Rare Decays in Kaons and Muons

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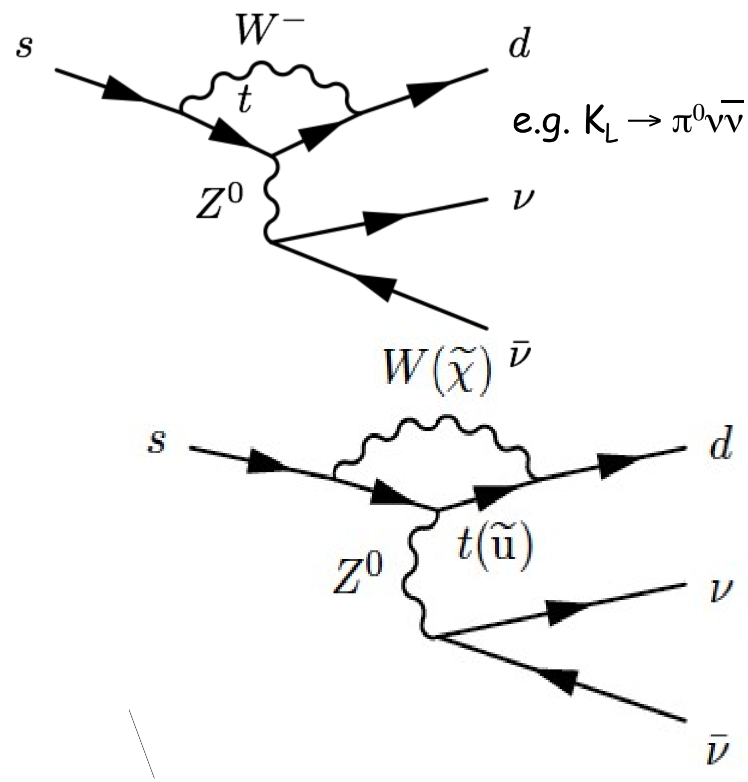
Why do we study Rare Decays?

- Standard Model (SM) is likely the low-energy limit of a more fundamental theory with more degrees of freedom.
  Expect New Physics (NP)

- How to search for NP?

1. Study physics processes that cannot proceed at tree level in SM but are dominated by loops (box,penguin) → loops can contain NP



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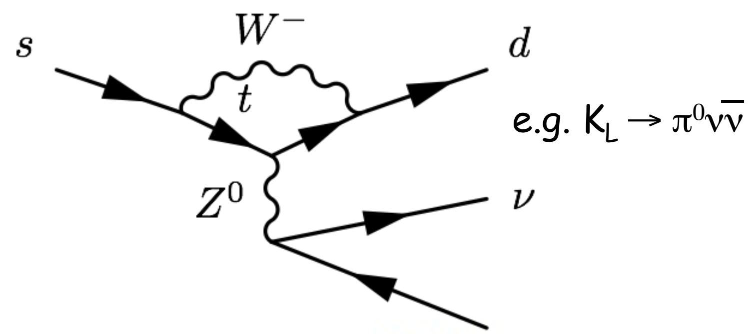

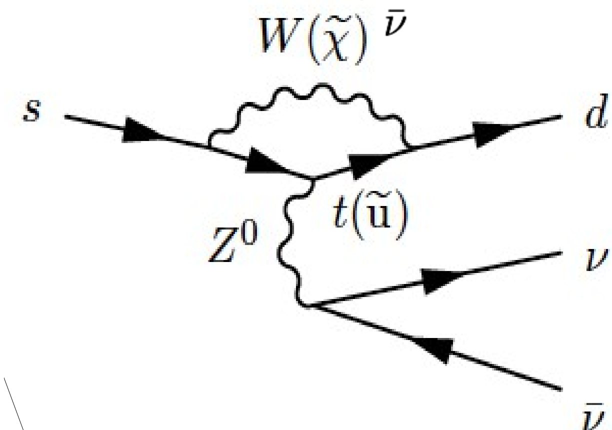

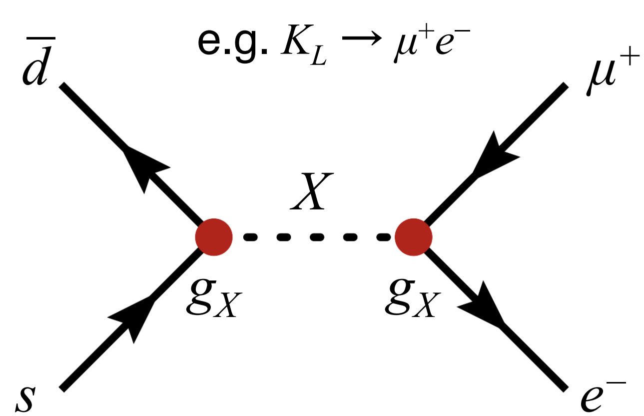

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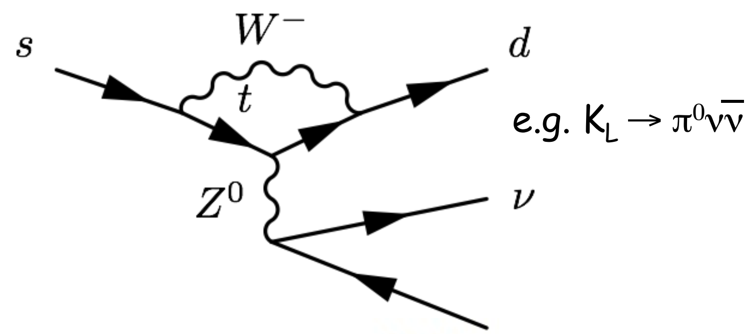
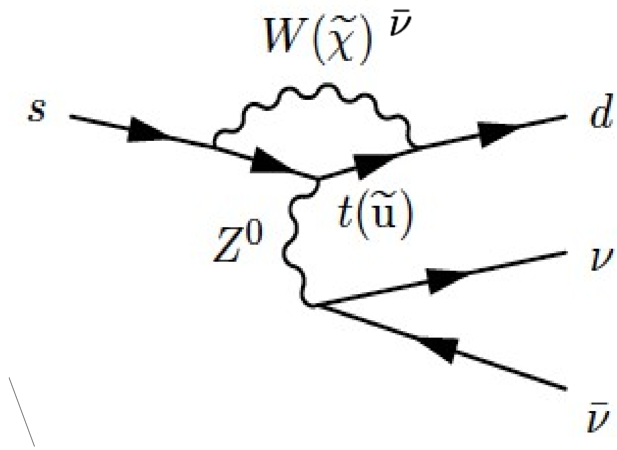
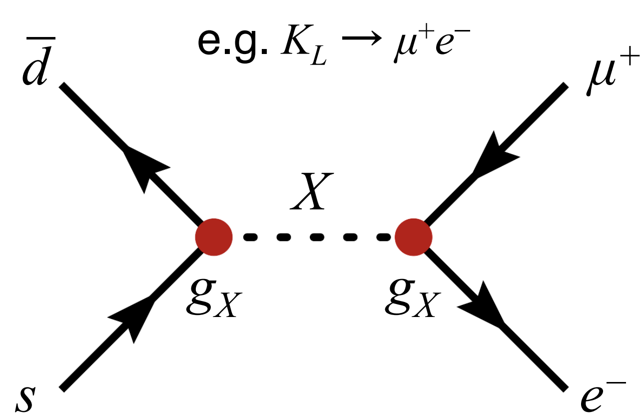
Rare processes are sensitive to NP







Why do we study Rare Decays in kaons and muons?

- Availability of high intense beams → high statistics samples
- Simple decay topologies → clean experimental signatures

Two kind of experimental approaches:

1. know where to look
   - Find observables where SM predictions are very accurate.
   - Measure these observable very precisely.
   - Extract NP if any deviation observed

2. just look for the implausible/impossible
   - If anything is seen, it must be NP

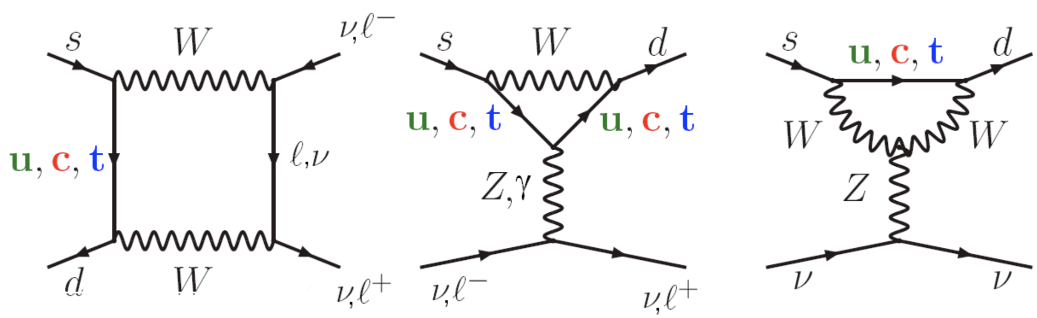
NEED STATE-OF-THE-ART DETECTORS

Rare Decays covered in this talk

- The kaon "golden" modes:
  - $K^+ \to \pi^+ \nu\bar{\nu}$ (NA62)
  - $K_L \to \pi^0 \nu\bar{\nu}$ (KOTO)
- Rare Muon Decays
  - $\mu^+ \to e^+\gamma$ (MEG)
  - $\mu^- + N \to e^- + N$ (Mu2e)
- BR($K^\pm \to \pi^\mp \mu^\pm \mu^\pm$) from NA48/2
- BR($K_S \to \mu^\pm \mu^\mp$) from LHCb
- BR($K_S \to \pi^0\pi^0\pi^0$) from KLOE

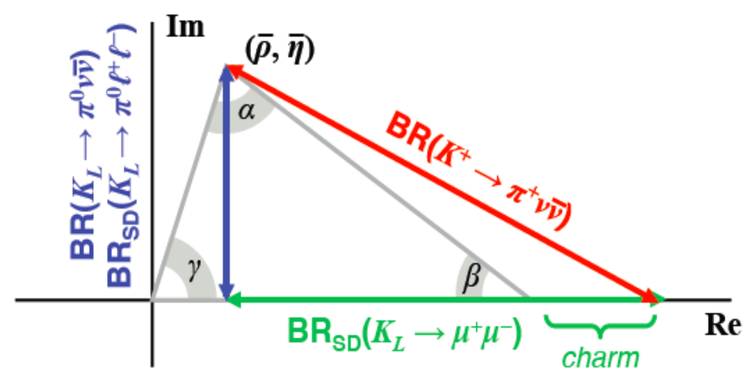
Kaon Golden Modes

- The two rare kaon decays, $K^+ \to \pi^+\nu\bar{\nu}$ & $K_L \to \pi^0\nu\bar{\nu}$, are FCNC processes, forbidden at tree level and dominated by one loop diagrams



- t quark intermediate states dominate (GIM suppression for u,c)
- long distance contributions are small
- relevant hadronic operator can be extracted from $K^+ \to \pi^0 e^+ \nu$

- Provide input to CKM unitarity triangle



Kaon Golden Modes and NP

Branching ratios theoretical prediction are good to 2-4% (excluding parametric uncertainty)

$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (7.81 \pm 0.75 \pm 0.29) \times 10^{-11}$

$BR(K_L \to \pi^0 \nu\bar{\nu}) = (2.43 \pm 0.39 \pm 0.06) \times 10^{-11}$

(Brod, Gorbhan, Stamou, PRD 83,0340030 (2011)

Direct measurements:

$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (17.3{+}11.5{-}10.5) \times 10^{-11}$ (BNL E787/E949: PRL 101 (2008) 191802)

$BR(K_L \to \pi^0 \nu\bar{\nu}) < 2.6 \times 10^{-8}$ (KEK E391a: PRD 81 (2010) 072004)

