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

A.Meregaglia (IPHC-Strasbourg)

On behalf of

A. Berra, S. Cecchini, F. Cindolo, C. Jollet, A. Longhin, L. Ludovici, G. Mandrioli, A. Meregaglia, A. Paoloni, L. Pasqualini, L. Patrizii, M. Pozzato, M. Prest, F. Pupilli, G. Sirri, F. Terranova, E. Vallazza, L. Votano

GDR neutrino - Saclay - 4th November 2015

Introduction

- Next generation of long baseline experiments aims at the measurement of the CP phase studying the $\nu_\mu \rightarrow \nu_e$ and the corresponding antineutrino transitions.
- Given the "large" value of θ_{13}, statistics is no more the issue but the sensitivity to the CP phase crucially depends on systematics.
- Lowering the systematics down to 1% (present systematics are ~10%) is by far the most cost effective way to improve the sensitivity to CP violation and mass hierarchy.
- In particular, the absolute electron neutrino cross section is known with large uncertainties (order of 10%).

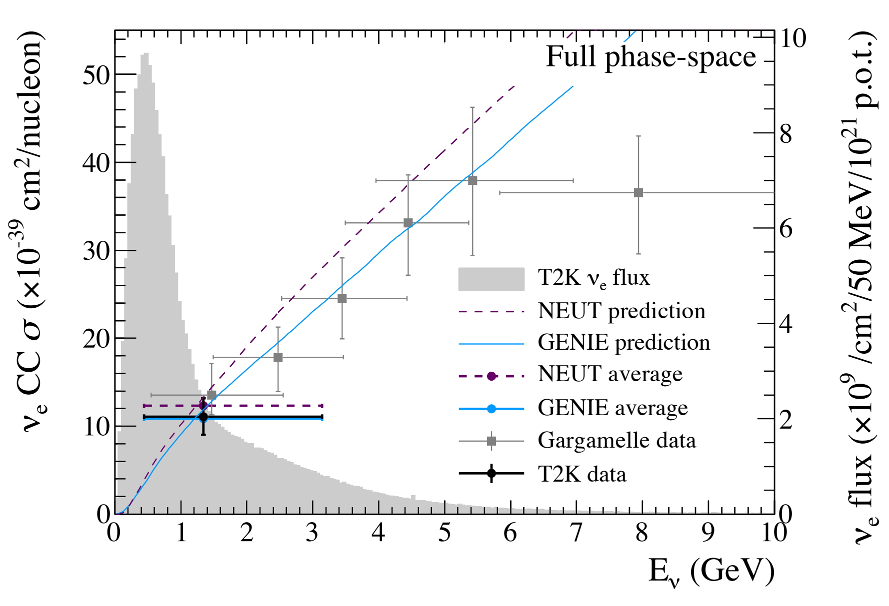
Can we reach the 1% error on $\sigma_{\nu e}$ from a pure and well controlled sample of $K^+ \rightarrow \pi^0 e^+ \nu_e$?

Based on A. Longhin, F. Terranova and L. Ludovici, Eur.Phys.J. C75 (2015) 4, 155

Cross section

Despite the huge improvements on ν cross section knowledge in the last ten years, thanks to a vigorous experimental program (Minerva, T2K, Sciboone, Miniboone etc.) we still have:

T2K - Phys.Rev.Lett. 113 (2014) 24, 241803



- **No cross section measurement with a precision smaller than ~ 10%.** Experiments are dominated by the uncertainty on the neutrino flux (although dedicated hadro-production experiments such as NA61 in case of T2K will reduce the impact on the extrapolation at far detector).

- **Most of the ν_e cross section measurements are based on ν_μ data** (lepton universality) due to lack of intense ν_e sources in the GeV range.

