Physics BSM with Kaons at NA62

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for the NA62 Collaboration

APS Division of Particles & Fields (DPF) Meeting
Northeastern University, 1 August 2019

Outline

Main analysis: $K^+ \to \pi^+ \nu \bar{\nu}$

lepton number violation

This talk

Yesterday talk

Hidden sector

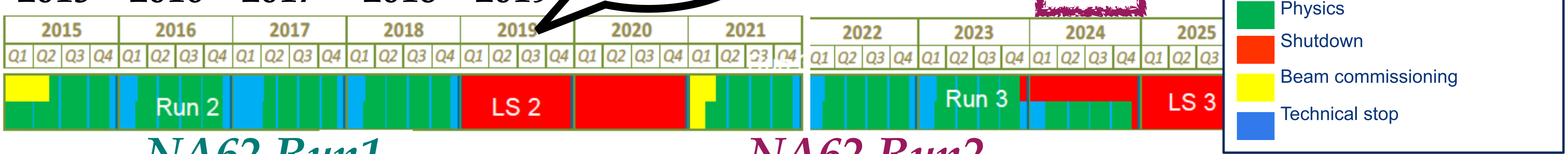
From kaon decays: published results and short term prospects

With a change in the beamline: Prospects (5 years time scale)

We are here!

2015 2016 2017 2018 2019

2024



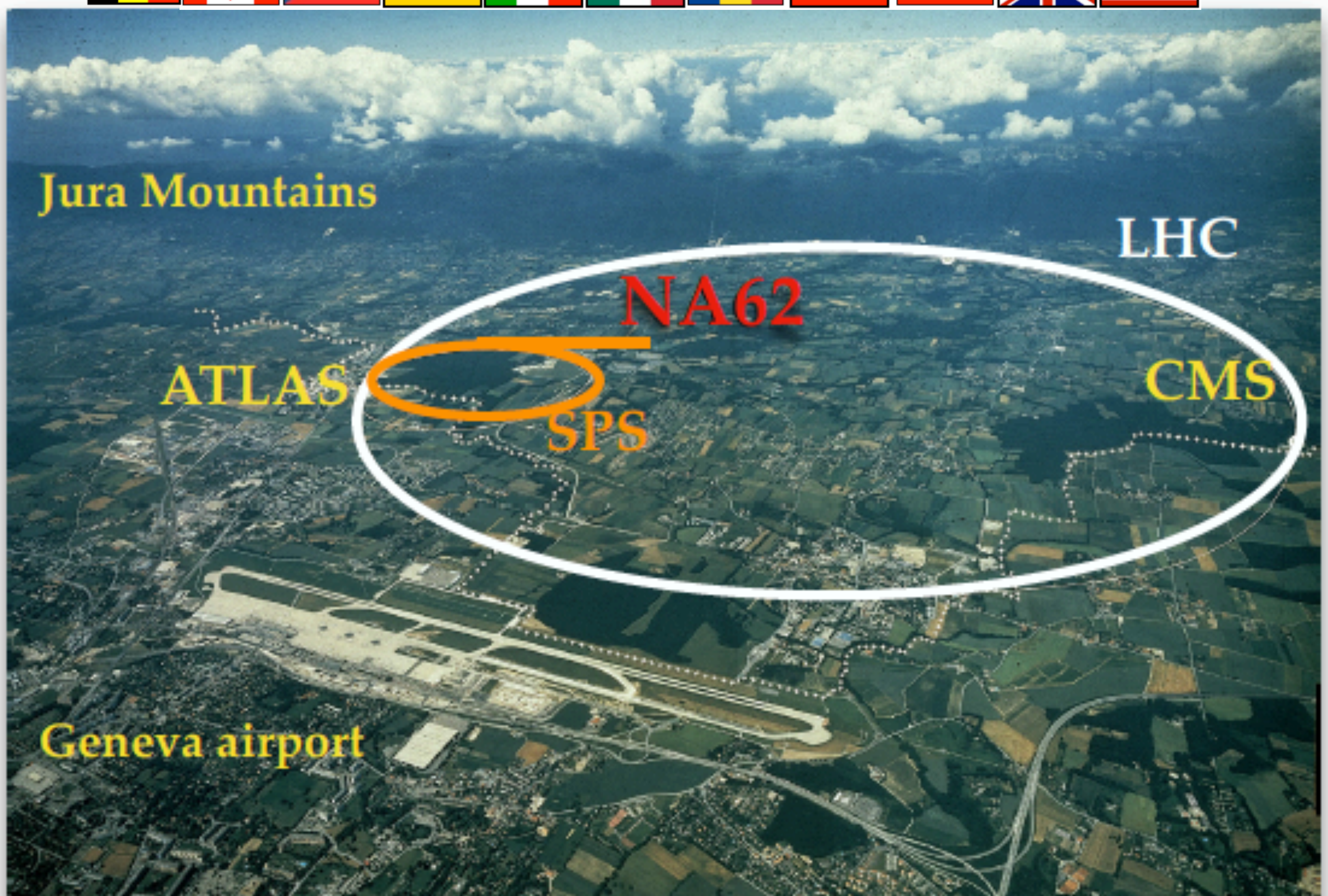
NA62 Run1

NA62 Run2

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)

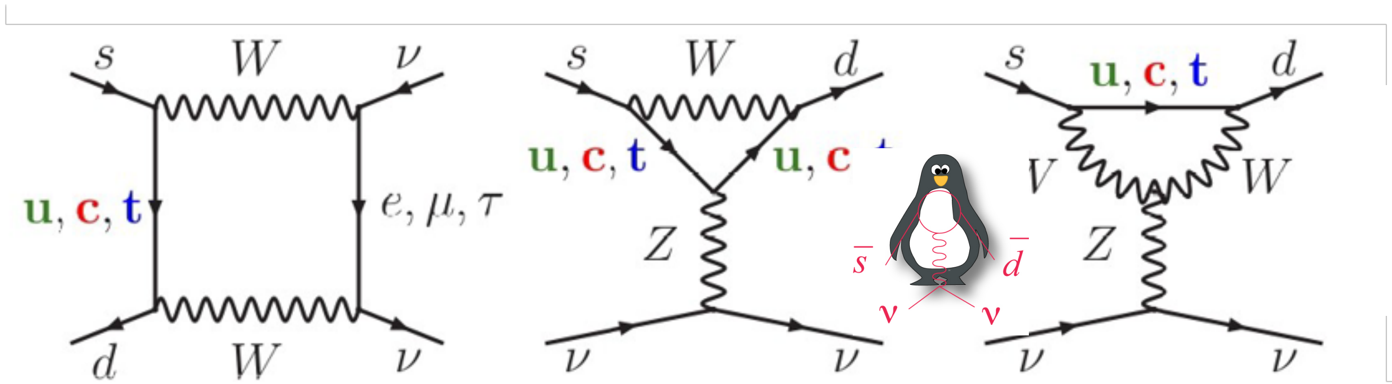


The main aim is the measurement of

BR(K->πνν)

with a precision better than 10%

K->πνν in the SM

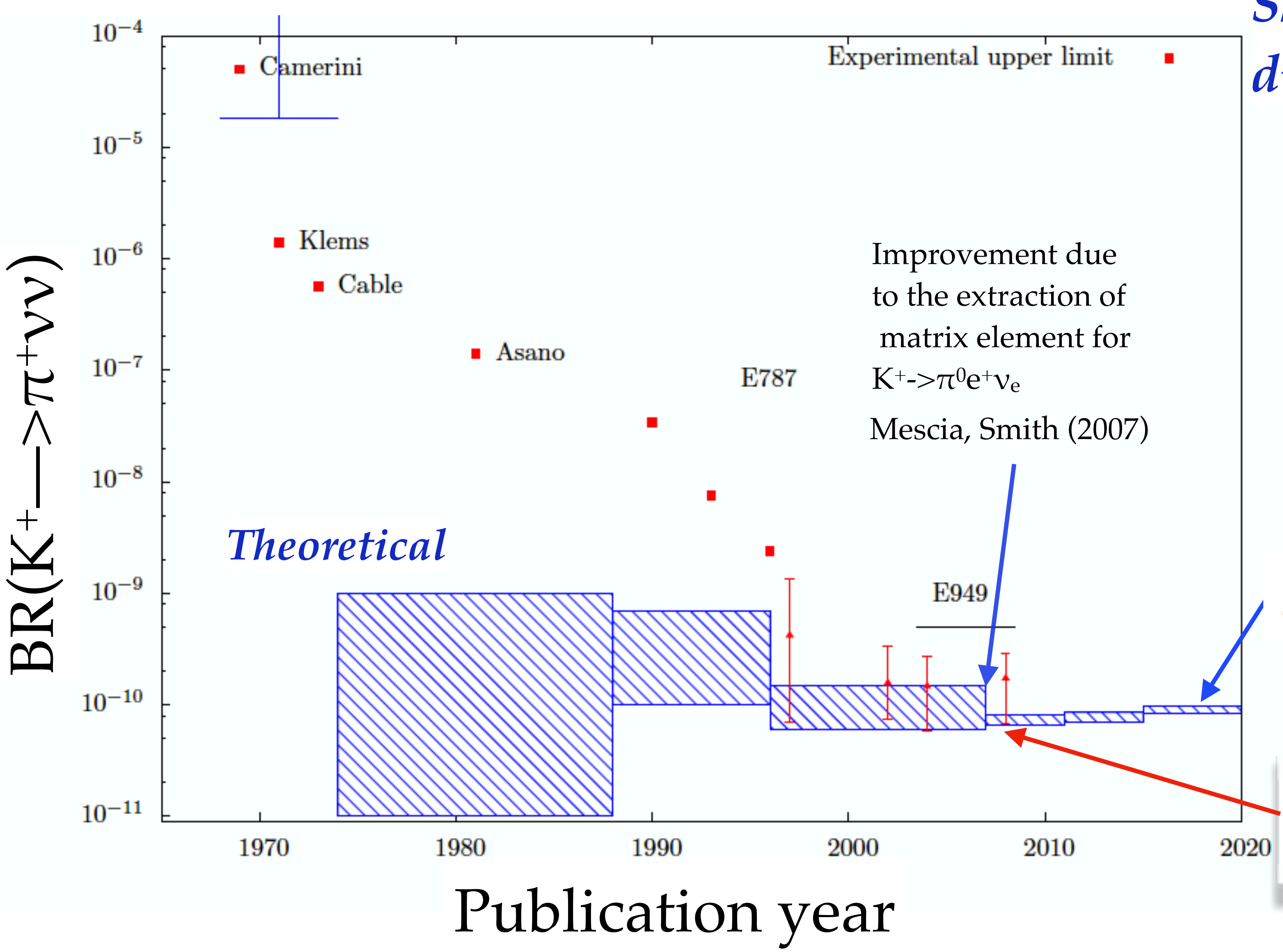


$$A(s \to d\nu\bar{\nu}) \sim$$

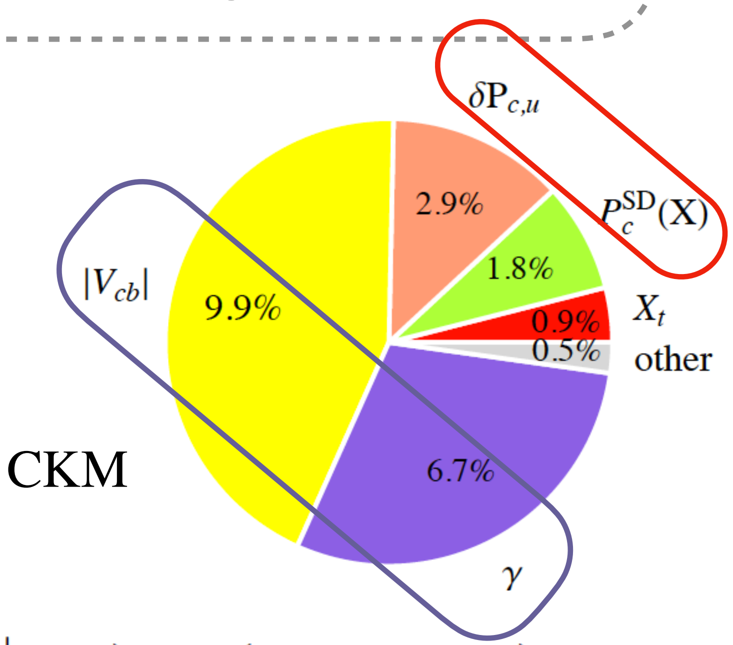
$$\sim \frac{m_t^2}{M_W^2}\lambda_t + \frac{m_c^2}{M_W^2}\ln\frac{M_W}{m_c}\lambda_c + \frac{\Lambda_{QCD}^2}{M_W^2}\lambda_u$$

t(68%) *c(29%)* *u(3%)*

Short distance *Long distance*



Error budget:



$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$

[Buras et al., JHEP11(2015)033]

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})_{\text{exp}} = (17.3^{+11.5}_{-10.5}) \cdot 10^{-11}$$

[E949, Phys. Rev. D 77, 052003 (2008)
Phys. Rev D 79, 092004 (2009)]

K->πνν for new physics

Search for New Physics at the EW scale with sizable coupling to SM particles via indirect effects in loops

- Custodial Randall-Sundrum

  [JHEP 0903 (2009) 108]

- MSSM scenarios:

  [JHEP 0608 (2006) 064]
  [Int.J.Mod.Phys A29 (2014) no.27, 1450162]

- Simplified Z, Z′ models

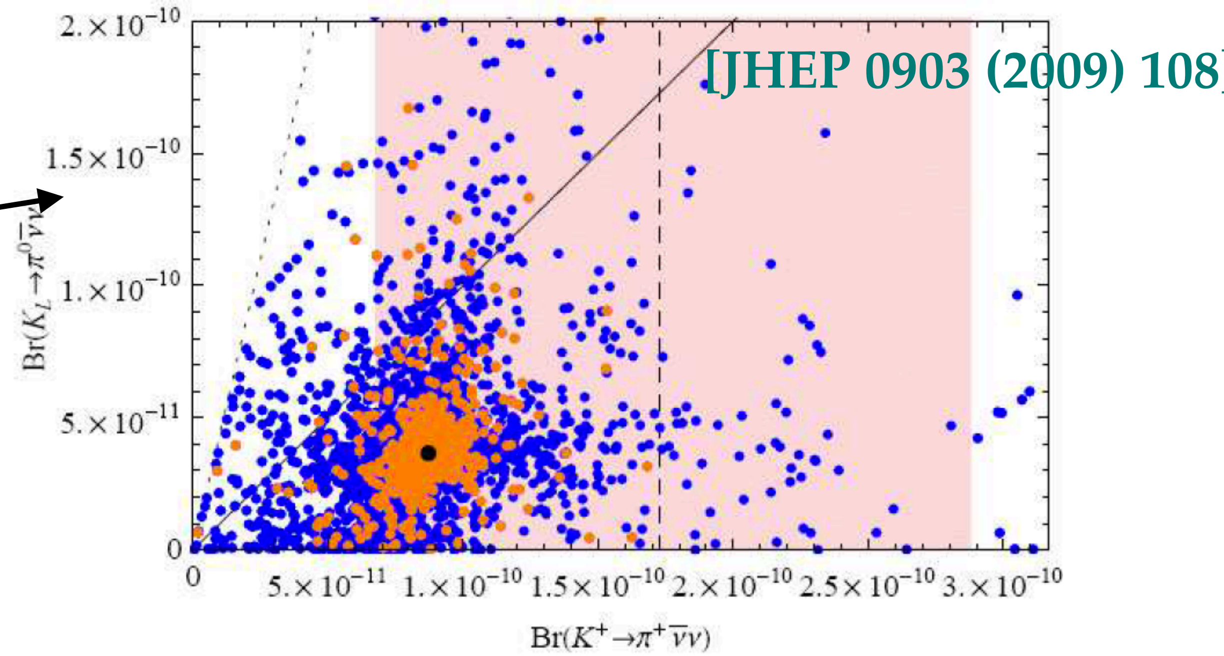
  [JHEP 1511 (2015) 166]

