LATEST RESULTS ON $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ DECAY AND PRECISION MEASUREMENTS WITH KAONS AT CERN

- $K^\pm \rightarrow \pi^0\pi^0\mu^\pm\nu$ ← NA48/2
- $K^+ \rightarrow \pi^+\nu\bar{\nu}$
- $K^+ \rightarrow \pi^0 e^+ \nu\gamma$
- $K^+ \rightarrow \pi^+\mu^+\mu^-$

(the last three ← NA62)

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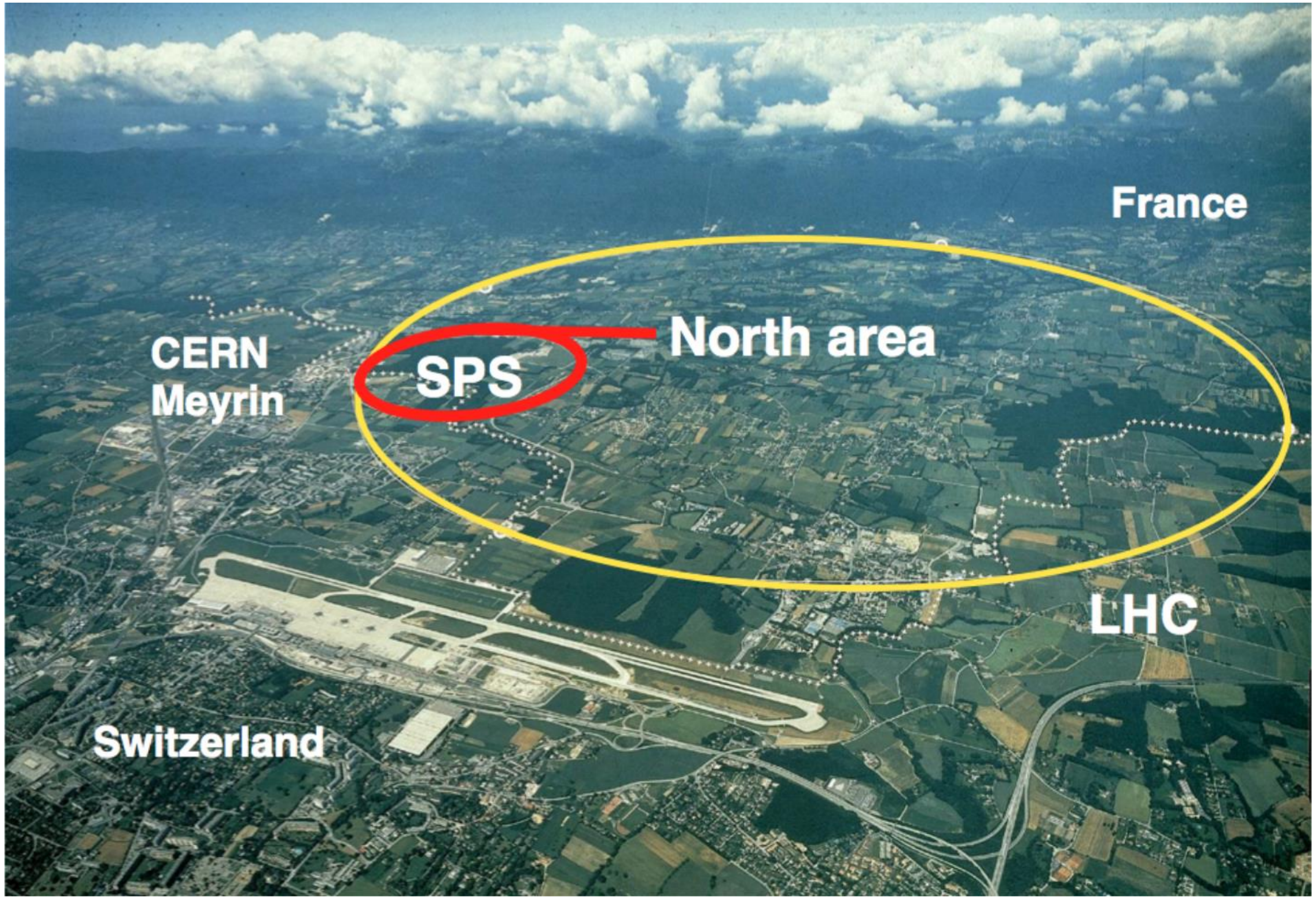
KAON EXPERIMENTS AT CERN

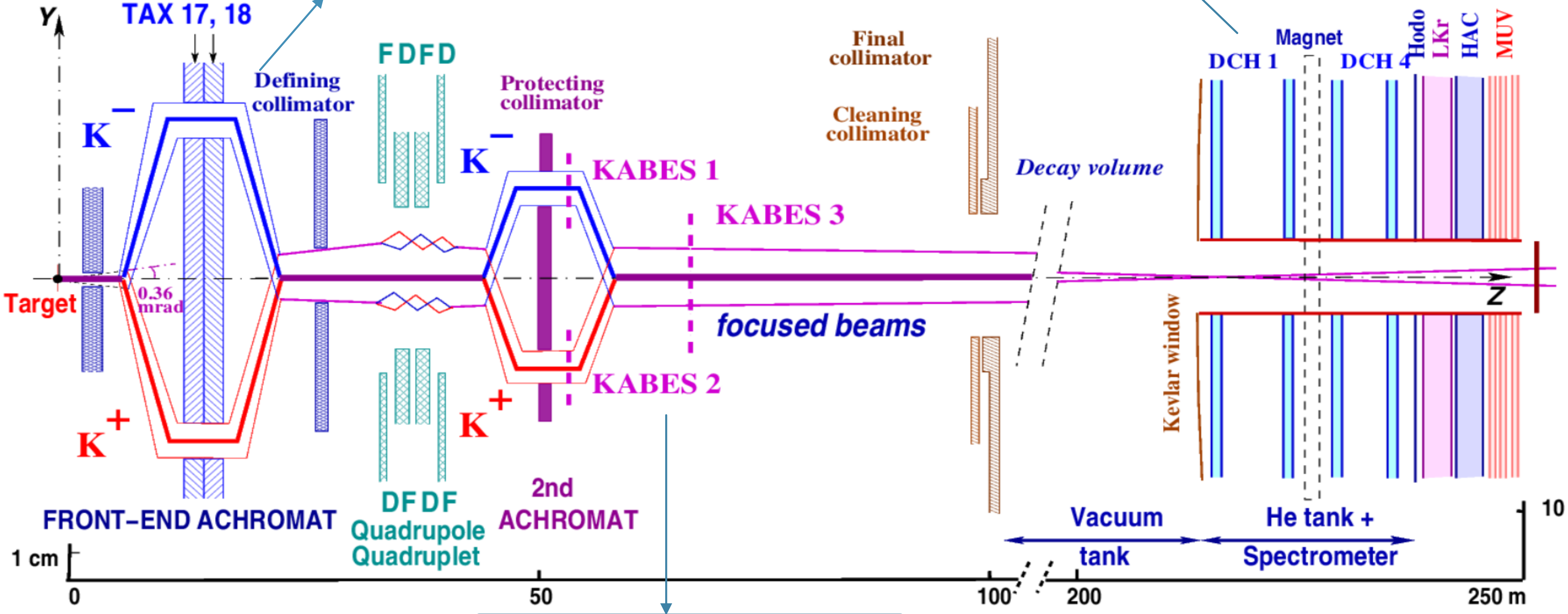


1984 – 1990	**NA31** (K_S / K_L) First evidence of CPV
1997 – 2002	**NA48, NA48/1** (K_S / K_L) Discovery of CPV, Re(ε'/ε) Rare K_S and hyperon decays
2003 – 2004	**NA48/2** (K^+ / K^-) Direct CPV, rare $K^\pm$ decays
2007 – 2008	**NA62** (K^+) $R_K = \Gamma(K_{\mu\nu}) / \Gamma(K_{e\nu})$
2016 – now	**NA62** (K^+) Rare K^+ decays

NA48/2 SETUP

6% kaons
p_K ~ 60 GeV/c

Drift CHambers
(magnetic spectrometer)



KAon BEam Spectrometer

Eur. Phys. J. C 52 (2007) 875

$K^{\pm} \rightarrow \pi^0\pi^0\mu^{\pm}\nu$ ($K_{\mu4}^{00}$)

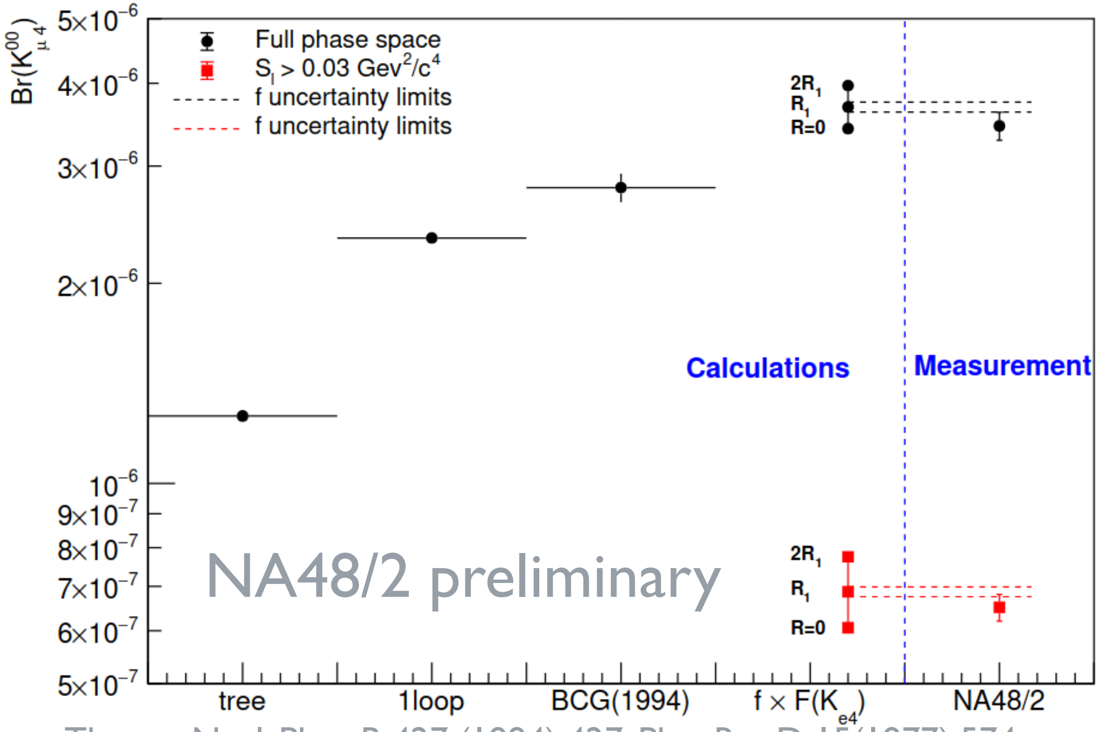
Theory and status

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)
$K_{\mu4}^{\pm}$	1.4 ± 0.9	7	Bisi et al. (1967)
$K_{\mu4}^{00}$	?	0	

- First observation
- Test of ChPT
- Test of lepton universality (experimental parametrization from K_{e4}^{00})

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

- 2437 events selected in signal region
- $354 \pm 33_{stat} \pm 62_{syst}$ background events expected



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

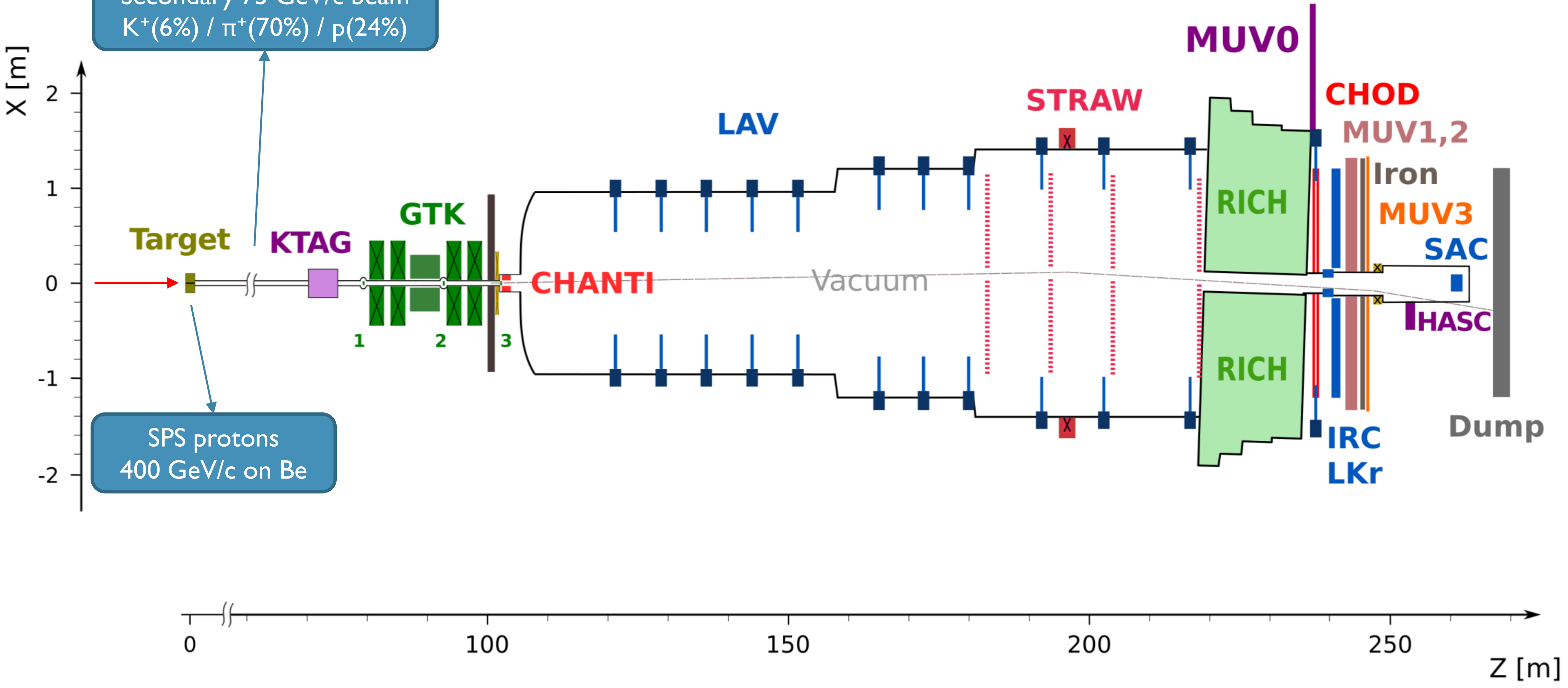
THE NA62 EXPERIMENT

- High-precision kaon experiment
- Technique:
  - Fixed target
  - Decay-in-flight
- Broad physics program:
  - Measurement of BR($K^+ \to \pi^+ \nu\bar{\nu}$) (main goal)
  - Precision measurements

