$K^+ \to \pi^+ \nu \bar{\nu}$ and search for exotic particles at the NA62 experiment

Francesco Gonnella *University of Birmingham*
on behalf of the NA62 collaboration

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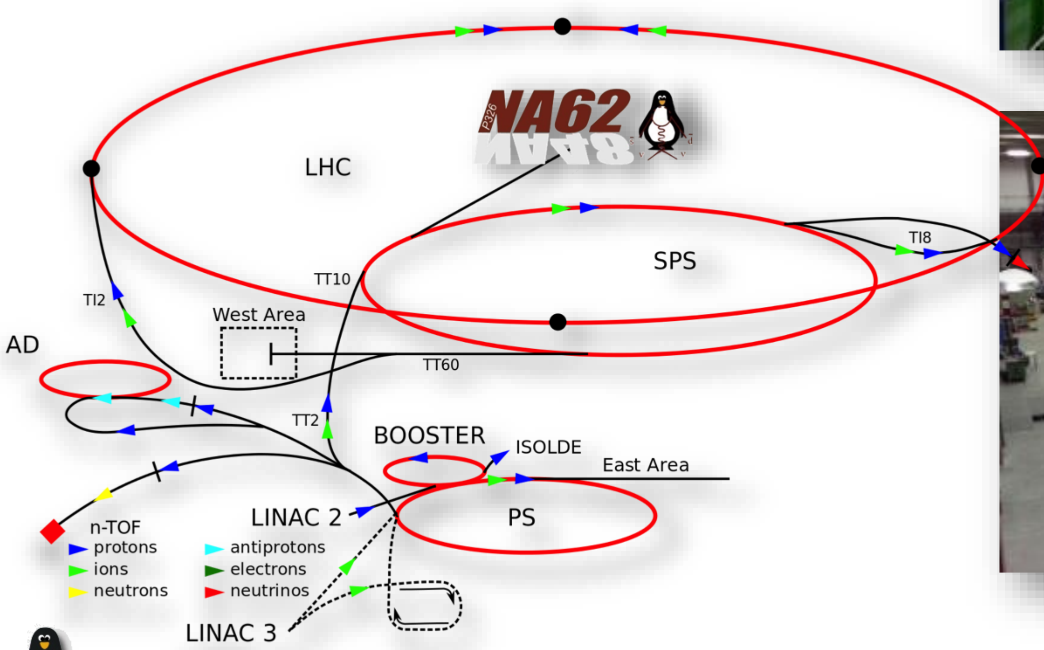
The NA62 experiment

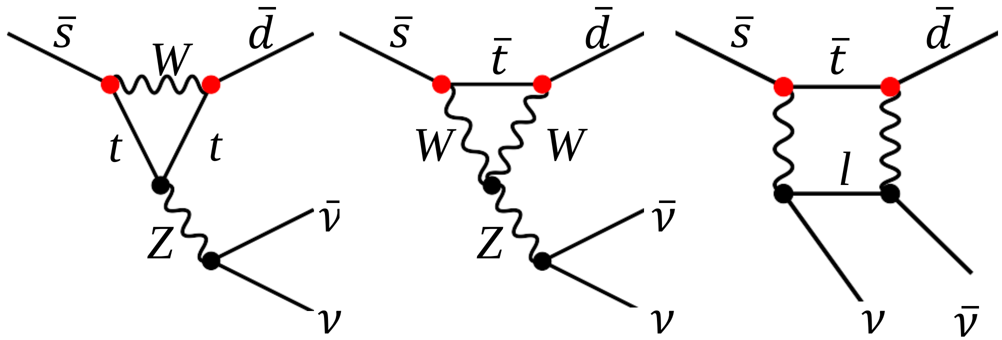
- 2014-2018 NA62: $K^+ \to \pi^+ \nu\nu$
  - 2014 Pilot run
  - 2015 Commissioning run
  - Full detector installation completed in September 2016
  - First $\pi\nu\nu$ dataset in 2016 (This talk)
  - Continuous data-taking until the end of 2018



Ultra-rare kaon decays

$K \rightarrow \pi\nu\nu$: theoretically pure and experimentally unexplored

- Hadronic matrix element obtained from BR(K_{e3}) via isospin rotation
- Hard GIM suppression
  - Loop functions favor top quark contribution

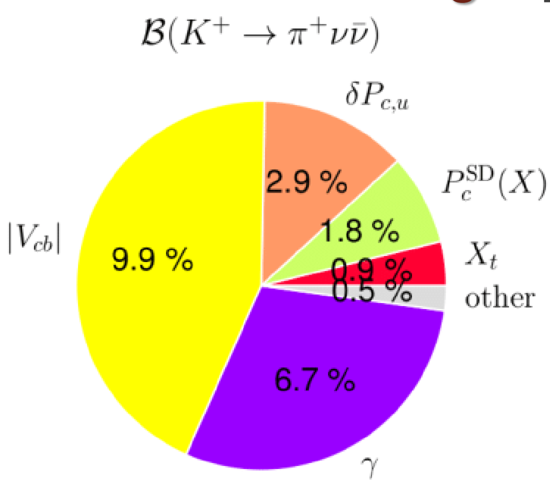


Very sensitive probes for new physics:

- They are highly suppressed
- They are predicted with very high accuracy

Decay	Branching Ratio (x 10^{11}) Theory (SM)		Experiment	
$K^+ \rightarrow \pi^+\nu\bar{\nu}$	8.4 ±1.0	[1]	17.3 $^{+11.5}_{-10.5}$	[2]
$K_L \rightarrow \pi^0\nu\bar{\nu}$	3.4 ±0.6	[1]	<2600 (90%CL)	[3]

Theoretical error budget [1]



[1] **Buras, A.J., Buttazzo, D., Girrbach-Noe, J. et al.** J. High Energ. Phys. 2015: 33 (2015)

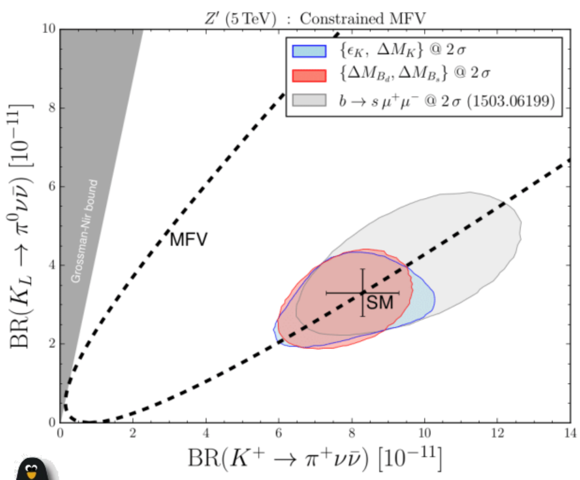
[2] **A. V. Artamonov *et al.* (E949 Collaboration @ BNL)** Phys. Rev. D **79**, 092004 (2009)

[3] **J. K. Ahn *et al.* (E391a Collaboration @ KEK)** Phys. Rev. D **81**, 072004 (2010)

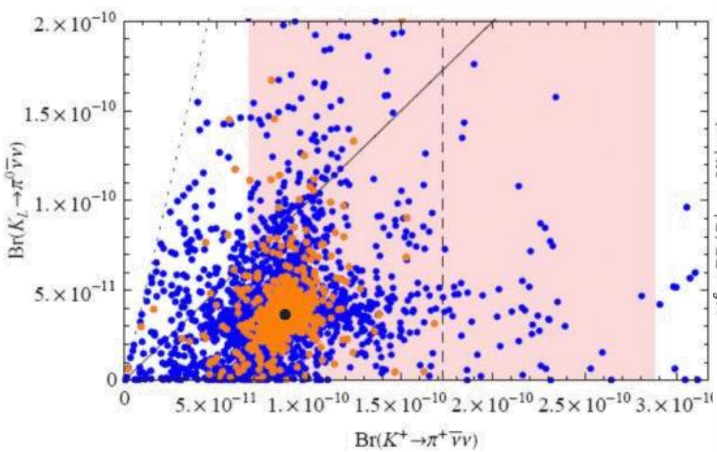
$K \to \pi\nu\bar{\nu}$ beyond the Standard Model

- **Custodial Randall-Sundrum** [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- **MSSM analyses** [Blazek, Matak, Int.J.Mod.Phys. A29 (2014) no.27],[Isidori et al. JHEP 0608 (2006) 064]
- **Simplified Z, Z' models** [Buras, Buttazzo,Knegjens, JHEP11(2015)166]
- **Littlest Higgs with T-parity** [Blanke, Buras, Recksiegel, Eur.Phys.J. C76 (2016) 182]
- **LFU violation models** [Isidori et al., Eur. Phys. J. C (2017) 77: 618]
- **Constraints from existing measurements (correlations model dependent)**
  - Kaon mixing, CKM elements, K, B rare meson decays, NP limits from direct searches

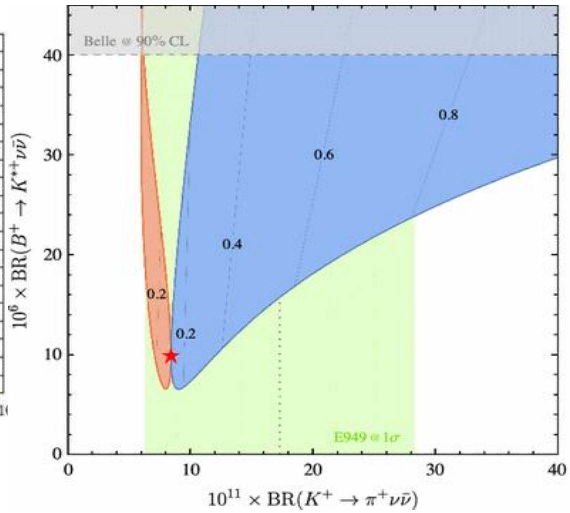
Z'(5 TeV) in Constrained MFV



Randall Sundrum



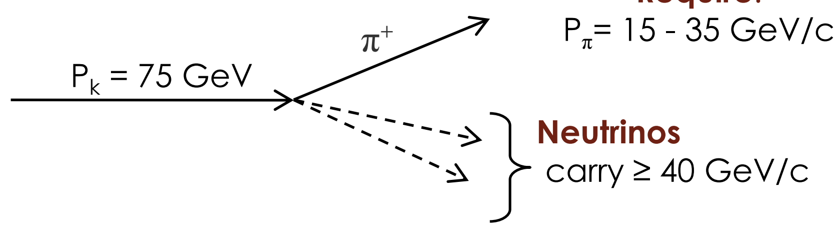
LFU violation



Analysis principles: in-flight decay

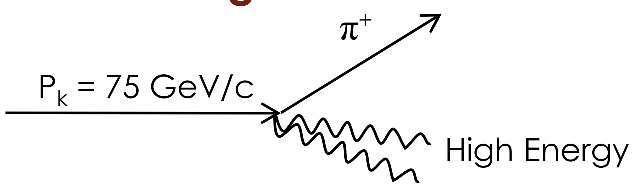
- Large missing momentum

Kinematic Signature



Consequence for the background

$K \rightarrow \pi^+\pi^0$
$\quad\hookrightarrow \gamma\gamma$

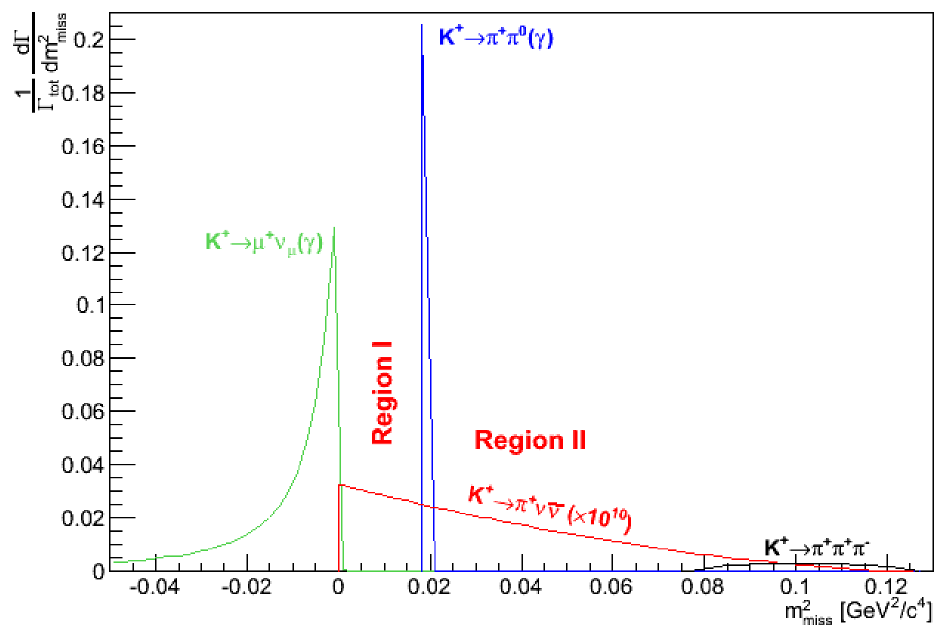


- Cuts on the missing mass

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

defines 2 regions

- Kinematical rejection is ~10^4
- Further rejection relies on PID and vetoes



$K \to \pi\nu\bar{\nu}$: signal and background

Signal: $BR_{SM} \sim 8 \times 10^{-11}$

Signature:

