Les Rencontres de Physique de la Vallée d'Aoste

# $K^+ \to \pi^+ \nu\nu$ decay and NP searches at NA62

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(**INFN Laboratori Nazionali di Frascati & CERN*)

La Thuile 2018. February 28th.

# Outline

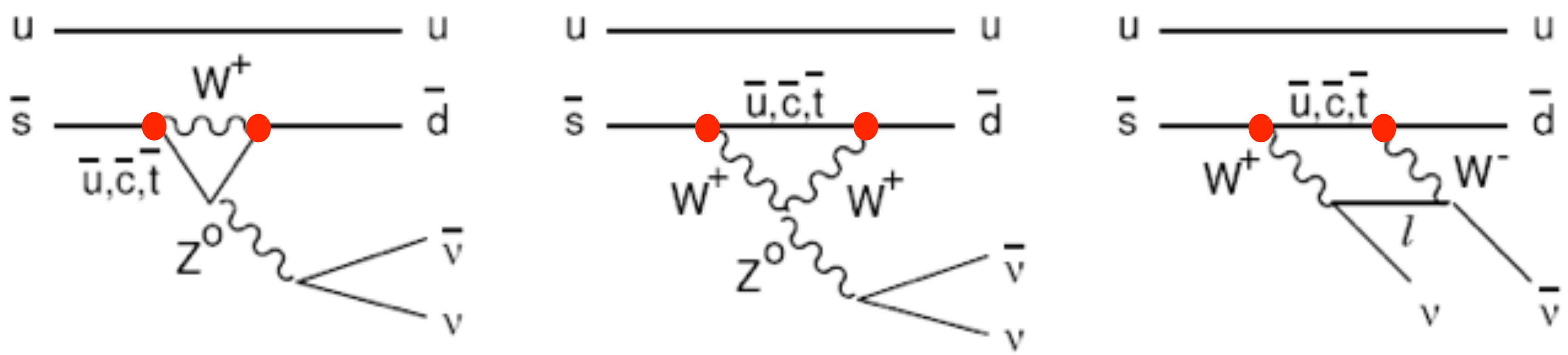
- Theoretical introduction to the $K \longrightarrow \pi\nu\nu$ rare decays
- NA62 experiment at the CERN SpS
  - Aim and strategy for the $BR(K^+ \longrightarrow \pi^+\nu\nu)$ measurement
  - Detector overview
  - Preliminary results with 2016 data
  - Prospects
  - Broader physics program

# SM theoretical framework

The **$K^+ \to \pi^+ \nu\nu$** decay is extremely suppressed

**Flavor-changing neutral current quark transition $s \to d\nu\nu$ .**

Forbidden at tree level, dominated by short-distance dynamics (GIM mechanism)




**Z-penguin** **W-box**

Is characterized by a theoretical cleanness in the SM prediction of the BR($K^+ \to \pi^+ \nu\nu$): loops and radiative corrections are under control.

**Highly suppressed & Very well predicted** ▶ **Excellent laboratory complementary to LHC**

Stringent test of the SM and possible **evidence for New Physics**

# Past measurement and prediction

## Current theoretical prediction:

$BR(K^+ \to \pi^+ \nu\nu)_{SM} = (9.11 \pm 0.72) \times 10^{-11}$

$BR(K_L \to \pi^0 \nu\nu)_{SM} = (3.00 \pm 0.30) \times 10^{-11}$

A.J. Buras, D.Buttazzo, J. Girrbach-Noe and R.Knegjens arXiv:1503.02693

- Main contribution to the errors comes from the uncertainties on the SM input parameters
- Intrinsic theoretical uncertainties (1-3%) slightly larger for the charged channel because of the corrections from lighter-quark contributions

## Experimental status:

$$BR(K^+ \to \pi^+ \nu\bar{\nu})_{exp} = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$$

Only measurement obtained by E787 and E949 experiments at BNL with **stopped kaon decays (7 candidates)**

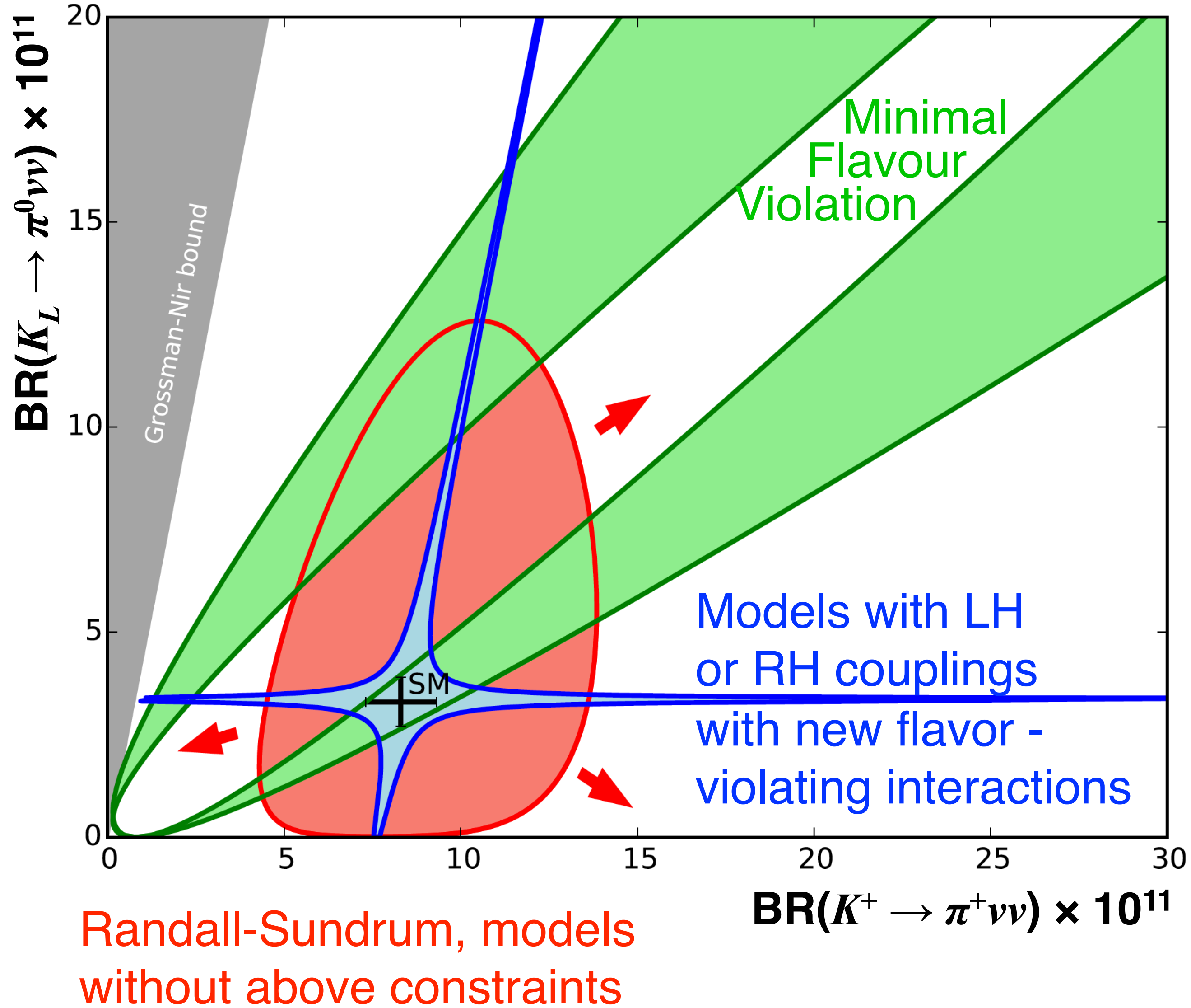
- Gap between theoretical precision and large experimental error motivates a strong experimental effort. **Significant new constraints can be obtained.**

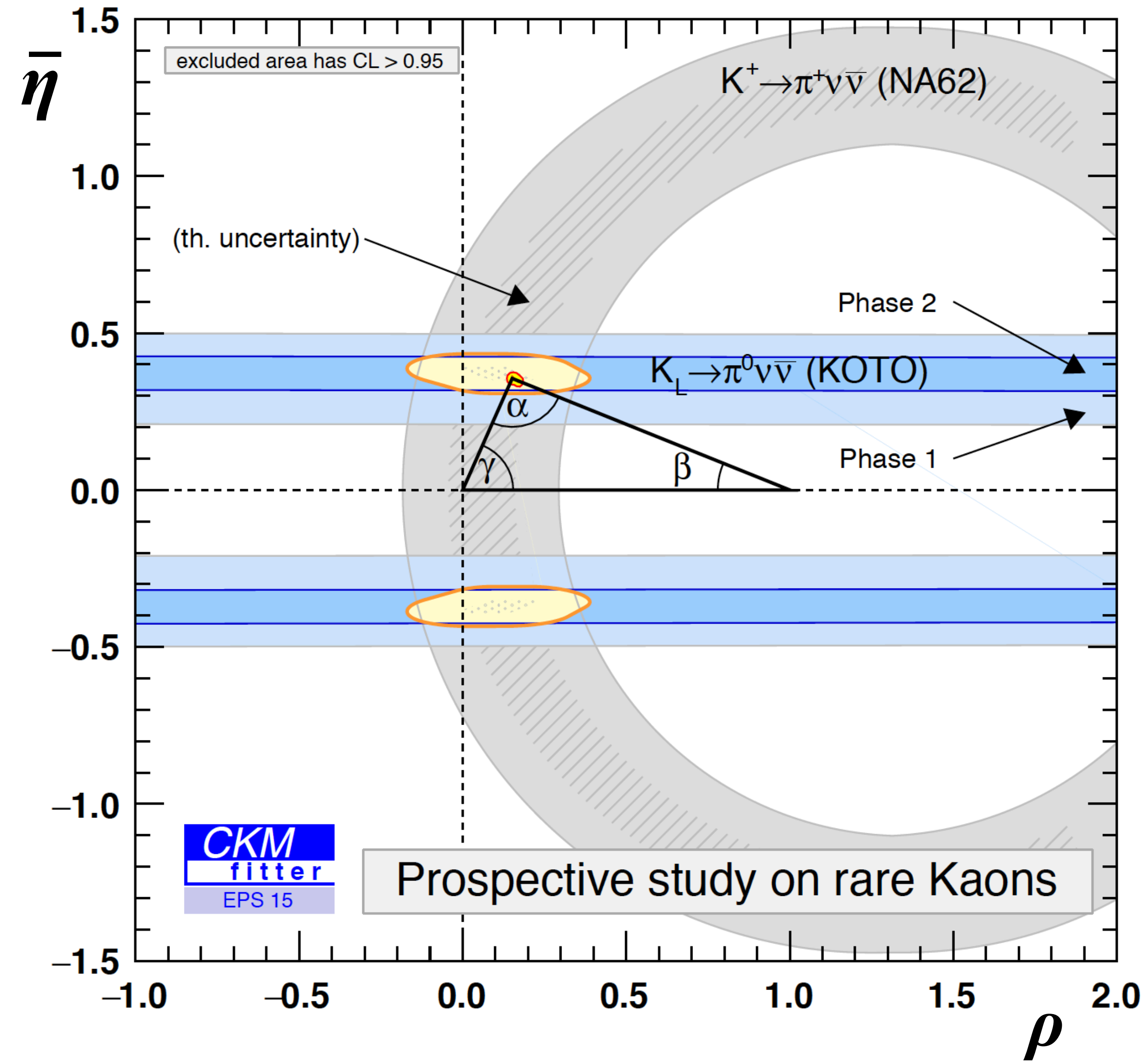
Neutral decay $K_L \to \pi^0 \nu\nu$ has never been measured

