ALPS 2023 - An Alpine Particle Physics Symposium

Latest results and precision measurement from the NA62 experiment

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on behalf of NA62 collaboration

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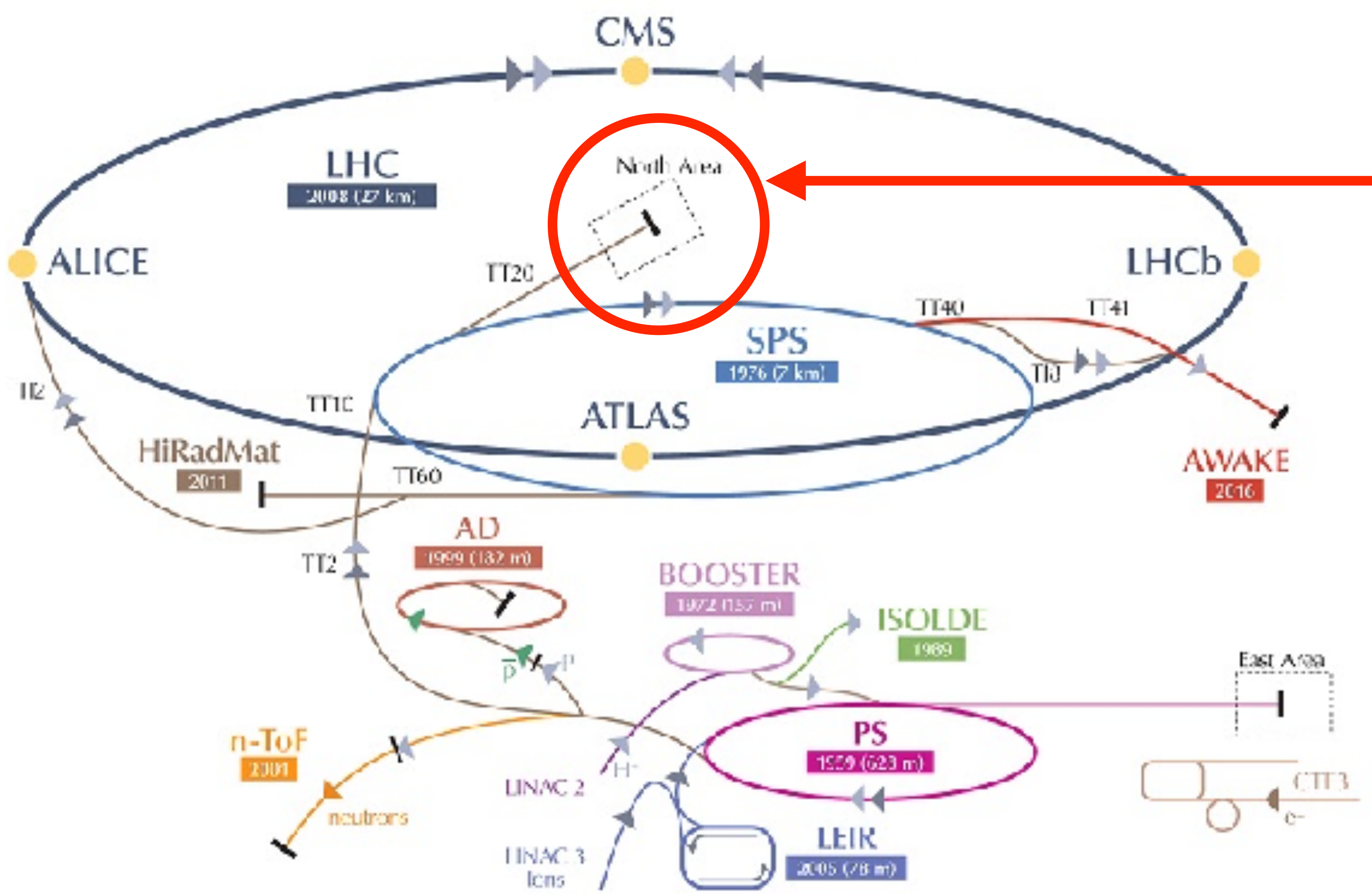
The Kaon factory

Searches in K decays are complementary to searches in B-physics and in pure leptonic processes



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

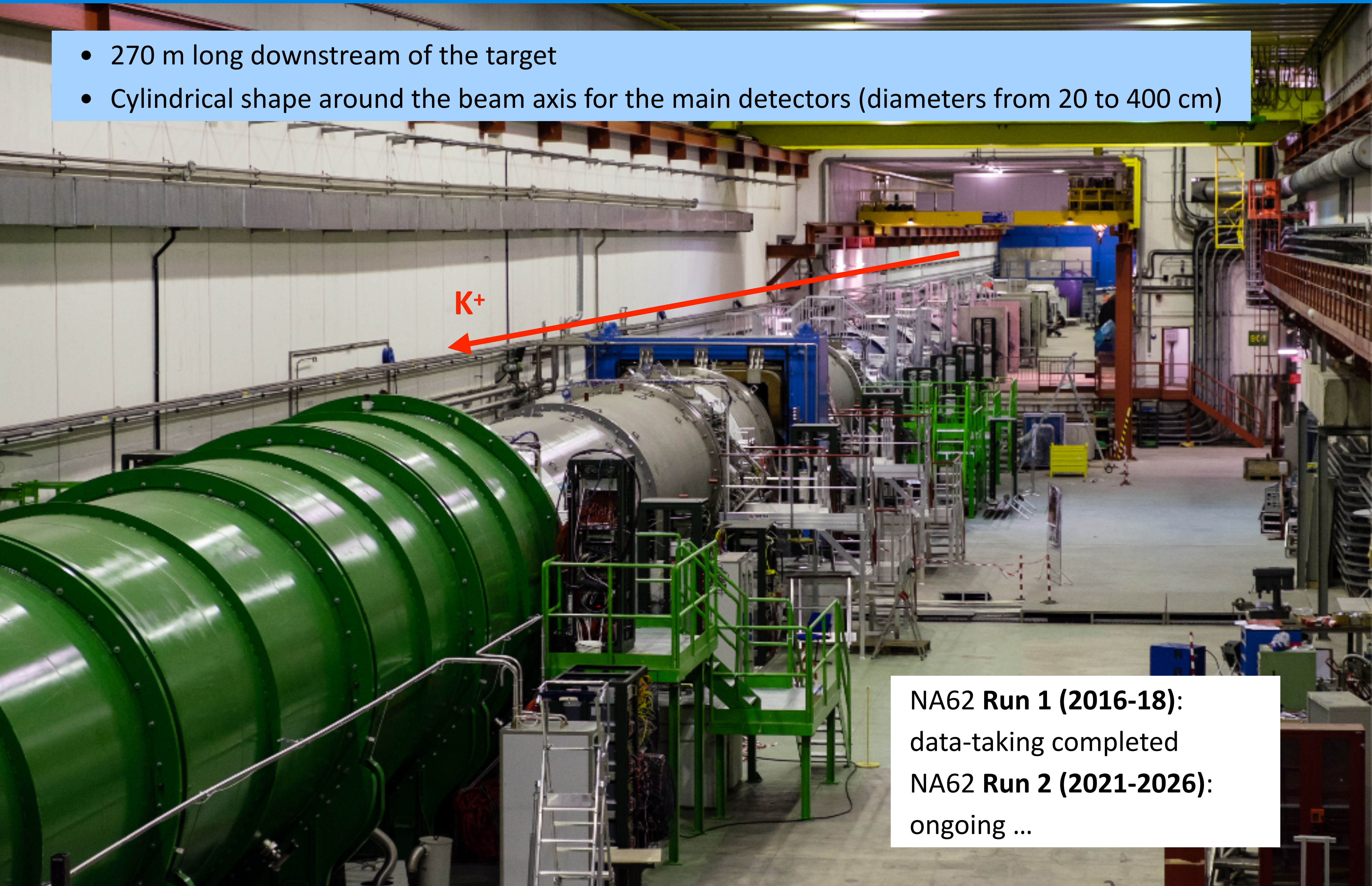
BEAM:

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%),** **p** ($\Delta p/p \pm 1\%$)

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

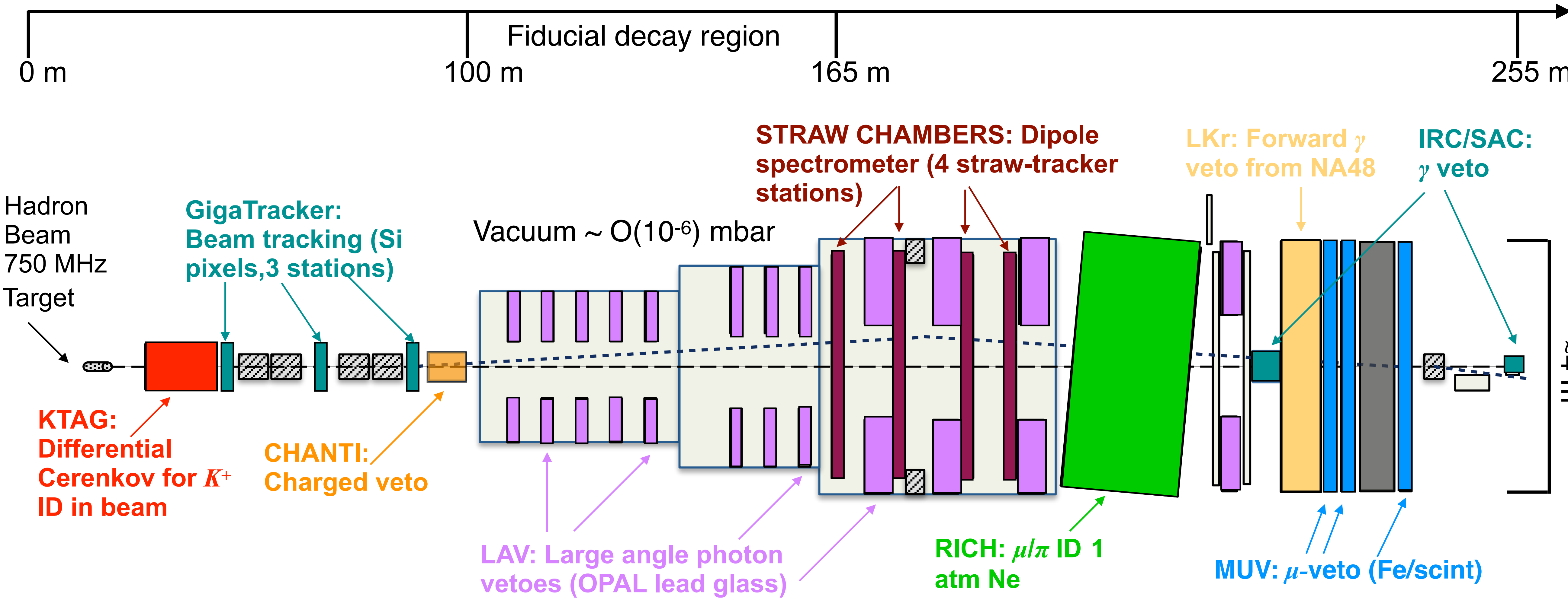
NA62 Experiment

- 270 m long downstream of the target
- Cylindrical shape around the beam axis for the main detectors (diameters from 20 to 400 cm)



NA62 **Run 1 (2016-18)**:
data-taking completed
NA62 **Run 2 (2021-2026)**:
ongoing …

NA62 setup



- **Beam tracker**: GTK
- **Kaon tagger**: KTAG ($\sigma_t \sim 70$ ps)
- **Downstream tracker**: (π/μ/e):
  Straw $\sigma_p/p = 0.3\% \oplus 0.005\% \cdot p$[GeV/c]
- **Photon veto detectors**: LAV, IRC, SAC
- **Cherenkov counter**: 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 detector**: MUV3 ($\sigma t \sim 500$ ps)

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

A general purpose experiment

NA62

Flavour Physics

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

Experiment main goal:

$$BR(K^+ \to \pi^+ \nu \bar{\nu})$$
$$= (11.0^{+4.0}_{-3.5}{}_{stat} \pm 0.9_{syst}) \times 10^{-11}$$

3.5 σ significance

JHEP06 (2021) 093

Search for lepton flavour and number violation, rare and forbidden decays (**HNL, LFV, LNV**). **Kaon precision physics**.

