High precision flux measurements in conventional neutrino beams with the ENUBET ERC project

A. Longhin (INFN-PD)
for the ENUBET Collaboration

NOW
Otranto 9/9/2016
Outline

• The problem of **flux uncertainty** in conventional beams
• Monitored beams
• ENUBET: challenges, goals and recent **achievements**
• Forthcoming activities and **conclusions**

- A. Berra et al., NIM A824 (2016) 693
- A. Berra et al., NIM A830 (2016) 345
Tackling the flux uncertainty problem

Last 10 years: knowledge of $\sigma(\nu_\mu)$ improved enormously (SCIBooNE, MiniBooNE, T2K, MINERvA)

Still:

- No absolute measurement with $< 10\%$ error.
- Main contribution: the **flux systematics “wall”**

- **Mitigations** and flux constraints already in place:
  
  - hadro-production experiments SPY, HARP, NA61
  - interactions on electrons (but small rates and only @ high-E)

- In particular for $\sigma(\nu_e)$ data are **sparse/old** (Gargamelle, T2K, NOvA) being based on the beam contamination (no intense/pure sources of GeV $\nu_e$).

- Ideal (but difficult) solution: D.I.F. of stored $\mu$ as in nuSTORM/nuPIL

- $\sigma(\nu_e)$ precious for CPV!

- “derivation” from $\sigma(\nu_\mu)$ “delicate” especially @ low-E (sub-GeV)
Impact of precision on $\sigma(\nu_e)$

The systematic uncertainty should be controlled to < 1-2% to minimize the impact on the CPV discovery sensitivity. Probe smaller and smaller values of $\sin \delta_{\text{CP}}$.

Exotic: sterile neutrinos, non-standard interactions and 3$\nu$ have a similar phenomenology →

a precise knowledge of $\sigma(\nu_e)$ vs $E$ is needed to get a deeper insight of the underlying physics.

De Gouvea et al., 1605.0937

Monitored beam: build a neutrino source employing conventional technologies reaching a precision on the initial flux < 1%
Monitored beams

- The idea behind existing $\mu$/hadron monitors is extended to the ultimate step of monitoring (~ inclusively) the decays in which $\nu$ are produced.
- Uncertainties from hadro-production, PoT, hadron beam-line efficiency (happening “before” the tagging) are “by-passed” by the tagging.

Traditional beam

- Passive decay region
- $\nu_e$ flux relies on ab-initio simulations of the full chain
- large uncertainties from hadro-production

Monitored beam

- Fully instrumented decay region
- $K^+ \rightarrow e^+ \nu_e \pi^0 \rightarrow$ large angle $e^+
- $\nu_e$ flux prediction = $e^+$ counting
Working principle and setup

- **1) Hadron beam-line**: $q$-selection, focusing, transfer of $\pi/K^+$ to a **50 m long** instrumented decay tunnel ($e^+$ tagger)
- **2) $e^+$ tagger**: real-time, "inclusive" **monitoring** of decay products

- Profiting of “kinematics” and a **good focusing** (important!) we can have: **only K decay products** (at large angles) being measured with $\pi^+$ and $\mu$ decaying at small angles and reaching the dump **without hitting the instrumented walls**.
- This allows:
  - **tolerable rates and irradiation** ($< 500 \text{ kHz/cm}^2$, $\sim 1.3 \text{ kGy}$)
  - full/continuous **control of all produced $\nu_e$**
    - contribution of $\nu_e$ from $\mu$ decays is $< 2\%$ using a “short” decay tunnel
  - **control of $\nu_\mu$ from K** (can be separated from $\pi$-$\nu_\mu$ using their radial distribution)
Decay kinematics and tagger acceptance

- **Baseline design:**
  \( p = 8.5 \text{ GeV/c} \pm 20\% \), \( \theta < 3 \text{ mrad} \)
  over \( 10 \times 10 \text{ cm}^2 \), \( L = 50 \text{ m} \)
  → **trade-off** to get \( E_\nu \) in R.O.I, few
  \( \nu_e \) from \( \mu \) decays, limited \( K \) loss in
  the beam-line, good \( e/\pi \) separation, reduced costs.

