Results from NA62
- The Kaon Factory -

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for the NA62 collaboration

Lake Louise Winter Institute
14/02/2020

Kaon physics – why?

Content

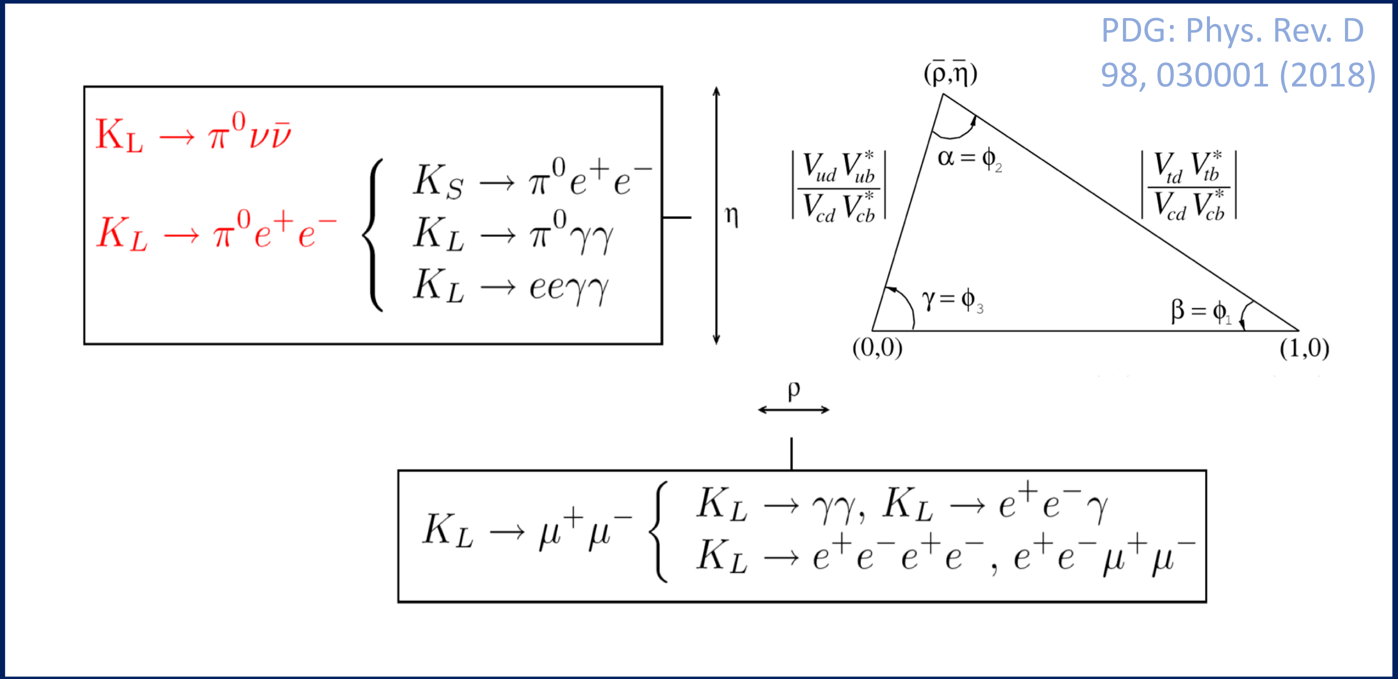
Kaon physics why? – test and challenge the Standard Model (SM)

This talk covers

- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
- K^+ decays and Lepton Number Violations (LNV)
- K^+ decays and Heavy Neutral Leptons (HNL)

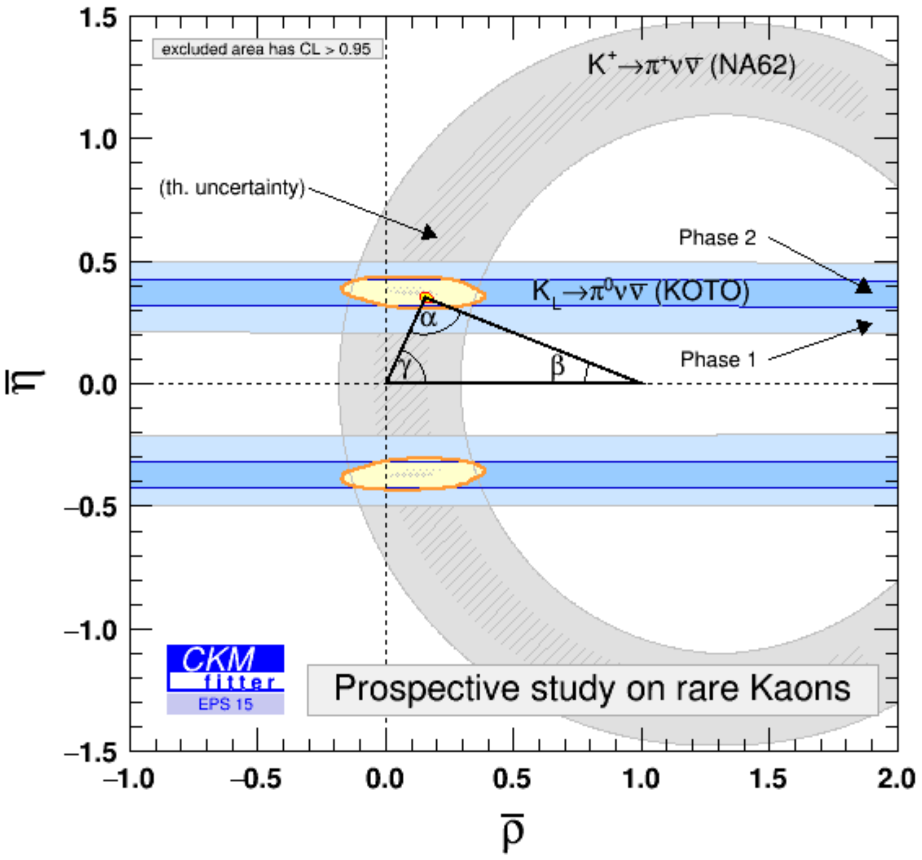
and a brief overview of other activities at NA62

Kaon physics – why?



The CKM unitarity triangle can be constrained by kaon physics alone.

Kaon physic



$K_L \to \pi^0 \nu\bar{\nu}$

$K_L \to \pi^0 e^+ e^-$ $\begin{cases} K_S \to \pi^0 e^+ e^- \\ K_L \to \pi^0 \gamma\gamma \\ K_L \to ee\gamma\gamma \end{cases}$

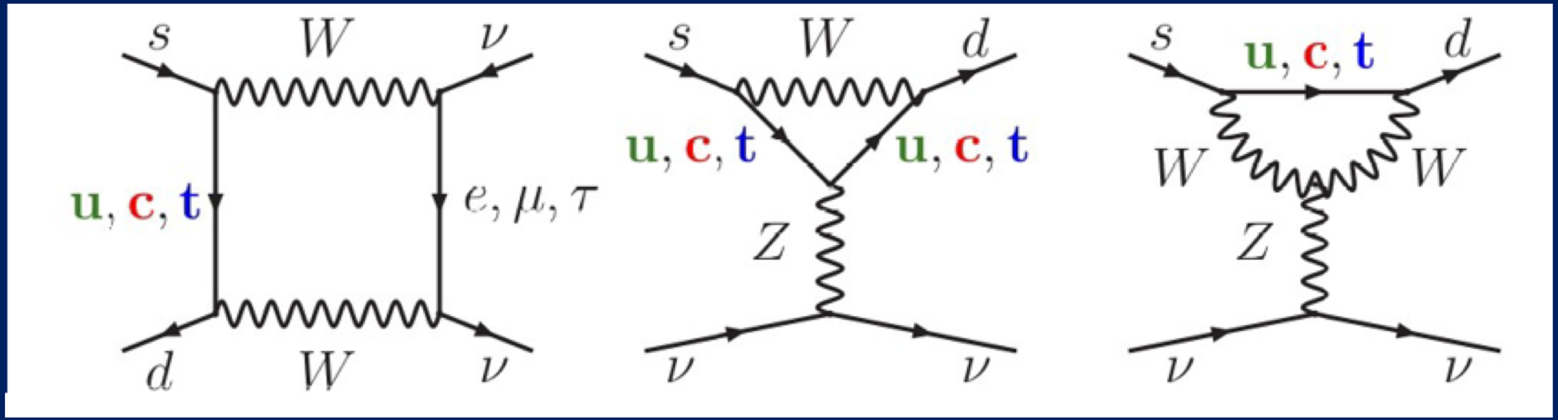
$K_L \to \mu^+\mu^-$ $\begin{cases} K_L \to \gamma\gamma,\ K_L \to e^+e^-\gamma \\ K_L \to e^+e^-e^+e^-,\ e^+e^-\mu^+\mu^- \end{cases}$

➔ Measuring both $K^+ \to \pi^+\nu\nu$ and $K_L \to \pi^0\nu\nu$ constrains the CKM unitarity triangle independently from measurements in B mesons sector.

The CKM unitarity triangle can be constrained by kaon physics alone.

The $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ decay

«These loop-induced rare decays are sensitive to new physics, and will allow a determination of β, independent of its value measured in B decays.»*



*PDG: Phys. Rev. D 98, 030001 (2018)

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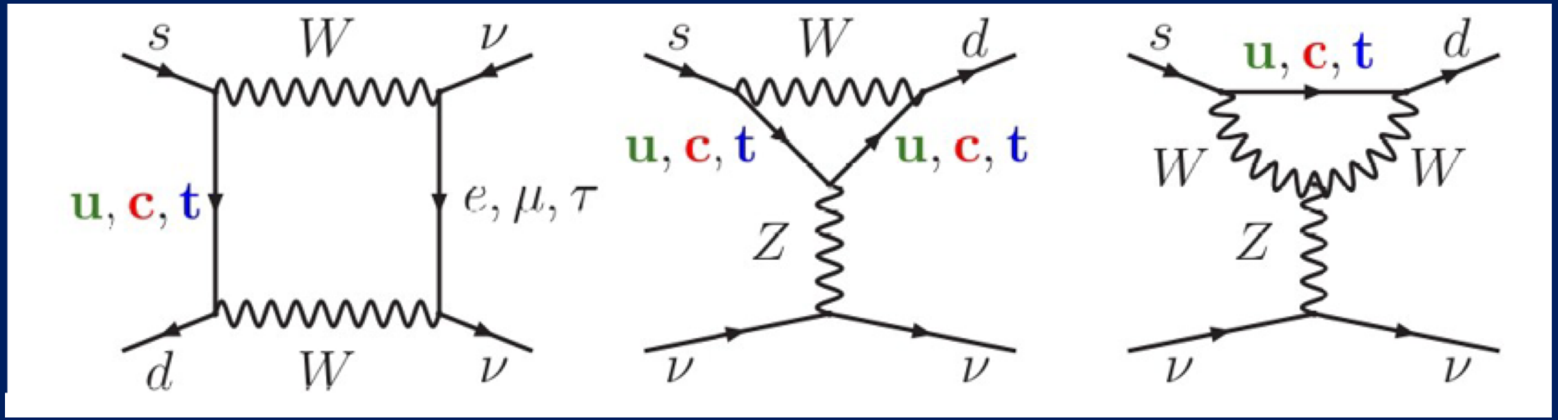

FCNC: Strongest CKM suppression in the Kaon sector → strongest constraints.
Very clean theoretically: Short distance contribution. No hadronic uncertainties.

[Buras. et. al., JHEP11(2015)033]

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (0.84 \pm 0.03) \times 10^{-10} \left(\frac{|V_{cb}|}{0.0407}\right)^{2.8} \left(\frac{\gamma}{73.2^\circ}\right)^{0.74} = (0.84 \pm 0.10) \times 10^{-10}$$

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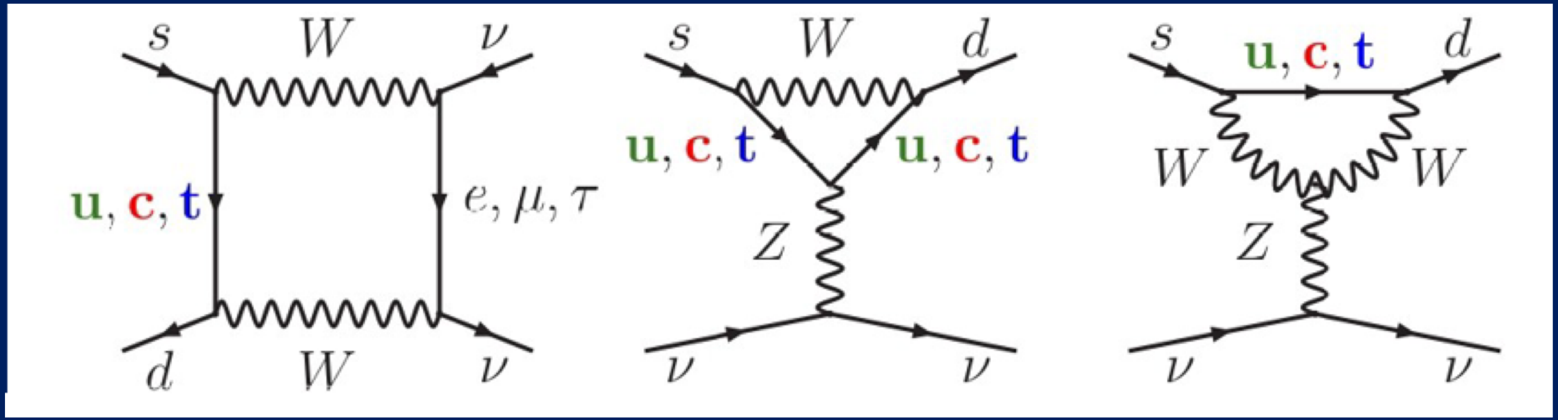

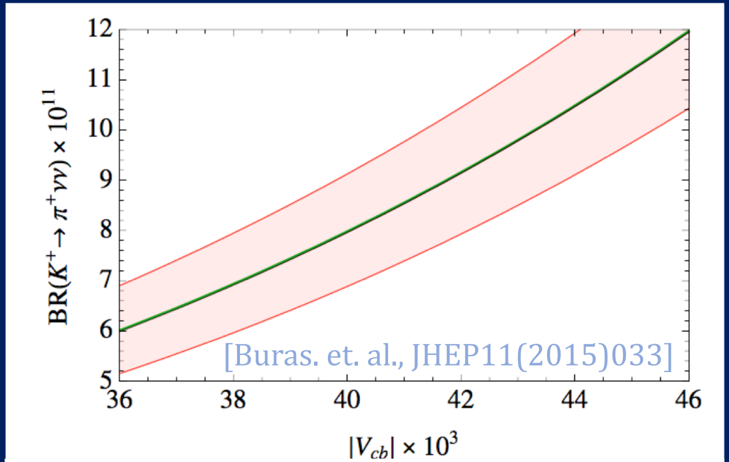

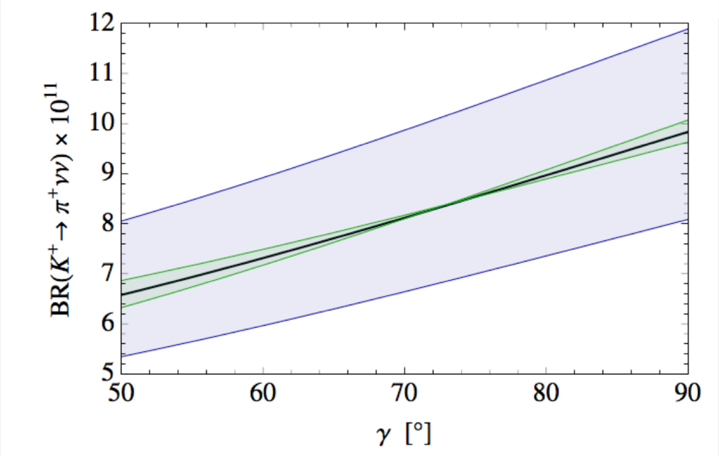

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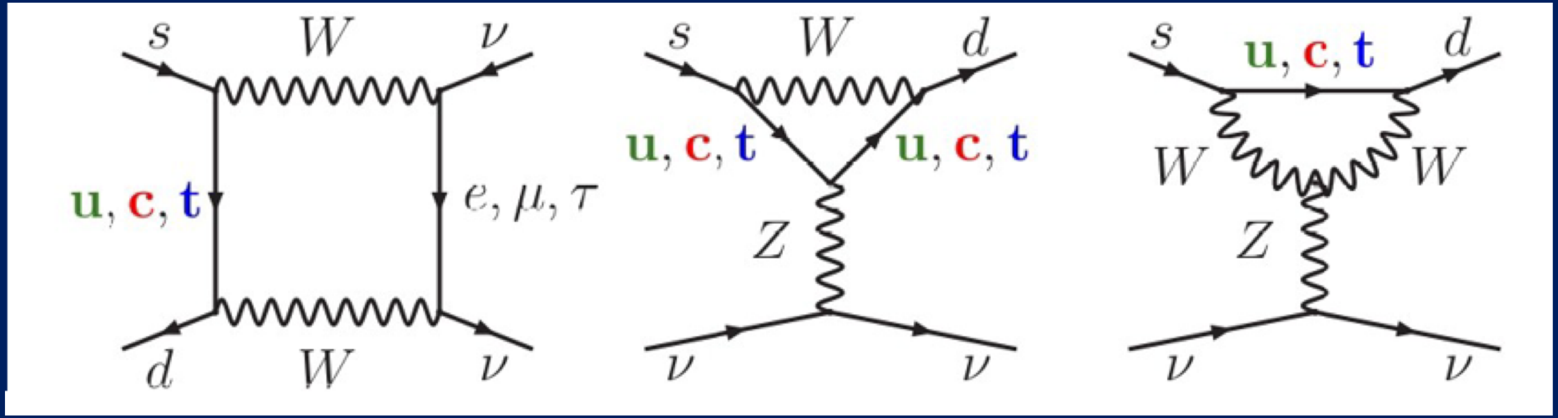

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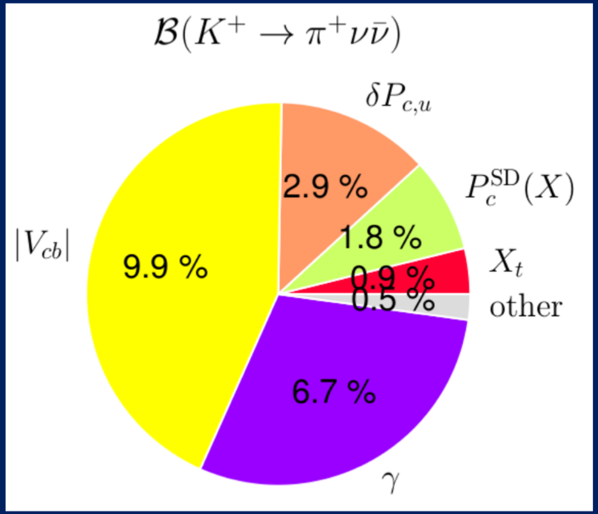

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Main uncertainties from CKM elements → precise measurement of BR helps to reduce these uncertainties!

