Status and prospects of the NA62 experiment

Antonino Sergi

University of Birmingham, United Kingdom

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Hadronic Contributions to New Physics Searches
Puerto de la Cruz, Tenerife, Spain

Outline

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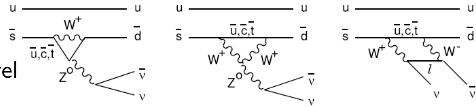
$K \to \pi\nu\overline{\nu}$

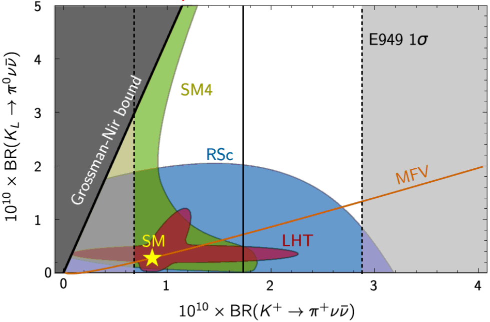


Ultra rare decay

- FCNC process forbidden at tree-level
- Very clean theoretical prediction: hadronic matrix element extracted from $BR(K \to \pi e\nu)$
- Golden modes:

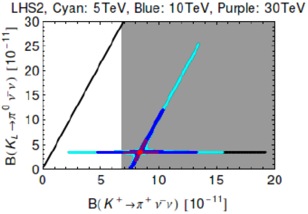
	BR_{SM}	from CKM	from theory	
$K_L \to \pi^0\nu\overline{\nu}$	(2.43	±0.39	±0.06)	10^{-11}
$K^+ \to \pi^+\nu\overline{\nu}$	(7.81	±0.75	±0.29)	10^{-11}

- Current existing measurement based on 7 events (E787/949): $(1.73^{+1.15}_{-1.05})10^{-10}$
- Lead to measurement of $V_{td} \approx 7\%$
- New Physics scenario →

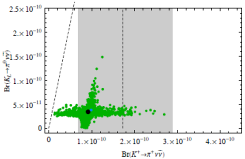


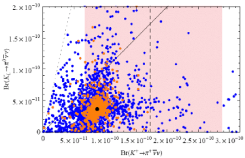
$K \to \pi\nu\bar{\nu}$ and New Physics

General model with new flavour structure:
Z gauge boson mediating FCNC at tree level
[A. Buras, F. De Fazio, J. Girrbach, JHEP 1302 (2013) 116]



K sensitive to mass scales beyond those explored by LHC (MZ > 5 TeV/c2)



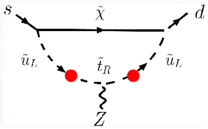


More specific NP models
Littlest Higgs with T-parity
Acta Phys. Polonica B41(2010)657
Custodial Randall-Sundrum
JHEP 0903 (2009) 108

Started to be probed at LHC, small effects in B physics

Best probe of MSSM non-MFV [JHEP 0608 (2006) 064]

- E.g. non-MFV in up-squarks trilinear terms
- Still not excluded by the recent LHCb data



$K \to \pi\nu\overline{\nu}$ foreseen experiments

Expt	Primary beam	Intensity (ppp)	SM evts/yr	Start date + run yrs	Total SM evts
NA62	SPS 400 GeV	3 ± 10^{12}	45	2015+2	100
E14(KoTO)	JPARC-I 30 GeV	2 ± 10^{14}	1-2	2013+3	3-7
E14	JPARC-II 30 GeV	3 ± 10^{14}	30	2020+3?	100

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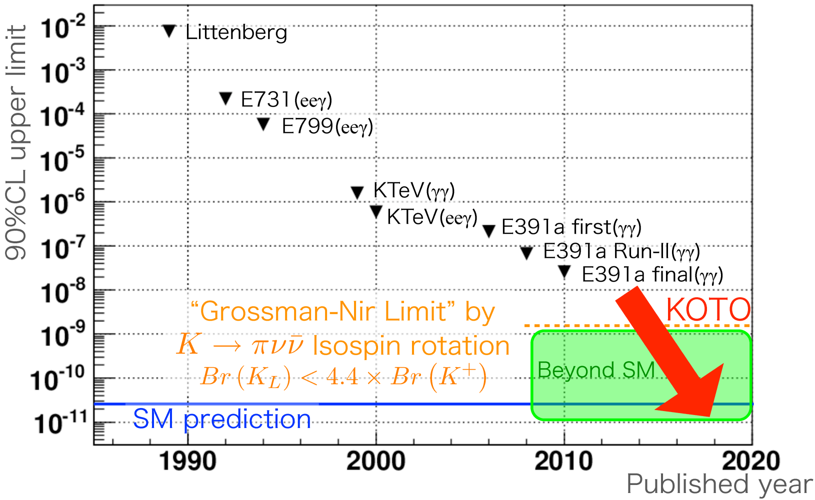

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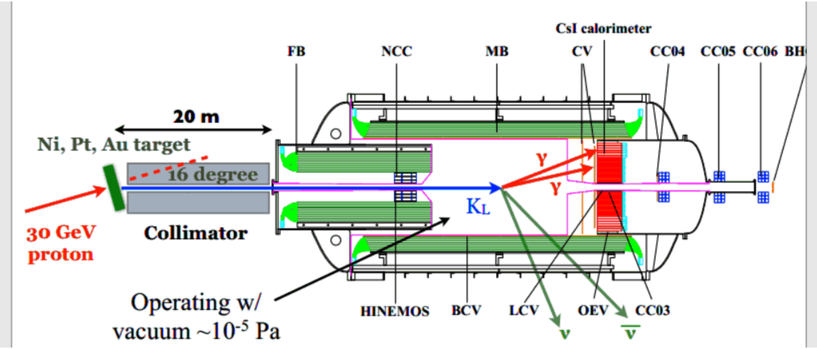