- **Good acceptance for \( K \) decays thanks to the large
  emission angle (~ \( m_K \))

- **Golden channel** for \( \nu_e : K^+ \rightarrow e^+\nu_e\pi^0 \) (\( K_{e3} \), BR ~ 5%)

Radial energy deposition (all decay modes)

Angular distribution of emitted
positrons from \( K_{e3} \)
Role of other K decays

- **Hadronic K decays** (~ overall rate) can be also used to infer the $\nu_e$ flux correcting for the ratio of leptonic and hadronic **branching ratios** (can be considered a “silver sample”)

- **On the other hand** $\pi^{+/0}$ from $K^+$ can mimic an $e^+$ and “pollute” the $K_{e3}$ golden sample → possible to **discriminate** with:
  - **1)** calorimetric **longitudinal profile** of energy deposition
  - **2)** tagging vertices by **timing**:

  \[ \sigma_t O(100 \text{ ps}) \sim \sigma_{z_{\text{VTX}}} O(1\text{m}) \]
  
  veto fake $e^+$ from $K^+ \rightarrow \pi^+\pi\pi^+$ and $K^+ \rightarrow \pi^+\pi^0$ reconstructed vertices
The $e^+$ tagger challenges

Injecting $10^{10} \pi^+$ in a 2 ms spill →

![Graph showing particle rates](image)

The decay tunnel: a harsh environment
- particle rates: > 200 kHz/cm²
- backgrounds: pions from K⁺ decays
  
  Require to veto 98-99 % of them

Moreover:
- extended source of ~ 50 m
- grazing incidence
- significant spread in the initial direction

![Histogram of particles](image)

<table>
<thead>
<tr>
<th>Max rate (kHz/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+$</td>
</tr>
<tr>
<td>$\gamma$</td>
</tr>
<tr>
<td>$\pi^+$</td>
</tr>
<tr>
<td>$e^+$</td>
</tr>
<tr>
<td>all</td>
</tr>
</tbody>
</table>
Hadron beam-line: scenario A

- \(t_{\text{impulse}} < 10 \text{ ms} \) (Joule heating, \(I \sim O(100) \text{ kA}\))
- **tagger rate limit** is hit injecting \(10^{10} \pi^+ \) in 2 ms
- Considering typical horn collection efficiencies this corresponds to \(0.3-2.5 \times 10^{12} \text{ PoT/spill}\) depending on \(E_p\) (spills with relatively “few” protons)
- Considering we need \(1.94 \times 10^{13} \text{ K}^+\) for \(\nu_e^{\text{CC}}\) with a 500 t \(\nu\) detector at \(100 \text{ m}\) asking for \(10^4 \nu_e^{\text{CC}}\) implies:
  - \(0.5-5 \times 10^{20} \text{ PoT}\) Well within present performances! A few years of run.
  - \(\sim 2 \times 10^8\) spills. More challenging/unconventional. A possible scheme is
    - multi-Hz slow resonant extraction + multi Hz-horn
    - R&D and machine studies are planned

A possible structure at the SPS:
a train of twenty 10 ms long spills with \(1.2 \times 10^{12}\) protons each spanning 2 s of the flat top (=50% SPS emptying).
Hadron beam-line: scenario B

- **Static focusing:** large aperture radiation-hard quadrupoles.
- Disadvantage: loss of acceptance w.r.t. horn-based focusing.
- PoT to get $10^4 \nu_e^{CC}: 0.5-7 \times 10^{21} \ O(\sim 10 \times)$ more but still feasible. Can be compensated by (data taking $\times$ detector mass)
- Far from tagger maximal rates
- **R&D on static focusing beam-line** to maximize the collection efficiency ($\sim$ increase “useful” hadrons/PoT).
- the single resonant slow extraction over O(s) times is less challenging than the multi-Hz version. Synergies with the needs of SHiP proposal at CERN.

SHiP: arXiv:1504.04956
Going beyond: "time tagged" beams

- Event time dilution → Time-tagging
- Associating a single $\nu$ interaction to a tagged $e^+$ with a small “accidental coincidence” probability through time coincidences
- $E_\nu$ and flavor of the neutrino know "a priori" event by event.

Superior purity. Combine $E_\nu$ from decay with the one deduced from the interaction.

