Tagged electron neutrinos

- Tagged neutrino beams
- **Concept: a beam design optimized for the use $K^+ \rightarrow e^+ \pi^0 \nu_e$ (K^+_{e3} decays) that takes advantage of the progress in fast and radiation-hard detectors at LHC**
- Applications: ν_e cross section, beam background veto
- Beamline and decay tunnel instrumentation
- Rates and dose at the tagger stations
- Background, efficiencies, rates at far detector
- Perspectives and conclusions

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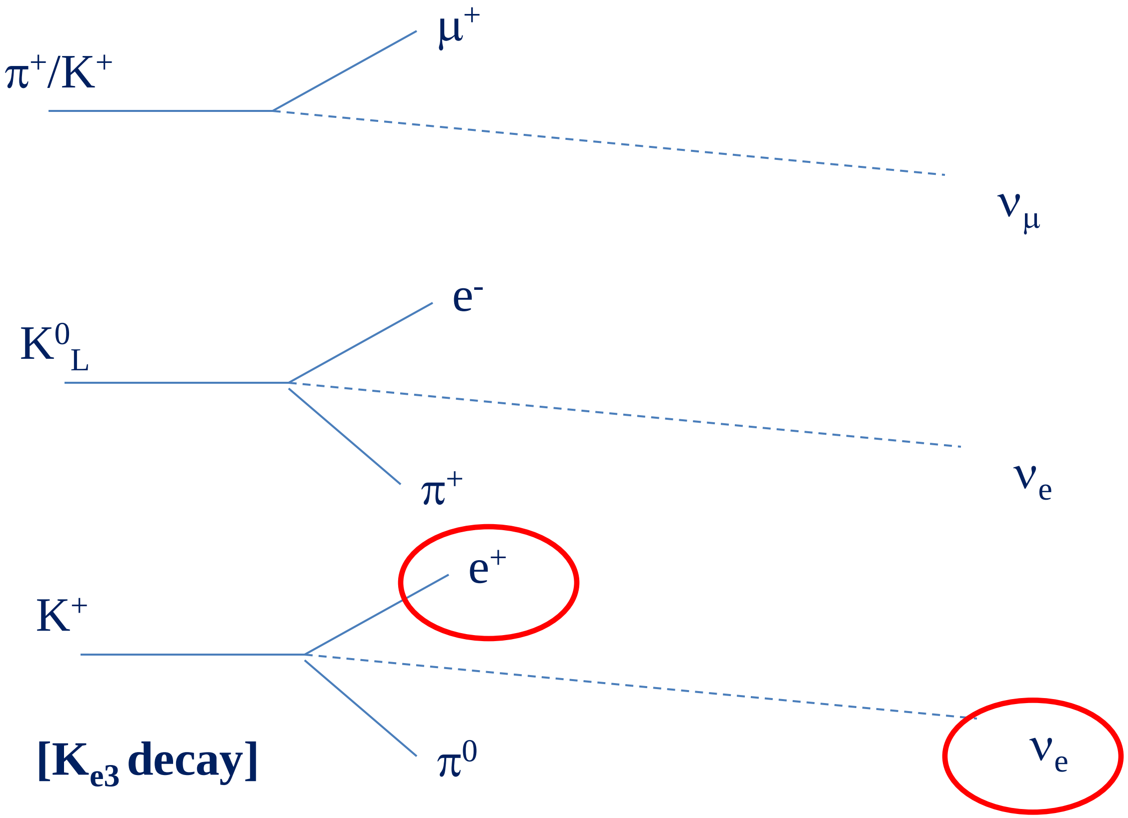
Special acknowledments to N. Cartiglia and T. Tabarelli

Tagged neutrino beams

One of the Holy Grails of neutrino physics (*): detect simultaneously both the neutrino at the far detector and the associated lepton at production →unique tag of flavor at production

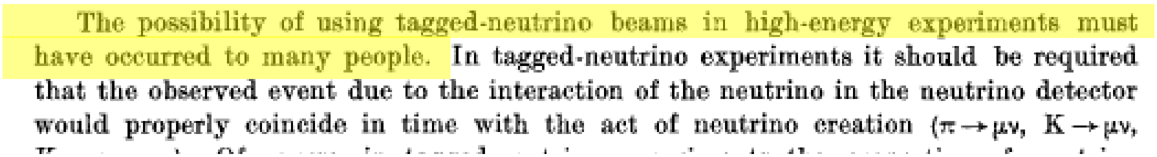


L. Hand, 1969, V. Kaftanov, 1979 …

G. Vestergombi, 1980, R. Bernstein, 1989 …

S. Denisov, 1981, R. Bernstein, 1989 …
L. Ludovici, P. Zucchelli, hep-ex/9701007
L. Ludovici, F. Terranova,
EPJC 69 (2010) 331
L. Ludovici, A. Longhin, F. Terranova,
this work

