The NA62 experiment at CERN

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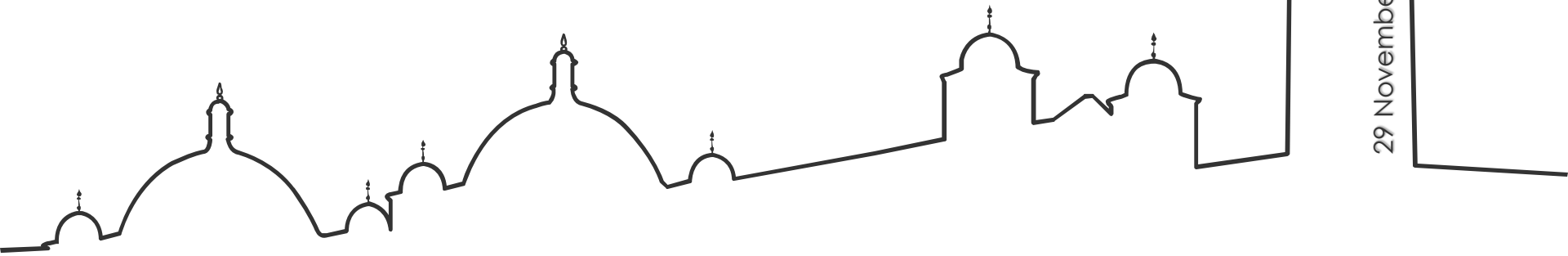
on behalf of the NA62 collaboration

DISCRETE2016 - *Warsaw, Poland*

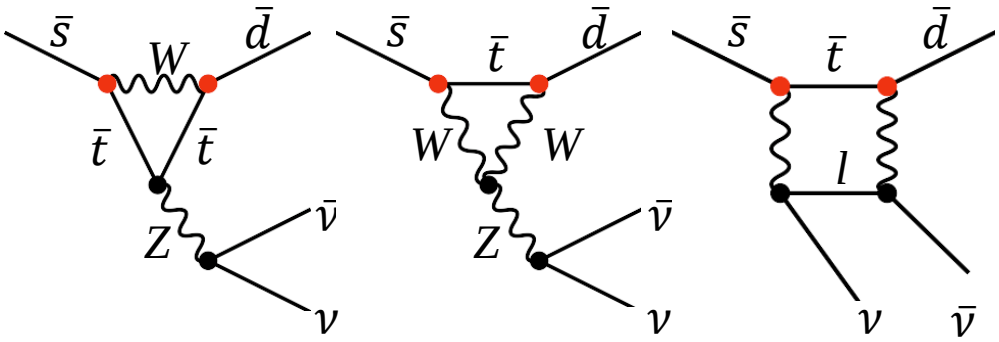


29 November 2016

Ultra-rare kaon decays

$K \to \pi\nu\nu$: 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		
$K^+ \to \pi^+\nu\bar{\nu}$	8.4	±1.0	[1]	17.3	+11.5 -10.5	[2]
$K_L \to \pi^0\nu\bar{\nu}$	3.4	±0.6	[1]	<2600 (90%CL)		[3]

NA62 goal is to measure BR($K^+ \to \pi^+\nu\bar{\nu}$) to 10% precision

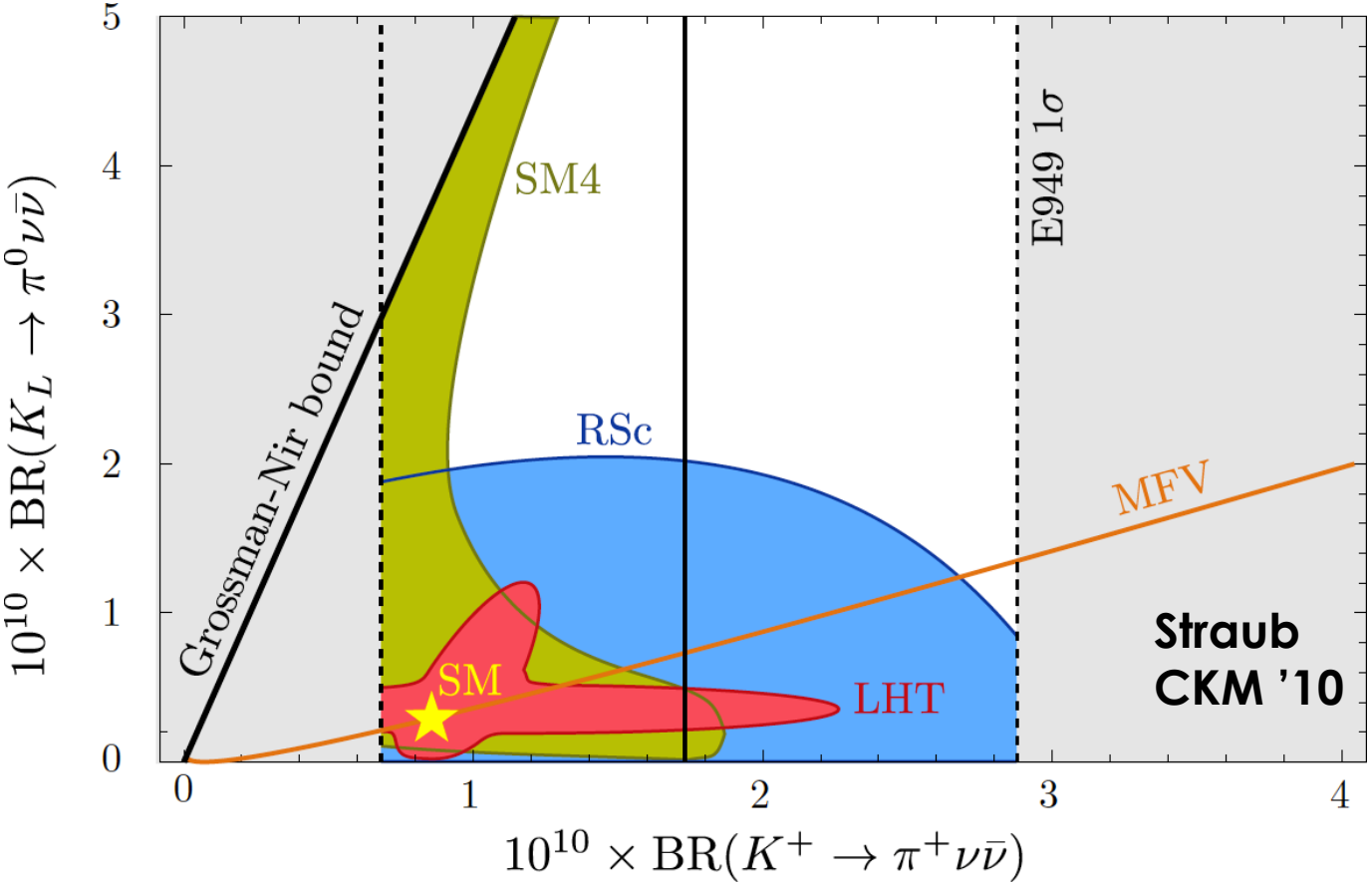
[1] **Buras, A.J., Buttazzo, D., Girrbach-Noe, J. et al.** J. High Energ. Phys. 2015: 33 (2015)

[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)

$K \to \pi\nu\nu$ and new physics

New physics affects BRs differently for different channels:
Multiple measurements can discriminate among NP scenarios



SM4: SM with 4th generation (Buras et al. '10) **LHT:** Littlest Higgs with T parity (Blanke '10)
RSc: Custodial Randall-Sundrum (Blanke '09) **MFV:** Minimal flavor violation (Hurth et al. '09)

$K \to \pi\nu\nu$: signal and background

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

Signature:

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

NA62 goal: Measure BR to 10% ⇨ **~100 signal events, Background < 20**

10^{13} K decays with:

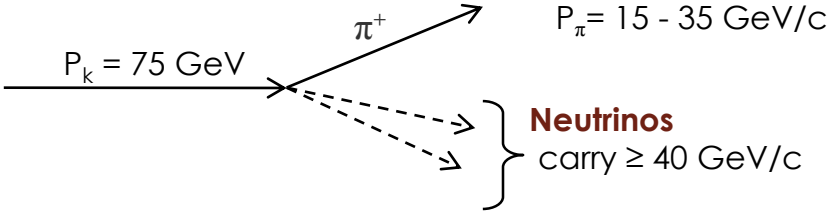
- Acceptance ~10%
- Background rejection ~10^{12}
- Background known to ~10%

