Recent results from the NA62 experiment at CERN

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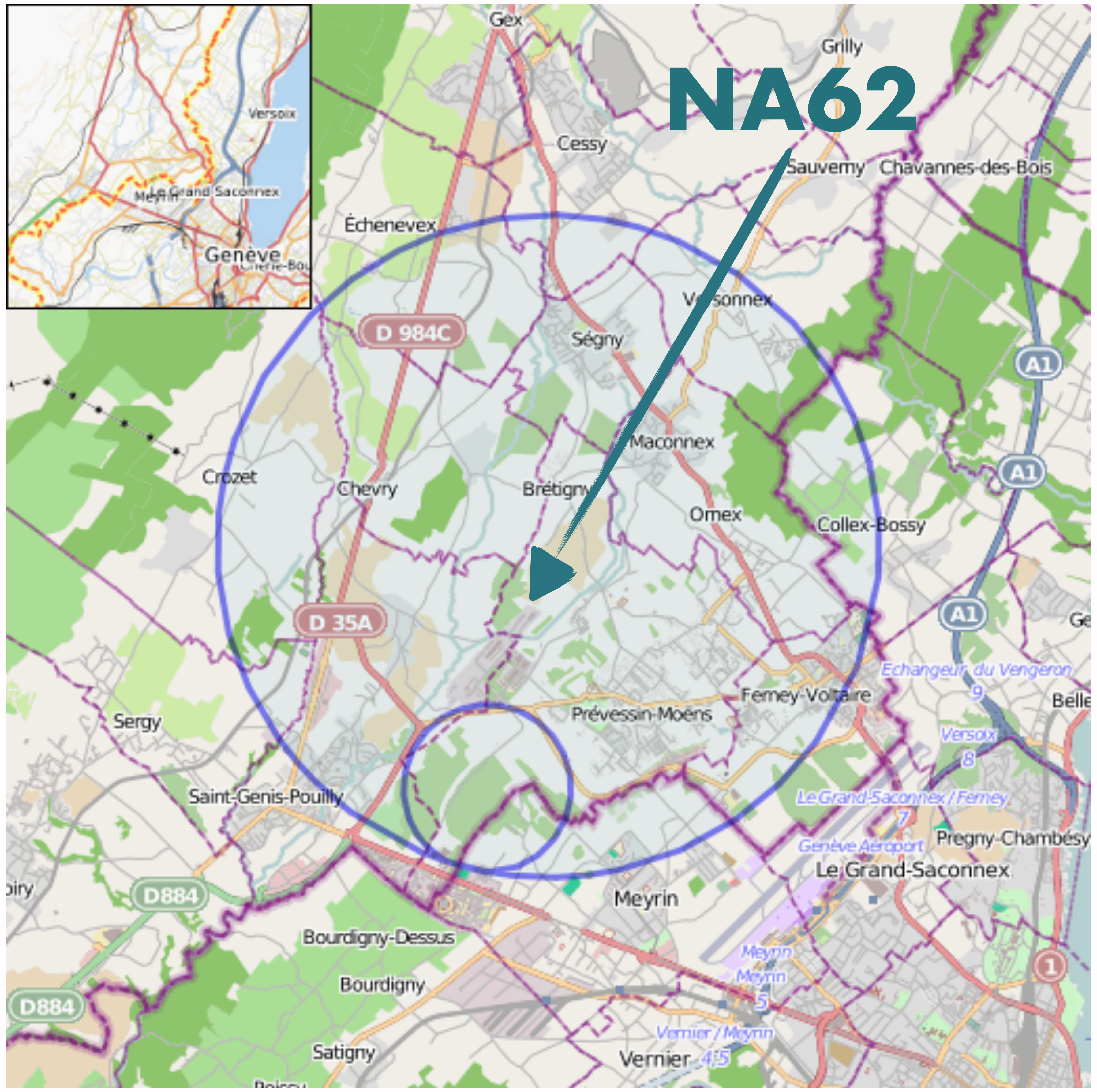
SSM Scuola Superiore Meridionale

INFN NAPOLI

NA62

A Kaon factory at CERN



- Beam from the SPS: **400 GeV/c protons** on Be target
- Secondary 75 GeV/c beam hadrons (70% π, 24% p and **6%** K)
- **Decay in flight:** Kaons decay in a 60 meters long volume

The main aim of NA62 is to study the FCNC process $K^+ \to \pi^+ \nu \bar{\nu}$

Theory
[arXiv:2109.11032]

$$\mathscr{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (8.60 \pm 0.42) \times 10^{-11}$$

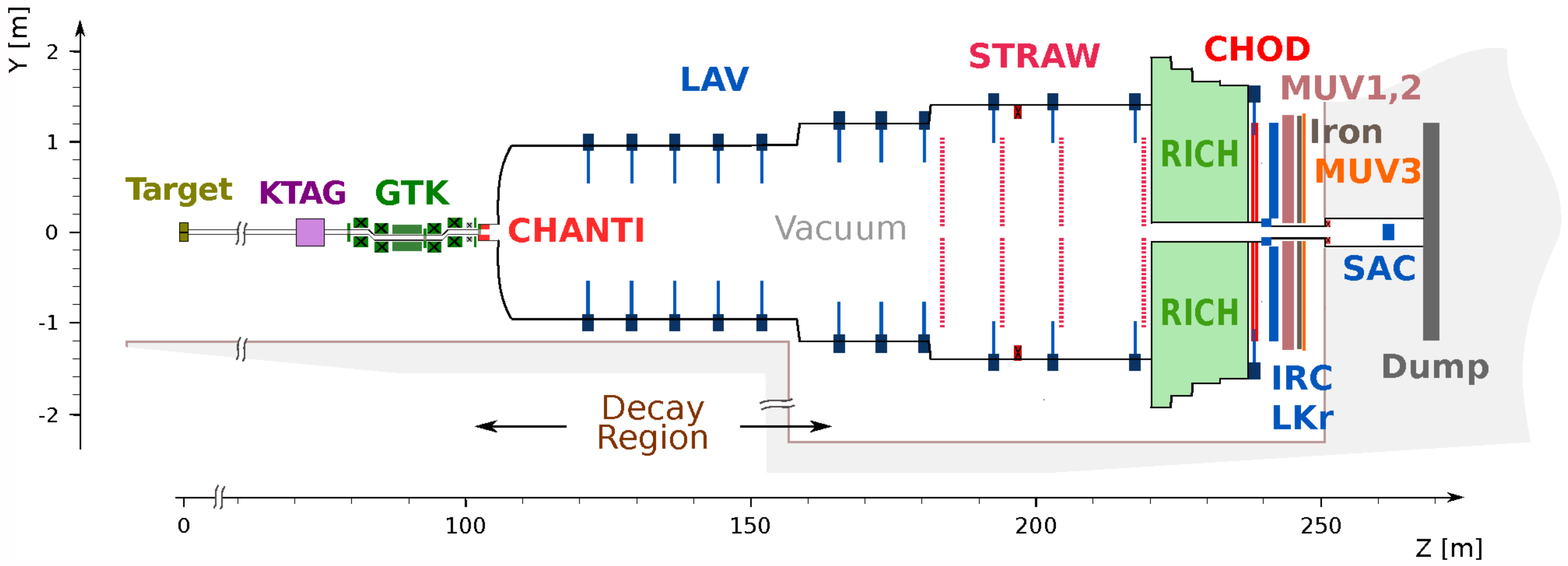
NA62
[JHEP06 (2021) 093]

$$\mathscr{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (10.4^{+4.0}_{-3.4\,stat} \pm 0.9_{syst}) \times 10^{-11}$$

Timeline of the NA62 Experiment:

2009-2014	2016-2018	2019-2021	2021-2025
Detector R&D Installation	Run1	LS2 upgrade	Run 2

Detector overview



Upstream Detectors

KTAG: Cherenkov differential detector

GTK: silicon pixel beam tracker

CHANTI: anti counter against inelastic beam-GTK3 interactions

Downstream Detectors

STRAW: track momentum spectrometer

CHOD: plastic scintillators for fast charged trigger

RICH: Cherenkov counter for π/μ/e ID

LKr and MUV1-2: calorimetric system

MUV3: muon veto

$K^+ \to \pi^+\gamma\gamma$ decay: overview

- Crucial test for Chiral Perturbation theory **(ChPT)**
- Two **kinematic variables** used to describe the decay

$$z = \frac{(q_1 + q_2)^2}{m_K^2} = \left(\frac{m_{\gamma\gamma}}{m_K}\right)^2$$

$$y = \frac{p \cdot (q_1 - q_2)}{m_K^2}$$

q_i photon momenta

p kaon momenta

- In the ChPT framework (at leading order O(p⁴) and including O(p⁶) contributions) the **decay rate** and **spectrum** are determined by a single priori unknown O(1) parameter $\hat{c}$

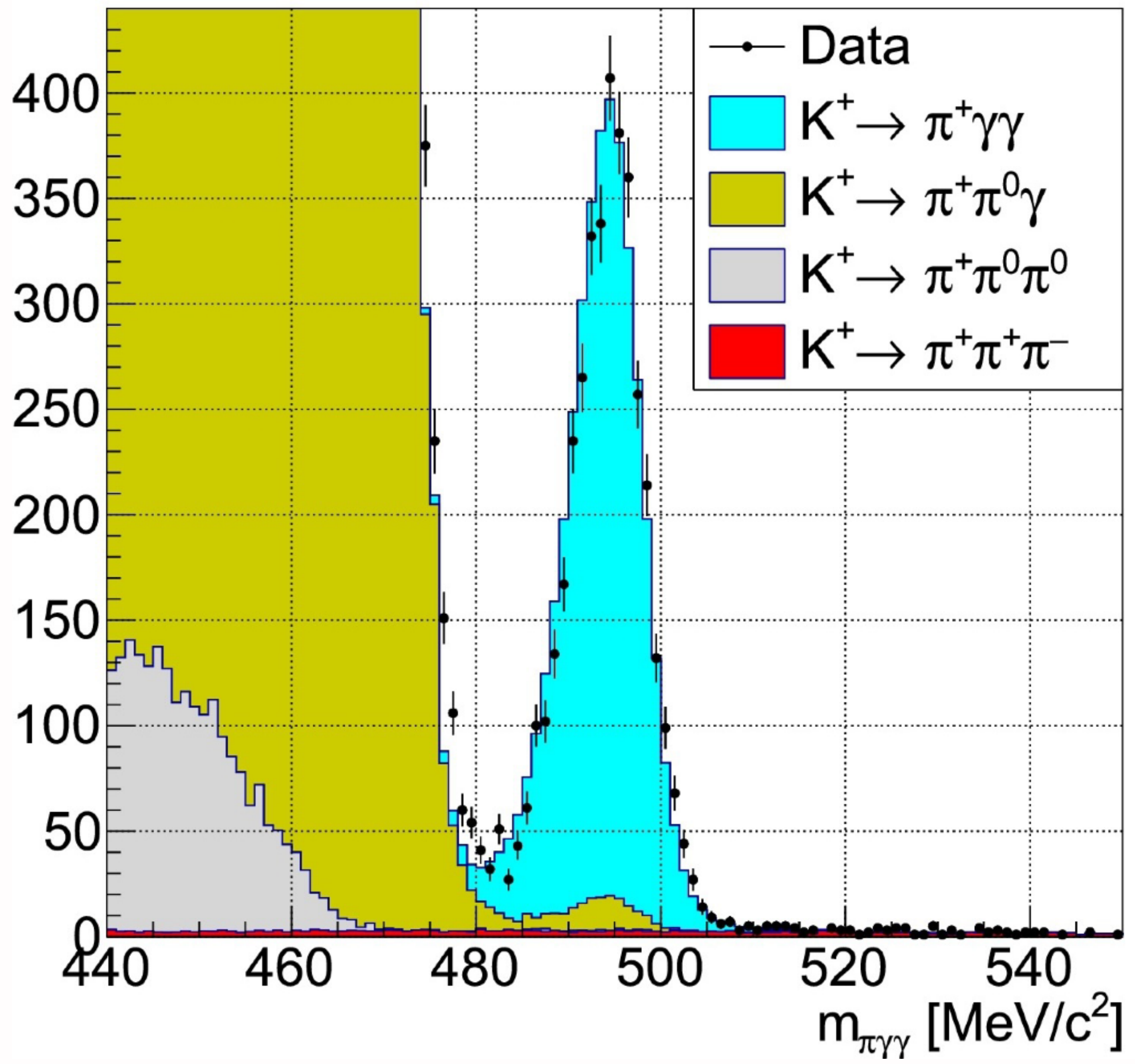
$$\frac{\partial^2\Gamma}{\partial y \partial z} = \frac{m_K}{2^9\pi^3}\left[z^2(|A(\hat{c},z,y^2) + B(z)|^2 + |C(z)|^2) + \left(y^2 - \frac{1}{4}\lambda(1,r_\pi^2,z)\right)^2 |B(z)|^2\right]$$

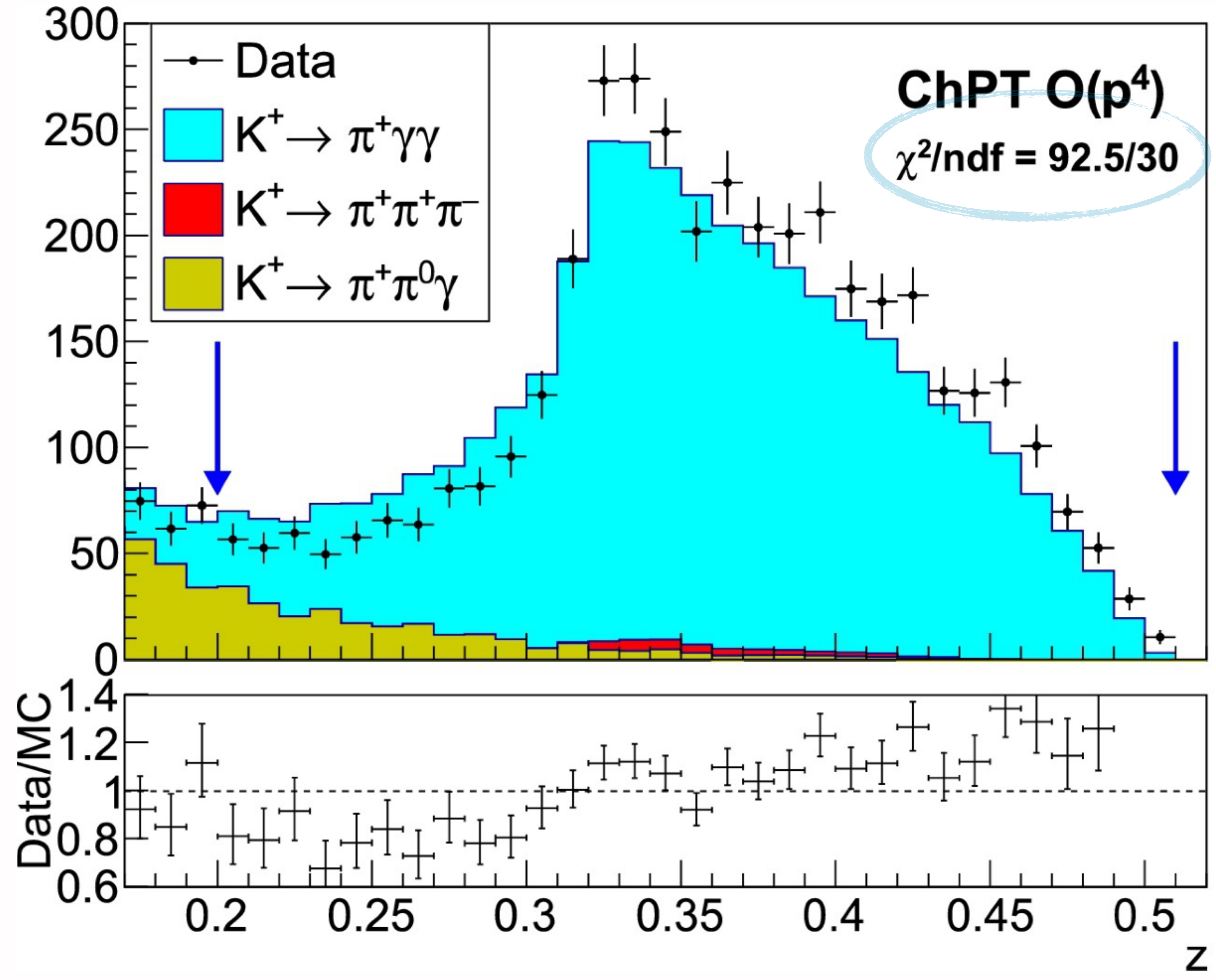
[D'Ambrosio and Portoles, PLB386 (1996) 403]

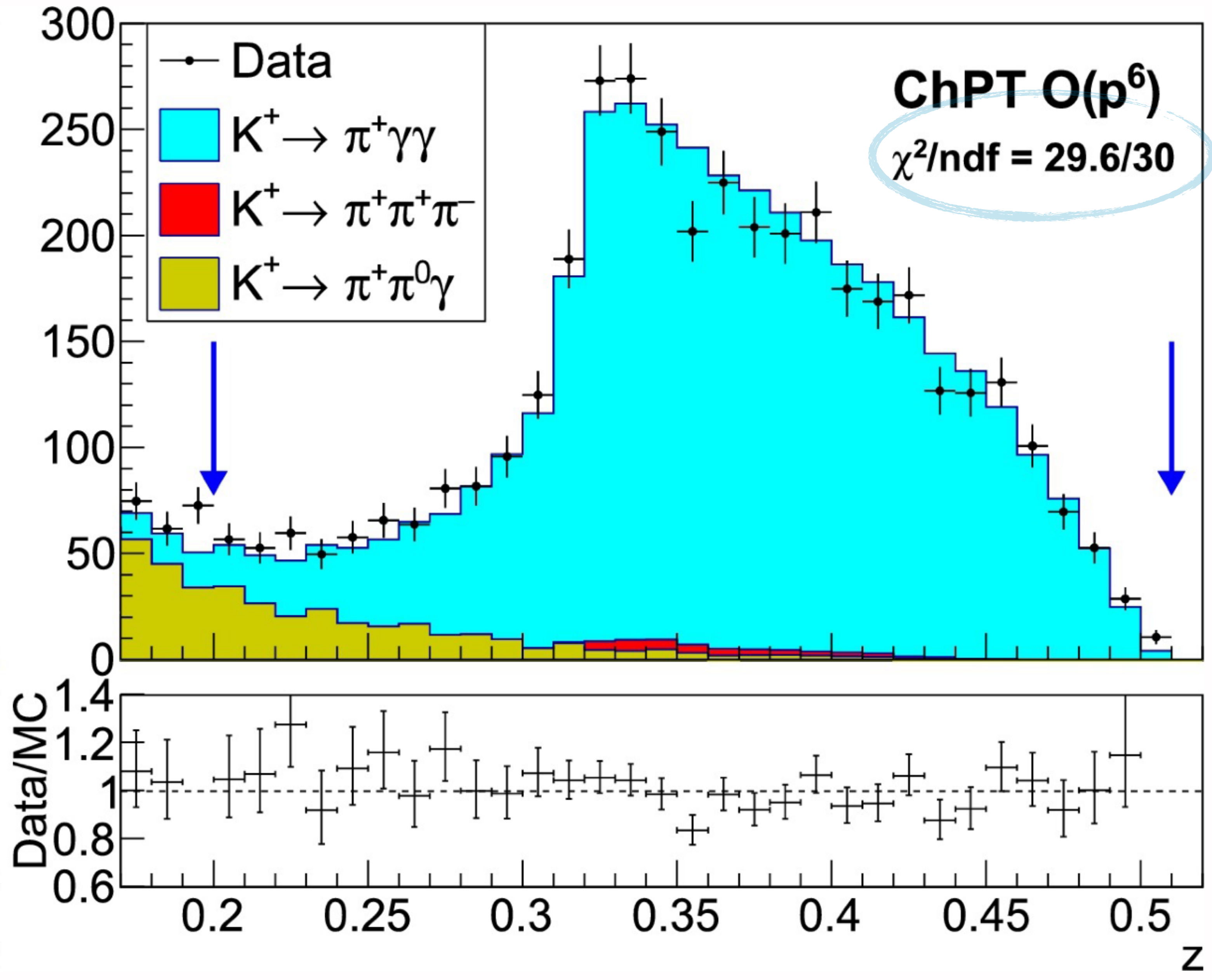
$K^+ \to \pi^+\gamma\gamma$ decay: data and selection

PLB850 (2024) 138513

- Downscaled control and non-muon **trigger lines.**
- **Normalisation:** $K^+ \to \pi^+\pi^0$ decay, effectively $(5.55 \pm 0.03)\times10^{10}$ kaon decays.
- **Candidates observed:** 3984.
- **Expected background:** 291±14.
- Kinematic variable **$z=(m_{\gamma\gamma}/m_K)^2$** computed using the missing mass (**K−p**).