- **No experimental measurement of anti-ν_e cross section exists yet.**

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

Electron neutrino source

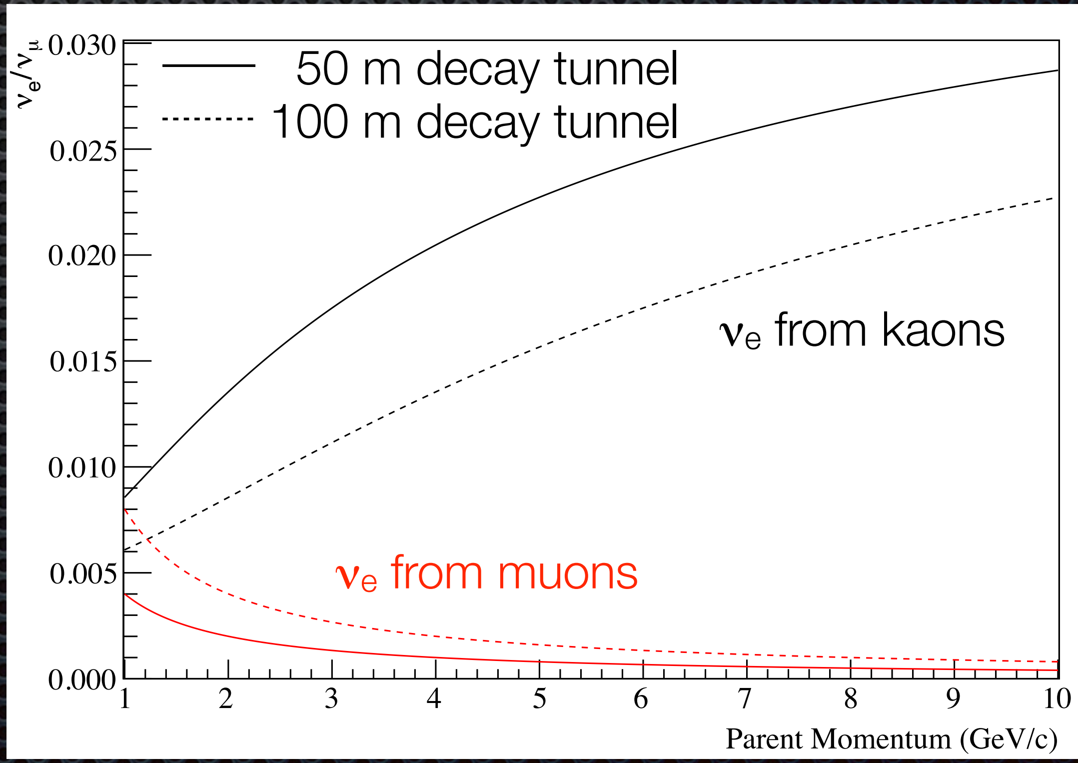
- The bulk of ν_μ are produced in a conventional beam by the pion decay: $\pi^+ \rightarrow \mu^+ \nu_\mu$.
- The ν_e are given by:

meson of 8.5 GeV

$\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \overline{\nu}_\mu \nu_\mu$	mean angular spread of 28 mad for e^+
$K^+ \rightarrow \pi^0 e^+ \nu_e$	mean angular spread of 88 mad for e^+

- A large angle positron is a clear indication of the production of a ν_e.

Eur.Phys.J. C75 (2015) 4, 155



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

Tagged Vs monitored beam

- The exploitation of the $K^+ \rightarrow \pi^0 e^+ \nu_e$ decay has been proposed a long time ago in the framework of the "**tagged neutrino beams**" i.e. where there is a unique correspondence between the lepton observed at the source and the neutrino measured at the detector.

  ($\pi/K \rightarrow \nu_\mu$) **L. Hand (1969), V. Kaftanov (1979)**

  (K_{e3}) **G. Vestergombi (1980), S. Denisov (1981), R. Bernstein (1989), L. Ludovici, P. Zucchelli (1997), L. Ludovici, F. Terranova (2010)**

- Here we discuss "**monitored beams**" i.e. without an event by event correlation between charged lepton and neutrino, which is **less challenging** with respect to tagged beams.

Technology	Readiness	Challenges
Monitored ν_e beams	Yes Strong physics case	- Cost effective instrumentation of the decay tunnel - Extraction scheme compatibility with present accelerators
Tagged ν_e beams	Not yet for physics Yes for proof of principle	Discussed elsewhere e.g.: EPJC 69 (2010) 331 EPJC 75 (2015) 155

Constraints for positron tagging

A conventional neutrino beam can be equipped with a positron monitoring system instrumenting the decay tunnel, however some constraints have to be considered:

- ν_e from K_{e3} must be the only source of ν_e at the far detector.
- The spectrum must be in the range of interest of future experiments i.e. 0.5-4 GeV.
- Positron spectrum has to be in the GeV region to allow for a e^+/π^+ separation from longitudinal sampling.

→ π/K of ~ 8 GeV and decay tunnel length shorter than 50 m

- The geometrical acceptance must be of order 1 at angles larger than the decay cone of $\pi^+ \rightarrow \mu^+ \nu_\mu$ (i.e. about 4 mrad).

→ Positron tagger all around the decay tunnel

- Photon conversions from π^0 ($K^+ \rightarrow \pi^+ \pi^0$) must be suppressed.

→ Need of a photon veto inside the beam-pipe

- To keep pile-up at negligible level the particle rate must be below few MHz/cm^2.