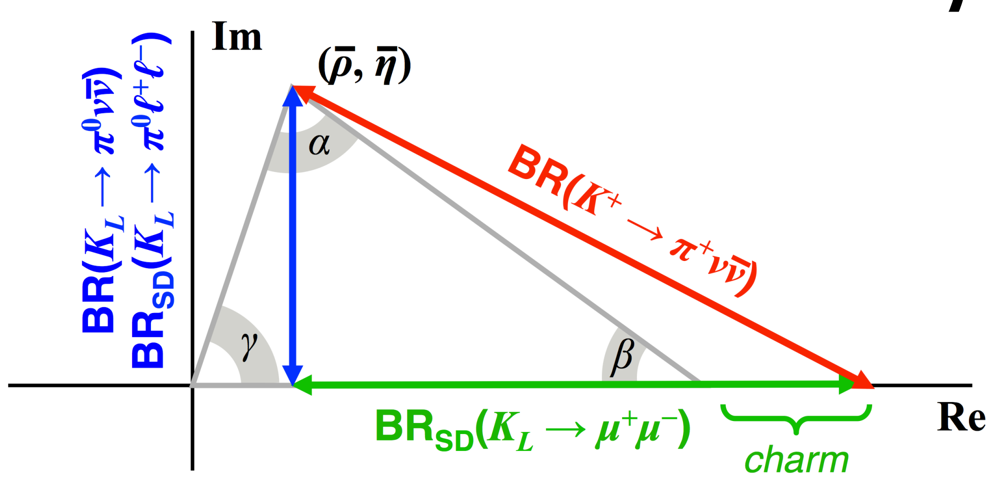
# New Physics from K⟶πνν decays

Measurement of BR of charged ($K^+ \to \pi^+\nu\nu$) and neutral ($K_L \to \pi^0\nu\nu$) modes can determine the **unitarity triangle** independently from B inputs

and can discriminate among NP scenarios:



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

$K \to \pi\nu\nu$ is uniquely sensitive to high mass scales.

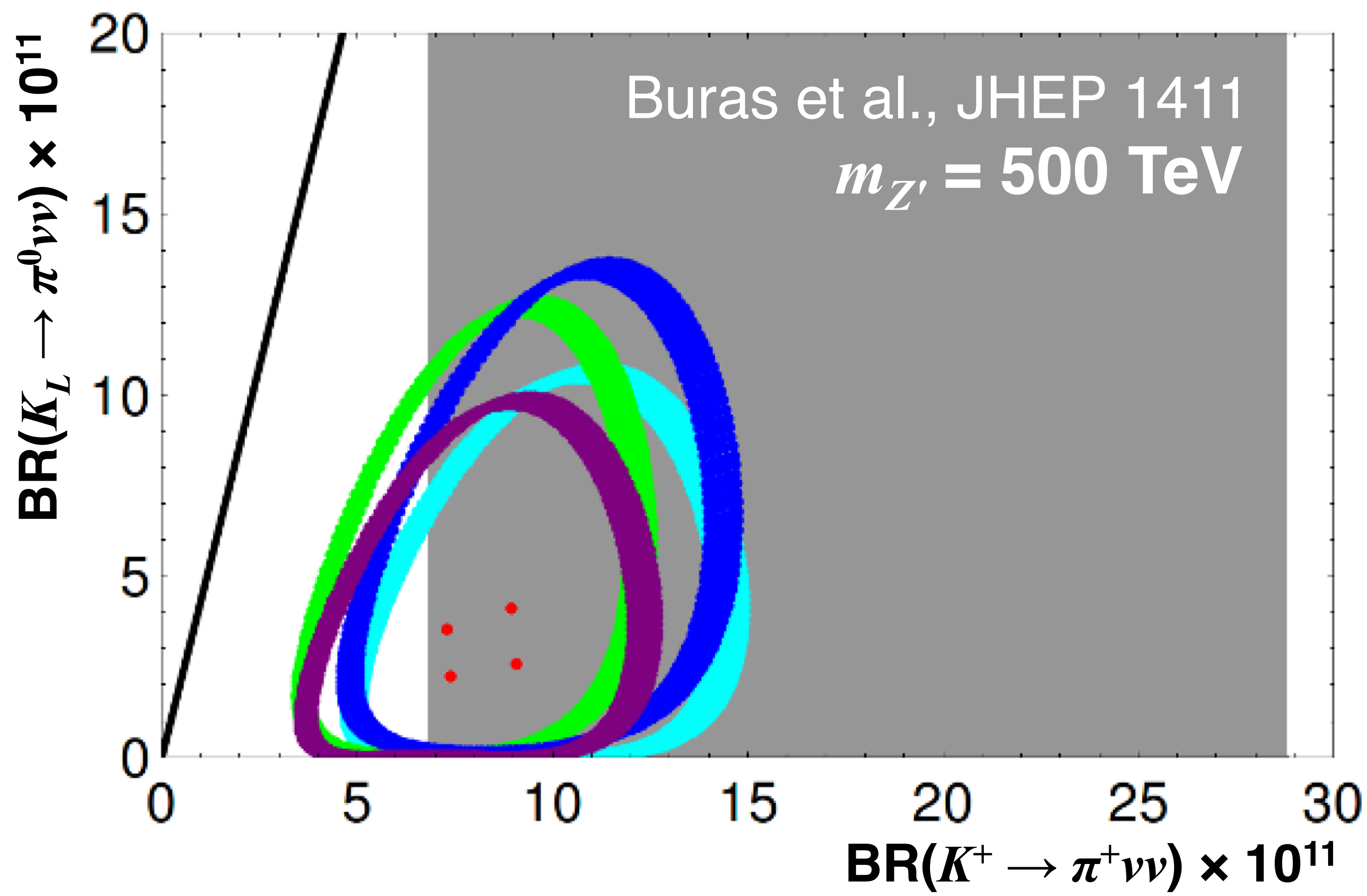
**NP may simply occur at a higher mass scale**

$\to$ Null results from direct searches at LHC so far

**Indirect probes to explore high mass scales become very interesting!**

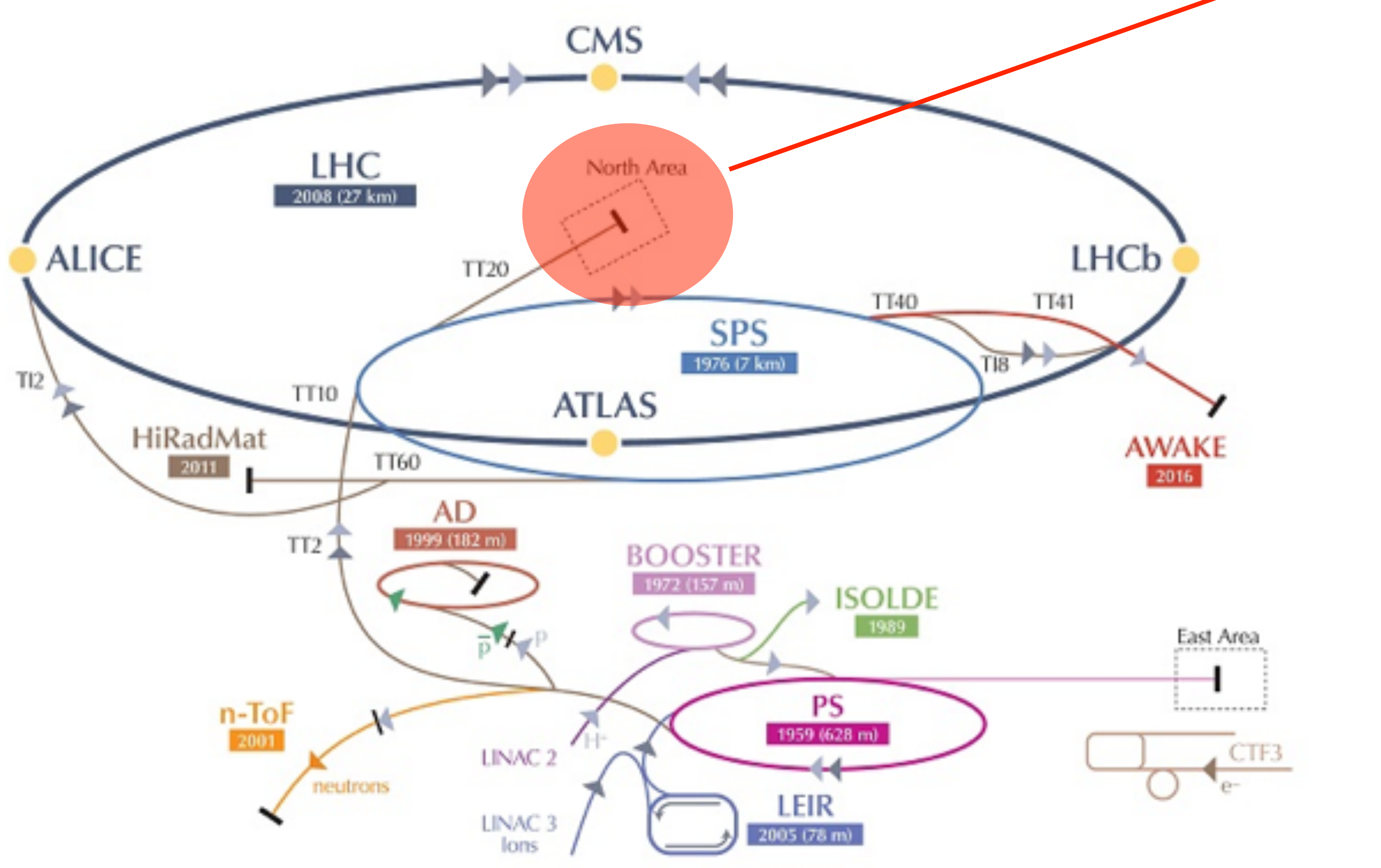
Es: Tree-level flavor changing Z′ LH+RH couplings

