# Rejection of Neutron Background in $\bar{\nu}_\mu p \to \mu^+ n$ QE on H

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# NEUTRON DETECTION IN STT+ECAL



✦ *Geometry with the SAND magnetic volume filled with LAr meniscus + full STT including both $CH_2$ and graphite targets (optimized for "solid" hydrogen concept).*

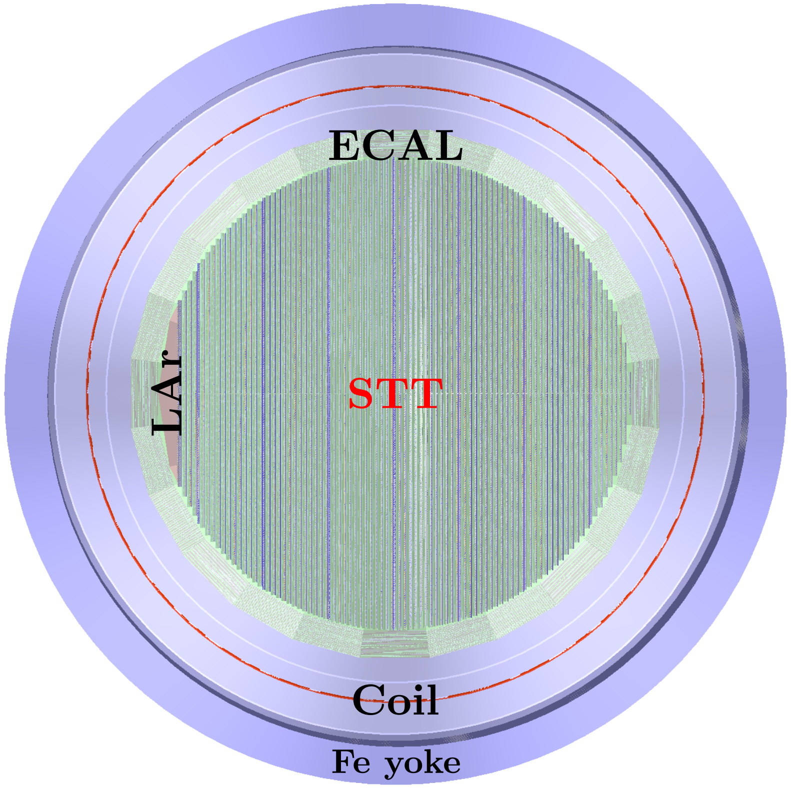
✦ *Generated inclusive CC and NC with gsimple+GENIE+edep-sim(GEANT4) and default RHC beam (Optimized Engineered Nov2017 flux):*

- *650k $\bar{\nu}_\mu$ CC interactions randomly distributed within the STT volume;*
- *4.9M $\bar{\nu}_\mu$ CC inrteractions randomly distributed in magnet+ECAL+LAr+STT (full SAND).*

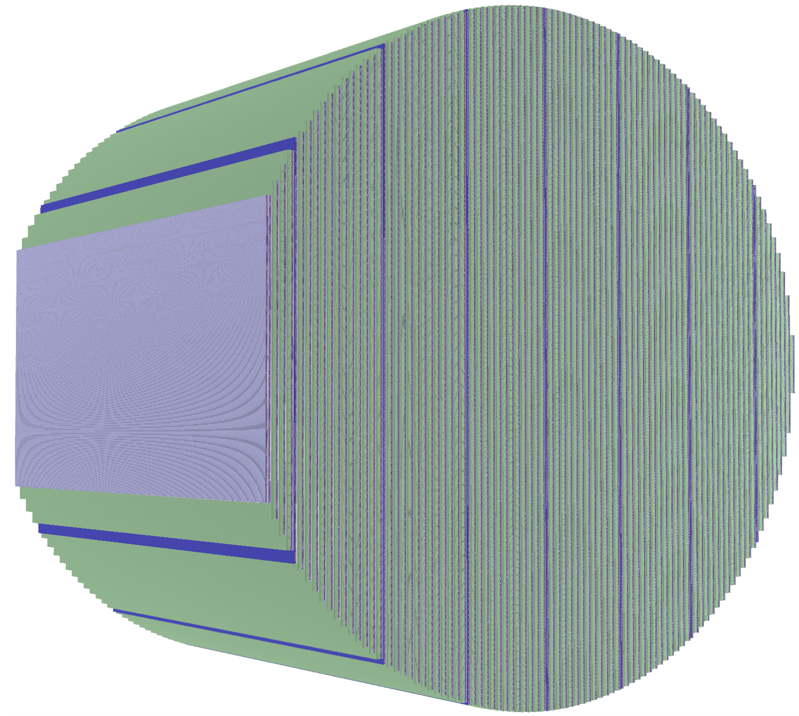
✦ *Default STT fiducial volume (30.3 m$^3$): 20 cm from the ECAL surface:*

- *Energy thresholds applied on hits/cells: 250 eV in STT and 100 keV in ECAL;*
- *ECAL (barrel+ end-caps) digitization including light attenuation and photo-statistics.*

✦ *Detailed comparisons between GEANT4 and FLUKA simulations are in progress (Lea, Federico, Paola) to understand the differences.*




*Green: polypropylene ($CH_2$) targets (4.7 t FV)*



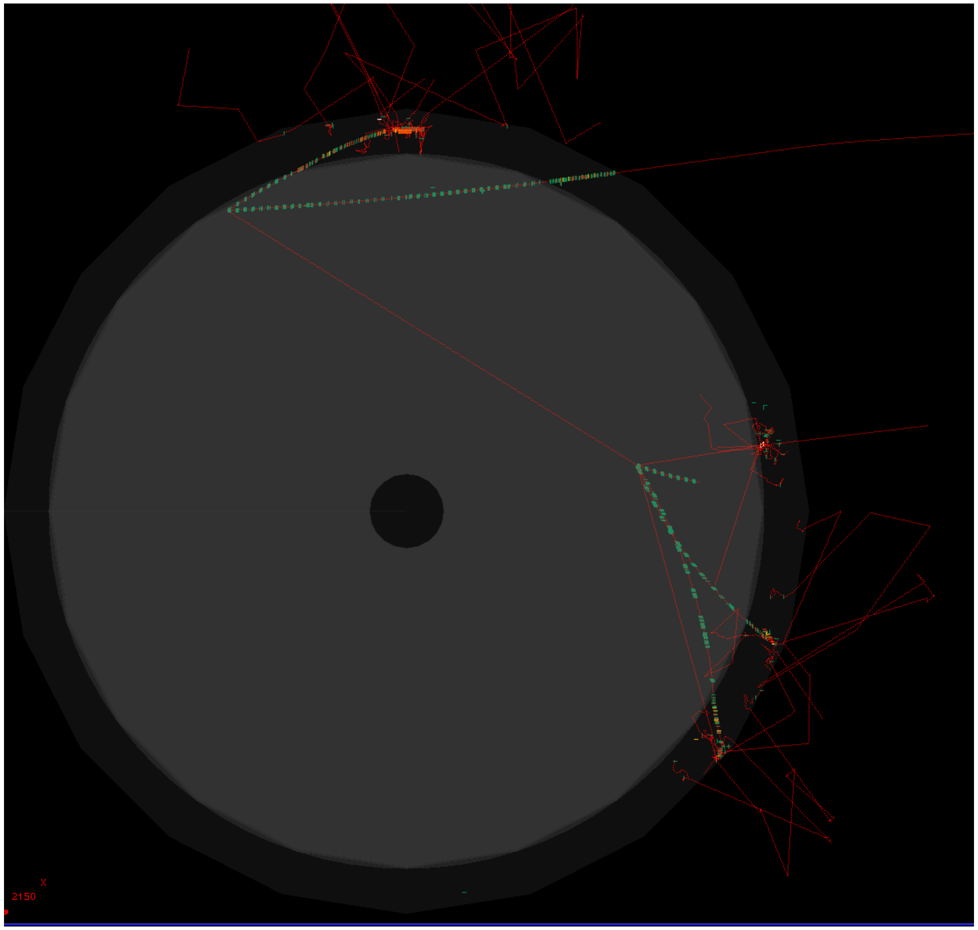
*Blue: graphite (C) targets (504 kg FV)*