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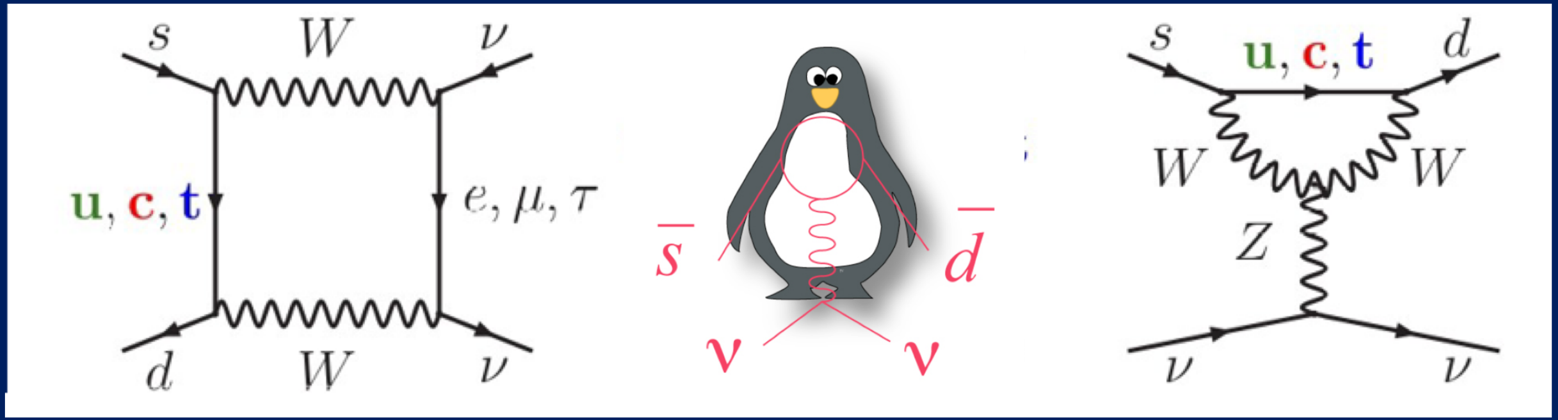

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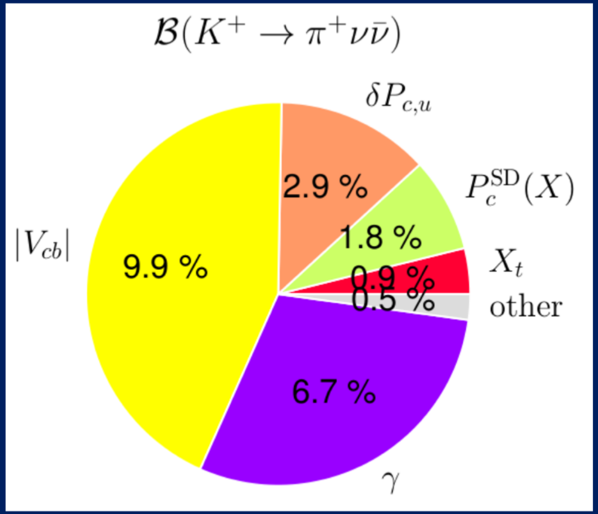

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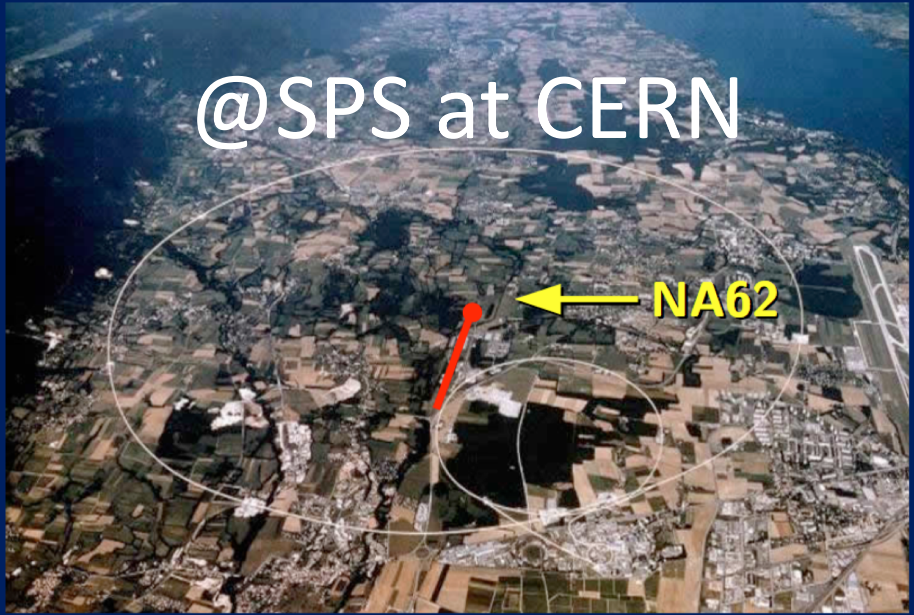
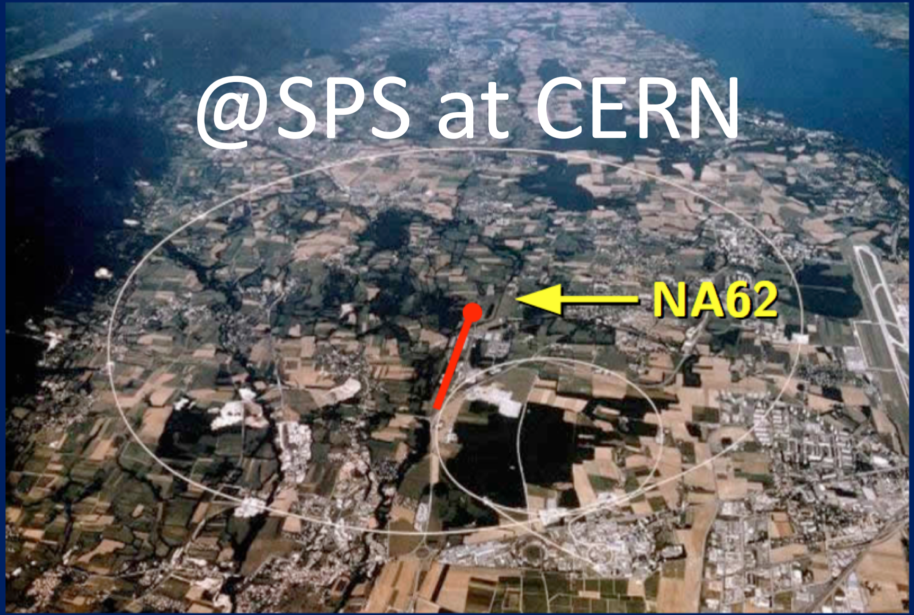


The Kaon Factory: NA62

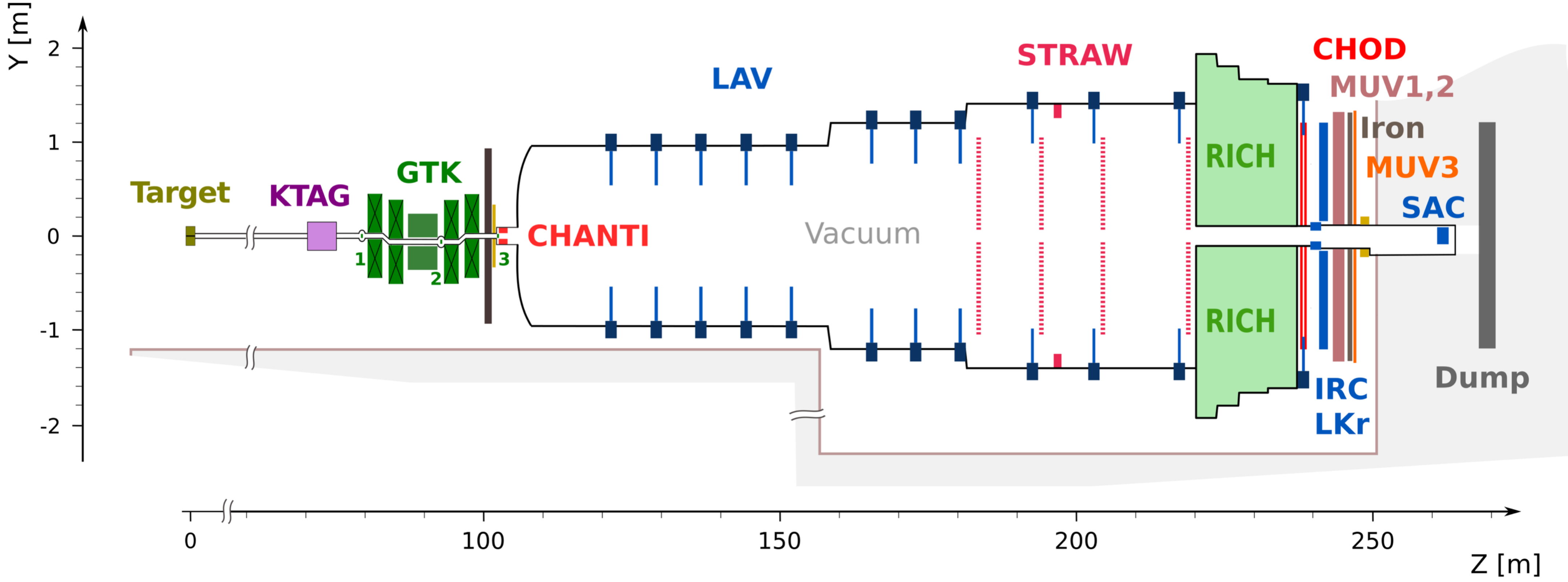
NA62 has around 200 participants from the following Universities or Institutes:

Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, Fairfax GMU, Ferrara, Florence, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Moscow, Naples, Perugia, Pisa, Prague, Protvino, Rome I, Rome II, San Luis Potosí, TRIUMF, Turin, Vancouver UBC



The Kaon Factory: NA62

[NA62 beam and detector, 2017 JINST 12 P05025]



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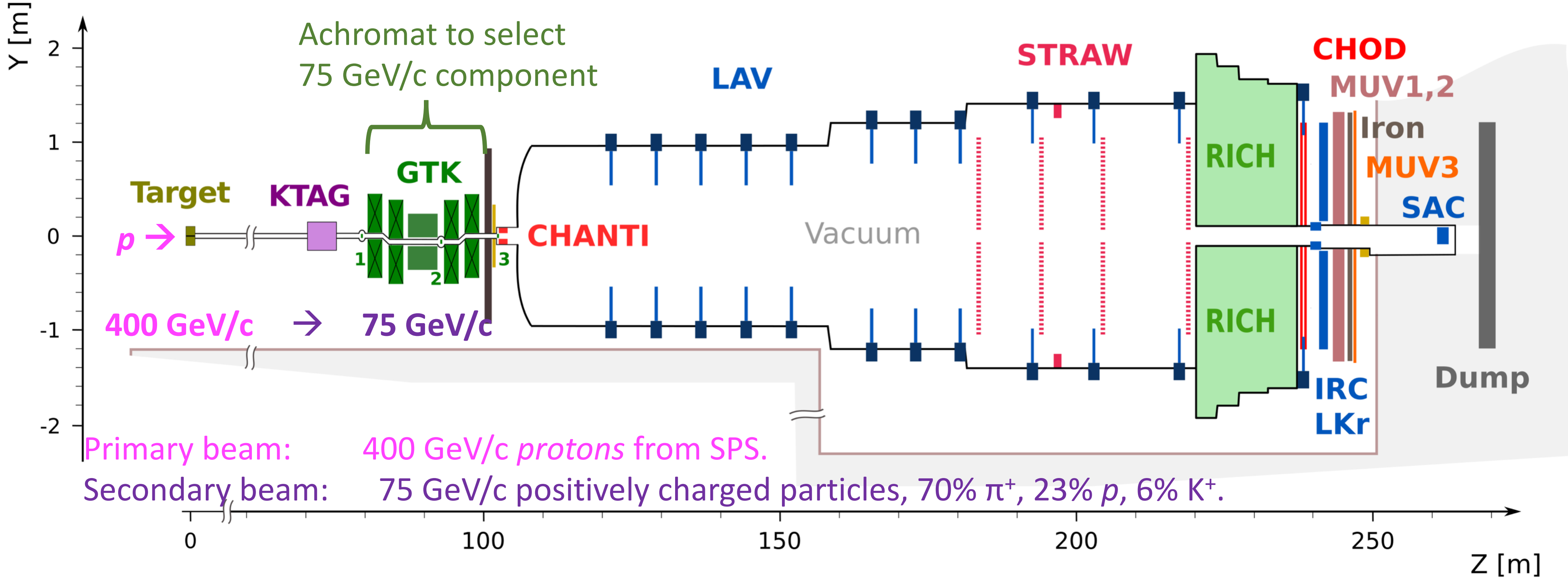

Primary beam: 400 GeV/c *protons* from SPS.

Secondary beam: 75 GeV/c positively charged particles, 70% π^+, 23% *p*, 6% K^+.

2017: $1.9\text{x}10^{12}$ protons/spill, 3.5s spill, particle rate at GTK: ca. 500 MHz

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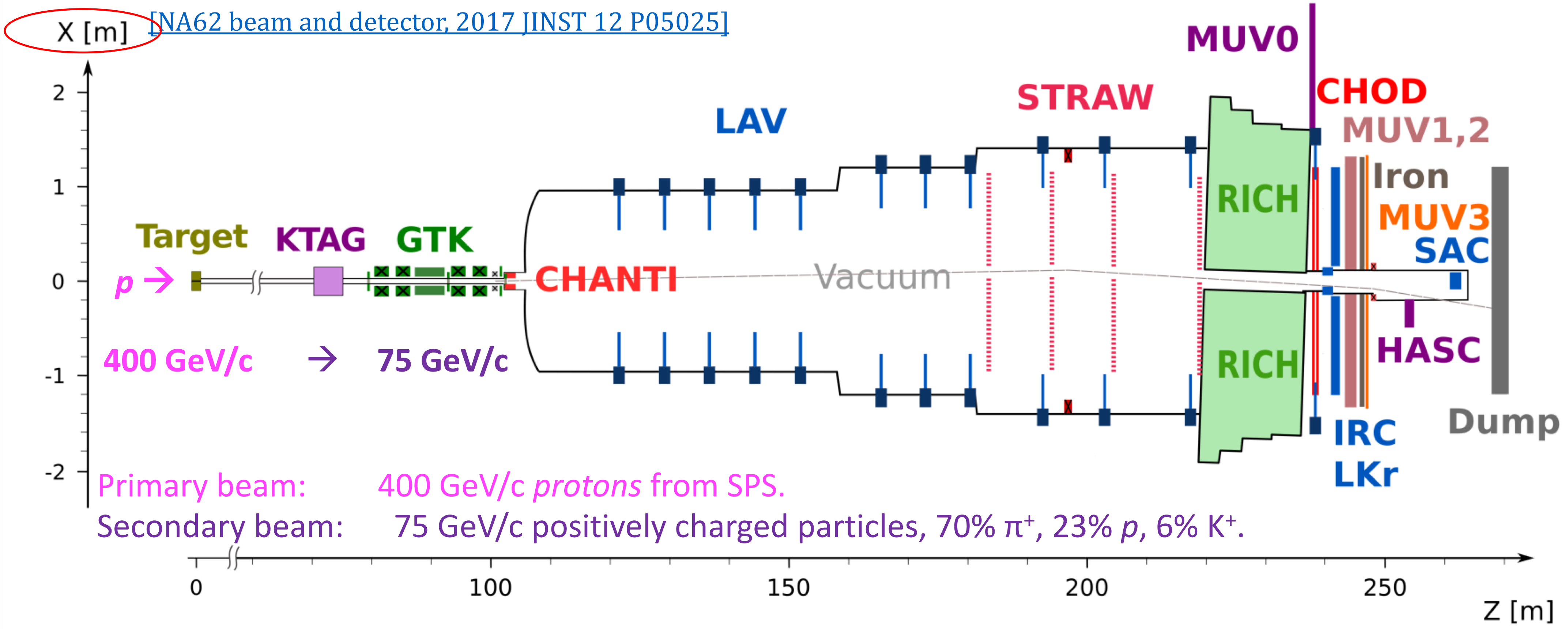

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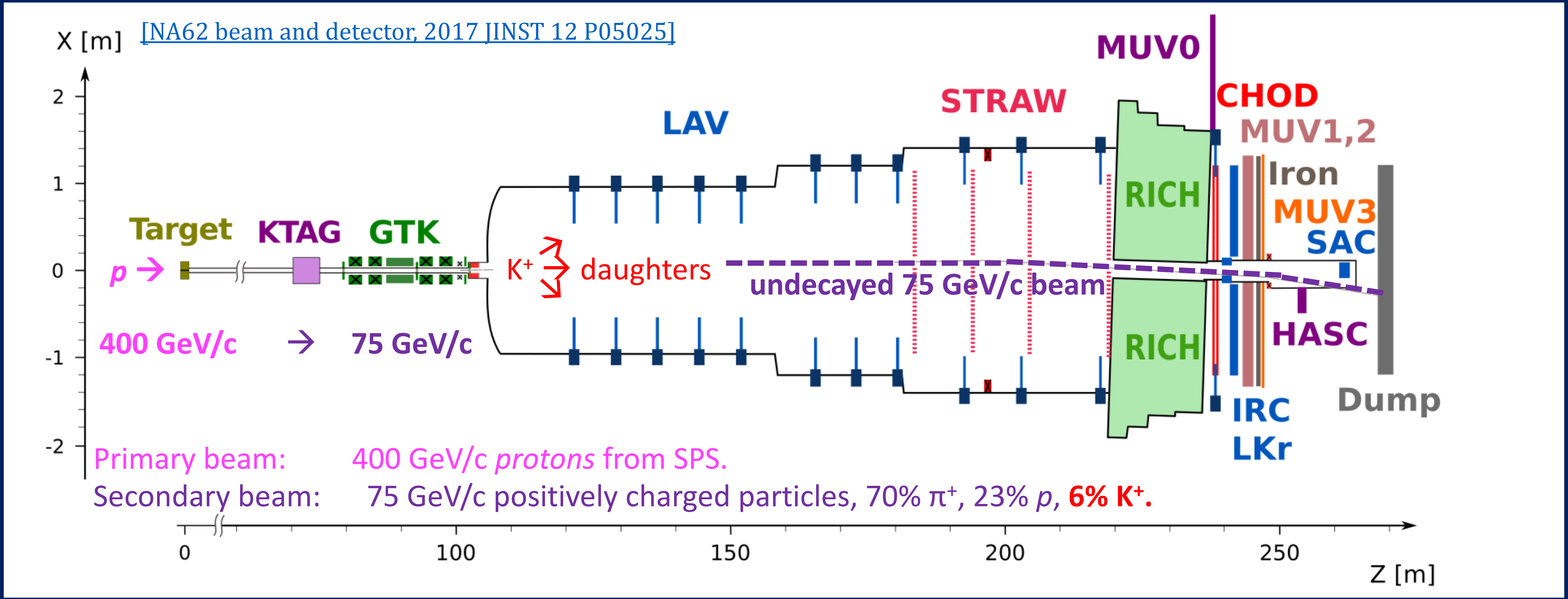
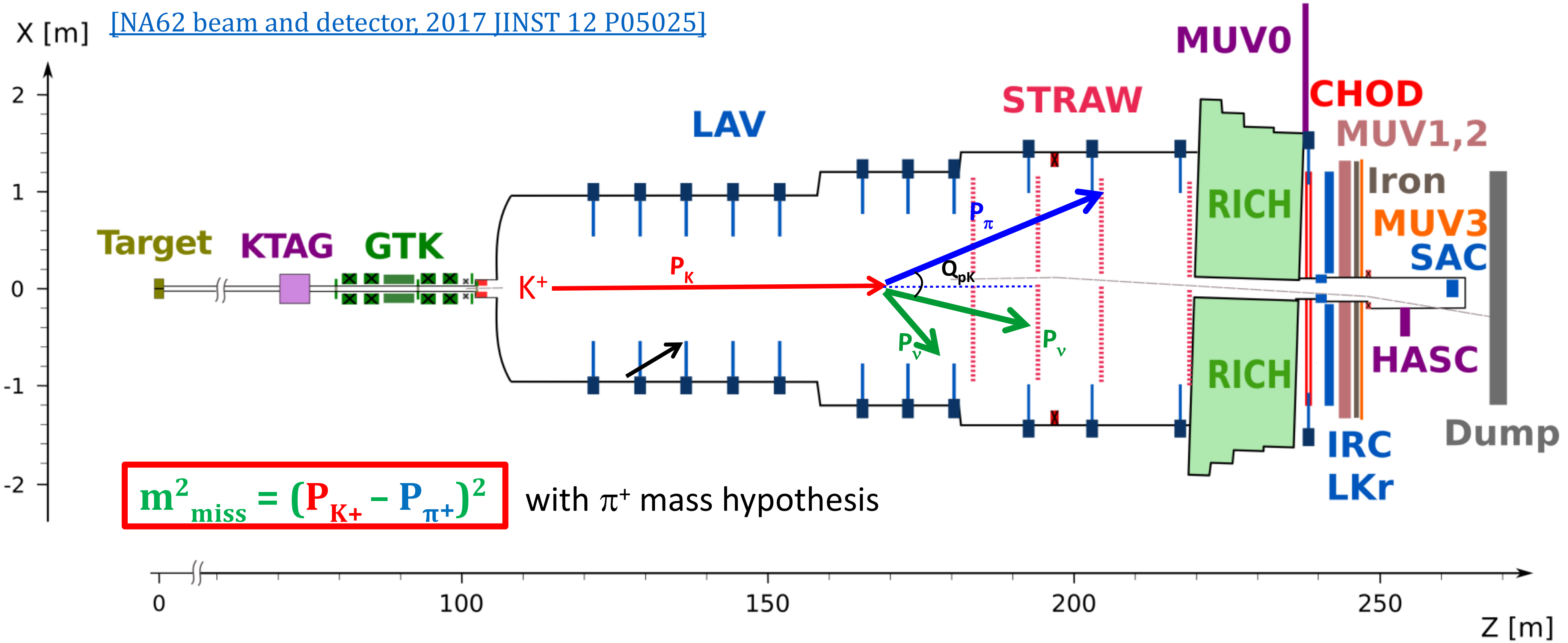


