Dark Matter searches with the NA62 experiment
DM workshop @ CP3

E.Cortina

UCL/CP3

Dec 7, 2017

NA62 Experiment

Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna(JINR), Fairfax, Ferrara, Florence, Frascati, Glasgow, Liverpool, Louvain-la-Neuve, Mainz, Merced, Moscow (INR), Naples, Perugia, Pisa, Prague, Protvino(IHEP) , Rome I, Rome II, San Luis Potosi, SLAC, Sofia, TRIUMF, Turin, Vancouver (UBC)

29 Institutes, 230 Collaborators

- NA62: Kaon experiment at CERN SPS
  - Main goal: 10% measurement BR($K^+ \to \pi^+ \nu \bar{\nu}$)
  - Decay in flight technique
- Broader physics program
  - LFV/LNV in K^+ decays
  - Hidden sector particle searches
- Status: NA62 is taking data
  - Approved until LS2
  - Proposed runs after LS2 under discussion

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
LHC		Run2				LS2		Run 3			LS3		Run 4
SPS										NA stop	SPS stop		

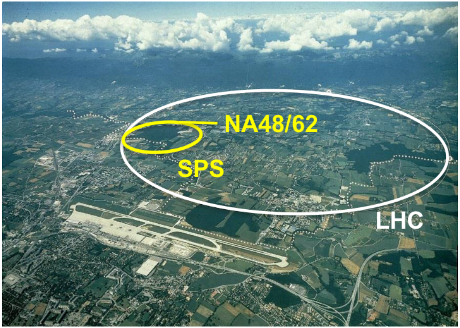
Kaons @ CERN

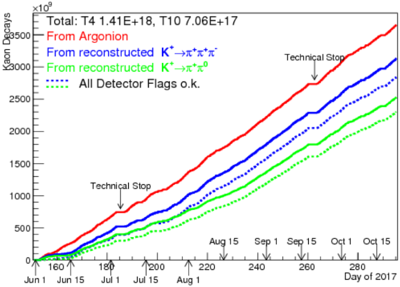
NA48/NA62

97-01	ε'/ε
02	K_s rare decays
03-04	$K^{\pm}$: CP violation semileptonic decays low energy QCD
07-08	R_K: lepton universality

NA62

2014	Detector commissioning
2015	Trigger ad beam line commissionig Detector quality studies
2016	Software trigger commissioning GTK commissioning Physics data taking (16/09-03/11)
2017	Full intensity Physics data taking
2018	Full intensity Physics data taking
2019 2020	LS2
2021 2022	Full intensity Physics data taking (?) Beam Dump mode (?)





Why a Kaon experiment?

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- Very well know system
  - Minimal flavor "lab"
  - Studied for decades
  - Simplest phenomenology

$K^+ \to \mu^+\nu(K_{\mu2})$	0.634
$K^+ \to \pi^+\pi^0$	0.209
$K^+ \to \pi^+\pi^+\pi^-$	0.056
$K^+ \to \pi^+\pi^0\pi^0$	0.016
$K^+ \to \pi^0 e^+\nu(K_{e3})$	0.049
$K^+ \to \pi^0\mu^+\nu(K_{\mu3})$	0.033
$K^+ \to \mu^+\nu\gamma$	6.2×10^{-3}
$K^+ \to \pi^+\pi^0\gamma$	2.7×10^{-4}
$K^+ \to \pi^+\pi^- e^+\nu(K_{e4})$	4.0×10^{-5}
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  - γ, e,μ and π
  - Low multiplicity events

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  - Long time expertise from NA31 and NA48
  - Perfectly known beam line and instrumentation

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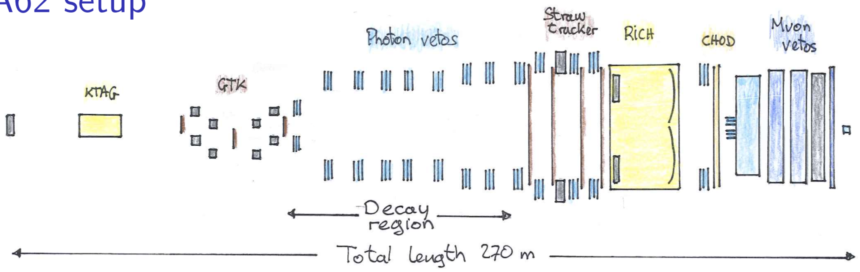
  - Perfectly known beam line and instrumentation
- "Cheap" experiment

NA62 setup



SPS protons

- 400 GeV/c
- 33×10^{11} POT/spill

Secondary Beam

- +75 GeV/c ($\Delta p/p \sim 1\%$)
- $K(6\%)$,$\pi(70\%)$,p(23%)

Kaon Decays

- ~5 MHz
- 4.5×10^{12}/year

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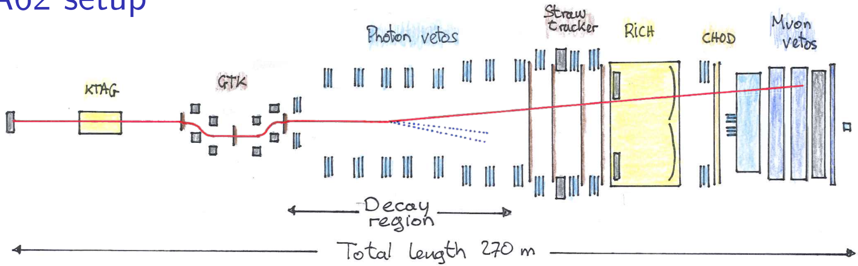

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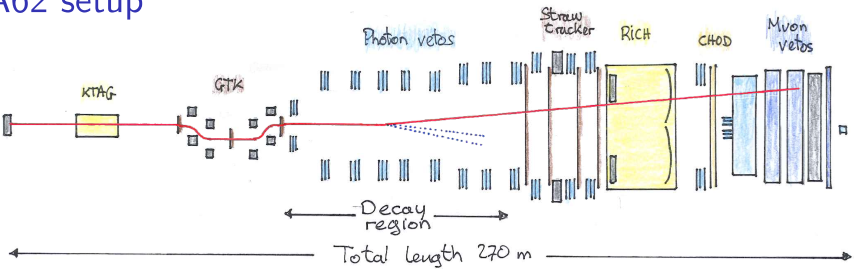