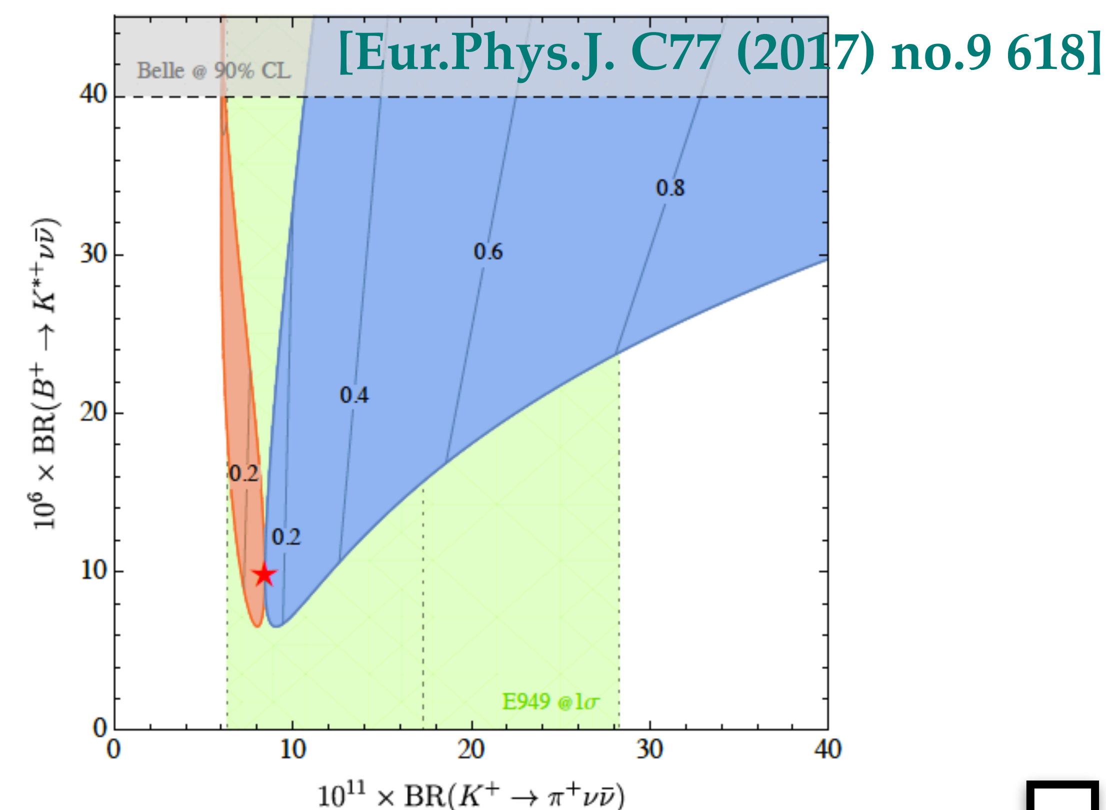
- Littlest Higgs with T-parity

  [Eur.Phys.J. C76 (2016) 182]

- LFU violation models

  [Eur.Phys.J. C77 (2017) no.9 618]





K->πνν for new physics

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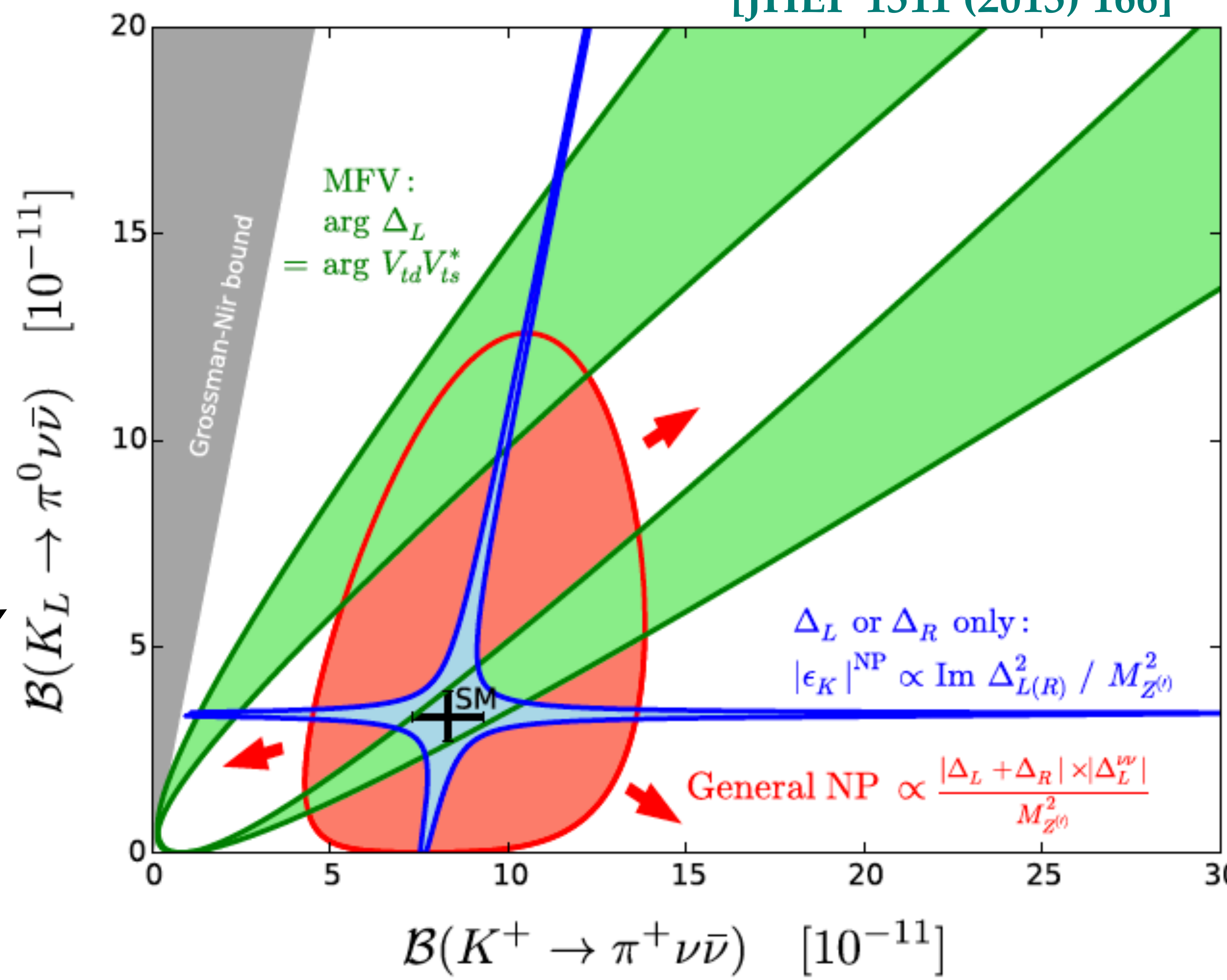
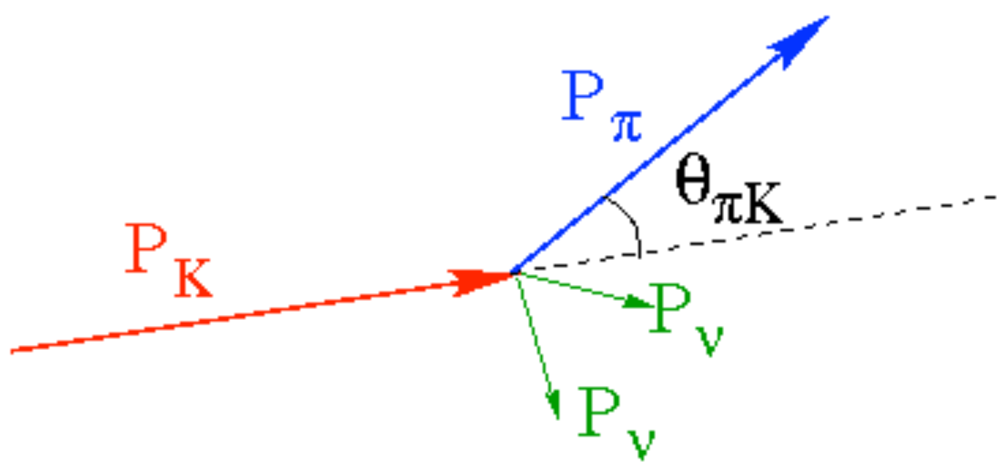
[JHEP 1511 (2015) 166]



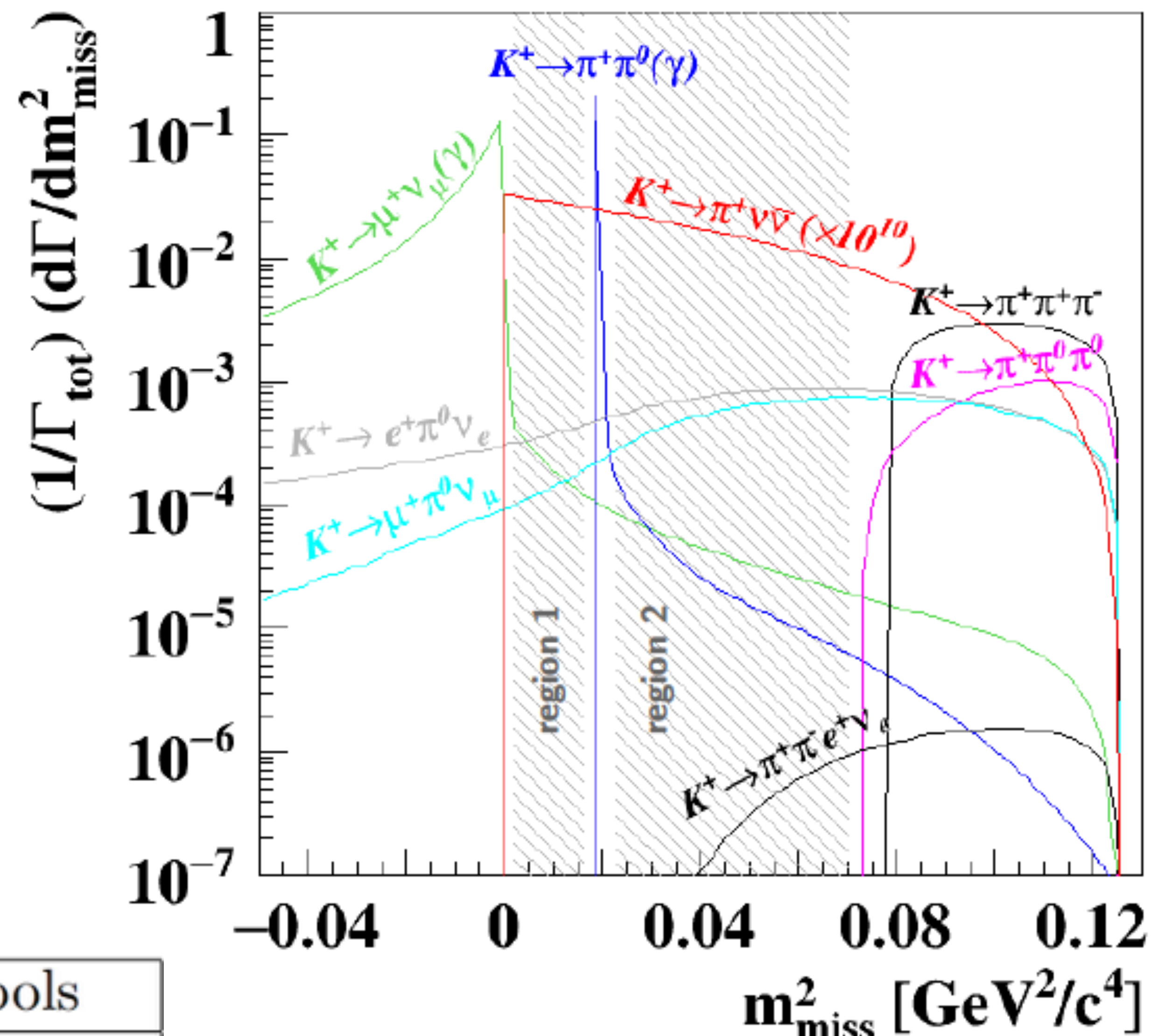
KOTO (KLEVER…)

Measurement strategy

Decay in flight technique:



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



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

- very good kinematic reconstruction
- time measurements
- K,π,μ identification
- Hermetic detection of muons
- Hermetic detection of photons

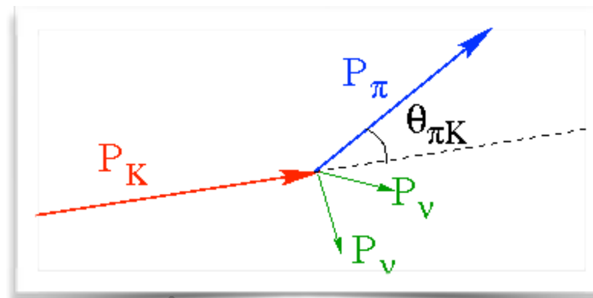
NA62 apparatus

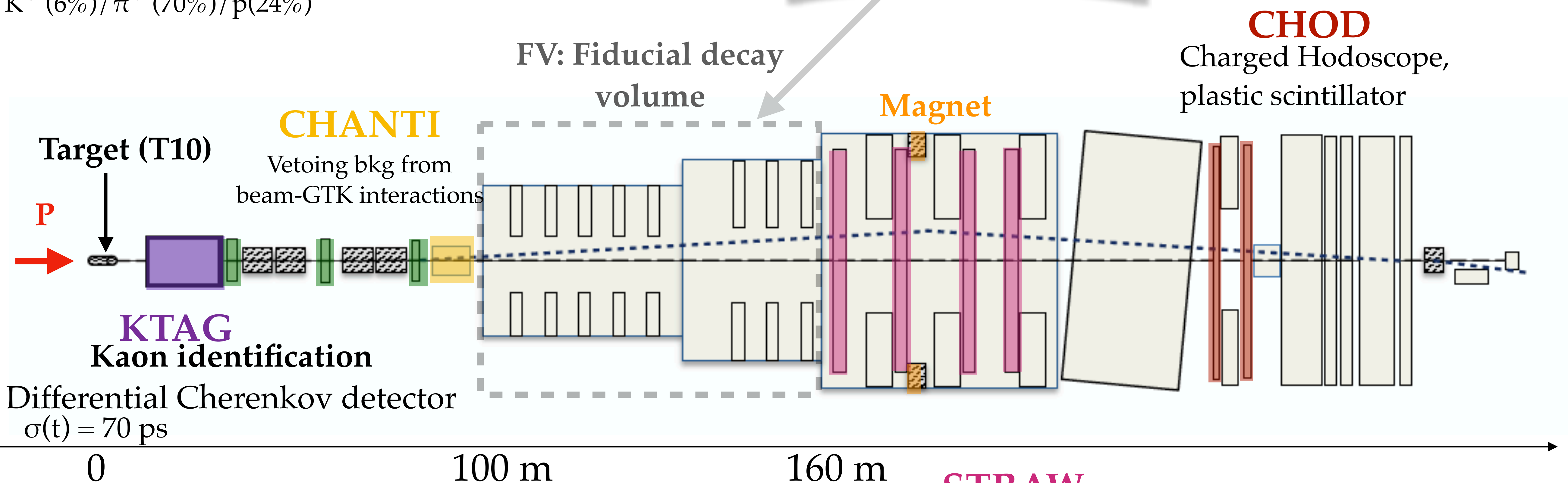
JINST 12 P05025 (2017), arxiv:1703.08501

- very good kinematic reconstruction
- Precise time measurements

33×10^{11} ppp on T10 (750 MHz at GTK3)
Secondary beam: 75 GeV/c momentum
K^+ (6%)/π^+ (70%)/p(24%)

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





GTK
Kaon tracking
Si pixel, 3 stations
σ(t) = 200 ps, σ(p)/p = 0.2%

120 m **tube in vacuum**
(500 m³ at 10^{-6} mbar)

STRAW
Downstream tracking: Dipole spectrometer
4 straw-tracker stations
σ(p)/p = 0.3%