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	

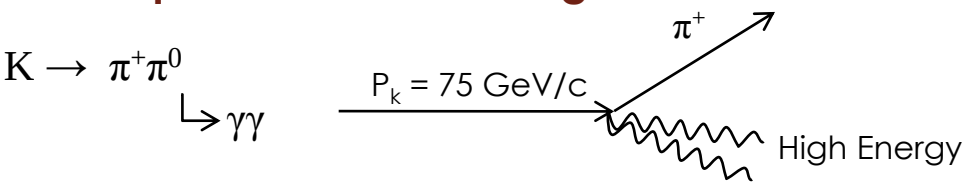
Analysis principles: in-flight decay

- Large missing momentum

Kinematic Signature



Consequence for the background

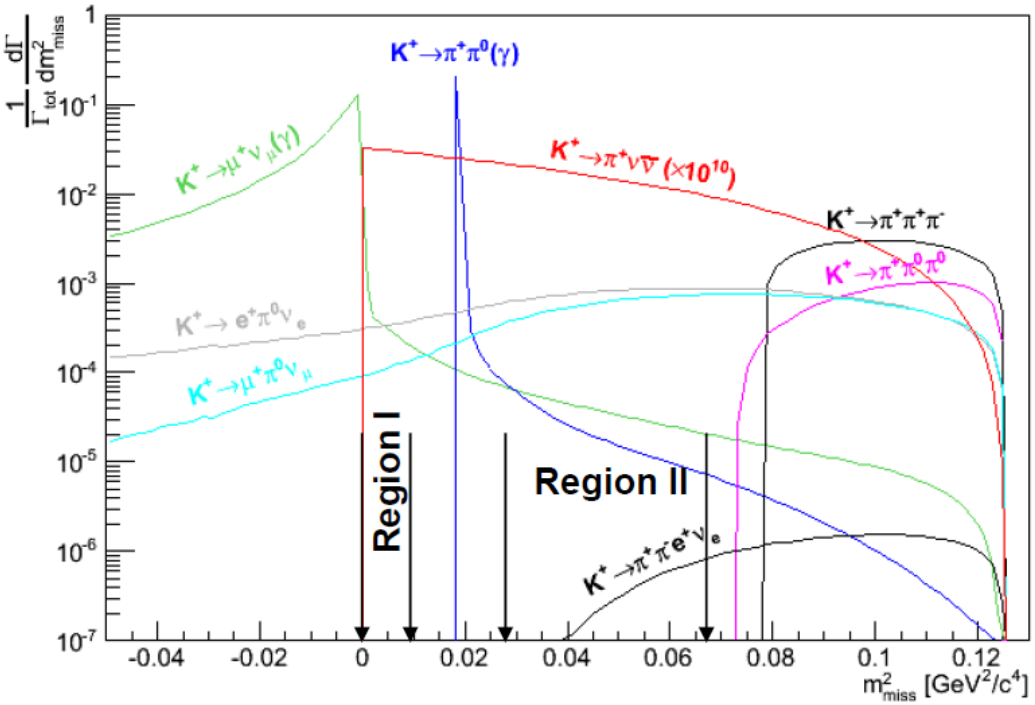


- Cuts on the missing mass

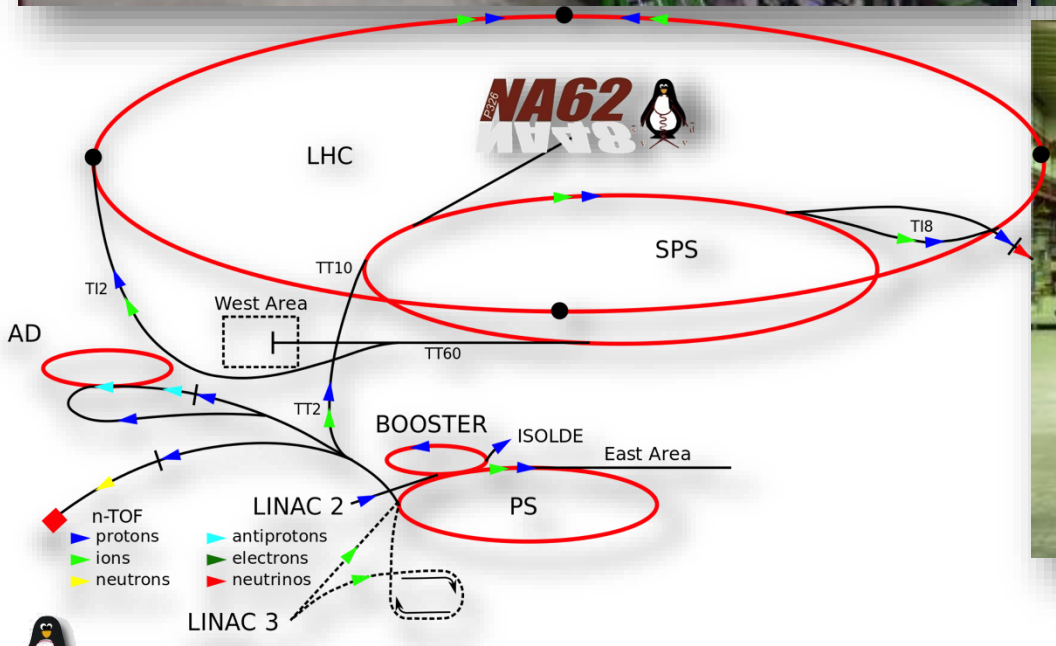
$$m^2_{miss} = (p_K - p_\pi)^2$$

defines 2 regions

- Kinematical rejection is ~10^5
- Further rejection relies on PID and vetoes

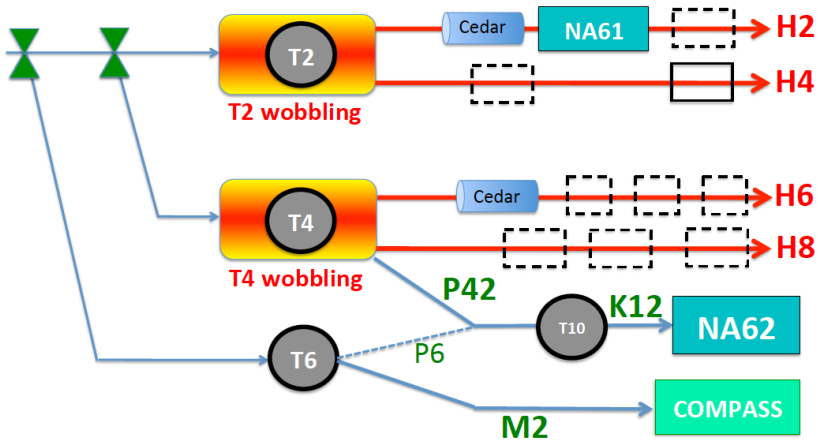


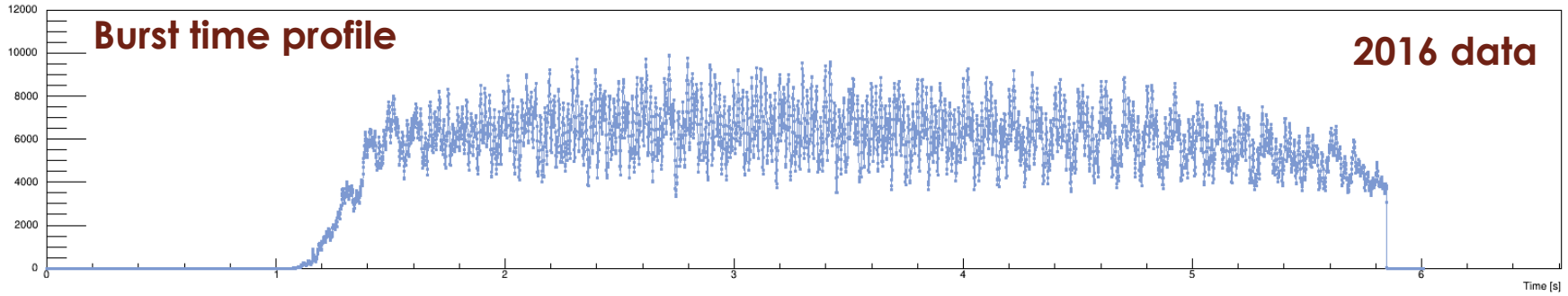
The NA62 experiment



NA62 beam

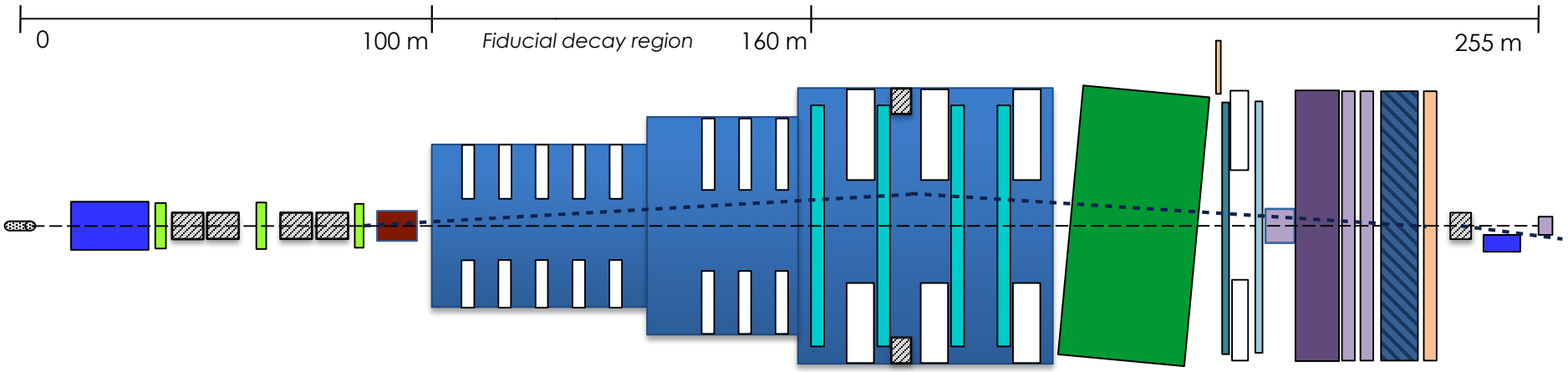
Beam Parameters	
400 GeV/c Protons on Target/s	10^{12}
75 GeV/c Hadrons/s	750 x 10^6
Beam composition	p 70% π 24% K 6%
K^+ rate (particle/s)	45 x 10^6
K^+ decays/s	4.5 x 10^6
K^+ decays/year	4.5 x 10^{12}





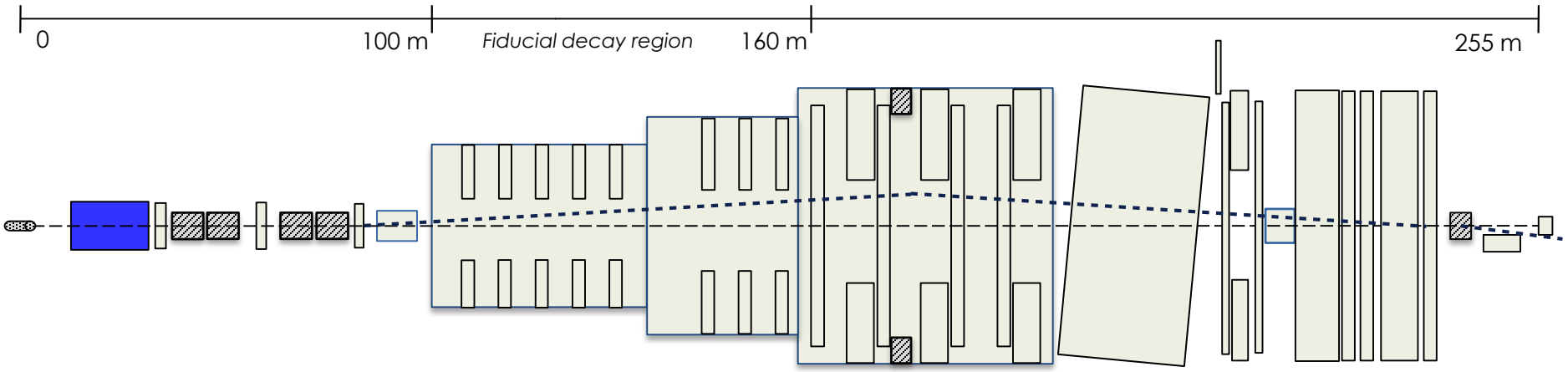
- NA62 uses SPS 400 GeV/c proton beam
- Proton beam interacts with a Beryllium target
- Among the interaction products, 75 GeV/c K^+ are selected
- Nonetheless kaons, are a minimal part of the beam (45 MHz / 750 MHz)

