Theory & Experiment in High Energy Physics

Rare Kaon Decays and Searches for Beyond Standard Model Physics

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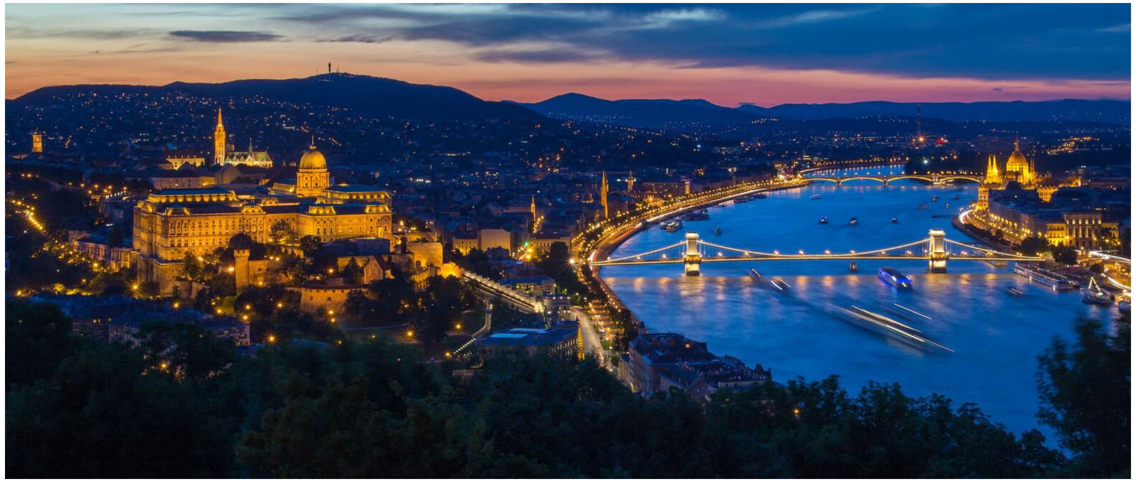

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Outline

1) Intro to Standard Model (SM)
2) Why going beyond the SM
3) How can rare decays help
4) NA62 Experiment results on rare Kaon decays

Standard Model

Based on work of many bright physicists 1955 ~ 1967
pushing to extend the successful Quantum Electrodynamics
gauge field theory to include also weak (& strong) interactions

1964 – marvellous idea: the „Higgs Mechanism“ Higgs,
Brout & Englert
Guralnik, Hagen, Kibble

2013

1967 – unified theory of EM & Weak force Abdus Salam, Steven Weinberg

1979

1971 – 1973 the theory is renormalisable: ‘t Hooft & Veltman

1999

1973 - … and QCD is asymptotically free: Politzer
Gross & Wilczek

2004

1973 – neutral currents observed: the first successful prediction
Gargamelle bubble chamber at CERN

1983 – W & Z boson discovery, UA1 & UA2 Experiments at CERN

1984

...

Standard Model

The missing piece

2012 – Higgs Boson discovery
ATLAS & CMS Experiments at CERN

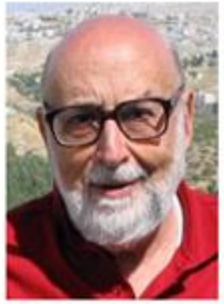


Photo: Pnicolet via Wikimedia Commons
François Englert

Photo: G-M Greuel via Wikimedia Commons
Peter W. Higgs

2013

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

The SM agrees with all CERN experiments, furthermore, it agrees with all accelerator experiments across the world.

Is there anything more to be done at the LHC?

Why Future Circular Collider (FCC) ?

What is the Standard Model?

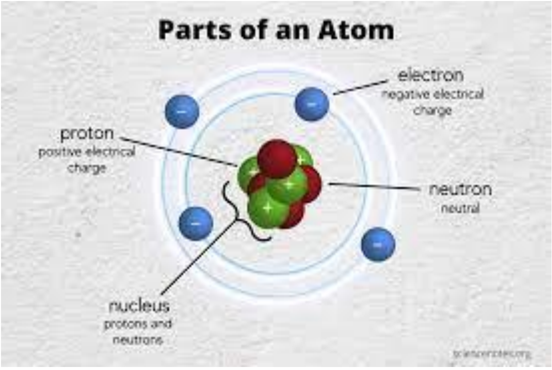
Elementary (point-like) particles:

u quark
d quark

} QUARKS

electron
electron neutrino

} LEPTONS



} This is where they are

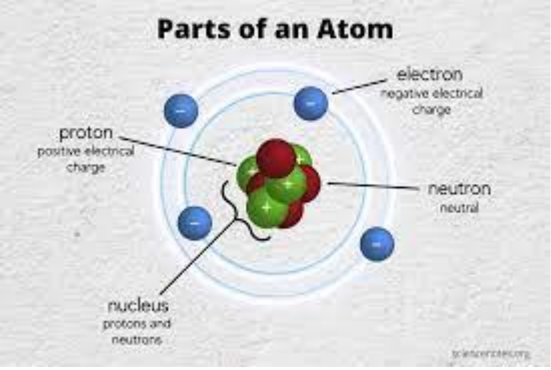
(except neutrinos)

What is the Standard Model?

In fact, we observe THREE generations of Quarks and Leptons:

u	**c**	**t**	} QUARKS
d	**s**	**b**	
e^-	μ^-	τ^-	} LEPTONS
ν_e	ν_μ	ν_τ	

The second part of the talk will be on the s-quark decays inside K mesons



} s,c,b,t quarks and 4 more leptons

are not here: they are massive and decay away

The Standard Model is a quantum theory

Gauge (& Yukawa) Interactions among Quarks & Leptons

Even the Vacuum State contains interactions among virtual particles

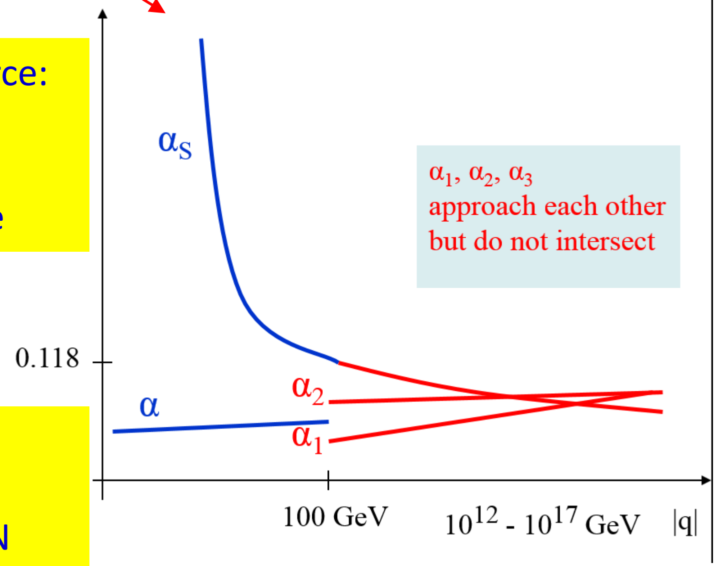
Interactions:		Gauge Symmetry: need to add
	elektromagnetic	PHOTONS
	strong	GLUONS
	weak	W & Z BOSONS
	gravity	GRAVITONS ?

