The KOTO Experiment

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on behalf of the KOTO Collaboration

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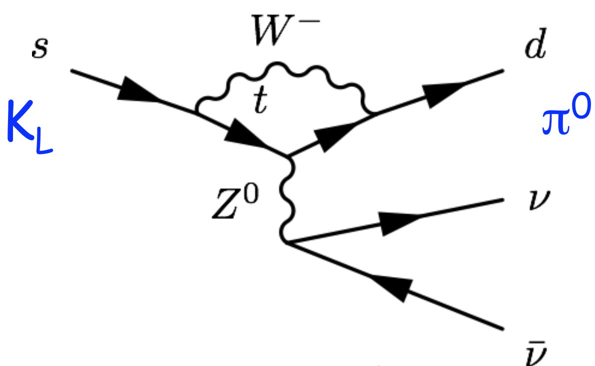
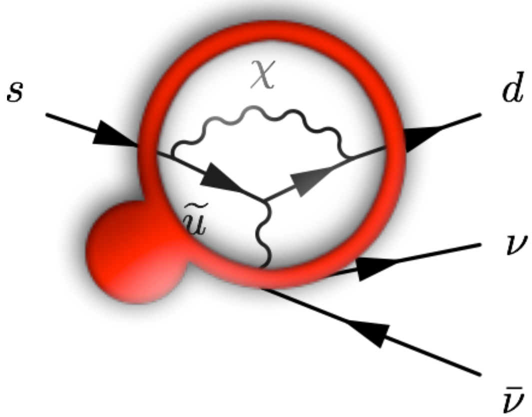
Physics Motivation

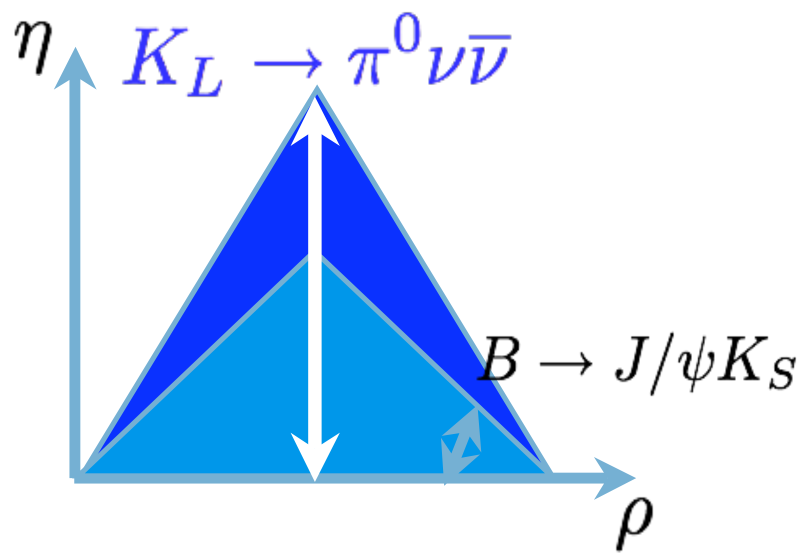
KOTO (K^0 at Tokai) aims at discovering the FCNC $K_L \to \pi^0 \nu\nu$

- SM predicts $BR(K_L \to \pi^0 \nu\nu) = 2.8 \times 10^{-11}$
- Direct CP violating process $\propto \eta^2$



- Sensitive to BSM physics





$K_L \rightarrow \pi^0 \nu\nu$ and BSM Physics

1. rare
2. small theoretical uncertainty (~15%)
   - ✓ hadronic matrix element from $BR(K^+ \rightarrow \pi^0 e^+ \nu)$ well known
   - ✓ short-distance physics dominated
   - ✓ small QCD corrections as heavy top dominates in the loop
3. Decays through loop processes

   ⇒ "Golden Mode", very sensitive to new physics

Present limits

a) from KEK E391a (PRL 100, 201802 (2008)) $Br < 6.7 \times 10^{-8} (90\% CL)$

b) from BNL E949 $(BR(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = 1.73^{+1.15}_{-1.05} \times 10^{-10})$

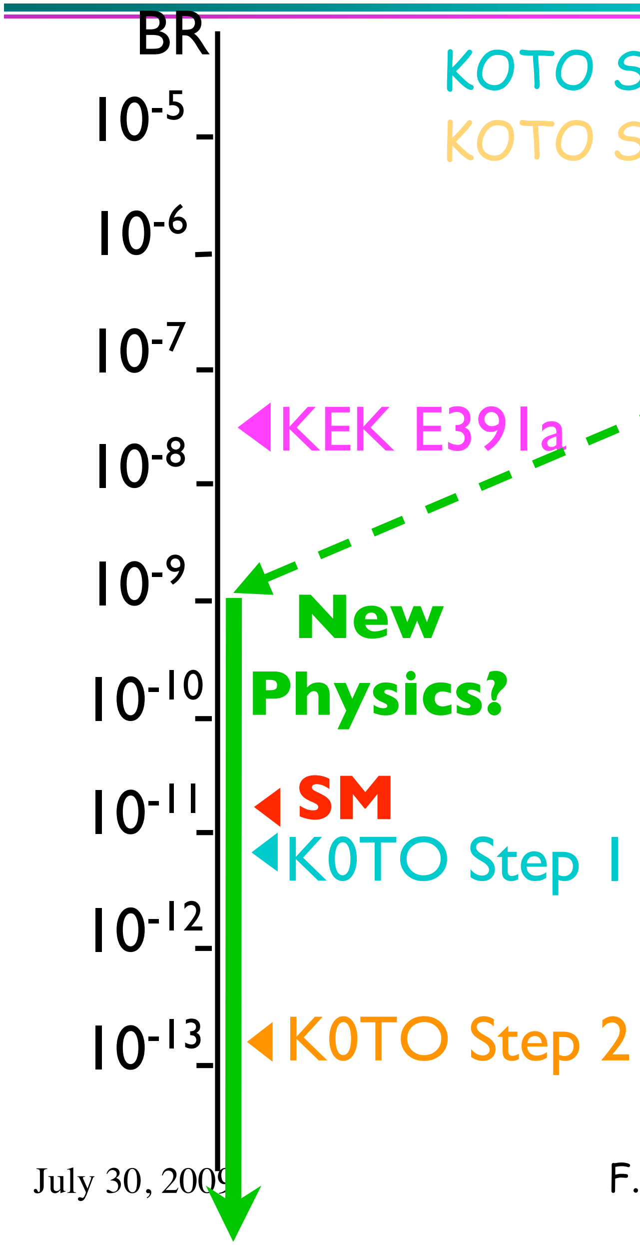
+ Grossman-Nir bound $Br < 1.5 \times 10^{-9} ("@90CL")$

