Latest results from Kaon experiments at CERN

On behalf of the NA62 collaboration

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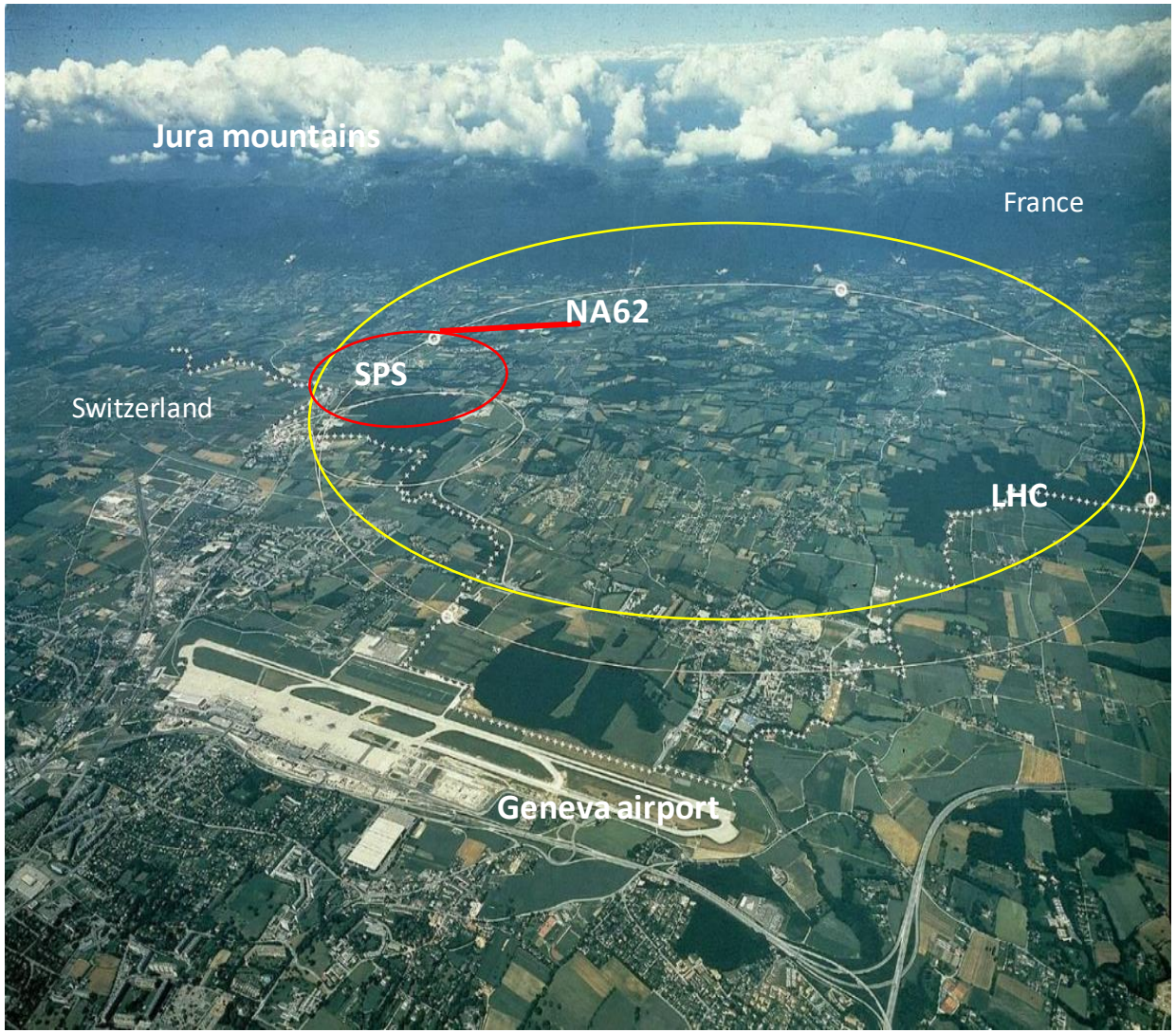
Excited QCD 2022, 27-10-2022

Outline

- The NA48/2 setup
  - $K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$
- The NA62 experiment and detector
  - $K^{+} \to \pi^{+}\nu\bar{\nu}$
  - $K^{+} \to \pi^0 e^{+}\nu\gamma$
  - $K^{+} \to \pi^{+}\mu^{+}\mu^{-}$
  - $K^{+} \to \pi^{+}\gamma\gamma$

Fixed target Kaon experiments at CERN



1984-1990
- **NA31 (K_S/K_L)**
  First evidence of CPV

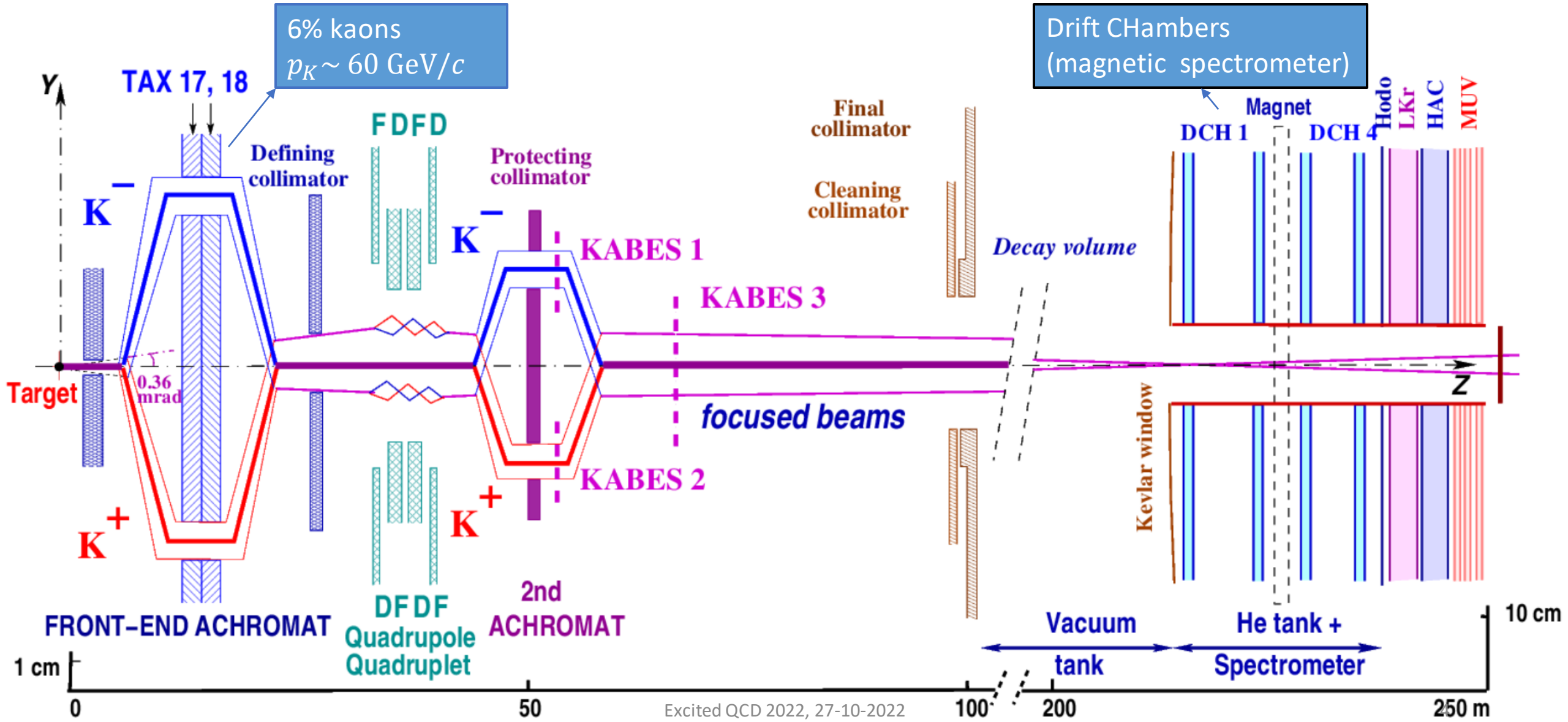
1997-2002
- **NA48, NA48/1 (K_S/K_L)**
  Discovery of CPV, Re(ε'/ε)
  Rare K_S and hyperon decays

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

2007-2008
- **NA62 (K^+)**
  $\mathrm{RK} = \Gamma(K_{\mu\nu})/\Gamma(K_{e\nu})$

2016-Now
- **NA62 (K^+)**
  Rare K^+ decays

The NA48/2 setup



The $K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$ decay

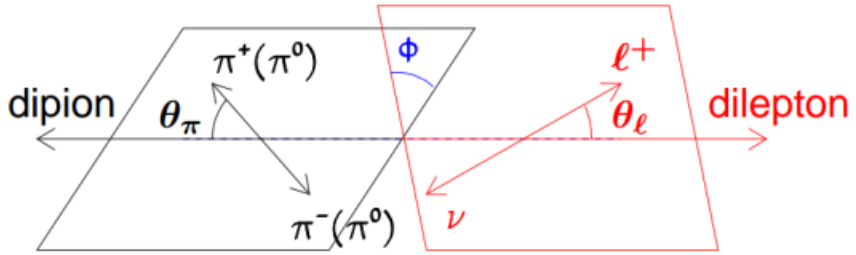
❑ Status of K_{l4} decays

- $\ell = \mu$ depends on two form-factors (F, R)
- F from lepton universality (experimental parametrization from K_{e4}^{00})
- R from ChPT