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

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**)

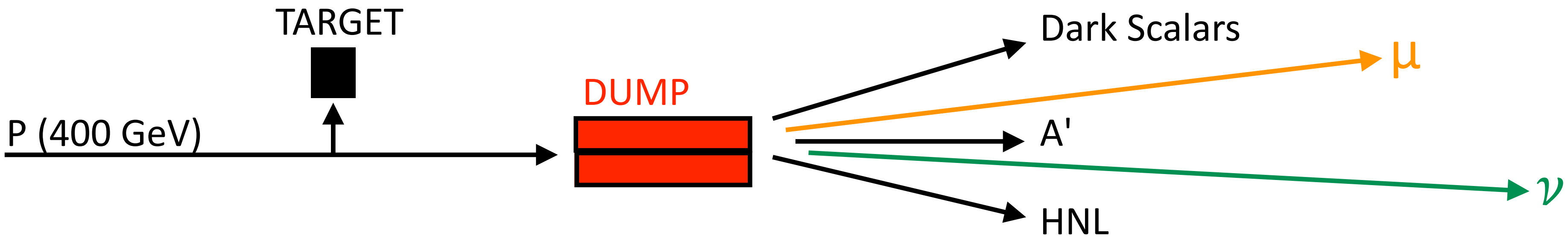
$$K^+ \to l^+ \nu N$$
$$N \to \pi^\pm l^\mp$$
$$A' \to l^+ l^-$$
$$\pi^0 \to \gamma A', A' \to \text{invisible}$$

NA62 recent results

The large data sample collected by NA62 provides sensitivities to rare kaon decays with branching ratios as low as 10^{-11}.

Decay	Dataset	Status	Reference
$K^+ \to \pi^+\mu^+\mu^-\ (K_{\pi\mu\mu})$	Run 1 (2017-2018)	Published	JHEP11 (2022) 011
$K^+ \to \pi^+\gamma\gamma\ (K_{\pi\gamma\gamma})$	Run 1 (2016-2018)	Preliminary	Talk at KAON 2022

NA62 can act as a "**beam dump experiment**" if the kaon production target is removed and the beam-defining collimator is closed (~11 λ_I Cu-based)



All beam-induced backgrounds are stopped but muons and neutrinos and any kind of **feebly-interacting long-lived particle**

Decay	Dataset	Status	Reference
$A' \to \mu^+\mu^-\ (A'_{\mu\mu})$	Run 2 (2021)	Preliminary	Talk at KAON 2022
$A' \to e^+e^-\ (A'_{ee})$	Run 2 (2021)	Preliminary	Talk at La Thuile 2023

$K^+ \to \pi^+\mu^+\mu^-$: Physics case

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

Weak low energy processes: the first non-trivial contribution to their decay rates comes from next-to-leading order ChPT, mediated by a single virtual-photon $K^{\pm} \to \pi^{\pm}\gamma^* \to \pi^{\pm} l^+ l^-$

Full differential decay width

$$\frac{d\Gamma(z)}{dz} = \frac{d\Gamma_{3-body}(z)}{dz} + \frac{d\Gamma_{4-body}(z)}{dz}$$

$$g(z) \cdot |W(z)|^2$$

Dalitz variable

$$z = \frac{m^2_{\mu^+\mu^-}}{M_K^2}, \quad \left(\frac{2m_\mu}{m_K}\right)^2 < z < \left(1 - \frac{m_\pi}{m_K}\right)^2$$

$g(z)$: Decay kinematics + next-to-leading order electromagnetic effects in term of radiative corrections

Form factor in NLO ChPT

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

Long-distance hadronic effects described by a vector interaction

$W^{\pi\pi}(z)$: $K_{3\pi}$ pion loop term

NA62 experimental measurement:

- **Form factor (FF) and parameter** a_+, b_+
- **Branching ratio model-independent** $BR(K_{\pi\mu\mu})$
- **Forward-backward asymmetry** —> possible hint of new physics

FF measurement contribute to experimental test of lepton flavour universality (**LFU**)

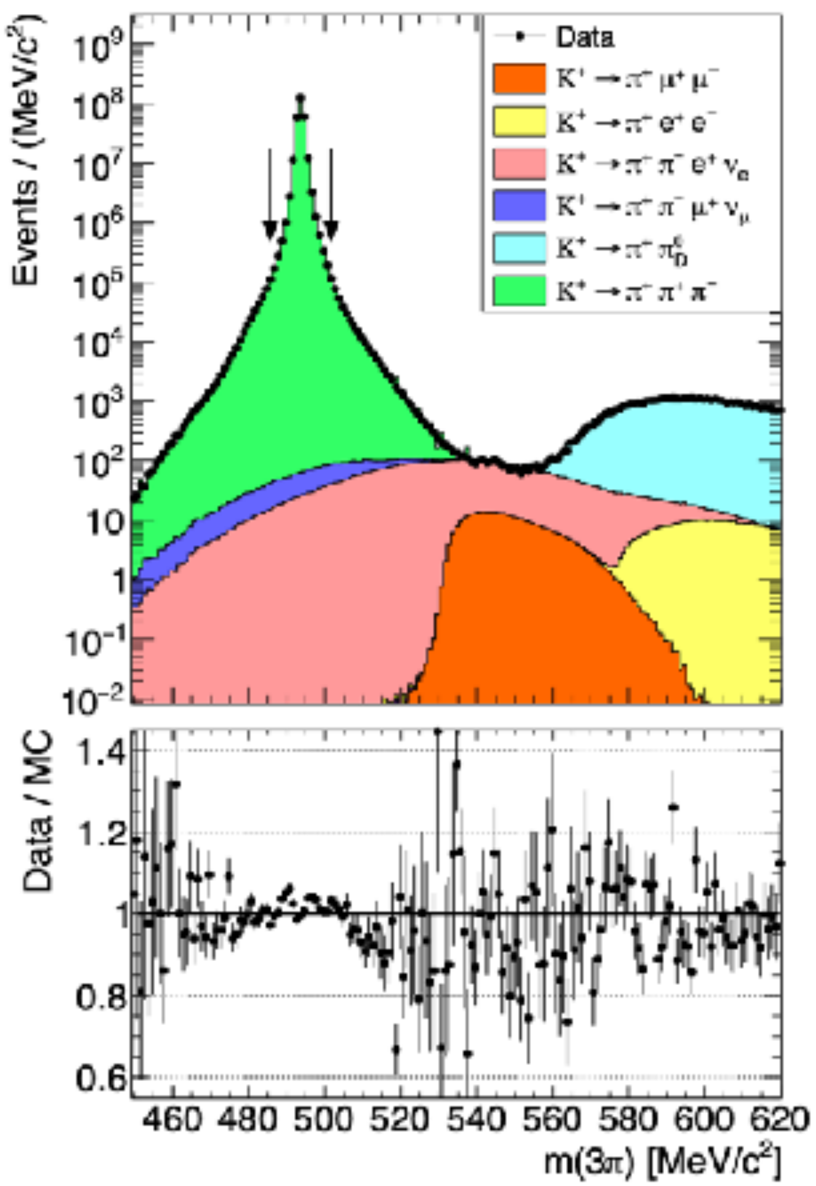
$K^+ \to \pi^+\mu^+\mu^-$: Signal selection

Normalization channel $K^+ \to \pi^+\pi^+\pi^-$ ($K_{3\pi}$)

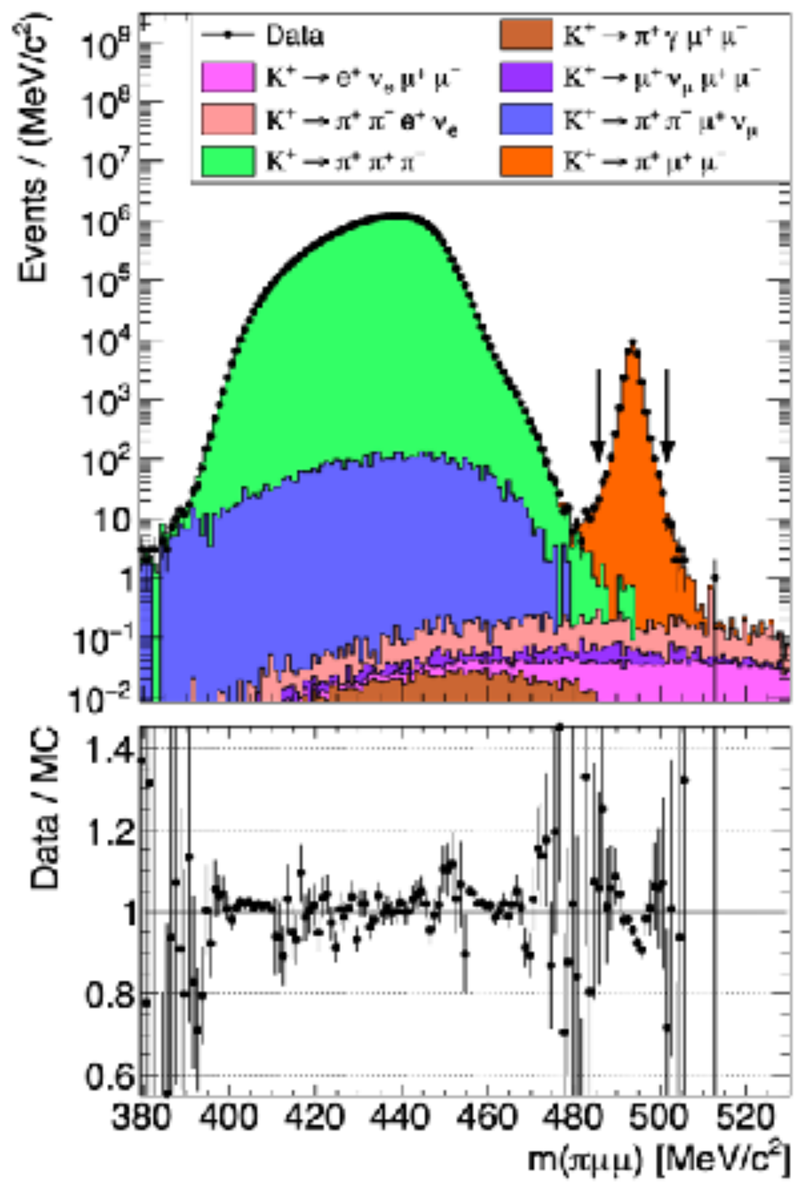
- Abundant: $B(K_{3\pi})$ = 5.583(24)%
- Similar event selections: cancellation of some inefficiencies, reduction of systematic effects

