$K^+ \rightarrow \pi^+ \nu\bar{\nu}$: Physics Sensitivity and Analysis

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Meeting with SPSC referee
04/11/2008

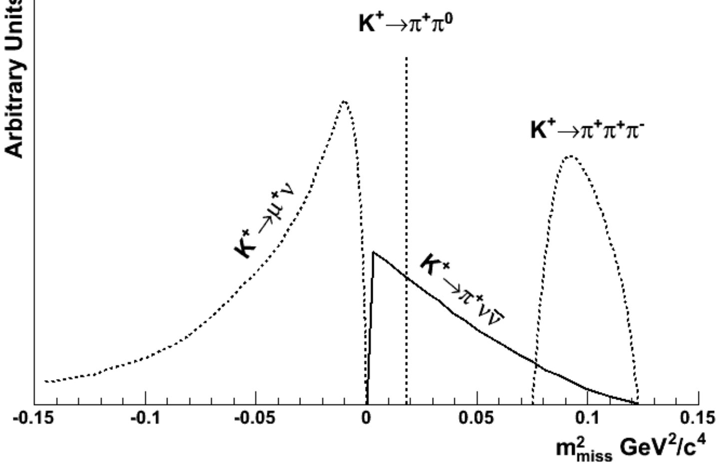
Outline

- Present status (2007 Status Report)

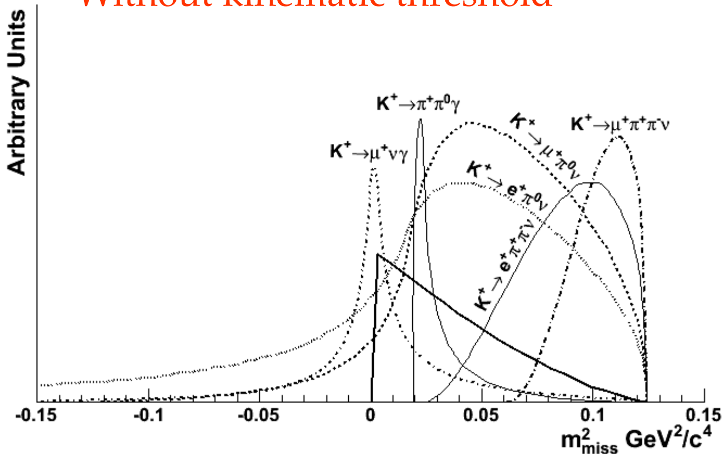
- Developments in the study of the sensitivity
  - Study of the sensitivity on the NA48/NA62 data
  - Work on a new detailed Monte Carlo simulation
  - Further studies on photon veto inefficiency
  - Review of the problem of the kinematic rejection inefficiency

Reminder: Background Rejection

With kinematic threshold



Without kinematic threshold



- Kinematic rejection (signal region definition)
  - $0<m^2_{miss}<0.01$ GeV /c^2 (region I) , $0.026<m^2_{miss}<0.068$ GeV /c^2 (region II)
  - Background enters in signal regions because of tails in the reconstructed m^2_{miss} due to non-gaussian Multiple Scattering and wrong Kaon π matching
- π^0 rejection: hermetic and high efficient photon vetoes
  - Main contribution to the residual background from LKr inefficiency at high energy ($E_\gamma>10$ GeV)
- Muon rejection: μ/π separation better tan 10^{-6}
  - Both RICH and MUD needed
- Maximum π momentum less than 35 GeV/c
  - Using K^+ of 75 GeV/c, at least 40 GeV of energy is deposited in the electromagnetic calorimeter and/or photon vetoes in $K^+ \to \pi^+\pi^0$ events
  - Better kinematic separation between $K^+ \to \mu^+\nu$ and signal and better μ/π separation

Present status (Status Report 2007)

