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

B. Guo and R. Petti

University of South Carolina, Columbia SC, USA

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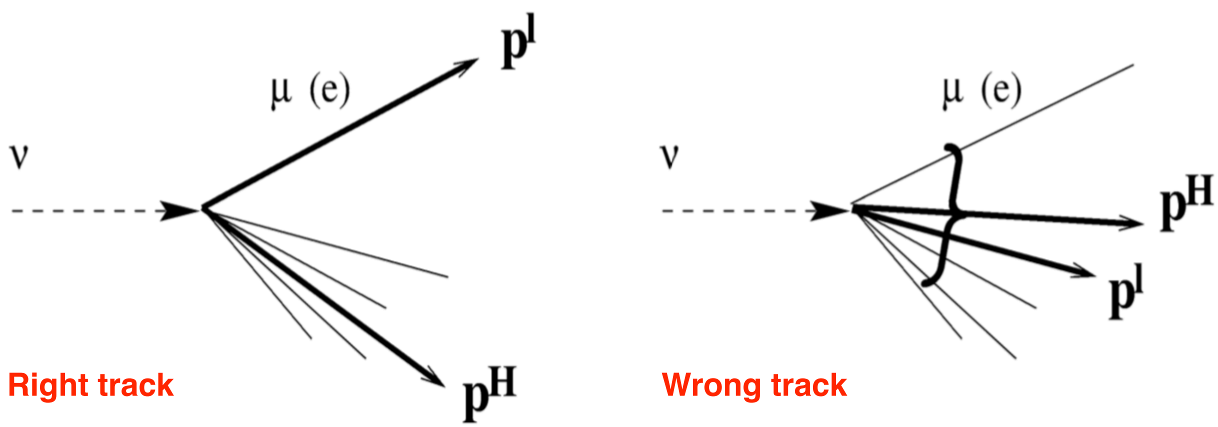
KINEMATIC VARIABLES

✦ *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 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 μ^- AND μ^+

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

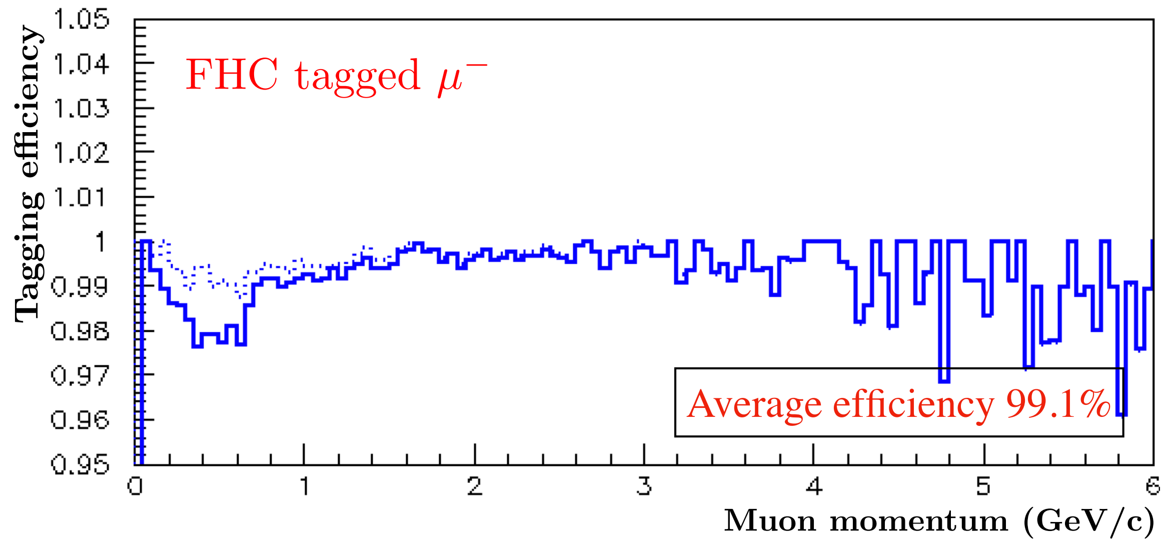
- *Veto tracks interacting within STT volume (both μ^- and μ^+ tagging).*

- *Veto protons for μ^+ tagging using NN for proton ID.*

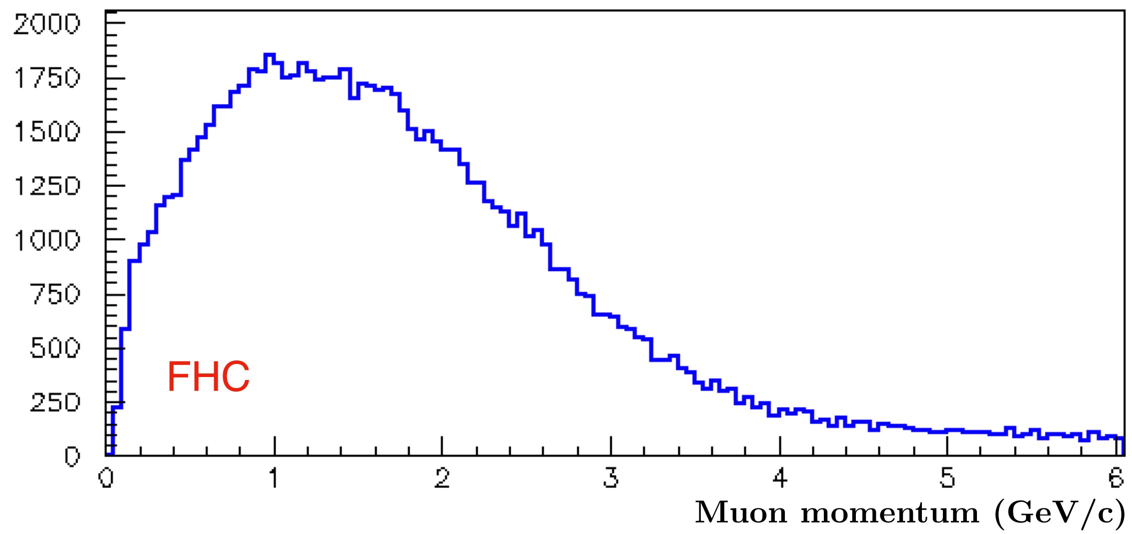
- *For events with ≥ 2 candidate tracks calculate a NN value for each candidate track using two separate NN trainings for the two samples:*
  - *Tracks reaching outer yoke: use training with all events with ≥ 2 candidate tracks, NN_1;*
  - *Tracks NOT reaching outer yoke: use training with events with ≥ 2 candidate tracks & $\mu^{\mp}$ 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:*