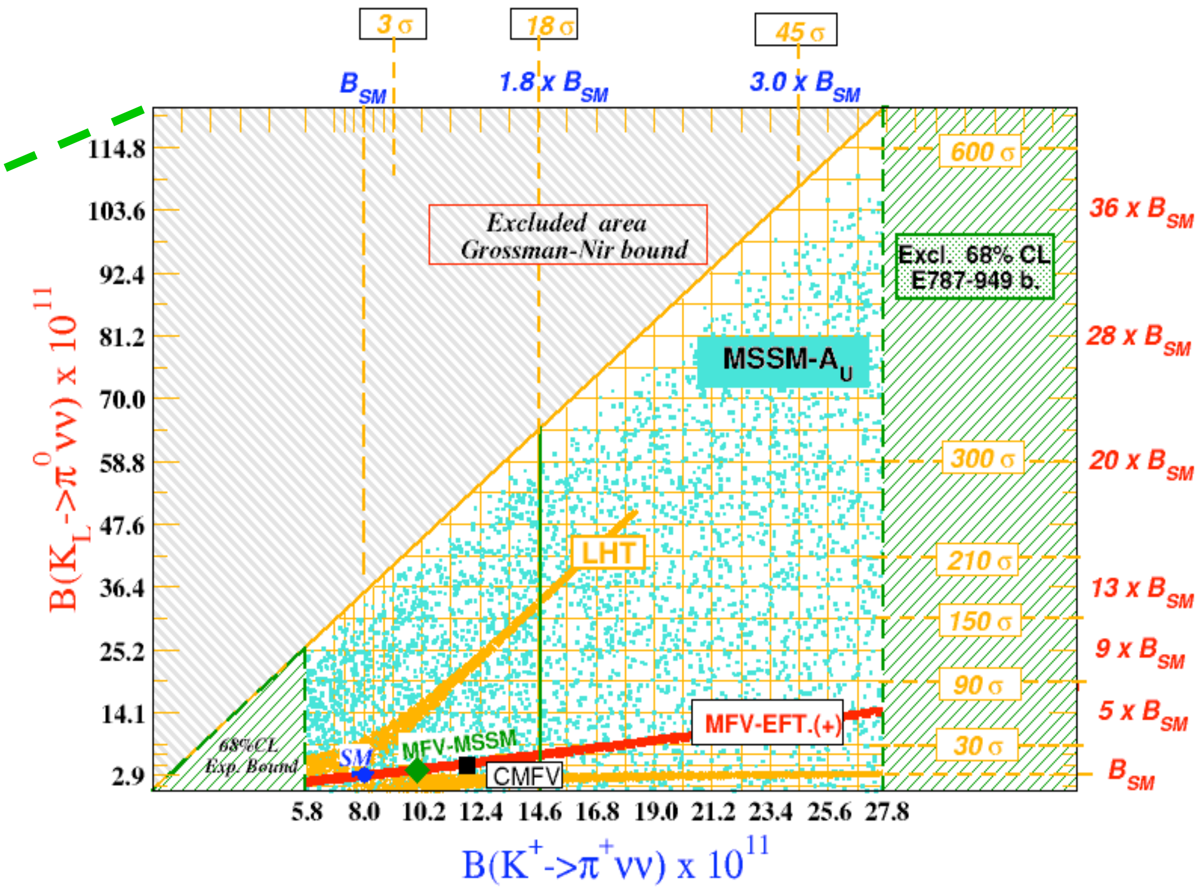
Still lot of room for BSM Physics!

KOTO and BSM Physics

KOTO Step 1: discovery

KOTO Step 2: 100 events for 5% η measurement



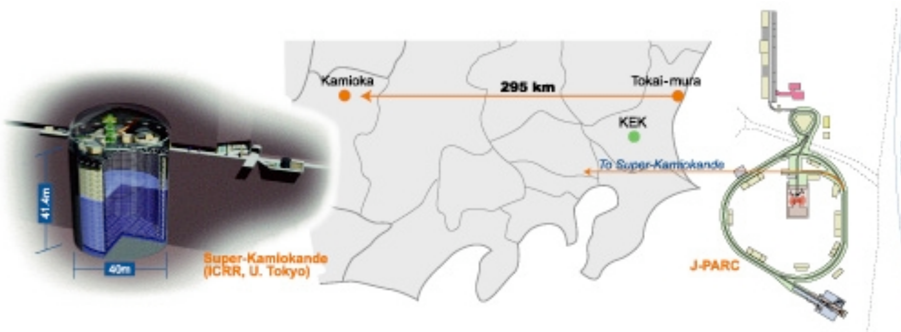


F. Mescia, Nov. 2008, http://www.lnf.infn.it/wg/vus/content/Krare.html

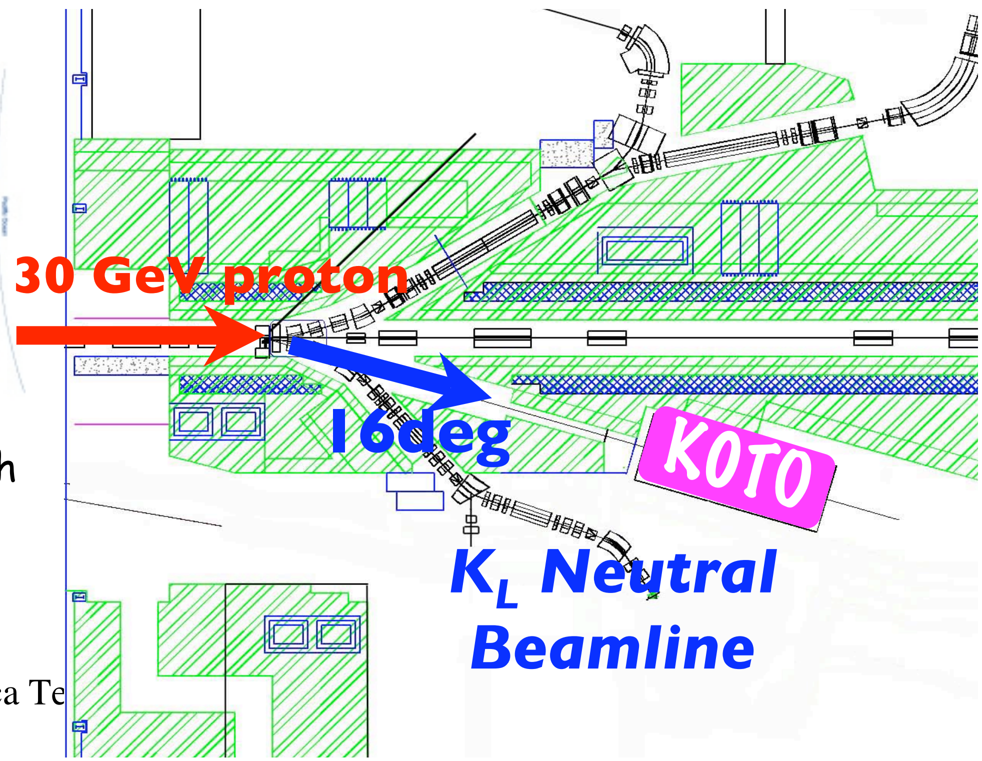
JPARC

JPARC (Japan Proton Accelerator Research Complex) is a joint project between KEK and Japan Atomic Energy Agency.

- Located in Tokai, 130 km NE of Tokyo
- Hosts, among other:
  - Neutrino facility, aiming beam to Kamiokande (T2K experiment)



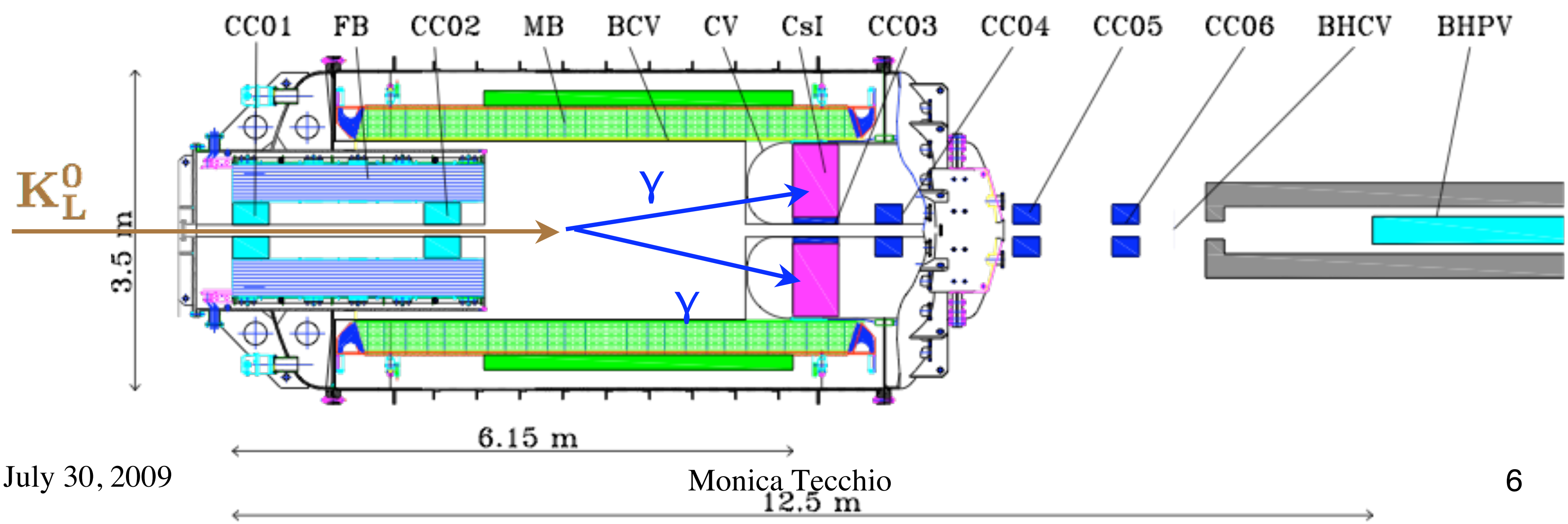
  - Nuclear and Particle Physics facility with 50 GeV PS with beam extraction to **Hadron Hall**



All pictures courtesy of KEK.

