Search for feebly interacting particles with NA62

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On behalf of the NA62 Collaboration

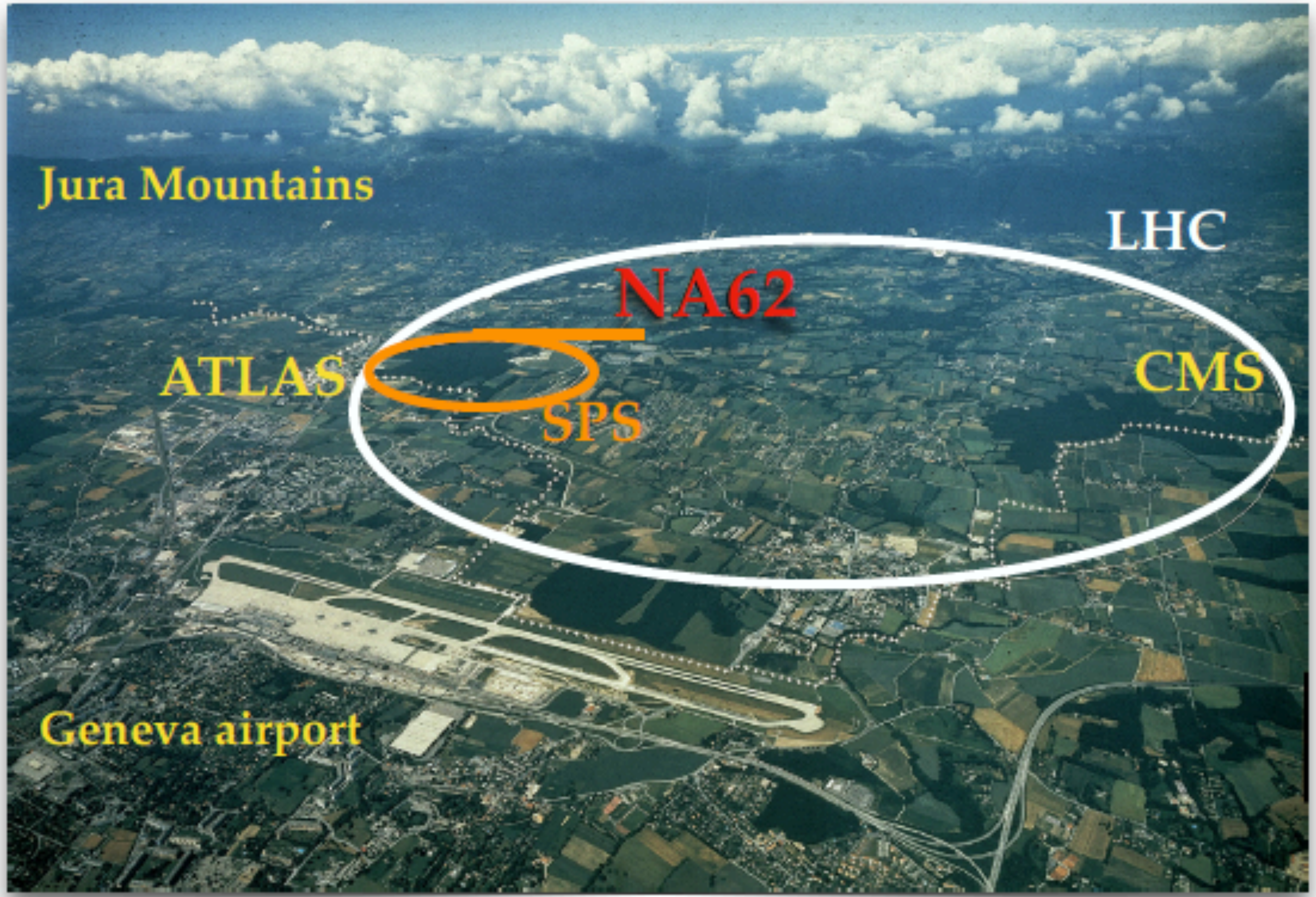
- Short introduction on NA62 experiment
- Three recent results on searches for feebly interacting particles
  - $K^+ \to \pi^+ X$, $X \to$ **invisible** with the full 2016-2018 data
  - $K^+ \to \pi^+ \pi^0$, $\pi^0 \to$ **invisible** with 2017 data
  - $K^+ \to \mu^+ \nu X$, $X \to$ **invisible** with the full 2016-2018 data

PHENO 2021
Pittsburg (US)/virtual, 24 May 2021

NA62 Collaboration

~ 200 participants

Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna (JINR), Fairfax (GMU), Ferrara, Florence, Frascati, Glasgow, Lancaster, Liverpool, Louvain-la-Neuve, Mainz, Moscow (INR), Naples, Perugia, Pisa, Prague, Protvino (IHEP) , Rome I, Rome II, San Luis Potosi, TRIUMF, Turin, Vancouver (UBC)



The main aim is the measurement of

BR(K^+->$\pi^+\nu\nu$)

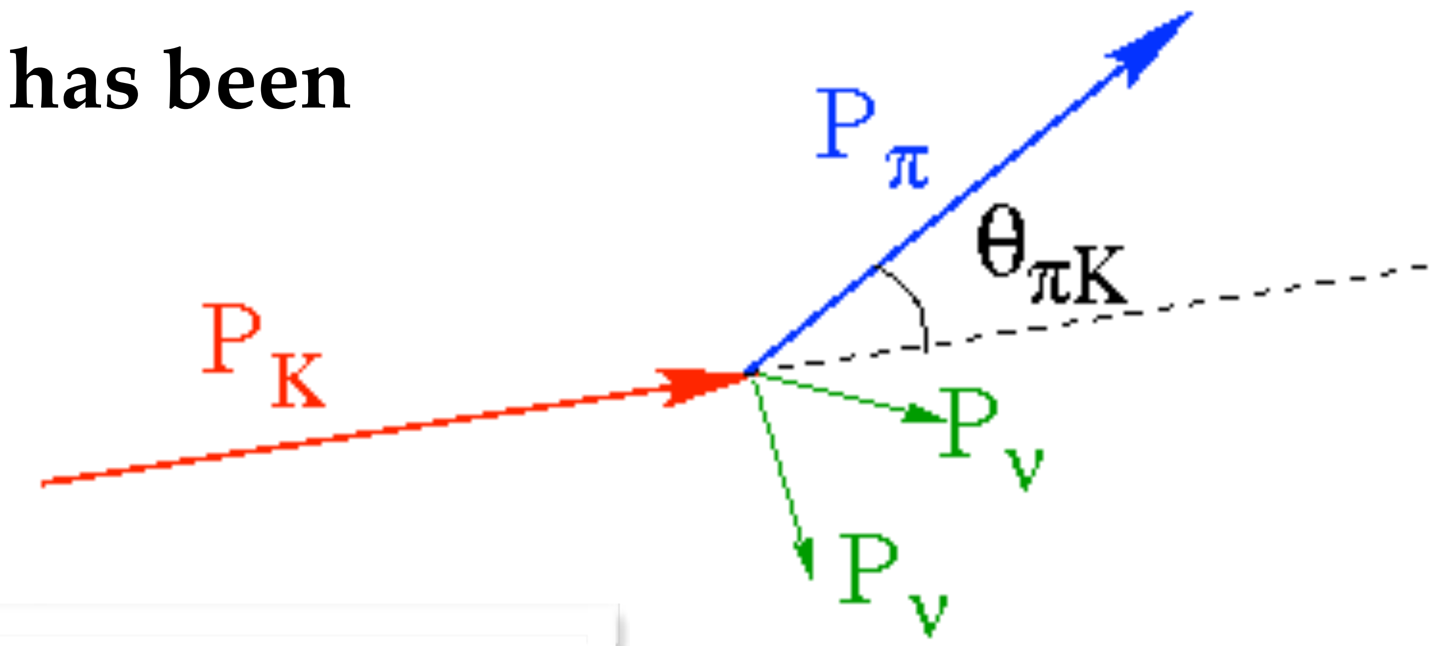
with a precision better than 10%

<u>Collected good quality data in 2016-2018</u>

Ready to start the new data taking

Features required for the BR($K^+ \to \pi^+\nu\nu$)

The experimental apparatus has been designed in order to detect:



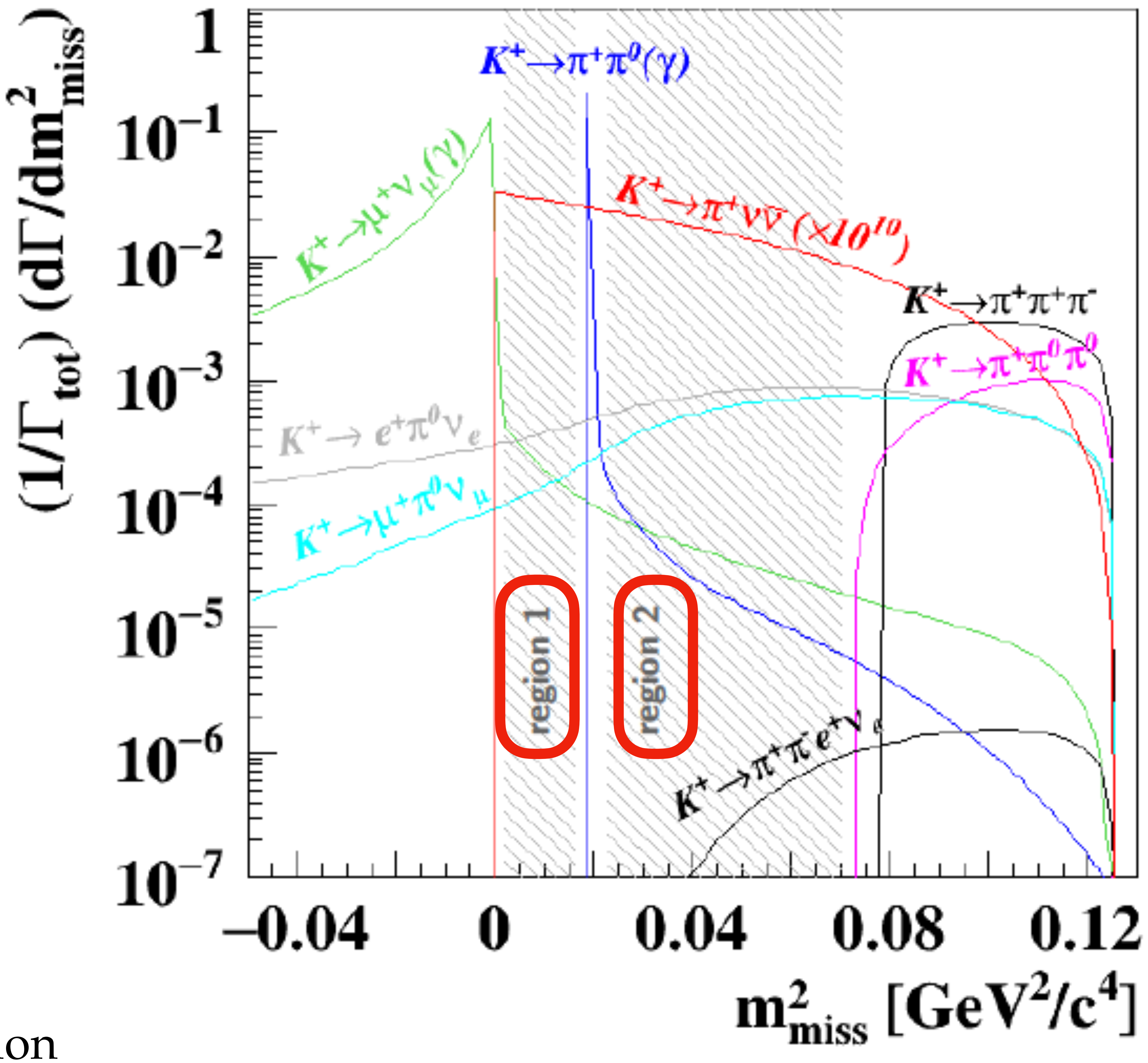
<u>Decay in flight</u>

$$m^2_{miss} = (p_K - p_\pi)^2$$

- very good kinematic reconstruction
- time measurements

Decay	BR	Main Rejection Tools
$K^+ \to \mu^+\nu_\mu(\gamma)$	63%	μ-ID + kinematics
$K^+ \to \pi^+\pi^0(\gamma)$	21%	γ-veto + kinematics
$K^+ \to \pi^+\pi^+\pi^-$	6%	multi-track + kinematics
$K^+ \to \pi^+\pi^0\pi^0$	2%	γ-veto + kinematics
$K^+ \to \pi^0 e^+\nu_e$	5%	e-ID + γ-veto
$K^+ \to \pi^0\mu^+\nu_\mu$	3%	μ-ID + γ-veto

- K,π,μ identification
- Hermetic detection of muons
- Hermetic detection of photons



NA62 Apparatus

Final states described in this presentation:
1 downstream track and nothing else

STRAW: Downstream tracking

JINST 12 P05025 (2017), arxiv:1703.08501

LAV: photon veto at large angles lead-glass blocks

RICH: Ring imaging Cherenkov kinematics and particle ID

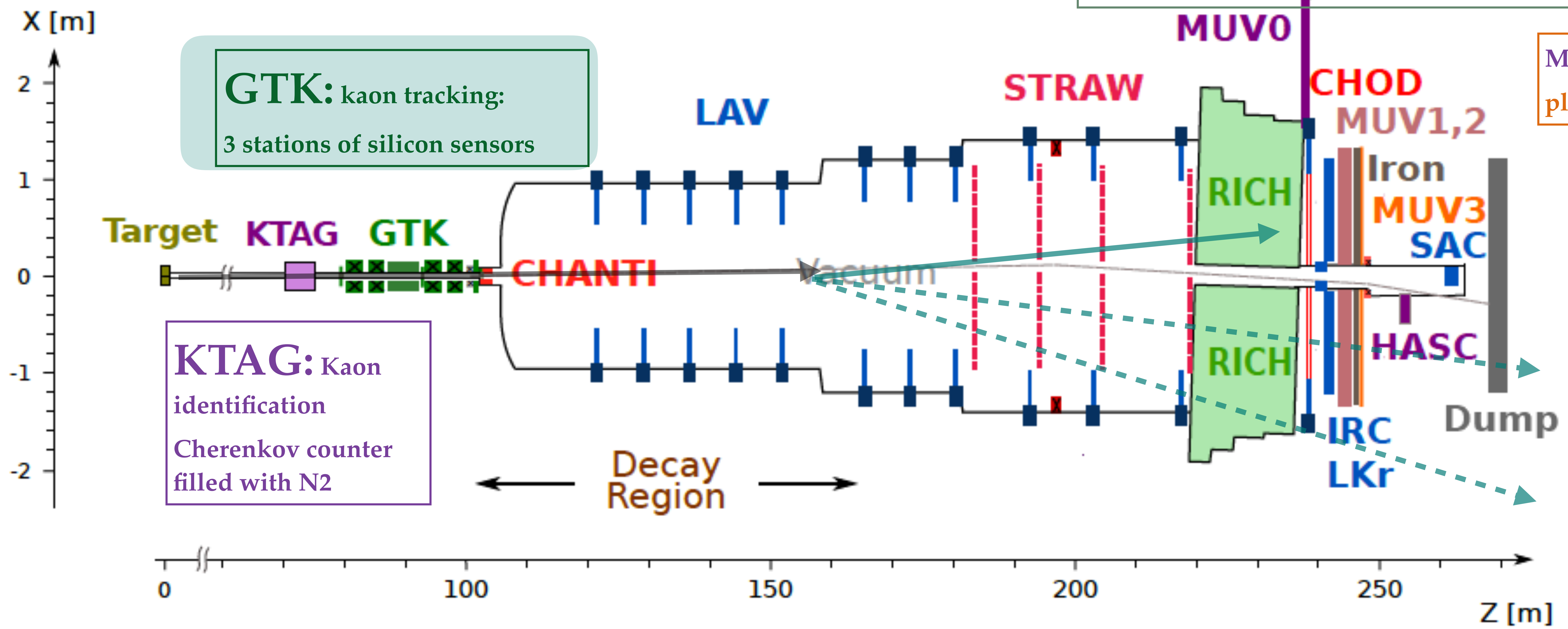
IRC, SAC: lead and scintillator plates Shashlyk configuration