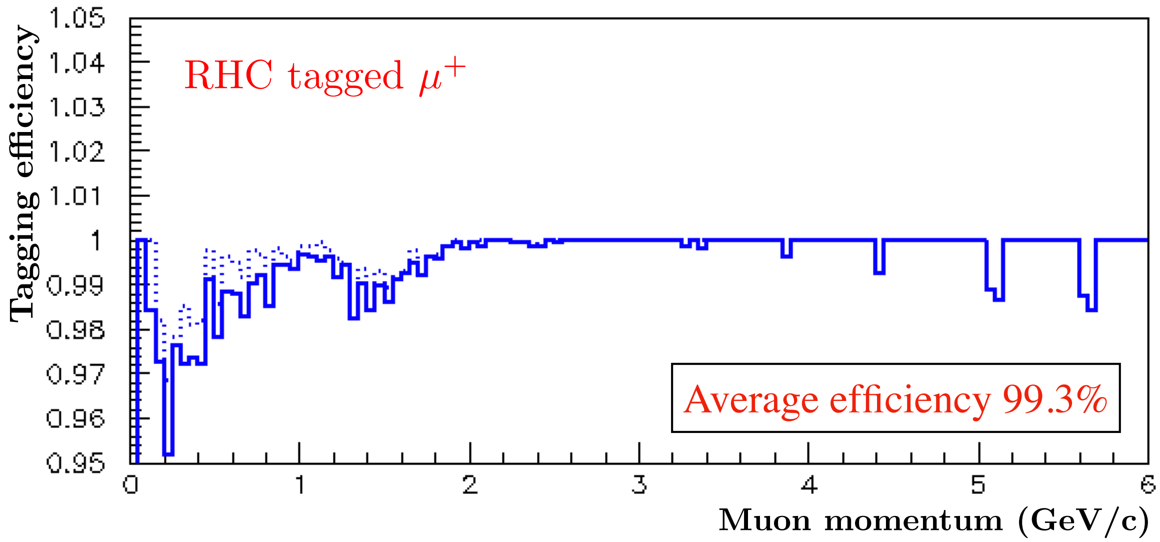
Event sample	Selected track	Tagging efficiency
FHC ν_μ CC	μ^-	**99.1%**
RHC $\bar{\nu}_\mu$ CC	μ^+	**99.3%**

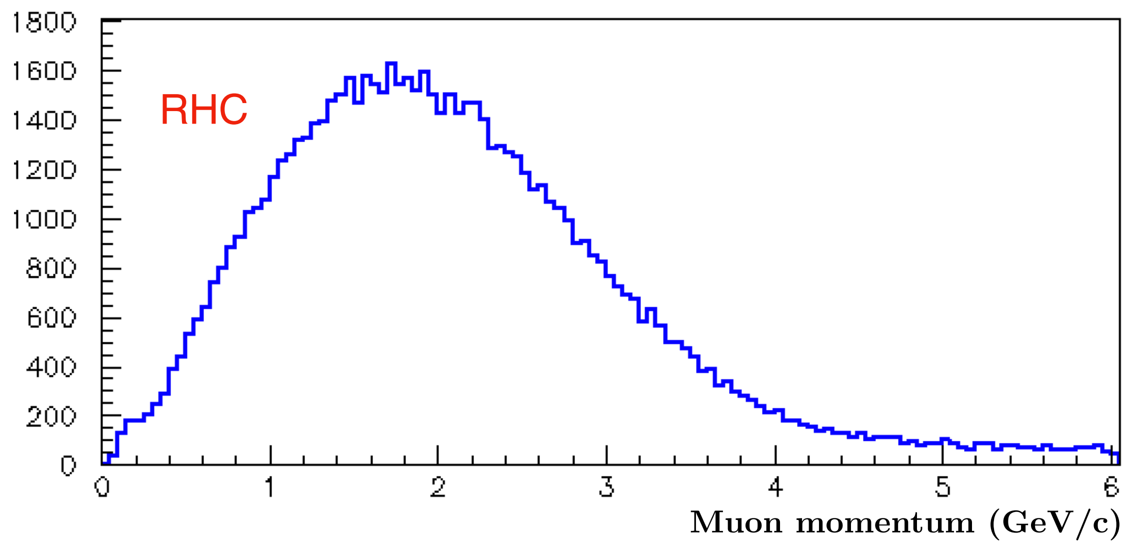


Tagging efficiency
FHC tagged μ^-
Average efficiency 99.1%
Muon momentum (GeV/c)



FHC
Muon momentum (GeV/c)


RHC tagged μ^+
Average efficiency 99.3%
Tagging efficiency
Muon momentum (GeV/c)


RHC
Muon momentum (GeV/c)

REJECTION OF NC BACKGROUND

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

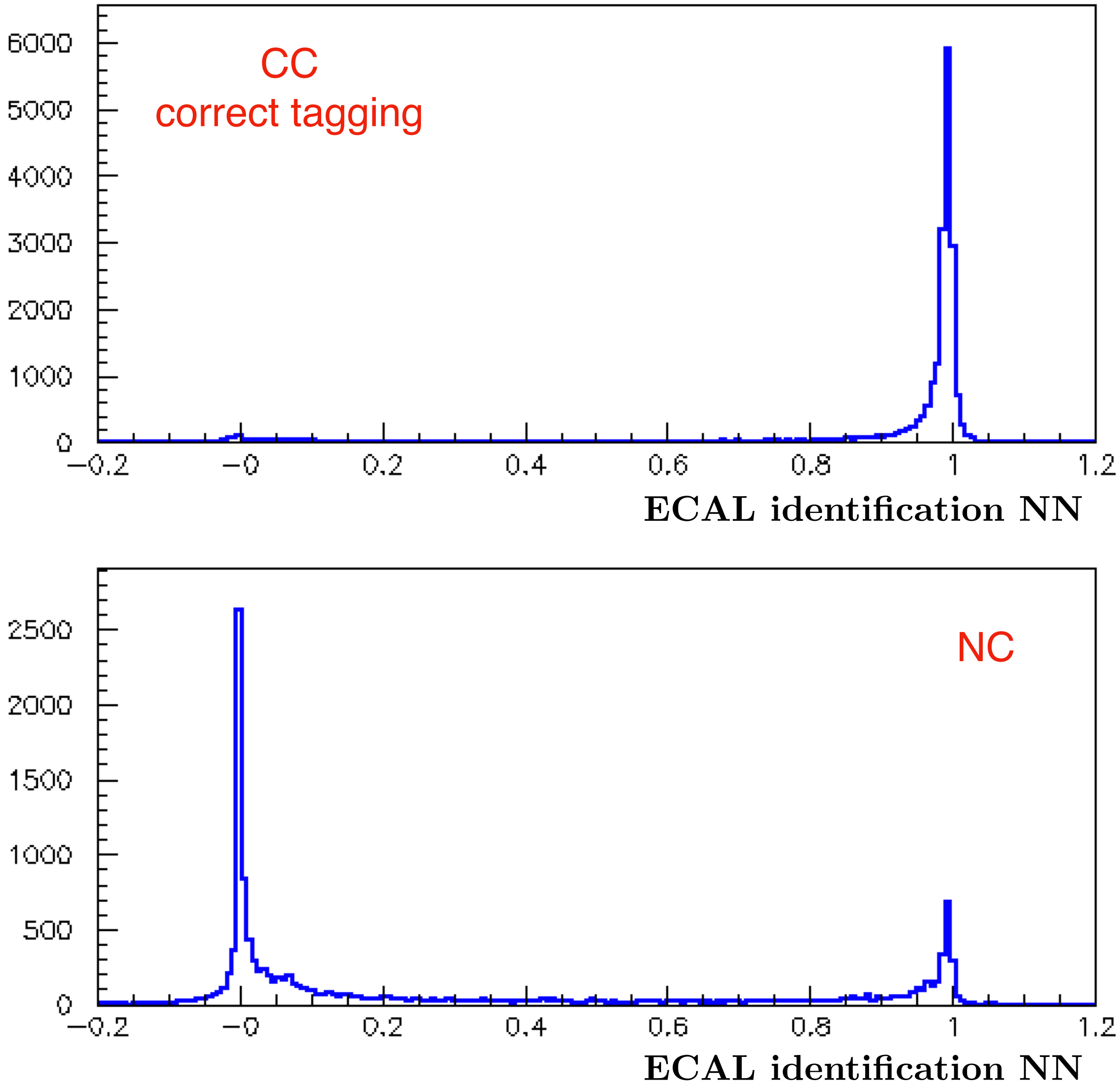
- *Three rejection criteria available*:
  - Energy deposition and topology (interactions) in ECAL;
  - Track variables related to the kinematic tagging;
  - Event kinematics based on isolation & transverse plane kinematics.

