High precision flux measurements with ENUBET

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

Outline

- The problem of flux uncertainty → monitored beams
- Challenges, goals and recent achievements for ENUBET
- Forthcoming activities and conclusions

This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement No 681647).
Tackling the flux uncertainty problem

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

- **Flux constraints already in place:**
  - Muon/proton monitoring
  - hadro-production exp. (A. Marino, M. Hartz)
  - interactions on electrons ($10^{-4} \nu_\mu CC$)
  - Low-$\nu$ method

Still ...

- The flux syst. “wall” is “up and kicking” being typically the dominant uncertainty for cross section measurements
- No absolute measurements below ~7-10%
Tackling $\sigma(\nu_e)$

- In addition to the flux uncertainty for $\sigma(\nu_e)$ we use the **beam contamination** (no intense/pure sources of GeV $\nu_e$): data still **sparse** (Gargamelle, T2K, NOvA, MINERvA)

- $\sigma(\nu_\mu) \leftrightarrow \sigma(\nu_e)$ delicate @ low-E (M. Farland)

- Poor knowledge of $\sigma(\nu_e)$ can spoil:
  - the **CPV discovery potential**
  - the insight on the **underlying physics** (standard vs exotic)

- D.I.F. of stored $\mu$ as in nuSTORM/nuPIL is the **ideal** solution but it is **not easy**.
Monitored beams

Based on conventional technologies, aiming for a 1% precision on the $\nu_e$ flux

protons $\rightarrow (K^+, \pi^+)$ $\rightarrow$ K decays $\rightarrow$ $\nu_e$ flux prediction = $e^+$ counting

- Monitor (~ inclusively) the decays in which $\nu$ are produced
- “By-pass” hadro-production, PoT, beam-line efficiency uncertainties

Traditional

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

Monitored

- Fully instrumented
- $K^+ \rightarrow e^+ \nu_e \pi^0 \rightarrow$ large angle $e^+$
- $\nu_e$ flux prediction = $e^+$ counting
The ENUBET monitored beam

- **Hadron beam-line**: charge selection, focusing, fast transfer of $\pi^+/K^+$
- **Tagger**: real-time, "inclusive" monitoring of K decay products

- With proper hadron focusing, only K decay products are measured in the tagger being emitted at large angles (unlike pion decay products) allowing
  - a complete control of produced $\nu_e$ using $e^+$ from $K_{e3}$ (~98%). Muon decays give a small contribution thanks to the short tunnel (~50 m).
  - tolerable rates / detector irradiation

\[ p_{K,\pi} = 8.5 \pm 20\% \text{ GeV/c} \]
\[ \theta < 3 \text{ mrad over } 10 \times 10 \text{ cm}^2 \]
\[ \text{Tagger: } L = 50 \text{ m, } r = 40 \text{ cm} \]

- $< 500 \text{ kHz/cm}^2$, $O(\sim 1 \text{ kGy})$
Not only $\nu_e$!

- $\nu_e$ flux constraint
  - $K_{e3}$ (golden sample)
    - $\pi^+/\pi^0$ from $K^+$ can mimic an $e^+$
      → discriminate $e/\pi$ with:
        1) longitudinal profile of showers
        2) reconstruct vertices by timing
  - non $K_{e3}$ (silver sample): only pay additional systematics from the $K_{e3}$ B.R.

- $\nu_\mu$ flux constraint
  - $\nu_\mu$ from $K$ are well constrained from the tagger (both from hadronic and $K_{e3}$ rates)
  - This class of neutrinos can be selected at the $\nu$-detector using radius-energy correlations → high precision $\sigma(\nu_\mu)$

- $K^+ \rightarrow \mu^+\nu_\mu$ (63%)
- $K^+ \rightarrow \mu^+\nu_\mu\pi^0$ (3.2%)
- $K^+ \rightarrow n^+\pi^0$ (21%)
- $K^+ \rightarrow n^+\pi^-\pi^+$ (6%)
- $K^+ \rightarrow n^+\pi^0\pi^0$ (2%)
Hadron beam-line scenarios