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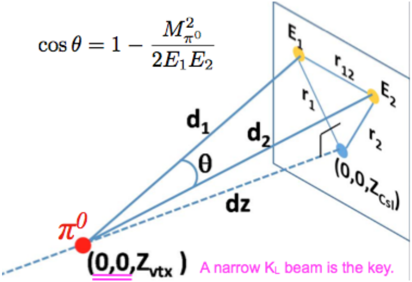
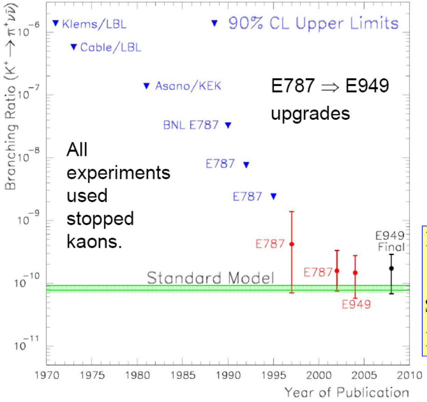
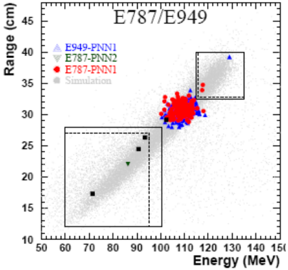


$K \to \pi\nu\bar{\nu}$ foreseen experiments

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





E787/E949 Final: 7 events observed

$$B(K^+ \to \pi^+\nu\bar{\nu}) = 1.73^{+1.15}_{-1.05} x10^{-10}$$

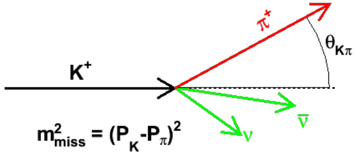
Standard Model:

$$B(K^+ \to \pi^+\nu\bar{\nu}) = (0.85 \pm 0.07) x10^{-10}$$

Measurement of $BR(K \to \pi\nu\bar{\nu})$

Measurement at 10% ($\approx$ SM prediction accuracy), 100 SM events

Missing mass



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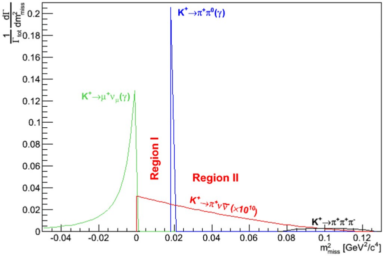
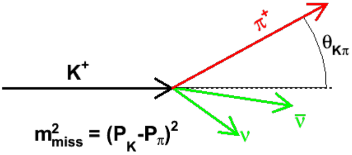
Constrained by kinematics



92% of K decays

Missing mass



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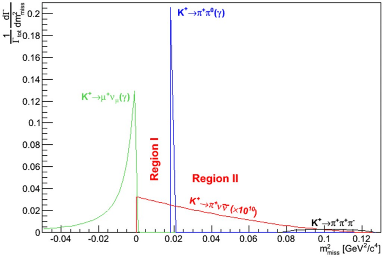

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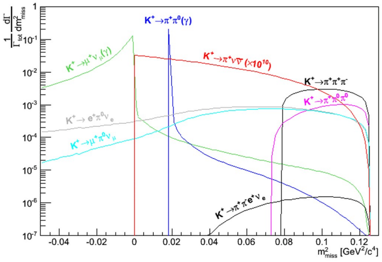
Not constrained by kinematics



8% of K decays

Measurement of $BR(K \to \pi\nu\overline{\nu})$

Experimental strategy:

Requirements

- $O(10^{12-13})$ K decays
- Systematics $< 10\%$

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Dream

1. K momentum
2. π momentum
3. No other particle
4. No interaction
5. 1 day

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Concept

1. K ID & p_K
2. π ID & p_π
3. Veto efficiency
4. Low mass detectors
5. High intensity beam

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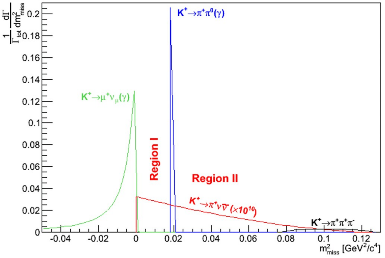
Real World

1. Efficiency, Resolution
2. Acceptance, Purity
3. High momentum
4. Gigatracker and Spectrometer in vacuum
5. Time resolution

Measurement of $BR(K \to \pi\nu\overline{\nu})$

Measurement at 10% (≈ SM prediction accuracy), 100 SM events

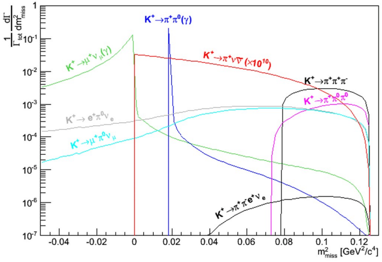
Constrained by kinematics



92% of K decays

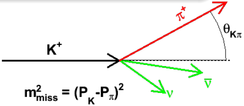
- 2 signal regions
- Minimize multiple scattering

Not constrained by kinematics



8% of K decays

- Particle ID
- Photon vetoes



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Measurement at 10% ($\approx$ SM prediction accuracy), 100 SM events

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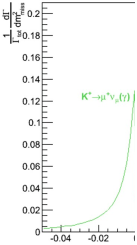

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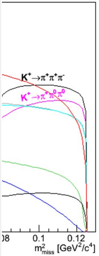


Background Rejection

- Main backgrounds:
  - $K^+ \to \mu^+\nu_\mu$ $(BR \approx 63\%)$
  - $K^+ \to \pi^+\pi^0$ $(BR \approx 21\%)$
- Rejection $\approx 10^{-12}$:
  - Kinematics $\approx 10^{-5}$
  - Vetoes $\approx 10^{-5}$
  - PID $\approx 5\ 10^{-3}$
- Time $K - \pi$:
  - Resolution $\approx 100ps$

92% of K dec

- 2 signal
- Minimize multiple scattering
- Photon vetoes

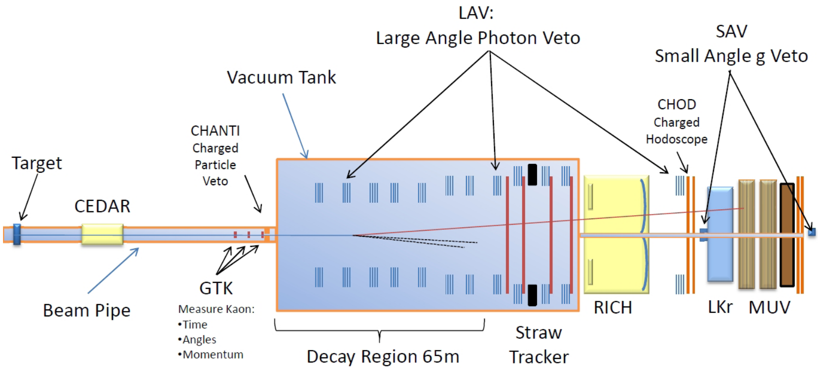
Backgrounds (MC)

