K^+ -> $\pi^+ \bar{\nu} \nu$ & Other Semileptonic Kaon Decays

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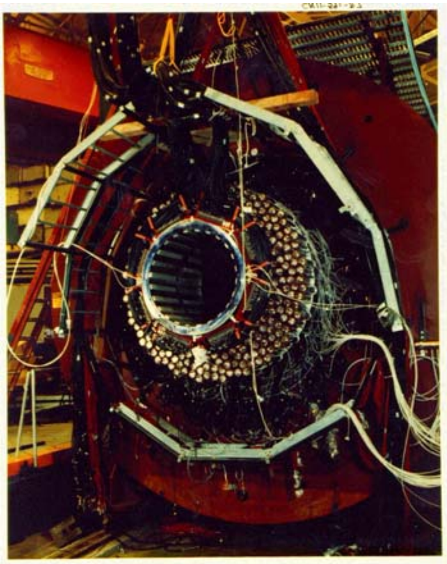
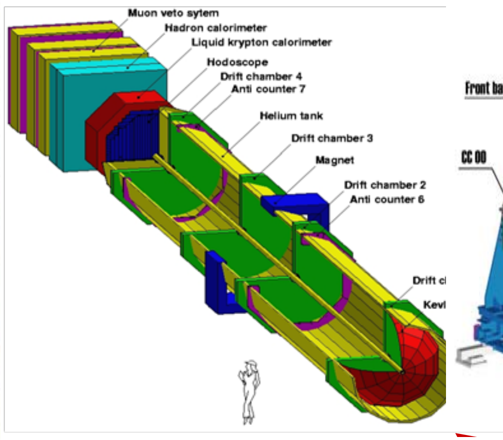
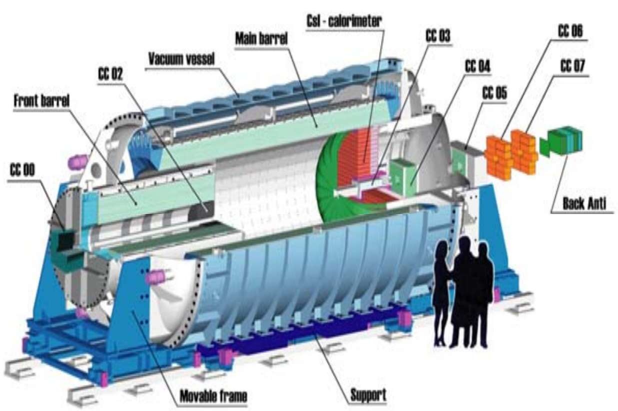
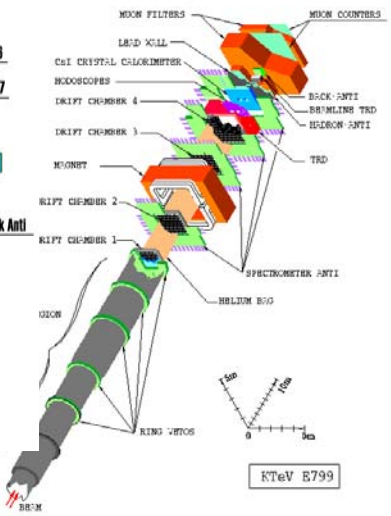








E949 **NA48** **E391a** **KTeV**

Outline:

I Rare Kaon decays

- $K^+ \to \pi^+ \nu \bar{\nu}$
- $K^0_L \to \pi^0 \nu \bar{\nu}$
- $K^0_L \to \pi^0 e^+e^-$ and $K^0_L \to \pi^0 \mu^+ \mu^-$

II Lepton Flavor Violation

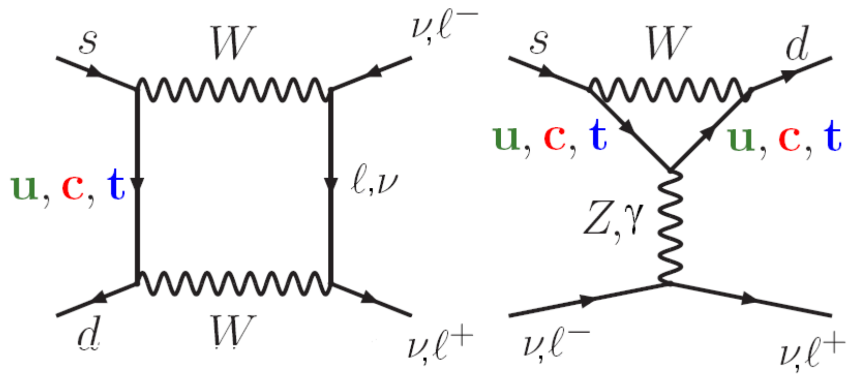
III Summary

- Apologies for the missing of many other interesting topics for lack of time

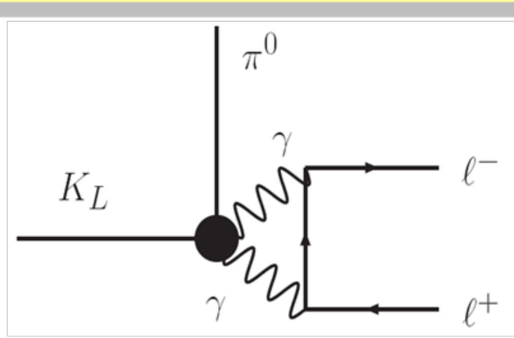
I Rare Kaon decays: $K \to \pi \ell \bar{\ell}$

Processes: $K^+ \to \pi^+ \nu \bar{\nu}$; $K^0_L \to \pi^0 \nu \bar{\nu}$;
$K^0_L \to \pi^0 e^+e^-$; $K^0_L \to \pi^0 \mu^+ \mu^-$

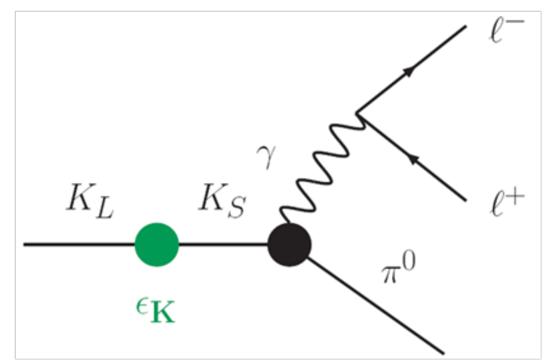
Direct CP Violating



Long distance CP Conserving

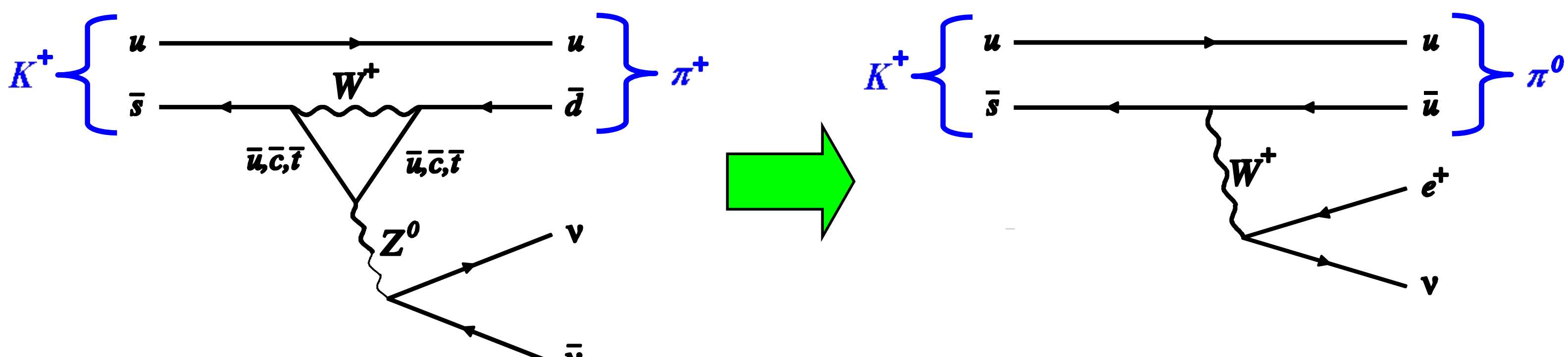


Indirect CP violating



Two golden channels: K^+->$\pi^+\nu\nu$ and K^0_L->$\pi^0\nu\nu$

- FCNC process is forbidden at tree level
- Only loop contributions: W Boxes and Z Penguins which can be precisely predicted by perturbation theory
- No long distance CP conserving and Indirect CPV contribution
- Relevant hadronic operator matrix element can be extracted from $K^+ \to \pi^0 e^+ \nu$



- Error mainly parametric: input CKM parameters

Theoretical Status for $\pi\nu\nu$ decays

- $BR(K^+ \to \pi^+ \nu\bar{\nu})_{theory}$

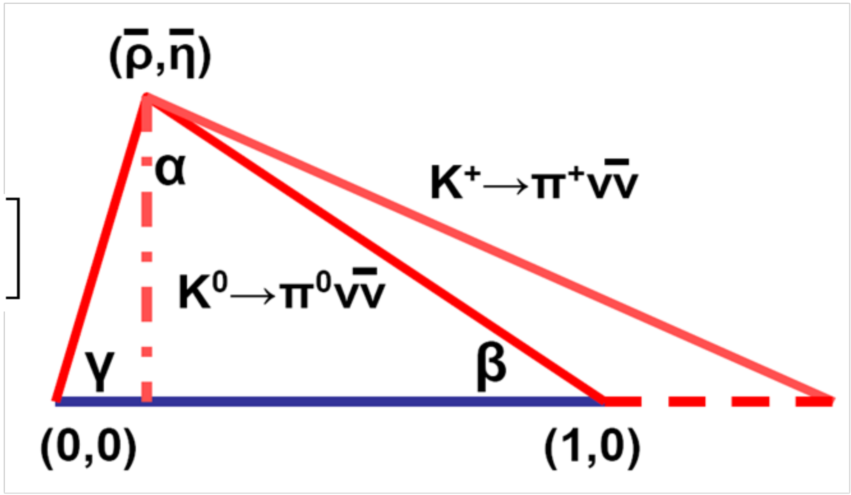
  $= (0.85 \pm 0.07) \times 10^{-10}$

  $$B(K^+) = C\left[\eta^2 + (\rho_0 - \rho)^2\right]$$

- $BR(K^0_L \to \pi^0 \nu\bar{\nu})_{theory}$

  $= (2.49 \pm 0.39) \times 10^{-11}$

  $$B(K^0_L) = C' \eta^2$$



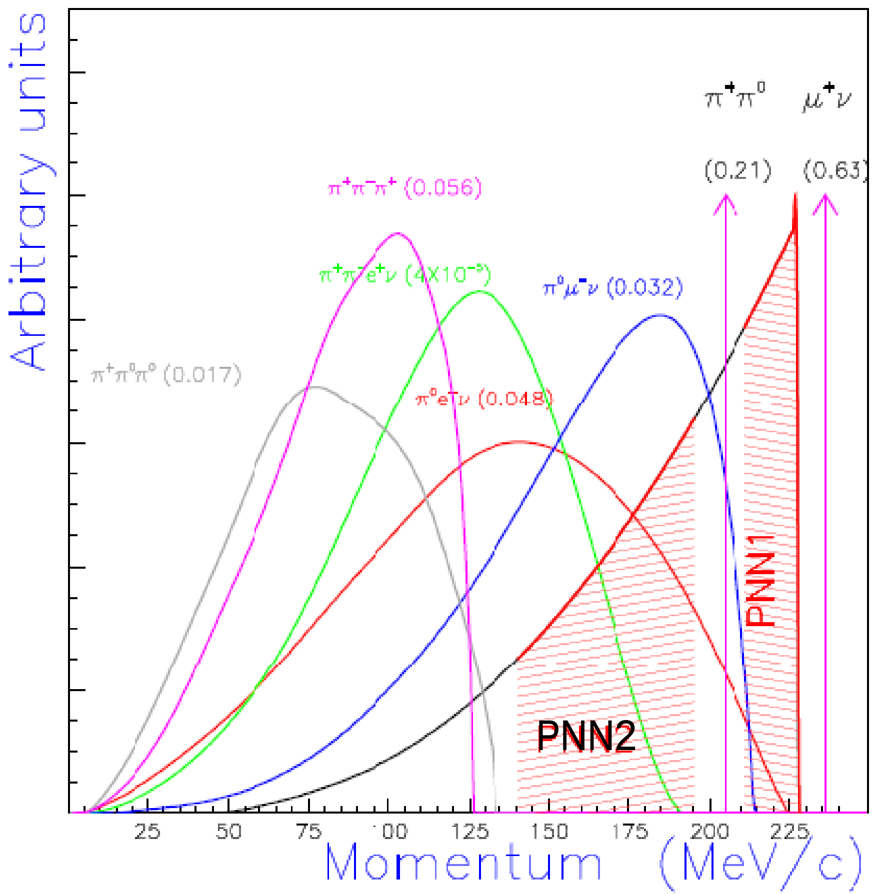
- Top quark contribution is dominant

~70% in $BR(K^+ \to \pi^+ \nu\bar{\nu})$ >99% in $BR(K^0_L \to \pi^0 \nu\bar{\nu})$

