ν_τ Appearance: the NOMAD Experience

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THE NOMAD DETECTOR

✦ **Multi-purpose electronic detector:**

I *Low-density tracking*: $\rho \sim \mathbf{0.1}\ g/cm^{3}$

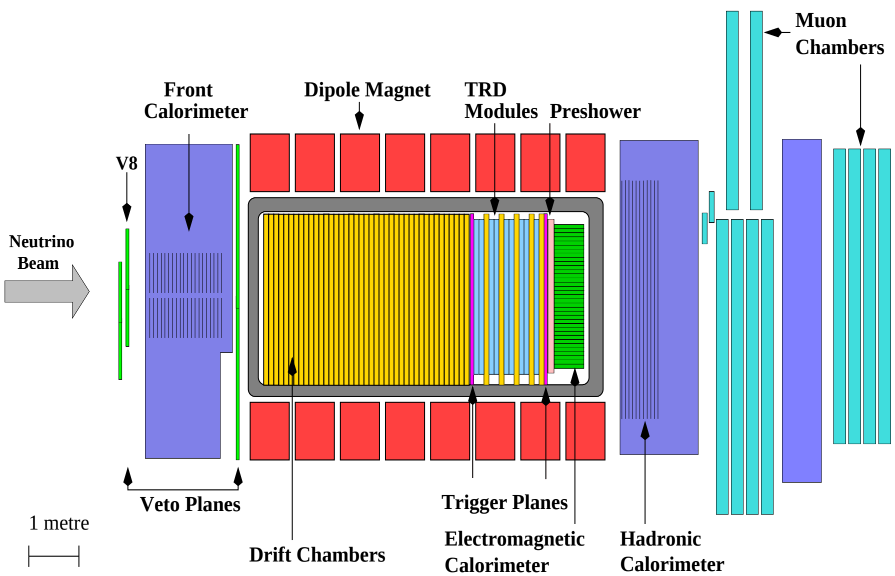
$\Longrightarrow \delta p/p \sim 3.5\%\ (p<10\mathrm{GeV}/c,\ B=0.4T)$;

II *Fine-grained calorimeter*

$\Longrightarrow \sigma(E)/E = 3.2\%/\sqrt{E[\mathrm{GeV}]} \oplus 1\%$;

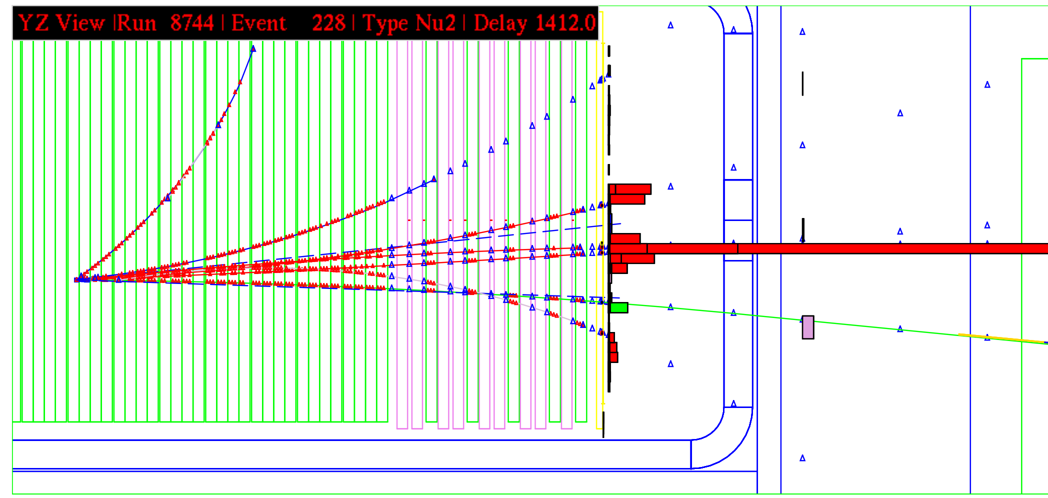
III *Excellent lepton identification & charge measurement*

$\Longrightarrow$ *Can detect* $\boldsymbol{\nu_\mu, \nu_e, \bar{\nu}_\mu, \bar{\nu}_e}$ **CC**.

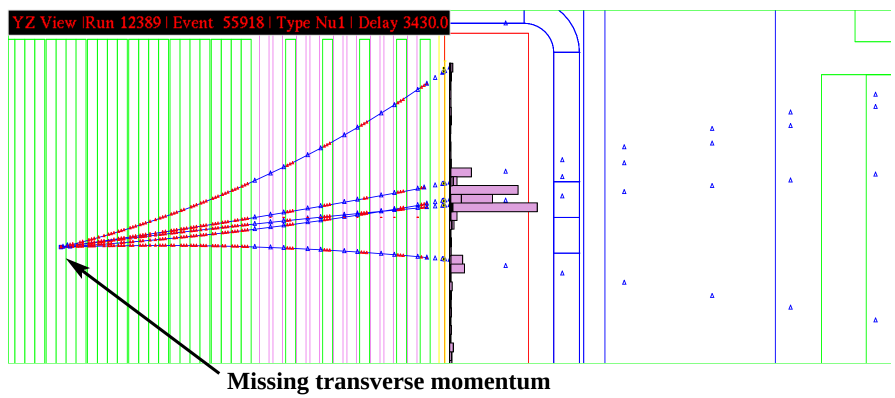


NOMAD Coll., NIM A 404 (1998) 96

ν_μ Charged Current



Neutral Current



THE NOMAD ν_τ SEARCH

- *Explicitly designed to search for* $\nu_\mu \to \nu_\tau$ *oscillations in the CERN SPS wide band neutrino beam at* $L \sim 620\ m$

- APPEARANCE *experiment.*
  ν_τ *is detected by CC interactions* $\nu_\tau + N \longrightarrow \tau^- + X$

- INDIRECT τ *identification throught its secondary visible decay products:*

$$\tau^- \longrightarrow \begin{cases} e^-\bar{\nu}_e\nu_\tau & 17.8\% \\ h^-(n\pi^0)\nu_\tau & 49.8\% \\ \pi^-\pi^-\pi^+(n\pi^0)\nu_\tau & 15.2\% \end{cases}$$

Total 82.8%

- *The signal is extracted from the tails of the background distributions by means of* KINEMATIC CRITERIA
  $\Longrightarrow\ \varepsilon_\tau \sim 1 \div 4\%,\ \varepsilon_{BKG} \sim 10^{-4} \div 10^{-6}$.

- *NOMAD also searched for* $\nu_\mu \to \nu_e$ *oscillations*

- *NOMAD is a detector suitable for general neutrino physics (a kind of "electronic bubble chamber")*

IDENTIFICATION OF ν_τ EVENTS

I Rejection of ν_μ (ν_e) Charged Current:

✦ LEPTONIC CHANNELS

Main background source:

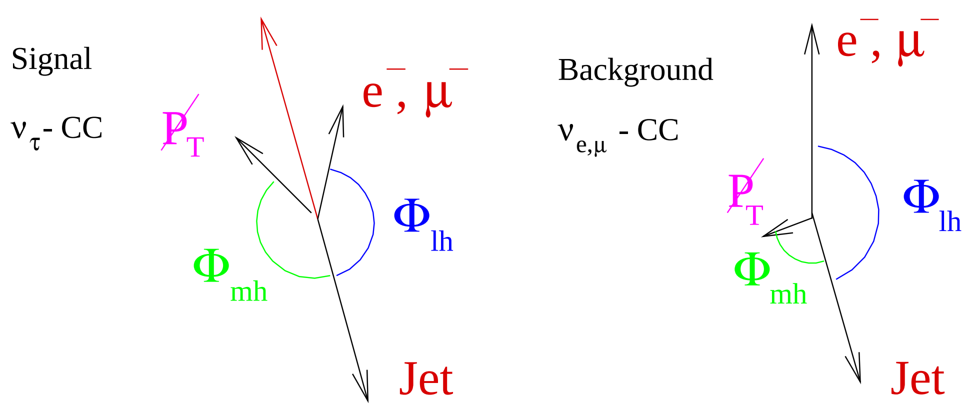
$\Longrightarrow$ *Kinematics based on momentum balance and angular relations in transverse plane*

✦ HADRONIC CHANNELS

Background from events where the leading muon is not identified:

$\Longrightarrow$ *Muon & electron veto - Muon and electron ID in detector, geometrical acceptance;*

$\Longrightarrow$ *Kinematics in transverse plane (looser).*



- *Amount of imbalance:*
  magnitude of the missing transverse momentum $\not{P}_T$
- *Direction of imbalance:*
  angle between lepton and hadronic jet transverse momenta Φ_{lh}
  angle between missing and hadronic jet transverse momenta Φ_{mh}
  ratios of transverse momenta $\rho_i \equiv P_T^i / \sum_i P_T^i$
- *Transverse mass* $M_T = \sqrt{(|\not{P}_T| + |P_T^l|)^2 - (P_T^{Jet})^2}$