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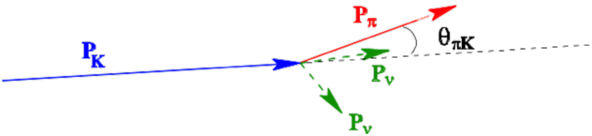

$$m^2_{miss} = (P_K - P_{\pi^+})^2$$
$$\simeq m_K^2\left(1 - \frac{|P_\pi|}{|P_K|}\right) + m_\pi^2\left(1 - \frac{|P_K|}{|P_\pi|}\right) - |P_K||P_\pi|\theta^2_{\pi K}$$

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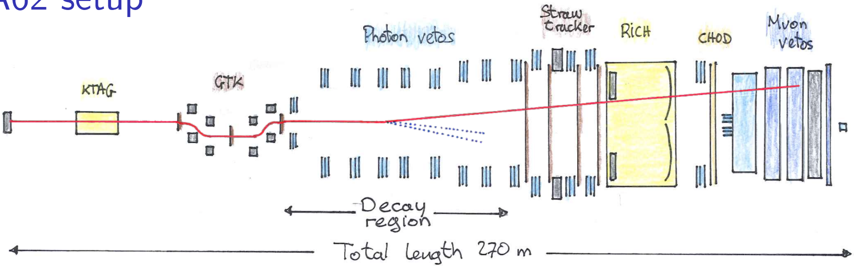

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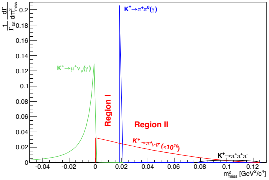

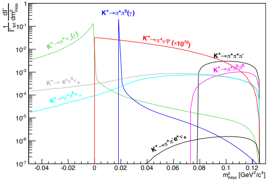

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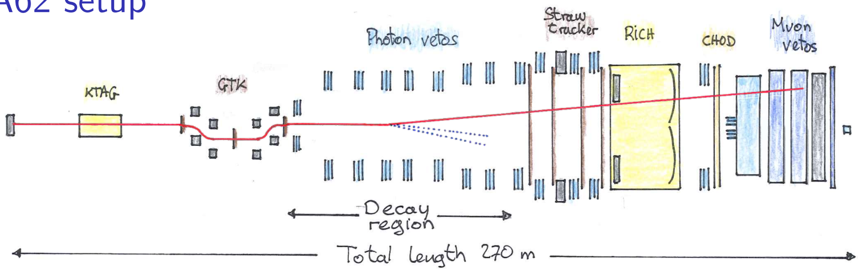

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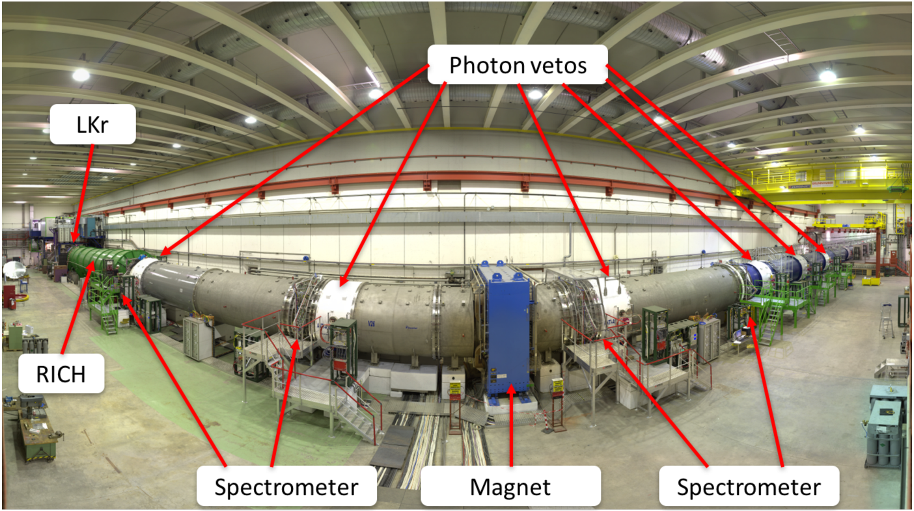
Experimental principles:

- Precise kinematic reconstruction
- PID: K upstream, $e/\mu/\pi$ downstream
- Hermetic γ detection
- sub-ns timing

NA62 setup



NA62 setup

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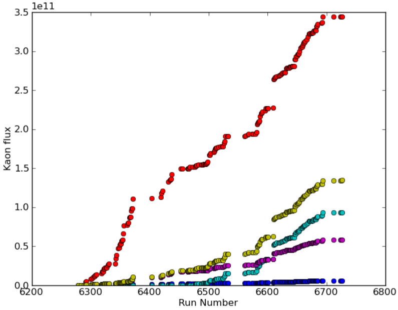
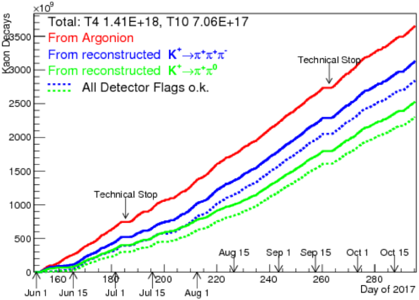
NA62 Data Taking

2016



2017



Run 2017

- Very successful run: $\sim 3 \times 10^{12}$ K^+ decays have been collected
- 10-15 $K^+\pi^+\nu\bar{\nu}$ events collected
  - Depending on tighter/looser selection cuts
  - 60% nominal intensity
  - Acceptance*efficiency a factor two smaller than expected

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- 60% nominal intensity $\rightarrow 19 \times 10^{11}$ POT instead of 33×10^{11}
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  - Minimize the effect of random veto
  - Minimize GTK mistagging $\rightarrow$ shield to better protect for early decays

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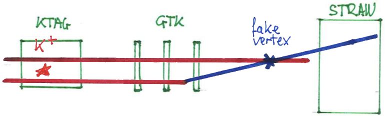
- Acceptance*efficiency a factor two smaller than expected
  - 10^{-12} rejection factor: all detectors should work perfectly.
  - Control of second order effects in tracking that mimic the signal.