  (the two items above) ⟶ this talk
  - Rare and forbidden decays (LFV, LNV) ⟶ R. Piandani, 06/09 15:50
  - Exotic searches (DP, DS, ALP, HNL) ⟶ S.A. Ghinescu, 10/09 11:20
- Timeline:
  - 2008: NA62 approval
  - 2016 – 2018: First data taking run (2.2×10^{18} protons on target) ⟶ this talk
  - 2021: Start of second data taking run with improved detector (ongoing)

THE NA62 DETECTOR

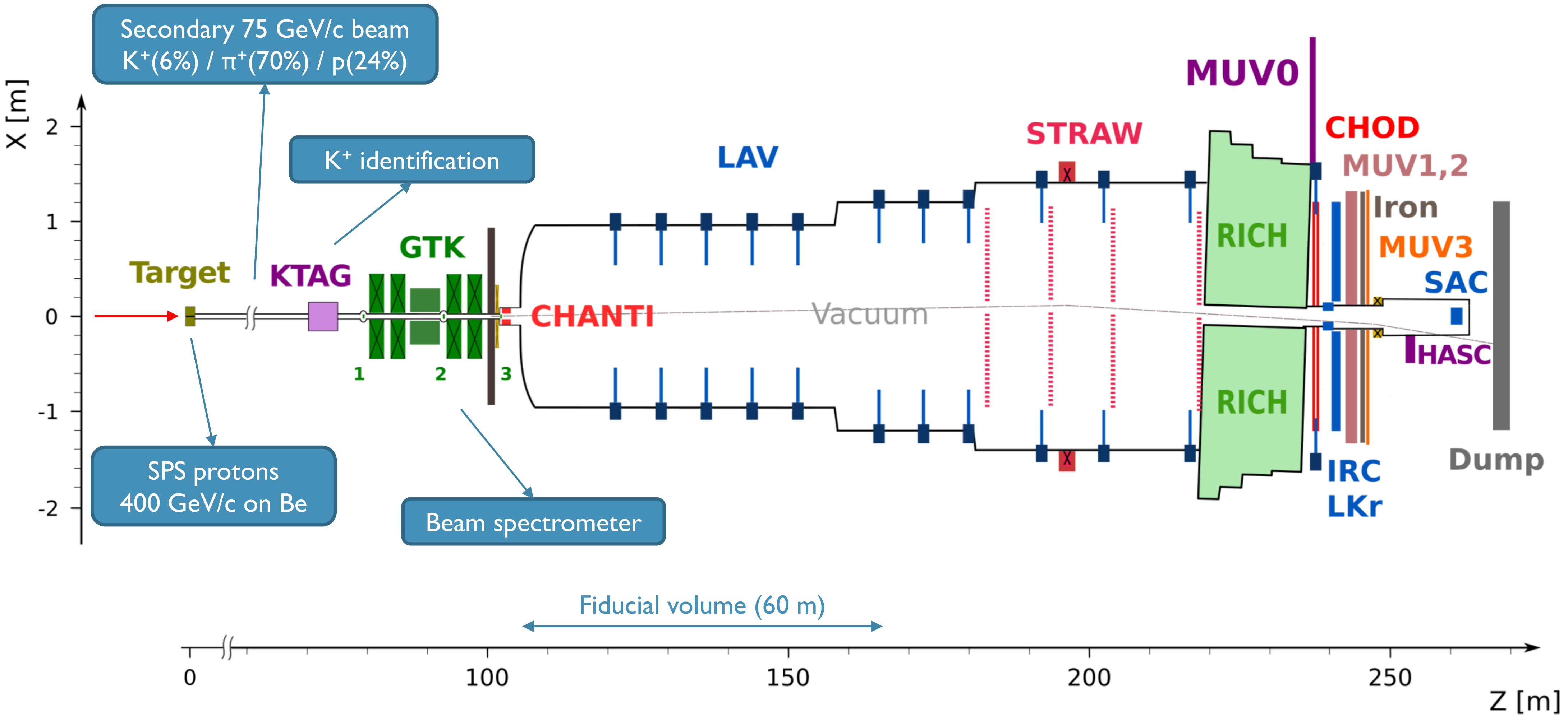
Secondary 75 GeV/c beam
K^+(6%) / π^+(70%) / p(24%)



SPS protons
400 GeV/c on Be

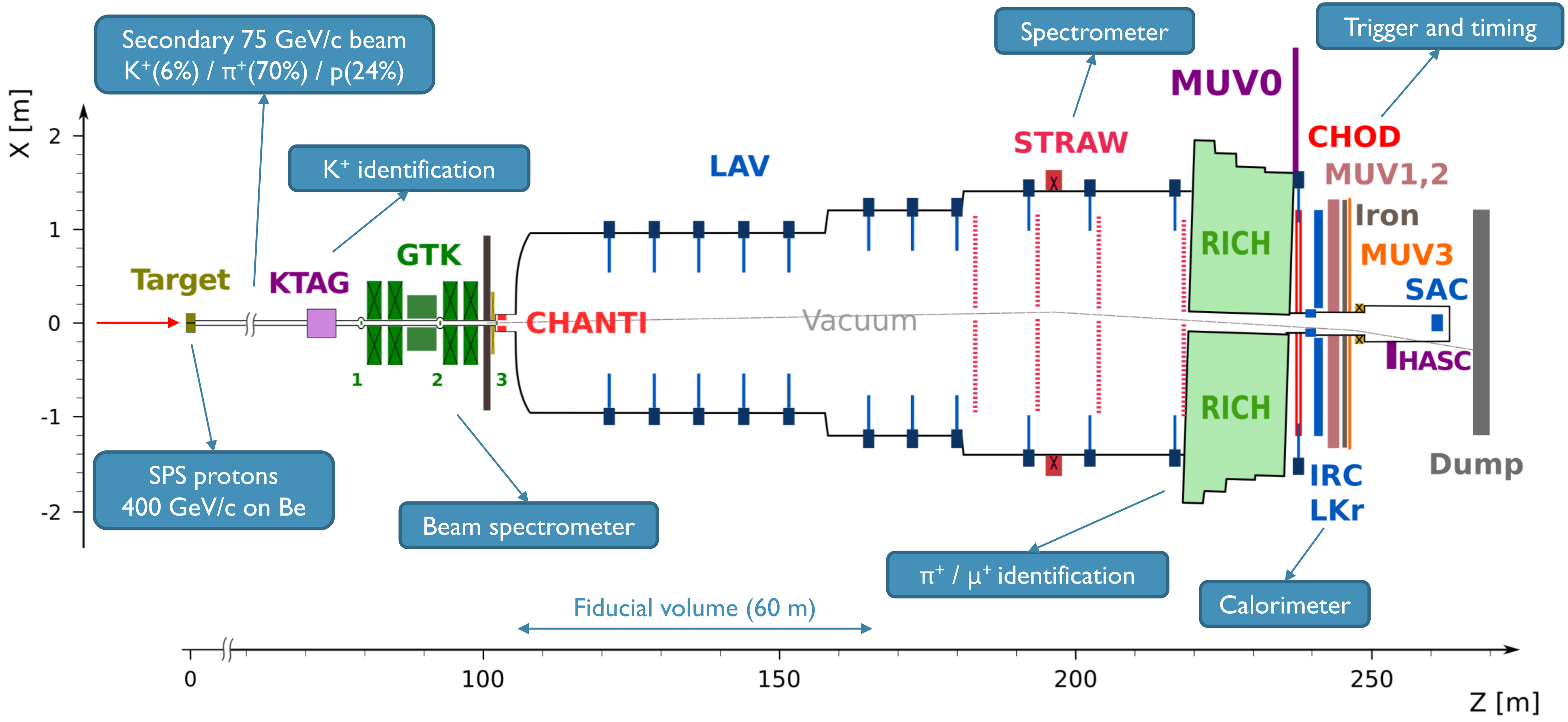
JINST 12 (2017) P05025

THE NA62 DETECTOR



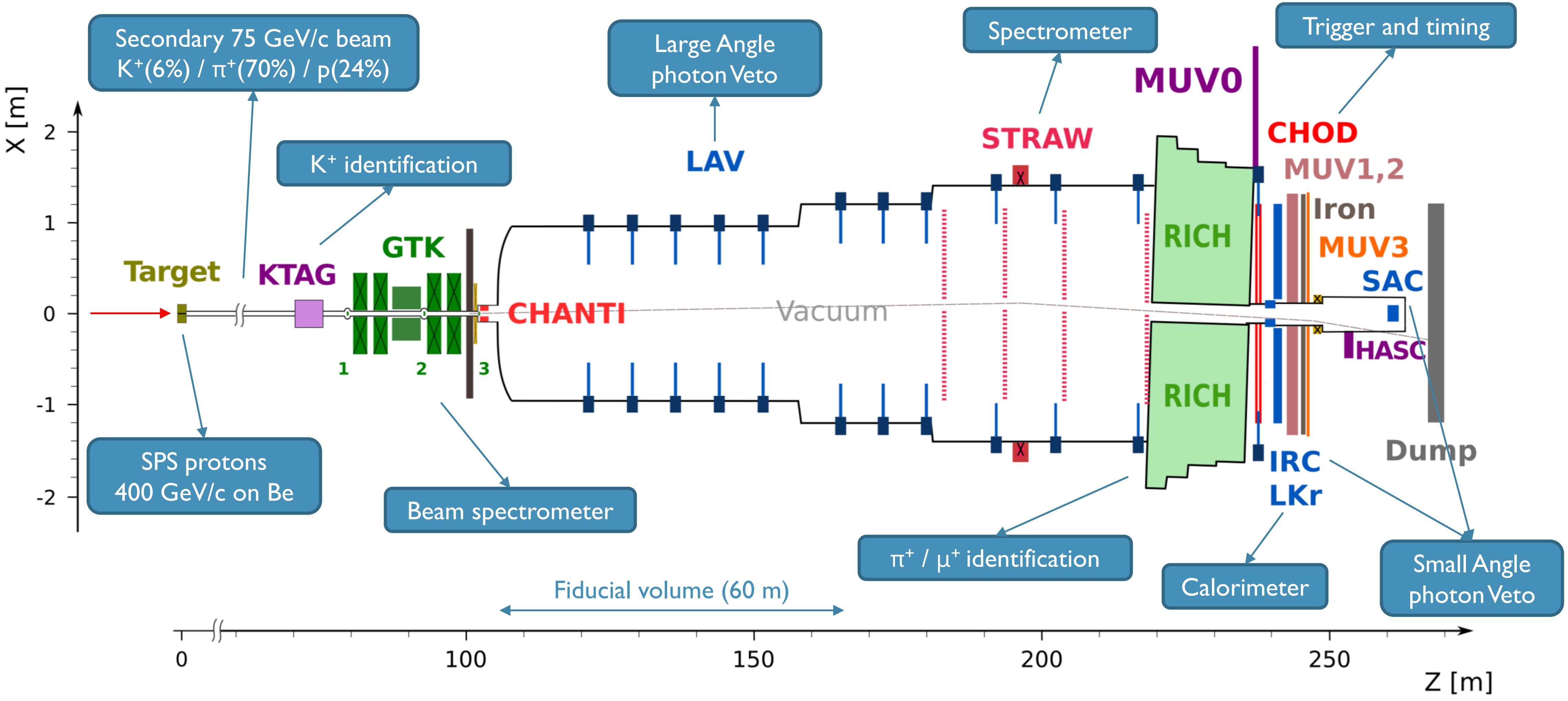
JINST 12 (2017) P05025

THE NA62 DETECTOR



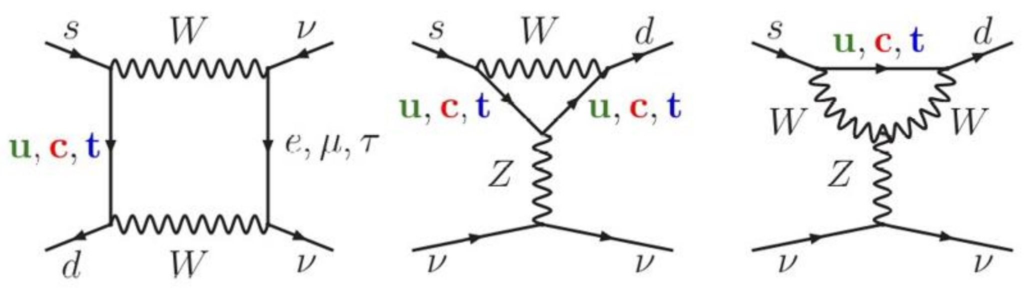
JINST 12 (2017) P05025

THE NA62 DETECTOR



JINST 12 (2017) P05025

THE $K^+ \to \pi^+ \nu\bar{\nu}$ DECAY: STATE OF THE ART



- FCNC s → d, high CKM suppression
- Theoretically clean: short distance contribution
- Hadronic form factor measured with $K_{\ell 3}$
- Largest theoretical uncertainty from CKM

