Physics Overview

Giuseppe Ruggiero (CERN)
NA62 Collaboration Meeting
Ferrara, 01/09/2014

$\pi\nu\nu$ Physics Program

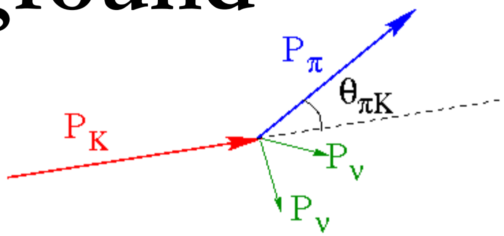
Goal of NA62: $K^+ \to \pi^+ \nu \bar{\nu}$

Decay	Physics	Present Result	SM expectation	NA62
$\pi^+ \nu\nu$	New Physics	$(17 \pm 11) \times 10^{-11}$	$(7.8 \pm 0.8) \times 10^{-11}$	10% precision measurement

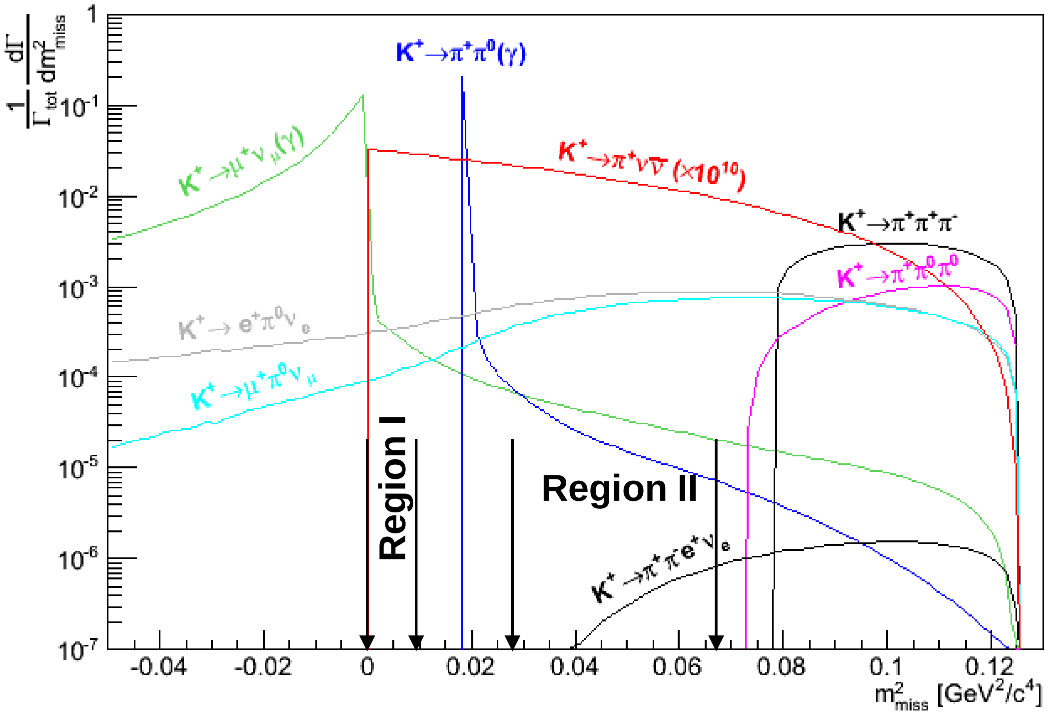
- NA62 has been designed for:
  - Getting O(100) SM $K^+ \to \pi^+ \nu \bar{\nu}$ events in 2 years of data
  - Reaching a 10^{-12} single event sensitivity for K^+ decay
    - Gigatracker
    - L-R asymmetric layout preventing the possibility of reversing B
    - Very long lever arm of the Straw Spectrometer

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



$\pi\nu\nu$ 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

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ Measurement

- Signal selection
  - L0, Higher Levels Trigger
  - Straw tracks reconstruction
  - Single pion track topology
  - Beam tracks reconstruction
  - Kaon ID (KTAG)
  - beam – pion matching
  - Event kinematics (m^2_{miss})
  - Pion ID using RICH
  - Pion ID using calorimeters (muon/electron rejection)
  - Single pion topology downstream to straw spectrometer
  - Beam-induced accidental rejection / measurement
  - Photon rejection
- Background measurement
- Acceptance measurement (trigger efficiency, detector efficiency, random veto ...)
- Normalization

πνν L0 Trigger

Goal: 10 MHz → < 1 MHz

- Acceptance:
  - Q1 (CHOD)
  - N RICH (Hits > 3)
- Energy (γ rejection):
  - $E_{em}(LKr + SAV) < 20$ GeV
  - $E_{tot}(em + MUV) < 40$ GeV
  - $E_{LAV,SAV} < 4$ GeV
- Muon rejection:
  - !MUV3
  - $E_{LKr} > 1.5$ *OR* $E_{MUV} > 8.5$ GeV

MC '14

Table 3: Expected particle rate (KHz) after applying L0 and trigger efficiency

Process	Original	Rate, no accidentals	Rate, with accidentals
$K_{\mu 2}$	8397	2.4±0.5	11.3±1.5
$\pi^+\pi^0$	2729.9	40±2	39±1
$\pi^+\pi^+\pi^-$	738.6	39.2±0.9	34.4±0.8
$\pi^+\pi^0\pi^0$	232.7	1.0±0.1	1.2±0.1
K_{e3}	669.9	13.9±0.5	12.9±0.5
$K_{\mu 3}$	443.0	8.7±0.3	6.9±0.3
Beam π^+	526000	48±5	48±5
Beam protons	173000	3.9±0.7	3.0±0.7
Muons upstream	135000	1±1	22±5
Total L0		158±6	179±8
		Efficiency, no accidentals	Efficiency, with accidentals
Signal		(91.13±0.004)%	(74.85±0.006)%

$\pi\nu\nu$ HLT Trigger

Goal: 1 MHz $\rightarrow$ < 20 KHz

- At least one track reconstructed (full pattern recognition in straw)
- Momentum between 10 and 45 GeV (no fit, only full pattern recognition)
- Z vertex < 180 m (no fit, only full pattern recognition, vertex done as intersection with the nominal beam axis)
- RICH, CHOD mulitplicity
- CEDAR

Track + P + Z requirements applied on events passing $\pi\nu\nu$ full L0 without accidentals (x5 reduction)

