A novel beam-line for the measurement of the electron neutrino cross section

Neutrino physics in the precision era challenges conventional technologies in terms of intensity, purity and reduction of systematics budget

The key role of the ν_e cross section → Can we reduce (by one order of magnitude!) the “intrinsic” limit due to flux uncertainty?

Measuring $\sigma_{\nu e}$ from a pure and well controlled sample of $K^+ \to \pi^0 e^+ \nu_e$

- Monitoring positron production in the decay tunnel using calorimetric techniques: **a new opportunity for technologies developed for LHC and linear colliders**
- Impact on the design of the neutrino beam-line
- **A measurement down to 1% is feasible using current beam and detector technologies**
- Conclusions

Based on A. Longhin, L. Ludovici, F. Terranova EPJC 75 (2015) 155

A. Berra, C. Jollet, A. Longhin, L. Ludovici, L. Patrizii, M Prest, A. Meregaglia, G. Sirri, **F. Terranova**, E. Vallazza

Cross sections

In the last ten years, our knowledge of ν cross sections has improved <u>enormously</u> thanks to a vigorous experimental programme (Minerva, T2K, Sciboone, Miniboone etc.) motivated by the needs of the precision oscillation physics. Still,

✓ No absolute cross section is known with precision smaller than ~10%

<u>Reason:</u> all measurements are limited by the uncertainty on the neutrino flux at source
<u>Mitigation:</u> dedicated hadro-production experiments.

See A. Bravar's talk

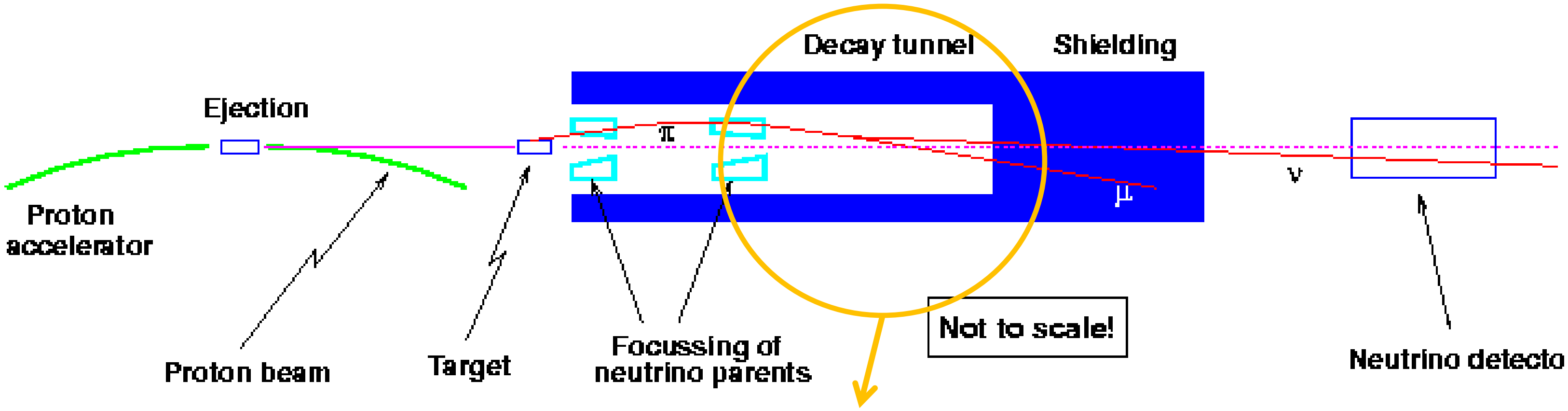
✓ ν_e cross sections are based on extrapolation from ν_μ data (lepton universality) and ν_e data are quite sparse (Gargamelle, T2K)

<u>Reason:</u> we don't have intense sources of ν_e in the GeV energy range
<u>Ideal solution:</u> Non conventional beams i.e. beams from decay in flight of stored muons (NUSTORM),

See A. Bross's talk

Can we build a **pure source of ν_e** employing conventional technologies reaching a **precision on the initial flux <1%?**

Inside a neutrino decay tunnel

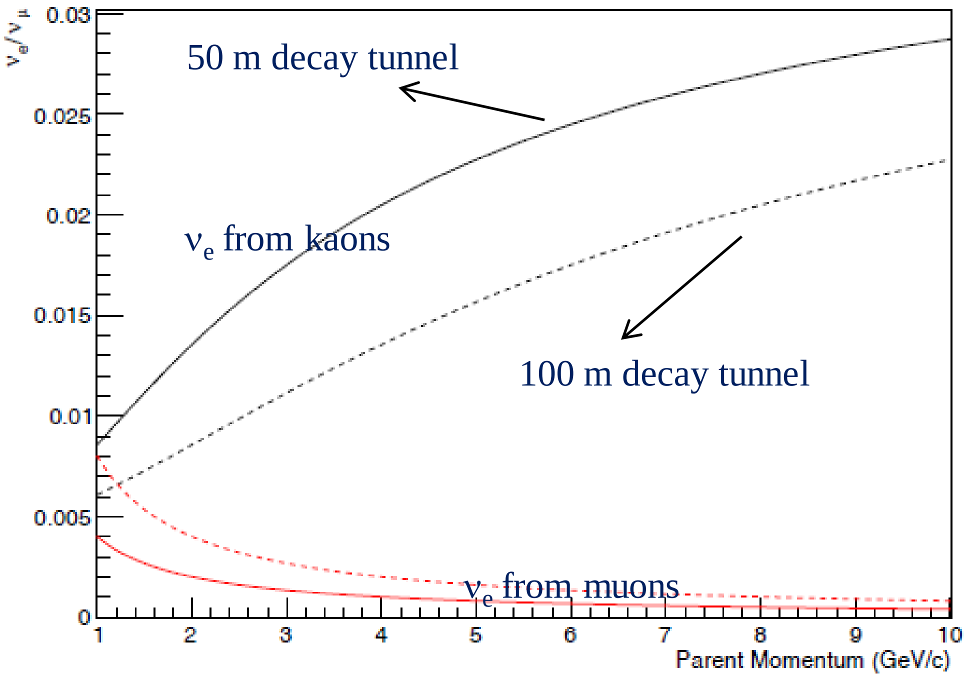


Channel	ν at detector	Angular spread(*)	Notes
$\pi^+ \to \mu^+ \nu_\mu$	Bulk of ν_μ	~ 4 mrad for μ^+	2-body decay
$\pi^+ \to \mu^+ \nu_\mu \to e^+ \nu_e \nu_\mu \nu_\mu$	ν_e from μ decay in flight (DIF)+(anti)ν_μ	~28 mrad for e^+	3-body decay (low parent mass)
$K^+ \to \pi^0 e^+ \nu_e$ (i.e. K_{e3})	ν_e from K_{e3}	**~ 88 mrad** for e^+	3-body decay (high parent mass)
Undecayed K^+,π^+ and protons	none	~3 mrad (see below)	
Other K^+ decays	ν_μ or none		no prompt positrons
Wrong sign and off-momentum π/K, neutrals			negligible if particles are sign selected after the horn

