Rare Kaon Physics

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Outline

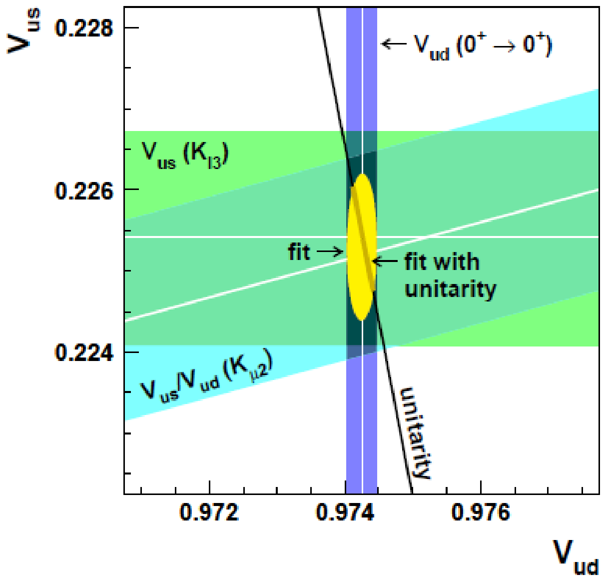
- Kaon Physics: overview
- Present days: setting the context
- (Brief) theoretical introduction to $K \to \pi\nu\bar{\nu}$
- NA62 @ CERN SPS
- A glance toward the future
- Conclusions

Kaon Physics: a Building Block of the Standard Model

- Discovery of strange particles: first observation of a quark-flavour not present in the ordinary matter *[Nature 160 4077 (1947) 855]*
- Postulation of neutral meson oscillation *[Phys. Rev 97 (1955) 1387]*
- θ - τ puzzle: first hint of P violation *[Phys. Rev. 104 (1956) 254]*
- Discovery of CP violation in the K^0 mixing *[Phys. Rev. Lett. 13 (1964) 138]*
- 3 quark-model to describe the observed meson / baryon spectra *[Phys. Lett. 8 (1964) 214]*
- Prediction of the c quark to explain the unexpectly low observed branching ratio of the decay $K_L \rightarrow \mu^+\mu^-$ *[Phys. Rev. D 2 (1970) 1285]*
- First evidence of CP violation in the K^0 decay (NA31@ CERN) *[Phys. Lett. B 206 (1988) 169]*
- Measurement of CP violation in the K^0 decay (NA48@CERN, KTeV@FNAL) $\mathcal{R}e(\varepsilon'/\varepsilon) = (16.8 \pm 1.4) \times 10^{-4}$ *[Phys. Lett. B 544 (2002) 97, Phys. Rev. D 83 (2010) 092001]*

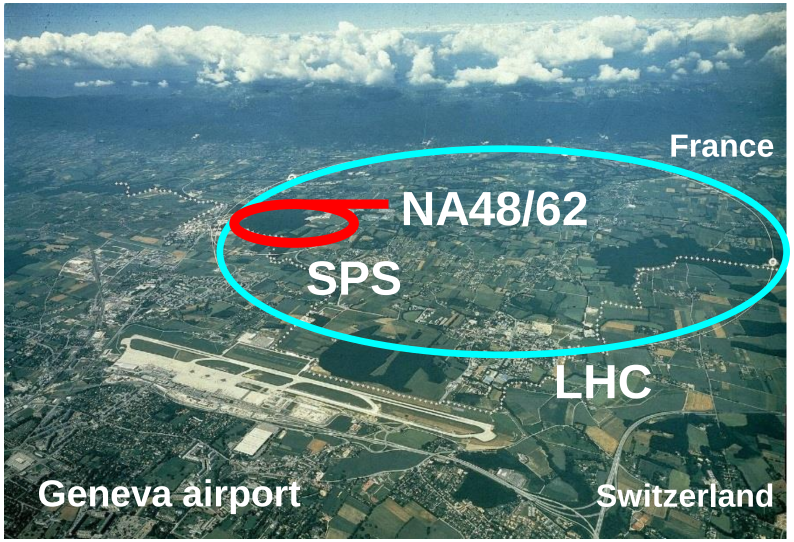
Kaon Physics: Toward the Present Era

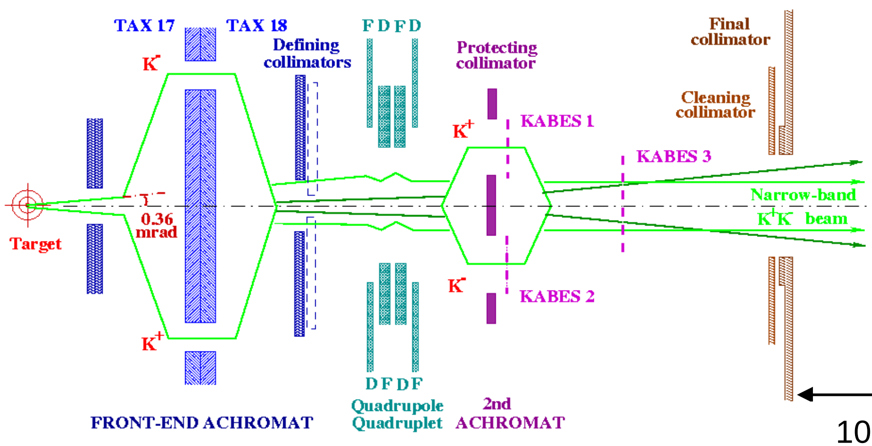
- Kaon Experiments [pre-LHC era 2000 – 2010]
  - NA48 (CERN), KTeV (FNAL), KLOE (LNF), CPLEAR (CERN), E865 (BNL), ISTRA+ (Protvino)
- Low energy QCD (e.g. χPT)
- Test of CPT symmetry invariance
- Precision test of the CKM unitarity
  - Most precise determination up to date of V_{us} from data on leptonic and semileptonic kaon decays *[Eur. Phys. J. C 69 (2010) 399].*
  - $|V_{us}| = 0.2253 \pm 0.0009$
- Test of lepton universality
- High order test of SM through rare K decays



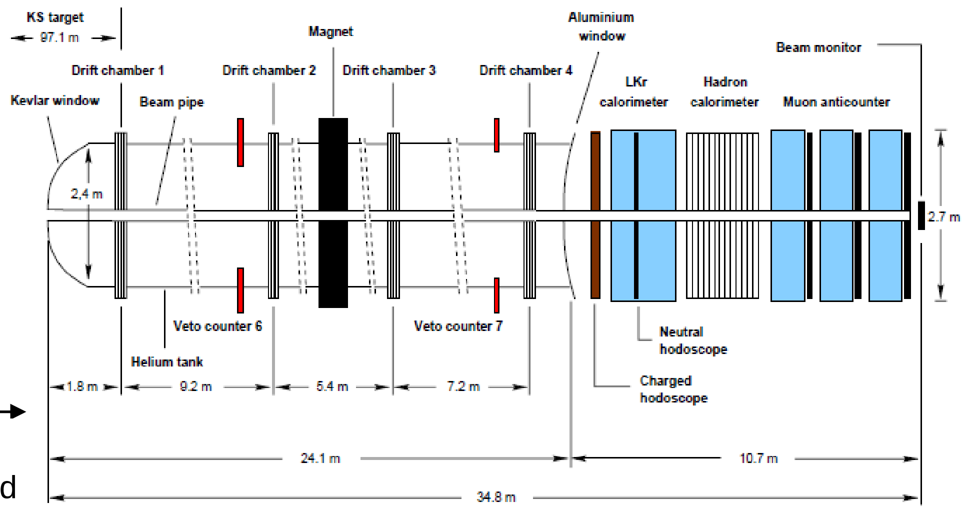
Kaon @ CERN - SPS

’97-’01	NA48: ε′/ε
’02	NA48/1: K_S (rare decays)
’03-’04	NA48/2: $K^{\pm}$ (CP violation), semileptonic, low energy QCD
’07-’08	NA62: Lepton universality



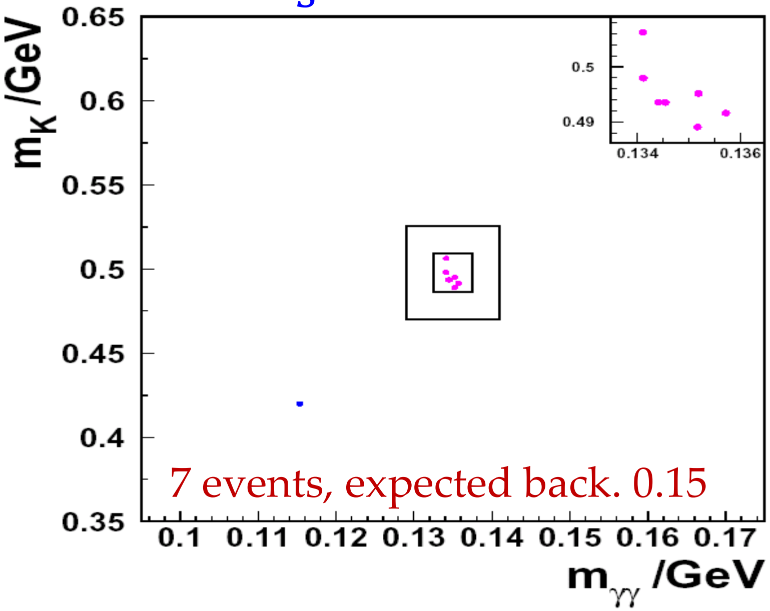


100 m evacuated volume

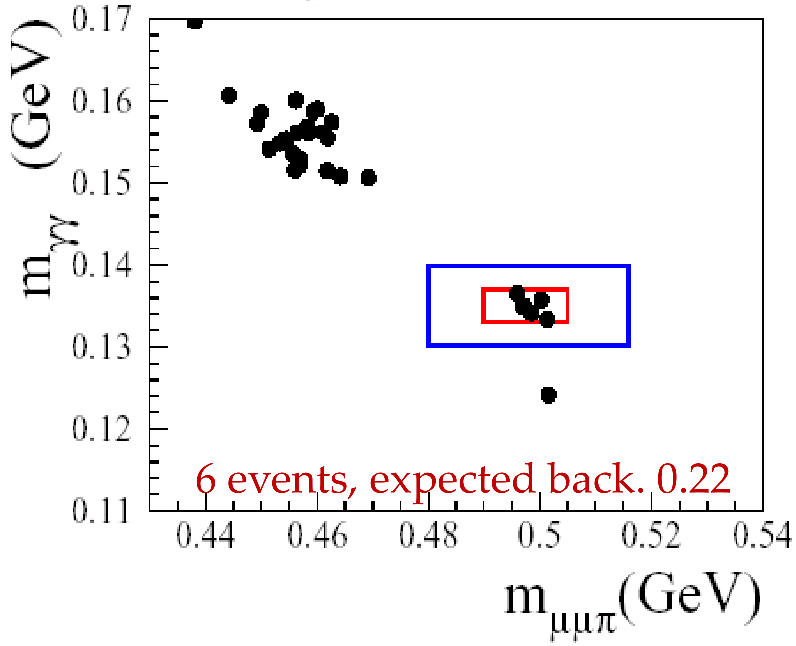


Rare Kaon Decays (NA48/1)

