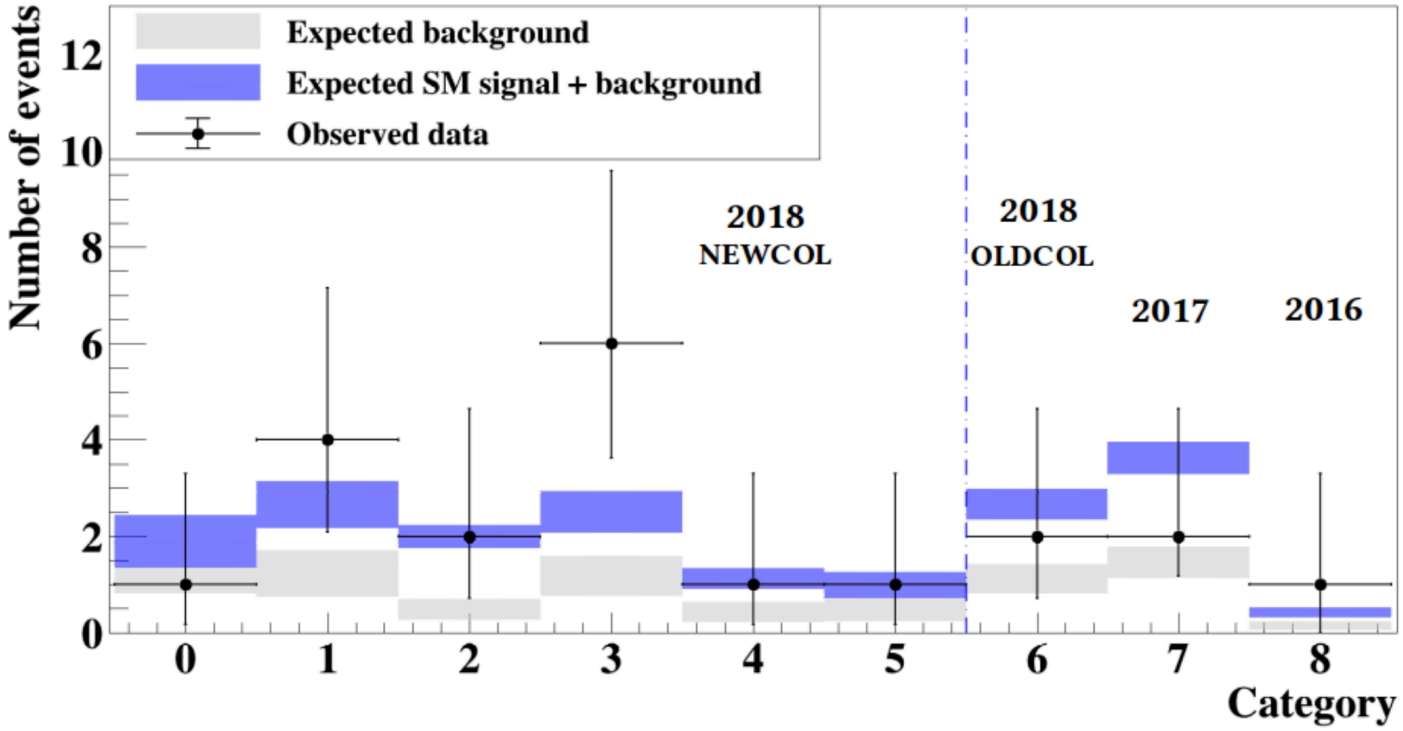
Open signal regions



- Expected SM $K^+ \to \pi^+ \nu\bar{\nu}$ events : $7.58 \pm 0.40_{syst} \pm 0.75_{ext}$, expected background : $5^{+0.99}_{-0.74}$
- Observe **17 events**

Preliminary NA62 Run1 $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})$ measurement

- Include published results from 2016 (1 observed event [PLB 791 (2019) 156]) + 2017 data (2 observed events [arXiv:2007.08218]) as additional categories.

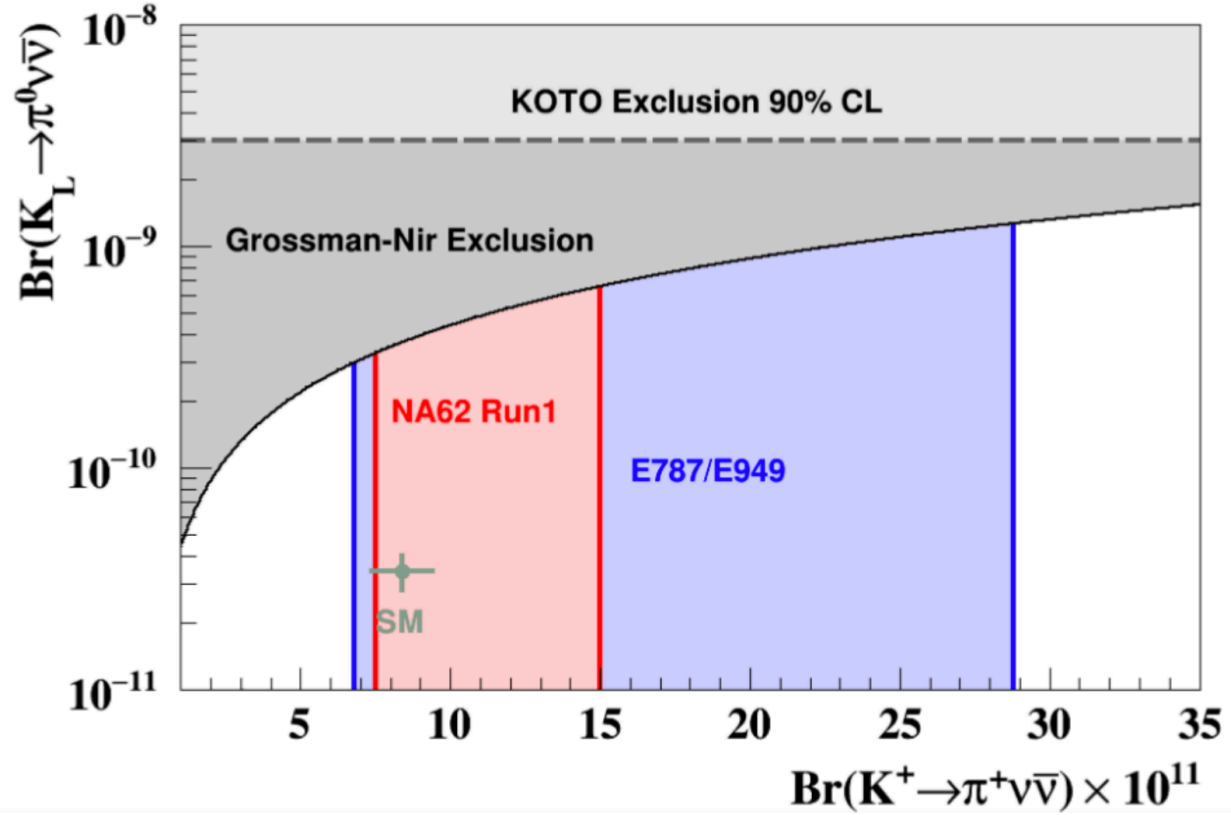


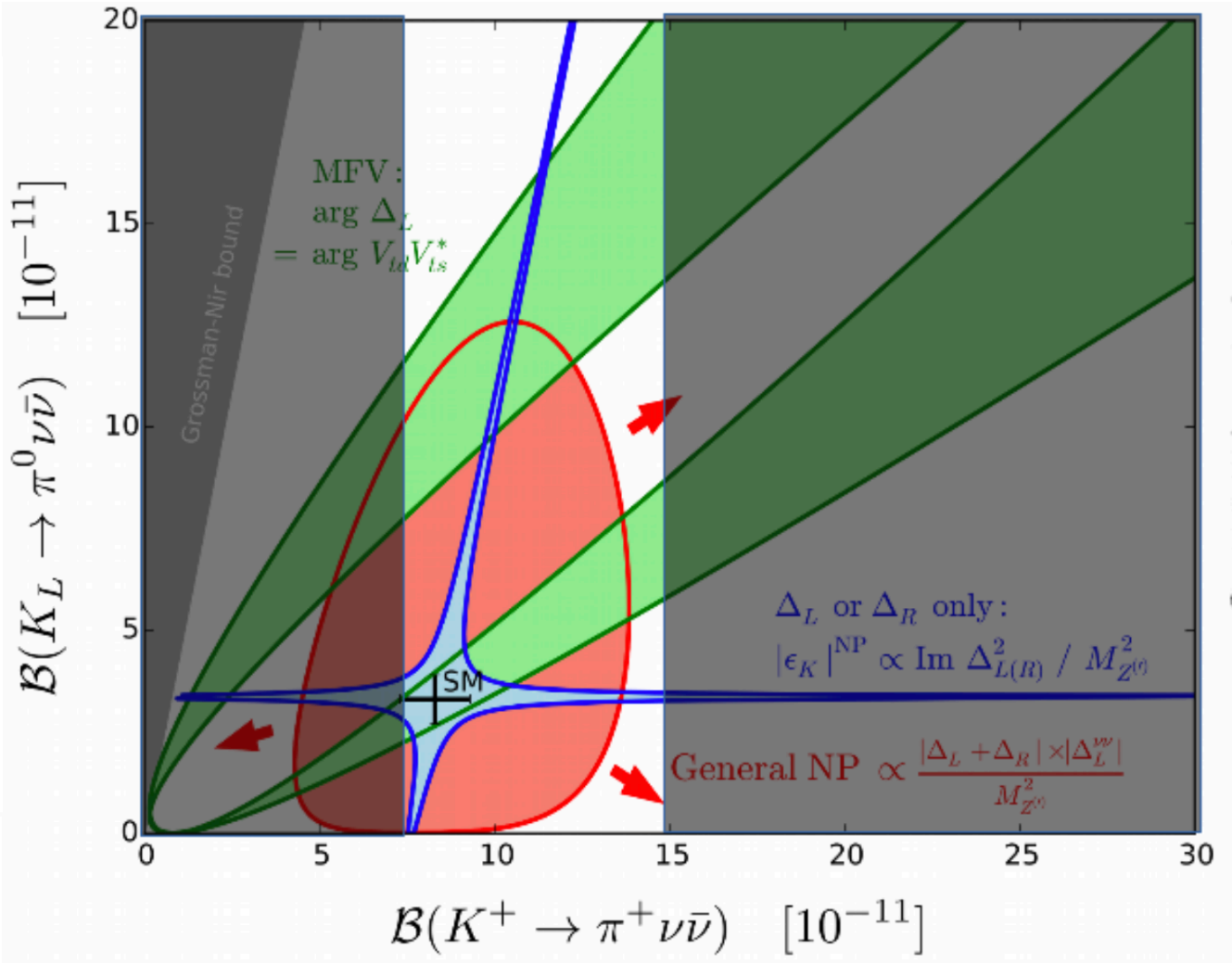
NA62 Run1 : $\mathbf{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (1.10^{+0.40}_{-0.35\ stat} \pm 0.03_{syst}) \times 10^{-10}$

SM : $BR(K^+ \to \pi^+ \nu\bar{\nu})_{SM} = (0.84 \pm 0.10) \times 10^{-10}$

3.5σ significance
P(bkg-only)=2×10^{-4}

Status of $\mathrm{BR}(K \to \pi\nu\bar{\nu})$ measurement & Constraining NP Models





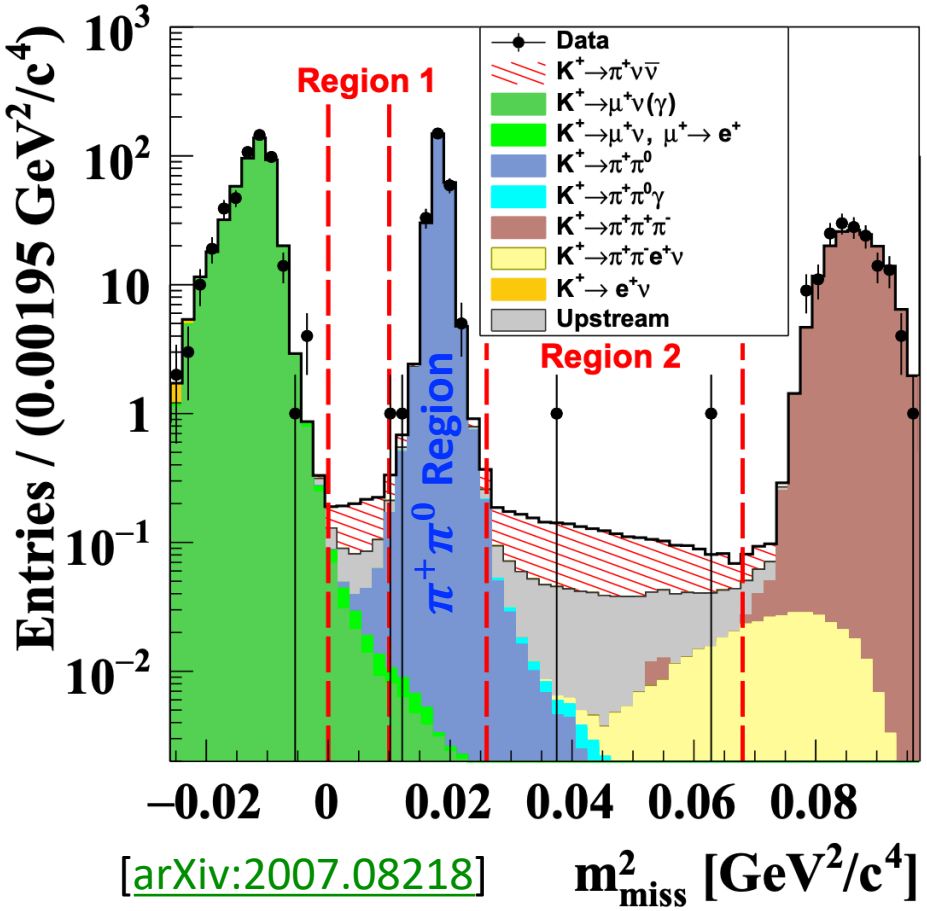
Part 2 : Exotic Searches in $K^+ \to \pi^+ \nu\bar{\nu}$ analysis framework

$K^+ \to \pi^+ X$

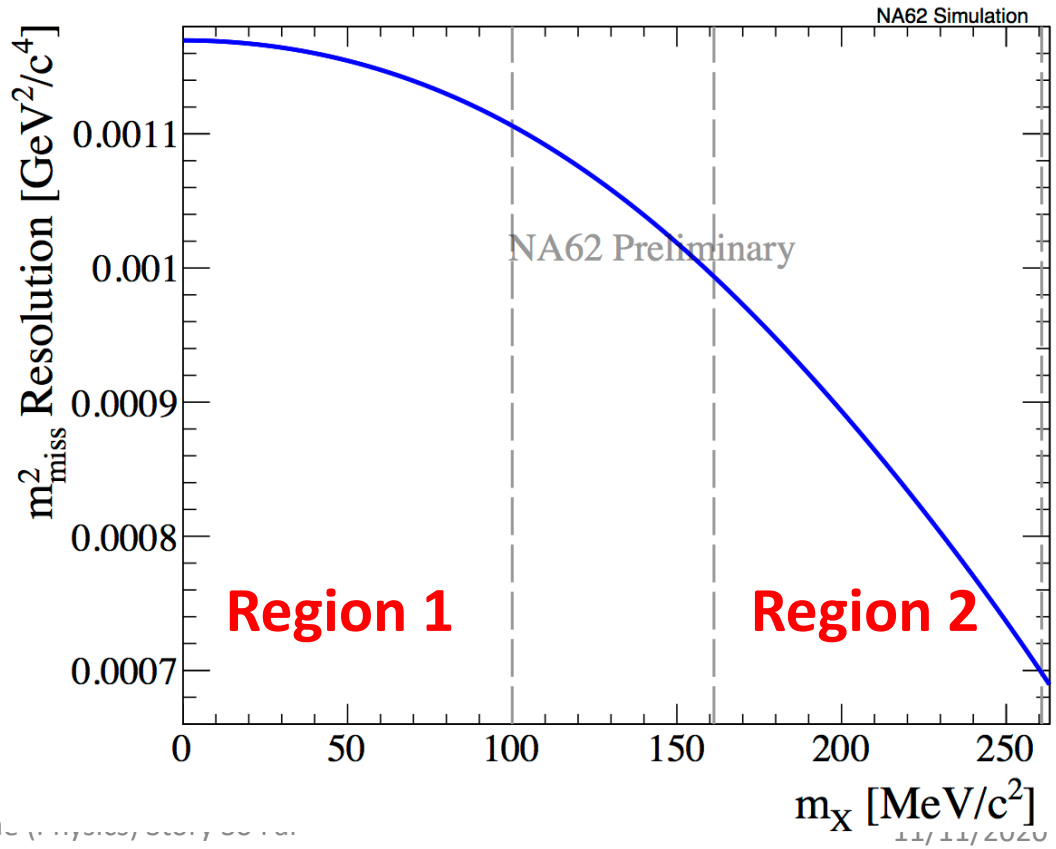
Where X could be:

- A dark scalar mixing with the Higgs boson.
- An ALP with coupling to fermions.

- Signature of $K^+ \to \pi^+ \nu\bar{\nu}$ and $K^+ \to \pi^+ X$ same…
- Except 2-body $K^+ \to \pi^+ X$ will produce a peak in $m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$ at ${m_X}^2$, with width determined by resolution.
- Perform search in **2017 data**. Must study distribution of background as a function of m^2_{miss}.