**Time coincidence of**

\[ \nu_e^{\text{CC}} \text{ and } e^+ \quad |\delta t - \Delta/c| < \delta \]

\[ \delta = \text{combined t-resolution (}e^+\text{ tagger and }\nu\text{ detector)} \]

**Accidental tag probability using** $10^{10}$ hadrons/burst:

\[ A \sim 2 \times 10^7 \frac{\delta}{T_{\text{extr}}} \]

$$T_{\text{extr}} = 1\text{s} \quad (\sim 1 \text{ observed } e^+ / 30 \text{ ns}) + \delta = 1\text{ ns} \quad \rightarrow \quad A = 2\% \quad \text{OK!}$$

Using such long extractions prevents* using $O(\text{ms})$ pulsed focusing devices (horns, scenario A) but could be feasible with a static based focusing with DC elements (quadrupole triplets, bending magnets, scenario B)

*$$T_{\text{extr}} = 2\text{ ms} \quad (1 \text{ } e^+ / 70 \text{ ps}) \text{ even } \delta = 50 \text{ ps gives } A = 50\%.$$
**ν detector and ν\textsubscript{e} CC rates**

- At 100 m from the hadron window
- A 500 t mass (e.g. ICARUS@Fermilab, Protodune SP/DP @CERN)
- Interesting region of long baseline future projects is covered
- Further tuning foreseen to go even lower in energy preserving an acceptable positron purity

- **tagger geometrical acceptance:**
  - 85% of ν\textsubscript{e} CC with a tagged e\textsuperscript{+} (15 % in the forward "hole")
  - 1.95 × 10\textsuperscript{13} K\textsuperscript{+}/ν\textsubscript{e} CC
- Radial profiles at the ν detector

\[<E> = 3 \text{ GeV}, \text{FWHM} \sim 3.5 \text{ GeV}\]
The ENUBET technology is well suited for short baseline experiment where the intensity requirement are less stringent. Major applications include:

• A new generation of cross section experiments operating with a ν source controlled at the < 1% level. A unique tool for precision oscillation physics and a new opportunity for the cross-section community

• A phase II sterile neutrino search, especially in case of positive signal from the Fermilab SBL program/reactor experiments

• The first step towards a time-tagged ν beam

NB. $\sigma(\bar{\nu}_e)$ is a “green field”
The ENUBET roadmap

- Construction of a **3 m section of the instrumented decay tunnel** (tagger prototype)
- **Test beams** at CERN-PS T9 and INFN-LNF
- Assessment of **systematics with a full simulation** supported by test beam results
- **Design of the beam-line** for collection/transport/focusing of hadrons in the tagger
- Design and test of suitable **proton extraction schemes** (CERN-SPS)

---

Tagger prototype

---

Tagger simulation example (FLUKA)

---

SPS resonant slow extraction

---

PS-T9 test beam (2015)

---

Beamline design early studies

---

(G4beamline)

→ The complete picture to move forward to a full scale experiment

**By-products** in calorimetry (new low-cost, ultra-compact detectors) and accelerator physics (novel extraction schemes for fixed-target, beam-dump experiments)
The ENUBET roadmap (contd.)

Proving a tagged neutrino beam for cross-sections is ENUBET's primary goal ("monitored beam"). Test beam activities based at the CERN-PS East area.

In the last phase of the project time synchronization could be tested at the EHN1 CERN neutrino platform:

with beam halo $\mu$ and low-angle cosmic rays

ENUBET tagger prototype $\leftrightarrow$ LAr (WA105, proto-DUNE w. scint. light)
Small scale WCh prototypes
Tagger current design

Conventional beam-pipe replaced by active instrumentation →

1) Calorimeter ("shashlik") → $\pi^+$ rejection
   - Ultra-Compact Module (UCM)

2) Integrated $\gamma$-veto → $\pi^0$ rejection
   - plastic scintillators or
   - large-area fast avalanche photodiodes
   - other fast detectors options

Detector R&D activities
Full simulation: e/π separation

GEANT4 simulation.
Reject simultaneously $\pi^+$ and $\pi^0$

Takes into account pile-up related restrictions in the event building.