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

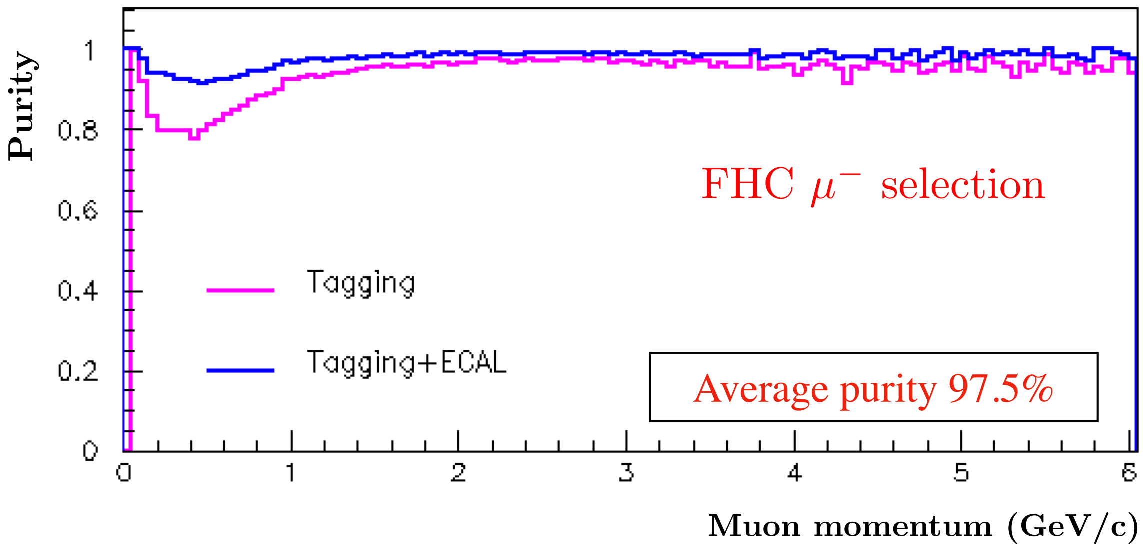
- For the selection of CC interactions on hydrogen only $\mu^\pm$ tagging needed: kinematic selection of H reduces NC backgrounds to $< 10^{-3}$.

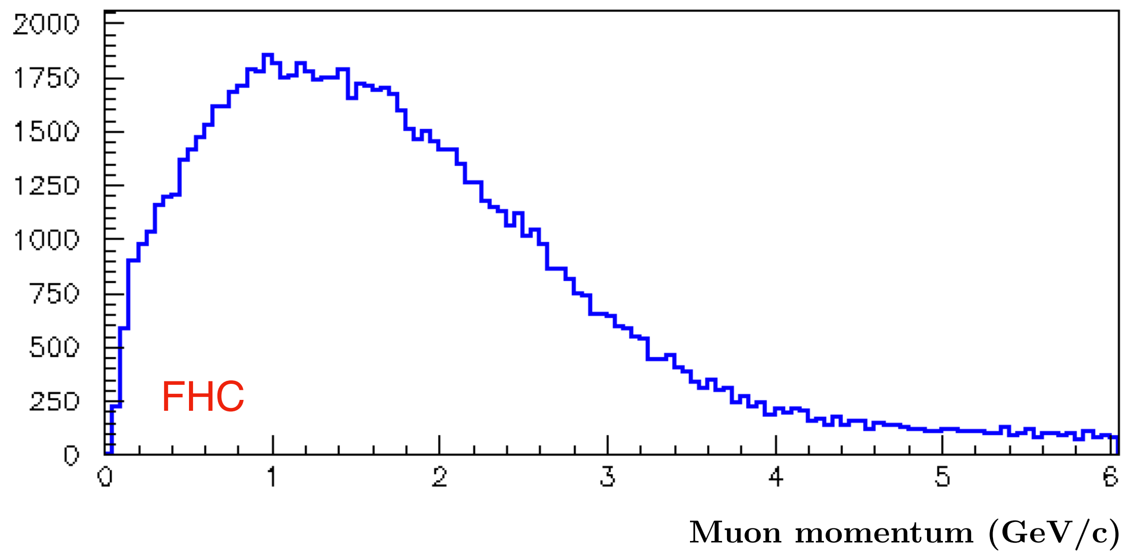
- Initial optimization of $\mu^\pm$ identification without global event kinematics.

  $\Longrightarrow$ ECAL identification with NN>0.36 (0.95) for FHC ν_μ CC (RHC)



Tagged tracks reaching barrel ECAL and NOT reaching outer yoke





ν_μCC+$\bar{\nu}_\mu$CC+NC: efficiency 98.4%, wrong sign 0.5%

Target	Cuts	Efficiency	Purity ν_μ CC + $\bar{\nu}_\mu$ CC + NC	Wrong sign contamination
STT	Kinematic tagging of μ^-	99.1 %	93.2 %	1.4 %
STT	ECAL on tagged μ^-	98.4 %	97.5 %	0.5 %
ECAL	Kinematic tagging of μ^-	99.7 %	96.2 %	0.4 %
ECAL	ECAL on tagged μ^-	97.9 %	98.4 %	0.2 %