(*) RMS assuming p = 8.5 GeV, 3 mrad in 10x10 cm^2 window [$\varepsilon_{xx'}=\varepsilon_{yy'}=0.15$ mm rad] (see below)

An electron neutrino source based on $K^+ \to \pi^0 e^+ \nu_e$

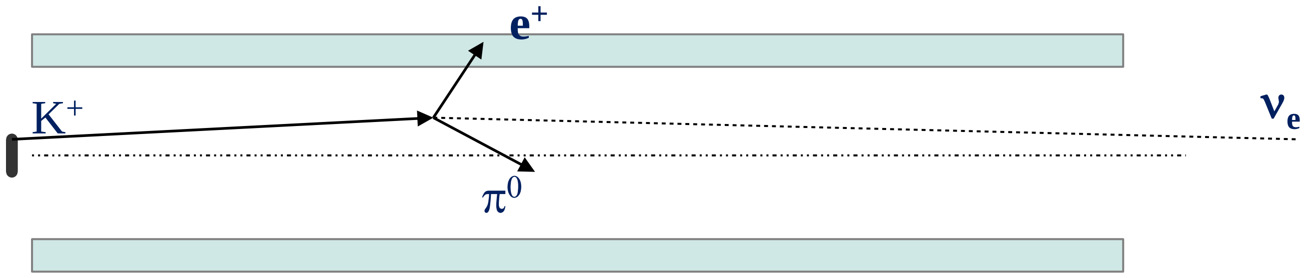
For high energy secondaries and short decay tunnels, the beam will be depleted in ν_e from decay-in-flight (DIF) of muons and enriched in ν_e from K_{e3}. **A large angle positron signals uniquely the production of a ν_e at source**. All other neutrinos are ν_μ from π and K decays.



$N_{e+} \sim N_{\nu e}$ and the coefficient $N_{e+}/N_{\nu e}$ mostly depends on the geometrical efficiency of the detector and the 3-body kinematics.

$$\frac{\Phi_{\nu_e}}{\Phi_{\nu_\mu}} = 1.8\ \%\ (\nu_e \text{ from } K_{e3})$$

$$\frac{\Phi_{\nu_e}}{\Phi_{\nu_\mu}} = 0.06\ \%\ (\nu_e \text{ from DIF})$$



“Tagged” vs “monitored” neutrino beams

The exploitation of K_{e3} ($K^+ \rightarrow \pi^0 e^+ \nu_e$) has been proposed since long in the framework of the “tagged neutrino beams” (uniquely link the lepton at source with the neutrino at the detector). Here we want to monitor the positron production rate without a event-by-event time link to ν_e CC at the detector

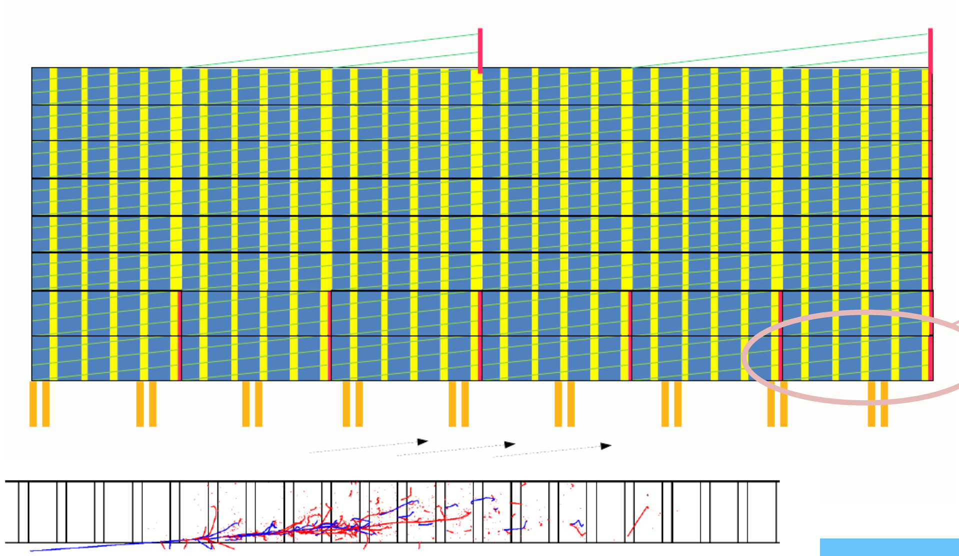
L. Hand, 1969, V. Kaftanov, 1979 ($\pi/K \rightarrow \nu_\mu$); G. Vestergombi, 1980; S. Denisov, 1981, R. Bernstein, 1989 (K_{e3}); L. Ludovici, P. Zucchelli, hep-ex/9701007 (K_{e3}) ; L. Ludovici, F. Terranova, EPJC 69 (2010) 331 (K_{e3}).

