Project X Physics Study, Fermilab, June 21, 2012

Kaon Physics WG -Experiment

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Outline

- **Near-term experiments**
  - **NA 62, KOTO, P36**
- **Future experiments pre-Project X**
  - **ORKA, TREK**
- **Project X**

Near-term experiments

- **NA 62 at CERN**
  - **$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ in-flight.**
  - **100 signal events (@SM), low background**
  - **Partial detector commissioning this year, Data in 2014**

- **KOTO at JPARC**
  - **$K_L \rightarrow \pi^0 \nu \bar{\nu}$ in-flight.**
  - **Few signal event events (@SM)**
  - **Low intensity run this year.**

- **P36 at JPARC**
  - **Test of lepton universality $\Gamma(K^+ \rightarrow e^+ \nu)/\Gamma(K^+ \rightarrow \mu^+ \nu)$**
  - **Run in 2015**

Proposed/considered experiments

- **E06/TREK at JPARC (same group/beamline as P36)**
  - **T violating transverse muon polarization in $K^+ \rightarrow \pi^0 \mu \nu$.**
  - **Needs ≥ 100 kW beam (want 270 kW)**
  - **Timeline for JPARC higher intensity unclear**
  - **Run after P36**

- **ORKA at Fermilab Main Injector**
  - **$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at rest**
  - **1000 signal events (@SM), estimates based upon BNL E787/996**

- **Next generation of KOTO at JPARC**
  - **$K_L \rightarrow \pi^0 \nu \nu$ in-flight.**
  - **Not proposed yet.**

Kaon Experiment Timeline

- **This is crude and dates approximate:**

			2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
NA62	CERN	K+ ->pi+ nu nubar	commish		running								
TREK/LFU	JPARC	T violation/universality				P36 rur	E06 run?						
KOTO	JPARC	K0->pi0nunubar	commish		running						stage 2?		
ORKA	Fermilab	K+ ->pi+ nu nubar					proposed						
Project X												stage 1	
			commisioning										
			run (run dates approximate)										
			proposed										
			considered										

NA62: the experimental technique

Decay-in-flight technique:

Advantages
(wrt decay at rest)

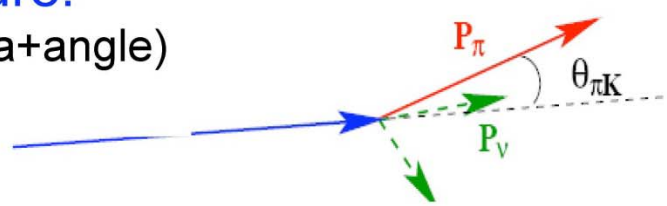
- ➔ easy to have high intensity beam
- ➔ easy to veto high energy photons

Disadvantages

- ➔ long detector and decay region
- ➔ event by event measurement of K momentum
- ➔ unseparated hadron beam

Signal signature:

1 track (momenta+angle)
+ nothing



Background:

All K decays + accidental charged particles
(beam particle interactions)

➔ A challenging experiment with weak signal signature ($BR_{SM}=8\times10^{-11}$) and huge background from kaon decays

Decay	BR
$\mu^+\nu$ ($K_{\mu2}$)	63.5%
$\pi^+\pi^0$ ($K_{\pi2}$)	20.7%
$\pi^+\pi^+\pi^-$	5.6%
$\pi^0e^+\nu$ (K_{e3})	5.1%
$\pi^0\mu^+\nu$ ($K_{\mu3}$)	3.3%
$\pi^+\pi^0\pi^0$	1.8%
$\mu^+\nu\gamma$ ($K_{\mu2\gamma}$)	0.62%
$\pi^+\pi^0\gamma$	2.7×10^{-4}
$\pi^+\pi^-e^+\nu$ (K_{e4})	4.1×10^{-5}
$\pi^0\pi^0e^+\nu$ (K_{e4}^{00})	2.2×10^{-5}
$e^+\nu$ (K_{e2})	1.5×10^{-5}
$\pi^+\pi^-\mu^+\nu$ ($K_{\mu4}$)	1.4×10^{-5}

NA62: guiding principles

GOAL: 10% precision measurement of BR($K^+ \to \pi^+ \nu\bar{\nu}$)

⇒ O(100) $K^+ \to \pi^+ \nu\bar{\nu}$ decays with ~10% background in 2 years data taking

Requirements:

Statistics:

- BR(SM) ~ 8 x 10^{-11}
- Acceptance: 10%
- K decays: ~10^{13}

Kaon intensity, signal efficiency

Systematics:

- ≥10^{12} background rejection
- ~10% precision on background measurement

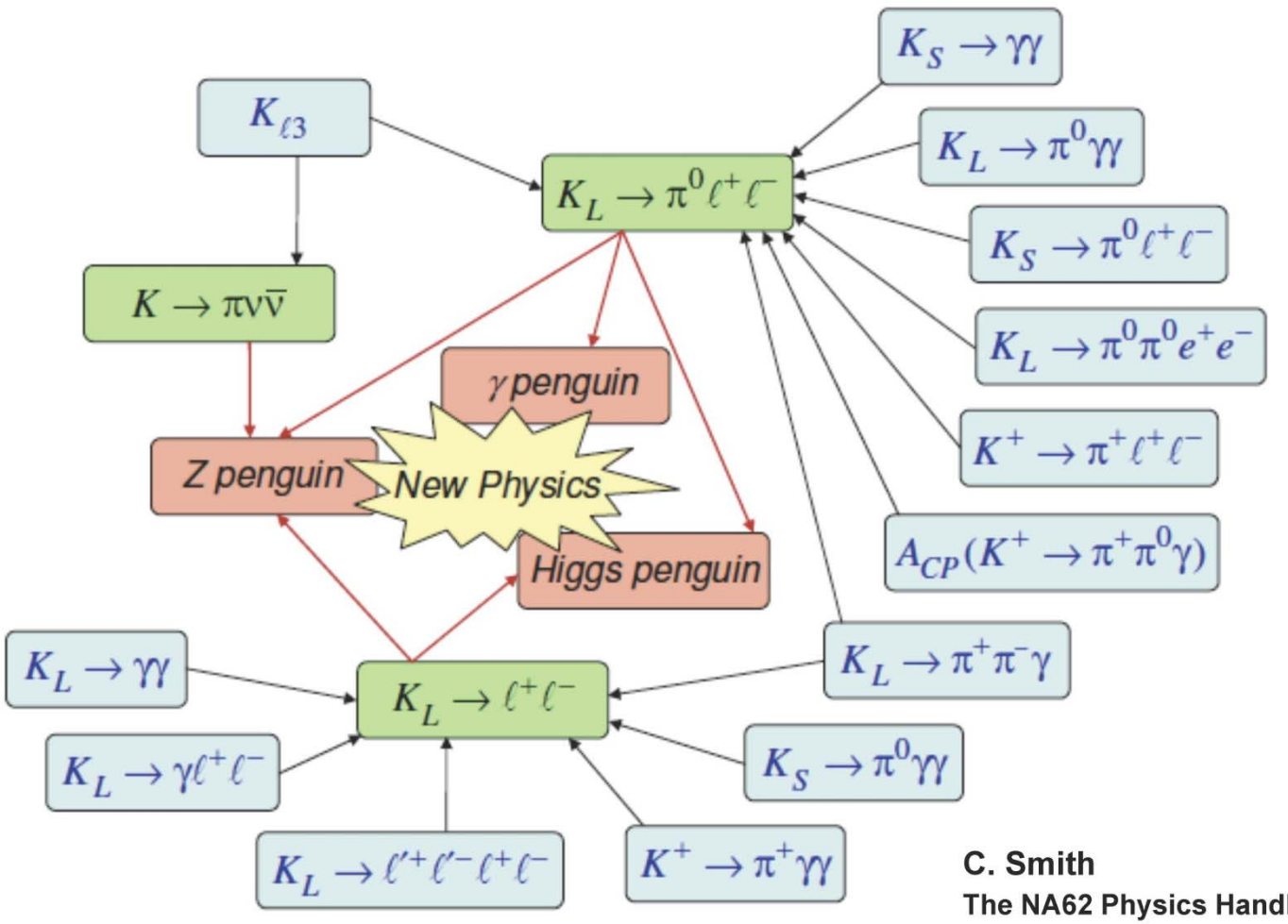
Signal purity, detector redudancy

- ➔ precise high-resolution timing, to support a high-rate environment;
- ➔ kinematic rejection, involving cutting on the square of the missing mass of the observed particles in the decay with respect to the incident kaon vector;
- ➔ particle identification of kaons, pions, muons, electrons and photons;
- ➔ hermetic vetoing of photons out to large angles and of muons within the acceptance;
- ➔ redundancy of information.

Patrizia Cenci

Outlook

Kaon decays: the full picture



C. Smith
The NA62 Physics Handbook Workshop
CERN, 10-12.12.2009

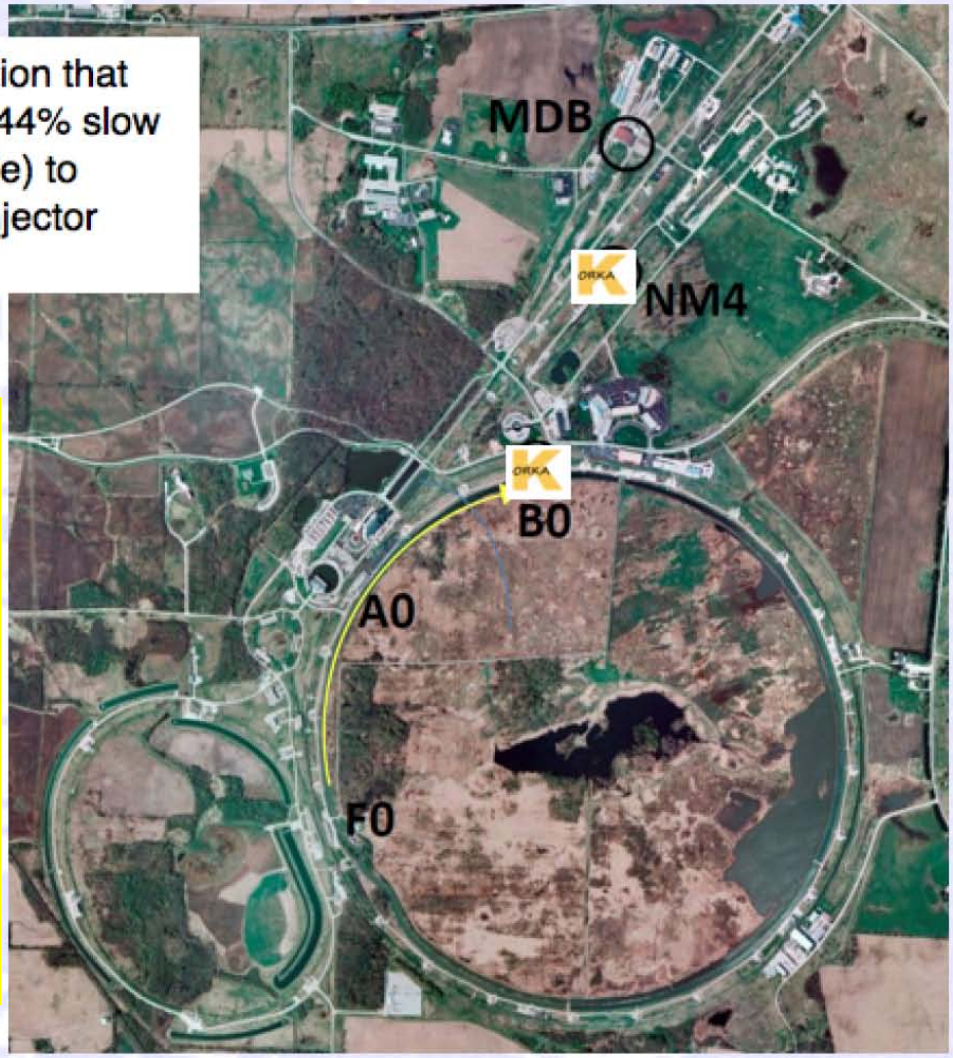
Patrizia Cenci

PXPS12 68

ORKA at Fermilab

Improvements for ORKA Kaon production and transport

ORKA is proposing a configuration that delivers 75kW (95 GeV) with a 44% slow spill fraction (4.4s spill, 10s cycle) to ORKA and a balance of Main Injector cycles to NOvA operations.