$K_S \rightarrow \pi^0 e^+ e^-$



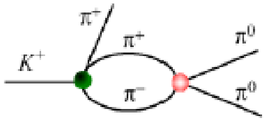
$K_S \rightarrow \pi^0 \mu^+ \mu^-$

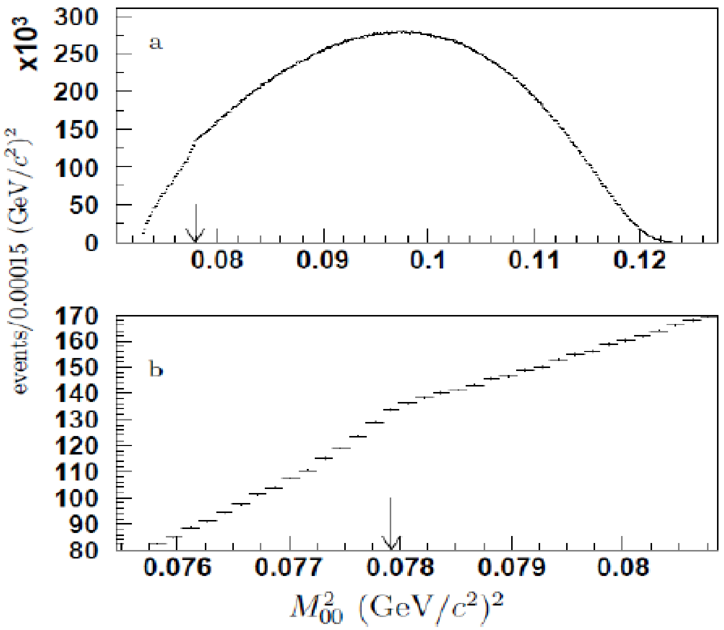


- $Br(K_S \rightarrow \pi^0 e^+ e^-) = (5.8^{+2.8}_{-2.3}(stat) \pm 0.8(syst)) \times 10^{-9}$ *[Phys. Lett. B 576 (2003)]*
- $Br(K_S \rightarrow \pi^0 \mu^+ \mu^-) = (2.9^{+1.4}_{-1.2}(stat) \pm 0.2(syst)) \times 10^{-9}$ *[Phys. Lett. B 599 (2004)]*

Low Energy Physics (NA48/2)

- $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$
- ππ scattering length

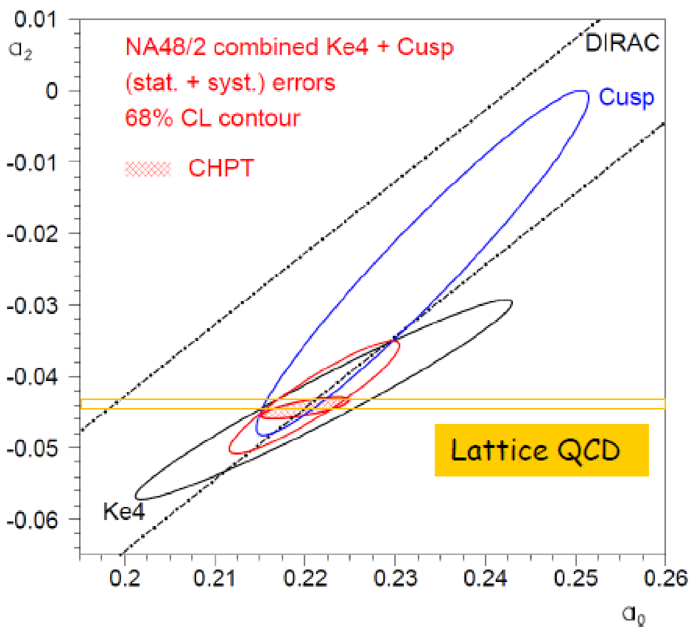




$$a_0^0 - a_0^2 = 0.2639 \pm 0.0020_{stat} \pm 0.0015_{syst}$$
$$a_0^2 = -0.0429 \pm 0.0044_{stat} \pm 0.0028_{syst}$$
$$a_0^0 = 0.2210 \pm 0.0047_{stat} \pm 0.0040_{syst}$$

[Eur. Phys. J. C 64 (2009) 589]

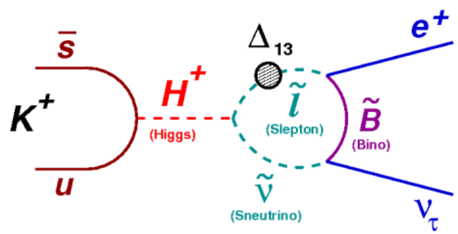
- $K^{\pm} \to \pi^{+}\pi^{-}e^{\pm}\nu$ (K_{e4})
- ππ scattering length
- 1.13 M, 0.6% background

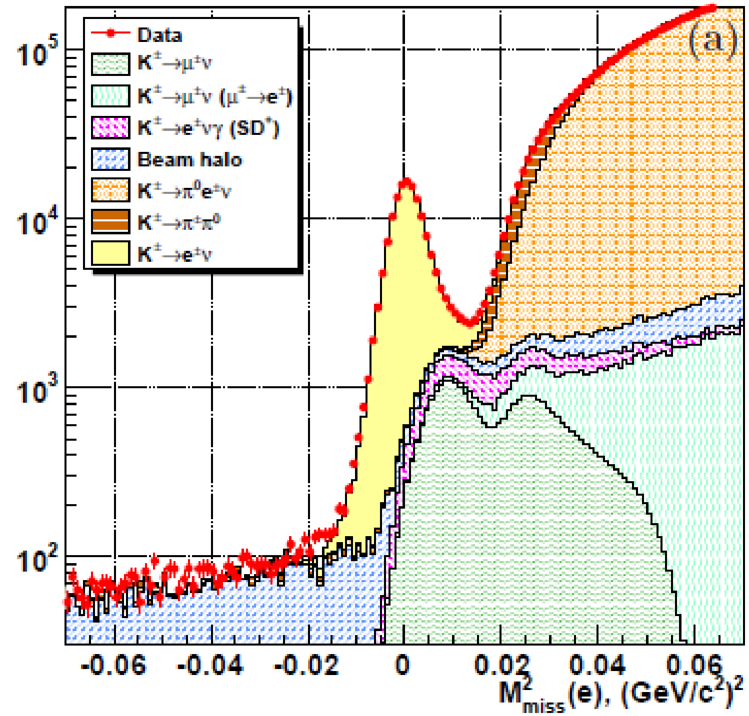


[Eur. Phys. J. C 70 (2010) 635]

Lepton Universality (NA62 '07)

- SM: $R_K^{SM} = \dfrac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = (2.477 \pm 0.001) \times 10^{-5}$
- SUSY:



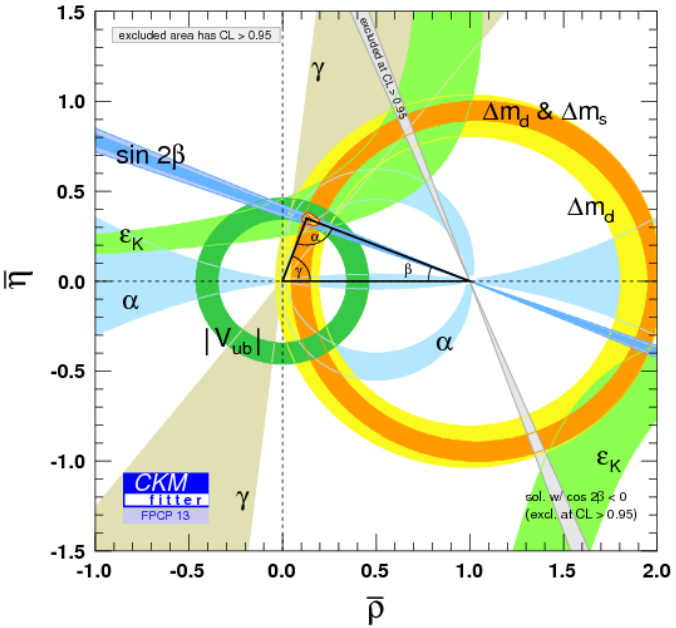


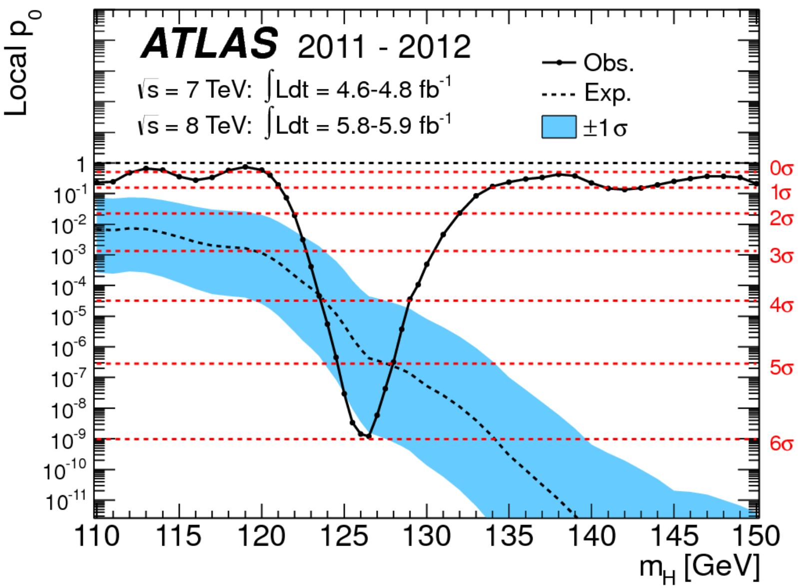
- NA62 4-months run ('07)
- NA48 apparatus
- Full data sample: 145'958 K_{e2}
- 10% background measured using data

$R_K = (2.488 \pm 0.007_{stat.} \pm 0.007_{syst.}) \times 10^{-5} = (2.488 \pm 0.010) \times 10^{-5}$ ($\chi^2/ndf = 47/39$)

[Phys. Lett. B 719 (2013) 326]

Present days: the LHC era

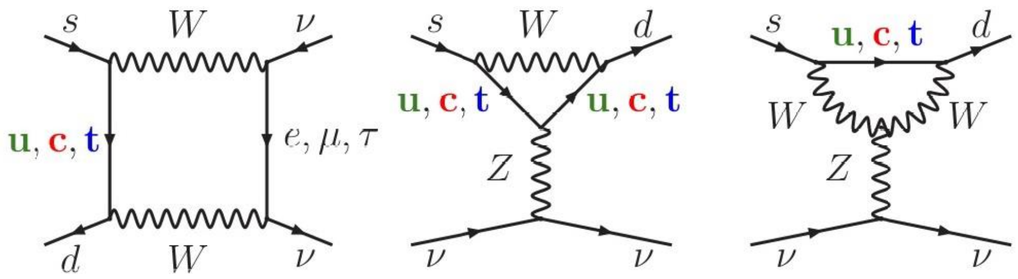




- SM Flavour dynamic studied (B-factories).
- Higgs – like boson found (LHC)
- SUSY not observed directly (LHC)
- Dark matter / energy
- Matter / anti-matter asymmetry
- ν mass and oscillation
- Hierarchy problem
- …

The $K \to \pi\nu\bar{\nu}$ decays: a theoretical clean environment

- FCNC loop processes: s→d coupling and highest CKM suppression



- Very clean theoretically
  - Short distance contribution dominate
  - No hadronic uncertainties

- SM predictions *[Brod, Gorbahn, Stamou, Phys. Rev. D 83, 034030 (2011)]*
  [G. Buchalla, A.J. Buras, Nucl. Phys. B 412, 106 (1994)]

$$BR(K_L \to \pi^0 \nu\nu) = (2.43 \pm 0.39 \pm 0.06)\times 10^{-11}$$
$$BR(K^+ \to \pi^+ \nu\nu) = (7.81 \pm 0.75 \pm 0.29)\times 10^{-11}$$

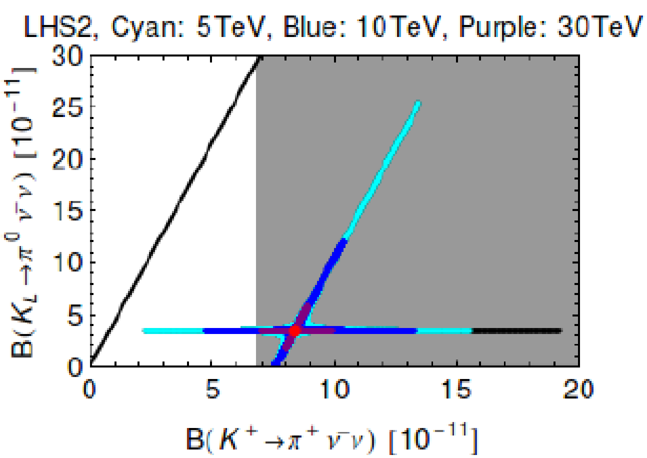
1° error: unceraintiy from input parameters

