Neutrino mass hierarchy determination via atmospheric neutrinos in future detectors

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Outline of talk

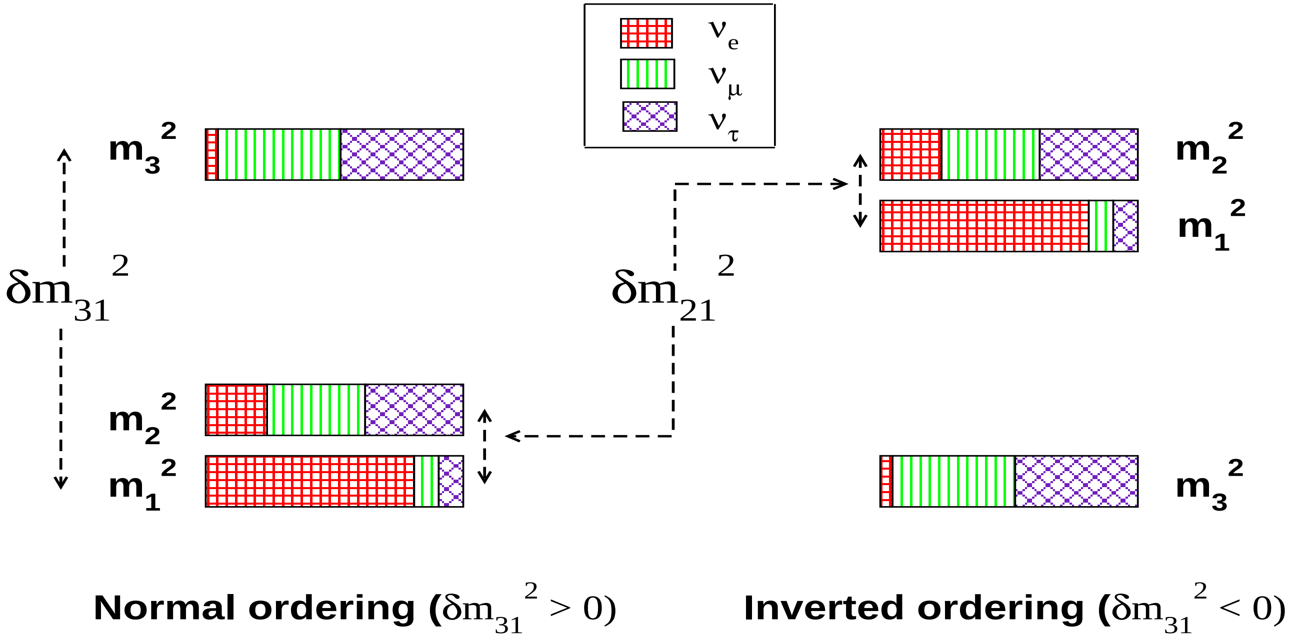
- Present status
- The neutrino mass hierarchy
- Hierarchy sensitivity at the probability level
- Atmospheric neutrinos as source
- Future detectors: INO, Hyper-K, Liquid Argon
- Results and summary

Present status

- Oscillation probabilities depend on the 3 mixing angles, the CP phase δ, and 2 mass squared differences, $\delta m^2_{21} = m^2_2 - m^2_1$ and $\delta m^2_{31} = m^2_3 - m^2_1$, with the best-fit values $\theta_{12} \approx 34^o$, $\theta_{23} \approx 45^o$, $\theta_{13} < 14^o$, $\delta m^2_{21} \approx 8 \times 10^{-5} eV^2$ and $|\delta m^2_{31}| \approx 2.4 \times 10^{-3} eV^2$.

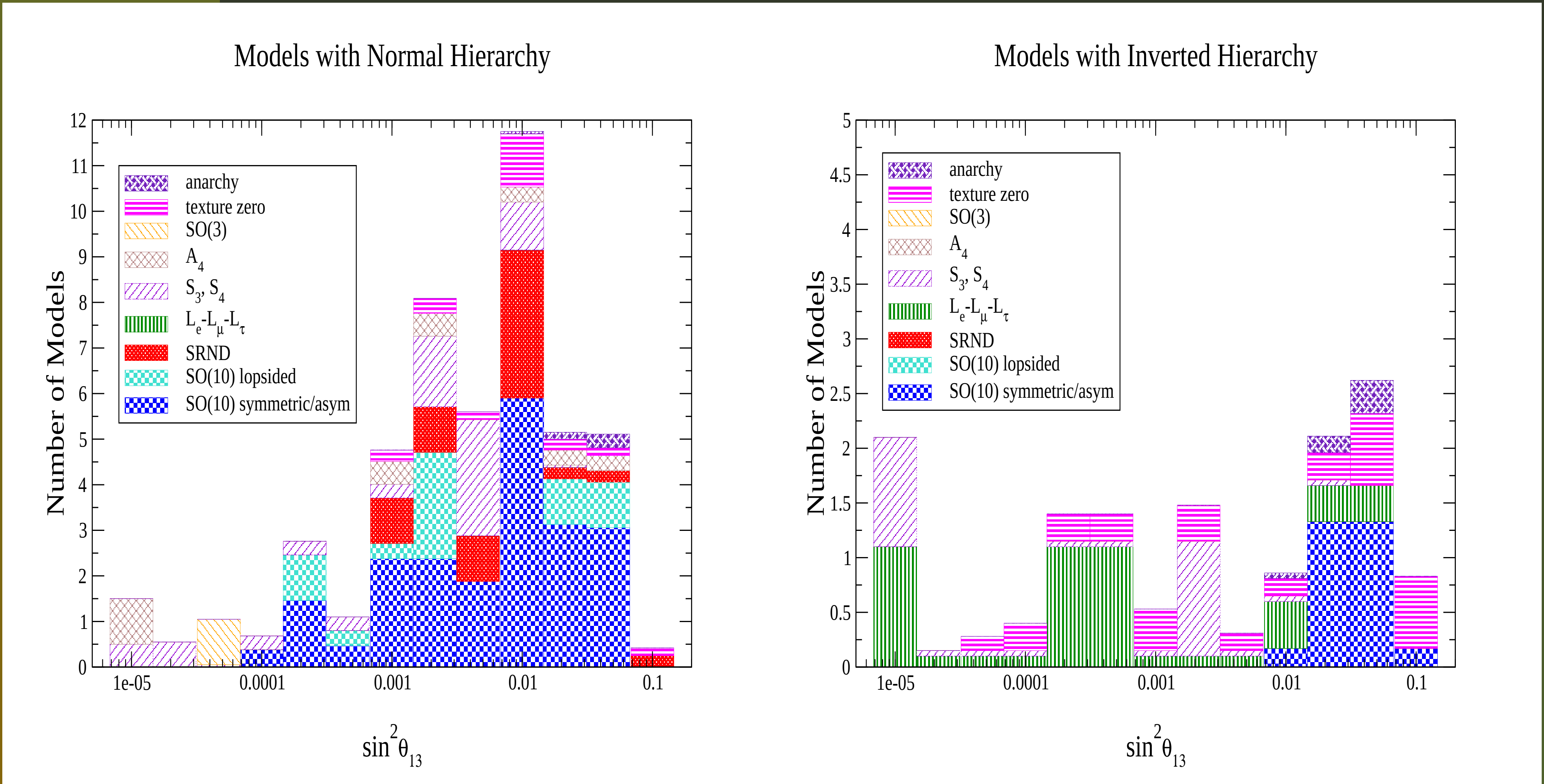
- Important future goals:
  - ➢ Precision measurement of known parameters
  - ➢ Determination of Sign(δm^2_{31})
  - ➢ Search for non-zero θ_{13}
  - ➢ Estimation of value of δ.