❑ Experimentally

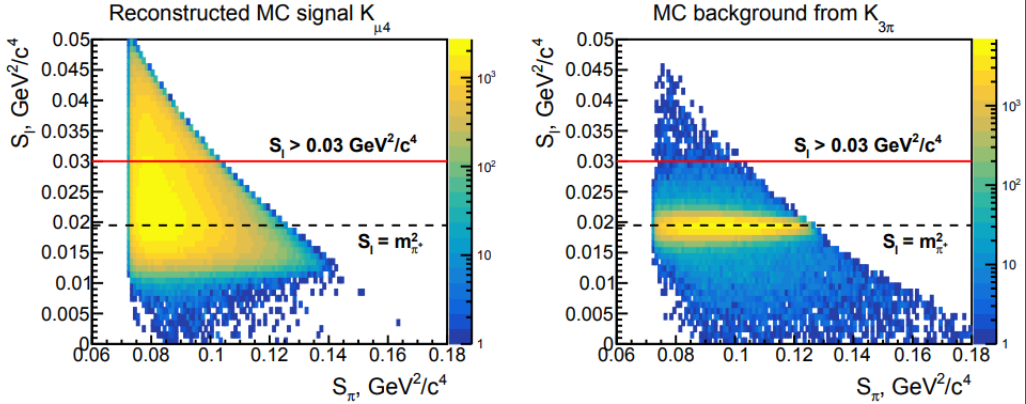
$K_{\ell 4}$ mode	BR $[10^{-5}]$	N_{cand}	
$K_{e4}^{\pm}$	4.26 ± 0.04	1108941	NA48/2 (2012)
K_{e4}^{00}	2.55 ± 0.04	65210	NA48/2 (2014)
$K_{\mu 4}^{\pm}$	1.4 ± 0.9	7	Bisi et al. (1967)
$K_{\mu 4}^{00}$	?	0	

- This analysis: first observation of $K_{\mu 4}^{00}$

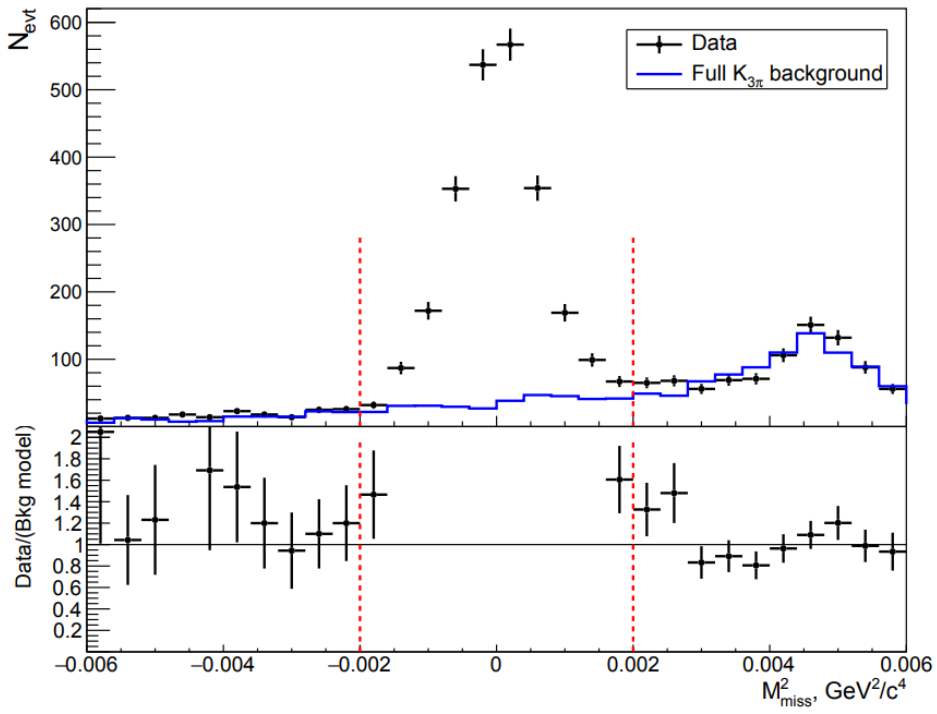


❑ Analysis strategy

- $K^{\pm} \to \pi^0\pi^0\pi^{\pm}$ as normalization channel
- Main background: $K^+ \to \pi^0\pi^0(\pi^{\pm} \to \mu^{\pm}\nu)$
  - Select phase space region
    $S_\ell = M^2(\mu^{\pm}\nu) > 0.03\ \mathrm{GeV}^2/c^4$

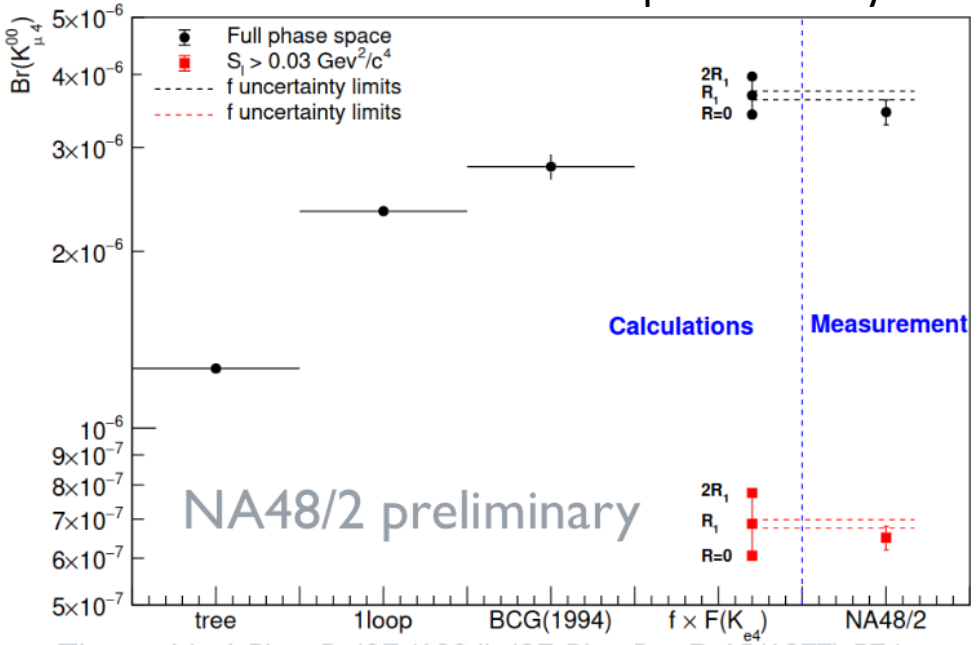


The $K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu$ decay



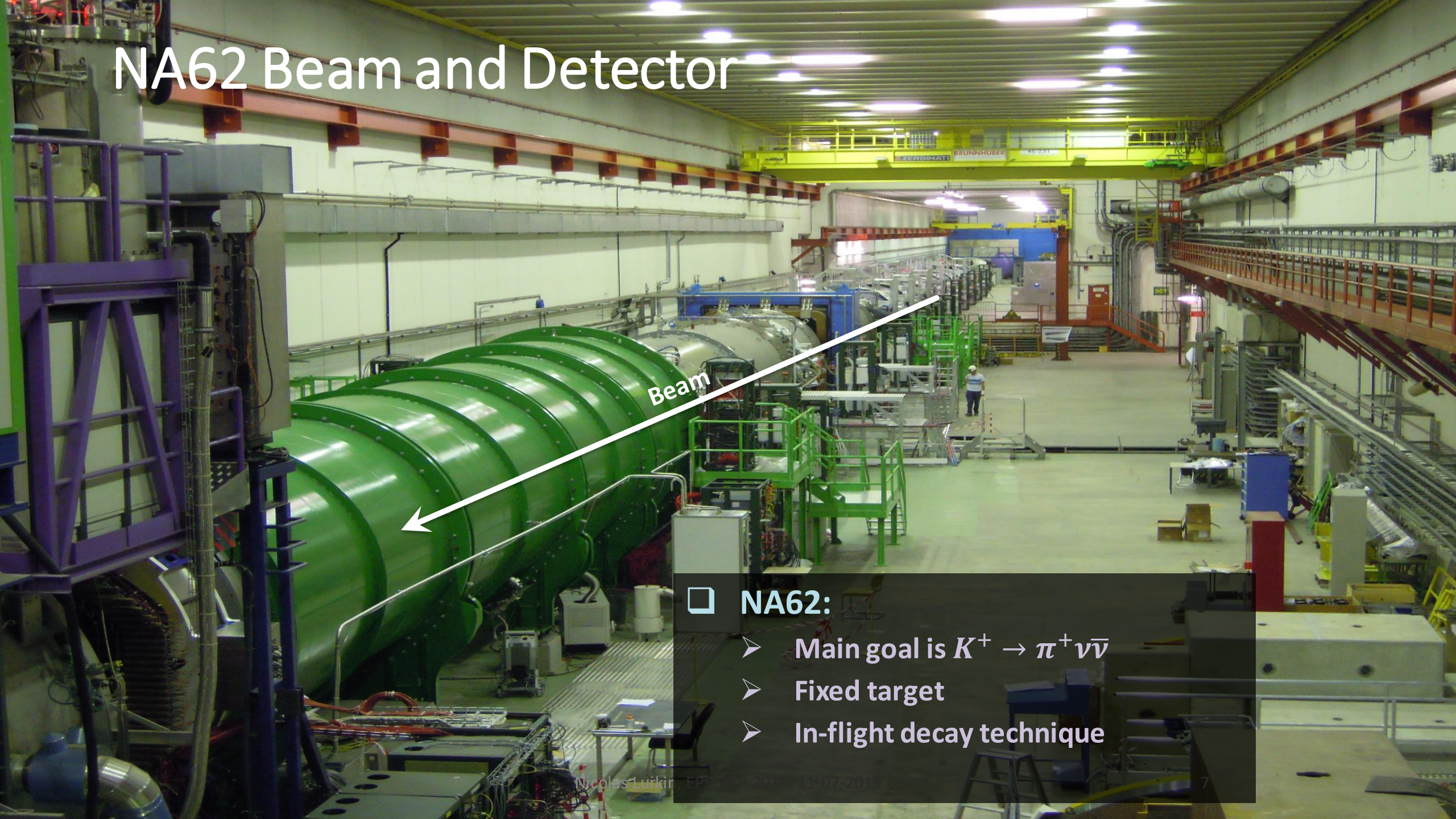
- Signal: 2437 events selected
- Normalization: 72.99×10^6
- Background: expect
  $354 \pm 33_{stat} \pm 62_{syst}$ events