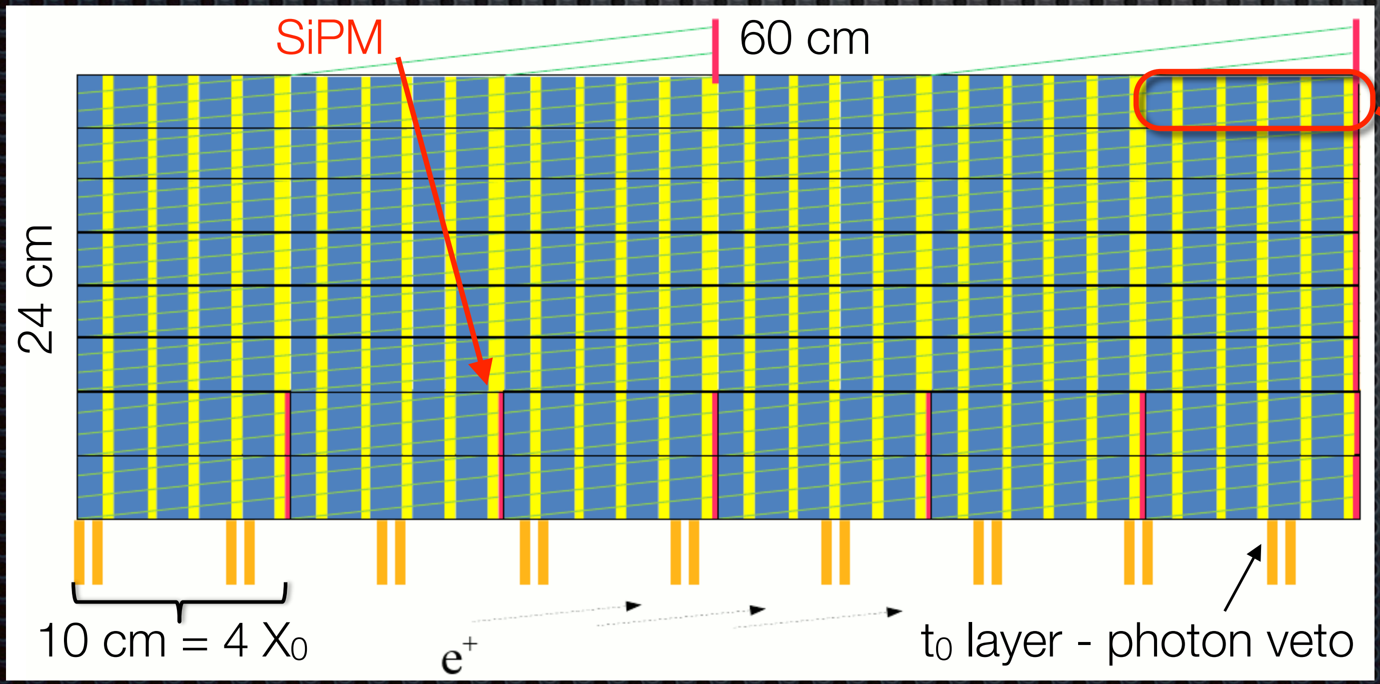
→ Proton extraction larger than 1 ms

Positron tagger → shashlik calorimeter
Photon veto → plastic scintillator hodoscopes