"Snakes"



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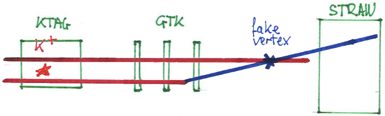
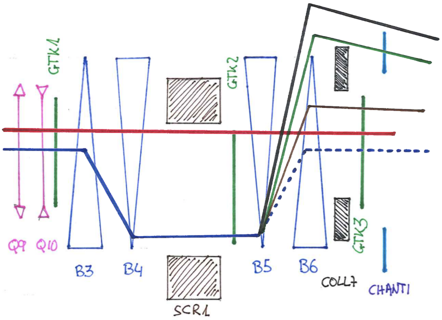

KTAG
K+
GTK
fake
vertex
STRAW


GTK1
GTK2
GTK3
Q9
Q10
B3
B4
B5
B6
SCR1
COLL7
CHANTI

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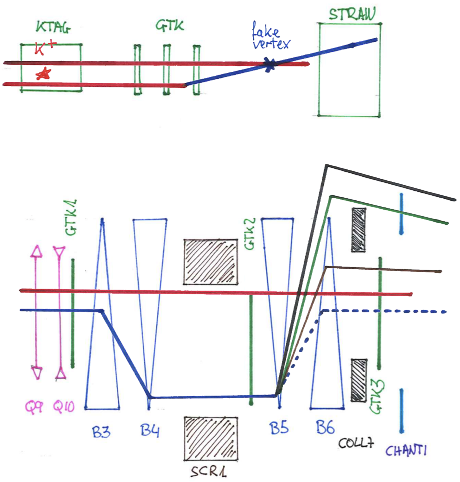
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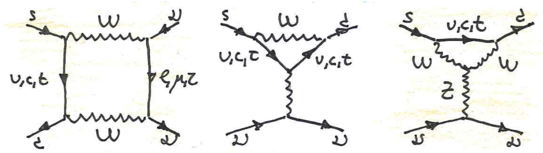
$K \to \pi\nu\bar{\nu}$ in the Standard Model

- FCNC processes dominated by Z-penguin and box diagrams



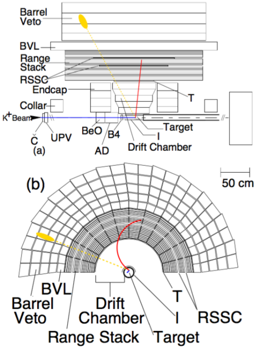
- Very clean theoretically:
  - GIM suppression + CKM suppression ($V_{ts}^{*} V_{td}$)
  - Short distances contributions: NLO (top) NNLO (charm)
  - Long-distance distributions under control:
    - ★ No amplitudes with intermediate photons
    - ★ Hadronic amplitudes from K_{e3} via isospin rotation

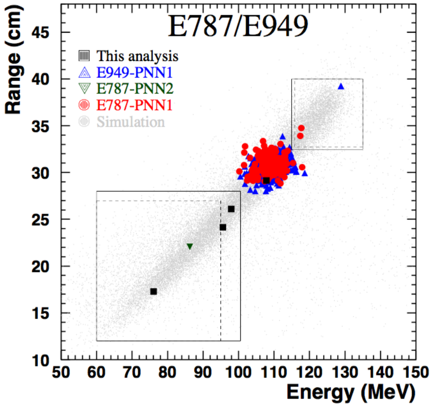
$$\mathrm{BR}(K^{+} \to \pi^{+}\nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$
$$\mathrm{BR}(K^{0} \to \pi^{0}\nu\bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11}$$

$K \to \pi\nu\bar{\nu}$: experimental status

$$BR(K^+ \to \pi^+\nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$$

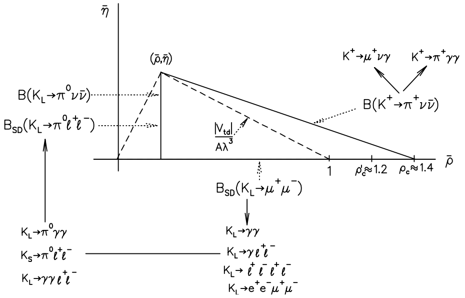
$$BR(K^0 \to \pi^0\nu\bar{\nu}) < 2.6 \times 10^{-11} \ 90\% \ \text{CL}$$



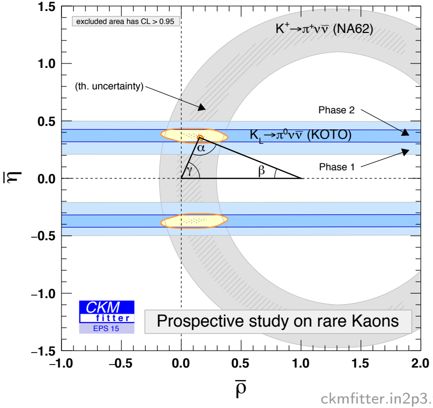


$K \to \pi\nu\bar{\nu}$ and CKM

$$BR(K^+ \to \pi^+\nu\bar{\nu}) \propto \sigma\bar{\eta}^2 + (\rho_c - \rho)^2$$
$$BR(K^0 \to \pi^0\nu\bar{\nu}) \propto \bar{\eta}^2$$