Interactions and the corresponding couplings (=charges) in the Standard Model at energies E « 100 GeV , E ≈ 100 GeV a E » 100 GeV

Running Couplings in the Standard Model

Quarks become confined within baryons and mesons

strong force: from GLUON exchange



electric force: PHOTON exchange

q = momentum transfer

The Weak Force is non-renormalisable at E « 100 GeV and in this regime it cannot be described the same way

Standard Model particle content & masses

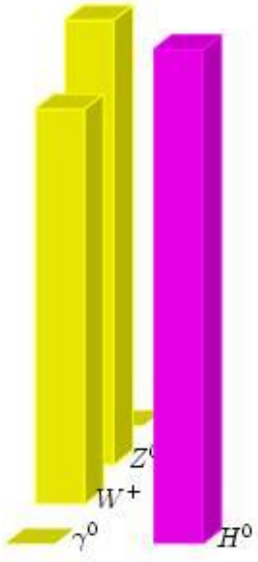
$M_{\text{top quark}} = 173 \pm 1\ \text{GeV}/c^2$

quarks and leptons

1st generation 2nd generation 3rd generation

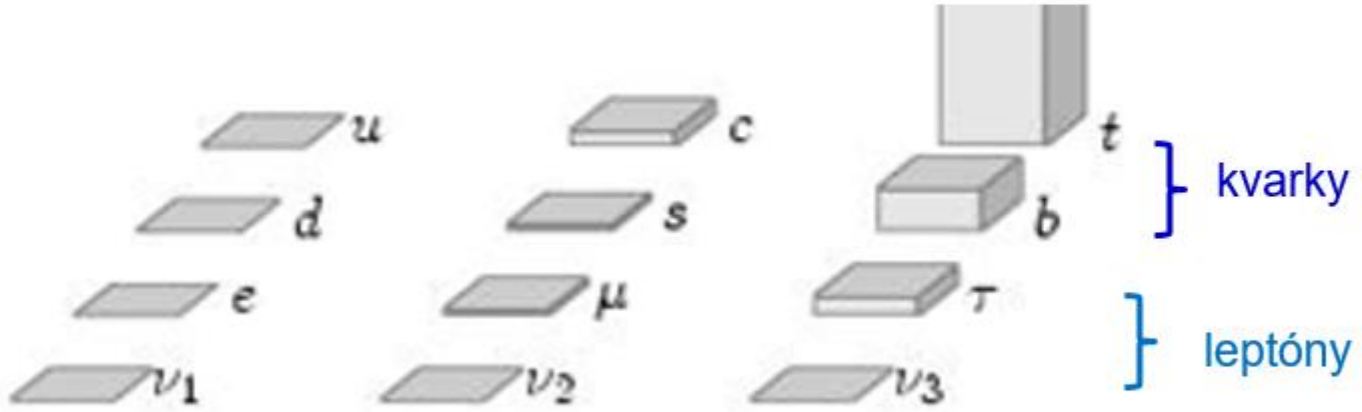
$M_{\text{Z boson}} = 91 \pm 0.002\ \text{GeV}/c^2$
$M_{\text{W boson}} = 80 \pm 0.02\ \text{GeV}/c^2$

$M_{\text{Higgs}} = 125.09 \pm 0.24\ \text{GeV}/c^2$



bosons

Standard Model particle content & masses - fermion mass details

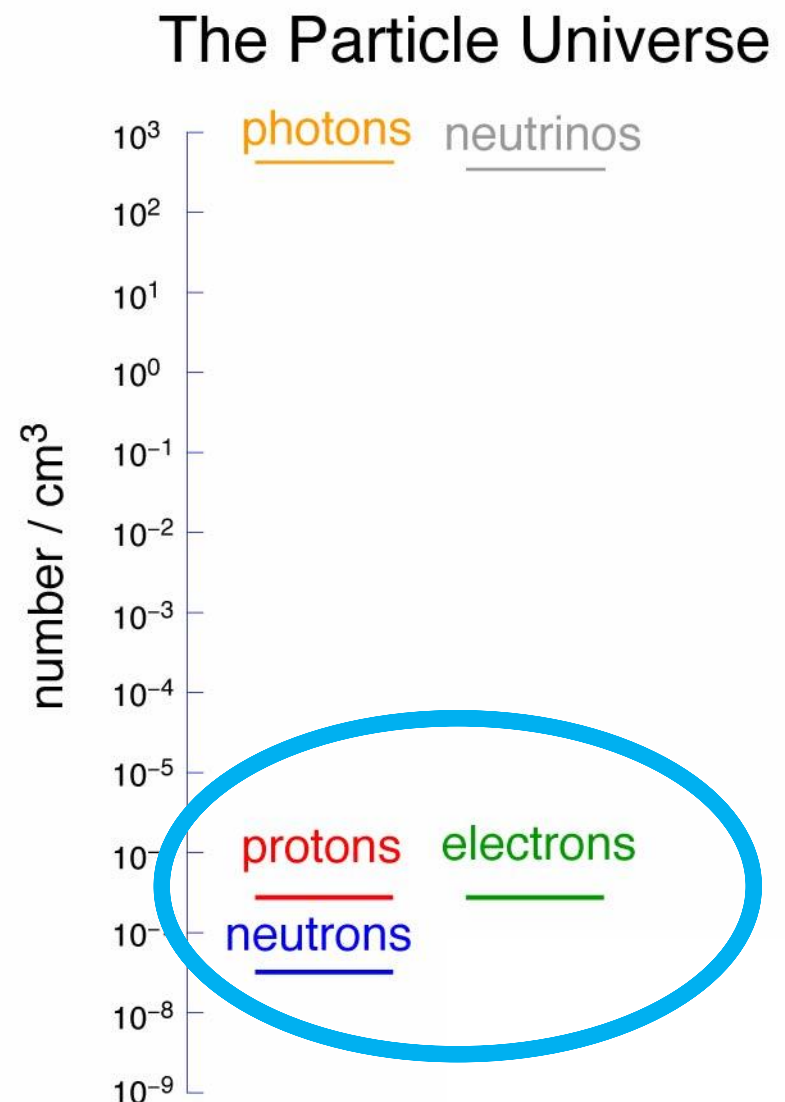


If the accelerator observations fit the SM with the discovered Higgs Boson why do we wish to advance the experiment

