WIFAI 2023, 8-10 November, Rome

Status and prospects of rare decays at NA62/HIKE

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CERN

Kaon physics: experimental side

How can we extend the search for new physics to high effective scales?

Direct search —> Energy frontier
Create new degrees of freedom in lab.
Explore spectroscopy of new d.o.f.
$\Lambda \sim$ 1-10 TeV

Indirect search —> Intensity frontier
Evidence of new degrees of freedom as alteration of SM rates. Explore symmetry properties of new d.o.f.
$\Lambda \sim$ 1-1000 TeV

A rare decay is useful as a New Physics (NP) probe if:

- Process is (strongly) suppressed in the SM
- Parameter to be measured precisely calculated in SM
- There are specific predictions for NP contributions

What may be studied with rare decays:

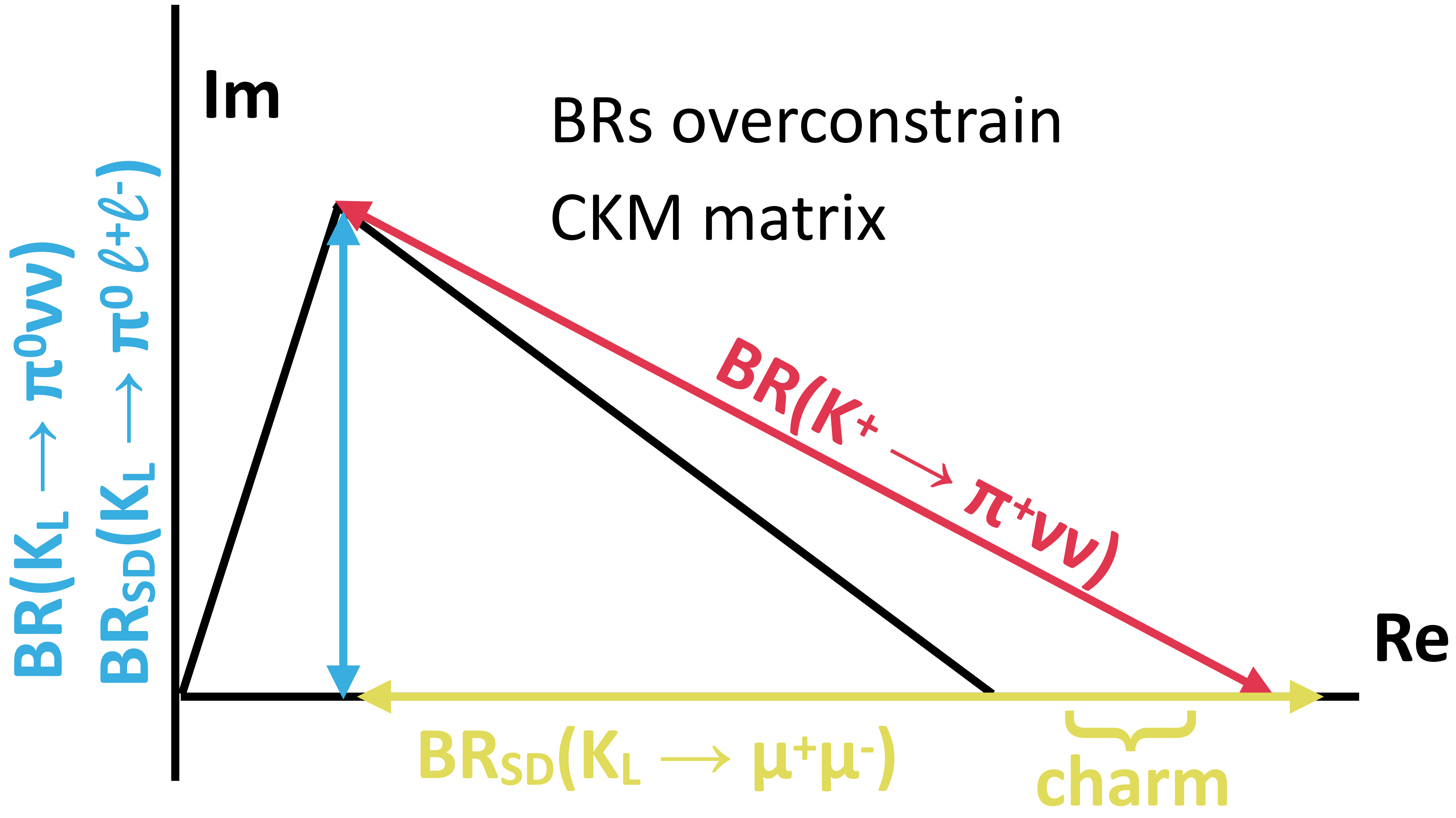
- Explicit violations of the SM (e.g., lepton flavor violation)
- Tests of fundamental symmetries such as CP and CPT
- Search for new d.o.f. in the flavor (e.g. FCNC processes)
- CKM unitary tests
- Low energy QCD tests

Kaon decay experiments: the quintessential precision frontier experiments

Large statistic → **Few decay modes** → **Simple final states**

The golden modes

Decay	Γ_{SD}/Γ	Theoretical error	**SM** BR $\times\ 10^{11}$	**Exp** BR $\times\ 10^{11}$	Experiment
$K_L \to \pi^0 \nu\bar{\nu}$	$> 99\%$	$\sim 2\%$	2.94 ± 0.15	< 300	KOTO (**2019**)
$K^+ \to \pi^+ \nu\bar{\nu}$	$\sim 90\%$	$\sim 4\%$	8.6 ± 0.4	$17.3^{+11.5}_{-10.5}$	BNL-787/949 (**2009**)
$K_L \to \pi^0 e^+ e^-$	$\sim 40\%$	$\sim 10\%$	3.2 ± 1.0	< 28	KTeV (**2004**)
$K_L \to \pi^0 \mu^+ \mu^-$	$\sim 30\%$	$\sim 15\%$	1.5 ± 0.3	< 38	KTeV (**2000**)
$K_L \to \mu^+ \mu^-$	$\sim 10\%$	$\sim 30\%$	79 ± 12 (SD)	684 ± 11	BNL-871 (**2000**)
$K_S \to \mu^+ \mu^-$	$\sim 4\%$	$> 30\%$	0.52 ± 0.15	< 80	LHCb (**2017**)



- FCNC forbidden at tree level (by GIM mechanism): 1-loop contributions as leading order (dominated by short-distance amplitude: Z-penguin and W-box diagrams)
- SM rates related to V_{CKM} with minimal non-parametric theory uncertainty
- Highest CKM suppression BR ~ $|V_{ts}^* V_{td}|^2 \sim \lambda^{10}$

The golden modes

Decay	Γ_{SD}/Γ	Theoretical error	**SM** BR $\times$ 10^{11}	**Exp** BR $\times$ 10^{11}	Experiment
$K_L \to \pi^0 \nu \bar{\nu}$	$> 99\%$	$\sim 2\%$	2.94 ± 0.15	< 300 → < 200	KOTO (**2019**) → KOTO (**2023**)
$K^+ \to \pi^+ \nu \bar{\nu}$	$\sim 90\%$	$\sim 4\%$	8.6 ± 0.4	$17.3^{+11.5}_{-10.5}$	BNL-787/949 (**2009**) → NA62
$K_L \to \pi^0 e^+ e^-$	$\sim 40\%$	$\sim 10\%$	3.2 ± 1.0	< 28	KTeV (**2004**)
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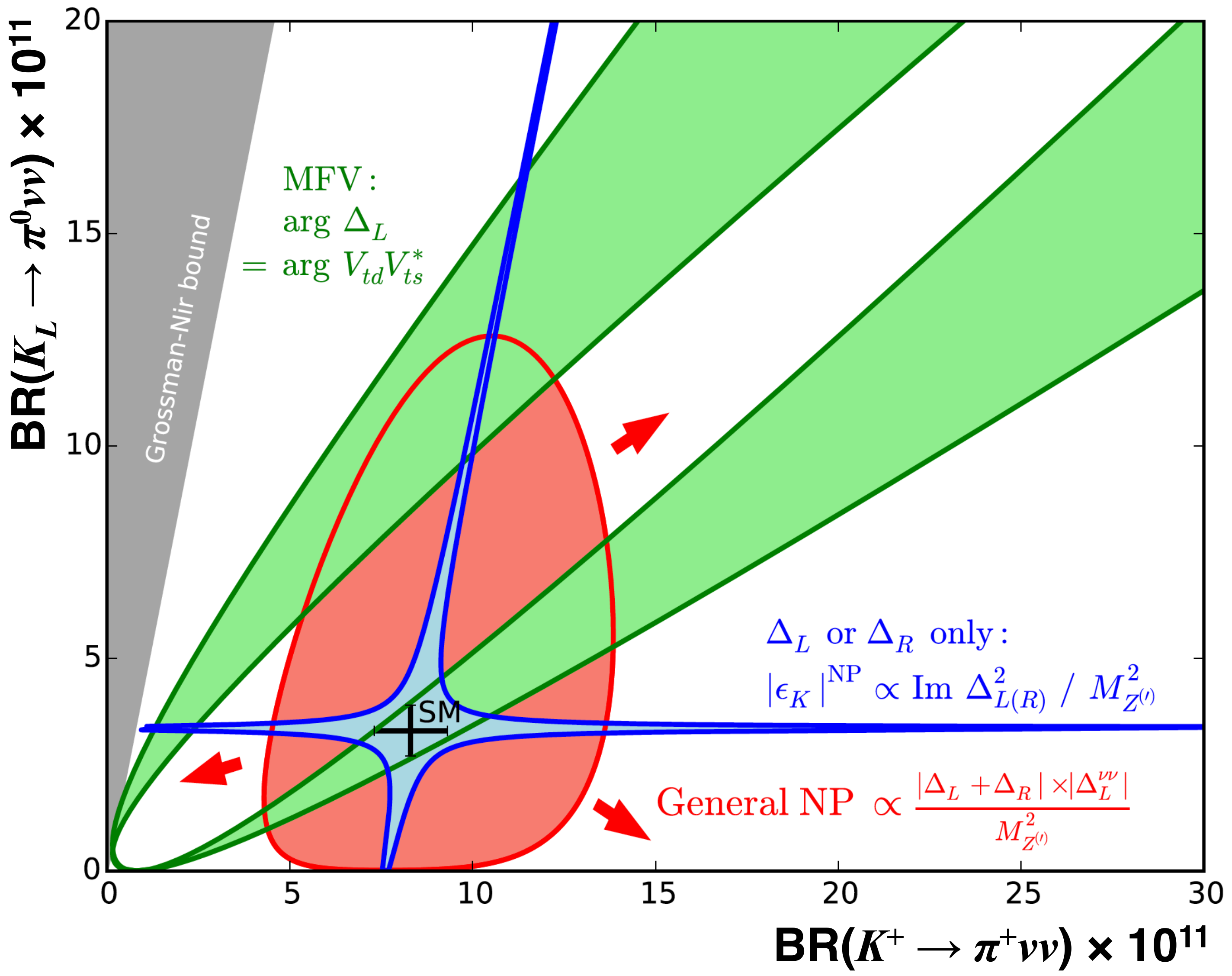
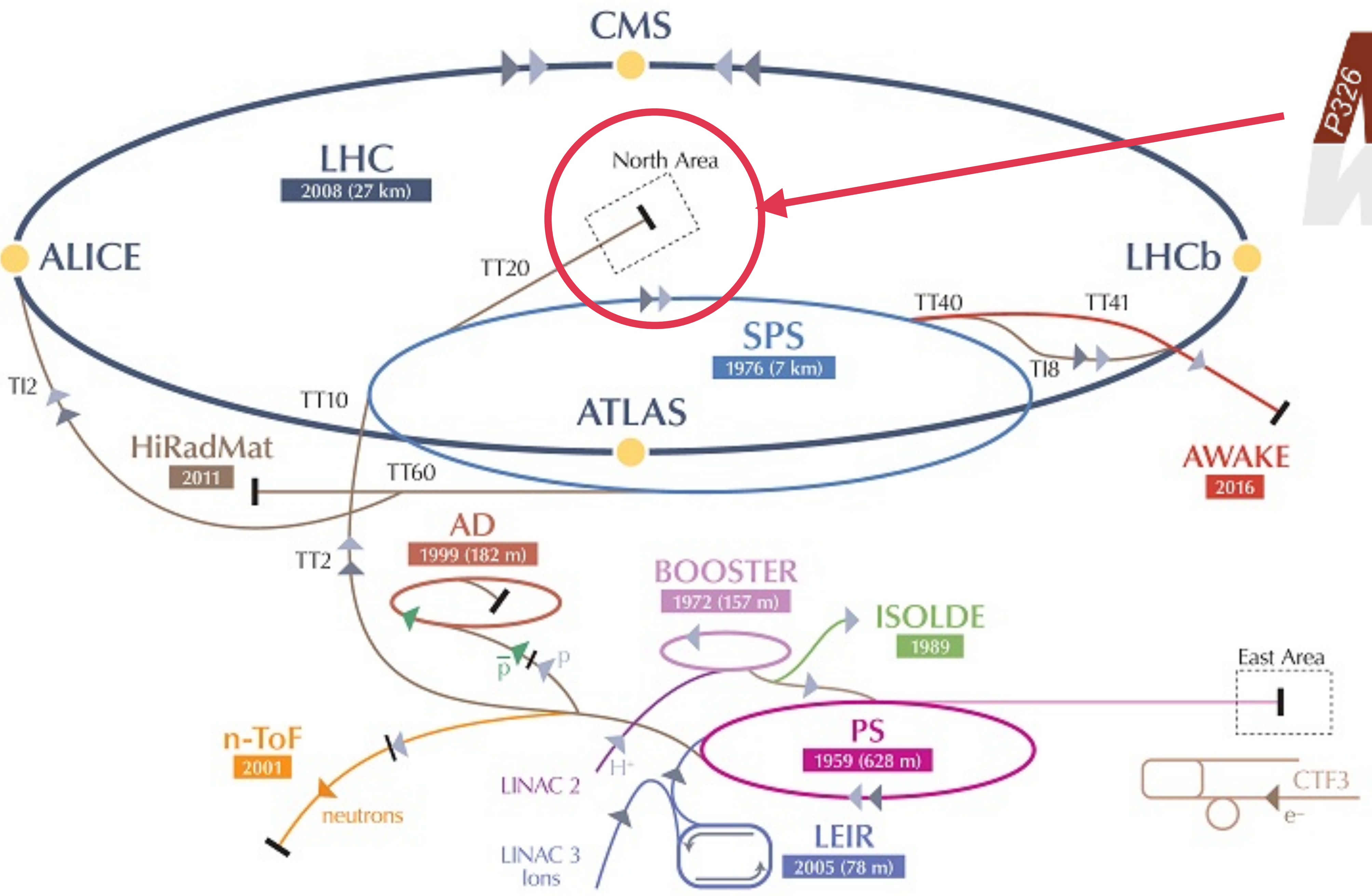


High sensitivity to **new physics that affects BR(K → πνν)** of charged and neutral channel differently. Measurements of both can discriminate among different scenarios:

- 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)

The Kaon Factory

In the CERN SPS North Area the K12 extraction line provides an extremely intense Kaon beam



- NA62 **Run 1 (2016-2018)**: data-taking
- Long shutdown 2 (LS2)
- NA62 **Run 2 (2021-2025)**: data-taking