(*) B. Pontecorvo, Lett. Nuovo Cimento, 25 (1979) 257 →



The possibility of using tagged-neutrino beams in high-energy experiments must have occurred to many people. In tagged-neutrino experiments it should be required that the observed event due to the interaction of the neutrino in the neutrino detector would properly coincide in time with the act of neutrino creation (π→μν, K→μν,

Concept

In conventional ν beams, prompt production of positrons is uniquely associated with the production of electron neutrinos. These neutrinos are intrinsic background for oscillation experiments (sterile neutrinos, standard oscillation) or a useful sample for ν_e cross section measurements. In a sign+momentum selected secondary beam, we find:

Channel	ν at far detector	Angular spread (*)	Kinematics
$\pi^+ \to \mu^+\nu_\mu$	Bulk of ν_μ	$\mu^+ \approx 4$ mrad	Two body decay
$\pi^+ \to \mu^+\nu_\mu \to e^+\nu_e\nu_\mu\nu_\mu$	ν_e contamination from decay-in-flight (DIF)	$e^+ \approx 28$ mrad	Low mass, three body decay
$K^+ \to \pi^0 e^+ \nu_e$	ν_e contamination from K_{e3}	$e^+ \approx 88$ mrad	High mass, three body decay
Undecayed π^+, K^+,p	none	O(3 mrad) $^{(**)}$	
Other K^+ decays	none/ν_μ		No prompt positrons

(*) RMS assuming $p_\pi \approx 8.5$ GeV (see below)
(**) depends on the focusing system

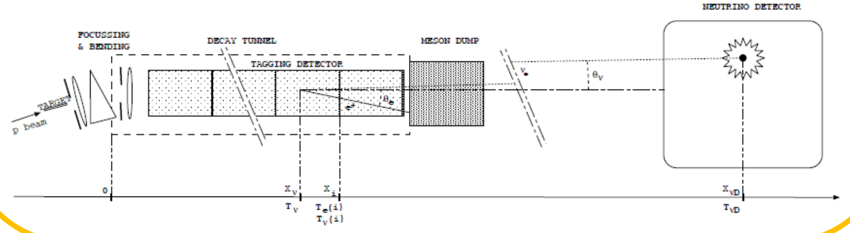
Tagging prompt positrons

Counting prompt positrons ("single tag"):
If we are able to count "all" prompt positrons, we know how many ν_e are produced in the decay tunnel and we can evaluate the ν_e crossing the detector relying only on the geometrical acceptance and the kinematics of π/K decay
Ideal technique to measure the ν_e cross-section decoupled from flux uncertainties

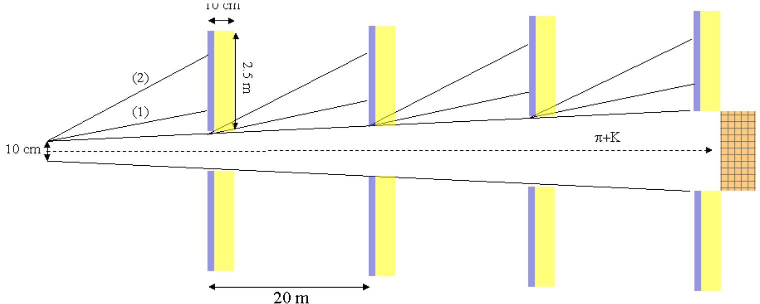
Identifying prompt positrons in time coincidence with ν_e at far detector ("double tag"): If we are able to detect ν_e CC interactions at far detector in time coincidence with positrons, we can **veto the intrinsic ν_e background in conventional neutrino beams** and measure the neutrino energy from the $e^+ \pi^0$ energy

Two possible strategies:

Cherenkov tagging:
[Ludovici, Zucchelli, hep-ex/9701007]
Instrument the decay tunnel with Cherenkov counters setting all particles but e+/e- below threshold
[very high rate but high efficiency]

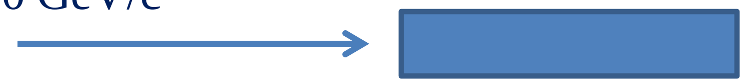


Beam scraping:
[Ludovici, Terranova, EPJC 69 (2010) 331]
Intercept particles beyond the cone of 2-body pion decay
[less rate/dose but lower efficiency]



Reference beamline

To test the effectiveness of the beam scraping approach, we considered a beamline specially tuned for the measurement of ν_e cross section.