TMVA multivariate analysis:
- E released in calorimeter
- E in photon-veto doublets (3 layers).
- $\Delta Z$ between inner e.m. layer peak and the 1st photon-veto doublet.
- N. photon veto doublets upstream of the inner e.m. layer peak

<table>
<thead>
<tr>
<th></th>
<th>$\varepsilon_{\text{geom}}$</th>
<th>$\varepsilon_{\text{sel}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+$</td>
<td>90.7 %</td>
<td>49.0 %</td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>85.7 %</td>
<td>2.9 %</td>
</tr>
<tr>
<td>$\pi^0$</td>
<td>95.1 %</td>
<td>1.2 %</td>
</tr>
</tbody>
</table>

Former estimates from parametrizations confirmed with a realistic and cost-effective setup.
The Ultra Compact Module

spring 2016 prototypes

9 SiPM signals are added to reduce R/O costs

1 Si-PM
1 WLS
Tagger detector R&D: SCENTTT
Shashlik Calorimeters for Electron Neutrino Tagging and Tracing

- INFN (CSN5) activity on shashlik calorimetry for neutrino applications started last year (MiB-Insubria, TS, BO, LNF. R.N. F. Terranova)
- First tests at CERN PS-T9 (Aug. 2015) of a shashlik calorimeter with WLS fibers coupled directly to individual SiPMs

- Working well!
- Energy resolution and $e/\pi$ separation in line with simulations
- achieved both with custom QDC electronics or sampling waveforms with commercial digitizers

A compact light readout system for longitudinally segmented shashlik calorimeters

A. Berra$^{a,b,*}$, C. Brizzolari$^{a,b}$, S. Cecchini$^c$, F. Cindolo$^c$, C. Jollet$^d$, A. Longhin$^e$, L. Ludovici$^f$, G. Mandrioli$^g$, N. Mauri$^c$, A. Meregaglia$^d$, A. Paolini$^c$, L. Pasqualini$^{c,g}$, L. Patrizii$^c$, M. Pozzato$^c$, F. Pupilli$^c$, M. Prest$^{a,b}$, G. Sirri$^{c}$, F. Terranova$^{b,h}$, E. Vallazza$^i$, L. Votano$^c$

A. Berra et al., NIM A824 (2016) 693
A. Berra et al., NIM A830 (2016) 345

http://dx.doi.org/10.1016/j.nima.2016.05.123 arXiv:1605:09630
First test beam validation of UCM

CERN-PS T9 test beam (July 2016). 12 ENUBET UCM modules (12 $X_0$) exposed to pions and electrons from 1-5 GeV. HD Si-PM with 20 μm cell size.

No dead zones, uniform long. sampling
Results from UCM prototypes

Cheap, fast (<10 ns), Rad-hard technological solution

Requirements for ENUBET:

- m.i.p. sensitivity w/o saturation for e.m. showers up to 4 GeV **DONE**
- E resolution < 25% / $E^{1/2}$ **DONE**
- No role for “nuclear counter” effects (direct ionization of SiPM in the e.m. shower) **DONE**
- recovery time ~10 ns (sufficient to cope with pile-up) → **NOV 2016**
- validation of MC for e/π separation → **NOV 2016**
Next test beam at CERN-PS T9

- Sufficient length and presence of outer modules (hadron catcher) allows for e/π validation thanks to hadronic containment (56+18 UCM, 666 SiPM)
- Orientable cradle to study the effect of grazing incidence.
- Test final readout with prototype custom fast digitizers
- Starting 2 November 2016
Conclusions

● The precision era of neutrino oscillation physics requires better control of its artificial sources. At the GeV scale the limited knowledge on the initial flux is the dominant contribution to cross section uncertainties.

● Such limit can be reduced by one order of magnitude exploiting $K^+ \rightarrow \pi^0 e^+ \nu_e$.

● In the next 5 years ENUBET will investigate this approach and its application to a new generation of cross section, sterile and time tagged neutrino experiments.

The results obtained in 2015-2016 are very promising:

● Full simulation of the decay tunnel supports the effectiveness of the calorimetric approach for large angle lepton identification.

● First prototypes demonstrate that shashlik calorimeters with longitudinal segmentation can be built without compromising energy resolution (19% at 1 GeV) and provide the requested performance.

The final goal of the ENUBET Collaboration is to demonstrate that:

● a “positron monitored” $\nu_e$ source based on $K_{e3}$ can be constructed using existing beam technologies and can be implemented at CERN, Fermilab or JPARC.