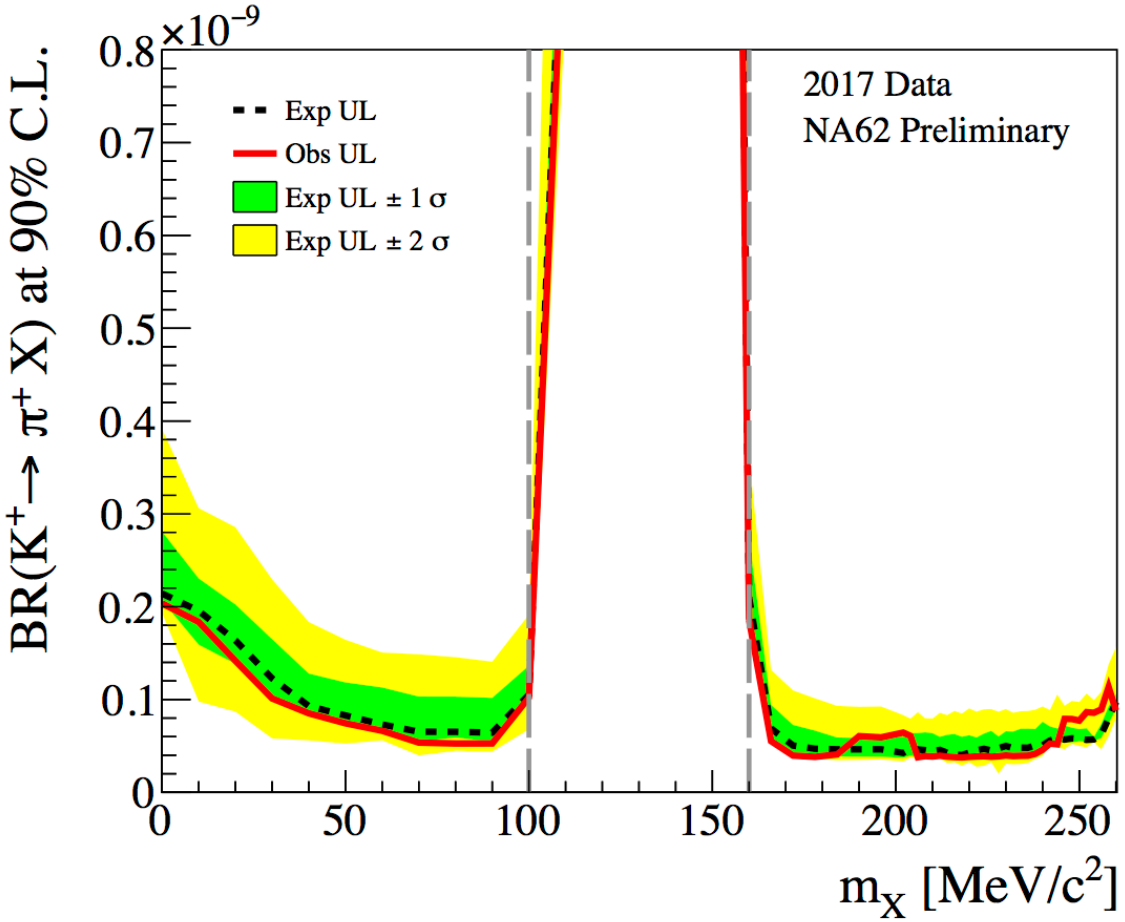
[arXiv:2007.08218]

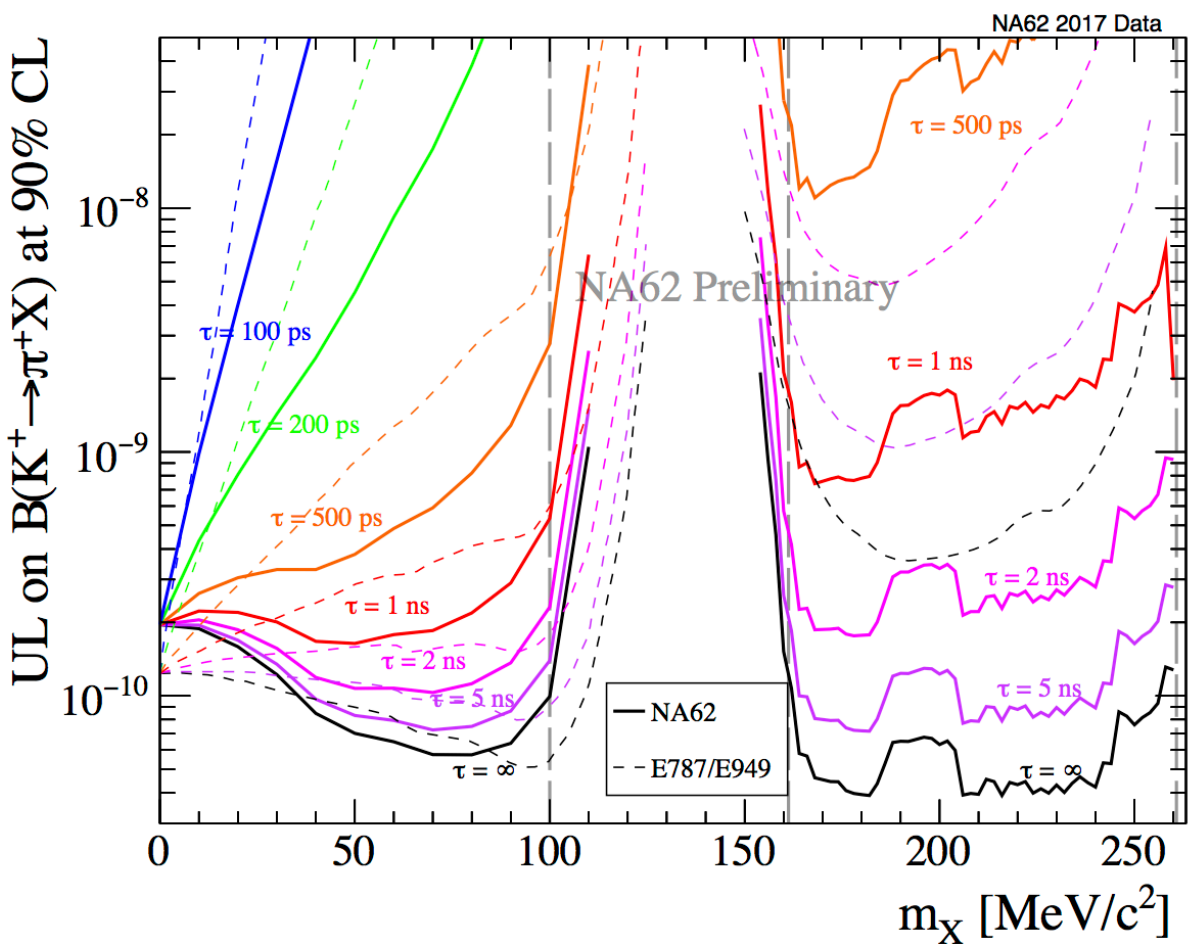


$K^+ \to \pi^+ X$ Preliminary results (2017 data)

[Paper in preparation]

- Upper limits of BR($K^+ \to \pi^+ X$), for different X mass and lifetime.
- Region 2: order of magnitude improvement on BNL E949 [PRD79 (2009) 092004].
- Not limited by background: significant improvements soon.



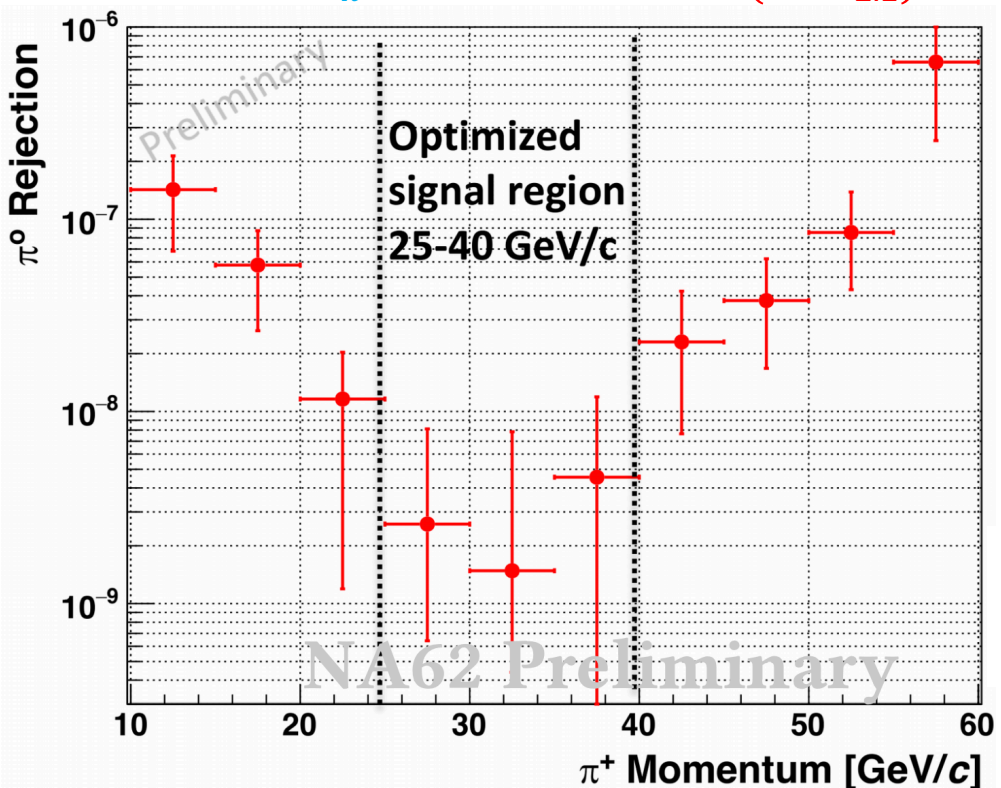


Search for $\pi^0 \to invisible$ @ NA62 with 2017 data

[arXiv:2010.07644]

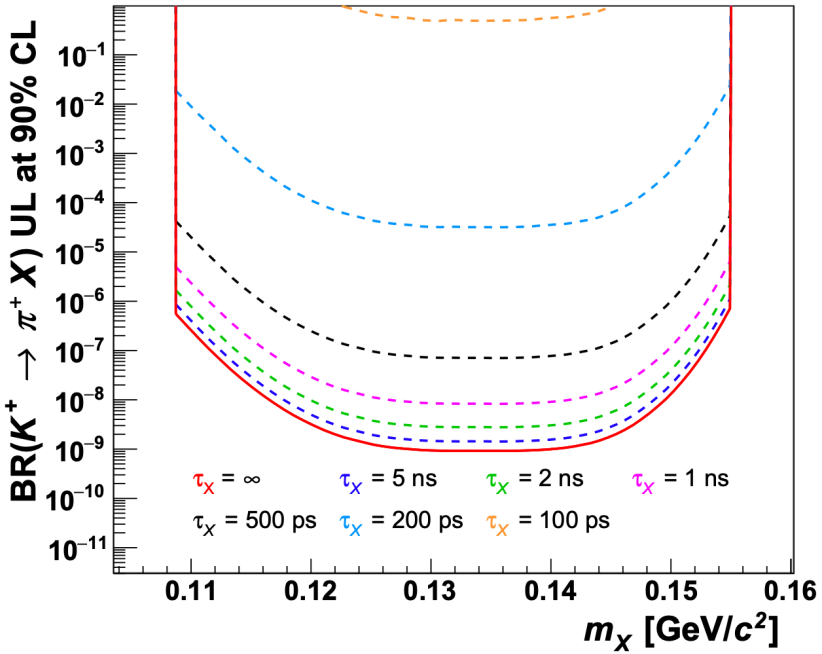
- **Same selection except look in $\pi^+\pi^0$ Region** ($0.015 < m^2_{miss} < 0.021\ GeV/c^2$) and choose p_{π^+} range to maximize background rejection.
- **Rejection of background** ($K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\gamma$) evaluated with MC based on **measurement of single γ detection efficiency in data.**
- **Validation:** side-bands with expected rejection $\mathcal{O}(10^{-7})$ where $\pi^0 \to invisible$ excluded [E949, PRD72 (2005)].
- **Results** with ~1/3 of 2017 dataset **:** Background expected: $\mathbf{10^{+22}_{-8}}$ **,** Events observed: **12**

π^0 rejection [$25 < p_{\pi^+} < 40\ GeV/c$] : $\varepsilon = (2.8^{+5.0}_{-2.1})\times10^{-9}$



$BR(\pi^0 \to invisible) < 4.4\times10^{-9}$ @90% CL

[UL 60 times stronger than previous measurement, 2.7×10^{-7} @ 90% CL E949, PRD72 (2005)]

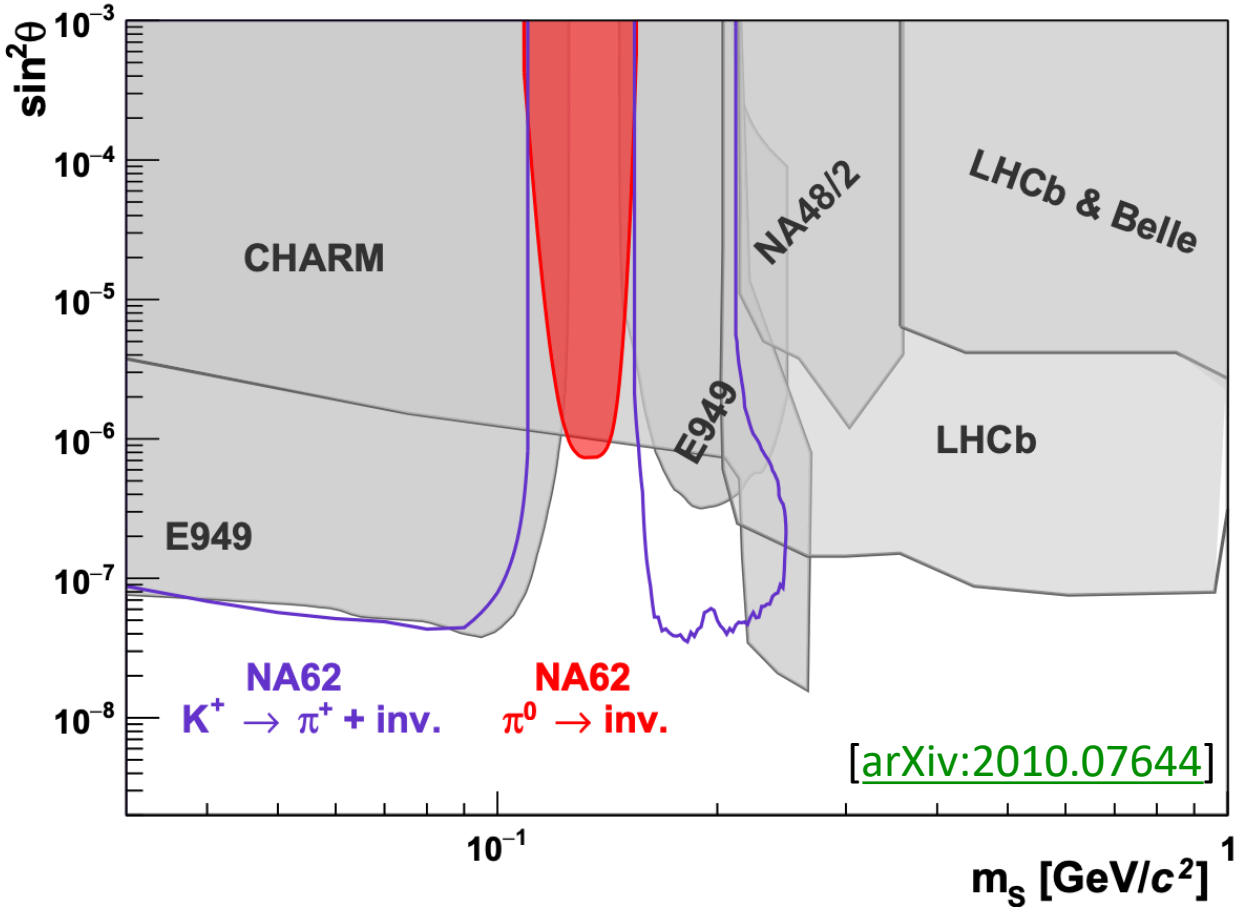


Interpretation: X decays to visible (SM) particles

[arXiv:2010.07644]