Neutrino mass hierarchy

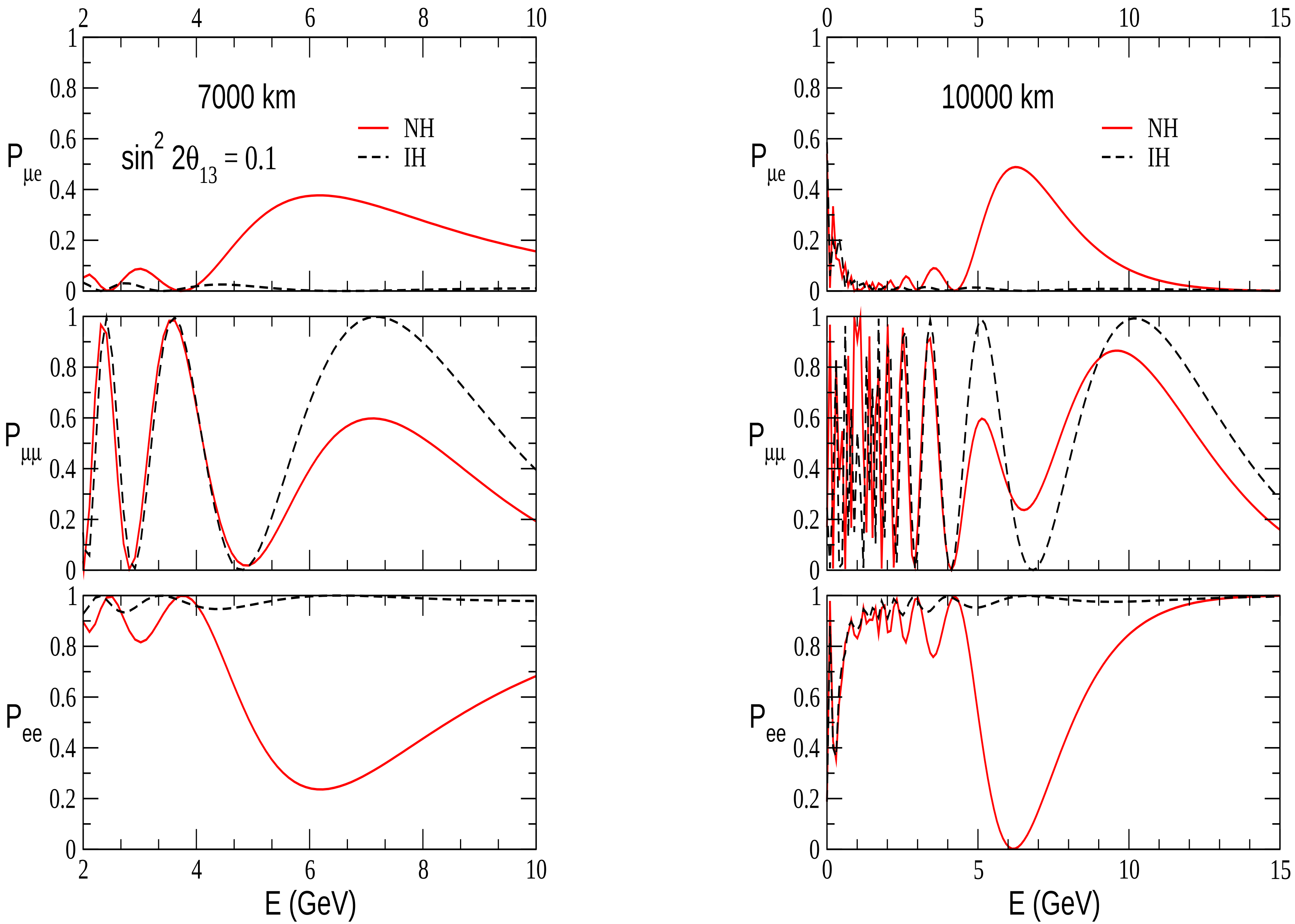


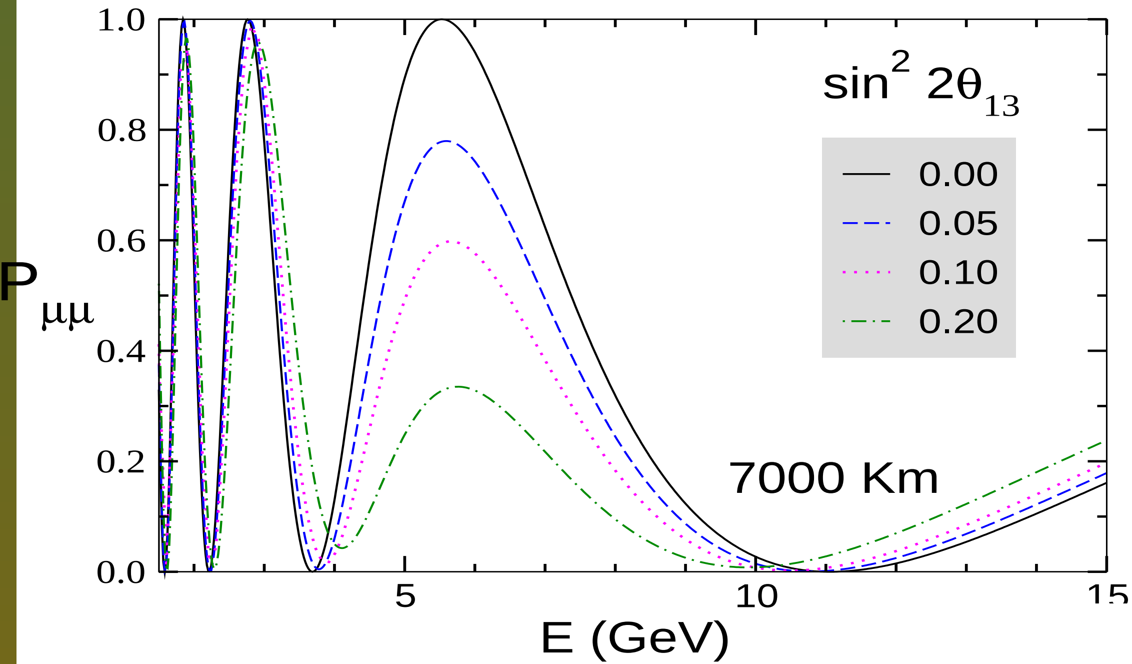
The 2 possible hierarchies of neutrino masses.
$\delta m_{21}^2 = 8 \times 10^{-5} eV^2 << |\delta m_{31}^2| = 2.4 \times 10^{-3} eV^2$.