- Sensitive to new physics (Probe SM at quantum level, thereby allowing an indirect test of high-energy scales through a low-energy process)

Search for $K^+ \to \pi^+ \nu \nu$ at E787/E949

PRL **101**, 191802; PR D **79**, 092004
Our web page: http://www.phy.bnl.gov/e949/

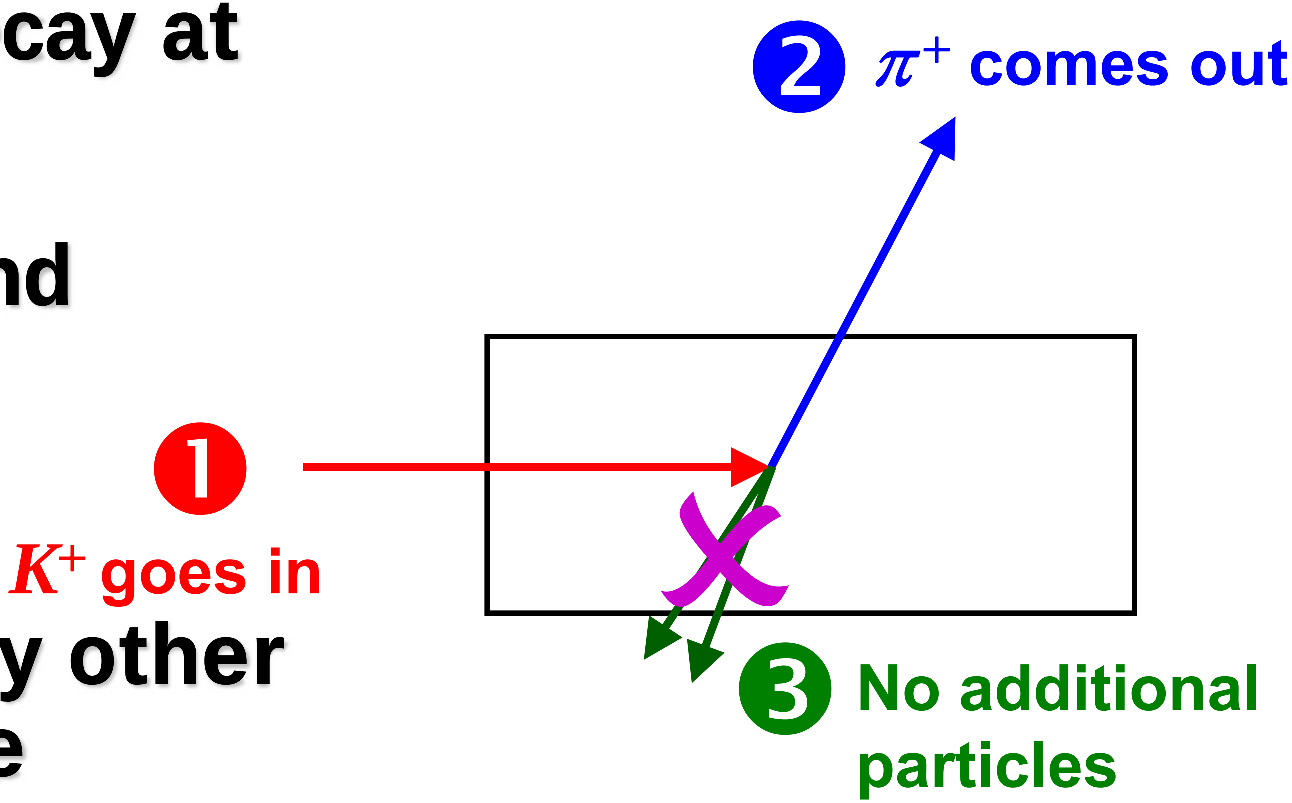


1. E787 is the predecessor of E949
2. There are two independent search regions, pnn1 and pnn2
3. **Previously E787 and E949 found 4 candidates**

Principle of searching $K^+ \to \pi^+ \nu \bar{\nu}$

1. K^+ stop in detector target and decay at rest

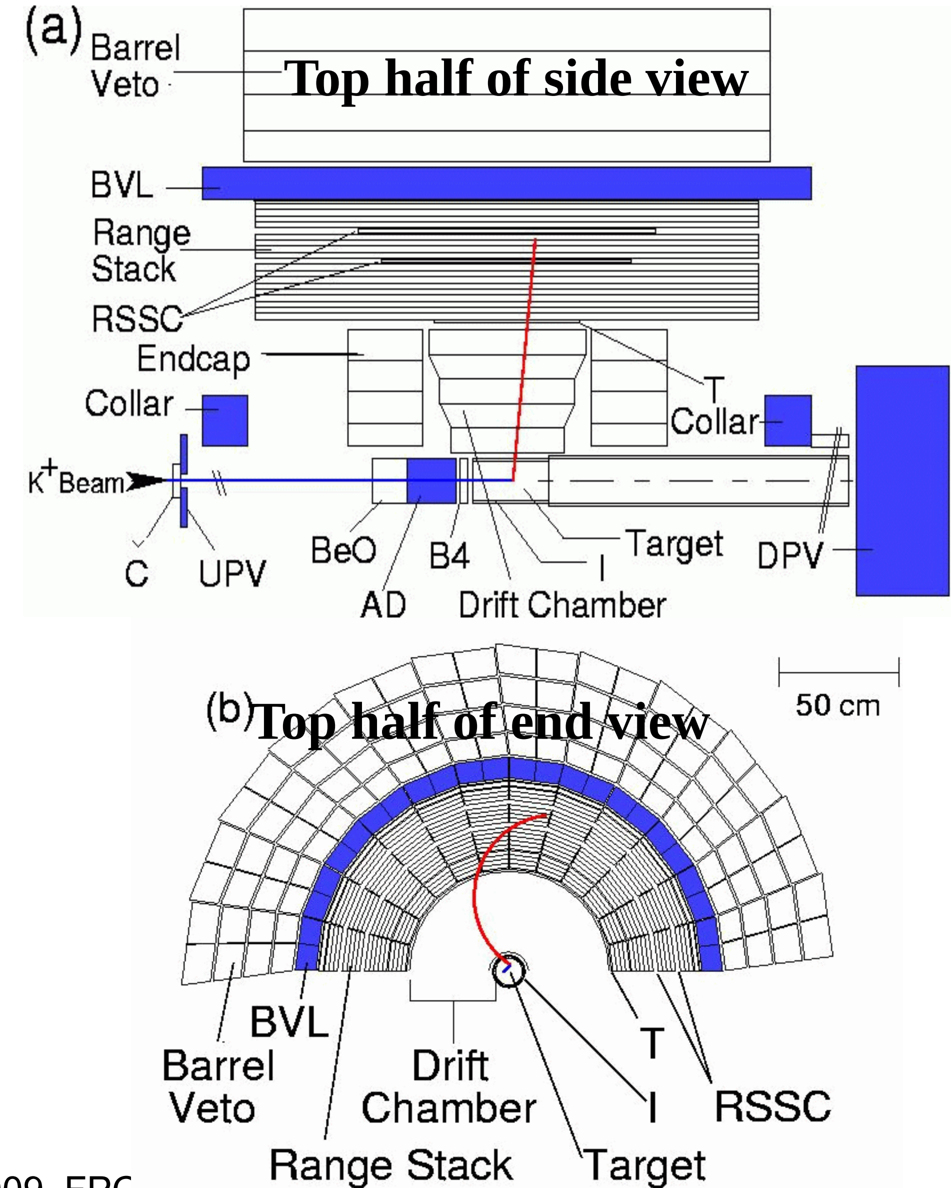
2. Measure and identify π^+



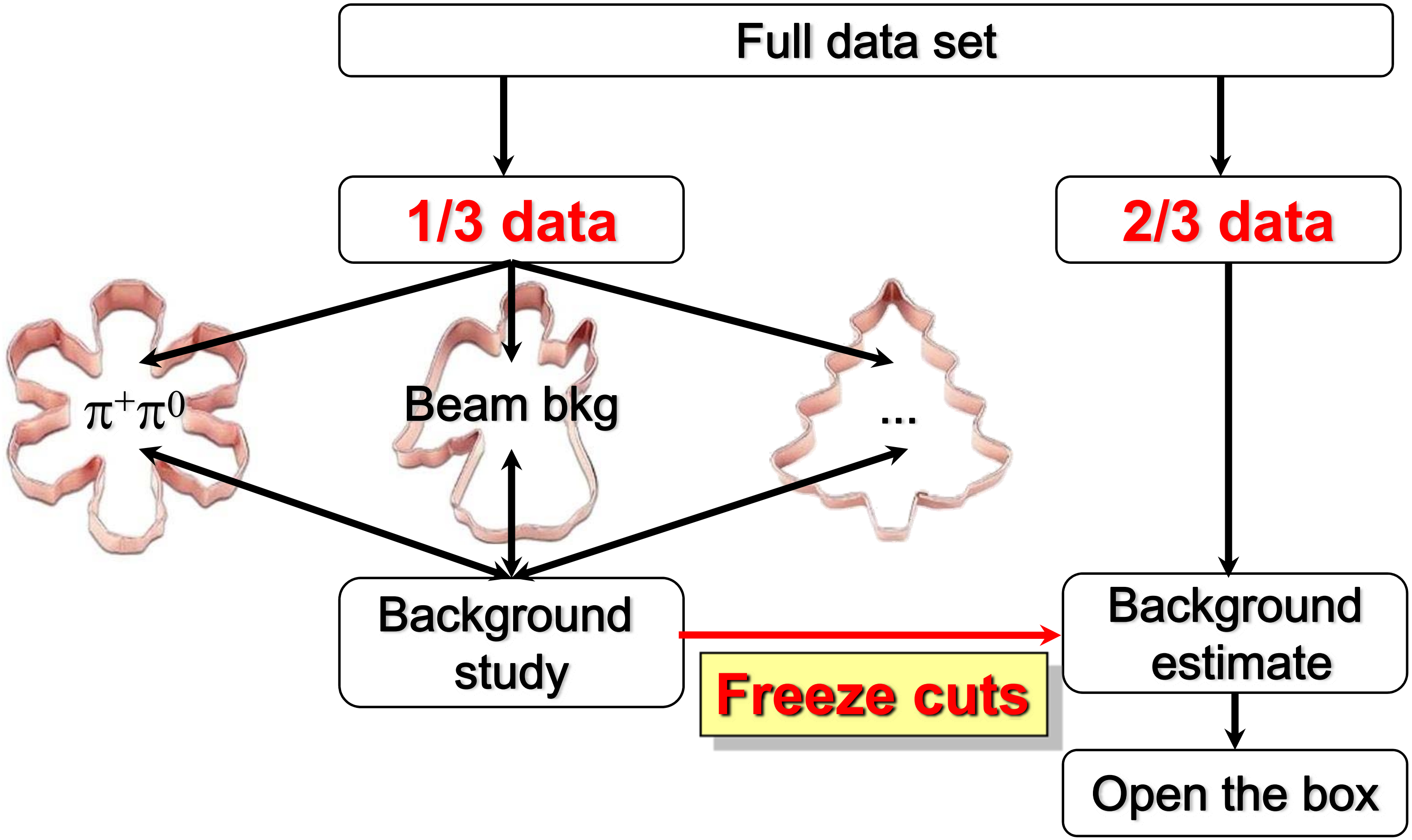
3. Veto on any other activity in the detector

