Recent results and prospects from the NA62 experiment at CERN

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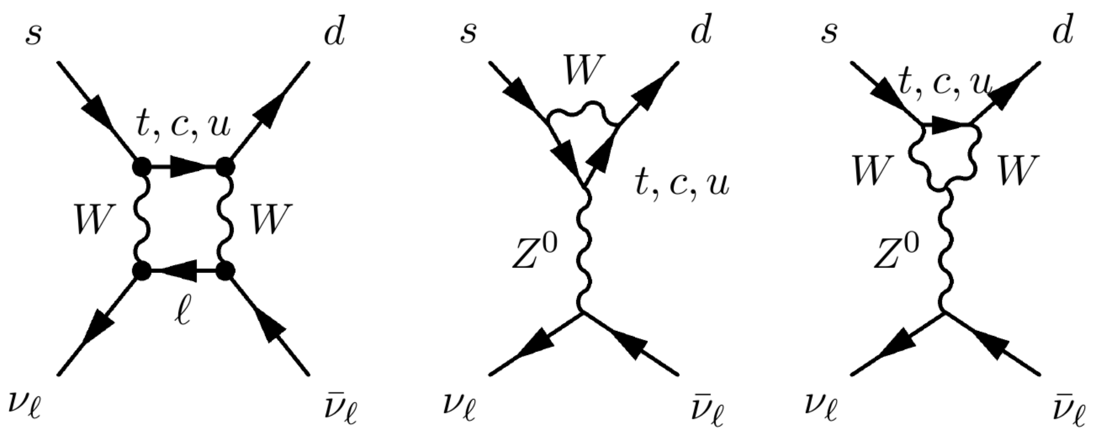
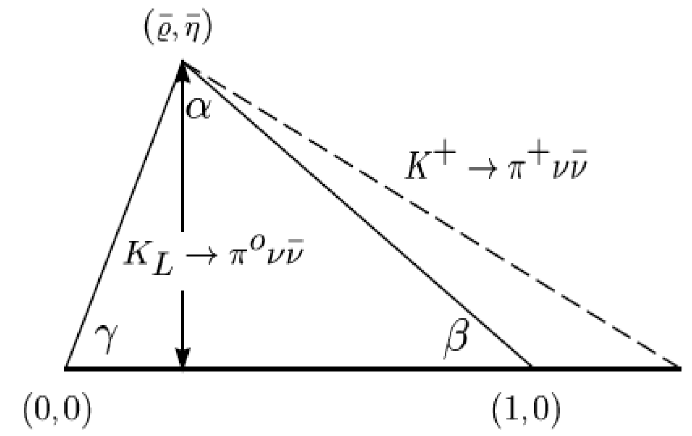
Particle physics seminar – Birmingham – 12/02/2020

$K^+ \to \pi^+ \nu\bar{\nu}$: Motivations & Theory





- FCNC forbidden at tree level: 1-loop contributions as leading order
- Highly CKM suppressed: $BR(K^+ \to \pi^+ \nu\bar{\nu}) \sim |V_{ts}^* V_{td}|^2 \sim \lambda^{10}$

} high sensitivity to new physics

- Dominated by short-distance contribution (top quark)
- *t* quark contribution @ NLO QCD and 2-loop EW corrections, *c* quark @ NNLO QCD and 1-loop EW corrections
- Hadronic matrix element from $BR(K^\pm \to e^\pm \pi^0 \nu)$

} high-precision theoretical prediction

- Measurement of $|V_{td}|$ complementary to those from $B-\bar{B}$ mixing or $B^0 \to \rho\gamma$
- Constraints on CKM unitary triangle

SM prediction:

$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (0.84 \pm 0.10) \times 10^{-10}$

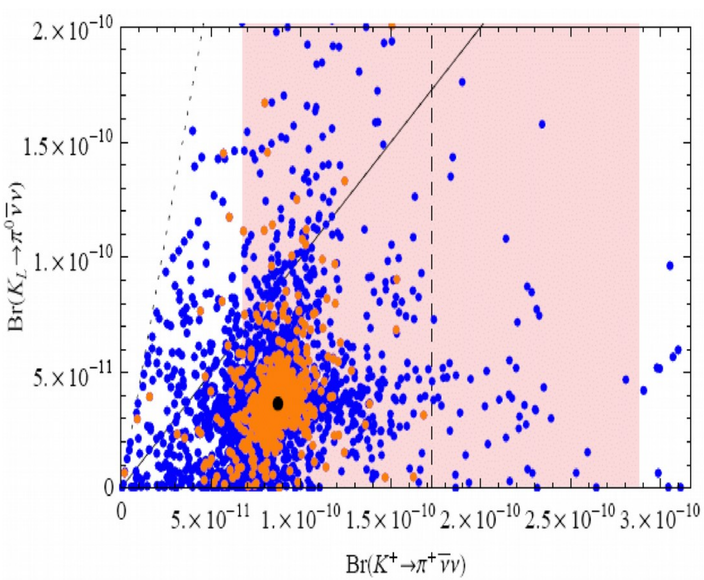
Buras *et al.*, JHEP 1511 (2015) 033.

$K^+ \to \pi^+ \nu\bar{\nu}$: New Physics scenarios

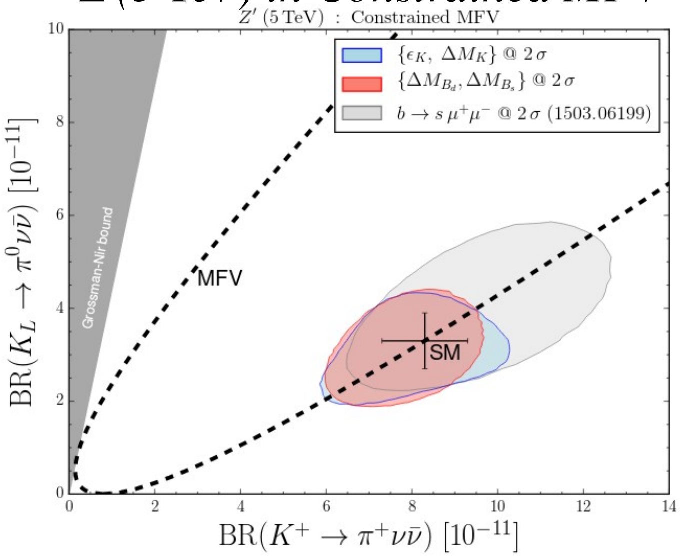
- Custodial Randall-Sundrum [Blanke *et al.*, JHEP 0903 (2009) 108]
- MSSM analyes [Blazek and Matak, Int. J. Mod. Phys. A 29 (2014) 1450162]
  [Isidori *et al.*, JHEP 0608 (2006) 064]
- Simplified Z, Z' models [Buras, Buttazzo, Knegjens, JHEP 1511 (2015) 166]
- Littlest Higgs with T-Parity [Blanke *et al.*, EPJ C76 (2016) 182]
- LFU violation models [Isidori *et al.*, EPJ C77 (2017) 618]
- Constraints from existing measurements (correlations model dependent)

  Kaon mixing, CKM elements, K, B rare meson decays, NP limits from direct searches

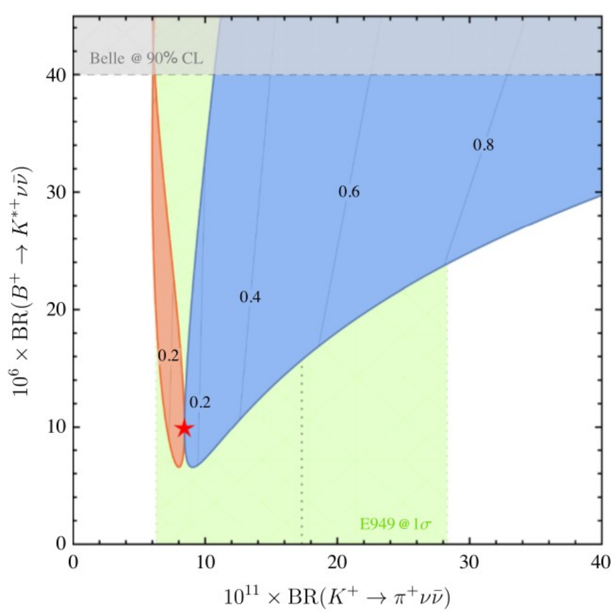
Randall-Sundrum



Z'(5 TeV) in Constrained MFV

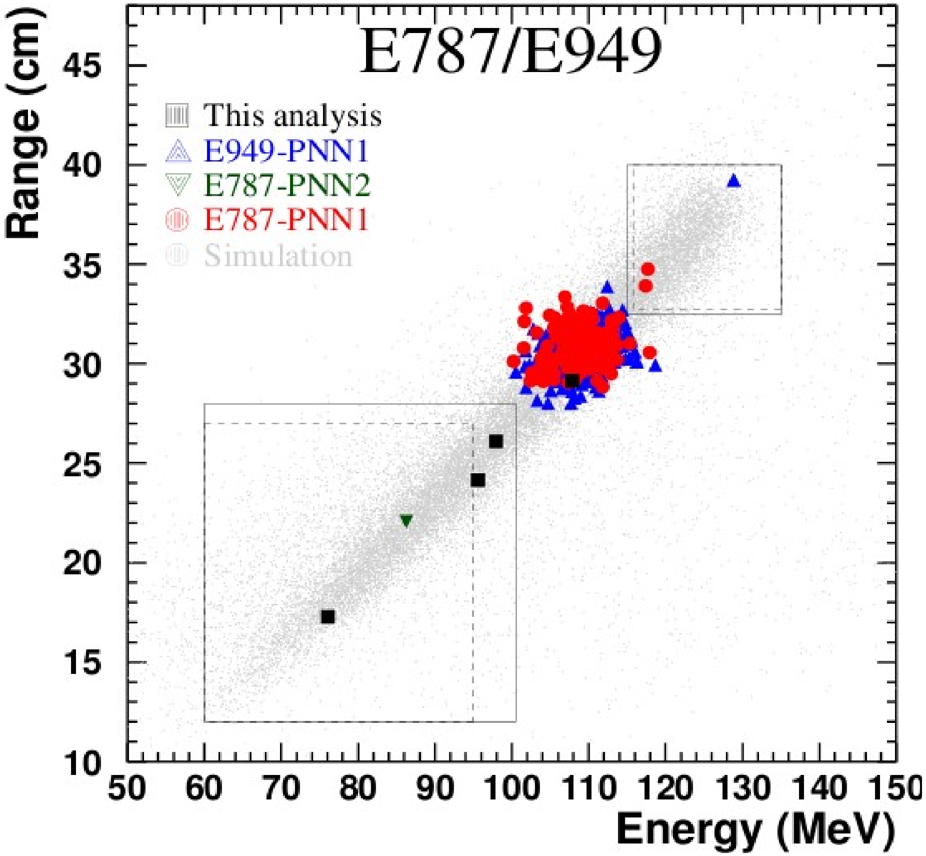


LFU violation



$K^+ \to \pi^+ \nu\bar{\nu}$: Experimental Results

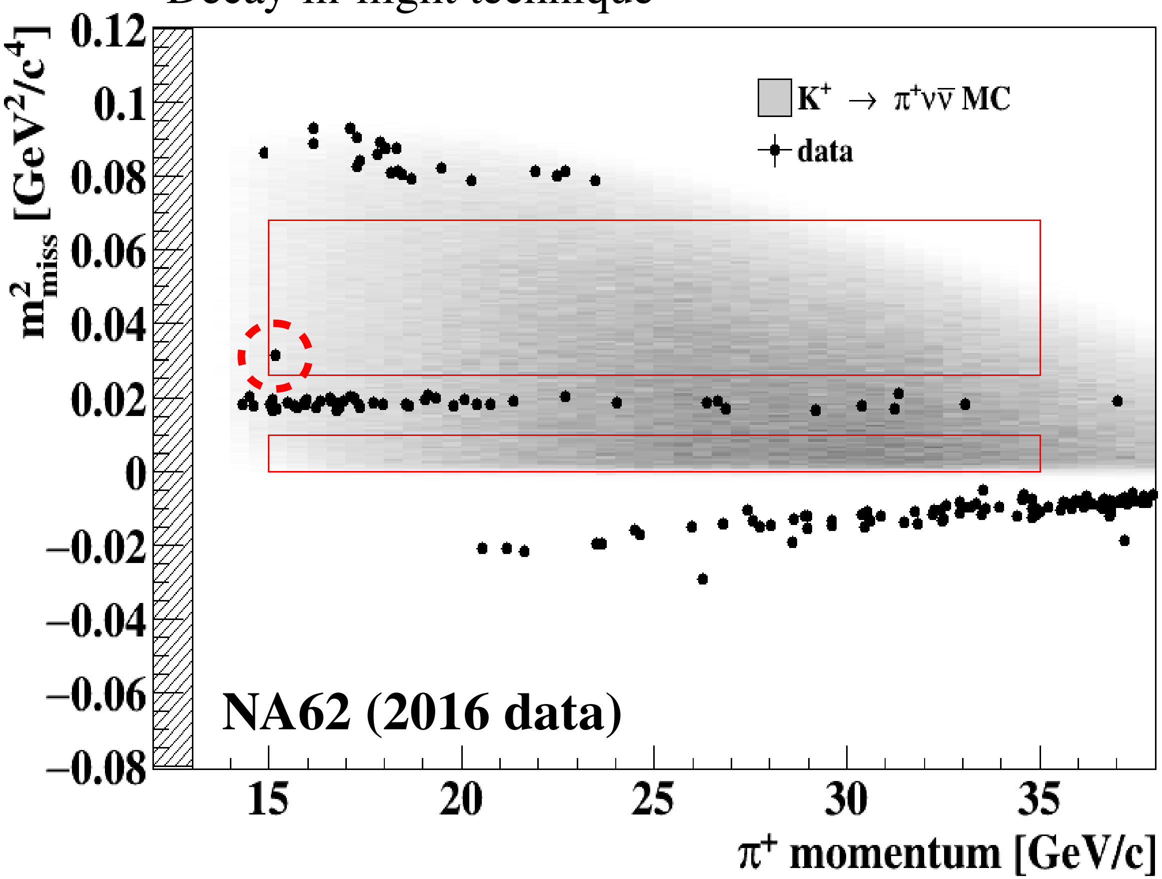
Decay-at-rest technique



$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$

E787/E949, PRL 101 (2008) 191802

Decay-in-flight technique

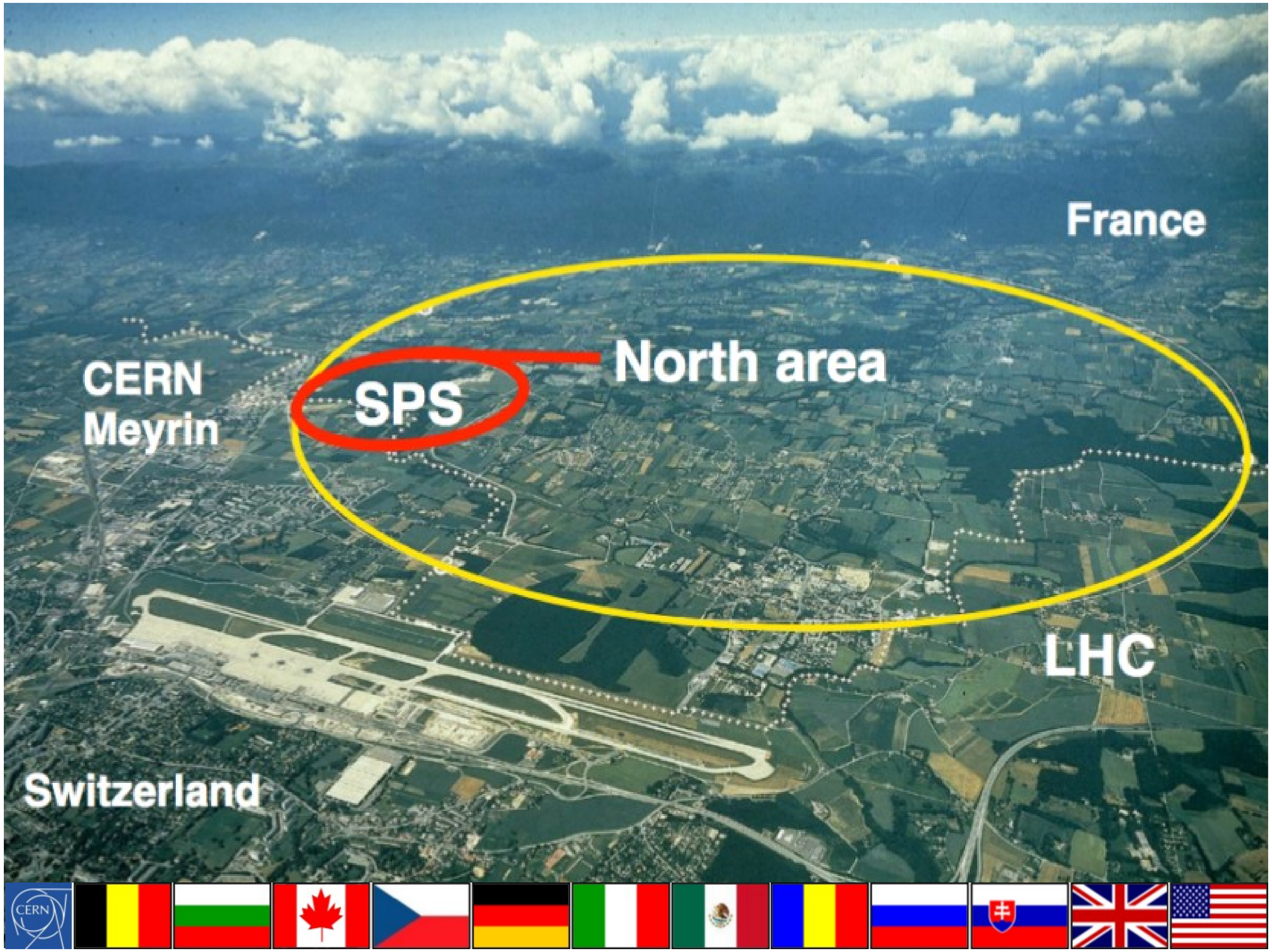


$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) < 14 \times 10^{-10}$ @ 95% CL

NA62, Phys. Lett. B 791 (2019) 156

The NA62 experiment @ CERN

NA62 is the last from a long tradition of fixed-target Kaon experiments in the CERN North Area



History of NA48/NA62 experiments		
1997 ↓ 2001	NA48 (K_S/K_L)	Re ε'/ε **Discovery of direct CPV**
2002	NA48/1 (K_S/hyperons)	Rare K_S and hyperon decays
2003 ↓ 2004	NA48/2 (K^+/K^-)	Direct CPV, Rare K^+/K^- decays
2007 ↓ 2008	NA62-R_K (K^+/K^-)	$R_K = K^{\pm}_{e2}/K^{\pm}_{\mu2}$, Rare K^+/K^- decays
2016 ↓ -	**NA62 (K^+)**	**$K^+ \rightarrow \pi^+ \nu\bar{\nu}$, Rare K^+ and π^0 decays**

NA62: currently ~ 200 participants, 29 institutions from 12 countries

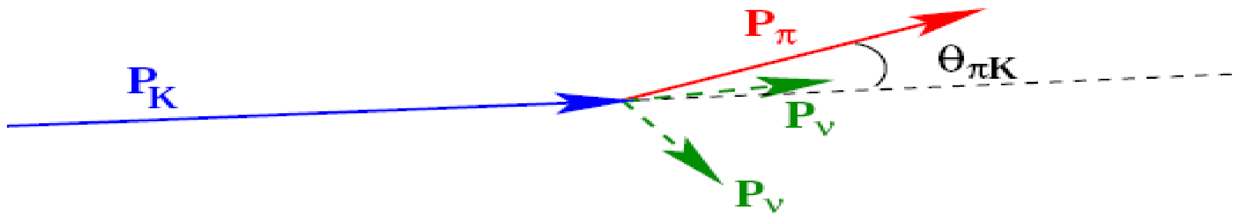
$K^+ \to \pi^+ \nu\bar{\nu}$ in NA62: strategy

