# Physics Beyond Standard Model with Kaons at NA62

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**on behalf of the NA62 collaboration**

Physics of Fundamental Symmetries and Interactions - PSI2019

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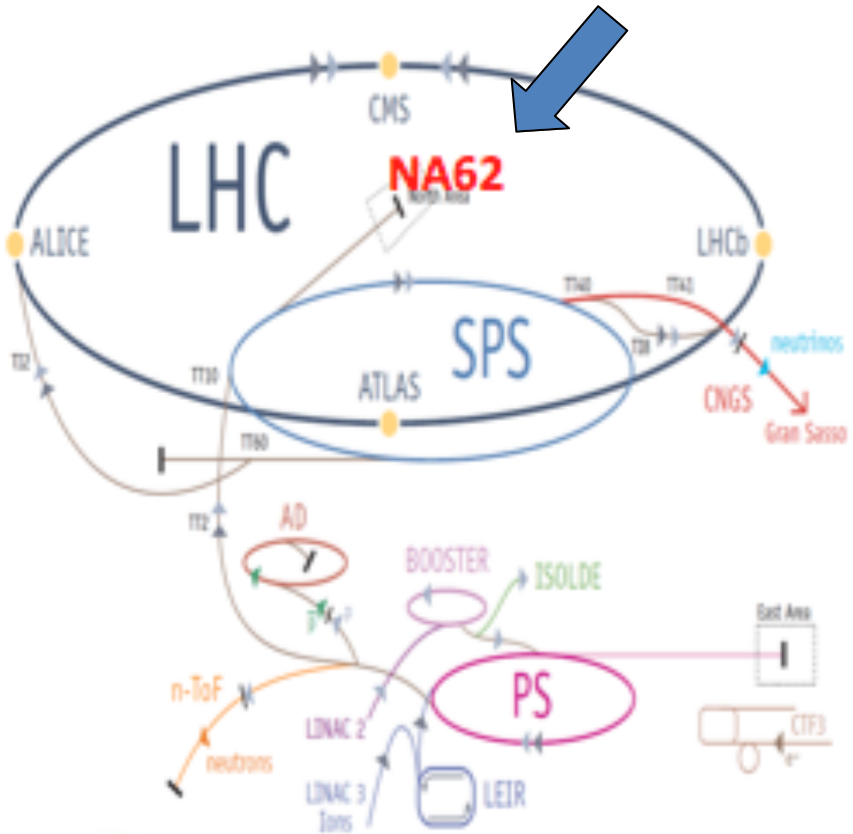
# Kaon physics at NA62




2008: NA62 Approval

2009-14: Detector R&D

2014: Pilot Run

2015: Commissioning Run

2016-18: Physics Run

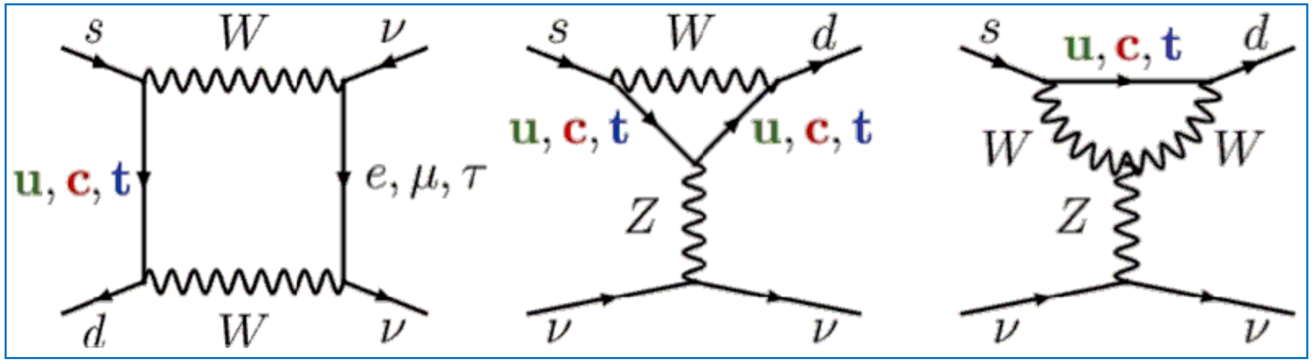
After LS2: Physics Run

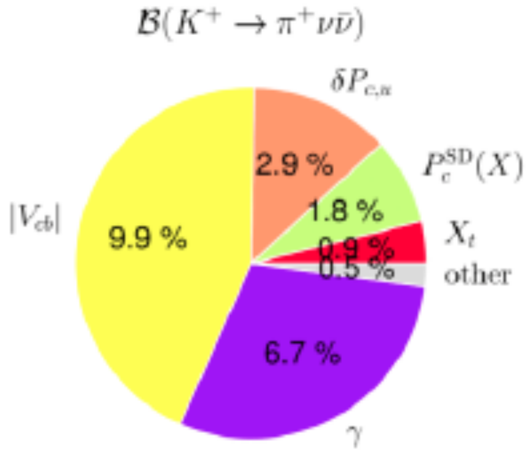
~**200** participants, **30** institutions

NA62 main goal: precise measurement of $K^+ \to \pi^+ \nu \bar{\nu}$
Broad physics programme: rare decays, precision measurements, searches for exotic particles

# Rare Kaon decays: $K^+ \to \pi^+ \nu\bar{\nu}$

**SM: box and penguin diagrams**




Theoretical error budget
Buras. et. al., JHEP11(2015)033

FCNC process with highest CKM suppression:

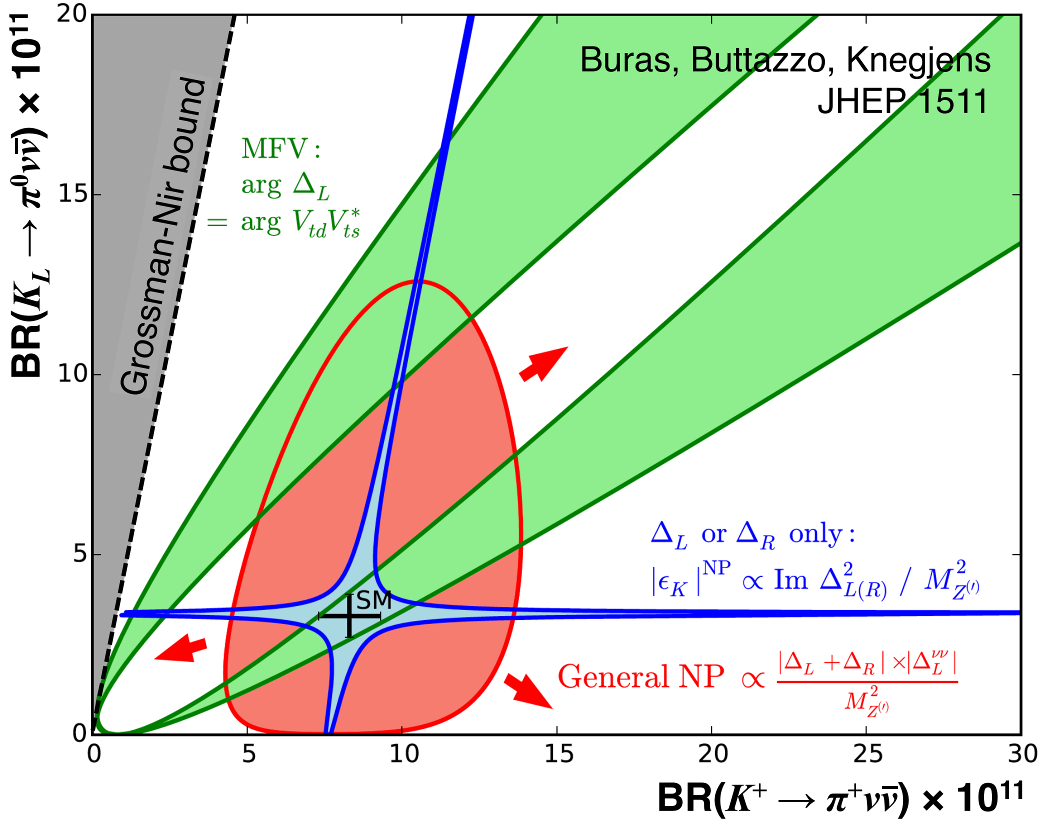
$A \sim (m_t/m_W)^2 |V^*_{ts} V_{td}| \sim \lambda^5$

Hadronic matrix element related to measured quantity
Free from hadronic uncertainties
Exceptional SM precision
Sensitive to New Physics

SM branching ratios
*Buras et al., JHEP 1511 (2015) 033*

| Mode | $BR_{SM} \times 10^{11}$ |
|---|---|
| $K^+ \to \pi^+ \nu\nu(\gamma)$ | 8.4±1.0 |
| $K_L \to \pi^0 \nu\nu$ | 3.00±0.31 |

# Sensitivity to new physics




- Models with CKM-like flavor structure
  - Models with MFV
- Models with new flavor-violating interactions in which either LH or RH couplings dominate
  - $Z/Z'$ models with pure LH/RH couplings
  - Littlest Higgs with $T$ parity
- Models without above constraints
  - Randall-Sundrum

Simplified Z,Z' models [JHEP 1511 (2015) 166]

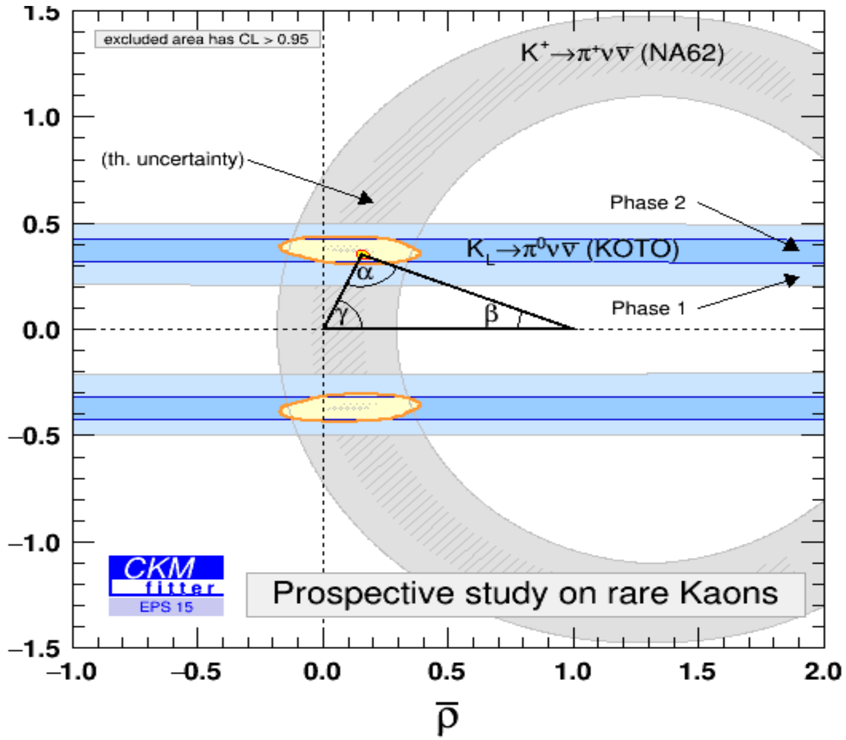
Littlest Higgs with T-parity [EPJ C76 (2016) 182]