GTK: kaon tracking: 3 stations of silicon sensors

MUV0, MUV3 plastic scintillators

Muon veto Hadronic calorimeters

KTAG: Kaon identification Cherenkov counter filled with N2



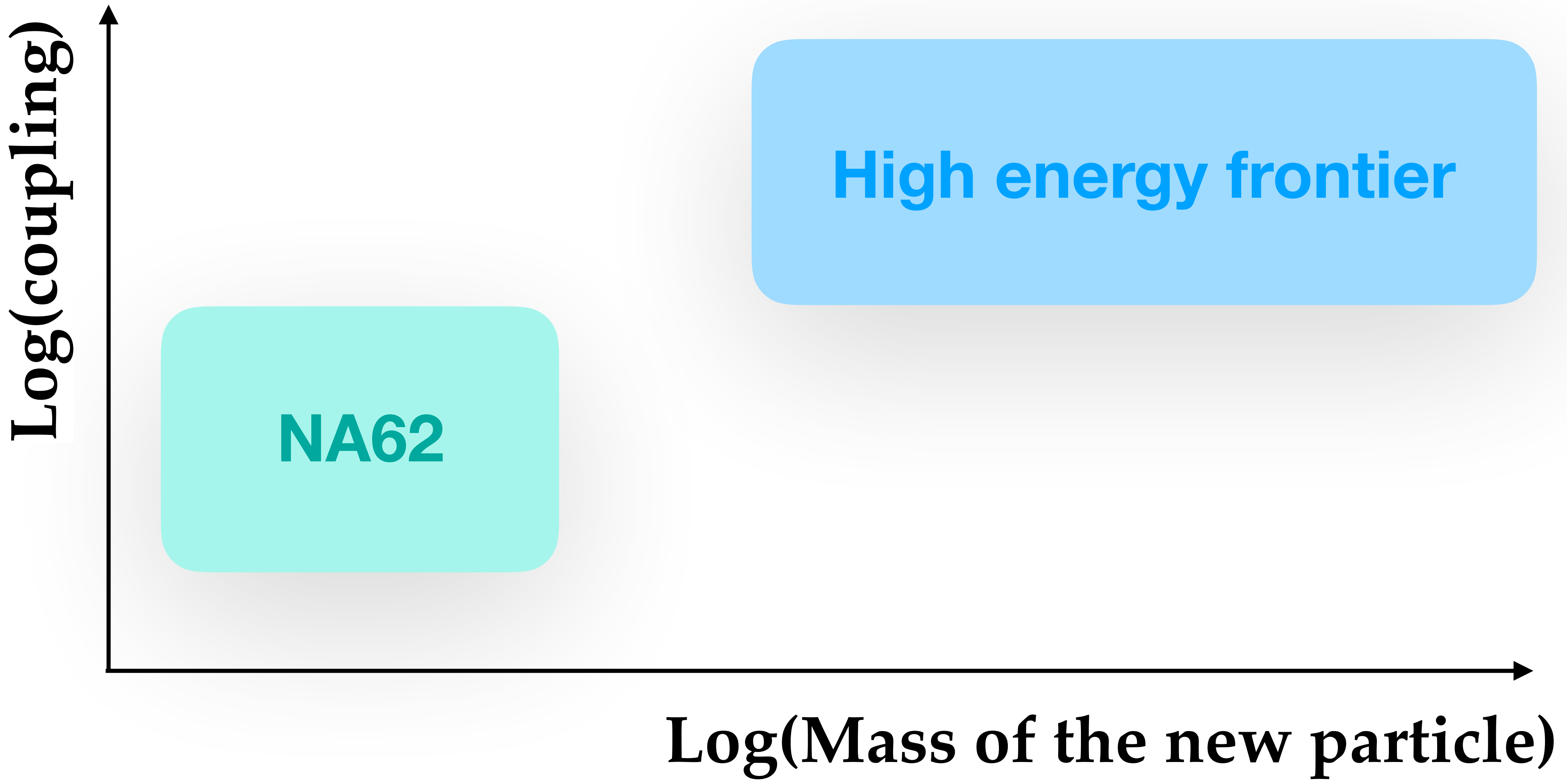
LKr: quasi-homogenous ionization chamber 27X0 deep

CHOD charged hodoscope

“Invisible” feebly interacting particles

NA62 is competitive in the search for FIPs at some parameter space

- ☑ High intensity beam => 6 10^{12} K^+ decays in fiducial volume collected in 2016-2018



Outline:

Searches for a new exotic particle X produced in Kaon decays through detecting missing mass:

- X decaying to invisible particles (neutrinos or dark matter)
- X So long-lived to escape the apparatus

[Also lifetime τ is an important parameter]

Signature: 1 track and missing mass

- $K^+ \to \pi^+ X$, $X \to$ **invisible** with the full 2016-2018 data NEW
- $K^+ \to \pi^+\pi^0$ (or X with $m_X \sim m_{\pi 0}$), $X/\pi^0 \to$ **invisible** with 2017 data
- $K^+ \to \mu^+ \nu X$, $X \to$ **invisible** with the full 2016-2018 data NEW

$K^+ \to \pi^+ X$, X invisible

Motivation: feebly interacting new particle X in $K^+ \to \pi^+$**X** foreseen in several models

For example:

Dark scalar: mixing with the Higgs

$$\mathcal{L}_{\text{scalar}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - (\mu S + \lambda S^2) H^\dagger H$$
$$\mu = \sin\theta \quad \lambda = 0$$

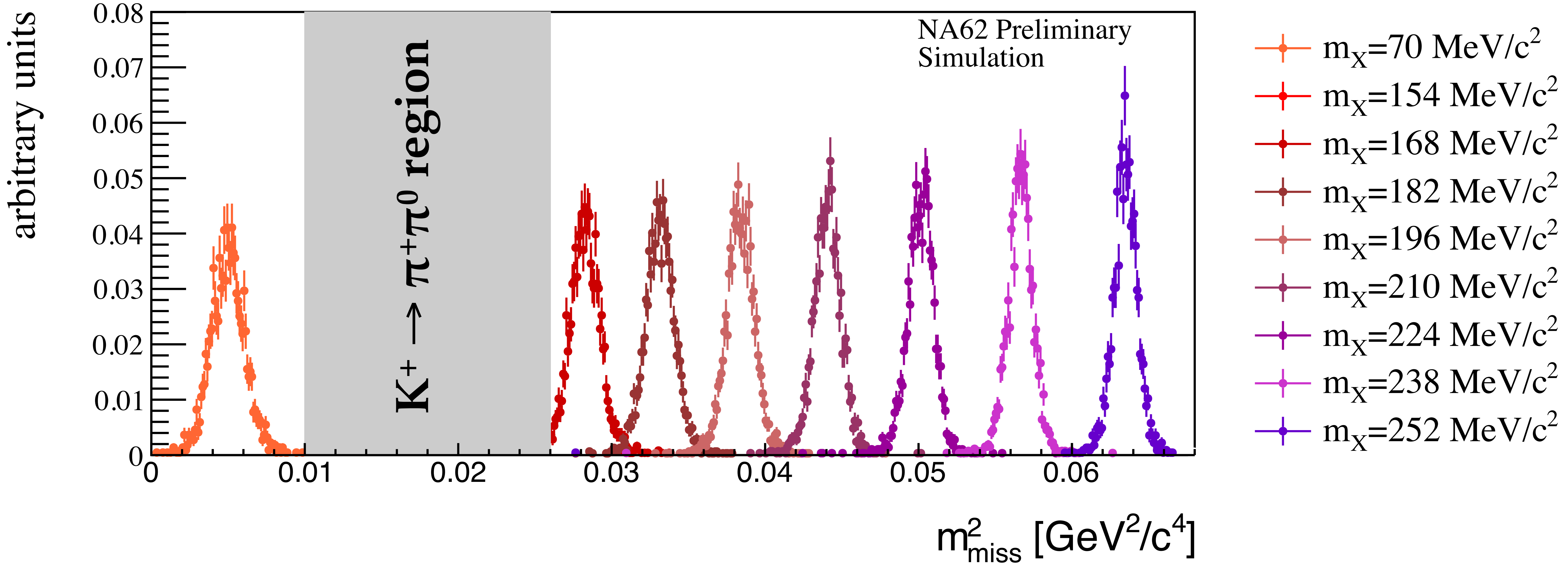
Pseudo-scalar

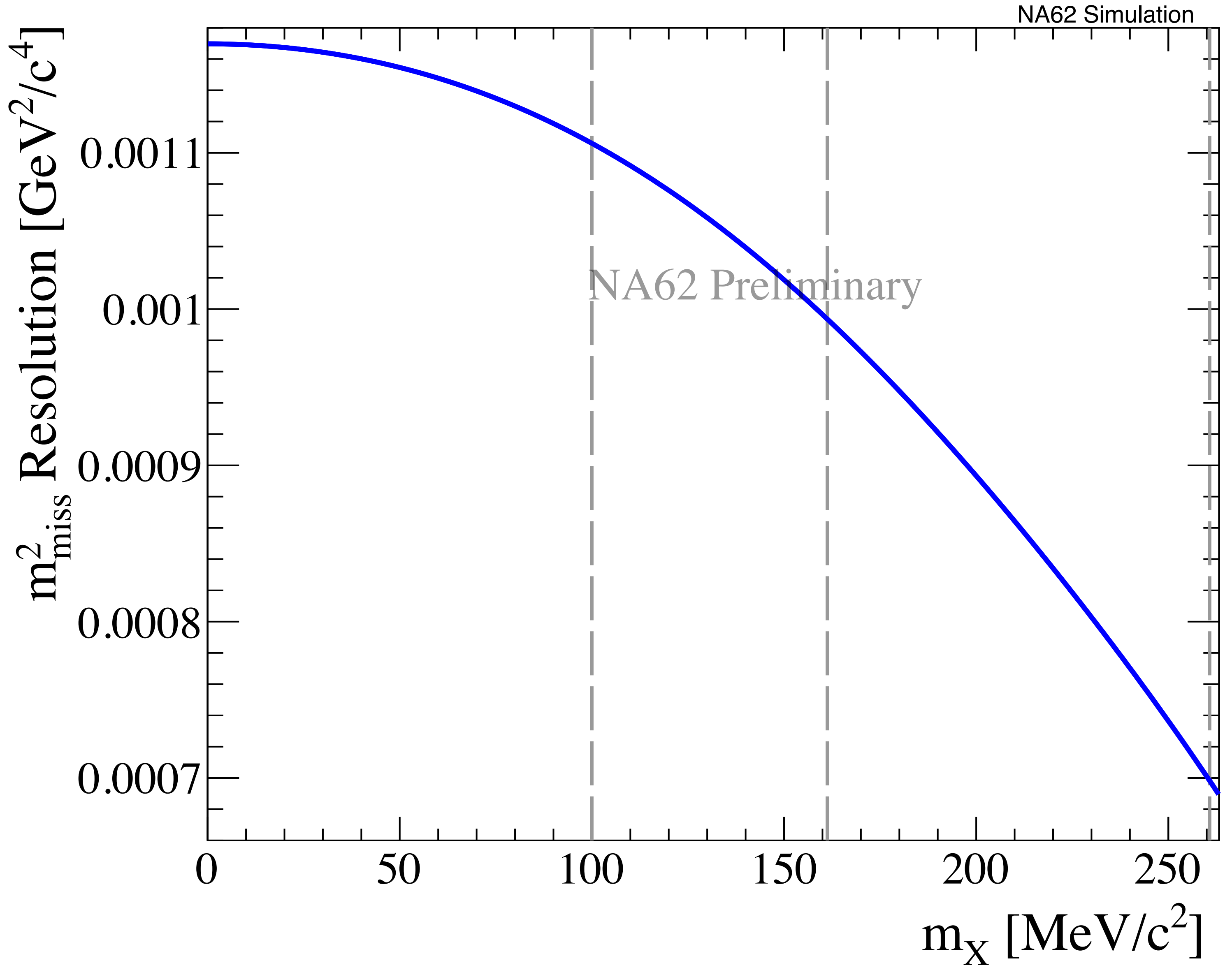
Axion-like particles (ALPs)
QCD axion, Axiflavon (m~0)

Analysis strategy: Same $K \to \pi\nu\nu$

- Use exactly the same selection, normalization and background evaluation of $\pi\nu\nu$ analysis
- Generate signal with two body decay for 200 mass hypotheses to compute acceptance and resolution in m2miss

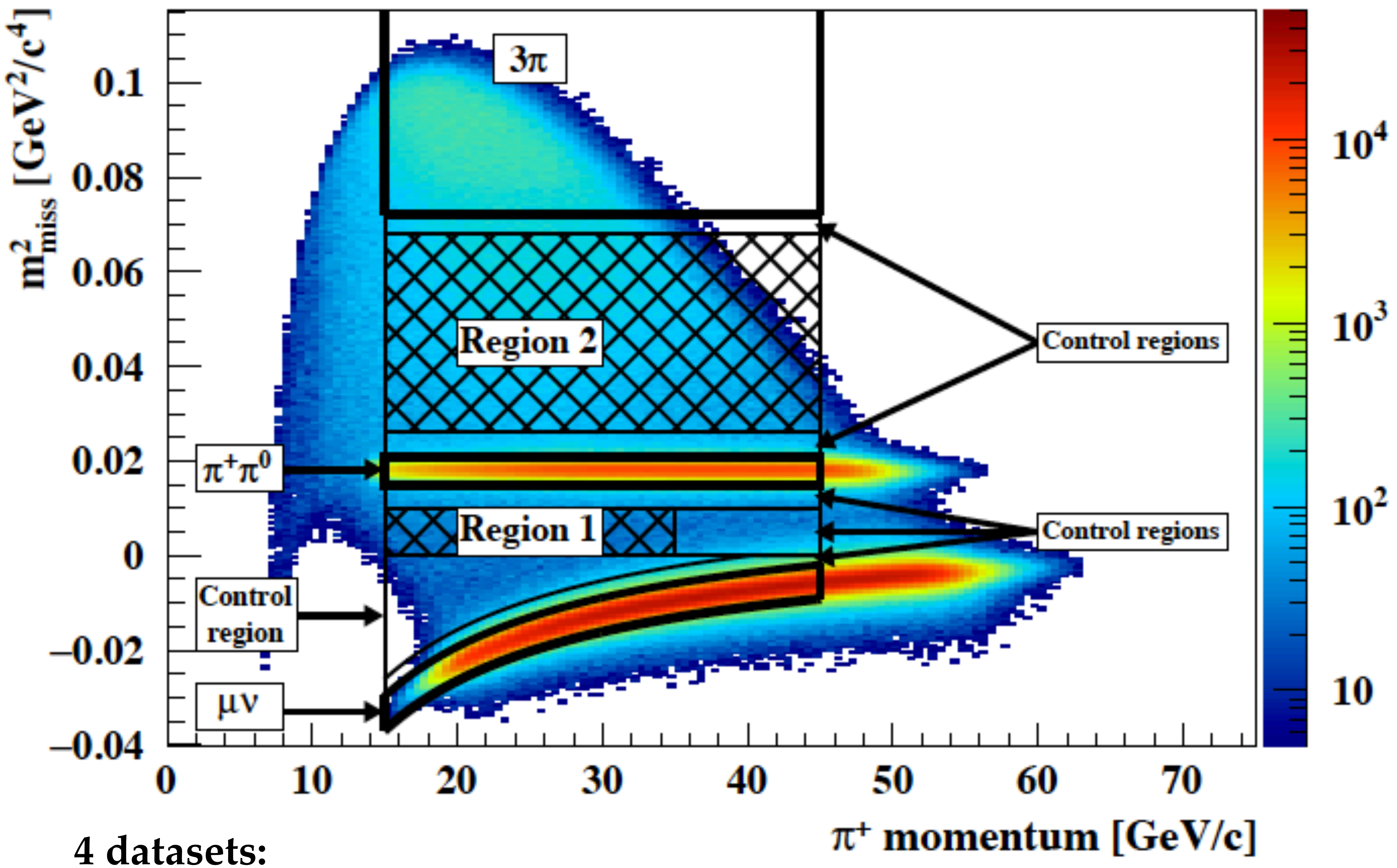
Few mass points after the full selection, normalized to unity