E949 is dedicated to rare kaon decay study

1. ~700 MeV/c K^+ beam
2. Stop K^+ in scintillation fiber target,
3. Powerful and redundant particle ID for beam and daughter particles
4. Photon veto: 4π coverage
5. Each target fiber is read out by ADC, TDC and CCD
6. Observe $\pi^+ \to \mu^+ \to e^+$ in RS



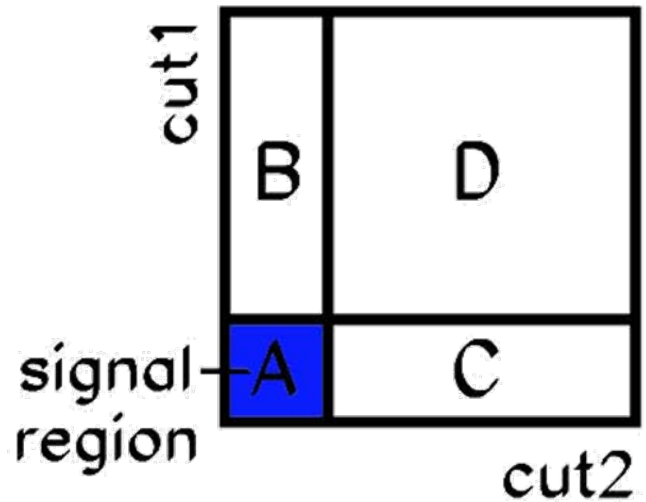
Strategy 1: avoid bias in cut tuning



Strategy 2: blind analysis - bifurcation

Step 1: Background isolation

Step 2: Suppress each background with two independent cuts



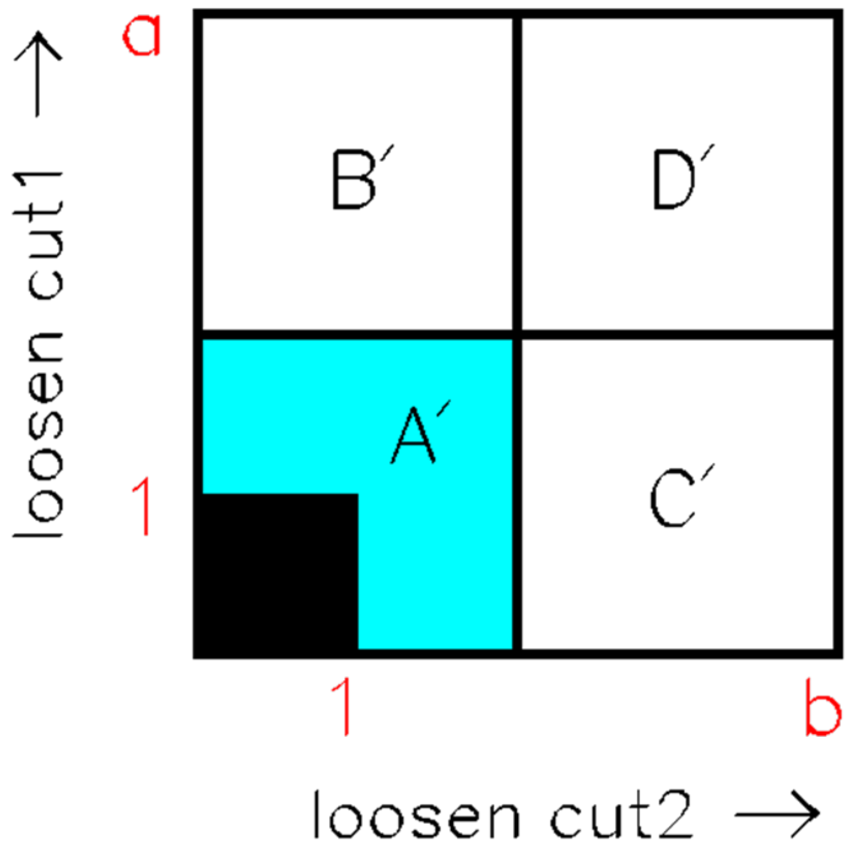
if cut1,cut2 uncorrelated,

$$A/B = C/D$$

$$A = BC/D$$

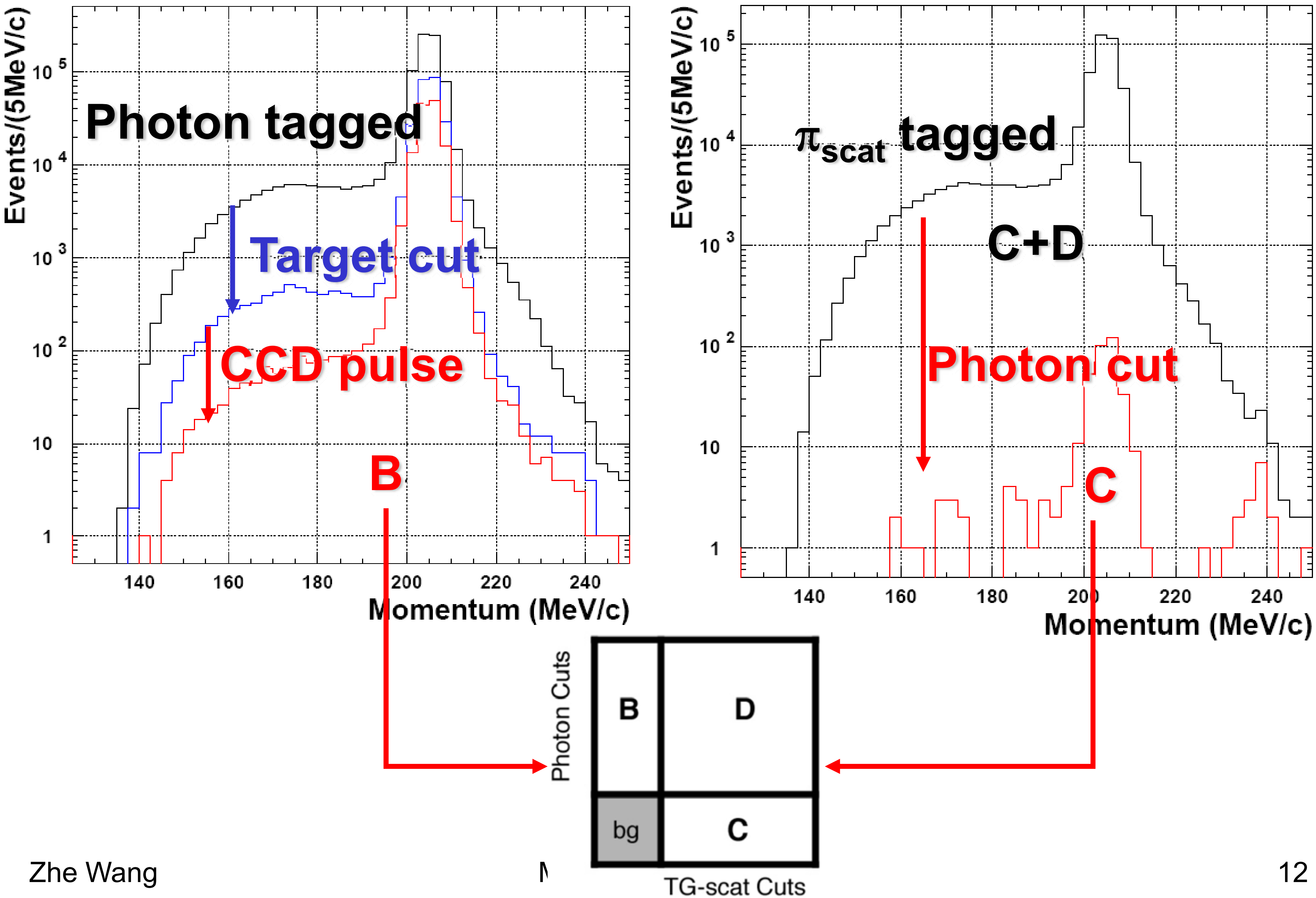
Strategy 2: blind analysis - bifurcation

Step 3: Check the correlation



$$bg' = bg(A') - bg(A) = B'C'/D' - BC/D$$

Measure $K^+ \to \pi^+\pi^0$ background



Total background and sensitivity

Process	Bkgd events (E949)	Bkgd events (E787)
$K_{\pi 2}$-scatter	$0.649 \pm 0.150^{+0.067}_{-0.100}$	1.030 ± 0.230
$K_{\pi 2\gamma}$	$0.076 \pm 0.007 \pm 0.006$	0.033 ± 0.004
K_{e4}	$0.176 \pm 0.072^{+0.233}_{-0.124}$	0.052 ± 0.041
CEX	$0.013 \pm 0.013^{+0.010}_{-0.003}$	0.024 ± 0.017
Muon	0.011 ± 0.011	0.016 ± 0.011
Beam	0.001 ± 0.001	0.066 ± 0.045
Total bkgd	$0.93 \pm 0.17^{+0.32}_{-0.24}$	1.22 ± 0.24

	E949 pnn2	E787 pnn2
Total Kaons	1.70×10^{12}	1.73×10^{12}
Total Acceptance	1.37×10^{-3}	0.84×10^{-3}
SES	4.3×10^{-10}	6.9×10^{-10}

For E787+E949 pnn1 SES=0.63×10^{-10}

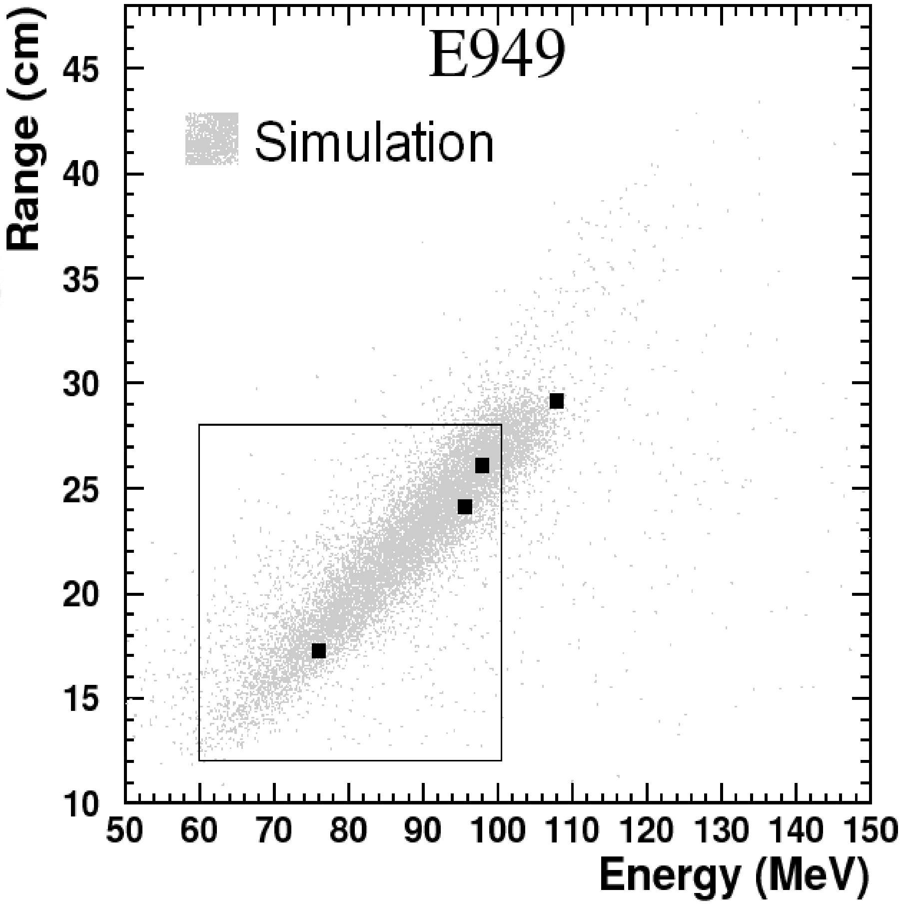
SES is the branching ratio for a single event observed w/o background

MC is used to estimate kinematics cuts acceptance and the rejection of some well understood cut in background study.