- K track in
- π track out
- No other particles in final state
- $M^2_{miss} = (p_K - p_\pi)^2$

Keystones of the analysis:

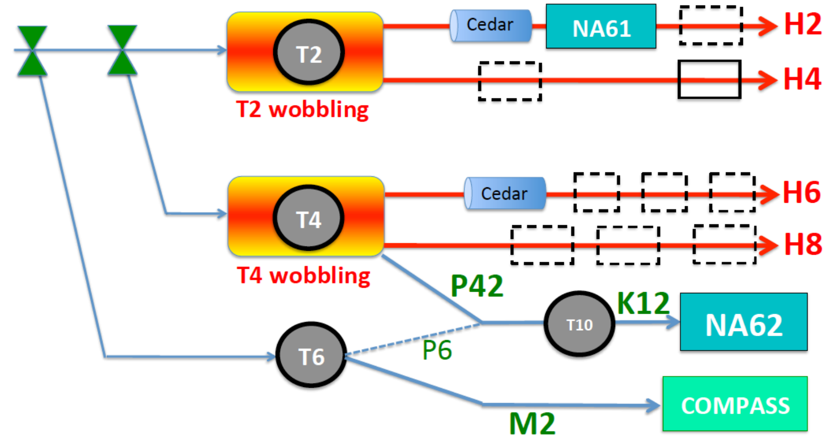
- Timing between sub-detectors ~ O(100 ps)
- Kinematic suppression ~ $O(10^4)$
- Muon suppression > 10^7
- π^0 suppression (from $K^+ \to \pi^+\pi^0$) > 10^7

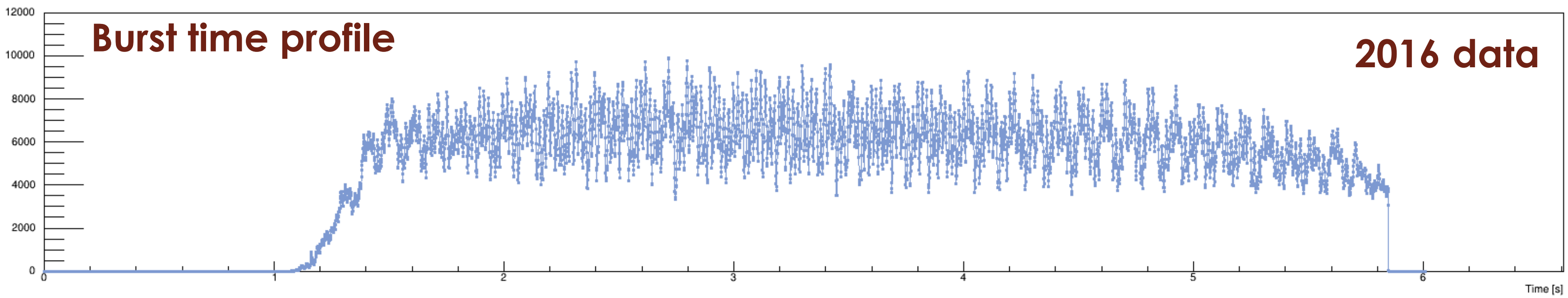
Signal and background control regions are kept blind throughout the analysis

Decay backgrounds	
Mode	**BR**
$\mu^+\nu(\gamma)$	63.5%
$\pi^+\pi^0(\gamma)$	20.7%
$\pi^+\pi^+\pi^-$	5.6%
$\pi^0 e^+\nu$	5.1%
$\pi^0\mu^+\nu$	3.3%
$\pi^+\pi^- e^+\nu$	4.1×10^{-5}
$\pi^0\pi^0 e^+\nu$	2.2×10^{-5}
$\pi^+\pi^-\mu^+\nu$	1.4×10^{-5}
$e^+\nu(\gamma)$	1.5×10^{-5}
Other backgrounds	
Beam-gas interactions	
Upstream interactions	

NA62 beam

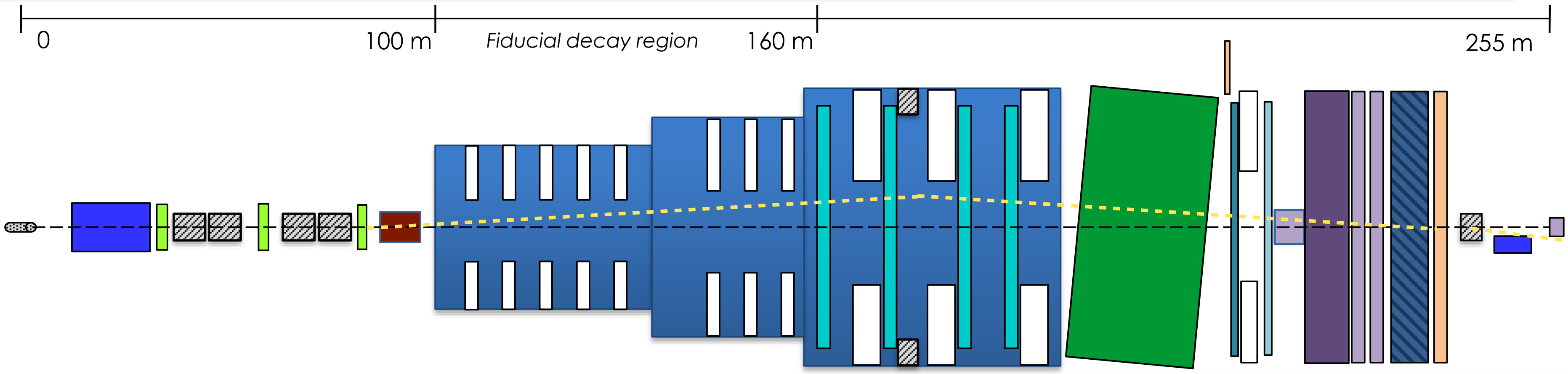
Beam Parameters	
400 GeV/c Protons on Target/s	10^{12} per spill
75 GeV/c Hadrons/s	750 x 10^6
Beam composition	p 70% π 24% **K 6%**
K^+ rate (particle/s)	45 x 10^6
K^+ decays/s	4.5 x 10^6





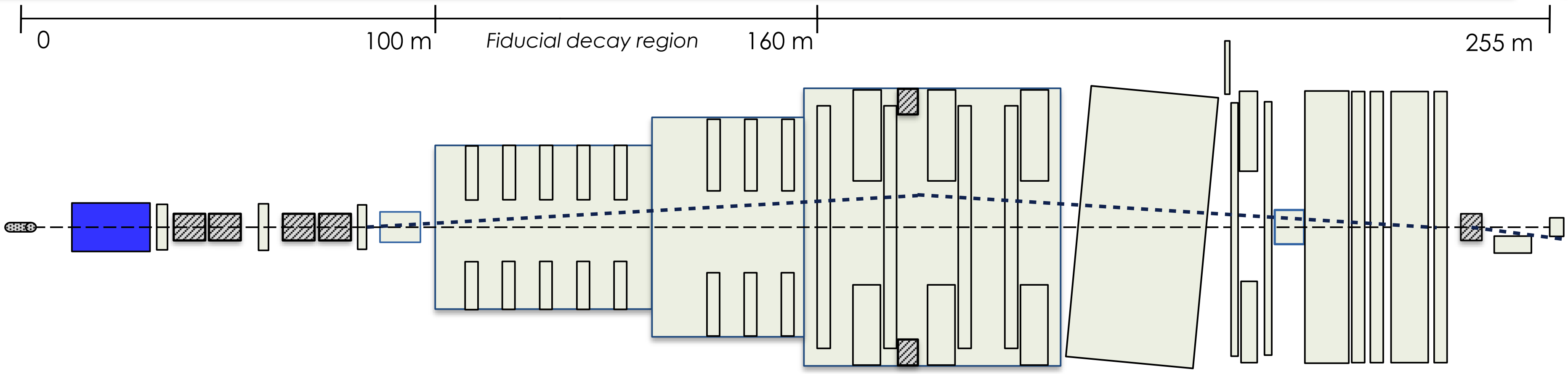
- NA62 uses SPS 400 GeV/c proton beam
- Proton beam interacts with a Beryllium target
- Among the interaction products, 75 GeV/c K^+ are selected
  - 750 MHz particle rate at GTK3
- 60 m long fiducial region with ~ 5 MHz K+ decay in Vacuum ~10^{-6} mbar

NA62 experimental principles



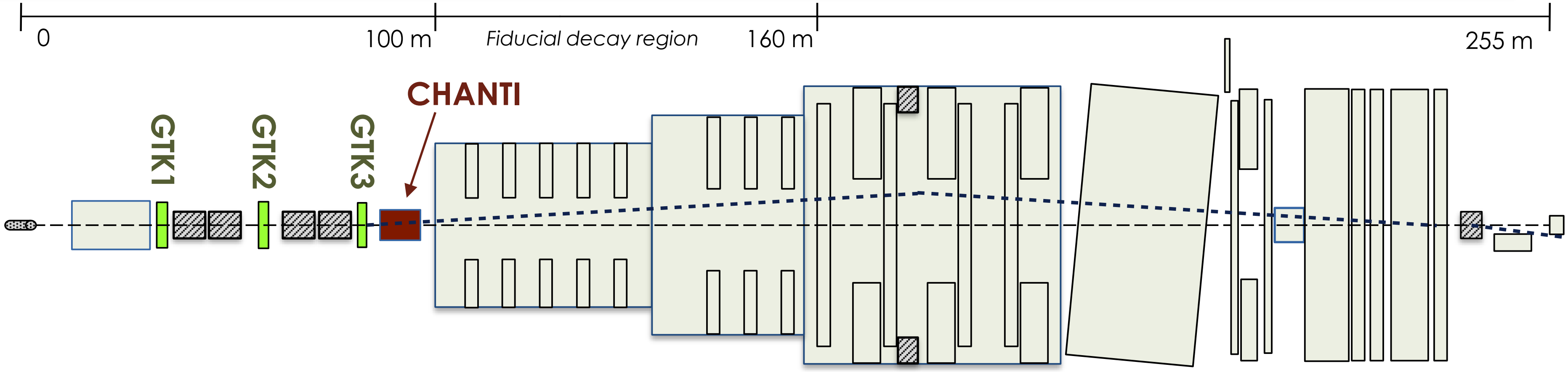
- High resolution missing mass reconstruction
  - Precise measurement of p_K and p_π
- Minimize multiple scattering
- Hermetic veto for π^0 rejection
- Upstream K^+ identification in hadron beam
- Downstream $\pi/\mu/e$ separation
- μ veto for $K\mu 2$ rejection
- Sub ns time resolution

Incoming kaon ID: KTAG

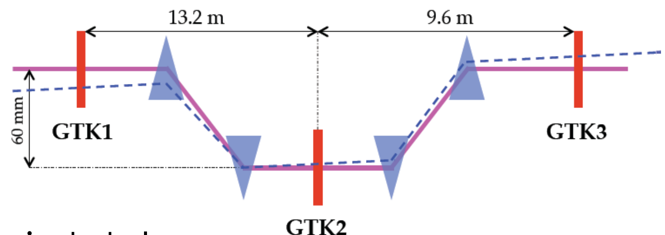


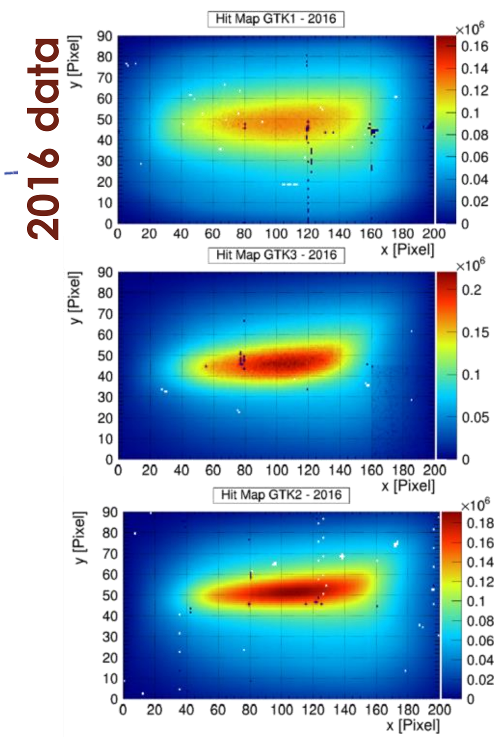
- The KTAG is an upgraded CERN CEDAR West
  - Blind to particles other than kaon thanks to a diaphragm
  - Extended external optics to reduce rate per single channel
    - High kaon rate (~45MHz)
  - New photo-detectors + readout
  - Very good timing ~100 ps to match with downstream decay

