FPCP 2024, 27–31 May 2024, Bangkok

INFN LNF
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

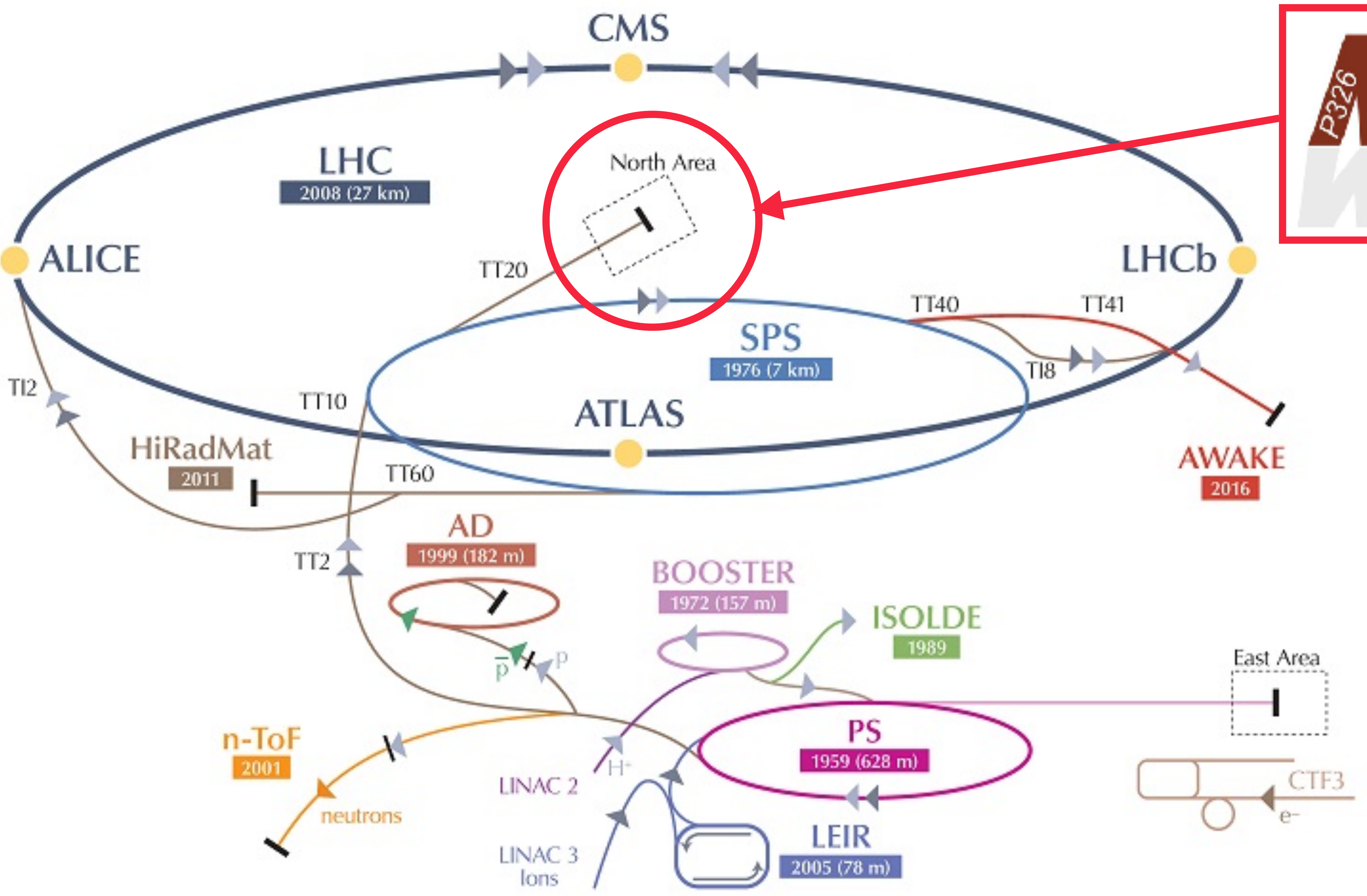
Recent results in Kaon physics: NA62

Silvia Martellotti, on behalf of NA62 collaboration

CERN

NA62 experiment at CERN: the K^+ factory

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



NA62 P326

Collaboration of ~ **200 participants** from ~ 30 institutions:
Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, Fairfax, Ferrara, Florence, Glasgow, Lancaster, Lausanne, Liverpool, LNF, Louvain, Mainz, Marseille, Moscow, Naples, Perugia, Pisa, Prague, Protvino, Rome I, Rome II, San Luis Potosi, Turin, TRIUMF, Vancouver

2014-2016
Commissioning

2016-2018
NA62 Run 1

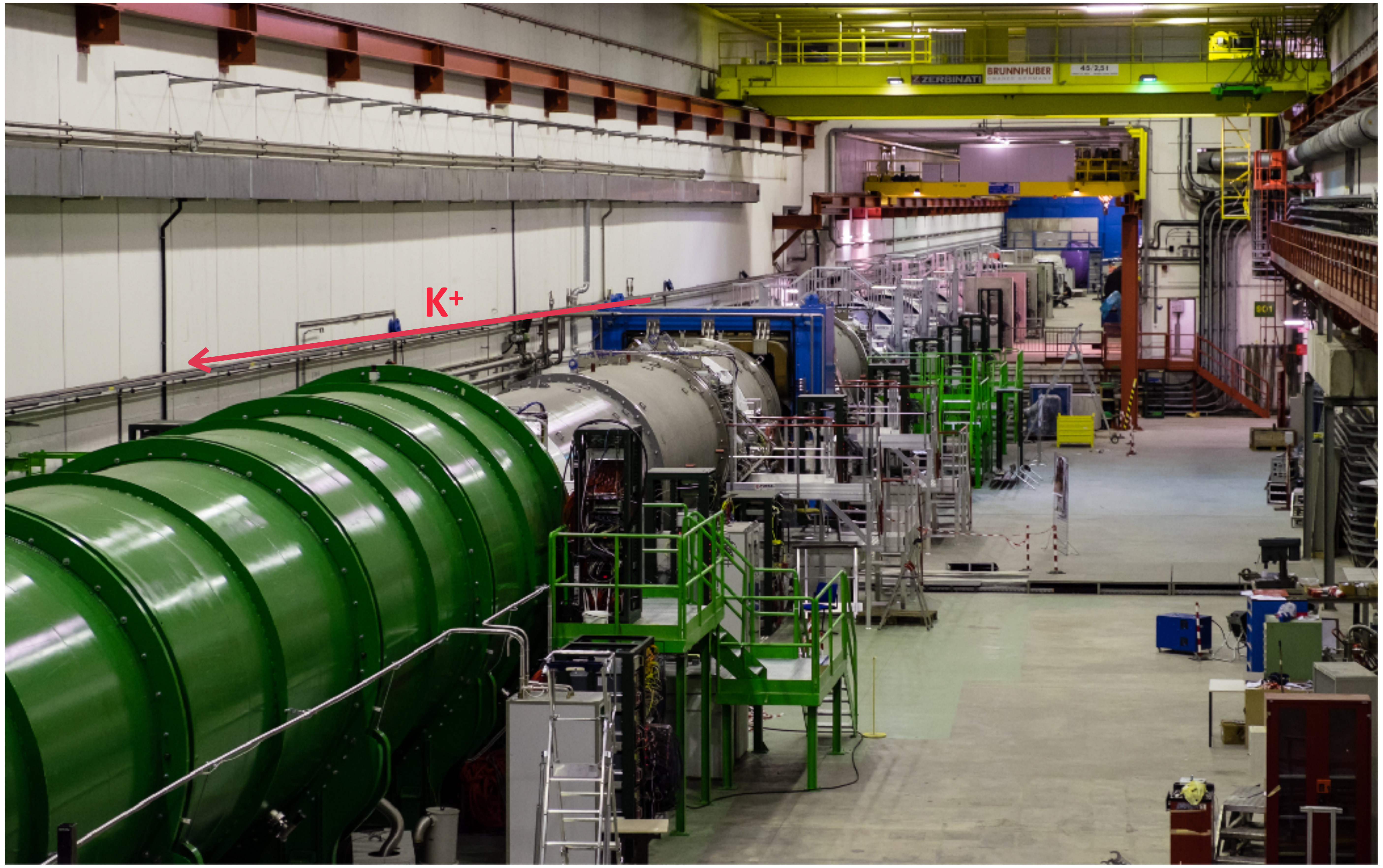
2019-2020
LS2

2021-2025
NA62 Run 2

2026
LS3

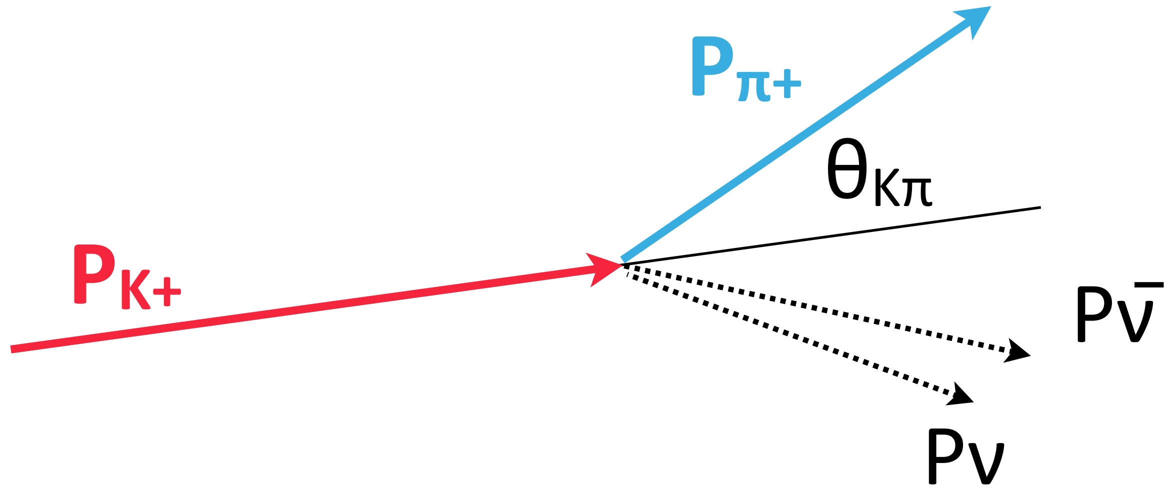
NA62 experiment at CERN: the K^+ factory

BEAM: 400 GeV/c **primary protons** (3×10^{12} p/pulse, 4.8 s spills) → 40 cm **Be target** → **75 GeV/c** unseparated secondary **hadrons beam** **π^+, p, K^+ .** ($\Delta p/p \pm 1\%$).

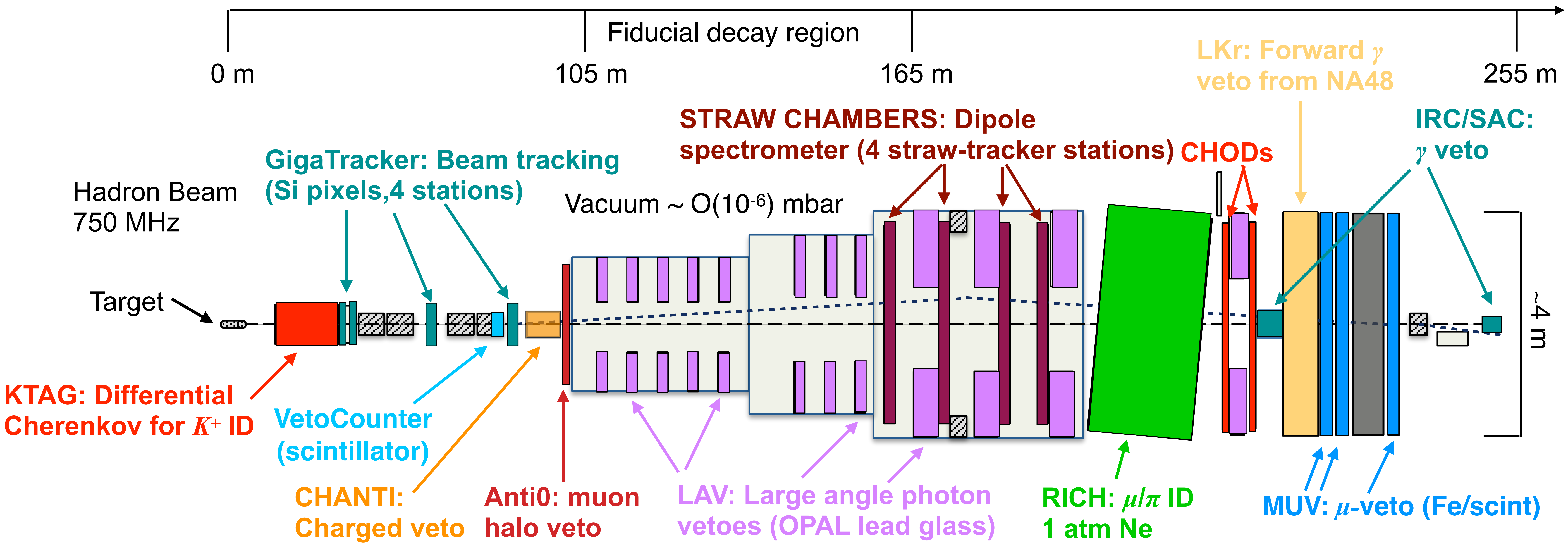


- 750 MHz total particle rate for the secondary hadron beam: **45 MHz of K^+ (6%)**
- Experiment: 270 m long downstream of the target
- Cylindrical shape around the beam axis for the main detectors (diameters from 20 to 400 cm)

NA62 goal:
measurement of the **BR($K^+ \longrightarrow \pi^+\nu\nu$).**
Highly suppressed and very well predicted: excellent test of the SM



NA62 detector



- **Beam tracker (GTK)**: Silicon Pixel spectrometer $\sigma_t < 100$ ps
- **Kaon tagger (KTAG)**: Nitrogen (1.75 bar) Cherenkov $\sigma_t \sim 70$ ps
- **Downstream tracker (STRAW)**: Straw tubes
  $\sigma_p/p = (0.3 \oplus 0.005 \cdot p)$ % [GeV/c]
- **Secondary particle ID (RICH)**: Neon (1 atm) Cherenkov $\sigma_t \sim 70$ ps
- **Trigger and timing (CHODs)**: Scintillator hodoscopes $\sigma_t \sim 200$ ps
- **12 large angle photon veto (LAV)**: lead glass blocks
- **Small angle photon veto (IRC, SAC)**: shashlik calorimeters
- **Electromagnetic calorimeter (LKr)**: 27 X_0 liquid-krypton
  $\sigma_E/E = (4.8/\sqrt{E} \oplus 11/E \oplus 0.9)\%$ [GeV]
- **Hadronic calorimeters (MUV1,2)**: iron/scintillator
- **Muon veto detector (MUV3):** trigger PID $\sigma_t \sim 500$ ps

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

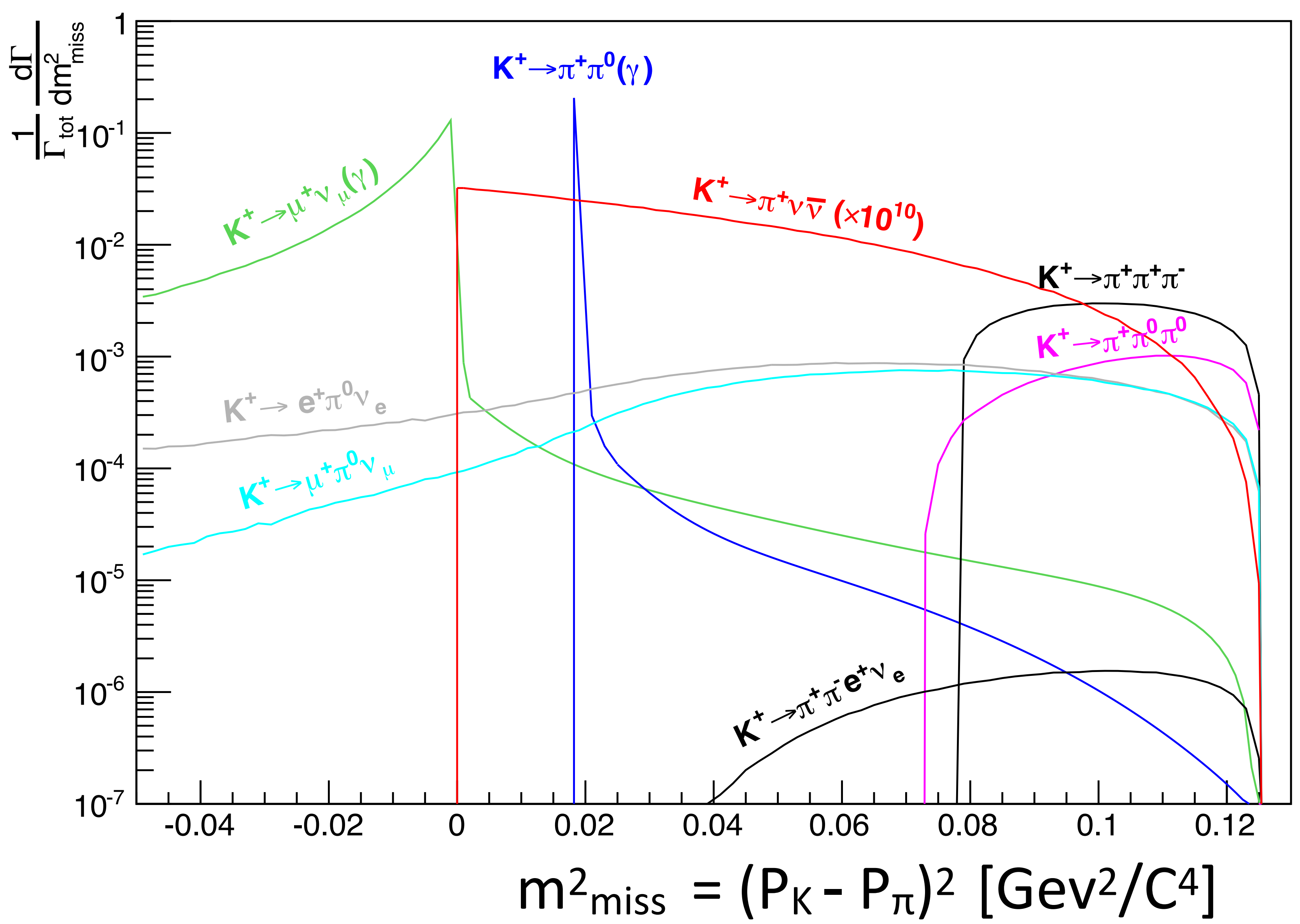
Most discriminating variable: **$m^2_{miss} = (P_{K+} - P_{\pi+})^2$** with m_π hypothesis for the charged daughter