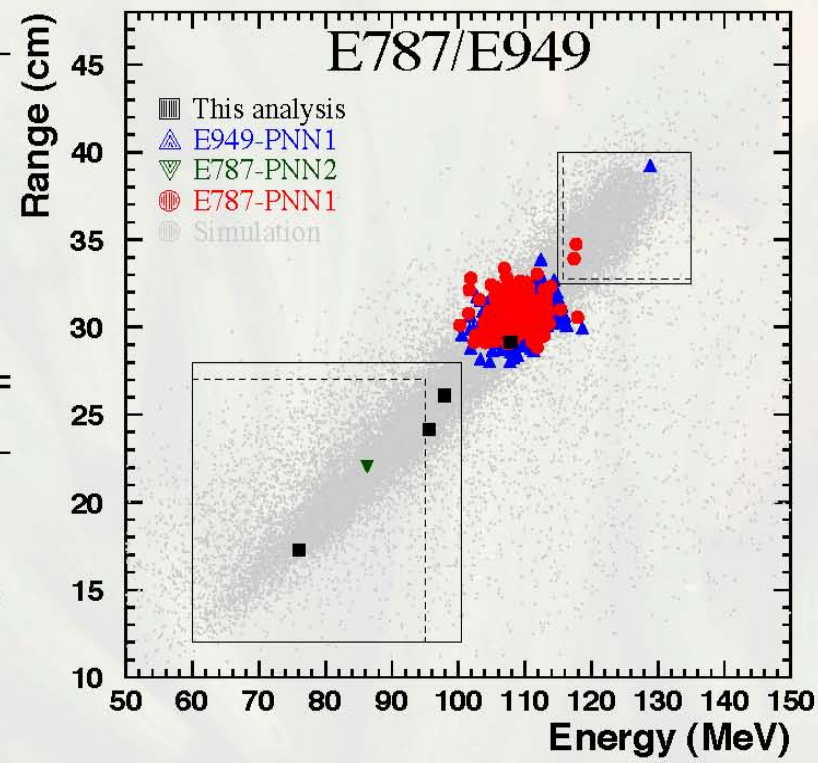
- **Main Injector beam**
- **Charged K's decay at rest**
- **Based upon BNL E787/949**
  - **Acceptance/detector/ beam improvements**
- **Preferred location is CDF**
  - **Need new transfer line**

David Jaffe

E949/E787 Results

PNN1	E949	E787
Kaons	1.8×10^{12}	5.9×10^{12}
Bkgd evts	0.30 ± 0.03	0.14 ± 0.05
Acceptance	2.2×10^{-3}	2.0×10^{-3}
$N_{\rm obs}$	1	2
S/B	1.1	8, 59

PNN2	E949	E787
Kaons	1.7×10^{12}	1.7×10^{12}
Bkgd evts	$0.93 \pm {}^{0.36}_{0.29}$	1.22 ± 0.24
Acceptance	1.37×10^{-3}	0.84×10^{-3}
$N_{\rm obs}$	3	1
S/B	0.20, 0.42, 0.47	0.20



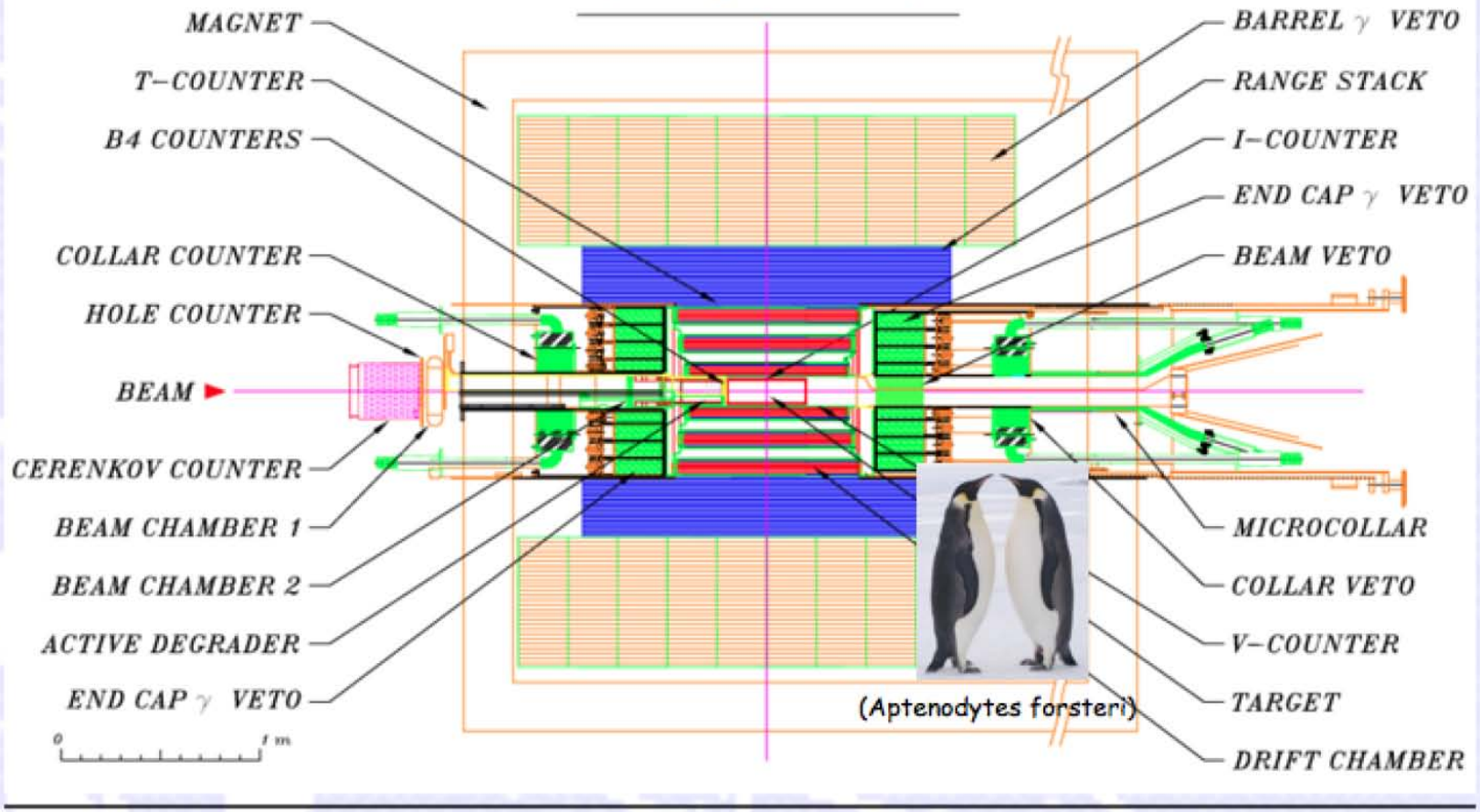
$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