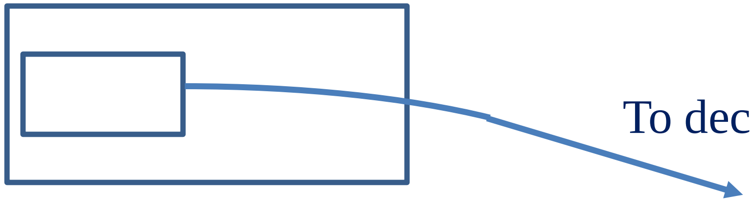


Target: Be,
110 mm length,
3 mm diameter

Protons:
30 GeV/c

[Fluka 2011]

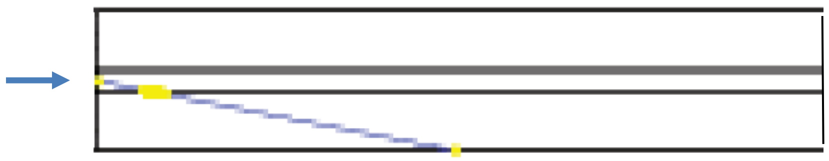
Focusing system
(3 mrad, p_{mean} = 8.5 GeV, momentum byte ±20%)



To decay tunnel

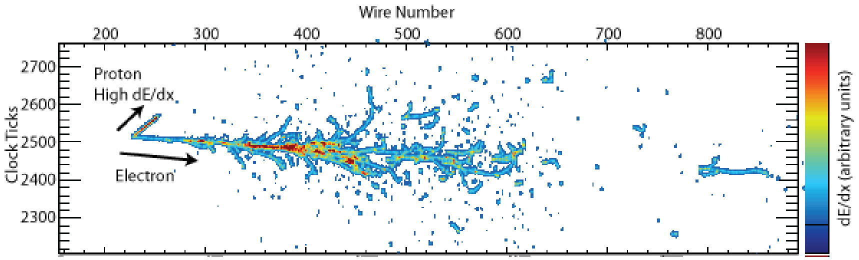
[Not simulated. Horns for fast extraction, quad/solenoid focusing for slow extraction,]

Decay tunnel: L=50 m instrumented with a fast calorimeter



[Geant 4 down to hits level. See below]

Far detector at 100 m from the entrance of the tunnel

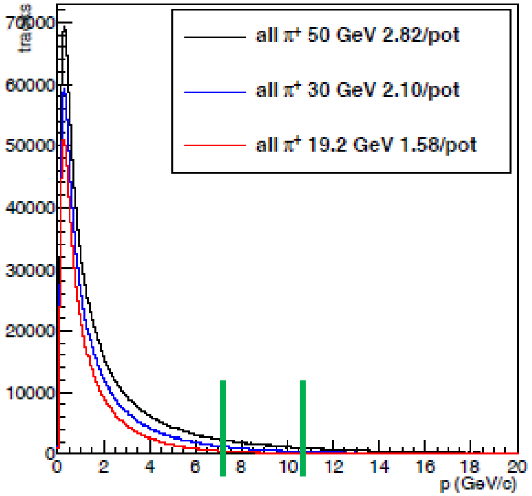


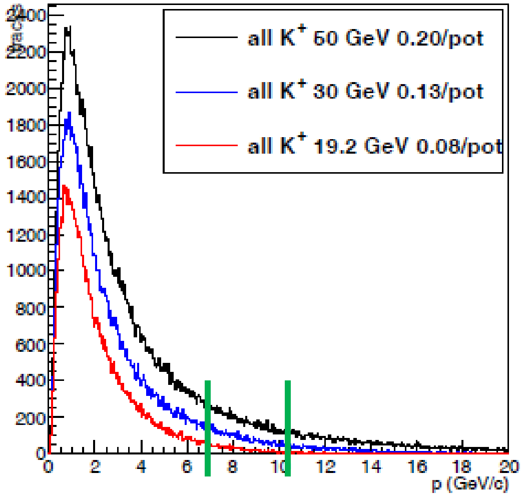
[Not simulated. Assuming time resolution 1-10 ns]

Fluxes

Short decay tunnel to enhance the ν_e from K_{e3} and suppress ν_e from DIF (larger spread: easier to be tagged)

