Final BNL E949 results on the search for the rare decay $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

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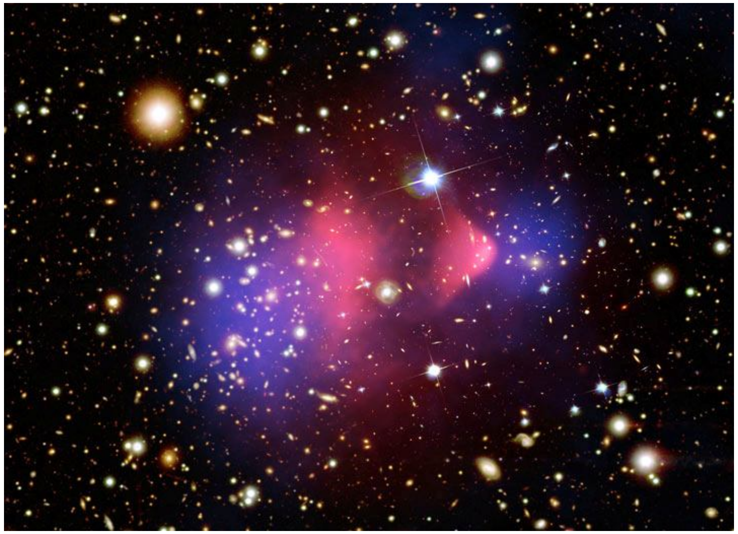
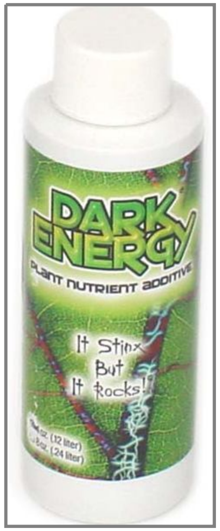
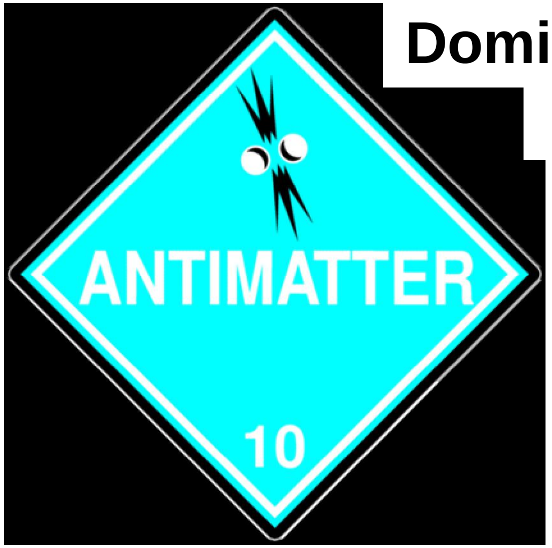
There's new physics beyond the Standard Model, but we don't know exactly what it is (yet)

Dark matter and dark energy





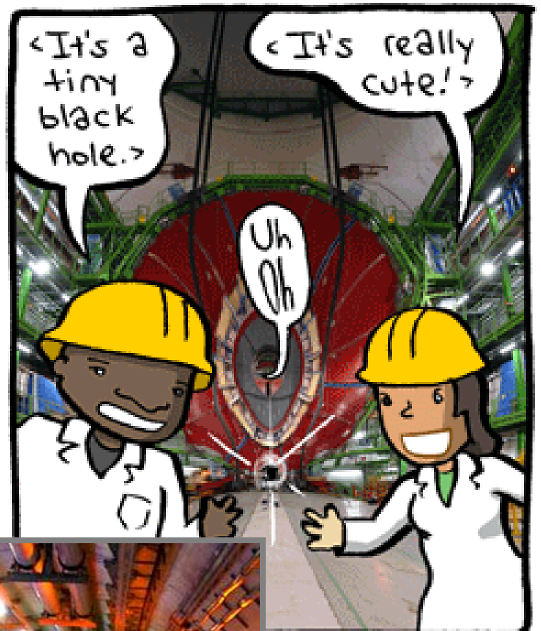
Dominance of matter over antimatter



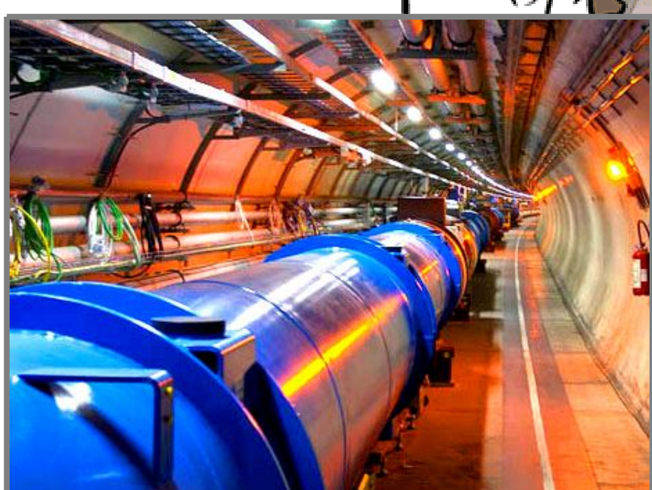
Neutrino mass and oscillations

To find physics beyond the Standard Model, we need to break the Standard Model

Energy frontier

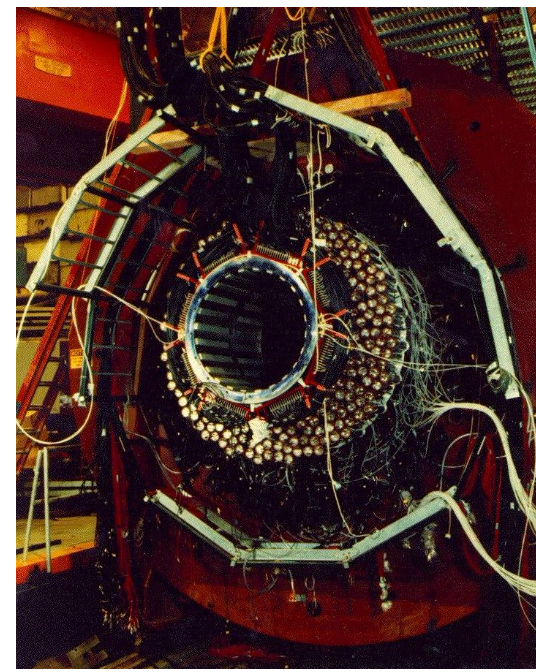


overcompensating.com



LHC

Precision/Intensity Frontier

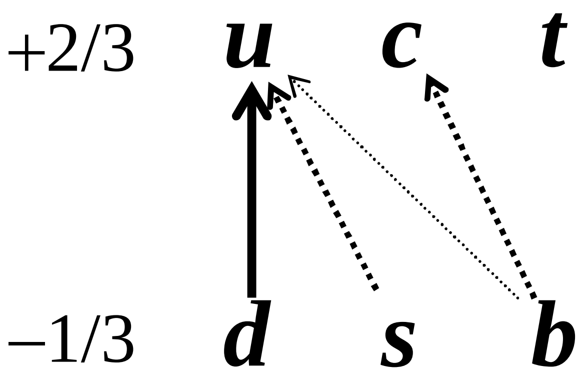


Rare decays such as

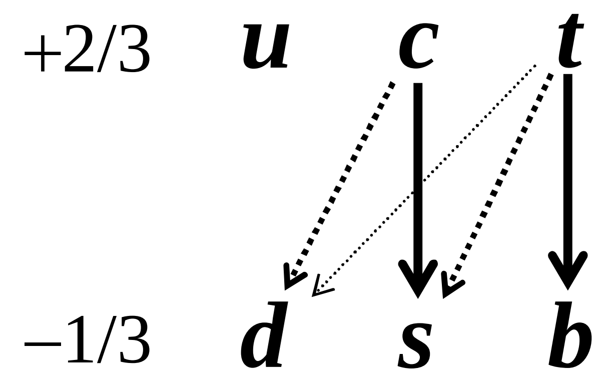
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$

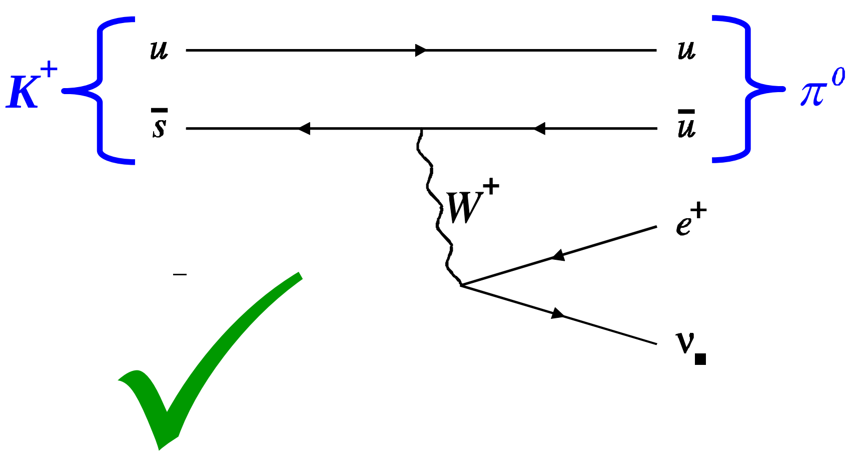
(E949/E787 @ BNL)

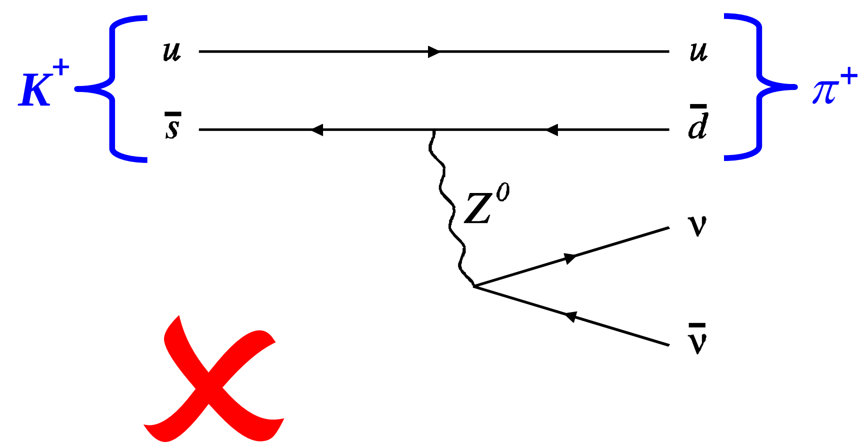
Quarks cannot decay to another quark of the same charge by a first-order process



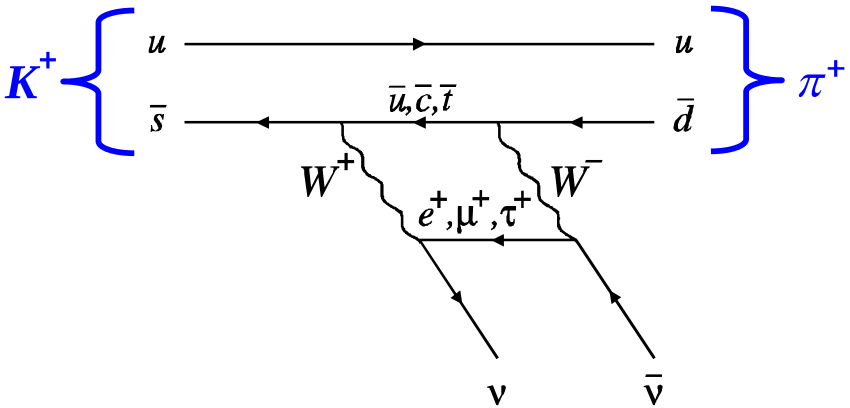
First-order weak decays of quarks



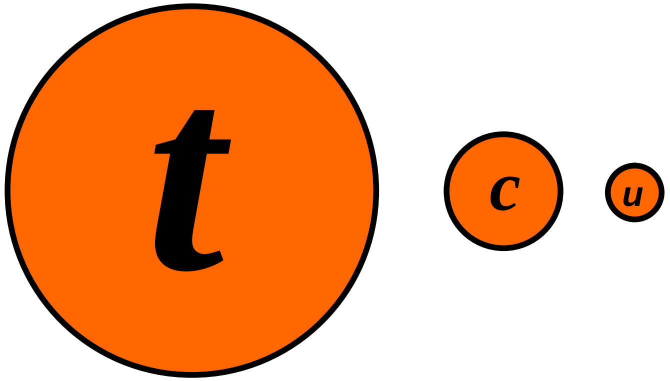


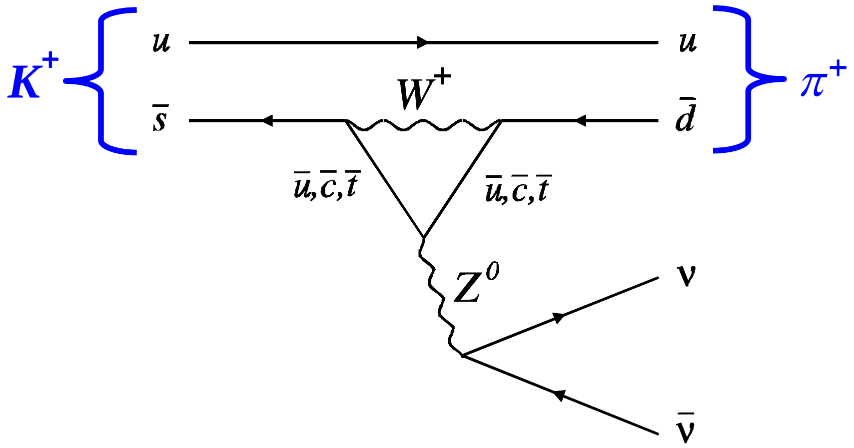


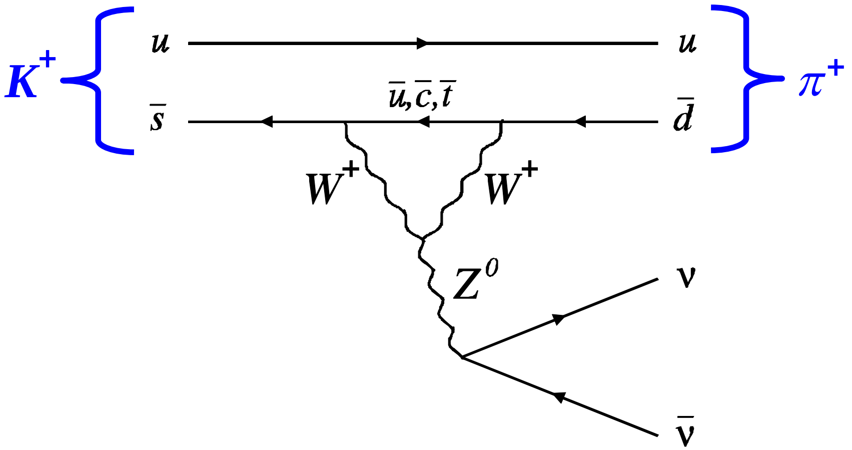
$K^+ \to \pi^+ \nu\bar{\nu}$ proceeds very slowly through second-order weak processes



The decay proceeds through second-order processes due to massive top quark

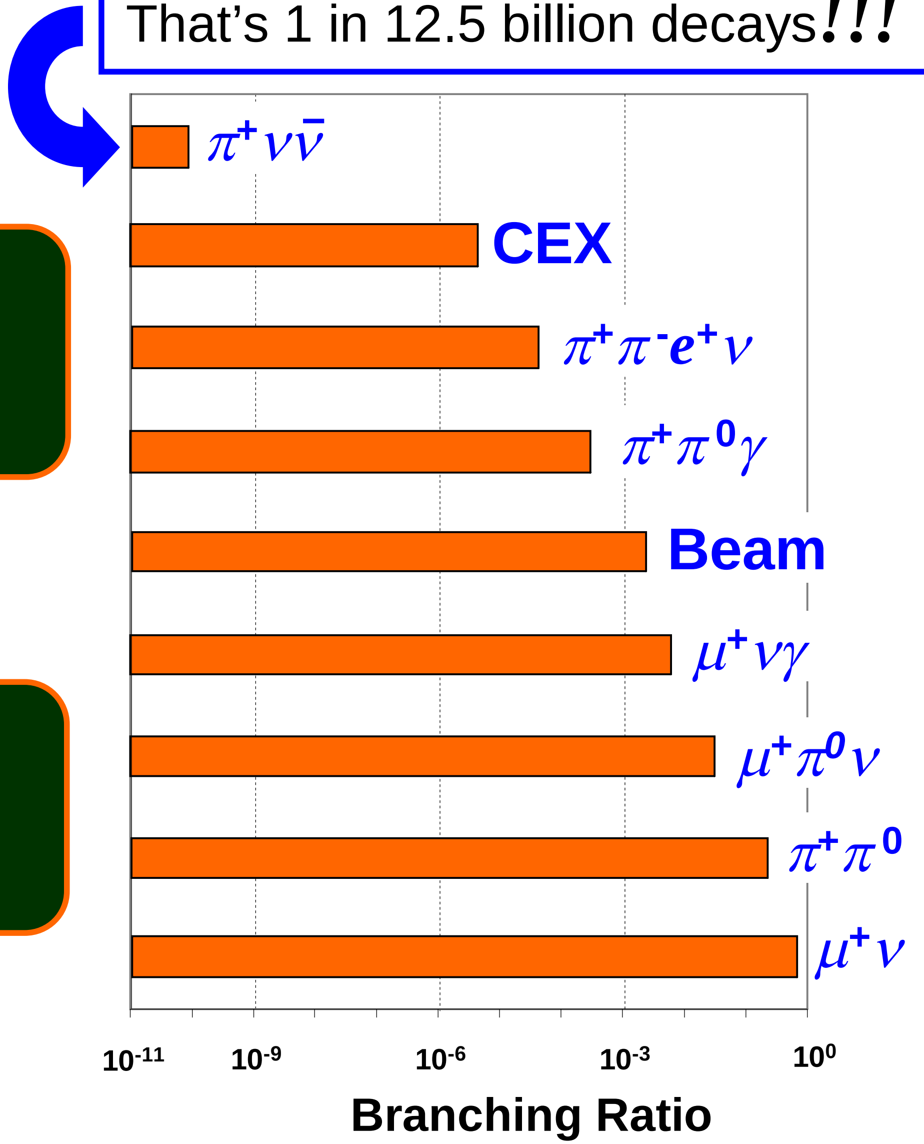






Observing the rare decay $K^+ \to \pi^+ \nu\bar{\nu}$ is an enormous experimental challenge