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

NA62: beam and experiment layout

State of the art detectors for new precision frontier down to 10^{-12}

- SPS primary protons @ 400 GeV/c
- 75 GeV/c ($\Delta P/P \approx 1\%$)
- Area @ beam tracker 16 cm^2
- Kaon decays/year 4.8×10^{12}
- Unseparated secondary charged beam
- $p/\pi/K$ (positron free, $K \approx 6\%$, $p \approx 23\%$)
- Integrated average rate @ beam tracker 750 MHz



Pilot Run in 2014 and physics data taking in 2015-2018

Extracting the signal

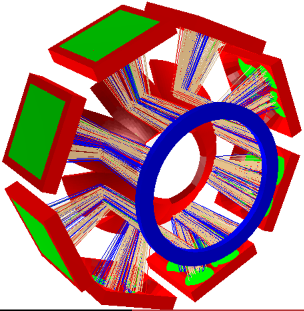
Missing mass

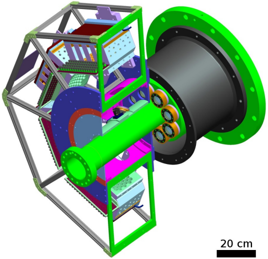
$$m_{miss}^2 \approx m_K^2 \left(1 - \frac{|P_\pi|}{|P_K|}\right) + m_\pi^2 \left(1 - \frac{|P_K|}{|P_\pi|}\right) - |P_K||P_\pi|\theta_{\pi K}^2$$

Kaon Tracking

Cedar-KTAG: kaon tagger

- 384 PMs, $\approx$ 4MHz/PM
- K @ 50MHz
- Filled with H_2 or N_2
- $\sigma_t < 100$ps
- Sub-percent π mis-tagging for K efficiency $> 95\%$





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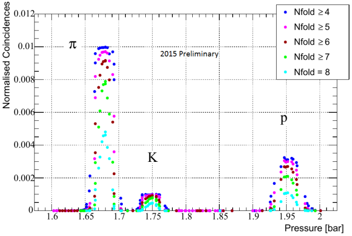

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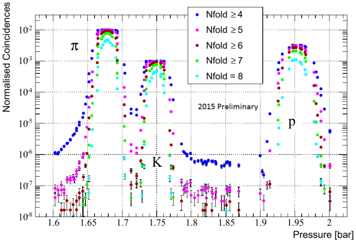

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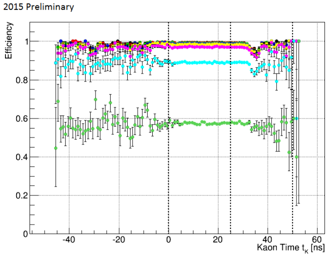

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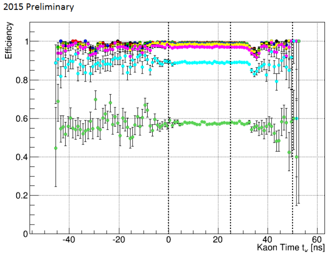

GigaTracker: beam tracker @ 750MHz

- Si μ-pixel $(300\mu\text{m}\times300\mu\text{m})$
- $< 3 \times 0.5\% X_0$ $(< 1mm)$
- $> 99\%$ efficiency
- $\sigma_p/p \approx 0.2\%$
- $\sigma_\theta \approx 16\mu$rad
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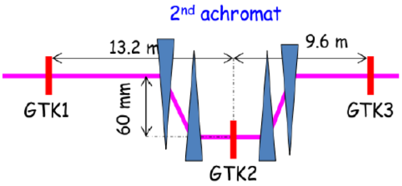

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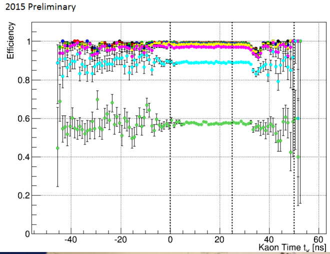

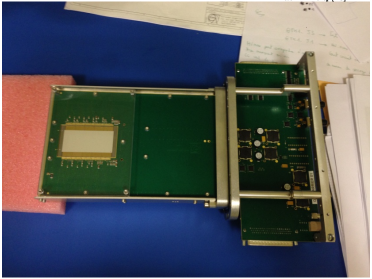

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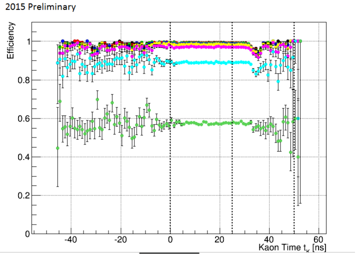

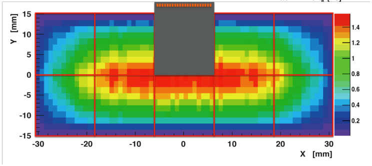

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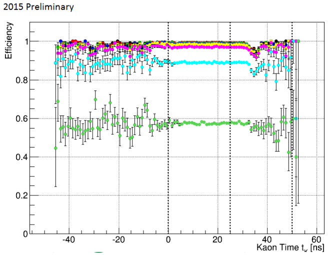

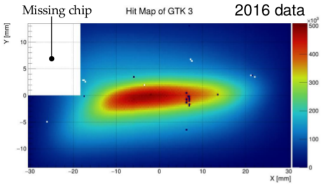

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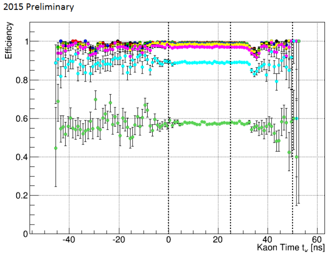

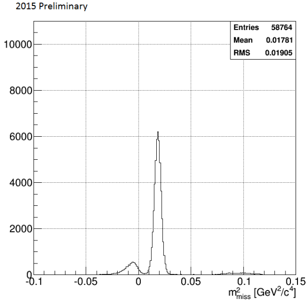

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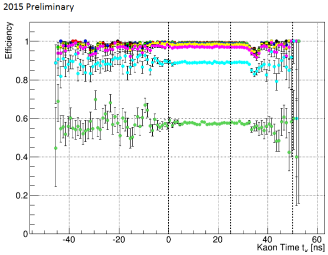