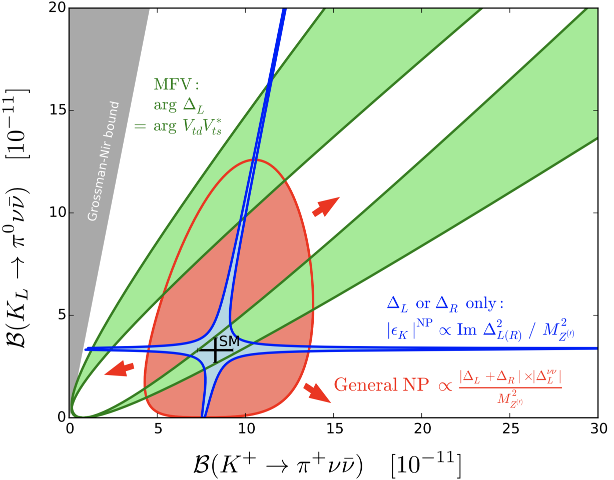


PDG - Rare Kaon Decays Review



ckmfitter.in2p3.fr

$K^+ \to \pi^+\nu\bar{\nu}$ and new physics



Buras et al. JHEP11(2015).166

Expected Signal and Background

N(K decays) $\sim 2.3 \times 10^{10}$ analyzed (5% 2016 statistics)

- Signal

$$N^{exp}_{\pi\nu\nu} = D^{control} \cdot N^{control}_{\pi\pi} \frac{BR_{\pi\nu\nu}}{BR_{\pi\pi}} \cdot \frac{A_{\pi\nu\nu}}{A_{\pi\pi}} \cdot \epsilon^{trig}$$

$N^{control}_{\pi\pi}$	3.3×10^8
$A_{\pi\pi}$	~ 0.07
$A_{\pi\nu\nu}$	~ 0.033
ϵ^{trig}	0.83

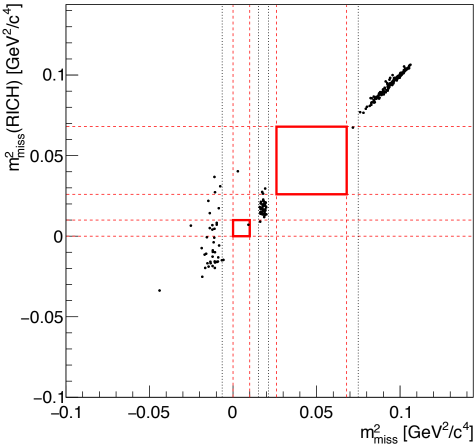
$N^{exp}_{\pi\nu\nu} \simeq 0.064$

- Background

$K^+ \to \pi^+\pi^0$	0.024
$K^+ \to \mu^+\nu$	0.011
$K^+ \to \pi^+\pi^+\pi^-$	0.017

$N^{exp}_{back} \simeq 0.052$

$K^+ \to \pi^+\nu\bar{\nu}$ in 2016

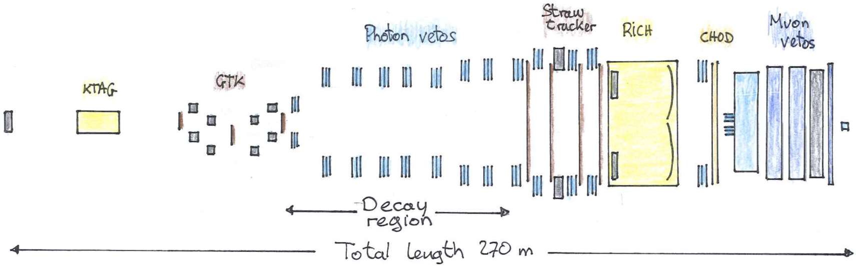


- N(K decays)
  - $\sim 2.3 \times 10^{10}$
  - 5% 2016 statistics
- PNN trigger
- No events in signal region

Event in box has m^2_{miss}(No GTK) outside the signal region

- Data taken at an average intensity of 13×10^{11} POT (40% nominal)

Decay mode vs Beam Dump mode



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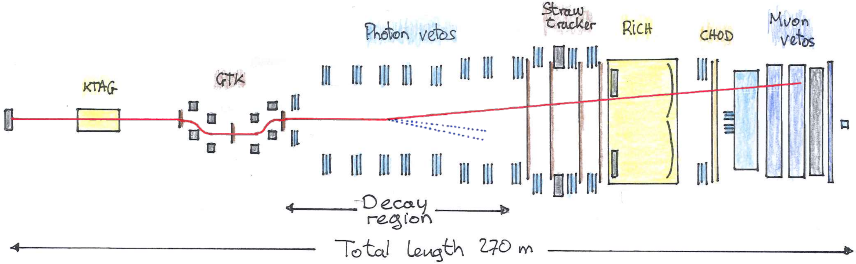

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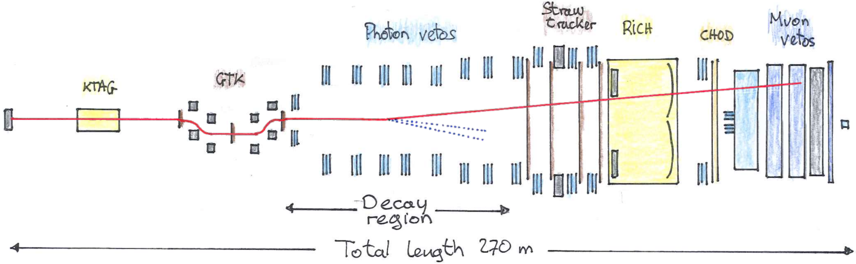

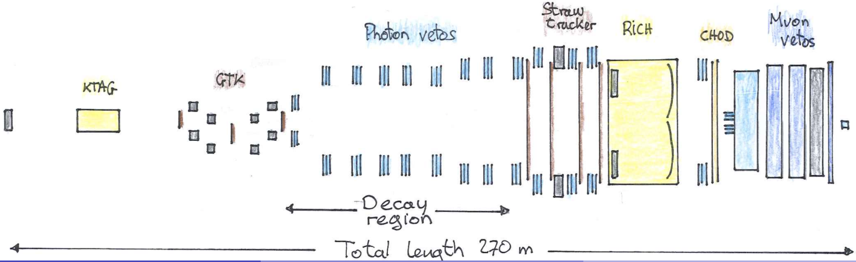

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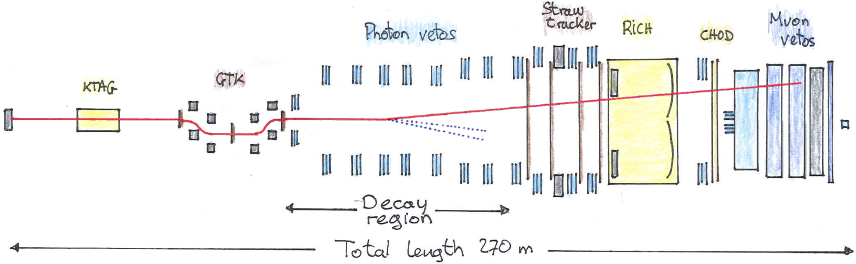

