The NA62 Experiment: Prospects for the $K^+ \rightarrow \pi^+ \nu\nu$ Measurement

Giuseppe Ruggiero (CERN)

Kaon 2013

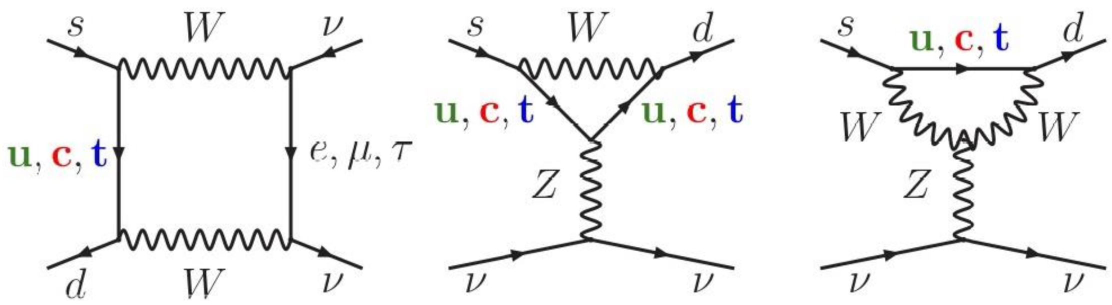
Ann Arbor, 01/05/2013

Outline

- Theory (short reminder)
- Principles of NA62
- Sensitivity Studies
- Results from the 2012 Technical Run
- Conclusions

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

- FCNC loop processes: $s\to d$ coupling and highest CKM suppression



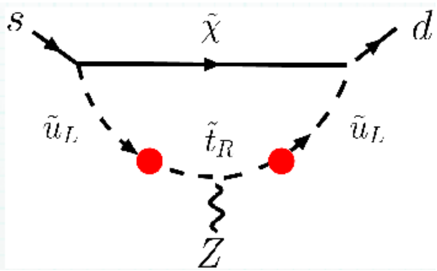
- Very clean theoretically: SD contributions dominate.
  - top quark contribution computed at NLO QCD and 2-loop EW corrections;
  - c quark loop contribution computed at NNLO QCD and NLO EW corrections;
  - correction for LD contributions;
  - hadronic matrix element related to the precisely measured $BR(K^+\to\pi^0 e^+\nu)$.
- BR proportional to $|V_{ts}^* V_{td}|^2$ → theoretical clean V_{td} dependence
- SM predictions [Brod, Gorbahn, Stamou, Phys. Rev. D 83, 034030 (2011)] :
  - $BR(K_L\to\pi^0\nu\nu) = (2.43 \pm 0.39 \pm 0.06)\times10^{-11}$
  - $BR(K^+\to\pi^+\nu\nu) = (7.81 \pm 0.75 \pm 0.29)\times10^{-11}$

Parametric error dominated by V_{cb}, ρ

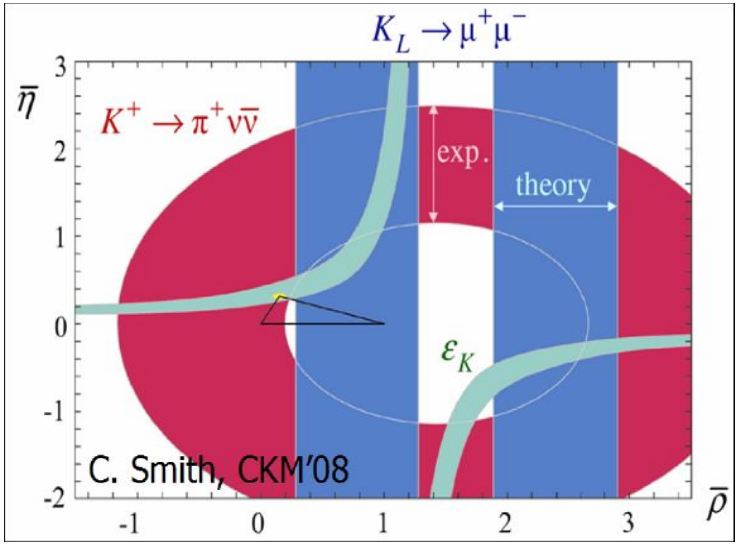
Pure theoretical error, mostly LD corrections

Experimental Measurements and NP Sensitivity

- Sensitive NP probe complementary to LHC
- Best probe of non-MFV (G.Isidori ESPP Open Symposium)
  - E.g. non-MFV in up-squarks trilinear terms.



- Present experimental results:
  - $BR(K^+ \to \pi^+ \nu\nu) = (1.73\ ^{+1.15}_{-1.05}) \times 10^{-10}$ [E787, E959]
  - $BR(K_L \to \pi^0 \nu\nu) < 2.6 \times 10^{-8}$ [E391a]



- Upcoming experiments:
  - NA62 @ CERN
  - KOTO @ JPARC
  - ORKA @ Fermilab

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

- Goal: 10% precision branching ratio measurement of $K^+ \to \pi^+ \nu\nu$
  - O(100) SM $K^+ \to \pi^+ \nu\nu$ events (2 years of data)

- Requirements
  - Statistics: BR(SM) ~ 8×10^{-11}
    - K decays (2 years): 10^{13}
    - Acceptance: ~ 10%
  - Systematics:
    - $>10^{12}$ background rejection (<20% background)
    - <10% precision background measurement

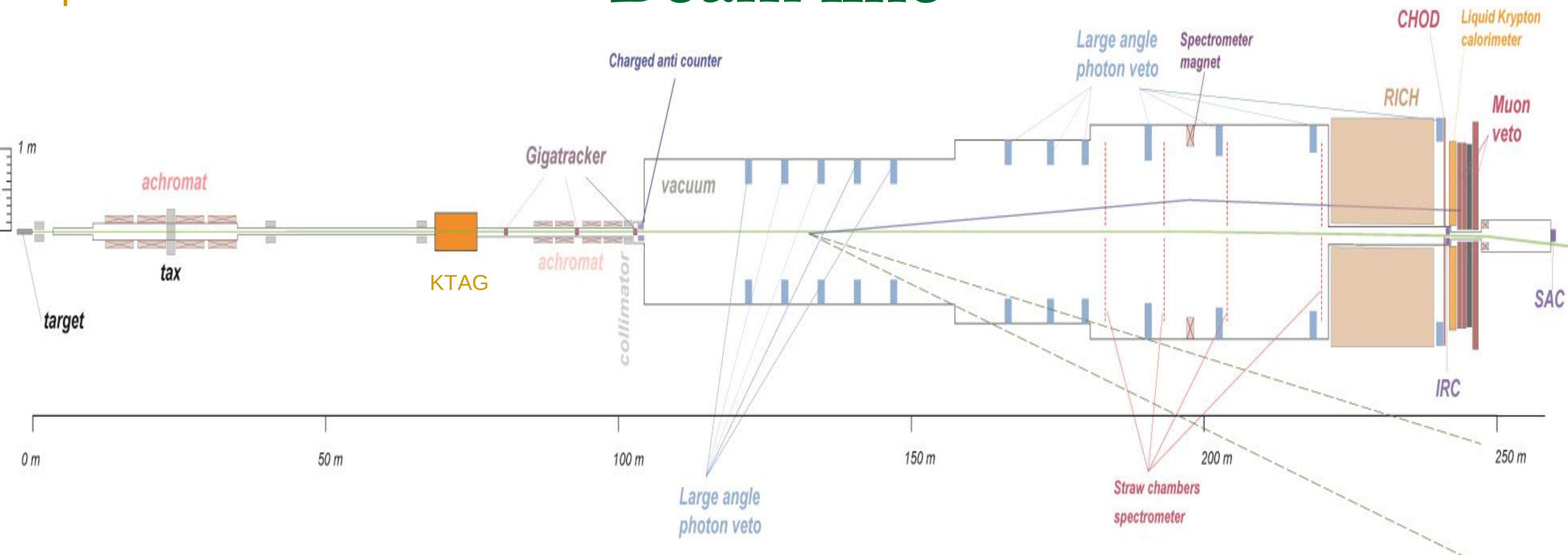
- Technique
  - "High" momentum K^+ beam