- Preliminary result:
  - Restricted phase-space ($S_\ell > 0.03$):
    $BR(K^{00}_{\mu 4}) = (0.65 \pm 0.019_{stat} \pm 0.024_{syst}) \times 10^{-6}$
  - Full phase space (model dependent):
    $BR(K^{00}_{\mu 4}) = (3.4 \pm 0.10_{stat} \pm 0.13_{syst}) \times 10^{-6}$
  - Consistent with R form-factor as predicted by ChPT



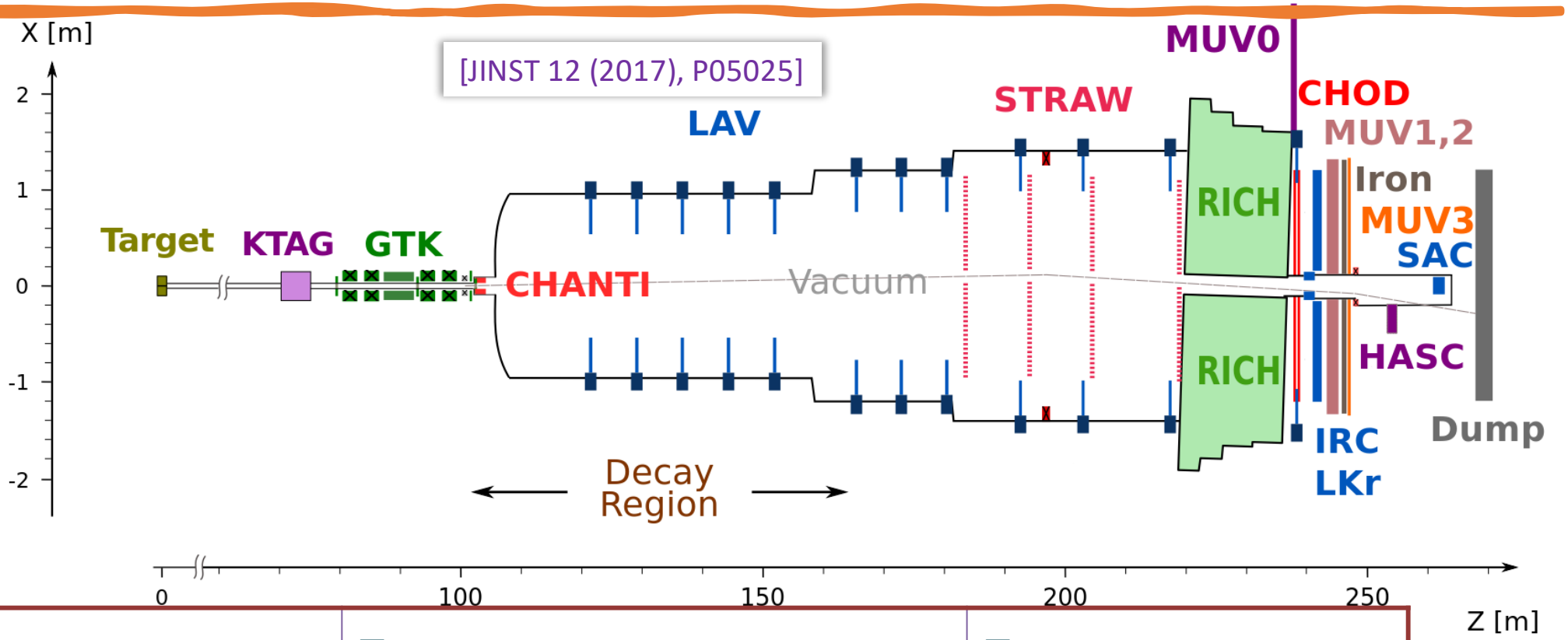
Theory: Nucl. Phys. B 427 (1994) 427, Phys.Rev.D 15(1977) 574

NA62 Beam and Detector



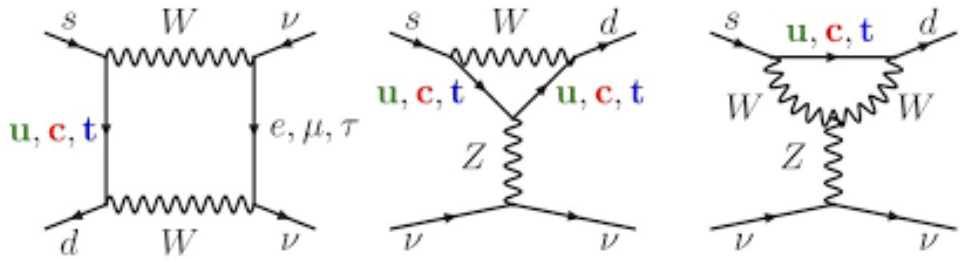
- **NA62:**
  - Main goal is $K^+ \to \pi^+ \nu\bar{\nu}$
  - Fixed target
  - In-flight decay technique

NA62 Beam & Detector



- SPS Beam:
  - 400 GeV/c protons
  - protons/spill
  - 3.5 s spill
- Secondary positive beam
  - 75 GeV/c momentum, 1% bite
  - $100\ \mu$rad divergence (RMS)
  - $60 \times 30\ \mathrm{mm}^2$ transverse size
  - $K^+(6\%)/\pi^+(70\%)/p(24\%)$
  - 33×10^{11} ppp on T10 (750 MHz at GTK3)
- Decay region
  - 60 m long fiducial region
  - ~ 5 MHz decay rate
  - Vacuum $\mathcal{O}(10^{-6})$ mbar

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



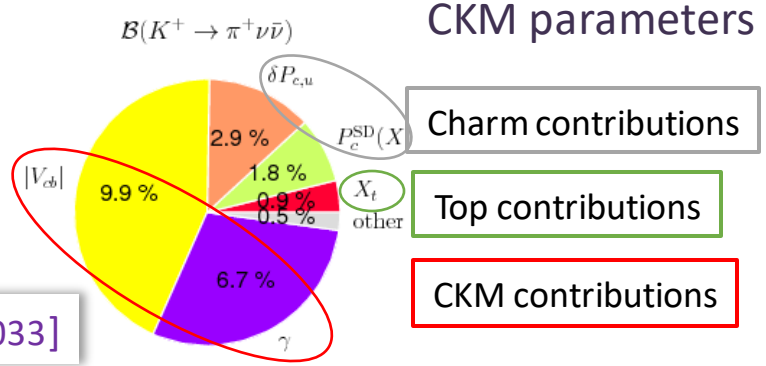
❑ Highly suppressed:

- ➢ FCNC process forbidden at tree level
- ➢ CKM suppression
  ($s \to d$ coupling, $BR \sim |V_{ts}V_{td}|^2$)

❑ Theoretically clean:

- ➢ Dominant short-distance contribution
- ➢ Hadronic matrix element extracted from $BR(K^+ \to \pi^0 e^+ \nu)$

- ➢ Theoretical error budget dominated by CKM parameters



[Buras et al., JHEP1511 (2015) 033]

❑ Previous exp. determination:

$BR(K^+ \to \pi^+ \nu\bar{\nu})$
E787/E949 at BNL
$\left(17.6^{+11.5}_{-10.5}\right) \times 10^{-11}$

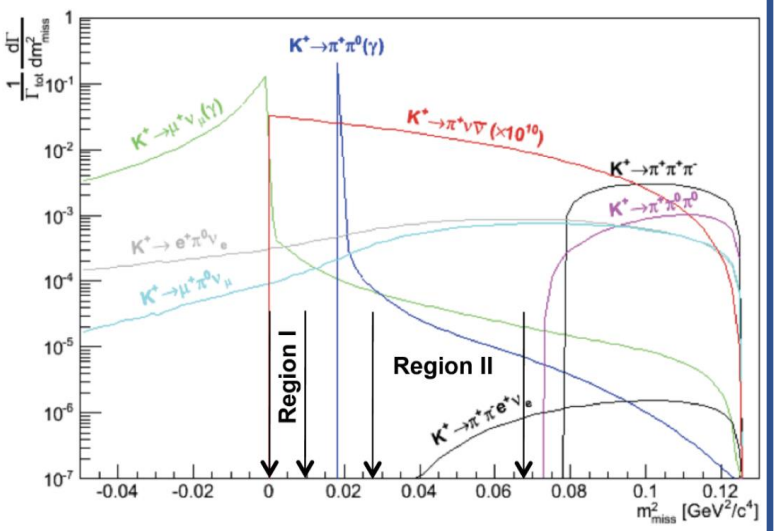
❑ SM Predictions:

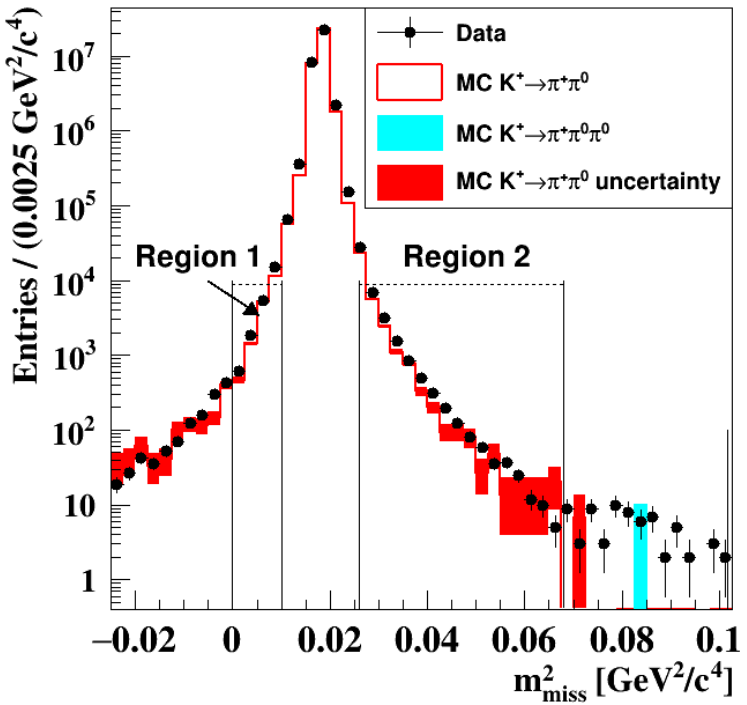
$BR(K^+ \to \pi^+ \nu\bar{\nu})$
$(8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{\lvert V_{cb}\rvert}{40.7 \times 10^{-3}}\right]^{2.8} \left[\frac{\gamma}{73.2°}\right]^{0.74}$
$(8.4 \pm 1.0) \times 10^{-11}$

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

Decay backgrounds	
Decay mode	BR
$K^+ \to \mu^+ \nu(\gamma)$	63.5%
$K^+ \to \pi^+ \pi^0(\gamma)$	20.7%
$K^+ \to \pi^+ \pi^+ \pi^-$	5.6%
$K^+ \to \pi^+ \pi^- e^+ \nu$	4.2×10^{-5}
Other backgrounds	
Beam-gas interactions	
Upstream interactions	

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



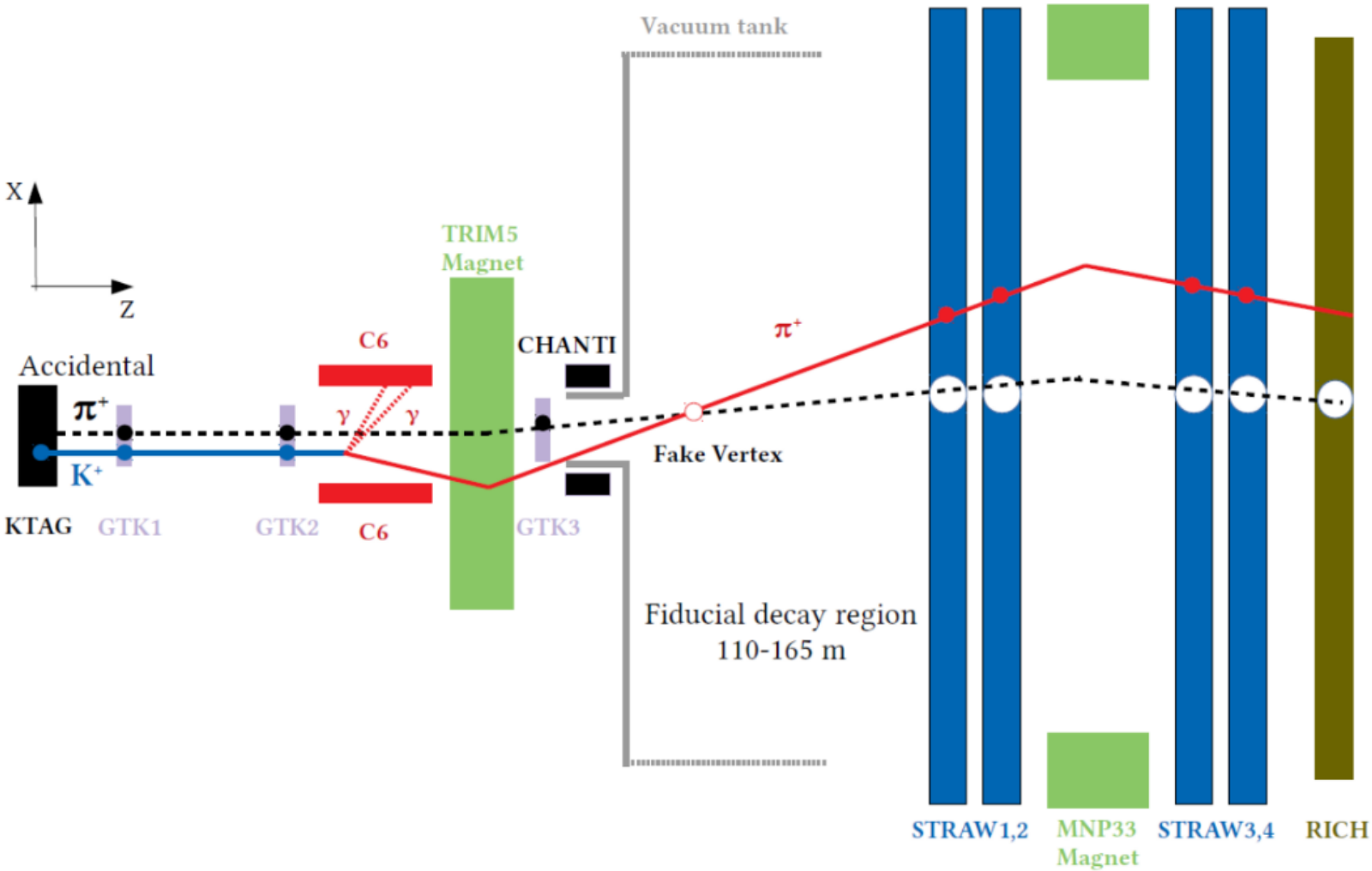


❑Strategy

- Kinematic suppression $\mathcal{O}(10^4)$
- MVA used for PID and upstream background rejection
  - $\mathcal{O}(10^7)$ muon rejection
  - $\mathcal{O}(10^7)$ π^0 rejection
- High efficiency VETO system with excellent time resolution (100 ps)
- Blind Analysis
- Data-driven background evaluation when possible