Selection of ν_μ CC in the FHC beam with tagged μ^-

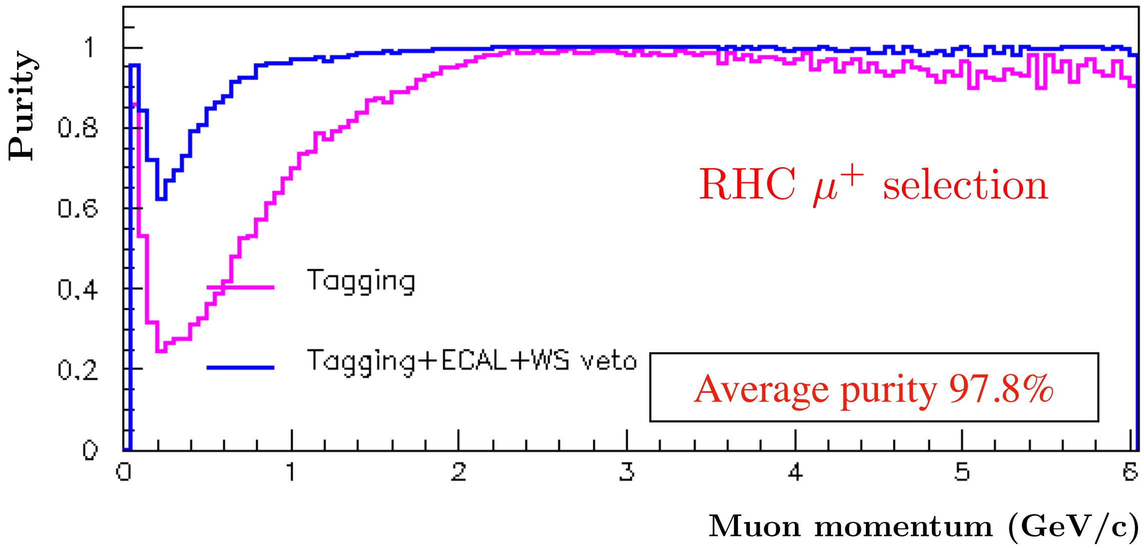
REJECTION OF WRONG SIGN BACKGROUND

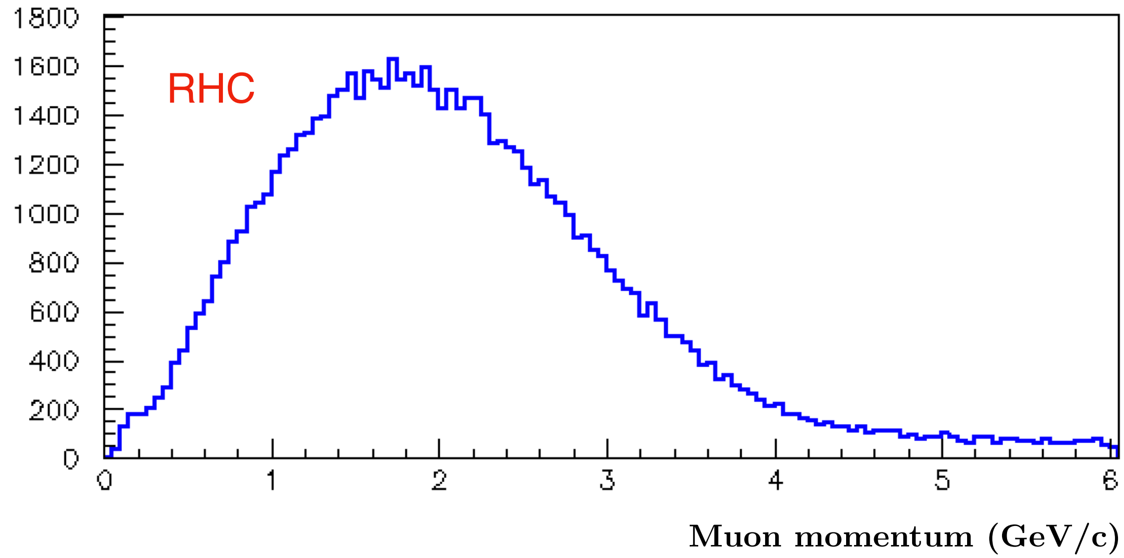
- *For each event apply BOTH μ^- and μ^+ tagging*

  $\Longrightarrow$ *Select single μ^- and single μ^+ 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.*

  $\Longrightarrow$ *Efficient tagging allows use of magnet yoke to filter out wrong sign background*

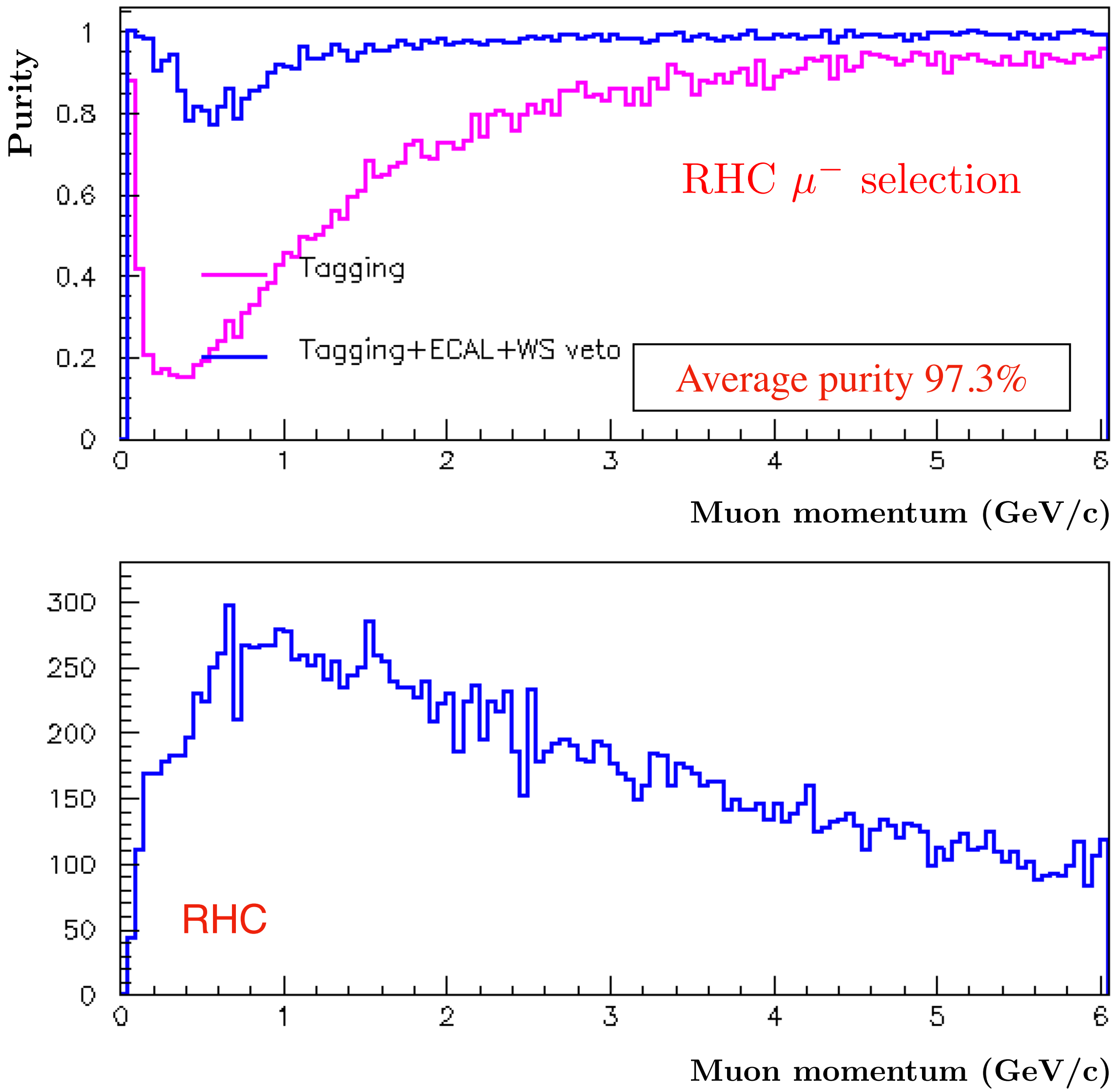




ν_μCC+$\bar{\nu}_\mu$CC+NC: efficiency 97.9%, wrong sign 0.3%

Cuts	Efficiency	Purity ν_μ CC + $\bar{\nu}_\mu$ CC + NC	Wrong sign contamination
Kinematic tagging of μ^+	99.3 %	76.2 %	11.1 %
ECAL on tagged μ^+	98.8 %	90.0 %	6.1 %
Wrong sign veto on tagged μ^-	97.9 %	97.8 %	0.3 %