II Rejection of ν_μ (ν_e) Neutral Current:

✦ HADRONIC CHANNELS

Largest background contribution:

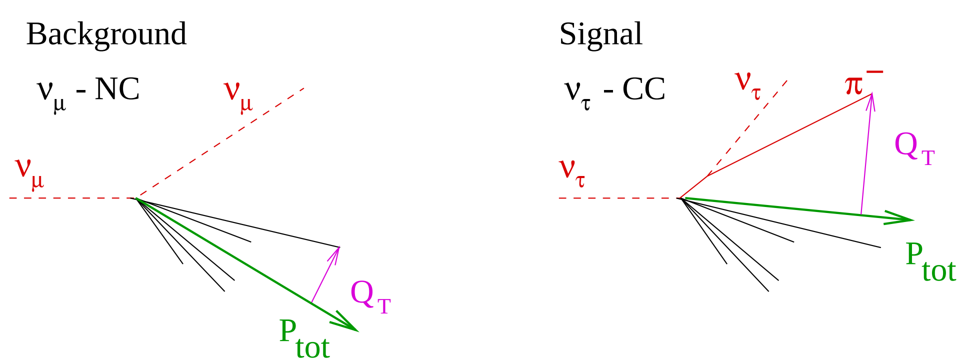
$\Longrightarrow$ *Isolation conditions*
between the τ visible decay product(s) and the hadronic jet.

✦ LEPTONIC CHANNELS

Wrong particle ID, genuine decays ($h^- \to e^-$, $\pi^0 \to \gamma e^+ e^-$ etc):

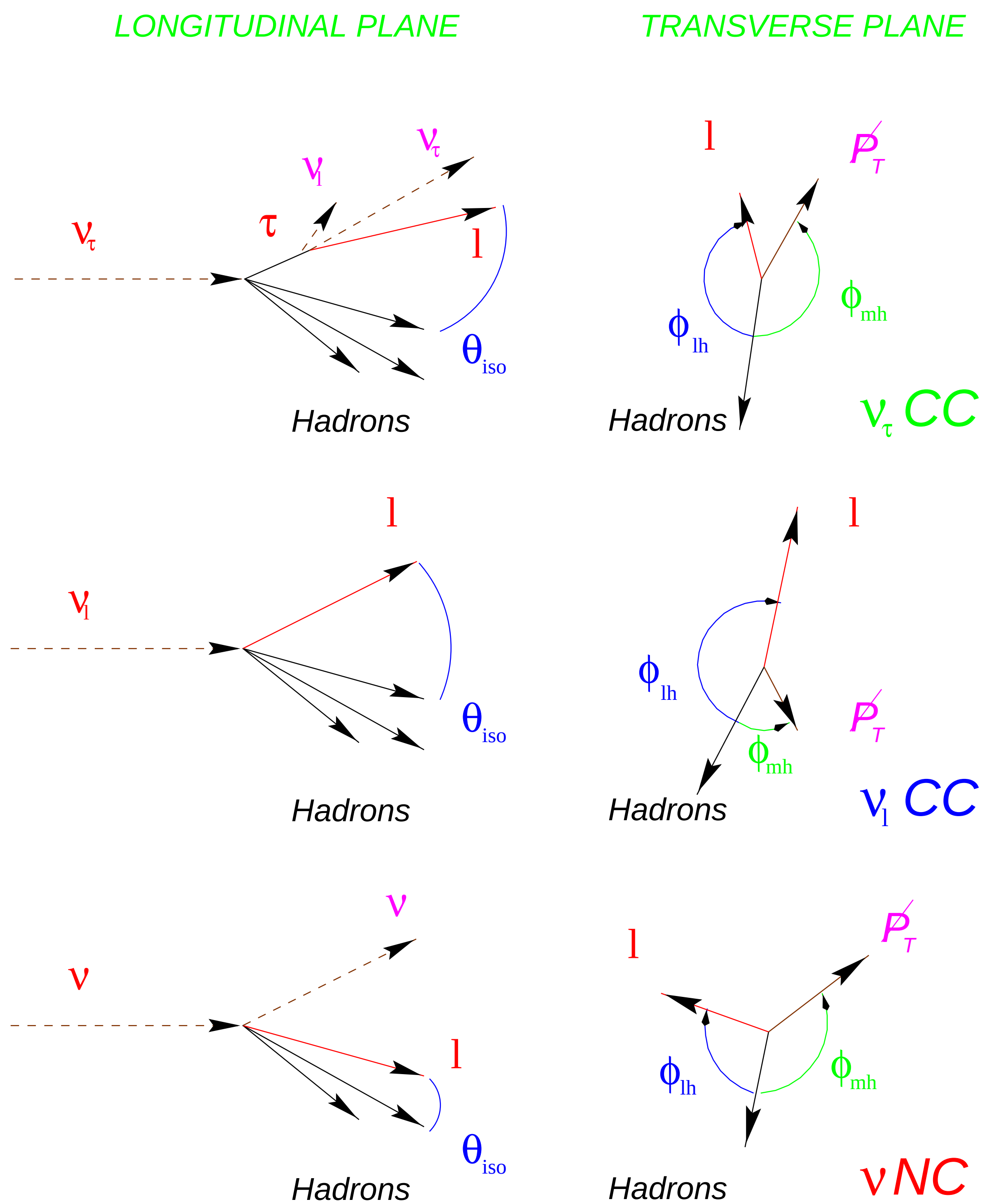
$\Longrightarrow$ *Lepton identification;*

$\Longrightarrow$ *Isolation with respect to the hadronic jet (looser).*



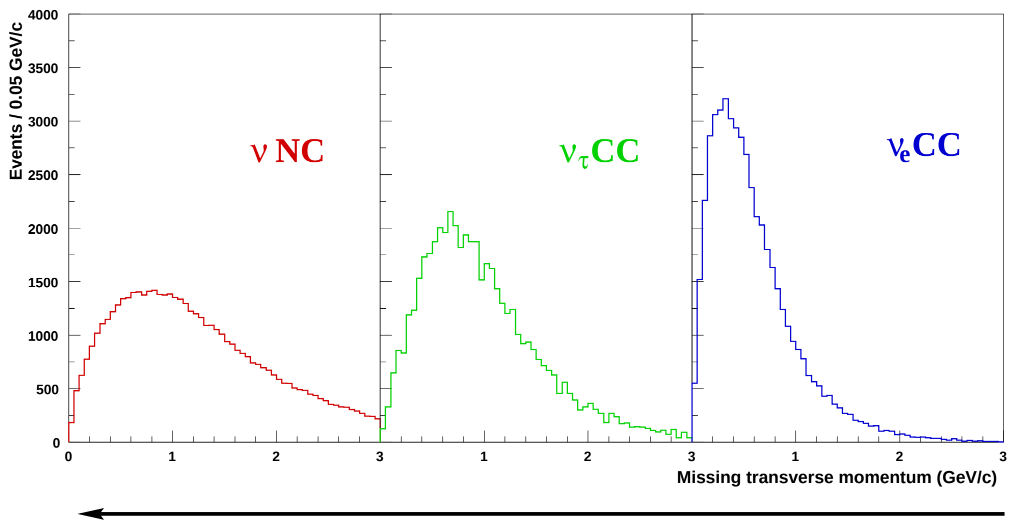
- *Momentum component of the τ visible decay products perpendicular to the visible momentum* $Q_T = \sqrt{(\vec{P}_{h^-})^2 - (\vec{P}_{h^-} \cdot \vec{P}_{tot})^2 / P_{tot}^2}$
- *Opening angle between the τ visible decay products and any other charged track* $\theta_{iso} = \arccos\,(\vec{P}_l \cdot \vec{P}_{h_i} / P_l P_{h_i})$

III Signal $\nu_\tau CC$ has intermediate properties between CC and NC backgrounds:

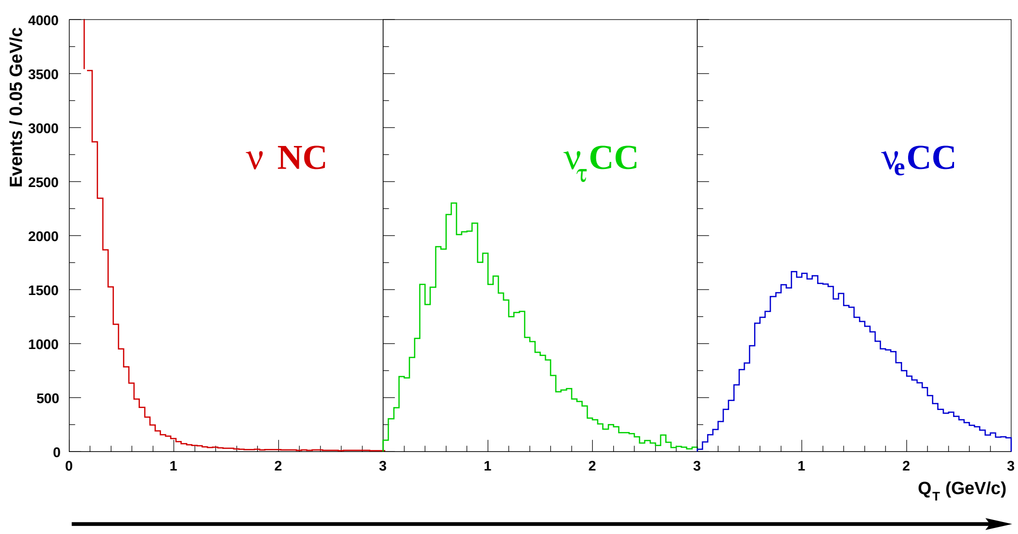


Difficult to reject efficiently both background sources with simple kinematic criteria $\Longrightarrow$ opposite requirements.