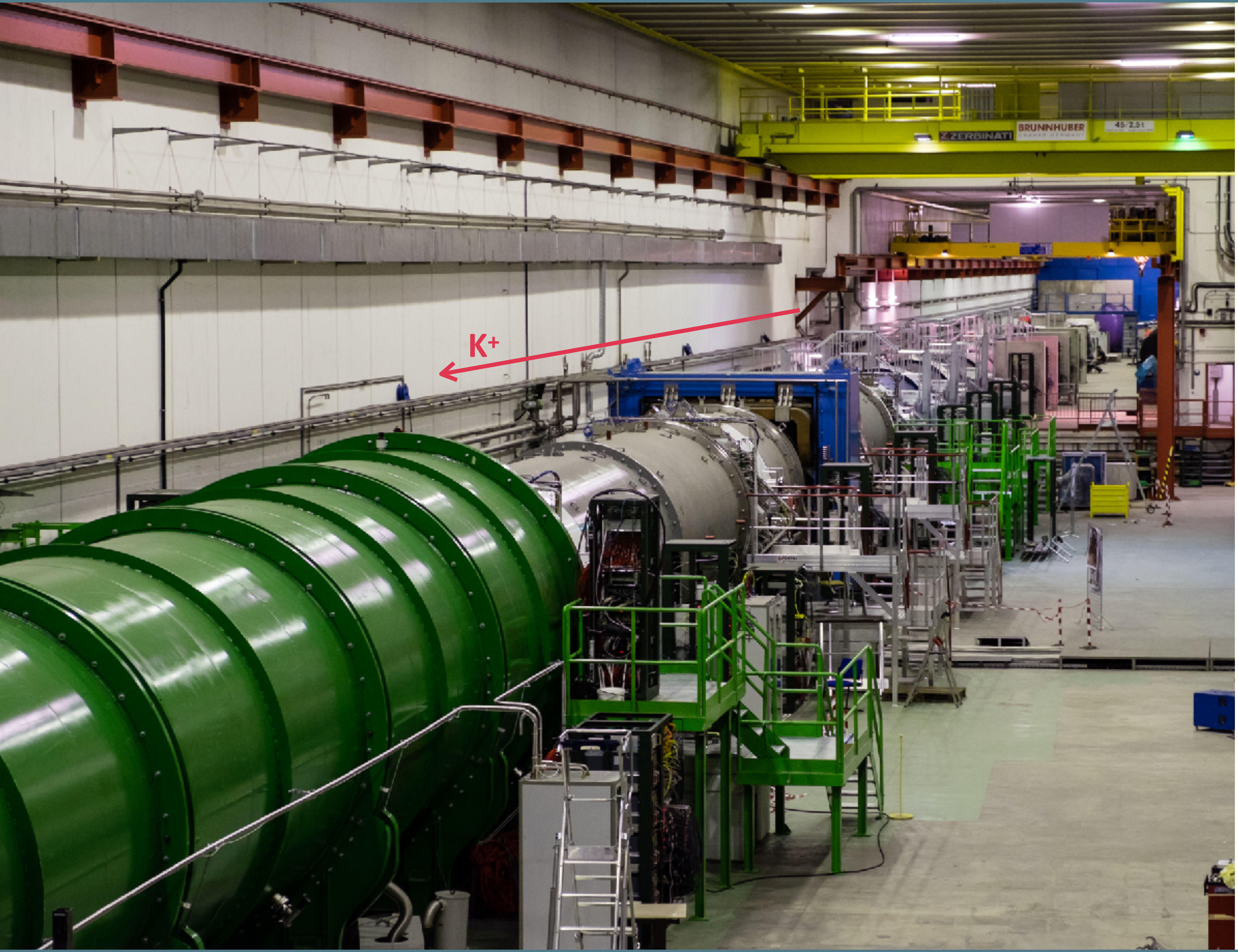
Collaboration of ~ 200 participants from 31 institutions:
Birmingham, Bratislava, Bristol, Bucharest, CERN, dubna, Fairfax, Ferrara, Florence, Glasgow, Lancaster, Lausanne, Liverpool, LNF, Louvain, Mainz, Marseille, Moscow, Munich, Naples, Perugia, Pisa, Prague, Protvino, Rome I, Rome II, San Luis Potosi, SLAC, Turin, TRIUMF, Vancouver UBC

BEAM:

400 GeV/c **primary protons** (3 x 10^{12} p/pulse) → 40 cm **Be target** → **75 GeV/c** unseparated secondary **hadrons beam** **π^+, p, K^+ (6%).** ($\Delta p/p \pm 1\%$)

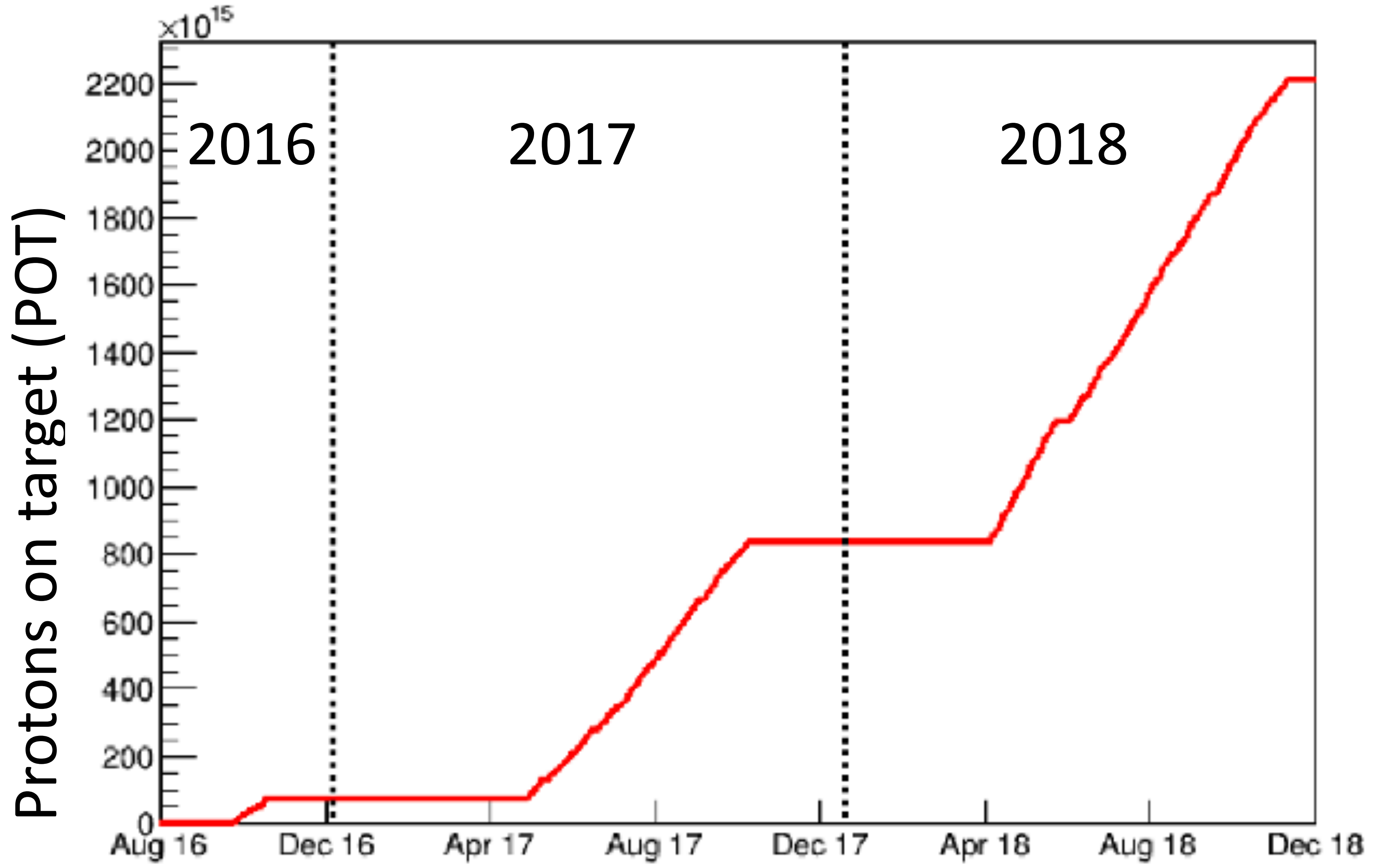
750 MHz total particle rate in secondary beam: 45 MHz of *K^+* (6%)

NA62 experiment at the CERN SPS

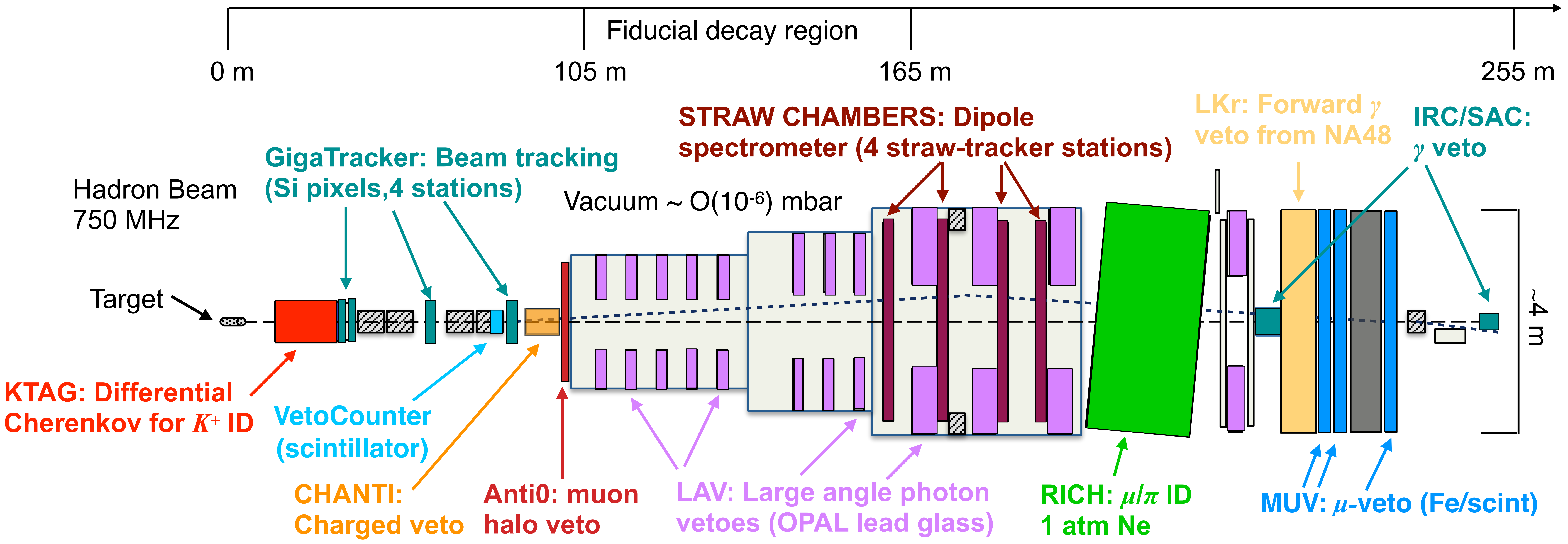


Kaon precision physics

- 270 m long downstream of the target
- Cylindrical shape around the beam axis for the main detectors (diameters from 20 to 400 cm)
- Kaons with high momentum: **decay in flight technique**.



NA62 detector

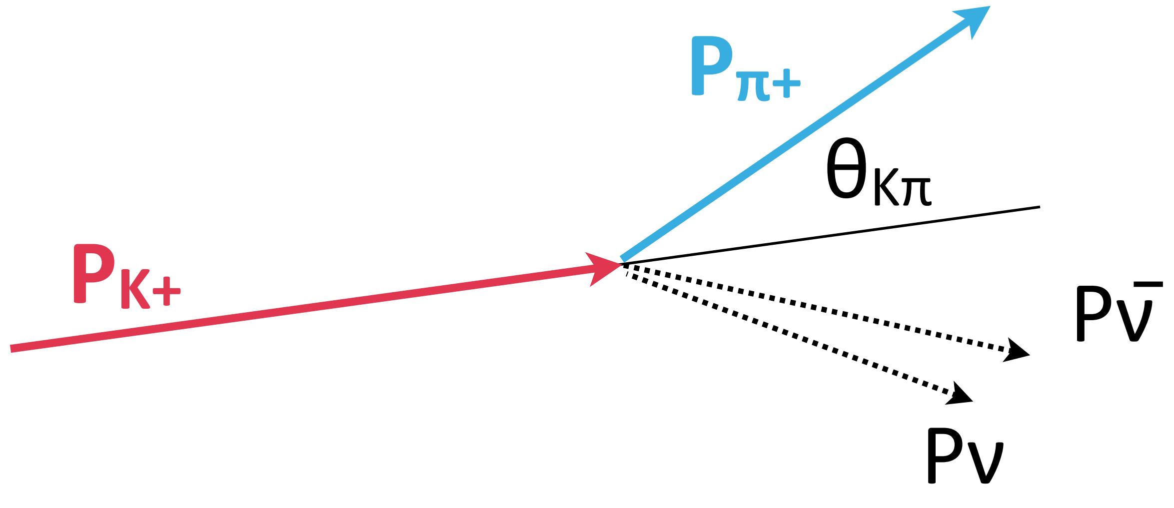


- **Beam tracker**: GTK
- **Kaon tagger**: KTAG ($\sigma_t \sim 70$ ps)
- **Downstream tracker**: (π/μ/e):
  Straw $\sigma_p/p = 0.3\% \oplus 0.005\% \cdot p[\mathrm{GeV}/c]$
- **Photon veto detectors**: LAV, IRC, SAC
- **Secondary particle ID**: RICH
- **Trigger and timing**: CHOD ($\sigma_t \sim 1$ ns), NA48-CHOD ($\sigma t \sim 200$ ps)
- **Electromagnetic calorimeter**:
  LKr $\sigma_E/E = 4.8\%/\sqrt{E} \oplus 11\%/E \oplus 0.9\%$, [E]=GeV
- **Hadronic calorimeters**: MUV1,2
- **Muon veto detector**: MUV3 ($\sigma t \sim 500$ ps)

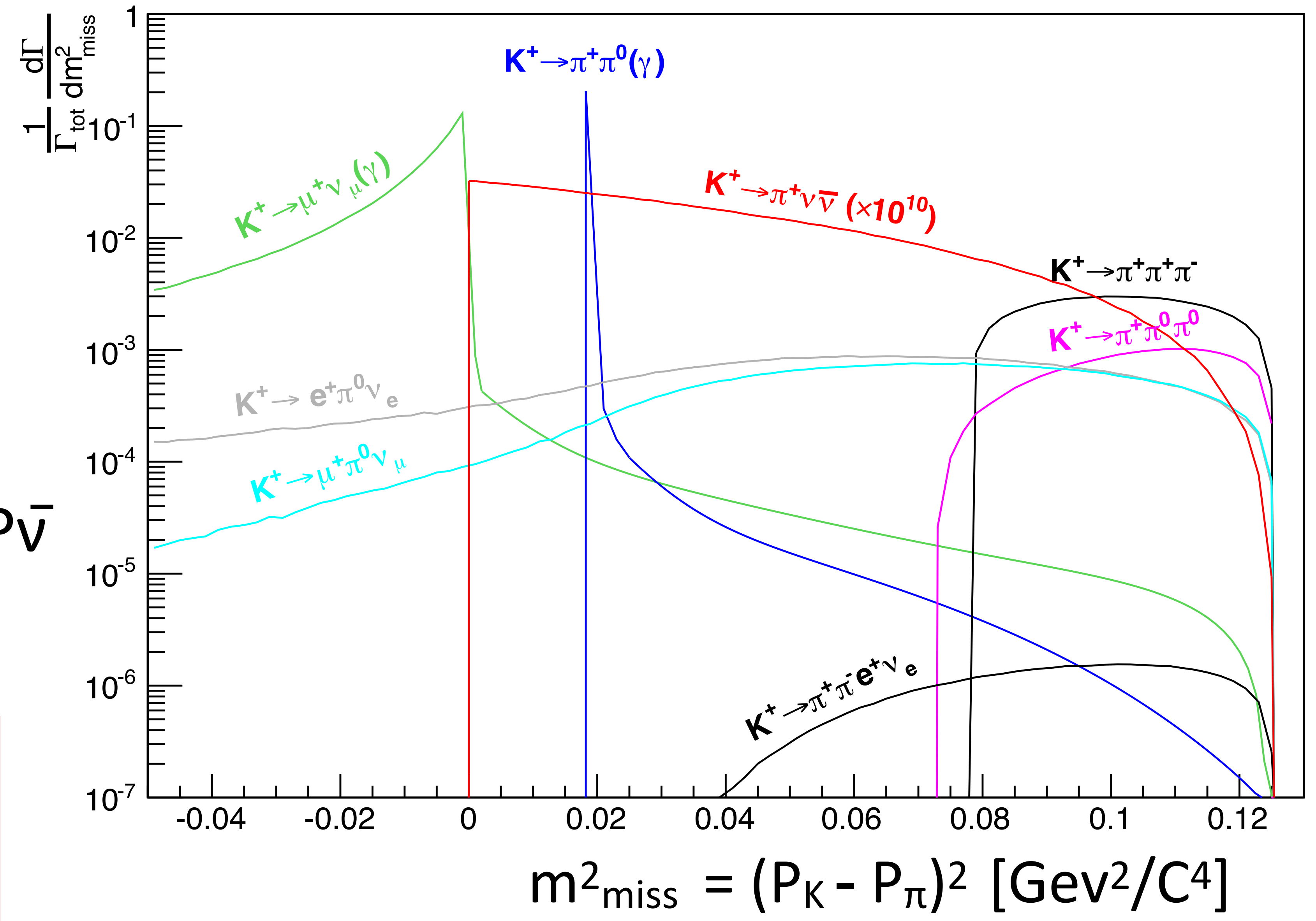
$BR(K^+ \longrightarrow \pi^+\nu\nu)$: NA62 analysis strategy

Selection:

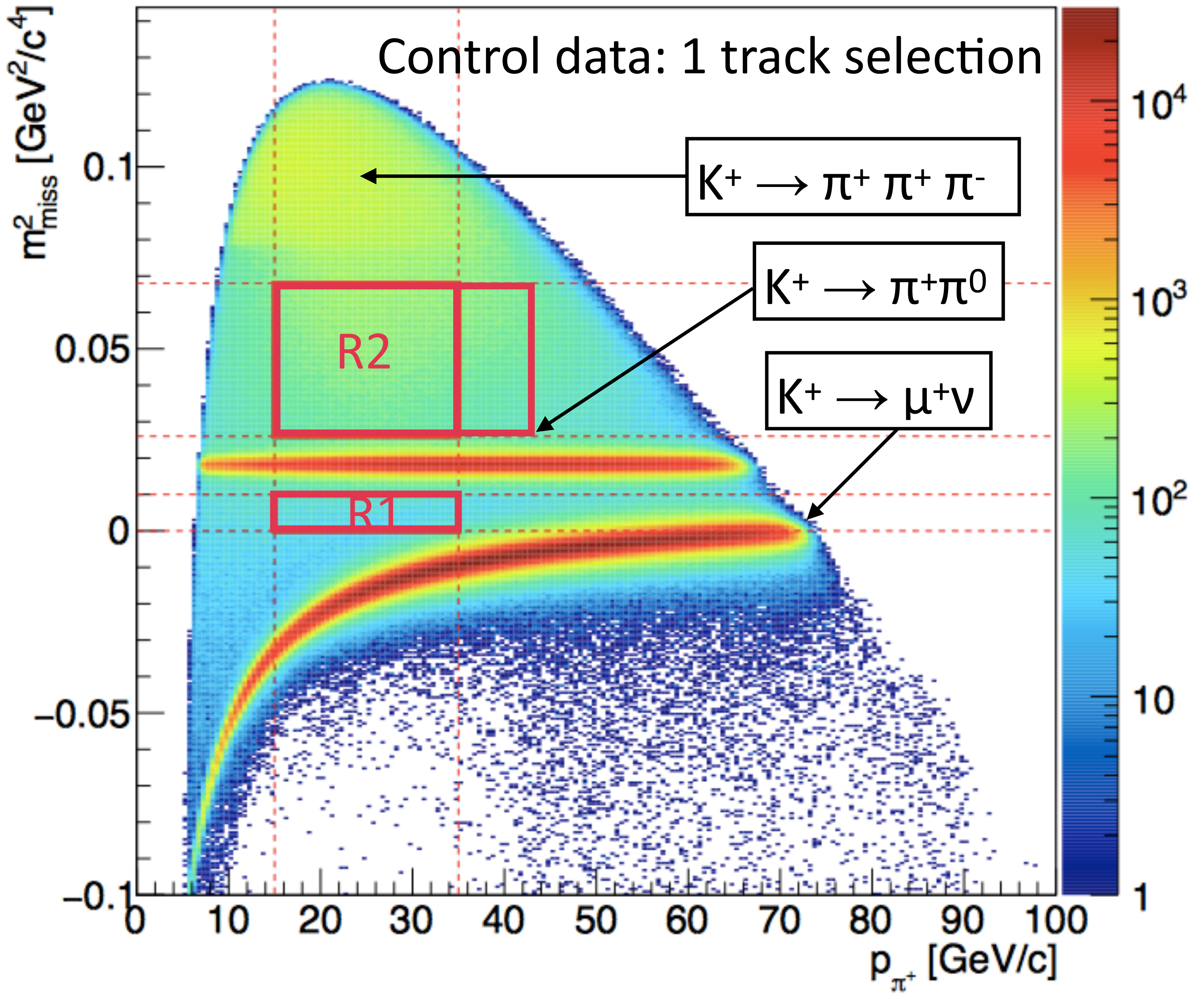
- K^+ - π^+ matching
- π^+ identification
- Photon rejection
- $110 < Z_{vertex} < 165$ m
- $15 < P_{\pi+} < 45$ GeV/c



Most discriminating variable:
$m^2_{miss} = (P_{K+} - P_{\pi+})^2$ with m_π hypothesis for the charged daughter



2 signal regions,
on each side of the $K^+ \longrightarrow \pi^+\pi^0$ peak
(to eliminate 92% of the K^+ width)



Performance:

- Kinematic rejection ~10^4
- μ^+ rejection > 10^7
- π^0 rejection > 10^7
- $\sigma(m^2_{miss}) = 1 \cdot 10^{-3}$ GeV^2
- σ_T ~ O(100ps)

Background sources:

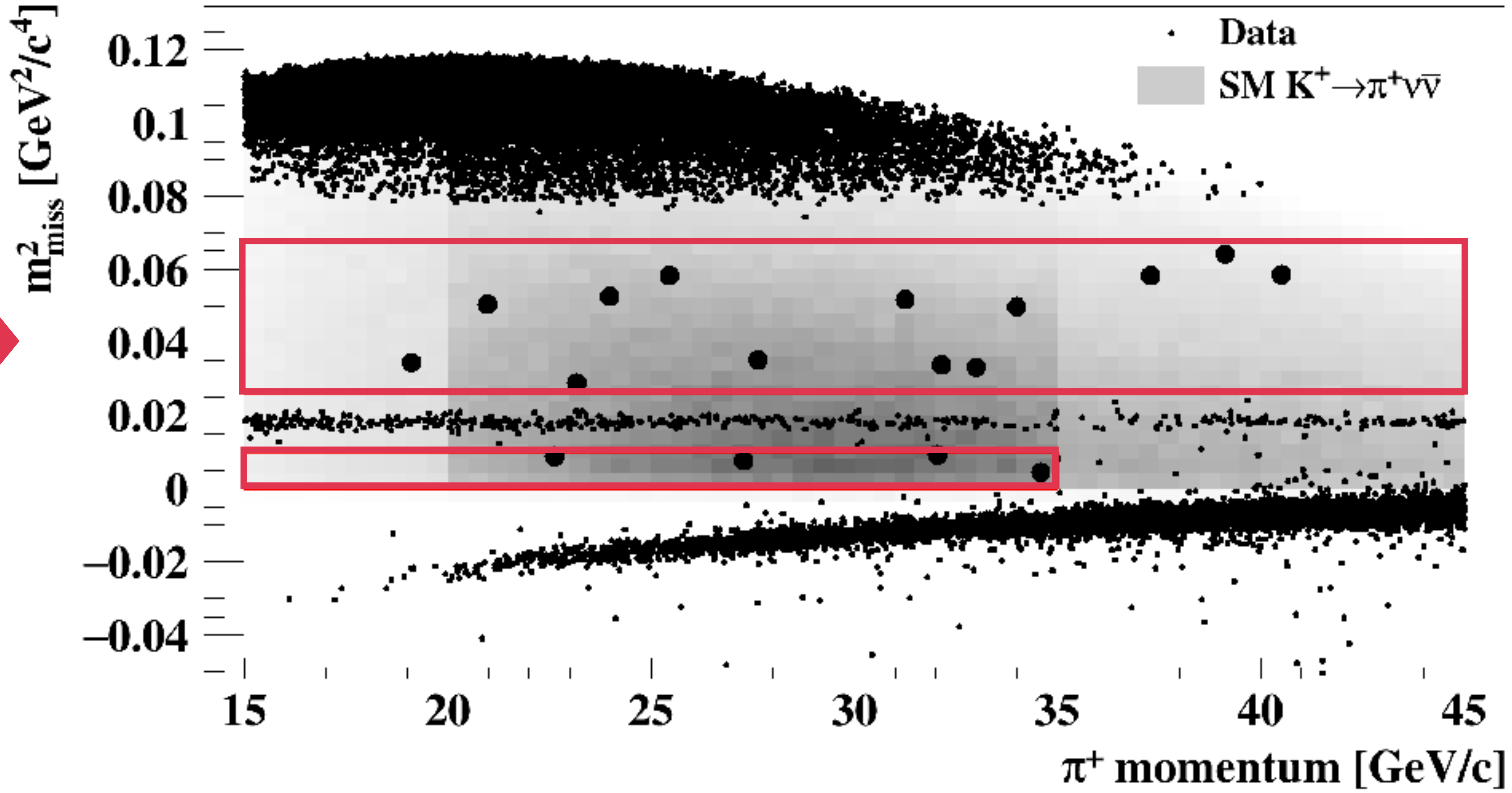
- $K^+ \longrightarrow \pi^+\pi^0$, $K^+ \longrightarrow \mu^+\nu$
- $K^+ \longrightarrow \pi^+\pi^+\pi^-$ non gaussian resolution tails
- decays with neutrino in final state
- Upstream interactions

BR($K^+ \longrightarrow \pi^+\nu\nu$): result from Run1 (2016-2018)

Process	Expected events in R1+R2
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	$7.58 \pm 0.40_{syst} \pm 0.75_{ext}$
$K^+ \to \pi^+\pi^0(\gamma)$	0.75 ± 0.04
$K^+ \to \mu^+\nu(\gamma)$	0.49 ± 0.05
$K^+ \to \pi^+\pi^-e^+\nu$	0.50 ± 0.114
$K^+ \to \pi^+\pi^+\pi^-$	0.24 ± 0.08
$K^+ \to \pi^+\gamma\gamma$	$0 < 0.01$
$K^+ \to l^+\pi^0\nu_l$	$0 < 0.001$
Upstream background	$3.3^{+0.98}_{-0.73}$
Total background	$5.28^{+0.99}_{-0.74}$

2018 data

Observed 17 $K^+ \longrightarrow \pi^+\nu\nu$ candidates



2016 + 2017 + 2018 data

Observed 20 (1+2+17) $K^+ \longrightarrow \pi^+\nu\nu$ candidates

$\mathrm{SES} = (8.39 \pm 0.53_{syst}) \times 10^{-12}$

Expected signal: $10.01 \pm 0.42_{syst} \pm 1.19_{ext}$

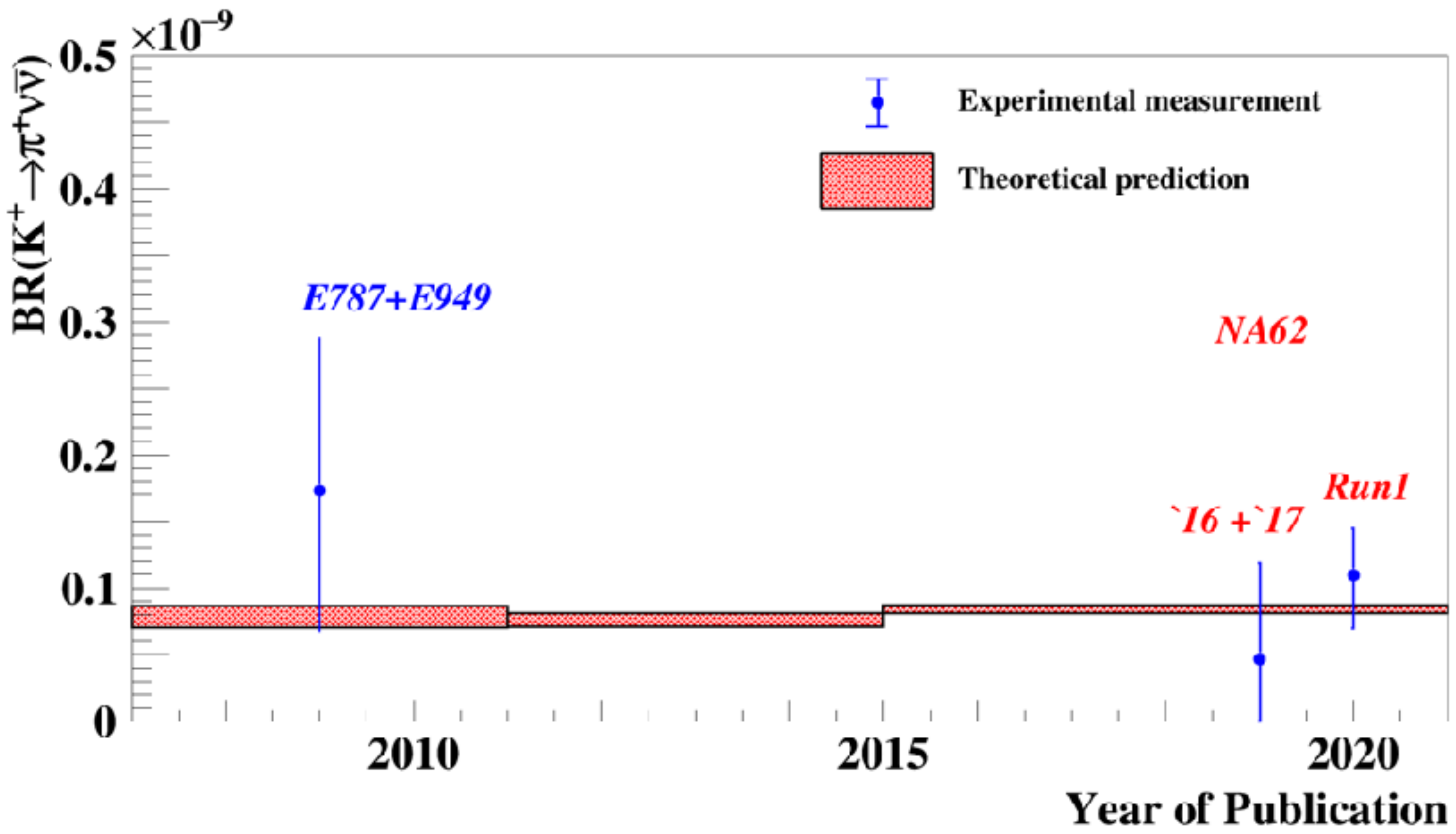
Expected background: $7.03^{+1.05}_{-0.82}$

$$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}{}_{stat} \pm 0.9_{syst}) \times 10^{-11}$$

3.4 σ significance most precise measurement to date!

[JHEP06 (2021) 093]

BR($K^+ \longrightarrow \pi^+\nu\nu$) overview



Theoretical SM prediction:

$$\mathrm{BR}^{\mathrm{SM}}(K^+ \to \pi^+\nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$
$$\mathrm{BR}^{\mathrm{SM}}(K_L \to \pi^0\nu\bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11}$$

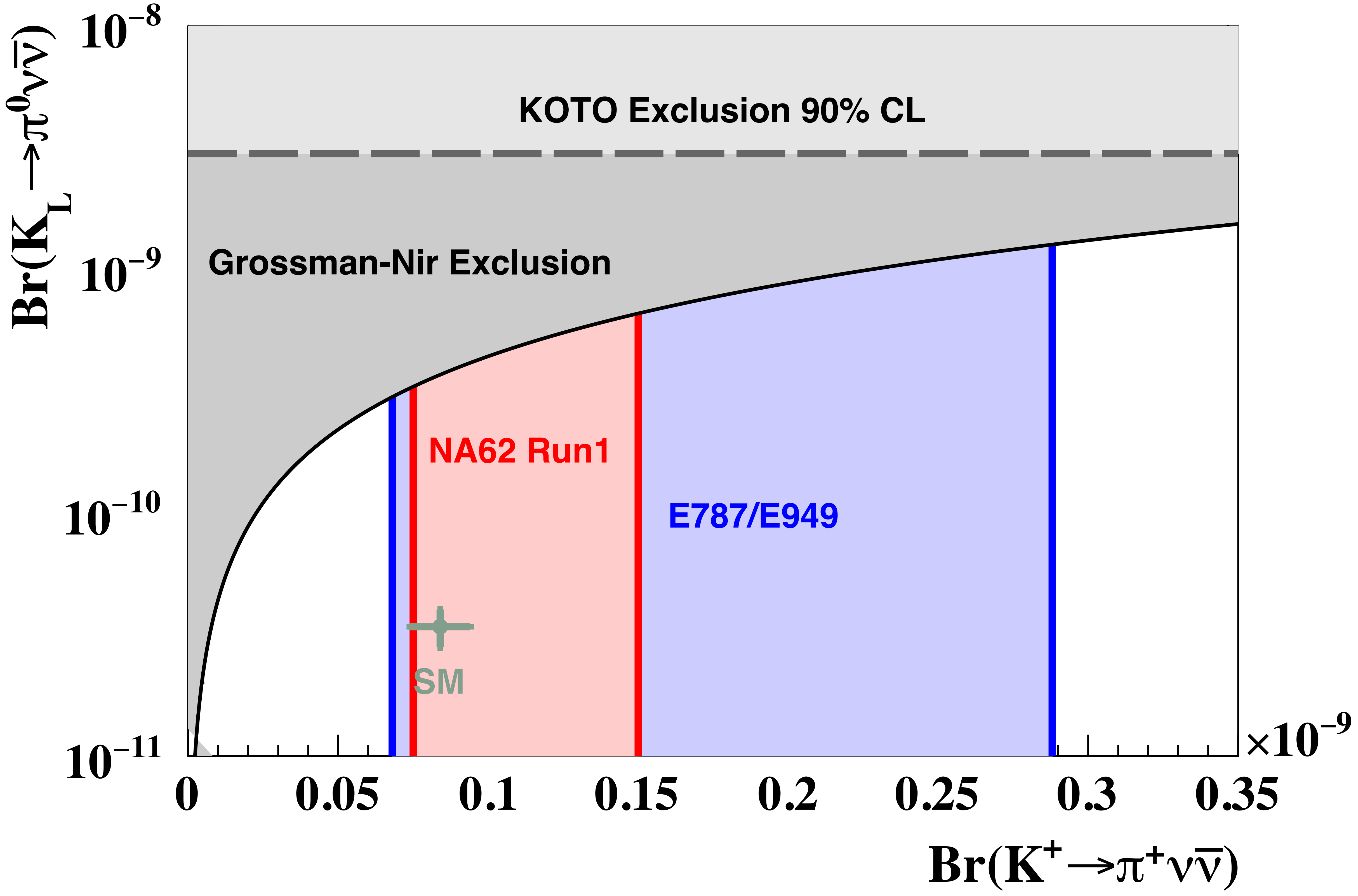
[Buras et al, JHEP11(2015)033]