Custodial Randall-Sundrum [JHEP 0903 (2009) 108]

MSSM non-MFV [PEPT 2016 123B02, JHEP 0608 (2006) 064

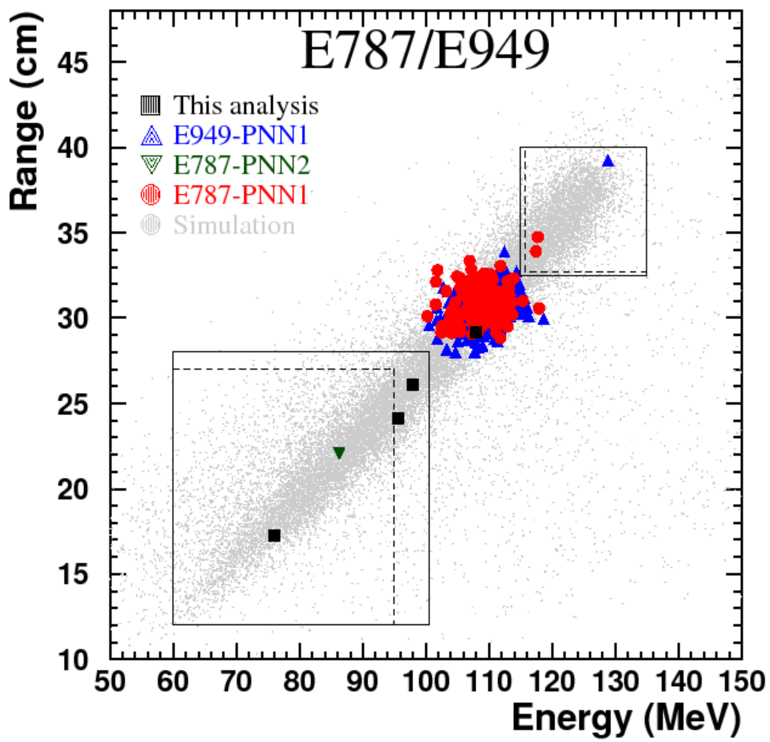
LVF models [Eur Phys J C (2017) 77]

Correlations are model-dependent

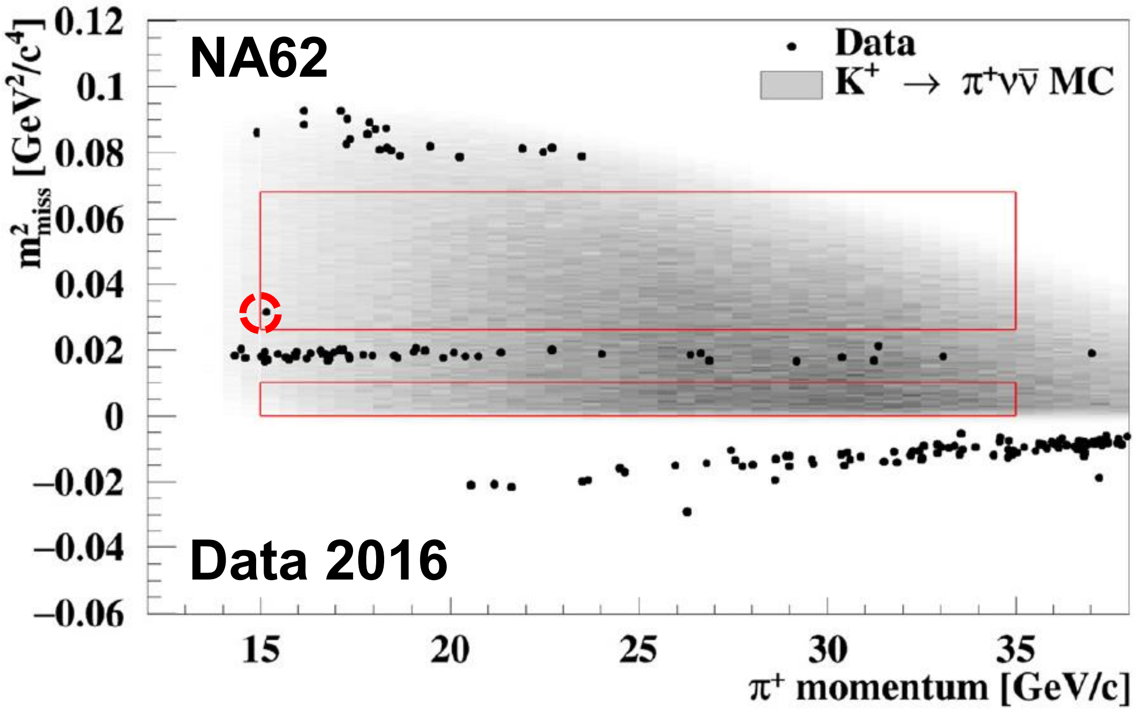


# Experimental state of the art

Decay at rest technique




Decay in flight technique




$BR(K^+ \to \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$

Phys. Rev. D 79, 092004 (2009)

Phys. Rev. D 77, 052003 (2008)

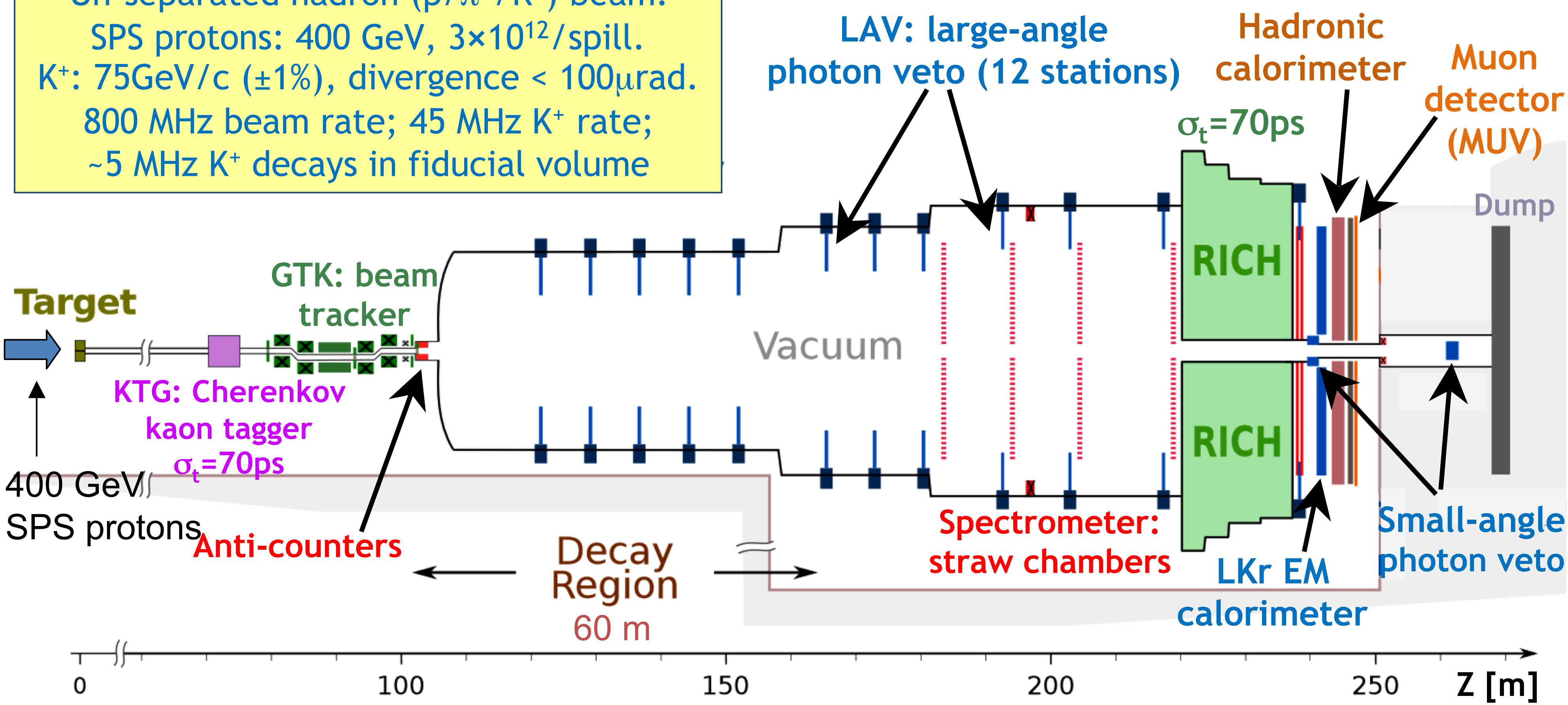
$BR(K^+ \to \pi^+ \nu \bar{\nu}) < 14 \times 10^{-10}$ @ 95% CL

Phys. Lett. B 791, 156 (2019)

# The NA62 experiment

*NA62 collaboration, JINST 12 (2017) P05025*

Un-separated hadron ($p/\pi^+/K^+$) beam.
SPS protons: 400 GeV, $3\times10^{12}$/spill.
$K^+$: 75GeV/c (±1%), divergence < 100μrad.
800 MHz beam rate; 45 MHz $K^+$ rate;
~5 MHz $K^+$ decays in fiducial volume