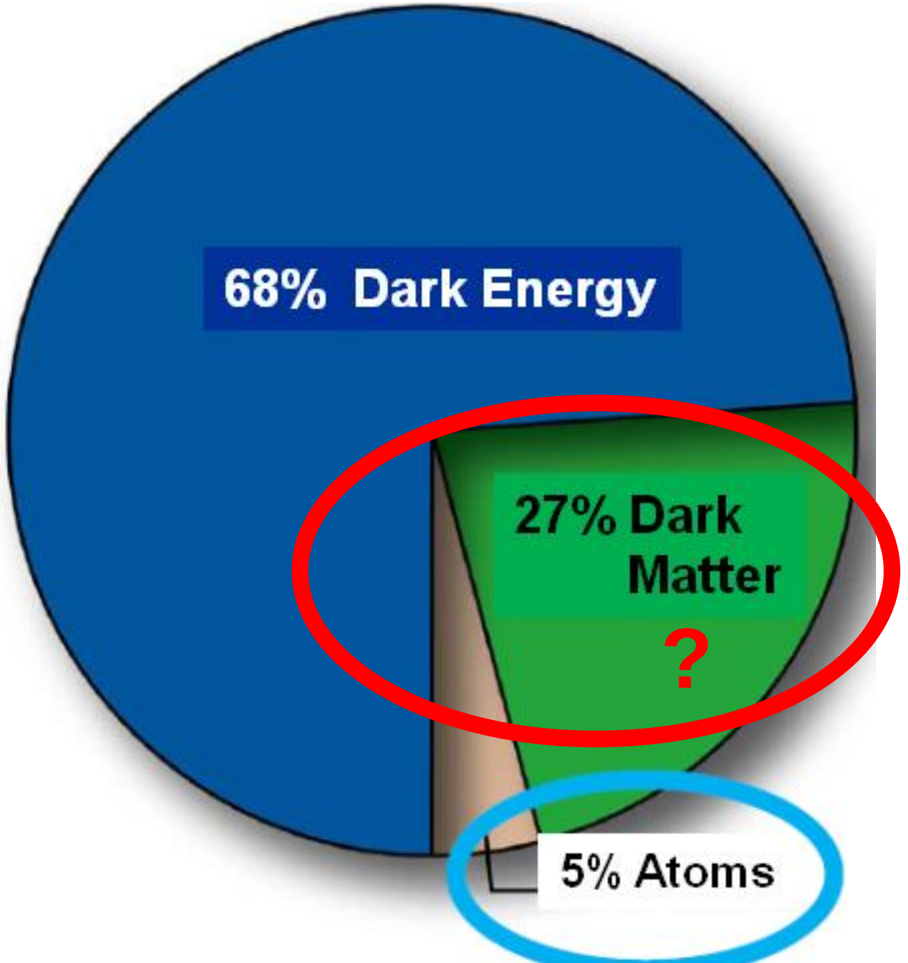
? ? ? ? ?

Our Universe

observed stable particle densities



energy density contributions



Why need to go Beyond the Standard Model

Experimental Motivation

What is **Dark Matter**?

Why does the Universe's Expansion accelerate? What is **Dark Energy**?

Why is there more matter than antimatter?

Theoretical Motivovation

Origin of Gauge Symmetry $SU(3)_c$ x spontaneously broken $SU(2)_L$ x $U(1)_Y$ **?**

Origin of the observed particle multiplets as low-dim irreps of the gauge symmetry

... in principle, many other irreps might be observed by quarks/leptons

Origin ... of 3 fermionic generations

Origin ... electric charge quantization

Origin ... observed fermionic masses & mixings

Origin ... ~ 100 GeV scale of EWSB

Origin ... Planck scale » 100 GeV?

... Dark Energy scale « 100 GeV?

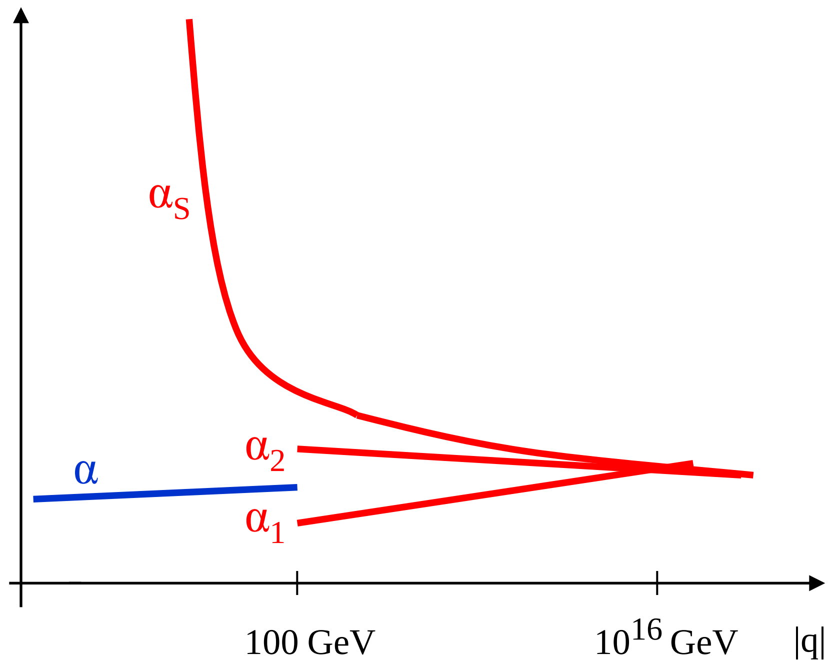
Motivation for more complete "Beyond Standard Model" theory

answers would be very welcome

Large number of Theoretical Ideas investigated

e.g., Beautiful idea of Supersymmetry - with its surprises

Gauge Coupling Unification at energies two orders below the Planck Scale



q = momentum transfer

Other example of a SUSY surprise:

Higgs mass to be below 140 GeV

The Large Hadron Collider:

13 years Searches for signals of Beyond Standard Model Physics

No clear cut signal found

New idea:

Keep looking for Direct production of new particles at the LHC

but at the same time

Pay attention also to rare or forbidden processes
(especially decays) at much lower energies

Indirect NEW PHYSICS Searches

Examples of rare or forbidden decays at low energies

$BR(B_s^0 \rightarrow \mu^+ \mu^-)$ — with P.Maták, Intl. J. Phys. 2014, PhD Thesis 2015

