Rare Decay Experiments: Exploring the Flavor Puzzle at the Precision Frontier

Douglas Bryman

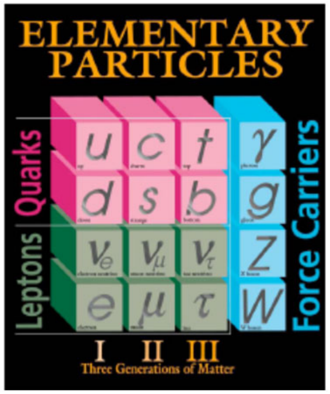
UBC and TRIUMF

Elementary Particle Physics: What are the basic forms of matter and forces in the Universe?

Known

Quarks

Leptons



+ Higgs (√)

Standard Model
- Strong
- Weak
- Electromagnetic

Gravity

Puzzles?

Ordinary matter (4%)
Dark Matter (22%)
Dark Energy (74%)
Matter – not anti-matter
3 copies of each particle
…

Approaches:

- High Energy Frontier: LHC and future colliders
- Cosmic Frontier: e.g. CMB; direct & indirect dark matter searches
- Precision Frontier: e.g. ***Rare decays***; CP violation; dipole moments

The Flavor Puzzle: 3 flavors of quarks and leptons

Quarks

u	c	t
d	s	b

Leptons

e	μ	τ
ν_e	ν_μ	ν_τ

Weak states ⇎ mass states; Quark, lepton flavors not conserved

Unexplained observations (no theory of flavor):

- Three ("identical") flavors/generations
  - Huge mass differences between and within the generations
  - Exceptionally small neutrino mass
- **Universality of lepton interactions**
- CP (T) violation
- Symmetry between lepton and quark sectors (GUT, scale?)

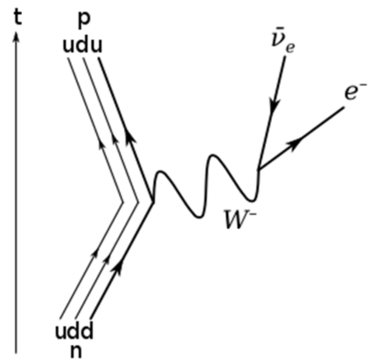
Rare Decay Strategies to Address Flavor

- Search for **forbidden** reactions.
- Measure **precisely calculated** reactions**.**

Even small new physics effects may be able to compete with reactions that are otherwise suppressed to low levels.

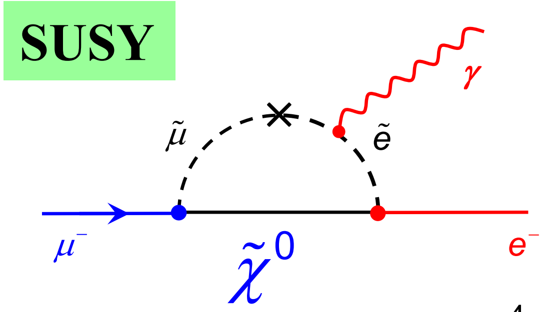
Rare Decays may shed light on high mass scales of new physics

Suppression of the rate of nuclear beta decay is due to exchange of the heavy weak force carrier W^-; m_W=80 GeV/c^2.



https://en.wikiversity.org/wiki/Beta_decay

Suppression of the rate of $\mu \to e\gamma$ could be due to exchange of very heavy particles e.g. related to supersymmetry; e.g. m_χ ~ 1000 TeV/c^2.



$$\mathrm{BR}(\mu^- \to e^-\gamma)\big|_{\mathrm{SUSY}} \quad \alpha \left(\frac{1}{m_\chi}\right)^4 \approx 10^{-14}$$

$$\mathrm{BR}(\mu^- \to e^-\gamma)\big|_{\mathrm{SM}} \sim 10^{-52}$$

Seeking Insight into the Flavor Puzzle

New Physics at High Mass Scales or Small Couplings

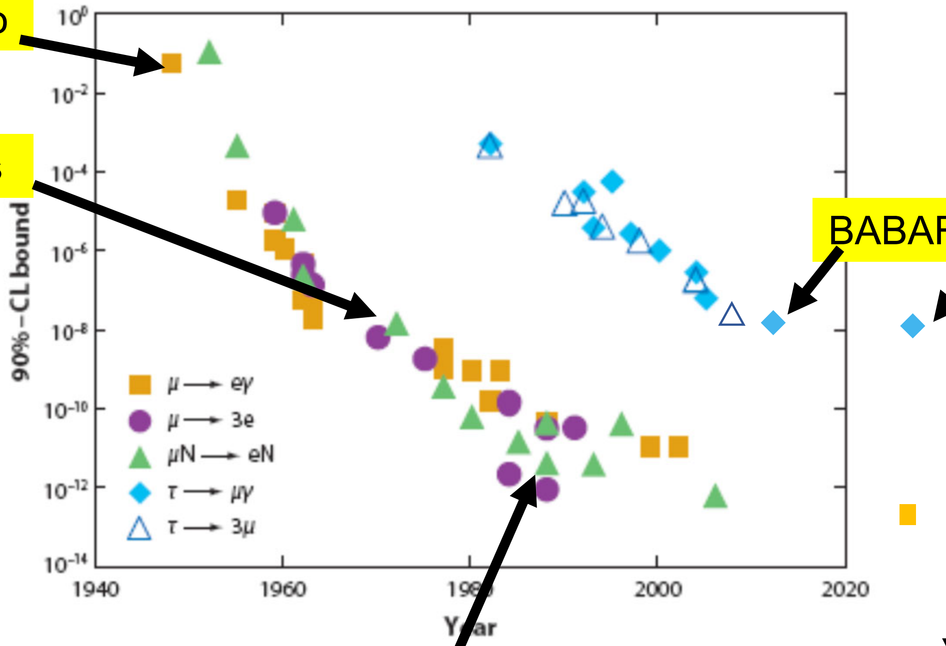
1. *High Sensitivity Searches* : ***New physics if seen.*** ***Experiments limit how far we can go.***	$\mu \to e\gamma, 3e$ **Lepton Flavor Violation** $\mu^- N \to e^- N$ $\tau \to e\gamma, \mu\gamma$ $K_L^0 \to \mu e$ $\beta\beta_{0\nu}$ Lepton Number Violation e, μ, n edm CP/T Violation
2. *High Precision Measurements:* ***New physics if deviations seen from precise SM predictions.*** ***Theory limits how far we can go.***	$(g-2)_\mu$ Higher order effects $\frac{\pi \to e\nu}{\pi \to \mu\nu}$ $\frac{\tau \to e\nu\bar{\nu}}{\tau \to \mu\nu\bar{\nu}}$; $\frac{B \to D^*\tau\nu}{B \to D^* l\nu}$ **Universality** $K^+ \to \pi^+ \nu\bar{\nu},\ K_L^0 \to \pi^0 \nu\bar{\nu}$ **SM Suppressed** $B \to \mu\mu, b \to s\gamma, \ldots$

History of **Lepton Flavor Violation** Experiments

90% CL

Hincks, Pontecorvo

D.B. Thesis



BABAR/Belle

TRIUMF TPC (1987)

New experiments coming.