- Some fine-tuning around constraint from $\varepsilon_K$
- $K \to \pi\nu\nu$ sensitive to mass scales up to 2000 TeV (up to tens of TeV even if LH couplings only)
- Order of magnitude higher than for B decays



# Kaon at CERN SPS

The **CERN-SPS secondary beam line** already used for the NA48 experiment can deliver the required $K^+$ intensity



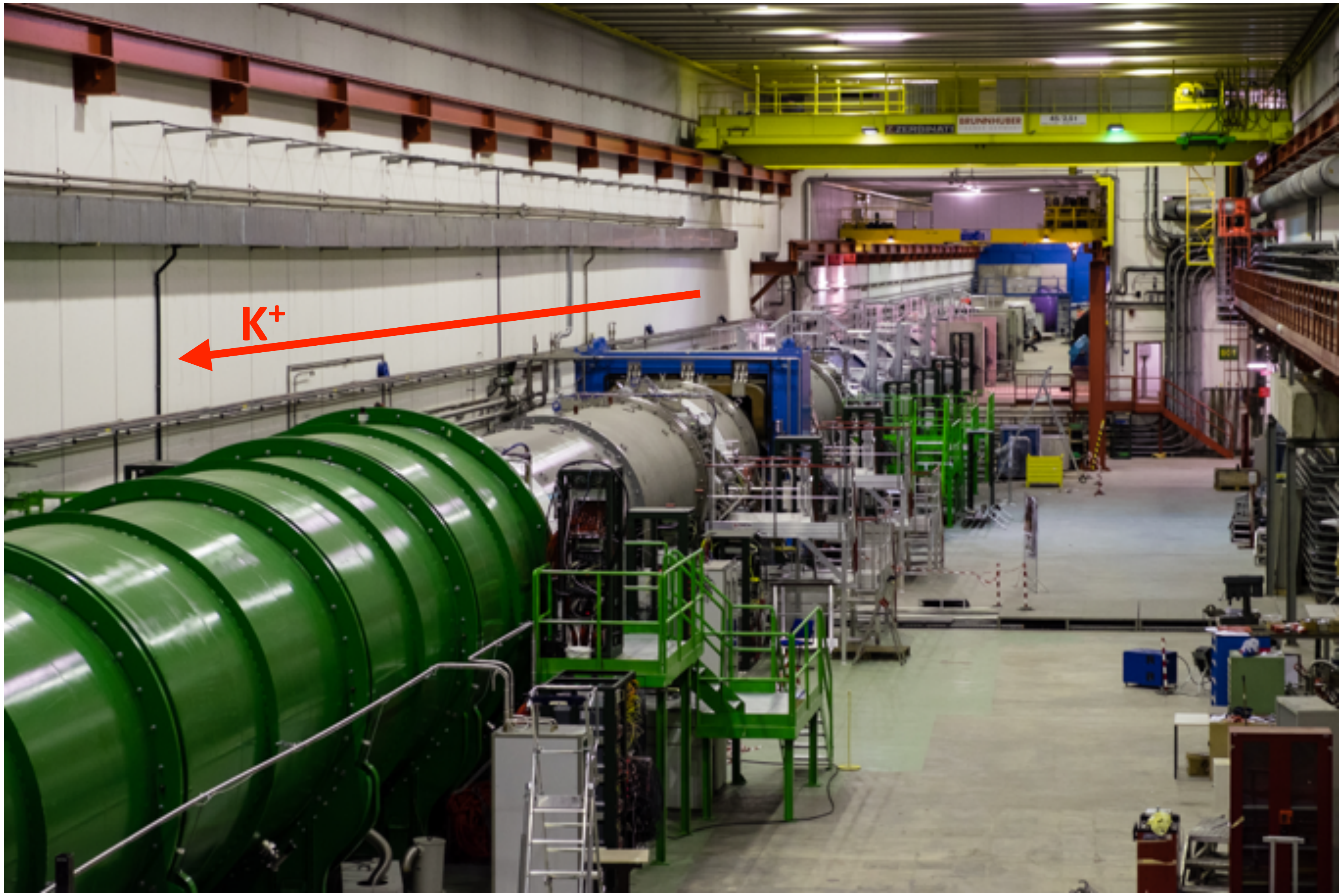

In the North Area the SpS extraction line is providing a secondary charged hadron beam

- 400 GeV/c primary proton beam
- $3 \times 10^{12}$ protons/pulse
- 40 cm berillium target
- **75 GeV/c** unseparated hadrons beam: **$\pi^+$, $K^+$ (6%), protons** ($\Delta p/p \pm 1\%$)
- $4.8 \times 10^{12}$ $K^+$ decays/year

# NA62 Experiment

# NA62 Apparatus

**270 m long** downstream of the beryllium target.
Useful $K^+$ decays are detected in a **65 m long fiducial volume**.



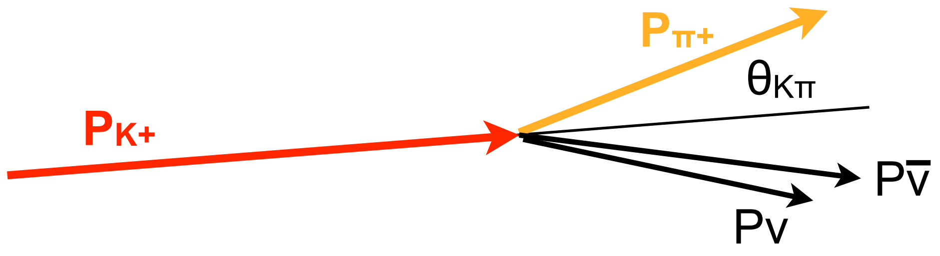

Approximately cylindrical shape around the beam axis for the main detectors.
Diameter varies from 20 to 400 cm.

Each detector sends ~ 10 MHz of raw input data to the Level 0 trigger (FPGA) that selects 1 MHz of events. L1 and L2 triggers (software) guarantee a maximum of 10 kHz of acquisition rate.

# NA62 Goal

Design criteria: **kaon intensity, signal acceptance, background suppression**

Kaons with high momentum.
**Decay in flight technique**.
Signal signature: $K^+$ track + $\pi^+$ track




**Backgrounds**

| Decay | BR | Main Rejection Tools |
|---|---|---|
| $K^+ \to \mu^+\nu_\mu(\gamma)$ | 63% | $\mu$-ID + kinematics |
| $K^+ \to \pi^+\pi^0(\gamma)$ | 21% | $\gamma$-veto + kinematics |
| $K^+ \to \pi^+\pi^+\pi^-$ | 6% | multi-track + kinematics |
| $K^+ \to \pi^+\pi^0\pi^0$ | 2% | $\gamma$-veto + kinematics |
| $K^+ \to \pi^0 e^+\nu_e$ | 5% | $e$-ID + $\gamma$-veto |
| $K^+ \to \pi^0\mu^+\nu_\mu$ | 3% | $\mu$-ID + $\gamma$-veto |

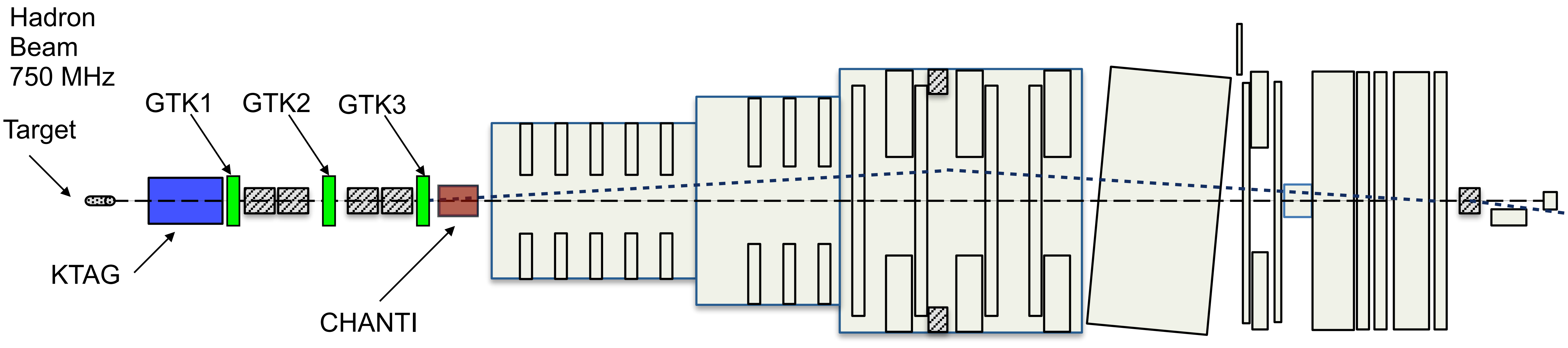
**Basic ingredients:**

- O(100 ps) Timing between sub-detectors
- $O(10^4)$ Background suppression from kinematics
- $O(10^7)$ μ-suppression ($K^+ \to \mu^+\nu$)
- $O(10^7)$ $\gamma$-suppression
  (from $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\gamma$)

BR($K^+ \to \pi^+\nu\nu$) with 10% accuracy: O(100) SM events + control of systematics at % level