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

Upstream background

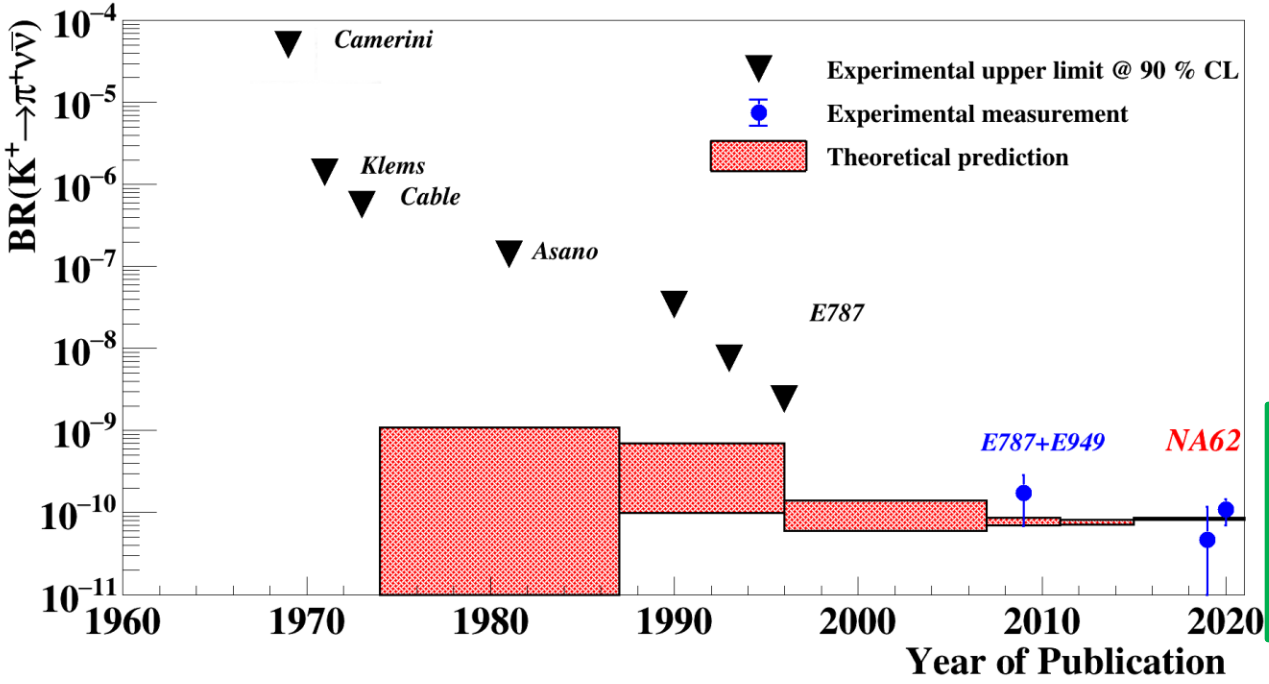


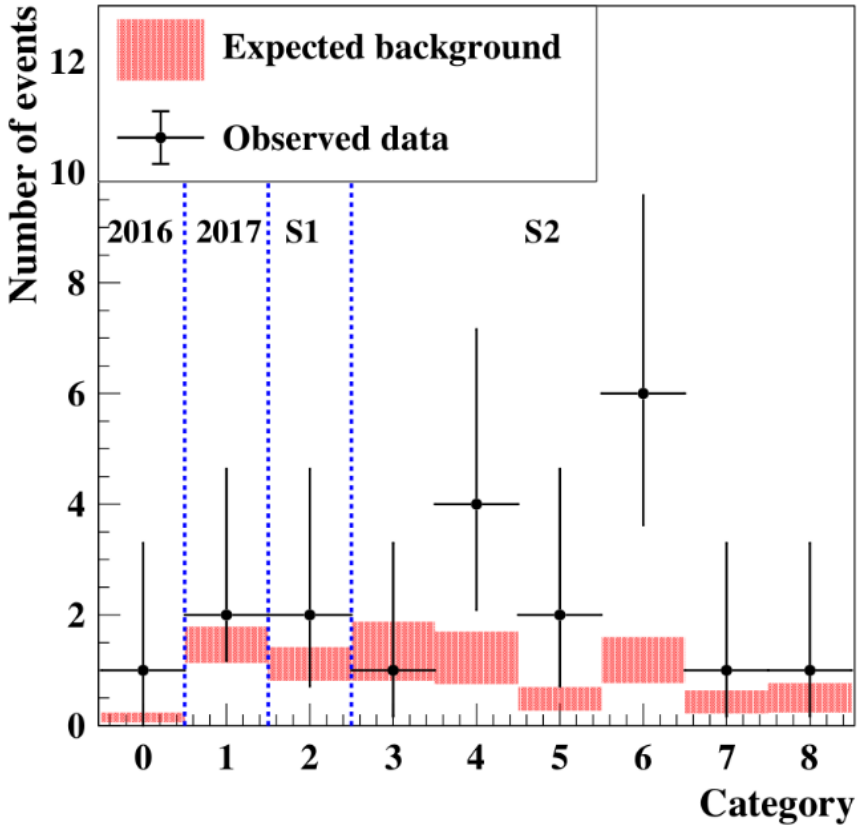
- Pions produced upstream of the fiducial volume
  - Early kaon decays
  - Interaction of beam particles with beam spectrometer material
- Fake association of detected pions to accidental particles
- Mitigation
  - Geometrical cuts & BDT cut on backtracked pion position
  - Kaon-pion association effective
  - Data-driven background estimation

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

❑2016+2017+2018 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

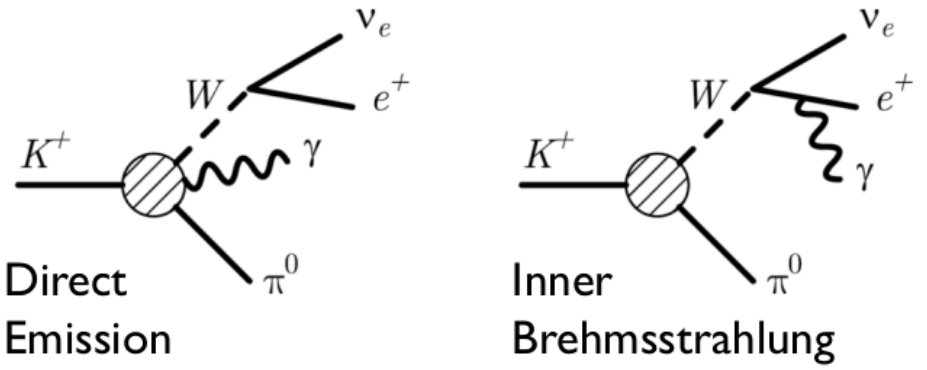




❑ Result

- $BR(K^+ \to \pi^+ \nu\bar{\nu}) = \left(10.6^{+4.0}_{-3.8}\big|_{stat} \pm 0.9_{syst}\right) \times 10^{-11}$
- Published in JHEP 06 (2021) 093

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



- Divergent decay amplitude for E_γ and $\theta_e, \gamma \to 0$ for the IB component
  - Three regions: $R_j = \frac{BR(\pi^0 e^+ \nu\gamma | j - \text{th region})}{BR(\pi^0 e^+ \nu(\gamma))}$
- T-odd observable: $\xi = \frac{\vec{p}_\gamma \cdot \vec{p}_e \times \vec{p}_\pi}{m_K^3}$
  - Measure asymmetry: $A_\xi = \frac{N_+ - N_-}{N_+ + N_-}$

- Analysis strategy

$$R_j = \frac{BR(K^j_{e3\gamma})}{BR(K_{e3})} = \frac{N^{Obs}_{K^j_{e3\gamma}} - N^{Bkg}_{K^j_{e3\gamma}}}{N^{Obs}_{K_{e3}} - N^{Bkg}_{K_{e3}}} \cdot \frac{A_{K_{e3}}}{A_{K^j_{e3\gamma}}} \cdot \frac{\epsilon^{trig}_{K_{e3}}}{\epsilon^{trig}_{K^j_{e3\gamma}}}$$

  - Normalization: K_{e3}
  - Background estimated with data and MC
  - Acceptances evaluated with MC
  - Cancellation of systematics
  - 2017+2018 data

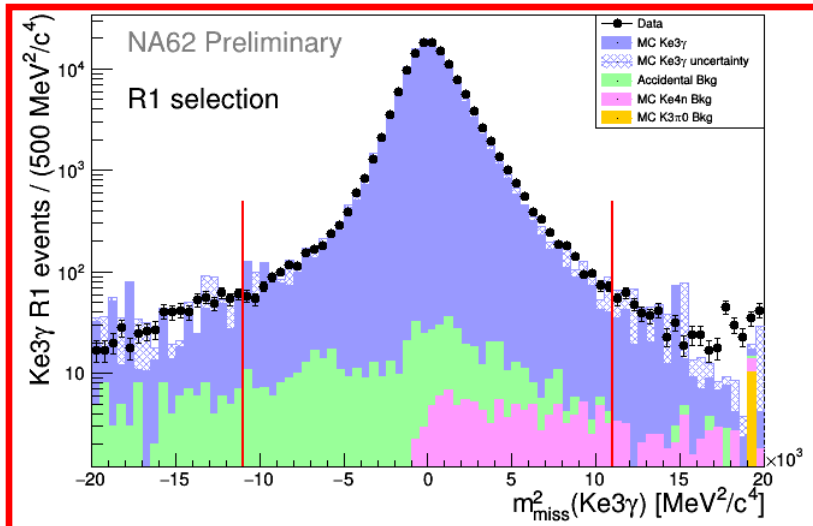
Theory

- $|A_\xi| < 10^{-4}$ (SM / BSM)

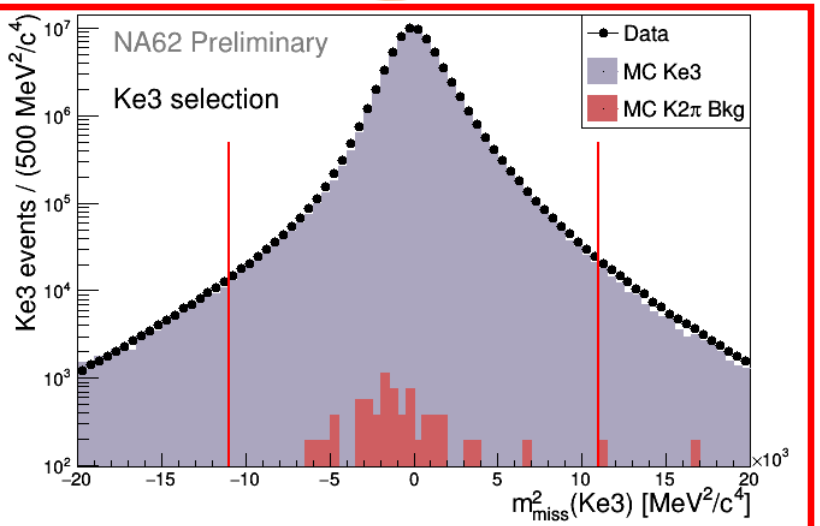
Experiment

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

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



- Main background: accidentals (K_{e3} decay with additional LKr cluster)
- Dedicated $m^2_{miss}(K_{e3})$ cut
- Normalization selection: 66M events
- Almost background free: $B/S \sim 10^{-4}$



Reg.	E_γ cut	θ_e,γ cut	Ratio $[10^{-2}]$				A_ξ
			$\mathcal{O}(p^6)$ ChPT (1)	ISTRA + (2)	OKA (3)	NA62 preliminary	NA62 preliminary
R_1	$E_\gamma > 10$ MeV	$\theta_e,\gamma > 10°$	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$	$1.684 \pm 0.005 \pm 0.010$	$-0.001 \pm 0.003 \pm 0.002$
R_2	$E_\gamma > 30$ MeV	$\theta_e,\gamma > 20°$	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$	$0.559 \pm 0.003 \pm 0.005$	$-0.003 \pm 0.004 \pm 0.003$
R_3	$E_\gamma > 10$ MeV	$0.6 < \cos\theta_e,\gamma < 0.9$	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$	$0.523 \pm 0.003 \pm 0.003$	$-0.009 \pm 0.005 \pm 0.004$

(1) [Eur. Phys. J. C 50 (2007)]

(2) [Phys. Atom. Nucl. 70 (2007)]

(3) [Eur. Phys. J. C 81.2 (2021)]

