Status of NA62 precision measurements on Chiral Perturbation Theory and form factor parameters

Mariaelena D'Errico *on behalf of NA62 collaboration*

Outline

- Brief introduction
- NA62 in general
- $K^+ \rightarrow \pi^+\mu^+\mu^-$
- $K^+ \rightarrow \pi^+\gamma\gamma$
- Summary

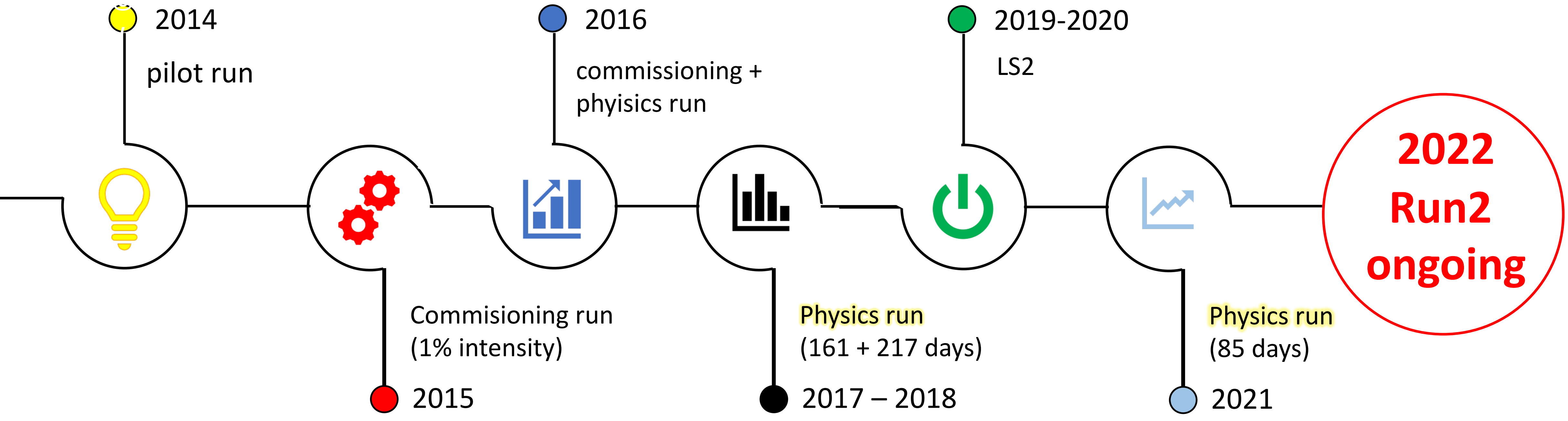
Introduction

- **Chiral Perturbation Theory (ChPT)** is a natural framework that embodies together an effective theory (satisfying the basic chiral symmetry of QCD) and a perturbative Feynman–Dyson expansion.
- It allows one to study the low-energy dynamics of QCD on the basis of the underlying chiral symmetry.

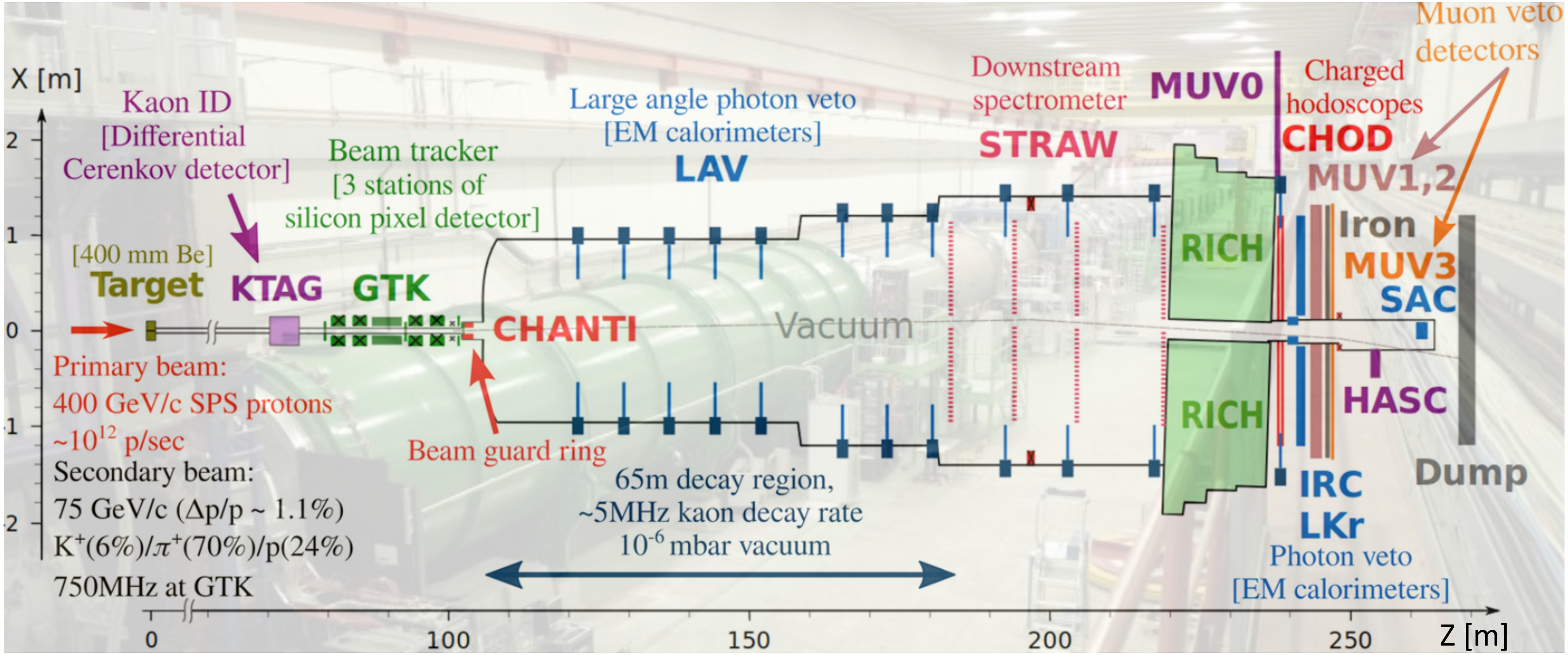
- Some precision measurements in NA62 are strongly related to ChPT and can validate it
- Form-factor ChPT parameters can be measured.

NA62 experiment [2017 JINST 12 P05025]

NA62 is a fixed-target experiment @ CERN SPS
Main goal: measure BR($K^+ \rightarrow \pi^+ \nu \bar{\nu}$) with 10% precision using **novel kaon-in-flight** technique
Broader physics: Rare/forbidden kaon decays; searches for exotic particles (K decays and beam dump)



NA62 experiment- setup [2017 JINST 12 P05025]



NA62 experiment – main goal

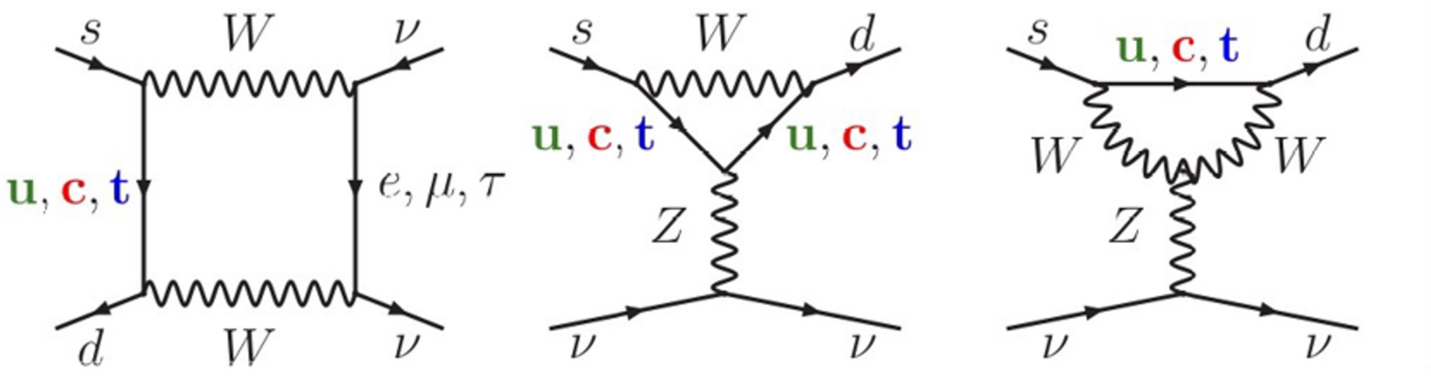
See Renato Fiorenza contribution from yesterday!

