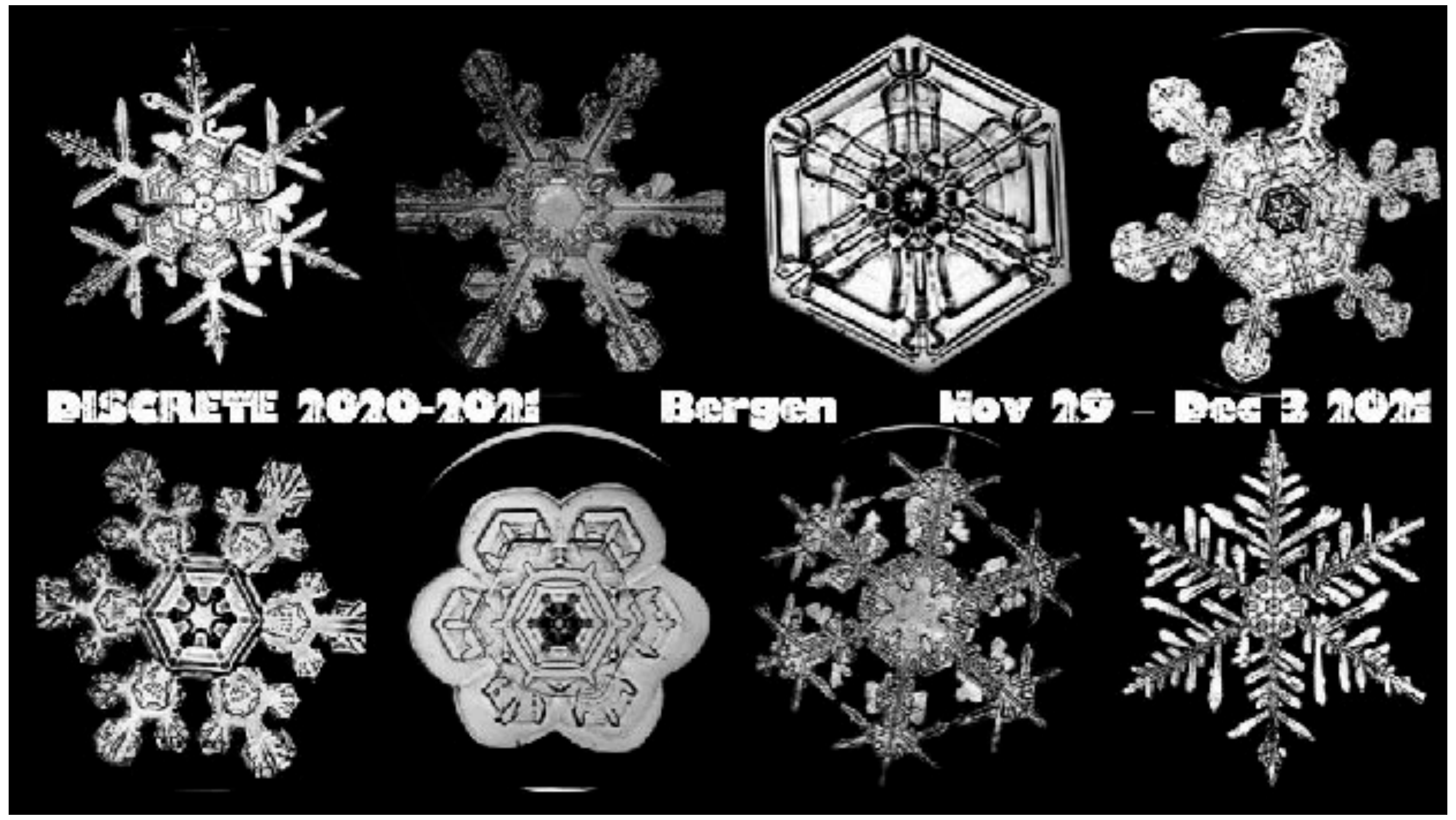
Search for K⁺ decays to a lepton and invisible particles

Roberta Volpe

roberta.volpe@cern.ch

Comenius University, Bratislava (SK)

On behalf of the NA62 Collaboration



DISCRETE 2021

Bergen, Norway, 30 November 2021

Outline

- The NA62 experiment
- Data analyses:
  - ✦ $K^+ \to e^+ X_{inv}$ — Phys. Lett. B 807 (2020) 135599
    - $K^+ \to e^+ N$
  - ✦ $K^+ \to \mu^+ X_{inv}$ — Phys. Lett. B 816 (2021) 136259
    - $K^+ \to \mu^+ N$
    - $K^+ \to \mu^+ \nu \phi$

N: Heavy Neutral Lepton

ϕ: new scalar or vector

Heavy neutral leptons

Massive sterile neutrinos generated with low scale seesaw mechanism

νMSM

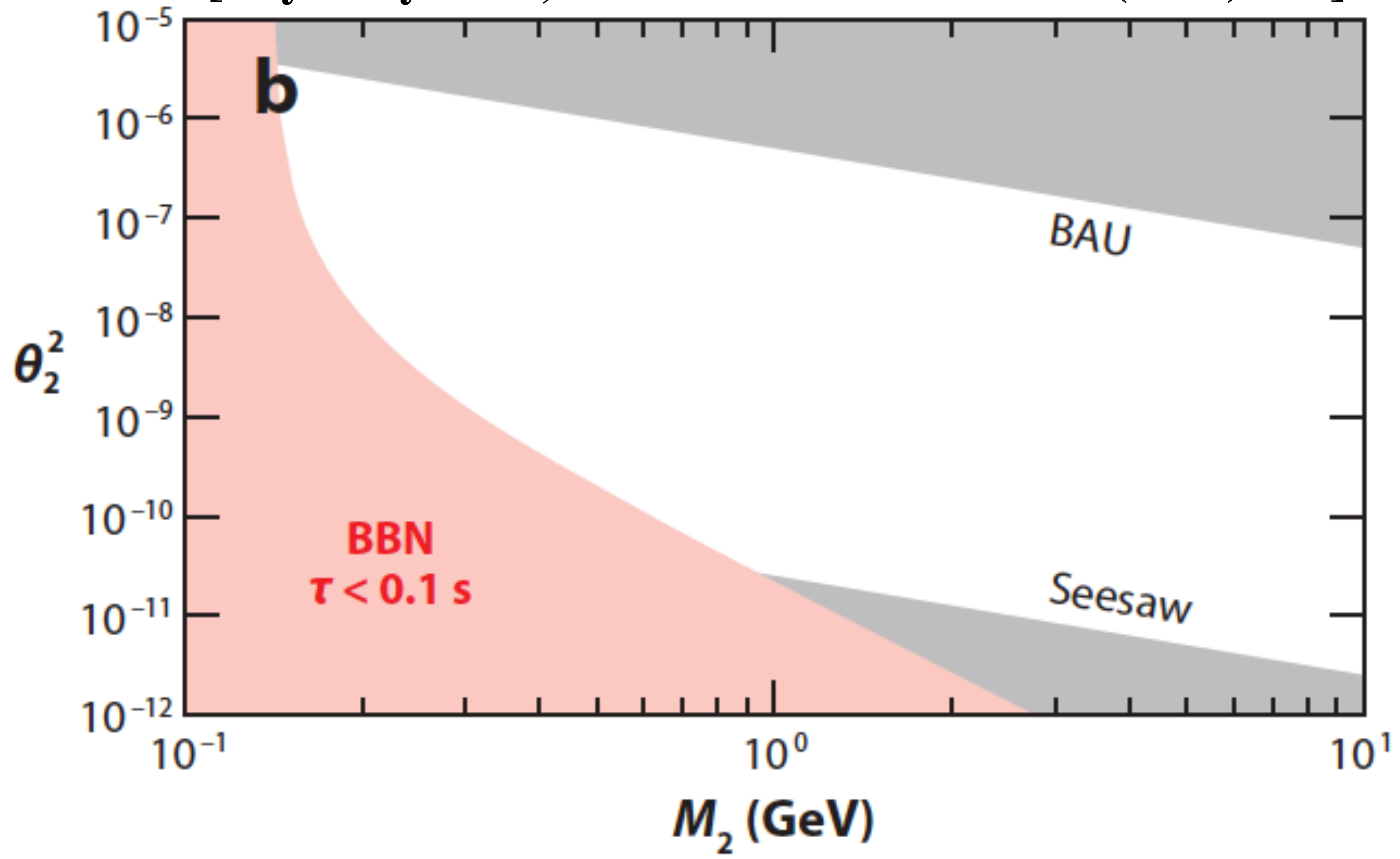
Neutrino Minimal Standard Model

T. Asaka, M. Shaposhnikov, Phys. Lett. B 620 (2005) 17.

3 right handed neutrinos

Considering the constrains from Neutrinos oscillation, Dark matter amount, Baryon Asymmetry of the Universe (BAU):

[Boyarsky et al., Ann.Rev.Nucl.Part.Sci.59 (2009) 191]

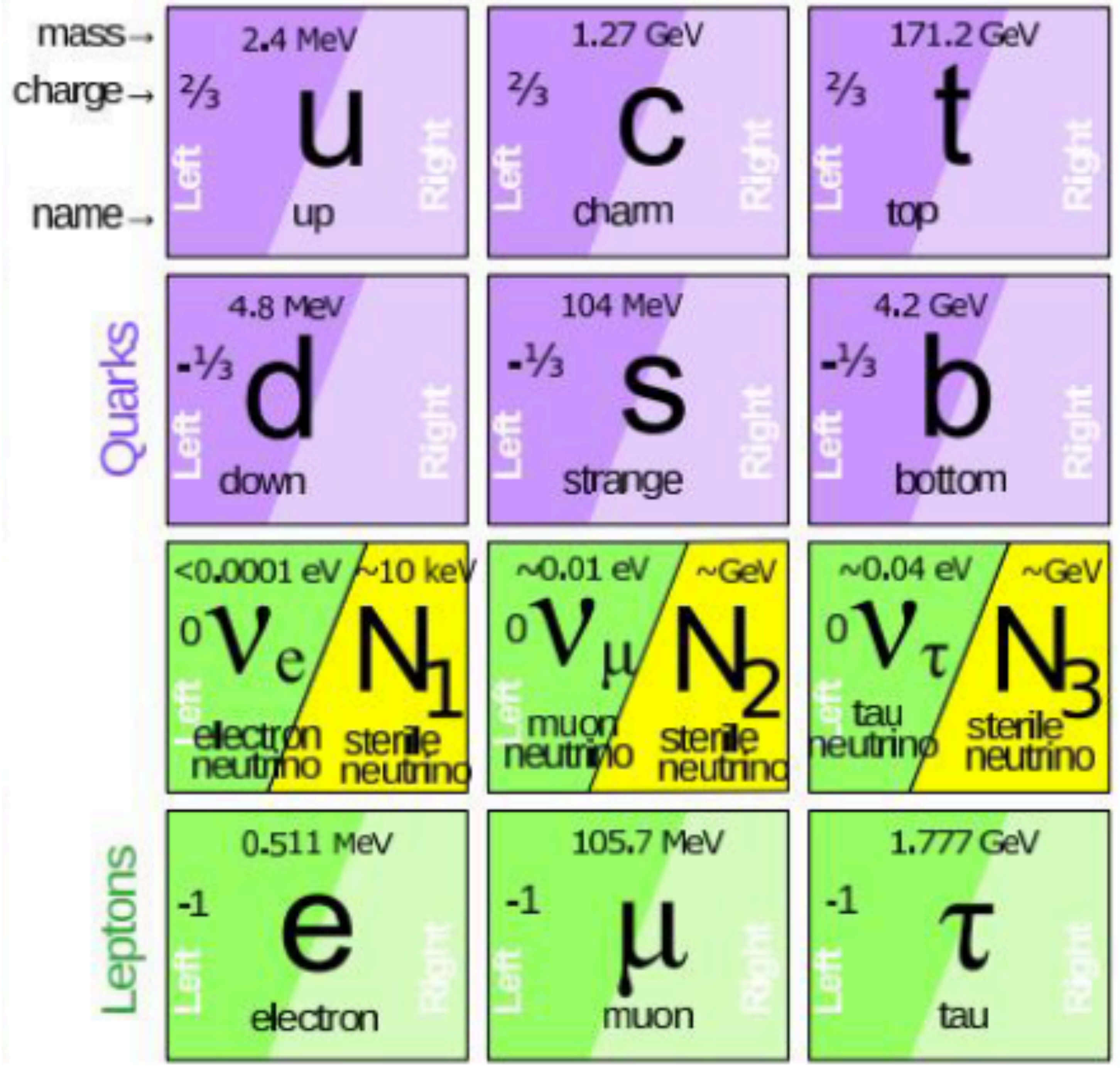


Lightest O(keV) → Dark Matter candidate,

the other two O(10 MeV – GeV)

