First results from BNL E949 on $K^+ \to \pi^+ \nu\bar{\nu}$

For the E949 collaboration:
Ilektra A. Christidi
SUNY at Stony Brook

After analyzing data taken in 2002, one candidate event of the rare decay was found by the experiment E949, in addition to the two found previously by its predecessor, E787, at the AGS at BNL. The branching ratio was updated to $BR(K^+ \to \pi^+\nu\nu) = (1.47^{+1.30}_{-0.89}) \cdot 10^{-10}$, a value twice the one predicted by the SM, but still consistent with it.

THEORY

The CKM matrix relates weak with mass eigenstates. In the Wolfenstein parametrization,

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 & 1 \end{pmatrix}$$

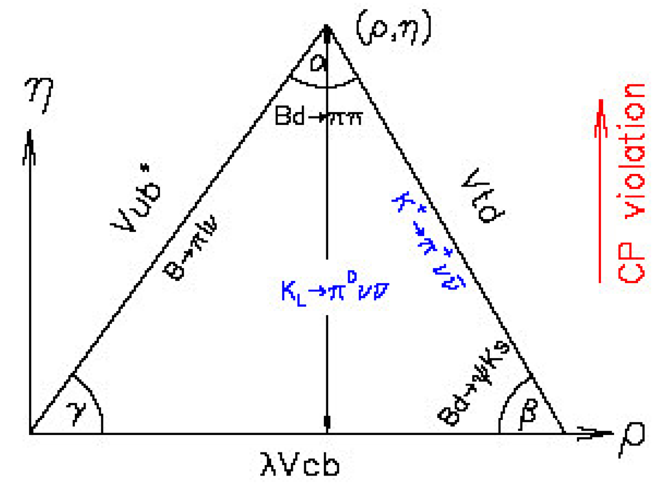
where $\bar{\rho} = \rho\left(1-\frac{\lambda^2}{2}\right)$, $\bar{\eta} = \eta\left(1-\frac{\lambda^2}{2}\right)$

CP violation arises from the irreducible phase of V_{CKM}, denoted by the parameter η. Therefore, a precise measurement of V_{td}, combined with other measurements, gives all the information on SM CP violation.

V_{CKM} is unitary, i.e. $VV^+ = I \Rightarrow$ 6 relations of $V_{ij} = 0$

For example, $V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$

⇒ A ***"Unitarity triangle"*** in the ρ-η plane ($V_{ud} \cong 1$, $V_{tb} = 1$) :

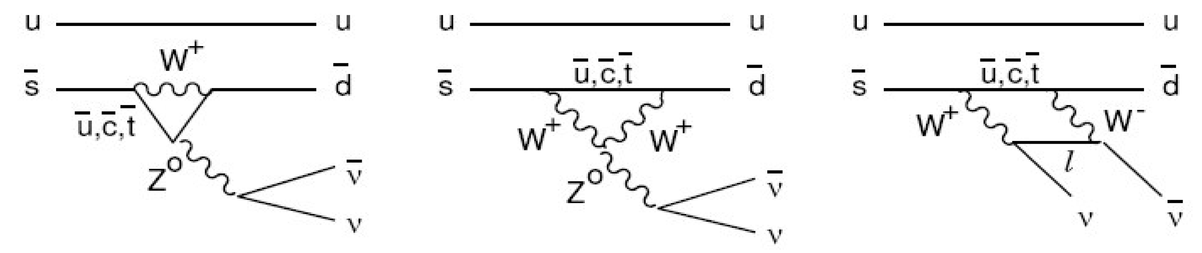


Processes w/ small theoretical uncertainties:

Process	Experiments
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	E787/E949, FNAL-E921
$\mathcal{B}(K^0_L \to \pi^0\nu\bar{\nu})$	KOPIO, E391a
$\mathcal{A}(B \to J/\psi K^0_S)$	BaBar, Belle
CP violating decay rate asymmetry	
$\Delta M_{B_s}/\Delta M_{B_d}$	CDF, D0, LHCb, BTeV
ratio of mixing frequencies of B_s and B_d mesons	

→ THE SM $K^+ \to \pi^+ \nu \bar{\nu}$ BRANCHING RATIO :