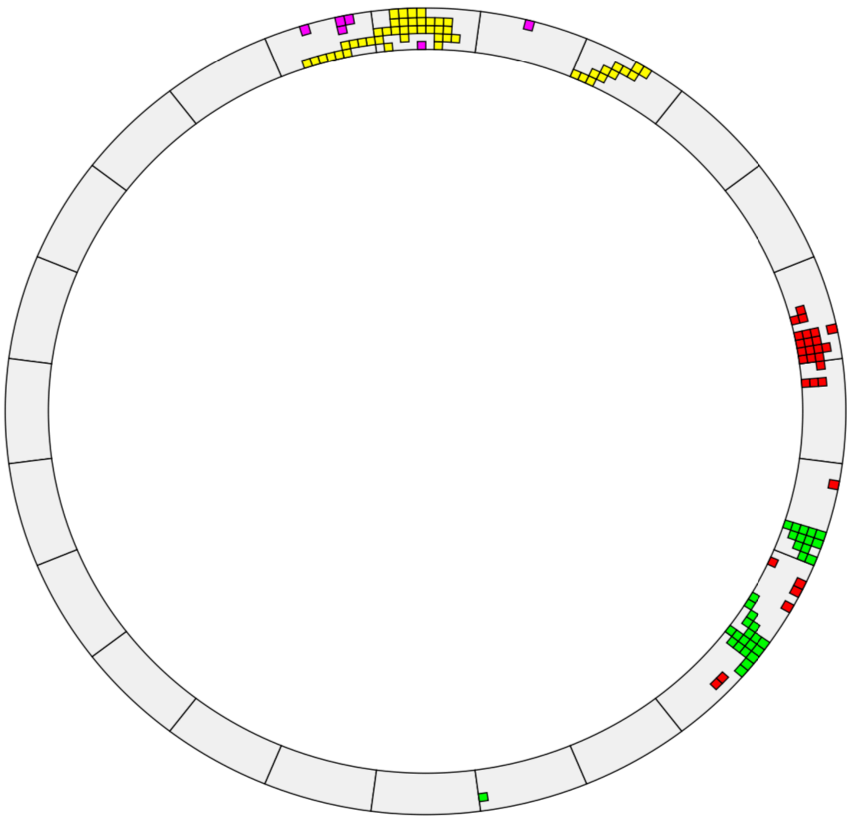
https://docs.dunescience.org/cgi-bin/private/ShowDocument?docid=13262

# DEFINITION OF NEUTRON CANDIDATE LIST



- *Assign a random time stamp within the 9.6 $\mu s$ spill for each event generated in SAND.*
- *N events in given spill: random from Poisson with mean = average events/spill.*
- *For each genuine $\bar{\nu}_\mu p \to \mu^+ n$, overlap (N-1) random pile-up events within SAND.*
- *List of $N_{\rm n}$ neutron candidates from topological criteria without using MC truth:*
  - *Any disconnected energy deposition/neutral vertex in STT with hits above a threshold of 250 eV;*
  - *Any disconnected cell/neutral cluster in ECAL above a threshold of 100 keV and not reached by charged tracks extrapolated from STT;*
  - *Multiple neutrons sharing the same neutral cluster merged into a single candidate;*
  - *Neutral clusters accepted as candidate can be originated by particles different from neutrons;*
  - *Timing and position of each candidate given by the earliest hit/cell within the cluster/vertex;*
  - *Smearing according to expected timing (1 ns in STT, 54ps/$\sqrt{E} \oplus 50$ ns) and position resolution.*





*Definition of neutron candidates from energy deposits above threshold:*
*select STT neutral vertices + ECAL neutral clusters (purple and red),*
*not connected to any charged track from STT (yellow and green)*

# RECONSTRUCTION OF NEUTRON MOMENTUM

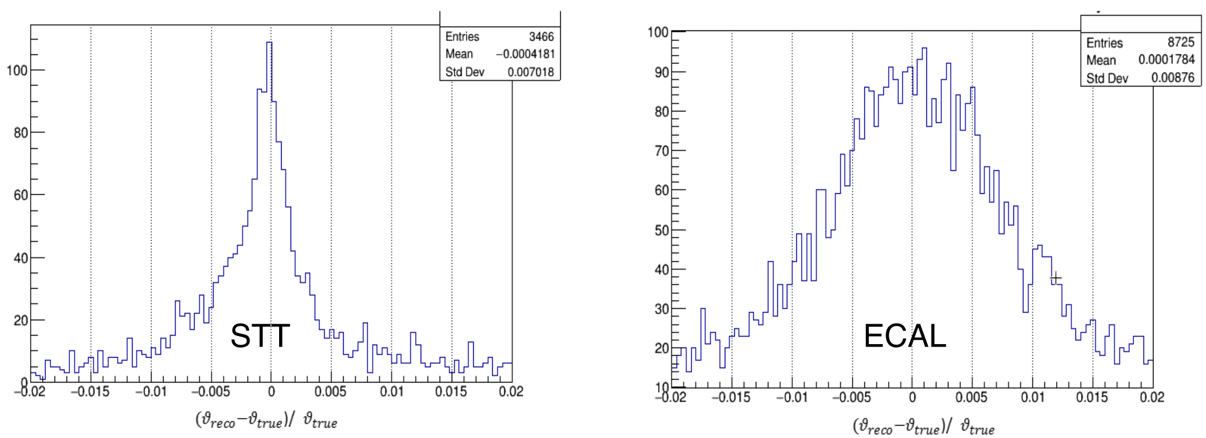


- *Assume target nucleon at rest and a single neutron produced in the final state ($\bar{\nu}$-H).*

- *For each of the $N_{\rm n}$ neutron candidates reconstruct the 4-momentum:*
  - *Energy of neutron calculated from energy-momentum conservation and measured $\mu^+$:*

$$E_n = \frac{M_n^2 - m_\mu^2 + 2M_p E_\mu - M_p^2}{2\,(M_p - E_\mu + \mid \vec{p}_\mu \mid \cos\theta_\mu)} + M_p - E_\mu$$

  - *Direction of neutron (line of flight) from line connecting vertex (first $\mu^+$ hit) and neutron candidate;*
  - *Smearing from parametrized $\delta p_\mu / p_\mu$ and $\delta\theta_\mu$ (Glukstern + multiple scattering);*
  - *Position of vertex (first hit) and neutron candidate smeared according to expected resolution.*




Angular resolution obtained from FLUKA analysis

# TIMING

✦ *Event timing randomly generated according to detailed time structure of neutrino spill.*