NA62 experimental principles



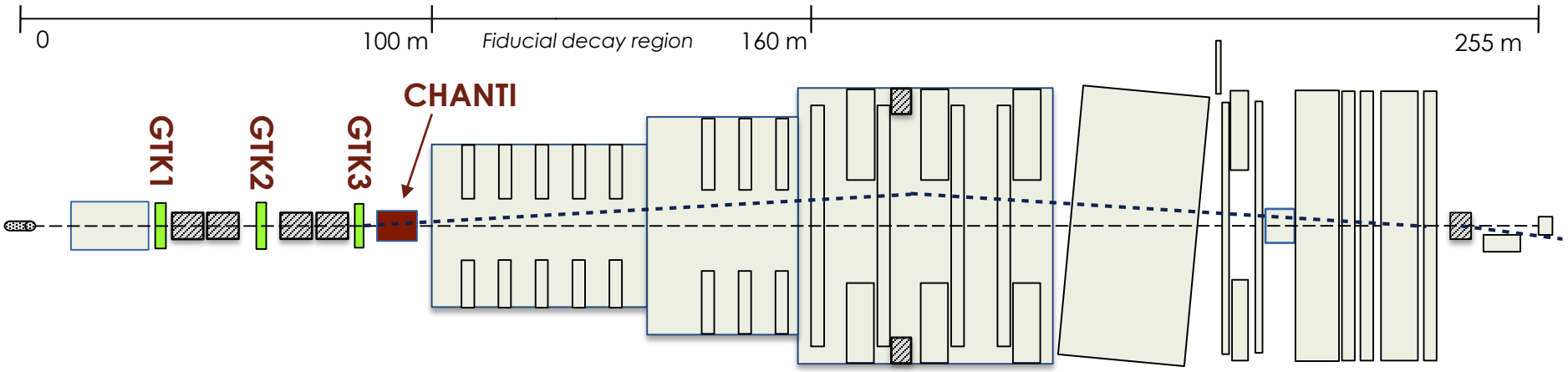
- High resolution missing mass reconstruction
  - Precise measurement of p_K and p_π
- Minimize multiple scattering
- Hermetic veto for π^0 rejection
- Upstream K^+ identification in hadron beam
- Downstream $\pi/\mu/e$ separation
- μ veto for $K_{\mu 2}$ rejection
- Sub ns time resolution

Incoming kaon ID: KTAG

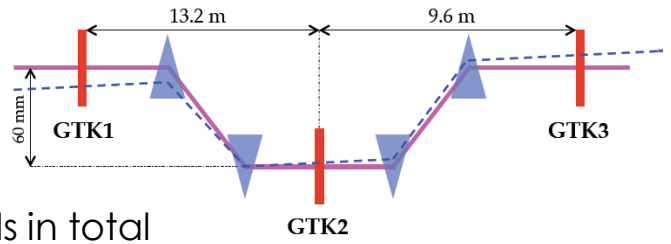


- The KTAG is an upgraded CERN CEDAR West
  - Blind to particles other than kaon thanks to a diaphragm
  - Extended external optics to reduce rate per single channel
    - High kaon rate (~45MHz)
  - New photo-detectors + readout
  - Very good timing ~300 ps to match with downstream decay

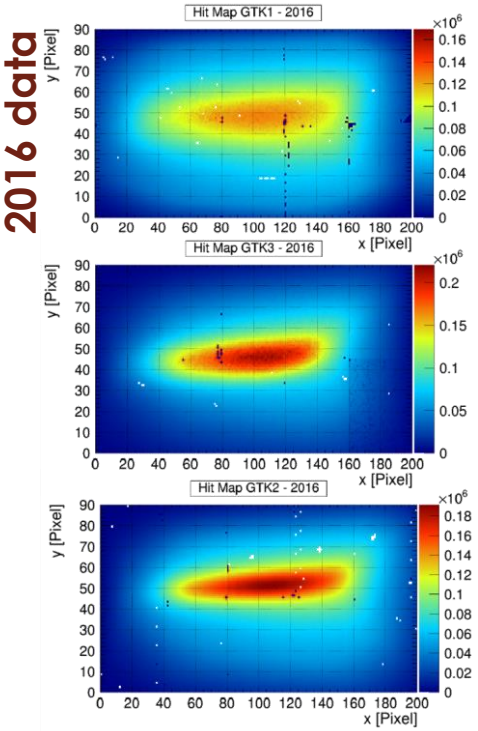
Incoming particle momentum: GTK



- 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
- Active area ≈ 60 (X) * 27 (Y) mm2 divided into 10 read-out chips



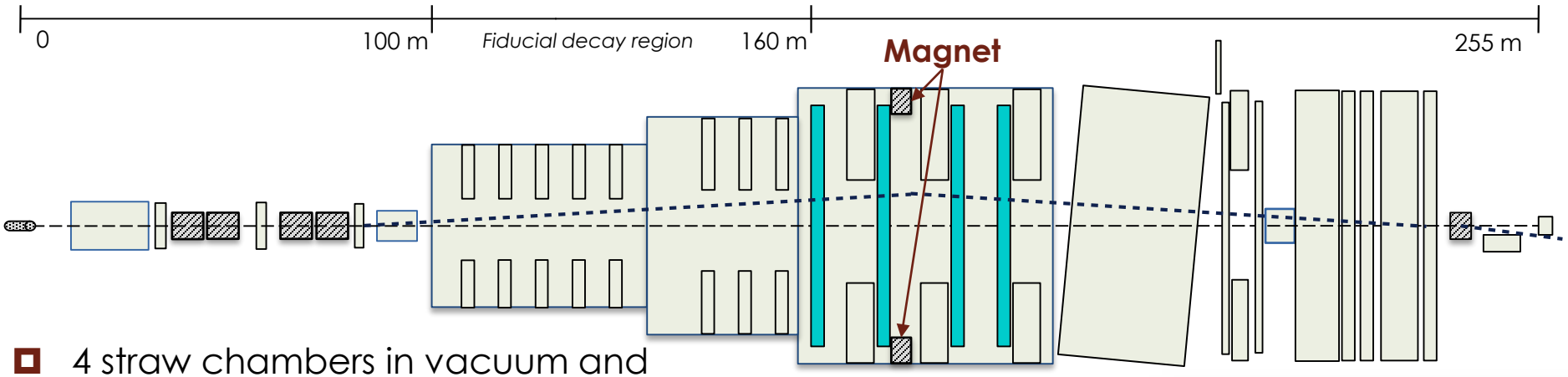
- Pixel size:
  - 300 x 300 μm^2 or 300 x 400 μm^2
  - 18'000 pixels/ station, 54'000 pixels in total



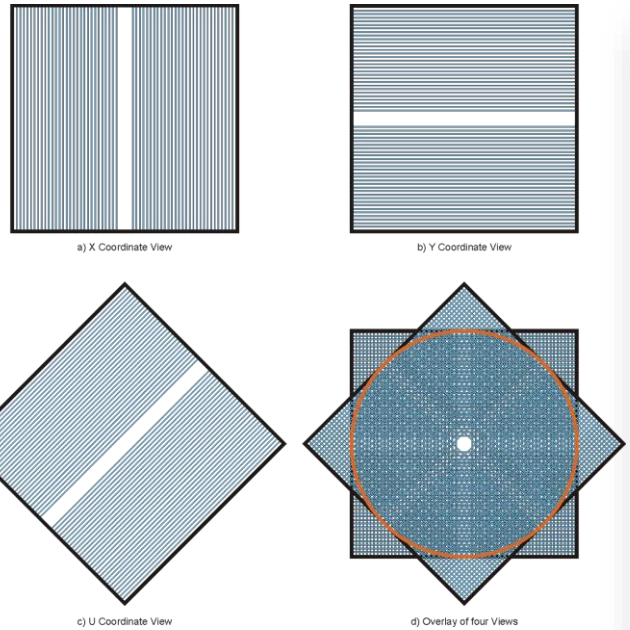
- Time : σ ≈ 200ps per station
- Direction: $\sigma_{dx,dy}$ ≈ 0.016mrad, Momentum: ΔP/P < 0.4%

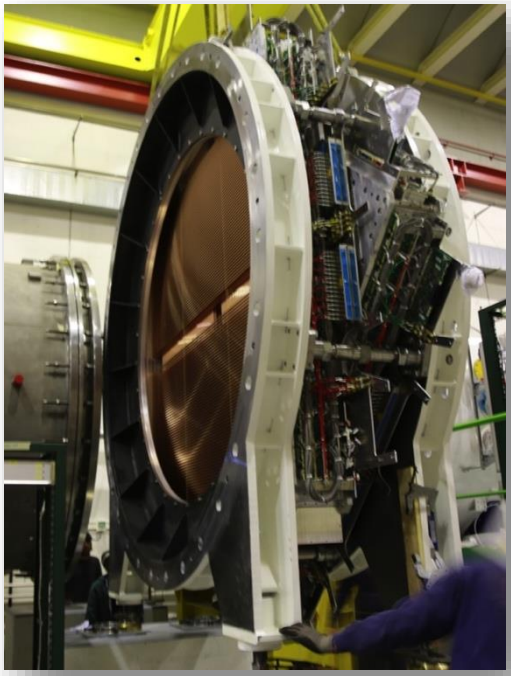
- CHANTI is placed just after GTK3 to veto inelastic scattering

Final-state momentum: the straw spectrometer

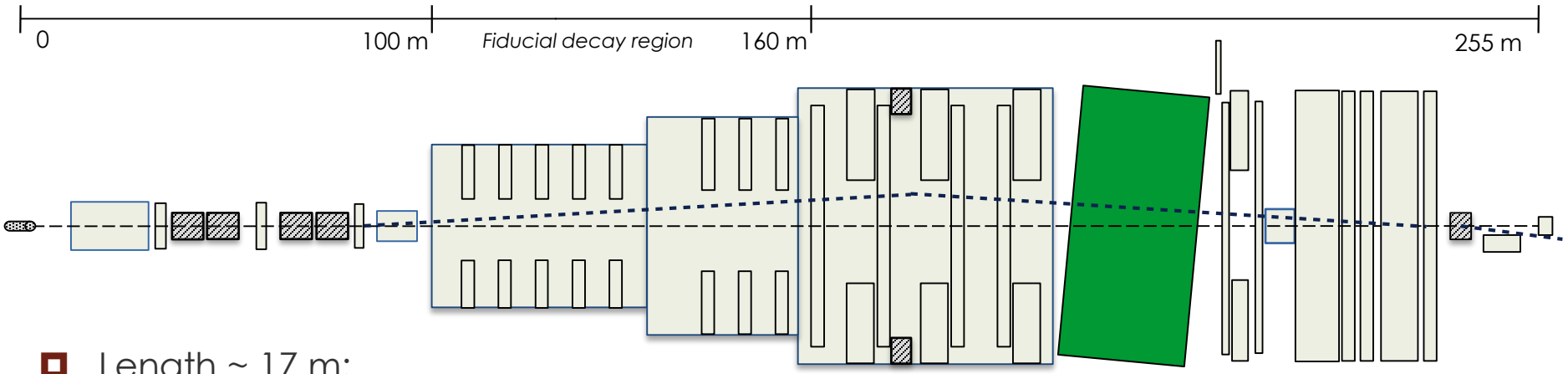


- 4 straw chambers in vacuum and a dipole magnet
- Each chamber measuring 4 coordinates (views)
- High accuracy: 130 μm/view
- Straw tube dimensions:
  - 2.1 m long and d = 9.8 mm;
  - Thickness: 50 nm Cu + 20 nm Au on 36 μm of Mylar
- Total 7168 Straws (4x4x4x112)

