Probing leptonic δ_{CP} using low energy atmospheric neutrinos

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Contents

1. Analytic approach
2. Oscillated events for different δ_{CP} values.
3. $\delta\chi^2$ with perfect detectors.
4. Future plans

Current status of neutrino oscillation parameters

- Known : $\theta_{12}, \Delta m^2_{21}, \theta_{13}$
- Going on : $\theta_{23}, |\Delta m^2_{32}|$
- UNKNOWN! : Sign of Δm^2_{32} (mass hierarchy) & octant of θ_{23} , δ_{CP}

The question of mass hierarchy

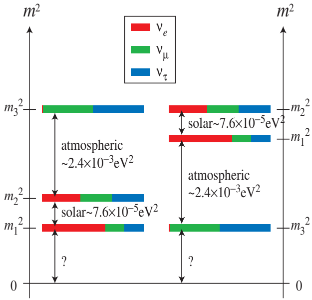


Figure 1: NH : $m_1 < m_2 < m_3$; IH : $m_3 < m_1 < m_2$

- **Octant of θ_{23} = ?**
- $\theta_{23} < 45^\circ$: Lower octant
- $\theta_{23} = 45^\circ$: Maximal
- $\theta_{23} > 45^\circ$: Higher octant
- δ_{CP} = ? (Slight hint towards $\delta_{CP} \approx -90^\circ$)

Motivation for this work

- Several experiments worldwide to probe leptonic δ_{CP}. eg. NOνA, DUNE, T2HKK etc $\rightarrow$ LBL.
- δ_{CP} measurement is ambiguous with neutrino hierarchy. Detectors like DUNE are specially designed/placed to measure δ_{CP} unambiguous of hierarchy.
- What about atmospheric neutrinos?
  - Atmospheric neutrino spectrum peaks at low energy. So good statistics.
  - **δ_{CP} can be measured independent of hierarchy in the low energy regime.**

A simple analytical approach

Flavour states $\rightarrow$ superimpositions of mass eigen states ν_i, $i = 1, 2, 3$;
$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$, $\alpha = e, \mu, \tau$, $i = 1, 2, 3$.

$$U_{\alpha i}^{vac} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix},$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$; $i, j \rightarrow$ mass eigenstates.
θ_{ij} $\rightarrow$mixing angles; δ_{cp} = leptonic CP violation phase

$$\overset{(-)}{P}{}^{vac}_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} Re\left[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}\right]\sin^2\left(\frac{1.27]\Delta m^2_{ij}L}{E}\right)$$
$$\pm\ 2\sum_{i>j} Im\left[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}\right]\sin\left(\frac{2.53\Delta m^2_{ij}L}{E}\right).$$

- $\alpha \neq \beta$: Transition; $\alpha = \beta$: Survival
- Transition probabilities $\rightarrow \sin\delta_{CP}$ dependence.

Single scale approximation

- For small E a few hundred MeV, the corresponding oscillatory terms average out whenever L/E is large compared to Δm^2_{ij}.
- $|\Delta m^2_{3j}| \sim 2.4 \times 10^{-3}$ eV$^2 \gg \Delta m^2_{21} \sim 7.6 \times 10^{-5}$ eV^2, $j = 1, 2$,
- For "atmospheric" terms $\to$ rapid oscillations and averaging out :

$$1.27 \Delta m^2_{3j} \; L/E \approx \pi (L/100)/(E/0.1 GeV) \; , \qquad (1)$$

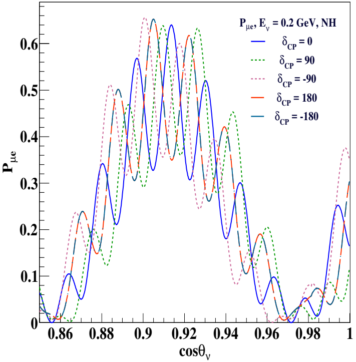
- For "solar terms $\to$ long wavelength oscillations :

$$1.27 \Delta m^2_{21} \; L/E \approx \pi (L/3000)/(E/0.1 GeV) \; . \qquad (2)$$

- Hence the event rates at these low energies and $L \gtrsim$ few 100 km are independent of Δm^2_{32} and Δm^2_{31} and hence of their ordering.
- Δm^2_{21} : remains, but its magnitude and sign are well-known.