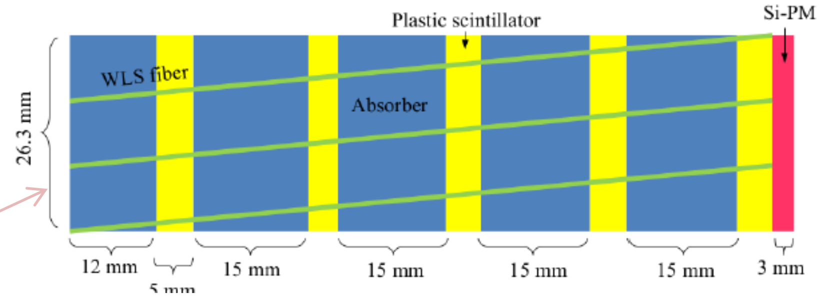
Monitored neutrino beams are much less challenging than “tagged neutrino beam”

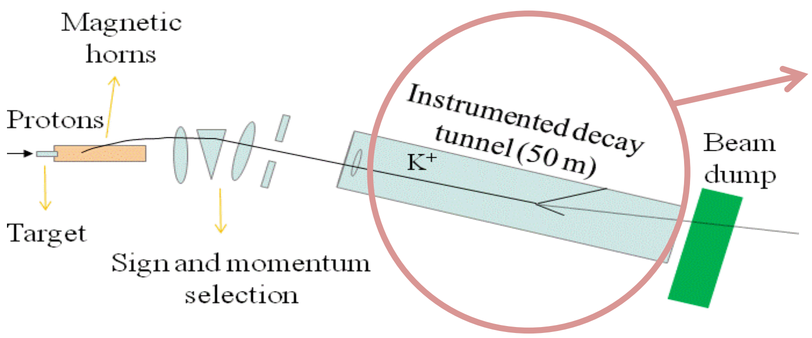
Technology	Readiness	Challenges
Monitored ν_e beams	Yes! Strong physics case!	• Cost effective instrumentation for the decay tunnel • Extraction scheme compatible with existing accelerators
Tagged ν_e beams	Not yet for physics measurements. Yes for a proof of principle	discussed elsewhere (see EPJC 69 (2010) 331 , EPJC 75 (2015) 155)

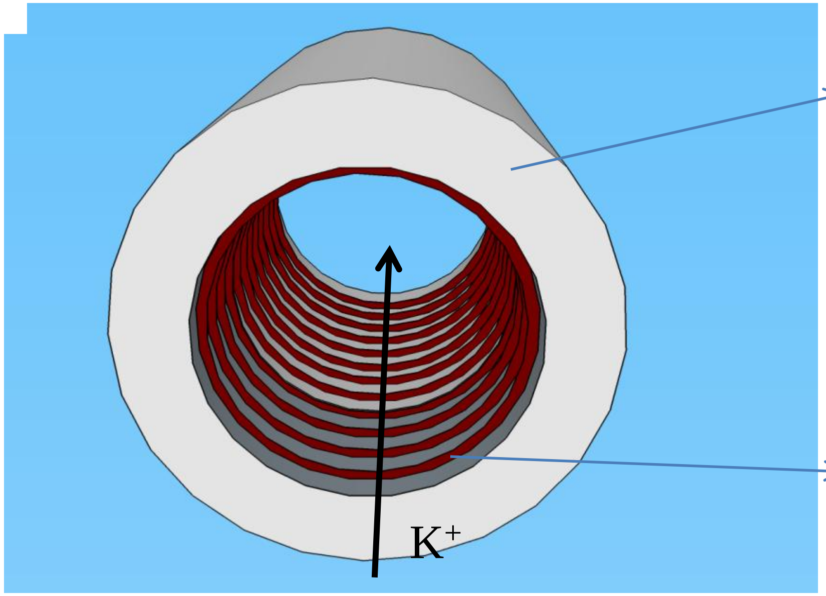
Positron identification

Calorimetric techniques offer the cheapest and safest mean to distinguish between positrons and charged pions exploiting the longitudinal development of the shower









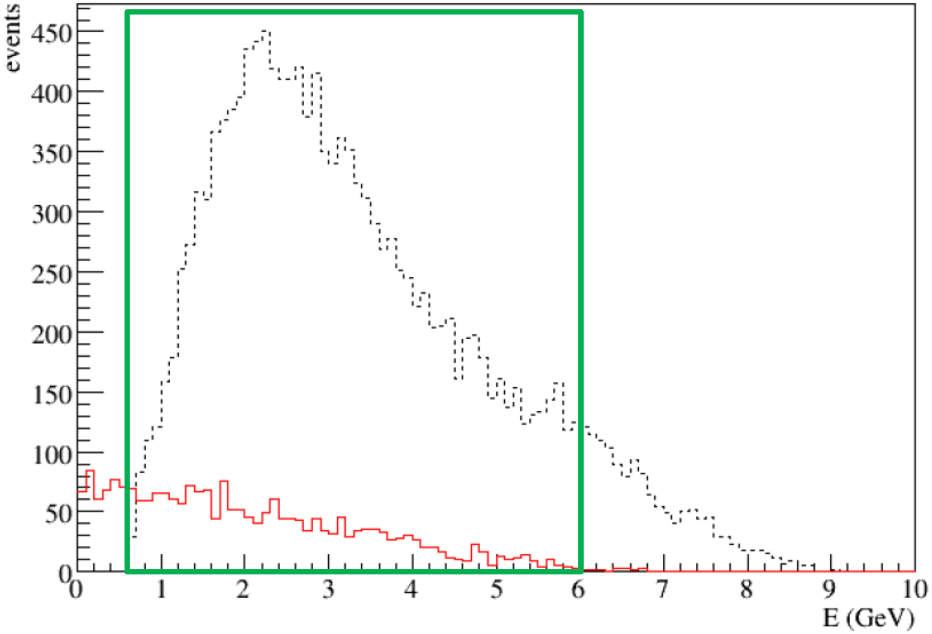
Shashlik calorimeter (e/π separation)

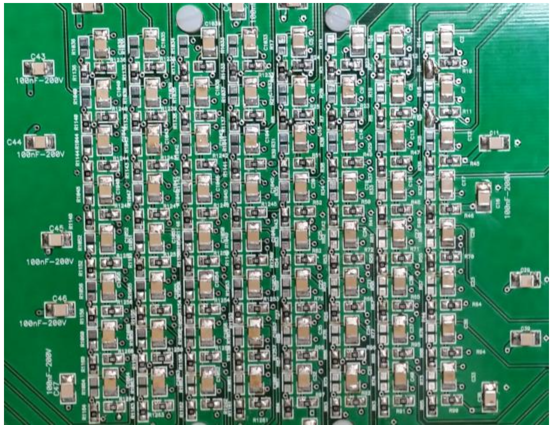
Photon veto (γ from π^0 decay)

Calorimeters with embedded SiPM light readout

Even outside neutrino physics, it is a very interesting light readout system: it solves the classical problem of longitudinal segmentation in “shashlik” (scint/Fe calorimeters with WLS fibers running through the tiles) calorimeters

Specs:
- e/π separation in the 0.5-6 GeV range with π→e misidentification <3%
- Rate capability ~500 kHz/cm^2
- Photon veto at 99%
- Radiation hardness: >1 kGy





Early results (tests at CERN-PS) very encouraging: stay tuned...

