LATEST RESULTS FROM KAON EXPERIMENTS AT CERN

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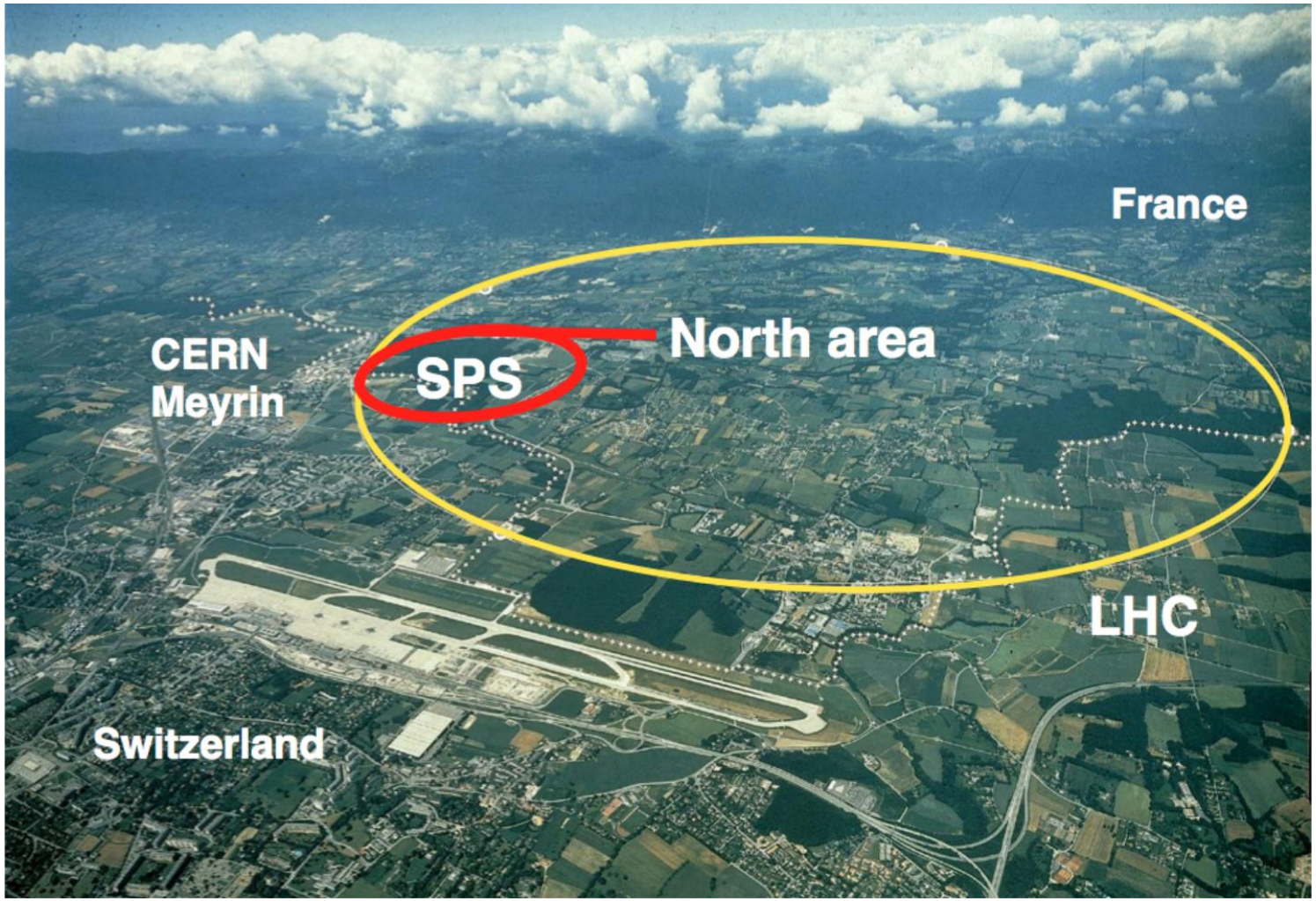
UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

INFN NAPOLI

KAON EXPERIMENTS AT CERN



NA31: K_S / K_L (1984-1990)
First evidence of CPV in K sector

NA48, NA48/1: K_S / K_L (1997-2002)
Re(ε'/ε), Rare K_S and hyperon decays

NA48/2: K^+ / K^- (2003-2004)
Direct CPV, rare $K^\pm$ decays

NA62: K^+ / K^- (2007-2008)
$R_K = \Gamma(Ke\nu) / \Gamma(K\mu\nu)$

NA62: K^+ (2016-2018)
Physics Run1

NA62: K^+ (2021-now)
Physics Run2

OUTLINE

NA48/2 (2003-2004)

- First observation of $K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$

NA62 Run1 data (2016-2018)

- Main goal: $K^+ \to \pi^+\nu\bar{\nu}$
- Precision measurements: $K^+ \to \pi^0 e^+\nu\gamma$, $K^+ \to \pi^+\mu^+\mu^-$, $K^+ \to \pi^+\gamma\gamma$
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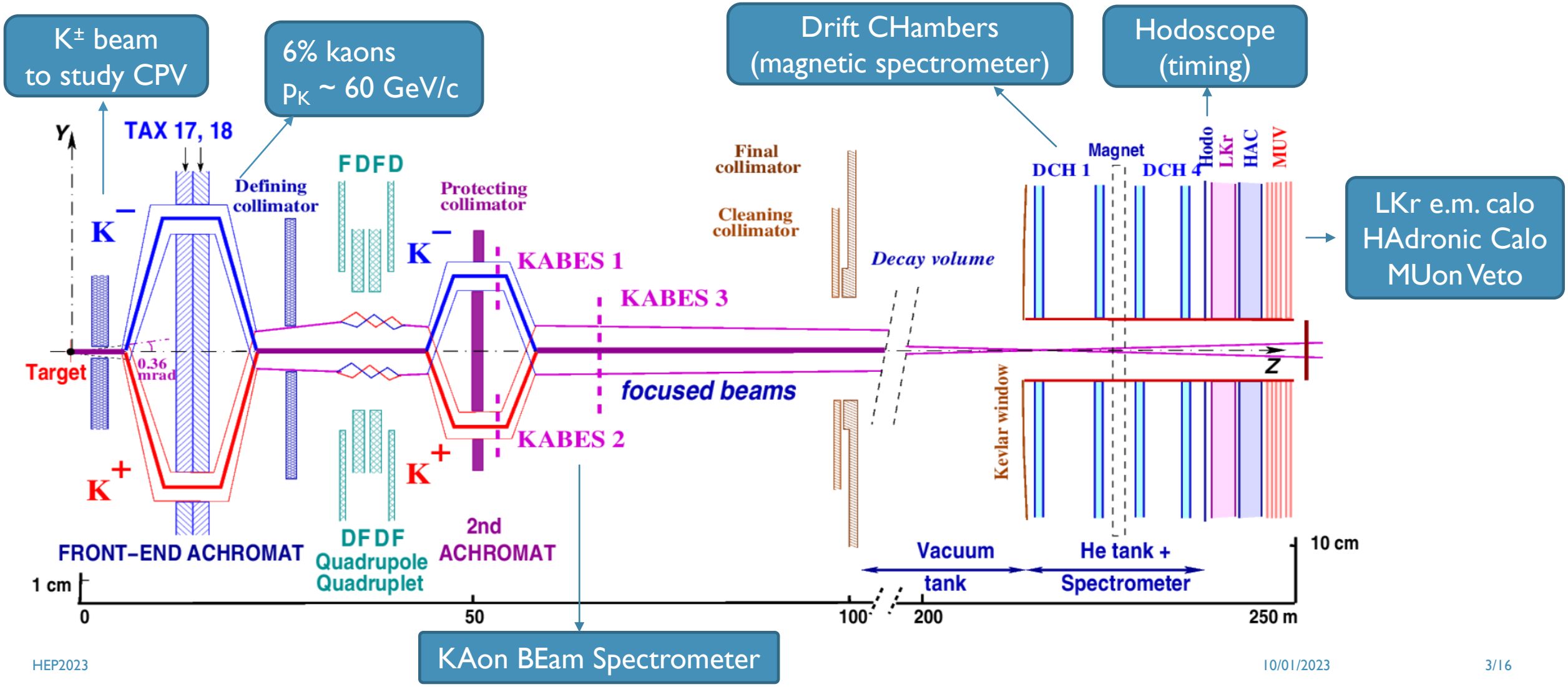
NA62 2021 data

- Dark photon searches: $A' \to \mu^+\mu^-$

THE NA48/2 DETECTOR



$K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$ ($K_{\mu 4}^{00}$)

Theory and status

K_{l4} mode	BR [10^{-5}]	N_{cand}	
$K_{e4}^{\pm}$	4.26 ± 0.04	1108941	NA48/2 (2012)
K_{e4}^{00}	2.55 ± 0.04	65210	NA48/2 (2014)
$K_{\mu 4}^{\pm}$	1.4 ± 0.9	7	Bisi et al. (1967)
$K_{\mu 4}^{00}$			

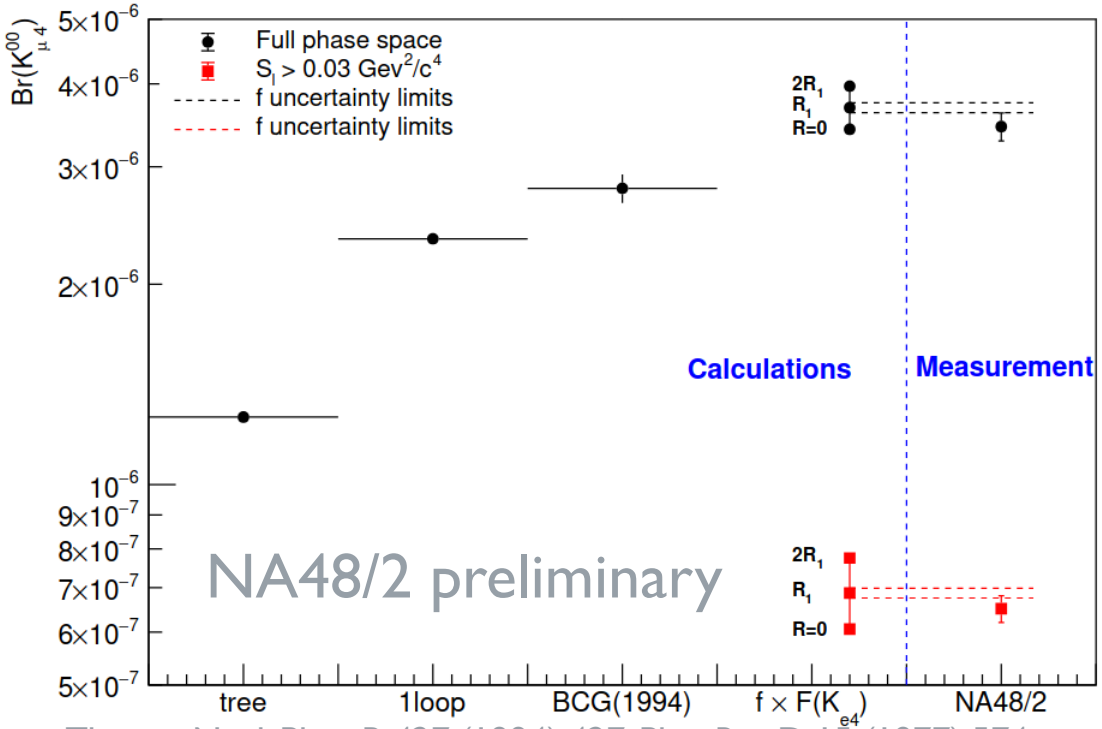
- First observation of muon mode with $\pi^0\pi^0$
- Test of ChPT