$K^+ \longrightarrow e/\mu^+ N$

nuMSM

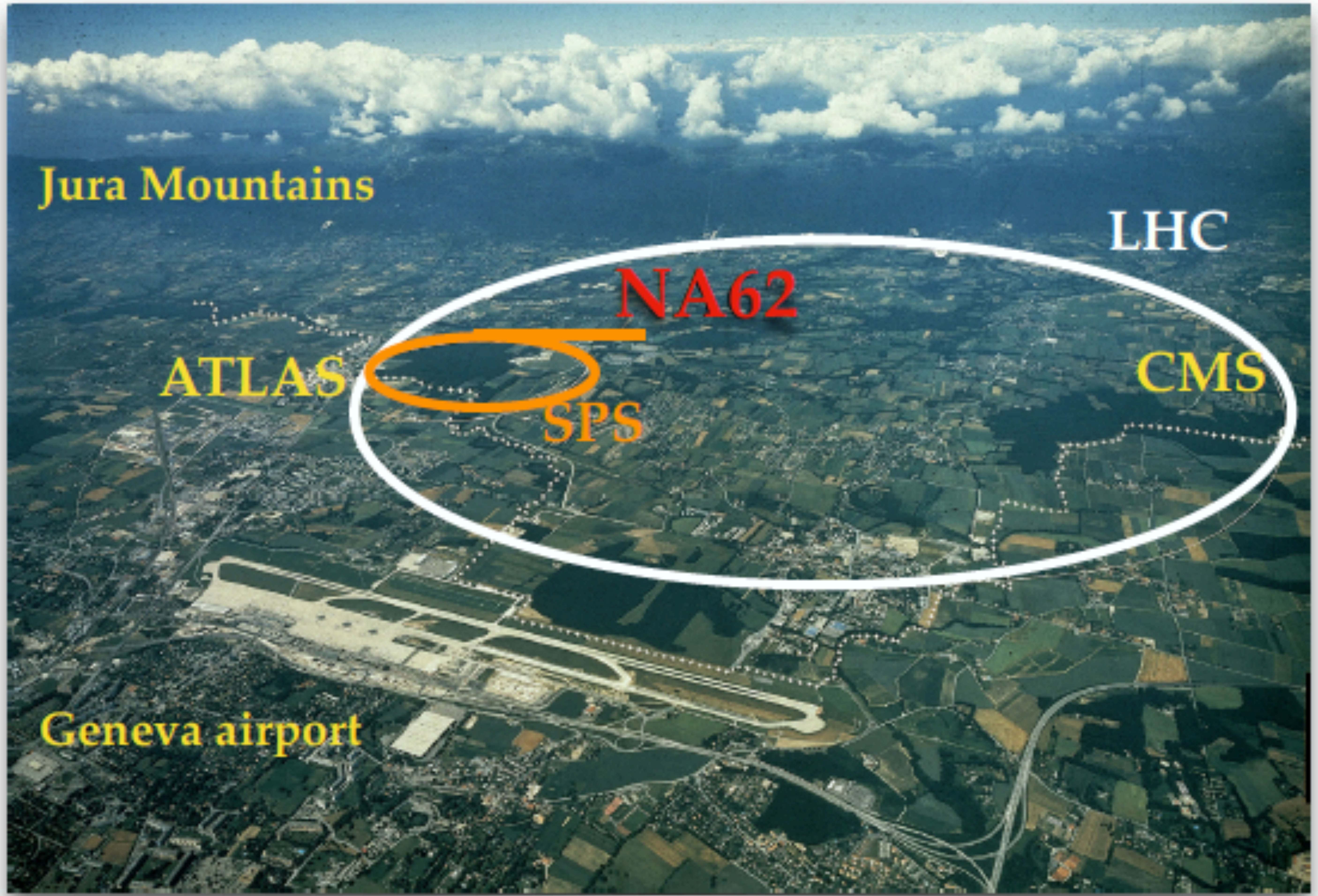


Mixing with SM neutrinos is assumed to be < 10^{-4} ⇒ **HNL decaying to SM particles only after ~10 Km** ⇒ **The signature is one single track**

NA62 Collaboration

~ 300 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)

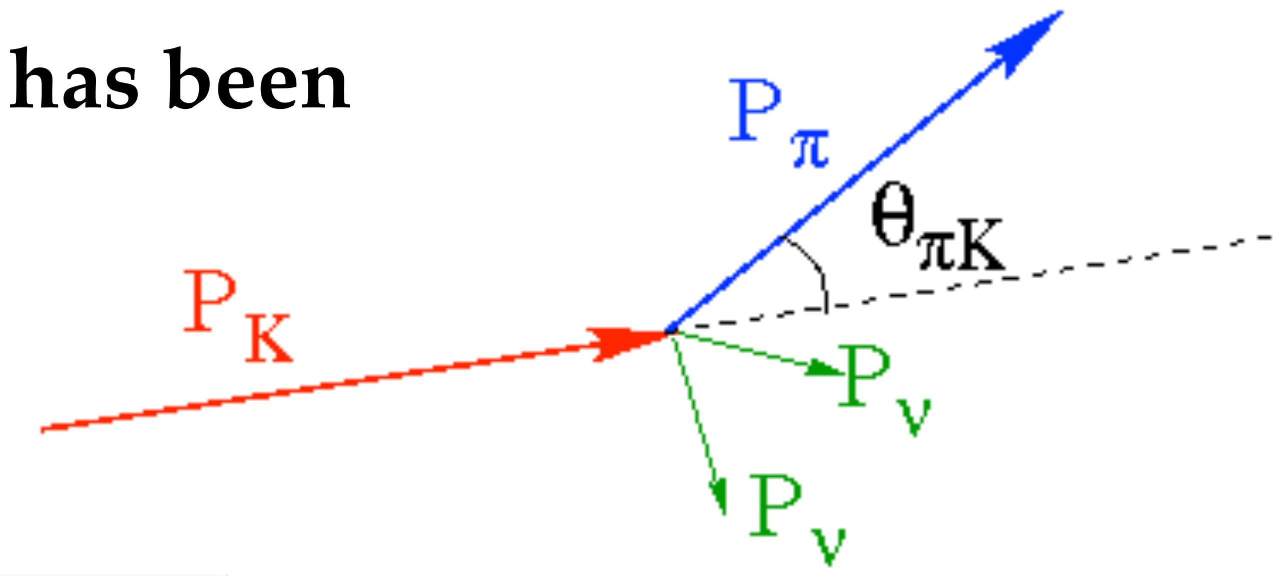


The main aim is the measurement of
BR($K^+ \to \pi^+ \nu\nu$)
with a precision better than 10%

Collected good quality data in 2016-2018

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

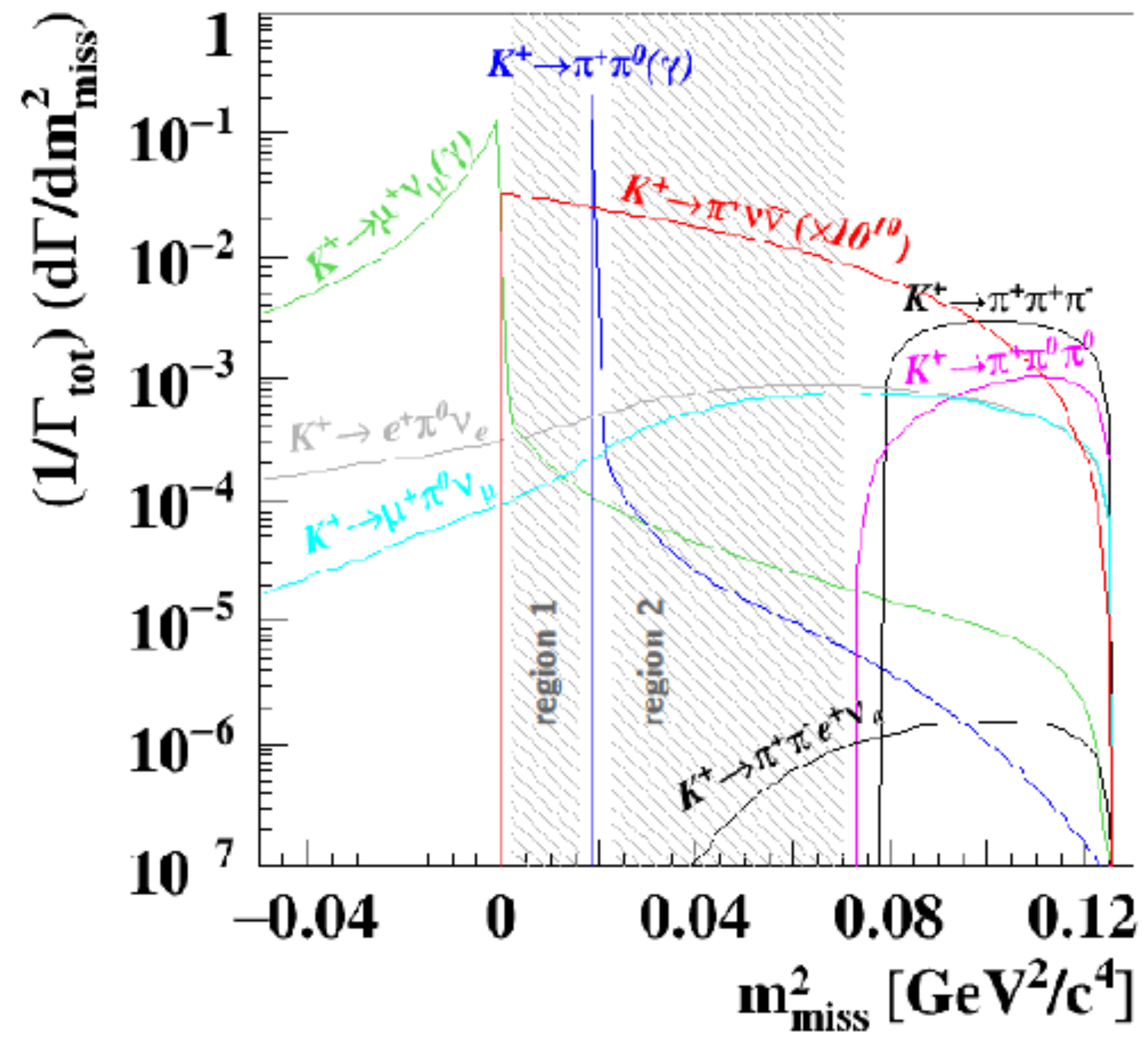
The experimental apparatus has been designed in order to detect:



Decay in flight

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

Talk by
M. Zamkovsky
https://indico.cern.ch/event/868021/contributions/4520768/



- 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

Features useful also for the "lepton+invisible" searches

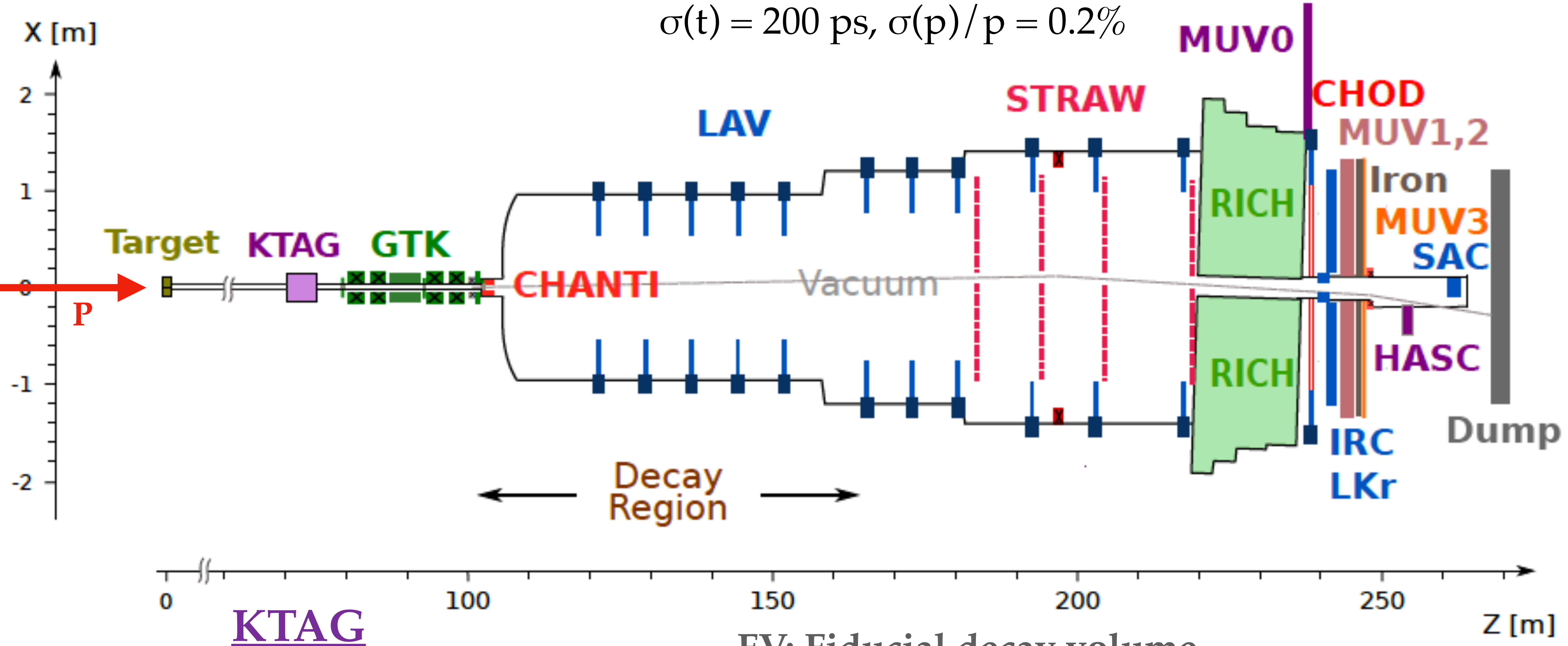
NA62 apparatus: the p and K beam

JINST 12 P05025 (2017), arxiv:1703.08501

33x10^{11} ppp on T10 (750 MHz at GTK3)
Secondary beam: 75 GeV/c momentum
K^+ (6%)/π^+ (70%)/p(24%)

Upstream track reconstructed by the GTK

Kaon tracking
Si pixel, 3 stations
$\sigma(t) = 200$ ps, $\sigma(p)/p = 0.2\%$



KTAG

Kaon identification
Differential
Cherenkov detector

FV: Fiducial decay volume

tube evacuated
(500 m^3 at 10^{-6} mbar)