- *Final state neutrino(s)* $\Longrightarrow$ $\not{P}_T(\nu_\tau CC) > \not{P}_T(\nu CC)$
  Visible τ *decay product(s)* $\Longrightarrow$ $\not{P}_T(\nu_\tau CC) < \not{P}_T(\nu NC)$



- *Visible* τ *decay product(s)* $\Longrightarrow$ $Q_T(\nu_\tau CC) > Q_T(\nu NC)$
  P_T *from large* τ *mass* $\Longrightarrow$ $Q_T(\nu_\tau CC) < Q_T(\nu CC)$



ANALYSIS & EVENT SELECTION

✦ FULL TOPOLOGY of visible *final-state particles*

$\Longrightarrow$ *Exploit complete set of* $X_{i=1,N}$ *kinematic variables*

✦ *Definition of probability density functions,* pdf $\mathcal{L}$,
for the given set X_i*, to be signal* ($\mathcal{L}_S$) *or background* ($\mathcal{L}_B$).

$\Longrightarrow$ *approximations to extract* $\mathcal{L}_S$ *and* $\mathcal{L}_B$ *from MC.*

✦ *The global pdf* $\mathcal{L}$ *is subdivided into n-dimensional partial pdf's with* $n < N$ *and* $n = 1, 2, 3, 4$*, chosen among the most discriminating internal* CORRELATIONS *of* X_i*:*

- *Can use product of the chosen n-dimensional partial pdf's* $P_n(X_i)$*:*

$$\mathcal{L} \;=\; \prod_{i=1}^{N} \mathrm{P}_n(\mathrm{X}_i) \qquad \mathrm{P}_n(\mathrm{X}_i) \;\equiv\; [X_1, ..., X_n]$$

- *Residual correlations among partial pdf's can also be considered:*

$$\mathcal{L} \;=\; [\mathrm{P}_{\mathbf{n}}, X_{n+1}, ..., X_N]$$

✦ *Event classification based on* LIKELIHOOD RATIO *between the signal S and background(s) B hypotheses:*

$$ln\,\lambda \;\stackrel{\mathrm{def}}{\equiv}\; ln\,\frac{\mathcal{L}_S}{\mathcal{L}_B}$$

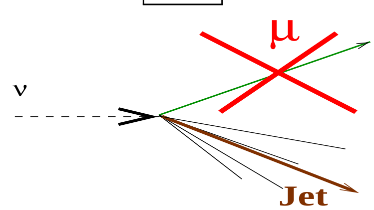
Final estimate corrected by Data Simulator:

- *The large kinematical suppression and the use of likelihood ratios exploiting multi-dimensional correlations require a precise knowledge of the relevant distributions down to a $\sim 10^{-4} \div 10^{-6}$ level. Not possible to rely entirely on the Monte Carlo (LEPTO/JETSET/GEANT) predictions (MC):*

TAILS *of*
- *nucleon Fermi motion;*
- *hadronic jet fragmentation;*
- *nuclear reinteractions;*
- *instrumental effects.*

- *Use* IDENTIFIED ν_μCC *in both Data (DS) and Monte Carlo (MCS) and replace the leading* μ^- *by:*

  - ν *(i.e. nothing)* $\Rightarrow$ *'Fake NC'*
  - e^- *from MC* $\Rightarrow$ *'Fake $\nu_e CC$'*
  - $\tau^- \to X$ *MC* $\Rightarrow$ *'Fake $\nu_\tau CC$'*

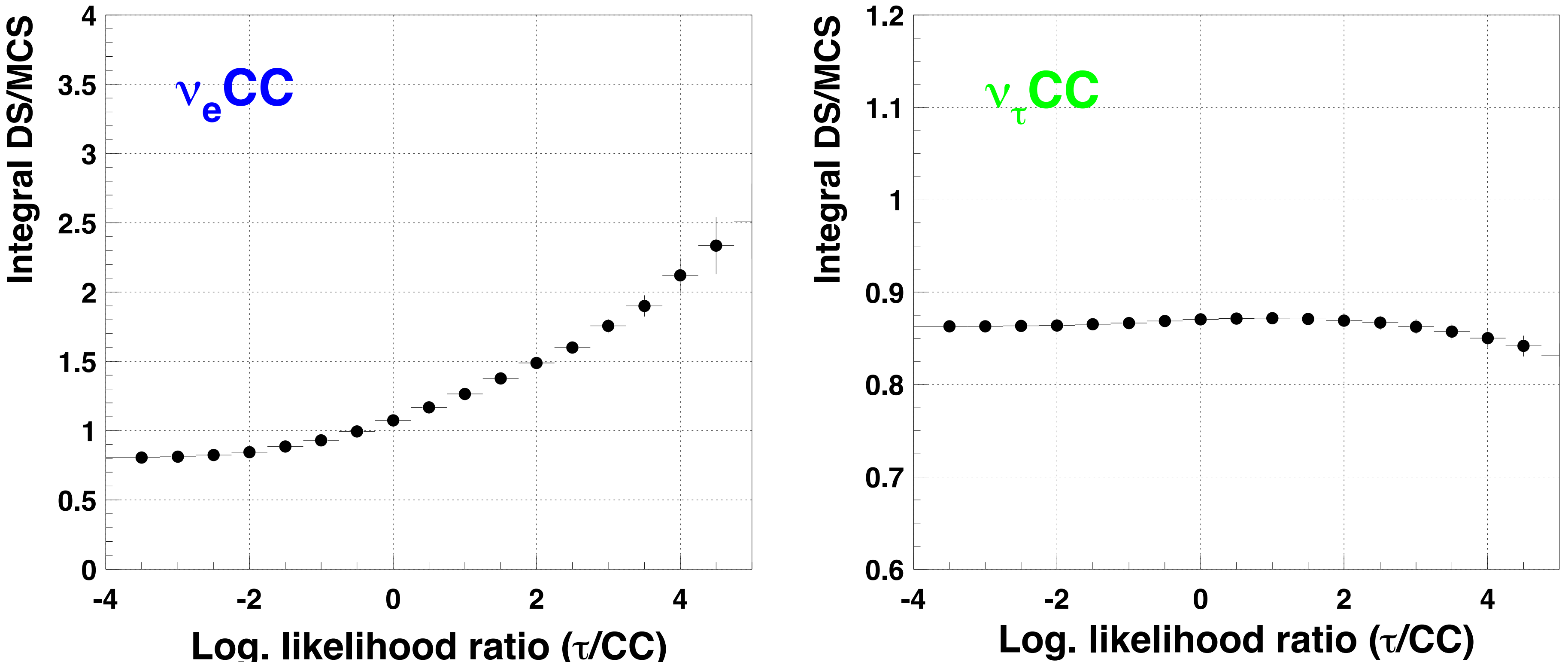


- *The three samples MC, MCS and DS are fully analyzed and the background and signal efficiencies are estimated from the DOUBLE RATIO*

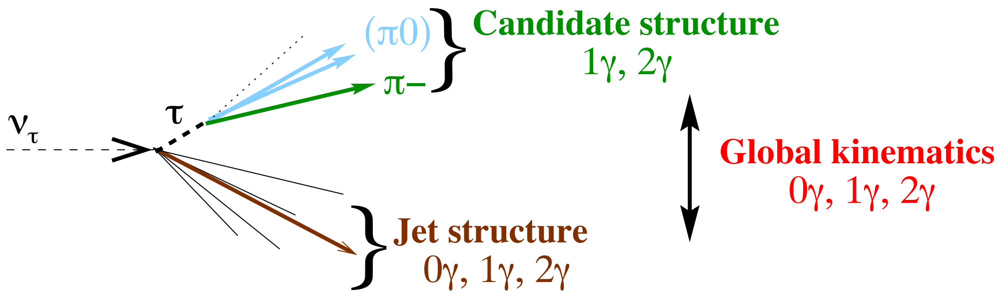
$$\varepsilon \stackrel{\mathrm{def}}{\equiv} \frac{\varepsilon(MC) \times \varepsilon(DS)}{\varepsilon(MCS)}$$

$\Longrightarrow$ *essentially LEPTON from MC & JET from DATA.*

- *Final background predictions must agree with data in τ^+ search where no detectable signal is expected. This comparison validates the Data Simulator corrections.*


Integral DS/MCS
ν_eCC
Log. likelihood ratio (τ/CC)
Integral DS/MCS
ν_τCC
Log. likelihood ratio (τ/CC)

EXAMPLE: $\tau^- \rightarrow h^-(n\pi^0)\nu_\tau$ CHANNEL



- *Most sensitive decay channel in NOMAD ν_τ appearance search:*
  large inclusive BR 49.8% & additional handles from internal structure of ν_τ candidate.