15 - 20% precision on BR measurement foreseen with final NA62 statistic (Run 1 + Run 2)

Grossman-Nir: model independent relation

$$\frac{\Gamma(K_L \to \pi^0\nu\bar{\nu})}{\Gamma(K^+ \to \pi^+\nu\bar{\nu})} = sin^2\theta$$ < 4.4 [Phys. Lett. B 398, 163 (1997)]

θ: CP violating phase between K-K mixing amplitude and $s \longrightarrow d\nu\nu$ decay amplitude



BR($K^+ \longrightarrow \pi^+\nu\nu$) in Run 2 (2021 - 2025)

NA62 upgrade after LS2:

- A **4th GTK** station for the K^+ tracking
- New VetoCounters: one to reduce upstream background (**VetoCounter**), one at the beginning of the fiducial volume to reduce muon halo (**Anti0**)
- New small calorimeter downstream to reject photons from conversion (**HASC**)

From 2023:

- New Trigger Processor (**L0TP+**)
- Cherenkov for K^+ ID filled with Hydrogen (before: Nitrogen) to reduce material along beam line (**Cedar-H**)

Signal efficiency increased: +60% wrt Run 1 analysis

Year	Weeks	Bursts (Good)	PoT	Intensity	PNN/burst
2023	22	$\sim 400K$ (WIP)			
2022	29	$\sim 400K(300K)$	$\sim 3.5 \cdot 10^{18}$	100%	$\sim 2.5 \times 10^{-5}$
2021	18	$\sim 140K(120K)$			
2018	31	520K (450K)		65%	1.7×10^{-5}
2017	24	300K (254K)	$3 \cdot 10^{18}$	50%	0.8×10^{-5}
2016	8	84K (67K)		40%	0.4×10^{-5}

Process	2018	2022
$K^+ \to \pi^+\pi^0(\gamma)$	0.75 ± 0.05	0.82 ± 0.03
$K^+ \to \mu^+\nu(\gamma)$	0.64 ± 0.08	0.74 ± 0.06
$K^+ \to \pi^+\pi^+\pi^-$	0.22 ± 0.08	0.09 ± 0.02
$K^+ \to \pi^+\pi^-e^+\nu$	0.51 ± 0.10	0.31 ± 0.16
Upstream	$3.30^{+0.98}_{-0.73}$	WIP
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	7.58 ± 0.85	8.00 ± 1.1

Expected events in signal region (2018 vs 2022)

Final goal: 40-50 expected SM signal events

NA62 as a multi-purpose experiment

Trigger system flexibility and detector performances make NA62 ideal for many kind of measurements

Flavour Physics

Search for New Physics at the EW scale with sizable coupling to SM particles via indirect effects in loops:

Experiment main goal:

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

Preliminary result with 2021-2022 data expected in winter 2024

Search for lepton flavor/number violation, rare/forbidden decays (**HNL, LFV, LNV**)

$K^+ \to \pi^\pm \mu^\mp e^+$
$K^+ \to \pi^- l^+ l^+$
$K^+ \to \pi^+ l^+ l^-$
$K^+ \to \pi^- \pi^0 e^+ e^+$
$K^+ \to \mu^- \nu e^+ e^+$
$\pi^0 \to \mathrm{invisible}$

Dump mode: Hidden sector Physics

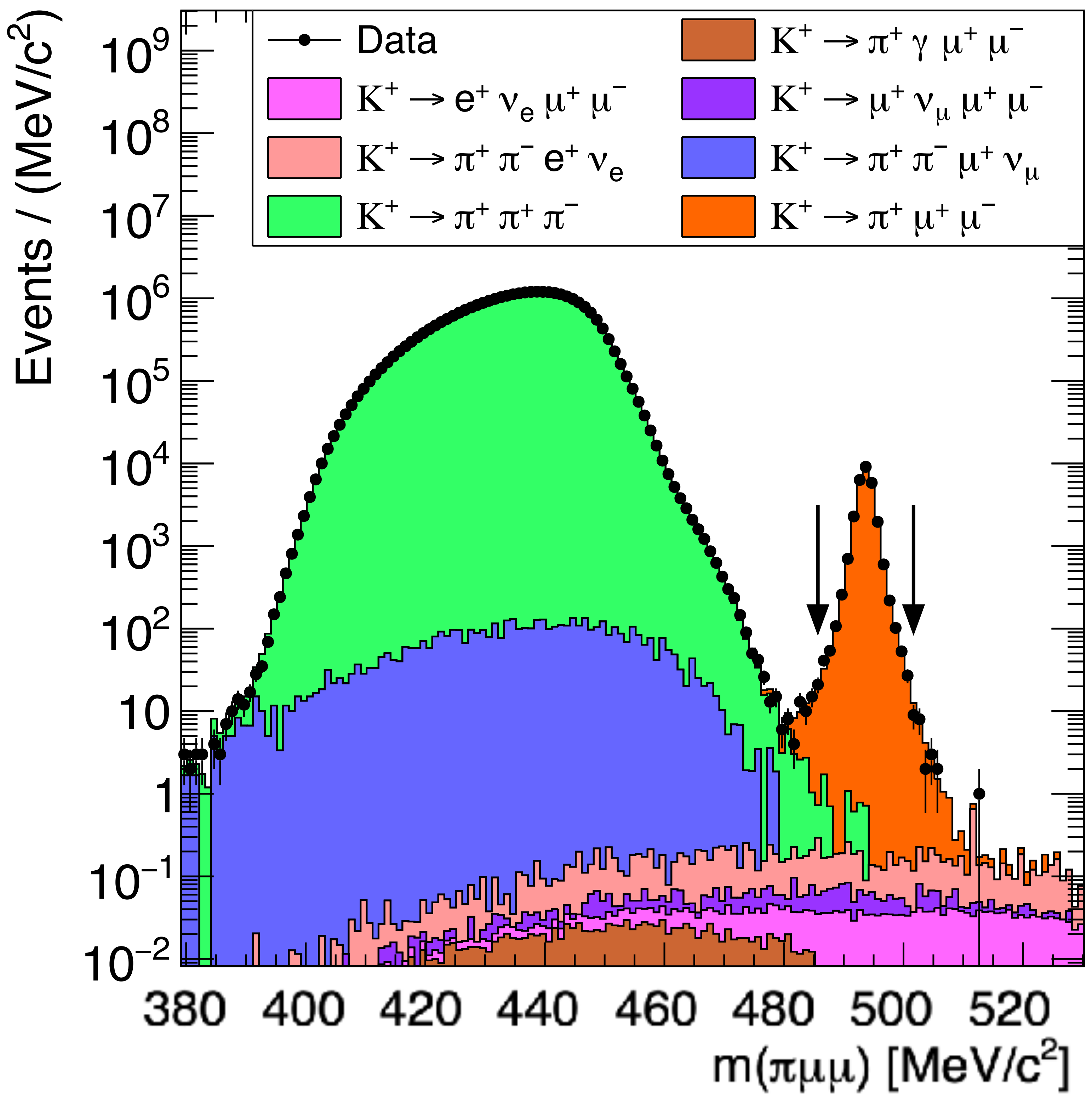
Search for New Physics below the EW scale (MeV-GeV) feebly-coupled to SM particles via direct detection of long-lived particles:

Dark Photon(**DP**), Axion Like Particle (**ALPs**), Dark Scalar (**S**), Heavy neutral Lepton(**N**)

$K^+ \to l^+ \nu N$
$A' \to l^+ l^-$
$N \to \pi^\pm l^\mp$

Test of lepton universality: $K^+ \longrightarrow \pi^+\mu^+\mu^-$

FCNC kaon decays allow crucial test of
Chiral Perturbation Theory (ChPT)



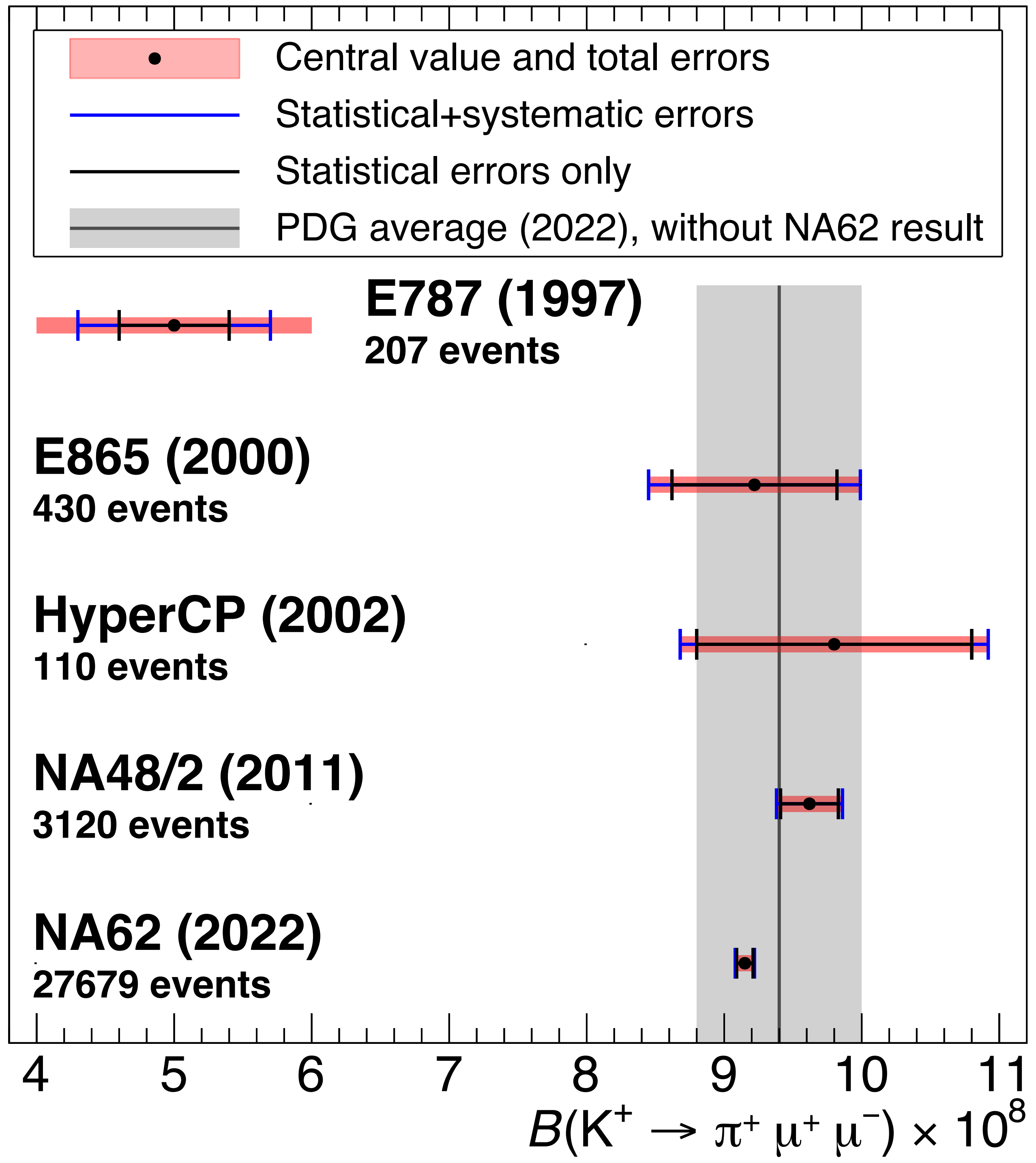
- Normalization channel $K^+ \rightarrow \pi^+\pi^+\pi^-$ ($K_{3\pi}$)
- Signal region: $|m_{\pi\mu\mu} - m_K| < 8$ MeV/c^2
- **2017+2018 data**: **27679 events** (~8 bkg)

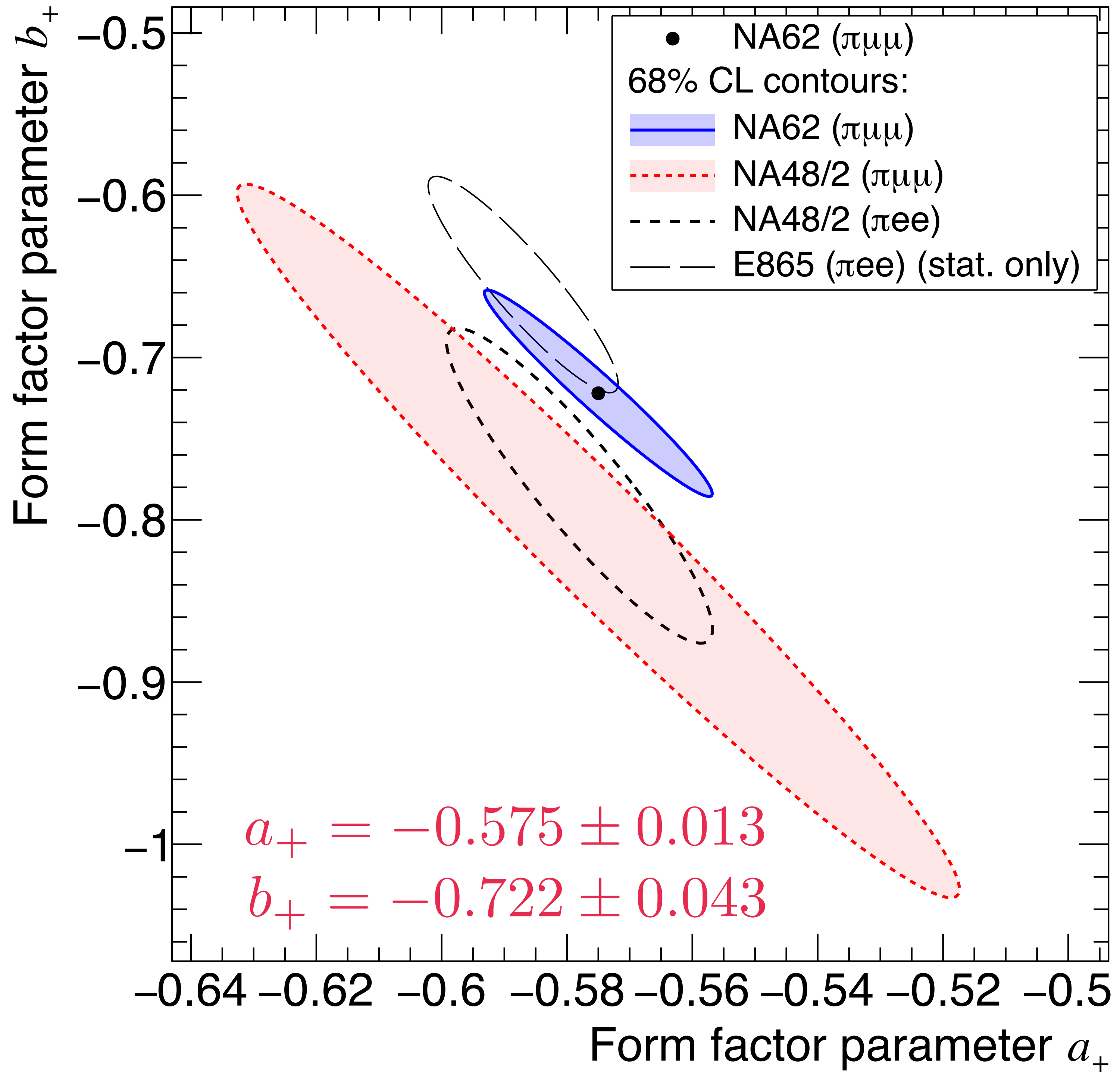
NA62 measurement: [JHEP11 (2022) 011]

- Form factor and parameter (in NLO ChPT)