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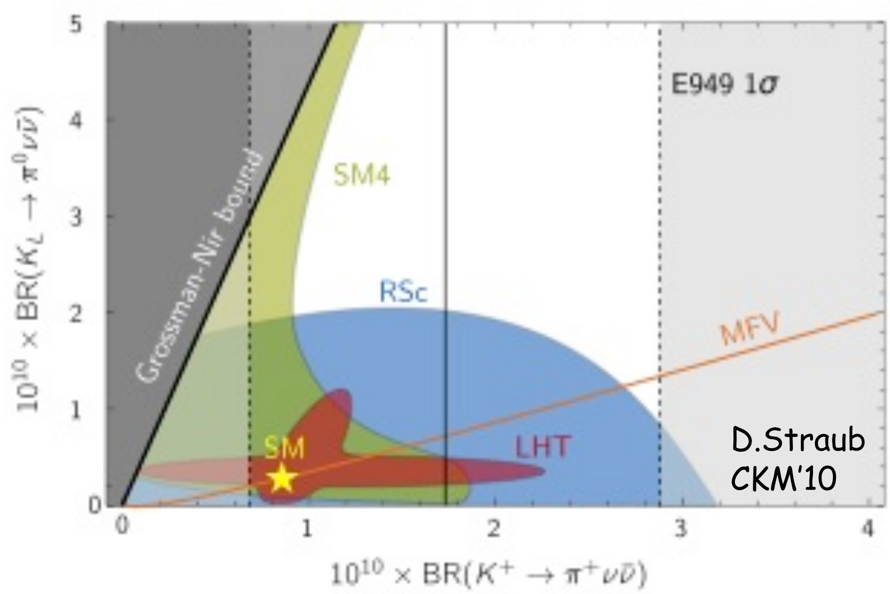
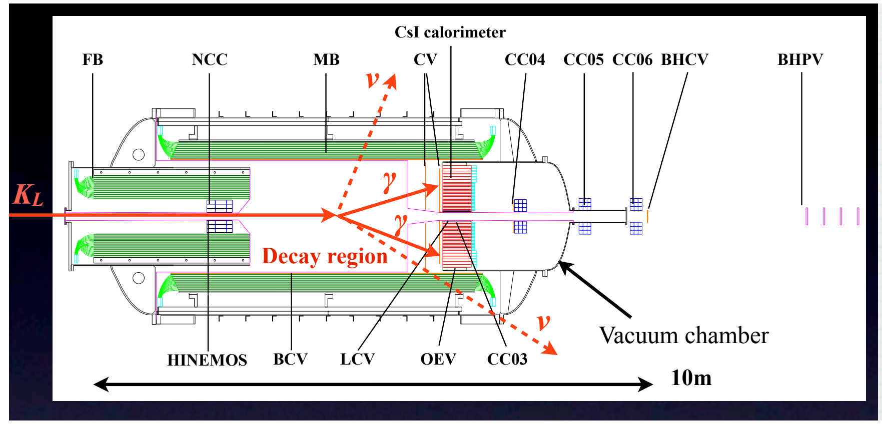
- Several NP scenarios predicts sizeable deviation from SM: correlation between the two modes can help distinguish models



Search for $K_L \rightarrow \pi^0 \nu \nu$

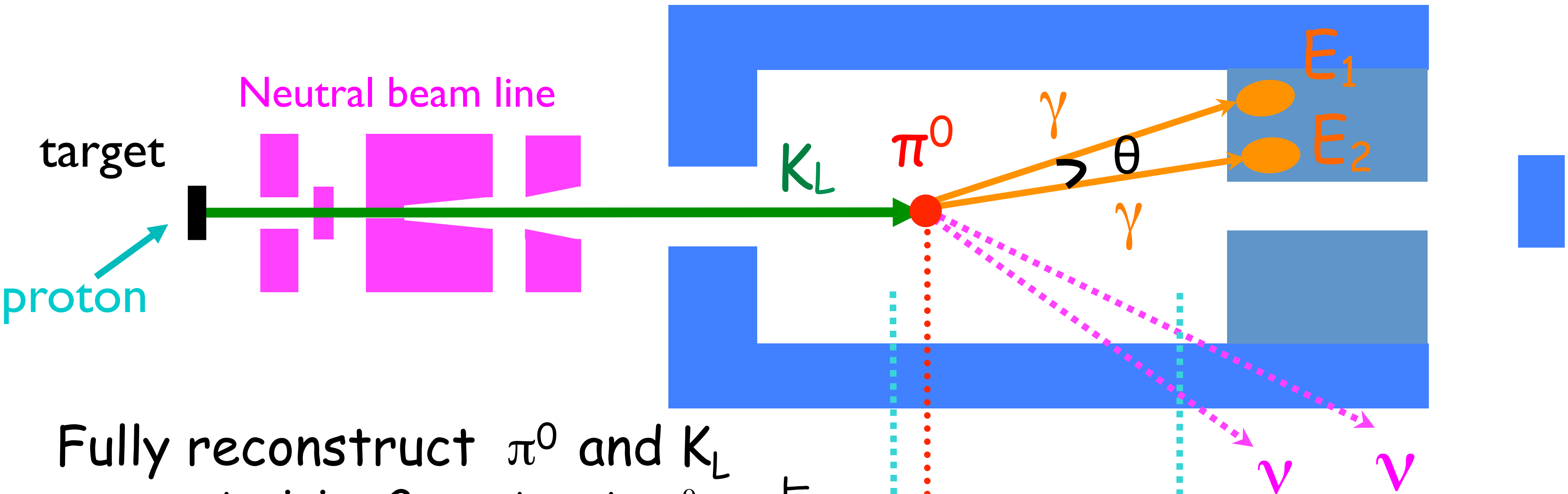
- KOTO (K^0 at Tokai) searches for $K_L \rightarrow \pi^0 \nu \nu$ at the 30 GeV/c proton beam in JPARC, Japan



- Nothing into 2 γ + nothing!
- Use E391a experimental setup:
  - Clean K_L beam (off-axis to lower n momentun below η production threshold)
  - Precisely shaped collimators to minimize halo particles
  - Highly segmented CsI calorimeter (KTeV) for γ detection
  - Hermetic veto system
- Phase I: Single Event Sensitivity (SES): 9×10^{-12}

  ➪ **observation at SM level**
- Phase II: 10% measurement

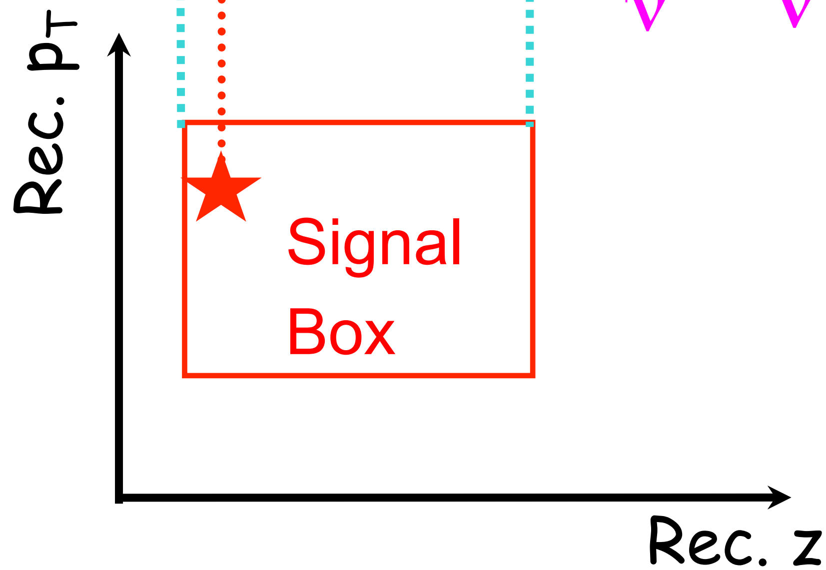
KOTO Experimental Technique



Fully reconstruct π^0 and K_L

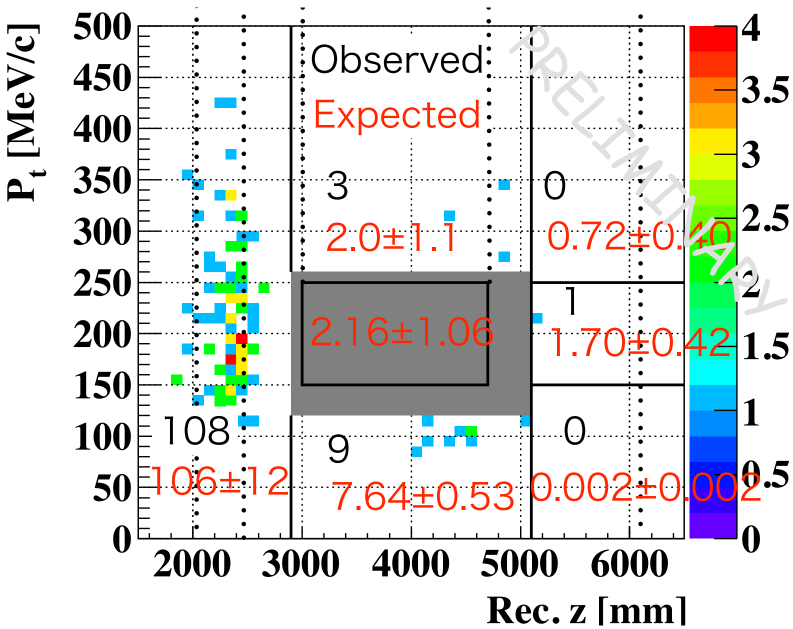
- constraining 2γ system to π^0 mass, get the two photon opening angle θ
- assuming K_L decay vertex on beam line, reconstruct P_t and z of π^0 decay

Any other K_L decay with only photons has no p_T



$K_L \to \pi^0 \nu \bar{\nu}$ Analysis

- First physics run: May, 2013
  - Beam power:24kW(10% of design intensity)
  - Terminated after 100 h due to radiation accident in Hadron Hall
- Blind Analysis
- After "loose" selection of events with 2 clusters in CsI, events outside the box are well predicted



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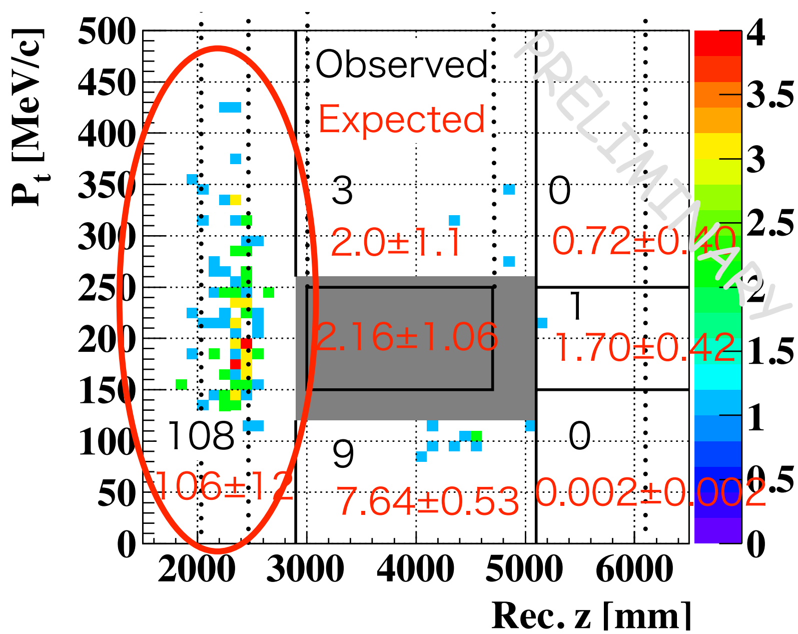

- Events in upstream low rec. z region (0.1 $K_L \to \pi^0 \nu \bar{\nu}$ evts) are due to halo neutron interactions generating π^0

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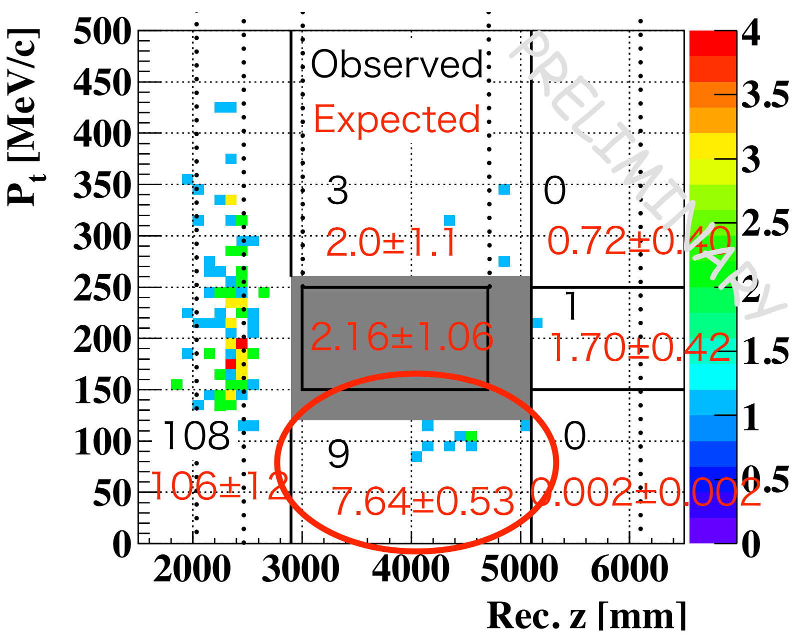