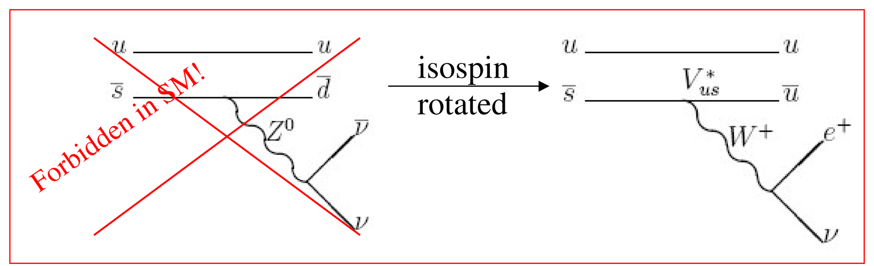
- All processes at 2nd order
- Main contribution of t in the loop (u & c almost cancel by GIM mechanism)
- Very theoretically "clean" calculation (precision < 5%, uncertainties mainly from c sector)



$$BR(K^+ \to \pi^+\nu\bar{\nu}) \propto \sum_{l=e,\mu,\tau} \left| \left[V_{cs}^* V_{cd} X(\chi_c) + V_{ts}^* V_{td} X(\chi_t) \right] \times (HADR) \times (\bar{\nu}_l \nu_l) \right|^2 \Rightarrow$$

$$\ldots BR \propto (\sigma\bar{\eta})^2 + (\rho_o - \bar{\rho})^2$$ → ellipse in ρ-η plane

$$\sigma = \left(\frac{1}{1-\lambda^2/2} \right)^2$$



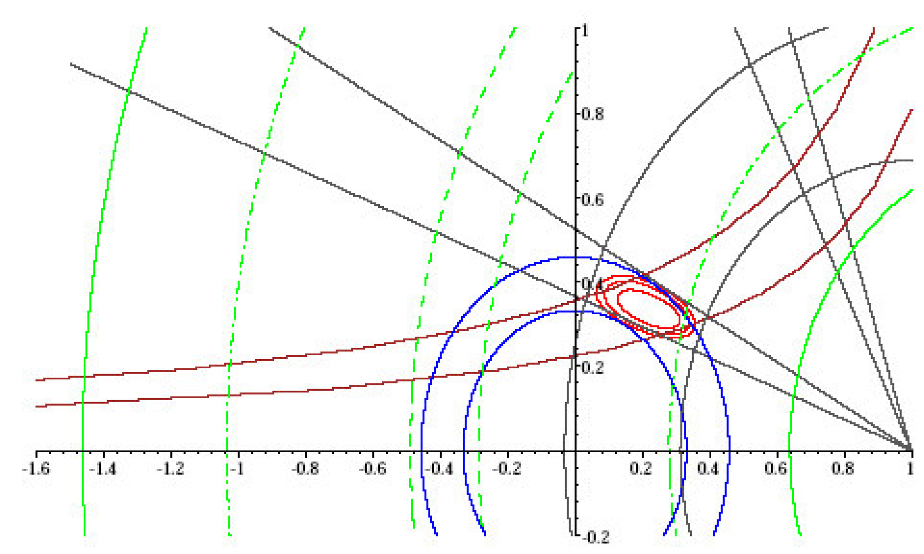
$$BR_{th}(K^+ \to \pi^+\nu\bar{\nu}) = (0.77 \pm 0.11) \times 10^{-10}$$

EFFECT ON CKM MATRIX

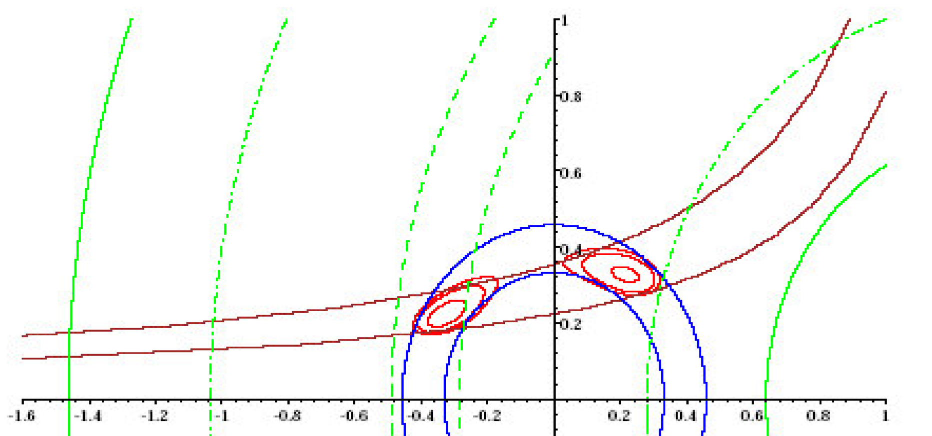
The latest CKM fits, by Gino Isidori …

The E949 result agrees with the SM within statistics, and all current measurements of the CKM parameters overlap in a region on the ρ-η plane. However, if after further measurements the high branching ratio for $K^+ \to \pi^+\nu\nu$ persists, a difference between the K and B sector will be illustrated, indicating new physics in either one or both of these sectors.