Standard model $(0.78 \pm 0.07) \times 10^{-10}$

$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ was evaluated with a likelihood method that takes into account the signal-to-background ratio S/B of the individual candidates.

David Jaffe

ORKA is a 4th Generation Detector
- x100 sensitivity -
x10 from kaon flux, x10 from detector



David Jaffe

David E. Jaffe (BNL) PXPS2012 18 June 2012 9 / 44

ORKA measurements & thesis 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}
- $K^+ \to \pi^+ \gamma\gamma\gamma$
- $K^+ \to \pi^+ \mathrm{DP}$; $\mathrm{DP} \to e^+ e^-$
- 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}
- $\pi^0 \to \gamma \mathrm{DP}$; $\mathrm{DP} \to e^+ e^-$
- $\pi^0 \to \gamma X$

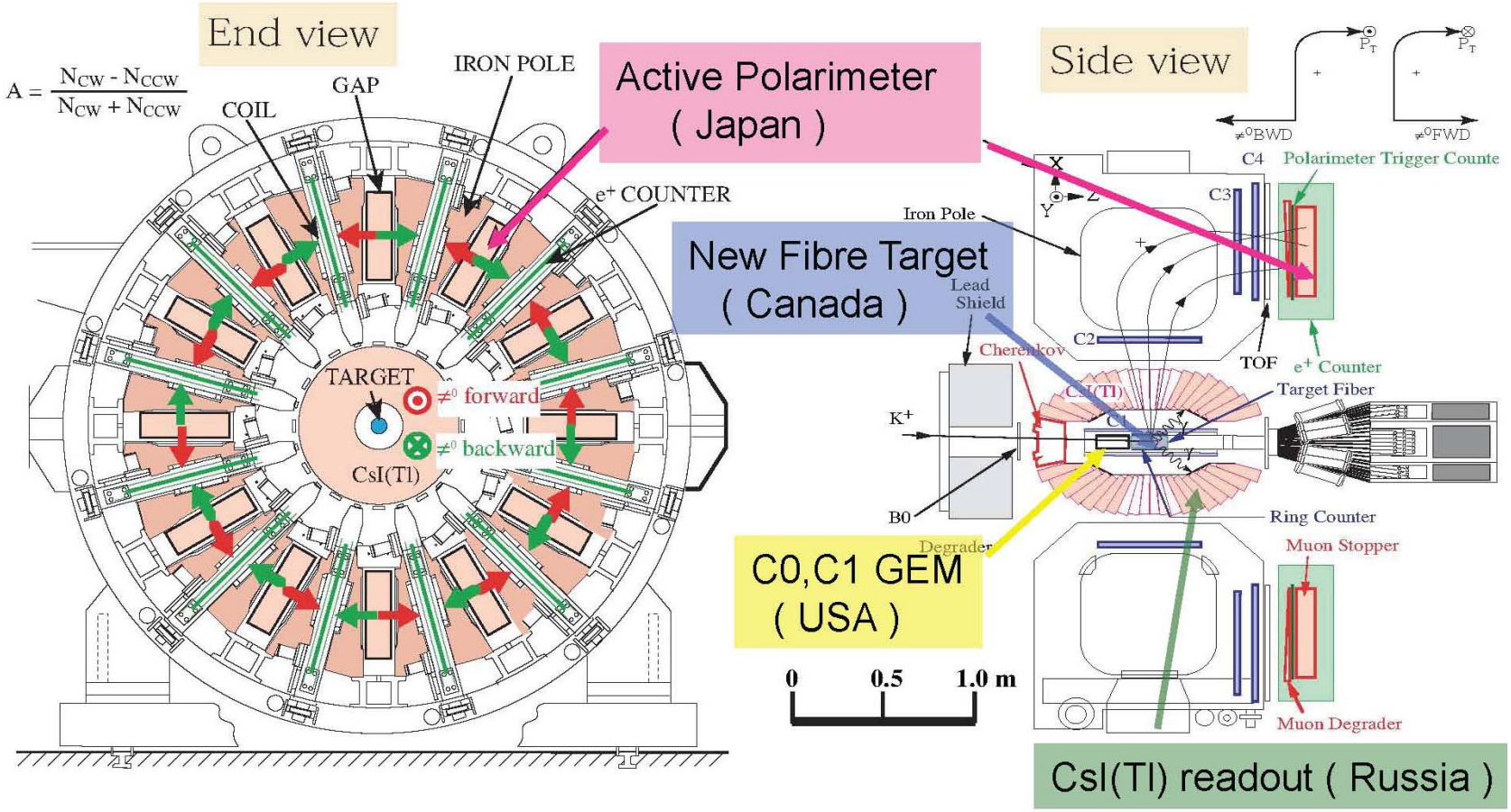
^{T}E787/E949 Thesis ; ^{P}E787/E949 Publication; DP≡Dark Photon

Elizabeth Worcester

TREK Experimental Apparatus

$K^+ \rightarrow \pi^0 \mu^+ \nu$

Use an upgraded E246 detector



P_T is measured as the azimuthal asymmetry A_{e^+} of the μ^+ decay positrons

Michael Hasinoff

Stopped K^+ Experiments @ K1.1BR

Run after P36 if intensity and beamline available.
Or maybe move to Project X?