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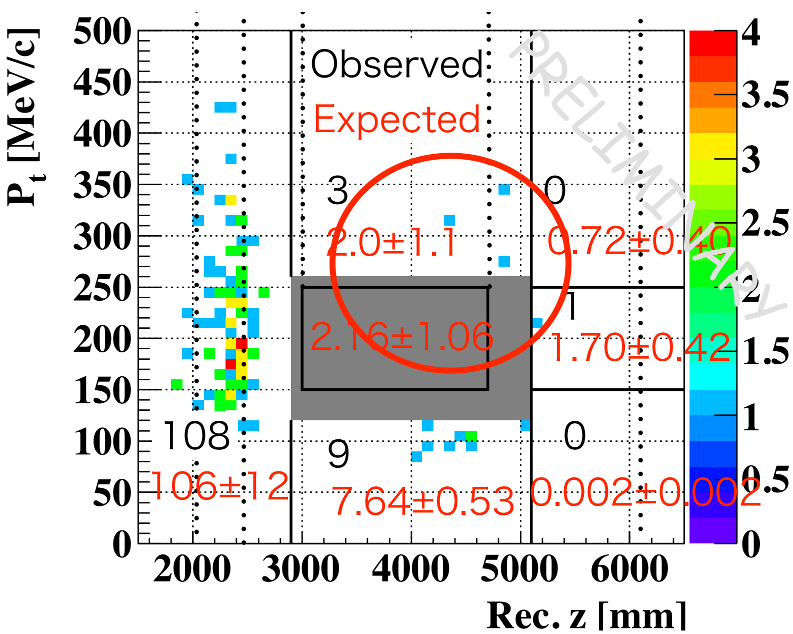

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- Events in low P_t region are due to $K_L \to \pi^+ \pi^- \pi^0$ events with $\pi^+ \pi^-$ going down the beam pipe (133 MeV/c kinematical limit)
- Events in high P_t downstream region are due to single halo neutrons generating two hadronic clusters in CsI.
  - most serious background (1.9±1.1 evt inside signal box)
  - modeled using special run with Al plate inserted in the beam core

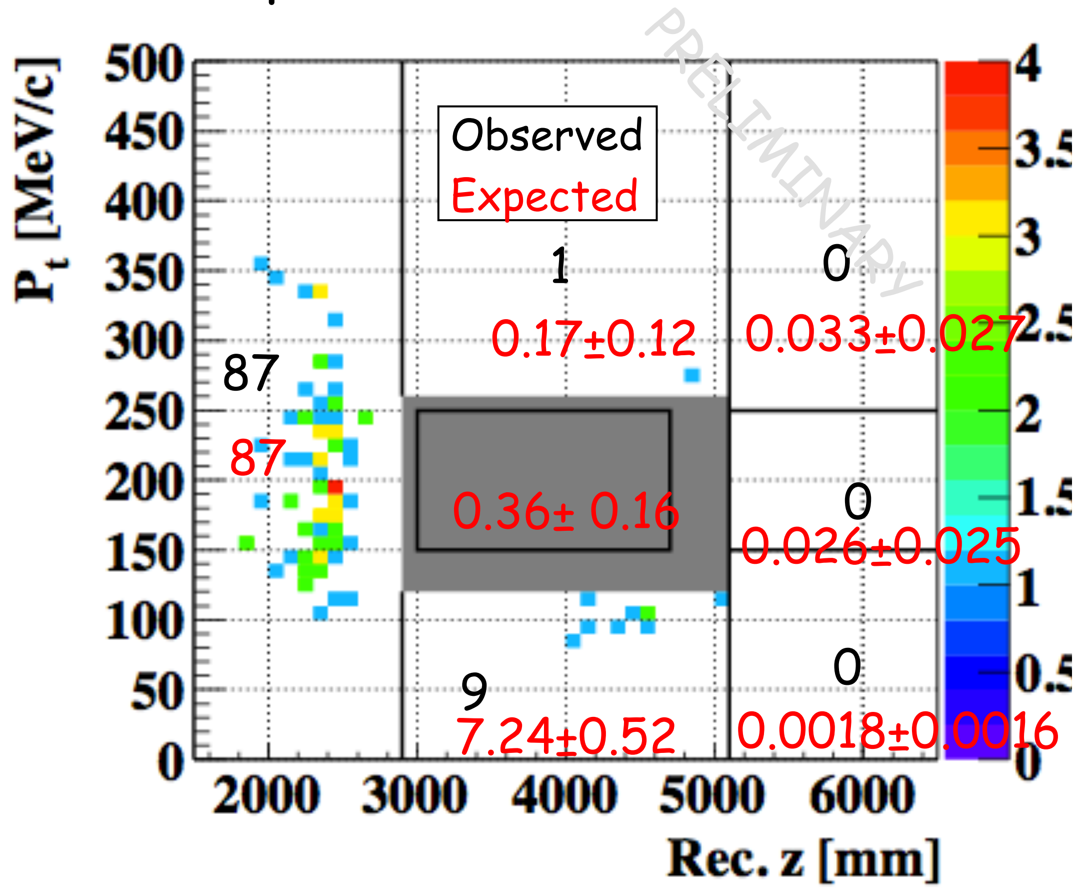
$K_L \to \pi^0 \nu \bar{\nu}$ Result

Apply neural net cut to separate hadron from photon clusters using both cluster kinematical and shape variables.

Final background prediction inside signal region

BG source	#BG
Hadron cluster events	0.18±0.15
Kaon decay events	0.11±0.04
Upstream events	0.06±0.06
Sum	0.36± 0.16

- S.E.S. of the first physics run: 1.29×10^{-8} (E391a: 1.1×10^{-8})

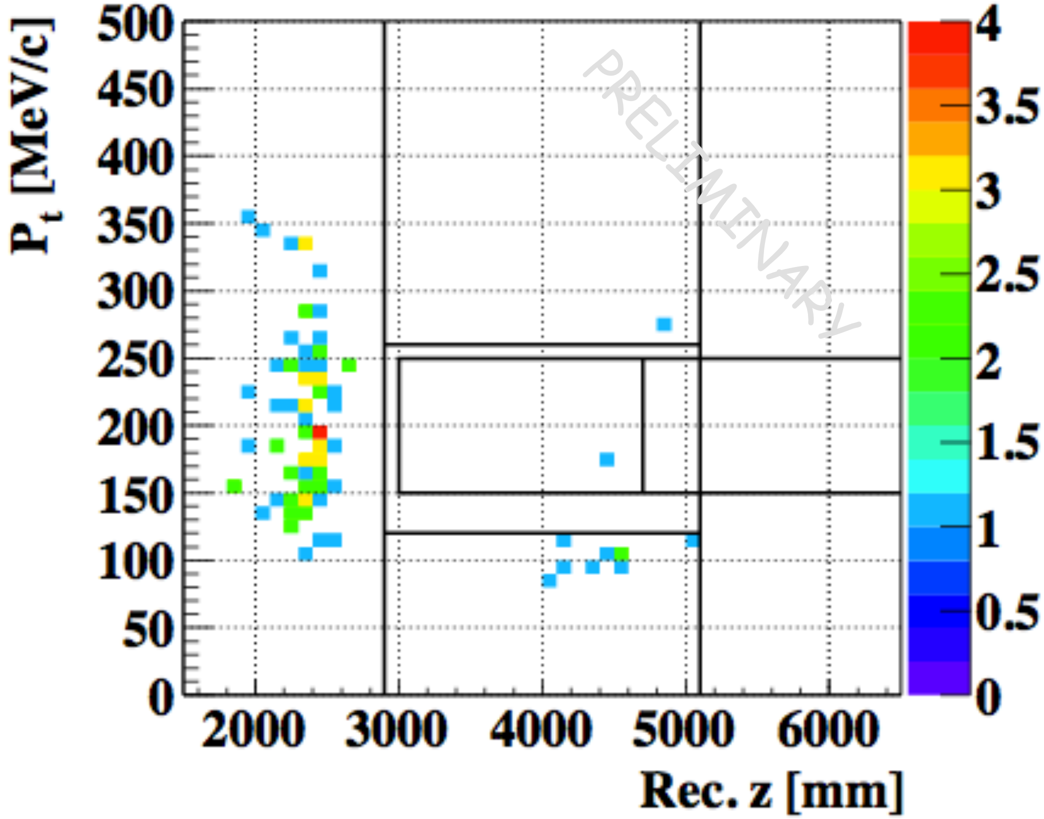


- KOTO achieved similar sensitivity as E391a in only 100 hours of data taking!

$K_L \to \pi^0 \nu \bar{\nu}$ Result

- 1 event found inside signal box after applying all cuts

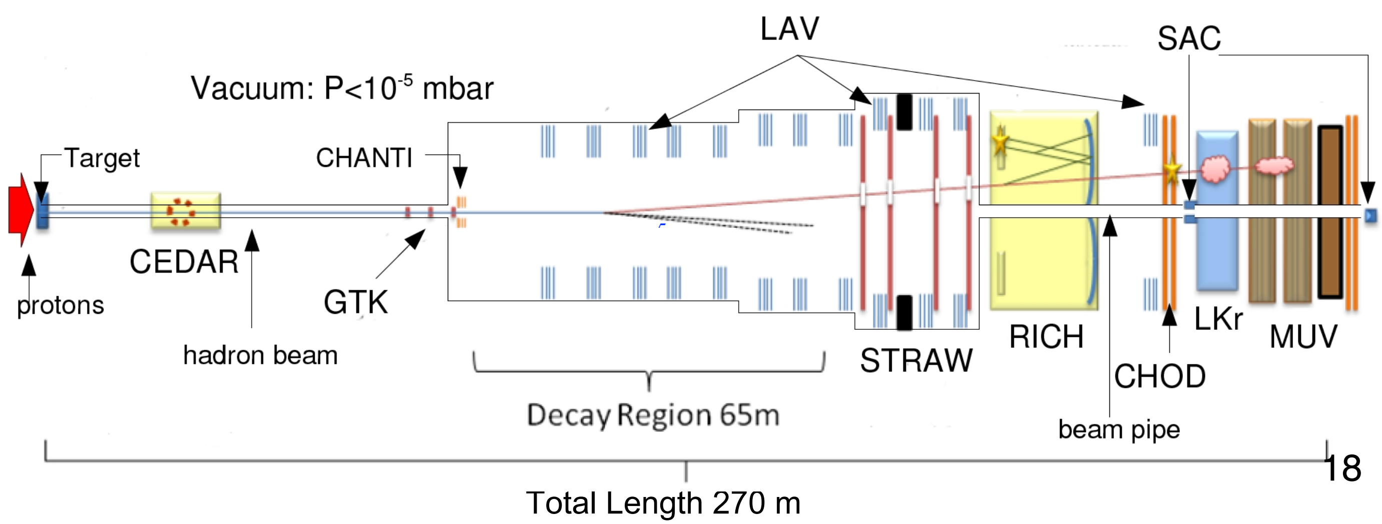
  (with loose cuts: 2 evts vs 2.11±1.06 expected)



- Next physics runs in 2015. Aims at GN limit sensitivity by improving veto coverage and analysis to control background.