Main goal : measurment of BR($K^+ \to \pi^+ \nu \bar{\nu}$) with 10% precision using **novel kaon-in-flight** technique

FCNC loop process

c⟶ *d* coupling and highest CKM suppression

Very **rare** but theoretically very **clean**



Prediction: $BR_{SM}(K^+ \to \pi^+ \nu\bar{\nu})$ = (8.4 ± 1.0) $\times 10^{-11}$

Measured: $BR(K^+ \to \pi^+ \nu\bar{\nu}) = \left(10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}\right) \times 10^{-11}$ (20 events observed in 2016 – 2018 data)

See also F. Brizioli and M. Corvino talks this afternoon

$$\mathbf{K}^+ \rightarrow \pi^+\mu^+\mu^-$$

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

- Flavour-changing neutral current (decay group: $K^\pm \rightarrow \pi^\pm \ell^+ \ell^-$).
- Dominant contributions mediated by virtual photon.
- Long-distance hadronic effects described by a vector interaction **form factor**.
- Comparison between Kπee and Kπμμ is a test of **Lepton Flavor Universality**.

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

- Kinematic variable $z = m^2(\mu\mu)/m^2_K$
- Differential decay width function of the transition form factor W(z):

$$\frac{d\Gamma(z)}{dz} = \frac{d\Gamma_{3-body}(z)}{dz} + \frac{d\Gamma_{4-body}(z)}{dz} = g(z) \cdot |W(z)|^2 + \frac{d\Gamma_{4-body}(z)}{dz}$$

- ChPT parametrization at $O(p^6)$ of W(z) is considered:

* 3-body: $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ final state
* 4-body: $K^+ \rightarrow \pi^+ \mu^+ \mu^- \gamma$ final state

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

where $W^{\pi\pi}(z)$ is a complex function describing the contribution from a two-pion loop and depends on additional real parameters taken from G. D'Ambrosio et al, arXiv:2209.02143.

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

- Normalization channel $K^+ \to \pi^+ \pi^+ \pi^-$: very similar channel

  → substantial overlap of the event selections
  → first-order cancellation of most detector and trigger inefficiencies
  → reduction of systematic uncertainties

- Trigger stream:

  *K*3π collected using Multi-track (MT) trigger:
  L0:RICH,CHOD;downscaling factor $D_{MT} \approx 100$
  L1: KTAG, Straw; no downscaling
  *K*πμμ collected using Di-muon multi-track (2μMT) ≈ (MT + 2 muons in MUV3) trigger:
  L0:RICH,CHOD,MUV3;downscaling factor $D_{2\mu MT} \approx 2$
  L1: KTAG, Straw; no downscaling

  Total trigger efficiencies of both trigger streams are ≈ 90%

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

Common selection (Generic 3-track selection cuts):

- Three track vertex topology (STRAW)
- Timing cuts (CHOD, KTAG, RICH)
- Particle ID using MUV3 and LKr:
  - $\mu^{\pm}$: in-time MUV3 signal, $E/p < 0.2$
  - π^{+}: no in-time MUV3 signal, $E/p < 0.9$

Additional for Kπμμ

- Tracks identified as π μ μ
- Additional kinematic cuts to suppress $K3\pi$
- $|m(\pi\mu\mu) - m_K| < 8 \mathrm{MeV}/c^2$

Acceptance: $A_{\pi\mu\mu} \approx 8.7\%$

Additional for K3π

- One positively charged track: ID as pion
- $|m(3\pi) - m_K| < 8 \mathrm{MeV}/c^2$

Acceptance: $A_{3\pi} \approx 6.6\%$

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

- Data sample collected in 2017 and 2018
- Effective number of Kaons $N_K = 3.5\times10^{12}$ (measured from K3π)
- Number of observed $K^+ \to \pi^+\mu^+\mu^-$, $N_{K\pi\mu\mu}$= **27679**

Performed measurements:

- Model independent branching fraction
- W(z) form factor
- a_+, b_+ ChPT parameters
- Forward-backward asymmetry

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

Data divided in 50 equipopulated bins in z:

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

integrating over z → $B_{\pi\mu\mu} = (9.15 \pm 0.06_{stat}) \times 10^{-8}$

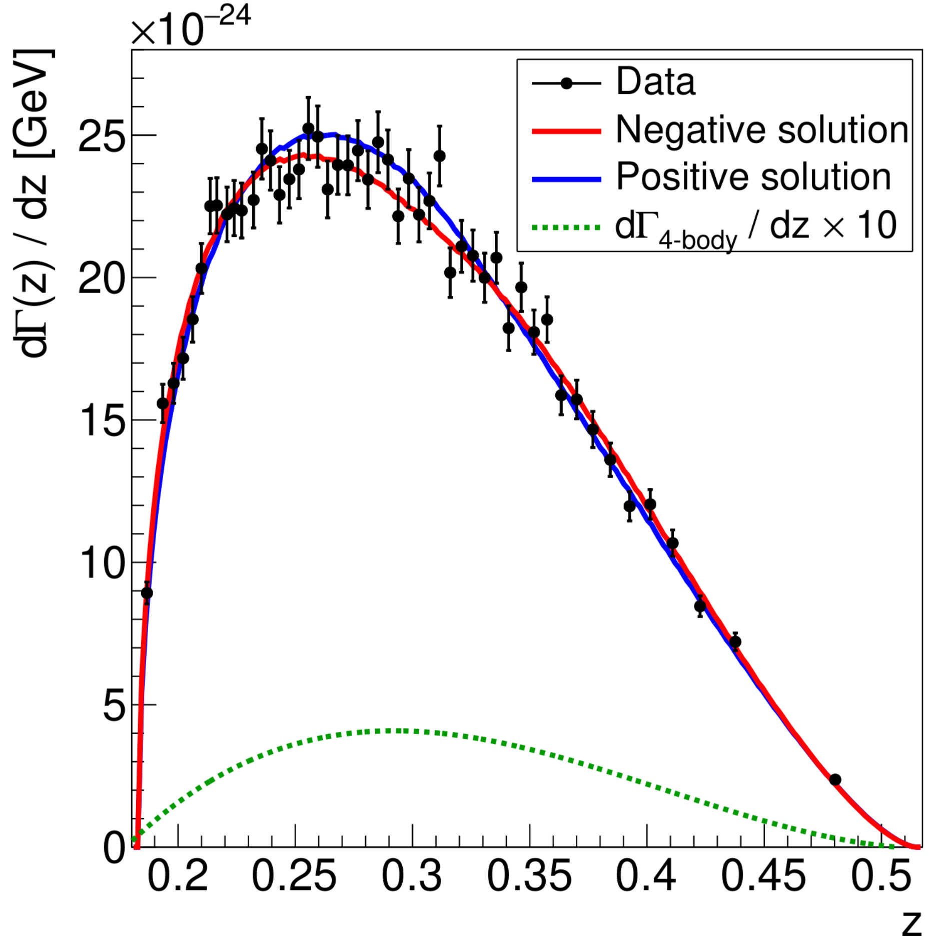
Δz_i : Bin width
$N_{\pi\mu\mu,i}$: Number of signal events
$A_{\pi\mu\mu,i}$: Signal acceptance
NK : Effective number of kaon decays
τ_K : mean *K*± lifetime