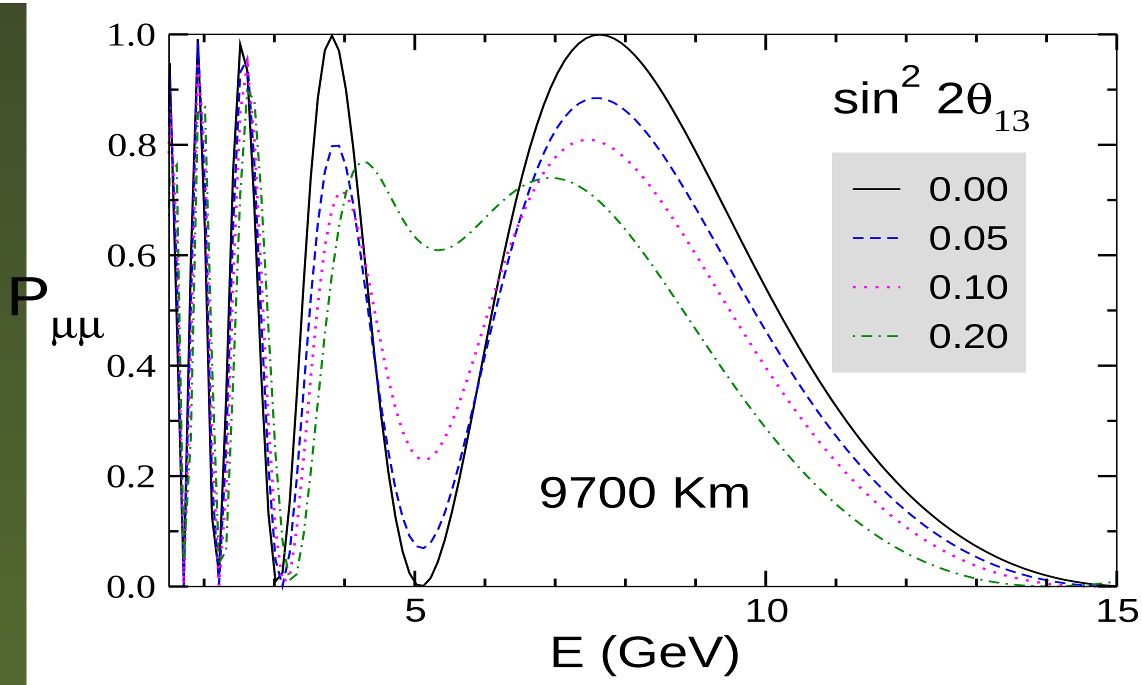
Mass models and hierarchy



(Albright et al, hep-ph/0608137)


7000 km
sin² 2θ13 = 0.1
NH
IH
Pμe
Pμμ
Pee
E (GeV)
10000 km
NH
IH
Pμe
Pμμ
Pee
E (GeV)





$P_{\mu\mu}$ vs E:

θ_{13} sensitivity

Atmospheric neutrinos as source

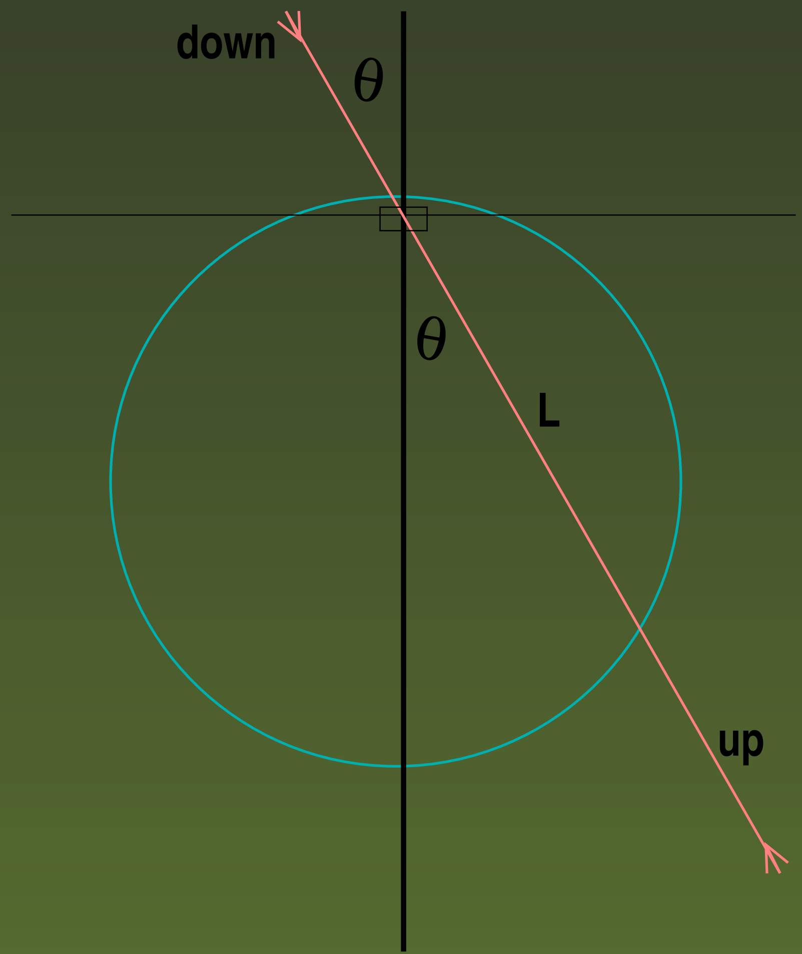
Advantages: ➢ Provides broad L/E band (1 to 10^5 km/GeV). Suitable ranges of L & E can be chosen.

