The ENUBET project

A. Longhin (Padova University and INFN) on behalf of the ENUBET Collaboration

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Bari (IT), 4/6/2019
Overview and outline

The goal of ENUBET is to demonstrate the technical feasibility and physics performance of a neutrino beam where lepton production at large angles is monitored at single particle level.

Two pillars:
- Build/test a **demonstrator** of the instrumented decay tunnel
- Design/simulate the layout of the **hadronic beamline**

Achievements
- **Beamline simulation + accelerator studies**
- Updated **physics performance**
- Experimental validation of detector **prototypes**

ENUBET: 54 physicists, 12 institutions
Monitored beams

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

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

- Fully instrumented decay region:
  \[ K^+ \rightarrow e^+ \nu_e \, n^0 \rightarrow \text{large angle } e^+ \]

- $\nu_e$ flux prediction = $e^+$ counting.

Removes the leading source of uncertainty in $\nu$ cross section measurements.

To get the correct spectra and avoid swamping the instrumentation → needs a collimated momentum selected hadron beam → only decay products in the tagger → Correlations with interaction radius allows an a priori knowledge of the $\nu$ spectra.
Neutrino beams for precision physics: the ENUBET project

The next generation of short baseline experiments for cross-section measurements and for precision v-physics (e.g. CP violation program, sterile ν NSI) should rely on:

- a direct measurement of the fluxes
- a narrow band beam: energy known a priori from beam width
- a beam covering the region of interest from sub- to multi-GeV

The ENUBET facility fulfills simultaneously all these requirements

~ 500 t neutrino detector @ 100 m from the target

e.g. ICARUS@FNAL or ProtoDUNE-SP/DP@CERN, a Water Cher. @ J-PARC?
The ENUBET beamline (baseline option)

- **Proton driver:** CERN (400 GeV), FNAL (120 GeV), J-PARC (30 GeV)
- **Target:** 1 m Be, graphite target. FLUKA.
- **Focusing**
  - **Horn:** 2 ms pulse, 180 kA, 10 Hz during the flat top [*not shown in fig.*]
  - **Static focusing system:** a quadrupole triplet before the bending magnet
- **Transfer line**
  - Kept **short** to: minimize early K the decays and those of off-momentum mesons out of tagger acceptance (untagged neutrino flux component)
  - Optics: optimized with TRANSPORT to a **10% momentum bite centered at 8.5 GeV/c**
  - Particle transport and interaction: full simulation with G4Beamline
  - Normal-conducting magnets
    - 2 quad triplets (15 cm wide, L < 2 m, B = 4 to 7 T/m)
    - 1 bending dipole (15 cm wide, L = 2 m, B = 1.8 T)
- **Decay tunnel:** r = 1 m. L=40 m, low power hadron dump at the end
- **Proton dump:** position and size under optimization
The ENUBET beam line – particle yields

<table>
<thead>
<tr>
<th>Focusing system</th>
<th>$\pi$/pot ($10^{-3}$)</th>
<th>K/pot ($10^{-3}$)</th>
<th>Extraction length</th>
<th>n/cycle ($10^{10}$)</th>
<th>K/cycle ($10^{10}$)</th>
<th>Proposal (c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horn</td>
<td>97</td>
<td>7.9</td>
<td>2 ms (a)</td>
<td>438</td>
<td>36</td>
<td>x 2</td>
</tr>
<tr>
<td>“static”</td>
<td>19</td>
<td>1.4</td>
<td>2 s</td>
<td>85</td>
<td>6.2</td>
<td>x 5</td>
</tr>
</tbody>
</table>

(a) 2 ms at 10 Hz during the flat top (2 s) to empty the accelerator after a super-cycle.
(c) A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155.

The horn-based option still allows $\sim x 5$ faster statistics but the static option gained momentum since initial estimates were $\sim x 5$ too conservative wrt to present simulations!

