Toy Monte Carlo Simulations Mirroring the Kaon Decay Explored in the KOto Experiment

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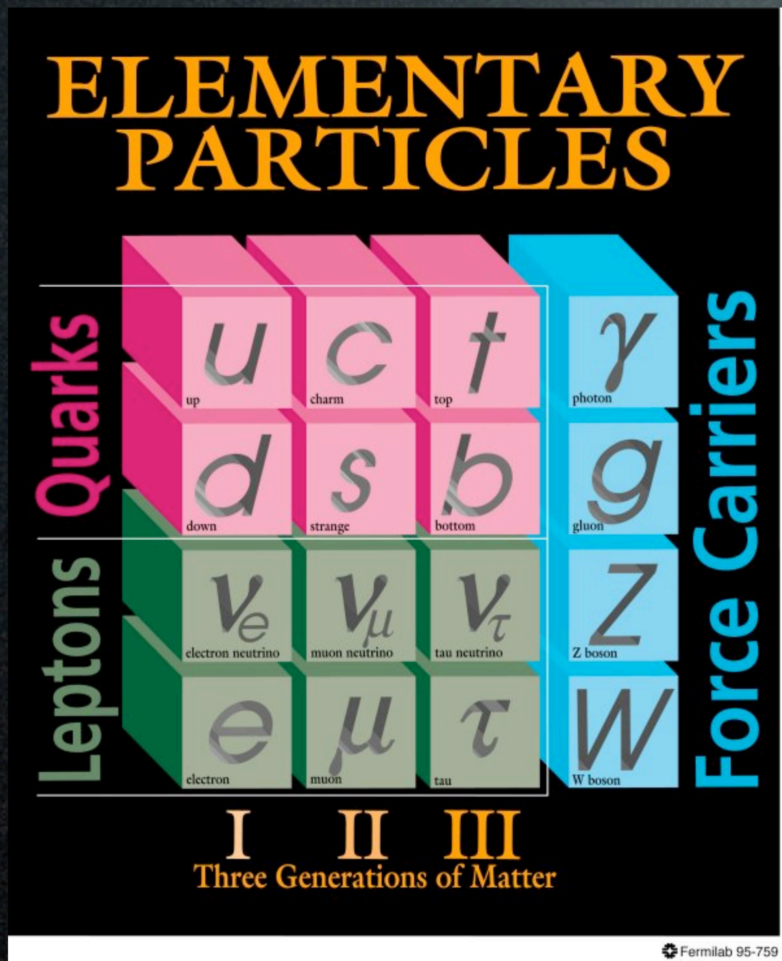
The Standard Model



Γ_{30}	$\pi^0\mu^+\mu^-$	CP,S1	[e]	<	3.8	$\times 10^{-10}$	CL=90%
Γ_{31}	$\pi^0 e^+ e^-$	CP,S1	[e]	<	2.8	$\times 10^{-10}$	CL=90%
Γ_{32}	$\pi^0\nu\overline{\nu}$	CP,S1	[f]	<	2.6	$\times 10^{-8}$	CL=90%
Γ_{33}	$\pi^0\pi^0\nu\nu$	S1		<	8.1	$\times 10^{-7}$	CL=90%
Γ_{34}	$e^\pm\mu^\mp$	LF	[a]	<	4.7	$\times 10^{-12}$	CL=90%
Γ_{35}	$e^\pm e^\pm\mu^\mp\mu^\mp$	LF	[a]	<	4.12	$\times 10^{-11}$	CL=90%
Γ_{36}	$\pi^0\mu^\pm e^\mp$	LF	[a]	<	7.6	$\times 10^{-11}$	CL=90%
Γ_{37}	$\pi^0\pi^0\mu^\pm e^\mp$	LF		<	1.7	$\times 10^{-10}$	CL=90%

- Quarks are now recognized as being one of three types of elementary particles, joining leptons and the force mediators as the fundamental units of all matter.
- Baryons (ex. protons, neutrons) have a 3-quark structure.
- Mesons (ex. kaons, pions) are composed of a quark-antiquark pair.

- Kaons come in three different varieties: two charged (K^+, K^-), and one neutral (K^0).
- K^0 is composed of a down quark (d) and an anti-strange quark (s*).
- More specifically, the K^0 is a superposition of two distinct eigenstates, each with a slightly different lifetime. K-Long refers to the longer-lived eigenstate.
  - $|K^0\rangle = 1/\sqrt{2} * (|K_S\rangle + |K_L\rangle)$
  - $K_L \rightarrow 3\pi$, $\tau \approx 10^{-8}$ sec
  - $K_S \rightarrow 2\pi$, $\tau \approx 10^{-10}$ sec
- Experiment has shown, however, that even these eigenstates are not "pure." This result provides strong evidence of CP Violation.
  - Ex. $|K_L\rangle = C * (|K_L\rangle + \varepsilon\, |K_S\rangle)$