⇒ completing E949 is critical to resolving the issue !



… with all the constraints



… without constraints that depend on B_d mixing

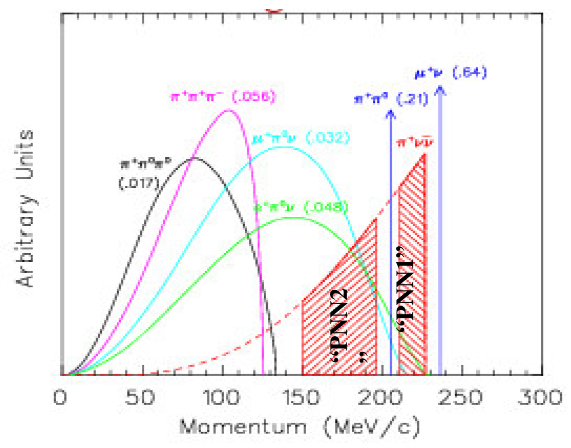
Limits from measurements of:
$BR(K^+ - \pi^+\nu\nu)$
ε_K
$|V_{ub}|/|V_{cb}|$
$\sin 2\beta$
ΔM_d, $\Delta M_s/\Delta M_d$ } Depend on B_d mixing
Combined all but $K^+ - \pi^+\nu\nu$ (68%, 90%, 95%)

MEASUREMENT

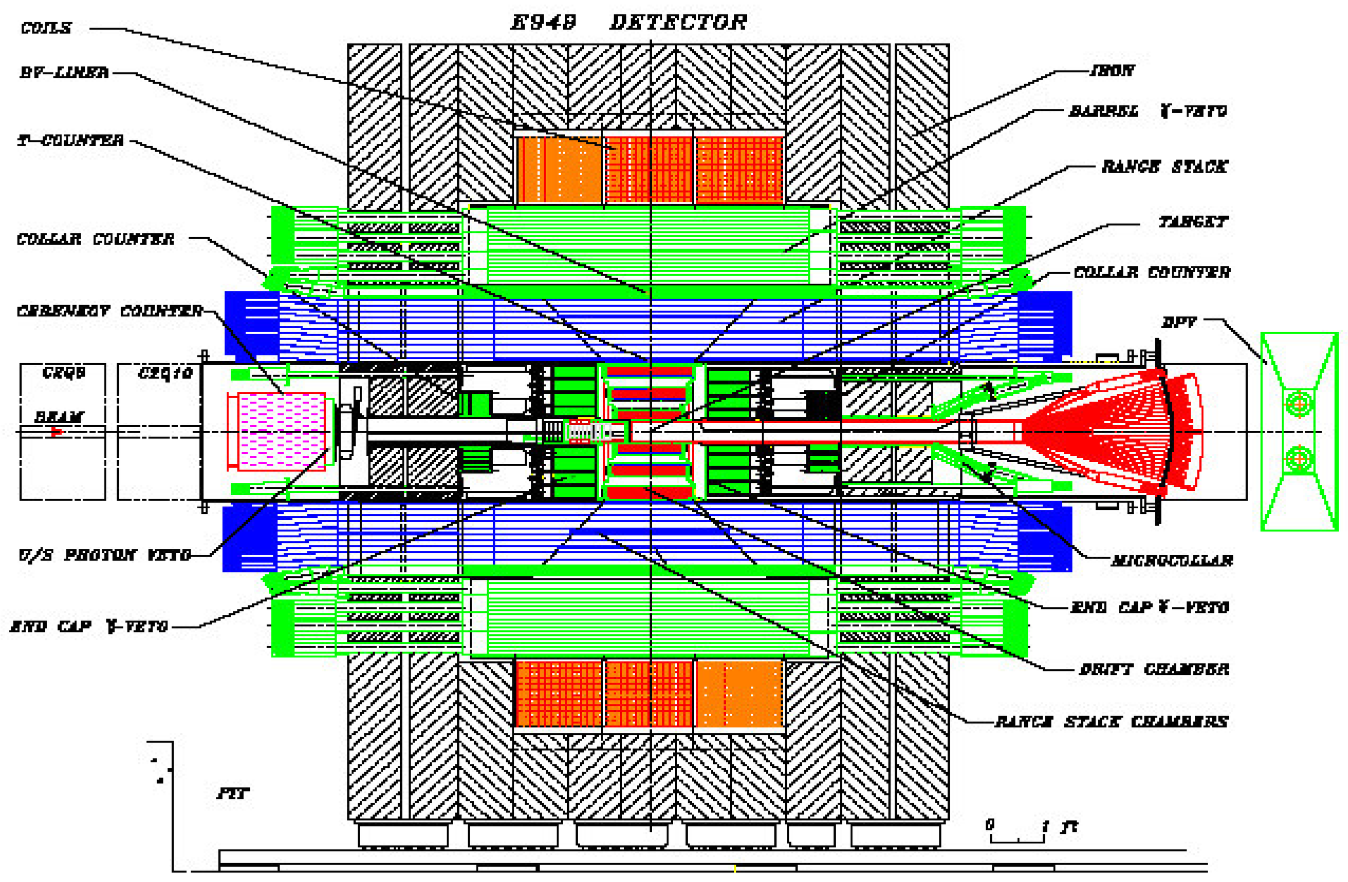
- 3-body decay with 2 missing particles: $0 \le p_{\pi^+} \le 227$ MeV/c ⇒ Signal: π^+ + nothing, backgrounds (bg) vetoed ~ 10^{-11} !