Charged pion background

Source	BR	Misid	$\epsilon_{X\to e^+}$	Contamination
$\pi^+ \to \mu^+\nu_\mu$	100%	$\mu \to e$ misid.	<0.1%	neglig. (outside acceptance)
$\mu^+ \to e^+\bar{\nu}_\mu\nu_\mu$	DIF	genuine e^+	<0.1%	neglig. (outside acceptance)
$K^+ \to \mu^+\nu_\mu$	63.5%	$\mu \to e$ misid.	<0.1%	negligible
$K^+ \to \pi^+\pi^0$	20.7%	$\pi \to e$ misid.	2.2%	13%
$K^+ \to \pi^+\pi^+\pi^-$	5.6%	$\pi \to e$ misid.	3.8%	5%
$K^+ \to \pi^0\mu^+\nu_\mu$	3.3%	$\mu \to e$ misid.	<0.1%	negligible
$K^+ \to \pi^+\pi^0\pi^0$	1.7%	$\pi \to e$ misid.	0.5%	negligible

Overall contamination for 59% efficiency: 18%

Overall contamination for 36% efficiency (tighter cuts – R_2>0.8): 7%

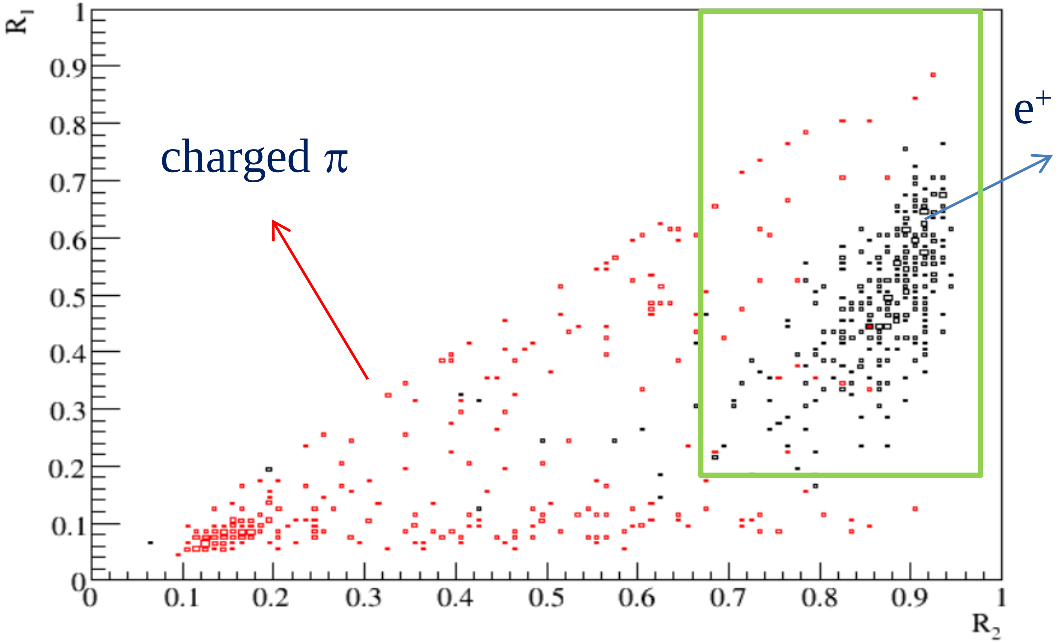
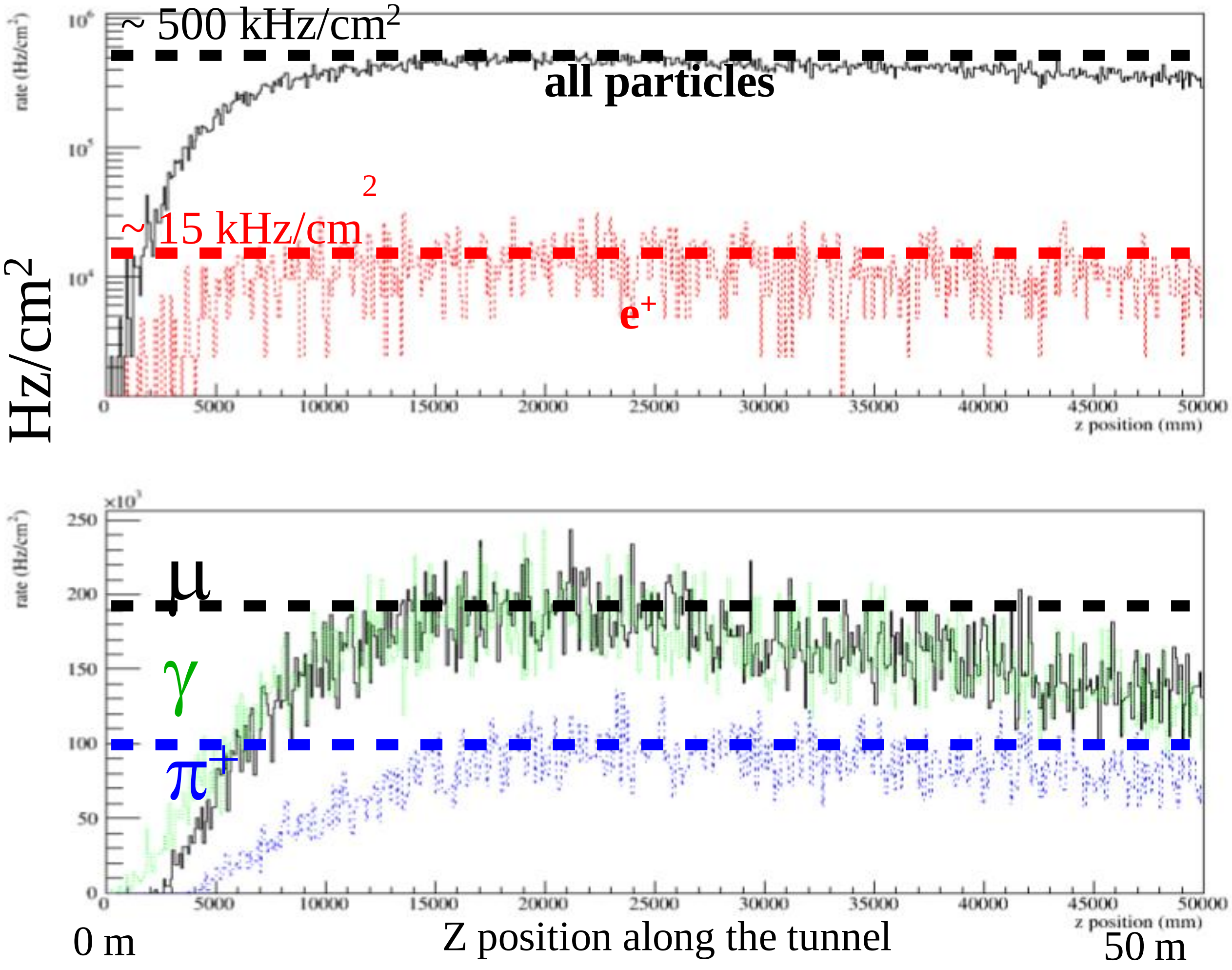