Measured $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ BR of this analysis

- $BR=(7.89 \pm ^{9.26}_{5.10}) \times 10^{-10}$
- The probability of all 3 events to be due to background alone is 0.037
- due to signal of SM prediction and background is 0.056
- SM prediction:

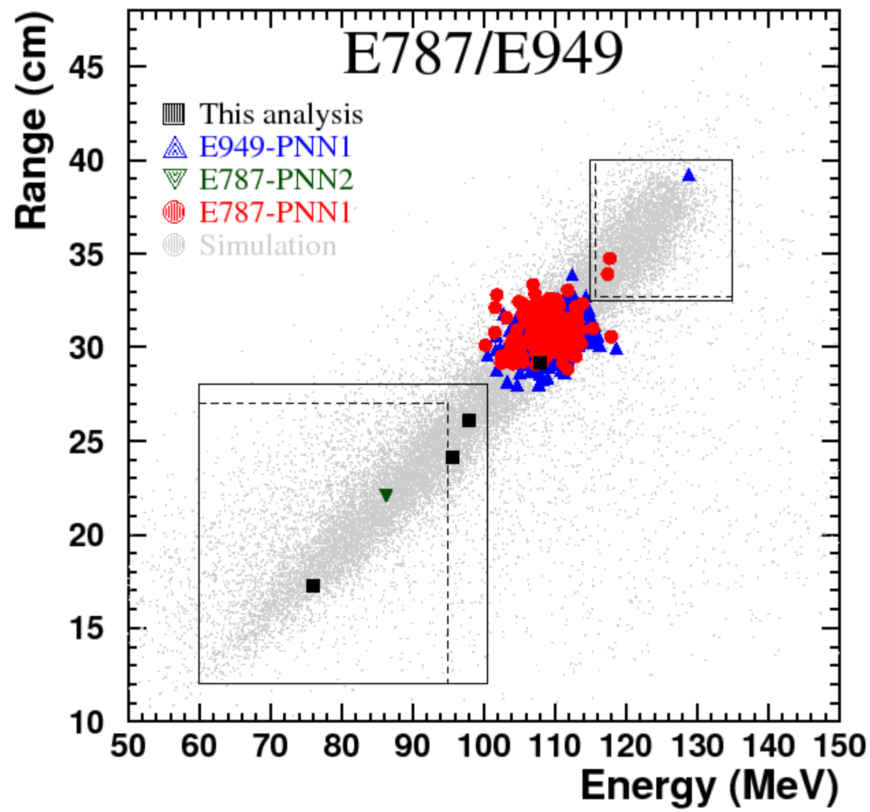
$BR=(0.85 \pm 0.07) \times 10^{-10}$



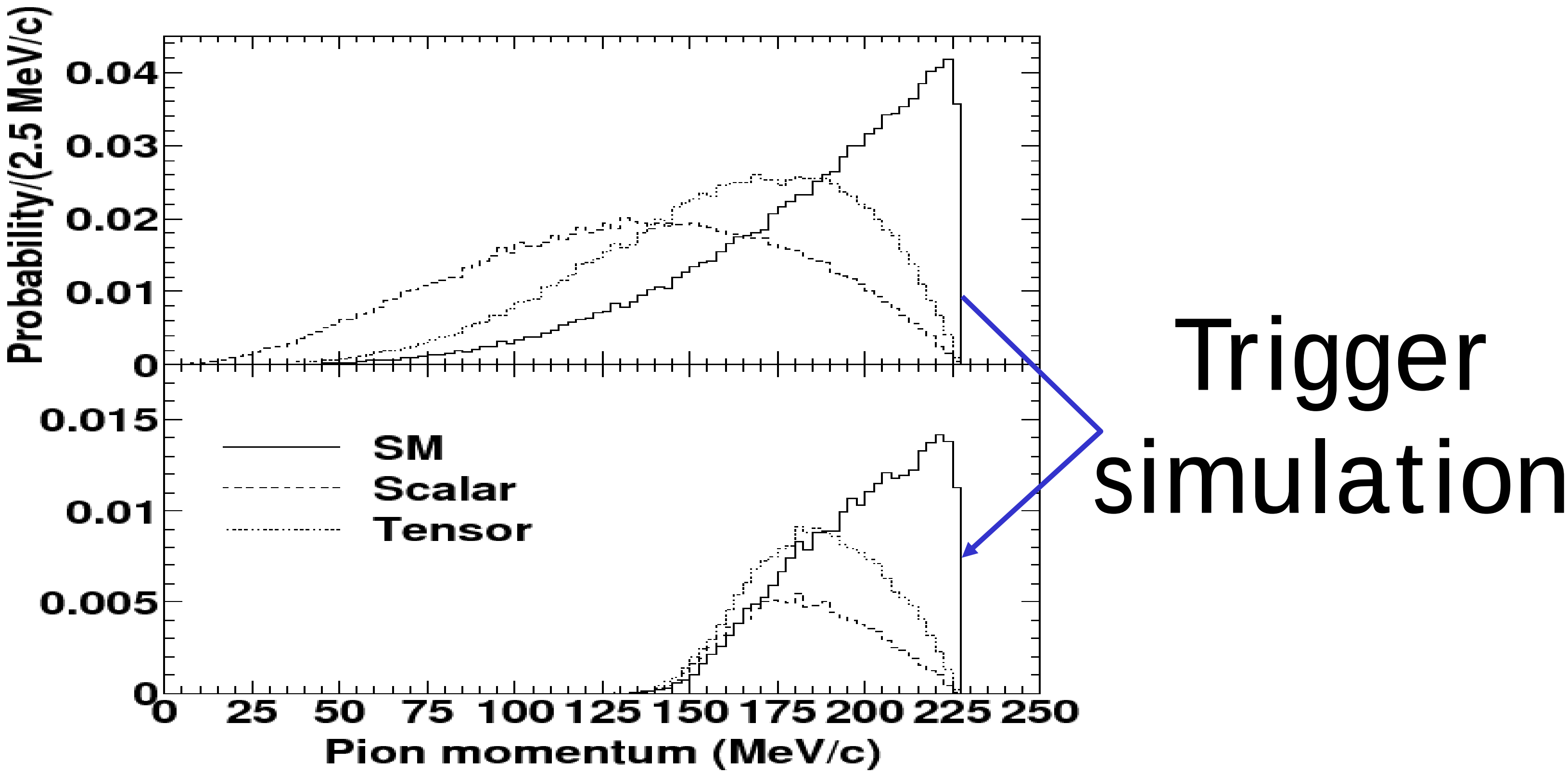
Combined with all E787/E949 result

- $BR=(1.73^{+1.15}_{-1.05})\times10^{-10}$ final
- The probability of all 7 events to be due to background alone is 0.001
- due to signal of SM prediction and background is 0.07
- SM prediction:

$BR=(0.85\pm0.07)\times10^{-10}$



BR of Scalar and Tensor form factors



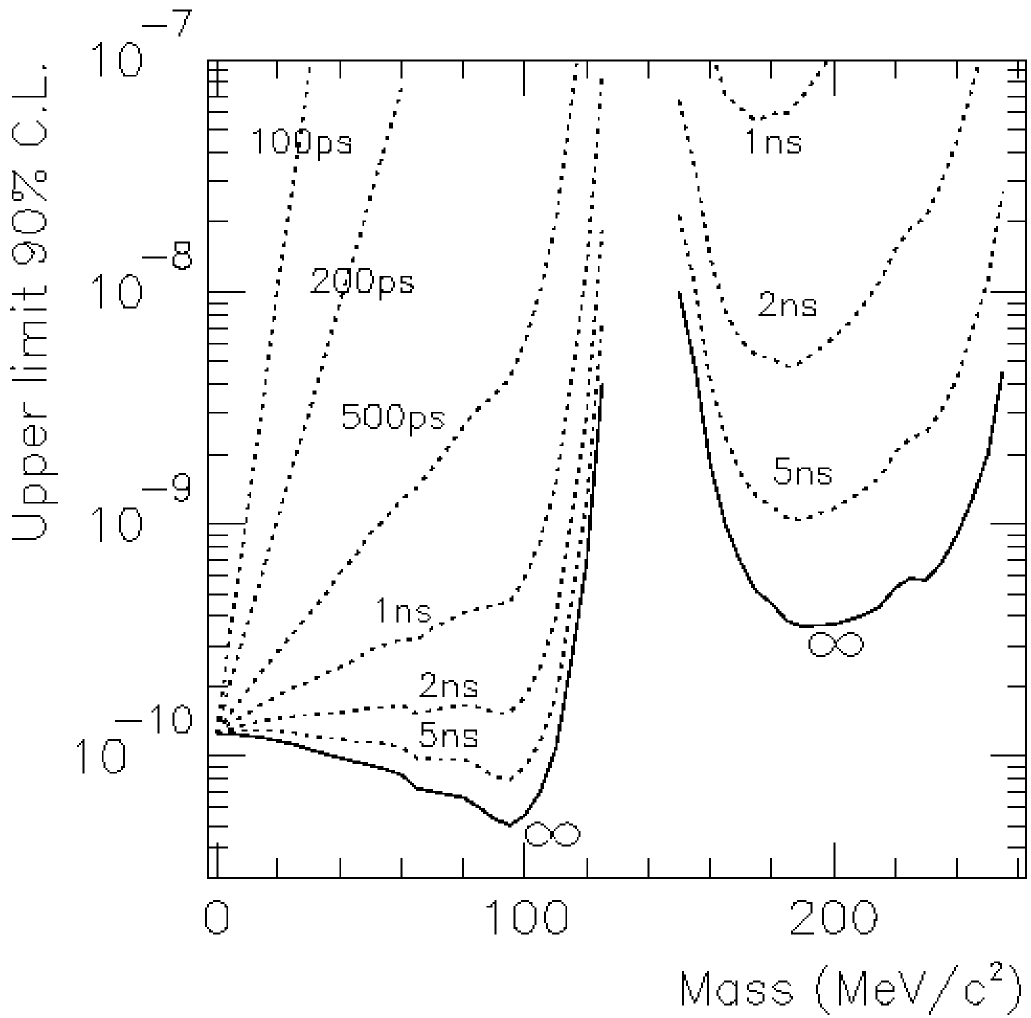
	Scalar	Tensor	SM
BR ($\times 10^{-10}$):	$9.94^{+8.48}_{-4.20}$	$4.87^{+3.91}_{-2.43}$	$1.73^{+1.15}_{-1.05}$

Limit on the BR of $K^+ \to \pi^+ X$

The mass of X is unknown.