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

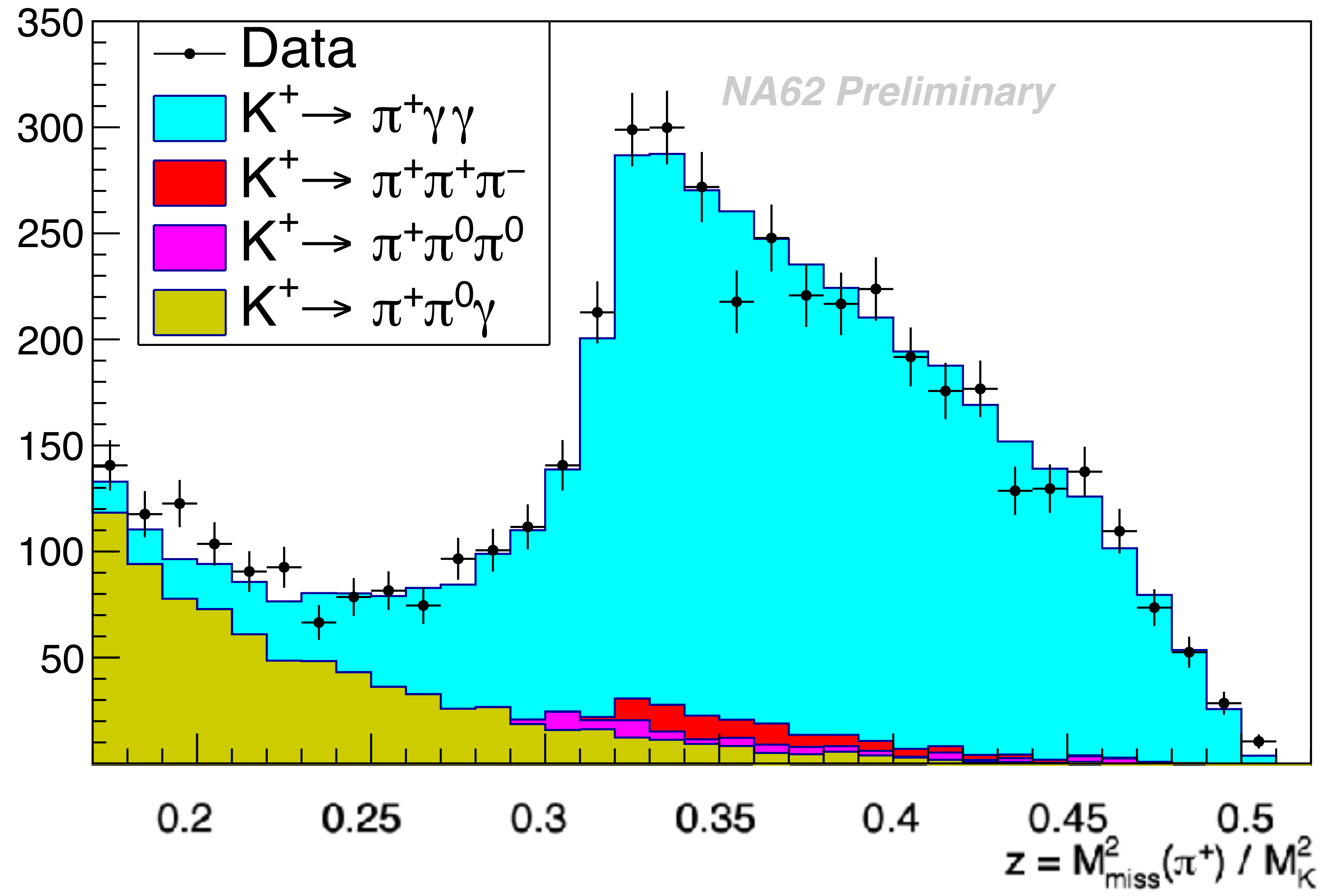
- Branching ratio model-independent $BR(K_{\pi\mu\mu}) = (9.15 \pm 0.08) \times 10^{-8}$
- Forward-backward asymmetry: $A_{FB} = (0.0 \pm 0.7) \times 10^{-2}$





Low energy QCD test: $K^+ \longrightarrow \pi^+\gamma\gamma$

Radiative non-leptonic kaon decays allow crucial test of **Chiral Perturbation Theory (ChPT)**



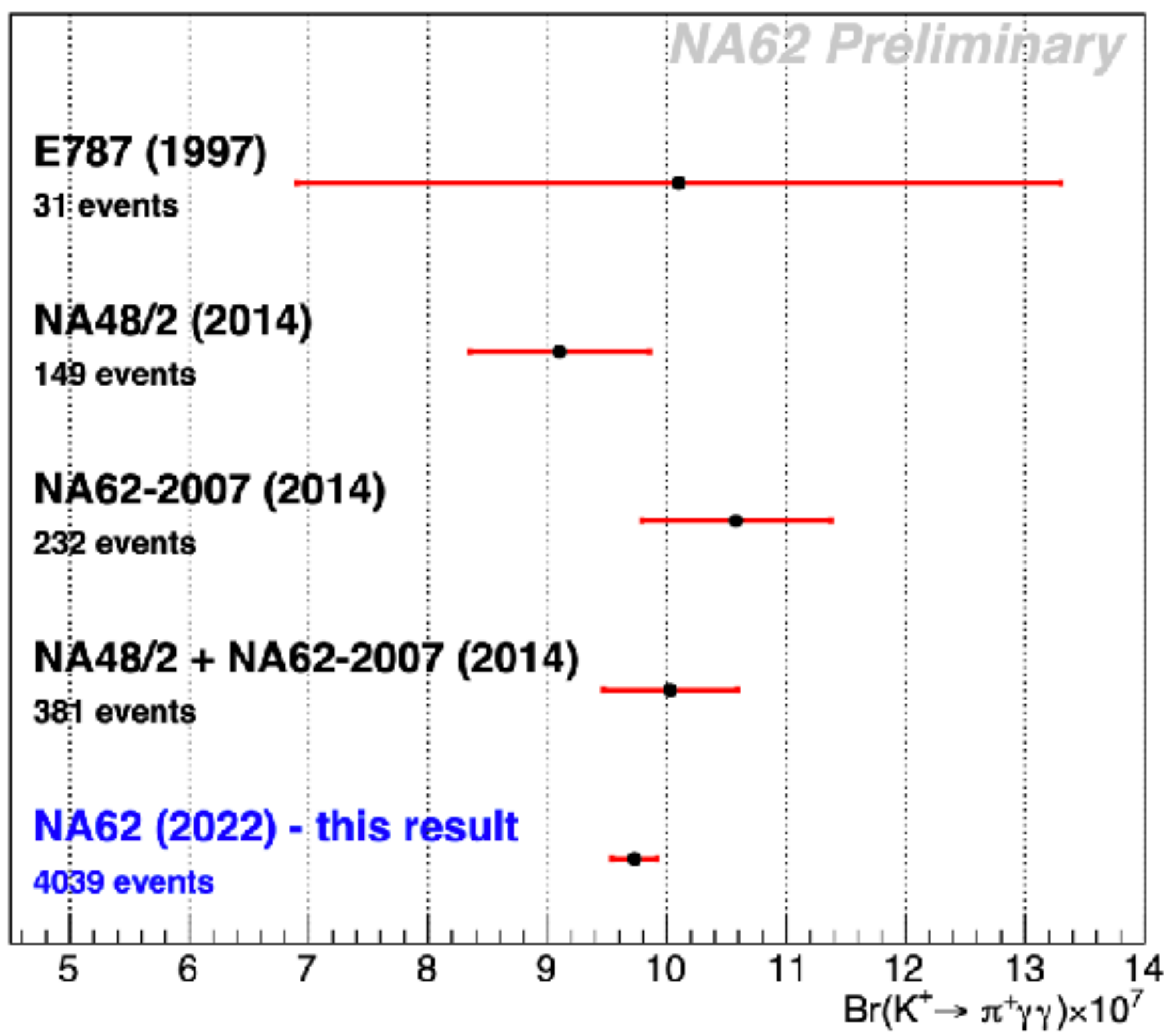
- Normalization channel: $K^+ \longrightarrow \pi^+\pi^0$ ($K_{2\pi}$)
- Signal region: $z > 0.25$
- **Run 1 (2016-2018) data**: **4039 events** (393 ± 20 background)
- **$\hat{c}$** obtained by reweighting of $K^+ \longrightarrow \pi^+\gamma\gamma$ MC and performing binned max-likelihood fit

[arXiv:2311.01837]

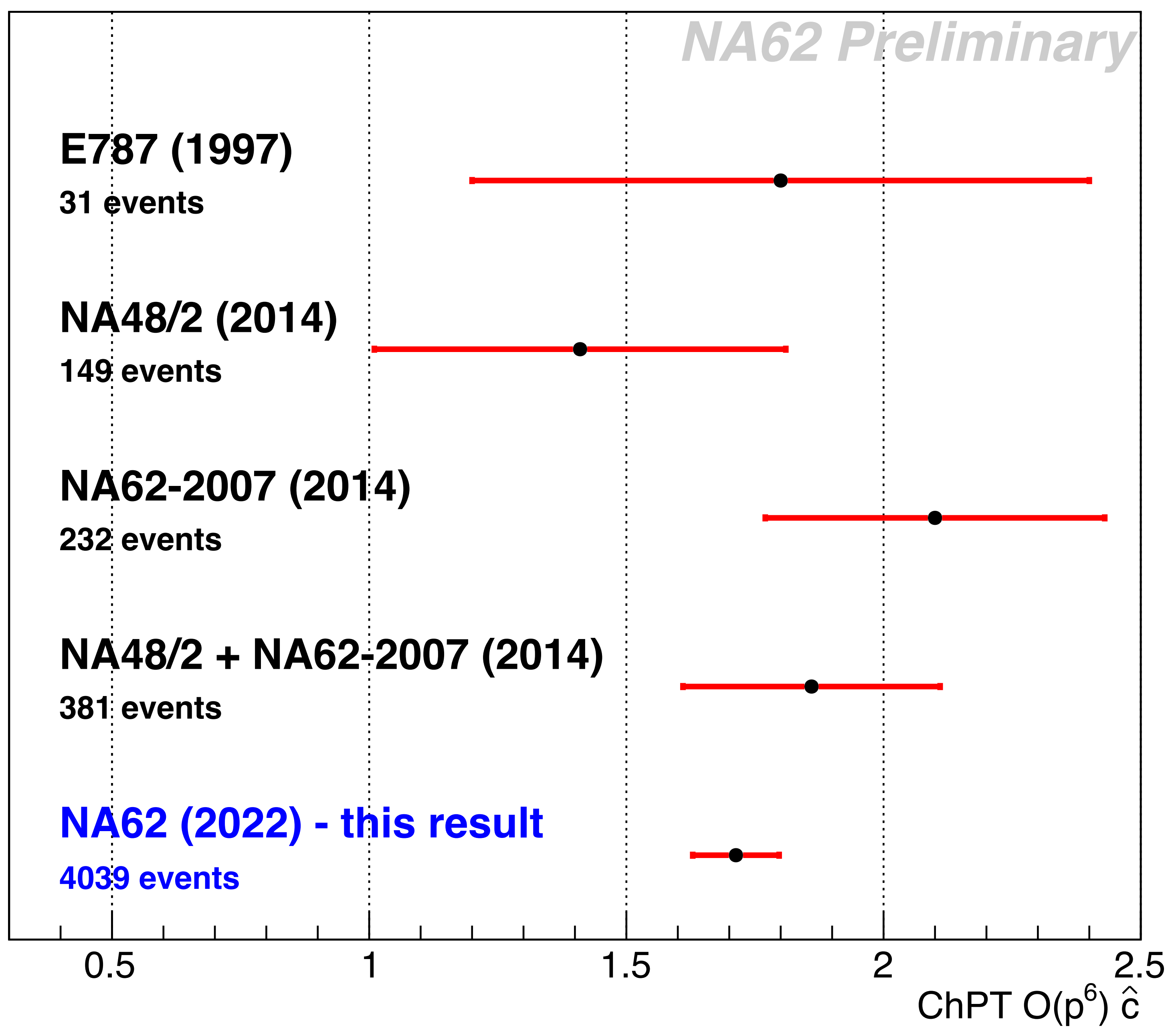
NA62 measurement:

- BR($K^+ \longrightarrow \pi^+\gamma\gamma$) parametrized in ChPT (NLO) by an unknown real parameter **$\hat{c}$** (that depends on several external parameters, fixed in this analysis, but recently updated: will be accounted for in the final result)
- Signal shape and rate depend on **$\hat{c}$**

$$BR(K_{\pi\gamma\gamma}) = (9.73 \pm 0.19) \times 10^{-7}$$



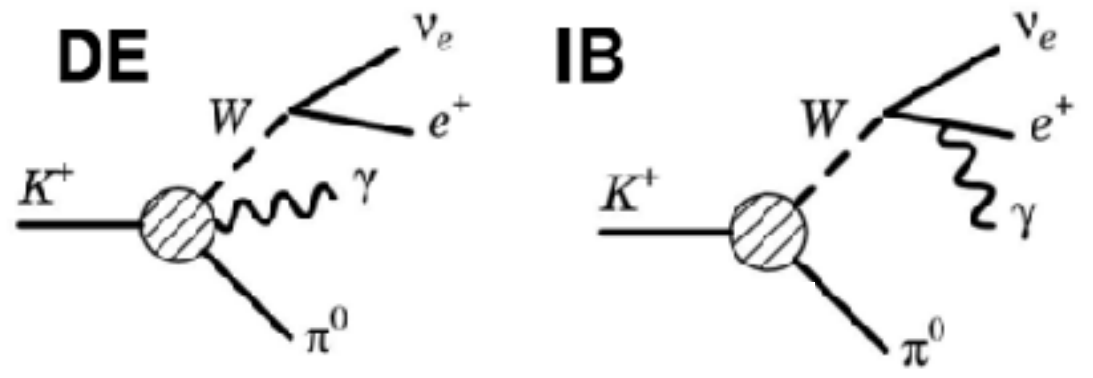
$$\hat{c} = 1.713 \pm 0.084$$



Low energy QCD test: $K^+ \longrightarrow \pi^0 e^+ \nu\gamma$

Decay described in ChPT as direct emission, inner bremsstrahlung and their interference

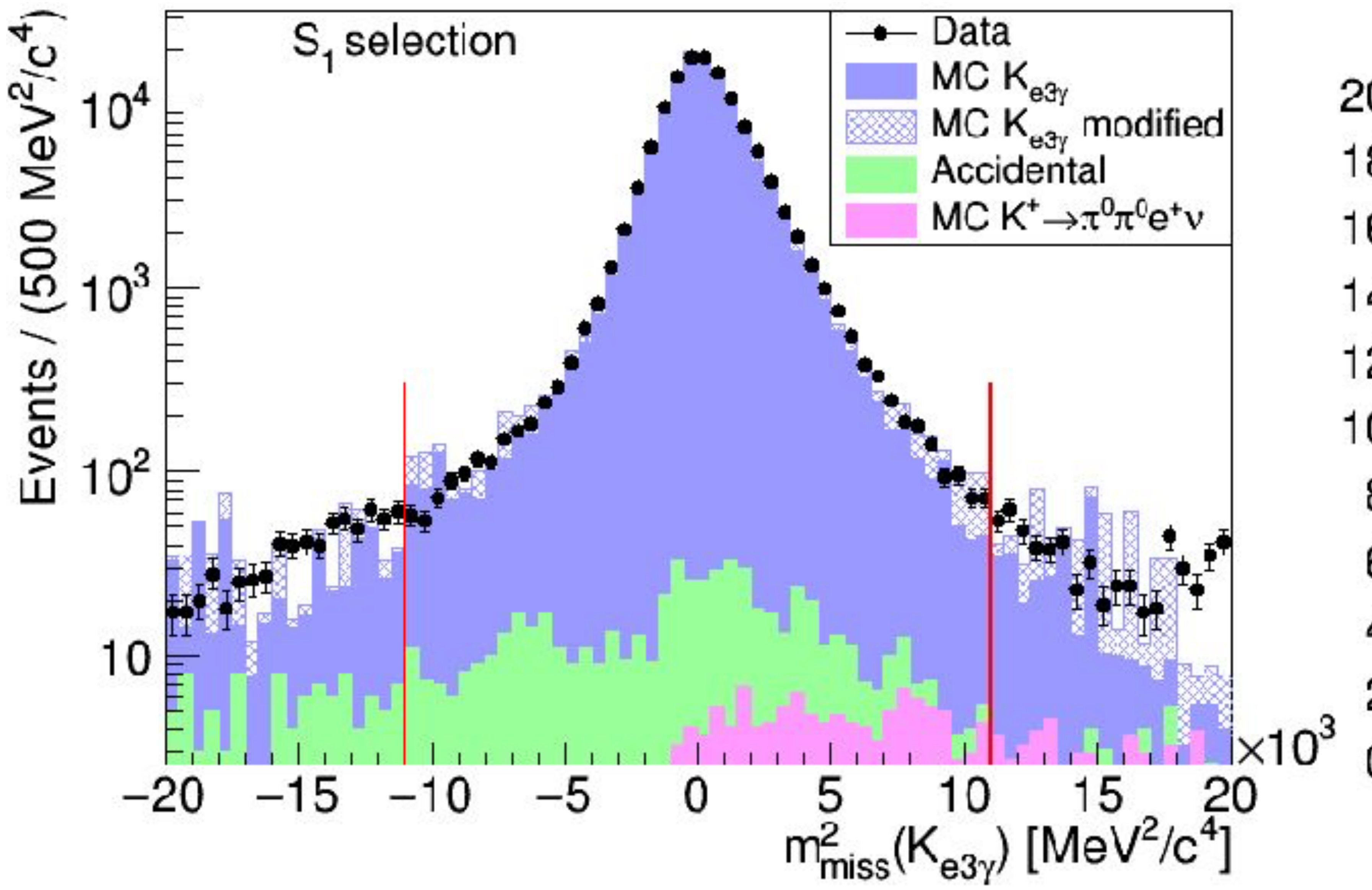
[JHEP09 (2023) 040]