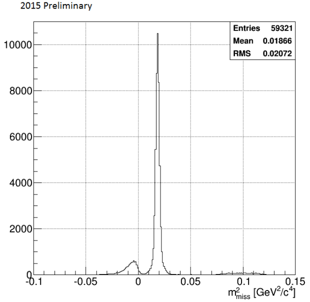

Extracting the signal

Missing mass

$$m^2_{miss} \approx m^2_K \left(1 - \frac{|P_\pi|}{|P_K|}\right) + m^2_\pi \left(1 - \frac{|P_K|}{|P_\pi|}\right) - |P_K||P_\pi|\theta^2_{\pi K}$$

Measurements

- N^{hits}_{cedar}
- $\vec{p}_{gtk}$

Constraints

- $|t_{gtk} - t_{cedar}| < n_1 \sqrt{\sigma^2_{t_{gtk}} + \sigma^2_{t_{cedar}}}$

Results

- K
- 1! trk$_{gtk}$
- $\vec{P}_K = \vec{p}_{gtk}$

Decay Tracking

Straw spectrometer:

- In vacuum ($< 10^{-6}$mbar)
- 7168 mylar straws
- $ArCO_2$ 70%:30%
- $< 4 \times 0.5\% X_0$
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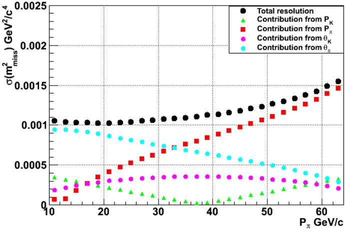

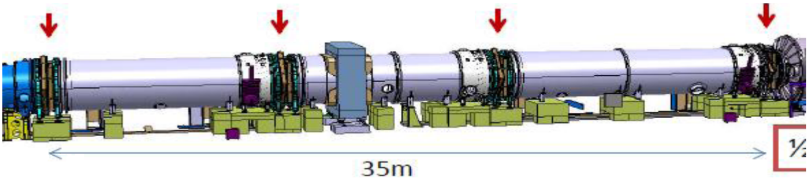

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Straw spectrometer:

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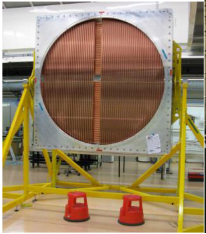
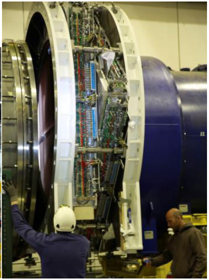

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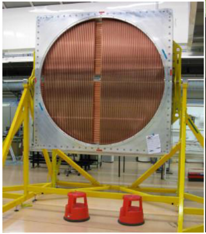
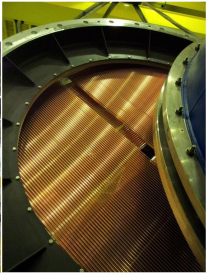


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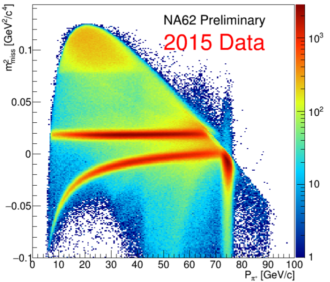
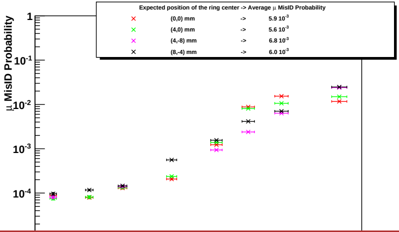


RICH: β_{trk} @ 10MHz

- Ne @ 1 atm ($\approx 5\% X_0$)
- 20 mirror segments ($\approx 20\% X_0$)
- $15 < \frac{p_{tr}}{GeV/c} < 35$
- Contamination of $\mu < 1\%$ (test beam)
- Level 0 Trigger
- $\sigma_t < 100ps$



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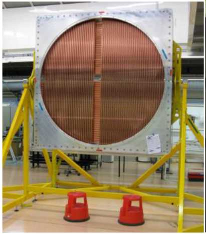

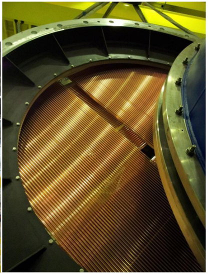

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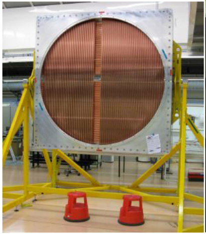

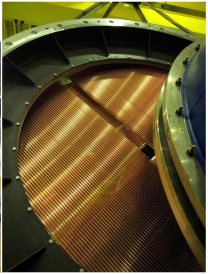

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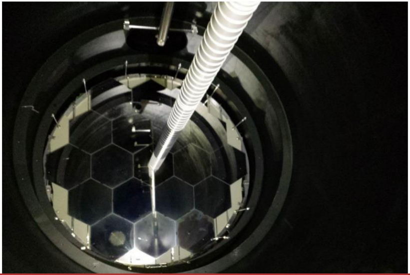

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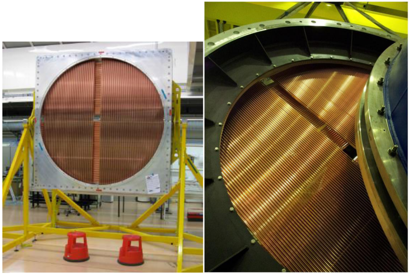

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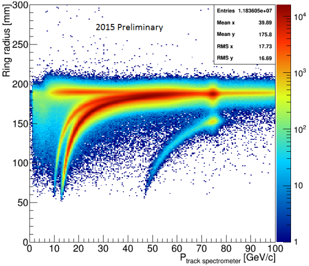

