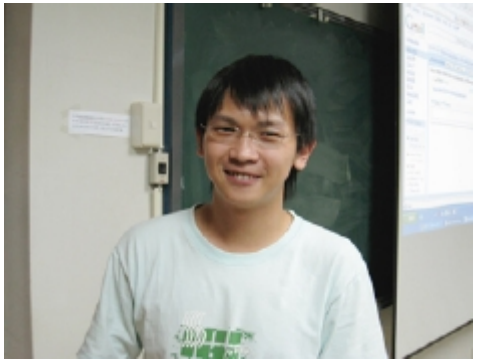
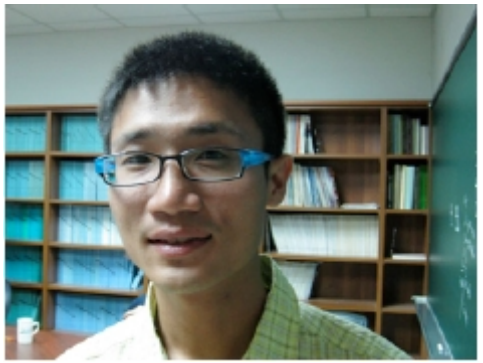
ARA Simulation and Analysis

Presented by *Melin Huang*, NTU LeCosPA

Major Work done by



Chia-Yu Hu



Shang-Yu Sun

Hsin-Yi Tu

Shi-Hao Wang

With Contributions from

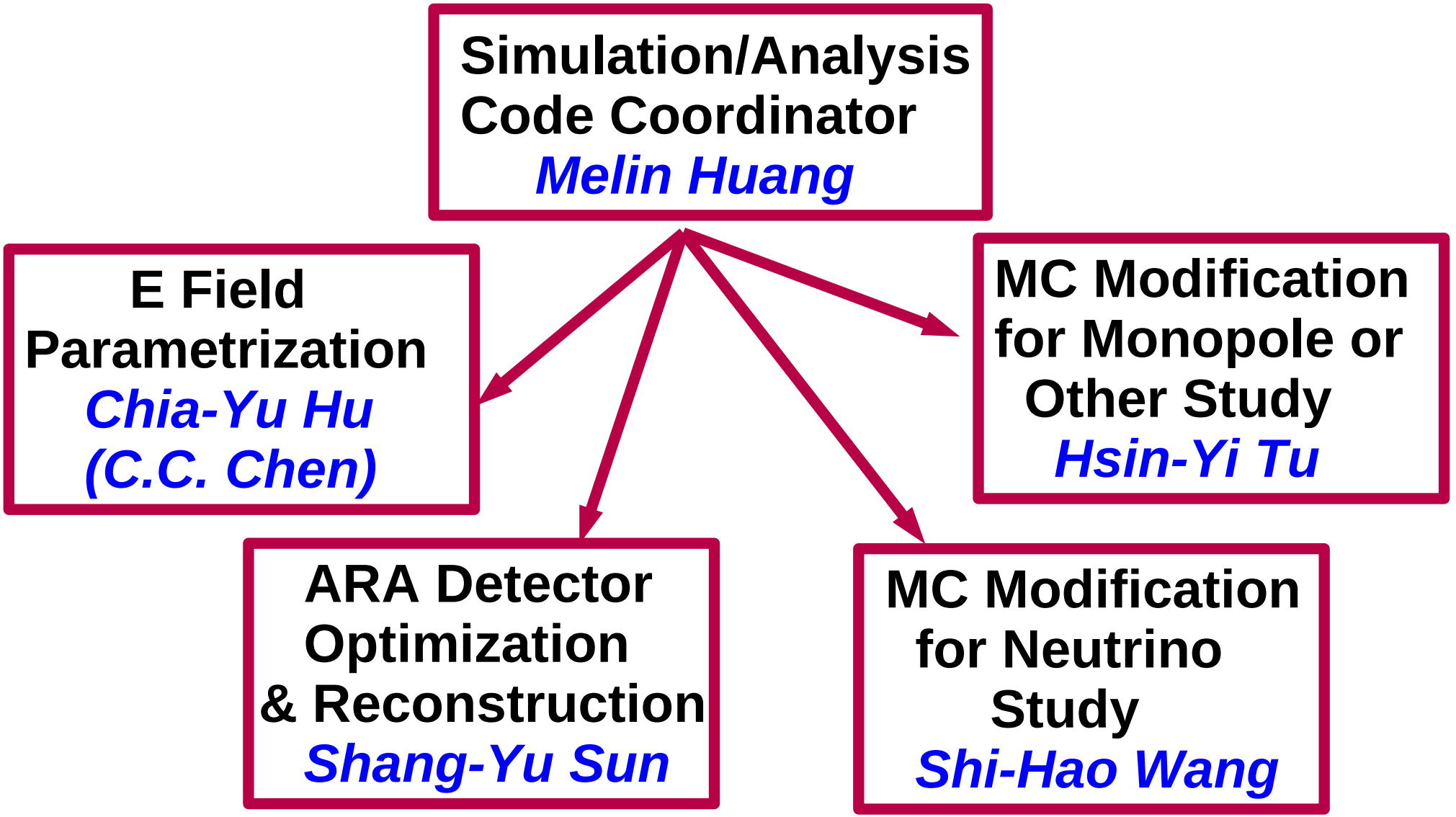
Chih-Ching Chen