- $K^{\pm} \to \pi^0\pi^0\pi^{\pm}$ as normalization channel
- $K^{\pm} \to \pi^0\pi^0(\pi^{\pm} \to \mu^{\pm}\nu)$ largest background
- $S_l = M^2(\mu^{\pm}\nu) > 0.03\ GeV^2 / c^4$

$BR(K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu, S_l > 0.03\ GeV^2) = (0.65 \pm 0.03) \times 10^{-6}$

$BR(K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu) = (3.4 \pm 0.2) \times 10^{-6}$

- 2437 events observed
- $354 \pm 33_{stat} \pm 62_{syst}$ background events expected



Theory: Nucl. Phys. B 427 (1994) 427, Phys.Rev.D 15 (1977) 574

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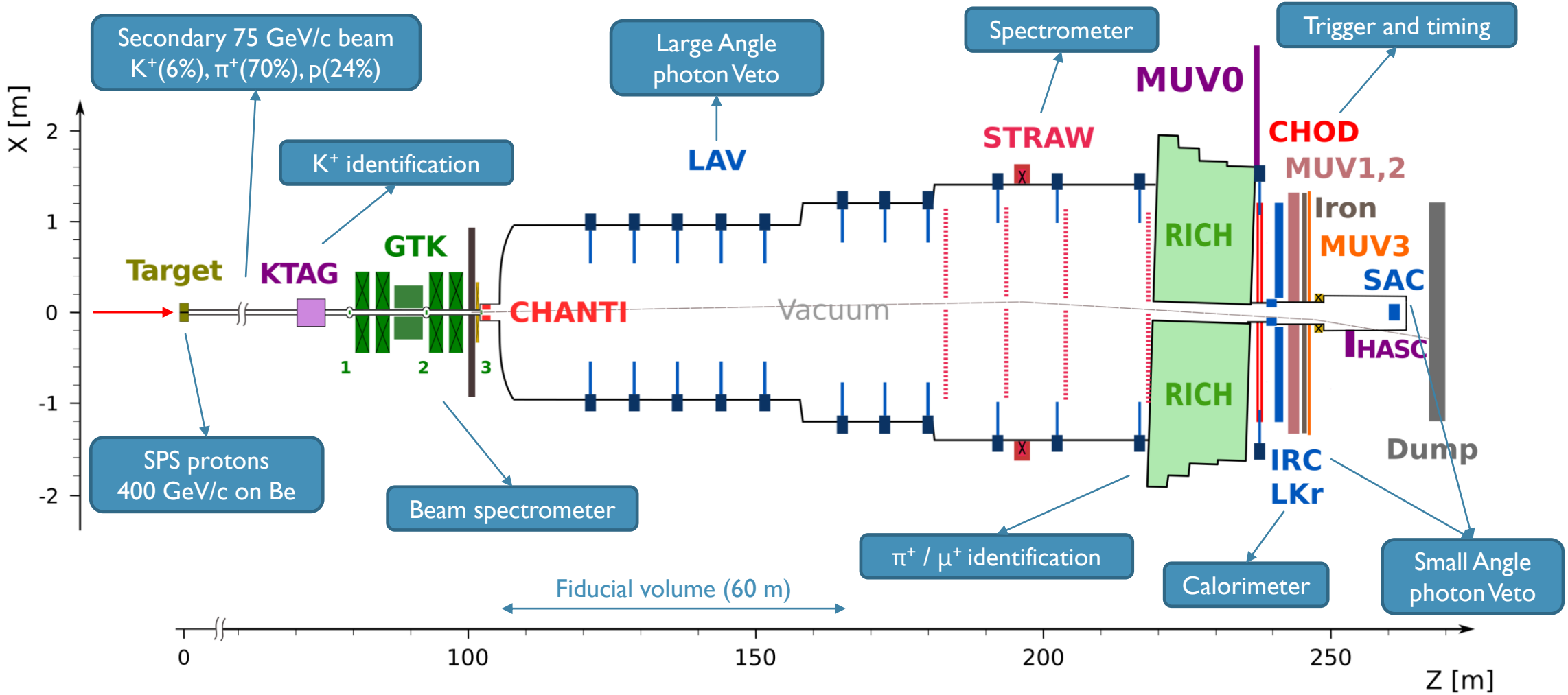
NA62 2021 data

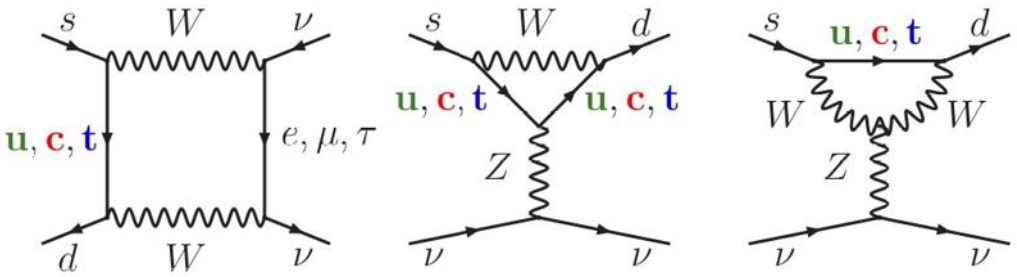
- Dark photon searches: $A' \to \mu^+\mu^-$

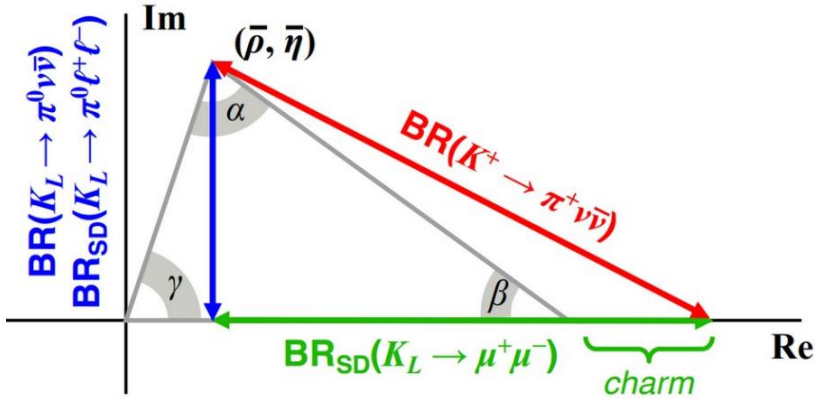
THE NA62 DETECTOR



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

THEORY

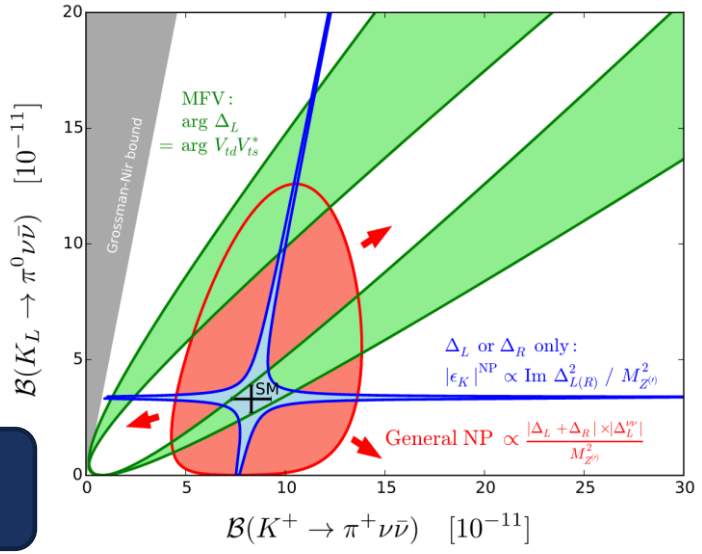




- FCNC s → d, high CKM suppression
- Theoretically clean, dominated by short distance
- Hadronic form factor extracted from $K_{\ell 3}$
- Uncertainty largely from CKM parameters