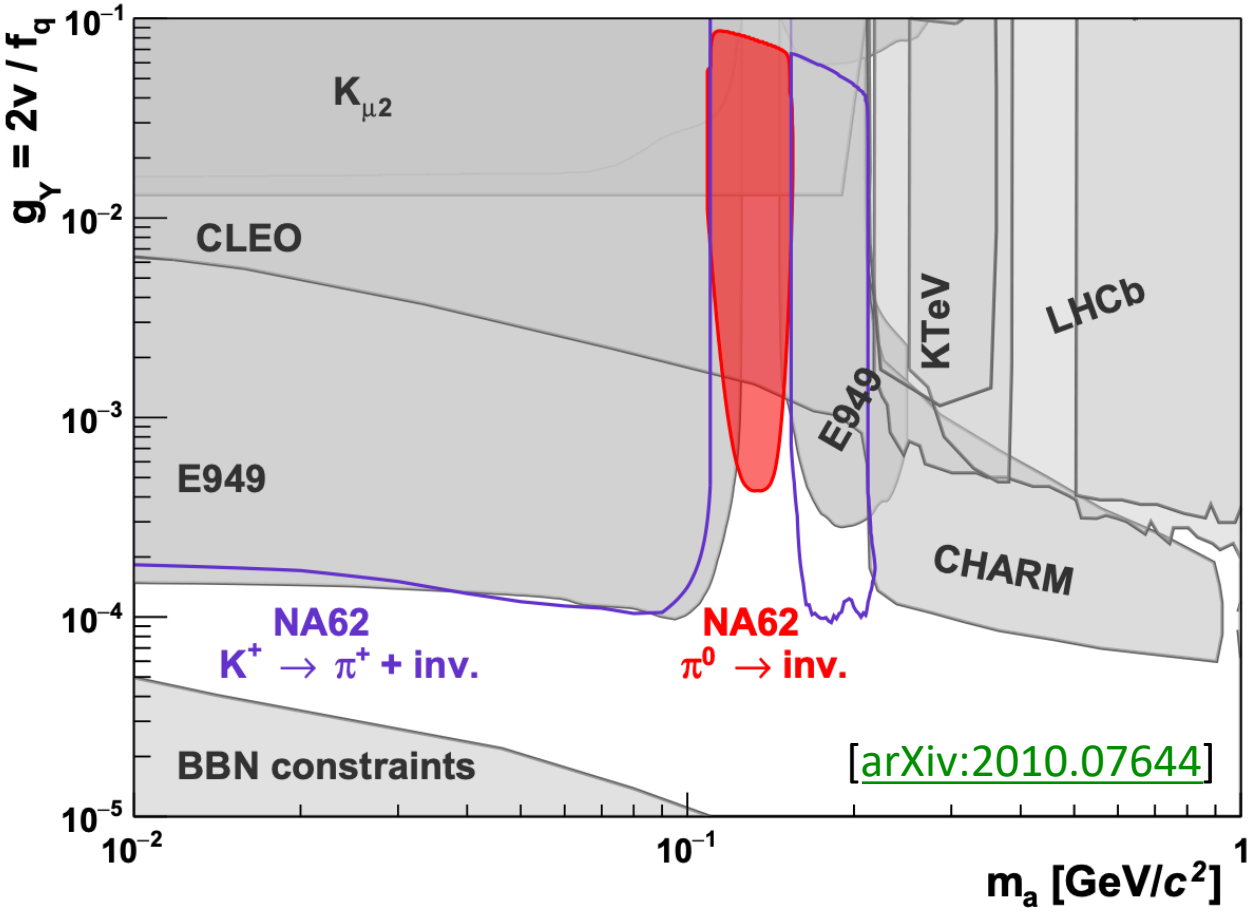
X is a dark scalar

[BC4 PBC model] [M. W. Winkler, Phys. Rev. D 99 (2019) 015018]



X is an ALP

[BC10 PBC model][M. J. Dolan et al., JHEP 03 (2015) 171]

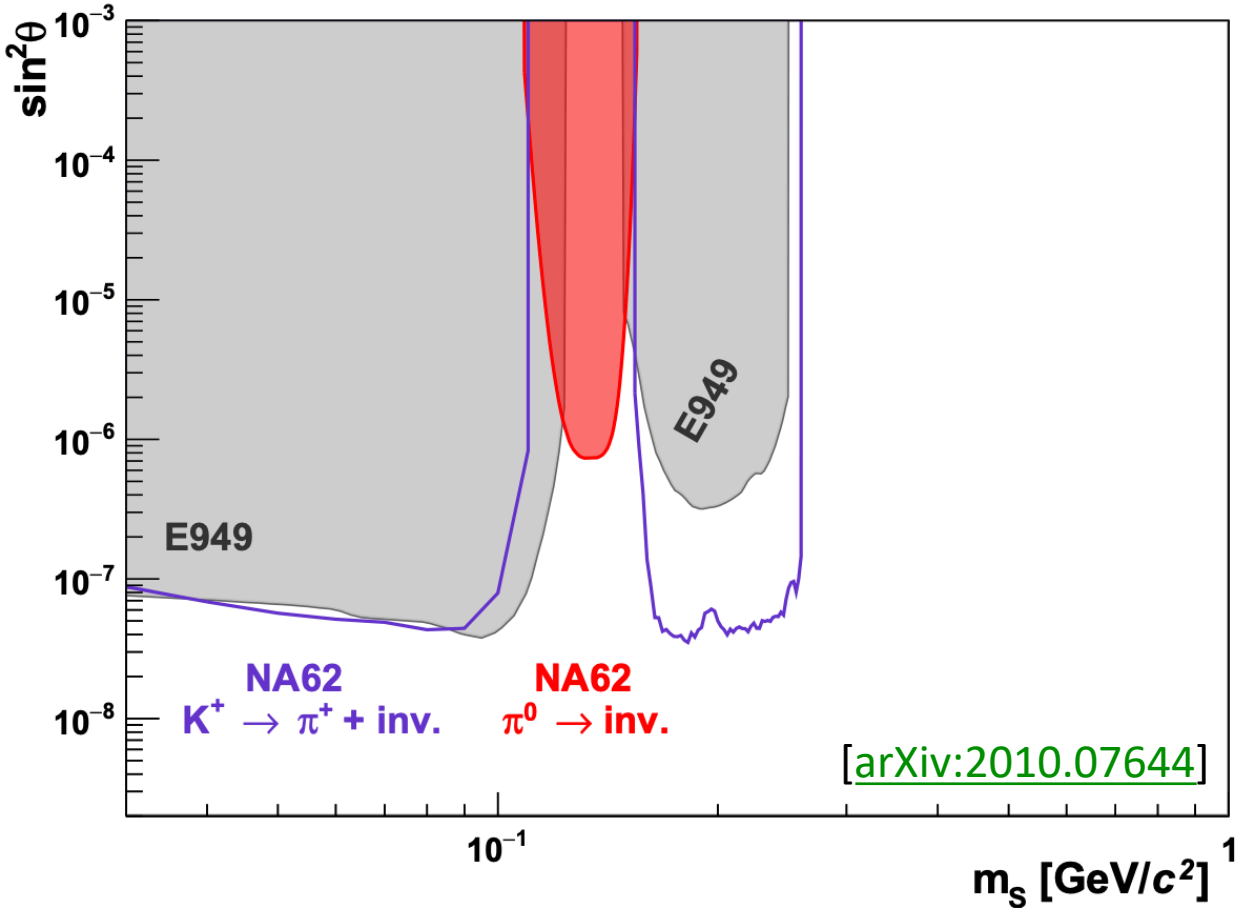


Interpretation: X decays to invisible particles (DM)

[arXiv:2010.07644]

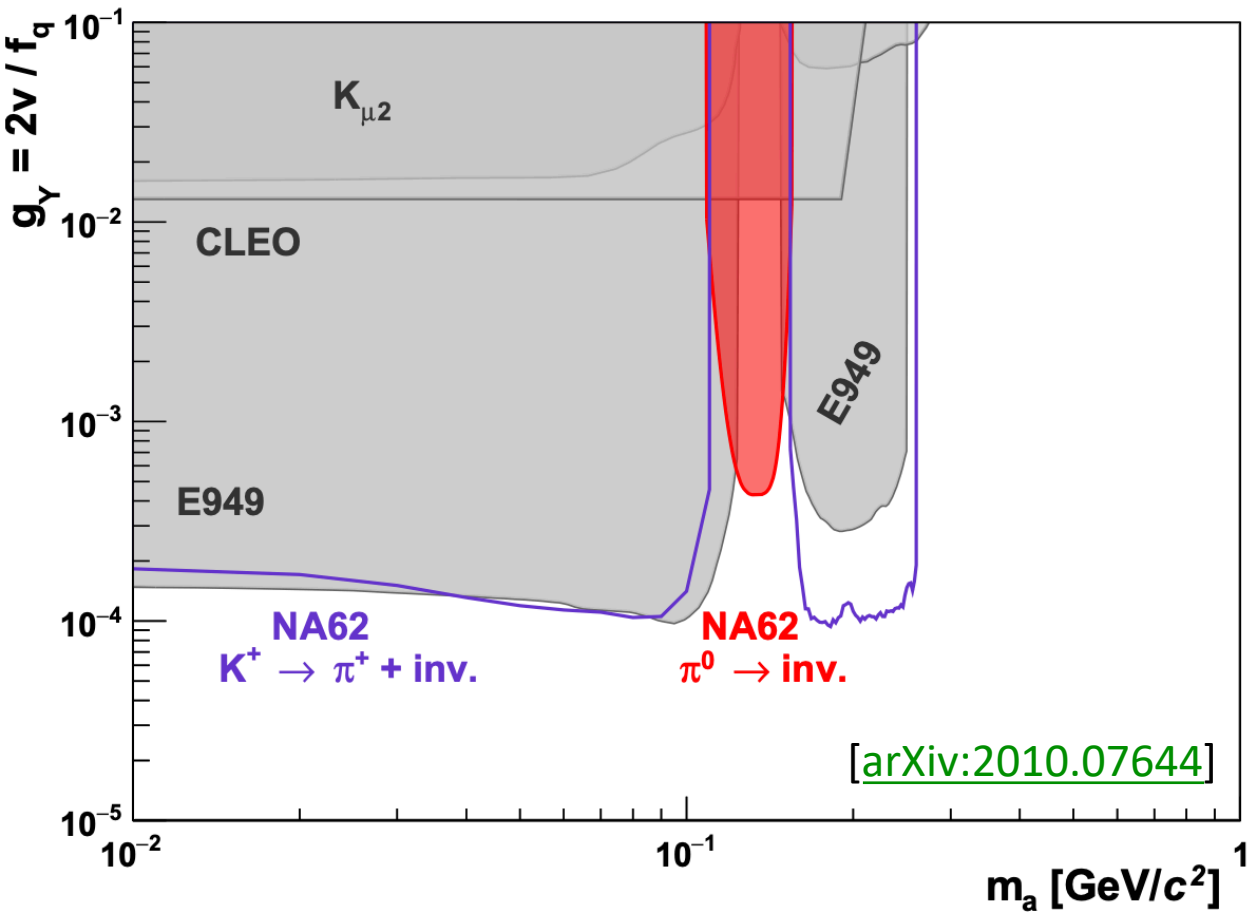
X is a dark scalar

[BC4 PBC model] [M. W. Winkler, Phys. Rev. D 99 (2019) 015018]



X is an ALP

[BC10 PBC model][M. J. Dolan et al., JHEP 03 (2015) 171]

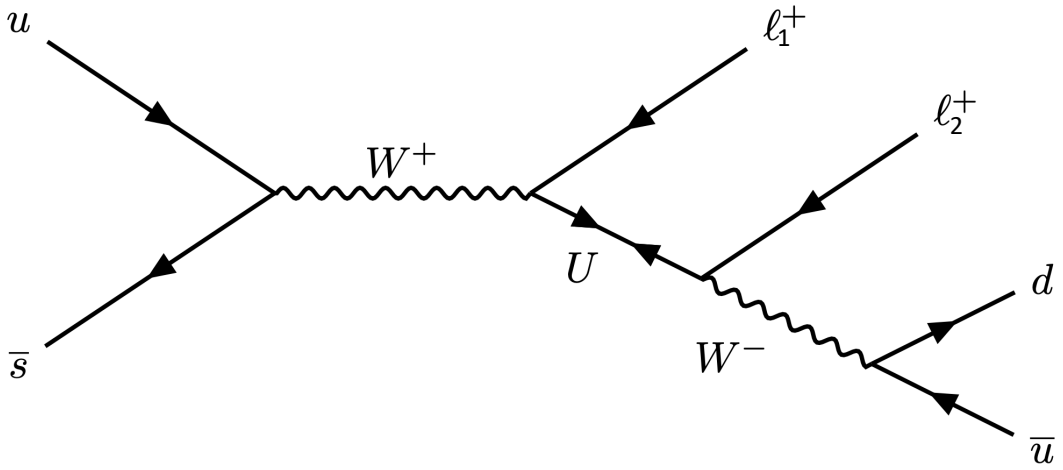


Part 3 : Searches for Lepton Number Violation (LNV) & Lepton Flavour Violation (LFV) in K^+ decays

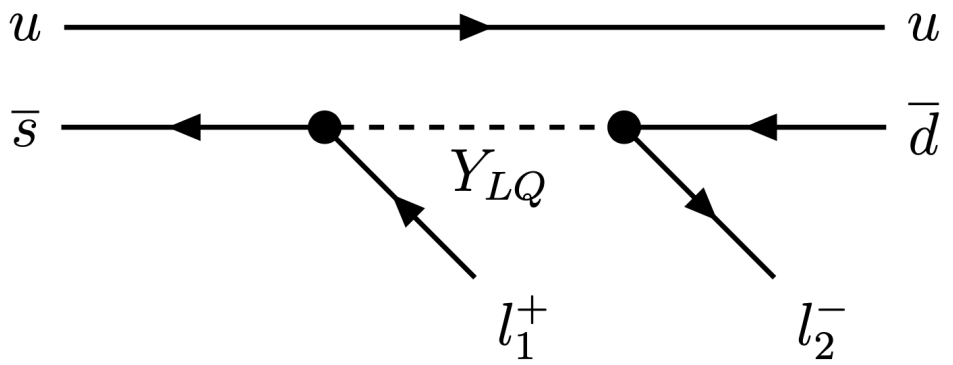
LFV & LNV in Kaon Decays

- 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. $K^+ \to \pi^+ \mu^- e^+$ decays ($\Delta L_\mu = 1$) 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.

LNV/LFV Searches at NA62

- Pre-NA62 Status :

	Decay	LNV/LFV ?	BR Upper Limit @ 90% CL	Experiment [Ref.]
$K^+ \to \pi^- \ell^+ \ell^+$	$K^+ \to \pi^- \mu^+ \mu^+$	LNV	8.6×10^{-11}	NA48/2 [PLB 769 (2017) 67]
	$K^+ \to \pi^- e^+ e^+$	LNV	6.4×10^{-10}	E865 [PRL **85**, 2877 (2000)]
$K^+ \to \pi^\pm \mu^\mp e^+$	$K^+ \to \pi^- \mu^+ e^+$	LNV	5.0×10^{-10}	E865 [PRL **85**, 2877 (2000)]
	$K^+ \to \pi^+ \mu^- e^+$	LFV	5.2×10^{-10}	E865 [PRL **85**, 2877 (2000)]
	$K^+ \to \pi^+ \mu^+ e^-$	LFV	1.3×10^{-11}	E865 [PRD **72**, 012005 (2005)]

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$\sim 2, \sim 8, \sim 10, 100$) & 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 & normalisation	
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 & normalisation	signal
Multi-Track	Minimum bias 3-track trigger		Signal & normalisation

- 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.
  - $BR < n^{UL} \times SES$

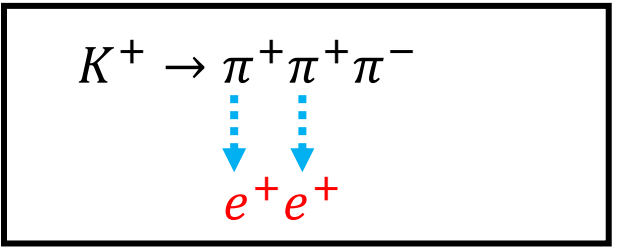
Background Studies

Background Mechanisms:

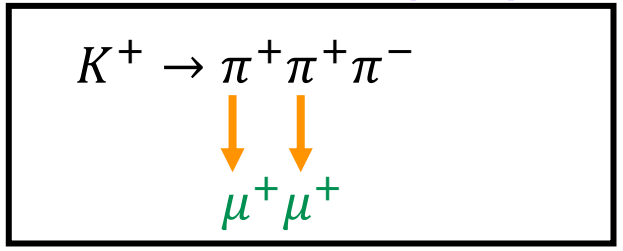
1. Misidentification (misID)
2. Decays in flight (DIF)

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

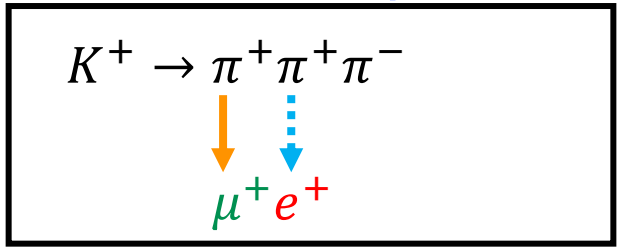
$K^+ \to \pi^- e^+ e^+$



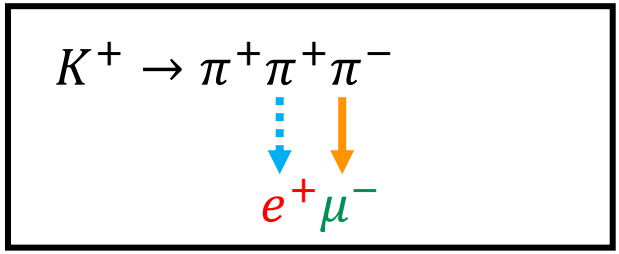
$K^+ \to \pi^- \mu^+ \mu^+$



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



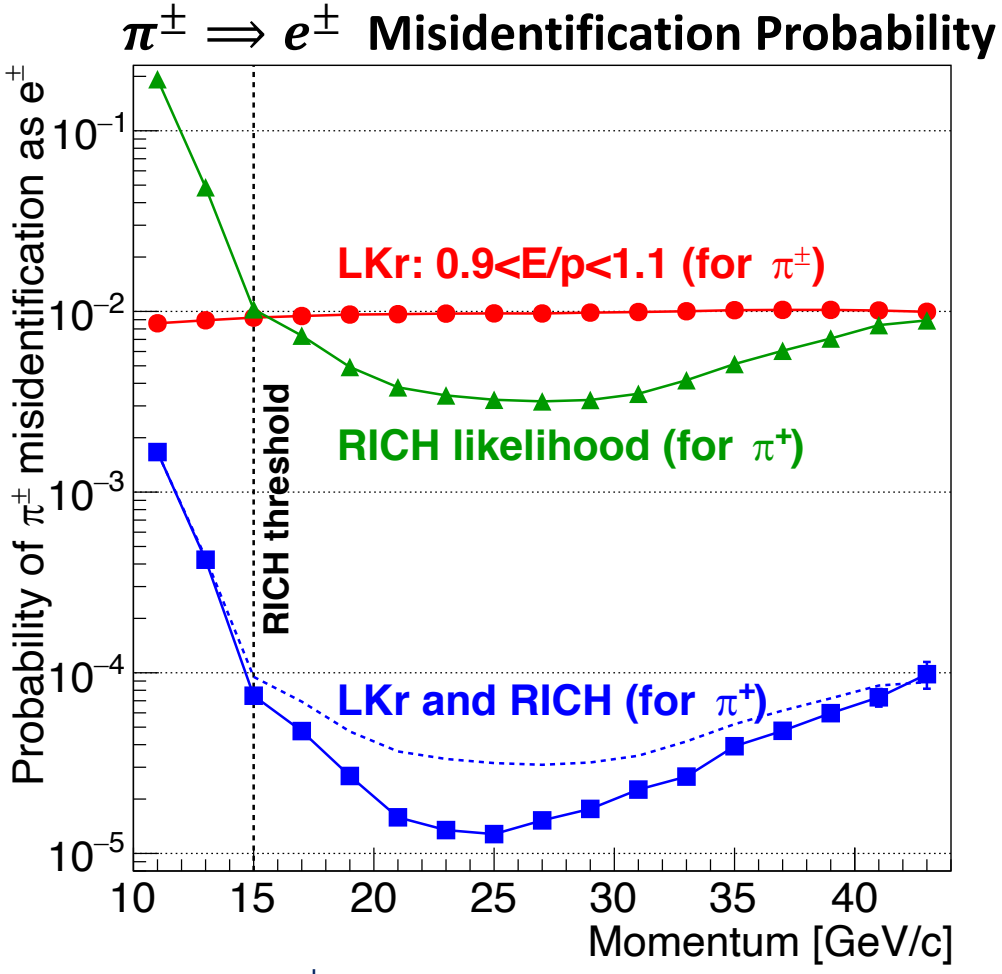
$K^+ \to \pi^+ \mu^- e^+$



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 $BR = 99.9\%$ $[1.2\times10^{-4}]$