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

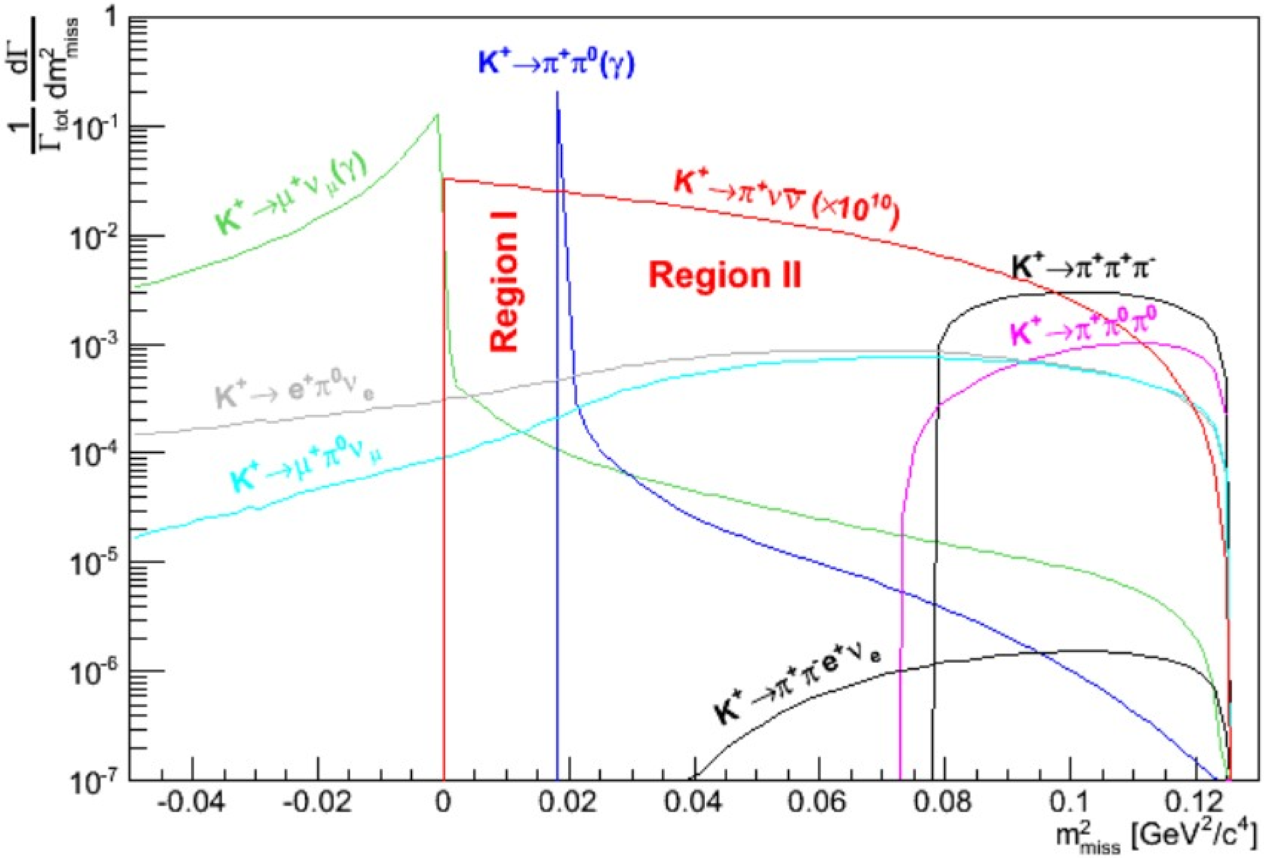
Kaon track +

Pion track +

NOTHING ELSE



$$m^2_{miss} \approx m^2_K \left(1 - \frac{|p_\pi|}{|p_K|}\right) + m^2_\pi \left(1 - \frac{|p_K|}{|p_\pi|}\right) - |p_K||p_\pi|\theta^2_{\pi K}$$

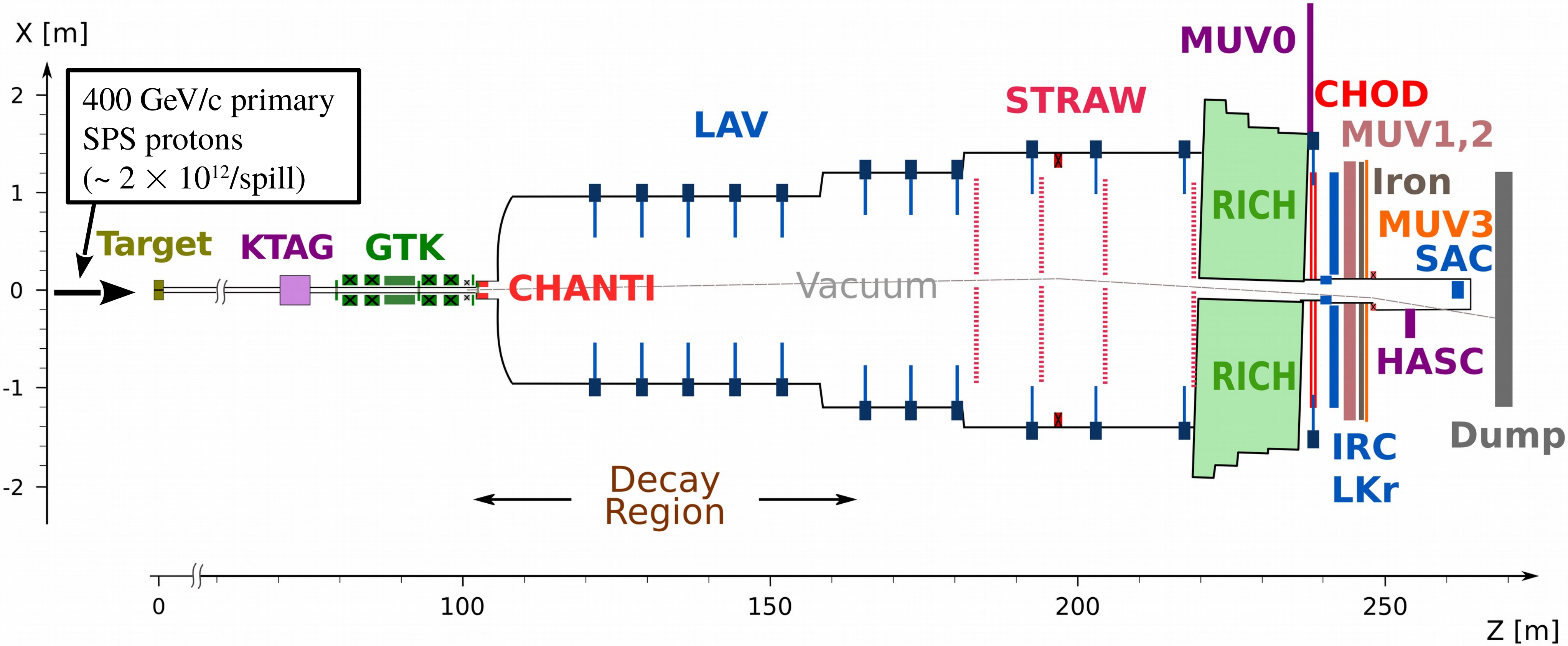


NA62 Keystones:

- Precise tracking
- Particle ID (in particular π/μ)
- Photon rejection
- Precise timing ~ O(100 ps)

Background rejection at ~ 10^{11} level

The NA62 beam and detector



Secondary hadron beam:

- Composition: K^+ (6%) / π^+ (70%) / p (24%)
- p = 75 GeV/c, $\Delta p/p \sim 1\%$
- 100 μrad divergence (RMS)
- 60×30 mm^2 transverse size
- Intensity: 750 MHz (45 MHz K^+)

Decay region:

- 60 m long fiducial volume
- Vacuum ~ O(10^{-6} mbar)
- ~ 5 MHz K^+ decay rate

The NA62 beam and detector

...and this is how it really looks!

The 2016–2018 Data Sample

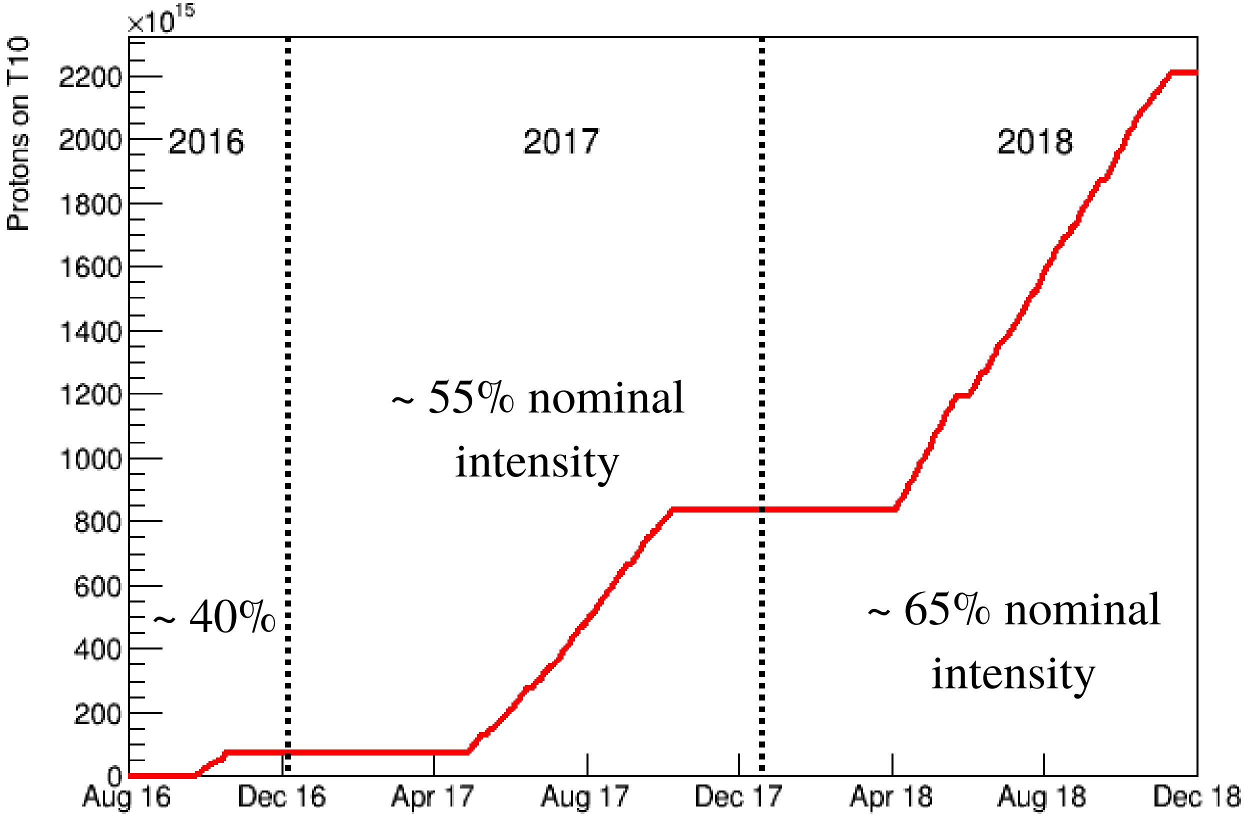
Full 2016-2018 sample:

~ 5× 10^{12} kaon decays, ~ 3 PB of raw data on disk

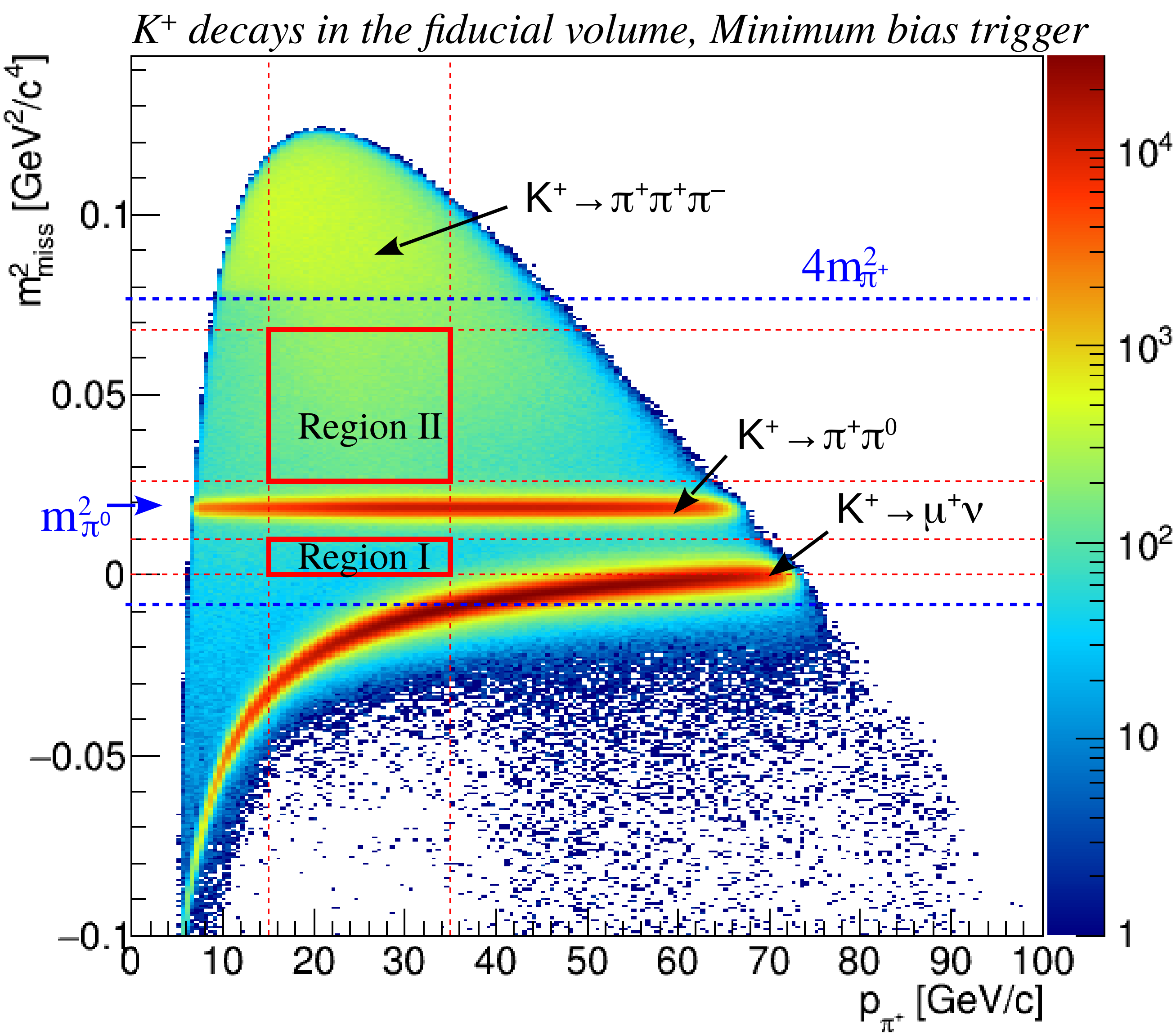
O(10) trigger streams, broad physics reach

Trigger mask	Downscale
πνν	1
2μ	2
e, multi-track	8
μ, multi-track	10
Multi-track	50-100
Non-μ	200
Minimum bias	400
...	

100% nominal intensity [= 750 MHz hadron beam]



Signal selection



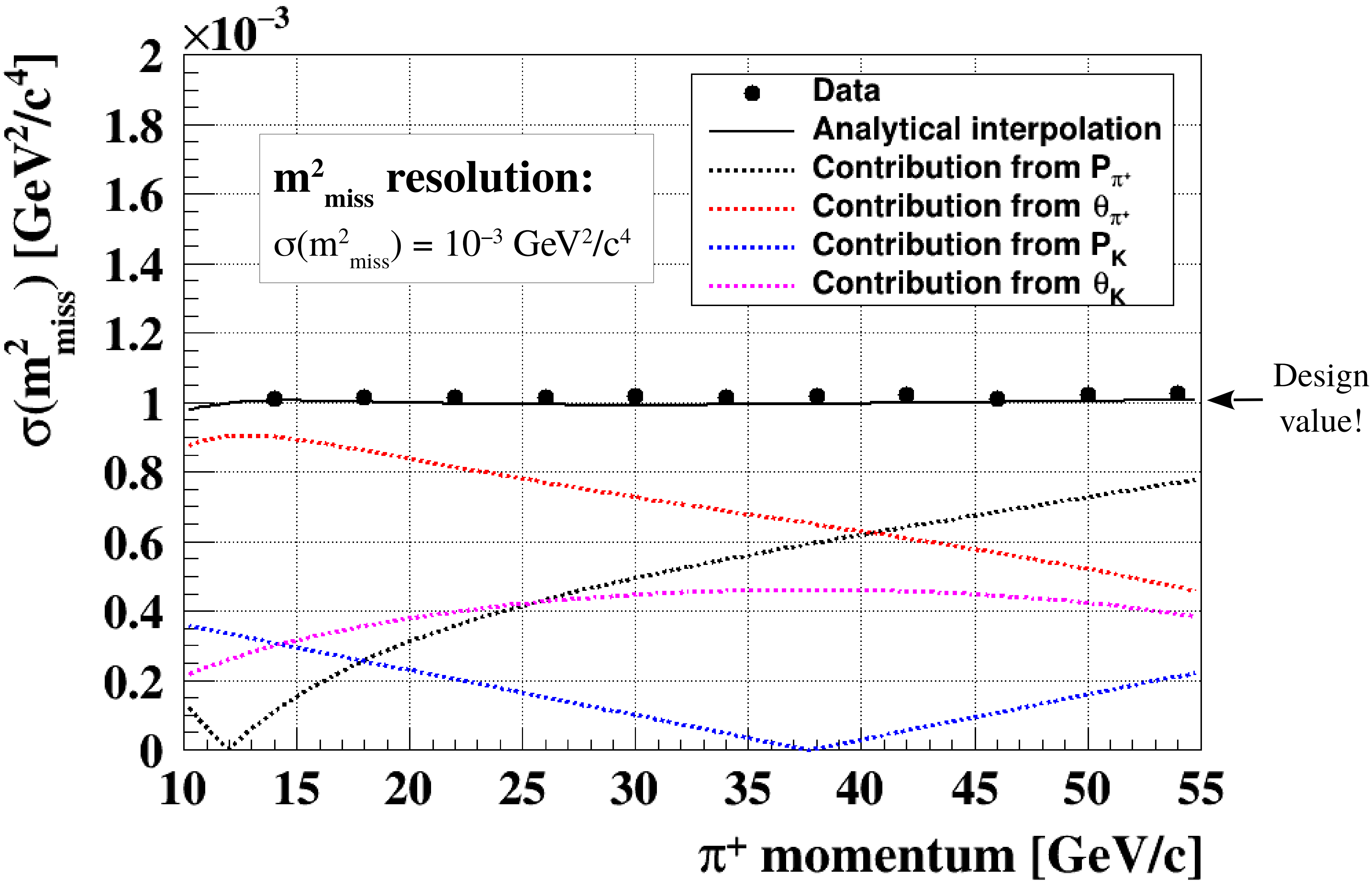
Selection criteria:

- Single track topology
- π^+ identification
- Photon rejection
- Multi-track rejection

Analysis strategy:

Signal and Control Regions kept blind throughout the analysis

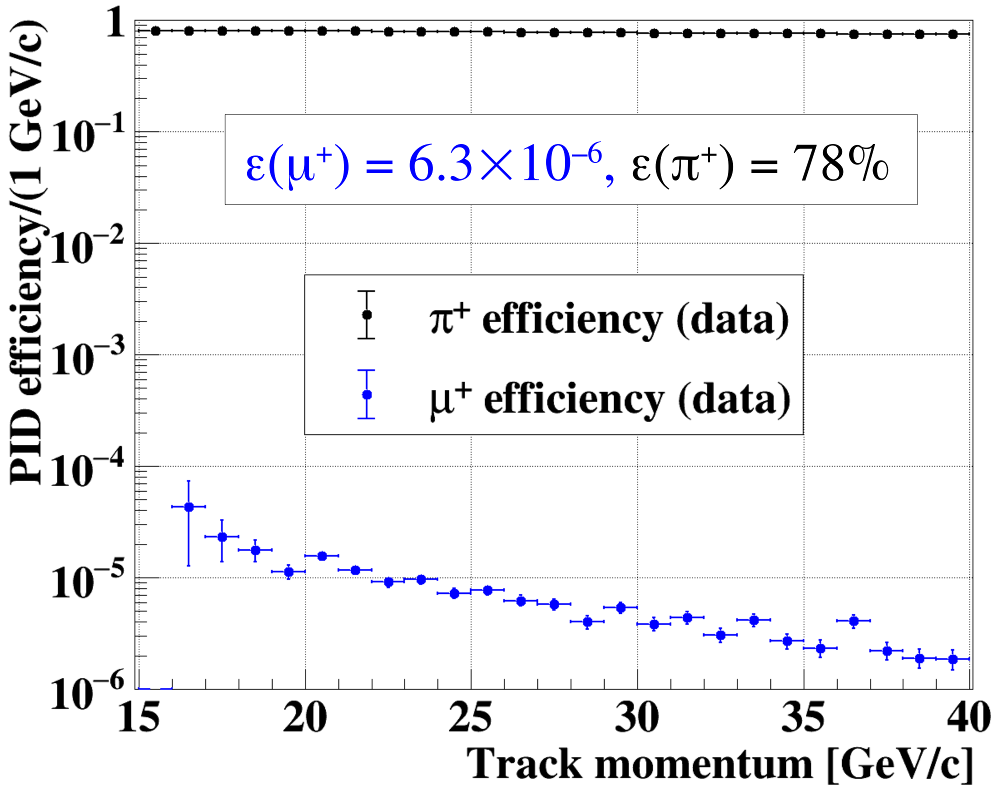
NA62 Keystone 1: Precise tracking



NA62 Keystone 2: Particle ID

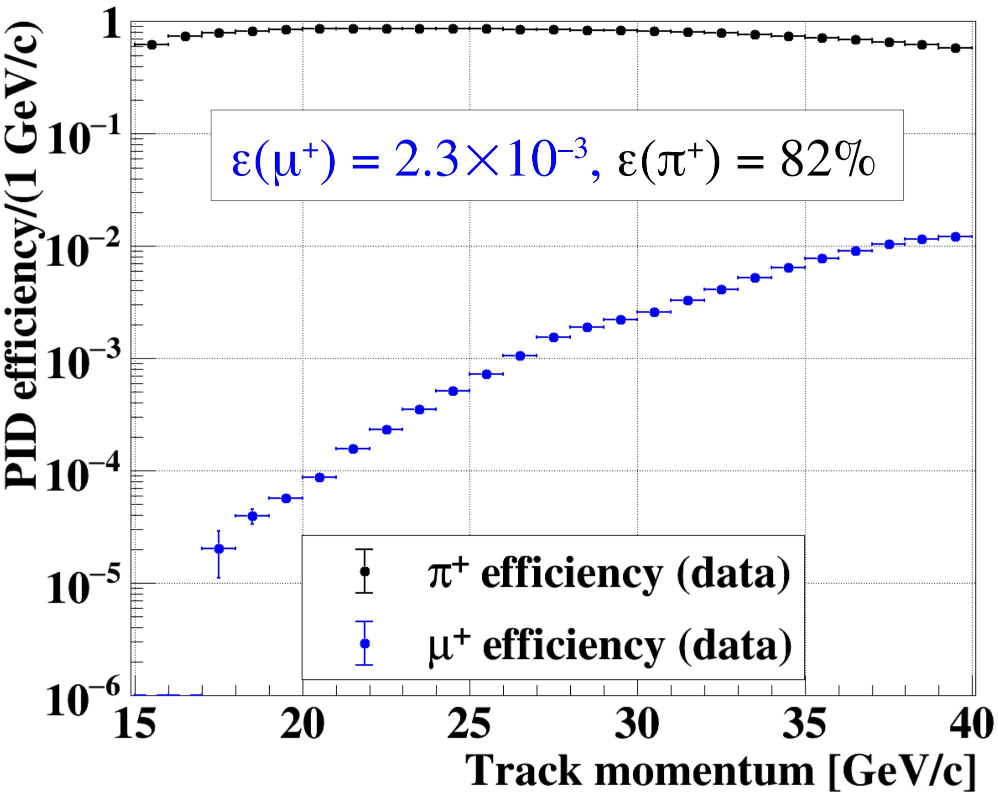
Calorimetric PID

- Machine learning approach (BDT)
  - Energy deposition
  - Energy sharing
  - Shower shape profiles