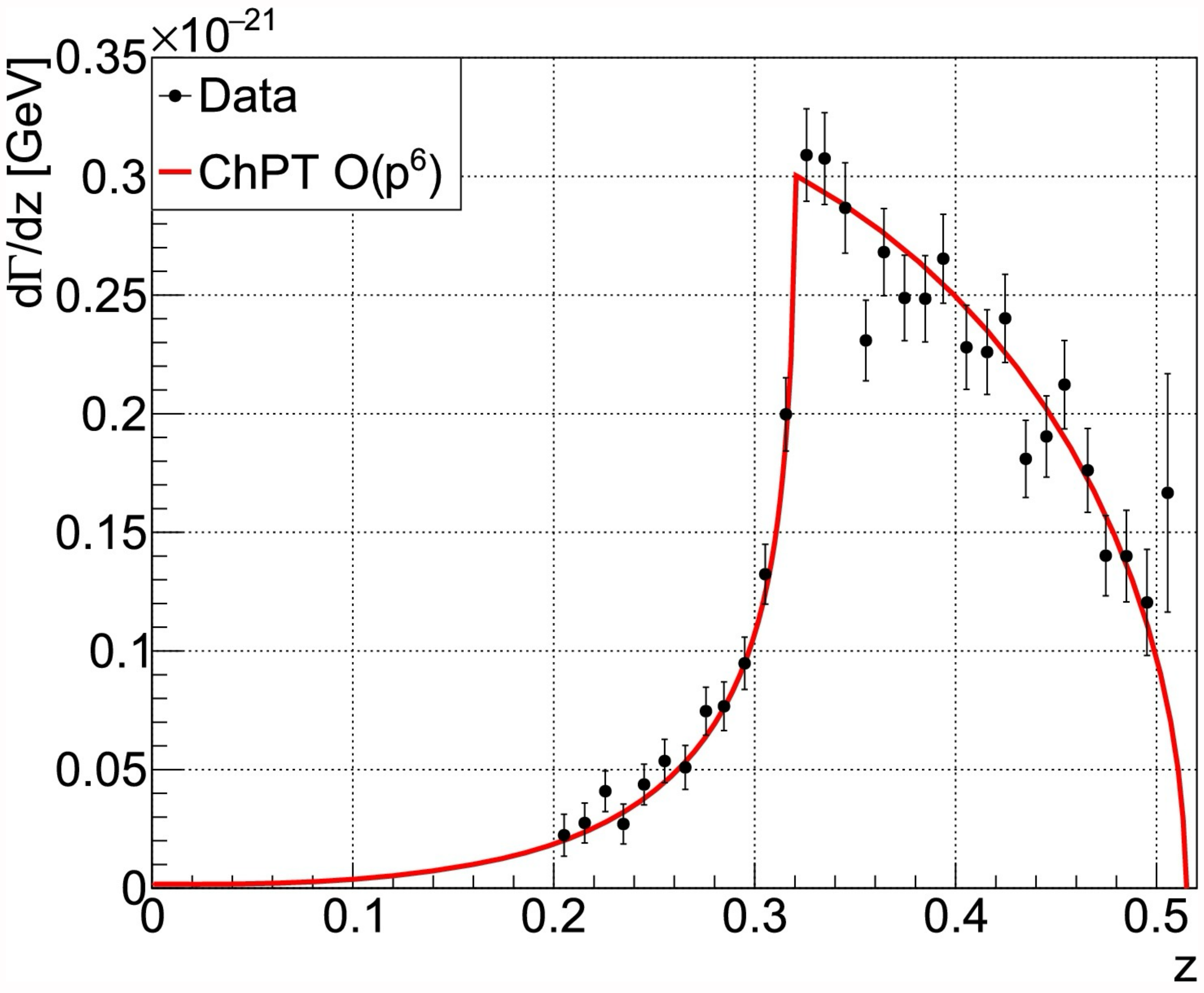


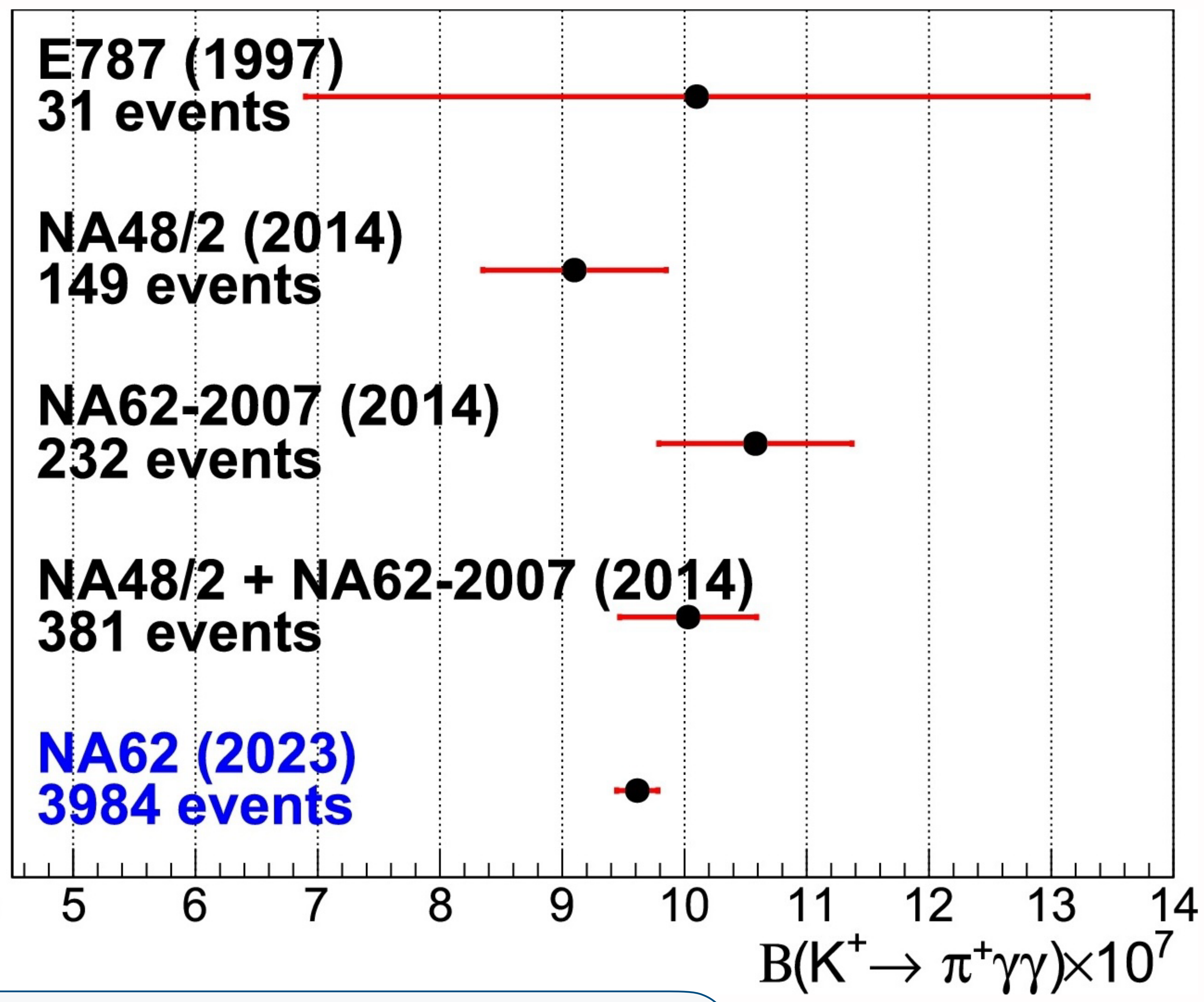


- ChPT O(p^4) p-value: 2.7×10^{-8} → not sufficient to describe di-photon mass spectrum
- ChPT O(p^6) p-value: 0.49

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

PLB850 (2024) 138513





$$\hat{c}_6 = 1.144 \pm 0.069_{stat} \pm 0.034_{syst}$$

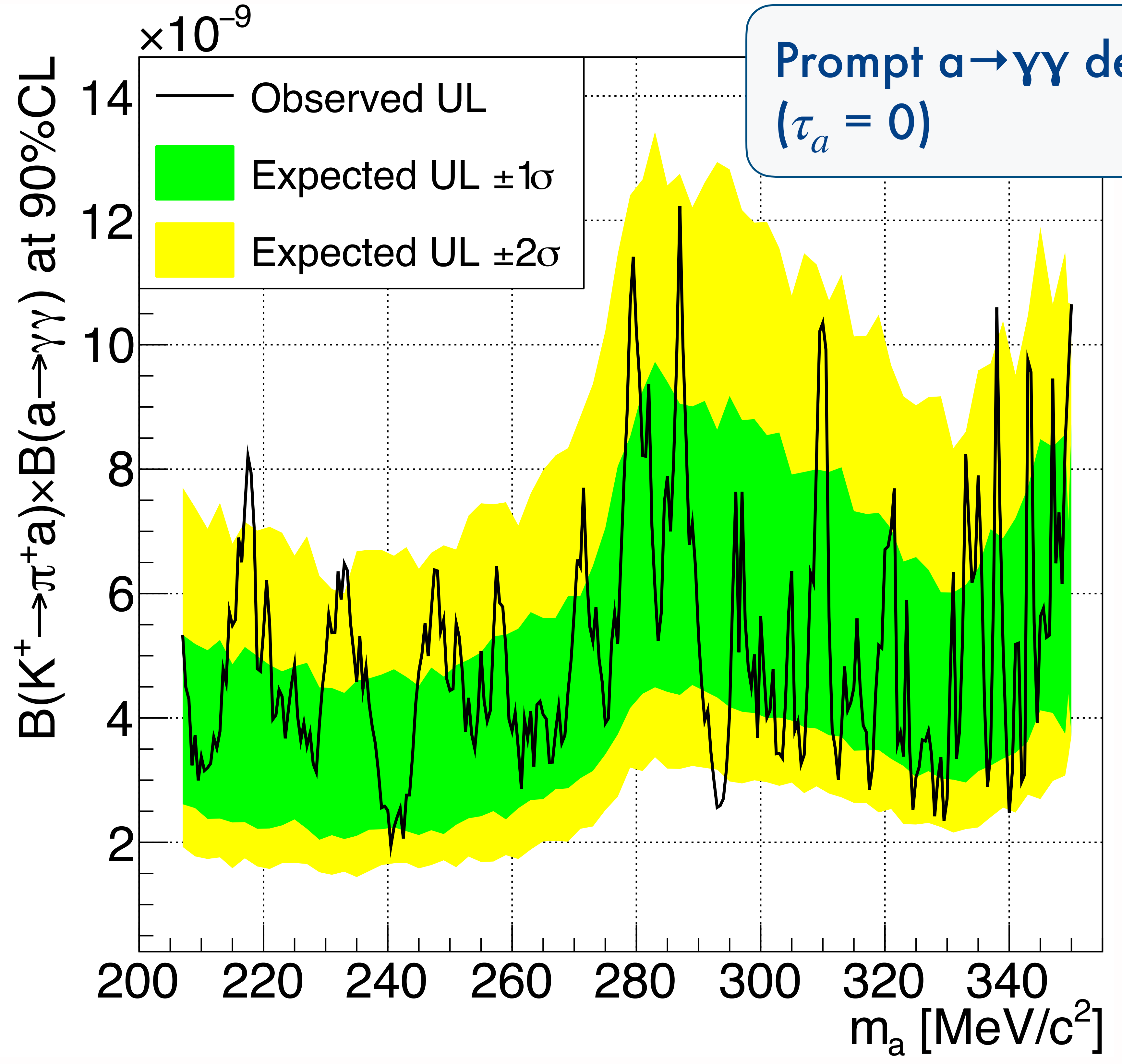
$$\mathcal{B}_{ChPT\mathcal{O}(p^6)}(K^+ \to \pi^+\gamma\gamma) = (9.61 \pm 0.15_{stat} \pm 0.07_{syst}) \times 10^{-7}$$

$$\mathcal{B}_{MI}(K^+ \to \pi^+\gamma\gamma \,|\, z > 0.2) = (9.46 \pm 0.19_{stat} \pm 0.07_{syst}) \times 10^{-7}$$

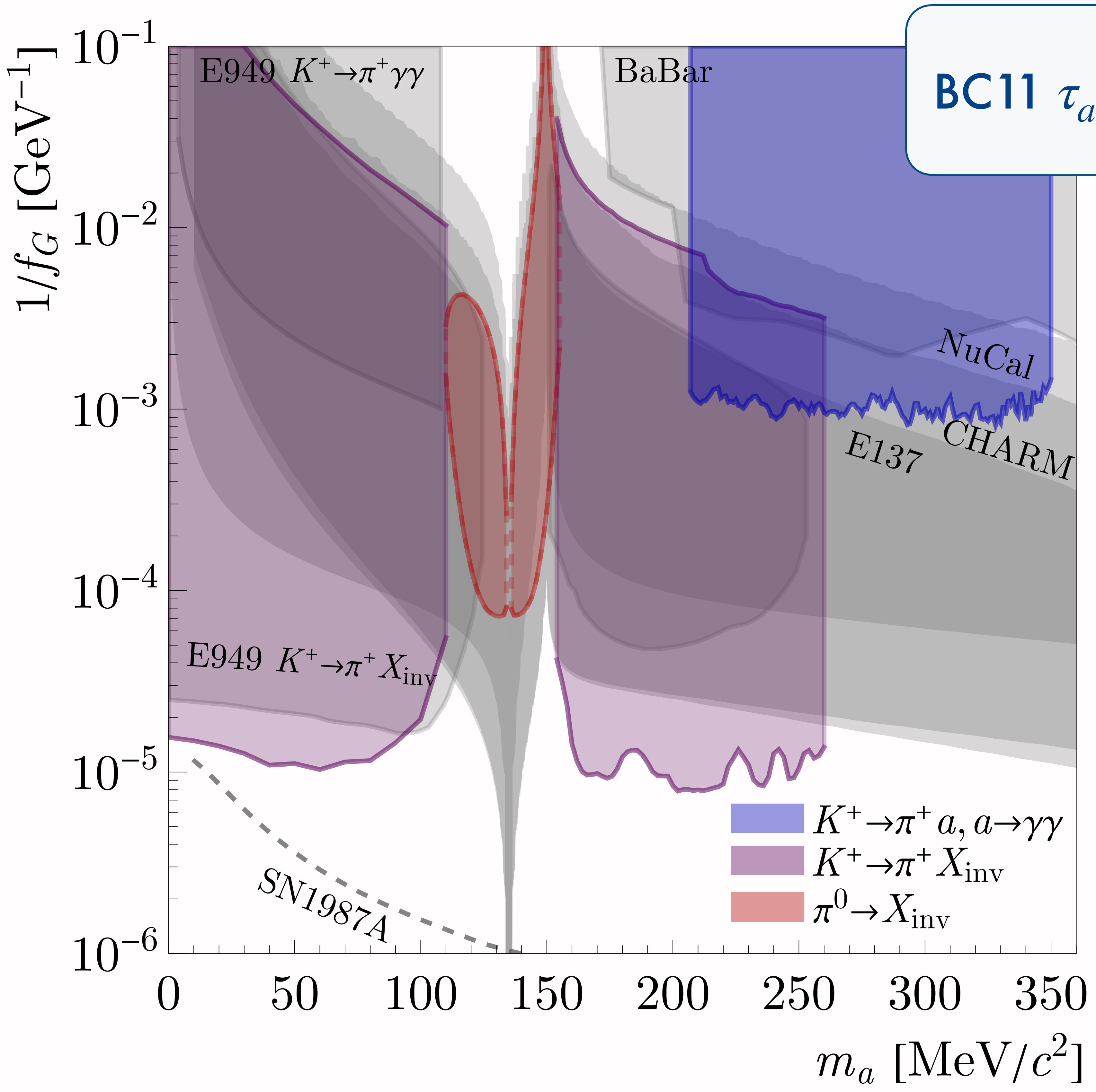
ALPs in $K^+ \to \pi^+ a$, $a \to \gamma\gamma$ decays

PLB850 (2024) 138513

- Peak search over $m_a = \sqrt{(P_K - P_\pi)^2}$ in the range 207-350 MeV/c² in steps of 0.5 MeV/c²
- m_a resolution: from 2.0 MeV/c² to 0.2 MeV/c² across the search range
- In each m_a hypothesis background estimated from simulations and UL on number of signal events set using CLs method



Prompt a→γγ decay (τ_a = 0)



BC11 $\tau_a \sim f_G^2$

$\pi^0 \to e^+e^-$ decay: overview

Preliminary

- Experimentally observable:

$$\mathscr{B}(\pi^0 \to e^+e^-(\gamma), x > x_{cut}),\ x = m_{ee}^2/m_{\pi^0}^2$$

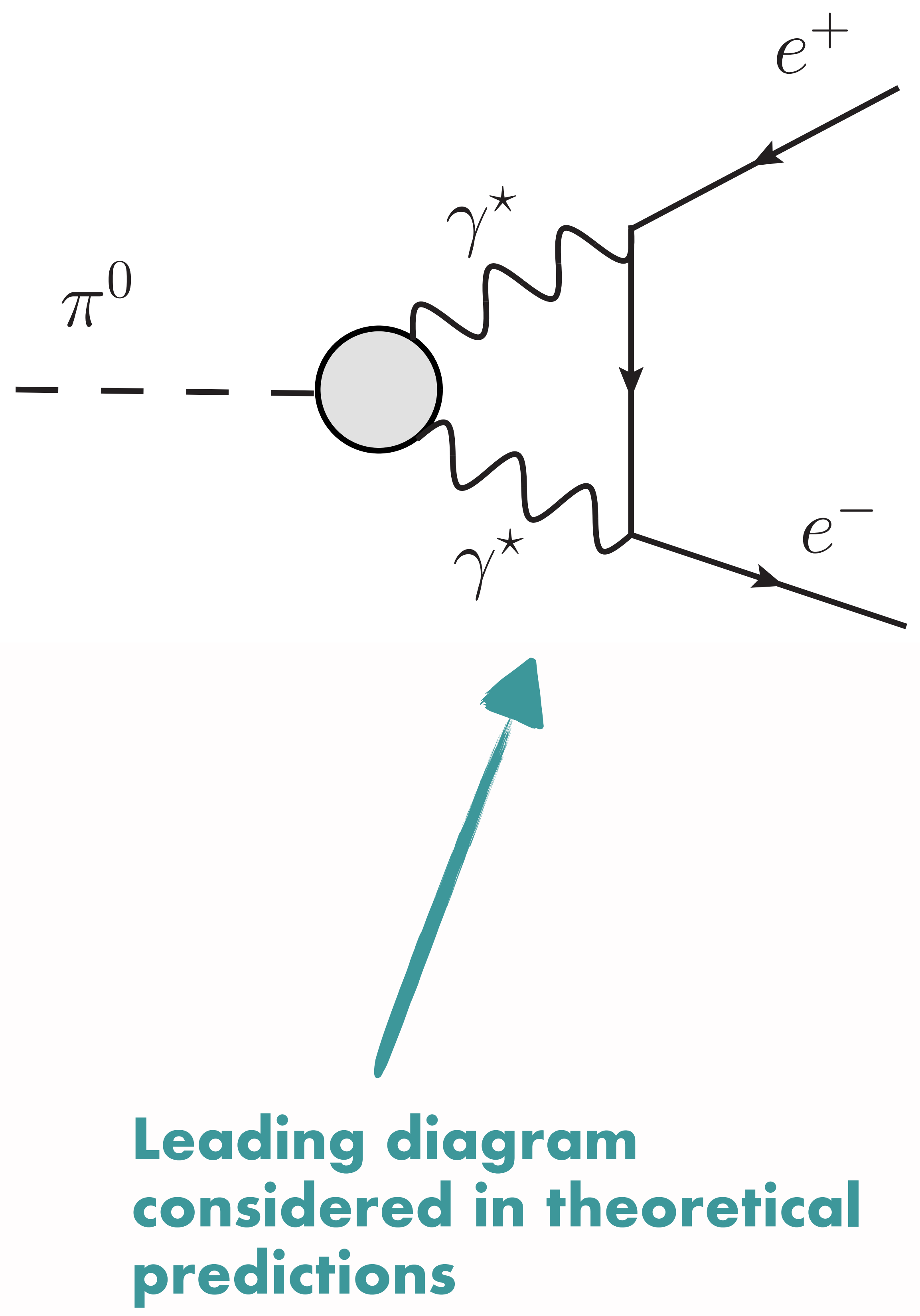
  - Dalitz decay $\pi^0 \to e^+e^-\gamma$ dominant in low-x region
  - For $x > x_{cut} = 0.95$, Dalitz decay ≈ 3.3 of $\mathscr{B}(\pi^0 \to e^+e^-(\gamma))$

- Previous best measurement by **KTeV** [Phys.Rev.D 75 (2007) 012004]

$$\mathscr{B}(\pi^0 \to e^+e^-(\gamma), x > 0.95) = (6.44 \pm 0.25 \pm 0.22) \times 10^{-8}$$

- Using **latest radiative corrections** in [JHEP 10 (2011) 122], [Eur.Phys.J.C 74 (2014) 8, 3010] the result can be extrapolated and compared with theory:

	$\mathcal{B}(\pi^0 \to e^+e^-, \text{no-rad}) \times 10^8$
KTeV, PRD 75 (2007)	6.84(35)
Knecht et al., PRL 83 (1999)	6.2(3)
Dorokhov and Ivanov, PRD 75 (2007)	6.23(9)
Husek and Leupold, EPJC 75 (2015)	6.12(6)
Hoferichter et al., PRL 128 (2022)	6.25(3)