$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})$

$R_K = \Gamma(K^+ \rightarrow e^+ \nu_e) \;/\; \Gamma(K^+ \rightarrow \mu^+ \nu_\mu)$ — with P.Maták, Z.Kučerová and Z.Šinská, M.S. Thesis 2016

$BR(\tau \rightarrow e\gamma)$

$BR(H \rightarrow \tau \mu)$ — with S.Beznák, M.S. Thesis 2017

constraining non-Minimal SUSY parameter space

A VERY BROAD topic

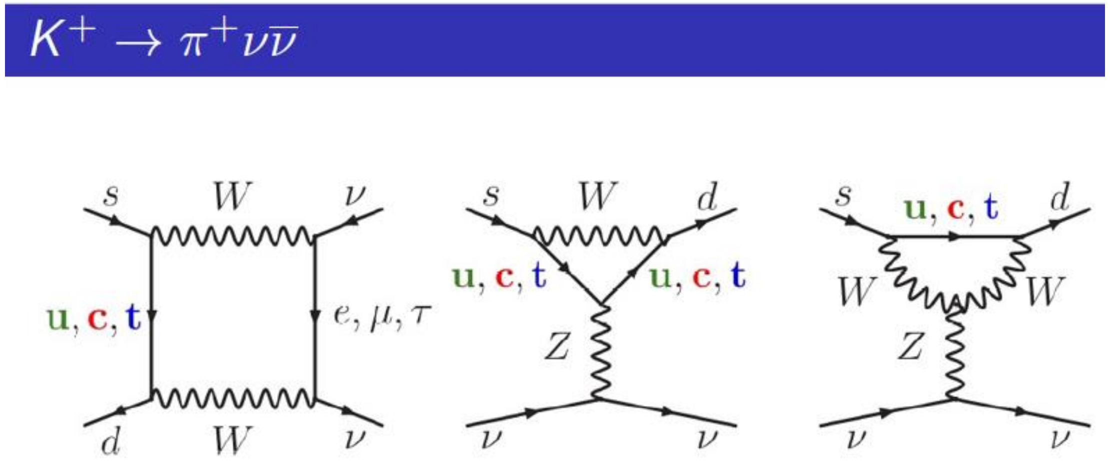
Kaon Decays: (weak decay of the *s*-quark)

easily accessible (mK ~ 0.5 GeV)

Flavor-changing neutral currents (FCNC) responsible for many decay channels (no tree-level amplitudes)

Studied by the NA62 Collaboration with the goal to observe

K+ → π+ ν ν

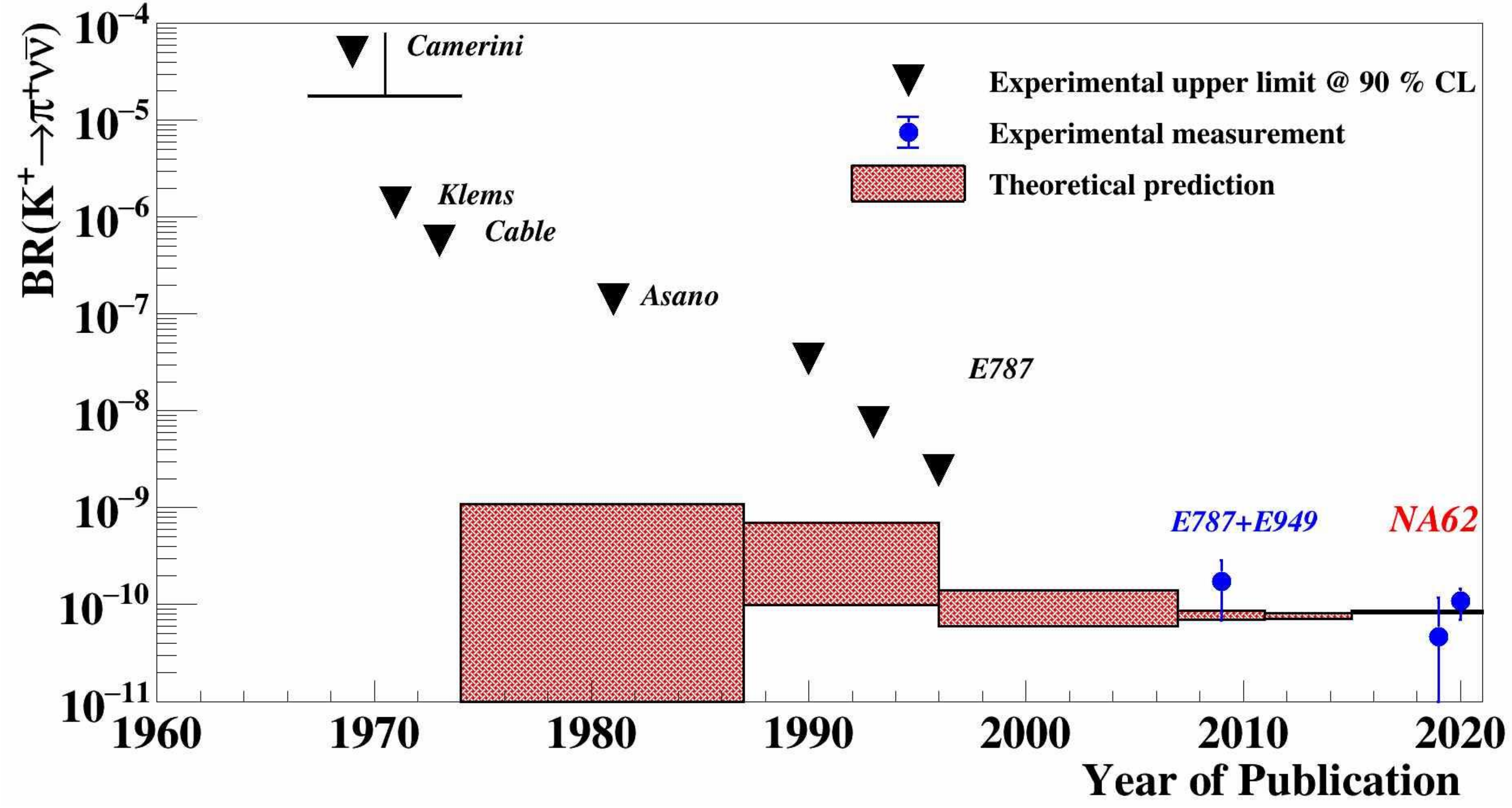


Dominated by top exchange
(suppression by top propagators, and by $V_{td}^{*}V_{ts}$)

Potentially competing with new heavy particles in the loop

Long range hadronic corrections more under control than elsewhere - theoretically very clean