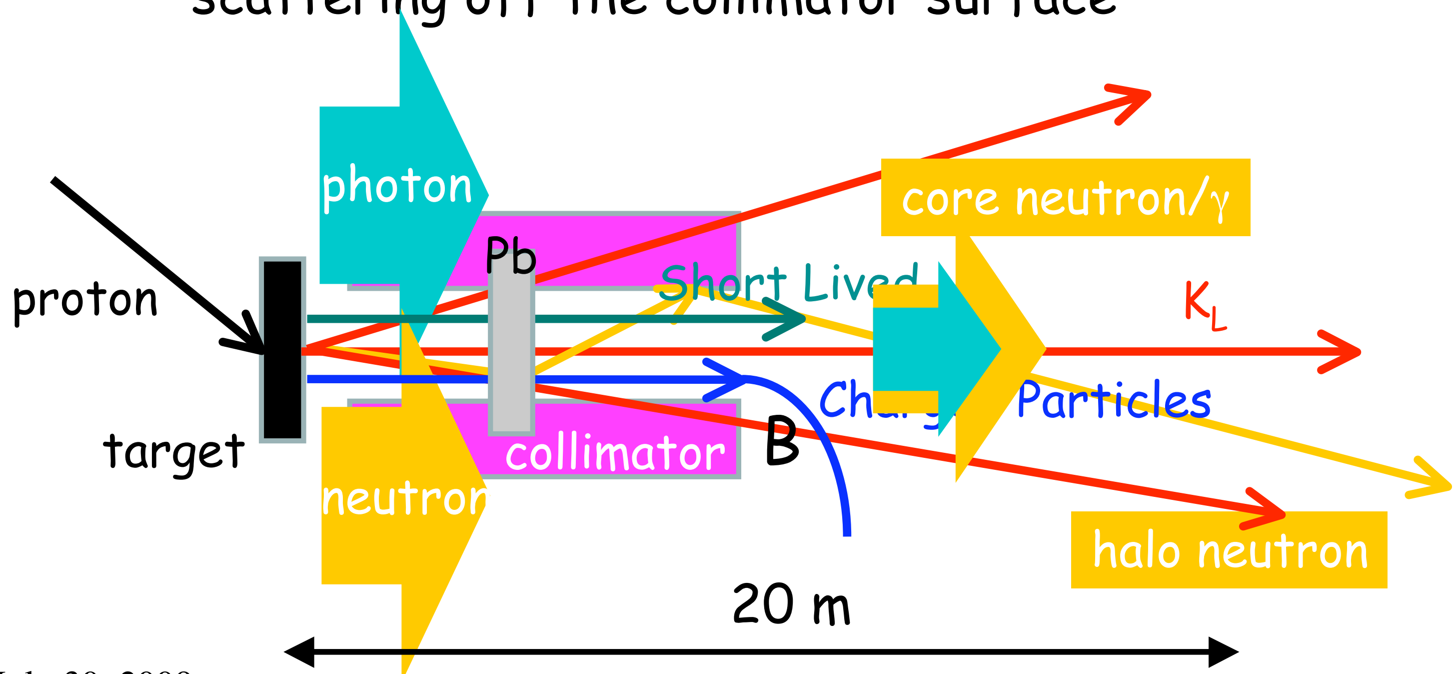
KOTO Detector

- Detector is un **upgrade** of E391a at KEK-PS, the first dedicated experiment for $K_L \rightarrow \pi^0 \nu \nu$
  - new beamline
  - new Csi calorimeter (from KTeV) and beam hole photon counter
  - new readout electronics
- Collaboration has ~65 collaborators from 5 countries (Japan-USA-Russia-Taiwan-Korea) and 15 institutions.



What does it take to catch a $K_L \to \pi^0 \nu\nu$?

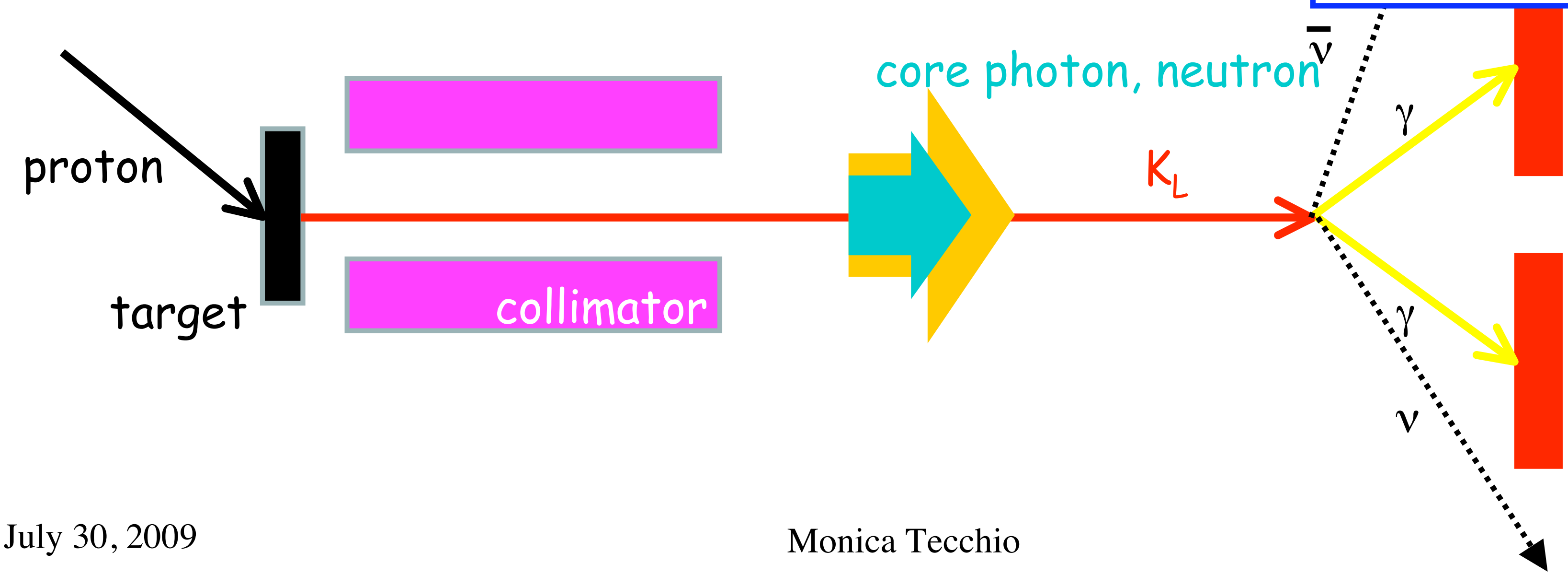
1. Clean K_L beam
   - shoot protons on target
   - collimate any particle produced off-beam
   - use long beam line to kill particles with short lifetime
   - absorb core photons and sweep away charged particles
   - shape collimators to minimize halo particles generated by scattering off the collimator surface



What does it take to catch a $K_L \to \pi^0 \nu\nu$?

1. Clean K_L beam ✓
2. High Acceptance Detector
   - $K_L \to \pi^0 \nu\nu$ is detected via $\pi^0 \to \gamma\gamma$ plus "nothing"
   - need thick finely-grained calorimeter
   - Any other K_L decay has either no p_T or extra photon/charged particle

K_L Decay	BR
$\pi^{\pm}e^{\mp}\nu_e$	3.88×10^{-1}
$\pi^{\pm}\mu^{\mp}\nu_\mu$	2.72×10^{-1}
$\pi^0\pi^0\pi^0$	2.10×10^{-1}
$\pi^+\pi^-\pi^0$	1.26×10^{-1}
$\pi^{\pm}e^{\mp}\nu_e\gamma$	3.53×10^{-3}
$\pi^+\pi^-$	2.09×10^{-3}
$\pi^0\pi^0$	9.32×10^{-4}
$\gamma\gamma$	5.90×10^{-4}
$\pi^{\pm}\mu^{\mp}\nu_\mu\gamma$	5.70×10^{-4}
$\pi^0\pi^{\pm}e^{\mp}\nu$	5.18×10^{-5}
$\pi^+\pi^-\gamma$	4.39×10^{-5}



What does it take to catch a $K_L \to \pi^0 \nu\nu$?