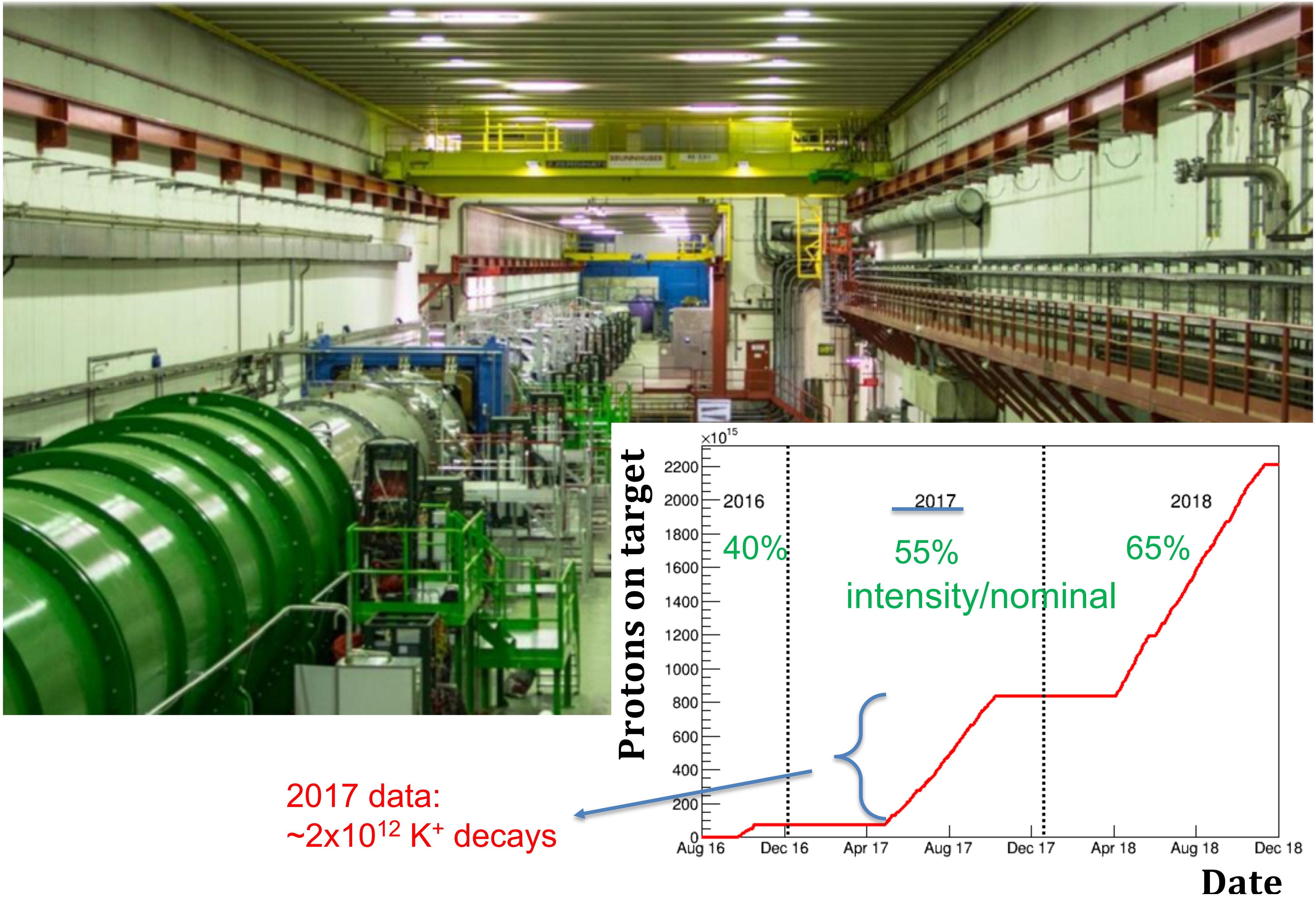

Timing between sub-detectors O(100 ps).

Kinematic rejection $O(10^4)$ for $K^+\rightarrow\pi^+\pi^0$ and $K\rightarrow\mu^+\nu$.

Photon veto: $\pi^0\rightarrow\gamma\gamma$ decay suppression from $K^+\rightarrow\pi^+\pi^0$ ($10^7$)

Particle ID (RICH+LKr+HAC+MUV): muon suppression from $K\rightarrow\mu^+\nu$ ($10^7$)

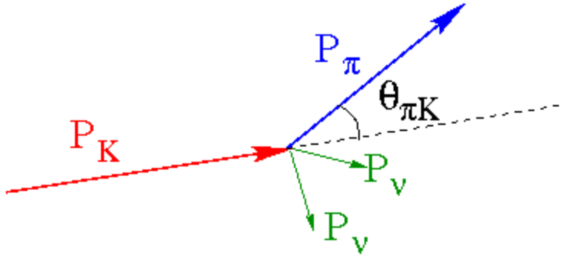
# NA62 data samples



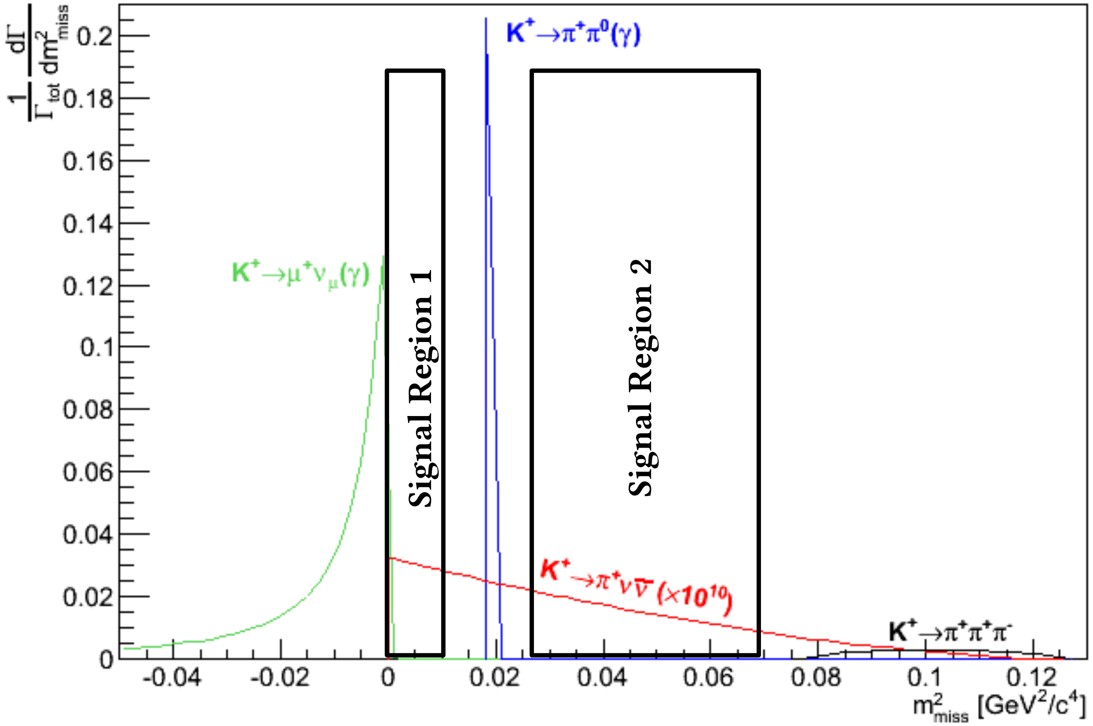

2017 data:
~2x10$^{12}$ $K^+$ decays

# Decay in flight technique

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




| *Process* | *Branching ratio* |
|---|---|
| $K^+ \rightarrow \pi^+\pi^0(\gamma)$ | 0.2067 |
| $K^+ \rightarrow \mu^+\nu(\gamma)$ | 0.6356 |
| $K^+ \rightarrow \pi^+\pi^+\pi^-$ | 0.0558 |
| $K^+ \rightarrow \pi^+\pi^-e^+\nu$ | $4.25 \cdot 10^{-5}$ |




Kinematic signal identification

**+**

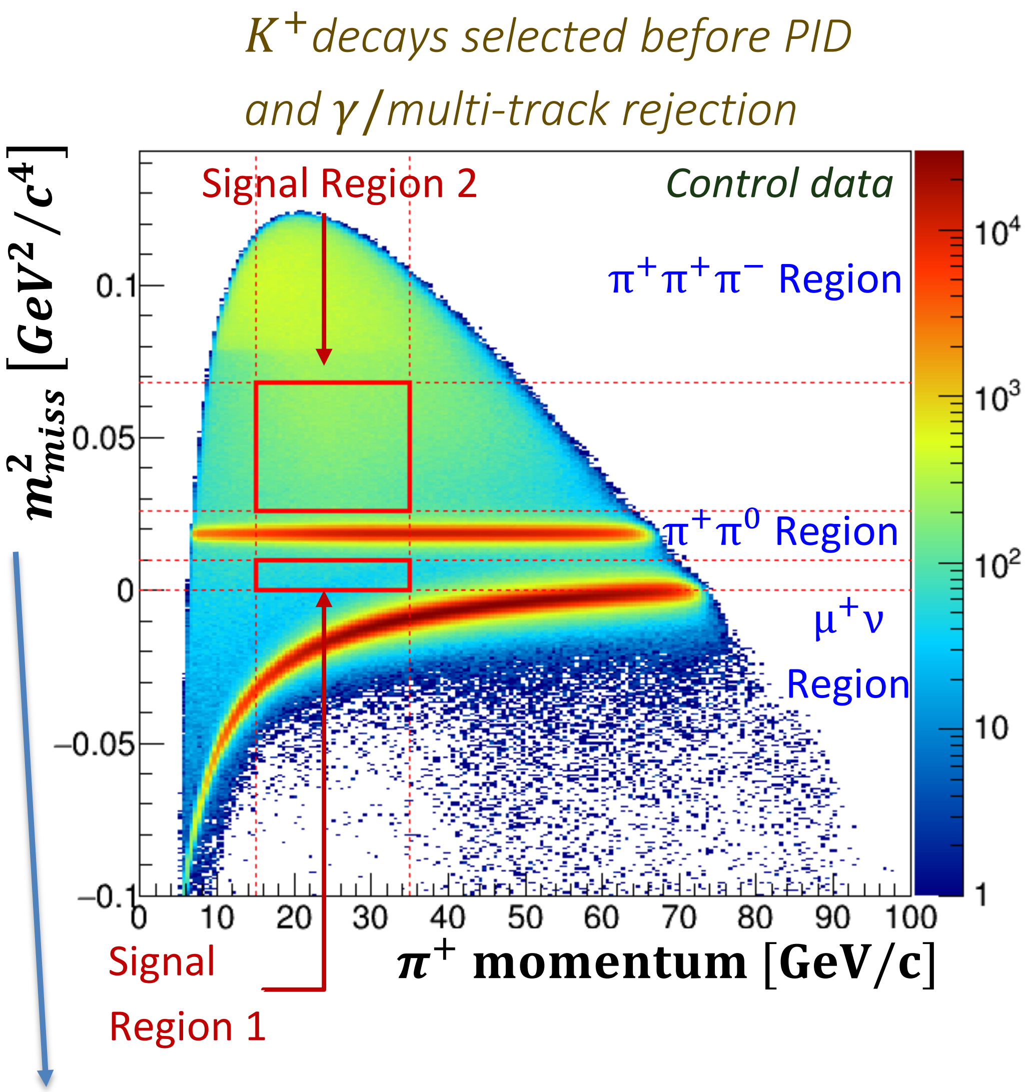
$\mathbf{15 < P_{\pi^+} < 35}$ GeV/c

Particle ID (Cherenkov detectors)

Particle ID (Calorimeters, $\mu$ - veto)

Photon veto

# Selection




## Selection:

$K^+$- $\pi^+$ matching

$K^+$ decays in the decay volume

$\pi^+$ identification (PID)

photon rejection

Multi-track rejection

## Measured performances:

GTK-KTAG-RICH timing: $\mathcal{O}(100 \text{ ps})$

$\sigma(m^2_{miss}) \sim 10^{-3}\ GeV^2/c^4$

$\pi^+$ ID: $\varepsilon_\mu \sim 10^{-8}$, $\varepsilon_{\pi^+} \sim 64\%$

$\pi^0$ rej: $\varepsilon_{\pi^0} \sim 1.4 \cdot 10^{-8}, p_{\pi^+} \epsilon [15,35]$ GeV/c

[pion/kaon 3-mom from STRAW/GTK, pion mass hypothesis]