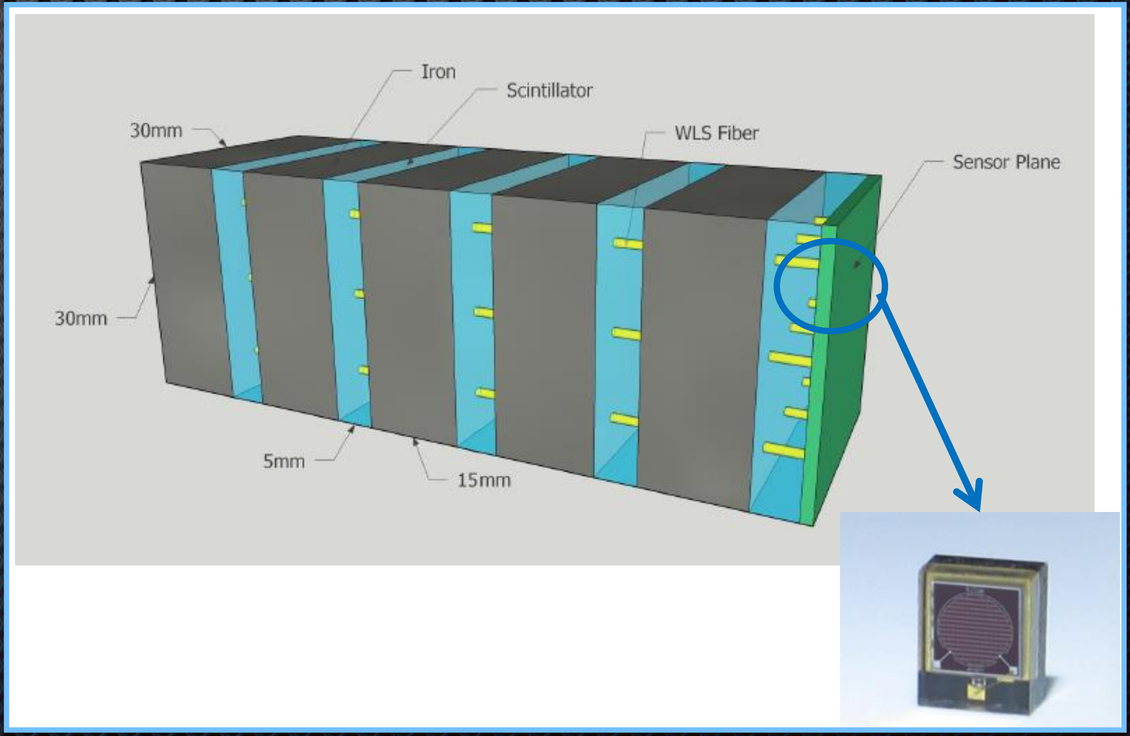
Positron tagger

- Calorimetric techniques offer the cheapest and safest mean to distinguish between positrons and charged pions exploiting the longitudinal development of the shower.
- The proposed **shashlik calorimeter (Iron/scintillator) coupled to a SiPM readout** solves the problem of longitudinal segmentation.
- The chosen base unit is a 4 X_0 e.m. module where the light is readout connecting WLS fibers directly to a 1 mm^2 SiPM in a plastic holder.
- The SiPM signals are grouped by 9 (or different granularity if needed).
- A full module is made of 2 e.m. layers and 1 hadronic layers (same structure but read out after 60 cm i.e. 2.6 interaction lengths.

Full module



Base e.m. unit

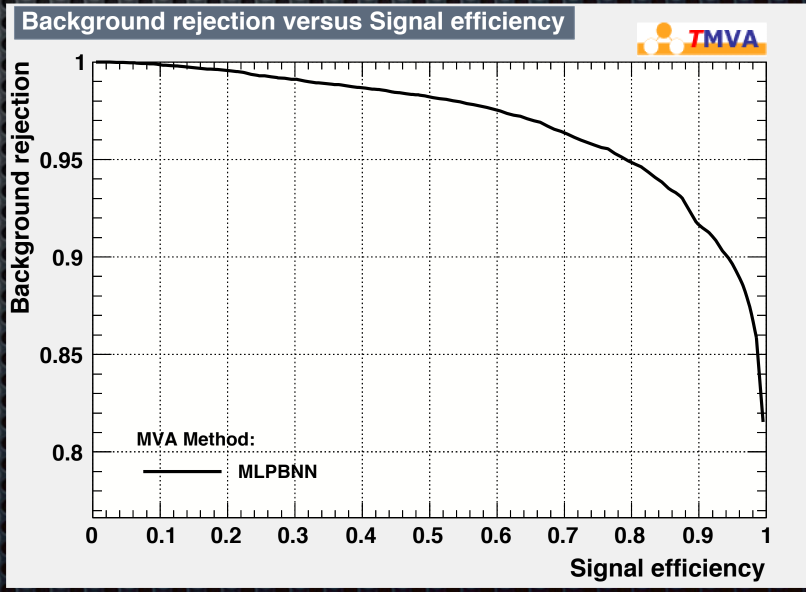


Positron tagger (2)

- Test of the readout have been performed at CERN showing the feasibility of the proposed scheme (no nuclear counter effects observed).
- Preliminary MC studies show that we can have a 60% positron efficiency rejecting 97.5% of the π^+ background according to the requirements.
- The overall contamination is at the level of 18% for an efficiency of 60% and it can be reduced to 7% with tighter cuts, for an efficiency of 36%.