Updated from Marciano, Mori, Roney 2010

HIgh Sensitivity: Charged Lepton Flavor Violation

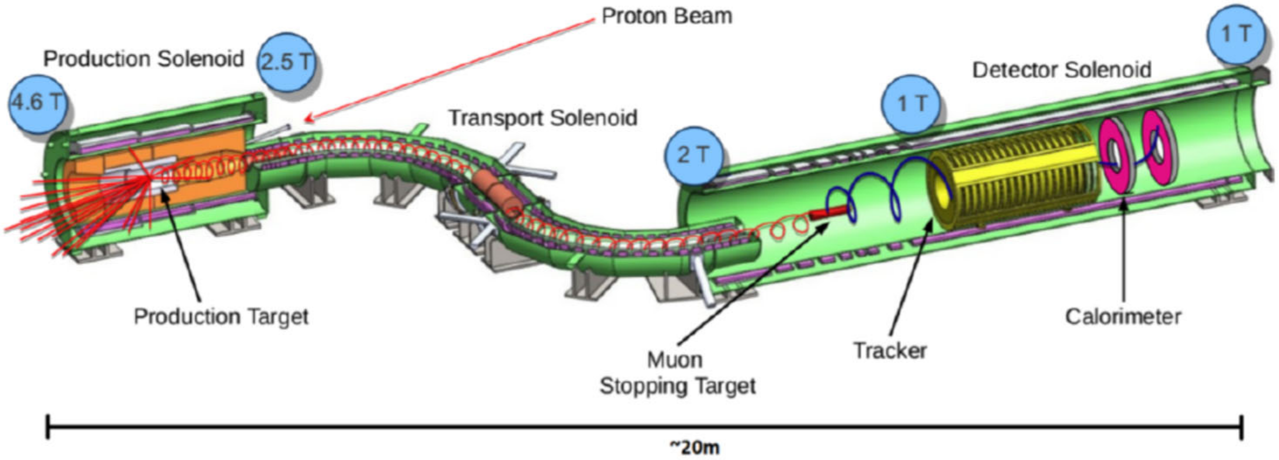
Next Generation Searches aim at improvements of 10,000 x.

$\mu^- Al \rightarrow e^- Al$

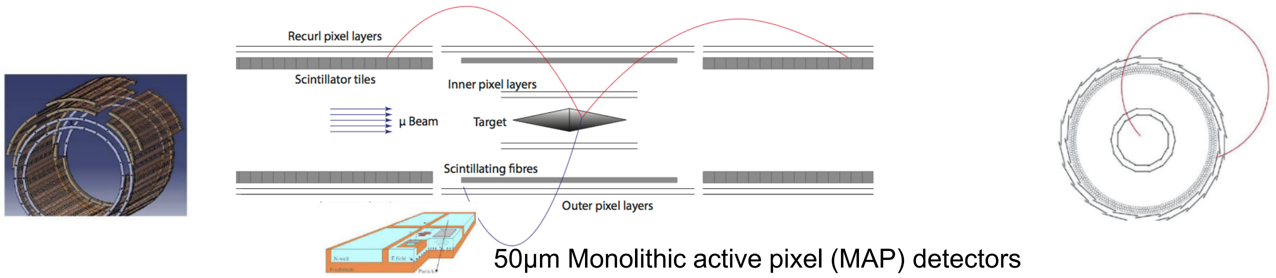
μ2E Experiment at FNAL

Sensitivity goal: <8 x 10^{-17}

(Similar to ***COMET*** at JPARC (Japan))



$\mu \rightarrow 3e$ at PSI: Goal $<10^{-16}$



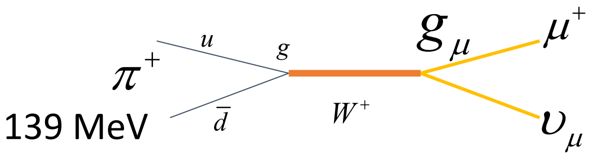
50μm Monolithic active pixel (MAP) detectors

$\tau \rightarrow e / \mu \ \gamma$ at Belle II

High Precision Test of SM Lepton Universality: Pion Decay

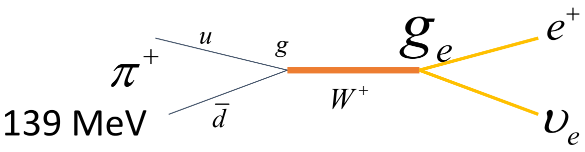
$$\pi^{+} \rightarrow \mu^{+} \nu_{\mu}$$

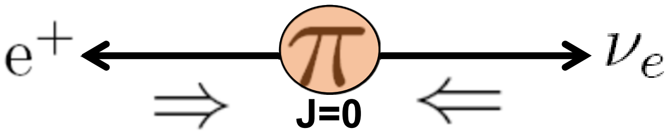
Classic SM process
1st Order Weak Interaction



$$\pi^{+} \rightarrow e^{+} \nu_{e}$$

SM helicity Suppression
→ 1 in 10 thousand pion decays.





High Precision Test of SM Lepton Universality: Pion Decay

SM Theory

$$R_{e/\mu}^{th} = \frac{\Gamma(\pi \rightarrow e\nu + \pi \rightarrow e\nu\gamma)}{\Gamma(\pi \rightarrow \mu\nu + \pi \rightarrow \mu\nu\gamma)} = 1.23524(15)x10^{-4} \quad (\pm 0.0012\%)$$

Cirigliano,Rosell 2007

The most precise SM weak interaction observable involving quarks!

Experiment: PDG (TRIUMF PIENU)

$$R_{e/\mu}^{\exp} = \frac{\Gamma(\pi \rightarrow e\nu + \pi \rightarrow e\nu\gamma)}{\Gamma(\pi \rightarrow \mu\nu + \pi \rightarrow \mu\nu\gamma)} = 1.2327 \pm 0.0023x10^{-4} \quad (\pm 0.18\%)$$

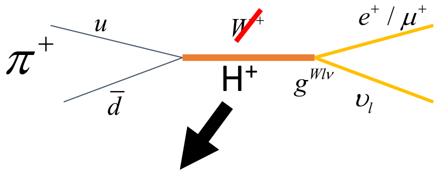
Electons and muons have same weak strength: $\frac{g_\mu}{g_e} = 1.0010 \pm 0.0009 \quad (\pm 0.1\%)$

High Precision Pion Decay

Sensitive to high mass scales and new physics

Example: Non-standard Higgs couplings e.g. Pseudoscalar or Scalar interactions

$$R_{e/\mu} = \frac{\Gamma(\pi \to e\nu + \pi \to e\nu\gamma)}{\Gamma(\pi \to \mu\nu + \pi \to \mu\nu\gamma)}$$



$W^+ \to H^+$

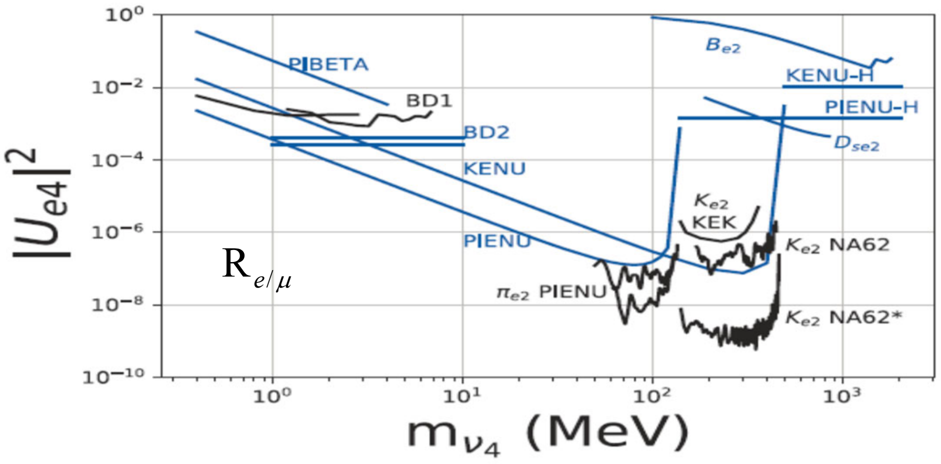
$80GeV \to 100TeV$

0.01% measurement sensitive to $m_{H^+} \sim 300$ TeV

Example: Addition of heavy neutrinos

$$R_{e/\mu} = \frac{\Gamma(\pi \to e\nu + \pi \to e\nu_H)}{\Gamma(\pi \to \mu\nu + \pi \to \mu\nu_H)}$$

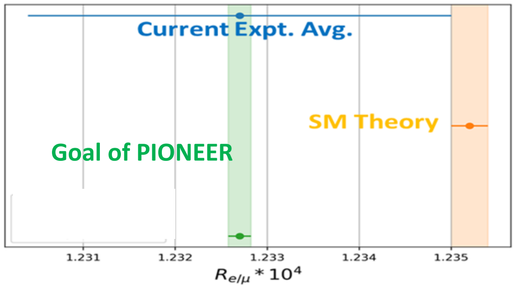
$$\nu_\ell = \sum_{i=1}^{3+n_s} U_{\ell i}\nu_i$$



DB, Shrock,Phys.Rev.D 100 (2019) 073011

PIONEER: Next Generation Lepton Flavor Universality test aims at 10 x precision.