Signal regions kept masked: blind analysis

# Single Event Sensitivity (SES)

$$N_{\pi\nu\nu}^{exp} \approx N_{\pi\pi}\, \varepsilon_{RV}\, \varepsilon_{trigger} \frac{A_{\pi\nu\nu}}{A_{\pi\pi}} \frac{Br(\pi\nu\nu)}{Br(\pi\pi)} \quad \Longrightarrow \quad S.E.S. = \frac{Br(\pi\nu\nu)}{N_{\pi\nu\nu}^{exp}}$$

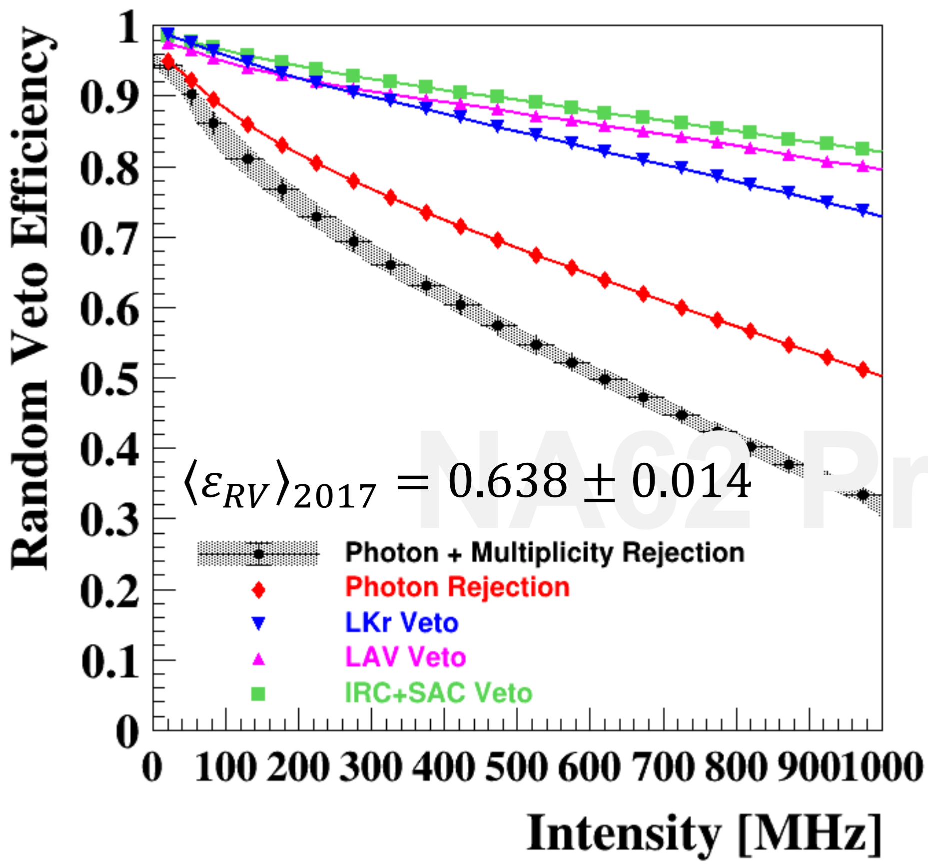
- $N_{\pi\nu\nu}^{exp}$ $\Rightarrow$ Expected number of $\pi\nu\nu$ events
- $Br(\pi\nu\nu)$ $\Rightarrow$ SM $\pi\nu\nu$ branching ratio
- $N_{\pi\pi}$ $\Rightarrow$ $K^+ \rightarrow \pi^+\pi^0$ from control $\pi\nu\nu$-like selected without $\gamma$/multiplicity rejection
- $\varepsilon_{RV}$ $\Rightarrow$ $\pi\nu\nu$ loss due to $\gamma$/multi-track rejection because of random activity
- $\varepsilon_{trigger}$ $\Rightarrow$ PNN trigger efficiency
- $A_{\pi\nu\nu,\pi\pi}$ $\Rightarrow$ Monte Carlo acceptances for $\pi\nu\nu$ ($\sim 3.0\%^*$) and $\pi^+\pi^0$ ($\sim 8.5\%$)
- $Br(\pi\pi)$ $\Rightarrow$ PDG $K^+ \rightarrow \pi^+\pi^0$ branching ratio

Computation in bins of pion momentum and instantaneous beam intensity

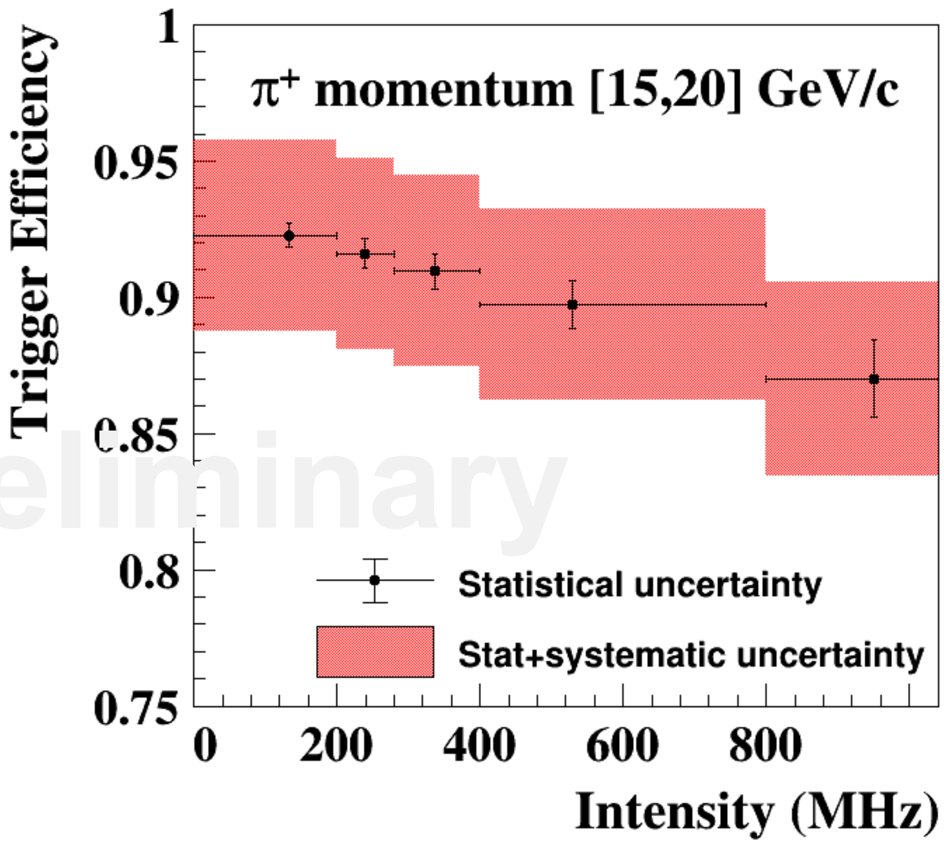
(* Vector Form Factors)