2° error: pure theoretical uncertainty

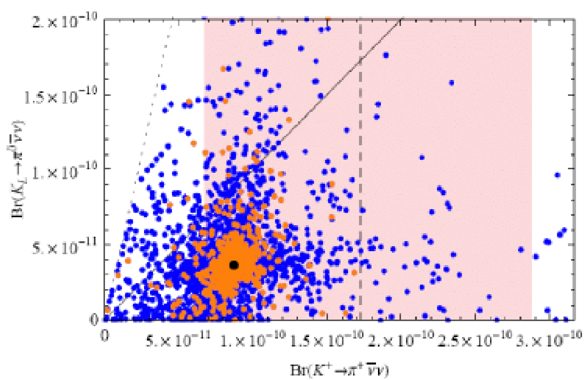
$K \to \pi\nu\bar{\nu}$ NP Sensitivity

- Z′ gauge boson mediating FCNC at tree level *[A.J.Buras et al., JHEP 1302 (2013) 116]*
- Little Higgs with T-parity *[JHEP 0903 (2009) 108]*
- Custodial Randall-Sundrum *[Acta Phys. Polon. B 41 (2010) 657]*
- Best probe of MSSM non-MFV (still not excluded by LHC) *[JHEP 0608 (2006) 088]*

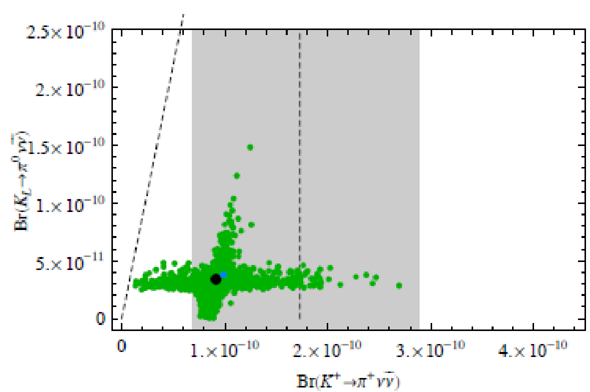
Z' model



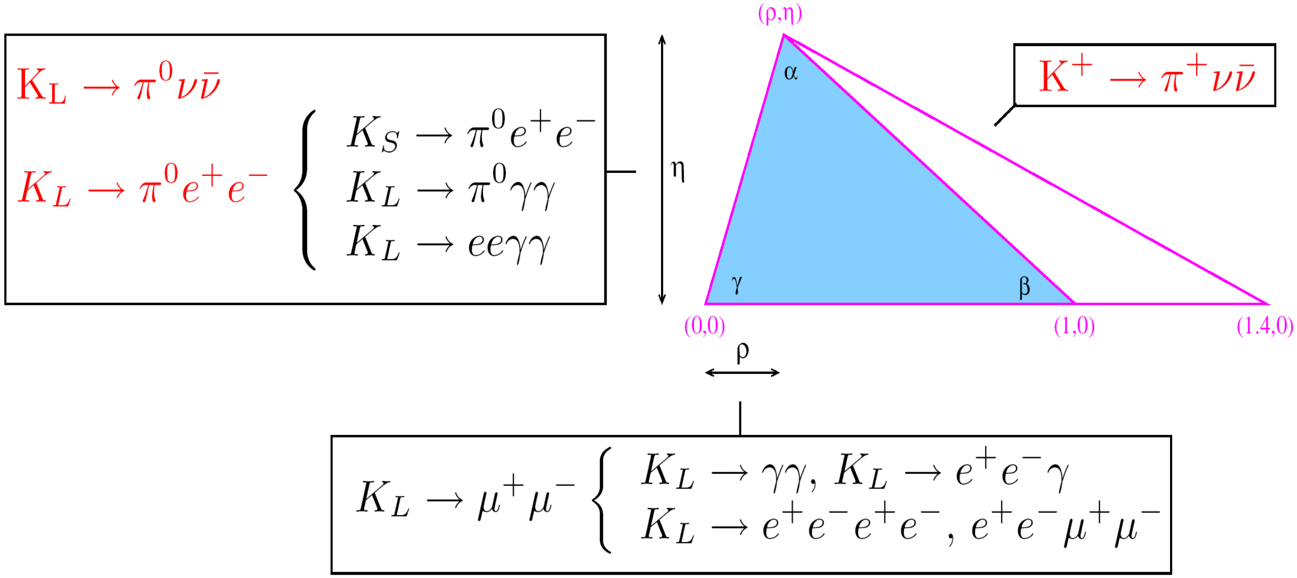
Randall - Sundrum



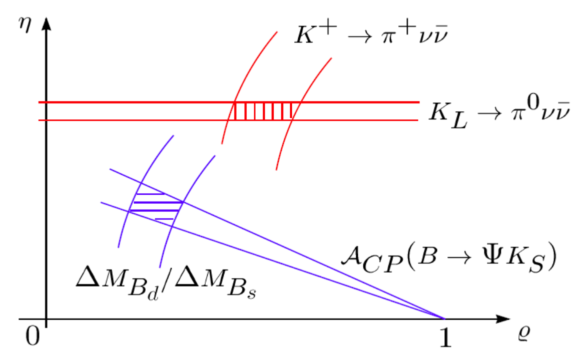
Little Higgs



Connection with Flavour Physics



- K physics alone can fully constraint the CKM unitarity triangle.
- Comparison with B physics can provide description of NP flavour dynamics

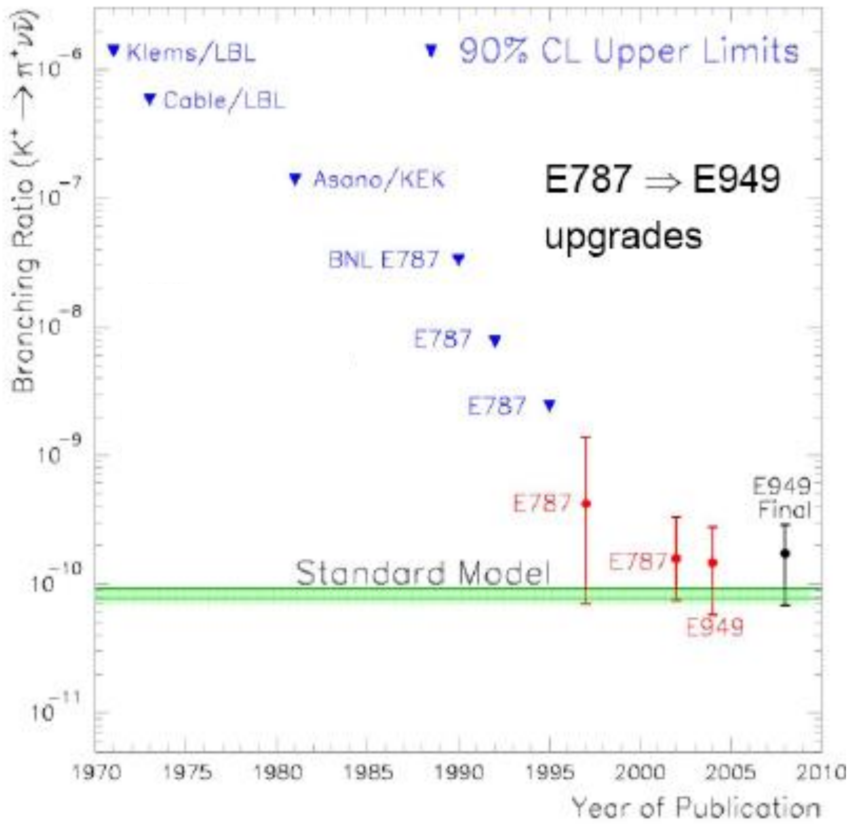


$K \to \pi\nu\bar{\nu}$ in LHC era: Experimental Requirement

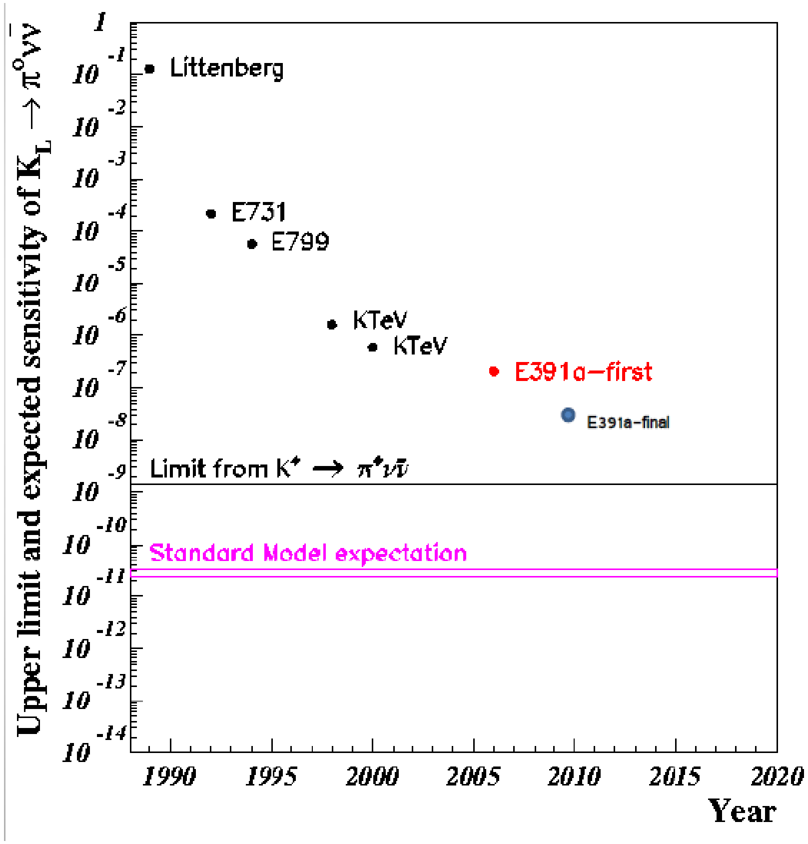
BR($K \to \pi\nu\bar{\nu}$) measurement with $< 10\%$ accuracy

$K \to \pi\nu\bar{\nu}$ Experimental State of the Art

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



$K_L \to \pi^0\nu\bar{\nu}$



The NA62 Experiment for $K^+ \to \pi^+ \nu \bar{\nu}$

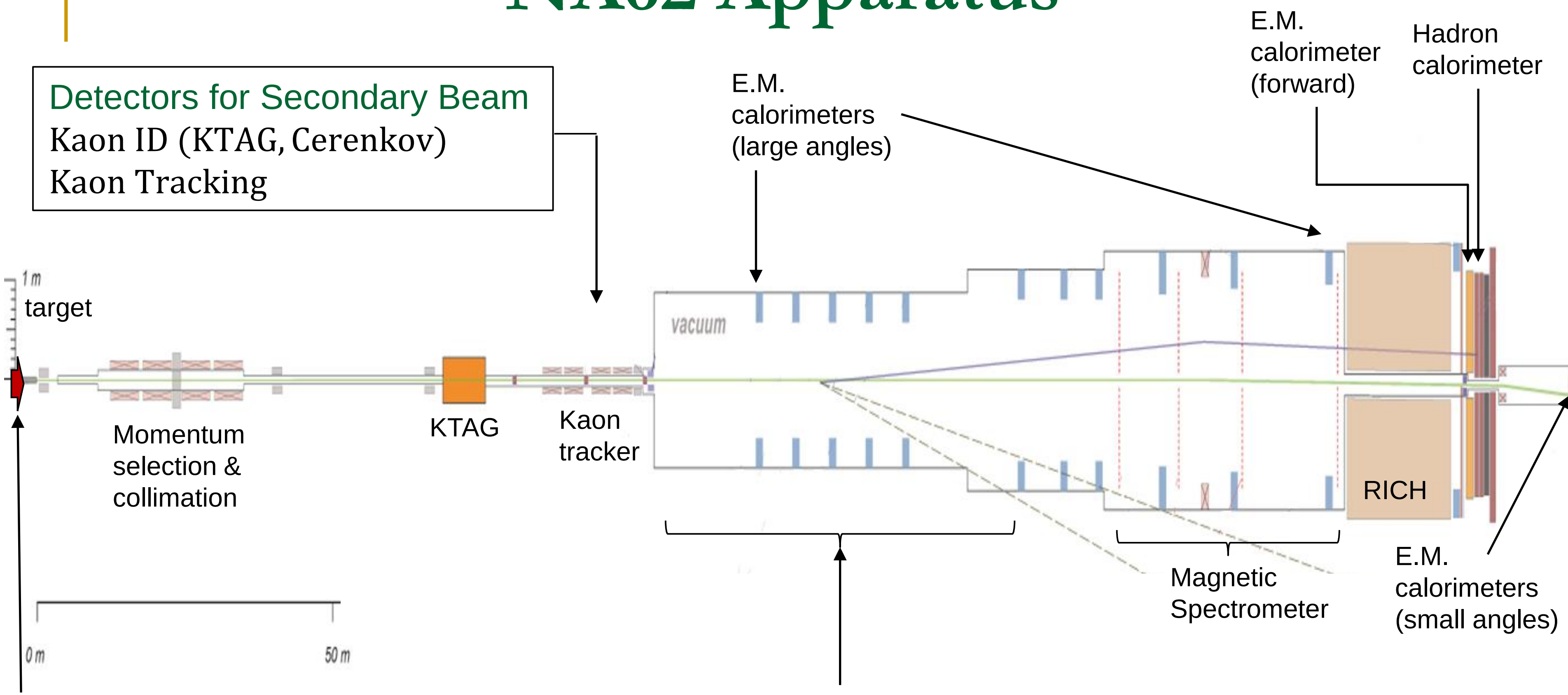
- Experiment at CERN – SPS, replacing the NA48 apparatus