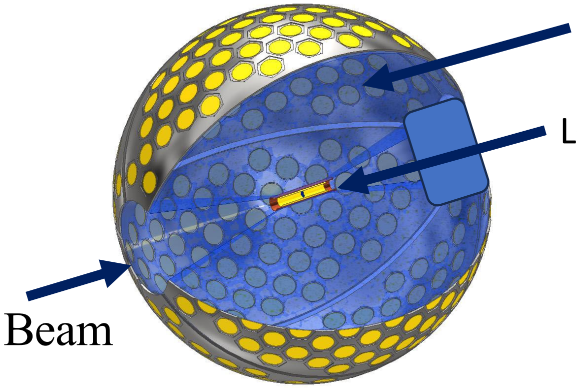
$$R_{e/\mu} = \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))} \Rightarrow \pm 0.01\% \text{ precision}$$



- Paul Scherrer Institut; most intense π beam
- LGAD (Si strip) Tracking target "ATAR"; $\pi \to e$ and $\pi \to \mu \to e$
- Scintillating calorimeter (LXe or LYSO)

Also $\pi^+ \to \pi^0 e^+ \nu$ (±0.05%)

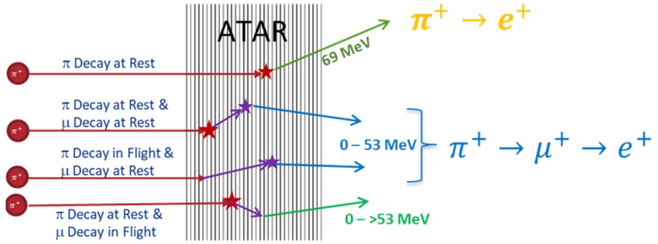
$\pi^+ \to e/\mu\ \nu_H, \ldots$ $10x$



Calorimeter (25 X0)

LGAD Si strip tracking target (ATAR)

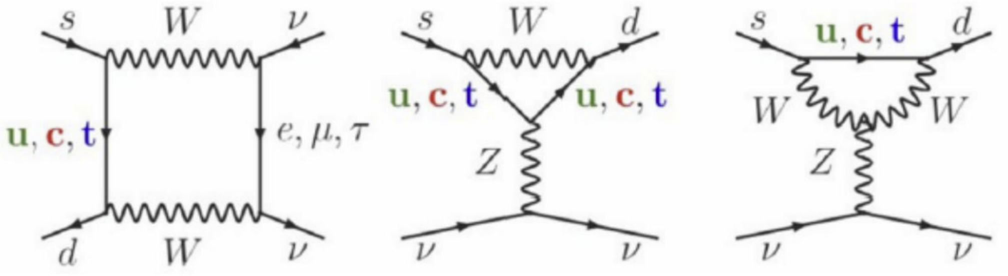
π^+ Beam



High Precision Flavor tests of SM with KAONS

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

$$K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$$



3 quark flavors
3 neutrino flavors
Charged and neutral bosons

- ∗Suppressed 2nd order weak flavor-changing neutral currents
- ∗Sensitive to CP-violating and CP- conserving effects

  $K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$ is purely CP-violating
- ∗Hadronic matrix elements from $K \rightarrow \pi l \nu$
- ∗Highly accurate SM predictions ($\pm 5\%$) limited by quark mixing (CKM) parameters

$$B^{SM}(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = 8.60 \pm 0.42 x 10^{-11} \qquad B^{SM}(K_L^0 \rightarrow \pi^0 \nu\bar{\nu}) = 2.94 \pm 0.15 x 10^{-11}$$

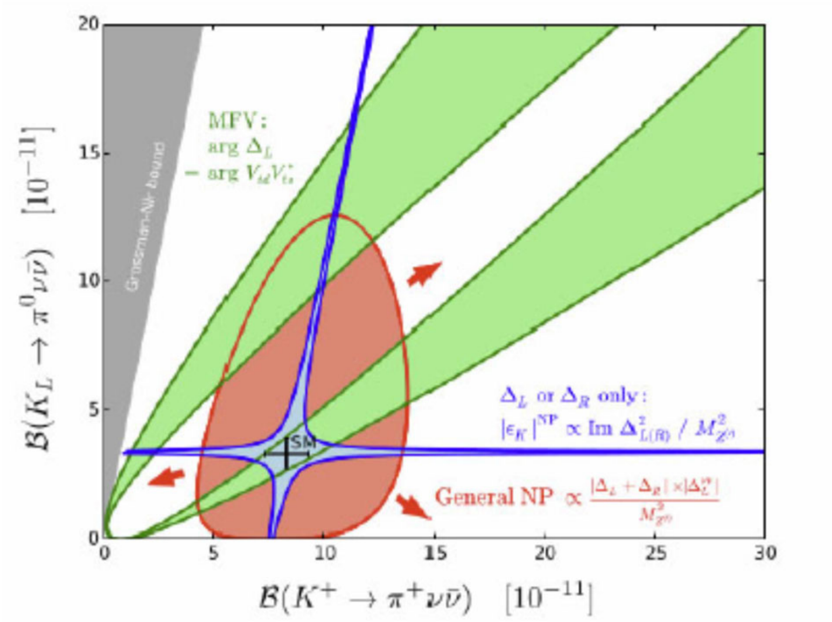
A. J. Buras arXiv:2307.15737v2 [hep-ph] 16 Sep 2023

$K \to \pi\nu\bar{\nu}$: High Sensitivity to New Physics

Sensitivity to new physics at high mass scales
complementary to B physics and lepton flavor violation