Oscillation probabilities in matter

Probabilities of interest : $P_{ee}, P_{e\mu}, P_{\mu e}, P_{\mu\mu}$ and $\bar{P}_{ee}, \bar{P}_{e\mu}, \bar{P}_{\mu e}, \bar{P}_{\mu\mu}$.



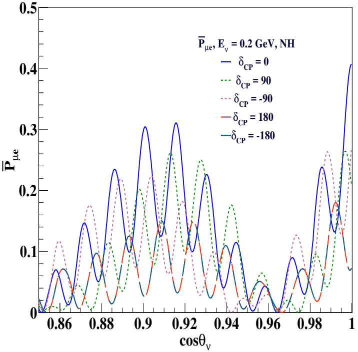


Figure 2: (Left) $P_{\mu e}$ and (right) $\bar{P}_{\mu e}$ as a function of $\cos\theta_\nu$ for $E_\nu =$ 0.2 GeV with different δ_{CP} values and true NH.

Simulation studies

- NUANCE neutrino generator is used to generate unoscillated charged current $\nu_\mu, \bar{\nu}_\mu, \nu_e$ and $\bar{\nu}_e$) events.
- Oscillations are applied event by event.
- Earth matter density is generated using PREM profile.
- Perfect hypothetical detector (for this study a 50 kton magnetised detector):
  - No energy or direction smearing.
  - 100% reconstruction efficiency.
  - Assumes that it can identify $\nu_\mu, \bar{\nu}_\mu, \nu_e$ and $\bar{\nu}_e$ separately.
- 100 years of events generated and then scaled down to 10 years of exposure.
- Events are binned in $E_l^{obs}, \cos\theta_l^{obs}, E_{had}^{\prime obs}$. $E_l^{obs}, \cos\theta_l^{obs} \rightarrow$ observed energy and direction of final state lepton $E_{had}^{\prime obs} \rightarrow$ observed energy of the hadron shower.
- E_l^{obs} = 0.1–30 GeV, $\cos\theta_l^{obs}$ = [-1, 1], $E_h^{\prime obs}$ = 0–15 GeV.
- Total event rates are plotted as a function of $E_l^{obs}, \cos\theta_l^{obs}$, where l is the final state lepton.

Simulation studies continued...

- Poissonian χ^2 with no systematic uncertainties.
- Both fixed parameter and marginalised.
- $\delta_{CP}^{true} = 0°, 90°$, NH.

Oscillation probabilities are generated using the following values of parameters :

Parameter	True value	Marginalization range
θ_{13}	$8.5°$	[7.80°, 9.11°]
$\sin^2\theta_{23}$	0.5	[0.39, 0.64]
Δm^2_{eff}	2.4×10^{-3} eV^2	[2.3, 2.6]$\times 10^{-3}$ eV^2
$\sin^2_{12}$	0.304	Not marginalised
Δm^2_{21}	7.6×10^{-5} eV^2	Not marginalised
δ_{CP}	0, ±90°, ±180°	[-180°, 180°]

Table 1: True values and 3σ ranges of parameters used to generate oscillated events. Values except that of δ_{CP} taken as in PRD 97, 033005 (2018).

- ν_e $(\bar{\nu}_e)$ are produced by $\nu_e \to \nu_e$ $(\bar{\nu}_e \to \bar{\nu}_e)$ and $\nu_\mu \to \nu_e$ $(\bar{\nu}_\mu \to \bar{\nu}_e)$ since the atmospheric neutrino flux contains ν_μ and ν_e in the ratio 2:1.