Ruo-Yu Shang

Contents

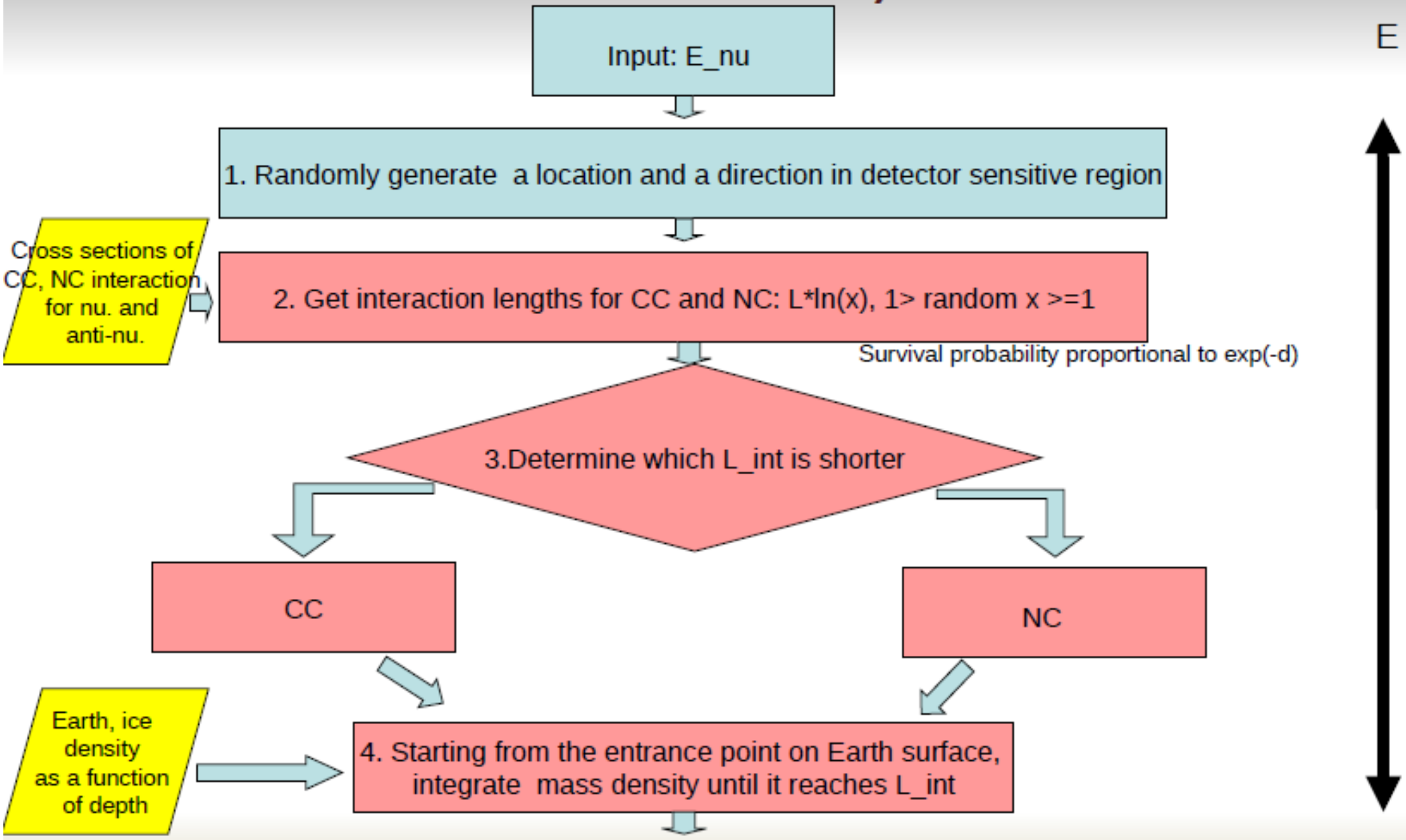
- **Physics Topics**
  - -- UHE Neutrino Flux
  - -- Monopole Search
  - -- Other physics topics ...
- **Monte Carlo (MC) Codes**
  - -- Peter Gorham code
  - -- Modified MC code
- **Optimization of ARA Antenna Spacing & Staion Spacing**