Channel	L0 Rate KHz (without multiplicity cuts)	
$\pi^+\pi^0$	0.5	
$\pi^+\pi^+\pi^-$	11.3	
$\pi^+\pi^0\pi^0$	0.01	
$\mu^+\nu$	1.0	Rough estimation, no accidentals
$\pi^0 e^+\nu$	1.0	
$\pi^0\mu^+\nu$	0.6	
Beam π^+	7.0	
Beam p	0.9	
Total	22.2	

Single pion track (Straw Spectrometer)

Goal: $\sigma(P)/P = 0.32\% \oplus 0.008\%\, P\ [GeV/c]$, $\sigma(dX,Y/dZ) = 20 - 50\ \mu rad$

Straw signal

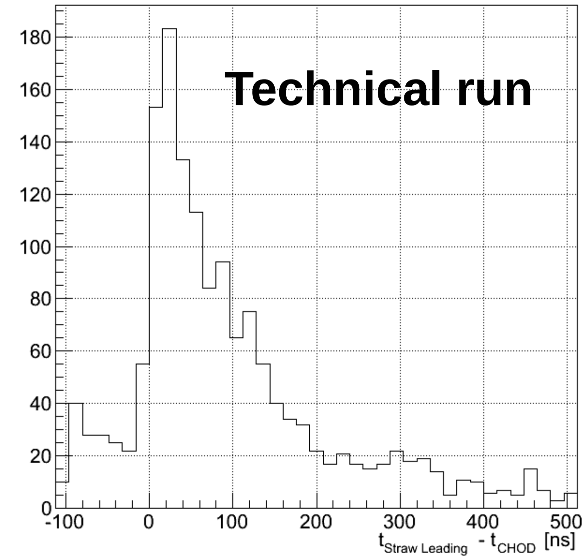
- T0 for leading and trailing time → trigger time
- Straw hit time window for leading time driven by the straw drift time (~ 160 ns).
- Expected resolution on trailing time of single hits → 20 ns (measured in lab 35 ns).

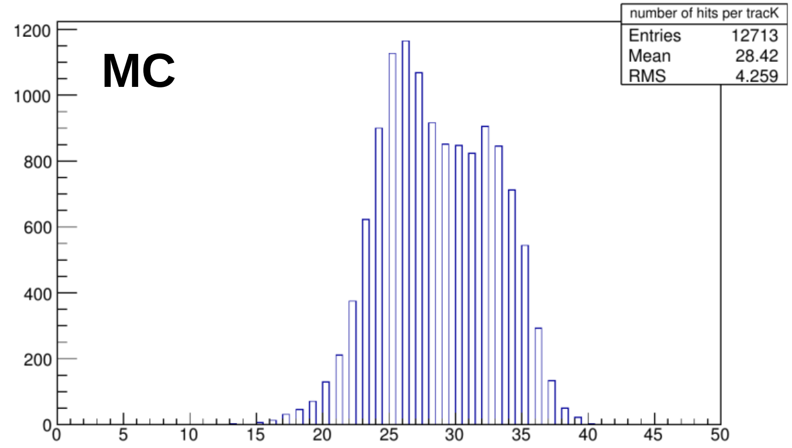
Identify single pion track event:

- Bad t0 for accidental tracks → mis-measured drift time → worsening of pattern recognition
- Time resolution of reconstructed track from trailing time: $\sigma(t_{hit})/\sqrt{N_{hit}} \sim 4 - 8$ ns

High resolution track measurement:

- Accurate straw by straw calibration/alignment
- Map of the MNP33 magnetic field
- Precise treatment of the MS in the fit



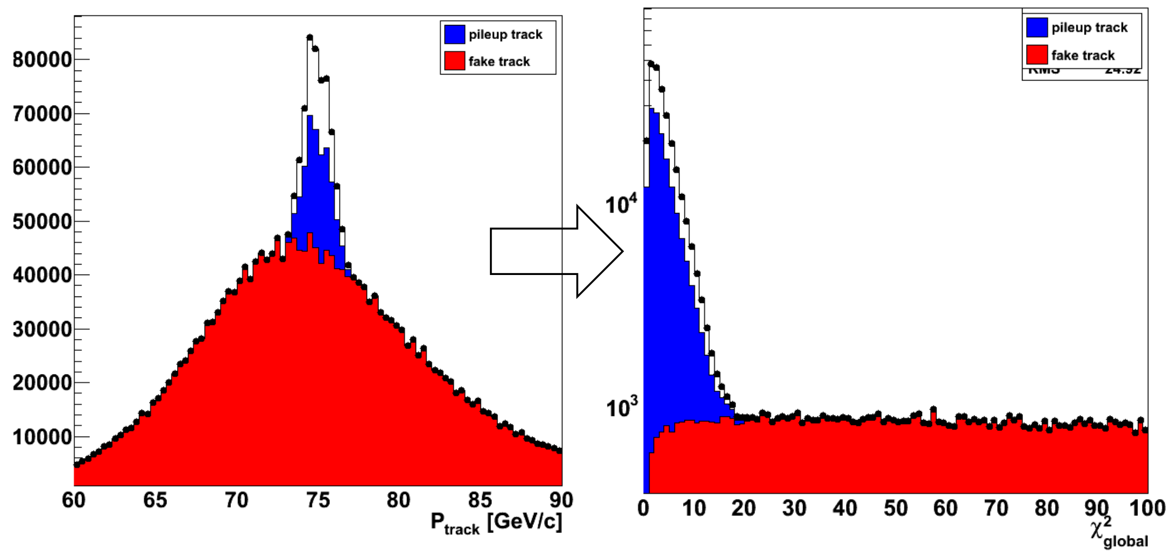


Beam track (Gigatracker)

Goal: $\sigma(P_K)/P_K = 0.2\%,\ \sigma\left(\frac{dX,Y}{dZ}\right)_K = 15\ \mu rad$

Pattern recognition

- Fake track reduction
  - Fraction of: Kaons 3.6%, Pileup 5.3%, Fake 91%
- Various methods for reduction under study
  - Best result reached on MC: fake < 0.5%.