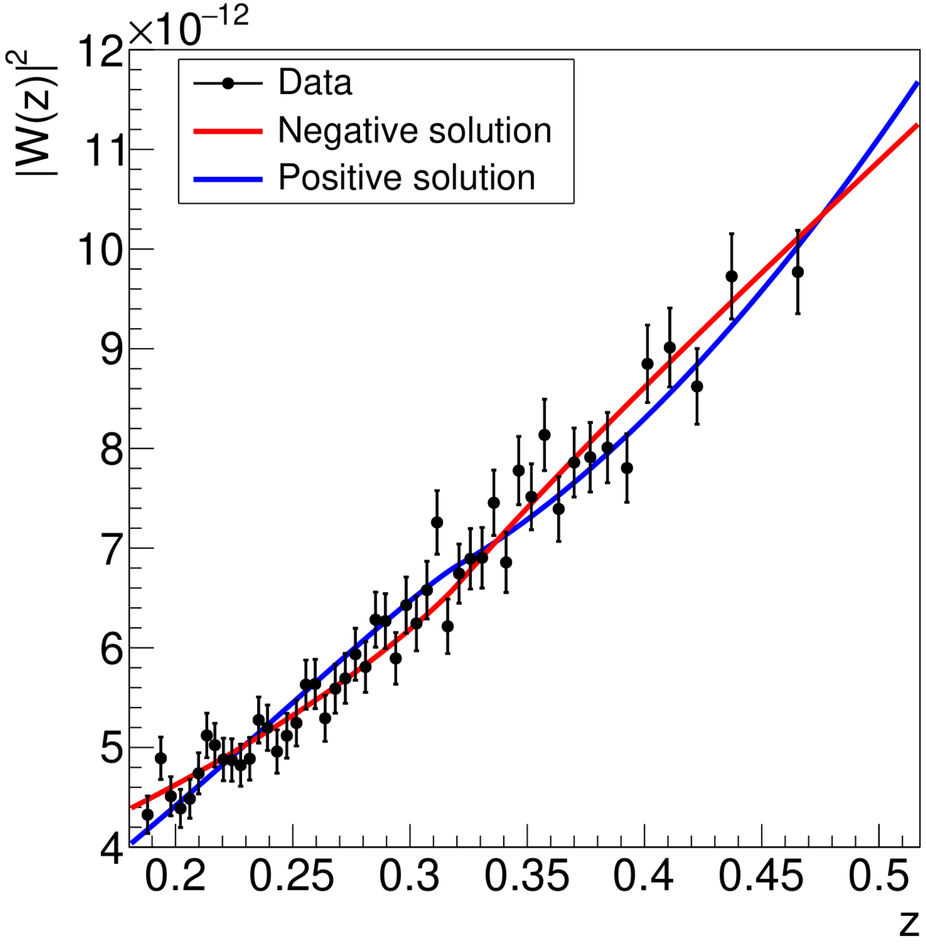
Form factor parameters a_+ and b_+ are determined by a χ^2 fit. Fits of $d\Gamma(z)/dz$ and $|W(z)|^2$ give identical results.

Negative solution (theoretically prefered):
χ^2/ndf = 45.1/48 (p-value = 0.59)
$a_+ = -0.575 \pm 0.012_{stat}$, $b_+ = -0.722 \pm 0.040_{stat}$,
$\rho(a_+, b_+) = -0.972$.

Positive solution:
χ^2/ndf = 56.4/48 (p-value = 0.19),
$a_+ = 0.373 \pm 0.012_{stat}$, $b_+ = 2.017 \pm 0.040_{stat}$,
$\rho(a_+, b_+) = -0.973$.

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





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

- Forward-backward asymmetry for $K_{\pi\mu\mu}$

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

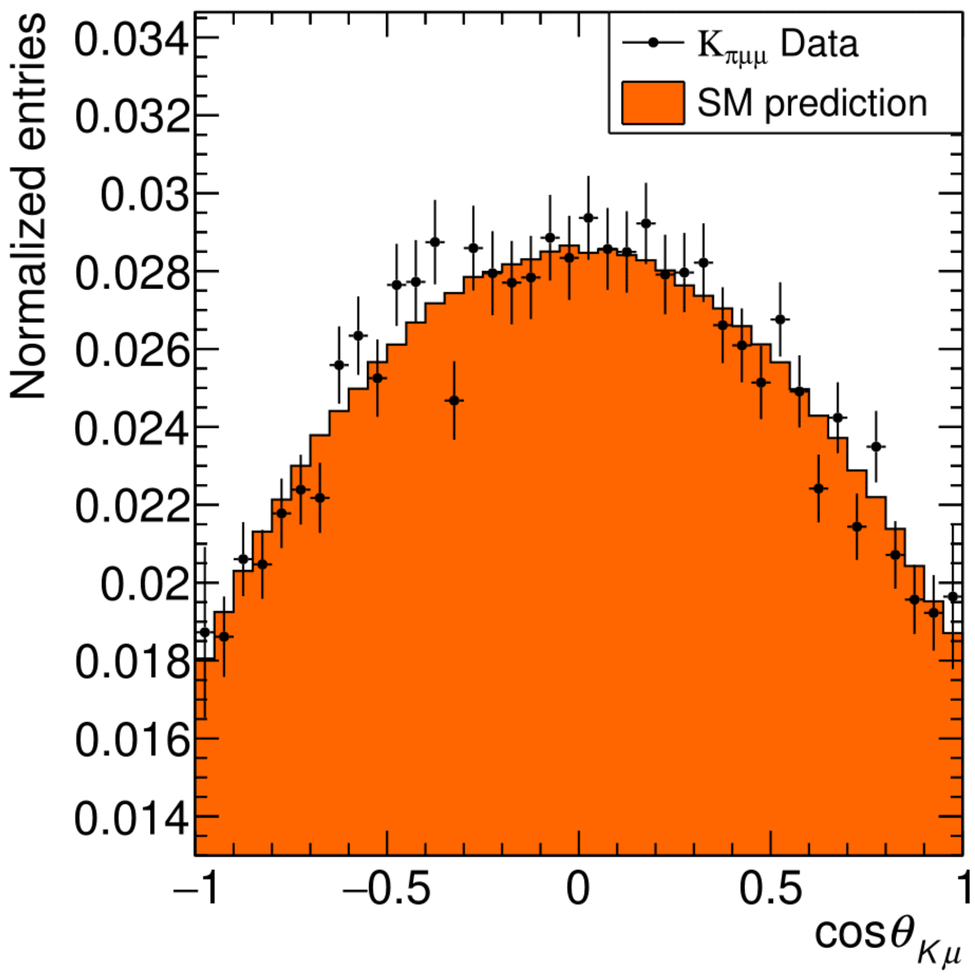
- $\theta_{K\pi}$ – angle between K^+ and μ^- in $\mu^+\mu^-$ rest frame