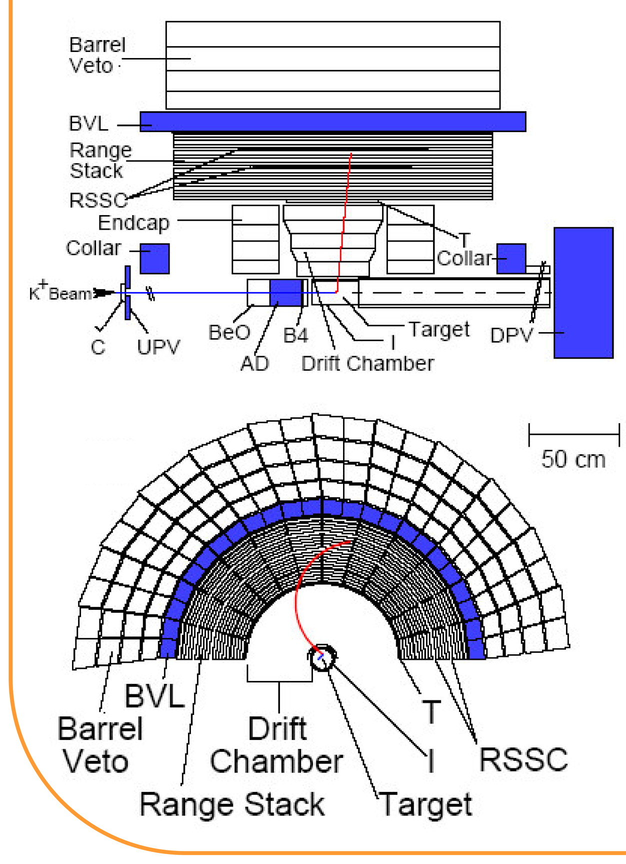
Search region divided to above ("PNN1") and below ("PNN2") the $K^+ \to \pi^+\pi^0$ peak. These results are from PNN1 only.

- Need
  - particle identification (PID)
  - all other charged particles vetoed < 10^{-3}
  - redundant precise kinematic measurements