K+ → π+ ν ν - the main goal of NA62 Experiment



$K^+ \to \pi^+ \nu \nu$ - the main goal of NA62 Experiment

Experiment: BR($K^+ \to \pi^+ \nu \nu$) = ($10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}$) x 10^{-11} NA62, 2020

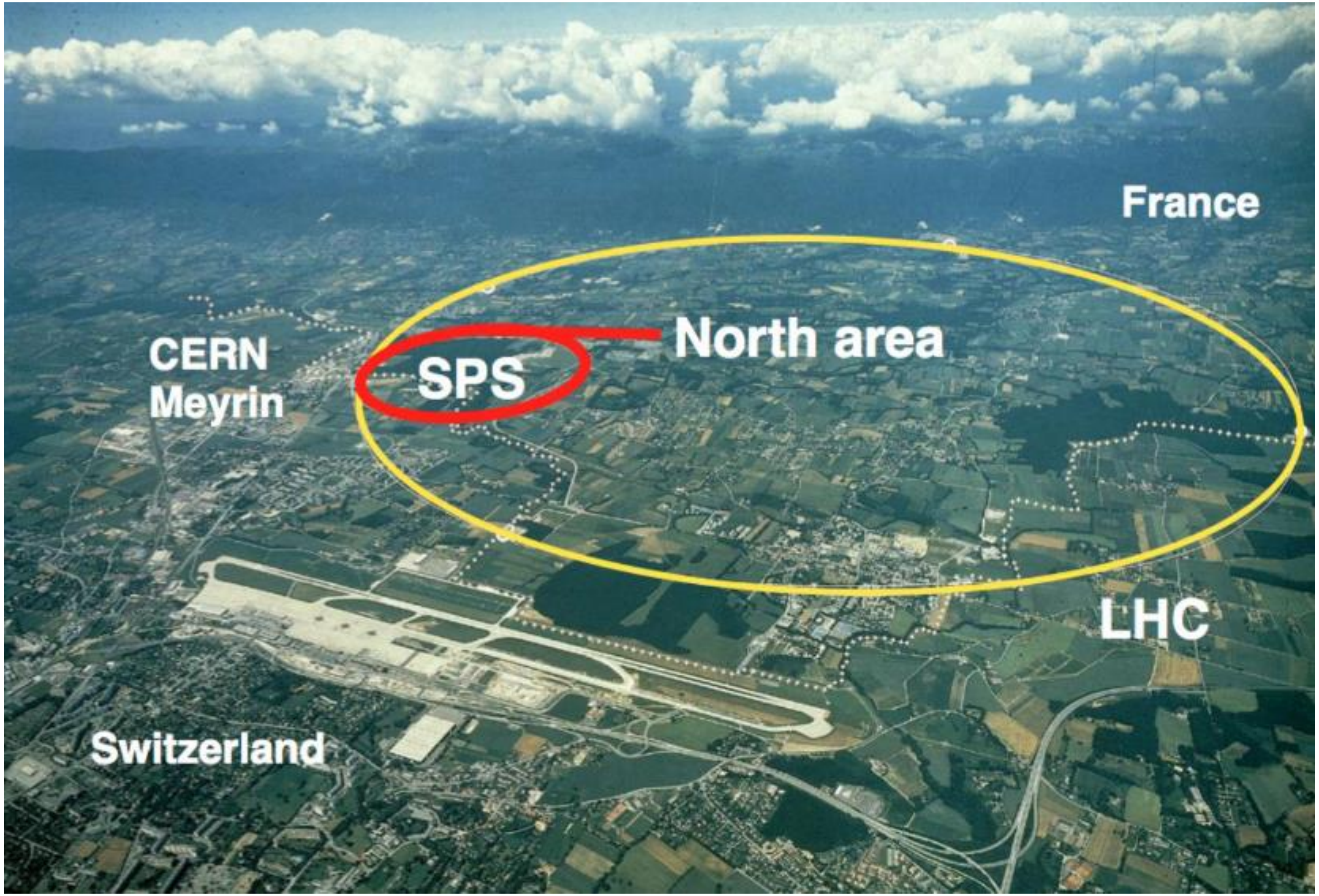
First experimental evidence

Theoretical SM prediction: BR($K^+ \to \pi^+ \nu \nu$) = (8.4 ± 0.4) x 10^{-11} Buras et al, 2022

Very demanding to measure, must understand the backgrounds to more than 10 orders!

However, NA62 measures many more other kaon decay channels due to large data samples (high intensity initial proton beam from SPS at CERN)