Measured value: $\boldsymbol{A_{\rm FB} = (0.0 \pm 0.7_{stat})\times 10^{-2}}$

No significant dependence on *z*

Statistical precision reaching upper limit from theory

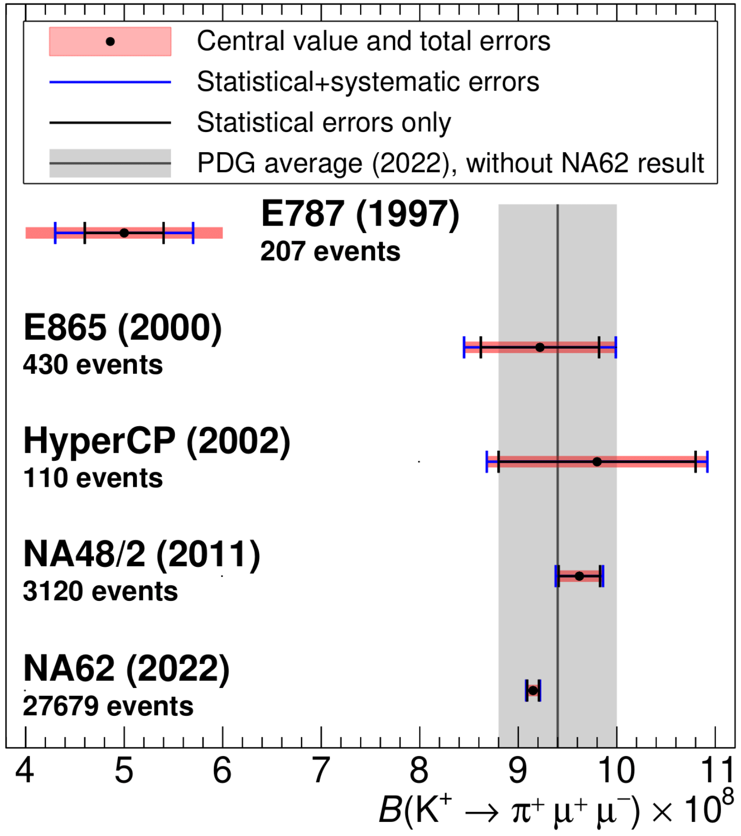
[PRD 67 (2003) 074029], [PRD 69 (2004) 094030]

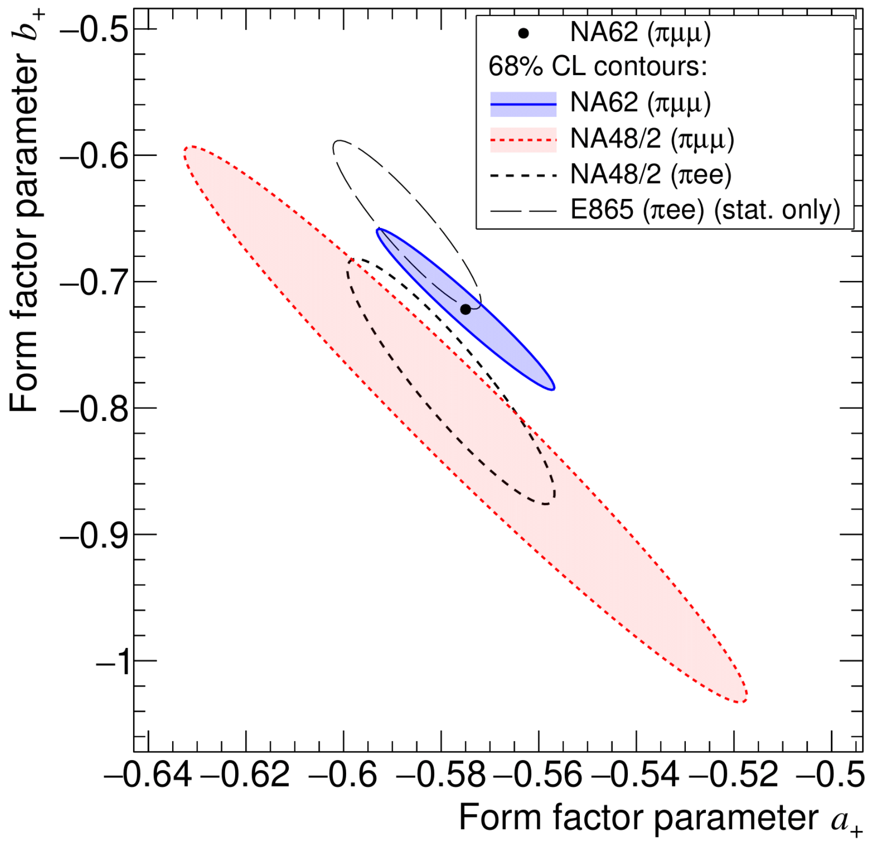


$K^+ \to \pi^+\mu^+\mu^-$

Published paper:

[The NA62 collab., Cortina Gil, E., Kleimenova, A. *et al.*, *J. High Energ. Phys.* **2022**, 11 (2022). https://doi.org/10.1007/JHEP11(2022)011](https://doi.org/10.1007/JHEP11(2022)011)





Factor ~ 3 improvement over previous $BR_{\pi\mu\mu}$ measurements

Agreement between the measurements:

$a_+, b_+, BR_{\pi\mu\mu}, BR_{\pi ee} \to$ LFU conservation

(Theory -> A.Crivellin, G. D'Ambrosio et al, Phys. Rev. D 93, 074038 2016)

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

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

q_1, q_2: photons 4-momenta,
p: K 4-momentum, m_K - kaon mass,
$M(\gamma\gamma)$: di-photon mass

- Crucial test of Chiral Perturbation Theory (ChPT)
- The decay is described by $z = M^2(\gamma\gamma)/ m_K^2$, $y = p\,(q_1 - q_2) / m_K^2$
- In the ChPT framework (at leading order $O(p^4)$ and including $O(p^6)$ contributions) the decay rate and spectrum are determined by a single apriori unknown O(1) parameter $\hat{c}$:

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

Experimental goals:

- Measurement of $\hat{c}$ parameter
- Corresponding mesurement of BR($K^+ \to \pi^+\gamma\gamma$)

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

- Data used: 2017 – 2018 (Run1)
- Trigger streams: CONTROL + nonMuon
- Data observed: 4039

Selection:

- One good track in the Spectrometer
- K-π matching using beam tracker GTK for kaon to define K_+ decay vertex
- Two good clusters in LKr
- Kinematic cuts on kaon decay daughters: total energy conservation, total transverse momentum, invariant mass of decay products should be consistent with kaon mass

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

Estimated backgrounds:

1) merging clusters 2) K3π with 2 non reconstructed tracks

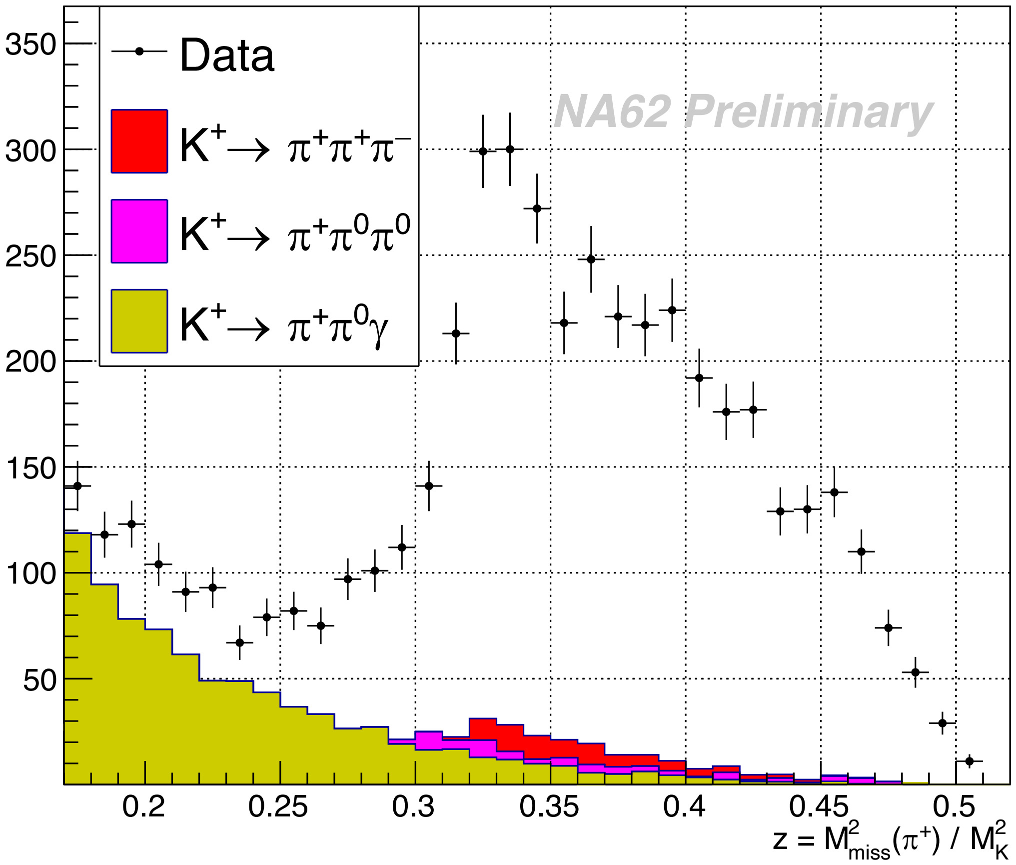
Common strategy → use control regions enriched of bkg events