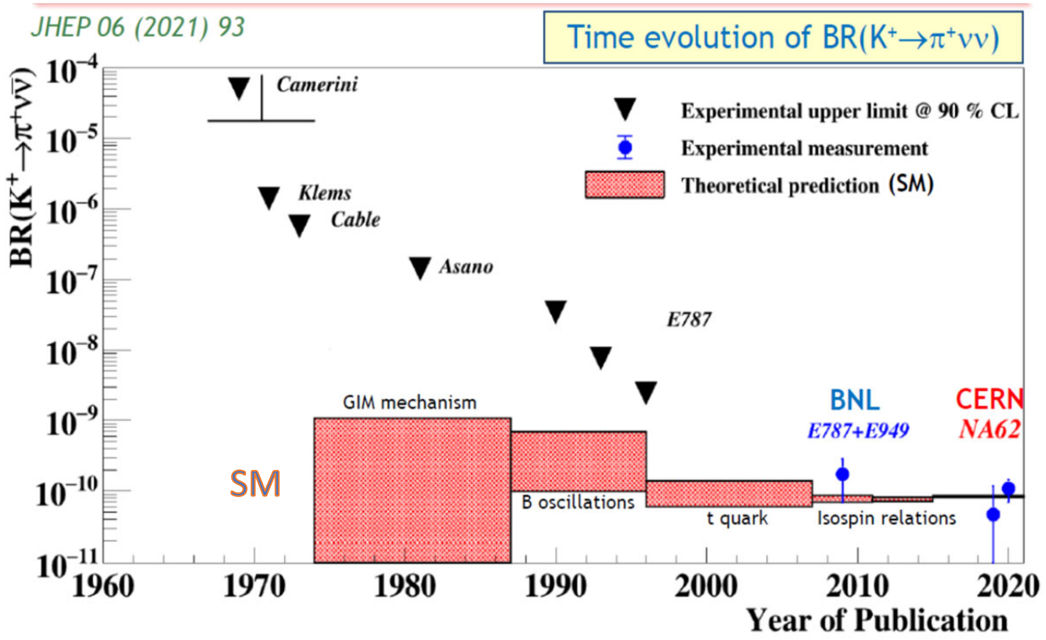
Extra Dimensions as a Theory of Flavor,Z’, Dark Sector, Sterile Neutrinos, Leptoquarks, MFV…

$$\mathrm{B}(K_L^0 \to \pi^0\nu\bar{\nu}) \text{ vs. } \mathrm{B}(K^+ \to \pi^+\nu\bar{\nu})$$



[Buras et al., JHEP11 (2015) 166]

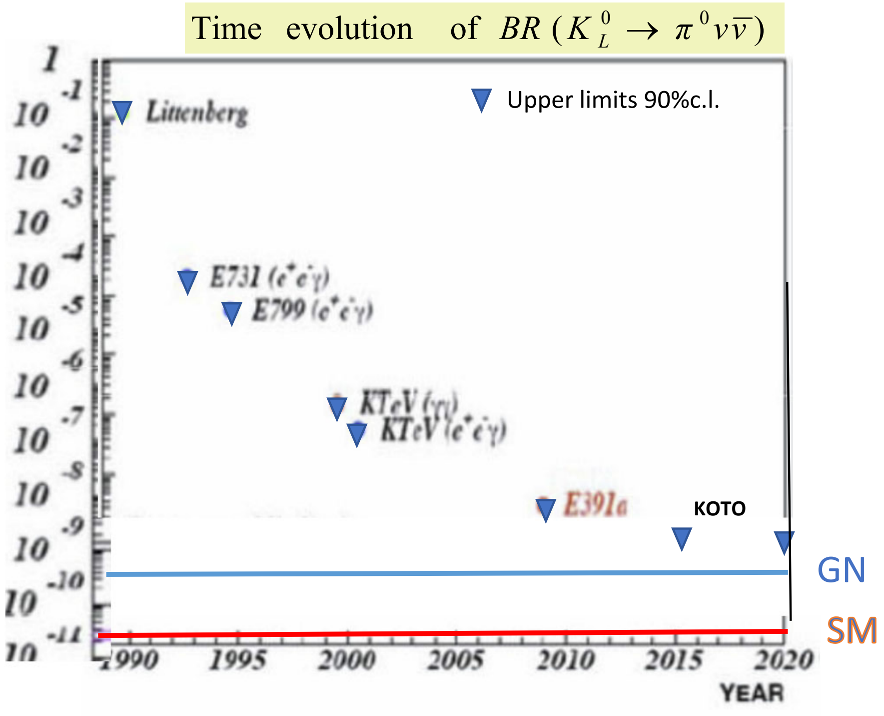
$K \to \pi\nu\bar{\nu}$ Experiment Histories



$E787 + E949: BR(K^+ \to \pi^+\nu\bar{\nu}) = 1.73^{+1.15}_{-1.05}\ \text{x}10^{-10}$

Prior to NA62, $K^+ \to \pi^+\nu\bar{\nu}$ experiments used stopped K^+.

NA62 uses 75 GeV/c K^+ decays-in-flight.



$K_L^0 \to \pi^0\nu\bar{\nu}$ limit from isospin (GN):

$BR(K_L^0 \to \pi^0\nu\bar{\nu}) < 4.4\,x\,BR(K^+ \to \pi^+\nu\bar{\nu})$

$< 4.6\,x\,10^{-10}$

(Grossman, Nir (1997))

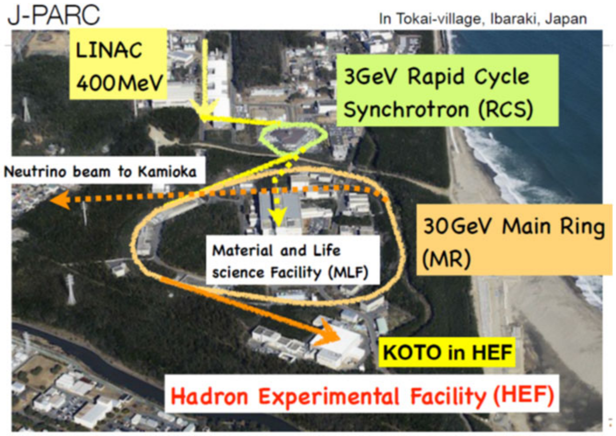
Current $K \to \pi\nu\bar{\nu}$ Experiments

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

NA62

J-PARC $K_L^0 \to \pi^0\nu\bar{\nu}$

KOTO



$K \to \pi\nu\bar{\nu}$ Experiments

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

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

Experimentally weak signatures: potential backgrounds may exceed signals by $>10^{10}$

Strategies

Determine everything possible about the K^+ and π^+

- Particle ID better than 10^6 ($\pi^+/\mu^+/e^+$)

Eliminate events with extra charged particles or ***photons* - *need highest efficiencies.***

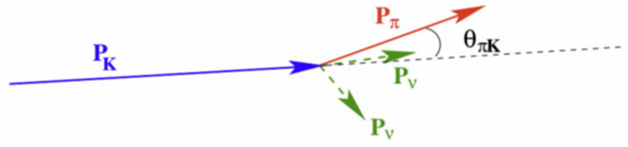
Suppress backgrounds below the expected signal

- Predict backgrounds *from data*
- Use "Blind analysis" techniques including blinded control regions