**Furthermore … advantages of the static extraction:**

- No need for fast-cycling horn
- Strong reduction of the rate (pile-up) in the instrumented decay tunnel
- Pave the way to a “tagged neutrino beam” →
  - $\nu$ interaction at the detector associated in time with the observation of the lepton from the parent hadron in the decay tunnel (more later)
- Monitor the $\mu$ after the dump at % level (flux of $\nu_\mu$ from $\pi$) [under evaluation]
Neutrino events per year at the detector

- **Detector mass**: 500 t (e.g. Protodune-SP or DP @ CERN, ICARUS @ Fermilab, WC at J-PARC?)
- **Baseline** (i.e. distance between the detector and the beam dump): 50 m
- 4.5 \times 10^{19} \text{ pot at SPS} (0.5 / 1 \text{ y in dedicated/shared mode}) or 1.5 \times 10^{20} \text{ pot at FNAL}

- \nu_\mu \text{ from } K \text{ and } \pi \text{ are well separated} \text{ in energy (narrow band)}
- \nu_e \text{ and } \nu_\mu \text{ from } K \text{ are constrained by the tagger measurement} (K_{e3}, \text{ mainly } K_{\mu2}).
- \nu_\mu \text{ from } \pi: \mu \text{ detectors downstream of the hadron dump? (under study)}

1.2 million \nu_\mu \text{ Charged Current per year}

14000 \nu_e \text{ Charged Current per year}

98.4\% \text{ from kaons } \mu \text{ contribution is small (tunnel is “short”)}
$\nu_\mu$ CC events at the ENUBET narrow band beam

The neutrino energy is a function of the distance of the neutrino vertex from the beam axis.

$E_{\nu}^\nu (\text{GeV})$ vs $E_{\nu}^\text{CC} (\text{GeV})$

$\nu_\mu$ CC in radial bins (1 norm.)

The beam width at fixed $R$ (\equiv $\nu$ energy resolution for $\pi$ component) is:

- 8% for $r \sim 50$ cm, $<E_{\nu}> \sim 3$ GeV
- 22% for $r \sim 250$ cm, $<E_{\nu}> \sim 0.7$ GeV

+ Binning in $R$ allows to explore the energy domains of DUNE/HK and enrich samples in specific processes (quasi-elastic, resonances, DIS) for cross section measurements.
Systematics on the $\nu_e$ flux

Golden sample  
$\epsilon \sim O(10^{-2})$

$\phi(\nu_e) = \alpha N(K_{e3}) + \epsilon N(\mu)$ → Uncertainties from K yields, efficiency and stability of the transfer line are by-passed by the $e^+$ tagging

$\alpha$ encodes the residual geometrical (decay lengths, beam spread) and kinematic factors from K decays → “easy” corrections.

The background in the positron sample has to be controlled → simple robust detector validated at test beams ($e/\pi^{\pm}/\mu$ separation)

Silver sample  
$\phi'(\nu_e) = \alpha N(K) \times BR(K_{e3})$

Measuring the inclusive rate of K decays is also very powerful. Branching ratios known to < 0.1% (additional uncertainty is small). Residual background is stray pions from beam tails (well characterized in terms of azimuth and longitudinal position)

• can we get to 1%? assessment in progress: toy Monte Carlos + full simulation

• Address the effect of each uncertainty and the degree of cancellations allowed by the large correlations between $e^+$ rate and $\nu_e$ flux.
Machine studies for the horn-based option

“burst” slow extraction: trigger the third integer betatron resonance with a periodic pattern

From an idea “on slide” to a working implementation!

Same integrated pot extracted. Protons squeezed into intervals with active horn

CERN-BE-OP-SPS, Velotti, Pari, Kain, Goddard

https://indico.cern.ch/event/777458/
The static beamline: emittance, particle content

Divergence of the kaon beam

K^+ @ tagger entrance  exit

1 m radius

Particle budget @ tagger entrance

p (MeV/c)  Momentum bite (8.5 ± 10%) GeV/c

\[ p (GeV/c) \]
\[ \pi^+ \]
\[ p^+ \]
\[ e^+ \]
\[ \mu^+ \]

Spectra @

tagger entrance  tagger exit

Low energy high angle \( \pi \)

Loss driven by decays

K^+
1) Optimize shielding to **reduce backgrounds** in the tagger ($\mu$, n, high angle $e^+$ and $\pi^+$)

2) Specs of **rad-hard** upstream focusing quads

3) **neutron** irradiation
Additional beamline options

We are also simulating other beamline schemes:

2 dipoles with an intermediate quadrupole. Increased length of beamline but ...