Incoming particle momentum: GTK



- 3 stations of Silicon pixel detectors
- Operating in the evacuated beam pipe inside an achromat
- Overall Rate 750 MHz, in the beam centre 140 kHz/pixel



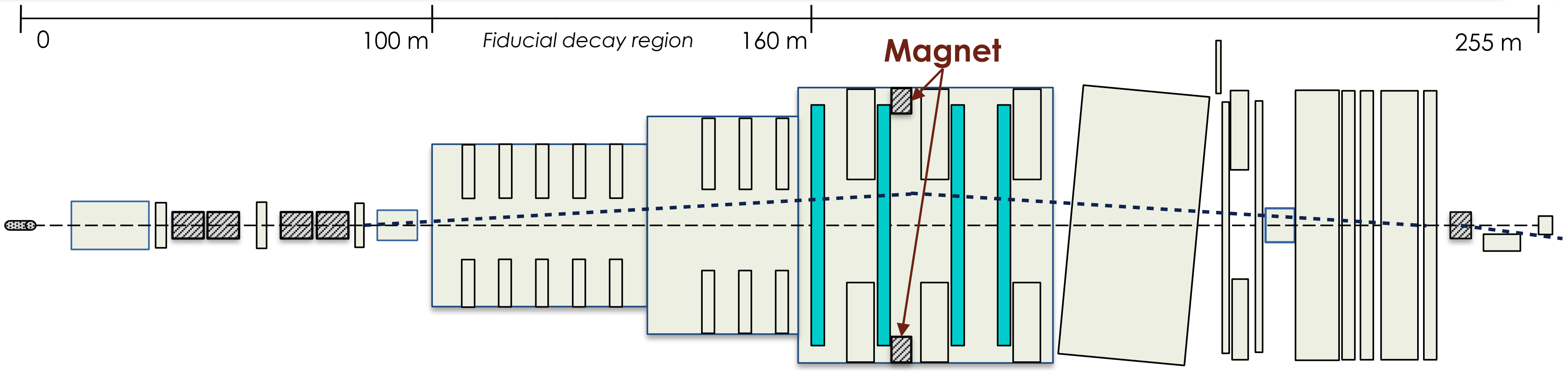


- Pixel size:
  - 300 x 300 μm^2 or 300 x 400 μm^2
  - 18'000 pixels/ station, 54'000 pixels in total

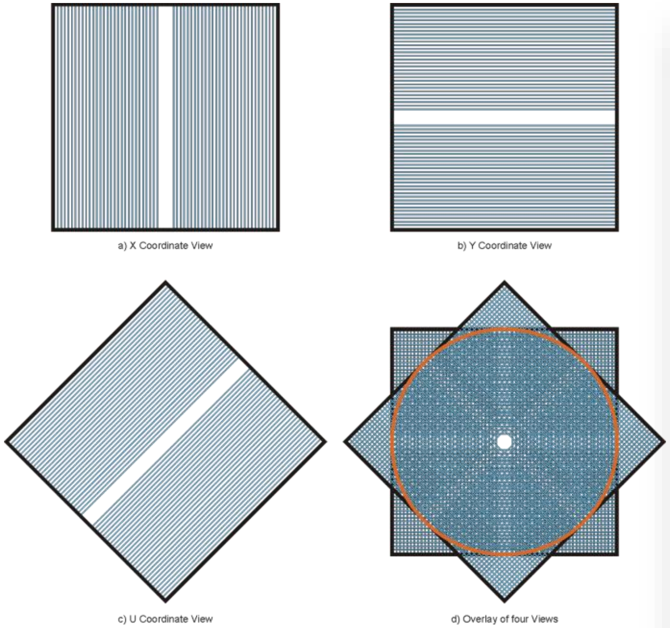
- Time : $\sigma \approx$ 200ps per station
- Direction: $\sigma_{dx,dy} \approx$ 0.016mrad, Momentum: $\Delta P/P < 0.4\%$

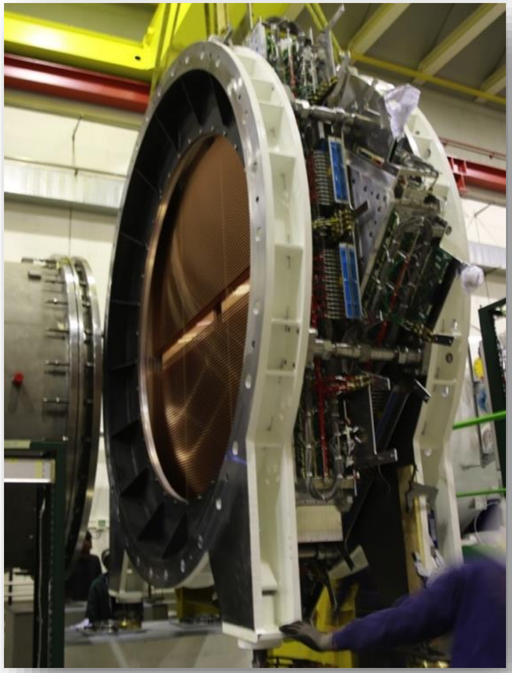
- CHANTI is placed just after GTK3 to veto inelastic scattering

Final-state momentum: the straw spectrometer

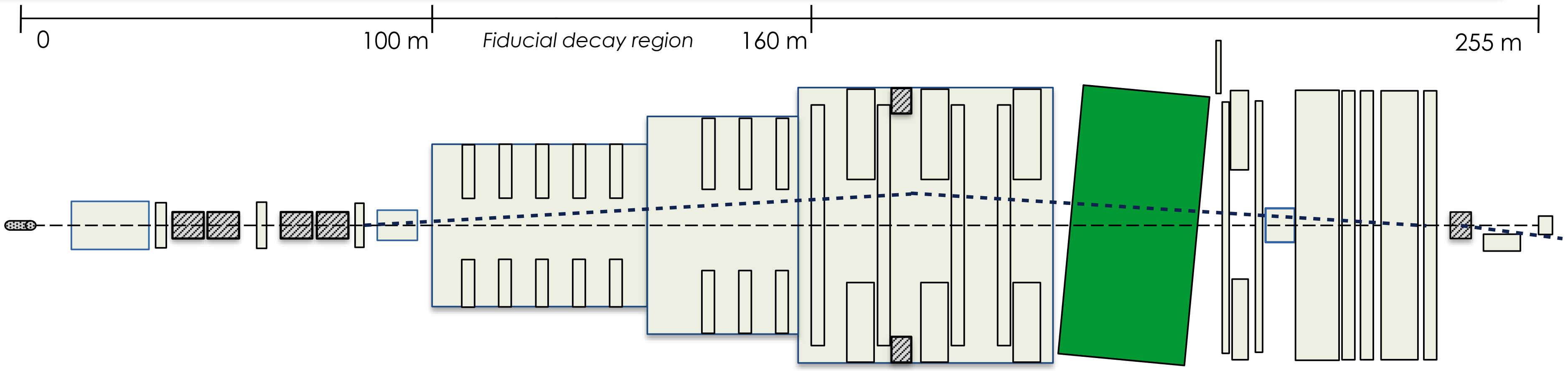


- 4 straw chambers in vacuum and a dipole magnet
- Each chamber measuring 4 coordinates (views)
- High accuracy: 130 μm/view
- Straw tube dimensions:
  - 2.1 m long and d = 9.8 mm;
  - Thickness: 50 nm Cu + 20 nm Au on 36 μm of Mylar
- Total 7168 Straws (4x4x4x112)

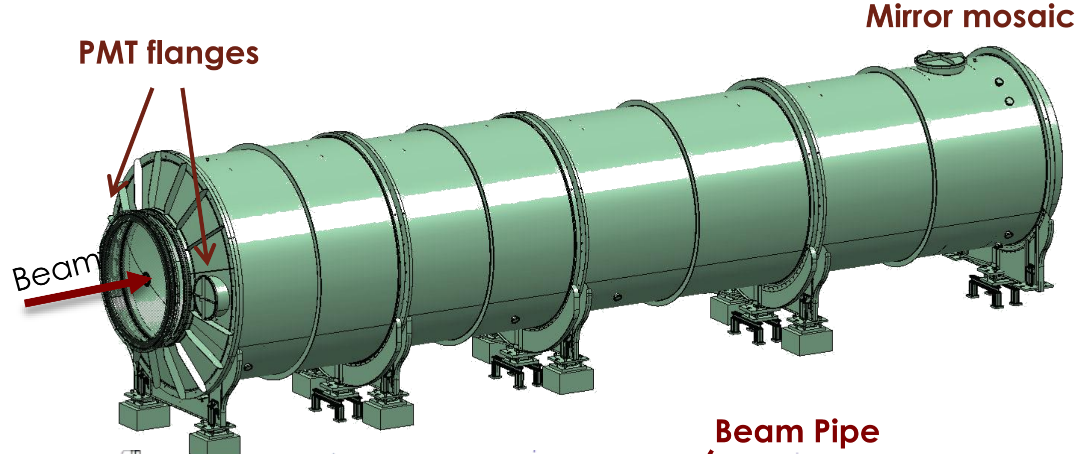


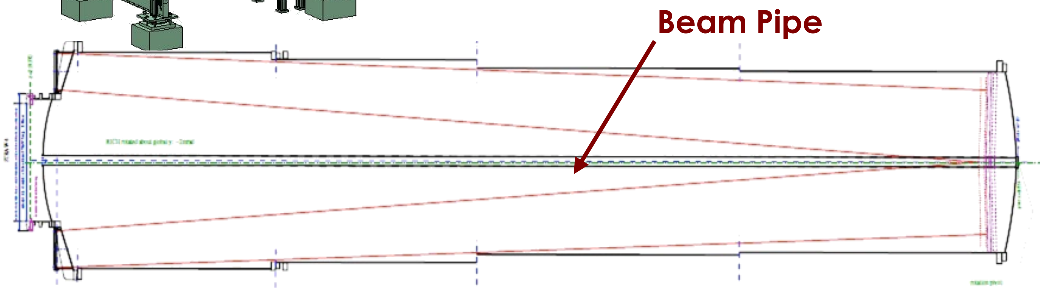


Final state particle ID: the RICH

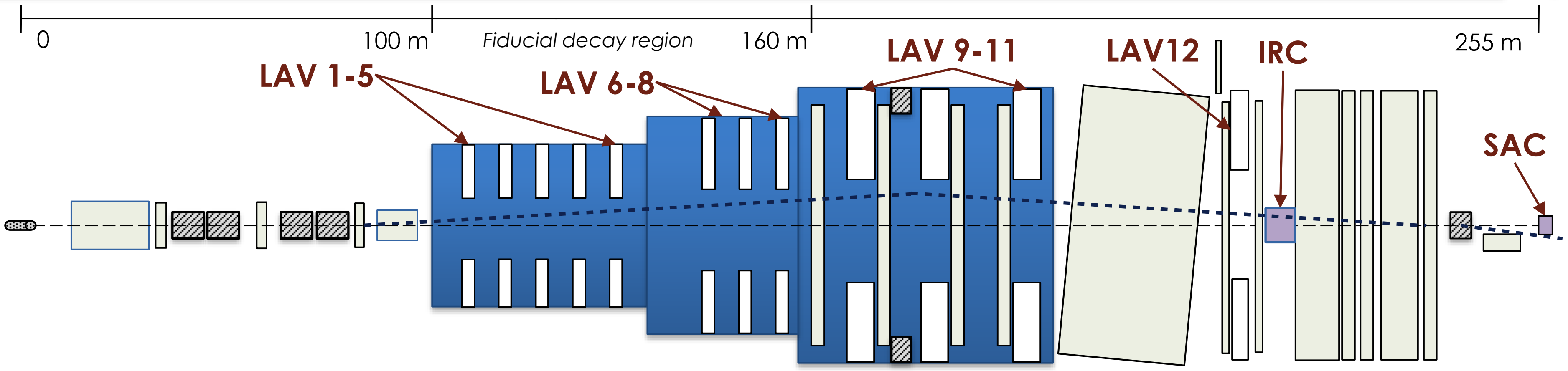


- Length ~ 17 m;
- ∅ = up to 4m
- Filled with Neon at 1 atm
- 2 flanges with 1000 PMTs each
- ~70 ps time resolution
- Used in Level-0 trigger as reference detector