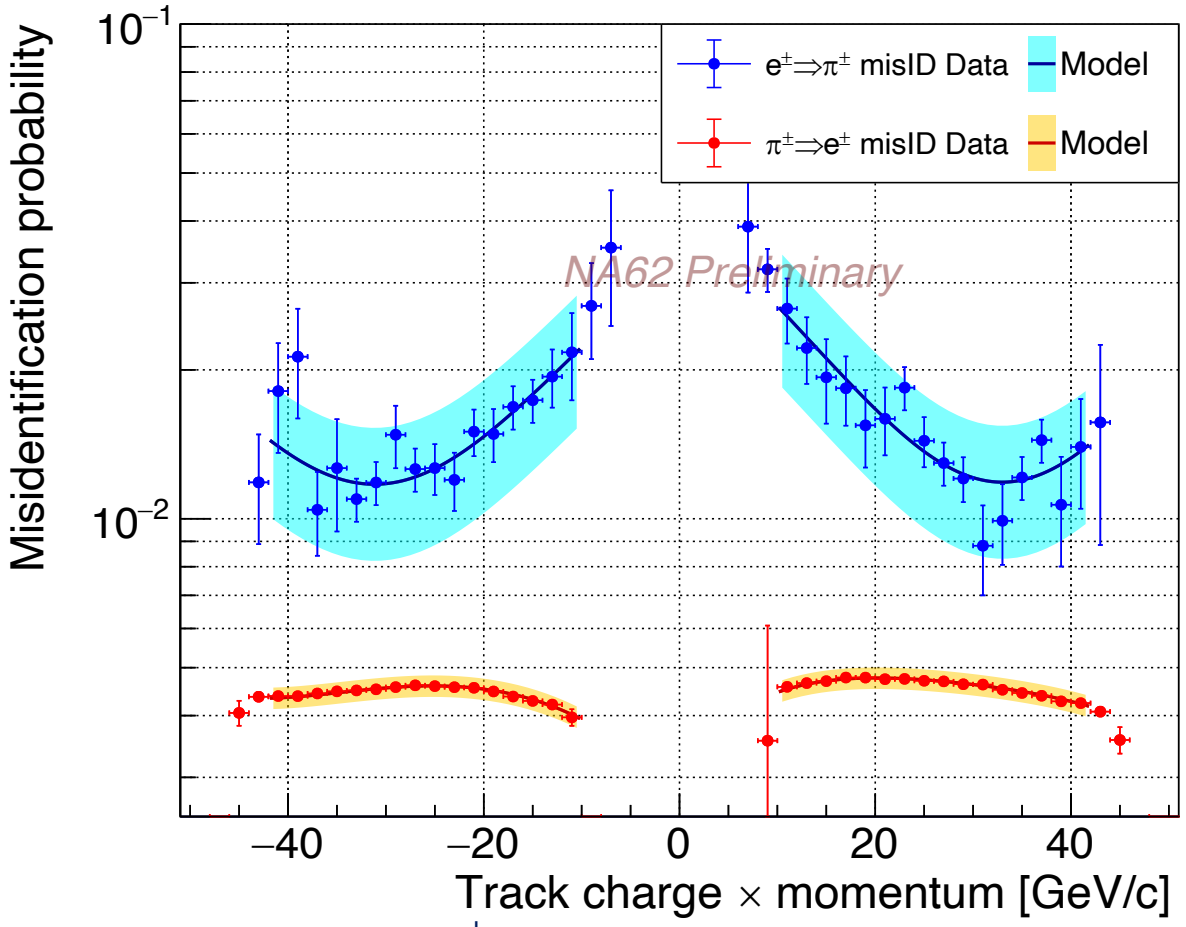
Background Studies : misID

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



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

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

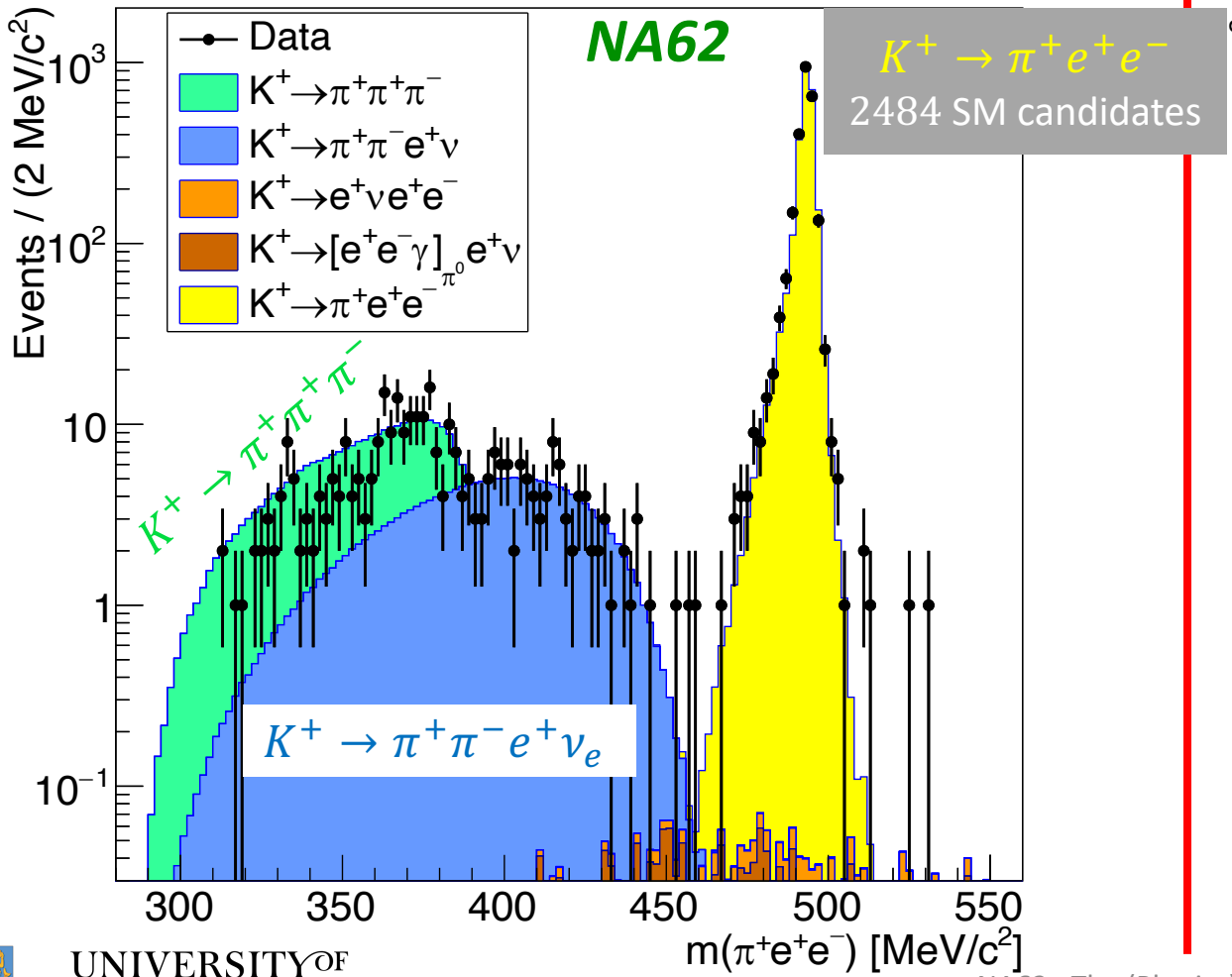


- $\pi^\pm$: $E/p < 0.9$
- $e^\pm$: $0.95 < E/p < 1.05$

$K^+ \to \pi^- e^+ e^+ : M_{\pi ee}$ 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).



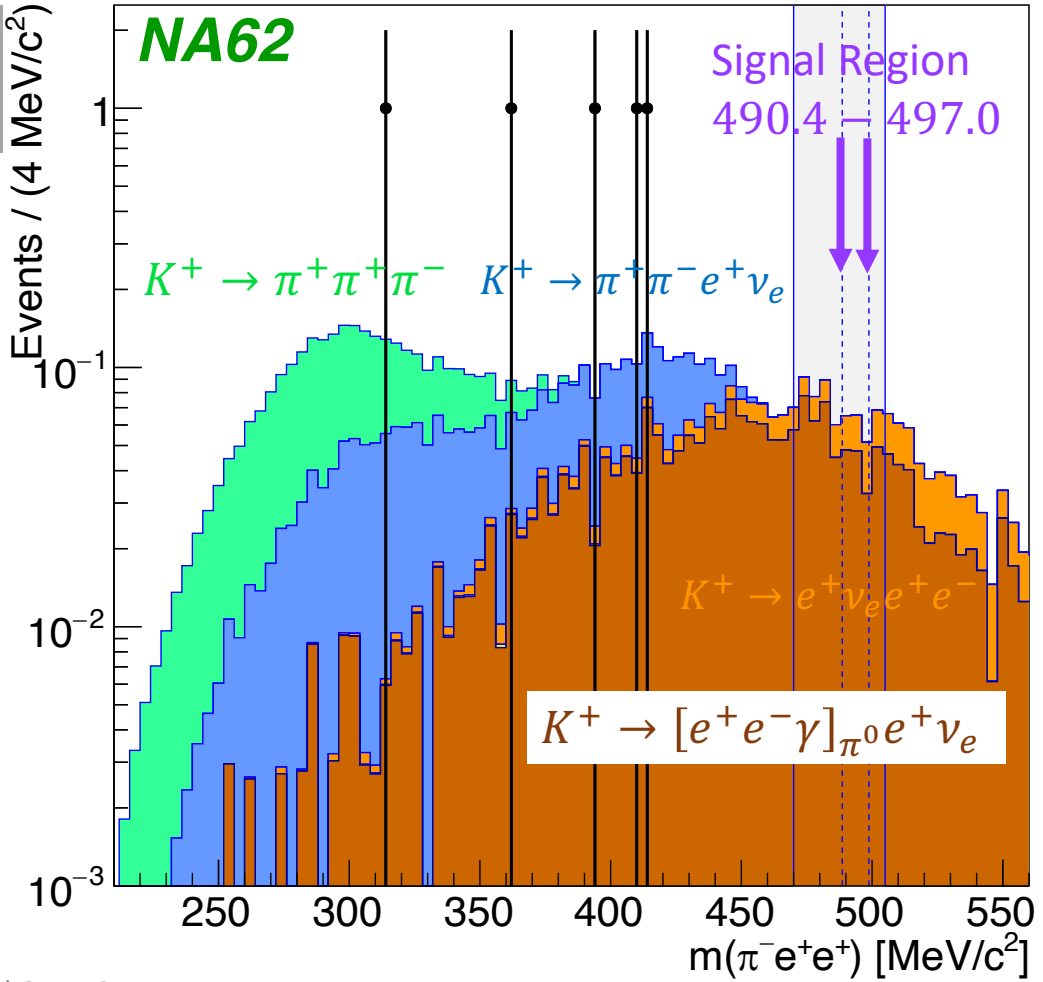
LNV : $K^+ \to \pi^- e^+ e^+$

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.

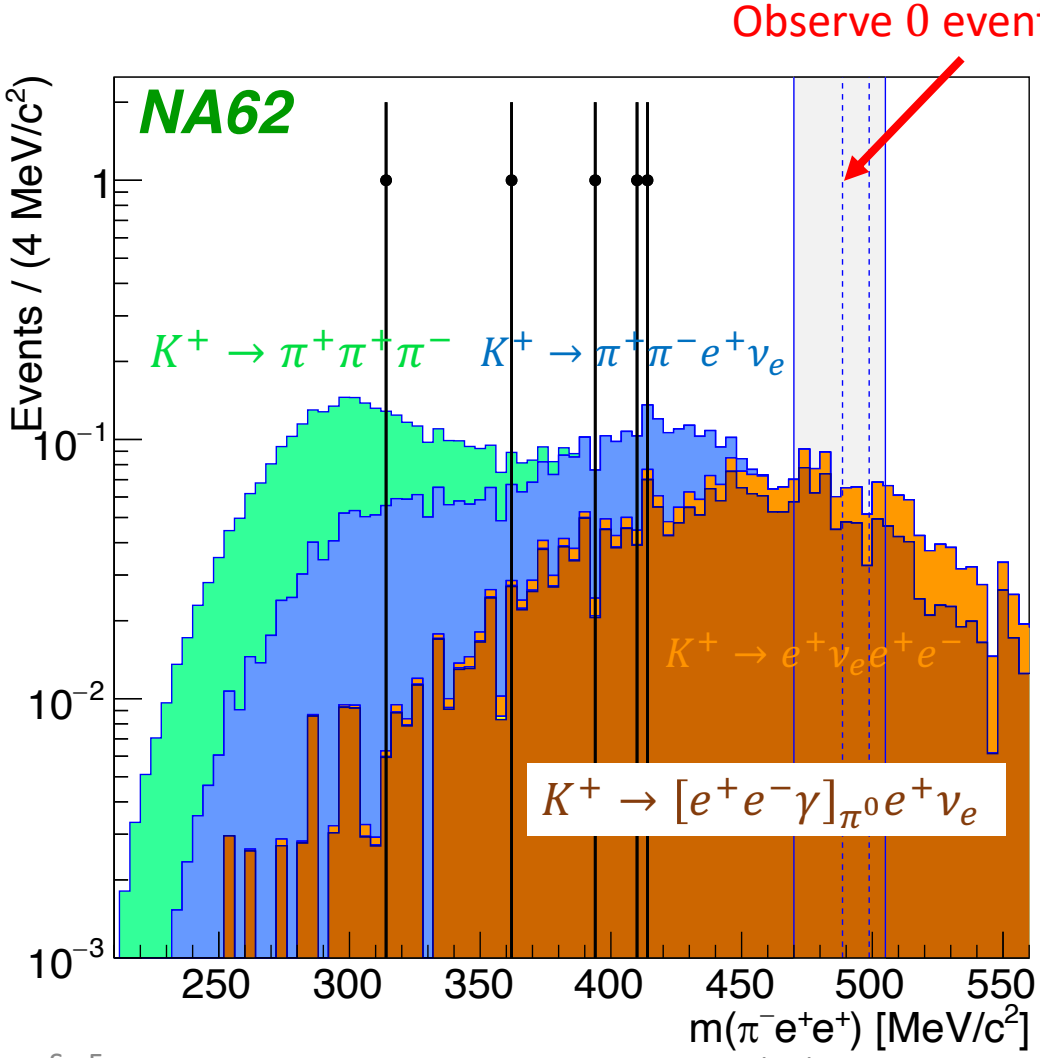
Signal Region

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

Observe : $n_{SR} = 0$

Result

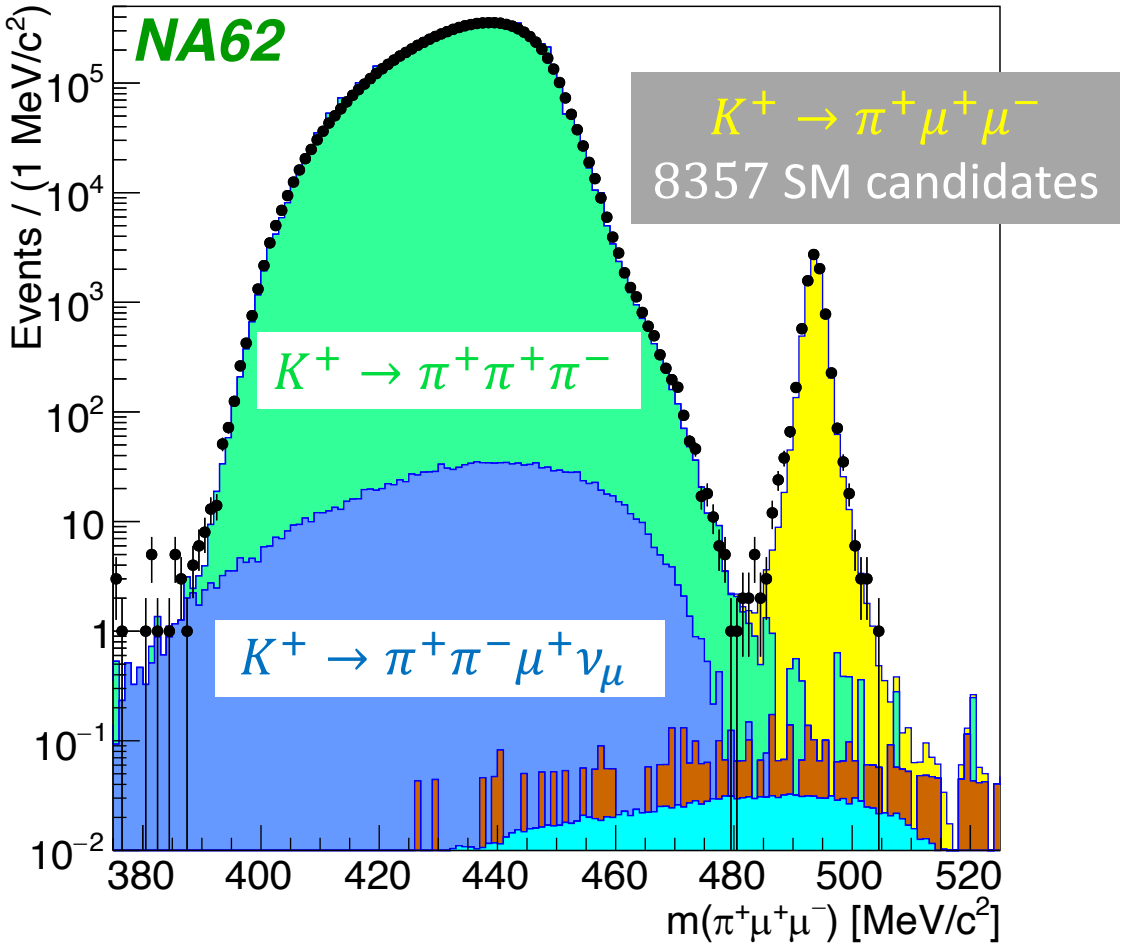
$$\boldsymbol{BR(K^+ \to \pi^- e^+ e^+) < 2.2\times10^{-10} \text{ @ } 90\% \text{ CL}}$$