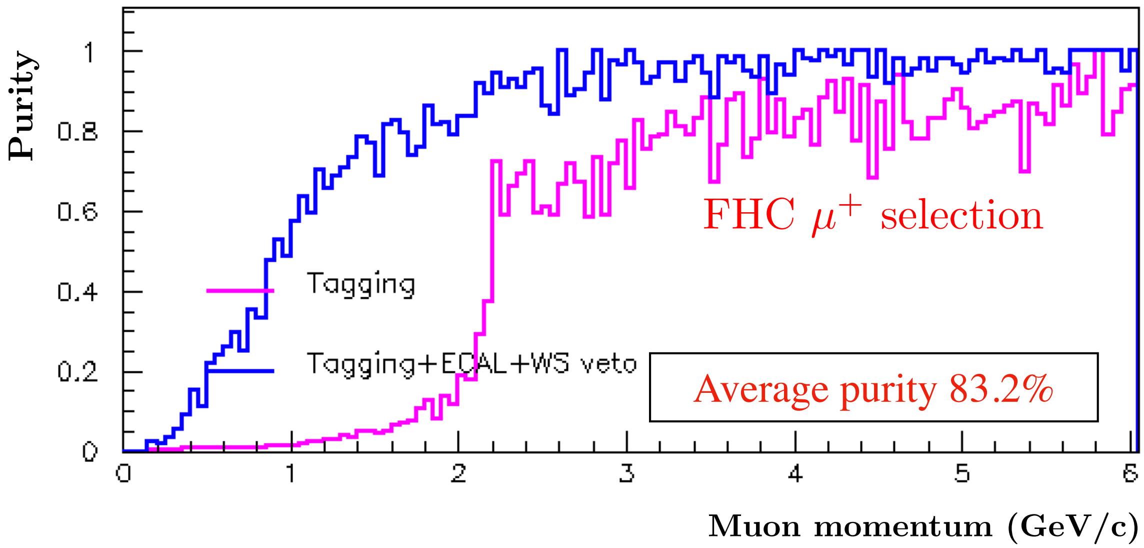
Selection of $\bar{\nu}_\mu$ CC in the RHC beam with tagged μ^+

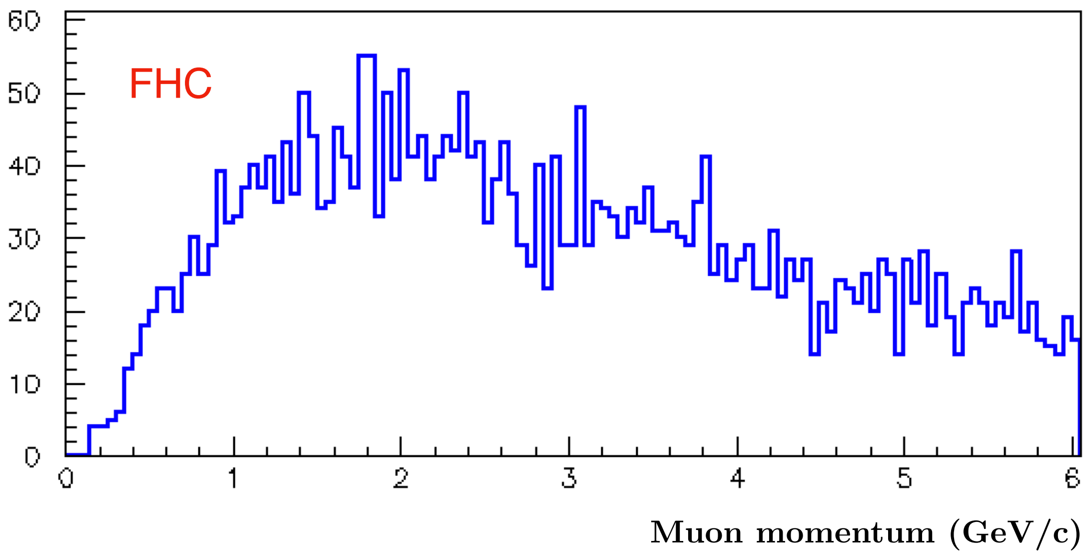


ν_μCC+$\bar{\nu}_\mu$CC+NC: efficiency 95.4%, wrong sign 0.3%

Cuts	Efficiency	Purity ν_μ CC + $\bar{\nu}_\mu$ CC + NC	Wrong sign contamination
Kinematic tagging of μ^-	98.7 %	66.4 %	22.7 %
ECAL on tagged μ^-	97.9 %	85.8 %	9.4 %
Wrong sign veto on tagged μ^+	95.4 %	97.3 %	0.3 %

Selection of ν_μ CC in the RHC beam with tagged μ^-





$\nu_\mu CC + \bar{\nu}_\mu CC + NC$: efficiency 97.1%, wrong sign 2.3%

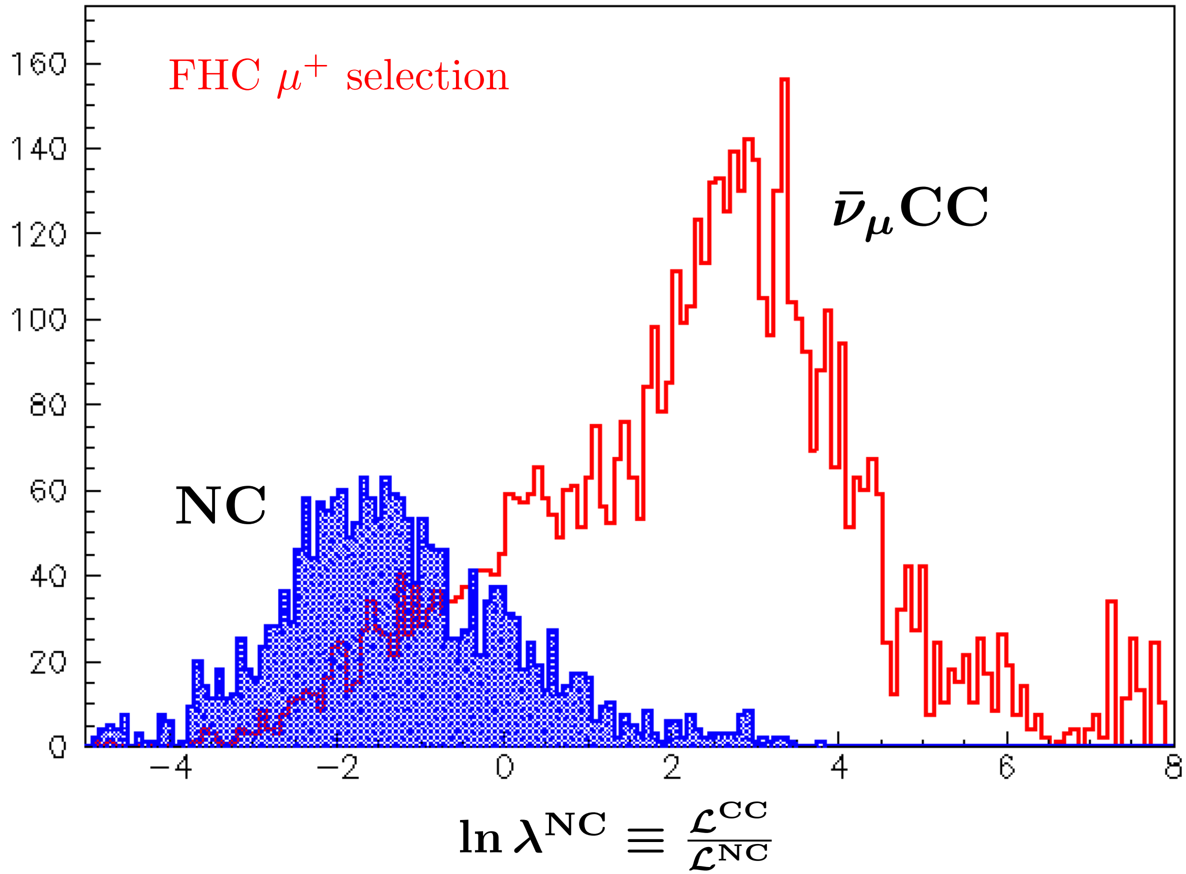
KINEMATIC REJECTION OF NC

- *Event kinematics from tagged $\mu^{\pm}$ and hadron momentum vectors: $\vec{p}_l, \vec{p}_H$.*
- *Likelihood function used to separate CC/NC:*