RICH PID

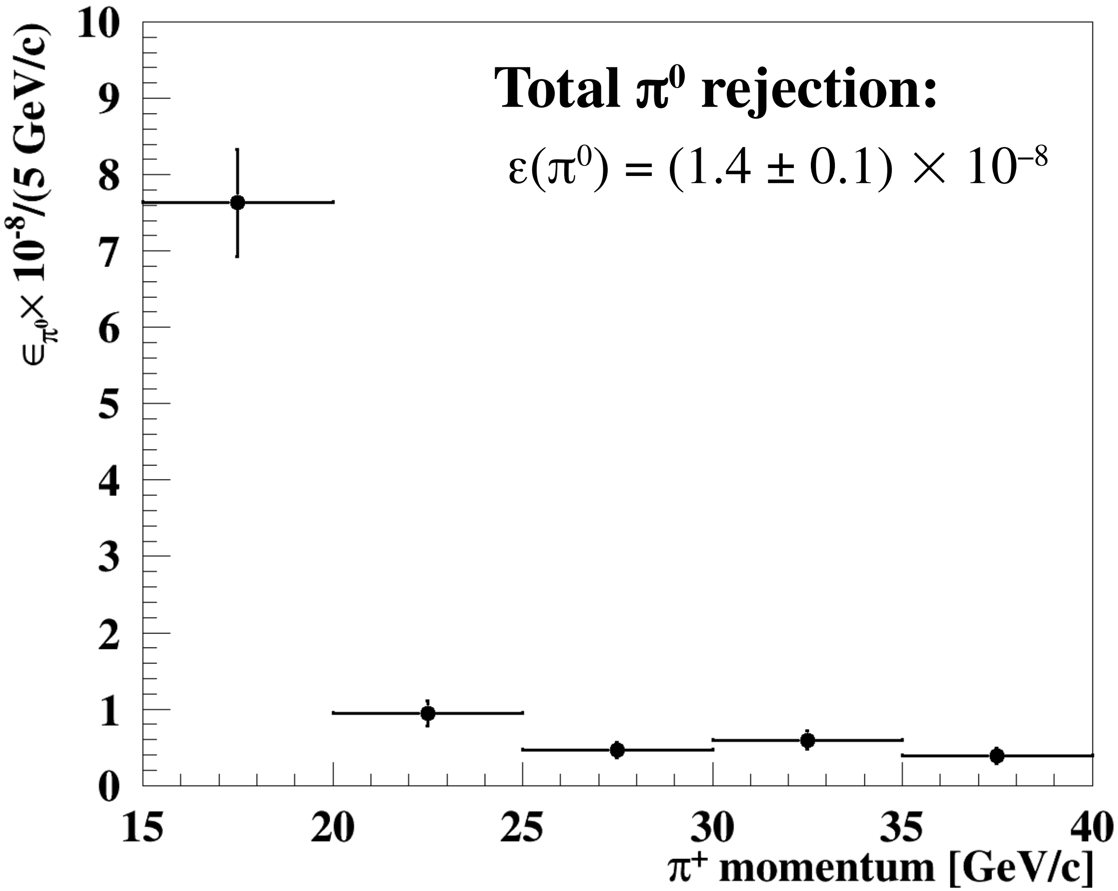
- Track-driven likelihood discriminant for p/m/e separation
- Particle mass using track momentum



Total PID performance: $\varepsilon(\mu^+) = 10^{-8}$, $\varepsilon(\pi^+) = 64\%$

NA62 Keystone 3: Photon rejection

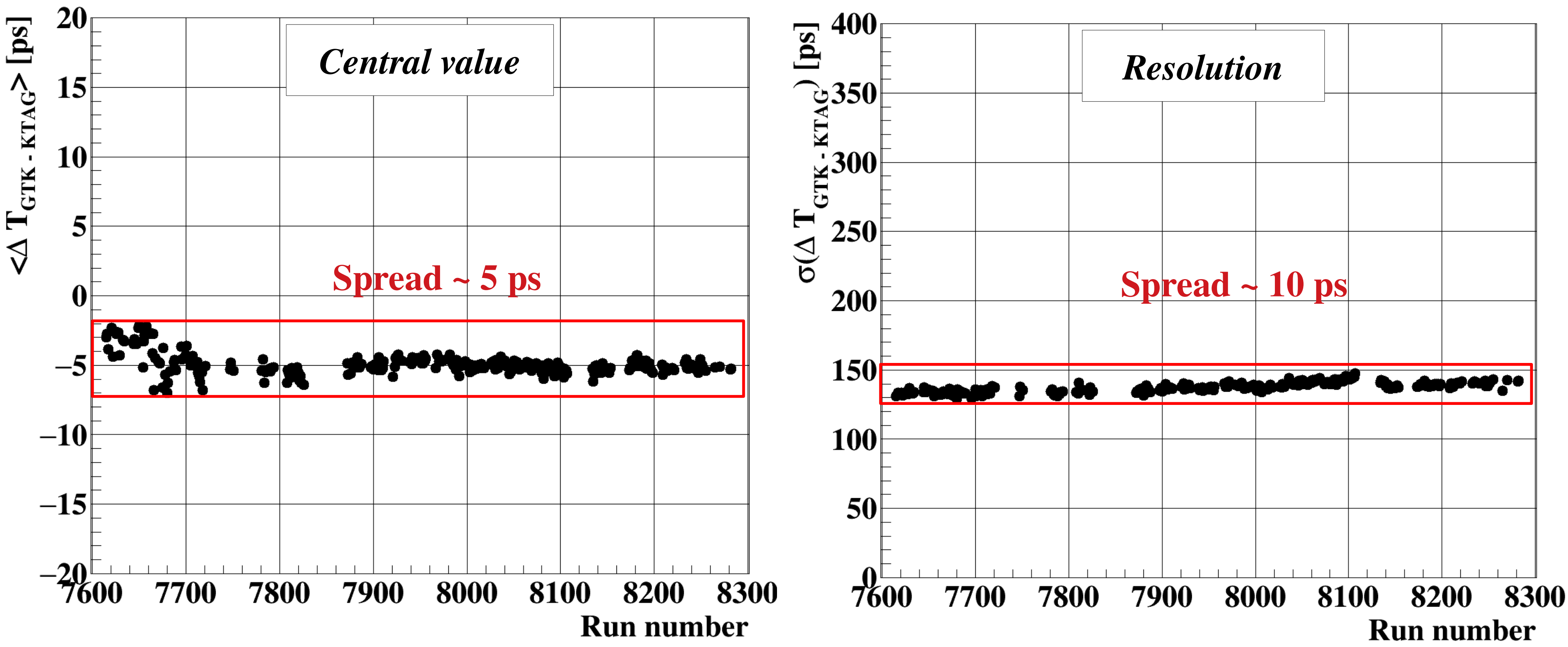
$$\varepsilon_{\pi^0} = \frac{N(\text{after } \gamma\text{-rejection, } \pi\nu\nu \text{ stream})}{N(\text{before } \gamma\text{-rejection, min bias}) \cdot D}$$



NA62 Keystone 4: Precise timing

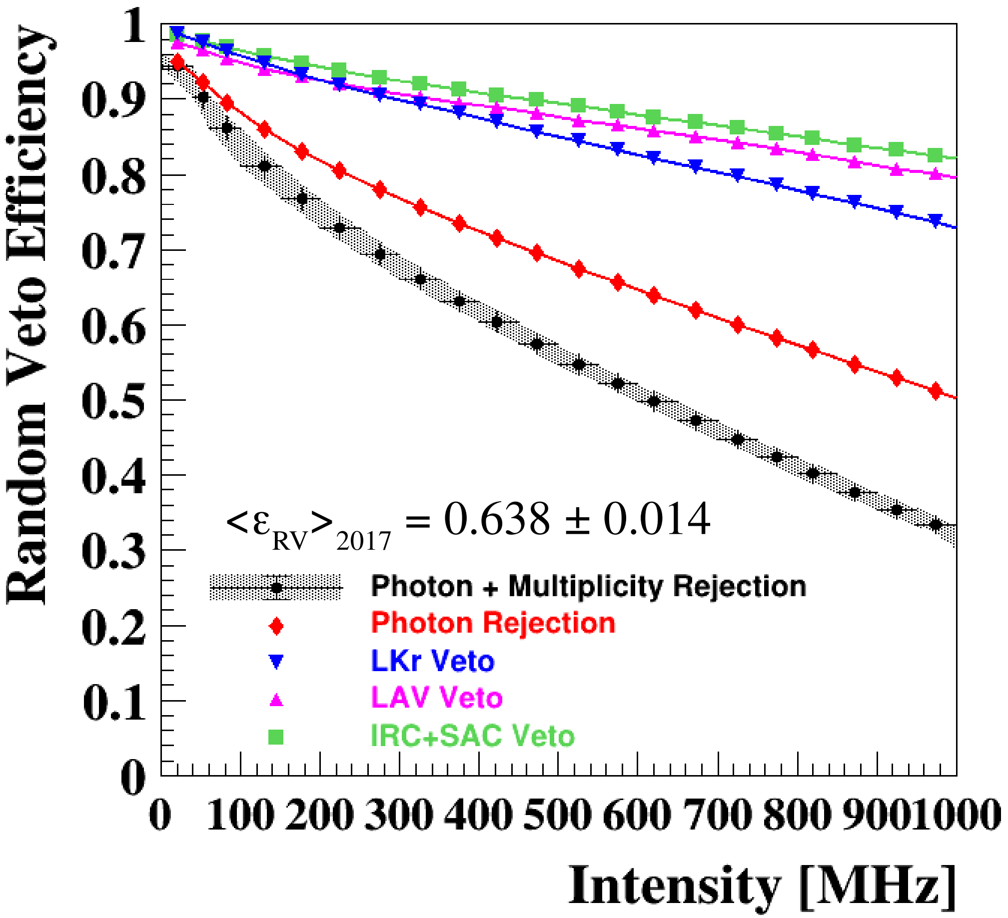
Time calibration stability

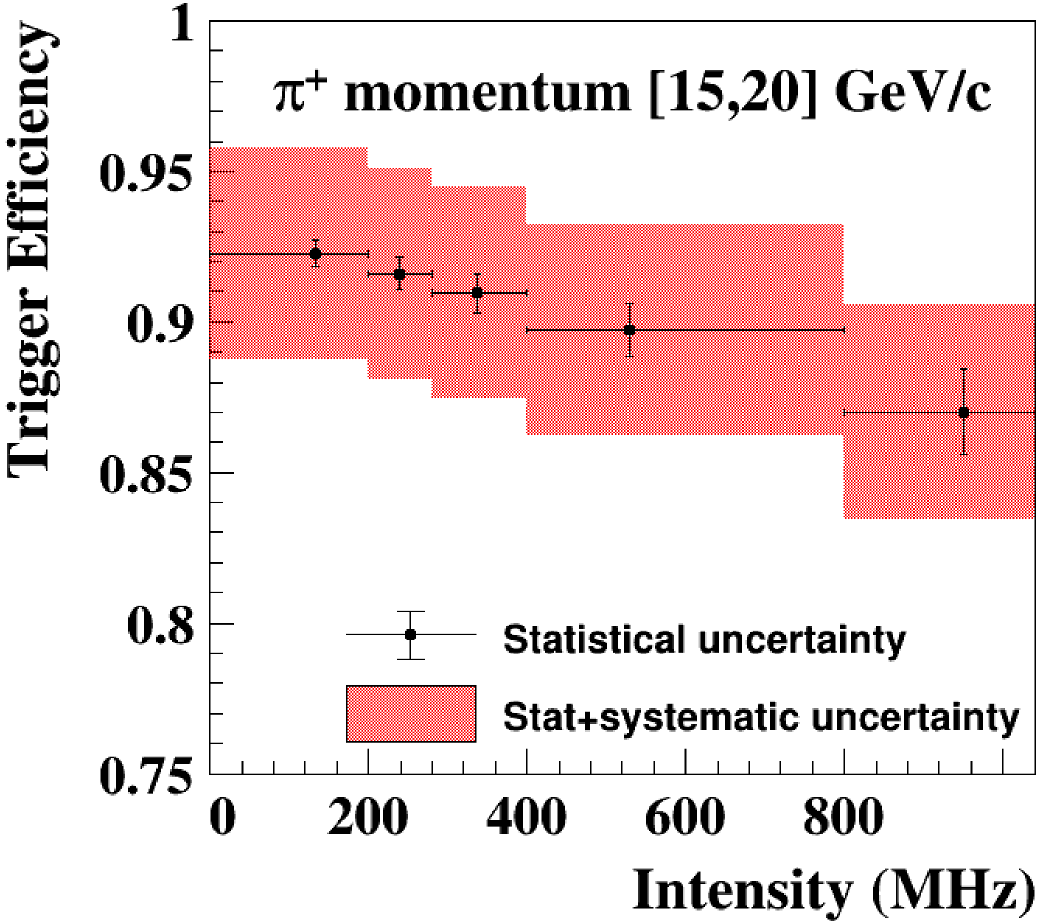
- Excellent automatic time calibration at the processing level
- Stable central value and time resolution (within few ps)
- Single-detector time resolution ~ 90 ps



Single Event Sensitivity (SES)

$$\mathrm{SES} = \frac{\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})}{N^{\mathrm{exp}}_{\pi\nu\nu}} = \frac{A_{\pi\pi}}{A_{\pi\nu\nu}} \frac{\mathcal{B}(K^+ \to \pi^+\pi^0)}{N_{\pi\pi}} \frac{1}{\varepsilon_{RV}\varepsilon_{trig}}$$

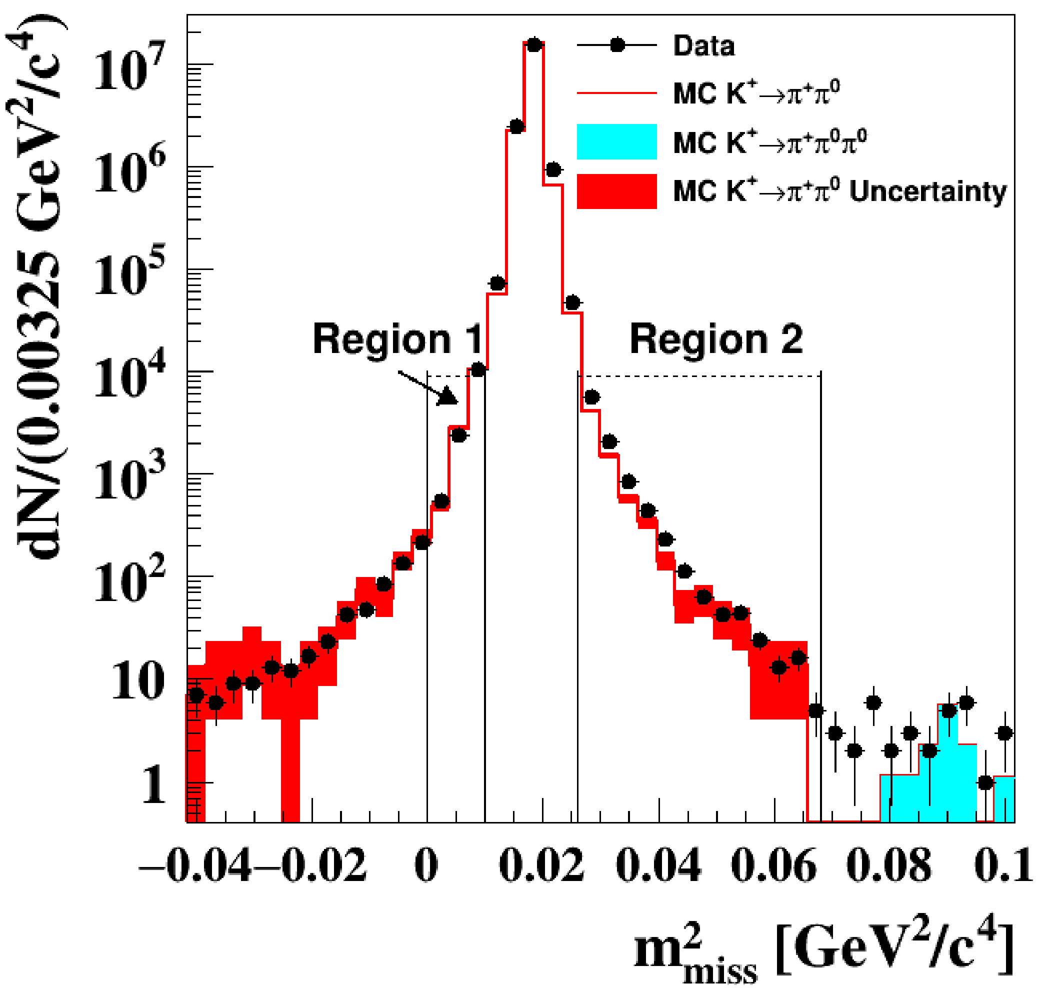




$$\mathrm{SES} = (0.389 \pm 0.021) \times 10^{-10} \longleftrightarrow N^{\mathrm{exp}}_{\pi\nu\nu} = 2.16 \pm 0.12 \pm 0.26_{ext}$$

$K^+ \to \pi^+\pi^0(\gamma)$ background

Data driven background estimation

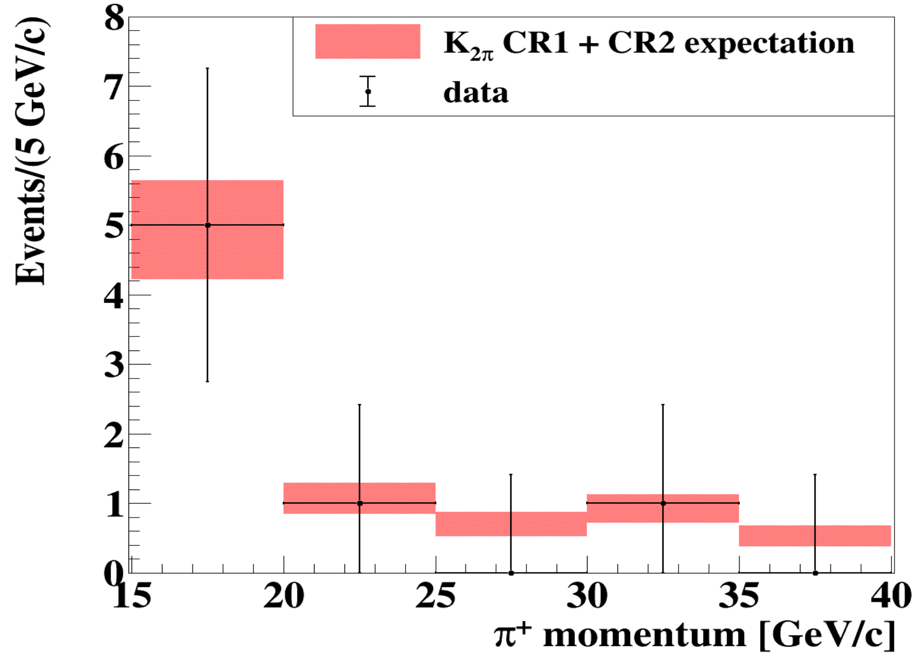


Data in $\pi^+\pi^0$ region after $\pi\nu\nu$ selection (including π^0 rejection)