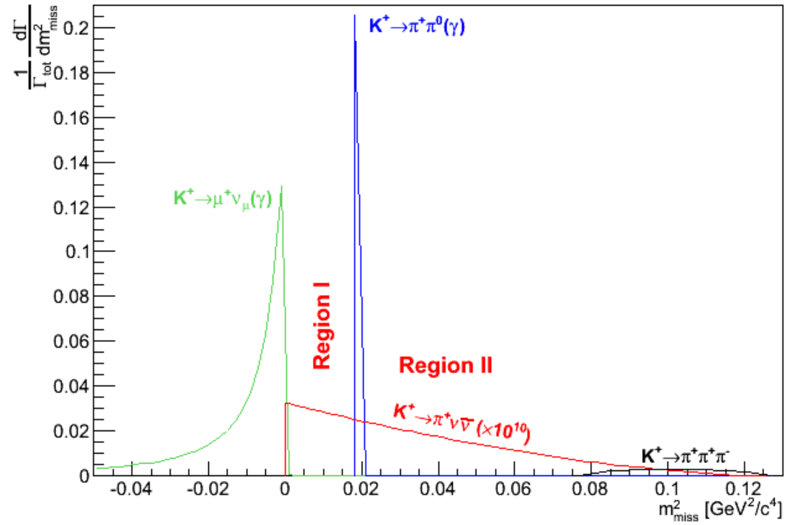
Search for $K^+ \rightarrow \pi^+\nu\bar{\nu}$

- NA62 at SPS400 GeV/c proton beam, CERN
- 75 GeV/c unseparated hadron beam (6% kaon component)
- 4.8×10^{12} K/year, acceptance ~10%
  ➪ SES ~ 10^{-12}
  ➪ 100 $K^+ \rightarrow \pi^+\nu\bar{\nu}$ in 2 yrs



NA62 Experimental Technique

- 92% of signal is separated from background just based on kinematics using $M^2_{miss} = (P_K - P_\pi)^2$



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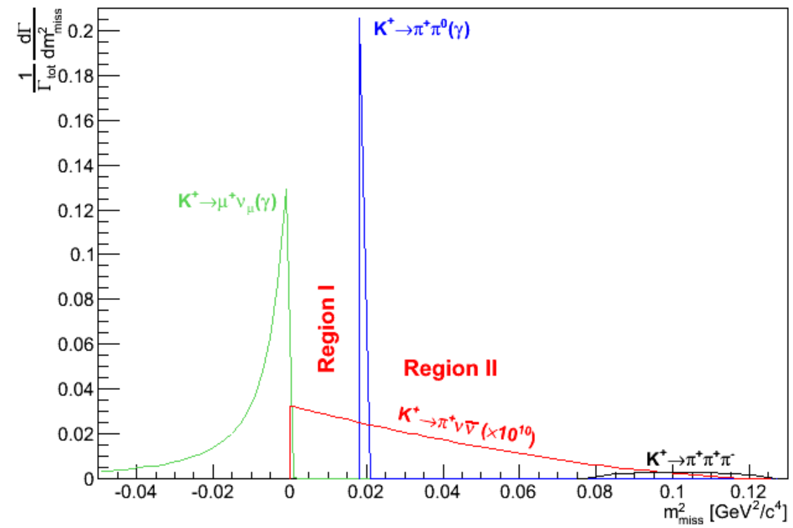
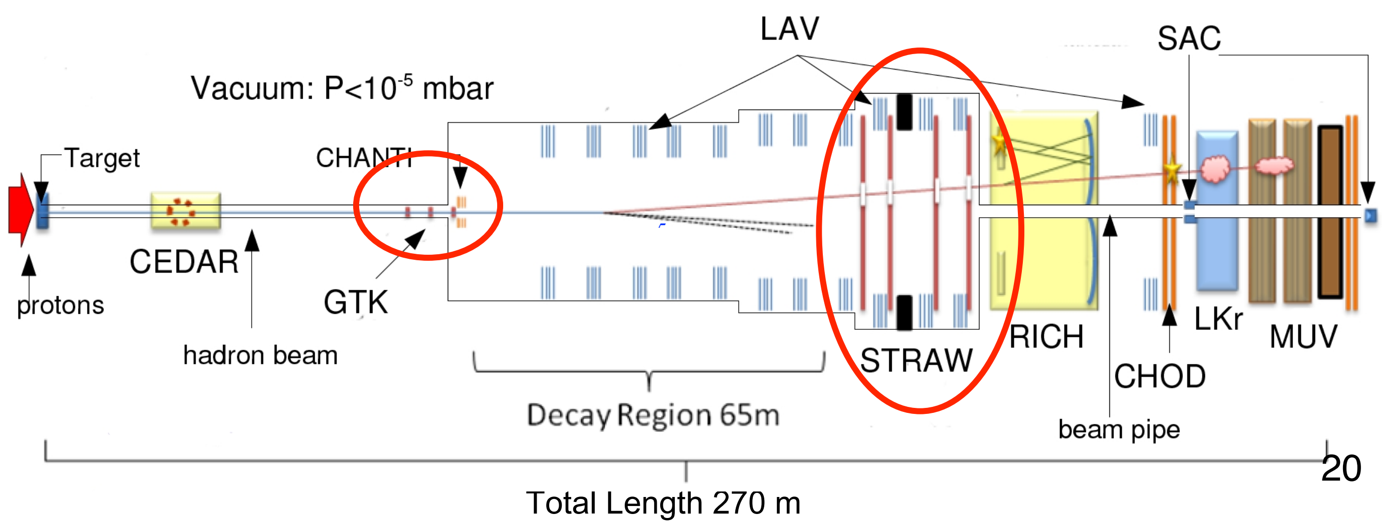
SIGNAL IDENTIFICATION

- Measure K and pion momentun with high resolution in low material trackers (GTK +STRAW)





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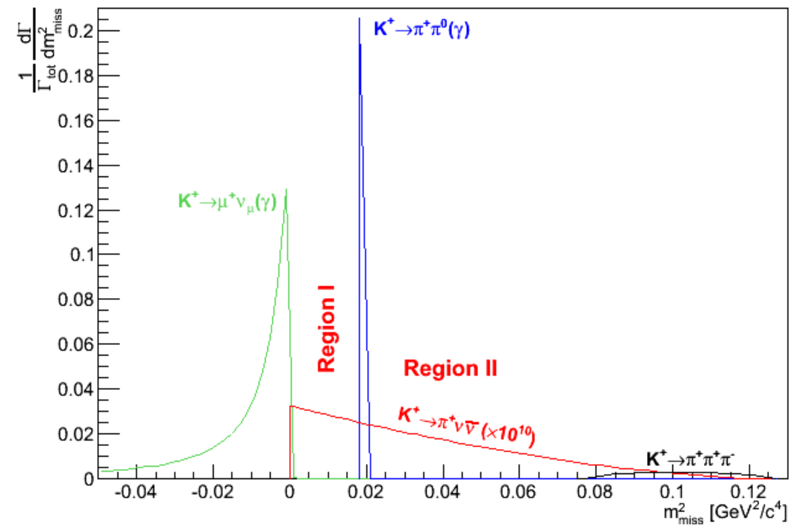
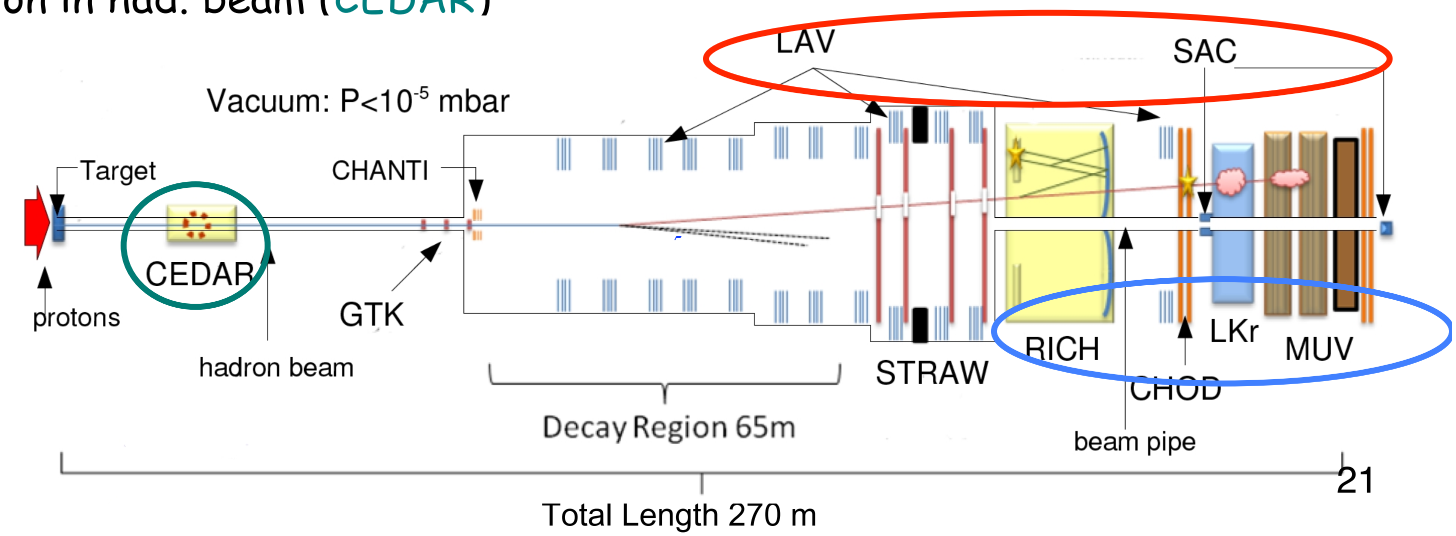
BACKGROUND REJECTION

- Reject events with photons (LAV+SAC)
- 10^{-3} $\pi-\mu$ separation (RICH+LKr+MUV)
- K^+ identification in had. beam (CEDAR)





NA62 Physics and Schedule

- Upcoming run (October-December 2014): commission detector with lower intensity beam. Likely reach SM sensitivity!

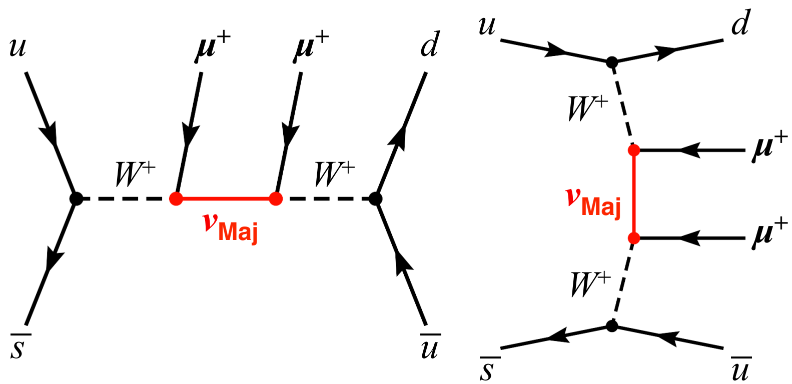
- Nominal intensity runs in 2015, 2016 and 2017 before LHC shutdown

- Planning for further physics measurements: real rare decay factory!

Decay	Physics	Present limit	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	$6.4*10^{-10}$	$2.0*10^{-12}$
$\pi^-\mu^+\mu^+$	LNV	$1.1*10^{-9}$	$0.4*10^{-12}$
$\mu^-\nu e^+e^+$	LFV/LNV	$2*10^{-8}$	$4.0*10^{-12}$
$e^-\nu\mu^+\mu^+$	LNV	No data	$1.0*10^{-12}$
$\pi^+\chi^0$	New particle	$5.9*10\text{-}11\ M\chi 0 = 0$	$1.0*10^{-12}$
$\pi^+\chi\chi$	New particle	No data	$1.0*10^{-12}$
$\pi^+\pi^+e^-\nu$	$\Delta S \neq \Delta Q$	$1.2*10^{-8}$	$1.0*10^{-11}$
$\pi^+\pi^+\mu^-\nu$	$\Delta S \neq \Delta Q$	$3.0*10^{-6}$	$1.0*10^{-11}$
$\pi^+\gamma$	Angular momentum	$2.3*10^{-9}$	$1.0*10^{-11}$
$\mu^+\nu_h,\ \nu_h\to\nu\gamma$	Heavy neutrino	Limits up to $M\nu_h$ = 350 MeV/c^2	$1.0*10^{-12}$
R_K	LU	$(2.488 \pm 0.010)*10^{-5}$	>*2 better
$\pi^+\gamma\gamma$	χPT	< 500 events	10^5 events
$\pi^0\pi^0e^+\nu$	χPT	66000 events	$O(10^6)$ events
$\pi^0\pi^0\mu^+\nu$	χPT		$O(10^5)$ events