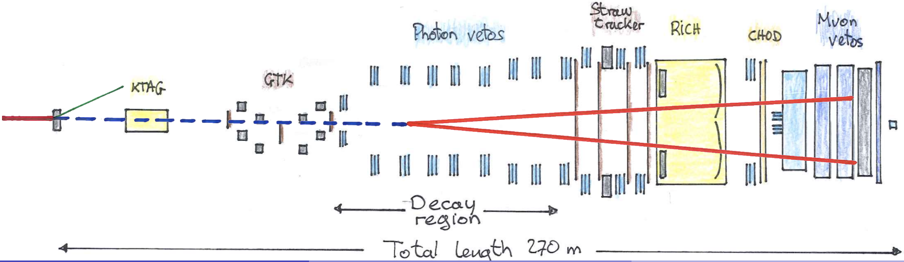

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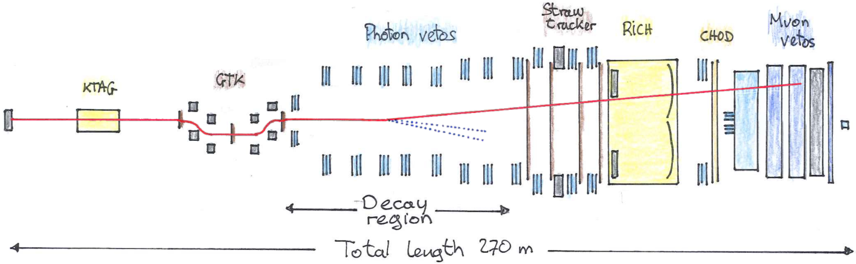

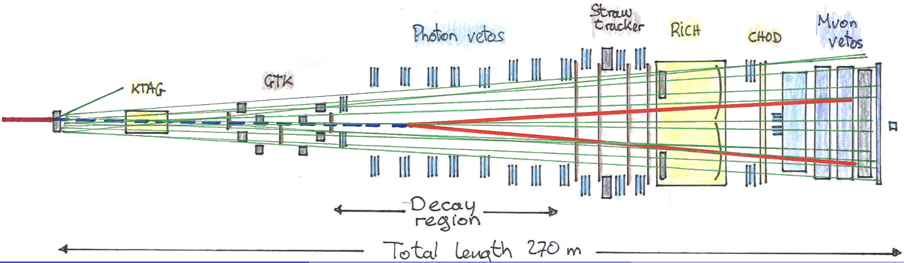

Decay mode vs Beam Dump mode

- "Decay" mode
  Measurement in parallel to $K^+ \to \pi^+ \nu\bar{\nu}$
  - $K^+ \to \pi^+ X$
  - $K^+ \to \ell^+ \nu$: sensitive to HNL
  - LFV/LNV: $K^+ \to \pi^- \ell_1^+ \ell_2^+$
    $K^+ \to \ell_1^- \bar{\nu} \ell_1^+ \ell_2^+$
    $K^+ \to \pi^+ \mu^\pm e^\mp$
  - Dark photon: $K^+ \to \pi + \pi^0$, $\pi^0 \to A'\gamma$, $A' \to$invisible
  - Protons on target: $A'/\mathrm{HNL} \to \gamma\gamma, \ell^+\ell^-, \ell^\pm\pi^\mp$

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- "Beam Dump" mode
  Special runs with TAXes closed
  - Proton on copper (TAX): A,HNL$\to \gamma\gamma, \ell^+, \ell^-, \ell^\pm\pi^\mp$
  - Few hours in 2016. Few days in 2017-18
  - Improvement of existing limits (CHARM)

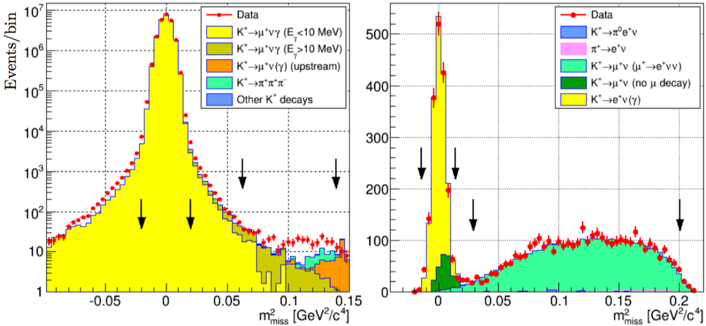
HLN in $K^+ \to \ell^+ N$

arXiv:1712.00297

- HNL should appear as peaks in $K^+ \to \ell^+ \nu$ M^2_{miss} distributions

$$\Gamma(K^+ \to \ell^+ N) = \Gamma(K^+ \to \ell^+ \nu) \times \rho(m_N) \times |U_{\ell 4}|^2$$

- Model independent searches based on 2015 data ($\sim 10^8$ K^+ decays)



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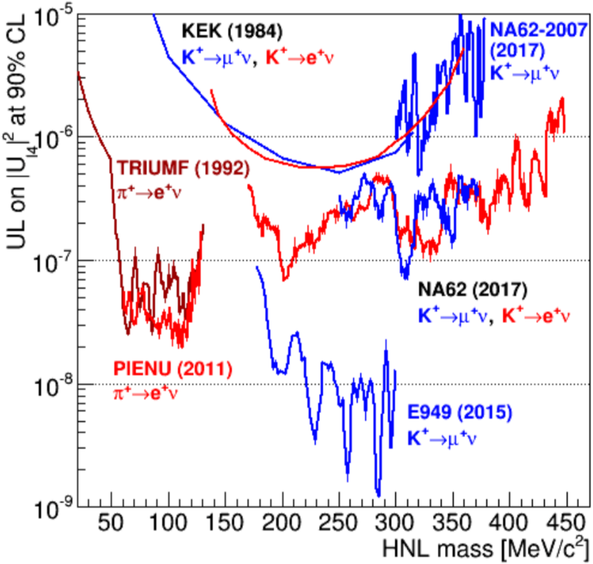
arXiv:1712.00297