$$BR(K^+ \to \pi^+ \nu\bar{\nu})_{SM} = (8.4 \pm 1.0) \times 10^{-11}$$

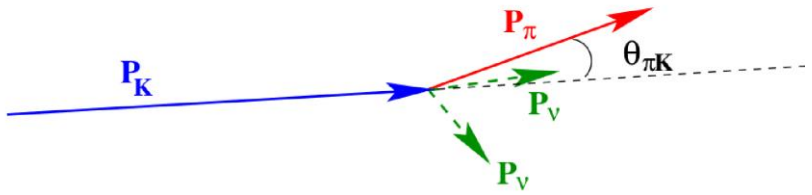
JHEP 11 (2015) 033



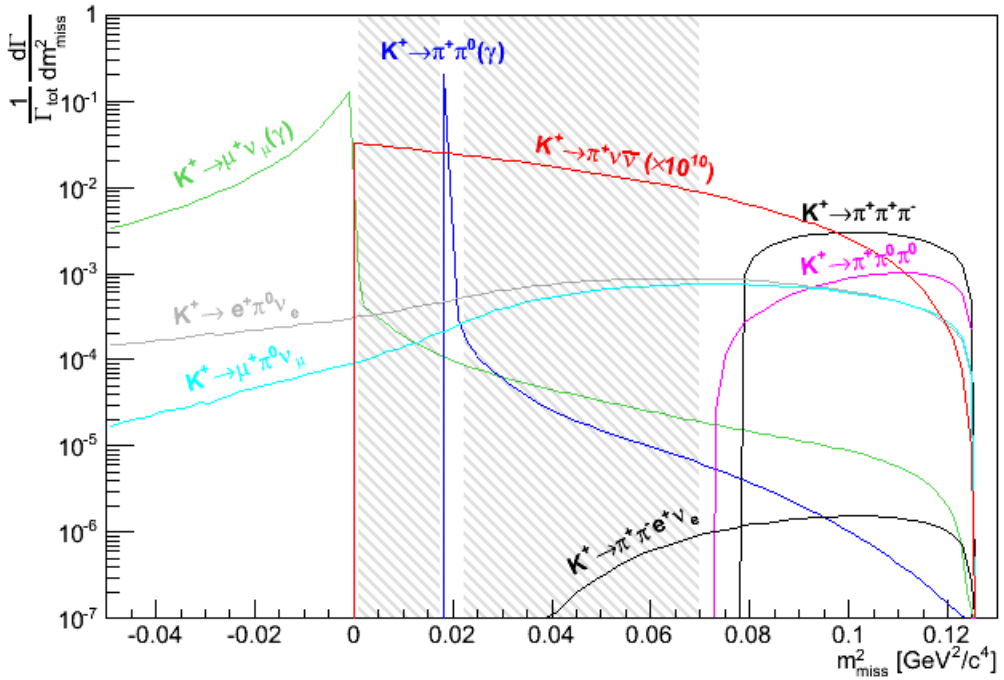
- $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ are correlated
- Very sensitive to new physics
- Kaons can constrain the UT independently from B physics

Acta Phys.Polon.B 53 6, A1 (2021)

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



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



Selection steps

- K^+, π^+ track reconstruction
- Track matching, vertex reconstruction
- π^+ identification, μ^+ rejection
- Multi-track rejection, photon veto
- Kinematics (m^2_{miss}, p_π)

Requirements

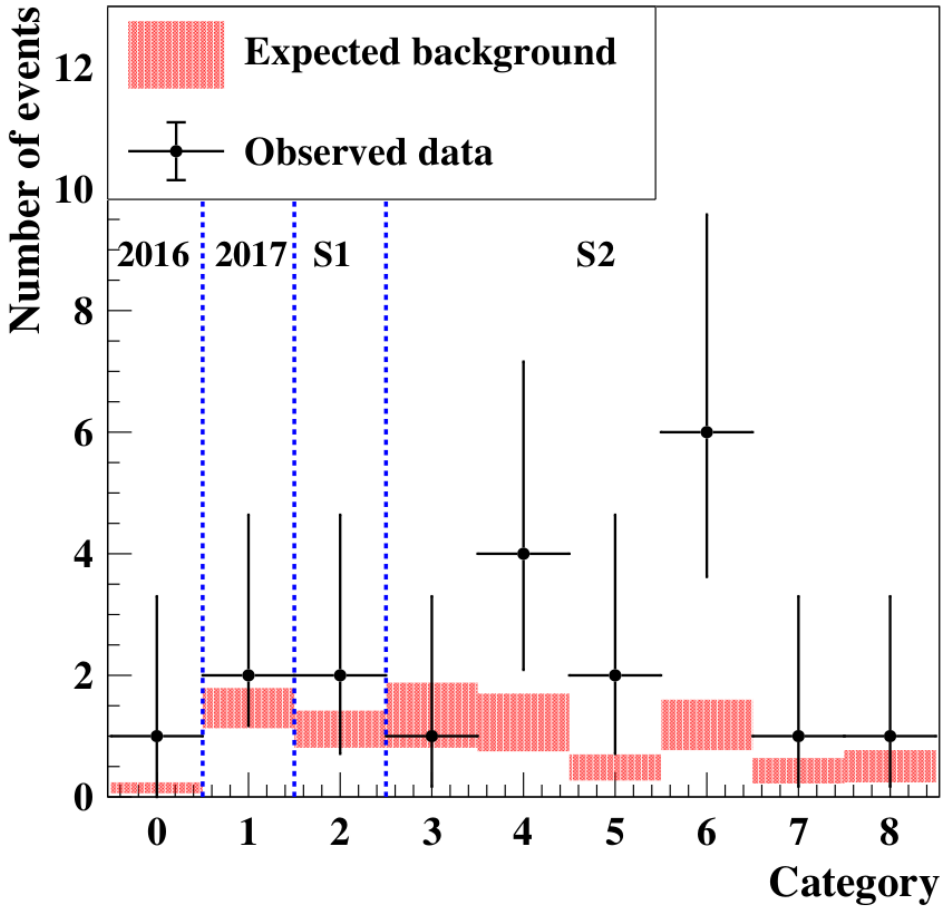
- Kinematic suppression O(10^4)
- Muon rejection O(10^7)
- π^0 rejection O(10^7)
- Time resolution O(100 ps)

Analysis

- Momentum range: 15 < p_π < 45 GeV/c
- Signal regions blinded during the analysis
- Optimized in 9 different categories

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

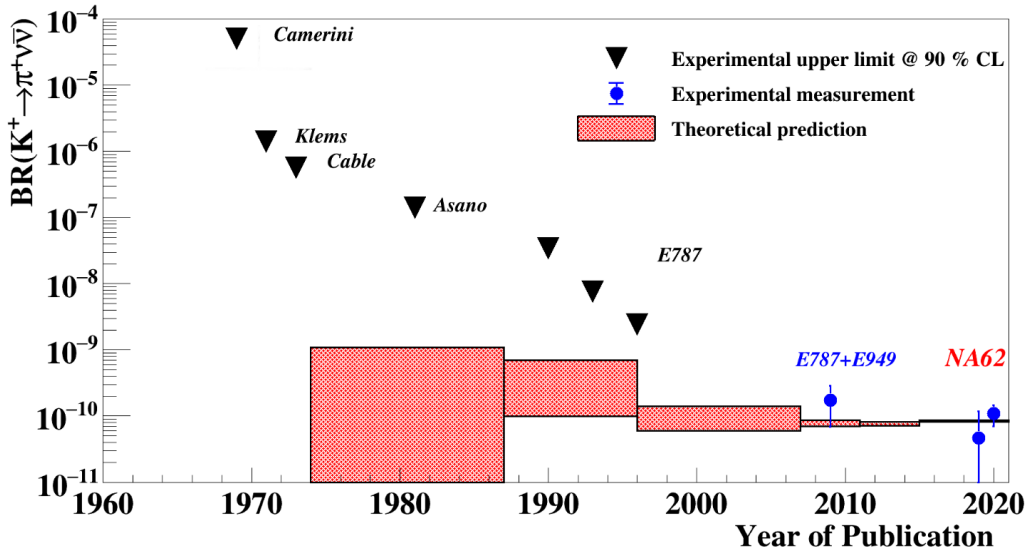
RESULTS



- Single Event Sensitivity: $(0.839 \pm 0.053_{syst}) \times 10^{-11}$
- Expected SM signal events: $10.01 \pm 0.42_{syst} \pm 1.19_{ext}$
- Expected background events: $7.03^{+1.05}_{-0.82}$
- Observed events: 20

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6\ ^{+4.0}_{-3.8}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$$

JHEP 06 (2021) 093



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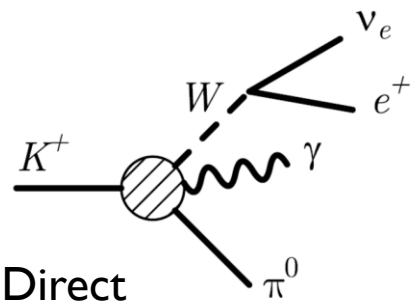
NA62 2021 data

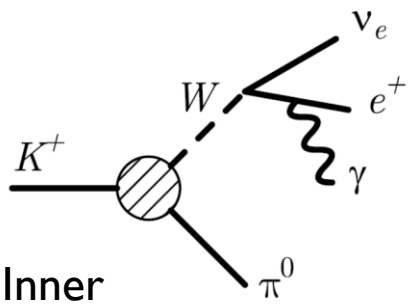
- Dark photon searches: $A' \to \mu^+\mu^-$

$K^+ \to \pi^0 e^+ \nu\gamma$

STATE OF THE ART



Direct Emission



Inner Brehmsstrahlung

Divergent decay amplitude for E_γ and $\theta_{e,\gamma} \to 0$ for the IB component

$$R_j = \frac{BR(\pi^0 e^+ \nu\gamma \mid j\text{-th region})}{BR(\pi^0 e^+ \nu(\gamma))}$$

Eur. Phys. J. C 50 (2007) Phys. Atom. Nucl. 70 (2007) Eur. Phys. J. C 81.2 (2021)

Range	E_γ cut	$\theta_{e,\gamma}$ cut	$O(p^6)$ $ChPT$ $[10^{-2}]$	$ISTRA+$ $[10^{-2}]$	OKA $[10^{-2}]$
R_1	$E_\gamma > 10\ MeV$	$\theta_{e,\gamma} > 10°$	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$
R_2	$E_\gamma > 30\ MeV$	$\theta_{e,\gamma} > 20°$	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$
R_3	$E_\gamma > 10\ MeV$	$0.6 < \cos\theta_{e,\gamma} < 0.9$	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$

T-odd observable

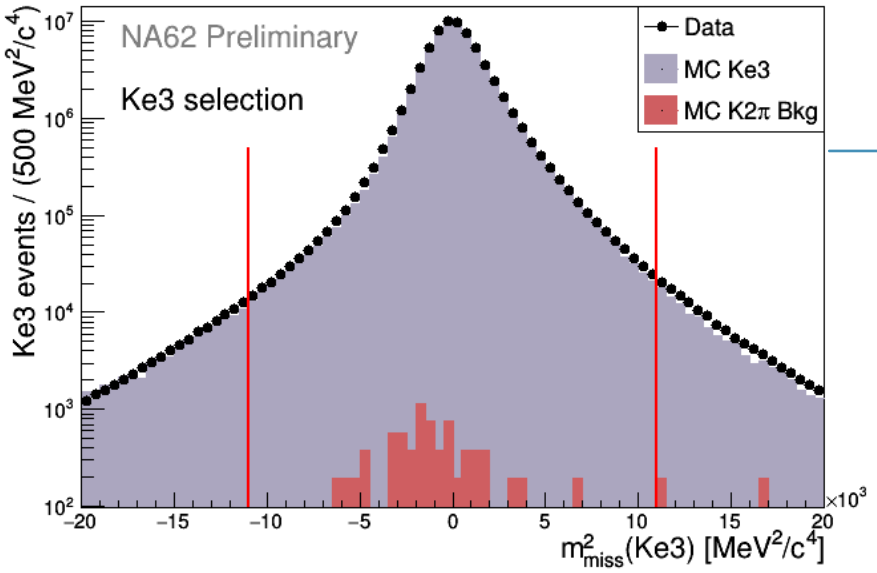
$$\xi = \frac{\vec{p_\gamma} \cdot \vec{p_e} \times \vec{p_\pi}}{m_K^3}$$