- E06 (TREK)

  "**Measurement of the T-violating transverse muon polarization (P_T) in $K^+ \rightarrow \pi^0 \mu^+ \nu$ decay**"

  Stage-1 approved needs 270 kW (≥ 100 kW)

- P36 (LFU)

  "**Measurement of $R_K = \Gamma(K^+ \rightarrow e^+\nu) / \Gamma(K^+ \rightarrow \mu^+\nu)$ and search for heavy sterile neutrinos**"

  Stage-1 recommended (PAC11-Jan'11) only 30 kW

R&D now
Plan to run in 2015

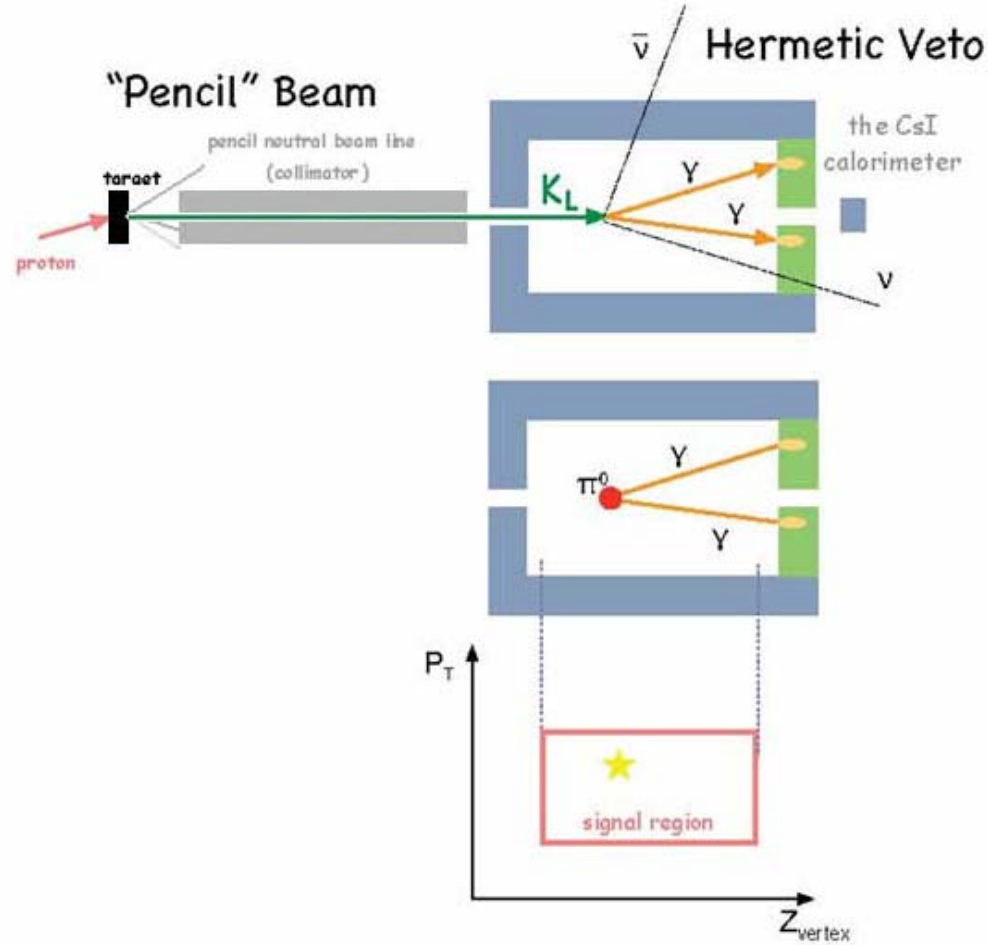
Michael Hasinoff

$K_L \rightarrow \pi^0 \nu\nu$ goal of sensitivity to few events @SM

KOTO at JPARC

The Basic Strategy

- Pencil beam
- Hermetic veto
- Reconstruction of π^0 vertex and P_t assuming π^0 mass



Yau Wah

Background and Sensitivity

	J-PARC KOTO	KEK-E391a	improvement
KL yield/spill	8.1×10^{6}	3.3×10^{5}	x30/sec
Run time	12 months	2 months	x6
Decay prob.	3.6%	2.1%	x2
Acceptance	4.7%	1%	x3.6
Sensitivity	0.8×10^{-11}	1.1×10^{-8}	x1300

Background source	#evts
$K_L \to \pi^0\pi^0$	1.8
$K_L \to \pi^+\pi^-\pi^0$	0.46
n + residual gas	0.04
n + upstream veto	0.13
accidental coincidence	0.10
sum	2.5
$K_L \to \pi^0\nu\bar{\nu}$ signal	3.5

Yau Wah

KOTO

- Gained much experience from E391a
  - Dealing with backgrounds
- Commissioning run later this year with ~30kW beam.
- Run again in late 2013.
- Need 3 years with 300 kW to get to SM sensitivity

- Thinking about a 100 event experiment for next generation.

Landscape later this decade

- BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$)
  - 10% measurement from NA 62
  - ORKA (maybe) in progress on way to few % BR
- BR($K^0 \rightarrow \pi^0 \nu\bar{\nu}$)
  - KOTO in progress on way to SM sensitivity
- Other measurements
  - Universality test from P36
  - Other measurements from NA 62
  - T violation search in progress (maybe) at TREK
  - Other measurements (maybe) from ORKA

- **Conclusion: significant but modest progress in kaon sector of the next few years. Much room for more experimental work in Project X era.**