Forbidden decays: LNV & LFV

LFV $K^+ \to \pi^+\mu^+e^-$ ***$B < 1.3 \times 10^{-11}$ (90% CL)*** [A. Sher, et al. Phys. Rev. D, 72 (2005), 012005]

LFV $K^+ \to \pi^+\mu^-e^+$ ***$B < 5.2 \times 10^{-10}$ (90% CL)*** [R. Appel, et al. Phys. Rev. Lett., 85 (2000), 2877]

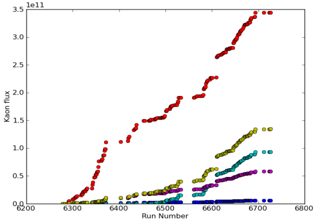
LNV $K^+ \to \pi^-\mu^+e^+$ ***$B < 5.0 \times 10^{-10}$ (90% CL)*** [R. Appel, et al. Phys. Rev. Lett., 85 (2000), 2877]

Data sample:

- 2016 SampleA (162 runs) → $N_K \sim 1.34\ 10^{11}$
- Trigger chain: L0: RICH • Q_x L1: !LAV • $STRAW_{exotics}$ (downscaling between 20 and 150)

  L0: RICH • Qx • MO1 L1: KTAG • !LAV • $STRAW_{exotics}$ (downscaling between 1 and 10)

  L0: RICH • Q_x • E_{LKr}>20GeV L1: !LAV • $STRAW_{exotics}$ (downscaling between 1 and 2)



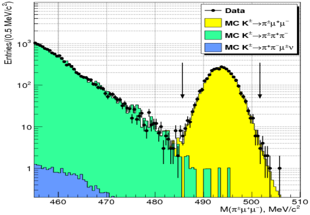
- Control triggers
- Multi tracks trigger
- Muon multi tracks trigger
- Electron multi tracks trigger
- MultiTrack+Muon multi tracks+Electron multi tracks

Kaon flux measured selecting K3π events with control triggers

Rare decays: $K^+ \to \pi^+\mu^+\mu^-$

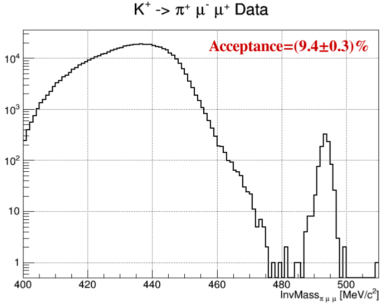
FCNC decay $K^+ \to \pi^+\mu^+\mu^-$ ***$B=(9.62\pm0.25) \times 10^{-8}$***

[J.R. Batley et al.(NA48/2 collaboration), Phys. Lett.B 697(2011) 107]



Data sample:

- 2016 SampleA (162 runs) → N_K~3.44 10^{11} (16/09/2016 - 03/11/2016)
- Dedicated trigger chain: L0: RICH • Q_x • MO2 L1: !LAV • $STRAW_{exotics}$



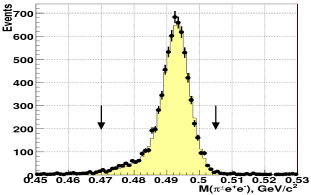
Selection not optimize for $K^+ \to \pi^+\mu^+\mu^-$ decay

PID procedure optimize for $K \to \pi\mu e$ selection

Rare decays: $K^+ \to \pi^+ e^+ e^-$

FCNC decay $K^+ \to \pi^+ e^+ e^-$ ***$B=(3.11\pm0.12) \times 10^{-7}$***

[J.R. Batley et al.(NA48/2 collaboration), Phys. Lett.B 677(2009) 246]

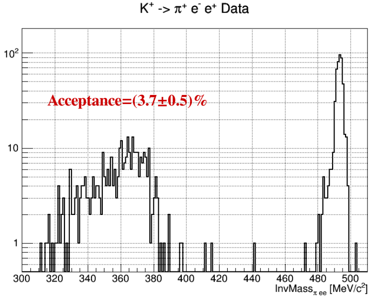


Data sample:

- 2016 SampleA (112 runs) $\to N_K \sim 5.85\ 10^{10}$ (03/10/2016 - 03/11/2016)
- Trigger chain: L0: RICH • Q_x • E_{LKr}>20GeV L1: !LAV • $STRAW_{exotics}$

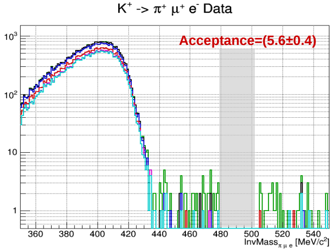
Selection not optimize for $K^+ \to \pi^+ e^+ e^-$ decay

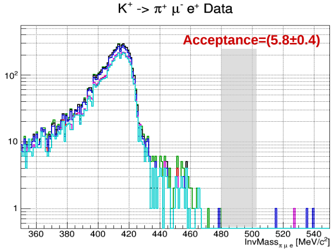
PID procedure optimize for $K \to \pi\mu e$ selection

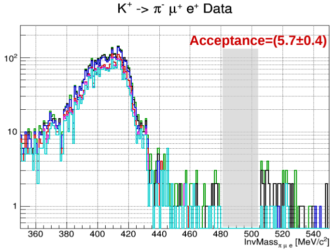


Forbidden decays: LNV & LFV

Blind analysis $M_{\pi\mu e}$=[480,505] MeV/c^2







Single Event Sensitivity: SES=1/N_k* Acc

SES for Sample A 2016 data taking ~ 1.3 10^{-10}

Full 2016 data taking (SampleA+B) possible improvement of the present upper limits for $K^+ \rightarrow \pi^+\mu^-e^+$ and $K^+ \rightarrow \pi^-\mu^+e^+$