That's 1 in 12.5 billion decays***!!!***

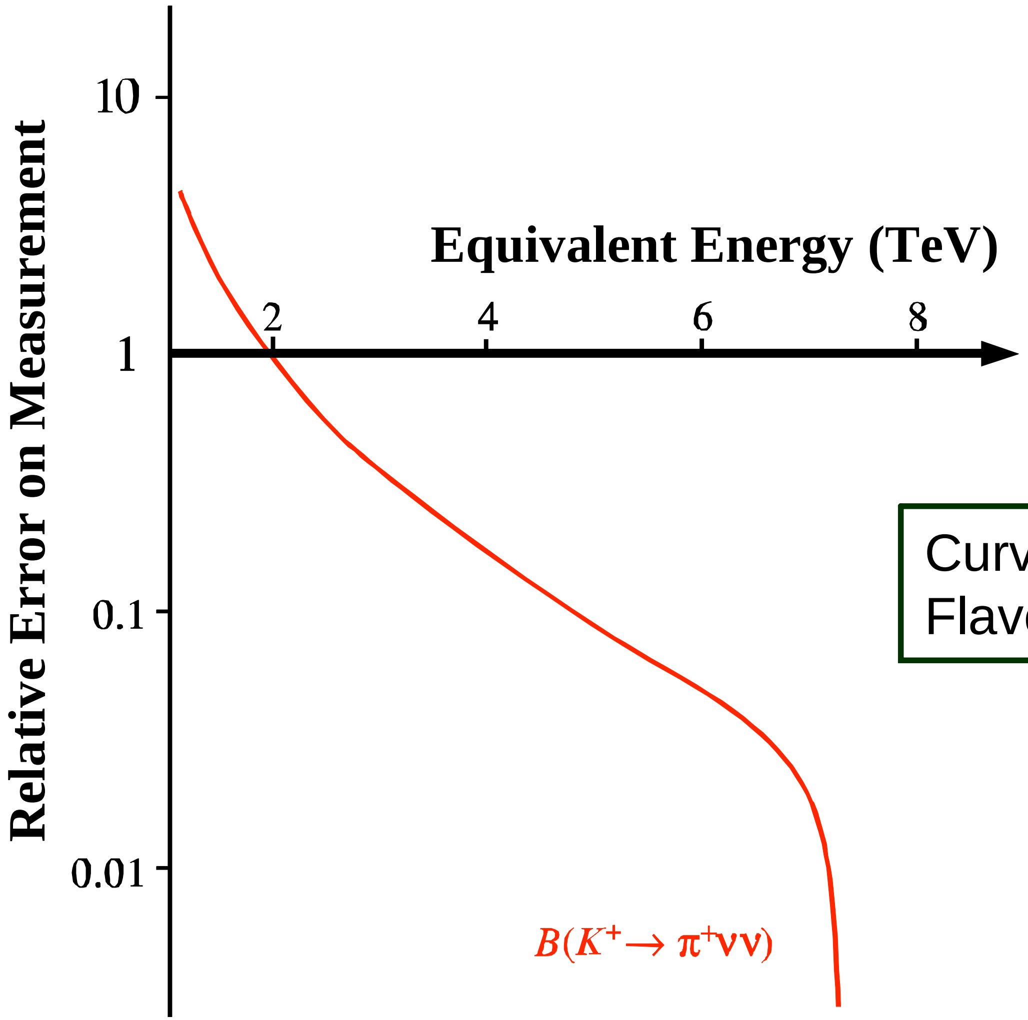


Standard Model branching ratio is $(0.84 \pm 0.7)\times 10^{-10}$

+

Experimental signature is π^+ + "nothing"

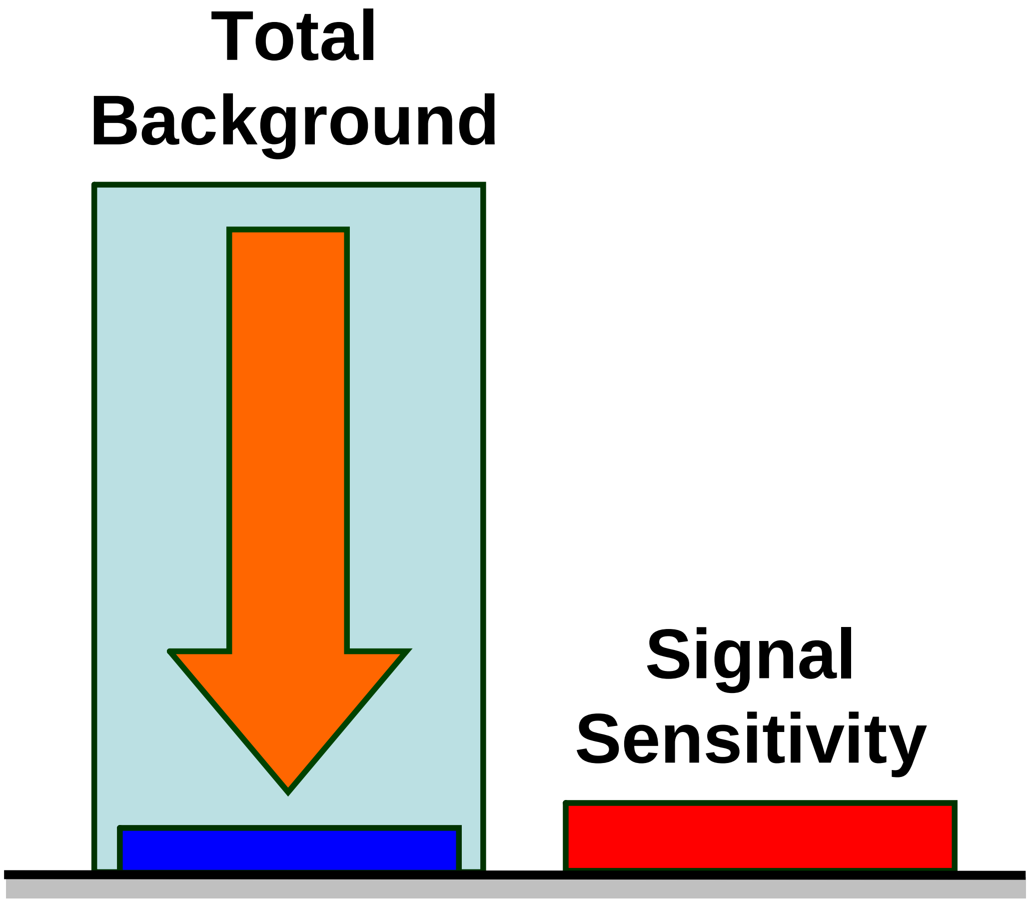
A precision measurement of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay rate probes for new physics



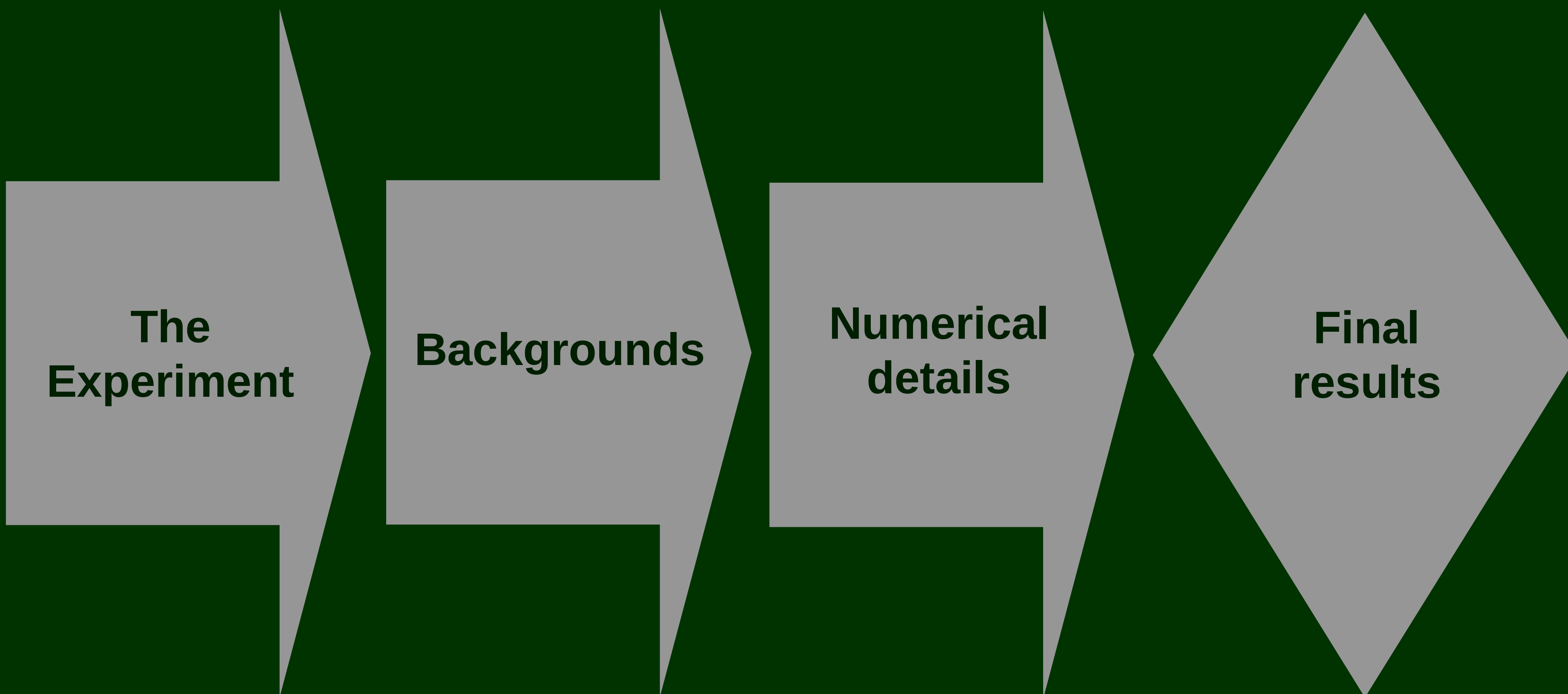
Curve assumes a Minimal Flavor Violation (MFV) model

Curve extracted from D.Bryman *et al*., IJMPA **21**, 487 (2006)

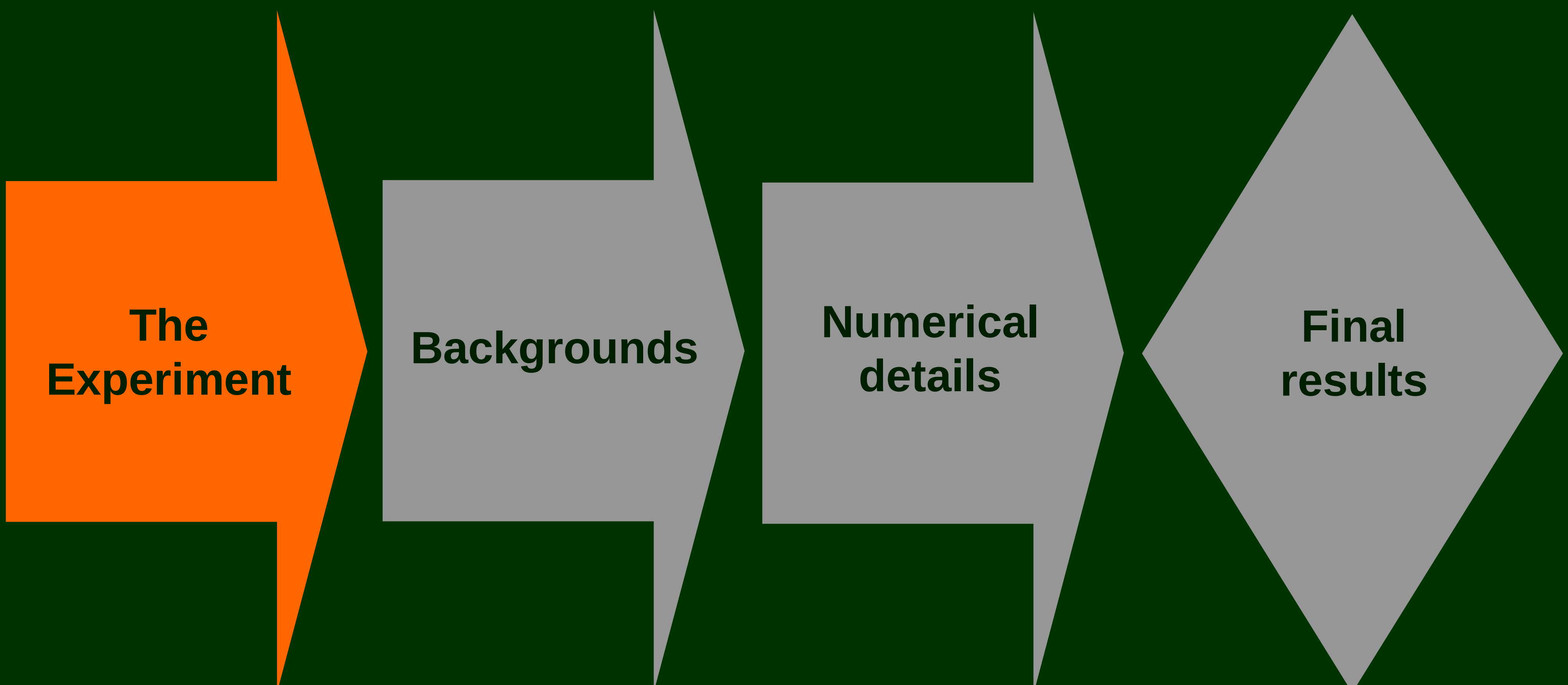
The E949 experimental goal is to suppress backgrounds to below the sensitivity level of the signal



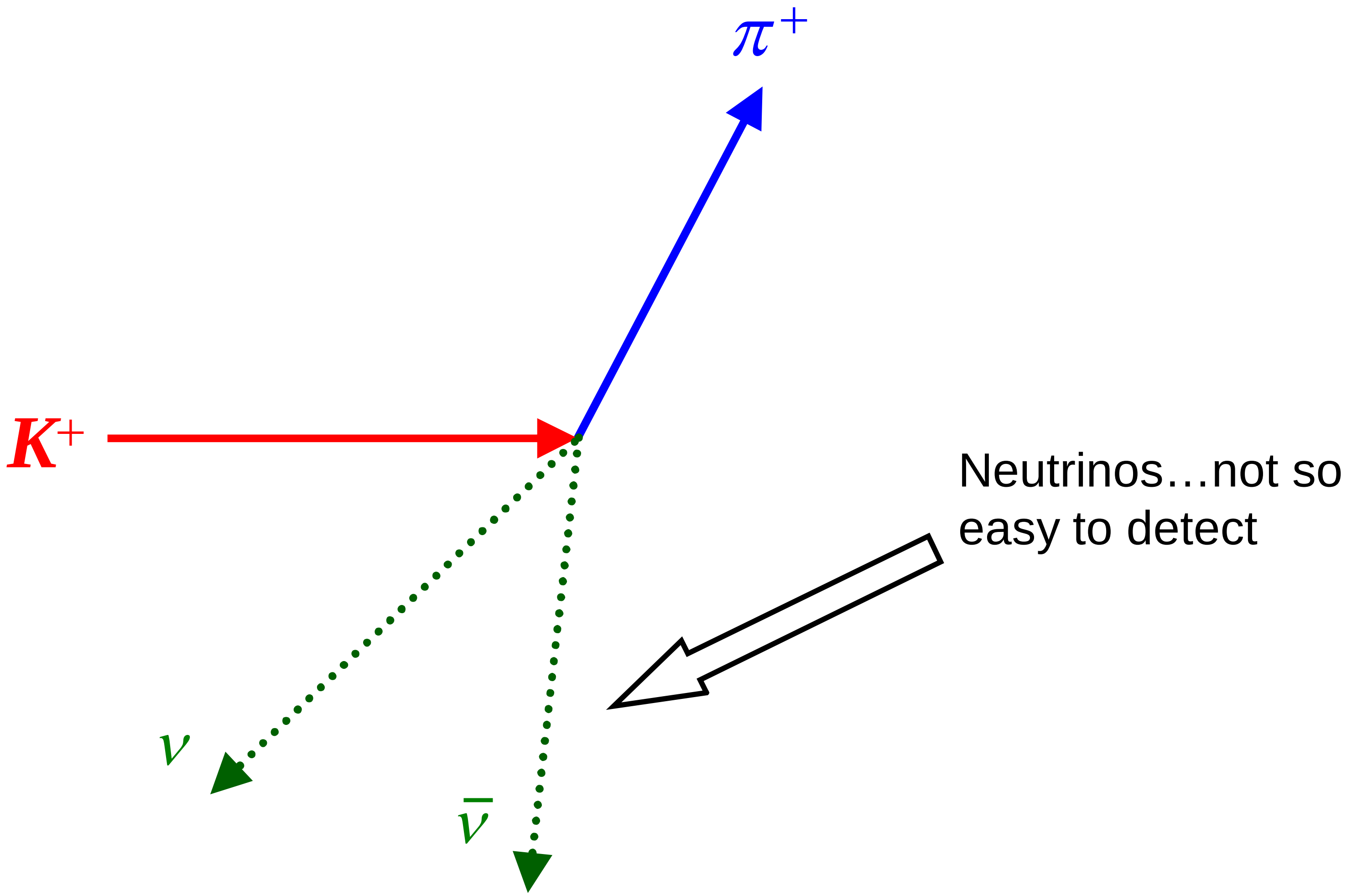
The rest of this talk will look at the E949 experiment in four sections



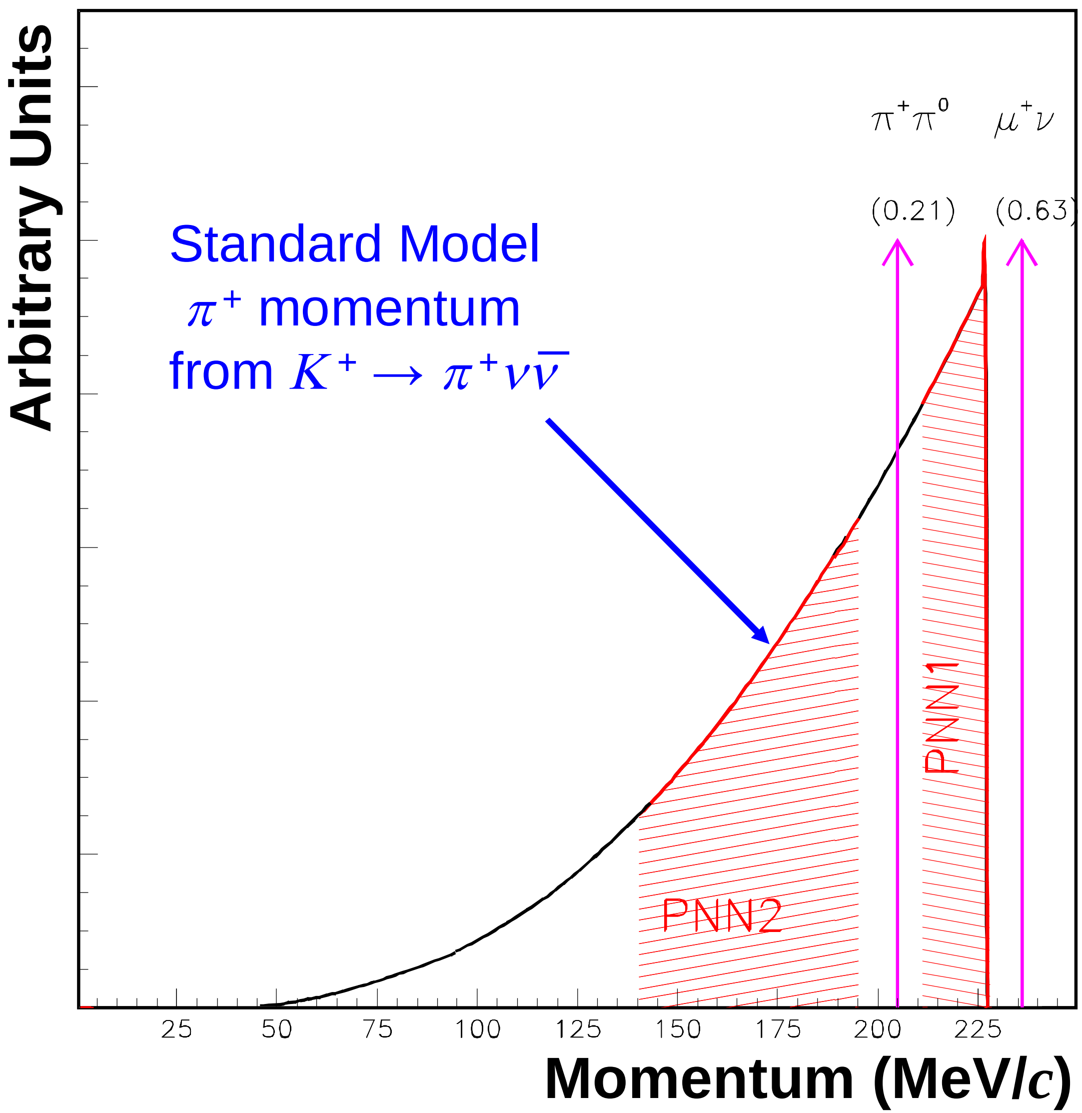
In this section I will discuss the experimental challenge and the blind analysis method