L= 50 m
Fraction of K^+ decayed = 54%
Fraction of π^+ decayed = 10%



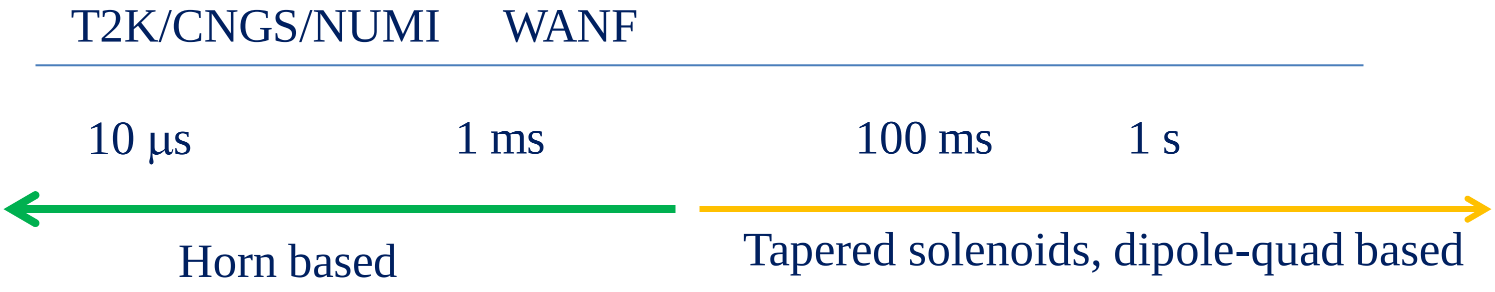


Selected:	Corresponding to:
P_{mean}= 8.5 GeV	2.45 10^{-4} π^+/pot
Δp = 20%	2.7 10^{-5} K^+/pot
$\Delta\Omega$ = 80 μsr	

10^{10} π^+ and 1.1 10^9 K^+ per extraction at the entrance of the decay tunnel assuming for 4 10^{13} protons (*)

(*) For reference: T2K@Run IV p=30 GeV, 1.2 10^{14} pot/pulse, PS@CERN p=20 GeV, 2 10^{13} pot/pulse

Focusing system: the performance of the positron tagger depends on the particle rate. Slow (ms) or very slow (s) extractions are preferred. Assuming variable extraction times:



T2K/CNGS/NUMI WANF

10 μs 1 ms 100 ms 1 s

Horn based

Tapered solenoids, dipole-quad based

Taggers

Rationale: fast and radiation hard hadron calorimeters to separate $e^+/\gamma/\mathrm{pi}$ with moderate granularity (10 cm^2) and longitudinal sample (2 samples). Scint(*) or Si-based(**) pre-shower for charged/neutral separation and t_0 (<10 ns).

Parameters:

R_I (inner radius): 40 cm (undecayed π, p and muons from 2-body decay of π flow inside the cylinder)

R_O (outer radius): 57 cm (on average a positron from K_{e3} crosses 3 interaction lengths)

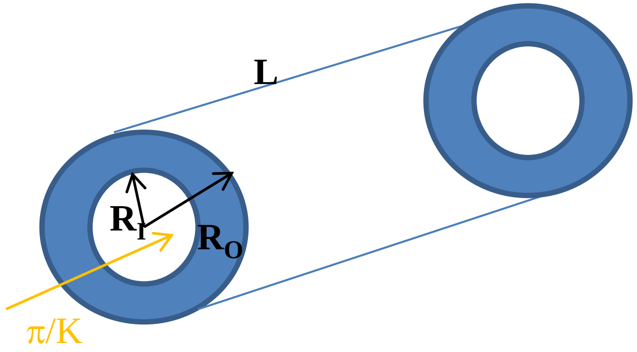
Length = 50 m (enhance K decay component)

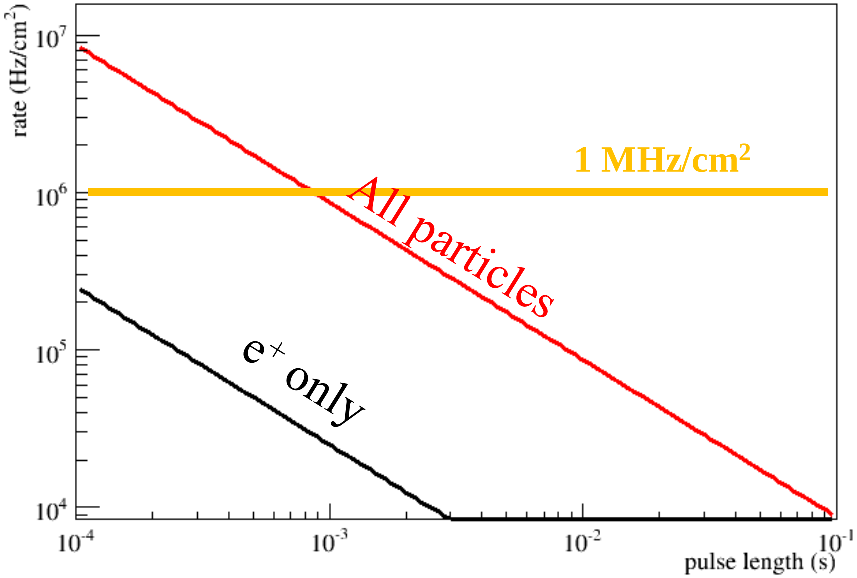
Max rate: 1 $\mathrm{MHz/cm}^2$. Max dose: 0.1 MGy/y