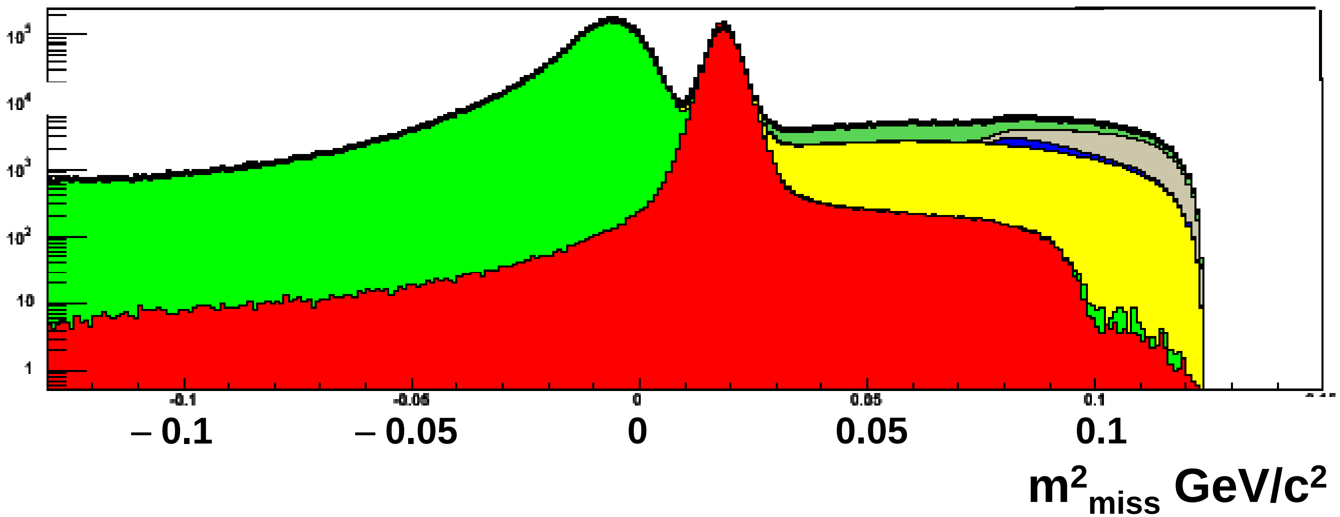
Decay Mode	
Signal	55 *evt/year*
$K^+ \to \pi^+\pi^0$	4.3% (7.5%)
$K^+ \to \mu^+\nu$	2.2%
$K^+ \to e^+\pi^+\pi^-\nu$	≤3%
Other 3 – track decays	≤1.5%
$K^+ \to \pi^+\pi^0\gamma$	~2%
$K^+ \to \mu^+\nu\gamma$	~0.7%
$K^+ \to e^+(\mu^+)\,\pi^0\nu$, others	negligible
Expected background	≤13.5% (≤17%)

- Kaon Flux: 4.8×10^{12} evt/year
- Signal Acceptance: 14.4%
- Kinematic rejection inefficiency:
  - $\sim 10^{-4}$ ($K^+ \to \pi^+\pi^0$), $\sim 10^{-5}$ ($K^+ \to \mu^+\nu$),
  - Results from simulation
- π^0 rejection inefficiency:
  - $2 \times 10^{-8} < \eta_{\pi 0} < 3.5 \times 10^{-8}$ ($K^+ \to \pi^+\pi^0$)
  - Single-γ inefficiency from data
- Muon rejection
  - MUD inefficiency 10^{-5}
  - $\mu \to \pi$ prob. 5×10^{-3} (RICH)
  - Inputs from simulation and data (2007 test beam)

Sensitivity of the NA48 Layout

- Search for $K^+ \to \pi^+ \nu\bar{\nu}$ using NA48/NA62 data
- Goal: measurement of the present level of sensitivity
- Preliminary studies on 2004 data (Kaon momentum 60 GeV/c)

m^2_{miss} before background rejection (NA48 2004 data)



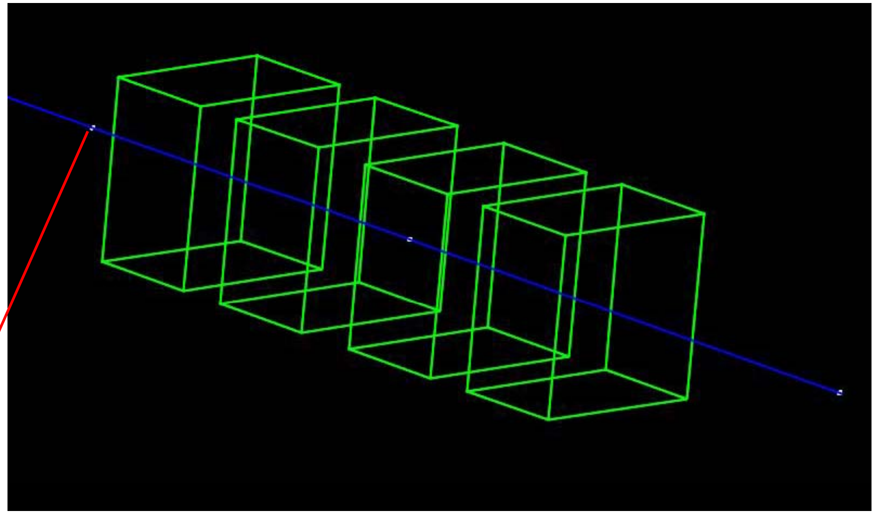
- Good description of background with Monte Carlo
  - Main sensitivity limitation from μ-rejection → RICH needed
- Sensitivity analysis to be done also using 2007 data.