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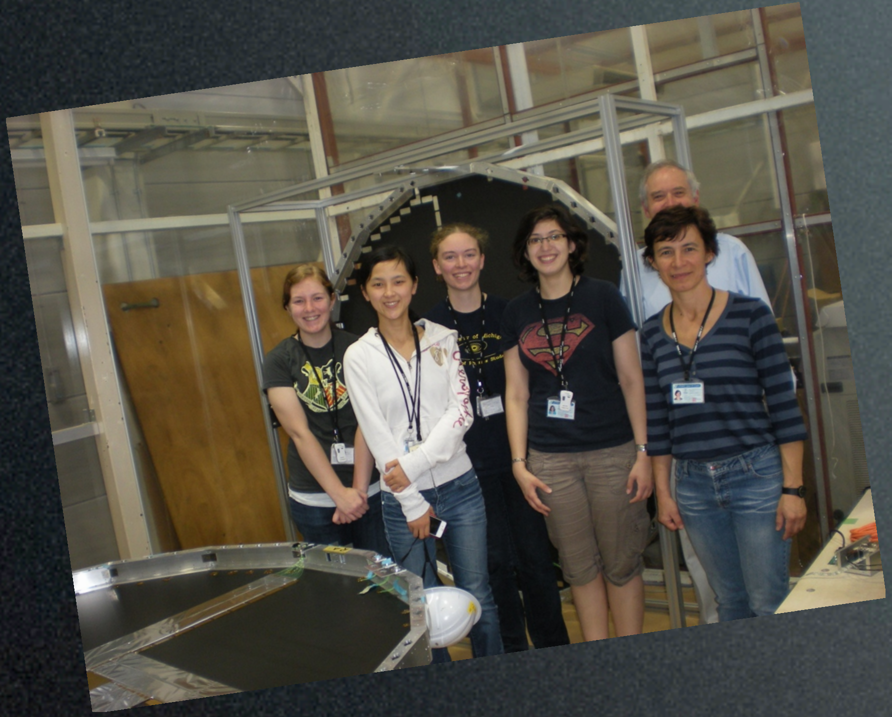
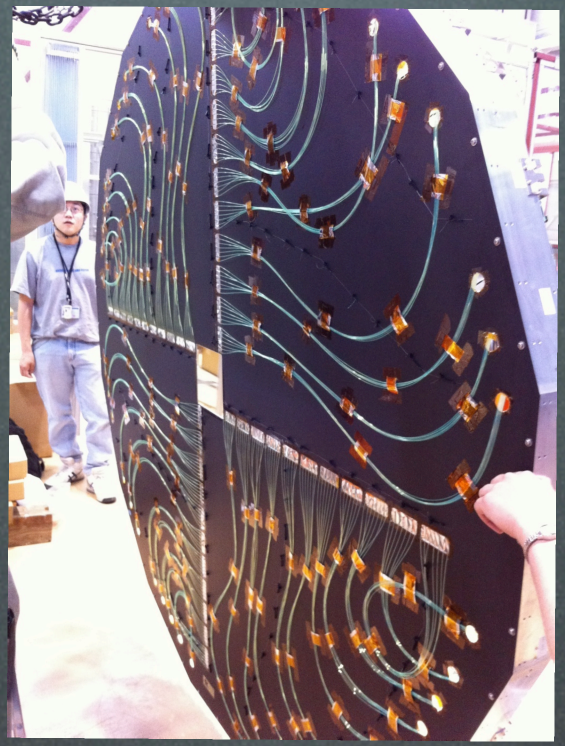
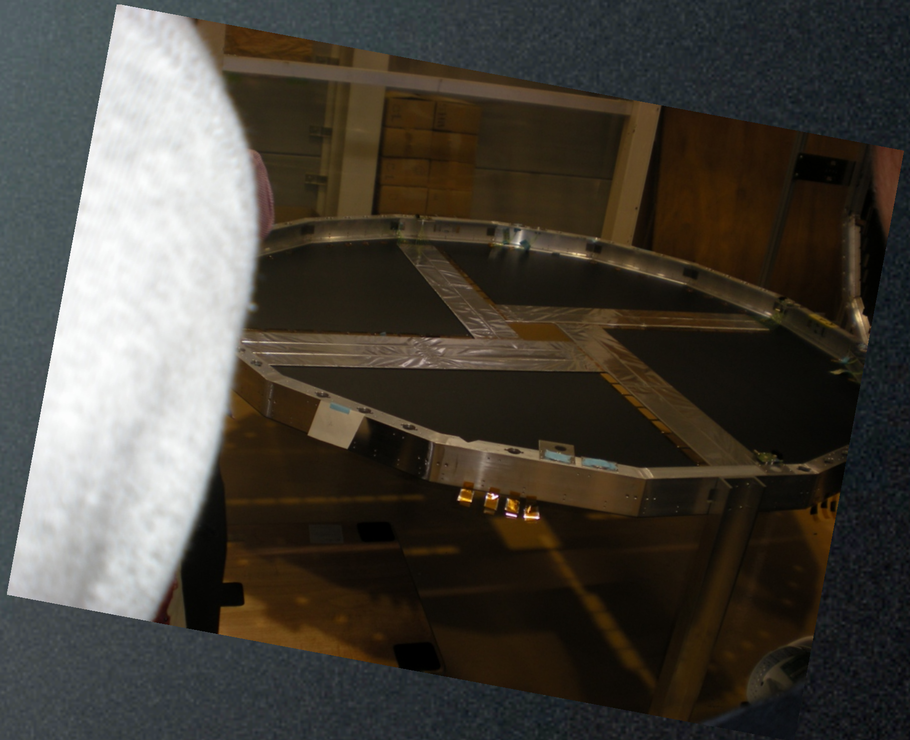
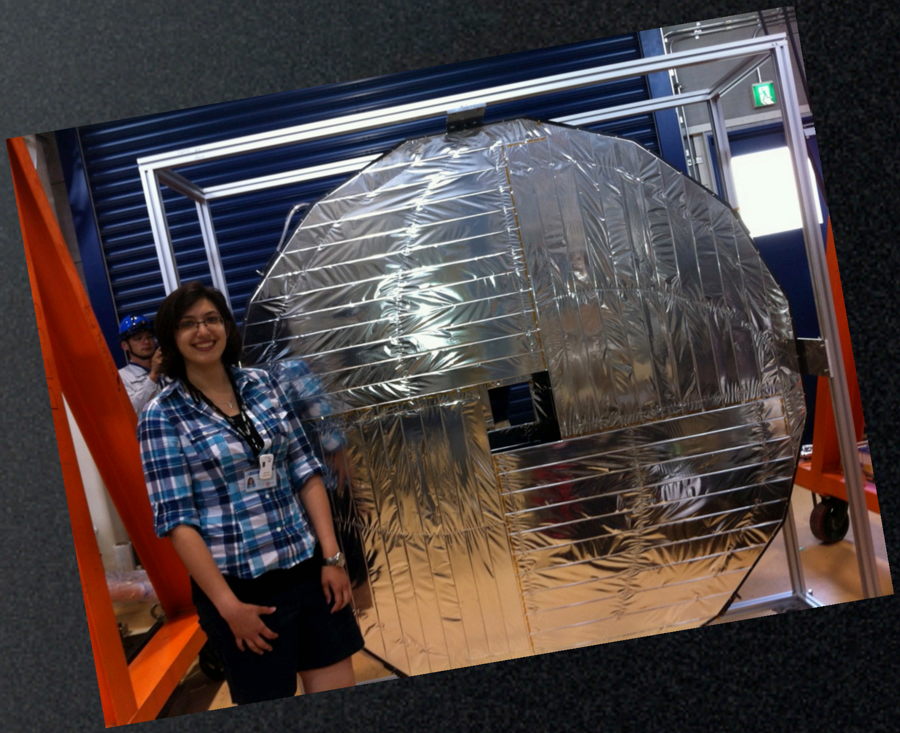
The KOto Experiment