Weight: 270 t (passive material: Cu)

Resolution:
$$\frac{13\%}{\sqrt{E(GeV)}} \oplus 3\%\ (\mathrm{e.m.})$$

$$\frac{95\%}{\sqrt{E(GeV)}} \oplus 7\%\ (\mathrm{hadr.})$$





(*) F. Simon et al., JINST 8 (2013) P12001

C. Adloff et al. et al., JINST 5 (2010) P05004

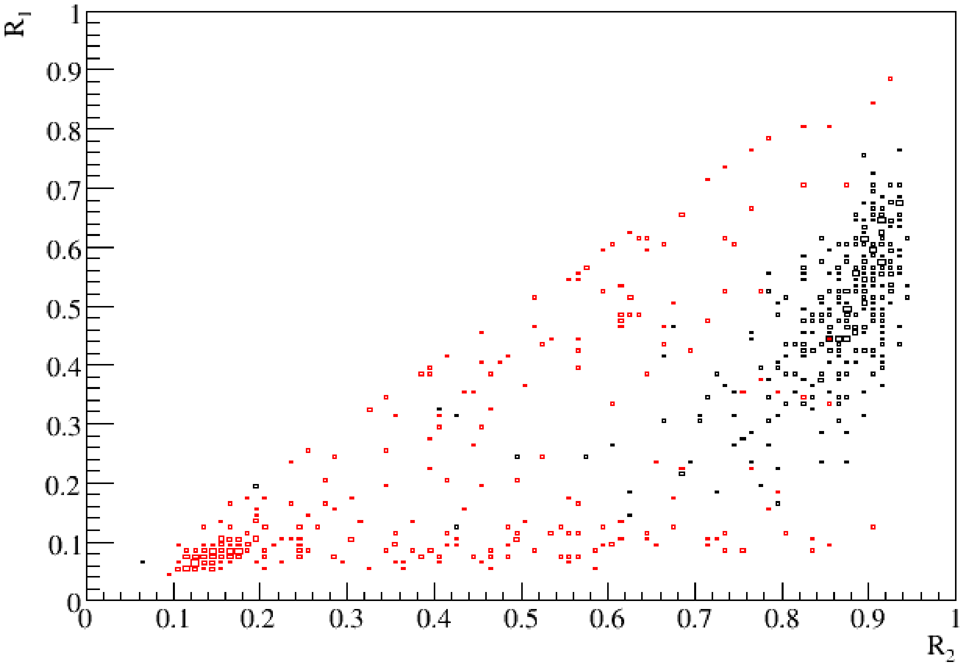
(**) N. Cartiglia et al., JINST 9 (2014) C02001

Positron efficiency

Signal: prompt positrons distributed uniformly below 4 GeV while most of the pion background (see below) peaks at 2 GeV.