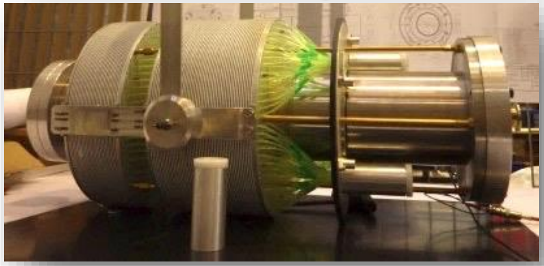
Photon vetos: LAVs and SAVs



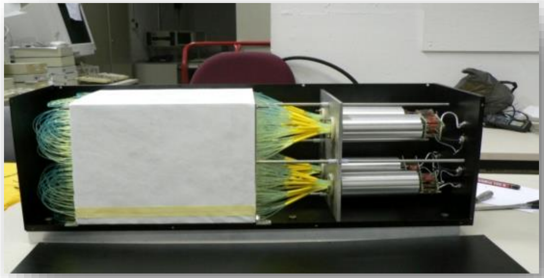
LAV: 8.5 – 50 mrad

- 12 stations along the vacuum tank, each station:
  - 4 – 5 layers
  - 160 – 256 lead glass blocks
- LAV12 is in Level-0 trigger
- IRC and SAC cover very small angle <1 mrad

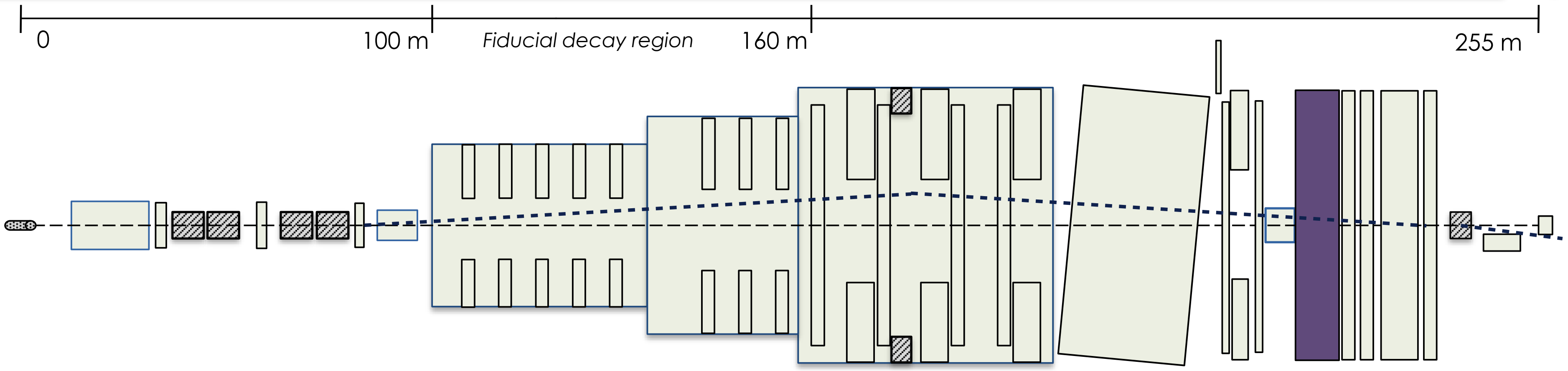
IRC Intermediate Ring Calorimeter



SAC Small Angle Calorimeter

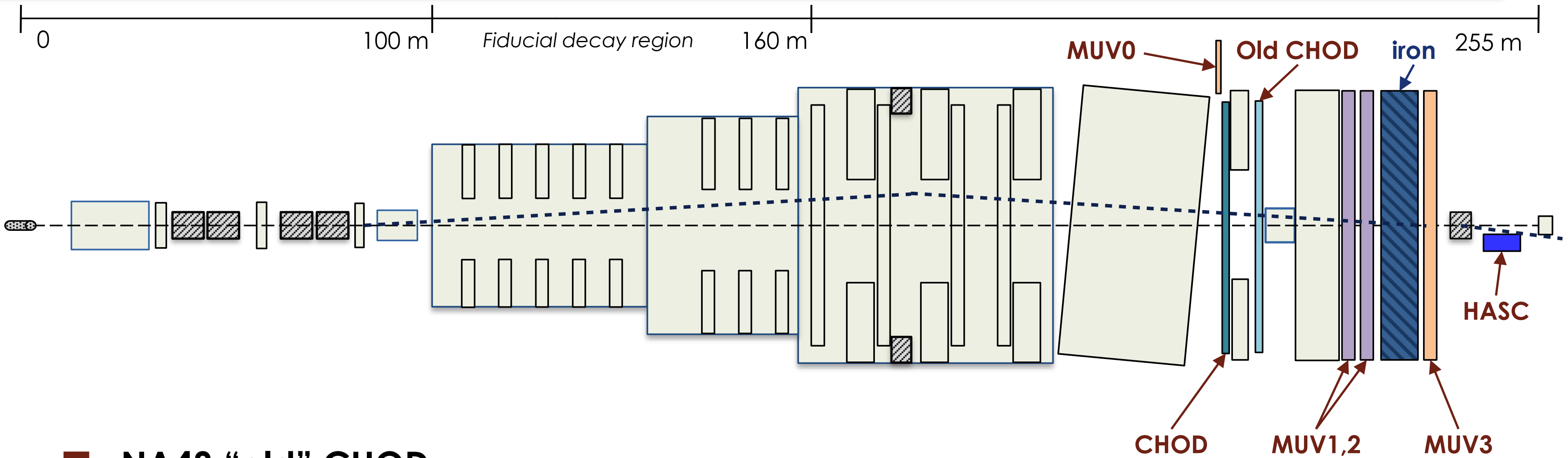


Liquid Krypton Calorimeter



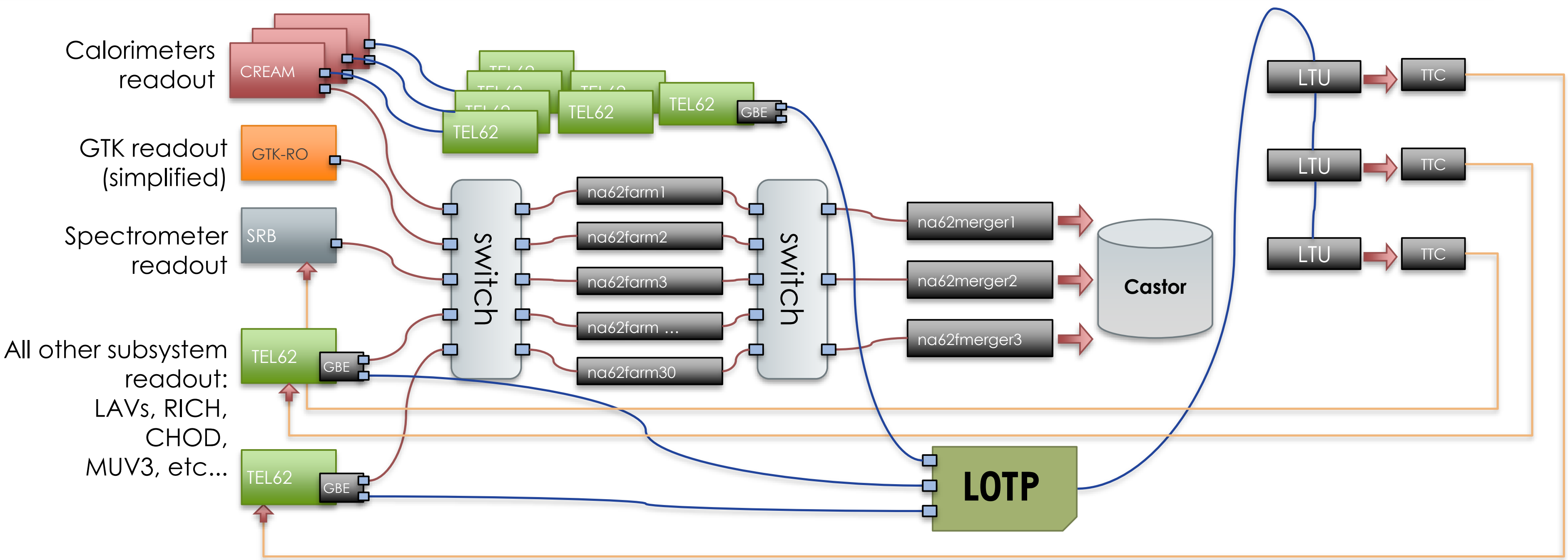
- **NA48 LKr calorimeter performance:**
  - Time resolution: ~500 ps
  - Spatial resolution: 1 mm
- Readout
  - 14 bit FADC, 40 Ms, 32 ch / module
  - 432 modules, 28 VME crates
- Photon veto coverage 1÷8.5 mrad
- LKr is in Level-0 trigger

Chod and muon-veto system



- **NA48 "old" CHOD**
  - Plastic scintillator hodoscope
  - ~1ns time resolution
  - Used in Level-0 trigger as control
- **CHOD**
  - Plastic tile scintillator
  - ~200 ps time resolution
  - Used in Lelvel-0 trigger
- **MUV0 and HASC**
  - Hermeticity for π and μ
- **MUV1/MUV2**
  - Hadronic calorimeters
  - Readout with LKr electronics
  - Can be used as hadron trigger
- **MUV3**
  - Placed after an iron wall
  - Requires very fast detector: time resolution $\sigma_T \leq 0.5$ ns
  - Used in Level-0 trigger: reduction factor >10
  - Rate: 10 MHz muon

Trigger and data acquisition



- Acquisition boards store data in local buffers
- A subset of detectors continuously send primitives to L0TP
  - L0 trigger is generated with a maximum latency of 1 ms
- All detectors except Calorimeters and GTK respond to L0
  - They send data to PC-Farm
- GTK and Calorimeters send data after L1 request
  - L1 Algorithms are run, if positive verdict data is stored

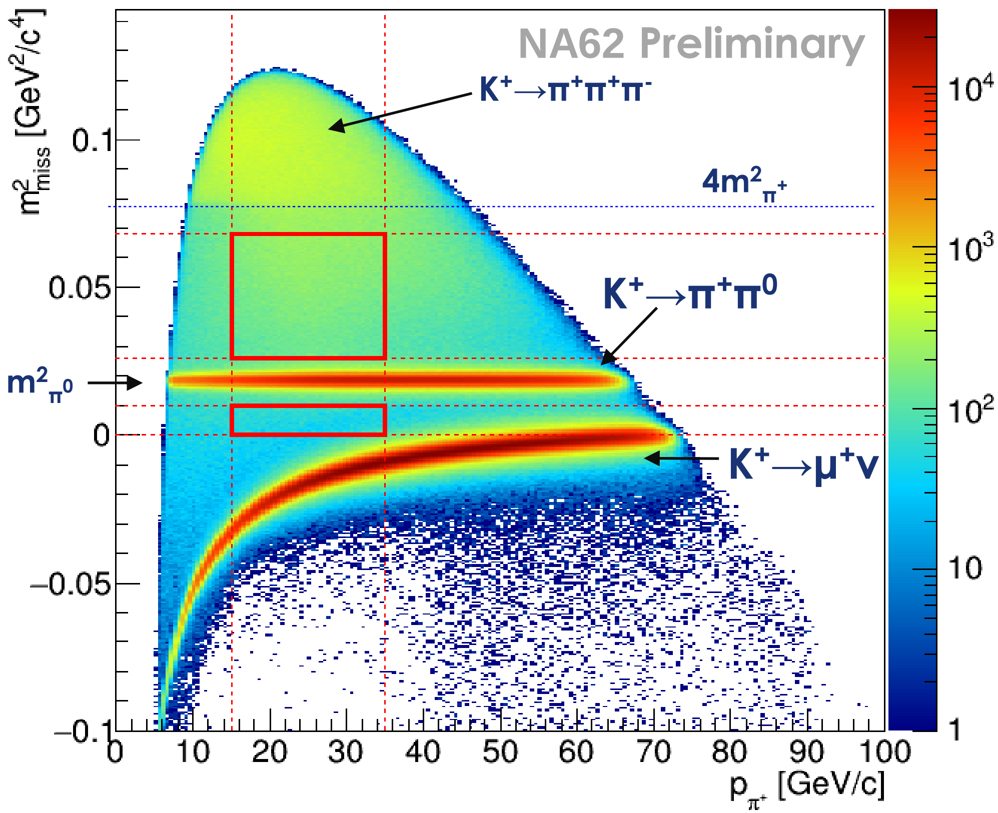
Trigger	Rate
Primitives	10 MHz
L0 (FPGA)	1MHz
L1 (software)	100KHz