Table drawn from the simplified setup of EPJC 75 (2015) 155. Full GEANT4 simulation for the Shashlik setup in progress.

Rates

For 10^{10} π^+
in a 2 ms spill at the
entrance of the tunnel
rates are well below
1 MHz/cm^2



Particle	Max. rate (kHz/cm^2)
μ^+	190
γ	190
π^+	100
e^+	20
all	**500**

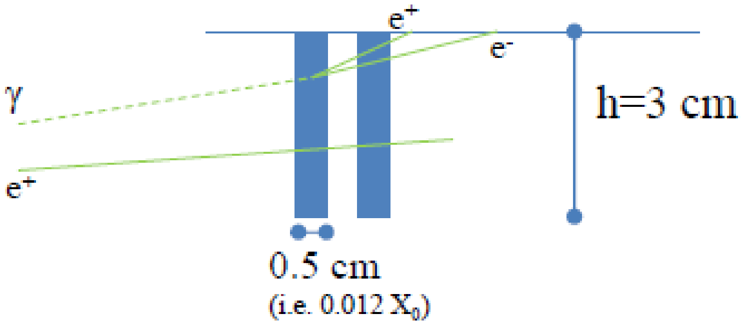
Pile-up comes mostly from the overlap of a muon from $K^+ \rightarrow \mu^+ \nu_\mu$ with a candidate positron

Recovery time, $\Delta t_{cal} = 10$ ns
Rate, R = 0.5 MHz/cm^2
Tile surface, S ~ 10 cm^2

$\}$ → 5% pile-up probability (= RS Δt_{cal})

It is already sustainable. Further mitigation an be achieved vetoing (offline) mip-like and punch-through particles using the longitudinal segmentation of the calorimeter.

Photon background comes mostly from π^0 decays



Subdominant if photon veto inside the beampipe
Negligible if both photon veto and calorimeter located inside the beampipe
Full simulation in progress.

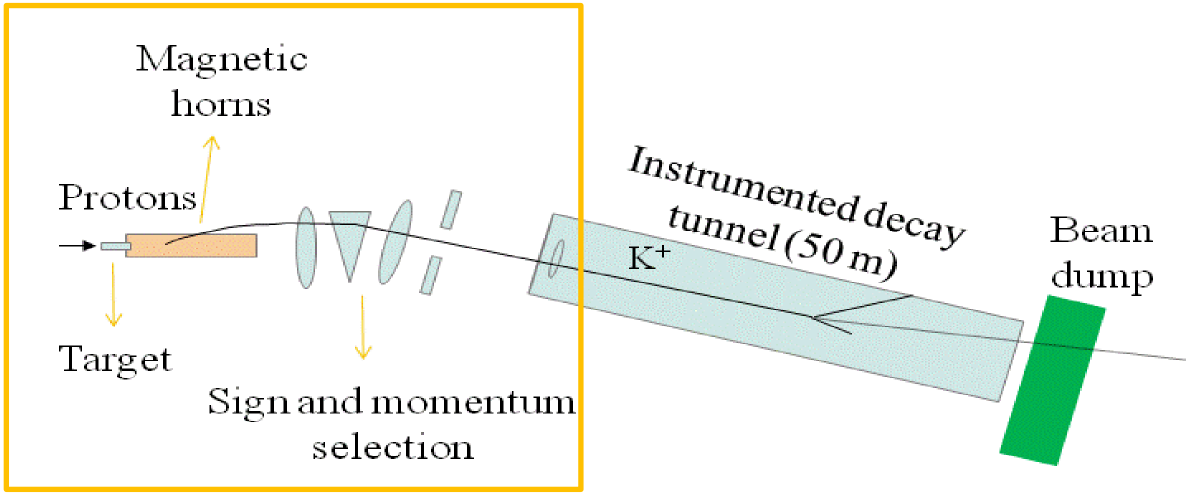
Radiation (doses)

For 10^4 ν_e CC events at the detector, 150 MJ are deposited into the calorimeter (but 64% into muons). **Integrated dose < 1.3 kGy** (remainder: integrated dose for the CMS forward ECAL is ~100 kGy). Not critical.