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

JHEP 11 (2015) 033

- Previous experimental measurement at E787/E949
- Decay-at-rest technique

$$BR(K^+ \to \pi^+ \nu\bar{\nu})_{BNL} = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$$

Phys. Rev. D 79 (2009) 092004

NA62 2016 data: 1 event observed

$$BR(K^+ \to \pi^+ \nu\bar{\nu})^{NA62}_{16} < 14 \times 10^{-10} \text{ @ 95\% CL}$$

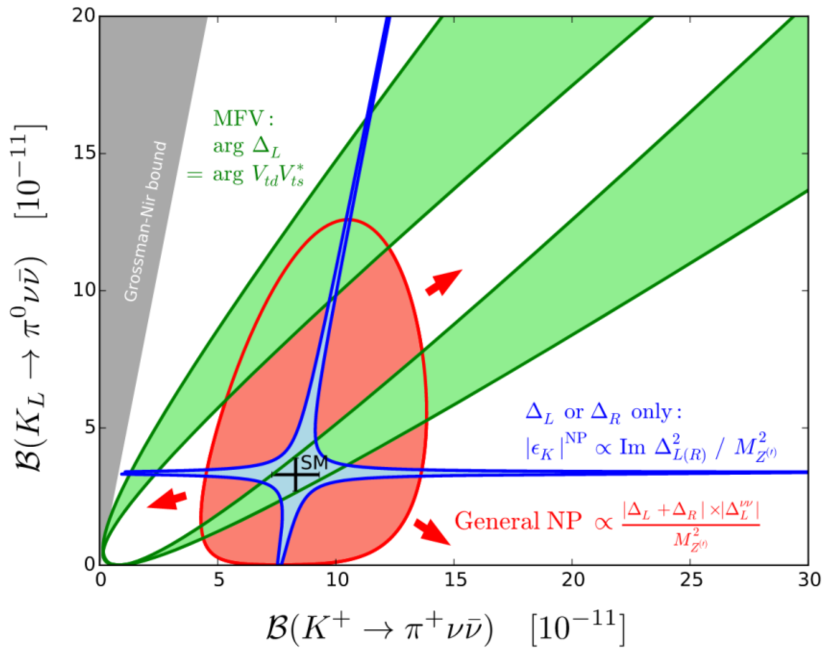
Phys. Lett. B 791 (2019) 156

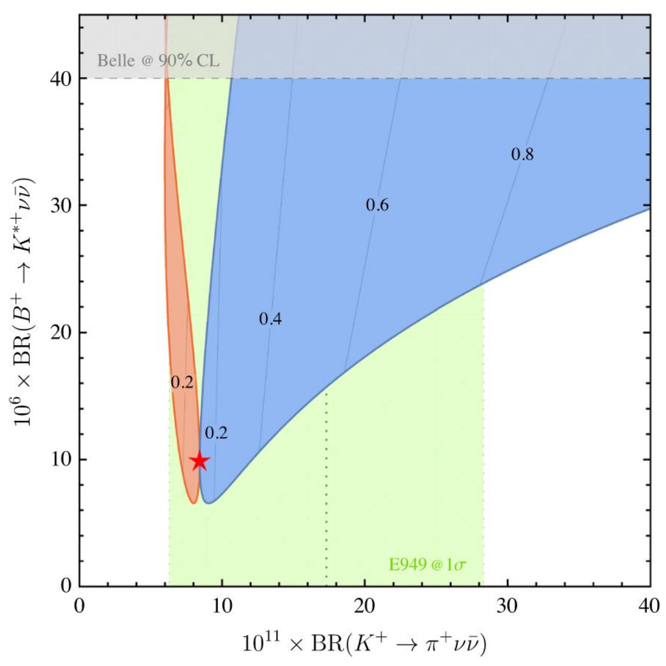
NA62 2017 data: 2 events observed

$$BR(K^+ \to \pi^+ \nu\bar{\nu})^{NA62}_{16+17} = (4.8^{+7.2}_{-4.8}) \times 10^{-11}$$

JHEP 11 (2020) 042

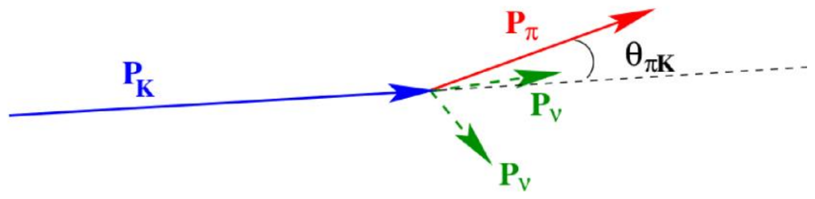
THE $K^+ \to \pi^+ \nu\bar{\nu}$ DECAY: NEW PHYSICS SENSITIVITY





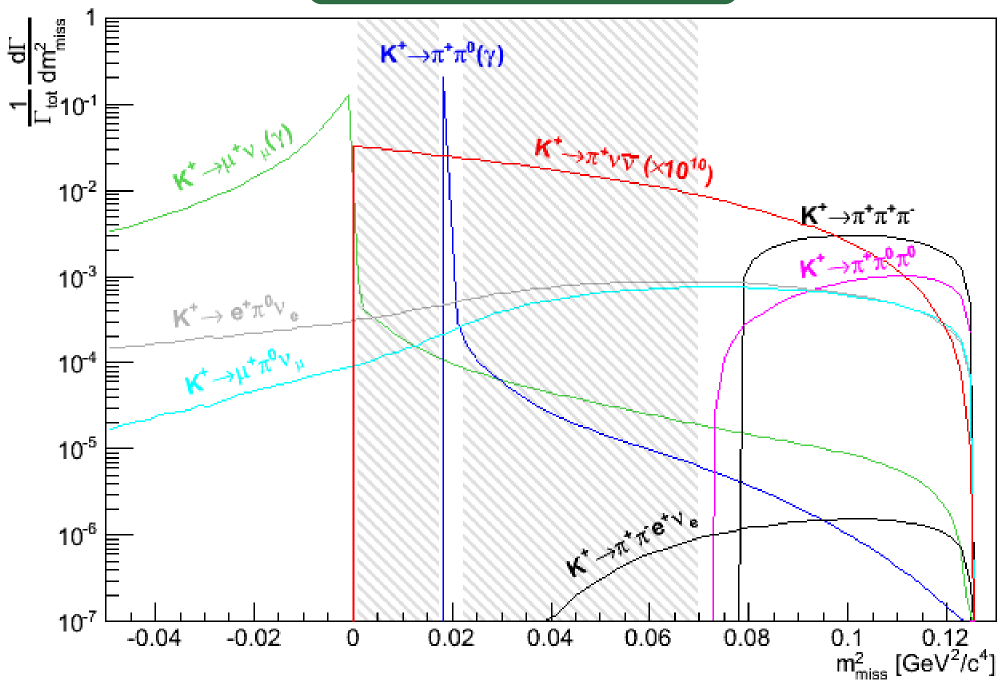
- Custodial Randall-Sundrum
  JHEP 0903 (2009) 108
- MSSM analyses
  JHEP 0608 (2006) 064
- Simplified Z, Z' models
  JHEP 11 (2015) 166
- Littlest Higgs with T-parity
  Eur.Phys.J. C76 (2016) 182
- LFU violation models
  Eur. Phys. J. C (2017) 77: 618
- Leptoquarks
  arXiv:1802.00786v1 (2018)
- Constraints from existing measurements (correlations model dependent)

ANALYSIS STRATEGY



Main K^+ (bkg) decay modes	BR
$K^+ \to \mu^+\nu$ ($K_{\mu 2}$)	64×10^{-2}
$K^+ \to \pi^+\pi^0$ ($K_{2\pi}$)	21×10^{-2}
$K^+ \to \pi^+\pi^+\pi^-$ ($K_{3\pi}$)	5.6×10^{-2}
$K^+ \to \pi^+\pi^- e^+\nu$ (K_{e4})	4.3×10^{-5}

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



Keystones

- Momentum range: $15 < P_\pi < 45$ GeV/c
- Blind analysis
- 7 categories depending on hardware and momentum
- MVA used for particle ID and upstream bkg rejection
- Kinematic bkg suppression $O(10^4)$
- Muon rejection $O(10^7)$
- π^0 rejection $O(10^7)$
- Excellent time resolution O(100 ps)

SINGLE EVENT SENSITIVITY

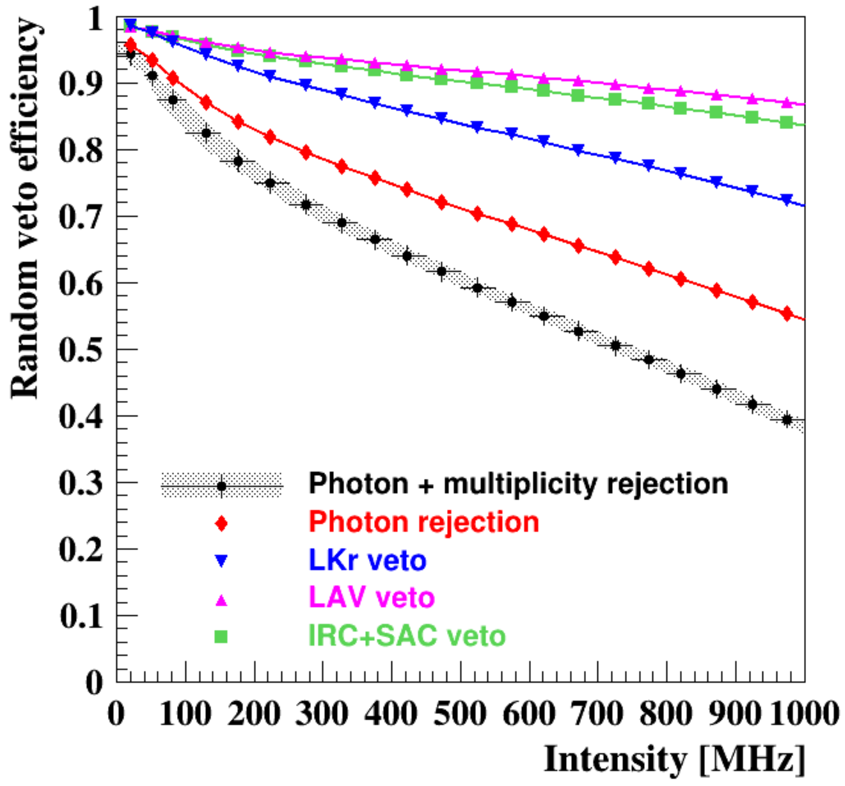
$$N^{exp}_{\pi\nu\nu} = N_{\pi\pi}\, \varepsilon^{PNN}_{trig}\, \varepsilon_{RV}\, \frac{A_{\pi\nu\nu}}{A_{\pi\pi}} \frac{BR(\pi\nu\nu)}{BR(\pi\pi)}$$

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

	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
ϵ^{PNN}_{trig}	0.89 ± 0.05	0.89 ± 0.05
ϵ_{RV}	0.66 ± 0.01	0.66 ± 0.01
$SES \times 10^{10}$	0.54 ± 0.04	0.14 ± 0.01
$N^{exp}_{\pi\nu\bar{\nu}}$	$1.56 \pm 0.10 \pm 0.19_{ext}$	$6.02 \pm 0.39 \pm 0.72_{ext}$