NTU Monte Carlo



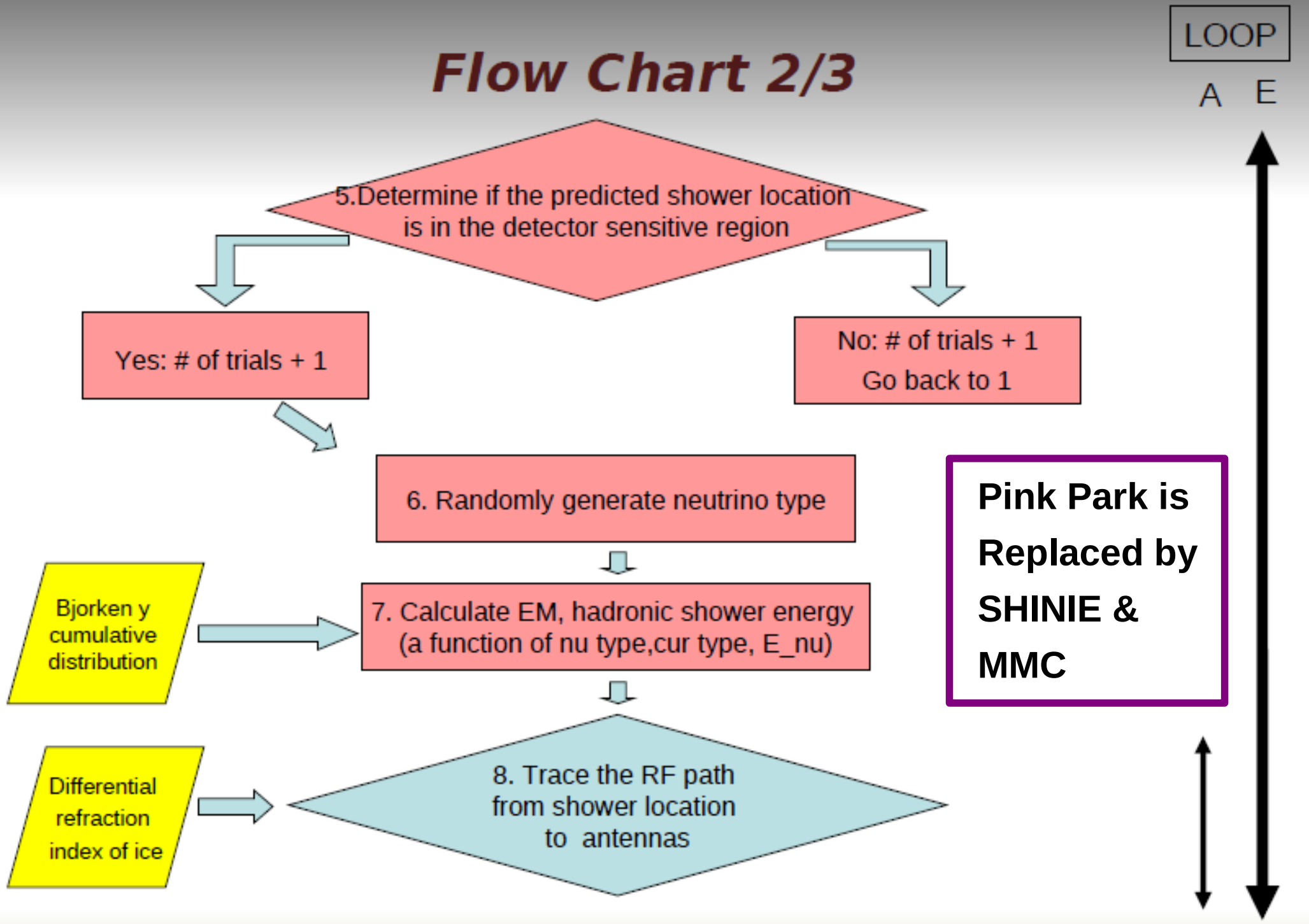
A new student, Huan-Ting Peng, will join us on ARA expt.