Kaon intensity
Signal efficiency

Signal purity
Detector redundancy

Decay in flight

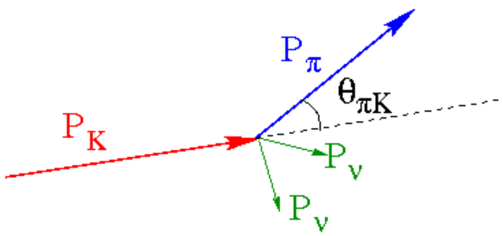
Beam line



- SPS proton beam @ 400 GeV/c
- Proton on target: 1.1 x 10^{12} / s
- P secondary charged beam 75 GeV/c
- Momentum bite 1%
- Angular spread in X and Y < 100 μrad
- Size @ beam tracker: 5.5 x 2.2 cm^2
- Rate @ beam tracker: 750 MHz
- 6% K^+ (others: π^+, proton)
- Rate downstream 10 MHz (K^+ decay mainly)
- K decay rates / year: 4.5 x 10^{12} (60 m decay volume)

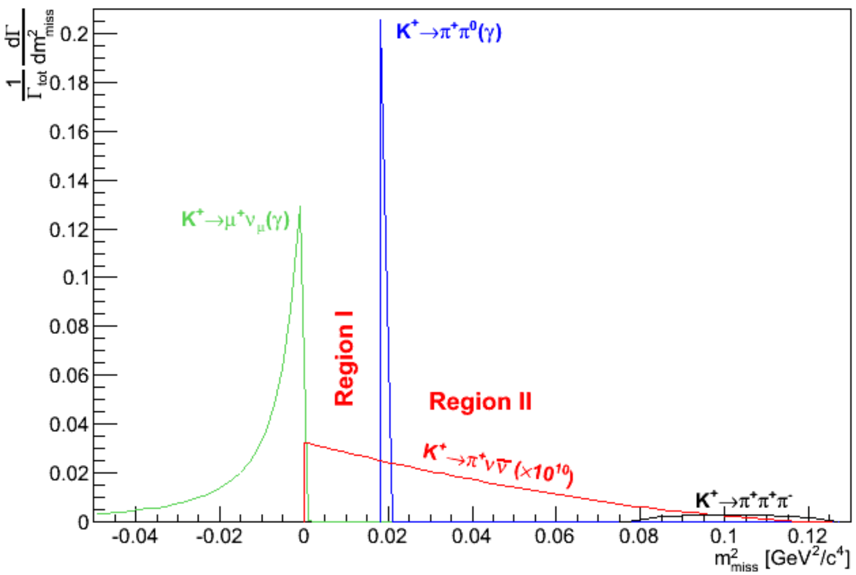
Signal and Background

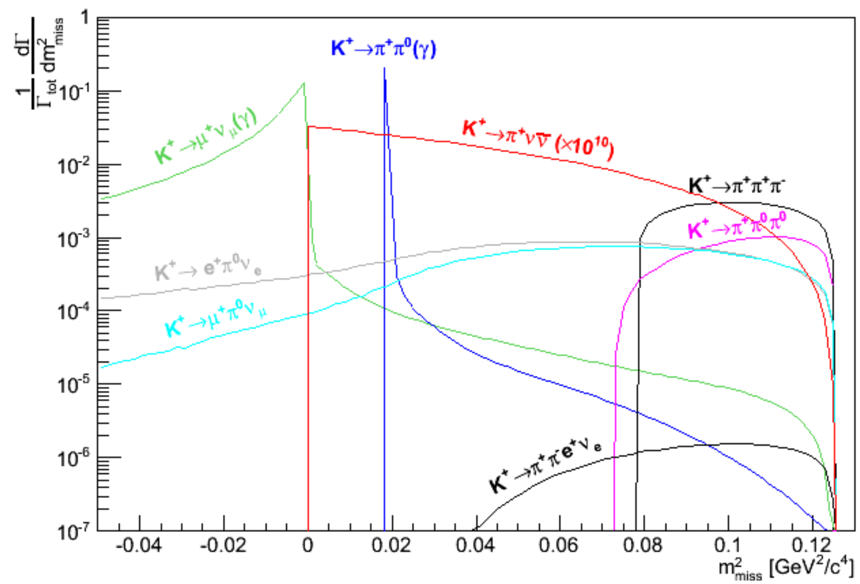
- Signal
  - Kinematic variable: $m^2_{miss} = (P_K - P_{\pi^+})^2$



- Background
  - 1) K^+ decay modes 2) Accidental single track matched with a K-like track

- Kaon Decays

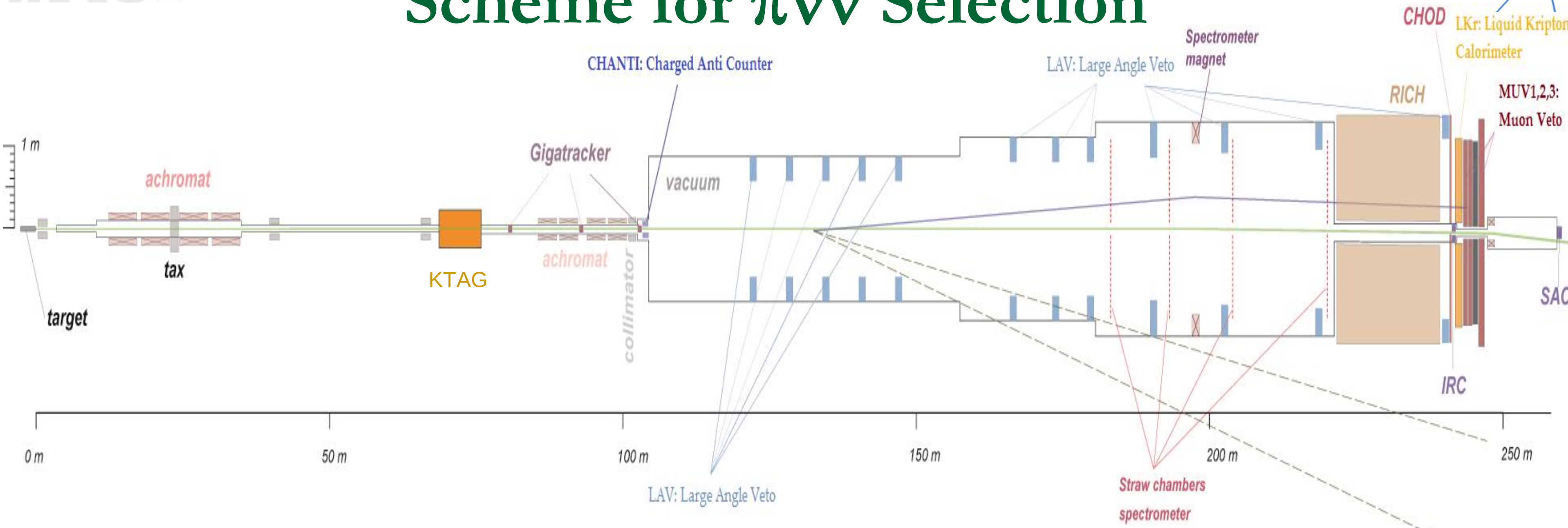




- Accidental single tracks
  - Beam interactions in the beam tracker
  - Beam interactions with the residual gas in the vacuum region.

