ORKA: The Golden Kaon Experiment
Physics Breadth

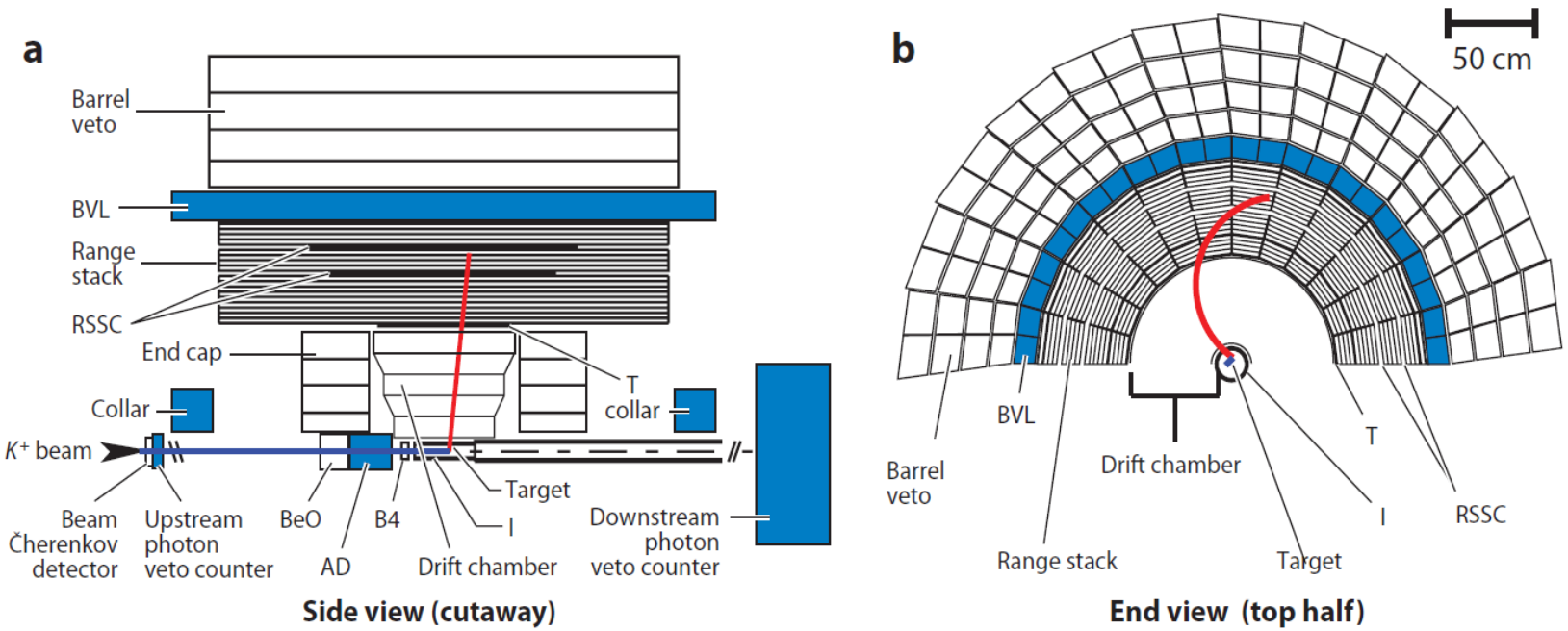
Elizabeth Worcester (BNL)
for the ORKA collaboration
June 19, 2012

Photo: Life of Sea blogspot

ORKA: The Golden Kaon Experiment

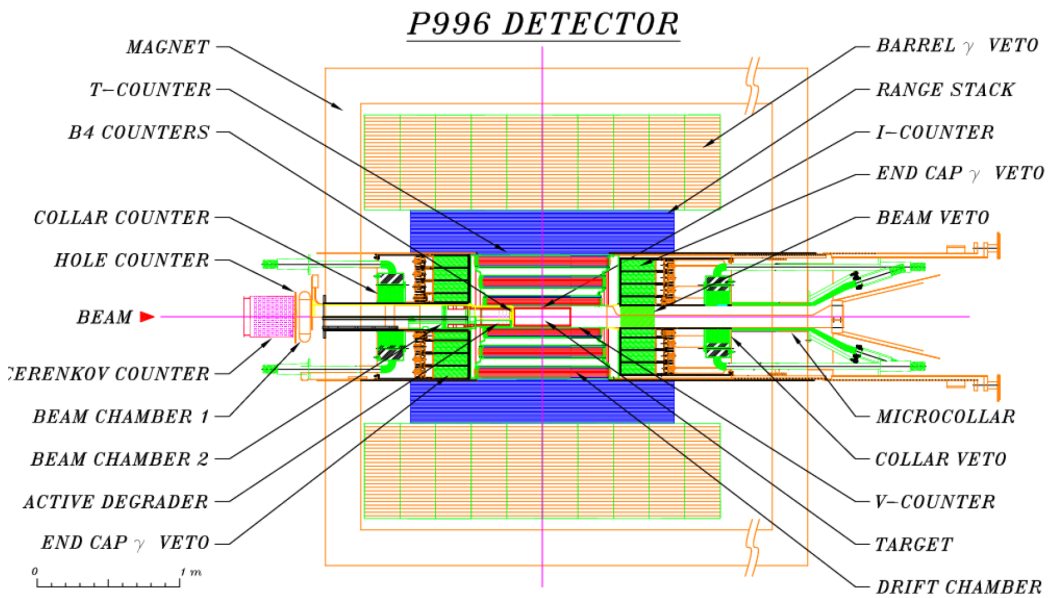
- Primary physics
  - Precision measurement of $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ BR with ~1000 expected events (SM) at FNAL MI
  - Expected BR uncertainty matches expected Standard Model uncertainty
  - Sensitivity to new physics at and beyond LHC mass scale
- 4th generation detector building on BNL E787/E949
- Projected cost ~$53M
- See David Jaffe's talk yesterday (June 18) for details of experiment and primary physics

BNL E787/E949
Stopped Kaon Technique



- K^+ decays at rest in the stopping target
- Decay π^+ track momentum analyzed in drift chamber
- Decay π^+ stops in range stack, range and energy are measured
- Range stack STRAW chamber provides additional π^+ position in range stack
- Barrel veto + End caps + Collar provide 4π photon veto coverage