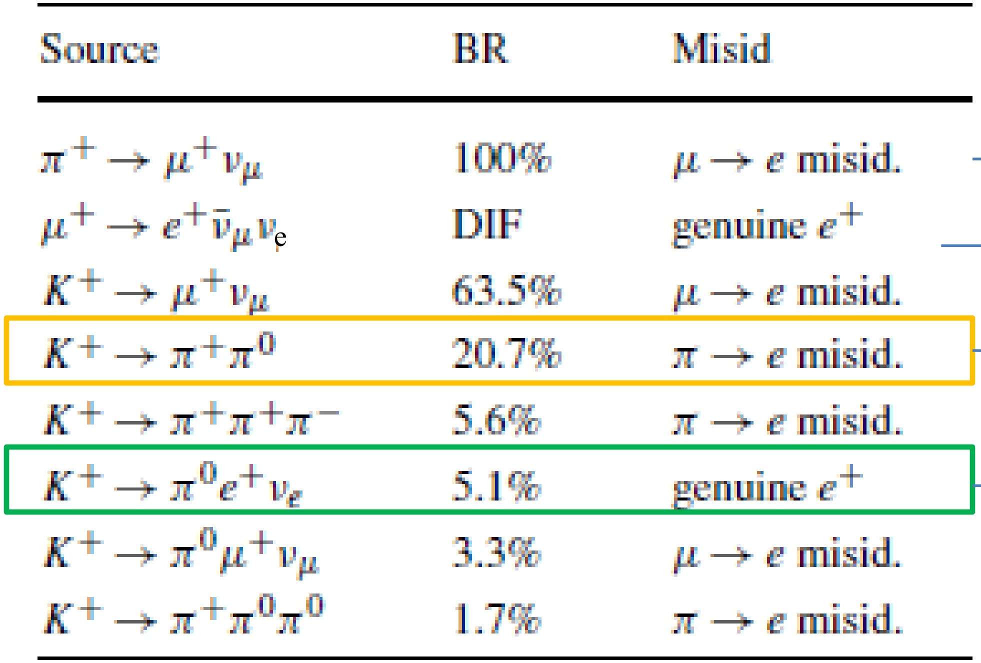
E_{vis}> 300 MeV
$R_1=D_1/E_{vis}$> 0.2
$R_2=D_2/E_{vis}$>0.7

$D_{n=1,2}$ is the energy deposited in a cylinder of radius $2R_{Moliere}$ (3.2 cm) and height = $n(t_{max}+1)X_0 \approx 5X_0$ for D_1 and $10X_0$ for D_2



Cut		
K_{e3} decay	100%	Prompt positron
e^+ in calorimeter	85%	Geometrical efficiency of tagger
R_1,R_2 cuts	67%	e/π separation
E_{vis}> 300 MeV	59%	e/mip separation

Background



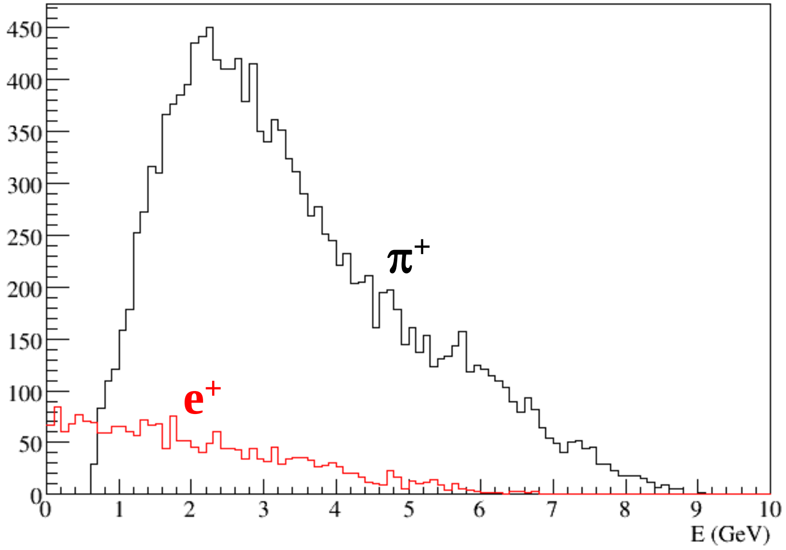
Source	BR	Misid
$\pi^+ \to \mu^+ \nu_\mu$	100%	$\mu \to e$ misid.
$\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$	DIF	genuine e^+
$K^+ \to \mu^+ \nu_\mu$	63.5%	$\mu \to e$ misid.
$K^+ \to \pi^+ \pi^0$	20.7%	$\pi \to e$ misid.
$K^+ \to \pi^+ \pi^+ \pi^-$	5.6%	$\pi \to e$ misid.
$K^+ \to \pi^0 e^+ \nu_e$	5.1%	genuine e^+
$K^+ \to \pi^0 \mu^+ \nu_\mu$	3.3%	$\mu \to e$ misid.
$K^+ \to \pi^+ \pi^0 \pi^0$	1.7%	$\pi \to e$ misid.