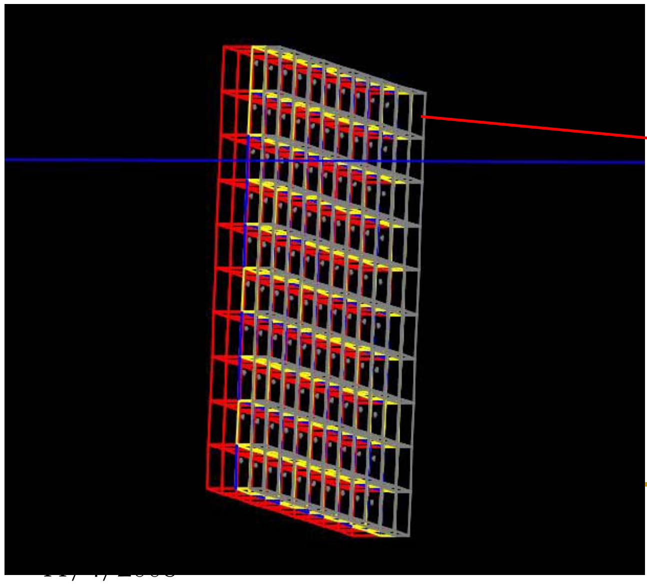
New Monte Carlo Simulation

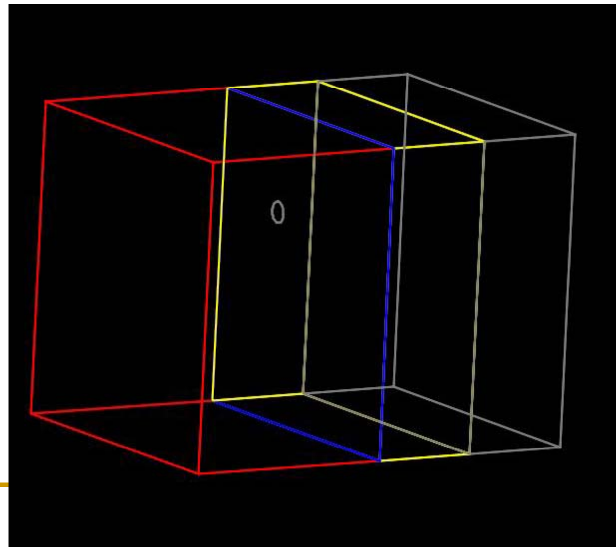
- The sensitivity analysis done up to now made use of a fast simulation
  - Approximations in the simulation of the detectors
  - Particle-matter interactions parametrized from standalone GEANT4-based simulations of various sub-detectors
- New Monte Carlo based on GEANT4 under development
  - Detailed simulation of the detector geometry and digitization
  - As much as possible realistic choice of the physical interactions
  - Construction of shower libraries to speed up the simulation

The work on the new Monte Carlo is on progress. Only the status of the Monte Carlo will be shown, not new results about the sensitivity (still some technical works to do)