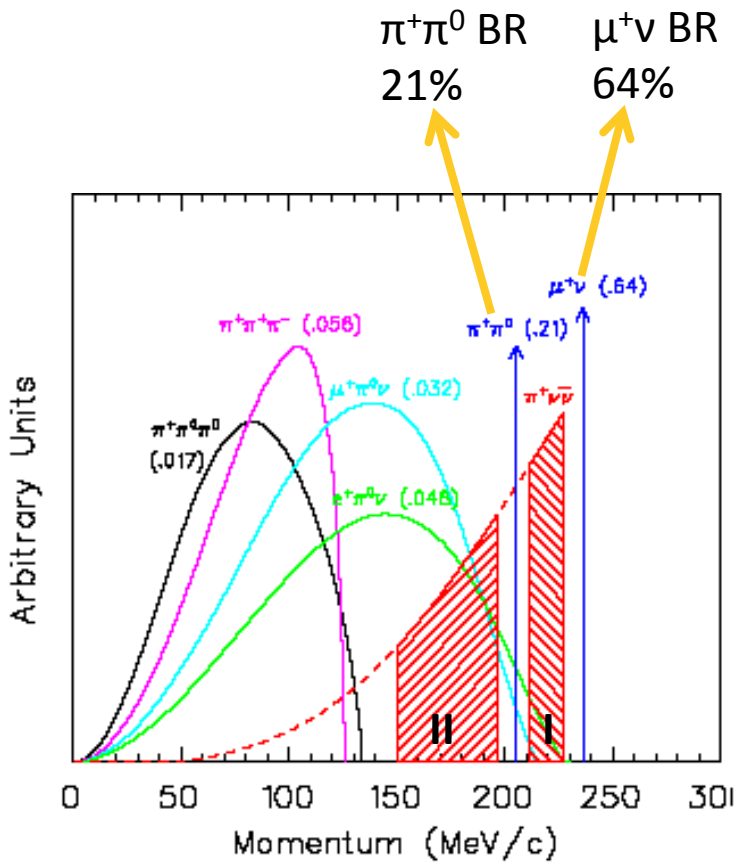
ORKA Detector



Good at reconstructing pions and muons
Good at decays with missing energy
Not so good at photons and electrons

- Highly optimized for $K^+ \rightarrow \pi^+ \nu\bar{\nu}$
- In center-of-mass frame (kaon decays at rest)
  - Low momentum charged particles
  - Can not access all of phase space
- Excellent photon veto coverage
- Lots of kaons and pions

Primary Physics



Momentum spectra of charged particles from K^+ decays in the rest frame

- Precise BR measurement of $K^+ \rightarrow \pi^+ \nu\bar{\nu}$
  - Current: $B\left(K^+ \rightarrow \pi^+ \nu\bar{\nu}\right) = 17.3^{+11.5}_{-10.5} \times 10^{-11}$
  - SM: $B\left(K^+ \rightarrow \pi^+ \nu\bar{\nu}\right) = \left(7.8 \pm 0.8\right) \times 10^{-11}$
- Observed signal:
  - $K^+ \rightarrow \pi^+ \rightarrow \mu^+ \rightarrow e^+$
- Background exceeds signal by > 10^{10}
- Requires suppression of background well below expected signal (S/N ~10)
- Requires π/μ/e particle ID > 10^6
- Requires π^0 inefficiency < 10^{-6}

ORKA Physics Topics

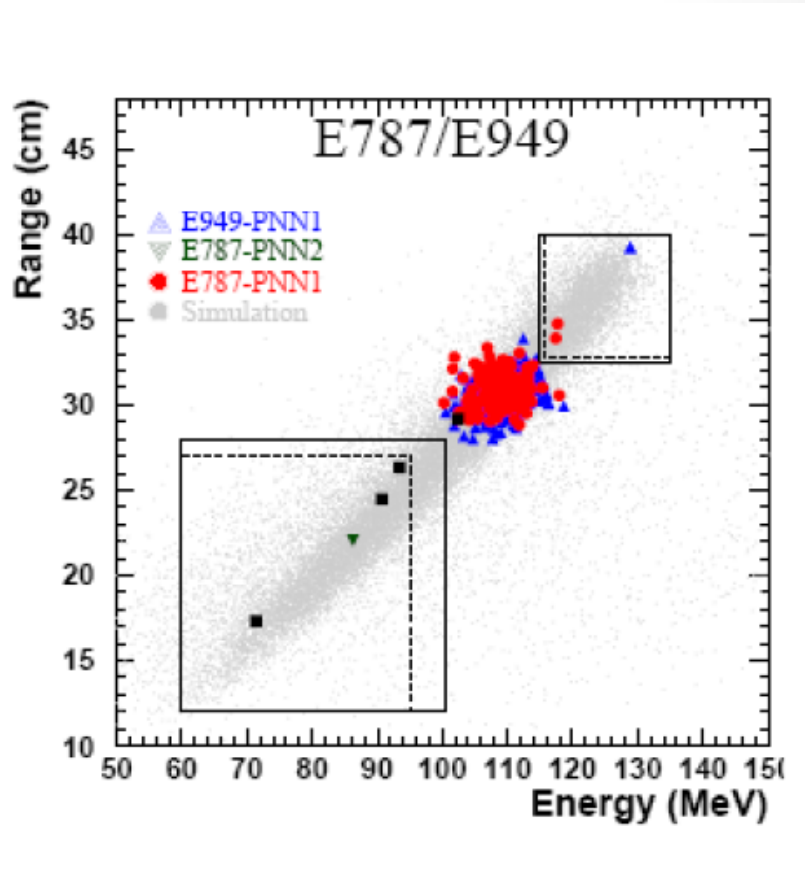
- $K^+ \to \pi^+ +$ missing energy
  - $K^+ \to \pi^+ \nu\bar{\nu}(1)$ ^{T,P}
  - $K^+ \to \pi^+ \nu\bar{\nu}(2)$ ^{T,P}
  - $K^+ \to \pi^+ \nu\bar{\nu}\gamma$
  - $K^+ \to \pi^+ X$ ^{P}
  - $K^+ \to \pi^+ \tilde{\chi}_0 \tilde{\chi}_0$(FF) ^{P}
- $K^+ \to \pi^+ \pi^0 +$ missing energy
  - $K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$ ^{T,P}
  - $K^+ \to \pi^+ \pi^0 X$
- $K^+ \to \mu^+ +$ missing energy
  - $K^+ \to \mu^+ \nu_h$ (heavy neutrino) ^{T}
  - $K^+ \to \mu^+ \nu M$ (M =majoran)
  - $K^+ \to \mu^+ \nu\bar{\nu}\nu$
- $K^+ \to \pi^+ \gamma$ ^{TP}
- $K^+ \to \pi^+ \gamma\gamma$ ^{P}
- $K^+ \to \pi^+ \gamma\gamma\gamma$
- $K^+ \to \pi^+$DP; DP $\to e^+ e^-$
- K^+ lifetime
- $\mathcal{B}(K^+ \to \pi^+ \pi^0)/\mathcal{B}(K^+ \to \mu^+ \nu)$
- $K^+ \to \pi^+ \pi^0 e^+ e^-$
- $K^+ \to \pi^- \mu^+ \mu^+$ (LFV)
- $\pi^0 \to$ nothing ^{T,P}
- $\pi^0 \to \gamma$DP; DP $\to e^+ e^-$
- $\pi^0 \to \gamma X$