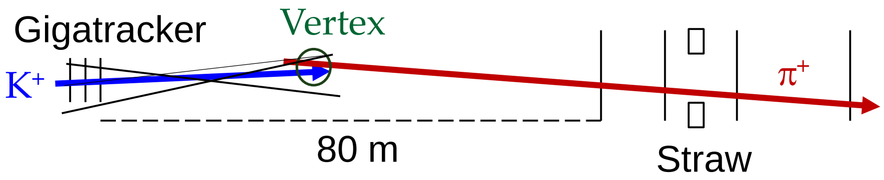
High resolution track measurement:

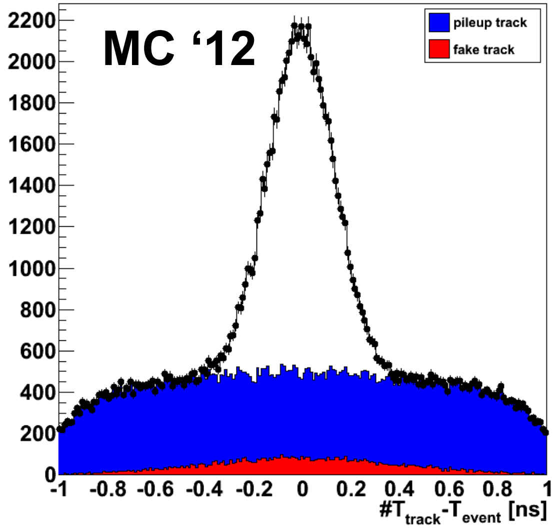
- 3 stations are not enough to use a fit for momentum and slope measurement
- Possibility of adding the target as additional point under study

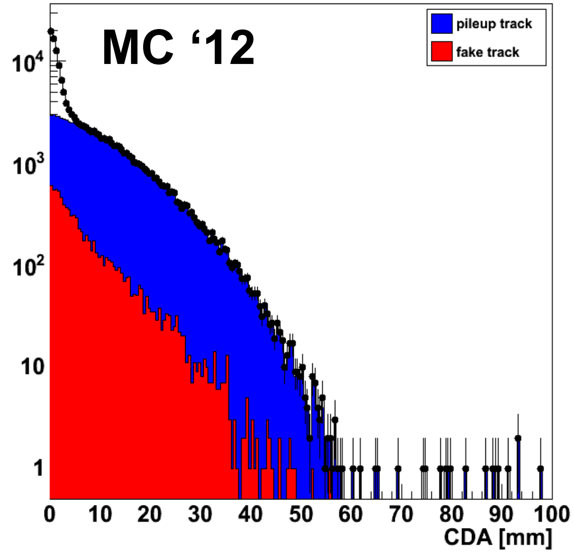
K^+ - π^+ Matching

Goal: Mis-matching probability < 1%

- K^+ and π^+ time matching
  - Gigatracker: $\sigma(t)$ = 200 ps / station
  - KTAG: $\sigma(t)$ < 100 ps
  - RICH: $\sigma(t)$ < 100 ps
- K^+ and π^+ spatial matching





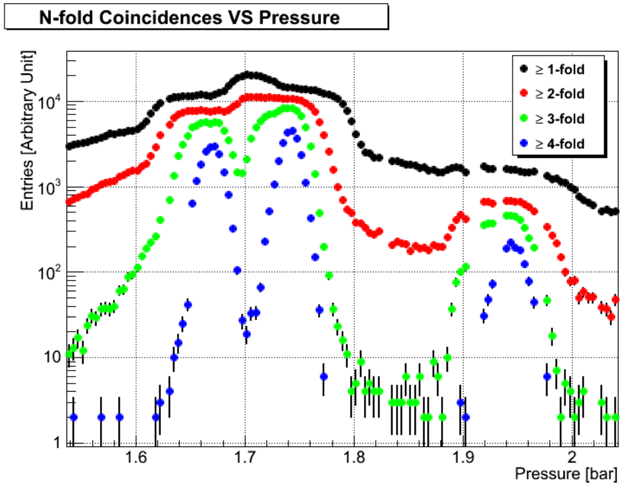


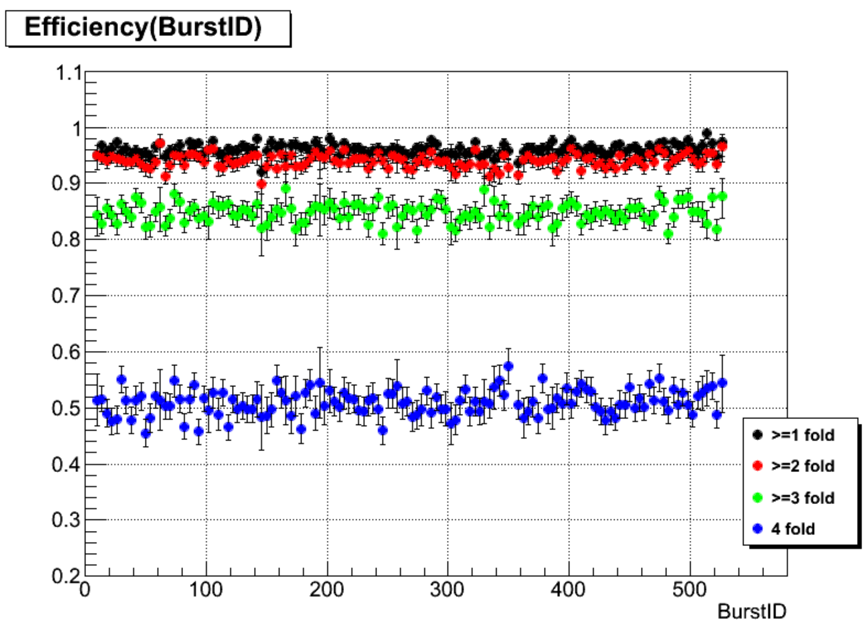
- Main limitations: time resolution, GTK inefficiency