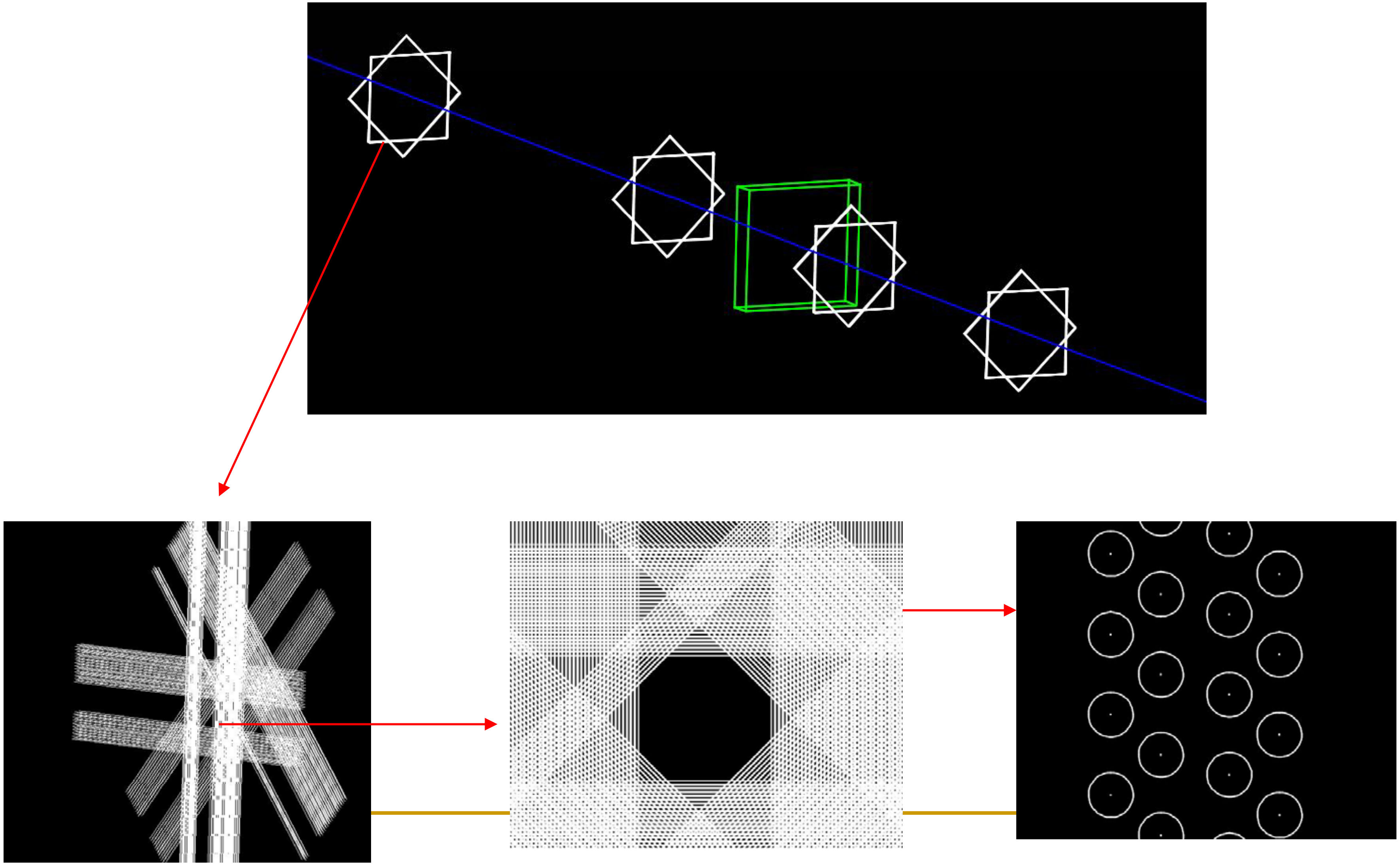
New Simulation: Gigatracker



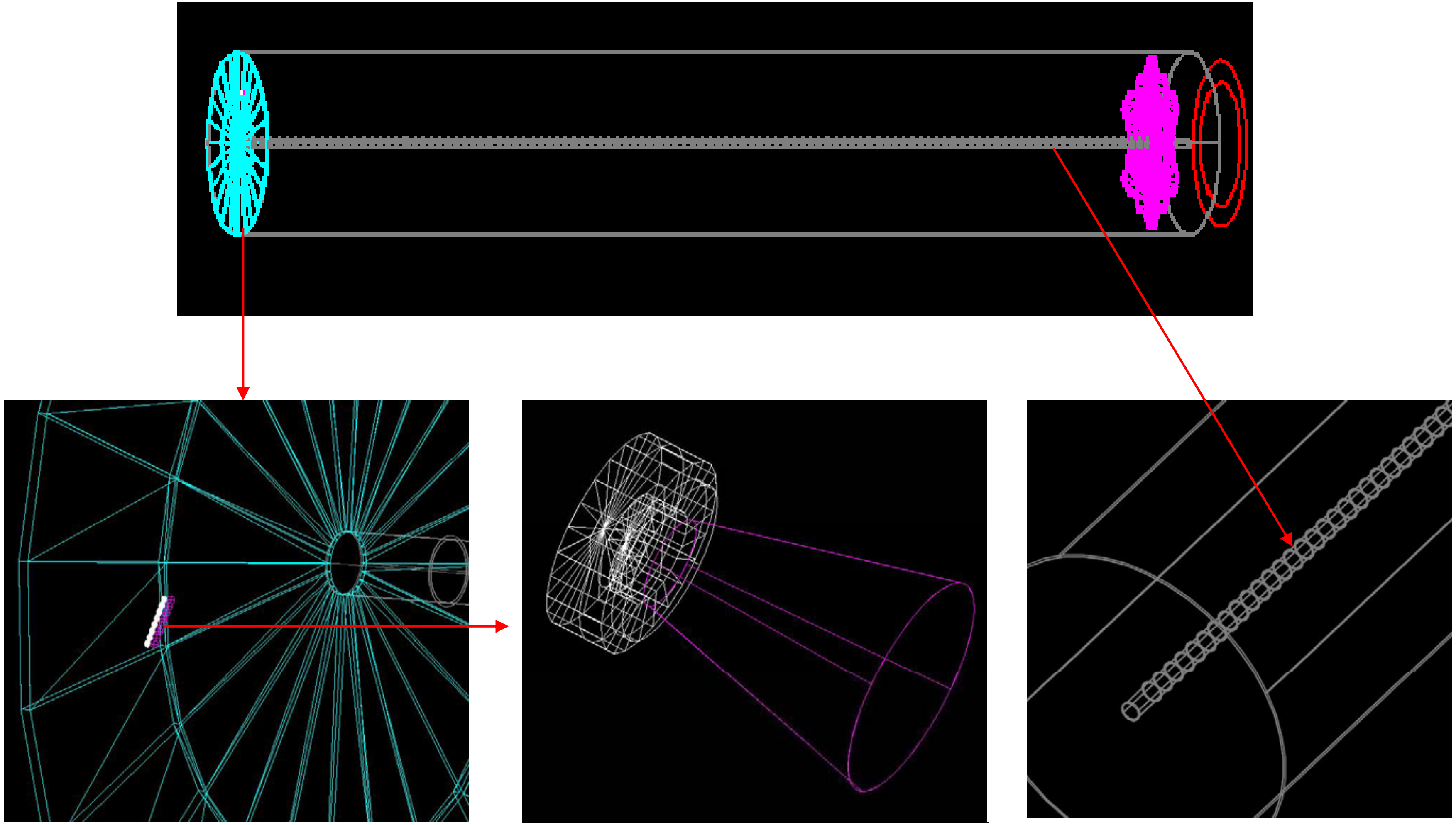




New Simulation: Spectrometer



New Simulation: RICH



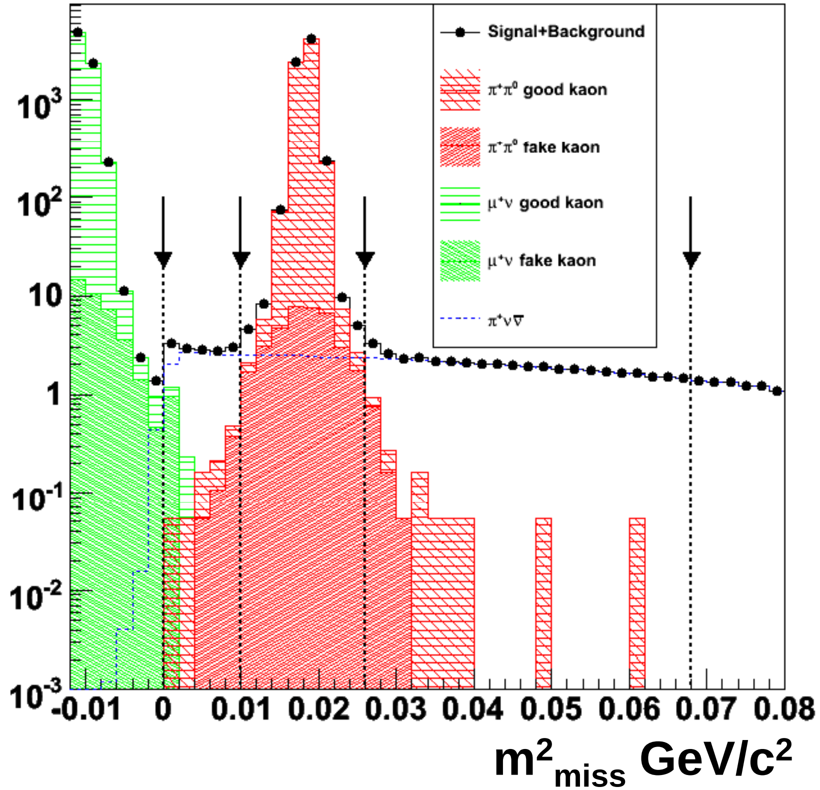
Studies on Photon Rejection

- Analysis of the interactions of γ in the RICH material
  - Goal: study of the impact of the RICH material on the γ detection inefficiency in LKr (must be lower than $\eta_{LKR} < 10^{-5}$)
  - Motivation: worried about interactions like: e.m. shower, γ-nuclear interactions in Ne, mirror, beam pipe
  - Most dangerous interactions: γ-nuclear interactions
    - Probability of γ-nuclear interaction in RICH material $>10^{-4}$
  - Question: could we veto these interactions ?
  - Analysis performed with the New Simulation using $K^+ \rightarrow \pi^+ \pi^0$ events
    - $\sim 2\times10^2$ γ-nuclear interactions found out of 6×10^5 γ
    - 1 event remaining after detecting the products of the γ-nuclear interaction downstream to the RICH.
  - Preliminary result: effect $\sim 10^{-6}$ on η_{LKr}

Analysis of the Kinematic Rejection