NA62

Scheme for πνν Selection



- One reconstructed track in the Straw (π^+ track)
- Signal in RICH compatible with only 1 π^+ hypothesis
- Signal in Calorimeters (CHOD, LKr, MUV1,2,3) compatible with only 1 π^+ hypothesis
- No clusters in LKr compatible with γ hypothesis
- No signals in LAVs, IRC, SAC compatible with γ hypotesis
- At least one track in Gigatracker matched in space and time with the π^+ track (K^+ track) and compatible with the beam parameters (75 GeV/c)
- No extra activity in CHANTI compatible with a MIP signal
- Signal in KTAG compatible with a K hypothesis
- Z vertex in the first 60 m of the decay volume

$15 < P_{\pi+} < 35$ GeV/c

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

Branching Ratio = ~21%

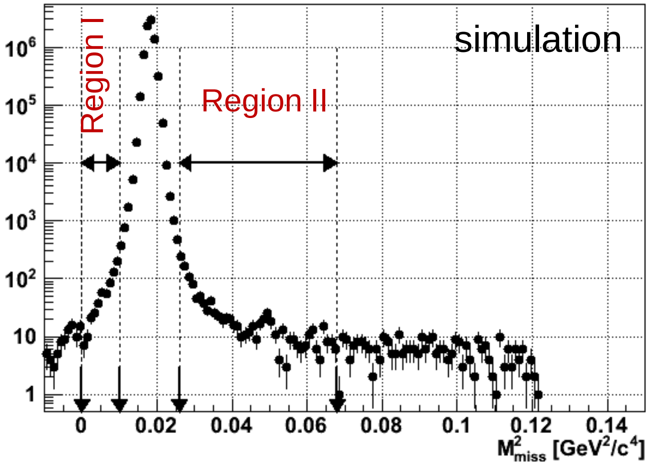
- Evaluation of the effect of the kinematic cuts using the simulation
- Evaluation of the single γ detection efficiency:
  - Intrisinc inefficiencies of the calorimeters from test-beam and NA48/NA62 data
  - Effect of the material in front of the calorimeter studied on simulation
  - Separation between π^+ cluster and γ cluster @ LKr taken into account
- Evaluation of the π^0 rejection power:
  - Single γ detection inefficiency applied parametrically to the γ's of $\pi^+\pi^0$ events
- Factorization of the kinematic and photon rejection
- Contribution from the radiative tails:
  - Evaluated by considering only the gaussian resolution of the tracking systems

- Result: 10% + 3% (radiative) (cut & count analysis without any optimization)
- Method to measure on data the γ detection efficiency from $K^+ \to \pi^+\pi^0$
- Kinematic rejection can be measured on data from $K^+ \to \pi^+\pi^0$ reconstructed by using the LKr
- Strongly momentum and Z vertex dependent.

$K^+ \rightarrow \pi^+ \pi^0$ Kinematics

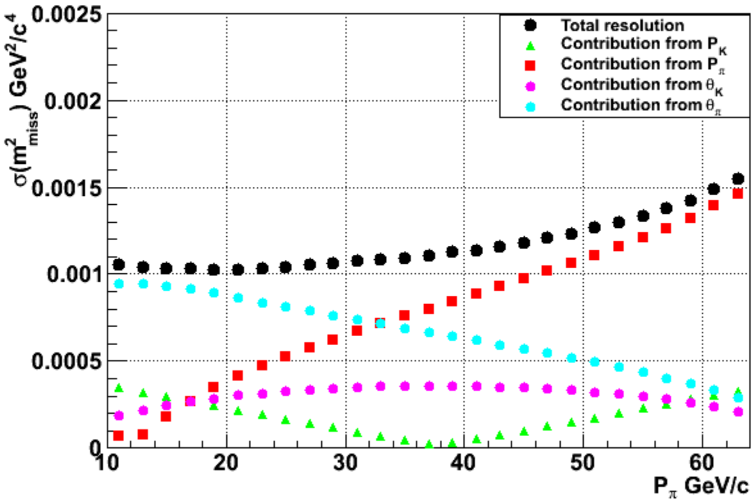
- Cut on m^2_{miss}

Reconstructed m^2_{miss} for $K^+ \rightarrow \pi^+ \pi^0$



- Source of inefficiency:
  - Tails due to the multiple scattering
  - Pileup in the Gigatracker.

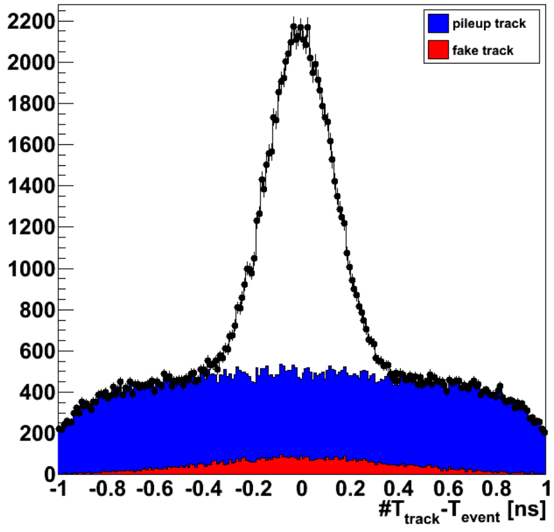
- Resolution:
  - $\sigma(P_K)/P_K = 0.2\%, \sigma\left(\frac{dX,Y}{dZ}\right)_K = 15\ \mu rad$
  - $\sigma(P)/P = 0.32\% \oplus 0.008\%\ P\ [GeV/c]$
  - $\sigma\left(\frac{dX,Y}{dZ}\right) = 20 - 50\ \mu rad$
  - Rejection factor: 5×10^3

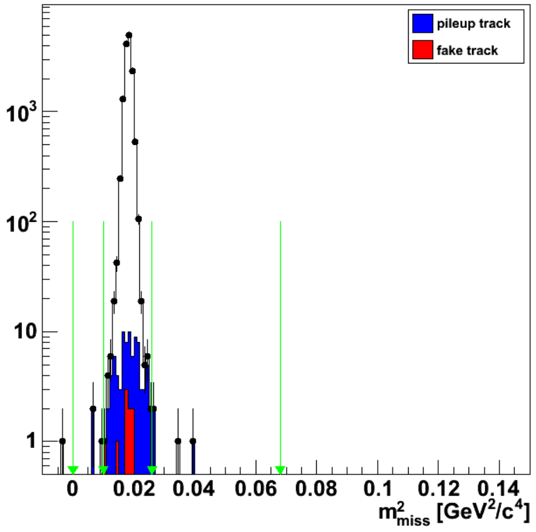


Kinematics and Pileup

- Different rate in Gigatracker (750 MHz) and in the downstream detectors (10 MHz)
- Possible wrong assignment of the K^+ measured in the Gigatracker to the π^+ downstream
- Factor 3 increase in $\sigma(m^2_{miss}) \rightarrow$ loss of kinematic rejection power
- Exploit spatial and timing correlations between the upstream and downstream detectors.

- Precise timing required between K^+ and π^+
  - Gigatracker: σ(t) = 200 ps / station
  - KTAG: σ(t) = 100 ps
  - RICH: σ(t) < 100 ps
- Mis-matching probability < 1%, further reducible after analysis optimization.
- 50% contribution to the inefficiency of the kinematic rejection.