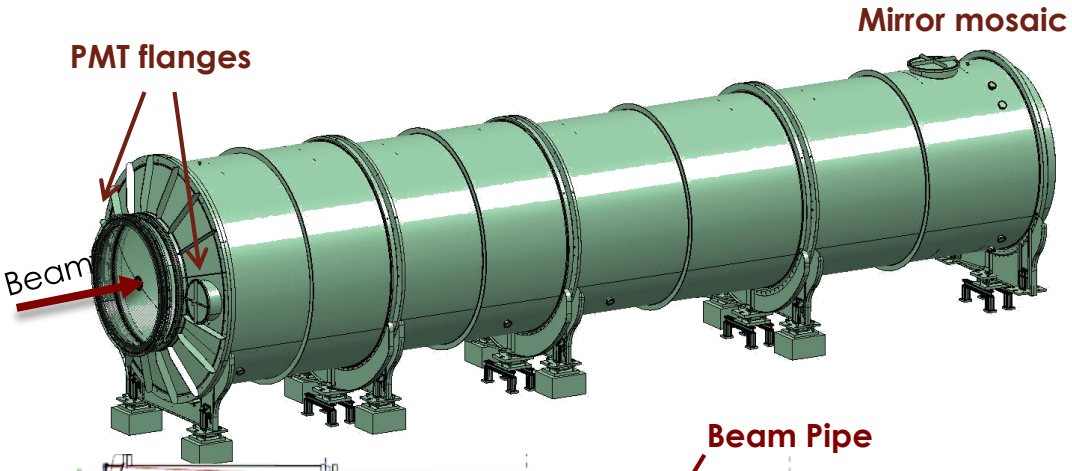




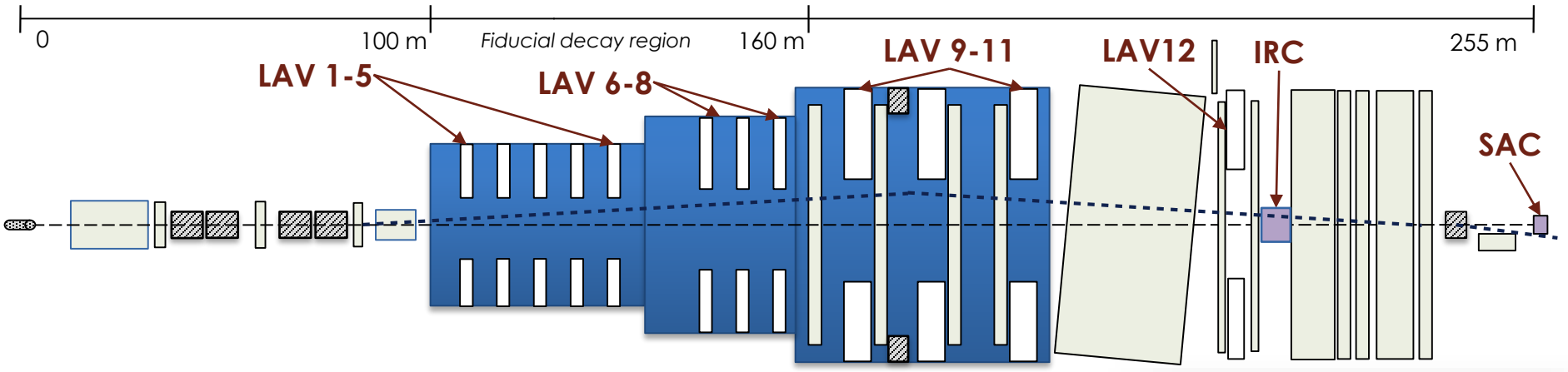
Final state particle ID: the RICH



- Length ~ 17 m;
- Ø = 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



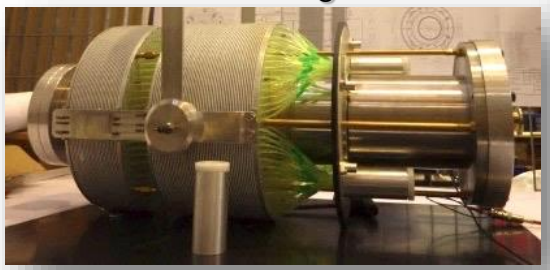
Photon vetos: LAVs and SAVs



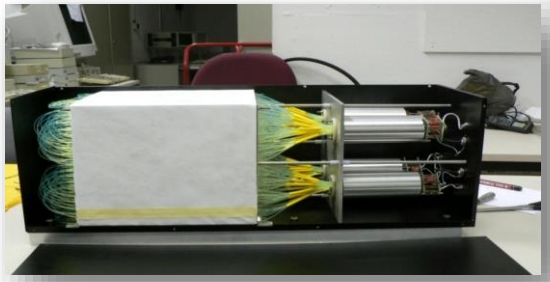
LAV: 8.5 – 50 mrad

- 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

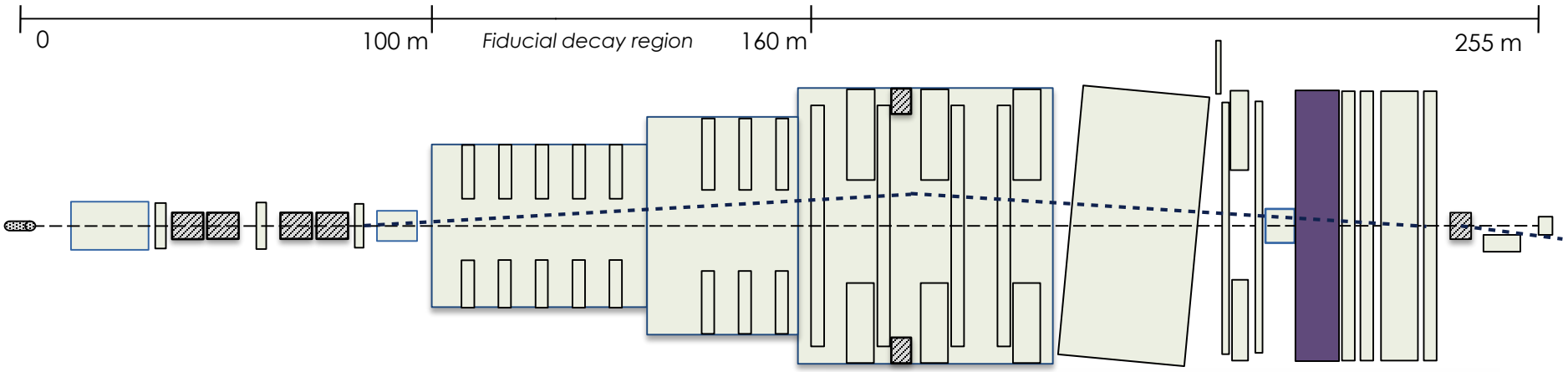
IRC Intermediate Ring Calorimeter



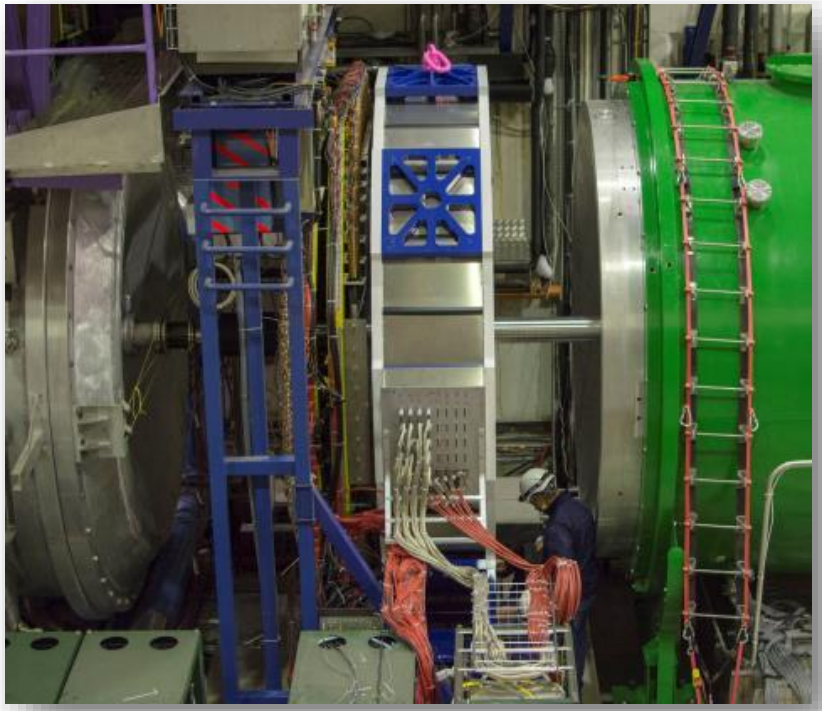
SAC Small Angle Calorimeter



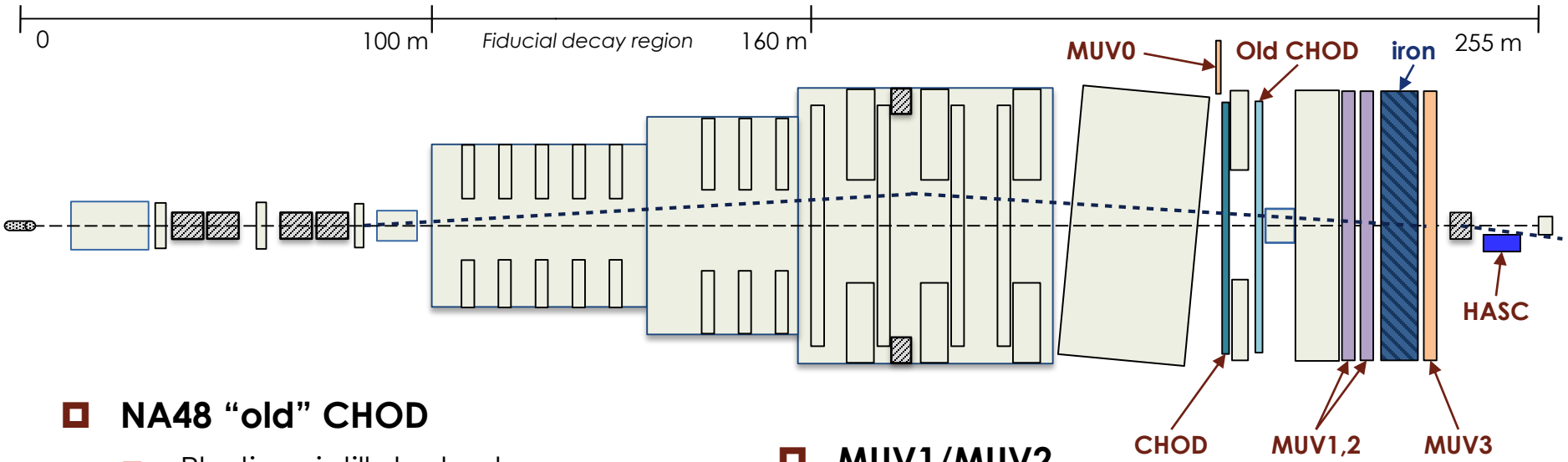
Liquid Krypton Calorimeter



- **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

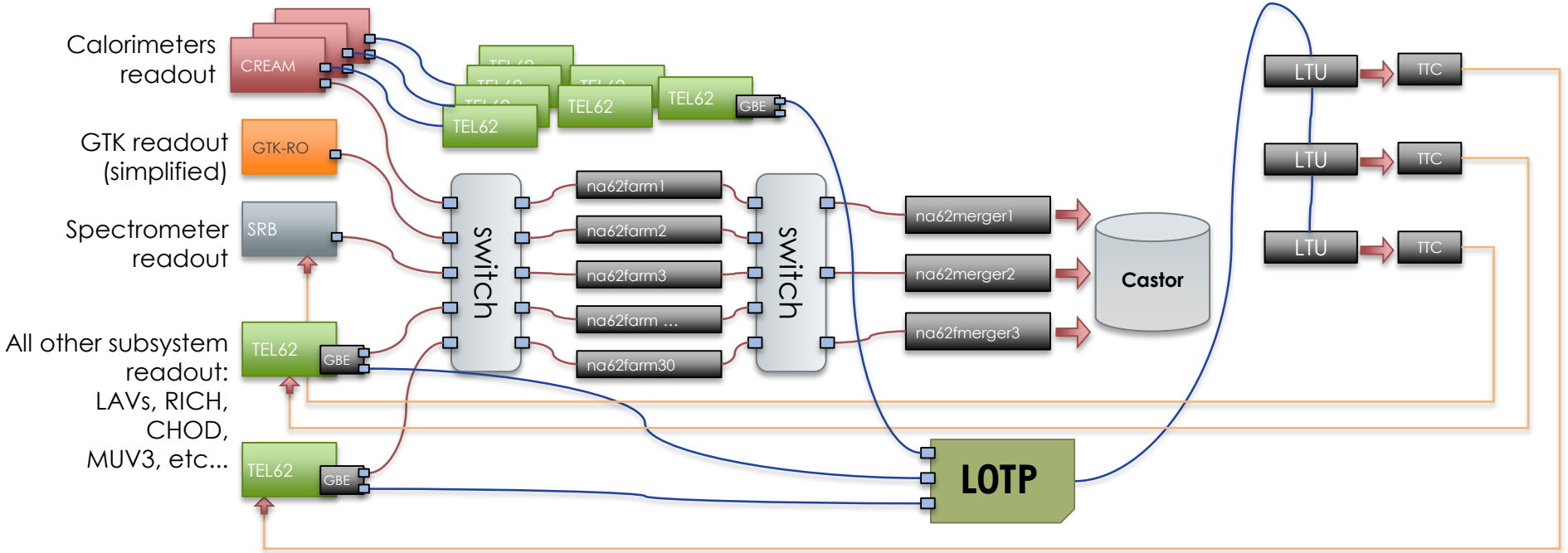


Chod muon Veto system



- **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 L0 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 L0 trigger: reduction factor >10
  - Rate: 10 MHz muon

Trigger and data acquisition



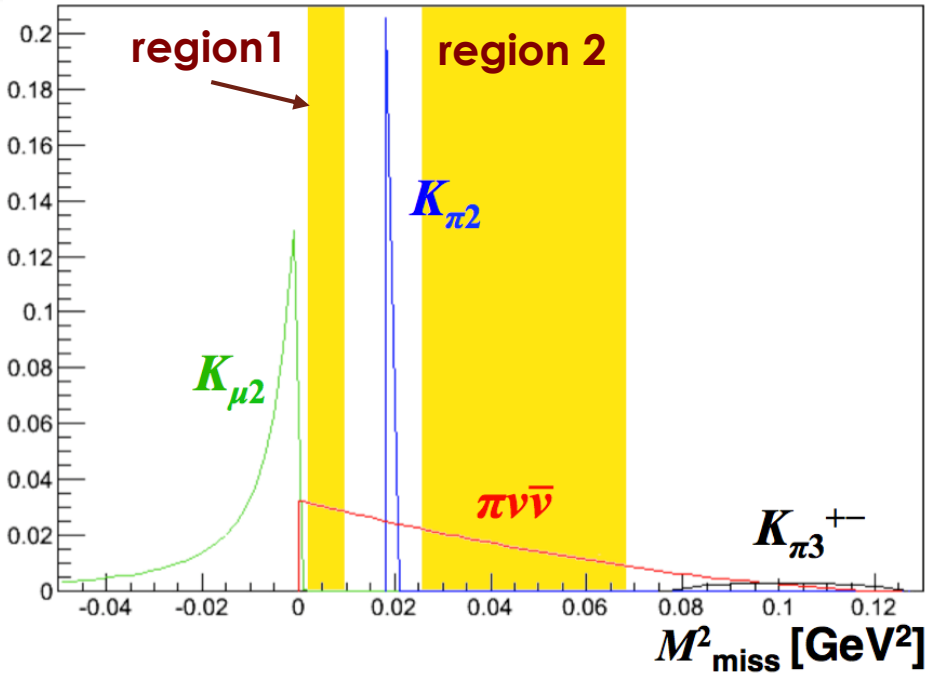
- Acquisition boards store data in local buffers
- Some detectors send primitives to L0TP
- L0 trigger is generated with a maximum latency of 1 ms
- All detectors except Calorimeters and GTK respond to L0
  - They send data to PC-Farm
- GTK and Calorimeters send data after L1 request
- L2 trigger algorithm is run over the complet event information

Trigger	Rate
Primitives	10 MHz
L0 (FPGA)	1MHz