- ☑ **Time resolution ~ 100 ps**
- ☑ **$\sigma(m^2_{miss}) = 10^{-3}$ GeV²/c⁴**

NA62 apparatus

JINST 12 P05025 (2017), arxiv:1703.08501

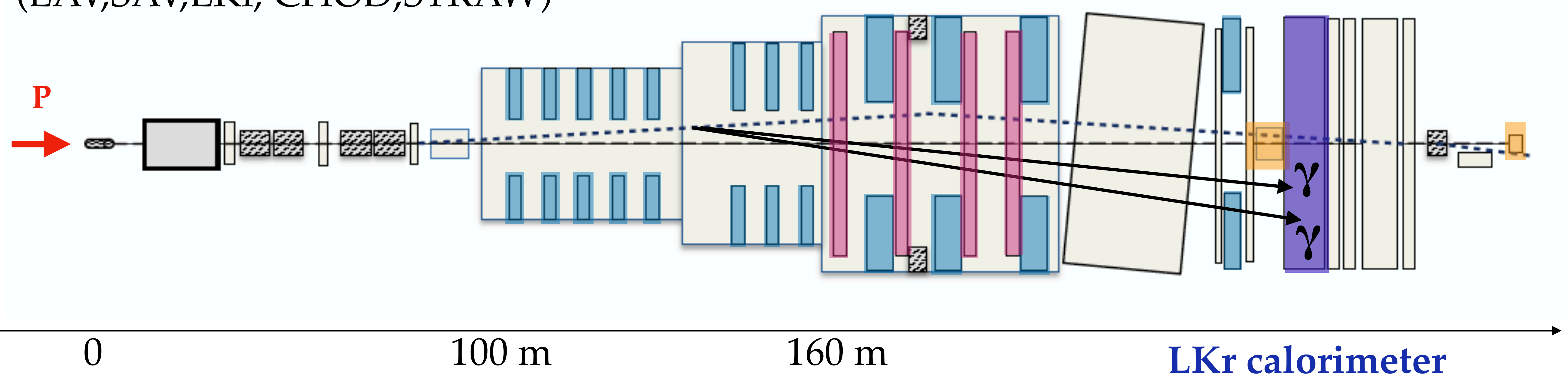
background rejection: $K^+ \to \pi^+\pi^0$

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

☑ $\varepsilon(\pi^0) = 3\ 10^{-8}$

Small Angle Veto (SAV)
IRC: Inner Ring Calorimeter
Small Angle Calorimeter
Covering angles <1 mrad

NA62 apparatus

JINST 12 P05025 (2017), arxiv:1703.08501

background rejection: $K \rightarrow \mu^+ \nu$

Particle identification:
To separate π/μ/e

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

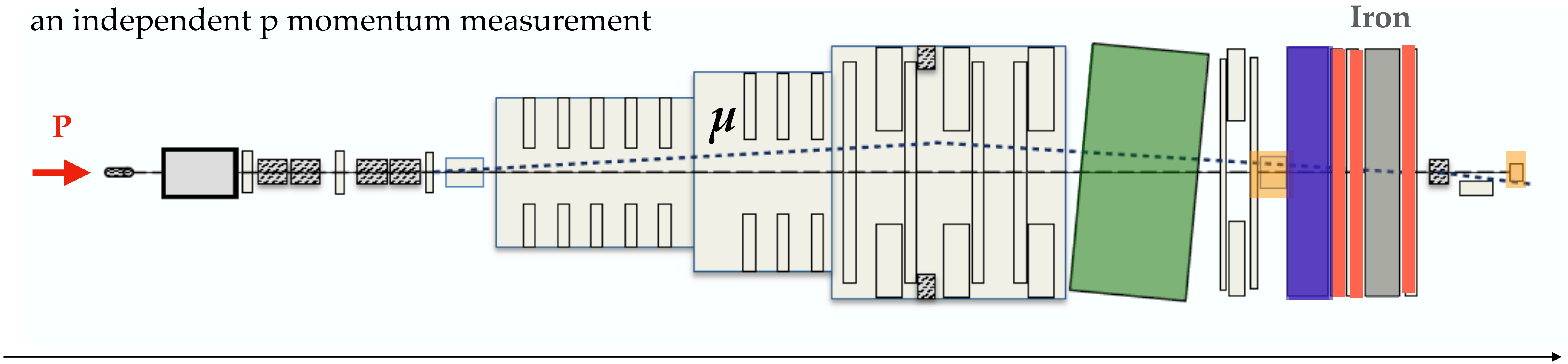
RICH
Ring Imaging Cherenkov detector

Neon 1 Atm
π/μ/e separation

MUV
Muon veto system

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

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



LKr calorimeter
Photon detection

Multivariate analysis
with MUV1, MUV2 and LKr info

2 algorithm for the RICH variables

☑ $\varepsilon(\mu^+) = 10^{-8}$ $\varepsilon(\pi^+) = 64\%$

NA62 in real life

JINST 12 P05025 (2017), arxiv:1703.08501

Same analysis strategy:

☑ **2016 run:**
published result

Phys. Lett. B 791 (2019) 156-166, arXiv.1811.08508

☐ **2017 run:**
work in progress
Preliminary studies in SPSC NA62 status report:

http://cds.cern.ch/record/2668548

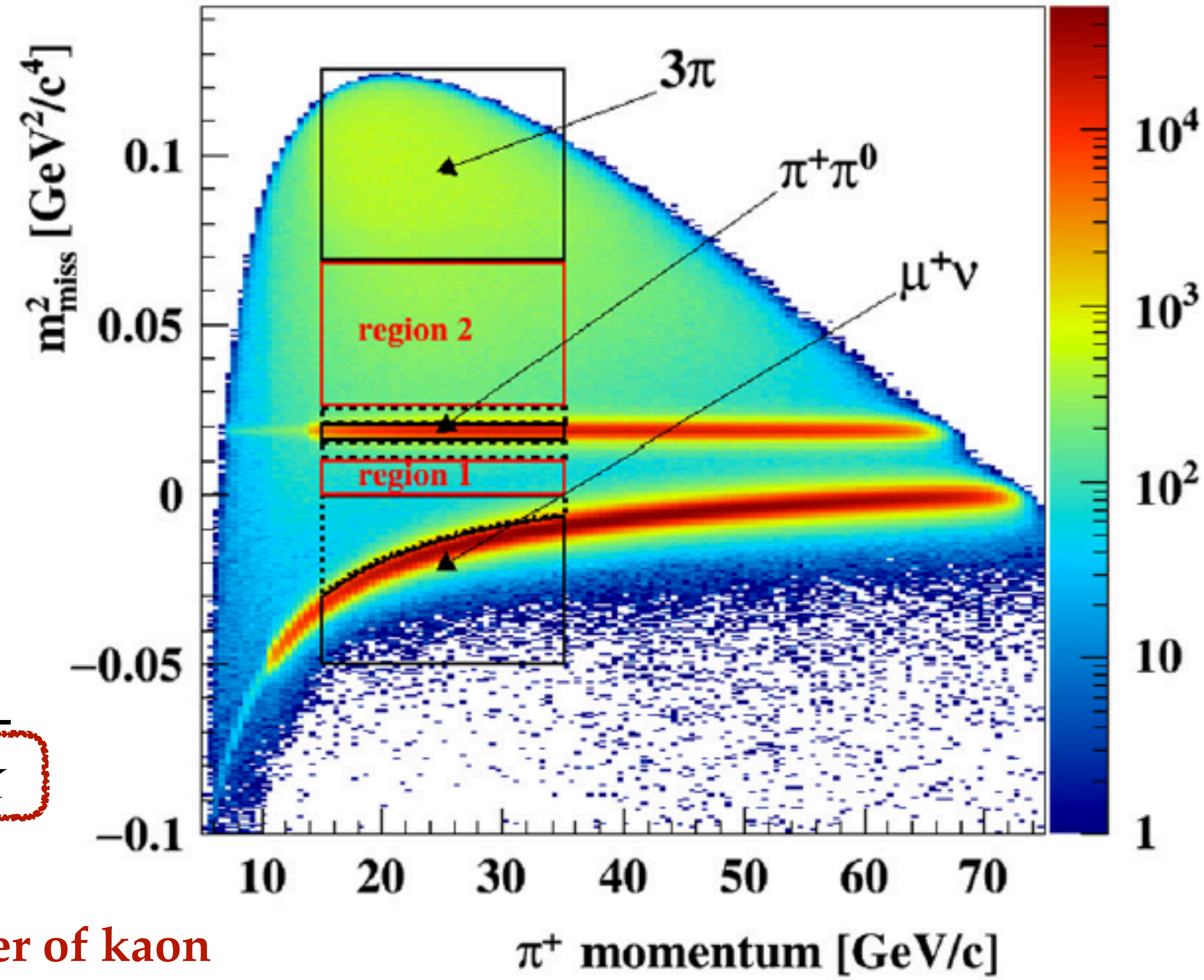
About 20% of K^+ decay inside the fiducial volume

2 years running at high intensity we collected:

- $O(10^{13})$ K^+ decays in fiducial volume

Analysis strategy

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



$$BR(K^+ \to \pi^+\nu\bar{\nu}) = \frac{D_{obs} - Bkg}{\epsilon_{\pi\nu\nu} \cdot \epsilon_{trigger} \cdot \epsilon_{RV} \cdot N_K}$$

Efficiencies not in common with K->$\pi^+\pi^0$

Number of kaon decays in FV Measured with K->$\pi^+\pi^0$

ε(RV), Random Veto efficiency: signal efficiency due to accidental activity

Results from 2016 run

Phys. Lett. B 791 (2019) 156-166

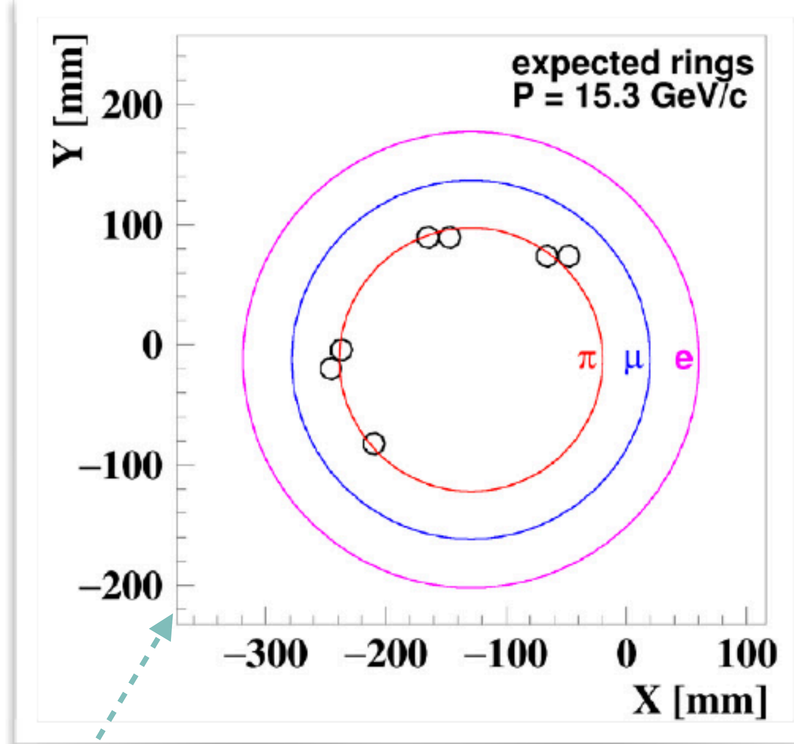
Process	Expected events
$K^+ \to \pi^+\pi^0(\gamma)$	$0.064 \pm 0.007_{stat} \pm 0.006_{syst}$
$K^+ \to \mu^+\nu(\gamma)$	$0.020 \pm 0.003_{stat} \pm 0.006_{syst}$
$K^+ \to \pi^+\pi^+\pi^-$	$0.002 \pm 0.001_{stat} \pm 0.002_{syst}$
$K^+ \to \pi^+\pi^-e^+\nu$	$0.013^{+0.017}_{-0.012}\vert_{stat} \pm 0.009_{syst}$
$K^+ \to \pi^0\mu^+\nu$, $K^+ \to \pi^0 e^+\nu$	< 0.001
$K^+ \to \pi^+\gamma\gamma$	< 0.002
Upstream background	$0.050^{+0.090}_{-0.030}\vert_{stat}$
Total background	$0.152^{+0.092}_{-0.033}\vert_{stat} \pm 0.013_{syst}$

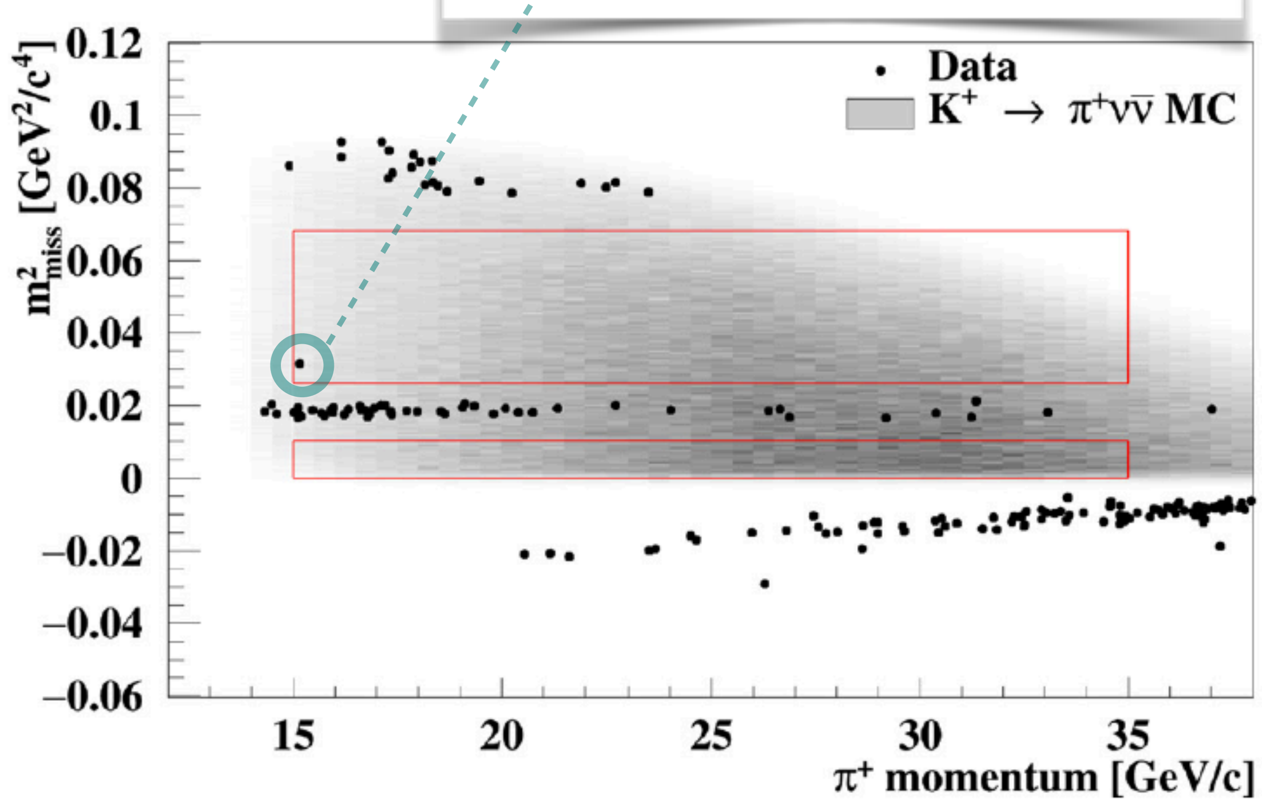
$\varepsilon(\pi\nu\nu) = 0.04 \pm 0.001$
$\varepsilon(\text{trigger}) = 0.87 \pm 0.02$
$\varepsilon(\text{RV}) = 0.76 \pm 0.04$

$NK = (1.21 \pm 0.02) \times 10^{11}$

$$N^{exp}_{\pi\nu\nu}(\text{SM}) = 0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$$

BR[obs] < 14×10^{-10} ~ 17 x BR(SM) @ 95% CL
BR[exp] < 11×10^{-10} ~ 12 x BR(SM) @ 95% CL