Selection:

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

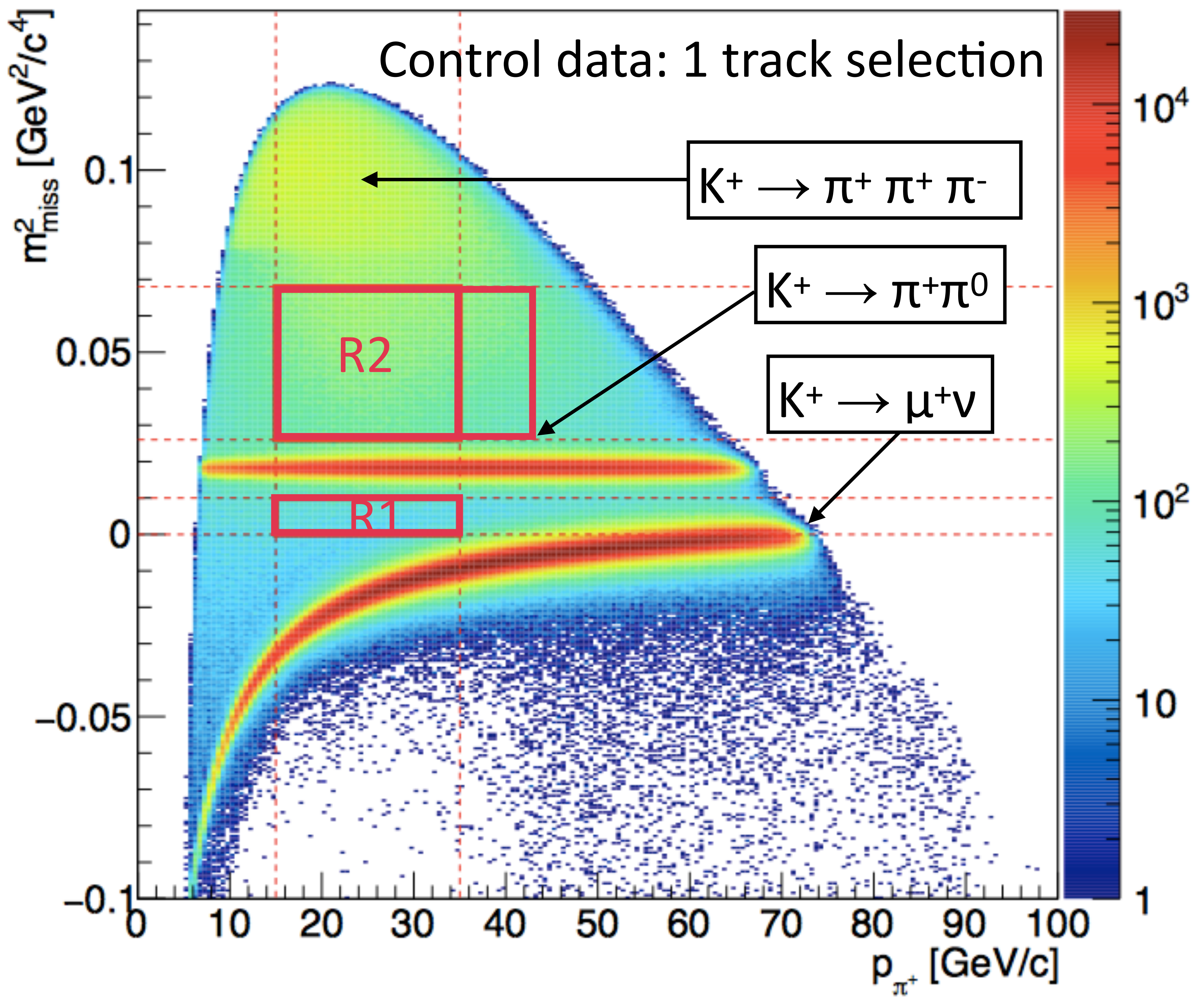
Performance:

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



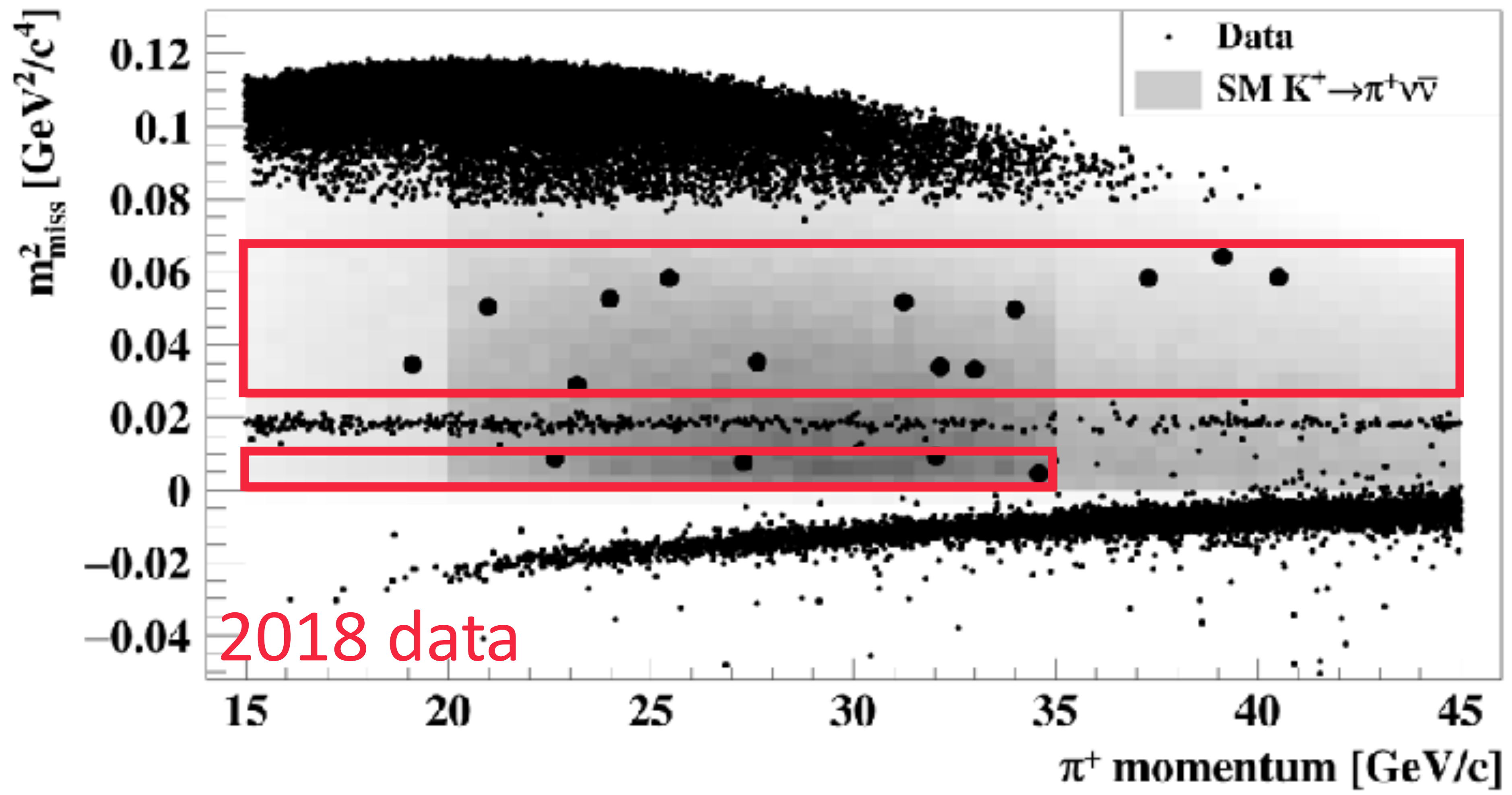
Background sources:

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



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

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



2016 + 2017 + 2018 data: **20** (1+2+17) $K^+ \longrightarrow \pi^+\nu\nu$ candidates

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

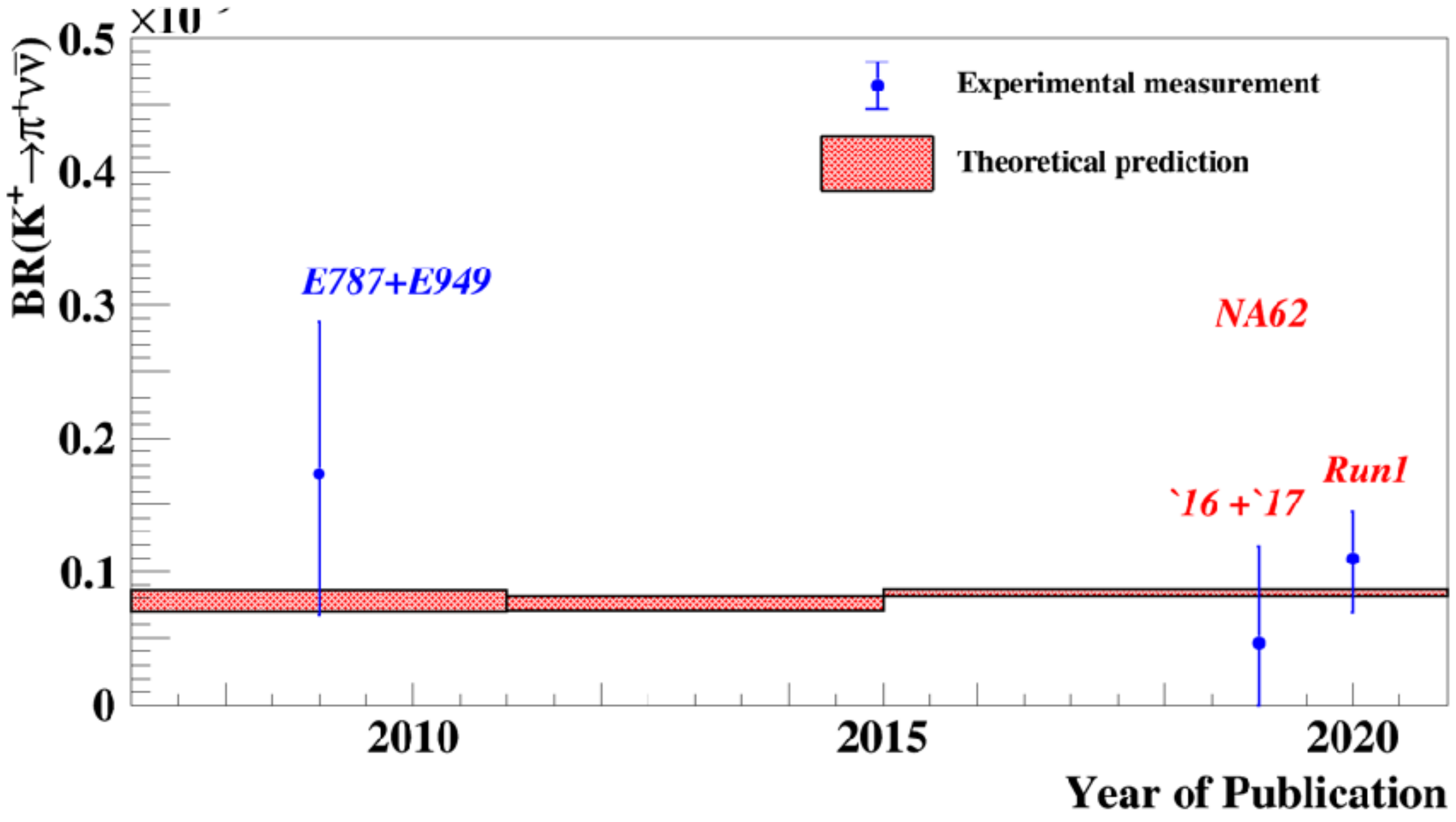
Expected signal: $10.01 \pm 0.42_{syst} \pm 1.19_{ext}$

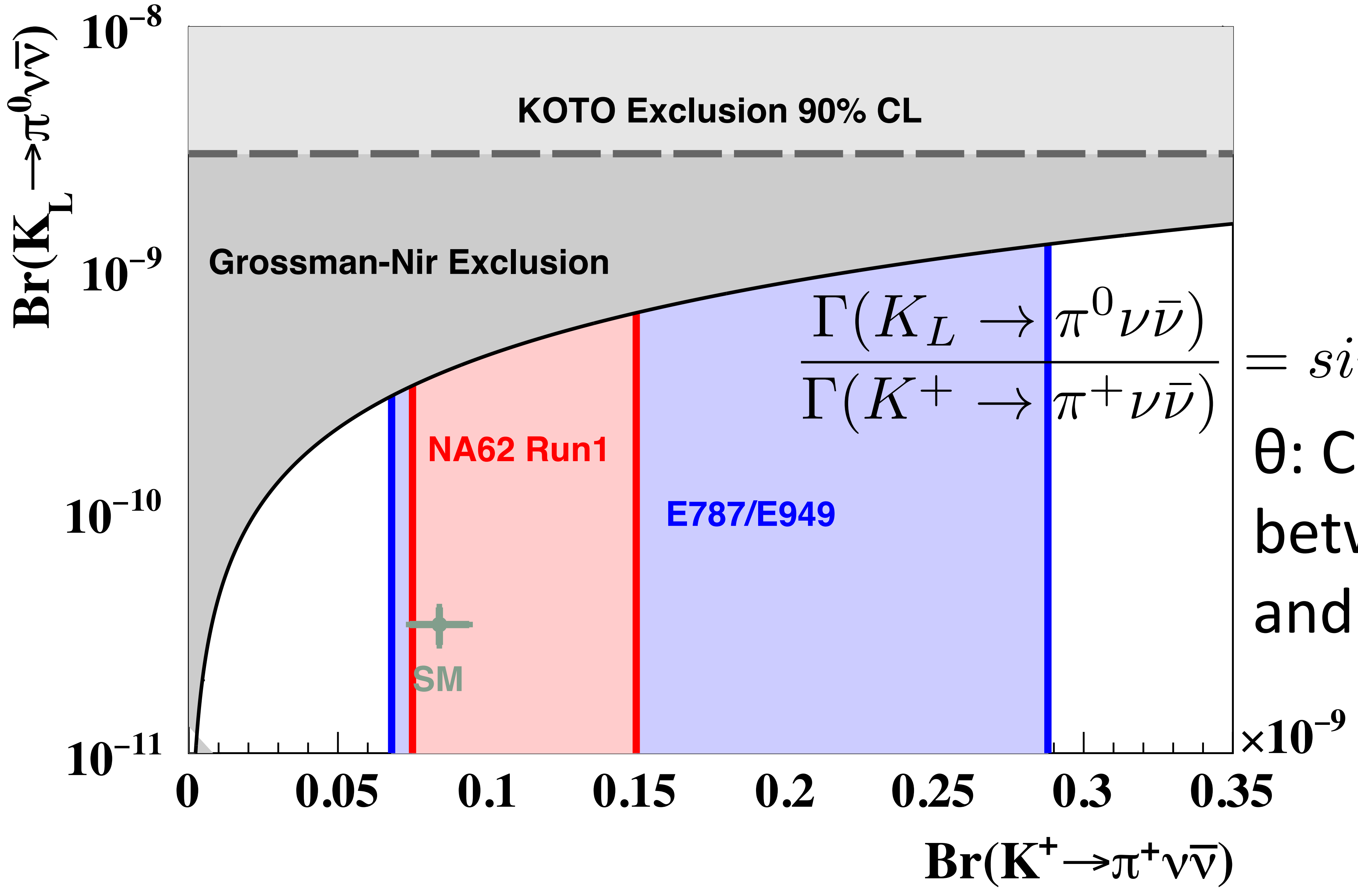
Expected background: $7.03^{+1.05}_{-0.82}$

JHEP06 (**2021**) 093

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

3.4 σ significance most precise measurement to date





$$\frac{\Gamma(K_L \to \pi^0\nu\bar{\nu})}{\Gamma(K^+ \to \pi^+\nu\bar{\nu})} = \sin^2\theta < 4.4$$

θ: CP violating phase between K-K mixing and s→dνν decay

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

Hardware improvements after LS2:

- A 4th GTK station for the K^+ tracking
- VetoCounter to reduce upstream background
- Anti0 to reduce muon halo
- HASC calorimeter downstream to reject γ from conversion
- Cedar-H: Cherenkov for K-id with Hydrogen in place of Nitrogen

Work in progress (*)

	2021 ($t > 2\,$s)	2022
$(N_{\pi\pi} D_0)/400$	3.713	16.374
ϵ_{trig}	$(83.5 \pm 1.3)\%$	$(86.3 \pm 1.5)\%$
ϵ_{RV}	$(63.0 \pm 0.5)\%$	$(63.8 \pm 0.5)\%$
$A_{\pi\pi}$	$(13.525 \pm 0.005)\%$	$(13.525 \pm 0.005)\%$
$A_{\pi\nu\bar{\nu}}$	$(7.7 \pm 0.2)\%$	$(7.7 \pm 0.2)\%$
$B_{SES}[\times 10^{11}]$	4.68 ± 0.17	1.01 ± 0.03
$N^{SM,exp}_{\pi\nu\bar{\nu}}$	1.80 ± 0.06	8.28 ± 0.24
$N^{SM,exp}_{\pi\nu\bar{\nu}}$/burst	1.7×10^{-5}	2.5×10^{-5}