✦ *"Measured" time of flight of neutron:*

$$\Delta t \equiv t_{\rm n} - t_{\rm vtx}$$

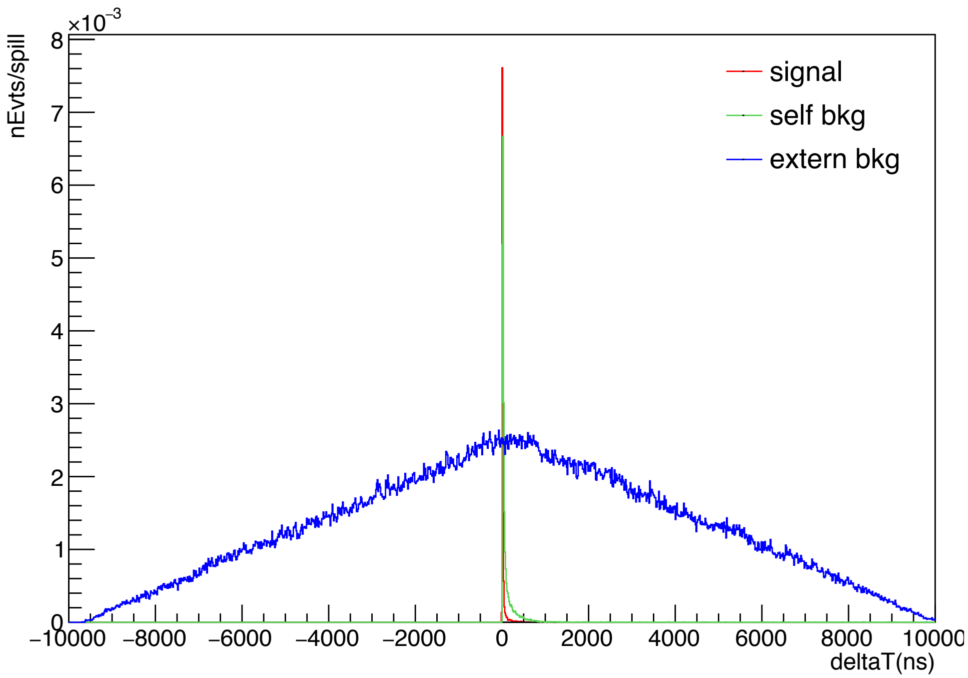
- $t_{\rm vtx}$ *measured time of the genuine* $\bar{\nu}_\mu p \to \mu^+ n$ *interaction on H from the* $\mu^+$*;*
- $t_{\rm n}$ *measured time of the neutron interaction in the detector (either STT or ECAL).*

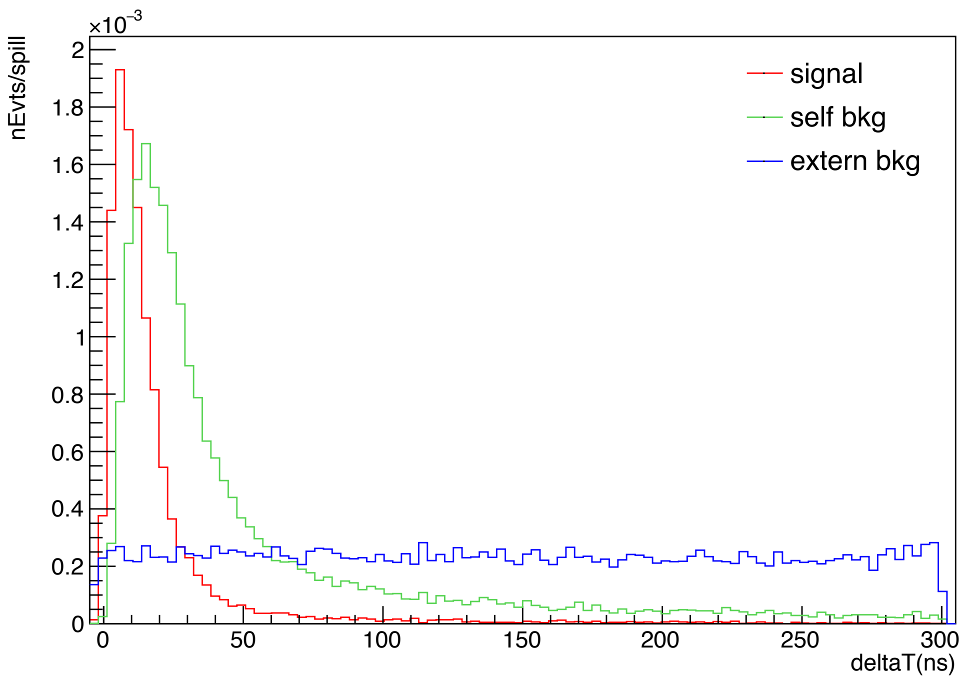
$\Longrightarrow$ *Discard neutron candidates with* $-4 < \Delta t < 300$ *ns*

✦ *Difference with the calculated time of flight of neutron:*

$$\Delta t' \equiv \Delta t - \frac{d}{\beta_{\rm n} c}$$

- $d$ *distance in space between vertex and the interaction point of the neutron;*
- $\beta_{\rm n}$ *derived from the calculated energy of the neutron* $E_n$ *from* $1/\sqrt{1-\beta_{\rm n}^2} = E_n/(M_n c^2)$*.*

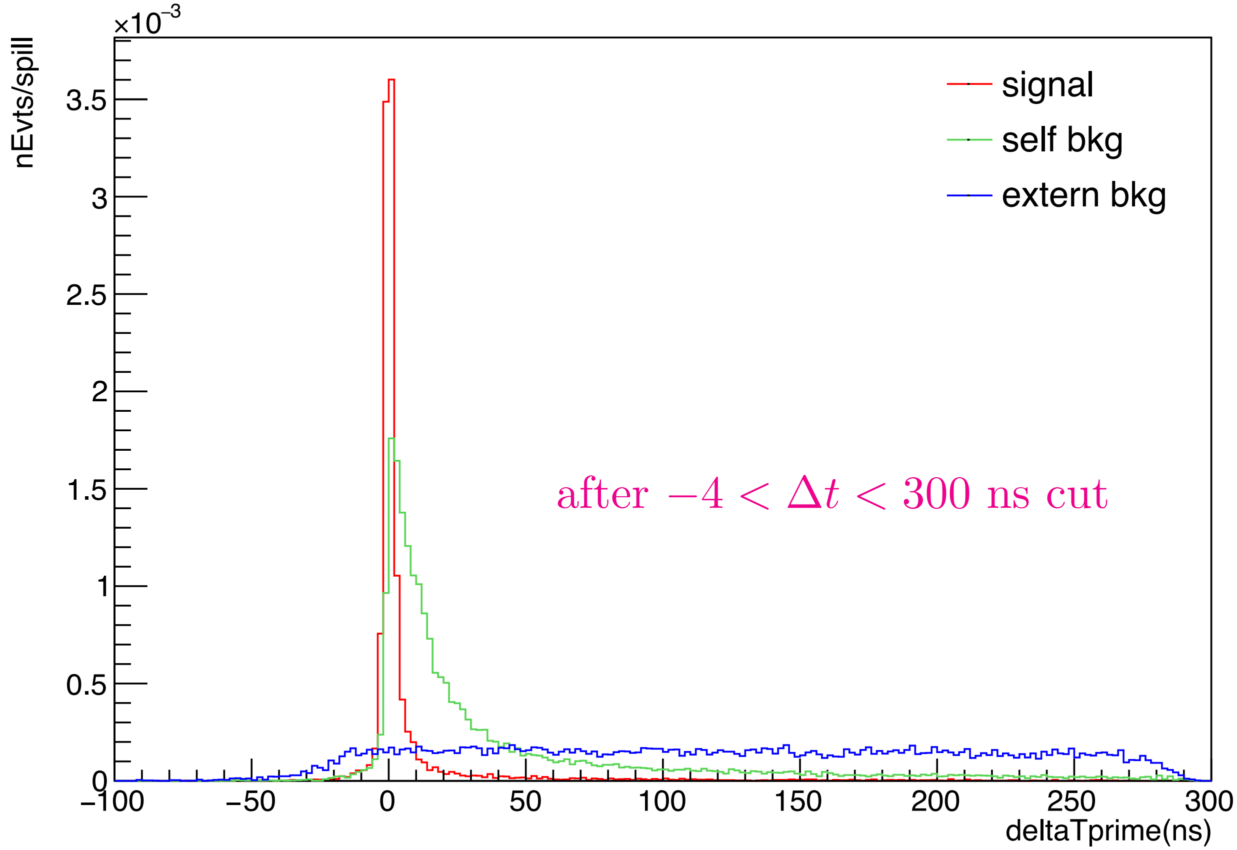



$$\Delta t \equiv t_{\mathrm{n}} - t_{\mathrm{vtx}}$$

| Cut | $\bar{\nu}_\mu p \to \mu^+ n$ on H: Primary neutron: Neutrons | $\bar{\nu}_\mu p \to \mu^+ n$ on H: Primary neutron: $\varepsilon$ (%) | $\bar{\nu}_\mu p \to \mu^+ n$ on H: Secondary neutron: Neutrons | $\bar{\nu}_\mu p \to \mu^+ n$ on H: Secondary neutron: $\varepsilon$ (%) | External events: Neutrons | External events: $\varepsilon$ (%) |
|---|---|---|---|---|---|---|
| No cut | 0.0143 | 100.0 | 0.0654 | 100.0 | 8.1548 | 100.0 |
| Neutron candidate | 0.0118 | 82.5 | 0.0240 | 36.7 | 1.5774 | 19.3 |
| $-2 < \Delta t < 300$ ns | 0.0116 | 81.0 | 0.0216 | 33.0 | 0.0472 | 0.6 |