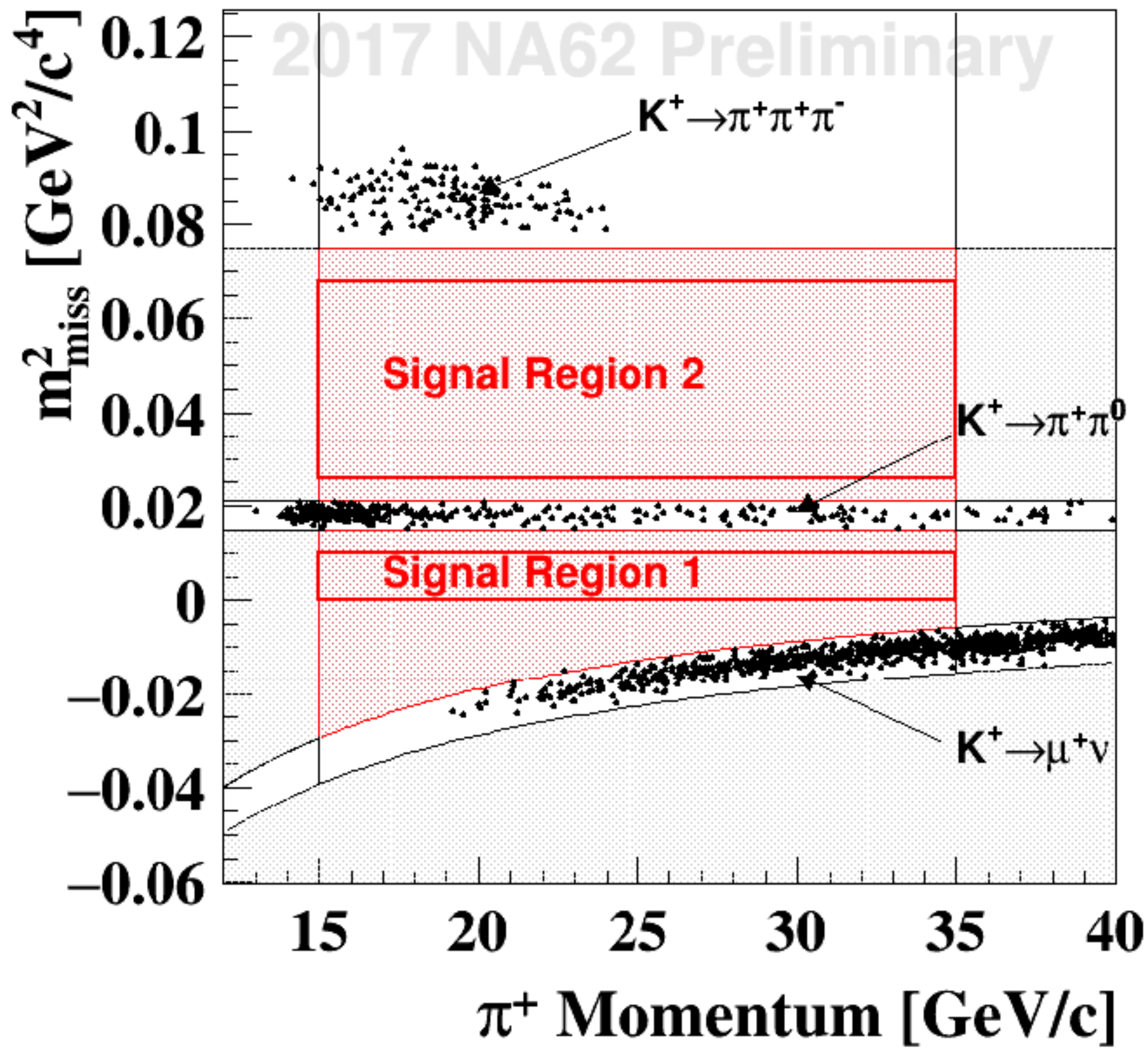


The decay in flight technique works

Analysis of 2017 run

http://cds.cern.ch/record/2668548

- ☑ **Higher intensity**
- ☑ **~10x more data**
- ☑ Improved LKr reconstruction
- ☑ 40% better π^0 rejection (it does not depend on intensity)
- ☑ Slightly improved usage of RICH variables
- ☑ No effect from intensity on π efficiency and μ rejection.



$$\epsilon_{\pi\nu\nu} \cdot \epsilon_{trigger} \cdot \epsilon_{RV} = 2.3\ \%$$

$$N_K = (1.3 \pm 0.1)\ 10^{12}$$

expect 2.5 SM $K^+ \to \pi^+ \nu\nu$ events

$K^+ \to \mu^+\nu$ background estimation

http://cds.cern.ch/record/2668548

j: bin in momentum

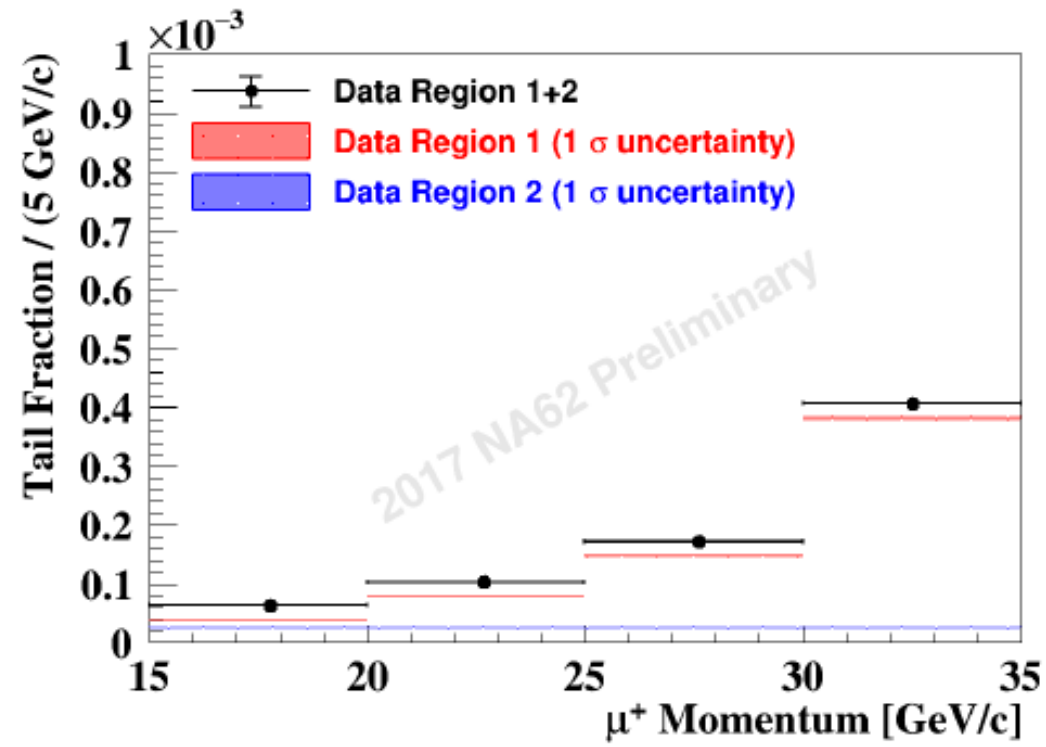
$$N^{exp}_{\mu\nu}(region) = \sum_j \left[N(\mu\nu)_j \cdot f^{kin}_j(region) \right]$$

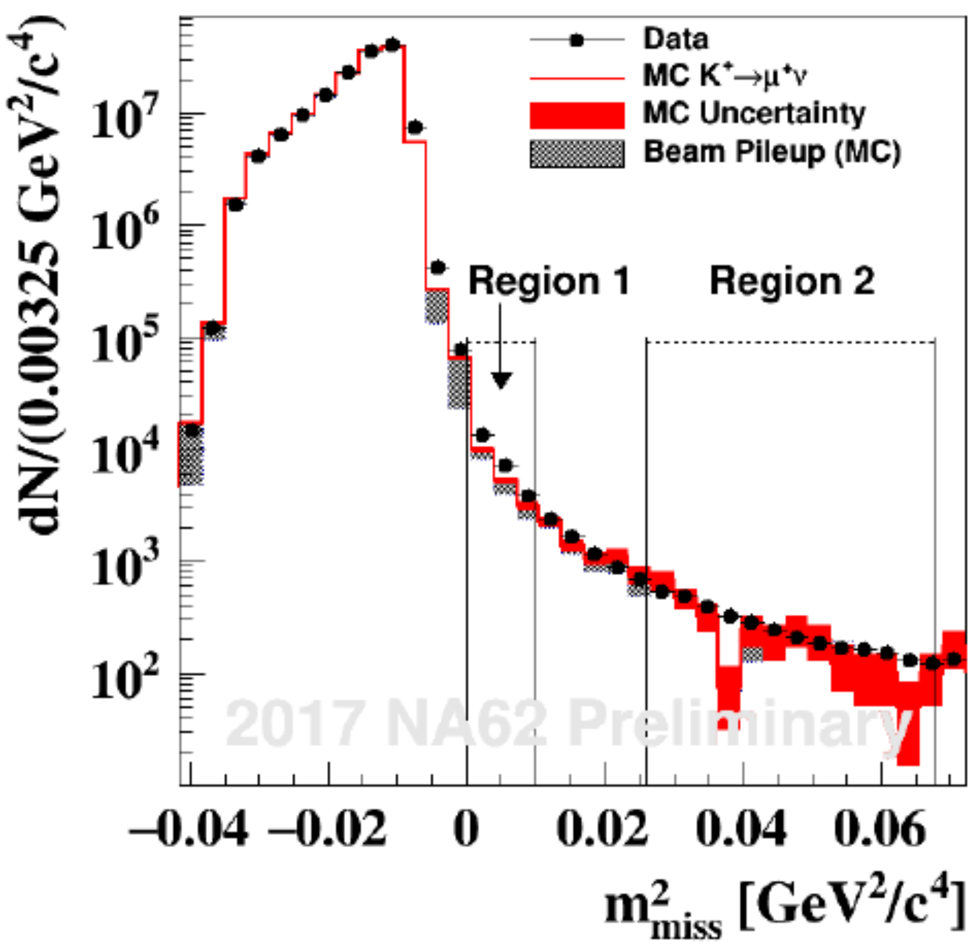
Nexp in the Signal (control) region

Sample selected on control data to get the shape

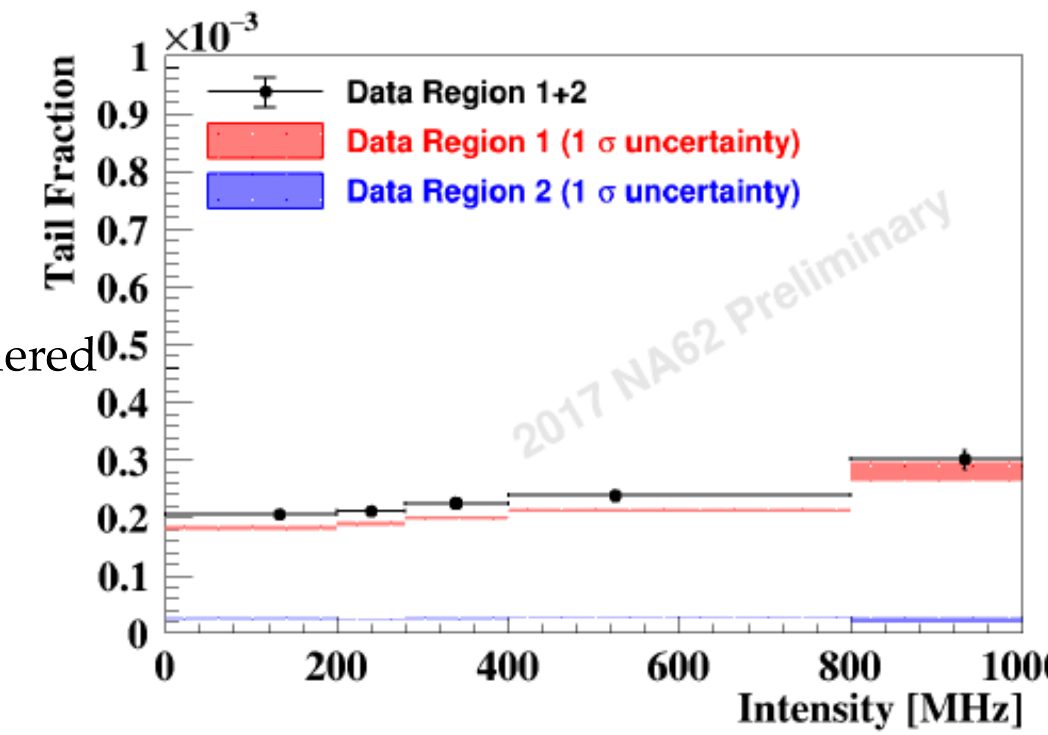
tagging μ^+ with MUV3 signals and offline PID requirements

Fraction of events in the signal (control) region





Also bins in intensity considered



$K^+ \rightarrow \pi^+\pi^0$ background estimation

http://cds.cern.ch/record/2668548

j: bin in momentum

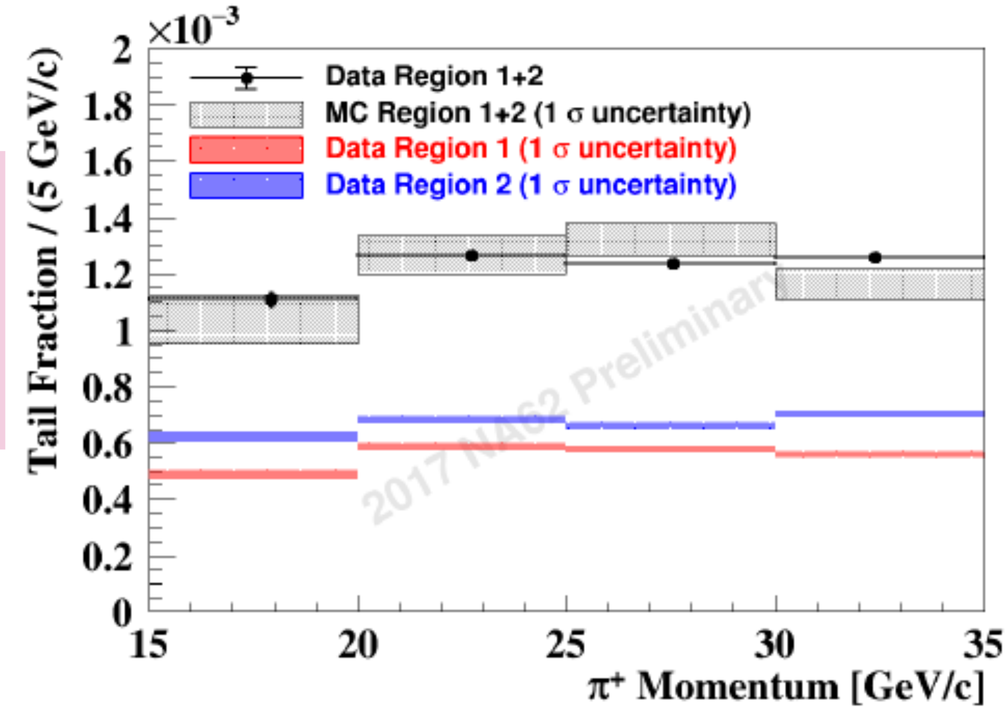
$$N^{exp}_{\pi\pi}(region) = \sum_j \left[N(\pi^+\pi^0)_j \cdot f^{kin}_j(region) \right]$$