Negligible due to geometry of the tagger

DIF "signal"

Main background (ε_{misid} = 2%)

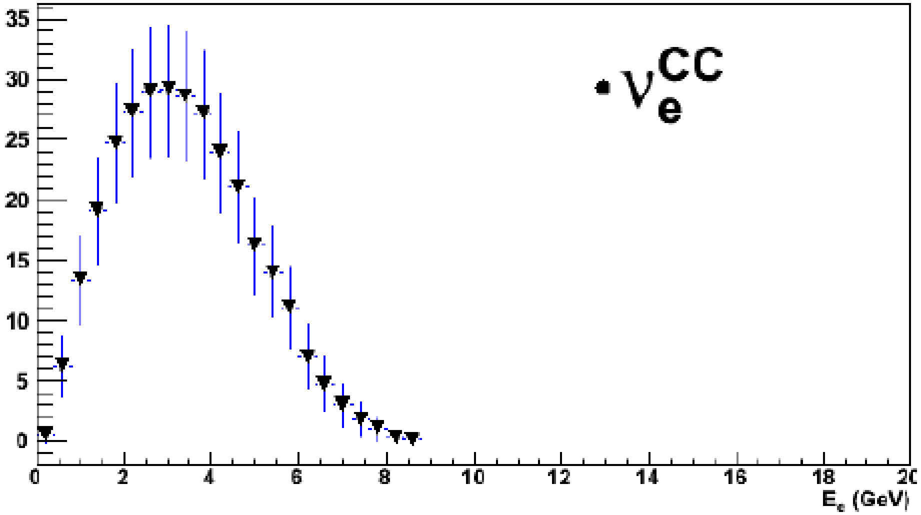
Signal (ε = 59%)



Overall signal to noise ratio S/N = 8 (mostly dominated by $K^+ \to \pi^+ \pi^0$ background)

Neutrinos at far detector

Particles (E>0.5 GeV)	Rate	Ratio ν_x/ν_μ
ν_μ	$2.35\ 10^{-5}\ \nu_\mu$/pot	1
ν_e from K_{e3}	$5.8\ 10^{-7}\ \nu_e$/pot	2.5%
ν_e from DIF	$1.6\ 10^{-8}\ \nu_e$/pot	0.1%



Corresponding to O(300) ν_e CC per 10^{20} pot (1 kton detector at L=100 m from the entrance of the tunnel)

Single tag mode

In this operation mode, positrons are simply counted at the tagger. Time resolution at far detector is immaterial. The number of positrons provide the initial ν_e flux. Corrections are due to:

- ν_e at far detector with forward (untagged) positrons
- Tagged positrons giving ν_e outside the geometrical acceptance of the detector
- Untagged DIF

These corrections come from 3-body kinematics of K, μ and from detector and tagger geometry. Associated systematics are very low.

Double tag mode

A ν_e interaction in the far detector can be correlated to the observation of a prompt positron in the tagger to measure the neutrino flavor at source. This can be used:

- To veto the ν_e intrinsic contamination in conventional beams
- To measure flavor transition on event-by-event basis
- To measure the neutrino energy event-by-event from the $e^+ \pi^0$ energy (“Serpukhov mode”)

Double tag depends critically on the time resolution Δ of the tagger (10 ns - 100 ps) and the far detector (<10 ns)

Accidental tag probability:

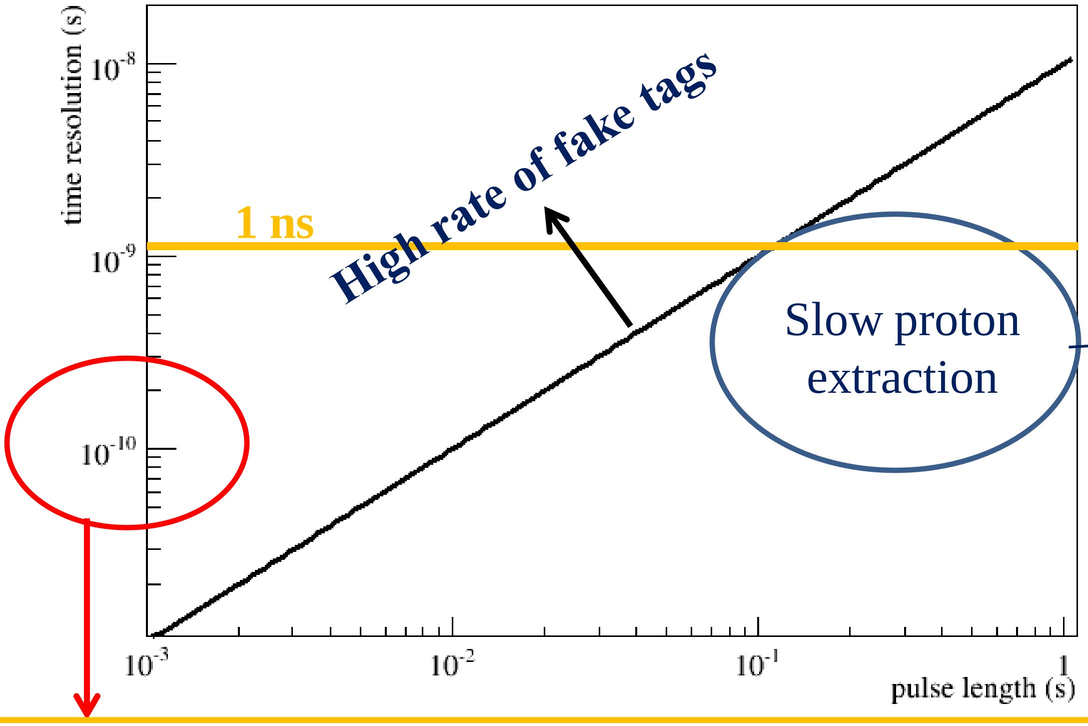
$$[N_K BR(K_{e3})(1 - e^{-\frac{\gamma_K c\tau_K}{L}})\varepsilon_{tag} + bkg] \times \Delta \approx 2 \times 10^7 \; \Delta / T_{extr}$$