*Neutrons/spill and selection efficiencies:*
*initial background candidates 136 times signal*




$$\Delta t' \equiv \Delta t - \frac{d}{\beta_n c}$$

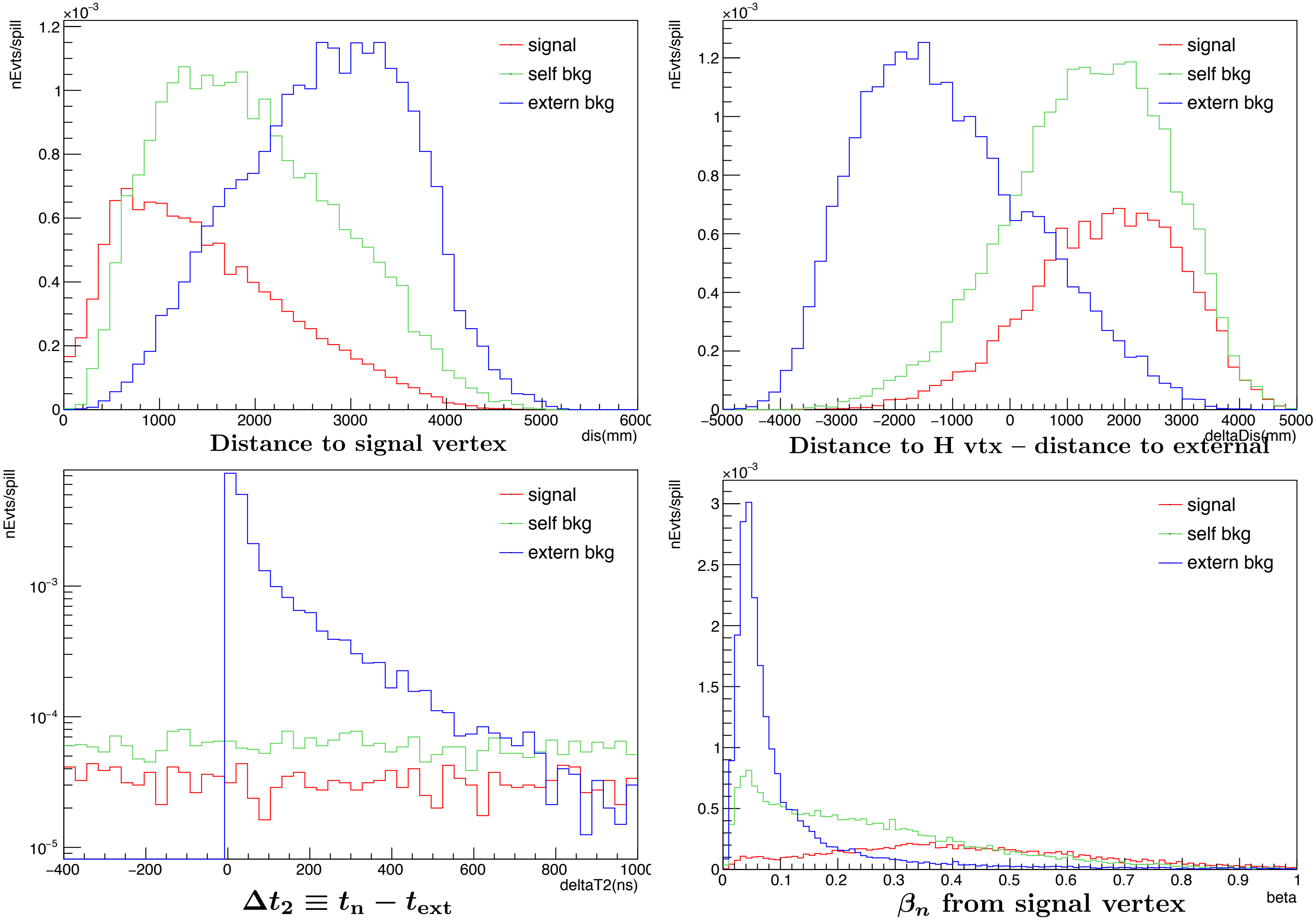
# REJECTION OF RANDOM PILE-UP NEUTRONS



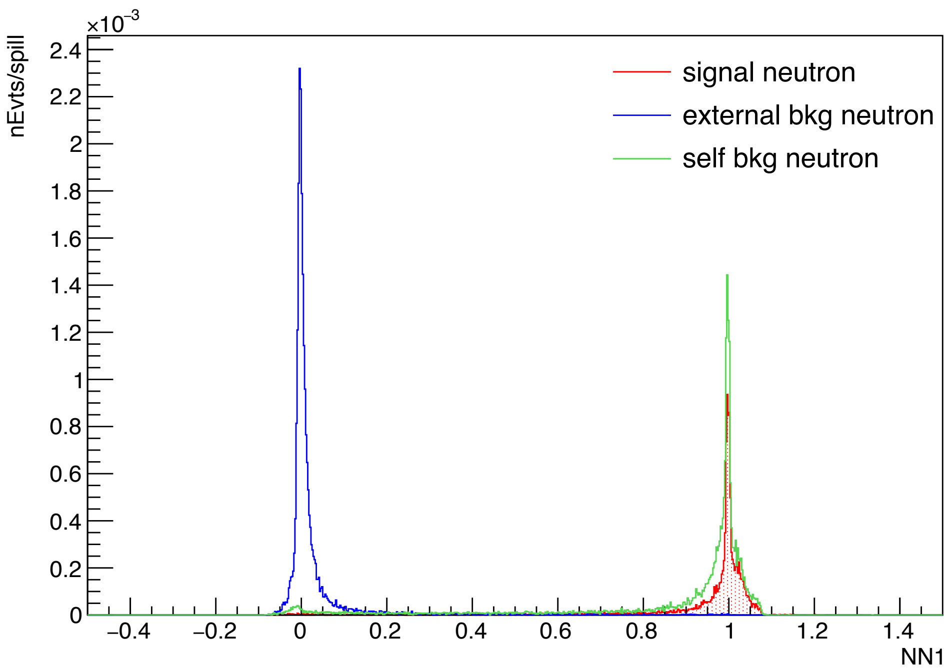
- *List of $N_{\rm ext}$ external activity regions from the (N-1) pile-up events within the spill:*
  - *Charged tracks in STT or energy depositions in ECAL with connected charged tracks;*
  - *Timing and position of external activity regions from earliest hit within region;*
  - *Some pile-up events without any visible primary activity detected (e.g. absorbed in yoke).*