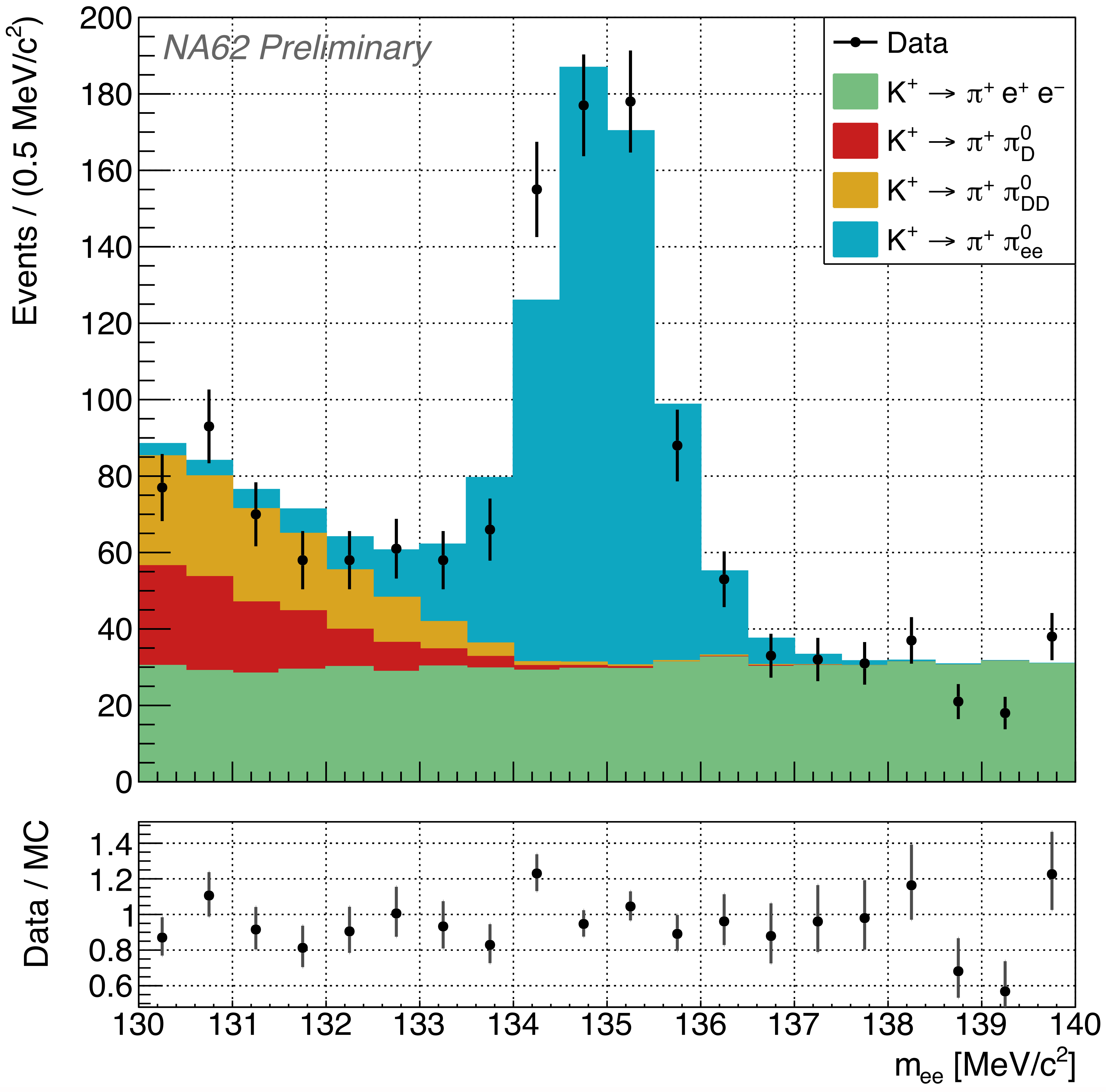


$\pi^0 \to e^+e^-$ decay: results

- Irreducible $K^+ \to \pi^+e^+e^-$ background
- Other backgrounds:
  - $K^+ \to \pi^+\pi^0_D$ with a lost or converted γ
  - $K^+ \to \pi^+\pi^0_{DD}$ with two undetected e^+e^-
- Fitted signal event yield: 597 ± 29
- **Branching fraction** of $\pi^0 \to e^+e^-$

$$\mathscr{B}(\pi^0 \to e^+e^-(\gamma), x > 0.95) = (5.86 \pm 0.30_{stat} \pm 0.11_{syst} \pm 0.19_{ext}) \times 10^{-8}$$

- result compatible with the KTeV measurement
- result in agreement with theoretical expectations when extrapolated using radiative corrections
- external uncertainty dominated by $\mathscr{B}(K^+ \to \pi^+e^+e^-)$



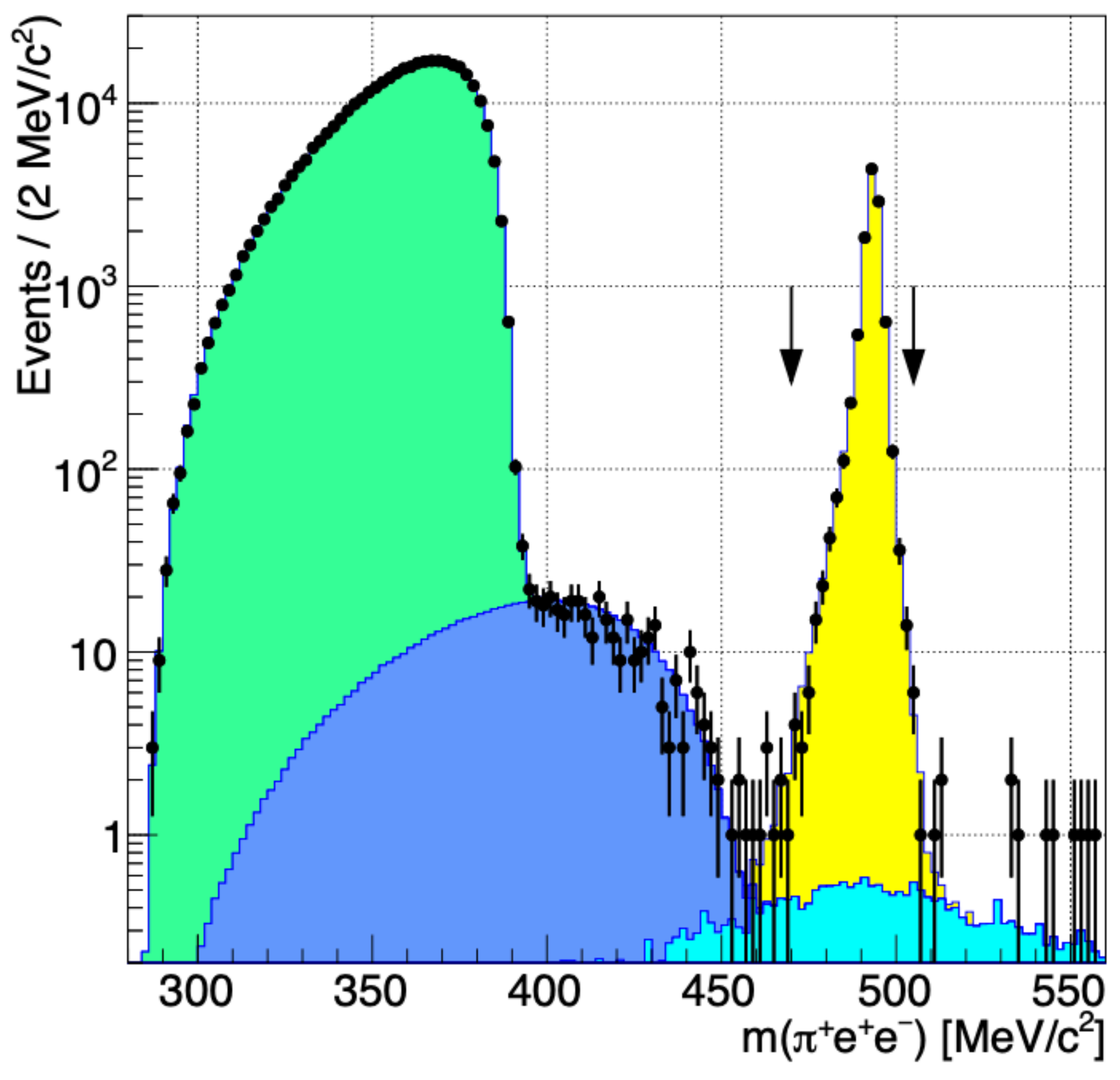
LFV and LNV

Search for $K^+ \to \mu^- \nu e^+ e^+$

PLB838 (2023) 137679

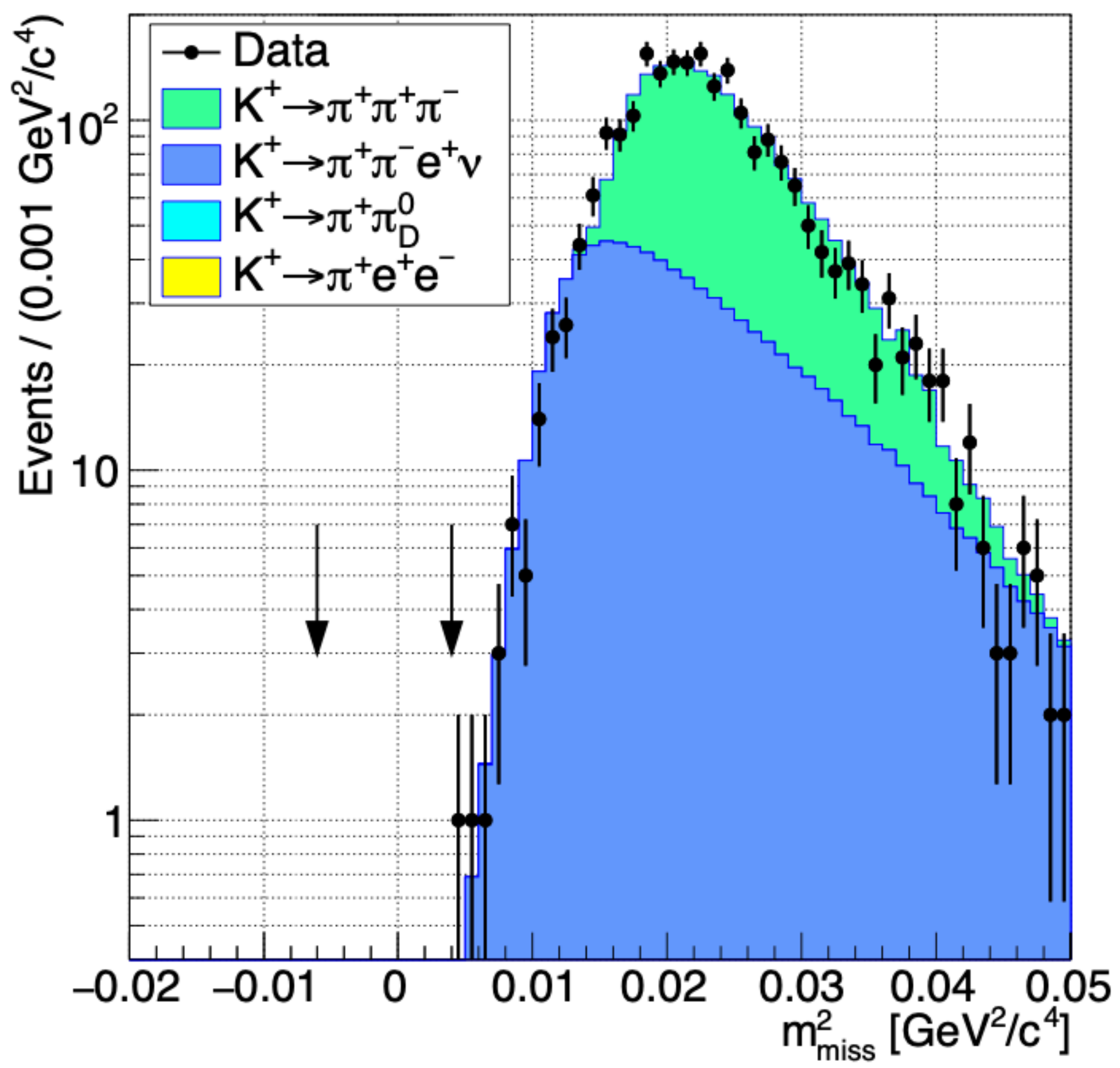
Normalisation selection

$N_{\pi ee}$= 21401, $N_K = (1.97 \pm 0.02_{stat} \pm 0.02_{syst} \pm 0.06_{ext}) \times 10^{12}$



Signal selection ($N_B = 0.26 \pm 0.04$)