K^+ decay rate: ca. 3MHz

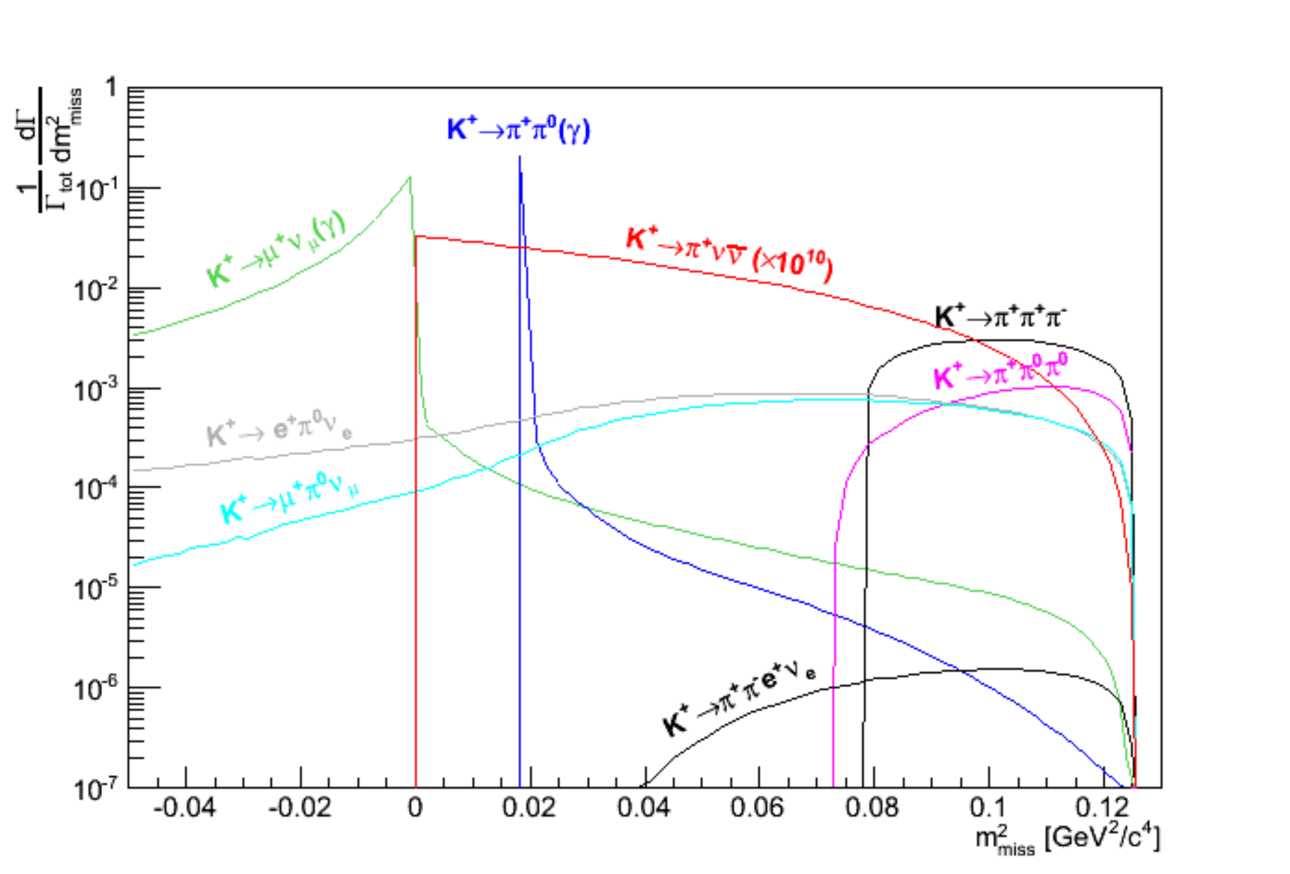
Decay-in-flight technique

[NA62 beam and detector, 2017 JINST 12 P05025]



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

$K^+ \to \pi \nu\bar{\nu}$: Main background decay modes



Decay mode	BR	Main rejection tools
$K^+ \to \mu^+\nu(\gamma)$	63%	μ–ID + kinematics
$K^+ \to \pi^+\pi^0(\gamma)$	21%	γ-veto + kinematics
$K^+ \to \pi^+\pi^+\pi^-$	6%	multi + 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

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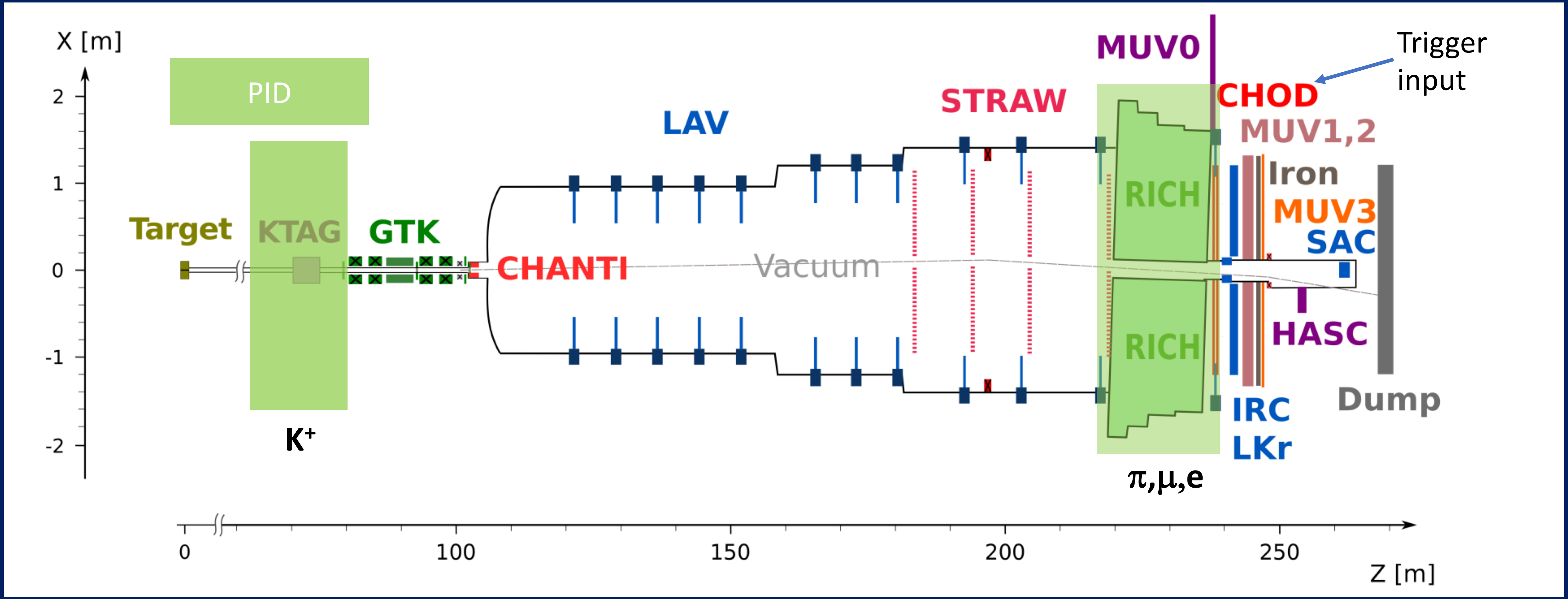

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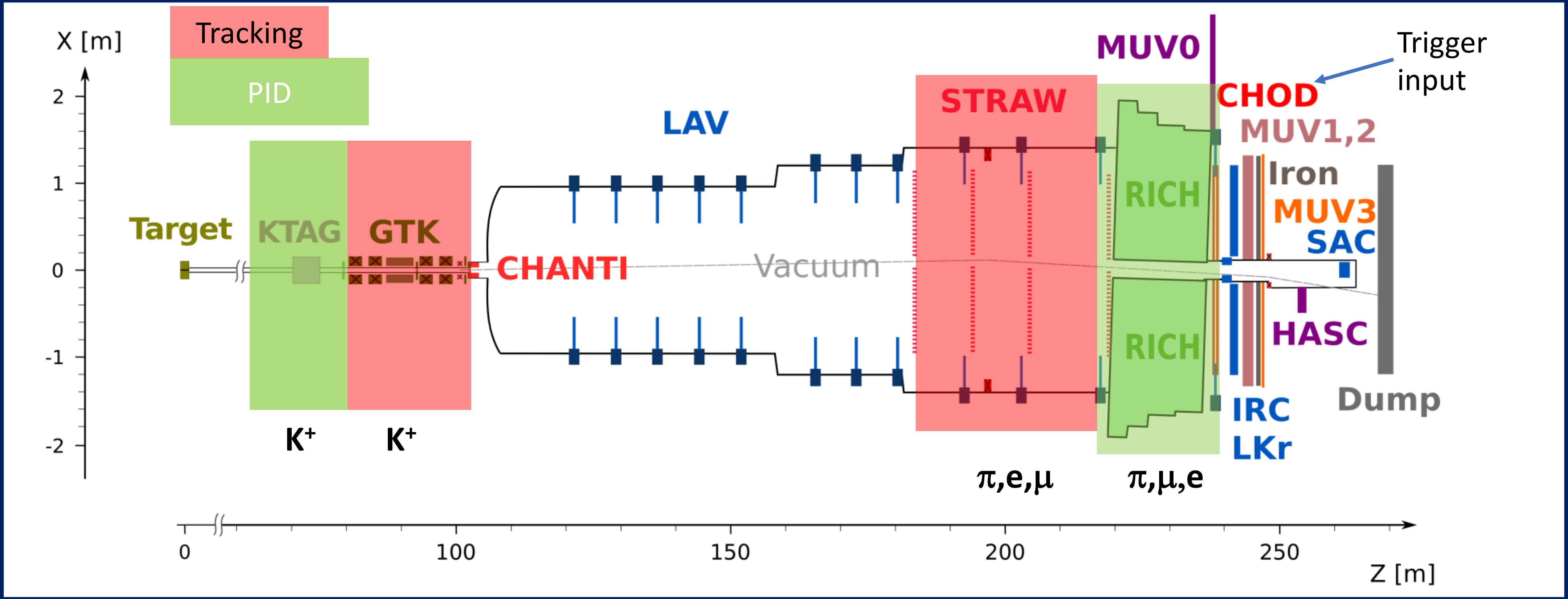

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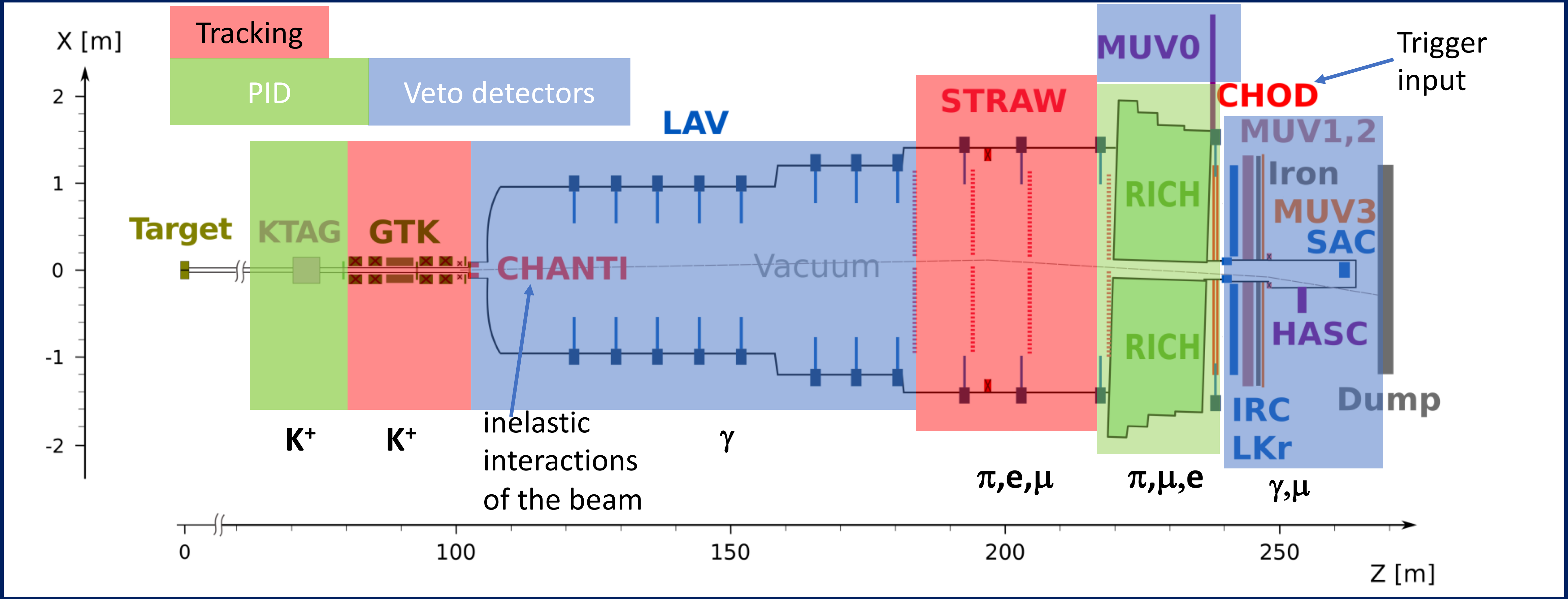


Trigger and data collected

Run 1:

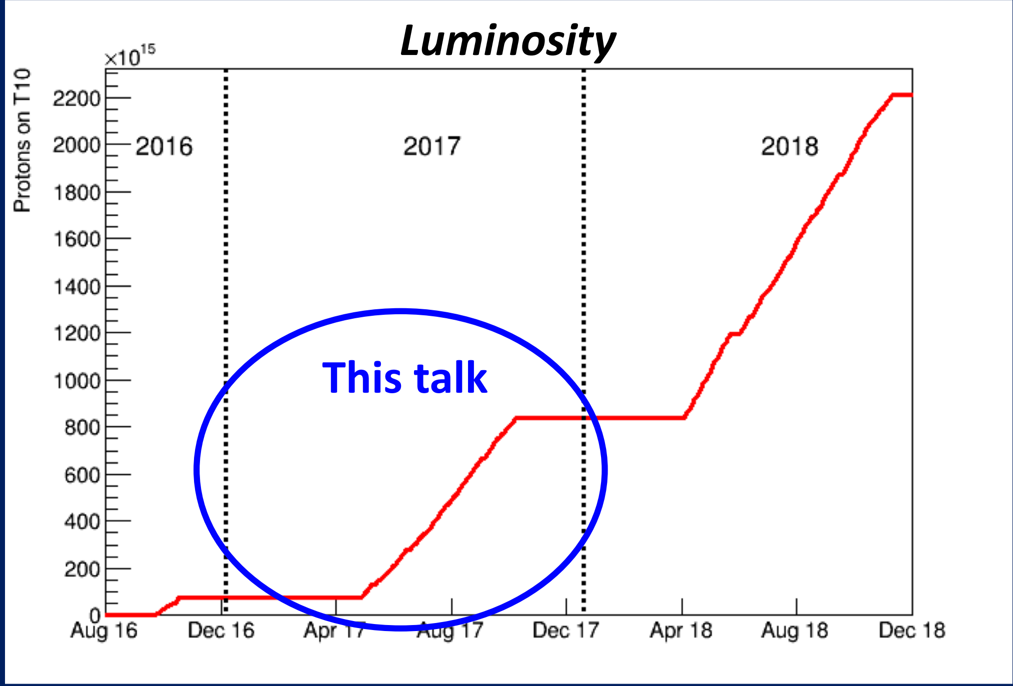
2016: Physics run (45 days*)

2017: Physics run (160 days*)

2018: Physics run (217 days*)

1.9 x 10^{12} proton per spill on target (3s)

~2 x 10^{12} K^+ decays



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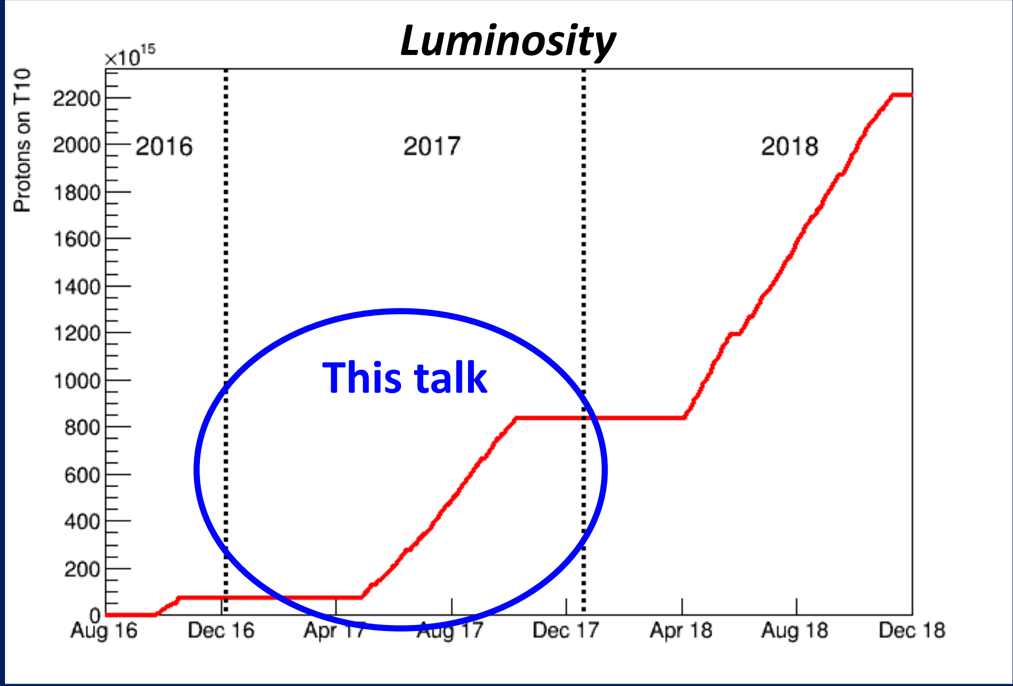