X might have some limited lifetime

We assume the detection efficiency of X's daughter particle is 100% if decay within detector



$K^+ \to \pi^+ \nu\nu$: Experimental Prospect

- The Sensitivity of E787/E949 experiment is limited by low statistics.
- The main background is from scattering and inefficiency of low energy photon detection

A well supported NA62: aiming at O(100) events

•K^+ Decay in-flight to avoid the scattering and the backgrounds introduced by the stopping target

→long decay region

•High momentum to improve the background rejection

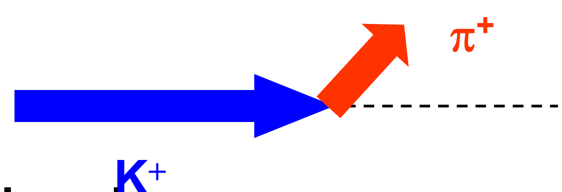
→ unseparated hadron beam

Signature:

•Incoming high momentum (75 GeV/c) K^+

•Outgoing low momentum (< 35 GeV/c) π^+

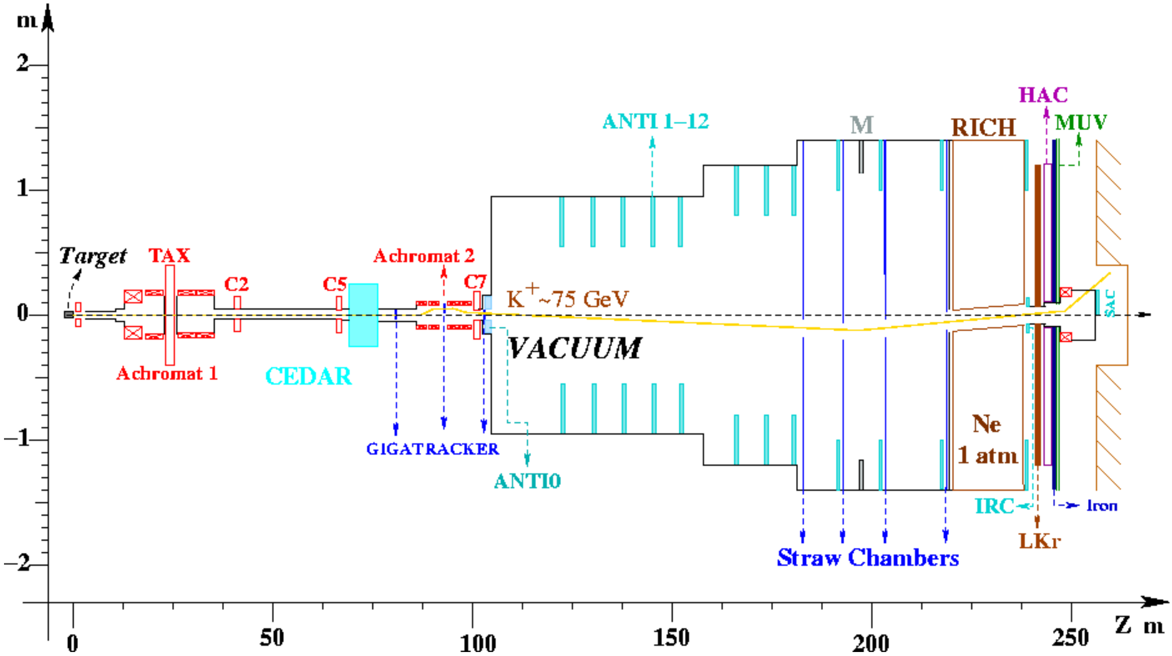
•For $K_{\pi 2}$ $P(\pi^0)$ > 40 GeV/c: it can hardly be missed



A. Ceccucci @ New Opportunities in the Physics Landscape at CERN

1. **Precise timing** to associate the decay to the correct incoming parent particle (K^+) in a ~800 MHz beam
   → Beam tracker with σ_t~100 (GTK)
2. Kinematical Rejection
   → low mass tracking (GTK + STRAW in vacuum tank)
3. Vetoes (γ and μ)
   → ANTI (OPAL lead glass) + NA48 LKR
   → MUV
4. Particle Identification
   → K/π (CEDAR)
   → π/μ (RICH)

Very challenging experimentally; aims at 50 evts/year, ready > 2012



II Search for $K_L \to \pi^0 \nu \bar{\nu}$

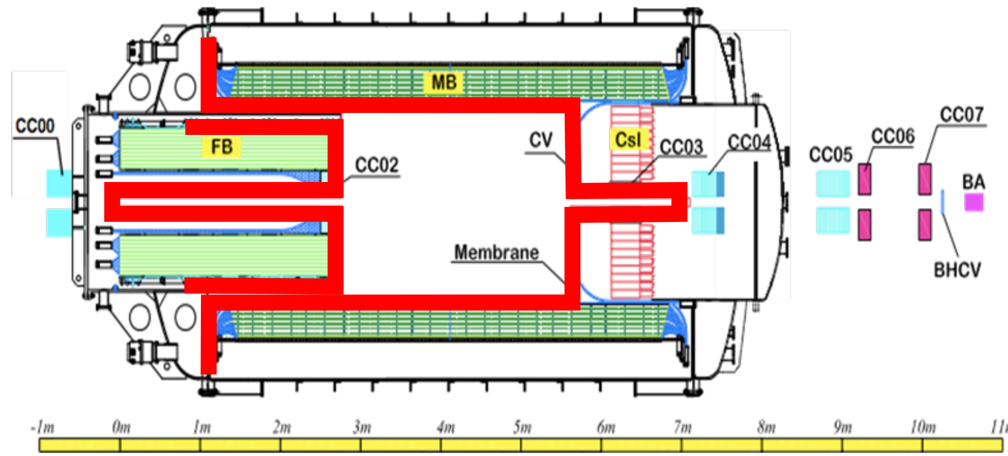
E391a, PRL 100, 201802

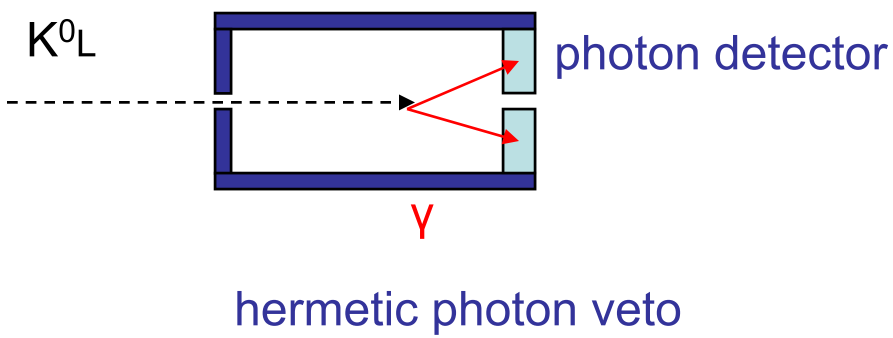
- $K_L \to \pi^0 \nu\bar{\nu}$ decay
  └ $\gamma\gamma$
  two photons w/o any other observable charged or neutral particles.

- Constraint of two photon effective mass,

  $m_{\gamma\gamma} = m_{\pi 0}$

  gives distance z to the decay point.



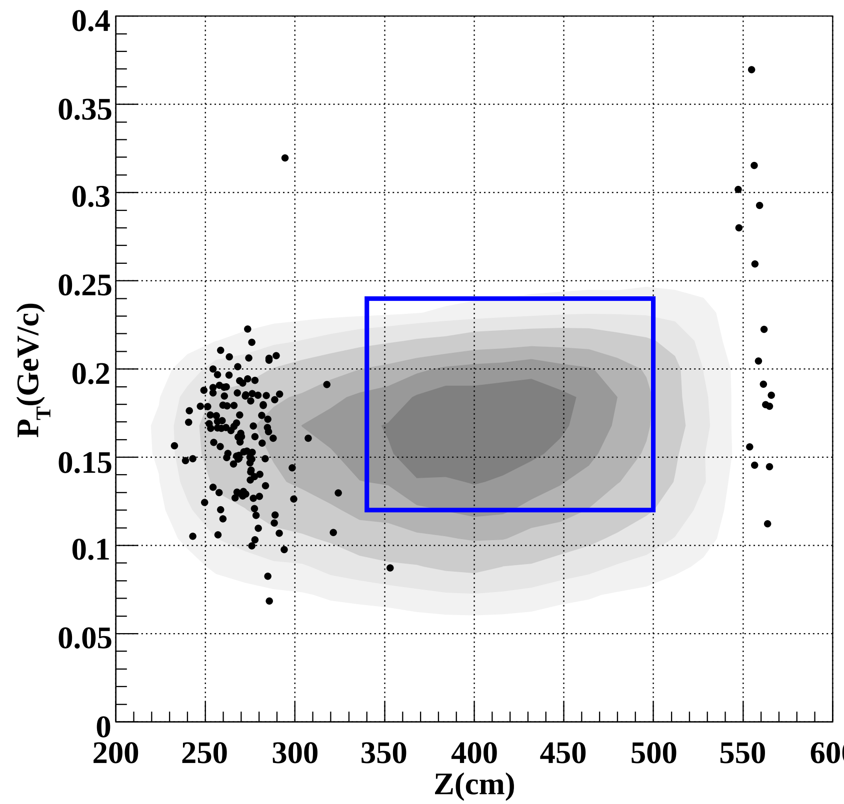


K_L -> $\pi^0 \nu \nu$ analysis result

- Background: 0.41 ±0.11
- Acceptance: A = 0.67%
- Flux: N_{KL} = 5.1 x 10^9
- S.E.S = 1 / (A•N_{KL})
  = (2.9 ± 0.3) x 10^{-8}

- Upper Limit
  - 0 event observed
    2.3 events w/ Poisson stat.
  - $Br(K_L \to \pi^0 \nu\nu) \le 6.7 \times 10^{-8}$
    (@90% C.L.)

- SM prediction
  = (2.49 ±0.39) x 10^{-11}



KEK E391a → J-PARC E14

Takao Shinkawa, seminar@BNL 2008

- **High intensity proton accelerator at Tokai**
  beam intensity x100 12-GeV PS
- **CsI**
  - **7x7x30cm^3→ 2.5x2.5x50cm^3 , 5x5x50cm^3 (from KTeV)**
    - **Reduce leakage**
    - **Better positioning**
- **Readout Electronics**
  - **Wave-form digitization**
- **New Detectors**
  - **Beam Hole Photon Veto**
  - **Full active CC02**
  - **MB liner**
  - **New CV**

E14 tentative schedule:

Private communication with Takeshi Komatsubara

- **JFY2009**

  (JFY2009 = Japanese Fiscal Year 2009: from April 2009 to March 2010)

  (Proton beam intensity might still be very low)

  Beam line construction is started and on schedule
  Beam survey
  KL flux measurement
  with $K^L \to \pi^+\pi^-\pi^0$ decay.
  Flux might be three times more.

  CsI-calorimeter prototype test

- **From late in JFY2009 to JFY2010**

  (Proton beam intensity would be higher)

  Begin CsI stacking

  Construct the CsI calorimeter and do Engineering run with it

  Beam survey again

- **JFY2011**

  Complete the detector construction

  Full engineering run

  First physics run (limited run time and beam intensity)

$K^0_L \to \pi^+ e^+ e^-$ and $K^0_L \to \pi^0 \mu^+ \mu^-$

- In SM three components (Direct CPV, indirect CPV and LD CP conserving) be of comparable size
- Long distance dominant (ChPT); Possible interference ➔ Can add to our understanding of flavor physics
- New physics might only appear in πee and $\pi\mu\mu$ channels while not in $\pi\nu\nu$ channels (C. Smith CKM 2008)

	Γ_{SD}/Γ	Irreducible theory err. (amp)	SM BR ($\times 10^{-11}$)	Experiment
$K^0_L \to \pi^+ e^+ e^-$	38%	15%	$3.54^{+0.98}_{-0.85}$	$< 28 \times 10^{-11}$ KTEV, PRL 93, 021805 (2004) 97, 99 data set
$K^0_L \to \pi^0 \mu^+ \mu^-$	28%	30%	$1.41^{+0.28}_{-0.26}$	$< 38 \times 10^{-11}$ KTEV, PRL 84, 5279 (2000) 97 data set A new result is coming

II Lepton Flavor Violation

KTeV: $K_L \to \pi^0 \mu^\pm e^\mp$

$K_L \to \pi^0 \pi^0 \mu^\pm e^\mp$

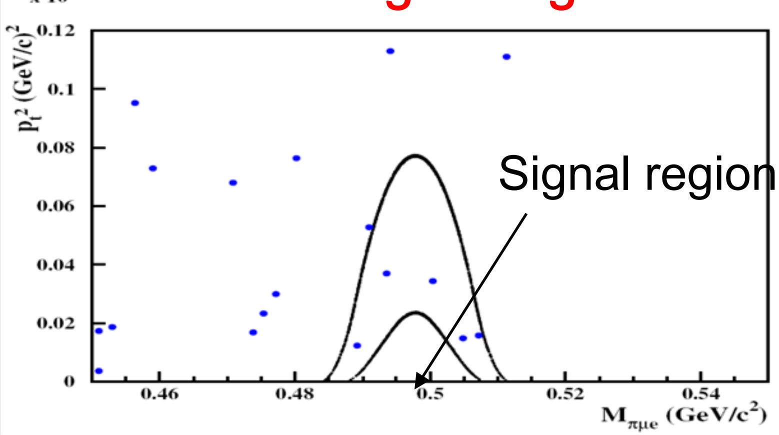
$\pi^0 \to \mu^\pm e^\mp$ (PRL 100, 131803)

- In SM lepton generation number violating decays are possible with nonzero neutrino masses and mixing, but beyond the reach of current experiment
- Total lepton number conservation may break with a heavy Majorana neutrino, like neutrinoless double beta decay ($0\nu\beta\beta$ only study the first generation)
- Many scenarios beyond SM could predict observable LFV decays, SUSY, Technicolor
- Searching LFV in kaon decays is independent and complementary. It provides important constrain to new physics.