2017 data taking ~ 10^{12} kaon decays → improvement of ULs of 1 order of magnitude

Search Hidden Particles in beam dump mode

- 400 GeV protons on TAXes (Fe-Cu collimators)
- Production of long-lived particles from beauty and charm hadrons.
  - 10^{18} POT: $\sim 2 \cdot 10^{15}$ D mesons, $\sim 10^{11}$ b-hadrons
  - 80 days with nominal NA62 intensity

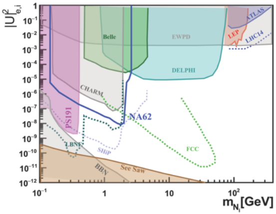
- Minimal changes wrt Decay mode (15 min setup)
- Signal: pair of tracks/photons from the same vertex. Overwhelming background.
- Needed a good understanding of the beam line
  - $\sim$ 30m between target and TAXes
  - Optimisation: obtain maximum intensity in ECN3

- Interplay among phenomenology and experiment

Heavy Neutral Leptons

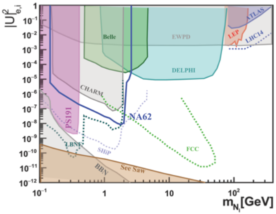
- 2-track final states
- Assumed zero background
- Searches possible in both modes!!!

Scenario 1



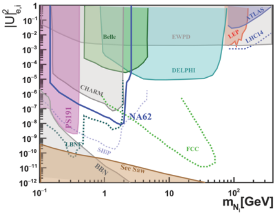
$U_e^2 : U_\mu^2 : U_\tau^2 = 52 : 1 : 1$

Scenario 2



$U_e^2 : U_\mu^2 : U_\tau^2 = 1 : 16 : 3.8$

Scenario 3



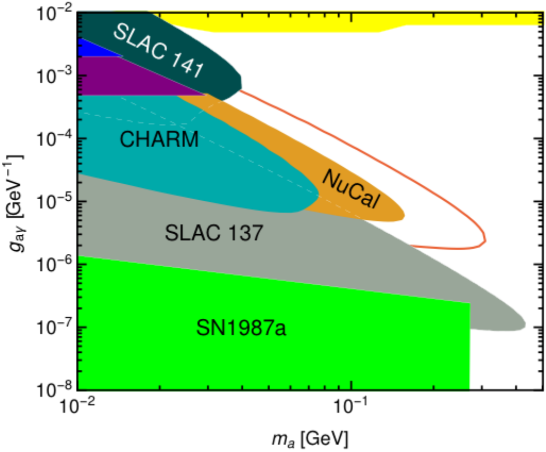
$U_e^2 : U_\mu^2 : U_\tau^2 = 0.061 : 1 : 4.3$

Asaka,Blanchet,Shaposhnikov, Phys. Lett. B631 (2005) 151
Asaka,Shaposhnikov, Phys. Lett. B620 (2005) 17
Lanfranchi, PoS(EPS-HEP2017)301

ALPs$\rightarrow \gamma\gamma$

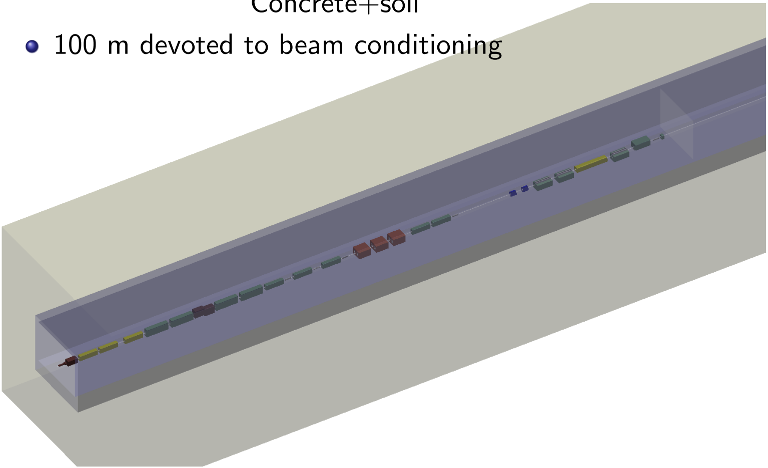
B. Dobrich et al.,JHEP 02 (2016) 018

- ALP production via Primakoff effect at target
- ALP$\rightarrow \gamma\gamma$ decay in NA62 fiducial volume
- Assumed zero background (90% exclusion plots)



K12 beamline

- TCC8 cavern: 9.5m x 6.5m x 150m
  Concrete+soil
- 100 m devoted to beam conditioning



M. Rosenthal (CERN)

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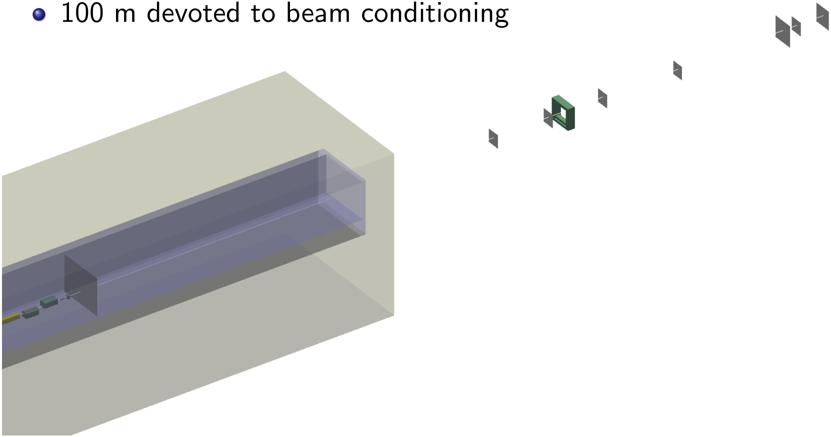