- *Unified approach with 3 different (inclusive) decay topologies:*
  - $\boxed{0\gamma}$: *τ candidate built from single π^-;*
  - $\boxed{1\gamma}$: *$\tau^- \rightarrow \nu_\tau \rho^- \rightarrow \nu_\tau \pi^- \pi^0$. Single γ reconstructed from π^0 (2γ overlap or missed γ);*
  - $\boxed{2\gamma}$: *$\tau^- \rightarrow \nu_\tau \rho^- \rightarrow \nu_\tau \pi^- \pi^0$. Both γs from π^0 decay are reconstructed.*

- *Kinematic selection requires 4 steps on event-by-event basis:*

(i) *Choice of the most likely τ decay products;*
(ii) *Choice of the most likely "leading lepton" candidate;*
(iii) *Rejection of CC backgrounds;*
(iv) *Rejection of NC backgrounds.*

NOMAD Coll., NPB 611 (2001) 3-39

Choice of τ decay products:

- *In general, for a given event more than one choice/combination possible*

- *Define the selection likelihood function:*

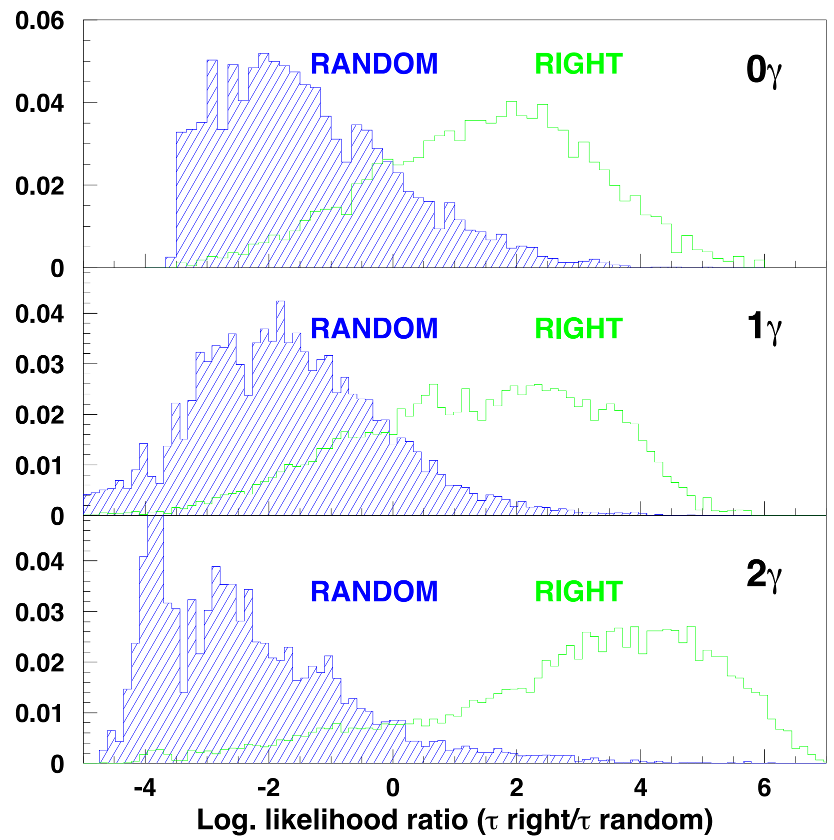
$$\mathcal{L}^{\rm S} \stackrel{\rm def}{\equiv} [(\mathcal{L}^{\rm IN}), R_{Q_T}, y_{Bj}, \theta_{\tau H}]$$

$$\mathcal{L}^{\rm IN}_{1\gamma} \stackrel{\rm def}{\equiv} [M_\rho, \theta_{\pi^-\pi^0}, E_{\pi^0}/E_{vis}], \qquad 1\gamma$$

$$\mathcal{L}^{\rm IN}_{2\gamma} \stackrel{\rm def}{\equiv} [M_{\pi^0}, \theta_{\gamma\gamma}, E_\gamma^{max}/E_{vis}], \mathcal{L}^{\rm IN}_{1\gamma}], \quad 2\gamma$$

- *Select the combination maximizing the likelihood ratio between correct and random choices in τ decays.*

  $\Longrightarrow$ *Build ν_τ CC event kinematics around the selected τ candidate*



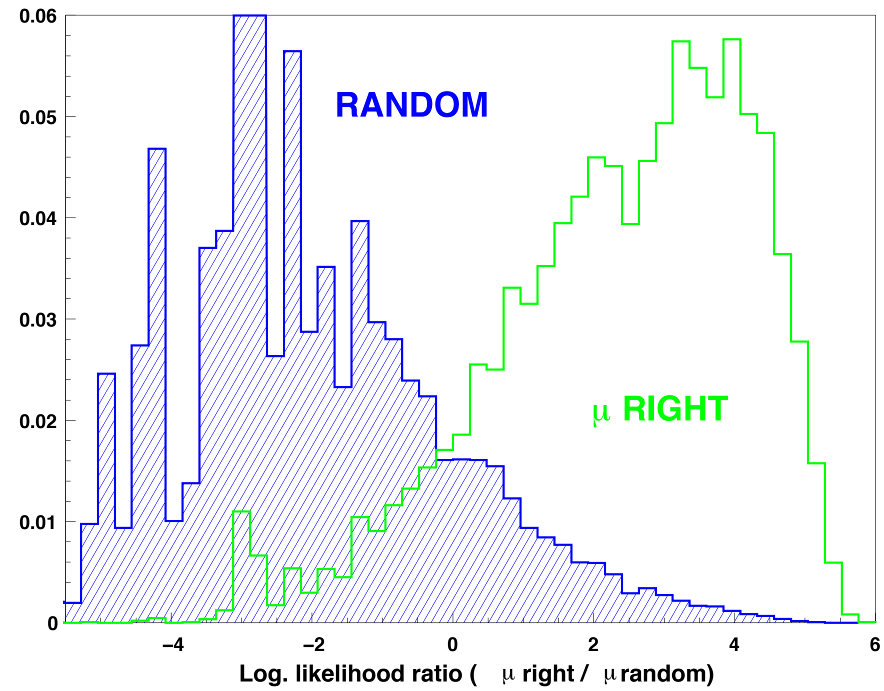
II Choice of "leading lepton" candidate:

- *Select kinematically the track most likely consistent to be an unidentified μ in ν_μ CC*
- *Define the tagging likelihood function:*

$$\mathcal{L}^{\mathrm{V}} \stackrel{\mathrm{def}}{\equiv} [R_{Q_T}, p_T^l, \theta_{\nu l}]$$

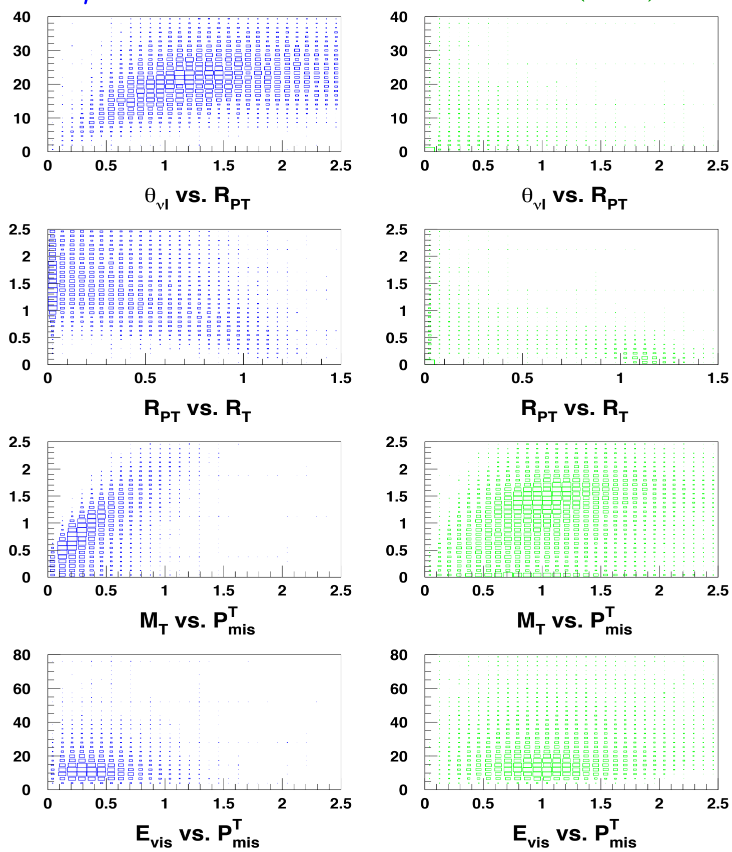
- *Select the track maximizing the likelihood ratio between correct and random choices in unidentified ν_μ CC events.*