# Efficiencies

$\boldsymbol{\varepsilon}_{\mathbf{RV}}$ measured on $K^+ \to \mu^+\nu$ data

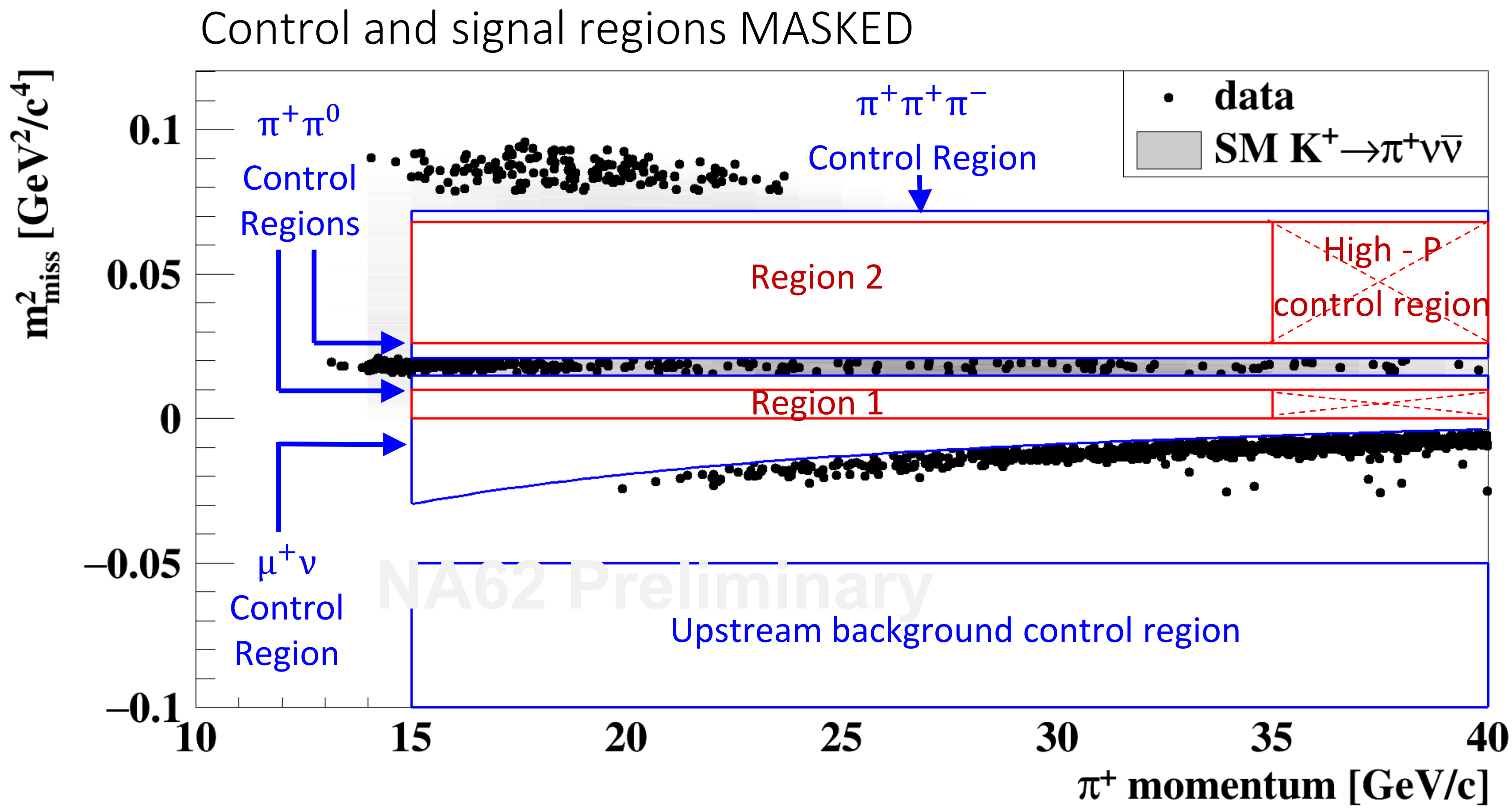



$\boldsymbol{\varepsilon}_{\boldsymbol{trigger}}$ measured on data

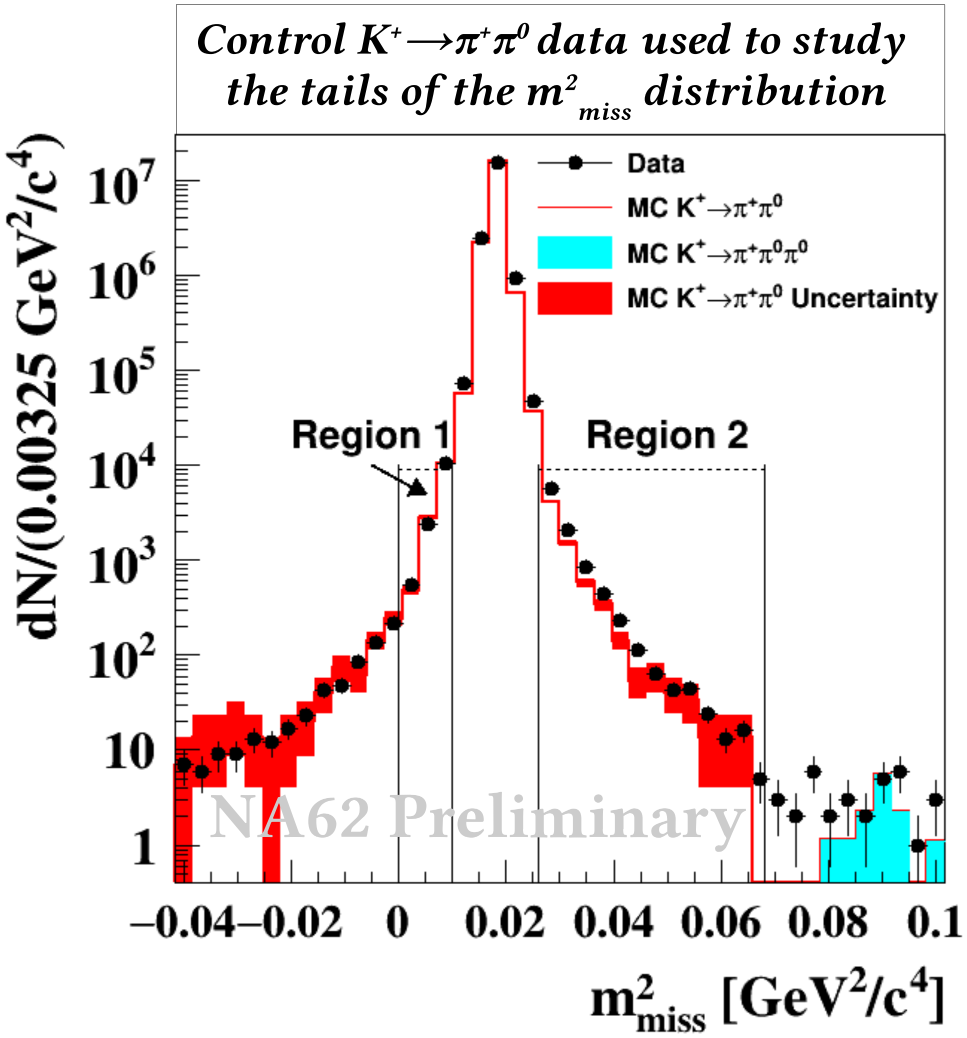



[Intensity: measured event-by-event using GTK time sidebands]

# 2017 data after selection



# Background from kaon decays in fiducial volume

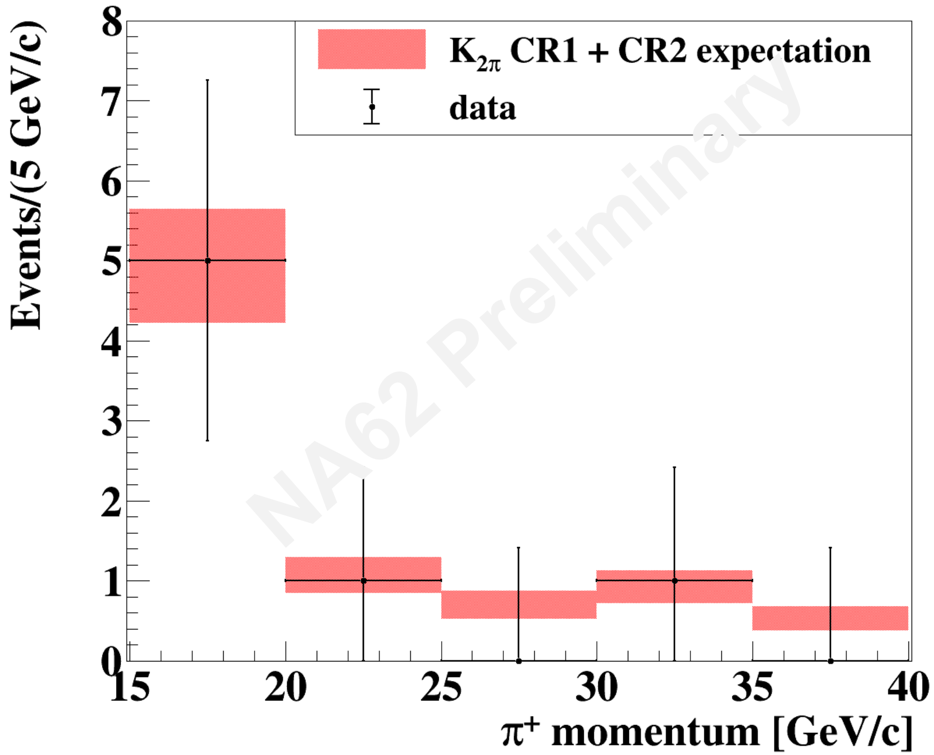



Data in $\pi^+\pi^0$ region after $\pi\nu\nu$ selection (including $\pi^0$ rejection)

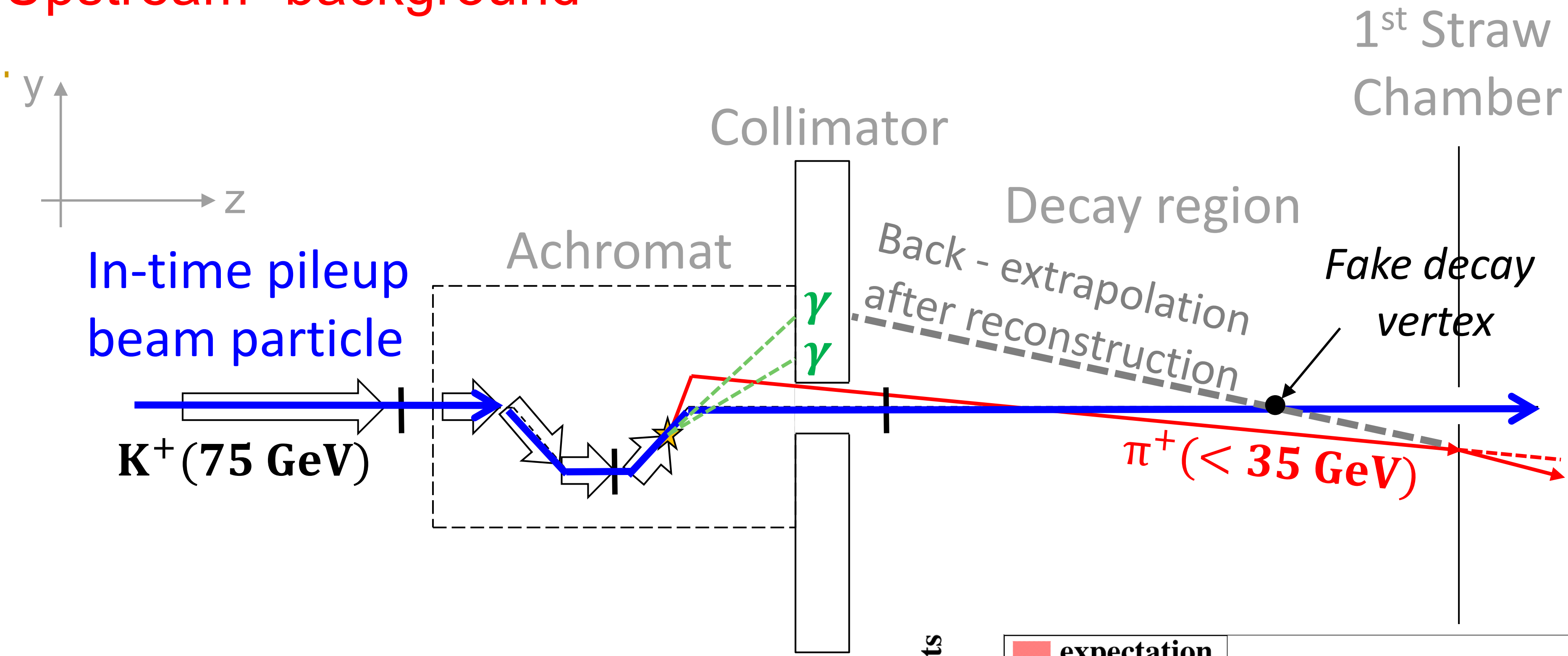
$$N_{\pi\pi}^{exp}(region) = N(\pi^+\pi^0) \cdot f_{kin}(region)$$

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

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

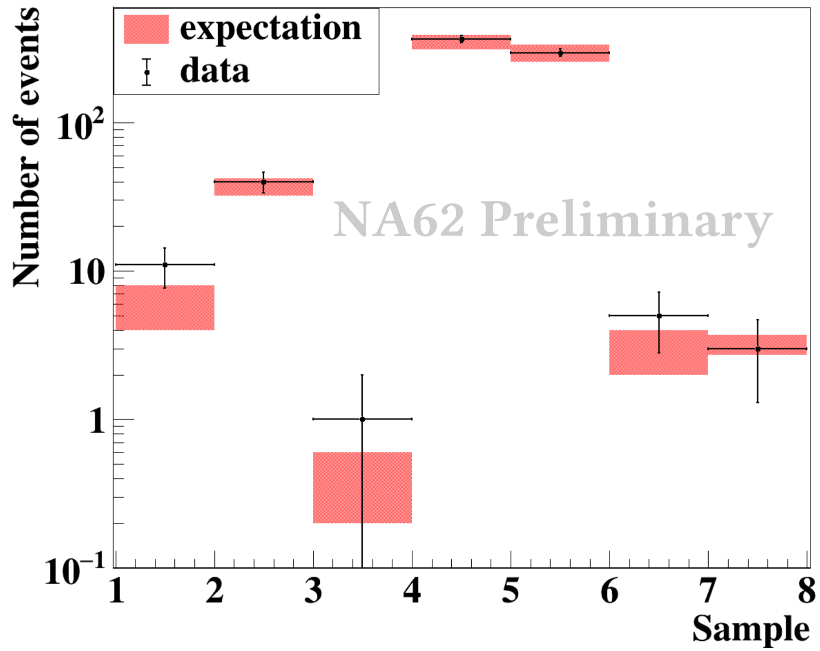


# “Upstream” background




- $K^+$ decays/interacts in the achromat
- Secondary $\pi^+$ downstream
- Beam elements block additional particles
- $\pi^+$ scattering in straw chamber 1
- Pileup beam particle tagged as $K^+$