Kaons at Project X

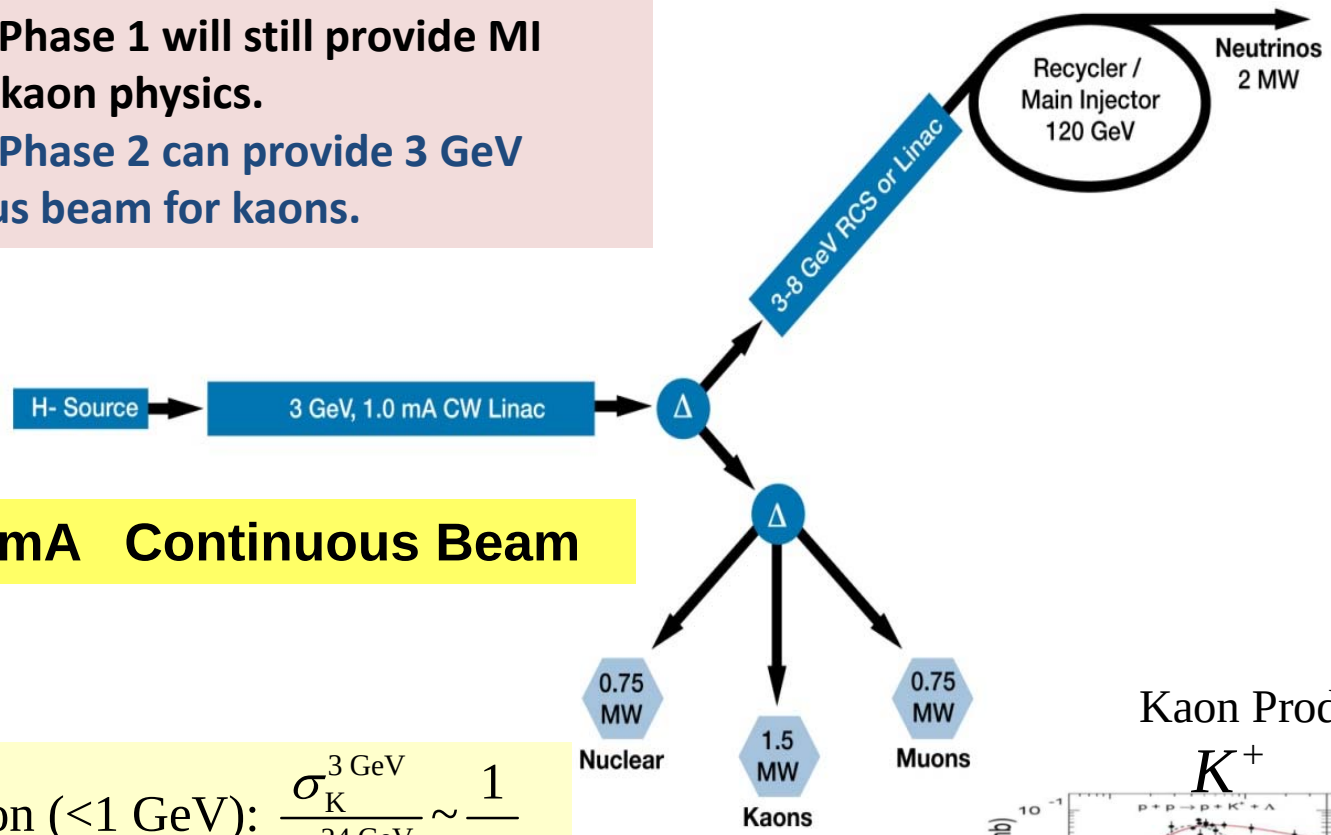
- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
  - but hopefully it's already done to a few %.

- $K_L \rightarrow \pi^0 \nu \bar{\nu}$
  - "This experiment was made for Project X" –L. Littenberg

- Many other modes of interest
  - T violation in $K^+ \rightarrow \pi^0 \mu \nu$ (TREK)
  - Universality $\Gamma(K^+ \rightarrow e^+ \nu)/\Gamma(K^+ \rightarrow \mu^+ \nu)$
  - $K_L \rightarrow \pi^0 \mu\mu$ and $\pi^0 ee$ (look at K_S/K_L interference?)
  - K^+, K_L lepton flavor violation e.g. $K_L \rightarrow \mu e$
  - $K_L \rightarrow \gamma\gamma$
  - ...

Fermilab Project X

Project X Phase 1 will still provide MI beam for kaon physics.
Project X Phase 2 can provide 3 GeV continuous beam for kaons.



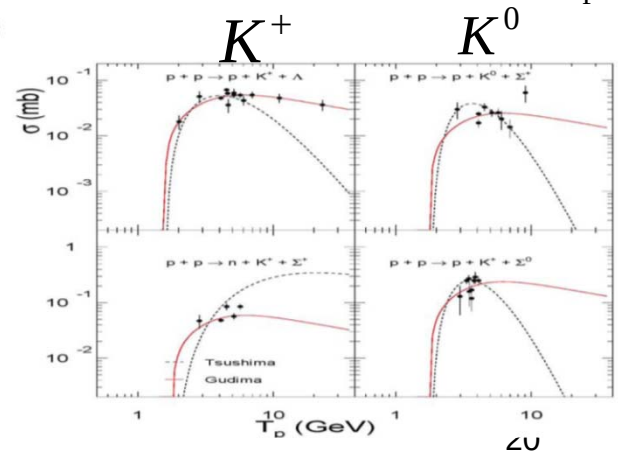
3 GeV 1 mA Continuous Beam

K production (<1 GeV): $\frac{\sigma_K^{3\ \mathrm{GeV}}}{\sigma_K^{24\ \mathrm{GeV}}} \sim \frac{1}{10}$