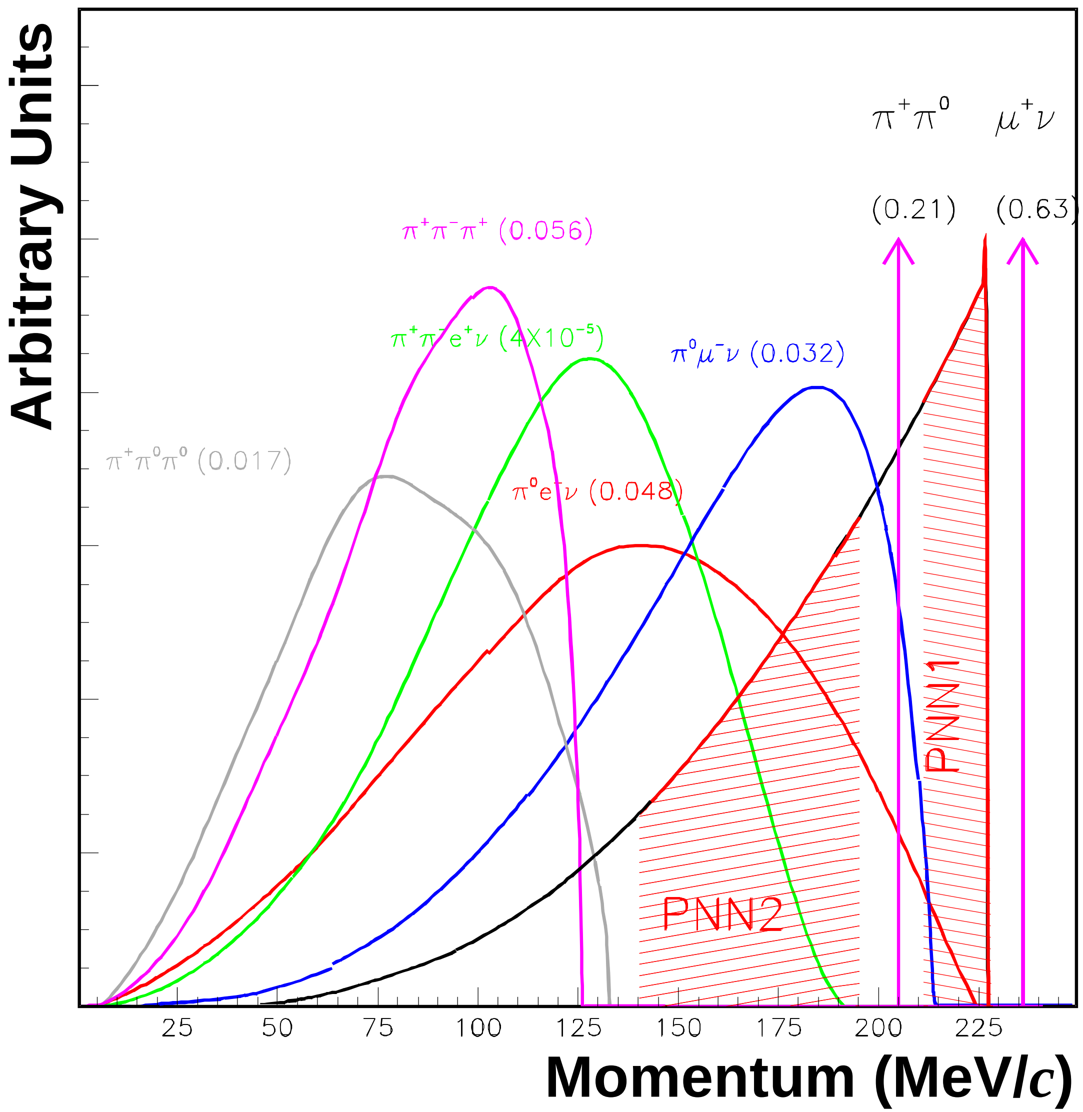
The experimental challenge is to observe π^+ + "nothing"



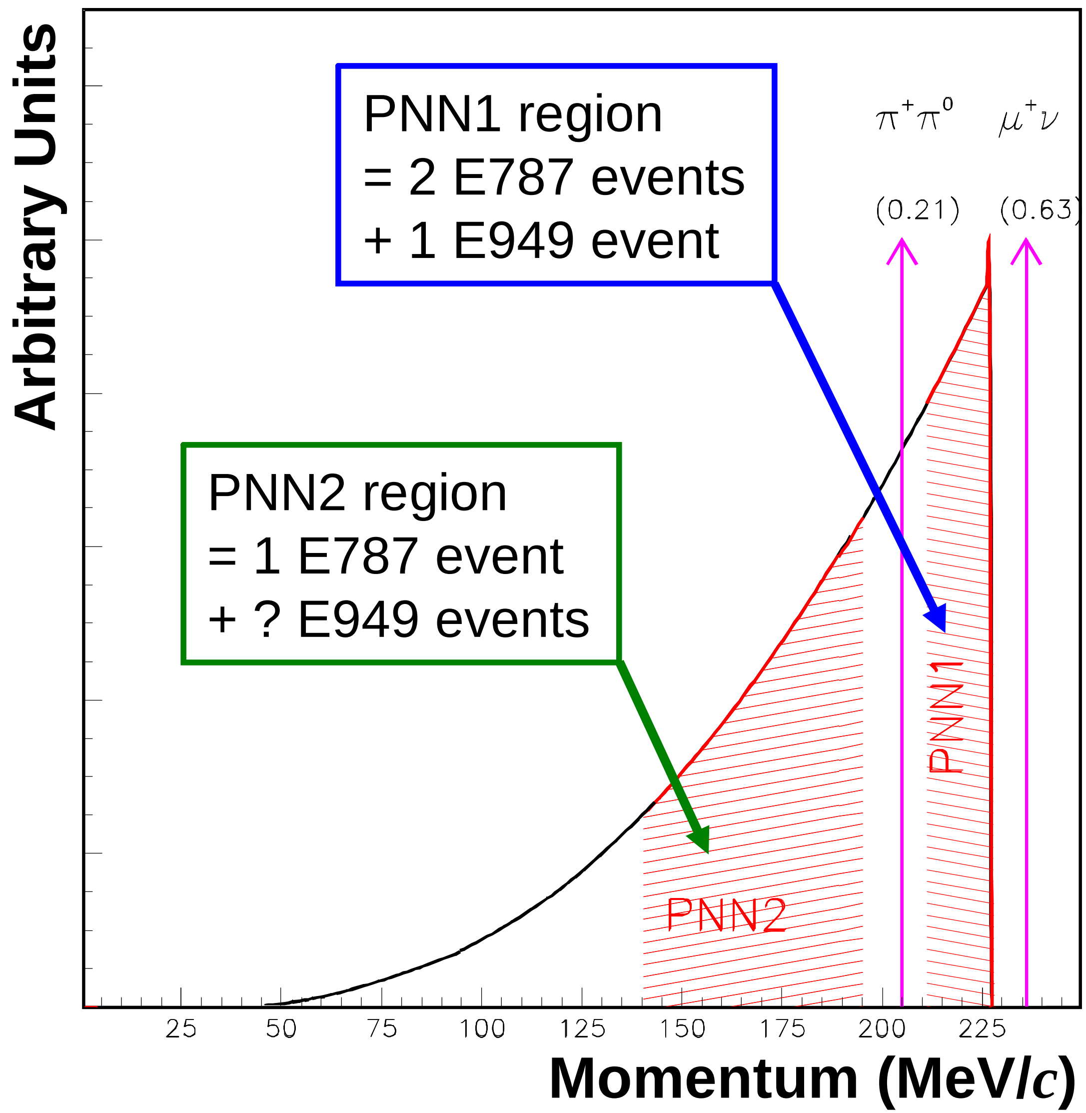
The $\pi^+\pi^0$ decay splits the signal region in two: PNN1 and PNN2



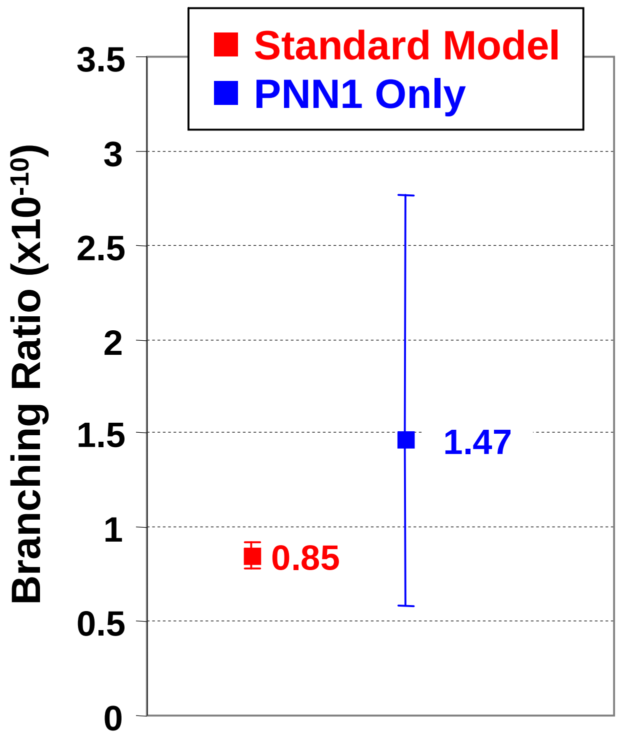
Things get ugly in the PNN2 region



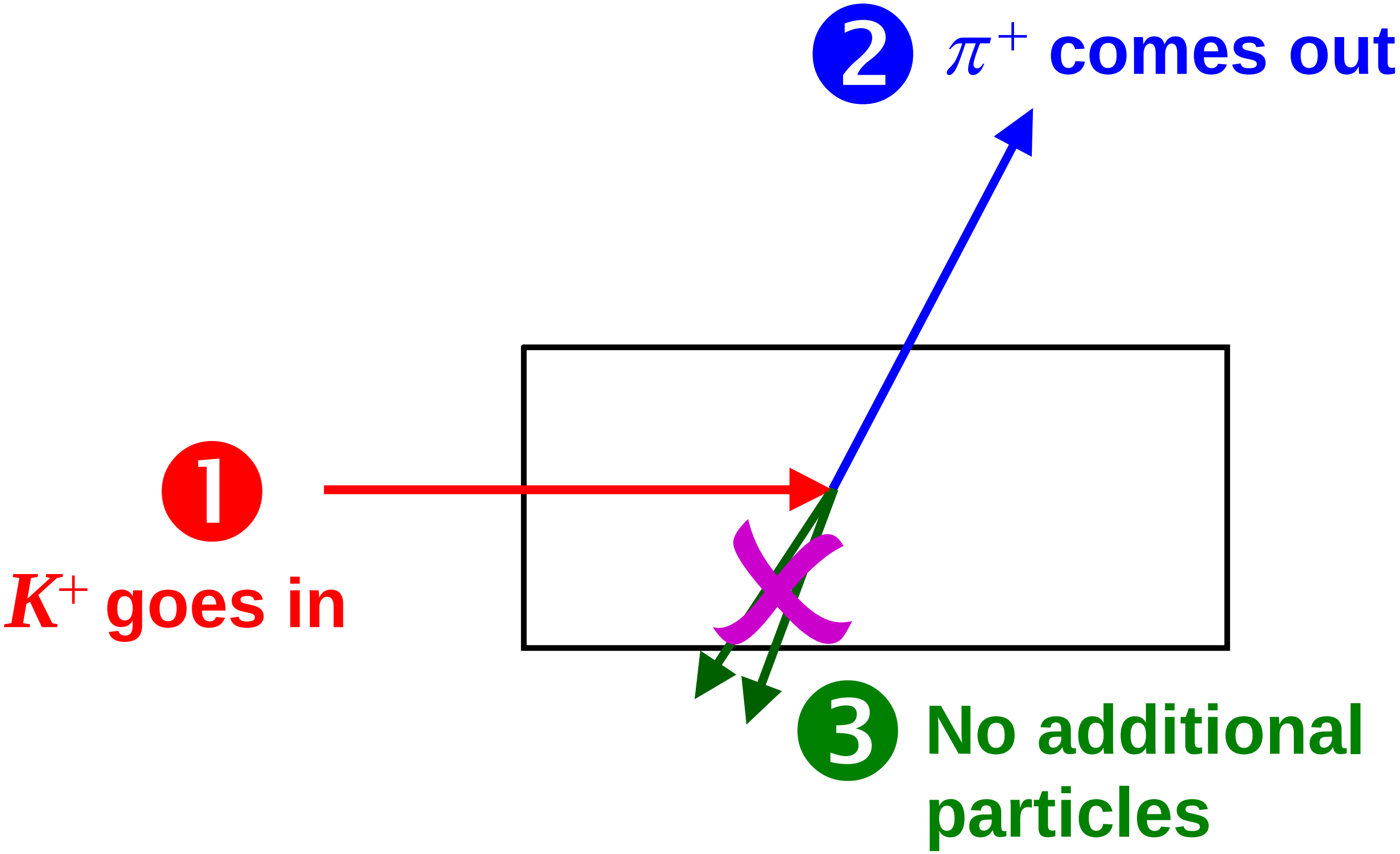
E949 & E787 have previously observed four candidate events showing that it can be done



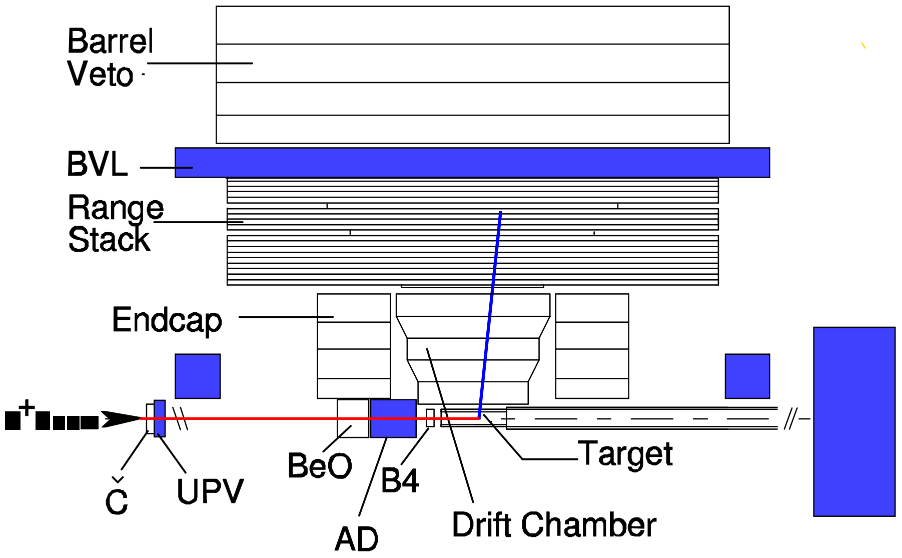
Refs: PRD**70**, 037102 (2004), PRD**77**, 052003 (2008)

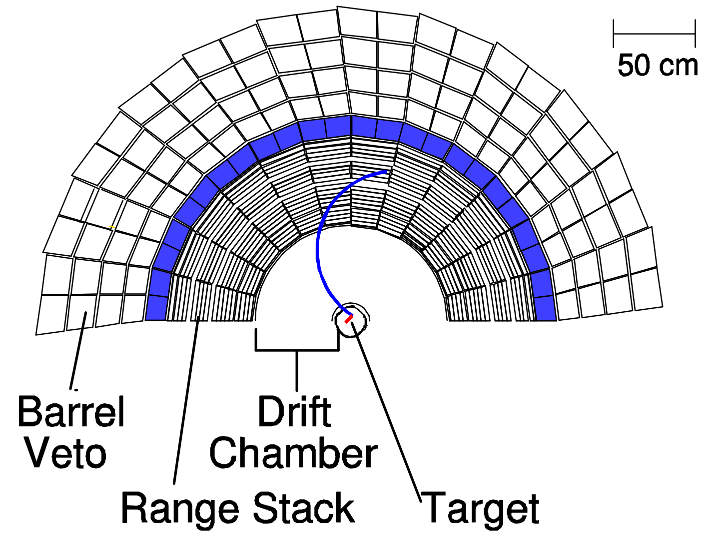


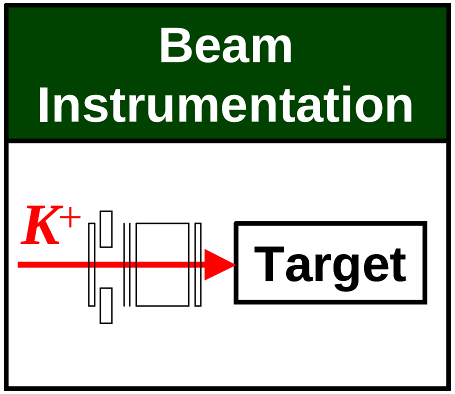
How to observe $K^+ \to \pi^+ \nu \bar{\nu}$ in three easy steps

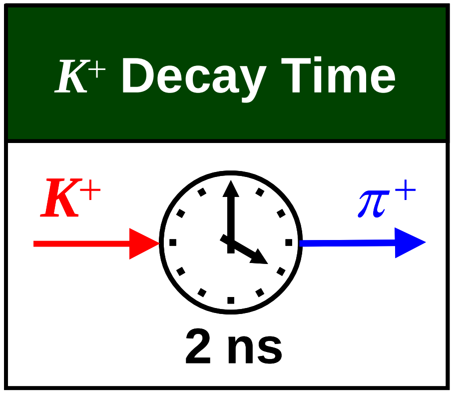


700 MeV/c kaon enters and decays-at-rest in the scintillator-fiber target





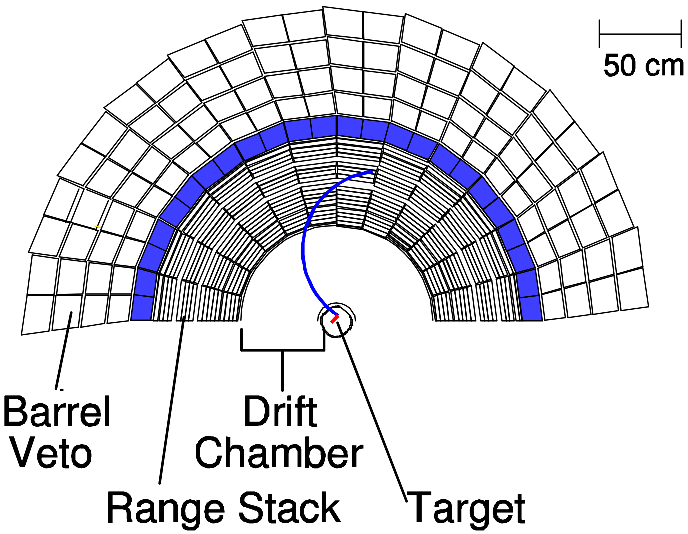




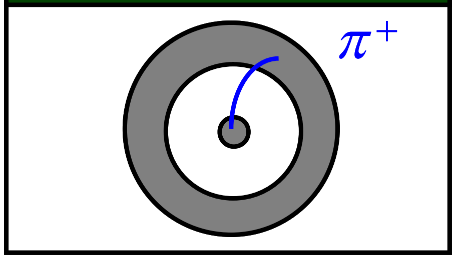
Beam instrumentation is used to identify a single K^+ from the beam