$K^{\pm}\rightarrow\pi^{\mp}\mu^{\pm}\mu^{\pm}$

- LNV process mediated by Maiorana neutrino



- In some LNV NP models, rate is close to experimental limit

  ex: resonant enhancement if Maiorana neutrino has intermediate mass

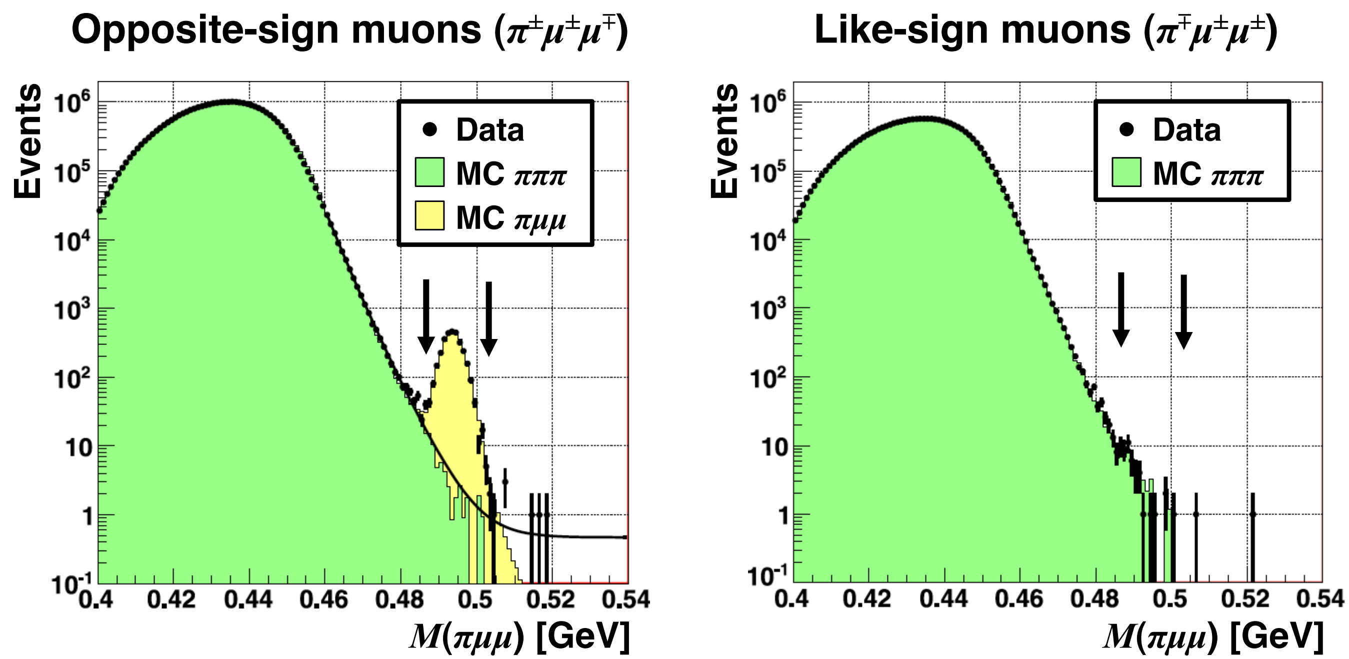
  $m_{\pi} < m_{\nu} < m_{K}$

- Previous limit:

  $BR(K^{\pm}\rightarrow\pi^{\mp}\mu^{\pm}\mu^{\pm}) < 3\times10^{-9}$ @ 90 CL (BNL E865: PRL 85 (2000) 2450)

- NA48/2 in 2003-2004 collected data with beams of $K^{+}+K^{-}$
- Normalize $K\rightarrow\pi\mu\mu$ sample to $K^{\pm}\rightarrow\pi^{\pm}\pi^{+}\pi^{-}$ to cancel many systematics

$K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$

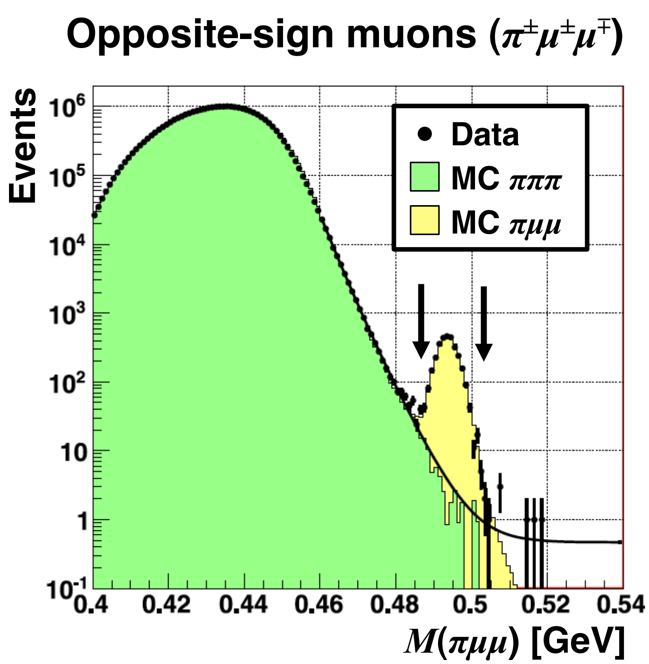


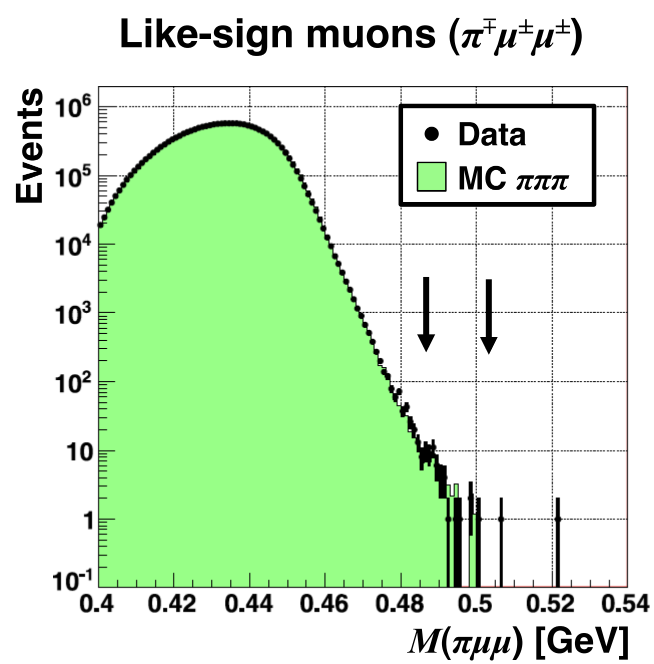
- 52 candidates in signal region
- 52.6 ± 19.8 expected background

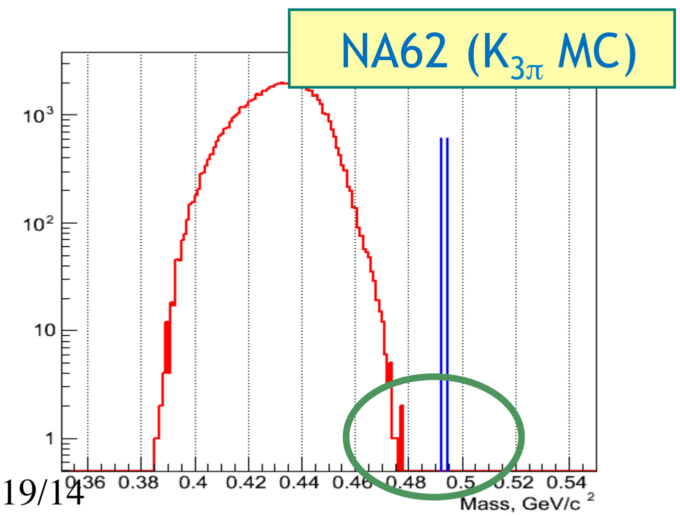
$BR(K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}) < 1.1 \times 10^{-9}$ @ 90 CL

(Phys. Lett. B 697 (2011), 107)

$K^{\pm}\rightarrow\pi^{\mp}\mu^{\pm}\mu^{\pm}$







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NA62 will collect 10^{13} K and reach SES ~ 10^{-12}

$K_S \to \pi^0\pi^0\pi^0$

- $3\pi^0$ is a pure CP=-1 state
- Analogously to $K_L \to \pi^0\pi^0$ (happy 50^{th} birthday!), $K_S \to \pi^0\pi^0\pi^0$ signals indirect CP violation in mixing and/or decay

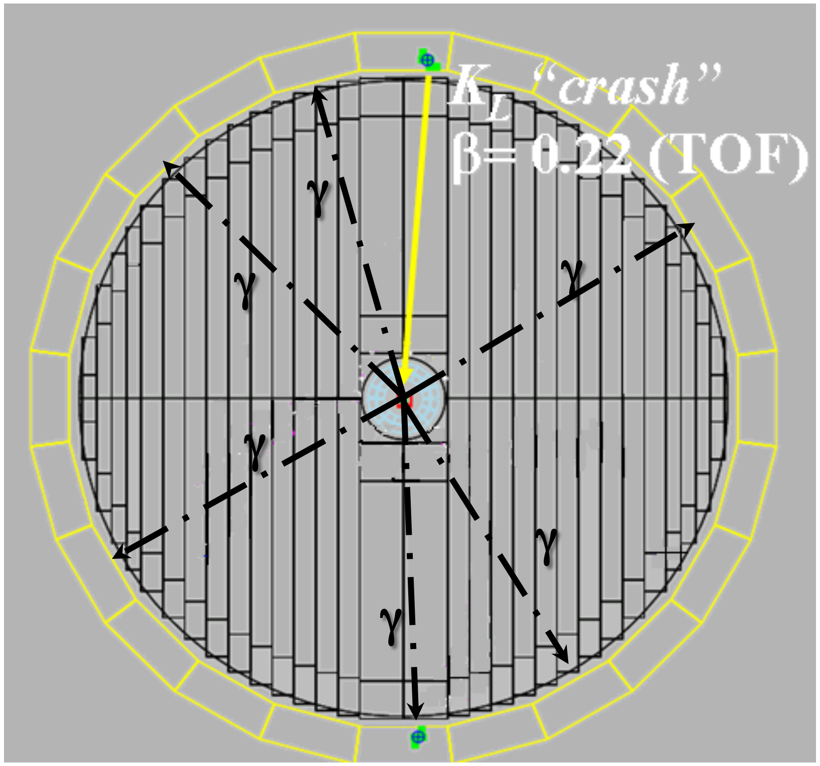
- SM predicts $BR(K_S \to 3\pi^0) \sim 2\times10^{-9}$

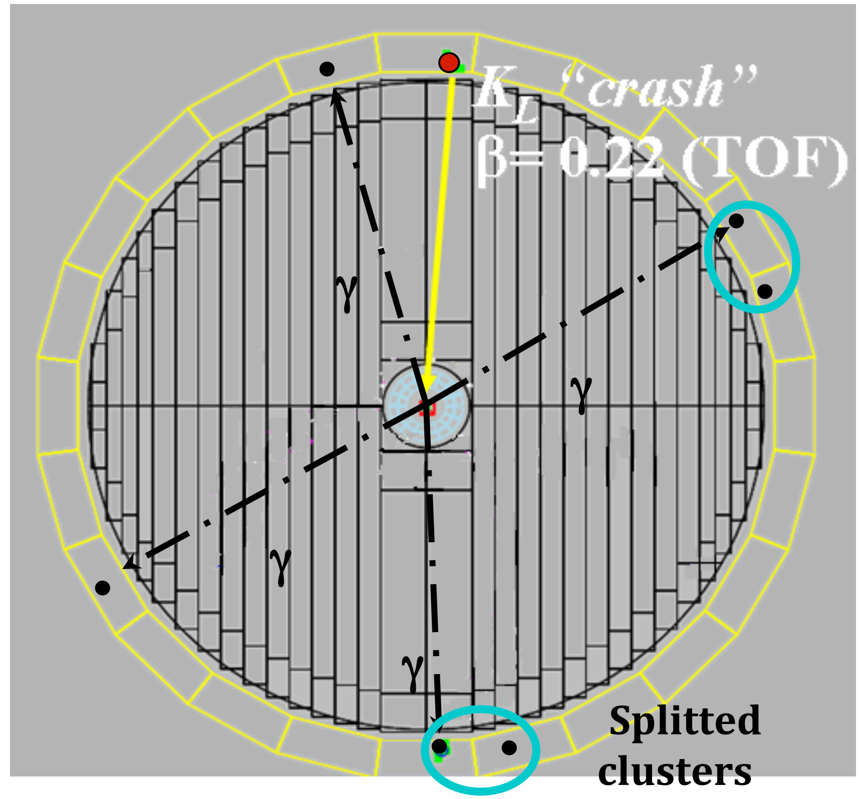
- Never observed so far

- KLOE at Frascati DAΦNE e^+e^- collider with $\sqrt{s} \sim m_\phi = 1019.4$ MeV
- Collected 8×10^9 ϕ decays (2×10^9 K_LK_S) between 2001 and 2005

