The ENUBET ERC project meeting, London QMUL 21-23 September 2016

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

• Kick-off meeting in Padova, 23-24 June 2016
  https://agenda.infn.it/conferenceDisplay.py?confId=11574

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.
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 $\sin \delta_{CP}$

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

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%
The ENUBET monitored beam

- 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 \( 10 \times 10 \text{ cm}^2, L = 50 \text{ m} \)
  \( \rightarrow \) 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 (\( \sim m_K \))

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

Angular distribution of emitted positrons from \( K_{e3} \)

Radial energy deposition (all decay modes)

\[ \frac{d^2N}{dE_d d\Omega} \text{ at } \theta = 88 \text{ mrad} \]
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 $K^{-}\pi^+$ golden sample → possible to **discriminate** with:
  - 1) calorimetric longitudinal profile of energy deposition
  - 2) tagging vertices by timing:

\[\sigma_t \text{O}(100 \text{ ps}) \sim \sigma_{z\text{VTX}} \text{O}(1m)\]

veto fake $e^+$ from $K^+ \rightarrow \pi^+\pi^+\pi^+$ and $K^+ \rightarrow \pi^+\pi^0 \text{ reconstructed vertices}$
The $e^+$ tagger challenges

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

The decay tunnel: a harsh environment

- **particle rates:** $>200$ kHz/cm$^2$
- **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**

<table>
<thead>
<tr>
<th></th>
<th>Max rate (kHz/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+$</td>
<td>190</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>190</td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>100</td>
</tr>
<tr>
<td>$e^+$</td>
<td>20</td>
</tr>
<tr>
<td><strong>all</strong></td>
<td><strong>500</strong></td>
</tr>
</tbody>
</table>
Hadron beam-line: scenario A

- $t_{\text{impulse}} < 10$ ms (Joule heating, I $\sim$ O(100) kA)
- **tager rate limit** is hit injecting $10^{10} \pi^+$ in 2 ms
- Considering typical horn collection efficiencies this corresponds to $0.3-2.5 \times 10^{12}$ PoT/spill depending on $E_p$ (spills with relatively “few” protons)
- Considering we need $1.94 \times 10^{13}$ $K^+$ for $\nu_e^{CC}$ with a 500 t $\nu$ detector at 100 m asking for $10^4 \nu_e^{CC}$ implies:
  - $0.5-5 \times 10^{20}$ 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 $10^4 \nu^\text{CC}_e$: $0.5-7 \times 10^{21}$ $O(\sim 10 \times)$ 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**

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

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

\[\text{Accidental tag probability using } 10^{10} \text{ hadrons/burst: } A \sim 2 \times 10^7 \frac{\delta}{T_{\text{extr}}}\]

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

Using such long extractions prevents* using O(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)

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

- 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 \( \nu_{e}^{CC} \) with a tagged \( e^{+} \) (15 % in the forward "hole")
- \( 1.95 \times 10^{13} K^{+}/\nu_{e}^{CC} \)
- Radial profiles at the \( \nu \) detector

\( <E> = 3 \text{ GeV, FWHM } \sim 3.5 \text{ GeV} \)

\[ \nu_{e}^{CC} \text{ rates} \]
New opportunities

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 $\nu$ 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 $\nu$ beam.

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

1% sys. + 1% overall stat. errors
(10,000 $\nu_e^{CC}$) Eur. Phys. J. C75 (2015) 155
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)

→ 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 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

R&D on innovative detectors/photosensors
Full simulation: $e/\pi$ 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 1$^{st}$ photon-veto doublet.
- N. photon veto doublets upstream of the inner e.m. layer peak

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<thead>
<tr>
<th></th>
<th>$\epsilon_{\text{geom}}$</th>
<th>$\epsilon_{\text{sel}}$</th>
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<tbody>
<tr>
<td>$\pi^+$</td>
<td>90.7 %</td>
<td>49.0 %</td>
</tr>
<tr>
<td>$\pi^0$</td>
<td>85.7 %</td>
<td>2.9 %</td>
</tr>
<tr>
<td>$e^+$</td>
<td>95.1 %</td>
<td>1.2 %</td>
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Former estimates from parametrizations confirmed with a **realistic** and **cost-effective** setup.
The Ultra Compact Module (UCM)