NA62 apparatus: kaon decays reconstruction

JINST 12 P05025 (2017), arxiv:1703.08501

Upstream track reconstructed by the GTK

Kaon tracking

Si pixel, 3 stations

$\sigma(t) = 200$ ps, $\sigma(p)/p = 0.2\%$

tracks reconstructed by the STRAW

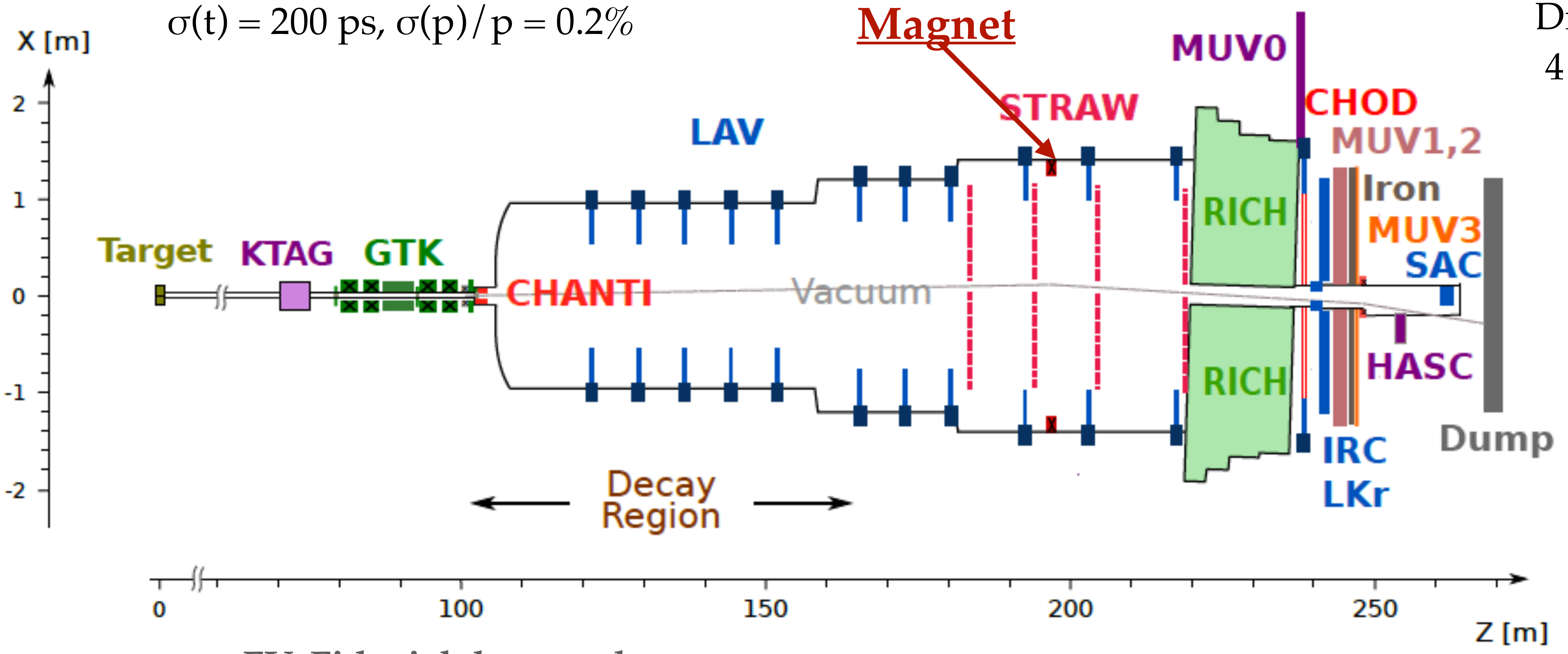
Downstream tracking:

Dipole spectrometer

4 straw-tracker stations

$\sigma(p)/p = 0.3\%$

Magnet



Charged particle

KTAG

Kaon identification

Differential Cherenkov detector

FV: Fiducial decay volume

evacuated tube

(500 m^3 at 10^{-6} mbar)

NA62 apparatus: photon veto system

JINST 12 P05025 (2017), arxiv:1703.08501

Hermetic photon veto system
(LAV,SAV,LKr)

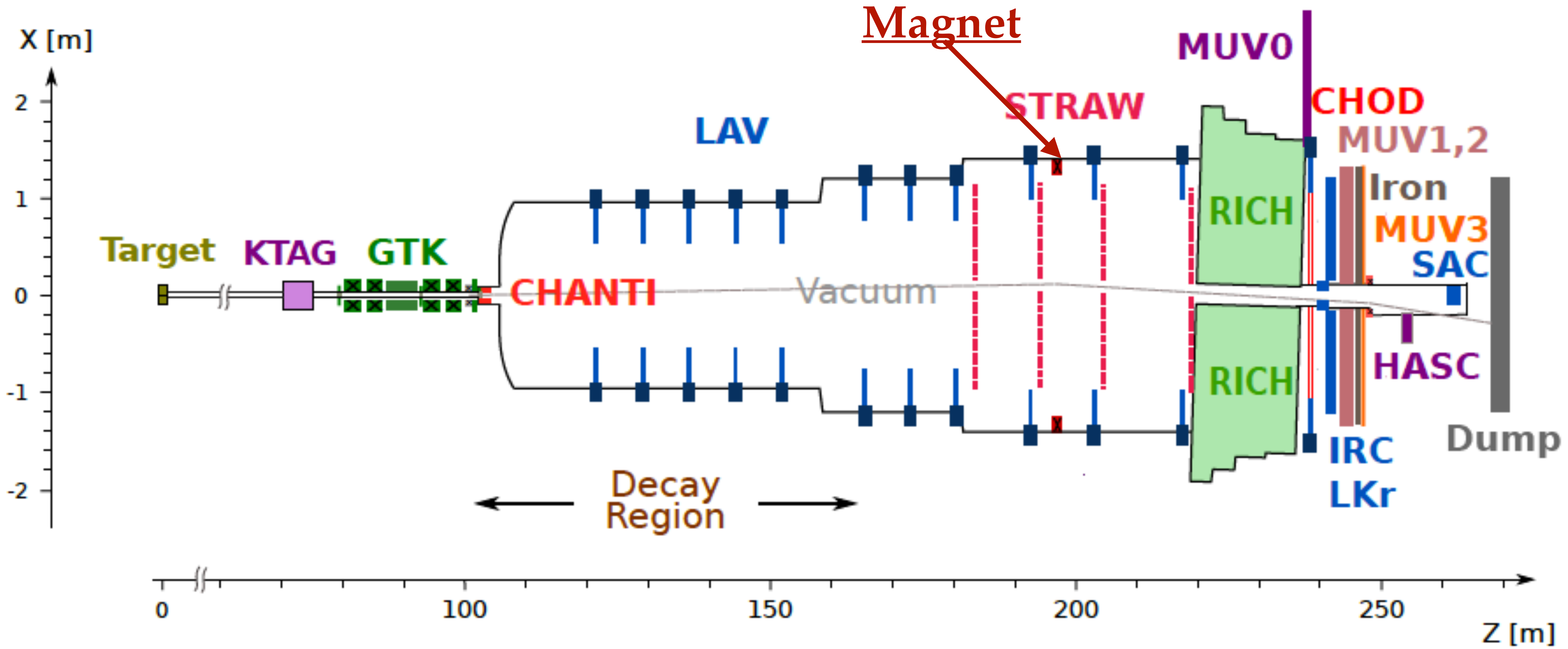
Multiplicity rejection
(LAV,SAV,LKr, CHOD,STRAW)

Large Angle Veto (LAV)

12 stations (lead glass blocks)
Covering angles 8.5 <θ <50 mrad

CHOD

Charged Hodoscope,
plastic scintillator



LKr calorimeter

Photon detection

Covering angles
1<θ<8.5 mrad

πνν background rejection: $K^+ \to \pi^+\pi^0$

☑ $\varepsilon(\pi^0)$= 3 10^{-8}

Small Angle Veto (SAV)

IRC: Inner Ring Calorimeter
Small Angle Calorimeter, Covering angles <1 mrad

NA62 apparatus: particle identification

JINST 12 P05025 (2017), arxiv:1703.08501

RICH
Ring Imaging Cherenkov detector

Neon 1 Atm
π/μ/e separation
Reference event time

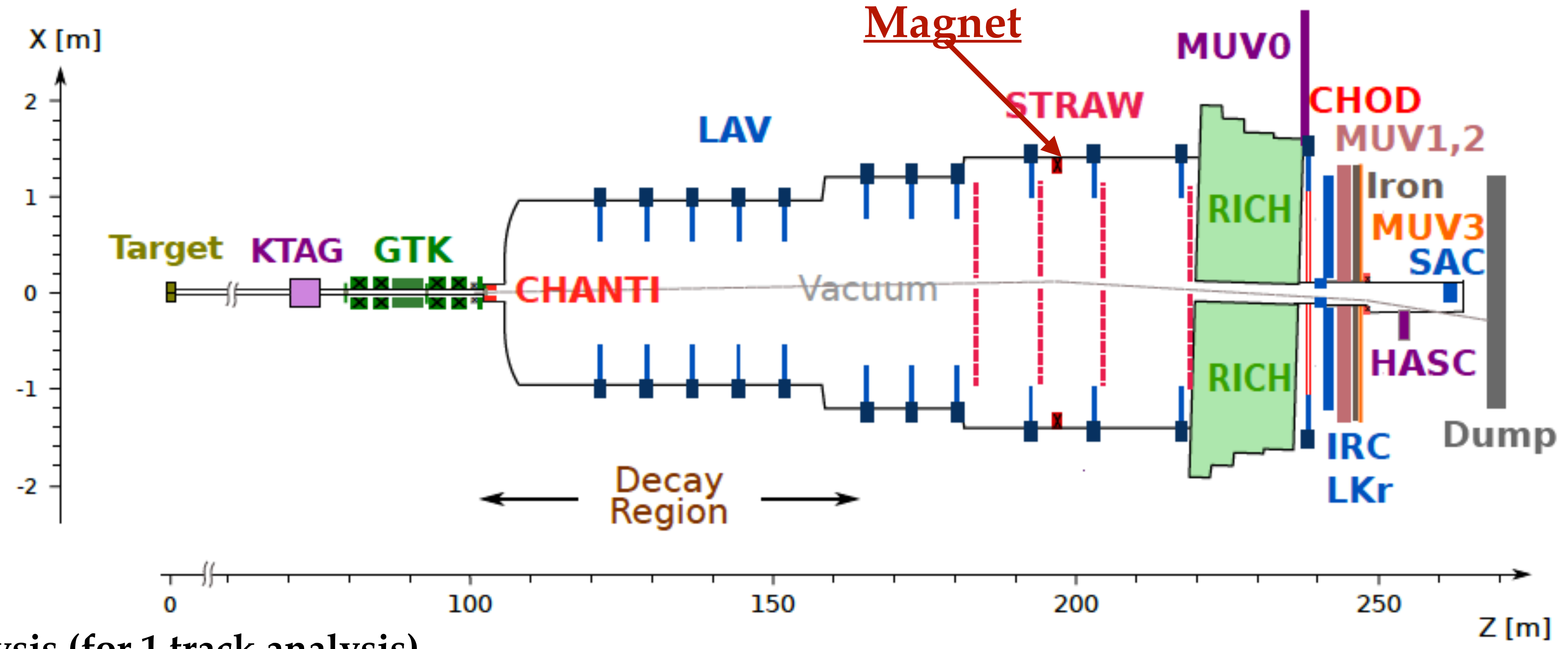
The RICH is used also to obtain an independent p momentum measurement

MUV **Muon veto system**

MUV1 & MUV2: Hadronic calorimeters for the μ/π separation

MUV3: Efficient fast Muon Veto used in the hardware trigger level.

E/p variable
E = energy deposited in LKr
p = track momentum



available PID tools in NA62:

Multivariate analysis (for 1 track analysis) with MUV1, MUV2 and LKr info

2 algorithms for the RICH variables

- very good kinematic reconstruction
- Precise time measurements by the CHOD, RICH, KTAG

Data taking timeline

NA62 Data Taking

- ☑ 2015 Commissioning run
- ☑ 2016 Commissioning + Physics run (45 days)
- ☑ 2017 Physics run (160 days)
- ☑ 2018 Physics run (217 days)
- ☐ New Physics run started this summer (2021 run just ended for the winter break)

Till the next LHC Long Shutdown

results on K->πνν and K->πX$_{inv}$:

[PLB 791 (2019) 156]

[JHEP 11 (2020) 042]

[JHEP 06 (2021) 093]

M. Zamkovsky https://indico.cern.ch/event/868021/contributions/4520768/

Much broader physics program

eg at DISCRETE 2020-2021:

LNV, LFV searches: S. Kholodenko https://indico.cern.ch/event/868021/contributions/4520326/

Radiative decays: C. Biino https://indico.cern.ch/event/868021/contributions/4621051/