Data sample: **N_K = 3.48 x 10^{12}** kaon decays. Obtained from the selected $K_{3\pi}$ data sample and MC

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



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

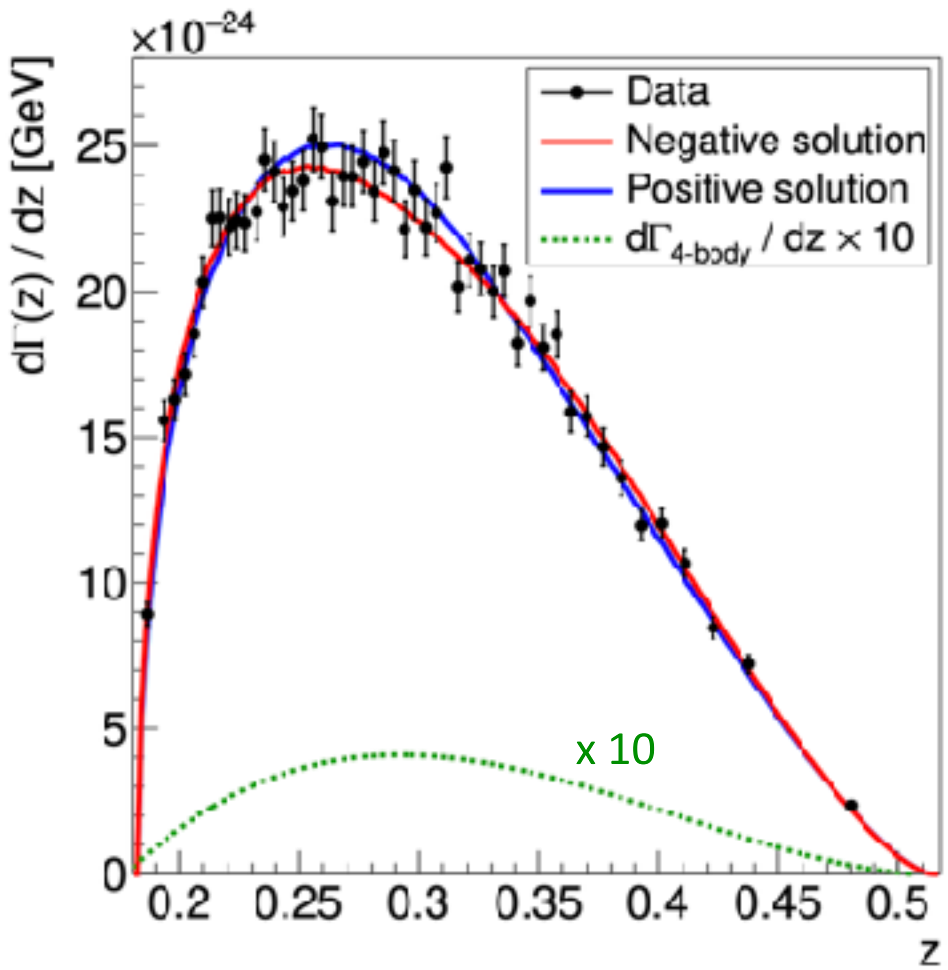


Selection

- Two different trigger streams to collect $K_{3\pi}$ and $K_{\pi\mu\mu}$ in parallel ("Multi-track", "Di-muon multi-track")
- Three track vertex topology
- π^+ PID: no signal in MUV3, E/p < 0.9
- $\mu^\pm$ PID: signal in MUV3, E/p < 0.2
- Kinematic cuts to suppress $K_{3\pi}$ background

Signal region:
$|m_{\pi\mu\mu} - m_K| < 8$ MeV/c^2
27679 events (~8 background)
(~9x more than NA48/2)

$K^+ \to \pi^+\mu^+\mu^-$: Form factor measurement



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

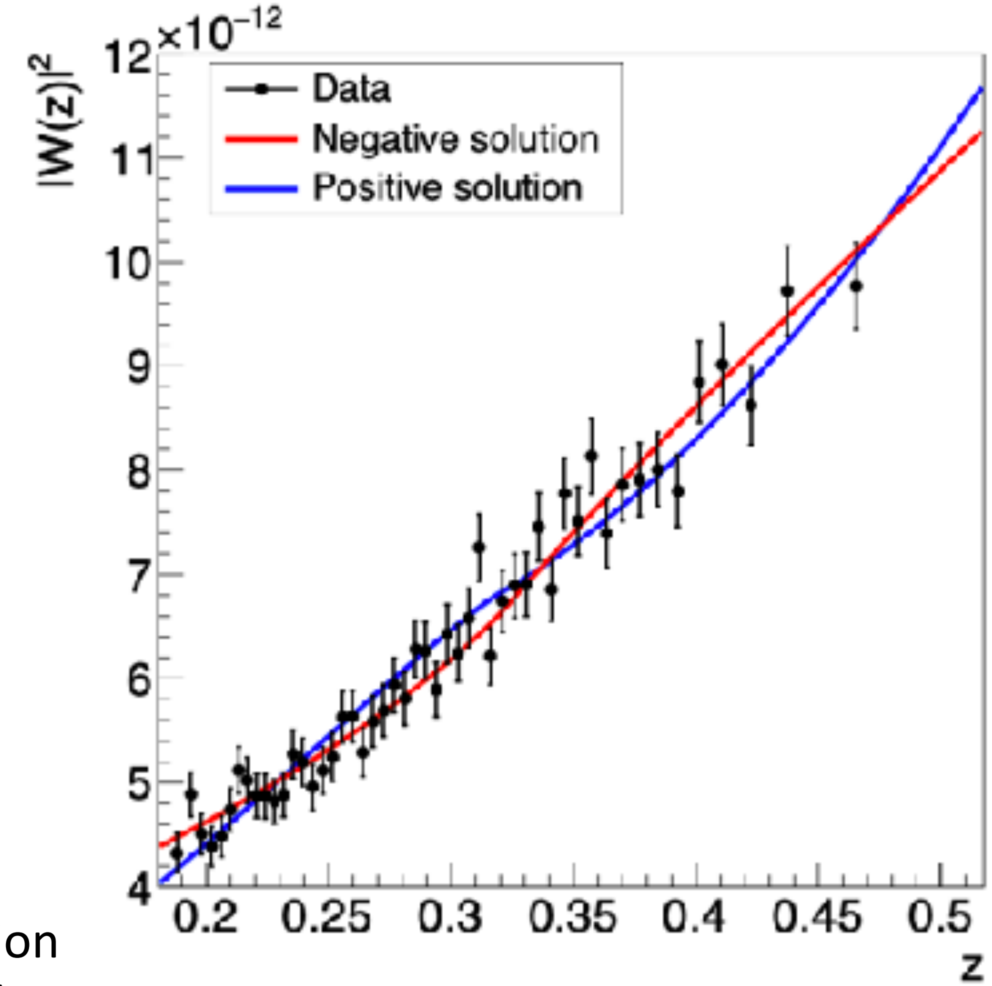
4-body decay width approximated by a unique function
(effects of approximation in systematic uncertainties)

50 equipopulated z-bins

$$\left(\frac{d\Gamma(z)}{dz}\right)_i = \frac{N_{\pi\mu\mu,i}}{A_{\pi\mu\mu,i}} \cdot \frac{1}{\Delta z_i} \cdot \frac{1}{N_K} \cdot \frac{\hbar}{\tau_K}$$

Integrating spectrum over z and multiplying by $\tau_K/\hbar$:

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



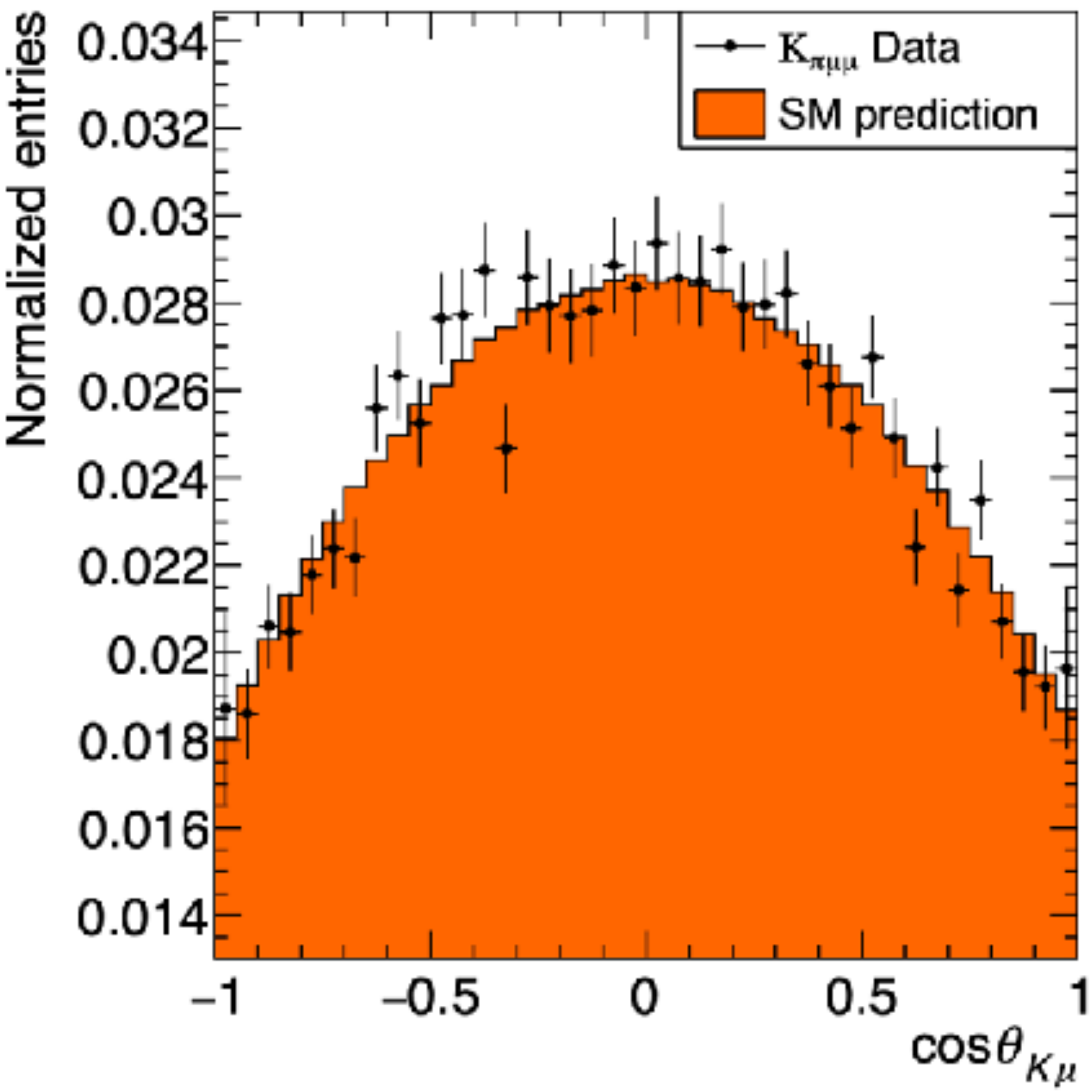
$|W(z)|^2$ reconstructed from the differential decay spectrum (assuming it linear in each z-bin)