(see spares for details)

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

Final background estimated contributions:

z > 0.25	Number of events
$K+ \to \pi+\pi^0\gamma$	252 ± 6(stat.)±15(syst.)
$K+ \to \pi^+\pi^0\pi^0$	58±5(stat.)±3(syst.)
$K+ \to \pi^+\pi^+\pi^-$	83±3(stat.)±2(syst.)
Total background	393±9(stat.)±16(syst.)
Data	4039
Data - background	3646±67



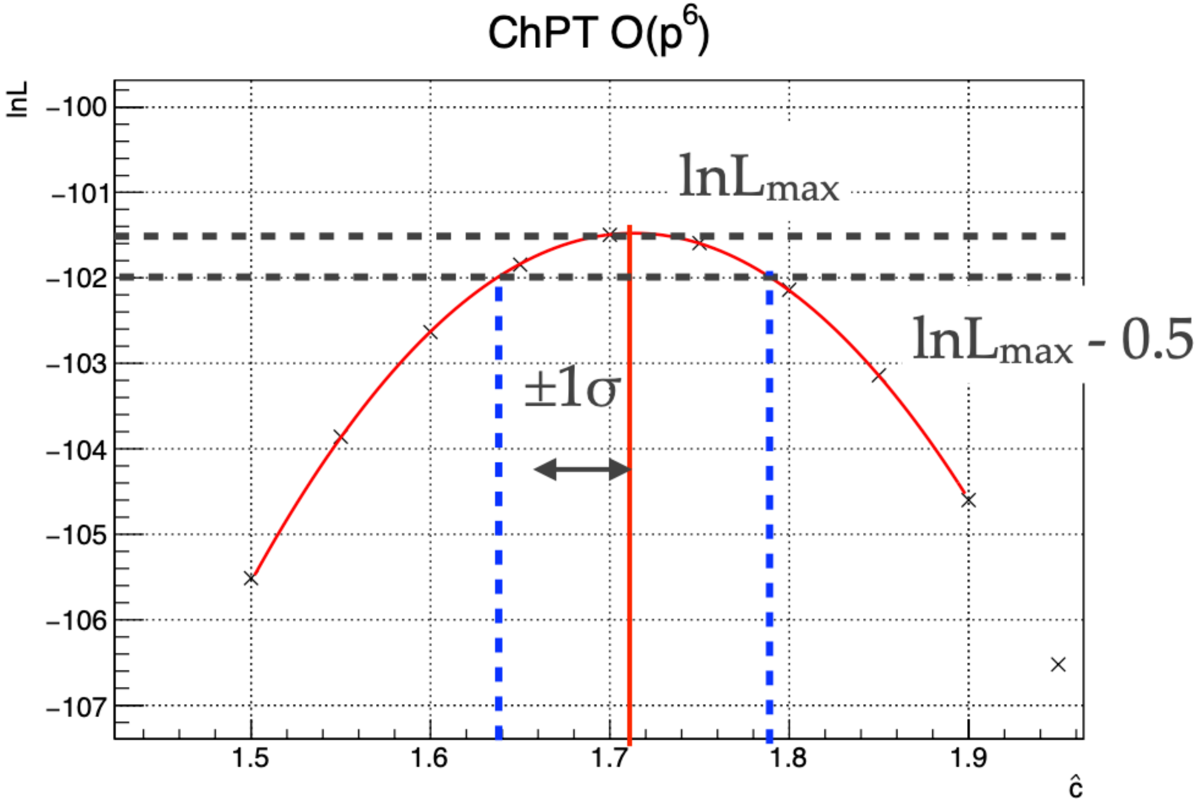
$K^+ \to \pi^+\gamma\gamma$

Final measurements → $\hat{c}$ fit procedure

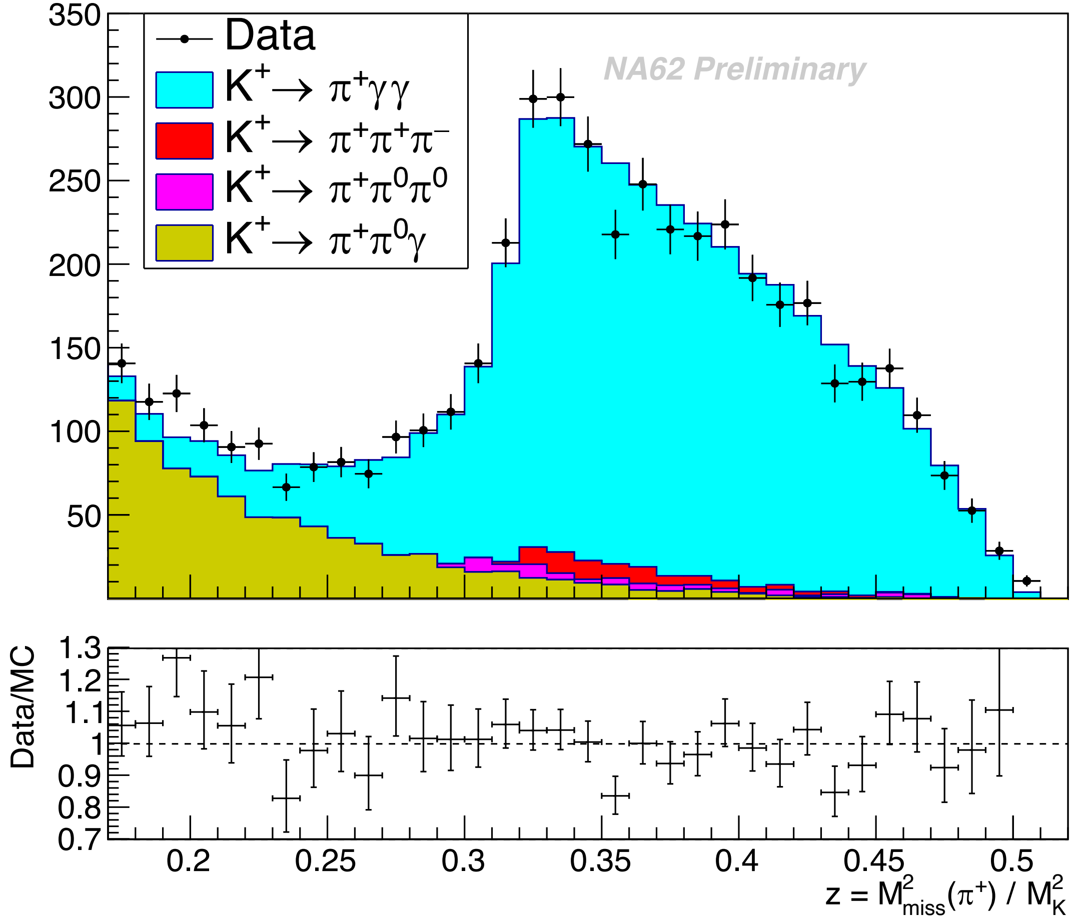
1. Z distribution divided in bins;
2. Maximization of Likelihood function:

$$\ln \mathcal{L} = \sum_i (k_i \ln \lambda_i - \lambda_i - ln(k_i!))$$

- k_i observed events in the i-th bin
- $\lambda_i = \lambda_i^S(\hat{c}) + \lambda_i^B$ expected events in the i-th bin