Kaon comes to rest in the target and we wait at least 2 ns for K^+ to decay

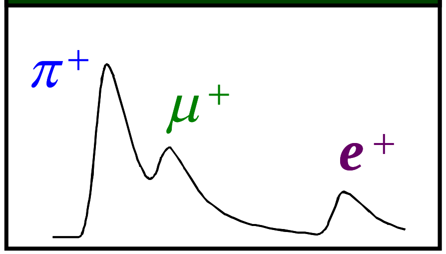
Decay pion comes to rest in the range-stack and undergoes the $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay sequence



π^+ Kinematics



$\pi^+ \rightarrow \mu^+ \rightarrow e^+$ Decay Sequence

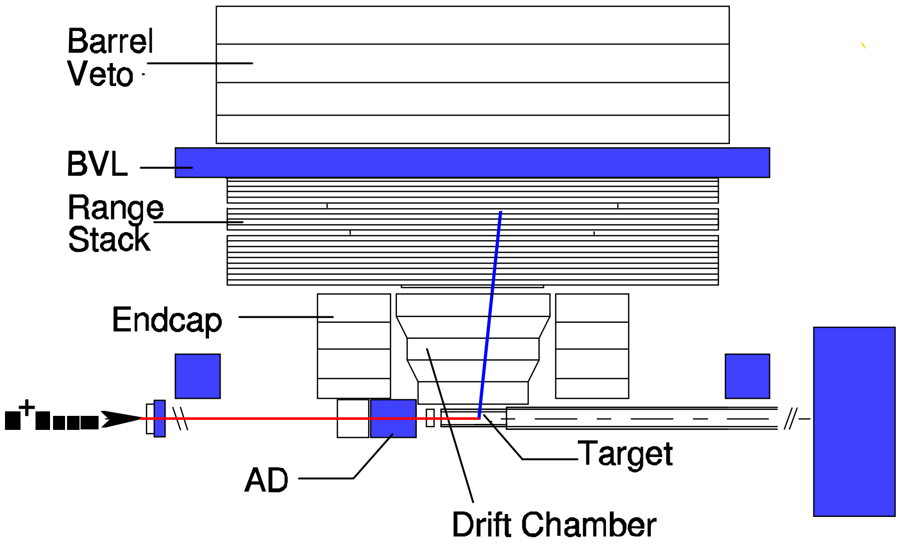


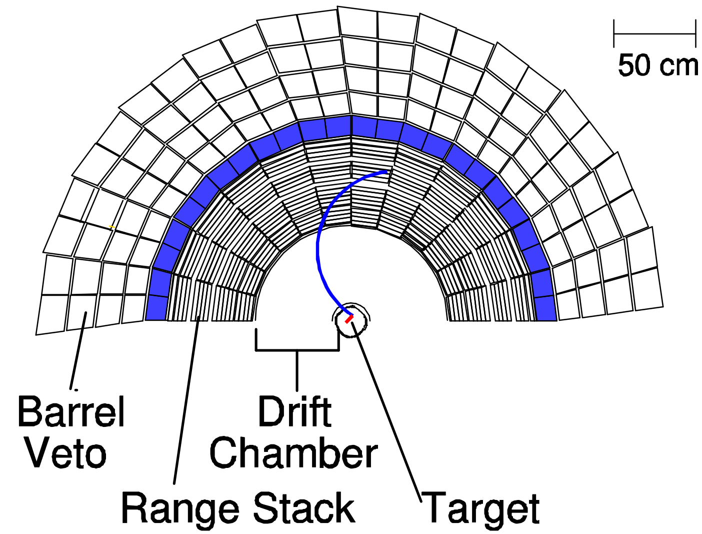
π^+ momentum is measured in the drift chamber

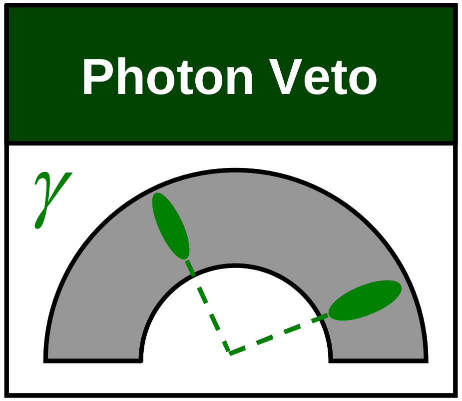
π^+ range and energy are measured target and range-stack

$\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay sequence is observed in the range-stack scintillator

Veto the photons and any addition charged particle activity

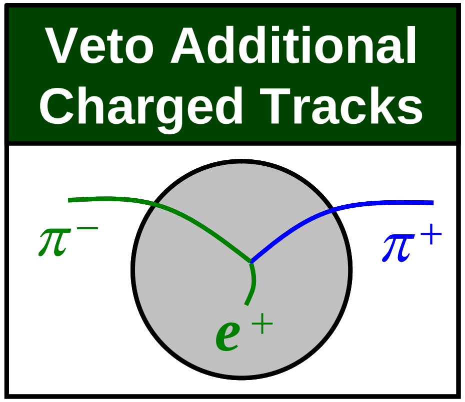






The photon veto gives full 4π sr coverage

Pattern recognition is used in the target, drift chamber and range-stack to identify additional charged tracks



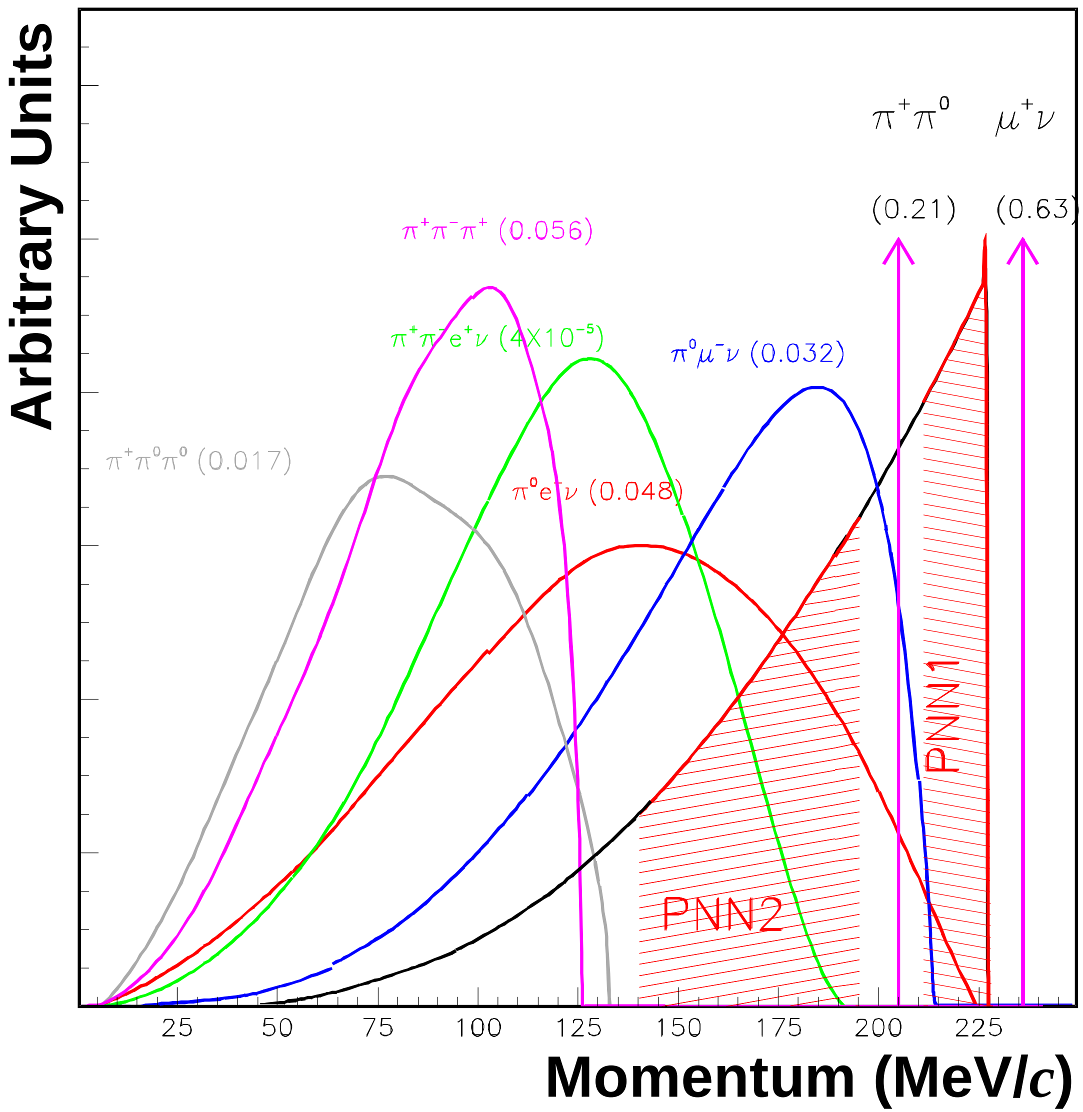
The blind analysis technique can be summed up as eliminating everything that is not $K^+ \to \pi^+ \nu \bar{\nu}$ without directly examining the signal region

"How often have I said to you that when you have eliminated the impossible, whatever remains, however improbable, must be the truth?"

- Sherlock Holmes to Watson
In The Sign of Four

*Thanks Benji

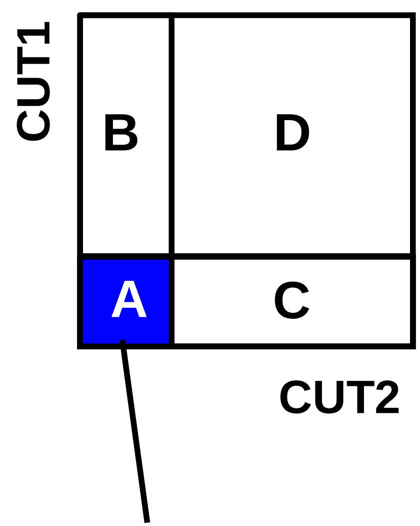
Backgrounds that can mimic $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ are identified ***a priori***



The bifurcation method uses two uncorrelated high-rejection cuts to estimate each background using information outside of the signal region

1 Measure B:
Invert CUT1 and apply CUT2

2 Measure C+D:
Invert CUT2



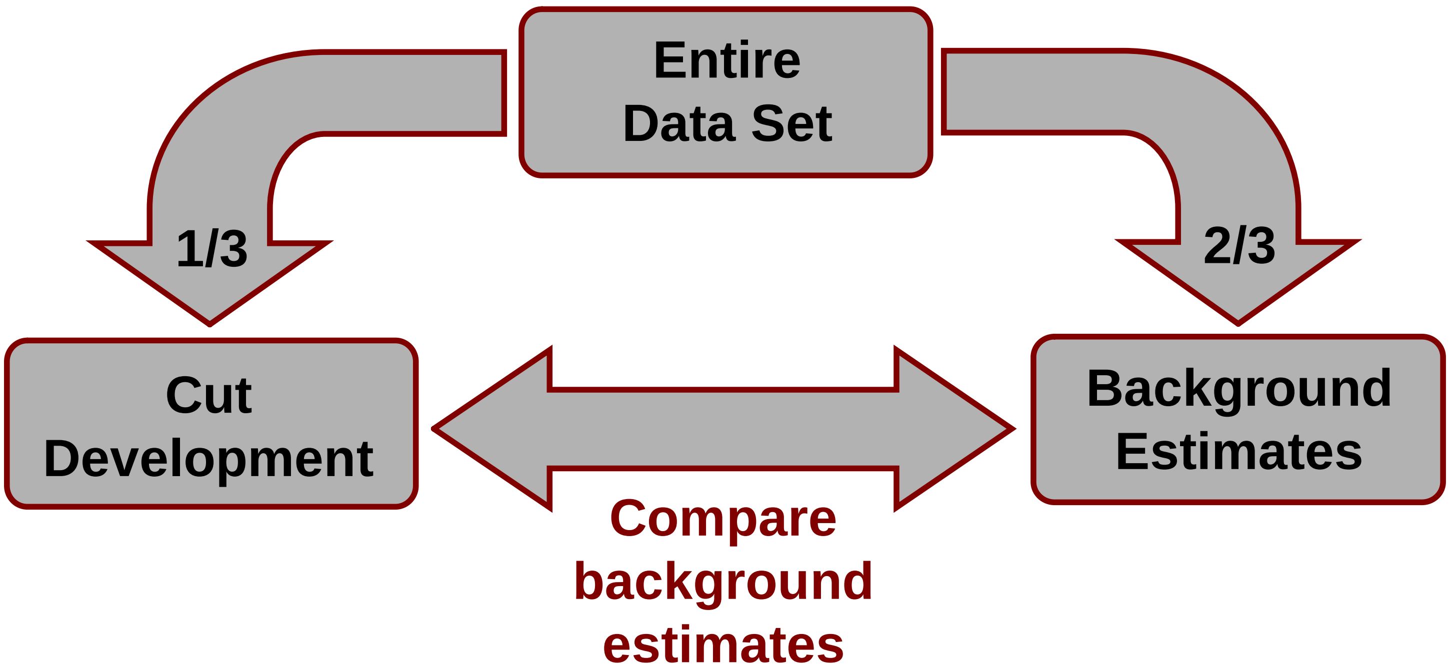
A is the signal region

3 Measure D:
Invert CUT2 and apply CUT1

4 Estimate A:
A = BC/D

Background estimate = A!

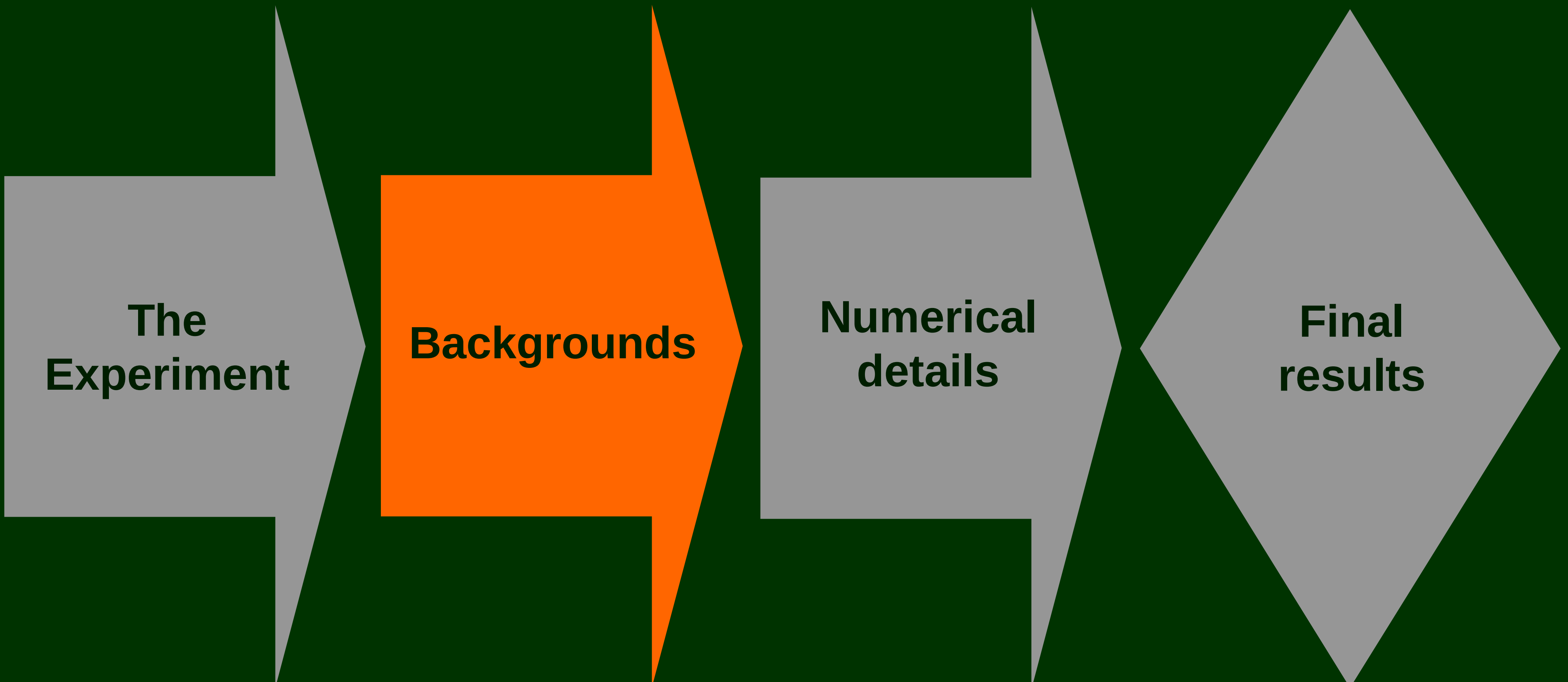
Background estimates are performed using data different from those used to develop cuts



Signal region is only examined once all background estimates have been finalized

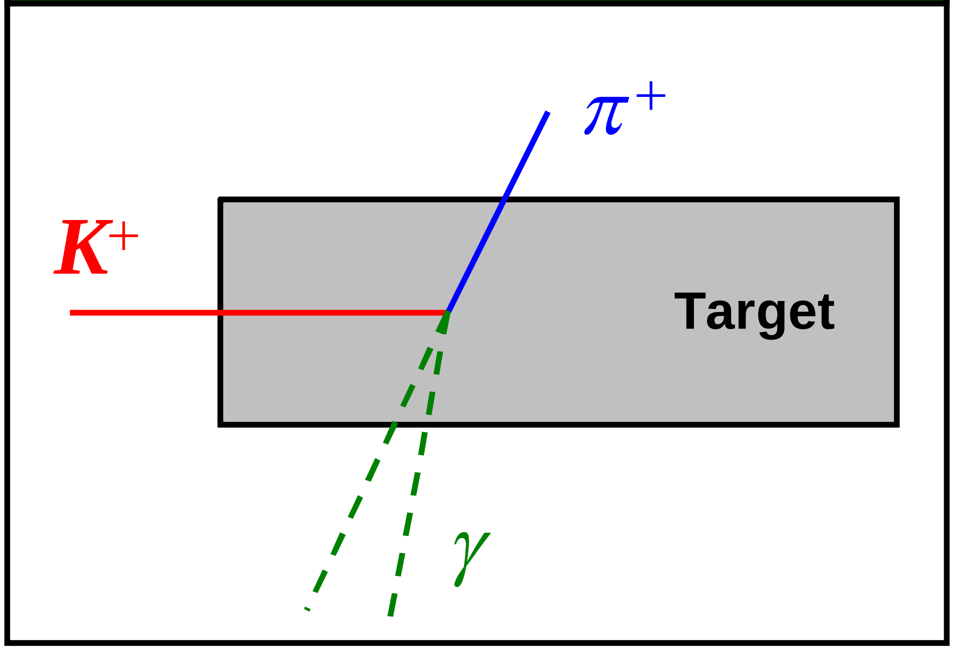
"Open the box"