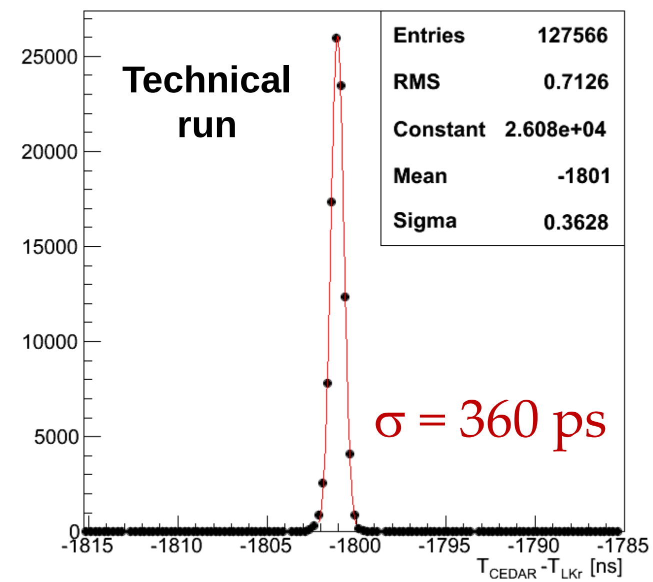
Kaon ID

Goal: σ(t) = 100 ps,
≤ % level pion mis-tagging > 95% K efficiency

- Purposes:
  - Suppression of accidentals
  - Pion – kaon matching

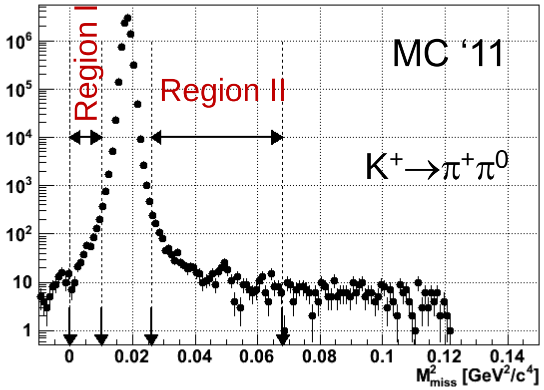


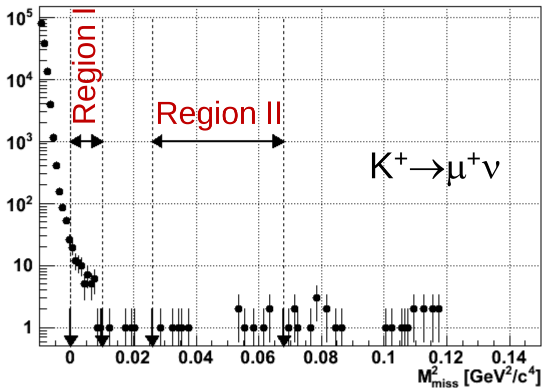


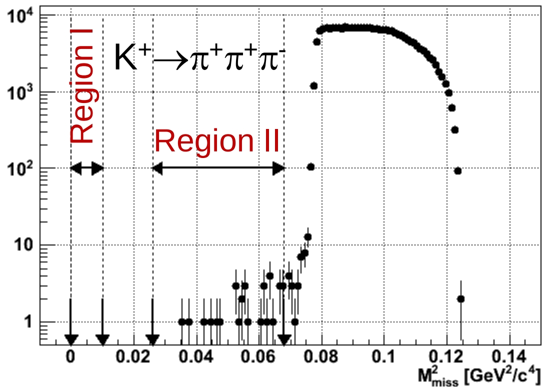


Event Kinematics

Goal: $\pi^+\pi^0$ rejection factor $\sim 5\times10^3$, $\mu^+\nu$ rejection factor $\sim 1.5\times10^4$

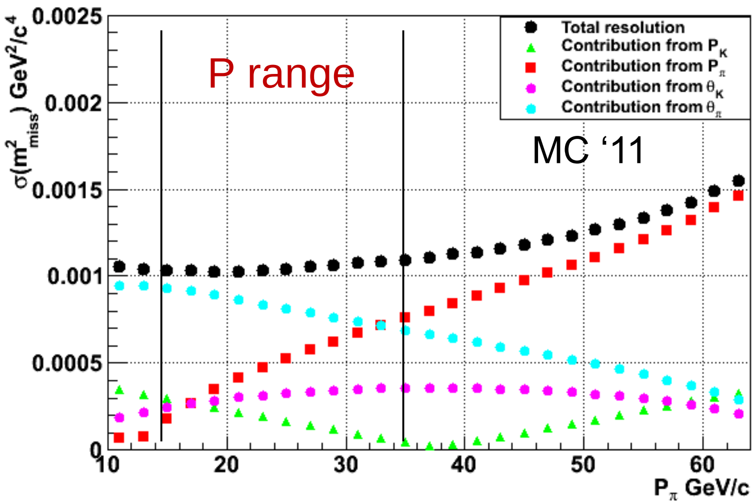






Cut on m^2_{miss}:

- Control of the non gaussian tails of the resolution
- Pileup reduction in Gigatracker
- Precise relative alignment between Straw and Gigatracker



Momentum range: (15, 35) GeV:

- Key requirement

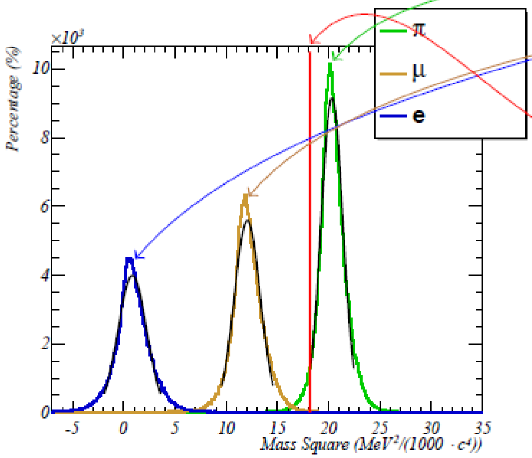
Pion ID (RICH)

Goal: $10^2 - 10^3$ π/μ separation up to 35 GeV, $\sigma(t) \leq 100$ ps

$$r_C = f \tan\theta_C \simeq f\theta_C$$

$$\theta^2_{max} - \theta^2_C \simeq \frac{m^2}{p^2}$$

MC



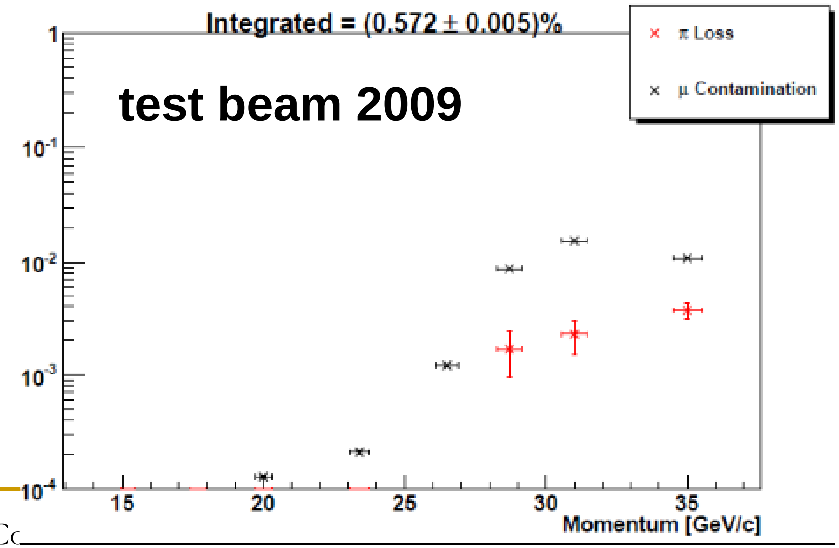
Fit the peaks:

$K^+ \longrightarrow e^+\nu_e$

$K^+ \longrightarrow \mu^+\nu_\mu$

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

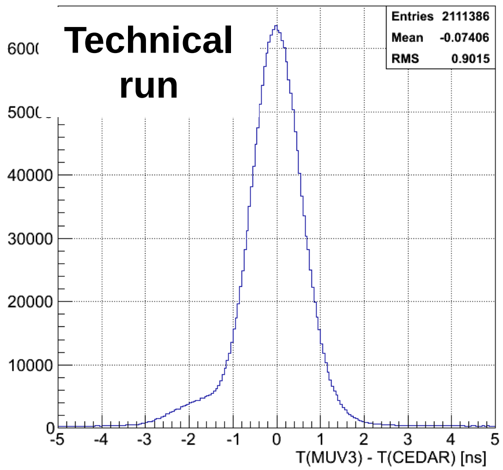
Apply a cut between the μ and π peak



Pion ID / Muon rejection (Calorimeters)

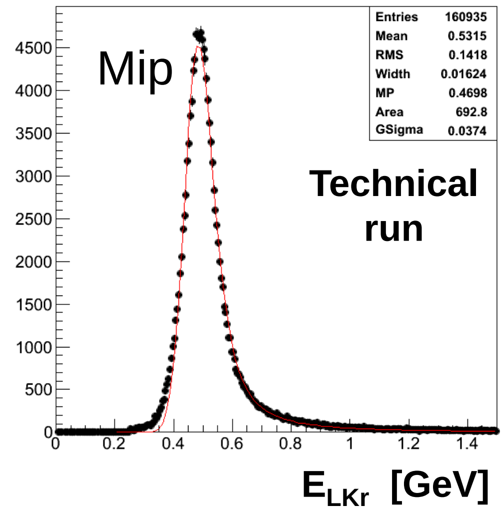
Goal: 10^4 - 10^5 π/μ separation

MUV3



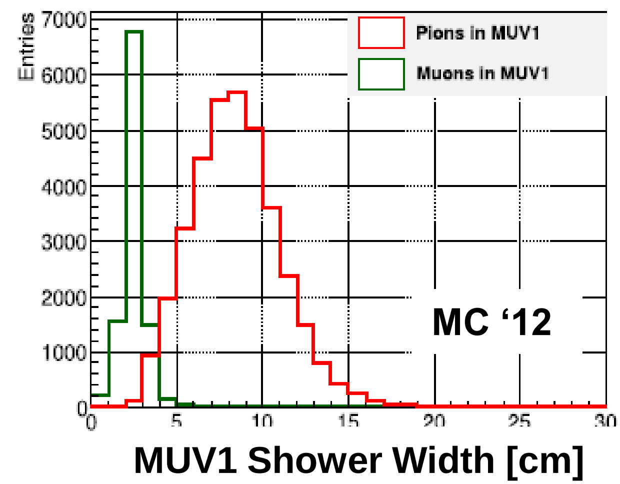
+

LKr

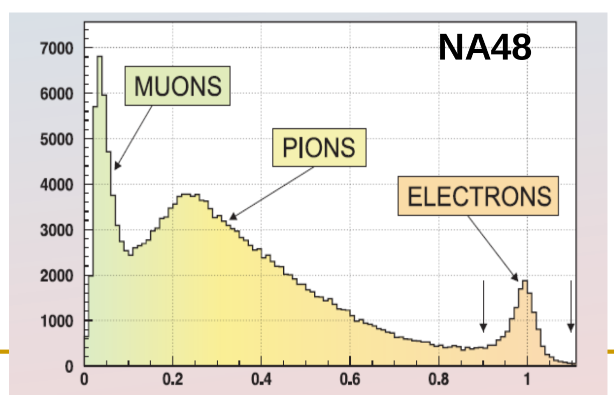


+

MUV1-2



- Bulk of the rejection at trigger level



Photon rejection

Goal: $10^8 - 10^3$ π^0 rejection from $K^+ \rightarrow \pi^+\pi^0$

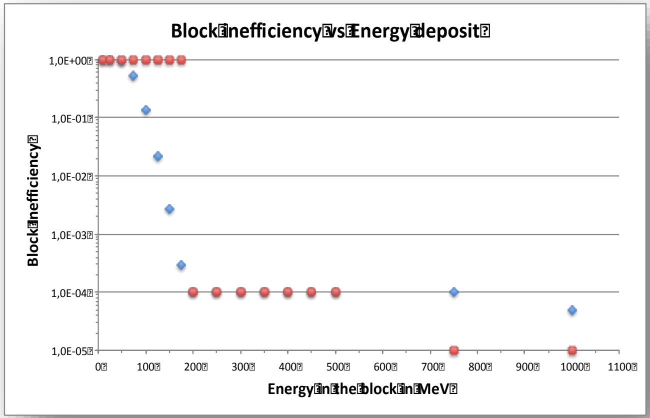
- Bulk of the rejection at trigger level (high energy photons).
- Offline rejection needed to cover mainly the low energy part of the photon spectrum

LKr

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

- Main issues:
- pion – photon cluster separation;
- identification of the clusters due to photo-nuclear interactions.

LAV



- Main issue:
- rejection vs energy threshold.