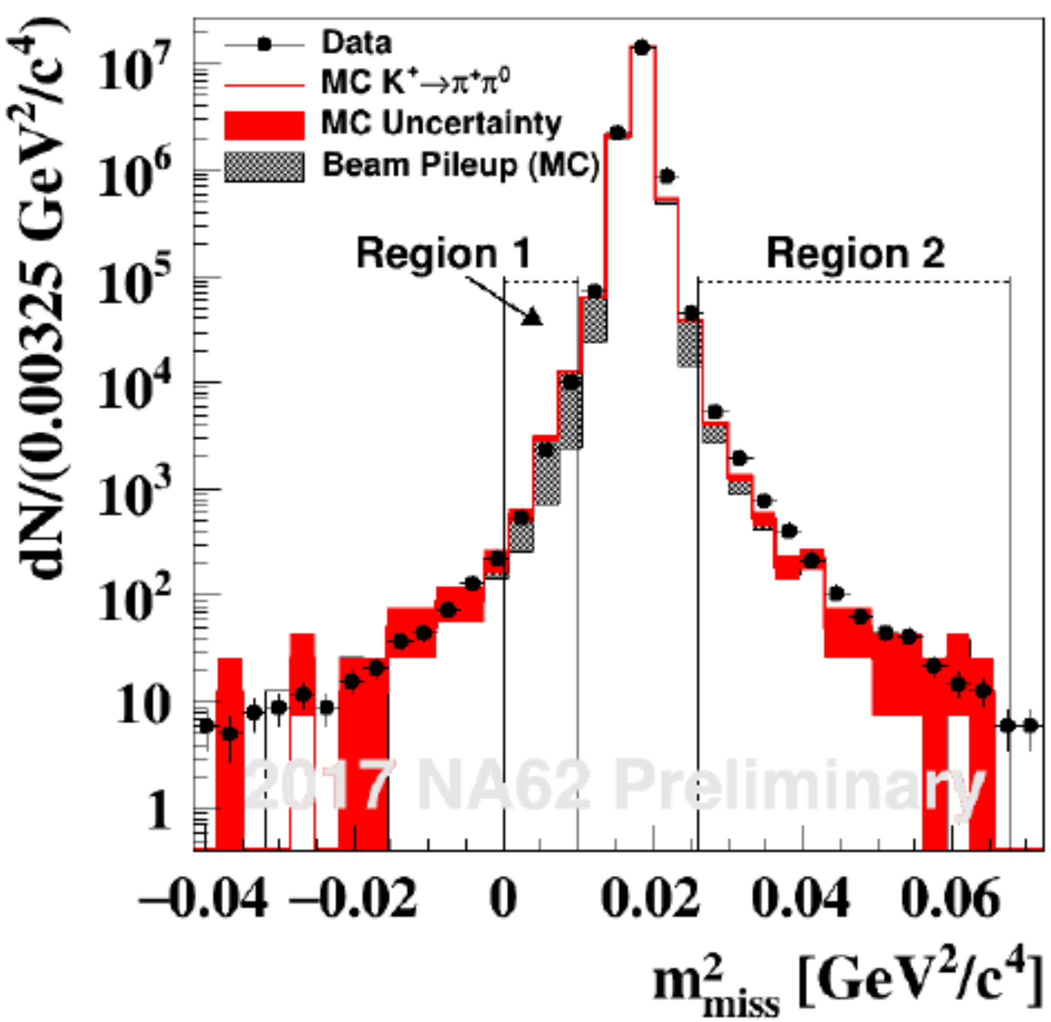
Nexp in the Signal (control) region

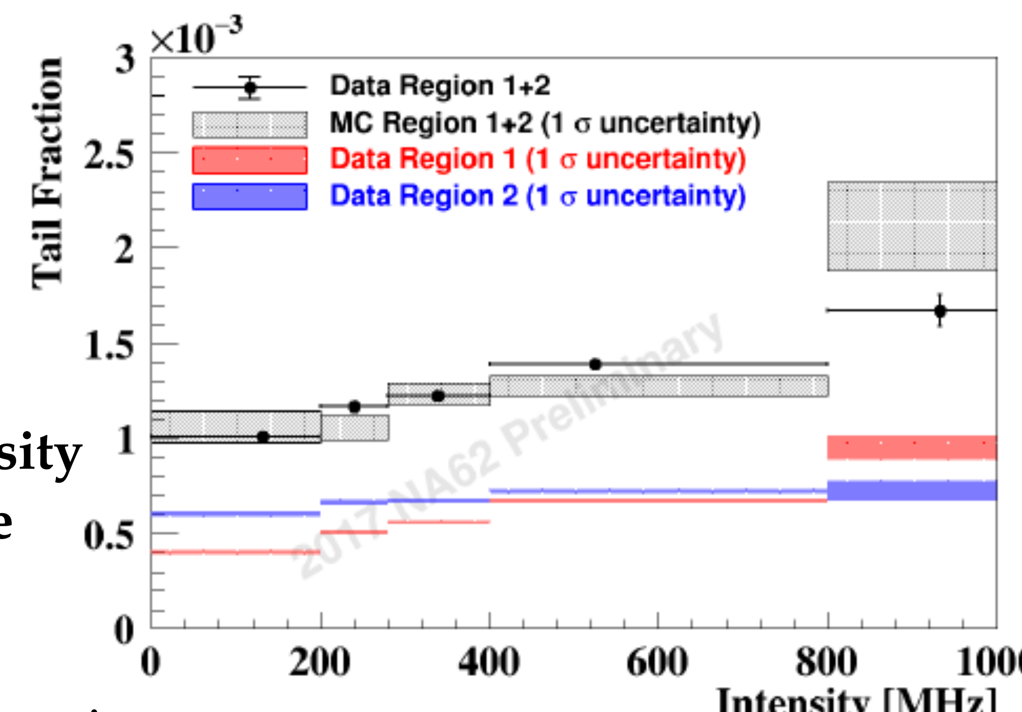
Sample selected on control data to get the shape

tagging π^0 with 2 photons in the LKr

Fraction of events in the signal (control) region





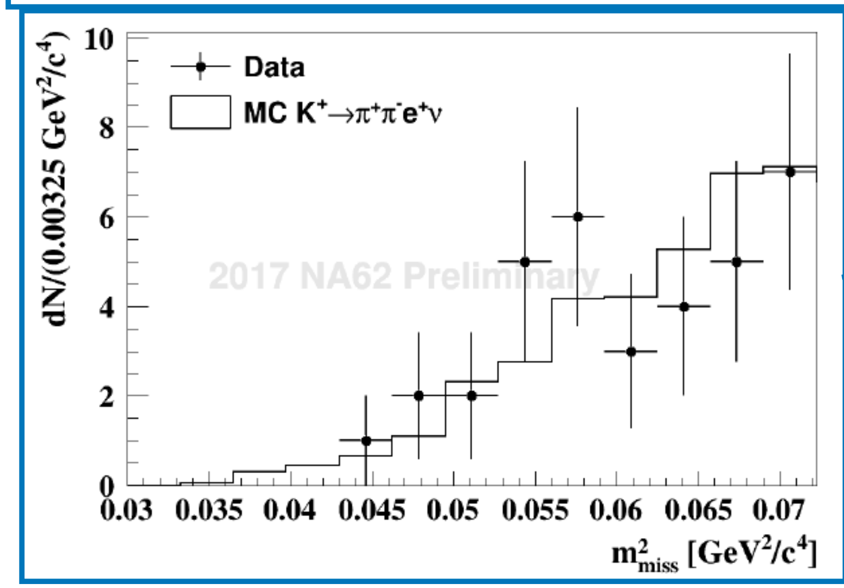


small intensity dependence due to K-π matching mis-reconstruction

Background estimation status

http://cds.cern.ch/record/2668548

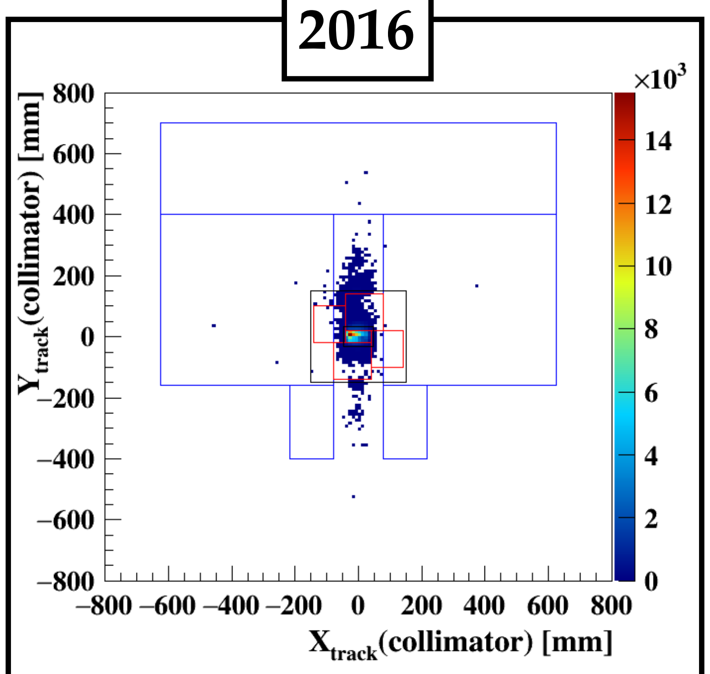
MC validated with control sample data



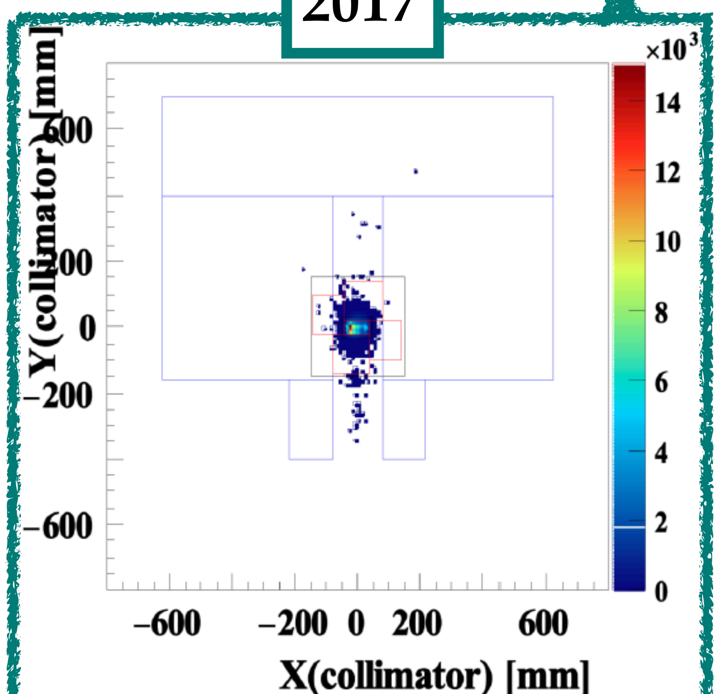
Process	Expected events in signal regions
$K^+ \to \pi^+\pi^0(\gamma)$ IB	$0.35 \pm 0.02_{stat} \pm 0.03_{syst}$
$K^+ \to \mu^+\nu(\gamma)$ IB	$0.16 \pm 0.01_{stat} \pm 0.05_{syst}$
$K^+ \to \pi^+\pi^- e^+\nu$	$0.22 \pm 0.08_{stat}$
$K^+ \to \pi^+\pi^+\pi^-$	$0.015 \pm 0.008_{stat} \pm 0.015_{syst}$
$K^+ \to \pi^+\gamma\gamma$	$0.005 \pm 0.005_{syst}$
$K^+ \to l^+\pi^0\nu_l$	$0.012 \pm 0.012_{syst}$
Upstream Background	Analysis on–going

WORK IN PROGRESS

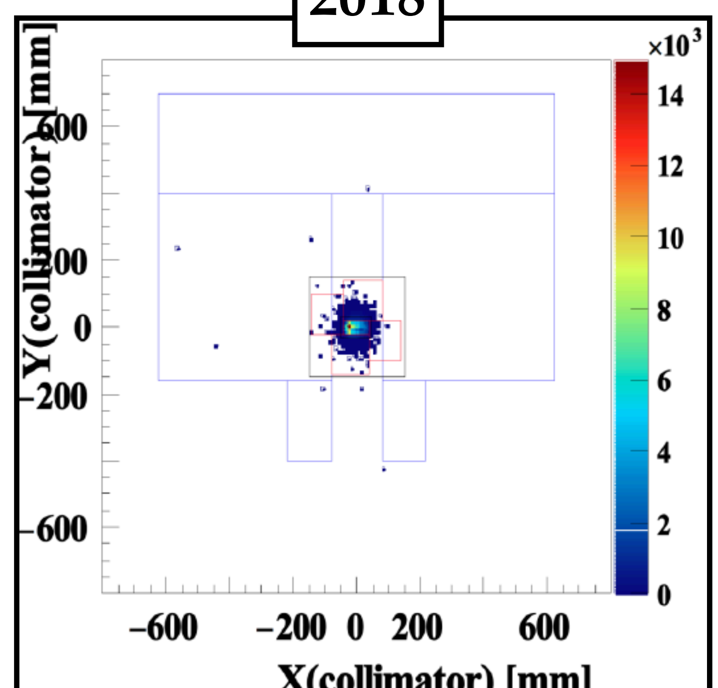
2016



2017

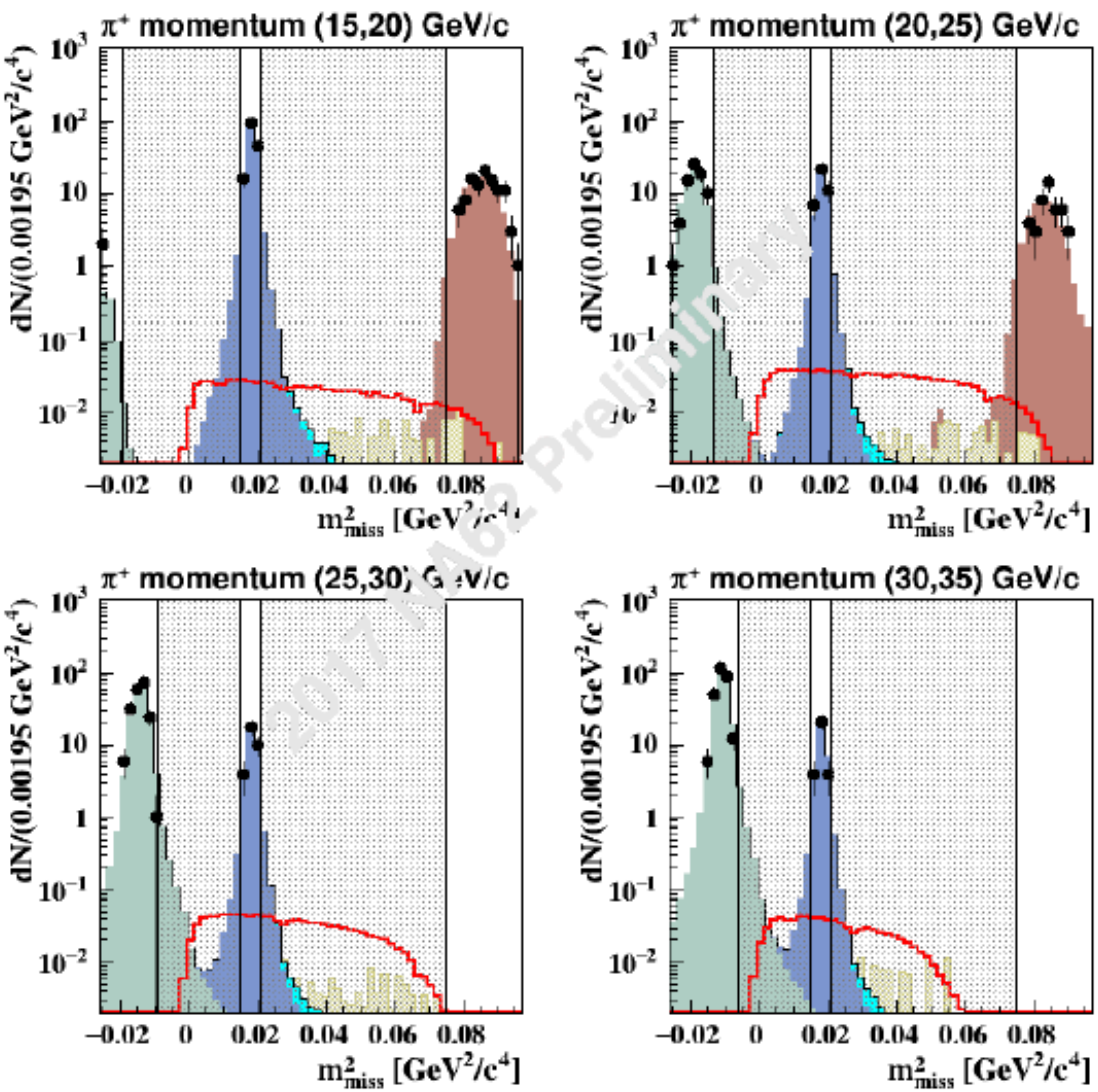


2018



M^2_{miss} distribution

http://cds.cern.ch/record/2668548



- Use the information from the distributions to
  - Increase the sensitivity for πνν
  - Search for a peak (sensitivity to several models in the hidden sector context:
    - dark scalar(Higgs-mixing)
    - axiflavon, ..