Analysis Steps (2016 data sample)

- Kaon decay selection
- Determination of the single-event sensitivity
- Estimation and validation of the expected background
- Un-blinding of the signal regions and results

Kaon decay selection

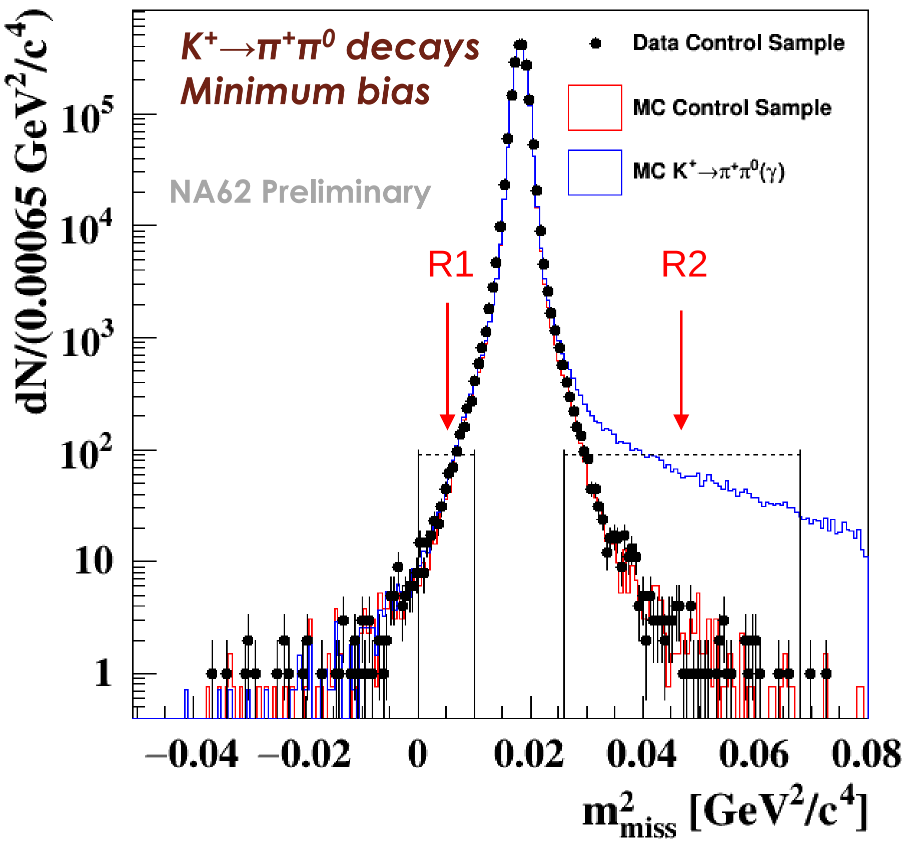
K^+ decay events in the fiducial decay region



- Selection criteria
  - Single track decay topology
  - π^+ identification
  - Photon rejection
  - Multi-track rejection
- Performance
  - $\epsilon_{\mu^+} = 1 \cdot 10^{-8}$ (64% π^+ efficiency)
  - $\epsilon_{\pi^0} = 3 \cdot 10^{-8}$
  - $\sigma(m^2_{miss}) = 1 \cdot 10^{-3} \text{GeV}/c^4$
  - $\sigma_T \sim O(100\ ps)$

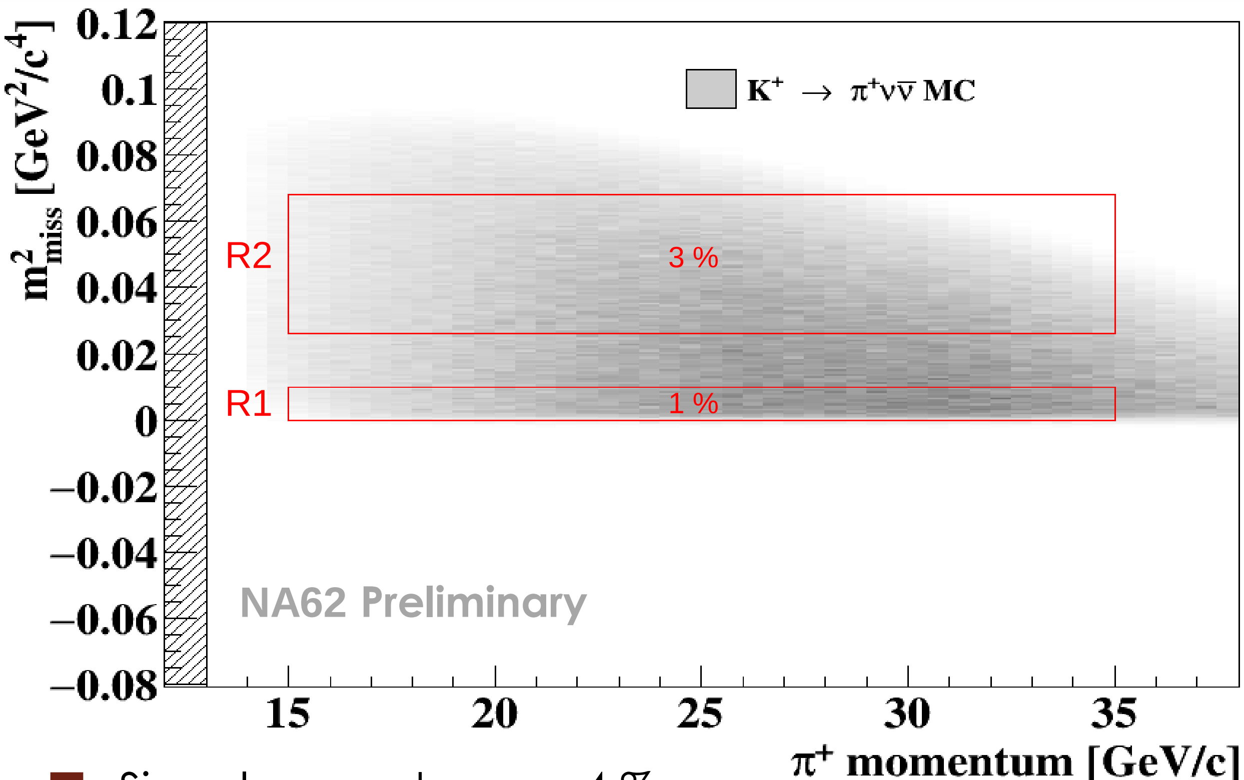
- Selected K^+ decays, before:
  - π^+ identification
  - Photon/multi-track rejection

Signal region definition



- Three ways to compute the m^2_{miss}
  - m^2_{miss}(STRAW, GTK)
  - m^2_{miss} (RICH, GTK)
  - m^2_{miss} (STRAW, Beam)
- Protects against mis-reconstruction
- Kinematic suppression
  - Measured using data
  - Samples of $K_{\pi\pi}$ and $K_{\mu\nu}$
  - Selected using calorimeters
- Fraction of events in signal regions
  - $K^+ \to \pi^+\pi^0 \sim 1 \cdot 10^{-3}$
  - $K^+ \to \mu^+\nu_\mu \sim 3 \cdot 10^{-4}$

Single Event Sensitivity (SES)

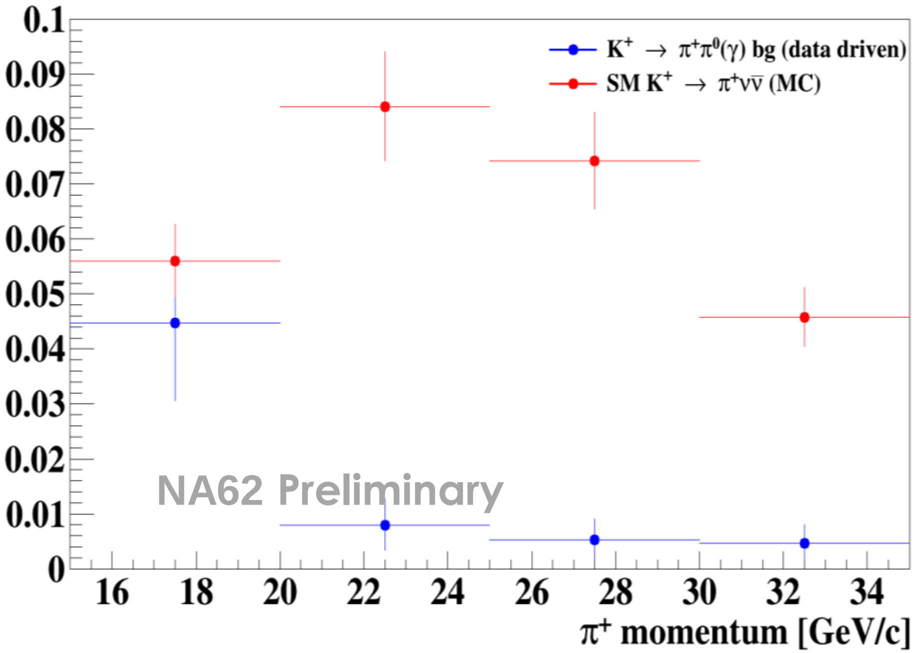


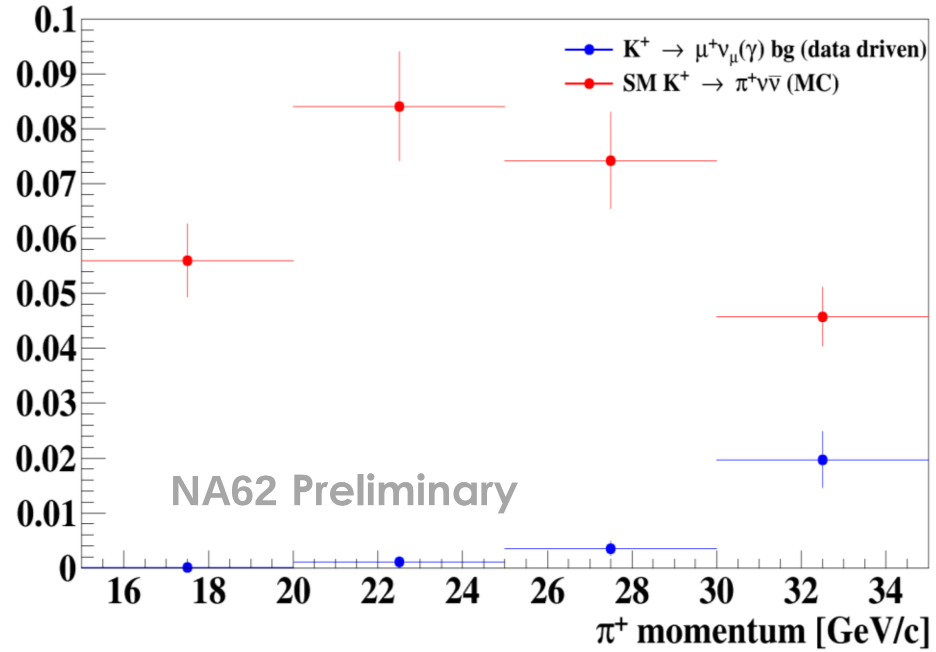
Source	$\delta SES\ [10^{-10}]$
Random Veto	0.09
Number of K	0.05
Trigger efficiency	0.04
Definition of $\pi^+\pi^0$ region	0.10
Momentum spectrum	0.01
Simulation of π^+ interactions	0.03
Extra activity	0.02
GTK pileup simulation	0.02
Total	**0.24**