X^2 fit of data (parameter values minimizing X^2):

$$\chi^2/\text{ndf} = 45.1/48 \ \ (p\text{-value} = 0.59)$$

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

$K^+ \to \pi^+\mu^+\mu^-$: Forward-Backward Asymmetry



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 K^+ and μ^- three-momenta in the $\mu^+\mu^-$ rest frame
- N = number of events after correction of the non-uniform acceptance in ($\cos\theta_{K\mu}$, z) plane

$$A_{FB} = (0.0 \pm 0.7) \times 10^{-2}$$

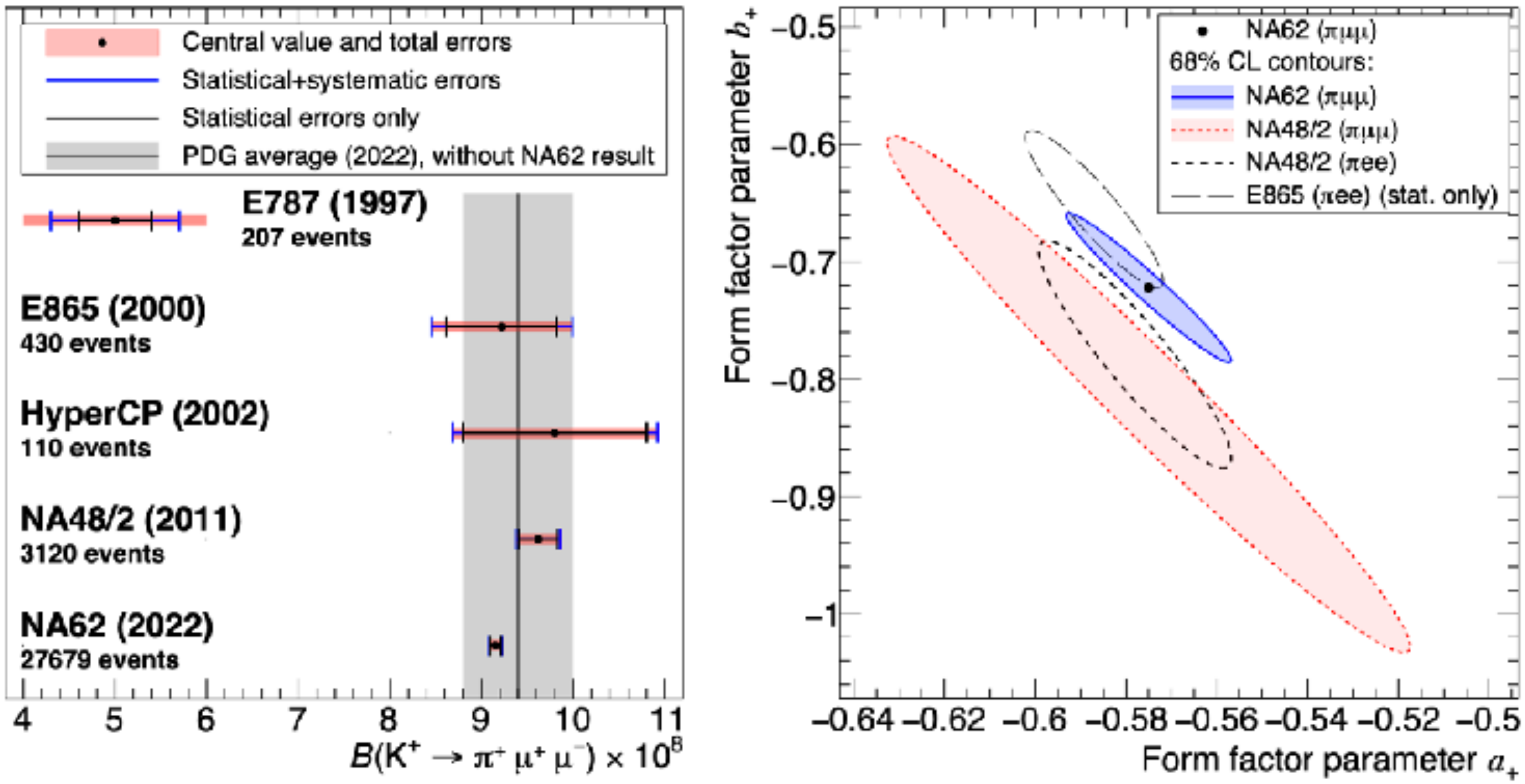
$$|A_{FB}| < 0.9 \times 10^{-2} \quad 90\% \text{ CL}$$

Statistical error dominates

- No significant dependence on *z*
- A factor 2.6 improvement in the precision with respect to NA48/2
- The statistical precision is at the level of the upper limit on A_{FB} predicted by the Minimal Supersymmetric Standard Model and by the calculation of the two-photon intermediate state $K^+ \to \pi^+\gamma^*\gamma^* \to \pi^+\mu^+\mu^-$

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

Size of the $K_{\pi\mu\mu}$ data sample is the main factor limiting the precision of the present analysis



- $B(K_{\pi\mu\mu})$ consistent with previous measurement and a factor 3 more precise
- NA48/2 used a different $K_{3\pi}$ branching fraction
- First measurement to employ inclusive radiative correction in the simulation of $K_{\pi\mu\mu}$
- Values of a_+ and b_+ parameters in any other form factor model can be obtained from $|W(z)|^2$

$K^+ \to \pi^+\gamma\gamma$: Physics case

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

The first non-trivial contribution to the decay rates comes from next-to-leading order ChPT

The decay rate and spectrum are determined by a single a-priori unknown O(1) parameter $\hat{c}$

Kinematic variables

$$y = \frac{p_K(p_{\gamma_1} - p_{\gamma_2})}{M_K^2},\ z = \frac{(p_{\gamma_1} + p_{\gamma_2})^2}{M_K^2} = \frac{m_{\gamma\gamma}^2}{M_K^2}$$

Full differential decay width

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

- Lowest order $O(p^4)$ + highest order $O(p^6)$, that modify the lowest order significantly
- Invariant amplitudes A, B, C depend on several external parameters, fixed in this analysis:

  Rev. Mod. Phys. 84 399 (2012) —> $G_8 = 9.034\times10^{-6}$ GeV^{-2},

  Science 368 (2020) 6490, 506-509 —> $\Gamma(\pi^0\to\gamma\gamma)$: $(7.80\pm0.12)\times10^{-9}$ GeV

  Nucl.Phys. B648 (2003) 317-344 —> $K_{3\pi}$ amplitude fits

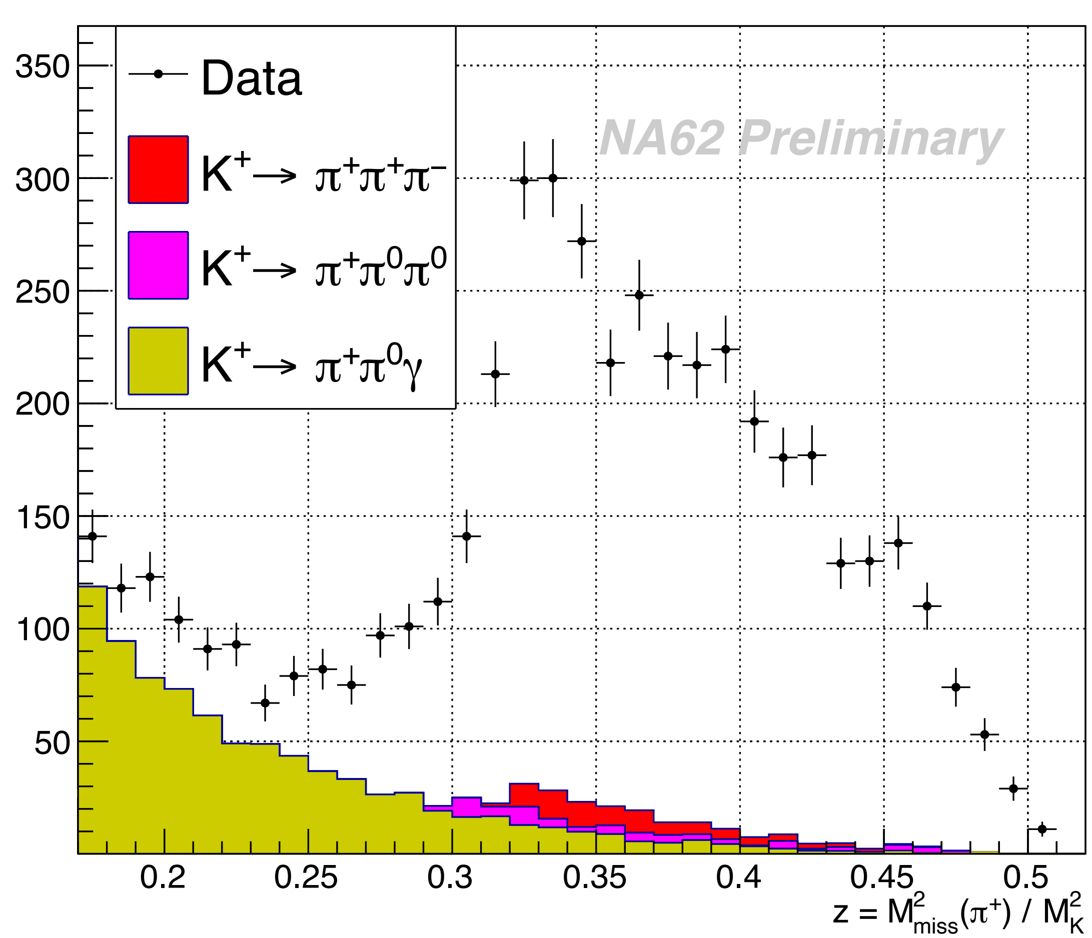
Data sample

- All Run 1 (2016-2018) data. Normalization channel: $K^+ \to \pi^+\pi^0$ ($K_{2\pi}$)