$K^+ \to \pi^+\nu\bar{\nu}, \pi^+X(inv)$ analysis overview

arXiv: 2103.15389 [hep-ex]



4 datasets:

- 2016 data
- 2017 data
- 2018 data with old collimator (20%)
- 2018 data Run with new collimator (80%)

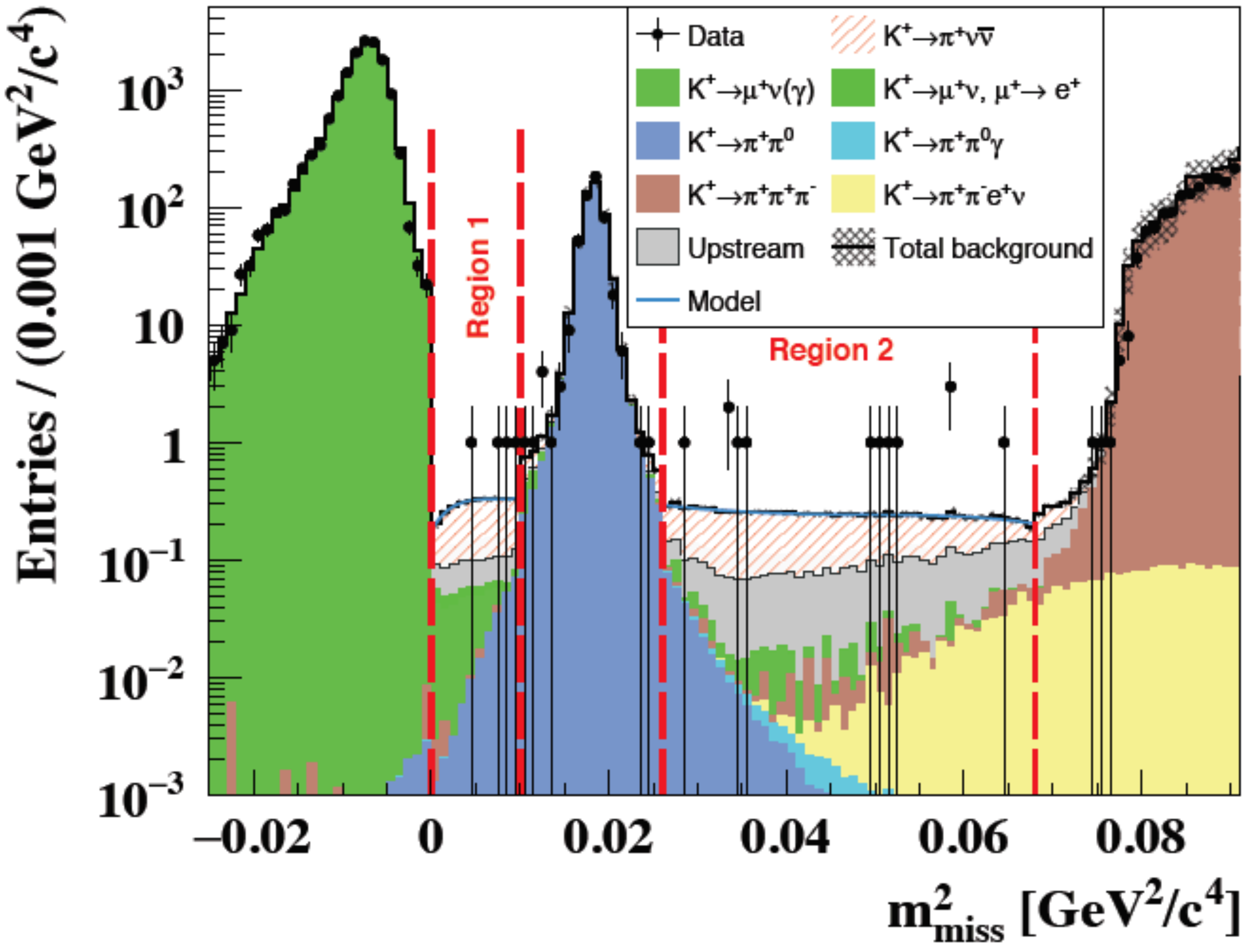
- Normalization to $K^+ \to \pi^+\pi^0$ decay (non-factorizing efficiencies evaluated with data driven methods)
- Data-driven background estimation
- Bins of $p(\pi^+)$ and intensity
- Control regions to validate it

Details in the presentation by Bob Velghe Flavor I session

https://indico.cern.ch/event/982783/contributions/4364555/

$K^+ \to \pi^+ X$, X invisible

2018 Dataset, for illustration



Bump hunting in m^2_{miss}

Background model

- **shape:** Parameterized with polynomial functions in R1 and R2
- **Bkg yield** from πνν analysis, including K->πνν from simulation and with SM BR

Signal model

- **shape**: Gaussian
- **Ns** from efficiency and normalization obtained in bins of p and intensity, as in πνν analysis

Details in

JHEP 03 (2021) 058
arXiv: 2011.11329 [hep-ex]

Update with full dataset

arXiv: 2103.15389 [hep-ex]
Submitted to JHEP

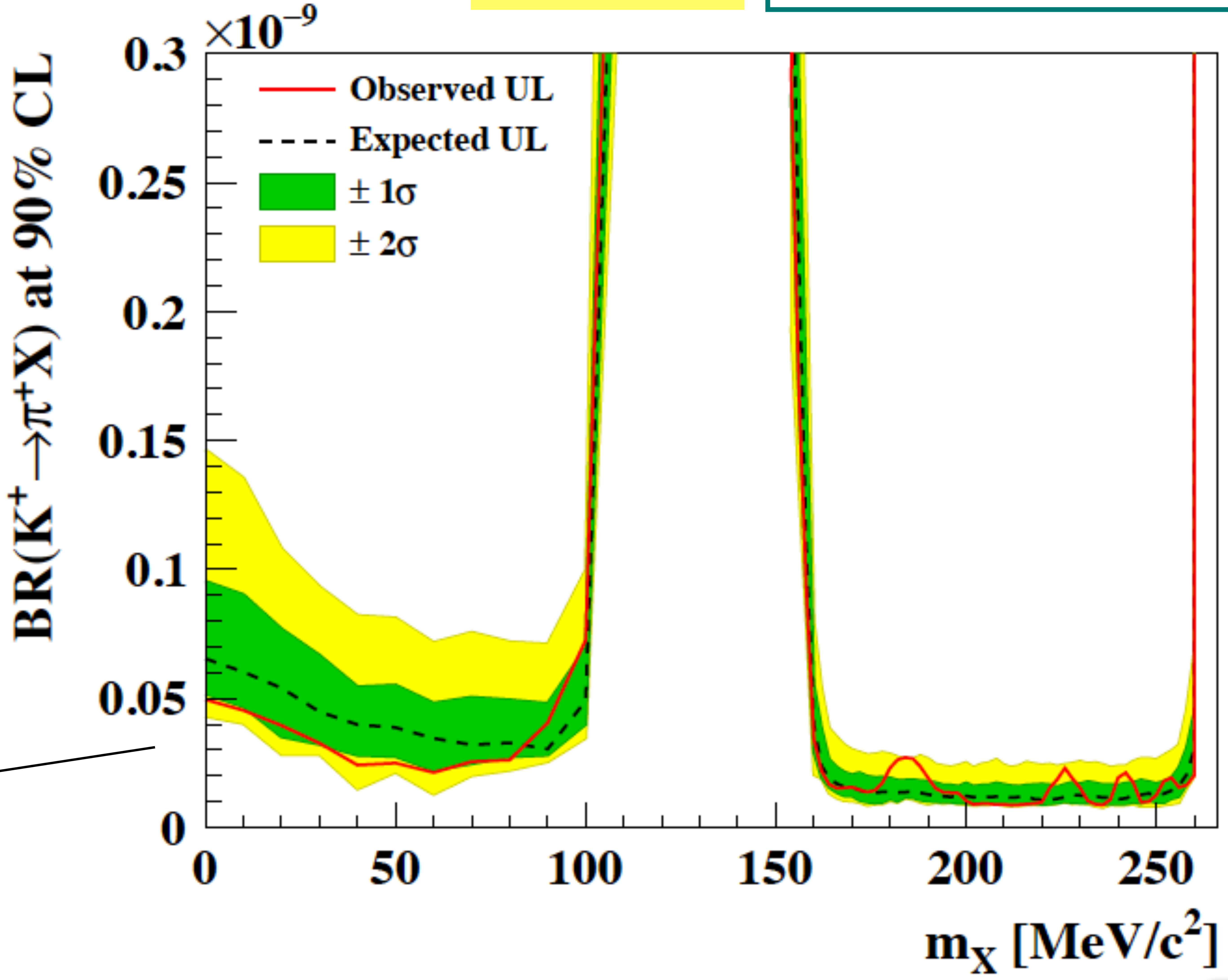
$K^+ \to \pi^+X$, X invisible

2016-2018 Data

arXiv: 2103.15389 [hep-ex]

- Shape analysis on m^2_{miss}
- Fully frequentist approach
- Profiled likelihood test statistic
- Combination of the 4 datasets

Assumption: X decays to invisible particles, or it is so long-lived to escape the apparatus



Sensitivity degrades at small m_X because of resolution.
In particular, for axion models, half of the signal is cut away

$K^+ \to \pi^+ X$, with X decaying to visible particles

2016-2018 Data

arXiv: 2103.15389 [hep-ex]

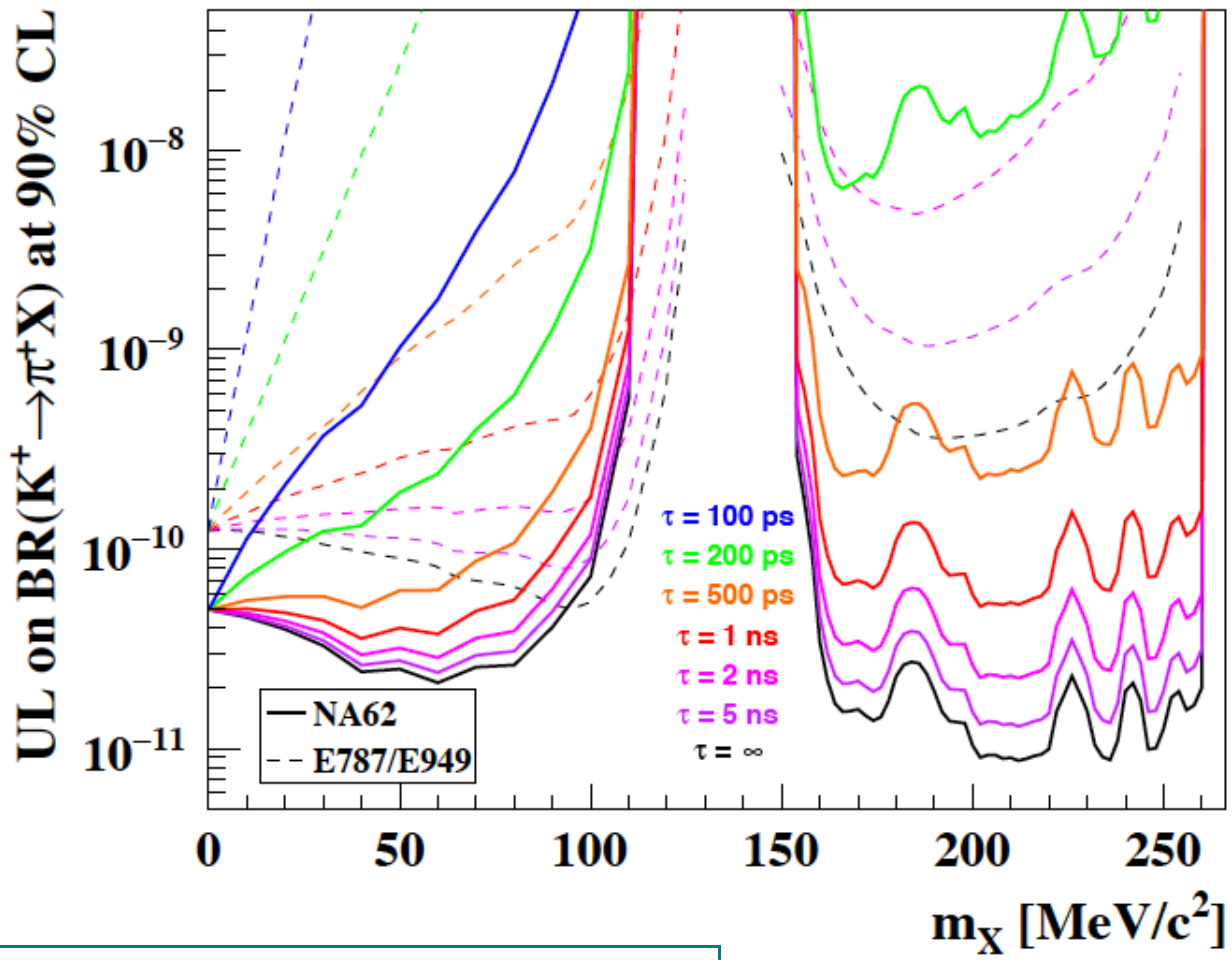
<u>If X decays to visible SM particles</u>

Probability that X does not decay within the NA62 apparatus:

$$P = e^{-\left(\frac{\Delta L}{\beta\gamma c\tau}\right)}$$

Dimensions of the experiment

cτ depends on the coupling parameters and the mass



Comparison with BNL result

A. V. Artamonov *et al.* (E949 Collaboration)

Phys. Rev. D 79, 092004

Improved upper limit over a the range [0,100] MeV and [160,260] MeV

$K^+ \to \pi^+ S$, S: scalar

Higgs mixing model

$$\mathcal{L}_{\text{scalar}} = -\left(\mu S + \lambda S^2\right) H^\dagger H$$

$$\lambda = 0$$

$$\mu = \sin\theta$$

(BC4 in PBC)

[J. Beacham et al., J. Phys. G 47 (2020) 010501]

[M. W. Winkler, Phys. Rev. D 99 (2019) 015018]