- Unique K_s tagging using K_L signature of delayed energy cluster not associated to any track ("K_L crash")

$K_S \to \pi^0\pi^0\pi^0$ Selection





Signal:

$K_S \to \pi^0\pi^0\pi^0$ signal using 6 γ

$$BR(K_S \to 3\pi^0) < 2.6x10^{-8} @ 90\ CL$$

(Phys. Lett. B 723 (2013) 54)

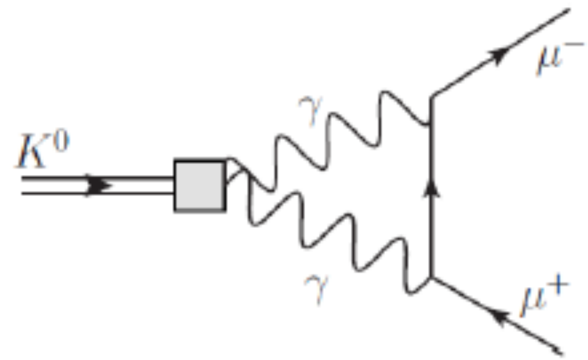
Dominant background:

$K_S \to 2\pi^0$ + 2 accidental/splitted clusters

Residual background:

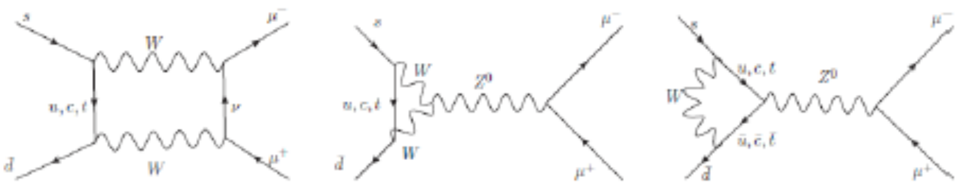
$K_L \to 3\pi^0$ plus $K_S \to \pi^+\pi^+$ faking K_L crash

$K_S \rightarrow \mu^{\pm}\mu^{\mp}$

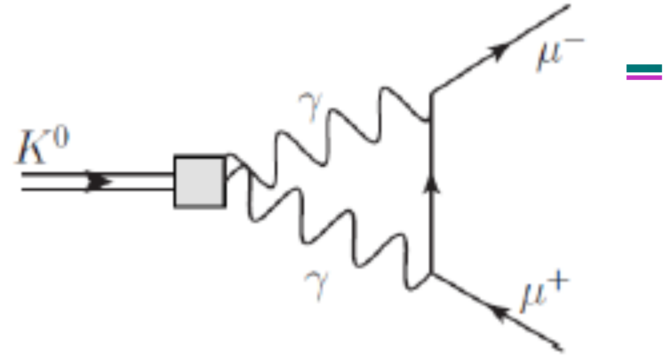


- FCNC decay suppressed in SM
- Dominated by long distance contributions via 2γ intermediate state
- Short distance contributions (similar to $K \rightarrow \pi\nu\nu$) are smaller
- SM expectation: $(5.0\pm1.5)\times10^{-12}$
- Experimental limit:
  - $BR(K_S \rightarrow \mu^{\pm}\mu^{\pm}) < 3.1 \times 10^{-7}$

    [CERN S128, Phys.Letters B44 (1973)]



$K_S \to \mu^{\pm}\mu^{\mp}$



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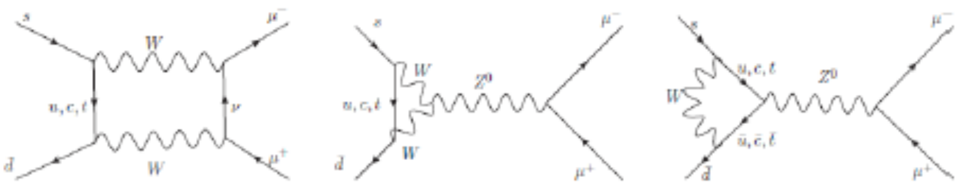
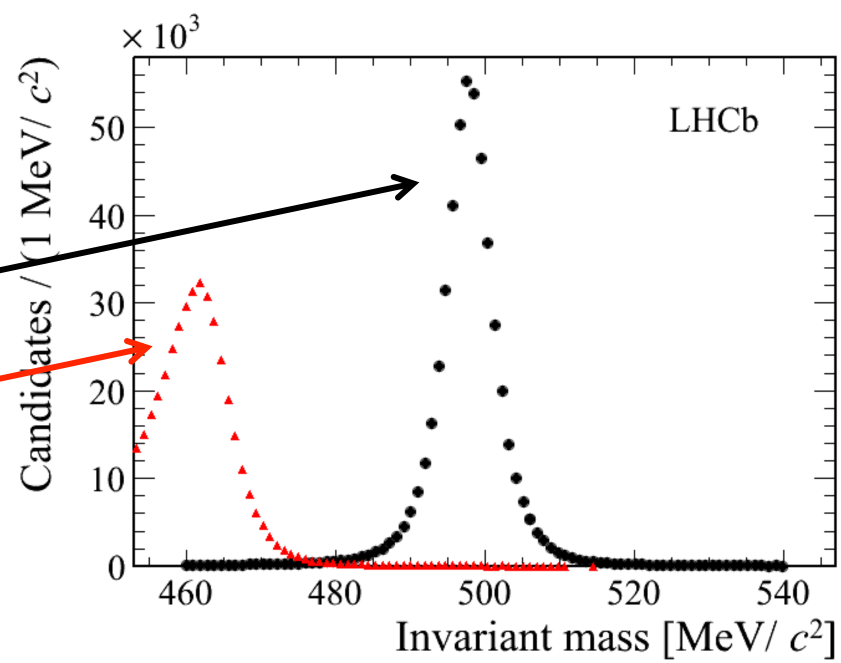
- Dominated by long distance contributions via 2γ intermediate state
- Short distance contributions (similar to K->$\pi\nu\nu$) are smaller



- SM expectation: $(5.0\pm1.5)\times10^{-12}$
- Experimental limit:
  - $BR(K_S \to \mu^{\pm}\mu^{\pm}) < 3.1 \times 10^{-7}$

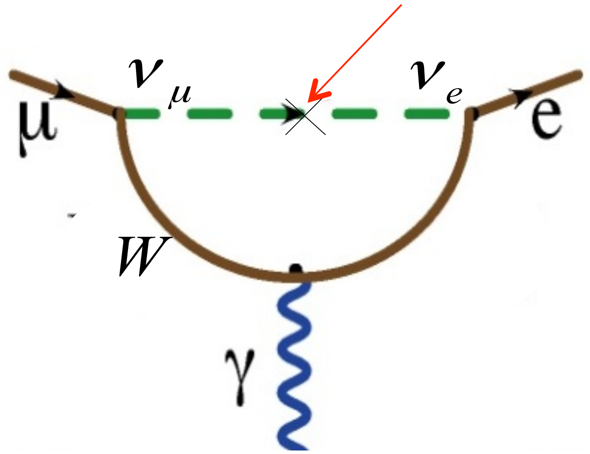
    [CERN S128, Phys.Letters B44 (1973)]
- LHCb did a search based on 1 fb^{-1} of data at $\sqrt{s}$ = 7 TeV (~10^{13} K_s per fb^{-1} within the acceptance)
- Use $K_S \to \pi^+\pi^-$ as normalization mode
- Blind analysis with signal region $492 < M_{\mu\mu} < 504$ MeV/c^2
- $BR(K_S \to \mu^+\mu^-) < 9\times10^{-9}$ @ 90 CL

  [JHEP 1310 (2013), 090]



Rare Muon Decays

- Neutrino oscillations allows for CLFV in higher order dipole penguin diagrams



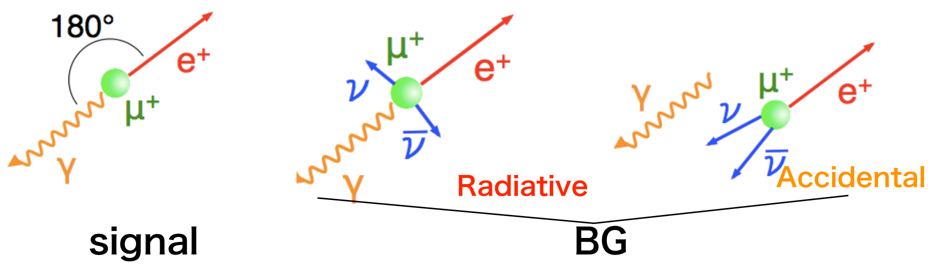
- Photon can be real ($\mu \rightarrow e\gamma$) or virtual ($\mu N \rightarrow eN$, $\mu \rightarrow eee$)

- SM predicts branching ratios beyond measurable levels: $\propto(m_\nu/m_W)^4 < 10^{-55}$

- Any detection of CLFV is unambiguous sign of NP

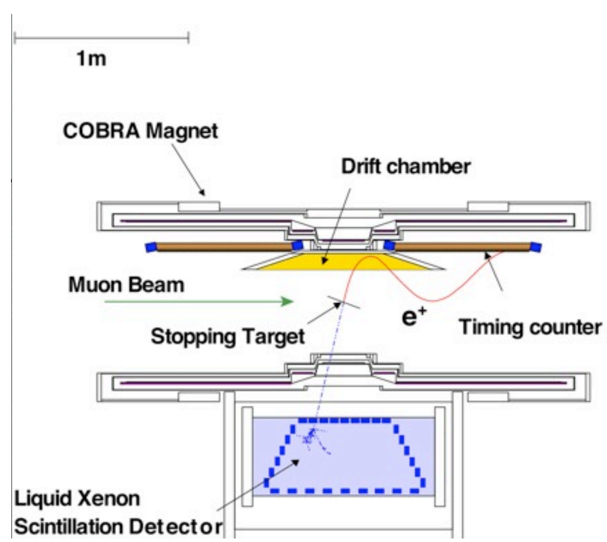
$\mu^+ \to e^+\gamma$

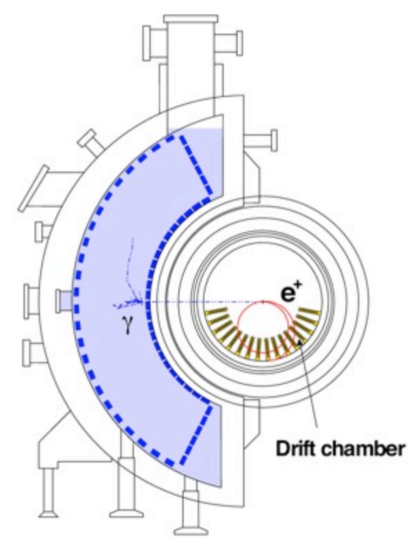
- Clear two-body signal topology with back to back e^+-γ
  - $E_{e+} = E_\gamma = 52.8$ MeV
  - $\Delta t_{e\gamma} = 0$



- Backgrounds:
  - Michel decay with accidental coincidence
  - radiative Michel decay

- MEG experiment at PSI 1.3MW Proton Cyclotron:
  - High intensity DC muon beam
  - high rate e^+ spectrometer in gradient magnetic field (which sweeps out Michel positrons)
  - high resolution Liquid Xenon scintillation detector for γ rays





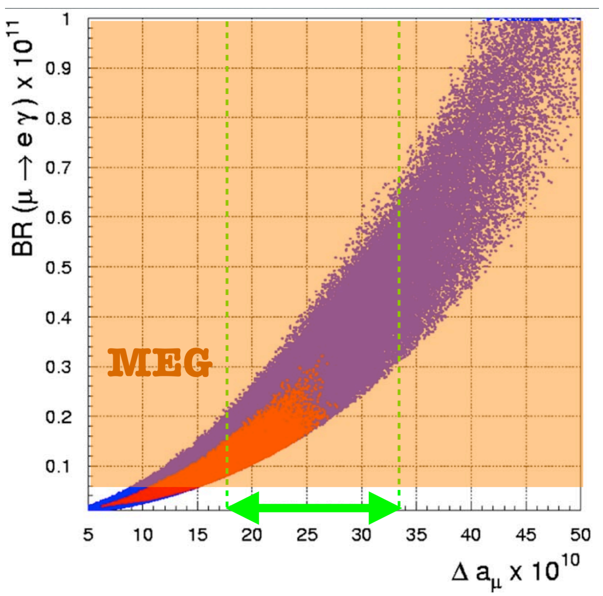
MEG Result and MEG-II

- Using data up to 2011:

  BR($\mu^+ \rightarrow e^+\gamma$)<5.7x$10^{-13}$ @90% C.L.