- The purpose of KOto is to study the (#32!) branching ratio $K_L \rightarrow \boldsymbol{\pi}^0\ \nu\ \nu^*$.
    - The decay, a flavor changing neutral current reaction, is carried out through 2nd-order weak interactions.
- The KOto collaboration includes universities from the U.S., Russia, S. Korea, Taiwan, and Japan. The detector is located at the JPARC facility, in Tokai-Mura, Ibaraki, Japan.
    - Studying a rare decay means generating a lot of data. The UMich team focuses mainly on the development of the Data Aquisition System (DAQ), and has also produced Monte Carlo Simulations as theoretical models of what should be seen experimentally.
- KOto's detection system essentially measures photons; however, by tracking their progress through the detector and by knowing the energy of each photon, we can ascertain information about the Kaon decay itself.

Logo Credits: http://hep0.physics.lsa.umich.edu/k0to/Physics/physics.html

Charged Veto Detector
JPARC, Tokai-Mura, Japan

Pi-0 Toy Monte Carlo Simulation

1. Generate a π^0 (CM Frame)

$$E_\pi = E_{\gamma 1} + E_{\gamma 2}$$

$$P_\pi = P_{\gamma 1} + P_{\gamma 2} = 0 \therefore P_{\gamma 1} = -P_{\gamma 2}$$