NA62 Experiment



Kaon Physics at CERN: history

NA31: K_S / K_L (1984-1990)
First evidence of direct CPV in kaons

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

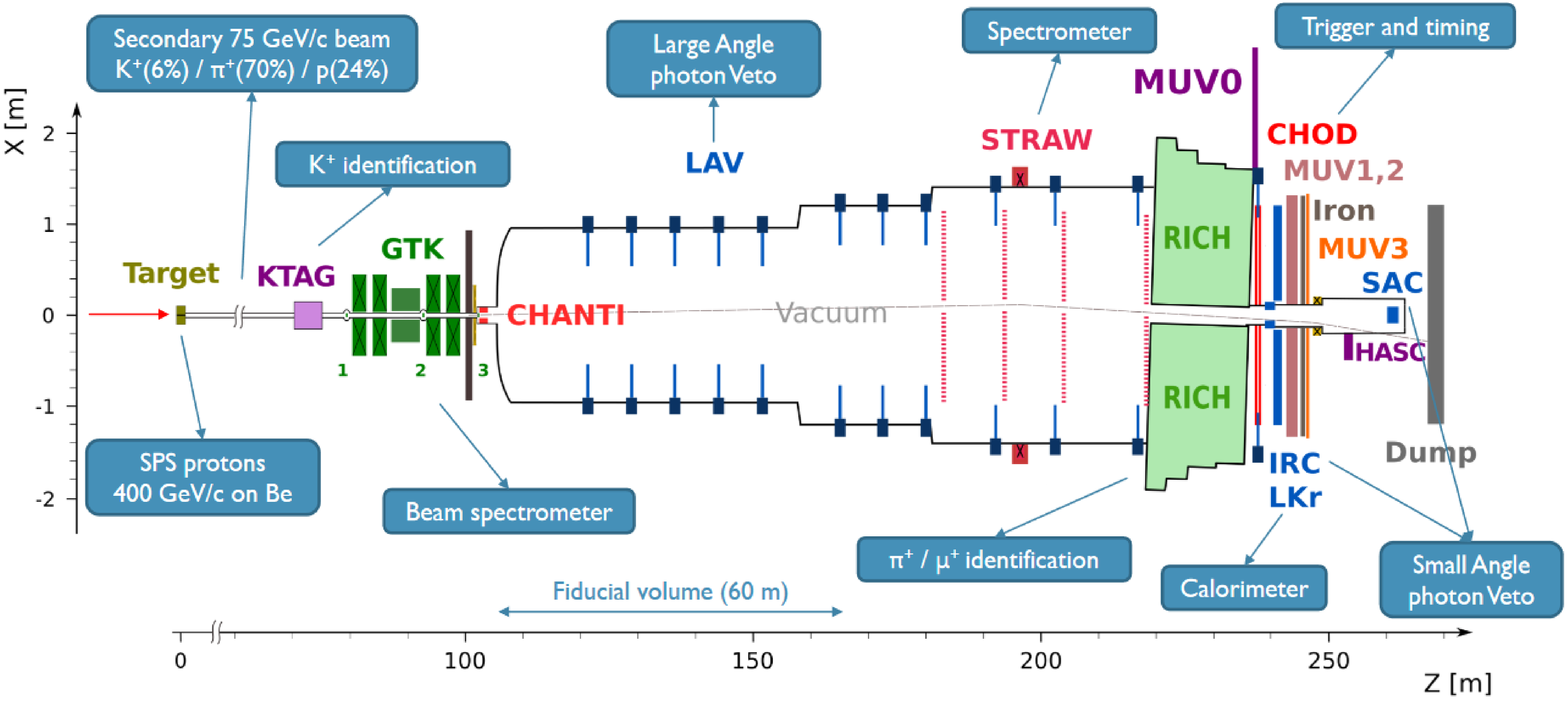
NA62: K^+ (2021-now)
Physics Run2

NA62 Experiment

- ~300 participants from ~30 institutions
- High-precision kaon experiment
- Technique:
  - Fixed target
  - Decay-in-flight
- Broad physics program:
  - Measurement of BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$)
  - Precision measurements
  - Tests of LFV / LNV
  - Exotic searches (DP, DS, ALP, HNL)

→ this talk

The NA62 Detector



Outline of the Kaon Decay results in this talk

NA62 main goal

- $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

NA62 latest precision measurements

- $K^+ \rightarrow \pi^0 e^+ \nu\gamma$ ($K_{e3\gamma}$)
- $K^+ \rightarrow \pi^+ \mu^+ \mu^-$
- $K^+ \rightarrow \pi^+ \gamma\gamma$

NA48/2 preliminary result

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

NA62 dataset

Run1 (this talk)

- 2016: 30 days, 2×10^{11} useful K decays
- 2017: 161 days, 2×10^{12} useful K decays
- 2018: 217 days, 4×10^{12} useful K decays

Run2 (analysis in progress)

- 2021: 85 days
- 2022: 215 days
- 2023 – LS3: ongoing

Table 2.1: Branching ratios of background decays

	$\mathcal{B}$
$K^+ \rightarrow \pi^+\pi^0$	$(20.67 \pm 0.08)\%$
$\pi^0 \rightarrow \gamma\gamma$	$(98.823 \pm 0.034)\%$
$\pi^0 \rightarrow e^+e^-\gamma$	$(1.174 \pm 0.0.035)\%$
$K^+ \rightarrow \pi^+\pi^0(\gamma)$	$(1.02 \pm 0.12) \times 10^{-5}$
$K^+ \rightarrow \pi^+\pi^+\pi^-$	$(5.583 \pm 0.024)\%$
$K^+ \rightarrow \pi^+\pi^0\pi^0$	$(1.760 \pm 0.023)\%$
$K^+ \rightarrow \pi^0 e^+\nu_e$	$(5.07 \pm 0.04)\%$
$K^+ \rightarrow \pi^0\mu^+\nu_\mu$	$(3.325 \pm 0.033)\%$

NA62 latest precision measurements

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

The ratio of the branching fractions of the radiative decay $K_{e3\gamma}$ to the inclusive decay K_{e3} is expressed as:

$$R_j = \frac{\mathcal{B}(K_{e3\gamma^j})}{\mathcal{B}(K_{e3})} = \frac{\mathcal{B}(K^+ \to \pi^0 e^+ \nu\gamma \mid E_\gamma^j,\, \theta_{e\gamma}^j)}{\mathcal{B}(K^+ \to \pi^0 e^+ \nu(\gamma))},$$

where $(E_\gamma^j, \theta_{e\gamma}^j)$ are the conditions corresponding to the kinematic regions labeled by the index j.

	$E_\gamma^j,\ \theta_{e\gamma}^j$	ChPT	ISTRA+	OKA
$R_1 \times 10^2$	$E_\gamma > 10$ MeV, $\theta_{e\gamma} > 10°$	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$
$R_2 \times 10^2$	$E_\gamma > 30$ MeV, $\theta_{e\gamma} > 20°$	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$
$R_3 \times 10^2$	$E_\gamma > 10$ MeV, $0.6 < \cos\theta_{e\gamma} < 0.9$	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$

NA62 latest precision measurements

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

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	ChPT $O(p^6)$	ISTRA+	OKA	NA62
$R_1 \times 10^2$	1.804 ± 0.021	1.81 ± 0.03 ± 0.07	1.990 ± 0.017 ± 0.021	1.715 ± 0.005 ± 0.010
$R_2 \times 10^2$	0.640 ± 0.008	0.63 ± 0.02 ± 0.03	0.587 ± 0.010 ± 0.015	0.609 ± 0.003 ± 0.006
$R_3 \times 10^2$	0.559 ± 0.006	0.47 ± 0.02 ± 0.03	0.532 ± 0.010 ± 0.012	0.533 ± 0.003 ± 0.004

- Factor > 2 more precise than previous measurements
- Relative uncertainty < 1%
- 5% smaller than ChPT prediction $O(3\sigma)$

NA62 latest precision measurements

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

- FCNC, long distance dominated, mediated by $K^+ \to \pi^+\gamma^*$ JHEP 02 (2019) 049
- Test of LFU by comparing $K^+ \to \pi^+e^+e^-$
- One-photon-inclusive differential decay width:

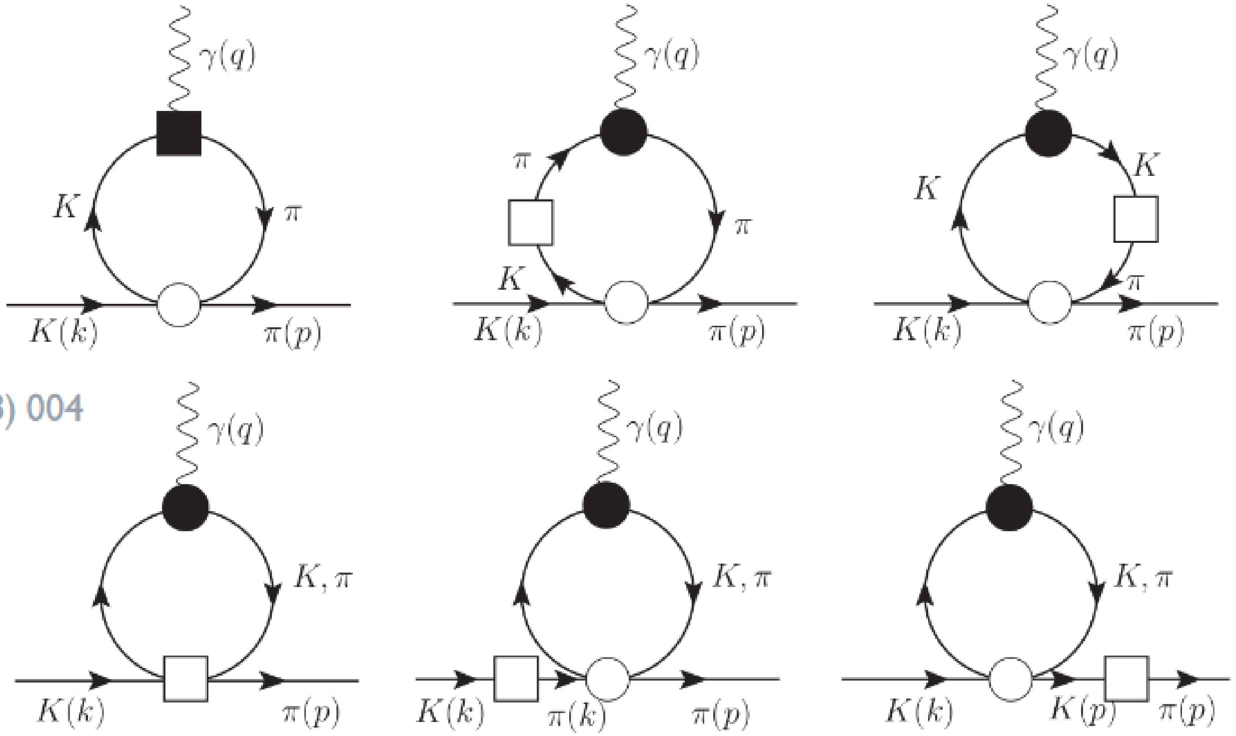
$$\frac{\mathrm{d}\Gamma(z)}{\mathrm{d}z} = g(z) \cdot |W(z)|^2 + \frac{\mathrm{d}\Gamma_{\text{4-body}}(z)}{\mathrm{d}z}$$

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

- Form factor parametrized by ChPT at $O(p^6)$ JHEP 08 (1998) 004

$$W(z) = G_F m_K^2(a_+ + b_+ z) + W^{\pi\pi}(z)$$

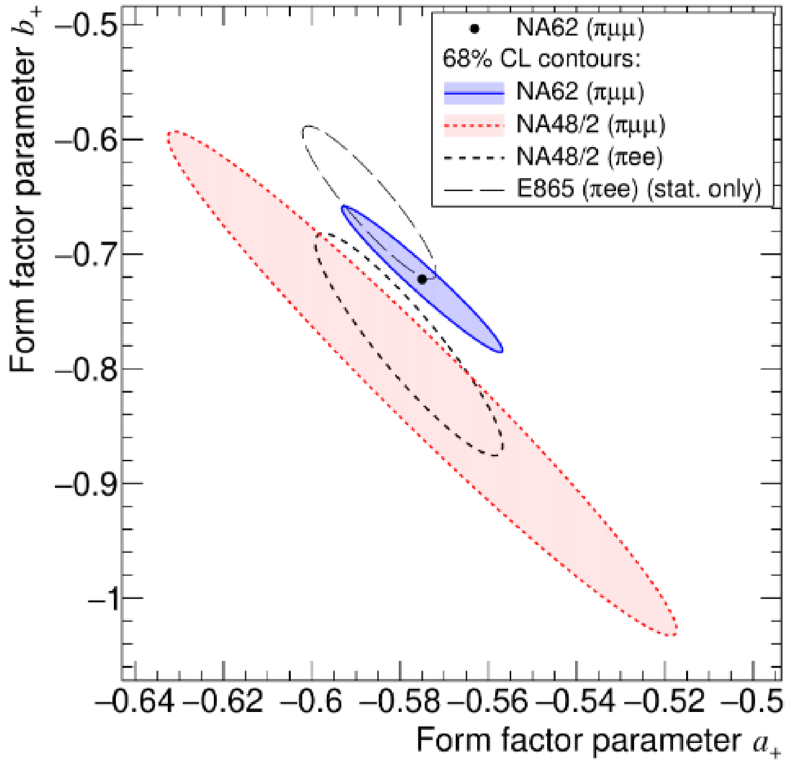
- Measure
  - a_+ , b_+

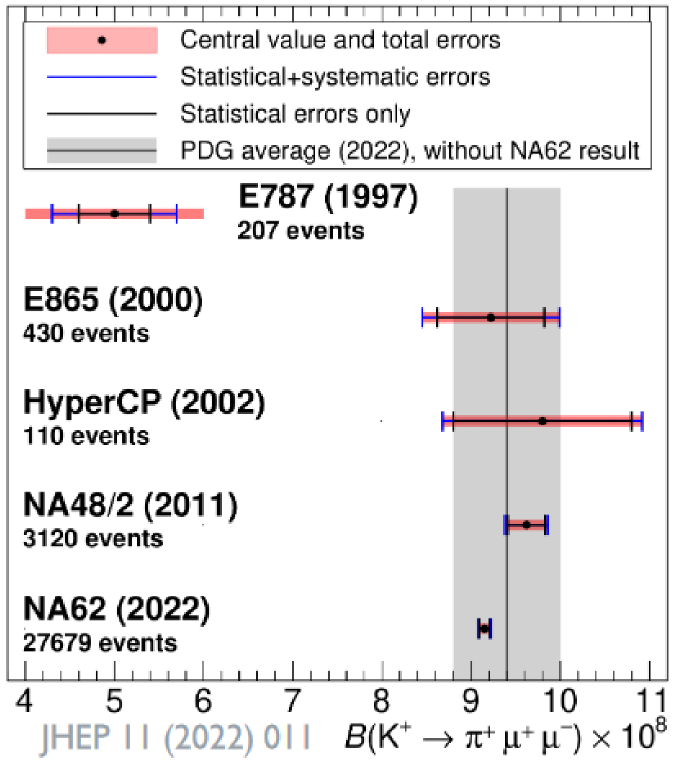


NA62 latest precision measurements

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

JHEP 11 (2022) 011





- Much improved precision
- Sample size ~9x larger than NA48/2
- No evidence for LFU violation