Work in progress (*)

Expected events (R1+R2)

	2018	2021+2022
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	$7.58 \pm 0.40_{syst} \pm 0.75_{ext}$	10.07 ± 0.31
$K^+ \to \pi^+\pi^0(\gamma)$	0.75 ± 0.05	0.86 ± 0.06
$K^+ \to \mu^+\nu(\gamma)$	0.64 ± 0.08	0.93 ± 0.20
$K^+ \to \pi^+\pi^- e^+\nu$	0.51 ± 0.10	$0.84^{+0.35}_{-0.28}$
$K^+ \to \pi^+\pi^+\pi^-$	0.22 ± 0.10	0.11 ± 0.03
$K^+ \to \pi^+\gamma\gamma$	< 0.01	0.01 ± 0.01
$K^+ \to \pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$3.30^{+1.00}_{-0.75}$	$8.0^{+2.2}_{-1.8}$
Total background	$5.42^{+1.00}_{-0.75}$	$10.8^{+2.2}_{-1.9}$

(*) CERN-SPSC-2024-012 / SPSC-SR-345

Analysis improvements with respect to Run 1:

- Signal acceptance improved by 20% with performance and background rejection at the same level (**$A_{\pi\nu\nu}$ (2018) = 6.4 ± 0.06 %**).
- Single event sensitivity improved significantly, from 7% to 4% improved precision in trigger efficiency and random veto evaluation
- Signal yield improved by 50% (**$N_{\pi\nu\nu}$/burst$^{(2018)}$ = 1.7 x 10^{-5}**)

Studies ongoing to understand the background scaling from Run 1 to Run 2

NA62 as a multi-purpose experiment

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

NA62 P326

Precision measurement

Search for new physics with precision measurement to test the standard model

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

Phys. Lett. B 850 (**2024**) 138513

$K^+ \to \pi^0 e^+ \nu_e \gamma$

JHEP 09 (**2023**) 040

Flavour Physics

Search for lepton flavor & lepton number violation, rare & forbidden decays

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

Phys. Lett. B 846 (**2023**) 138193

$K^+ \to \mu^- \bar{\nu}_\mu e^+ e^+$

Phys. Lett. B 838 (**2023**) 137679

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**)

$X \to \text{hadrons}$

$A' \to \mu^+\mu^-$

$A' \to e^+e^-$

Results will be shown in the parallel session of tomorrow by Gemma Tinti

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

Radiative non-leptonic kaon decays allow crucial test of Chiral Perturbation Theory (ChPT) which describes low-energy QCD processes: **$K^+ \longrightarrow \pi^+\gamma\gamma$ out of π^0 peak**

The decay is described by the 2 kinematic variables:

Kinematic variables

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

The differential decay rate depends **strongly on z** and weakly on y

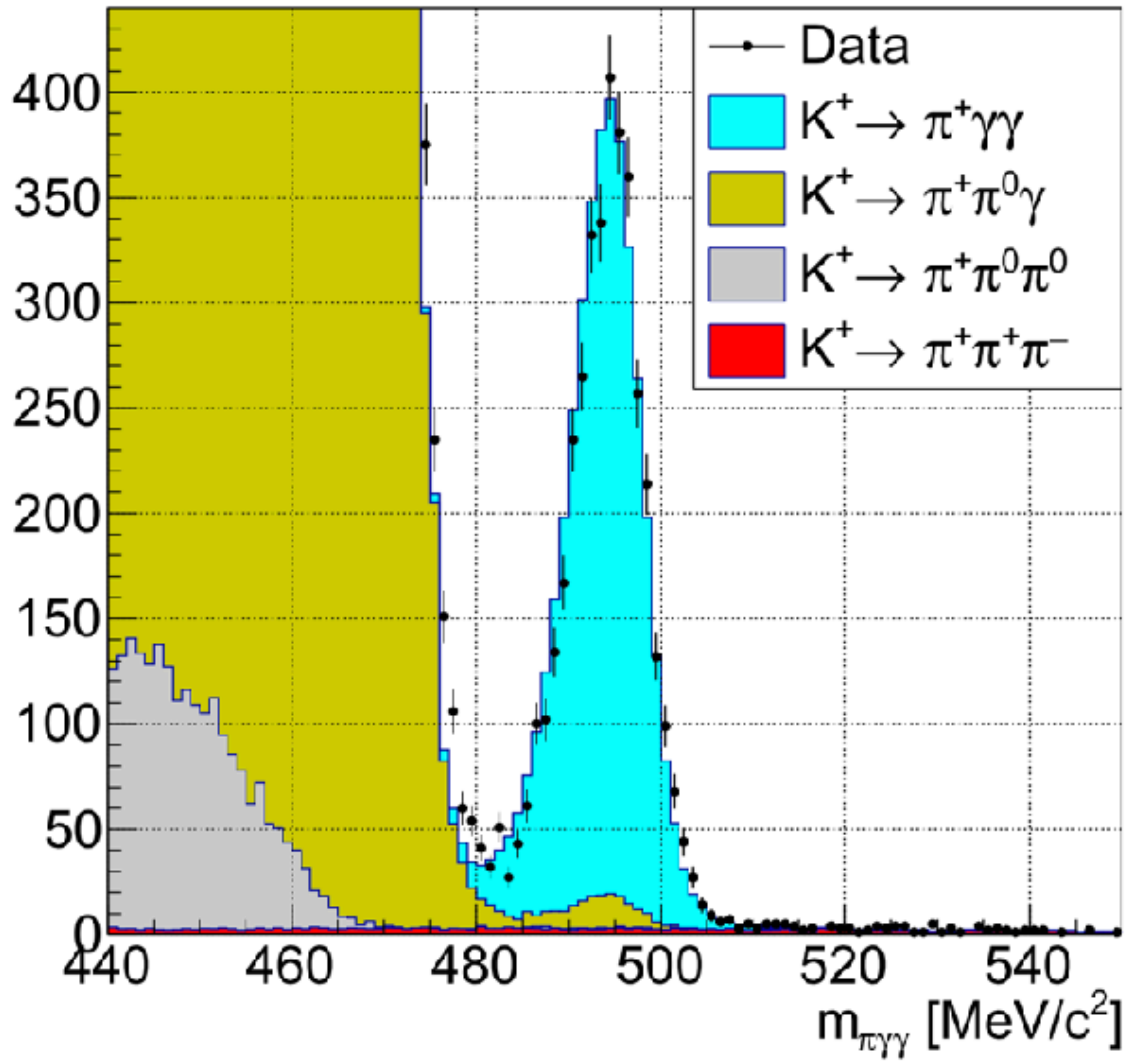
The decay rate in ChPT is parametrized as follows:

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

- **$A(\hat{c}, z, y^2)$** and $B(z)$ are the loop amplitudes in **lowest order $O(p^4)$** and in the **next to leading order $O(p^6)$**, that modify significantly
- The **parameter $\hat{c}$ is the only free parameter**
- BR and $\hat{c}$ depend on **8 external parameters fixed** according to PLB 835 (2022) 137594

Analysis has been performed with **Run 1** data sample

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



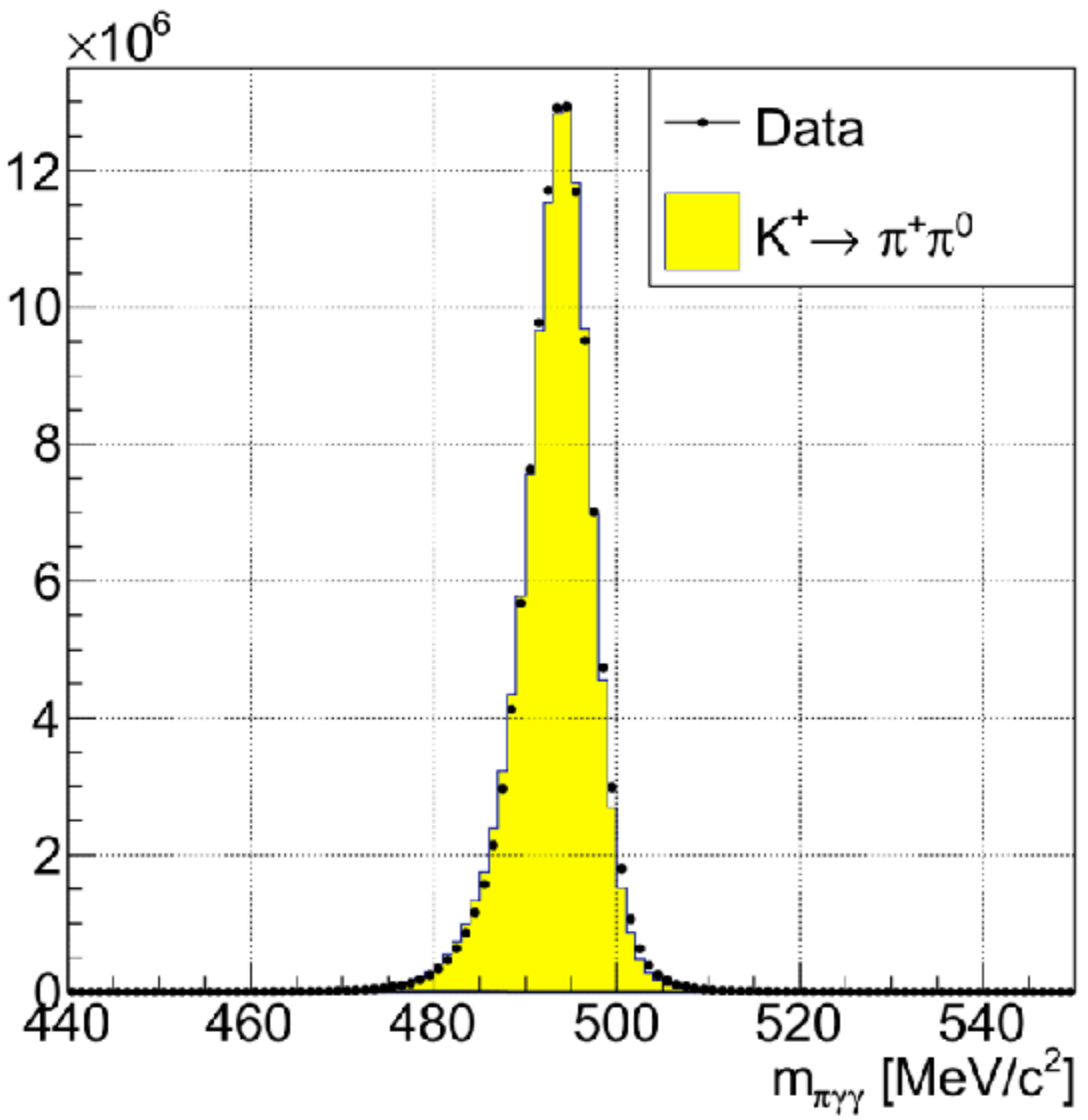
K⁺ decays in FV: $N_K = (5.55 \pm 0.03) \times 10^{10}$
$K^+ \rightarrow \pi^+\gamma\gamma$ candidates: **3984**
(~10x more than NA48/2+NA62-2007)
Estimated background: **291 ± 14**

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

- One single positive track identified as π^+
- K^+- π^+ matching and vertex reconstruction
- 2 good γ cluster in LKr calorimeter
- Kinematic cuts on total E, total p_T , and $m_{\pi\gamma\gamma}$ consistent with M_K
- Signal region: $0.20 < z < 0.51$

Main background sources

- 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

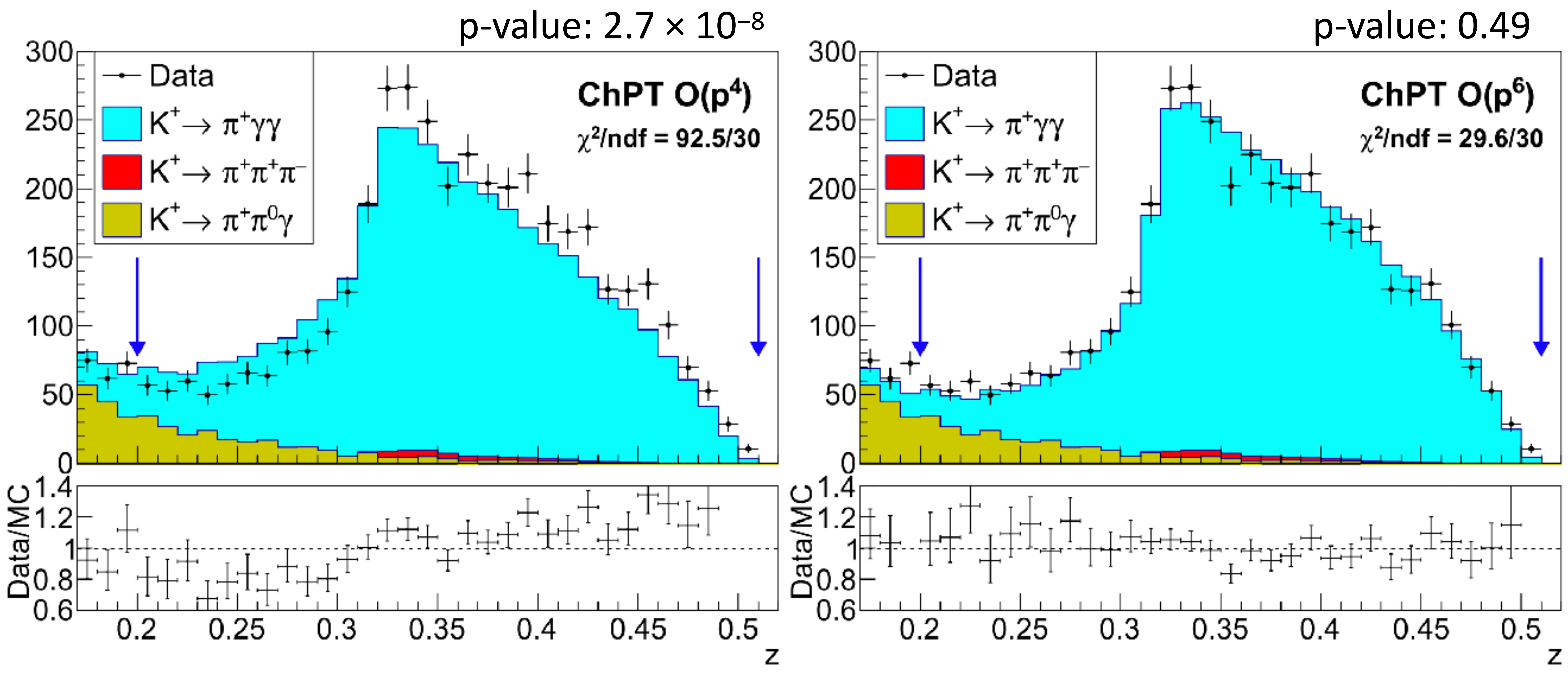


Normalization channel $K^+ \rightarrow \pi^+\pi^0$ to measure N_K

- Same particles in the final state. Reduced systematic uncertainties and inefficiencies cancellation
- $m_{\gamma\gamma} \sim m_{\pi^0}$: $0.04 < z < 0.12$

$K^+ \longrightarrow \pi^+\gamma\gamma$ analysis

Reconstructed z spectrum of the signal candidates: $Z = (P_K - P_\pi)^2/M_K^2$ used (better resolution than $m_{\gamma\gamma}^2/M_K^2$)

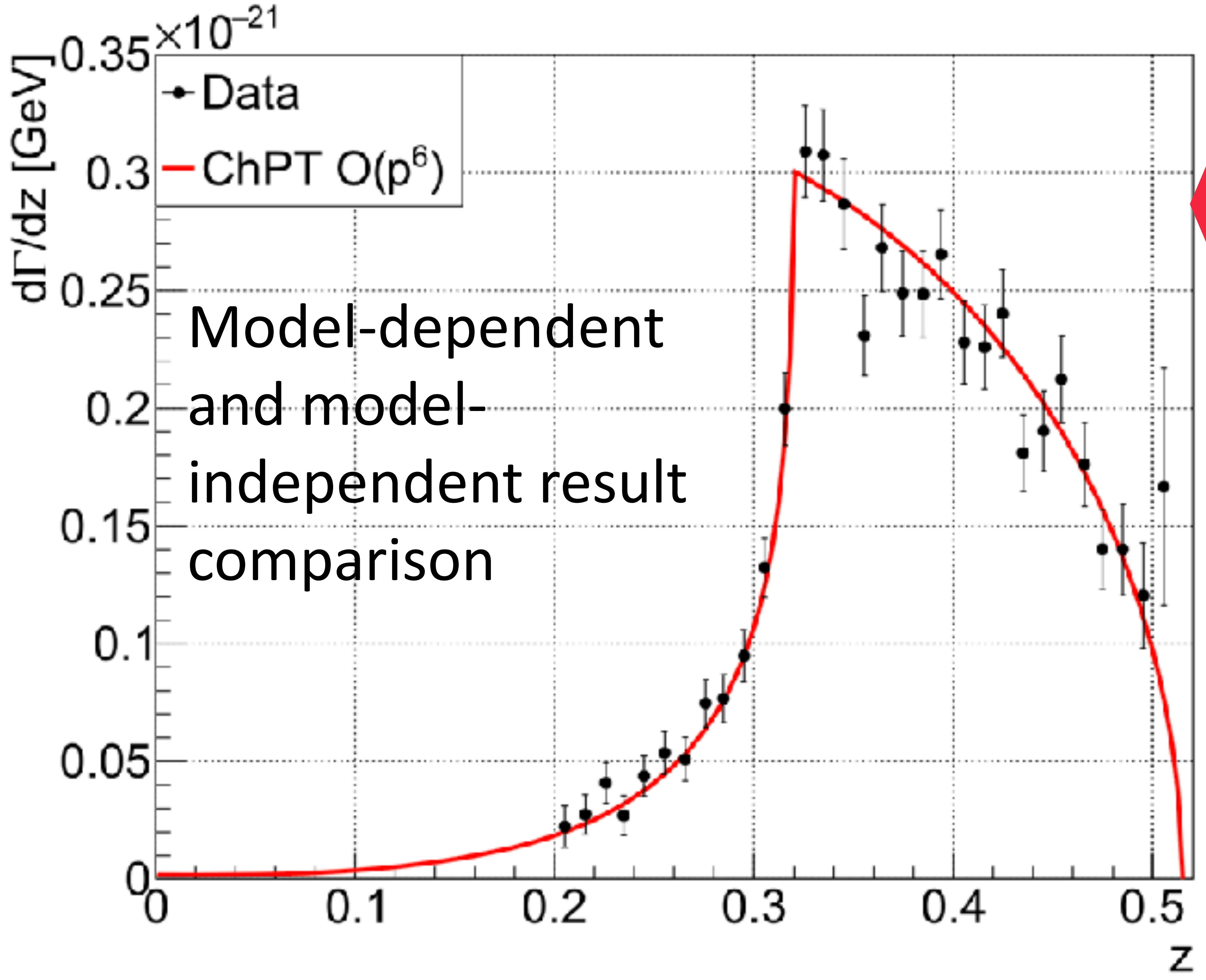


Model-dependent measurement: performed by reweighing MC spectrum for different values of $\hat{c}$ and extracting the best-fit value

z spectrum is fitted according to the theoretical parametrization in 31 bins of z (width $\delta z = 0.01$)