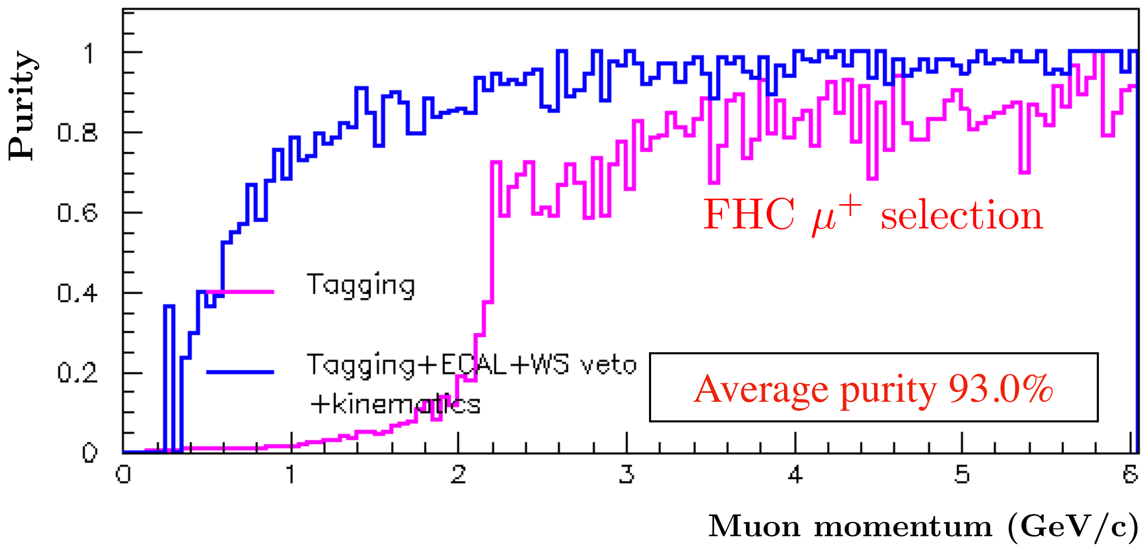
$$\mathcal{L}^{\rm NC} = [[[\ \theta_{\nu H},\ \theta_{\nu T}\ ], \theta_{lh_i},\ Q_T]\ ,\ p_T^m,\ \phi_{lH}\ ]$$

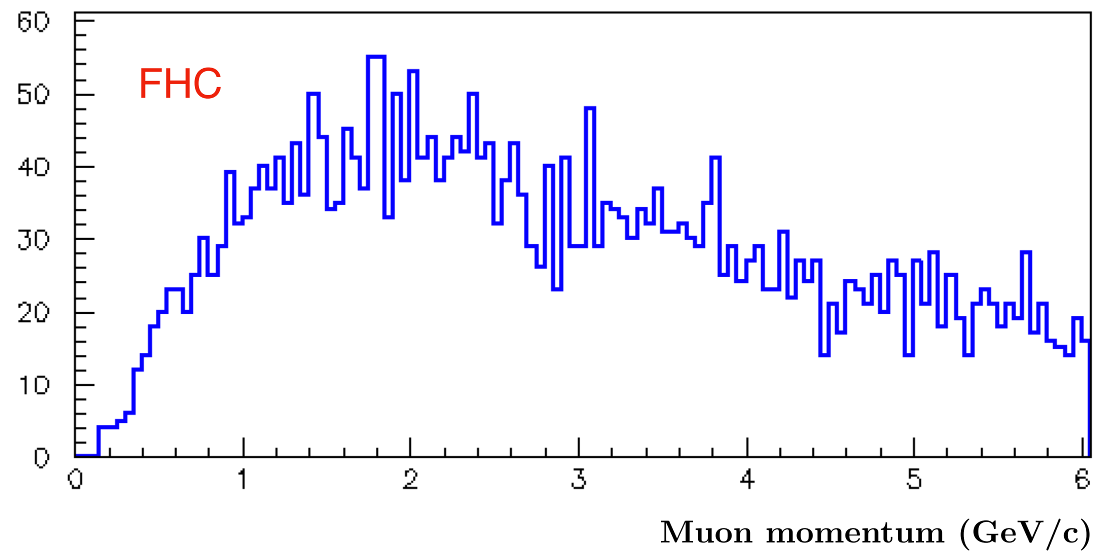
  - $\theta_{\nu H}$ *angle of the total hadron momentum with respect to the beam direction;*
  - $\theta_{\nu T}$ *angle of total visibl momentum with respect to the beam direction;*
  - θ_{lh_i} *minimum opening angle between muon and any other primary track;*
  - Q_T *component of the muon momentum perpendicular to the total visible momentum;*
  - p_T^m *missing transverse momentum;*
  - Φ_{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*

$\Longrightarrow$ *Kinematic rejection of NC needed for $\bar{\nu}_\mu$ CC selection in FHC*