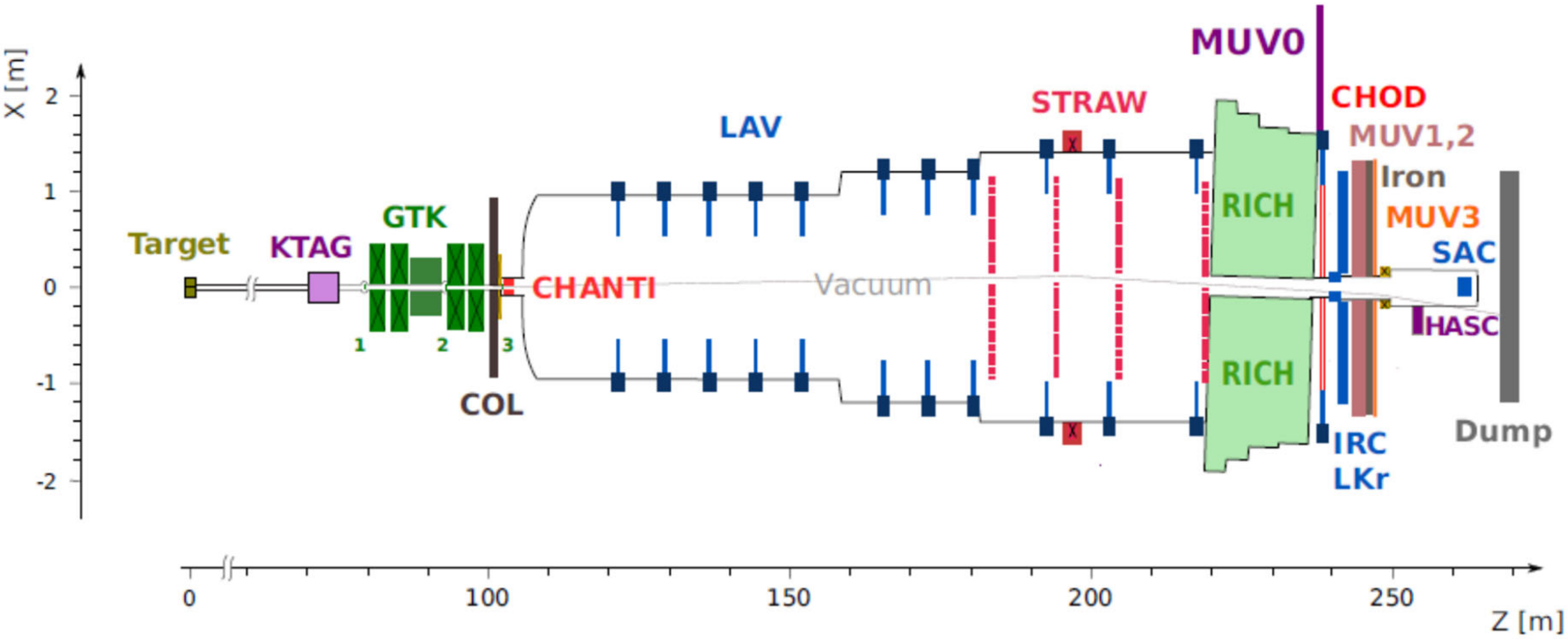
"…**when you have eliminated the impossible, whatever remains, *however improbable*, must be the truth**? "

Sherlock Holmes in The Sign of the Four (1890)

- Hadron Beam   75 GeV/c (± 1%)
- 6% kaons, 24% protons, 70 % pions
- Average beam rate (2018): 500 MHz



Pion momentum range: [15,45] GeV/c



Measurements :