Test of T-asymmetry

$$A_\xi = \frac{N_+ - N_-}{N_+ + N_-}$$

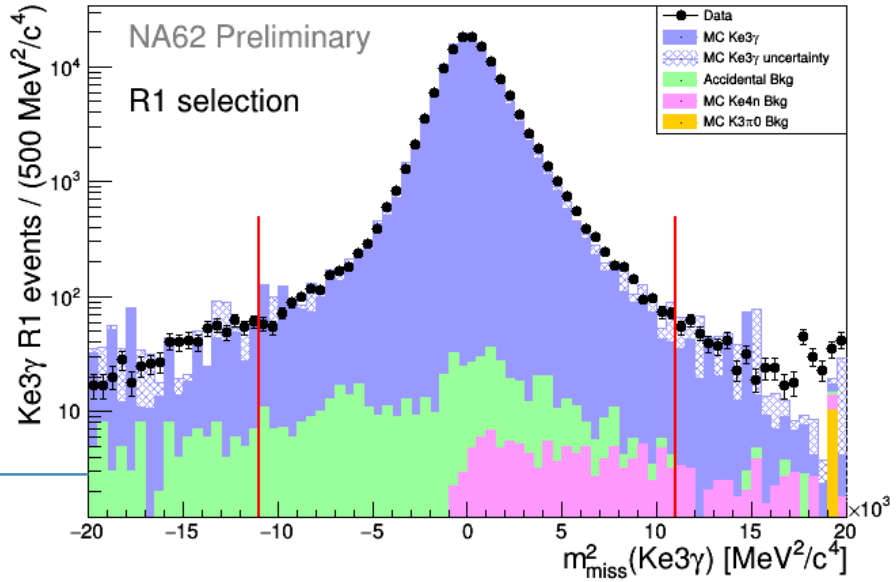
- $|A_\xi(\text{SM and beyond})| < 10^{-4}$
- $A_\xi^{ISTRA+}(R_3) = (1.5 \pm 2.1) \times 10^{-2}$
- No measurements of A_ξ for R_1 and R_2

$K^+ \to \pi^0 e^+ \nu\gamma$ RESULTS



- Normalization selection: 66M events
- Almost background free: B/S ~ 10^{-4}

- Main bkg source: accidental activity in LKr
- Dedicated $m^2_{miss}(K_{e3})$ cut

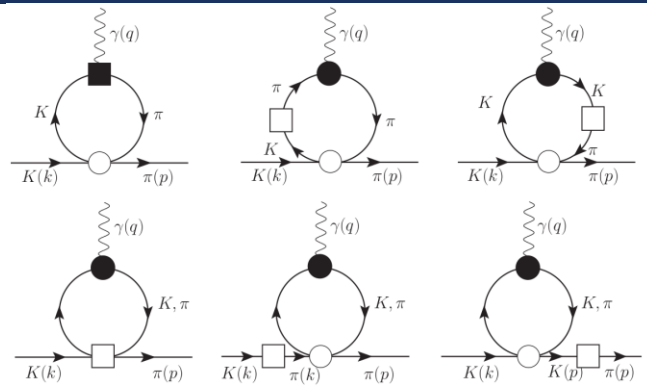


NA62 Preliminary	range 1	range 2	range 3
$\mathcal{R} \times 10^2$	$1.684 \pm 0.005 \pm 0.010$	$0.599 \pm 0.003 \pm 0.005$	$0.523 \pm 0.003 \pm 0.003$
$A_\xi \times 10^2$	$-0.1 \pm 0.3_{stat} \pm 0.2_{MC}$	$-0.3 \pm 0.4_{stat} \pm 0.3_{MC}$	$-0.9 \pm 0.5_{stat} \pm 0.4_{MC}$

PoS (EPS-HEP2021) 553

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

THEORY, SELECTION



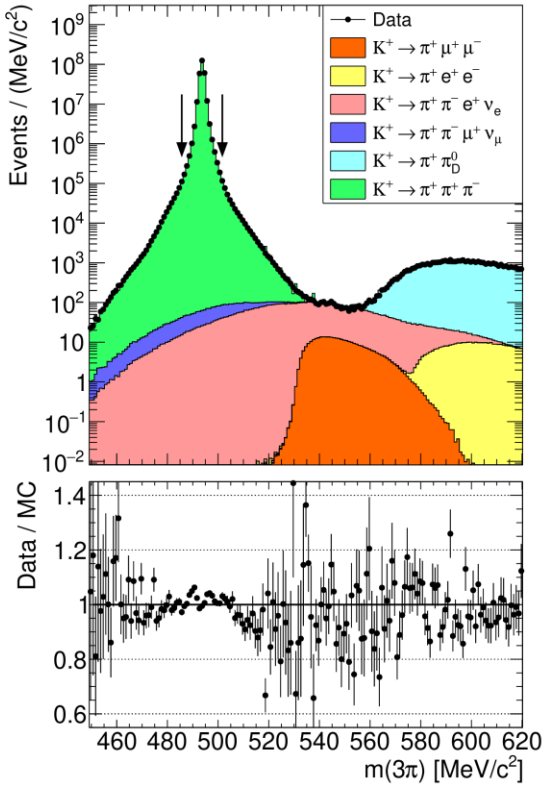
- FCNC mediated by one photon exchange $K^+ \to \pi^+\gamma^*$
  Nucl. Phys. B291 (1987) 692–719, Phys. Part. Nucl. Lett. 5 (2008) 76–84
- Test of LFU by comparing $K^+ \to \pi^+e^+e^-$
- Form factor parametrized by ChPT at $O(p^6)$

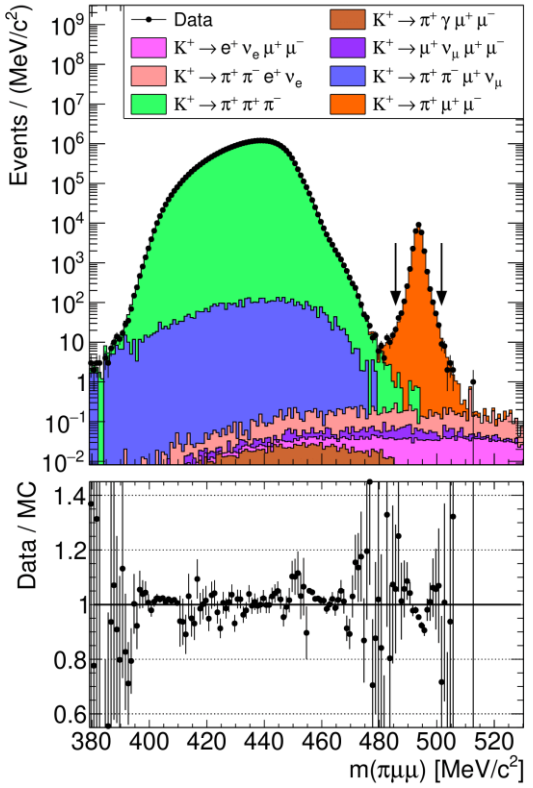
  $$W(z) = G_F M_K^2 (a + bz) + W^{\pi\pi}(z)$$

  where $z = m(\mu^+\mu^-)^2 / M_K^2$ JHEP 08 (1998) 004
- Measurements:
  - Model independent BR
  - *a*, *b* (by reweighting MC)

Normalization: $K^+ \to \pi^+\pi^+\pi^-$
- Abundant (BR ~ 5.6%)
- Cancellation of systematics