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

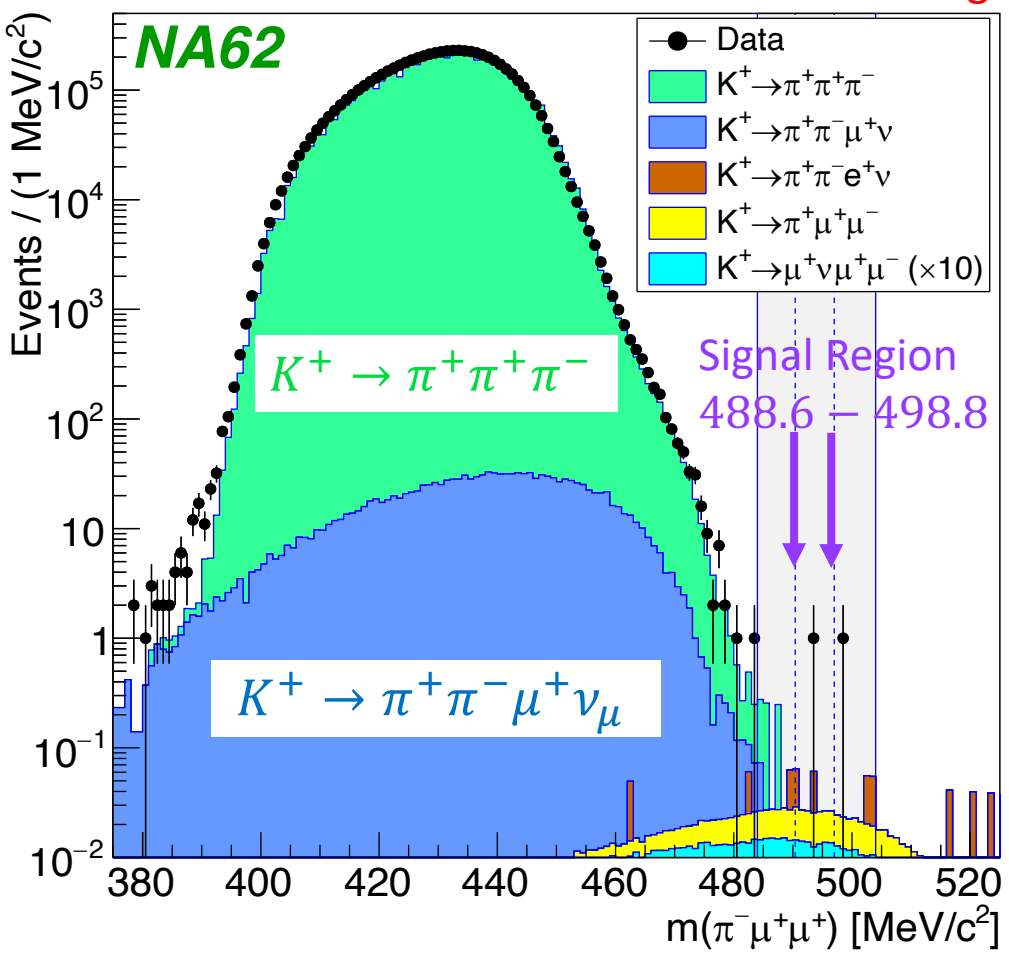
SM : $K^+ \to \pi^+\mu^+\mu^-$

$BR = (9.4 \pm 0.6)\times10^{-8}$: 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

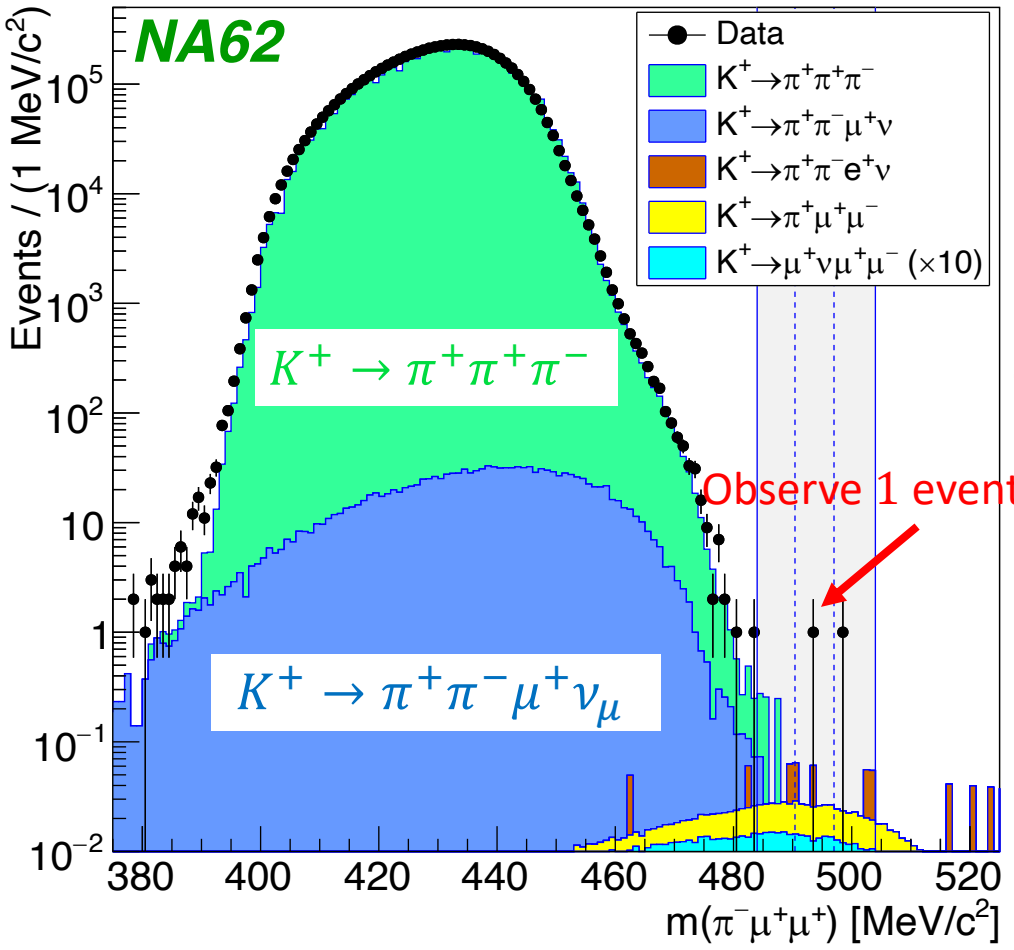
LNV : $K^+ \to \pi^-\mu^+\mu^+$

Signal Region

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

Result

$$\boldsymbol{BR(K^+ \to \pi^-\mu^+\mu^+) < 4.2\times10^{-11}\ @\ 90\%\ CL}$$



Predicted Background in Signal Region

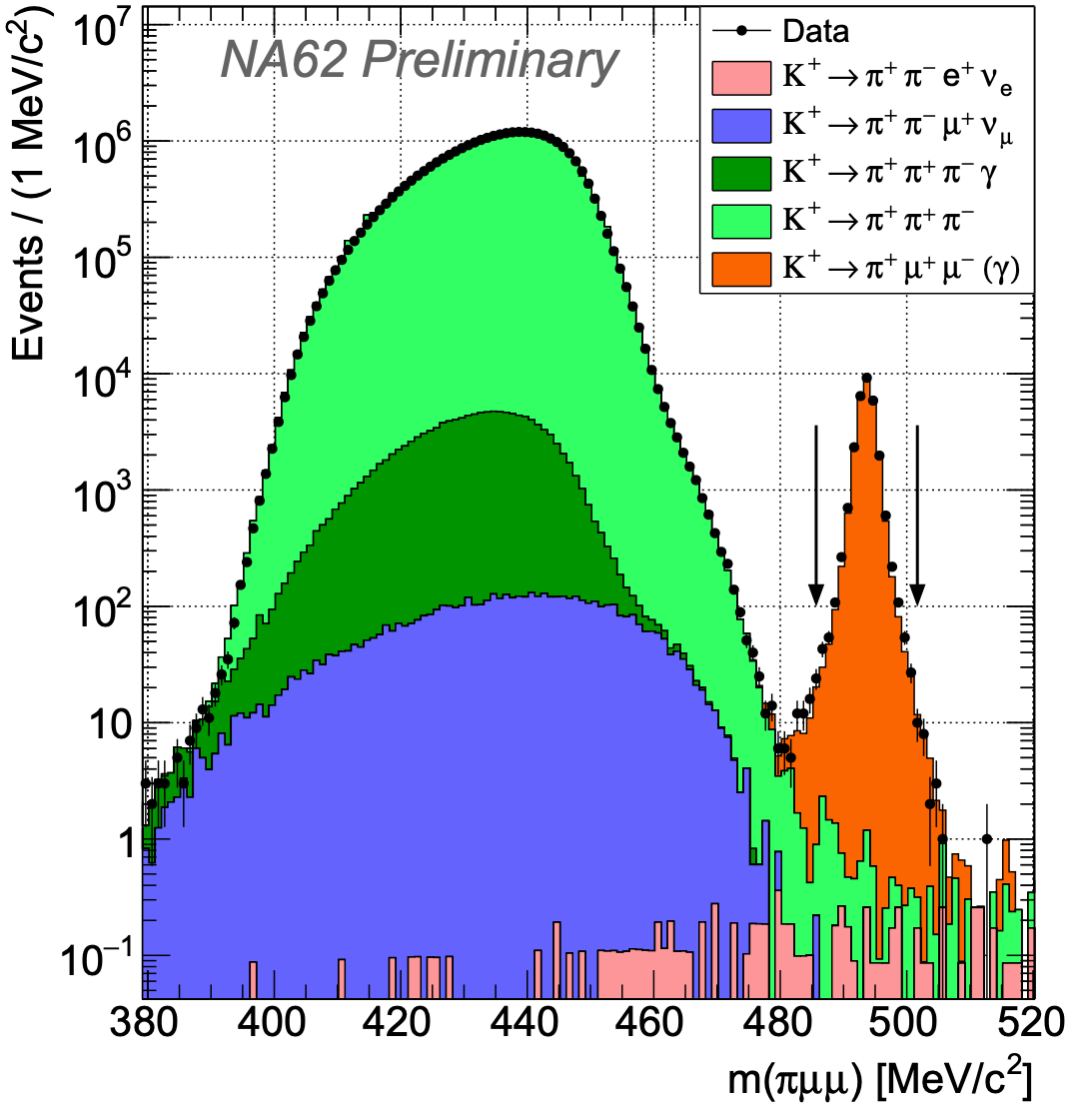
0.70 ± 0.40
0.05 ± 0.05
0.07 ± 0.05
0.08 ± 0.02
0.01

Total = $\boldsymbol{0.91 \pm 0.41}$

Observe 1 event in SR

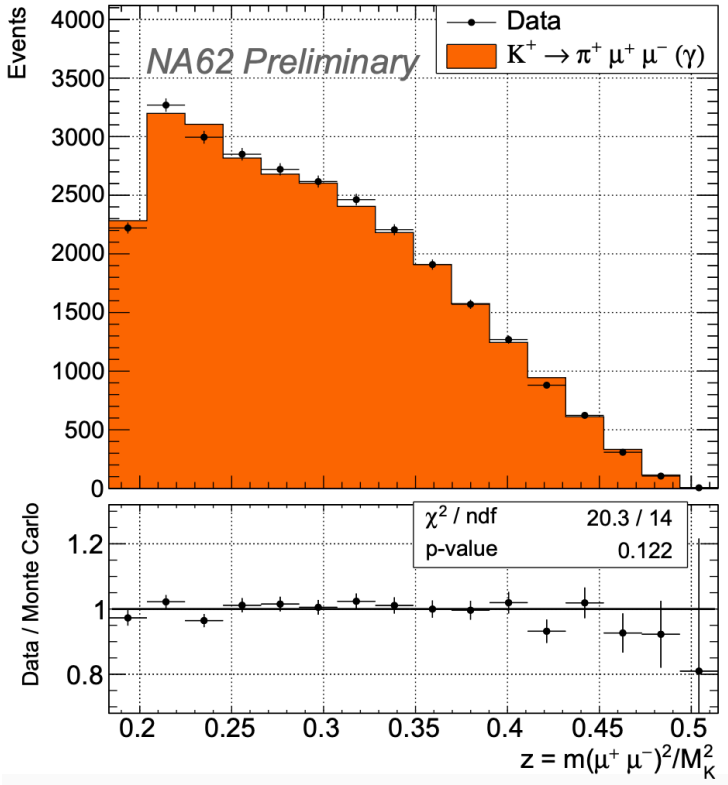
Aside : SM $K^+ \to \pi^+\mu^+\mu^-$

[reported at ICHEP L. Bican]



- N(πμμ) = 28011
  - ~ 9× more than NA48/2
  - Expected bkg = $12.5 \pm 1.7_{stat} \pm 12.5_{syst}$

- Dalitz variable : $z = \frac{M(\mu\mu)^2}{m_K{}^2}$



Aside : SM $K^+ \to \pi^+\mu^+\mu^-$ & LFU

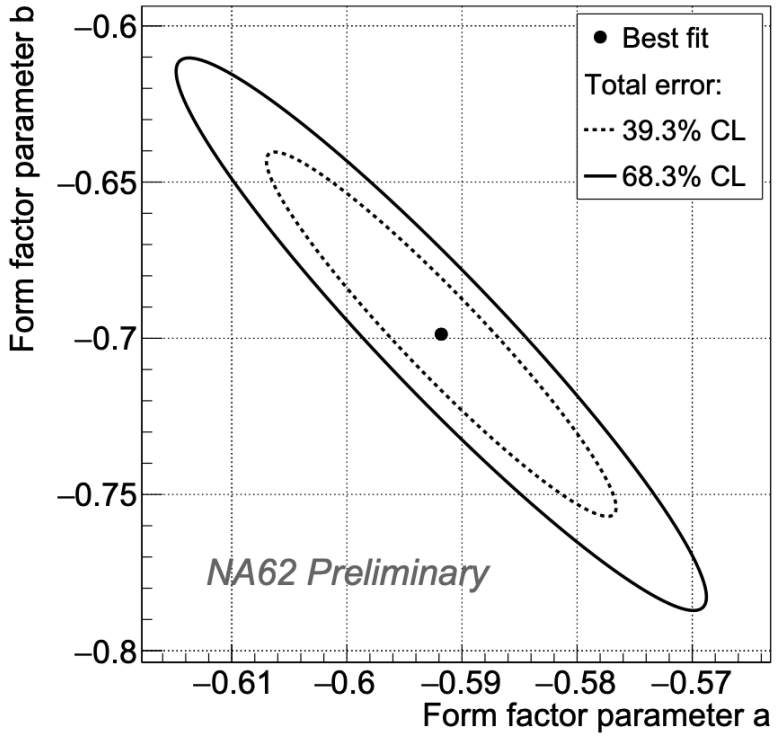
[reported at ICHEP L. Bican]

- Parameterize Form Factor $W(z)$ in NLO ChPT [JHEP 08 (1998) 004]

$$W(z) = G_F {m_K}^2 (a + bz) + W^{\pi\pi}(z)$$

where $W^{\pi\pi}(z)$ is the $K_{3\pi}$ pion loop term.