- **Baseline choice:** magnetic horns focusing. $t_{\text{impulse}} < O(1-10)$ ms
- Tagger rate limit (~200 kHz/cm$^2$) with $\sim 10^{12}$ PoT/spill
  - i.e. (many) spills with relatively “few” protons are needed
- Requiring $10^4$ $\nu_e^{\text{CC}}$ in a 500 t $\nu$-detector at 100 m implies:
  - $< 10^{20}$ PoT $\rightarrow$ a fraction of a year run at present proton drivers.
  - $\sim 10^8$ spills. More challenging/unconventional.
- Solution: multi-Hz (slow resonant extraction + horn pulsing)

Possible time-structure at the CERN-SPS:

- ~ 50% SPS emptying

**Alternative choice:** static focusing devices + long extraction.

Much less efficient focusing ($\rightarrow$ more POT) but would open the intriguing opportunity of “time tagging” $\rightarrow$ $T_{\text{extr}} = 1$ s ($\sim 1$ observed $e^+$ / 30 ns) + $\delta = 1$ ns $\rightarrow$ Accidental tag = 2 %
Hadron beam-line deliverables/progress

- A realistic implementation of the beam-line/focusing layout.
- Site-independent. We are considering existing proton driver energies.
- Assess beam-related backgrounds.
- Machine studies of multi-Hz slow resonant extraction at CERN-SPS
Neutrino samples

- Need good e-tagging capabilities e.g.
  - ICARUS / \( \mu \)BooNE @ FNAL
  - proto-DUNE SP/DP @ CERN
  - Water Cherenkov (i.e. E61 @ J-PARC)
- ~500 t detector at 100 m \((\text{Ar:} 6\times6\times10 \text{ m}^3)\)

<table>
<thead>
<tr>
<th>( E_p ) (GeV)</th>
<th>POT ((10^{20})) for (10^4 \nu_e^{CC}) on-axis</th>
<th>time</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>1.03</td>
<td>~0.2 J-PARC y</td>
</tr>
<tr>
<td>120</td>
<td>0.24</td>
<td>~0.4 NuMI y</td>
</tr>
<tr>
<td>400</td>
<td>0.11</td>
<td>~0.25 CGNS y</td>
</tr>
</tbody>
</table>

- **Baseline design** better suited for DUNE.
- For HK, off-axis configurations can help at the expense of larger exposures.
- Further handles: reduce the initial hadrons momentum (in progress).
- For \( \nu_\mu \) in the HK region one can use pion sample and constrain the initial overall hadron flux with Beam Current Transformer at low intensity and use the K constraint from the tagger.
Systematics on the $\nu_e$ flux

**Positron tagging** eliminates the most important contributions. Assessing in detail the viabilities of the 1% systematics on the flux is one of the final goals of **ENUBET**. Full analysis is being setup profiting from a detailed simulation of the beamline, the tagger (WP5) and inputs from test beams.

<table>
<thead>
<tr>
<th>Sources</th>
<th>Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall statistical error</td>
<td>$&lt; 1 % \ (10000 \nu_e^{CC})$</td>
</tr>
<tr>
<td>Integrated PoT</td>
<td>Irrelevant (e$^+$ tag)</td>
</tr>
<tr>
<td>$K/\pi$ production yields in the target</td>
<td>Irrelevant (e$^+$ tag)</td>
</tr>
<tr>
<td>Secondary transport efficiency</td>
<td>Irrelevant (e$^+$ tag)</td>
</tr>
<tr>
<td>Branching ratios</td>
<td>well known + only enter enter in $\pi$ bckg estimation</td>
</tr>
<tr>
<td>3-body kinematics and mass</td>
<td>$&lt; 0.1%$. <em>Chin. Phys. C38 (2014) 090001 [PDG]</em></td>
</tr>
<tr>
<td>Uncertainty on phase space at entrance</td>
<td>can be checked with low-intensity runs</td>
</tr>
<tr>
<td>Electron/pion separation</td>
<td>being checked directly at test beams</td>
</tr>
</tbody>
</table>
Tagger technology

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

2) Integrated $\gamma$-veto
   - plastic scintillators or
   - large-area fast APDs
   - Cherenkov radiator + LAPPD
     → $\pi^0$ rejection

We aim at building/testing a scalable **demonstrator** consisting of a 3 m long section of the instrumented tunnel by 2021.
Event building, pile-up, eff., purity

- **Multivariate** analysis to select $e^+$ and reject simultaneously $\pi^+$ and $\pi^0$ using a GEANT4 simulation of the tagger.
- "**Event-building**" : clustering based on position and timing of UCM waveforms with realistic treatment of background (up to 500 KHz/cm$^2$).
- **Pile-up** effect on $K_{e3}$ efficiency seen at nominal rates. Mitigation enlarging the radius: $\sim 25\%$ ($\sim 50\%$ purity).