- Relative precision improved by a factor >2 ($\leq 1\%$ relative)
- Relative discrepancy with theory: $6-7\%$
- R_3 asymmetry precision improved by a factor >3
- First measurement ever for R_1 and R_2

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

- FCNC mediated by virtual photon exchange $K^+ \to \pi^+\gamma^*$

  [Phys. Part. Nucl. Lett. 5 (2008) 76–84]

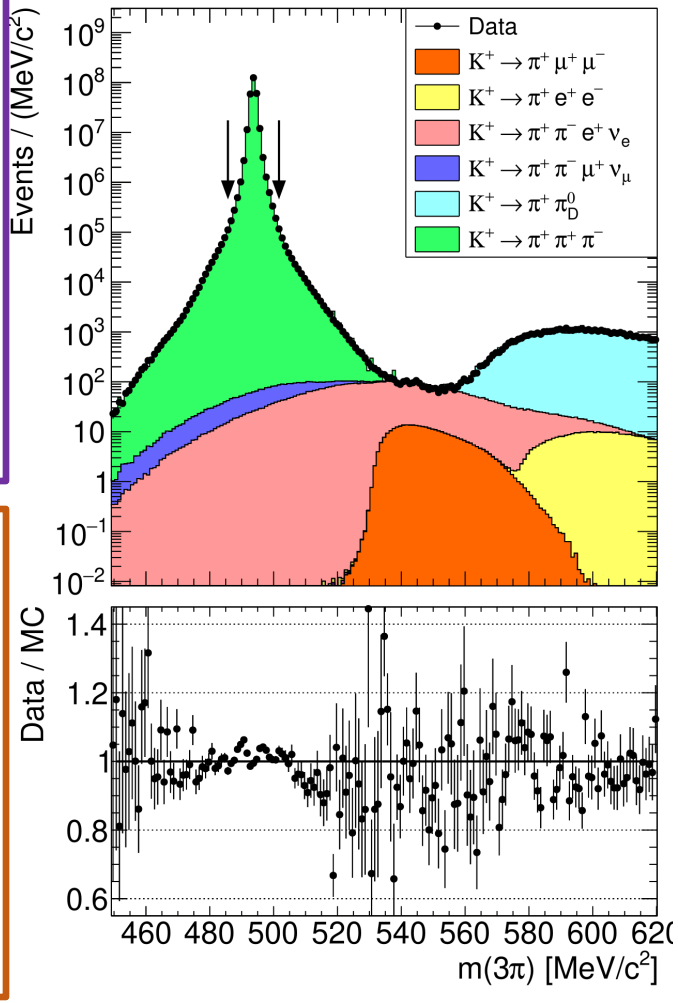
  [Nucl. Phys. B291 (1987) 692–719)]

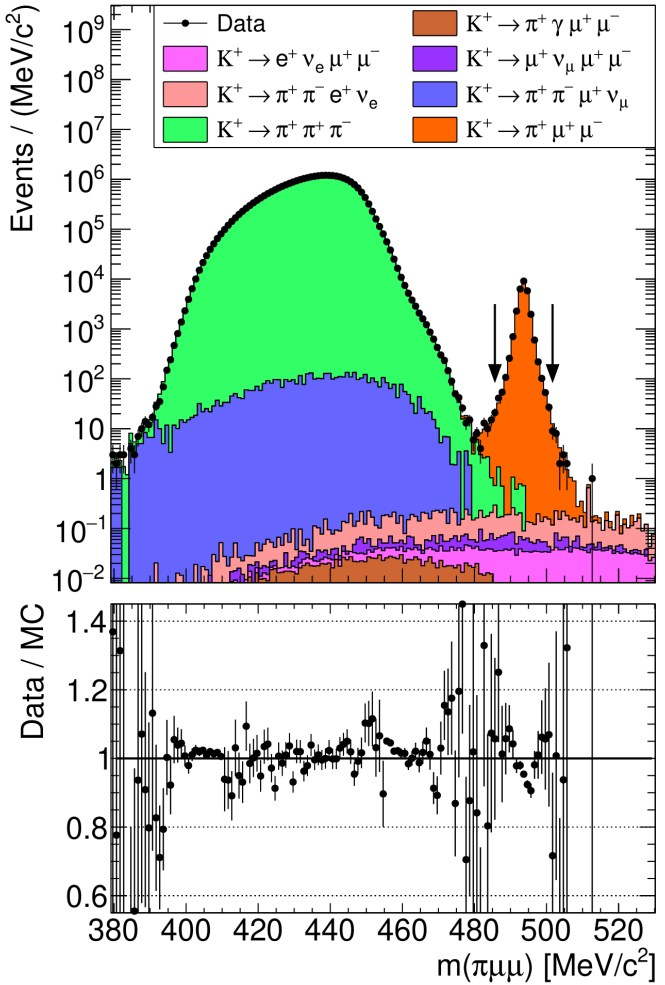
- Form factor parametrized in NLO ChPT

  $W(z) = G_F m_K^2(a_+ + b_+ z) + W^{\pi\pi}(z), \mathrm{z} = \frac{\mathrm{m}_{\mu\mu}^2}{m_K^2}$

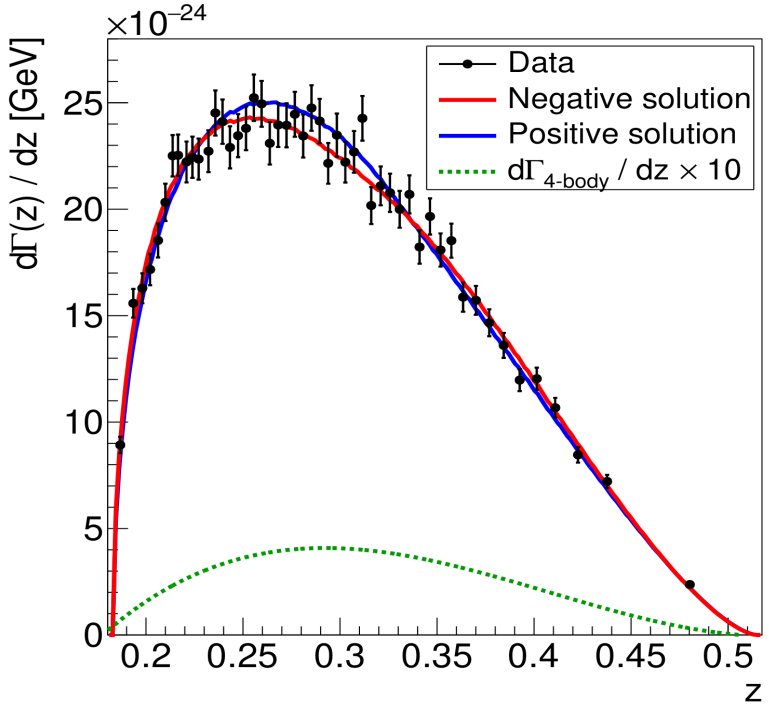
  [JHEP 08 (1998) 004]

- Analysis
  - 2017+2018 data
  - Normalization with $K_{3\pi}$: $N_{K_{3\pi}} \approx 3.5 \times 10^{12}$
  - Signal:
    - Acceptance: $A_{\pi\mu\mu} \approx 8.7\%$
    - Expected background: ≈ 8 events ($K_{3\pi}$ with two pion decays $\pi \to \mu\nu$)
    - 27679 events observed