$$\frac{d^2N}{dE_\nu \; d\cos\theta_\nu} = t \times n_d \times \sigma_{\nu_e} \times \left[P^m_{ee} \frac{d^2\Phi_{\nu_e}}{dE_\nu \; d(\cos\theta_\nu)} + P^m_{\mu e} \frac{d^2\Phi_{\nu_\mu}}{dE_\nu \; d(\cos\theta_\nu)} \right], \tag{3}$$

where, t = exposure time, n_d = no.of targets in the detector,
σ_{ν_μ} = neutrino interaction cross section,
$\Phi_{\nu_\mu} = \nu_\mu$ flux, $\Phi_{\nu_e} = \nu_e$ flux and
$P^m_{\alpha\beta}$ = oscillation probability of $\nu_\alpha \to \nu_\beta$ in matter,
α, β different flavours.
Similarly for $\bar{\nu}_e, \nu_\mu$ and $\bar{\nu}_\mu$ events.

$\Phi_\mu \sim 2\Phi_e$, the $\sin\delta_{CP}$ dependence $>$ in N_e rather than in N_μ.

Hierarchy independence at low energies

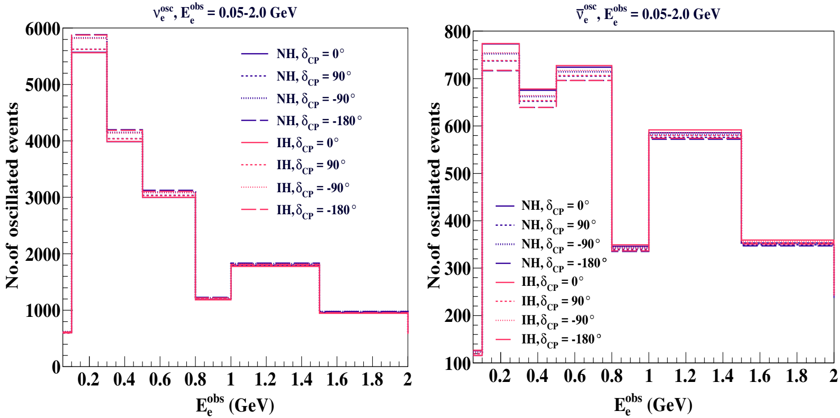
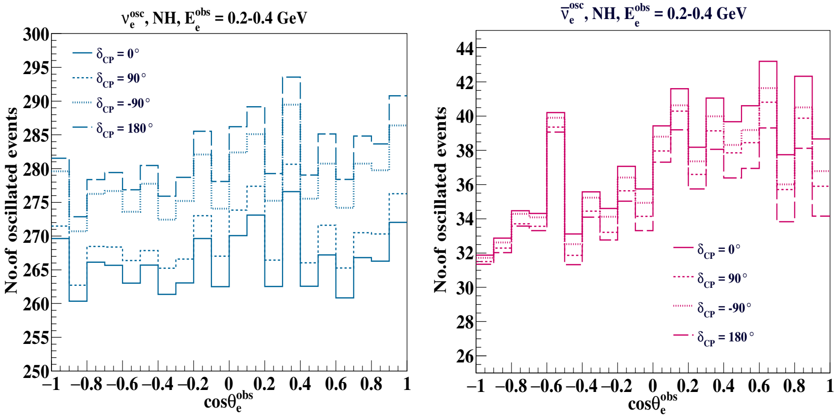


Figure 3: Low energy ν_e (left) and $\bar{\nu}_e$ events as a function of E_l^{obs} averaged over $\cos\theta_l^{obs}$, where $l = e, \mu$, for both NH and IH.

[21]

Oscillated events for different δ_{CP} values as a function of $\cos^{obs}\theta_e$ for E_e^{obs} =0.2–0.4 GeV.