\[\text{e}^+ \text{ in 2 ns at nominal rates and 40 cm radius}\]
Test beam at CERN-PS T9 Nov. 2016

- Test data/MC agreement and e/n separation at grazing incidence (~ 30 $X_0$, orientable cradle)
- 56 (e.m.) + 18 (had.) UCM, 666 SiPM
e/n separation analysis with test beam data

- Electrons/muons tagged by T9 Cherenkov counters and a muon catcher. Silicon strip chambers for μm tracking and fiducialization.
- Current GEANT4 simulation is working reasonably well already.
Irradiation studies

- **Neutron** and ionizing doses have been studied for a tagger radius of 40, 80 and 100 cm with FLUKA and cross-checked with GEANT4.

- Choosing 100 cm allows $\sim 1 \times 10^{12} \text{ n 1MeV-eq/cm}^2$ and $\sim 0.25 \text{ kGy}$ in the innermost layers in the detector lifetime.

- **Test irradiation with 1-3 MeV neutrons** performed at **INFN-LNL CN Van de Graaff** on 12-27 June 2017.

- Characterise **rad-hard SiPM** with 12-15-20 $\mu$m cell size (FBK, SensL) up to $10^{11-12} \text{ 1MeV-eq n/cm}^2$.

- Test viability of **self-calibration** with m.i.p.

\[ p(5\text{MeV}) + {}^9\text{Be} \rightarrow n + X \]
Lots of ongoing R&D activities

**CERN-PS**: 4 weeks this year at T9 (July and Oct.)

- Test response of *irradiated* SiPM
- Achieve *recovery time* <~10 ns (to cope with pile-up)
- Test of *custom digitizers electronics*
- *Photon veto* prototypes with plastic scintillators

- Scalable/reproducible technological solutions
  - Molded scintillators, *water-jet holes machining* for absorbers
  - *Polysiloxane* scintillators/powder absorbers
Conclusions

- Flux error limit could be reduced by one order of magnitude exploiting $K^+ \rightarrow \pi^0 e^+ \nu_e$
- In the next 4 years ENUBET will investigate this approach and its application to a new generation of cross section experiments with possible extensions for a phase-II sterile neutrino search and a time-tagged facility

- 1st year of the project: a rich simulation and prototyping program is giving very promising results. Challenging open items ahead. No showstoppers so far.

- ENUBET is working to demonstrate that a “positron monitored” $\nu_e$ source can be built using existing technologies at CERN, FNAL or J-PARC giving a measurement of $\sigma(\nu_e)$ at 1% with a detector of moderate mass (500 t)
Enhanced NeUtrino BEams from kaon Tagging

Project approved by the European Research Council (ERC)
5 years (06/2016 – 06/2021)
overall budget: 2 MEUR

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

Expression of Interest (CERN-SPSC, Oct. 2016)

41 physicists, 10 institutions:
CERN, IN2P3 (Strasbourg), INFN (Bari, Bologna, Insubria, Milano-Bicocca, Napoli, Padova, Roma-I)

In the CERN Neutrino Platform (NP03, PLAFOND)

A. Berra\textsuperscript{a,b}, M. Bonesini\textsuperscript{b}, C. Brizzolari\textsuperscript{a,b}, M. Calviani\textsuperscript{m}, M.G. Catanesi\textsuperscript{l}, S. Cecchini\textsuperscript{c}, F. Cindolo\textsuperscript{c}, G. Collazuol\textsuperscript{b,j}, E. Conti\textsuperscript{j}, F. Dal Corso\textsuperscript{j}, G. De Rosa\textsuperscript{p,q}, A. Gola\textsuperscript{p}, R.A. Intonti\textsuperscript{l}, C. Jollet\textsuperscript{d}, M. Laveder\textsuperscript{b,j}, A. Longhin\textsuperscript{i+s}, P.F. Loverre\textsuperscript{o,f}, L. Ludovici\textsuperscript{i}, L. Magaletti\textsuperscript{l}, G. Mandrioli\textsuperscript{c}, A. Margotti\textsuperscript{c}, N. Mauri\textsuperscript{c}, A. Meregaglia\textsuperscript{d}, M. Mezzetto\textsuperscript{j}, M. Nessi\textsuperscript{m}, A. Paoloni\textsuperscript{i}, L. Pasqualini\textsuperscript{c-g}, G. Paternoster\textsuperscript{o}, L. Patrizii\textsuperscript{c}, C. Piemonte\textsuperscript{o}, M. Pozzato\textsuperscript{c}, M. Prest\textsuperscript{a,b}, F. Pupilli\textsuperscript{c}, E. Radicioni\textsuperscript{l}, C. Riccio\textsuperscript{p,q}, A.C. Ruggeri\textsuperscript{p}, G. Sirri\textsuperscript{c}, F. Terranova\textsuperscript{b,h}, E. Vallazza\textsuperscript{l}, L. Votano\textsuperscript{o}, E. Wildner\textsuperscript{m}
Thank you!