NA62 latest precision measurements

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

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$$a_+ = -0.575 \pm 0.013, \quad b_+ = -0.722 \pm 0.043$$

$$\chi^2 / \text{ndf} = 45.1 / 48, \qquad \rho(a_+, b_+) = -0.972$$

$$BR(K^+ \to \pi^+\mu^+\mu^-) = (9.15 \pm 0.08) \times 10^{-8}$$

MESON2023

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Factor 3 improvement

NA62 latest precision measurements

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

Theory: Phys.Lett. B386 (1996) 403

- Long distance dominated ⟶ crucial ChPT test
- Kinematic variables

$$z = \frac{(q_1+q_2)^2}{m_K^2} = \left(\frac{m_{\gamma\gamma}}{m_K}\right)^2, \quad y = \frac{p(q_1-q_2)}{m_K^2}$$

p: K^+ 4-momentum
$q_{1,2}$: γ 4-momenta
m_K: K^+ mass
$m_{\gamma\gamma}$: di-photon invariant mass

- Decay width parametrized by a real parameter $\hat{c}$

$$\frac{\partial\Gamma}{\partial y \partial z}(\hat{c},y,z) = \frac{m_K}{2^9\pi^3}\left[z^2\left(|A(\hat{c},z,y^2)+B(z)|^2+|C(z)|^2\right)+\left(y^2-\frac{1}{4}\lambda(1,r_\pi^2,z)\right)^2|B(z)|^2\right]$$

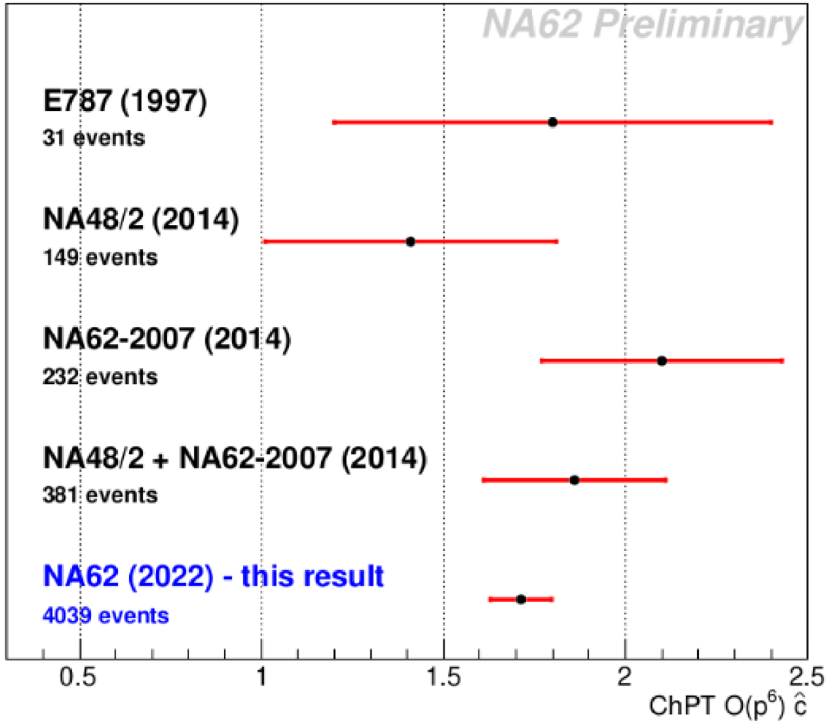
nonzero at $O(p^6)$

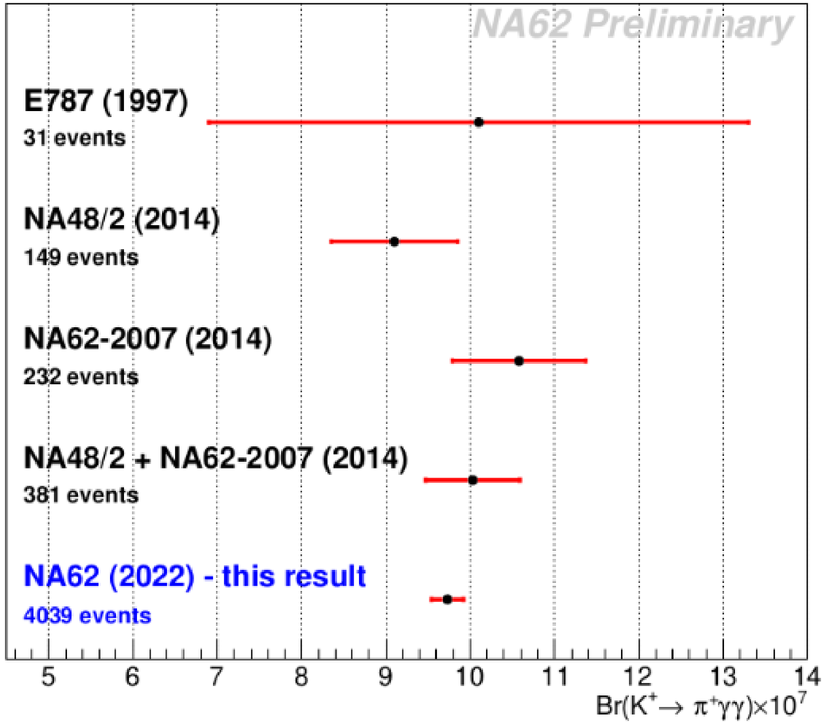
- Goals:
  - Measure $\hat{c}_6$
  - Extrapolate model-dependent BR

NA62 latest precision measurements

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

Preliminary from MESON2023





$$\hat{c}_6 = 1.713 \pm 0.075_{stat} \pm 0.037_{syst}$$

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

Summary

1) Low-energy indirect searches for new physics beyond Standard Model are in place and have the potential to find signals before the LHC experiments

2) NA62 Kaon Physics program is an example of such a search

3) NA62 search is ongoing by the start of Long Shutdown at end of 2025 ?

4) Examples of the latest precision measurement results from the NA62 Experiment were given:

- $K^+ \to \pi^+ \nu\bar{\nu}$ NA62 Run I JHEP 06 (2021) 093
- $K^+ \to \pi^0 e^+ \nu\gamma$ NA62 Run I arXiv:2304.12271, submitted to JHEP
- $K^+ \to \pi^+ \mu^+ \mu^-$ NA62 Run I JHEP 11 (2022) 011
- $K^+ \to \pi^+ \gamma\gamma$ NA62 Run I preliminary, final results in progress

No clear-cut signals of new physics have been found so far.