Signal selection
- 27679 events observed
- 8 bkg events expected



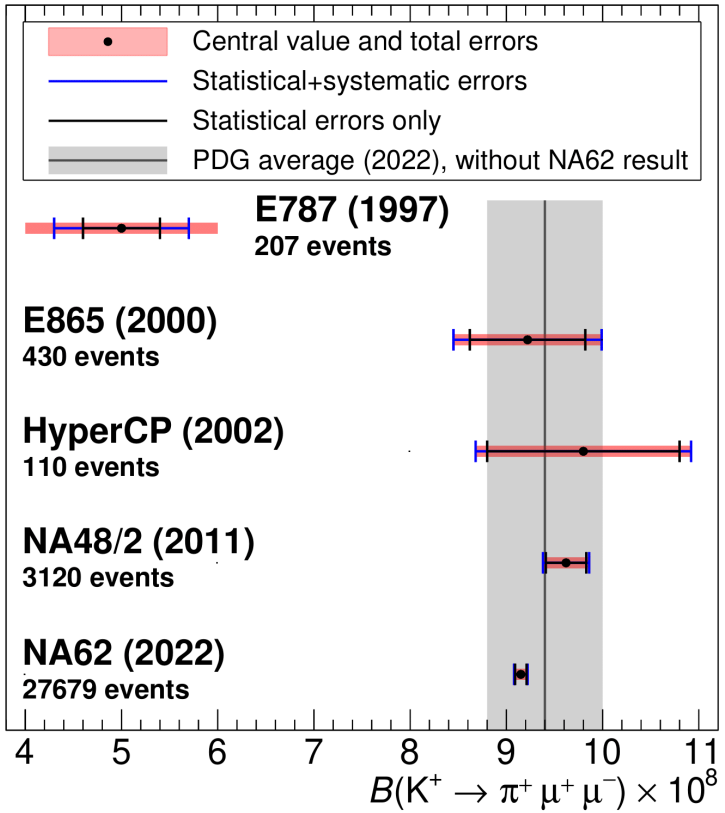


$K^+ \to \pi^+ \mu^+ \mu^-$

RESULTS

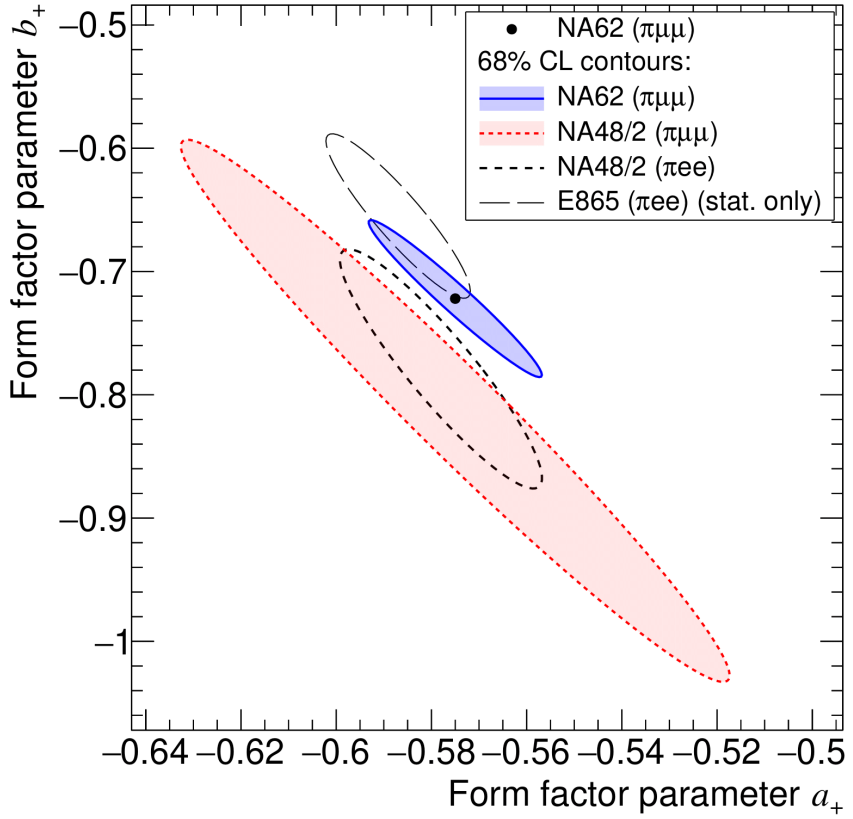
BR = (9.15 ± 0.08) × 10^{-8}

- Consistent with previous measurements
- Large improvement in precision



***a* = -0.575 ± 0.013, *b* = -0.722 ± 0.043**

- Compatible with previous measurements
- No evidence for LFU violation



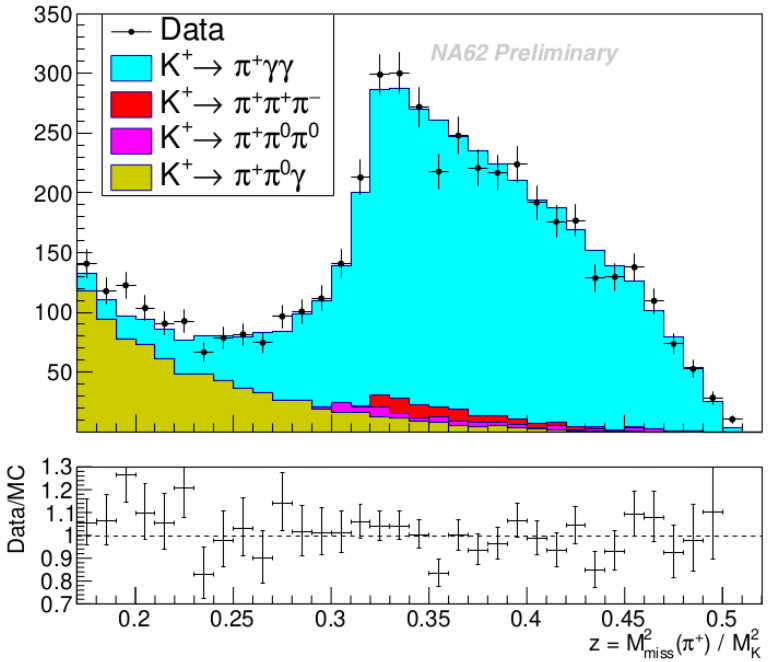
JHEP 11 (2022) 011

$K^+ \to \pi^+\gamma\gamma$

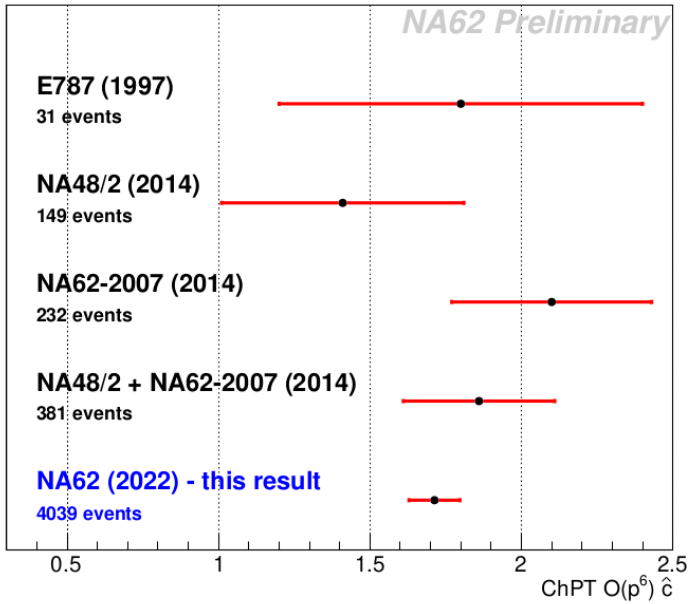
- Allows for crucial tests of ChPT
- Kinematic variables:

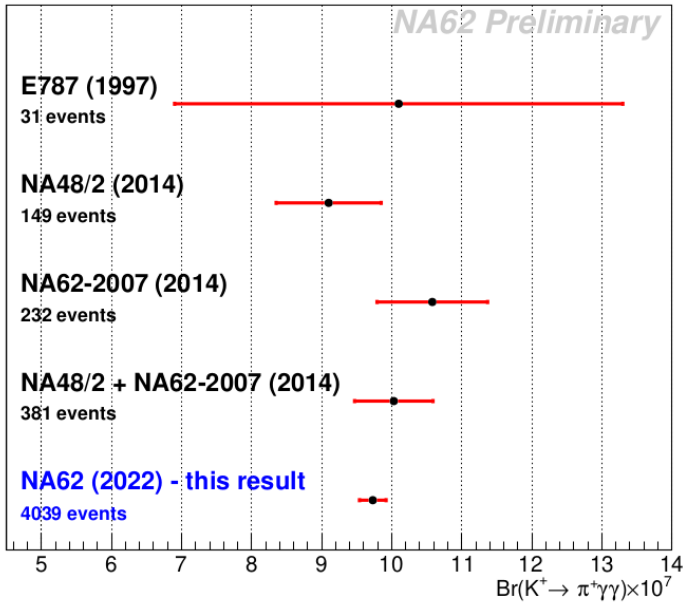
$$z = \left(\frac{m_{\gamma\gamma}}{m_K}\right)^2 , \quad y = \frac{P_K(Q_{\gamma_1} - Q_{\gamma_2})}{m_K^2}$$

- BR($K^+ \to \pi^+\gamma\gamma$) at O($p^6$) parametrized by a real parameter $\hat{c}$



- 4039 events observed
- 393 ± 20 bkg events expected
- Main bkg: cluster merging in calorimeter
- Reweighting and fit of MC gives $\hat{c}$ = 1.713 ± 0.075_{stat} ± 0.037_{syst}





$$BR(K^+ \to \pi^+\gamma\gamma) = (9.73 \pm 0.17_{stat} \pm 0.08) \times 10^{-7}$$

OUTLINE

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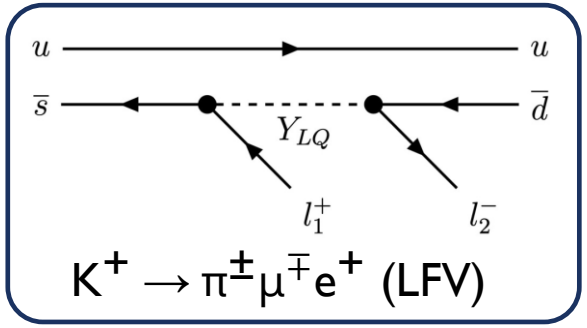
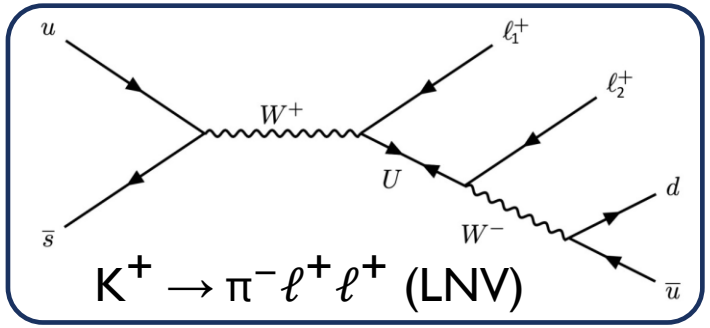
LFV / LNV SEARCHES

- Lepton number and lepton flavour are accidental symmetries in SM (neutrino oscillations are LFV)
- LFV: mediated by leptoquark
- LNV: mediated by heavy Majorana neutrino



$K^+ \to \pi^\pm \mu^\mp e^+$ (LFV)



$K^+ \to \pi^- \ell^+ \ell^+$ (LNV)

	Previous UL PDG 2019	NA62 UL at 90% CL	
$K^+ \to \pi^- \mu^+ e^+$	BR < 5.0×10^{-10}	BR < 4.2×10^{-11}	PRL 127 (2021) 131802
$K^+ \to \pi^+ \mu^- e^+$	BR < 5.2×10^{-10}	BR < 6.6×10^{-11}	PRL 127 (2021) 131802
$\pi^0 \to \mu^- e^+$	BR < 3.4×10^{-9}	BR < 3.2×10^{-10}	PRL 127 (2021) 131802
$K^+ \to \pi^- \mu^+ \mu^+$	BR < 8.6×10^{-11}	BR < 4.2×10^{-11}	PLB 797 (2019) 134794
$K^+ \to \pi^- e^+ e^+$	BR < 6.4×10^{-10}	BR < 5.3×10^{-11}	PLB 830 (2022) 137172
$K^+ \to \pi^- \pi^0 e^+ e^+$	N/A	BR < 8.5×10^{-10}	PLB 830 (2022) 137172
$K^+ \to \mu^- \nu e^+ e^+$	N/A	BR < 8.1×10^{-11}	preliminary