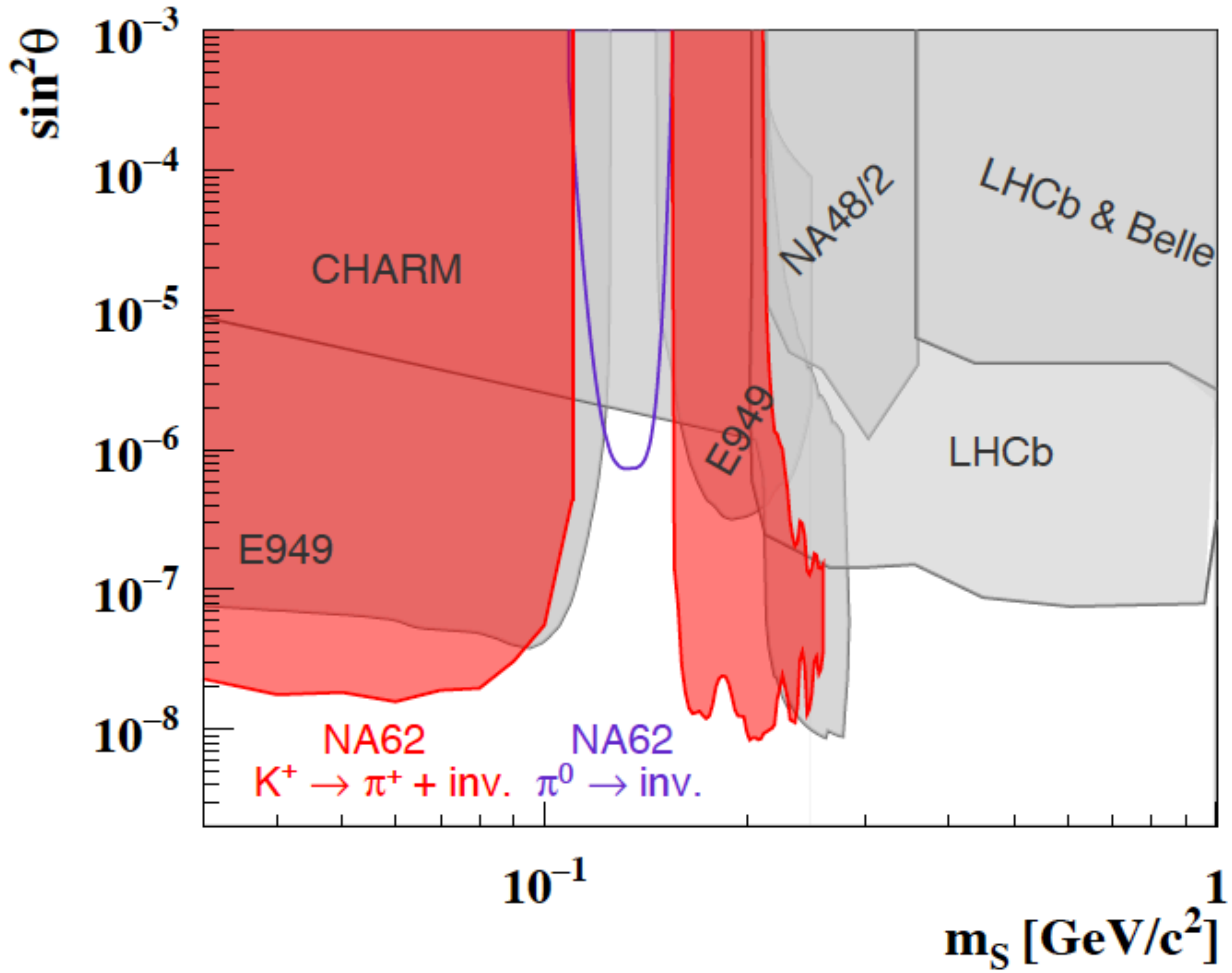
Used for BR computation

If S decays to visible SM particles the acceptance is reduced because the decay products (e or μ) are vetoed

τ depends on sinθ and m_S

2016-2018 Data

arXiv: 2103.15389 [hep-ex]



$K^+ \to \pi^+\pi^0,\ \pi^0 \to$ inv

JHEP 02 (2021) 201
2010.07644 [hep-ex]

2017 Data

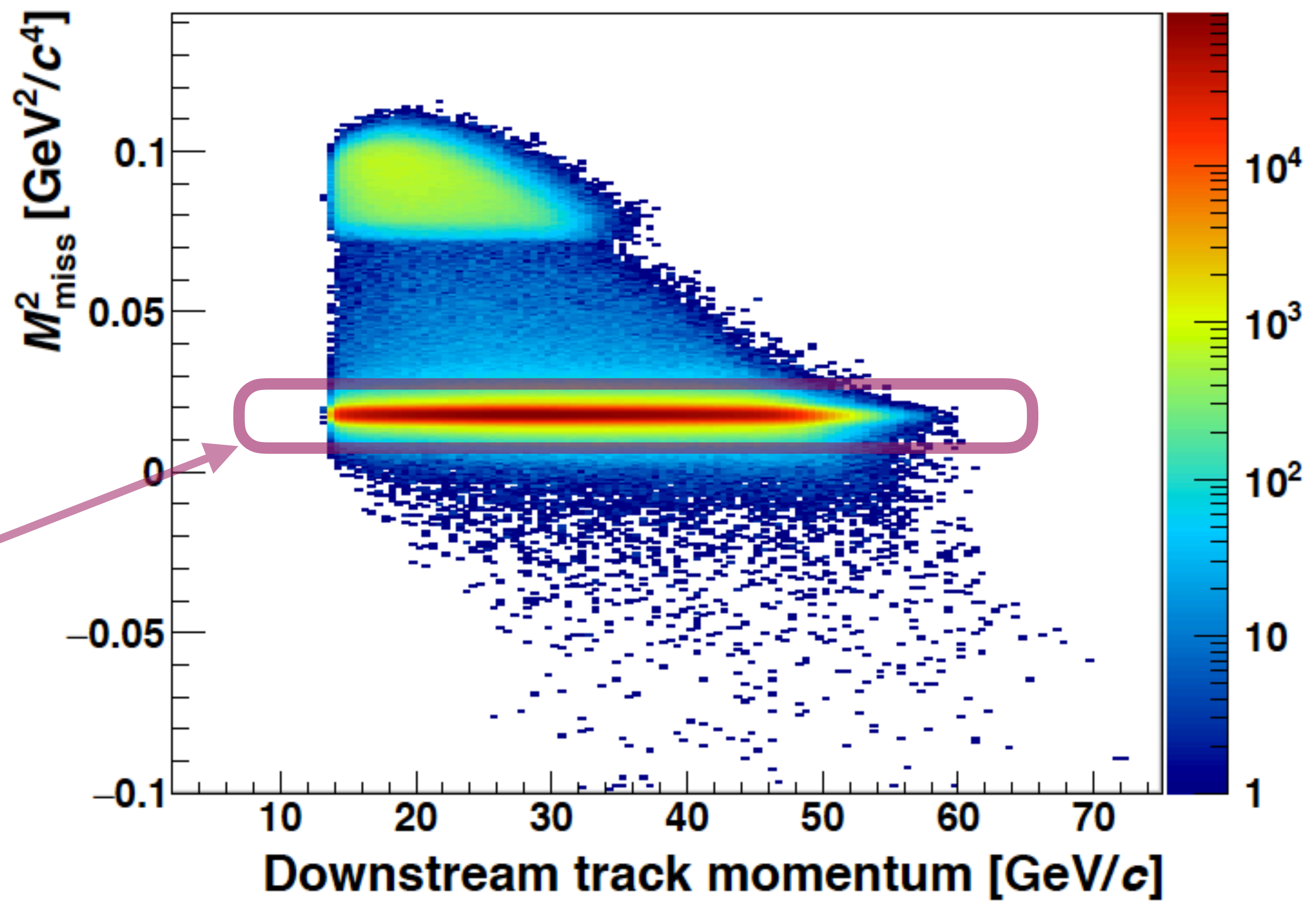
- $\pi^0 \to \nu\nu$ is not forbidden because of neutrino non-zero masses, but in the SM: **BR($\pi^0 \to \nu\nu$) ~ O(10^{-24}), so any observation ==> BSM**
- The previous experimental limit is 2.7 10^{-7} at 90% CL, from BNL experiments

The hermetic photon veto in NA62, essential for $\pi\nu\nu$ analysis, allows for the search in the Kaon decay

$$K^+ \to \pi^+\pi^0(\gamma), \quad \pi^0 \to \text{invisible}$$

With the same analysis we can also search for

$K^+ \to \pi^+ X$, $X \to$ invisible, for $m_X \sim m_{\pi 0}$



Search in the m^2_{miss} range which is a background region for the $K \to \pi\nu\nu$ analysis

$K^+ \to \pi^+\pi^0$, $\pi^0 \to$ inv

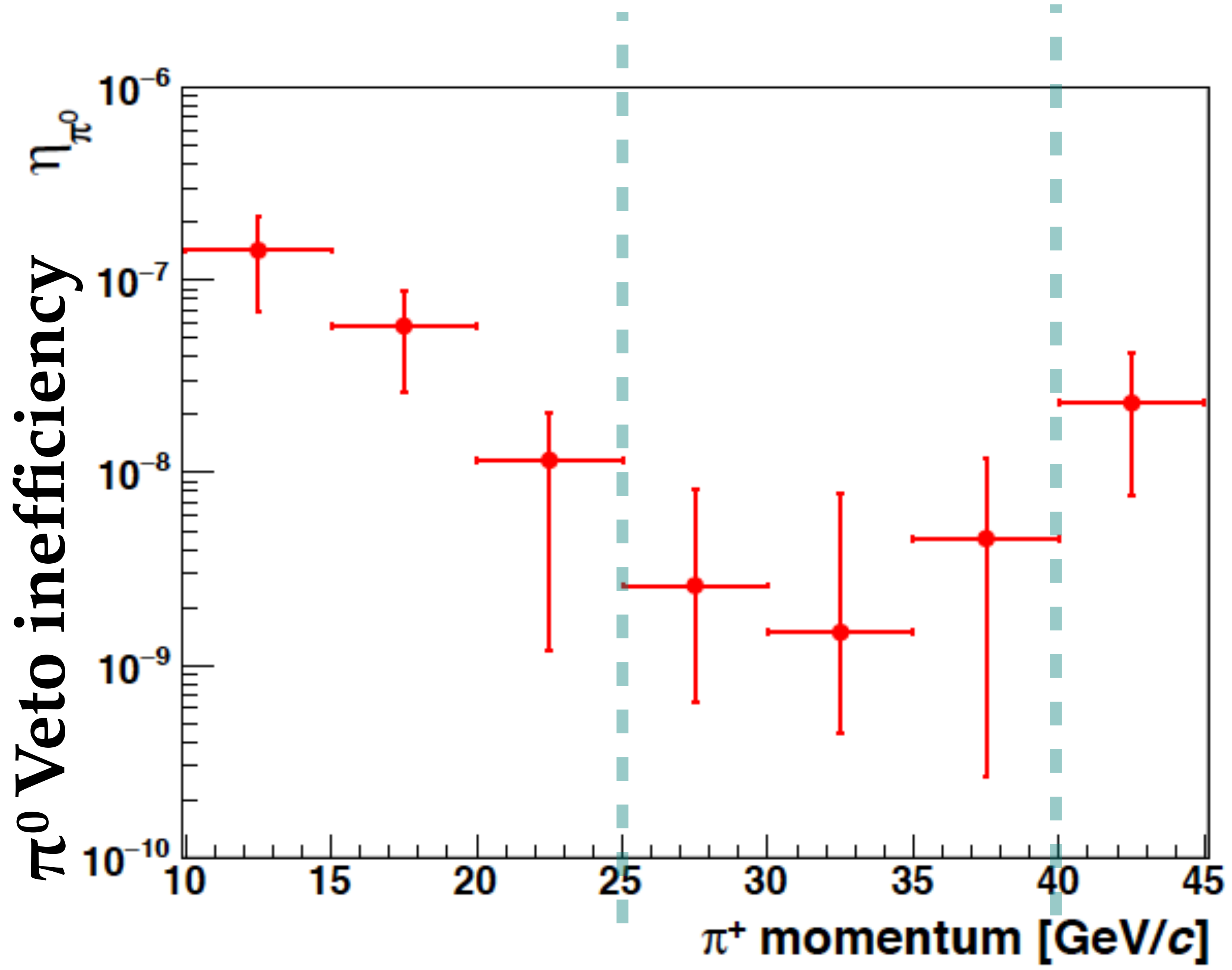
JHEP 02 (2021) 201
2010.07644 [hep-ex]

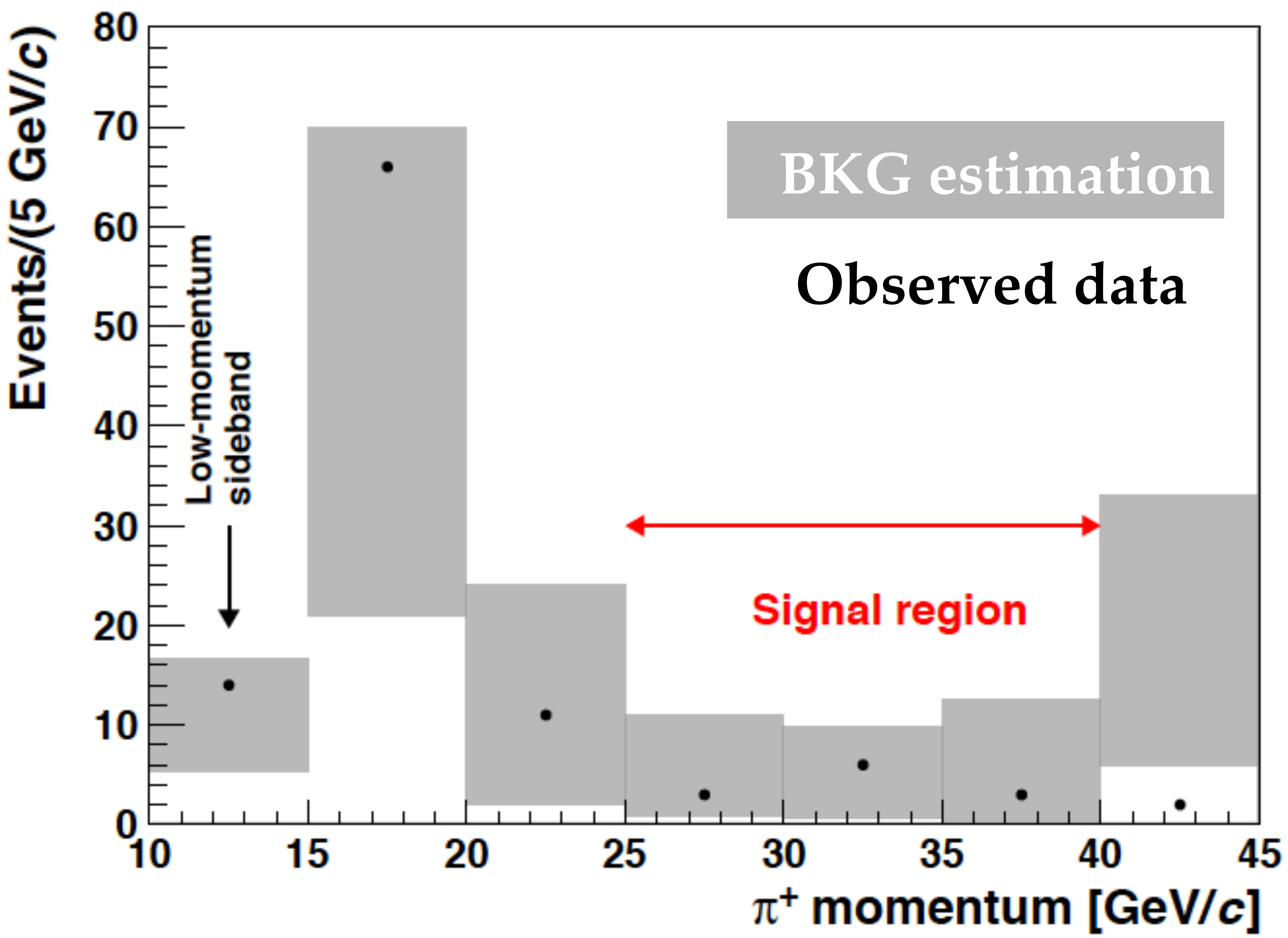
2017 Data

Analysis strategy:

$$\mathrm{BR}(\pi^0 \to \text{invisible}) = \mathrm{BR}(\pi^0 \to \gamma\gamma) \times \frac{N_s}{N_{\pi^0} \times \epsilon_{sel} \times \epsilon_{trig}}$$

The main background is $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\gamma$ with undetected photons





An improvement of a factor 60 wrt the previous experimental result

Counting experiment in the region: 25<p<40 GeV/c and square missing mass in [0.015,0.021] GeV²/c⁴

$\mathrm{BR}(\pi^0 \to \text{invisible}) \le 4.4 \times 10^{-9}$ at 90% C.L.