Extracting the signal

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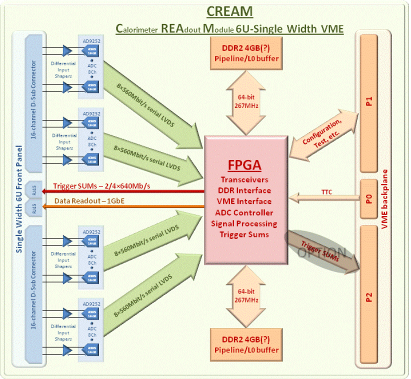
PID: calorimeters

$\pi/\mu/e$ separation ($\pi/\mu \approx 10^5$)

- NA48 LKr calorimeter:
  - Em/hadronic/mip cluster id
  - Very good mip signal



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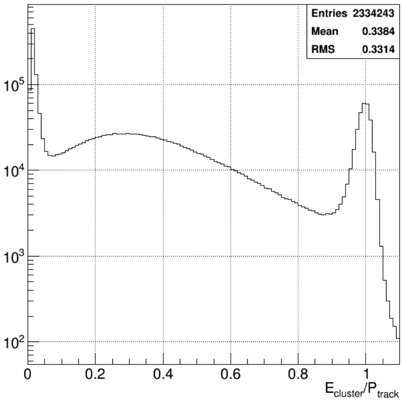

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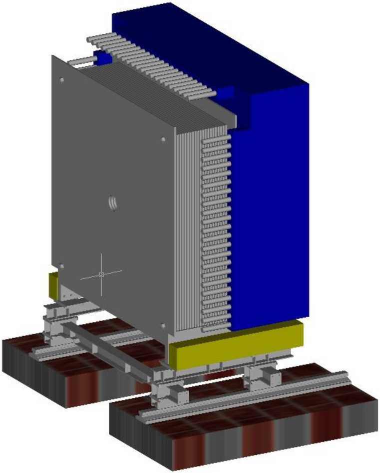

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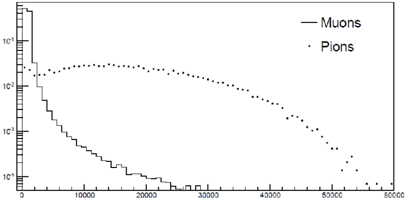

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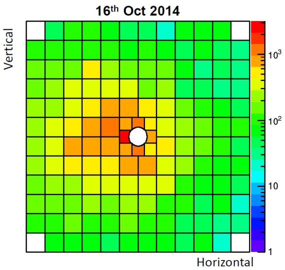

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- $\vec{p}_{straw}$
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- K
- 1! trk$_{gtk}$
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Photon Vetoes

$K^+ \to \pi^+\pi^0$ rejection $O(10^8)$

- LAV: ≈8 to 50 mrad:
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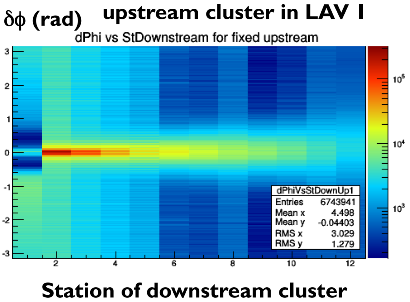

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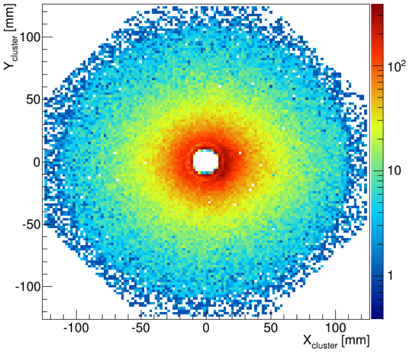

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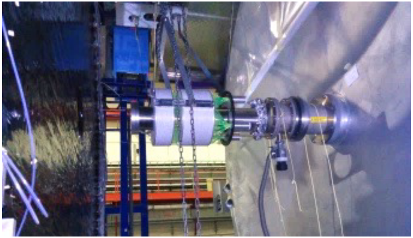

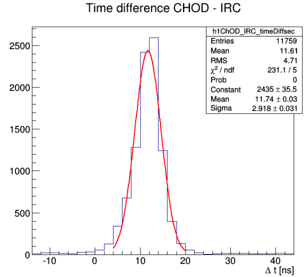

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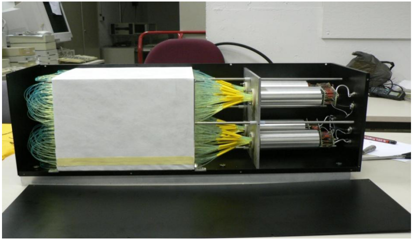

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Results

- K
- 1! trk$_{gtk}$
- $\vec{P}_K = \vec{p}_{gtk}$
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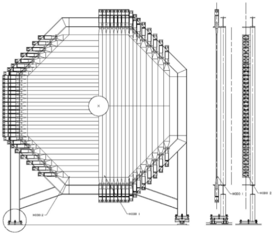
Charged Vetoes

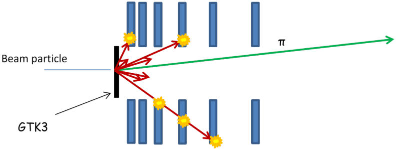
CHOD: detect photonuclear interactions in RICH

- 10MHz
- NA48
- Provisional
- BC408 + PMs
- $\sigma_t = 200$ps



CHANTI: veto inelastic interactions in GTK3

- 2MHz μ halo + inelastic interactions $(O(10^{-3}))$
- WLS fibers + SiPMs
- $\approx$ 7-15 pe/MIP
- $\sigma_t < 2$ns



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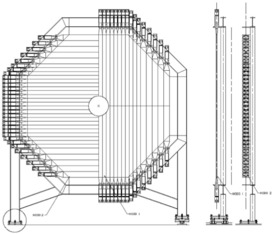

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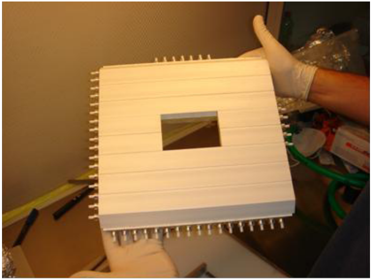

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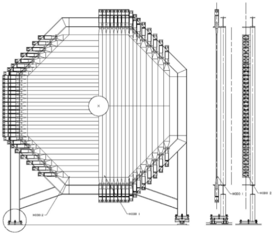

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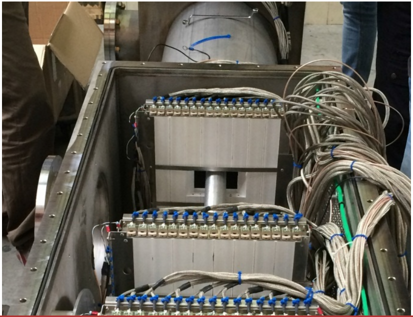

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- r_{ring}
- E_{lkr}
- E_{muv}
- $E_{\gamma Veto}$
- N^{MIPs}_{chod}
- N^{MIPs}_{chanti}

Constraints

...