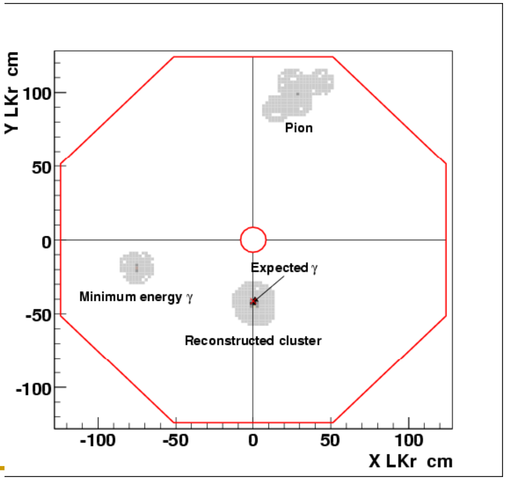




Photon rejection

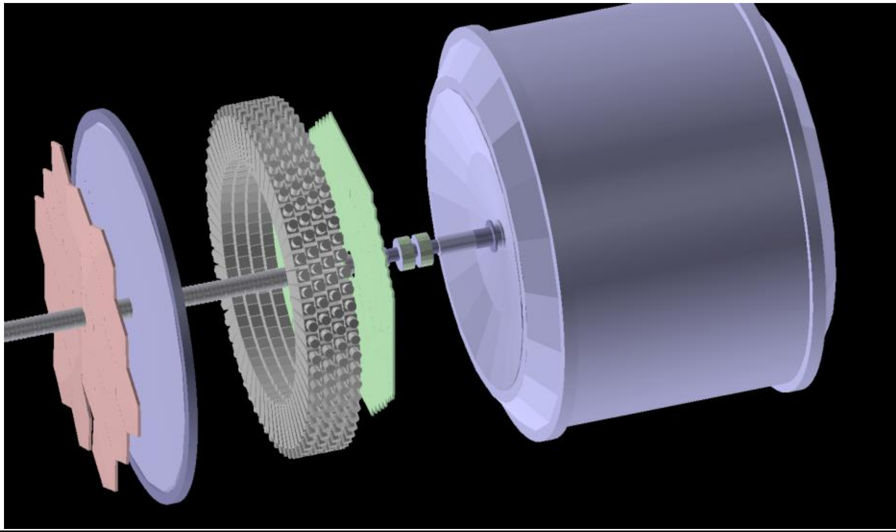
- $P_{\pi^+} < 35$ GeV/c → $E_{\pi^0} > 40$ GeV in $K^+ \to \pi^+\pi^0$
- Requirement $O(10^8)$ on π^0 rejection
- Hermeticity:
  - LKr, IRC, SAC detect the photon in the forward region (0 to 8.5 mrad full coverage)
  - LAV detect the photons at high angle (coverage up to 50 mrad down to 100 MeV)
- Geometrical inefficiency:
  - 0.2% $\pi^+\pi^0$ with one γ out from the acceptance:
    - No events with the other photon in the LAV acceptance or outside
    - The other photon always in the forward region
    - $Z_{decay} < 65$ m → γ in the forward region with energy > 1 GeV (mainly > 10 GeV)
- Intrinsic inefficiency of the LKr:
  - Measured on NA48 data by selecting $K^+ \to \pi^+\pi^0$ events
  - It fits the requirement on the overall π^0 detection inefficiency
  - Can be monitored with enough precision along the data taking.

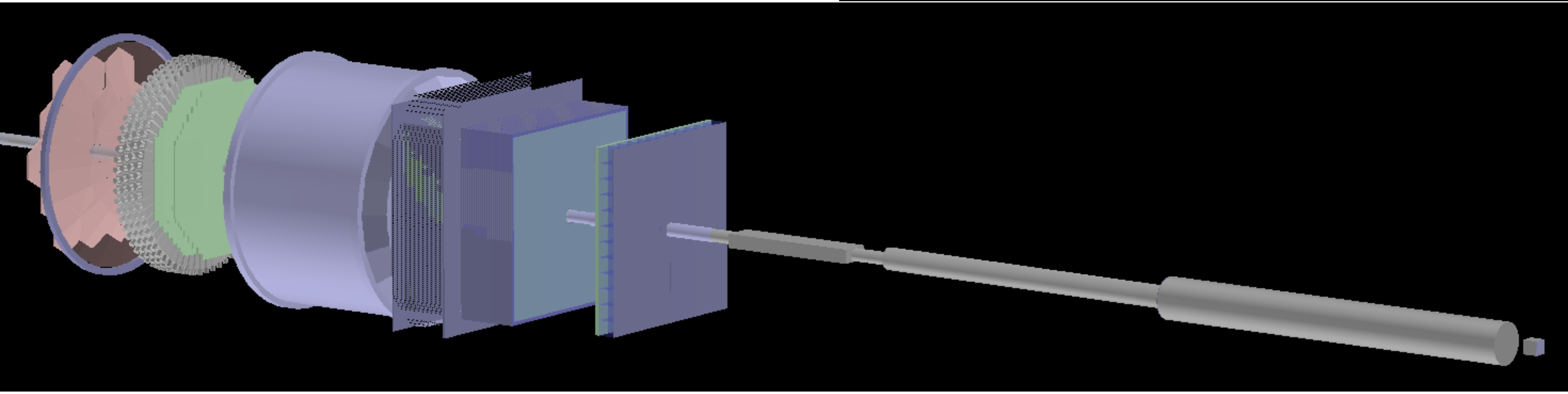
E_γ (GeV)	Inefficiency
2.5 – 5.5	$<10^{-3}$
5.5 – 7.5	$<10^{-4}$
7.5 – 10	$< 5 \times 10^{-5}$
> 10	$< 8 \times 10^{-6}$



Effect of the material on the photon rejection

- Studied using a detailed GEANT4 simulation
- Dominant effect for photons in SAC: equivalent inefficiency 7.9×10^{-4} (conversions in straws)
- Important effect for photons in IRC: equivalent inefficiency 3.6×10^{-4} (γ-nuclear interactions with the beam pipe)
- Negligible effect for photons in LKr and LAVs.





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

Branching Ratio = ~64%

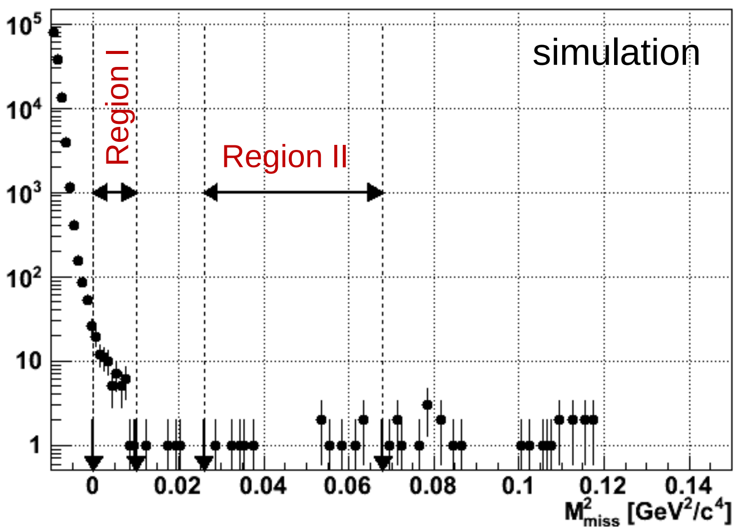
- Evaluation of the effect of the kinematic cuts using the simulation
- Calorimeters for π^+ identification and $\mu - \pi$ separation
- RICH for $\mu - \pi$ separation
- Factorization of the Kinematic rejection factor, the Particle ID from Calorimetry and Particle ID from RICH assumed.
- Contribution from the radiative tails evaluated

- Result: 2.2% + 1% (radiative) (cut & count analysis without any optimization)
- The RICH (Calorimeters) can be used to select a pure sample of $K^+ \to \mu^+ \nu$ in order to measure on data the rejection power from the Calorimeters (RICH).
- The RICH can be used to cross – check the momentum measured in the spectrometer