Distributions after muon tagging, ECAL identification and wrong sign veto



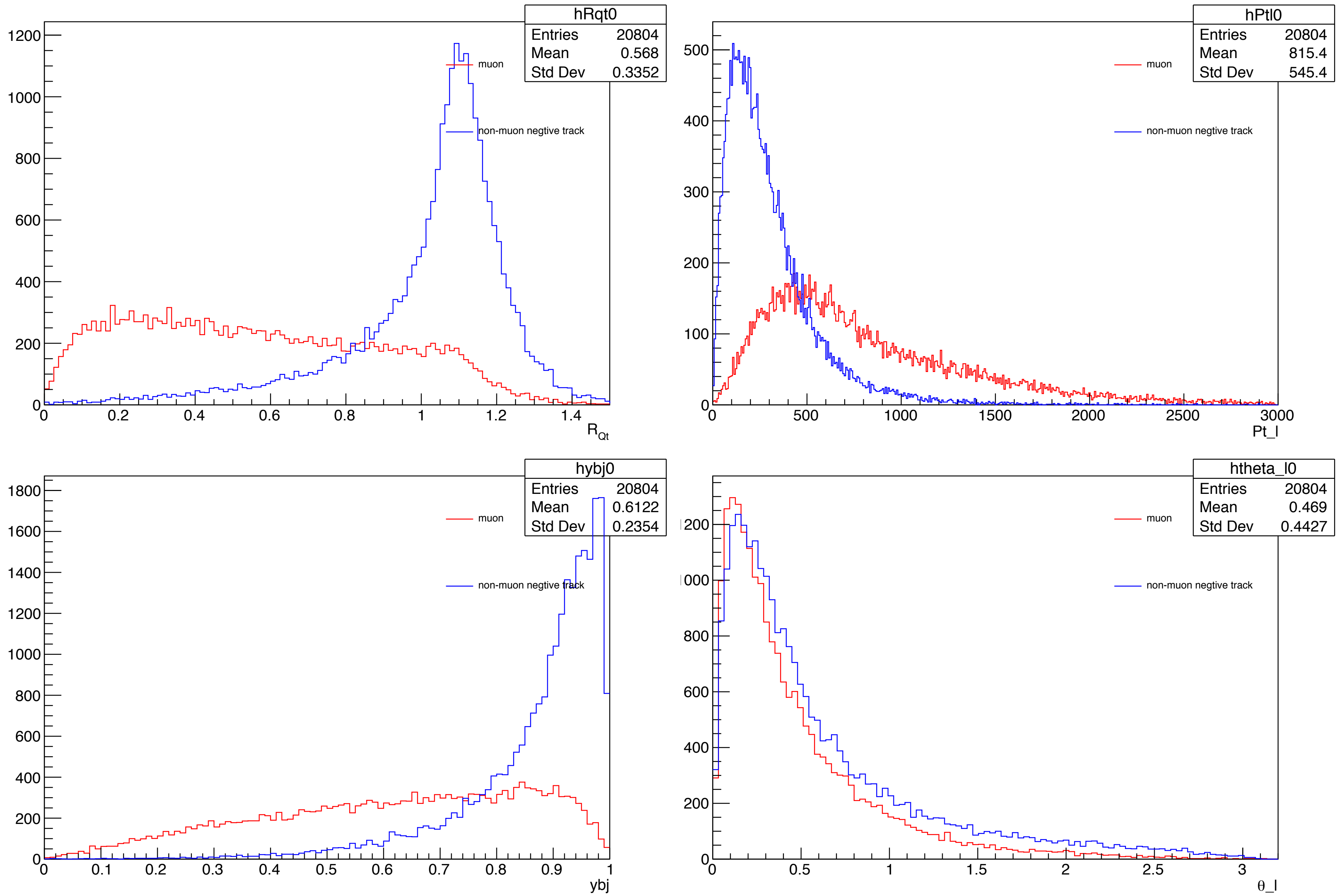


$\nu_\mu CC+\bar{\nu}_\mu CC+NC$: efficiency 95.8%, wrong sign 2.6%

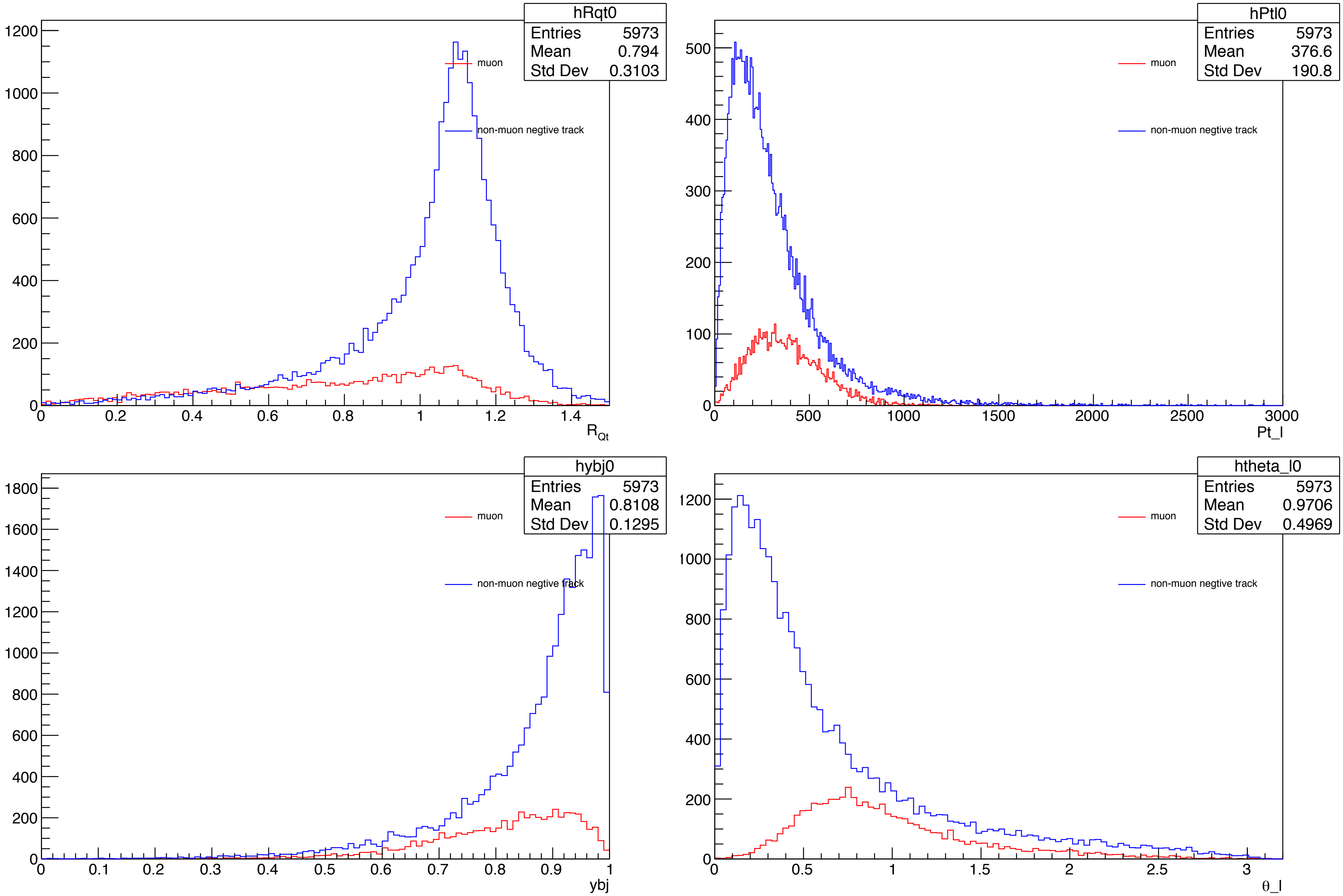
Cuts	*Efficiency*	*Purity* ν_μ CC + $\bar{\nu}_\mu$ CC + NC	*Wrong sign contamination*
Kinematic tagging of μ^+	99.3 %	9.9 %	78.0 %
ECAL on tagged μ^+	98.2 %	34.2 %	55.1 %
Wrong sign veto on tagged μ^-	97.1 %	83.2 %	2.3 %
Kinematics	95.8 %	93.0 %	2.6 %