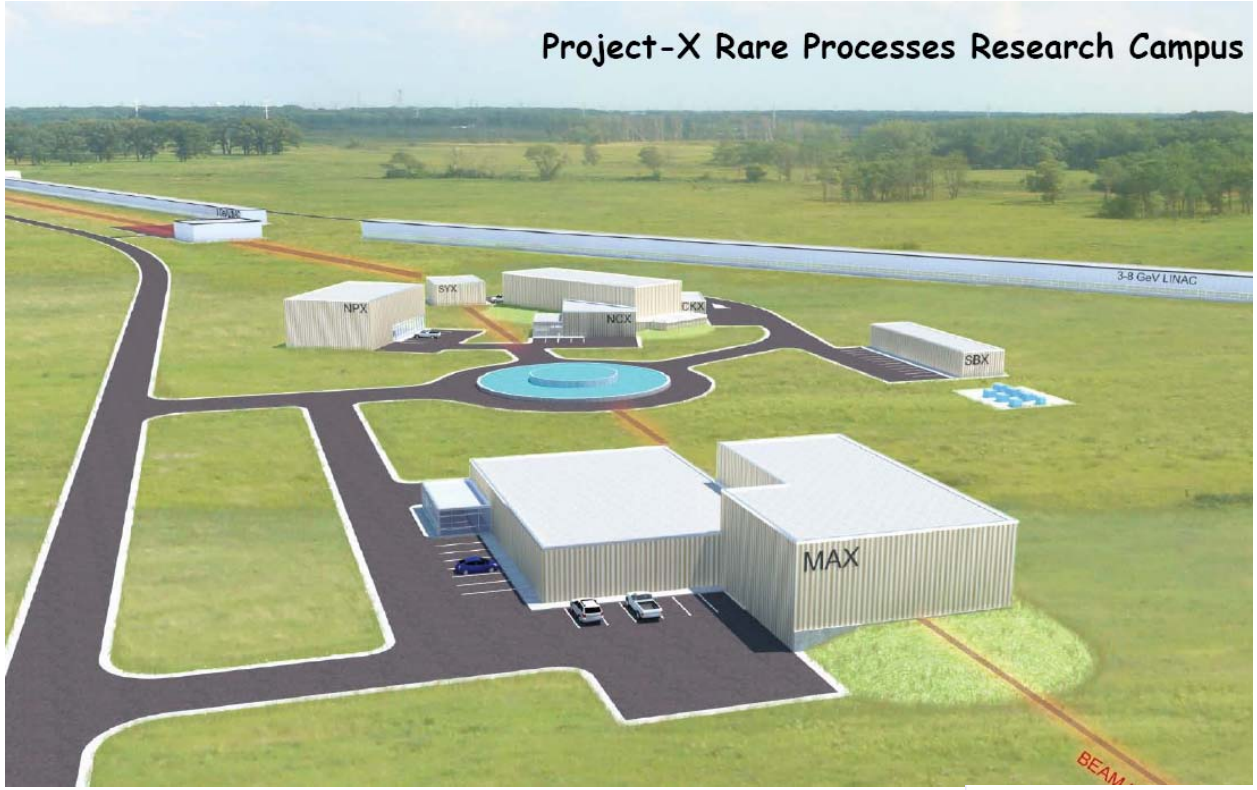
p beam intensity: $\frac{\text{Proj. X}}{\text{AGS}} \sim 300$