- Signal acceptance : 4 %
- Normalization acceptance: 10 %
- Control triggered $K^+ \rightarrow \pi^+\pi^0$ used for normalization
- Number of kaon decays in the fiducial volume : $N_K = 1.21(2) \times 10^{11}$

$$SES = (3.15 \pm 0.01_{stat} \pm 0.24_{syst}) \cdot 10^{-10}$$

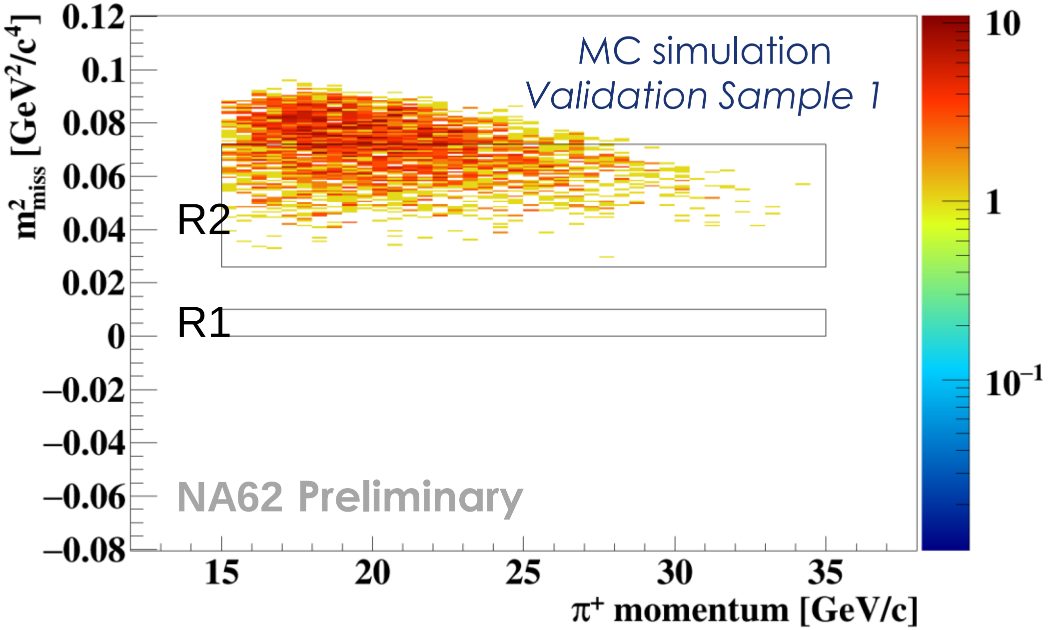
$K^+ \to \pi^+\pi^0(\gamma)$ and $K^+ \to \mu^+\nu_\mu(\gamma)$ background





- Data-driven background estimation
- Validation for k2π: **1 event observed (1.5 expected)**
  - $N^{bg}_{\pi\pi(\gamma)} = 0.064 \pm 0.007_{stat} \pm 0.006_{syst}$
- Validation for kμ2: **2 event observed (1.1 expected)**
  - $N^{bg}_{\mu\nu(\gamma)} = 0.020 \pm 0.003_{stat} \pm 0.003_{syst}$

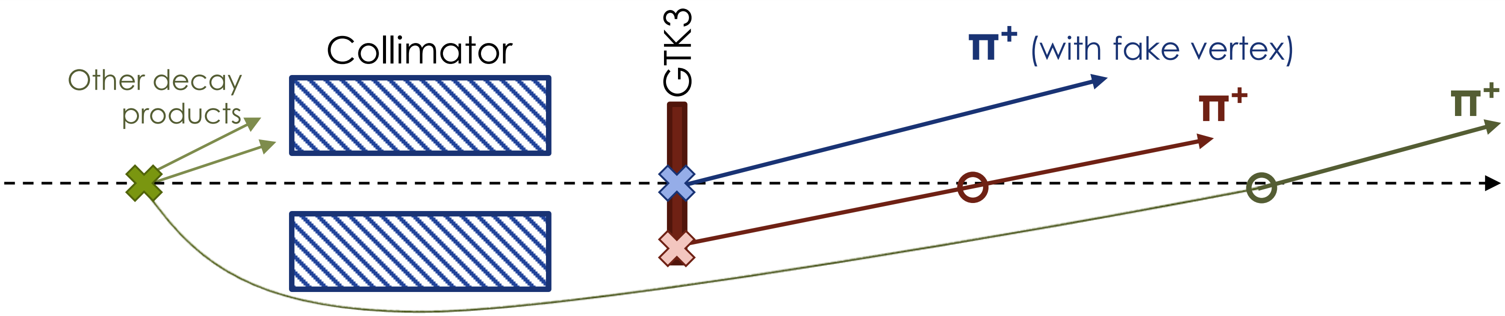
$K^+ \to \pi^+\pi^- e^+\nu_e$ background (K_{e4})



Validation sample	N expected	N observed
1	15.5(4)	8
2	4.0(4)	2
3	3.2(2)	3
4	0.7(1)	1
5	1.2(1)	5

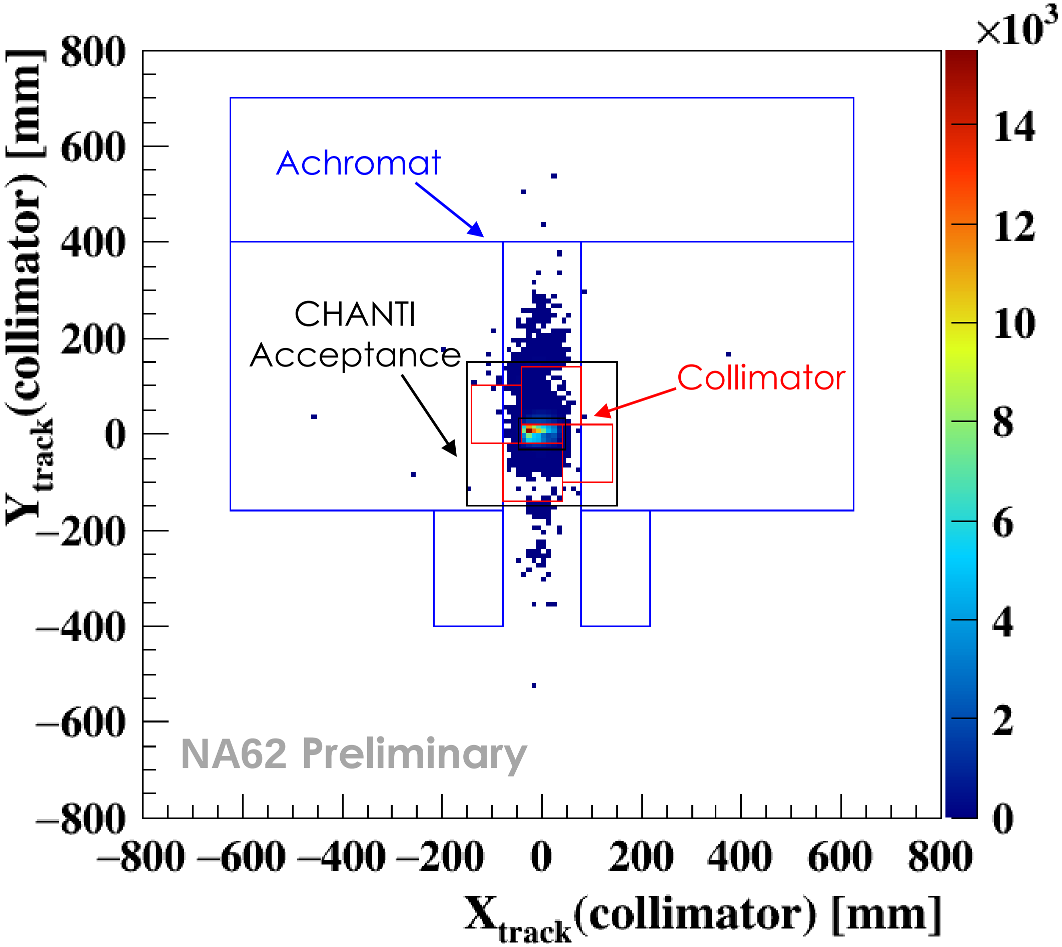
- Background estimated with 400 million MC generated $K^+ \to \pi^+\pi^- e^+\nu_e$ decays
- Good agreement across the 5 validation samples
  - $N^{bg}_{K_{e4}} = 0.018^{+0.024}_{-0.017}|_{stat} \pm 0.009_{syst}$

Upstream background



- Accidental particles from the beam line
- Pions from interactions with GTK material
- Against this background
  - K-π matching
  - Geometrical cuts
  - Z vertex
  - CHANTI
- Data driven estimation:

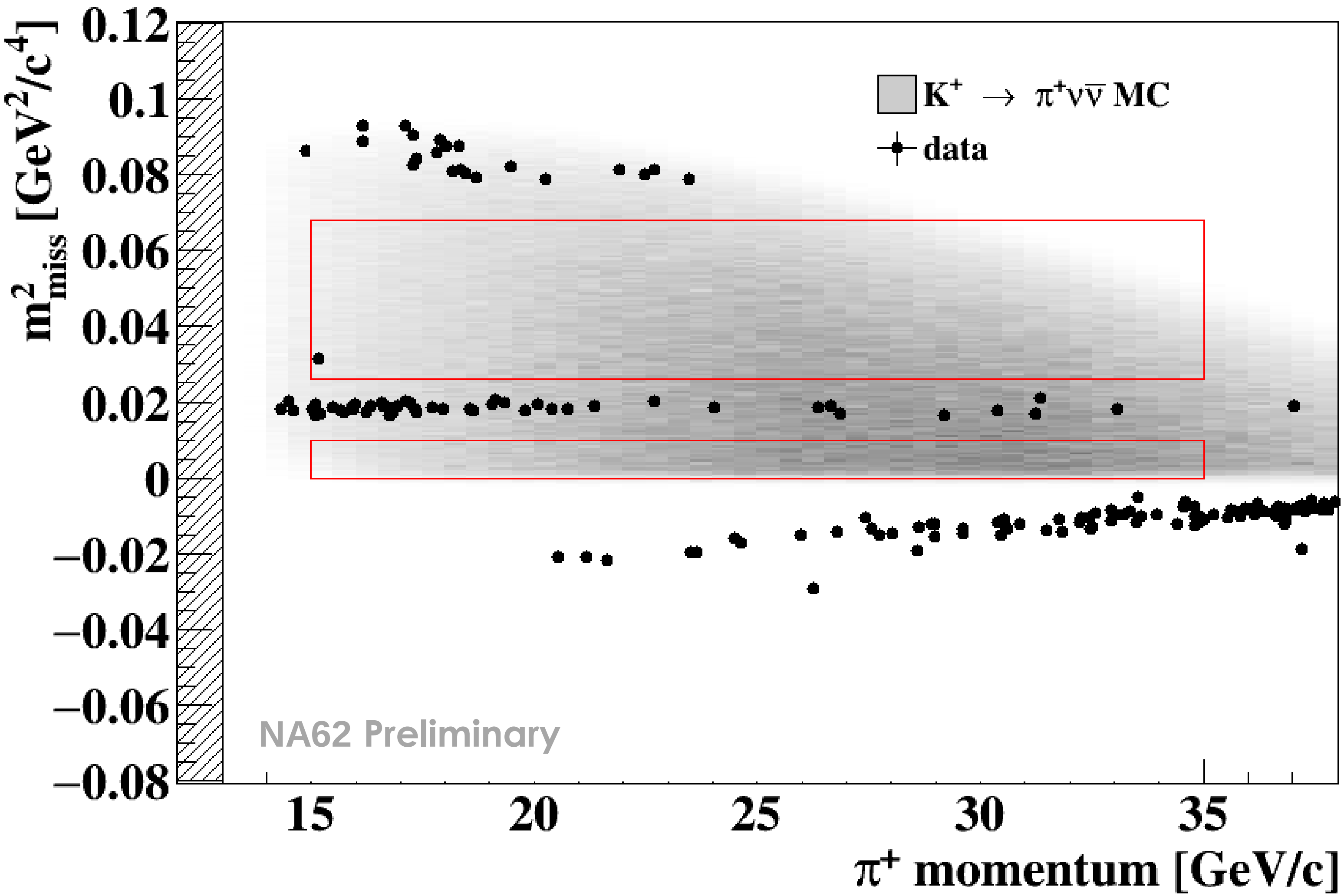
$$N^{bg}_{upstream} = 0.50^{+0.090}_{-0.030}\Big|_{stat}$$