● a 1% measurement of the absolute $\nu_e$ cross section can be achieved with detector of moderate mass (500 ton).
ENUBET

Enhanced NeUtrino BEams from kaon Tagging

ENUBET is a project approved by the European Research Council (ERC) for a 5 years (06/2016 – 06/2021) with an overall budget of 2 MEUR

ERC-Consolidator Grant-2015, n° 681647 (PE2)
P.I.: A. Longhin
Host Institution: INFN

Collaboration (as for Sep. 2016):
~ 40 physicists from 10 institutions: INFN, CERN, IN2P3, Univ. of Bologna, Insubria, MI-Bicocca, Napoli, Padova, Roma, Strasbourg

Expression of Interest planned for submission to CERN-SPSC this autumn. Allow official commitment of CERN collaborators, support for beam test campaigns. Visibility. Possibility for CERN NP.

Available upon request for interested colleagues.

• Kick-off meeting in Padova, 23-24 June 2016
  https://agenda.infn.it/conferenceDisplay.py?confId=11574
Thank you!
The photon-veto baseline option

Background from $\gamma$ conversions from $\pi^0$ emitted mainly in $K_{e2}$ decays ($K^+ \rightarrow \pi^+ \pi^0$)

All particles will intercept at least one doublet
A positron on average will cross 5 doublets

Exploit 1 mip – 2 mip separation

- Possible alternative/attractive solutions under scrutiny allowing a reduced material budget and superior timing.
- Test beams at Frascati: electronics response at high rates and low-$E_e e^+, 1$ mip/2 mip
The final prototype

- Dimensions: $3 \text{ m} \times \pi$
- # SiPM: 34000
- Channels: 3800
- Weight: $\sim 5 \text{ t}$
- WLS fiber length: $\sim 10000 \text{ m}$
- **Readout:** custom waveform digitizers, 2 ns granularity over $\sim 10 \text{ ms}$
Pion decays induced backgrounds

- $\pi^+ \rightarrow \mu^+ \nu_\mu$ creates the bulk of $\nu_\mu$ ($\sim 95\% \pi @ 400\text{ GeV}$)
- $\nu$ detector must have good $\nu_e$ PID: reject NC $\pi^0$ in the $\nu_e^{CC}$ sample
- 2-body decay, $m_\mu \sim m_\pi$: $\mu^+ \sim 4\text{ mrad} \rightarrow$ few in the tagger, easy to reject
- $\mu$ D.I.F: suppressed $L_\mu >> L$(decay tunnel)
- 3-body but $m_\mu \sim 0.2 \cdot m_K \rightarrow e^+_{DIF} \sim 28\text{ mrad}$ ($e^+_Ke3 \sim 88\text{ mrad}$)
  - $\nu_e^{CC,DIF} \sim 3.3\% \rightarrow \sim$ all $\nu_e$ are from $K_{e3}$
    $$\frac{\Phi_{\nu_e}}{\Phi_{\nu_\mu}} = 1.8\% \ (\nu_e \text{ from } K_{e3})$$

\[\text{Diagram of pion decay processes with tagged particles.}\]
\( \sigma(\nu_e) \) from \( \sigma(\nu_\mu) \) ?

0) \( \sigma(\nu_\mu) \) is also poorly known due to flux systematics

1) Lepton universality in weak interactions is not the full story:

- Uncertainties from the interplay of
  - radiative corrections
  - nucleon form factors
    - \( F_p, F_V^{1,2}, F_A \), second class currents
  - alteration of kinematics due to mass

→ Differences between \( \sigma(\nu_\mu) \) and \( \sigma(\nu_e) \) (\( \Delta, \delta \))

- can be significant (10-20%) espec. at low-E
- with different energy trends for \( \nu \) and \( \bar{\nu} \)

---


---

![Graphs showing differences in \( \sigma(\nu_\mu) \) and \( \sigma(\nu_e) \)]
Working packages

WP1: beam-line
Precise layout of the hadron beam. Study of the injection schemes.

WP2: tagger prototype
Feasibility of tagging under realistic conditions with the desired background and systematics suppression. Radiation hardness.

WP3: electronics and readout
testing the readout performances of the front-end electronics for horn-based (< 10 ms proton extraction) or static (1s proton extraction) focusing systems.

WP4: photon veto and timing system
validating the timing accuracy of the tagger and the photon veto $e^+/\pi^0$ separation. Vertex reconstruction inside the tunnel. Pave the way to “tagged neutrino beams” (time synchronization studies with existing LAr or water Cherenkov prototypes).