  $\Longrightarrow$ *Build entire CC event kinematics around the selected "lepton" track*



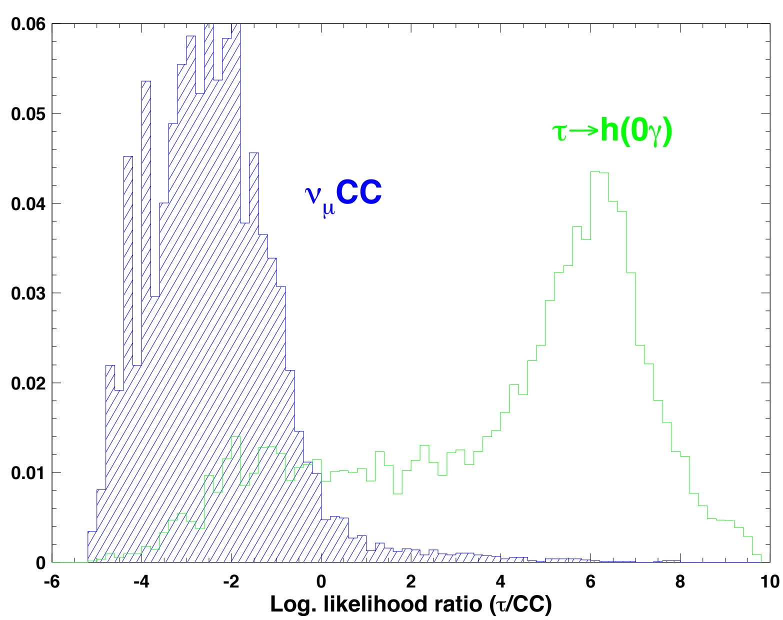
III Rejection of CC backgrounds:

ν_μ CC $\qquad\qquad$ $\tau \rightarrow h(0\gamma)$

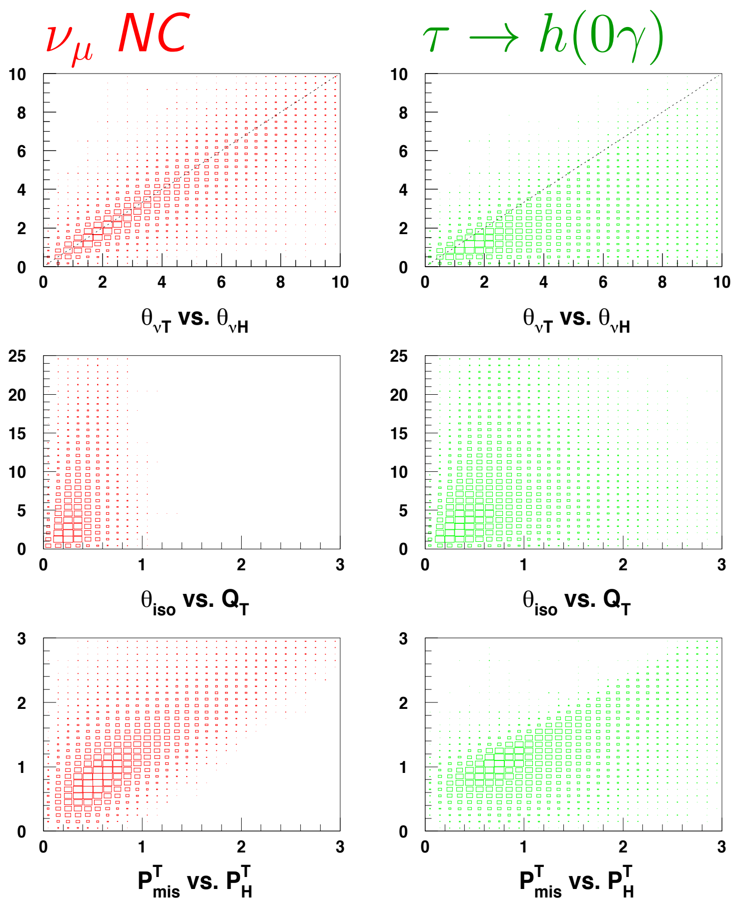


- $\theta_{\nu l}$ *Angle between lepton and beam axis;*
- R_{p_T} *Ratio between* p_T *of lepton and* p_T^m*;*
- R_{Q_T} *Ratio between transverse size of hadronic system with and without lepton;*
- E_{vis} *Total visible energy in the event;*
- M_T *Transverse invariant mass between* p_T *of* τ *candidate and* p_T^m*;*

$$\mathcal{L}^{\rm CC} \stackrel{\rm def}{\equiv} [[R_{Q_T}, R_{p_T}, \theta_{\nu l}], E_{\rm vis}, p_T^m, M_T]$$



IV Rejection of NC backgrounds:



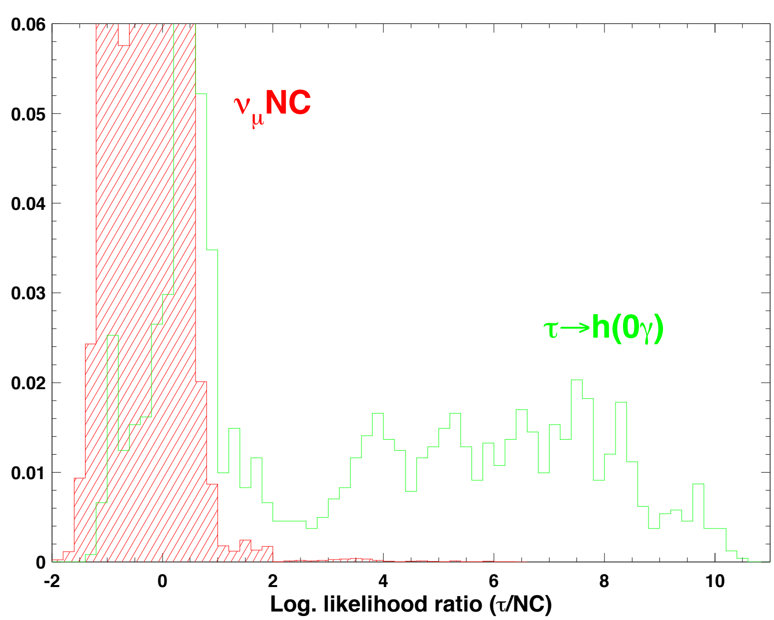
$\theta_{\nu T}$ *Angle between the direction of the incident ν and the total momentum of the event;*

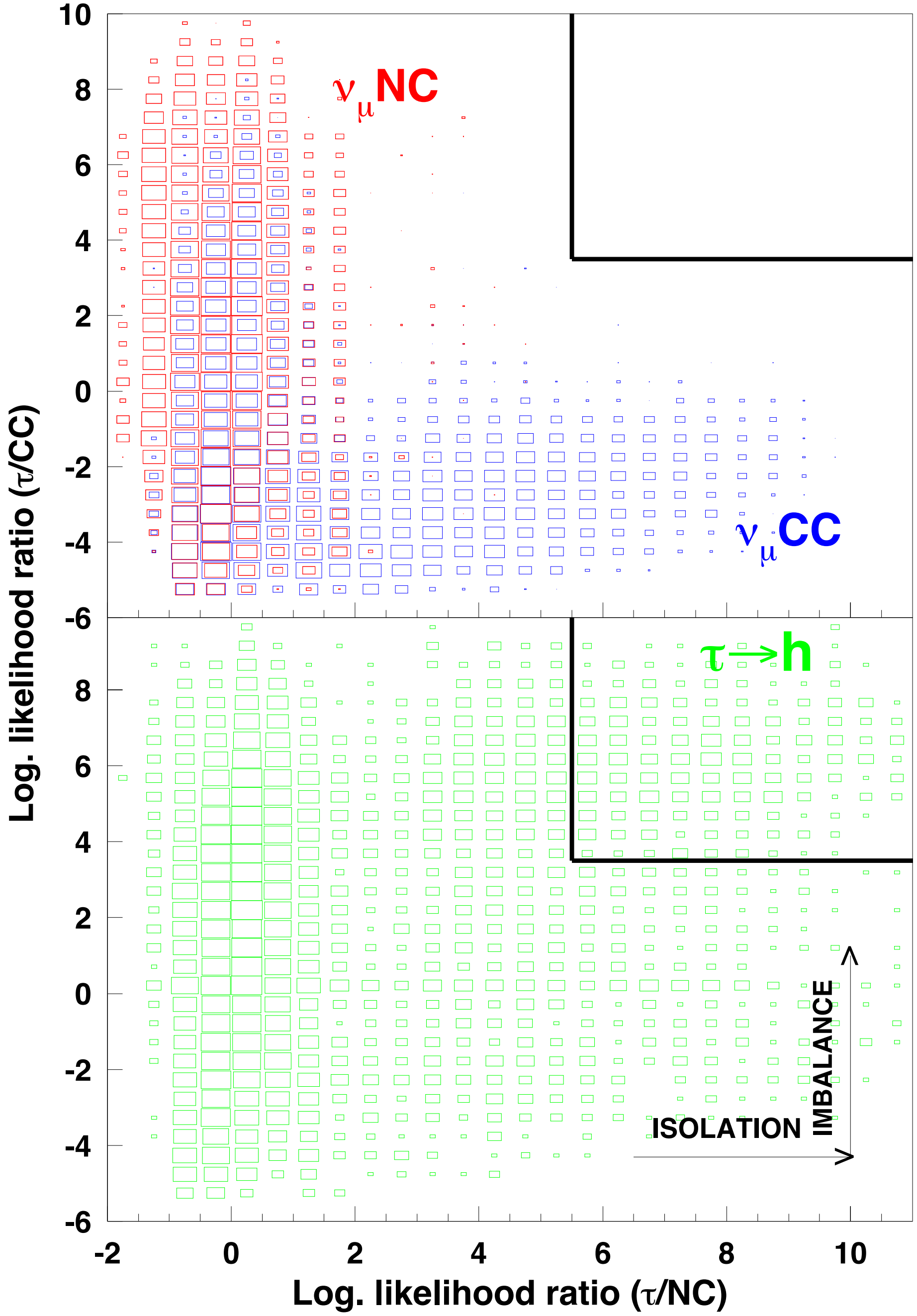
$\theta_{\nu H}$ *Angle between the direction of the incident ν and the hadronic jet momentum;*