$K^+ \longrightarrow \ell^+ N$: Analysis strategy

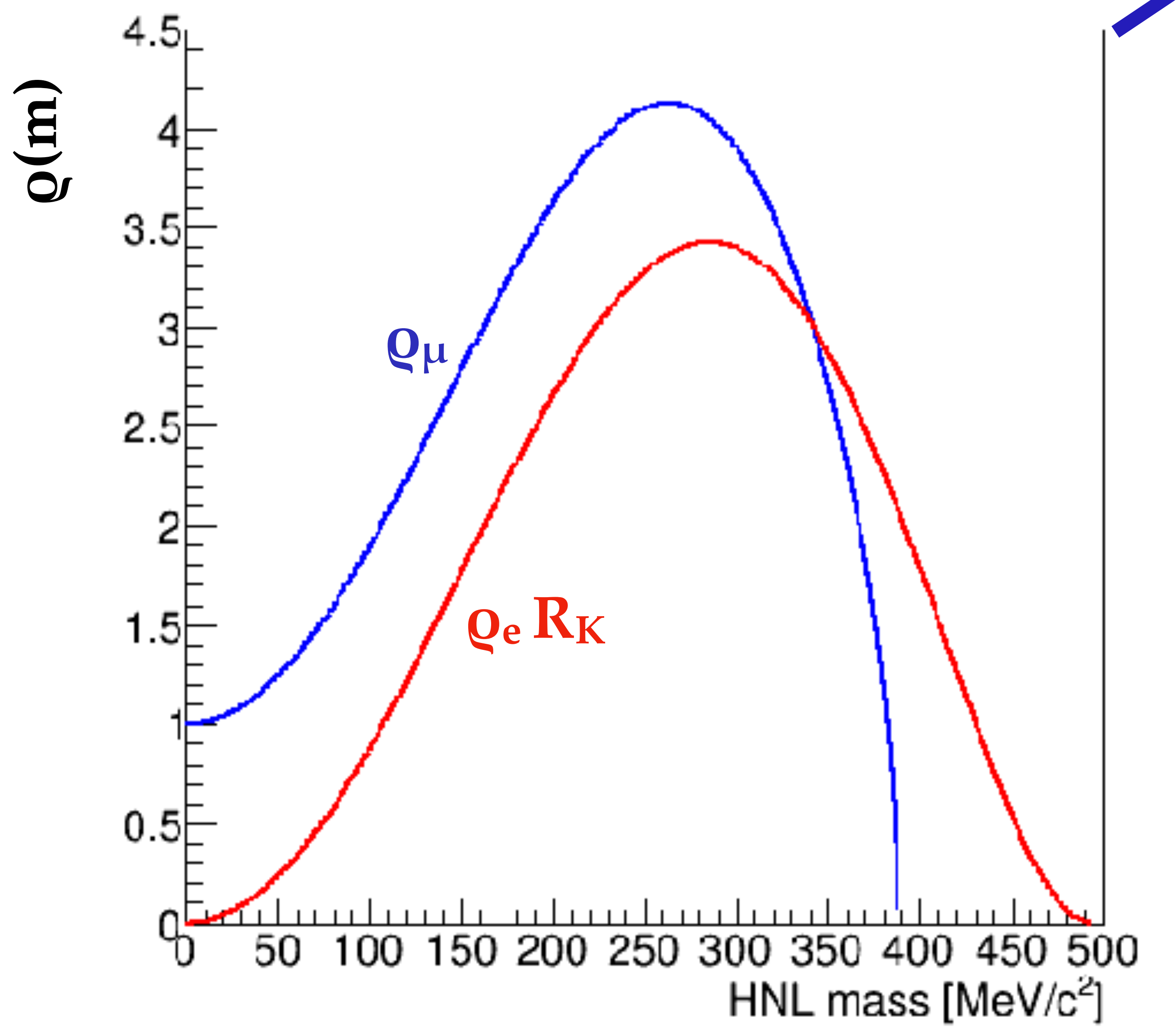
ℓ=e,μ

$$N_S^\ell = N_K^\ell \cdot \mathcal{B}(K^+ \to \ell^+ N) \cdot A_\ell^N$$

Number of SM decays: $K^+ \to \ell^+ \nu$

$$\mathcal{B}(K^+ \to \ell^+ N) = \mathcal{B}(K^+ \to \ell^+ \nu) \cdot \rho_\ell(m_N) \cdot |U_{\ell 4}|^2$$

Phase-space factor



Strength of mixing with SM neutrinos, <u>parameter of interest</u>

Minimal model:
Assuming that there is one dominant flavor mixing

<u>Discriminant variable:</u>

Kaon tracker — Downstream tracker

$$m^2_{\text{miss}} = (P_K - P_\ell)^2$$

<u>SM and HNL common event selection:</u>

- Single positive track
- Muon and positron identification with:
  - E/p
  - Muon Veto
  - RICH
- Photon vetoes

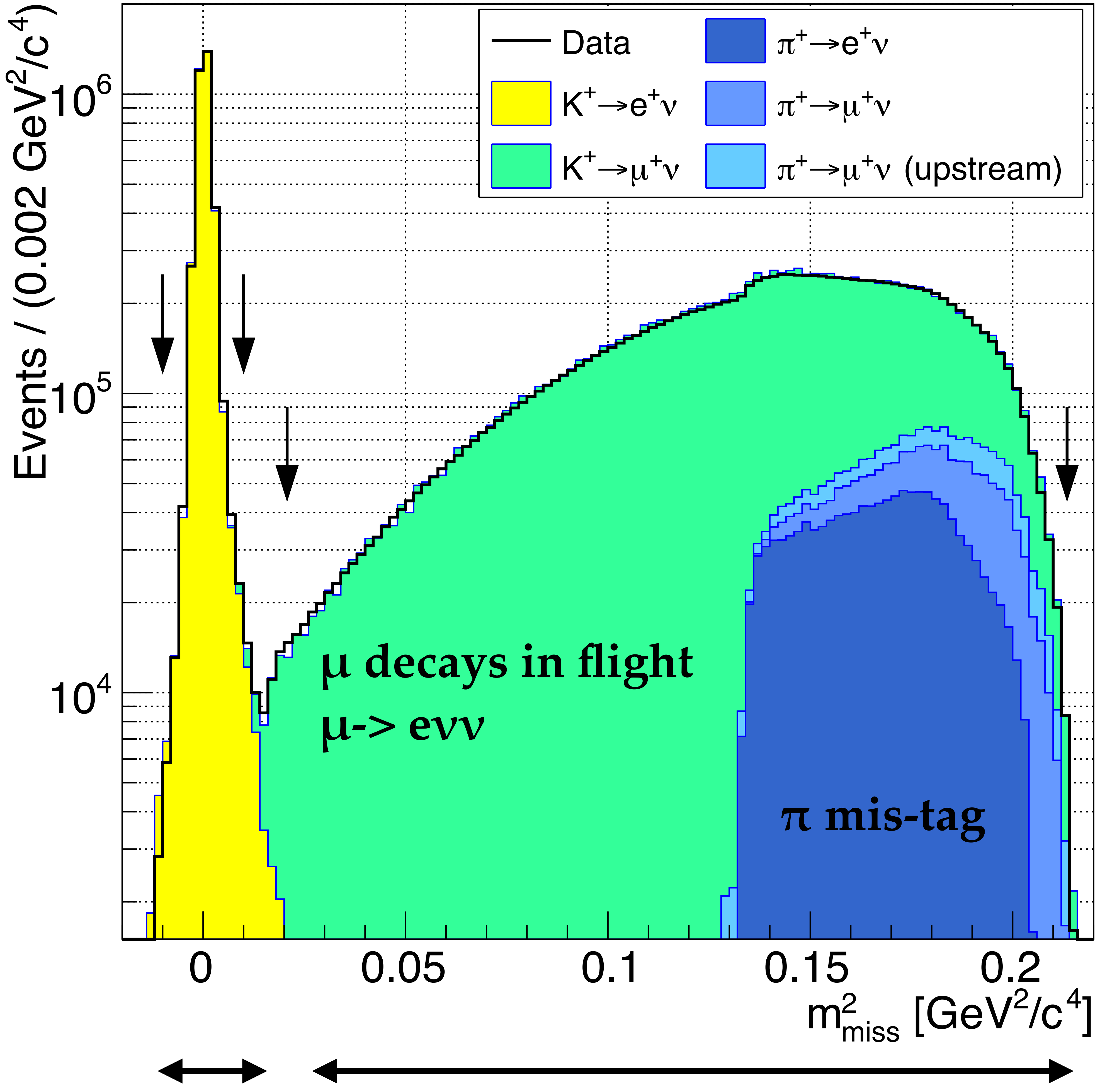
$K^+ \to e^+ N$

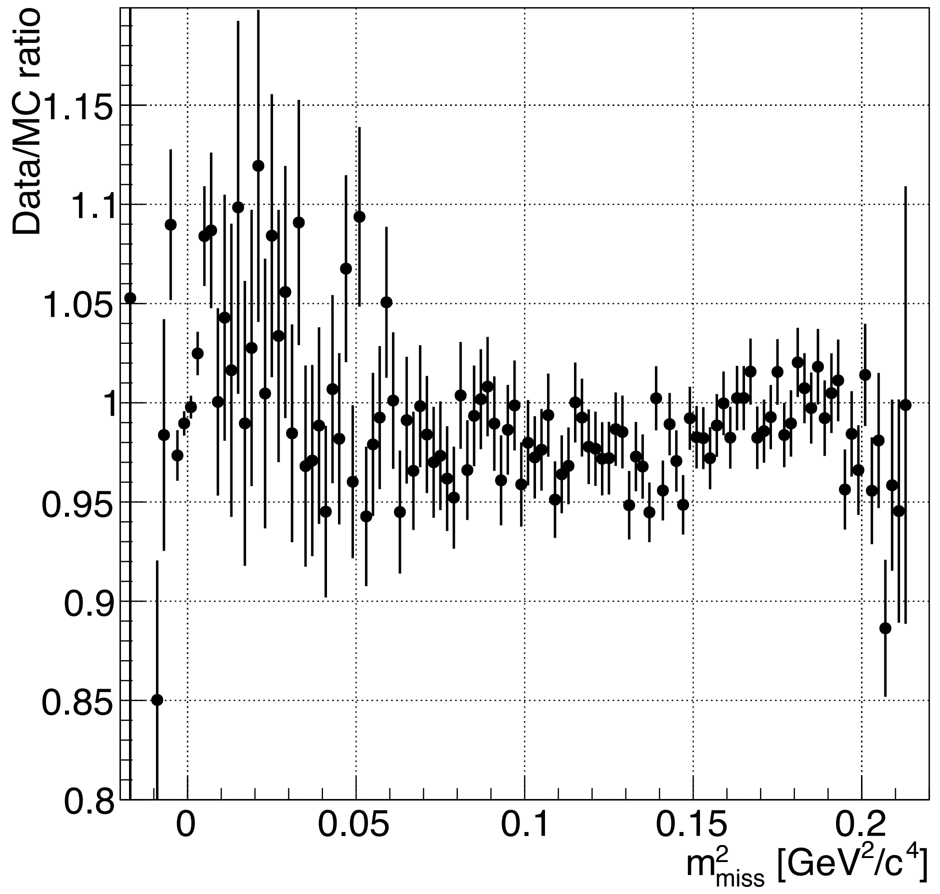
Phys. Lett. B 807 (2020) 135599

- 2017-2018 data
- $\pi\nu\nu$ trigger
- 1 track with p in [5-30] GeV
- PID: E/p and RICH
- KTAG signal
- STRAW-GTK matching
- Vetoes for photons and multitrack events

$$N_K = \frac{N_{SM}}{A_e \cdot \mathcal{B}(K^+ \to e^+\nu) + A_\mu \cdot \mathcal{B}(K^+ \to \mu^+\nu)}$$