➢ The longer baselines allow matter effects to develop for Sign(δm^2_{31}) sensitivity.

$$p + A_{air} \rightarrow \pi^+ + \ldots$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$



Future Detectors for Atm ν

- Magnetized Iron Detector (Prototype: INO)
  - ➢ 50 - 100 kT
  - ➢ Muon detection & charge discrimination capability
- Megaton Water Cerenkov Detector (Prototype: HK, UNO, MEMPHYS)
  - ➢ SK-type detector with no charge ID
  - ➢ Both electron and muon events can be used
- Liquid Argon detector (Prototype: ICARUS)
  - ➢ Time projection chamber, 100 kT
  - ➢ Both electron and muon events can be used, charge ID for both (partial ID for electron events)
- Neutrino Telescope (Prototype: IceCube)

Detector Resolution

- Finite detector resolution in θ_z & E in both INO and HK
-

$$R_E(E_T, E_M) = N_E \exp\left[\frac{-(E_M - E_T)^2}{2\sigma_E^2}\right]$$

$$\mathrm{R}_{\Theta_z}({\Theta_z}^T, {\Theta_z}^M) = N_z \exp\left[\frac{-({\theta_z}^M - {\theta_z}^T)^2 - \sin^2{\theta_z}^T(\phi^T - \phi^M)^2}{2\sigma_{\theta_z}^2}\right]$$

- For INO and HK, detector resolution of 10^o, 15% unless otherwise stated
- For Liq.Ar, detector resolution of 10^o in angle, 3% in electron energy, 15% in muon energy, 30% in hadron energy

Statistical analysis

- Energy and $\cos\theta_z$ range divided into 8 × 18 = 144 bins for HK, INO, 9 × 18 = 162 bins for Liq.Ar.
- INO $\chi^2 = \chi^2_{\mu} + \chi^2_{\bar{\mu}}$
- HK $\chi^2 = \chi^2_{\mu+\bar{\mu}} + \chi^2_{e+\bar{e}}$
- Liq.ar.
  $\chi^2 = \chi^2_{\mu} + \chi^2_{\bar{\mu}} + n(\chi^2_{e} + \chi^2_{\bar{e}})_{1-5} + (1-n)(\chi^2_{e+\bar{e}})_{1-5} + (\chi^2_{e+\bar{e}})_{5-10}$
- Sensitivity for n bins:
  $\chi^2_{\rm stat} = \sum_{i=1}^{n} (\mathrm{N}^{\rm i}_{\rm theory} - \mathrm{N}^{\rm i}_{\rm expt})^2/(\sigma^{\rm i})^2$, where $\sigma^i = \sqrt{\mathrm{N}_{\rm expt}}$
- $\mathrm{N}_{\rm expt} = \mathrm{N}_{\rm NH}$, $\mathrm{N}_{\rm theory} = \mathrm{N}_{\rm IH}$
- With systematic uncertainties,
  $\chi^2_{\rm pull} = \min_{\xi_{\rm k}} [\sum_{\rm i=1}^{\rm n} \frac{(\mathrm{N}^{\rm i}_{\rm theory} - \mathrm{N}^{\rm i}_{\rm expt} + \sum_{\rm k=1}^{\rm npull} \xi_{\rm k} c^{\rm k}_{\rm n})^2}{(\sigma^{\rm i})^2} + \sum_{\rm k=1}^{\rm npull} \xi^2_{\rm k}]$