Assuming 10% signal acceptance and a BR($K^+ \to \pi^+\nu\nu$) ~$10^{-10}$ at least **$10^{13}$ $K^+$ decays are required**

# NA62: Beam ID & Tracking



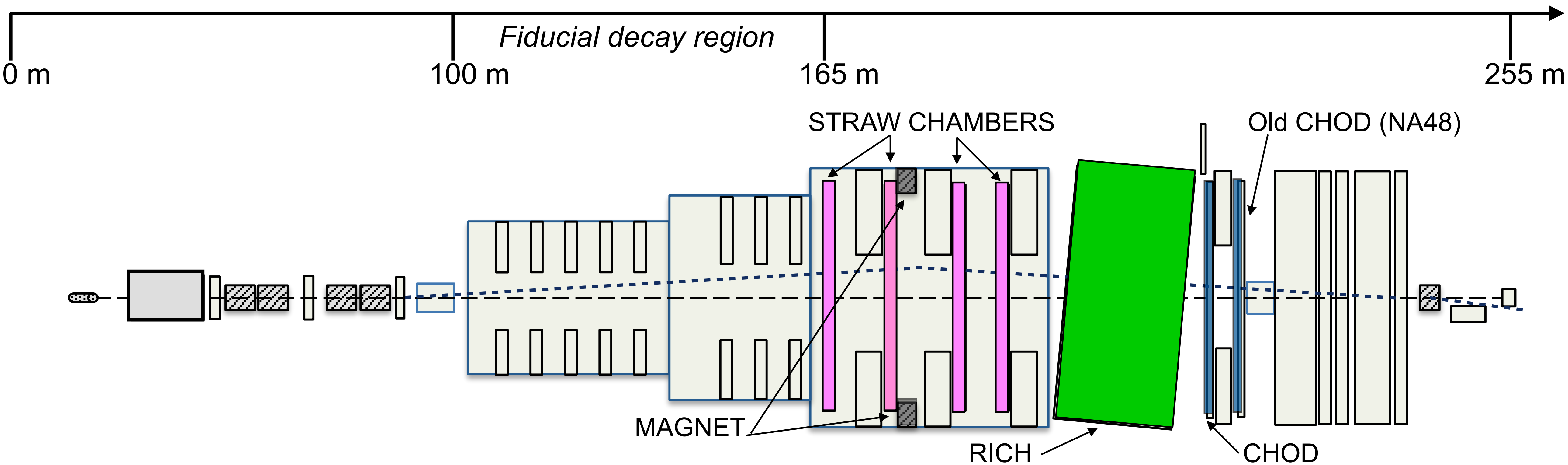

**Beam ID & Tracking**

**KTAG:** Differential Čerenkov counter blind to all particles but kaons of appropriate momentum (75 GeV, K+ rate:~45MHz). **$\sigma_t$ ~70 ps, efficiency > 99%.**
*Steel vessel, 4.5 m long, filled with compressed nitrogen.*

**GTK:** GigaTracKer Spectrometer for $K^+$ momentum and timing measurement.
**$\sigma_t$ ~100 ps, $\sigma_{dx,dy} \approx 0.016$ mrad, $\Delta P/P < 0.4\%$.**
*750 MHz beam environment. 3 stations of 18000 silicon pixels (140 KHz/pixel).*

**CHANTI:** Charged particle veto to reduce the background induced by inelastic interactions.
*6 stations of X-Y plastic scintillator bars coupled with optical fibers.* **Efficiency > 99%.**

# NA62: Secondary ID & Tracking



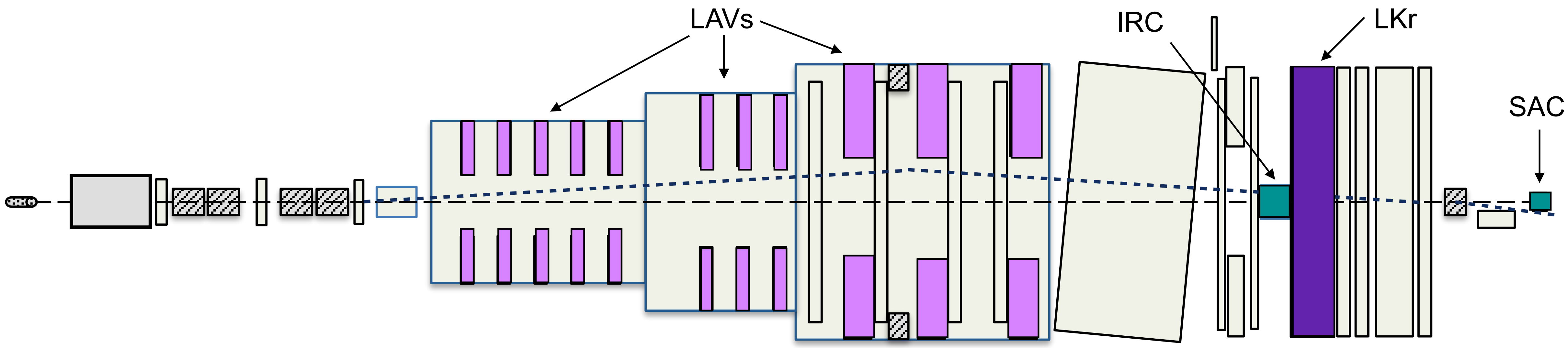

**Secondary particle ID & Tracking**

**STRAW:** Spectrometer with STRAW tubes for secondary particle momentum measurement. *4 chambers (4 layers < 0.5 $X_0$) in vacuum, 7168 STRAW tubes. Magnet provides a 270 MeV/c momentum kick in the horizontal plane.* **$\sigma_t$ ~ 6 ns, $\sigma_{dx,dy}$ ~130 μm.**

**CHOD:** Charged Hodoscope of *plastic scintillator* to provide fast signal of the beam. **Old CHOD $\sigma_t$ ~ 250 ns, CHOD $\sigma_t$ ~ 1 ns**

**RICH:** Ring Imaging Cherenkov detector for the secondary particle identification. *17 m long tank. Neon gas (1 atm). Downstream: mosaic of 20 spherical mirrors. Upstream: ~2000 PMTs.* ***μ/π separation ~ $10^{-2}$, $\sigma_t$ of a ring < 100 ps***

# NA62: Photon Veto System



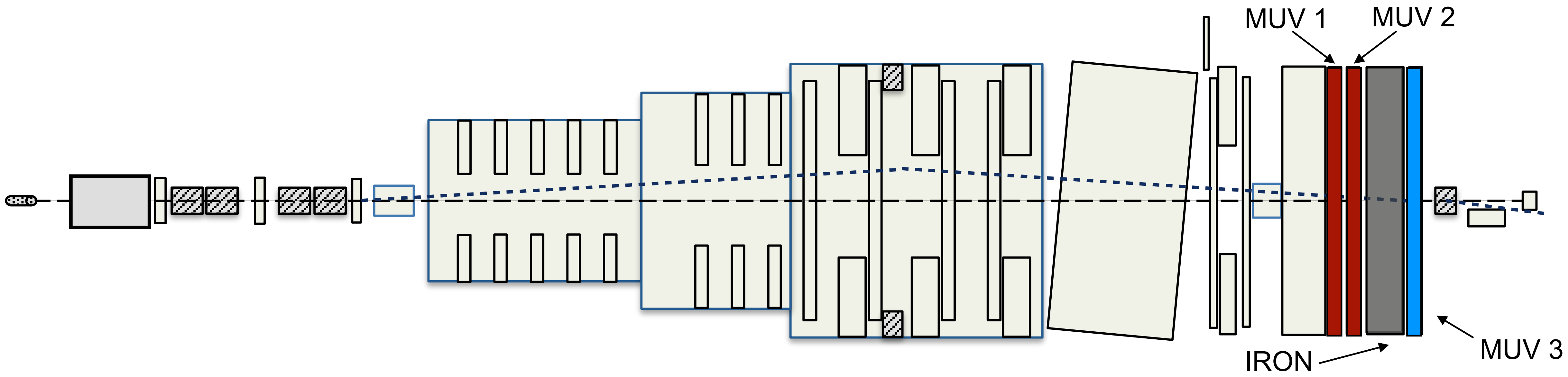

**Photon Veto**

**LAV:** Large Angle Veto. 12 stations to veto $\gamma$ with angles $8.5 < \theta < 50$ mrad.
*4 or 5 rings of lead glass crystals read out by PMTs. First 11 stations are in vacuum.*
***$\sigma_t$ ~ 1 ns, $10^{-3}$ to $10^{-5}$ inefficiency (on $\gamma$ down to 150 MeV).***

**IRC/SAC:** Inner Ring Calorimeter and Small Angle Calorimeter. To veto $\gamma$ with angles <1 mrad.
*Shashlik calorimeters. Lead and plastic scintillator plates.* **$\sigma_t$ < 1 ns, $10^{-4}$ inefficiency.**

**LKr:** NA48 LKr Calorimeter: to veto $\gamma$ with angles $1 < \theta < 8.5$ mrad and for PID.
*Ionization chamber + liquid Krypton, 2x2 cm2 cells.* **$\sigma_t$~500 ps ($E_{clusters}$ > 3 GeV), $\sigma_t$~1 ns (hadronic and MIP clusters), $\sigma_{dx,dy}$ ~1 mm, $10^{-5}$ inefficiency ($E\gamma$ > 10 GeV).**

# NA62: Muon Veto System




**Beam ID & Tracking**

**MUV3:** Efficient fast Muon Veto (reduction factor > 10) used in the hardware trigger level.

*Placed after an iron wall. 1 plane of 148 5cm thick scintillator tiles. Muon Rate: 10 MHz.*

**$\sigma_t$ ~500 ps, efficiency ~99.5%**

**MUV1/2:** Hadronic calorimeters for the μ/π separation.

*2 modules of iron-scintillator plate sandwiches. Readout with LKr electronics.*

**Cluster reco at ~20 ns from $T_{track}$, and at ±150 mm from the expected impact point**

# NA62 Timescale

**2014** Pilot Run

**2015** Commissioning Run

**2016** Commissioning + Physics Run → SM sensitivity reached $O(10^{-10})$.

**2017** Physics Run → Improve on the present state of the art.

**2018** > 6 months of data taking expected…

Assuming that the 2018 run is as successful as the 2017 one,
by the end of 2018 NA62 should have collected
between 20 and 30 PNN events at the SM sensitivity