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NA62 2021 data

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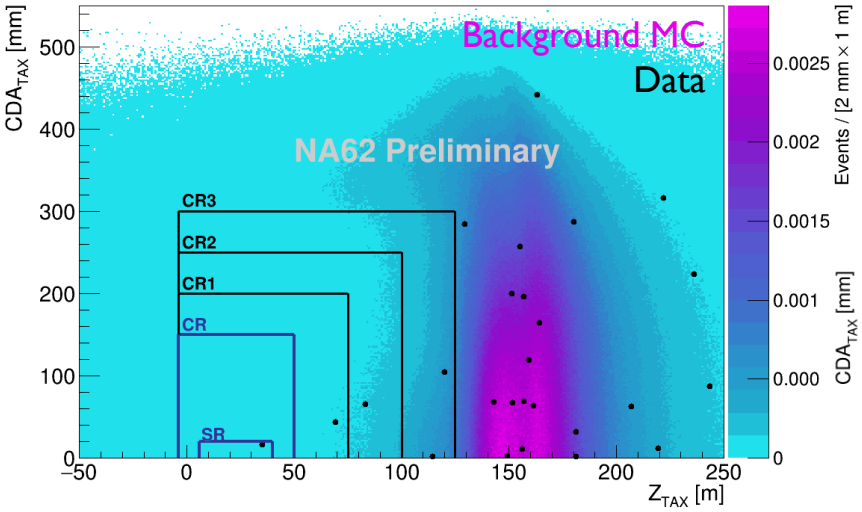
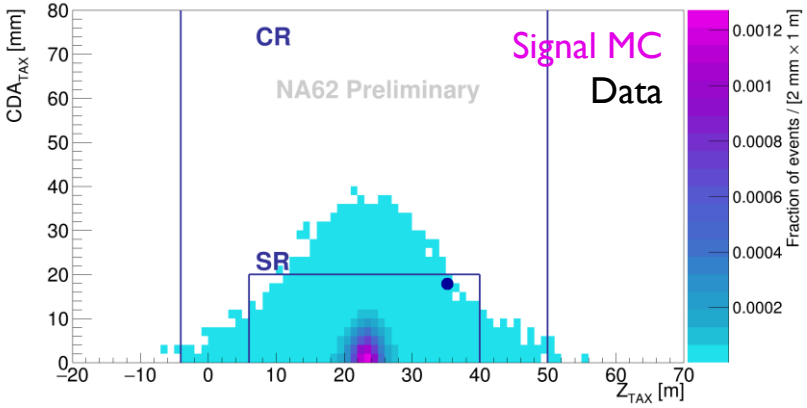
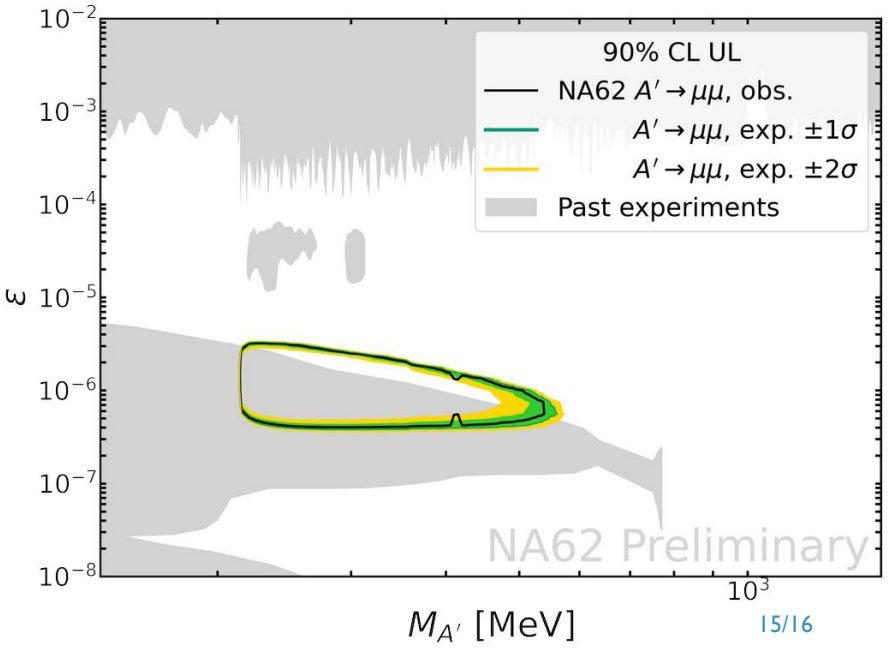
DARK PHOTON SEARCHES: $A' \rightarrow \mu^+\mu^-$

- Dark photon feebly interacting with SM particles with free mass and coupling ε
- **Beam dump mode**: 3.2 m Cu-Fe collimators (TAX) used as target
- Search for dark photon production in interaction with TAXs
- 1.5x nominal intensity, $(1.40 \pm 0.28) \times 10^{17}$ POT collected in ~10 days

- 0.016 ± 0.002 bkg events expected
- 1 event observed
- 2.4σ significance (counting experiment)







SUMMARY

$K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$	NA48/2	preliminary, final results in progress
$K^{+} \to \pi^{+}\nu\bar{\nu}$	NA62 Run1	JHEP 06 (2021) 093
$K^{+} \to \pi^0 e^{+}\nu\gamma$	NA62 Run1	PoS (EPS-HEP2021) 553
$K^{+} \to \pi^{+}\mu^{+}\mu^{-}$	NA62 Run1	JHEP 11 (2022) 011
$K^{+} \to \pi^{+}\gamma\gamma$	NA62 Run1	preliminary, final results in progress
$K^{+} \to \pi^{\pm}\mu^{\mp}e^{+}$	NA62 Run1	PRL 127 (2021) 131802
$K^{+} \to \pi^{-}(\pi^0)e^{+}e^{+}$	NA62 Run1	PLB 830 (2022) 137172
$K^{+} \to \pi^{-}\mu^{+}\mu^{+}$	NA62 Run1	PLB 797 (2019) 134794
$K^{+} \to \mu^{-}\nu e^{+}e^{+}$	NA62 Run1	preliminary, final results in progress
$A' \to \mu^{+}\mu^{-}$	NA62 2021 data	preliminary, final results in progress

NA62 Run2 will last until LS3
…stay tuned!

SUMMARY

$K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$	NA48/2	preliminary, final results in progress
$K^{+} \to \pi^{+}\nu\bar{\nu}$	NA62 Run1	JHEP 06 (2021) 093
$K^{+} \to \pi^0 e^{+}\nu\gamma$	NA62 Run1	PoS (EPS-HEP2021) 553
$K^{+} \to \pi^{+}\mu^{+}\mu^{-}$	NA62 Run1	JHEP 11 (2022) 011
$K^{+} \to \pi^{+}\gamma\gamma$	NA62 Run1	preliminary, final results in progress
$K^{+} \to \pi^{\pm}\mu^{\mp}e^{+}$	NA62 Run1	PRL 127 (2021) 131802
$K^{+} \to \pi^{-}(\pi^0)e^{+}e^{+}$	NA62 Run1	PLB 830 (2022) 137172
$K^{+} \to \pi^{-}\mu^{+}\mu^{+}$	NA62 Run1	PLB 797 (2019) 134794
$K^{+} \to \mu^{-}\nu e^{+}e^{+}$	NA62 Run1	preliminary, final results in progress
$A' \to \mu^{+}\mu^{-}$	NA62 2021 data	preliminary, final results in progress

NA62 Run2 will last until LS3
…stay tuned!

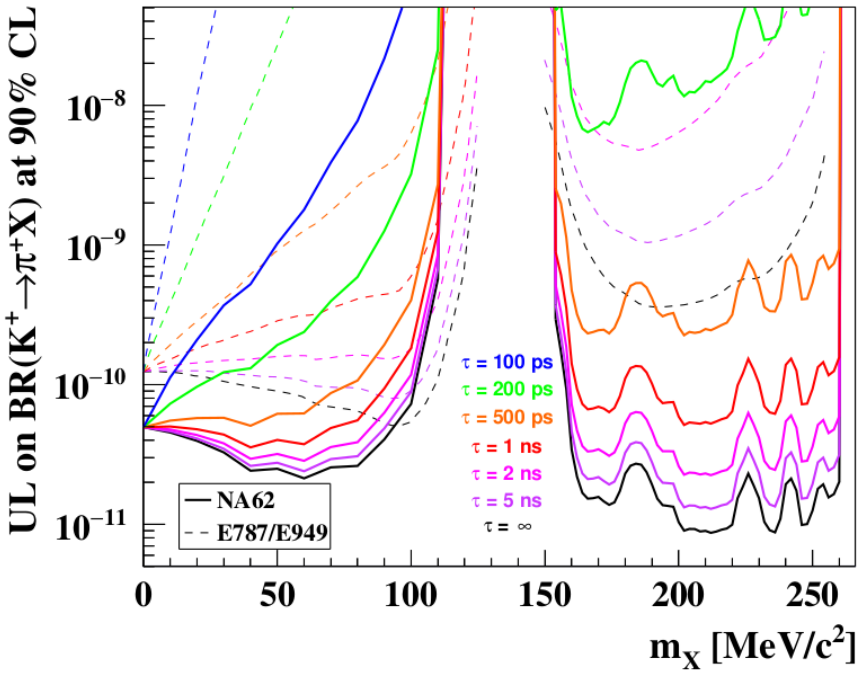
THANK YOU!