First evidence that the $O(p^4)$ description is not compatible with the data: the next to leading order contribution $O(p^6)$ in chiral perturbation theory was found to be necessary

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



Model-dependent and model-independent result comparison

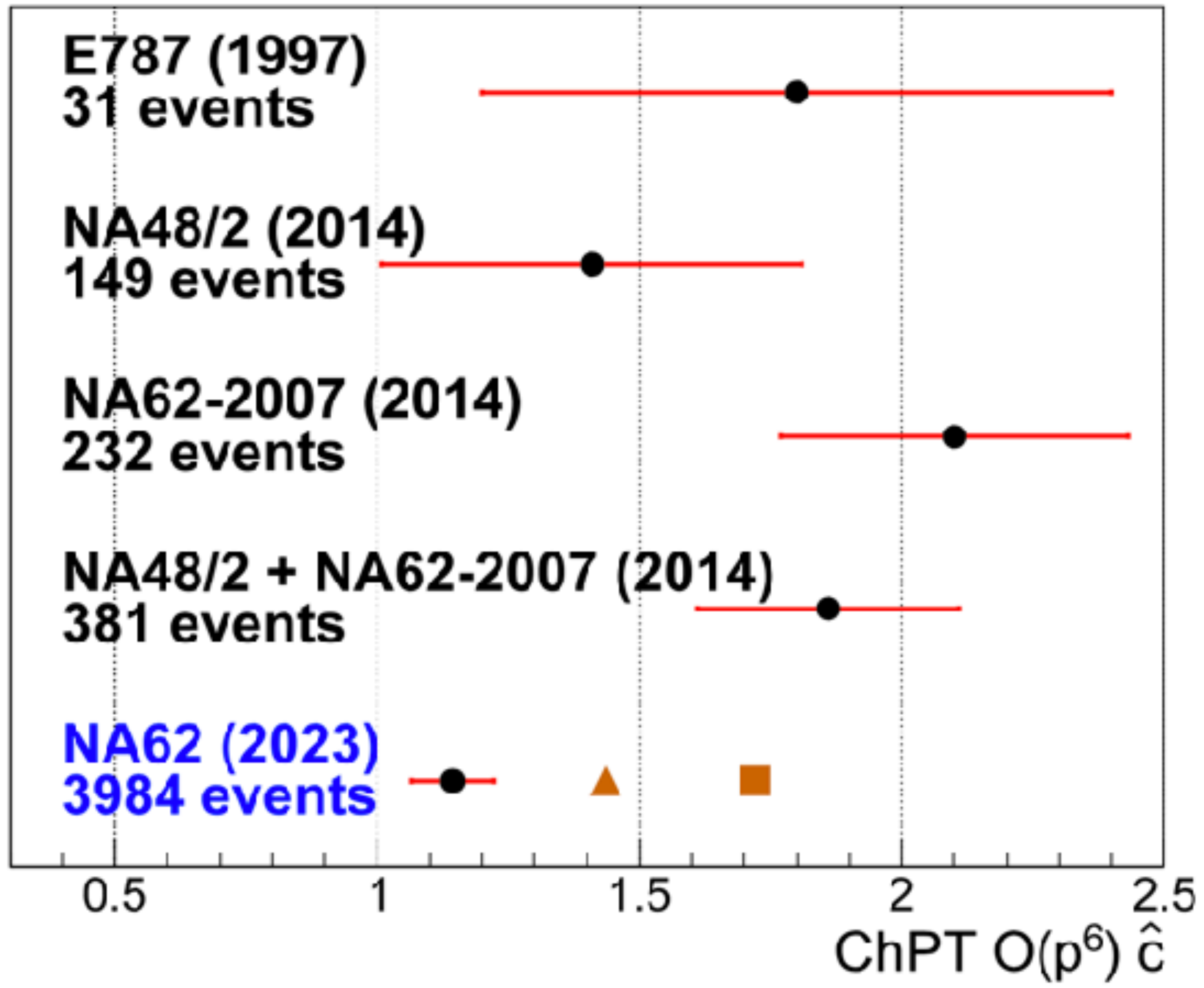
Model-independent BR($K_{\pi\gamma\gamma}$) and corresponding decay width are also computed in each z bin (*i*)

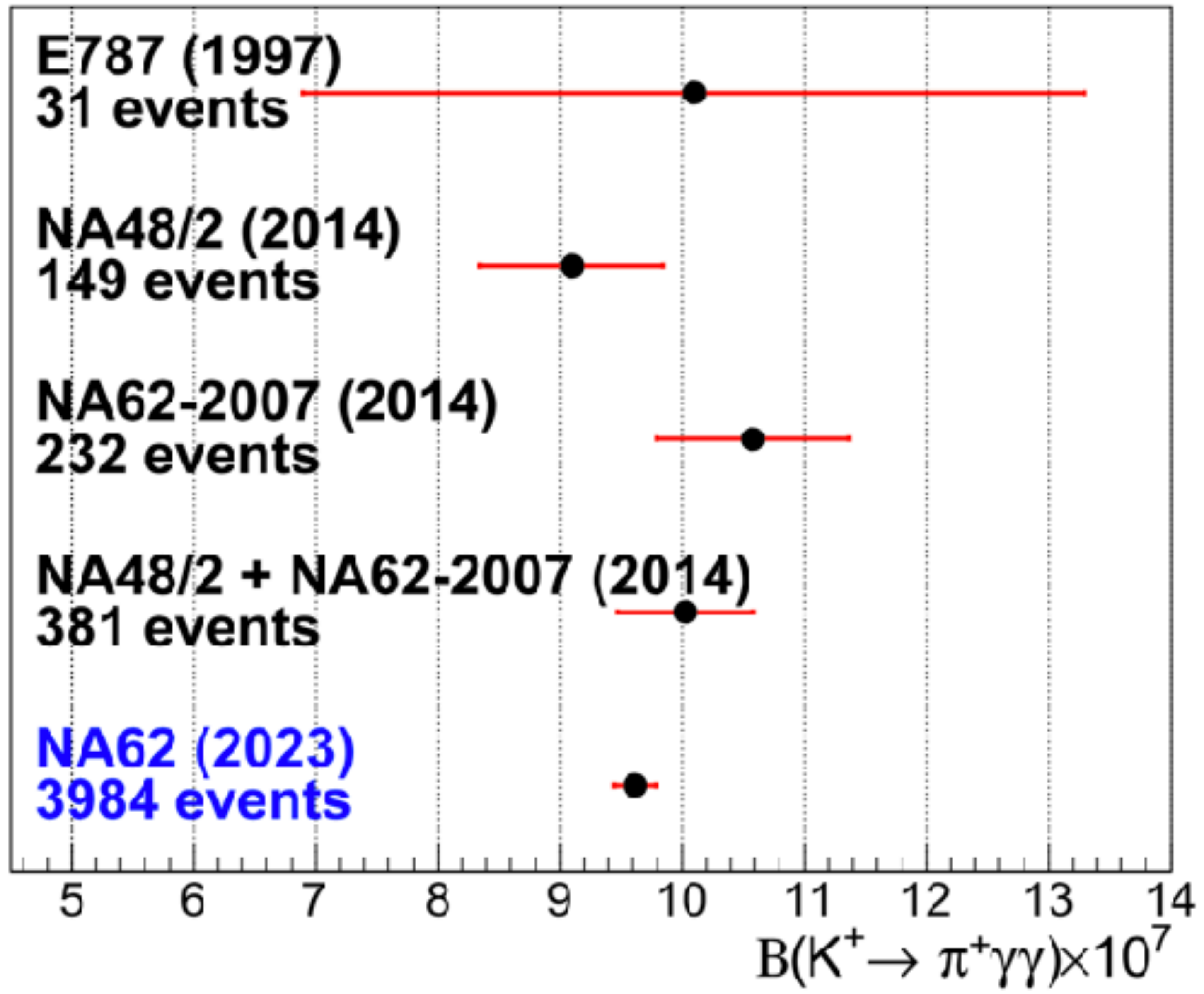
$$BR(K_{\pi\gamma\gamma})_i = \frac{N_i^{obs} - N_i^{bkg}}{N_K \cdot A_i}$$

$$\hat{c} = 1.144 \pm 0.069_{\mathrm{stat}} \pm 0.034_{\mathrm{syst}}$$

$$BR(K^+ \to \pi^+\gamma\gamma)_{\mathrm{ChPT}} = (9.61 \pm 0.15_{\mathrm{stat}} \pm 0.07_{\mathrm{syst}}) \times 10^{-7}$$
$$BR(K^+ \to \pi^+\gamma\gamma)_{\mathrm{MI}} = (9.46 \pm 0.19_{\mathrm{stat}} \pm 0.07_{\mathrm{syst}}) \times 10^{-7}$$

ĉ value depends significantly on the external parameter values. To test the consistency of the result with the old measurement ĉ is also calculated with the same E787 (▲) and NA48/2 - NA62/2007 (■) parameters set

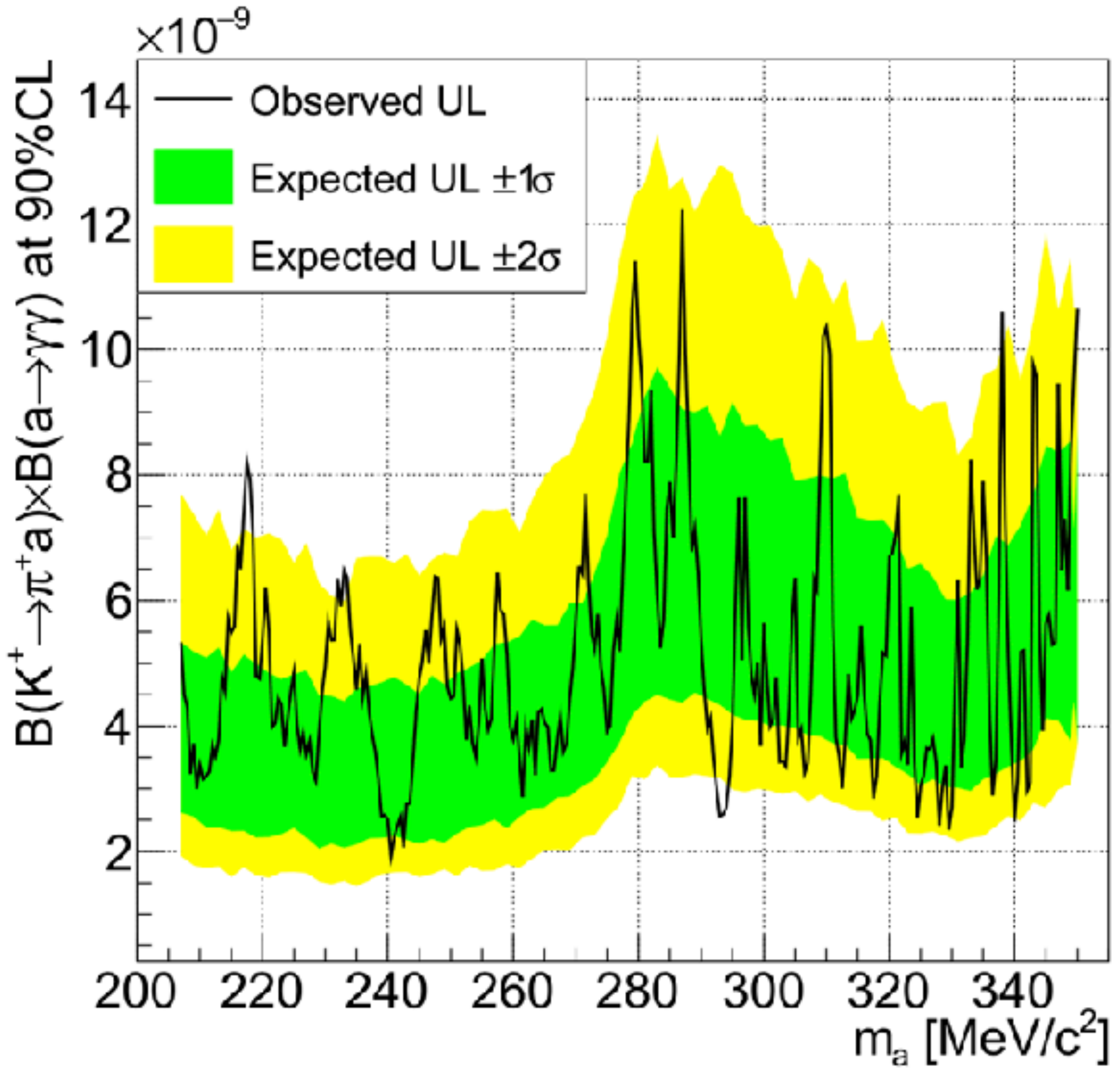


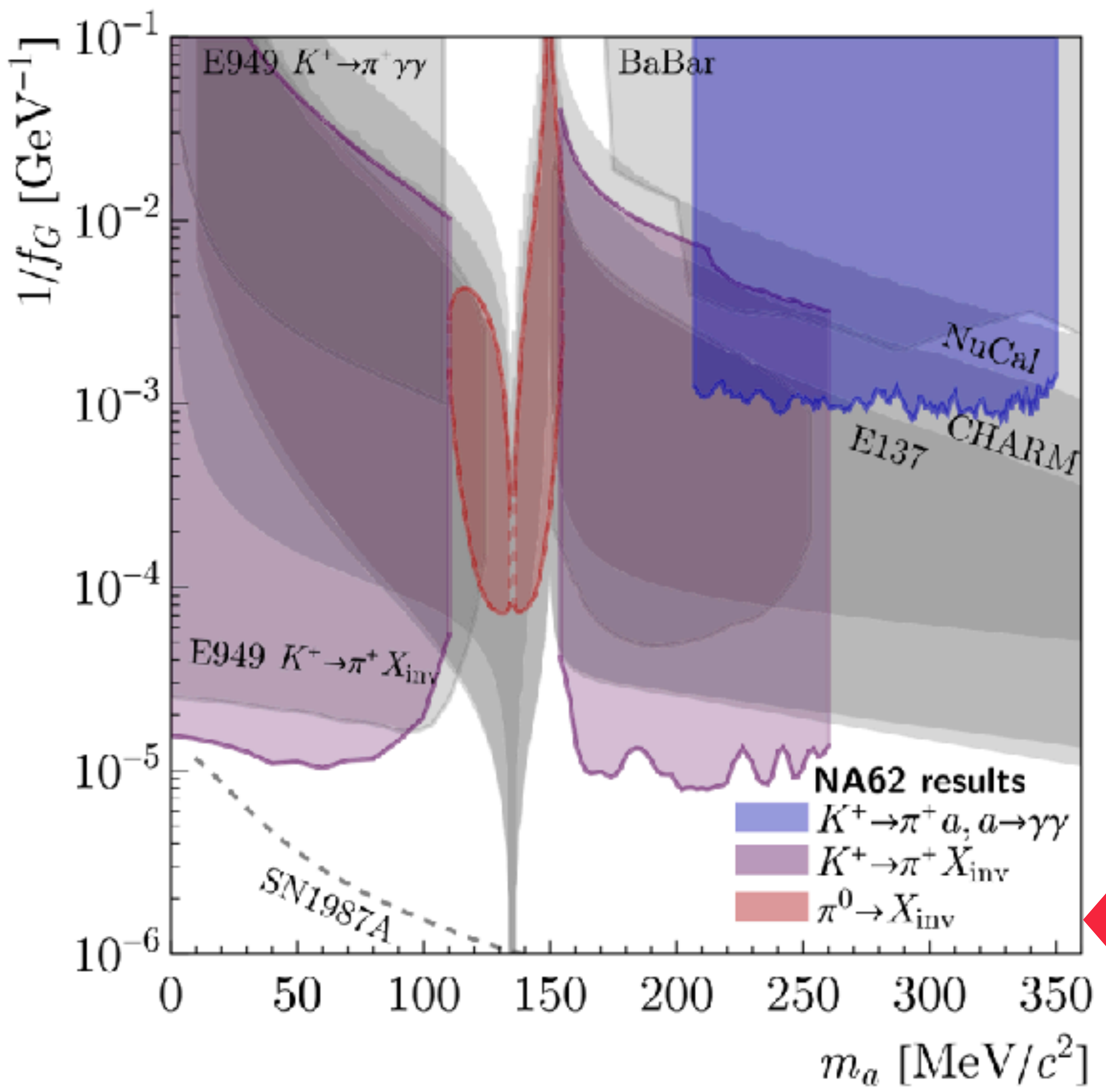


Search for ALP in $K^+ \longrightarrow \pi^+ a$, $a \longrightarrow \gamma\gamma$ decays