$K^+ \rightarrow \pi^+\gamma\gamma$: Signal selection

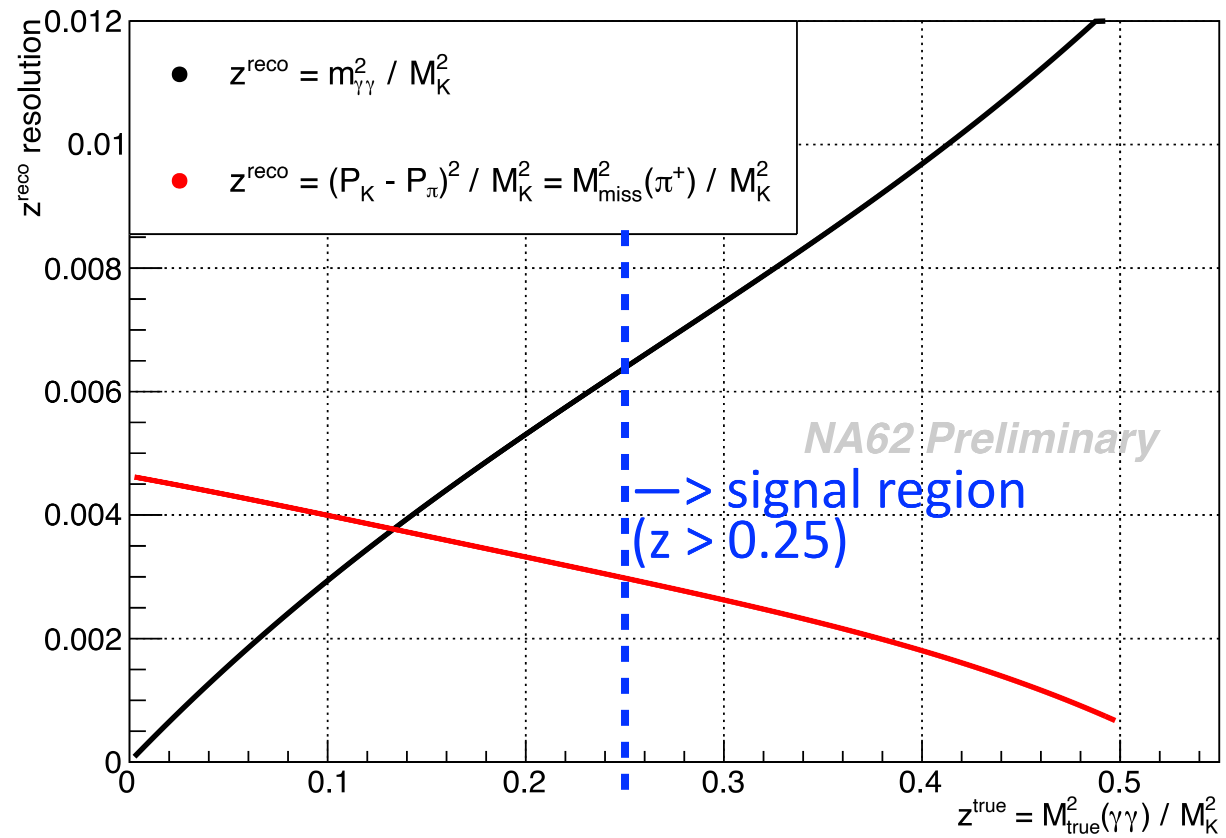
Selection

- Two different trigger streams used: control trigger and 1-track-not-muon
- One good track, π^+ PID
- K^+– π^+ matching and vertex reconstruction
- 2 good cluster in LKr calorimeter
- Kinematic cuts on daughter particles: total E, total p_T , $m_{\pi\gamma\gamma}$ consistent with M_K



$Z = (P_K - P_\pi)^2/M_K^2$ used:

better resolution than $m_{\gamma\gamma}^2/M_K^2$



Main background

- Cluster merging in LKr:

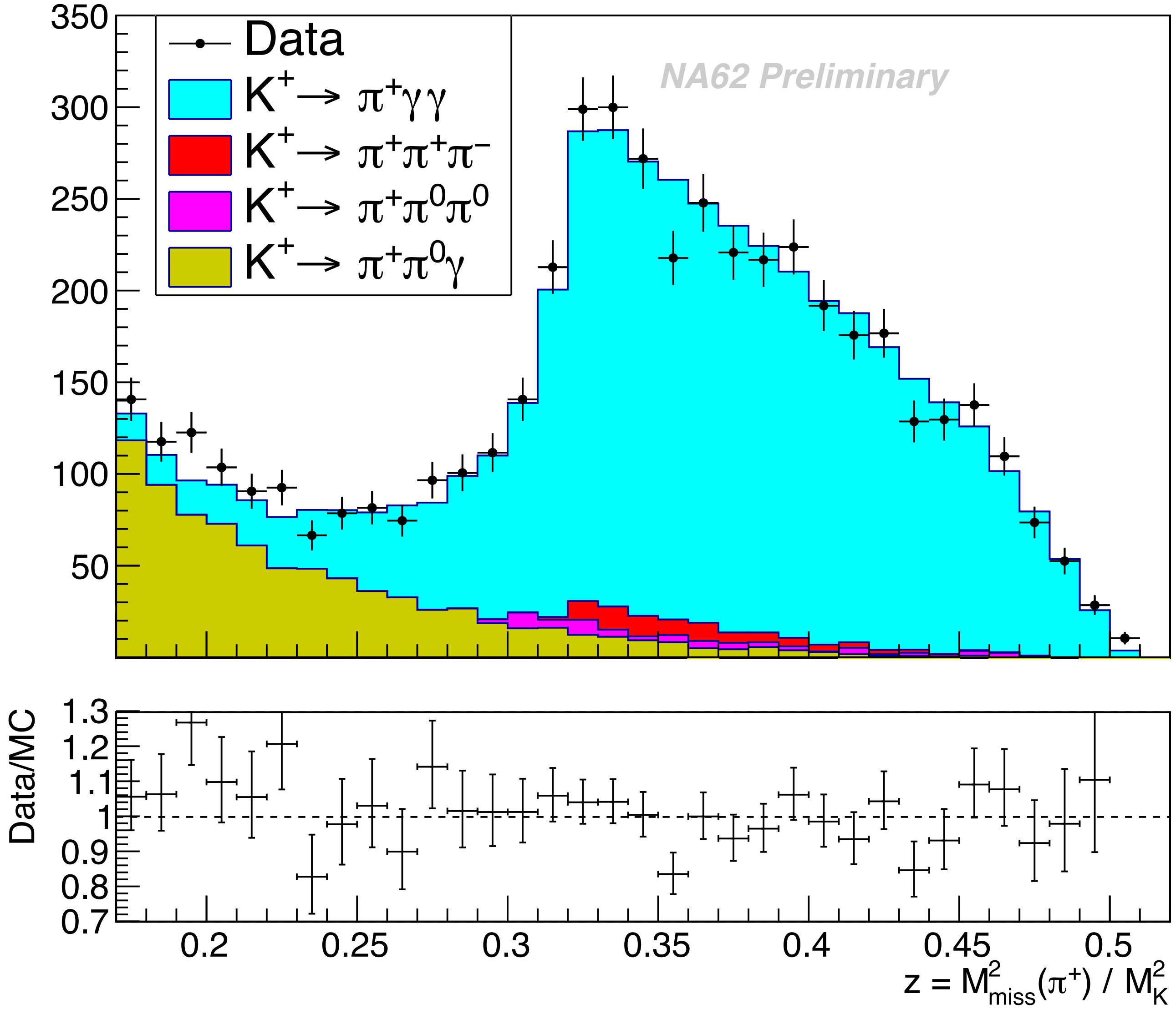
$$K^+ \rightarrow \pi^+\pi^0\gamma, \pi^0 \rightarrow \gamma\gamma$$
$$K^+ \rightarrow \pi^+\pi^0\pi^0, \pi^0 \rightarrow \gamma\gamma$$

- Multi track events with tracks missing: mainly $K_{3\pi}$ due to large BR

$K^+ \to \pi^+\gamma\gamma$: ĉ parameter

- Signal region z > 0.25 contains **4039** events → ~ 10x more than NA48/2 + NA62-2007
- To validate background model: use control regions with enhanced background and check Data/MC agreement. Background contamination: **393 ± 20** events

Signal shape and rate depend on **ĉ**.