particles/second

Sum of time resolution of tagger and neutrino detector

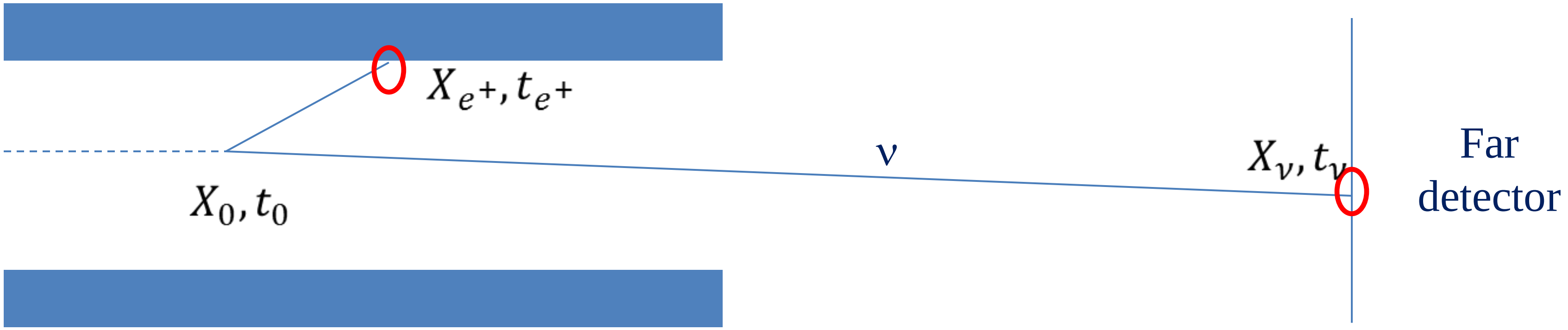
Proton pulse length

For the reference beamline, the ratio between the time resolution and the proton pulse length must be smaller than 10^8 . For instance, for 1 ns detector resolution, the proton pulse length must exceed 100 ms.



Critical issues:
Focusing system
Cosmics at far
detector

Intrinsic limit: in principle, we would like to measure t_ν-t_0 and X_ν-X_0.
In fact, we measure t_ν-t_{e+} and X_ν-X_{e+}



It introduces **an additional time spread** <1 ns that can be reduced <100 ps using the positron direction

Conclusions

The development of fast, radiation hard detector allows for a reconsideration of the old idea of tagged neutrino beams. Here we focus on positron taggers instrumenting the peripheral areas of the decay tunnel (“beam scraping”) .

- This technique is particularly well suited for tagging K_{e3} decays in medium energy short baseline beams ($E_{\pi/K} = 8.5$ GeV, $E_{\nu\mu} = 3$ GeV)
- Tagging efficiencies are 59% and background contamination (mostly from $K \rightarrow \pi^+\pi^0$) is <10%
- Single tag mode can be employed to reduce systematics in the determination of the initial flux (flux depends on kinematic corrections) and measure absolute ν_e cross section
- Double tag mode can be implemented to veto ν_e intrinsic component of the beam and reconstruct the ν energy at source.
- Double tagging is challenged by the accidental rates and require long proton extractions (1 s)
- Other options (e.g. Cherenkov based) are available to tackle the forward region of the decay tunnel.

Tagger units may become an important tool for the next generations of ν beams. The very encouraging results obtained with the beam scraping approach surely deserve further investigation