K^+ momentum

π^+ momentum, energy

Particle ID : π, μ, e

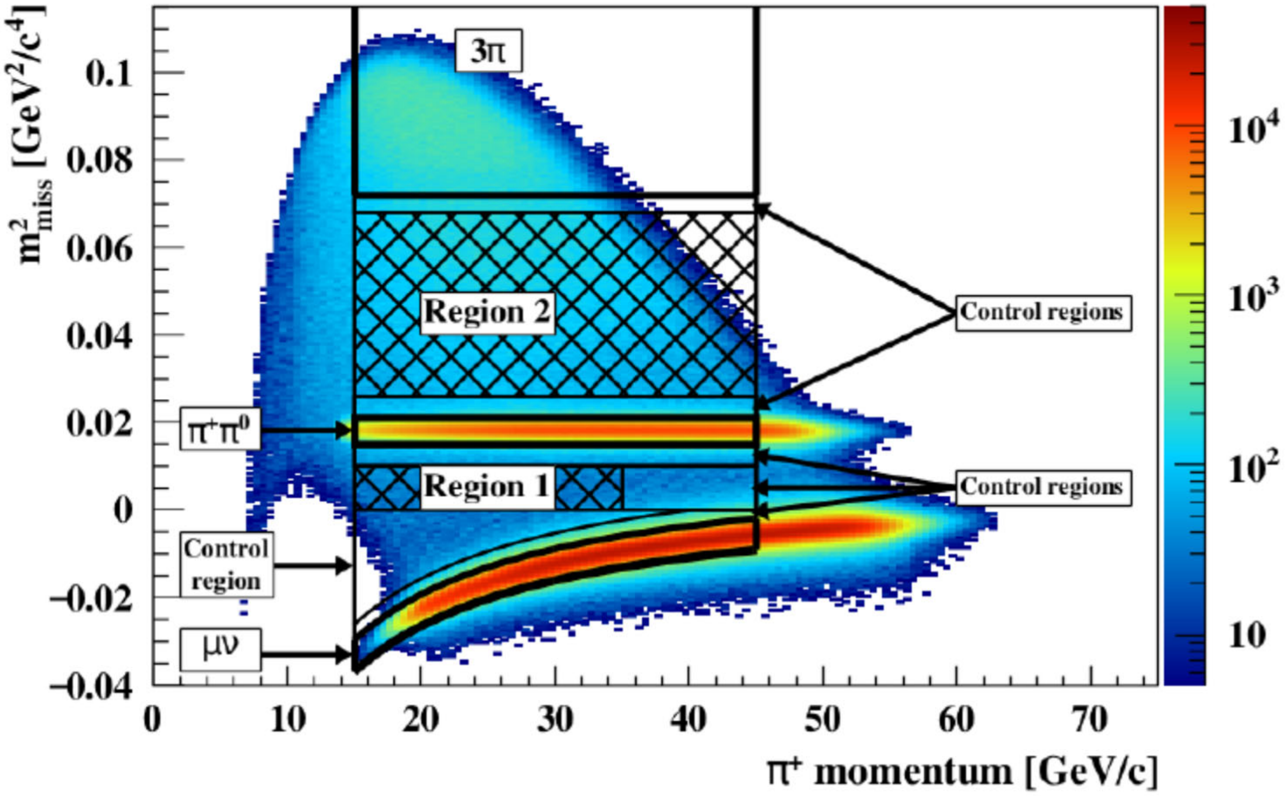
RICH, Calorimeters

Photon Vetos

LKr, LAV, others

JINST 12 (2017) P05025
JHEP 06 (2021) 093

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ m^2_{miss} vs. P_{π^+}



Key Techiques

- **Main kinematic variable: missing mass:**

$$m^2_{miss} = (P_K - P_\pi)^2$$

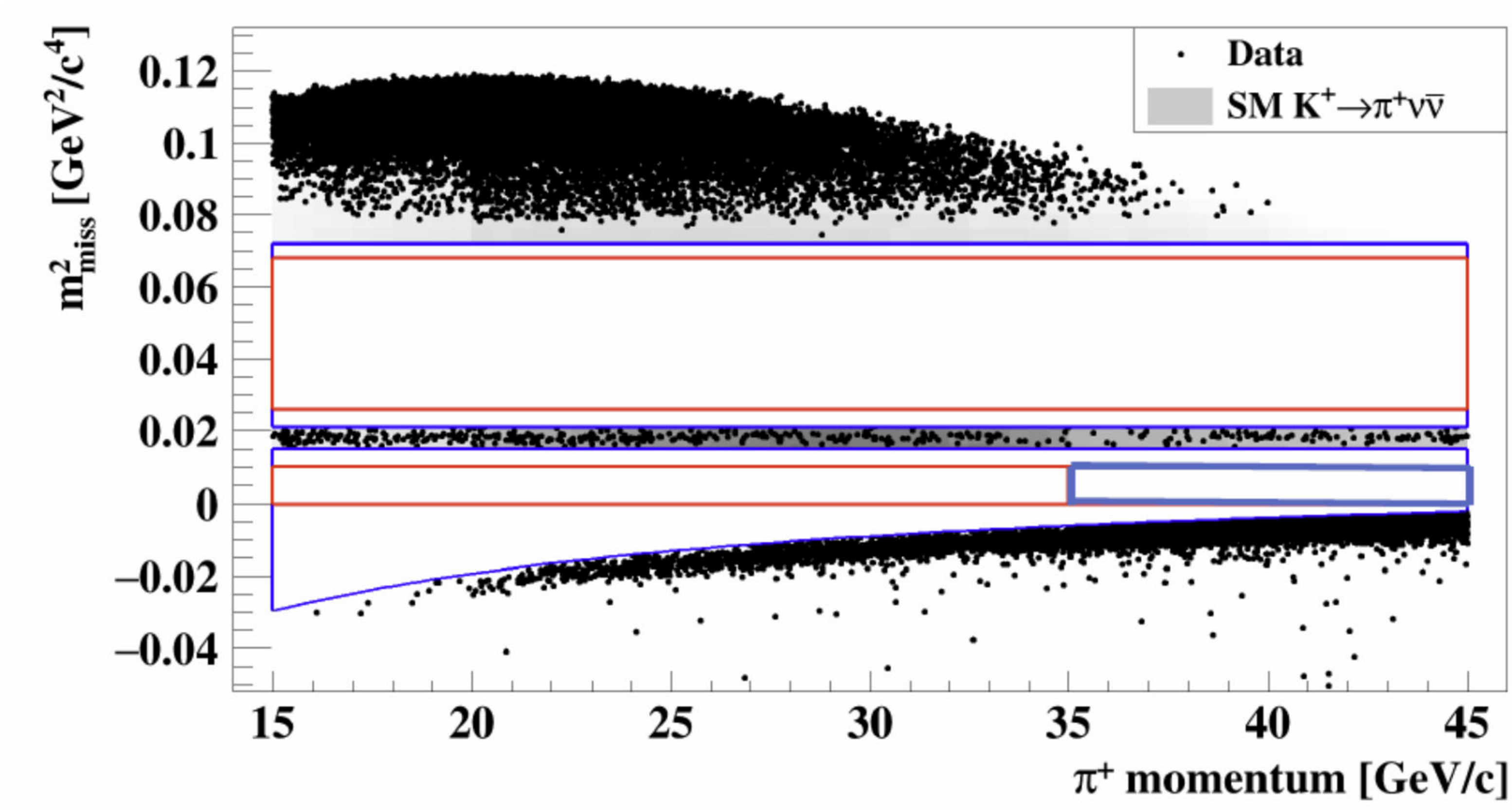
- Kinematic regions above/below $\mathrm{K}_{\pi 2}$
- Signal and contol regions blinded

Main Backgrounds

- Random K,π accidentals
- $K^+ \rightarrow \pi^+\pi^0$ ($K_{\pi 2}$)
- $K^+ \rightarrow \mu^+\nu$ ($K_{\mu 2}$)
- $K^+ \rightarrow \pi^+\pi^- e^+\nu$ (K_{e4})
- $K^+ \rightarrow \pi^+\pi^+\pi^-$ ($K_{\pi 3}$)

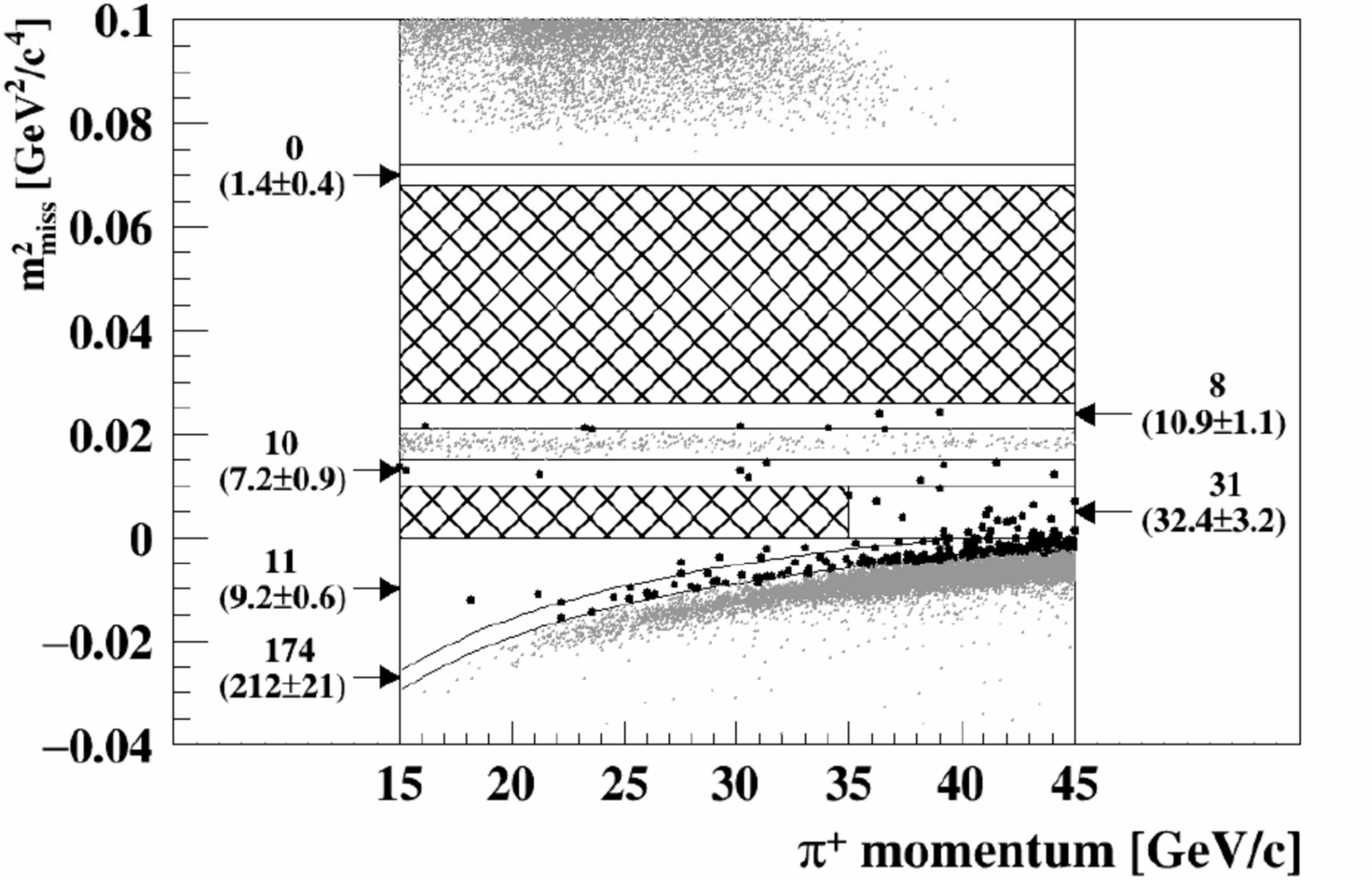
2018 Data Set

Control (blue) and signal (red) regions **blinded**



2018 Data Set

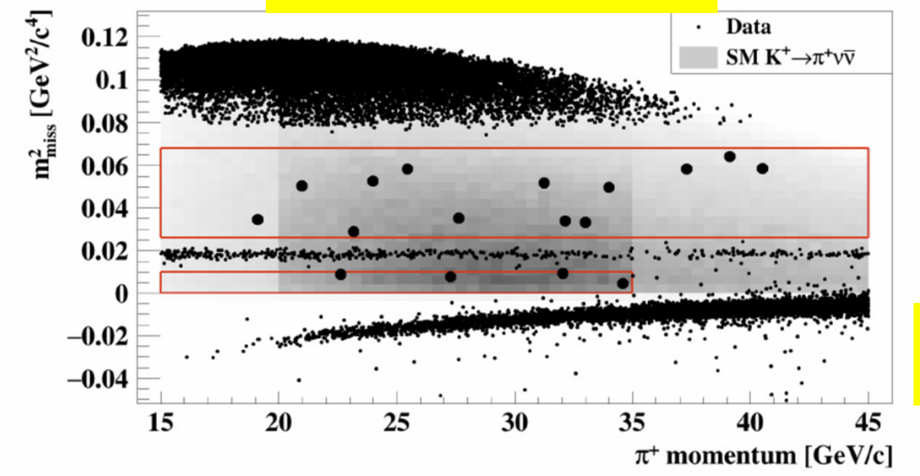
Observed (expected) events in control regions. Signal regions **blinded**