- Goal:
  - 10% precision BR($K^+ \to \pi^+ \nu \bar{\nu}$) in 2 years of data

- Requirements:
  - Statistics: O(100) events [BR(SM) ~ 8 x 10^{-11}]
  - K decays (2 years) 10^{13} , Signal acceptance ~ 10%
  - Systematics: <10% precision background measurement
  - >10^{12} background rejection (<20% background)

- Technique:
  - K Decay – in – flight

NA62 Apparatus



SPS proton
400 GeV
10^{12} p/s

Secondary Beam
$75 \pm 1\ GeV/c$
$20\ cm^2, < 100\ \mu rad$
$K(6\%), \pi^+, p$
$750\ MHz$

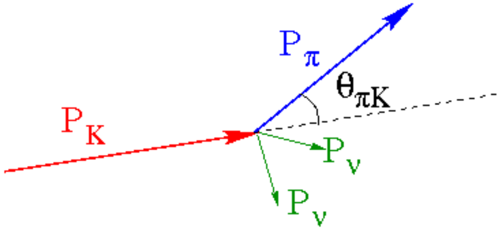
Kaon Decay
~5 MHz
$4.5 \times 10^{12}/year$
60 m volume
10^{-6} mbar vacuum

Detectors for decay products
Charged particle tracking
Charged particle Time Stamping
Photon detection
Charged particle ID
Pion and muon identification

Status of NA62

- Installed (almost completely)
- First run: mid October – mid December 2014
- Detector commissioning
- Data quality studies

Scheme for $K^+ \to \pi^+ \nu\bar{\nu}$ Analysis



- Signal (10% accetpance)

- Background
- K^+ decay modes
- Non-K decay events

K^+ main decays	BR
$K^+ \to \mu^+\nu$	0.6355
$K^+ \to \pi^+\pi^0$	0.2066
$K^+ \to \pi^+\pi^+\pi^-$	0.0559
$K^+ \to \pi^+\pi^0\pi^0$	0.0176
$K^+ \to \pi^0 e^+\nu$	0.0507
$K^+ \to \pi^0\mu^+\nu$	0.0335
$K^+ \to \pi^+\pi^- e^+\nu$	4.257×10^{-5}

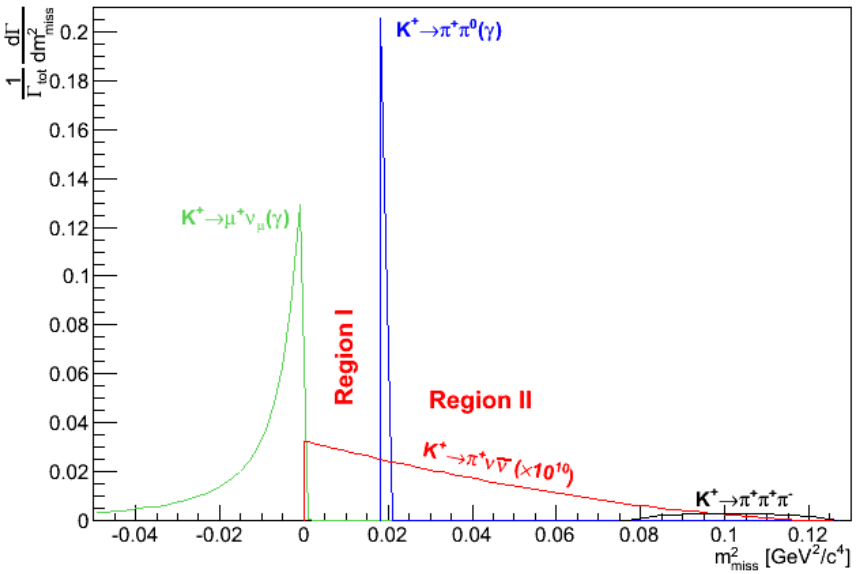
- Background suppression factors $O(10^{12})$

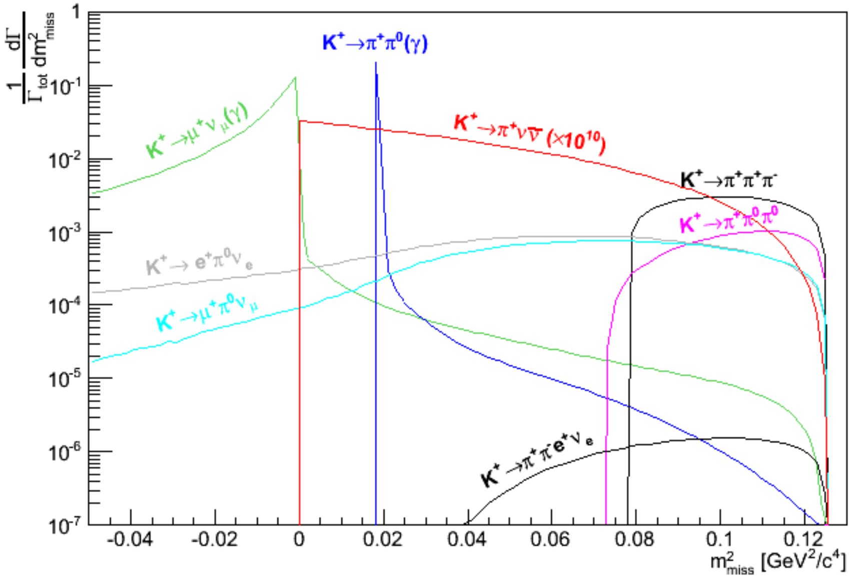
Kinematics	$O(10^4\text{-}10^5)$
Particle ID	$O(10^7)$
γ detection	$O(10^8)$
Non K decays	$O(10^8\text{-}10^9)$

- Measurement of background suppression factors from data
- Signal acceptance determination and BR measurement

Kinematics and Background Suppression

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

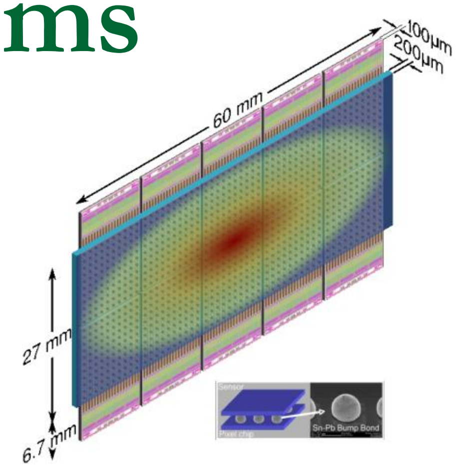




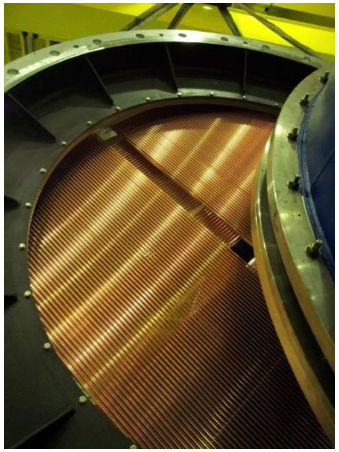
- Measurement of the K track $[\sigma(P_K)/P_K \leq 0.2\%, \sigma(\theta_K) \leq 20\ \mu m]$
- Mesurement of the π^+ track $[\sigma(P_\pi)/P_\pi \leq 1\%, \sigma(\theta_\pi) \leq 60\ \mu m$ in 10-50 GeV region]
- Analysis requirement: $P_{\pi^+} < 35$ GeV/c (separation from $K^+ \to \mu^+\nu$).
- Expected performances: O(10^4) suppression of the main background modes.
- Limitations to backgroud suppression: resolution tails, $\pi - K$ matching

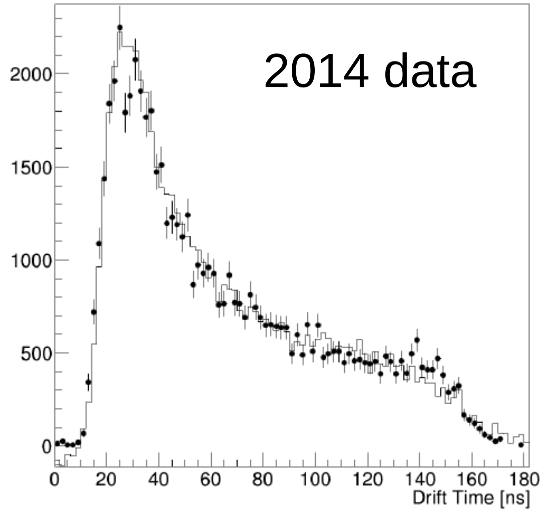
Tracking Systems

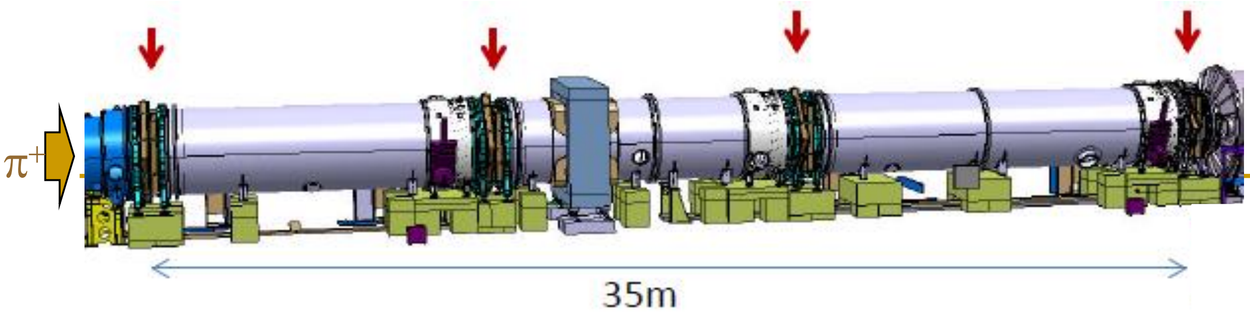
- Kaon tracker
- 3 Si pixel stations on the beam
- Rate: 750 MHz
- $X/X_0 < 0.5\%$ / station, $\sigma(t) \sim 200\ ps$
- Partially commissioned in 2014