Hidden sector scenario in which axion-like particle coupling to gluons: **BC11** (if $m_a < 3m_\pi$: $a \longrightarrow \gamma\gamma$)

- Peak search over $m_a = \sqrt{(P_K - P_\pi)^2}$ in 287 mass hypotheses (range 207–350 MeV/c^2, steps 0.5 MeV/c^2)
- m_a resolution: from 2.0 MeV/c^2 to 0.2 MeV/c^2 across the search range
- In each m_a hypothesis, background in signal region is estimated with simulation ($K_{\pi\gamma\gamma}$ in ChPT $O(p^6)$ and his bkg)
- Upper limit at 90% using CL_s method is set to N_S (number of signal events) in each bin





Assuming **prompt a $\longrightarrow \gamma\gamma$** decay ($\tau_a = 0$), UP on BR is evaluated:

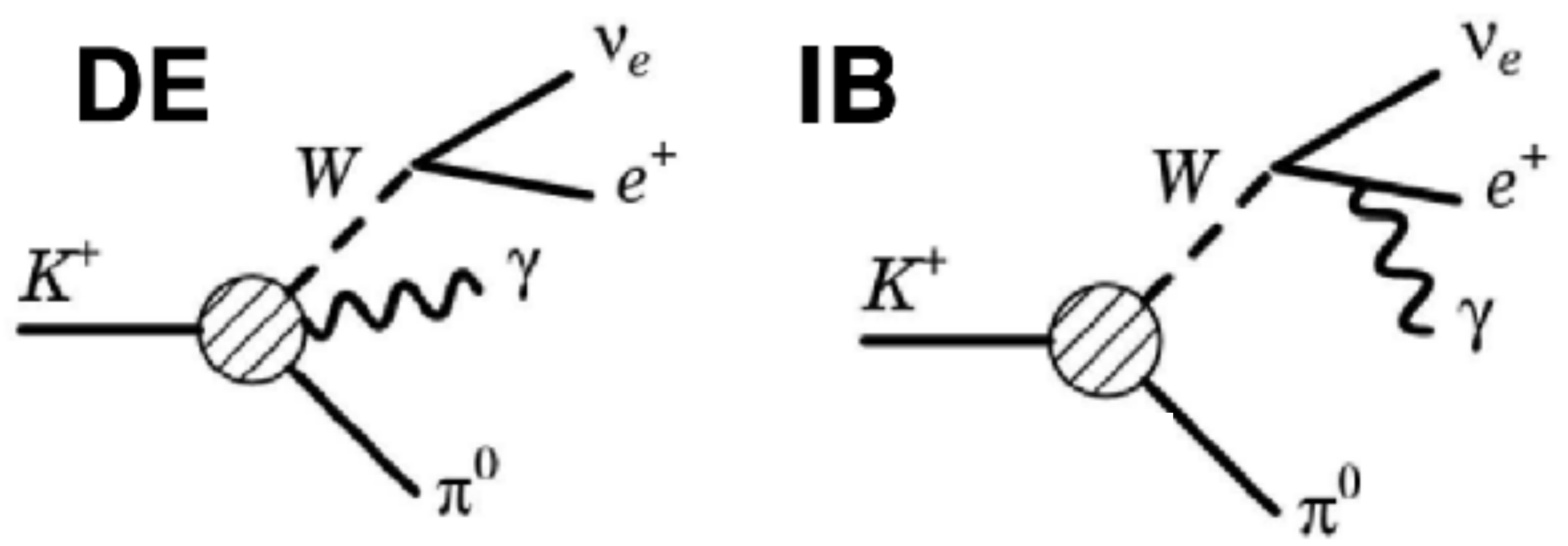
$$BR(K^+ \to \pi^+ a) = \frac{N_s}{N_K \cdot A_S}$$

Assuming **$\tau_a \neq 0$** a **signal acceptance loss function** is considered (increasing with τ_a due to vertex displacement)

Associated exclusion region for mass and coupling strength $f_G^{-1} \sim \tau_a^{-0.5}$

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

Described in ChPT by **structure dependent (SD) processes**, **inner bremsstrahlung (IB)** and their **interference**



- $BR(K^+ \longrightarrow \pi^0 e^+ \nu\gamma)$ strongly depends on $E\gamma$ and $\theta e\gamma$ in K^+ rest frame
- Three kinematic ranges of **$E\gamma$** and **$\theta e\gamma$** are considered
- Measure:

  $B(K^+ \longrightarrow \pi^0 e^+ \nu\gamma)$ in the **3** ranges **normalized** to **$B(K^+ \longrightarrow \pi^0 e^+ \nu(\gamma))$**

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

$j = 1, 2, 3$

	E_γ cut	$\theta_{e\gamma}$ cut	$\mathrm{O}(p^6)$ ChPT
$R_1(\times 10^2)$	$E_\gamma > 10$ MeV	$\theta_{e\gamma} > 10°$	1.804 ± 0.021
$R_2(\times 10^2)$	$E_\gamma > 30$ MeV	$\theta_{e\gamma} > 20°$	0.640 ± 0.008
$R_3(\times 10^2)$	$E_\gamma > 10$ MeV	$0.6 < \cos\theta_{e\gamma} < 0.9$	0.559 ± 0.006

- How the normalized BR is experimentally measured:

$$R_j = \frac{BR(K_{e3\gamma})_j}{BR(K_{e3})} = \frac{(N^{\mathrm{obs}}_{K_{e3\gamma}} - N^{\mathrm{bkg}}_{K_{e3\gamma}})_j}{N^{\mathrm{obs}}_{K_{e3}} - N^{\mathrm{bkg}}_{K_{e3}}} \cdot \frac{A_{K_{e3}} \cdot \epsilon^{\mathrm{trig}}_{K_{e3}}}{(A_{K_{e3\gamma}})_j \cdot (\epsilon^{\mathrm{trig}}_{K_{e3\gamma}})_j}$$

- Test of T-conservation thanks to T-odd observable ξ and its asymmetry:

$$\xi = \frac{\vec{p}_\gamma \cdot (\vec{p}_e \times \vec{p}_\pi)}{(M_K \cdot c)^3}, \quad A_\xi = \frac{N_{\xi>0} - N_{\xi<0}}{N_{\xi>0} + N_{\xi<0}}$$

$K^+ \longrightarrow \pi^0 e^+ \nu \gamma$ analysis

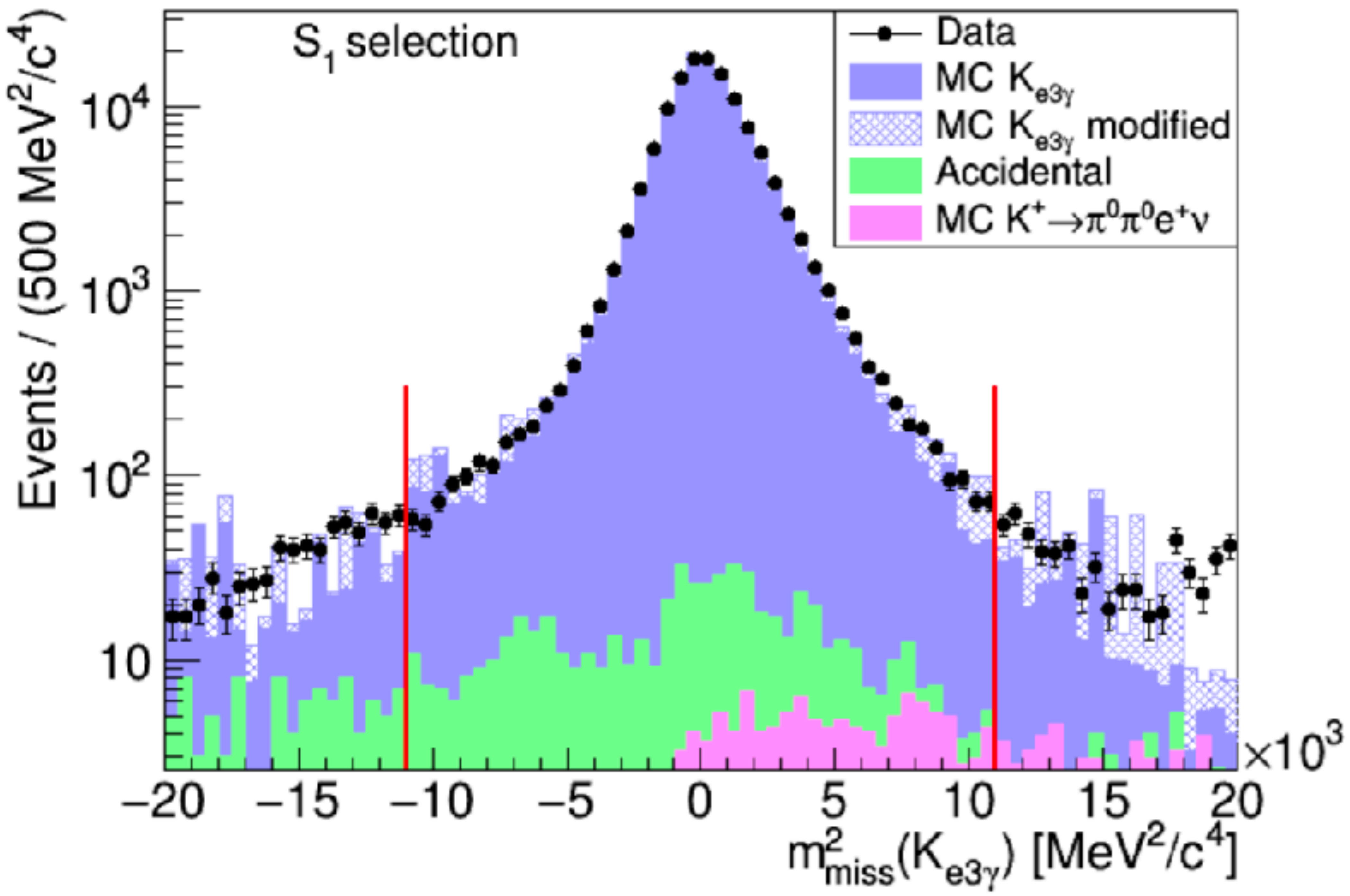
Signal selection

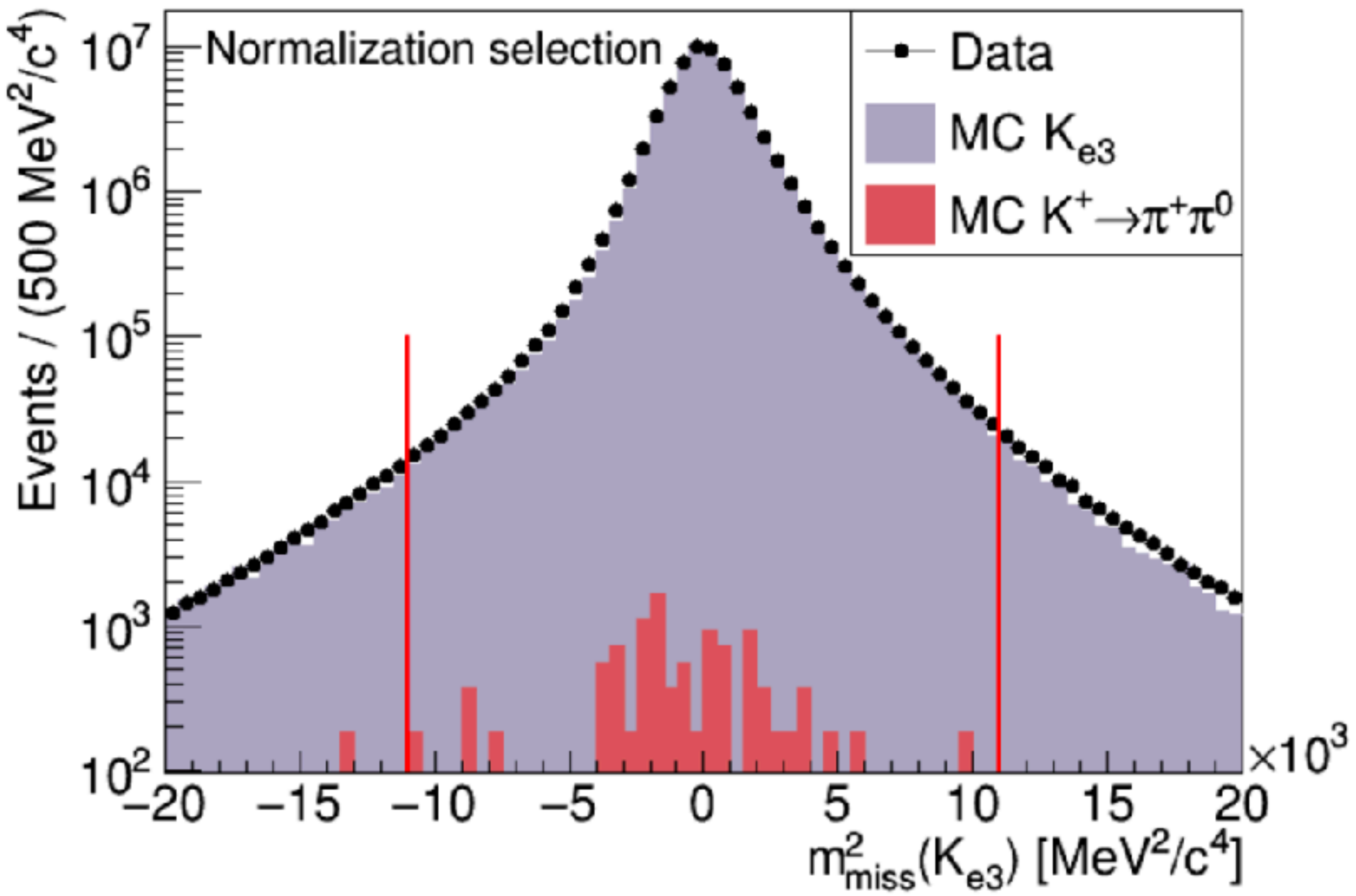
- Reconstruction and matching of K^+ and e^+ tracks (vertex in FV)
- Reconstruction of $\pi^0 \rightarrow \gamma\gamma$ as 2 LKr clusters ($E\gamma > 4$ GeV)
- Radiative γ identified as isolated LKr cluster ($E\gamma > 2$ GeV)
- No other signals in calorimeters (LAV, IRC, SAC)
- Kinematic constraint $m^2_{miss} = (P_K - P_e - P_{\pi 0} - P_\gamma)^2 < 11000$ MeV/c^2

Normalization selection

- Same signal selection: reduced systematic effects
- No additional isolated LKr cluster with E > 2 GeV
- Kinematic constraint