[22]

$\Delta\chi^2$ vs δ_{CP}^{test} - CCE and CCMU

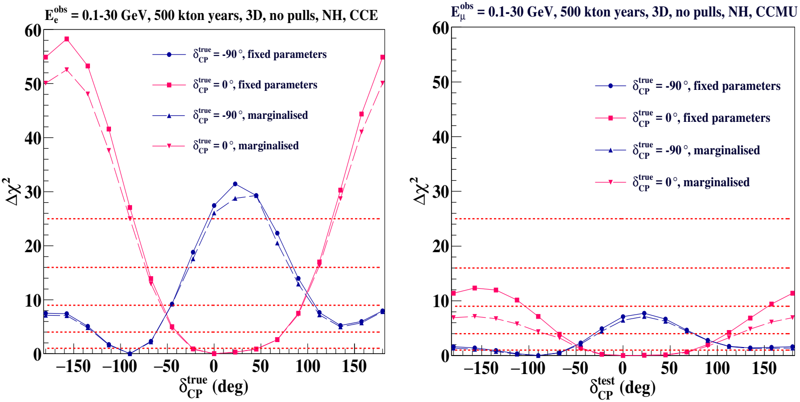


Figure 4: $\Delta\chi^2$ vs δ_{CP}^{test} (deg) from CC $\nu_e + \bar{\nu}_e$ (left) and CC $\nu_\mu + \bar{\nu}_\mu$ (right) events obtained with 500 kton year of an Fe detector (isoscalar) target and with cid, with fixed parameters (solid curves) and marginalisation (dashed curves). $\delta_{CP}^{true} = 0, \ -90°$ (deg) and true NH are taken.

$\Delta\chi^2$ vs δ_{CP}^{test} - With $\nu_e - \bar{\nu}_e$ and $\nu_\mu - \bar{\nu}_\mu$ separation

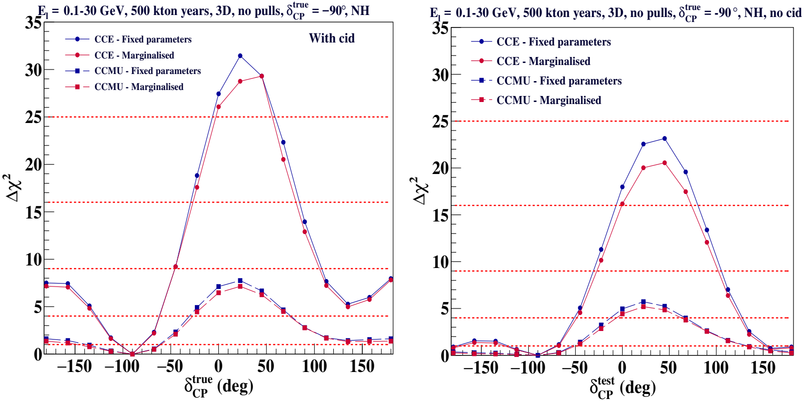


Figure 5: $\Delta\chi^2$ vs δ_{CP}^{test} (deg) from CC $\nu_e + \bar{\nu}_e$ (solid) and CC $\nu_\mu + \bar{\nu}_\mu$ (dot dashed) events obtained with 500 kton year of an Fe detector (isoscalar) target and (left) with cid and (right) no cid. $\delta_{CP}^{true} = -90^\circ$ (deg) and true NH is taken.

Future plans

The χ^2 analysis for the sensitivity to δ_{CP} from low energy atmospheric neutrinos.

1. Check for fluctuations with 1000 years of NUANCE data scaled to 10 years.
2. Usually no cid for $\nu_e + \bar{\nu}_e$ events. Gadolinium doping helps in the cid of $\bar{\nu}_e$ events. $\rightarrow$ Study more about this.
3. Implement realistic detector efficiencies and resolutions $\rightarrow$ Explore for different detectors like SK, HK and DUNE.
4. Add systematic uncertainties via pull method. Study the effect of these systematic uncertainties on δ_{CP} sensitivity.

Acknowledgements

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References

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2. Takaaki Mori, “Status of the Super-Kamiokande gadolinium project”, NIM Physics Research A **732** 316319 (2013).