- Better quality of the beam in the tagger
- Larger bending angle (15.2 °) reducing
  - backgrounds from muons
  - probability for neutrinos produced in the straight section to reach the $\nu$ detector

- We are putting all these inputs together
- $\rightarrow$ pindown the best scheme in terms of physics and technical feasibility
The ENUBET tagger

Calorimeter
Longitudinal segmentation
Plastic scintillator + Iron absorbers
Integrated light readout with SiPM

$\rightarrow e^+/\pi^\pm/\mu$ separation

Integrated photon veto
Plastic scintillators
Rings of $3\times3$ cm$^2$ pads

$\rightarrow \pi^0$ rejection

Ultra Compact Module
$3\times3\times10$ cm$^3$ – 4.3 $X_0$

$e^+ (signal)$ topology
$\pi^0 (background)$ topology
$\pi^+ (background)$ topology
**K_{e3} positrons reconstruction**

Full **GEANT4 simulation** of the detector, **validated** by prototype tests at CERN in 2016-2018. Includes particle **propagation** and **decay**, from the transfer line to the detector, hit-level detector response, **pile-up** effects.

**Analysis chain**

- **Event Builder**
  - Identify the **seed** of the event (UCM with largest energy deposit in inner layer and > 20 MeV).
  - **Cluster neighboring cells** close in time.
  - **Iterate** on not-yet-clustered cells.

- **e/π/μ separation**
  - **Multivariate** analysis based on 6 variables (pattern of the energy deposition in the calorimeter) with TMVA
  - Signal on the tiles of the **photon veto** (0-1-2 mip)

- **e/γ separation**

**Before tuning of shielding**

Reco level full sim.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{\text{geom}}$</td>
<td>0.36</td>
</tr>
<tr>
<td>$\varepsilon_{\text{sel}}$</td>
<td>0.55</td>
</tr>
<tr>
<td>$\varepsilon_{\text{tot}}$</td>
<td>0.20</td>
</tr>
<tr>
<td>Purity</td>
<td>0.26</td>
</tr>
<tr>
<td>S/N</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Φ cut 0.46

Instrumenting half of the decay tunnel:

$K_{e3} e^+ e^+$ at single particle level with a $S/N = 0.46$
Time tagged neutrino beams?

- Event time dilution → **Time-tagging**
- Associating a single neutrino interaction to a tagged e\(^+\) with a small "accidental coincidence" probability through **time coincidences**

\(E_\nu\) and flavor of the \(\nu\) measured "a priori" event by event.

Compare "\(E_\nu\) from decay kinematics" ↔ "\(E_\nu\) from \(\nu\) interaction products"

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

Presently with \(2.5 \times 10^{13} \text{ pot / 2s slow extraction:}\)

- genuine \(K_{e3}\) cand. : 80 MHz → 1 every ~ 12 ns
- background \(K_{e3}\) cand. ~ 2 x → 1 cand. every ~ 4 ns

With \(\delta = 0.5 \oplus 0.5 \text{ ns resolutions: already interesting!}\)

\(S/N\) ratio will likely improve with further tuning.
The tagger: shashlik with integrated readout

10 cm = 5 $X_0$

**UCM**: ultra compact module.
SiPM and electronics embedded in the shashlik calorimeter

CERN PS test beam Nov 2016
Test beam results with shashlik readout

Calorimeter prototype performance with test-beam data @ CERN-PS T9 line 2016-2017

Tested response to MIP, e and \( \pi \)

- e.m. energy resolution: \( 17\% / \sqrt{E} \) (GeV)
- Linearity deviations: <3% in 1-5 GeV range
- From 0 to 200 mrad \( \rightarrow \) no significant differences
- Work to be done on the fiber-to-SiPM mechanical coupling \( \rightarrow \) dominates the non-uniformities
- Equalizing UCM response with mips MC/data already in good agreement
- Longitudinal profiles of partially contained \( \pi \) reproduced by MC @ 10% precision
Polysiloxane shashlik prototypes