WP5: systematic assessment. Overall flux systematics reachable by the exploiting the $e^+$ rate and the impact on a direct measurement of the $\sigma(\nu_e^{CC})$. Tagger simulation.
Choosing the $K^\pm/\pi^\pm$ momentum and tunnel length

1) keeping the tunnel "short"
2) increasing the $K^\pm/\pi^\pm$ energy

increases $\nu_e$ from $K_{e3}$ with few $\nu_e$ from $\mu$ D.I.F.

High momentum

Benefits:
- small loss in the transport line
- improved $e/\pi$ separation

Costs:
- $E(\nu_e)$ above the R.O.I.
- longer decay region

A trade-off: further optimization in ENUBET

Current scenario
- $p = 8.5$ GeV/c ± 20%
- $L = 50$ m
e\(^+\) tagger: background rejection

Key point:
- longitudinal sampling
- perfect homogeneity $\rightarrow$ integrated light-readout

Hadronic modules
Electro-magnetic modules
Hit modules

- e\(^+\) (signal) topology
- \(\pi^0\) (background) topology
- \(\pi^+\) (background) topology
Towards the first tagged $\nu_e$ beam

A schematic setup to implement this idea:

- **Hadron beam-line**: collects, focuses, transports $K^+$ to the $e^+$ tagger
- **$e^+$ tagger**: real-time, "inclusive" **monitoring** of produced $e^+$

**Positron tagging**: uncertainties from $K$ hadro-production, PoT, hadron beam-line efficiency become irrelevant for the $\nu_e$ flux prediction

**Hadron collimation**: allows having only decay products in the tagger.

- tolerable rates
- good S/N

$p = 8.5$ GeV $\pm 20\%$
$\theta < 3$ mrad
Demonstrate experimentally that a new-concept $\nu_e$ source, with $\times 10$ better precision is feasible

$\sigma(\nu_e)$ 1% sys. + 1% overall stat. errors (10,000 events) in realistic terms

What's peculiar with ENUBET:

- a compelling, new physics case: a beam design optimized for $\sigma(\nu_e)$
- taking advantage of the progress in fast, cheap, radiation-hard detectors

ERC program: 2 pillars

- $e^+$ tagger prototype validated at test beams
- a detailed design for the hadron beam-line

The complete picture to move to a full experiment

By-products

- calorimetry $\rightarrow$ new low-cost, ultra-compact detectors
- accelerator physics $\rightarrow$ novel extraction schemes for fixed-target, beam-dump exp.
The golden channel: $K^+ \rightarrow \pi^0\ e^+\ \nu_e$

- **Golden sample**: good acceptance for $e^+$ from $K_{e3}$ thanks to the large emission angle ($\sim$ K mass)
- $L_\mu \gg L$(decay tunnel) $\nu_e$, CC,DIF $\sim 3.3\%$ 
  $\Rightarrow \sim$ all $\nu_e$ are from $K_{e3}$

Angular distribution of $e^+$ from $K_{e3}$
Hadron beamline with horn focusing

<table>
<thead>
<tr>
<th>E (GeV)</th>
<th>$\pi^+$/PoT ($10^{-3}$)</th>
<th>$K^+$/PoT ($10^{-3}$)</th>
<th>PoT for a $10^{10}$ $\pi^+$ spill ($10^{12}$)</th>
<th>PoT for $10^4 \nu_e$ CC ($10^{20}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>4.0</td>
<td>0.39</td>
<td>2.5</td>
<td>5.0</td>
</tr>
<tr>
<td>50</td>
<td>9.0</td>
<td>0.84</td>
<td>1.1</td>
<td>2.4</td>
</tr>
<tr>
<td>60</td>
<td>10.6</td>
<td>0.97</td>
<td>0.94</td>
<td>2.0</td>
</tr>
<tr>
<td>70</td>
<td>12.0</td>
<td>1.10</td>
<td>0.83</td>
<td>1.76</td>
</tr>
<tr>
<td>120</td>
<td>16.6</td>
<td>1.69</td>
<td>0.60</td>
<td>1.16</td>
</tr>
<tr>
<td>450</td>
<td>33.5</td>
<td>3.73</td>
<td>0.30</td>
<td>0.52</td>
</tr>
</tbody>
</table>

* J-PARC $> 1.5 \times 10^{21}$ PoT
CNGS $= 1.8 \times 10^{20}$ PoT
NuMI $= 1.1 \times 10^{21}$ PoT
Tagged neutrino beams: the origins

The "forbidden dream" of neutrino physicists:

- L. Hand, 1969, V. Kaftanov, 1979 ($\pi/K \rightarrow \nu_{\mu}$)
- G. Vestergombi, 1980, R. Bernstein, 1989 ($K \rightarrow \nu_e$)
- S. Denisov, 1981, R. Bernstein, 1989 ($K_{e3}$)


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 ($\pi \rightarrow \mu \nu$, $K \rightarrow \mu \nu$).