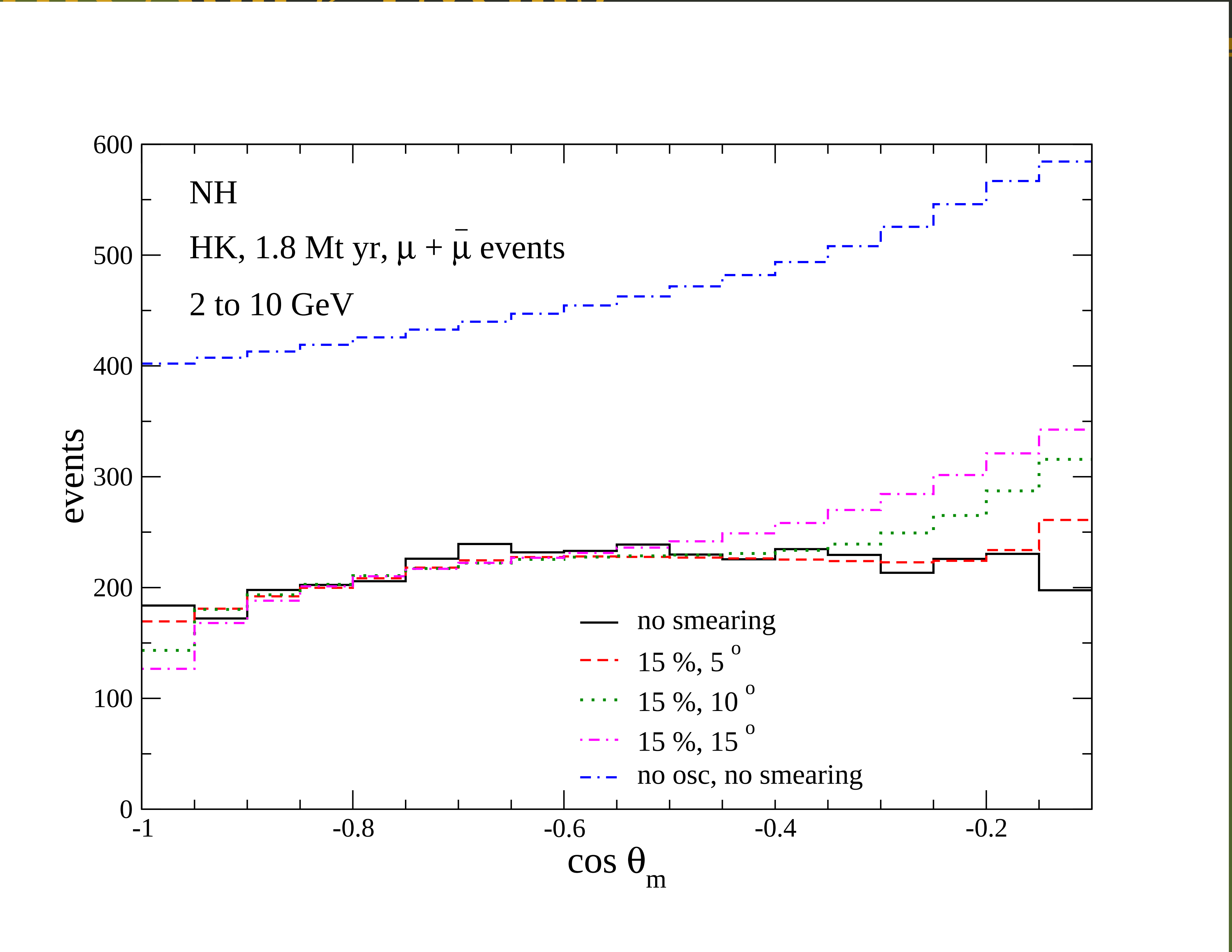
Statistical analysis

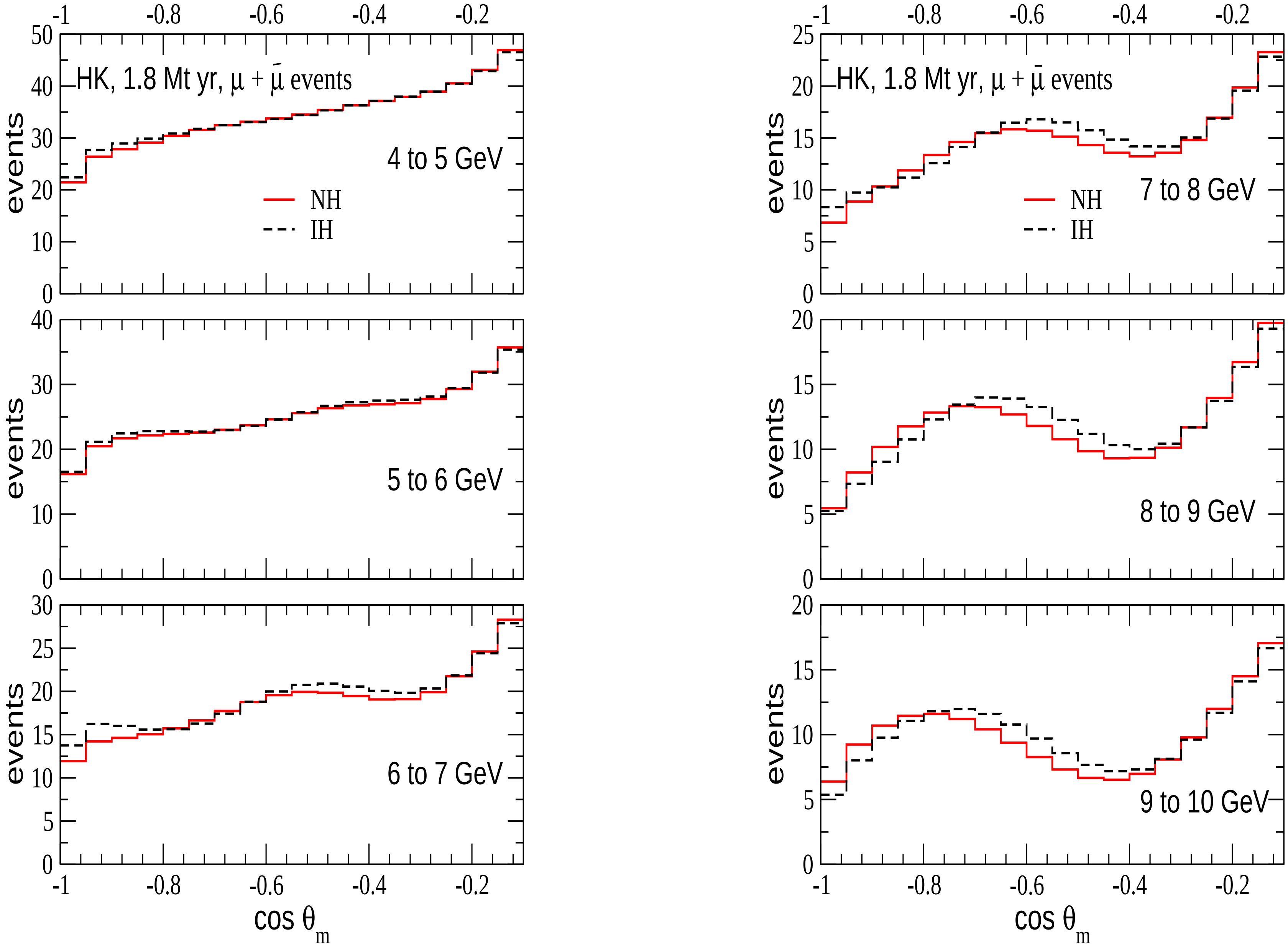
- Marginalization: In $N_{\rm theory}$, Δ_{21}, θ_{12} fixed, other parameters varied in the range:
  - $\Delta_{31} = 2.35 \times 10^{-3} - 2.6 \times 10^{-3}$ eV^2
  - $\sin^2\theta_{23} = 0.4 - 0.6$
  - $\sin^2\theta_{13} = 0.0 - 0.05$ (3σ bound from CHOOZ is < 0.044)
  - "True" values of parameters fixed in $N_{\rm expt}$
- Priors added in the form:

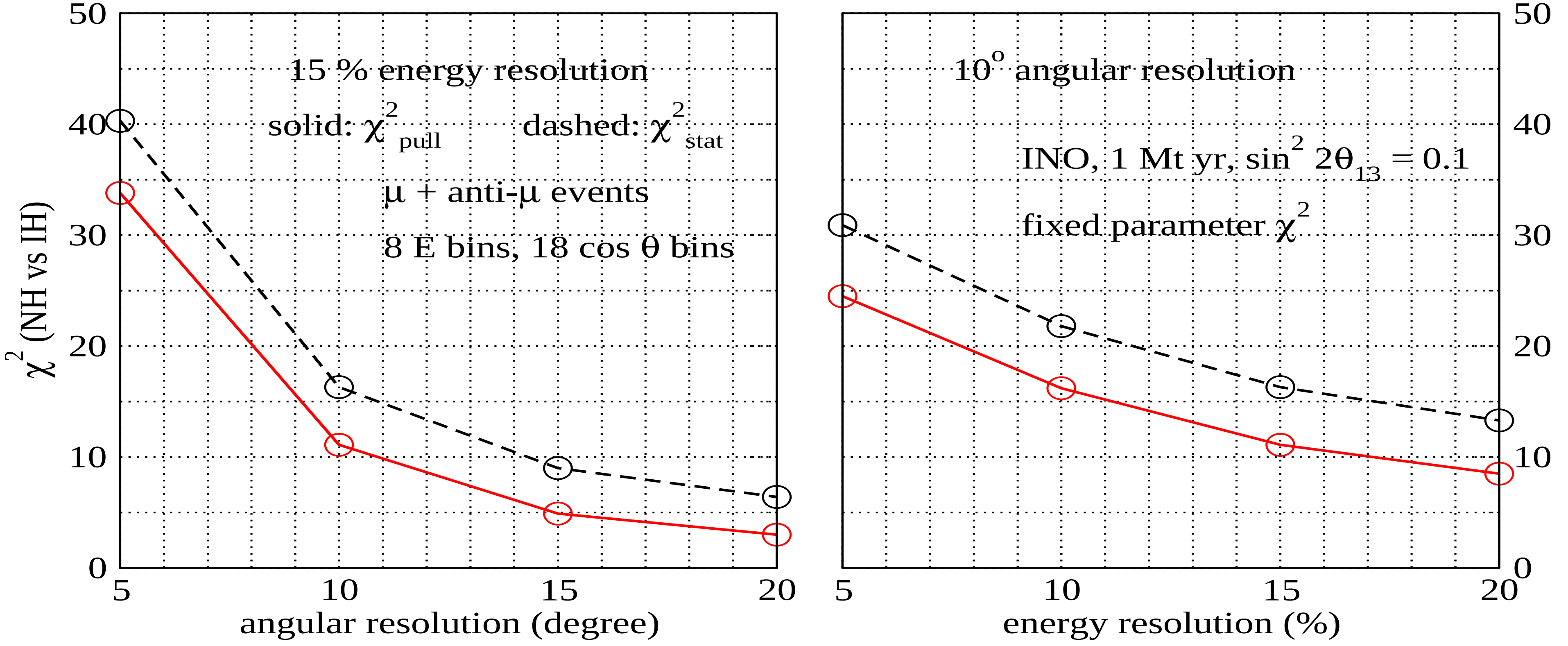
$$\chi^2_{\rm prior} = \frac{((\delta {\rm m}^2_{31}) - (\delta {\rm m}^2_{31})^{\rm true})^2}{(\sigma_{\delta {\rm m}^2_{31}})^2} + \frac{((\sin^2 2\theta_{13}) - (\sin^2 2\theta_{13})^{\rm true})^2}{(\sigma_{\sin^2 2\theta_{13}})^2} + \frac{((\sin^2 2\theta_{23}) - (\sin^2 2\theta_{23})^{\rm true})^2}{(\sigma_{\sin^2 2\theta_{23}})^2}$$