  $m^2_{miss} = (P_K - P_e - P_{\pi 0})^2 < 11000$ MeV/c^2



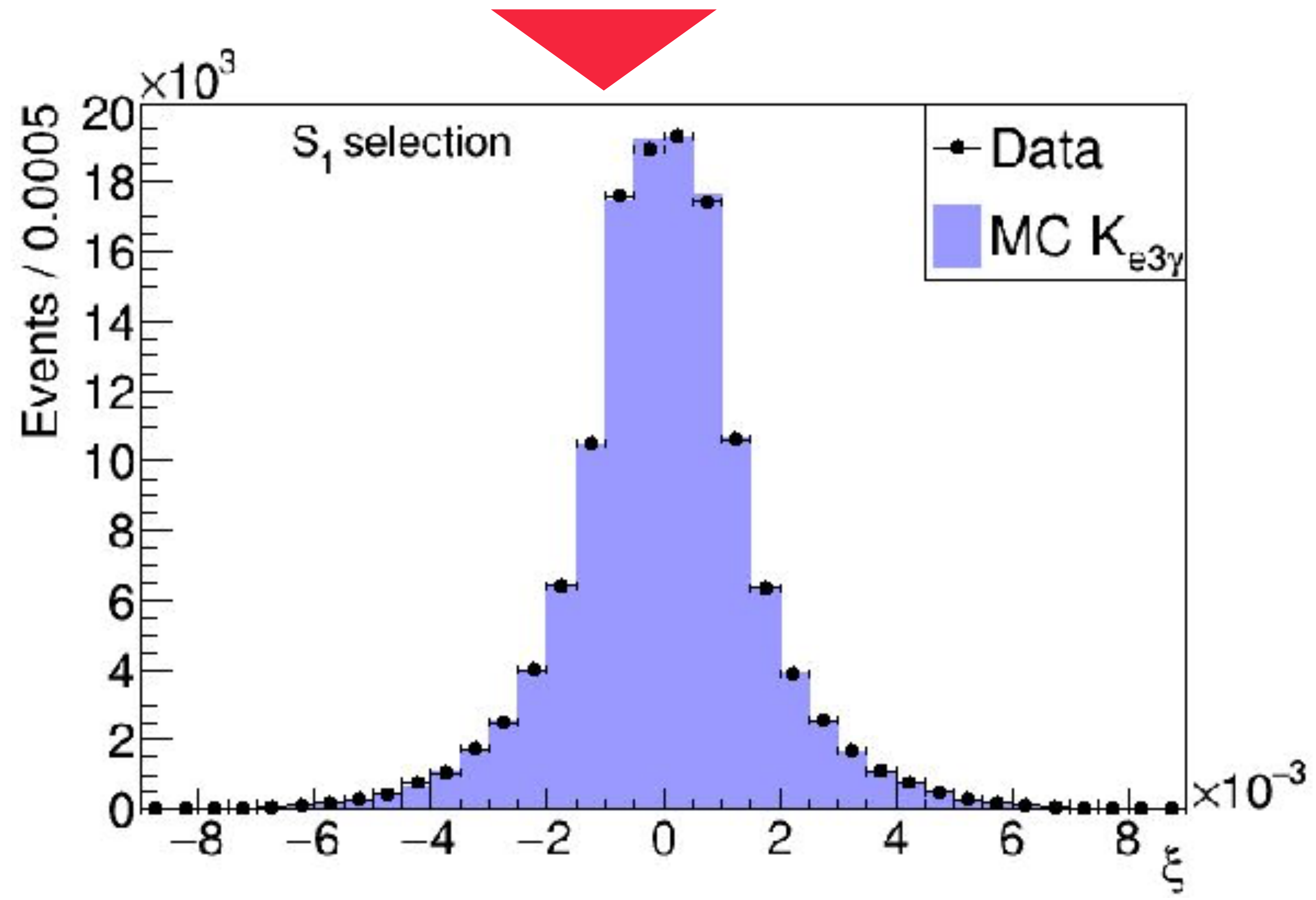


$K^+ \longrightarrow \pi^0 e^+ \nu \gamma$ results

	Normalization	S_1	S_2	S_3
Selected candidates	6.6420×10^7	1.2966×10^5	0.5359×10^5	0.3909×10^5
Acceptance	$(3.842 \pm 0.002)\%$	$(0.444 \pm 0.001)\%$	$(0.514 \pm 0.002)\%$	$(0.432 \pm 0.002)\%$
Accidental background	—	$(4.9 \pm 0.2 \pm 1.3) \times 10^2$	$(2.3 \pm 0.2 \pm 0.3) \times 10^2$	$(1.1 \pm 0.1 \pm 0.5) \times 10^2$
$K^+ \to \pi^0\pi^0 e^+\nu$	$< 10^2$	$(1.1 \pm 1.1) \times 10^2$	$(1.1 \pm 1.1) \times 10^2$	$(0.1 \pm 0.1) \times 10^2$
$K^+ \to \pi^+\pi^0\pi^0$	$< 10^2$	< 20	< 20	< 20
$K^+ \to \pi^+\pi^0$	$(1.0 \pm 1.0) \times 10^4$	—	—	—
Total background	$(1.0 \pm 1.0) \times 10^4$	$(6.0 \pm 1.8) \times 10^2$	$(3.4 \pm 1.2) \times 10^2$	$(1.2 \pm 0.6) \times 10^2$
Fractional background	1.6×10^{-4}	0.46×10^{-2}	0.64×10^{-2}	0.29×10^{-2}

Analysis has been performed with **Run 1** data sample

Reconstruction of ξ observable (for S1)



	R $(\times 10^2)$	$A_\xi \times 10^2$ *	$O(p^6)$ ChPT
S_1	$1.715 \pm 0.005_{stat} \pm 0.010_{syst}$	$-0.1 \pm 0.3_{stat} \pm 0.2_{syst}$	1.804 ± 0.021
S_2	$0.609 \pm 0.003_{stat} \pm 0.006_{syst}$	$-0.3 \pm 0.4_{stat} \pm 0.3_{syst}$	0.640 ± 0.008
S_3	$0.533 \pm 0.003_{stat} \pm 0.004_{syst}$	$-0.9 \pm 0.5_{stat} \pm 0.4_{syst}$	0.559 ± 0.006

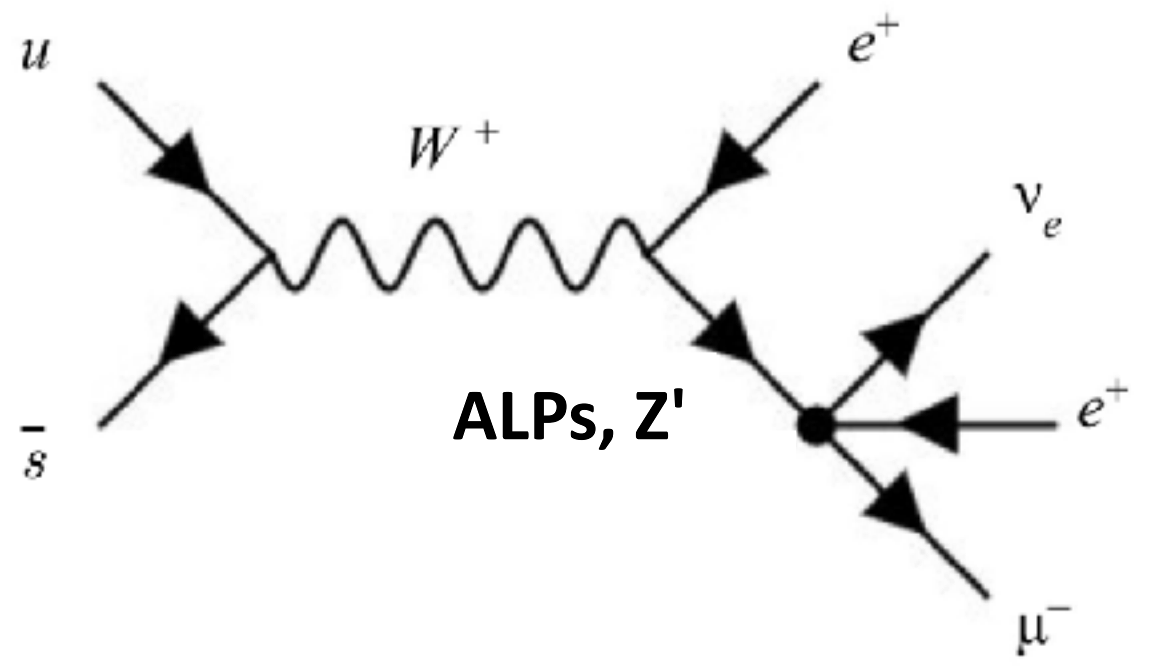
- Improvement wrt previous measurement (ISTRA+, OKA) by a factor > 2
- R_j smaller than $O(p^6)$ ChPT by 5% relative (disagreement: 3 σ)
- Result compatible with no asymmetry

*$(A_\xi^{NA62} = A_\xi^{Data} - A_\xi^{MC})$

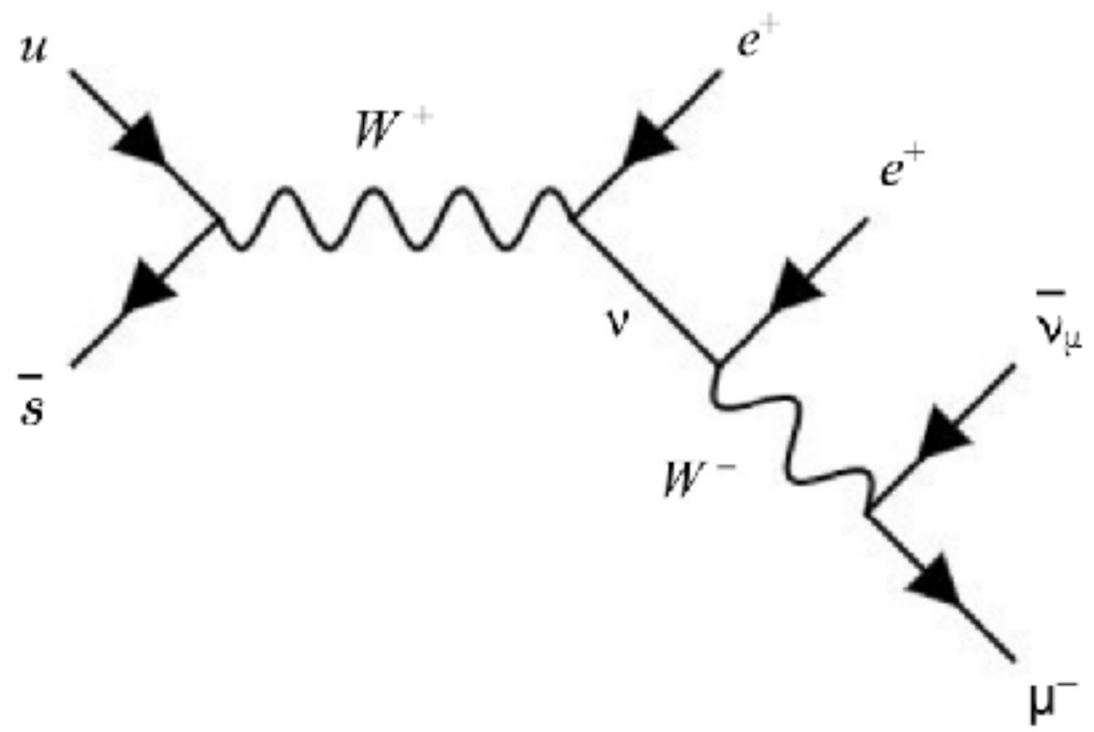
LFV and LNV searches: $K^+ \longrightarrow \mu^-\nu\, e^+e^+$

To may this decay happen lepton flavor or lepton number must be violated depending on the neutrino flavor: ν_e or ν_μ

$L = 0, L_e = -1, L_\mu = 1$



$L = -2, L_e = -2, L_\mu = 0$



Observing this decay

- Provide evidence for BSM models involving flavor violating ALPs and Z' (LFV)
- Provide evidence of Majorana neutrino (LNV)

Past upper limit

$BR(K^+ \to \pi^+\nu e^+ e^+) < 2.1 \times 10^{-8}$ @ 90% CL

Signal selection

- Exactly 3 well separated downstream track events (STRAW)
- Tracks forming a vertex with Q_{TOT} = +1 in the fiducial volume
- Correct PID of the track candidates (μ^-, e^+, e^+)
- $|P_{beam} - P_{vtx}|$ > 10 GeV/c ($K_{3\pi}$ suppression)
- Photon veto downstream of the vertex for mitigation of Dalitz

$$K^+ \to \pi^+\pi^0_D,\ K^+ \to \pi^0_D e^+\nu\,(\pi^0_D \to \gamma e^+ e^-)$$

Normalization selection $K^+ \to \pi^+ e^+ e^-$

- Same 3 tracks vertex selection
- Correct PID of the track candidates (π^+, e^+, e^-)
- $|P_{beam} - P_{vtx}|$ < 2 GeV/c

Analysis has been performed with **Run 1** data sample

$K^+ \longrightarrow \mu^- \nu e^+ e^+$ analysis and result

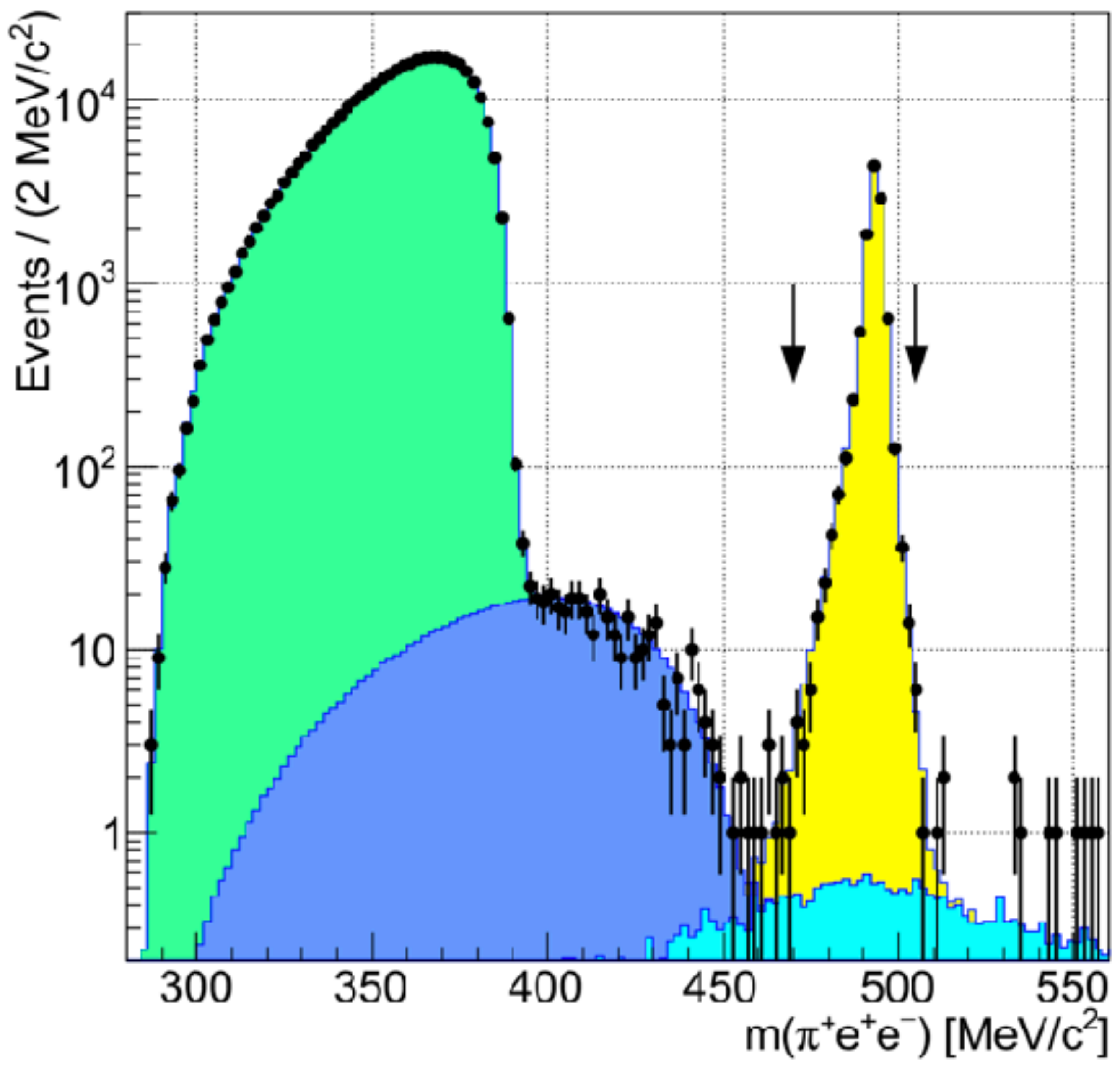
Signal region:

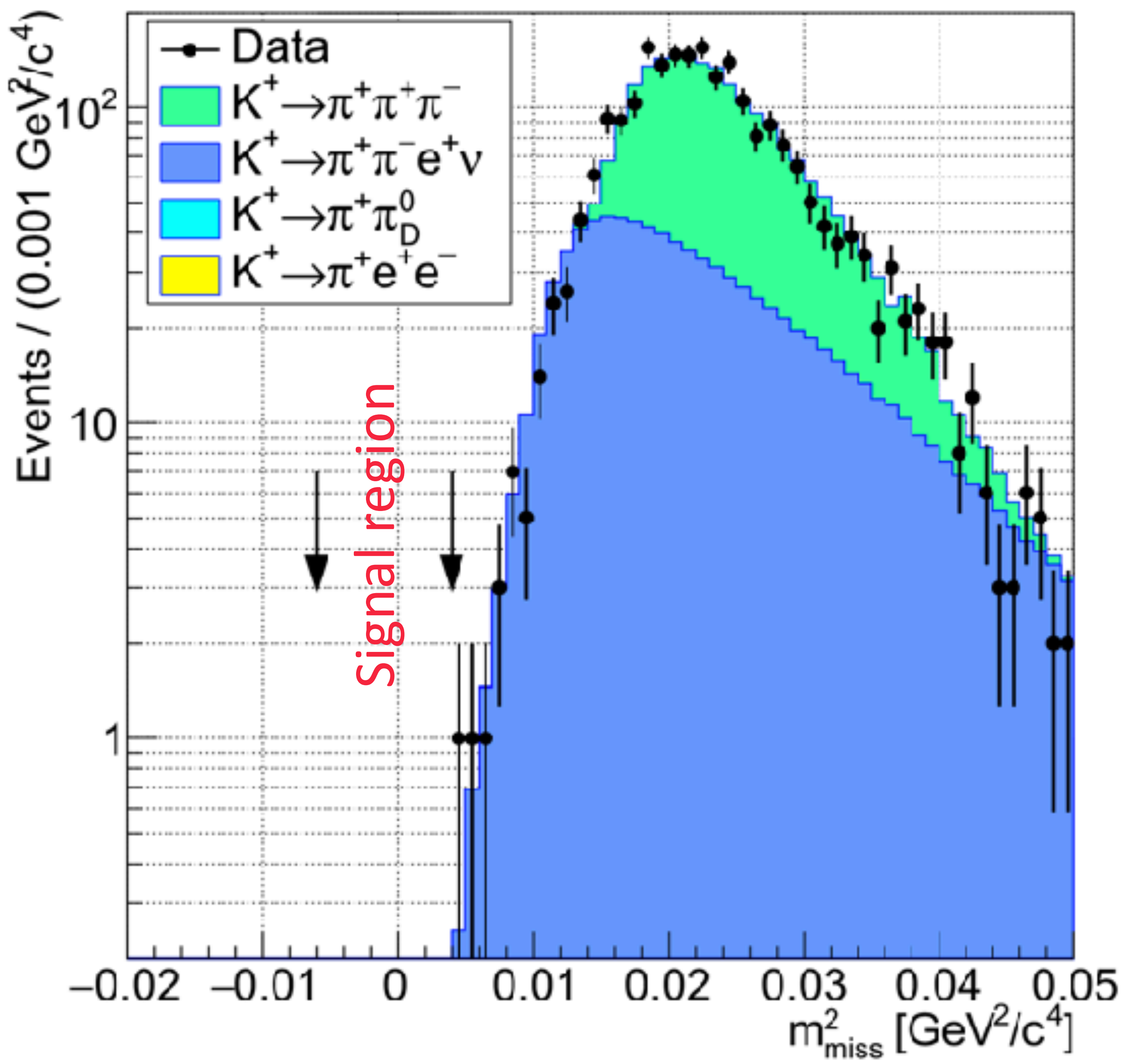
$$(-6 \times 10^{-3} < m^2_{\text{miss}} < 4 \times 10^{-3})\ \text{GeV}^2/c^4$$

$$m^2_{\text{miss}} = (P_K - P_\mu - P_{e_1} - P_{e_2}) = m^2_\nu$$

- K^+ decays in FV: $(1.97 \pm 0.02_{stat} \pm 0.02_{syst} \pm 0.06_{ext}) \times 10^{12}$
- **0 events observed** in signal region
- Expected background **0.26 ± 0.04**