Search for $K^+ \to \pi^+ X$, $m_X \sim m_{\pi 0}$

Model independent upper limit to BR(K->πX)

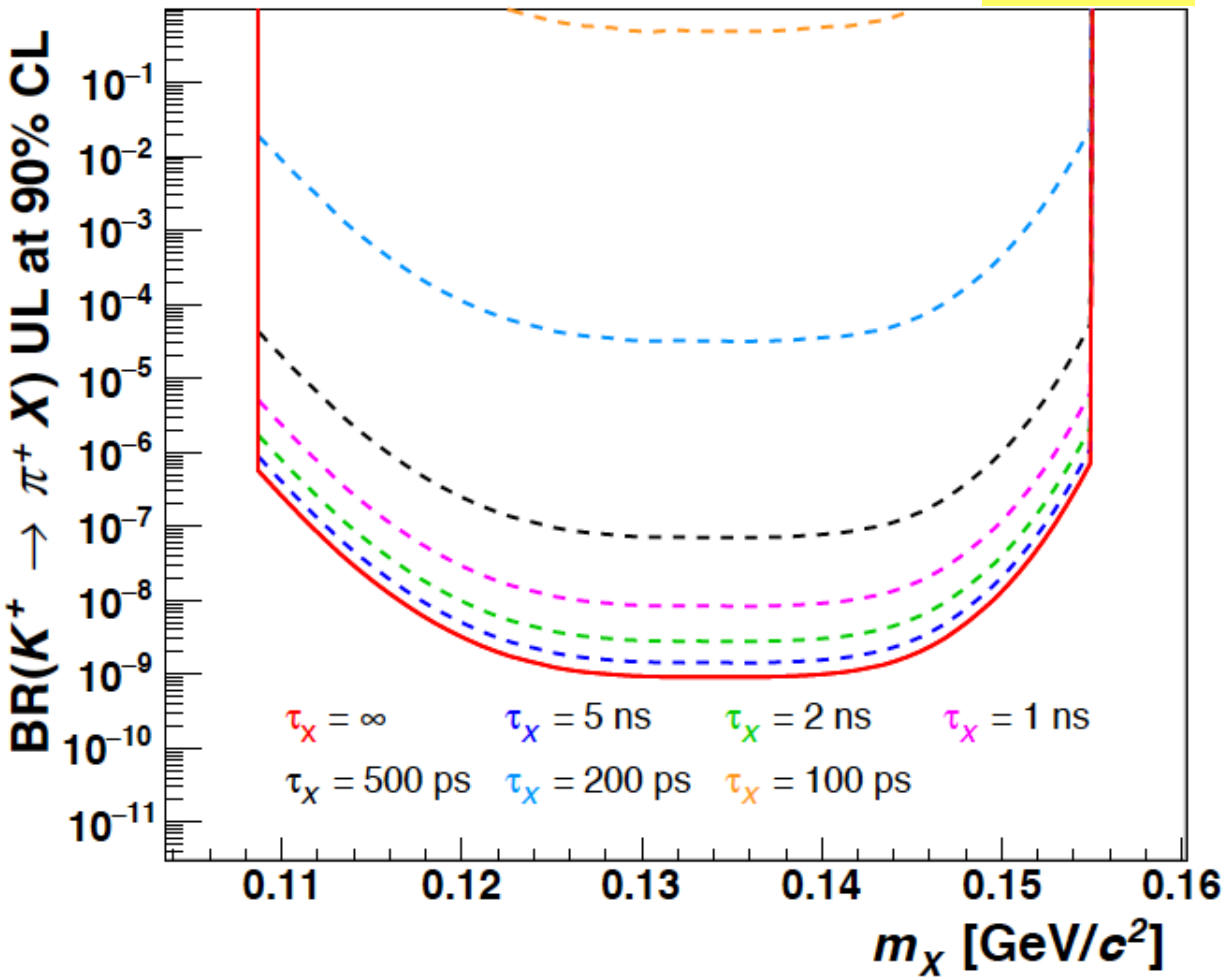
JHEP 02 (2021) 201
2010.07644 [hep-ex]

$$\mathrm{BR}(K^+ \to \pi^+ X) = \frac{N_s}{N_{K^+} \times R(m_X) \times \varepsilon_{\mathrm{sel}} \times \varepsilon_{\mathrm{trig}}}$$

Acceptance of the cut on m^2_{miss} depends on the mass hypothesis

If X decays to visible particles inside the apparatus, the acceptance is reduced and the upper limit is weaker

2017 Data



$K^+ \to \pi^+$ a, a: ALP

Pseudoscalar axion-like particle

$$\mathcal{L}_{SM} = \frac{\partial_\mu a}{f_\ell} \sum_\alpha \bar{\ell}_\alpha \gamma_\mu \gamma_5 \ell_\alpha + \frac{\partial_\mu a}{f_q} \sum_\beta \bar{q}_\beta \gamma_\mu \gamma_5 q_\beta$$

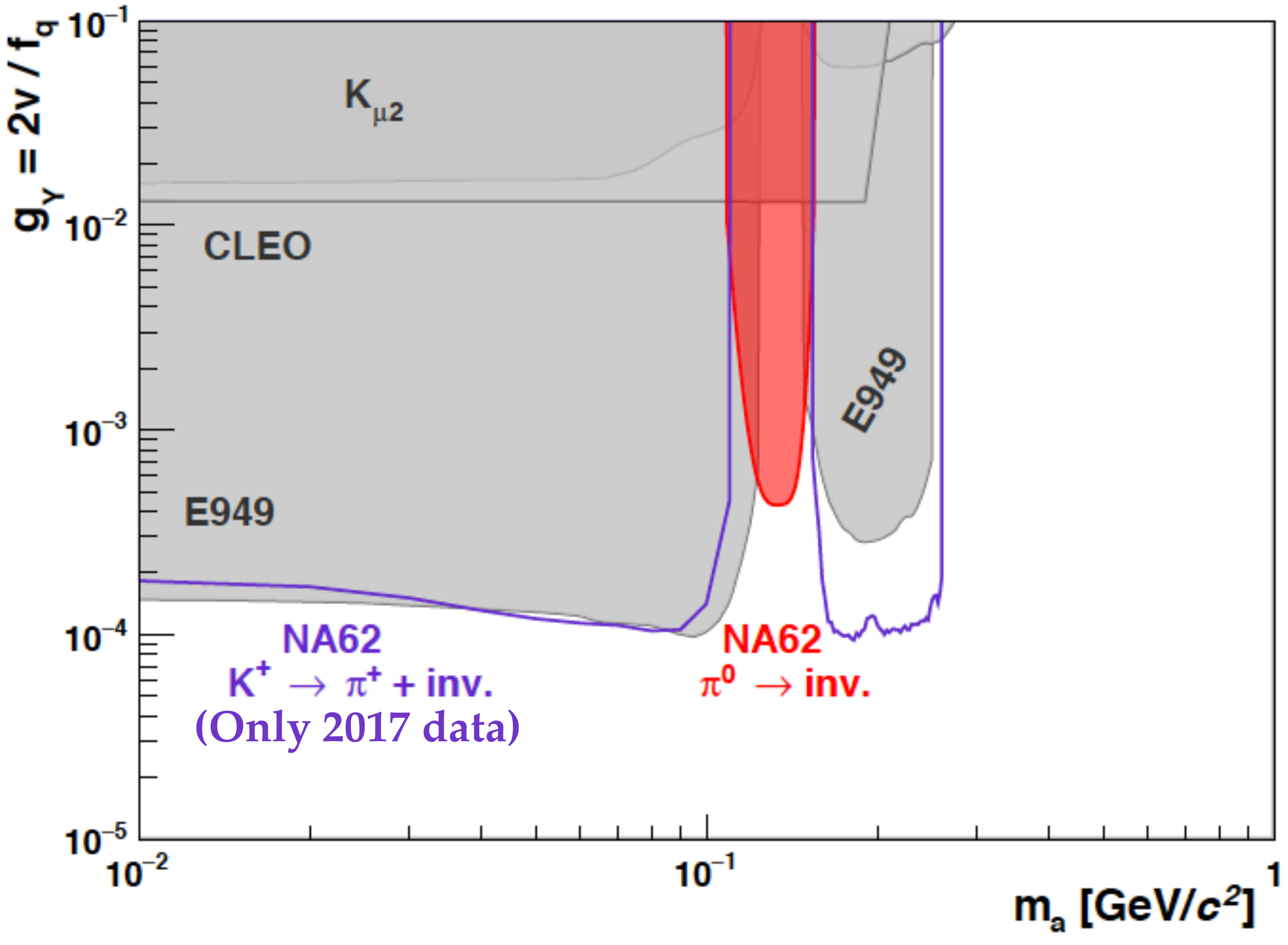
JHEP 02 (2021) 201
2010.07644 [hep-ex]

2017 Data

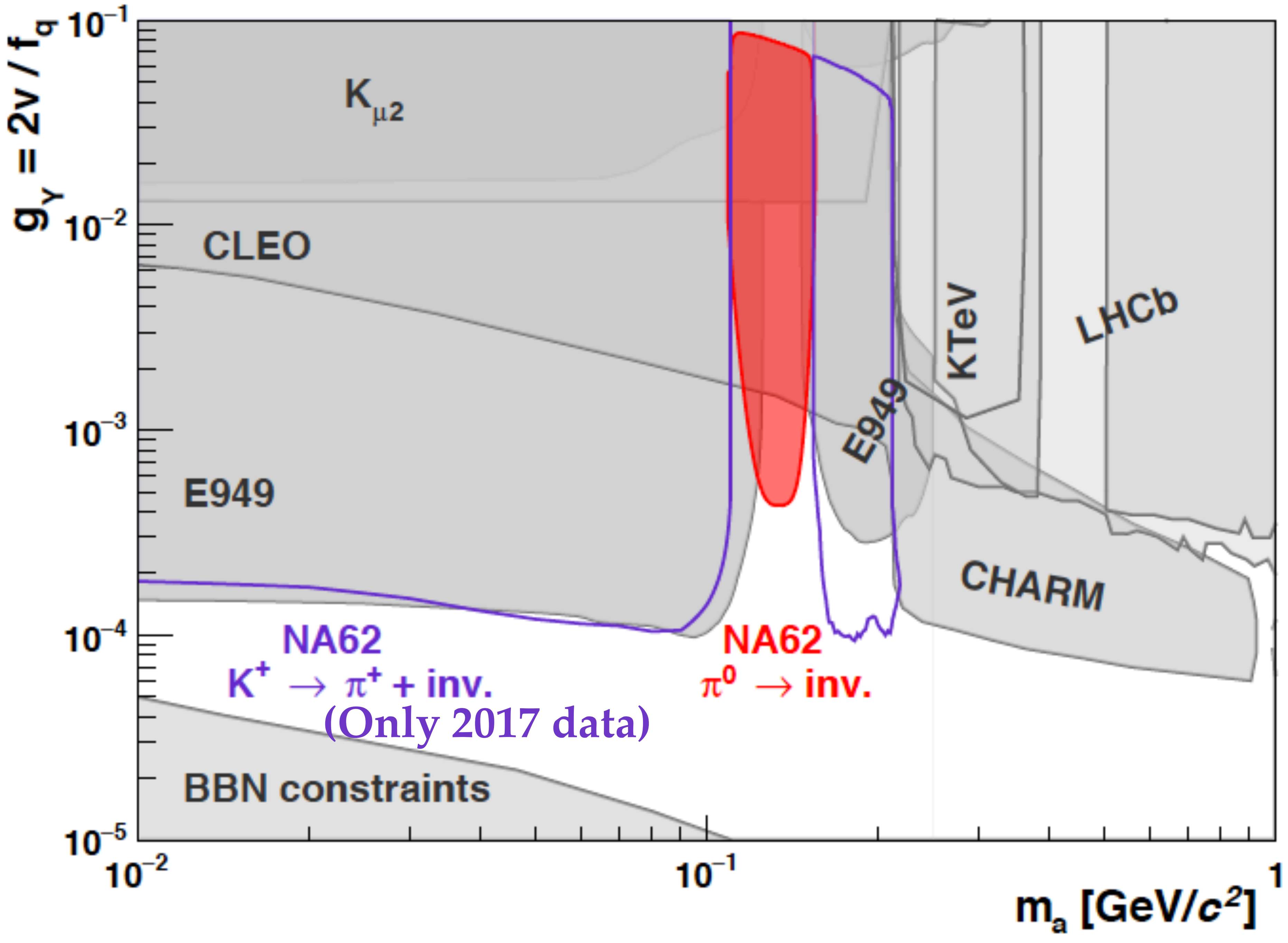
(BC10 in PBC) [J. Beacham et al., J. Phys. G 47 (2020) 010501] $f_q = f_\ell$

M. J. Dolan et al., JHEP 03 (2015) 171
Used for BR and lifetime computation

If *a* decays to invisible particles,
or it is so long-lived to escape the apparatus



If *a* decays to visible SM particles the acceptance is reduced because the decay products (e or μ) are vetoed



$K^+ \to \mu^+\nu X$, $X \to$ invisible

Motivation

A possible explanation of the **anomalous muon magnetic momentum g-2** is the existence of a new light gauge boson

S.N. Gninenko and N.V. Krasnikov, *Phys.Lett.B* 513 (2001) 119, https://arxiv.org/pdf/hep-ph/0102222.pdf

In a scenario with dark matter freeze out, it could be a scalar or vector mediator of an hidden sector decaying to Dark Matter $X \to \chi\chi$

Phys. Rev. Lett. 124, 041802 (2020)
arXiv:1902.07715 [hep-ph]

$K^+ \to \mu^+\nu X$, with $X \to$ invisible, $\gamma\gamma$, $\mu^+\mu^-$

Work in progress

Same final state as

$K^+ \to \mu^+$ N, N: Heavy Neutral Lepton

One μ^+ and missing mass

Phys.Lett.B 816 (2021) 136259
2101.12304 [hep-ex]