^{T}E787/E949 Thesis ; ^{P}E787/E949 Publication; DP≡Dark Photon

ORKA physics breath document:
http://projects-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1644

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ PNN1/PNN2 ratio

- PNN1 and PNN2 kinematic regions analyzed separately
- Different background and acceptance issues
- If ratio of BRs measured in the two regions differs from SM, could indicate new physics
  - (ex: unparticles)



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

- Typically not experimentally measurable
  - For low energy γ, radiative mode not distinguishable from $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
  - For high energy γ, veto event
- Expect ~0.25% of events from radiative mode when experiment can detect photon energies > 10 MeV
- Expect 2-3 radiative events in 1000 event sample

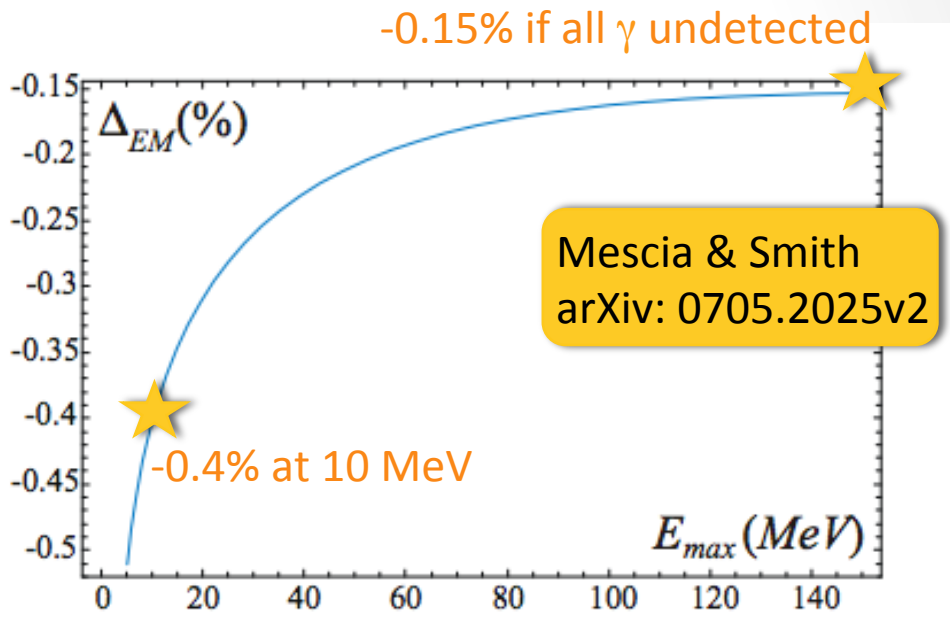


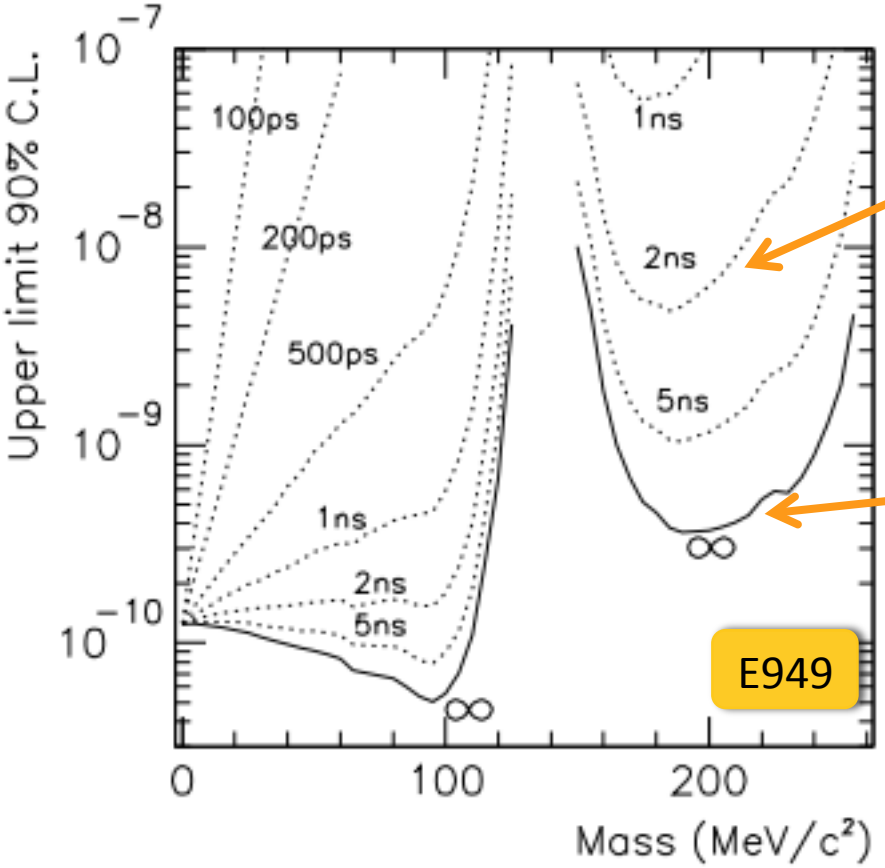
Figure 1: The QED correction to $K^+ \rightarrow \pi^+ \nu \bar{\nu} (\gamma)$ in %, as a function of the maximum energy of the undetected photon

$K^+ \rightarrow \pi^+ X^0$

- Familon
  - Wilczek, Phys. Rev. Lett. 49, 1549 (1982)
- Axion
  - arXiv:hep-ph/9807363
- Light scalar pseudo-NG boson
  - arXiv:0908.2004
- Sgoldstino
  - arXiv:hep-ph/0007325
- Gauge boson corresponding to new U(1) symmetry
  - Aliev et al, Nucl. Phys. B 335, 311 (1990)
  - arXiv:0811.1030
- Light dark matter
  - arXiv:0711.4866
  - arXiv:hep-ph/0702176
  - arXiv:hep-ph/0509024