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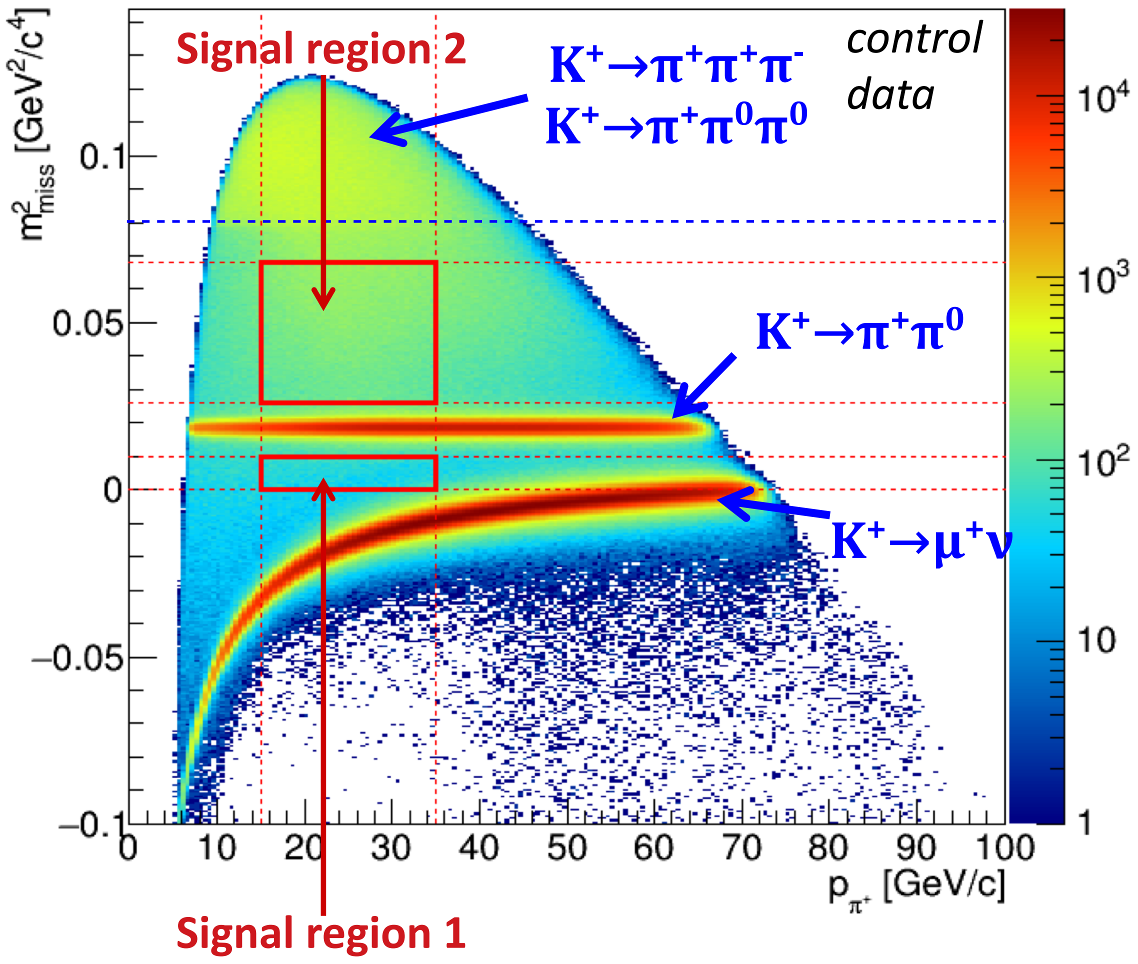
- **Trigger streams (hardware L0 + software L1)**
  - **“PNN”:**
    - **L0: presence of a charged particle, photon and muon veto**
    - **L1: kaon identification, photon veto, STRAW track reconstruction**
  - **“Control”: minimum bias, presence of a charged particle downscaled by 400**
- **Offline analysis**
  - **Data samples: PNN; Control: $K^+ \to \pi^+\pi^0$, $K^+ \to \mu^+\nu$, $K^+ \to \pi^+\pi^+\pi^-$, $K^+ \to \pi^+\pi^-e^+\nu$**
  - **Blind analysis procedure: signal/validation regions masked during the analysis**

$K^+ \to \pi \nu\bar{\nu}$: Signal selection

K^+ decay events in the fiducial decay region selected before PID and γ/multi-track rejection



Signal region 1 and 2 are blinded.

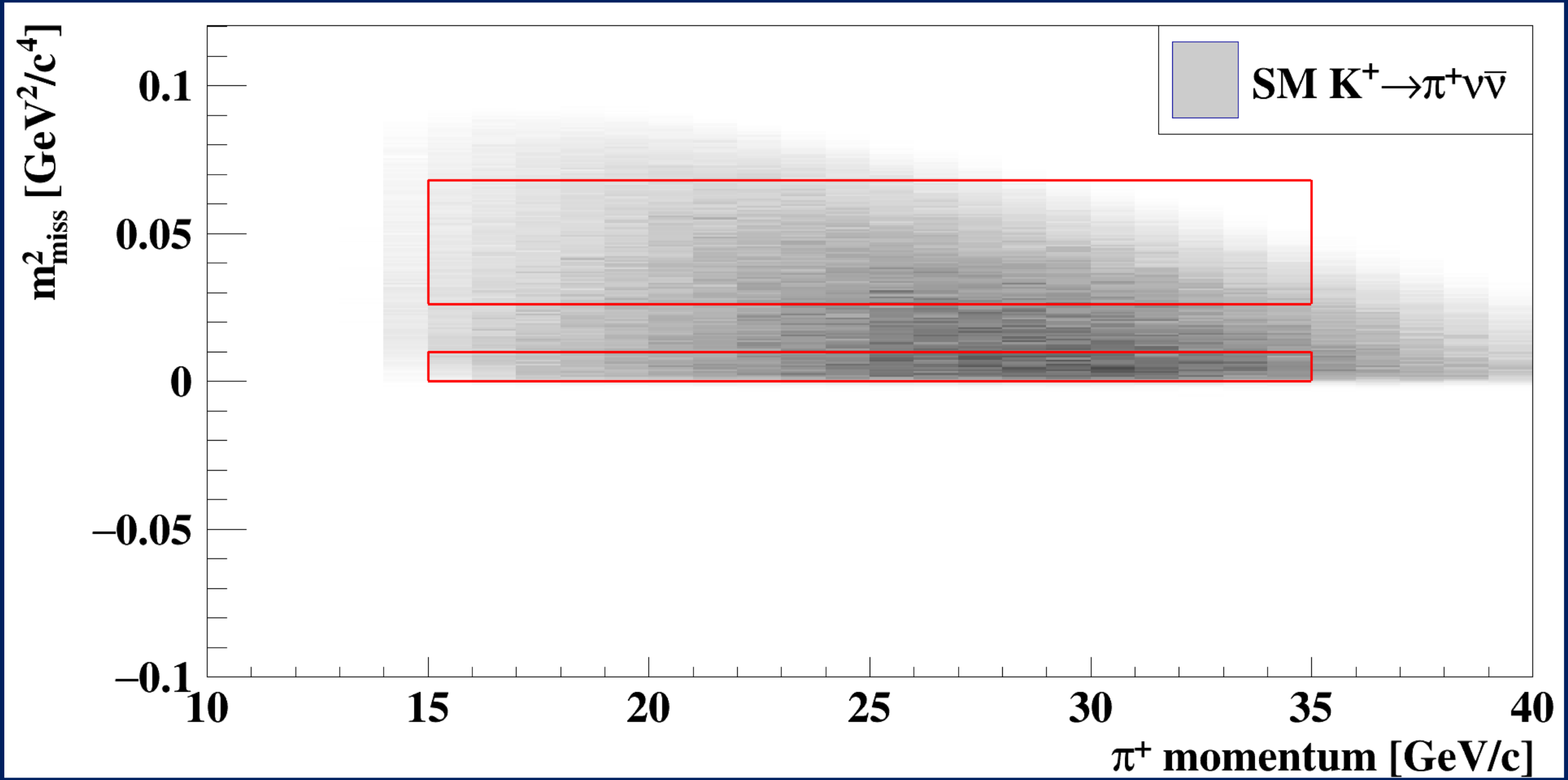
Selection criteria

- **π^+ identification: $\varepsilon_{\pi+} \sim 64\%$**
- **Single track decay topology**
- **→ multi-track rejection**
- **K^+ - π^+ matching: 110 m < Z_{vertex} < 165 m**
- **Photon suppression**
- **15 GeV/c < $p_{\pi+}$ < 35 GeV/c, in order to have an optimal π/μ separation in the RICH and reduction of early decays.**

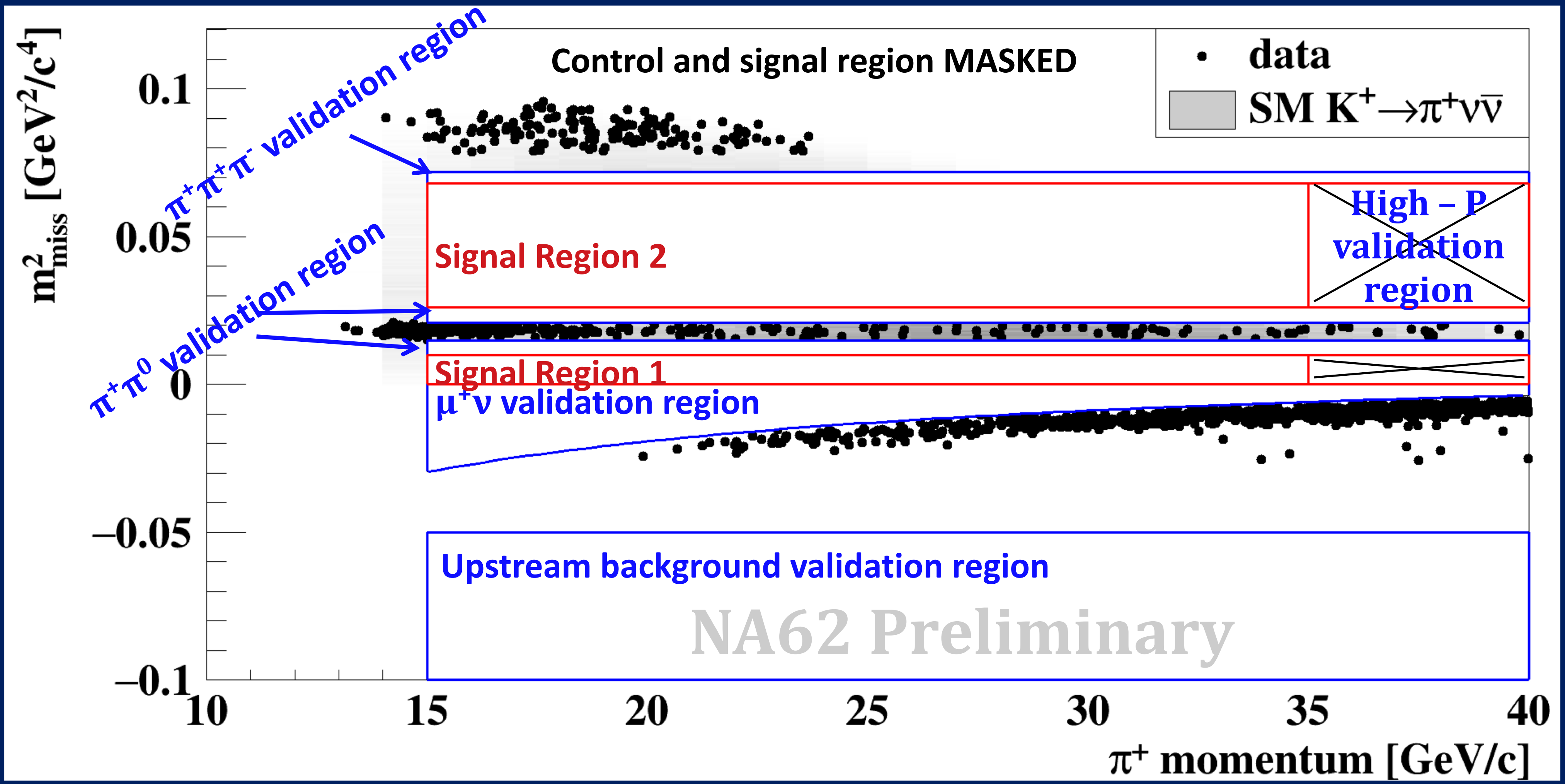
Background suppression details:

- **Muon suppression > 10^7**
- **π^0 suppression (from $K^+ \to \pi^+\pi^0$) > 10^7**
- **Excellent time resolution O(100 ps)**
- **Kinematic suppression ~ O(10^4)**

$K^+ \to \pi \nu\bar{\nu}$: Signal acceptance



$K^+ \rightarrow \pi \nu\bar{\nu}$: 2017 data-set



$K^+ \to \pi \nu\bar{\nu}$: Single event sensitivity

$$N_K = \frac{N_{\pi\pi} \cdot R}{A_{\pi\pi} \cdot BR_{\pi\pi}} = (1.3 \pm 0.1) \times 10^{12}$$

NA62 Preliminary

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

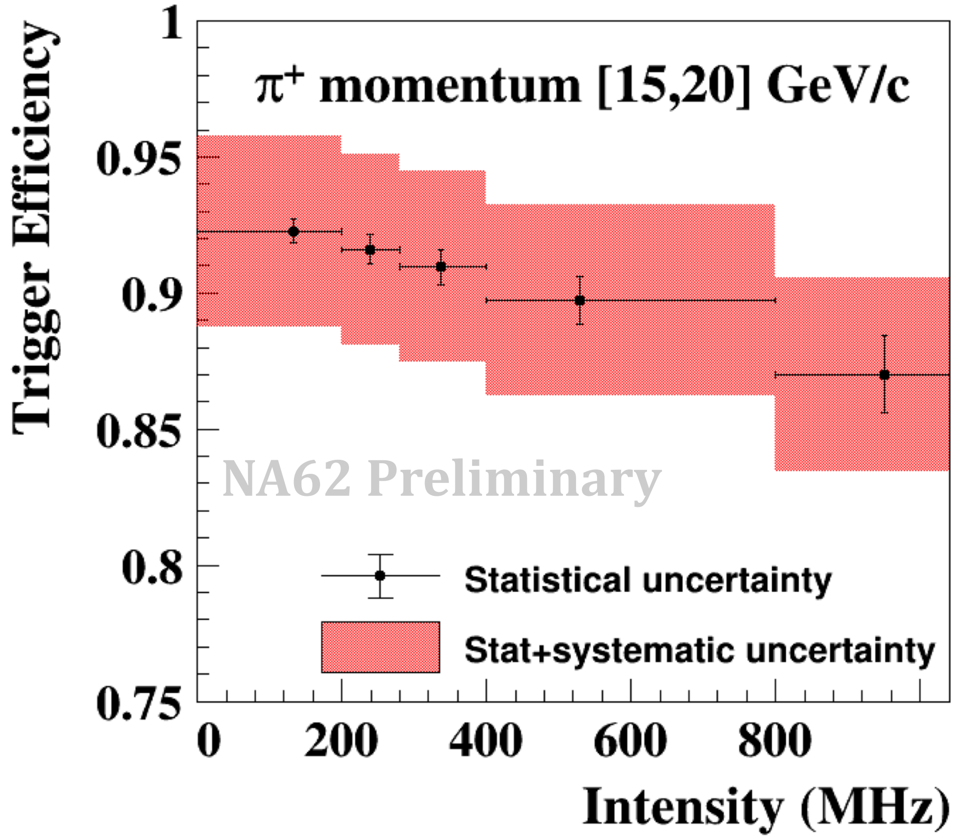
$N_{\pi\pi}$: # observed $K^+ \to \pi^+\pi^0$
$A_{\pi\pi}$: signal acceptance from simulation (~8.5% *)
$BR_{\pi\pi}$: branching ratio
R: reduction factor applied to CTRL trigger

$A_{\pi\nu\nu}$: signal acceptance from simulation(~3%*)
ε_{trig}: trigger efficiency
ε_{RV}: random veto efficiency
j: momentum and intensity bins

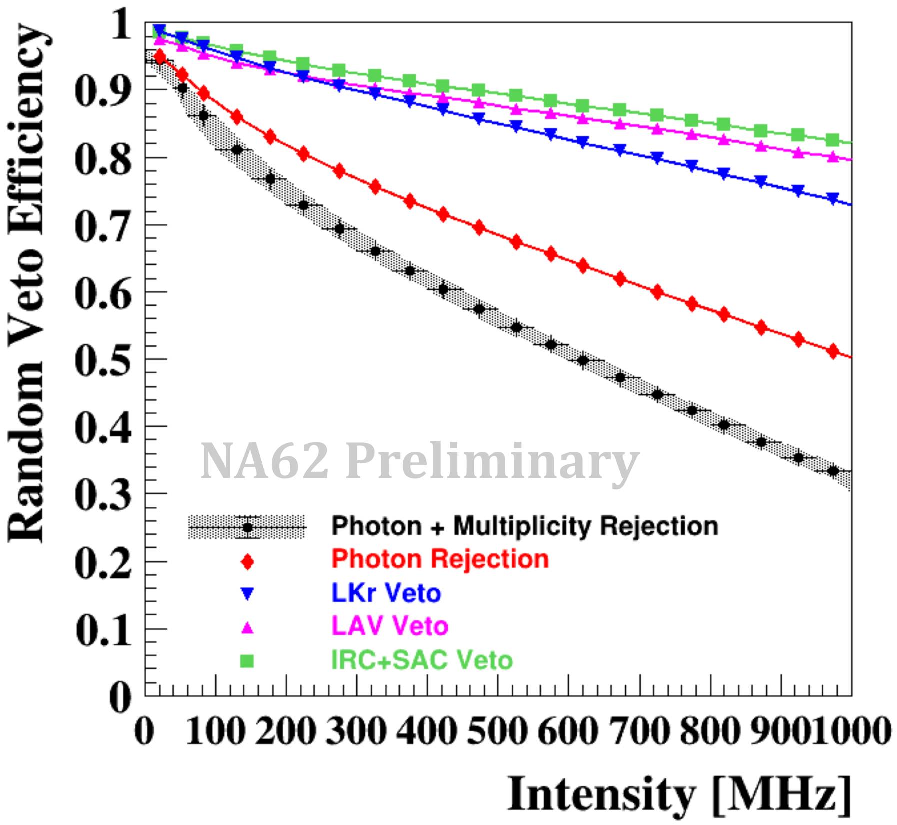
* vector form factor hypothesis

Trigger and random veto efficiency

ε_{trigg}: trigger efficiency measured on data



ε_{RV}: measured on $K^+ \rightarrow \mu^+ \nu$ decays in data



$K^+ \rightarrow \pi \nu\bar{\nu}$: Single event sensitivity 2017 data-set

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

Source	Uncertainty $\times 10^{-10}$
L0 trigger	± 0.015
Acceptance	± 0.012
Random veto	± 0.008
L1 trigger	± 0.003
Normalization background	negligible

$N_{\pi\pi}$: **# observed $K^+ \rightarrow \pi^+\pi^0$**
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ε_{trig}: **trigger efficiency**
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j: **momentum and intensity bins**