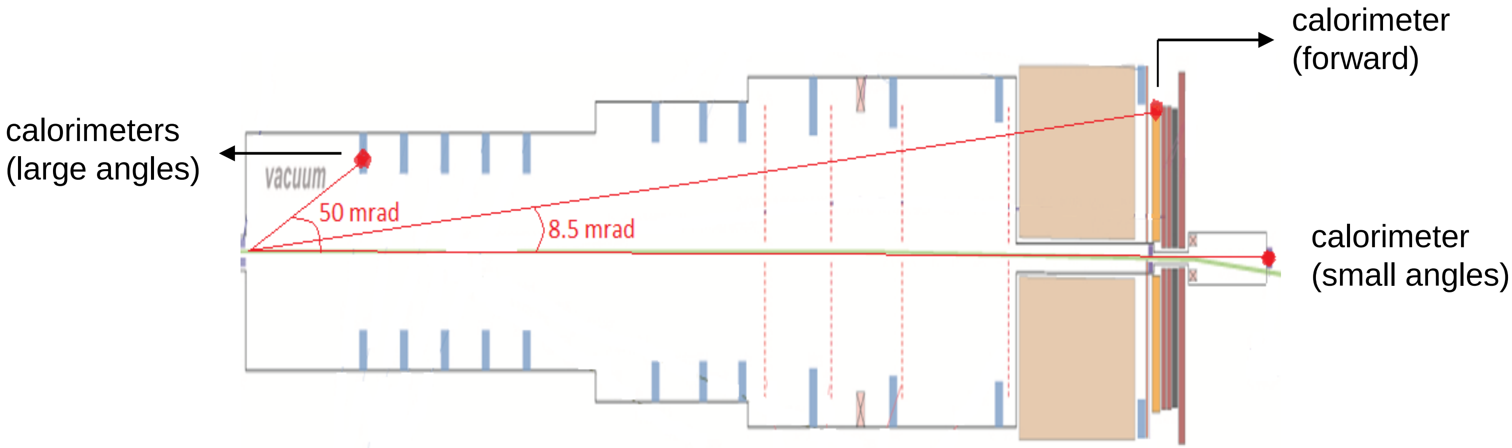
- Pion tracker
- Straw spectrometer in vacuum
- Rate 10 MHz
- $X/X_0 < 0.5\%$ / chamber
- Fully commissioned in 2014



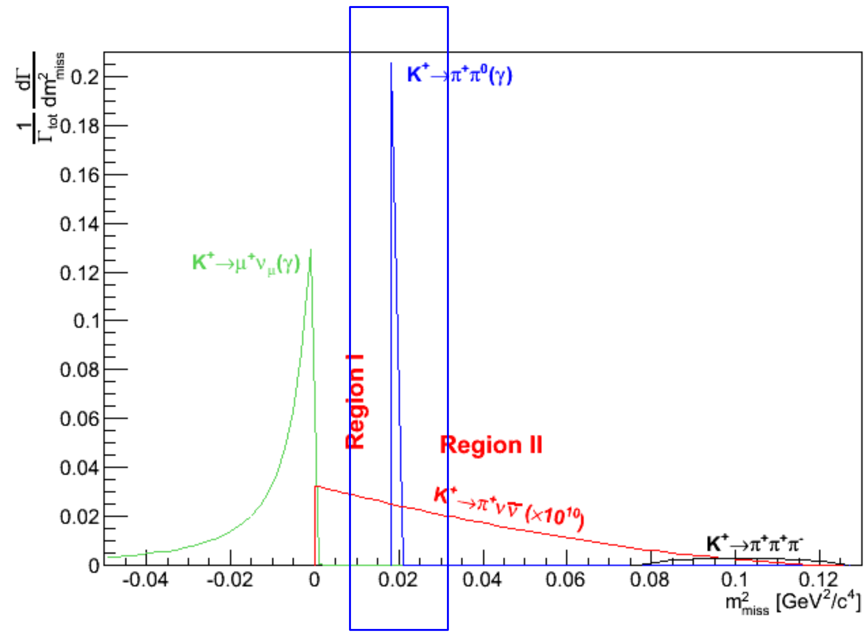




Photon rejection



- Mainly to suppress $K^+ \to \pi^+\pi^0$
- Analysis: $P_{\pi^+} < 35$ GeV/c $\to E_{\pi^0} > 40$ GeV
- Geometrical hermeticity: up to 50 mrad
- Inefficiency requirements on γ: $10^{-3} - 10^{-5}$
- Expected: $O(10^8)$ on π^0 rejection from $K^+ \to \pi^+\pi^0$

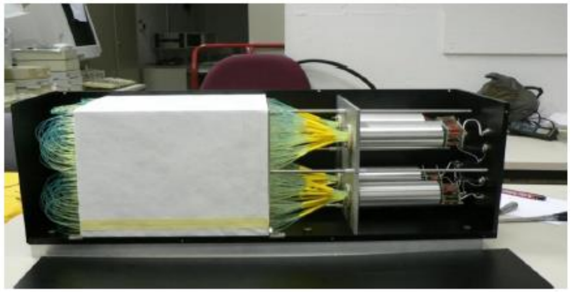


Photon Detectors

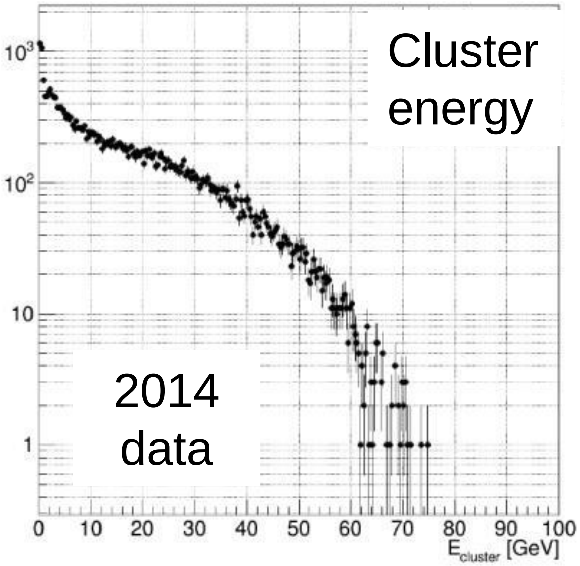
calorimeters
(large angles)

calorimeter
(forward)

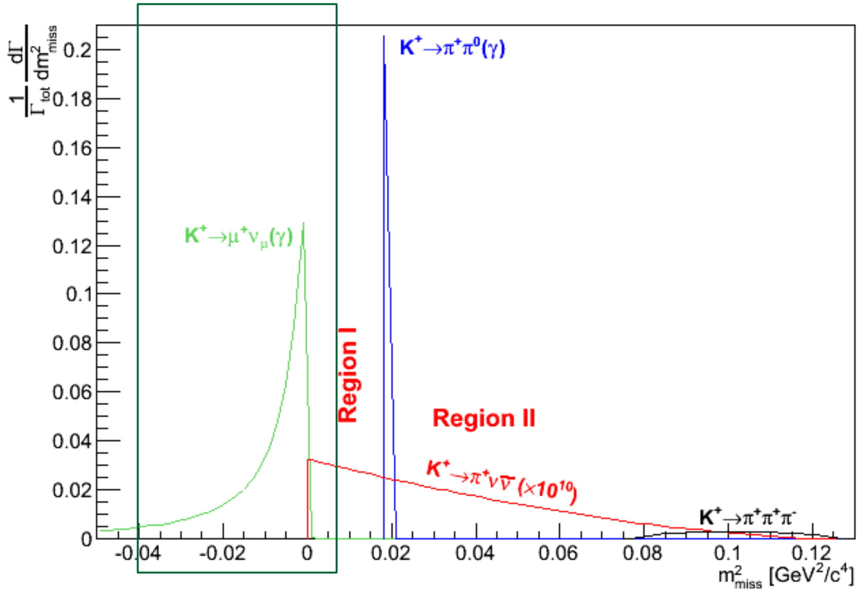
calorimeter
(small angles)

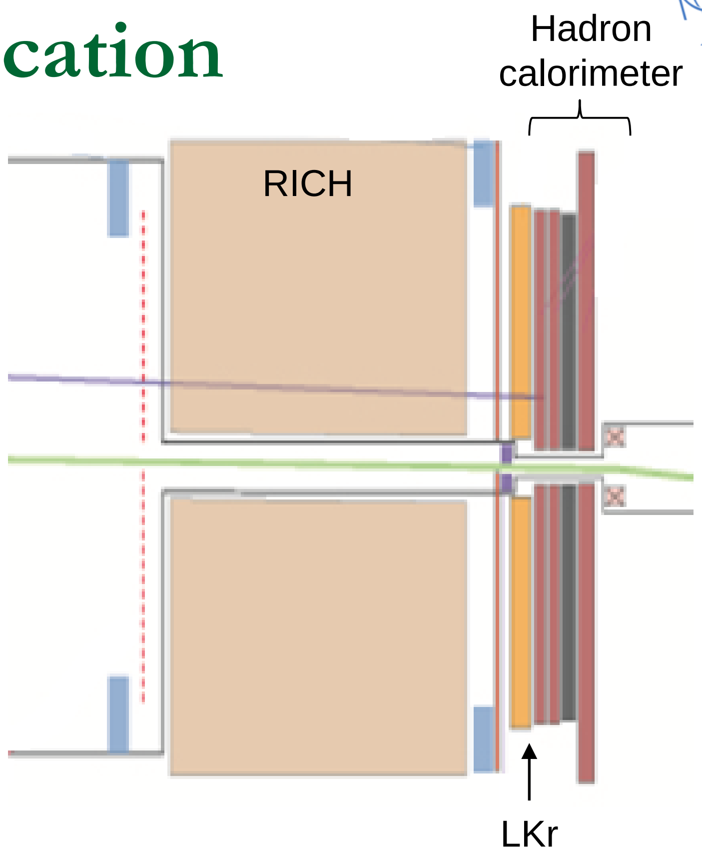


- Forward region
- Calorimeter at liquid Kripton (LKr, NA48)
- High energy, time, position resolution
- $< 10^{-5}$ efficiency for $\gamma > 10$ GeV (measured)
- New electronics commissioned in 2014



Particle Identification



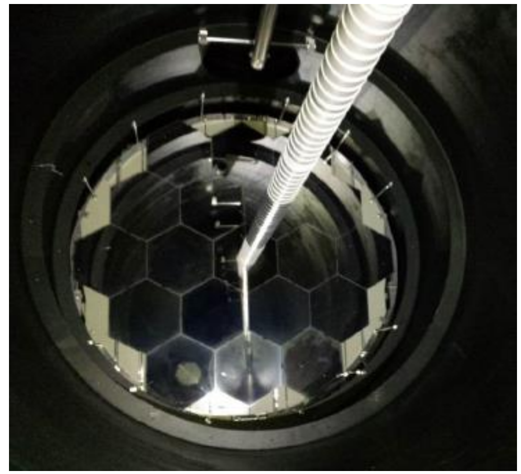


- π/μ/e separation
- Cerenkov and calorimetry technique emploied
- Analysis: $P_{\pi^+} < 35$ GeV/c to get the best μ/π separation using the Cerenkov technique
- Expected μ/π separation O(10^7)