L1 (software)	100KHz
L2 (software)	10KHz

Present status

- Beam line, detectors, trigger and DAQ fully commissioned
- NA62 data taking periods:
  - 2014: detector commissioning
  - 2015: trigger commissioning, detector quality studies, beam line commissioning up to nominal intensity
  - 2016: high level trigger (L1) commissioning,
    full beam tracker commissioning, physics data taking
- Data samples for analysis:
  - 2015:
    - Low intensity data with minimum bias trigger for detector quality studies (this talk)
  - 2016:
    - $K \to \pi\nu\nu$ data (up to 40% of nominal intensity)
    - non $K \to \pi\nu\nu$ – data (up to 40% of nominal intensity)

Expected performance



- 1 track with 15 < p < 35 GeV
  - π PID in RICH
- No γs in LAV, LKr, IRC, SAC
- No μs in MUVs
- 1 beam particle in Gigatracker
  - K PID by KTAG
- z_{vtx} in 60 m fiducial volume

Signal acceptance: ~10%

Rejection factors:

- Kinematics 10^4-10^5
- Charged Particle ID 10^7
- Photon detection 10^8
- Timing 10^2

45 SM signal events/yr

Decay	Ev/year
$K^+ \to \pi^+\pi^0$	5
$K^+ \to \pi^+\pi^0\gamma_{IB}$	1.5
$K^+ \to \mu^+\nu$	1
$K^+ \to \mu^+\nu\gamma_{IB}$	<1
$K^+ \to \pi^+\pi^+\pi^-$	< 1
K^+_{e4}, other 3 track decays	< 1
K^+_{e3}, $K^+_{\mu 3}$	< 1
Total	**< 10**

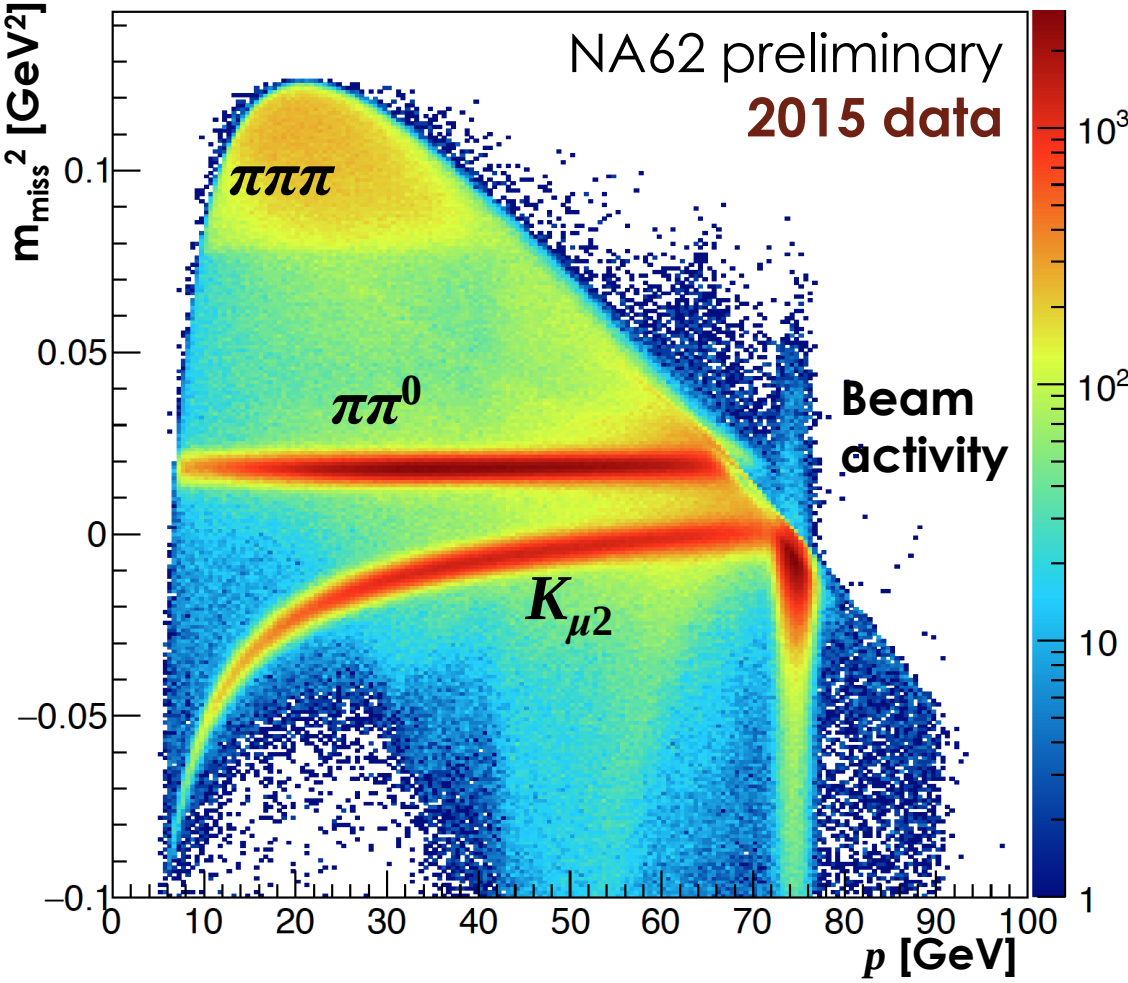
Reconstruction & signal selection

2015 Minimum-bias data at 1% beam intensity

1-track selection:

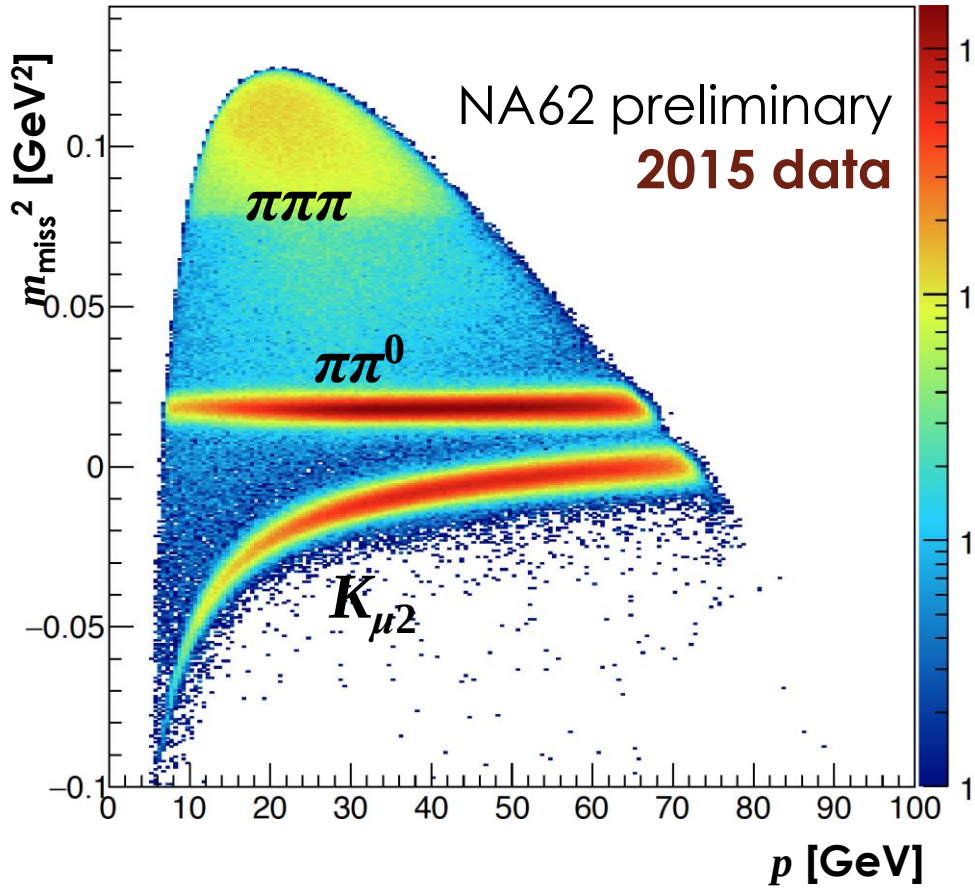
- 1 positive track
- Acceptance/quality cuts
- Track origin in fiducial region
- Matched to hit on CHOD
  - (σ_t ~ 200 ps)
- Matched to KTAG beam ID
  - (σ_t ~ 100 ps)
- Forming vertex with beam track from GTK
- Further associated to hits on LKr, RICH, muon vetoes