THANK YOU

Back Up Slides

Three flavour mixing matrix in vacuum

NuFIT 3.2 (2018)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.14$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.272 \to 0.346$
$\theta_{12}/^\circ$	$33.62^{+0.78}_{-0.76}$	$31.42 \to 36.05$	$33.62^{+0.78}_{-0.76}$	$31.43 \to 36.06$	$31.42 \to 36.05$
$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$	$0.418 \to 0.613$	$0.554^{+0.023}_{-0.033}$	$0.435 \to 0.616$	$0.418 \to 0.613$
$\theta_{23}/^\circ$	$47.2^{+1.9}_{-3.9}$	$40.3 \to 51.5$	$48.1^{+1.4}_{-1.9}$	$41.3 \to 51.7$	$40.3 \to 51.5$
$\sin^2\theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$	$0.01981 \to 0.02436$	$0.02227^{+0.00074}_{-0.00074}$	$0.02006 \to 0.02452$	$0.01981 \to 0.02436$
$\theta_{13}/^\circ$	$8.54^{+0.15}_{-0.15}$	$8.09 \to 8.98$	$8.58^{+0.14}_{-0.14}$	$8.14 \to 9.01$	$8.09 \to 8.98$
$\delta_{CP}/^\circ$	234^{+43}_{-31}	$144 \to 374$	278^{+26}_{-29}	$192 \to 354$	$144 \to 374$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$6.80 \to 8.02$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.494^{+0.033}_{-0.031}$	$+2.399 \to +2.593$	$-2.465^{+0.032}_{-0.031}$	$-2.562 \to -2.369$	$\begin{bmatrix} +2.399 \to +2.593 \\ -2.536 \to -2.395 \end{bmatrix}$

Figure 6: 3-flavor oscillation parameters from the fit to global data. JHEP **01** (2017) 087, NuFIT 3.2 (2018), `www.nu-fit.org`

$$
\begin{aligned}
P_{\alpha\beta}^{vac} &= -4Re[U_{\alpha 2}U_{\beta 2}^{*}U_{\alpha 1}^{*}U_{\beta 1}]\sin^2(1.27\Delta m_{21}^2 L/E) \\
&\quad -2Re[U_{\alpha 3}U_{\beta 3}^{*}(\delta_{\alpha\beta} - U_{\alpha 3}^{*}U_{\beta 3})] \\
&\quad +2Im[U_{\alpha 2}U_{\beta 2}^{*}U_{\alpha 1}^{*}U_{\beta 1}]\sin(2.53\Delta m_{21}^2 L/E)
\end{aligned}
$$

- Independent of $\Delta m_{32}^2 \to$ independent of hierarchy ambiguity.

$$
\begin{aligned}
P_{e\mu} &= A + B\cos\delta - C\sin\delta = \bar{P}_{\mu e}; \\
P_{\mu e} &= A + B\cos\delta + C\sin\delta = \bar{P}_{e\mu}
\end{aligned}
$$

$A = c_{13}^2\sin^2(2\theta_{12})(c_{23}^2 - (s_{23}s_{13})^2)\sin^2(\delta_{21}/2) + \frac{1}{2}s_{23}^2\sin^2(2\theta_{13}),$
$B = (1/4)c_{13}\sin(4\theta_{12})\sin(2\theta_{13})\sin(2\theta_{23})\sin^2(\delta_{21}/2),$
$C = (1/4)c_{13}\sin(2\theta_{12})\sin(2\theta_{13})\sin(2\theta_{23})\sin(\delta_{21}),$
$\delta_{21} = 2.534\Delta m_{21}^2 L/E.$

- A, B, C : limited only by precisions of oscillation parameters.
- Asymmetry : $A_{CP} = \frac{P_{e\mu}-P_{\mu e}}{P_{e\mu}+P_{\mu e}} = -\frac{C}{A+B\cos\delta}\sin\delta$ for ν;
  $\bar{A}_{CP} = \frac{C}{A+B\cos\delta}\sin\delta$ for $\bar{\nu}$
- In matter, A, B, C are modified according to Earth matter effects on the oscillation parameters. The linear dependence on $\cos\delta_{CP}$ and $\sin\delta_{CP}$ remains unaltered.

Bins [??]