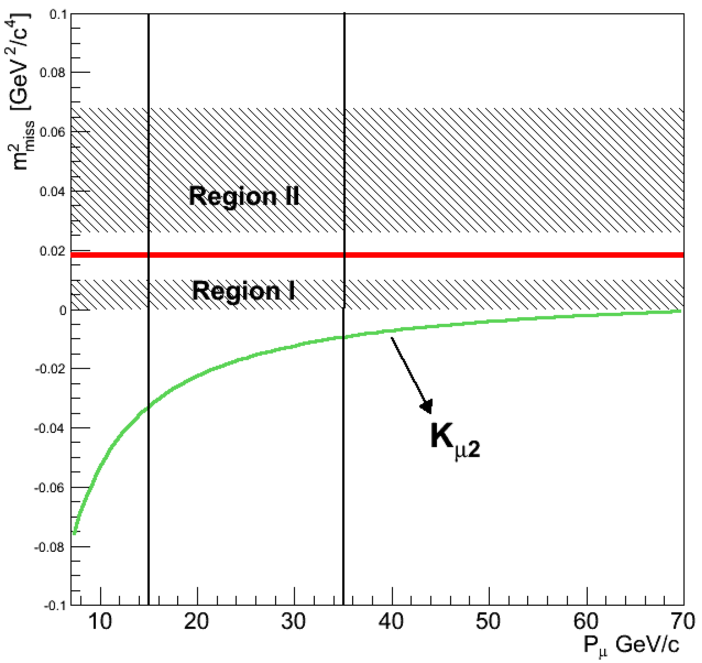
$K^+ \to \mu^+ \nu$ Kinematics

- Cut on m^2_{miss}

Reconstructed m^2_{miss} for $K^+ \to \mu^+ \nu$



- Analytical relation between m^2_{miss} and P_μ
  - P_{track} < 35 GeV/c crucial to enhance the kinematic rejection power

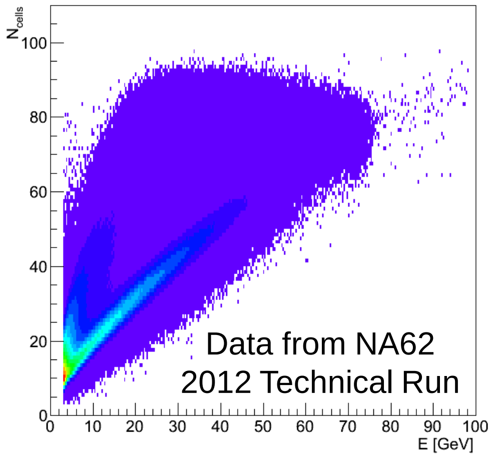


- Source of inefficiency:
  - Tails due to the multiple scattering
  - Pileup in the Gigatracker.

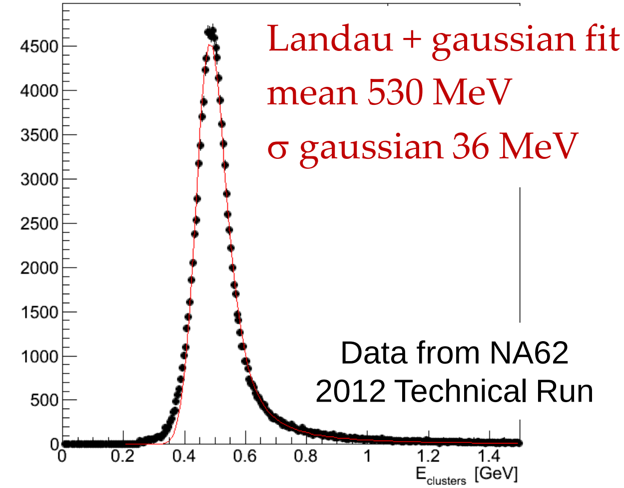
- Rejection factor 1.5×10^4
- Pileup contribution marginal

Calorimetry: Particle ID

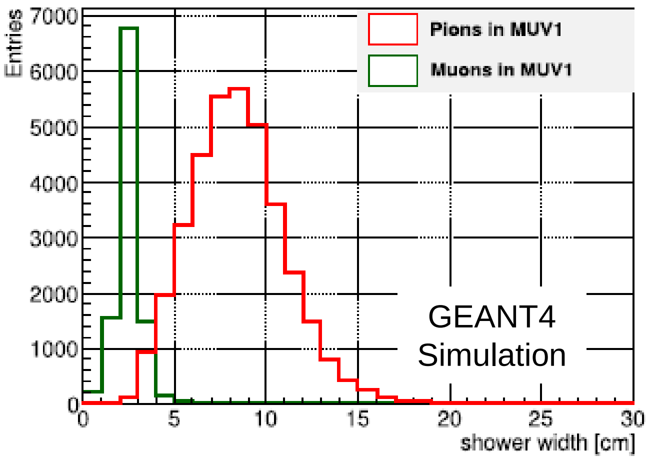
- LKr: em / hadronic clusters discrimination



Clear MIP signal



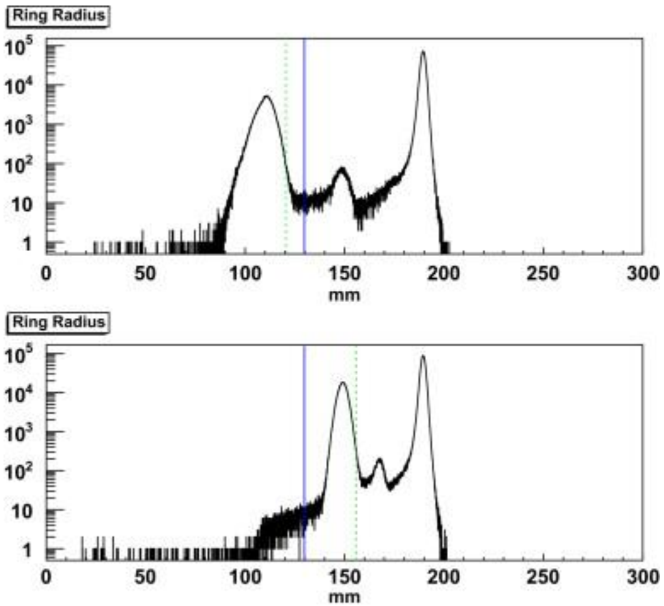
- MUV1,2: μ / π discrimination
- MUV3: pure μ counter (<% inefficiency)

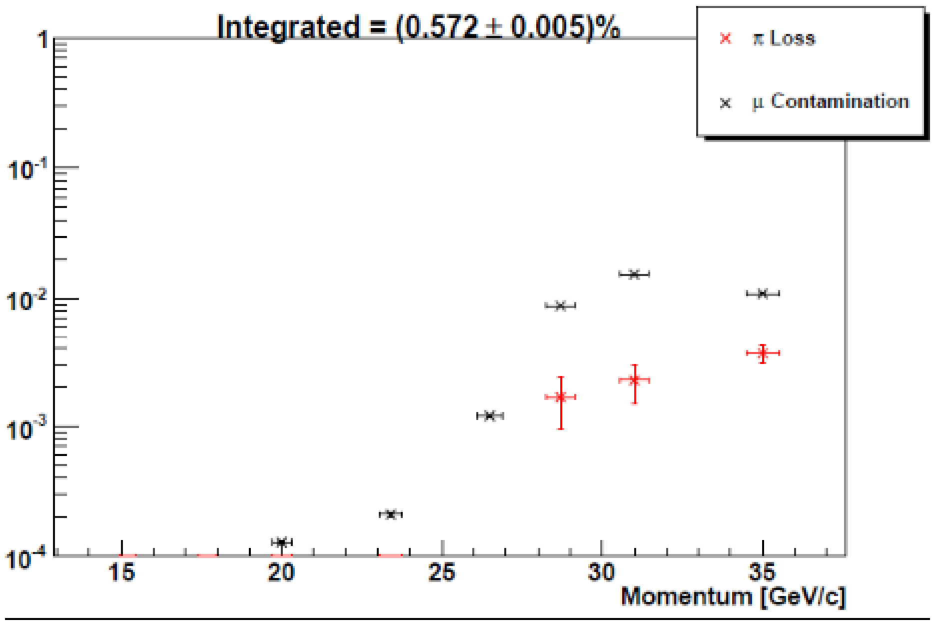


- Limitation: muon catastrophic energy loss
  - Ranging out from MUV1,2 (worst case 2 / 15 GeV)
  - Inefficiency 10^{-5} (effect studied in detail for R_K measurement)
  - Coarse Z segmentation of the calorimetric system may provide additional rejection power