Opening signal regions

2018 Data Set

Observed events : 17



Combined Run 1 Data

Events observed: 20

Background expected: $N^{exp}_{bkg} = 7.03^{+1.05}_{-0.82}$

Single event sensitivity : $SES = (0.839 \pm 0.053)x10^{-11}$

$$BR^{NA62}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4} \pm 0.9_{syst})x10^{-11}$$

Background only p - value : $3.4x10^{-4}$

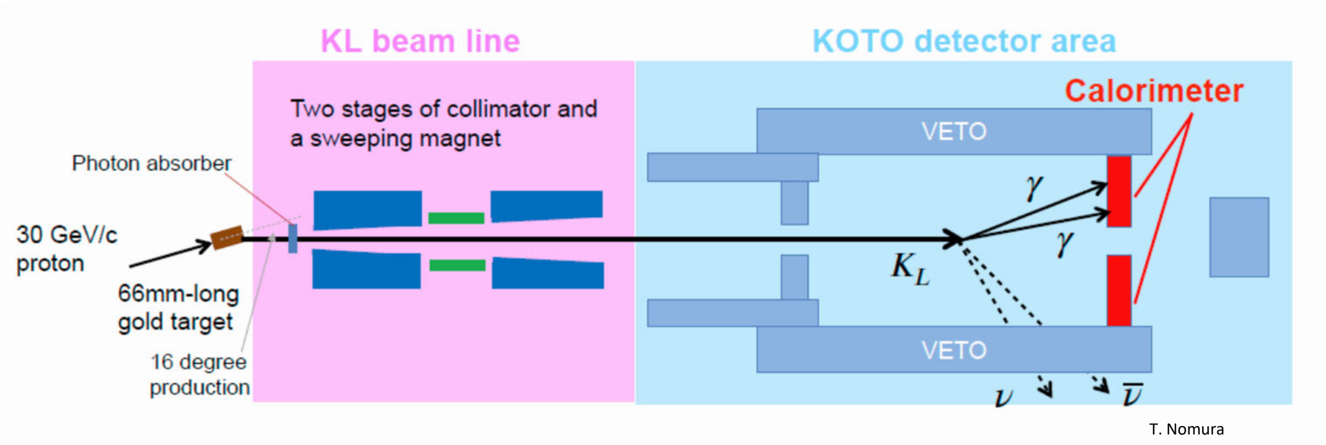
Significance : 3.4σ

$$BR^{SM} = 8.60 \pm 0.42x10^{-11}$$

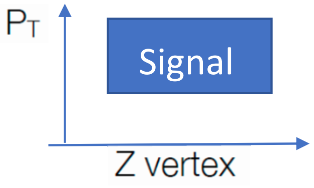
JHEP 06 (2021)093

JPARC KOTO: Search for $K_L^0 \to \pi^0 \nu\bar{\nu}$

Measurement Principles



T. Nomura



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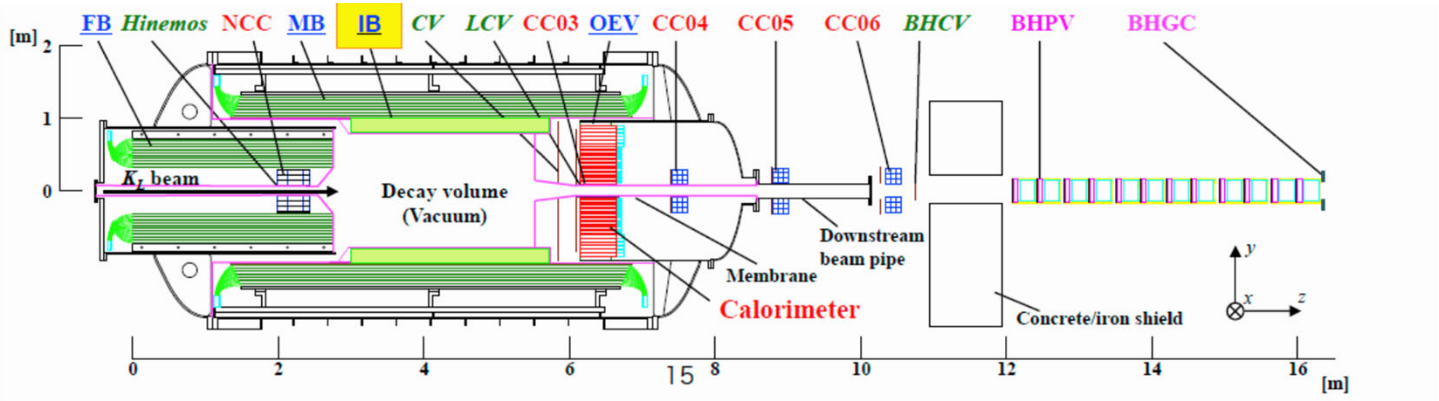
Signal: “2γ+Nothing+Pt”

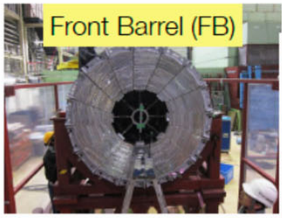
- Assume 2γ from π^0,
- Calculate z vertex on the beam axis
- Calculate π^0 transverse momentum P_t
- Invariant masss $m^2(\pi^0)=2E_1E_2(1-\cos\theta)$
- Collimated beam → high resolution P_t

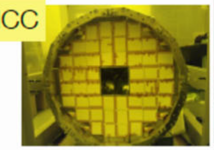
Backgrounds:

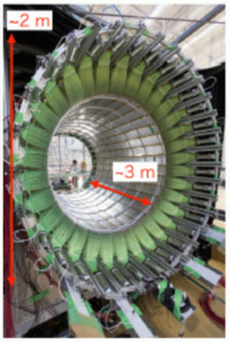
- Kaon decays
- π^0/η production from neutrons
- Hadron cluster background

Detector



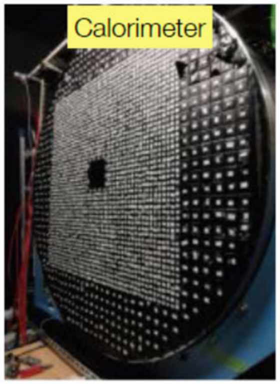

Front Barrel (FB)


NCC

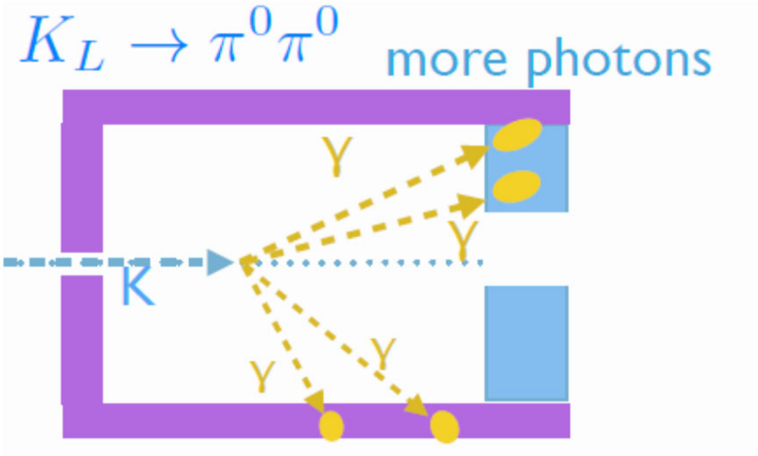

Inner Barrel (IB)