2. Choose Θ, φ at random:

$$0 < \Theta < \pi$$

$$0 < \varphi < 2\pi$$

3. Describe Momentum in 3D-Space:

$$P_x = P * \text{Sin}\,\Theta * \text{Cos}\,\varphi$$

$$P_y = P * \text{Sin}\,\Theta * \text{Sin}\,\varphi$$

$$P_z = P * \text{Cos}\,\Theta$$

4. Give it a γ boost factor, and boost into lab frame (in Z-Direction)

$$E' = \gamma * E + \beta * \gamma * P_z$$

$$P_x' = P_x$$

$$P_y' = P_y$$

$$P_z' = \beta * \gamma * E + \gamma * P_z$$

5. Propagate to CsI Crystals and Graph (X,Y) Positions

$$(X/Z) = (P_x/P_z);\ (Y/Z) = (P_y/P_z)$$

```
masspi0 = ParticleData["PiZero", "Mass"]
egam = masspi0/2;
phi = RandomReal[{0, 2*π}];
theta = ArcCos[RandomReal[{-1, 1}]];
px1 = egam*Sin[theta]*Cos[phi];
py1 = egam*Sin[theta]*Sin[phi];
pz1 = egam*Cos[theta];
px2 = -1*px1;
py2 = -1*py1;
pz2 = -1*pz1;
γ = 4;
β = Sqrt[1 - 1/γ^2];
pxpr1 = px1;
pypr1 = py1;
pzpr1 = γ*β*egam + γ*pz1;
pxpr2 = px2;
pypr2 = py2;
pzpr2 = γ*β*egam + γ*pz2;
z = 2;
x1 = (pxpr1/pzpr1)*z;
y1 = (pypr1/pzpr1)*z;
x2 = (pxpr2/pzpr2)*z;
y2 = (pypr2/pzpr2)*z;
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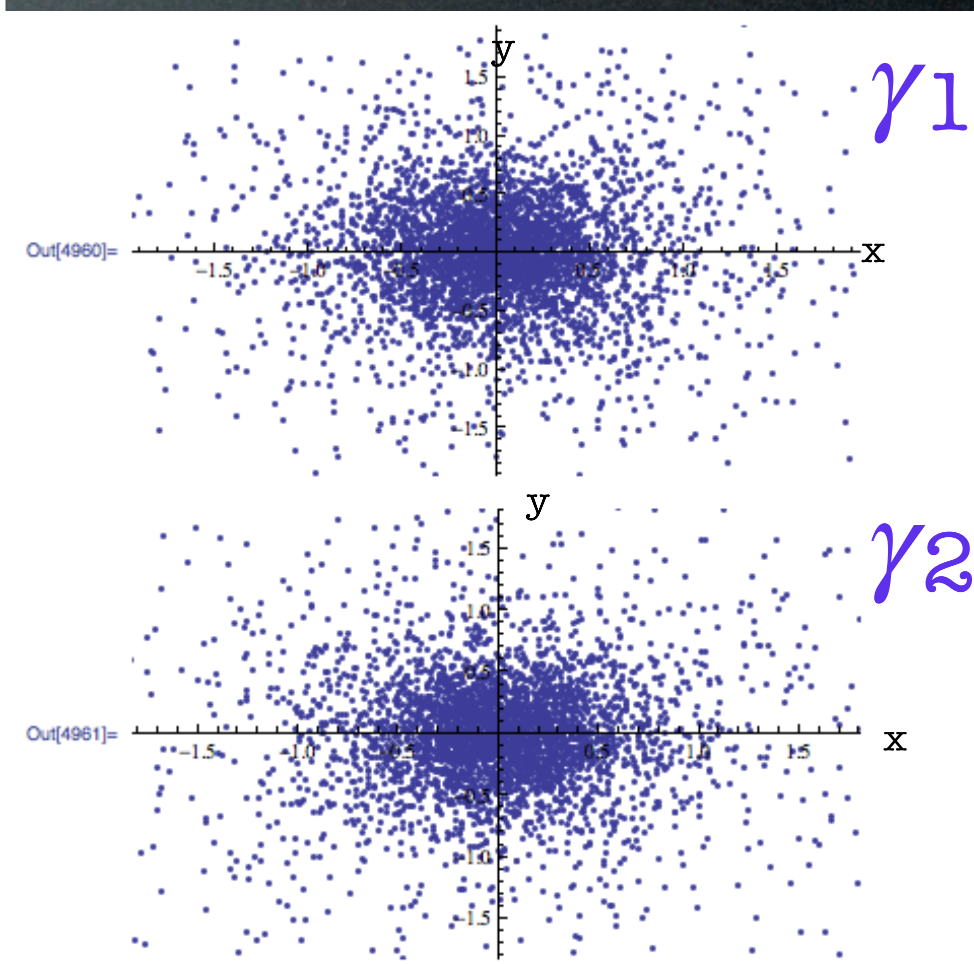


n = 4000

1	-46.7123	32.9329	46.7123	-32.9329	-0.230713	0.162656	0.792922-0.559023