$m_{miss}(m_{track} = m_{\pi+})$ vs p_{track}

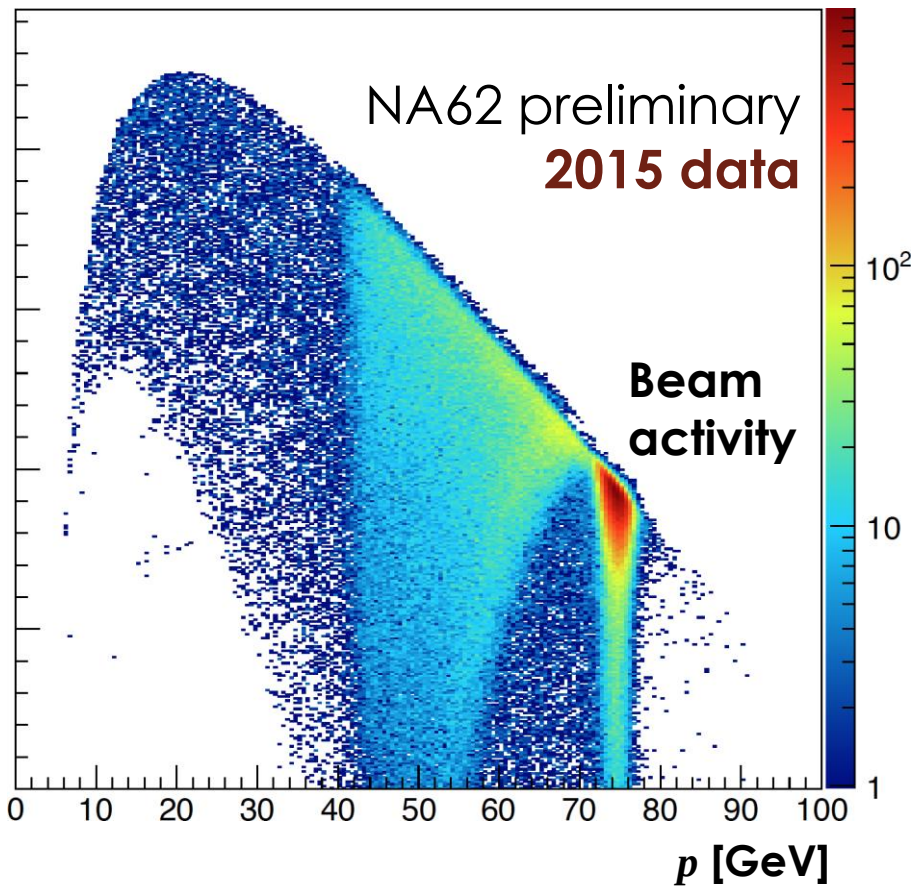


Signal selection and kaon ID

1-track selection require K^+ ID in KTAG

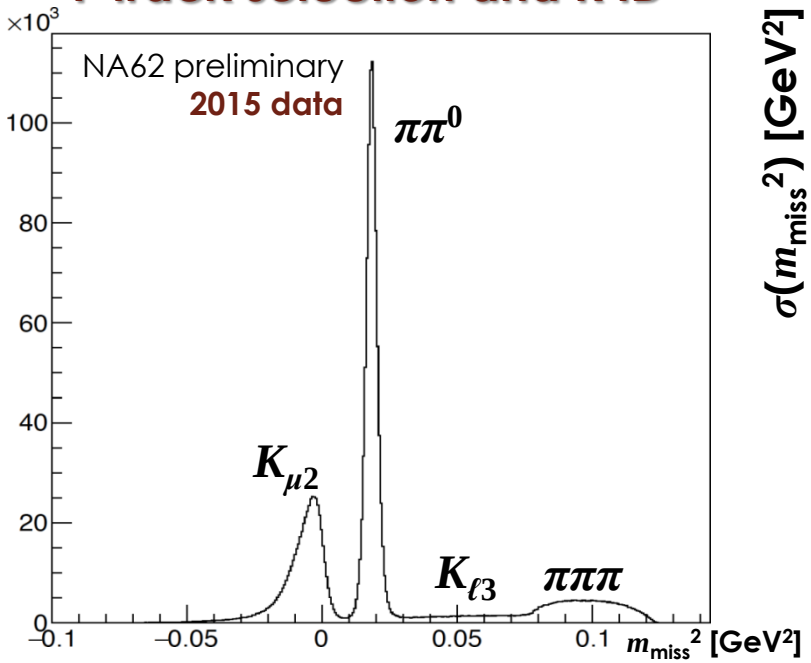


1-track selection veto on K^+ ID in KTAG

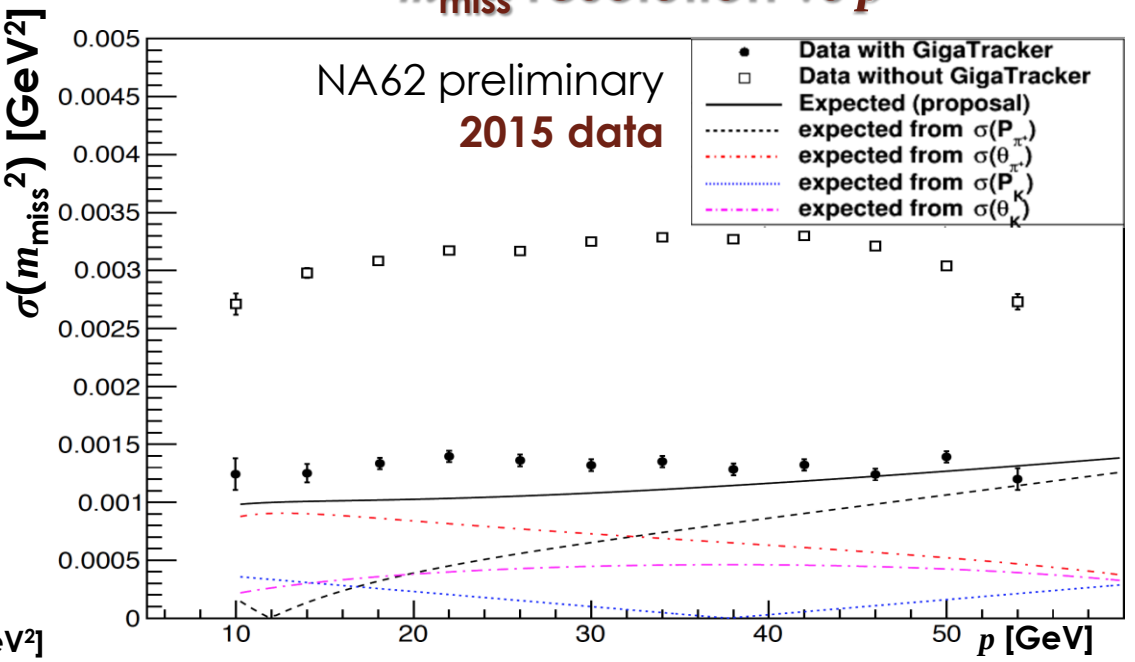


Reconstruction of kinematics

1-track selection and K ID



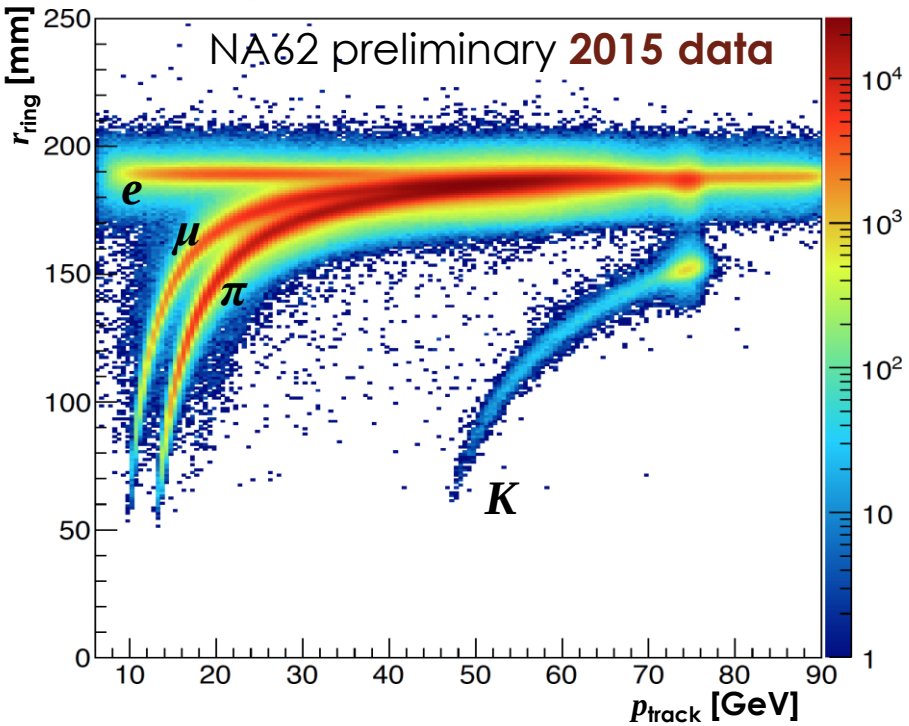
m_{miss} resolution vs p



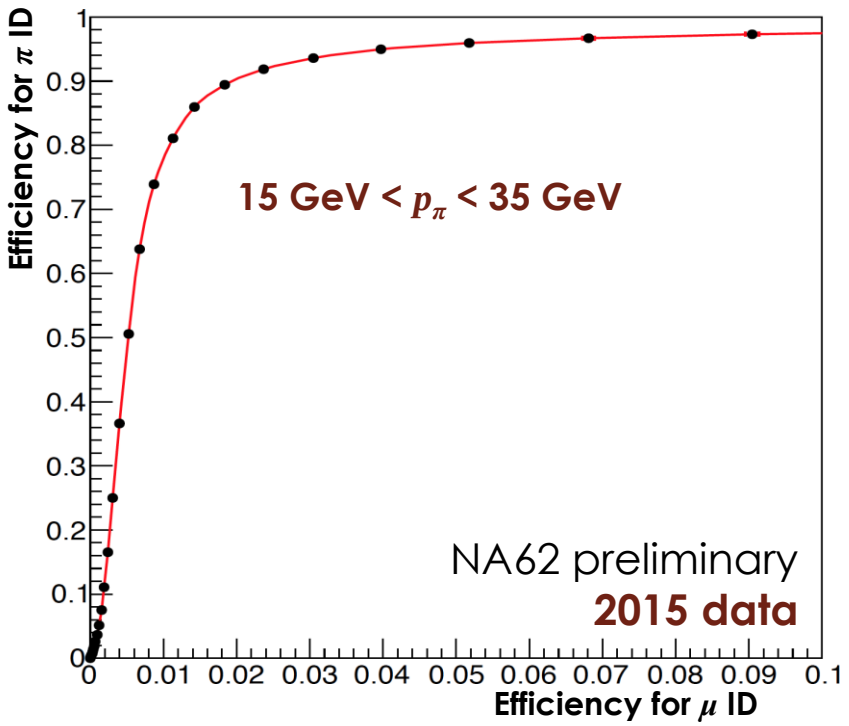
- **Technique:** GTK (beam) + spectrometer (downstream)
- **Goal:** O($10^4 \div 10^5$) suppression factor of the main kaon decay modes
- p_π < 35 GeV/c: best $K^+ \to \mu^+ \nu$ suppression (π/μ separation)
- Kinematics studied on $K^+ \to \pi^+ \pi^0$ selected using LKr calorimeter
- Resolutions close to the design
- O(10^3) kinematic suppression factor measured

Downstream particle identification

RICH ring radius vs track momentum

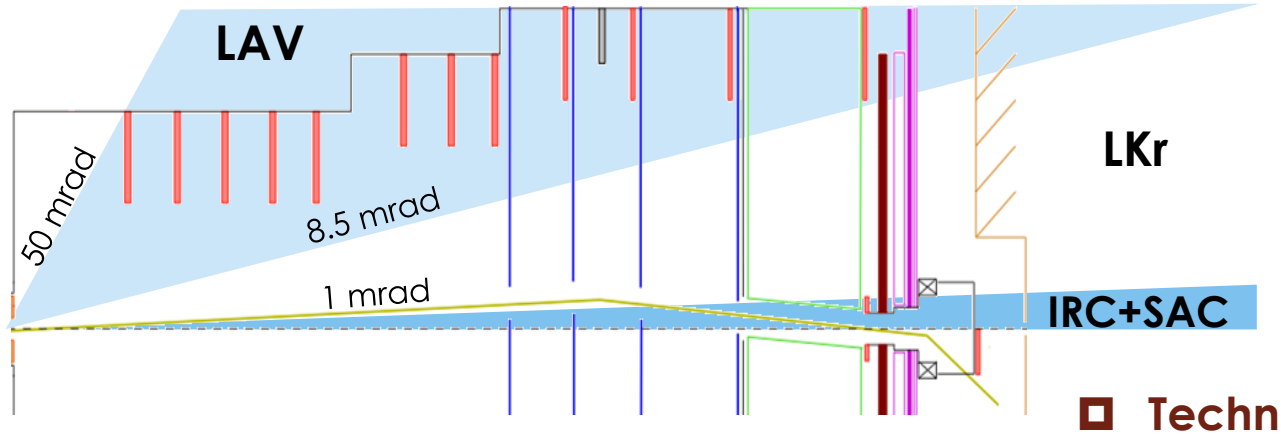


RICH π ID efficiency vs μ ID efficiency

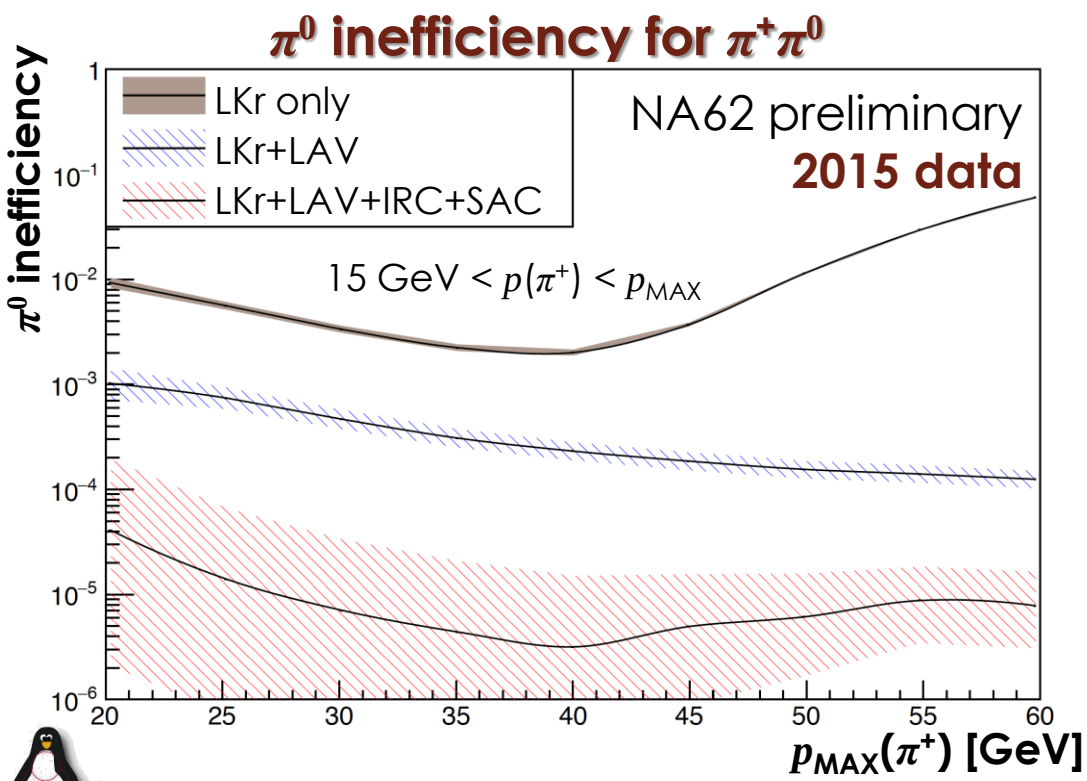


- **Technique:** RICH and calorimeters
- **Goal:** O(10^7) μ/π separation to suppress mainly $K^+ \rightarrow \mu^+\nu$
- Pure samples of pions and muons selected using kinematics
- RICH: O(10^2) π/μ separation, 80% (**90%**) π^+ efficiency in 2015 (**2016**)
- Calorimeters: $10^4 \div 10^6$ μ suppression, (90% ÷ 40%) π^+ efficiency in 2015 using a cut analysis. Room for improvements.

Photon rejection



Detector	θ [mrad]
LAV	8.5 - 50
LKr	1 - 8.5
IRC+SAC	< 1



- **Technique:** using correlations between photons from π^0
- **Goal:** 10^8 rejection of π^0
- Requiring $p(\pi^+) < 35$ GeV ensures $E(\pi^0) > 40$ GeV
- Clean sample of $K \to \pi\pi^0$ selected kinematically
- $O(10^6)$ rejection obtained in 2015
  - Measurement with minimum-bias data limited by statistics

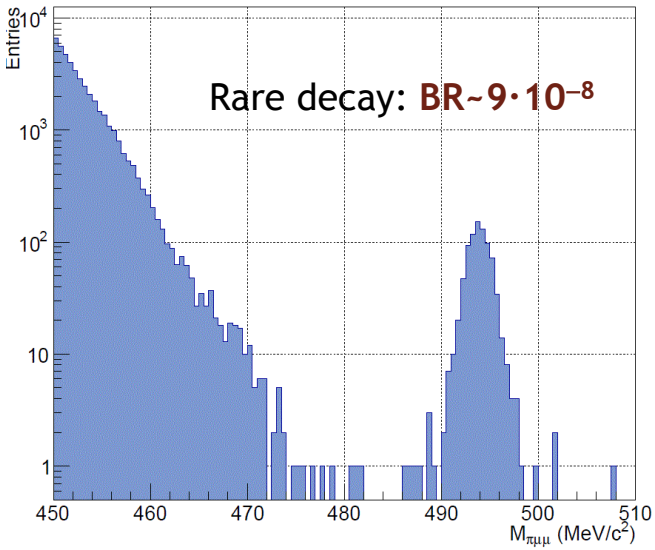
Broader NA62 physics programme

- **Standard kaon physics**
  - ChPT studies: $K^+ \to \pi^+\gamma\gamma$, $K^+ \to \pi^+\pi^0 e^+ e^-$, K_{e4}
  - Precision test of lepton universality: $R_K = \Gamma(K \to ev(\gamma))/\Gamma(K \to \mu v(\gamma))$
- **Searches for lepton-flavor or -number violating decays**
  - $K^+ \to \pi^+\mu e$, $K^+ \to \pi^-\mu^+ e^+$, $K^+ \to \pi^-\ell^+\ell^+$
- **Searches for heavy neutrinos**
  - $K^+ \to \ell^+ \nu_h$ (inclusive)
  - ν_h from upstream K, D decays with $\nu_h \to \pi\ell$
- **Searches for long-lived dark sector particles**
  - Dark photon γ' produced in π/ρ decays in target, with $\gamma' \to \ell^+\ell^-$
  - Axion-like particle A^0 produced in target/beam dump, with $A^0 \to \gamma\gamma$
- **Neutral pion**
  - π^0 form factor (see M. Zamkovsky's talk)
  - $\pi^0 \to$ invisible; $\pi^0 \to 3\gamma$, 4γ; $\pi^0 \to \gamma\gamma'$