* vector form factor hypothesis

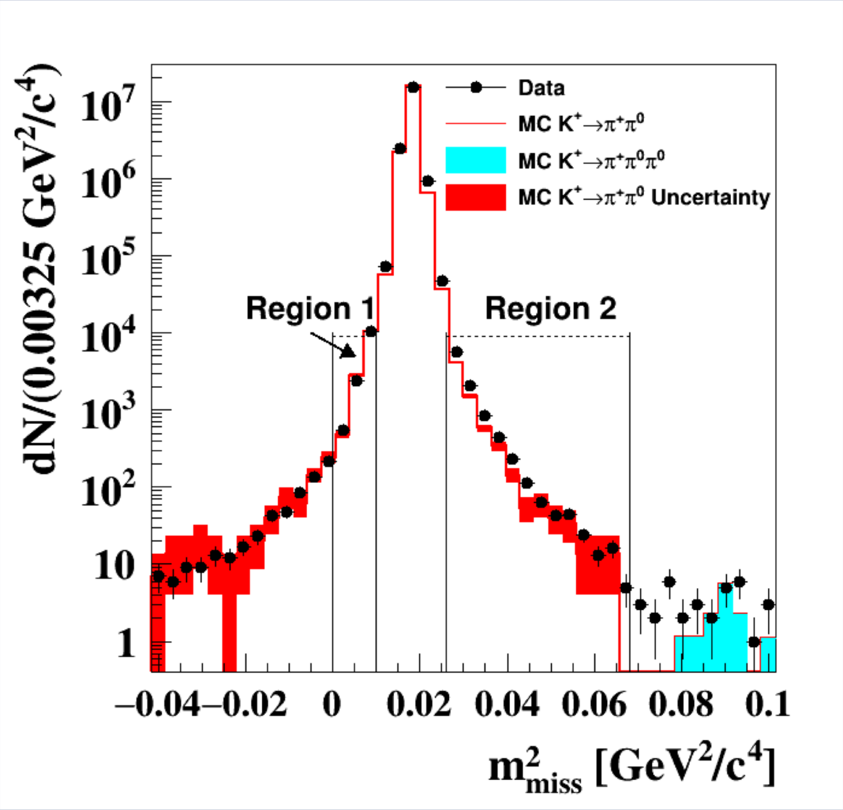
$$\text{S.E.S.} = (0.389 \pm 0.021) \times 10^{-10}$$

BR(SM)/S.E.S. =

$$N^{exp}_{\pi\nu\nu} = 2.16 \pm 0.12 \pm 0.26_{ext} \quad \text{(SM)}$$

$K^+ \to \pi \nu\bar{\nu}$: 2017 data-set: background

Control $K^+ \to \pi^+\pi^0$ data used to study the tails of the m^2_{miss} distribution



$K^+ \to \pi \nu\bar{\nu}$: 2017 data-set:

Data in $\pi^+\pi^0$ region after $\pi^+\nu\bar{\nu}$ selection (including π^0 rejection)

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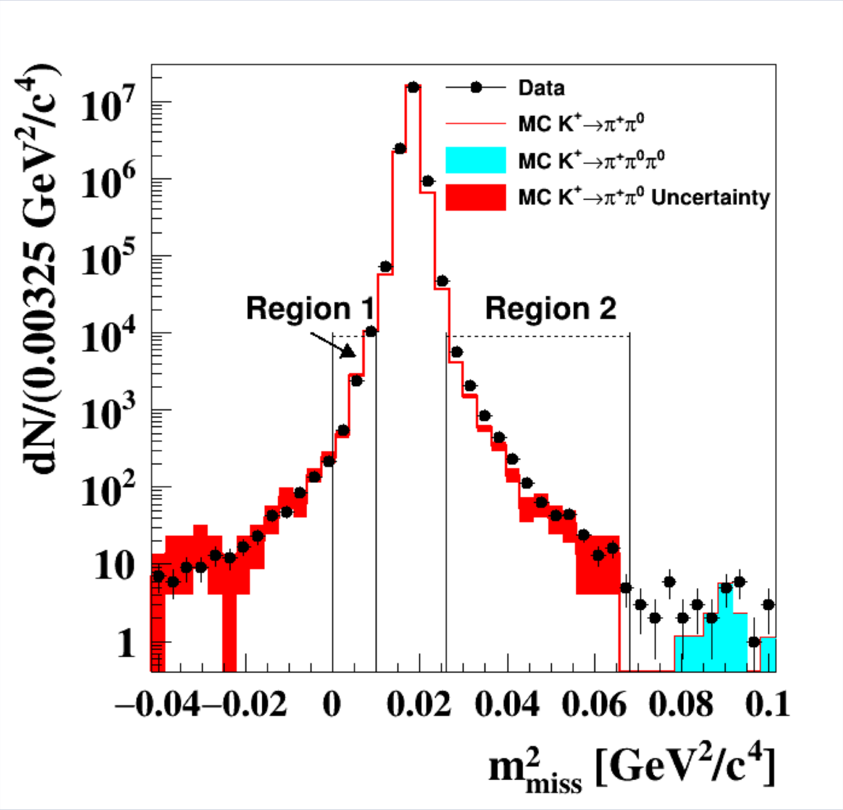

$$N^{exp}_{\pi\pi}(region) = N(\pi^+\pi^0) \cdot f_{kin}(region)$$

Expected $K^+ \to \pi^+\pi^0$ in signal regions after the $\pi^+\nu\bar{\nu}$ selection

Fraction of $\pi^+\pi^0$ in signal region measured on control data

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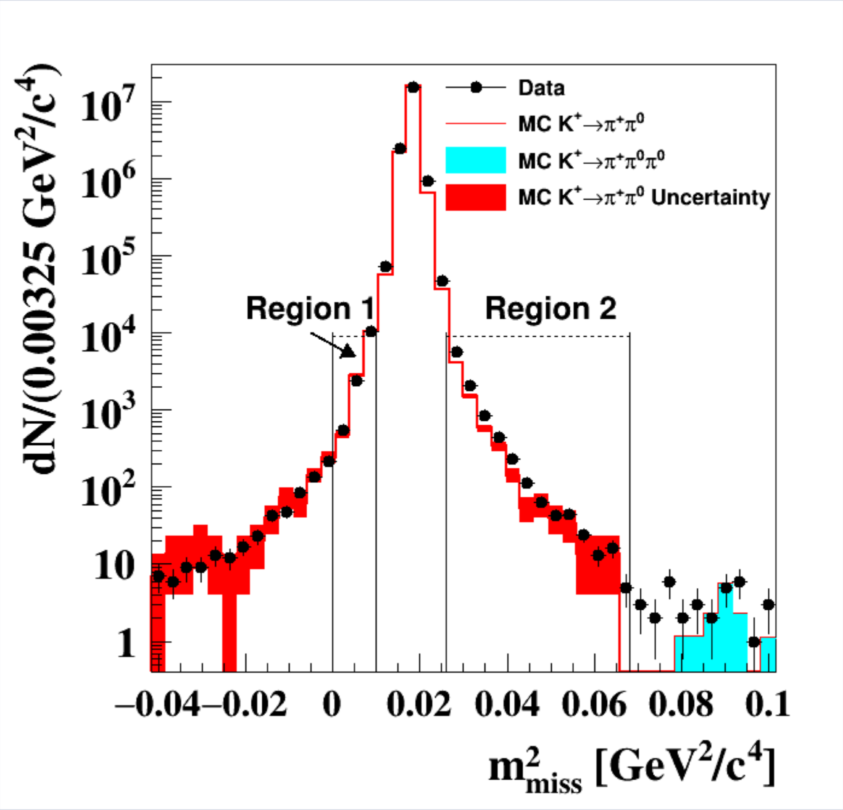

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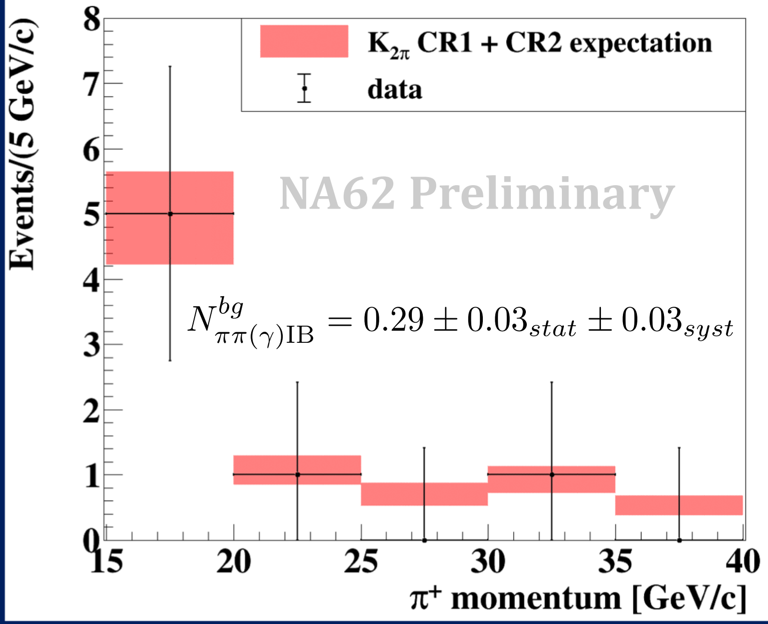

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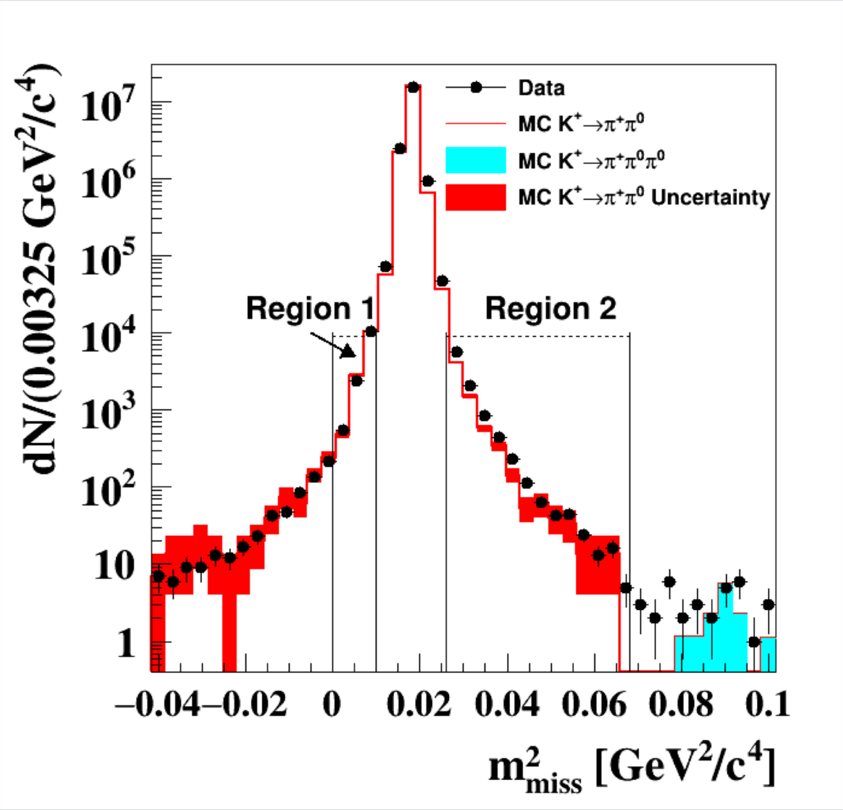

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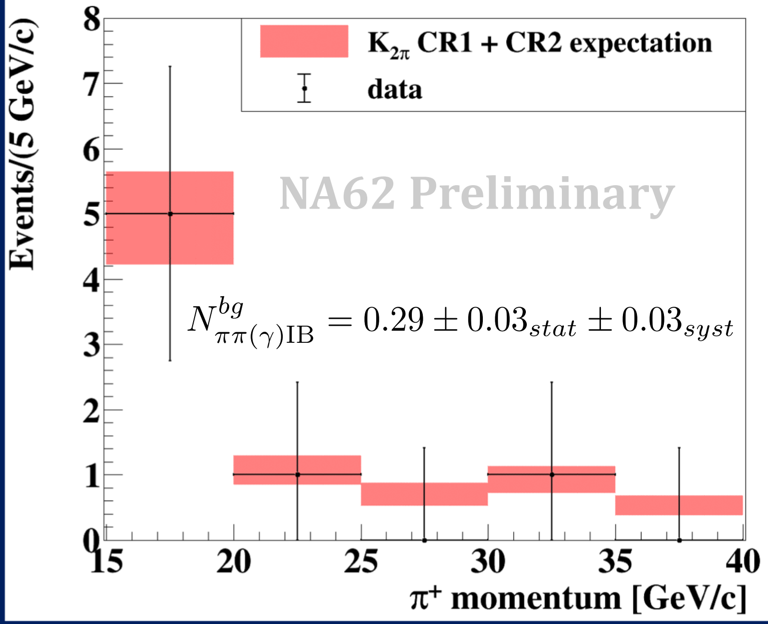
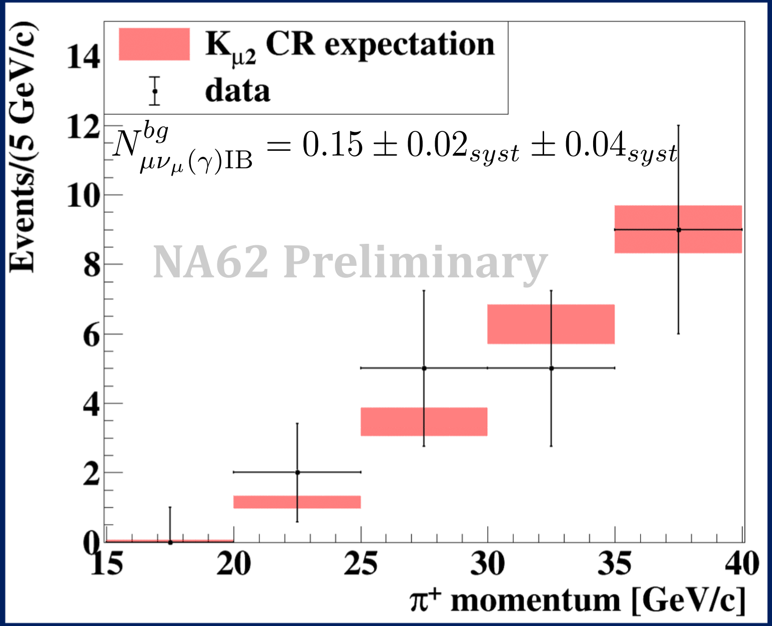




$K^+ \rightarrow \pi \nu\bar{\nu}$: 2017 data-set: background

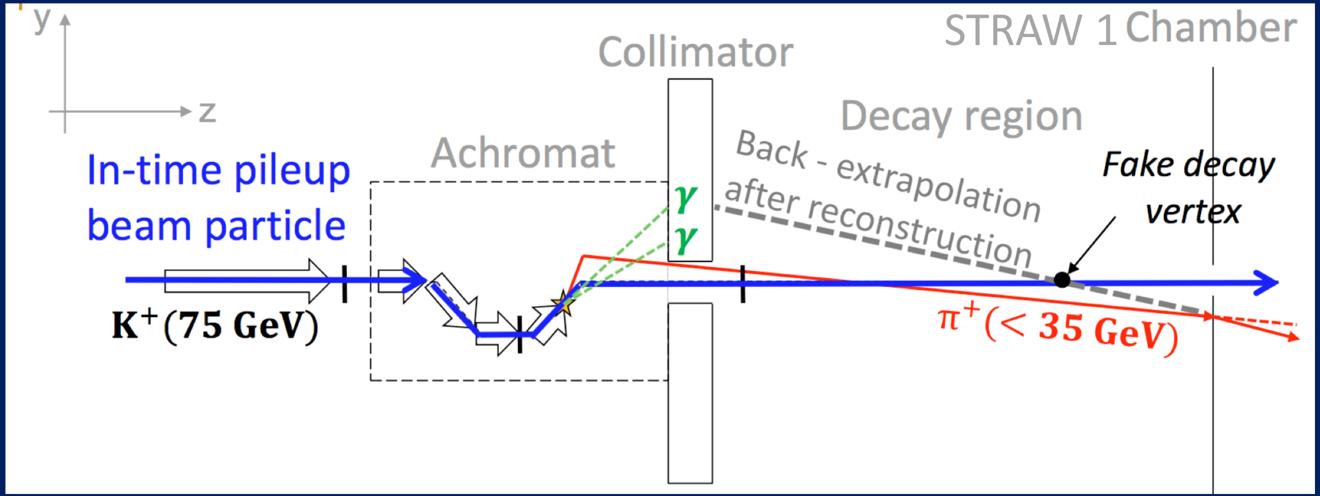
Further background source:

Upstream background = Kaon decays or interactions before the fiducial volume (FV):

→ loss of all daughters except one π^+ that reaches FV

→ π^+ may undergo scattering in first tracking chamber (STRAW 1)

- ➢ back-extrapolation leads to a fake vertex with other beam particle falsely tagged as Kaon



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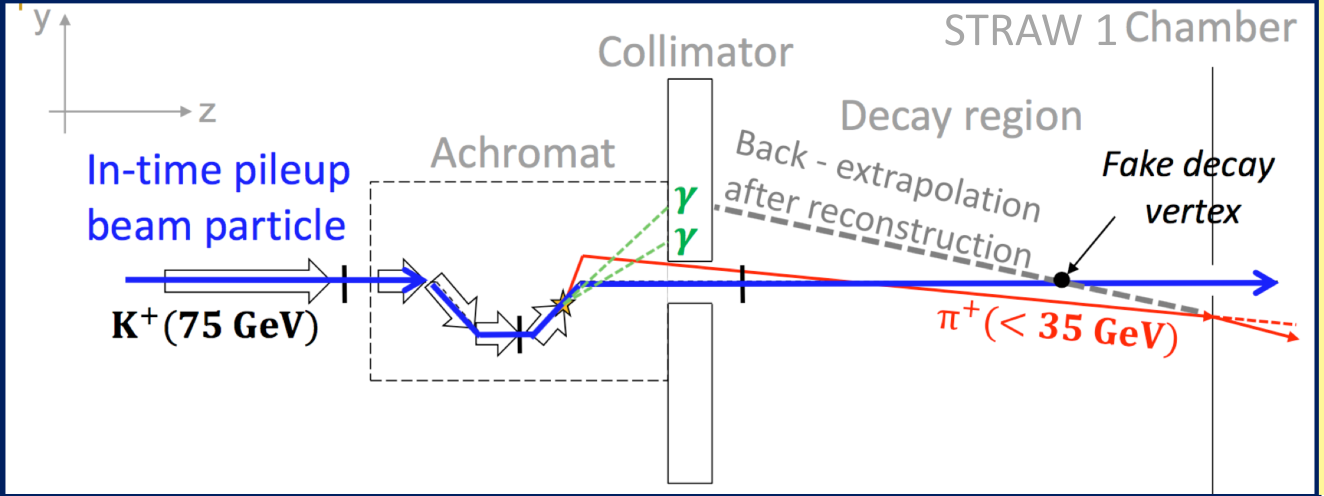