2	-27.7722	-46.1137	27.7722	46.1137	-0.563555	-0.935741	0.1309390.217414
3	10.5057	-61.9038	-10.5057	61.9038	0.0583078	-0.343572	-0.1293740.762322
4	57.2048	1.10501	-57.2048	-1.10501	0.967824	0.0186952	-0.282808-0.00546292
5	48.589	-32.1358	-48.589	32.1358	0.776908	-0.513831	-0.2443630.161617
6	-26.7481	60.259	26.7481	-60.259	-0.262643	0.59169	0.167659-0.377707
7	6.22638	-58.9117	-6.22638	58.9117	0.0942993	-0.892225	-0.03187240.301565
8	17.4271	-15.4975	-17.4271	15.4975	4.32557	-3.84661	-0.0677170.0602189
9	10.7104	-45.6282	-10.7104	45.6282	0.0470148	-0.200291	-0.3190321.35913

K-Long Toy Monte Carlo Simulation

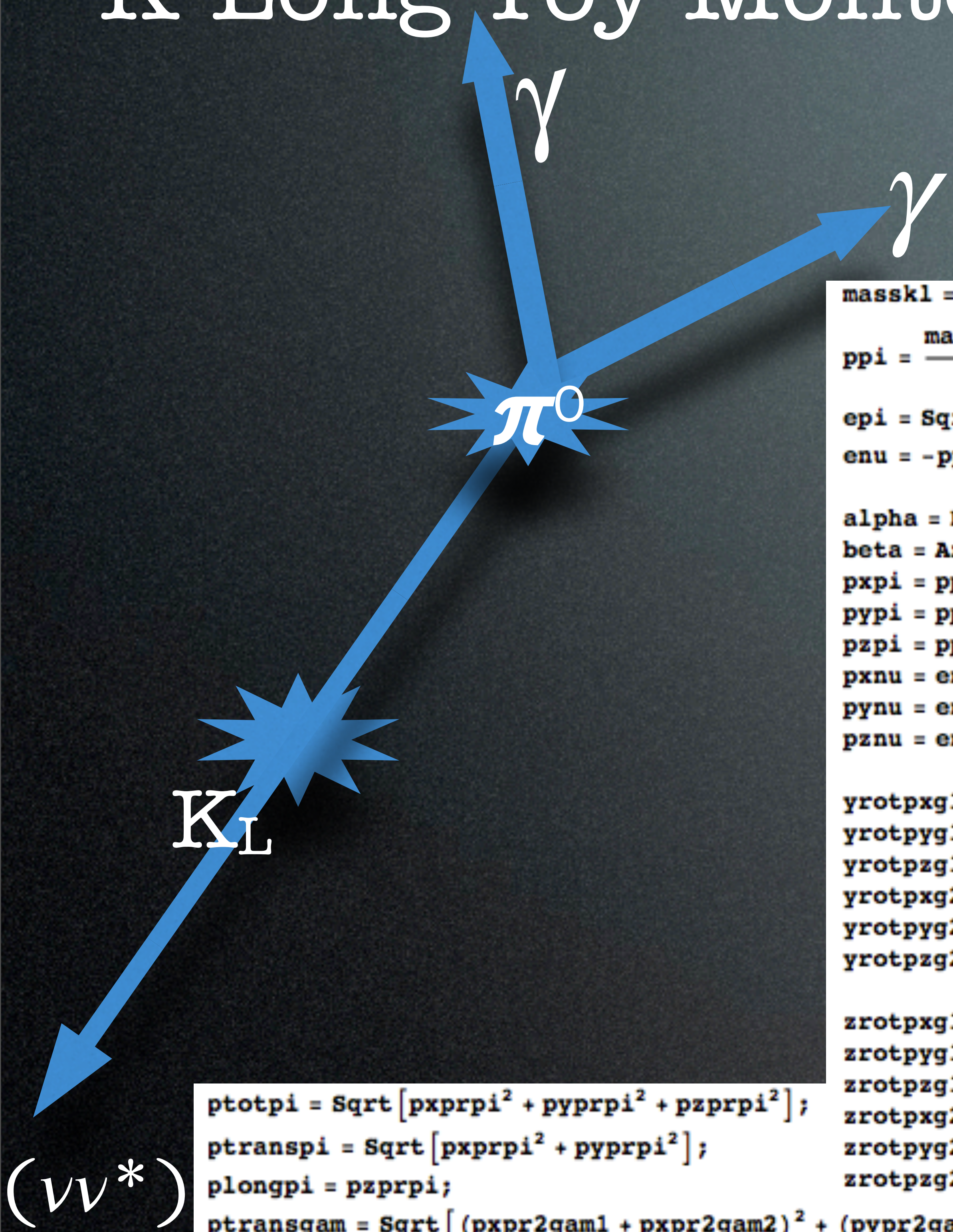
π^0 K_L $(\nu\,\nu^*)$

1. Start with $\pi^0 \to \gamma\gamma$
2. Choose random Θ_γ, φ_γ for γ's in π^0 CM frame.
3. Boost γ's to π^0 "lab" frame = kaon CM frame.
4. Consider $K_L \to \pi^0(\nu\,\nu^*)$. Choose random Θ_π, φ_π
5. Boost particles to kaon "lab" frame
6. Graph (x, y) positions; Calculate Center of Energy (CoE) of γ's, and the transverse momentum (P_T) of the pion:

$$P_T = \sqrt{[(\sum P_{x,i})^2 + (\sum P_{y,i})^2]}$$

$$CoE = \sqrt{[(\sum E_i * x_i)^2 + (\sum E_i * y_i)^2]}$$

K-Long Toy Monte Carlo Simulation, Ctd.