Work Packages (WP)

<table>
<thead>
<tr>
<th>WP</th>
<th>Description</th>
<th>Coordinator</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP1</td>
<td>Conceptual design of the beamline</td>
<td>L. Ludovici</td>
</tr>
<tr>
<td>WP2</td>
<td>Design and prototyping of the positron taggers</td>
<td>M. Pozzato</td>
</tr>
<tr>
<td>WP3</td>
<td>SiPM and front-end electronics for the instrumented decay tunnel</td>
<td>V. Mascagna</td>
</tr>
<tr>
<td>WP4</td>
<td>Design and prototyping of the photon veto (e/γ separation)</td>
<td>G. Sirri</td>
</tr>
<tr>
<td>WP5</td>
<td>Simulation and assessment of the systematics</td>
<td>A. Meregaglia</td>
</tr>
</tbody>
</table>

- A. Berra et al., NIM A824 (2016) 693
- A. Berra et al., NIM A830 (2016) 345
- CERN-SPSC-2016-036 ; SPSC-EOI-014
The Ultra Compact Module (UCM)

Concept validated by SCENTT R&D within INFN Gruppo 5 (2016-17)

- 1 SiPM ↔ 1 WLS fiber
- 9 SiPM signals are added (reduce R/O costs)
- Add SiPM signals in place of light → no WLS bundling = optimal homogenity in longitudinal sampling (UCM)

NIM A824 (2016) 693
NIM A830 (2016) 34
The $e^+$ tagger challenges

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

![Graph showing particle rates versus coordinate along the beam (cm)].

- **Max rate** (kHz/cm$^2$)
  - $\mu^+$ 190
  - $\gamma$ 190
  - $\pi^+$ 100
  - $e^+$ 20
  - all 500

The decay tunnel: a **harsh environment**

- **particle rates:** > 200 kHz/cm$^2$
- **backgrounds:** pions from $K^+$ decays

Moreover:

- **extended source of** ~ 50 m
- **grazing incidence**
- **significant spread in the initial direction**
Hadron beam-line: “static” scenario

- Static focusing: large aperture radiation-hard quadrupoles
- Advantage: tagger far from maximal tolerable rates
- Disadvantage: loss of acceptance w.r.t. horn-based
  - PoT to get $10^4 \nu_e^{CC}: >\sim \times 10^{21}$ ($\sim X10$ more wrt horn focusing).
- Still feasible. Can be compensated by (run time $\times$ det. mass)
- R&D on static focusing beam-line:
  - maximize collection efficiency ($\sim$ “useful” hadrons/PoT)
  - Single resonant slow extraction over O(s) $\leftarrow$ synergies with SHiP

Intriguing opportunity: “time tagging” $\rightarrow$

$T_{\text{extr}} = 1s$ ($\sim 1$ observed $e^+ / 30$ ns) + $\delta = 1$ ns $\rightarrow$ Accidental tag = 2 %
ENUBET: the roadmap

Demonstrate the technique, prepare a “full-scale” experiment

1) Construction, tests of a **tagger demonstrator** (three m of the instrumented decay tunnel)
2) **Systematics** with full simulation supported by **test beam campaigns** at CERN-PS and INFN-LNF/LNL
3) **Design** of the hadronic **beam-line**
4) Test new **proton extraction schemes** at CERN-SPS

**By-products:**

- **Calorimetry:** compact, modular, low-cost detectors (UCM)
- **Accelerator physics:** Multi-Hz slow resonant extraction
Results from UCM prototypes

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

Geant4

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**

First test beam validation of UCM

CERN-PS T9 test beam (July 2016). Beam: π, e, μ from 1-5 GeV.
12 ENUBET UCM modules (~13 $X_0$). 1 mm$^2$ HD Si-PM with 20 μm cell size (FBK).