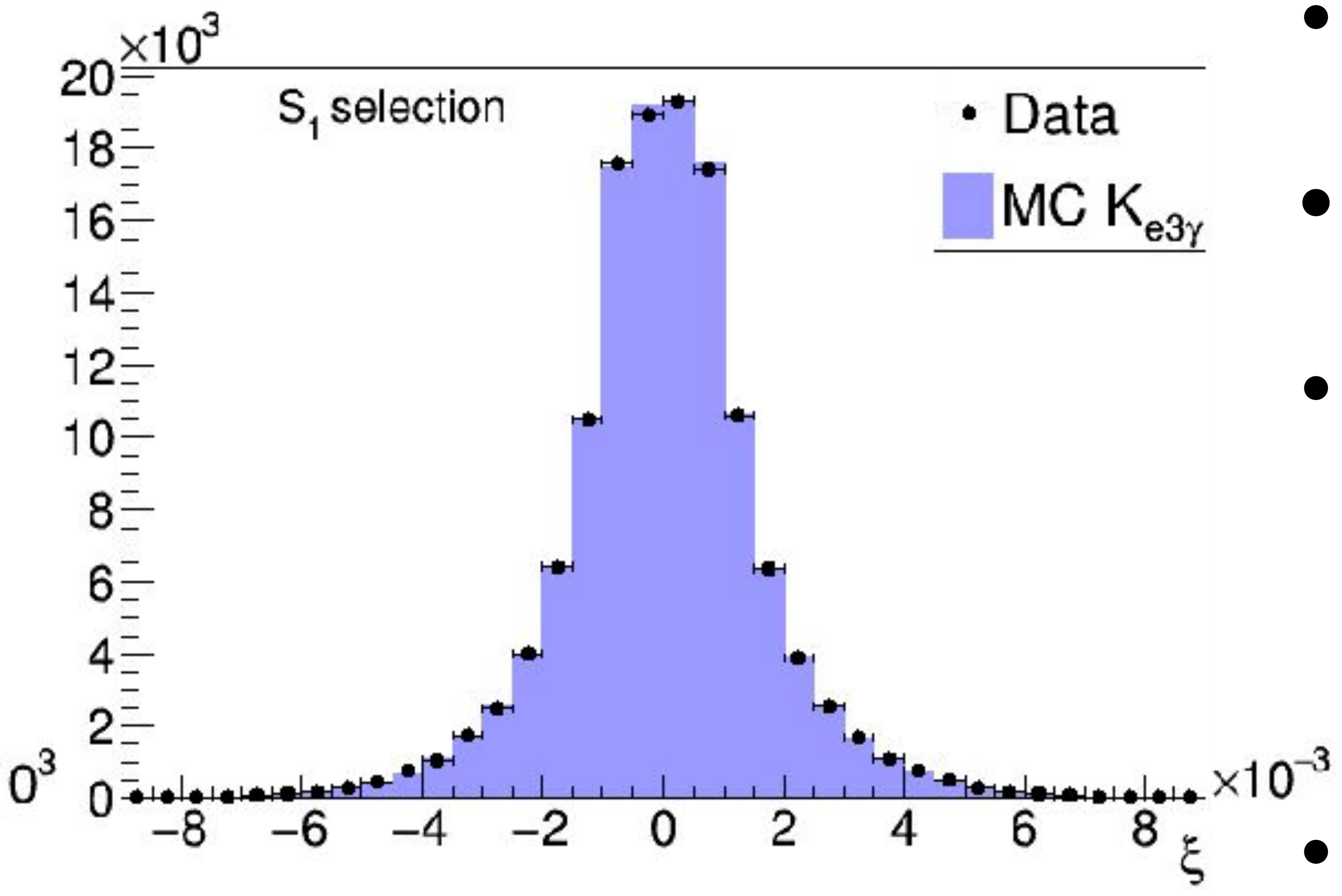


$$R_j = \frac{\mathrm{BR}(K^+ \to \pi^0 e^+ \nu\gamma \,|\, E_\gamma^j, \theta_{e\gamma}^j)}{\mathrm{BR}(K^+ \to \pi^0 e^+ \nu(\gamma))}$$

BR strongly depends on Eγ and θeγ, 3 ranges are considered:

	E_γ cut	$\theta_{e\gamma}$ cut	$O(p^6)$ ChPT	NA62
$R_1(\times 10^2)$	$E_\gamma > 10$ MeV	$\theta_{e\gamma} > 10°$	1.804 ± 0.021	$1.715 \pm 0.005 \pm 0.010$
$R_2(\times 10^2)$	$E_\gamma > 30$ MeV	$\theta_{e\gamma} > 20°$	0.640 ± 0.008	$0.609 \pm 0.003 \pm 0.006$
$R_3(\times 10^2)$	$E_\gamma > 10$ MeV	$0.6 < \cos\theta_{e\gamma} < 0.9$	0.559 ± 0.006	$0.533 \pm 0.003 \pm 0.004$





- **2017+2018 data**: **1.3 x 10⁵ events** (1% background)
- **improvement on experimental precision by a factor 2**
- Test of T-conservation thanks to T-odd observable:

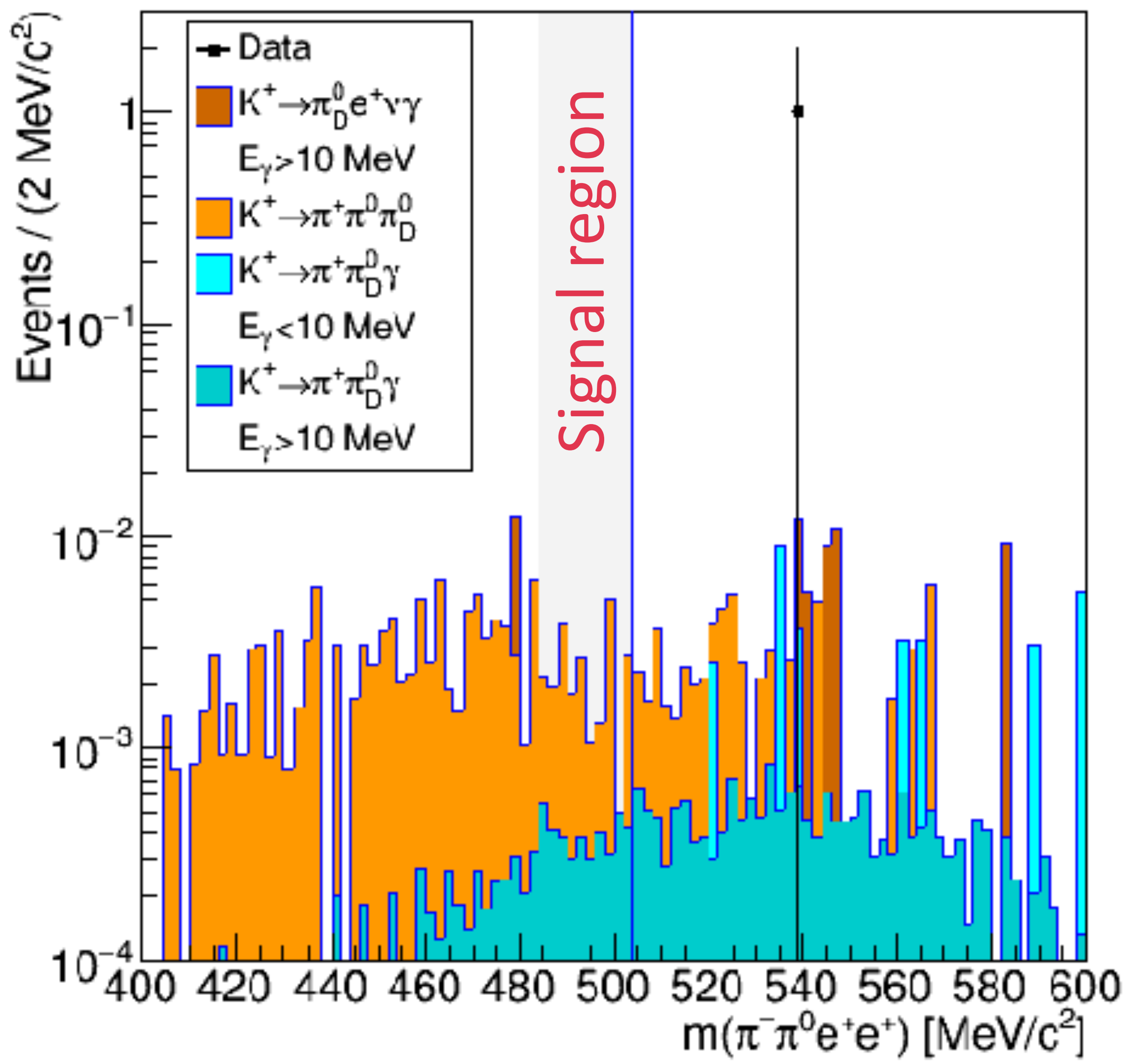
$$\xi = \frac{\vec{p_\gamma} \cdot (\vec{p}_e \times \vec{p}_\pi)}{m_K^3}, A_\xi = \frac{N_+ - N_-}{N_+ + N_-}$$

- Result compatible with **no asymmetry**

LFV and LNV searches: $K^+ \longrightarrow \mu^-\nu e^+e^+$, $K^+ \longrightarrow \pi^-\pi^0 e^+e^+$

Lepton flavor or lepton number are violated depending on the neutrino flavor

[PLB 830 (2022) 137172]



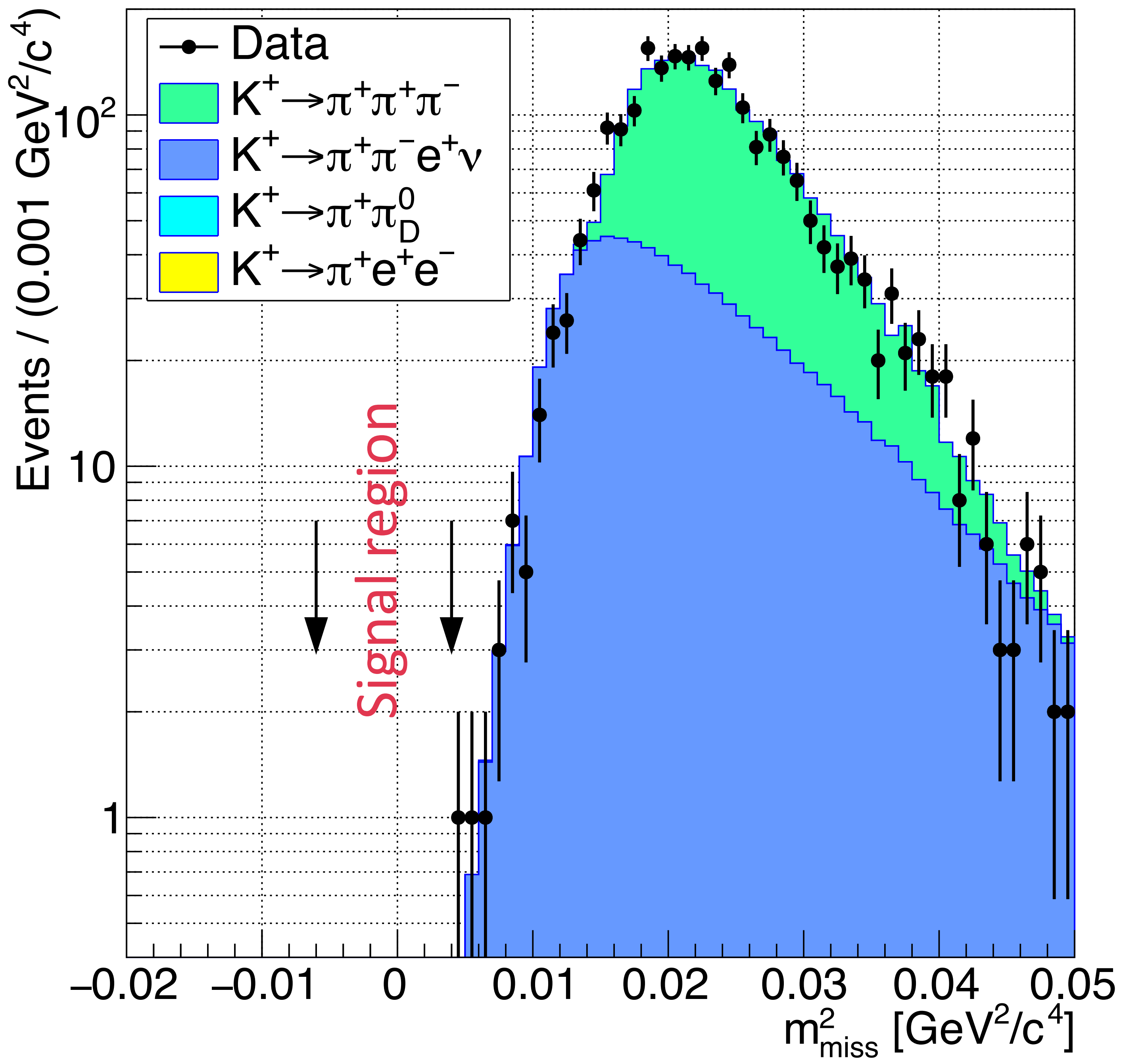
- Normalization channel: $K^+ \longrightarrow \pi^+e^+e^-$

Run 1 (2016-2018) data:
0 candidates observed
Expected background 0.044 ± 0.020
First search of this mode

$\mathrm{BR}(K^+ \to \pi^-\pi^0 e^+ e^+) < 8.5 \times 10^{-10}$ @ 90% CL

[PLB 838 (2023) 137679]

- Normalization channel: $K^+ \longrightarrow \pi^+e^+e^-$
- $BR_{SES} = (3.53 \pm 0.12) \times 10^{-11}$
- Background mainly from : $K^+ \longrightarrow \pi^+\pi^-e^+\nu$
- K^+ decays in fiducial volume $(1.97 \pm 0.02_{stat} \pm 0.02_{syst} \pm 0.06_{ext}) \times 10^{12}$
- Signal region defined on: $m^2_{miss} = (P_K - P_\mu - P_{e_1} - P_{e_2})^2$



Run 1 (2016-2018) data:
0 candidates observed
Expected background 0.26 ± 0.040
Improvement by a factor 250 over previous searches

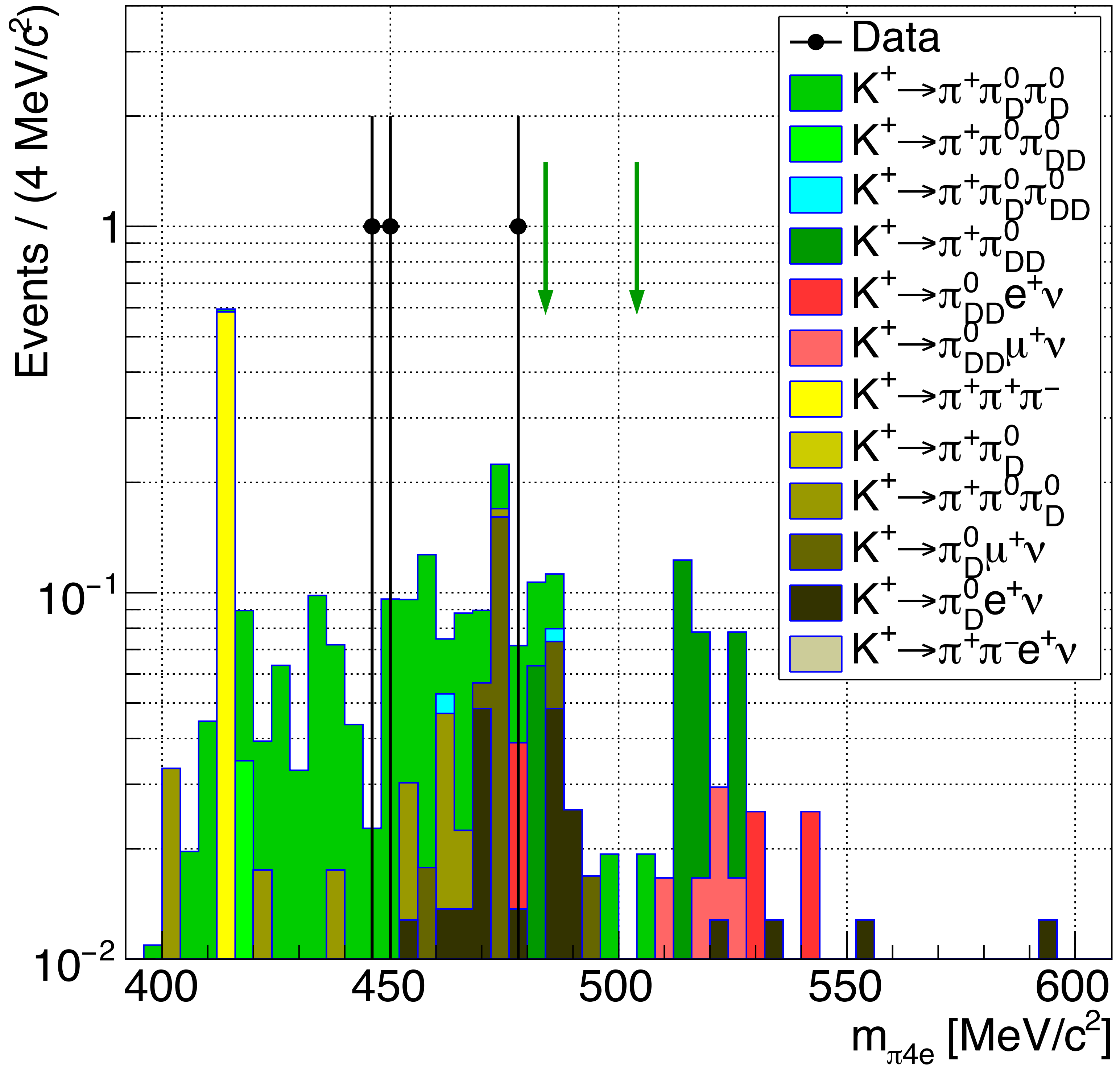
$\mathrm{BR}(K^+ \to \mu^-\nu e^+ e^+) < 8.1 \times 10^{-11}$ @ 90% CL