1. Clean K_L beam ✓
2. High Acceptance Detector ✓
3. Hermetic veto for photon and charged particles
   - with photon detection inefficiency ~ $10e^{-4}$
4. Pencil size beam
   - maximize calorimeter acceptance
   - constrain K_L decay vertex

K_L Decay	BR
$\pi^{\pm}e^{\mp}\nu_e$	3.88×10^{-1}
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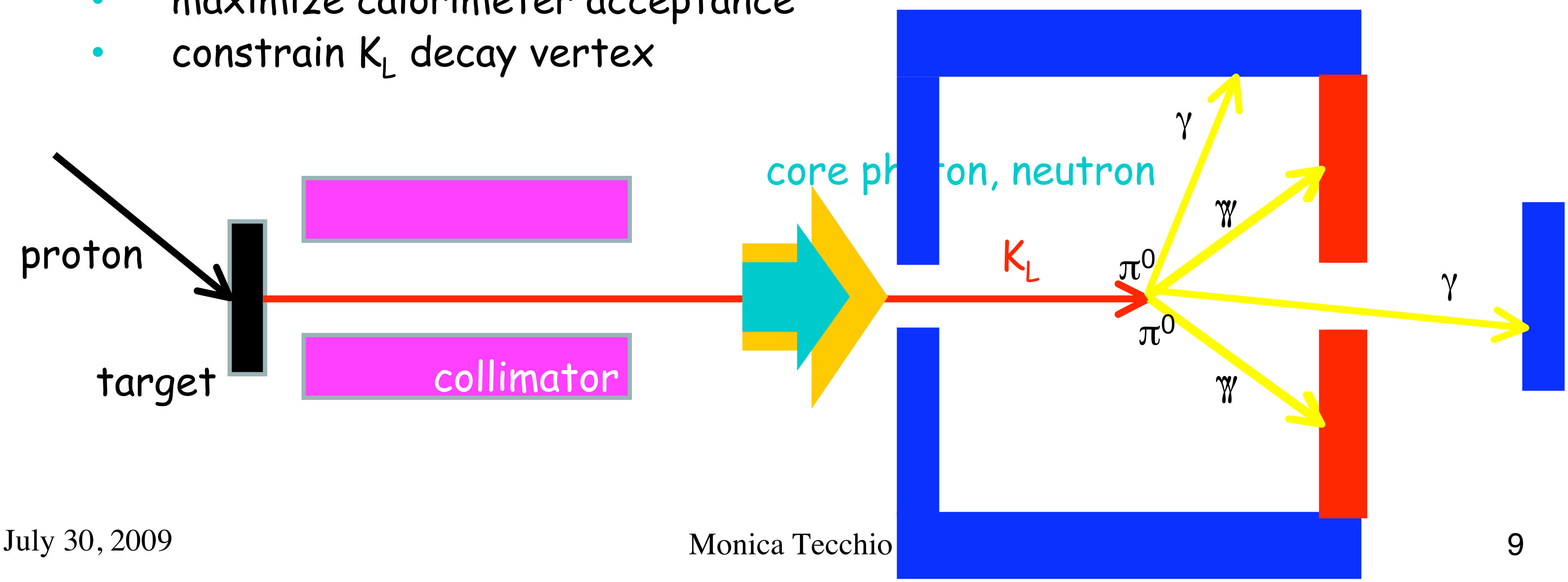

What does it take to catch a $K_L \to \pi^0 \nu\nu$?

1. Clean K_L beam ✓
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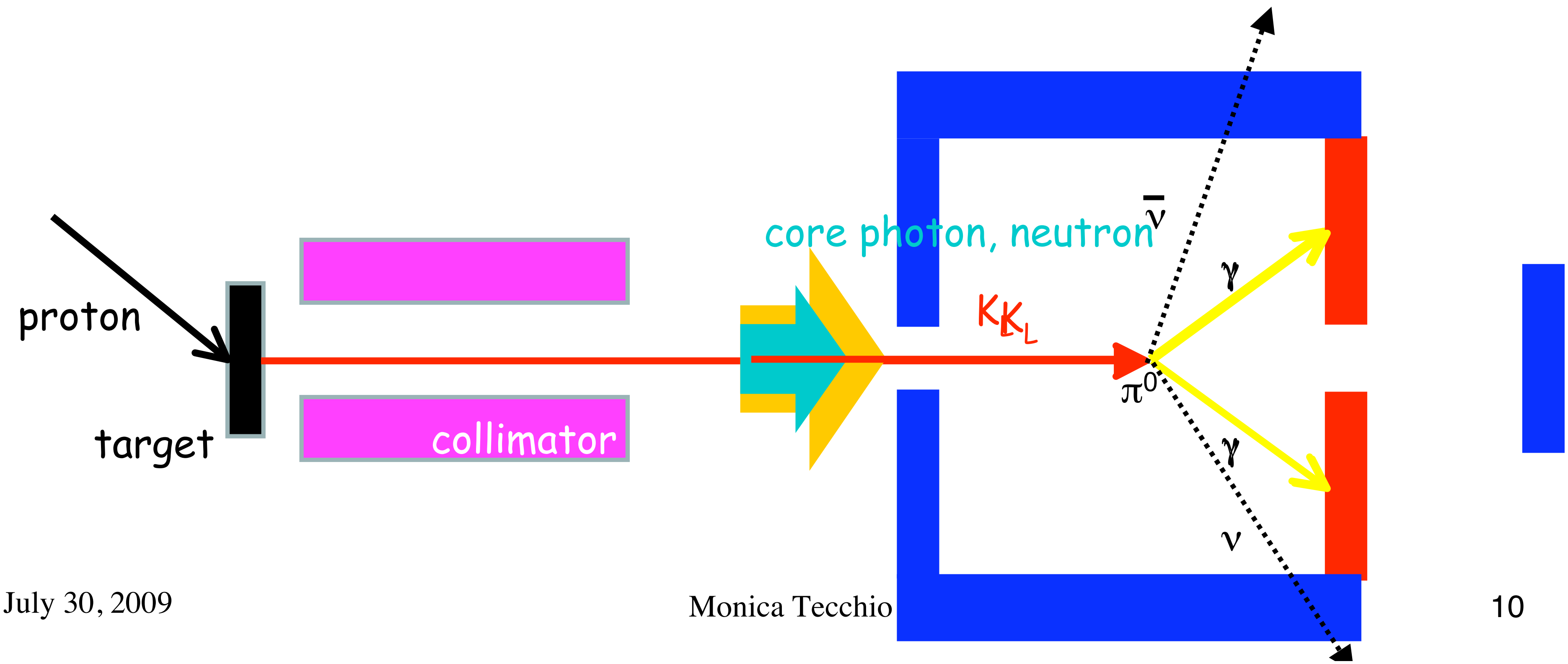
4. Pencil size beam ✓



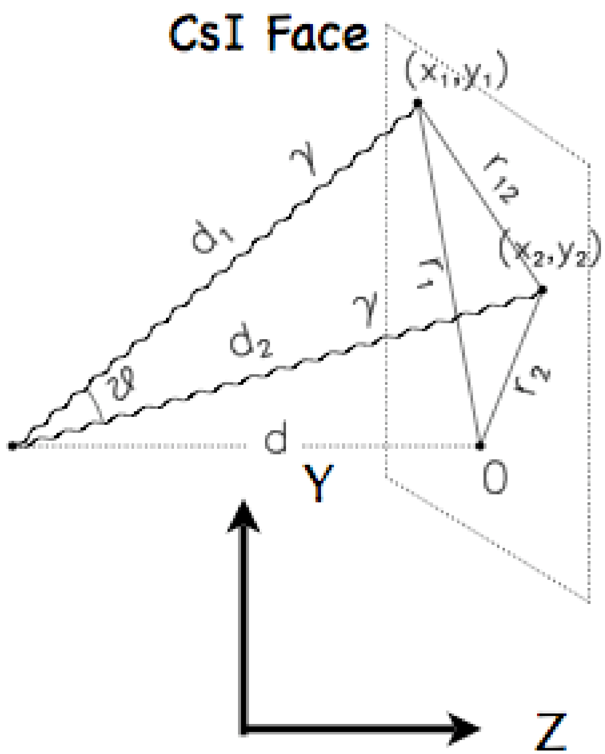
What does it take to catch a $K_L \to \pi^0 \nu\nu$?