$$= (3.52 \pm 0.02) \times 10^{12}$$

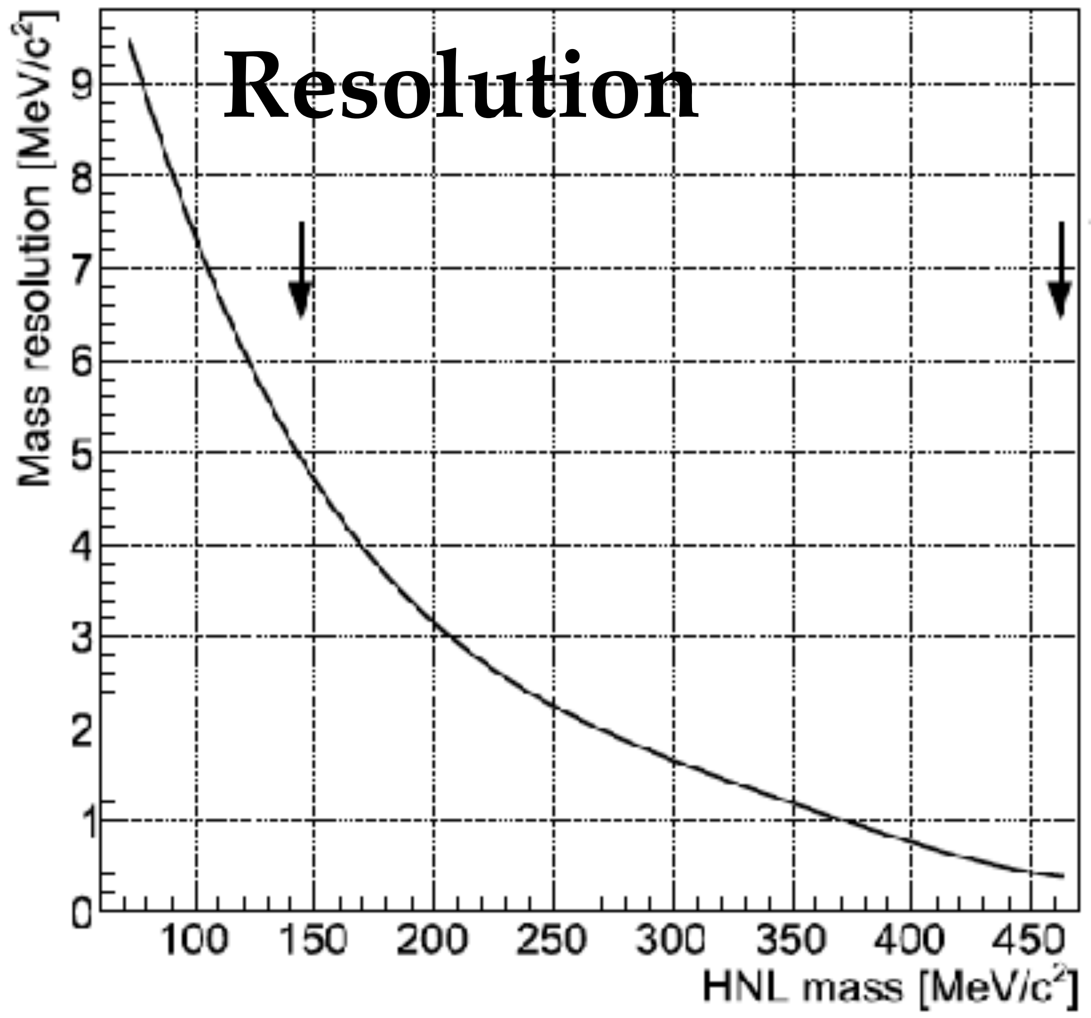


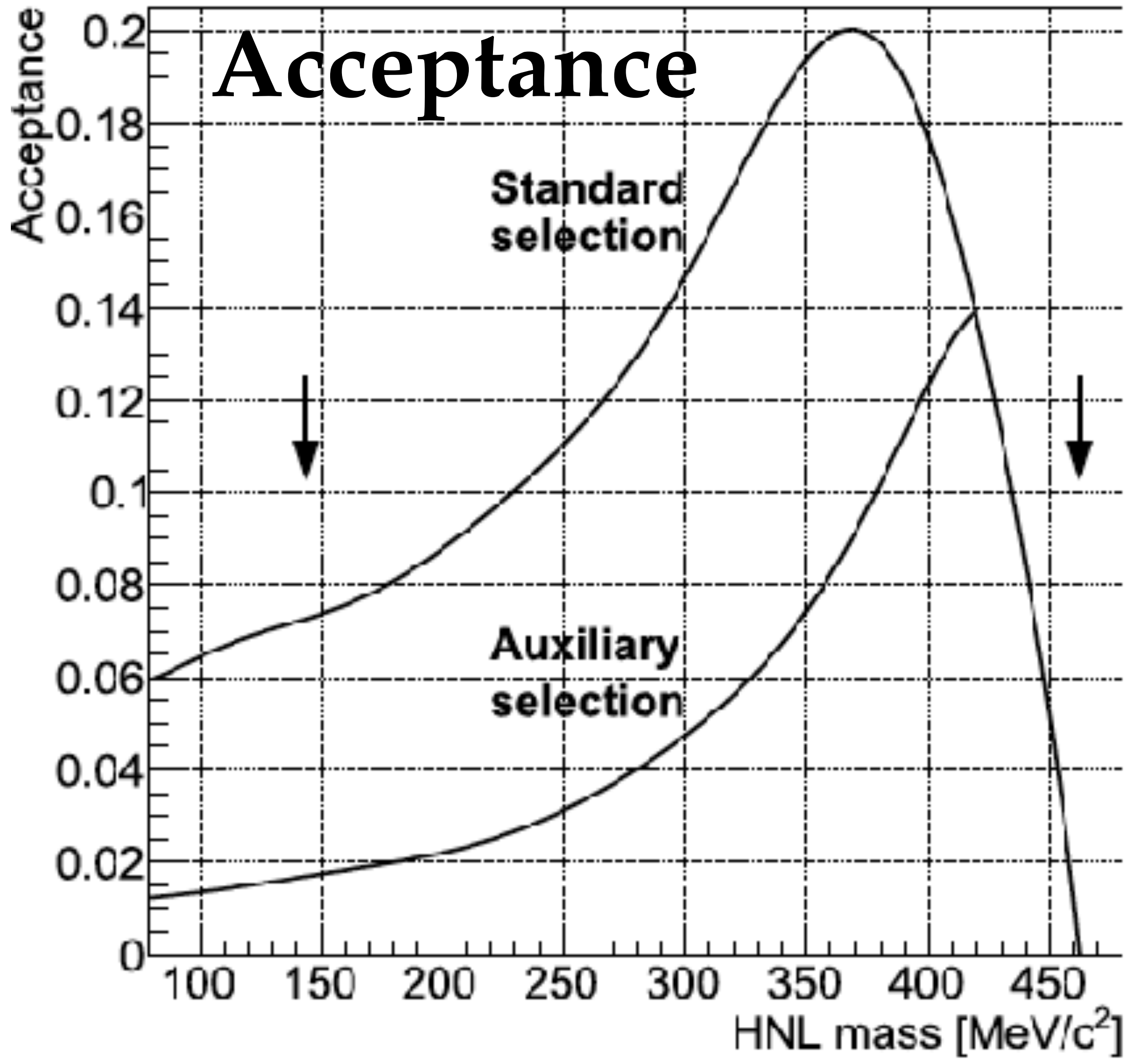


Search for a peak over the smooth background distribution

$K^+ \to e^+ N$

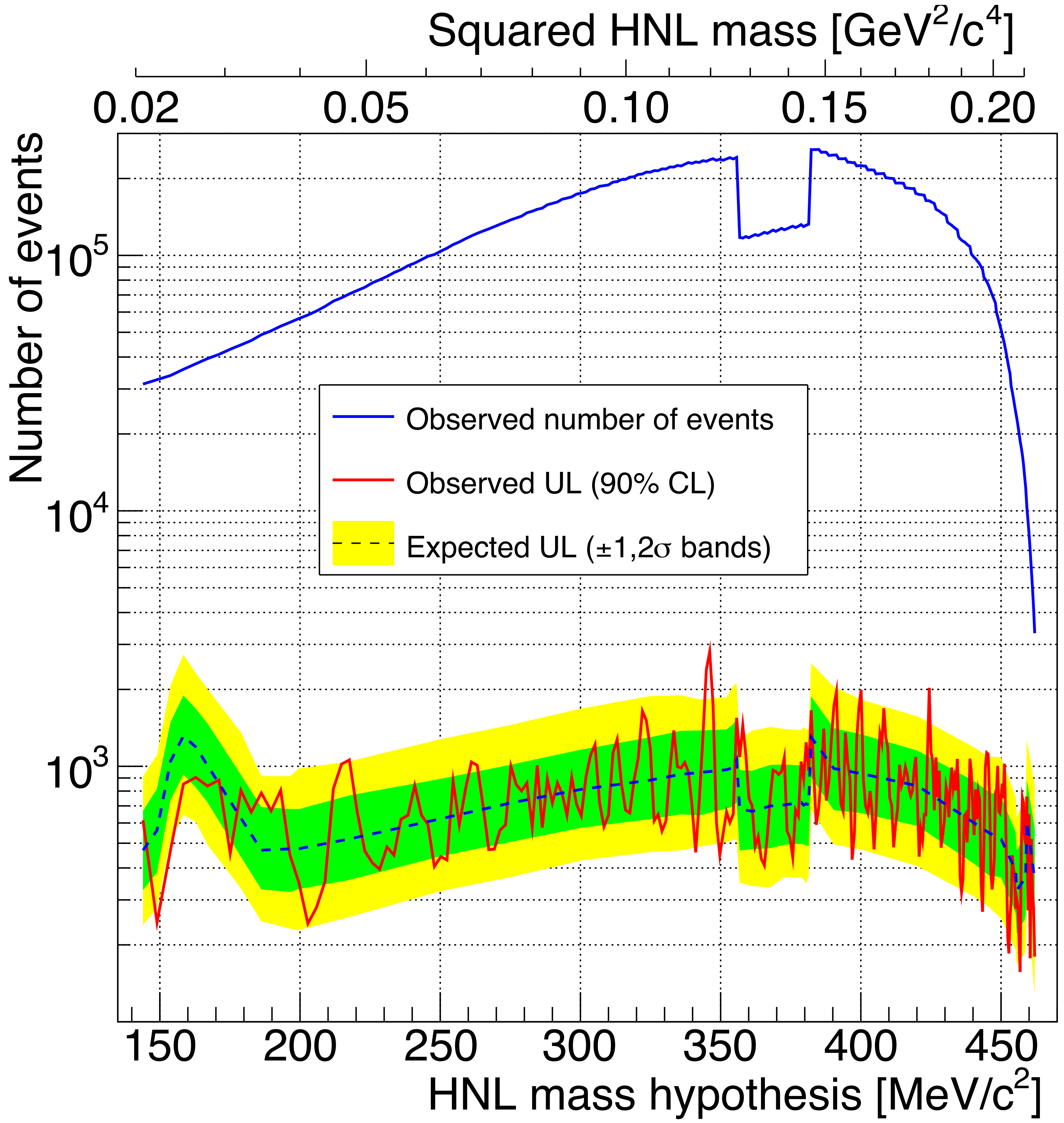
Phys. Lett. B 807 (2020) 135599





For each HNL mass hypothesis (m_N):

- m^2_{miss} in 1.5 σ
- Background evaluated from sidebands in m^2_{miss} distributions
- MC used only to check that no structures are present in the signal region



Auxiliary selection:

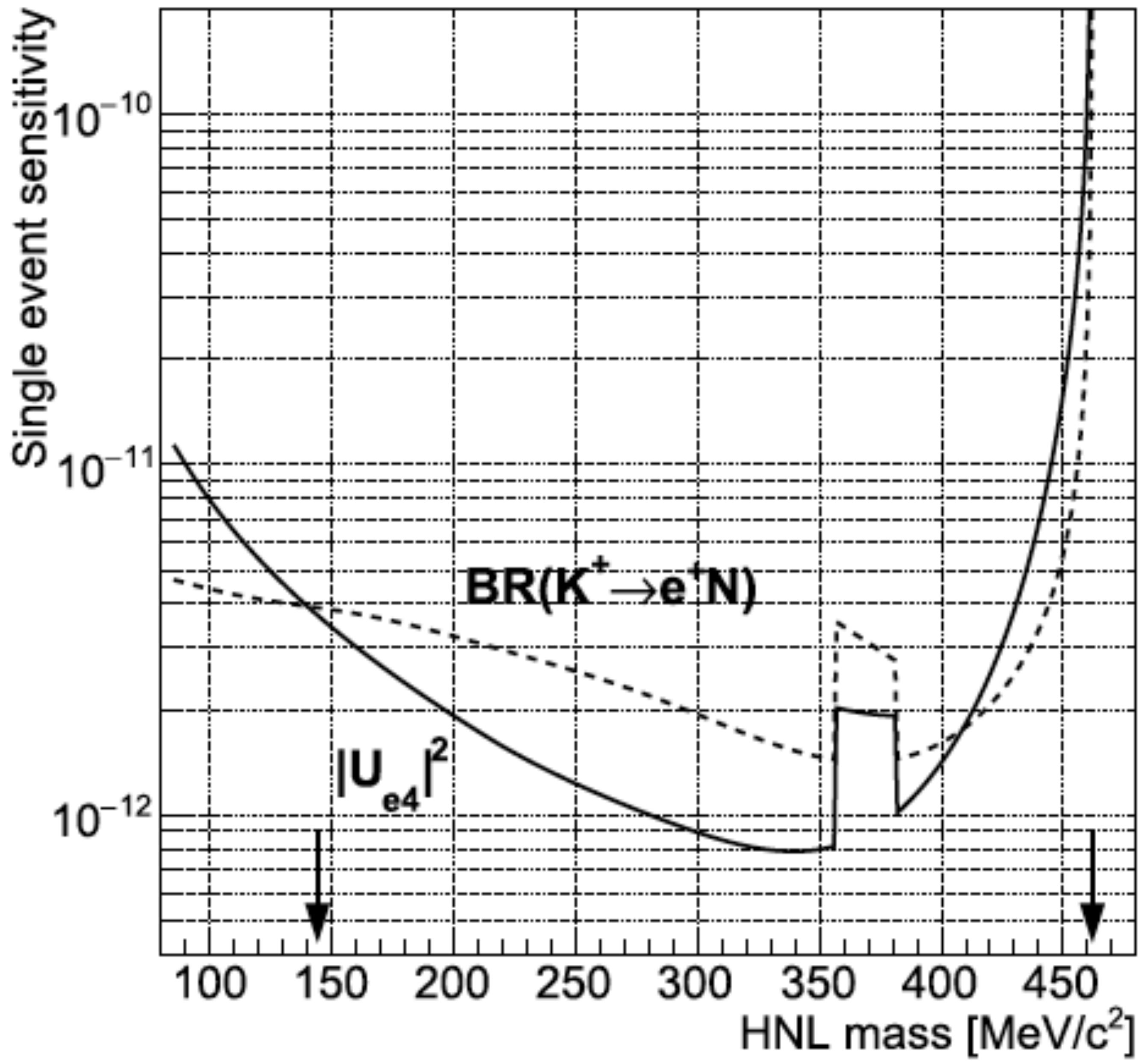
p(e) < 20 GeV/c in order to get smoother background near the $\pi^+ \to e^+\nu$ threshold.