BSM searches: $K^+ \longrightarrow \pi^+e^+e^-e^+e^-$

[PLB 846 (2023) 138193]

SM prediction (suppressed): $BR(K^+ \longrightarrow \pi^+e^+e^-e^+e^-) = (7.2 \pm 0.7) \times 10^{-11}$
Main interest in the dark sector context: $K^+ \longrightarrow \pi^+ a\, a$ ($a \longrightarrow e^+e^-$)
Short-lived QCD axion. If m_a = 17 MeV: $BR(K^+ \longrightarrow \pi^+e^+e^-e^+e^-) > 2 \times 10^{-8}$

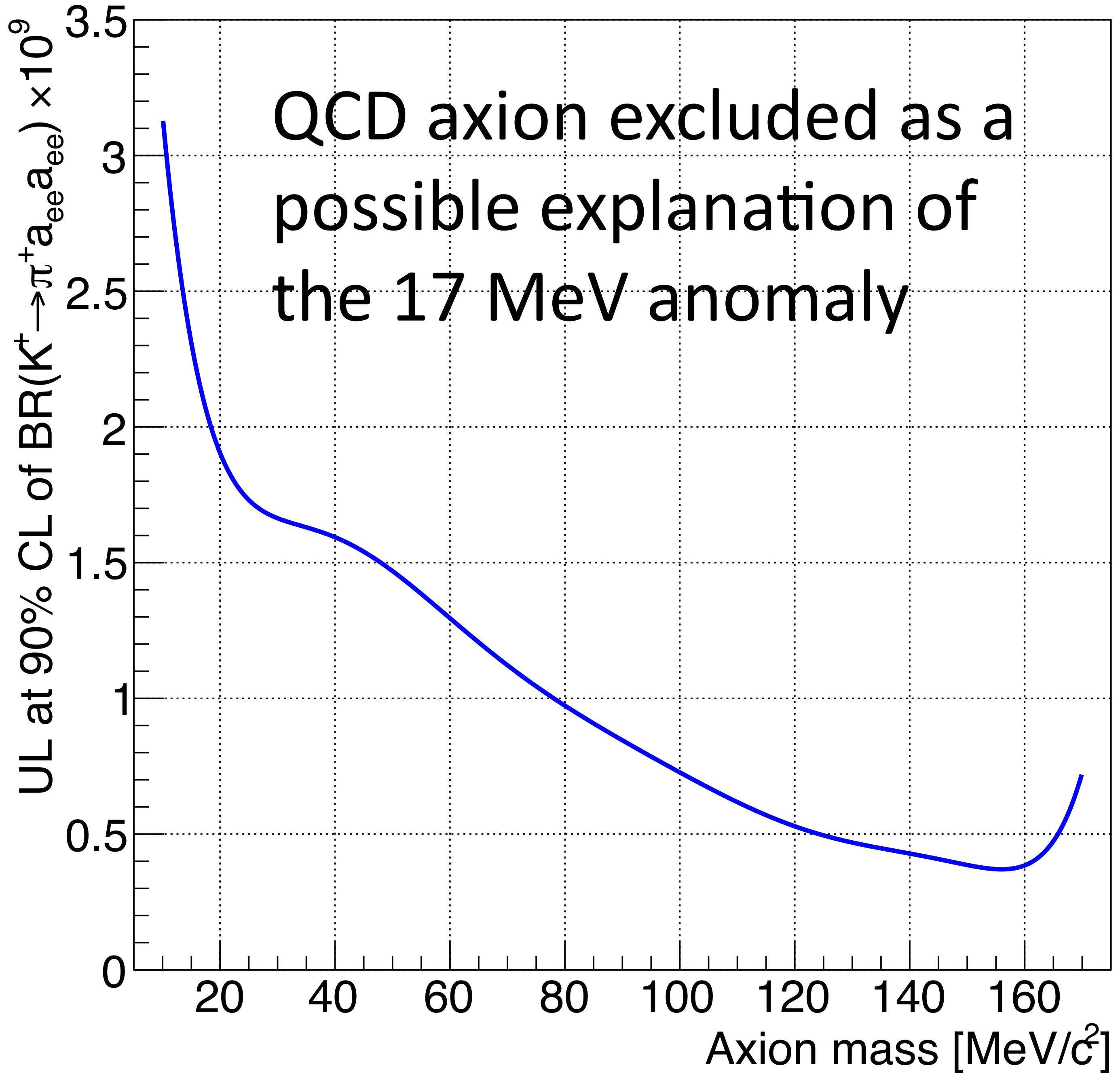
Possible explanation for the 17 MeV anomaly (Phys.Rev.D103(2021)055018)



- Normalization channel: $K^+ \longrightarrow \pi^+\pi^0$ ($\pi^0 \longrightarrow e^+e^-e^+e^-$)
- K^+ decays in fiducial volume $(8.58 \pm 0.19_{stat} \pm 0.07_{MC} \pm 0.41_{ext}) \times 10^{11}$
- Signal region: invariant mass around the K^+ mass

Analysis with **2017 + 2018 data**:
0 candidates observed
Expected background 0.18 ± 0.14
First search ever performed

- consistency of the two reconstructed e^+e^- mass values
- for each mass hypothesis m_X: $|m_{ee} - m_X| < 0.02 \cdot m_X$



$$BR(K^+ \to \pi^+e^+e^-e^+e^-) < 1.4 \times 10^{-8} \text{ @ } 90\% \text{ CL}$$

Summary of NA62 results

$K^+ \to \pi^-\mu^+\mu^+$	NA62 Run 1	PBL 797 (2019) 134794
$K^+ \to \pi^+\nu\bar{\nu}$	NA62 Run 1	JHEP 06 (2021) 093
$K^+ \to \pi^-\mu^+e^+$	NA62 Run 1	PRL 127 (2021) 131802
$K^+ \to \pi^+\mu^-e^+$	NA62 Run 1	PRL 127 (2021) 131802
$\pi^0 \to \mu^-e^+$	NA62 Run 1	PRL 127 (2021) 131802
$K^+ \to \pi^+\mu^+\mu^-$	NA62 Run 1	JHEP 11 (2022) 011
$K^+ \to \pi^-e^+e^+$	NA62 Run 1	PLB 830 (2022) 137172
$K^+ \to \pi^-\pi^0e^+e^+$	NA62 Run 1	PLB 830 (2022) 137172
$K^+ \to \mu^-\nu e^+e^+$	NA62 Run 1	PLB 838 (2023) 137679
$K^+ \to \pi^0e^+\nu\gamma$	NA62 Run 1	JHEP 09 (2023) 040
$K^+ \to \pi^+e^+e^-e^+e^-$	NA62 Run 1	PLB 846 (2023) 138193
$K^+ \to \pi^+\gamma\gamma$	NA62 Run 1	arXiv:2311.01837
$A' \to \mu^+\mu^-$	beam dump mode	JHEP 09 (2023) 035
$A' \to e^+e^-$	beam dump mode	paper in preparation

- Several new physics results obtained by the collaboration
- Multiple analyses are ongoing
- New result on BR($K^+ \to \pi^+\nu\nu$) expected in 2024
- NA62 will take data till 2026

…. Further results will be obtained and new searches developed with the full statistic

And what about Kaon Physics after 2026?

Kaon Physics future plan: HIKE experiment

HIKE project: high-intensity beam and kaon decay measurements at a new level of precision

An integrated program with multiple phases: **K^+ and K_L beams** + dump mode, exploiting high intensity Kaon beam (4× NA62) in the CERN NA after LS3

Principal HIKE-Phase1 physics goal: BR($K^+ \to \pi^+\nu\nu$) at 5% precision. Estimate start ~ 2031

- Max possible beam intensity in HIKE-Phase1 (after major beam line upgrades): 1.2 x 10^{13} POT/spill = 4 x NA62

  2 x 10^{13} kaon decays in fiducial volume/year. Full statistic ~ 8x wrt NA62

Principal HIKE-Phase2 physics goal: BR($K_L \to \pi^0 \ell^+ \ell^-$) at 20% precision

- Max possible intensity in HIKE-Phase2 (upgraded NA48 neutral beam line): 2 x 10^{13} POT/spill

  3.8 x 10^{13} kaon decays in fiducial volume/year

[CERN-SPSC-2023-031: https://cds.cern.ch/record/2878543/files/SPSC-P-368.pdf]

In March 2023, SPSC strongly recommended **intensity upgrade of the beam** in ECN3 and CERN Research Board supported it conditioned to the SPC (also supportive) and Medium Term Plan funding

Kaon Physics future plan: HIKE experiment

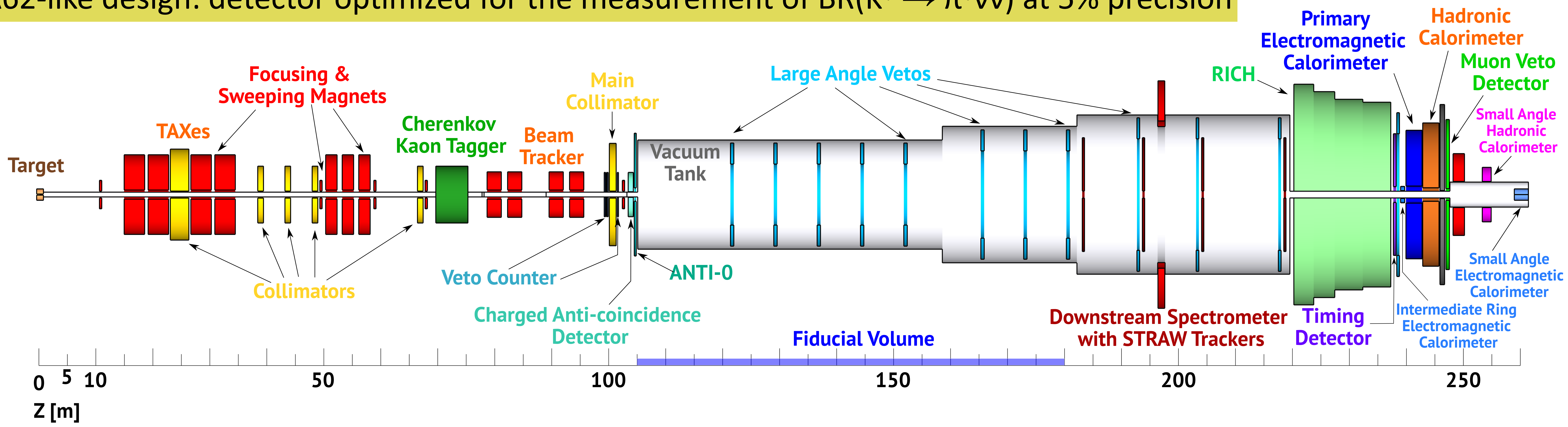
Summary of HIKE sensitivity for flavor observables

$K^+ \to \pi^+ \nu\bar{\nu}$	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 5\%$	BSM physics, LFUV
$K^+ \to \pi^+ \ell^+ \ell^-$	Sub-% precision on form-factors	LFUV
$K^+ \to \pi^- \ell^+ \ell^+$, $K^+ \to \pi \mu e$	Sensitivity $\mathcal{O}(10^{-13})$	LFV / LNV
Semileptonic K^+ decays	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 0.1\%$	V_{us}, CKM unitarity
$R_K = \mathcal{B}(K^+ \to e^+\nu)/\mathcal{B}(K^+ \to \mu^+\nu)$	$\sigma(R_K)/R_K \sim \mathcal{O}(0.1\%)$	LFUV
Ancillary K^+ decays (e.g. $K^+ \to \pi^+\gamma\gamma$, $K^+ \to \pi^+\pi^0 e^+ e^-$)	% – ‰	Chiral parameters (LECs)
$K_L \to \pi^0 \ell^+ \ell^-$	$\sigma_{\mathcal{B}}/\mathcal{B} < 20\%$	Imλ_t to 20% precision, BSM physics, LFUV
$K_L \to \mu^+ \mu^-$	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 1\%$	Ancillary for $K \to \mu\mu$ physics
$K_L \to \pi^0 (\pi^0) \mu^\pm e^\mp$	Sensitivity $\mathcal{O}(10^{-12})$	LFV
Semileptonic K_L decays	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 0.1\%$	V_{us}, CKM unitarity
Ancillary K_L decays (e.g. $K_L \to \gamma\gamma$, $K_L \to \pi^0\gamma\gamma$)	% – ‰	Chiral parameters (LECs), SM $K_L \to \mu\mu$, $K_L \to \pi^0 \ell^+ \ell^-$ rates

Challenges: **20-40 ps time resolution** for key detectors to keep random veto under control, while maintaining all other NA62 specifications. Appropriate modifications to the current design to cope with higher intensity. Technology challenges aligned with HL-LHC projects and future flavor/dark matter experiments

HIKE Phase 1: charged beam

NA62-like design: detector optimized for the measurement of BR($K^+ \to \pi^+\nu\nu$) at 5% precision



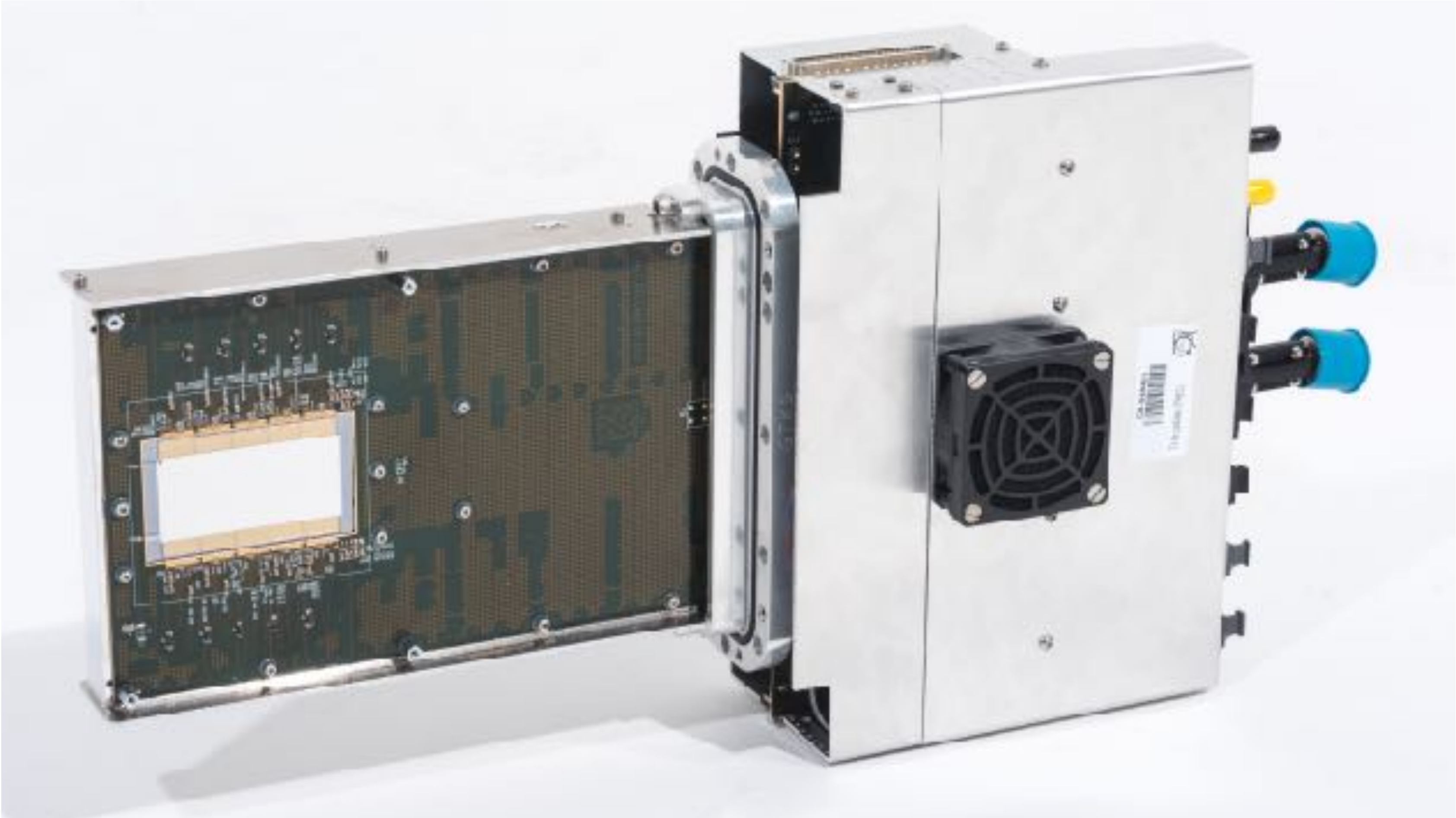
Full tracking of 3 GHz beam particle with 25 ps time resolution, tagging of 200 MHz K^+ and high-rate precision tracking of secondary particles