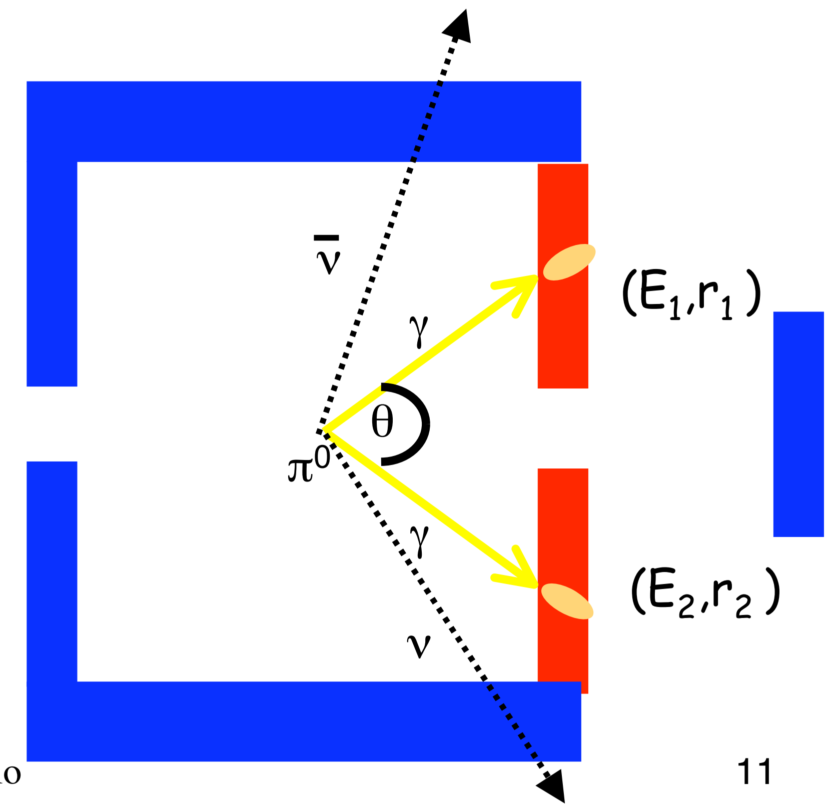
5. Fully reconstruct $K_L \to \pi^0 \nu\nu$ kinematics
   - calorimeter gives γ energy and position
   - by constraining 2γ system to π^0 mass, get the two photon opening angle θ
   - assuming K_L decay vertex on beam line, determine Z_{vtx} of π^0 decay

$$m_\pi^2 = (p_{\gamma_1} + p_{\gamma_2})^2 = 2\,E_1\,E_2 \times (1 - \cos\,\theta)$$

$$r_{12}^2 = d_1^2 + d_2^2 - 2\,d_1\,d_2 \cos\,\theta$$

NB: $E \propto 1/\theta$ while $m \propto \theta$

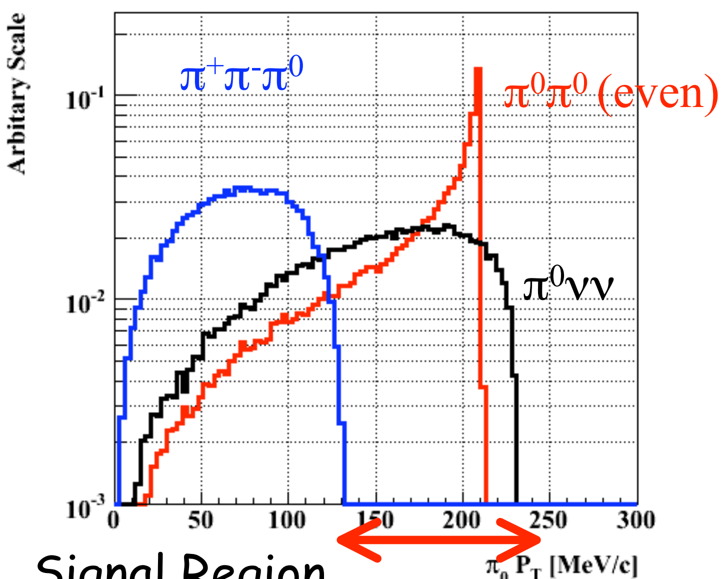




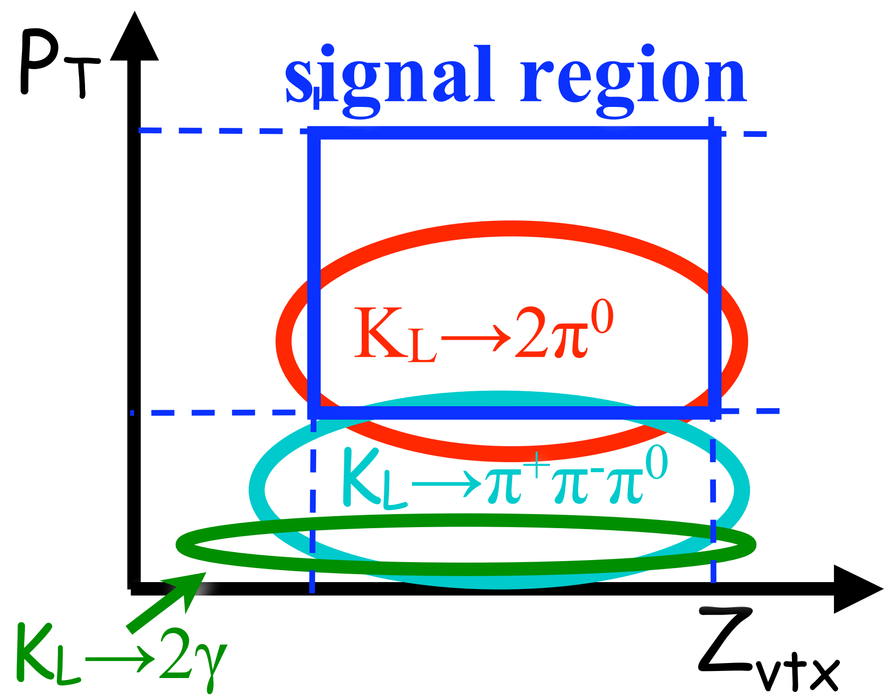
What does it take to catch $K_L \rightarrow \pi^0 \nu\nu$?

5. Fully reconstruct $K_L \rightarrow \pi^0 \nu\nu$ ✓
6. Identify kaon backgrounds
   - define signal box in π^0 P_T-Z_{vtx} using:
     - fiduciality cuts for Z_{vtx}
     - P_T above $K_{\pi 3}$ threshold and above (V-A) maximum of 231 MeV/c
   - no activity in vetoes

- kaon decays w/w.o. particles escaping detection:
  - low P_T or Z shifted upstream
  - have unphysical γ (E-θ) relation
  - larger 2γ energy ratio
  - fused clusters with wrong e.m. shower profile