```
masskl = ParticleData["KLong", "Mass"];
ppi = (masskl^2 - masspi0^2)/(2 * masskl);
epi = Sqrt[masspi0^2 + ppi^2];
enu = -ppi;

alpha = RandomReal[{0, 2 * π}];
beta = ArcCos[RandomReal[{-1, 1}]];
pxpi = ppi * Sin[beta] * Cos[alpha];
pypi = ppi * Sin[beta] * Sin[alpha];
pzpi = ppi * Cos[beta];
pxnu = enu * Sin[beta] * Cos[alpha];
pynu = enu * Sin[beta] * Sin[alpha];
pznu = enu * Cos[beta];

yrotpxg1 = Cos[beta] * pxprgam1 + Sin[beta] * pzprgam1;
yrotpyg1 = pyprgam1;
yrotpzg1 = -Sin[beta] * pxprgam1 + Cos[beta] * pzprgam1;
yrotpxg2 = Cos[beta] * pxprgam2 + Sin[beta] * pzprgam2;
yrotpyg2 = pyprgam2;
yrotpzg2 = -Sin[beta] * pxprgam2 + Cos[beta] * pzprgam2;

zrotpxg1 = Cos[alpha] * yrotpxg1 - Sin[alpha] * yrotpyg1;
zrotpyg1 = Sin[alpha] * yrotpxg1 + Cos[alpha] * yrotpyg1;
zrotpzg1 = yrotpzg1;
zrotpxg2 = Cos[alpha] * yrotpxg2 - Sin[alpha] * yrotpyg2;
zrotpyg2 = Sin[alpha] * yrotpxg2 + Cos[alpha] * yrotpyg2;
zrotpzg2 = yrotpzg2;
```

```
Γ = 5;
B = Sqrt[1 - 1/Γ^2];
epr2gam1 = Γ * eprgam1 + B * Γ * zrotpzg1;
pxpr2gam1 = zrotpxg1;
pypr2gam1 = zrotpyg1;
pzpr2gam1 = Γ * B * eprgam1 + Γ * zrotpzg1;
epr2gam2 = Γ * eprgam2 + B * Γ * zrotpzg2;
pxpr2gam2 = zrotpxg2;
pypr2gam2 = zrotpyg2;
pzpr2gam2 = Γ * B * eprgam2 + Γ * zrotpzg2;