Scan **ĉ** parameter to find maximum of:

$$\ln \mathcal{L} = \sum (k_i \ln \lambda_i(\hat{c}) - \lambda_i(\hat{c}) - \ln(k_i!))$$

31 bins (i) of z of fixed width δz = 0.01 in the kinematic region 0.20 < z < 0.51

- k_i = number of observed events
- $\lambda_i(\hat{c}) = \lambda_i^S(\hat{c}) + \lambda_i^B$
- λ_i^S = expected signal events
- λ_i^B = expected background events

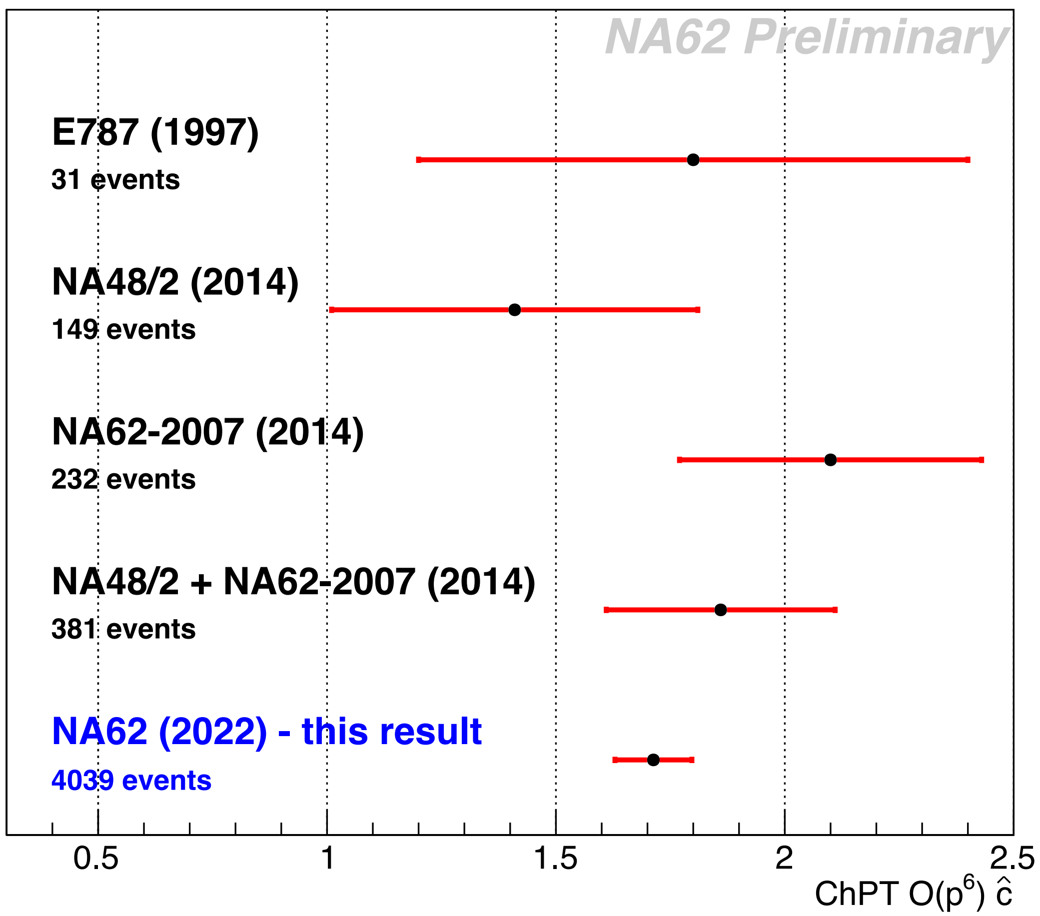
Signal MC samples with different **ĉ** are available: re-weighting of uniform phase space $K^+ \to \pi^+\gamma\gamma$ MC

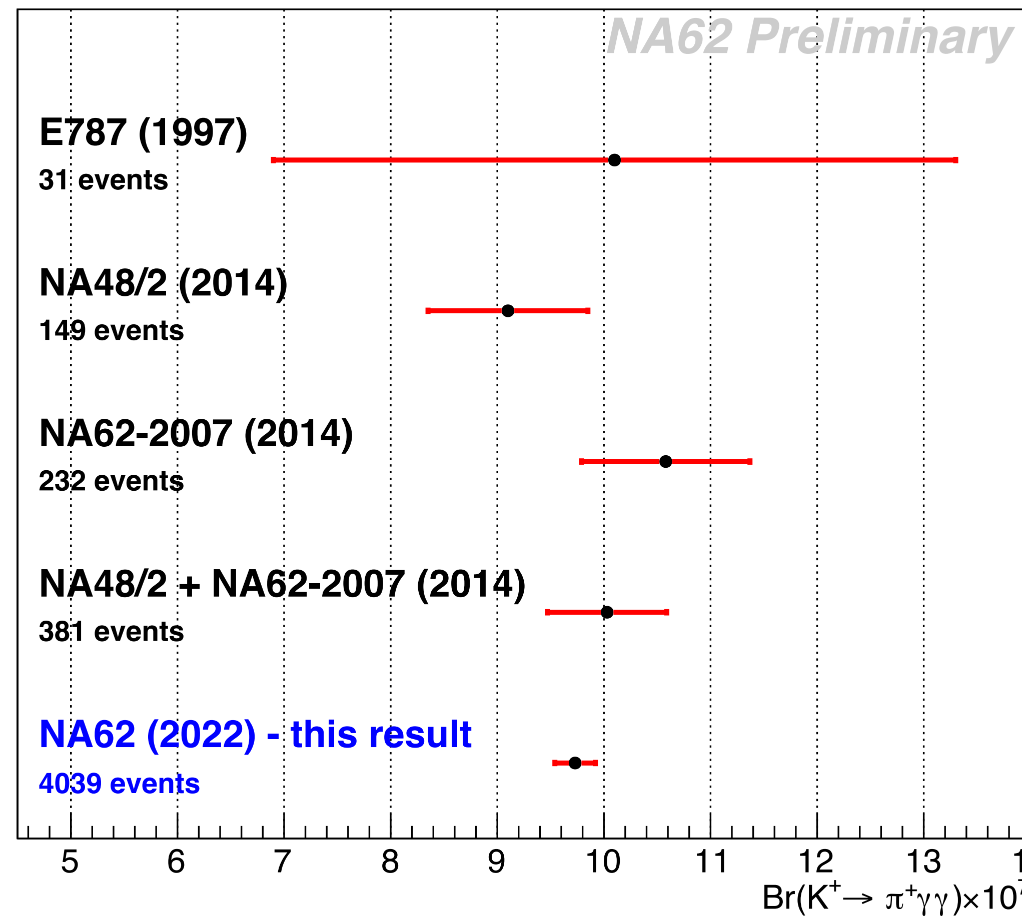
$K^+ \to \pi^+\gamma\gamma$: Results

$$\text{ChPT } O(p^6):\ \hat{c}_6 = 1.713 \pm 0.075_{stat} \pm 0.037_{syst} \Rightarrow BR(K_{\pi\gamma\gamma}) = (9.73 \pm 0.17_{stat} \pm 0.08_{syst})$$

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

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





- Total error is reduced by a factor of 3 with respect to previous best measurement from NA48/2 + NA62 2007
- Updated analysis taking into account new external parameter values is ongoing arXiv:2209.02143 (2022, G. D'Ambrosio et al.)

Search for Dark Photon in NA62

Several extensions of the Standard Model

- Vector portal ⟶ **Dark Photon**
- Scalar Portal ⟶ Dark Scalar
- Neutrino portal ⟶ HNL
- Axion portal ⟶ ALP

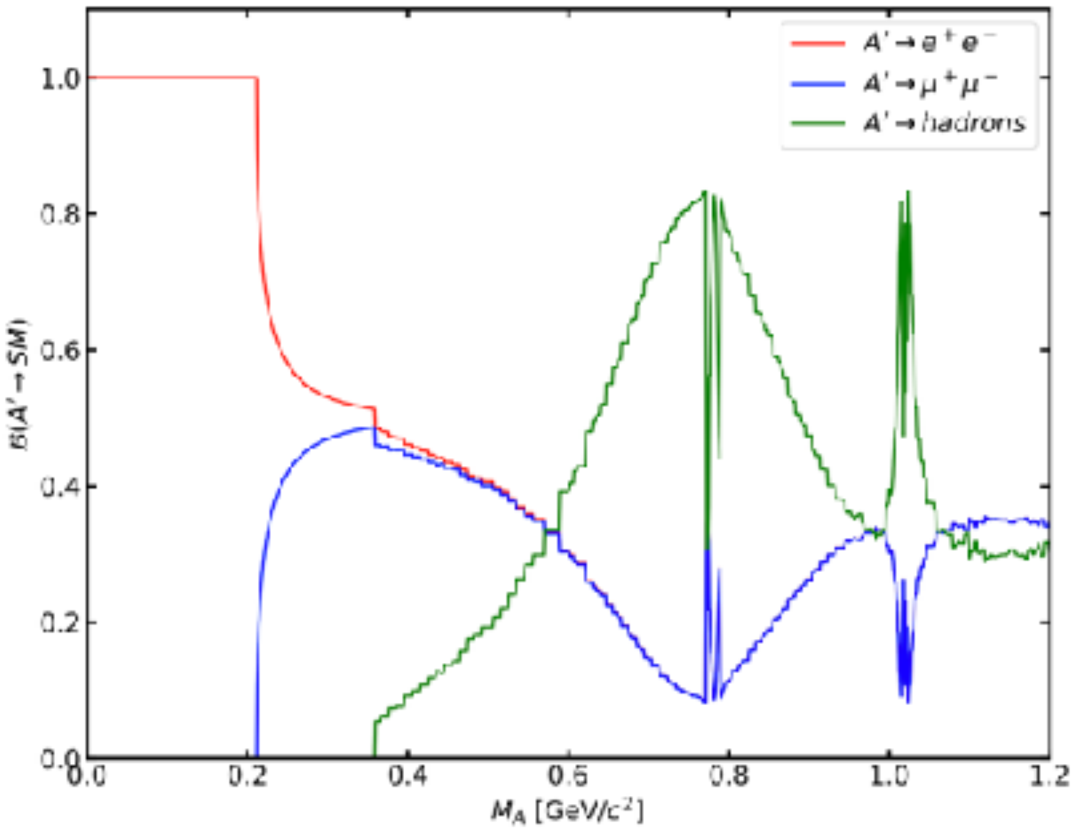
The Dark Photon model introduces a new vector field $F_{\mu\nu}$ symmetric under a new U(1) symmetry feebly interacting with the SM fields

A specific constrained model: kinetic mixing interaction with the SM hypercharge $B_{\mu\nu}$

$$\mathcal{L} \propto -\epsilon \frac{1}{2\cos\theta_W} F'_{\mu\nu} B_{\mu\nu}$$

Mass $M_{A'}$ of the DP and coupling ε are free parameters

For M_A < 600 MeV/c^2, lepton-antilepton final states dominate:



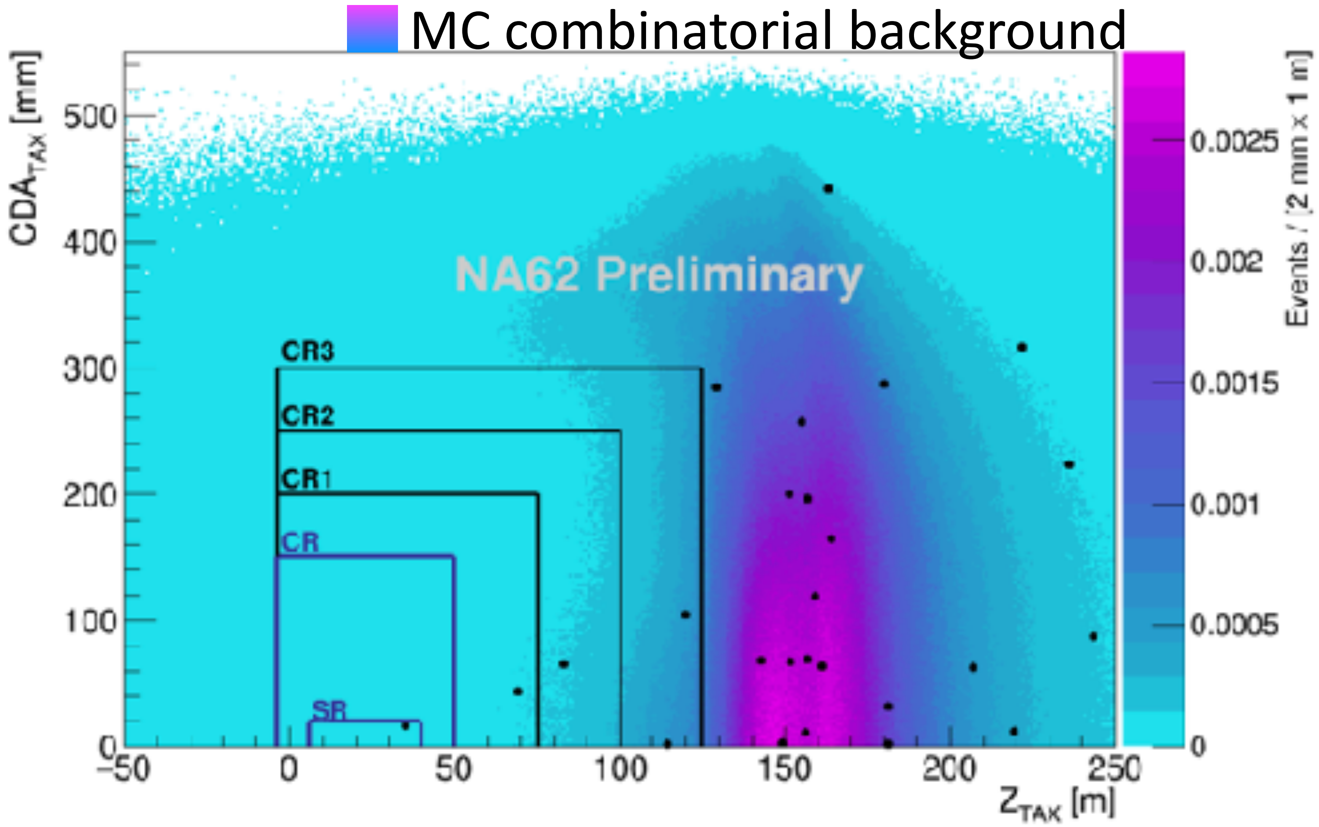
NA62 beam-dump mode

- Target removed
- 3.2 m Cu-Fe collimators put in the p^+ beam path
- ~ 1.5× nominal beam intensity
- In 2021, NA62 collected (1.4 ± 0.28) × 10^{17} PoT

$A' \rightarrow \mu^+\mu^-$ Analysis

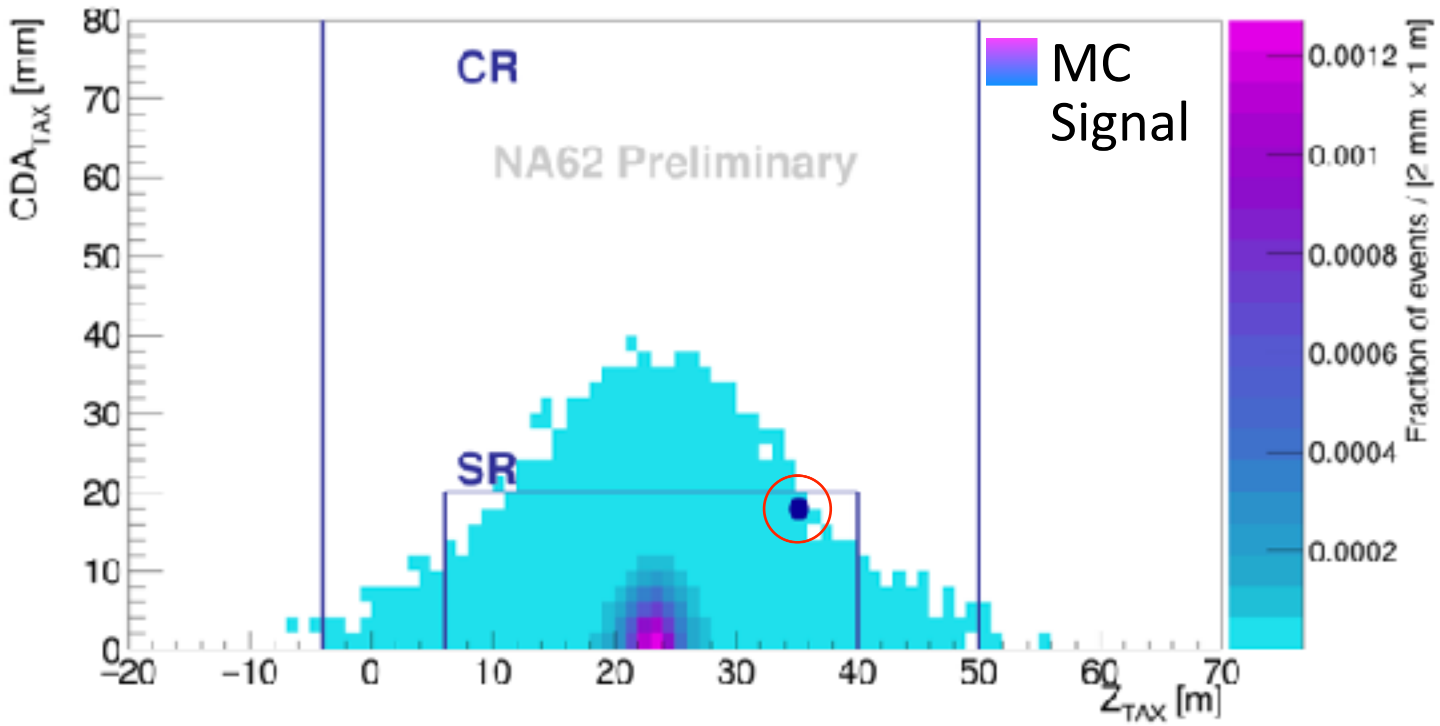
Signal selection

- Primary vertex close to p beam impact point
- $\mu^+\mu^-$ vertex within NA62 fiducial volume
- $\mu^\pm$ PID using LKr and MUV3
- Photon veto (no activity in LAV)
- CRs and SR blinded until analysis approval



Z_{TAX} → longitudinal position of the primary vertex

CDA_{TAX} → closest distance of approach between beam direction and the $\mu^+\mu^-$ pair direction, , $\sigma_{CDA} \sim 7$ mm



Results

- Expected background in SR: **0.016 ± 0.002** events

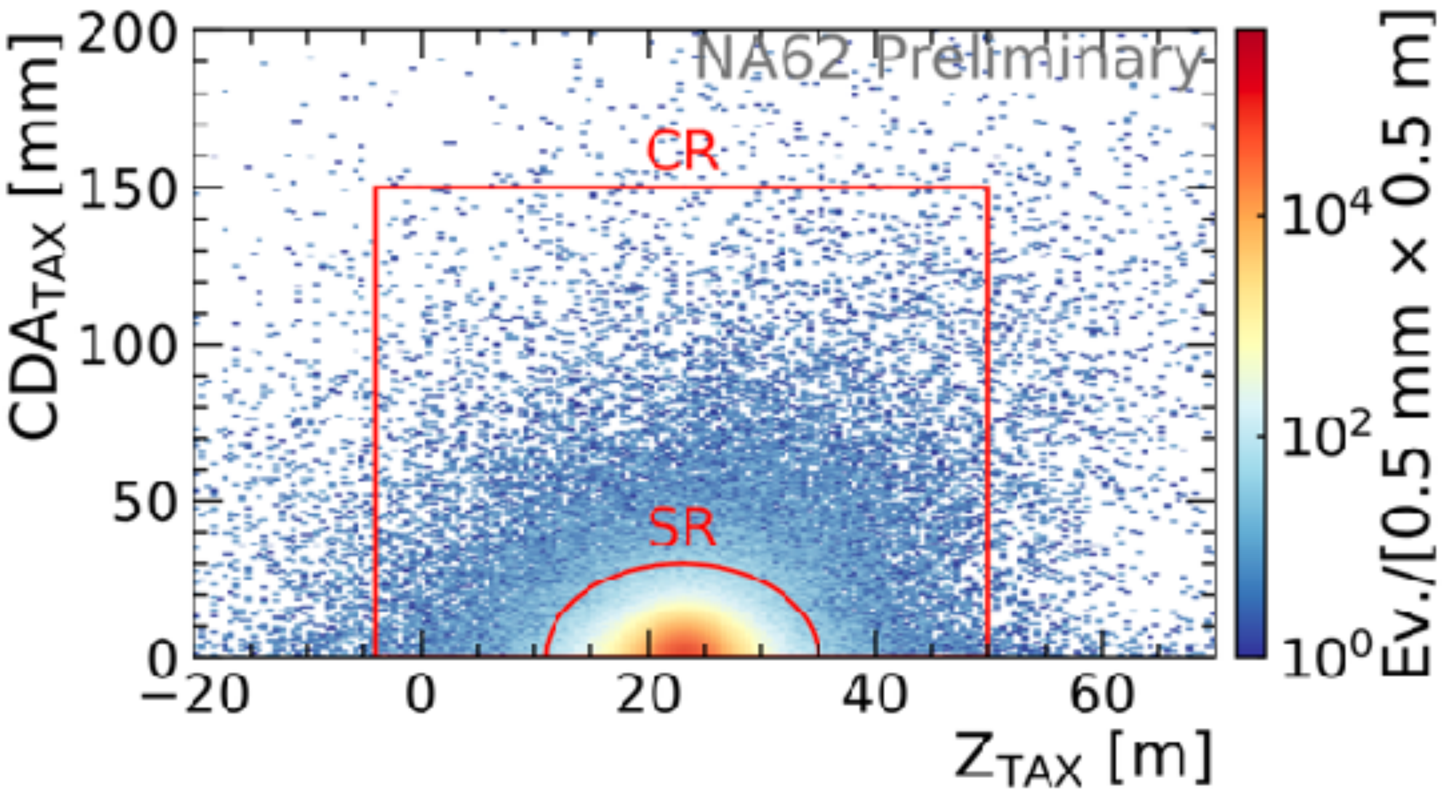
  Probability for a non-zero observation in SR is 1.6%

- Observed number of events in SR: **1**
- Counting experiment with 2.4σ global significance (signal shape not taken into account)

A'→ e^+e^- Analysis

Signal selection

- e^+e^- vertex within NA62 fiducial volume
- $e^\pm$ PID using LKr and MUV3
- No in time activity in muon detector
- no in-time activity at large angle veto detectors (LAV) to reduce possible selection of vertices derived by interaction of incoming muons with the material in the LAVs
- CRs and SR blinded until analysis approval