K flux: $\frac{\text{Proj. X}}{\text{AGS}} \sim 30$

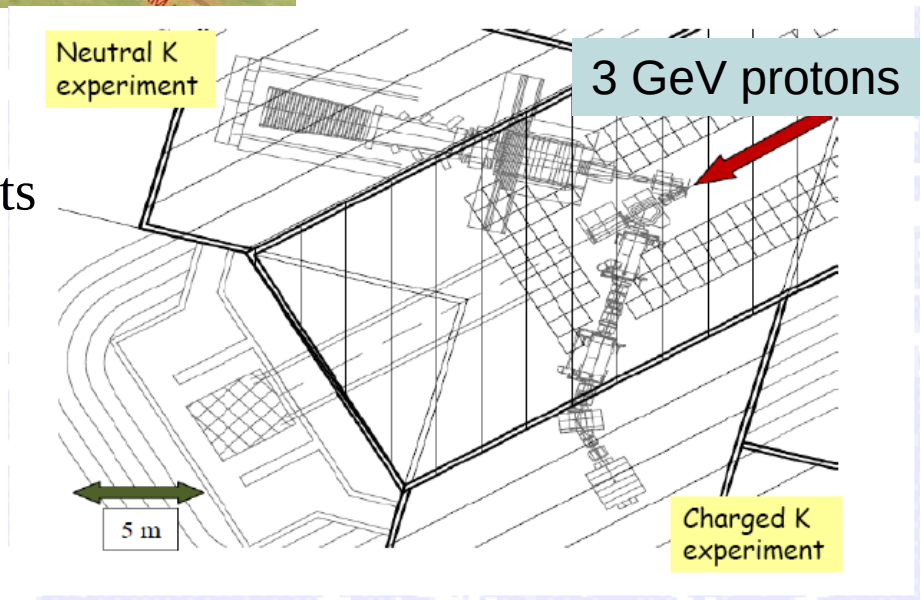
Kaon Production *vs.* T_P



Doug Bryman



Project X Kaon Hall

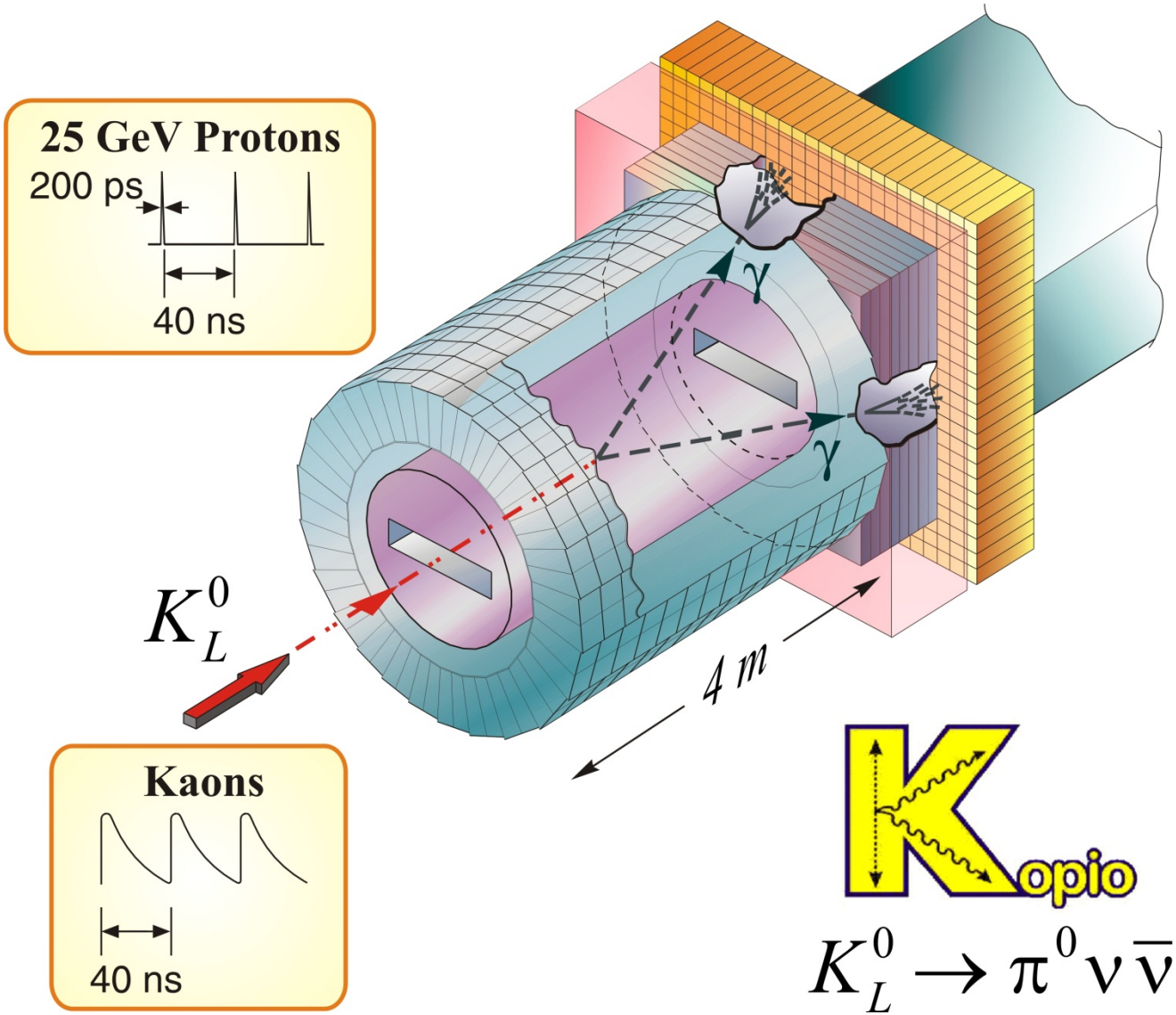


Common target for K^+ and K_L^0 Experiments

e.g. $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L^0 \to \pi^0 \nu\bar{\nu}$

Doug Bryman

KOPIO-type experiment at Project-X



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

The Challenge of $K_L \rightarrow \pi^0 \nu\nu$ at Project X

- "Nothing in – Nothing out"
- $B(K_L \rightarrow \pi^0 \nu\bar{\nu}) \sim 3\times10^{-11}$, need huge flux of K's
  - rates inevitably rather high
- Kinematic signature weak (2 particles undetectable)
- Backgrounds with π^0 up to 10^{10} times larger
- Veto inefficiency on extra particles must be $\leq 10^{-4}$
- Huge flux of neutrons in beam
  - can make π^0 off residual gas – require high vacuum
  - halo must be very small
  - hermeticity requires photon veto in this beam
- Need convincing measurement of background

Laurie Littenberg

Project-X Stage 2 Advantages for $K_L \rightarrow \pi^0 \nu\nu$

- K spectrum better for timing
- Smaller beam has enormous benefits:
  - Nearly impossible vacuum vessel disappears
  - Geometric acceptance increases since horizontal plane accessible
  - Makes beam-line simpler, cheaper, better
  - Upstream background disappears, so do some types of background in the fiducial volume
  - Same micro-bunch event spoilage diminished
  - Random vetoes much reduced
  - Extra kinematic constraint increases S/B
  - In-beam veto probably unnecessary
  - Apparatus shorter, DS vetoes simpler, less lossy
  - Beam spoiler probably unnecessary
    - Gives 72% more kaons/proton
    - Much reduces neutron spreading
  - Detector can be symmetrized, geometric acceptance increased
- Crude estimate ~ 300 events/year

Laurie Littenberg

Observations

- **Near term experiments: NA 62, KOTO, P36 need to succeed.**

- **ORKA needs to run later this decade**
  - **high precision $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ interesting, timely & doable**
  - **Seeds the effort (physics, people, technology) for a Project X kaon program.**

- **Project X kaon experiments**
  - **Will definitely be interesting in the next decade**
  - **Need a high precision measurement of $K_L \rightarrow \pi^0 \nu\bar{\nu}$**
    - **KOTO experience indicates that it may take 2 generations to get to 1000 event sensitivity.**
  - **Can we design a multipurpose experiment that will do lots of other modes?**

Technology Issues for PX Kaon Experiments

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

  ~20 ps for Calorimeter would match beam pulse width

- Calorimetry

  Veto function -- sub-ns timing resolution at low visual energies, e.g. 1 MeV

  -- limitations from photonuclear effects

  Crystals vs. plastic scintillator/Pb sandwich

  Pointing function for photon measurements - ~10-20 mrad

- Particle ID

  π/μ

  Energy, range, momentum, TOF, dE/dx

  π-μ-e pulse shape analysis

  Extruded scintillator-wls readout-SiPM:

  Need faster, brighter performance

  K/π (beam particle id)

  Low momentum separation

- Tracking

  Low mass -- 100 μm resolution

  Applications of large area GEM or Micromegas

Doug Bryman

Conclusion

- **Kaon physics is an important and complimentary part of our "portfolio" of new physics probes.**

- **High precision and rare kaon decay experiments will continues to be interesting and relevant for the foreseeable future.**

- **Project X provides new opportunities**

Project X Campaign

Program:	Onset of NOvA operations in 2013	Stage-1: 1 GeV CW Linac driving Booster & Muon, n/edm programs	Stage-2: Upgrade to 3 GeV CW Linac	Stage-3: Project X RDR	Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2450 kW	2450-4000 kW
8 GeV Neutrinos	15 kW + 0-50 kW**	0-42 kW* + 0-90 kW**	0-84 kW*	0-172 kW*	3000 kW
8 GeV Muon program e.g, (g-2), Mu2e-1	20 kW	0-20 kW*	0-20 kW*	0-172 kW*	1000 kW
1-3 GeV Muon program, e.g. Mu2e-2	-----	80 kW	1000 kW	1000 kW	1000 kW
Kaon Program	0-30 kW** (<30% df from MI)	0-75 kW** (<45% df from MI)	1100 kW	1870 kW	1870 kW
Nuclear edm ISOL program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Ultra-cold neutron program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Nuclear technology applications	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
# Programs:	4	8	8	8	8
Total max power:	735 kW	2222 kW	4284 kW	6492 kW	11870kW

* Operating point in range depends on MI energy for neutrinos.
** Operating point in range depends on MI injector slow-spill duty factor (df) for kaon program.