Main Barrel (MB)


Charged Veto (CV)

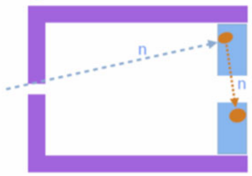

Calorimeter

Example Background Mechanisms



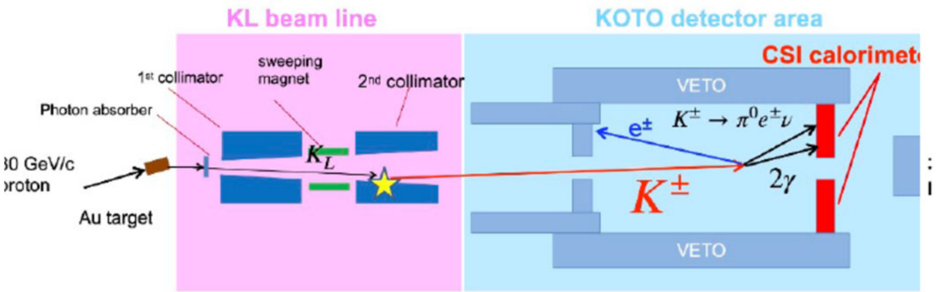
Hadron cluster background

Neutron make 2 clusters through hadronic interactions

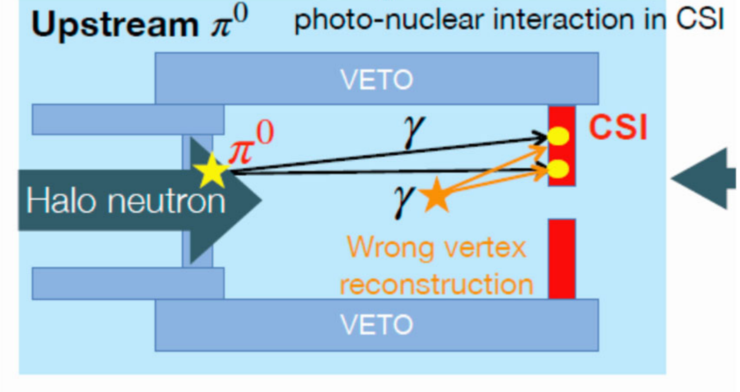


- Discriminate “neutron cluster” from “photon cluster”

K+ Background



Wrong E measurement due to photo-nuclear interaction in CSI



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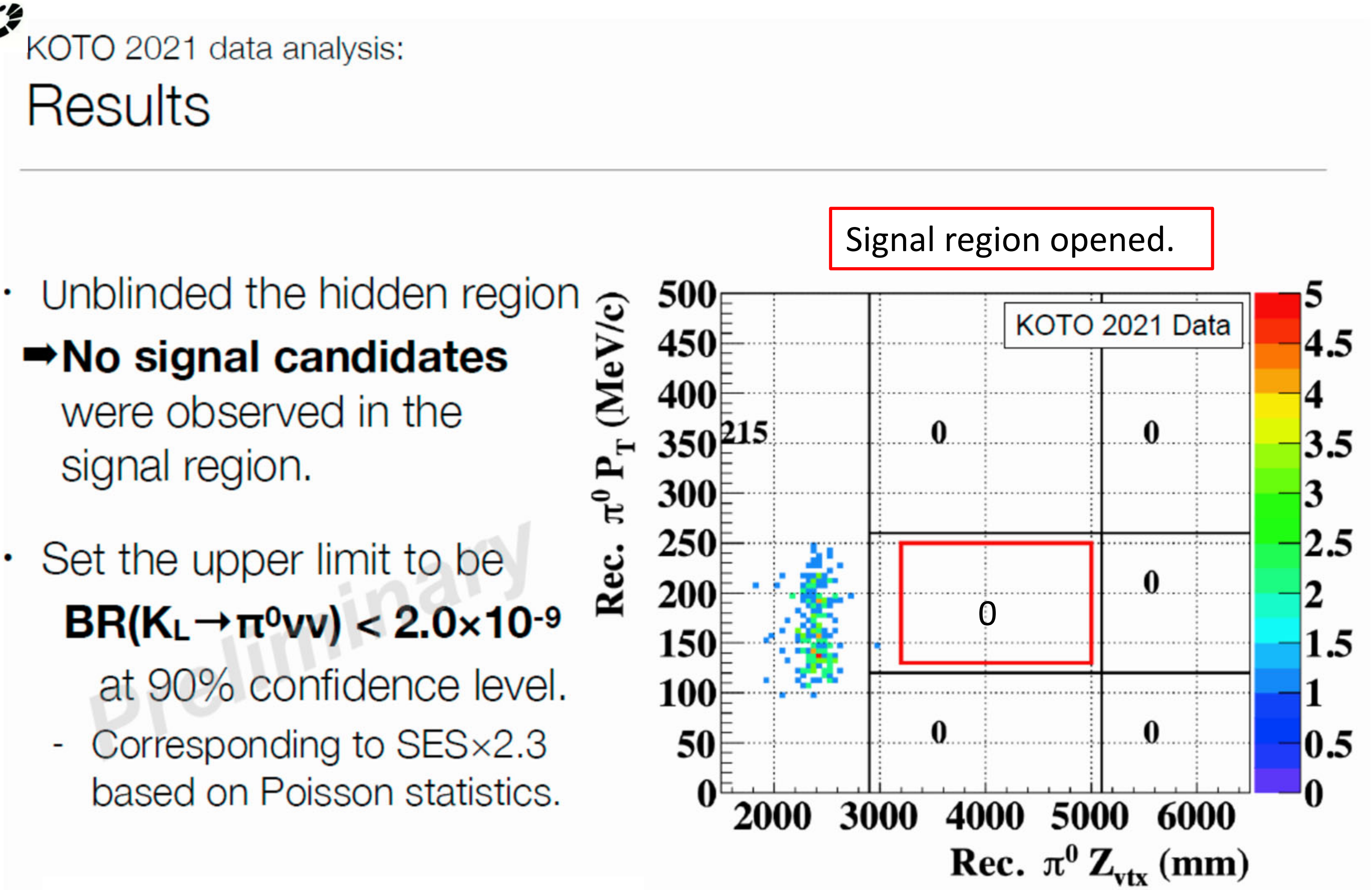

KOTO 2021 data analysis:

Results

- Unblinded the hidden region
  ➡No signal candidates were observed in the signal region.
- Set the upper limit to be
  $BR(K_L \to \pi^0 \nu\nu) < 2.0\times10^{-9}$
  at 90% confidence level.
  - Corresponding to SES×2.3 based on Poisson statistics.

Signal region opened.

$$BR^{SM} = 2.94 \pm 0.15x10^{-11}$$

T. Nomura

Conclusions: Rare decays probing the Lepton Flavor Puzzle

- **Rare π, μ, K, B and τ decays have unique and important roles to play in the search for new physics involving exotic effects like *Lepton Flavor Universality and Lepton Flavor Violation* --- especially sensitive to very high mass scales.**

- **New π/K/B/τ results expected from PIENU, PEN, NA62, KOTO, and LHCb, BESSIII, BELLE-II…. Important connections with searches for sterile neutrinos/dark sector particles, high mass scale physics, and Lepton Flavor/Number Violation tests from Mu2e, COMET, μ3e, 0νββ.**

- **Next generation pion decay experiment PIONEER aims at order of magnitude improvements in high precision for measurements of π →eν and pion beta decay to provide unique new information on Lepton Flavor Universality and quark mixing matrix (CKM) unitarity.**