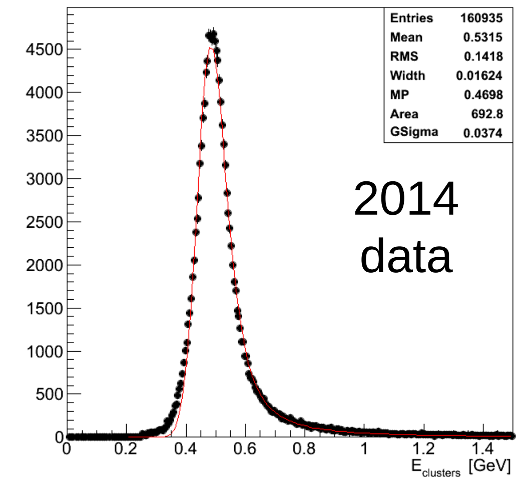
Particle ID Detectors

RICH Vessel

RICH Mirrors

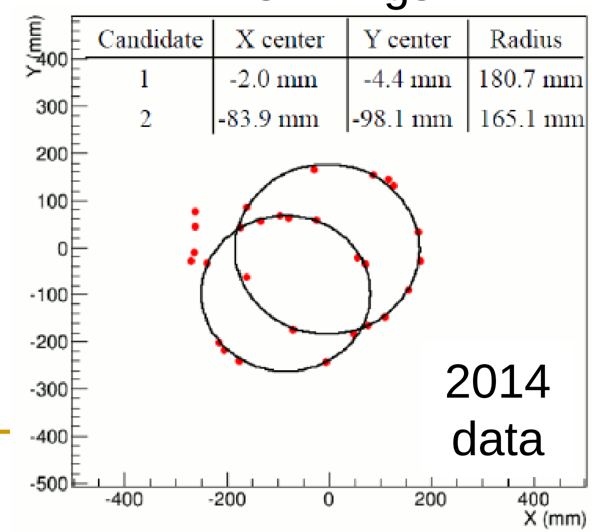


LKr MIP



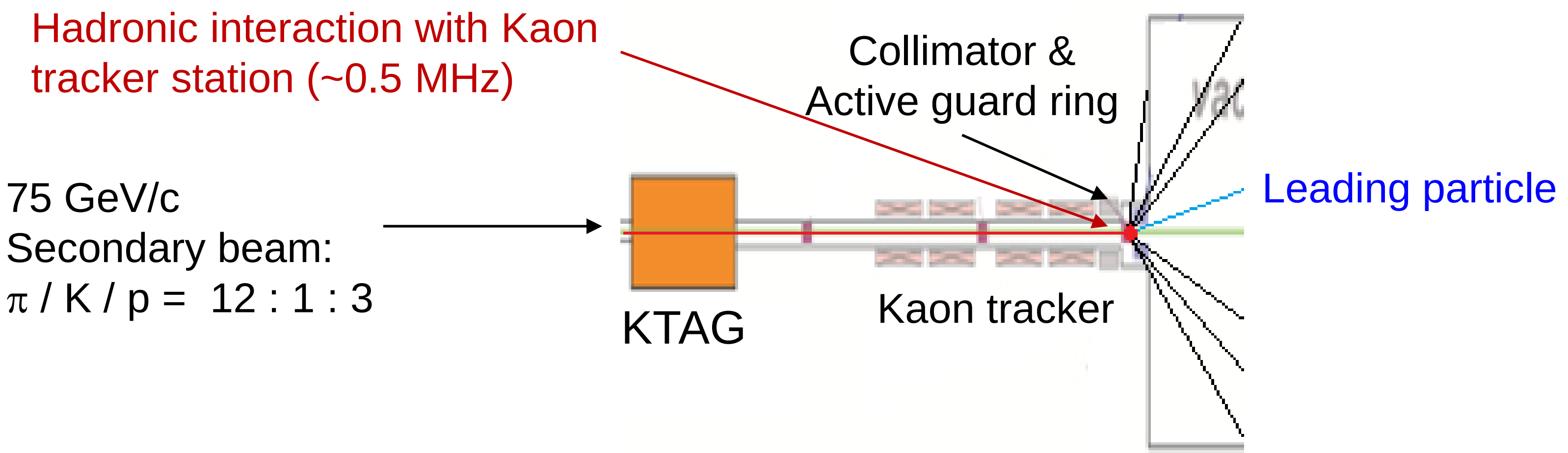
- RICH detector: 17 m, Ne @ 1 atm
- Cerenkov angle resolution ≤ 100 μrad
- Time resolution < 80 ps
- μ/π separation $>10^2$ measured on a prototype
- Redundancy in kinematic reconstruction
- Fully commissioned in 2014

RICH rings



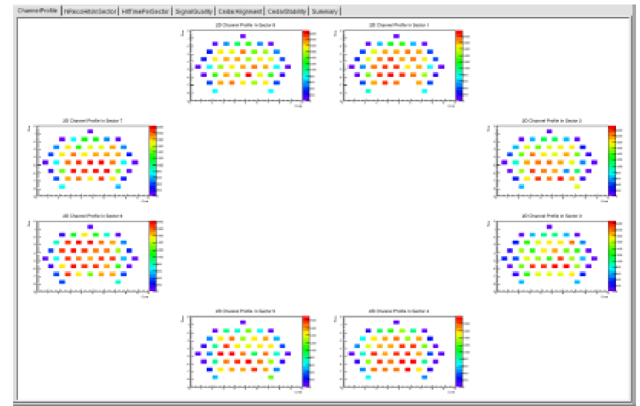
Candidate	X center	Y center	Radius
1	-2.0 mm	-4.4 mm	180.7 mm
2	-83.9 mm	-98.1 mm	165.1 mm

Non Kaon decay Background

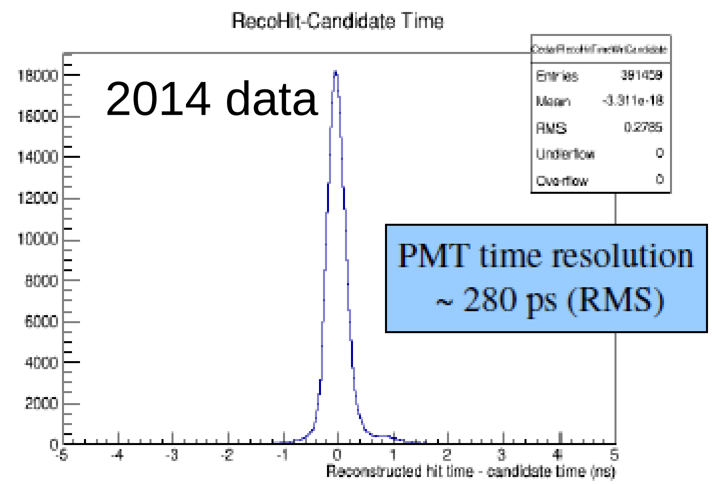


- Identify Kaon: KTAG
- Detect low energy products: guard - ring detector
- Reconstruct the origin of the leading particle: tracking systems

Beam K / π separation

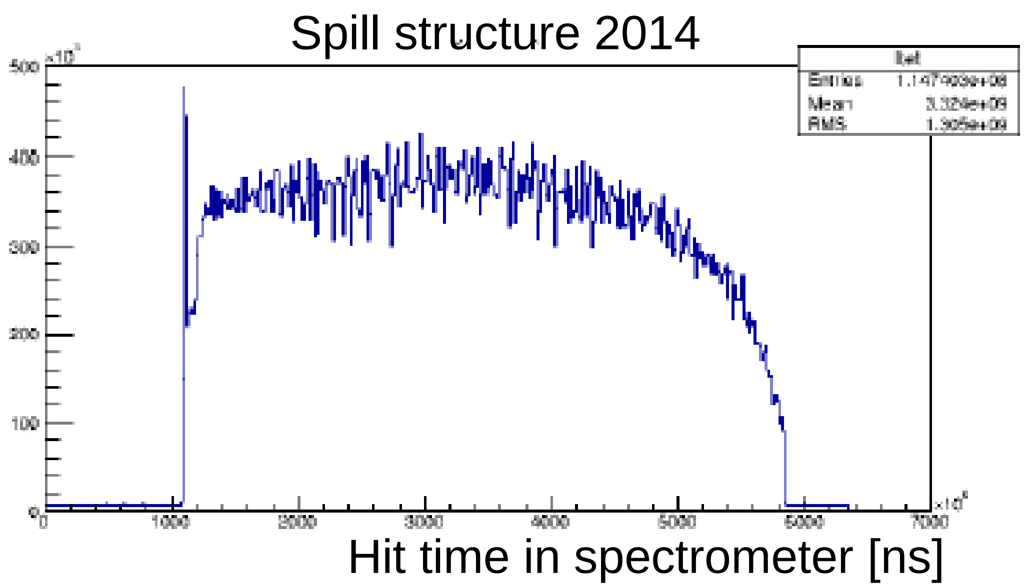


- KTAG Cerenkov counter
- Radiator N_2
- New external optics, PMs and readout
- < 80 ps time resolution
- 95% efficiency in K ID (> 99.9% purity)
- 50 MHz particle rate
- Fully commissioned in 2014



~18 PM/Kaon

Run 2014 (November - December)



- Run conditions:
- Continuous spill of protons on target for 6 s (every 20 s)
- 5% of the nominal beam intensity in 2014
- Trigger built from the signals in the downstream detectors (20 KHz)
- Data size: 20 Kbyte / event (~100 K events per spill).
- (last) 2 weeks of run dedicated to physics studies.

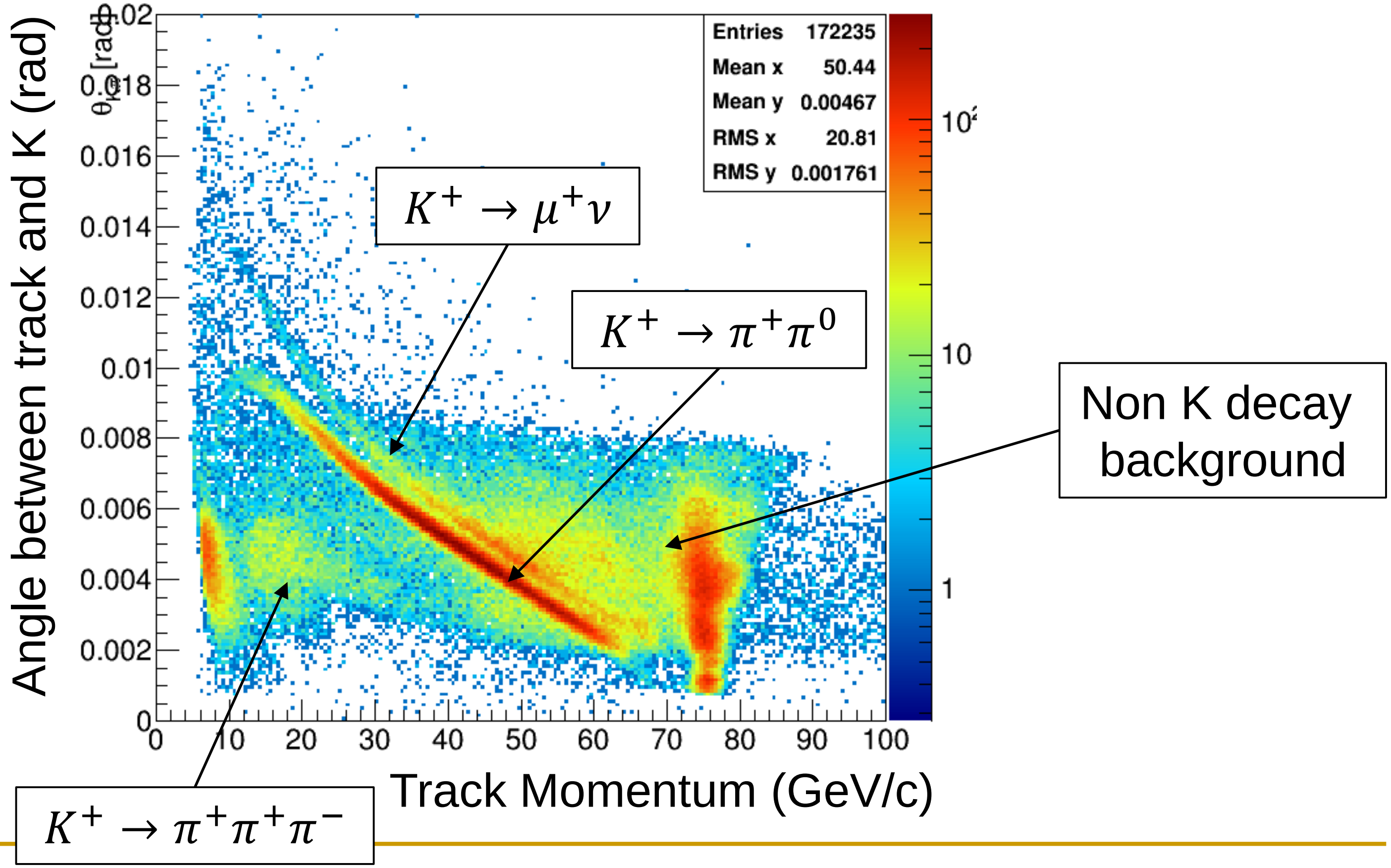
First Look to 2014 Data Quality

CAVEAT: Every plot is very preliminar

- Fresh data with complex detectors running for the first time
- No kaon tracker
- No detector calibrations / alignment
- First and un-complete versions of detector reconstructions
- Analysis from data at raw level
- 0.2% of the total statistics studied
- ...