No candidate observed in the signal region

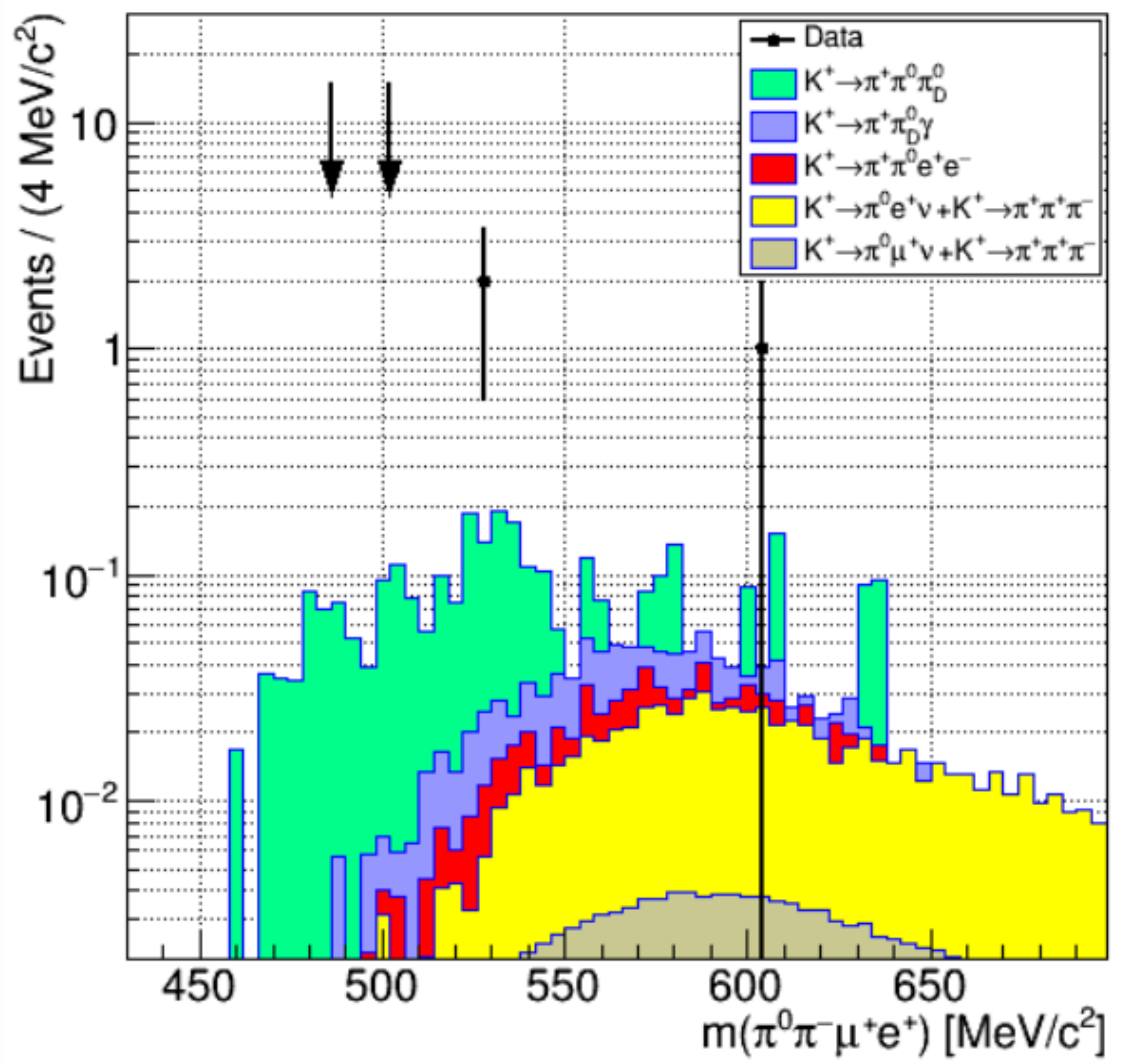


$$\mathscr{B}(K^+ \to \mu^- \nu e^+ e^+) < 8.1 \times 10^{-11} @ 90\,\%\,C.L.$$

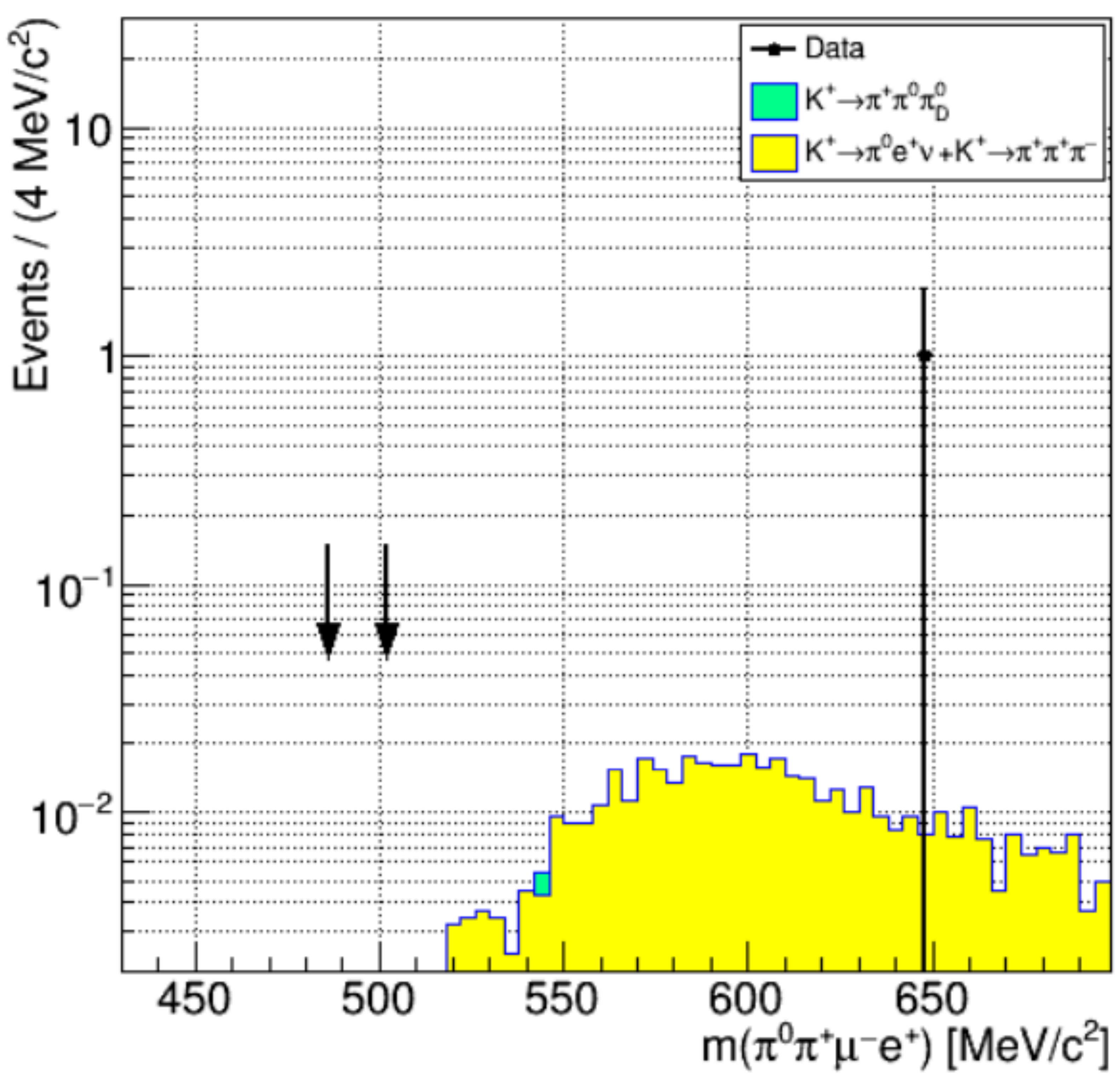
Search for $K^+ \to \pi^0\pi\mu e$

Preliminary

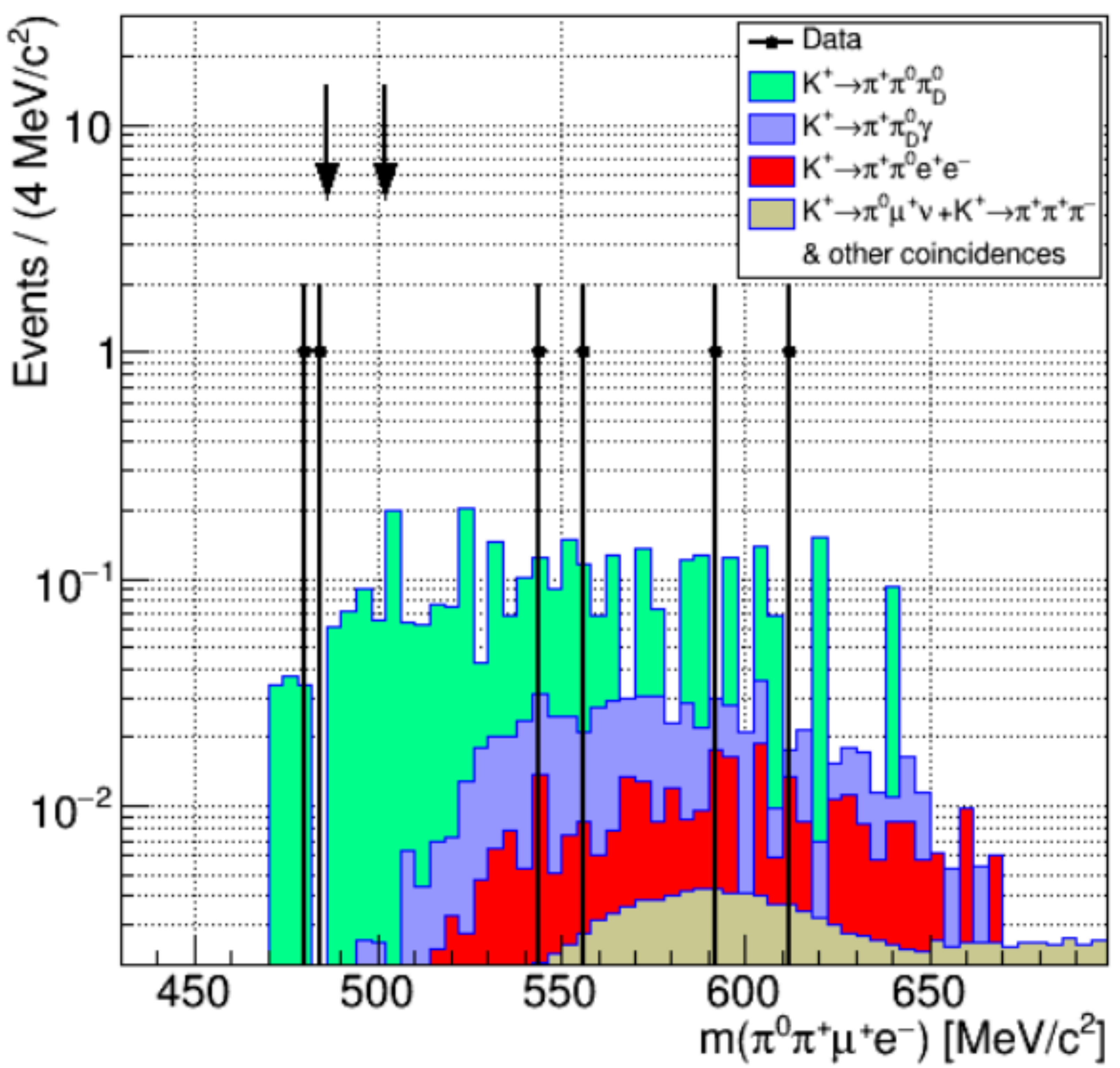
$K^+ \to \pi^0\pi^-\mu^+e^+$



$K^+ \to \pi^0\pi^+\mu^-e^+$



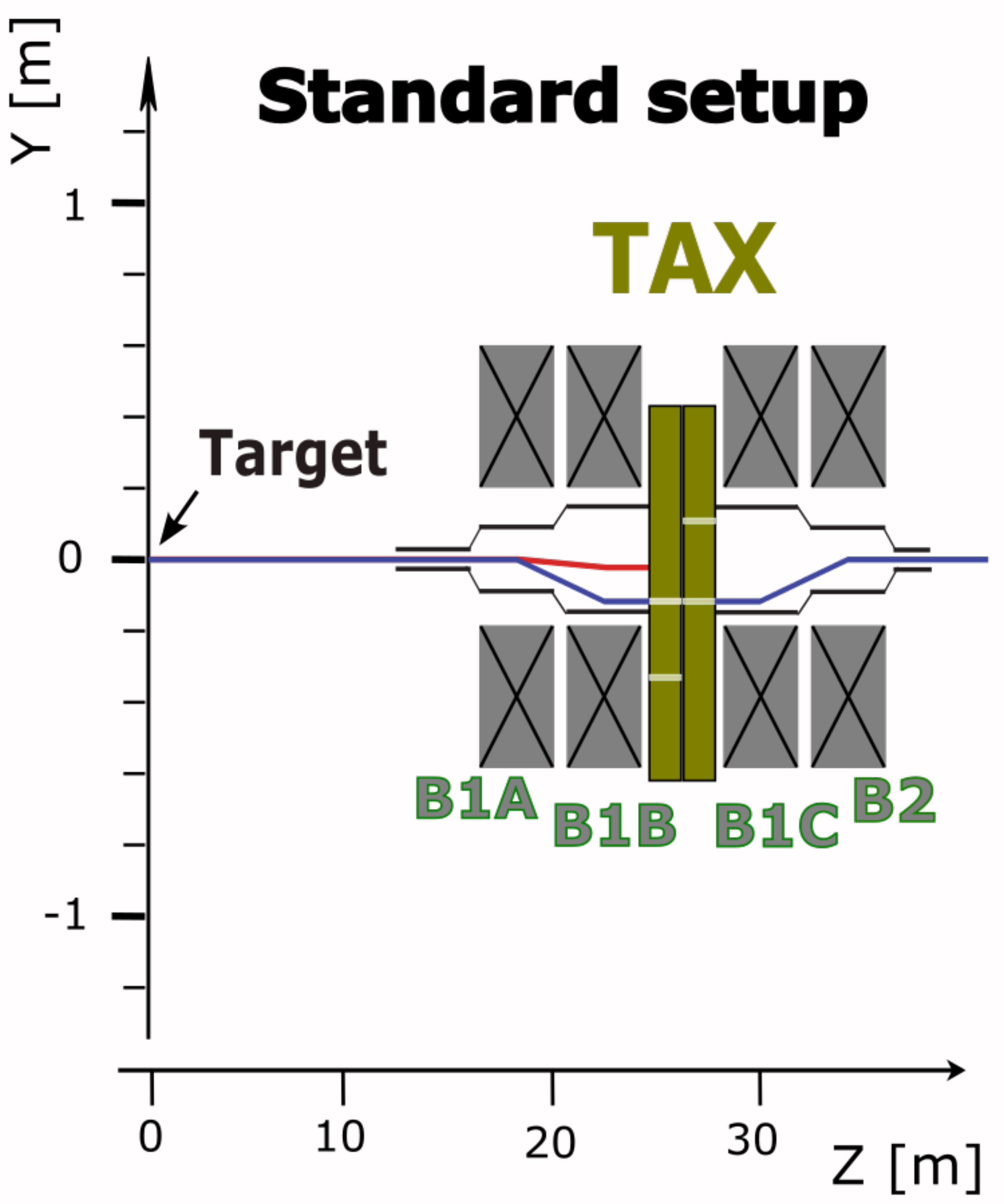
$K^+ \to \pi^0\pi^+\mu^+e^-$

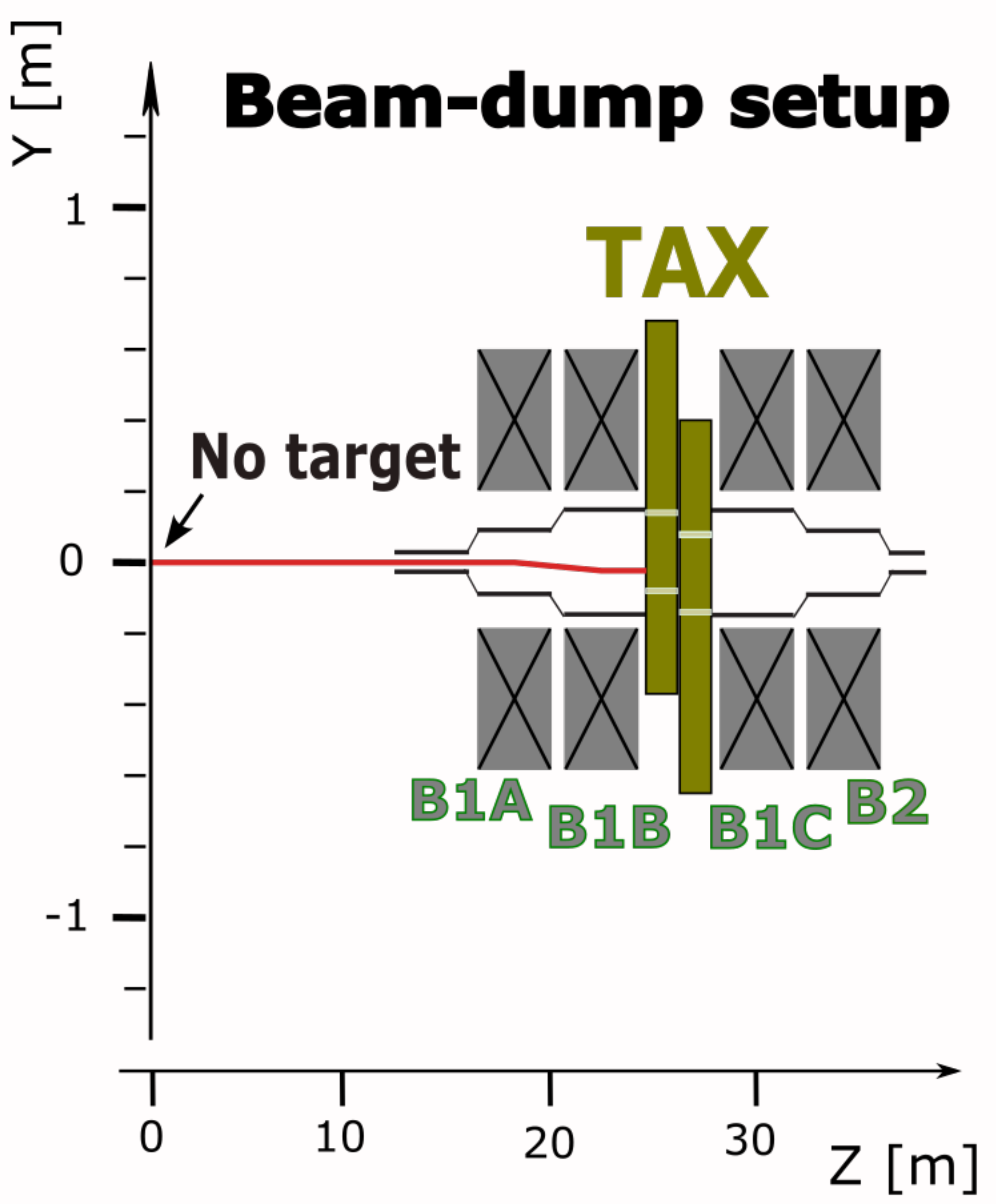


Mode	Expected Bkg	Candidates observed	U.L. @ 90% CL
$K^+ \to \pi^0\pi^-\mu^+e^+$	0.33 ± 0.07	0	2.9×10^{-10}
$K^+ \to \pi^0\pi^+\mu^-e^+$	0.004 ± 0.003	0	3.1×10^{-10}
$K^+ \to \pi^0\pi^+\mu^+e^-$	0.29 ± 0.07	0	5.0×10^{-10}

NA62 in dump mode

NA62 in beam dump mode





Trigger lines

- **Single track trigger,** at least one signal in the CHOD

  Q1/D, D = 20 → 14 KHz

- **Two-tracks trigger,** at least two in-time signals form CHOD in two different tiles

  H2 → 18 kHz

- **Control trigger** LKr-based to measure efficiency of the charged triggers, 1MeV threshold

  CTRL → 4 kHz

Q1 trigger efficiency = 99.8%

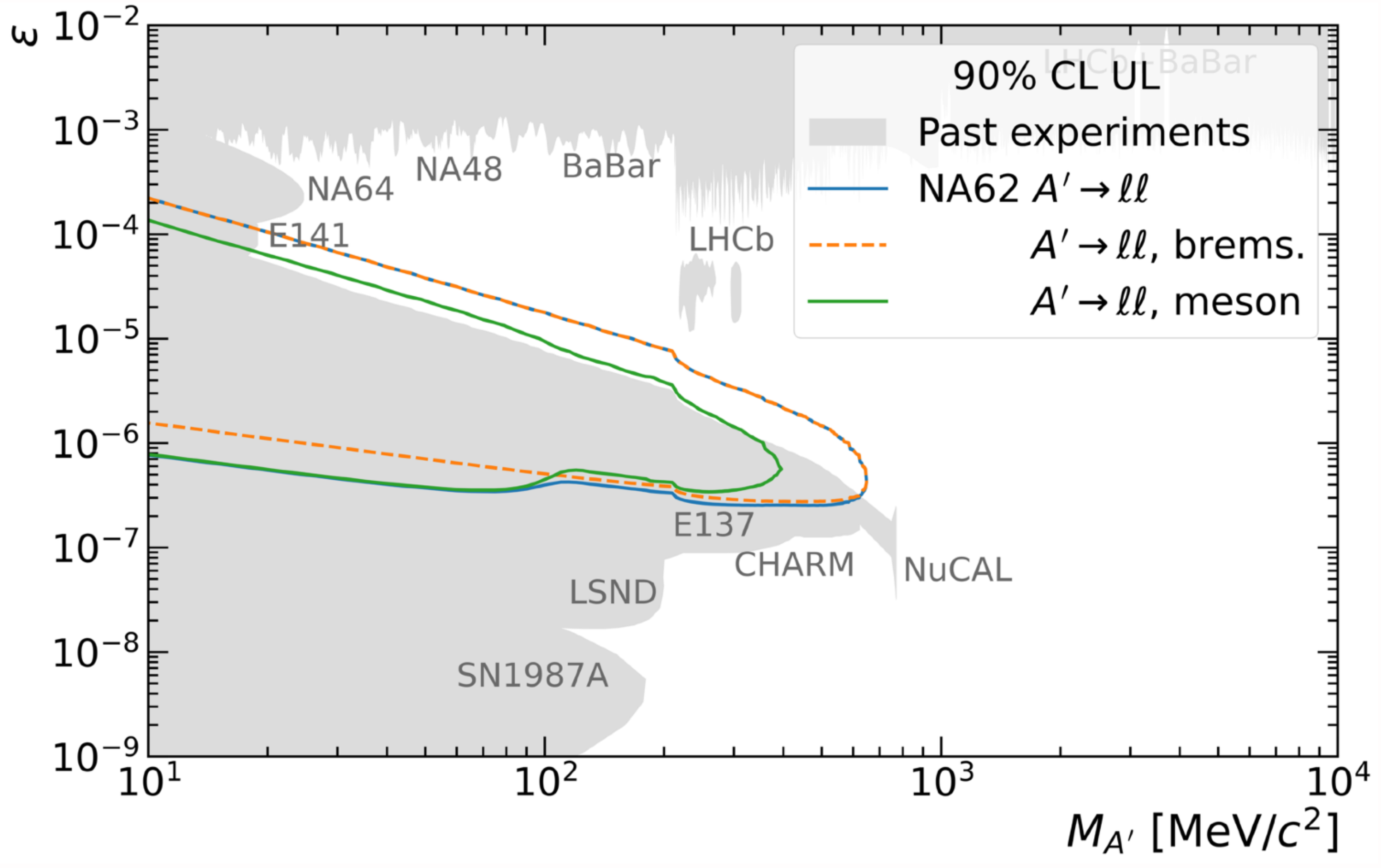
H2 trigger efficiency = 98%

$1.40 \pm 0.28 \times 10^{17}$ POT collected in ~ 10 days of data taking during the 2021 run

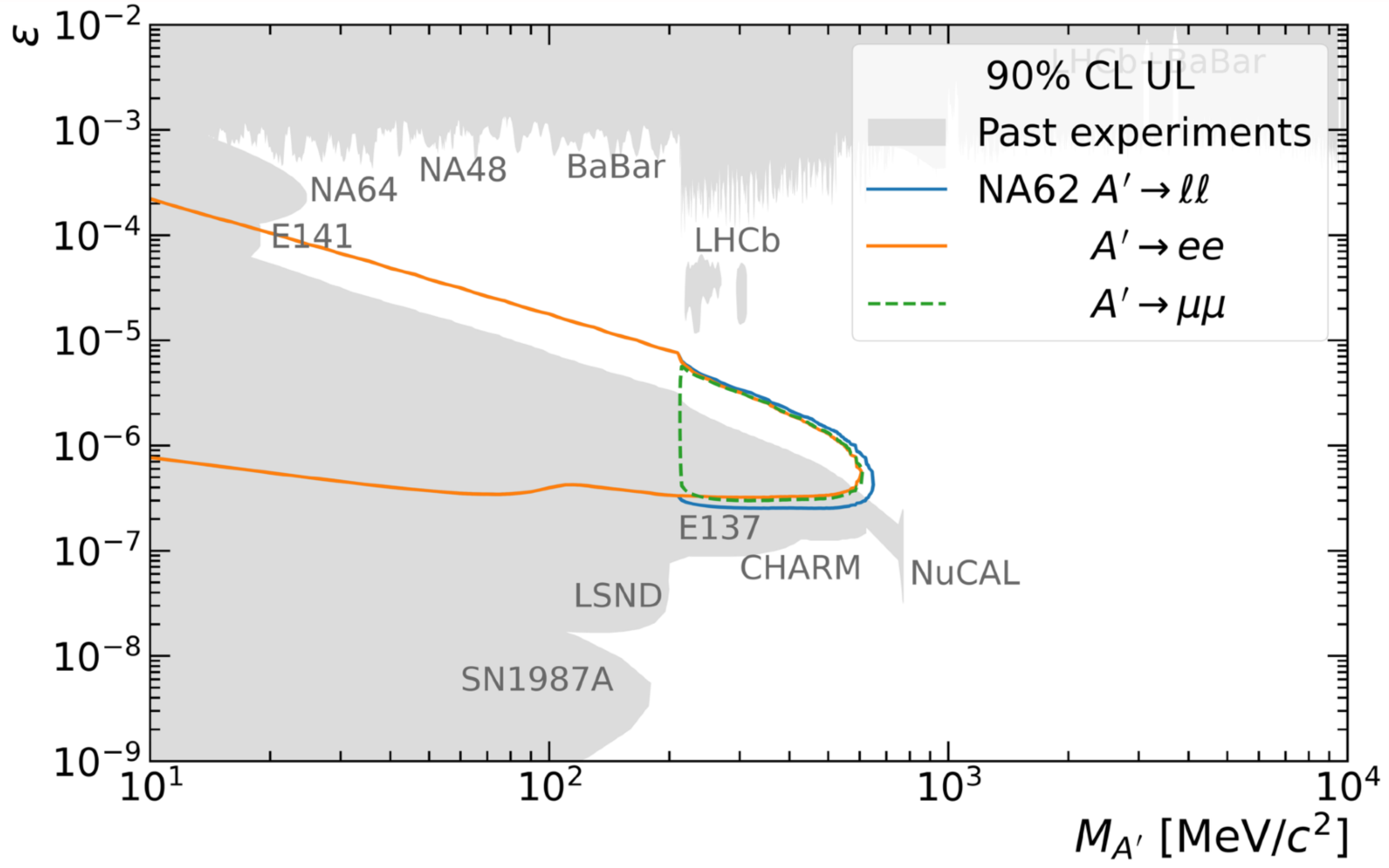
Search for DP in NA62 beam dump

Two production mechanisms are in action in proton-nucleus interaction scenario:

1. **Bremsstrahlung production: pN→A′X**
2. **Meson-mediated production: pN→MX, M→A′γ (π⁰, η), where M = π⁰, η⁽′⁾, ρ, ω, etc.**



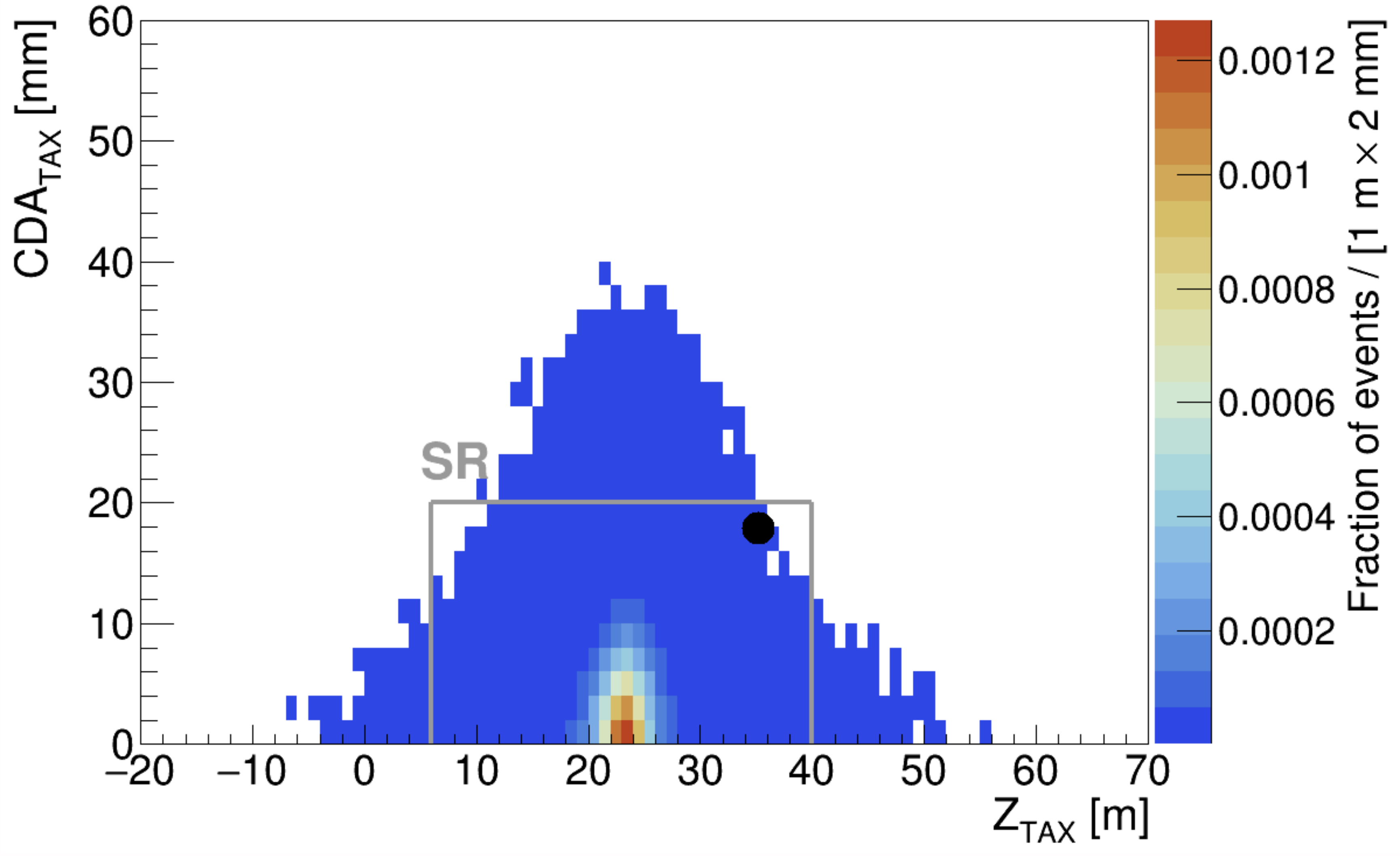
Sensitivity per production mechanism assuming 0 observed events in 1.4×10¹⁷ POT