Particle ID with RICH

- π–μ separation measured during a test beam of a full length RICH prototype [NIM A 621 2010]





- $P_{\pi} < 35$ GeV crucial
- Ne Cerenkov threshold forces a requirement $P_{\pi} > 15$ GeV
- Time resolution < 80 ps [NIM A 593 2008]
- The RICH provides an even better π – e separation

Estimation of $K^+ \rightarrow \pi^+\pi^+\pi^-$ Background

Branching Ratio = ~5.6%

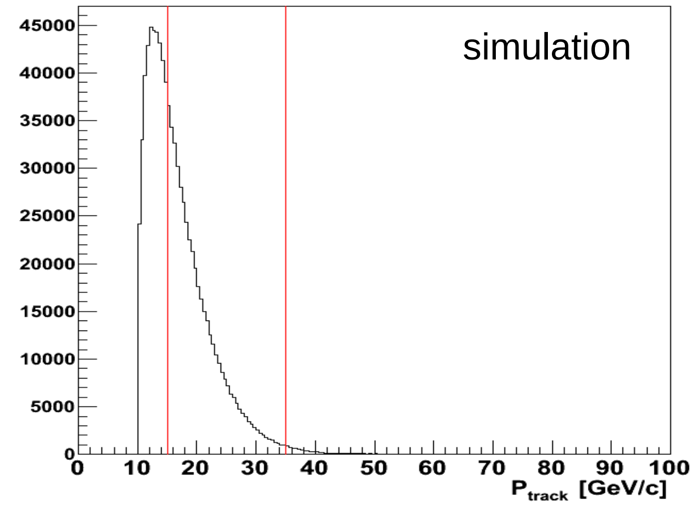
- Evaluation of the effect of the kinematic cuts using the simulation
- Evaluation of the effect of the cuts against extra charged particles in the final state
  - RICH
  - LAVs
  - Forward calorimeters (LKr, MUV1,2, IRC)
  - Straws
- Factorization of the cut on m^2_{miss} and the multiplicity cuts.

- Result: 1 - 2% (cut & count analysis without any optimization)
- High level of redundancy in the multplicity analysis

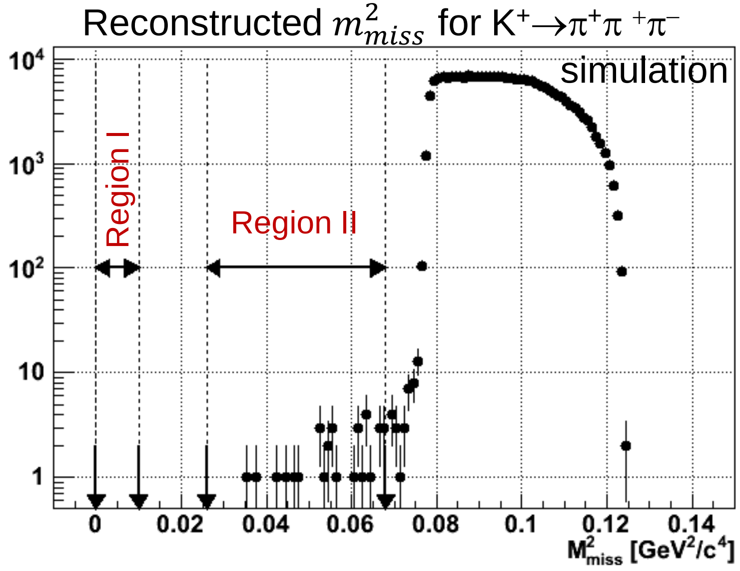
- Similar study performed for $K^+ \rightarrow \pi^+\pi^- e^+ \nu$ (Branching Ratio ~4.3×10^{-5})
- Contribution <2%.

$K^+ \to \pi^+\pi^+\pi^-$ Kinematics

- 1 track reconstructed in straws
- Cut on m^2_{miss}
- $P_{track} > 15$ GeV/c
- Overall rejection factor 1.5×10^6
  - Cut on m^2_{miss} and P_{track} strongly correlated



- Source of inefficiency:
  - Tails due to the multiple scattering
  - Marginal effect from the pileup in the Gigatracker.

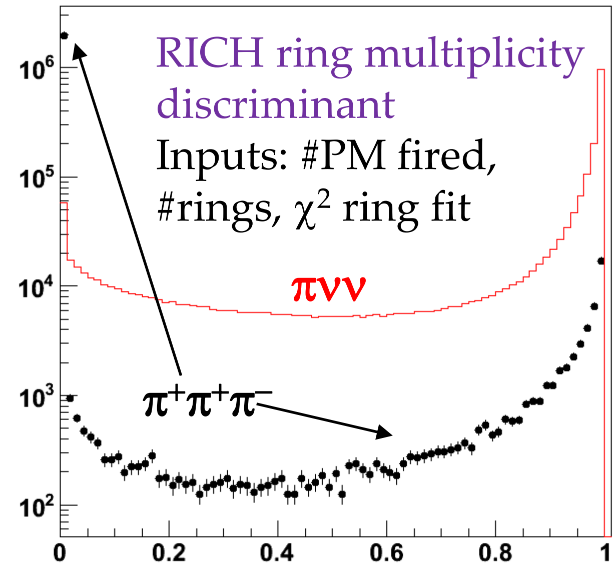


- Topology of the residual events:
  - One good π^+ reconstructed in straws
  - The other π^+ and the π^- in the beam hole of the first 2 straw chambers.

$K^+ \to \pi^+\pi^+\pi^-$ Multiplicity

- Full geometrical coverage downtream to the magnet of the spectrometer against π^- up to 65 GeV/c
  - 20 m lever arm between the magnet of the straw spectrometer and the last straw chamber
  - Lateral displacement of the detectors following the path of the positive particles

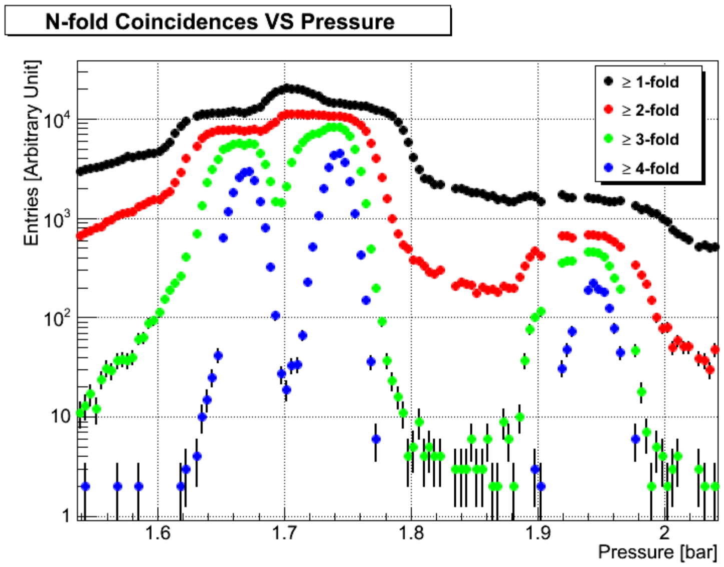
- Rejection methods (simplified scheme):
  - RICH to detect π^- with energy larger than 15 GeV/c
  - Forward Calorimetries (LKr, MUV1,2) to detect the π^- (eventually the π^+) without energy constraint
  - CHOD and LKr to detect products of the nuclear interactions of the π^- in the material of the RICH
  - LAVs to detect low energy π^- decaying in muons or the products of the nuclear interactions of the π^-
  - Extra segments in the straws to detect cases with a high energy π^+ hitting the first two chambers, but continuing the path along the beam line downtream to the magnet.