$$N^{exp}_{\pi\pi}(region) = N(\pi^+\pi^0) \cdot f_{kin}(region)$$

Expected $K^+ \to \pi^+\pi^0$ in signal regions after the $\pi\nu\nu$ selection

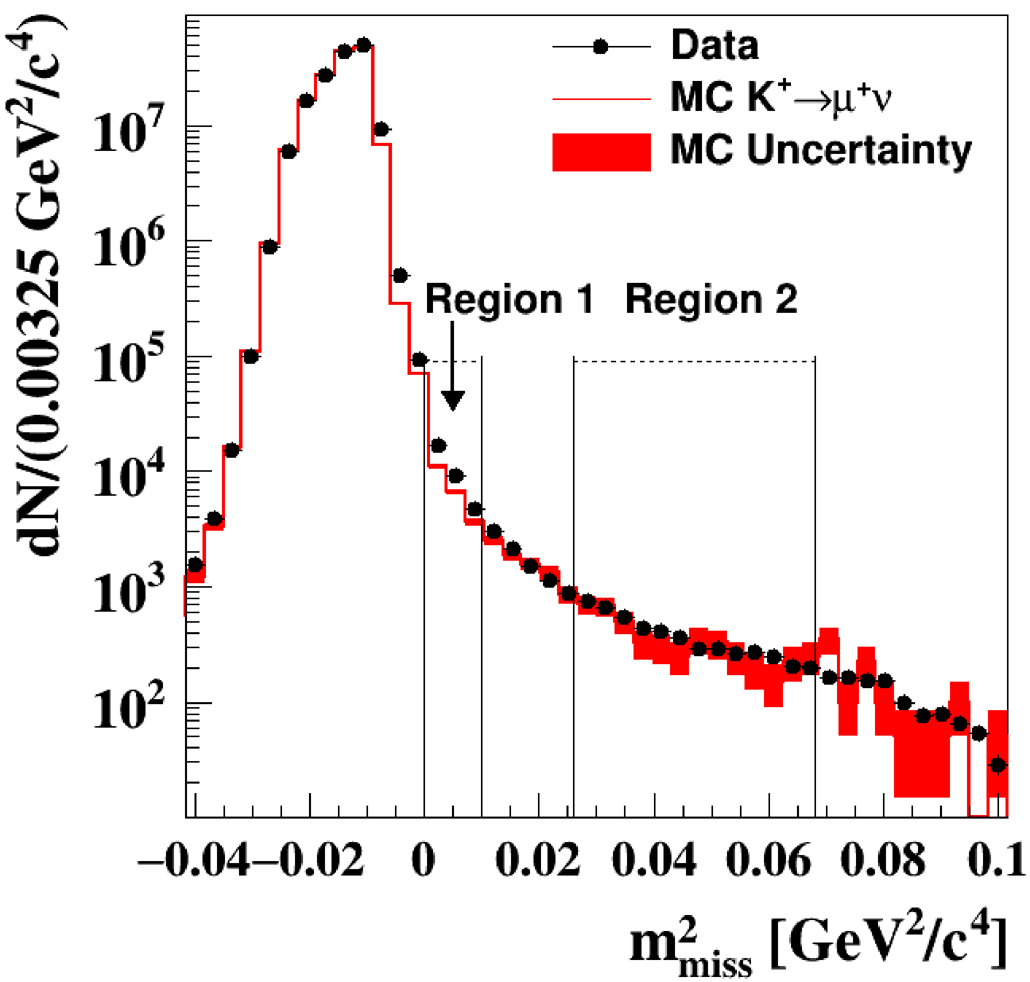
Fraction of $\pi^+\pi^0$ in signal region measured on control data



$$N^{bkg}_{\pi\pi(\gamma)} = 0.29 \pm 0.03_{stat} \pm 0.03_{syst}$$

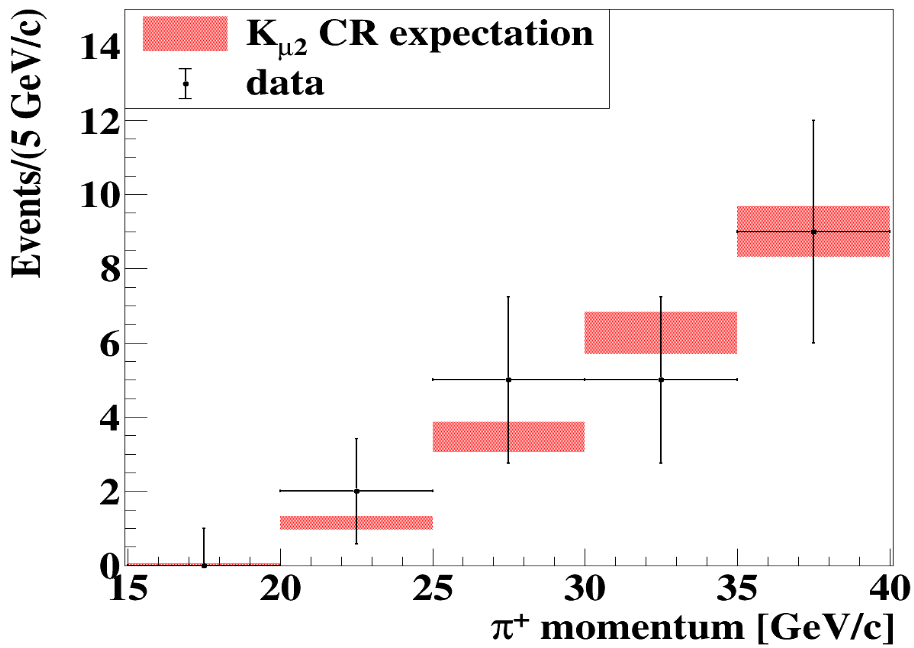
$K^+ \to \mu^+\nu(\gamma)$ background

Data driven background estimation



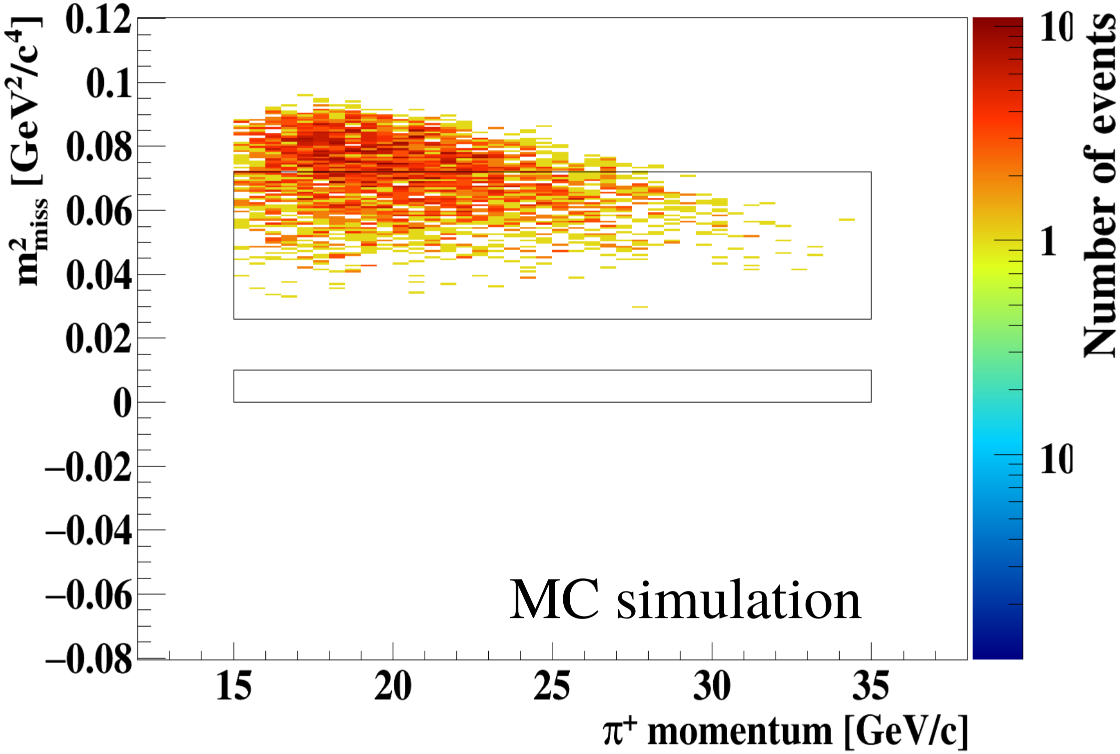
$$N^{exp}_{\mu\nu}(region) = N(\mu^+\nu_\mu) \cdot f_{kin}(region)$$

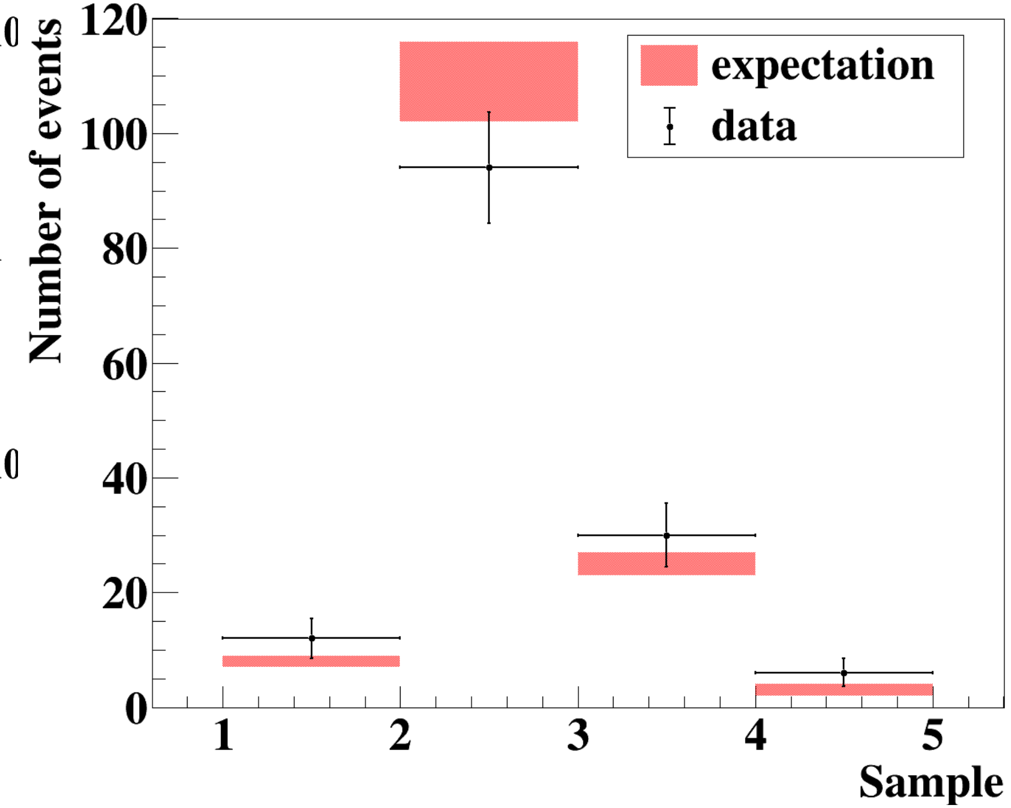
- $N^{exp}_{\mu\nu}(region)$: Expected $K^+ \to \mu^+\nu_\mu$ in signal regions after the $\pi\nu\nu$ selection
- $N(\mu^+\nu_\mu)$: Data in $\mu^+\nu_\mu$ region after $\pi\nu\nu$ selection
- $f_{kin}(region)$: Fraction of $\mu^+\nu_\mu$ in signal region measured on control data



$$N^{bkg}_{\mu\nu(\gamma)} = 0.15 \pm 0.02_{stat} \pm 0.04_{syst}$$

$K^+ \to \pi^+\pi^- e^+\nu$ (K_{e4}) background



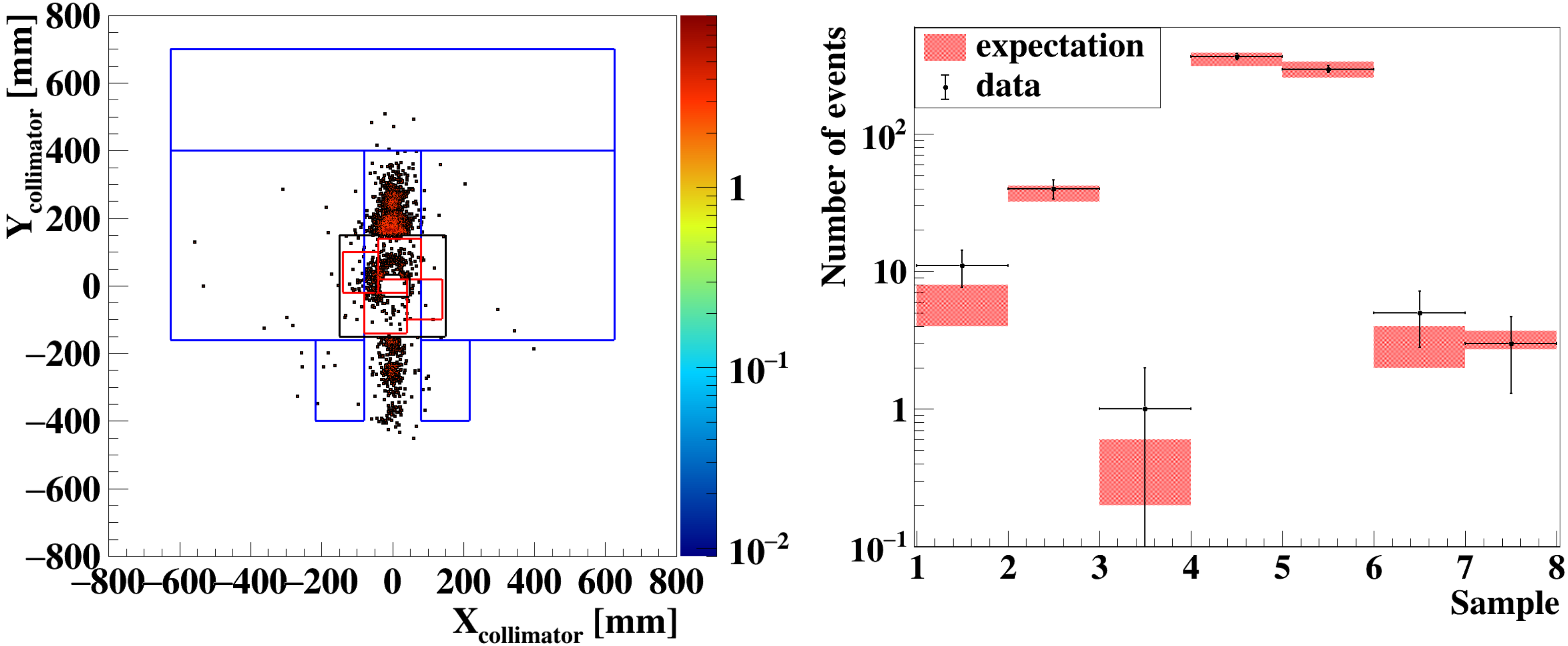


- Background estimated with 2×10^9 MC generated $K^+\to\pi^+\pi^- e^+\nu$ decays
- Good agreement across the 4 validation samples

$$N^{bkg}_{Ke4} = 0.12 \pm 0.05_{stat} \pm 0.03_{syst}$$

Upstream background

- Decays along the beam line; beam particle interactions in GTK
- Random track matched in GTK and/or possible additional energy not detected



- Data driven background estimation
- Good agreement across the 7 validation samples

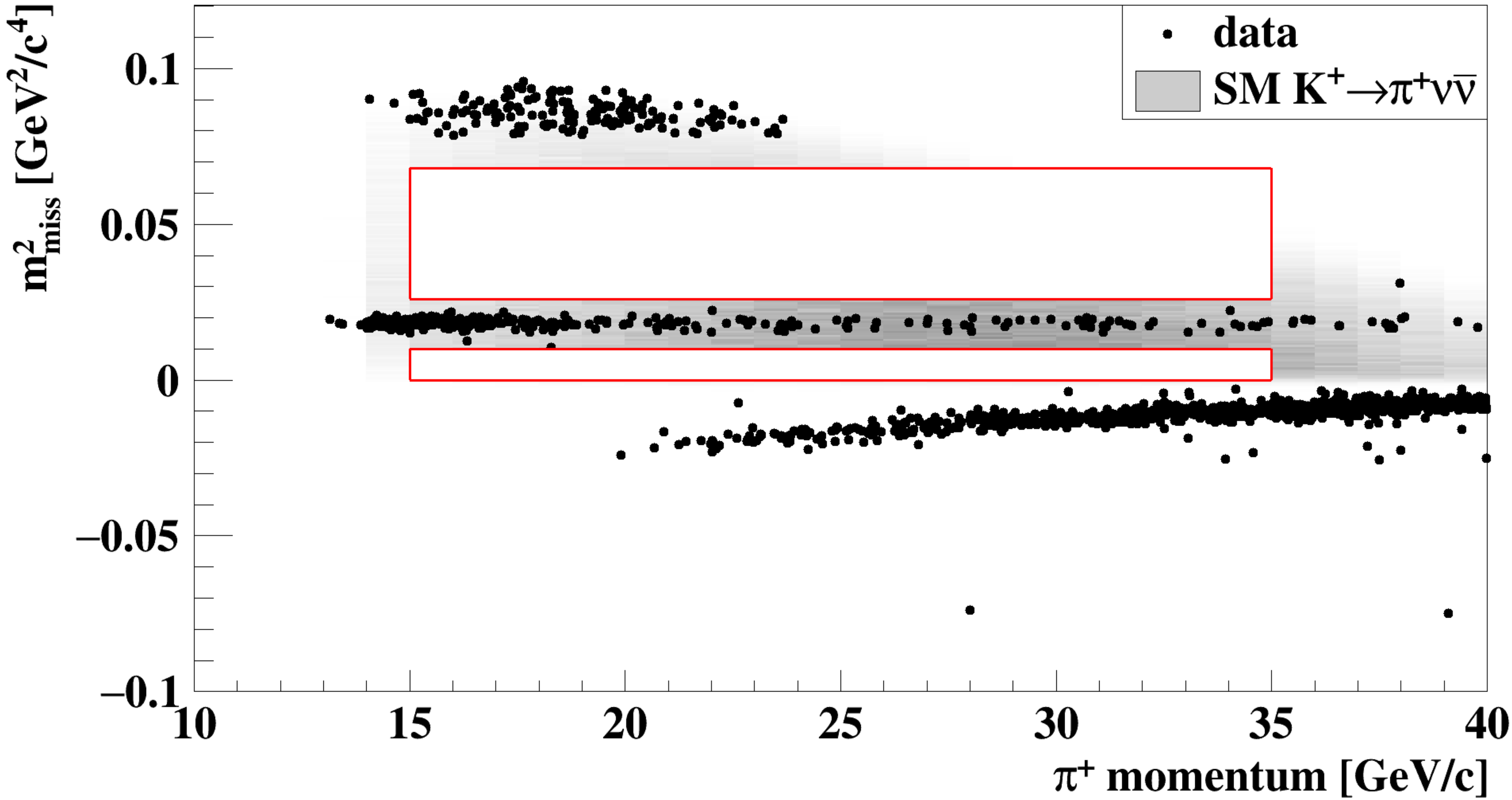
$$N^{bkg}_{upstream} = 0.9 \pm 0.2_{stat} \pm 0.2_{syst}$$

Total expected background

Process	Expected events
$K^+ \to \pi^+ \nu \overline{\nu}$ (SM)	$2.16 \pm 0.12_{stat} \pm 0.26_{ext}$
$K^+ \to \pi^+ \pi^0 (\gamma)$ IB	$0.29 \pm 0.03_{stat} \pm 0.03_{syst}$
$K^+ \to \mu^+ \nu_\mu (\gamma)$ IB	$0.11 \pm 0.02_{stat} \pm 0.03_{syst}$
$K^+ \to \mu^+ \nu_\mu (\mu^+ \to e^+ \text{decay})$	$0.04 \pm 0.02_{syst}$
$K^+ \to \pi^+ \pi^- e^+ \nu_e$	$0.12 \pm 0.05_{stat} \pm 0.03_{syst}$
$K^+ \to \pi^+ \pi^- \pi^+$	$0.02 \pm 0.02_{syst}$
$K^+ \to \pi^+ \gamma\gamma$	$0.005 \pm 0.005_{syst}$
$K^+ \to l^+ \pi^0 \nu_l$	negligible
Upstream background	$0.9 \pm 0.2_{stat} \pm 0.2_{syst}$
Total background	$1.5 \pm 0.2_{stat} \pm 0.2_{syst}$

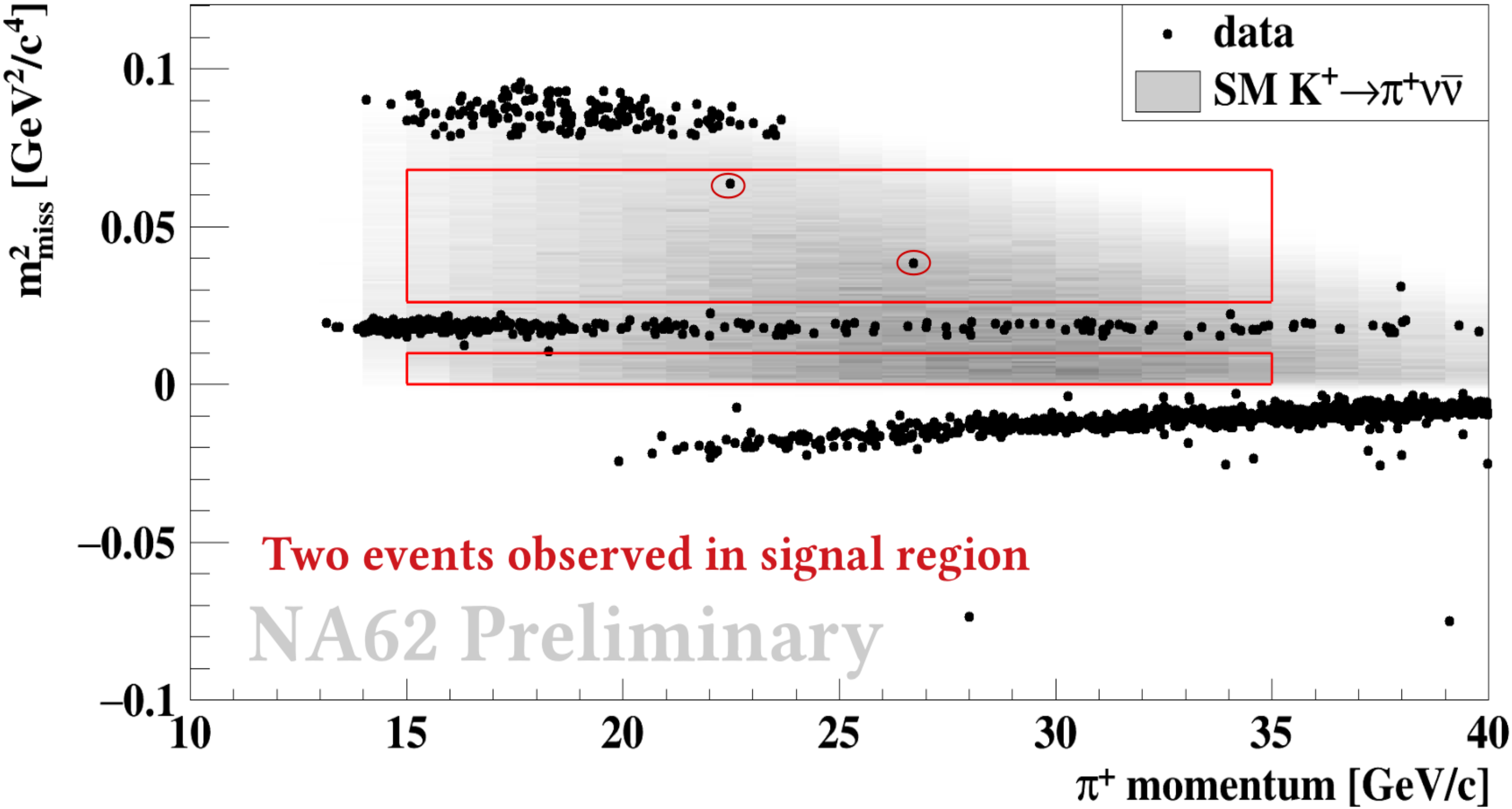
Results

Opening the box..