2016-2018 Data

Details in the presentation by Marco Mirra, Neutrino I session

https://indico.cern.ch/event/982783/contributions/4362325/

$K^+ \to \mu^+ \nu X$, $X \to$ invisible

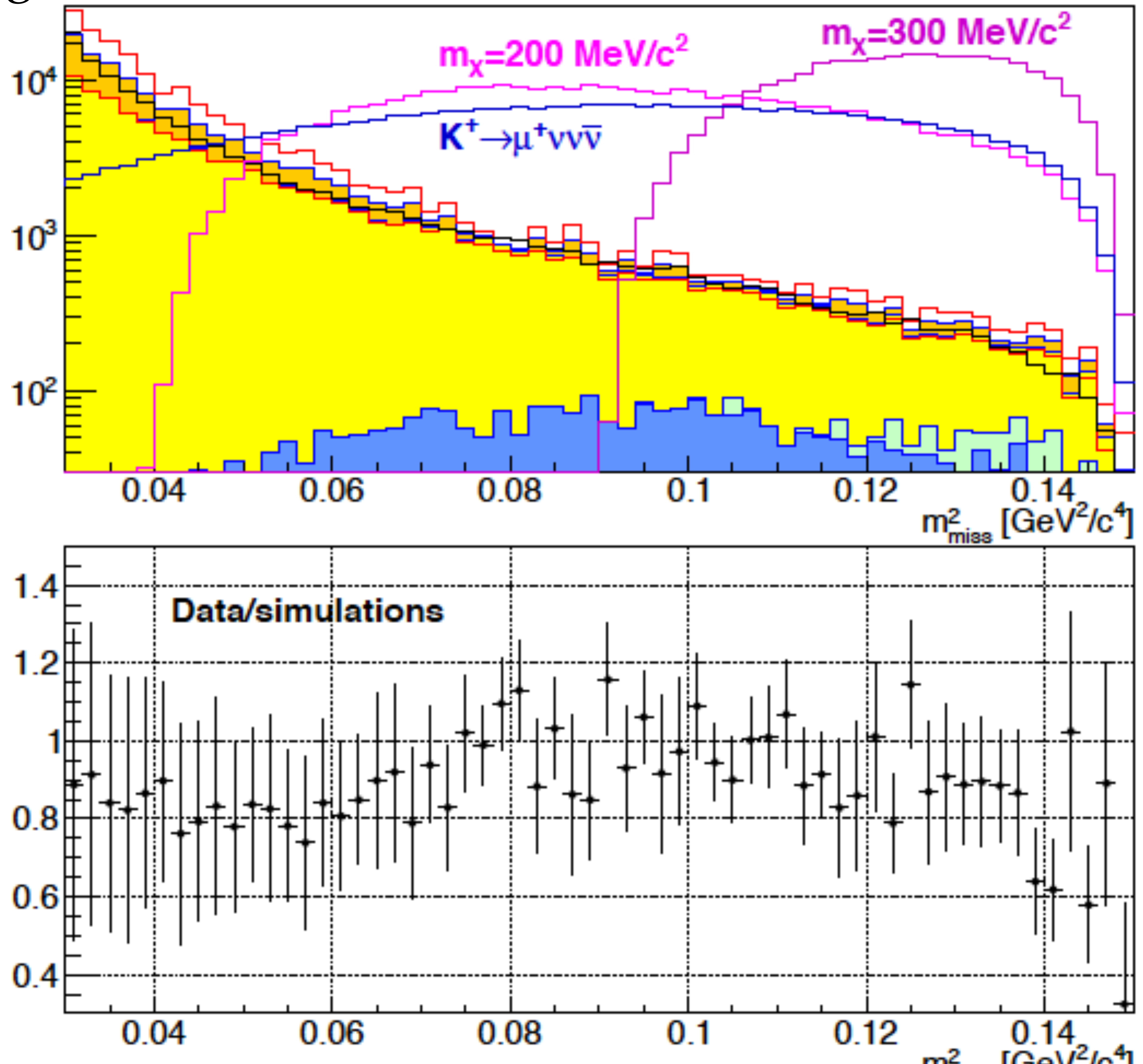
2016-2018 Data

Phys.Lett.B **816 (2021) 136259**
2101.12304 [hep-ex]

3 body decay, the signal has a broad distribution in

$$m^2_{miss} = (p_K - p_\mu)^2$$

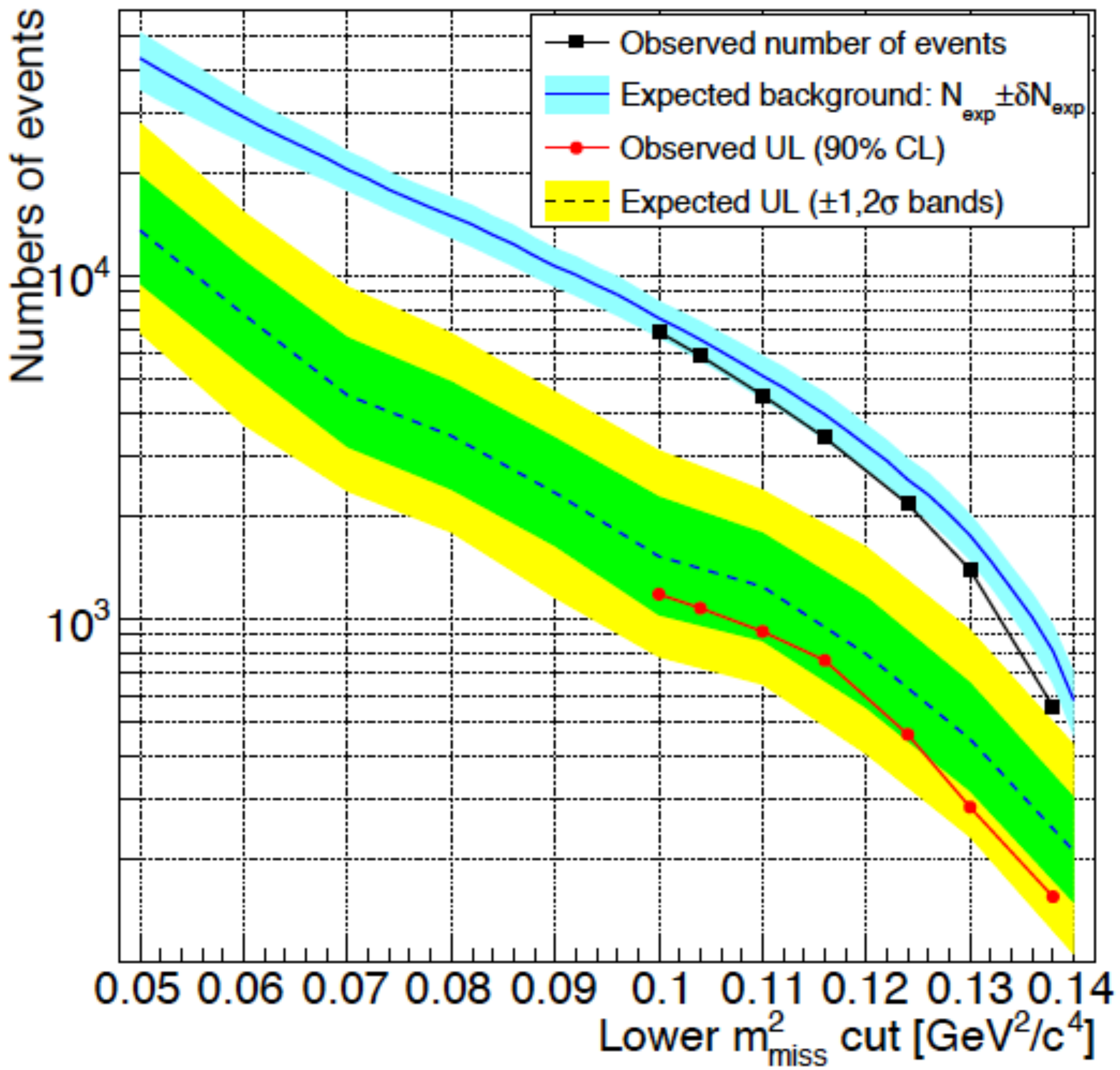
background estimation from MC:



Good Data/MC agreement

Counting experiment with lower cut on m^2_{miss}

optimized independently for each mass hypothesis, requiring the strongest upper limit



$K^+ \to \mu^+ \nu X$, $X \to$ invisible

2016-2018 Data

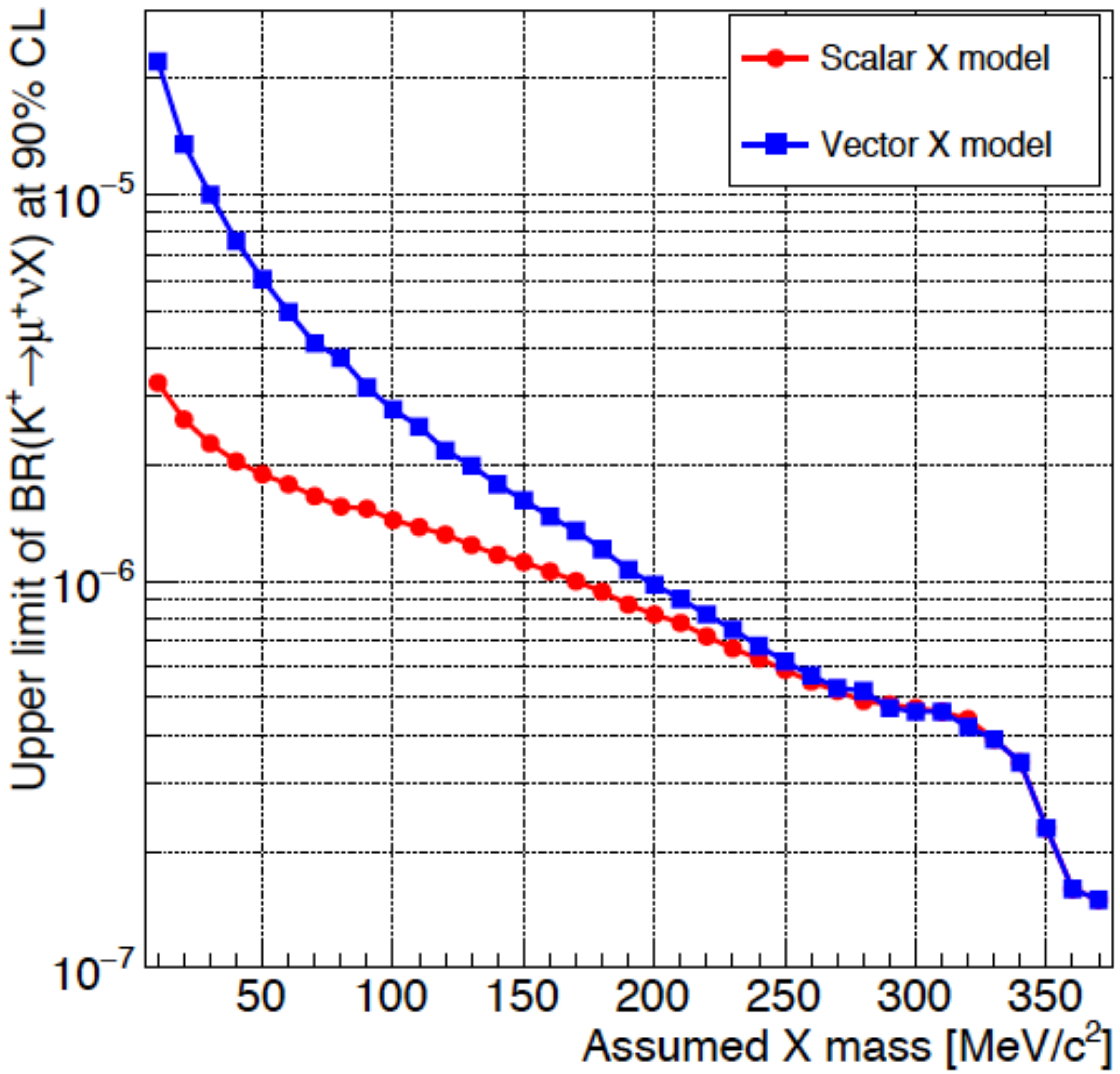
Phys.Lett.B 816 (2021) 136259
2101.12304 [hep-ex]

$$N_K = \frac{N_{SM}}{A_{SM} \cdot \mathcal{B}(K^+ \to \mu^+ \nu)} = (1.14 \pm 0.02) \times 10^{10}$$

Tested mass hypotheses from 10 to 370 MeV

In the model with scalar mediator the mean value of m^2_{miss} is larger compared to the vector mediator.

This results in a stronger upper limit for the scalar X model



Also an upper limit to the very rare SM decay has been established:

$$\mathcal{B}(K^+ \to \mu^+ \nu \nu \bar{\nu}) < 1.0 \times 10^{-6} \quad \text{at } 90\% \text{ CL}$$

Conclusions

☑ Improved bounds on feebly interacting particles X with the signatures:

- **$K^+ \to \pi^+ X$, $X \to$ invisible, in almost the full the mass range ~[0, 250] MeV**
- **$K^+ \to \mu^+ \nu X$, $X \to$ invisible, in the mass range [10, 370] MeV**

☐ Ongoing analyses to finalize other searches with 2016-2018 dataset

☐ Getting ready for the new data taking (Kaon beam and beam dump), starting soon (July 2021)

Stay tuned!