Measured on data on enriched sample



# Background evaluation

| Process | Expected events |
| --- | --- |
| $K^+ \to \pi^+ \nu \overline{\nu}$ (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 | $1.5 \pm 0.2_{stat} \pm 0.2_{syst}$ |



Background expectations validated in Control Regions on data

# NA62 2017 data sample

Single Event Sensitivity: $\text{S.E.S.} = (3.89 \pm 0.21) \times 10^{-11}$

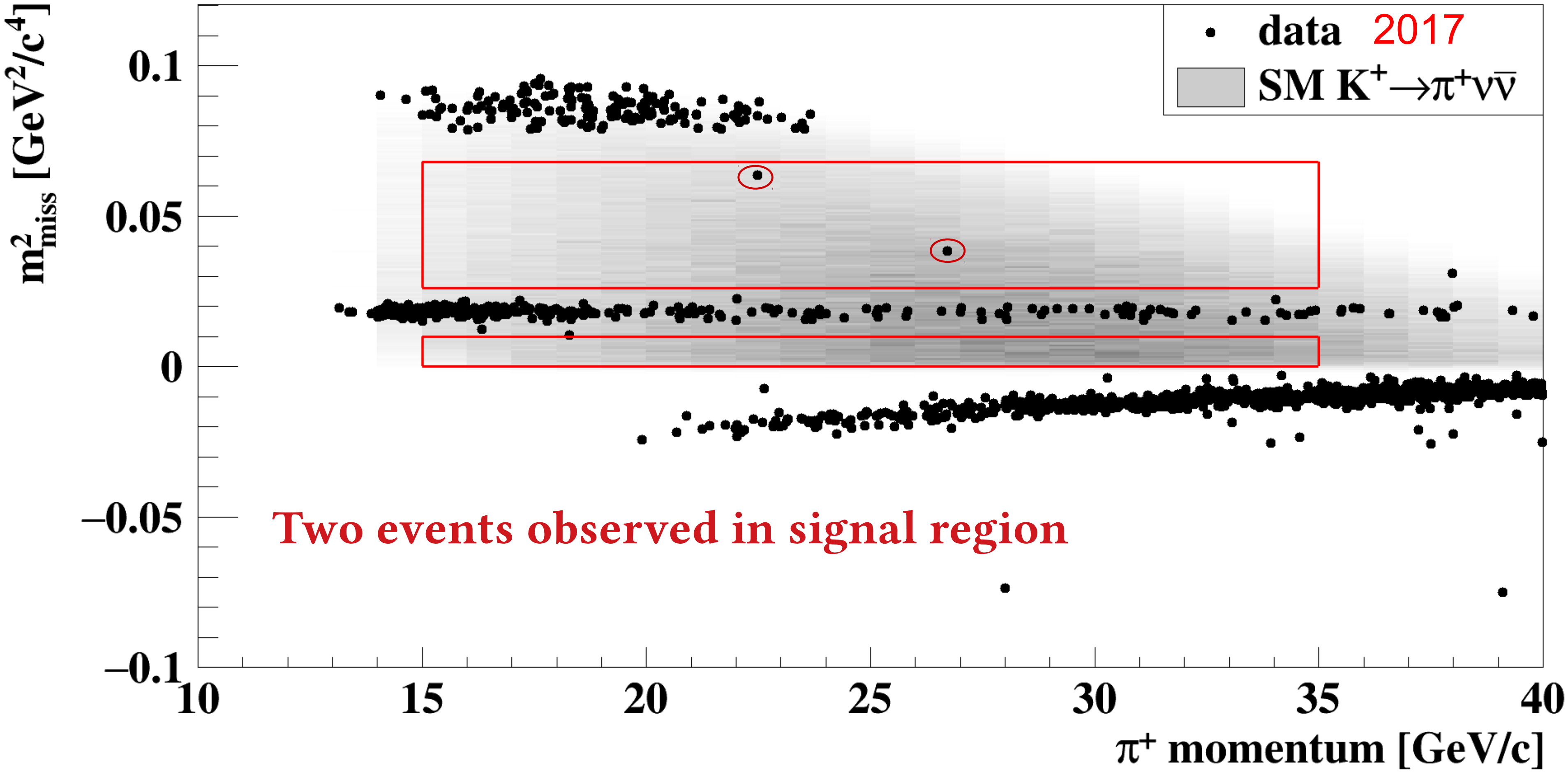
Expected $K^+ \rightarrow \pi^+ \nu\overline{\nu}$ (SM) $2.16 \pm 0.12_{stat} \pm 0.26_{ext}$

K decays background $0.59 \pm 0.06_{stat} \pm 0.06_{syst}$

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 2017 data – opening the box



# Result

2016 and 2017 data uncorrelated, both similar analysis techniques: results can be combined

## 2016+2017:

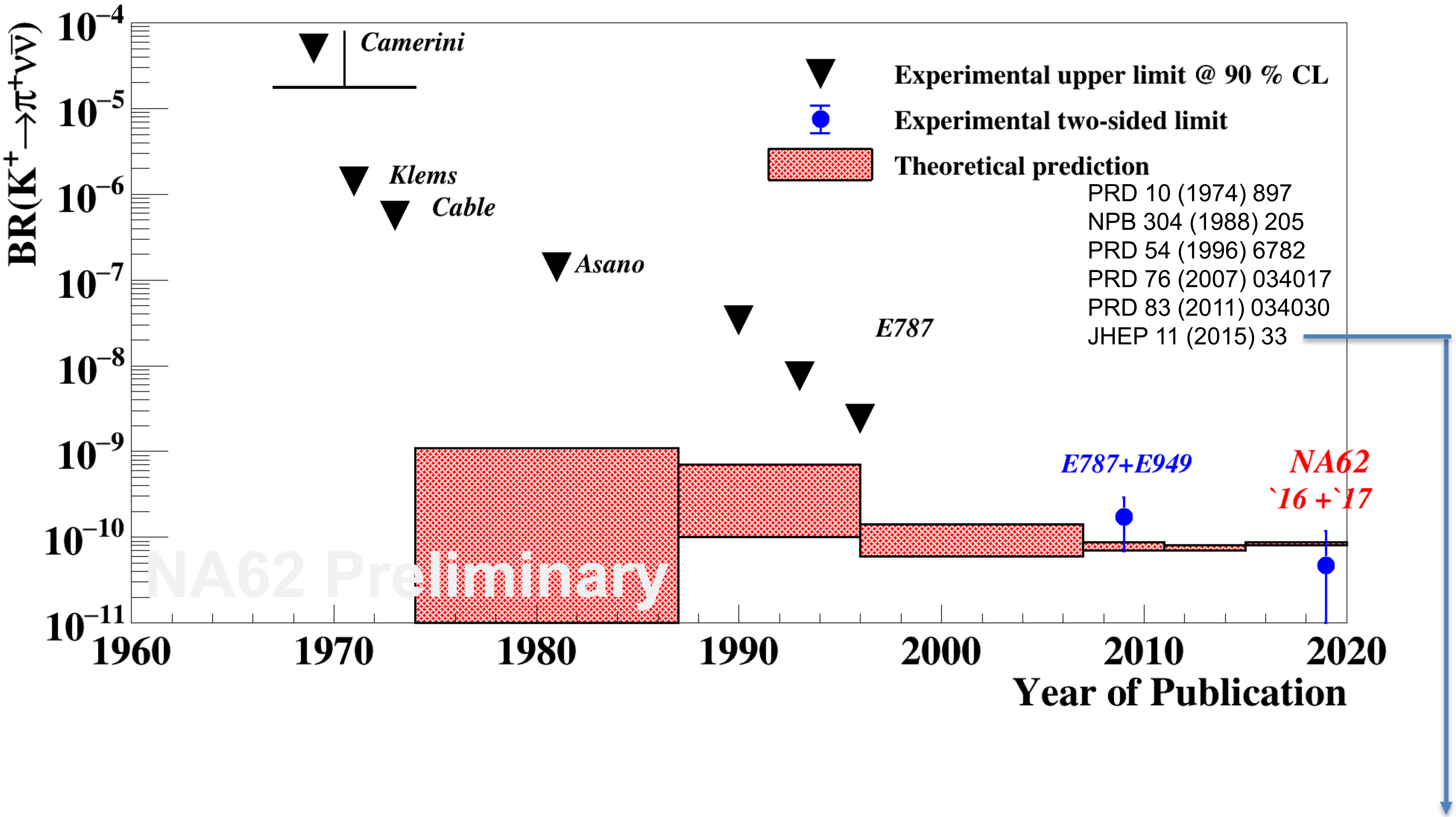
Upper Limits (CLs method):

| Observed | Expected (background only) | CL |
|---|---|---|
| $Br(K^+ \to \pi^+ \nu\bar{\nu}) < 1.85 \times 10^{-10}$ | $Br(K^+ \to \pi^+ \nu\bar{\nu}) < 1.32 \times 10^{-10}$ | 90% |
| $Br(K^+ \to \pi^+ \nu\bar{\nu}) < 2.44 \times 10^{-10}$ | $Br(K^+ \to \pi^+ \nu\bar{\nu}) < 1.62 \times 10^{-10}$ | 95% |