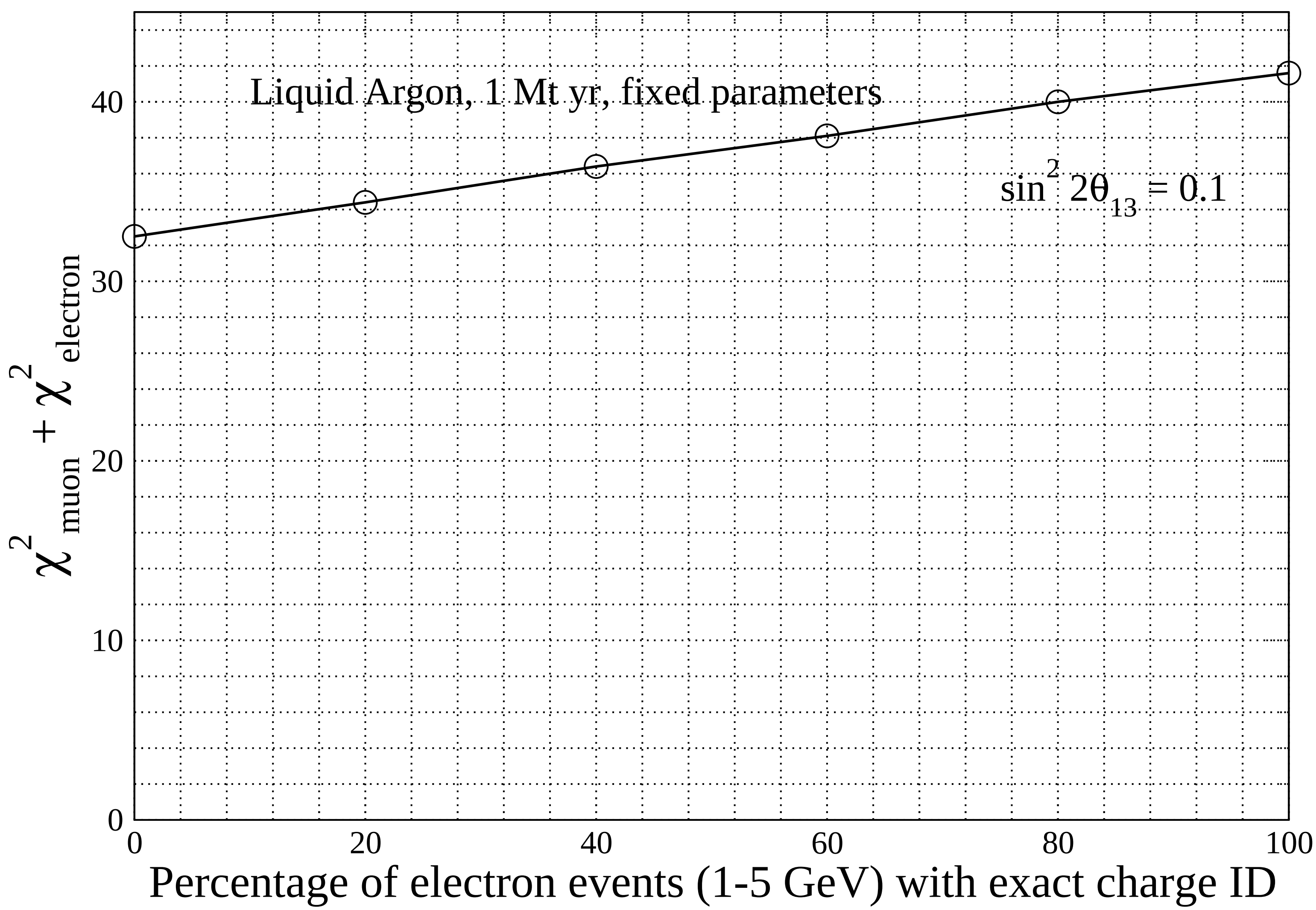
where $\sigma_{\delta m^2_{31}} = 0.1 \times (\delta m^2_{31})^{true}$, $\sigma_{\sin^2 2\theta_{13}} = 0.02$, $\sigma_{\sin^2 2\theta_{23}} = 0.1(\sin^2 2\theta_{23})^{true})$