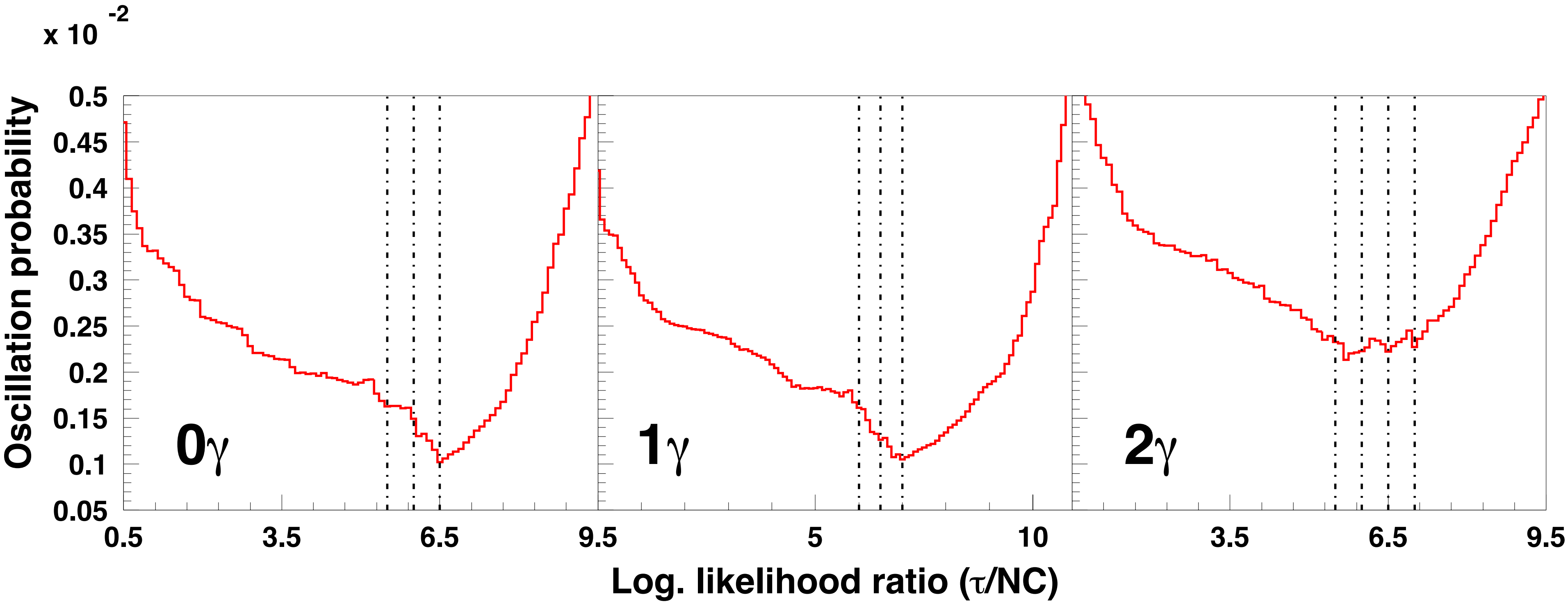
θ_{iso} *Minimum opening angle between the electron and any other track in the hadronic system;*

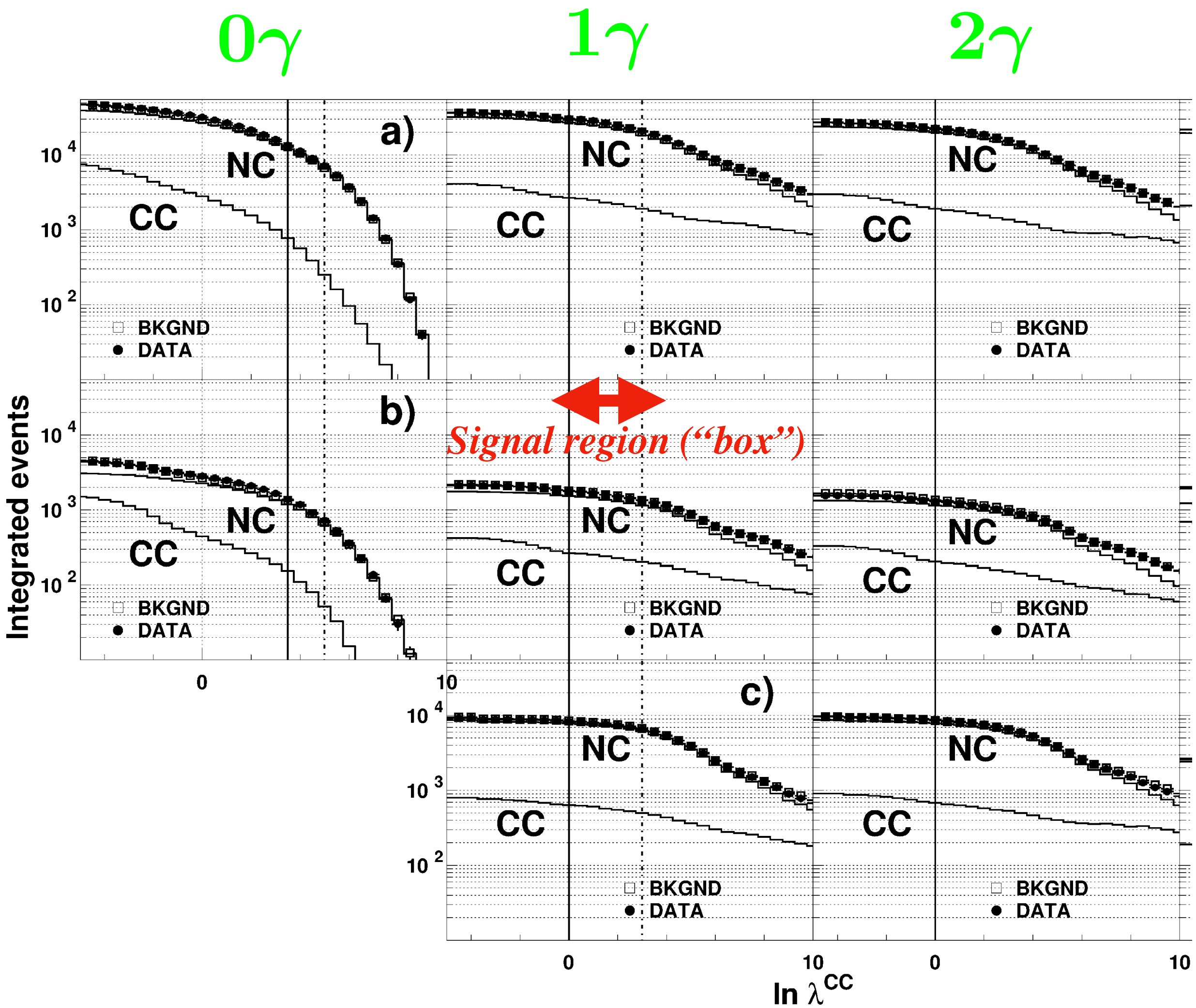
p_T^m *Missing p_T.*

$$\mathcal{L}^{\mathrm{NC}} \stackrel{\mathrm{def}}{\equiv} [[[\theta_{\nu T}, \theta_{\nu H}], \theta_{iso}, Q_T], p_T^m, p_T^H]$$