In this section I will detail the suppression of various backgrounds and reveal the total background



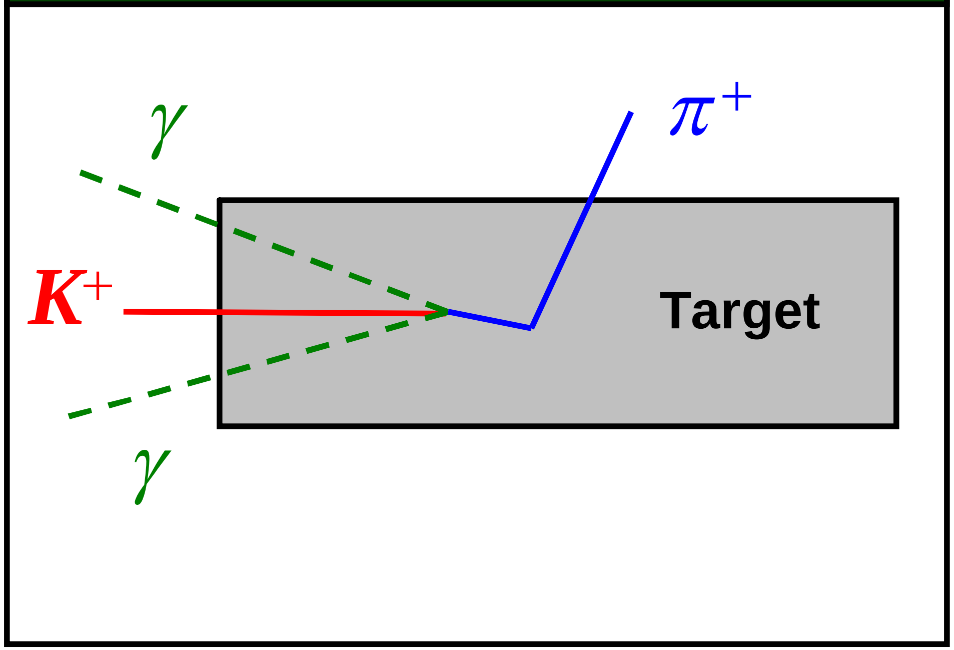
The number one enemy is $\pi^+\pi^0$ when the π^+ scatters in the target

Regular $\pi^+\pi^0$



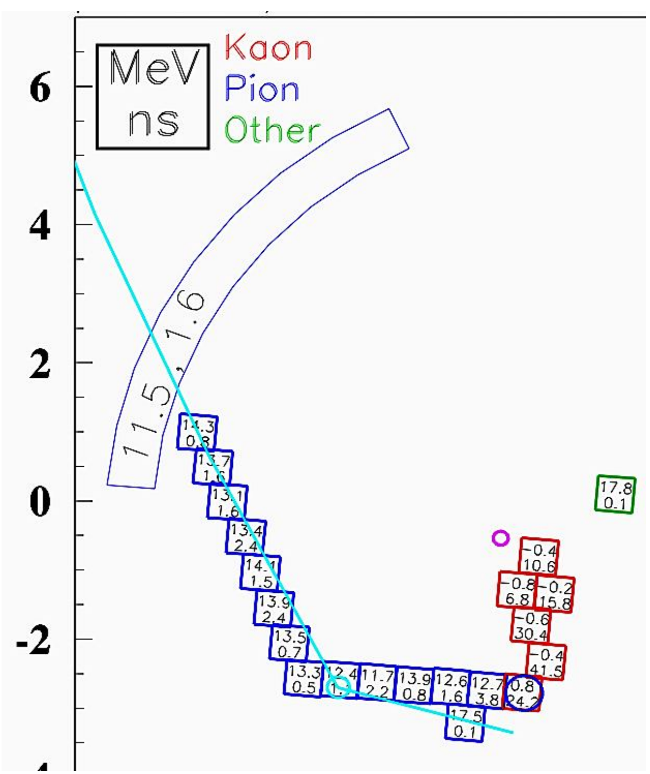
π^+ and π^0 are back to back so photons are directed to efficient part of the photon veto

π^+ Target Scatter

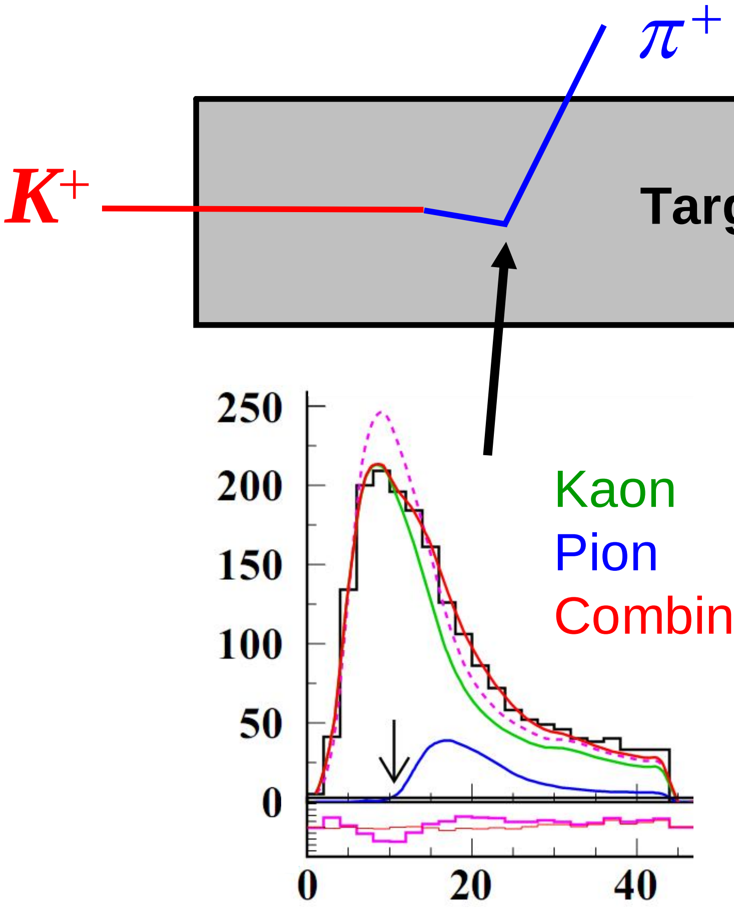


When the π^+ scatters in the target it loses energy and the photons lose directional correlation with the π^+

This background is suppressed by the photon veto and identification of π^+ scattering



A scatter can be identified by finding a kink in the π^+ track

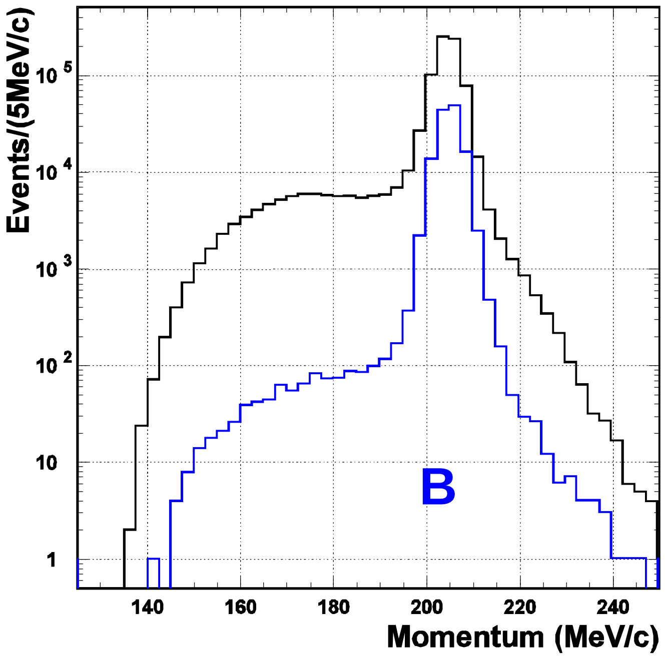


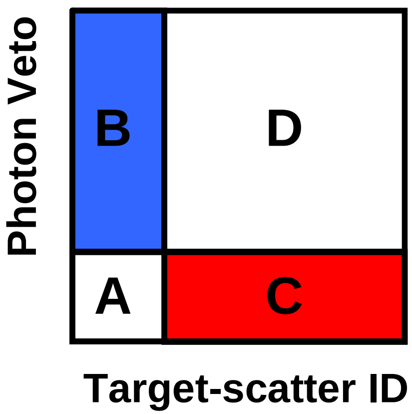
A scatter can also be identified by large energy deposits in a pion fiber or hidden energy in a kaon fiber

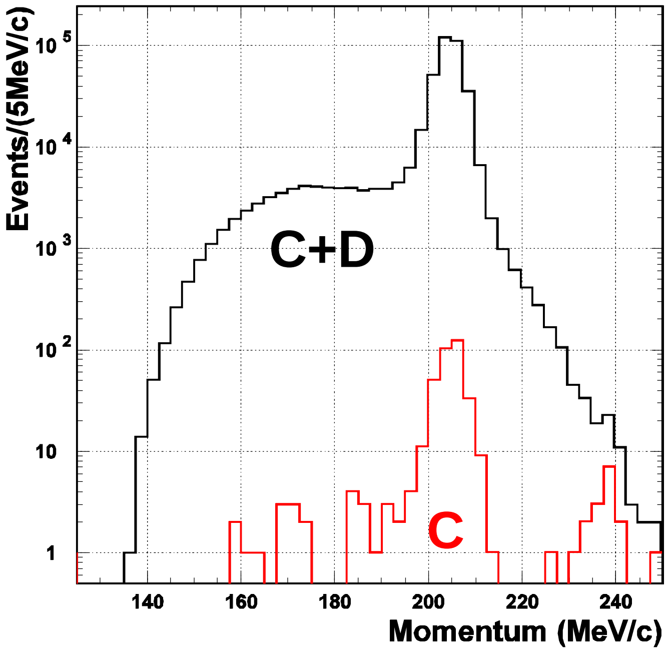
The bifurcation cuts used for π^+ target-scatters are the photon veto and the target-scatter cuts

Photon veto is inverted (black curve) and the target cuts are applied (blue curve)

Target-scatter cuts are inverted (black curve) and the photon veto is applied (red curve)

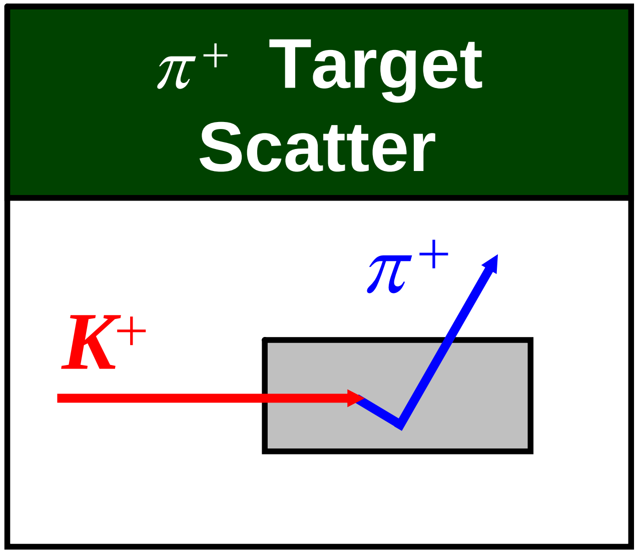


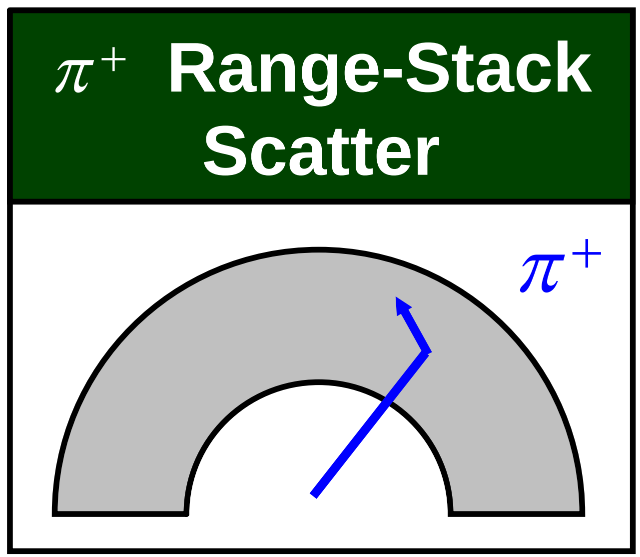




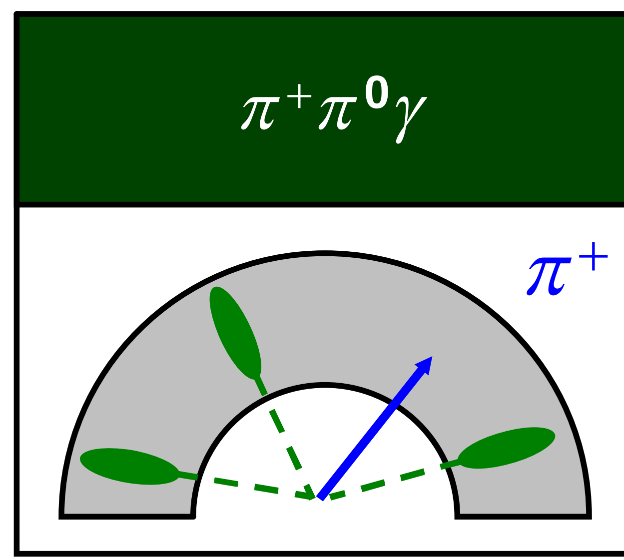
Background
A = BC/D

In practice the three $\pi^+\pi^0$ backgrounds have to be disentangled



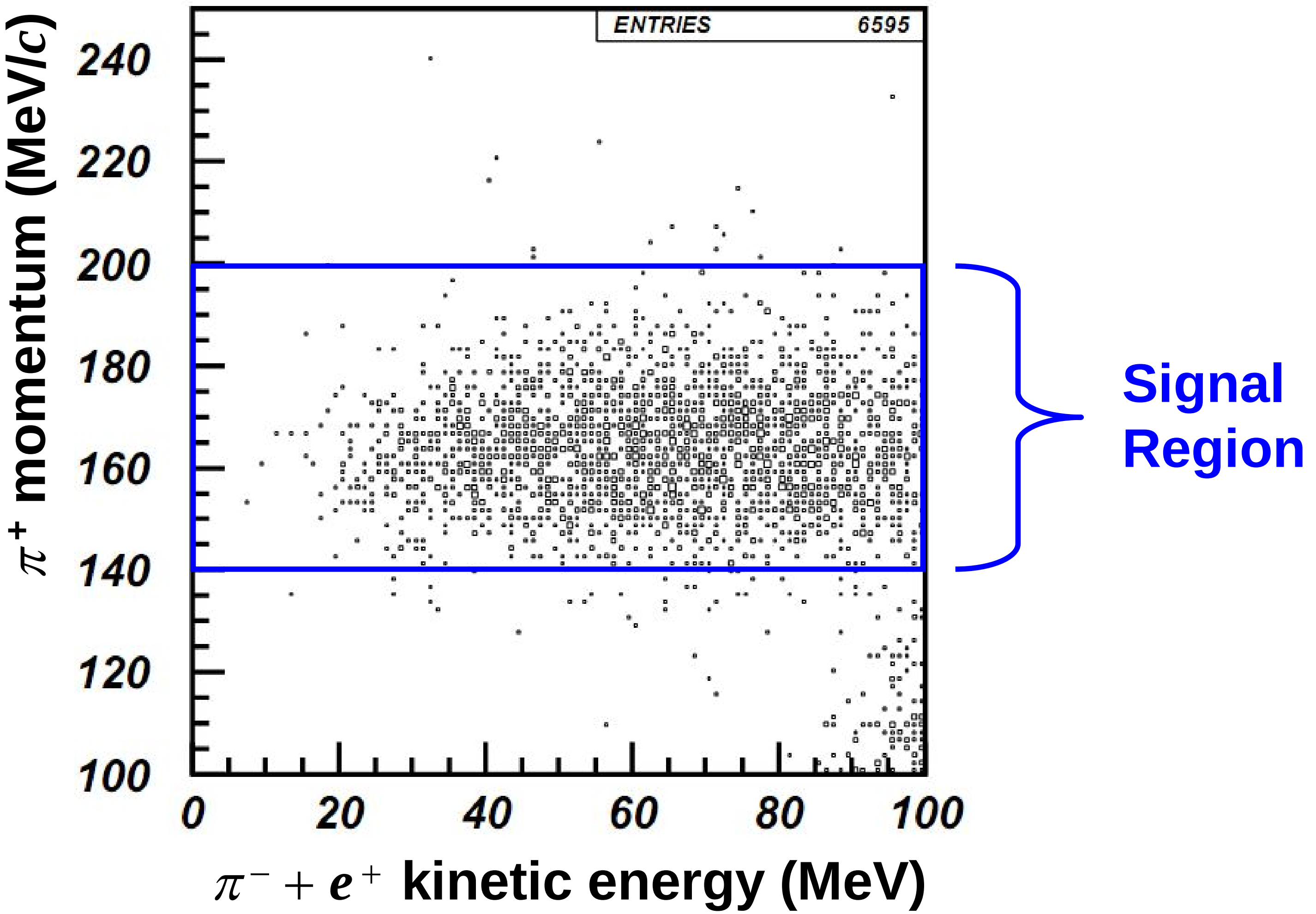


The π+ target scatter sample made by inverting the photon veto has contamination from π+ range-stack scatter and $K^+ \rightarrow \pi^+ \pi^0 \gamma$ processes

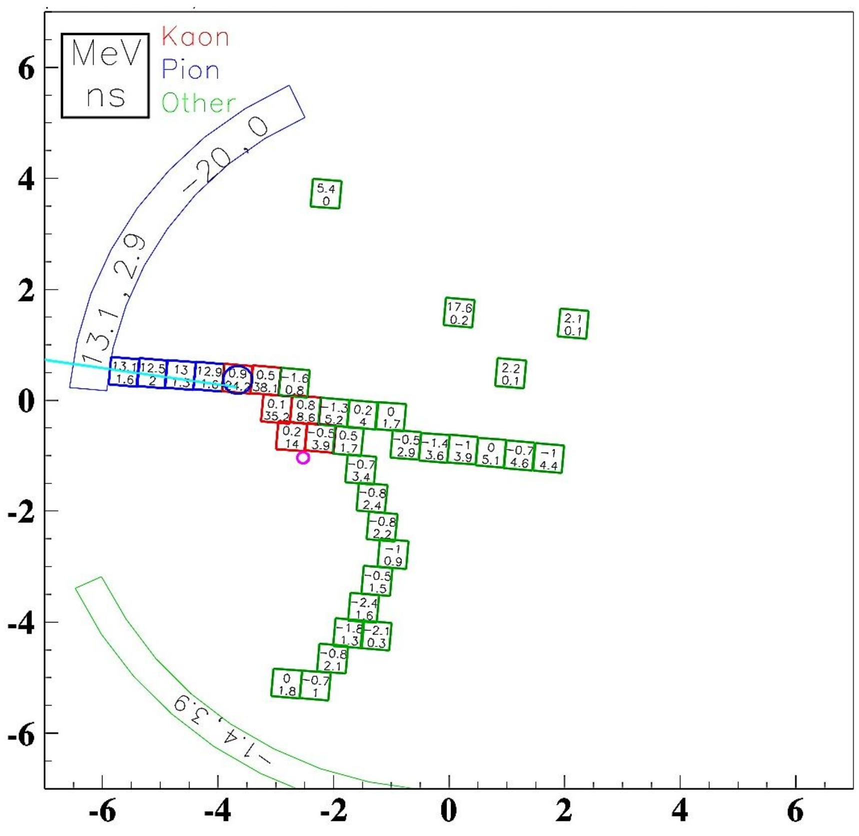


The $\pi^+\pi^-e^+\nu$ decay can mimic signal when the π^+ and e^+ have low kinetic energies