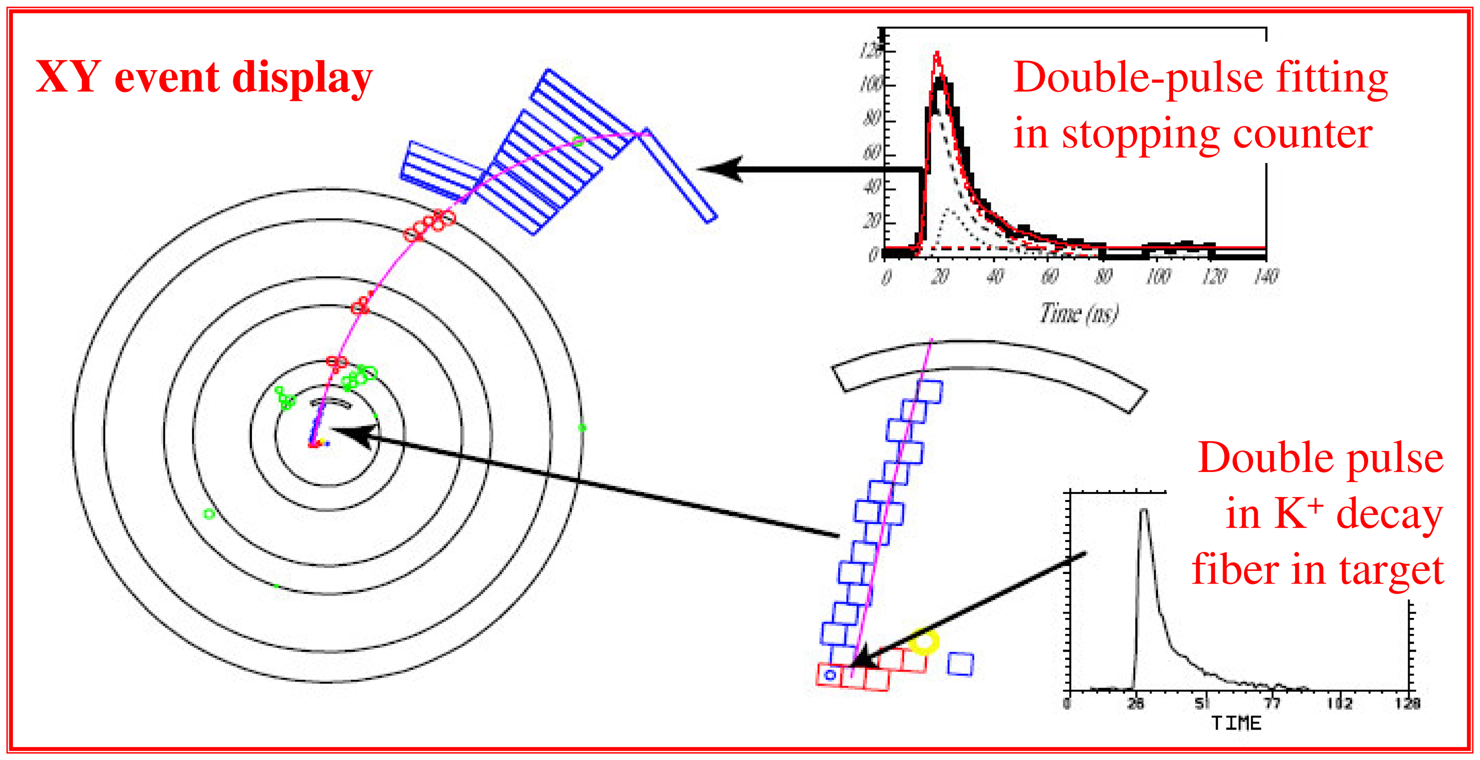


Decay	$\mathcal{B}$	PID	veto	kine.
$K^+ \to \pi^+\pi^0$	0.21	-	√ √	√
$K^+ \to \mu^+\nu$	0.63	√	-	√
$K^+ \to \mu^+\nu\gamma$	0.005	√	√	-
$K^+ \to \pi^0\mu^+\nu$	0.032	√	√ √	-
$K^+ \to \pi^0 e^+\nu$	0.048	√	√ √	-
$K^+ \to \pi^+\pi^-\pi^+$	0.056	-	√	√ √





- Incoming 700MeV/c beam K^+: identified by beam instrumentation, slowed down by active & inactive degrader.
- K^+ stops & decays at rest in scintillating fiber target – measure delay (2ns)
- Outgoing π^+ : verified by trigger counters, momentum measured in UTC, energy & range in RS and target (1T magnetic field parallel to beam)
- π^+ stops & decays in RS – detect $\pi^+ \to \mu^+ \to e^+$ pulse chain
- Photons vetoed hermetically in BV-BVL, RS, EC, CO, USPV, DSPV
- New/upgraded elements



THE E949 CANDIDATE :