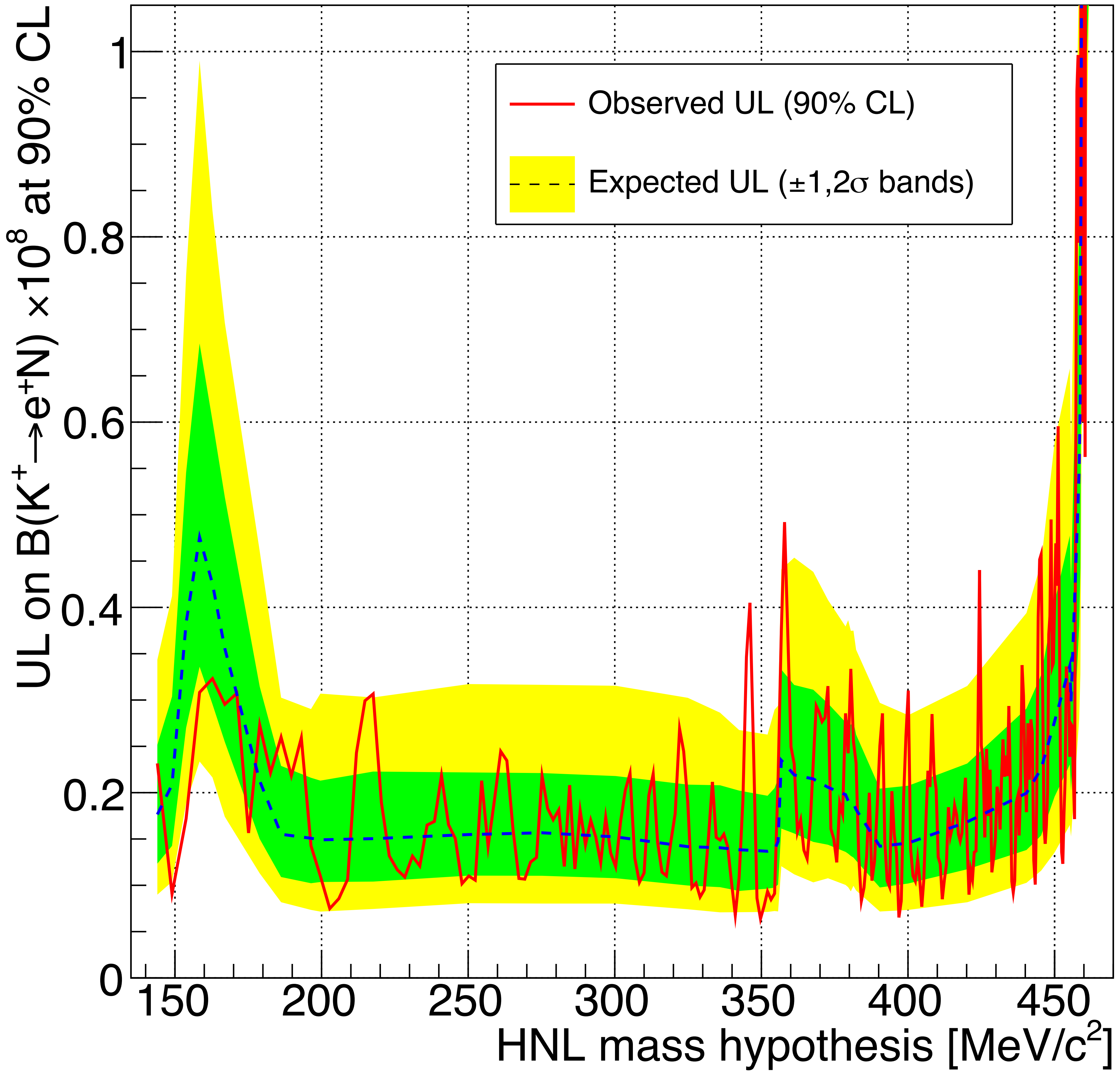
Used for m_N~[356,382] MeV

$K^+ \to e^+ N$

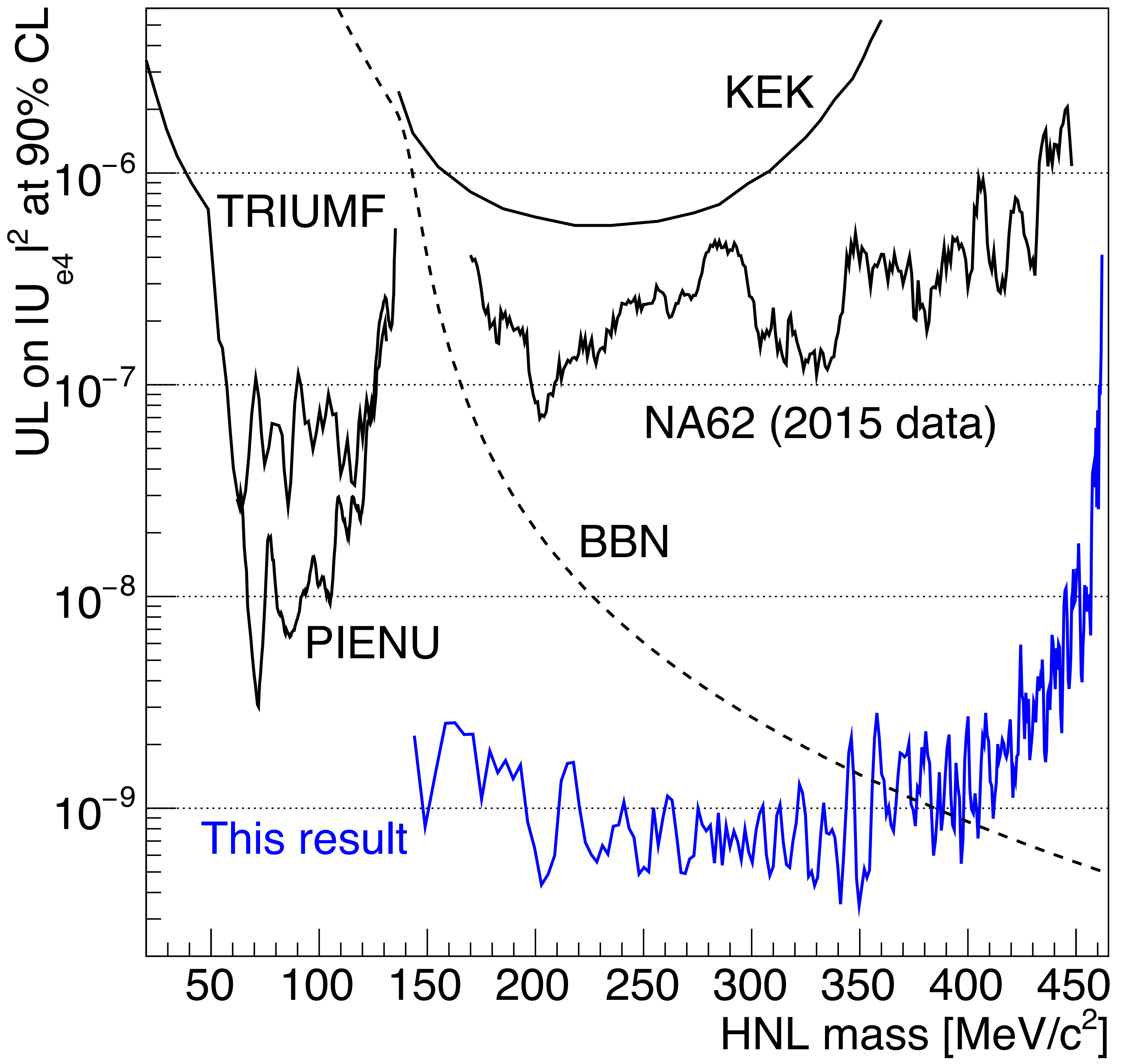
Phys. Lett. B 807 (2020) 135599

$$\mathcal{B}_{\mathrm{SES}}(K^+ \to e^+ N) = \frac{1}{N_K \cdot A_N}$$





$$|U_{e4}|^2_{\mathrm{SES}} = \frac{\mathcal{B}_{\mathrm{SES}}(K^+ \to e^+ N)}{\mathcal{B}(K^+ \to e^+ \nu) \cdot \rho_e(m_N)}$$



- Maximum local significance of 3.6 σ
- Accounting for look-elsewhere effect, global significance is 2.2 σ

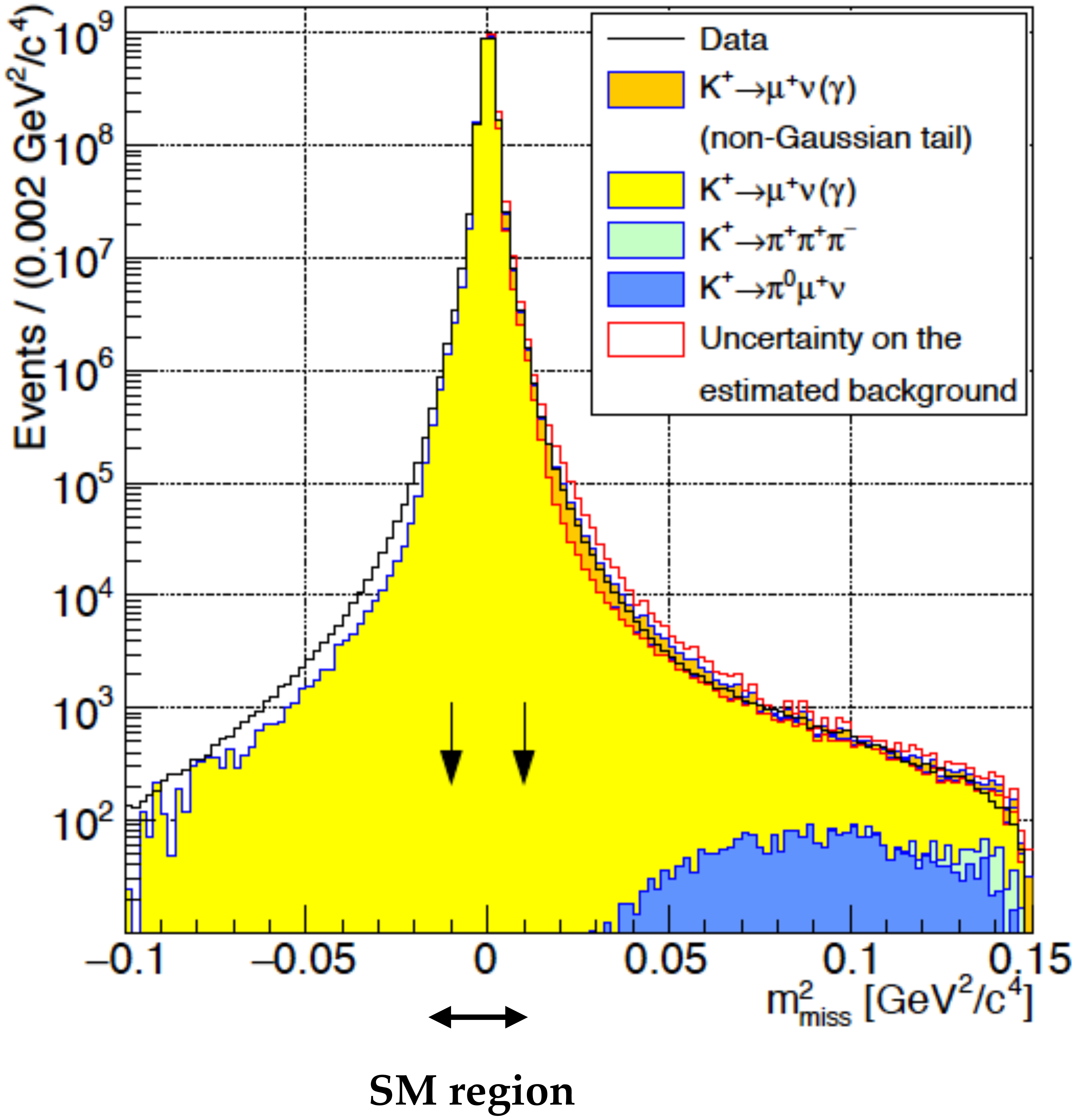
$K^+ \rightarrow \mu^+ N$

Phys. Lett. B 816 (2021) 136259

- 2016-2018 data
- downscaled trigger
- 1 track with p in [5-30] GeV
- PID: E/p, RICH and MUV3
- KTAG signal
- STRAW-GTK matching
- Vetoes for photons and multitrack events

$$N_K = \frac{N_{SM}}{A_{SM} \cdot \mathcal{B}(K^+ \rightarrow \mu^+\nu)}$$

$$= (1.14 \pm 0.02) \times 10^{10}$$



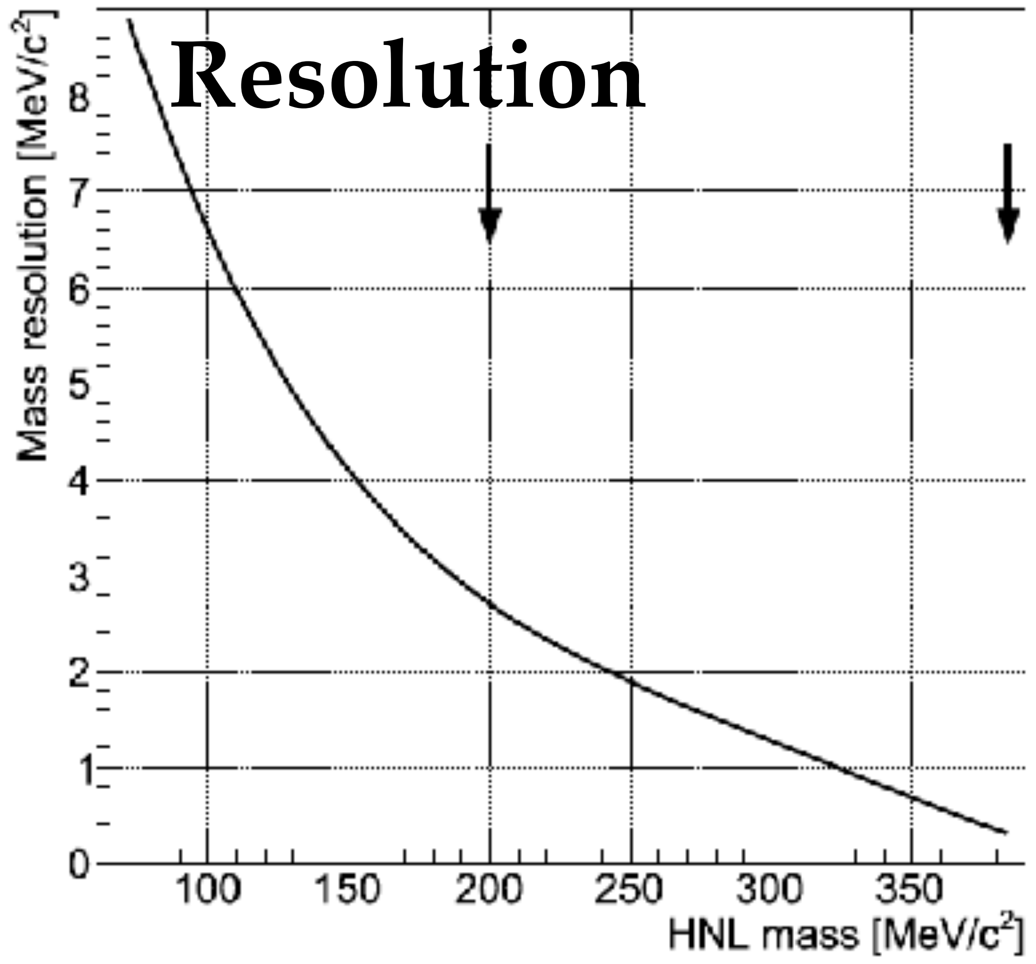
Assumption: the non-Gaussian tails of the m^2_{miss} spectrum are left-right symmetrical.