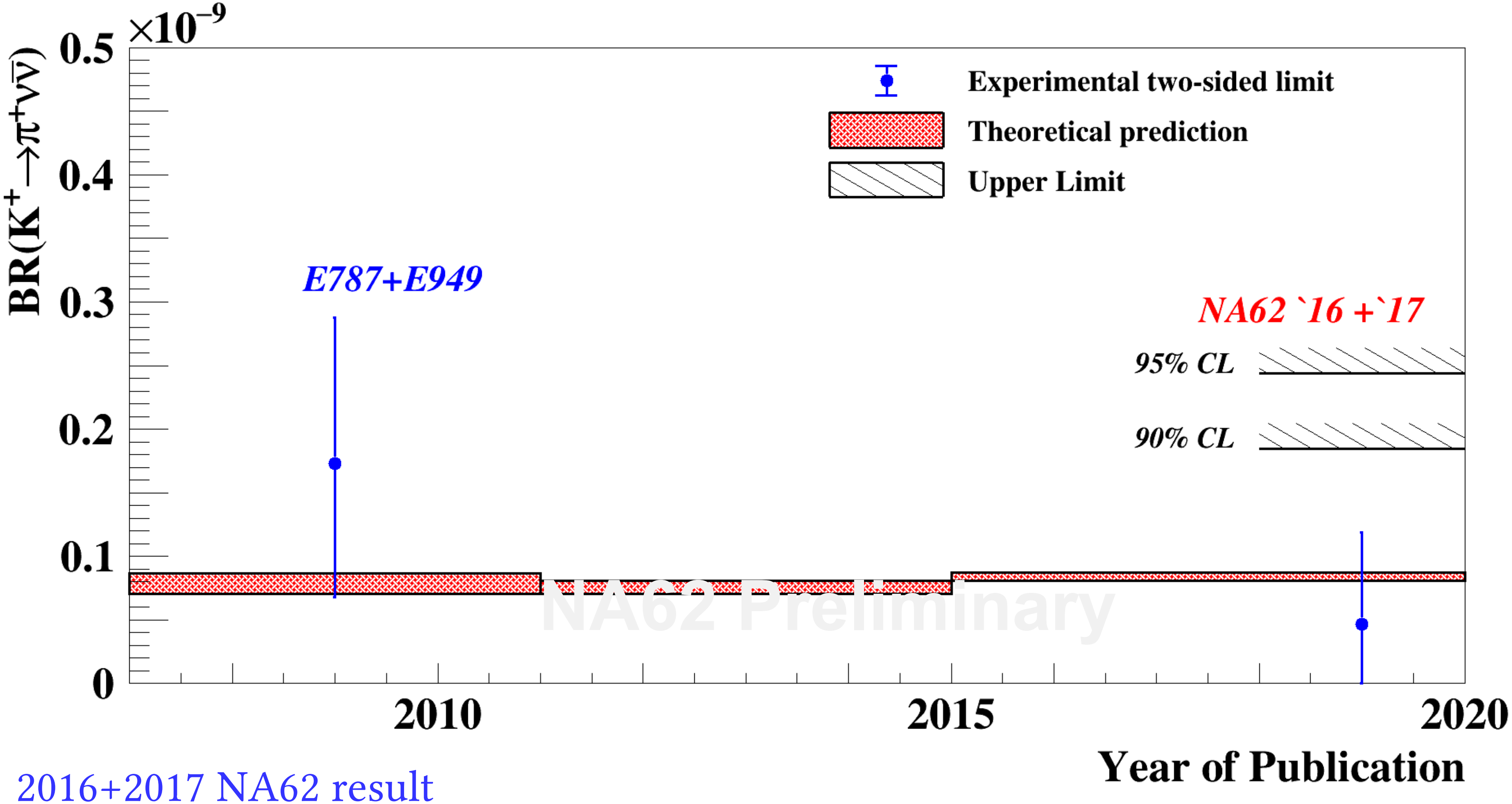
Two-sided 68% band: $Br(K^+ \to \pi^+ \nu\bar{\nu}) = (0.47^{+0.72}_{-0.47}) \times 10^{-10}$

# Historical perspective




SM $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \cdot 10^{-11} \left(\frac{|V_{cb}|}{0.0407}\right)^{2.8} \left(\frac{\gamma}{73.2°}\right)^{0.74} = (0.84 \pm 0.10) \cdot 10^{-10}$

# 2017 Result in context




2016+2017 NA62 result

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

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

Constraints on the largest enhancements allowed by NP scenarios

## Prospects for 2018 data set

2018 data analysis in progress (~2 x 2017 data)

On-going studies to increase signal efficiency

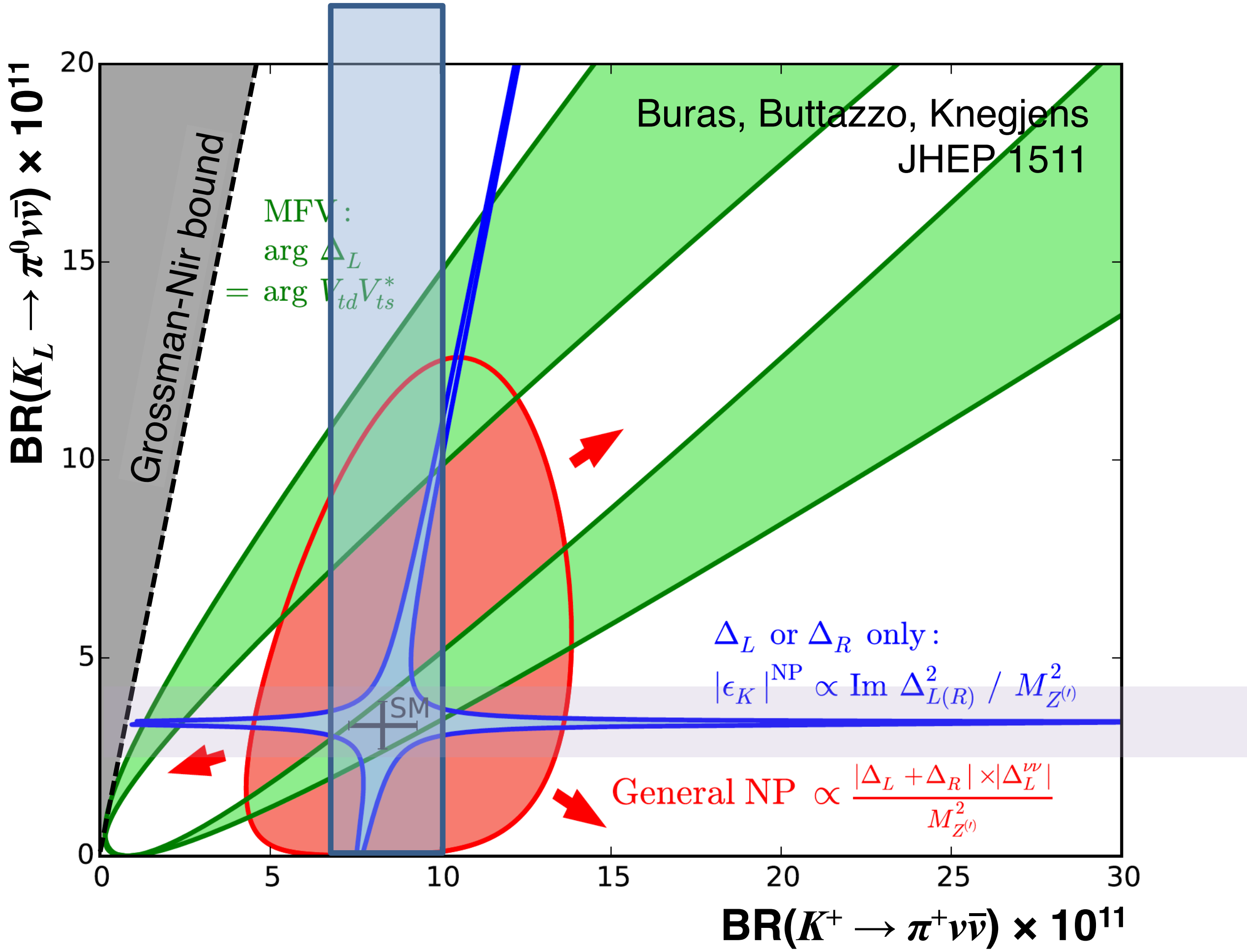
Presence of a new collimator in beam line:
reduced background allows for increase in signal acceptance

Optimization of particle identification and kinematic selection

Improvement in kaon-pion association algorithm

# Prospects after LS2

Take data at higher intensity, increase signal acceptance, reduce background contamination

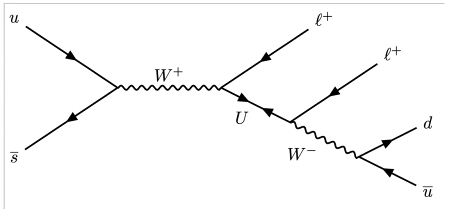


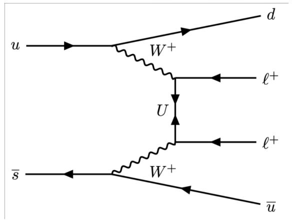

- Models with CKM-like flavor structure
  - Models with MFV
- Models with new flavor-violating interactions in which either LH or RH couplings dominate
  - $Z/Z'$ models with pure LH/RH couplings
  - Littlest Higgs with $T$ parity
- Models without above constraints
  - Randall-Sundrum

KOTO II, KLEVER > 2026
~ 60 events, B/S=1
~22% precision

NA62 at LS3:
~50 events, B/S=0.35
~18% precision

# Lepton Number / Lepton Flavour Violation




**Analysis strategy:**

- Main kinematical variable $M(\pi^- l^+ l^+)$
- Blind analysis
- Signal region $|M(\pi^- l^+ l^+) - M_K| < 3\,\sigma(M)$
- CLs method to set upper limits on BR

## Background:

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

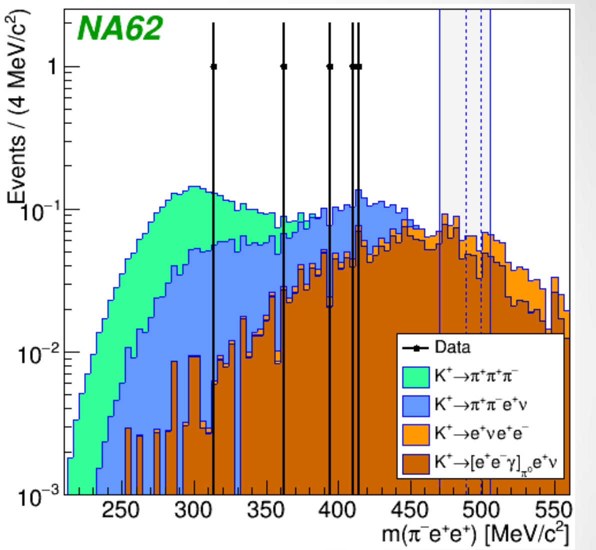
- Decay in flight (DIF) or misID $\pi^+ \Rightarrow \mu^+$

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

- misID $e^- \Rightarrow \pi^-$
- misID $\pi^+ \Rightarrow e^+$

**Normalisation decay modes:**

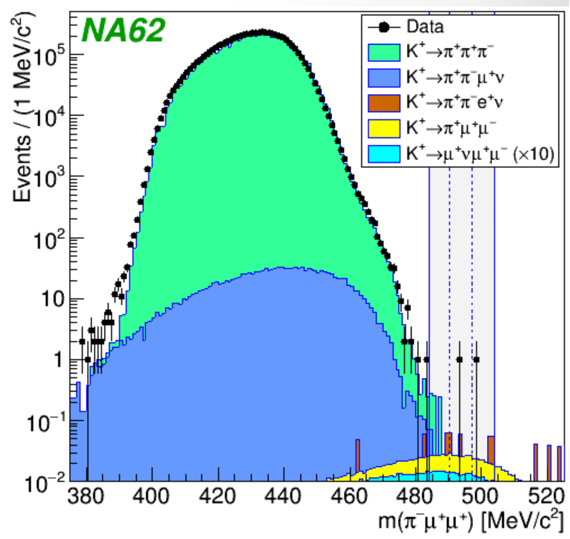
- $K^+ \to \pi^+ e^+ e^-$ — 2484 candidates
- $K^+ \to \pi^+ \mu^+ \mu^-$ — 8357 candidates