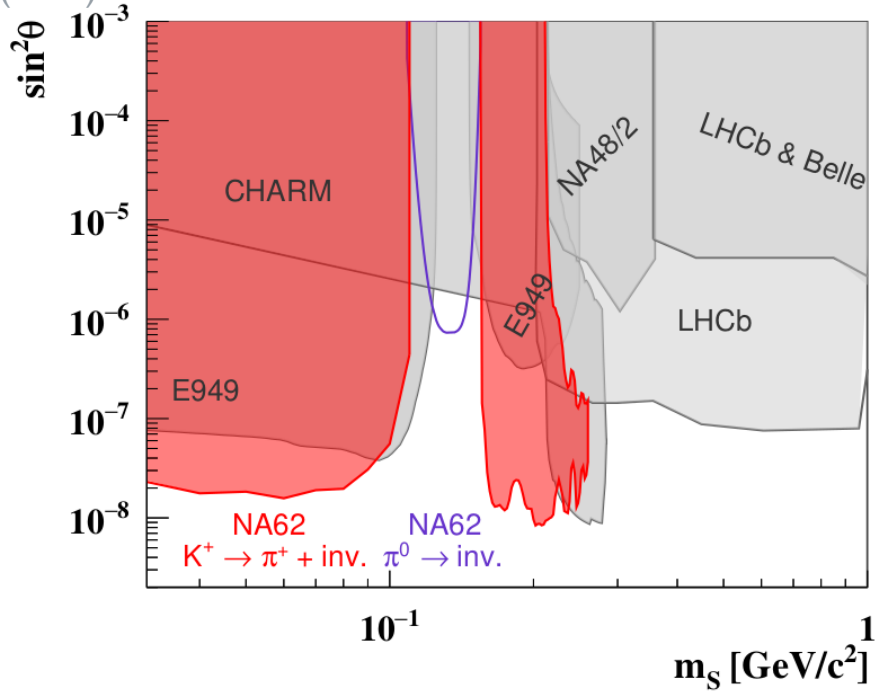
BACKUP

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

- Peak search in m^2_{miss} distribution
- Width from resolution
- Main background: SM $K^+ \to \pi^+ \nu\bar{\nu}$
- Acceptance from MC simulation

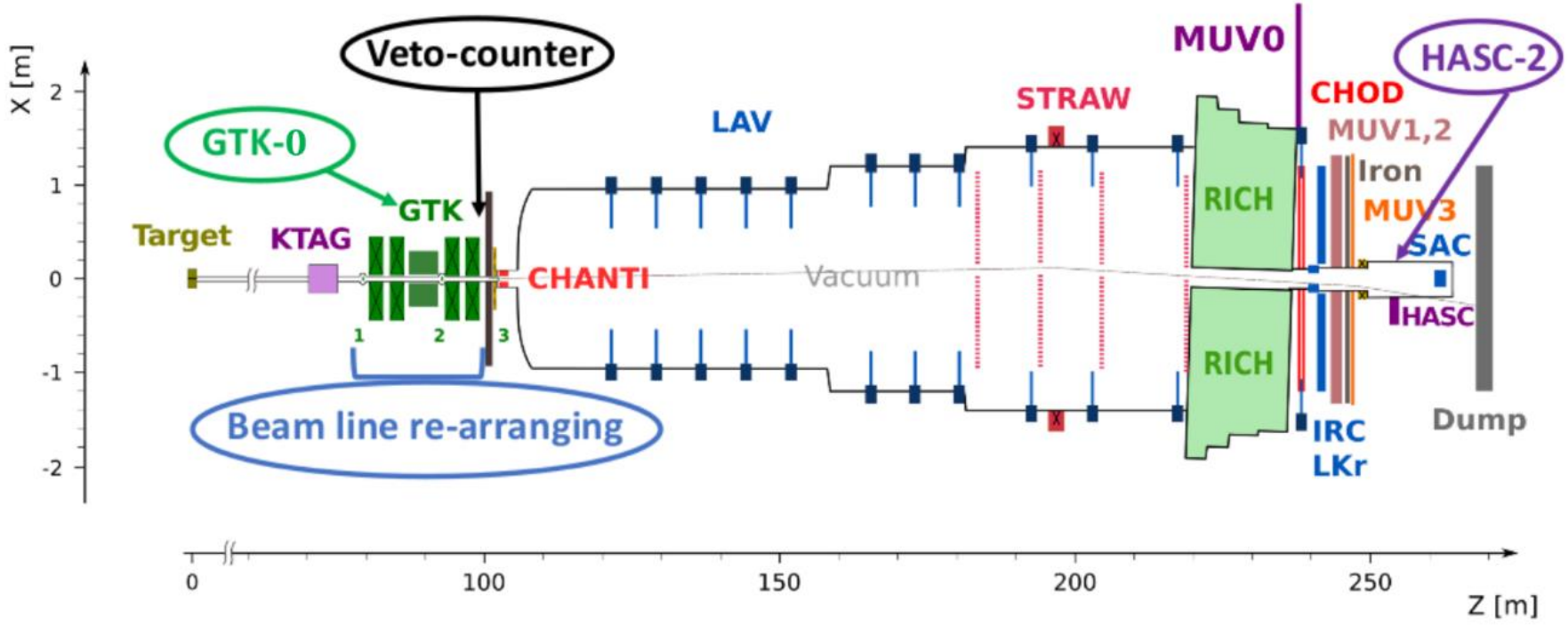
JHEP 06 (2021) 093





- Limits with finite lifetime: assume decay to visible particles in geometric acceptance
- Interpretation in dark scalar model with mixing with Higgs ($\sin^2\theta$)

FUTURE



- Additional GTK station
- Beam line re-arranging to swipe away upstream π^+
- New VetoCounter to detect upstream decays
- HASC-2 to further suppress $K^+ \rightarrow \pi^+ \pi^0$ decays
- Intensity increased from 60% to 100% of nominal

Goal: reach O(10%) precision by LS3

- Improvements in LKr reconstruction
- Optimizations in the analysis: random veto stable, background rejection, acceptance increased

Beyond LS3

HIKE:
High Intensity Kaon Experiments

arxiv.org/abs/2204.13394

RECENT THEORETICAL PROGRESS

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.60 \pm 0.42) \times 10^{-11}$$

$$BR(K_L \to \pi^0 \nu\bar{\nu}) = (2.94 \pm 0.15) \times 10^{-11}$$

Acta Phys. Polon. B 53.6 (2021) A1

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (7.73 \pm 0.61) \times 10^{-11}$$

$$BR(K_L \to \pi^0 \nu\bar{\nu}) = (2.59 \pm 0.29) \times 10^{-11}$$

PoS BEAUTY2020 (2021) 056

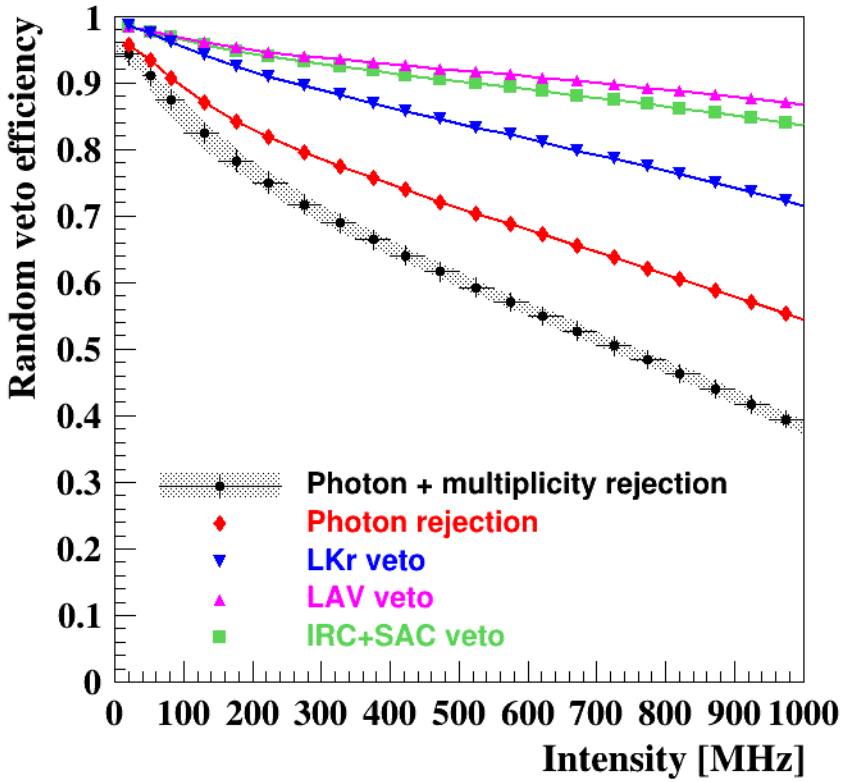
SINGLE EVENT SENSITIVITY

$$N_{\pi\nu\nu}^{exp} = N_{\pi\pi}\, \varepsilon_{trig}^{PNN}\, \varepsilon_{RV}\, \frac{A_{\pi\nu\nu}}{A_{\pi\pi}}\, \frac{BR(\pi\nu\nu)}{BR(\pi\pi)}$$

$$SES = \frac{BR(\pi\nu\nu)}{N_{\pi\nu\nu}^{exp}}$$

	Subset S1 *	Subset S2 *
$N_{\pi\pi} \times 10^{-7}$	3.14	11.6
$A_{\pi\pi} \times 10^{2}$	7.62 ± 0.77	11.77 ± 1.18
$A_{\pi\nu\bar{\nu}} \times 10^{2}$	3.95 ± 0.40	6.37 ± 0.64
$\epsilon_{\rm trig}^{\rm PNN}$	0.89 ± 0.05	0.89 ± 0.05
$\epsilon_{\rm RV}$	0.66 ± 0.01	0.66 ± 0.01
$SES \times 10^{10}$	0.54 ± 0.04	0.14 ± 0.01
$N_{\pi\nu\bar{\nu}}^{\rm exp}$	$1.56 \pm 0.10 \pm 0.19_{\rm ext}$	$6.02 \pm 0.39 \pm 0.72_{\rm ext}$