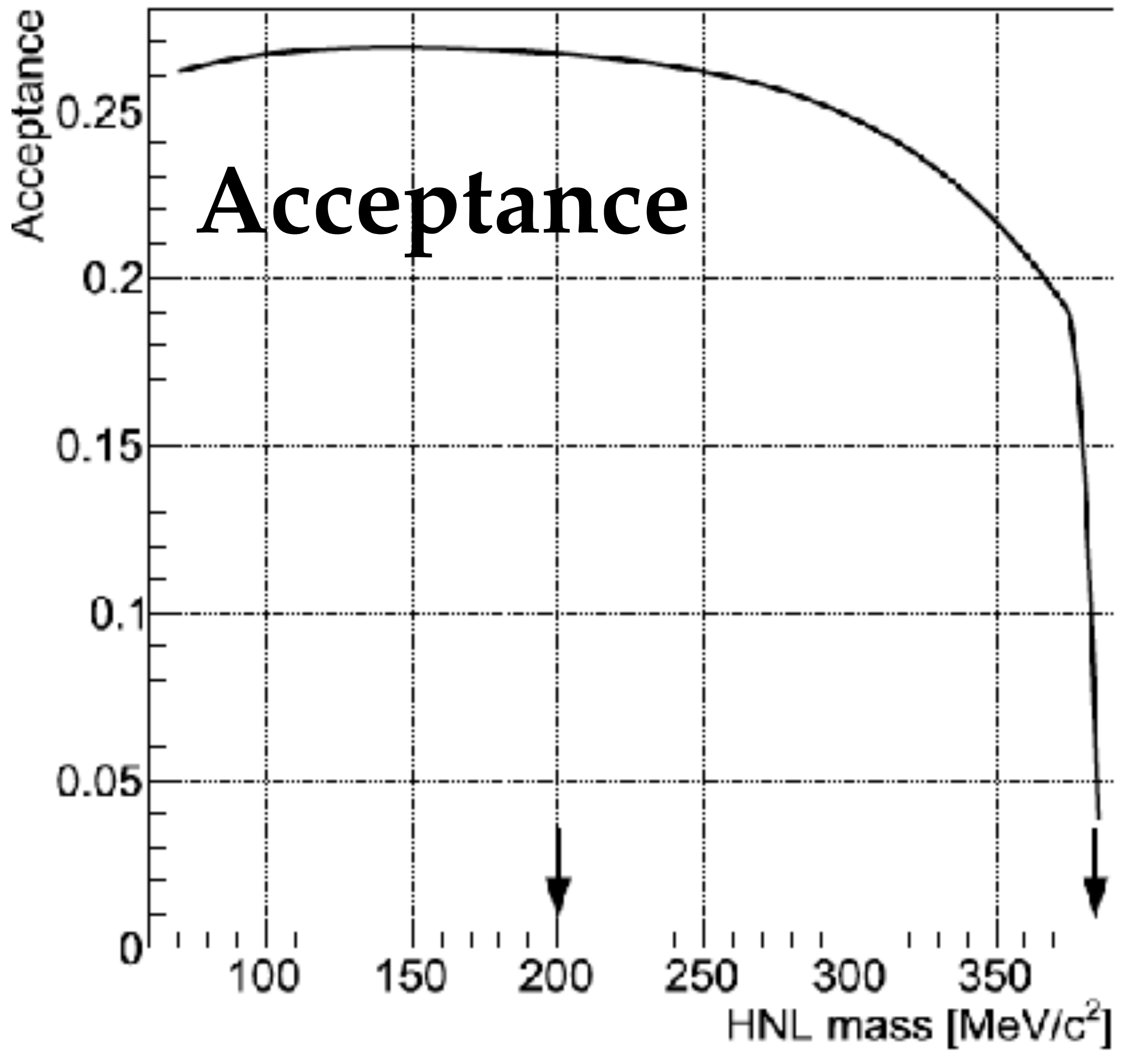
A "tail" component is added to the estimated background in each m^2_{miss} bin in the region $m^2_{miss} > 0$ equal to the difference between the data and simulated spectra in the symmetric mass bin with respect to $m^2_{miss} = 0$.

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

$K^+ \rightarrow \mu^+ N$

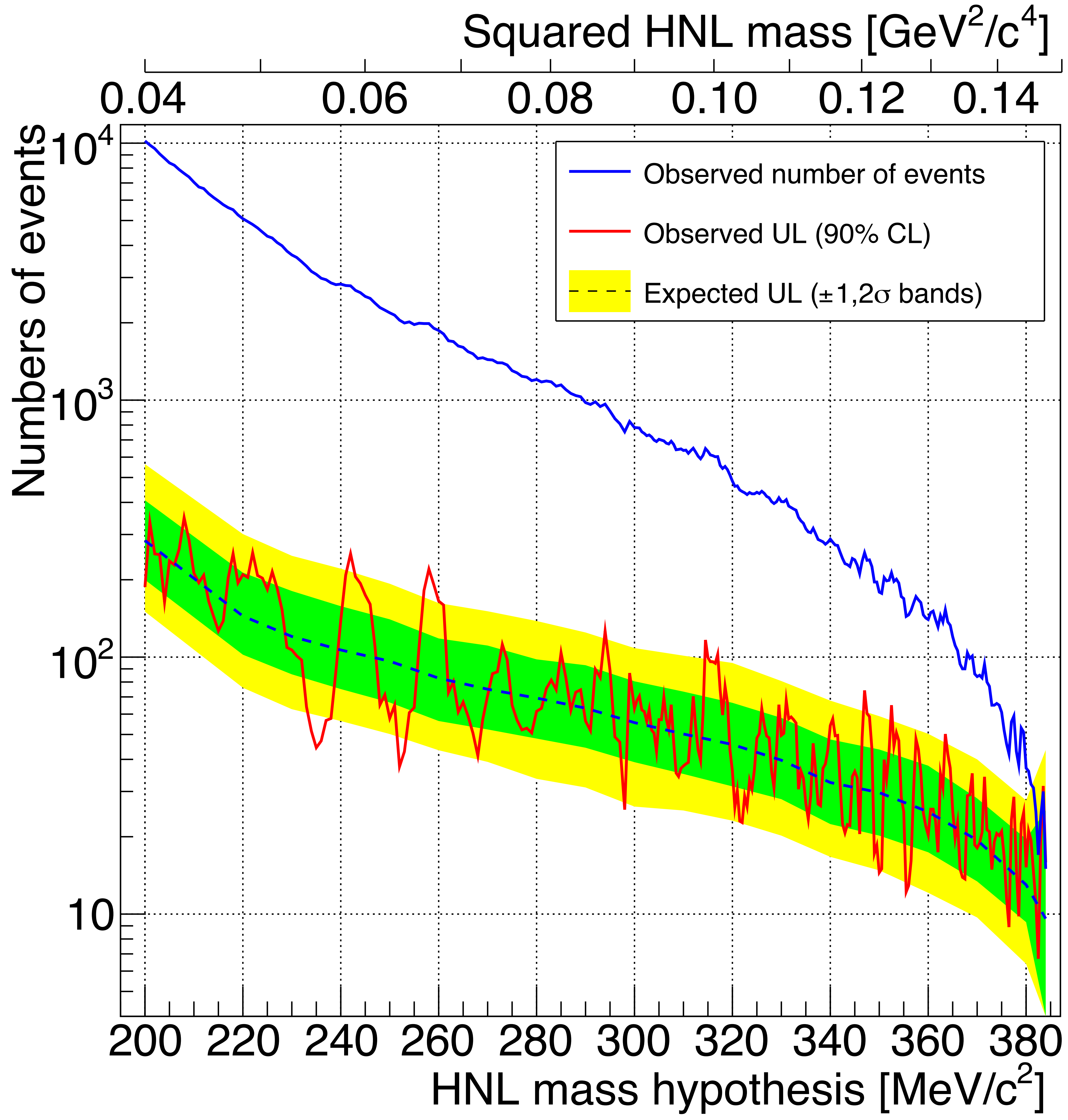
Phys. Lett. B 816 (2021) 136259





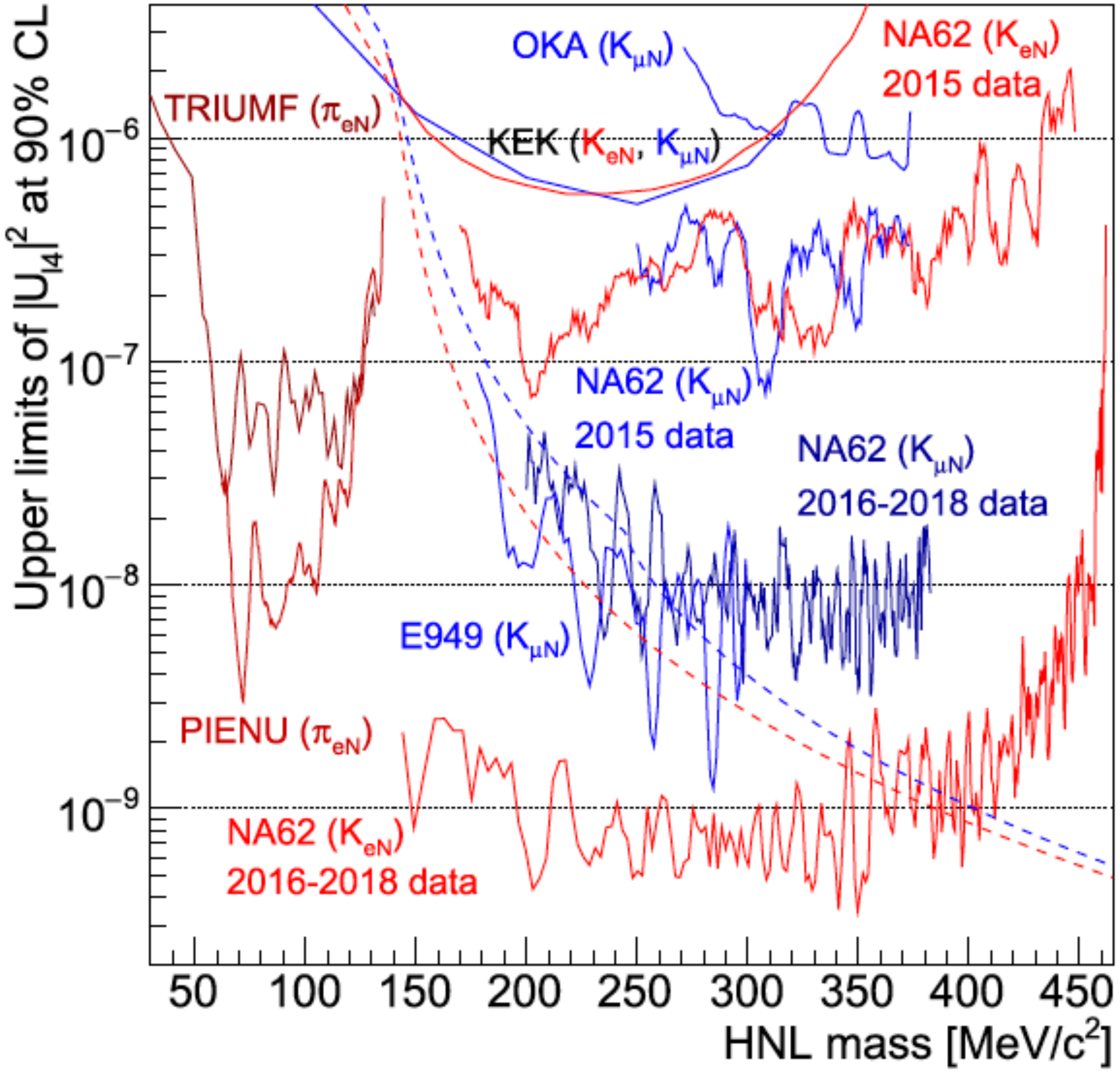
For each HNL mass hypothesis (m_N):

- m^2_{miss} in 1.5 σ
- Background evaluated from sidebands in m^2_{miss} distributions
- MC used only to check that no structures are present in the signal region



Summary of HNL searches

Phys. Lett. B 816 (2021) 136259



Muon mode

reached BNL-E949 sensitivity
and extended the HNL mass range to 384 MeV

Positron mode

Improved of ~ O(100)
over the 2015 result

Dashed lines:
BBN constraint
From Nuclear Physics B 590 (2000)

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

A possible explanation of the **anomalous muon magnetic moment 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