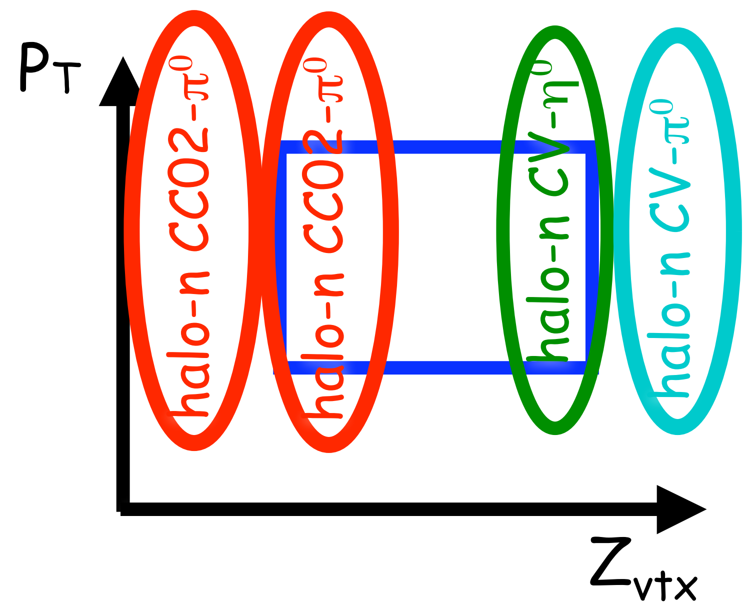


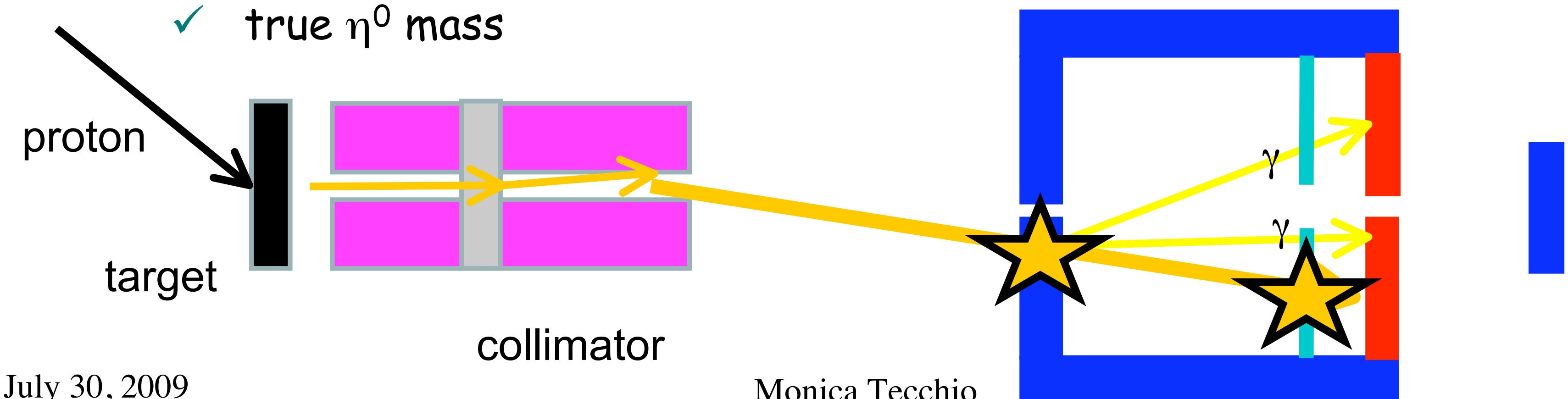
Signal Region



What does it take to catch $K_L \to \pi^0 \nu\nu$?

5. Fully reconstruct $K_L \to \pi^0 \nu\nu$ ✓
6. Identify kaon backgrounds ✓
7. Reduce halo neutron background due to **n interaction with gas/detector material** which creates π^0 / η^0
   - most material is at vacuum chamber entry (CC02 collar) or in the Charged Veto (CV) counter in front of the calorimeter
   - Z_{vtx} vertex position can shift and enter fiducial region if
     - ✓ energy mis-measurement
     - ✓ true η^0 mass





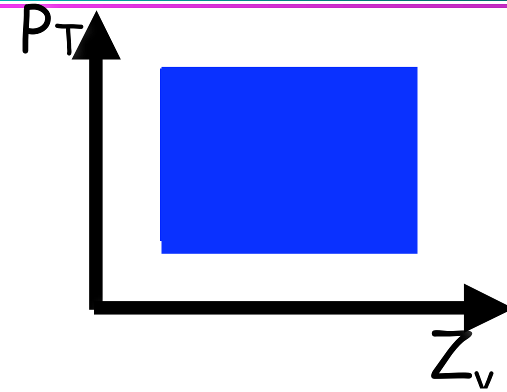
How many $K_L \rightarrow \pi^0 \nu\nu$ will we catch?

$K_L \rightarrow \pi^0 \nu\nu$ Single Event Sensitivity

$$S.E.S = \frac{1}{N_K \times D \times A} = 9 \times 10^{-12}$$

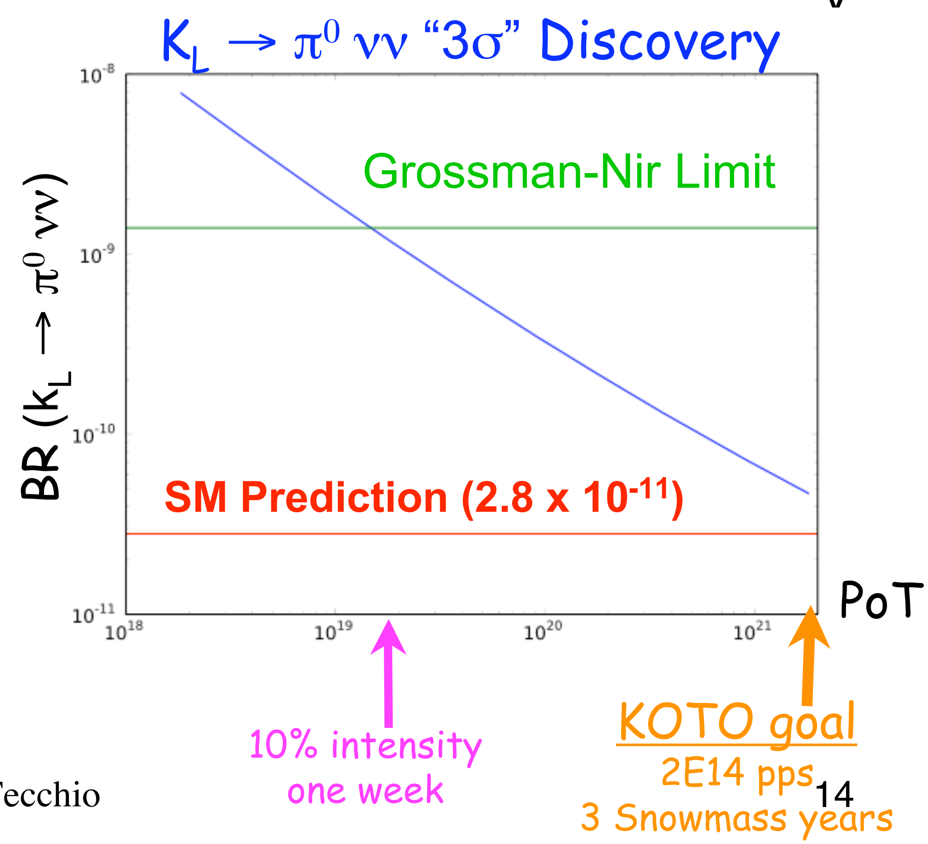
from table in next slide

- D = decay probability
- A = acceptance(*)
- N_K = Total K_L yield (over 3 Snowmass yr) = 7.4×10^{13}



Background simulation predicts

S/B = 1.4



(*) includes Acceptance Loss due to accidental/back-splash

Lessons from E391a

Basic experimental method is sound: BR < 6.7x10-8 (at 90%CL)

a) Need to suppress halo-n and especially reduce $n \to \eta^0$ production
b) Need better calorimeter
c) Need more kaons