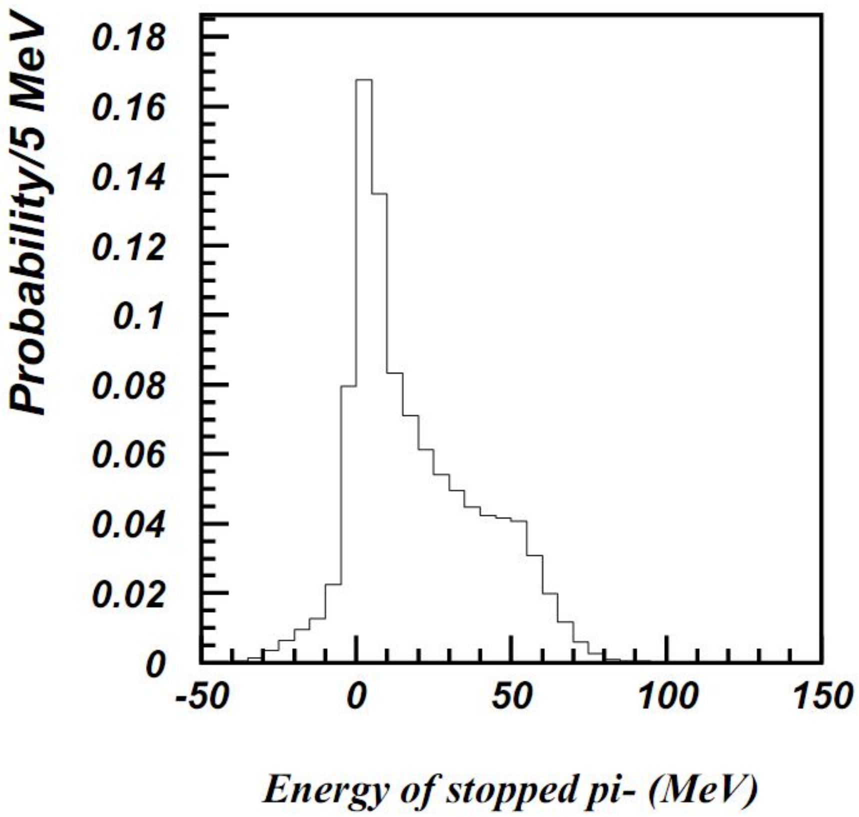
Simulated $K^+ \rightarrow \pi^+ \pi^- e^+ \nu$



Use target pattern recognition to isolate sample and estimate rejection power using simulation

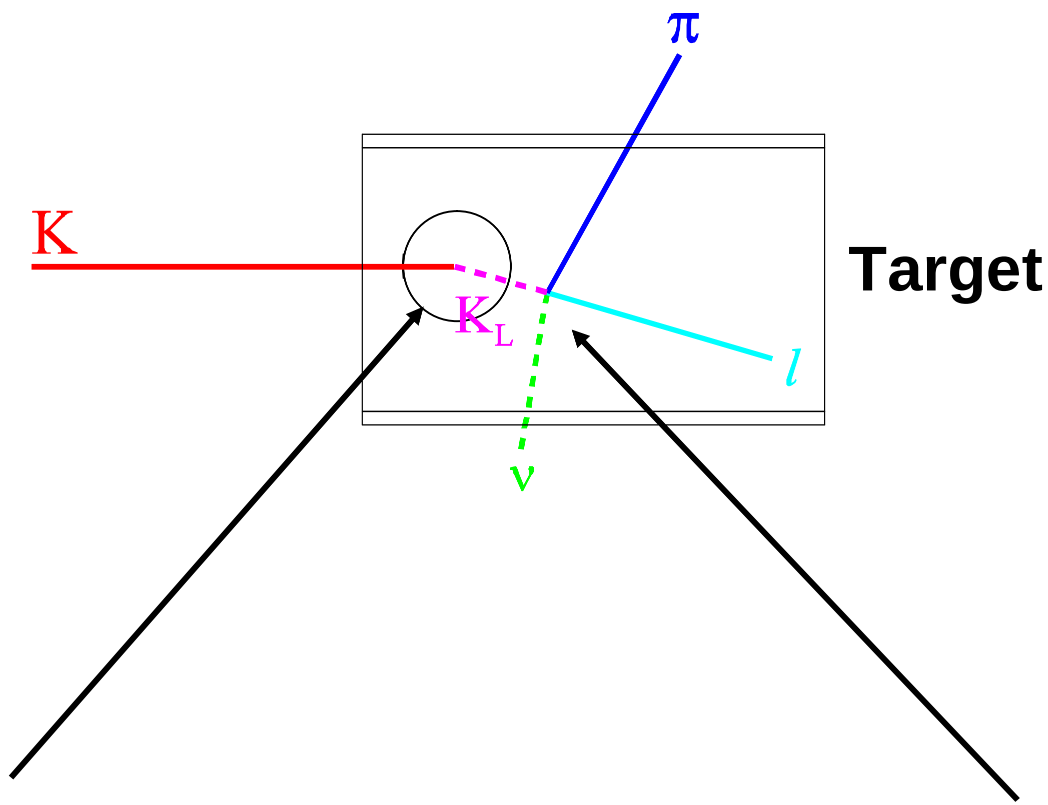


$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$ sample is isolated using target pattern recognition



Estimate the rejection power of the target pattern recognition using simulated data supplemented by the measured π^- energy deposit in scintillator

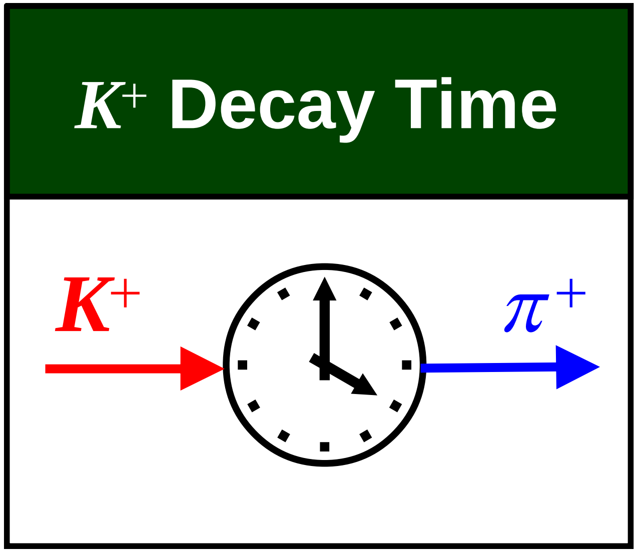
The charge exchange background is dominated by the neutral kaon decay $K_L \rightarrow \pi^+ l^- \nu$



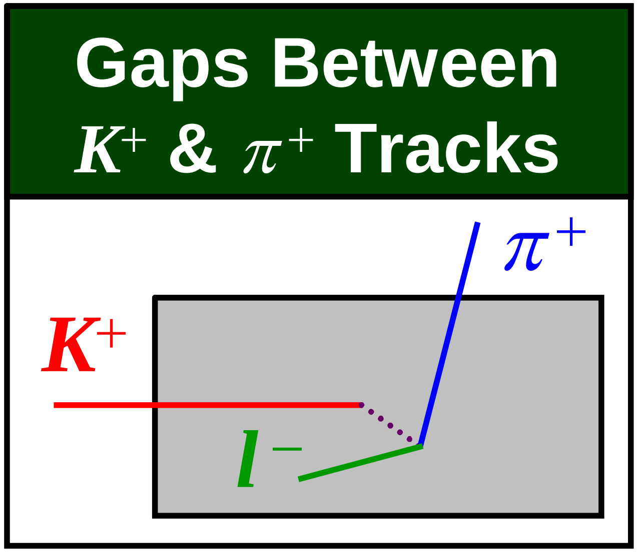
$$K^+ n \rightarrow K_L^0 p$$

$$K_L^0 \rightarrow \pi^+ l^- \nu_l$$

K_S is suppressed by K^+ decay time condition and K_L by gaps between the K^+ and π^+ tracks



K_S lifetime is only 0.1 ns so the K^+ decay time condition suppresses K_S decays



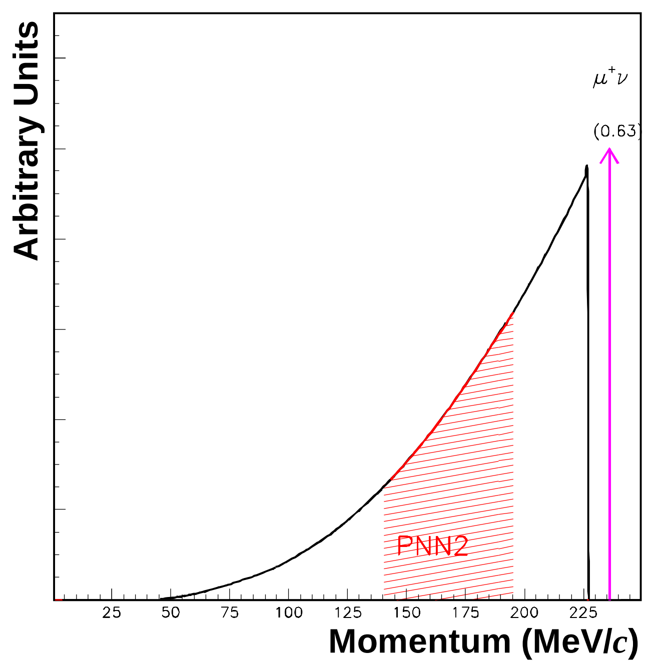
K_L lifetime is 50 ns so target pattern recognition is used to identify gaps between the K^+ and π^+ tracks

Additional suppression is provided by detecting the negatively charged lepton

Due to kinematic constraints, the troublesome μ^+ decays are the multi-body ones

$$K^+ \rightarrow \mu^+ \nu_\mu$$

Not a big deal in the PNN2 region

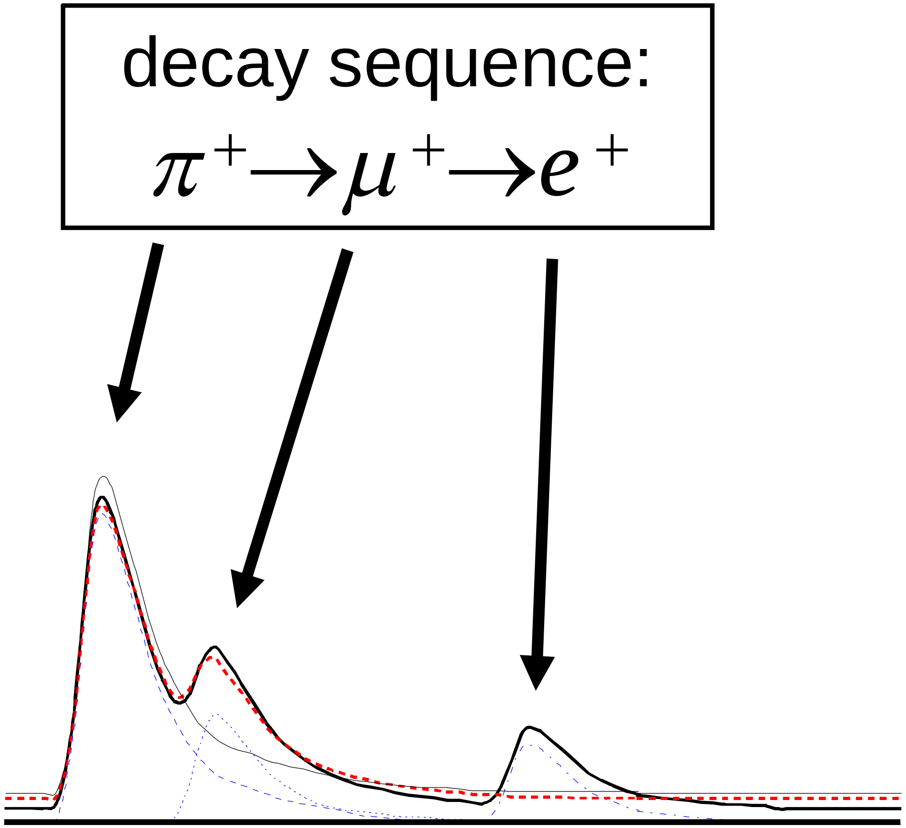


$$K^+ \rightarrow \mu^+ \nu_\mu \gamma$$

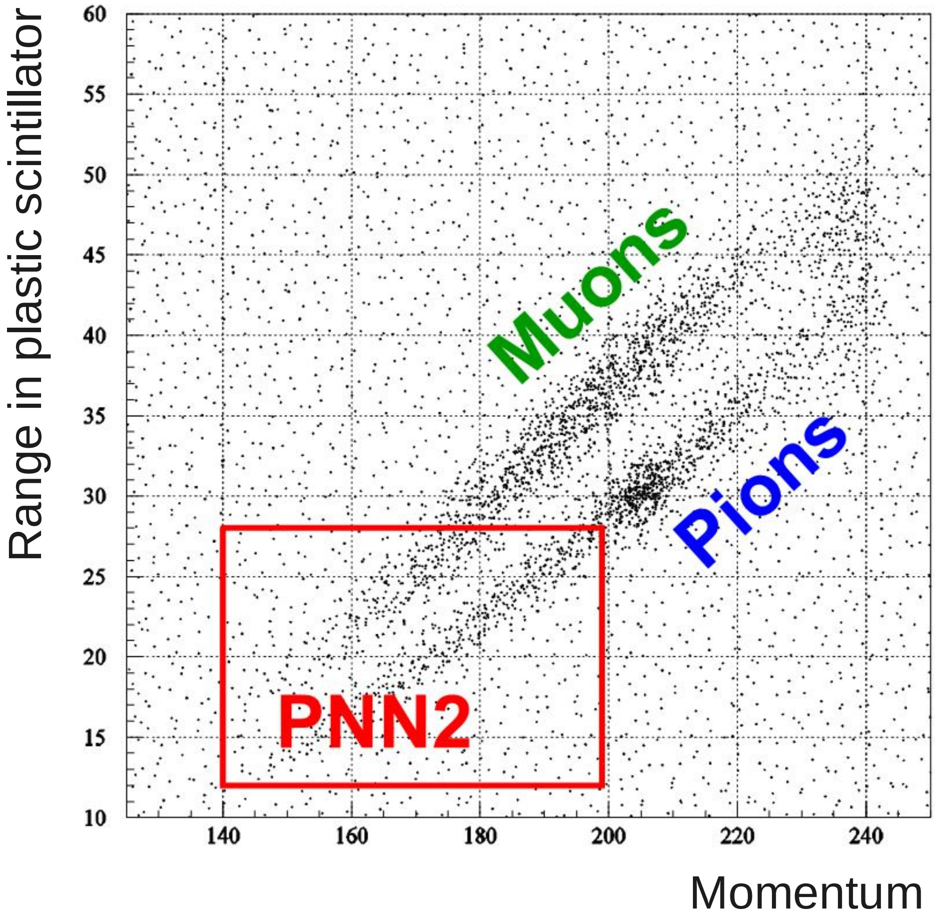
!

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

Muon processes are suppressed kinematically and by identification of the π^+ decay



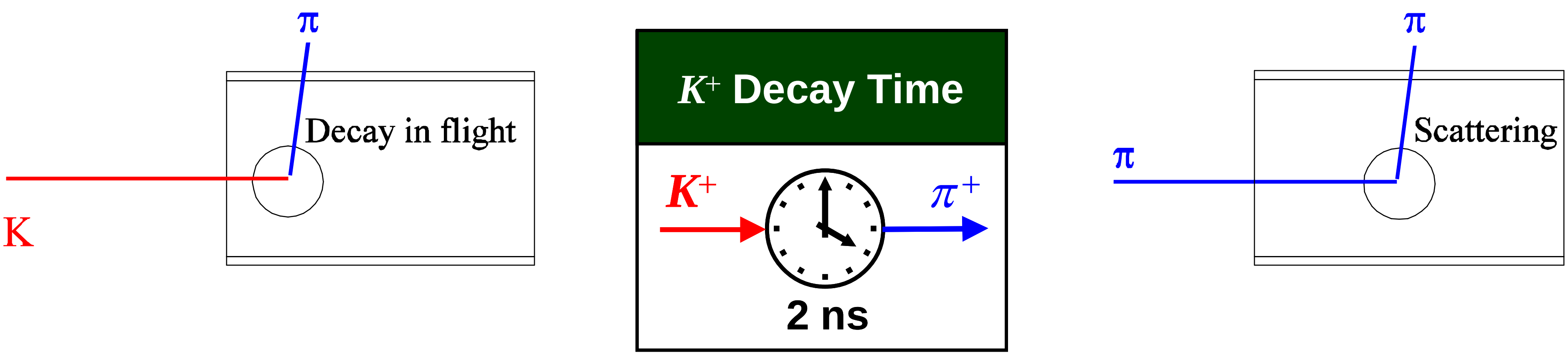
Pulse shape in the range-stack stopping counter



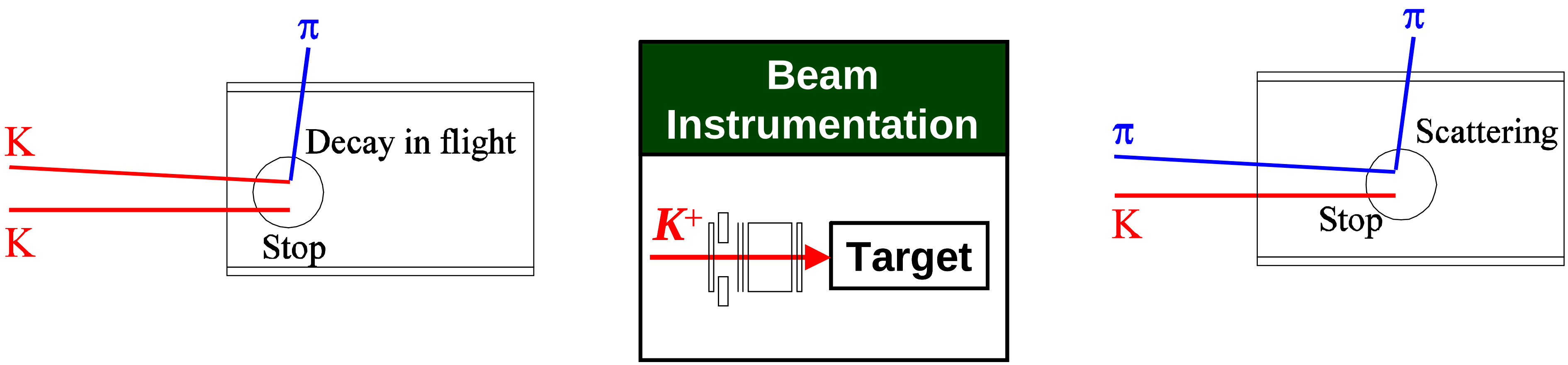
Muons have different kinematic signature in the detector than pions

Beam backgrounds come from events other than a single kaon decaying at rest in the target