IRC / SAC

Expected inefficiency limited by the γ interactions with the material in front 10^{-2} and 10^{-4}

- Main issue:
- Thresholds to avoid the high rate in IRC and dump back-scattering in SAC

Single pion event topology

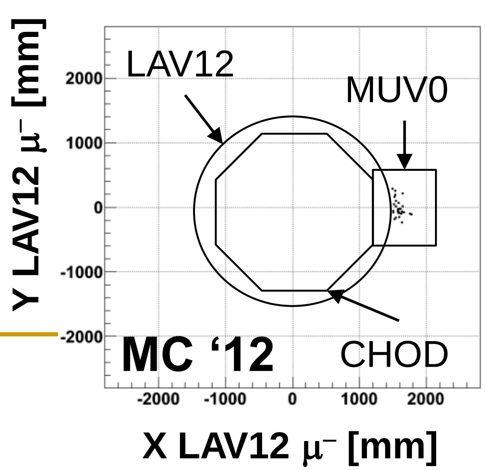
Goal: >10^5 rejection factor on $K^+ \rightarrow \pi^+\pi^+\pi^-$

- Multiplicity in RICH
- Multiplicity in CHOD
- Multiplicity in LKr
- Multiplicity in MUV1,2
- Segments in Straws
- LAV 9,10,11,12
- MUV0
- HAC

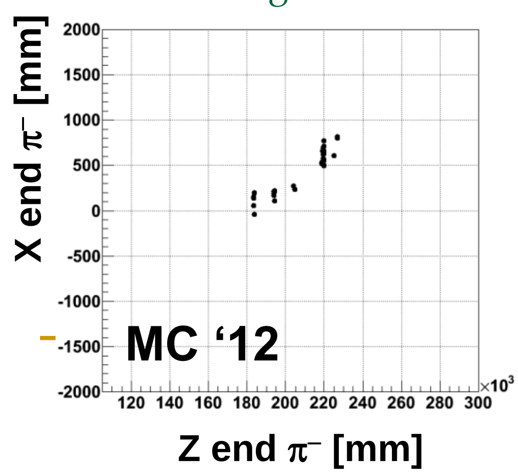
	$N(K^+\rightarrow\pi^+\pi^+\pi^-)$	$N(K^+\rightarrow\pi^+\nu\nu)$
No CHOD	(63 ± 9)	53
No RICH	(12 ± 2)	48
No Segment	(54 ± 8)	48
No LAV	(63 ± 9)	47
No MUV0	(52 ± 8)	47
No HAC	(10 ± 4)	47
No Segment, RICH, CHOD	$(181 \pm 5)\ \mathrm{x}10^3$	54

Major issue (RII): $\pi^+\pi^+\pi^-$

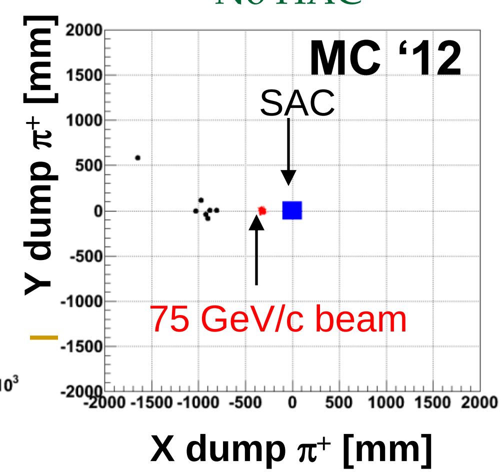
No MUV0



No Segment



No HAC



Accidental rejection

Goal: 10^8 - 10^9 rejection factor

K interaction

- CEDAR
- CHANTI
- Gigatracker

Final state topology

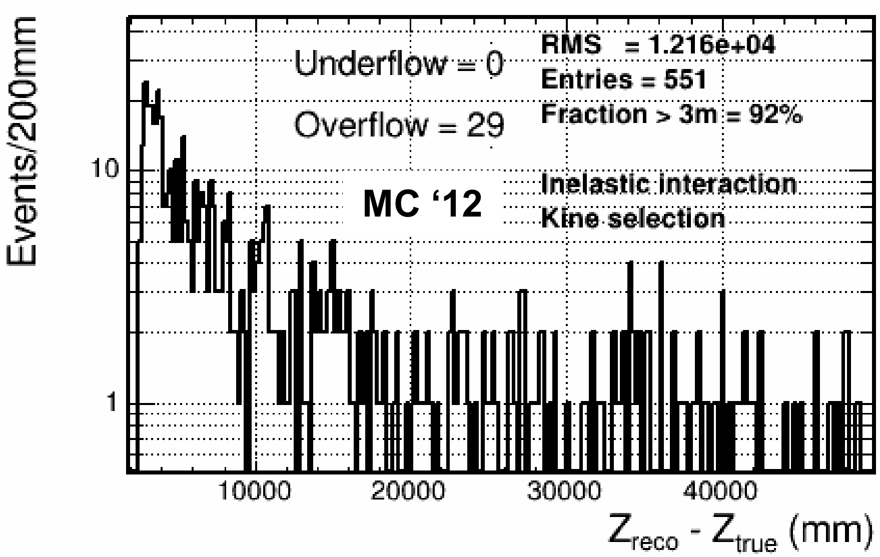
- All the detectors downstream.

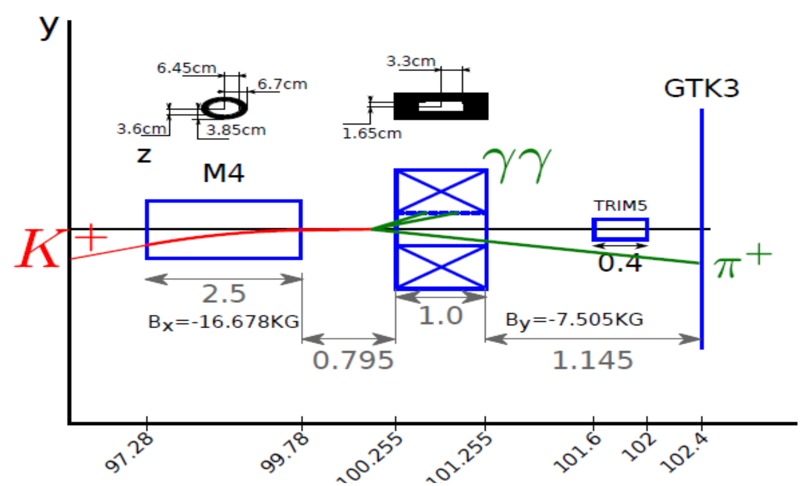
Rate at first straw plane (MC)

Hit Type	N2
Elastic	461 ± 20
CEDAR Gas Inelastic	18 ± 4
GTK1 Inelastic	0 ± 1
GTK2 Inelastic	3 ± 1
GTK3 Inelastic	161 ± 12
Other Inelastic	56 ± 7
Total Rate from Scattering	699 ± 25
Total Rate from Decays	9200

Rates in kHz

Tails of the reconstructed Z vertex





- $K^+ \to \pi^+\pi^0$ occuring at end of GTK with both photons stopped in Collimator 6