K_L->π^0 $\mu^\pm e^\mp$

- Background estimate:

- 0.66±0.23 in signal region



- Blind regions opened:

- 0 events in signal region

BR(K_L->π^0 $\mu^\pm e$)< 7.6×10^{-11}

90% C.L. Factor of 83 lower than previous limit

K_L-> π^0 π^0 $\mu^\pm e^\mp$

- 0.43±0.23 background
- 0 events found

BR(K_L->π^0 $\pi^0 \mu^\pm e^+$)<1.7×10^{-10}

90% C.L. First

π^0 -> $\mu^\pm e^\mp$

- 0.03±0.015 background
- 0 events found

BR(π^0 -> $\mu^\pm e^+$)<3.6×10^{-10}

10(2) times lower

A brief summary of LFV experimental result in semileptonic kaon decays (CL=90%)

$K_L \to \pi^0 \mu^\pm e$	$<7.6\times10^{-11}$	
$K_L \to \pi^0 \pi^0 \mu^\pm e$	$<1.7\times10^{-10}$	
$K^+ \to \pi^+ \mu^+ e^-$	$<1.3\times10^{-11}$	**
$K^+ \to \pi^+ \mu^- e^+$	$<5.2\times10^{-10}$	*
$K^+ \to \pi^- \mu^+ e^+$	$<5.0\times10^{-10}$	*
$K^+ \to \pi^- \mu^+ \mu^+$	$<6.4\times10^{-10}$	*
$K^+ \to \pi^- e^+ e^+$	$<3.0\times10^{-9}$	*

* E865, PRL 85, 2877;
** E865, PR D72, 012005; PDG 2008

III Summary

- E787/E949: found 7 candidates

$BR(K^+\rightarrow\pi^+\nu\bar{\nu}) = (1.73 \pm^{1.15}_{1.05}) \times 10^{-10}$ (final)

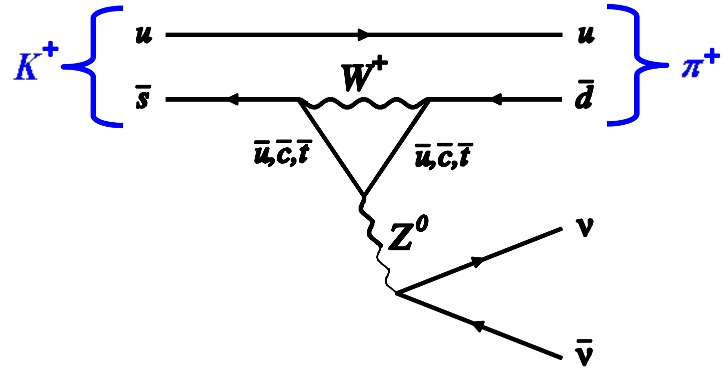
This result is twice of standard model prediction, however consistent with it within uncertainty

E787/E949 is the first experiment reaching the SM prediction level.

- E391a presented $Br(K_L\rightarrow\pi^0\nu\nu) < 6.7 \times 10^{-8}$
- KTeV improved Kaon LFV search result.
- So far no NP is found in rare kaon decay and LFV
- Expect the new result from E391a/E14 and NA62

Backup slides

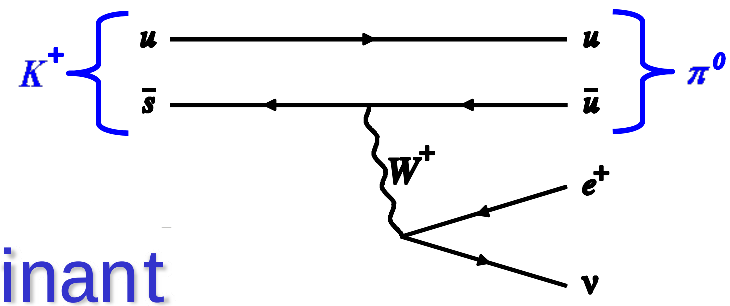
Branching ratio prediction: $K^+ \to \pi^+ \nu \nu$



Effective Hamiltonian:

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2 \theta_W}$$

$$\cdot \sum_{l=e,\mu,\tau} [V_{cs}^* V_{cd} X_{NL}^l + V_{ts}^* V_{td} X(x_t)](\bar{s}d)_{V-A}(\bar{\nu}_l \nu_l)_{V-A}$$

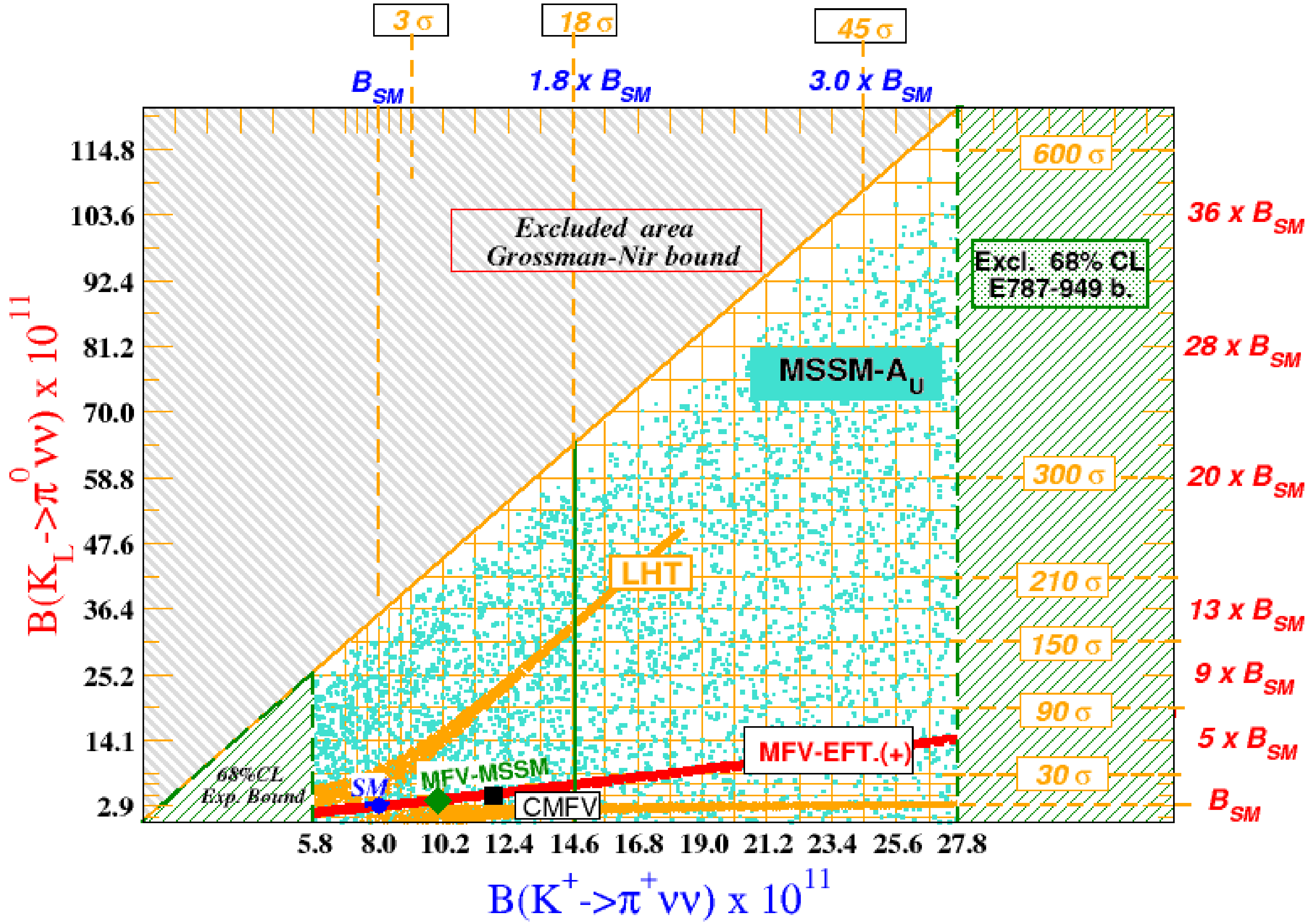


X: Wilson coefficients

Short-distance interaction dominant

Relevant hadronic operator matrix element can be extracted from $K^+ \to \pi^0 e^+ \nu$

M.K. Gailard and Benjamin W. Lee 1974

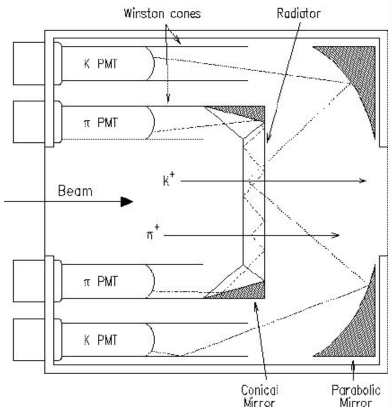


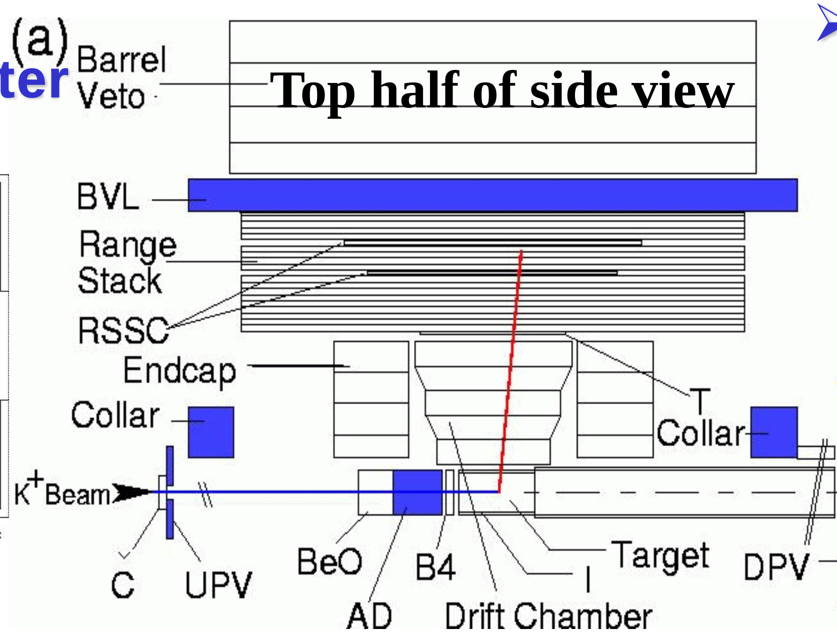
3 σ
18 σ
45 σ
B_{SM}
$1.8 \times B_{SM}$
$3.0 \times B_{SM}$
114.8
103.6
92.4
81.2
70.0
58.8
47.6
36.4
25.2
14.1
2.9
$B(K_L \to \pi^0 \nu\nu) \times 10^{11}$
Excluded area
Grossman-Nir bound
Excl. 68% CL
E787-949 b.
MSSM-A_U
LHT
MFV-EFT.(+)
MFV-MSSM
SM
CMFV
68%CL
Exp. Bound
600 σ
300 σ
210 σ
150 σ
90 σ
30 σ
$36 \times B_{SM}$
$28 \times B_{SM}$
$20 \times B_{SM}$
$13 \times B_{SM}$
$9 \times B_{SM}$
$5 \times B_{SM}$
B_{SM}
5.8
8.0
10.2
12.4
14.6
16.8
19.0
21.2
23.4
25.6
27.8
$B(K^+ \to \pi^+ \nu\nu) \times 10^{11}$