Results

Opening the box..

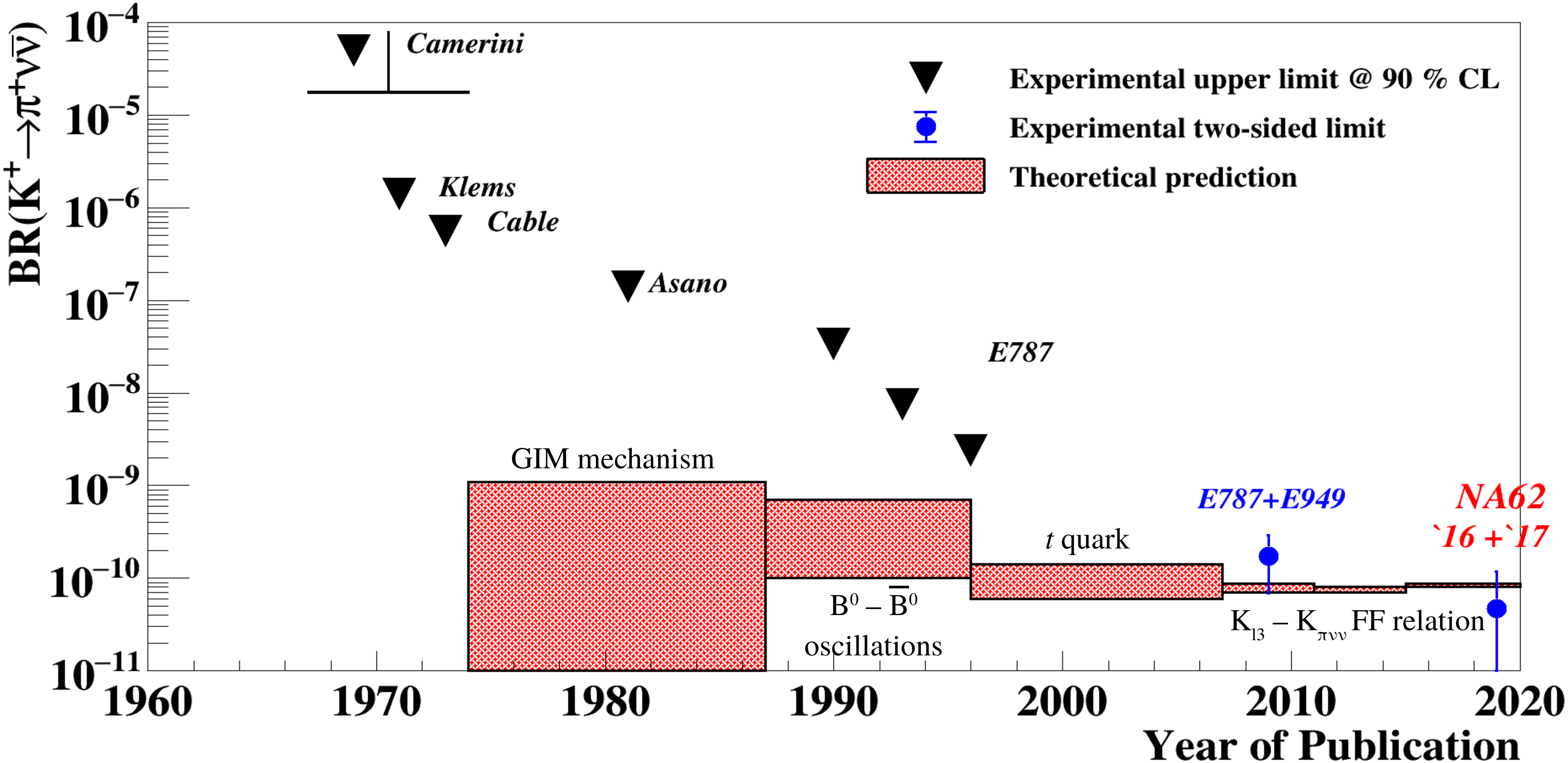


Results

2016+2017 NA62 result (3 candidates):

$BR(K^+\rightarrow\pi^+\nu\bar{\nu}) < 1.85\times10^{-10}$ @ 90% CL

$BR(K^+\rightarrow\pi^+\nu\bar{\nu}) = 0.47^{+0.72}_{-0.47}\times10^{-10}$



Results

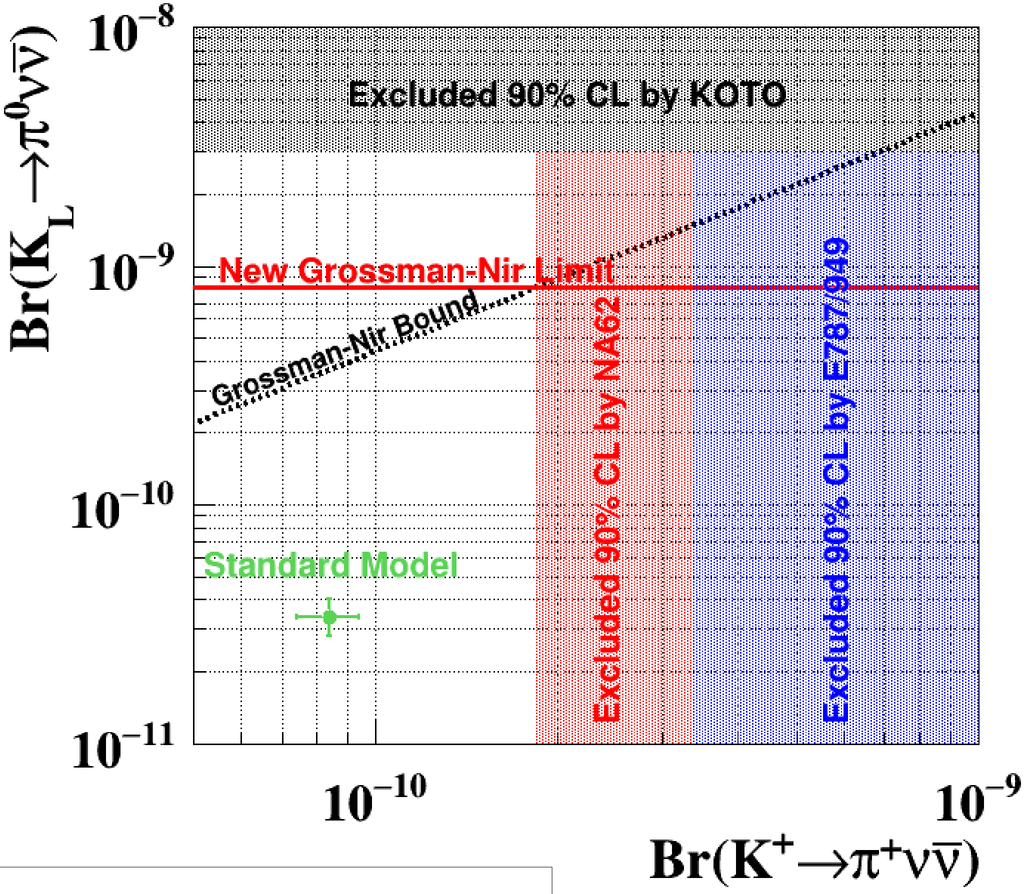
2016+2017 NA62 result (3 candidates):

$BR(K^+ \to \pi^+ \nu\bar{\nu}) < 1.85 \times 10^{-10}$ @ 90% CL

$BR(K^+ \to \pi^+ \nu\bar{\nu}) = 0.47^{+0.72}_{-0.47} \times 10^{-10}$

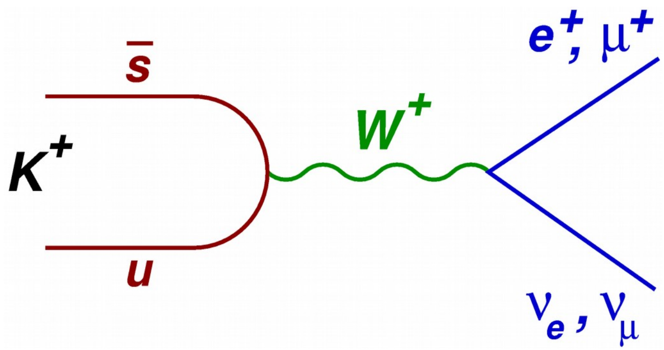
Competitive also on $BR(K_L \to \pi^0 \nu\bar{\nu})$

(via Grossman-Nir bound)



$BR(K_L \to \pi^0 \nu\bar{\nu}) < 8.14 \times 10^{-10}$ @ 90% CL

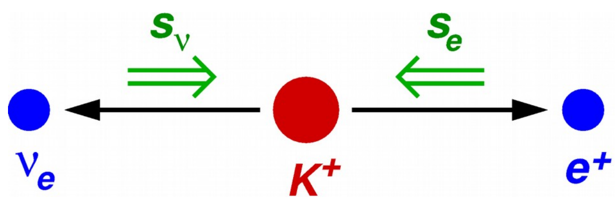
Lepton universality test



$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \frac{m_e^2}{m_\mu^2} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot (1 + \delta R_K^{\mathrm{rad.corr.}})$$

Helicity suppression: $\sim 10^{-5}$

Radiative correction (well known, few %)



- Helicity suppressed: <u>high sensitivity to new physics</u>

<u>High-precision theoretical prediction:</u>

- Hadronic uncertainties cancel in the R_K ratio
- Radiative corrections @ $O(e^2p^4)$ ChPT

SM prediction:

$R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$

Cirigliano and Rosell, PRL 99 (2007) 231801

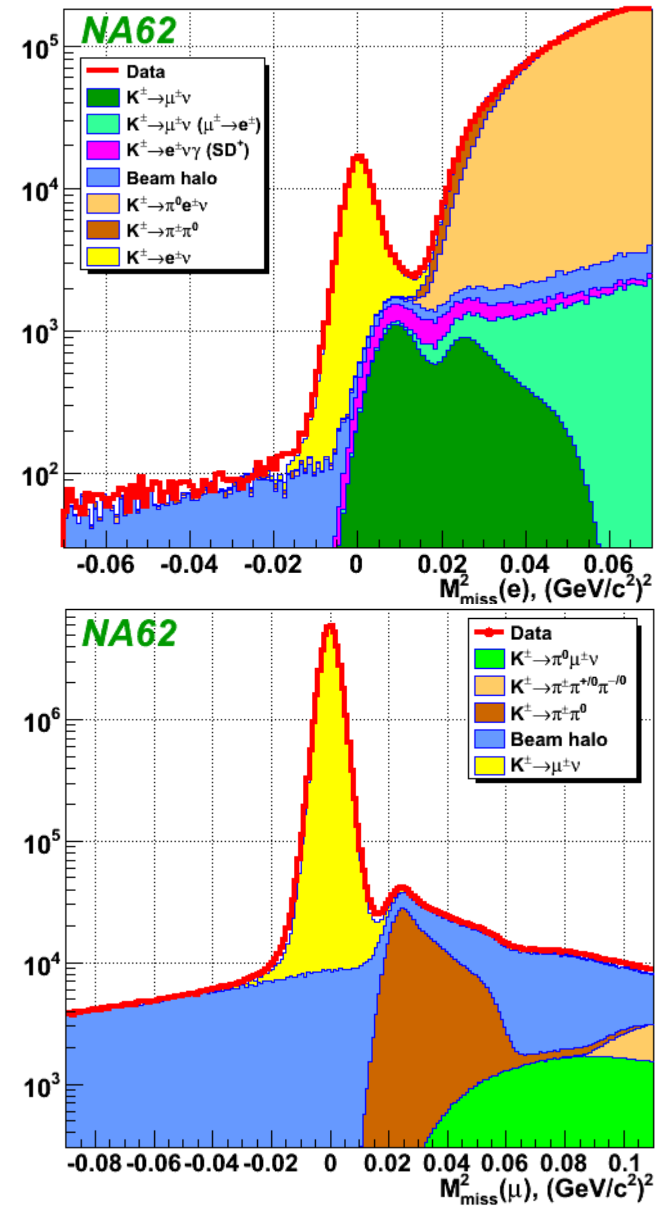
Best measurement from NA62 2007 data (NA48/2 detector):

$$R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2}) = (2.488 \pm 0.007_{stat} \pm 0.007_{syst}) \times 10^{-5}$$

Phys. Lett. B 719 (2013) 326

Lepton universality test

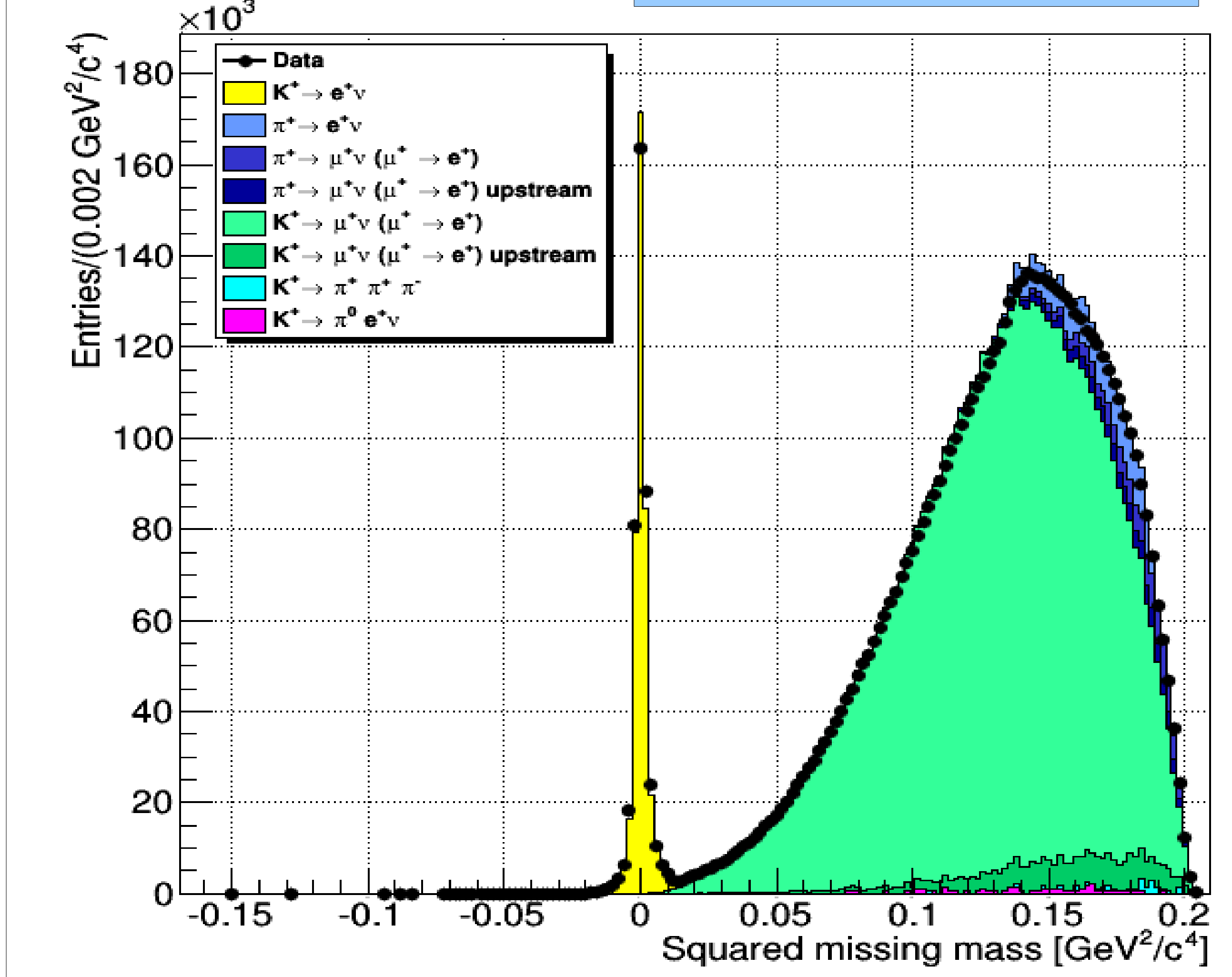
2007 data, NA48 detector



<u>Novel approach</u>: collect K_{e2} and $K_{\mu 2}$ in same trigger stream

(trick: look at $K_{\mu 2}$ with subsequent $\mu^+ \to e^+ \nu \bar{\nu}$ decay!)

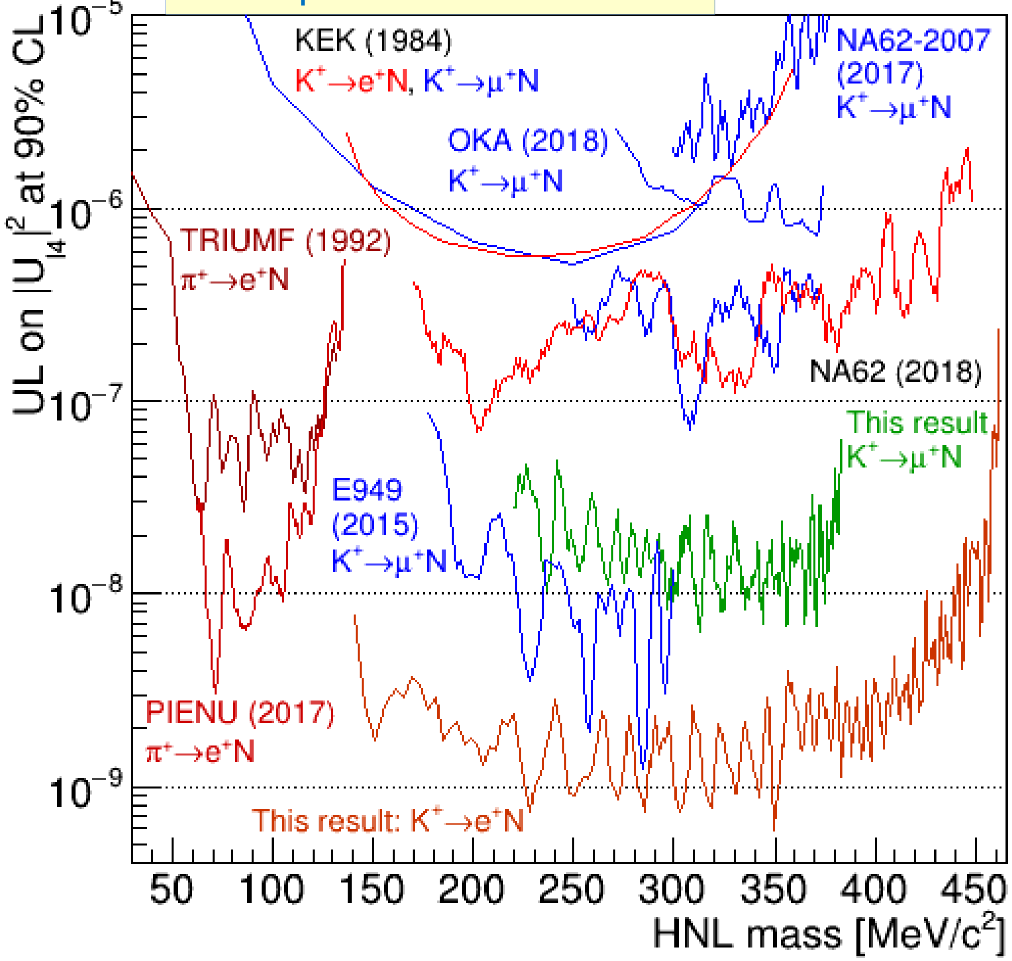
2017 data, NA62 detector

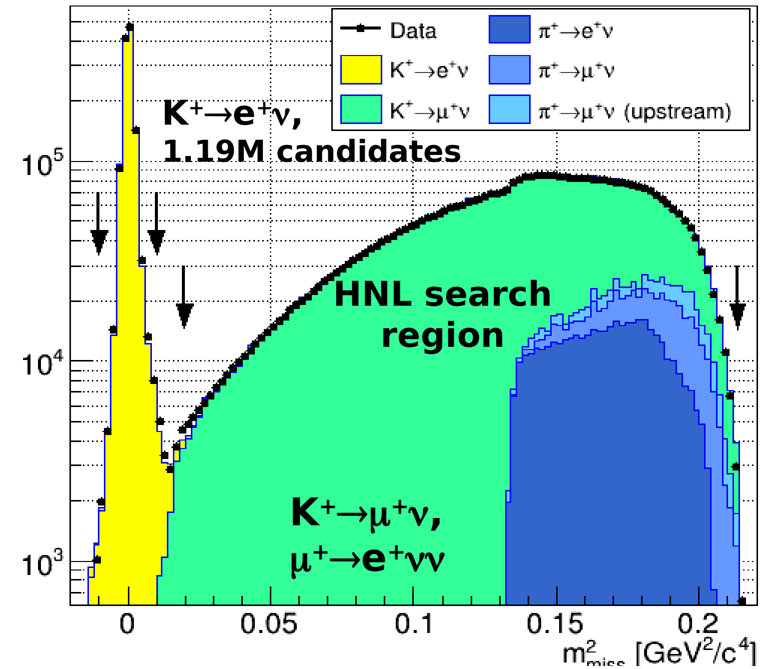


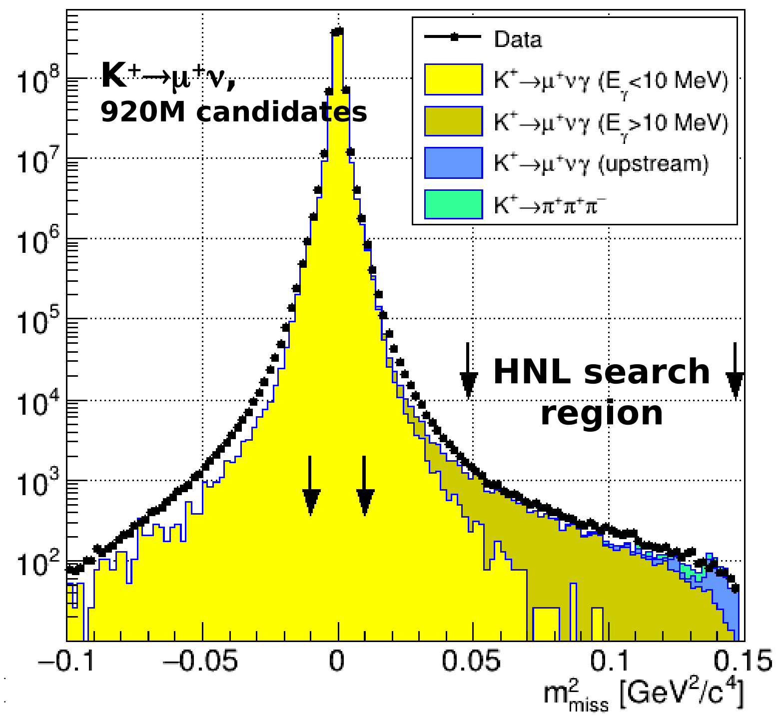
Search for Heavy Neutral Leptons

HNL signal: **a spike above continuous missing mass spectrum**

$|U_{\ell 4}|^2$ limits vs m_{HNL} from production searches







New preliminary NA62 results

based on **~1/3** of the data set (2016-2017)