First Look to 2014 Data Quality

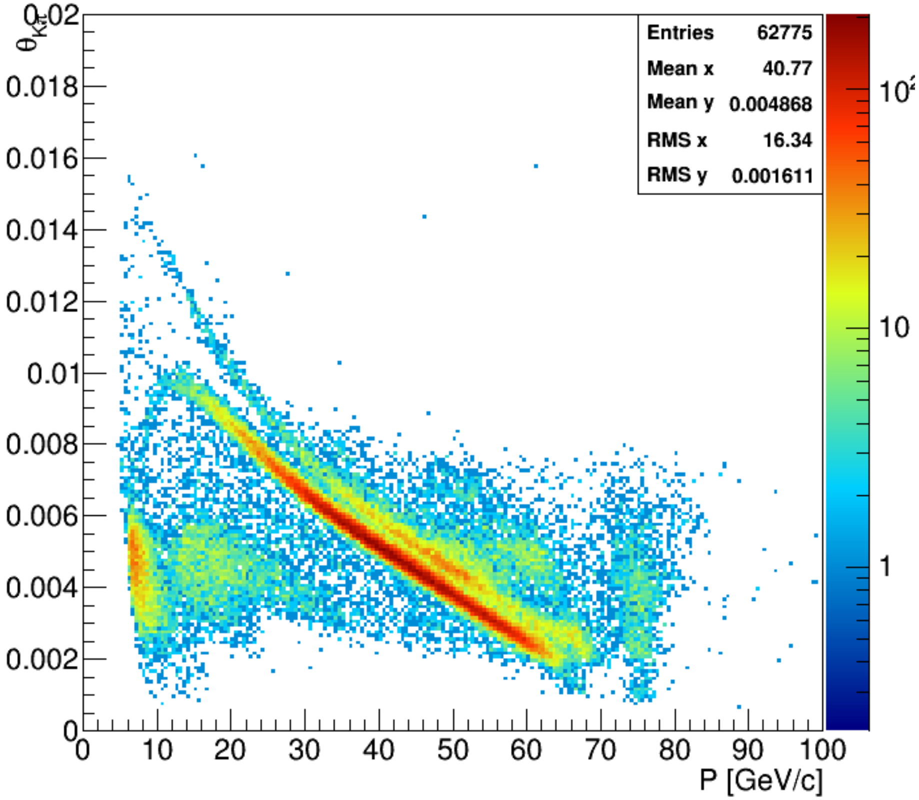
- Events with only 1 track in the spectrometer reconstructed (40 ns time window)
- 10^2 muon rejection at trigger level.



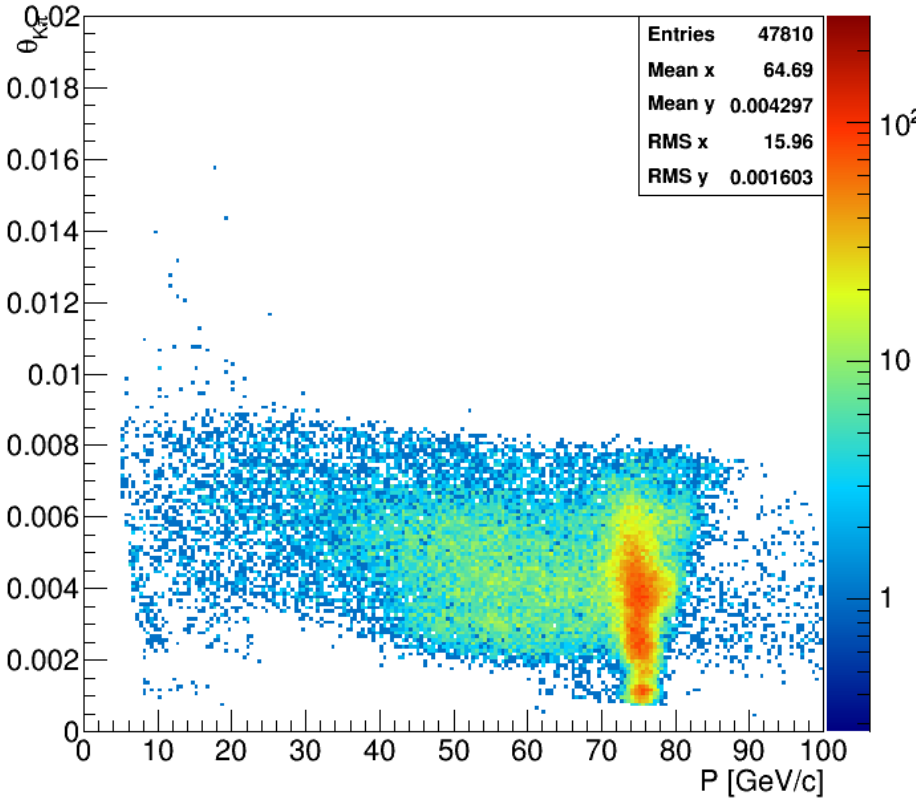
First Look to 2014 Data Quality

- Apply KTAG for K ID

K ID from KTAG in time with the track

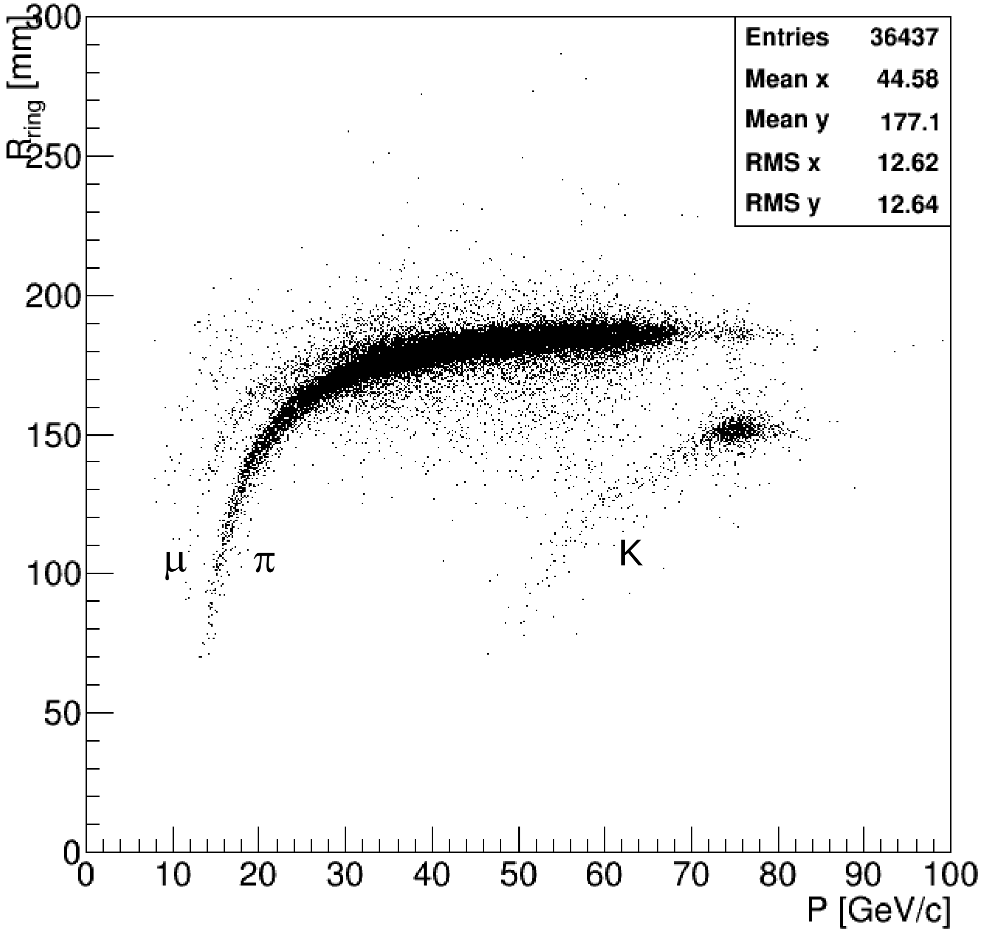


No K ID from KTAG



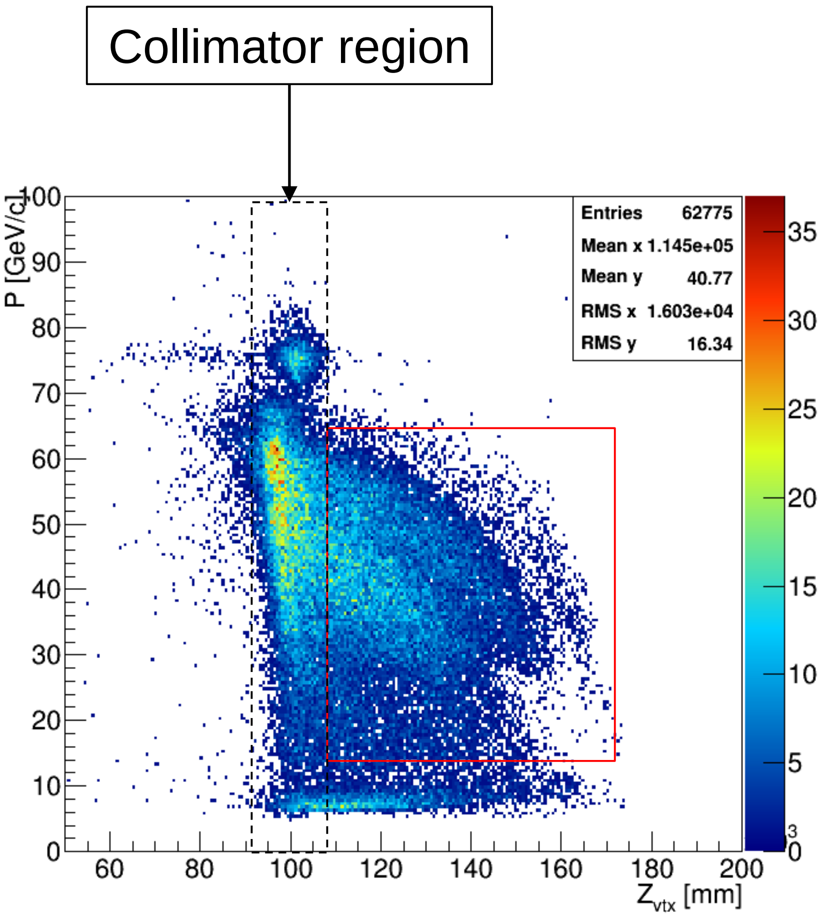
First Look to 2014 Data Quality

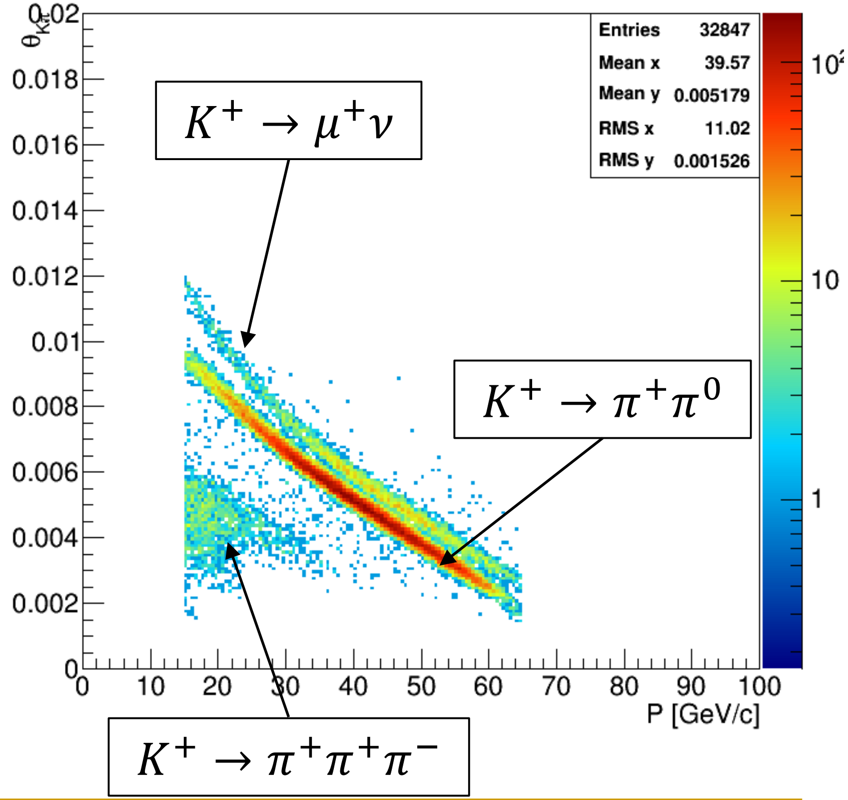
- Matching between tracks and RICH rings to study the particle content