Search for $K^+ \to \pi^+ \nu \nu$ at E949

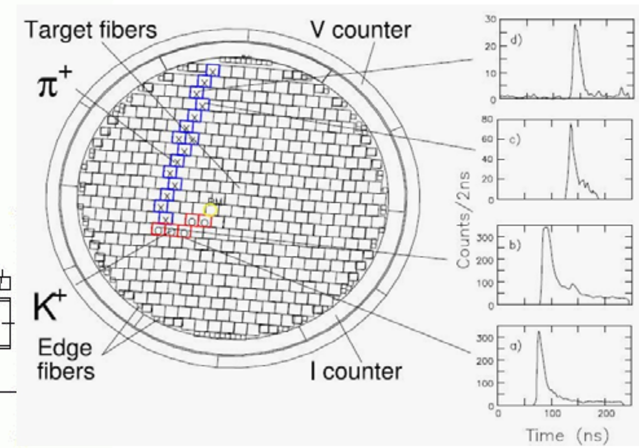
E949 detectors: A dedicated detector for rare kaon study

- **Cerenkov counter**

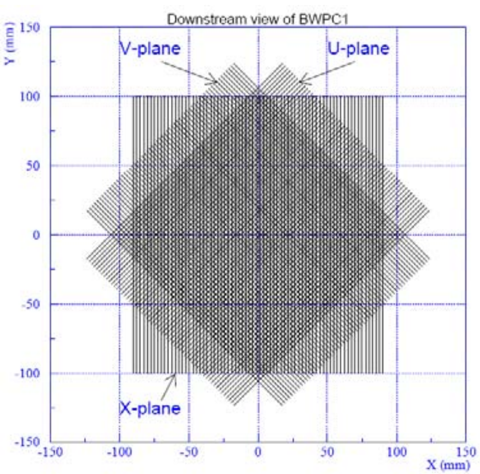




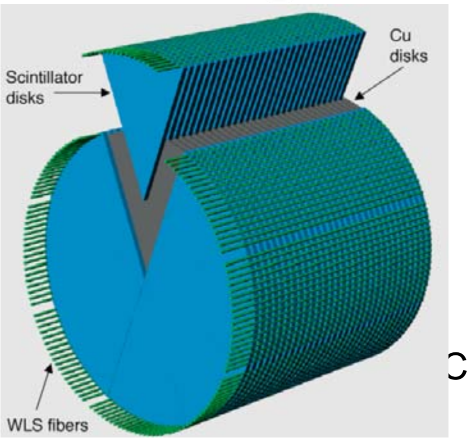
- **Target**
  (ADC, TDC and CCD)



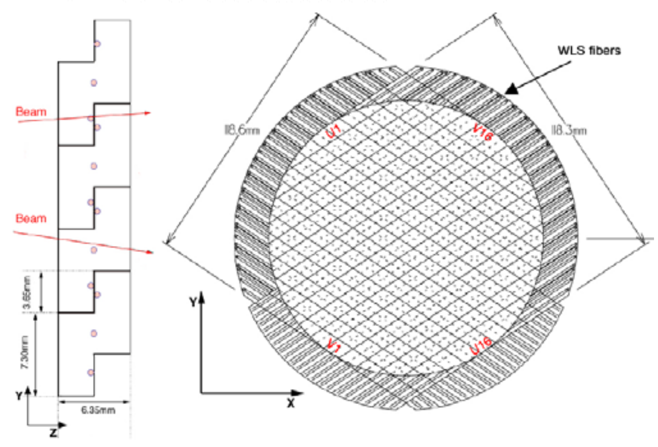
- **Wire chamber**



- **Active degrader**

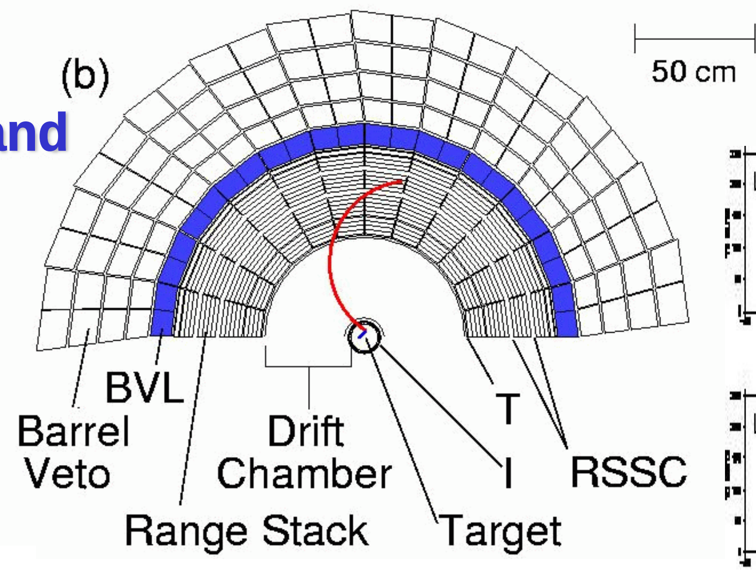


- **B4 counter**

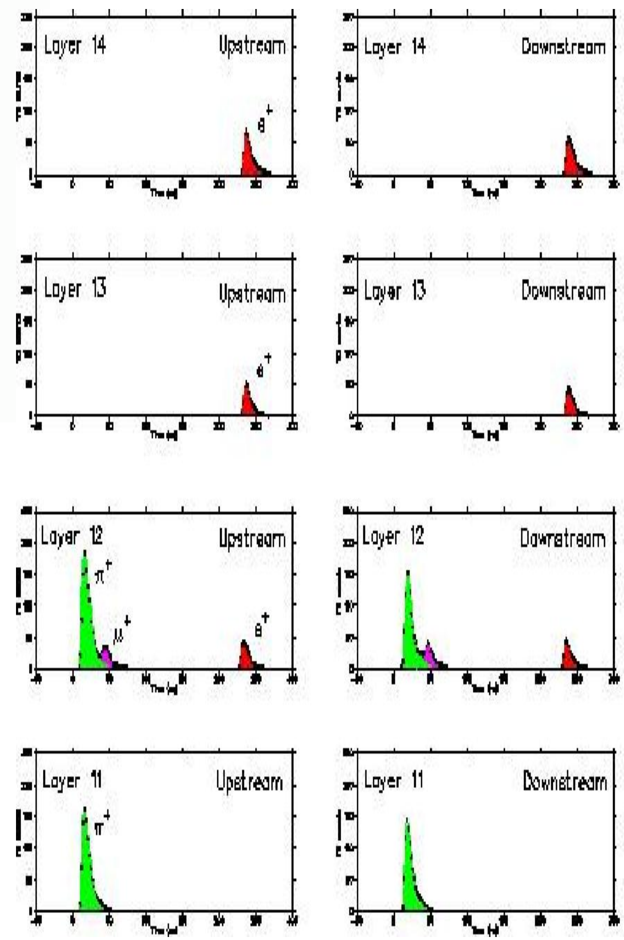


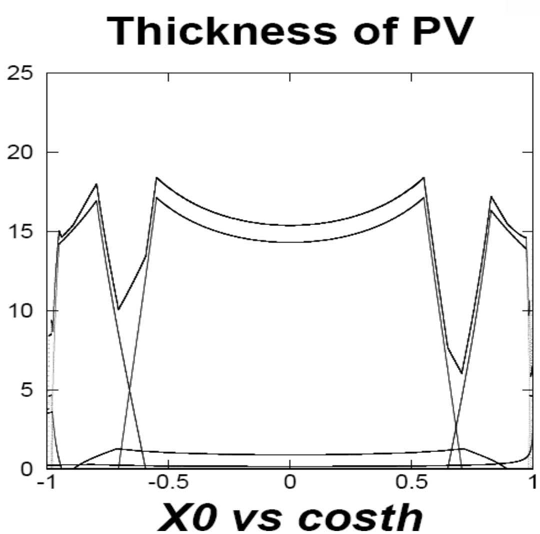
E949 detectors: Powerful and redundant particle ID

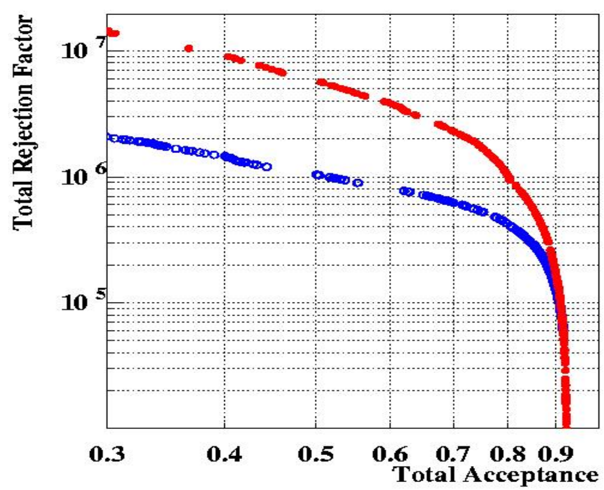
- Drift chamber, UTC
- Range stack
  Momentum, energy and range measurement
- Hermetic PV



π-ID from its decay chain.