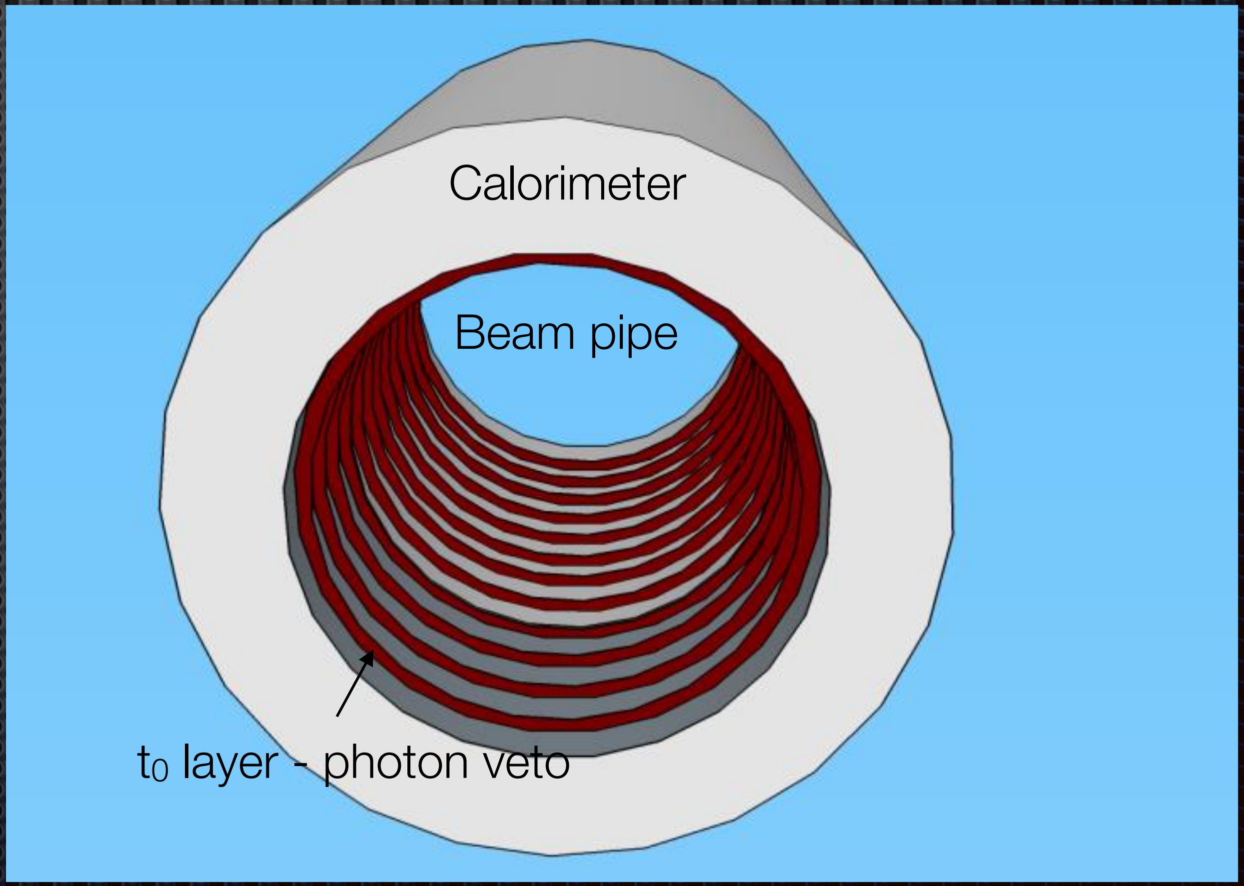
Eur.Phys.J. C75 (2015) 4, 155

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



Photon veto

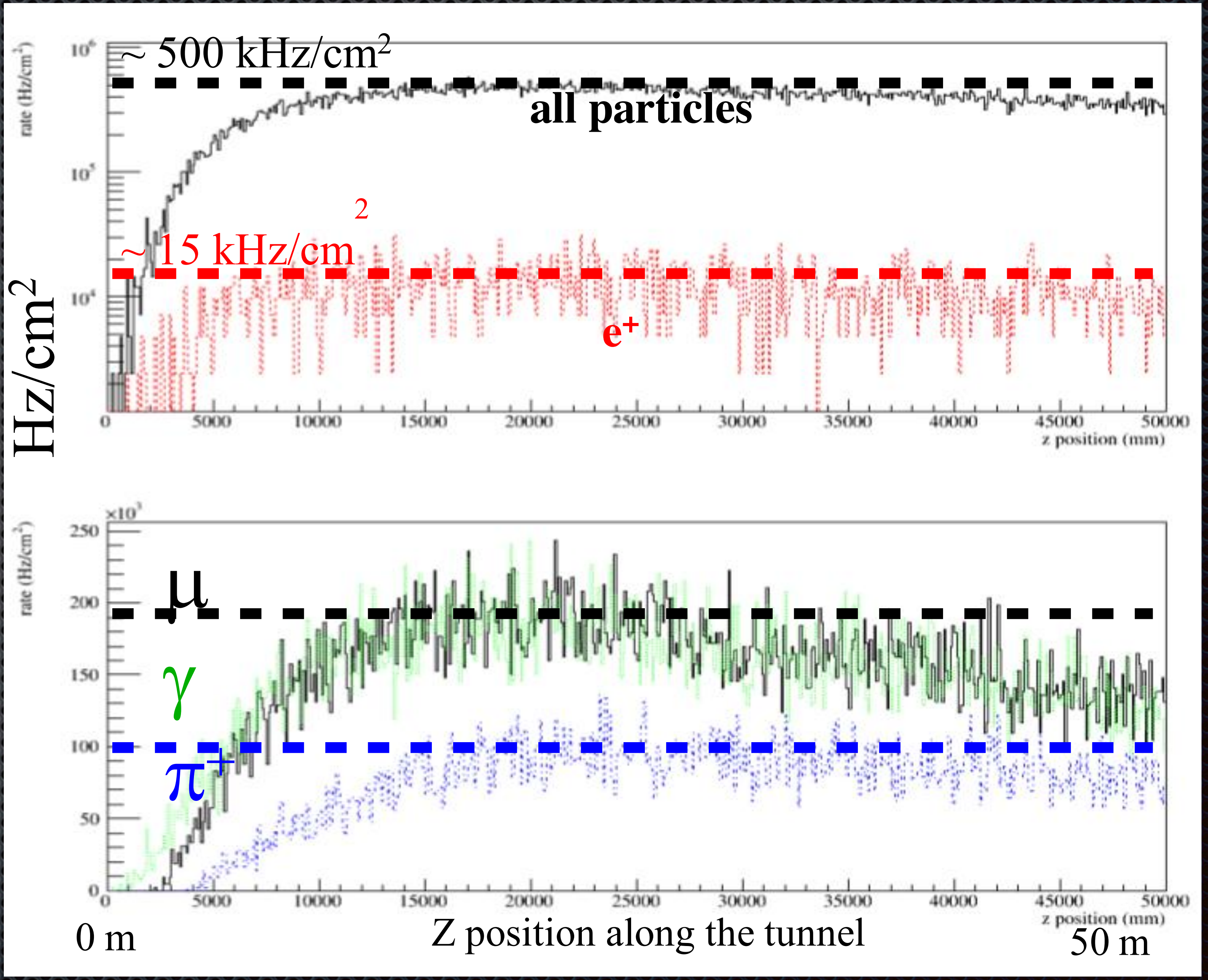
- The photon veto, or "t_0 layer", has to be instrumented in the decay tunnel and it will be used as a trigger and as a veto for gammas from π^0 decays.
- Each unit is made of a doublet of plastic scintillator tiles (3 cm x 3 cm and a thickness of 0.5 cm) separated by 0.5 cm, each one readout by a WLS fiber coupled to a SiPM.
- The distance of 7 cm between consecutive doublets was chosen to have at least one doublet hit by any particle entering the calorimeter considering that all particles generated by Kaons have an angle smaller than 400 mrad.
- A positron is defined as a m.i.p. signal in each layer of the doublet, allowing also for a rejection of photons converting into $e^+ e^-$ in the first tile t_0 layer.