- $|t_{\gamma Veto} - t_{rich}| < n_5\sqrt{\sigma^2_{t_{\gamma Veto}} + \sigma^2_{t_{rich}}}$
- $E_{\gamma Veto} < \alpha_3$ MIP
- $|t_{chod} - t_{rich}| < n_5\sqrt{\sigma^2_{t_{chod}} + \sigma^2_{t_{rich}}}$
- $N^{MIPs}_{chod} = 1$
- $|t_{chanti} - t_{rich}| < n_6\sqrt{\sigma^2_{t_{chanti}} + \sigma^2_{t_{rich}}}$
- $N^{MIPs}_{chanti} = 0$

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- 1! trk$_{straw}$
- $\vec{P}_\pi = \vec{p}_{straw}$
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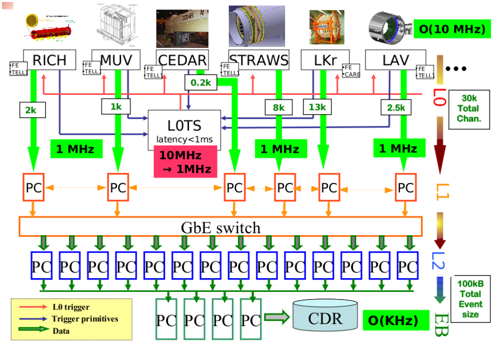
Integrated Trigger and DAQ

- High trigger efficiency ($> 95\%$)
- Low random veto ($< 1\%$)
- Fully digital after FE



- Level 0:
  - 10MHz → 1MHz
  - FPGA based, 1ms max latency
  - Digital primitives from fast detectors
- Level 1:
  - 1MHz → 100kHz
  - PC based, few ms latency
  - Data from all detectors but LKr
- Level 2:
  - 100kHz → 10kHz
  - PC based, few ms latency
  - All data used

Beam

- Expected composition and intensity
- Tail (small) of the undecayed beam in acceptance
- Residual muon halo from muon scraper
- Found beam intensity fluctuations beyond NA62 design specifications

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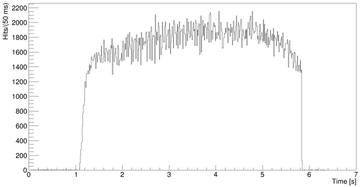

Expected spill

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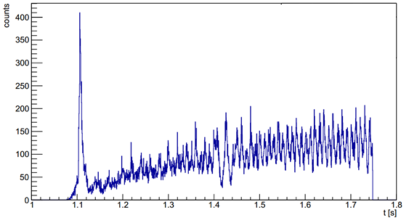
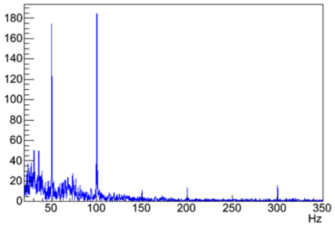
- Residual muon halo from muon scraper
- Found beam intensity fluctuations beyond NA62 design specifications



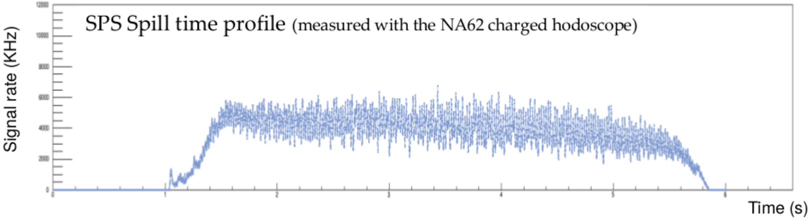
A bad spill



FFT

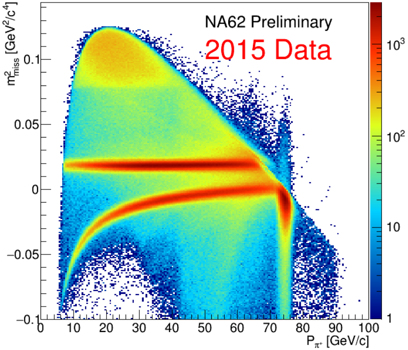
Beam

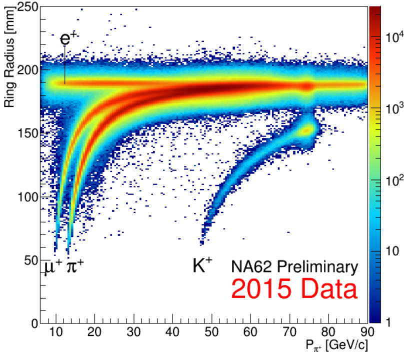
- Expected composition and intensity
- Tail (small) of the undecayed beam in acceptance
- Residual muon halo from muon scraper
- Found beam intensity fluctuations beyond NA62 design specifications



Few weeks ago

Single track events in 2015 data

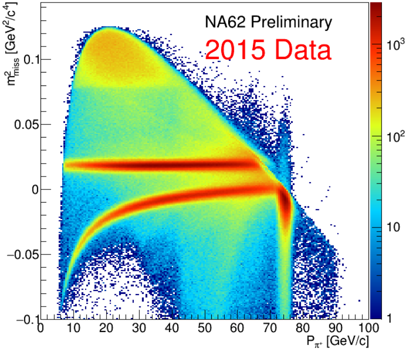


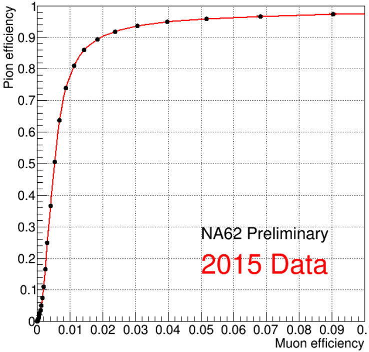


- Single tracks with 5ns time resolution
- Tracks matched to downstream detectors