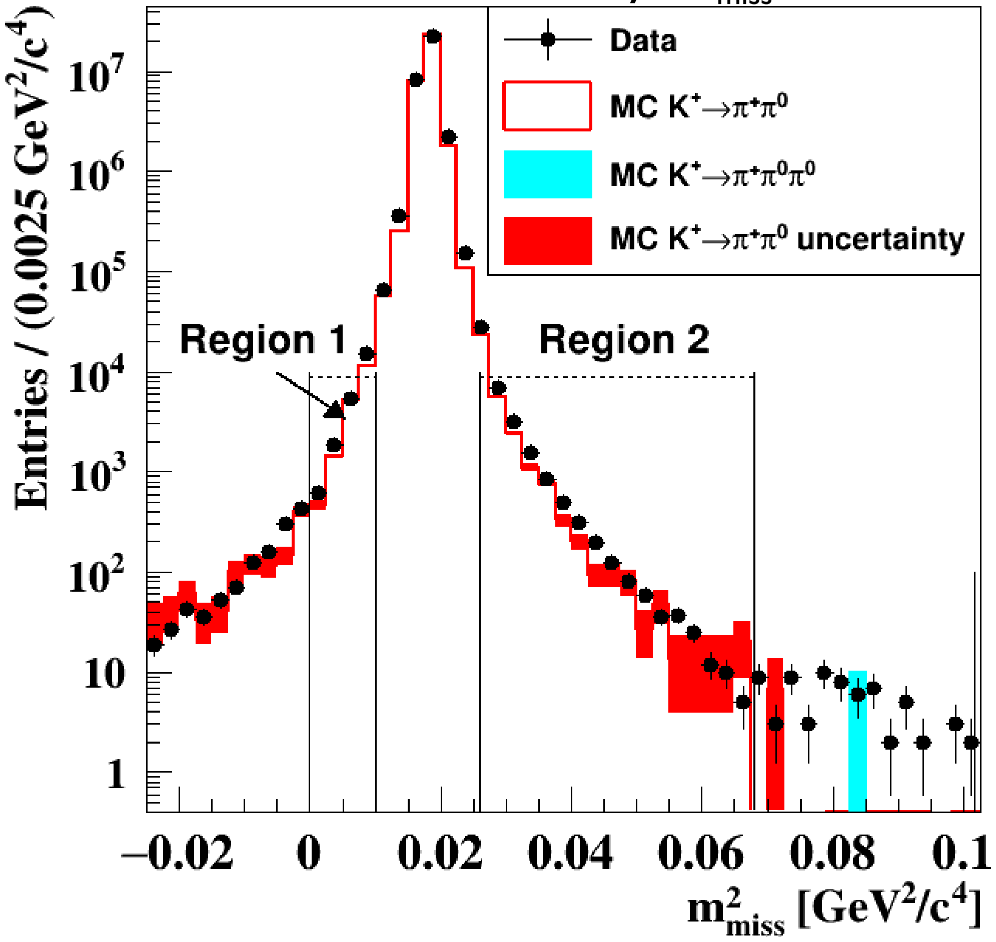
* different hardware configurations

- $K^+ \to \pi^+ \pi^0$ 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

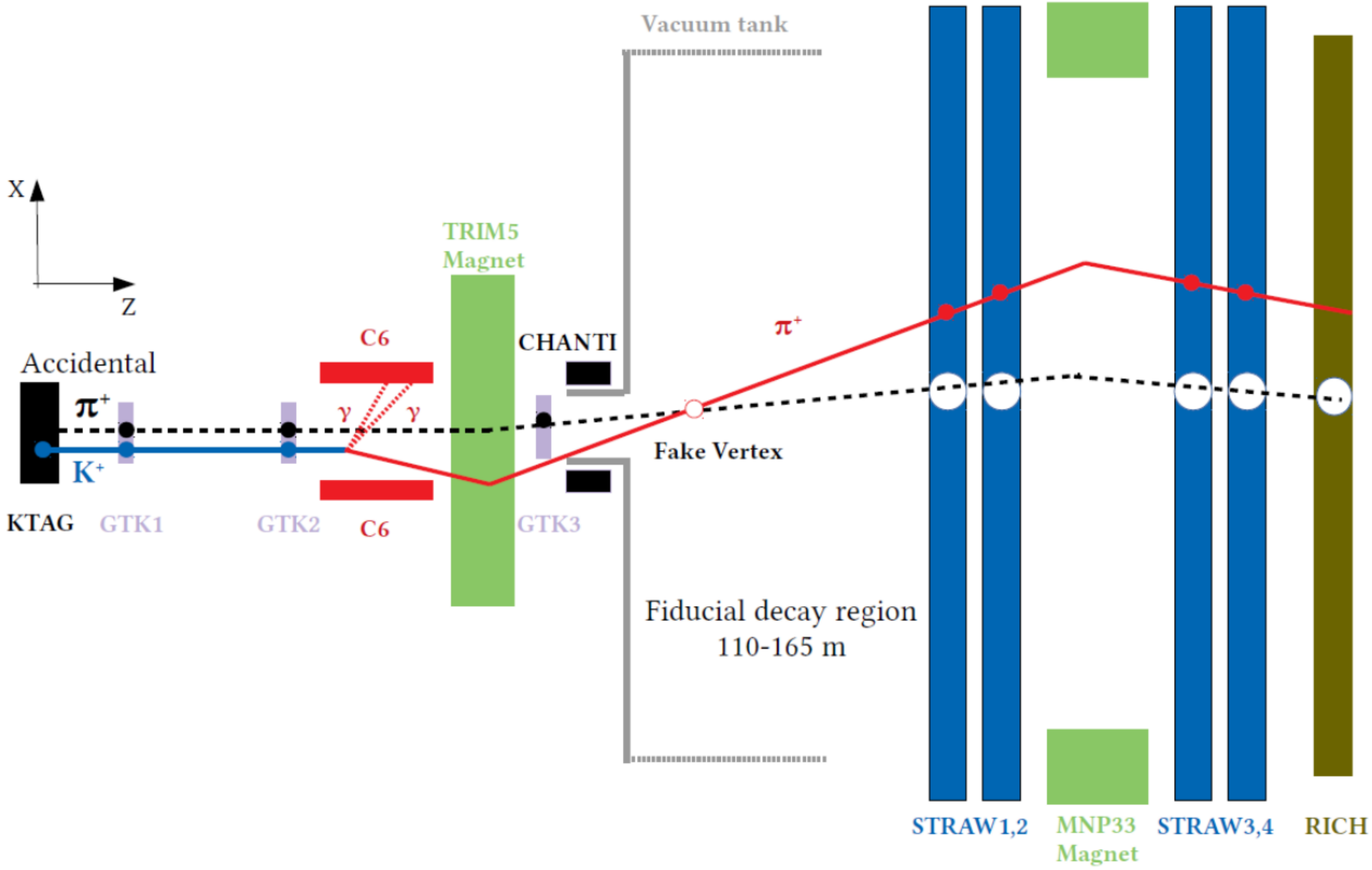
$$N^{exp}_{\pi\pi}(SR) = N(\pi^+\pi^0)\, f_{kin}(SR)$$

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

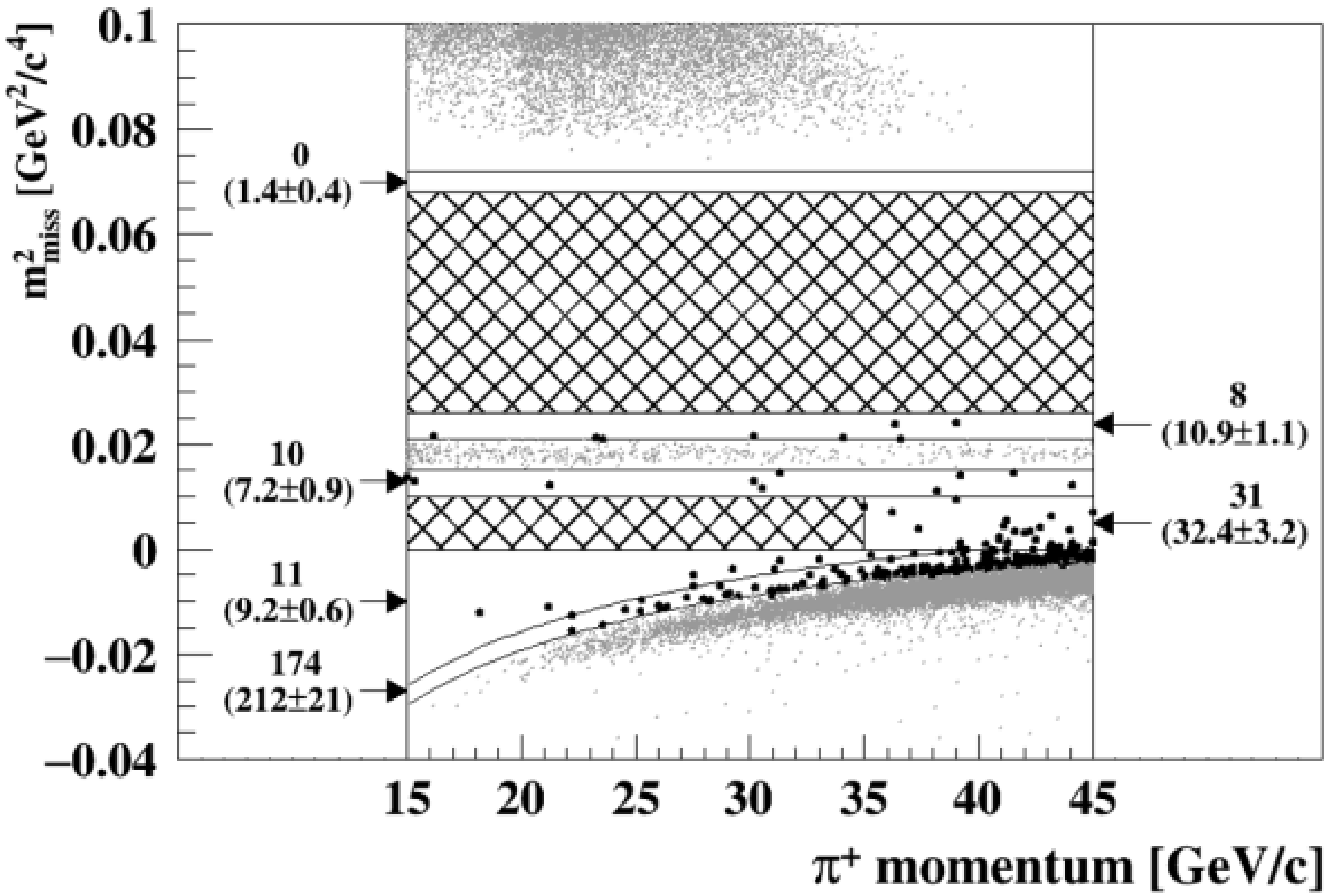
UPSTREAM BACKGROUND



- 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

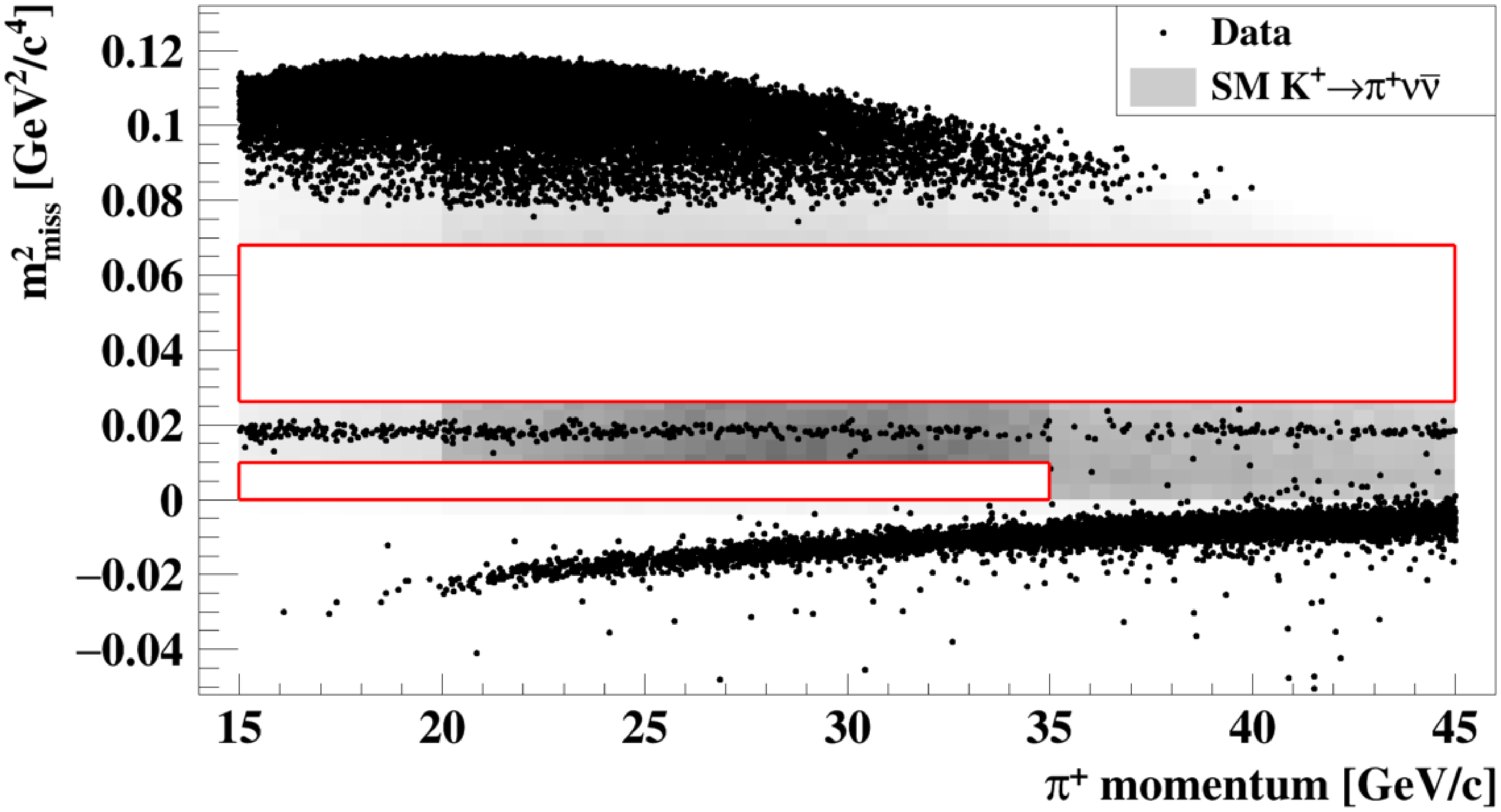
- Geometrical cuts & BDT cut on backtracked pion position
- Kaon-pion association effective
- Data-driven background estimation