The beamline

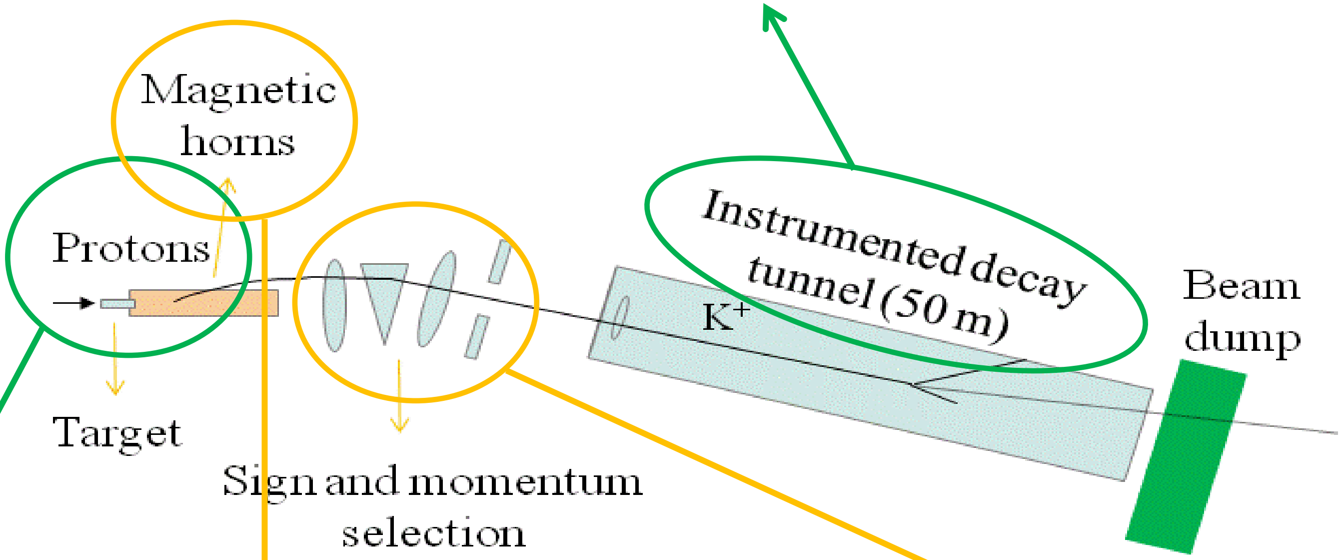
The positron tagger fixes (quite) uniquely the constraints on the beamline

Proton extraction	Sign selection	Focusing and transfer line
1-10 ms extractions (or slower)	Needed before the entrance of the decay tunnel	Unlike "tagged ν beams", in "monitored ν beams" horns are viable options. Emittance of 0.15 mm rad are well matched with horn acceptance
Reason: keep pile up and instantaneous local rate at O(1) MHz/cm2	Reason: No means to measure the sign of particle in the proposed tagger	Reason: beam at the entrance of the decay tunnel (and muons from π decays) must be fully contained inside the hollow cylinder of the positron tagger



The beamline: status of simulation

Full GEANT4 simulation at hit-level (done) and digi-level (in progress)

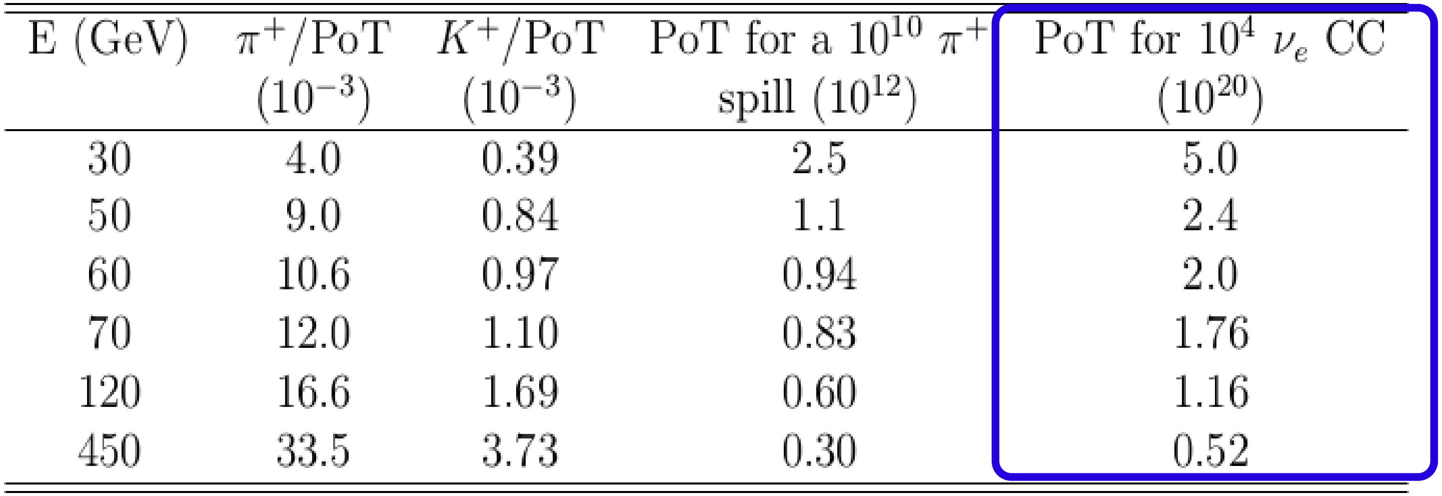


FLUKA2011 simulation. Cross checked with hadro-production data

Not fully simulated, yet. Assuming 85% efficiency for secondaries inside the ellipse $\varepsilon_{xx'}=\varepsilon_{yy'}=0.15$ mm rad in the (x,x',y,y') phase space

Not fully simulated, yet. Assuming 20% momentum bite at 8.5 GeV and flux reduction due to decay (15 m).

Reference parameters: 10^{10} π^+/spill (1.02×10^9 K^+/spill). **500 ton neutrino detector** at 100 m from the entrance of the tunnel. How many protons-on-target are needed to observe 10^4 ν_e CC events in the detector (1% statistical uncertainty on cross section)?



	E (GeV)	π^+/PoT (10^{-3})	K^+/PoT (10^{-3})	PoT for a 10^{10} π^+ spill (10^{12})	PoT for 10^4 ν_e CC (10^{20})
JPARC	30	4.0	0.39	2.5	5.0
Protvino	50	9.0	0.84	1.1	2.4
	60	10.6	0.97	0.94	2.0
	70	12.0	1.10	0.83	1.76
Fermilab	120	16.6	1.69	0.60	1.16
CERN-SPS	450	33.5	3.73	0.30	0.52

In a nutshell:

- Integrated protons-on-target (pot) are well within reach of JPARC-PS, Main Ring and CERN-SPS. Protvino U-70 (currently a 10 kW machine) should be upgraded to enter this game
- The number of protons per extraction is quite small. Large number of extractions of protons to target (2×10^8 - several Hz) are needed to reach the ntegrated P.o.T.