- Fit to z spectrum used to determine best-fit a and b parameters (minimizing $\chi^2(a, b)$)



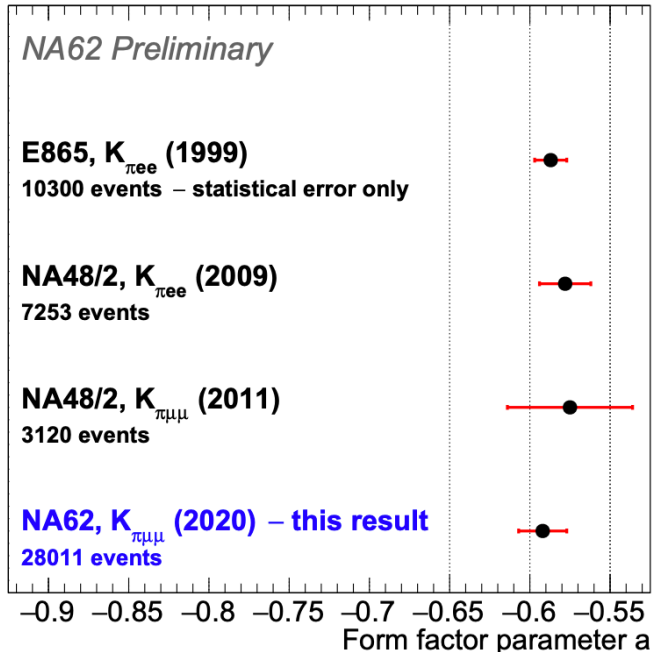
Best fit of FF parameters:

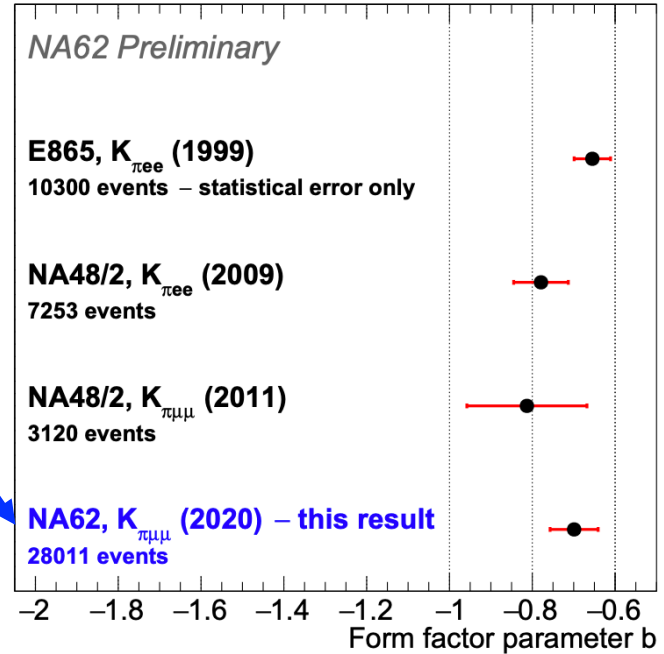
- $a = -0.592 \pm 0.013_{\text{stat}}$
- $b = -0.699 \pm 0.046_{\text{stat}}$
- Goodness of fit: $\chi^2/\text{ndf} = 20.3/14$, p-value $= 0.122$

Model-Dependent BR:

$BR(K^+ \to \pi^+\mu^+\mu^-)$
$= (9.27 \pm 0.07_{stat}) \times 10^{-8}$

No tension with LFU

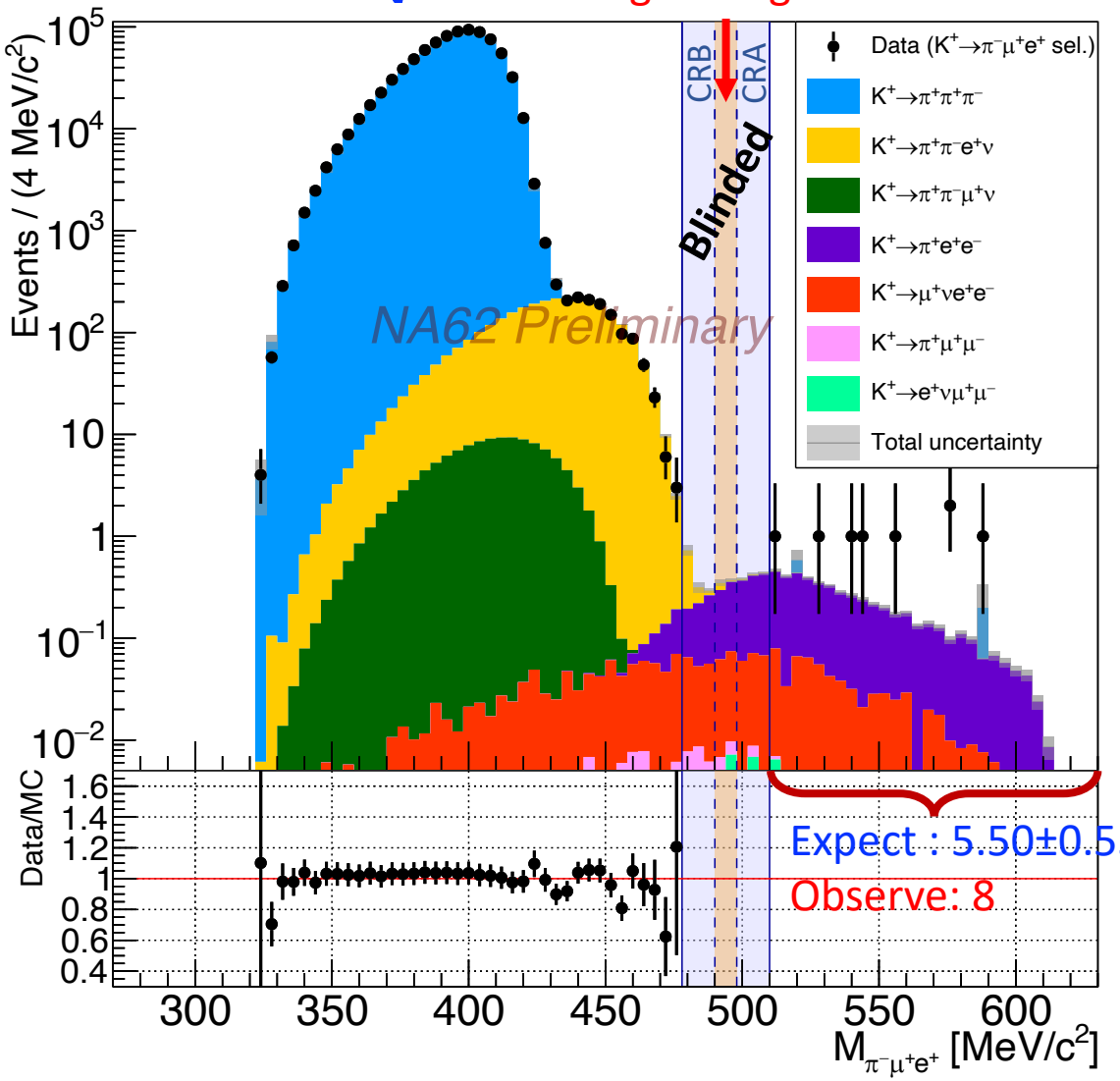




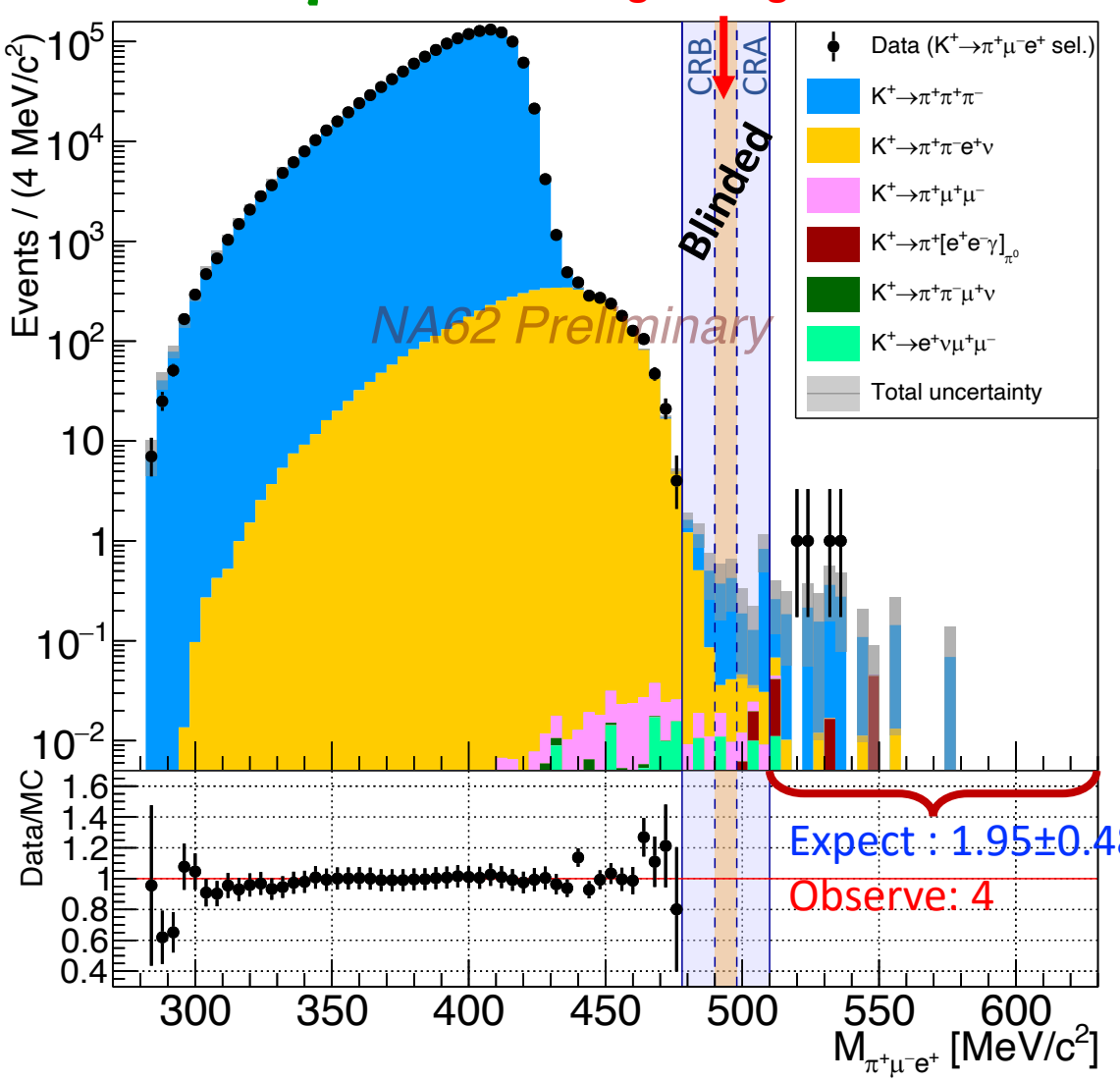
Searches for $K^+ \to \pi^\pm \mu^\mp e^+$

[J. Swallow @ ICHEP]

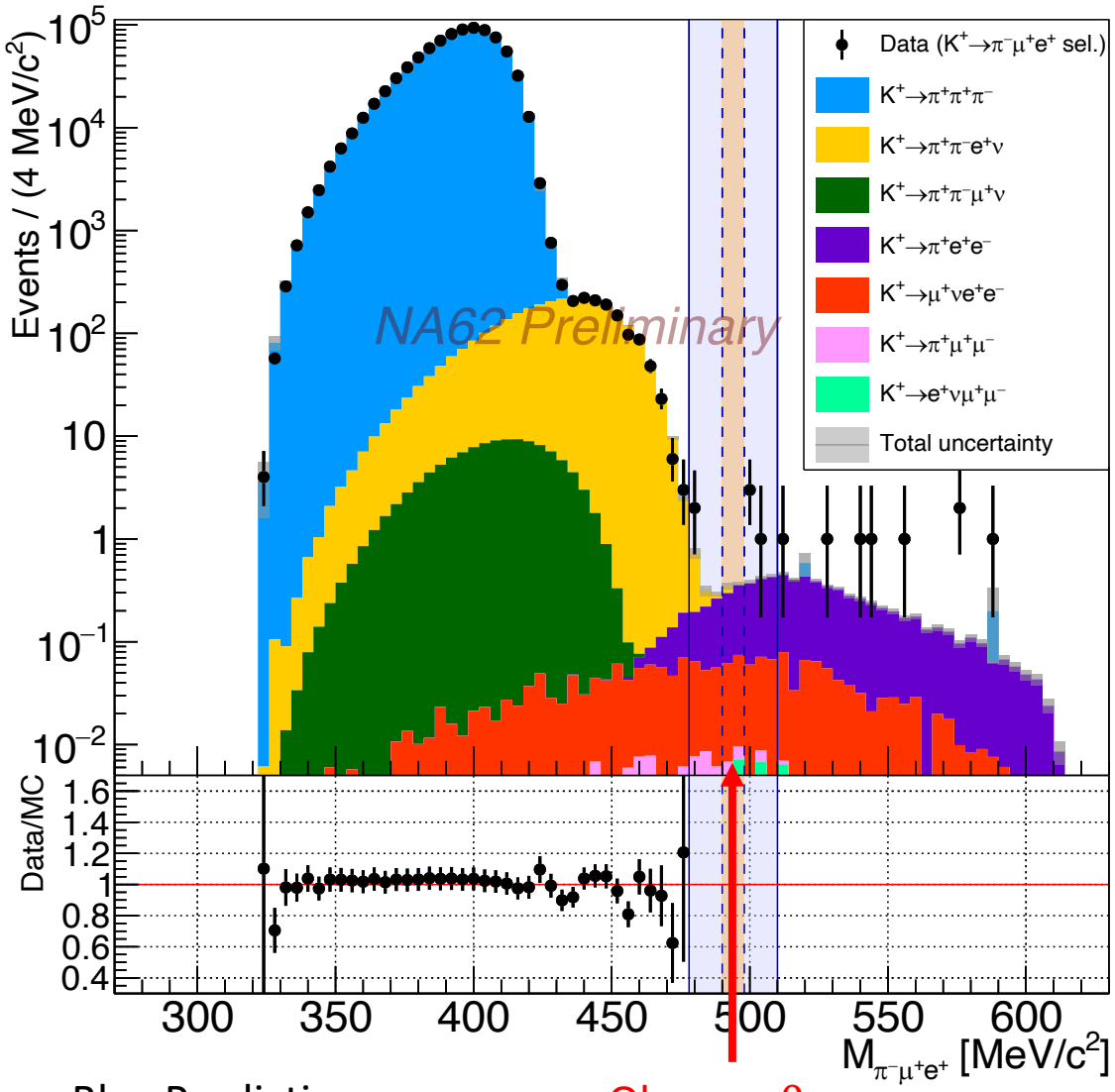
$K^+ \to \pi^- \mu^+ e^+$ Signal Region



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



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



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

Observe 0 events in SR

Signal Region

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

Result

$$\boldsymbol{BR(K^+ \to \pi^-\mu^+e^+) < 4.2\times10^{-11}\ @\ 90\%\ CL}$$

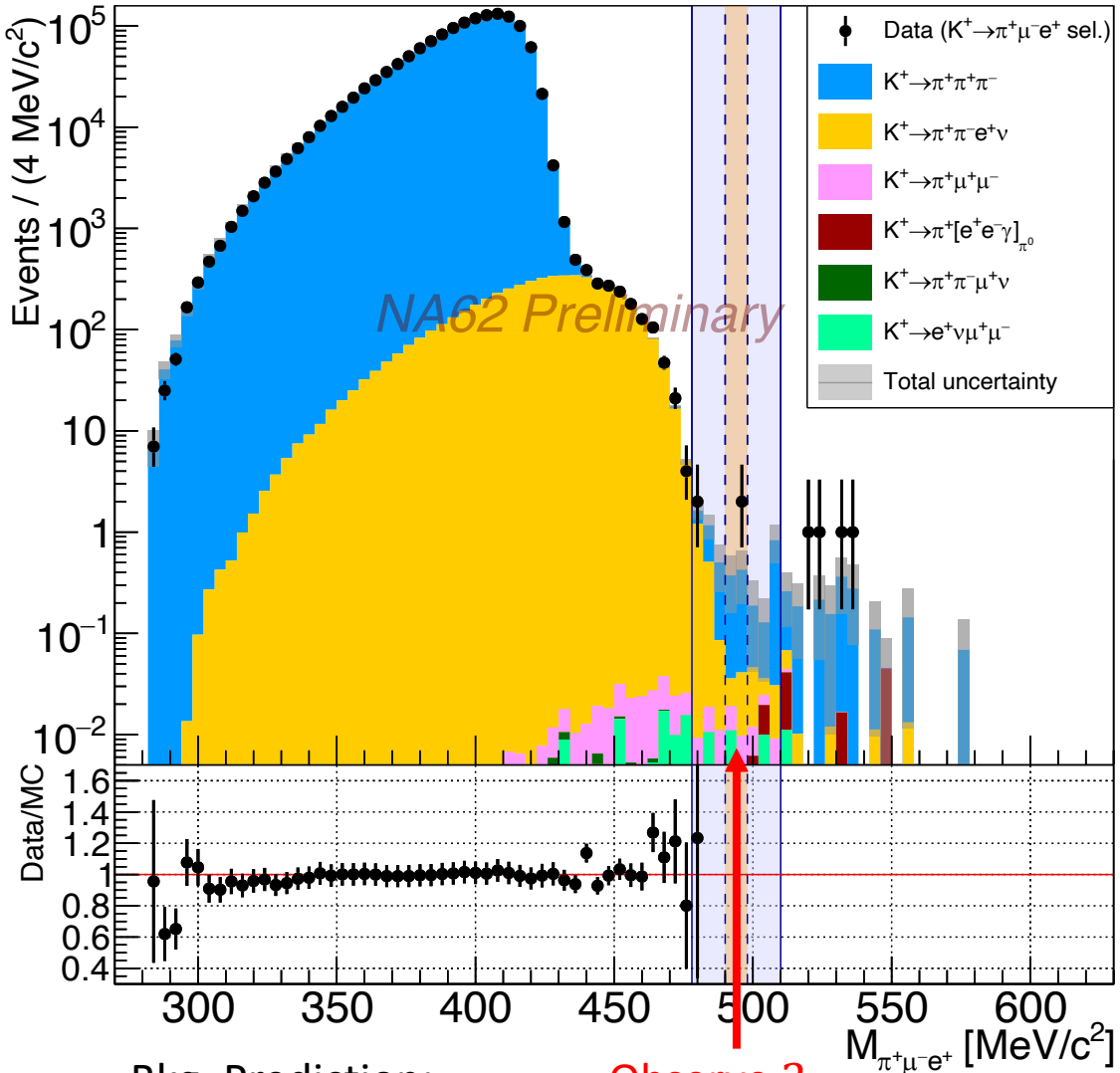
$K^+ \to \pi^+\mu^-e^+$: Results

Signal Region

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

Result

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



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

Observe 2 events in SR

LNV & LFV 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 density.