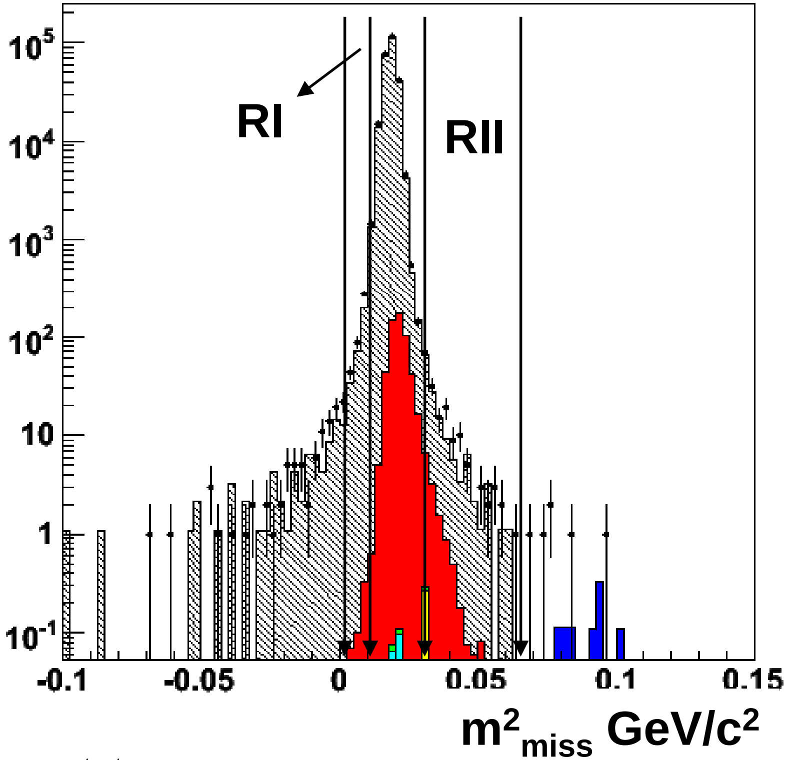
- Kinematic rejection inefficiency:
  - Non gaussian Multiple Scattering: depends on detector material → irreducible
    - ~30%÷40% of the inefficiency
  - Kπ mismatching: depends on beam rate and track time resolution → reducible

- Effect studied using the fast simulation
  - Uncertainty in the irreducible component due to the limitations of the GEANT4 description of the non gaussian Multiple Scattering



Analysis of the kinematic rejection

- Study of the kinematic rejection inefficiency on data (NA62)
  - $K^+ \rightarrow \pi^+\pi^0$ selected on 2007 data using LKr information only
  - Look at the tails in the m^2_{miss} reconstructed with the NA48 DCH
  - Compare data and Monte Carlo (NA48 MC based on GEANT) in the tail regions*



- Preliminary analysis
  - $\sim 2.5\times10^5$ $\pi^+\pi^0$
  - Overall background $\sim 2\times10^{-3}$
  - Background in the tail regions ~5%
  - Expected sensitivity $\sim 10^{-4}$
  - Hint about the reproducibility of the non gaussian tails in GEANT within a factor 2 (at least).