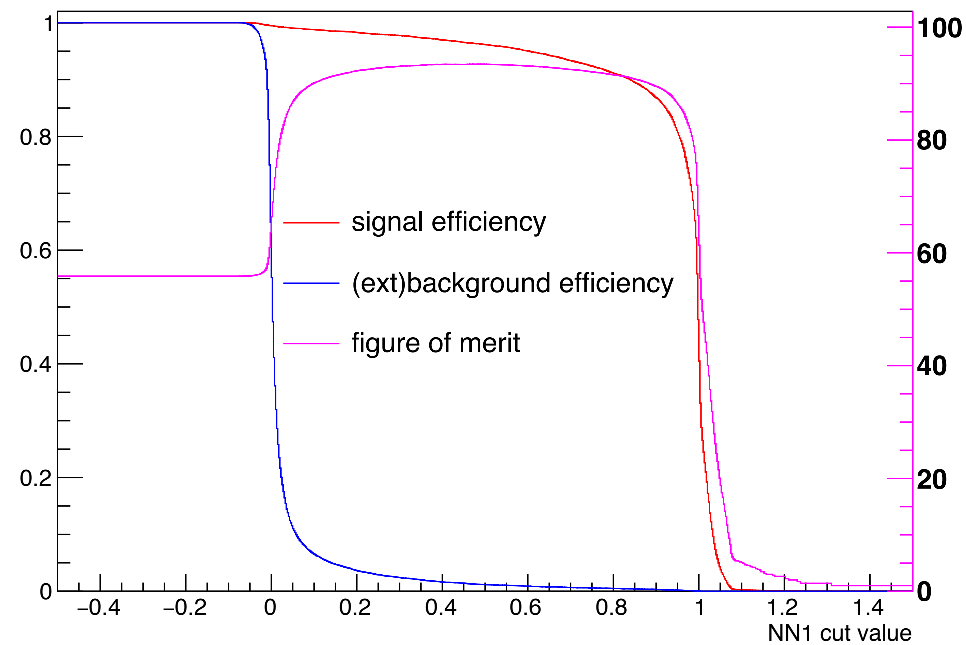
- *Combine 7 discriminating variables into $NN_1$ to evaluate if each neutron candidate comes from the signal vertex or from one of the $N_{\rm ext}$ external activity regions:*
  - *$\Delta t$ with respect to the signal vertex;*
  - *$\Delta t'$ with respect to the signal vertex;*
  - *"Time-of-flight" $\Delta t_2$ with respect to the external activity considered;*
  - *Distance in space between the signal vertex in STT and the external activity considered;*
  - *Distance in space between the external activity considered and the neutron candidate;*
  - *$\beta$ of the neutron candidate with respect to the signal vertex;*
  - *$\beta_2$ of the neutron candidate calculated using the external activity considered.*

- *$NN_1$ training: background from pile-up neutrons with their own correct external activity (if detected), signal from primary n on H with random external activity.*




after $-4 < \Delta t < 300$ ns cut




*Results for $NN_1$ trained with signal neutron and external neutron background*

# TAGGING OF THE PRIMARY NEUTRON



- *No cut on NN$_1$: for each $\bar{\nu}_\mu p \to \mu^+ n$ event select a single n among the $N_{\rm n}$ candidates.*

- *For each of the $N_{\rm n}$ neutron candidates evaluate the $N_{\rm ext}$ possible values of NN$_1$ in combination with all available external activity regions:*
  - *Consider all possible combinations of neutron candidates and external activity regions;*
  - *Find the minimum value of NN$_1$, NN$_1^{\rm min}$, corresponding to the most likely external activity region to originate the given candidate;*
  - *Among the $N_{\rm n}$ possible candidates select the single neutron maximizing NN$_1^{\rm min}$.*

$\Longrightarrow$ *Use NN$_1$ to tag the most likely primary signal neutron*

| | $\bar{\nu}_\mu p \to \mu^+ n$ on H | | External events |
|---|---|---|---|
| | Primary n | Secondary n | |
| Maximum NN$_1^{\rm min}$ | 77 % | 16 % | 7% |