- For the spring 2018 the results from the full 2016 statistics will be presented
- Processing of the 2017 data is on-going after calibrations were performed

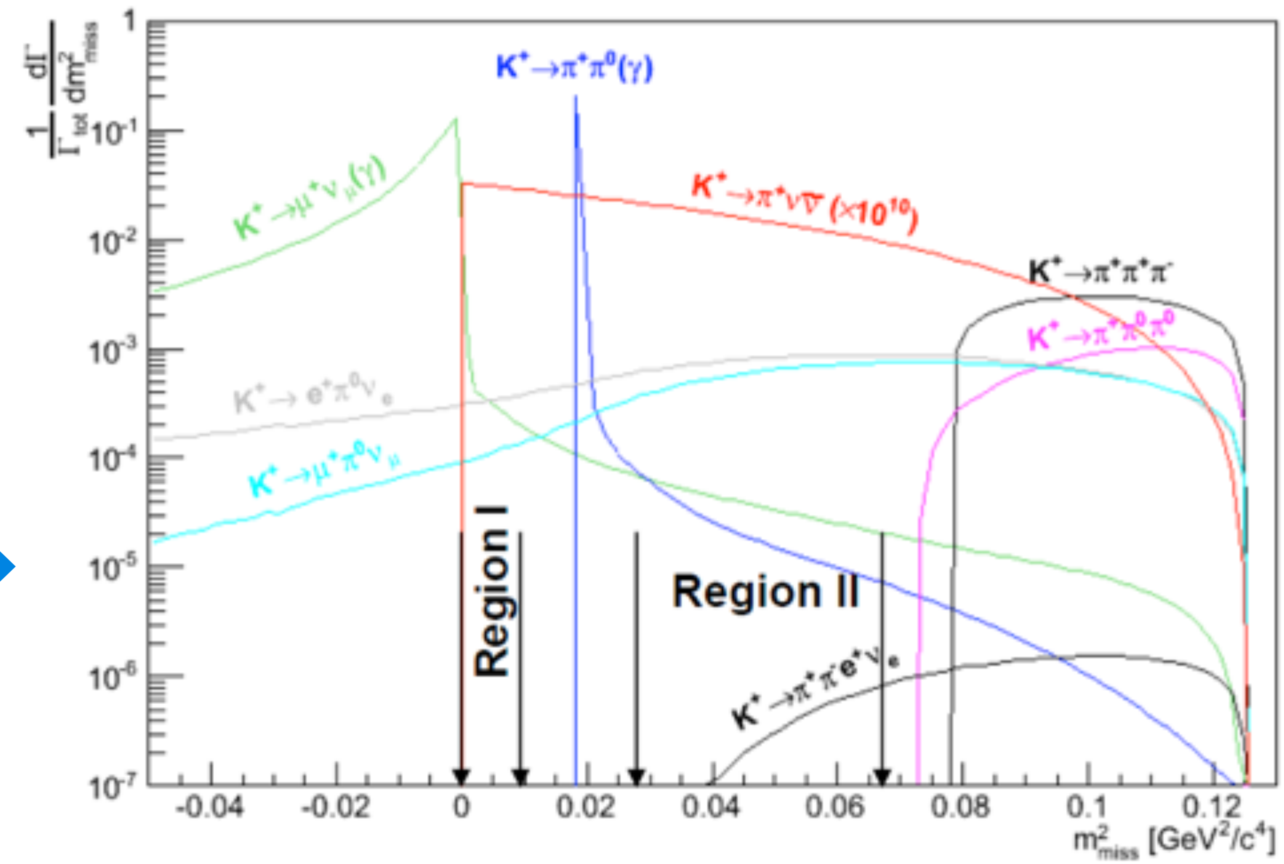
**2019-2020** LS2 (Long shutdown 2)

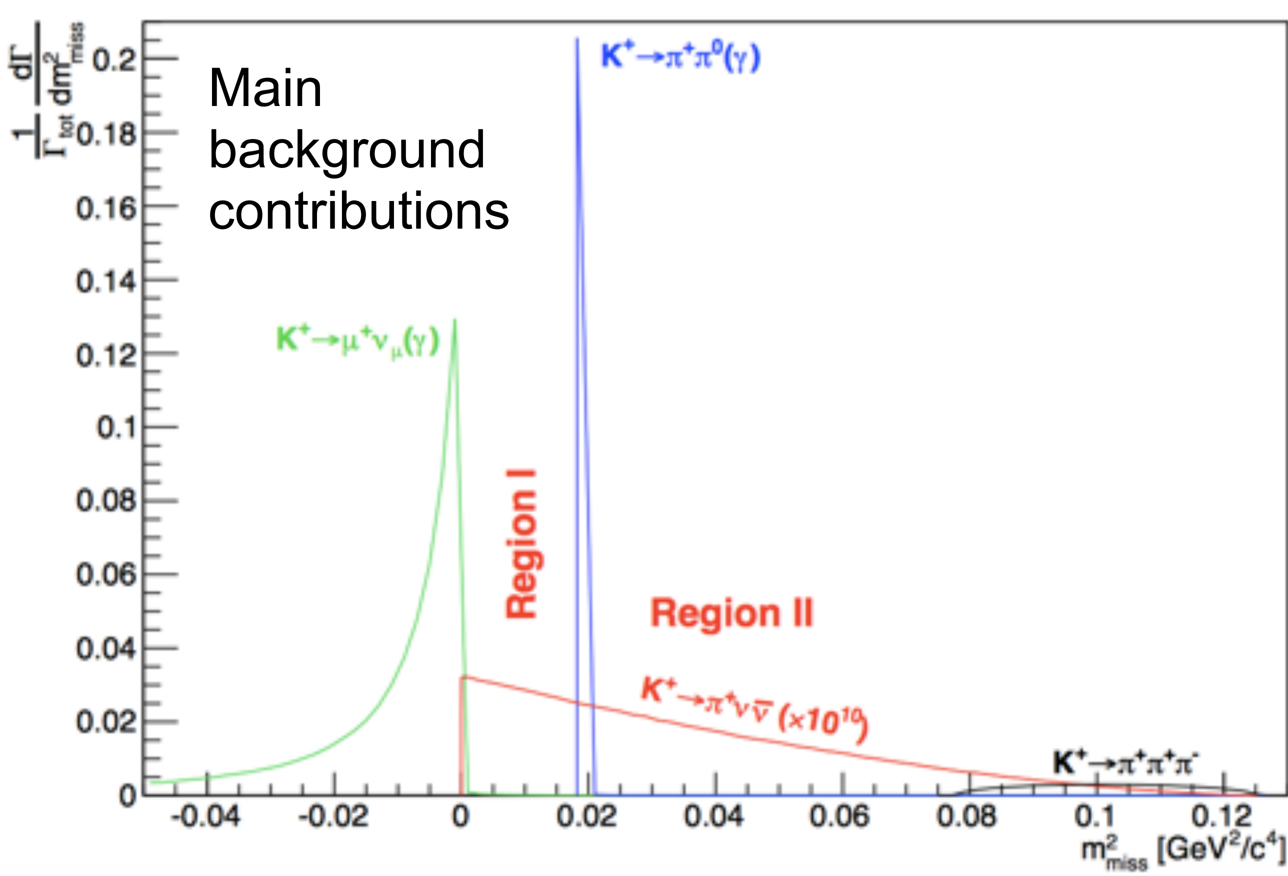
# Analysis Strategy

Most discriminating variable:
**$m^2_{miss} = (P_{K+} - P_{\pi+})^2$**

*Where the daughter charged particle is assumed to be a pion*

Theoretical $m^2_{miss}$ distribution for signal and backgrounds of the main $K^+$ decay modes: (signal is multiplied by a factor $10^{10}$).