No dead zones, uniform long. sampling

Going beyond: "time-tagged" beams

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

Superior purity. Combine E_ν from decay with the one deduced from the interaction.

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

Time-tagging not possible using magnetic horns, (scenario A):

T_{\text{extr}} = 2 \text{ ms} (1 \text{ e}^+ / 70 \text{ ps}) \text{ even } \delta = 50 \text{ ps} \text{ gives } A = 50\%
The photon-veto baseline option

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

- 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 $e^+$, 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

- \( p^+ \rightarrow m^+ n_m \) creates the bulk of \( n_m \) (\( \sim 95\% \) p @ 400 GeV)
- **n detector must have good** \( n_e \) **PID**: reject NC \( p^0 \) in the \( n_e^{cc} \) sample
- 2-body decay, \( m_m \sim m_p \): \( m^+ \sim 4 \) mrad \( \rightarrow \) few in the tagger, easy to reject
- \( m \) D.I.F: suppressed \( L_m \gg L(\text{decay tunnel}) \)
- 3-body but \( m_m \sim 0.2 \) \( m_K \) \( \rightarrow e^+_\text{DIF} \sim 28 \) mrad \( (e^+_\text{Ke3} \sim 88 \) mrad)
  - \( n_e^{cc,DIF} \sim 3.3\% \rightarrow \sim \) all \( n_e \) are from \( K_{e3} \)

\[
\frac{\Phi_{\nu_e}}{\Phi_{\nu_\mu}} = 1.8 \% \ (\nu_e \text{ from } K_{e3})
\]
Inferring $\sigma(\nu_e)$ 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
       - $F_p, F_V^{1,2}, F_A^1$, second class currents
     - alteration of kinematics due to mass

   $\rightarrow$ Differences between $\sigma(\nu_\mu)$ and $\sigma(\nu_e)$ ($\Delta$)
   - can be significant (10-20%) espec. at low-E
   - with different energy trends for $\nu$ and $\bar{\nu}$

Choosing the $K^+/\pi^+$ momentum and tunnel length

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

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

$p = 8.5\text{ GeV}/c \pm 20\%$
$L = 50\text{ m}$
**e⁺ tagger: background rejection**

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

**Hadronic modules**
**Electro-magnetic modules**
**Hit modules**

---

### e⁺ (signal) topology

---

### $n^0$ (background) topology

---

### $n^+$ (background) topology
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)

- $L_m >> L(\text{decay tunnel}) \nu_e, \text{CC,DIF} \sim 3.3\%$
  $\rightarrow \sim \text{all } \nu_e \text{ are from } K_{e3}$

Angular distribution of $e^+$ from $K_{e3}$

$88 \text{ mrad}$
## 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 $> 2 \times 10^{21}$ PoT
  CNGS = $0.18 \times 10^{21}$ PoT
  NuMI = $1.1 \times 10^{21}$ PoT

Simple conversion $1.94 \times 10^{13} K^+ / \nu_e^{cc}$
Tagged neutrino beams: the origins

The "holy grail" of neutrino physicists:

- L. Hand, 1969, V. Kaftanov, 1979 (p/K $\to$ n$_m$)
- G. Vestergombi, 1980, R. Bernstein, 1989 (K $\to$ n$_e$)
- S. Denisov, 1981, R. Bernstein, 1989 (K$_{e^3}$)

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 $\to \mu \nu$, K$_{e^3}$ decays).


Literature:
- L. Ludovici, P. Zucchelli, hep-ex/9701007 (K$_{e^3}$)
- L. Ludovici, F. Terranova, EPJC 69 (2010) 331 (K$_{e^3}$)

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$^+$ $\to$ e$^+$ n$^0$ $\nu_e$ (K$_{e^3}$ decays)
**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 $K_{\mu2}$ and a candidate $e^+$

- Recovery time, $\Delta t_{\text{tag}} = 10$ ns
- Rate, $R = 0.5$ MHz/cm$^2$
- Tile surface, $S \sim 10$ cm$^2$

$\rightarrow 5\%$ 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 $\mu$ 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 $O (1 \text{ kGy})$ ($\sim 100 \text{ kGy for CMS forward ECAL}$)