$K^+ \rightarrow \pi^+ X^0$

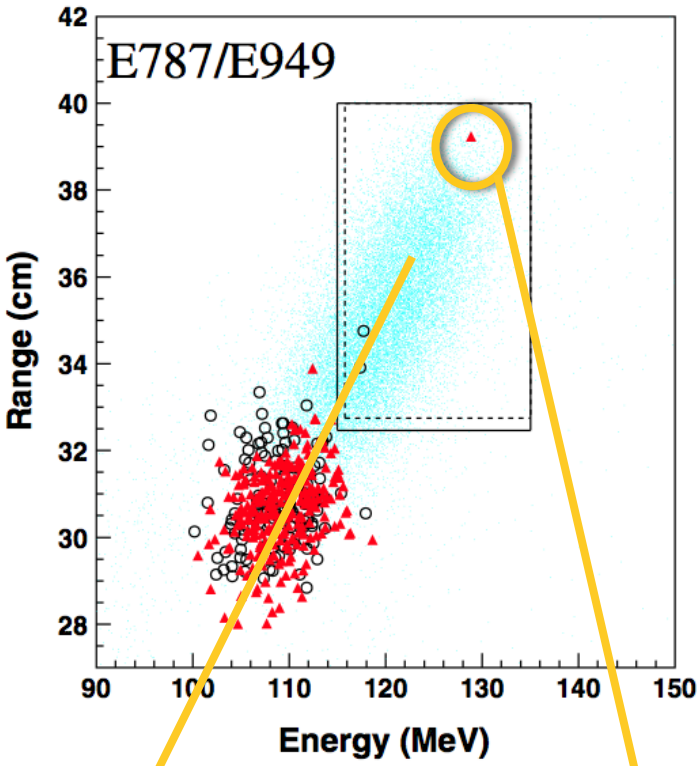
- E787/E949: $B(K^+ \rightarrow \pi^+ X^0) < 0.73 \times 10^{-10}$ (arXiv:0709.1000)
  - 1 event in E949, no events in E787
- $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ is a background



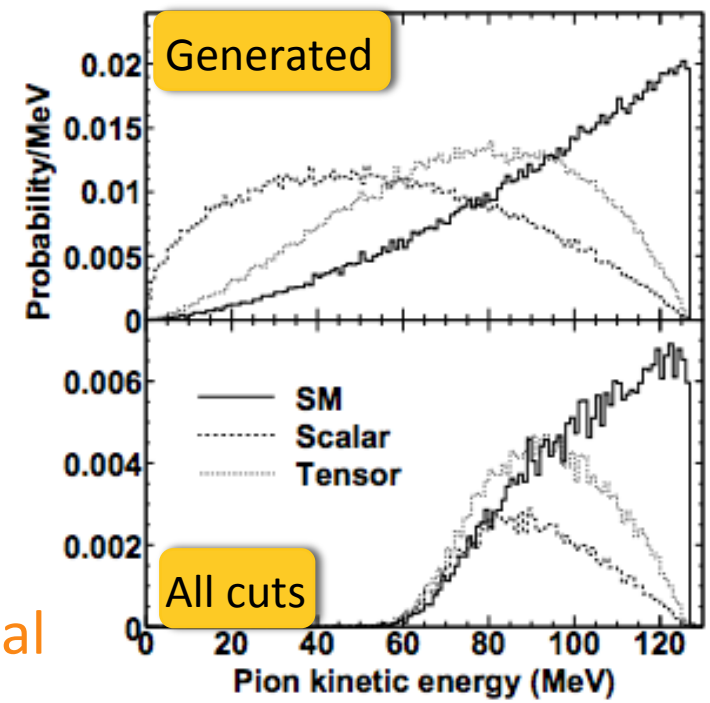
Upper limit on $K^+ \rightarrow \pi^+ X$ where X has listed lifetime

Upper limit on $K^+ \rightarrow \pi^+ X$ where X is stable

$K^+ \rightarrow \pi^+ X^0$ "event"



- One event seen in E949 $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ PNN1 signal region is near kinematic endpoint and also in $K^+ \rightarrow \pi^+ X^0$ signal region
- Corresponds to a massless X^0
- Central value of measured $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ BR higher than SM expectation

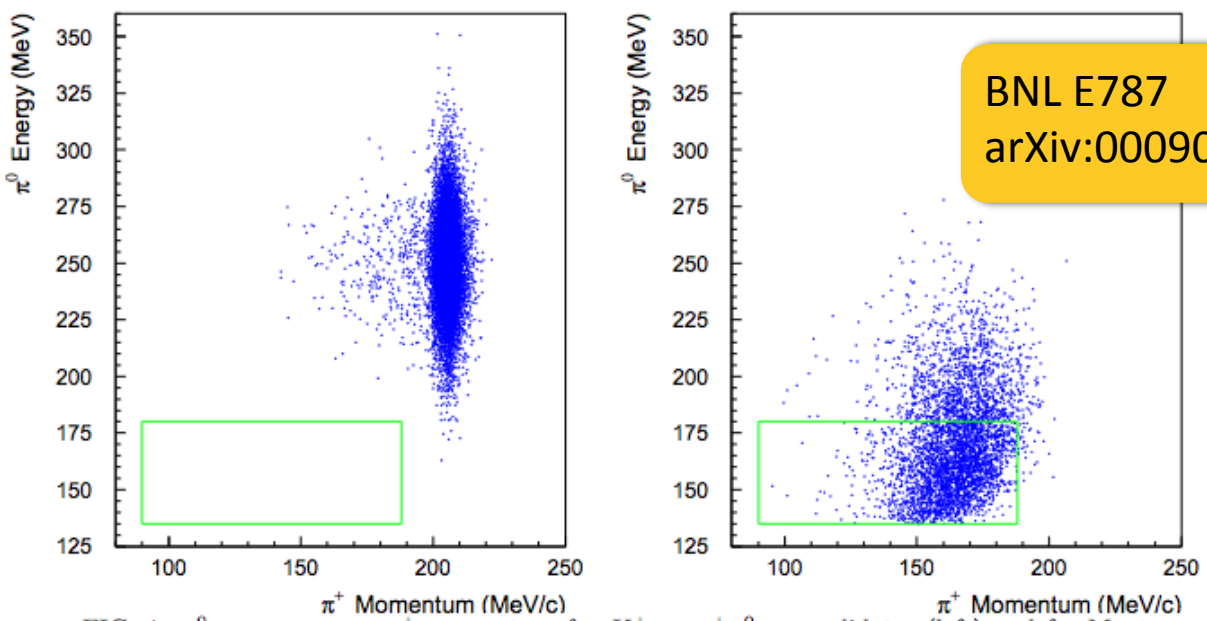


Expected distribution of $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ (MC)