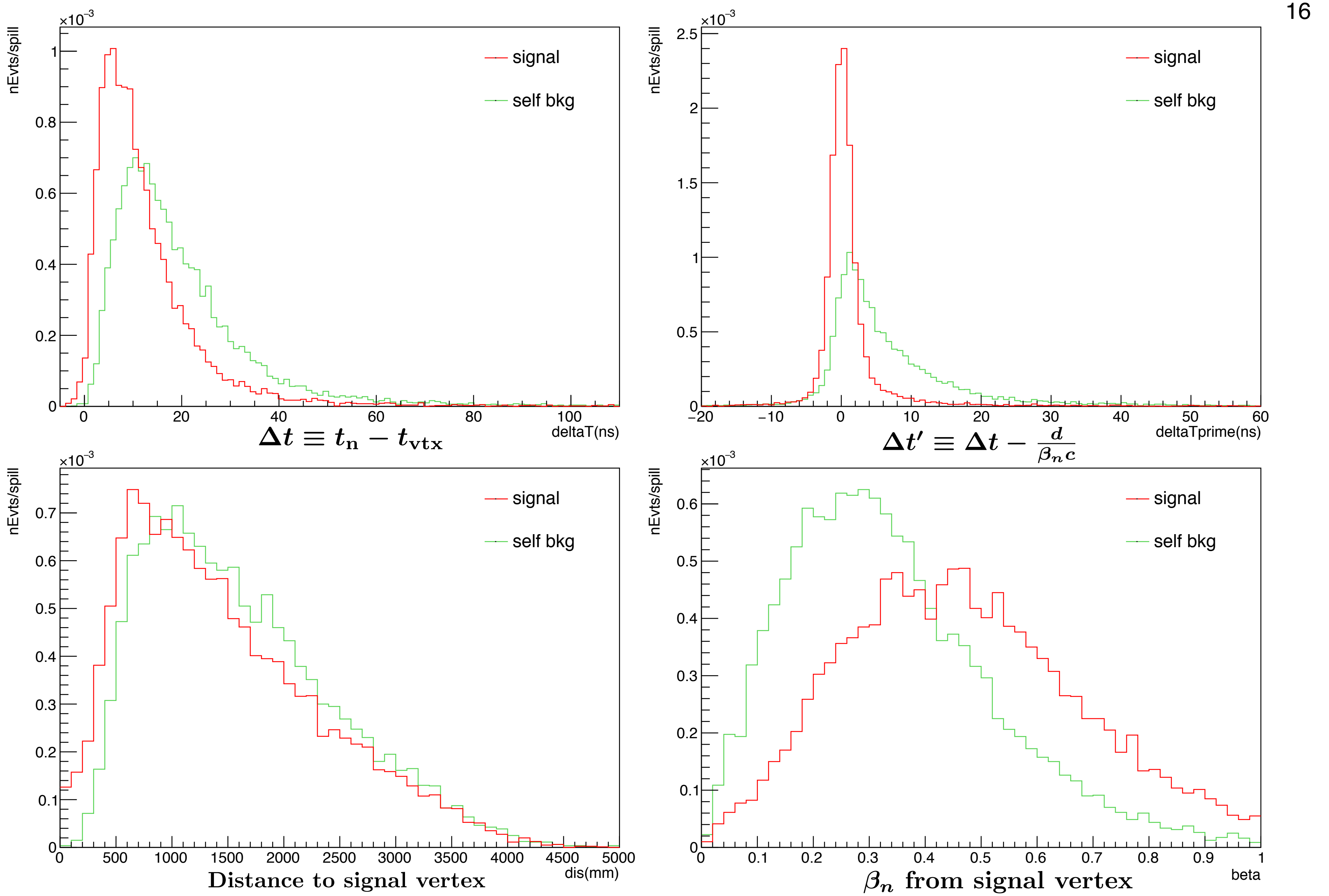
# REJECTION OF SECONDARY NEUTRONS IN H



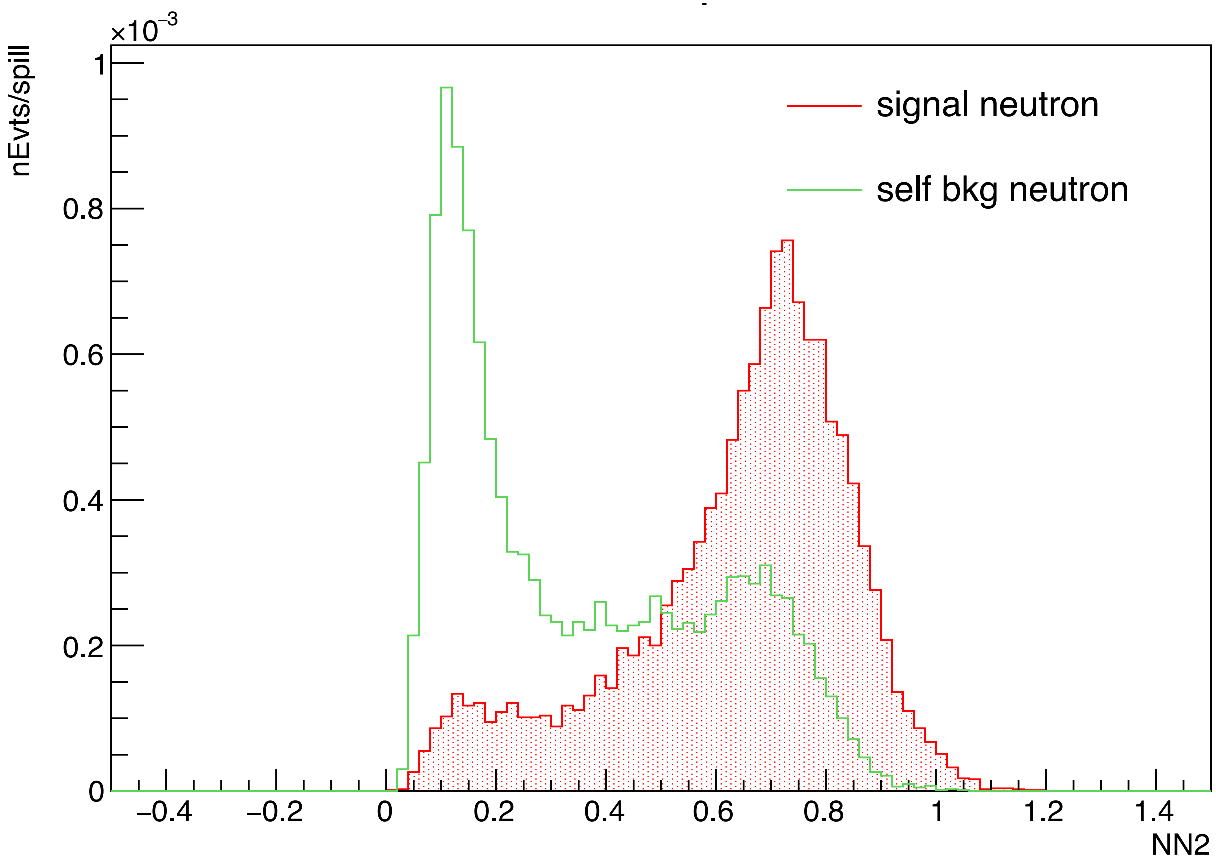
- *Most of the wrong n choices with $NN_1$ from secondary neutrons on H.*

- *Combine 6 discriminating variables into $NN_2$ to evaluate if each neutron candidate is a primary or secondary neutron within the same H event:*
  - *Minimum value of $NN_1$ among the $N_{\rm ext}$ external activity regions;*
  - *Maximum value of $NN_1$ among the $N_{\rm ext}$ external activity regions;*
  - *$\Delta t$ with respect to the signal vertex;*
  - *$\Delta t'$ with respect to the signal vertex;*
  - *Distance in space between the signal vertex and the neutron candidate;*
  - *$\beta$ of the neutron candidate with respect to the signal vertex.*

- *$NN_2$ training: background from secondary neutrons on H, signal from primary neutrons on H with values of $NN_1$ within 0.05.*




*Variables used for $NN_2$ training: signal neutron and self-generated secondary n*




*Results for $NN_2$ trained with signal neutron and self-generated secondary n*

# CHOICE OF THE PRIMARY NEUTRON



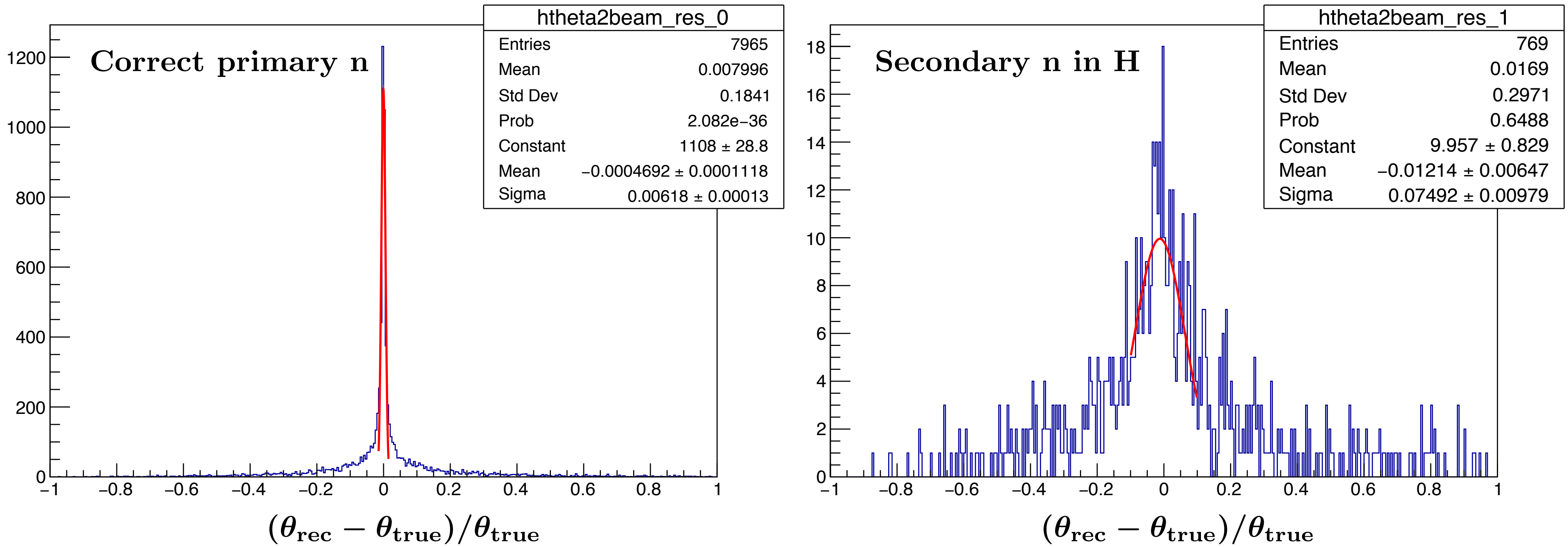
✦ *For each of the $N_{\rm n}$ n candidates, define a linear combination of NN$_1^{\rm min}$ and NN$_2$:*