Is such operation mode compatible with high energy (>100 GeV) accelerators? The case of CERN-SPS

CERN-SPS: 400-450 GeV, 4.5 10^{13} protons per super-cycle.
A super-cycle every 15 s with a 2 s flat top

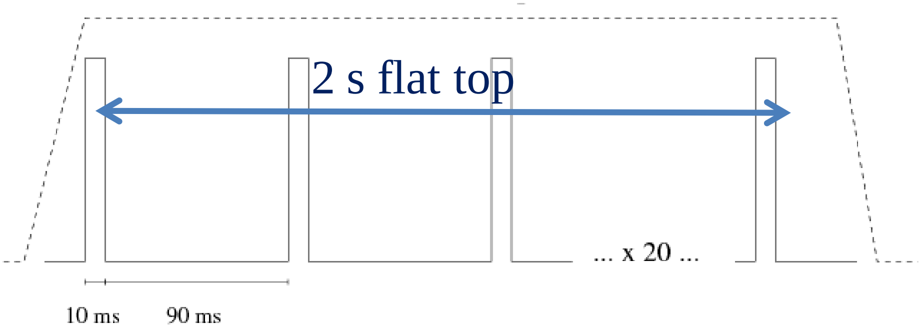
Slow resonant estraction (SRE): slow extraction on third integer resonance.

- ideal solution for beam dump experiment (SHIP experiment @ CERN)
- ideal solution for tagged neutrino beams
- possible solution for monitored neutrino beams (this talk) with static focusing system.

Under development within the SHIP R&D

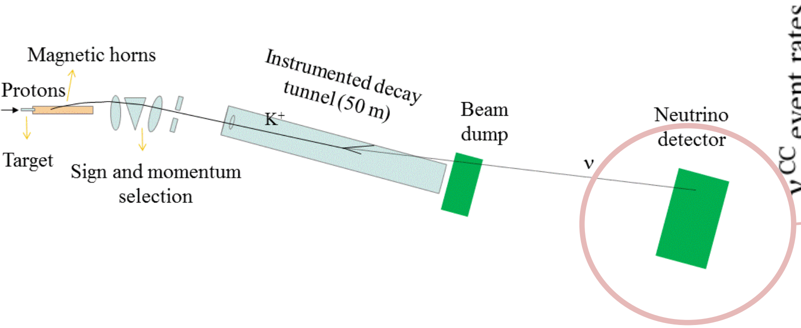
Multiple SRE: multiple slow extraction on third integer resonance.

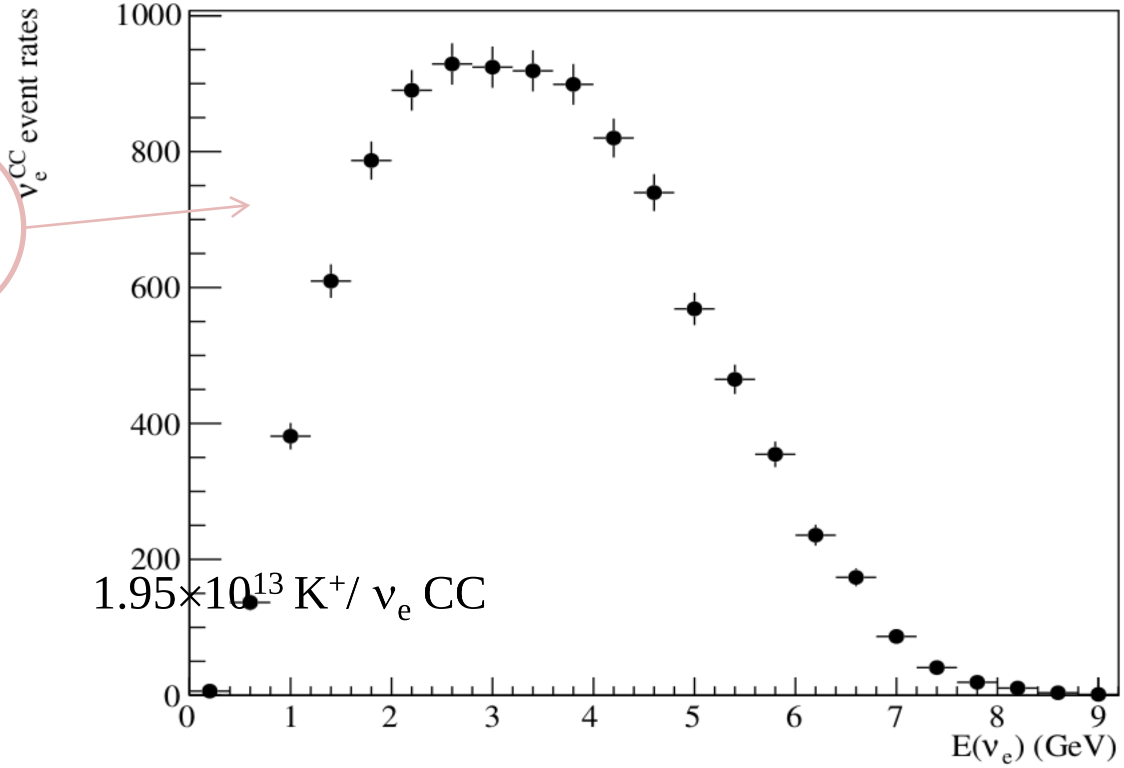
- ideal solution for monitored neutrino beams (this talk) with a horn-based focusing system.