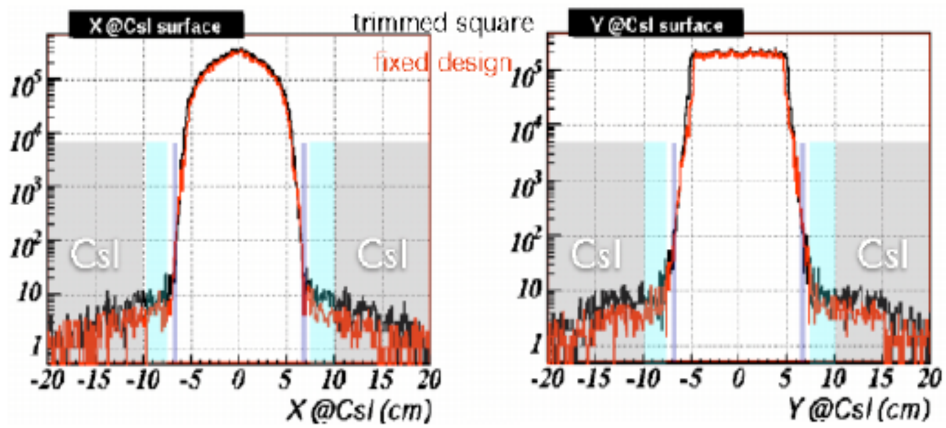
	KOTO	E391a (Run2)	
Proton energy	30 GeV	12 GeV	
Proton intensity	$2e^{14}$	$2.5e^{12}$	
Spill/cycle	0.7/3.3sec	2/4sec	
Extraction Angle	16 deg	4 deg	
Solid Angle	9μStr	12.6μStr	
K_L yield/spill	$8.1e^6$	$3.3e^5$	x25
Run Time	12 months/ (3 Snowmass years)	1 month	x10
Decay Prob.	4%	2%	x 2
Acceptance	3.6%	0.67%	x5

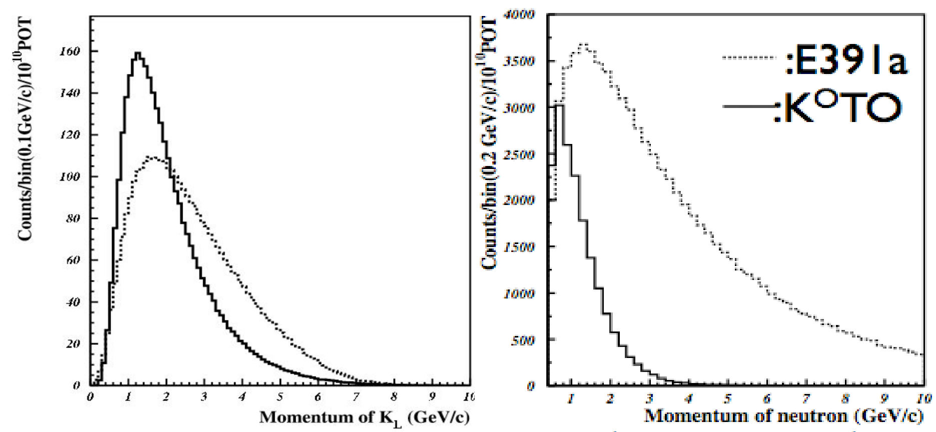
Halo-neutron Suppression

E391a halo/core is already ~ 10^{-4}!

- New collimator design:
  - with highly faceted surface geometry and material optimization
  - beam of rectangular shape to adjust X and Y components independently

  ⇒ halo/core suppression < 10^{-5}
- Lower neutron momentum by increasing beam extraction angle:
  - below η production threshold!
- Veto upgrades:
  - new upstream collar veto (NCC), moved upstream of entrance to fiducial region

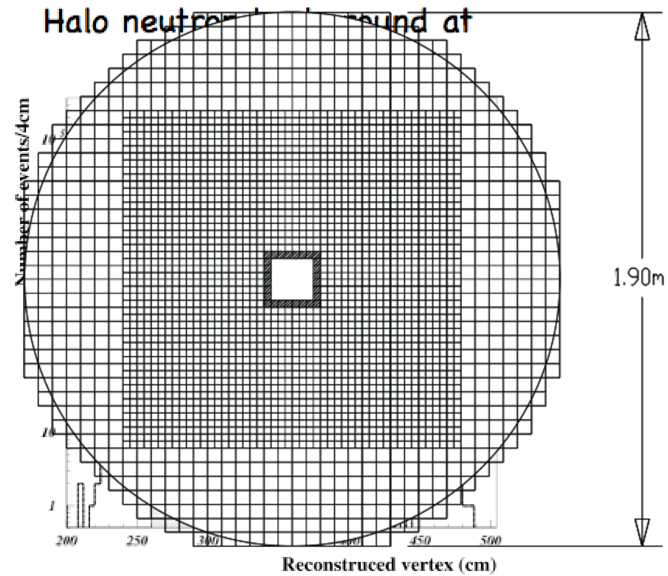




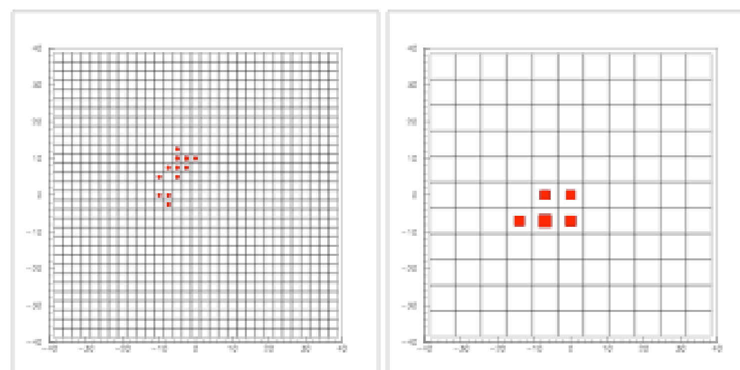
Improve Calorimeter

KTeV "loaned" CsI crystals:

- $\sigma(E)/E \sim 2\%$ for 1 GeV showers
- longer: 30 cm ⇒ 50 cm
  - reduce energy leakage which shifts decay vertex downstream (due to $m_{\pi 0}$ constrain)
  - ⇒ suppress halo-n from CC02
  - eliminate photon detection inefficiency due to punch-through (below inefficiency from photonuclear interaction)



- finer granularity: 7 cm^2 ⇒ 2.5(5) cm^2
  - position resolution from 5mm to 1mm
  - reduced 2γ fusion from 15 cm to 5 cm

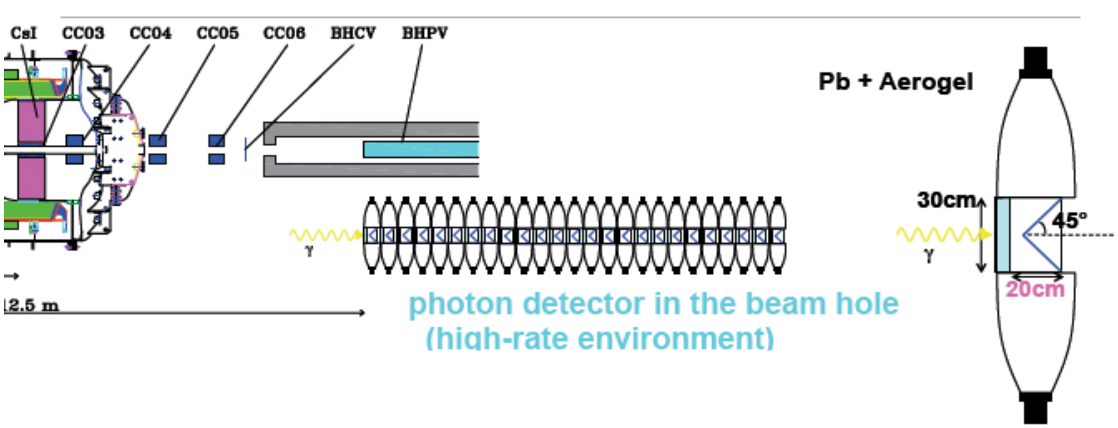


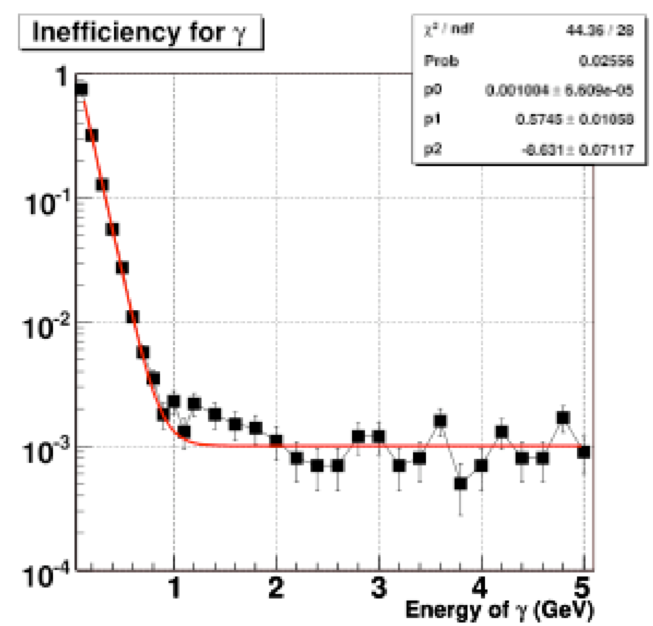
Increase Total Kaon Flux

Require detector more able to handle high rates

1. New Beam Hole Photon Veto (BHPV):
   - Immersed in high flux from core neutrons, K_L's and photons
   - Use Pb converter + Aerogel Cerenkov radiator + Winstone cone for light collection
   - detect e+/e- from e.m. showers while blind to "slow" neutrons