First Look to 2014 Data Quality

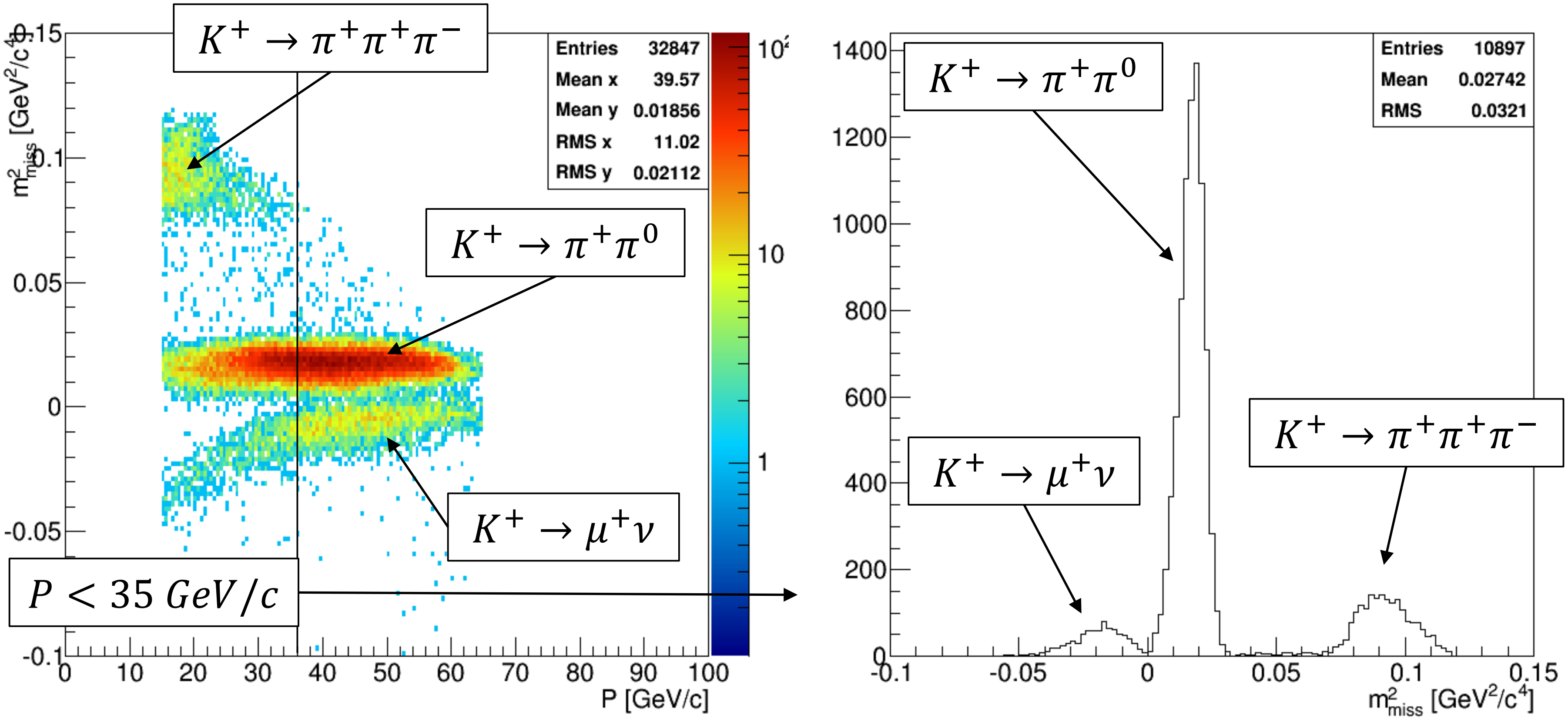
- Use track origin to suppress the background from kaon interactions





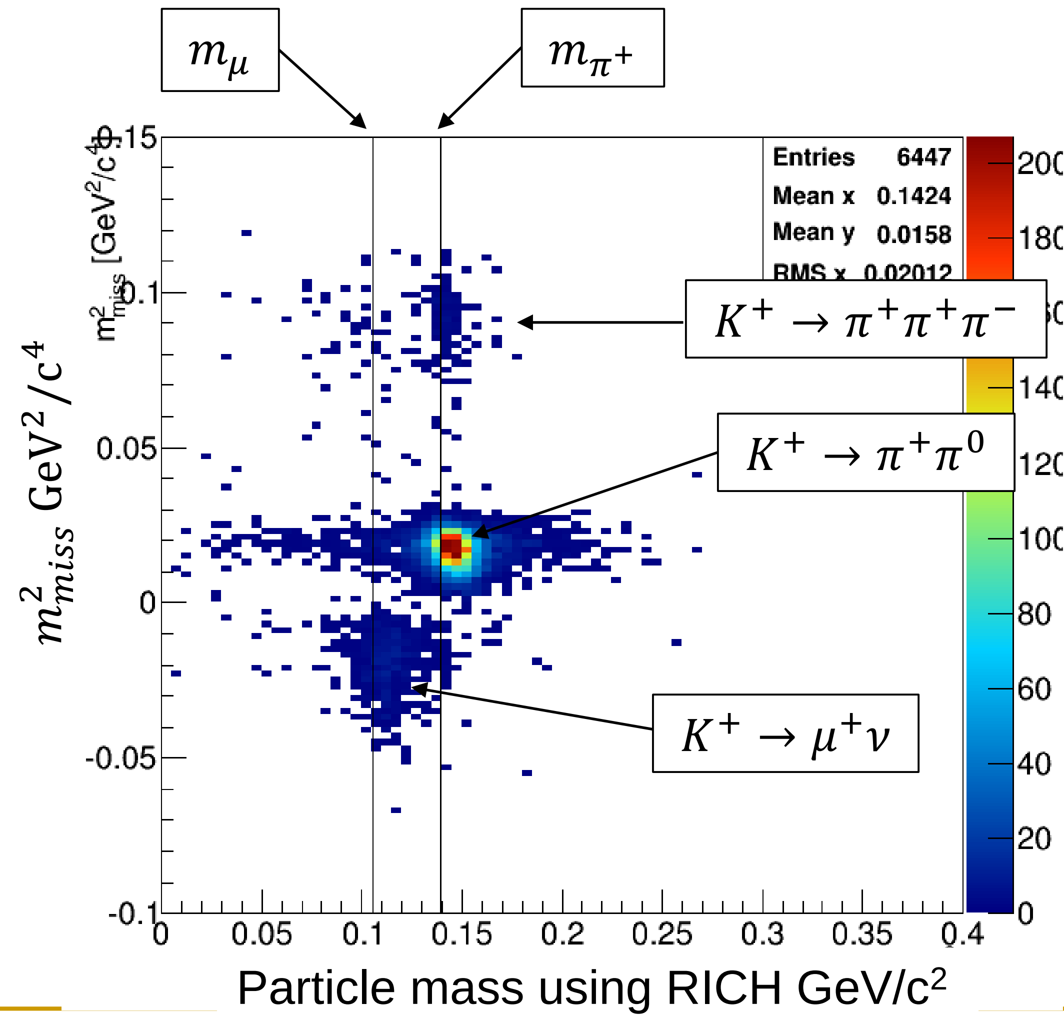
First Look to 2014 Data Quality

- Kinematic variable: $m^2_{miss} = (P_K - P_{\pi^+})^2$
- Nominal K momentum and direction assumed (No Kaon tracker)



First Look to 2014 Data Quality

- Joining kinematics and particle ID



First Look to 2014 Data Quality

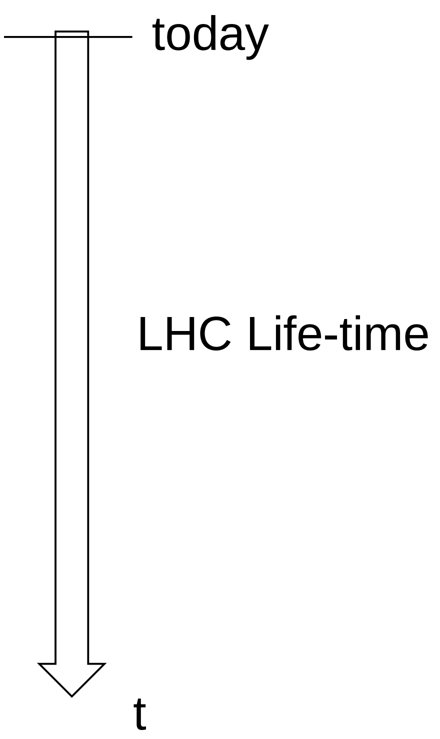
- NA62 is ready to collect and study $K^+ \to \pi^+ \nu \bar{\nu}$

Further NA62 K Physics Program

Decay	Physics	Present limit (90% C.L.) / Result	NA62
$\pi^+\mu^+e^-$	LFV	1.3×10^{-11}	0.7×10^{-12}
$\pi^+\mu^-e^+$	LFV	5.2×10^{-10}	0.7×10^{-12}
$\pi^-\mu^+e^+$	LNV	5.0×10^{-10}	0.7×10^{-12}
$\pi^-e^+e^+$	LNV	6.4×10^{-10}	2×10^{-12}
$\pi^-\mu^+\mu^+$	LNV	1.1×10^{-9}	0.4×10^{-12}
$\mu^-\nu e^+e^+$	LNV/LFV	2.0×10^{-8}	4×10^{-12}
$e^-\nu\mu^+\mu^+$	LNV	No data	10^{-12}
π^+X^0	New Particle	$5.9\times10^{-11}\ m_{X^0}=0$	10^{-12}
$\pi^+\chi\chi$	New Particle	–	10^{-12}
$\pi^+\pi^+e^-\nu$	$\Delta S\neq\Delta Q$	1.2×10^{-8}	10^{-11}
$\pi^+\pi^+\mu^-\nu$	$\Delta S\neq\Delta Q$	3.0×10^{-6}	10^{-11}
$\pi^+\gamma$	Angular Mom.	2.3×10^{-9}	10^{-12}
$\mu^+\nu_h,\nu_h\rightarrow\nu\gamma$	Heavy neutrino	Limits up to $m_{\nu_h}=350\ MeV$	
R_K	LU	$(2.488\pm0.010)\times10^{-5}$	>×2 better
$\pi^+\gamma\gamma$	χPT	< 500 events	10^5 events
$\pi^0\pi^0e^+\nu$	χPT	66000 events	$O(10^6)$
$\pi^0\pi^0\mu^+\nu$	χPT	-	$O(10^5)$

K rare decays: a look forward

- $K^+ \to \pi^+ \nu \bar{\nu}$
  - 10% branching ratio measurement (NA62 now)
- $K^+ \to \pi^+ \nu \bar{\nu}$
  - < 5% branching ratio measurement (NA62 upgrade)
- $K_L \to \pi^0 e^+ e^- (\mu^+ \mu^-)$
  - 10 % measurement (from K^+ to K_L beam and few detector modifications)
- $K_L \to \pi^0 \nu \bar{\nu}$
  - Observation
- $K_L \to \pi^0 \nu \bar{\nu}$
  - 10% branchig ratio measurement (significant accelerator imporvement)



Conclusions

- Kaons are partner of LHC in the quest for physics beyond the Standard Model.
- CERN has a bright tradition in Kaon Physics
- NA62 is officially scheduled at CERN to run up to 2018 (at least).
- NA62 is working and ready to do physics.

Next run:
1^{st} July – 15^{th} November 2015