EXPECTED BACKGROUND SUMMARY

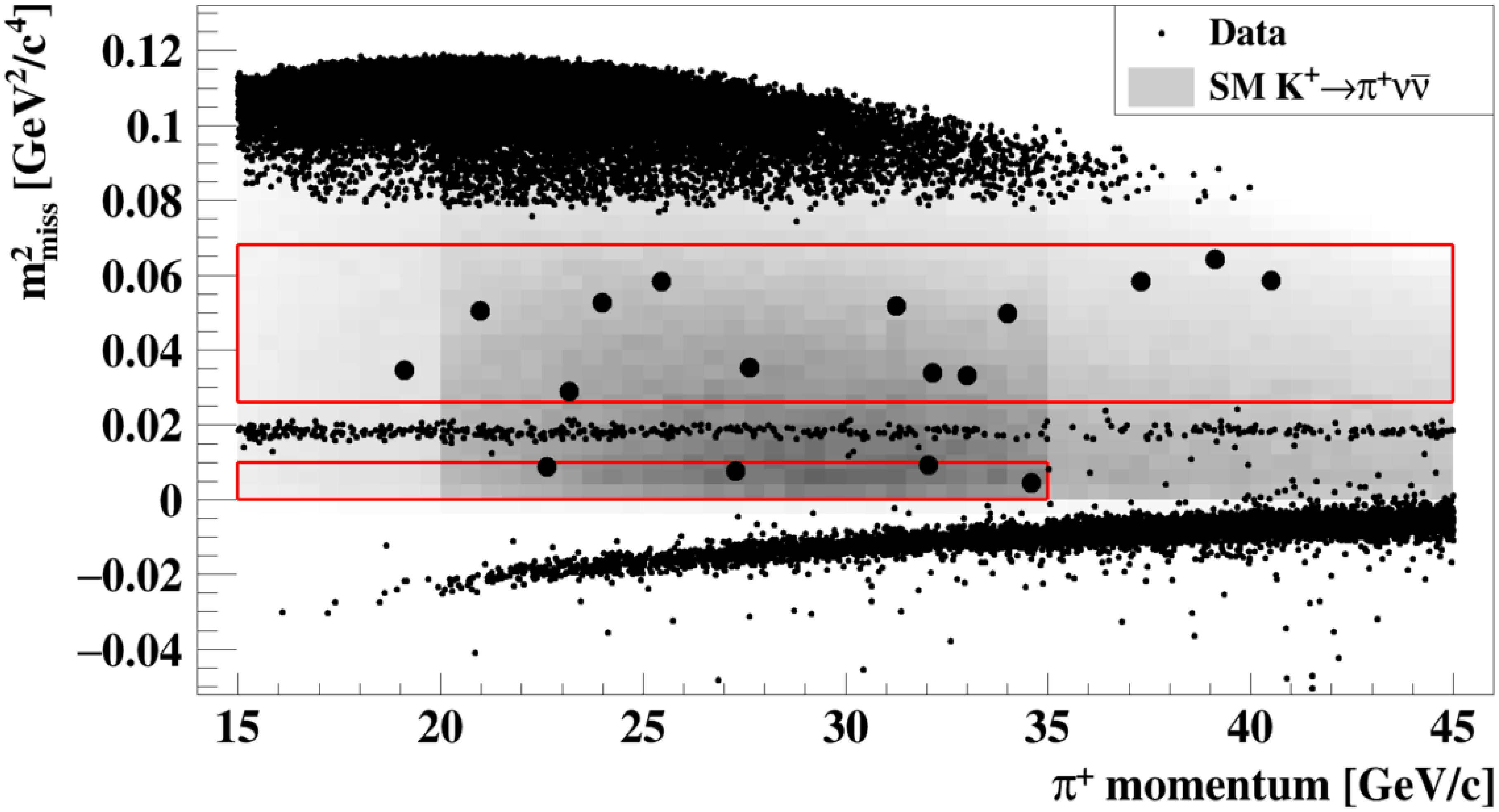


Background	Subset S1	Subset S2
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^-e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$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

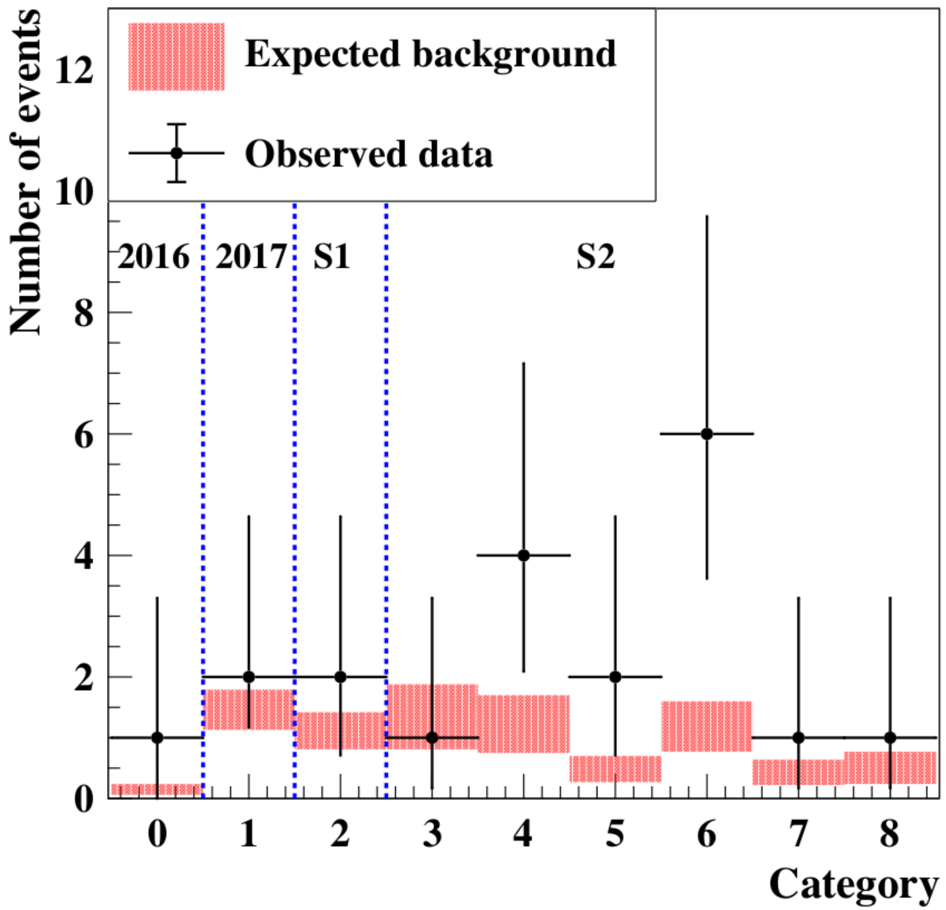
2018 DATA: BEFORE UNBLINDING



2018 DATA: AFTER UNBLINDING



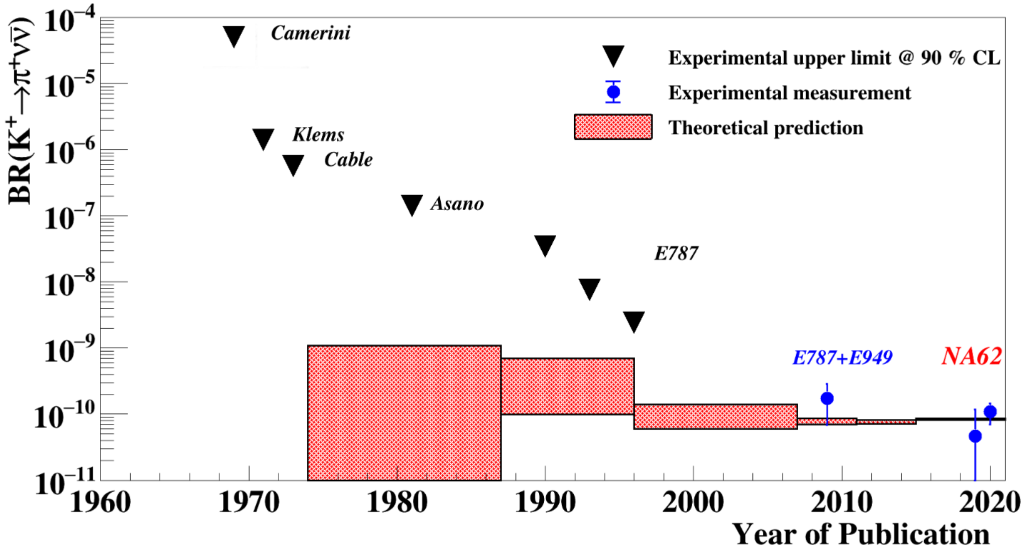
2016+2017+2018 RESULT SUMMARY



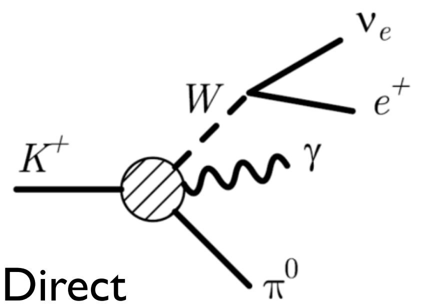
- Single Event Sensitivity: $(0.839 \pm 0.053_{syst}) \times 10^{-11}$
- Expected SM signal events: $10.01 \pm 0.42_{syst} \pm 1.19_{ext}$
- Expected background events: $7.03^{+1.05}_{-0.82}$
- Observed events: 20
- 3.4σ significance

$$BR(K^+ \to \pi^+ \nu\bar{\nu})^{NA62}_{16+17+18} = (10.6\ ^{+4.0}_{-3.8}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$$

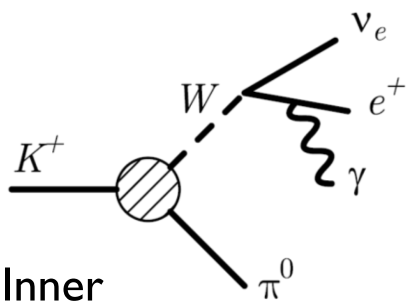
JHEP 06 (2021) 093



$K^+ \to \pi^0 e^+ \nu\gamma$ ($K_{e3\gamma}$): 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

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

Asymmetry

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

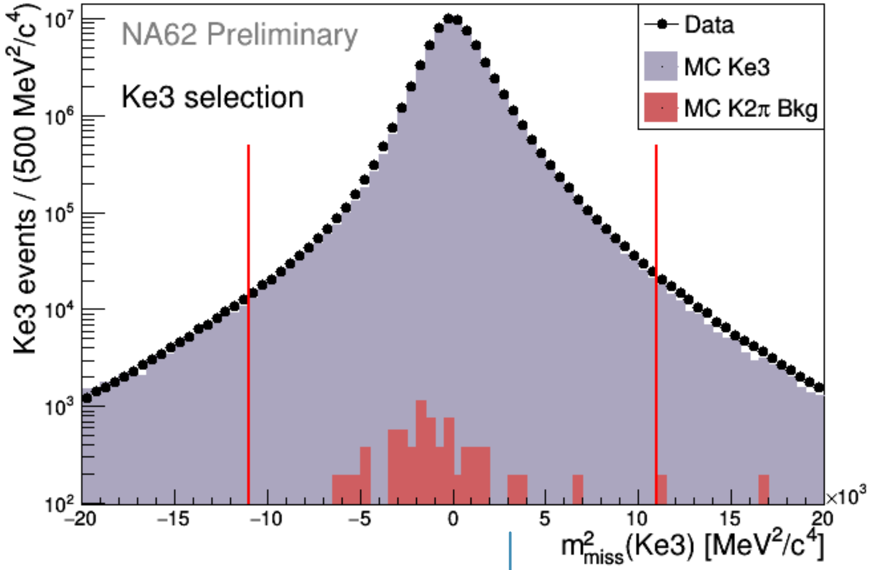
- $|A_\xi$(SM and beyond)$| < 10^{-4}$
- $A_\xi^{ISTRA+}(R_3) = (1.5 \pm 2.1) \times 10^{-2}$
- No measurements of A_ξ for R_1 and R_2

$K^+ \to \pi^0 e^+ \nu\gamma$ ($K_{e3\gamma}$): ANALYSIS

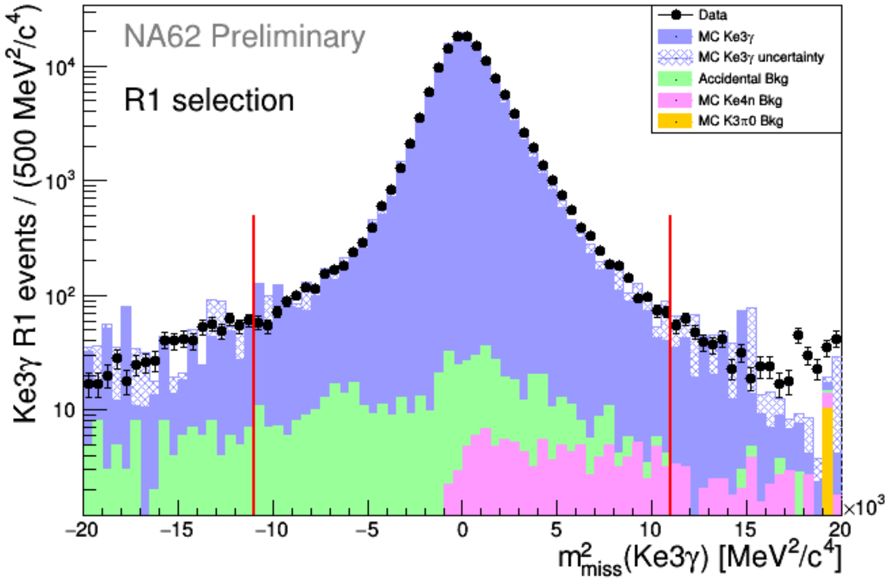
Strategy

$$R_j = \frac{\mathcal{B}(Ke3\gamma^j)}{\mathcal{B}(Ke3)} = \frac{N^{obs}_{Ke3\gamma^j} - N^{bkg}_{Ke3\gamma^j}}{N^{obs}_{Ke3} - N^{bkg}_{Ke3}} \cdot \frac{A_{Ke3}}{A_{Ke3\gamma^j}} \cdot \frac{\epsilon^{trig}_{Ke3}}{\epsilon^{trig}_{Ke3\gamma^j}}$$