E949 signal event

$K^+ \rightarrow \pi^+\pi^0\nu\bar{\nu}$

- Ke4 BR allows firm SM prediction
- New physics from axial-vector in addition to vector currents
- E787: $B(K^+ \rightarrow \pi^+\pi^0\nu\bar{\nu}) < 4.3 \times 10^{-5}$
- Limited by trigger bandwidth and detector resolution
- Expect × 1000 improvement at ORKA

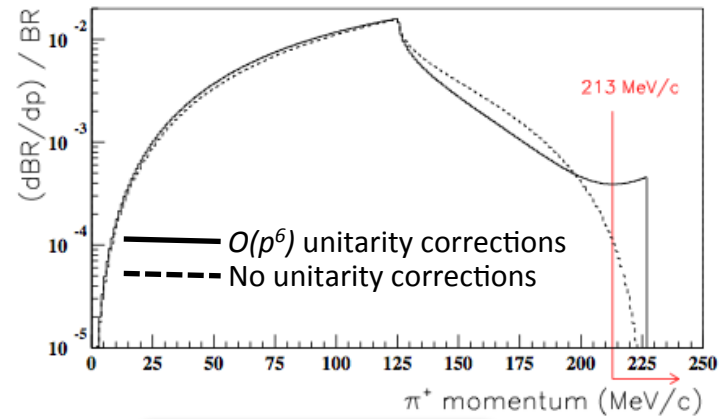


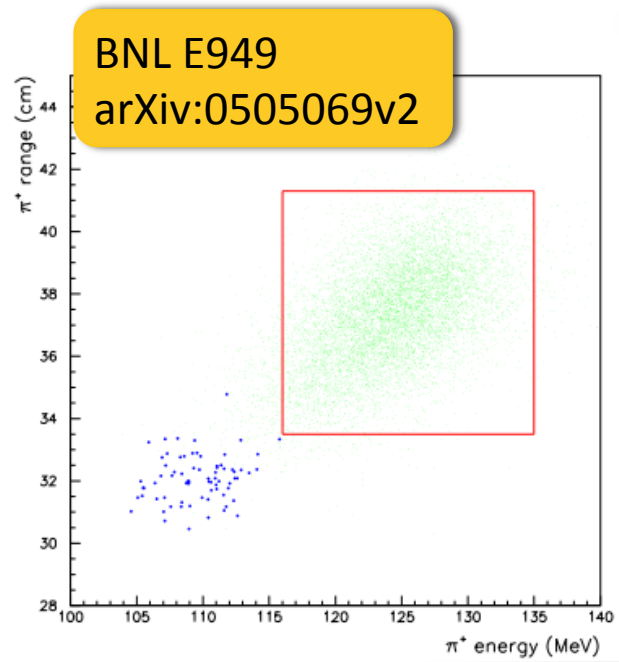
BNL E787
arXiv:0009055v1

FIG. 4. π^0 energy versus π^+ momentum for $K^+ \rightarrow \pi^+\pi^0\nu\bar{\nu}$ candidates (left) and for Monte Carlo signal events (right). Box indicates the signal acceptance region. $K_{\pi 2}$ events cluster at the upper right in the top plot.

$K^+ \to \pi^+\gamma\gamma$ & $K^+ \to \pi^+\gamma$

- $K^+ \to \pi^+\gamma\gamma$
  - $B(K^+ \to \pi^+\gamma\gamma) = (1.1 \pm 0.3) \times 10^{-6}$
    - Extrapolated from 100 MeV/c < p_π < 180 MeV/c region
    - Test of Chiral Perturbation Theory
      - Contributions start at $O(p^4)$
    - Expect large increase in statistics ($\times 10^4$)
  - $B(K^+ \to \pi^+\gamma\gamma)$ (p_π > 213 MeV/c) < 8.3×10^{-9}
- $K^+ \to \pi^+\gamma$
  - Violates conservation of angular momentum and gauge invariance
  - Allowed in non-commutative/ Lorentz violating theories
  - E949: $B(K^+ \to \pi^+\gamma) < 2.3 \times 10^{-9}$
  - Expect limit to scale with exposure ($\times$ 360)



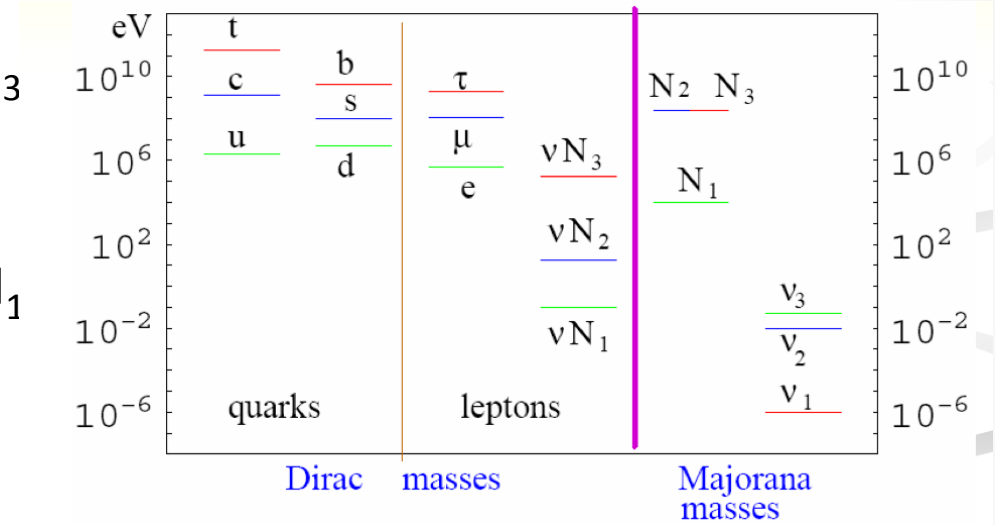


Sterile Neutrinos (νMSM)