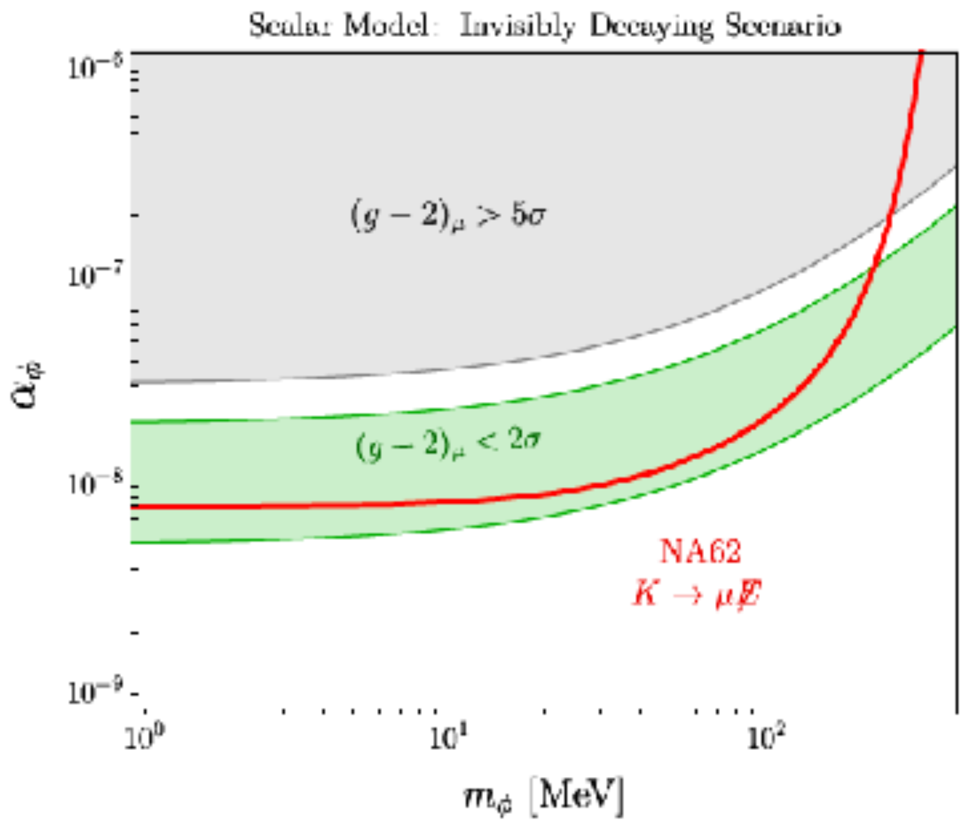
In a scenario with dark matter freeze out, it could be a scalar or vector mediator of an hidden sector decaying to Dark Matter $X \to \chi\chi$

$K^+ \to \mu^+\nu X$, 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. Rev. Lett. 124, 041802 (2020)
arXiv:1902.07715 [hep-ph]



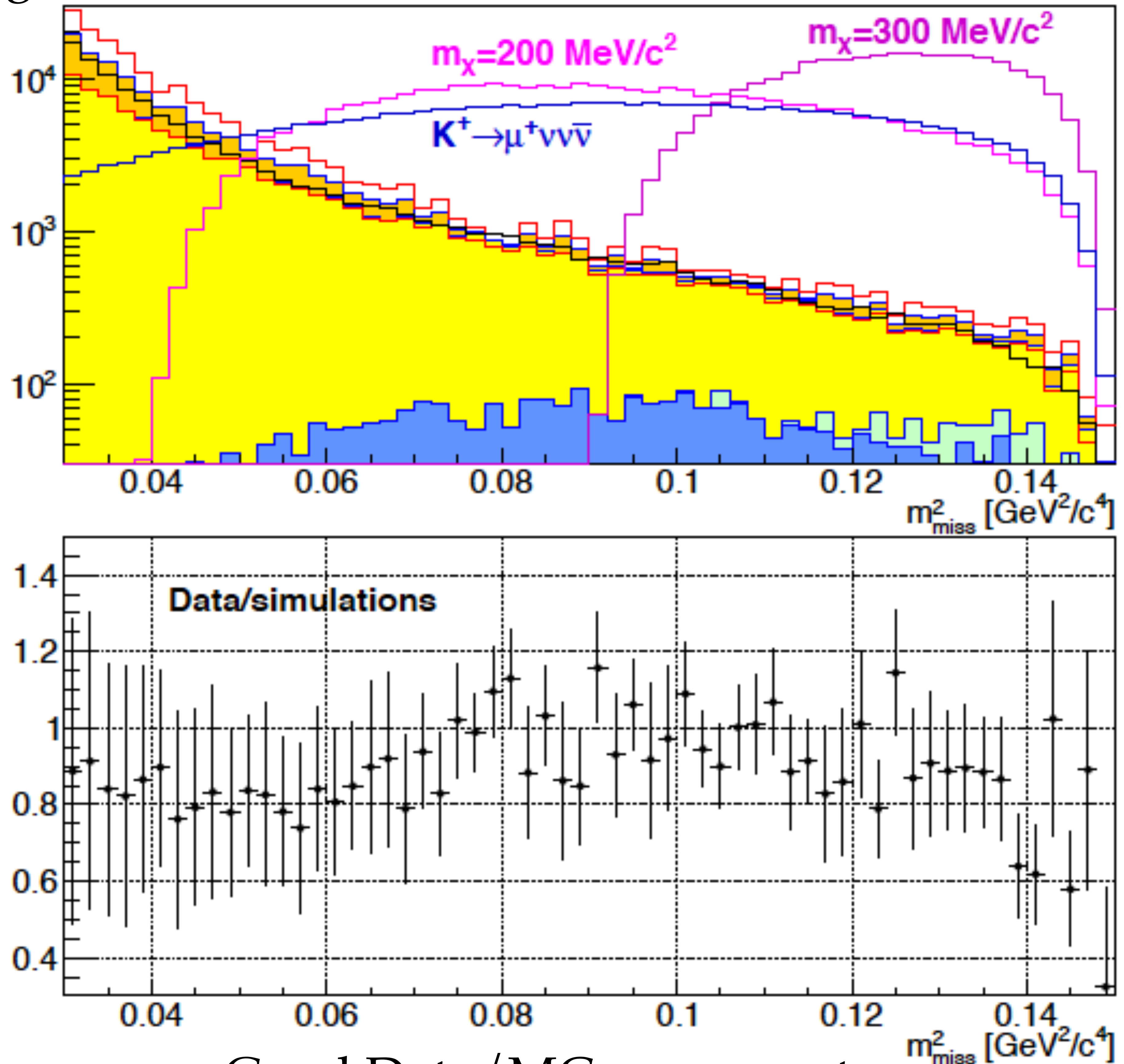
$K^+ \to \mu^+\nu X$, $X \to$ invisible

Phys. Lett. B 816 (2021) 136259

3 body decay, the signal has a broad distribution in

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

background estimation from MC:

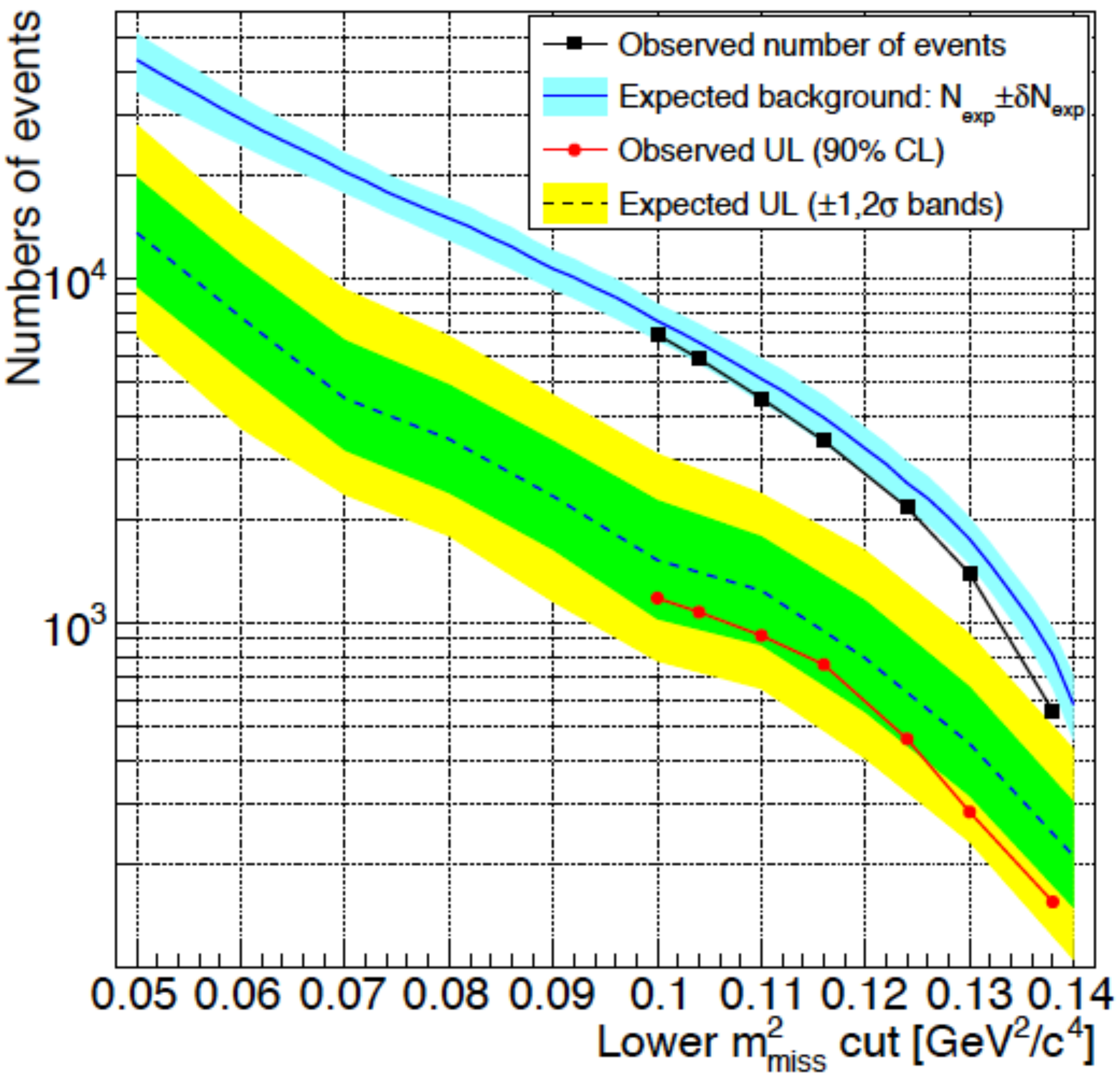


Good Data / MC agreement

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

Phys. Lett. B 816 (2021) 136259

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

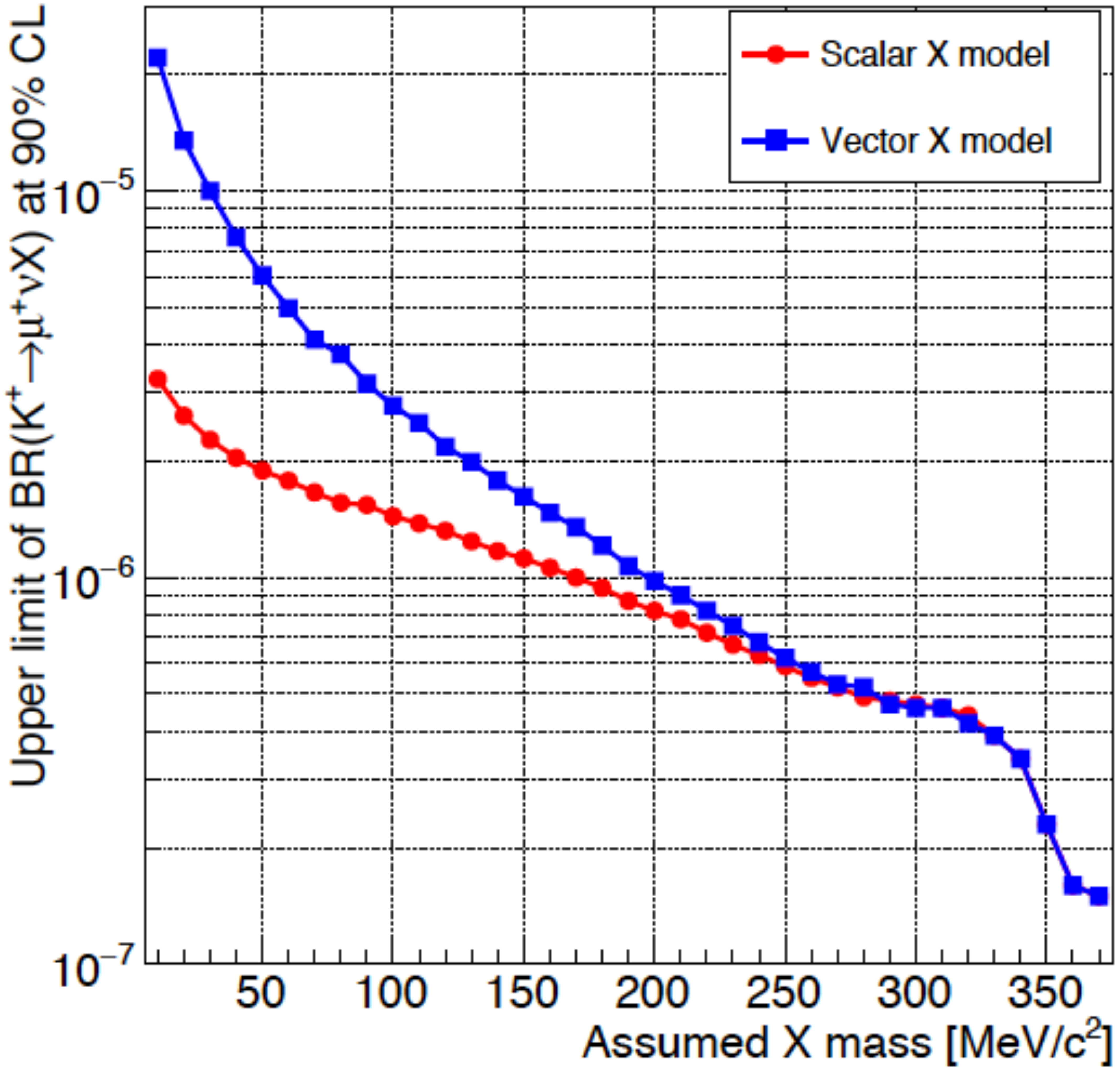
Tested mass hypotheses from 10 to 370 MeV

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

- With the 2016-2018 data taking NA62 experiment set the world best constraints to the Heavy Neutral Leptons with mass [140,460] MeV for electron dominance and with mass [300,380] MeV for muon dominance.

- First search for a new exotic particle X in $K^+ \to \mu\nu X$ decays with mass in [10,370] MeV and best constraint to the decay $K^+ \to \mu^+\nu\nu\nu$

- NA62 has started the new data taking which will go on till the next LHC long shutdown, and will run both in kaon and in dump mode, an additional powerful way to search for new exotic particles

Stay tuned!

Thank you for your attention