Pros: *increased resistance to irradiation* (no yellowing), *simpler* (just pouring + reticulation)

A 13X₀ shashlik prototype tested in May 2018 and October 2017 (*first application* in HEP)

15 mm thick scintillators to compensate reduced light yields
SiPM irradiation measurements at INFN-LNL and CERN

- @ the CN Van de Graaf on July 2017 → 1-3 MeV n with fluences up to $10^{12}/\text{cm}^2$ in a few hours

A shashlik calorimeter equipped with irradiated SiPMs later tested at CERN-PS T9 in Oct 2017

By choosing SiPM cell size and scintillator thickness (~light yield) properly, mip signals remain well separated from the noise even after typical expected irradiation levels.

Mips can be used from channel-to-channel intercalibration even after maximum irradiation.

The tagger: lateral readout option

Light collected from scintillator sides and bundled to a single SiPM reading 10 fibers (1 UCM). SiPM are not immersed anymore in the hadronic shower → less compact but much reduced neutron damage (larger safety margins), better accessibility, possibility of replacement. Better reproducibility of the WLS-SiPM optical coupling.
Achievable neutron reduction with lateral readout

- 30 cm of borated polyethylene in front of SiPM
- FLUKA full simulation. 400 GeV protons.

- Very good suppression especially below 100 MeV.
- Factor ~18 reduction averaging over spectrum.

Neutron energy

FLUKA

- entering CAL
- exiting shielding ~ @SiPM in lateral r/o mode

Si n damage weight function x 1e-10

n longitudinal position along the tunnel
The Tagger – Detector R&D

September 2018 CERN-PS: a module with hadronic cal. for pion containment and integrated $t_0$-layer

Simulation

- Efficiency maps
- Simulation

Resolution

- PID

- Good signal amplitude
- Checking impact of light connection uniformity and reproducibility of WLS-SiPM optical match. In progress.

Efficiency maps

Resolution

PID
The photon veto

@ CERN-PS T9 line 2016-2018

• $\gamma/e^+\text{discrimination} + \text{timing}$
  scintillator ($3\times3\times0.5\text{ cm}^3$) + WLS Fiber (40 cm) + SiPM
• light collection efficiency $\rightarrow >95\%$
• time resolution $\rightarrow \sigma_t \sim 400\text{ ps}$
• 1mip/2mip separation

charge exchange: $\pi^- + p \rightarrow n \pi^0 (\rightarrow \gamma\gamma)$
Trigger: PM1 + VETO + PM2

Input for simulations
The tagger demonstrator

- Length ~ 3 m
- allows the containment of shallow angle particles in realistic conditions
- Fraction of $\phi$
- Due by 2021
ENUBET in the CERN Neutrino Platform

- **CERN**: already gave a prominent contribution for the success of ENUBET
  - machine studies performed at the SPS
  - East Area beamline for the characterization of the prototypes
  - For 2019-2021 → recognition in the Neutrino Platform as ENUBET/NP06
    - support and consulting from CERN accelerator experts in collaboration with personnel by the project
    - test of the final proton extraction scheme in the SPS after LS2
    - use of the renovated East Area for the final validation of the demonstrator

5.12 The physics case of the ENUBET project and the exciting possibilities of a tagged neutrino beam are recognized by the SPSC. The committee recognizes the technological development for a neutrino beam without a horn using a quadrupole-based solution, and appreciates the close collaboration of the ENUBET collaboration with the CERN accelerator sector. The SPSC supports the proposed programme, and welcomes the opportunity to continue reviewing the experiment; test-beam requests will be considered via the standard annual procedure. The Research Board approved the participation of ENUBET in the Neutrino Platform, with reference NP06, on the understanding that

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MoU being finalized

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132\textsuperscript{th} meeting of the SPSC, 22\textsuperscript{nd}-23\textsuperscript{rd}/01/2019

228\textsuperscript{th} meeting of the Research Board, 5/3/2019
https://cds.cern.ch/record/2668519/files/M-228.pdf