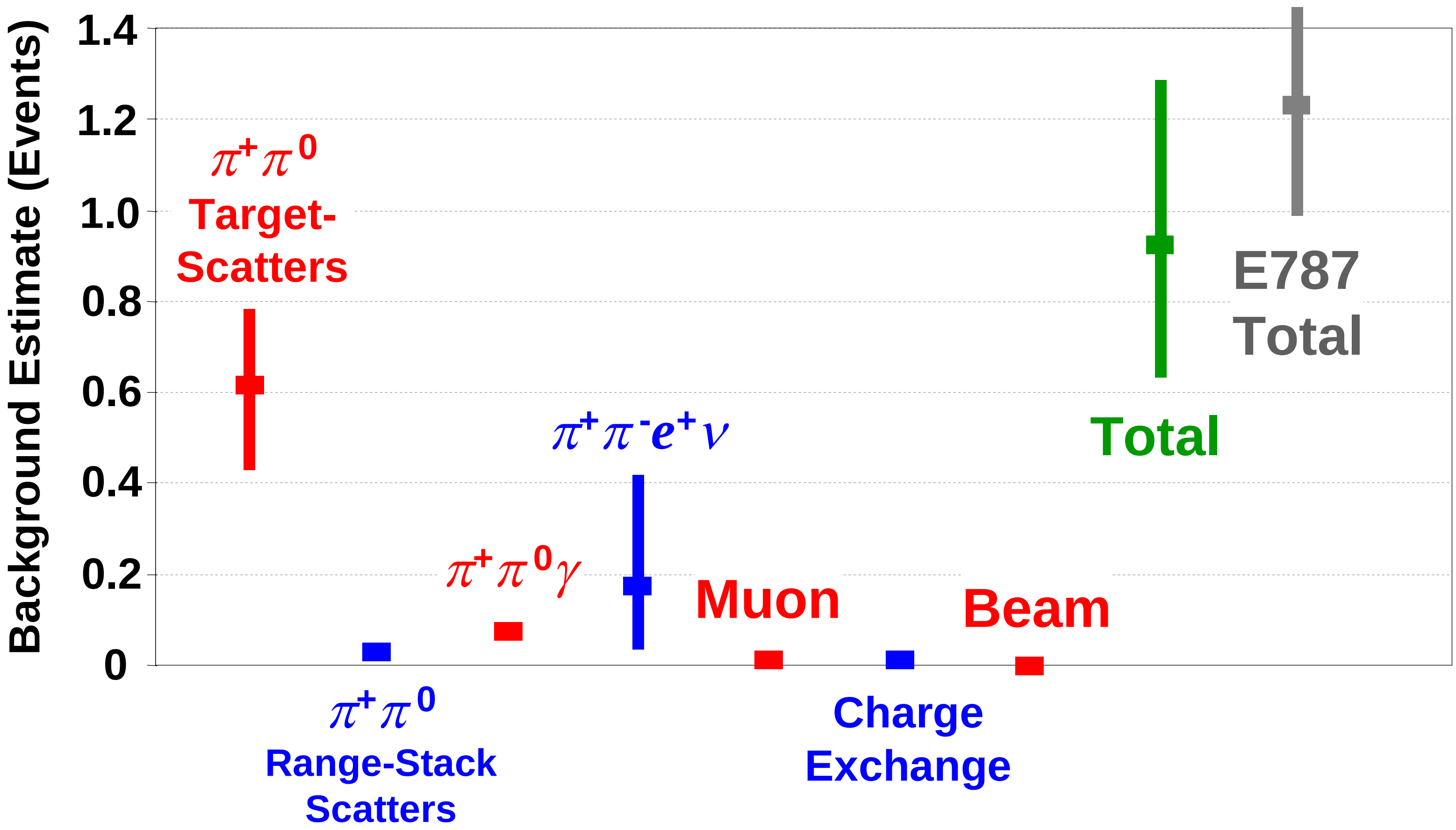
Single-beam



Double-beam



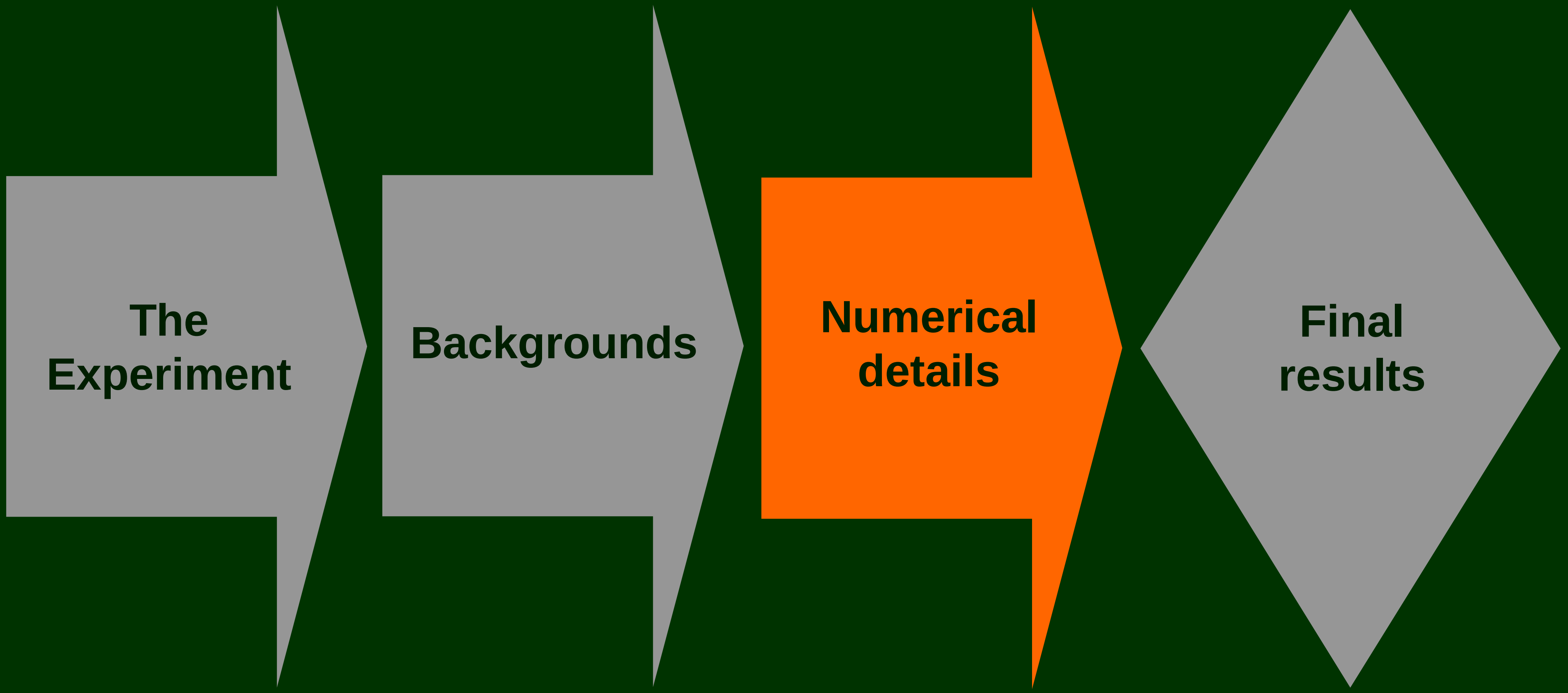
Compared to the E787-PNN2 analysis, our total background was decreased by 24% and total acceptance increased by 63%



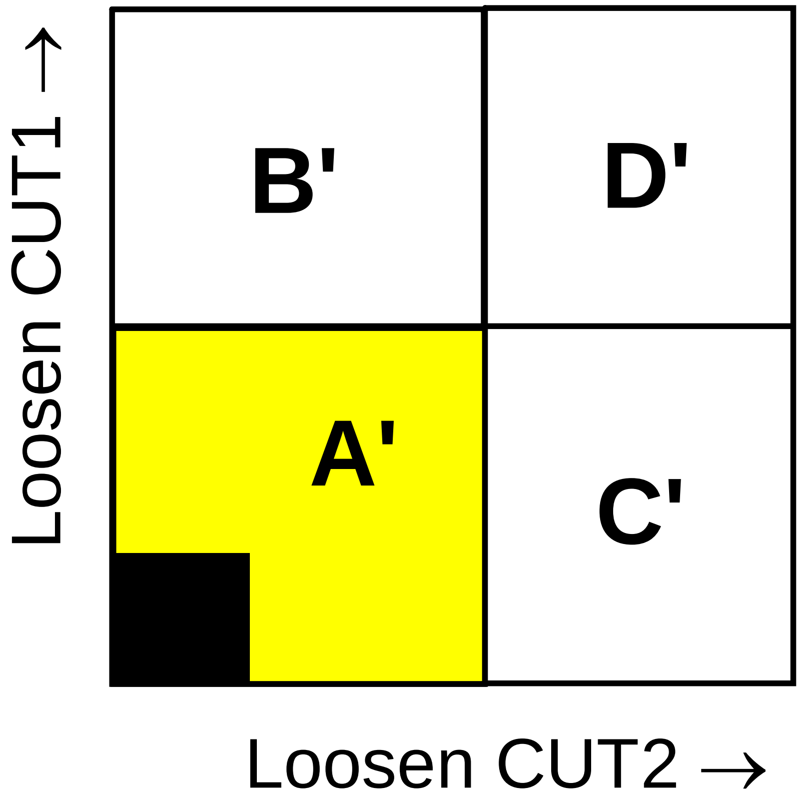
	E787-PNN2	This Analysis
Total kaons	1.73×10^{12}	1.70×10^{12}
Total acceptance	0.84×10^{-3}	1.37×10^{-3}

Only 20% of the approved beam time ☹

In this section I will discuss some last numerical details before getting to the grand opening



Outside-the-box studies compare background estimates to direct measurements just outside the signal region



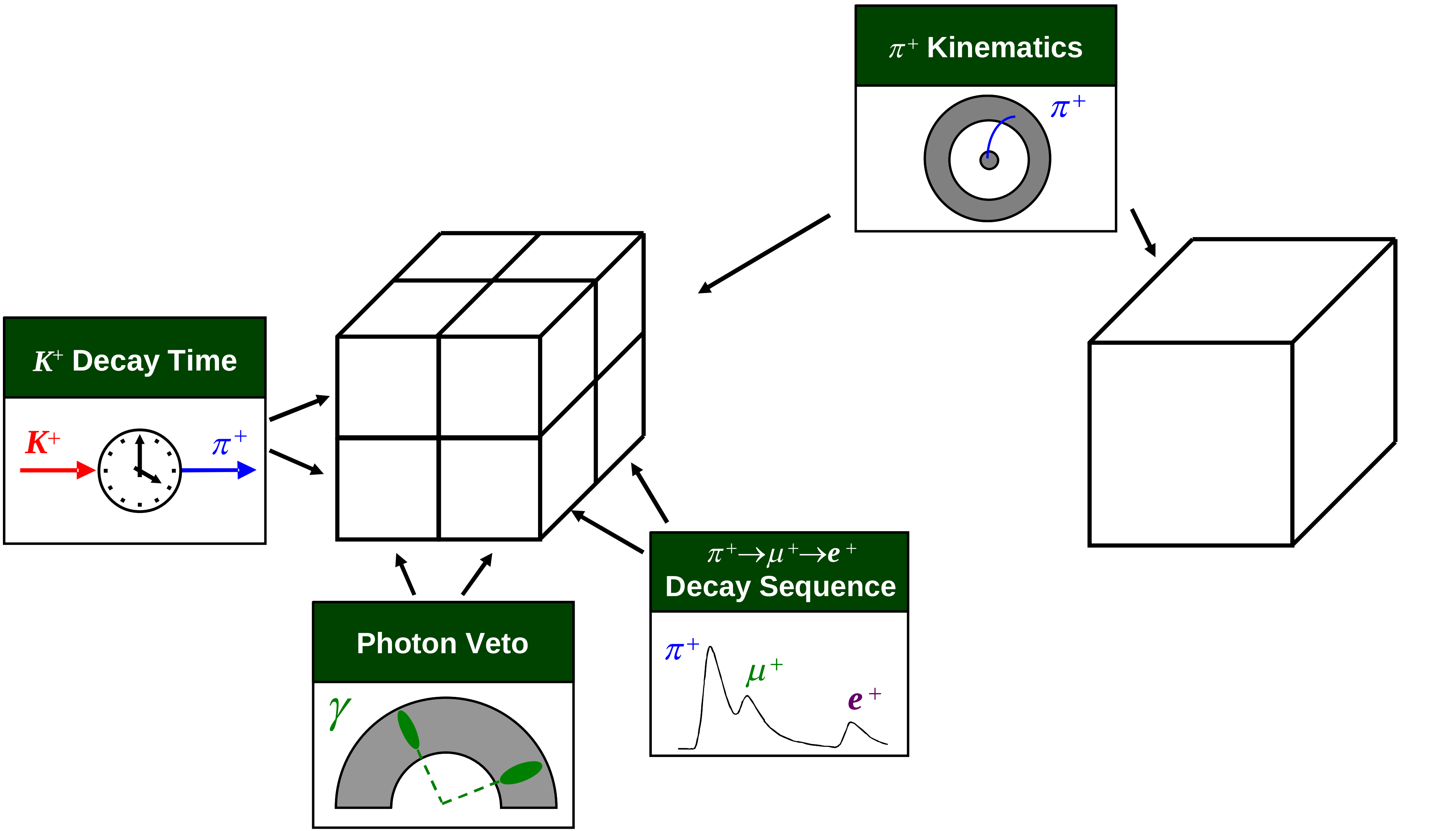
Signal region is masked out; the background estimate and direct measurement for region A′ are compared directly

If CUT1 and CUT2 are uncorrelated, the two values will agree

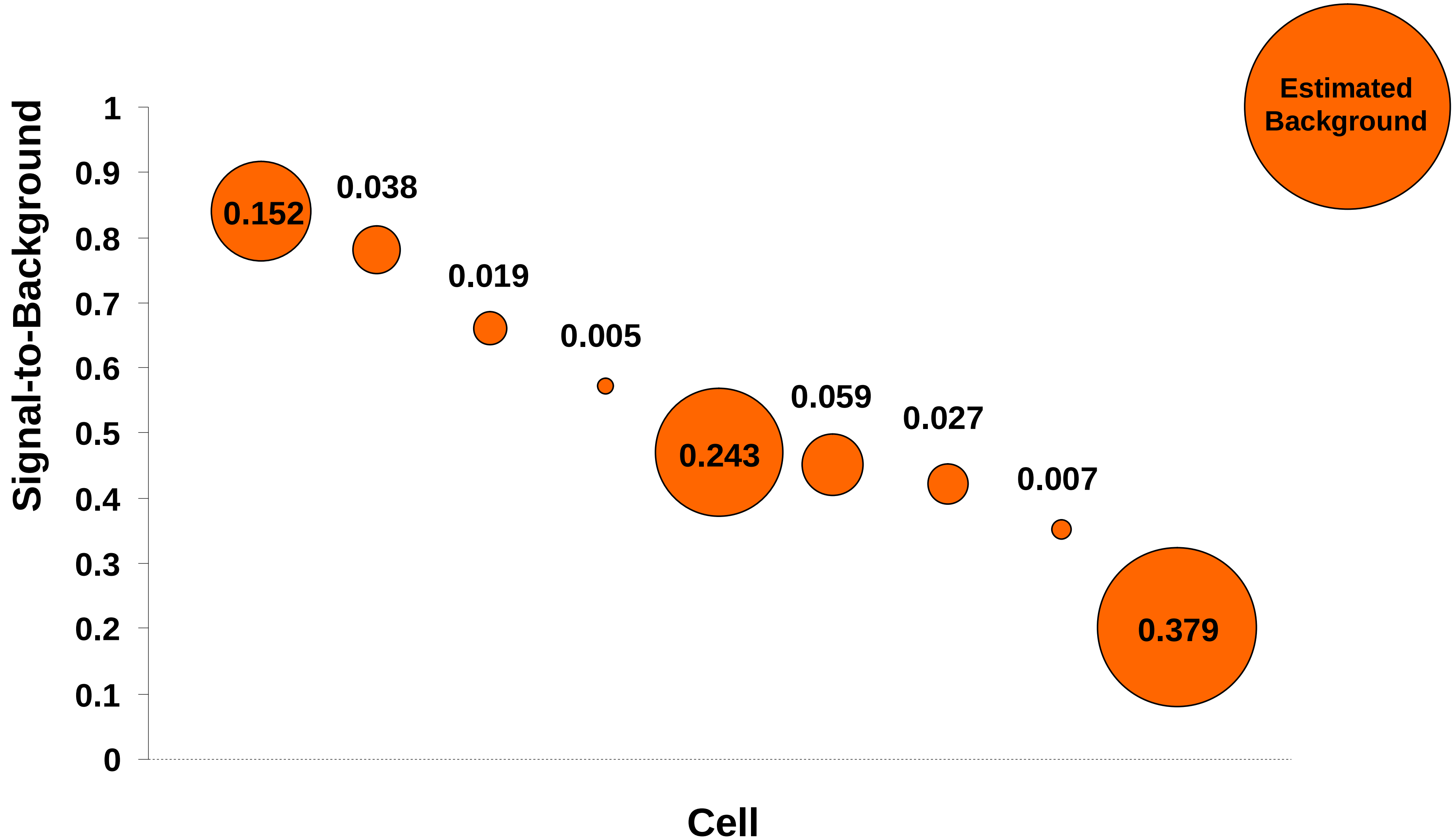
The outside-the-box results demonstrate that the systematic uncertainties assigned to the backgrounds were reasonable

Region	$N_{\text{exp.}}$	$N_{\text{obs.}}$	$\mathcal{P}(N_{\text{obs.}}; N_{\text{exp.}})$	Combined
Target-scatter ID	$0.79^{+0.46}_{-0.51}$	0	0.45 [0.29,0.62]	N/A
Photon Veto 1	$9.09^{+1.53}_{-1.32}$	3	0.02 [0.01,0.05]	0.05 [0.02,0.14]
Photon Veto 2	$32.4^{+12.3}_{-8.1}$	34	0.61 [0.05,0.98]	0.14 [0.01,0.40]

By further tightening four of the cuts, the signal region was divided into nine cells