HK Atm ν Events

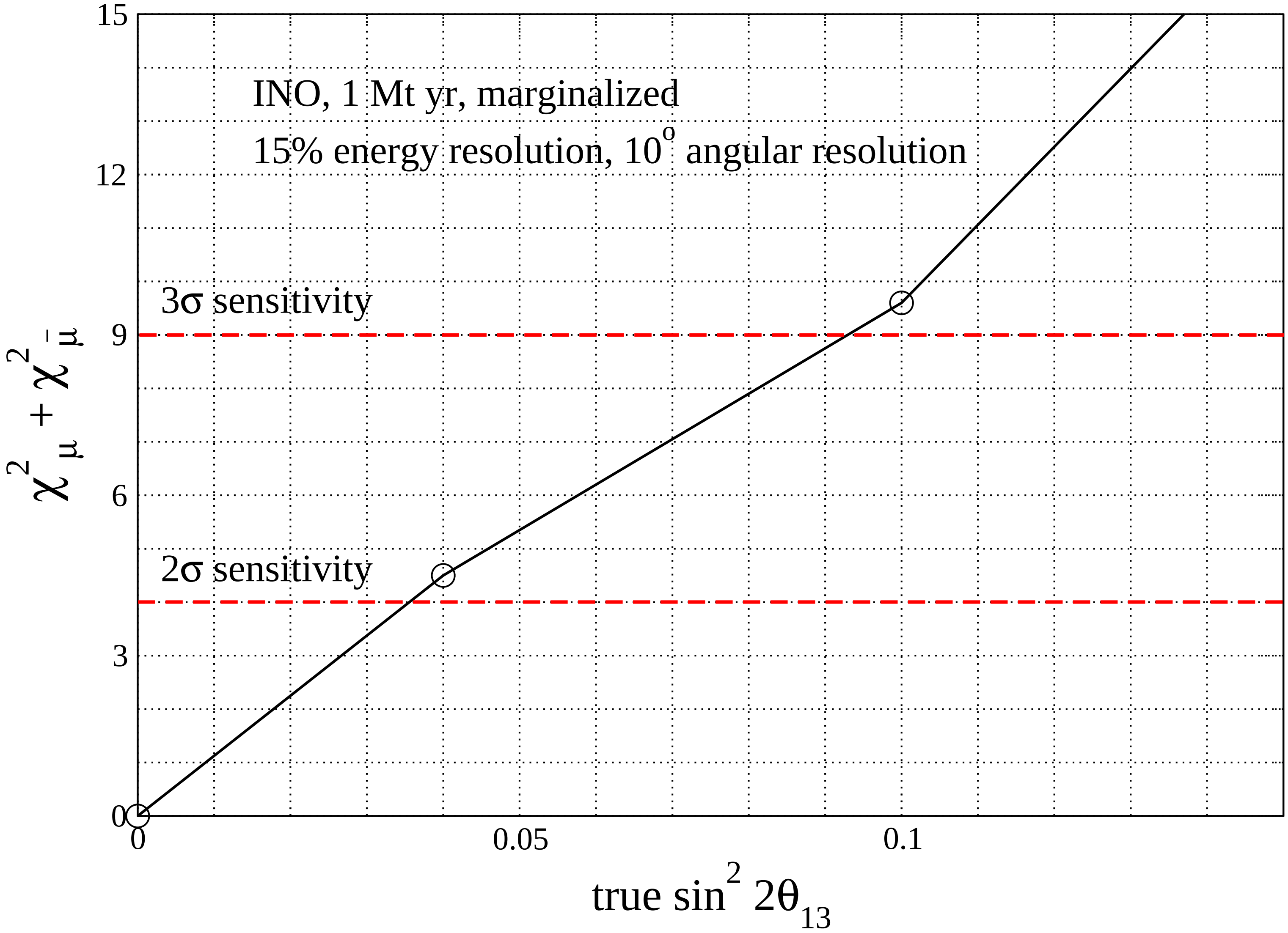


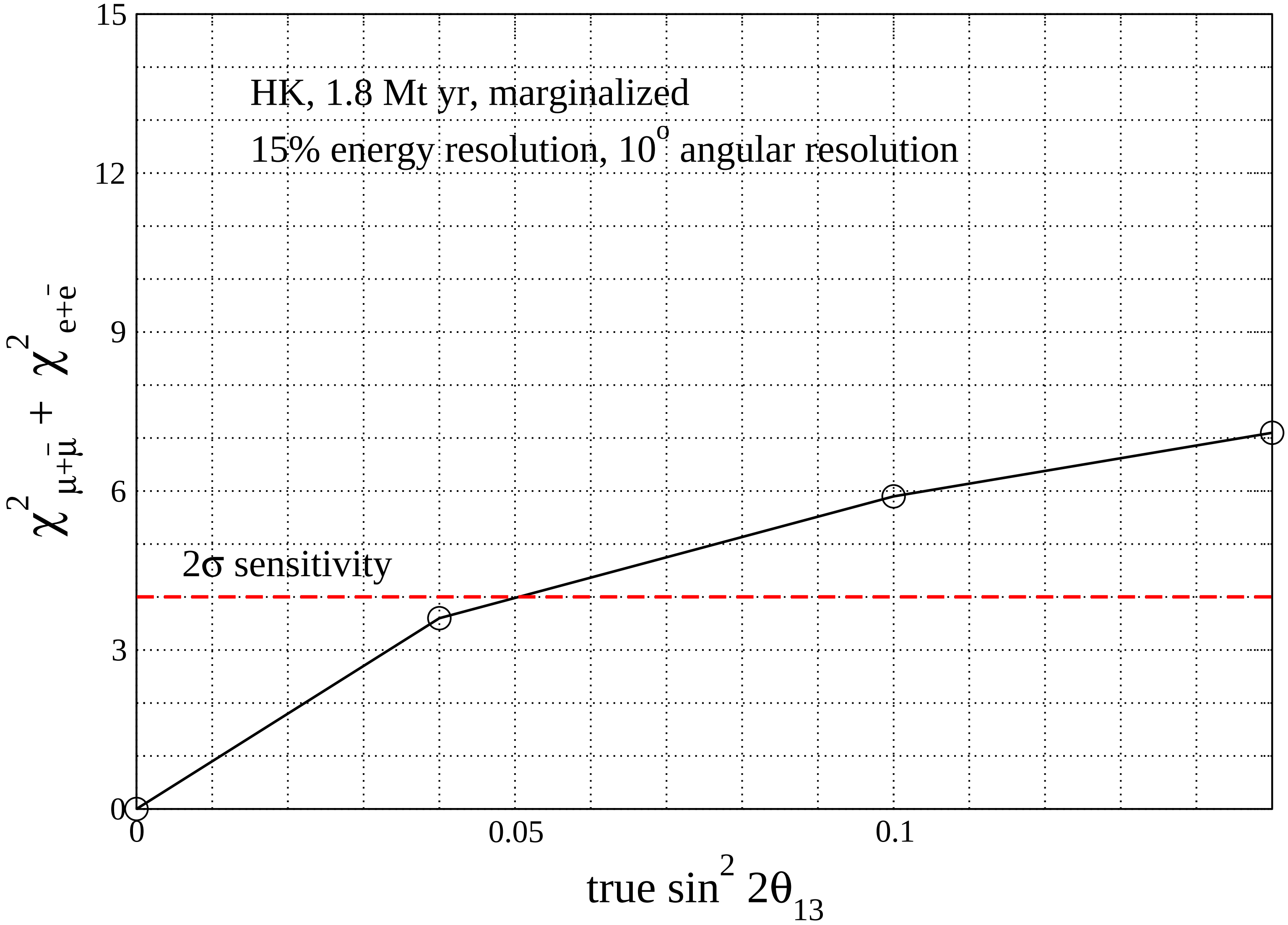

HK, 1.8 Mt yr, μ + μ̄ events
4 to 5 GeV
5 to 6 GeV
6 to 7 GeV
7 to 8 GeV
8 to 9 GeV
9 to 10 GeV
NH
IH
events
cos θm