Z_{TAX} → longitudinal position of the primary vertex, $\sigma_Z \sim 5.5$ mm

CDA_{TAX} → closest distance of approach between the beam direction and the e^+e^- pair direction, $\sigma_{CDA} \sim 7$ mm

Results

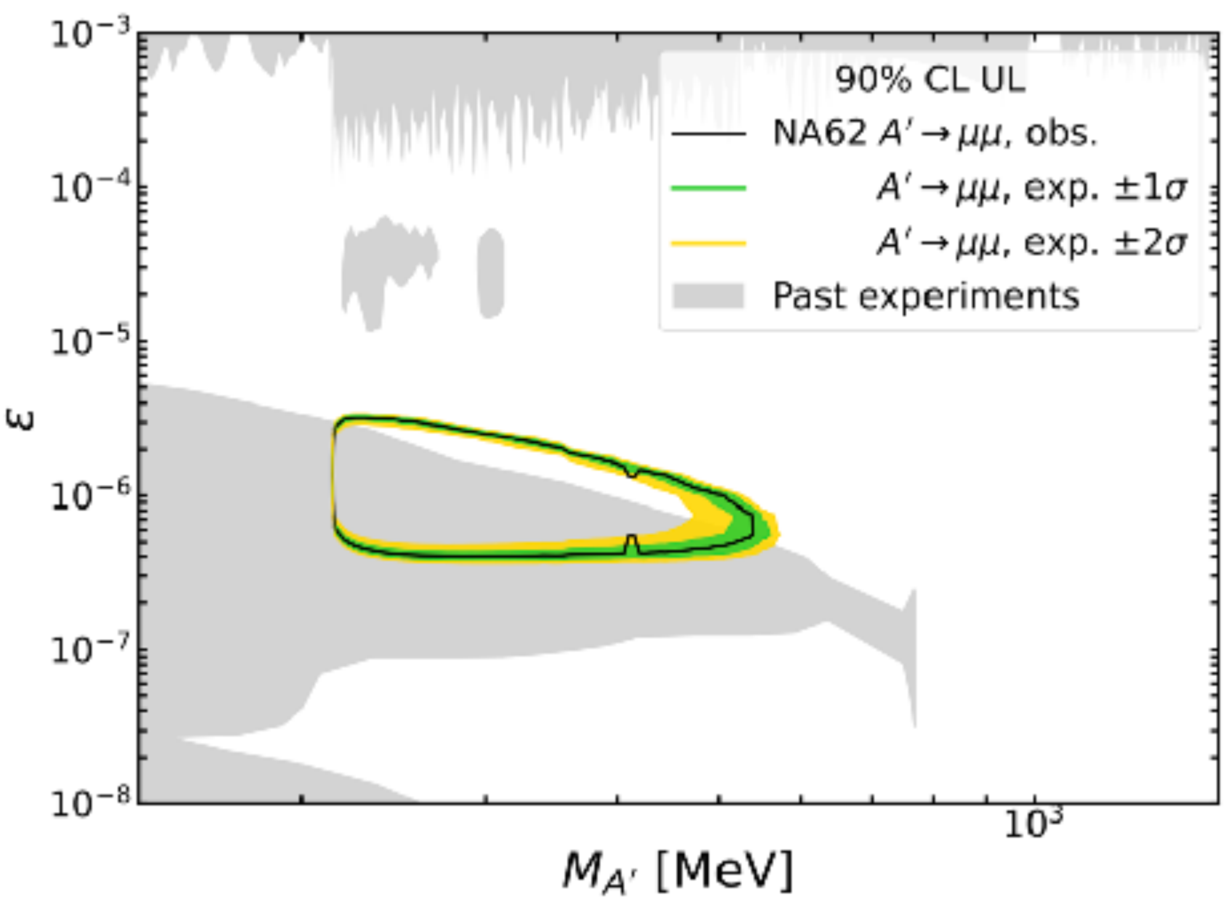
- Expected background in SR: **0.0094** $^{+0.049}_{-0.009}$ events

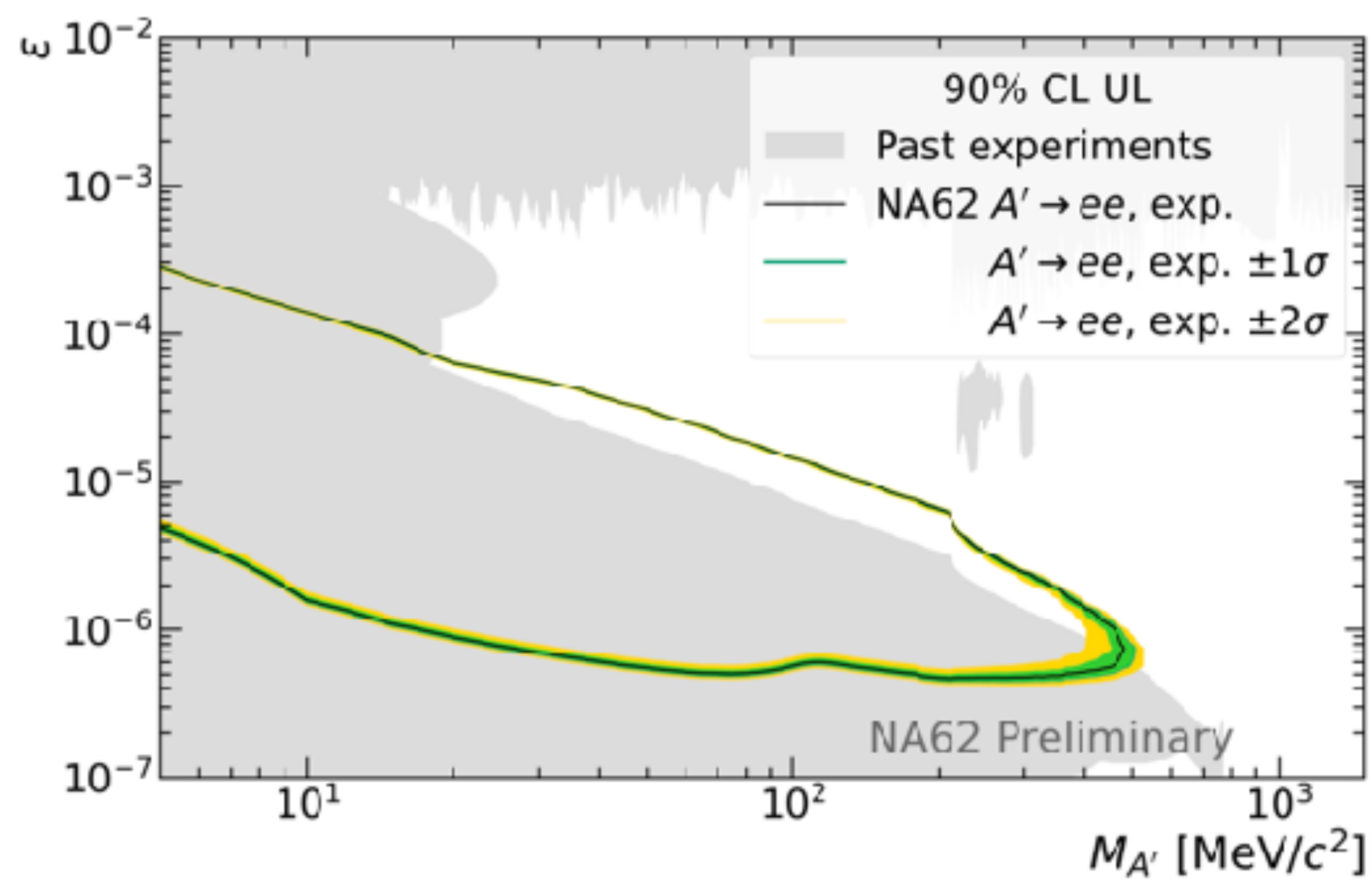
Probability for a non-zero observation in SR is 1.6%

- Observed number of events in SR: **0**
- Counting experiment with 2.4σ global significance (signal shape not taken into account)

A’⟶ $\mu^+\mu^-$, A’⟶ e^+e^- Result

With $(1.4 \pm 0.28) \times 10^{17}$ PoT, from a cut-based counting experiment blind analysis a 90% CL upper limit has been set for A’⟶$\mu^+\mu^-$ and A'⟶ e+e- exploring a new region of the parameter space





- Search for decays of exotic particles to γγ, π+π-γ, and other hadronic final states using the data collected in 2021 are ongoing
- NA62 intends to collect 10^{18} PoT in beam-dump in 2022-2025 with interesting perspectives on dark photons, ALPs, dark scalars and HNLs

Conclusions

- **The NA62 experiment is a powerful laboratory to make searches for extremely rare kaon decays, new hidden sector physics and to perform precision measurement**

- **Results of recent analysis have been shown**
  - **$K^+ \rightarrow \pi^+\mu^+\mu^-$**. Model-independent branching fraction: **$B(K_{\pi\mu\mu}) = (9.15 \pm 0.08) \times 10^{-8}$**, form factor measurement with parameters extraction: **$a_+ = -0.575 \pm 0.013$**, **$b_+ = -0.722 \pm 0.043$**, forward-backward asymmetry: **$A_{FB} = (0.0 \pm 0.7) \times 10^{-2}$**
  - **$K^+ \rightarrow \pi^+\gamma\gamma$**. Branching fraction: **$B(K_{\pi\gamma\gamma}) = (9.73 \pm 0.19) \times 10^{-7}$**, form factor parameter **$\hat{c} = 1.713 \pm 0.084$**
  - **$A' \rightarrow \mu^+\mu^-$** and **$A' \rightarrow e^+e^-$**: 90% CL exclusion regions have been established in the m_A, ε parameter space

- **NA62 will take data till LS3 in 2026: larger data sets will be available**

Conclusions

Decay channel	Data set	
$K^+ \to \pi^+ \nu \bar{\nu}$	NA62 Run 1	JHEP 06 (2021) 093
$K^+ \to \pi^+ \mu^+ \mu^-$	NA62 Run 1	JHEP 11 (2022) 011
$K^+ \to \pi^+ \gamma \gamma$	NA62 Run 1	preliminary
$K^+ \to \pi^- \mu^+ e^+$	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	PLB 797 (2019) 134794
$K^+ \to \pi^- e^+ e^+$	NA62 Run 1	PLB 830 (2022) 137172
$K^+ \to \pi^- \pi^0 e^+ e^+$	NA62 Run 1	PLB 830 (2022) 137172
$K^+ \to \mu^- \nu e^+ e^+$	NA62 Run 1	preliminary
$A' \to \mu^+ \mu^-$	NA62 2021 data	preliminary

…Further results will be obtained and new searches developed !