Mode / Region	Lower	Signal	Upper
$K^+ \to \pi^+\pi^+\pi^-$	< 0.07	< 0.07	1412 ± 11
$K^+ \to \pi^+\pi^- e^+\nu$	0.01 ± 0.01	0.16 ± 0.02	867 ± 1
$K^+ \to \pi^+\pi^+\pi^-$ (upstream)	< 0.03	0.06 ± 0.03	1.5 ± 0.3
$K^+ \to \pi^+\pi^- e^+\nu$ (upstream)	0.01 ± 0.01	0.01 ± 0.01	0.14 ± 0.03
$K^+ \to \pi^0_D e^+\nu$	0.02 ± 0.01	0.01 ± 0.01	0.02 ± 0.01
$K^+ \to e^+\nu\mu^+\mu^-$	< 0.01	< 0.01	0.05 ± 0.02
Total expected	0.04 ± 0.02	0.26 ± 0.04	2281 ± 11
Data	0	0	2271





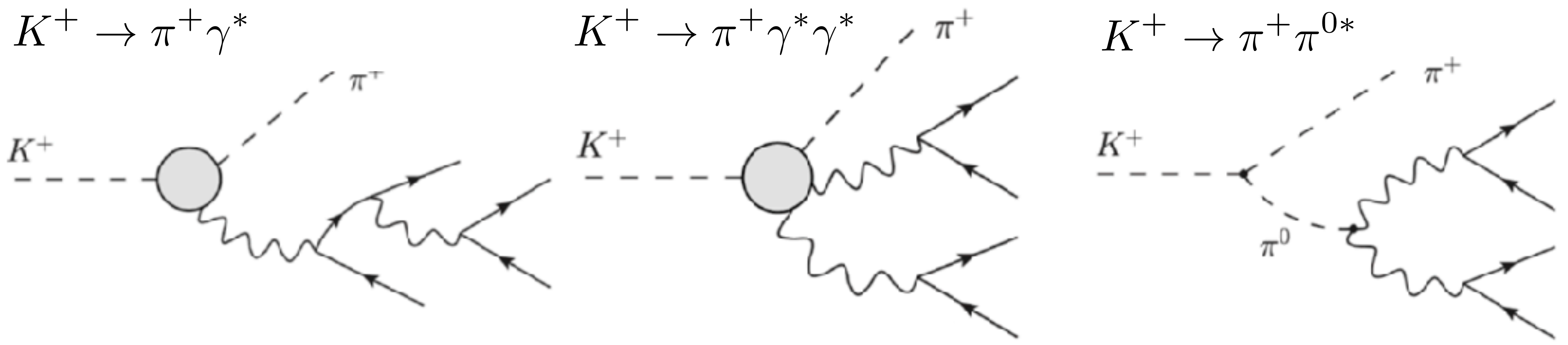
$$\text{BR}(K^+ \to \mu^- \nu e^+ e^+) < 8.1 \times 10^{-11}$$

@ 90% CL

- Improving by a **factor 250** over previous search
- Achieved sensitivity still not sufficient for exclusion of LF/LN modes

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

Ultra rare decay extremely **suppressed in the SM** (outside π^0 pole). Topologies at leading QED/ChPT order:



Never searched before!

$$BR(K^+ \to \pi^+ e^+ e^- e^+ e^-)_{SM} = (7.2 \pm 0.7) \times 10^{-11}$$

Main interest in the dark sector context: **pair production of dark state** followed by **prompt e^+e^- decay**

- **Short-lived QCD axion**:

  $K^+ \to \pi^+ a\, a (a \to e^+ e^-)$

  $BR(K^+ \to e^+ e^- e^+ e^-) > 2 \times 10^{-8}$ if **m_a = 17 MeV**

  possible explanation of the 17 MeV anomaly*

- **Dark Scalar (S)** and **Dark Photon (A')**

  $K^+ \to \pi^+ S, S \to A' A' (A' \to e^+ e^-)$

  possible if $m_S > 2m_{A'}$ **

Normalization channel for the analysis:

double Dalitz decay:

$K^+ \to \pi^+ \pi^0 \, (\pi^0_{DD} \to e^+ e^- e^+ e^-)$

$BR(K_{2\pi DD}) = (6.9 \pm 0.3) \times 10^{-6}$

*Phys.Rev.D103(2021)055018 **[Phys.Rev.D105 (2022)015017]

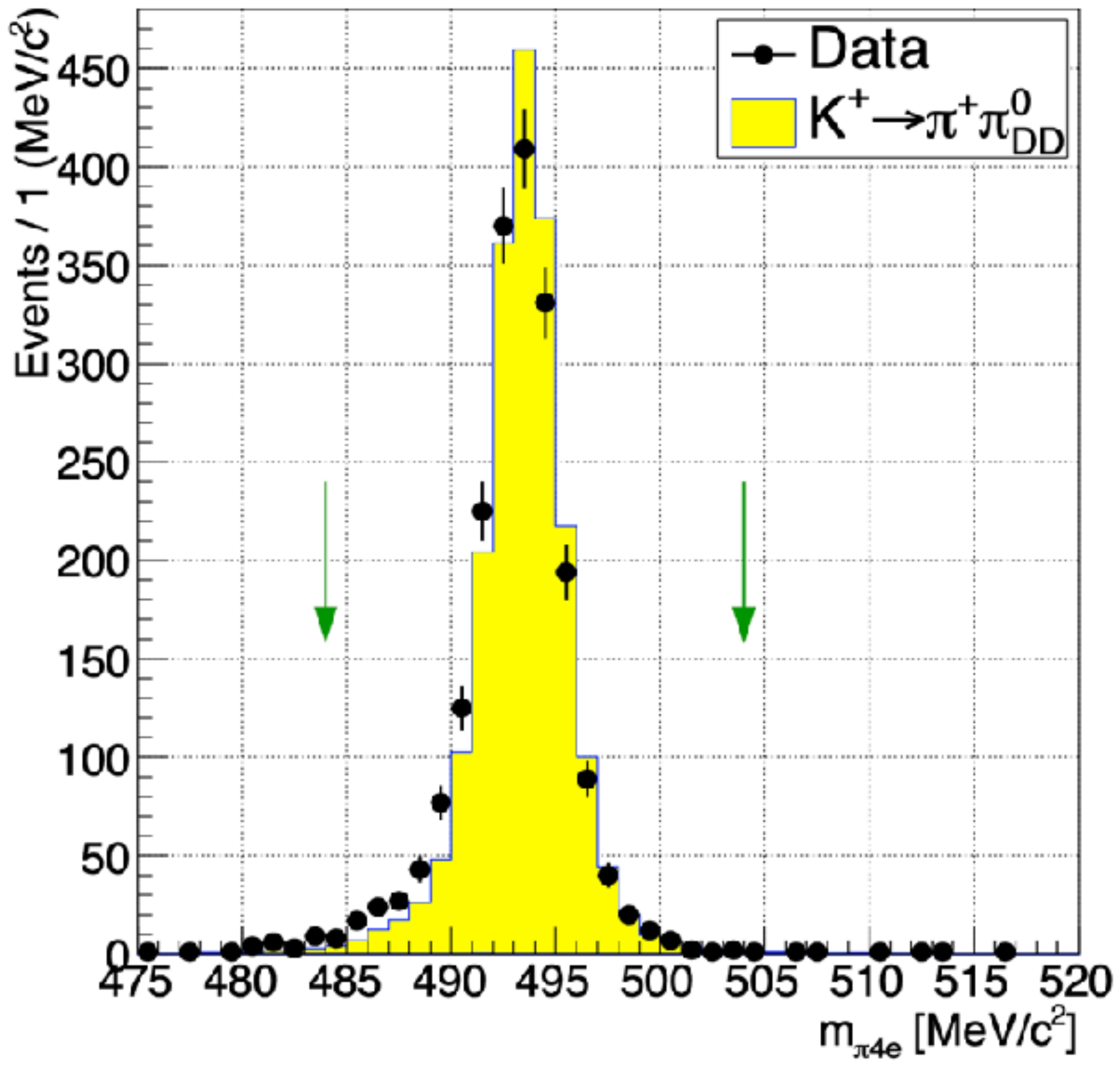
$K^+ \longrightarrow \pi^+ e^+ e^- e^+ e^-$: analysis

Normalization selection $K^+ \longrightarrow \pi^+ \pi^0_{DD}$

- Same signal selection: reduced systematic effects
- $|m_{\pi 0} - m_{4e}| < 10$ MeV/c^2

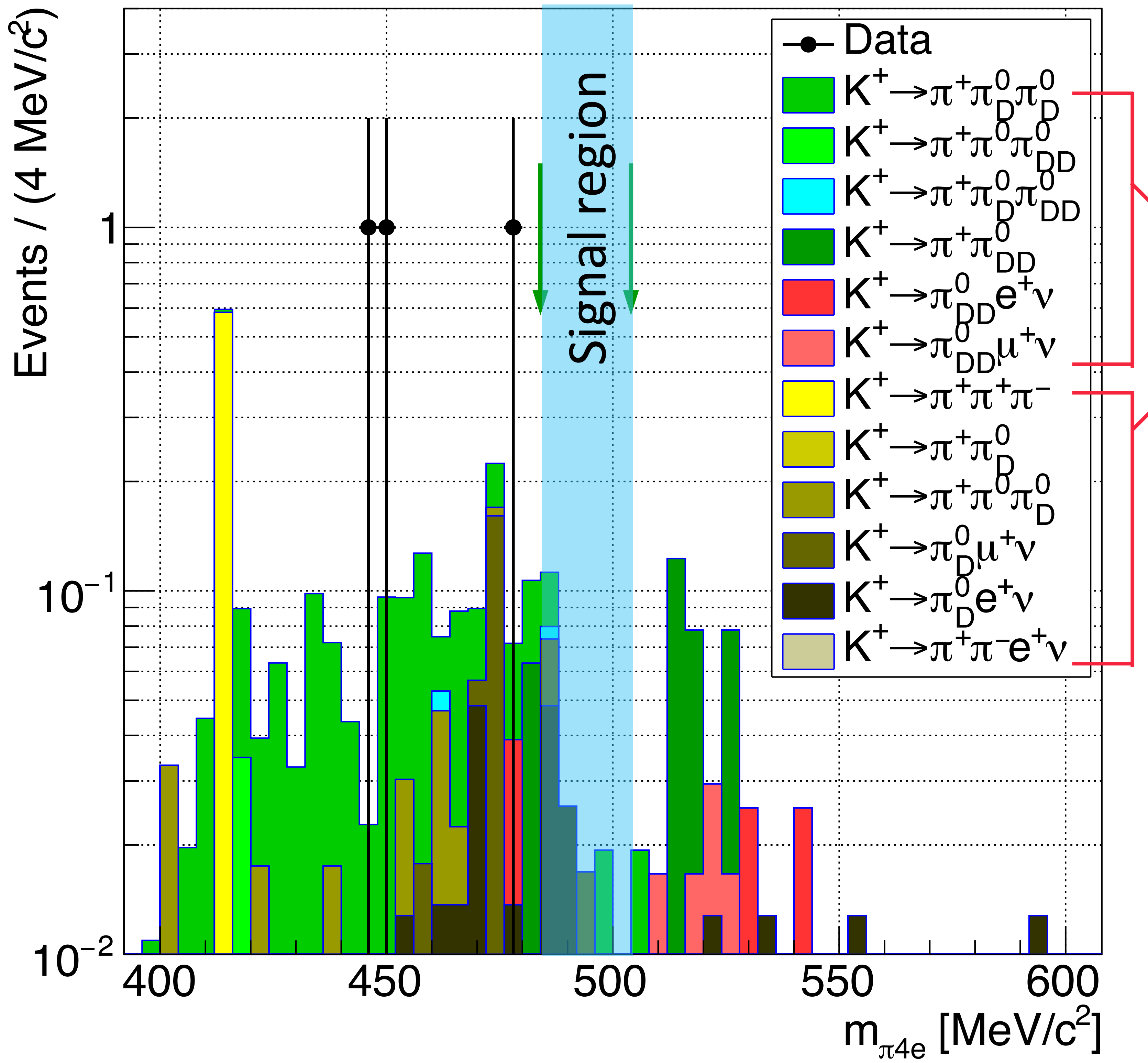
$K^+ \longrightarrow \pi^+$ X X selection

- Minimization of a discriminant $\propto |m_{ee1} - m_{ee2}|$



Signal selection

- 5 track vertex topology using only STRAW information
- Particles ID (mass ID that minimize $|m_K - m_{\pi 4e}|$)
- $|P_{vtx} - P_{beam}| < 2$ GeV
- **$|m_{\pi 0} - m_{4e}| > 10$ MeV/c^2**, $|m_{\pi 0} - m_{miss}| > 40$ MeV/c^2



Background

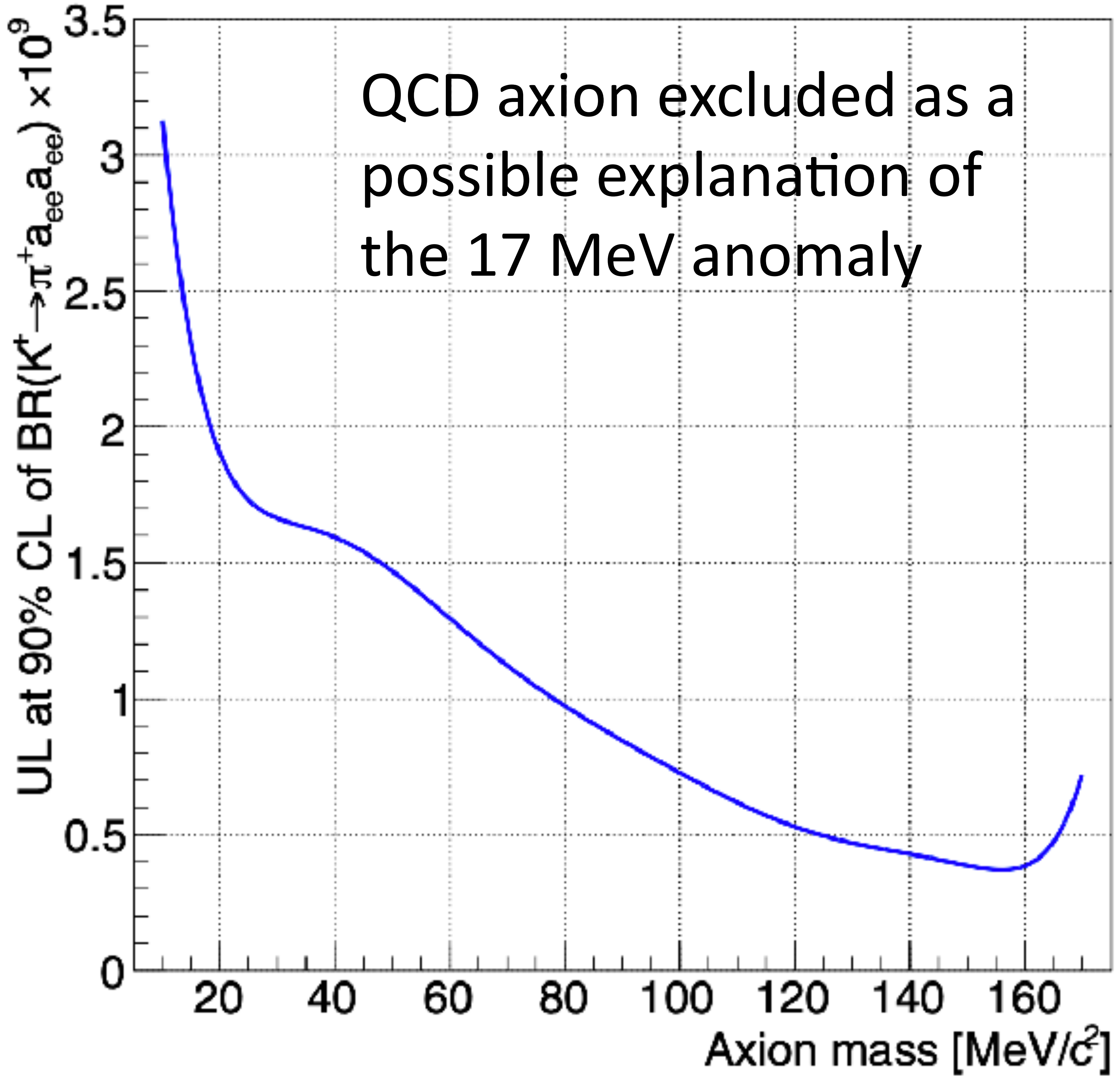
- 5 track-like K^+ decays
- 3-track K^+ decays overlapping with a $K \longrightarrow 3\pi$ decay