Thank you for your attention

Spares

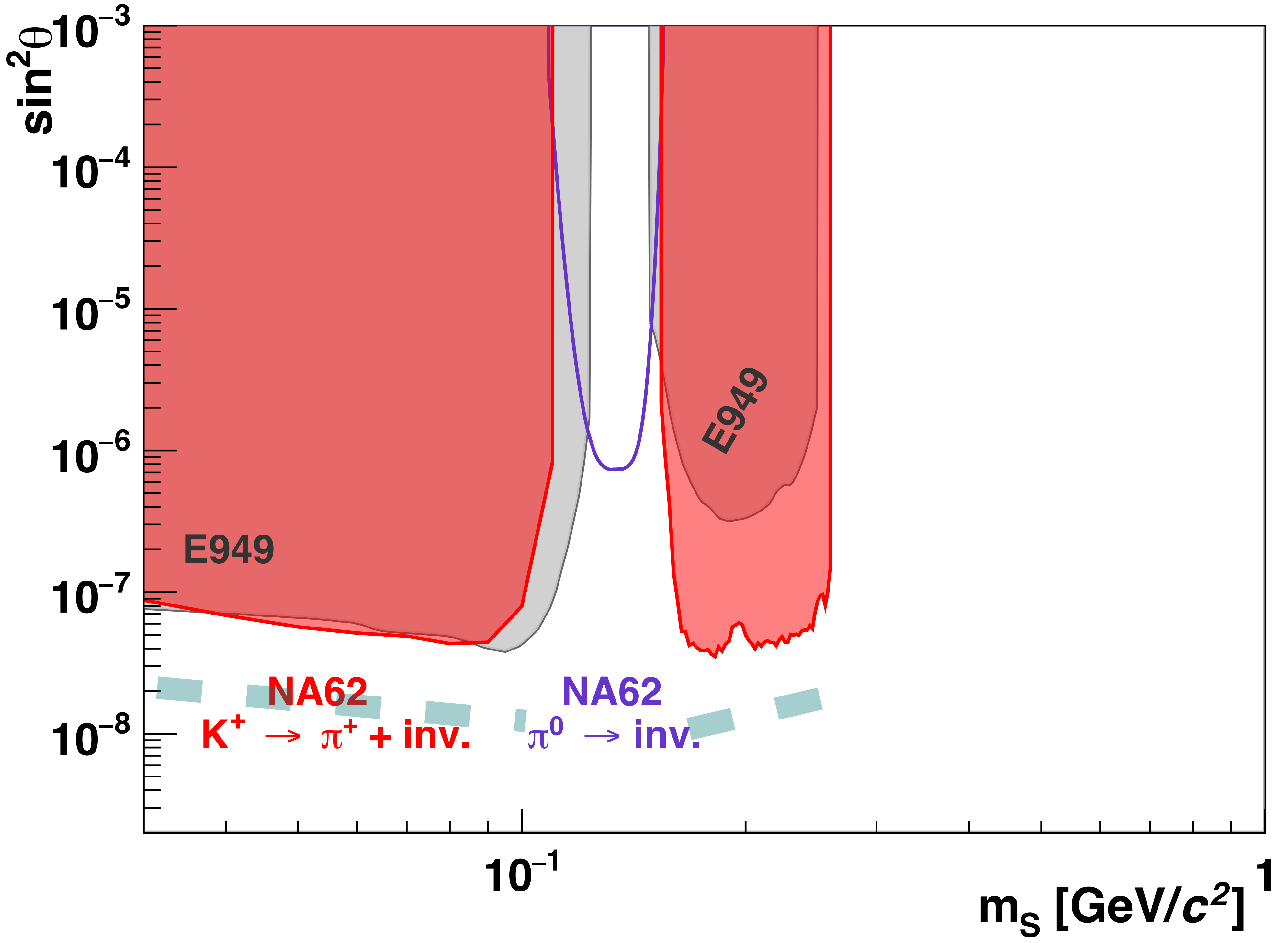
$K^+ \to \pi^+ S$, S: scalar

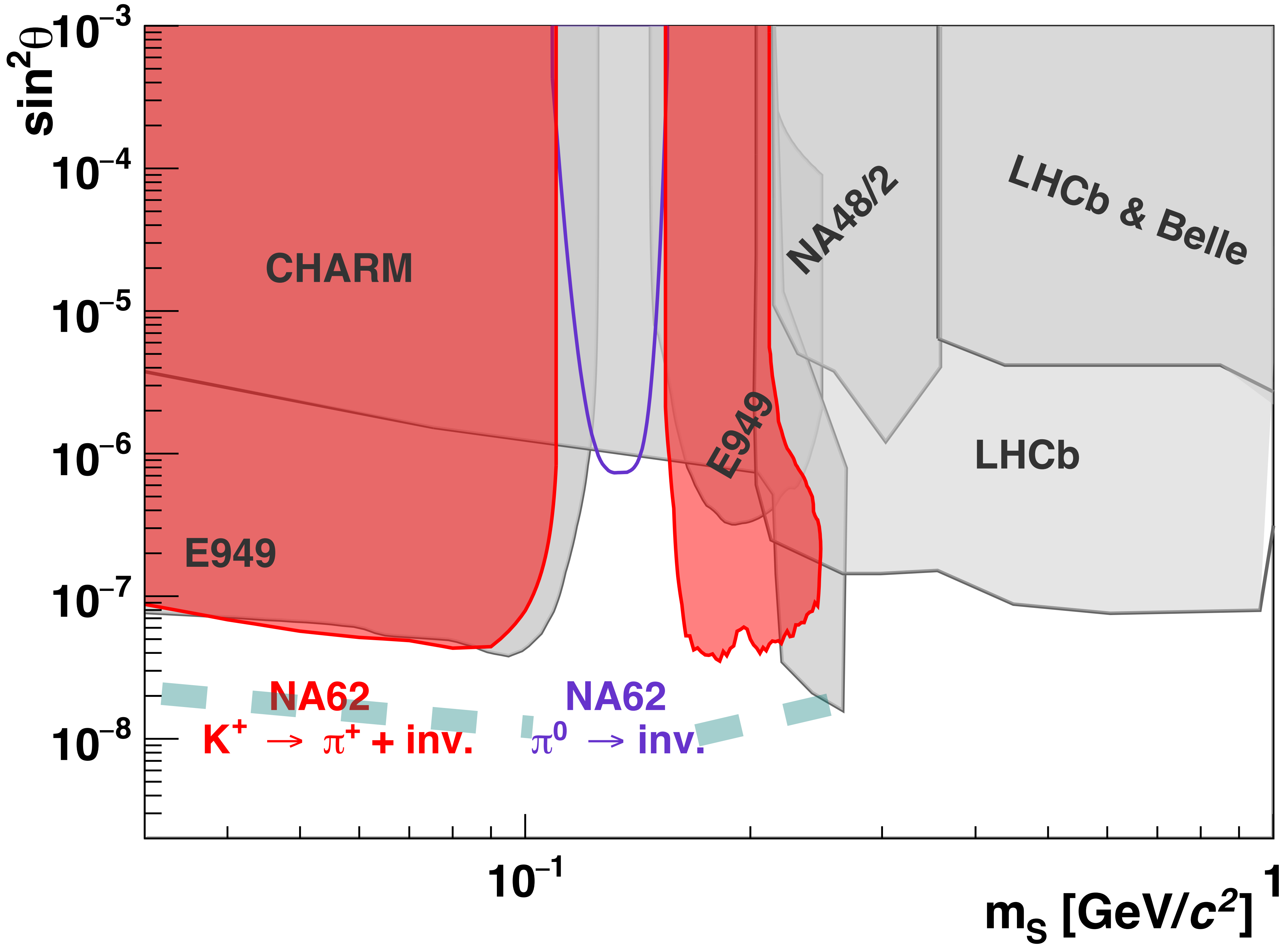
2017 dataset

https://www.hepdata.net/record/ins1832447
https://www.hepdata.net/record/ins1822910

HEPData

JHEP 03 (2021) 058
arXiv: 2011.11329 [hep-ex]





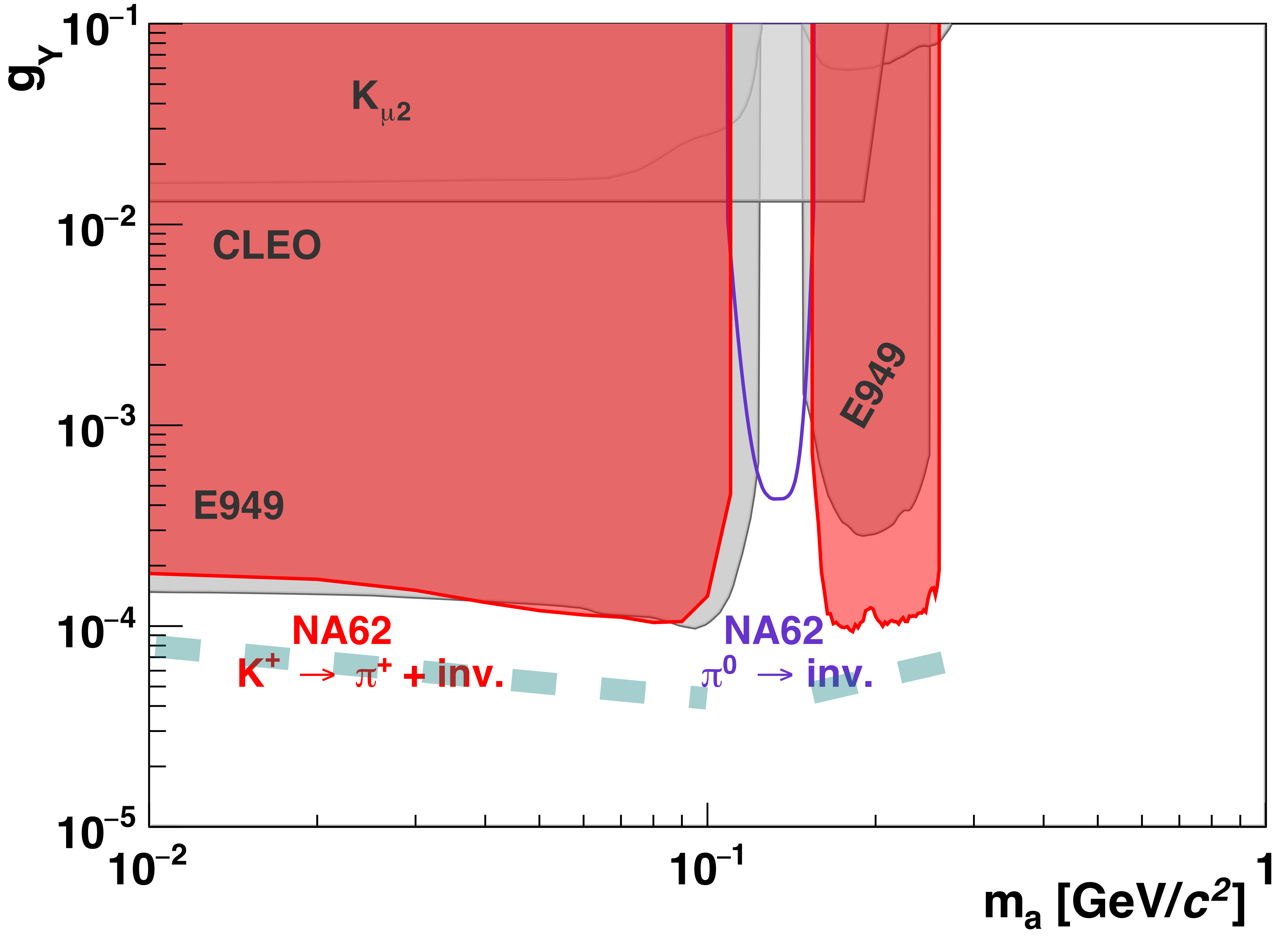
$K^+ \rightarrow \pi^+$ a, a: ALP

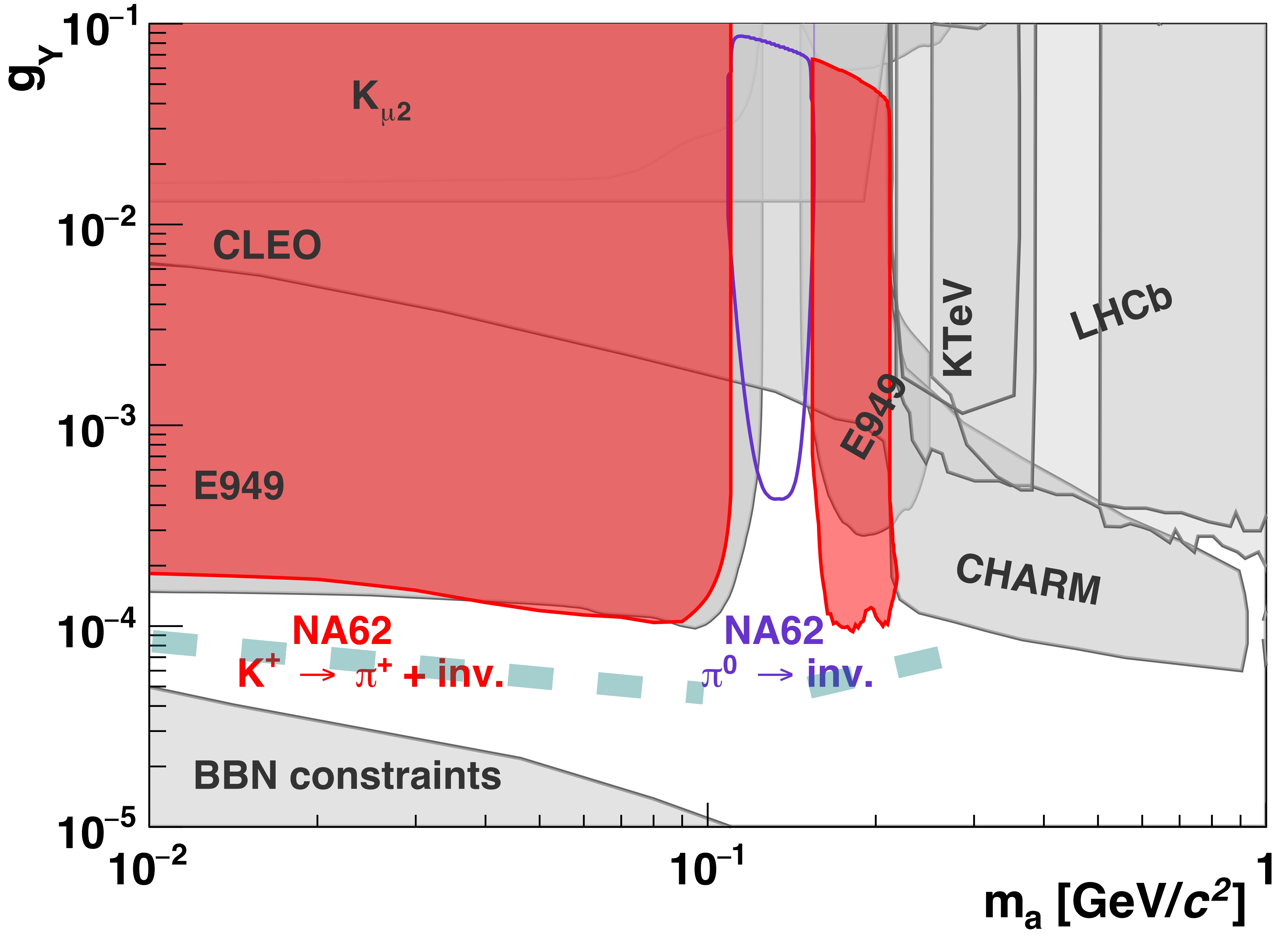
2017 dataset

JHEP 03 (2021) 058
arXiv: 2011.11329 [hep-ex]

https://www.hepdata.net/record/ins1832447
https://www.hepdata.net/record/ins1822910

HEPData



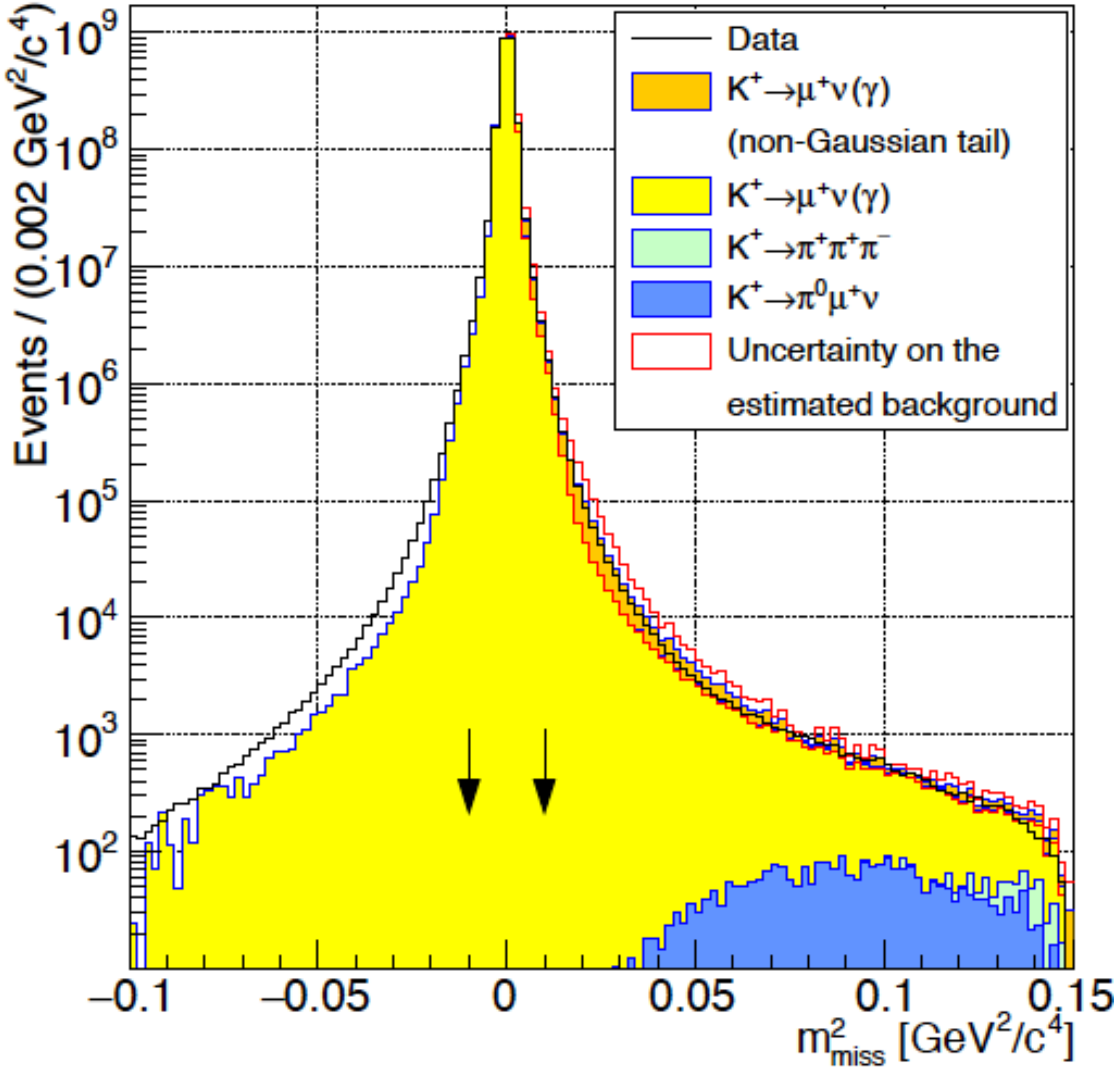


Background estimation for $K^+ \to \mu^+\nu X$, $X \to$ invisible

Assumption: the non-Gaussian tails of the m miss 2 spectrum are left-right symmetrical.