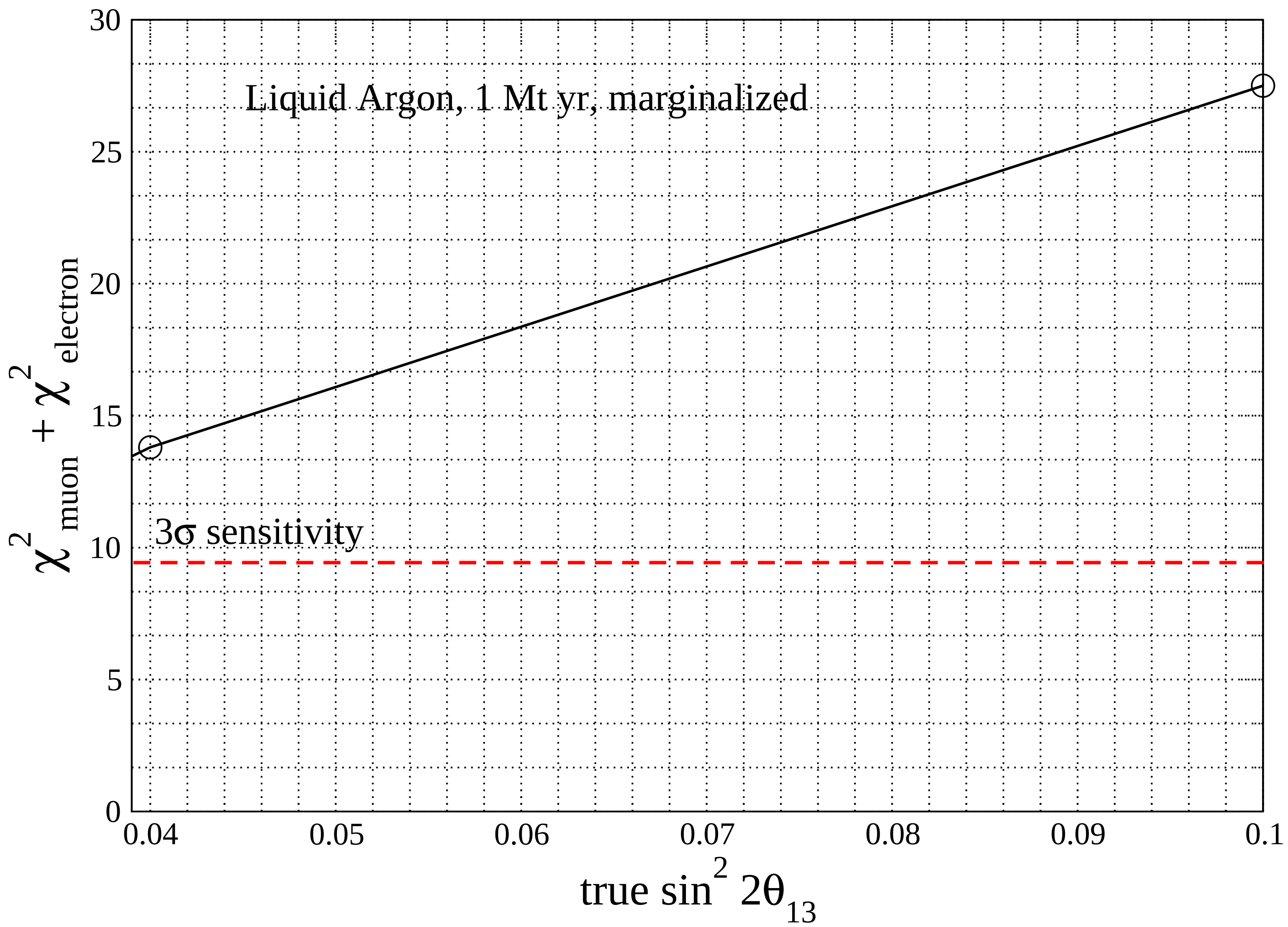

15 % energy resolution
solid: χ^2_{pull} dashed: χ^2_{stat}
μ + anti-μ events
8 E bins, 18 cos θ bins
10^o angular resolution
INO, 1 Mt yr, $\sin^2 2\theta_{13} = 0.1$
fixed parameter χ^2
χ^2 (NH vs IH)
angular resolution (degree)
energy resolution (%)
0
10
20
30
40
50
5
15



Liquid Argon, 1 Mt yr, fixed parameters
$\sin^2 2\theta_{13} = 0.1$
$\chi^2_{muon} + \chi^2_{electron}$
0
10
20
30
40
0
20
40
60
80
100
Percentage of electron events (1-5 GeV) with exact charge ID


INO, 1 Mt yr, marginalized
15% energy resolution, 10° angular resolution
3σ sensitivity
2σ sensitivity
$\chi^2_\mu + \chi^2_{\bar{\mu}}$
true $\sin^2 2\theta_{13}$
15
12
9
6
3
0
0
0.05
0.1


HK, 1.8 Mt yr, marginalized
15% energy resolution, 10° angular resolution
2σ sensitivity
15
12
9
6
3
0
0
0.05
0.1
true sin² 2θ13
χ²μ+μ̄ + χ²e+ē


Liquid Argon, 1 Mt yr, marginalized
3σ sensitivity
30
25
20
15
10
5
0
0.04
0.05
0.06
0.07
0.08
0.09
0.1
$\chi^2_{muon} + \chi^2_{electron}$
true $\sin^2 2\theta_{13}$

HK, INO, Liq.Ar: comparative study

Values of total marginalized χ^2 with pull and priors, for HK (1.8 Mt yr), INO (1 Mt yr), Liquid Argon (1 Mt yr):

$\sin^2 2\theta_{13}$	$HK\chi^2_{pull,prior}$	$INO\chi^2_{pull,prior}$	$Liq.Ar\chi^2_{pull,prior}$
0.0	0.0	0.0	0.0
0.04	3.6	4.5	13.8
0.1	5.9	9.6	27.5

Other possibilities..

- Looking at possible hierarchy sensitivity for small values of θ_{13} and in vacuum, apart from sensitivity related to matter effects.
- Problem in this case:
  ➢ Hierarchy sensitivity dictated by δm^2_{21}-driven effect, very small.
  ➢ Experiments determine linear combination of δm^2_{31} and δm^2_{32}. If atmospheric measurement sees the same combination, hierarchy determination not possible.
  ➢ Work in progress.

Summary

- The interplay of the survival and oscillation probabilities gives rise to large sensitivity to matter effects $\&$ Sign(δm^2_{31}) at a probability level.
- The dependence of muon and electron-like events on Sign(δm^2_{31}) in atm neutrino experiments may give a statistically significant signal for the hierarchy, after various errors and parameter uncertainties are taken into account.
- This gives a method for determining the neutrino mass hierarchy via atmospheric neutrinos in the planned iron calorimeter detector INO, megaton Water Cerenkov detector Hyper-Kamiokande, Liquid Argon-based detectors and other future detectors.