Rates

- If we ask for **10^{10} π^+ in a 2 ms spill** at the entrance of the decay tunnels, the rates are well below 1MHz/cm^2 and therefore **acceptable for the proton tagger** (limit of < 1 MHz/cm^2 set by the pile-up constraint discussed later).

Particle	Max Rate (kHz/cm^2)
μ^+	190
γ	190
π^+	100
e^+	20
All	500



Rates (2)

The expected rates do not represent a problem both in term of pile-up and radiation.

Pile-up

- The pile-up comes mostly from the overlap of a muon from $K^+ \rightarrow \mu^+ \nu_\mu$ with a candidate positron.
- Considering:
  - Recovery time $\Delta t = 10$ ns
  - Rate R = 0.5 MHz/cm^2
  - Tile surface S = O(10 cm^2)

  → **5% pile-up probability (=RSΔt)**
- The obtained pile-up is sustainable. A further reduction could be done vetoing offline m.i.p. like and punch-through particles.

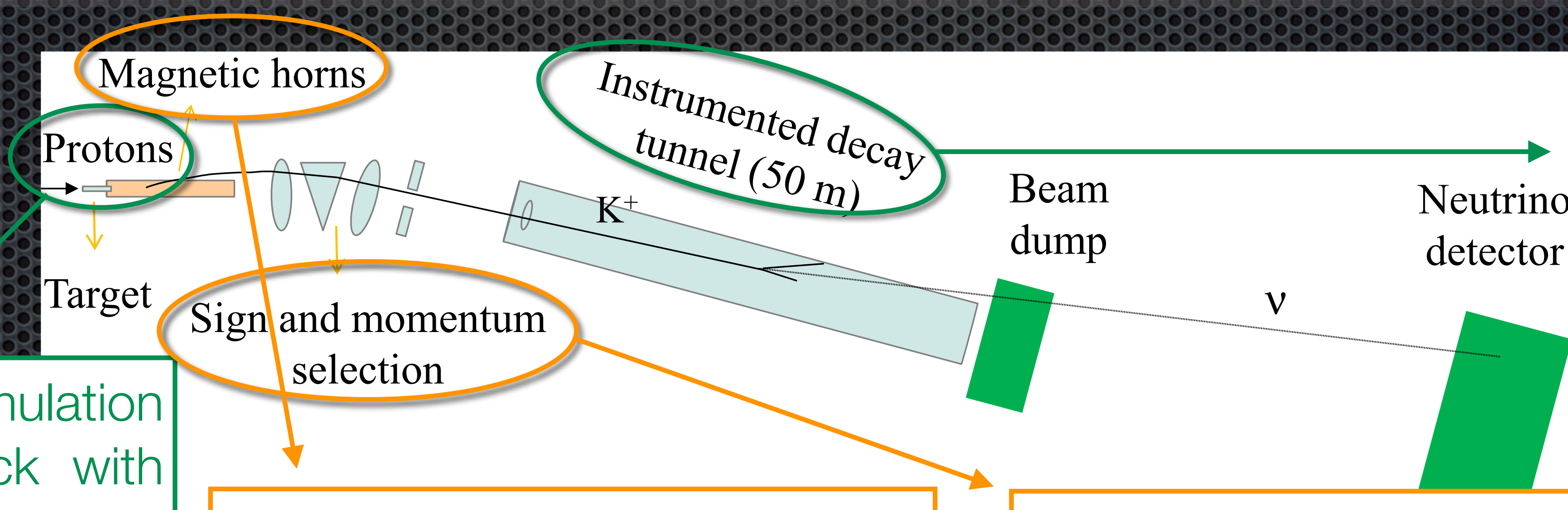
Radiation (doses)