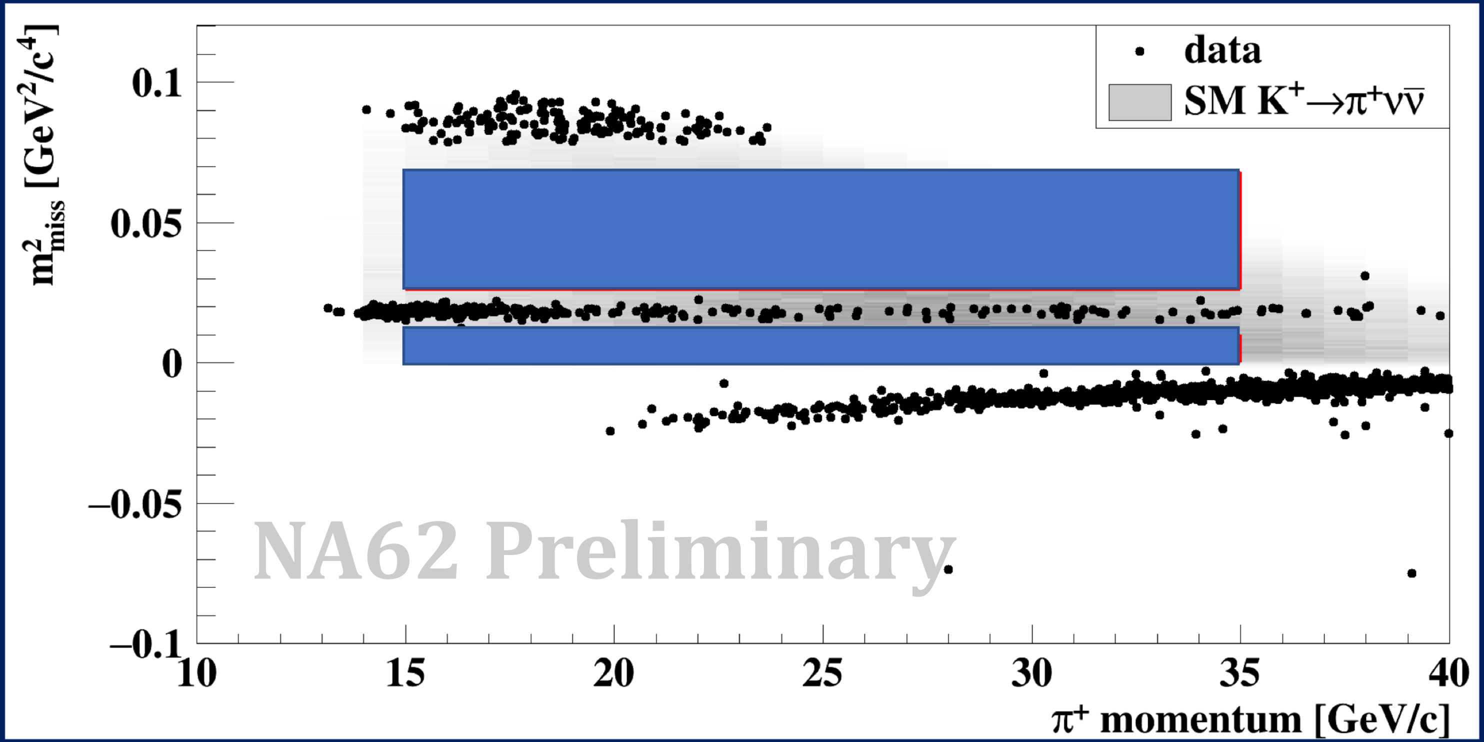
Total background

Process	Expected events
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	$2.16 \pm 0.12_{stat} \pm 0.26_{ext}$
$K^+ \to \pi^+\pi^0(\gamma)$ IB	$0.29 \pm 0.03_{stat} \pm 0.03_{syst}$
$K^+ \to \mu^+\nu_\mu(\gamma)$ IB	$0.15 \pm 0.02_{stat} \pm 0.04_{syst}$
$K^+ \to \pi^+\pi^-e^+\nu_e$	$0.12 \pm 0.05_{stat} \pm 0.03_{syst}$
$K^+ \to \pi^+\pi^-\pi^+$	$0.02 \pm 0.02_{syst}$
$K^+ \to \pi^+\gamma\gamma$	$0.005 \pm 0.005_{syst}$
$K^+ \to l^+\pi^0\nu_l$	negligible
Upstream background	$0.9 \pm 0.2_{stat} \pm 0.2_{syst}$
Total background	$1.5 \pm 0.2_{stat} \pm 0.2_{syst}$

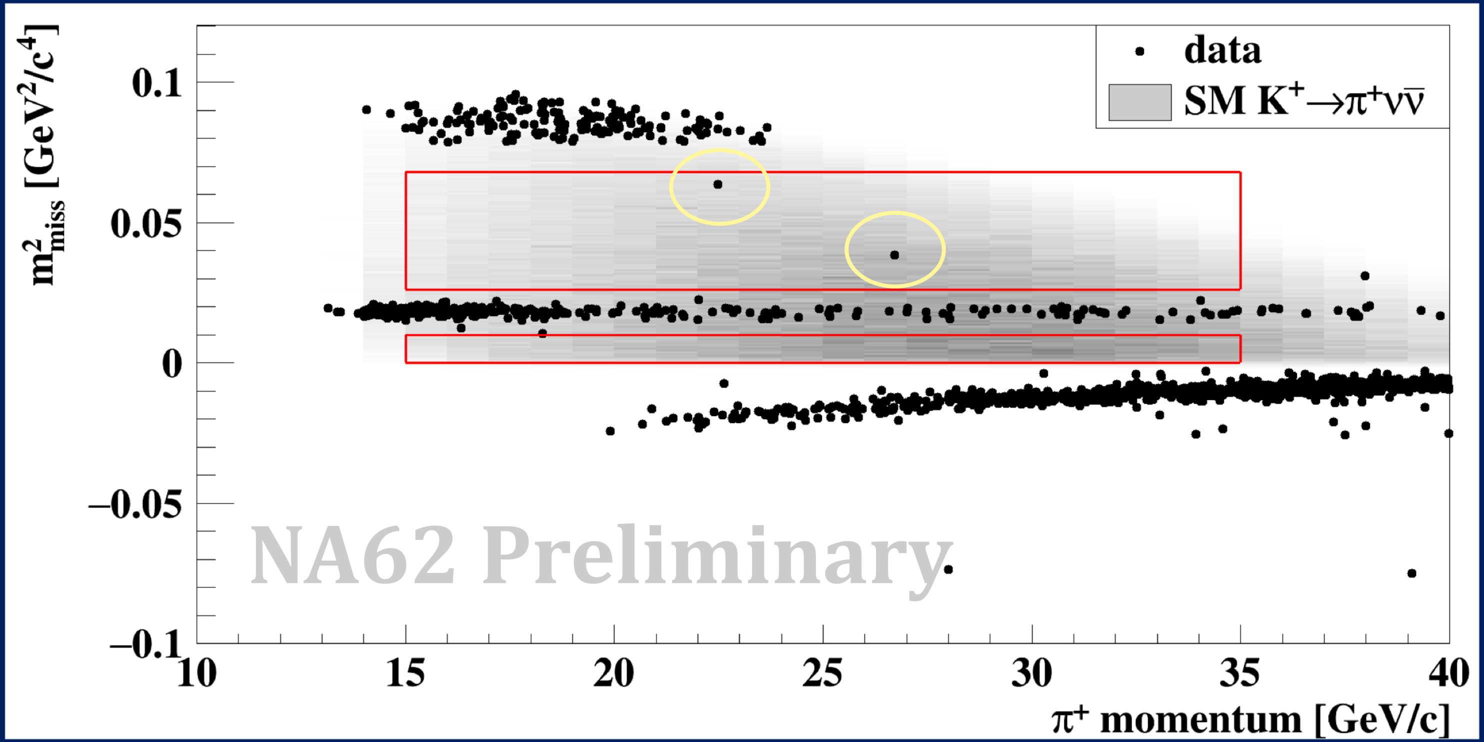
NA62 Preliminary

NA62 Preliminary

$K^+ \to \pi\, \nu\bar{\nu}$: 2017 data-set: result



$K^+ \rightarrow \pi \nu\bar{\nu}$: 2017 data-set: result



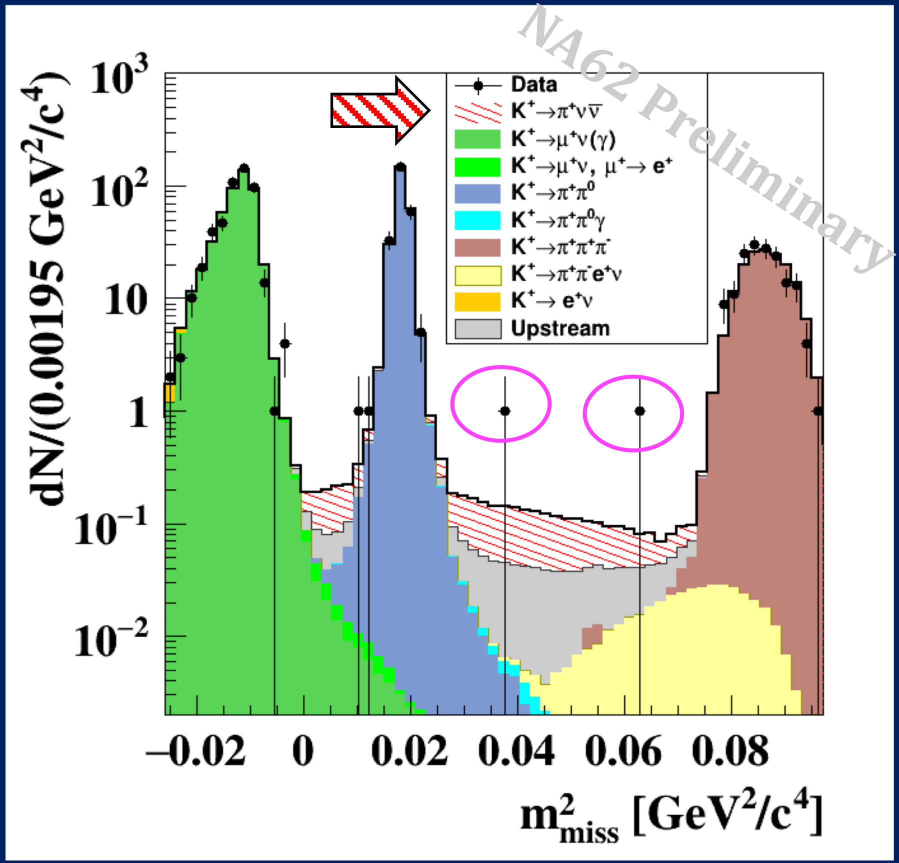
Two events observed in signal region.

Single event sensitivity	$(0.389 \pm 0.021) \times 10^{-10}$
Expected background	1.5 ± 0.30
Expected signal events (SM)	$2.16 \pm 0.12 \pm 0.26_{ext}$
Events observed	2

NA62 Preliminary

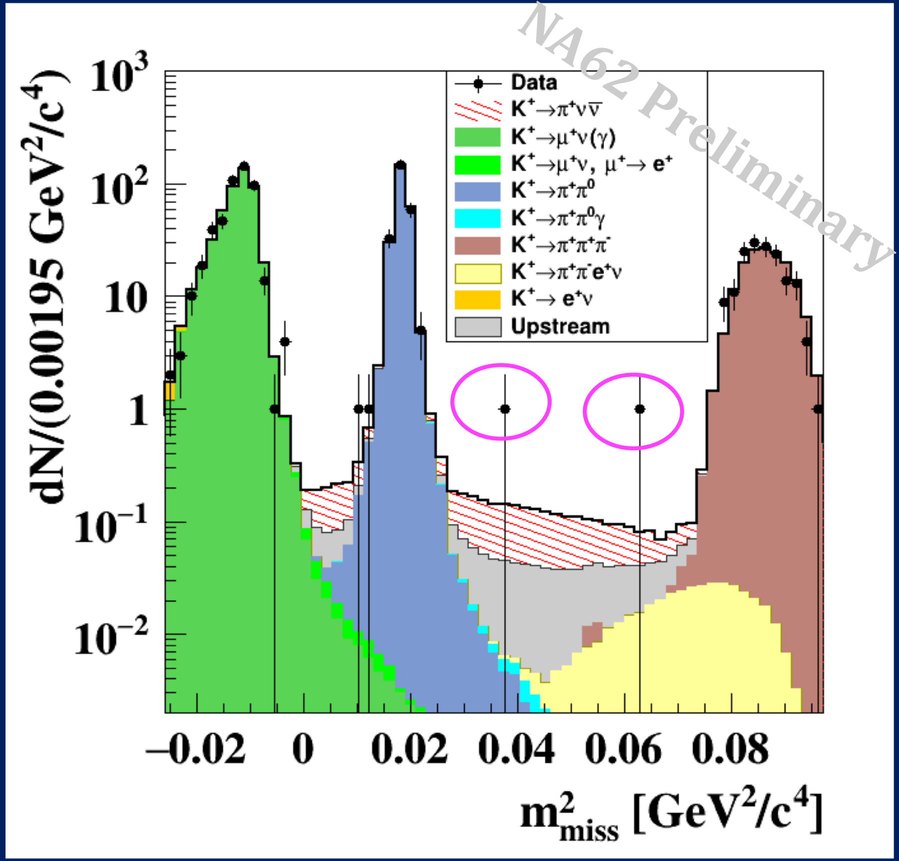
NA62 Preliminary

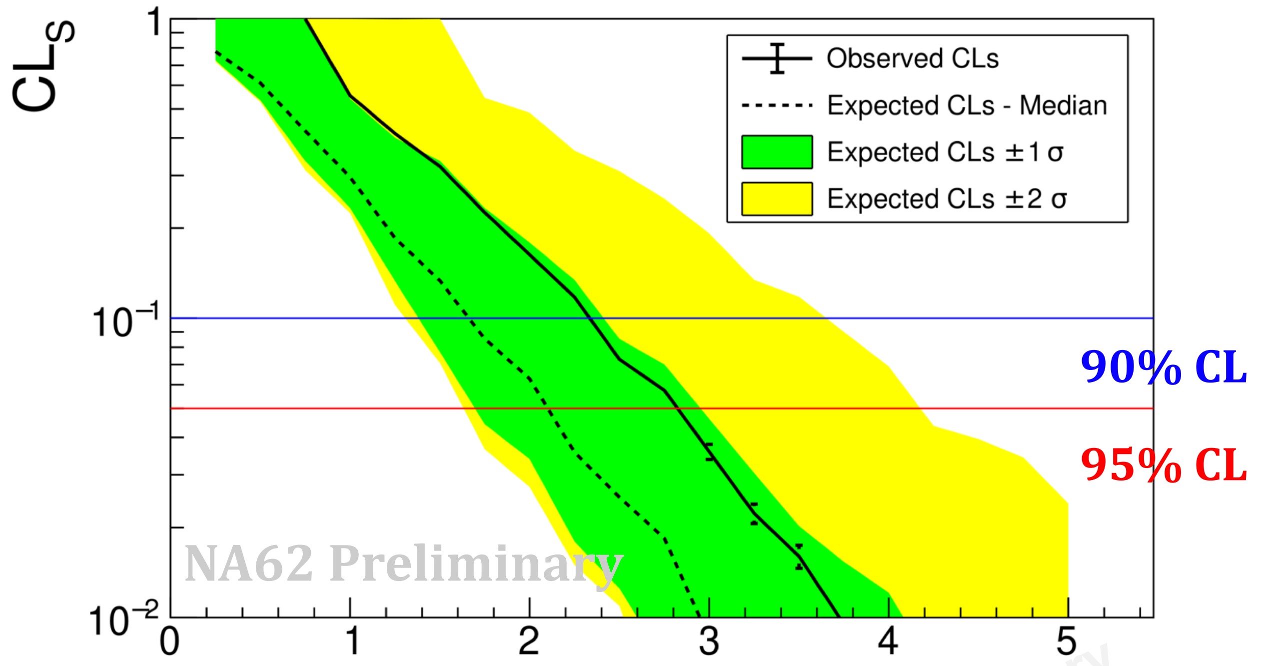
$K^+ \to \pi \nu\bar{\nu}$: 2017 data-set: result



$K^+ \to \pi\nu\bar{\nu}$: 2017 dat

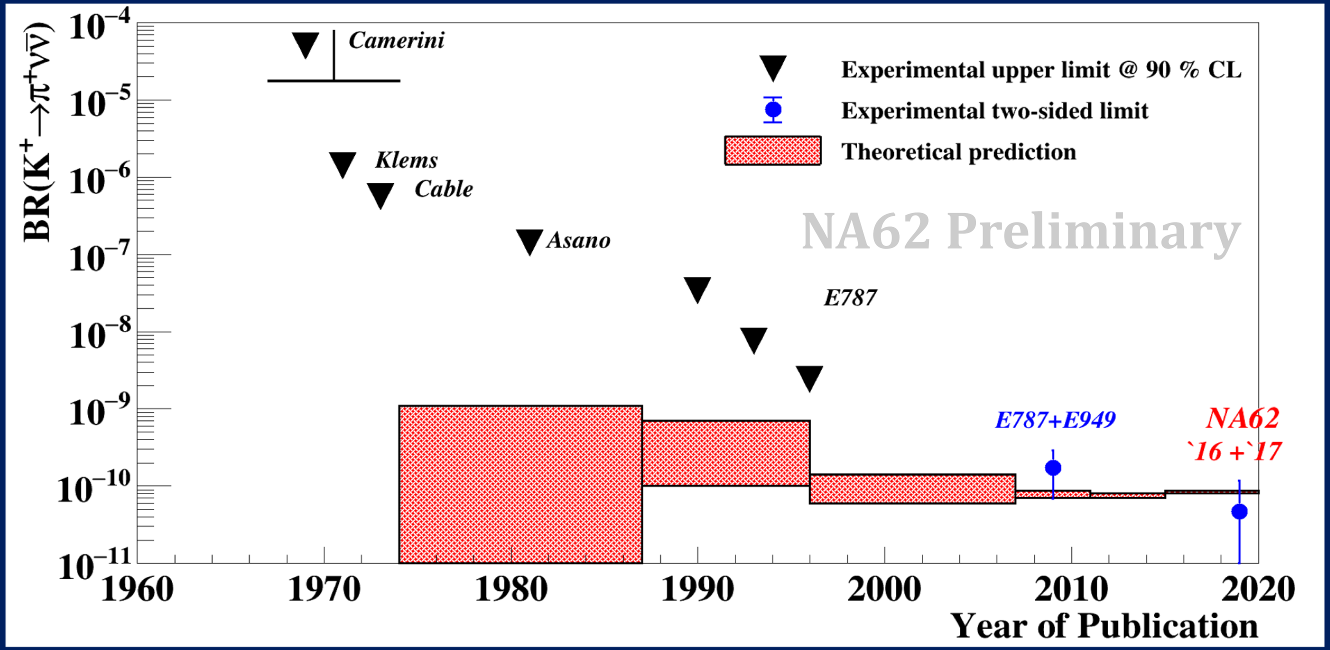
Observed	Expected (background only)	CL
$Br(K^+ \to \pi^+\nu\bar{\nu}) < 1.76 \times 10^{-10}$	$Br(K^+ \to \pi^+\nu\bar{\nu}) < 1.41 \times 10^{-10}$	90%
$Br(K^+ \to \pi^+\nu\bar{\nu}) < 2.11 \times 10^{-10}$	$Br(K^+ \to \pi^+\nu\bar{\nu}) < 1.76 \times 10^{-10}$	95%





Two sided 68% band: $Br(K^+ \to \pi^+\nu\bar{\nu}) = (0.20^{+0.69}_{-0.20}) \times 10^{-10}$

Historical evolution of measurements



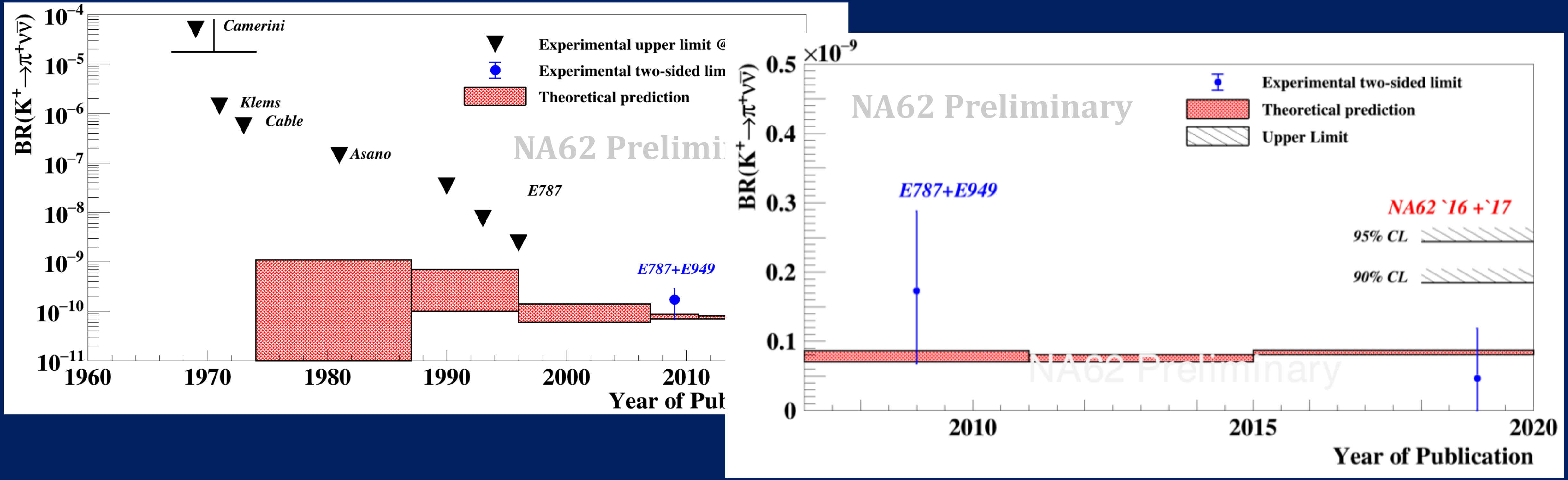
2016 and 2017 result combined

Events observed	3
Single event sensitivity	$(0.346 \pm 0.017) \times 10^{-10}$
Expected background	1.65 ± 0.31