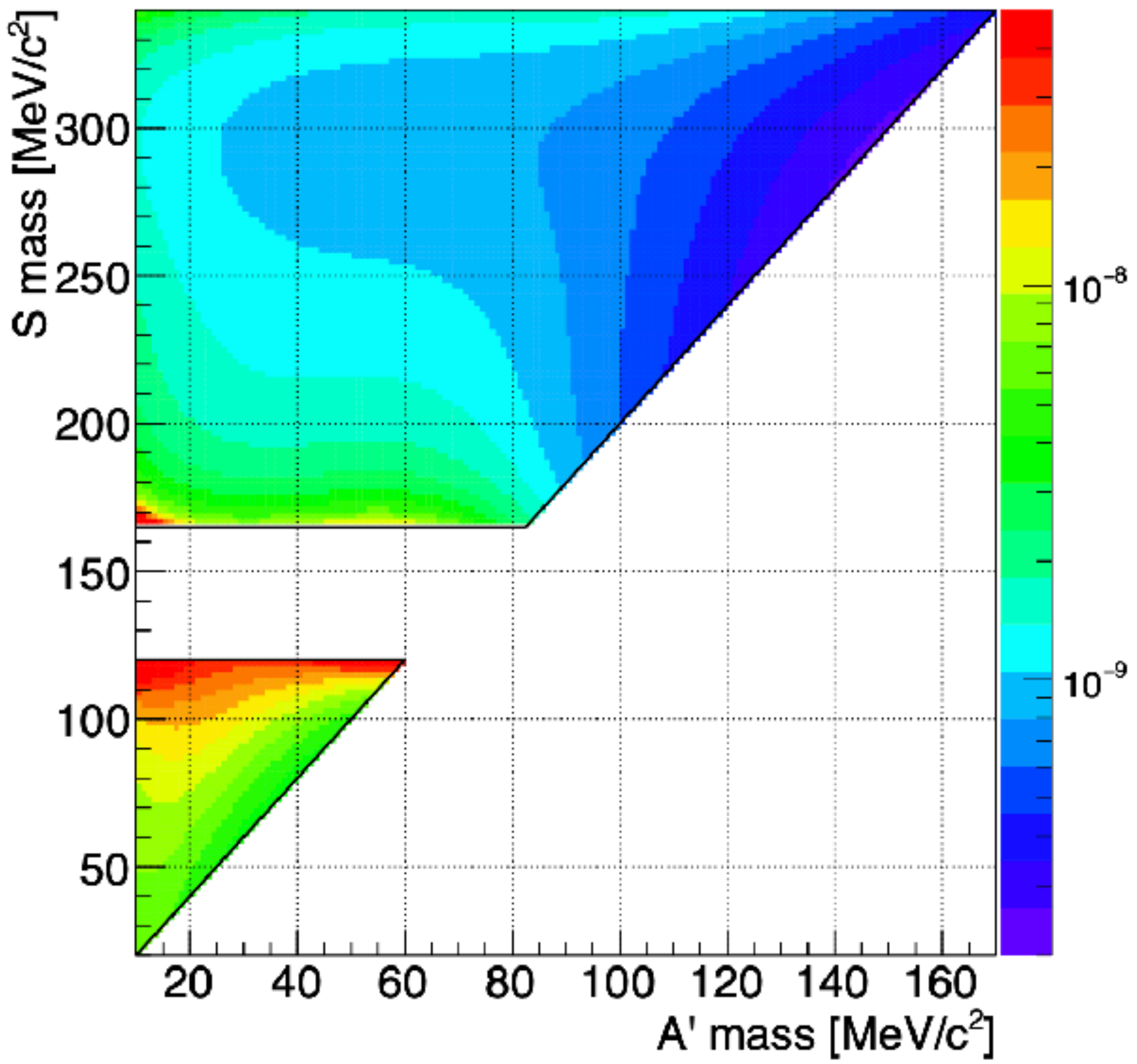
Analysis has been performed with **Run 1** data sample

$K^+ \longrightarrow \pi^+e^+e^-e^+e^-$: results

- K^+ decays in FV: $(8.58 \pm 0.19_{stat} \pm 0.07_{MC} \pm 0.41_{ext}) \times 10^{11}$
- **0 events observed** in signal region
- Expected background **0.18 ± 0.14**

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





- Consistency of the two reconstructed e^+e^- mass values
- For each mass hypothesis m_X: $|m_{ee} - m_X| < 0.02 \cdot m_X$
- Uniform phase space assumed for K^+ decays
- isotropic decays of dark states for 33 equally spaced m_a hypothesis (scan: 5 MeV/c^2)

Upper limit at 90% CL for the branching rations $BR(K_{\pi aa})$ and $BR(K_{\pi S})$ decay chains as function of the assumed masses of the dark-sector mediators

Conclusion

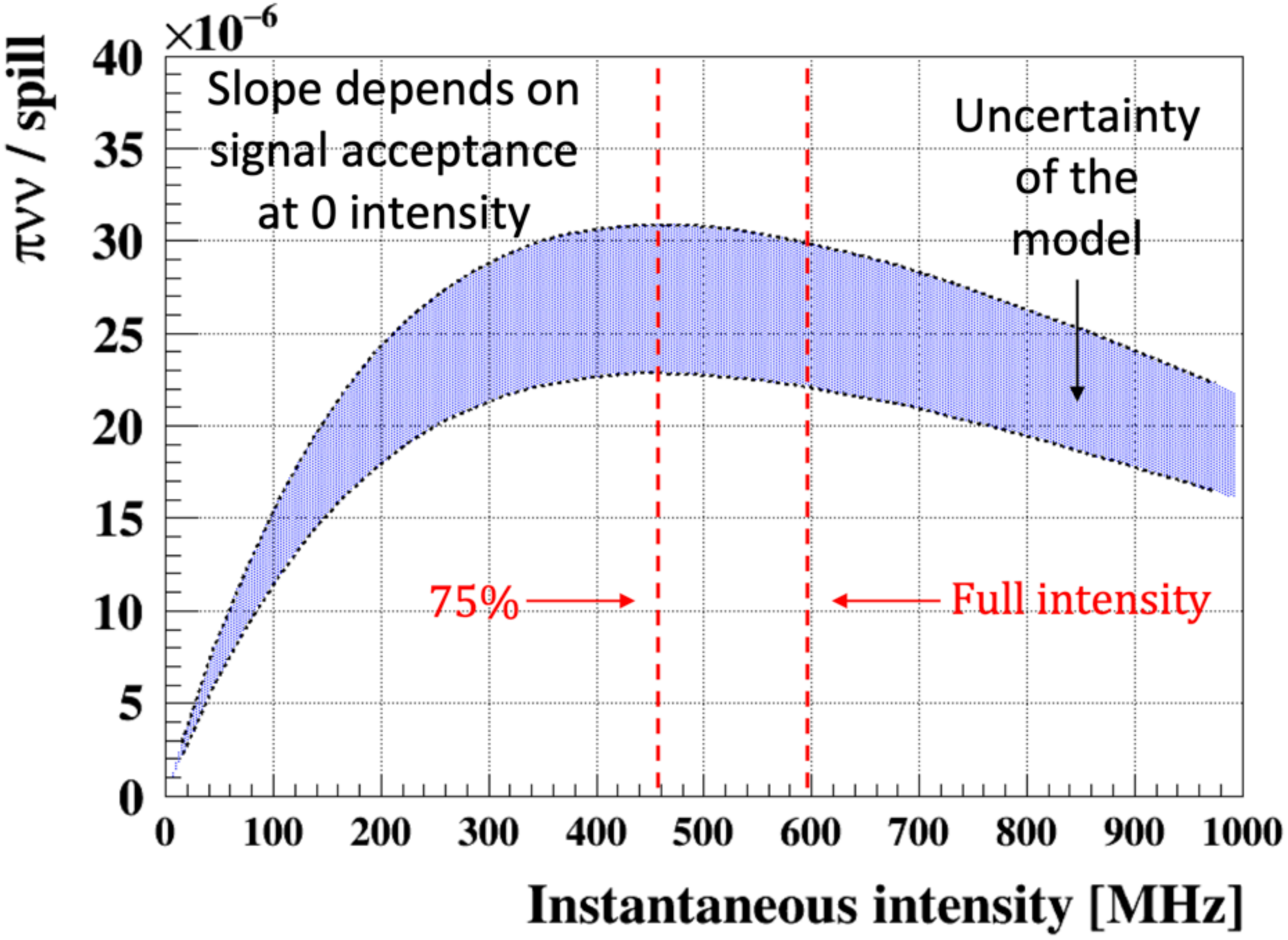
$K^+ \to \pi^+\gamma\gamma$	NA62 Run 1	PLB 850 (2024) 138513
$K^+ \to \pi^+e^+e^-e^+e^-$	NA62 Run 1	PLB 846 (2023) 138193
$K^+ \to \mu^-\nu e^+e^+$	NA62 Run 1	PLB 838 (2023) 137679
$K^+ \to \pi^0e^+\nu\gamma$	NA62 Run 1	JHEP 09 (2023) 040
$K^+ \to \mu^-\nu e^+e^+$	NA62 Run 1	PLB 838 (2023) 137679
$K^+ \to \pi^-(\pi^0)e^+e^+$	NA62 Run 1	PLB 830 (2022) 137172
$K^+ \to \pi^+\mu^+\mu^-$	NA62 Run 1	JHEP 11 (2022) 011
$\pi^0 \to \mu^-e^+$	NA62 Run 1	PRL 127 (2021) 131802
$K^+ \to \pi^+\mu^-e^+$	NA62 Run 1	PRL 127 (2021) 131802
$K^+ \to \pi^-\mu^+e^+$	NA62 Run 1	PRL 127 (2021) 131802
$K^+ \to \pi^+\nu\bar{\nu}$	NA62 Run 1	JHEP 06 (2021) 093
$\ldots.$		

- Several new physics results obtained by the collaboration
- Multiple analyses are ongoing
- We are working to finalize the first result on BR($K^+ \to \pi^+\nu\nu$) with Run 2 data (2021+2022)
- NA62 will take data till 2025 … further results will be obtained and new searches developed with the full statistic

Thank you for the attention from NA62 collaboration!

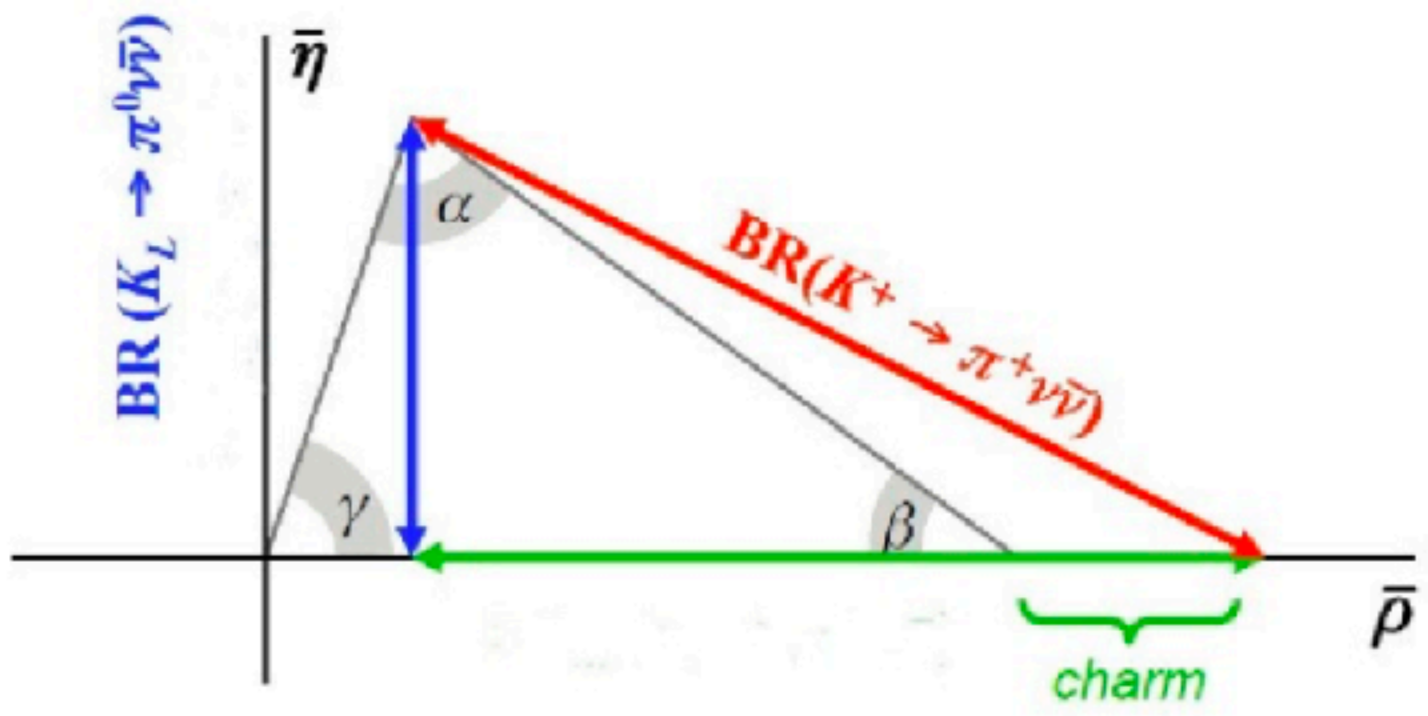
Backup

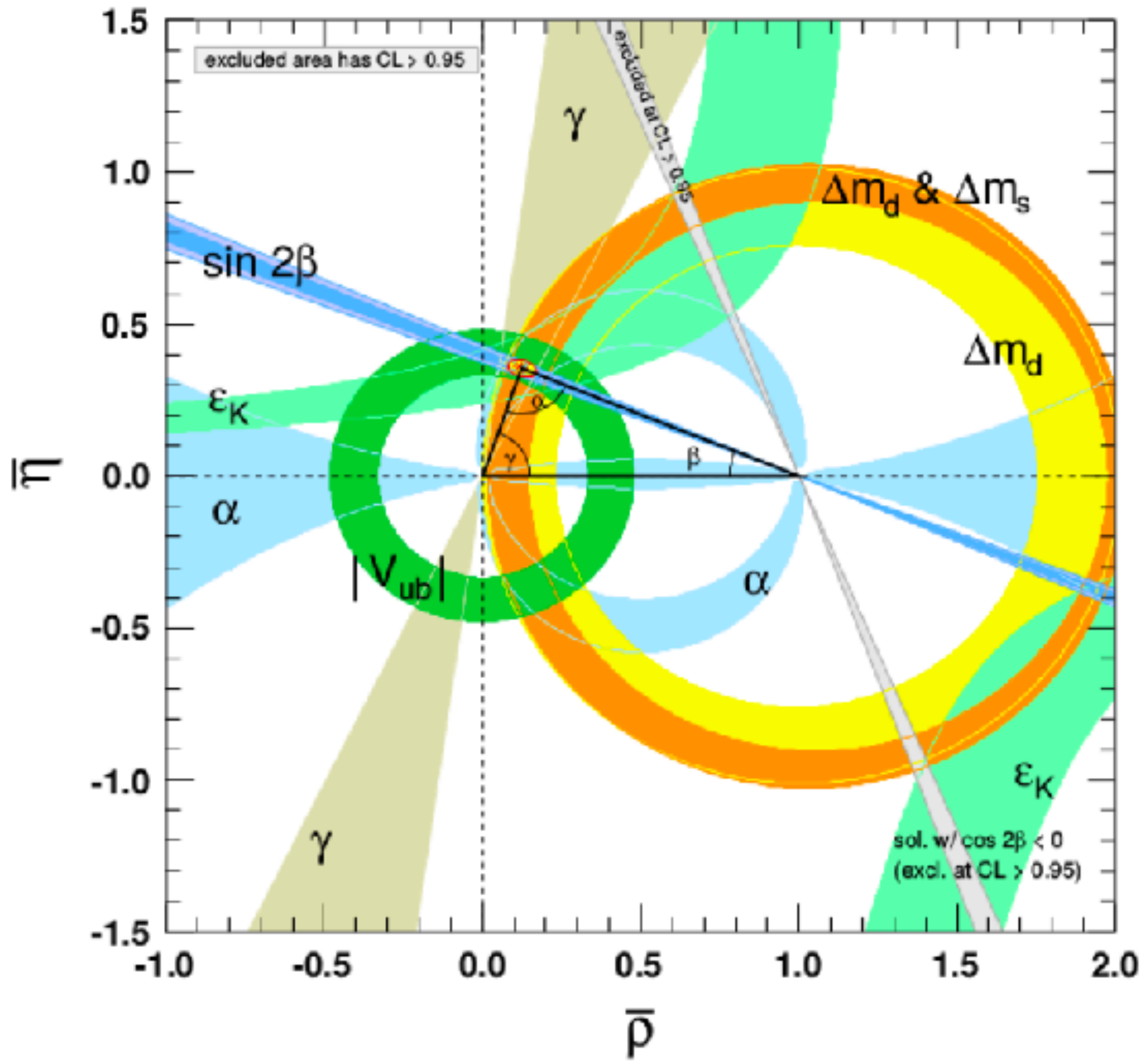
NA62 beam intensity



- We are working to finalise the firs result on RUN2 data (2021+2022).
- This data was taken pushing to the (hardware) limit of intensity for NA62.
- We studied these limits and understood how the yield of signal events evolves with intensity.
- This allowed us to determine an optimum operating condition, which was adopted starting from mid 2023

BR($K^+ \longrightarrow \pi^+\nu\nu$) and the unitary triangle





Standard Model calculation *[Buras et al., JHEP 11 (2015) 033]*

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = \kappa_+(1+\Delta_{EM}) \cdot \left[\left(\frac{\Im(\lambda_t)}{\lambda^5}X(x_t)\right)^2 + \left(\frac{\Re(\lambda_c)}{\lambda}P_c(X) + \frac{\Re(\lambda_t)}{\lambda^5}X(x_t)\right)^2\right]$$

$$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) = \kappa_L \cdot \left(\frac{\Im(\lambda_t)}{\lambda^5}X(x_t)\right)^2$$