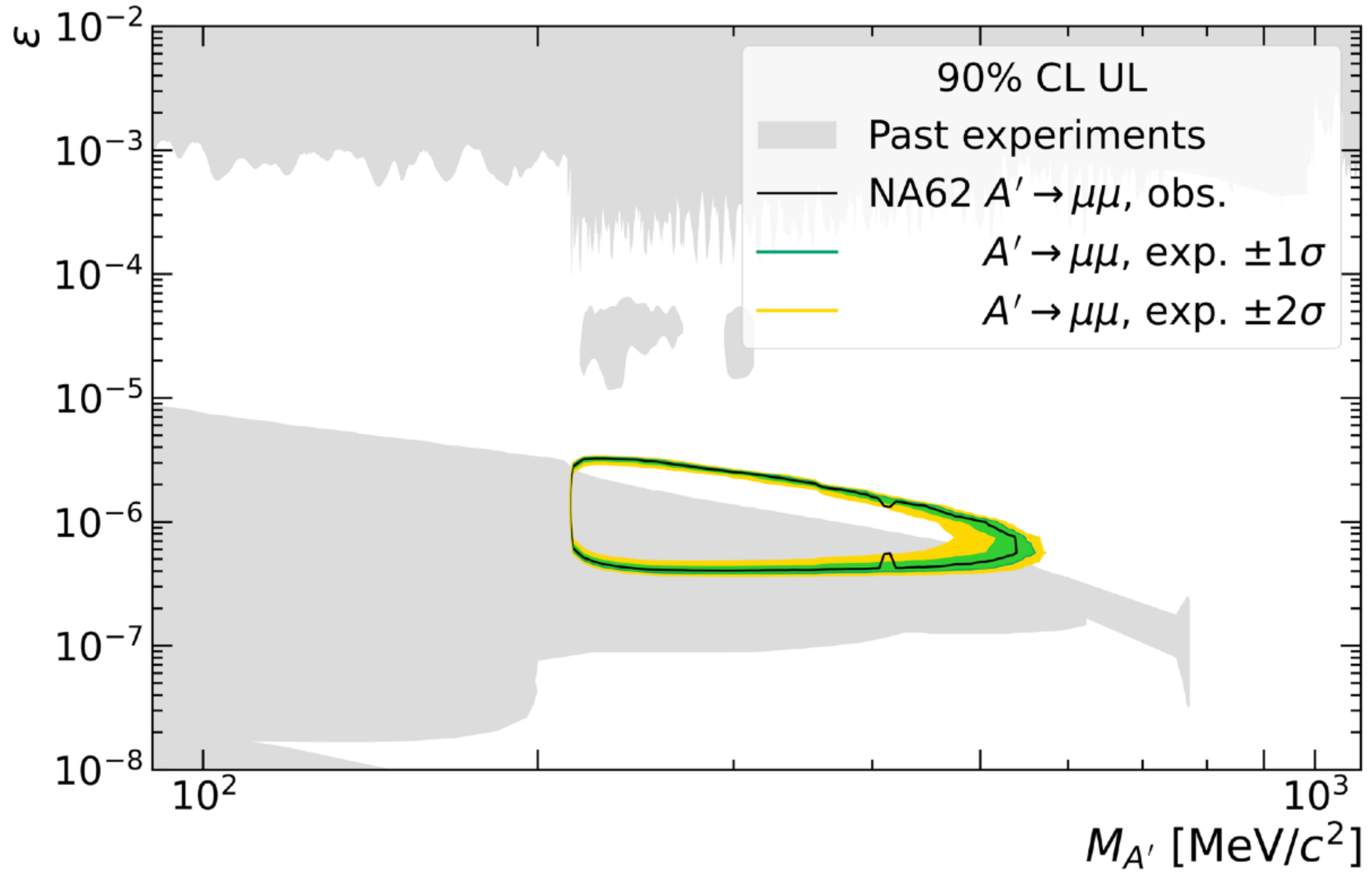


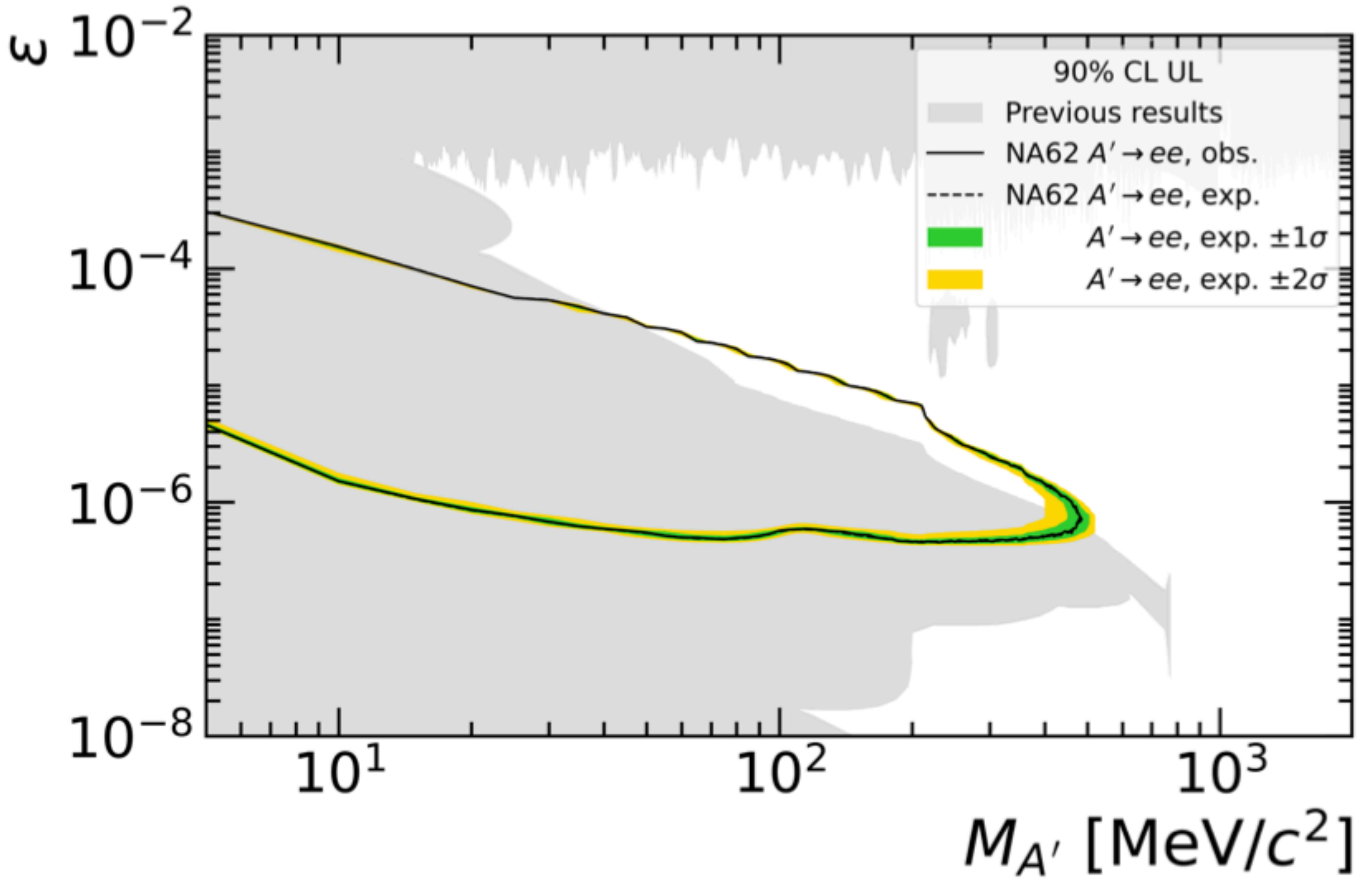
Sensitivity per decay mode assuming 0 observed events in 1.4×10¹⁷ POT

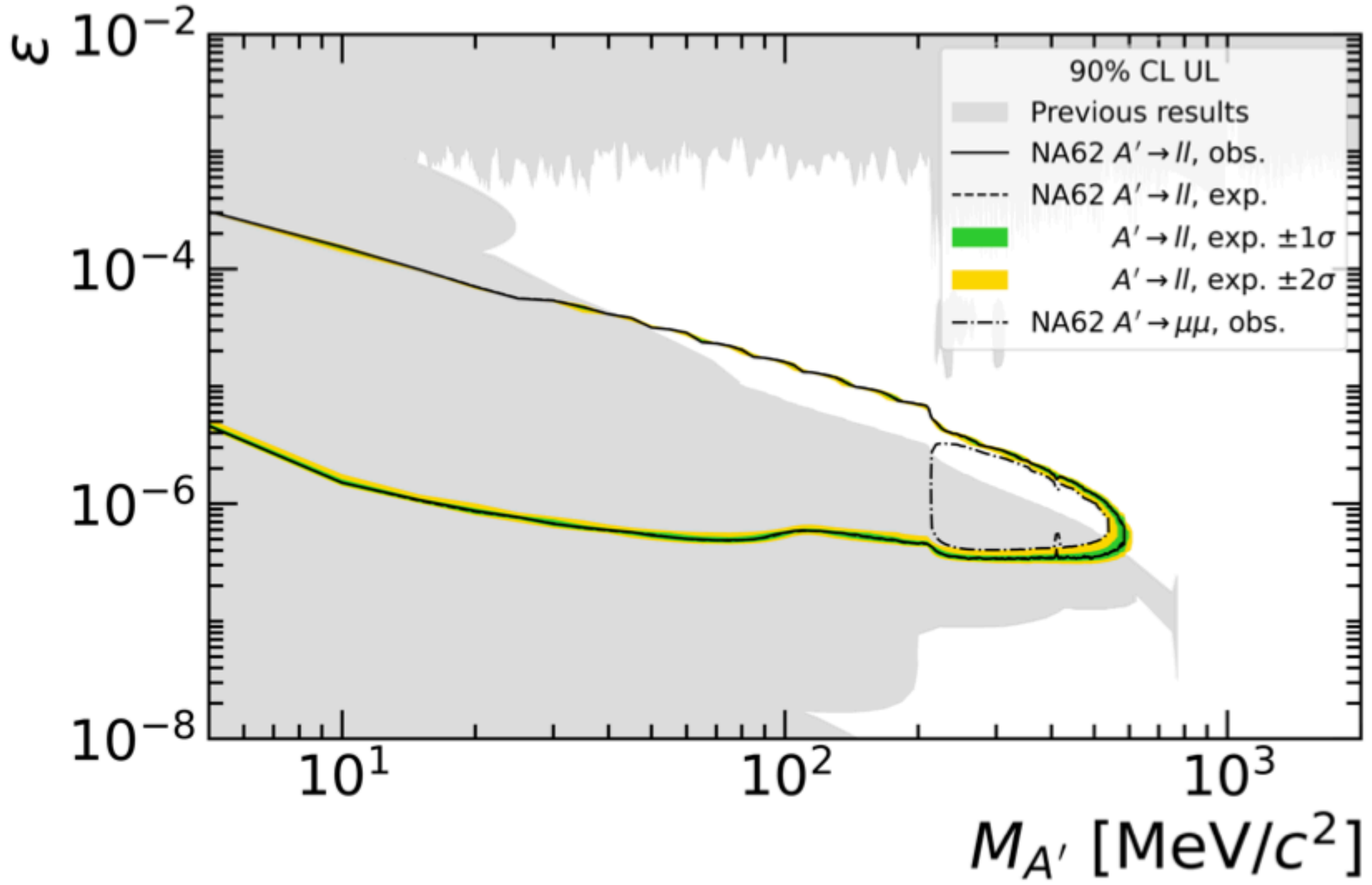
Results for $A' \to \ell^+\ell^-$

JHEP 09, 035 (2023)
arXiv:2312.12055









$A' \to \mu^+\mu^-$ N_{obs}= 1 (2.6 σ global significance)

$A' \to e^+e^-$ N_{obs}= 0

Model New Physics searches in hadronic decays

Numerous possibilities for exotic particle X being a dark photon (DP), dark scalar (DS), axion-like particle (ALP), ...

Decay

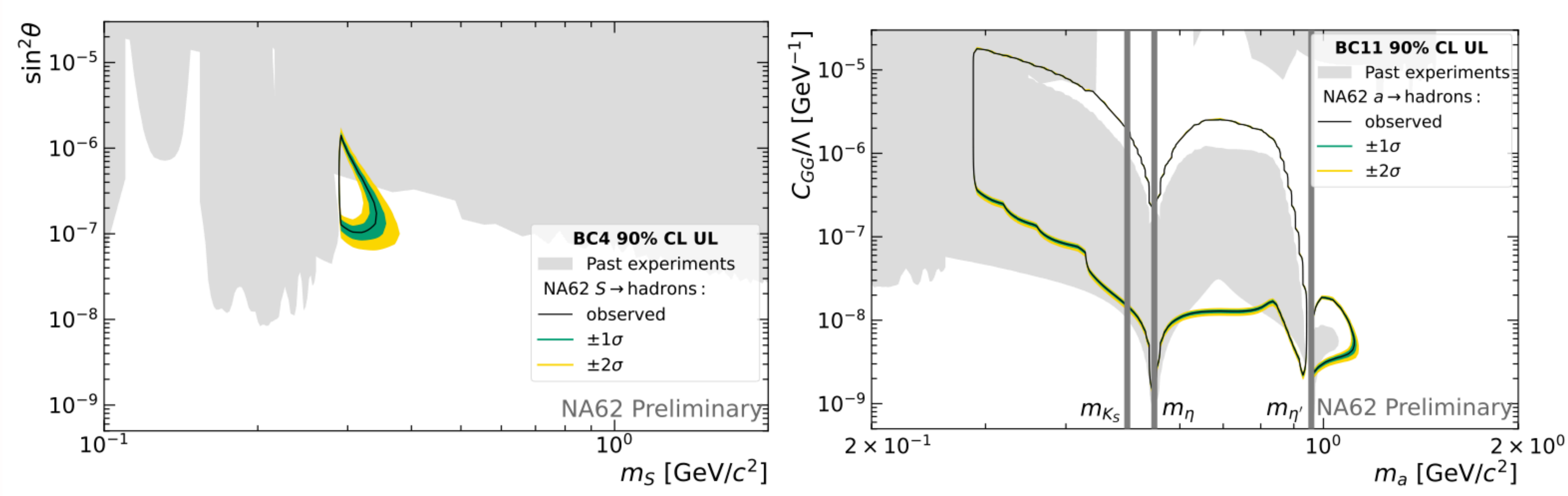
Decay modes		
DP	DS	ALP
$\pi^+\pi^-$	$\pi^+\pi^-$	$\pi^+\pi^-\gamma$
$\pi^+\pi^-\pi^0$		$\pi^+\pi^-\pi^0$
$\pi^+\pi^-\pi^0\pi^0$	$\pi^+\pi^-\pi^0\pi^0$	$\pi^+\pi^-\pi^0\pi^0$
		$\pi^+\pi^-\eta$
K^+K^-	K^+K^-	
$K^+K^-\pi^0$		$K^+K^-\pi^0$

Production

- **ALP: Primakoff (on and off.shell), mixing with** $P = \{\pi^0, \eta, \eta'\}, B^{\pm,0} \rightarrow K^{\pm,0,(*)}a$
- **DP: Bremsstrahlung, decay of PS and V particles** $P \rightarrow A'\gamma, V \rightarrow A'P \ \ (V = \{\rho, \omega, \phi\}\ and\ (P = \{\pi^0, \eta, \eta'\})$
- **DS:** $B^{\pm,0} \rightarrow K^{\pm,0,(*)}S$

Altogether 36 combinations of production and decay channels studied

Results and interpretation



0 event observed in the all the control and signal regions

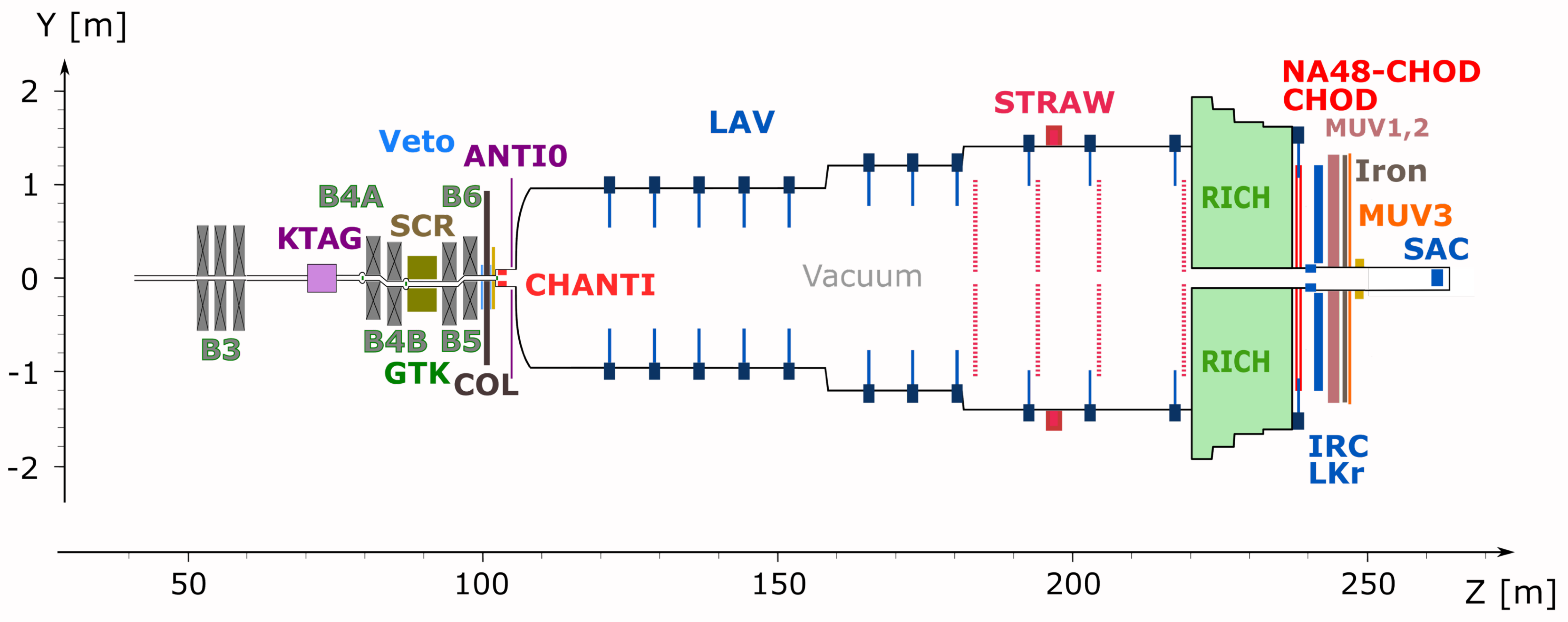
Summary

- $K^+ \to \pi^+ \gamma\gamma$
  - Results consistent with previous measurements
  - Improved precision, by a factor > 3, statistically dominated
  - ChPT $O(p^4)$ is not sufficient to describe data
  - First search for ALP with gluon coupling in $K^+ \to \pi^+ a, a \to \gamma\gamma$ decays
- $\pi^0 \to e^+ e^-$ (new preliminary):
  - Precision comparable with previous measurements, statistically dominated
  - Full agreement with the latest theoretical expectations
- LFV/LNV searches:
  - Presented U.L. on $K^+ \to \mu^- \nu e^+ e^+$ decay
  - NA62 performed the first search for the $K^+ \to \pi^0 \pi \mu e$ process
- $A' \to \ell^+ \ell^-$ and X → hadrons:
  - Blind analyses to search for exotic particle decays $A' \to \ell^+ \ell^-$ and X → hadrons have been performed on the data collected in 2021 exploring new regions of parameter space

Stay tuned!!!

Backup

Detector overview in beam dump mode



Sweeping

- B3 a triplet of magnetization-satured dipole magnets
- SCR a toroidally-magnetized iron collimator
- B5 and B6 magnets

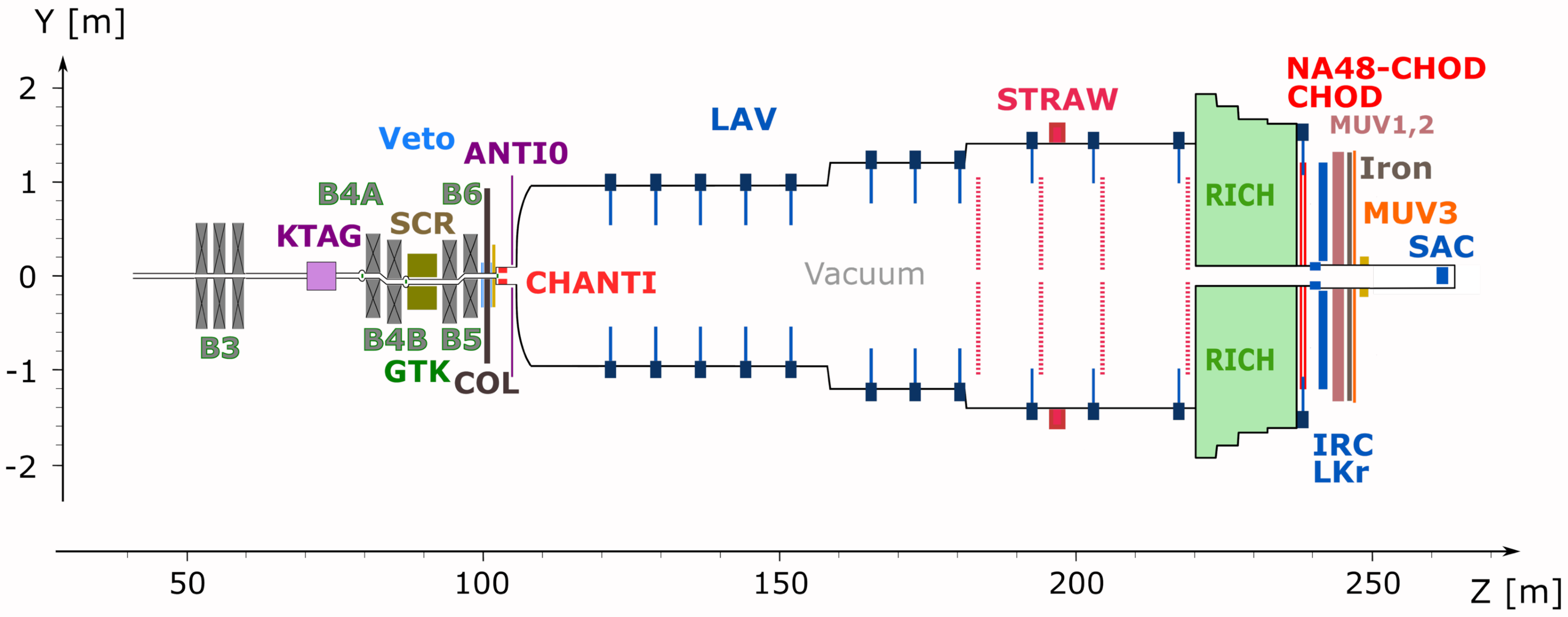
Upstream

- COL cleaning collimator
- ANTI0 scintillator hodoscope

Downstream

- STRAW spectrometer for momentum and direction measurements
- LKr, LAV, IRC and SAC photon veto system

Detector overview in kaon mode



Performances

- GTK-KTAG-RICH time resolution $\mathcal{O}(100\,ps)$
- $\mathcal{O}(10^4)$ background suppression from kinematics
- $\mathcal{O}(10^7)$ muon rejection for $15 < p(\pi^+) < 35\ GeV$
- $\mathcal{O}(10^8)$ π rejection for $E(\pi^0) > 40\,GeV$