Background summary

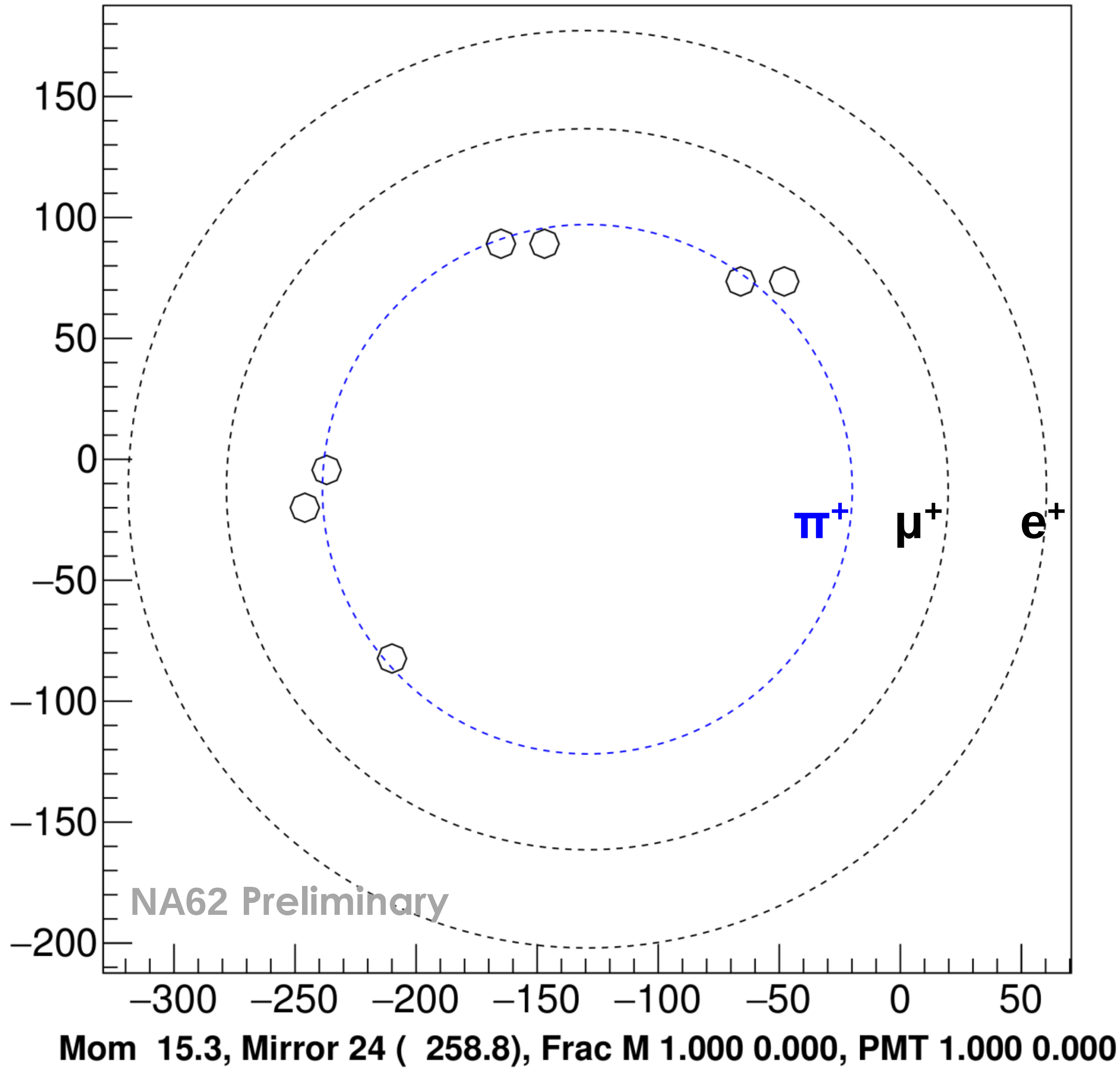
Process	Expected events in Region1 + Region2
$K^+ \to \pi^+ \nu\bar{\nu}$ (SM)	$0.267 \pm 0.001_{stat} \pm 0.029_{syst} \pm 0.032_{ext}$
$K^+ \to \pi^+\pi^0(\gamma)$ IB	$0.064 \pm 0.007_{stat} \pm 0.006_{syst}$
$K^+ \to \mu^+\nu_\mu(\gamma)$ IB	$0.020 \pm 0.003_{stat} \pm 0.003_{syst}$
$K^+ \to \pi^+\pi^-e^+\nu_e$	$0.018^{+0.024}_{-0.017}\vert_{stat} \pm 0.009_{syst}$
$K^+ \to \pi^+\pi^-\pi^+$	$0.002 \pm 0.001_{stat} \pm 0.002_{syst}$
Upstream background	$0.050^{+0.090}_{-0.030}\vert_{\text{stat}}$
Total background	$\mathbf{0.15 \pm 0.09_{stat} \pm 0.01_{syst}}$

Results on 2016 data sample



One event observed

RICH ring for the event



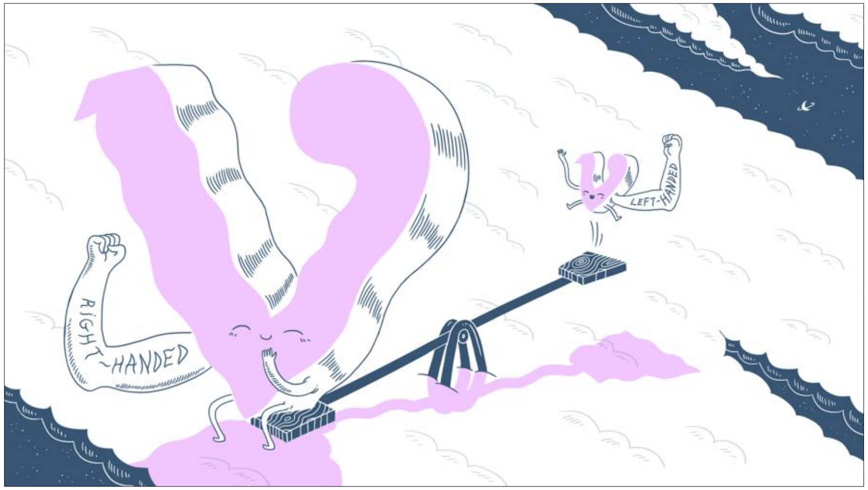
Results and prospects on $K^+ \to \pi^+\nu\bar{\nu}$

- One event observed in Region 2
- Preliminary BR:
  - $\boldsymbol{BR(K^+ \to \pi^+\nu\bar{\nu}) < 11 \times 10^{-10} @ 90\%\ \mathrm{CL}}$
  - $\boldsymbol{BR(K^+ \to \pi^+\nu\bar{\nu}) < 14 \times 10^{-10} @ 95\%\ \mathrm{CL}}$
- These results are compatible with the Standard Model
  - $BR(K^+ \to \pi^+\nu\bar{\nu})_{SM} = (0.84 \pm 0.10) \times 10^{-10}$
- For comparison: $BR(K^+ \to \pi^+\nu\bar{\nu}) = 2.8^{+4.4}_{-2.3} \times 10^{-10} @\ 68\%\ \mathrm{CL}$
- State of the art: $BR(K^+ \to \pi^+\nu\bar{\nu}) = 1.73^{+1.15}_{-1.05} \times 10^{-10}$ (BNL E949/E787)
- Processing of 2017 data is ongoing
  - Expected reduction of upstream background
  - Improvements of the reconstruction efficiency under study
- 2018 data taking in progress
  - 218 days including stops
  - Ongoing studies to improve the signal acceptance
- ~20 SM events expected from 2017+2018 data samples before LS2

Exotics searches at NA62

- With the discovery of the Higgs boson, all the building blocks of the SM have been found
- No evidence for New Physics (NP) at LHC
- However, SM does not explain:
  - Dark Matter, Dark Energy
  - Baryon asymmetry
  - Neutrino masses and oscillations
- New Physics could be in the MeV – GeV range
- Light dark matter with light mediators, weakly coupled to SM (hidden/dark)

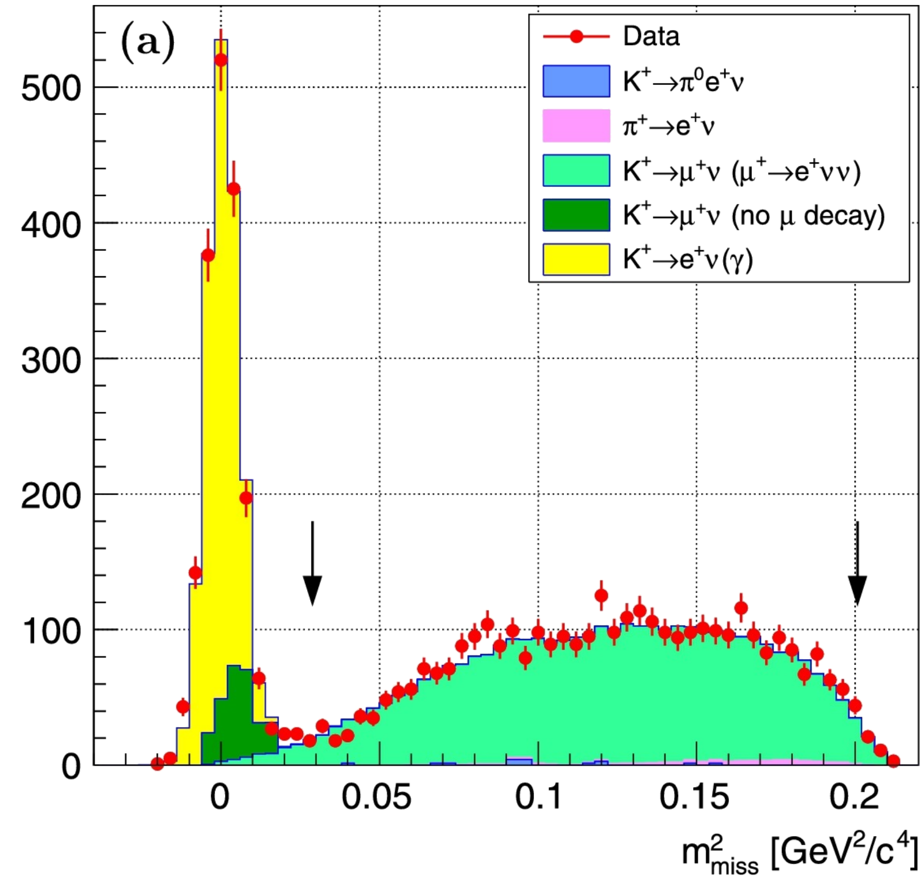
- NA62 is particularly suitable for NP searches:
  - High-intensity beam
  - Trigger system flexibility
  - High-frequency tracking of beam particles
  - Redundant PID
  - Ultra high-efficiency photon vetoes
- New Physics analyses at NA62:
  - Heavy neutral leptons (HNLs)
  - Axion-like particles (ALPs)
  - Invisible vector bosons (dark photons)
  - Lepton number/flavour violation (LNV, LFV)



Heavy neutral leptons at NA62 (1/2)

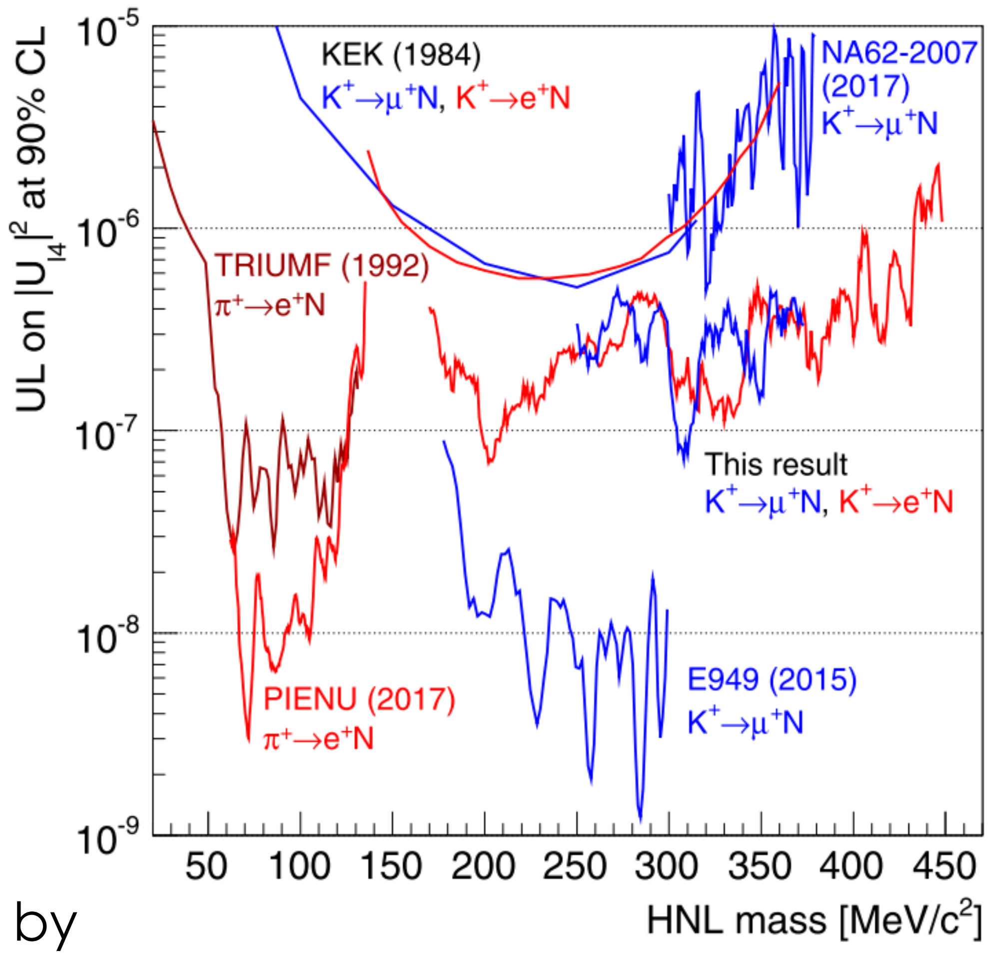
- Neutrino Minimal SM: 3 additional right-handed Majorana HNLs [arXiv:0705.1729v2 (2007)]
  - N_1 mass ~10 keV/c^2, **DM candidate**
  - $N_{2,3}$ mass ~1 GeV/c
- HNL production searches in $K^+ \to l^+N$
  - Published [PLB778, 137-145 (2018)] with 5 days of data taking in 2015 at 1% intensity
  - GTK was not fully operational
- HNL signal regions:
  - **.030**< m^2_{miss}< **.200** GeV²/c⁴: **$K^+ \to e^+N$**
  - **.063**< m^2_{miss}< **.140** GeV²/c⁴: **$K^+ \to \mu^+N$**
- BR($K^+ \to l^+N$) depends on:
  - $BR_{SM}(K^+ \to l^+\nu)$, HNL-lepton coupling U^2_l, kinematic factor
- Peak searches in squared missing mass spectrum: $\mathbf{m^2_{miss} = (P_K - P_l)^2}$