- Population seen by the RICH
- RICH performance close to design

Single track events in 2015 data





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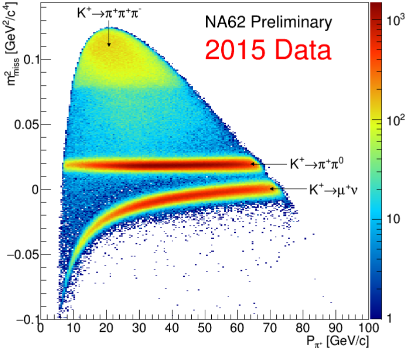
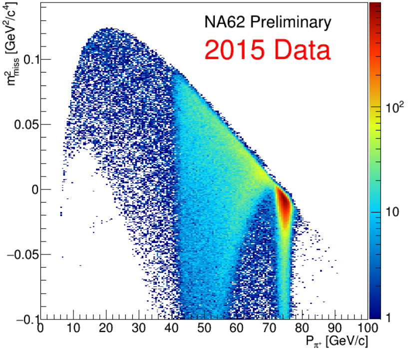
Single track events in 2015 data

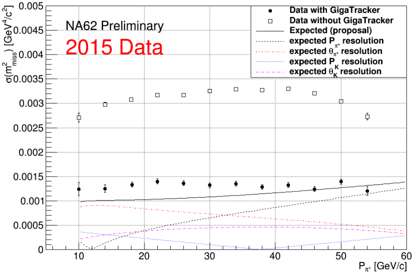




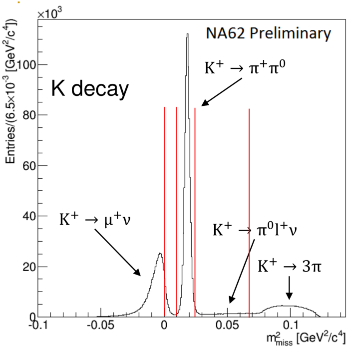
- With K ID
- $K \to \mu\nu$, $K \to \pi\pi^0$, $K \to \pi\pi\pi$

- With !K ID
- Beam particles and beam pion decays

Single track events in 2015 data



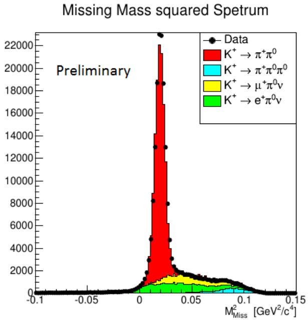
- Essential contribution of the GigaTracker
- Resolution close to design

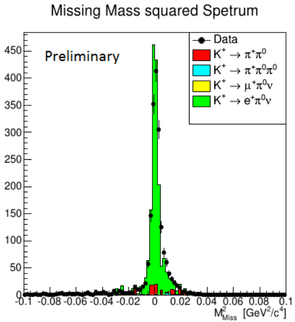


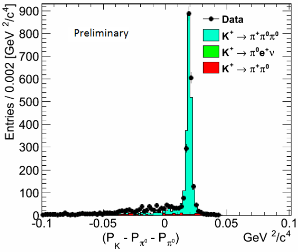
- $O(10^4)$ kinematic suppression factor (still improving)
- Photon rejection and PID being studied

Example of control samples

- Selected from minbias using only LKr
- Useful to measure efficiencies, PID ..



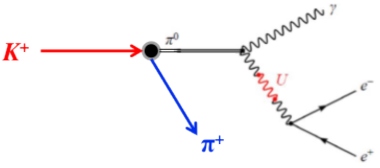


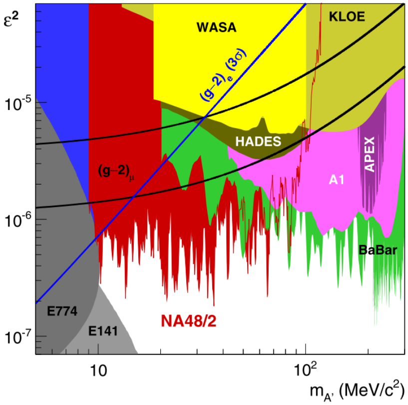


Further Kaon Physics Opportunities

Decay	Physics	Present limit	NA62 potential
$K^+ \to \pi^+ \mu^+ e^-$	LFV	1.3×10^{-11}	0.7×10^{-12}
$K^+ \to \pi^+ \mu^- e^+$	LFV	5.2×10^{-10}	0.7×10^{-12}
$K^+ \to \pi^- \mu^+ e^+$	LNV	5.0×10^{-10}	0.7×10^{-12}
$K^+ \to \pi^- e^+ e^+$	LNV	6.4×10^{-10}	2×10^{-12}
$K^+ \to \pi^- \mu^+ \mu^+$	LNV	1.1×10^{-9}	0.4×10^{-12}
$K^+ \to \mu^- \bar{\nu}_\mu e^+ e^+$	LNV/LFV	2×10^{-8}	4×10^{-12}
$K^+ \to e^- \bar{\nu}_e \mu^+ \mu^+$	LNV	No data	10^{-12}
$K^+ \to \pi^+ \chi^0$	New particle	5.9×10^{-11}, $M_{\chi^0} = 0$	10^{-12}
$K^+ \to \pi^+ \chi\chi$	New particle	No data	10^{-12}
$K^+ \to \pi^+ \pi^+ e^- \bar{\nu}_e$	$\Delta S \neq \Delta Q$	1.2×10^{-8}	10^{-11}
$K^+ \to \pi^+ \pi^+ \mu^- \bar{\nu}_\mu$	$\Delta S \neq \Delta Q$	3.0×10^{-6}	10^{-11}
$K^+ \to \pi^+ \gamma$	Angular momentum	2.3×10^{-9}	10^{-12}
$K^+ \to \mu^+ \nu_h$, $\nu_h \to \nu\gamma$	Heavy neutrino	Limits up to $M_{\nu_h} = 350$ MeV/c^2	
R_K	LU	$(2.488 \pm 0.010) \times 10^{-5}$	$> 2\times$ better
$K^+ \to \pi^+ \gamma\gamma$	χ_{PT}	$<$ 500 events	10×10^5
$K^+ \to \pi^0 \pi^0 e^+ \bar{\nu}_e$	χ_{PT}	66000 events	$O(10^6)$
$K^+ \to \pi^0 \pi^0 \mu^+ \bar{\nu}_\mu$	χ_{PT}	no observation yet	$O(10^5)$