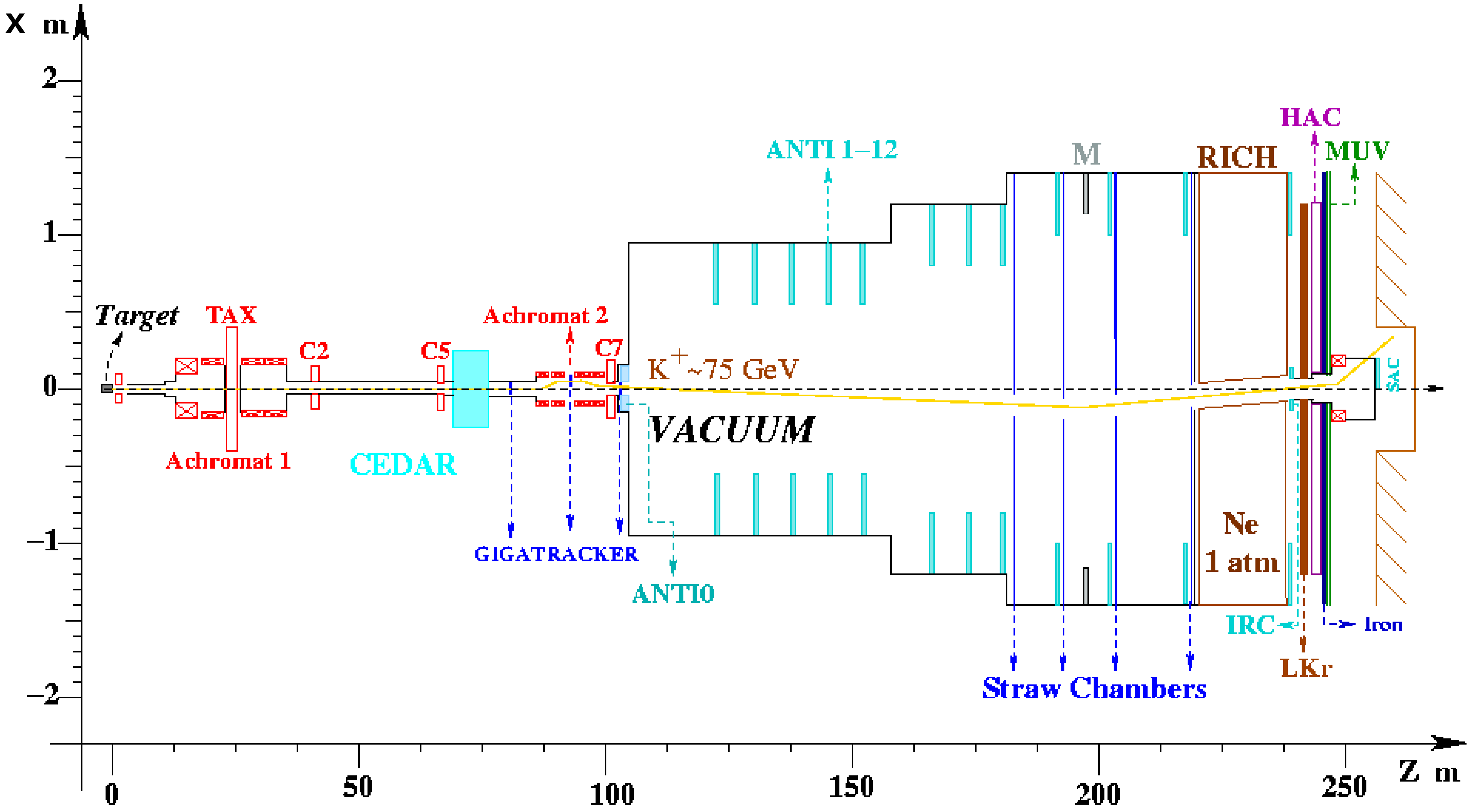
* *Tail regions ≡ region I and region II*

Conclusions

- 2007 results about sensitivity still valid
- The project of a new complete and detailed simulation already started
- Analyses using NA48/NA62 data and the new Monte Carlo on going to complete the review of the sensitivity of the experiment in 2009.