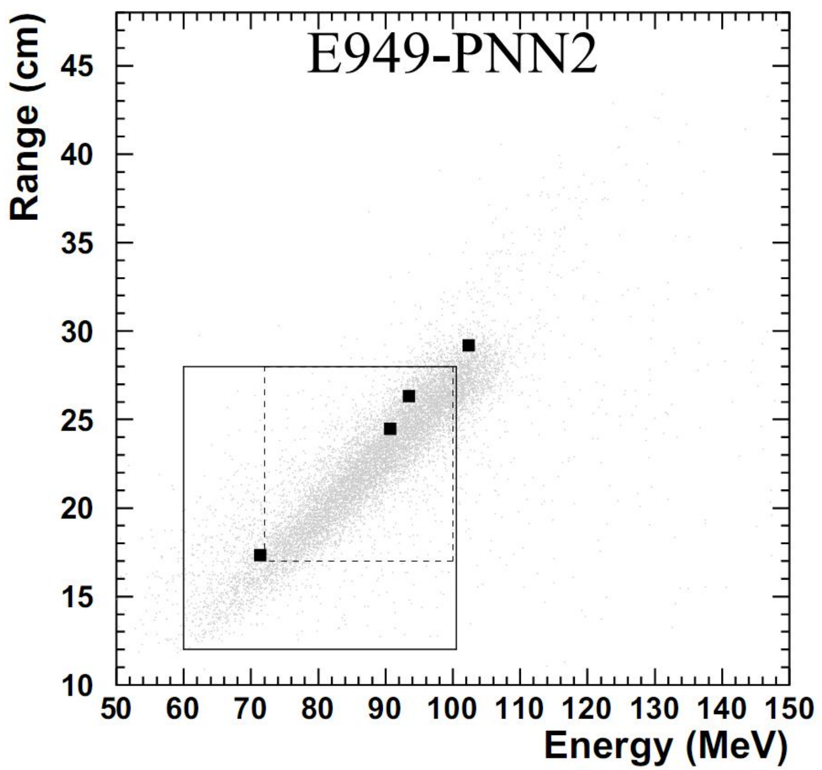


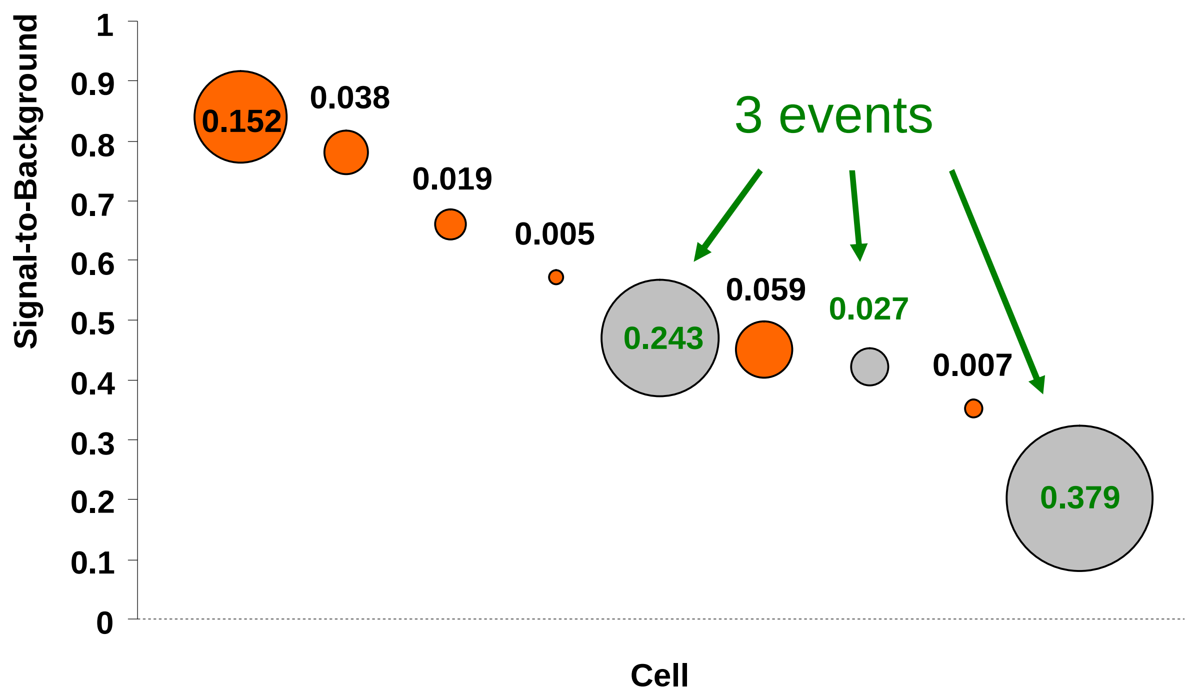
The relative signal-to-background levels of the nine cells varied by about a factor of 4



Now it's time to open the box…

…and three events were observed



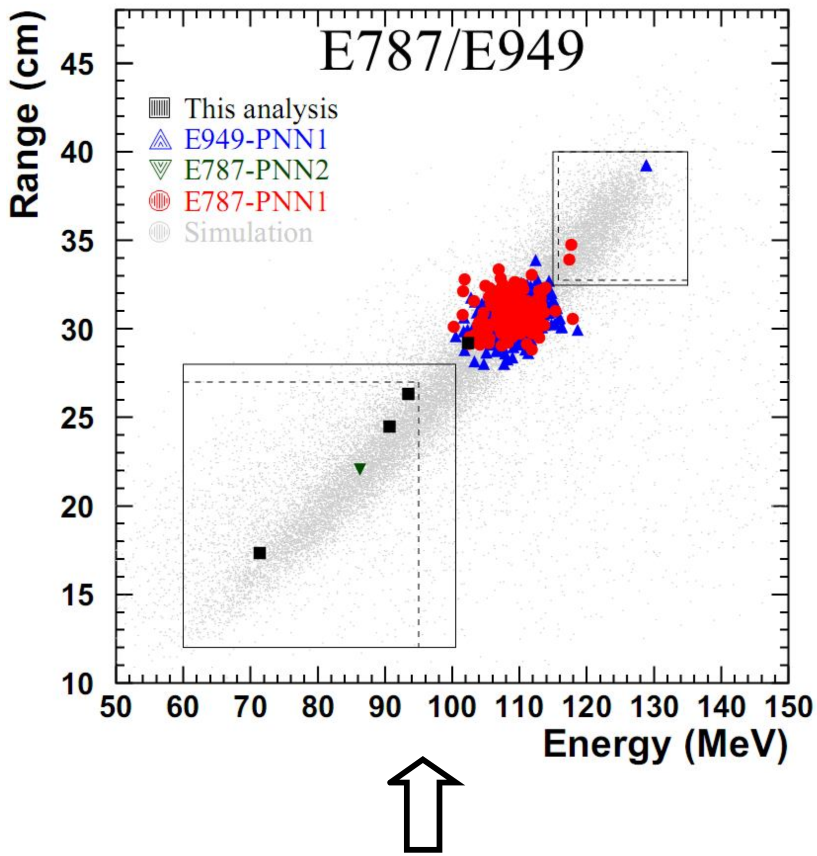


The probability that all three events were due to background only is 3.7%

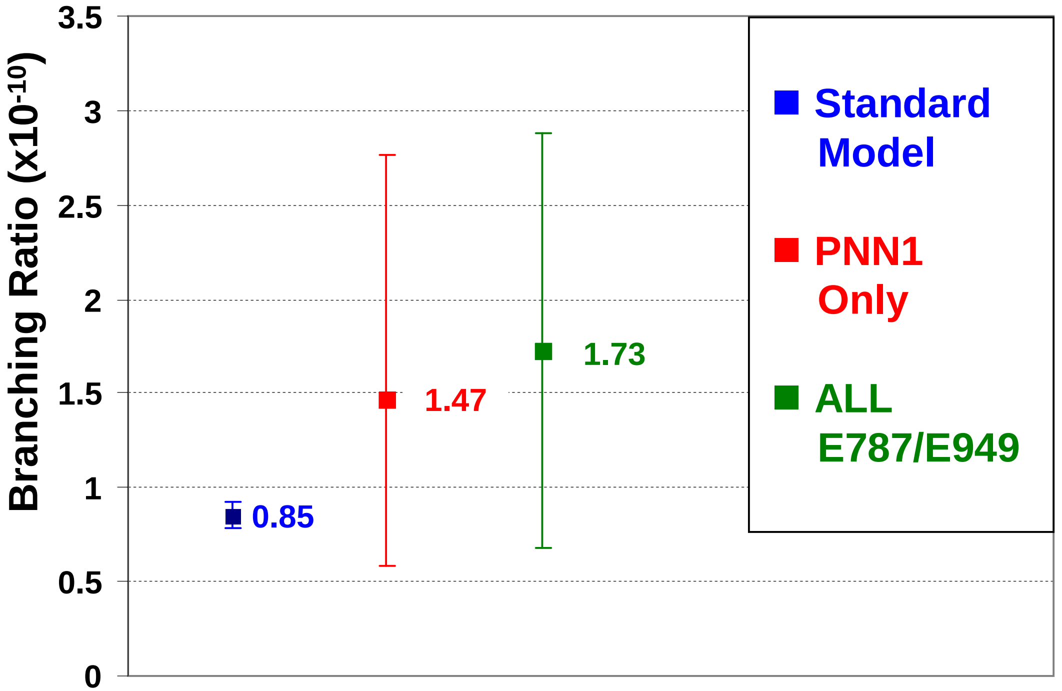
Measured branching ratio is

$$B\left(K^{+} \rightarrow \pi^{+} \nu \bar{\nu}\right) = \left(7.89^{+9.26}_{-5.10}\right) \times 10^{-10}$$

The combined E787/E949 branching ratio is twice as high, but consistent with Standard Model expectation

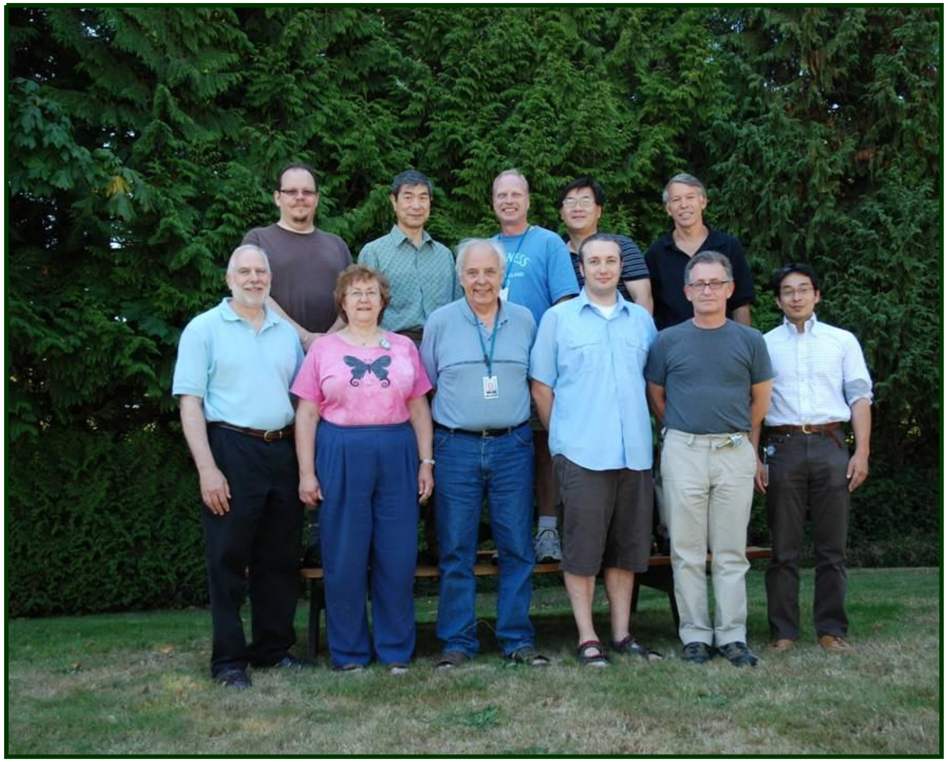


Despite the sizes of the boxes PNN1 analyses are 4.2 times more sensitive than PNN2 analyses



The probability that all seven events were due to background only is 0.1%

The E787/E949 collaboration
a.k.a. the fine folks behind these results



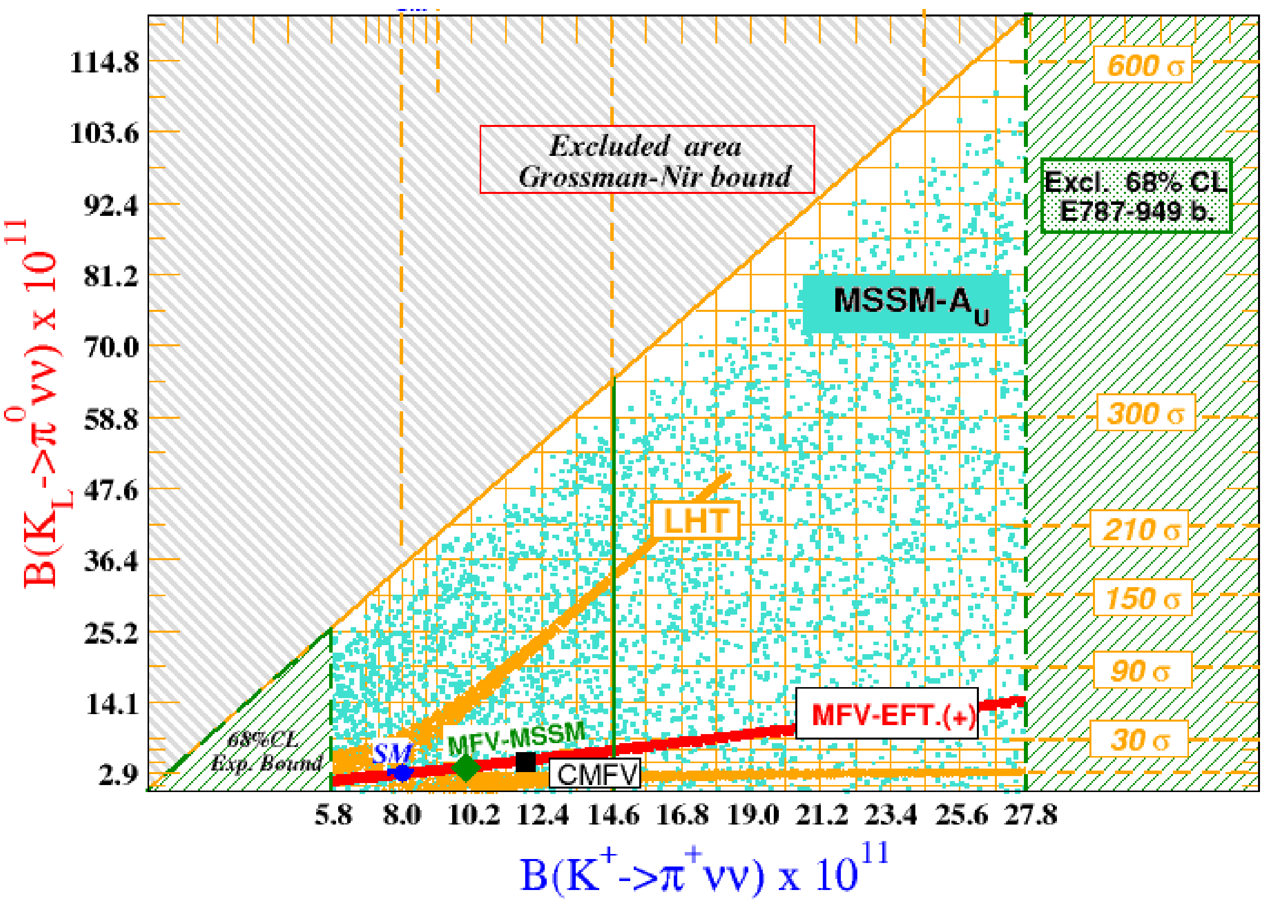
The next measurements of $K^+ \to \pi^+ \nu\bar{\nu}$ are just around the corner

Future experiments

NA62 (formerly NA48/3) in preparation at CERN

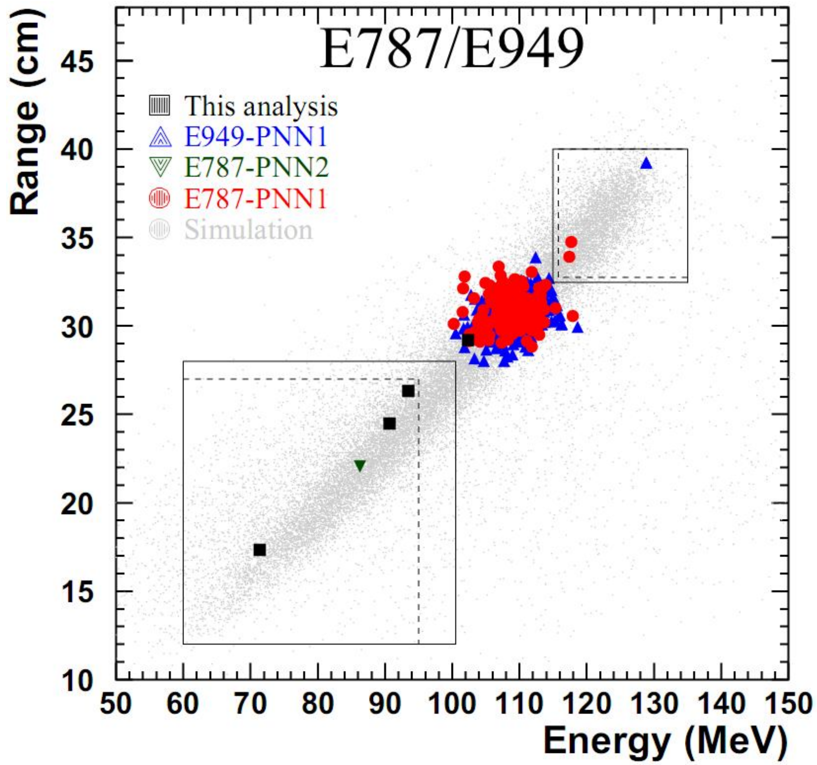
Letter of intent for using best E949 bits in Japan

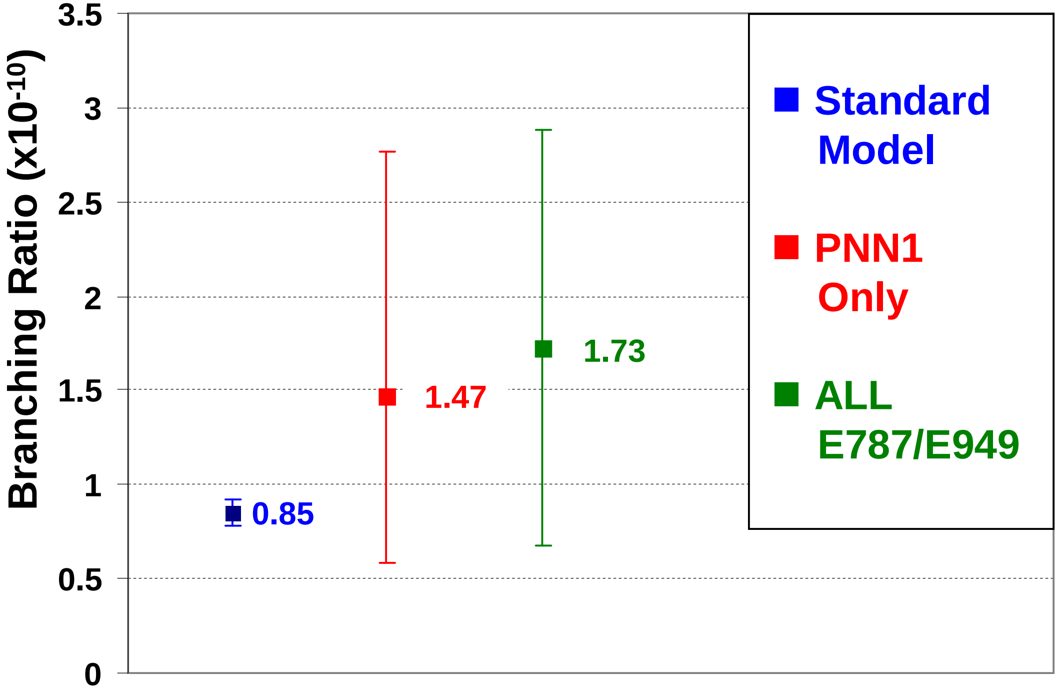
Fermilab Project X?



Ref: FlaviaNet - http://www.lnf.infn.it/wg/vus/

Thank you…questions?





Thank you to David Jaffe for the resources that made this talk possible