To be tested

Neutrinos at the far detector





1.95×10^{13} K$^+$/ ν_e CC

$$\frac{\Phi_{\nu_e}}{\Phi_{\nu_\mu}} = 1.8\ \%\ (\nu_e \text{ from } K_{e3})$$

$$\frac{\Phi_{\nu_e}}{\Phi_{\nu_\mu}} = 0.06\ \%\ (\nu_e \text{ from DIF})$$

Spectrum of events at CERN-SPS (10^4 events, 1.5 y, 500 t detector, multiple SRE)

Other operations mode:

- High intensity extractions (x10): useful to increase the statistics and study differential and exclusive channels (at price of increase of flux systematics coming from extrapolation of low intensity runs)
- Anti-neutrino runs

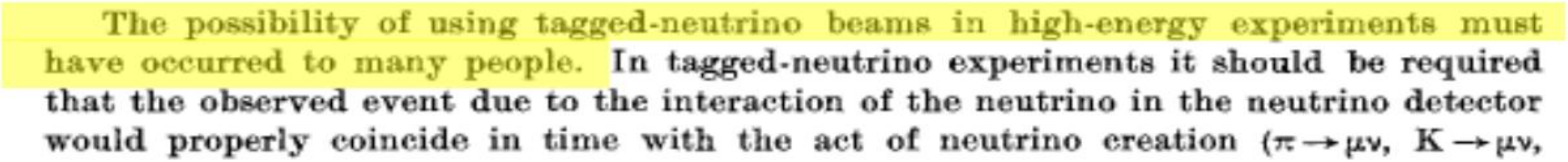
Systematics

The positron rate eliminates the most important source of systematics (see above). Can we get to 1%? Not demonstrated yet (need a full simulation with final setup) but **very likely**:

Source of uncertainties	**Size and mitigation**
Statistical error	<1%
kaon production yield	**irrelevant (positron tag)**
uncertainty on integrated pot	**irrelevant (positron tag)**
geometrical efficiency and fiducial mass	<0.5% PRL 108 (2012) 171803 [Daya Bay]
uncertainty on 3-body kinematics and mass	<0.1% Chin. Phys. C38 (2014) 090001 [PDG]
uncertainty on phase space at entrance	**can be checked directly with low intensity pion runs**
uncertainty on Branching Ratios	**irrelevant (positron tag)** except for background estimation (<0.1%)
e/π^+ separation	**can be checked directly at test-beams**
detector background from NC π^0 events	<1% uncertainty EPJ C73 (2013) 2345 [ICARUS]
detector efficiency	**Irrelevant for CPV if the target is the same as for the long-baseline experiment**

Beyond cross section measurements

This facility is, indeed, the first step toward a **Tagged Neutrino Beam**. The "forbidden dream" of ν physicists: detect simultaneously both the neutrino at the far detector and the associated lepton at production → unique tag of flavor at production



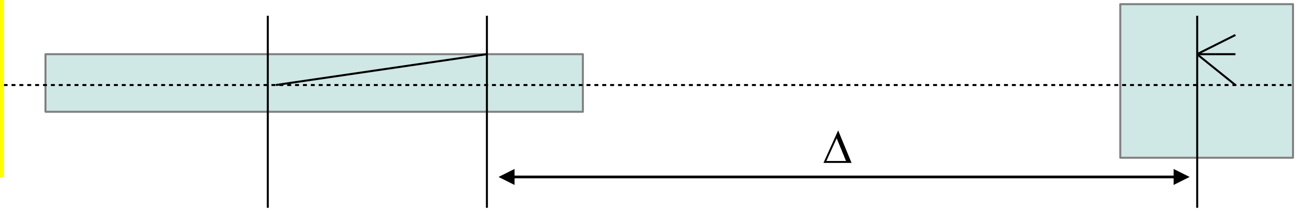
The possibility of using tagged-neutrino beams in high-energy experiments must have occurred to many people. In tagged-neutrino experiments it should be required that the observed event due to the interaction of the neutrino in the neutrino detector would properly coincide in time with the act of neutrino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

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

A "**double tag facility**" is aimed at observing the positron in time coincidence with ν_e at the detector. It can be used to:

- **veto the intrinsic ν_e background** in conventional neutrino beams
- **measure E(ν_e) event-by-event** from the energies of e^+ and π^0

Time coincidence between the ν_e CC and the positron: $|\delta t - \Delta/c| < \delta$



δt is the difference between the e^+ and the ν_e CC time (~100 ns).
δ is the linear sum of the timing resolutions of the e^+ tagger and neutrino detector

The double tag mode can work if we **can beat the number of accidentals**:

$$\mathcal{A} \equiv \left[N_K \cdot \mathrm{BR}(K_{e3})\left(1 - e^{-\frac{\gamma_K c\tau_K}{L}}\right)\epsilon + \mathrm{bkg} \right] \cdot \delta \simeq 2 \times 10^7 \frac{\delta}{T_{extr}}$$

positron rate per extraction

fake e^+ per extraction

extraction time

The proton extraction time must be ~1s	Cannot use any more the horns. Must rely on static systems → reduction of acceptance → reduction of flux by a factor of ~10
The time resolution of the tag must be <1 ns	OK
The time resolution of the neutrino detector must be ~1 ns	Feasible but at the limit of present technologies
The cosmic background increases by x10 [i.e. by A× (1s)/(2 ms)]	Non negligible background at small overburden
The momentum bite of the K^+ must be small enough not to limit the ν_e energy reconstruction	Feasible but can imply further reduction of flux
Time synchronization between the tagger and the detector ≪1 ns	OK [direct optical link at short baselines]

Conclusions

- The study of 3-family interference effects and CP violation set new experimental standards in terms of intensity, purity and control of systematics for the next generation of neutrino facilities
- New approaches to reduce the systematic budget are **extremely cost effective** and will increase significantly the physics reach of new long baseline facilities.
- The "intrinsic limit" to our knowledge of ν cross section (initial flux) **can be reduced by one order of magnitude exploiting the $K^+ \rightarrow \pi^0 e^+ \nu_e$ channel (K_{e3})**

A "positron monitored" ν_e source based on K_{e3}

- Can be build using existing beam technologies (horns, transport lines) and with a beam intensity (10^{20} pot) well within reach of present accelerators at CERN, Fermilab and JPARC
- Positrons can be tagged employing standard calorimetric techniques developed for colliders with efficiencies of the order of 50% and good (≈10) S/N ratio.
- A 1% measurement of the absolute ν_e cross section can be achieved with detector of moderate mass (500 ton)

The strong physics case (ν_e cross section measurement) and the readiness of the underlying technology highly support a dedicated R&D (e.g. in the framework of the CERN Neutrino Platform) to ground the physics potential of this technique