- Background estimated with data and MC
- Acceptances evaluated with MC
- Cancellation of systematics
- 2017+2018 data



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



- Main background source: *accidentals* (K_{e3} decay with additional LKr cluster)
- Dedicated $m^2_{miss}(K_{e3})$ cut

$K^+ \to \pi^0 e^+ \nu\gamma$ ($K_{e3\gamma}$): RESULTS (PRELIMINARY)

	$O(p^6)$ ChPT	ISTRA+	OKA	**NA62 preliminary**
R_1 ($\times 10^2$)	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$	$1.684 \pm 0.005 \pm 0.010$
R_2 ($\times 10^2$)	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$	$0.599 \pm 0.003 \pm 0.005$
R_3 ($\times 10^2$)	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$	$0.523 \pm 0.003 \pm 0.003$

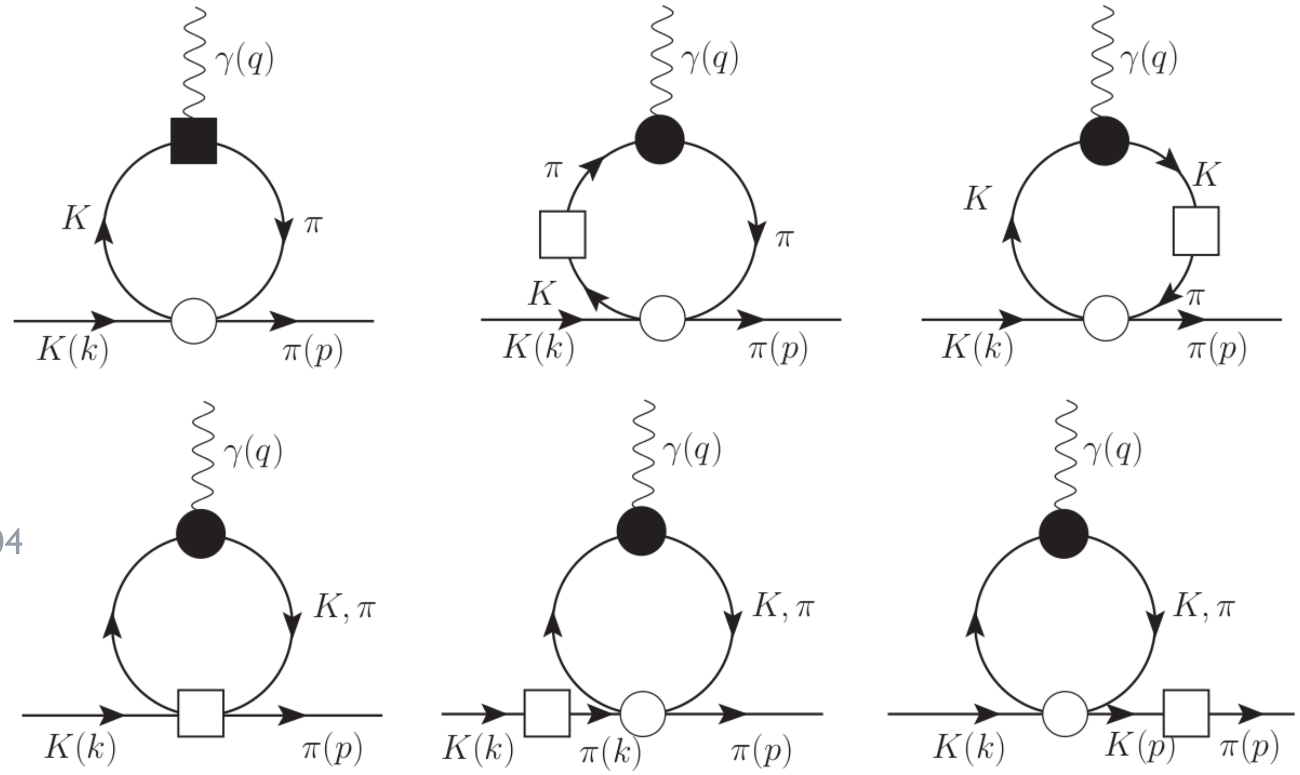
- Precision equal or better than 1% relative
- Relative precision improved by a factor >2
- Relative discrepancy with theory: 6-7%

	R1	R2	R3
A_ξ	$-0.001 \pm 0.003 \pm 0.002$	$-0.003 \pm 0.004 \pm 0.003$	$-0.009 \pm 0.005 \pm 0.004$

- R_3 asymmetry precision improved by a factor >3
- First measurement ever for R_1 and R_2

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

- FCNC mediated by one photon exchange $K^+ \to \pi^+\gamma^*$
  Nucl. Phys. B291 (1987) 692–719, Phys. Part. Nucl. Lett. 5 (2008) 76–84
- Together with $K^+ \to \pi^+e^+e^-$ allows for tests of Lepton Flavour Universality.
  A precise measurement of these decays could provide an evidence complementary to the B anomaly seen by LHCb.
  J. Phys. Conf. Ser. 800 (2017) 1, 012014



- Form factor parametrized in NLO ChPT JHEP 08 (1998) 004

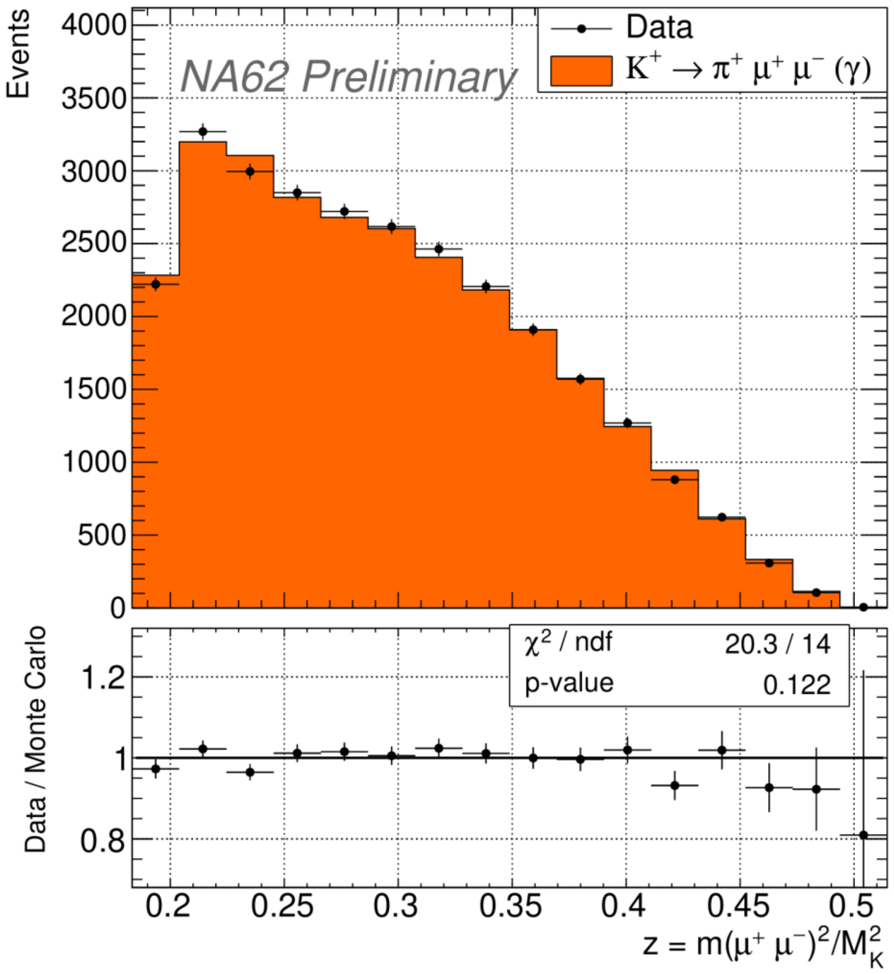
$$W(z) = G_F M_K^2 (a + bz) + W^{\pi\pi}(z)$$

where $z = m(\mu^+\mu^-)^2 / M_K^2$

- Goal: measurement of *a*, *b*, model-dependent BR

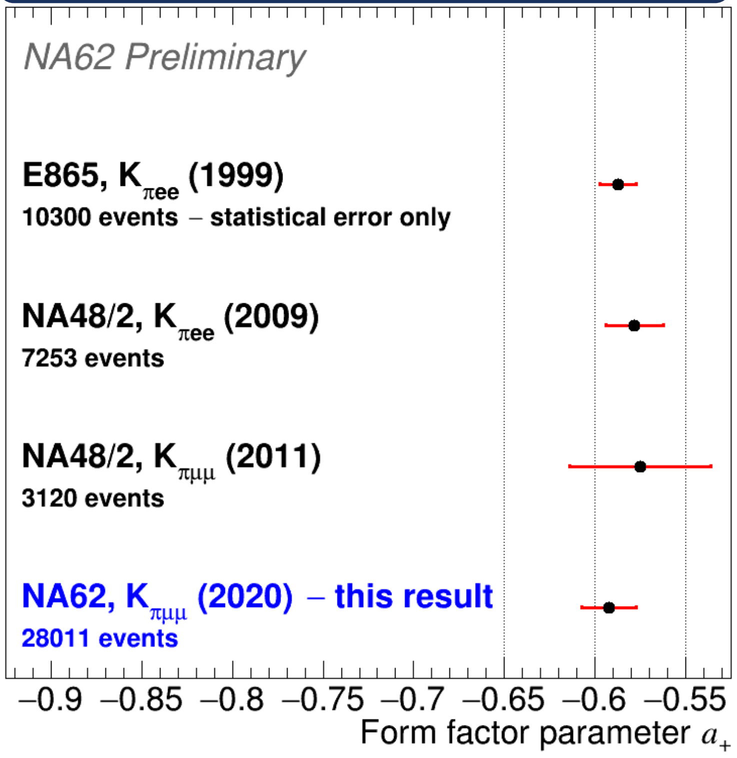
$K^+ \to \pi^+\mu^+\mu^-$: ANALYSIS

- 2017+2018 data sample
- Normalization decay channel: $K^+ \to \pi^+\pi^+\pi^-$
  - Abundant: BR ~ 5.6%
  - Kinematically similar
  - Reduced systematics
- Signal sample selected: 28011 events
  - MUV3 and LKr-based particle ID
  - 9x more than NA48/2
    Phys. Lett. B 697 (2011) 107-115
  - Expected background: $12.5 \pm 1.7_{stat} \pm 12.5_{syst}$
- Fit spectrum of MC, reweighted to minimize $\chi^2(a, b)$

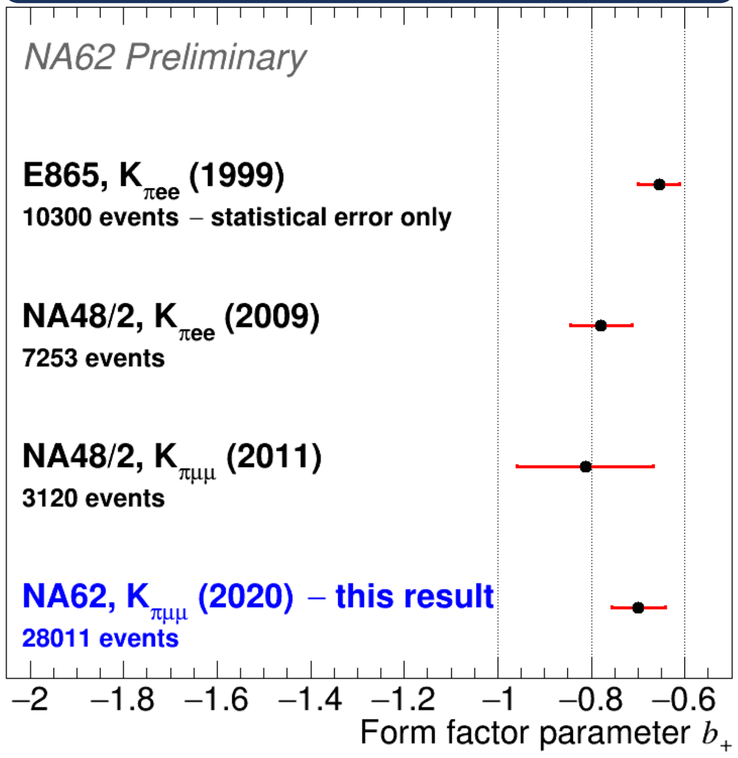


$K^+ \to \pi^+\mu^+\mu^-$: RESULTS (PRELIMINARY)