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

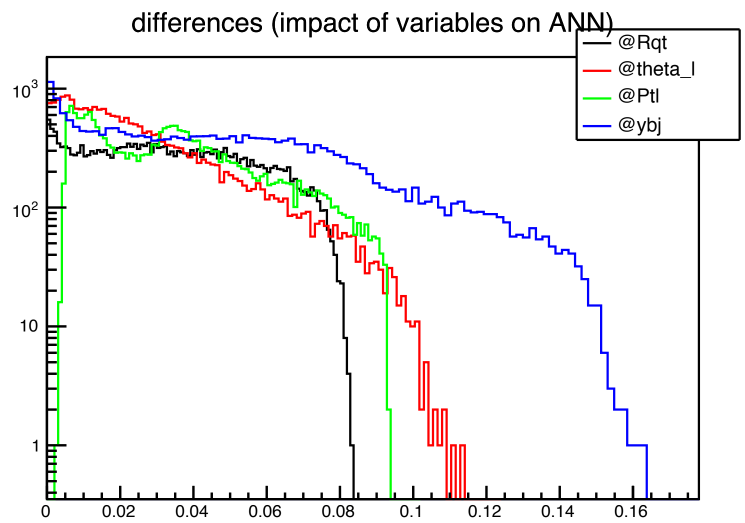
Backup slides

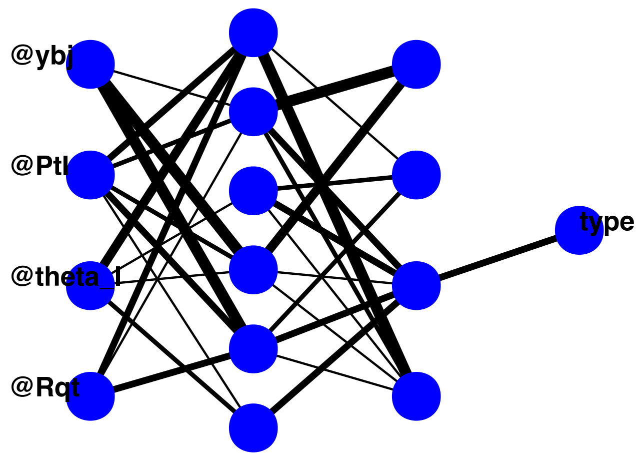


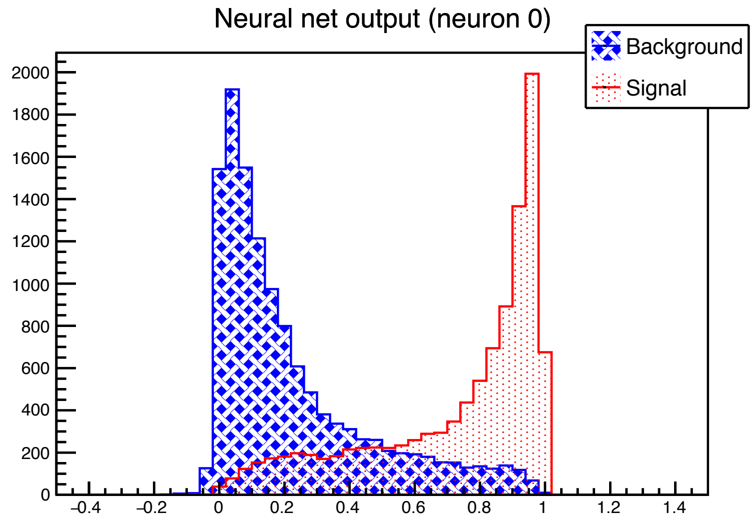
CC events with more than one negative track: <u>all tracks</u>

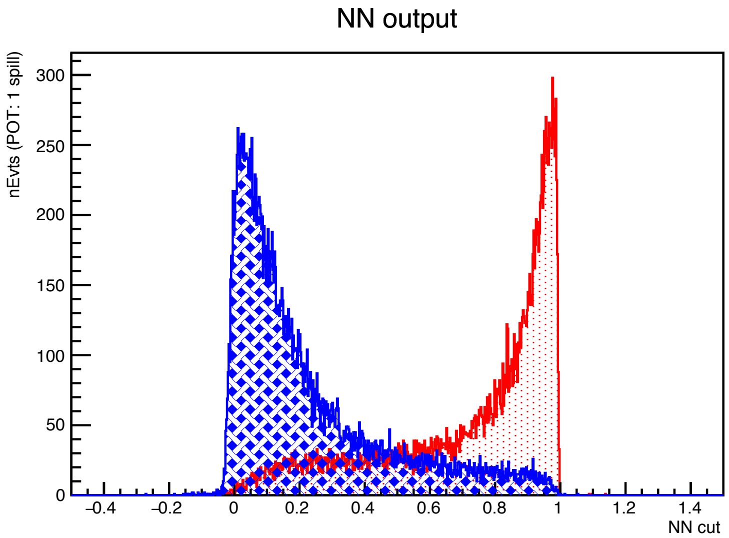


CC events with more than one negative track: <u>tracks not reaching outer yoke</u>









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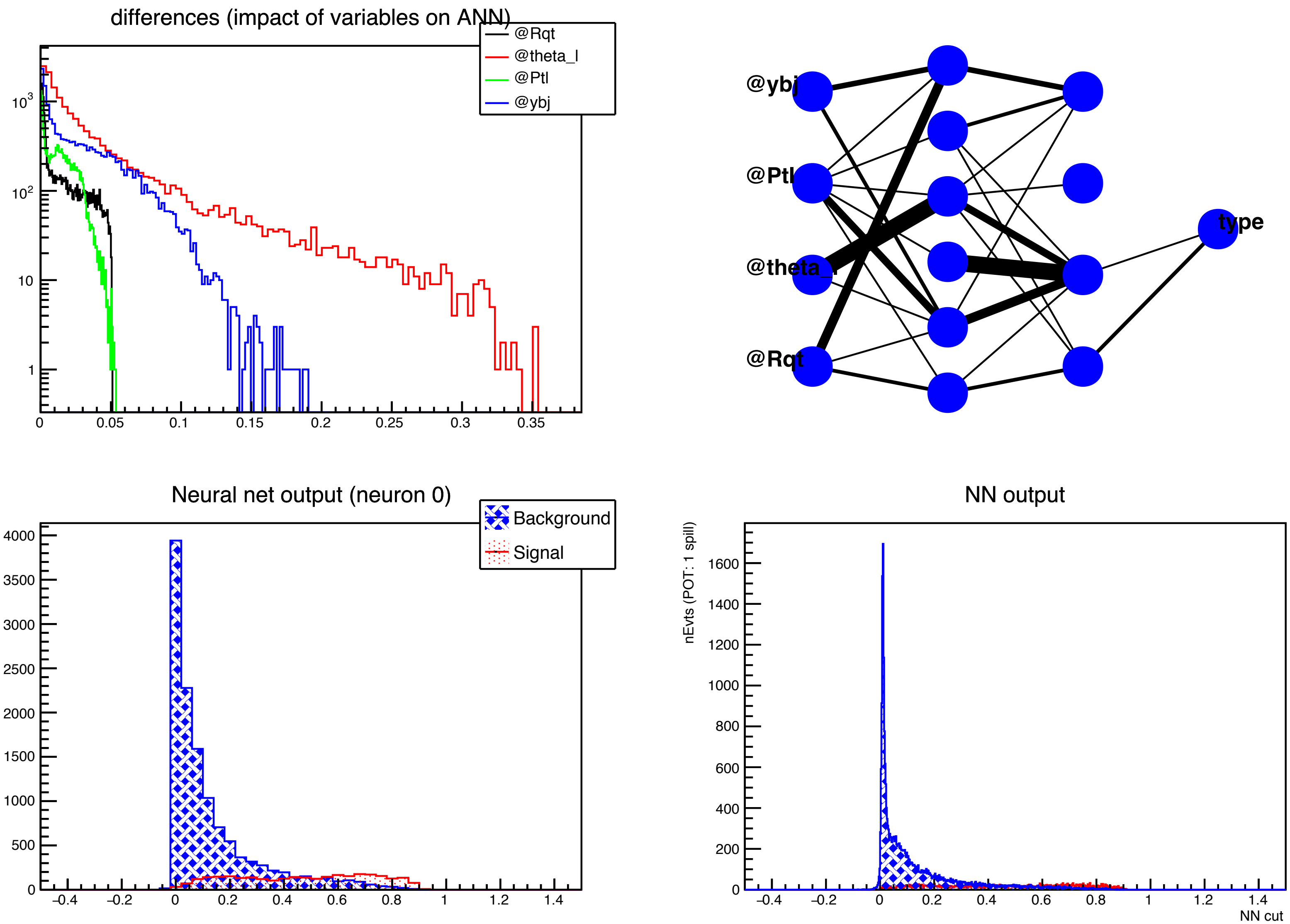

CC events with more than one negative track: <u>tracks not reaching outer yoke</u>