**2 signal regions**, on each side of the $K^+\to\pi^+\pi^0$ peak (to eliminate 92% of the $K^+$ width)

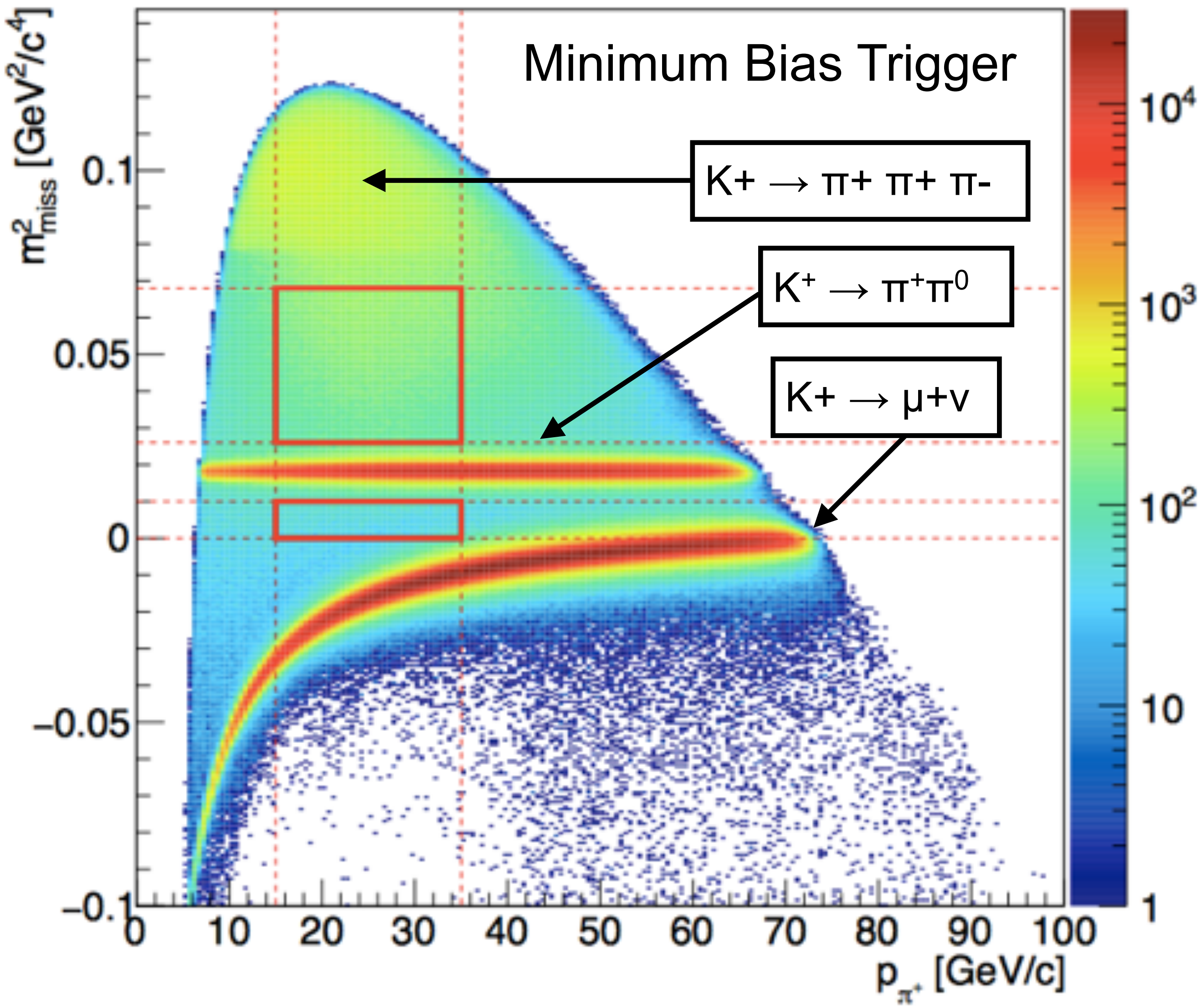
**Main background sources:**

- $K^+\to\pi^+\pi^0$, $K^+\to\mu^+\boldsymbol{\nu}$ non gaussian resolution and radiative tails
- $K^+\to\pi^+\pi^+\pi^-$ non gaussian resolution tails
- decays with neutrino in final state

# 2016 Data

**2016 data Goal**: study the single event sensitivity of the apparatus down to 1 event over $10^{10}$ (reach **SM-expectation sensitivity**).

**Data sample**: preliminary exploratory analysis has been performed on about **$2.3 \times 10^{10}$ $K^+$ decays** in fiducial region (**5%** of 2016 statistics, at 40% of the nominal beam intensity)

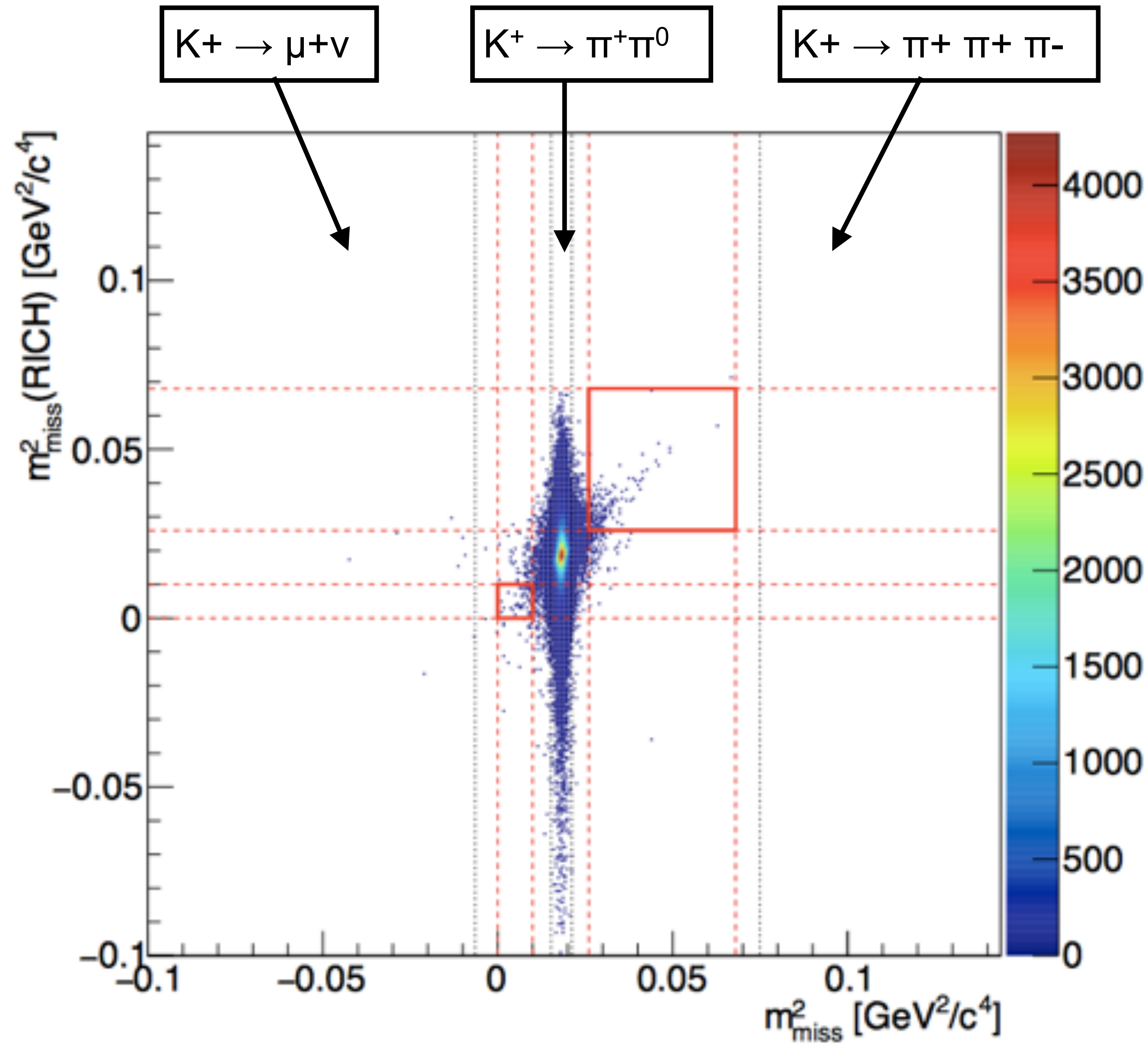



**Single downstream track selection with $K^+$ matching:**

- Timing $\pi^+$:
  $\sigma(T_{CHOD})$ ~ 250 ps, $\sigma(T_{RICH})$ ~ 150 ps
- Timing $K^+$:
  $\sigma(T_{KTAG})$ ~ 80ps, $\sigma(T_{GTK})$ ~ 100 ps
- Spatial matching, i.e intersection of GTK and Straw track:
  $\sigma(CDA)$ ~ 1.5 mm, $115 < Z_{vertex} < 165$ m
- Mis-tagging probability: ~1.7%

**$15 < P_{\pi+} < 35$ GeV/c** selected, to leave at least 40 GeV of missing energy.

# Kinematic reconstruction




**3 Missing Mass definition**

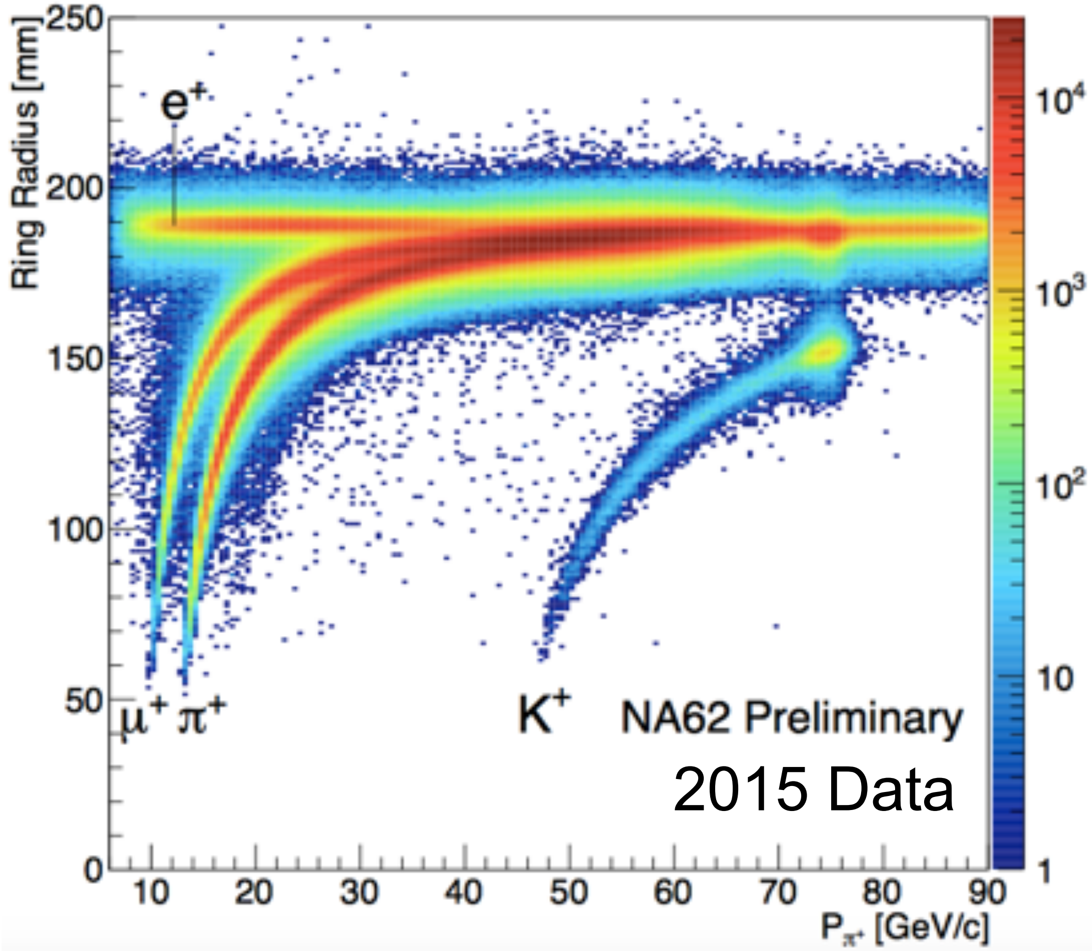
- $m^2_{miss} = (P_{K+}^{GTK} - P_{\pi+}^{STRAW})^2$
- $m^2_{miss}$ (RICH) $= (P_{K+}^{GTK} - P_{\pi+}^{RICH})^2$
- $m^2_{miss}$ (no GTK) $= (P_{K+}^{beam} - P_{\pi+}^{STRAW})^2$