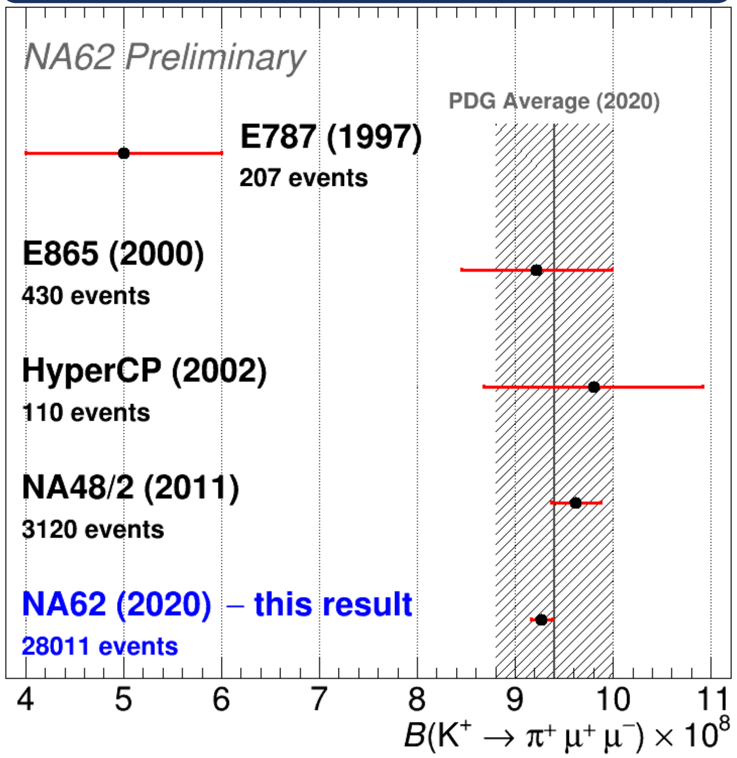
a = -0.592 ± 0.015



b = -0.699 ± 0.058



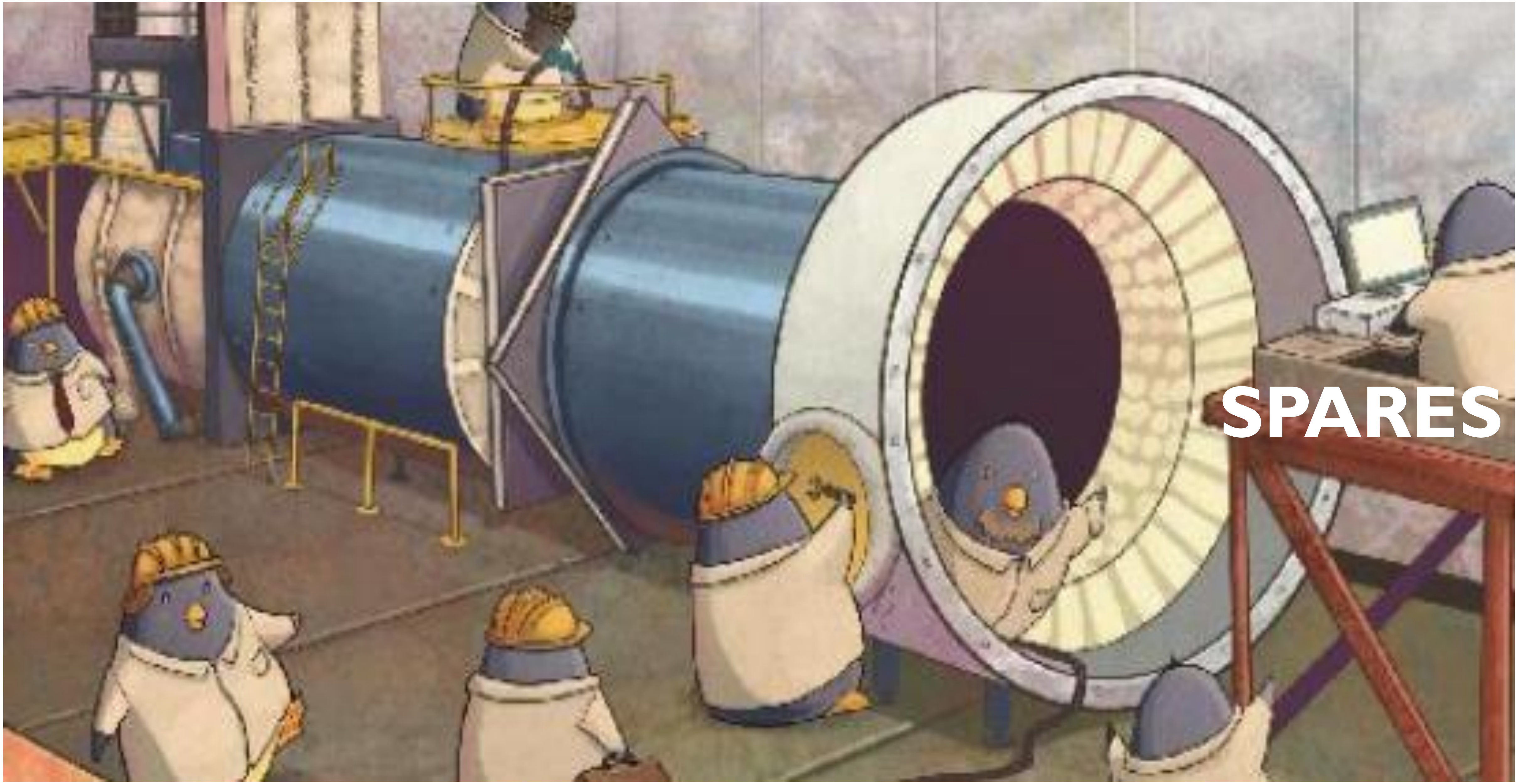
BR = (9.27 ± 0.11) × 10^{-8}



E865, $K_{\pi ee}$: Phys. Rev. Lett. 83 (1999) 4482-4485
NA48/2, $K_{\pi ee}$: Phys. Lett. B 677 (2009) 246-254
NA48/2, $K_{\pi\mu\mu}$: Phys. Lett. B 697 (2011) 107-115

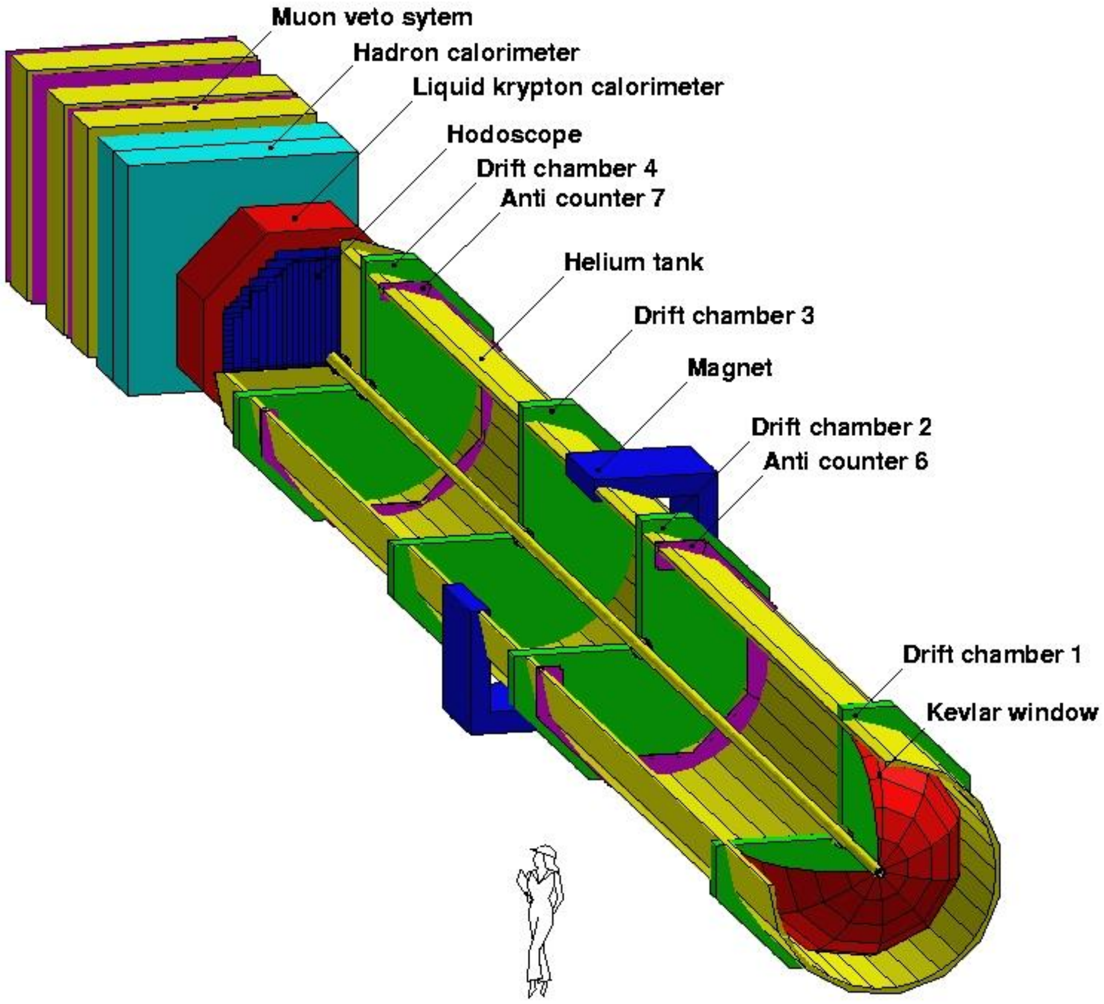
CONCLUSION

- CERN North Area has a significant history of kaon studies
- First ever measurement of $BR(K^{\pm} \rightarrow \pi^0\pi^0\mu^{\pm}\nu)$ by NA48/2 has been shown
- $BR(K^{+}\rightarrow\pi^{+}\nu\bar{\nu})$ has been found by NA62 to be compatible with the SM within one standard deviation (most precise measurement so far)
- NA62 is now in the second run of data taking with improved detector layout, analysis improvements are on their way
- Measurement of $BR(K^{+} \rightarrow \pi^0 e^{+}\nu\gamma)$ has been brought to a relative precision of 1% or better
- First ever T-asymmetry measurement in regions R_1 and R_2, precision improvement of a factor 3 in region R_3
- Large clean sample of $K^{+} \rightarrow \pi^{+}\mu^{+}\mu^{-}$
- Measured $K_{\pi\mu\mu}$ form factor parameters, no LFU violation found
- Papers in preparation, stay tuned!



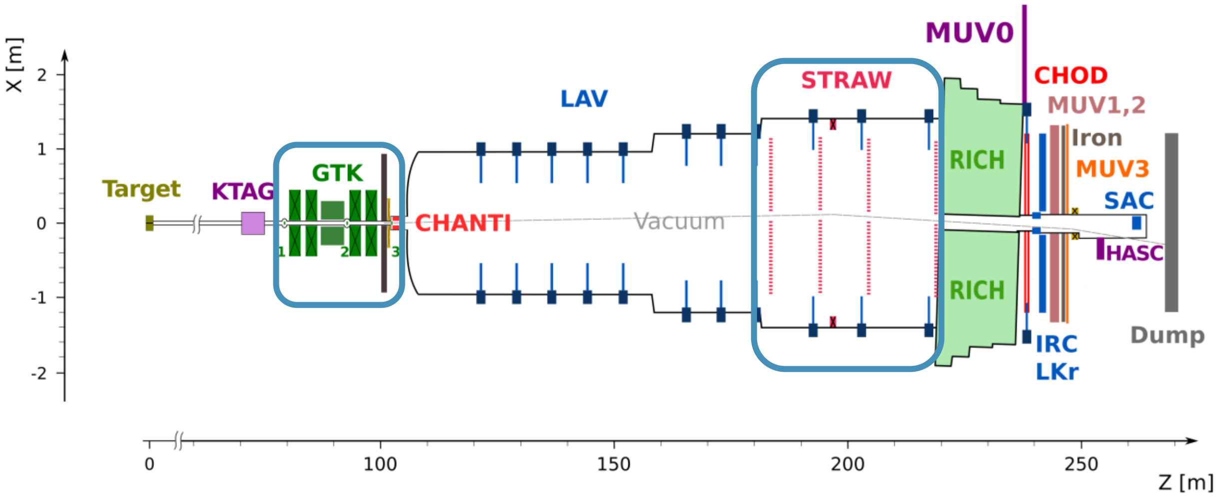
SPARES

NA48/2 DETECTOR



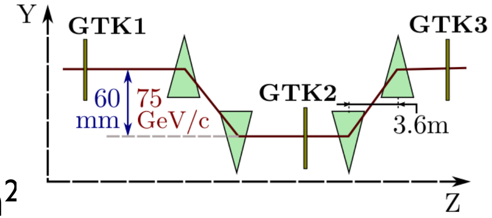
- KABES
  - $\sigma(X,Y) \sim 800\ \mu m$
  - $\sigma(p_K) / p_K \sim 1\%$
  - $\sigma(T) \sim 600$ ps
- Magnetic spectrometer (DCH1-DCH4)
  - $\sigma(X,Y) \sim 90\ \mu m$ per chamber
  - $\sigma(p_{DCH}) / p_{DCH} = (1.02 \oplus 0.044\ GeV^{-1} \times p_{DCH})\%$
- Scintillator HODoscope
  - $\sigma(T) \sim 150$ ps
- Liquid Krypton EM calorimeter (LKr)
  - $\sigma_x = \sigma_y = (0.42\ GeV^{1/2} / \sqrt{E_\gamma} \oplus 0.06)$ cm
  - $\sigma(E_\gamma) / E_\gamma = (3.2\ GeV^{1/2} / \sqrt{E_\gamma} \oplus 9.0\ GeV / E_\gamma \oplus 0.42)\%$

NA62 DETECTOR



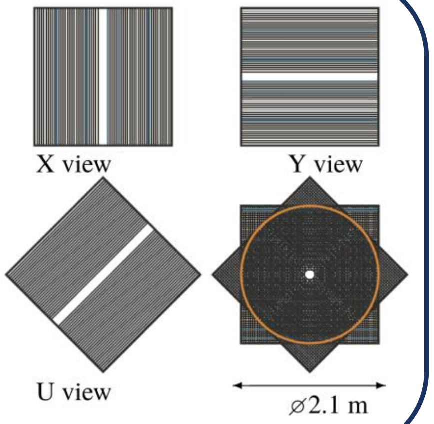
GigaTracKer

- 3 stations
- Si pixel size 300 × 300 μm^2
- σ_p / p = 0.2%, σ_θ = 16μrad, σ_t = 100 ps