  J.Adam et al., PRL 110 (20), 201801

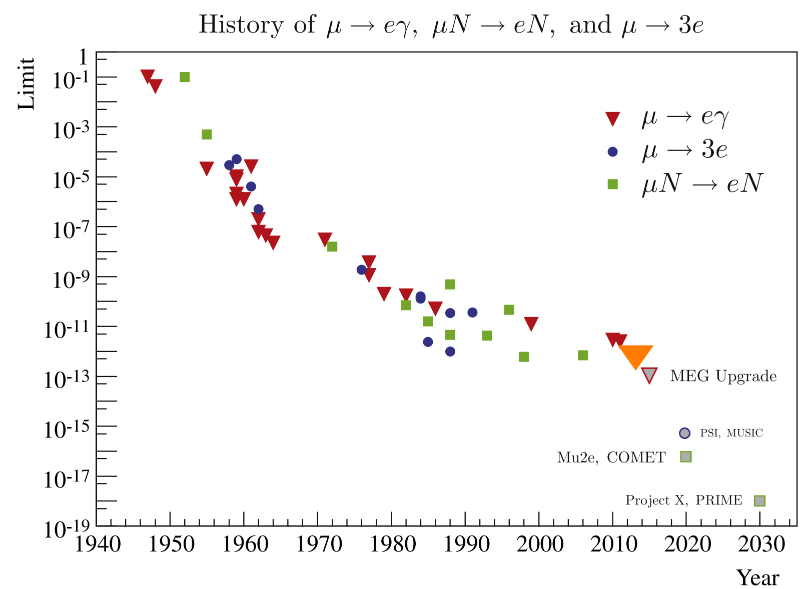
- Set constraints on NP models accommodating anomalous muon magnetic moment (G.Isidori, PRD 75, 115019 (2007))



- In 2012-2013 already collected more than twice the statistics (analysis in progress) but reaching MEG final sensitivity of 5x10^{-13}

- MEG-II upgrade with larger acceptance and better resolution for higher beam intensity promises to reach 5x10^{-14} in sensitivity.

R.H. Bernstein, P.S. Cooper / Physics Reports 532 (2013) 27–64



$\mu^- + N \rightarrow e^- + N$

- Two experiments, Mu2e @ FNAL and COMET @ J-PARC, have been proposed for searching $\mu \rightarrow e$ conversion in presence of a nucleus (Al)

- Present limit from SINDRUM-II @ PSI: $BR(\mu^+ \rightarrow e^+\gamma) < 5.7 \times 10^{-13}$ @90% C.L.

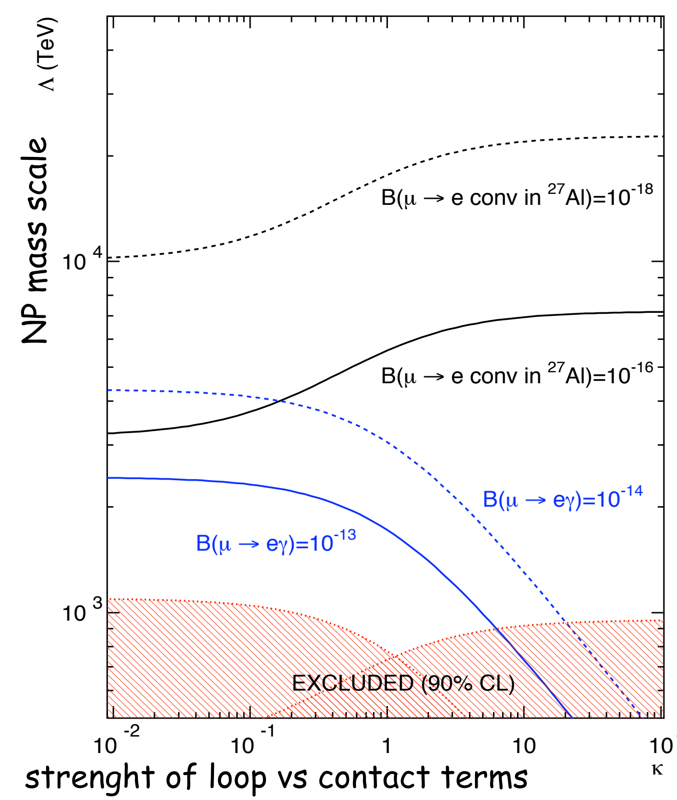
- Experimental signature is a mono-energetic electron of energy:

$$E_{\mu e} = m_\mu - E_b - E_\mu{}^2/2m_N$$
$$\approx 104.973 \text{ MeV (for Al)}$$

  where E_b is muonic binding energy ($E_b \propto Z^2 \Rightarrow$ low Z nucleus is preferred)

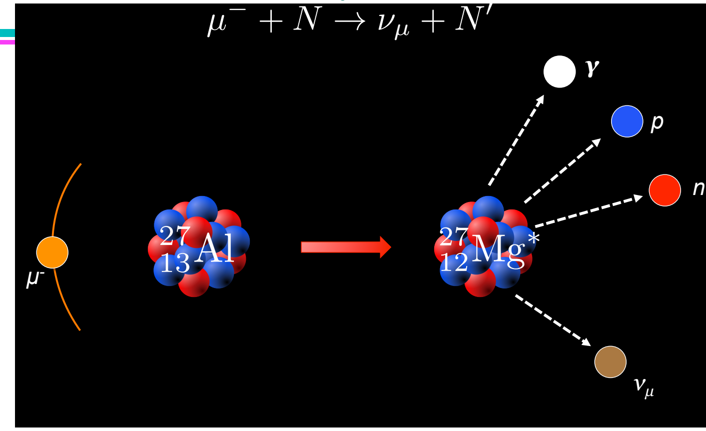
- New experiments promise an increase in sensitivity up to 10^{-17} and probe NP mass scale in the 10^3-10^4 TeV range

Govea and Vogel, arXiv:1303.4097v2 [hep-ph], 2013



- $B(\mu \rightarrow e^{conv}$ in $^{27}Al)$ curves are for Mu2e and Mu2e upgrade sensitivity
- $B(\mu^+ \rightarrow e^+\gamma)$ are for MEG and MEGII sensitivity

Mu2e Experimental Principle



- Mu2e measures the ratio:

$$R_{\mu e} = \frac{\Gamma[\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)]}{\Gamma[\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N+1)]}$$

for which details of nuclear wave function cancel

Muons “stop” in 1s state of target nucleus and emit X-rays with characteristic spectrum.

Muonic atom can undergo:

a) nuclear capture (61% in Al)

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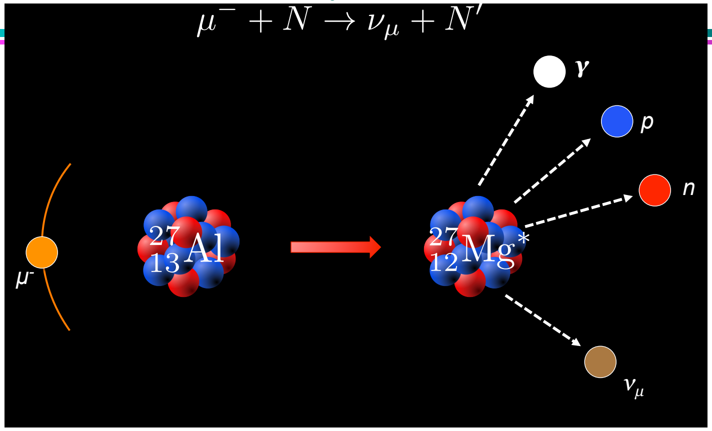

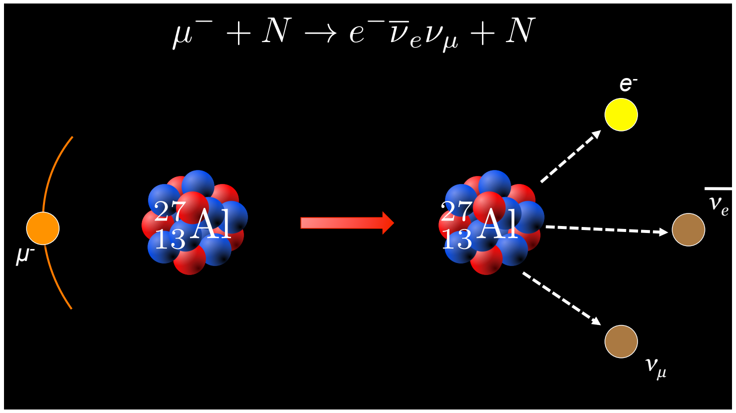

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Muonic atom can undergo:

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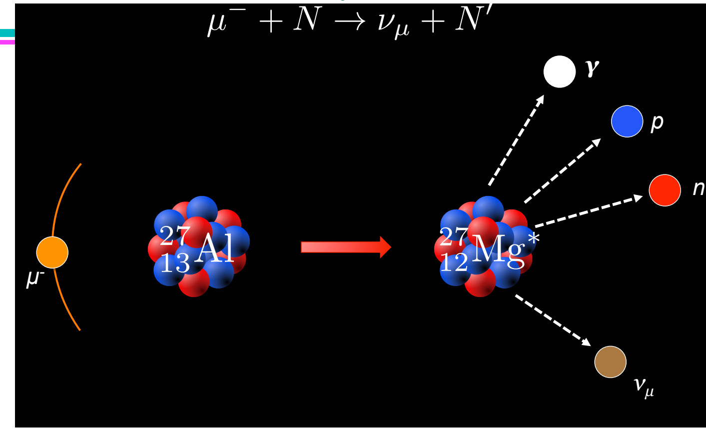
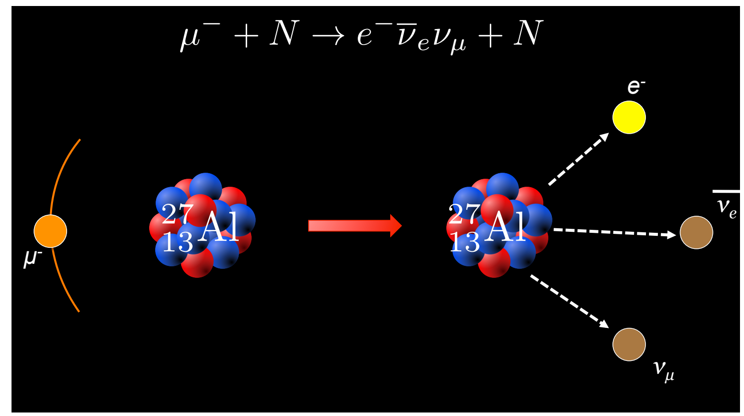
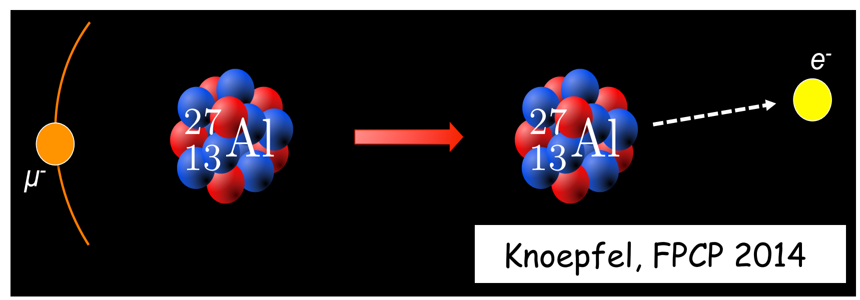
b) decay in orbit (DIO: 39%)
c) conversion.