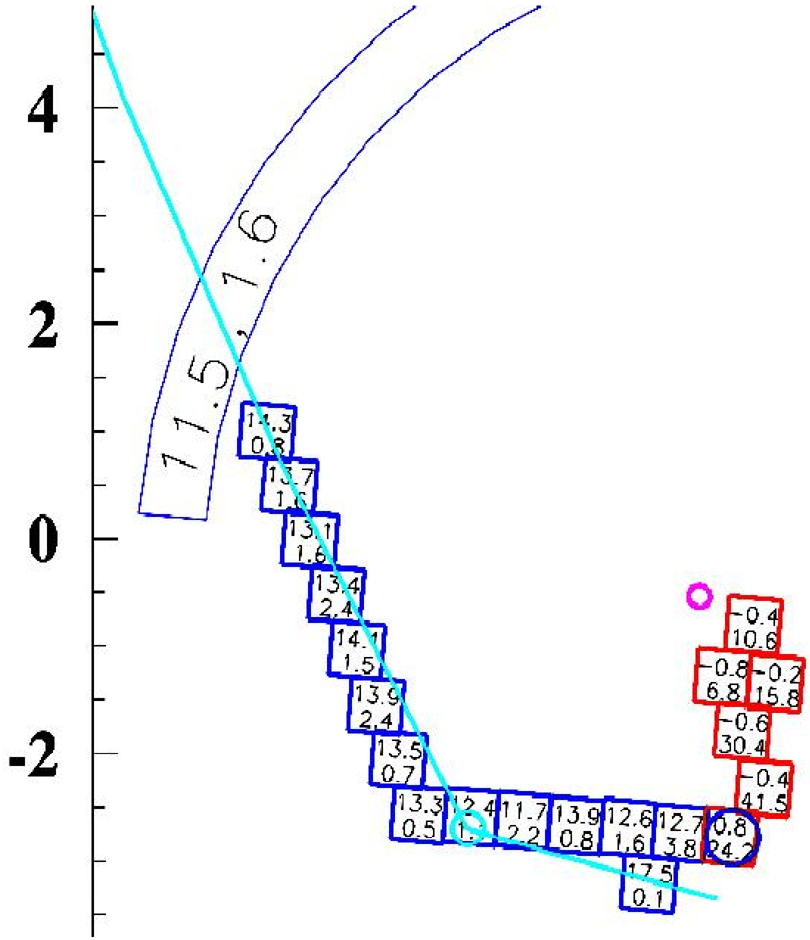


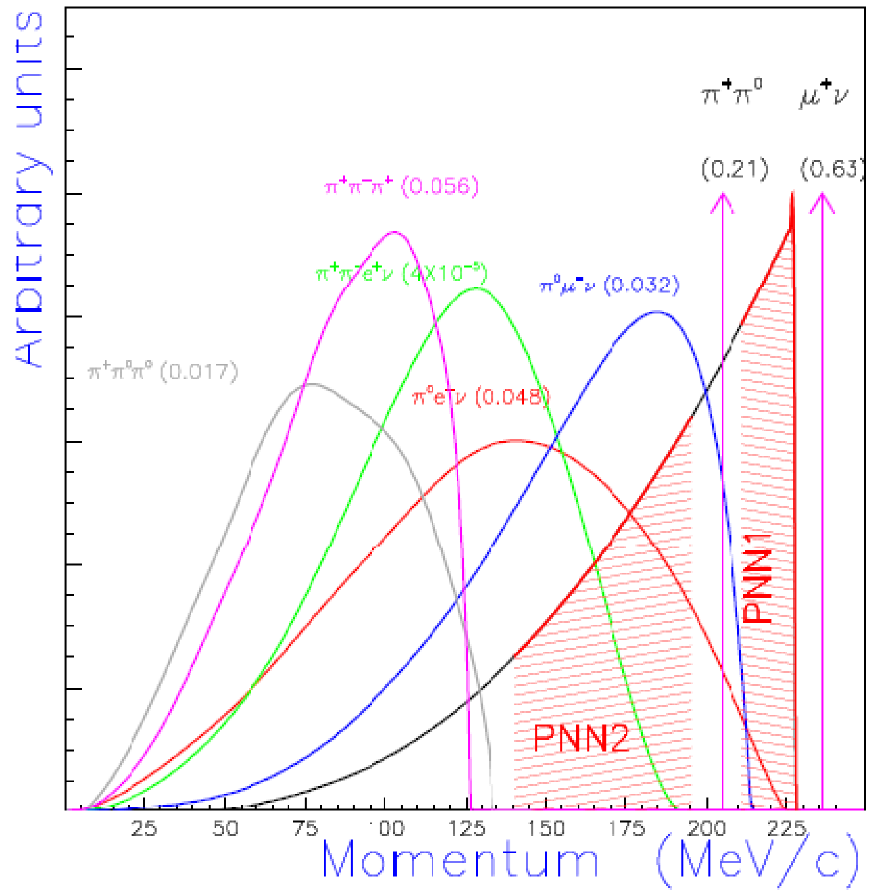
Important background list

Cut / Bkg	Kinematics cuts (P/R/E)	Particle ID ($K/\pi/\mu$)	Photon veto	Target pattern	Timing cuts
$K^+ \to \pi^+\pi^0$ scattering			√	√	
$K^+ \to \pi^+\pi^0\gamma$	√		√		
Beam		√		√	√
muon	√	√	√		
$K^+ \to \pi^+\pi^- e^+\nu$			√	√	
Charge exchange $K^+n \to K^0p$			√	√	√

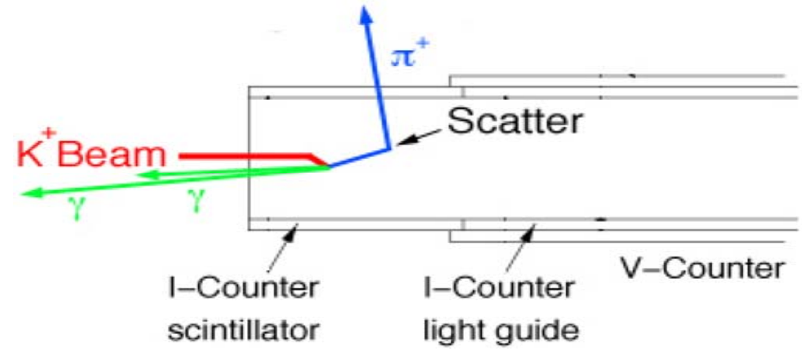
An example: $K^+ \rightarrow \pi^+\pi^0$ target scattering

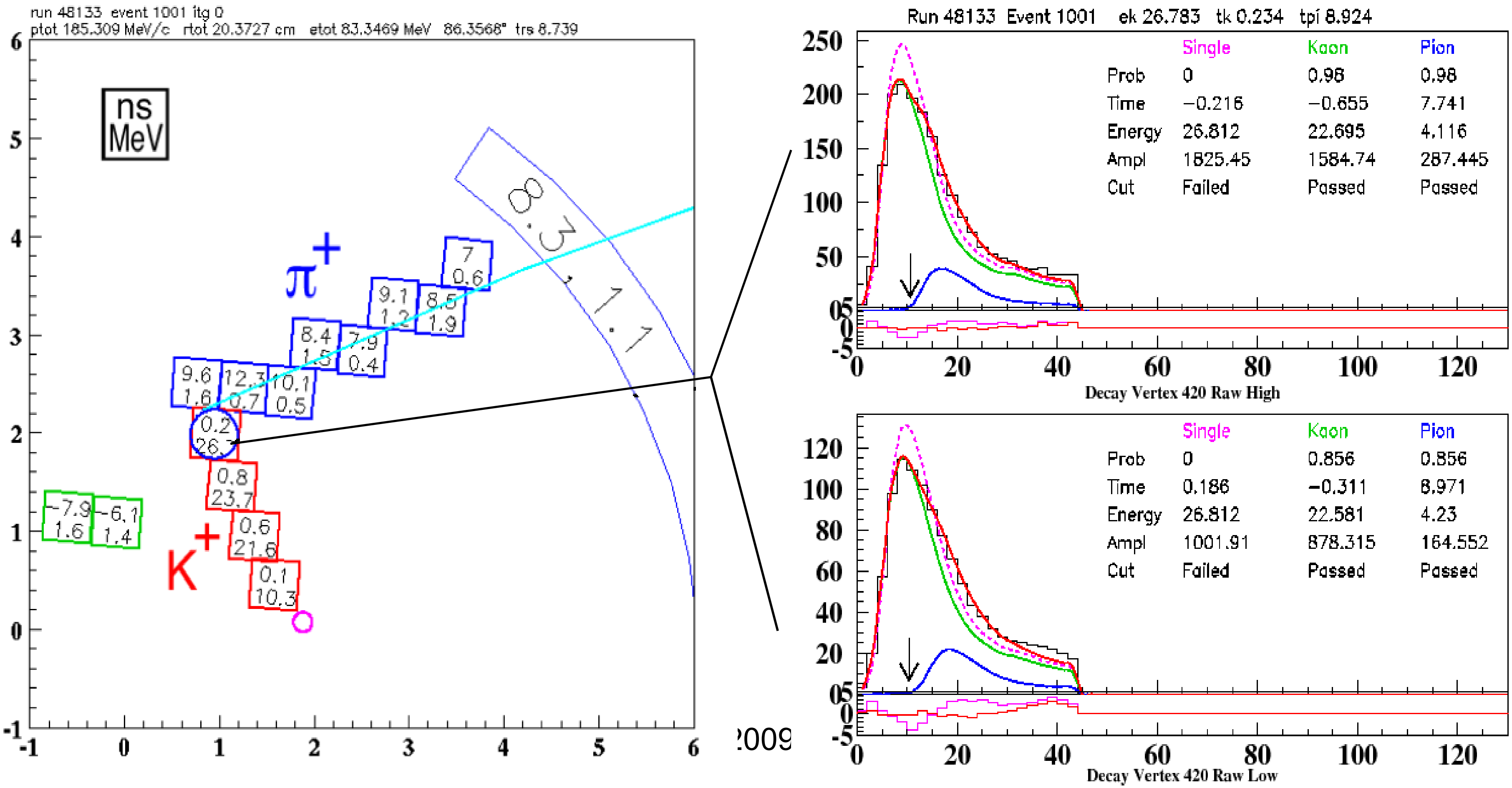
Transversal Scattering:





Longitudinal scattering
CCD pulse cut



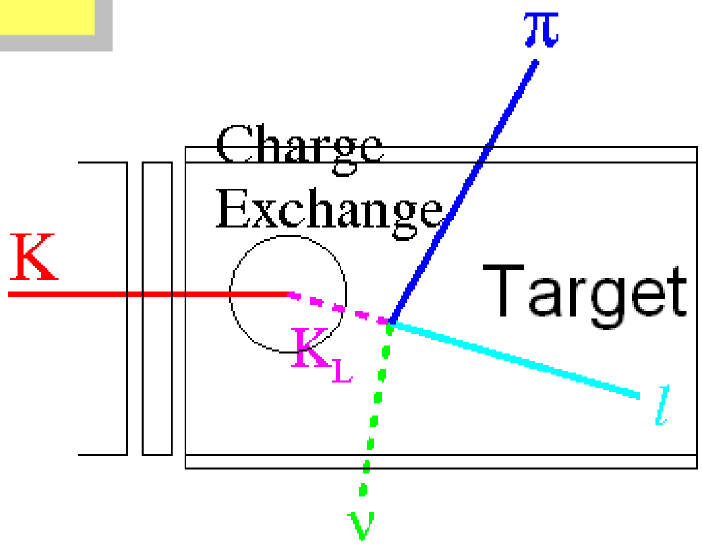


In some case we need MC to estimate background

Charge exchange ($K^+n \rightarrow K^0p$)

$$K^+n \rightarrow K^0p, \quad K^0_L \rightarrow \pi^+l^-\nu$$

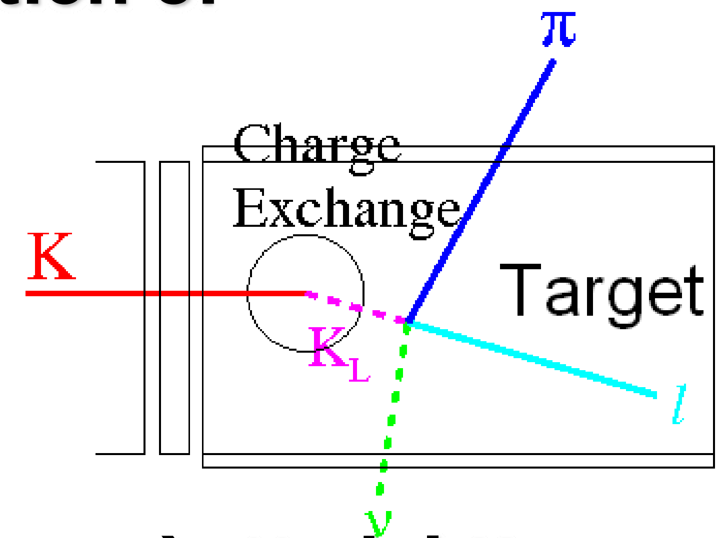
One serious background from low energy K^+ nuclear interaction



- **The momentum of proton is very low and e or μ could also be missing**
- **Cross section varies with K^+ momentum (0-50MeV) and different nucleus**

- **Cross section is not completed measured**
- **K^+ momentum (close to stop) are not measurable**
- **K^0_L momentum and vertex are not known**

MC is used to estimate the rejection of some well understood cut



MC study found:

- a gap between K^+ and π^+
- z info of π^+ is not consistent with K^+ track

- A K_S sample is collected ($K_S \to \pi^+\pi^-$). Model K_L momentum and vertex distribution with this K_S sample
- A CEX rich sample is tagged in data by selecting events with a gap between K^+ and π^+
- Use MC to evaluate the rejection of the gap cut which only needs the knowledge of K_L lifetime