$$NN \equiv c \times NN_1^{\rm min} + NN_2$$

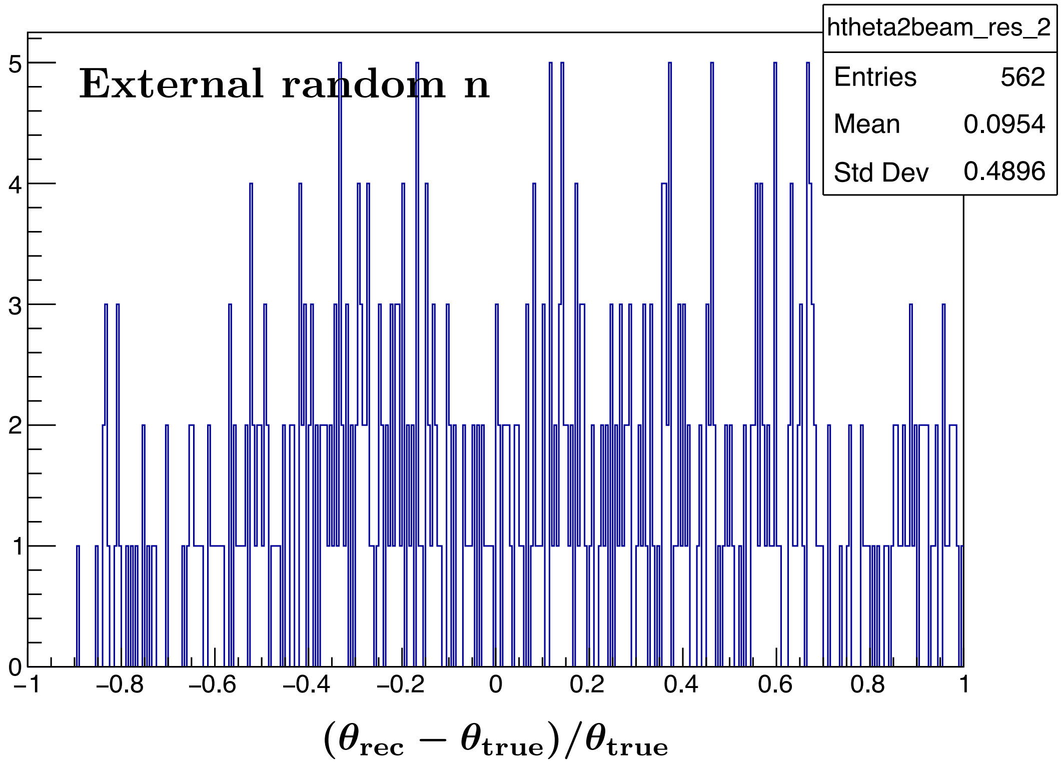
- *Value of the coefficient $c = 4.5$ optimized to maximize correct choices of the primary signal neutron;*
- *Among the $N_{\rm n}$ possible candidates select the single neutron maximizing NN.*

$\Longrightarrow$ *Associate one neutron candidate to each $\bar{\nu}_\mu p \to \mu^+ n$ event*

| | $\bar{\nu}_\mu p \to \mu^+ n$ on H | | External events |
|---|---|---|---|
| | Primary n | Secondary n | |
| Without isolated $\gamma$ candidates | 85.4 % | 8.5 % | 6.0% |
| Including isolated $\gamma$ candidates | 83.8 % | 10.2 % | 5.9% |




*Angular resolution for different types of n candidate selected*




*Angular resolution for different types of n candidate selected*

# KINEMATIC ANALYSIS

- *Build complete event kinematics from* $\mu^+$ *and n momentum vectors:* $\vec{p}_\mu, \vec{p}_n$.

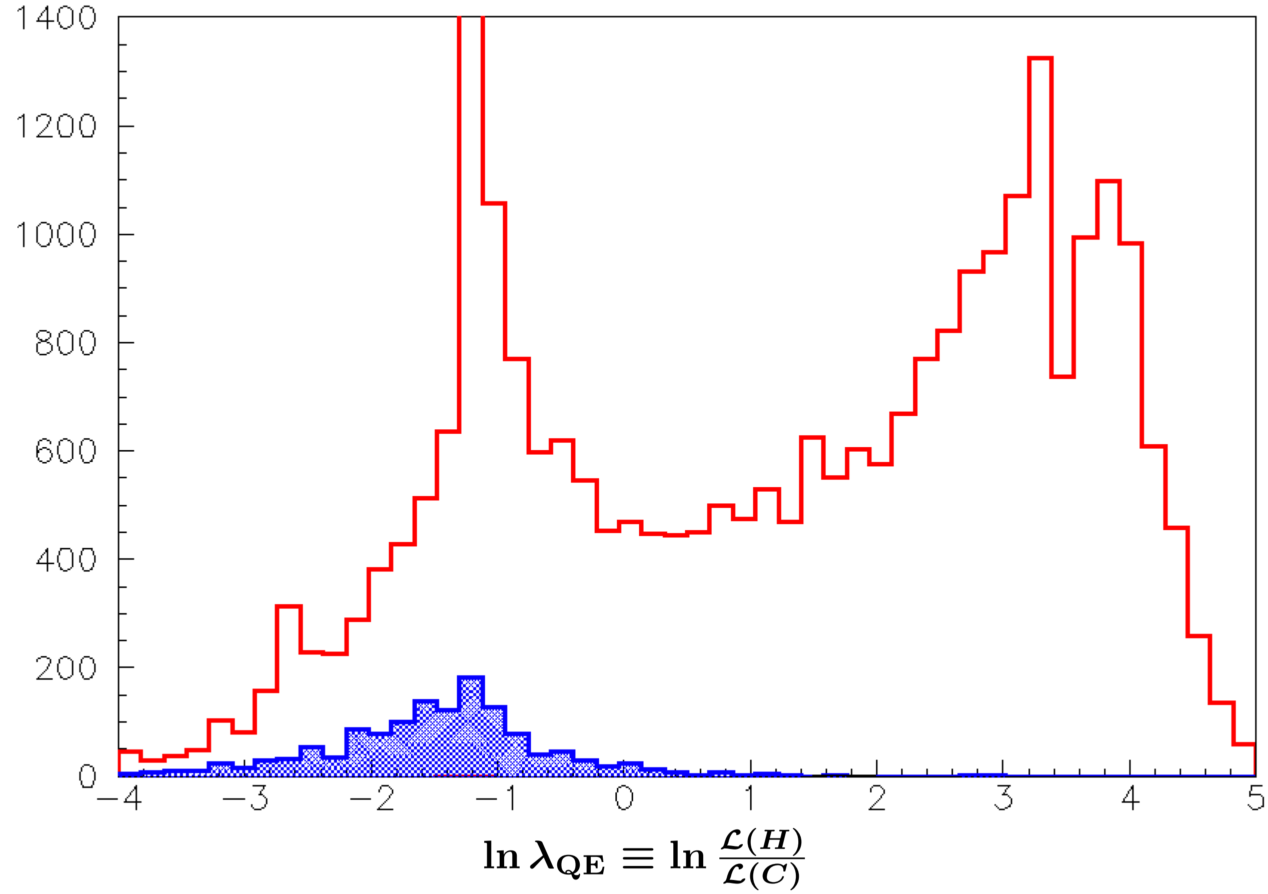
- *Likelihood function used to select H signal from C background:*

$$\mathcal{L}^{\rm H}_{\rm QE} = \left[ [\, p_T^H,\ p_T^m,\ \Phi_{lH},\ \theta_{\nu T}\, ],\ \Delta E_n,\ p_L^n\ \right]$$