Part 4 : Searches for Hidden Sector Particles

Searches for Dark Photons

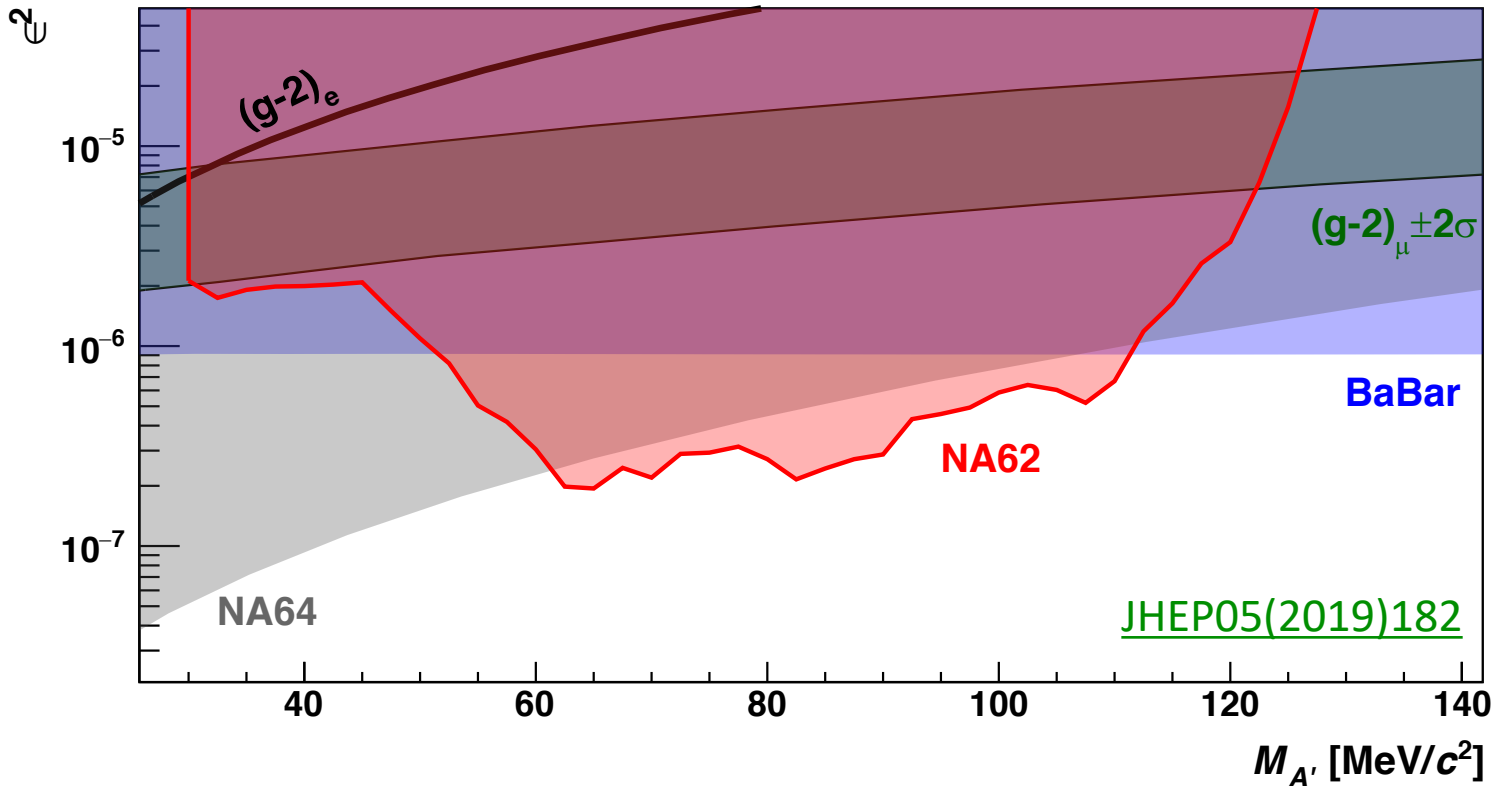
JHEP05(2019)182

- NA62 Search for: $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma A'$, $A' \to$ Invisible ($\chi\bar{\chi}$)

$$\mathrm{BR}\left(\pi^0 \to A'\gamma\right) = 2\epsilon^2 \left(1 - \frac{M_{A'}^2}{M_{\pi^0}^2}\right)^3 \times \mathrm{BR}\left(\pi^0 \to \gamma\gamma\right).$$

$$\mathrm{BR}(\pi^0 \to A'\gamma) = \mathrm{BR}(\pi^0 \to \gamma\gamma)\frac{n_{\mathrm{sig}}}{n_{\pi^0}}\frac{1}{\varepsilon_{\mathrm{sel}}\varepsilon_{\mathrm{trg}}\varepsilon_{\mathrm{mass}}},$$

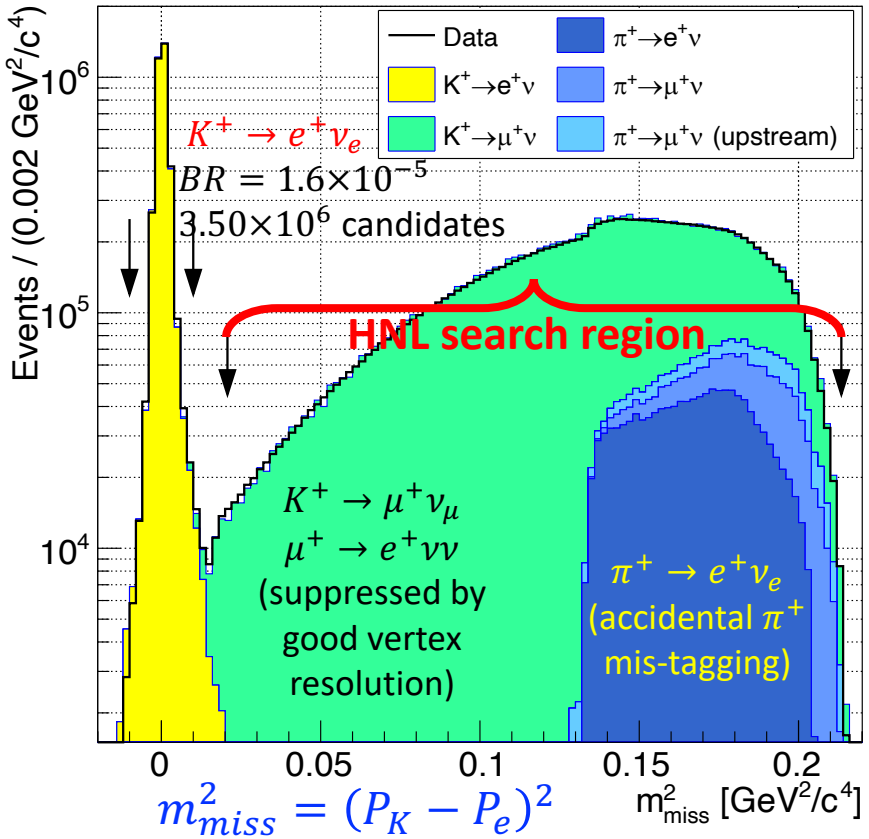
- Peak search in $m^2_{miss} = \left(P_{K^+} - P_{\pi^+} - P_{\gamma}\right)^2$.
- Using 1% of Run 1 statistics (with $n_{\pi^0} \approx 412\times10^6$ selected $K^+ \to \pi^+\pi^0$ events with $< 10^{-3}$ relative contamination).
- Result superseded by later NA64 result [Phys. Rev. Lett. **123**, 121801]



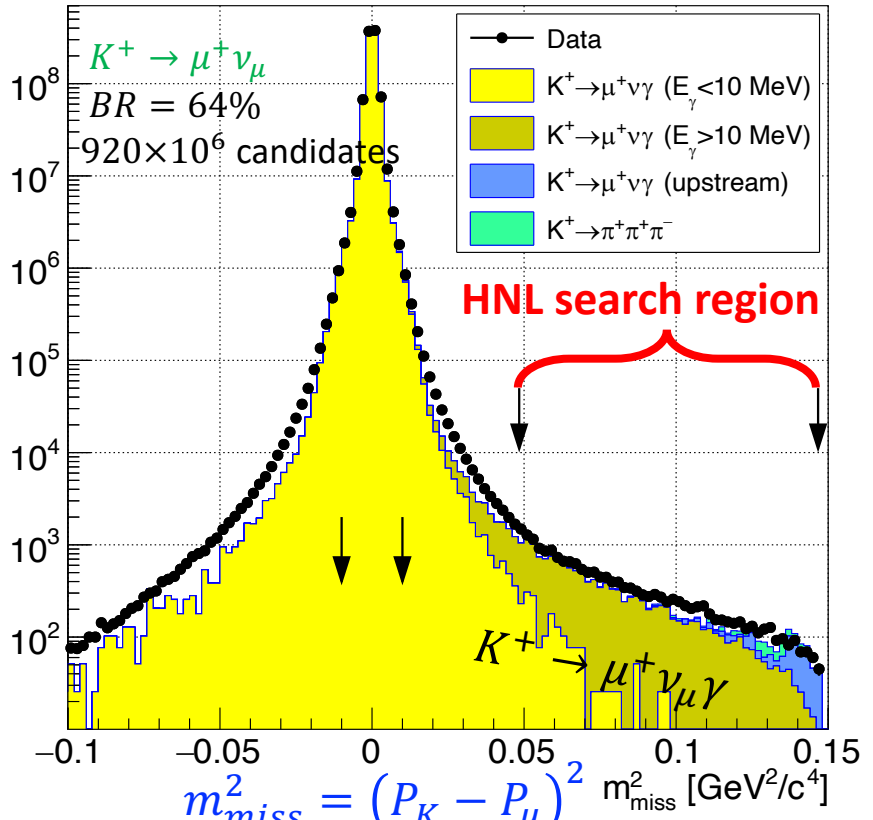
Searches for Heavy Neutral Leptons: $K^+ \to \ell^+ N$

- Triggers: same as for $K^+ \to \pi^+ \nu\bar{\nu}$ for $K^+ \to e^+ N$, and min. bias control trigger for $K^+ \to \mu^+ N$.
- Numbers of K^+ decays in FV: $N_K(K^+ \to e^+ N\ search) = (3.52 \pm 0.02)\times 10^{12}$, $N_K(K^+ \to \mu^+ N\ search) = (4.29 \pm 0.02)\times 10^{9}$.
- Squared missing mass: $m^2_{miss} = (P_K - P_\ell)^2$, using STRAW and GTK tracksers.
- HNL production signal**: a spike above continuous missing mass spectrum**.

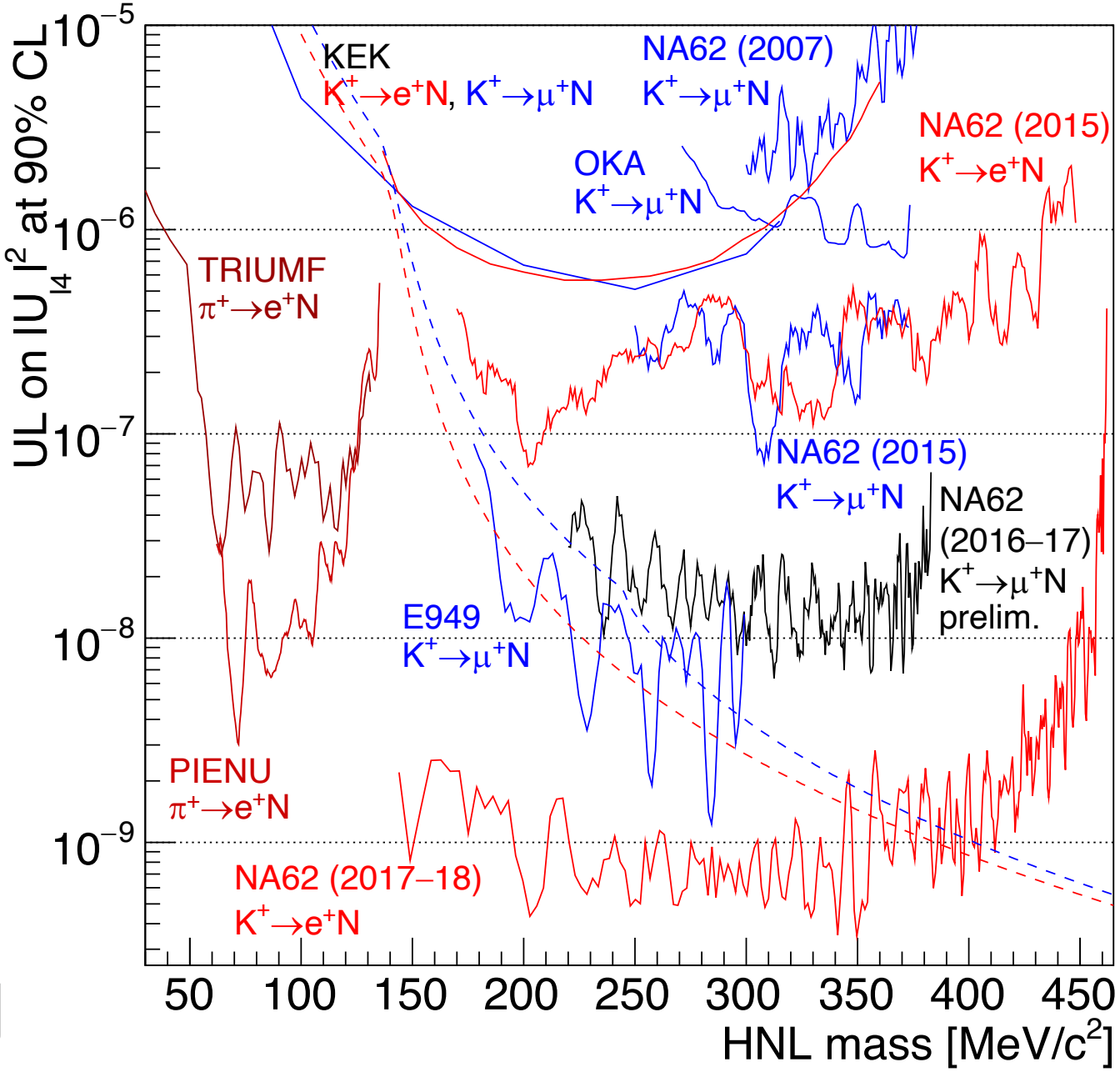
HNL search: $K^+ \to e^+ N$ [Full Run1 (17+18 data)
[Phys. Lett. **B807** (2020) 135599]]



HNL search: $K^+ \to \mu^+ N$ [PRELIMINARY (16+17 data)]
[ICHEP20 E. Goudzovski]



Searches for Heavy Neutral Leptons: $K^+ \to \ell^+ N$



- Full data-set for $|U_{e4}|^2$, $\sim \frac{1}{3}^{\text{rd}}$ of data-set for $|U_{\mu 4}|^2$.
- Improvement in limits on $|U_{\ell 4}|^2$ over earlier production searches by up to two orders of magnitude.
- BBN-allowed phase-space right of dashed lines (potential updates to this? [arXiv:2008.00749]).
  - To left of BBN line N lifetime long enough to over-produce ${}^4_2He$ in early universe.
- $|U_{e4}|^2$ BBN-allowed excluded to 340 MeV.
- $|U_{\mu 4}|^2$ sensitivity for NA62 approaches E949 sensitivity and extends up to 383 MeV.