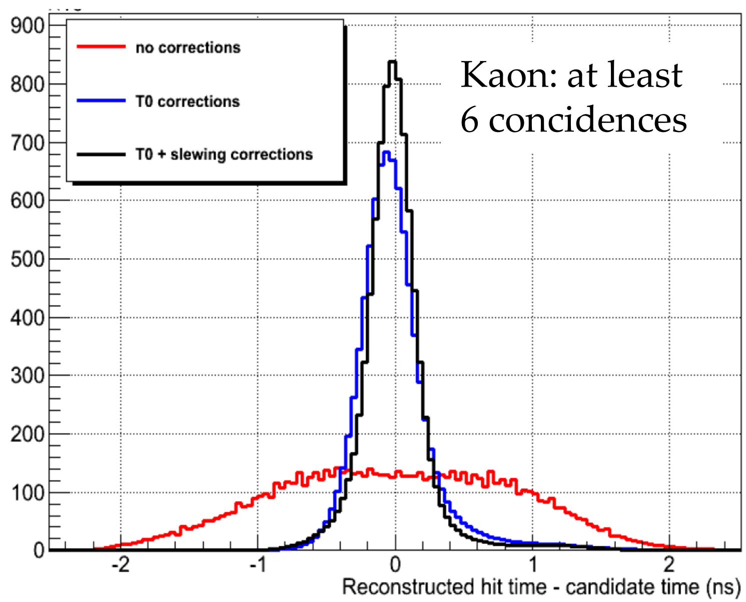
- Overall rejection factor $O(10^6)$

Background from Beam Interactions

- Decay in flight → < 1.5% X_0 on the beam from the tracker
- Kaon ID detector to suppress the contribution from the π^+ and p interactions (94%): KTAG
  - Requirements: σ(t) = 100 ps, ≤ % level pion mis-tagging, > 95% K efficiency
- N_2 filled detector mounted on the beam line during the 2012 NA62 Technical Run.
- 50% of readout electronics mounted.
- Measured performances match the requirements

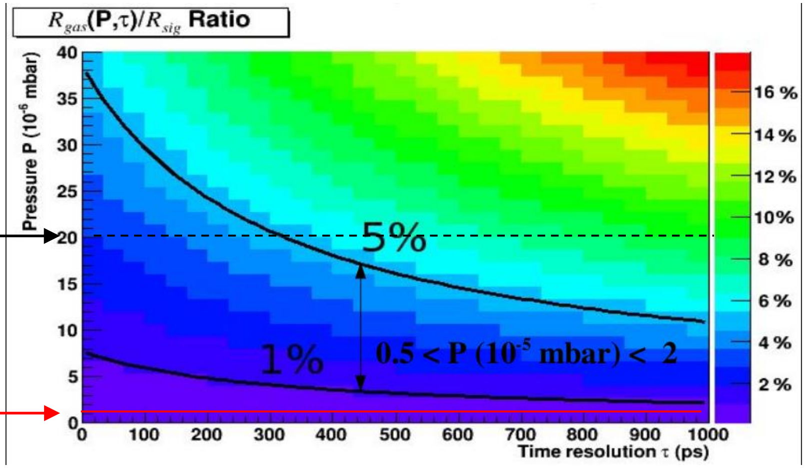


RMS 280 ps/coincidence



Background from Beam Interactions

- Decay in flight → < 1.5% X_0 on the beam from the tracker
  - Beam interactions with the residual gas
  - Single nuclear processes simulated with Fluka.
  - Vacuum level (mbar):
    - Technical run 2×10^{-5} (1 pump only)
    - Expected for 2014: 10^{-6} (scaled from the technical run)



  - Beam interactions in the last Gigatracker Station
  - Rejection power needed $O(10^9)$
  - Kinematic constraint from the reconstructed vertex → rejection factor $>10^3$
    - Fiducial volume 5 m downstream to the last Gigatracker station ($\sigma(Z_{vertex}) < 20$ cm)
  - Detect multiplicity of the nuclear interaction → rejection factor $>10^5$ (we look for at least 40 GeV)
    - Gigatracker itself, CHANTI, LAV + downstream detectors
  - Ultimate limit: charge exchange processes $K^+n \to K_L p$ & $K_L \to e^-\pi^+\nu$
  - Background to be measured on data. Strongly Z vertex dependent.

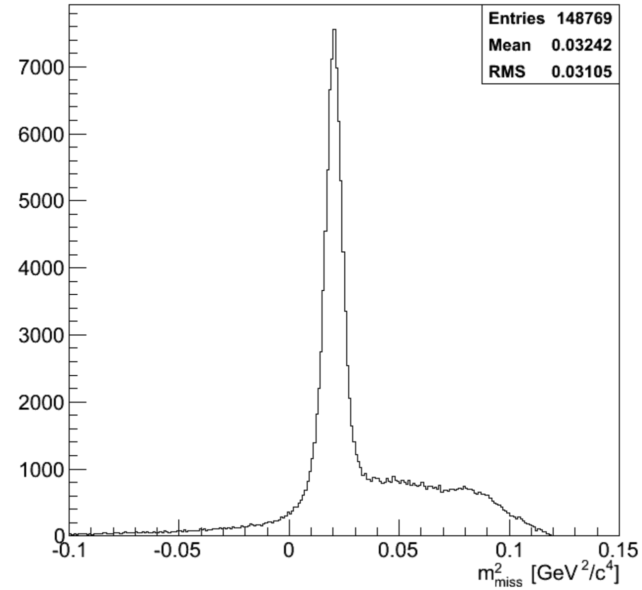
Physics Sensitivity

Decay	evt/year
$K^+ \to \pi^+ \nu\nu$ [SM] (flux 4.5×10^{12})	45
$K^+ \to \pi^+ \pi^0$	5
$K^+ \to \mu^+ \nu$	1
$K^+ \to \pi^+ \pi^+ \pi^-$	< 1
$K^+ \to \pi^+ \pi^- e^+ \nu$ + other 3 tracks decays	< 1
$K^+ \to \pi^+ \pi^0 \gamma$(IB)	1.5
$K^+ \to \mu^+ \nu\gamma$(IB)	0.5
$K^+ \to \pi^0 e^+(\mu^+)\nu$, others	negligible
Total background	< 10

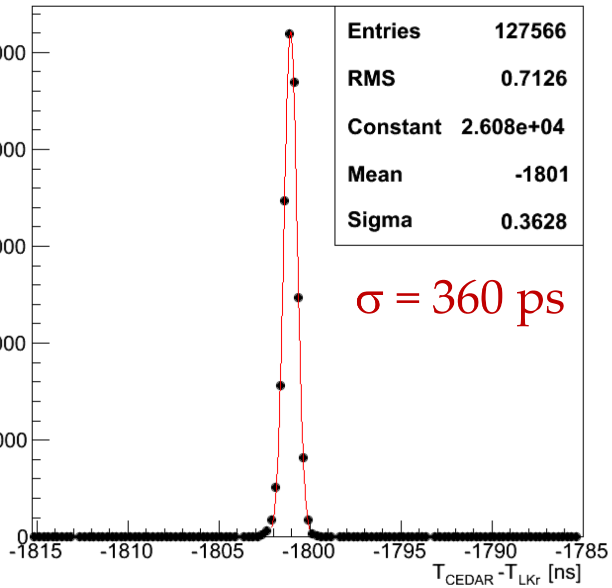
- Cut & count analysis without any optimization
  - e.g. Use of the m^2_{miss} shape to add further signal/background discrimination
- The background must be measured with at least 10% precision
  - Background evaluation to be done on data