Observable	Range	Bin width	No.of bins
E_l^{obs} (GeV) (17 bins)	[0.1, 0.2]	0.1	1
	[0.2, 0.4]	0.2	1
	[0.4, 0.5]	0.1	1
	[0.5, 1.0]	0.3	2
	[1.0, 4]	0.5	6
	[4, 7]	1	3
	[7, 11]	4	1
	[11, 12.5]	1.5	1
	[12.5, 15]	2.5	1
	[15, 30]	15	1
$\cos\theta_\mu^{obs}$	[-1.0, 1.0]	0.10	20
E'^{obs}_{had} (GeV) (4 bins)	[0, 2]	1	2
	[2, 4]	2	1
	[4, 15]	11	1

- With hadron analysis (3D) : $(E_\mu^{obs}, \cos\theta_\mu^{obs}, E'obs_{had})$:

Hierarchy independence at low energies - muon events

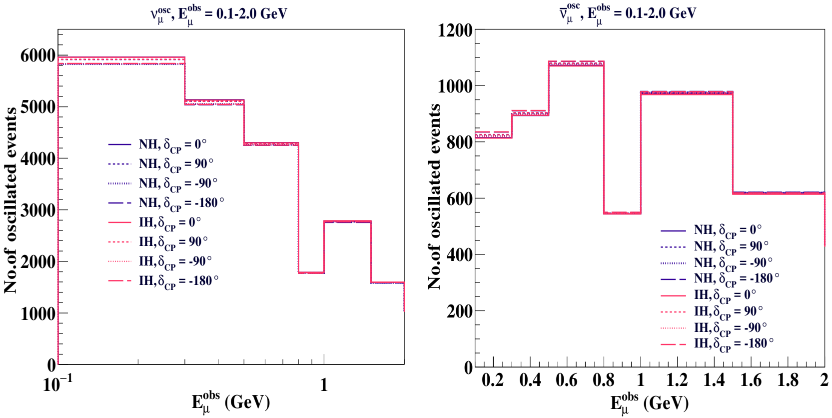
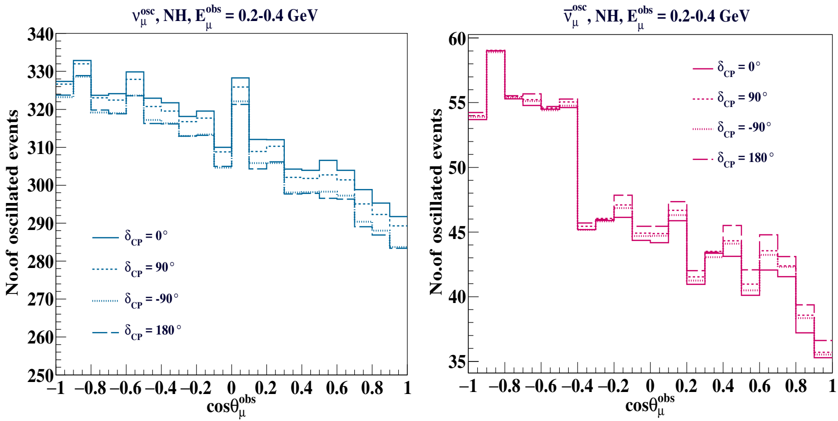


Figure 7: Events averaged over $\cos\theta_l^{obs}$, $l = e, \mu$.

[11]

Effect of δ_{CP} at low energies - muon events

Oscillated events for different δ_{CP} values as a function of $\cos^{obs}\theta_\mu$ for E_μ^{obs} = 0.2–0.4 GeV.



[12]

Poissonian χ^2 with no pulls

$$\chi^2{}_{\pm} = \sum_{i=1}^{N_{E_l^{obs}}} \sum_{j=1}^{N_{\cos\theta_l^{obs}}} \sum_{k=1}^{N_{E'^{obs}_{had}}} 2\left[\left(T^{\pm}_{ij(k)} - D^{\pm}_{ij(k)}\right) - D^{\pm}_{ij(k)} \ln\left(\frac{T^{\pm}_{ij(k)}}{D^{\pm}_{ij(k)}}\right)\right] \tag{4}$$

$\chi^2 = \chi^2_+ + \chi^2_-$ [13]