- 4 bins in pion momentum
- Unbinned analysis in missing mass

Further flavor physics program

- **Standard Kaon Physics:**
  - Measurements of the BR of all the main K^+ decay modes:
  - χPT: $K^+ \to \pi^+ \gamma\gamma$, $K^+ \to \pi^+ \pi^0 e^+ e^-$, $K^+ \to \pi^{0(+)} \pi^{0(-)} l^+ \nu$
  - Lepton Universality: $R_K = \Gamma(K^+ \to e^+ \nu_e)/(K^+ \to \mu^+ \nu_\mu)$

- **Rare/forbidden K^+ and π^0 decays at SES ~10^{-12}:**
  - K^+ physics: $K^+ \to \pi^+ l^+ l^-$, $K^+ \to \pi^+ \gamma l^+ l^-$, $K^+ \to l^+ \nu\gamma$,
  - LFV/LNV searches: $K^+ \to \pi^+ \mu^\pm e^\mp$, $K^+ \to \pi^- \mu^+ e^+$, $K^+ \to \pi^- l^+ l^+$, ...
  - π^0 physics: $K^+ \to \pi^+ \pi^0$, $\pi^0 \to e^+ e^-$, $\pi^0 \to e^+ e^- e^+ e^-$, $\pi^0 \to \gamma\gamma(\gamma)$, ...

Published result:

Lepton number violation (LNV)

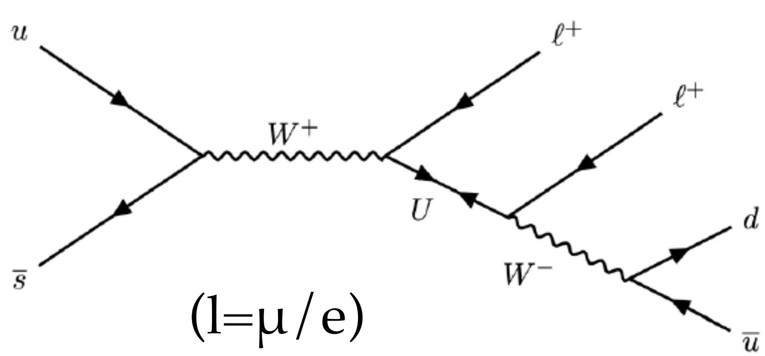
arXiv.1905.07770
Phys. Lett. B 797 (2019) 134794

Next slide

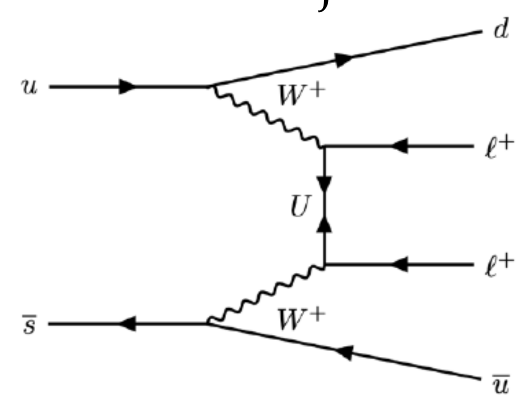
All the other analyses are work in progress

Violation of lepton flavor/number conservation laws is predicted in BSM models:

- $K^+ \to \pi^- l^+ l^+$: $\Delta L=2$ and $\Delta L\mu=2$ or $\Delta Le=2$ via Majorana neutrinos U



(l=μ/e)

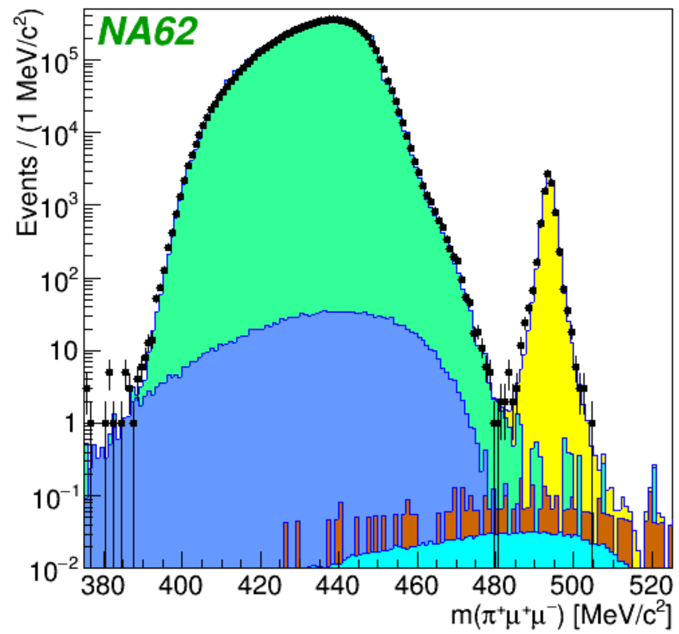


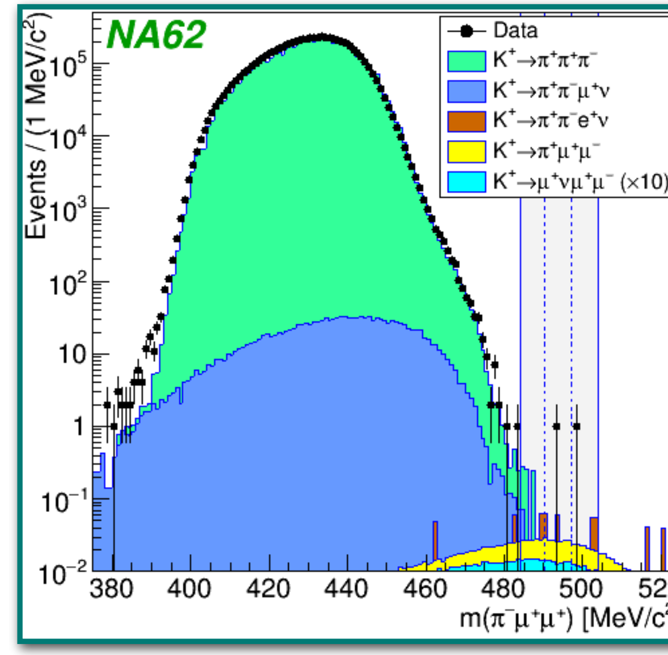
[JHEP 0905 (2009) 030]
[PL B491 (2000) 285-290]

Lepton number violation

arXiv.1905.07770
Phys. Lett. B 797 (2019) 134794

- Subset of 2017 data, corresponding to 3 months of data taking (3 times more data still to be analyzed.)
- dedicated, downscaled triggers
- Normalization from corresponding SM channels





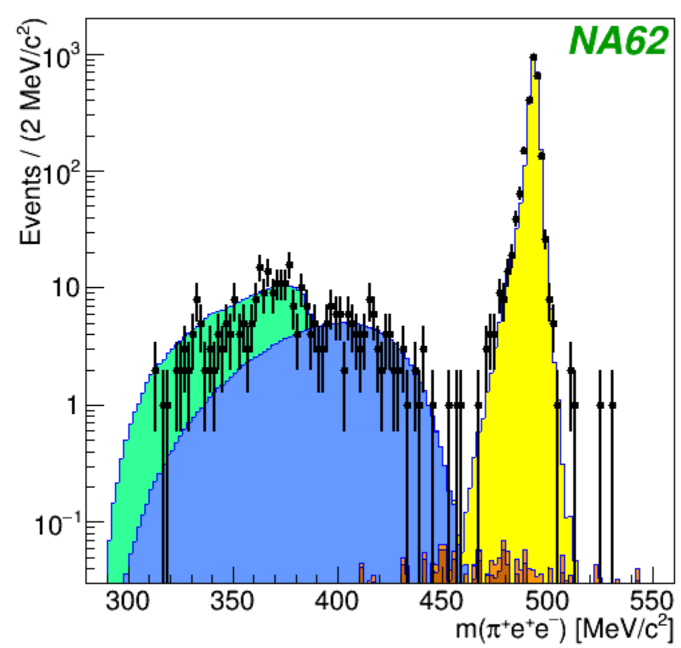
$\pi^-\mu^+\mu^+$

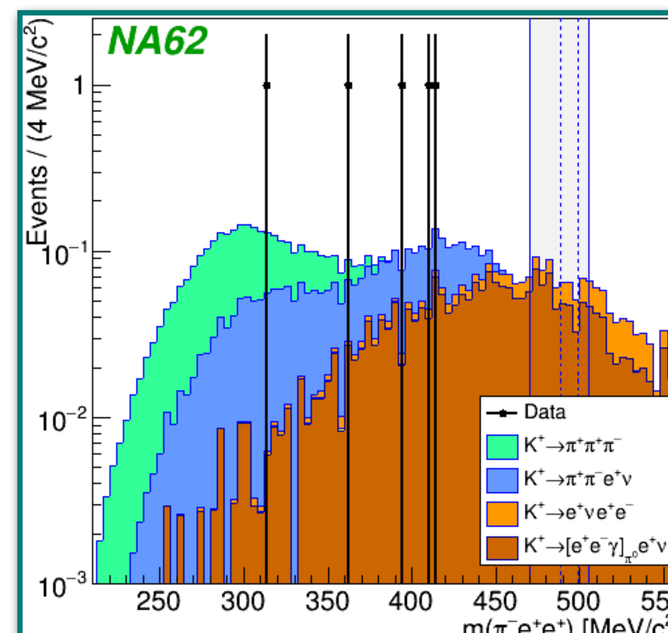
$$BR(K^+ \to \pi^-\mu^+\mu^+) < 4.2\times 10^{-11} @ 90\,\%\,CL$$

Improved previous PDG upper limits:

$BR(K^+ \to \pi^-\mu^+\mu^-) < 8.6\times 10^{-11} @ 90\,\%\,CL$ [NA48/2]

$BR(K^+ \to \pi^-e^+e^-) < 6.4\times 10^{-10} @ 90\,\%\,CL$ [BNL, E865]





$\pi^-e^+e^+$

$$BR(K^+ \to \pi^-e^+e^+) < 2.2\times 10^{-10} @ 90\,\%\,CL$$

Conclusions

2016-2018

☑ **2016 data:**

decay in flight technique works, 1 candidate event observed:

$BR\,(K^{+} \to \pi^{+} \nu\nu) < 14 \times 10^{-10}$ @95% CL,

Published in [Phys. Lett. B 791 (2019) 156-166]

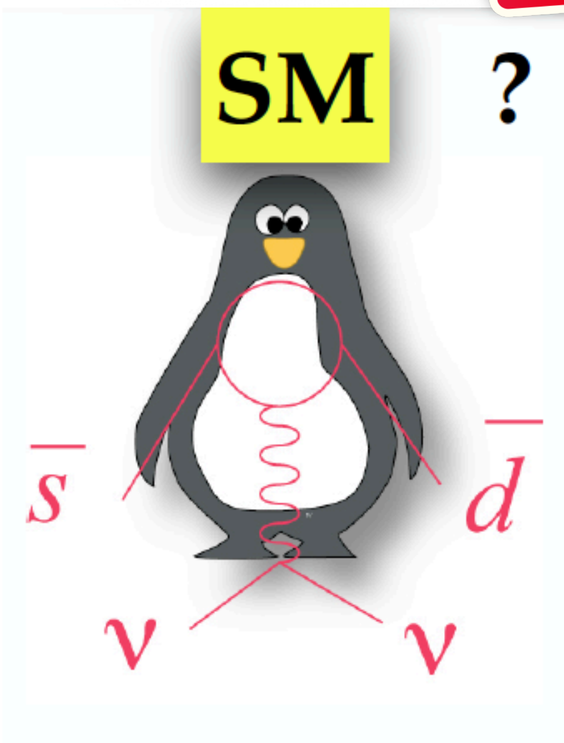
☐ <u>**2017 data:** completing the analysis</u>

2019-2021

☐ Developing improved analysis for the full NA62Run1 dataset 2016-2018

~ 4 years

☐ After LS2 ~ 2 years of data taking to achieve 5-10% uncertainty

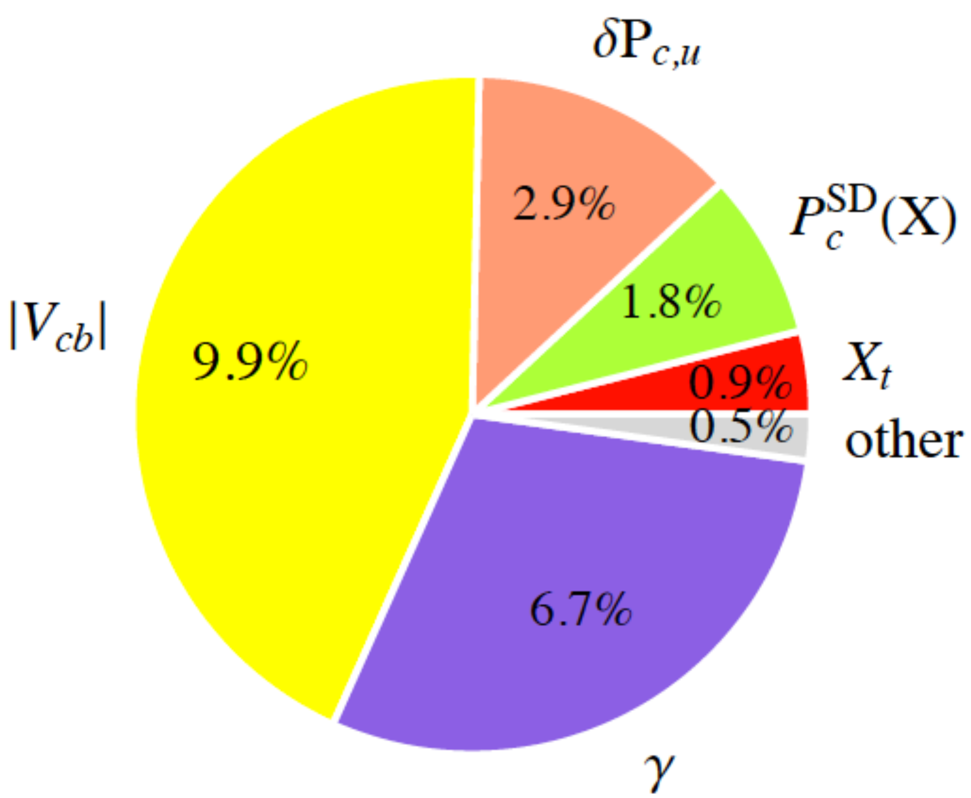


Prague (2015)
NA62 Collaboration Meeting

Thank you for your attention

$$\sim \frac{m_t^2}{M_W^2}\lambda_t + \frac{m_c^2}{M_W^2}\ln\frac{M_W}{m_c}\lambda_c + \frac{\Lambda_{\rm QCD}^2}{M_W^2}\lambda_u$$