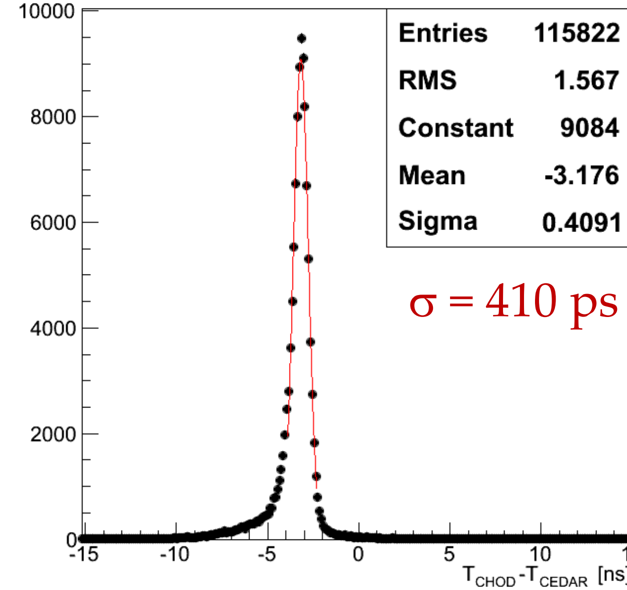
Results from the 2012 Technical Run

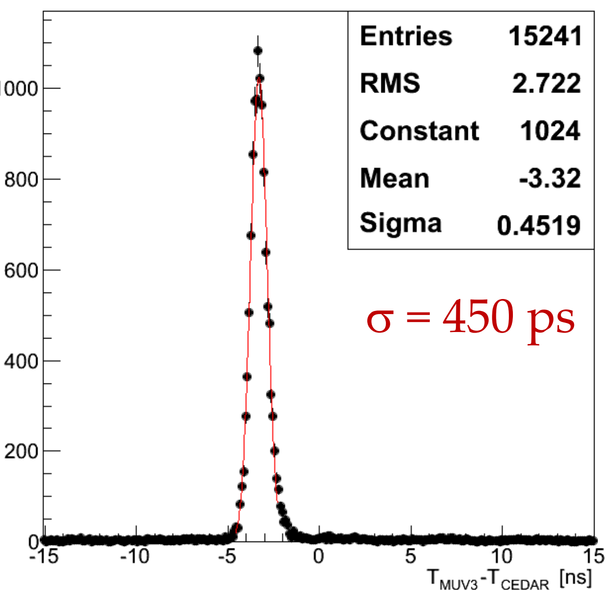
- Goals:
  - Analysis of the time and spatial correlation between the subdetectors.
  - Estimation of the time resolution and efficiency of the subdetectors.
- Partial set – up:
  - KTAG (50% PMs), 1 straw plane, CHOD, LKr (30% readout), MUV2, MUV3
- Analysis Method: selection of $K^+ \to \pi^+\pi^0$ events
  - Selection based on the Liquid Kripton Calorimeter
  - Photon tagging from the shape of the reconstructed clusters
  - π^0 reconstruction:
    - Z vertex from 2 γ on the LKr assuming m_{π^0}
    - X and Y vertex from the assumed K direction
  - K momentum (P_K) and divergence well defined by the beam line
  - $P_{\pi^+} = (P_K - P_{\pi^0}) \to P_{\pi^+}^2 = m_{\pi^+}^2$ for $K^+ \to \pi^+\pi^0$

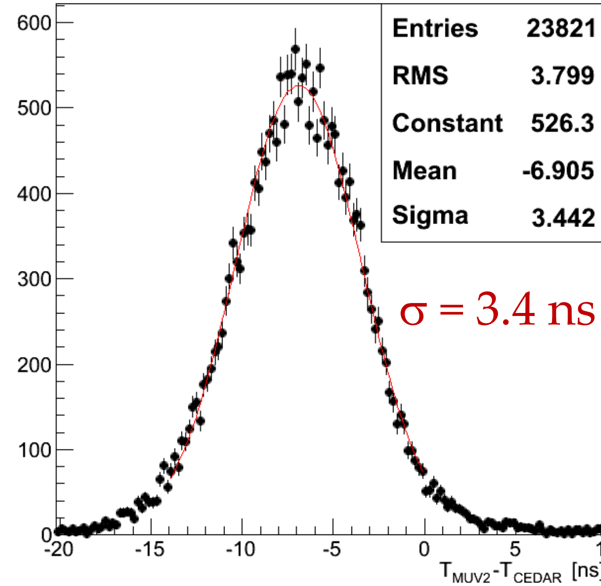


Timing Correlations





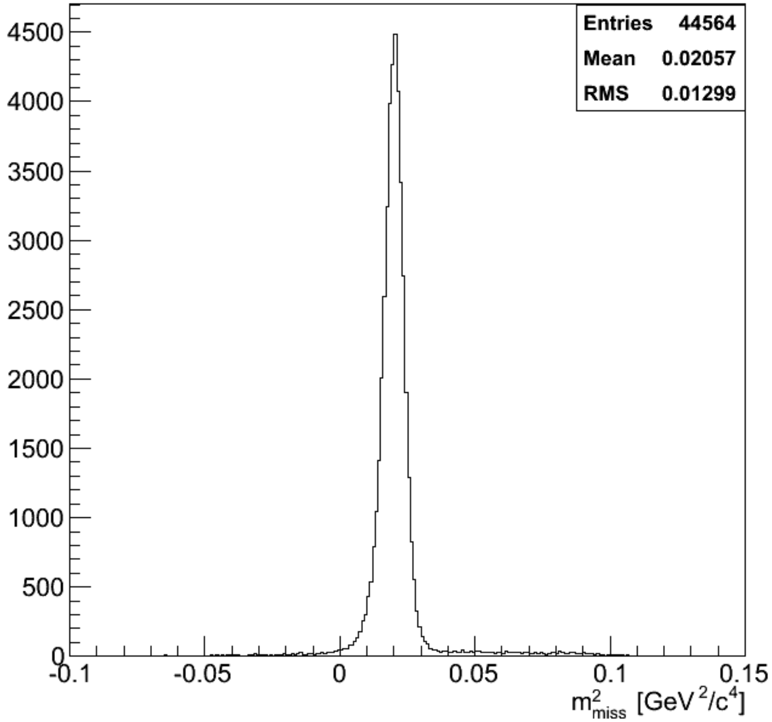




The Final $K^+ \to \pi^+\pi^0$ Sample

- Exploit the timing and spatial correlations between the subdetectors to define a Kaon candidate, pion candidate and a muon candidate.

- Signal region:
  - $0 < m^2_{miss} < 0.04\ GeV^2/c^4$
- Background @ % level
- $\langle m^2_{miss} \rangle = (0.0199 \pm 0.0005)\ GeV^2/c^4$
- $\sigma(m^2_{miss}) = 3.8 \times 10^{-3} GeV^2/c^4$
- $m^2(\pi^+) = 0.0195\ GeV^2/c^4$
- Time resolution: KTAG 150 ps, LKr 350 ps, CHOD 400 ps, MUV3 450 ps.
- KTAG efficiency about 87% (corresponding to 95% for a fully instrumented detector).
- 6% of events with a muon in-time (upper limit to the punch-through)



- This analysis will be used in the final analysis to monitor the tails of the m^2_{miss} reconstructed with the tracking system.

Conclusions

- We look forward to the 2014 data