$K^+ \to e^+N$



Heavy neutral leptons at NA62 (2/2)

- For each HNL mass hypothesis, no signal observed
- Results improve existing limits on HNL production searches
- New upper limits:
  - m_N in (170, 448) MeV/c^2:
  - $|U^2_e|$ in (10^{-7}, 10^{-6})
  - m_N in (250, 373) MeV/c^2:
  - $|U^2_\mu|$ in (10^{-7}, 10^{-6})



[Phys. Lett. B 778, 137-145 (2018)]

- Opportunity to further improve by analysing 2016-2018 data sample
  - Can reach a sensitivity better than 10^{-8} for both channels

Search for dark photons at NA62 (1/2)

- Peak searches in squared missing mass spectrum: $m^2_{miss} = (P_K - P_\pi - P_\gamma)^2$
- Peak expected at $m^2_{A'}$
- Main background from $\pi^0 \to \gamma\gamma$ with lost photon
- Data-driven background estimation
- No signal observed in 2016 partial data sample (ongoing analysis)
  - New upper limits at 90% CL

Searches for DP invisible decay:

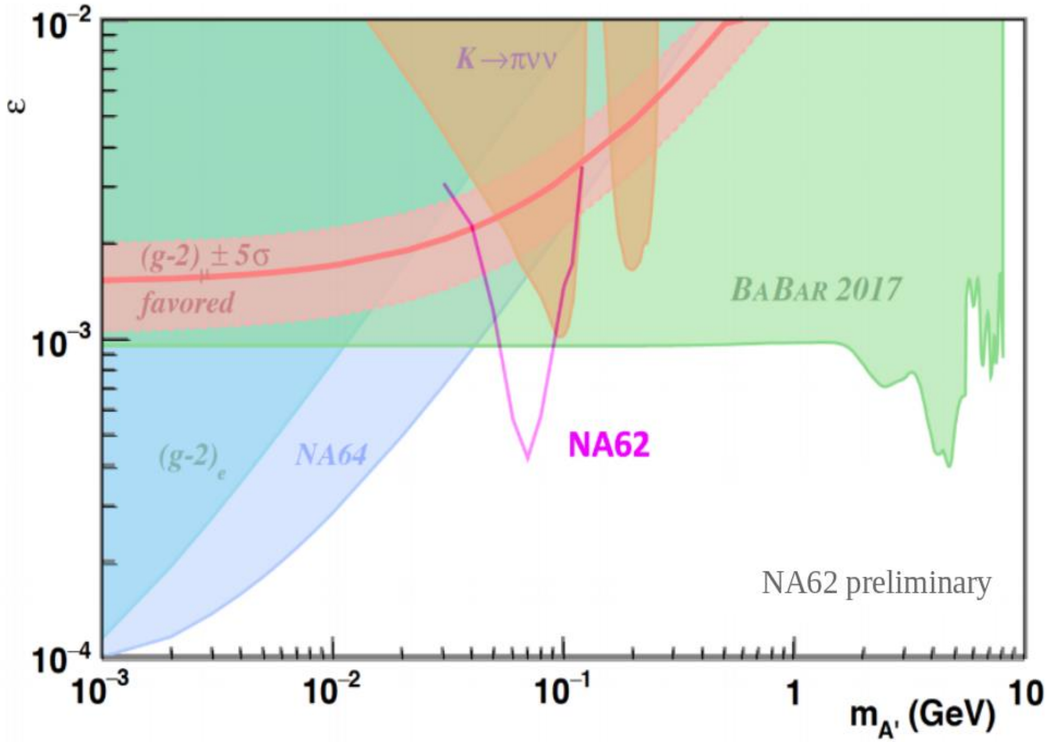
$K^+ \to \pi^+\pi^0$

$\pi^0 \to A'\gamma$

$A' \to$ invisible

$K^+ \to \pi^+ A'$

$A' \to$ invisible



Search for dark photons at NA62 (2/2)

- DP produced in proton beam interactions with target (Bremsstrahlung and meson decays)
- Zero-background hypothesis and 10^{18} Protons On Target (POT) expected to evaluate NA62 sensitivity to DP visible decays
- Expected better sensitivity including TAX and QCD productions (only target production considered for now)
- $3 \cdot 10^{17}$ POT collected in 2016/2017 with di-muon trigger and $5 \cdot 10^{16}$ POT with di-electron trigger

Searches for DP visible decay:

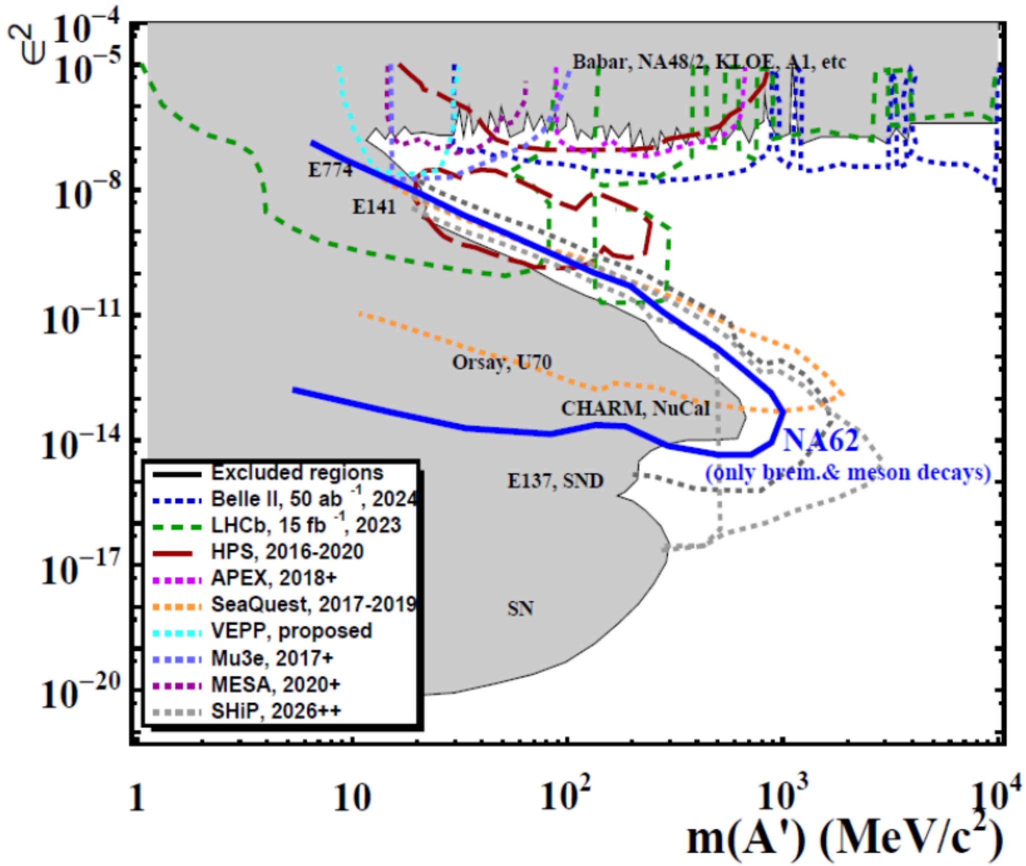
$pN \to X\pi^0$

$\pi^0 \to A'\gamma$

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

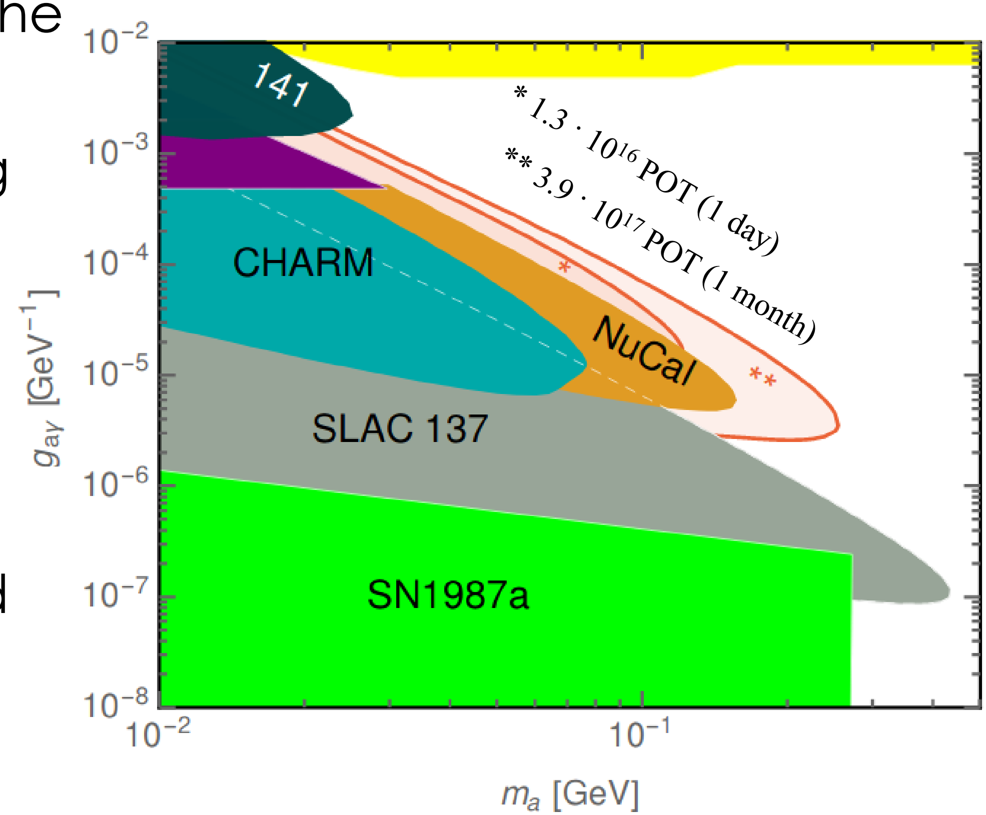
$pN \to XA'$

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



Axion-like particle searches at NA62

- Candidate for cold dark matter
- Decay searches for A → γγ in the MeV-GeV mass range
- Produced via elastic scattering of beam proton with high-Z material (Primakoff effect)
- Proton beam dumped onto NA62 Cu collimators (TAXes)
- ALP produced with low transverse momentum → good acceptance coverage for detector far from production point



- Ongoing analysis of 2017 data taken in beam-dump mode (closed TAXes) with $5 \cdot 10^{15}$ POT
- Zero-background hypothesis to evaluate NA62 sensitivity to A → γγ

Conclusions

- **$K^+ \to \pi^+ \nu\bar{\nu}$**
  - The new decay-in-flight technique to study $K^+ \to \pi^+ \nu\bar{\nu}$ works
  - One event observed in 2016 data sample
  - $BR(K^+ \to \pi^+ \nu\bar{\nu}) < 14 \times 10^{-10} @ 95\% \, CL$
  - ~20 events expected from 2017+2018 data sample

- **Searches for exotic particles**
  - 2018 data taking ongoing
  - Heavy neutral leptons
    - new limits in ($|U_e|^2$, m_{HNL}) and ($|U_\mu|^2$, m_{HNL})
    - 2016-2018 data analysis ongoing
  - Dark photon
    - New limits in (ε, $m_{A'}$) using 4% of 2016 sample
    - Waiting for new results with 2016-2018 data samples
    - Fully operational GTK: ~3 times better m_{miss} resolution
  - Axion-like particles: analysis ongoing


Thank you for your attention