ν_μNC
ν_μCC
$\tau \rightarrow h$
ISOLATION
IMBALANCE
Log. likelihood ratio (τ/CC)
Log. likelihood ratio (τ/NC)
10
8
6
4
2
0
-2
-4
-6
-2
0
2
4
6
8
10


x 10 -2
Oscillation probability
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0γ
1γ
2γ
0.5
3.5
6.5
9.5
5
10
3.5
6.5
9.5
Log. likelihood ratio (τ/NC)

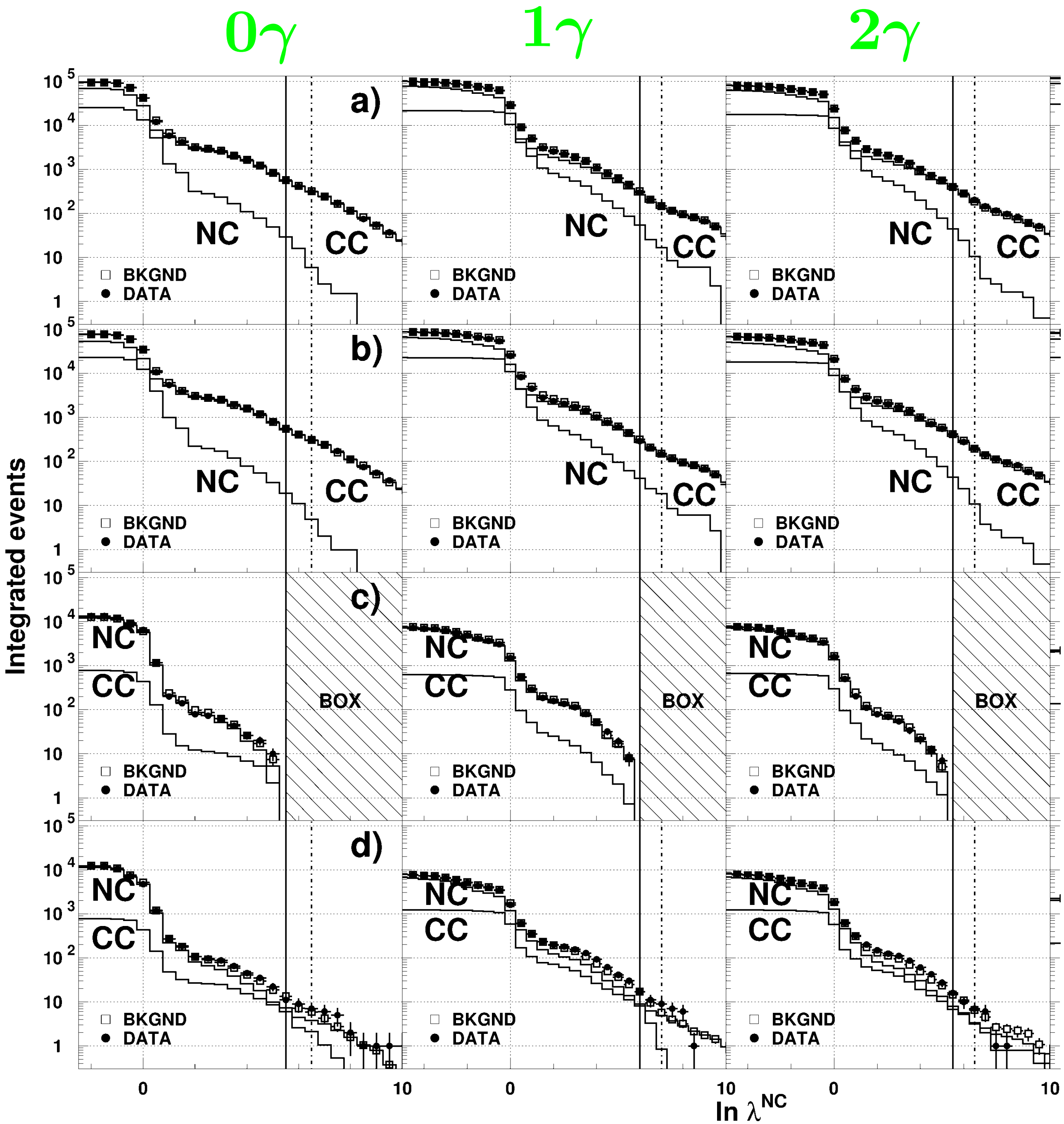


no cuts on $\ln\lambda^{NC}$ and $\ln\lambda^{IN}$

moderate (x10) $\ln\lambda^{NC}$ cut no $\ln\lambda^{IN}$ cut

$\ln\lambda^{IN}$ cut (signal) no $\ln\lambda^{NC}$ cut

Likelihood functions crucial to define control samples to validate NC & CC backgrounds

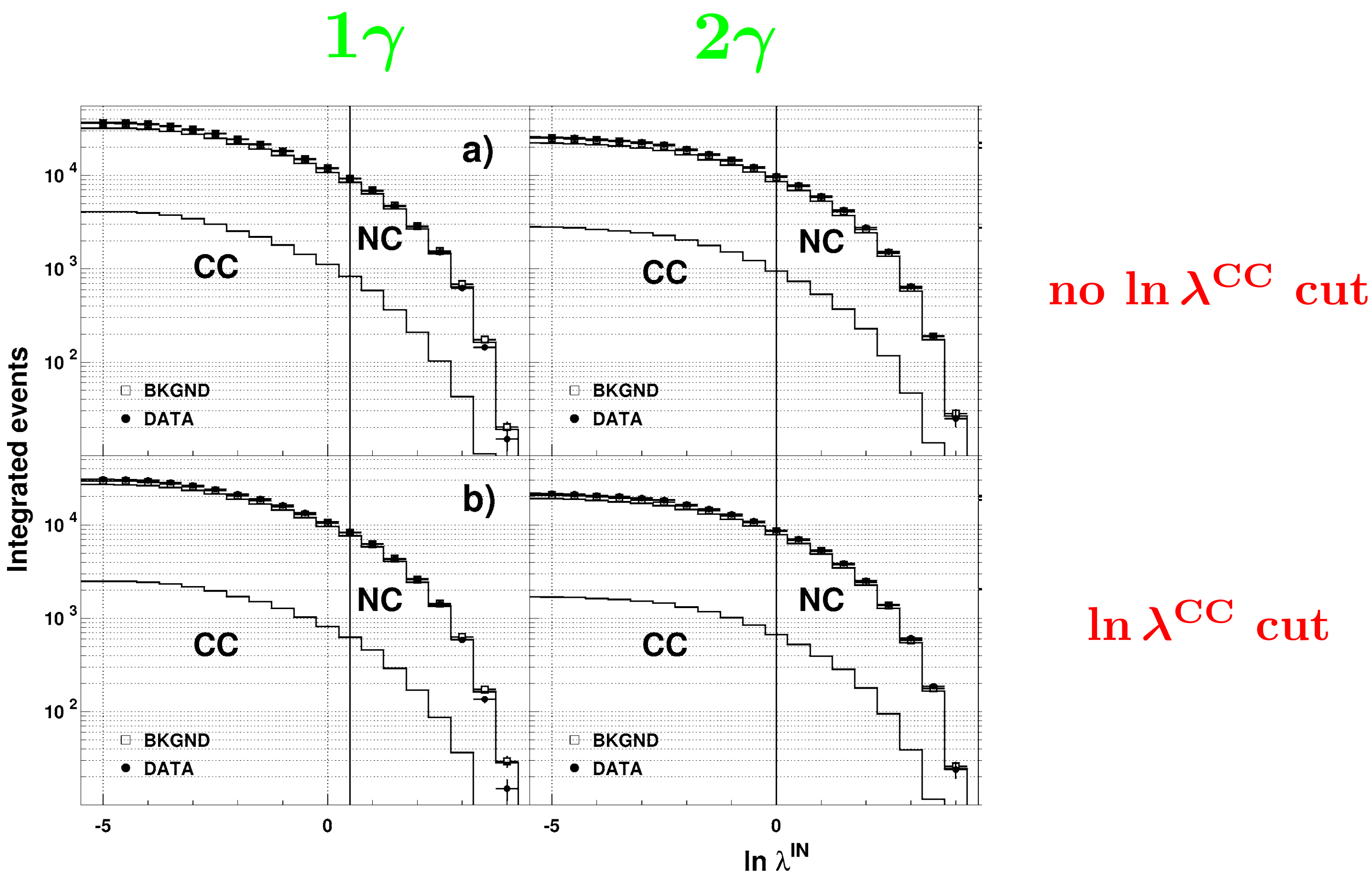


before kinematic cuts

CC control sample

final outside signal "box"

τ^+ (wrong sign)



Reduction of background systematics
from multiple NC & CC control samples (redundancy)