- MSM + 3 RH neutrinos
- Sterile neutrinos: N_1, N_2, N_3
- Active-sterile neutrino mixing
- Lightest sterile neutrino: N_1
  - Mass 4-50 keV
  - Dark matter candidate
- N_2 and N_3
  - mix with active neutrinos

$$\nu_{L\alpha} = U_{\alpha i}\,\nu_i + \Theta_{\alpha I}\,N_I$$

$$\Theta_{\alpha I} = \frac{[M_D]_{\alpha I}}{M_I} = \frac{F_{\alpha I}\langle\Phi\rangle}{M_I}$$



Sterile Neutrinos

Neutrino Yukawa couplings for $N_{2,3}$

16

$$F = U_{\rm PMNS}\, D_\nu^{1/2}\, \Omega\, D_N^{1/2} / \langle \Phi \rangle$$ **(in NH)**

[Casas, Ibarra '01]

- Parameters of active neutrinos

$D_\nu^{1/2} = \mathrm{diag}(\sqrt{m_1} = 0, \sqrt{m_2}, \sqrt{m_3})$: active ν masses

Dirac phase δ

$$U_{\rm PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\eta} & \\ & & 1 \end{pmatrix}$$

Majorana phase η

- Parameters of sterile neutrinos

$D_N^{1/2} = \mathrm{diag}(\sqrt{M_2}, \sqrt{M_3})$: sterile ν masses

$$\Omega = \begin{pmatrix} 0 & 0 \\ \cos\omega & -\sin\omega \\ \xi\sin\omega & \xi\cos\omega \end{pmatrix}$$

ω: complex number

$\xi = \pm 1$

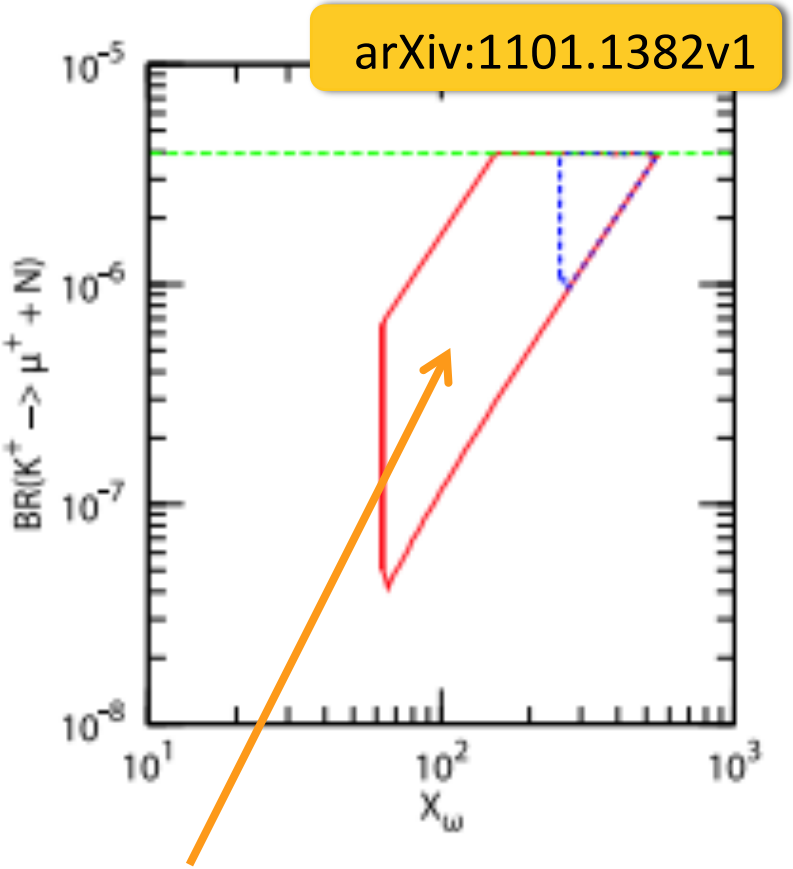
Imω

- **For Imω ≫ 1**, $\Omega \propto e^{\mathrm{Im}\omega}$

$$F, \Theta \propto e^{\mathrm{Im}\omega} \equiv X_\omega$$

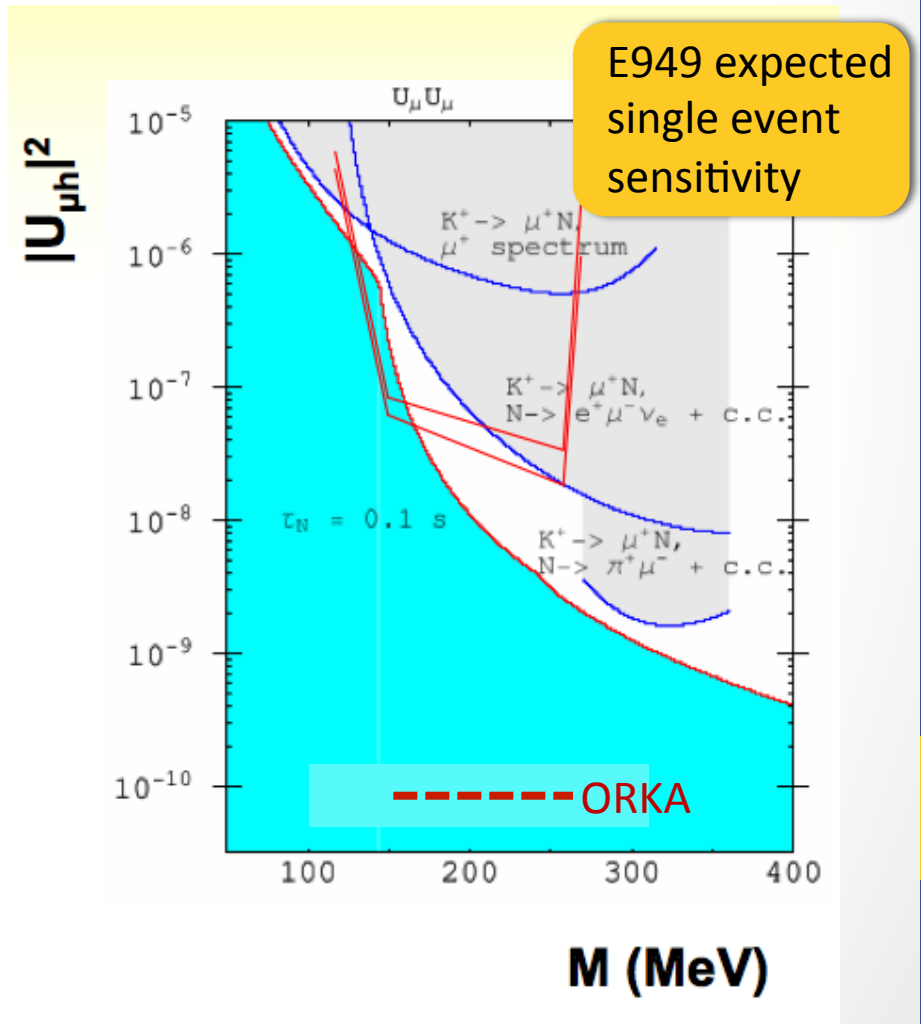
Takehiko Asaka (Niigata Univ.) 07 March, 2011