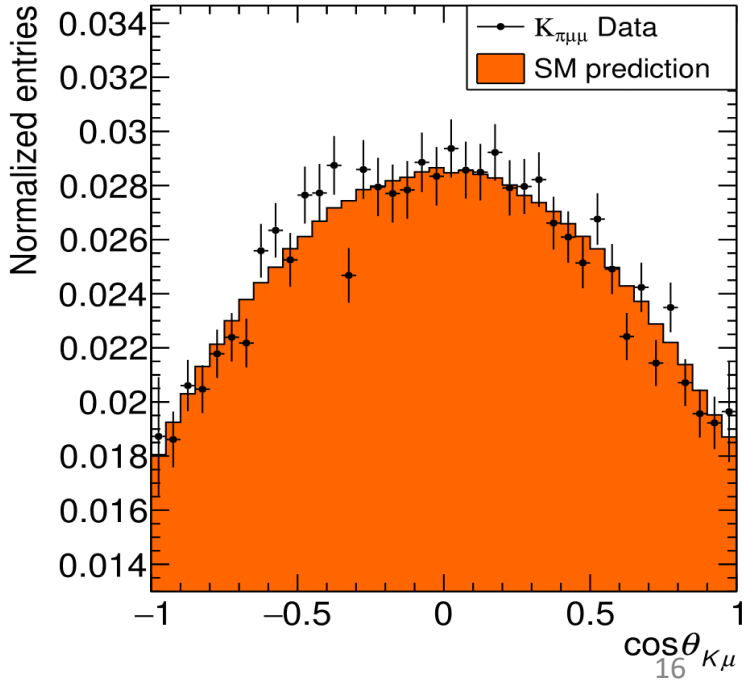




The $K^+ \to \pi^+\mu^+\mu^-$ decay



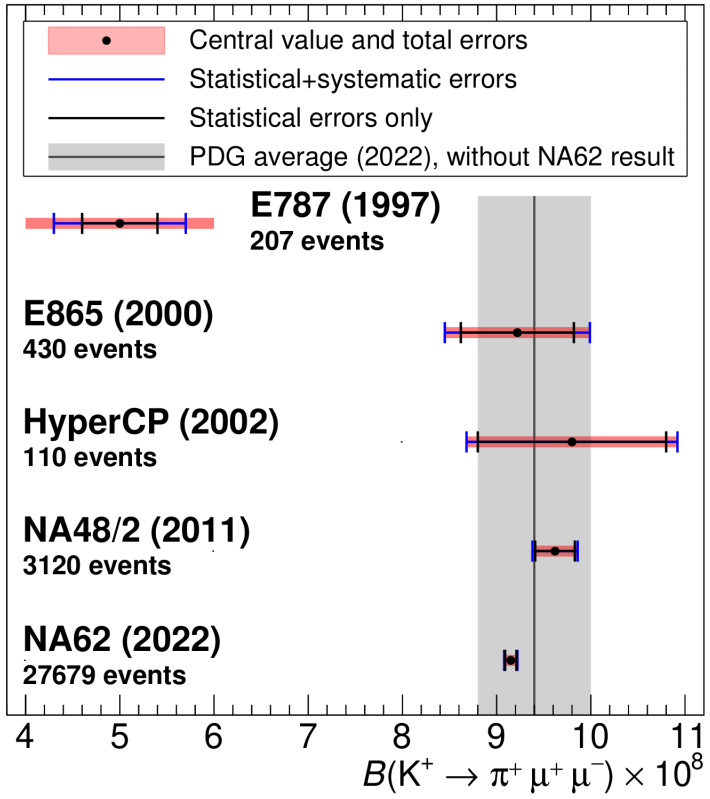
- $\frac{d\Gamma(z)}{dz}$ profile in 50 equipopulous bins
  - Model independent BR measurement
    - Integrate profile
  - Extraction of $|W^{\pi\pi}(z)|^2$ function values
    - From measured dΓ(z)/dz (assuming linearity of $|W^{\pi\pi}(z)|^2$ in each bin)
  - ChPT form factor parameter measurement
    - From fit of data points

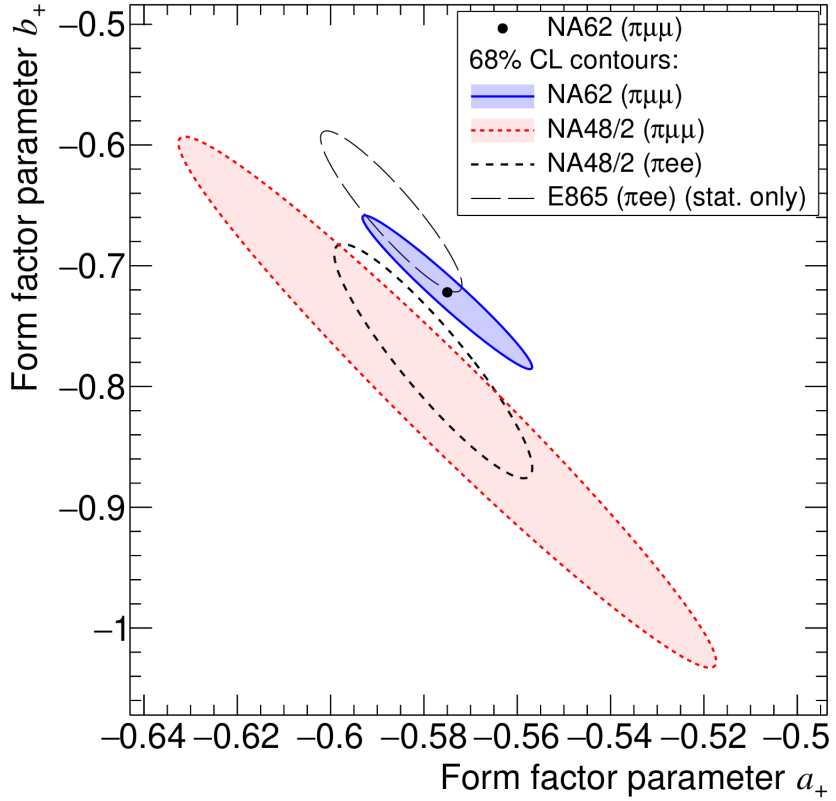


- Forward-backward asymmetry
  - $A_{FB} = \frac{N(\cos\theta_{K\mu}>0) - N(\cos\theta_{K\mu}<0)}{N(\cos\theta_{K\mu}>0) + N(\cos\theta_{K\mu}<0)}$

$\theta_{K\mu}$: angle between 3-momenta of K^+ and μ^- in $\mu^+\mu^-$ rest frame

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





- ❑ Model independent BR measurement
  - ➢ $BR(K^+ \to \pi^+\mu^+\mu^-) = (9.15 \pm 0.08) \times 10^{-8}$
  - ➢ Improvement by a factor > 3
  - ➢ Consistent with previous measurements
- ❑ ChPT form factor parameter measurement
  - ➢ Negative solution preferred
  - ➢ $a_+ = -0.575 \pm 0.013, \quad b_+ = -0.722 \pm 0.043$
  - ➢ Compatible with previous $K_{\pi\mu\mu}$ and $K_{\pi ee}$ measurements, as expected by LFU

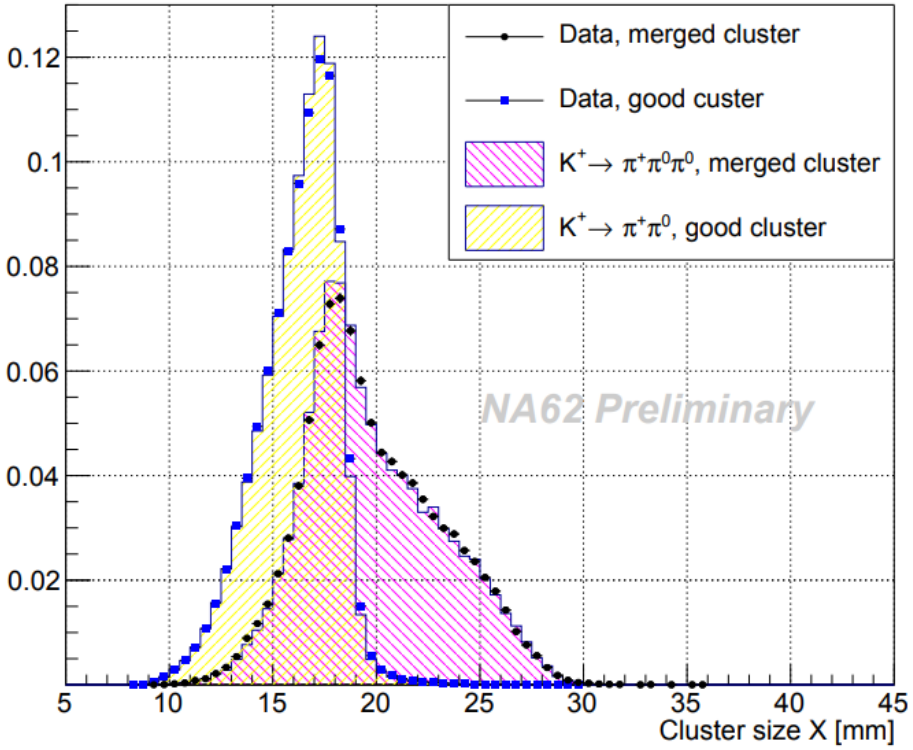
The $K^+ \to \pi^+\gamma\gamma$ decay

- Described by kinematic variables
  - $z = \frac{(q_1+q_2)^2}{m_K^2} = \left(\frac{m_{\gamma\gamma}}{m_K}\right)^2, y = \frac{(q_1-q_2)^2}{m_K^2}$
- Decay rate and spectrum determined by a single ChPT parameter $\hat{c}$

[Phys. Lett. B386 (1996) 403]

- Normalization: $K^+ \to \pi^+\pi^0$
- Main backgrounds:
  - Cluster merging
  - $K^+ \to \pi^+\pi^+\pi^-$ with two non-reconstructed tracks
- Use control region with enhanced background contribution