Analysis		τ^- Obs	τ^- Tot Bkgnd	τ^+ Obs	τ^+ Tot Bkgnd	ϵ_τ (%)	$N_\tau^{\mu\tau}$	$N_\tau^{e\tau}$	$S_{\mu\tau}$ ($\times 10^{-4}$)
$\nu_\tau \bar{\nu}_e e$	DIS	5	$5.3^{+0.7}_{-0.5}$	9	8.0 ± 2.4	3.6	4318	88.0	8.0
$\nu_\tau h(n\pi^0)$	DIS	21	19.5 ± 3.5	44	44.9 ± 4.6	2.2	7522	177.4	4.0
$\nu_\tau 3h(n\pi^0)$	DIS	3	4.9 ± 1.5	10	9.9 ± 1.6	1.3	1367	33.3	22.2
$\nu_\tau \bar{\nu}_e e$	LM	6	5.4 ± 0.9	3	2.2 ± 0.5	6.3	864	8.8	55.2
$\nu_\tau h(n\pi^0)$	LM	12	11.9 ± 2.9	40	44.1 ± 9.2	1.9	857	16.7	88.9
$\nu_\tau 3h(n\pi^0)$	LM	5	3.5 ± 1.2	1	2.2 ± 1.1	2.0	298	5.2	161.0

Final NOMAD results [NPB 611 (2001) 3-39]

Analysis			Bin #	Tot Bkgnd	Data	$N_\tau^{\mu\tau}$	$N_\tau^{e\tau}$
$\nu_\tau e\bar{\nu}_e$	DIS		III	$0.18^{+0.18}_{-0.08}$	0	680	15.0
			VI	0.16 ± 0.08	0	1481	32.7
($E_{vis} < 12$ GeV)			II+III+VI	0.27 ± 0.13	0	665	8.7
$\nu_\tau h(n\pi^0)$	DIS	0γ	III	$0.05^{+0.60}_{-0.03}$	0	288	6.9
		0γ	IV	$0.12^{+0.60}_{-0.05}$	0	1345	31.1
		1γ	III	$0.07^{+0.70}_{-0.04}$	0	223	5.7
		1γ	IV	$0.07^{+0.70}_{-0.04}$	0	1113	26.6
		2γ	IV	$0.11^{+0.60}_{-0.06}$	0	211	4.9
		$1/2\gamma$	III	$0.20^{+0.70}_{-0.06}$	1	707	16.9
		$0/1\text{–}2\gamma$	IV	$0.14^{+0.70}_{-0.06}$	0	1456	34.2
$\nu_\tau 3h(n\pi^0)$	DIS	$3h$	V	$0.32^{+0.57}_{-0.32}$	0	675	16.6
Total				$1.69^{+1.85}_{-0.39}$	1	8844	199.3

Most of the NOMAD sensitivity from low background regions/bins

THE NOMAD EXPERIENCE

✦ *NOMAD pioneered the use of transverse plane kinematics for the selection of various exclusive (anti)neutrino processes.*

$\Longrightarrow$ *Efficient technique with low-density high-resolution detector.*

✦ *The NOMAD experience demonstrated that the kinematic selection of ν_τ CC can be controlled up to the extreme tails of the distributions:*

- *Need to extract & calibrate all efficiencies and backgrounds with data themselves;*
- *Optimal use of degrees of freedom with multi-dimensional (correlations) pdfs;*
- *Definition of multiple control samples to validate each beckground source (redundancy);*
- *Combination of lepton (μ, e) ID & kinematics.*

✦ *Kinematic techniques originally developed for ν_τ appearance search extended to broad range of analyses including NC indentification, measurement of exclusive cross-sections & particle production, etc.*

[e.g. NOMAD Coll., NPB 700 (2004) 51]

OUTLOOK

- *NOMAD kinematic selection of ν_τ CC can be useful in DUNE for both FD & ND once adapted to the different detector and beam conditions.*

  $\Longrightarrow$ *Less critical S/B ratio in FD but lower resolution detector*

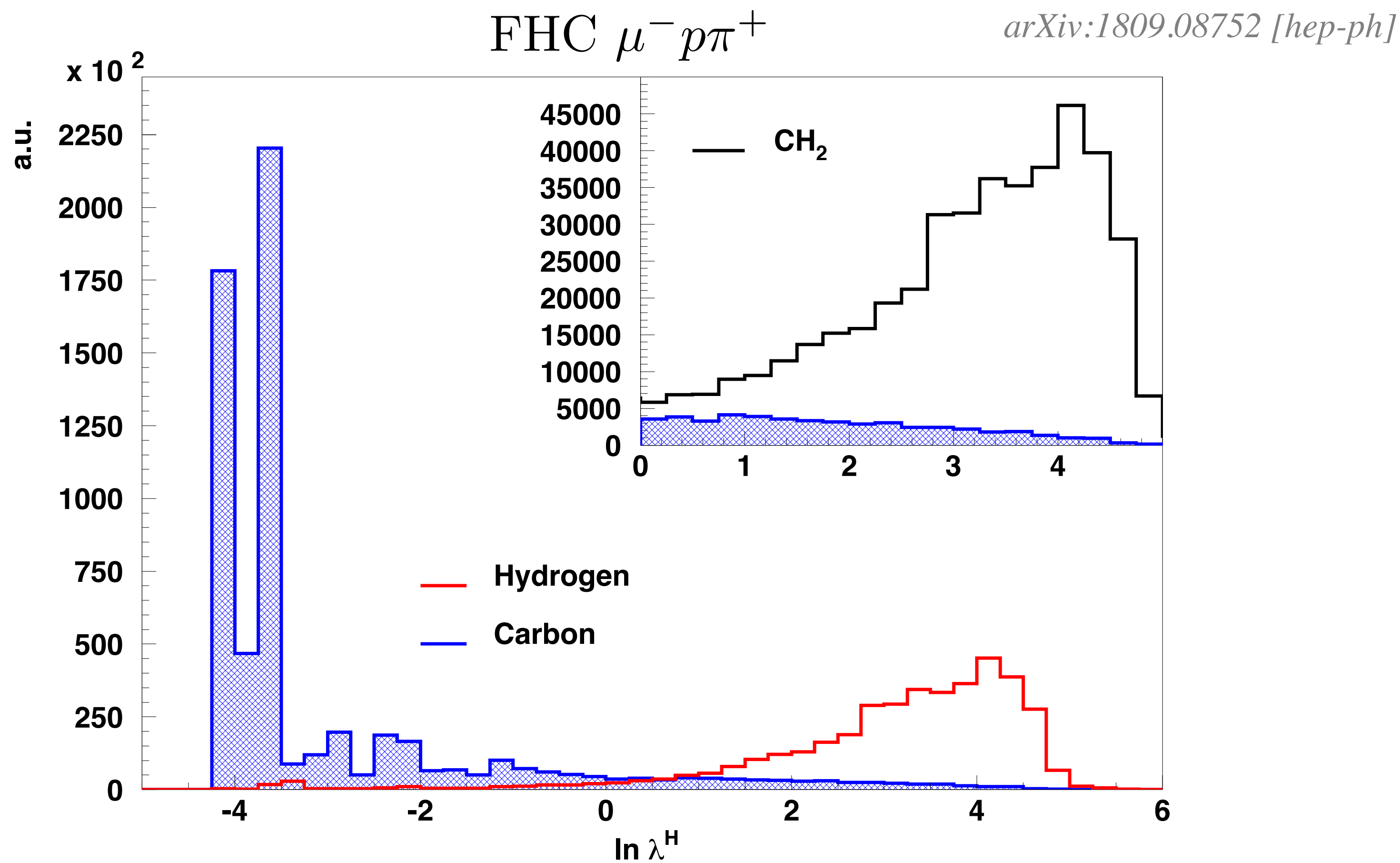
- *Recent proposal to European Strategy Group for Particle Physics to enhance LBNF/DUNE physics potential with addition of highly capable ND component:*

  https://indico.cern.ch/event/765096/contributions/3295805/

  - *Low-density ($\rho \sim 0.16$ g/cm^3) high-resolution specrometer based upon NOMAD concept;*
  - *General ND facility for precision tests of fundamental interactions & searches for New Physics;*
  - *Option of LBNF high-energy beam optimized for ν_τ appearance crucial part of physics program.*

- *Kinematic techniques similar to NOMAD applied to various sensitivity studies in proposed ND addition (e.g. H. Duyang, B. Guo, S. R. Mishra, and RP, arXiv:1809.08752 [hep-ph]).*

- *Proposed ND addition excellent detector option for ν_τ search in ND (higher segmentation than NOMAD) related to sterile neutrinos (e.g. MiniBooNE), non-standard interactions, etc.*



$$\mathcal{L}^{\rm H} \equiv \left[\left[\; R_{mH}, \; p_{T\perp}^{H}, \; \theta_{\nu T} \; \right], \; p_T^m, \; \Phi_{lH} \; \right]$$