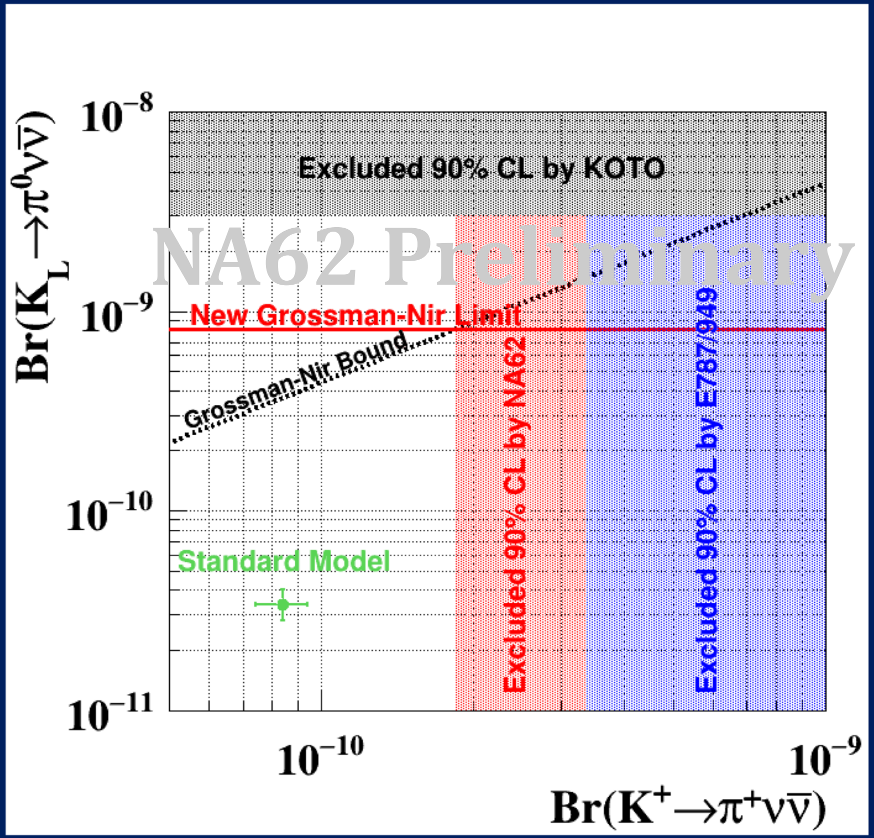
Two sided 68% band:

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (0.47^{+0.72}_{-0.47}) \times 10^{-10}$$

Historical evolution of measurements



The ‘Exclusion plot’ compared to SM prediction



Approaching the SM prediction limits …

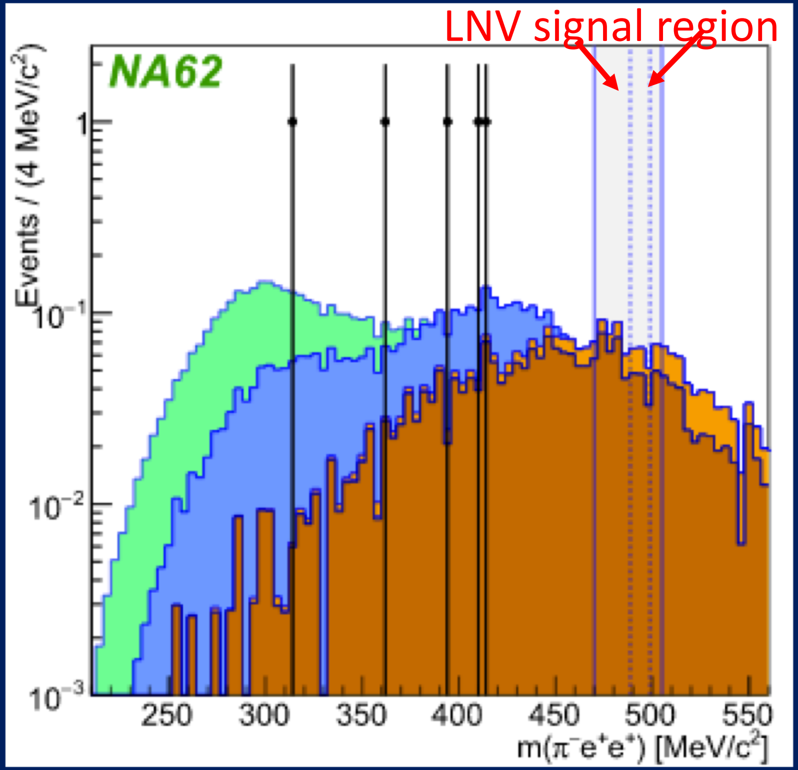
Testing the SM – other probes in NA62

- $\pi^0 \rightarrow$ *invisible* with π^0 from K^+ decays : **Preliminary result: BR($\pi^0 \rightarrow$ inv.) < 4.4.10^{-9} @ 90% C.L.** → factor 60 improvement wrt. state of the art.
- Lepton Number Violation (LNV) and Lepton Flavour Violations (LFV): test for Majorana (massive) nature of the neutrino. → next slides
- Heavy Neutral Leptons (HNL): three right-handed (sterile) neutrinos N_i are added to the SM , they mix with classical neutrinos (Neutrino Minimal SM)→ next slides
- Lepton universality: R_K
- Dark photons from Kaon decays: $K^+ \rightarrow \pi^+\pi^0$, $\pi^0 \rightarrow A'\gamma$, with $A' \rightarrow$ *invisible* .
- Axion like particles (*ALP*s)→ dark matter candidates: dump the beam ahead of detectors with copper collimators closed → produce B and D mesons decaying promptly into exotic mediators and SM particle → e.g. study $ALP \rightarrow \gamma\gamma$
- Dark photons from visible decay e.g. $A' \rightarrow l^+l^-$ in beam dump events.
- HNL and Dark Scalar in beam dump events.

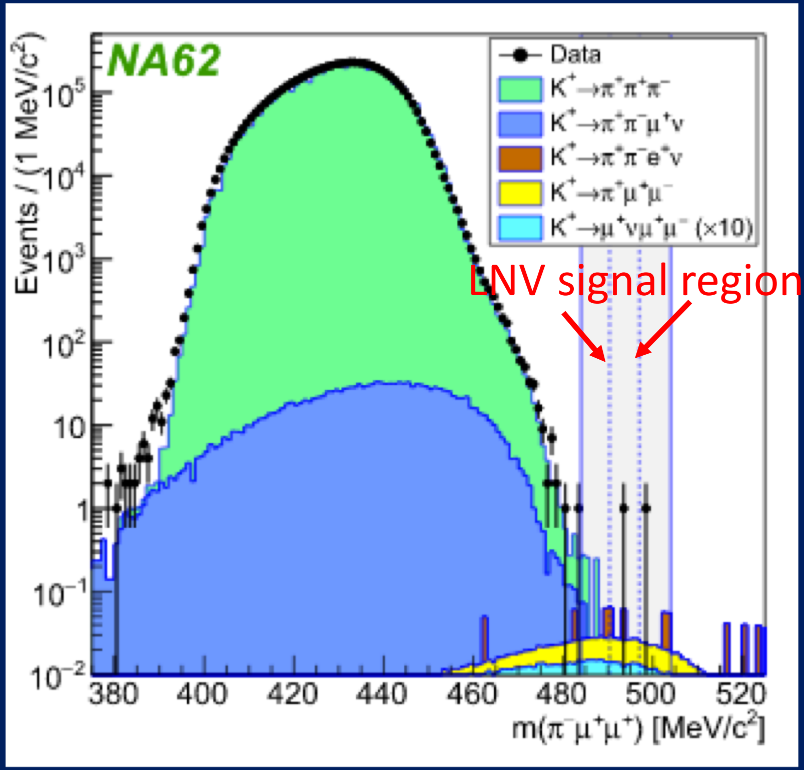
… more exotic, rare decay studies and precision measurements.

LNV: 2017 sub-data-set

Physics Letters B 797 (2019) 13479



$K^+ \rightarrow \pi^- e^+ e^+$: no event observed.



$K^+ \rightarrow \pi^- \mu^+ \mu^+$: 1 event observed.

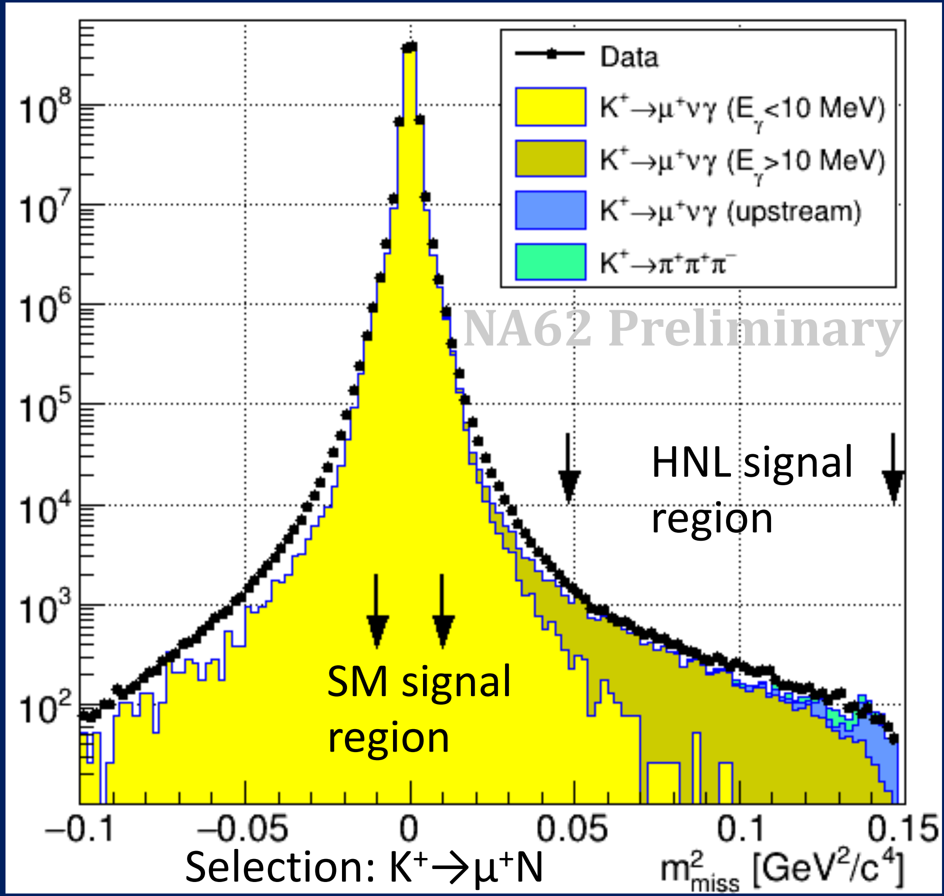
- **No new physics observed**

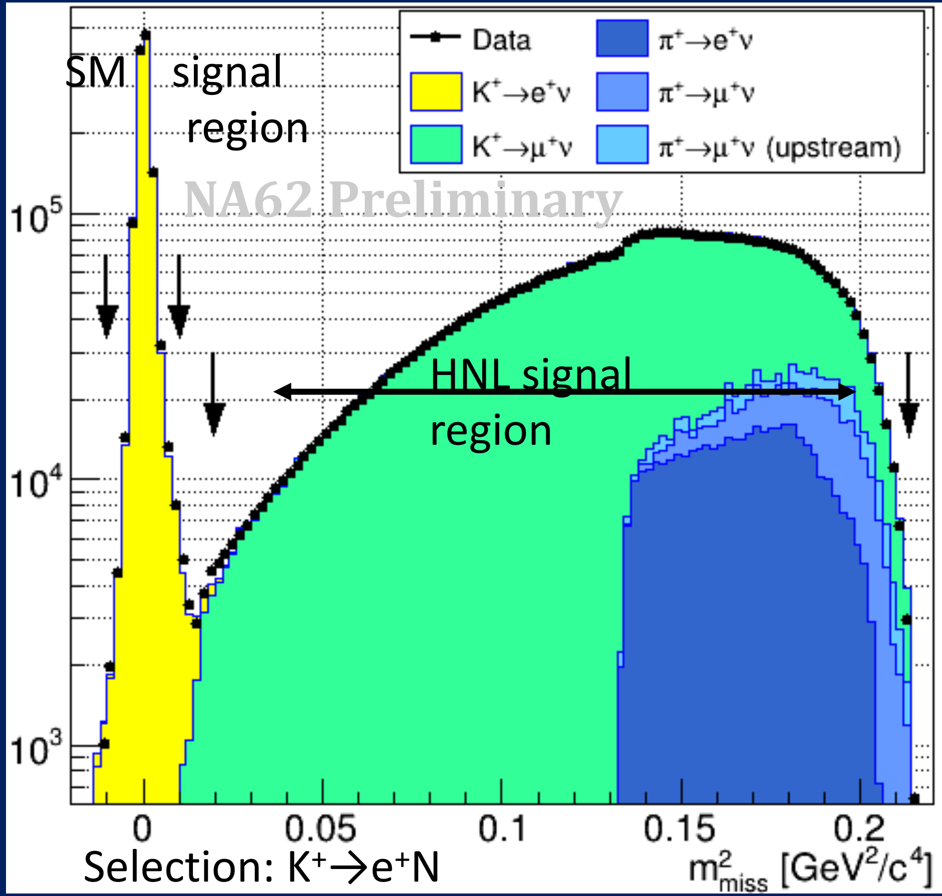
$K^+ \rightarrow \pi^- \mu^+ \mu^+$:	**BR UL @ 90%**
• **NA62:**	**$4.2\ 10^{-11}$**
• PDG:	$8.6\ 10^{-11}$

$K^+ \rightarrow \pi^- e^+ e^+$:	**BR UL @ 90%**
• **NA62:**	**$2.2\ 10^{-10}$**
• PDG:	$6.4\ 10^{-10}$

- **factor 2 and 3 improvement in world upper limits.**

HNL: 2016 + 2017 data-set





- **Preliminary results, 1/3 of the full NA62 data set.**

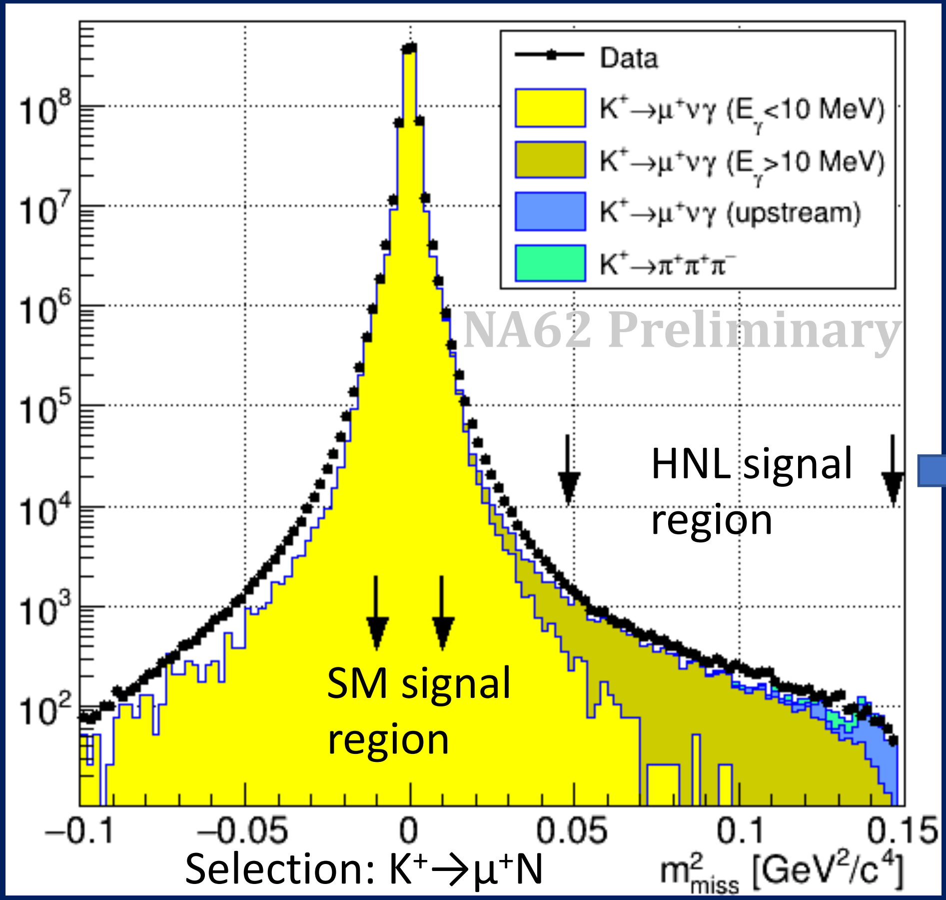
➢ **No HNL production signals are observed.**

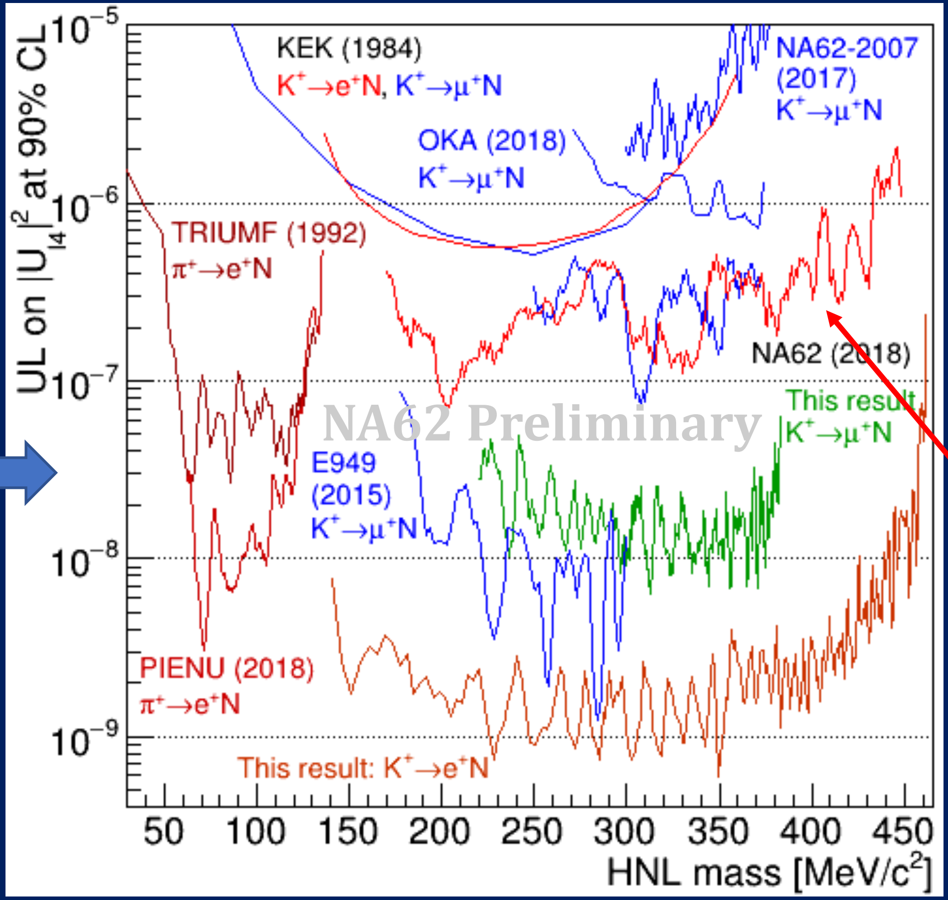
$|U_{l4}|^2$: elements of the extended neutrino mixing matrix