For S/B = 10 we need bkg reduction between $10^{-8/-9}$

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

$$\frac{BR(K^+ \to \pi^+ \nu\bar{\nu})}{BR(norm.)} = \frac{(N^{data}_{\pi\nu\nu} - N^{bckg}_{\pi\nu\nu}) \cdot \mathcal{A}_{norm} \cdot \varepsilon^{trig}_{norm}}{(N^{data}_{norm} - N^{bckg}_{norm}) \cdot \mathcal{A}_{\pi\nu\nu} \cdot \varepsilon^{trig}_{\pi\nu\nu}}$$

- Background: $N^{bckg}_{\pi\nu\nu} = N^{\pi^+\pi^0}_{\pi\nu\nu} + N^{\mu\nu}_{\pi\nu\nu} + \cdots \approx \boldsymbol{\mathcal{O}(0.1)} \cdot N^{data}_{\pi\nu\nu}$
- Acceptance: $\mathcal{A}_{\pi\nu\nu} \approx \mathcal{A}^{geom}_{\pi\nu\nu} \cdot \varepsilon^{CEDAR}_{K} \cdot \varepsilon^{GTK}_{K} \cdot \varepsilon^{Straw}_{\pi} \cdot \cdots \approx \mathbf{0.1}$
  - Choice of the normalization to avoid the precise measurement of the signal acceptance and trigger efficiency.
- Measurement of the background
  - Measurement by extrapolation from control regions
  - Measurement by «orthogonal» samples
  - Measurement via the direct evaluation of the acceptance factors using control samples

$$N^{source}_{\pi\nu\nu} = N^{decay}_{K} \cdot \mathrm{Prob(source)} \cdot \mathcal{A}^{source}_{\pi\nu\nu} \approx \boldsymbol{\mathcal{O}(10^{-13})} \cdot N^{decay}_{K}$$

example: $\mathcal{A}^{\pi^+\pi^0}_{\pi\nu\nu} \approx \mathcal{A}^{\pi^+\pi^0}_{geom} \cdot \varepsilon^{CEDAR}_{K} \cdot \varepsilon^{GTK}_{K} \cdot \varepsilon^{Straw}_{\pi} \cdot \eta_{\pi^0} \cdot \eta_{kine}$

Background measurement

Goal: 10% background measurement

- Direct measurement:
  - Definition of control regions in m^2_{miss}vs ... plane
  - Direct estimation of the photon / muon / multi-particle event rejection factor

- Measurement from orthogonal samples:
  - Profit from «detector redundancy» to define background-enriched samples
  - Ad-hoc triggered control samples: e.g. sample of events triggered with CEDAR in veto to measure the background from accidentals

- Rejection factor measurements:
  - Measurement of the non-gaussian tails of the reconstruction using $K^+ \to \pi^+\pi^0$ selected with the LKr only (technical run - like).
  - Mesurement of the photon veto inefficiency using $K^+ \to \pi^+\pi^0$ and $K^+ \to \pi^+\pi^0\pi^0$ selected with the spectrometer only (sensitivity to single photon inefficiency < 10^{-5}).
  - ...

Detector Performances

Performance	Expected	Measured
Kinematic rejection inefficiency	$10^{-3} \div 10^{-4}$	-
Muon ID RICH inefficiency	$10^{-2} \div 10^{-3}$	-
Pion ID RICH efficiency	> 90%	-
Positron ID RICH inefficiency	10^{-3}	-
Muon ID Calorimeter inefficiency	10^{-5}	-
Pion ID Calorimeter efficiency	> 90%	-
Positron ID LKr inefficiency	10^{-2}	-
Photon rejection inefficiency in LKr	10^{-5} (> 10 GeV)	-
Photon rejection inefficiency in LAV	$10^{-3} \div 10^{-4}$	-
Photon rejection inefficiency in SAC	$10^{-2} \div 10^{-3}$	-
Kaon ID efficiency in KTAG	95%	-
Kaon – Pion mis-ID	<1%	-

non – πνν Physics Program

NA62 as a K^+ facility (1)

LFV

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}

NA62 as a K^{+} facility (2)

Forbidden (non LFV)

Decay	Physics	Present limit (90% C.L.) / Result	NA62
$\pi^+ X^0$	New Particle	$5.9 \times 10^{-11}\ m_{X^0} = 0$	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}

NA62 as a K^+ facility (3)

Others

Decay	Physics	Present limit (90% C.L.) / Result	NA62
$\mu^+\nu_h, \nu_h \rightarrow \nu\gamma$	Heavy neutrino	Limits up to $m_{\nu_h} = 350\ MeV$	
R_K	LU	$(2.488 \pm 0.010) \times 10^{-5}$	>×2 better
$\pi^+\gamma\gamma$	χPT	< 500 events	10^5 events
$\pi^0\pi^0 e^+\nu$	χPT	66000 events	$O(10^6)$
$\pi^0\pi^0 \mu^+\nu$	χPT	-	$O(10^5)$

NA62 as a π^0 facility

Single event sensitivity for π^0 decays: 10 $^{-11}$

Decay	Physics	Present limit (90% C.L.)	Prediction	NA62
μ^+e^-	LFV	3.8×10^{-10}	Forbidden	
μ^-e^+	LFV	3.4×10^{-8}	Forbidden	
3 γ	CV	3.1×10^{-8}	Forbidden	10^{-10}
4 γ	Light Scalar	2.0×10^{-8}	10^{-11}	10^{-10}
$\nu\nu$	RH ν	2.7×10^{-7}	$< 10^{-13}$	$< 10^{-9}$
$e^+e^-e^+e^-$	TV	$3.34(16) \times 10^{-5}$	$3.26(18) \times 10^{-5}$	
$e^+e^-\gamma$	U boson	$< 10^{-5}, M_U = 30MeV$ $< 3 \times 10^{-6}\ M_U = 100MeV$	-	×100 better