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

Beamline

- The beam line has to match the positron tagger specifics:

	Proton extraction	Sign selection	Focusing and transfer line
Specifics	1-10 ms (or slower)	Needed before the decay tunnel	Emittance of 0.15 mm rad are well matched with horn acceptance
Reason	To ensure low pile-up with a local rate of < MHz/cm^2	The proposed tagger does not measure the charge	The beam has to be contained in the 40 cm radius hollow cylinder decay tunnel



Full GEANT4 simulation at hit level (done) and digitization level (on-going)

FLUKA2011 simulation and cross check with hadro-production data

Not fully simulated. Assuming 85% efficiency for secondaries in the ellipse $\varepsilon_{xx'} = \varepsilon_{yy'} = 0.15$ mm rad

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

Beamline (2)

- Using the actual simulations and keeping as a constraint the **10^{10} π^+ per spill** (2 ms spill), the beam characteristics were computed.
- In addition, assuming **500 ton neutrino detector at 100 m from the tunnel entrance**, we computed the number of PoT needed to observe 10^4 ν_e CC i.e. to have a 1% statistical uncertainty on the cross section.

Eur.Phys.J. C75 (2015) 4, 155
Pion and kaon yields for horn focusing at (8.5±1.7) GeV/c.

	E_p (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

The number of protons per spill is low
↓
The number of extractions is high (order of 2 x 10^8)
↓
Assuming about 200 days per year and 2 years data taking gives ~ 5 Hz extraction rate

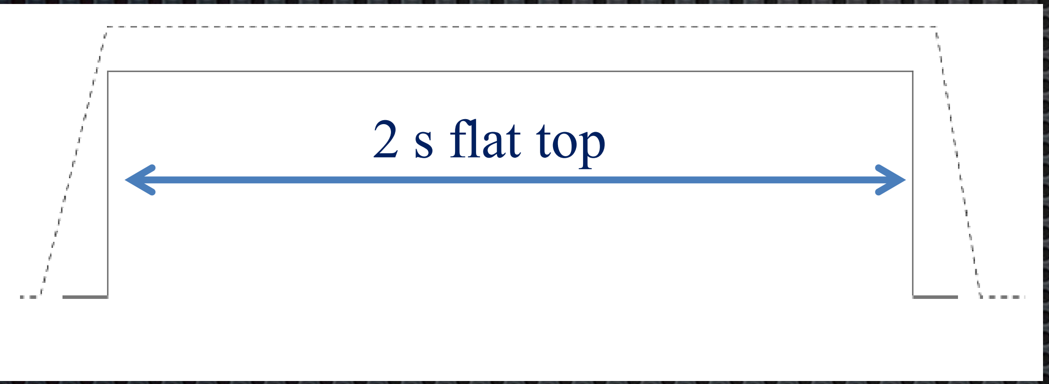
Number of integrated PoT well within reach of JPARC, Main Ring and CERN SPS

Beamline (3)

- Although the total number of PoT is not a constraint in terms of accelerators, the slow extraction mode has to be proven compatible with high energy accelerators.
- Taking the CERN SPS an example we have two possible options.

400 -450 GeV protons
4.5×10^{13} protons per super-cycle
A super-cycle every 15 s with a 2 s flat top