Decays in the fiducial volume: ~1.6×10⁸ K⁺ → μ⁺ν and ~3.7×10⁵ K⁺ → e⁺ν

$$\Gamma(K^+ \to \ell^+ N) = \Gamma(K^+ \to \ell^+ \nu) \times \rho_\ell(m_N) \times |U_{\ell 4}|^2.$$

HNL: 2016 + 2017 data-set



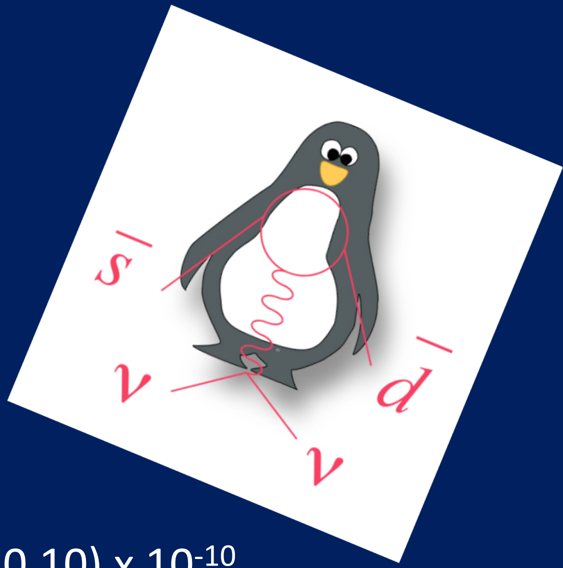


- **Preliminary results, 1/3 of the full NA62 data set.**
  - **No HNL production signals are observed.**
  - **More than 2(1) orders of magnitude improvements with respect to previous result from 2015 min. bias data for e(μ).**
- **Muon case: NA62 consistent with the E949 result and extends UL to higher masses.**

Decays in the fiducial volume: ~1.6×10⁸ $K^+ \rightarrow \mu^+\nu$ and ~3.7×10⁵ $K^+ \rightarrow e^+\nu$

Summary

$K^+ \rightarrow \pi \nu\bar{\nu}$: summary and plans



Preliminary 2017 result

$\mathrm{S.E.S.} = (0.389 \pm 0.021) \times 10^{-10}$

Expected background: 1.50 ± 0.30 events

2 events in signal region observed

Preliminary 2016 + 2017 result

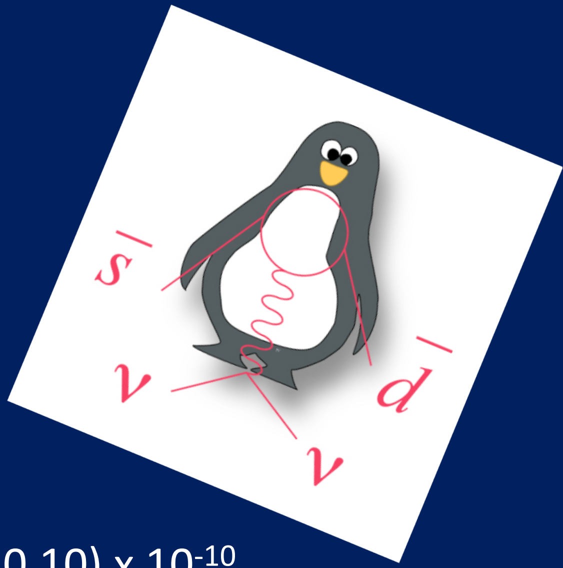
$$BR(K^+ \rightarrow \pi^+ \nu\nu) < 1.85 \times 10^{-10} \text{ @ } 90\ \%\ \mathrm{CL}$$

Two sided 68% band:

$$BR(K^+ \rightarrow \pi^+ \nu\nu) = 0.47^{+0.72}_{-0.47} \times 10^{-10}$$

vs SM prediction: $(0.84 \pm 0.10) \times 10^{-10}$

$K^+ \to \pi \nu\bar{\nu}$: summary and plans



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$\text{S.E.S.} = (0.389 \pm 0.021) \times 10^{-10}$

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$BR(K^+ \to \pi^+ \nu\nu) < 1.85 \times 10^{-10}$ @ 90 % CL

Two sided 68% band:

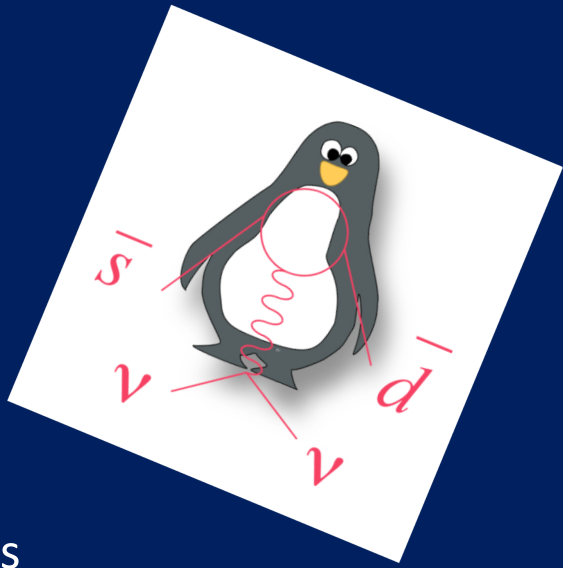
$BR(K^+ \to \pi^+ \nu\nu) = 0.47^{+0.72}_{-0.47} \times 10^{-10}$

vs SM prediction: $(0.84 \pm 0.10) \times 10^{-10}$

<u>Plans and outlook</u>

- 2018 data analysis on-going: 2 × 2017 data-set.
- On-going studies to increase signal efficiency.
- On-going studies to reduce the random veto.
- Event shape analysis.
- Plans to strongly suppress the upstream background in future runs.
  - Hardware improvements such as beam line optimisation.
- **Run 2 (2021-2023):** Run at higher beam intensity foreseen.

Summary and outlook: NA62



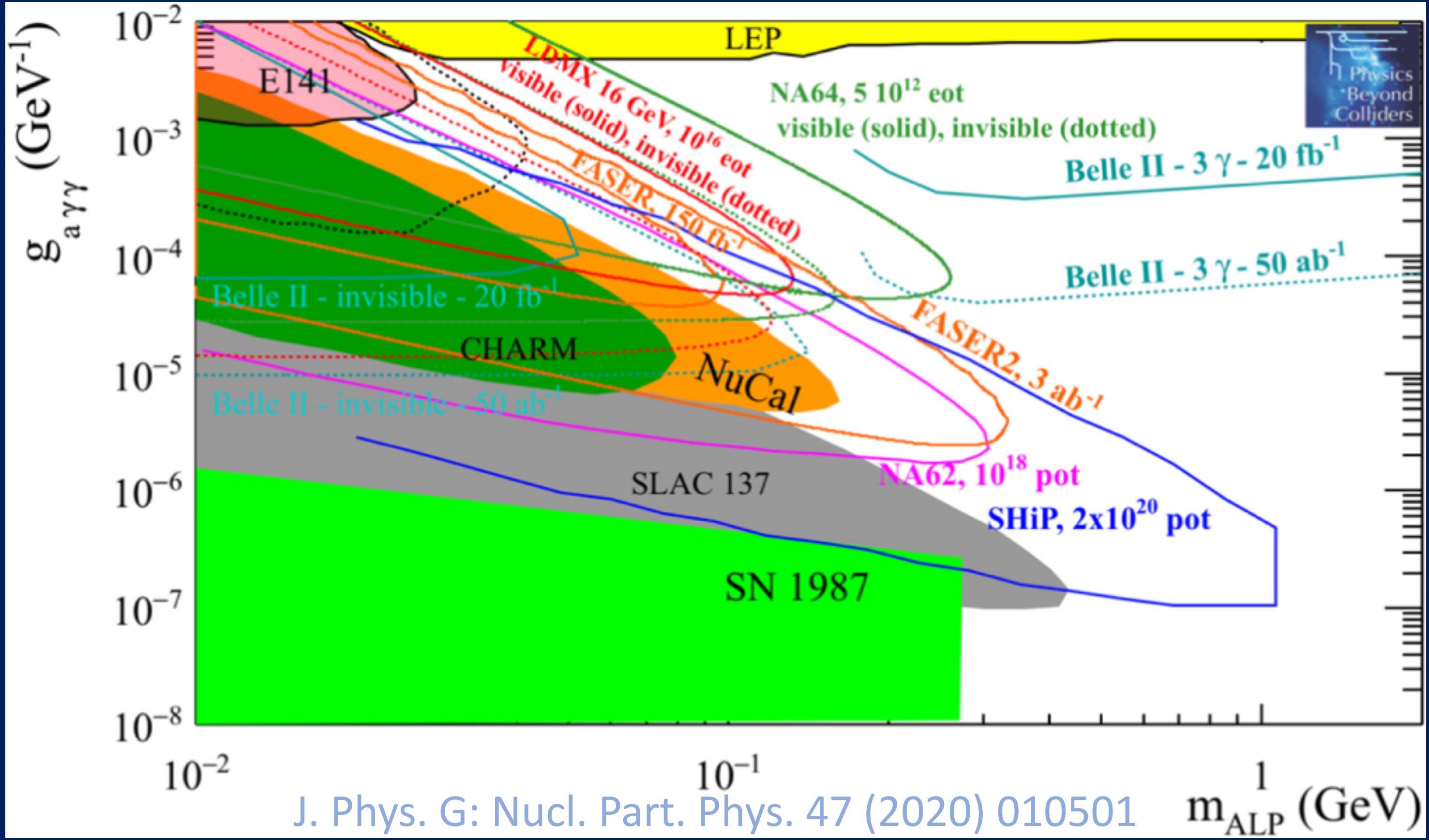
- With the NA62 experiment at CERN, a considerable spectrum of ongoing and potential measurements to test and challenge the Standard Model is available.
- The high intensity Kaon beam and the beam dump configuration provide the basis for rare decay studies, precision measurements as well as Dark Matter and New Physics searches.
- Three $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ events observed (2016-17), moving the measured BR closer to SM prediction and challenging its uncertainties.
- Results on Lepton Number Violation and preliminary searches for Heavy Neutral Leptons suggest no new physics so far.
- More precise measurements to come with analysis of all data 2016-2018 …
- … and with future data recordings in Run 2 with higher intensity and $O(10^{18})$ POT for beam dump.

Backup

ALP

ALPs with photon coupling. Current bounds (filled areas) and prospects for PBC projects on 10–15 years timescale (solid lines) in the plane coupling $g_{a\gamma\gamma}$ versus mass of ALP.

Prospects of NA62 with $O(10^{18})$ POT.

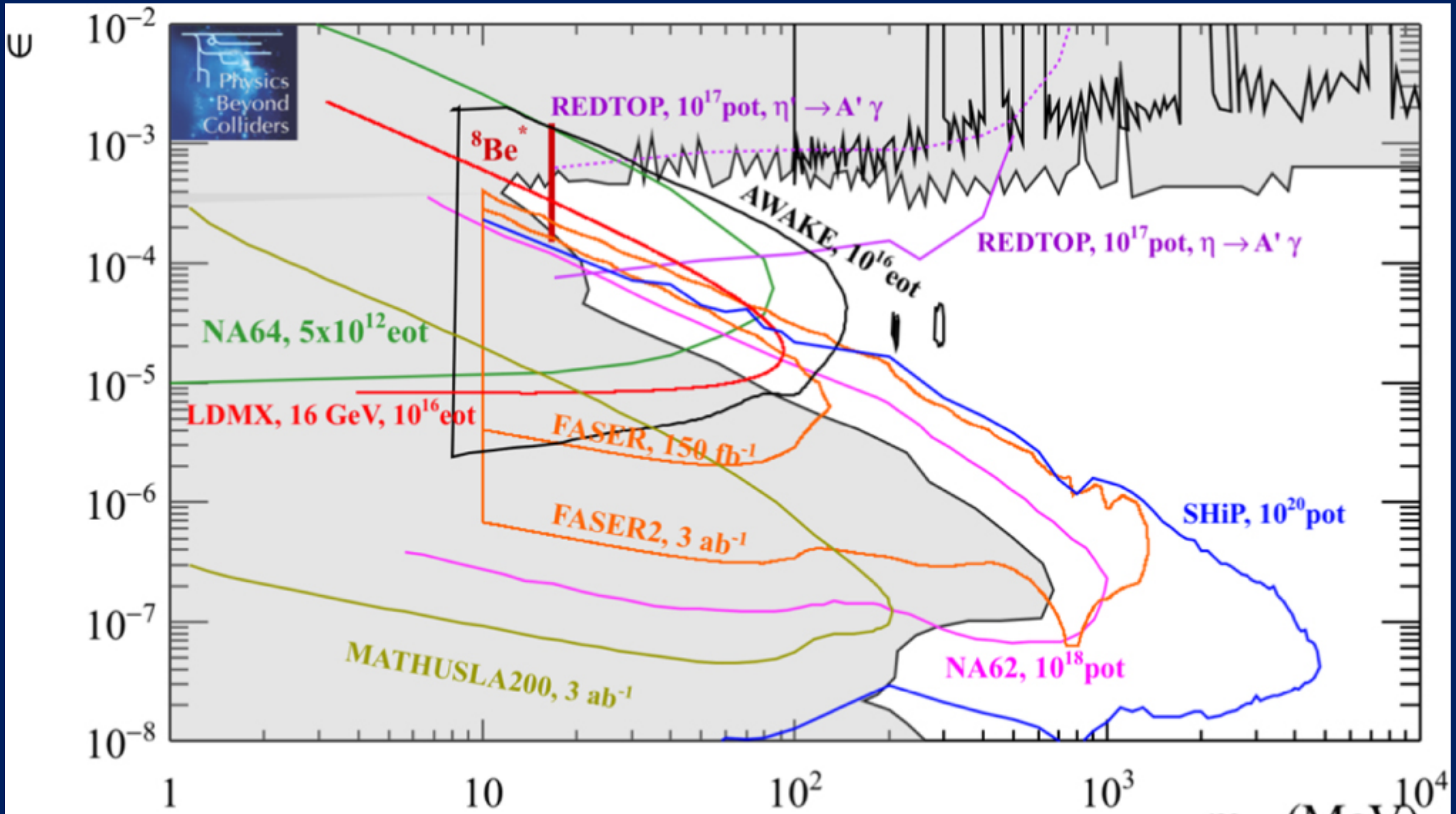


J. Phys. G: Nucl. Part. Phys. 47 (2020) 010501

Dark photon in beam dump

Future upper limits at 90% CL for dark photon in visible decays in the plane mixing strength ε versus mass $m_{A'}$ for PBC projects on a ~10–15 year timescale.

Prospects of NA62 with $O(10^{18})$ POT.



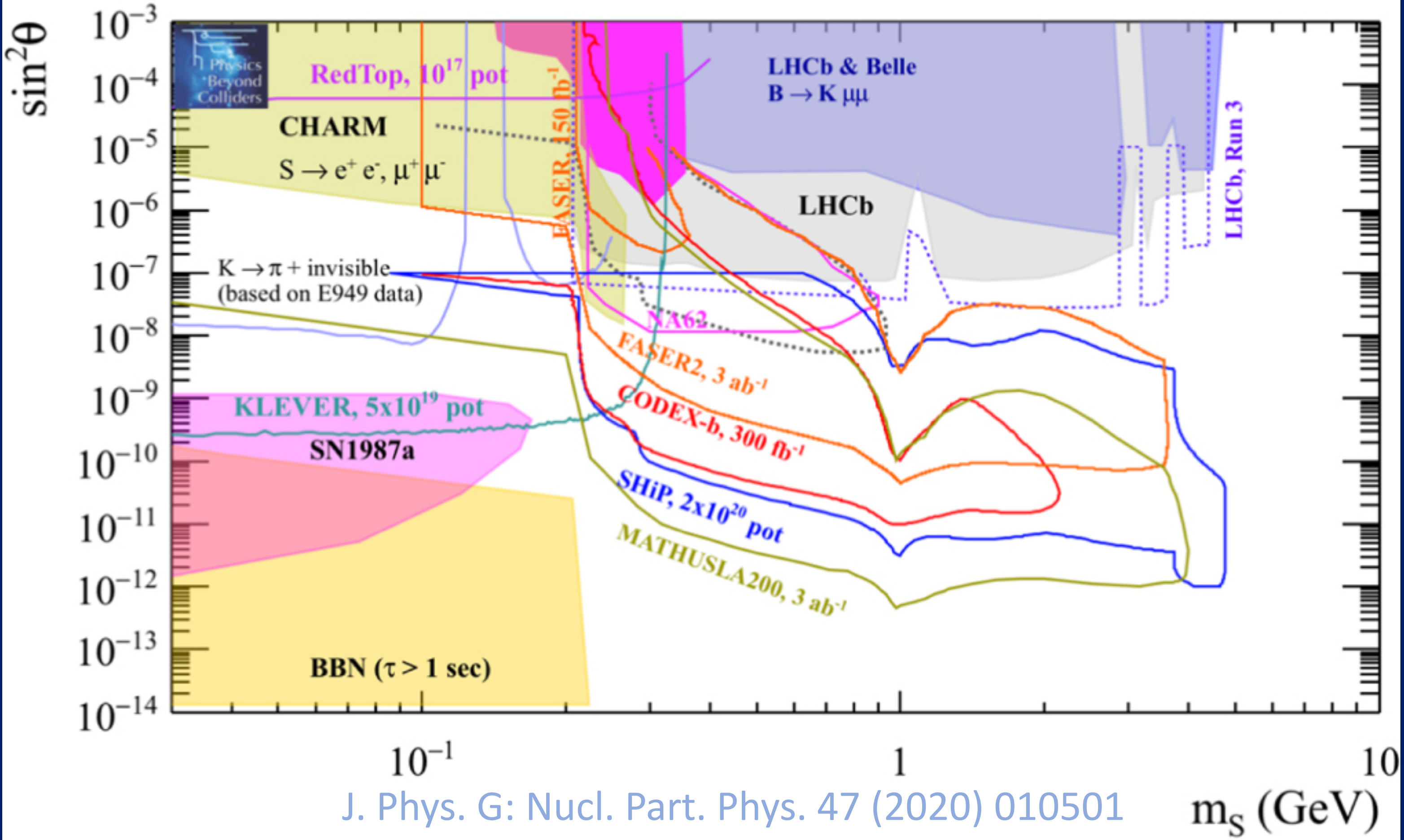
J. Phys. G: Nucl. Part. Phys. 47 (2020) 010501

Dark Scalar in beam dump

Prospects on 10–15 year timescale for PBC projects for the Dark Scalar mixing with the Higgs in the plane mixing angle $\sin^2\theta$ versus dark scalar mass m_S

$(\mu S+\lambda S^2)H^{\dagger}H$
$\mu = \sin\theta$
$\lambda = 0$

$S \rightarrow \mu^+\mu^-$



J. Phys. G: Nucl. Part. Phys. 47 (2020) 010501

Search for two opposite sign charged tracks in the NA62 fiducial volume.

Expected 90% CL exclusion contours

- Including trigger/acceptance/selection efficiencies
- Assume zero background