- Use direction of shower developments along beam to distinguish between particles from K_L decay vs. particles from neutron interaction
- Photon inefficiency: 10^{-3} @ 1 GeV
- false hit rate: 2MHz (require special readout)

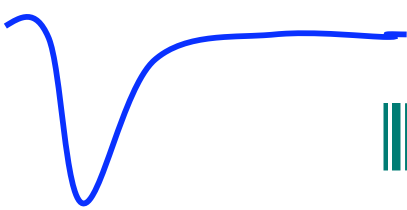




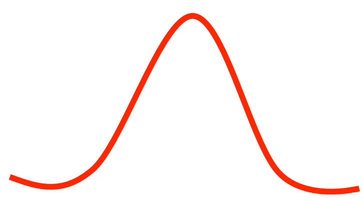
Increase Total Kaon Flux

2. New Frontend Electronics:

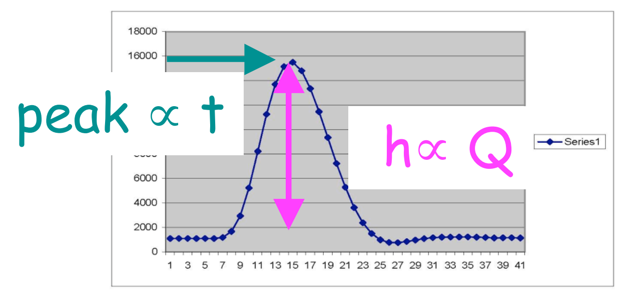
- Fully pipelined dead-timeless design
- New waveform digitization with 10-pole filter shaping
- readout with 125 MHz, 14 bit
  (500 MHz/12 bit for beam hole veto)
- sub-nanosecond timing resolution, 20 ns two pulse resolution
- 16-channels FADC already designed and tested!



PMT signal



After 10-pole filter

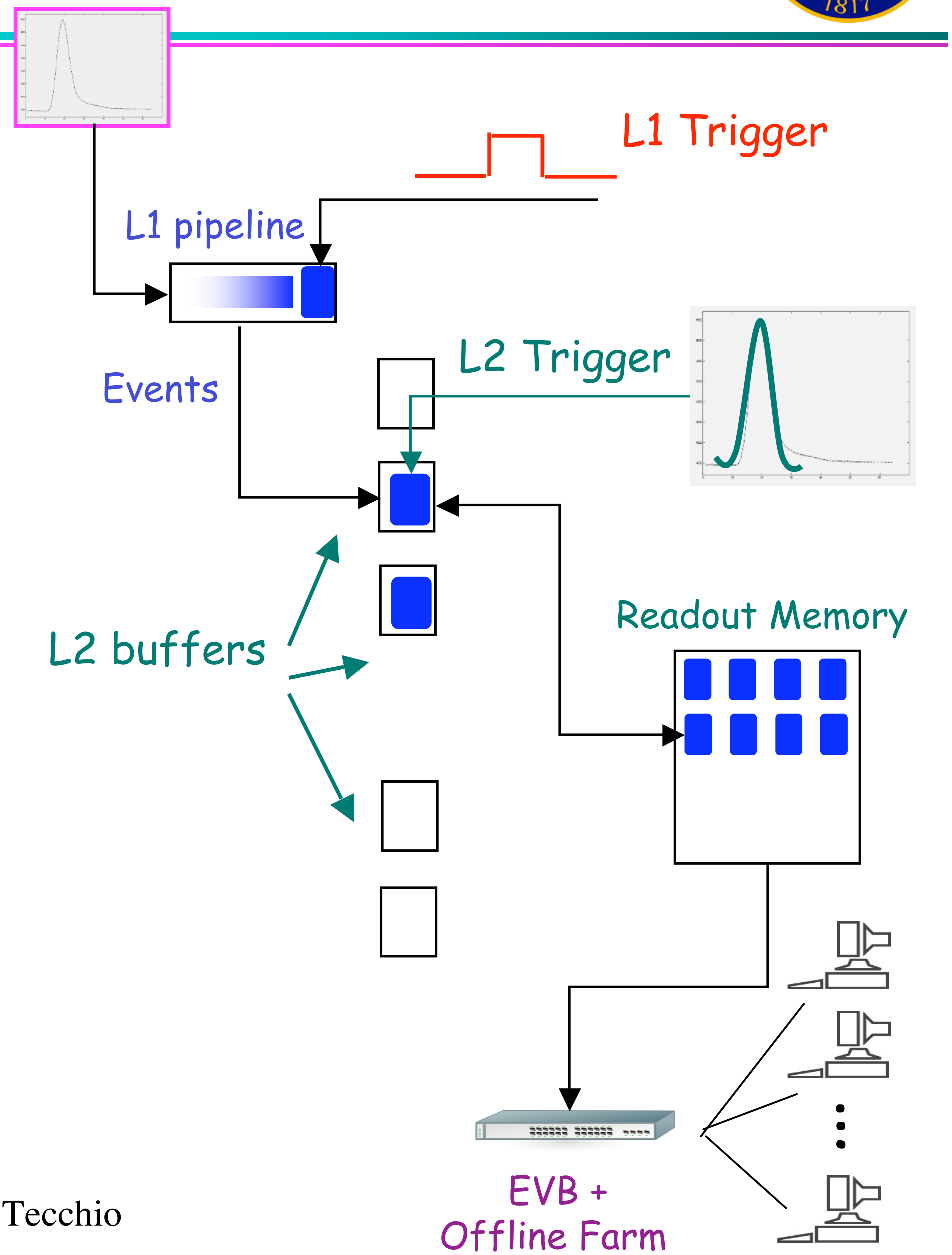


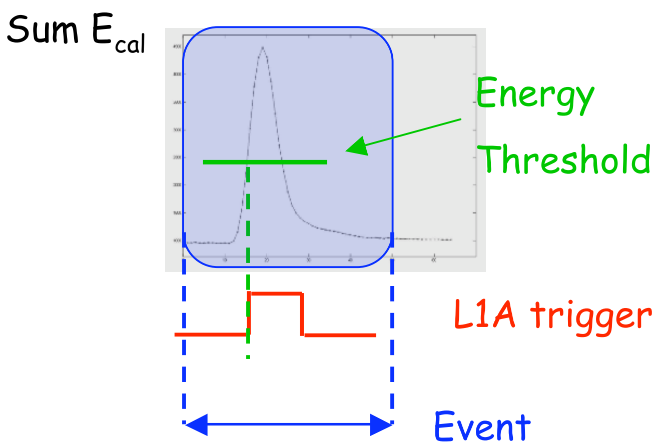
After digitization

Increase Total Kaon Flux

3. New Trigger and DAQ:

- two-level hardware trigger
- Level 1 is synchronous with 125 MHz sampling clock
- few hundreds kHz L1A rate
- Level 2 for energy clustering + gaussian fit + Ethernet readout
- EVB + Offline farm





Schedule

- 2009
  - Beamline construction done
  - Beam survey:
    - Measure of K_L yield/spectrum
    - Measure core neutron or confirm n/K_L ratio
    - Measure halo neutron
- 2010
  - CsI calorimeter stacking
  - Frontend electronics and Trigger/DAQ production
  - Engineering Run with full calorimeter readout
- 2011
  - Run with full detector

Summary

- KOTO experiment is to discover $K_L \to \pi^0 \nu\nu$
- New beamline and upgraded detector to keep up with new 50 GeV proton beam at JPARC
- Building on E391a experience (and mistakes)
- **Don't blink or will miss it**: beamline survey this year, detector engineering run in 2010, first run in 2011!