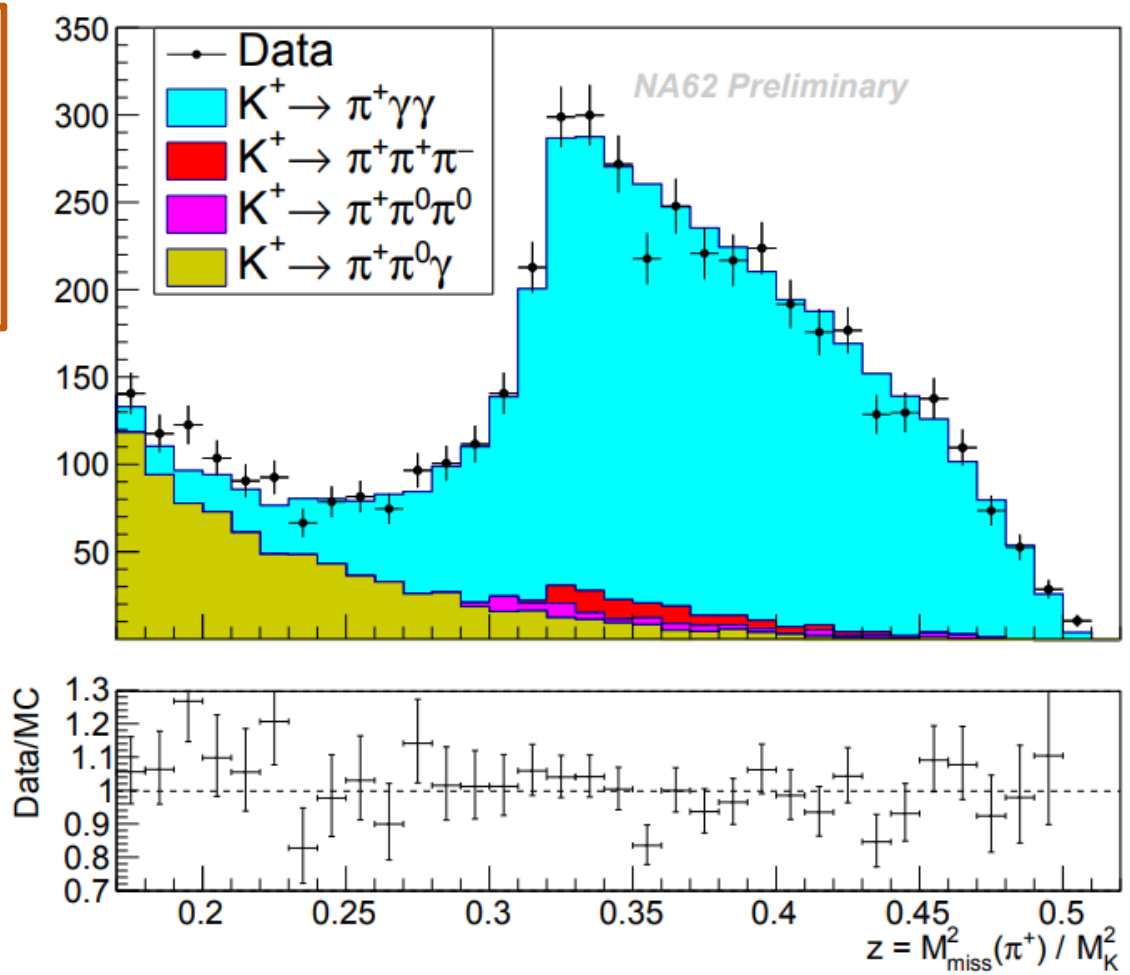
- Cluster merging:
  - Select events with 1 track and 3 clusters
  - tag $K^+ \to \pi^+\pi^0\pi^0$ (merged cluster energy matches expected)



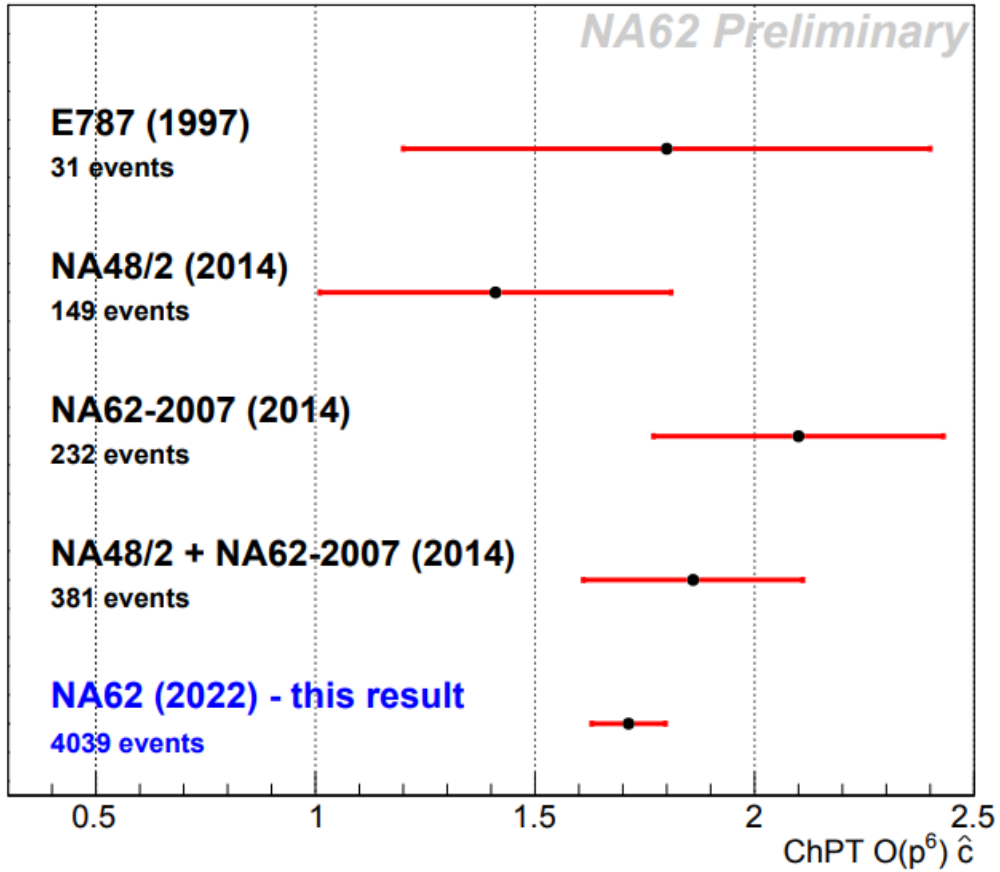
The $K^+ \to \pi^+\gamma\gamma$ analysis

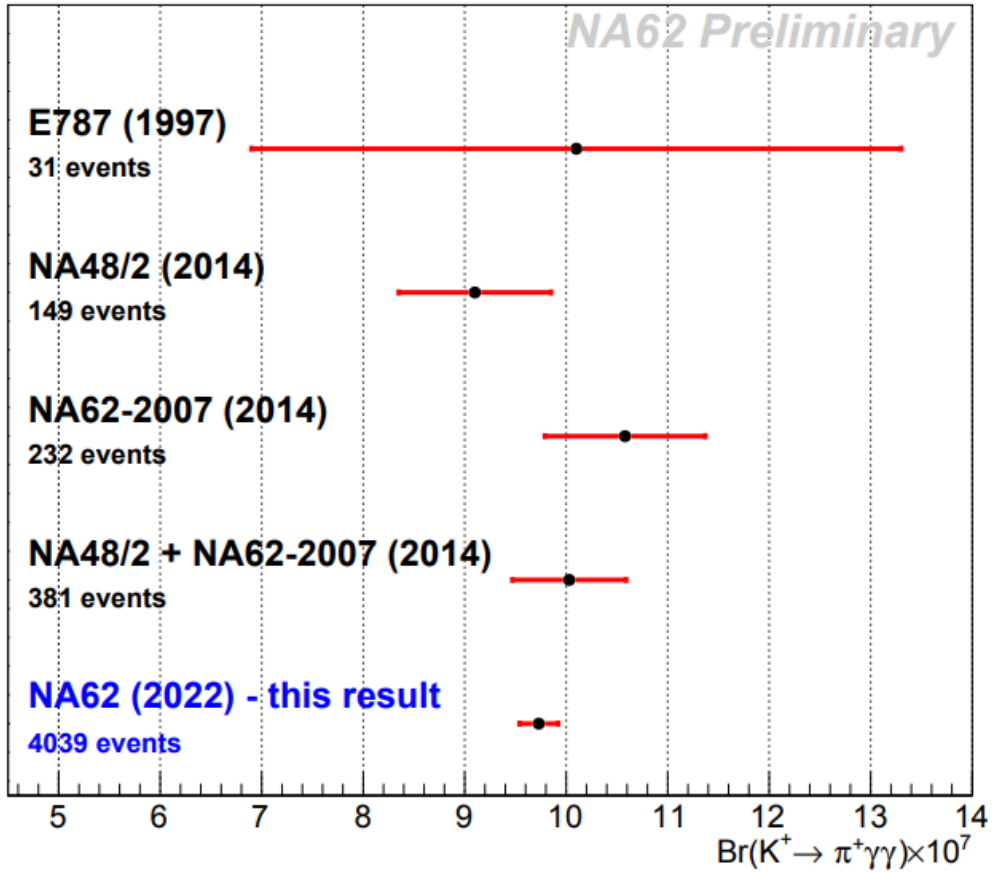
- Measurement
  - 2016-2018 dataset
  - z distribution sensitive to parameter
  - Signal region $z > 0.25$
  - Fit distribution to extract $\hat{c}$

	Number of events
$K^+ \to \pi^+\pi^0\gamma$	$252 \pm 6_{stat} \pm 15_{syst}$
$K^+ \to \pi^+\pi^0\pi^0$	$58 \pm 5_{stat} \pm 3_{syst}$
$K^+ \to \pi^+\pi^+\pi^-$	$83 \pm 3_{stat} \pm 2_{syst}$
Total background	$393 \pm 9_{stat} \pm 18_{syst}$
Data	4039
Data - background	3646 ± 67



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





- Preliminary result
  - $\hat{c} = 1.713 \pm 0.075_{stat} \pm 0.037_{syst}$
  - $BR(K^+_{\pi\gamma\gamma}) = (9.73 \pm 0.17_{stat} \pm 0.08_{syst}) \times 10^{-7}$
  - Total error reduced by a factor 3

Conclusions

- Long tradition of kaon measurements at CERN
  - NA48/2 result: First measurement of $BR(K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu)$
  - Updated measurement of $BR(K^+ \to \pi^+\nu\bar{\nu})$, compatible with SM predictions
  - Relative precision of $BR(K^+ \to \pi^0 e^+\nu\gamma)/BR(K_{e3})$ better than 1% in 3 regions, and measurement of T-asymmetry (first measurement in R2 and R3)
  - Improvement of factor >3 on $BR(K^+ \to \pi^+\mu^+\mu^-)$ and a_+, b_+ ChPT form factor parameters
  - Factor 3 improvement on measurement of $\hat{c}$ ChPT parameter in $K^+ \to \pi^+\gamma\gamma$
- Incoming
  - Papers in preparation
  - New data-taking period started in 2021 with improvement detector setup

THANK YOU