P_π = 227.3 MeV/c

S/b of cell where candidate was found: 0.9

Probability that it is bg: ~7%

Probability that *ALL 3* events are bg: 0.1%

COMBINED E949 & E787 RESULT *(68% CL)* ***:***

$$BR(K^+ \to \pi^+\nu\bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$$

ANALYSIS STRATEGY

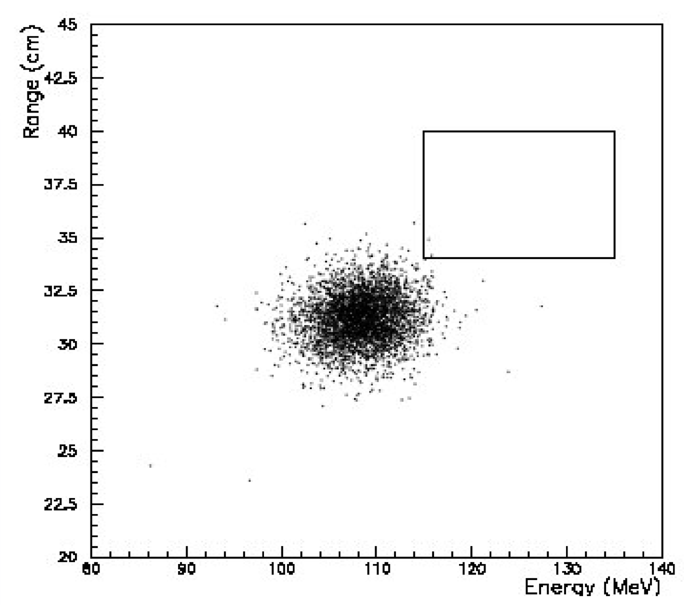
- "Blind" analysis: don't examine signal region until all bg are verified.
- A priori identification of bg sources.
- Suppress each bg source w/ at least two independent cuts.

Source	Suppresion method			
	Kinematics	Particle ID	Veto	Timing
$K^+ \to \mu^+\nu(\gamma)$ ($K_{\mu 2}$)	√	√	(√)	
$K^+ \to \pi^+\pi^0$ ($K_{\pi 2}$)	√		√	
Scattered π^+ beam		√		√
CEX			√	√

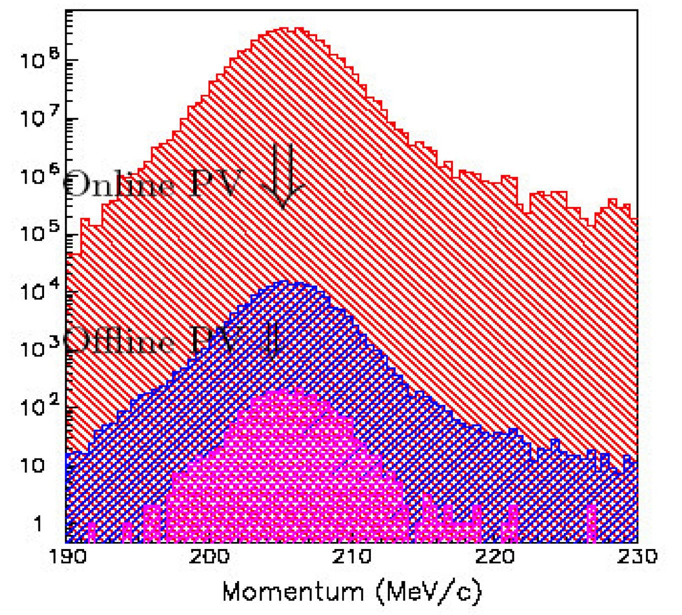
$CEX \equiv K^+ n \to K^0 p$, $K^0_L \to \pi^+ \ell^- \nu$

- Bg cannot be reliably simulated ⇒ measure w/ data by inverting cuts and measuring rejection.
- Verify bg estimates & check for correlations by loosening cuts and comparing observed and predicted number of events remaining.

Example: $K^+ \to \pi^+\pi^0$



Select events with photons, measure rejection of kinematic cuts (P, R, E "box")



Select $K^+ \to \pi^+\pi^0$ kinematically, measure rejection of photon veto

- Use MC to measure geometrical acceptance, verify by measuring $BR(K^+ \to \pi^+\pi^0)$.
- Divide signal region into cells, calculate expected bg (b_i) and signal (s_i) for each cell.
- Calculate BR using s_i/b_i of cells where event(s) are found, using likelihood ratio method.

⇒ Total bg expected in signal region: 0.30 ±0.03 events

For more info:

"Improved Measurement of the $K^+ \to \pi^+\nu\nu$ Branching Ratio", E949 collaboration, PRL 93, 031801 (2004)

"$K \to \pi\nu\nu$ and High Precision Determinations of the CKM Matrix", G. Buchalla et al., hep-ph/9607447 (1996)