Invisible Vector Boson from π^0 decay

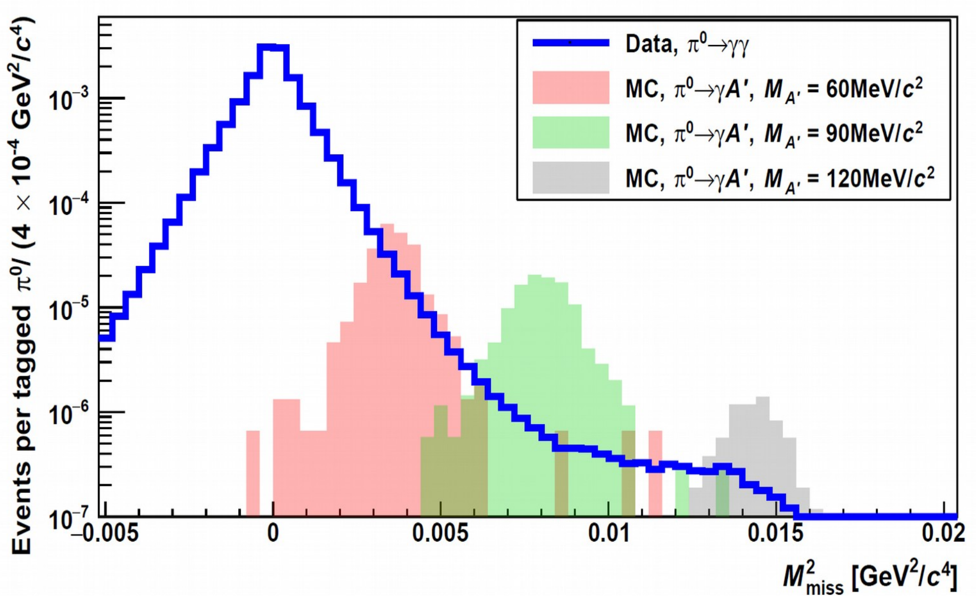
$K^+ \to \pi^+\pi^0$, $\pi^0 \to A'\gamma$, $A' \to$ invisible

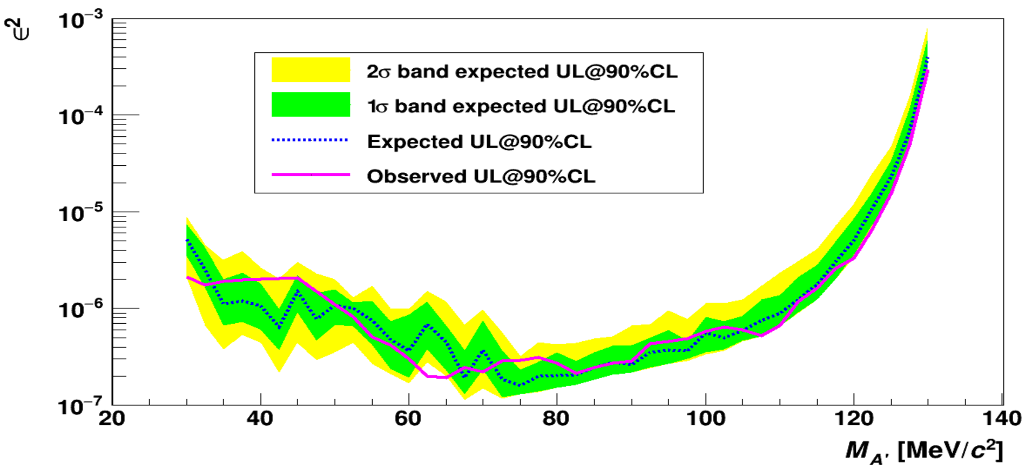
Journal of High Energy Physics, Volume 2019, Issue 05, page 182

Minimal A' scenario: $$\mathrm{BR}\left(\pi^0 \to A'\gamma\right) = 2\epsilon^2 \left(1 - \frac{m_A^2}{m_{\pi^0}^2}\right)^3 \times \mathrm{BR}\left(\pi^0 \to \gamma\gamma\right)$$

Data from 2016, ~ 412 M π^0s tagged from K2π decays (1% of full data set)

Peak search around $m^2_{A'}$ in the $M^2_{miss} = (p_K - p_\pi - p_\gamma)^2$



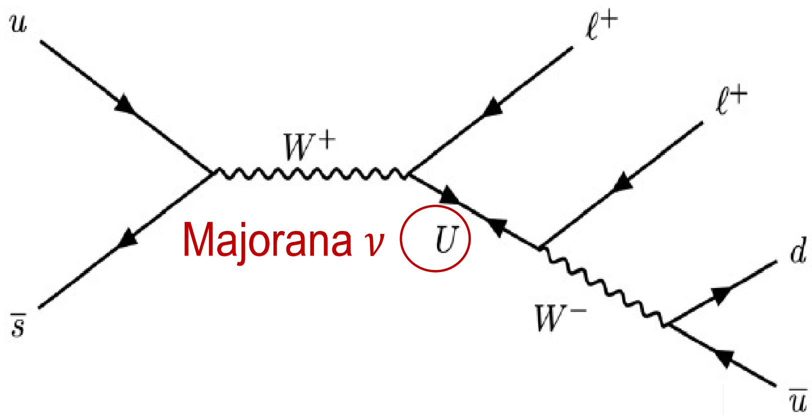


JHEP 1905 (2019) 182

Prospects with full data set: expected yield increased by O(10)

Lepton Number/Lepton Flavour violation

Search for LNV $K^+ \to \pi^- e^+ e^+$ and $K^+ \to \pi^- \mu^+ \mu^+$ decays with 2017 data



Obtained upper limits

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

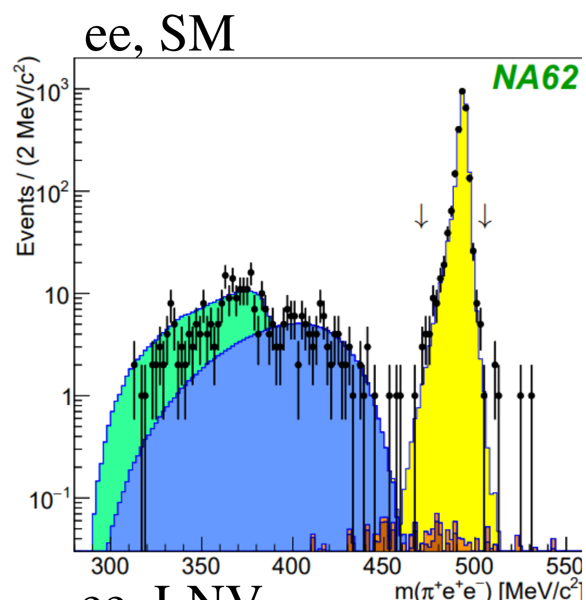
BR($K^+ \to \pi^- \mu^+ \mu^+$) < 4.2 x 10^{-11} @ 90% CL

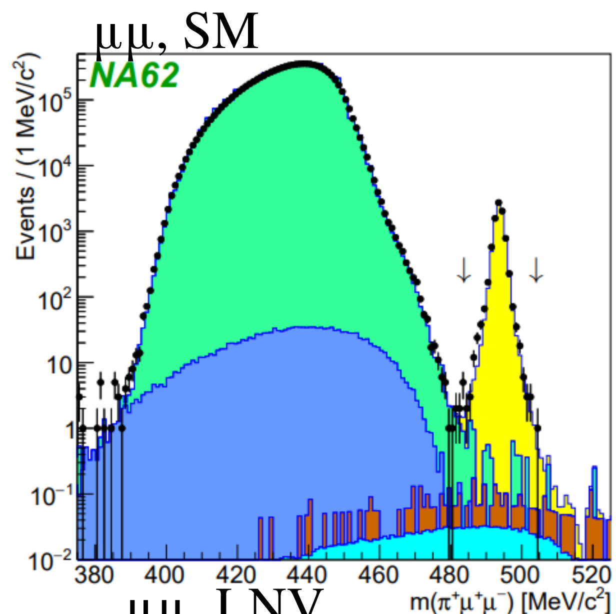
PLB 797 (2019) 134794

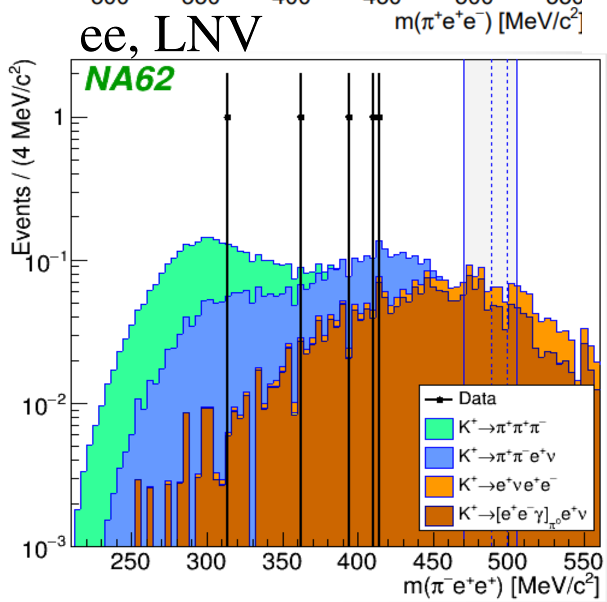
x2-3 improvements wrt previous results

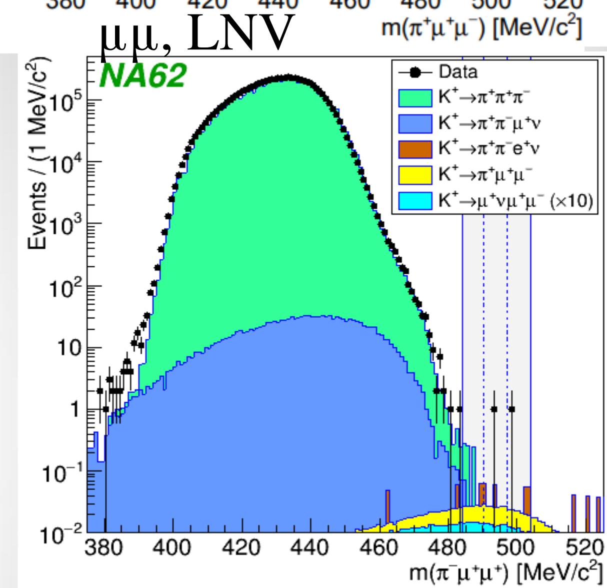
Prospects:

Further x3 improvement expected with full 2016-2018 sample









Acceptance: A = 4.98%
SES = (0.94 ± 0.03) * 10^{-10}
Expected background: 0.16 ± 0.03
N_{obs} = 0

$SES = \frac{1}{N_K A}$

Acceptance: A = 9.81%
SES = (1.28 ± 0.04) * 10^{-11}
Expected background: 0.91 ± 0.41
N_{obs} = 1

$SES = \frac{1}{N_K A}$

Prospects – 2016-2018 data set

- **$K^+ \to \pi^+ \nu \bar{\nu}$**
  - 2018 data analysis in progress (~2 x 2017 data)
  - Wider final collimator installed during 2018, lower upstream background
  - On-going studies to increase signal efficiency
  - Optimization of particle identification and kinematic selection
  - Improvement in kaon-pion association algorithm

With improvement factor, expect ~10 SM events in 2016-2018 data

- **Broader physics programme**
  - Rare & forbidden decay analyses with full 2016-2018 sample in progress
  - Substantial improvements expected in HNL, LNV/LFV and exotic searches

Prospects – Next run (2021-2024)

Addendum I to P326 submitted in October 2019 to SPSC

ADDENDUM I TO P326
Continuation of the physics programme of the NA62 experiment

The NA62 Collaboration

Abstract

The NA62 experiment took data successfully in 2016-2018, and has proven that the novel decay-in-flight technique employed for ultra-rare kaon decays works. The NA62 Collaboration proposes to continue the data taking of the experiment during the period after CERN Accelerators Long Shutdown 2 (LS2) and before Long Shutdown 3 (LS3). The continuation will allow NA62 to perform a measurement of the branching ratio of the ultra-rare kaon decay $K^+ \to \pi^+ \nu\bar{\nu}$ with significantly improved accuracy, to substantially increase its sensitivity on several rare and forbidden kaon decays, and to reach unprecedented sensitivity in the investigation of several Standard Model (SM) extensions involving faintly interacting long-lived particles.

to continue NA62 data taking during the period after CERN Accelerators Long Shutdown 2 (LS2) and before Long Shutdown 3 (LS3)

- O(50) $K^+ \to \pi^+ \nu\bar{\nu}$ events expected
- BR($K^+ \to \pi^+ \nu\bar{\nu}$) with ~ 20% accuracy
- O(10) SES increase on several rare and forbidden kaon decays

SPSC recommended approval of NA62 operation after LS2
(Data taking in 2021 has been approved)

Prospects – Next run (2021-2024)

Planned actions:

- Take data at higher intensity, aiming for 100% nominal
- Reduce background contamination:
  - add GTK4: better track fitting with higher efficiency, identify pileup tracks
  - modify beam line and add anti-counter to reduce upstream background
  - new HASC module to improve background rejection
- Reduce random veto, improving treatment of accidental activity and exploiting detector correlations
- Increase signal acceptance further (e.g. different selections for 2 SRs)

Prospects – Next run (2021-2024)

Wide programme of rare and forbidden processes

Trigger and DAQ improvements will allow reduction of pre-scaling factors and collection of even larger data samples

Enter a new high precision era, down to 10^{-12}

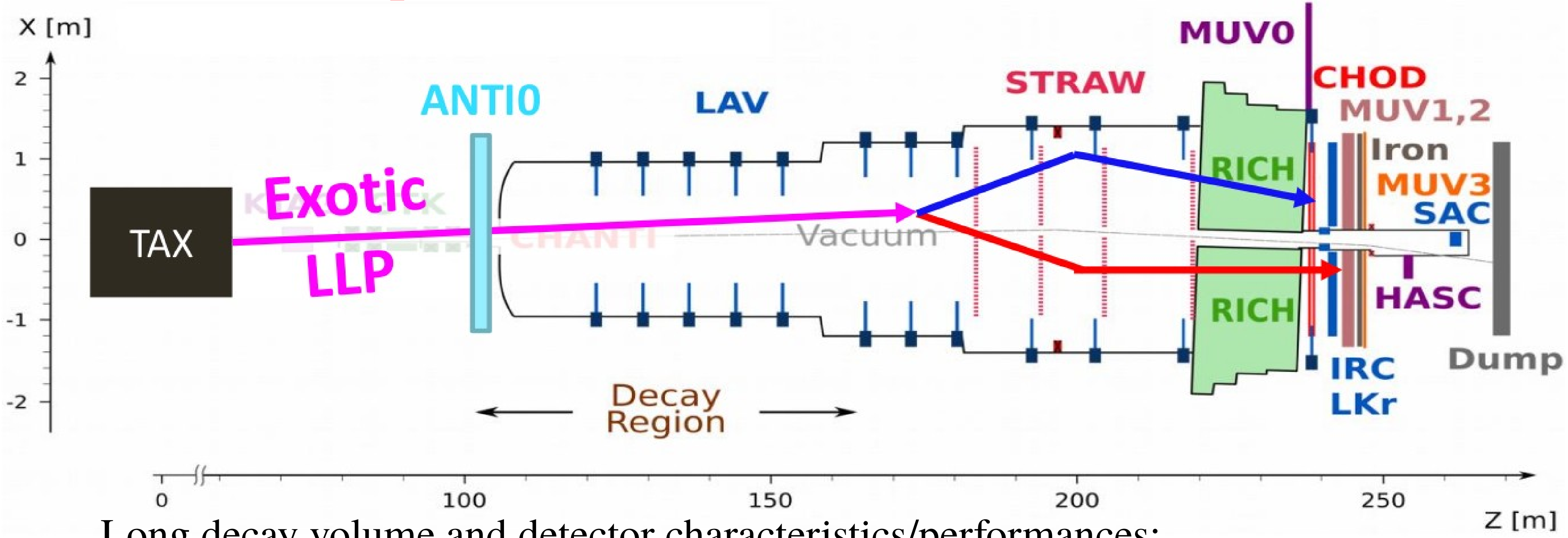
Rare decays	$K^+ \to \pi^+ e^+ e^-$ / $K^+ \to \pi^+ \mu^+ \mu^-$, $K^+ \to \pi^+ \gamma\gamma$
	$K^+ \to e^+ \nu(\gamma)$, $R_K = \Gamma(K^+ \to e^+ \nu)/\Gamma(K^+ \to \mu^+ \nu)$
Forbidden LFV - LNV	$K^+ \to \pi^- e^+ e^+$ / $K^+ \to \pi^- \mu^+ \mu^+$, $K^+ \to \pi^+ \mu^\pm e^\mp$
Production of dark particles	$K^+ \to \pi^+ X$, $K^+ \to \mu^+ N$ / $K^+ \to e^+ N$

+ Control of systematics with data-driven methods:

Collect special samples to address specific effects and background sources

Prospects – Next run (2021-2024)

NA62 in dump mode



Long decay volume and detector characteristics/performances:
suitable to search for feebly-interacting long-lived particles
Extend Dark Particle mass range beyond m_K (D, B associated production)

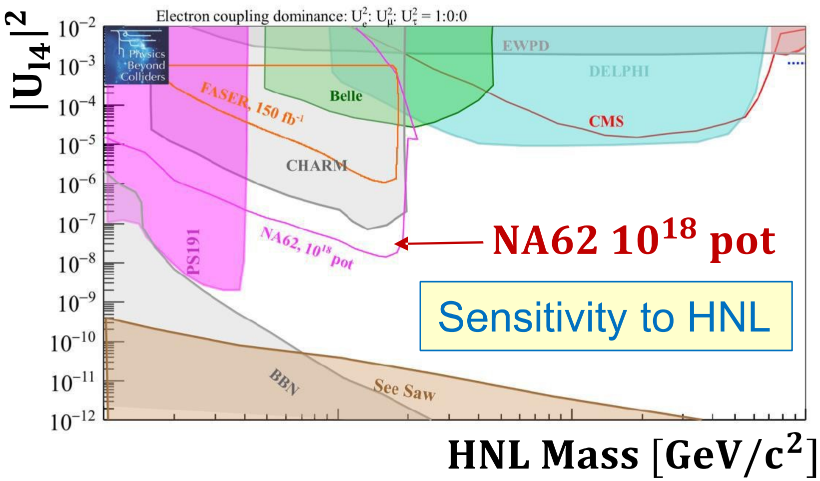
Collect 10^{18} Protons On Target before LS3
New ANTI0 under construction to veto muons produced in TAX