Acceptance: A = 4.98%
SES = (0.94 ± 0.03) * $10^{-10}$
Expected background: 0.16 ± 0.03
$N_{obs}$ = 0

$$SES = \frac{1}{N_K A}$$

Upper limit at 90% CL:
BR ($K^+ \to \pi^- e^+ e^+$) < 2.2 * $10^{-10}$




Acceptance: A = 9.81%
SES = (1.28 ± 0.04) * $10^{-11}$
Expected background: 0.91 ± 0.41
$N_{obs}$ = 1

$$SES = \frac{1}{N_K A}$$

Upper limit at 90% CL:
BR ($K^+ \to \pi^- \mu^+ \mu^+$) < 4.2 * $10^{-11}$

Factor of 2-3 improvement wrt previous results

Prospects with the full data sample (2016-2018): statistics x3

- $K^+ \to \pi^- \mu^+ e^+$, $K^+ \to \pi^+ \mu^- e^+$
  SES ~5 x $10^{-11}$ (factor ~5 improvement on BNL E865)
- $K^+ \to e^- \nu \mu^+ \mu^+$
  SES ~5 x $10^{-11}$ (first search)
- $K^+ \to \mu^- \nu e^+ e^+$
  SES ~1 x $10^{-10}$ (factor ~100 improvement on PDG)

# Heavy Neutral Leptons

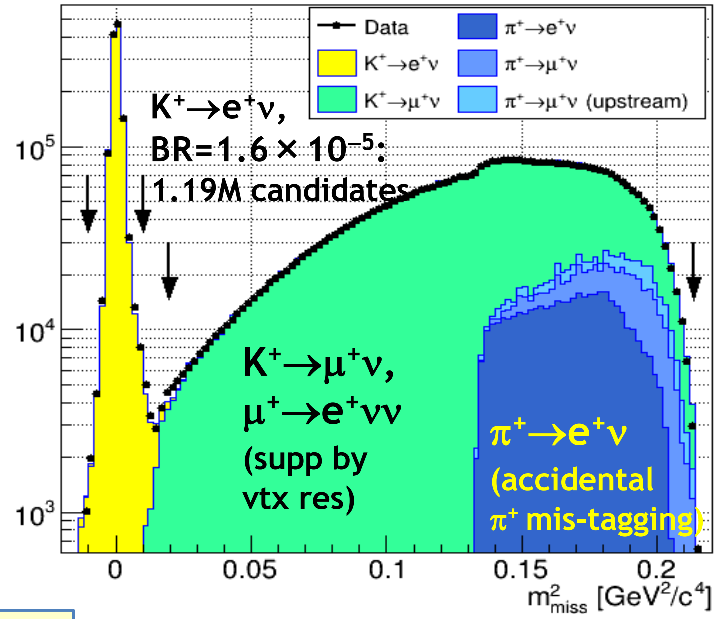
## HNL production in $K^+ \to \ell^+ N$

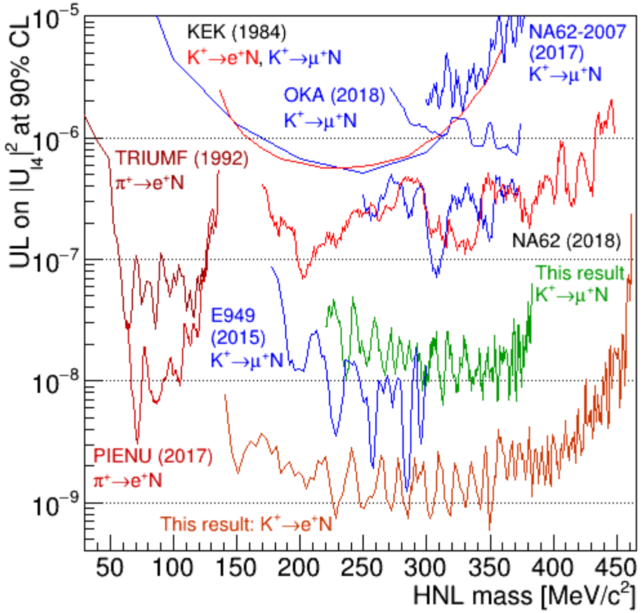
$\Gamma(P^+ \to \ell^+ N) = \Gamma(P^+ \to \ell^+ \nu) \times \rho_\ell(m_N) \times |U_{\ell 4}|^2$

Data **2016–17**, Numbers of $K^+$ decays in fiducial volume: $N_K = (1.17 \pm 0.01) \times 10^{12}$ e+ case, $N_K = (4.29 \pm 0.02) \times 10^9$ muon case.

Squared missing mass: $m^2_{miss} = (P_K - P_\ell)^2$

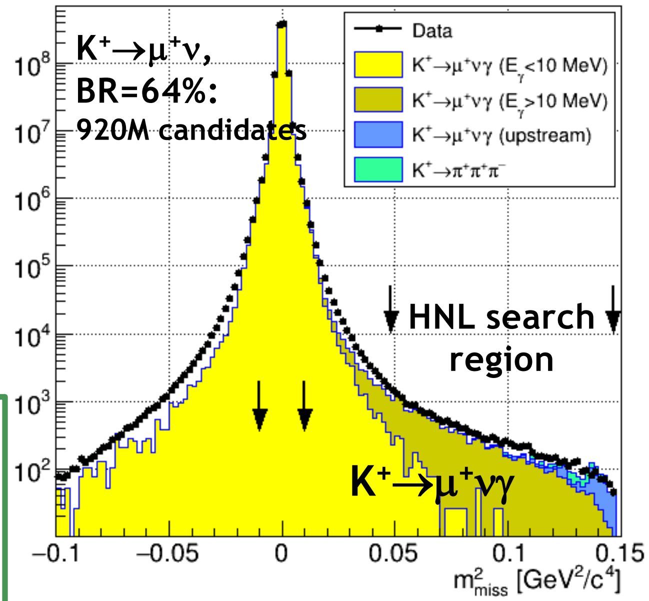
HNL signal: **a spike above continuous missing mass spectrum**.




$|U_{\ell 4}|^2$ limits vs $m_{HNL}$ from production searches

**New preliminary NA62 results** based on **~1/3** of the data set




Dump operation: Be target removed; **400 GeV** protons dumped into a $20\lambda_I$ Fe/Cu collimator at $z \approx 25$ m. Part-time NA62 beam dump operation in **2021–23** offers a discovery potential across multiple hidden-sector scenarios (HNL, ALP, Dark Scalar, Dark Photon

# Conclusions

2016+2017 result:

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

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



Constraints on the largest enhancements allowed by NP models

2018 data analysis on-going

Excellent prospects for after LS2

Broad physics programme to be explored with existing and future data sets:
rare kaon decays, precision measurements of branching ratios and form factors, tests of Lepton Number/ Flavour violation, searches for exotic particles

Limits on HNL and LNV/LFV

# Additional material

# Dark Photon

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

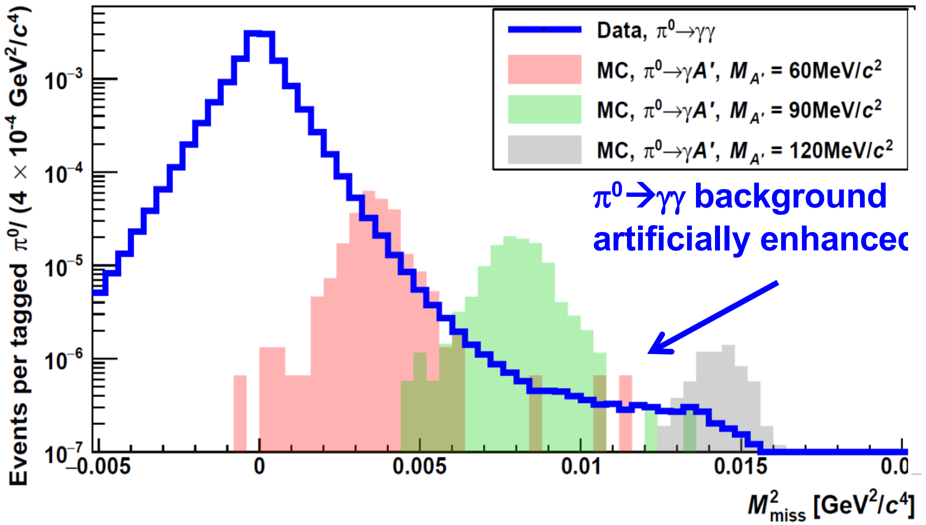
**pure, intense $\pi^0$ beam of known momentum from $K^+ \to \pi^+\pi^0$ decays**

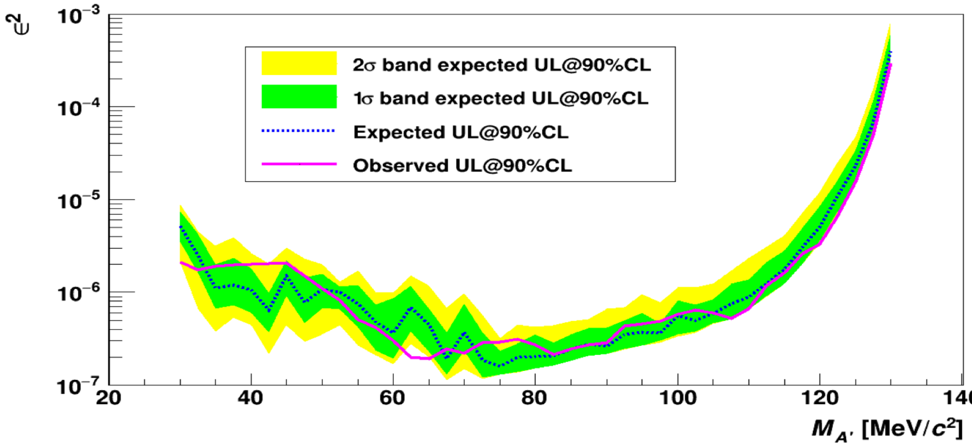
**Signal signature: $\pi^0$ tagging, one photon + missing momentum, no further activity**

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

**Data from 2016, $n_{\pi 0}$ ~ 412 M $\pi^0$s tagged from $K_{2\pi}$ decays (~1% of full data set)**

**Search for a peak around $M_{A'}^2$ from $M_{\mathrm{miss}}^2 = (p_K - p_{\pi+} - p_\gamma)^2$**




Prospects with full data set: expected yield increased by O(100)

# Result

## 2017:

Upper Limits (CLs method):

| 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: $Br(K^+ \to \pi^+ \nu\bar{\nu}) = (0.20^{+0.69}_{-0.20}) \times 10^{-10}$

## 2016+2017:

Upper Limits (CLs method):

| Observed | Expected (background only) | CL |
|---|---|---|
| $Br(K^+ \to \pi^+ \nu\bar{\nu}) < 1.85 \times 10^{-10}$ | $Br(K^+ \to \pi^+ \nu\bar{\nu}) < 1.32 \times 10^{-10}$ | 90% |
| $Br(K^+ \to \pi^+ \nu\bar{\nu}) < 2.44 \times 10^{-10}$ | $Br(K^+ \to \pi^+ \nu\bar{\nu}) < 1.62 \times 10^{-10}$ | 95% |

Two-sided 68% band: $Br(K^+ \to \pi^+ \nu\bar{\nu}) = (0.47^{+0.72}_{-0.47}) \times 10^{-10}$