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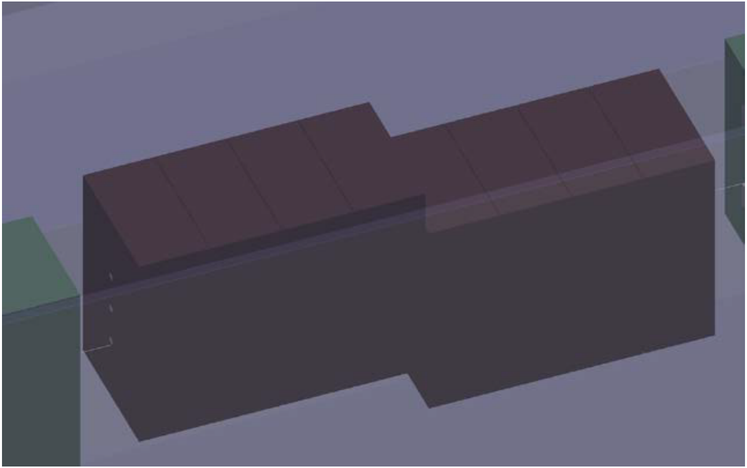

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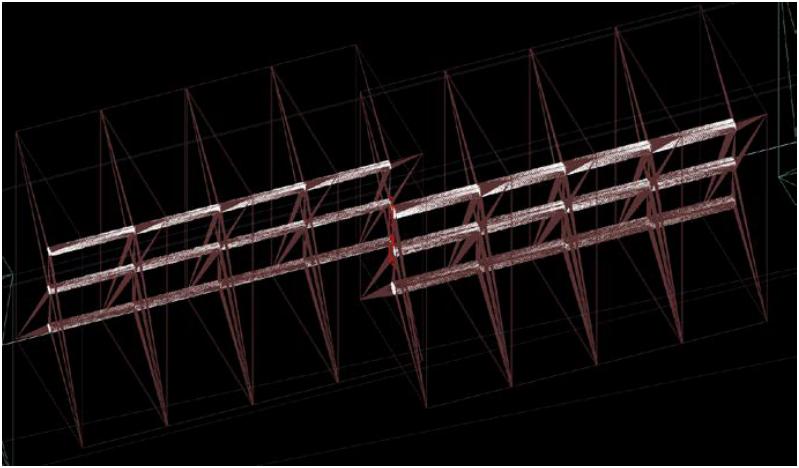

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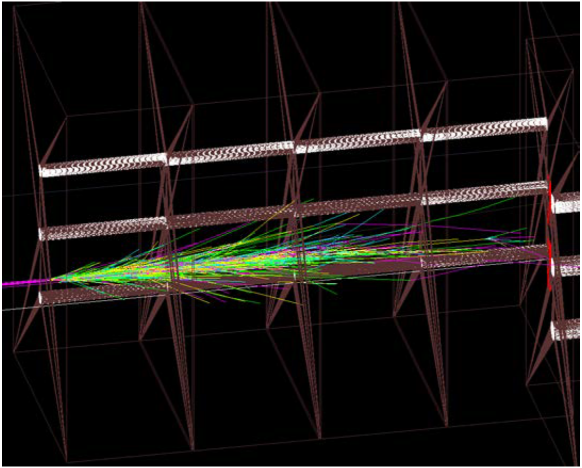
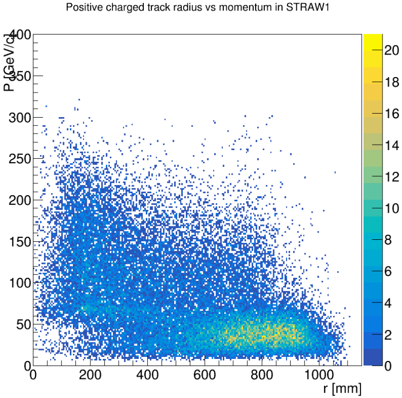
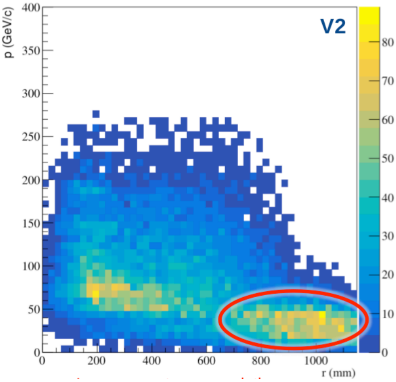


G4 simulations for NA62 beam line (target out and TAX closed)

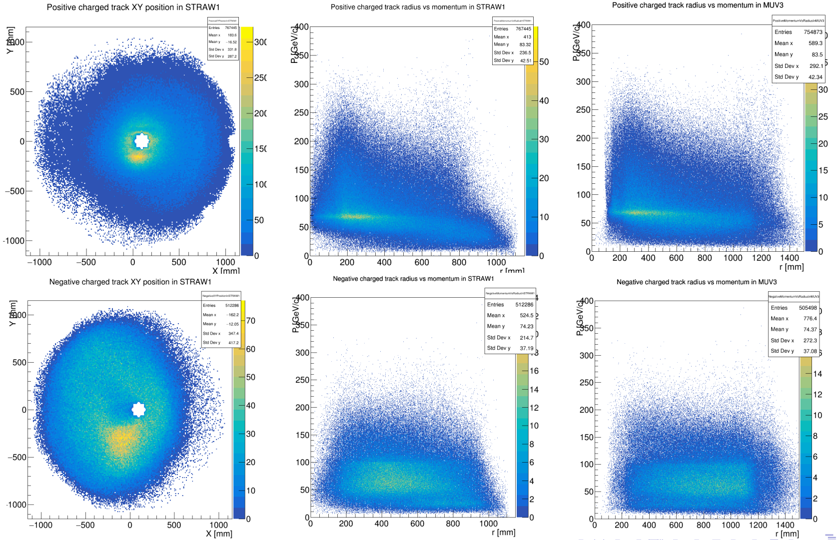




Data: run 6688 -
T out, TAX closed

MC: TAX interactions
included

Run 6687 (T in TAX closed)



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- Unique opportunity to test models in two configurations with the same setup by 2023.