$K^+ \rightarrow \mu^+$ + missing energy



Allowed $BR(K^+ \rightarrow \mu^+ N)$ for normal hierarchy

Ongoing E949 analysis (A. Shaykhiev, INR)



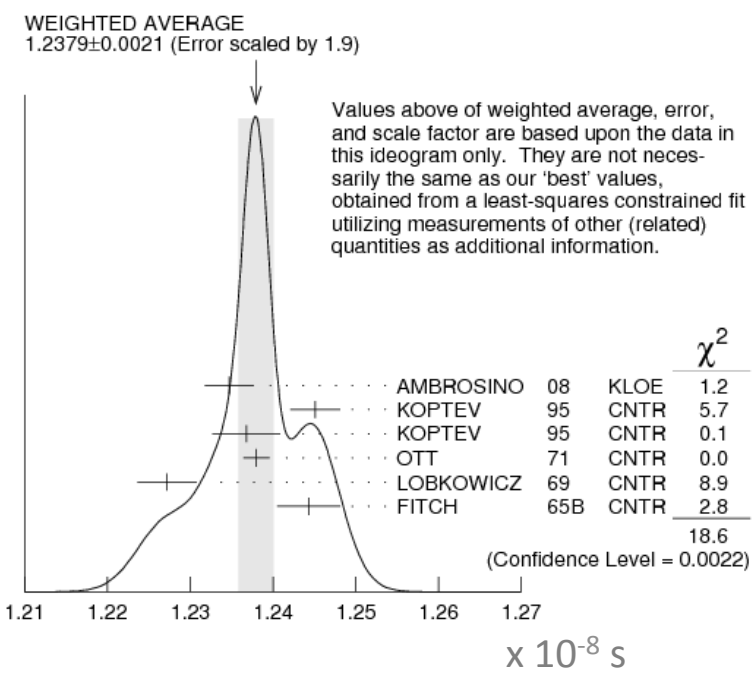
Precision Measurement of Ke2/Kμ2

$$R_K \equiv \frac{\Gamma\left(K^+ \to e^+\nu\right)}{\Gamma\left(K^+ \to \mu^+\nu\right)}$$

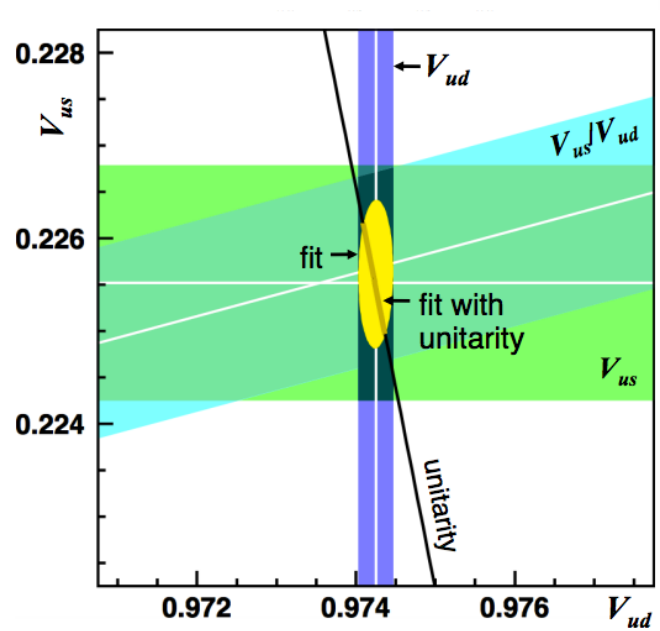
- $R_{SM} = (2.477 \pm 0.001) \times 10^{-5}$ arXiv:0707.4464
  - Extremely precise because hadronic form factors cancel in ratio
  - Sensitive to new physics effects that do not share V-A structure of SM contribution
- $R = (2.487 \pm 0.013) \times 10^{-5}$ (NA62) arXiv:1101.4805
- $R = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$ (KLOE) arXiv:0907.3594
- Expect ORKA statistical precision of ~0.1%
  - More study required to estimate total ORKA uncertainty

Fundamental K^+ Measurements

- K^+ lifetime
  - Not a major source of uncertainty for unitarity tests
  - Some discrepancies among experimental results in PDG