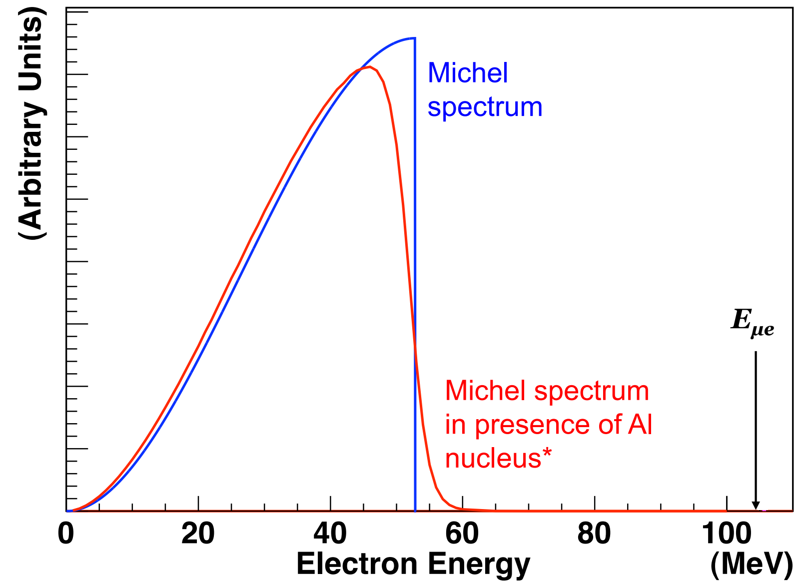






μ^- -> e^- conversion

- The energy distribution of electrons from DIO muon decay is given by a modified Michel spectrum:
  - presence of atomic nucleus momentum transfer stretches DIO electron energies up to signal energy $E_{\mu e}$
- Only 10^{-17} of DIO spectrum is within 1 MeV of energy endpoint
  - Limits maximum sensitivity of conversion experiments



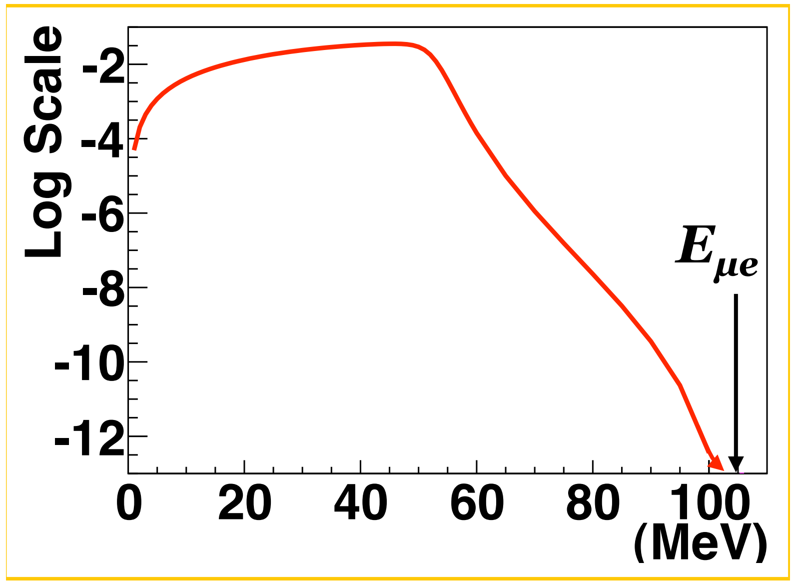
Energy resolution below 1 MeV and minimal energy loss for e^- are at premium.

background #1: Cosmic muon producing e in stopping target

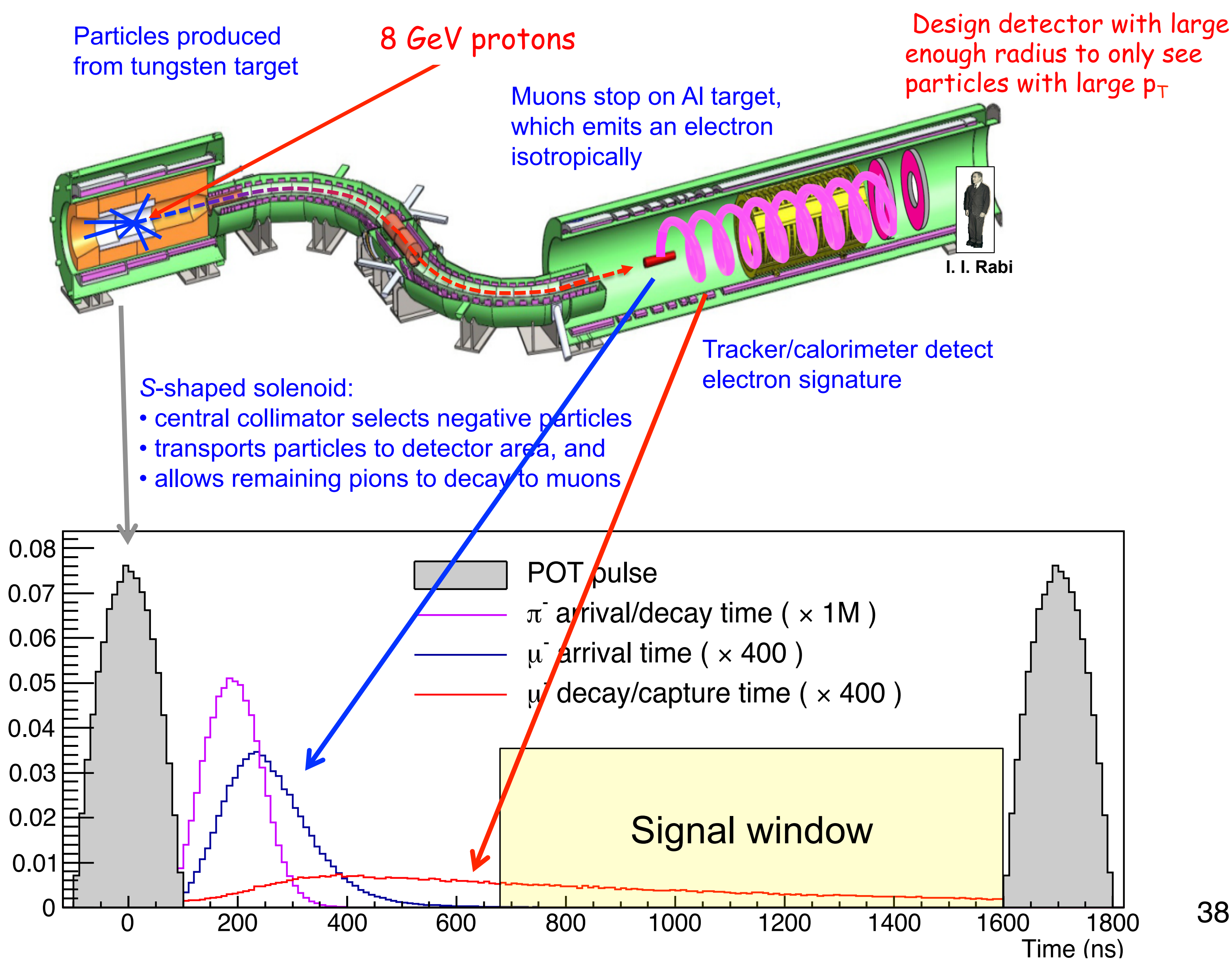
- Need cosmic veto

background #2: radiative pion capture $\pi + N \rightarrow \gamma + N$, with $\gamma \rightarrow e^+e^-$

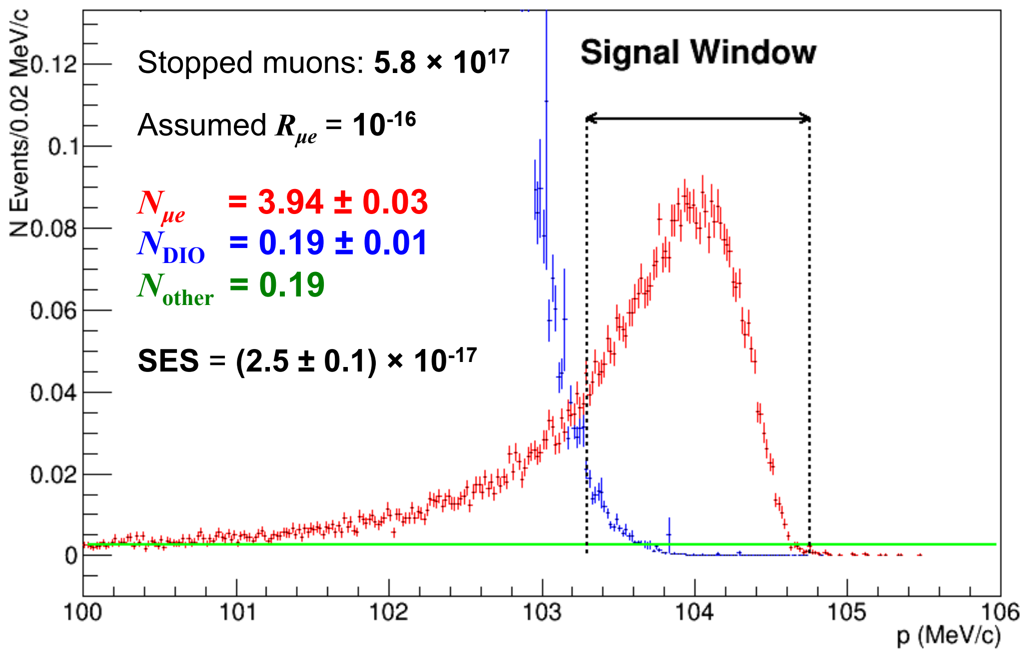
- Much faster decay: can be controlled with beam time structure.



Mu2e Experiment



Mu2e Experiment



- design goal SES: 2.5×10^{-17}
- Need at least 10^{18} Al-bound muons
- 3 yrs run with 10^{10} stopped muon per second

- Endorsed by P5.
- Construction of muon campus at FNAL to start this winter
-
- First run in 2019!

Summary

- Kaons and muons rare decays processes gives us a window on NP
- Golden kaon modes are being “attacked” by KOTO and NA62
- LFV and LNV searches in kaon decays show no NP smoking gun yet but they are helping eliminating some models
- Rare muon decays are pursued by multiple experiments, either mature or ready to go online soon

Summary

- Kaons and muons rare decays processes gives us a window on NP
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- Rare muon decays are pursued by multiple experiments, either mature or ready to go online soon
- Future looks yummy!

Backup slides

XXXIV Physics in Collision Symposium

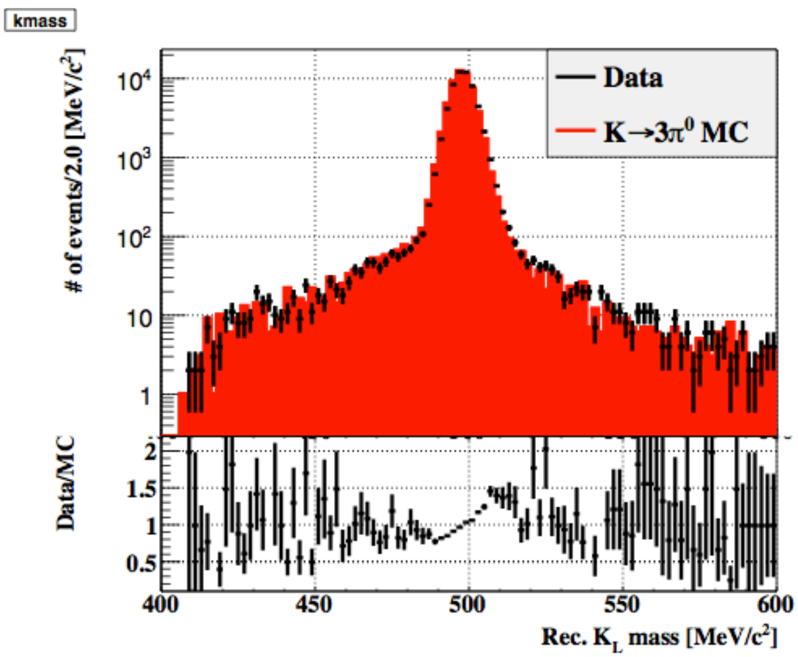
Bloomington, IN

Sept 19th, 2014

Detector Performance

Calorimeter response

Reconstruct K_L mass in $K_L \rightarrow \pi^0\pi^0\pi^0$ decays (BR≈20%) using events with 6 photon clusters in CsI calorimeter



Veto response

Reconstruct K_L mass in $K_L \rightarrow \pi^0\pi^0$ decays (BR≈8.6x10^{-4}) using events with 4 photon clusters before (top) and after (bottom) applying veto