Resolution

- Spectrometer $\sigma_p/p = (0.30 \oplus 0.005 \times p)\,\%$ [GeV/c]
- CHOD and NewCHOD resolution of 600 and 200 ps
- LKr $\sigma_E/E = (4.8/\sqrt{E} \oplus 11/E \oplus 0.9)\,\%$ [GeV]

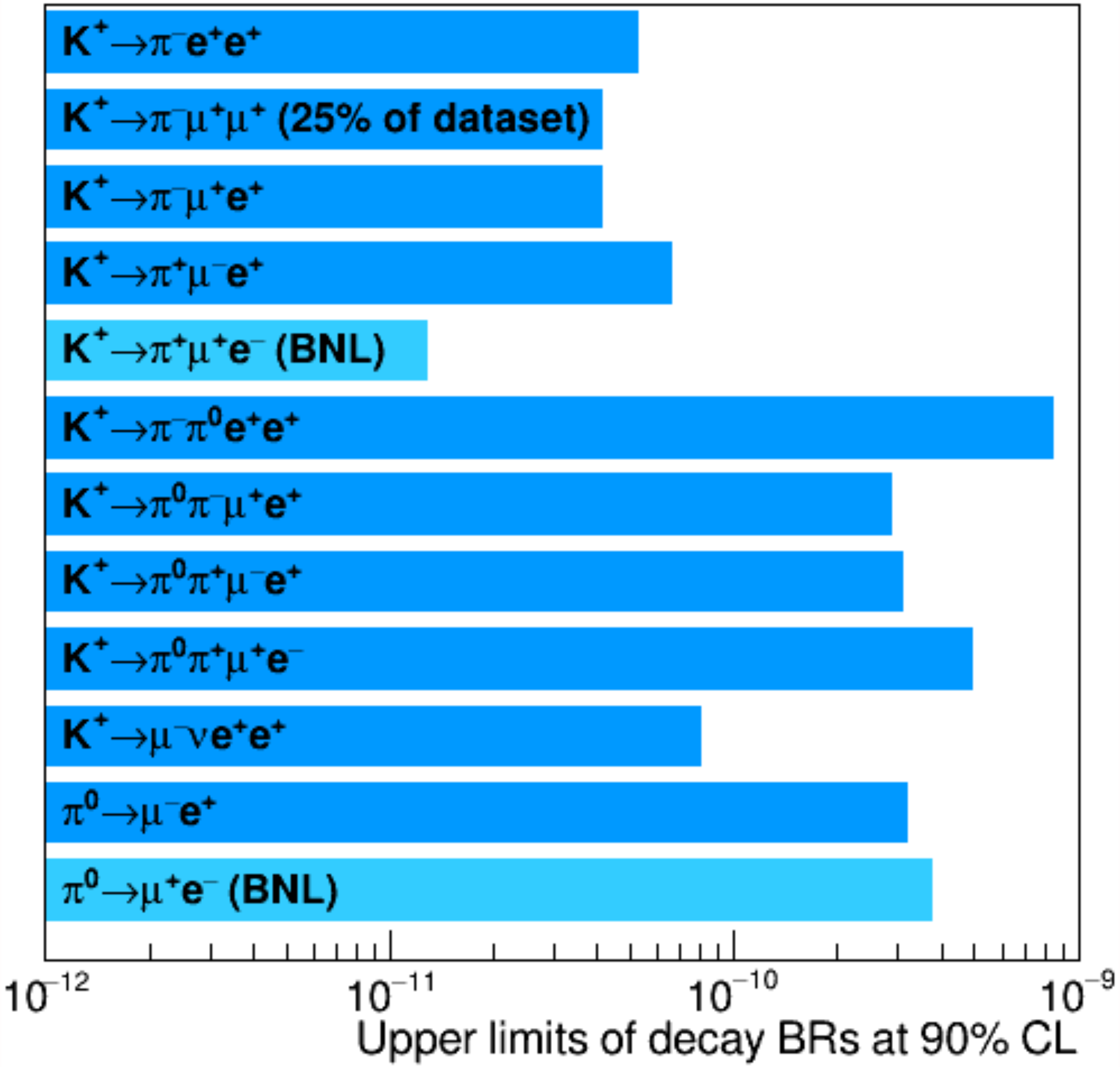
$K^+ \to \pi^+\gamma\gamma$ decay: event selection and bkg

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

Use beam tracker GTK and Spectrometer to measure z variable

- Cluster merging in LKr
  - $K^+ \to \pi^+\pi^0\gamma, \pi^0 \to \gamma\gamma$
  - $K^+ \to \pi^+\pi^0\pi^0, \pi^0 \to \gamma\gamma$ decays
- Multitrack events with tracks out of the Spectrometer acceptance
  - $K^+ \to \pi^+\pi^+\pi^-$ decay (main contribution due to large branching fraction)
- To validate background model: use control regions with enhanced background and check Data/MC agreement

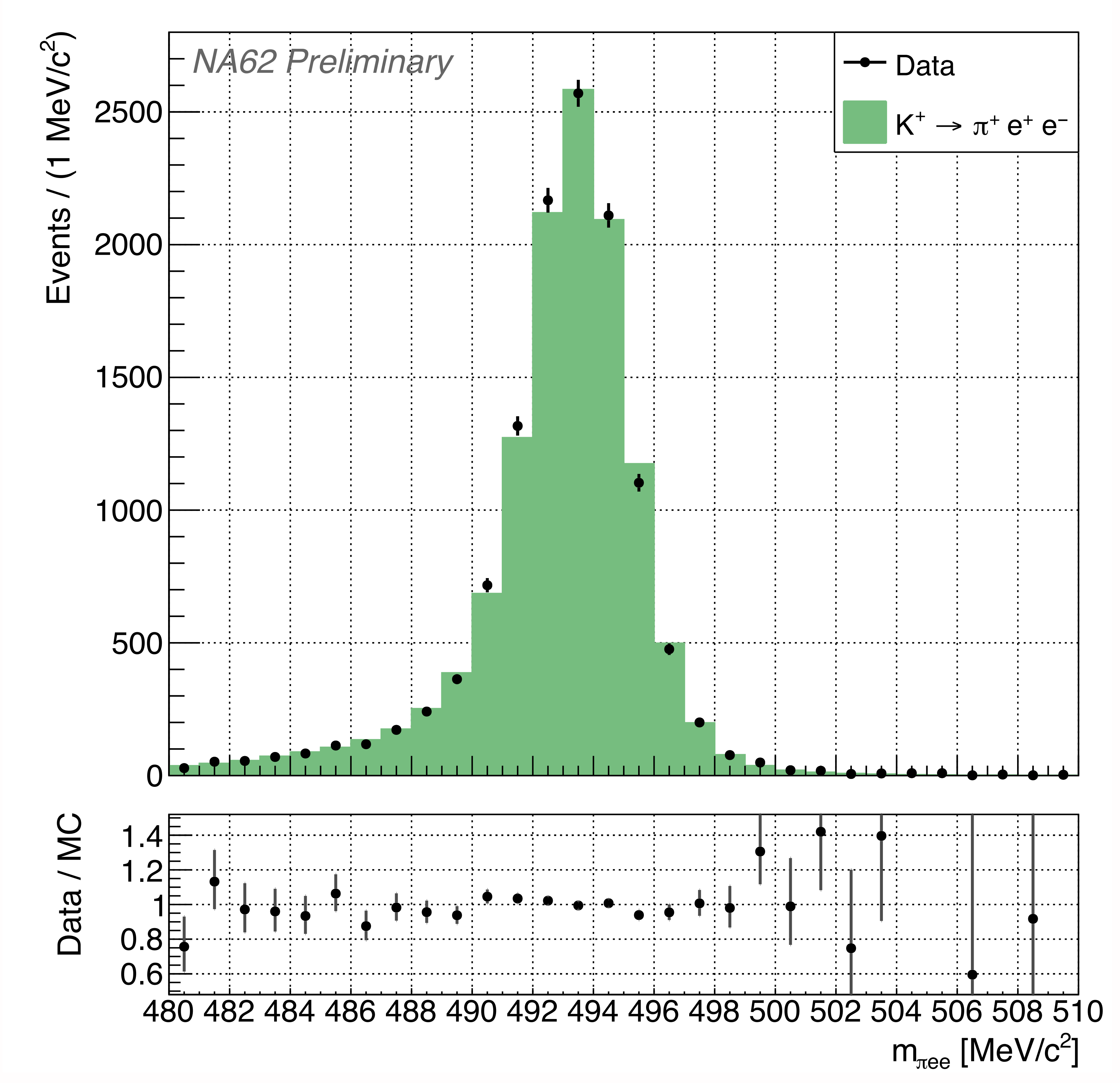
LFV/LNV K⁺ and π^0 decays: state of the art

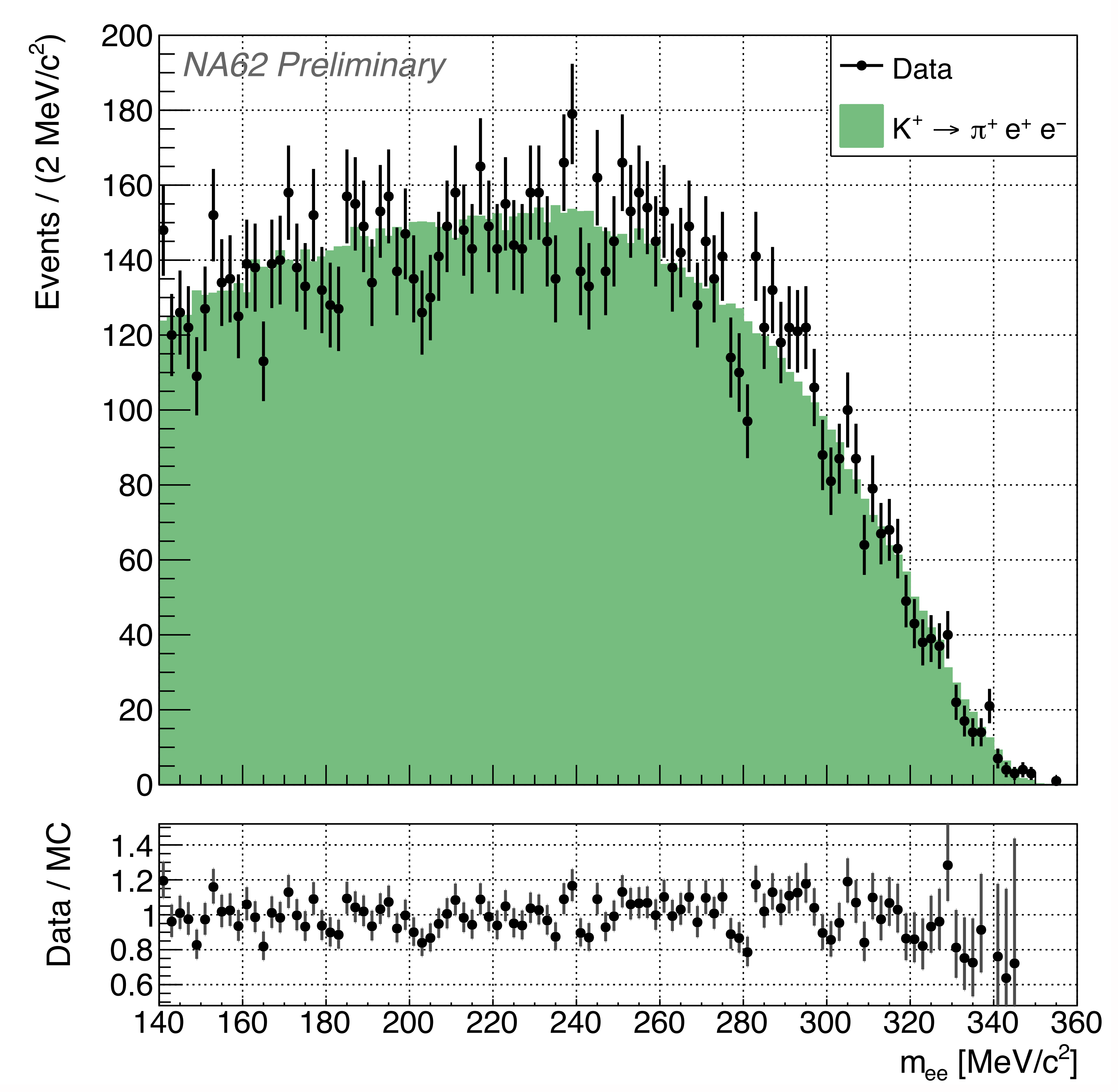


$\pi^0 \to e^+e^-$ decay: normalisation sample

Preliminary

- ➡ Multi-track electron **trigger line**
- ➡ **Signal** decay chain: $K^+ \to \pi^+\pi^0, \pi^0 \to e^+e^-$
- ➡ **Normalisation:** $K^+ \to \pi^+e^+e^-$ decay selecting region $m_{ee} > 140$ MeV (8.62×10^{11} kaon decays collected)





Benchmarks and production mechanism

BC4

New scalar singlet S, so-called dark scalar (DS) which, below to electroweak symmetry breaking scale, mixes with the SM H boson. In the minimal scenario this mixing is parametrised by an angle

$$sin\theta_S = \frac{\mu v}{m_H^2 - m_S^2}$$

Where $v = 256\,GeV$ is the EW vacuum expectation value, $m_H = 125\,GeV$ is the mass of the physical H boson and μ is the coupling parameter parametrising the strength of the corresponding portal.

Production

The most efficient production mechanism of DS at a fixed target experiment is in the FCNC decays of heavy flavour mesons

$$B \to K^{(*)} S$$

BC11

The third benchmark model is the BC11, an axion-like particle (ALP) a coupled to SM gluons in a dimension 5 portal

$$\mathscr{L}_{ALP} \supset g_s^2 \frac{C_{gg}}{\Lambda} a G^{i,\mu\nu} \tilde{G}^i_{\mu\nu}$$

Where $G_{i,\mu\nu}$ is the gluon field strength tensor, $\tilde{G}_{i,\mu\nu}$ is its dual and g_s is the strong coupling constant. The strength of the coupling is fixed by the ratio C_{gg}/Λ involving the energy scale Λ of the UV completion.

Production

On of the production mechanism of ALPs at a fixed target experiment is in the FCNC decays of heavy flavour mesons

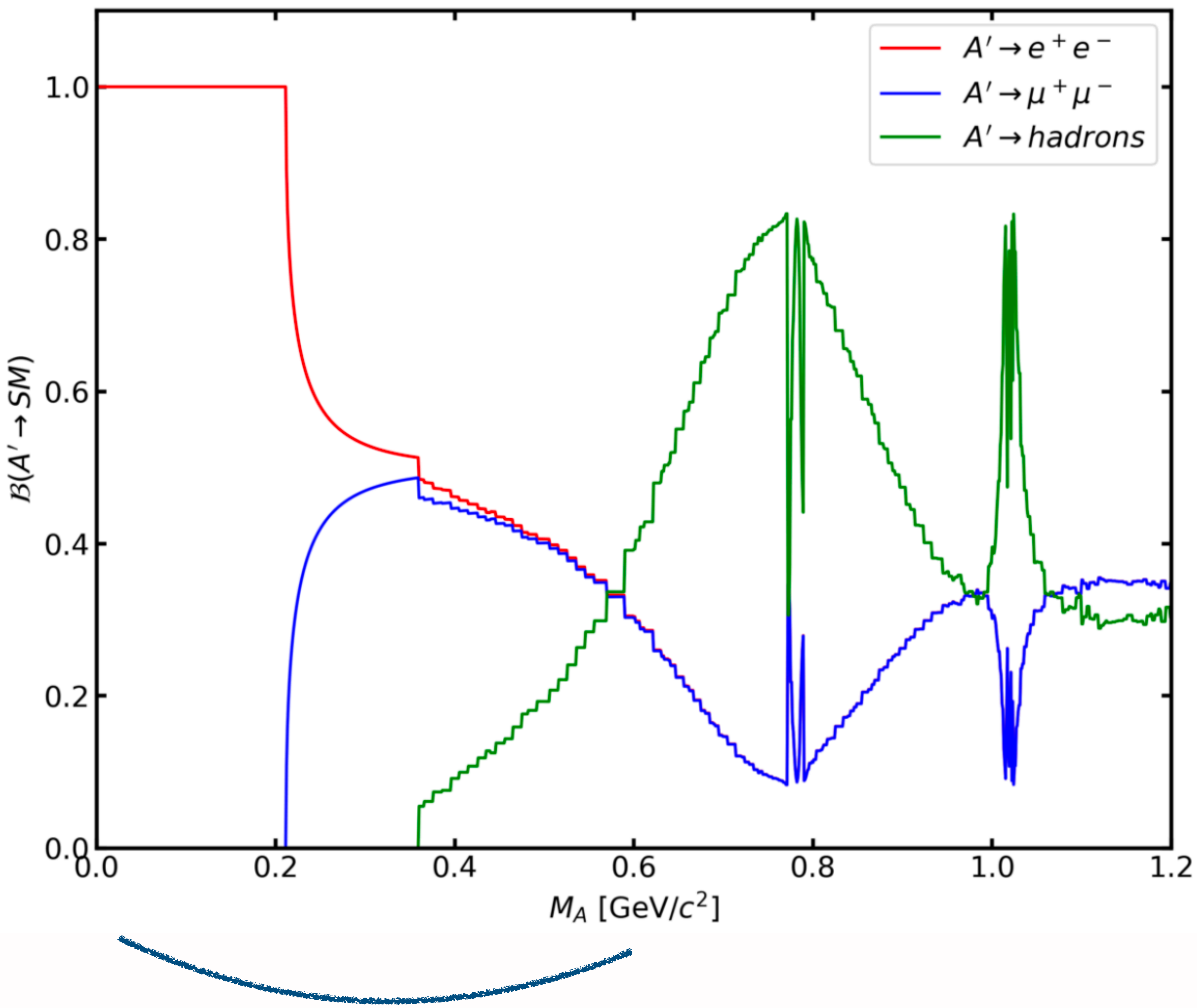
At lower ALPs mass the Primakoff like effect is dominant

Dark photon: a detailed view

- New vector field $F'_{\mu\nu}$ symmetric under a new U(1) symmetry feebly interacting with the SM fields
- A minimal extension to the SM: kinetic mixing with the SM hypercharge

$$-\frac{\epsilon}{2}F'^{\mu\nu}B_{\mu\nu}$$

M(A′) and ε are free parameters



Decay width dominated by lepton antilepton final states for M(A′)< 700 MeV

DP searches in $\ell^+\ell^-$ final states

JHEP 09, 035 (2023)
arXiv:2312.12055

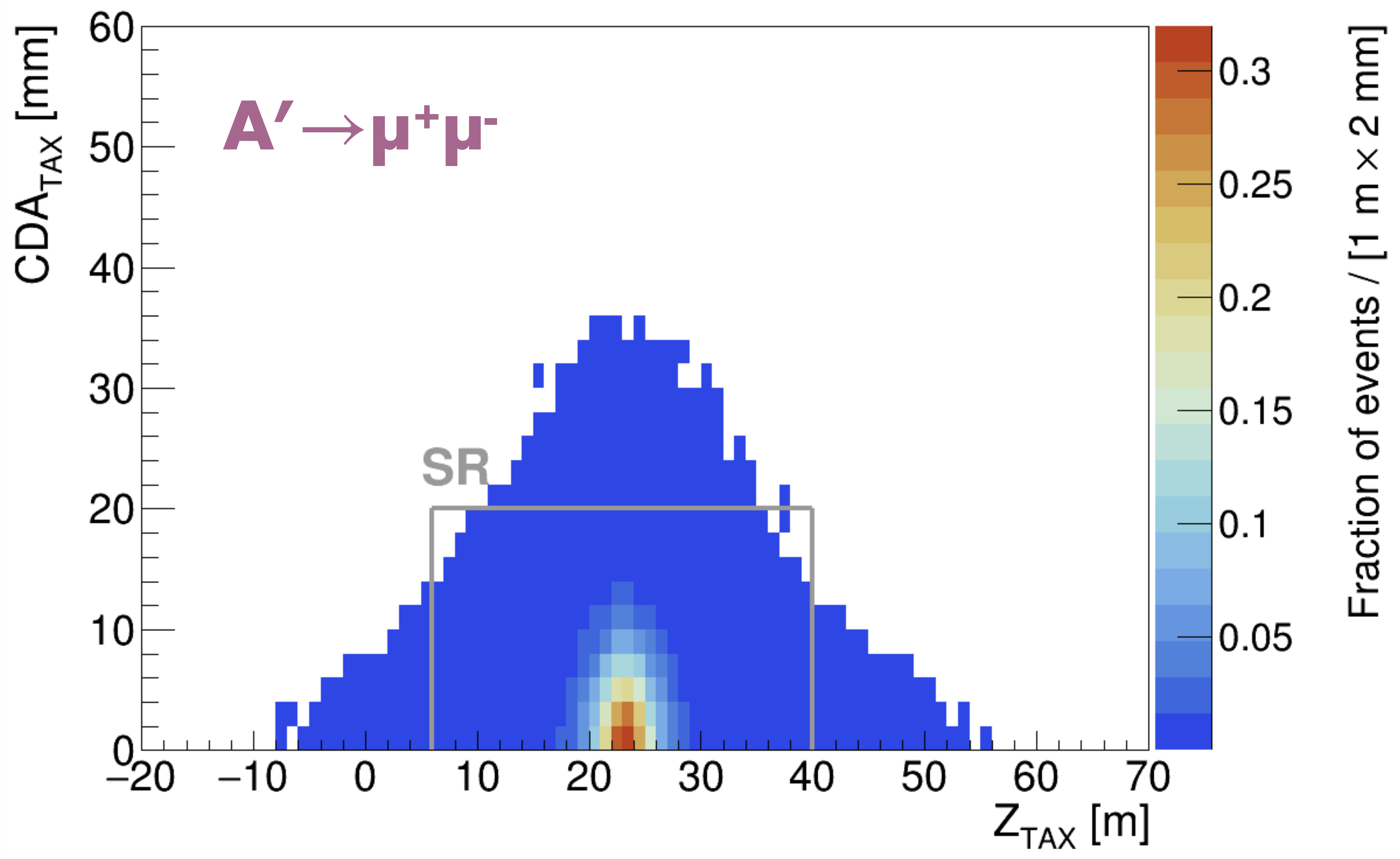
Signal signature

- $\ell^+\ell^-$ vertex in the NA62 fiducial volume
- Primary production vertex close to the proton TAX interaction point