Dark photon

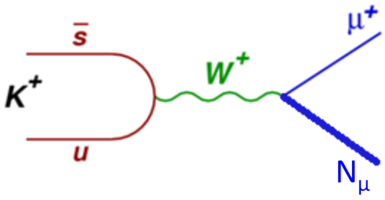




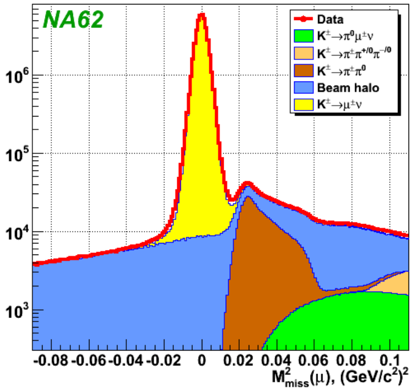
- Irreducible background from π^0 dalitz
- NA48/2 constraints exclude dark photon explanation of the $(g-2)_\mu$ discrepancy
- NA62 could improve statistics and resolution

- Recently published in PLB 746 (2015) 178-185

Heavy neutrino

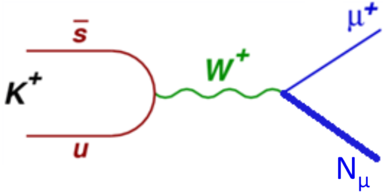


- Ongoing analysis on $\mathrm{NA62}_{RK}$(2007) data
- The new detector can do better, both in resolution and hermeticity
- Ongoing analysis on 2015 data



- $K \to \mu\nu$ selection with $\mathrm{NA62}_{RK}$ detector

Heavy neutrino



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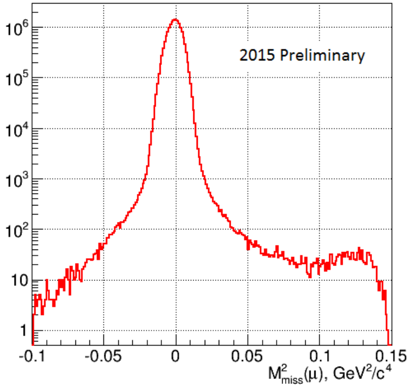
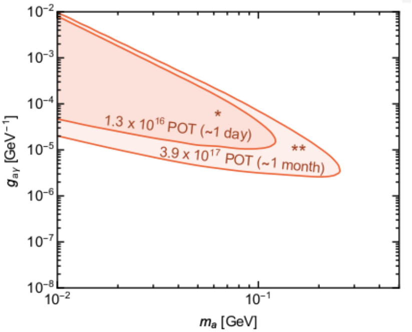
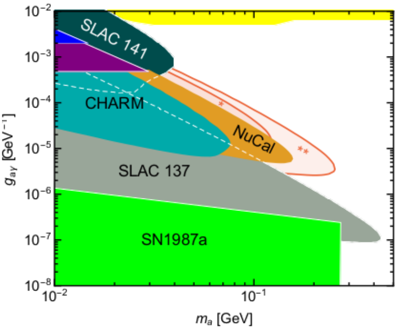


- $K \to \mu\nu$ selection on 2015 data
- $\approx$ 2 orders of magnitude better

Axion





- Toy MC for 1 day or 1 month
- 1 day already taken in 2015

- Potentially competitive at low cost
- Ongoing analysis

NA62 construction completed

Timeline

- Beam line, detectors, trigger and DAQ fully commissioned
- NA62 data taking periods:
  - 2014: detector commissioning
  - 2015: trigger commissioning, detector quality studies, beam line commissioning up to nominal intensity
  - 2016:high level trigger commissioning (done), full beam tracker commissioning (done), physics (ongoing)
- Data samples for analysis:
  - 2015: Low intensity data with minimum bias trigger for detector quality studies (this talk)
  - 2016: $K^+ \to \pi^+\nu\overline{\nu}$ data (up to 30% of nominal intensity), not $K^+ \to \pi^+\nu\overline{\nu}$ data (up to 30% of nominal intensity)

Status

- Time resolution: close to the design
- Kinematics: Resolution close to the design. Prospects to reach the designed signal-background separation.
- Pion/muon ID: Separation with RICH close to expectations. Study of the separation with calorimeters on going. Results from simple cut analysis promising.
- Photon veto: $O(10^6)$ π^0 rejection already obtained. Statistically limited. 2016 already enough to address the 10^8 rejection level (analysis ongoing).
- Stable data taking since beginning of August at 20-30% of nominal intensity
- L0 $K^+ \to \pi^+ \nu\bar{\nu}$ trigger: hits in RICH & CHOD, !muons, E(LKr) <20 GeV
- L1 $K^+ \to \pi^+ \nu\bar{\nu}$ trigger: KTAG, LAV, Straw (P < 50 GeV/c)
- Data type (simultaneously): $K^+ \to \pi^+ \nu\bar{\nu}$ (no downscaling), di-lepton, minimum bias
- Average rate at L0 (25% of nominal beam intensity): 500 kHz
- Average rate after L1 (25% of nominal beam intensity): 60 kHz
- Online $\pi^+\pi^0$ reduction factor ($K^+ \to \pi^+ \nu\bar{\nu}$ trigger): 6 (room for improvements $\times$ 2 at least)
- Online muon reduction factor ($K^+ \to \pi^+ \nu\bar{\nu}$ trigger): O(100)
- Data collected so far: $K^+ \to \pi^+ \nu\bar{\nu}$ sensitivitiy below 10^9 (assuming O(10%) signal acceptance)

Summary

- Construction was completed for 2015 run
- Commissioning in 2015 and 2016
- We are learning how to exploit the new detector to its full potential
- Analysis ongoing
- Once NA62 is able to measure $K \to \pi\nu\overline{\nu}$ ...
- ... the road is open for a number of other studies (in parallel of after LS2):
  - New particles
  - Radiative decays
  - Lepton Universality
  - Semi-leptonic decays and form factors
  - Already some good prospect with 2015 data
- We expect to reach the SM sensitivity this year