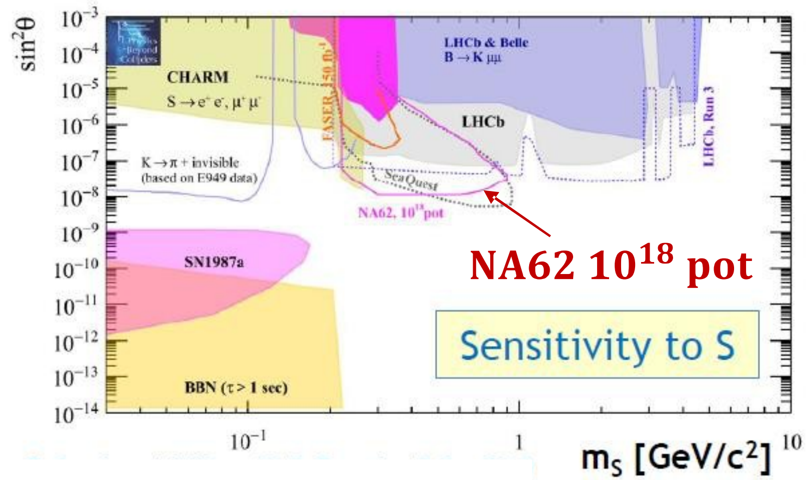
Possibility to increase beam intensity beyond nominal being investigated

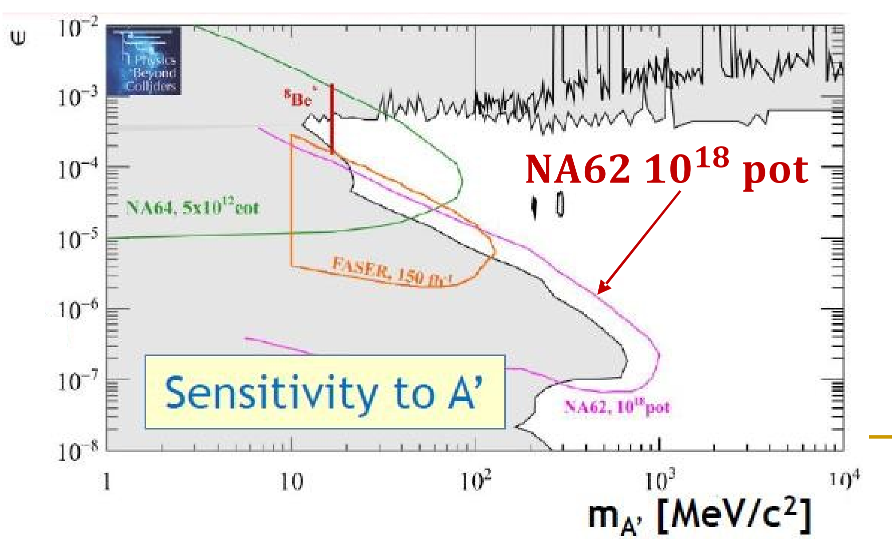
Prospects – Next run (2021-2024)

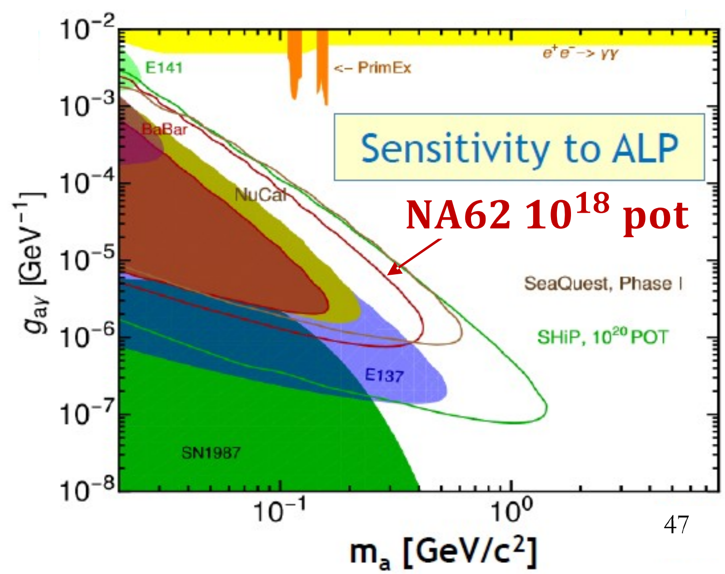
NA62 in dump mode

Sensitivity studies included in Physics Beyond Collider initiative









Bridge towards future dump facilities

Prospects – After 2026

Jorgen D'Hondt (Chair of the European Committee for Future Accelerators),

from the talk "EU Strategy scenario" (https://indico.cern.ch/event/845054/)

	2020-2040 *HL-LHC era*	2040-2060 *Z/W/H/top-factory era*	2060-2080 *energy frontier era*
precision frontier	H couplings to few % ν mass/mixing/nature QGP phase-transition b/c-physics	H couplings to % EW & QCD & top QGP vs Lattice QCD b/c/τ-physics	H couplings to ‰ H self-coupling to % proton structure di-boson processes
breaking the SM	next-gen K-beams proton precision e & n EDM lepton flavor (μ→e)	p EDM storage rings	rare top decays small-x physics
direct searches	Beam Dump Facility eSPS (light DM) Long-Lived Signals / ALPs DM vs neutrino floor	heavy neutral lepton	new high-mass part. next-gen hidden exp. low-mass DM

Prospects – After 2026

Long-Term Future and the big picture: high intensity kaon beams beyond 2026

BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$) with precision <10% can test New Physics up to O(100 TeV) in a model-independent way

Measuring both charged and neutral modes can give insight about the new physics flavour structure

The most intense kaon facility: 4 x K^+ , 6 x K_L intensity

Limited by radioprotection issues

Large commonality of upgrades required, two aspects/phases of the same kaon facility

The decay-in-flight techniques works for $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

But setup needs to be made resilient to intensity effects

Challenges: Time resolution O(<40 ps), high flux of particles

→ R&D synergy with LHC HiLumi

Prospects – After 2026

Broader physics programme

Charged Kaons

Rare decays	$K^\pm \to \pi^\pm\gamma\gamma$, $K^\pm \to \pi^\pm e^+e^-$ / $K^\pm \to \pi^\pm\mu^+\mu^-$ $K^\pm \to \pi^\pm l^+l^-$ CPV charge asymmetry, A_{FB} $R_K = \Gamma(K^\pm \to e^\pm\nu)/\Gamma(K^\pm \to \mu^\pm\nu)$
Forbidden LFV - LNV	$K^\pm \to \pi^\mp e^+e^+$ / $K^+ \to \pi^\mp\mu^+\mu^+$, $K^\pm \to \pi^\pm\mu^\pm e^\mp$
Production of dark particles	$K^+ \to \pi^+X$, $K^\pm \to \mu^\pm N$ / $K^\pm \to e^\pm N$

Neutral Kaons

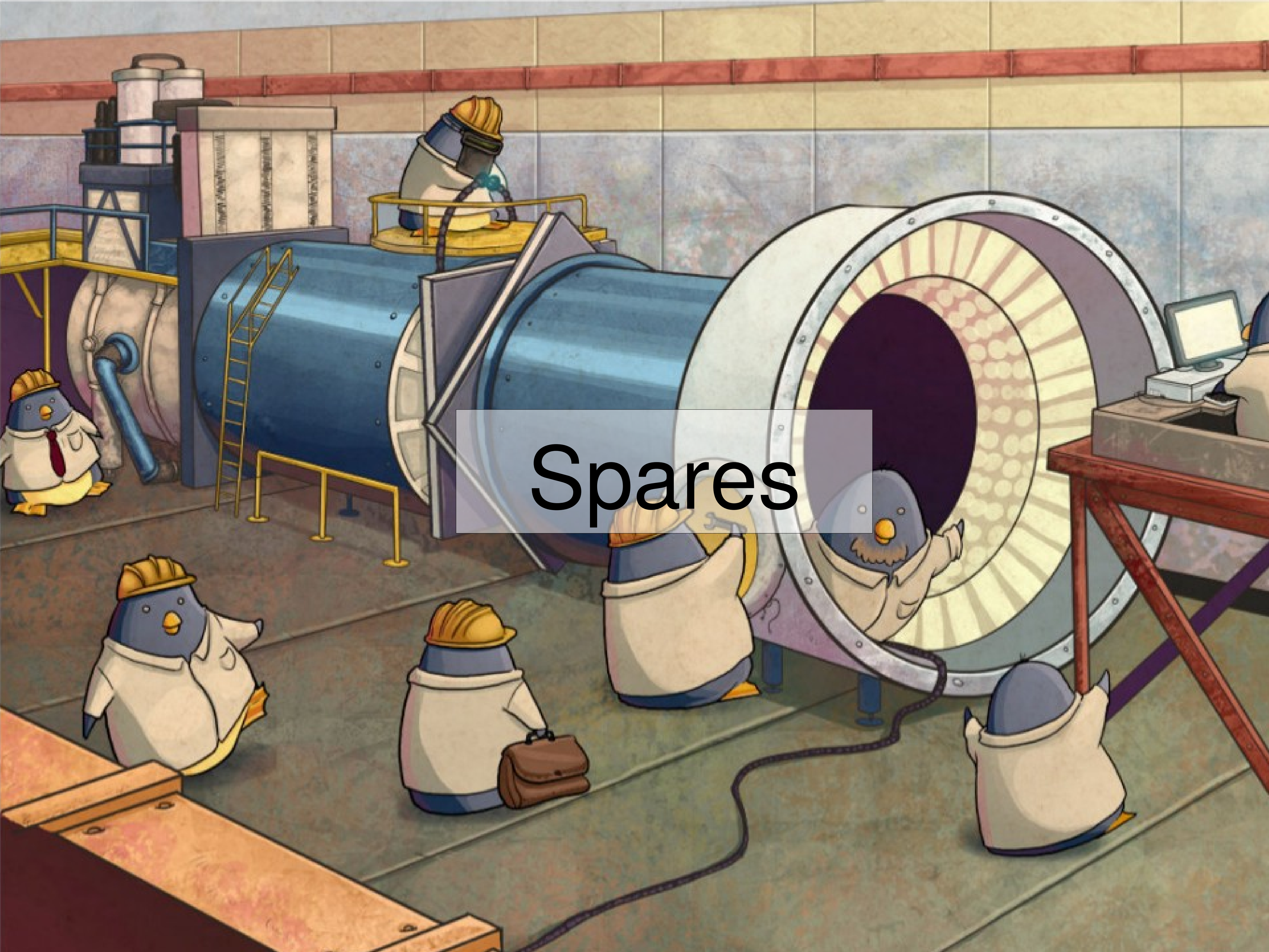
Rare decays	$K_L \to \pi^0e^+e^-$ / $K_L \to \pi^0\mu^+\mu^-$, $K_L \to \pi^0\gamma\gamma$ $K_L \to \mu^+\mu^-$, $K_L \to e^+e^-e^+e^-$, $K_L \to e^+e^-\mu^+\mu^-$ $K_L \to \gamma\gamma e^+e^-$
Production of exotics	$K_L \to \pi^0\pi^0X$
Forbidden LFV - LNV	$K_L \to \pi^0e^\pm\mu^\mp$, $K_L \to \mu^\pm e^\mp$

White paper in preparation

Conclusions

Kaon physics is still a very sensitive probe for New Physics

- **NA62 measurement of $K^+ \to \pi^+ \nu\bar{\nu}$**
  - 2016+2017 result released: $BR(K^+ \to \pi^+ \nu\bar{\nu}) < 1.85 \times 10^{-10}$ @ 90% CL
  - Constraints on the largest enhancements allowed by NP models
  - 2018 data analysis on-going
  - Excellent prospects for after LS2
- **Broader NA62 physics programme:**
  - Lepton universality (R_K)
  - LNV/LFV kaon decays
  - Search for exotic particles (HNL, Dark photon, ALPs)
- **Prospects:**
  - Request for extended data taking (2021 → 2024) well received
  - Data taking in 2021 has already been approved
  - Next generation Kaon beams: a powerful tool to break the Standard Model
  - Programme of K^+ and K_L experiments at CERN


Spares

The K12 high-intensity K^+ beam line

Primary SPS proton beam:

p = 400 GeV protons

3×10^{12} protons/pulse ($3 \times$ NA48/2)

Duty factor ~ 0.3

Expected similar to 4.8s/16.8s duty cycle for NA48/2

Simultaneous operation of LHC and fixed target experiments

High Intensity, unseparated secondary beam:

Momentum selection chosen to optimise K decays

P = 75 GeV ($1.4 \times$ more K^+ than NA48/2 at same proton beam intensity)

$\Delta p/p$ ~ 1% ($3 \times$ smaller than NA48/2)

Total Rate 750 MHz $\begin{cases} 525 \text{ MHz } \pi \\ 170 \text{ MHz } p \\ 45 \text{ MHz } K \end{cases}$

Beam Timing and Kaon Identification

Gigatracker (750 MHz)	← Must precisely match events →	Downstream detectors (~10 MHz)

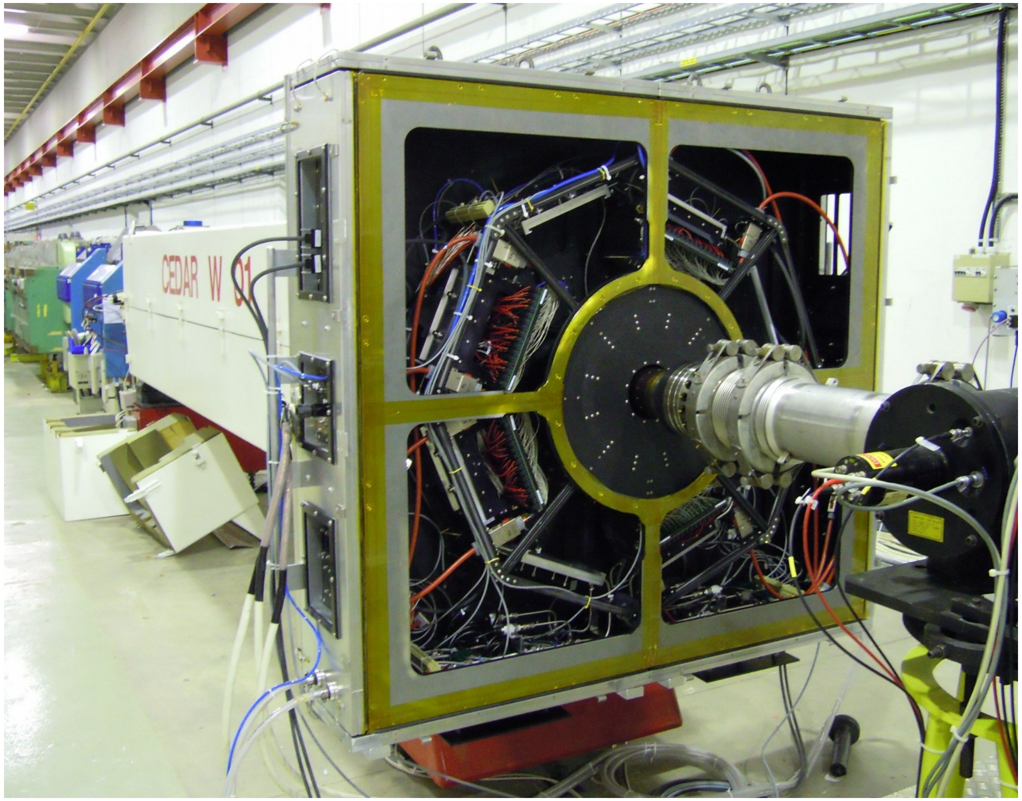
GigaTracker:	σ_t < 200 ps/station
KTAG:	σ_t < 100 ps
RICH:	σ_t < 100 ps

Mismatch probability < 1%

Wrong matching → 3 × increase in $\sigma(m_{miss})$

CEDAR/KTAG characteristics:

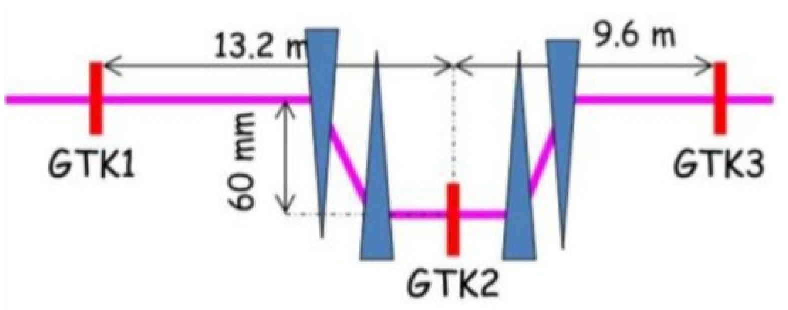
- Differential Cherenkov, 1.1 m^3 of Hydrogen @ 3.7 bar as radiator
- 8 light boxes with 48 PMTs each
- Kaon Time resolution < 100 ps
- Kaon Tagging efficiency > 95%
- Pion Mis-ID probability < 0.001



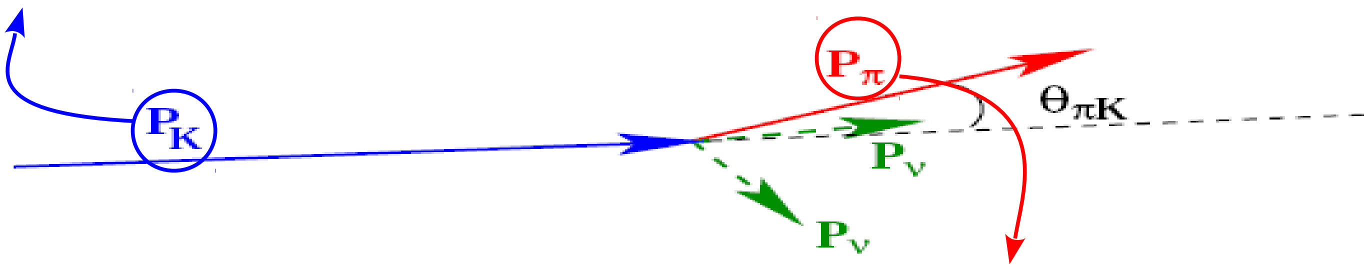
CEDAR/KTAG working conditions:

- Kaon Rate (average) ~ 45 MHz
- Rate on single PMT ~ 4 MHz

The Tracking detectors

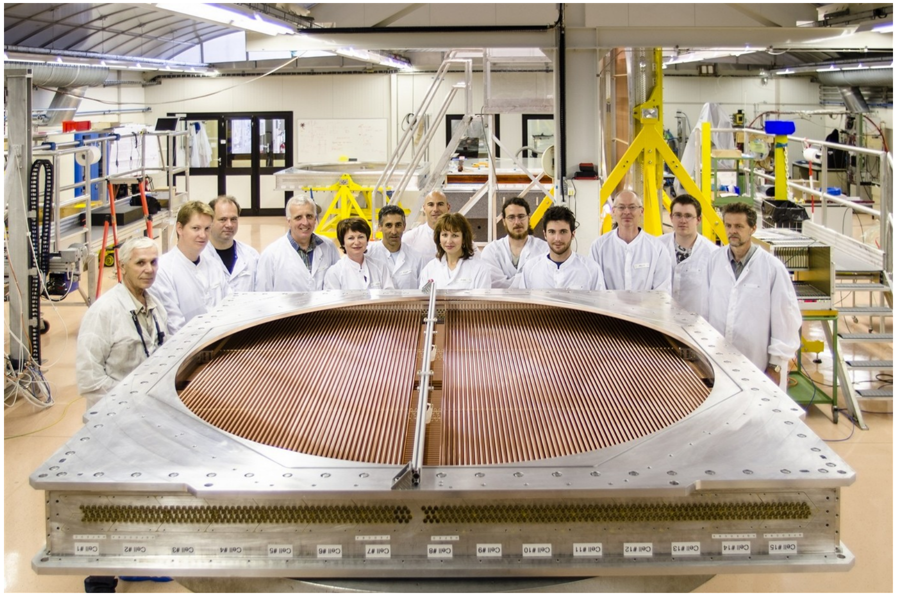


GIGATRACKERS: Beam spectrometer for Kaon momentum, time and angular measurements, based on 3 Silicon sensors with $300\times300\mu m^2$ pixels ($\sigma_p/p \sim 0.2\%$, $\sigma_\theta = 16\ \mu rad$)



STRAW CHAMBERS: Spectrometer for position and momentum measurements of charged decay products, based on 4 straw chambers, 2.1 m in diameter

[16 layers (4 views) of straws per chamber]



MNP33 dipole: 0.36T ($p_\perp = 270$ MeV)

$\sigma \leq 130\ \mu m$ (1 view)

0.45 X_0 per chamber

$\sigma_p/p = 0.32\% \oplus 0.008\% p$

$\sigma_\theta(K\pi) = 20\text{-}50\ \mu rad$

The Photon Veto System

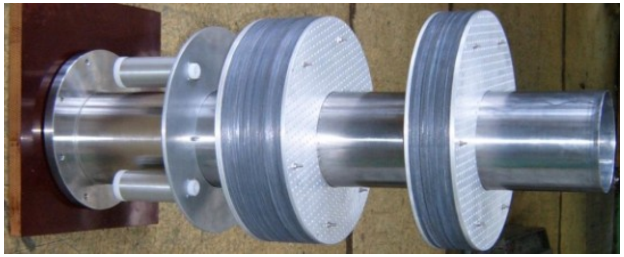
Hermetic Photon Vetoes up to 50 mrad

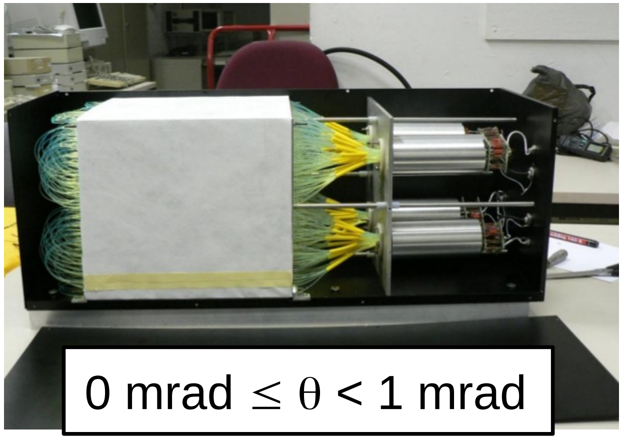
LAV: 12 counters surrounding the vacuum tank providing full coverage for photons at large angles