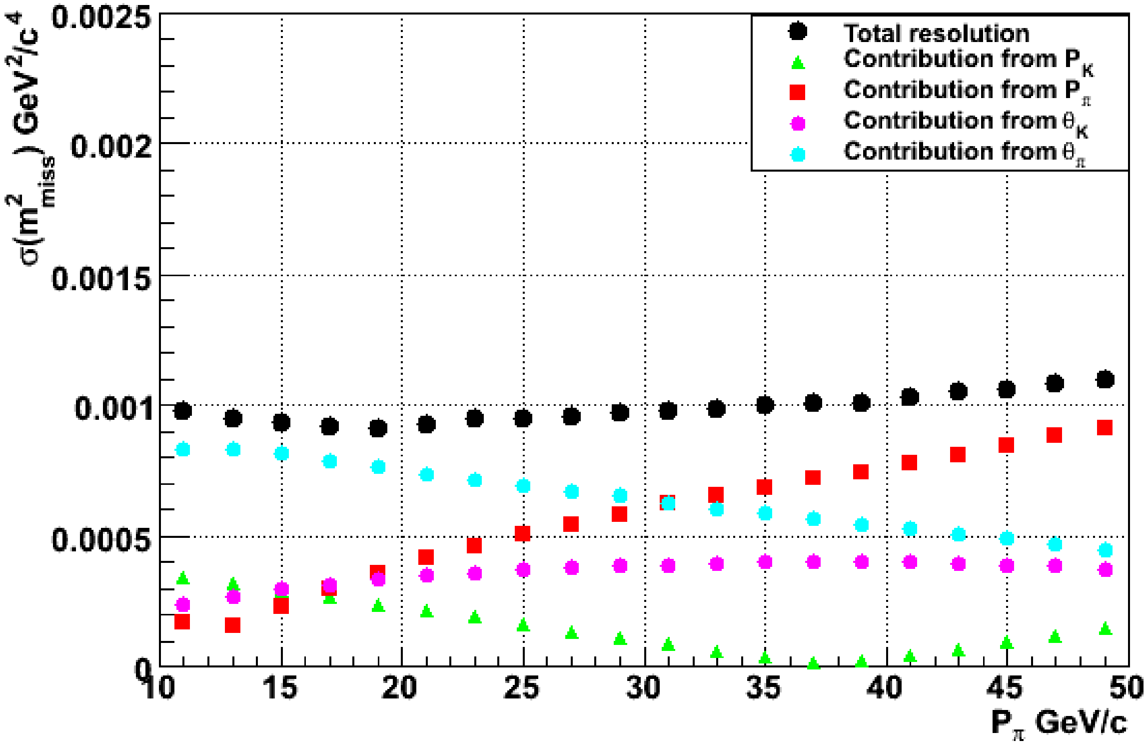
SPARES

Layout



X m
2
1
0
−1
−2
Target
TAX
Achromat 1
C2
CEDAR
C5
Achromat 2
C7
GIGATRACKER
ANTI0
K+~75 GeV
VACUUM
ANTI 1–12
M
RICH
HAC
MUV
SAC
Ne
1 atm
IRC
LKr
Iron
Straw Chambers
0
50
100
150
200
250
Z m

Kinematic resolution (fast simulation)



- Resolutions
  - Gigatracker: $\sigma(P_K)/P_K = 0.2\%$, $\sigma(dX,Y/dZ) \sim 12$ µrad
  - Straw spectrometer: $\sigma(P)/P = 0.3\% \oplus 0.007\%P$, $\sigma(dX,Y/dZ) = 45 \div 15$ µrad

Wrong K π matching

- Pile-up in Gigatracker
  - 800 MHz/station → probability of more than 1 K^+ track within $\mathcal{O}$(200 ps) >20 %
  - If an additional track in Gigatracker is identified as the K^+ related to the π^+ reconstructed downstream → $\sigma(m^2_{miss})$ will depend on momentum bite and beam divergence.
    - $\Delta P_K/P_K$=1.2% >> $\sigma(P)_{giga}$~0.2%
    - $\Delta\Theta_{X,Y}$ = 70 μrad >> $\sigma(\theta_{X,Y})_{giga}$ = 14 μrad

⇒ $\sigma(M^2_{miss})_{fake\ track}$ >> $\sigma(M^2_{miss})_{good\ track}$

⇓

New background source for decays with kinematic threshold.

- K-π matching
  - Variables: CDA e $\Delta T \equiv T_{beamtrack} - T_{event}$

- This source of background depends on
  - Track time resolution (Gigatracker and RICH)
  - Spatial resolution
  - Beam phase space (momentum bite and divergence)
  - Beam rate

Rejection of π^0 (from $K^+ \rightarrow \pi^+\pi^0$) (fast simulation)

- Without cuts on π^+ momentum : Inefficiency 1.6×10^{-7}
  - geometrical + intrinsic detector inefficiency
- P_π<35 GeV/c: Inefficiency 1.7×10^{-8}
  - 82% events with both photons in LKr
  - 17.8% events with one photon in LAV and one in LKr
  - 0.2% events with one photon outside of LAV acceptance and the other in LKr or SAC (IRC)
  - Photons outside of the LAV acceptance have E<100MeV
  - Contribution from geometrical inefficiency and LKr inefficiency dominant
  - Contribution from intrinsic LAV inefficiency <20%
- P_π<35 GeV/c + cut on minimum distance from π^+ cluster in LKr: Inefficiency ~3.5×10^{-8}
  - Contribution reducible using a LKr cell by cell analysis (to be done)