A. Longhin - ENUBET
Conclusions

ENUBET is a narrow band beam with a high precision monitoring of the flux at source (O(1%)) and control of the $E_\nu$ spectrum (20% @ 1 GeV $\rightarrow$ 8% @ 3 GeV)

In the first two and a half years
- first end-to-end simulation of the beamline
- Tested the “burst” slow extraction scheme at the CERN-SPS
- feasibility of a purely static focusing system ($10^6 \nu_\mu^{CC}, 10^4 \nu_e^{CC}/y/500$ t)
- full simulation of $e^{+}$ reconstruction: single particle level monitoring
- completed the test beams campaign before LS2
- Strengthened the physics case: $\rightarrow$ slow extraction + “narrow band off-axis technique”

The ENUBET technique is very promising and the results we got so far exceeded our expectations
Next steps

- 2019: freeze light readout technology (shashlik versus “lateral readout”)
- 2019: Further tuning of the beamline design (improve current S/N for $e^+$)
- Full assessment of systematics on the neutrino fluxes
- **CDR** at the end of the project (2021): physics and costing
- Build the **demonstrator prototype** of the tagger (2021)

Grazie!
Backup
Time tagged neutrino beams: challenges

- Proton extraction \( \sim 2s \) \( \rightarrow \) Static focusing with slow extraction is mandatory
- \( \sigma_t \) of the tagger < 1 ns \( \rightarrow \) OK
- \( \sigma_t \) of the \( \nu \) detector < 1 ns \( \rightarrow \) Feasible but at the limit of present technology
- Cosmic background \( \times 10 \) \( \rightarrow \) Foresee overburden/cosmic ray tagger
- Small K\(^+\) momentum bite small (not to spoil the \( \nu_e \) energy reco.) \( \rightarrow \) Feasible but implies flux reduction
- Tagger-detector time sync. << 1 ns \( \rightarrow \) OK (direct optical links)

In parallel to the \( t_0 \)-layer baseline option (light plastic scintillator tracker) we are considering alternative technologies (NUTECH project MIUR). Improve the timing both:
- at the tagger
  - direct readout of cherenkov light, LYSO crystals with embedded SiPM, MicroMegas
- and at the neutrino detector side
  - SiPM based readout of Ar scintillation light
Polysiloxane shashlik prototypes

Light yield (normalized to thickness) is ~ 1/3 of plastic scintillator

→ tests light transmission on WLS fibers in absence of air gap

Energy resolution, particle-ID and uniformity in line with the one achieved with plastic scintillator
SiPM irradiation measurements at INFN-LNL

- SiPM were irradiated at the CN Van de Graaf on July 2017
- 7MV and 5 mA proton currents on a Be target
  - $^9$Be($p,n)^9$B, $^9$Be($p,np)2\alpha$, $^9$Be($p,np)^8$Be and $^9$Be($p,n\alpha)^5$Li
  - $\rightarrow$ 1-3 MeV n with fluences up to $10^{12}/cm^2$ in a few hours

- n spectra (from previous works at the same facility)

$\rightarrow$ Tested 12, 15 and 20 $\mu$m SiPM cells up to $\sim 2 \times 10^{11} n/cm^2$ 1 MeV-eq
(max non ionizing dose for $10^4 \nu_e^{CC}$ at a 500 t $\nu$ detector at $r = 1$ m)

- Expected n doses from K decays (FLUKA)
- n spectra (from previous works at the same facility)
**ν_μ CC events at the ENUBET narrow band beam**

The neutrino energy is a function of the distance of the neutrino vertex from the beam axis.

**ν_μ CC in radial bins (1 norm.)**

### Momentum of ν_μ CC μ^- on Ar.

**GiBUU generator (Gauss flux approx.)**

**E_ν (GeV)** vs. **E_ν^cc (GeV)**

**R (m)** vs. **ν_μ^cc**

- ν_μ from K
- ν_μ from π

**ν_μ in radial bins (1 norm.)**

- R = (0.5 ± 0.1) m
- R = (1.5 ± 0.1) m
- R = (2.5 ± 0.1) m

**HK r.o.i.**

**DUNE r.o.i.**
Machine studies for the horn-based option

- Difficult to get below 20 ms → implemented a feed-forward mechanism using BCT data
- Iterative procedure (AutoSpill) → can “sharpen” peaks up to 10 ms in 3 iterations
- at the cost of a somewhat larger variance in peak intensity.