"beam"- i.e. with nominal $P_k$ = 75 GeV/c -

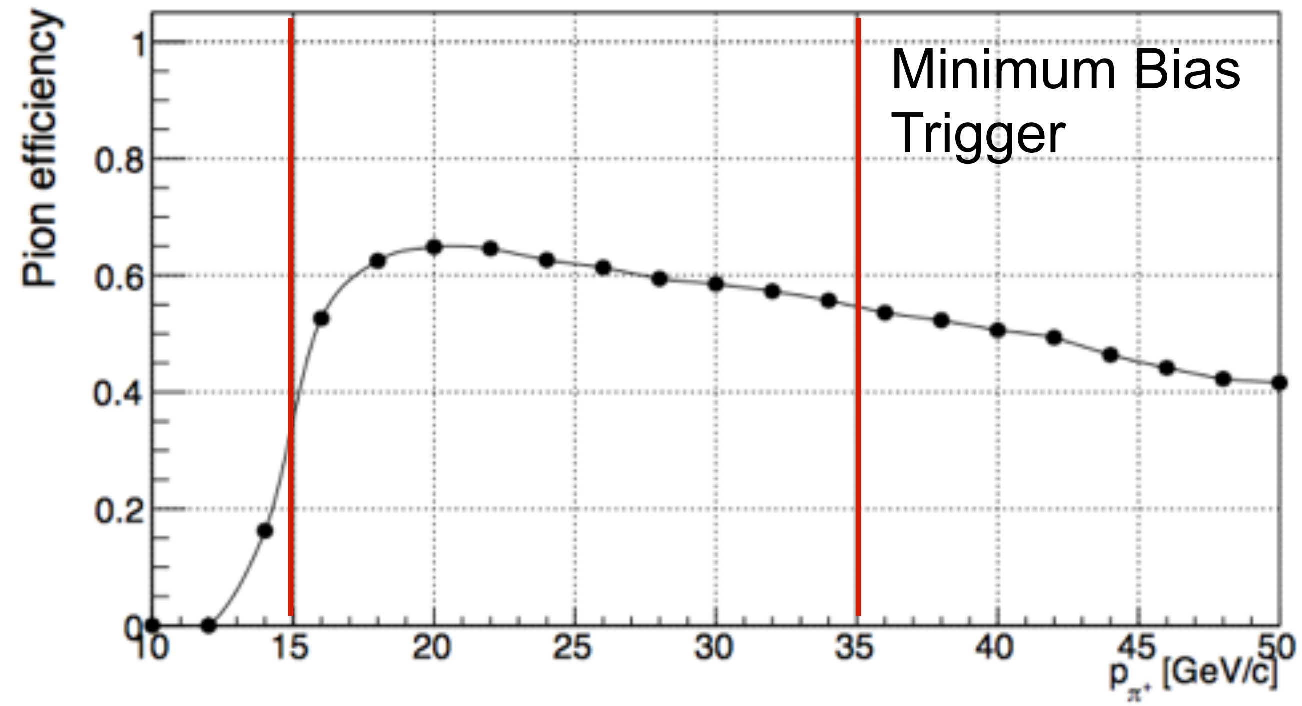
Kinematical background suppression measured on data:
**$K^+ \to \pi^+\pi^0$: $6\times10^{-4}$**
**$K^+ \to \mu^+\nu$: $3\times10^{-4}$**

# Particle ID: π-μ separation

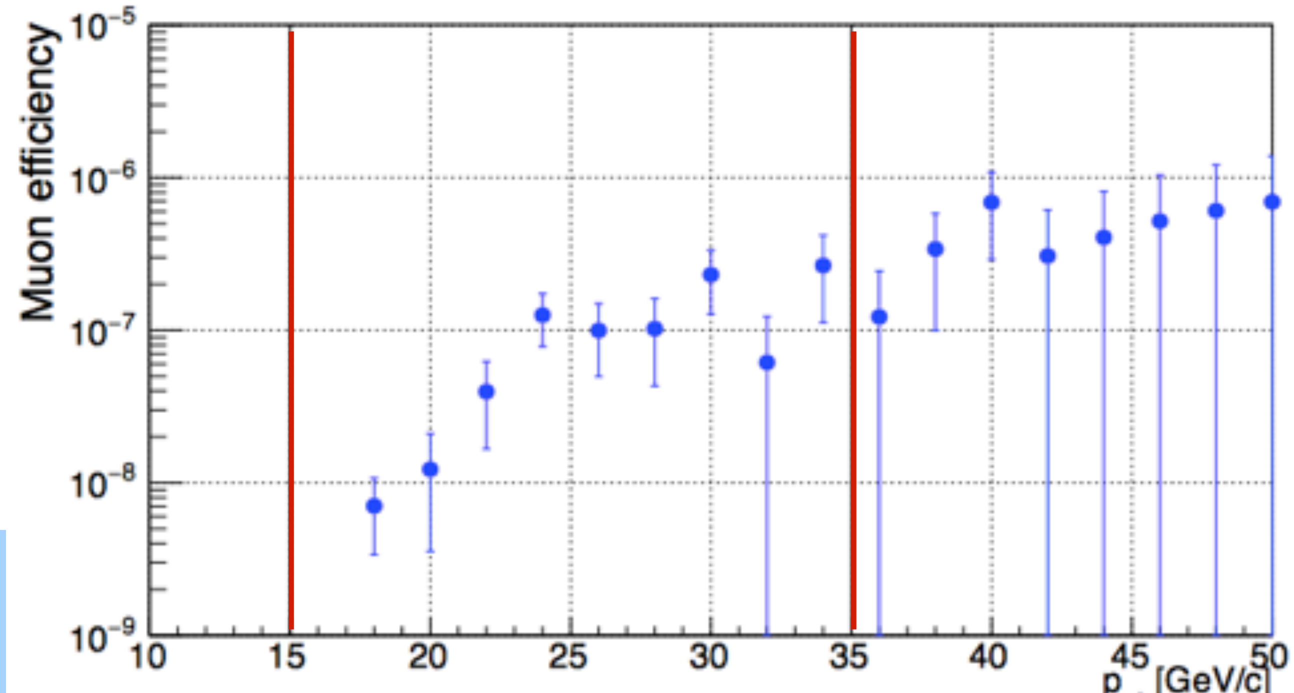
**RICH Ring Radius Vs Track Momentum:**




**Calorimeters + RICH π-ID efficiency:**




**Calorimeters + RICH μ-misID efficiency:**



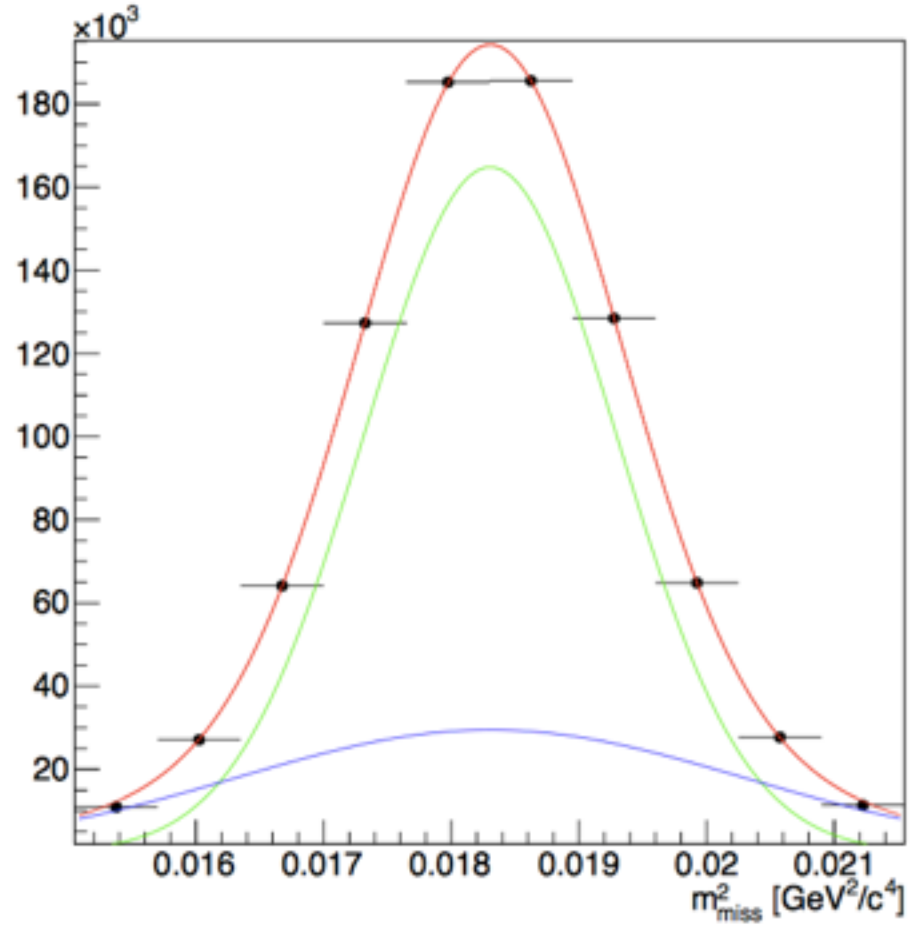

- Particle ID with calorimeters (MVA on LKr and MUVs): **ε(μ) ≃ $10^{-5}$, ε(π) ≃ 80%**
- Particle ID with RICH: $\varepsilon(\pi)_{ring}$ ≃ 90% (Pπ function), **$\varepsilon(\pi)_{ID}$ ≃ 80%, ε(μ) ≃ $10^{-2}$**

PID performance measurement with RICH and calorimeter combined: μ-suppression <$10^{-7}$