eprpi = Γ * epi + B * Γ * pzpi;
pxprpi = pxpi;
pyprpi = pypi;
pzprpi = Γ * B * ppi + Γ * pzpi;
eprnu = Γ * enu + B * Γ * pznu;
pxprnu = pxnu;
pyprnu = pynu;
pzprnu = Γ * B * enu + Γ * pznu;
```

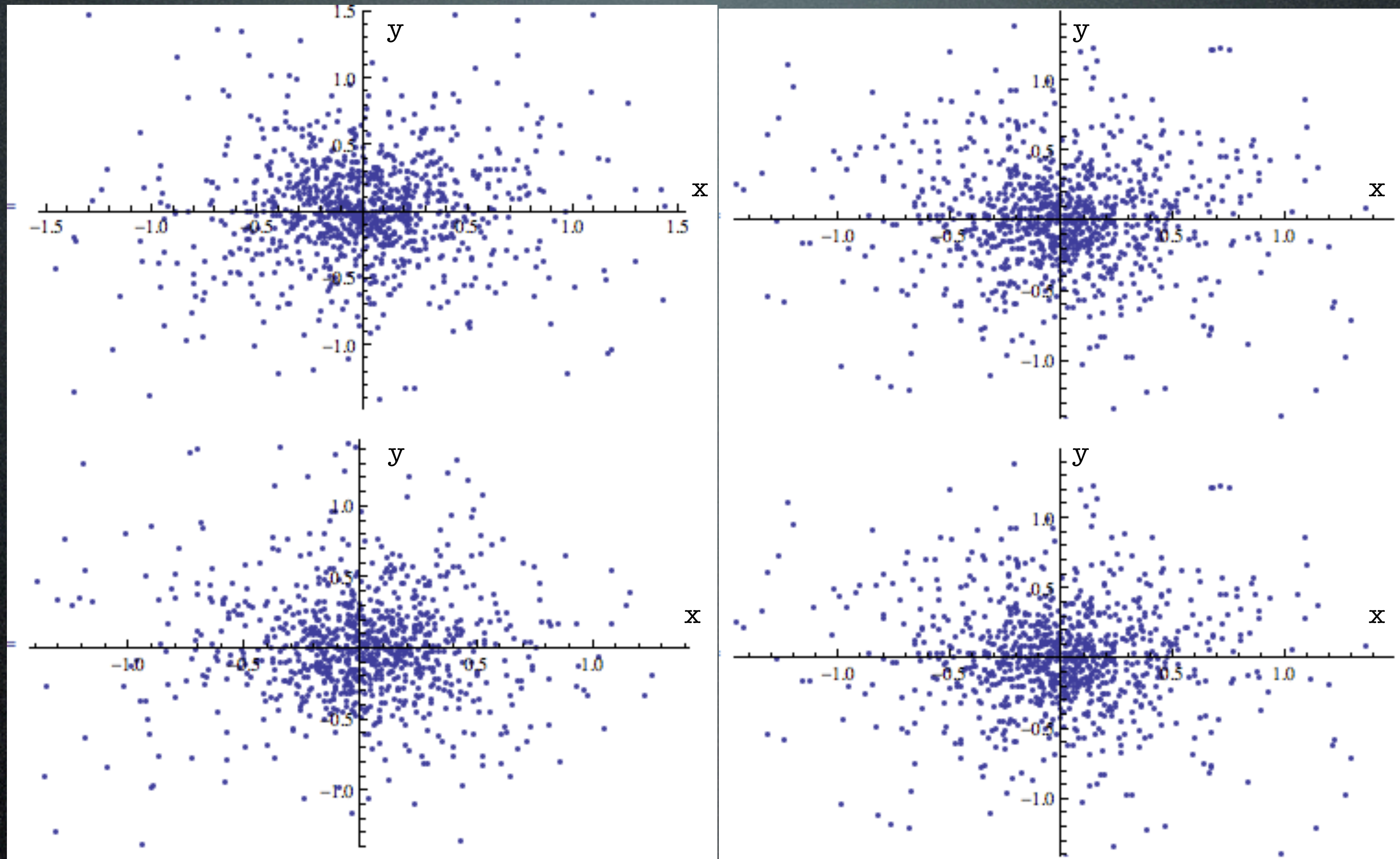
```
k = 2;
igam1 = (pxpr2gam1/pzpr2gam1) * k;
jgam1 = (pypr2gam1/pzpr2gam1) * k;
igam2 = (pxpr2gam2/pzpr2gam2) * k;
jgam2 = (pypr2gam2/pzpr2gam2) * k;
ipi = (pxprpi/pzprpi) * k;
jpi = (pyprpi/pzprpi) * k;
inu = (pxprnu/pzprnu) * k;
jnu = (pyprnu/pzprnu) * k;
```