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



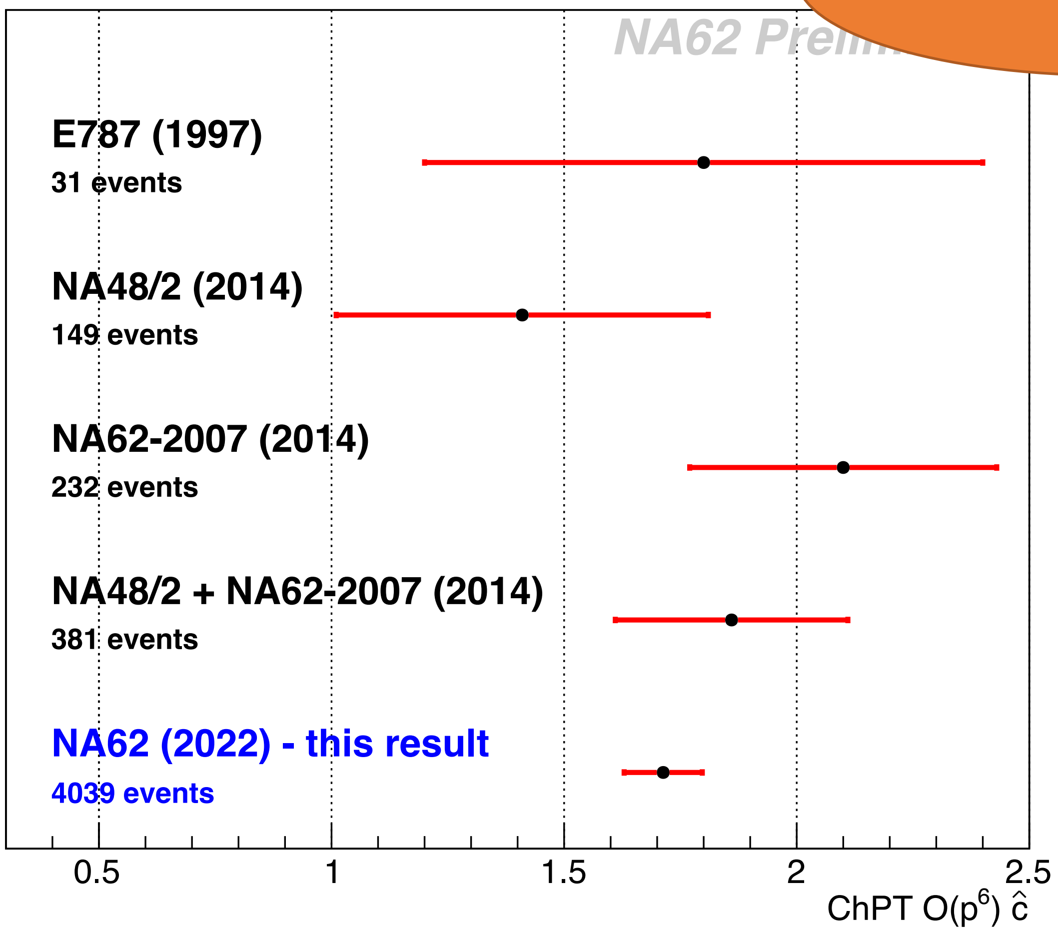
Final results:

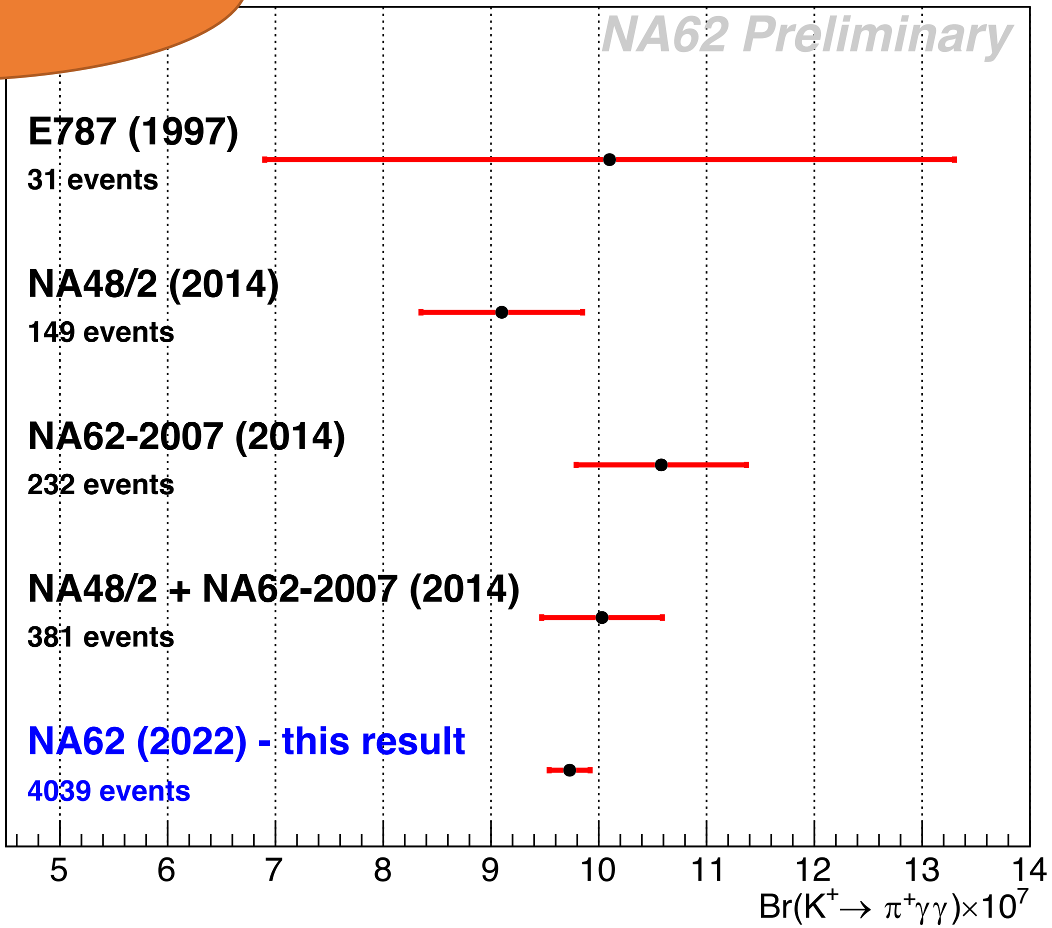
$\hat{c} = 1.713 \pm 0.075_{stat.}$

$BR(K_+ \to \pi_+\gamma\gamma) = (9.73 \pm 0.17\ ) \times 10^{-7}$

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

Factor 3 improvement



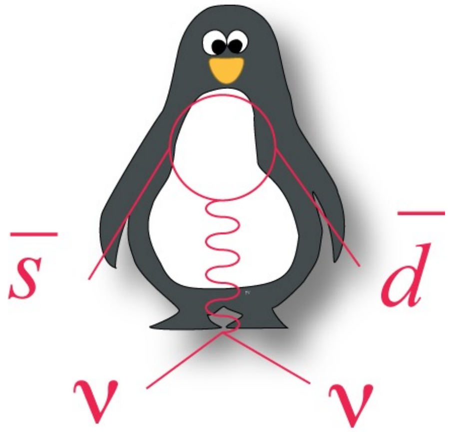


Summary&Conclusions

- Some precision measurements in NA62 are strongly related to ChPT;
- Some form-factors and their ChPT parametrization can be measured;
- Decay $K^+ \rightarrow \pi^+ \mu^+ \mu^-$:
  - Form factor of the $K^\pm \rightarrow \pi^\pm \gamma*$ transition: $W(z)$
  - BR($K^+ \rightarrow \pi^+ \mu^+ \mu^-$), W(z) and its parameters a+ and b+ from ChPT at $O(p^6)$ measured
  - Precision increased by a factor of 3
  - Comparison with NA48/2 results on $K^+ \rightarrow \pi^+ e^+ e^-$ validates lepton universality
- Decay $K^+ \rightarrow \pi^+ \gamma\gamma$:
  - Measured ChPT parameter $\hat{c}$ applying a maximum likelihood fit
  - $\hat{c} = 1.713 \pm 0.075 \pm 0.037 = 1.713 \pm 0.084$
  - $B(K^+ \rightarrow \pi^+ \gamma\gamma) = (9.73 \pm 0.17 \text{ stat.} \pm 0.08 \text{ syst.}) \times 10^{-7} = (9.73 \pm 0.19) \times 10^{-7}$ (corresponding to $\hat{c}$)
  - Errors reduced by a factor of 3 with respect to previous best measurement from NA48/2+NA62-2007

➢ Work is also ongoing in other relevant channels:
  - $K^+ \rightarrow \pi^+ e^+ e^-$
  - $K^+ \rightarrow \ell^+ \nu \gamma$
  - $K^+ \rightarrow \pi^+ \pi^0 e^+ e^-$
  - $K^+ \rightarrow \ell^+ \ell^+ \ell^-$

Thank you!

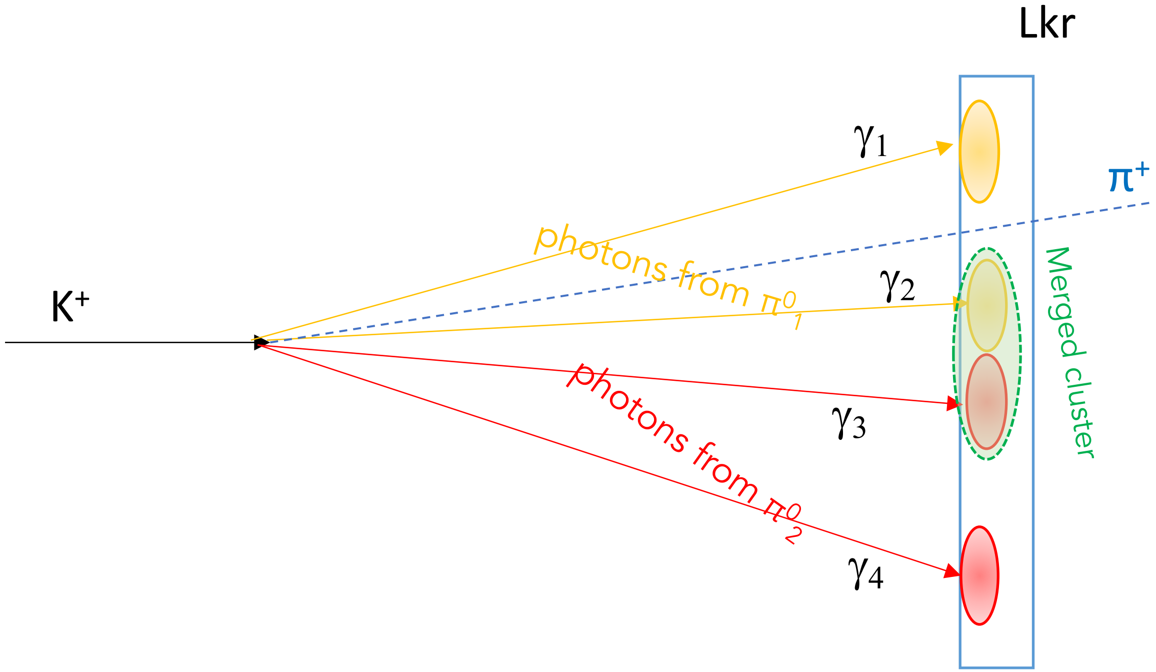


Spares

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

Estimated backgrounds:

1) merging clusters



1. Decay $K^+ \rightarrow \pi^+ \pi^0\pi^0$
2. Select events with 1 track and 3 clusters
3. Check reconstructed cluster energy with expected E_{merged} to tag cluster as a merged cluster.