Key points of π^0 rejection:
- Cut on maximum momentum of charged pion
- The average energy of photon hitting the LKr is high (~10 GeV)
- The LKr inefficiency for photons above 10 GeV is $<10^{-5}$

Muon rejection and other backgrounds

- Muon Detector (modified NA48 HAC + Muon Veto)
  - Inefficiency ~10^{-5}.
  - Assumption based on the NA48 experience and a standalone simulation
- RICH
  - Probability of $\mu - \pi$ misidentification = 5×10^{-3}
  - Upper limit from standalone simulations and results from test beam
  - Cut on P_π>15 GeV/c needed as a consequence of the Cerenkov threshold in Ne

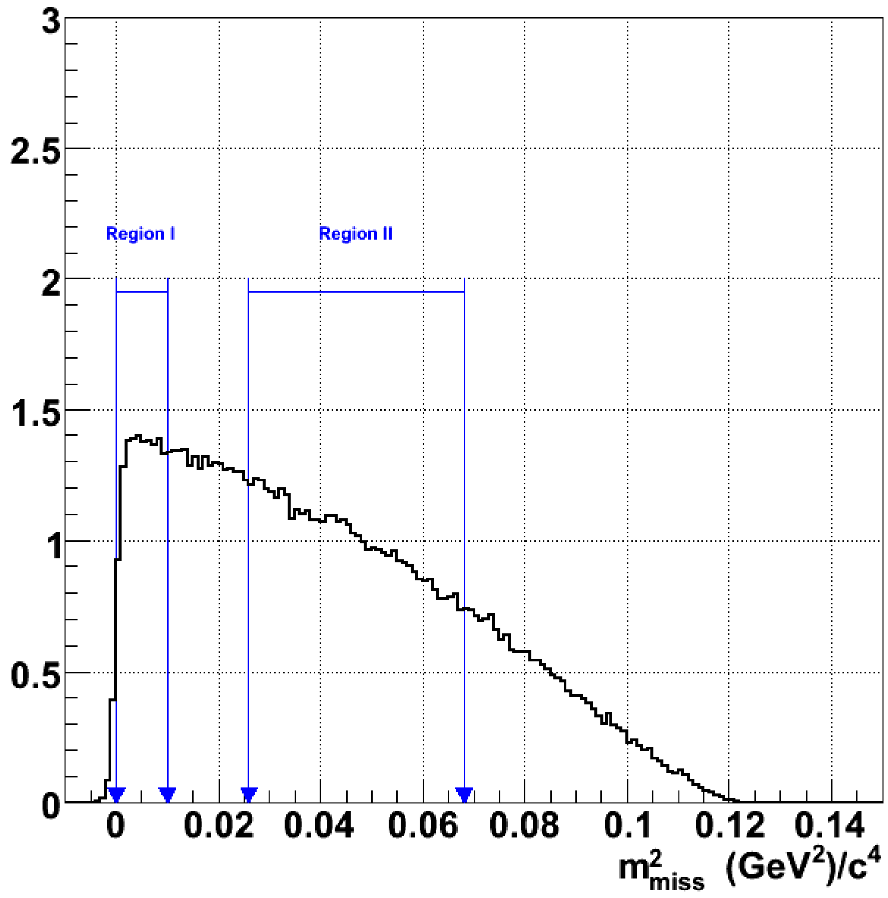
- Backgrounds with >2 charged particles in final state:
  - $K^+ \to e^+\pi^+\pi^-\nu$ (K_{e4}), $K^+ \to \pi^+\pi^+\pi^-$
  - Dangerous K_{e4} configuration : e^+ not detected in LAV, π^- (high E) in the hole of the straw spectrometer.
  - Way to catch it: magnet deflects π^- in the chamber after the magnet
    - Shift of the center of the straws to follow the positive beam path
    - Long lever arm after the magnet
    - The existing analysis is based on the old fast simulation. The analysis using the new simulation is on progress.

Accidental background

- Beam interactions with the residual gas
  - Hadronic interactions simulated using GEANT e FLUKA
  - Dangerous events: only one charged particle reconstructed in the straw spectrometer
  - All the subdetectors used to detect the secondaries
  - K identification with CEDAR needed (~90% efficiency assumed)
  - Results: <1 event/year with a vacuum of $\sim 10^{-6}$ mbar
  - This analysis will be redone using the new simulation

- Beam interactions with the 3rd station of the Gigatracker
  - Background studied using a standalone GEANT3 simulation:
  - Dangerous events: one positive particle in the straw spectrometer acceptance, suffering for a scattering at high angle in the first straw chamber $\rightarrow$ decay vertex reconstructed in the decay region
  - 3rd station must be placed downstream to the final collimator
  - ANTI0 around the 3rd station to detect the products of the interactions
  - CEDAR for vetoing the K interaction
  - Result: background negligible
  - This analysis will be redone using the new simulation

Signal acceptance



- Acceptance = 14.4%
(3.5% Region 1, 10.9% Region 2)
- Gigatracker reconstruction efficiency ~90%.
- Main contribution: cuts on P_π
(50% reduction in acceptance)