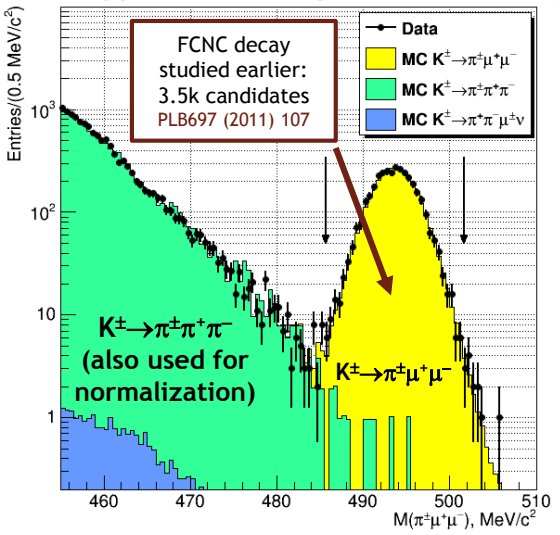
New physics searches in K→πμμ decays

- Search for Majorana neutrinos in lepton-number violating decays $K^+ \to \pi^- \mu^+ \mu^+$ ($BR < 8.6\ 10^{-11}$)
- Search for resonances (N, X, etc.) in the opposite-sign muons sample
  - Heavy neutral lepton peak in $K^+ \to \mu^+ (\pi^+ \mu^-)$
  - Inflatons peak in $K^+ \to \pi^+ (\mu^+ \mu^-)$
- First look at the 2016 data: ~60K bursts taken at 18% intensity
- Dedicated trigger for three-track di-muon events which runs in parallel with the main trigger
- The mass resolution at NA62 is better by a factor ~2 as compared to NA48/2
- NA62 can potentially improve by two orders of magnitude the NA48/2 results

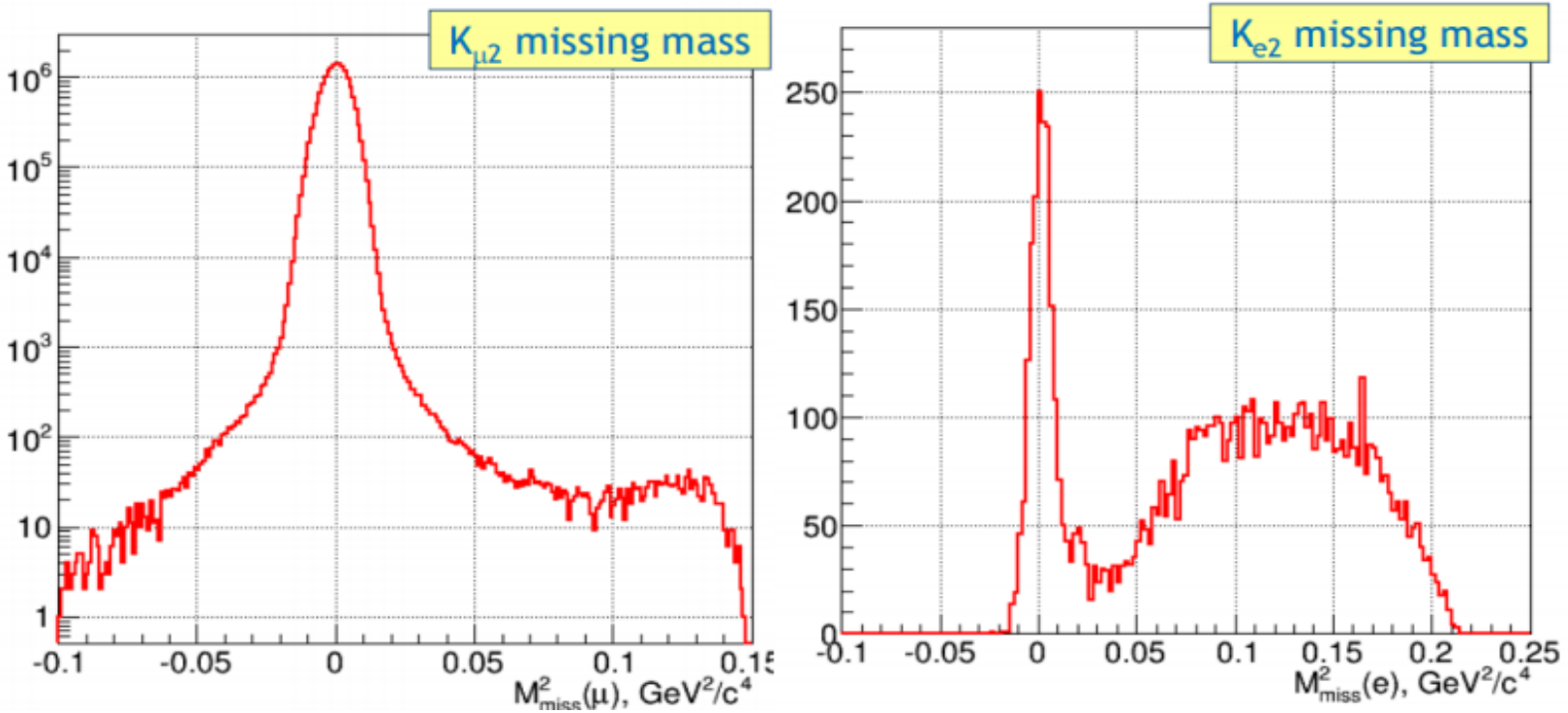
$K^+ \to \pi^+ \mu^+ \mu^-$ signal (2016)



Kπμμ candidates (NA48/2 2003-2004)



Heavy neutral leptons: $K^+ \to \ell^+ \nu_H$

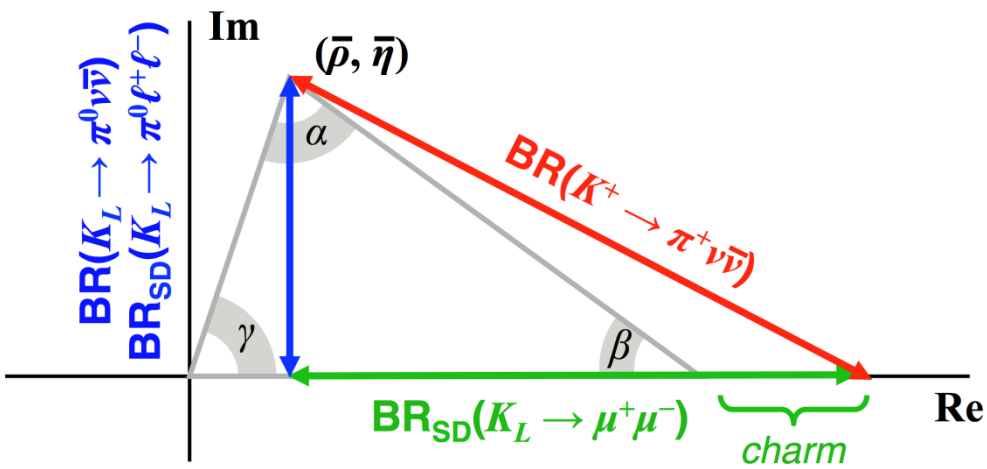
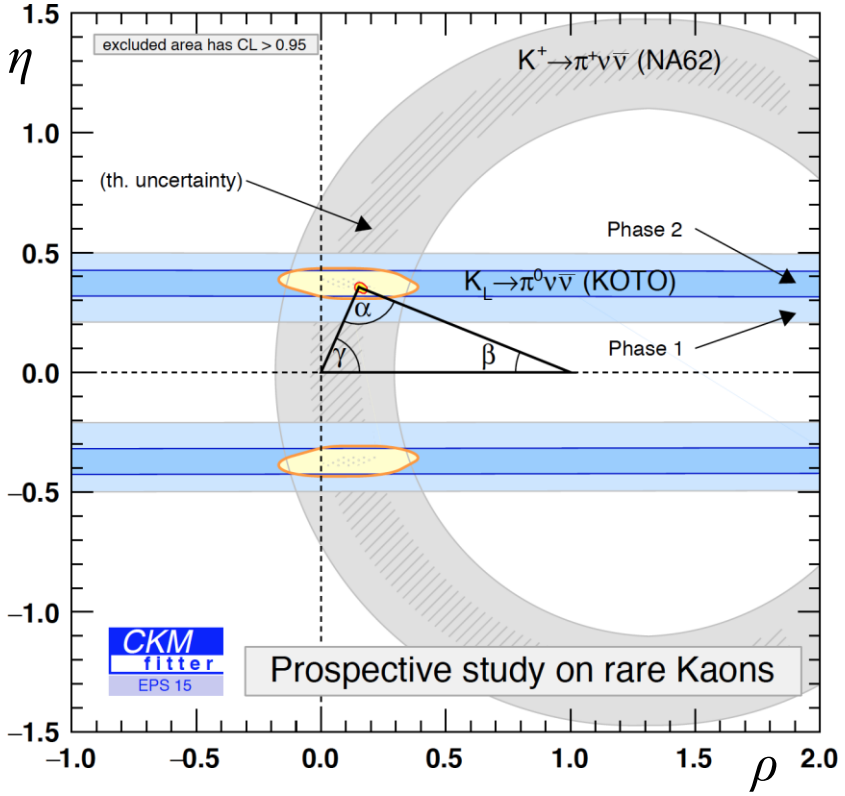


- Minimum bias data 2015 @ 1% intensity: 10.4k bursts
- Search for HNL in $K^+ \to \ell^+ \nu_H$ where ν_H does not decay inside the detector fiducial volume
- $K^+ \to \ell^+ \nu_H$ events would appear as peaks in the $K^+ \to \ell^+ \nu$ missing mass distribution
- Searches are model independent

Conclusions

- The NA62 experiment runs in stable conditions
- About 10^{12} kaon decays collected in 2016
- Data quality studies:
  - Physics sensitivity for $K^+ \to \pi^+ \nu\nu$ measurement in line with the design
- Analysis of the 2016 data is on going
  - Aim to reach the SM sensitivity for $K^+ \to \pi^+ \nu\nu$
- $K^+ \to \pi^+ \nu\nu$ program until LS2
  - End 2017: improve present status of the art (BNL measurement).
  - End 2018: reach the 10% precision
- Broader physics programme will run in parallel to main trigger

Thank you for your attention

$K \to \pi\nu\nu$ and the unitarity triangle

- Dominant uncertainties for SM BRs come from CKM matrix elements
- Intrinsic theory uncertainties are of few percent
- BR measurements over-constrain CKM matrix and may provide evidence for NP