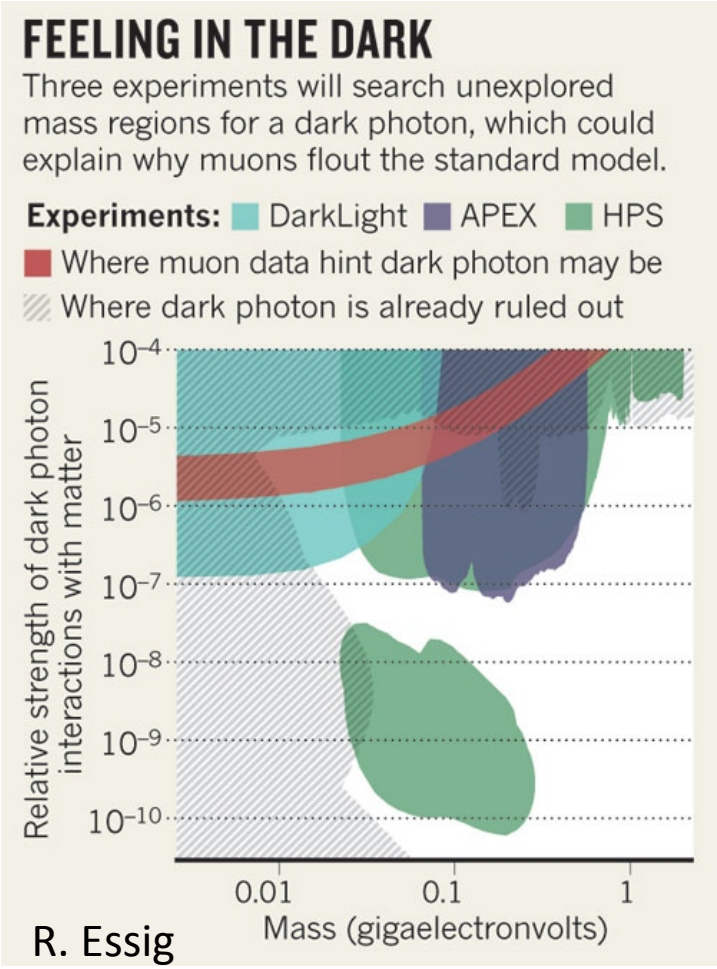


- $B(K^+ \to \pi^+\pi^0)/B(K^+ \to \mu^+\nu)$
  - Contributes to fit for $|V_{us}/V_{ud}|$
  - Expect improvements in lattice calculations so that experimental errors may soon be dominant



M. Moulson, CIPANP 2012

Dark Photons?



R. Essig

- A´: same interactions as SM photon with reduced coupling
- Multiple dedicated experiments to search for A´ at JLab
- ORKA search:
  - $K^+ \rightarrow \pi^+ A' \rightarrow \pi^+ e^+ e^-$
  - $\pi^0 \rightarrow \gamma A' \rightarrow \gamma e^+ e^-$
  - Signal would appear as resonance above continuum in e^+e^- invariant mass distribution
  - Electron resolution and background from conversion could be a problem
  - No ORKA sensitivity estimate yet

Summary

(preliminary estimate of sensitivity)

Process	Current	ORKA	Comment
$K^+ \to \pi^+ \nu\bar{\nu}$	7 events	1000 events	
$K^+ \to \pi^+ X^0$	$< 0.73 \times 10^{-10}$ @ 90% CL	$< 2 \times 10^{-12}$	$K^+ \to \pi^+ \nu\bar{\nu}$ is a background
$K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$	$< 4.3 \times 10^{-5}$	$< 4 \times 10^{-8}$	
$K^+ \to \pi^+ \pi^0 X^0$	$<\sim 4 \times 10^{-5}$	$< 4 \times 10^{-8}$	
$K^+ \to \pi^+ \gamma$	$< 2.3 \times 10^{-9}$	$< 6.4 \times 10^{-12}$	
$K^+ \to \mu^+ \nu_{heavy}$	$< 2 \times 10^{-8} - 1 \times 10^{-7}$	$< 1 \times 10^{-10}$	150 MeV $< m_\nu <$ 270 MeV
$K^+ \to \mu^+ \nu_\mu \nu\bar{\nu}$	$< 6 \times 10^{-6}$	$< 6 \times 10^{-7}$	
$K^+ \to \pi^+ \gamma\gamma$	293 events	200,000 events	
$\Gamma(Ke2)/\Gamma(K\mu2)$	$\pm 0.5\%$	$\pm 0.1\%$	
$\pi^0 \to \nu\bar{\nu}$	$< 2.7 \times 10^{-7}$	$< 5 \times 10^{-8}$ to $< 4 \times 10^{-9}$	depending on tech nique
$\pi^0 \to \gamma X^0$	$< 5 \times 10^{-4}$	$< 2 \times 10^{-5}$	

- ORKA, while highly optimized for $K^+ \to \pi^+ \nu\bar{\nu}$, is capable of making important, precise measurements of many other physics processes.

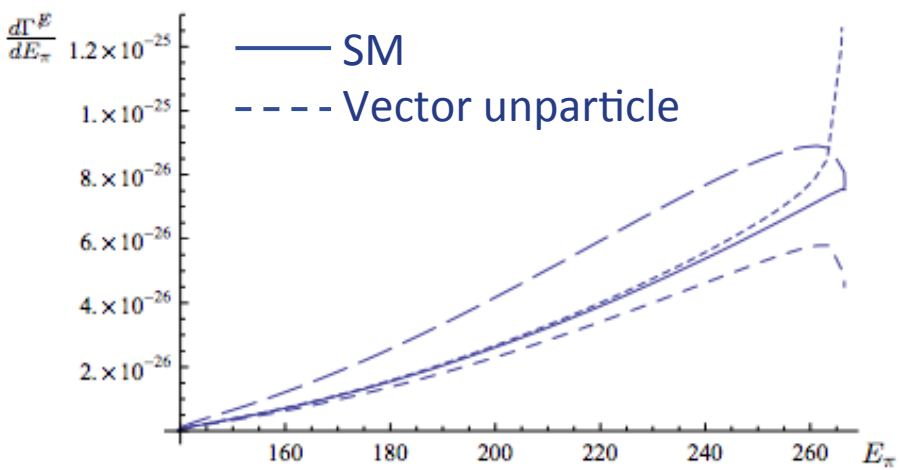
Extra Slides

Unparticles

Georgi
(arXiv: 0703260v3)

Abstract

I discuss some simple aspects of the low-energy physics of a nontrivial scale invariant sector of an effective field theory — physics that cannot be described in terms of particles. I argue that it is important to take seriously the possibility that the unparticle stuff described by such a theory might actually exist in our world. I suggest a scenario in which some details of the production of unparticle stuff can be calculated. I find that in the appropriate low energy limit, unparticle stuff with scale dimension $d_{\mathcal{U}}$ looks like a non-integral number $d_{\mathcal{U}}$ of invisible particles. Thus dramatic evidence for a nontrivial scale invariant sector could show up experimentally in missing energy distributions.



Wu & Zhang
arXiv: 0712.3923v1
"For large c's, the spectra can be quite different from the SM prediction in the region when the πs are hard"

Figure 9: The energy spectra for the charged π in the vector unparticle model. $d_{\mathcal{U}} = 1.3$, $c_{\mathcal{V}}^q = 6.6\times10^{-14}$, $c_{\mathcal{V}}^l = -0.05$ for the shortest dash-length, $d_{\mathcal{U}} = 1.8$, $c_{\mathcal{V}}^q = 5.0\times10^{-15}$, $c_{\mathcal{V}}^l = -0.05$ for the middle dash-length, $d_{\mathcal{U}} = 2.3$, $c_{\mathcal{V}}^q = 1.0\times10^{-15}$ $c_{\mathcal{V}}^l = -0.08$ for the longest dash-length. The solid line represents the SM spectrum.