L0 Trigger for non - $\pi\nu\nu$ decays

Condition	α, kHz	β, kHz/ns	
Track multiplicity			
$R_4 \cdot Q_1$	10340	10	$\boxed{F[R_4 \cdot Q_1/1000] \approx 10\ \text{kHz}}$
$R_{10} \cdot C_2$	1667	84	
$R_{10} \cdot Q_2$	1486	72	
$R_{10} \cdot Q_X$	1197	38	$\boxed{F[R_{10} \cdot Q_X/100] \approx (10 + 0.4\Delta t/\text{ns})\ \text{kHz}}$
Track + EM energy			
$R_4 \cdot Q_1 \cdot E(10)$	2504	18	$\boxed{F[R_4 \cdot Q_1 \cdot E(10)/50] \approx (50 + 0.4\Delta t/\text{ns})\ \text{kHz}}$
Di-electron			
$R_{10} \cdot Q_X \cdot E(10)$	905	19	$\boxed{F[R_{10} \cdot Q_X \cdot E(10)/10] \approx (90 + 2\Delta t/\text{ns})\ \text{kHz}}$
Di-muon			
M_2	632	103	
MO_2	244	46	
$R_{10} \cdot M_2$	195	83	
$R_{10} \cdot MO_2$	95	42	
$R_{10} \cdot Q_X \cdot M_2$	0	25	
$R_{10} \cdot Q_X \cdot MO_2$	0	15	$\boxed{F[R_{10} \cdot Q_X \cdot MO_2] \approx (10 + 15\Delta t/\text{ns})\ \text{kHz}}$
Muon + tracks + EM energy			
$R_{10} \cdot Q_X \cdot M_1 \cdot E(10)$	150	34	
$R_{10} \cdot Q_X \cdot MO_1 \cdot E(10)$	111	26	$\boxed{F[R_{10} \cdot Q_X \cdot MO_1 \cdot E(10)] \approx (100 + 25\Delta t/\text{ns})\ \text{kHz}}$

2014 run: Pilot Physics Run

2014 Run: General Overview

Goals:

1) Detector commissioning
2) Assess physics sensitivity

- Assumptions:
  - 60 days of data taking (vs nominal run 100 days)
  - 10% of the nominal Intensity x data taking efficiency

$$N_K = 0.06 \cdot 4.5 \times 10^{12} = 2.7 \times 10^{11}$$

$$N_{\pi\nu\nu}^{selected} = N_K \cdot BR(\pi\nu\nu) \cdot \mathcal{A}_{\pi\nu\nu} = (2.7 \times 10^{11}) \cdot (0.8 \times 10^{-10}) \cdot 0.1$$

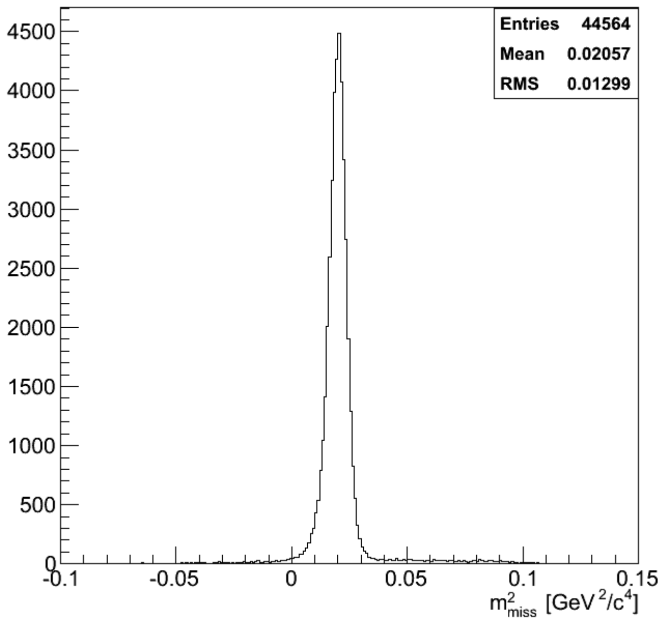
$$\boxed{N_{\pi\nu\nu}^{selected} \approx 2.2\ (SM)}$$

- We can reach the SM sensitivity.

2014 Run: Detector commissioning

- Use physics: e.g. $K^+ \rightarrow \pi^+\pi^0$ method already used for the 2012 Technical run.

- Analysis Method: selection of $K^+ \rightarrow \pi^+\pi^0$ events
  - Selection based on the LKr
  - π^0 reconstruction
    - Z vertex from 2 γ on the LKr assuming m_{π^0}
  - Beam kinematics well defined by the beam line
  - $P_{\pi^+} = (P_K - P_{\pi^0}) \rightarrow P_{\pi^+}^2 = m_{\pi^+}^2$ for $K^+ \rightarrow \pi^+\pi^0$
  - Powerful method to study the time correlations between sub-detectors
  - The position of the charged pion can be predicted with a resolution of few cm at each detector



- Different methods needed for commissioning LAV, IRC, SAC

2014 Run: Physics Goals

1. Reconstruct all the 6 K^+ main decay modes

2. Establish the level of sensitivity to $\pi\nu\nu$

3. Level of sensitivity to LFV/forbidden K^+/π^0 decay modes

2014 Run Strategy

- Beam tuning
- Low intensity (<1%) kaon run with a minimal L0 trigger configuration
  - Detector commissioning
  - L0 trigger commissioning and definition
  - Sub-detector reconstructions
- Muon run
  - Alignement
- Reduced instensity (1-10%) kaon run with a more specific L0 trigger configuration
  - HLT trigger definition
  - Event reconstruction
- Special runs
- Reduced → «Full» intensity kaon run with L0 and, possibly, HLT trigger

2014 Run: L0 Trigger Strategy

- Minimal configuration (minimum bias triggrs):
- Q1, Q1 × MUV3, Q1 × !MUV3, Q1 × NHOD, Q1 × NHOD × !MUV3, Q2, ...

- $\pi\nu\nu$ main stream:
- Starting configuration
- Q1 × !MUV3 × (E LKr < 20)
- Final 2014 configuration :
- Q1 × (RICH > 3) × !MUV3 × (E LKr < 20) × (E MUV < 40) × (E SAV, LAV < 4)

- Other rare decays:
- Q1 × (RICH > 3) × (E LKr > 10) / D
- QX × (RICH > 10) × (E LKr > 10) / D
- QX × (RICH > 10) × (MUV3 ≥ 2)
- QX × (RICH > 10) × (MUV3 ≥ 1) × (E LKr > 10)

- Control samples / Main kaon decay modes:
- Minimum bias, Random, Specific for accidental, ...

Status of the software (a user point of view)

- CEDAR ok
- Gigatracker ok/new version under development
- STRAW problems in the last revision/new version (completely revised) soon
- LKr ok/new calibration on progress
- RICH ok
- CHANTI, LAV not tested recently, but on progress.
- MUV1,2 missing
- MUV3 missing
- IRC, SAC, HAC missing
- MUV0 missing (but the detector is missing too)

User requests to the software WG for the 2014 run:

- Frozen version of the reconstruction software as soon as possible during the run
- Backward compatibility preserved during the software developments
- Data reconstructed with a central NA62Reconstruction version

Conclusion