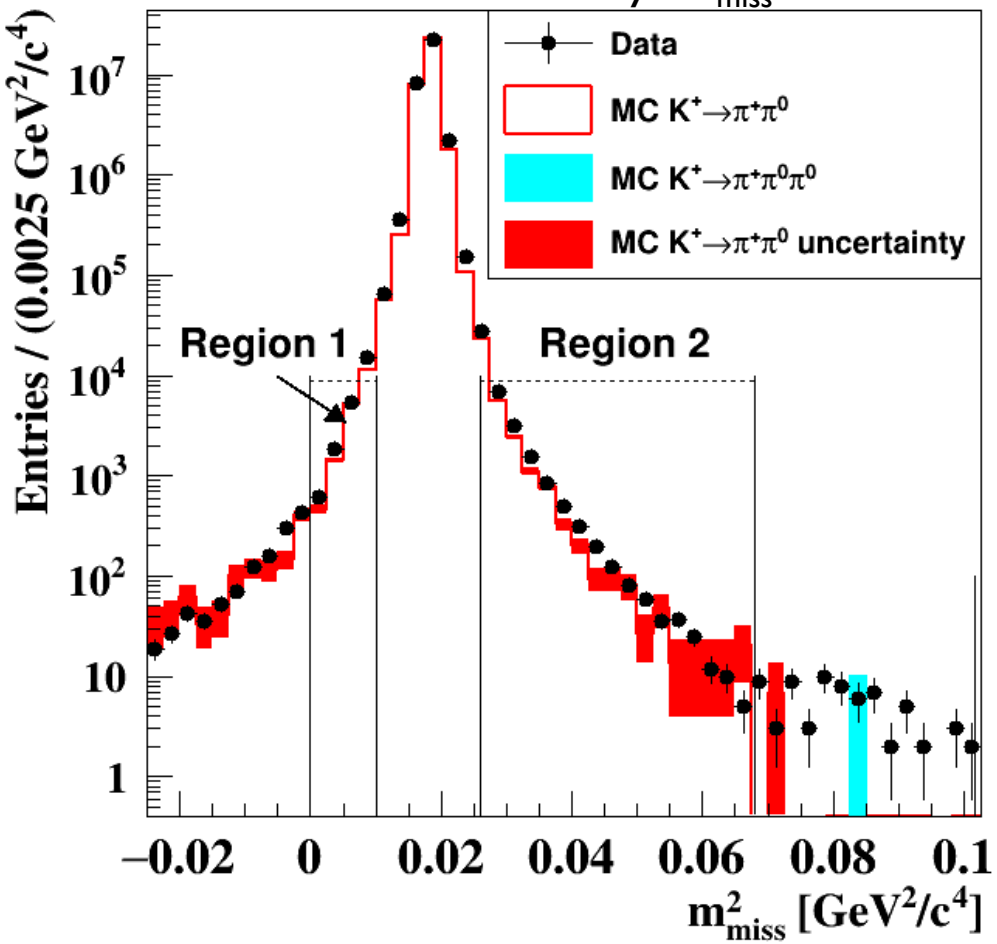
* different hardware configurations



- $K^+ \rightarrow \pi^+ \pi^0$ normalization channel
- Cancellation of systematic effects
- Random Veto: efficiency loss due to beam activity

BACKGROUND FROM K^+ DECAYS

Control $\pi^+\pi^0$ data to study m^2_{miss} distribution



Number of events in $\pi^+\pi^0$ region after $\pi\nu\nu$ selection

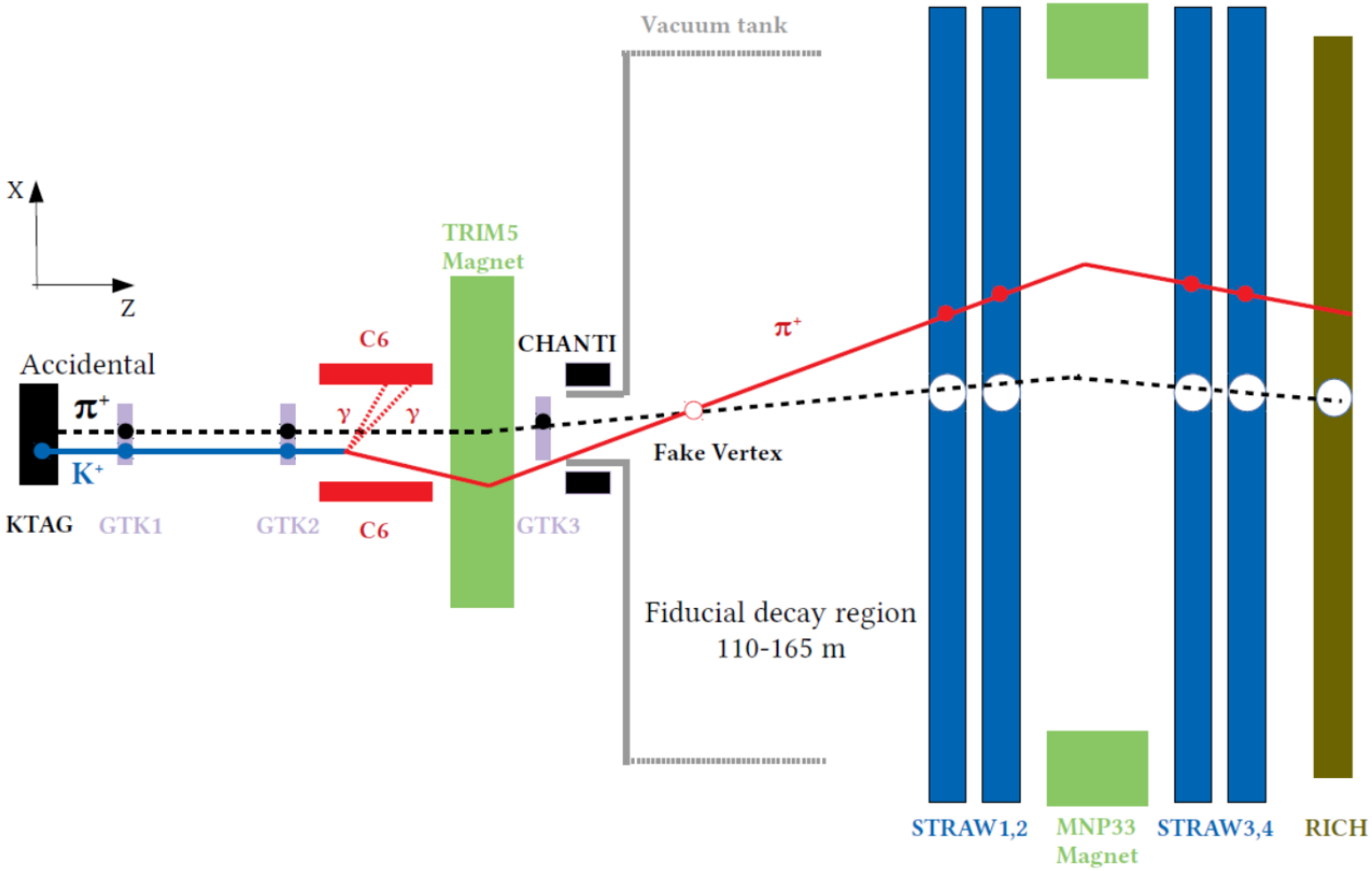
$$N^{exp}_{\pi\pi}(SR) = N(\pi^+\pi^0)\, f_{kin}(SR)$$

Expected $K^+ \to \pi^+\pi^0$ events in signal region

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

- $K^+ \to \mu^+\nu_\mu$ and $K^+ \to \pi^+\pi^+\pi^-$ backgrounds: similar procedure
- $K^+ \to \pi^+\pi^- e^+\nu_e$ evaluated with MC simulations
- Validation with control regions

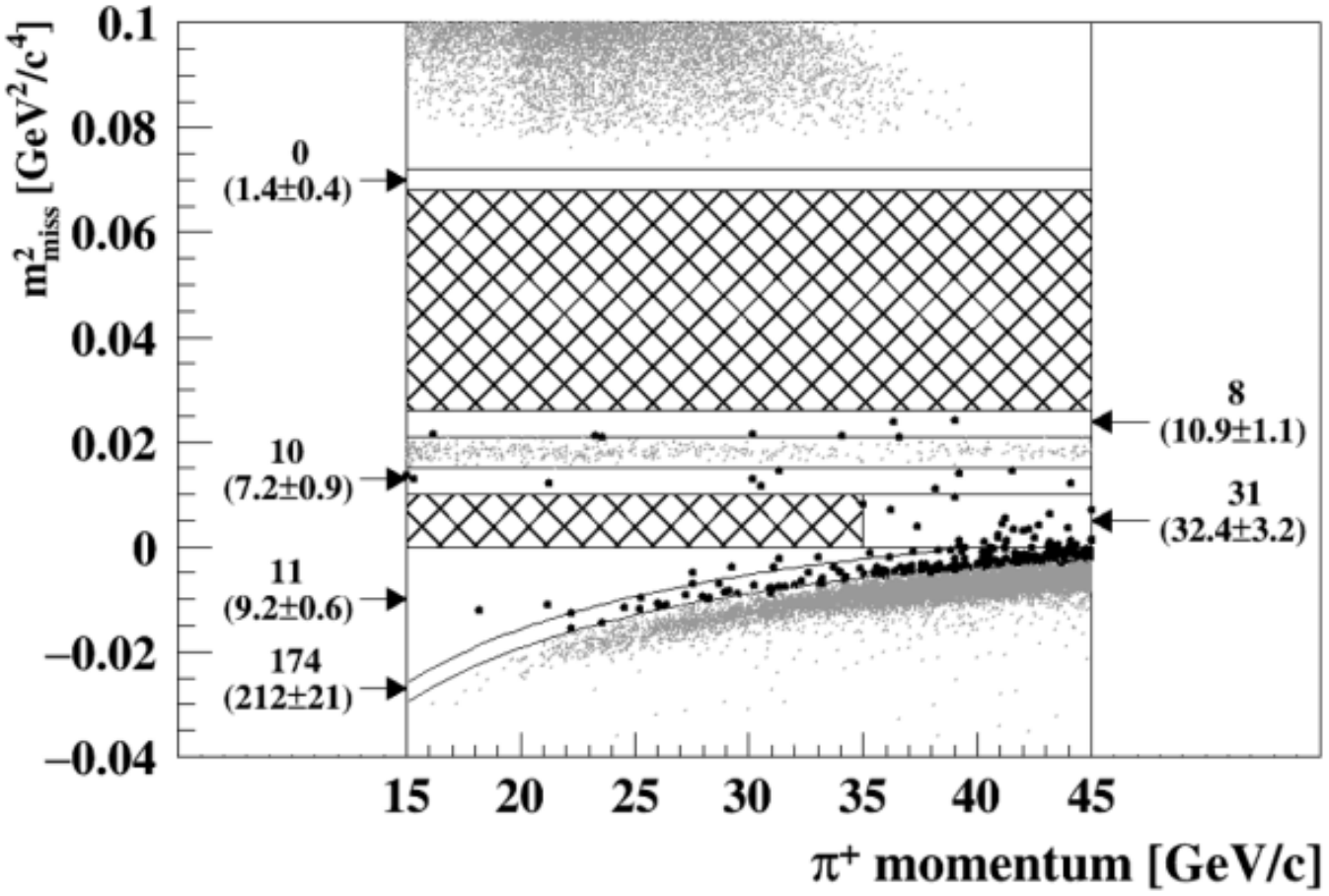
UPSTREAM BACKGROUND



- Pions produced upstream of the fiducial volume
  - Early kaon decays
  - Interaction of beam particles with beam spectrometer material
- Fake association of detected pions to accidental particles

- New collimator installed in June 2018
- Geometrical cuts & BDT cut on backtracked pion position
- Kaon-pion association effective
- Data-driven background estimation

EXPECTED BACKGROUND SUMMARY



Background	Subset S1	Subset S2
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^-e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$
Total	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$