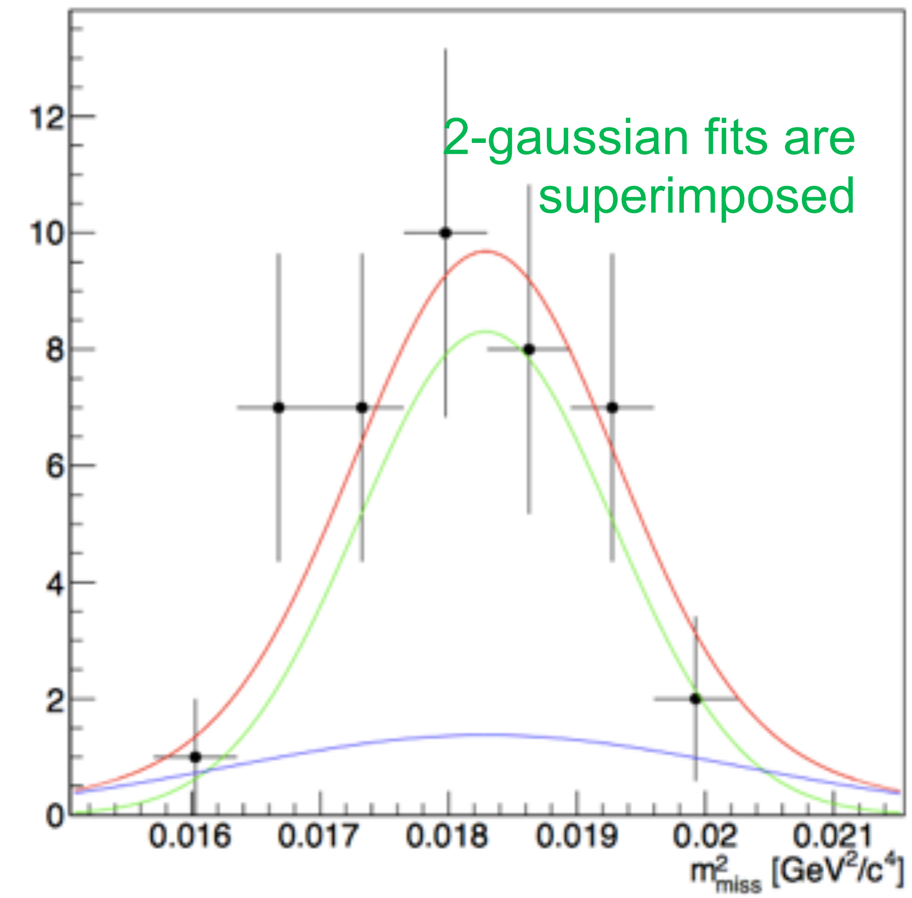
# Photon Rejection

Photon Veto condition: LKr, LAV, IRC, SAC

**$K^+ \rightarrow \pi^+\pi^0$ events before the $\gamma$ rejection (minimum bias trigger*):**




**$K^+ \rightarrow \pi^+\pi^0$ events after $\gamma$ rejection (PNN trigger):**




*x 400 (Downscaling) to get the total number

- $K^+ \rightarrow \pi^+\pi^0$ suppression (in $K^+ \rightarrow \pi^+\pi^0$ mass region):

  **$\varepsilon(\pi^0) = (1.2 \pm 0.2) \times 10^{-7}$**

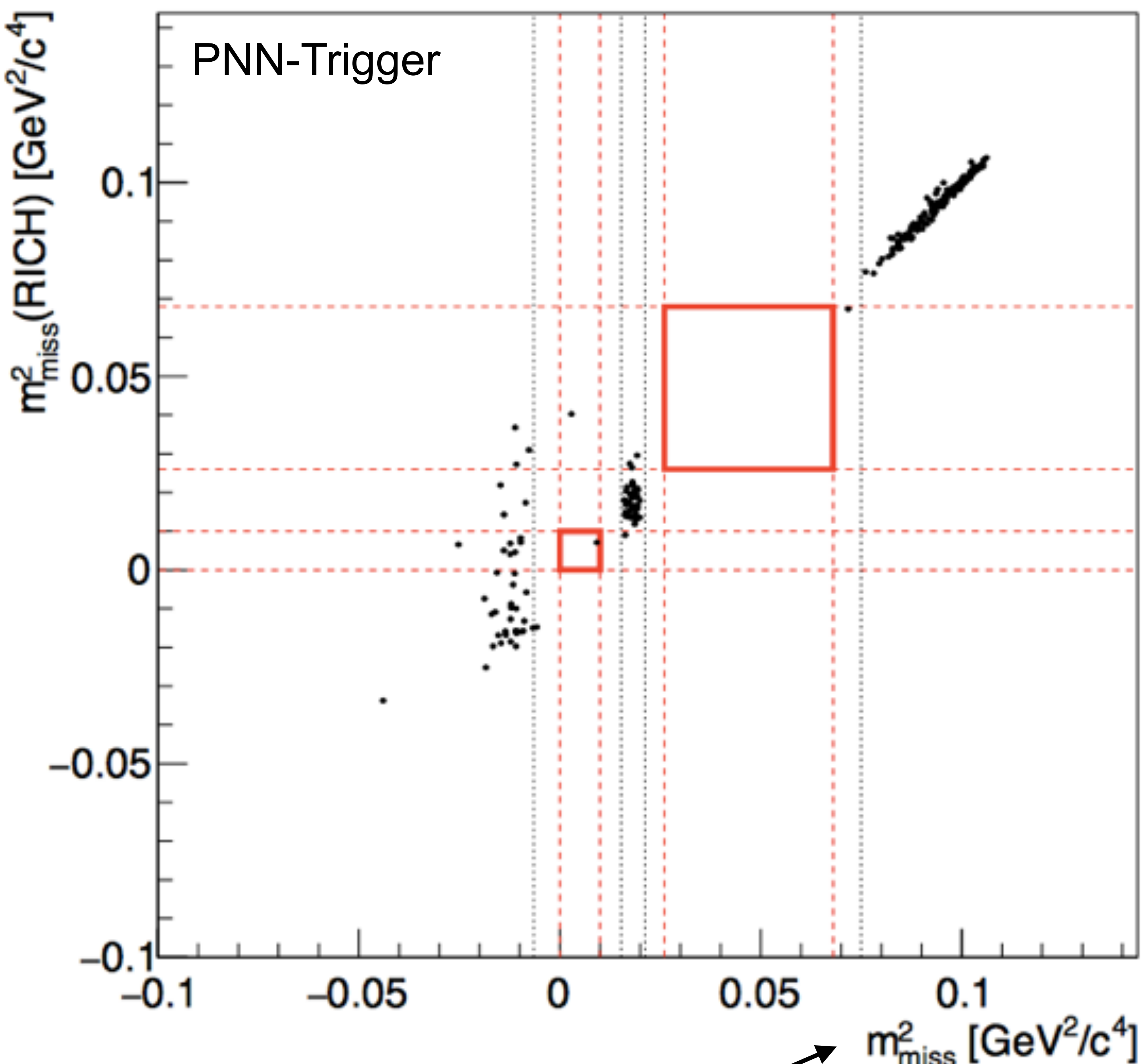
- $O(10^{-8})$ assuming 25-30% of accidental losses (measured with data)

Hermetic $\gamma$ veto suppression of $\pi^0 \rightarrow \gamma\gamma$ decays $< 10^{-7}$

# Preliminary Result

$P_\pi$ estimated with RICH

From $2.3 \times 10^{10}$ $K^+$ decays in fiducial volume




$P_\pi$ estimated with Spectrometer

**Expected signal:**

- $K^+ \to \pi^+\nu\nu \simeq 0.064$

(normalization $K^+ \to \pi^+\pi^0$)

**Expected background:**

- $K^+ \to \pi^+\pi^0 \simeq 0.024$
- $K^+ \to \mu^+\nu \simeq 0.011$
- $K^+ \to \pi^+ \pi^+ \pi^- \simeq 0.017$
- Beam-induced < 0.005

(estimated with data-driven method)

No event in signal region*

*Event in box has $m^2_{miss}$(NoGTK) outside the signal region

# Conclusion

- **Results from 5% of 2016 data has been presented ($2.3\times10^{10}$ kaon decays)**
  No signal observed compared to expectation of 0.064 events

- **Results from the full 2016 dataset ($\sim 4\times10^{11}$ kaon decays) will be presented at Rencontres de Moriond (SES $\sim O(10^{-10})$)**
  The complete analysis is done blindly

- **Processing of the 2017 data is on-going ($\sim 3\times10^{12}$ kaon decays)**
  Expected 10-15 $K^+ \to \pi^+\nu\nu$ signal events

- **Data taking will continue through 2018 (april-november)**

- **Along with the BR($K^+ \to \pi^+\nu\nu$) measurement a rich program of physics will be addressed**

# Broader NA62 Physics Program

The high-intensity, high-performance NA62 setup is ideal for many other **measurements** and **new physics searches**

**Standard Kaon Physics**

- Measurements of the BR of all the main $K^+$ decay modes
- Chiral perturbation theory studies: $K^+ \rightarrow \pi^+\gamma\gamma$, $K^+ \rightarrow \pi^+\pi^0 e^+e^-$, $K^+ \rightarrow \pi^{0(+)}\pi^{0(-)} l^+\nu$
- Precision measurement of $R_K = \Gamma(K^+ \rightarrow e^+\nu_e)/(K^+ \rightarrow \mu^+\nu_\mu)$

**Searches for lepton-flavour or lepton-number violating decays**

- $K^+ \rightarrow \pi^+\mu^\pm e^\mp$, $K^+ \rightarrow \pi^-\mu^+e^+$, $K^+ \rightarrow \pi^-e^+e^+$, $K^+ \rightarrow e^+\nu\gamma$, $K^+ \rightarrow \pi^-\mu^+\mu^+$ (+ radiative modes)

$10^{13}$ $K^+$: expected sensitivity $10^{-12}$. Improve by ~x100 the past results.

**Neutral pion**

- $\pi^0$ form factor
- Ultra-rare/forbidden decays ($\pi^0 \rightarrow \gamma\gamma\gamma$, $\pi^0 \rightarrow \gamma\gamma\gamma\gamma$, $\pi^0 \rightarrow \nu\nu$)

**Searches for exotic particles** → *Talk from T. Spadaro!*

- Heavy neutral leptons, axion-like particles, dark photons

Thank you for the attention from the NA62 Collaboration!

28 institutions, ~200 participants,

Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna(JINR), Fairfax, 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, Sofia, TRIUMF, Turin, Vancouver(UBC)