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



LAV: photon veto at large angles lead-glass blocks

STRAW: Downstream tracking

IRC, SAC: lead and scintillator plates Shashlyk configuration

RICH: Ring imaging Cherenkov kinematics and particle ID

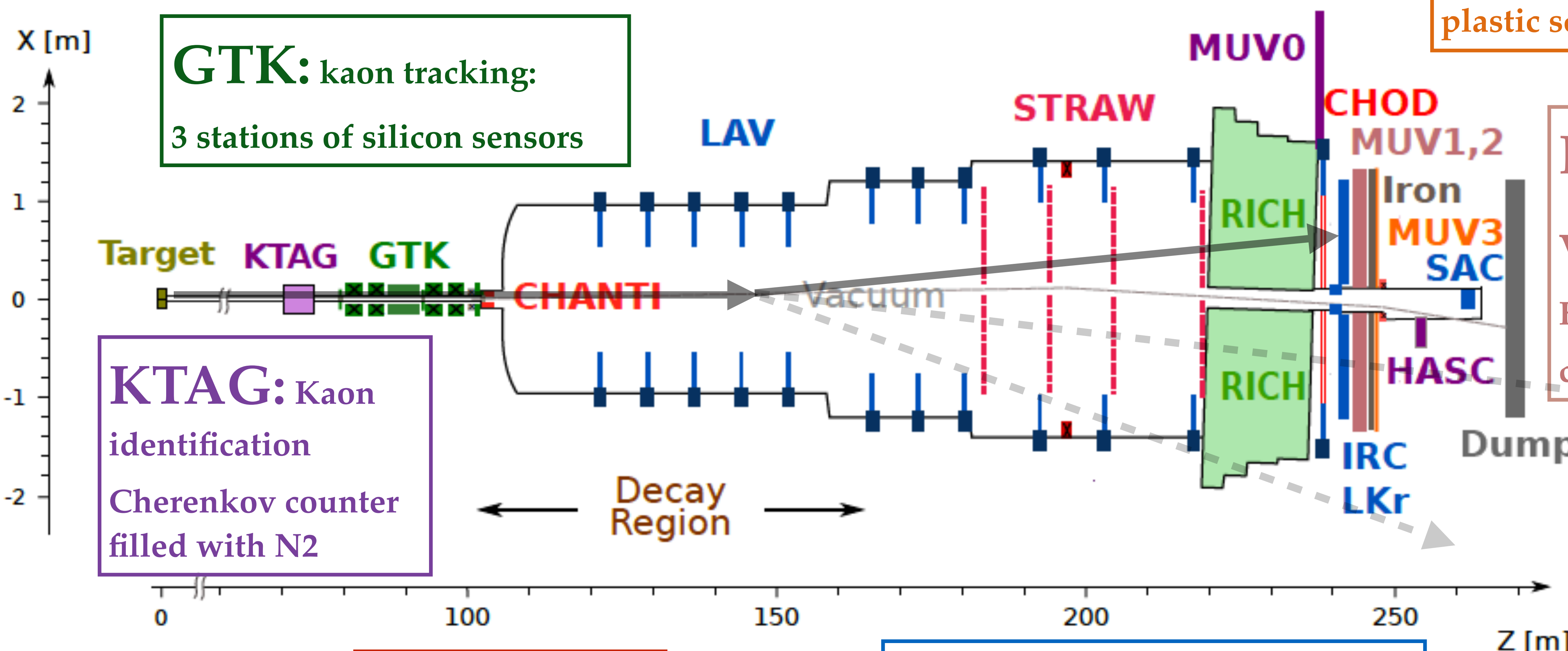
MUV0, MUV3 plastic scintillators

GTK: kaon tracking: 3 stations of silicon sensors

Muon veto

Hadronic calorimeters

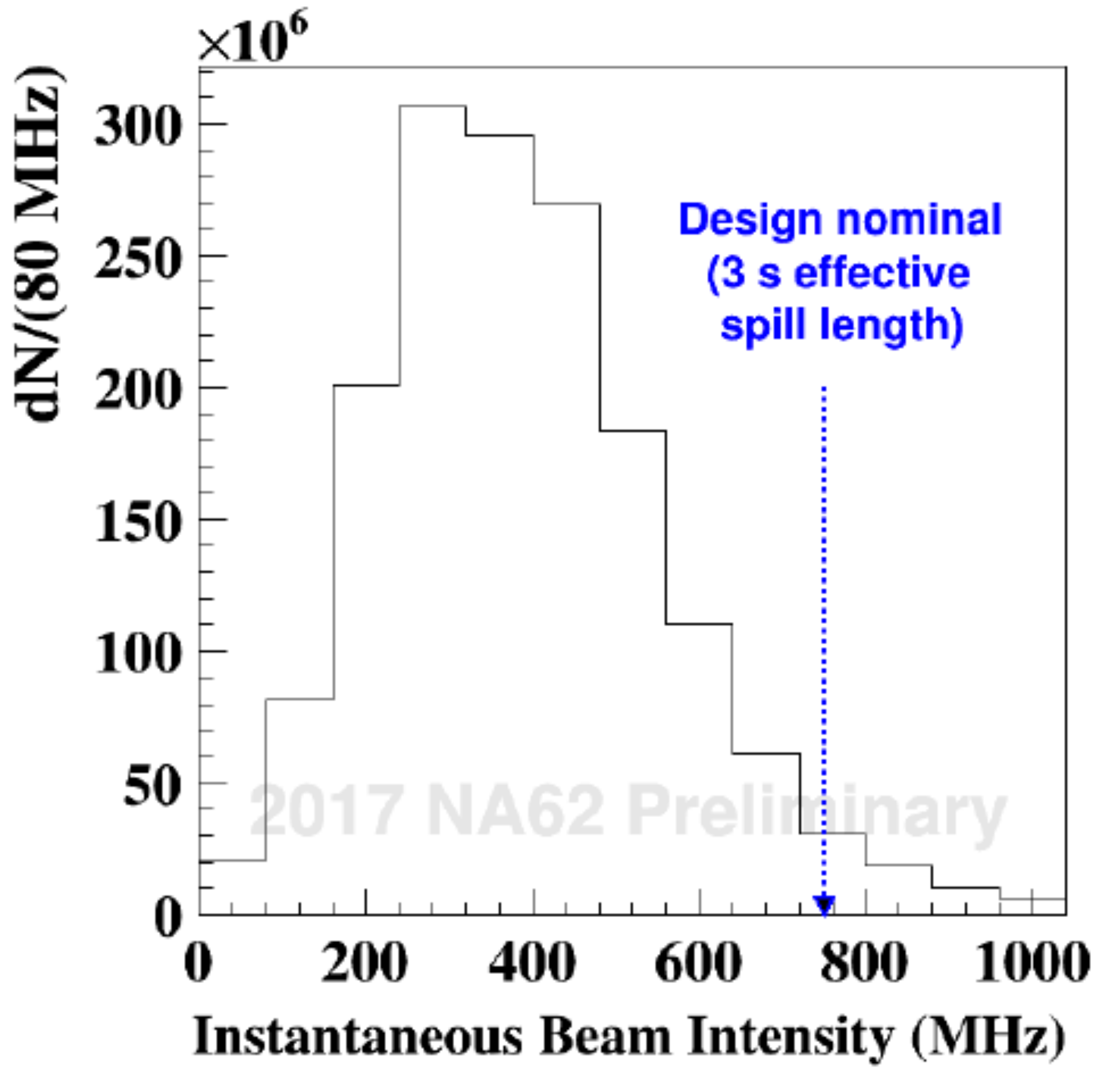
KTAG: Kaon identification Cherenkov counter filled with N2

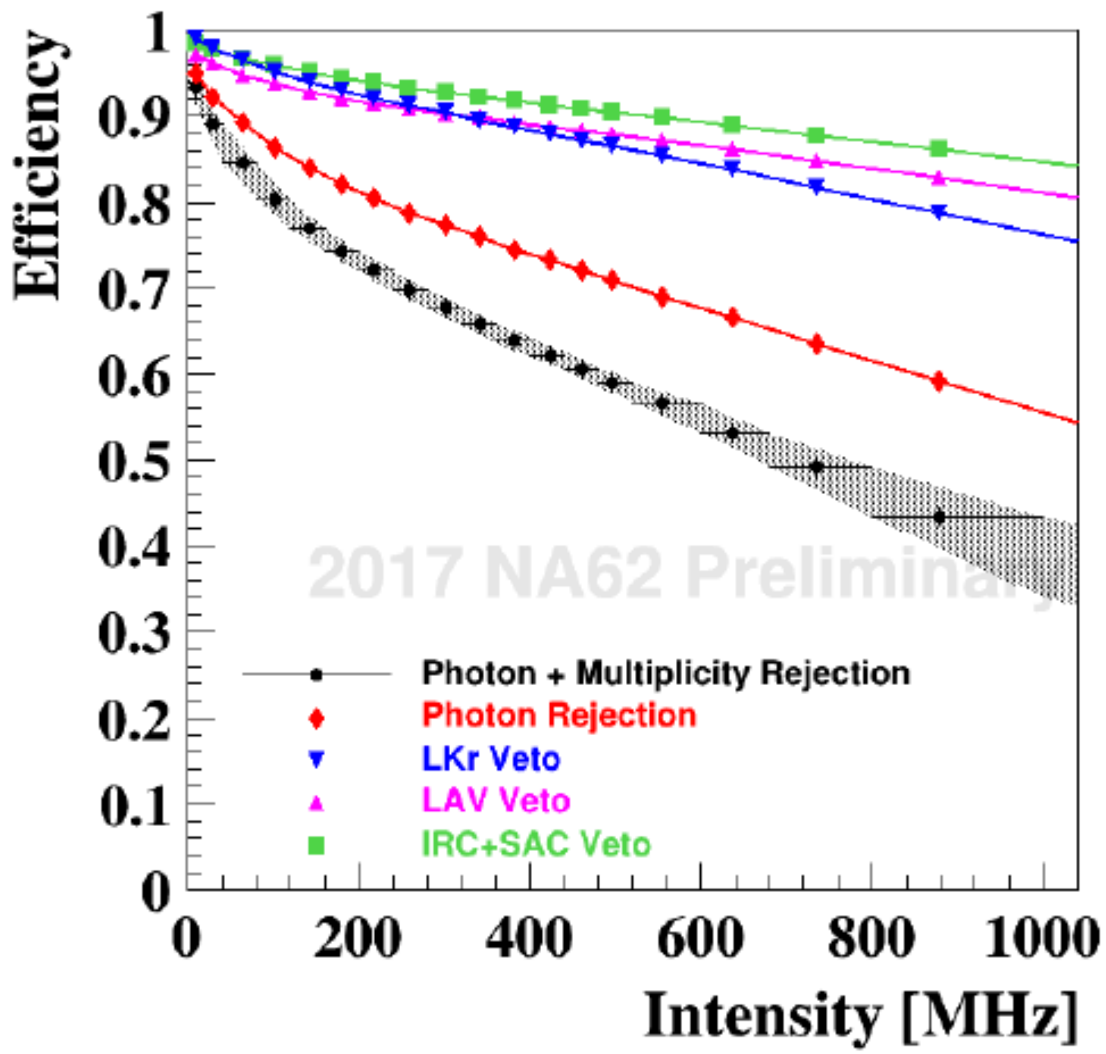


CHOD charged hodoscope

LKr: quasi-homogenous ionization chamber 27X0 deep

Random veto


×10^6
dN/(80 MHz)
300
250
200
150
100
50
0
0
200
400
600
800
1000
Instantaneous Beam Intensity (MHz)
Design nominal
(3 s effective
spill length)
2017 NA62 Preliminary

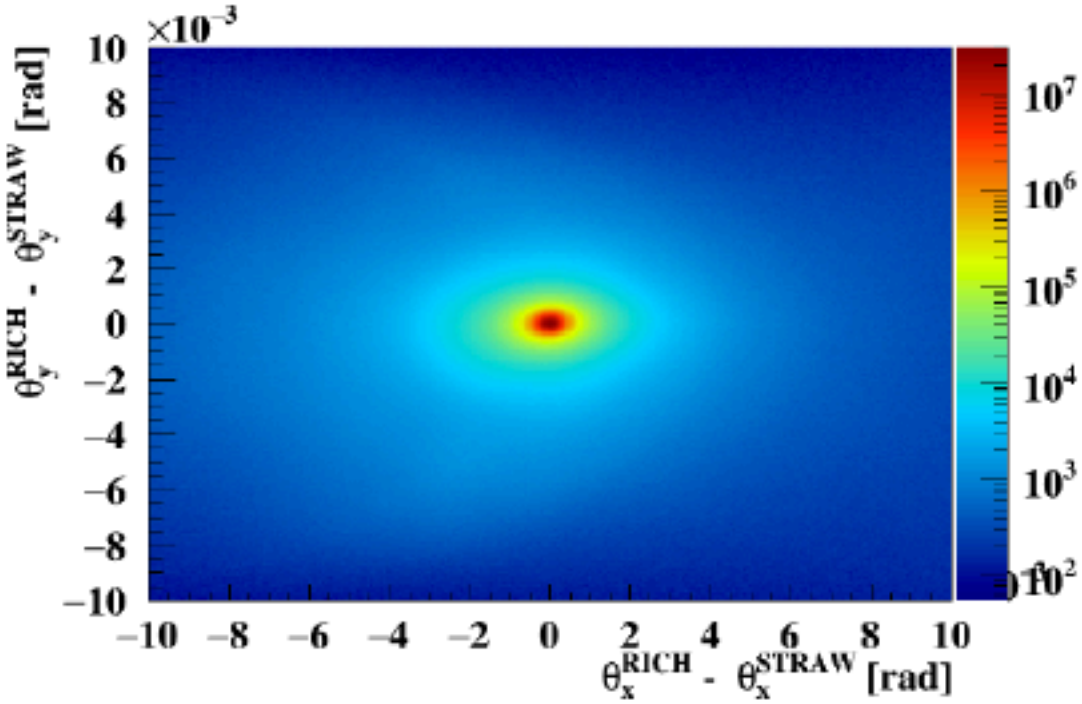

Efficiency
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
200
400
600
800
1000
Intensity [MHz]
2017 NA62 Preliminary
Photon + Multiplicity Rejection
Photon Rejection
LKr Veto
LAV Veto
IRC+SAC Veto

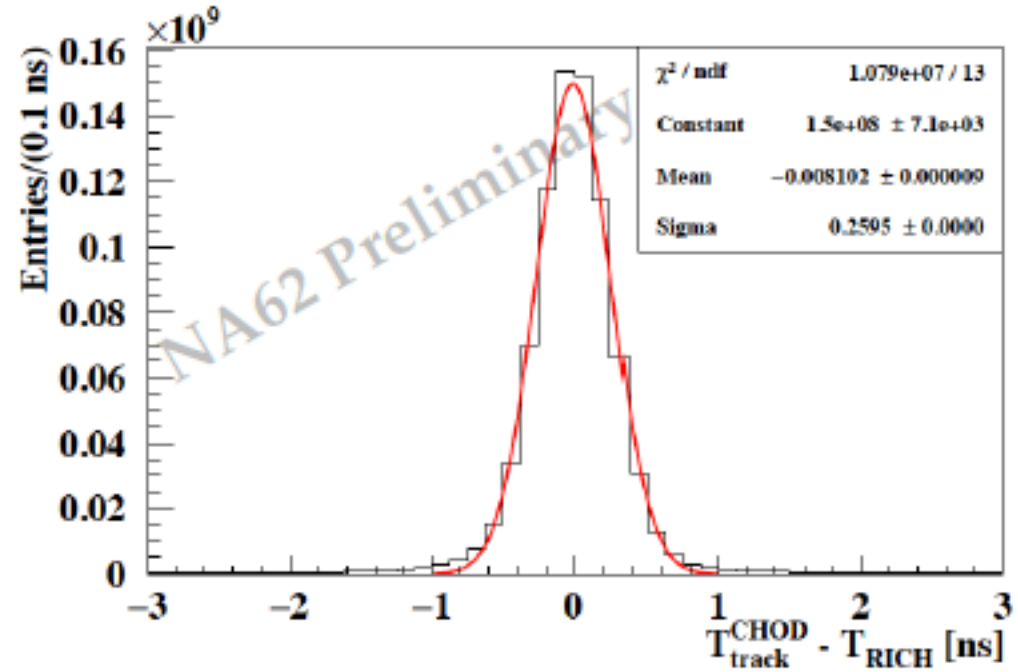
Standalone RICH

RICH candidate -Track association

$$D_{RICH} = \left(\frac{|\mathbf{X}_{center} - \mathbf{X}_{PM}|}{\sigma_X}\right)^2 + \left(\frac{T_{RICH} - T^{CHOD}_{track}}{2\sigma_T}\right)^2$$

The charged hodoscope (CHOD) hit is matched to track candidate through spacial criteria, and CHOD time is used as Track Time





The candidate which minimizes D(RICH) is chosen if it satisfies:

- $D_{RICH} < 50$;
- the fit probability is larger than 0.01;
- T_{RICH} is within ±2 ns of T^{CHOD}_{track}.

