Kinematic Tagging and Identification of $\mu^\pm$

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DUNE ND meeting
October 16, 2020
Kinematic tagging must discriminate between the true $\mu^\pm$ track and wrong $h^\pm$ track inside the SAME CC event: total visible momentum is constant (3 constraints).

Consider 4 kinematic variables for muon tagging:

- $p_T^l$: transverse momentum of the track candidate;
- $\theta_{\nu l}$: angle of the track candidate with respect to beam direction;
- $y_{Bj}$: ratio between the energy of the “hadron system” (visible energy minus track energy) and the total visible energy;
- $R_{Q_T}$: ratio between the transverse size of the “hadron system” $\langle Q_T^2 \rangle_H$ and that of the full event $\langle Q_T^2 \rangle$, where $Q_T$ component of the track momentum perpendicular to the total visible momentum.
KINEMATIC TAGGING OF $\mu^-$ AND $\mu^+$

- From reconstructed momentum vector determine if the track will reach outer yoke: (i) sample reaching outer yoke; (ii) sample NOT reaching outer yoke.

- Veto tracks interacting within STT volume (both $\mu^-$ and $\mu^+$ tagging).

- Veto protons for $\mu^+$ tagging using NN for proton ID.

- For events with $\geq$ 2 candidate tracks calculate a NN value for each candidate track using two separate NN trainings for the two samples:
  - Tracks reaching outer yoke: use training with all events with $\geq$ 2 candidate tracks, $NN_1$;
  - Tracks NOT reaching outer yoke: use training with events with $\geq$ 2 candidate tracks & $\mu^+$ NOT reaching outer yoke ($NN_2$), multiply $NN_2$ values by optimized constant $c = 15.0$.

- Select the single negative/positive track in the event with the highest NN output:

<table>
<thead>
<tr>
<th>Event sample</th>
<th>Selected track</th>
<th>Tagging efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>FHC $\nu_\mu$ CC</td>
<td>$\mu^-$</td>
<td>99.1%</td>
</tr>
<tr>
<td>RHC $\bar{\nu}_\mu$ CC</td>
<td>$\mu^+$</td>
<td>99.3%</td>
</tr>
</tbody>
</table>
Costs and Detector Design

R. Petti
University of South Carolina

LBNE Near Detector Workshop
Columbia SC, December 12, 2009

FHC tagged $\mu^-$

Average efficiency 99.1%

FHC

Tagging efficiency

Muon momentum (GeV/c)

Muon momentum (GeV/c)
HiResM

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RHC tagged $\mu^+$

Average efficiency 99.3%

RHC

Tagging efficiency

Muon momentum (GeV/c)
REJECTION OF NC BACKGROUND

✦ Focus on tagged tracks NOT reaching outer yoke ($\sim 30\%$ of $\mu^-$, $14\%$ of $\mu^+$):
  ● NC background from tagged tracks reaching outer yoke $\sim 0.1\%$;
  ● No cuts for tagged tracks reaching outer yoke $\implies$ external muon identifier with single active layer.

✦ Three rejection criteria available:
  ● Energy deposition and topology (interactions) in ECAL;
  ● Track variables related to the kinematic tagging;
  ● Event kinematics based on isolation & transverse plane kinematics.

$\implies$ Specific cuts applied will depend on the particular physics analysis

✦ For the selection of CC interactions on hydrogen only $\mu^\pm$ tagging needed: kinematic selection of H reduces NC backgrounds to $< 10^{-3}$.

✦ Initial optimization of $\mu^\pm$ identification without global event kinematics.
$\implies$ ECAL identification with $NN > 0.36$ (0.95) for FHC $\nu_\mu$ CC (RHC)
Tagged tracks reaching barrel ECAL and NOT reaching outer yoke
νμCC+̅νμCC+NC: efficiency 98.4%, wrong sign 0.5%
### Selection of $\nu_\mu$ CC in the FHC beam with tagged $\mu^-$

<table>
<thead>
<tr>
<th>Target</th>
<th>Cuts</th>
<th>Efficiency</th>
<th>$\nu_\mu$ CC + $\bar{\nu}_\mu$ CC + NC</th>
<th>Wrong sign contamination</th>
</tr>
</thead>
<tbody>
<tr>
<td>STT</td>
<td>Kinematic tagging of $\mu^-$</td>
<td>99.1 %</td>
<td>93.2 %</td>
<td>1.4 %</td>
</tr>
<tr>
<td>STT</td>
<td>ECAL on tagged $\mu^-$</td>
<td>98.4 %</td>
<td>97.5 %</td>
<td>0.5 %</td>
</tr>
<tr>
<td>ECAL</td>
<td>Kinematic tagging of $\mu^-$</td>
<td>99.7 %</td>
<td>96.2 %</td>
<td>0.4 %</td>
</tr>
<tr>
<td>ECAL</td>
<td>ECAL on tagged $\mu^-$</td>
<td>97.9 %</td>
<td>98.4 %</td>
<td>0.2 %</td>
</tr>
</tbody>
</table>
REJECTION OF WRONG SIGN BACKGROUND

✦ For each event apply BOTH $\mu^-$ and $\mu^+$ tagging

$\implies$ Select single $\mu^-$ and single $\mu^+$ candidate within same event

✦ If wrong sign candidate exists:

● Reject events with wrong sign candidate reaching outer yoke;

● Reject events with wrong sign candidate identified in ECAL if right sign one NOT reaching outer yoke.