```
ptotpi = Sqrt[pxprpi^2 + pyprpi^2 + pzprpi^2];
ptranspi = Sqrt[pxprpi^2 + pyprpi^2];
plongpi = pzprpi;
ptransgam = Sqrt[(pxpr2gam1 + pxpr2gam2)^2 + (pypr2gam1 + pypr2gam2)^2];
plonggam = pzpr2gam1 + pzpr2gam2;
etotg1 = Sqrt[pxpr2gam1^2 + pypr2gam1^2 + pzpr2gam1^2];
etotg2 = Sqrt[pxpr2gam2^2 + pypr2gam2^2 + pzpr2gam2^2];
cmx = (igam1 * etotg1) + (igam2 * etotg2);
cmy = (jgam1 * etotg1) + (jgam2 * etotg2);
coe = Sqrt[cmx^2 + cmy^2];
```

Results

γ_1 π^0

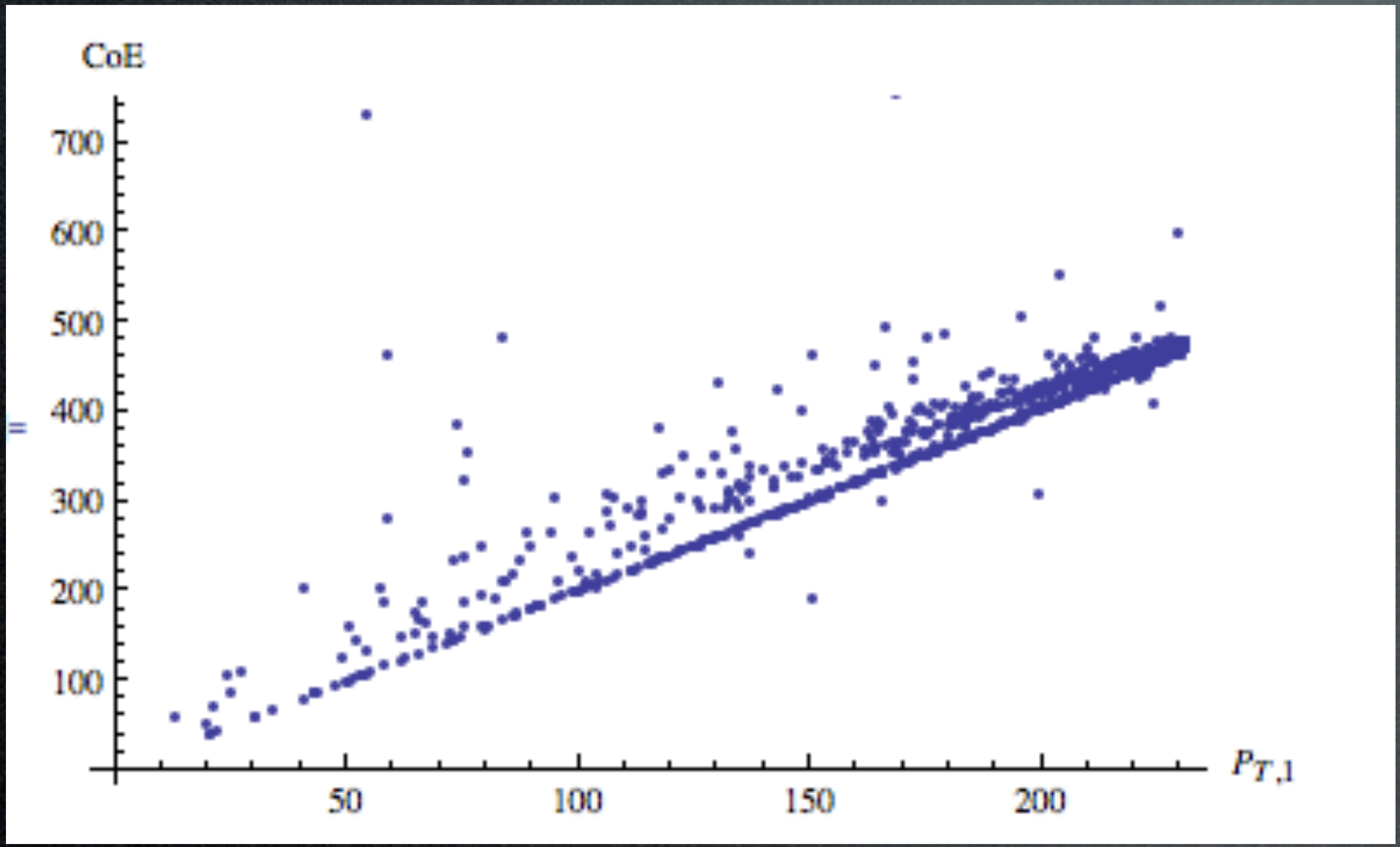
γ_2 $(\nu\nu^*)$



n = 1000

1	-159.116	-81.3151	-18.1012	43.4426	-177.217	-37.8725	177.217	37.8725	181.219	181.219
2	4.24769	-107.399	106.039	-20.6071	110.286	-128.006	-110.286	128.006	168.963	168.963
3	28.6571	-51.1575	60.2525	71.4683	88.9096	20.3108	-88.9096	-20.3108	91.2	91.2
4	54.0666	-47.5428	-76.8708	-15.0796	-22.8042	-62.6223	22.8042	62.6223	66.6452	66.6452
5	112.44	-63.3233	102.218	-10.9271	214.657	-74.2504	-214.657	74.2504	227.136	227.136
6	31.7916	-43.0226	-72.3749	2.72617	-40.5832	-40.2964	40.5832	40.2964	57.1909	57.1909
7	58.0148	-53.8449	165.235	36.8082	223.25	-17.0367	-223.25	17.0367	223.899	223.899
8	226.615	52.8229	-3.76883	-22.0787	222.846	30.7443	-222.846	-30.7443	224.957	224.957
9	131.316	73.1708	8.66759	97.5561	139.983	170.727	-139.983	-170.727	220.778	220.778

Results, ctd.



- There is a clear linear relationship between the CoE of the photons and P_T of the pion, However, the uneven scattering towards the top of the graph remains unexplained.

- It has been suggested that this is due to statistical error, or is possibly the result of a single photon hitting the virtual detector.

Questions?