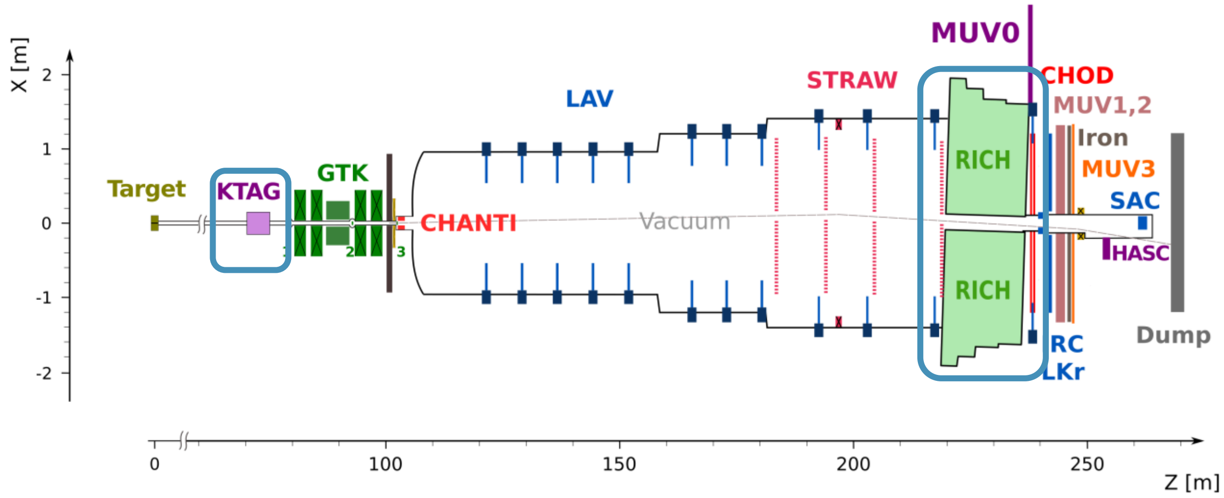


STRAW

- 4 straw tube chambers
- 4 views each
- $\sigma_p/p = 3\times10^{-3} \oplus 5\times10^{-5}\,\mathrm{GeV}^{-1}\,p$
- $\sigma_\theta/\mu\mathrm{rad} = 10 + 500\,\mathrm{GeV}/p$



NA62 DETECTOR



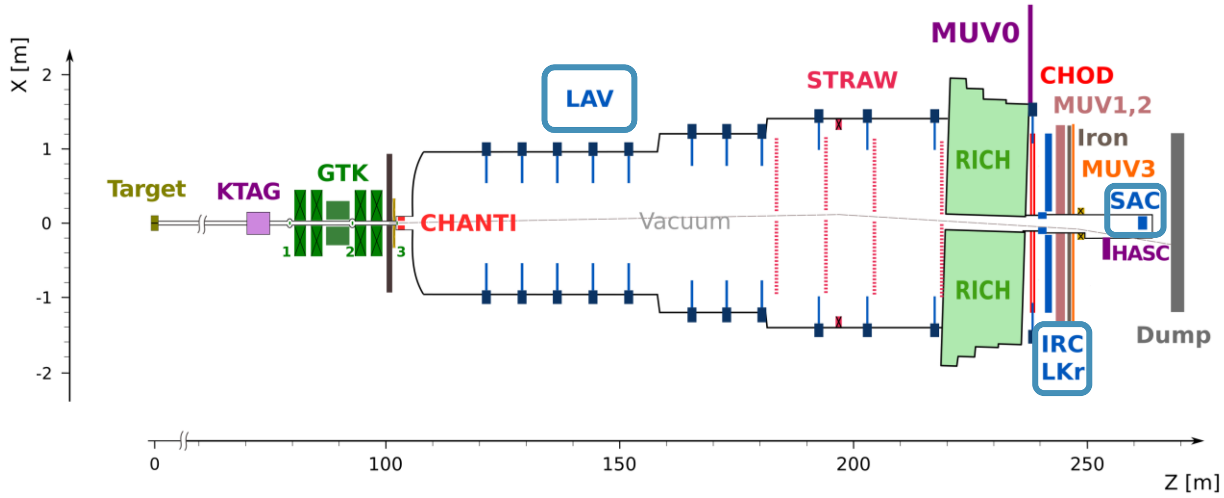
Kaon TAGger

- Differential Cherenkov counter
- 5 m long vessel
- N_2 at 1.75 bar
- σ_t = 70 ps

Ring Imaging CHerenkov counter

- Differential Cherenkov counter
- Ne at atmospheric pressure
- σ_t = 100 ps

NA62 DETECTOR



Large-Angle Veto

- 12 stations
- EM calorimeters (PbO 75%)
- Hermetic for photons between 10 and 50 mrad

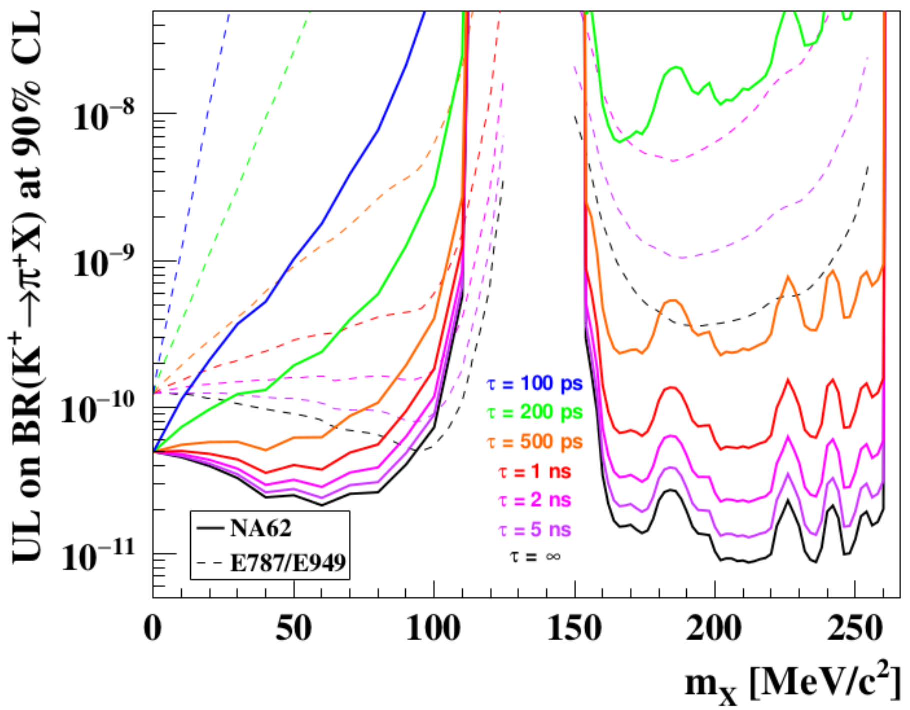
LKr

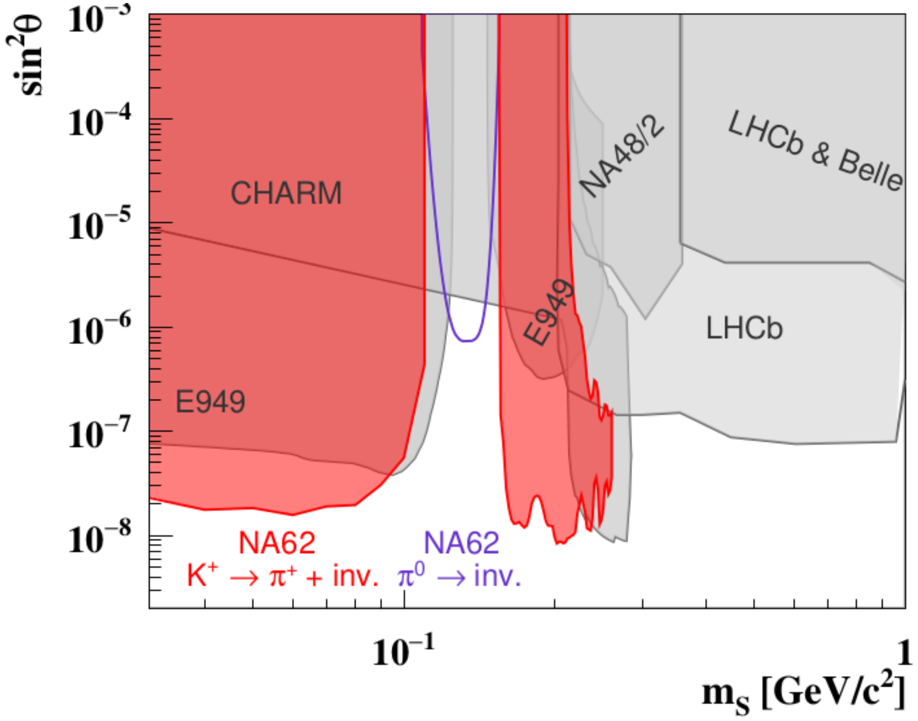
- Photons emitted between 1 and 10 mrad + particle ID
- σ_E / E = 1.4% for E ~ 25 GeV
- $\sigma_{X,Y}$ ~ 1mm
- σ_t ~ 0.5 to 1 ns

Small-Angle Veto

- IRC + SAC
- Ensure hermeticity for photons down to 0°

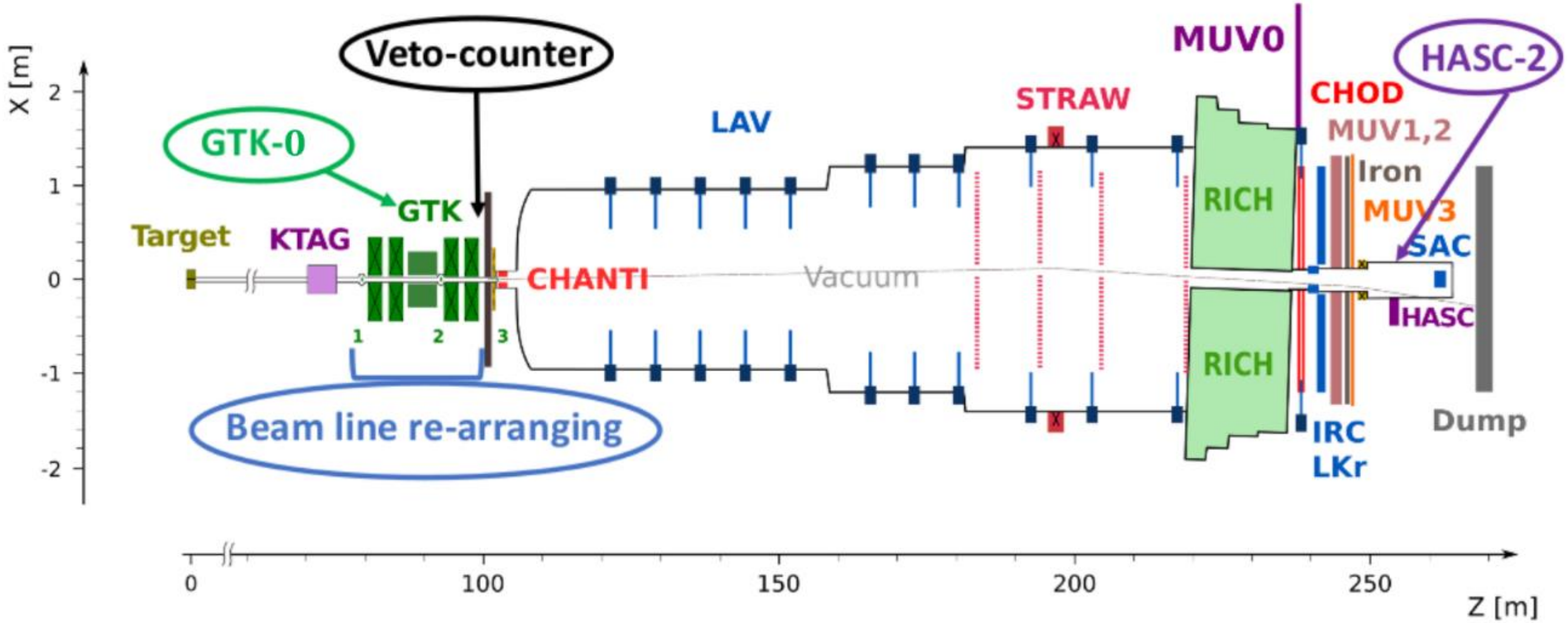
$K^+ \to \pi^+ X$





- Peak search using m^2_{miss} for m_X in the 0 – 260 MeV/c^2 range
- Backgrounds: same as $K^+ \to \pi^+ \nu\bar{\nu}$, plus SM $K^+ \to \pi^+ \nu\bar{\nu}$ itself
- 90% UL on $BR(K^+ \to \pi^+ X)$ in $10^{-11} – 10^{-10}$
- Dark Scalar interpretation: mixing with Higgs

$K^+ \to \pi^+ \nu\bar{\nu}$ BETWEEN 2021 AND LS3



- Additional GTK station
- Beam line re-arranging to swipe away upstream π^+
- New VetoCounter to detect upstream decays
- HASC-2 to further suppress $K^+ \to \pi^+ \pi^0$ decays
- Intensity increased by ~30%

Beyond LS3

HIKE:
High Intensity Kaon Experiments

arxiv.org/abs/2204.13394