Improvements wrt NA62

- improved timing and double pulse resolution crucial elements to withstand the beam intensity increase
- equal or better key performance at high-rate to achieve background rejection at $\sim 10^{11}$ level
- up to x2 improvement in signal acceptance (improved detector performance, software trigger)
- improved suppression of background from upstream K^+ decays

Technological solutions exist for all detectors

HIKE tracking and ID systems



Beam tracker:

NA62 GTK	New beam tracker
$\sigma_{T(hit)} < 200$ ps	< 50 ps
$\sigma_{T(track)} < 100$ ps	< 25 ps
Peak hit rate 2 MHz/mm^2	8 MHz /mm^2
Pixel efficiency $> 99\%$	$> 99\%$
Peak fluency/year $4 \cdot 10^{14}$ MeV n_{eq}/cm^2	$16 \cdot 10^{14}$

A strong option that can satisfy all requirements: **Hybrid 3D-trenched technology.**

TimeSPOT: shared interest with HL-LHC experiments

K+ ID with differential Cherenkov:

- Max detected photon rate: >8 MHz/cm2
- High granularity
- σ_T (Kaon) = 15-20 ps
- K+ tagging efficiency with 4 sectors: > 95%
- Good radiation resistance

Solution: Microchannel plate (MCP) PMTs

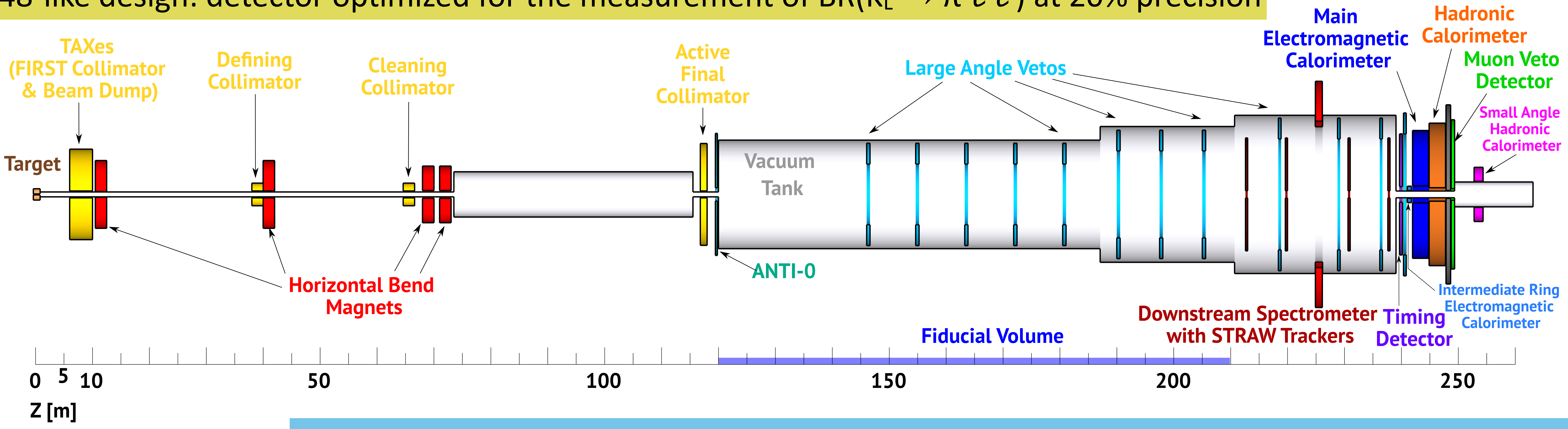
- Single-photon sensitivity, excellent σ_T ~20 ps
- Low dark noise, high gain, good QE
- Input rate capability ~MHz/cm2

New STRAW design for secondary particle tracking

	NA62 → HIKE
STRAW diameter	9.82 mm → 4.82 mm
Planes per view	4 → 8
STRAWs per plane	112 →∼ 160
Mylar Thickness	36 μm → 12 or 19 μm
Material budget	$1.7\%X_0 \rightarrow (1.0-1.5)\%X_0$
Drift time	∼ 150 ns →∼ 80 ns

HIKE Phase 2: neutral beam

NA48-like design: detector optimized for the measurement of BR($K_L \rightarrow \pi^0 \ell^+ \ell^-$) at 20% precision



Challenges: 90m long instrumented decay volume, 100 ps time resolution for π^0 of few GeV energies

120 m long neutral (NA48-like) beam line:

- Secondary beam opening angle = 0.4 mrad. 2.4 mrad production angle
- Mean momentum of K_L = 46 GeV/c

Reconfigured HIKE-Phase1 detectors:

- Kaon tagger, beam spectrometer, RICH removed
- STRAW spectrometer shortened and chambers realigned

R&Ds on Calorimetry for Phase1&2:

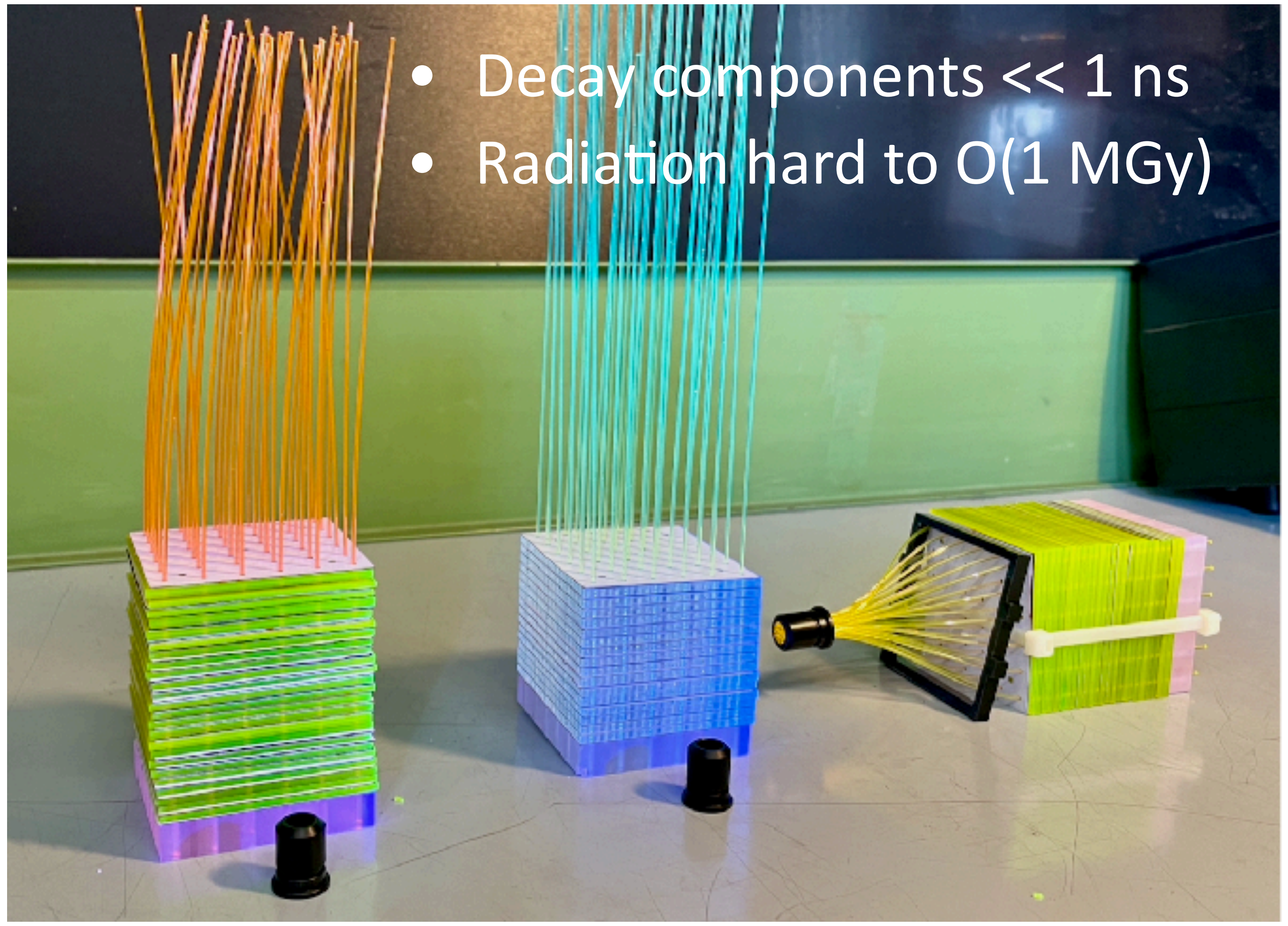
- **innovative scintillator materials**
- **longitudinal segmentation techniques**
- **oriented crystals**

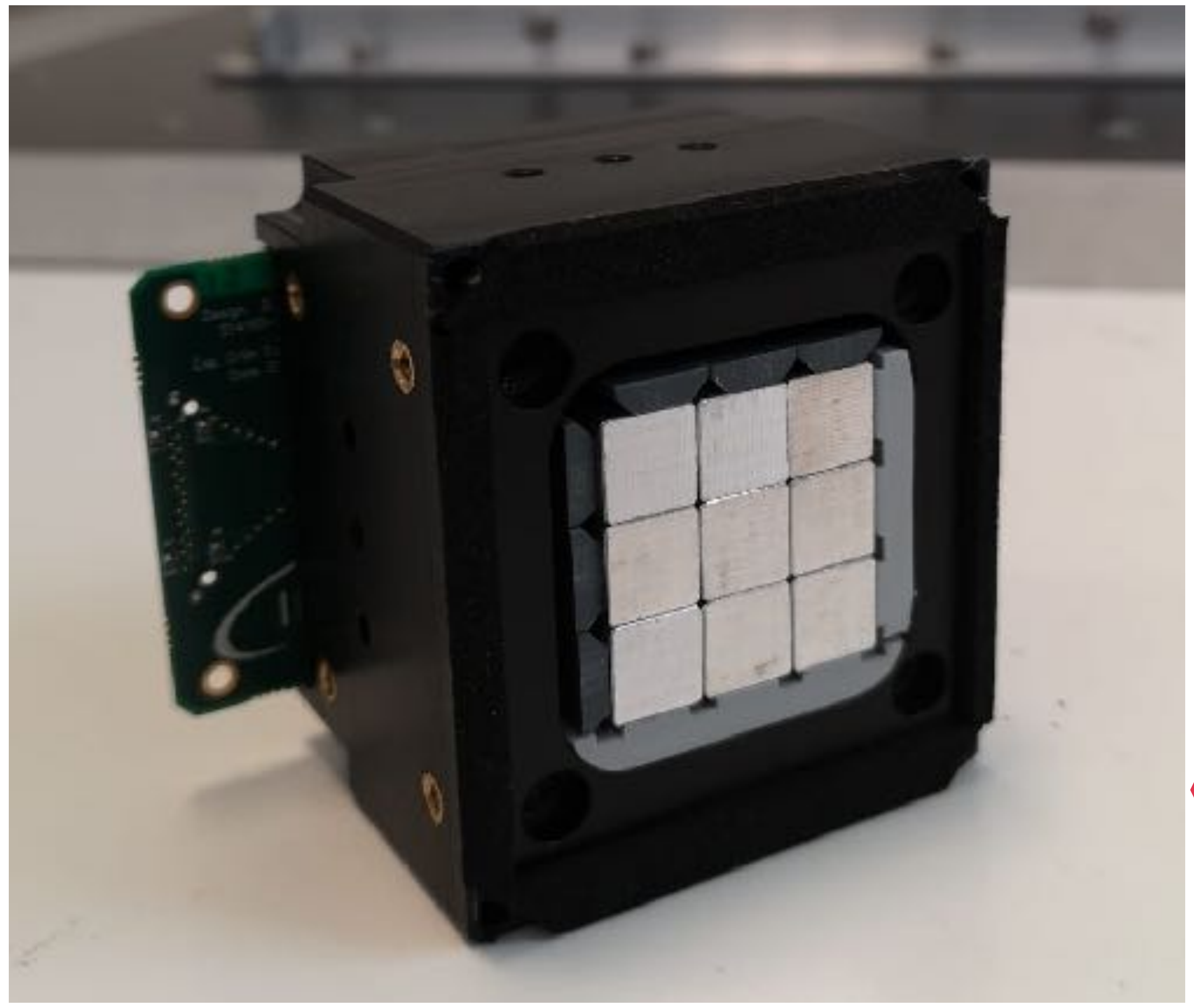
HIKE Calorimeters for the photon veto

Main electromagnetic calorimeter

- Baseline solution: **fine-sampling Shashlyk** based on PANDA forward calorimeter produced at Protvino (**0.275 mm Pb + 1.5 mm scintillator**)
- **$\sigma_t \sim 72$ ps, $\sigma_E/\sqrt{E} \sim 3\%$, $\sigma_x \sim 13$ mm ($/\sqrt{E}$ in GeV)**
- **Longitudinal shower information from spy tiles: PID**
- Neutron rejection ~ 10^3

Use of **nanocomposite scintillators** under investigation in collaboration with AIDAinnova project NanoCal: Perovskite ($CsPbX_3$, X = Br, Cl...) nanocrystals cast into polymer matrix





Small angle calorimeter (SAC)

- Rejects photons from $K_L \rightarrow \pi^0 \pi^0$ escaping through beam hole, operates inside neutral beam: as insensitive as possible to 430 MHz of neutron.
- Baseline solution: **highly segmented, homogeneous calorimeter with dense, high-Z crystals providing very fast light output**

R&D in collaboration with **CRILIN (Muon collider)**: PWO-UF (good light yield, high radiation tolerance), $\sigma_T < 100$ ps, coherent interactions in crystals to reduce thickness, transverse and longitudinal segmentation for γ/n discrimination

Conclusion

Decay	Γ_{SD}/Γ	Theoretical error	**SM** BR $\times$ 10^{11}	**Exp** BR $\times$ 10^{11}	Experiment	Year
$K_L \to \pi^0 \nu\bar{\nu}$	$> 99\%$	$\sim 2\%$	2.94 ± 0.15	20% precision	KOTO-II	~ 2040
$K^+ \to \pi^+ \nu\bar{\nu}$	$\sim 90\%$	$\sim 4\%$	8.6 ± 0.4	5% precision	HIKE-Phase1	~ 2035
$K_L \to \pi^0 e^+ e^-$	$\sim 40\%$	$\sim 10\%$	3.2 ± 1.0	20% precision	HIKE-Phase2	~ 2040
$K_L \to \pi^0 \mu^+ \mu^-$	$\sim 30\%$	$\sim 15\%$	1.5 ± 0.3	20% precision	HIKE-Phase2	~ 2040
$K_L \to \mu^+ \mu^-$	$\sim 10\%$	$\sim 30\%$	79 ± 12 (SD)	1% precision	HIKE-Phase2	~ 2040
$K_S \to \mu^+ \mu^-$	$\sim 4\%$	$> 30\%$	0.52 ± 0.15	SM sensitivity	LHCb	~ 2040

A big effort has been devoted to design a future project for Kaon Physics in ECN3:
CERN north area is the only place worldwide where this program can be addressed experimentally

- LoI submitted in November 2022 [arXiv: 2211.16586]
- Proposal for HIKE Phases 1 and 2 submitted in August 2023 to SPSC
- **SHIP experiment** compete for the same experimental area

Final research board decision on which experiment will be realized in ECN3 is very close:
SPSC Meeting November 15th + Cern Council December 6th, 2023.

[PBC report on ECN3: arXiv:2310.17726]