$$E_2 = \frac{1}{2}\frac{M^2_{\pi^0}}{E_1(1-\cos\theta_{1m})}$$

$$E_3 = \frac{1}{2}\frac{M^2_{\pi^0}}{E_4(1-\cos\theta_{4m})}$$

$$E_{merged} = E_2+E_3$$

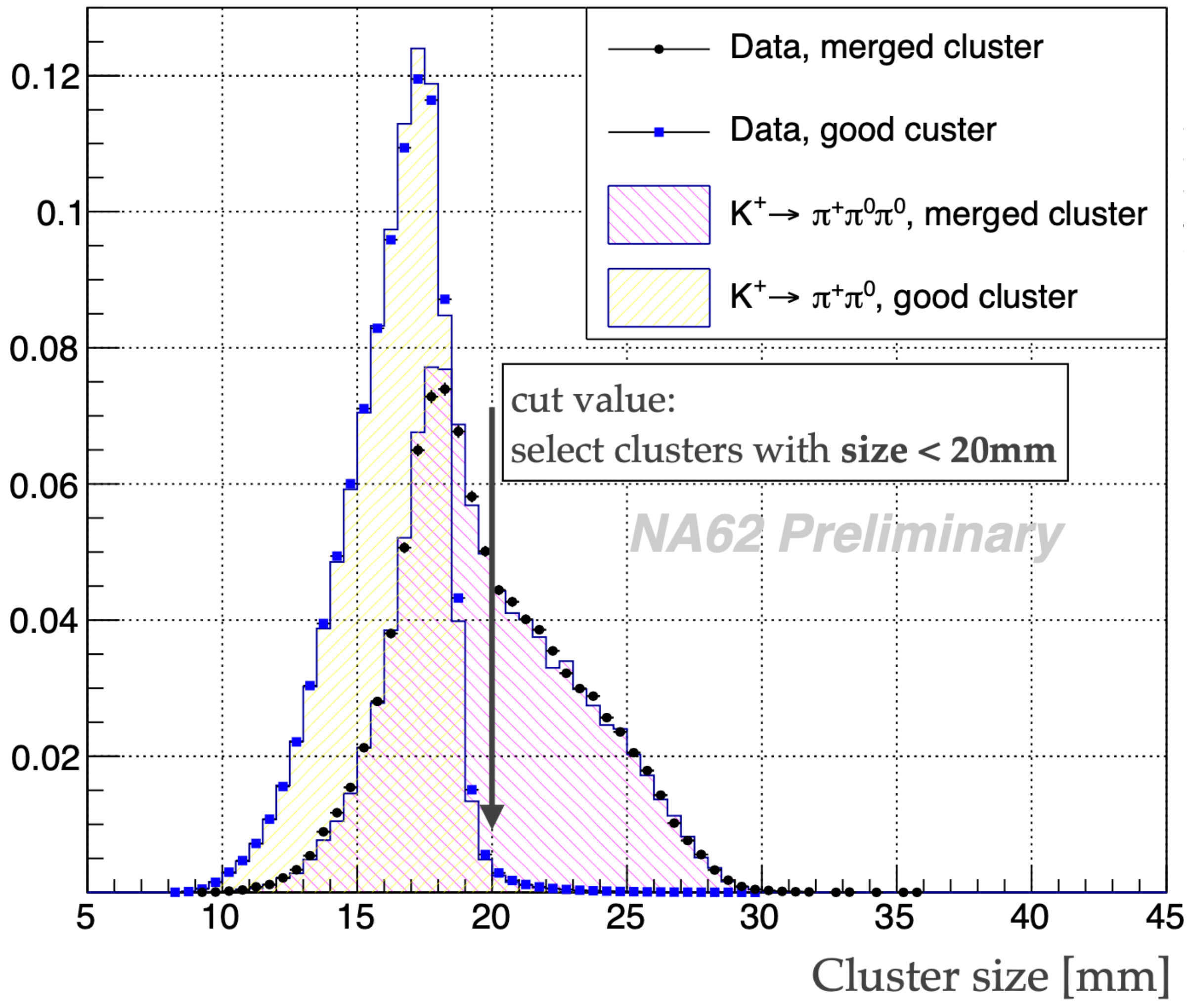
$K^+ \to \pi^+\gamma\gamma$

Estimated backgrounds:

1) merging clusters

- Distribution of cluster size merged clusters / good clusters
- Control region (merged clusters) compared to $K^+ \to \pi^+ \pi^0$ (good clusters)

Cluster size = RMS_x



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

Estimated backgrounds:

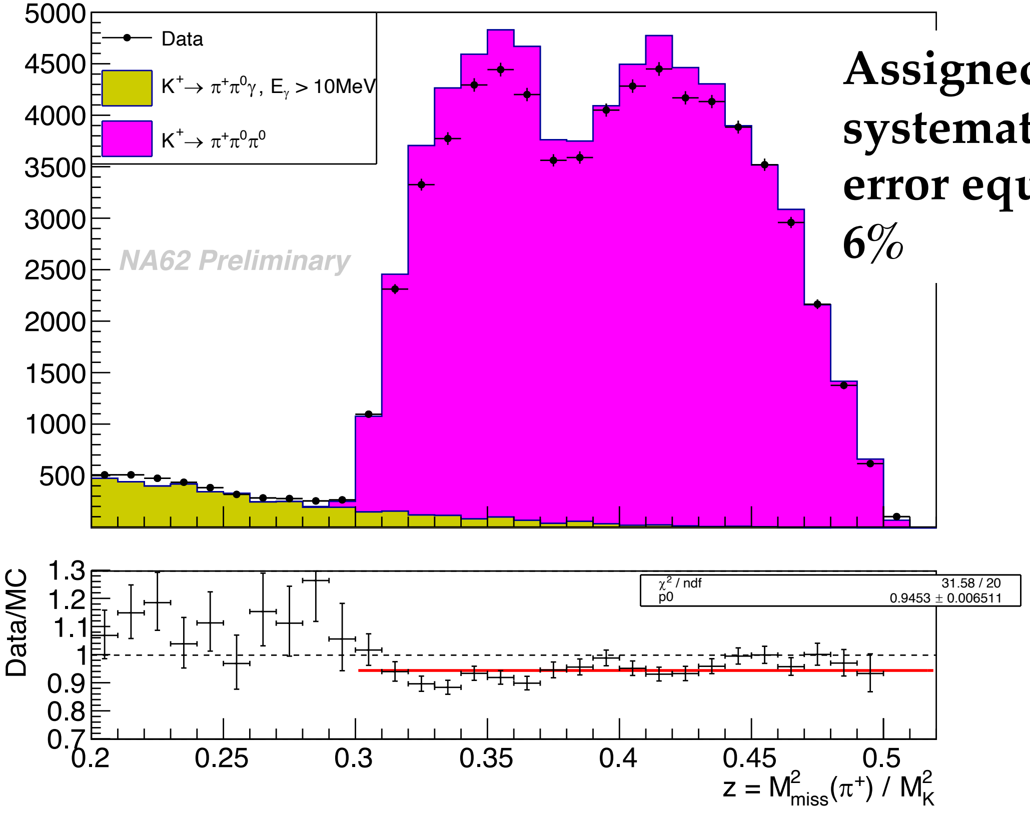
✓ merging clusters 2) K3π with 2 non reconstructed tracks

- Do not trust G4 pion energy deposit simulation in LKr
- Use $K^+\rightarrow\pi^+ \pi^+ \pi^-$ data to study pion energy deposit in LKr and implement it into NA62MC
- Relax kinematic cuts in the final selection to perform Data/MC comparison

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

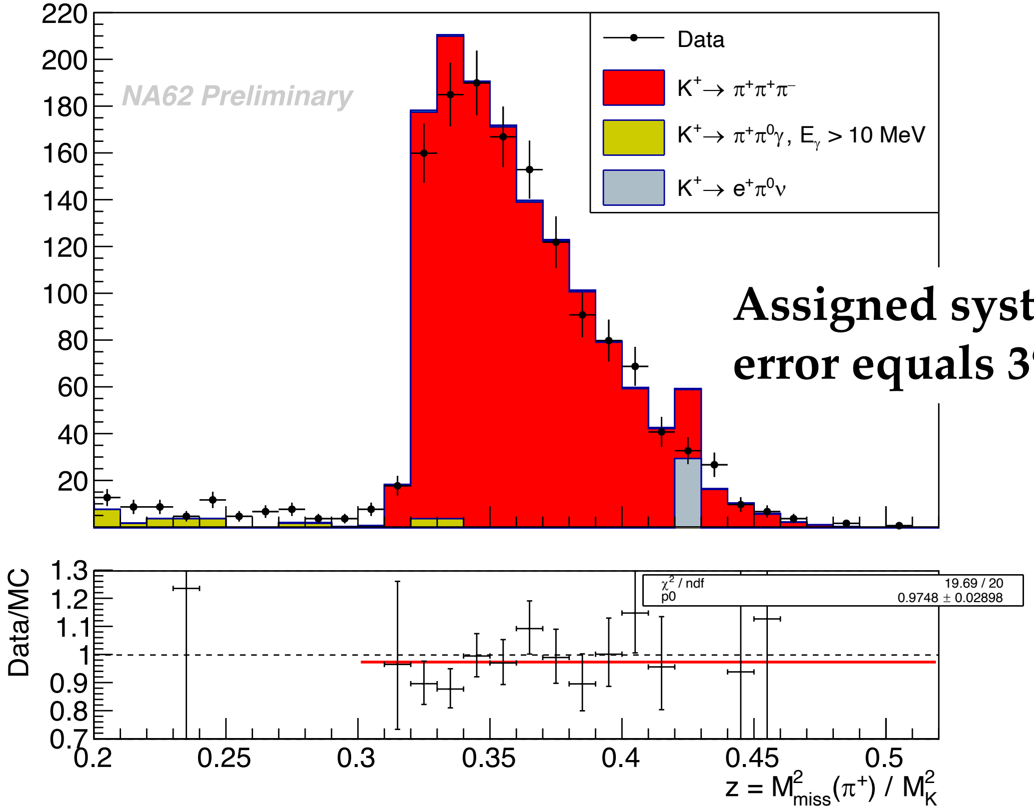
Control regions Data/MC comparison

1)



Assigned systematic error equals 6%

2)



Assigned systematic error equals 3%

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

Final background estimated contributions:

z > 0.25	Number of events
$K+ \rightarrow \pi+\pi^0\ \gamma$	252 ± 6(stat.)±15(syst.)
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