$\implies$ Efficient tagging allows use of magnet yoke to filter out wrong sign background
νμCC+νμ̅CC+NC: efficiency 97.9%, wrong sign 0.3%
<table>
<thead>
<tr>
<th>Cuts</th>
<th>Efficiency</th>
<th>Purity $\nu_\mu$ CC + $\bar{\nu}_\mu$ CC + NC</th>
<th>Wrong sign contamination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematic tagging of $\mu^+$</td>
<td>99.3 %</td>
<td>76.2 %</td>
<td>11.1 %</td>
</tr>
<tr>
<td>ECAL on tagged $\mu^+$</td>
<td>98.8 %</td>
<td>90.0 %</td>
<td>6.1 %</td>
</tr>
<tr>
<td>Wrong sign veto on tagged $\mu^-$</td>
<td>97.9 %</td>
<td>97.8 %</td>
<td>0.3 %</td>
</tr>
</tbody>
</table>

*Selection of $\bar{\nu}_\mu$ CC in the RHC beam with tagged $\mu^+$*
HiResM

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Muon momentum (GeV/c)

RHC

Purity

Average purity 97.3%

RHC $\mu^-$ selection

$\nu_\mu CC + \bar{\nu}_\mu CC + NC$: efficiency 95.4%, wrong sign 0.3%
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</tr>
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<tbody>
<tr>
<td>Kinematic tagging of $\mu^-$</td>
<td>98.7 %</td>
<td>66.4 %</td>
<td>22.7 %</td>
</tr>
<tr>
<td>ECAL on tagged $\mu^-$</td>
<td>97.9 %</td>
<td>85.8 %</td>
<td>9.4 %</td>
</tr>
<tr>
<td>Wrong sign veto on tagged $\mu^+$</td>
<td>95.4 %</td>
<td>97.3 %</td>
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Selection of $\nu_\mu$ CC in the RHC beam with tagged $\mu^-$
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μν:

FHC

Average purity 83.2%

FHC μ⁺ selection

νμCC+νμCC+NC: efficiency 97.1%, wrong sign 2.3%
Event kinematics from tagged $\mu^\pm$ and hadron momentum vectors: $\vec{p}_l, \vec{p}_H$.

Likelihood function used to separate CC/NC:

$$\mathcal{L}^{\text{NC}} = [[[\theta_{\nu H}, \theta_{\nu T}], \theta_{\mu i}, Q_T], p_T^m, \phi_{lH}]$$

- $\theta_{\nu H}$ angle of the total hadron momentum with respect to the beam direction;
- $\theta_{\nu T}$ angle of total visible momentum with respect to the beam direction;
- $\theta_{\mu i}$ minimum opening angle between muon and any other primary track;
- $Q_T$ component of the muon momentum perpendicular to the total visible momentum;
- $p_T^m$ missing transverse momentum;
- $\Phi_{lH}$ angle between transverse momenta of muon and hadron system.
- The square brackets denote multi-dimensional correlations.

Discriminant variable $\ln$ of likelihood ratio between CC signal and NC bkgnd

$\implies$ Kinematic rejection of NC needed for $\bar{\nu}_\mu$ CC selection in FHC
Distributions after muon tagging, ECAL identification and wrong sign veto
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Average purity 93.0%

$\nu_\mu CC + \bar{\nu}_\mu CC + NC$: efficiency 95.8%, wrong sign 2.6%
<table>
<thead>
<tr>
<th>Cuts</th>
<th>Efficiency</th>
<th>( \nu_\mu ) CC + ( \nu_\mu ) CC + NC</th>
<th>Wrong sign contamination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematic tagging of ( \mu^+ )</td>
<td>99.3 %</td>
<td>9.9 %</td>
<td>78.0 %</td>
</tr>
<tr>
<td>ECAL on tagged ( \mu^+ )</td>
<td>98.2 %</td>
<td>34.2 %</td>
<td>55.1 %</td>
</tr>
<tr>
<td>Wrong sign veto on tagged ( \mu^- )</td>
<td>97.1 %</td>
<td>83.2 %</td>
<td>2.3 %</td>
</tr>
<tr>
<td>Kinematics</td>
<td>95.8 %</td>
<td>93.0 %</td>
<td>2.6 %</td>
</tr>
</tbody>
</table>

Selection of \( \bar{\nu}_\mu \) CC in the FHC beam with tagged \( \mu^+ \)
Backup slides
CC events with more than one negative track: all tracks
CC events with more than one negative track: tracks not reaching outer yoke
CC events with more than one negative track: all tracks
CC events with more than one negative track: tracks not reaching outer yoke