Literature:
- L. Ludovici, P. Zucchelli, hep-ex/9701007 ($K_{e3}$)
- L. Ludovici, F. Terranova, EPJC 69 (2010) 331 ($K_{e3}$)

What's new with ENUBET:
- a compelling and new physics case: a beam design optimized for $\sigma(\nu_e$)
- taking advantage of the progress in fast, cheap, radiation-hard detectors
- using $K^+ \rightarrow e^+ \pi^0 \nu_e$ ($K_{e3}$ decays)
# Systematics on the $\nu_e$ flux

The positron tagging eliminates the most important source of systematics but can we get to 1%? Very likely, to be demonstrated by ENUBET

<table>
<thead>
<tr>
<th>Sources</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical error</td>
<td>&lt; 1 %</td>
</tr>
<tr>
<td>K production yield</td>
<td>Irrelevant (e$^+$ tag)</td>
</tr>
<tr>
<td>Secondary transport efficiency</td>
<td>Irrelevant (e$^+$ tag)</td>
</tr>
<tr>
<td>Integrated PoT</td>
<td>Irrelevant (e$^+$ tag)</td>
</tr>
<tr>
<td>Geometrical efficiency and fiducial mass</td>
<td>&lt; 0.5%. <em>PRL 108 (2012) 171803</em> [Daya Bay]</td>
</tr>
<tr>
<td>3-body kinematics and mass</td>
<td>&lt; 0.1%. <em>Chin. Phys. C38 (2014) 090001</em> [PDG]</td>
</tr>
<tr>
<td>Branching ratios</td>
<td>&lt; 0.1%. Irrelevant (e$^+$ tag) except for bckg. estim.</td>
</tr>
<tr>
<td>e/$\pi$ separation</td>
<td>To be checked directly at test beam</td>
</tr>
<tr>
<td>Detector backg. From NC $\pi^0$ events</td>
<td>&lt; 1%. <em>EPJ C73 (2013) 2345</em> [ICARUS]</td>
</tr>
<tr>
<td>Detector efficiency</td>
<td>&lt; 1%. Irrelevant for CPV if the target is the same as for the long baseline experiment</td>
</tr>
</tbody>
</table>
e⁺ tagger: pile-up and radiation

Pile-up
Not decayed π, K do not intercept the tagger “by construction”. Pile-up mostly from overlap between a Kµ2 and a candidate e⁺

\[
\text{Recovery time, } \Delta t_{\text{tag}} = 10 \text{ ns}
\]
\[
\text{Rate, } R = 0.5 \text{ MHz/cm}^2
\]
\[
\text{Tile surface, } S \sim 10 \text{ cm}^2
\]
→ 5% pile-up probability (= RS\Delta t_{\text{tag}})

Possible mitigation: veto (also offline) mip-like and punch-through particles using the longitudinal segmentation of the tagger + eventually a µ catcher

Radiation
Only contribution comes from K/π decay products. Thanks to bending of the secondaries, non-interacting protons or neutrons are not dumped in the tagger.

Livetime integrated dose < 1.3 kGy (~100 kGy for CMS forward ECAL)

Both issues not critical
The hadron beam-line challenge

At the tunnel entrance particles must be **collimated** (< 3 mrad) and **energy selected** (20% spread)

**The proton extraction must be efficient and** **“slow”** (saturation)

**Short** transport line to prevent early decays

<table>
<thead>
<tr>
<th>Focusing system</th>
<th>Proton extraction from accelerator</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A: pulsed device</strong> (magnetic horn)</td>
<td><strong>Unconventional:</strong> many ($10^8$), short (2 ms) pulses with few protons ($&lt; 3 \times 10^{11}$)</td>
</tr>
<tr>
<td><strong>B: static devices</strong> (DC magnets)</td>
<td><strong>O(1s) long slow extractions</strong></td>
</tr>
</tbody>
</table>