LKr: Electromagnetic calorimeter built for the NA48 experiment for the photon veto in the forward region

IRC/SAC: Photon veto at small angles

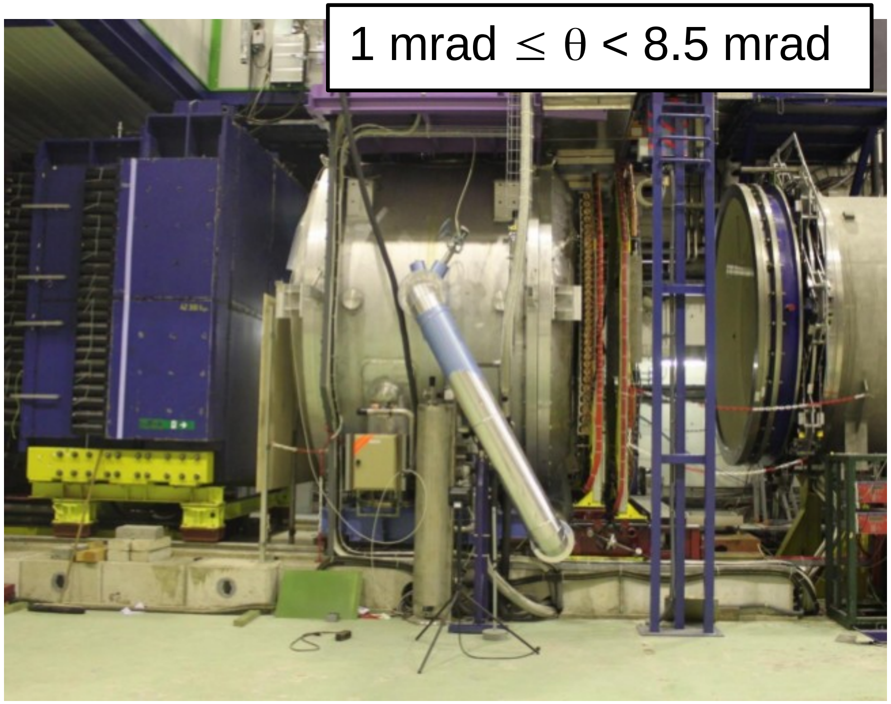
8.5 mrad $\leq \theta < 50$ mrad





0 mrad $\leq \theta < 1$ mrad

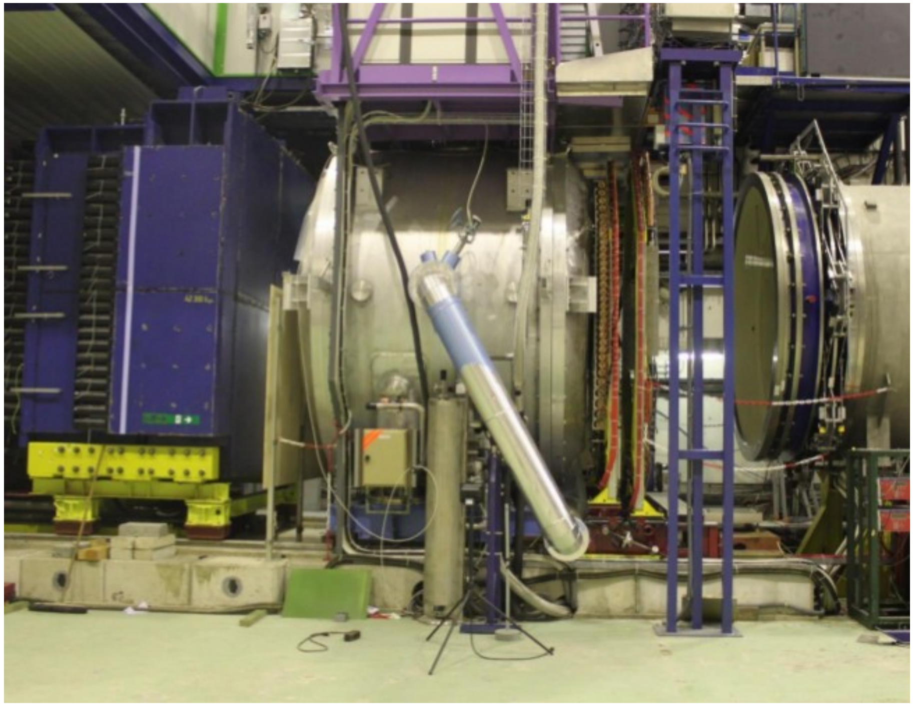
1 mrad $\leq \theta < 8.5$ mrad



$K^+ \rightarrow \pi^+\pi^0$ Photons:

81.2%: 2 in LKr/SAC
18.6%: 1 in LKr/SAC + 1 in LAV
0.2%: 1 in LAV + 1 lost (θ>50mrad)

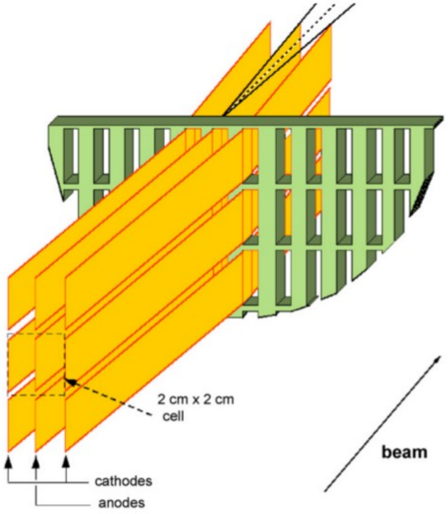
The LKr calorimeter

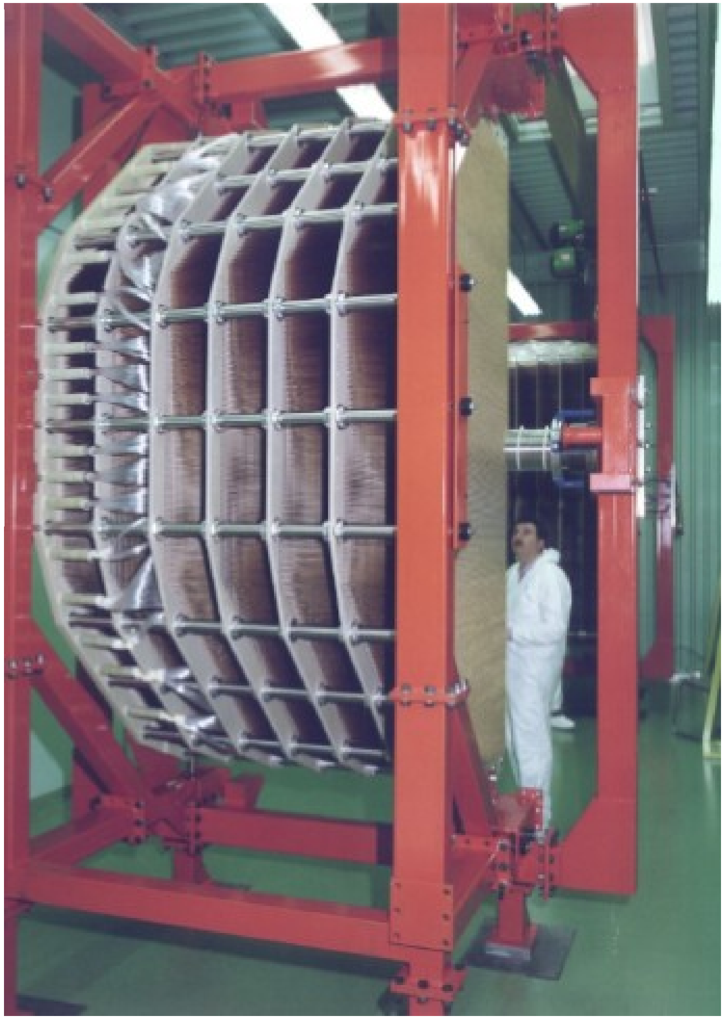


Quasi-homogeneous ionisation calorimeter

Readout towers $2\times2\text{cm}^2$ = 13248 channels

Depth 127 cm = 27 X_0





Photon Inefficiency (E_γ > 10 GeV) < 8×10^{-6}

$$\frac{\sigma_E}{E}=\frac{3.2\%}{\sqrt{E(GeV)}}\oplus\frac{9\%}{E(GeV)}\oplus0.42\%$$

$$\sigma_{x,y}=\frac{4.2\text{mm}}{\sqrt{E(GeV)}}\oplus0.6\text{mm}$$ [= 1.5 mm @ 10 GeV]

The Pion ID detectors

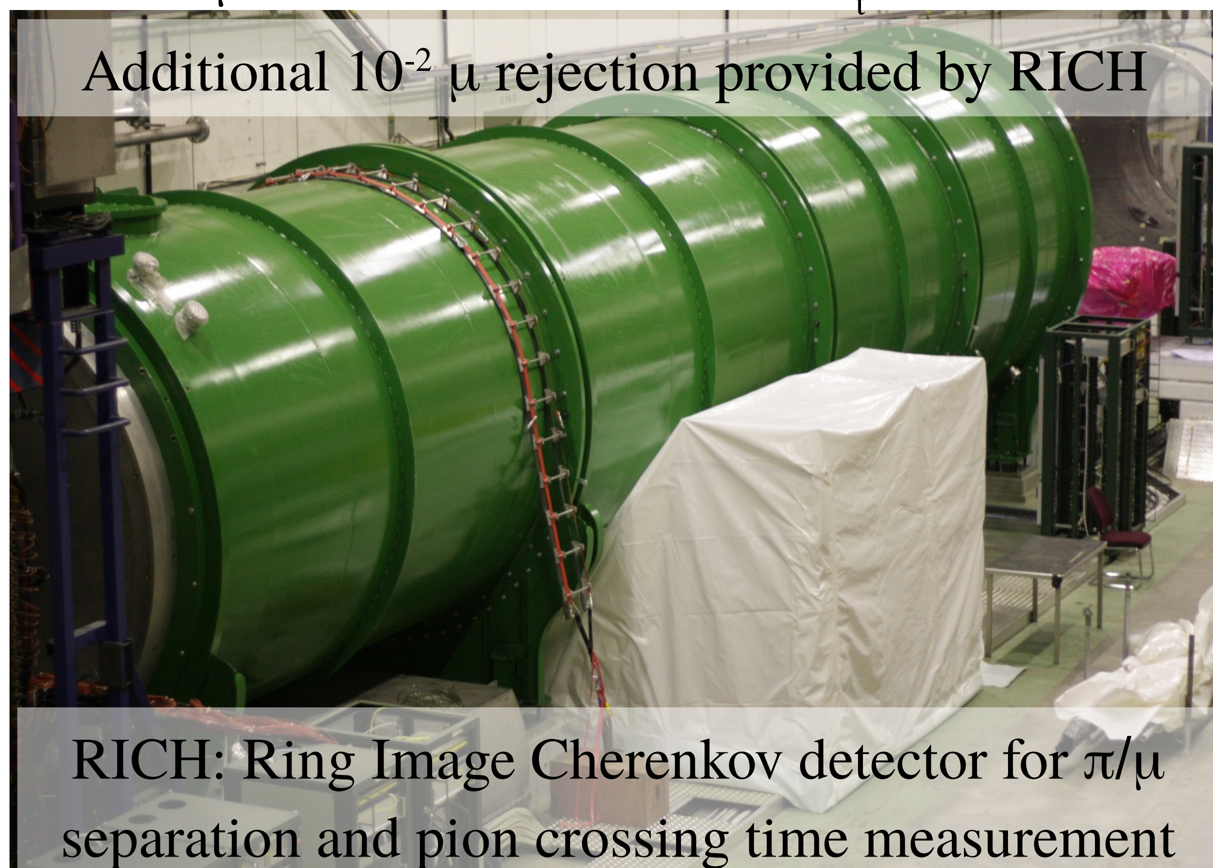
Primary π/μ separation from downstream muon vetoes (MUV)

MUV1-2: Fe/scintillator hadron calorimeter

Used offline to reject μ up to 10^{-5} level

MUV3: Fast μ identification for trigger

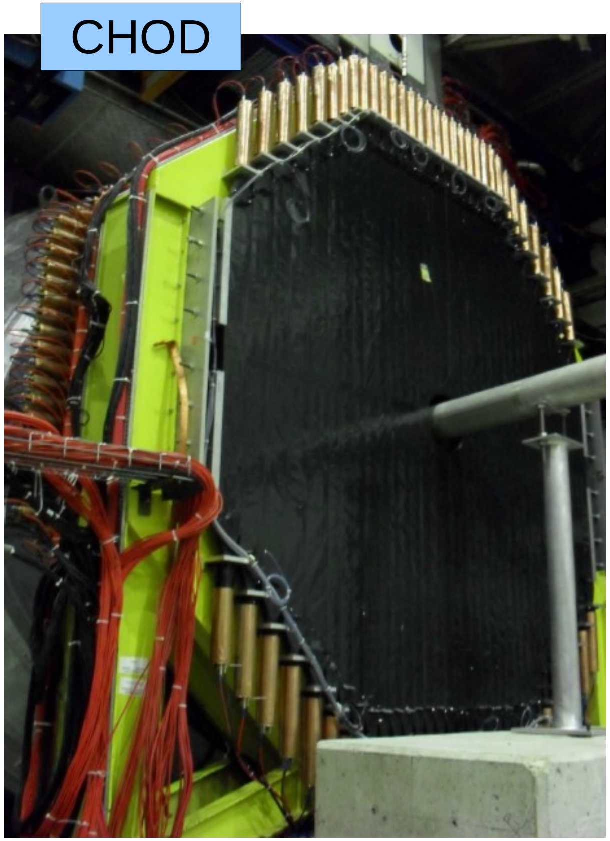
Vetoes μ online @ 10 MHz with $\sigma_t < 1$ ns



Additional 10^{-2} μ rejection provided by RICH

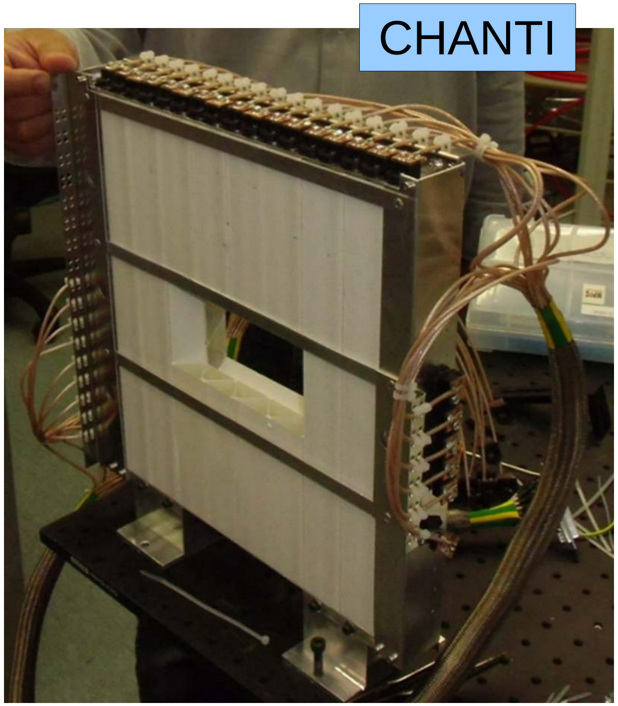
RICH: Ring Image Cherenkov detector for π/μ separation and pion crossing time measurement

The Hodoscopes (CHODs) and the CHANTI



2 planes (horizontal + vertical) of 64 plastic scintillator strips each

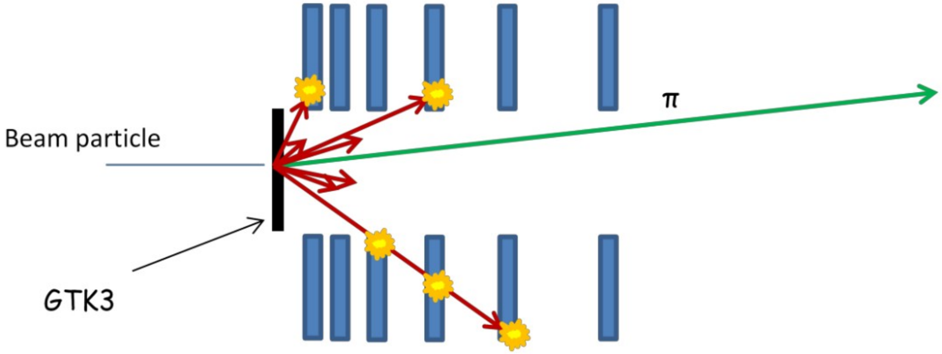
1 plane of 152 scintillator tiles



Veto for interactions in GTK3
6 scintillator stations hermetic between 1.31 and 49 mrad

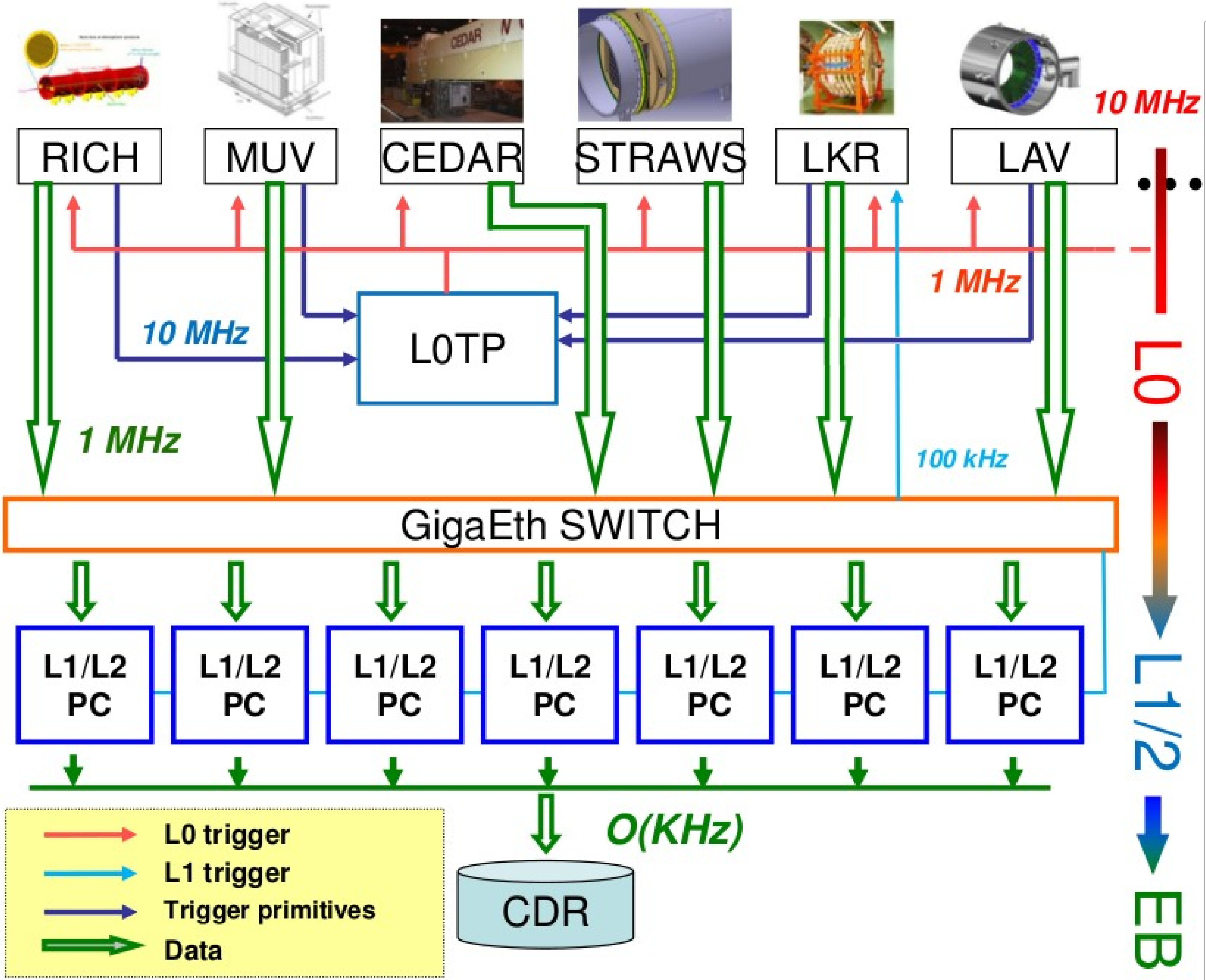
Fast charged particles signal for trigger

σ_t ~ 300 ps (after impact point corrections using track extrapolation)



Trigger and Data Aquisition (TDAQ) system

16 sub-detectors, ~ 100000 channels, 25 GB/s raw data



L0: Hardware synchronous level. 10 MHz to 1 MHz. Max latency 1 ms.

L1: Software level. "Single detector". 1 MHz to 100 kHz. Max latency O(1 s).

L2: Software level. "Complete information". 100 kHz to 10 kHz. Max latency O(30 s).