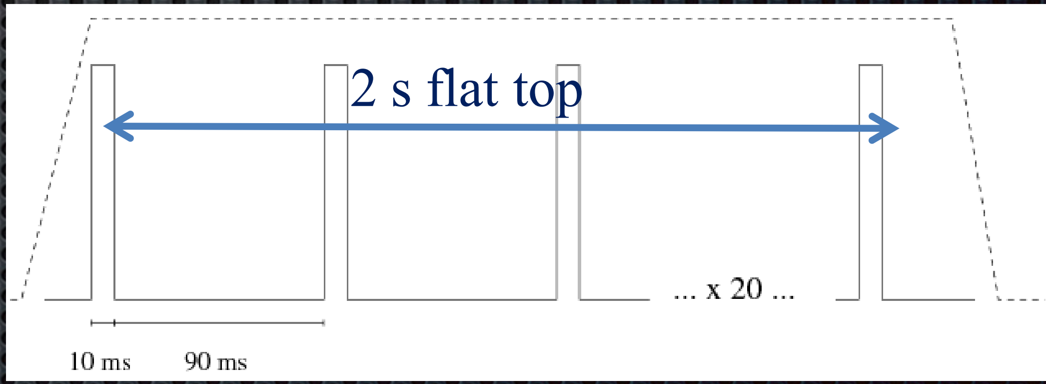
Slow Resonant Extraction



Static focusing system

Under development for the SHIP R&D

Multiple Slow Resonant Extraction

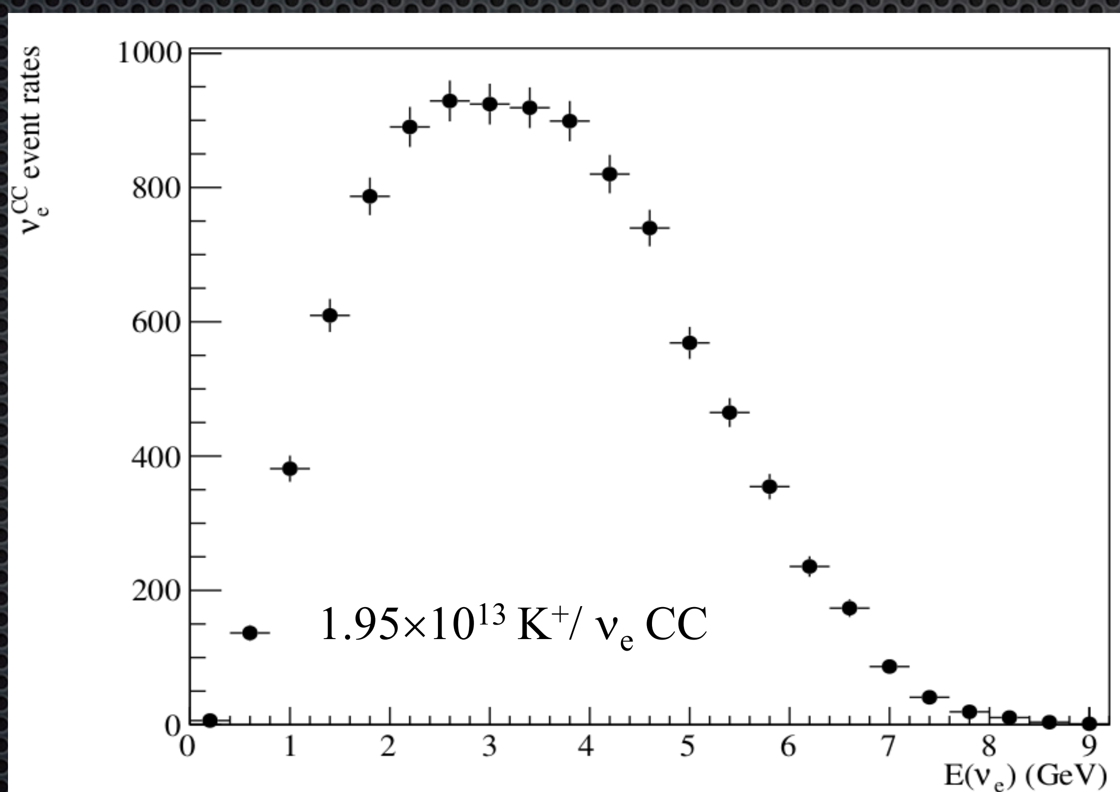


Horn based focusing system

To be tested

Neutrinos

- The neutrino spectrum was computed assuming:
  - The CERN-SPS as a proton source
  - A multiple SRE
  - A 500 ton (isoscalar) target at 100 m from the beginning of the decay tunnel
  - A data taking of 1.5 years in order to have 10^4 ν_e CC



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

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

systematics

- The positron tagging eliminates the most important source of systematics but **can we get to 1%?** **Not fully demonstrated yet but very likely…**

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

What's next?

We want to build a full module to be tested at CERN on charged particles beams (e^-, π^-, π^+) to validate the simulations in particular addressing the following items.

- Measurement of the energy resolution of e^- and hadrons between 1—5 GeV and study the e^+/π^+ separation with a detailed characterization of the lateral leakage.
- Determine the maximum acceptable particle rate without compromising the identification performance.
- Characterize the tagger response in order to maintain the flux systematics below 1%.
- Optimize the granularity to reach the best price-performance ratio (e.g. size of SiPM and their readout grouping).
- Develop a light readout system for the photon veto without increasing the material budget.
- Validate the 1 m.i.p. versus 2 m.i.p. separation capability of the photon veto and study the background induced by lateral leakage from the calorimeter.

Status and conclusions

- The precise knowledge of neutrino cross section is a key element for future generation neutrino experiments aiming at the CP violation measurement.
- The intrinsic limit on the ν cross section (flux uncertainty) can be **reduced by one order of magnitude exploiting the $K^+ \rightarrow \pi^0 e^+ \nu_e$ channel (K_{e3})**.
- We proposed a **positron monitored source based on existing beam and detector technologies to reach a 1% precision on the absolute ν_e cross section** measurement with a neutrino detector of moderate mass (500 tons).
- Full beam line and detector simulation are almost finished and optimization of the selection algorithms is ongoing.
- First tests at CERN on the SiPM readout were done with promising results (publication in preparation).
- An EoI is in preparation.
- The next step, thanks to the support of CERN at the neutrino platform, would be the construction and test of a full module (depending of fundings).

Interested People are welcome!