Spring 2016 prototypes

9 SiPM signals are added to reduce R/O costs

1 Si-PM
1 WLS
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 $\mu$m 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 $e/\pi$ separation → **NOV 2016**

Preliminary

19% stochastic term
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 $\nu$ physics requires **better control of its artificial sources**
• At the GeV limited knowledge on the **initial flux**: the dominant contribution to cross section uncertainties
• Such a 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 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 J-PARC
  • a 1% measurement of the absolute $\nu_e$ cross section can be achieved with detector of moderate mass (500 ton)
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

$D = 7 \text{ cm}$

$R-h = 37 \text{ cm}$

$h = 3 \text{ cm}$
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 $L_\mu >> L(\text{decay tunnel})$
- 3-body but $m_\mu \sim 0.2 \, m_K \rightarrow e^+_{\text{DIF}} \sim 28 \text{ mrad} \,(e^+_{K_{e3}} \sim 88 \text{ mrad})$
  - $\nu_{e, \text{CC,DIF}} \sim 3.3\% \rightarrow \sim$ all $\nu_e$ are from $K_{e3}$
  - $\frac{\Phi_{\nu_e}}{\Phi_{\nu_\mu}} = 1.8 \% \,(\nu_e \text{ from } K_{e3})$
$\sigma(\nu_e)$ 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 $\bar{\nu}$

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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

\[ \text{increases } \nu_e \text{ from } K^e_3 \text{ with few } \nu_e \text{ from } \mu \text{ D.I.F.} \]

Current scenario $p = 8.5 \text{ GeV/c ± 20\%}$ $L = 50 \text{ m}$

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
**e^+ tagger: background rejection**

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

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**Hadronic modules**

**Electro-magnetic modules**

**Hit modules**
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

$p = 8.5 \text{ GeV} \pm 20\%$
$\theta < 3 \text{ mrad}$
The ENUBET goals and program

Demonstrate experimentally that a new-concept $\nu_e$ source, with $\times 10$ better precision is feasible

$\rightarrow \sigma(\nu_e) \, 1\% \, \text{sys.} \, + \, 1\% \, \text{overall stat. errors} \, (10,000 \, \text{events})$ 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)

- $L_\mu \gg L(\text{decay tunnel}) \nu_e,^{\text{CC,DIF}} \sim 3.3\%$
  $\rightarrow \sim \text{all } \nu_e \text{ are from } K^-_{e3}$

Angular distribution of $e^+$ from $K^-_{e3}$

- 88 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>
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<td>60</td>
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<td>70</td>
<td>12.0</td>
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<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 x 10$^{21}$ PoT
CNGS = 1.8 x 10$^{20}$ PoT
NuMI = 1.1 x 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 ($K_{e3}$)

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)

Literature:
- L. Ludovici, P. Zucchelli, hep-ex/9701007 ($K_{e3}$)
- L. Ludovici, F. Terranova, EPJC 69 (2010) 331 ($K_{e3}$)
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>
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<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 [Daya Bay]</em>]</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>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 [ICARUS]</em>]</td>
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<tr>
<td>Detector efficiency</td>
<td>$&lt; 1%$. Irrelevant for CPV if the target is the same as for the long baseline experiment</td>
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</table>
$e^+ $ tagger: pile-up and radiation

**Pile-up**
Not decayed $\pi$, $K$ 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 $K/\pi$ 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 ($\sim 100$ kGy for CMS forward ECAL)

Both issues not critical
The hadron beam-line challenge

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

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

**Short** transport line to prevent early decays

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**Focusing system**

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<tr>
<th>Scenarios</th>
<th>Proton extraction from accelerator</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: pulsed device (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>B: static devices (DC magnets)</td>
<td><strong>O(1s)</strong> long slow extractions</td>
</tr>
</tbody>
</table>