A “tail” component is added to the estimated background in each m^2_{miss} bin in the region $m^2_{miss} > 0$ equal to the difference between the data and simulated spectra in the symmetric mass bin with respect to $m^2_{miss} = 0$.

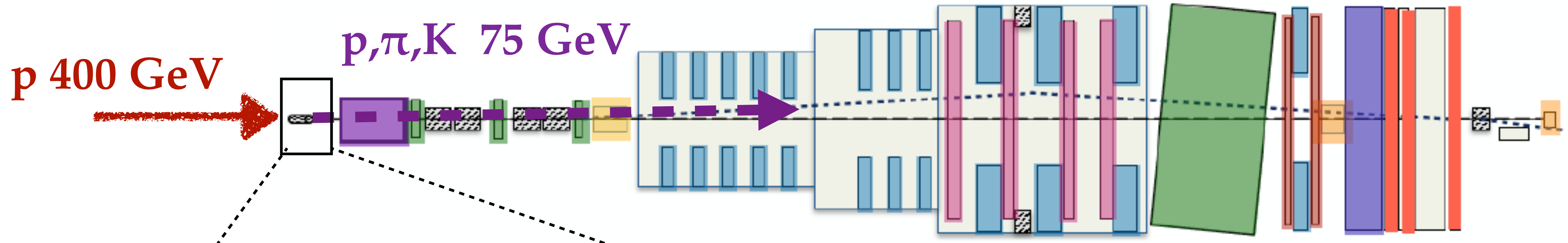
A 100% uncertainty is conservatively assigned to this component to account for the above assumption.

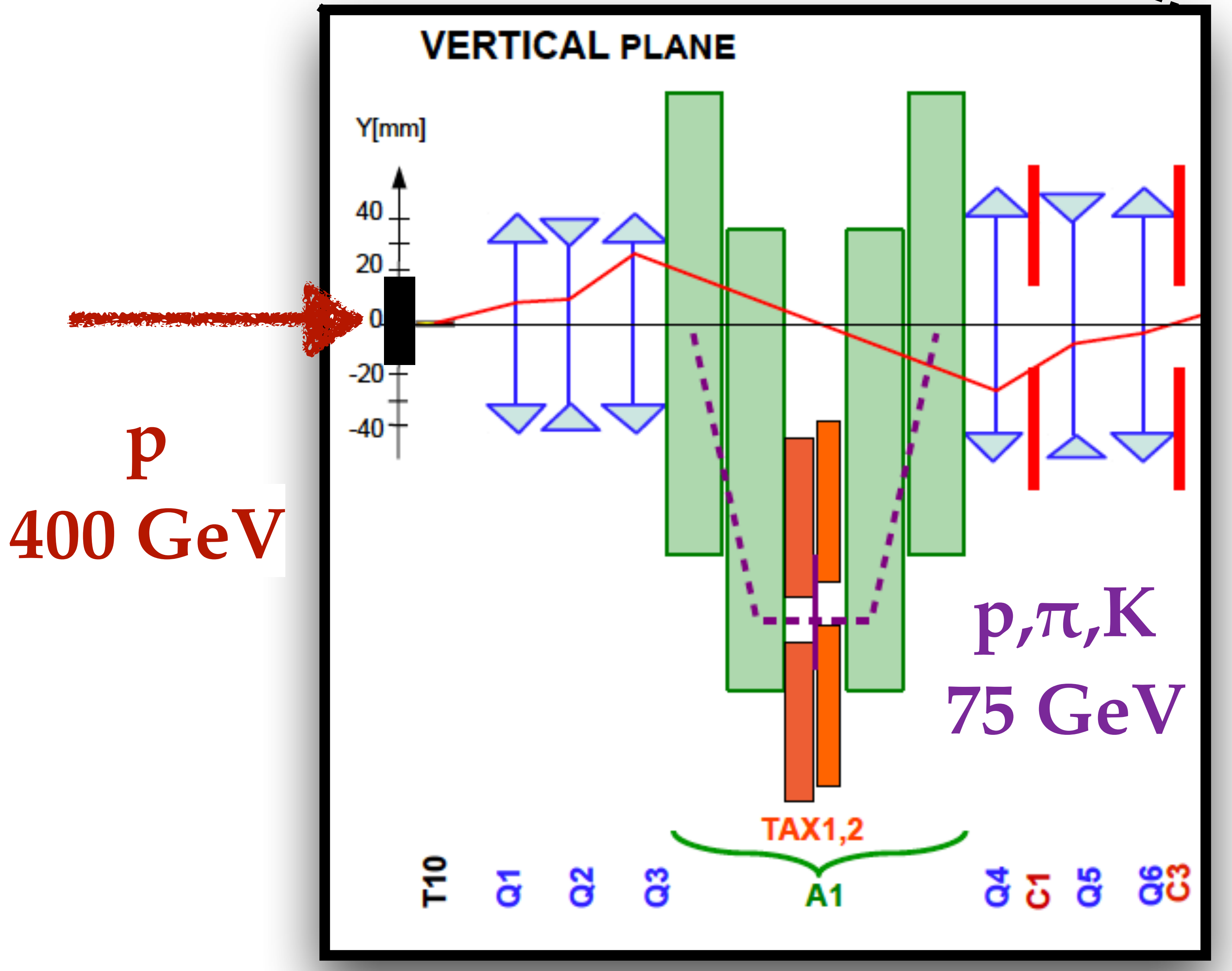


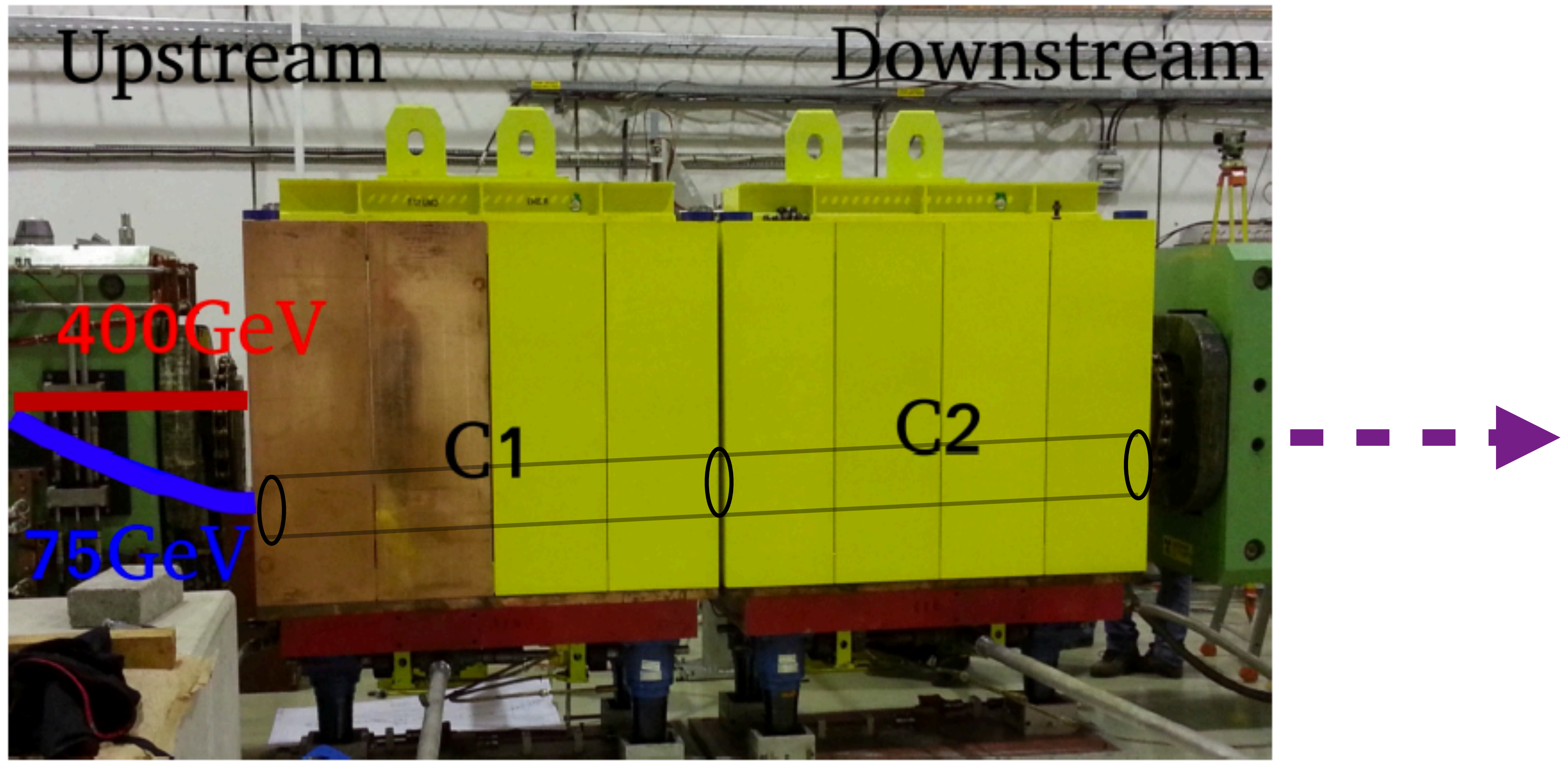
Not-only Kaons

A large Kaon sample is ready to be analyzed but:
searches for exotic particles are limited by the kaon mass

<u>Standard kaon mode</u>



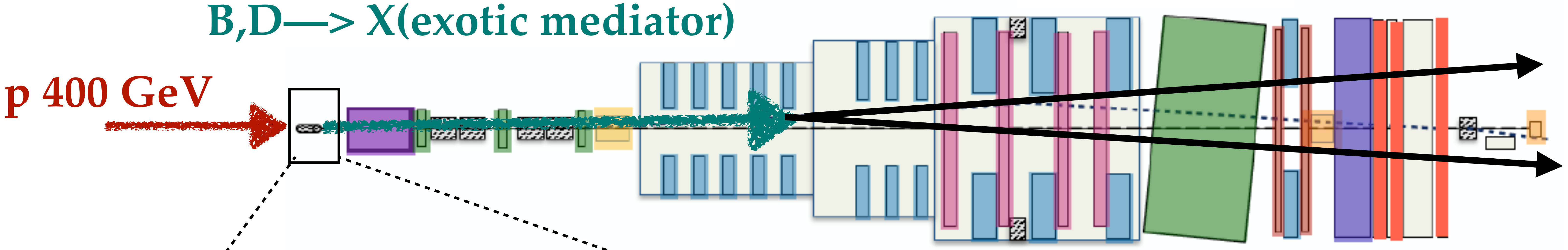


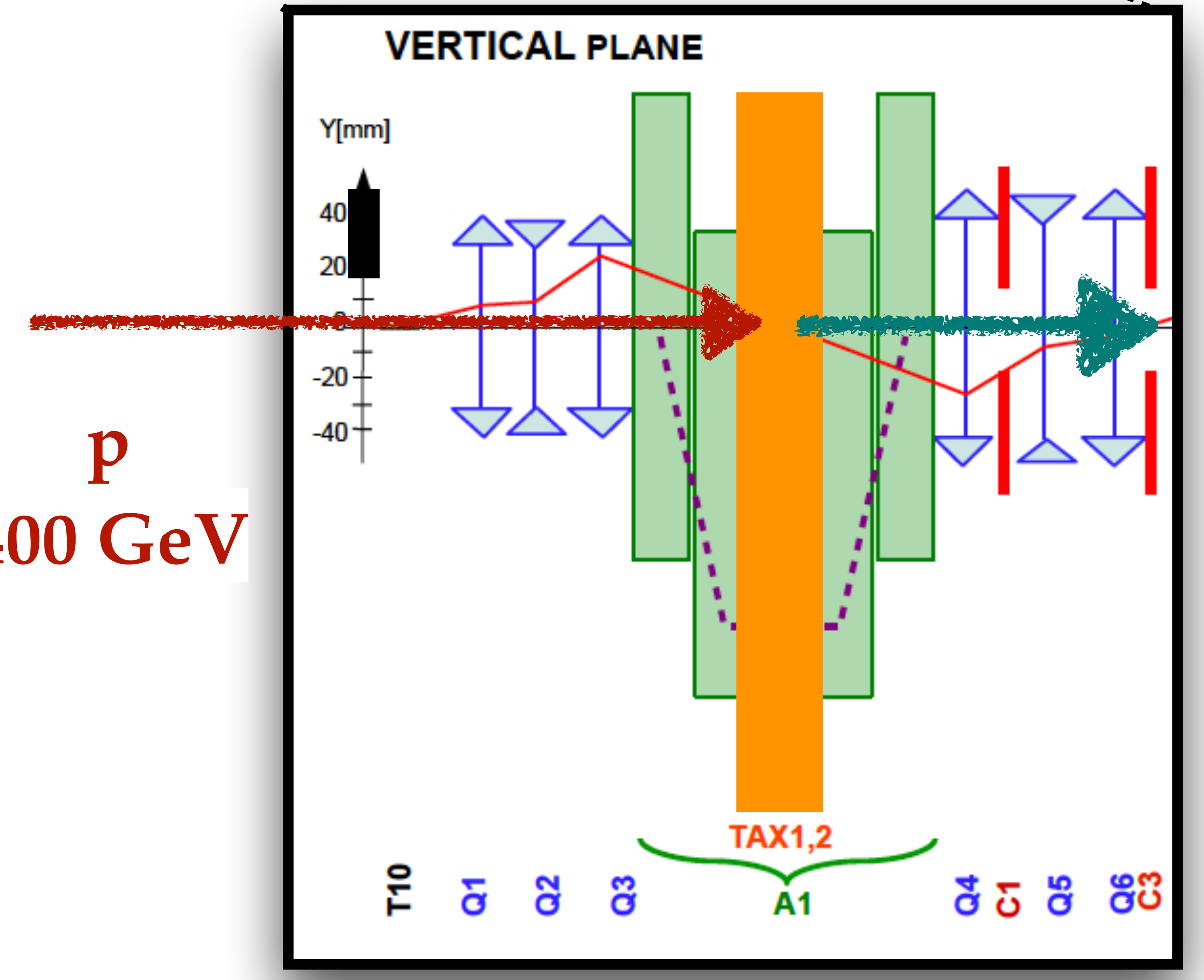


Not-only Kaons

Beam dump mode

B and D instantaneously decay to exotic mediators and SM particles which are stopped/deviated





Also $\gamma\gamma$ signature to search for ALPs from Primakoff