Event selection

- Good quality tracks with timing in coincidence with each other and the trigger
- PID with LKr and MUV3
- In e^+e^- analysis: decay region & PID optimization and no in-time activity in muon veto detector MUV3
- No in-time activity in LAV (and ANTI0 in e^+e^-)
- Signal region (SR) selection (redefinition of SR for e^+e^-)

Signal region is kept blinded till the analysis freezing



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

Z_{TAX} longitudinal position $\sigma_Z \sim 5.5\,m$

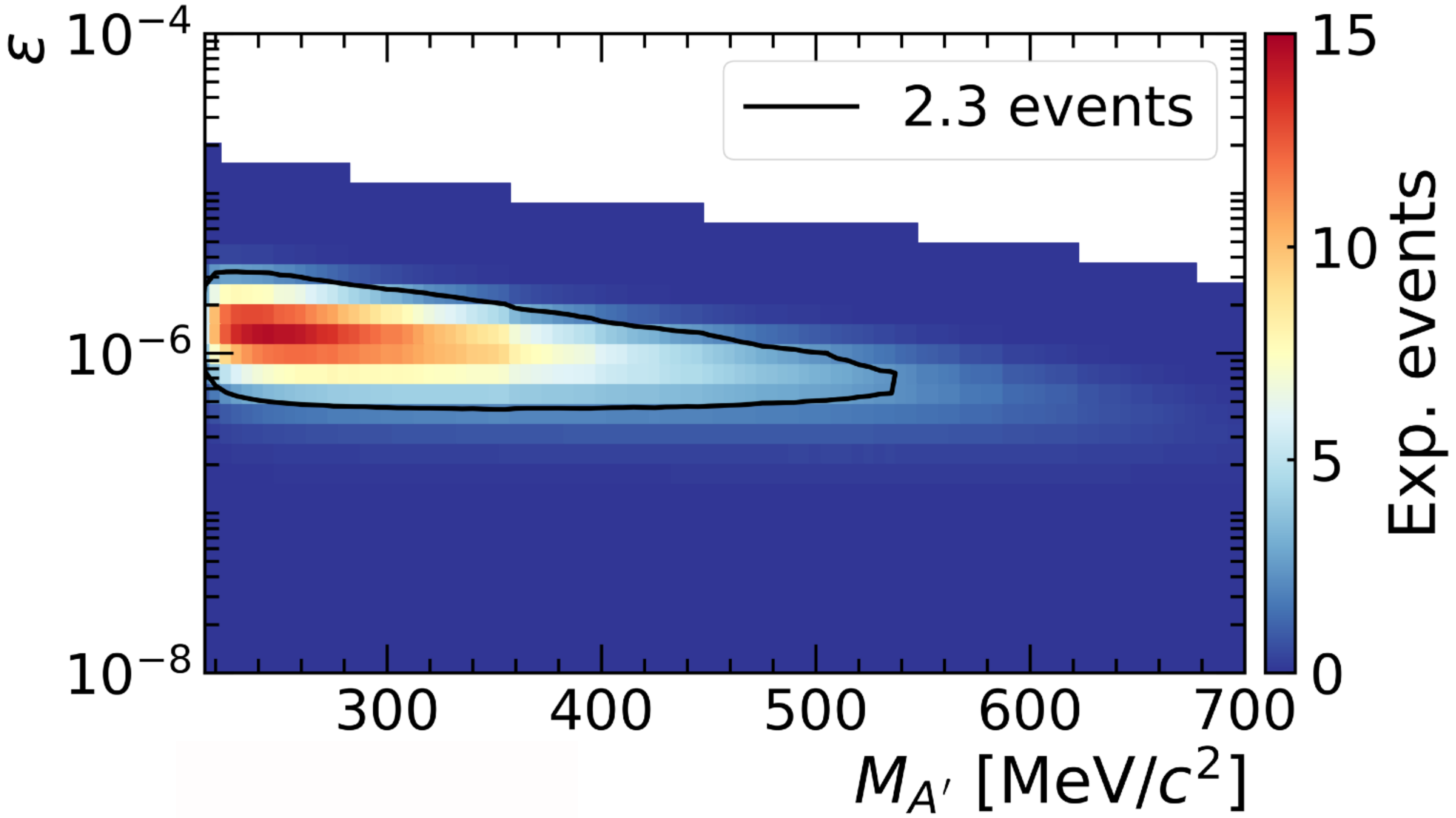
Expected yield on $A' \to \ell^+\ell^-$

JHEP 09, 035 (2023)
arXiv:2312.12055

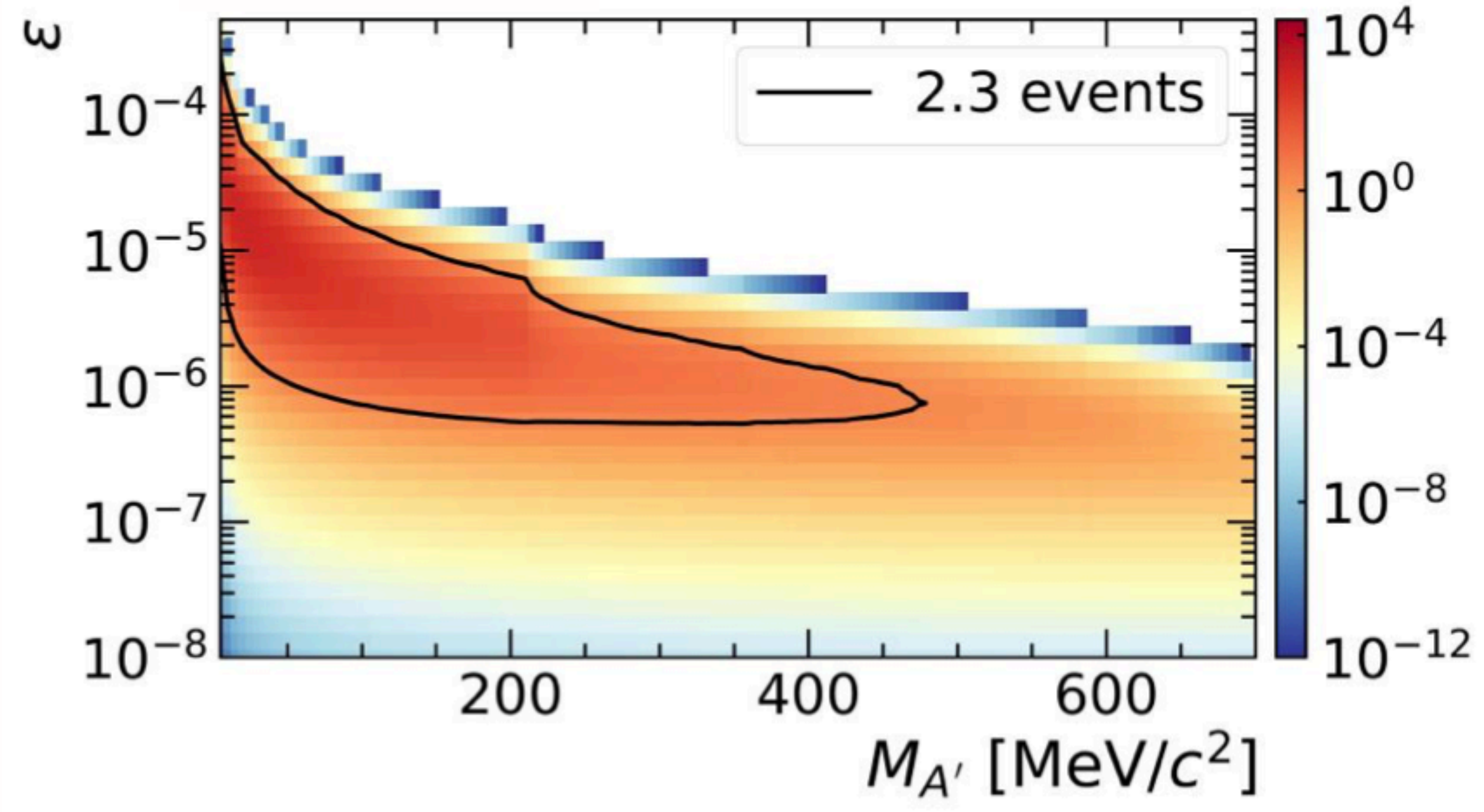
$$N_{exp} = POT \times P(pN \to A') \times \mathcal{B}(A' \to \ell^+\ell^-) \times P_D \times A_{sel}$$

- POT = $1.40 \pm 0.28 \times 10^{17}$, proton on target collected in 2021
- $P(pN \to A')$ DP production probability
- $\mathcal{B}(A' \to \ell^+\ell^-)$ decay branching fraction
- P_D probability for DP to reach the NA62 fiducial volume and decay therein
- A_{sel} signal selection and trigger efficiencies

A′→μ⁺μ⁻



A′→e⁺e⁻



Background studies

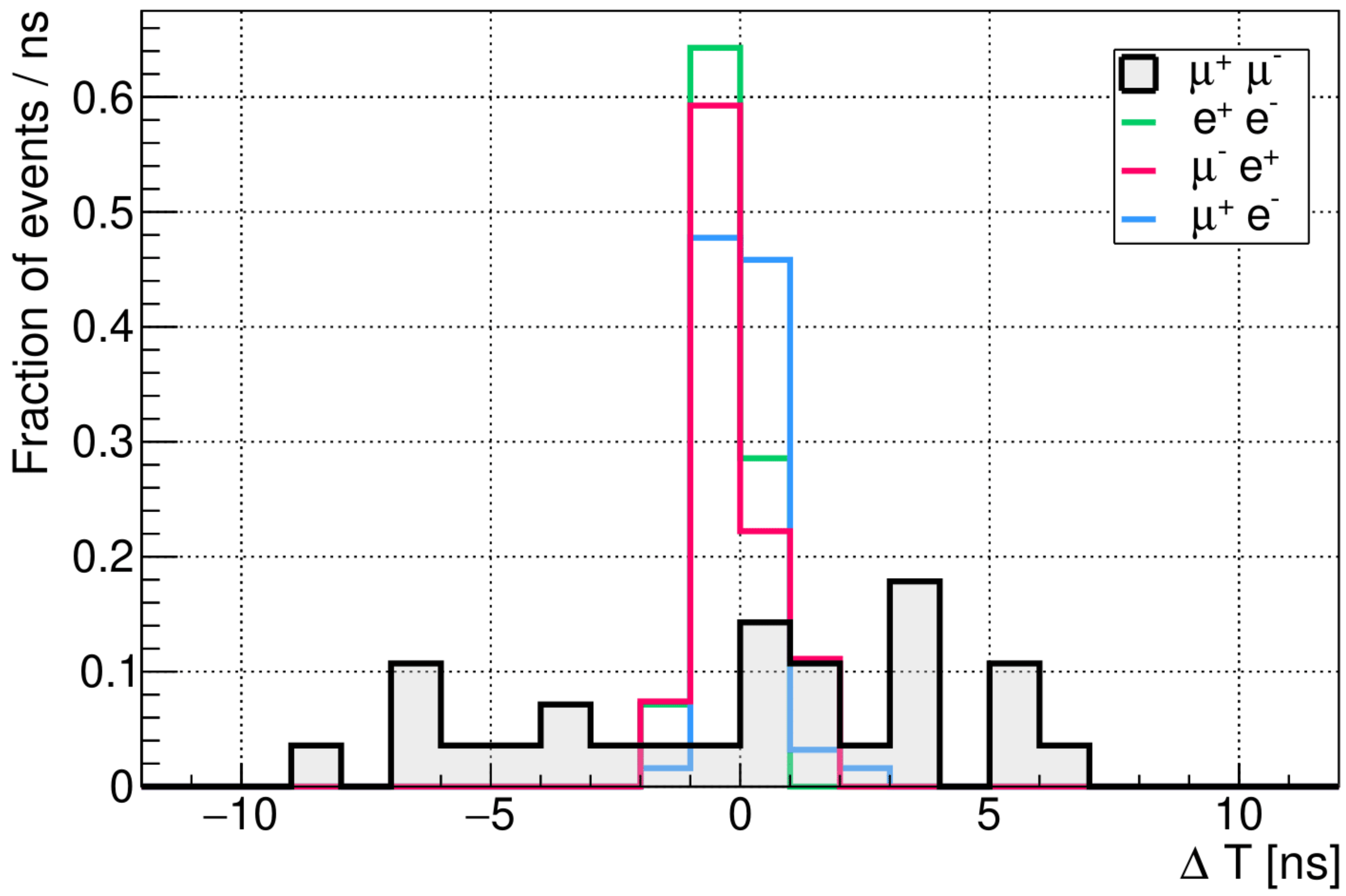
The main expected backgrounds can be divided in two categories

Combinatorial background:

- Random superposition of two uncorrelated "halo" muons
- Dominant for $A' \to \mu^+\mu^-$

Prompt background:

- Secondary interactions of incoming muons with the material traversed
- Dominant for for $A' \to e^+e^-$

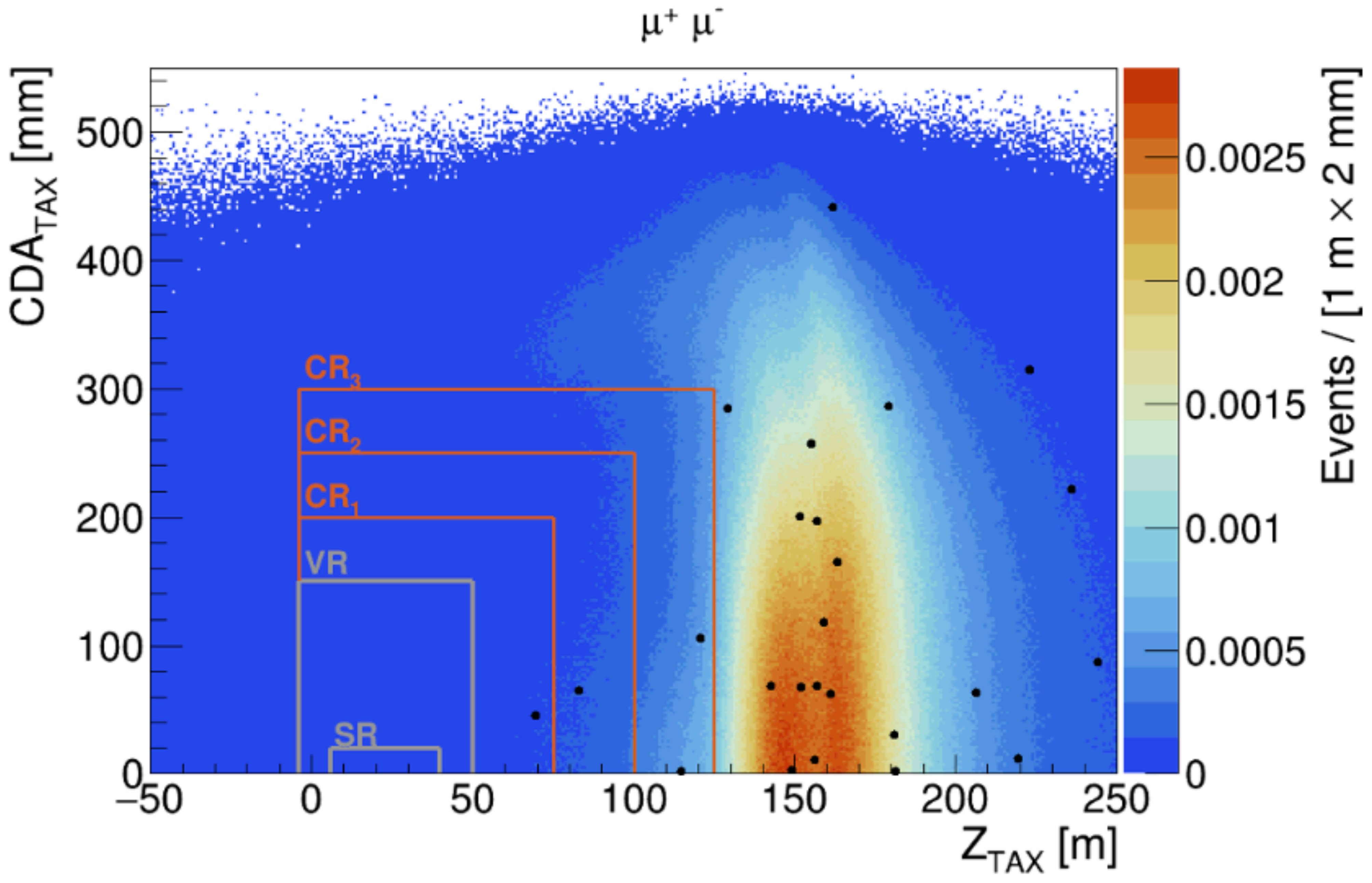


Background summary

JHEP 09, 035 (2023)
arXiv:2312.12055

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

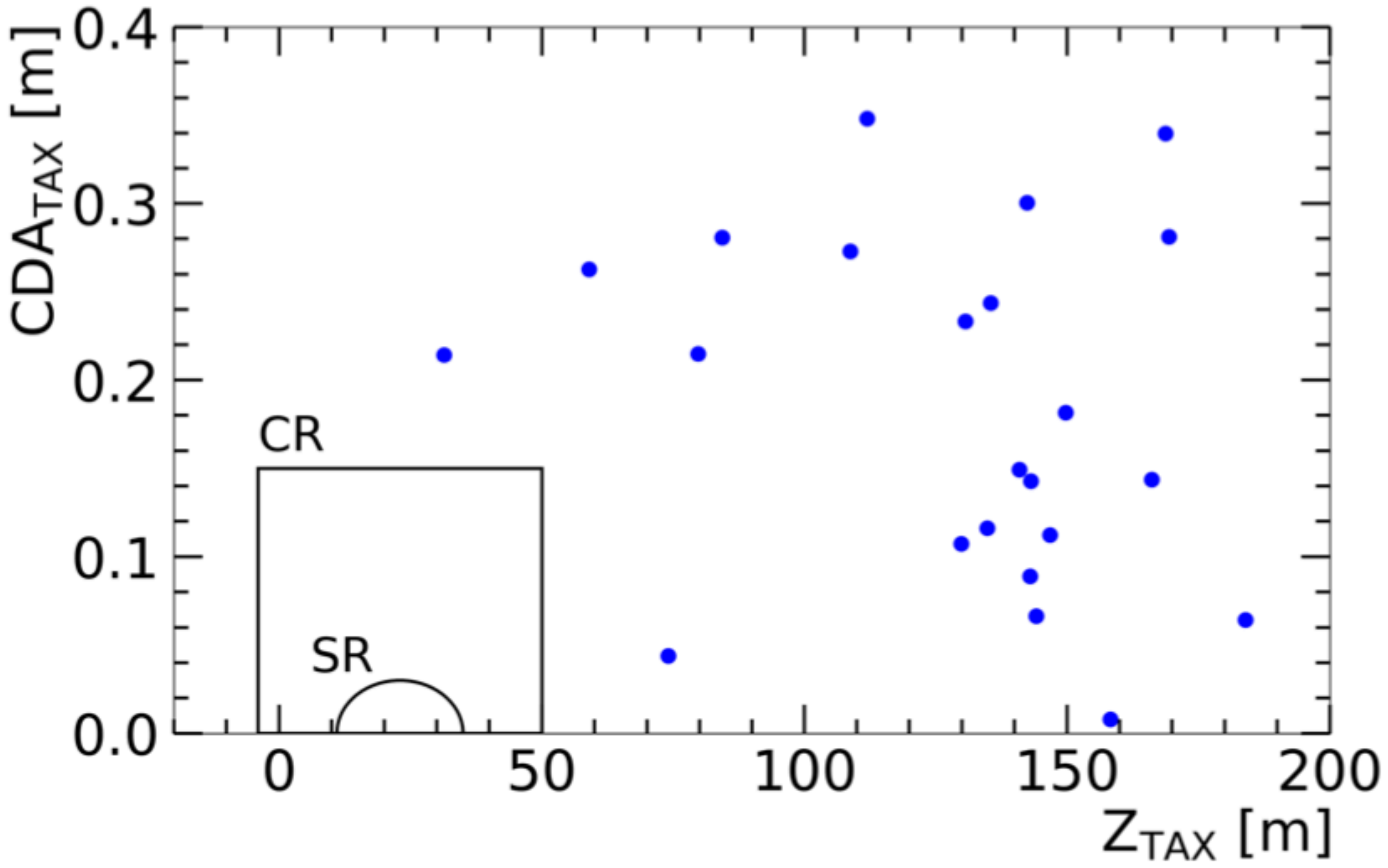
	Combinatorial	Prompt @90% C.L.	Upstream prompt @90% C.L
Validation Region	0.17 ± 0.02	< 0.004	< 0.069
Signal Region	0.016 ± 0.002	< 0.0004	< 0.007



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

$$N^{CR}_{bkg} = 0.0097^{+0.049}_{-0.009} @ 90\% C.L.$$

$$N^{SR}_{bkg} = 0.0094^{+0.049}_{-0.009} @ 90\% C.L.$$



$A' \to \ell^+\ell^-$ statistical analysis

- The exclusion limits are dirived using the CLs method on a grid of A′ mass and coupling values
- The test statistic is the profiled likelihood ratio

$$q = -2\ln\frac{L_{s+b}}{L_b}$$

computed by maximising separately the numerator and the denominator with respect to the nuisance parameters: the number of protons on TAX, the expected number of background events in SR and for L_{s+b} the expected signal yield.