Conclusions & Outlook

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
> Target 10% precision on $BR_{\pi\nu\nu}$

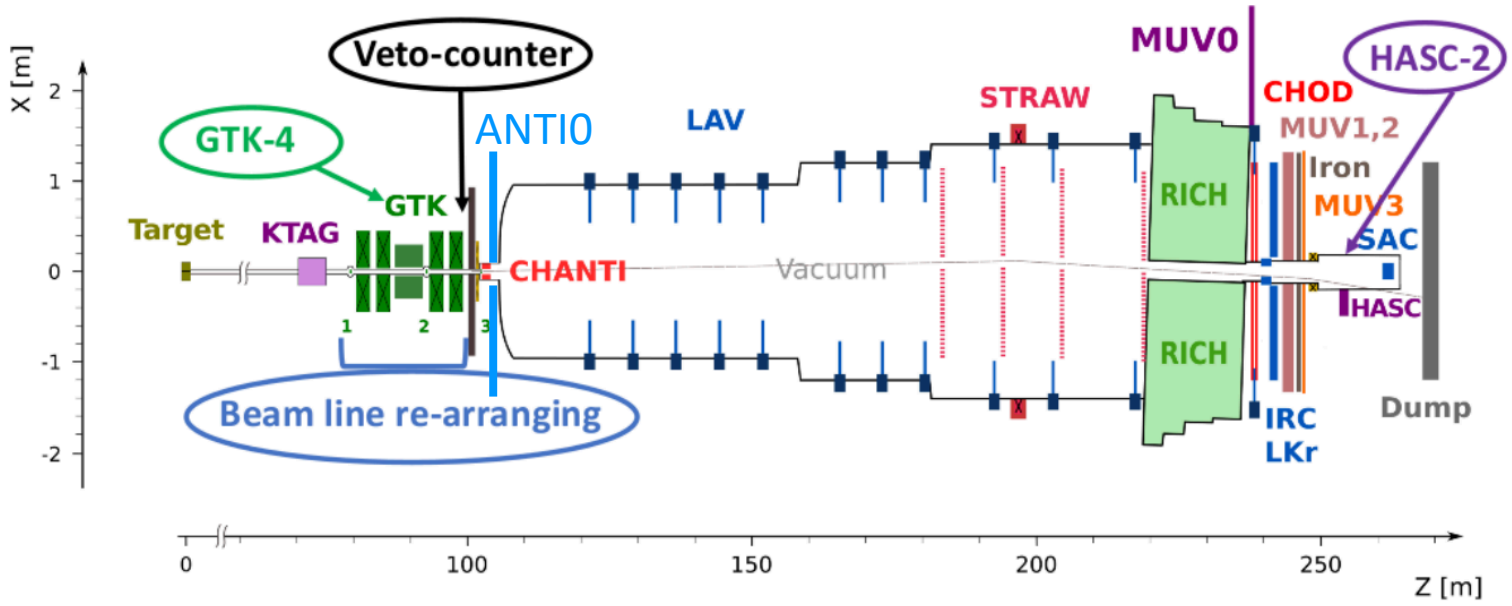
Future targets for NA62…
+ $K^+ \to e^-\nu\mu^+\mu^+$ (no limit in PDG)

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…

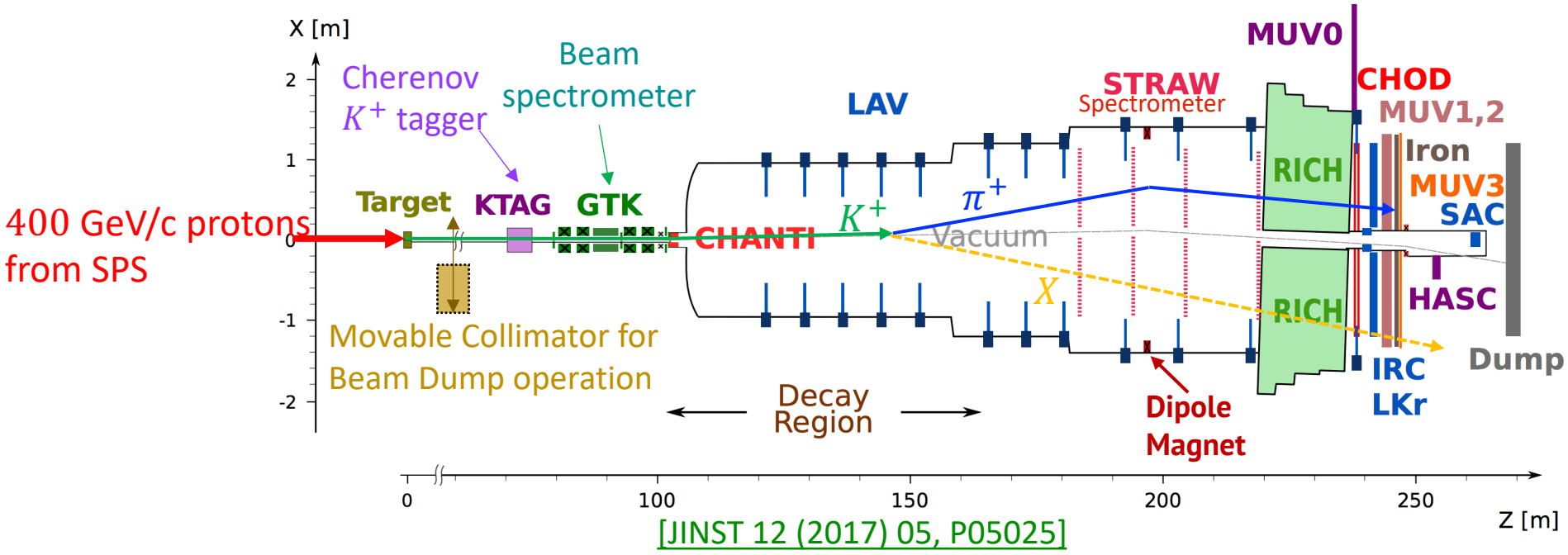
Beam-line & Detector Upgrades



- Re-arranging upstream portion of beam-line and adding new veto detectors to further suppress upstream background for $K^+ \to \pi^+ \nu\bar{\nu}$. (Can also help in hidden sector searches).
- Additional off-axis calorimeter (HASC-2) to further suppress $K^+ \to \pi^+ \pi^0$ background for $K^+ \to \pi^+ \nu\bar{\nu}$.
- Goal: **measure $BR(K^+ \to \pi^+ \nu\bar{\nu})$ with 10% statistical precision** with data to be taken between LS2 & LS3.

Dump Mode & Hidden Sector Searches

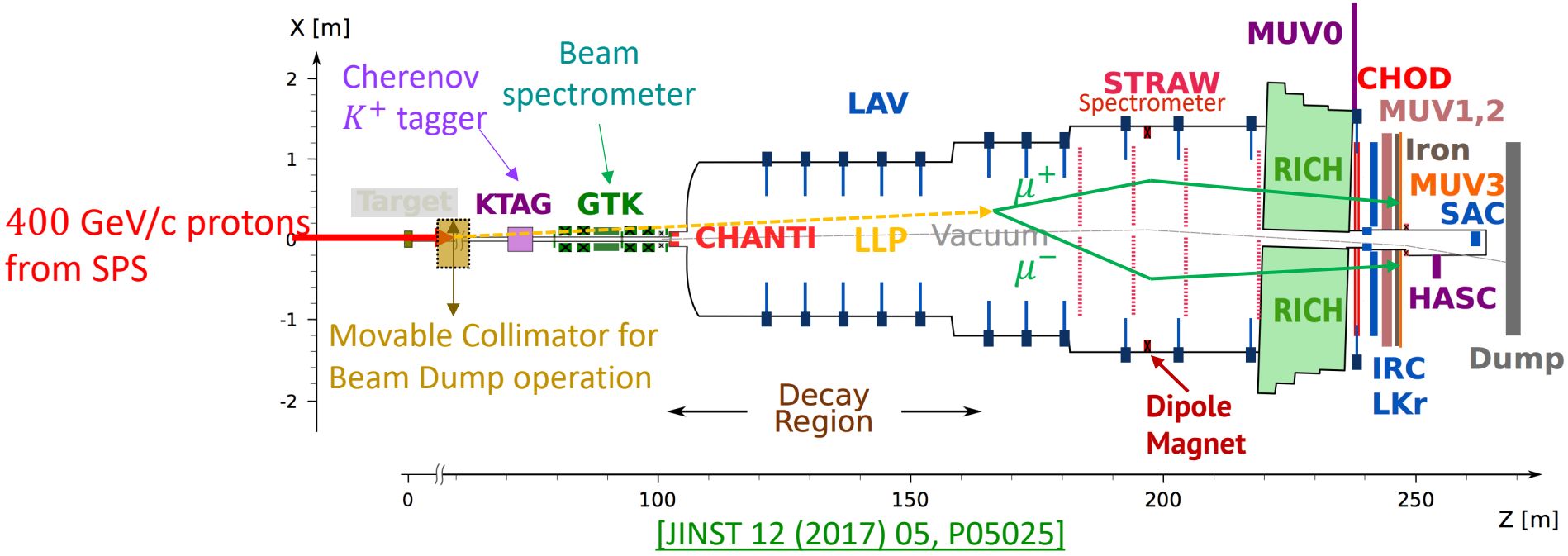
Search in ‘parasitic mode’ during normal data-taking for **LLP production***



*(can also look for production and decay of LLP : e.g. $K^+ \to \pi^+ X$ then $X \to \mu^+\mu^-$ with displaced vertex)

Dump Mode & Hidden Sector Searches

Search in **dump mode** for **LLP decay**

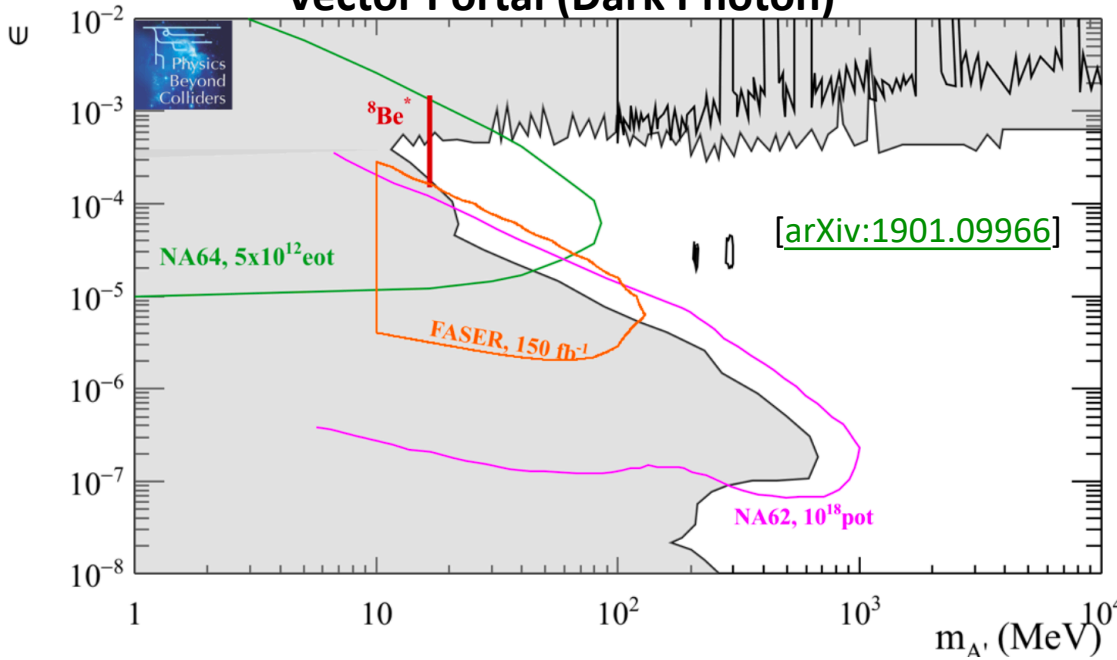


[JINST 12 (2017) 05, P05025]

Proposed to run in Dump mode for ~month during next data-taking (Run2) collecting $\sim 10^{18}$ POT.

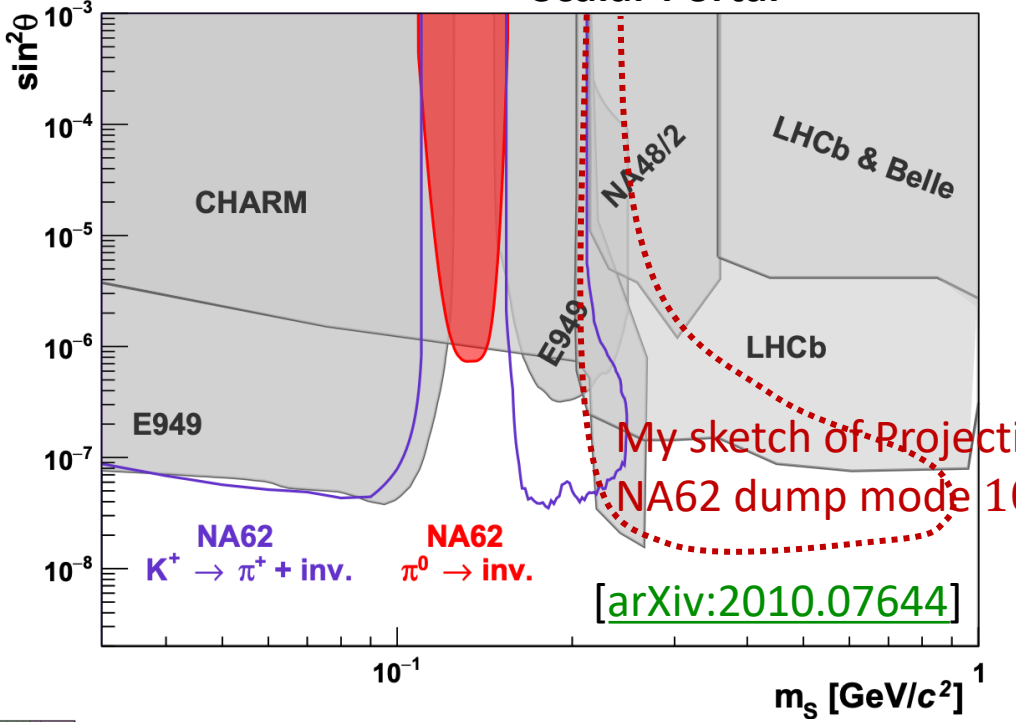
Dump Mode & Hidden Sector Searches

Vector Portal (Dark Photon)



[arXiv:1901.09966]

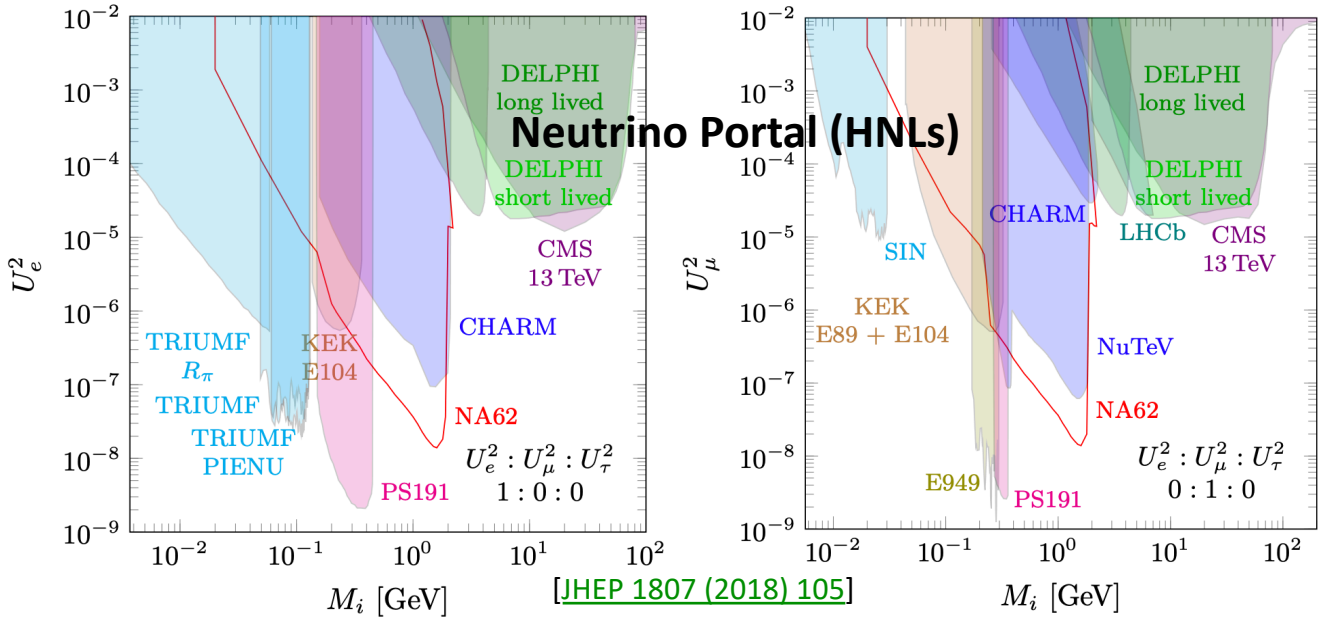
Scalar Portal



My sketch of Projection:
NA62 dump mode 10^{18} POT

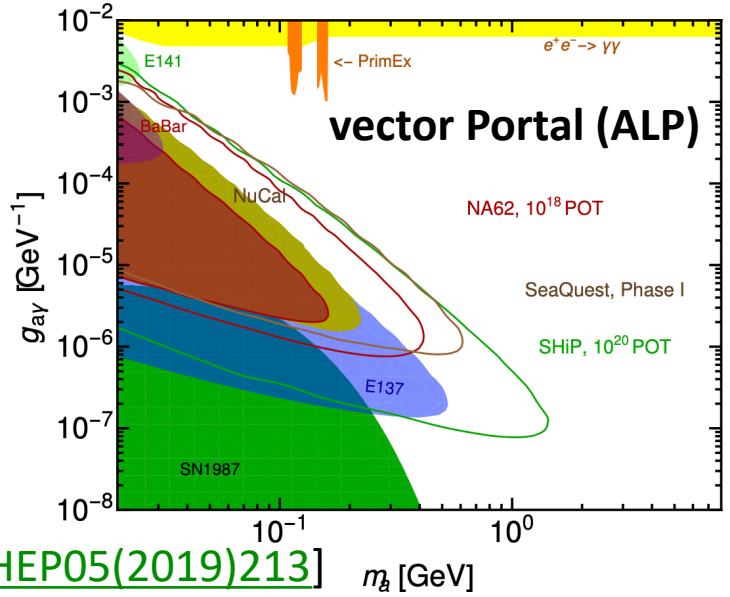
[arXiv:2010.07644]

Neutrino Portal (HNLs)



[JHEP 1807 (2018) 105]

vector Portal (ALP)



[JHEP05(2019)213]

Conclusions And Outlook

- Headline preliminary Run1 result :
  - $\mathbf{BR}(\boldsymbol{K^+ \to \pi^+ \nu\bar{\nu}}) \quad = (\mathbf{1.10}^{+\mathbf{0.40}}_{-\mathbf{0.35}}\ \boldsymbol{stat} \pm \mathbf{0.03}_{\boldsymbol{syst}}) \times \mathbf{10^{-10}}$ (3.5σ significance)
- 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.
  - Background is not limiting – expect improvements in sensitivity.
- NA62 contributing to active hidden sector field (searches for FIPs / LLPs).
  - All 4 portals: HNLs, Dark Photon, Dark Scalar, ALPs.
- The story continues in 2021 when NA62 resumes data-taking...
  - Beamline & detector development will help reach the goal of $BR(K^+ \to \pi^+ \nu\bar{\nu})$ measurement with 10% precision using Run 2 data.