- Versatile/general: mixed continuous-burst possible.
- General software tool developed for CR operations.
- Present studies suggest that this mode does not increase significantly radiation losses at septa
- ENUBET: would the static focusing be preferred, burst mode could be used to constrain cosmics background.
- Now focusing on simulation/further ideas, improvement in diagnostics used for feedback (BCT).
- Studies performed in a limited time → will benefit greatly of more data in the future!
Beamline shielding tuning studies

- Studies in progress to optimize the shielding to shield muons and other backgrounds.

**G4Beamline**

**Copper**

**Inermet180**

**Particle budget @ tagger entrance**

**Factor >3 reduction** in muons at ~ constant background from other sources (e⁺, π⁺)

**Azimuthal angle**

The bulk of μ⁺ along dipole bending plane

Besides shielding a further reduction of muons can be achieved by removing a section in φ in the upstream part of the tagger
Particle rates in the tunnel

Static focusing system
$4.5 \times 10^{13}$ pot in 2 s (400 GeV)

Radius = 1 m from the axis of the tunnel

Rates vs longitudinal position in the tunnel (before any reconstruction)

- Primary particles background largely reduced with tuning in the shielding
- The second part of the tunnel is significantly favored in terms of signal-to-background
- With static focusing scheme rates in the second half are below 10 kHz/cm$^2$
Machine studies for the horn-based option

- Performed Jul/Aug/Nov 2018 at the SPS

**CERN-BE-OP-SPS, Velotti, Pari, Kain, Goddard**

- **Idea:** synchronize proton beam and horn current pulses
- + keep rates compatible with tagger (10 ms pulses “slow extr.”)

“burst” slow extraction: trigger the third integer betatron resonance with a periodic pattern

M. Pari (CERN doctoral student, Univ. of Padova) @ SLAWG meeting of 5/12/2019

https://indico.cern.ch/event/777458/

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**New proposed tune functions**

- Original Tune
- Burst SE - Manual
- Burst SE - Optimized
- Burst SE - Parabolic
- Burst SE - Parabolic2

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**New proposed tune functions**

- Original Tune
- Original Tune - Reco
- Burst SE - Manual
- Burst SE - Optimized
- Burst SE - Parabolic
- Burst SE - Parabolic2
Positron ID from K decay

Full GEANT4 simulation of the detector, validated by prototype tests at CERN in 2016-2018. Includes particle propagation and decay, from the transfer line to the detector, hit-level detector response, pile-up effects.

Analysis chain:
- **Event Builder**: Identify the seed of the event (UCM with large energy deposit) and cluster neighboring modules (in time and space).
- **e/π/μ separation**: Multivariate analysis based on 6 variables (pattern of the energy deposition in the calorimeter) with TMVA.
- **e/γ separation**: Signal on the tiles of the photon veto.

**Purity x Efficiency (Ke3 e⁺)**

- ε_{geom} = 0.36
- ε_{sel} = 0.55
- ε_{tot} = 0.20
- Purity = 0.26
- S/N = 0.36
- φ cut = 0.46

Instrumenting half of the decay tunnel: Ke₃ e⁺ at single particle level with a S/N = 0.46.
The Tagger – positron ID from K decay

Event Builder

Seed of the event = UCM in first layer with energy deposit > 20 MeV → link neighboring modules with time (1ns) and position requirements

e/π separation

Neural network

TMVA multivariate analysis based on 5(+6) variables (pattern of the energy deposition in the calorimeter)

Response to signal and background

TMVA overtraining check for classifier: MLPBNN

Cut efficiencies and optimal cut value

For 1000 signal and 1000 background events the maximum S/S+B is 27.21 when cutting at 0.63

Background rejection versus Signal efficiency

MVA Method: MLPBNN

e/γ separation

n⁰ rejection: we require 3 layers of t0 before first calorimeter energy deposit compatible with a mip (0.65-1.7 MeV)