- After unmasking, no events were observed in the validation region. The probability of a non-zero observation is 15%.
- After unmasking, one event was observed in the signal region. In the absence of a dark photon signal, the probability of a non-zero observation is 1.6%. The two-track invariant mass of the observed event is 411 MeV/c^2.
- A limit on the number of signal event counts is obtained using Poisson statistics with negligible background, accounting for the uncertainty on the number of protons on target (POT) using a Bayesian nuisance parameter.
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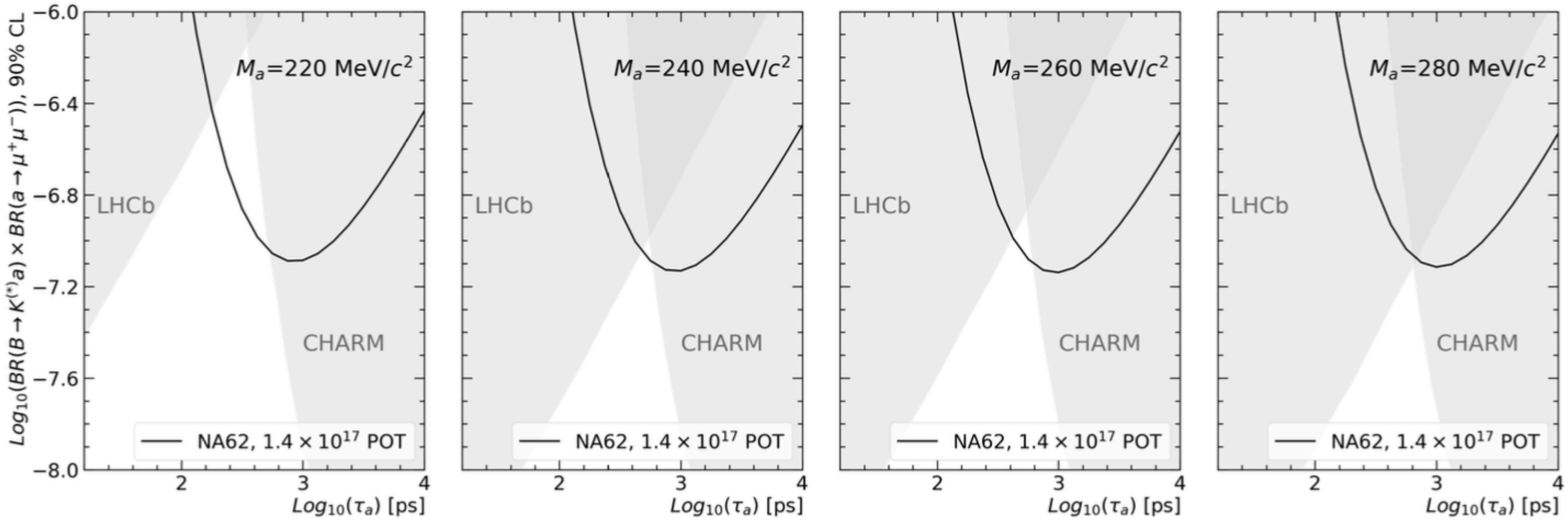
Model independent limit for $a \to \mu^+\mu^-$

JHEP 09, 035 (2023)
arXiv:2312.12055

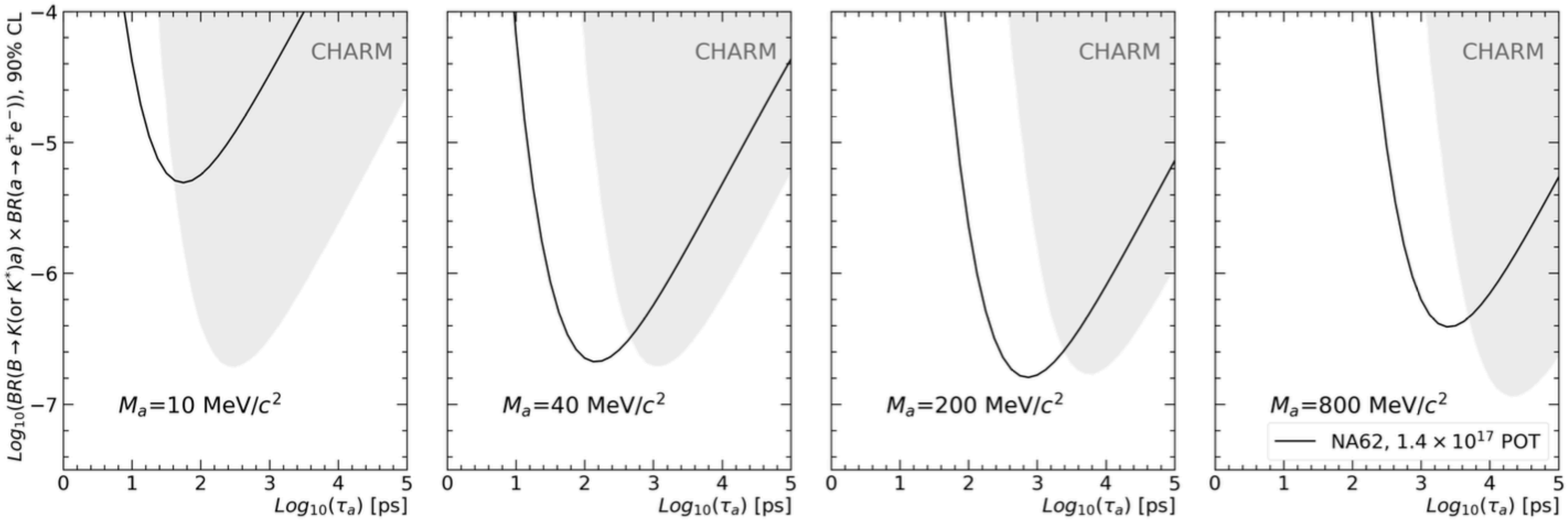
- The result is interpreted in terms of the emission of axion-like particles in a model-independent approach. [Phys. Lett. B 790 (2019) 537]
- Set limits in $BR(B \to K^*a) \times BR(a \to \mu^+\mu^-)$ vs. τ_a parameter space for each mass separately
- The result is found to improve on previous limits for masses below 280 MeV/c².



Model independent limit for $a \to e^+e^-$

JHEP 09, 035 (2023)
arXiv:2312.12055

- ➡ The result is interpreted in terms of the emission of axion-like particles in a model-independent approach. [Phys. Lett. B 790 (2019) 537]
- ➡ Set limits in $BR(B \to K^*a) \times BR(a \to e^+e^-)$ vs. τ_a parameter space for each mass separately

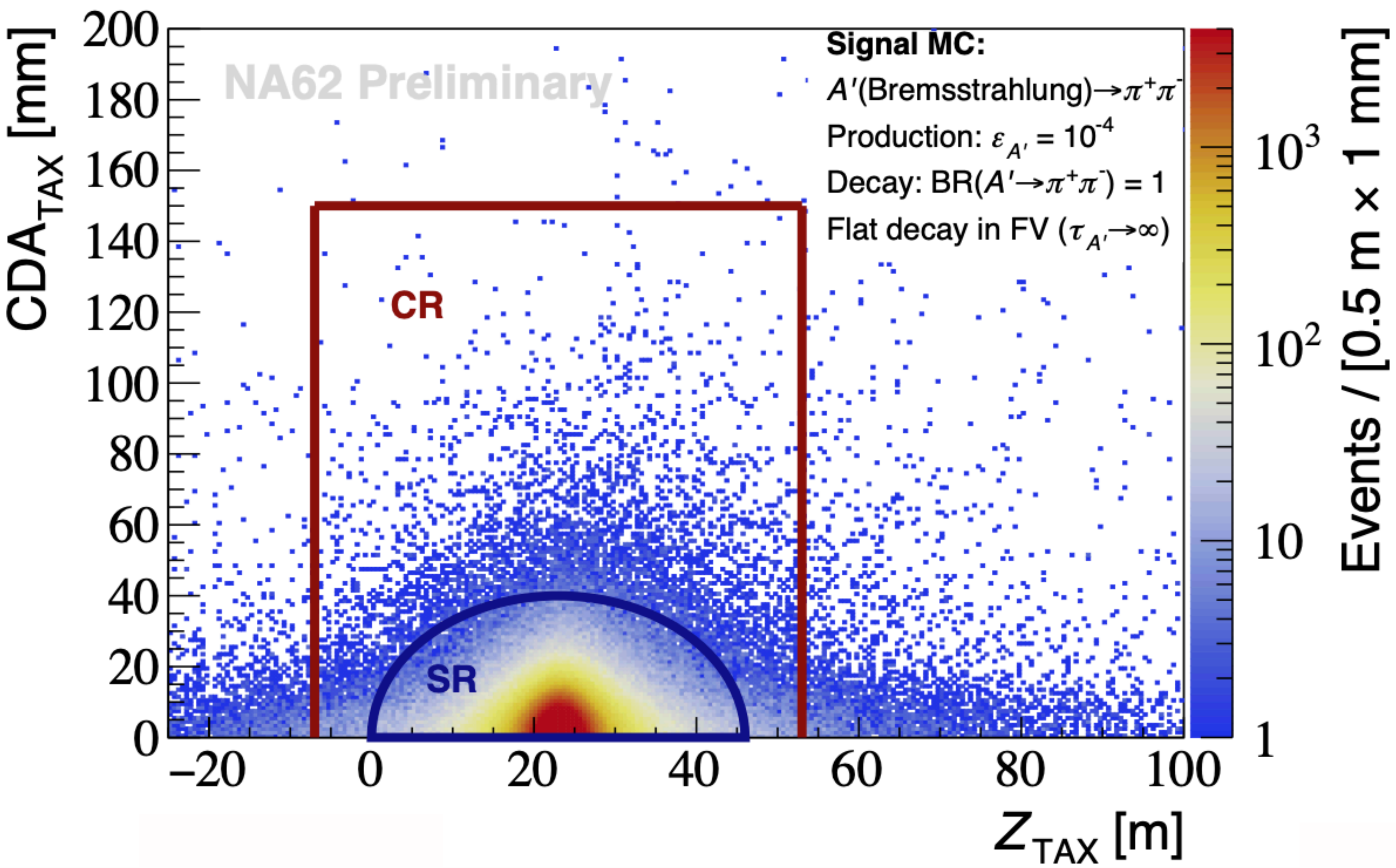


DP to hadrons

Analysis strategy

2 hadronic track selection:

- 2 good quality tracks in coincidence with each other and with the trigger
- **BDT particle ID** selecting hadrons (calo. and MUV3), RICH used for tagging K
- No in-time activity in LAV, SAV and ANTI0
- decay vertex reconstructed in FV



Search strategy:

- Search **neutral clusters** in LKr and reconstruction of γ, π^0, η based in time and opening angle
- Vertex reconstructed from final states is in the NA62 decay region and pointing back to the proton beam interaction point at the TAX.

Signal efficiency and expected yield

In model-independent case $X \to \pi^+\pi^- (BR(X \to \pi^+\pi^-) = 1)$:

$$N_{exp}(M_X, \Gamma_X) = POT \times \chi_{pp\to X}(C_{ref})) \times P_{rd} \times A_{acc} \times A_{trig}$$

- where $\chi_{pp\to X}(C_{ref})$ is X production probability for reference coupling
- P_{rd} is the probability to reach NA62 FV and decay therein
- $A_{acc} \times A_{trig}$ is the product between the signal selection and the trigger efficiencies

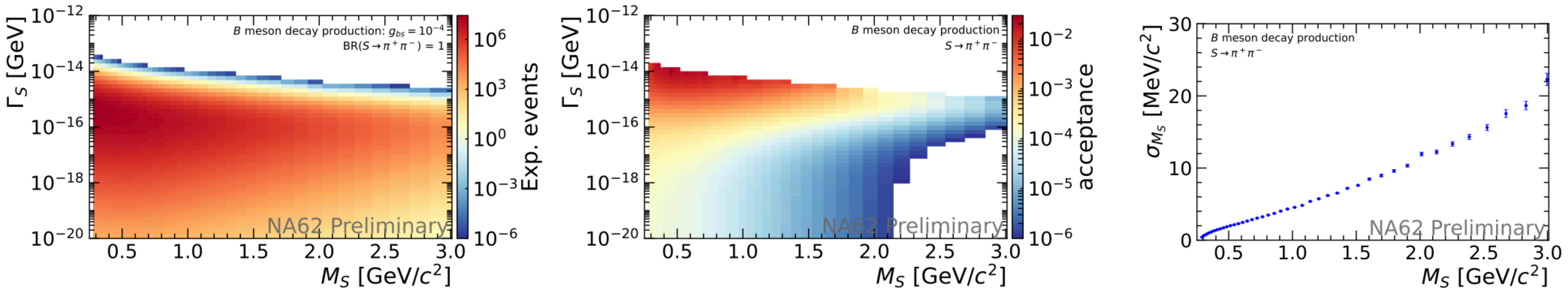


Figure: Left: expected $S \to \pi^+\pi^-$ yield after full selection, assuming $g_{bs} = 10^{-4}$ and BR = 1. Center: acceptance after full selection for exotic particles that reached the FV and decayed therein. Right: Mass resolution of the reconstructed exotic particle.

Distributions obtained for 36 combinations of production and decay channels

Total background estimation

Background estimations with MC:

- combinatorial and neutrino-induced backgrounds: negligible contributions
- prompt background: inelastic interaction of halo muons can produce hadrons
- upstream background: formed by particles that are collected by the GTK achromat

Number of background events estimated at 68% CL

Channel	$N_{\text{exp,CR}} \pm \delta N_{\text{exp,CR}}$	$N_{\text{exp,SR}} \pm \delta N_{\text{exp,SR}}$	$N^{p>5\sigma}_{\text{obs,SR}}$	$N^{p>5\sigma}_{\text{obs,SR+CR}}$
$\pi^+\pi^-$	0.013 ± 0.007	0.007 ± 0.005	3	4
$\pi^+\pi^-\gamma$	0.031 ± 0.016	0.007 ± 0.004	3	5
$\pi^+\pi^-\pi^0$	$(1.3^{+4.4}_{-1.0}) \times 10^{-7}$	$(1.2^{+4.3}_{-1.0}) \times 10^{-7}$	1	1
$\pi^+\pi^-\pi^0\pi^0$	$(1.6^{+7.6}_{-1.4}) \times 10^{-8}$	$(1.6^{+7.4}_{-1.4}) \times 10^{-8}$	1	1
$\pi^+\pi^-\eta$	$(7.3^{+27.0}_{-6.1}) \times 10^{-8}$	$(7.0^{+26.2}_{-5.8}) \times 10^{-8}$	1	1
K^+K^-	$(4.7^{+15.7}_{-3.9}) \times 10^{-7}$	$(4.6^{+15.2}_{-3.8}) \times 10^{-7}$	1	2
$K^+K^-\pi^0$	$(1.6^{+3.2}_{-1.2}) \times 10^{-9}$	$(1.5^{+3.1}_{-1.2}) \times 10^{-9}$	1	1

background-free hypothesis not only at $N_{POT} = 1.4 \times 10^{17}$ but also in the future full **Run 2 dataset** of $N_{POT} = 10^{18}$

Background studies

Background estimations with MC:

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Background studies

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Estimation using data-driven backward MC with measured μ halo + unfolding for correct kinematics

MC size equivalent of POT = 1.53 × 1017 (exceeding the data)

$\pi\pi$ outside CR (in ANTI0 acceptance + no vetoes applied):

- N_{exp} = 1.8 ± 1.4 vs N_{obs} = 1 (Upstream region)
- N_{exp}= 0.20 ± 0.15 vs N_{obs}= 1 (FV)

After applying full selection the prompt background expectations in CR and SR are below 10^{-4} in all channels

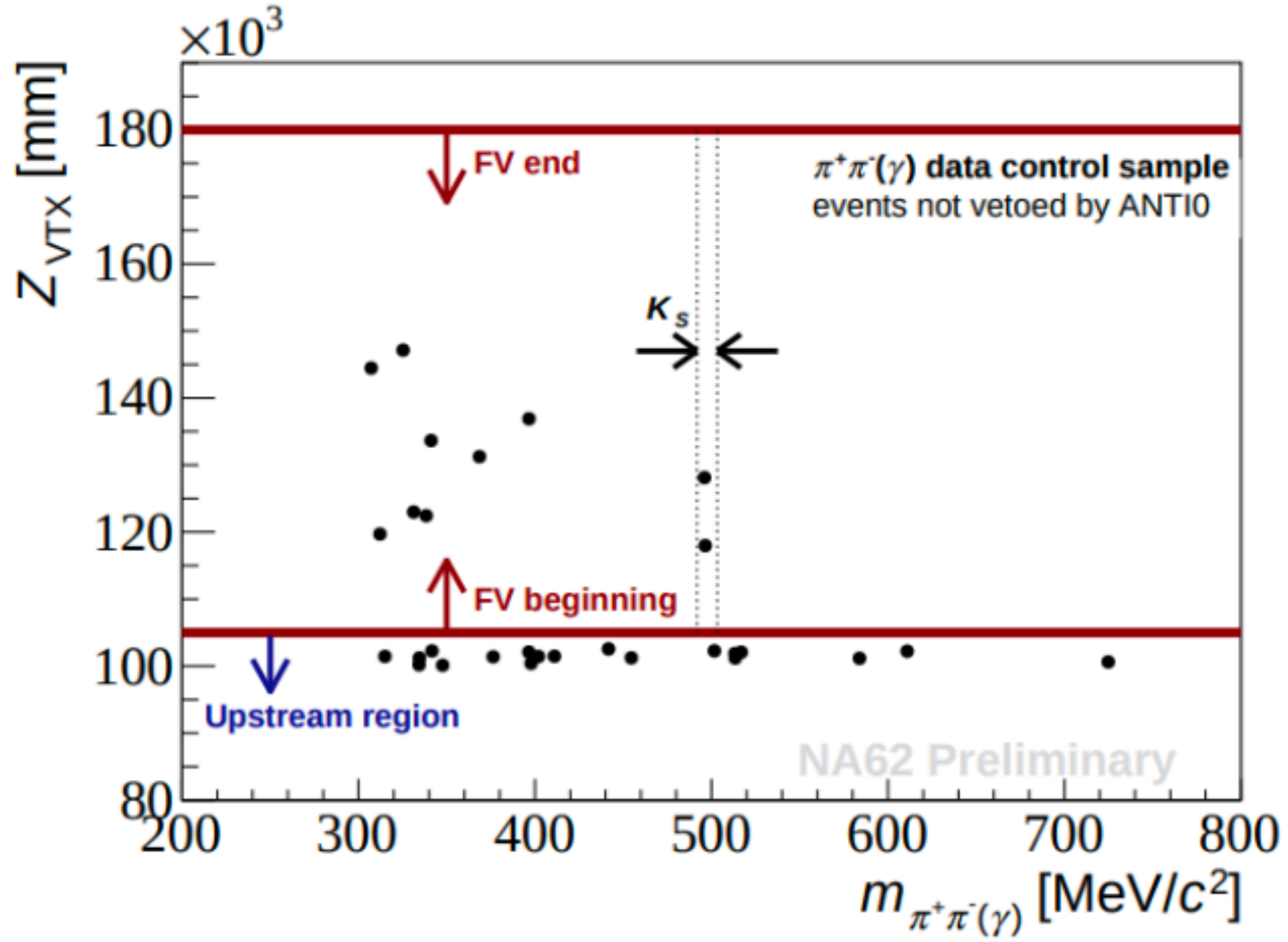
Channel	$N_{\mathrm{exp,CR}} \pm \delta N_{\mathrm{exp,CR}}$	$N_{\mathrm{exp,SR}} \pm \delta N_{\mathrm{exp,SR}}$
$\pi^+\pi^-$	$(5.7^{+18.5}_{-4.7}) \times 10^{-5}$	$(5.5^{+18.0}_{-4.5}) \times 10^{-5}$
$\pi^+\pi^-\gamma$	$(1.7^{+5.3}_{-1.4}) \times 10^{-5}$	$(1.6^{+5.2}_{-1.3}) \times 10^{-5}$
$\pi^+\pi^-\pi^0$	$(1.3^{+4.4}_{-1.0}) \times 10^{-7}$	$(1.2^{+4.3}_{-1.0}) \times 10^{-7}$
$\pi^+\pi^-\pi^0\pi^0$	$(1.6^{+7.6}_{-1.4}) \times 10^{-8}$	$(1.6^{+7.4}_{-1.4}) \times 10^{-8}$
$\pi^+\pi^-\eta$	$(7.3^{+27.0}_{-6.1}) \times 10^{-8}$	$(7.0^{+26.2}_{-5.8}) \times 10^{-8}$
K^+K^-	$(4.7^{+15.7}_{-3.9}) \times 10^{-7}$	$(4.6^{+15.2}_{-3.8}) \times 10^{-7}$
$K^+K^-\pi^0$	$(1.6^{+3.2}_{-1.2}) \times 10^{-9}$	$(1.5^{+3.1}_{-1.2}) \times 10^{-9}$

Background studies

Background estimations with MC:

- combinatorial and neutrino-induced backgrounds: negligible contributions
- prompt background: inelastic interaction of halo muons can produce hadrons
- upstream background: formed by particles that are refocused by the GTK achromat

- 3 upstream background subcomponents observed in the control sample in the $Z_{VTX} - m_{\pi\pi}$ plane:
  - 19 interactions in the region upstream the FV
  - 2 $K_S \to \pi^+\pi^-$ candidates
  - 8 $K^+ \to \pi^+\pi^+\pi^-$candidates, 6 of which identified as $\pi^+\pi^-$and 2 as $\pi^+\pi^-\gamma$
- upstream interactions vetoed by ANTI0 acceptance and vertex location
- for K_S 3σ window (± 5.7 MeV/c²) around m_{K_S} kept masked
- K^+-induced background simulated using selected single track K^+forced to decay as $K^+ \to \pi^+\pi^+\pi^-$ in the FV



Channel	$N_{exp,CR} \pm \delta N_{exp,CR}$	$N_{exp,SR} \pm \delta N_{exp,SR}$
$\pi^+\pi^-$	0.013 ± 0.007	0.007 ± 0.005
$\pi^+\pi^-\gamma$	0.031 ± 0.016	0.007 ± 0.004

Why we don’t have BC1?

After combining all the exotic particle production and decay channels, the expected number of events after full selection for the BC-1 benchmark with the hadronic decays is below one event for all the masses and coupling. Therefore there is no standalone exclusion counter for the hadronic decays at 90% C.L.. Nevertheless, the results of this analysis is expected to improve the overall sensitivity of the NA62 experiment for the BC1.