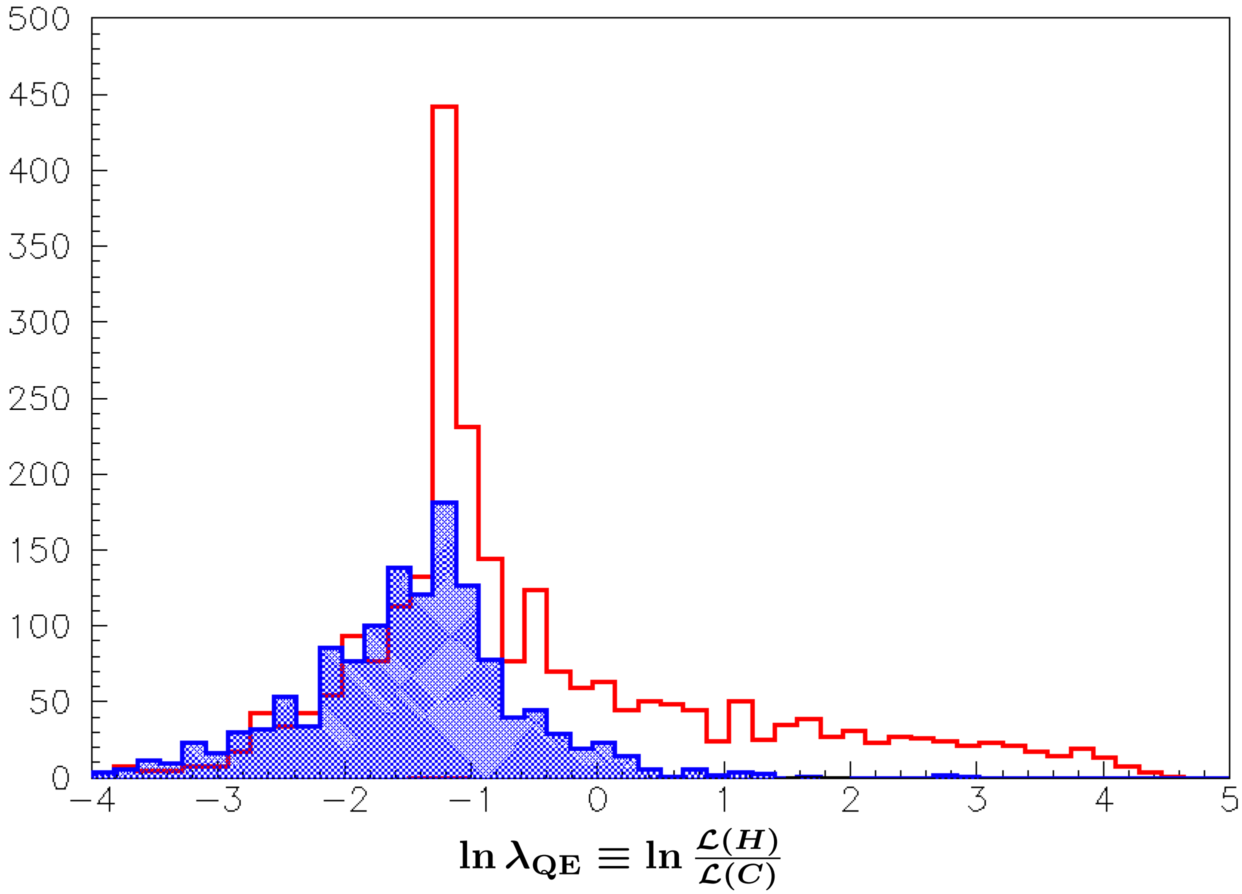
  - $p_T^H, p_T^m$ *transverse momentum of neutron and missing transvrse momentum;*
  - $\Phi_{lH}$ *angle between transverse momenta of muon and neutron;*
  - $\theta_{\nu T}$ *angle of total visibl momentum with respect to the beam direction;*
  - $\Delta E_n = E_\nu - \mid \vec{p}_\mu + \vec{p}_n \mid$ *where* $E_\nu$ *calculated from energy-momentum coonservation;*
  - $p_L^n$ *longitudinal momentum (along beam) of the neutron;*
  - *The square brackets denote multi-dimensional correlations.*

- *Discriminant variable* $\ln$ *of likelihood ratio between H signal and C bkgnd in* $CH_2$

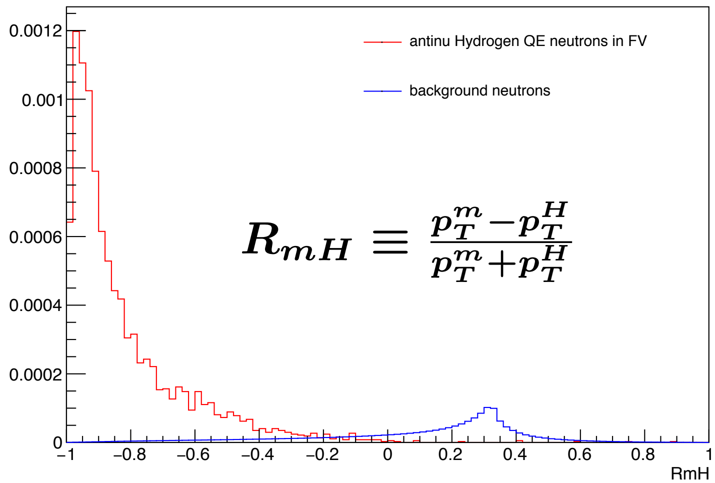
  $\Longrightarrow$ *Background likelihood not re-calculated for random neutrons*

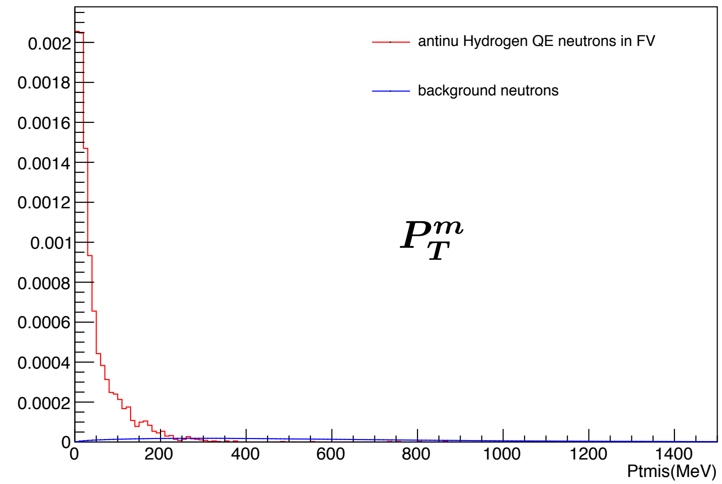


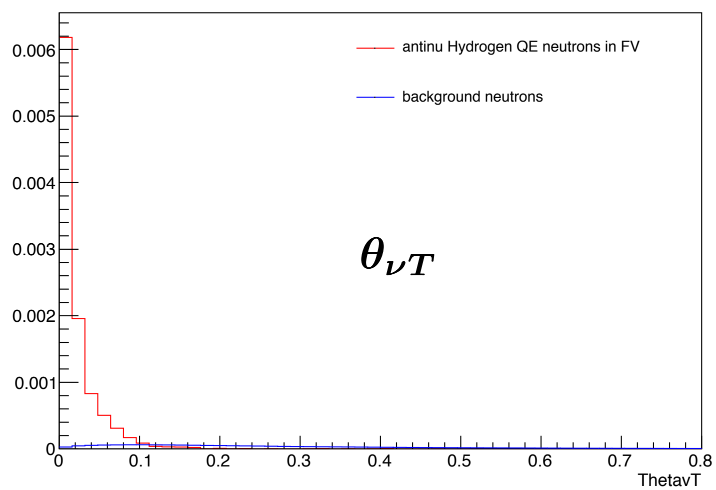

*Distribution of H/C likelihood ratio for H events with correct choice of primary n (red) and wrong choice of external random n (blue)*

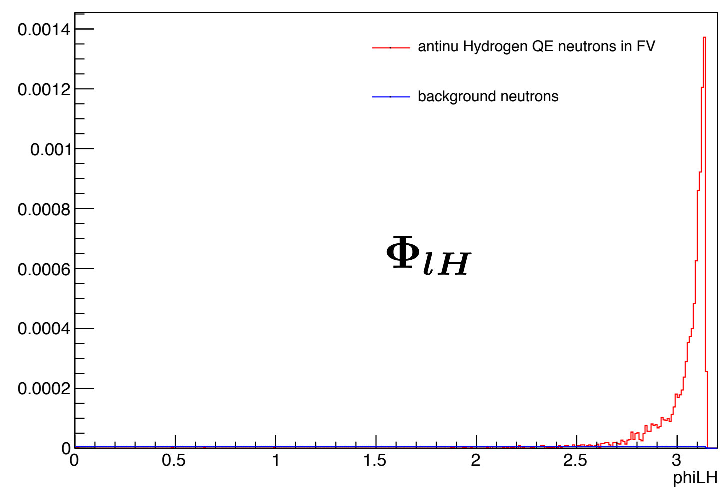



*Distribution of H/C likelihood ratio for H events with wrong choices of secondary n in H (red) and random external n (blue)*


antinu Hydrogen QE neutrons in FV
background neutrons
$R_{mH} \equiv \frac{p_T^m - p_T^H}{p_T^m + p_T^H}$
RmH


antinu Hydrogen QE neutrons in FV
background neutrons
$P_T^m$
Ptmis(MeV)


antinu Hydrogen QE neutrons in FV
background neutrons
$\theta_{\nu T}$
ThetavT


antinu Hydrogen QE neutrons in FV
background neutrons
$\Phi_{lH}$
phiLH