σ(TTrack-TRICH)~ 260 ps

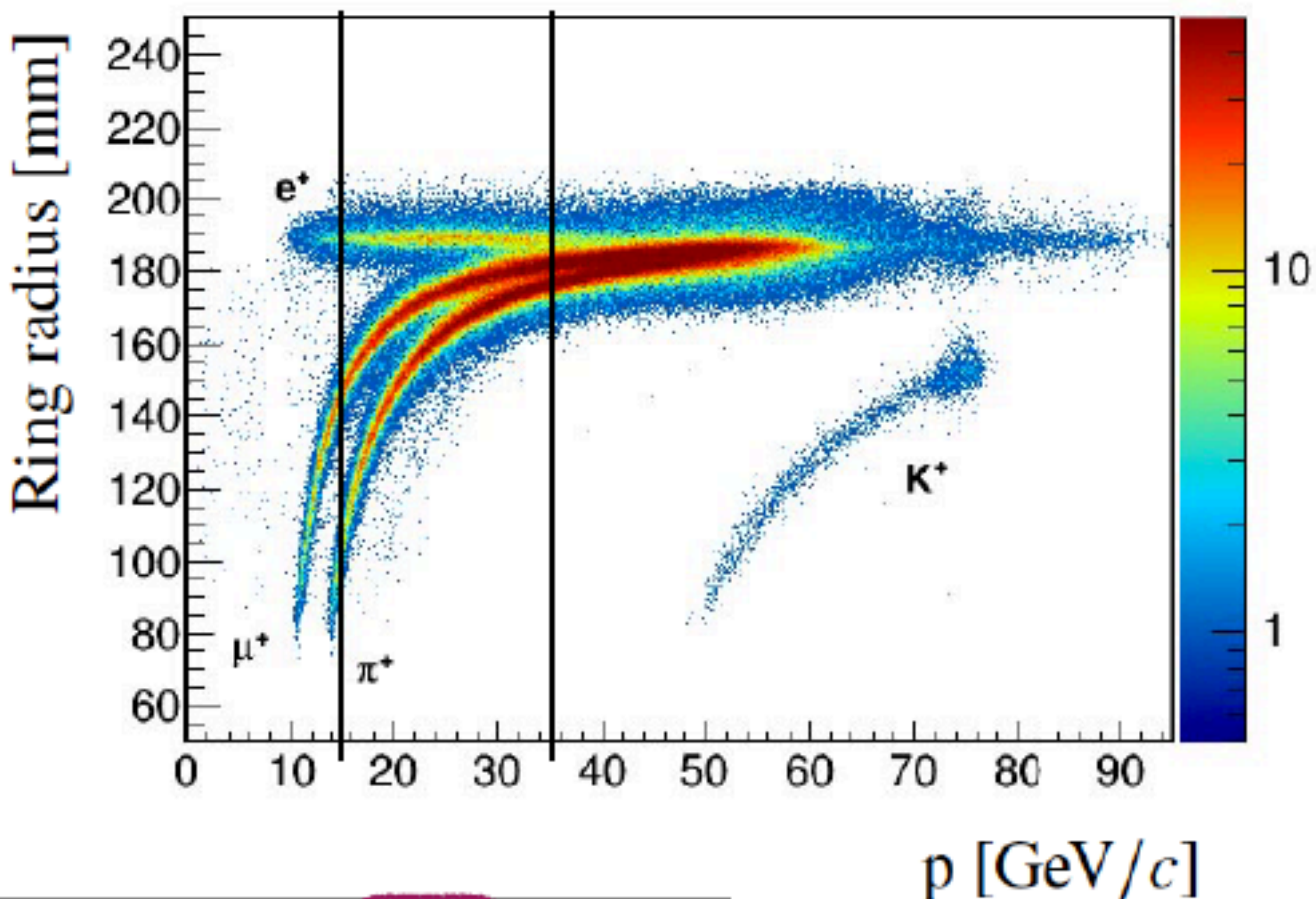
Time resolution for

a RICH candidate is <100 ps

Standalone RICH

- RICH Radius from the fit
- Momentum measured by the tracking

Radius is measured by the only RICH detector
No possible bias from other detector

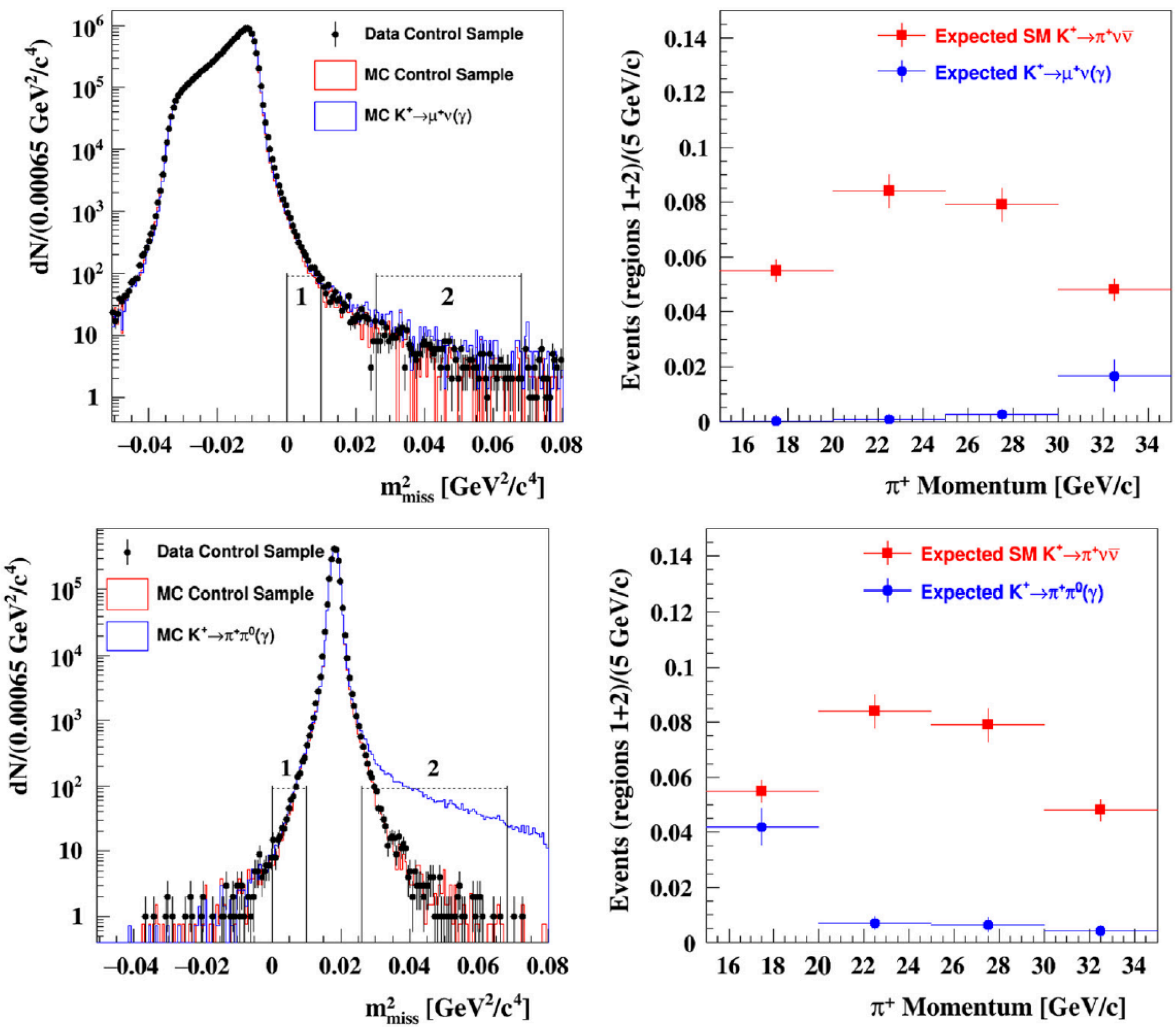


$$M_{RICH} = P_{\pi} \, n_{in} \cdot \sqrt{\cos^2\left(tan^{-1}\left(\frac{R_{ring}}{f_{length}}\right)\right) - 1}$$

Focal length ~17 m

2016 Background evaluation

Phys. Lett. B 791 (2019) 156-166

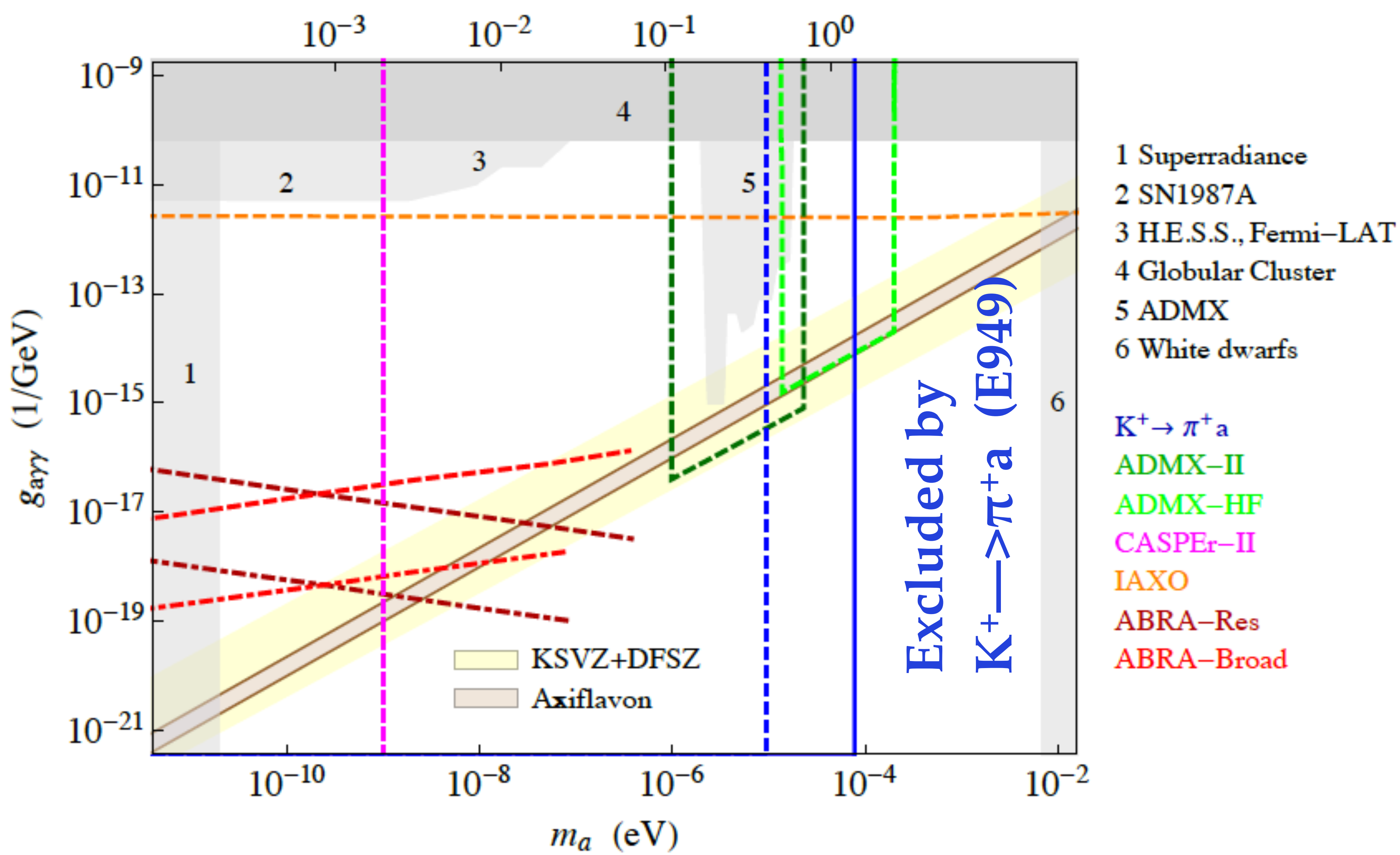


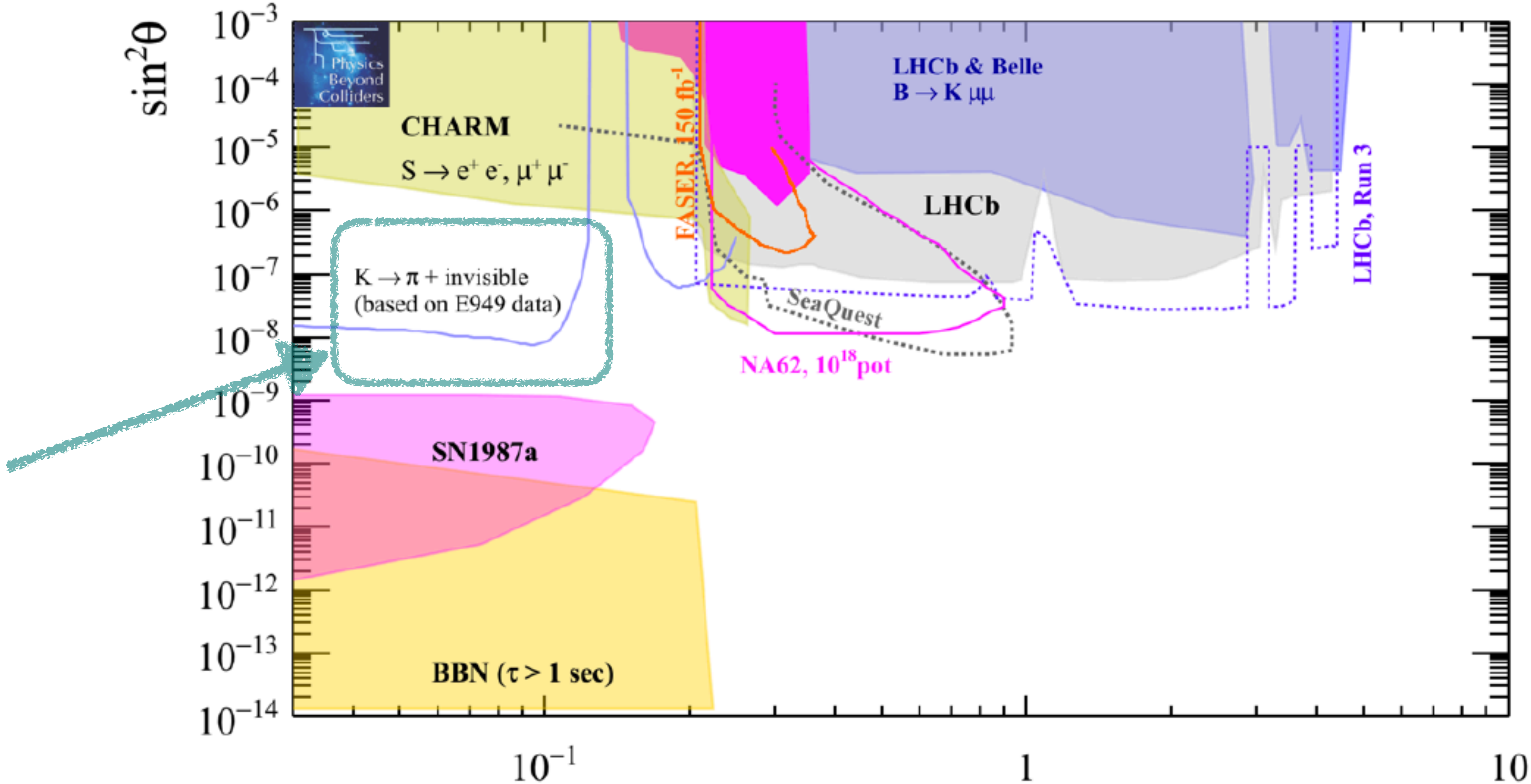
The Axiflavon

Calibbi, Goertz, Redigolo, Ziegler, Zupan, Phys. Rev. D 95, 095009 (2017) **arXiv:1612.08040**

Besides the strong CP problem, it solves the flavor hierarchy puzzle in the SM

$$\mathrm{BR}(K^+ \to \pi^+ a) \simeq 1.2 \times 10^{-10} \left(\frac{m_a}{0.1\ \mathrm{meV}}\right)^2 \left(\frac{\kappa_{sd}}{N}\right)^2$$





$$BR(K^+ \to \pi^+ S) \simeq \sin^2\theta \times 0.002 \times \frac{2|\vec{p_S}|}{m_K^+}$$