Peter Gorham's code: Flow Chart 1/3



Made by Shang-Yu Sun & Shi-Hao Wang

Flow Chart 2/3



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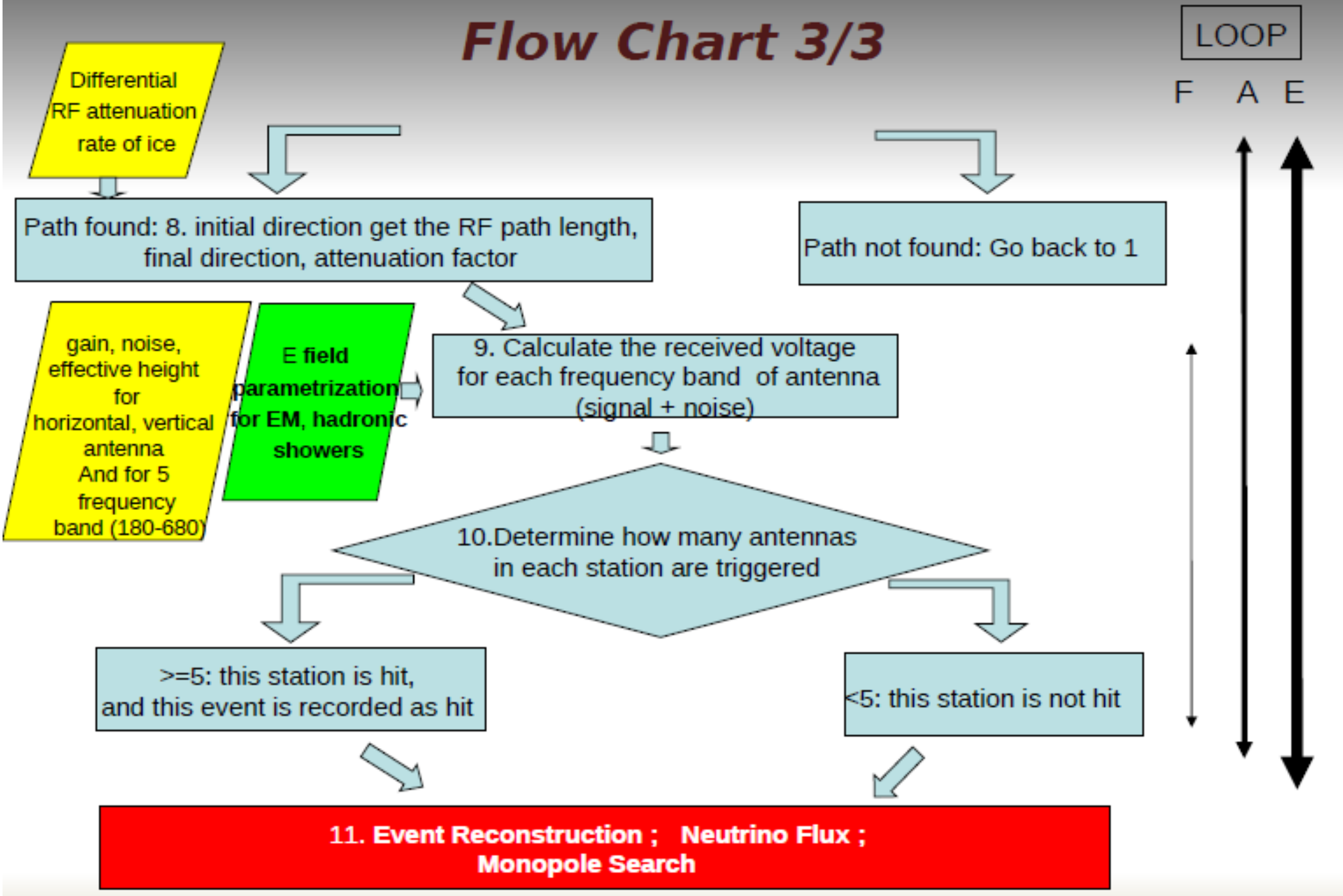
Flow Chart 3/3



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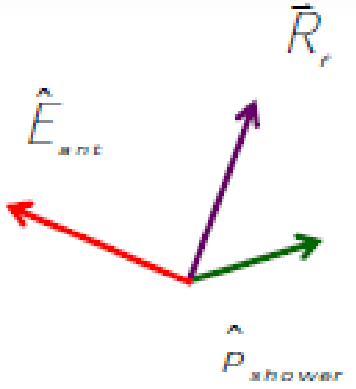
Parametrization E Field

- E field direction (linear pol.)

$$\hat{E}_{ant} = \hat{R}_r \times \left(\hat{R}_r \times \hat{p}_{sh}\right)$$



- E field strength

$$E(\theta) = E(\theta_c) \cdot \exp\left[-\ln 2 \cdot (\theta - \theta_c/\sigma)^2\right] \qquad \theta_c = \cos^{-1}(1/n)$$

$$E(\theta_c) = 2.57\times10^{-7} \cdot \frac{1}{L} \cdot \frac{E}{10^{12}\,eV} \cdot \frac{\nu}{1.15\times10^{9}\,Hz}$$

(For Far Field Only)

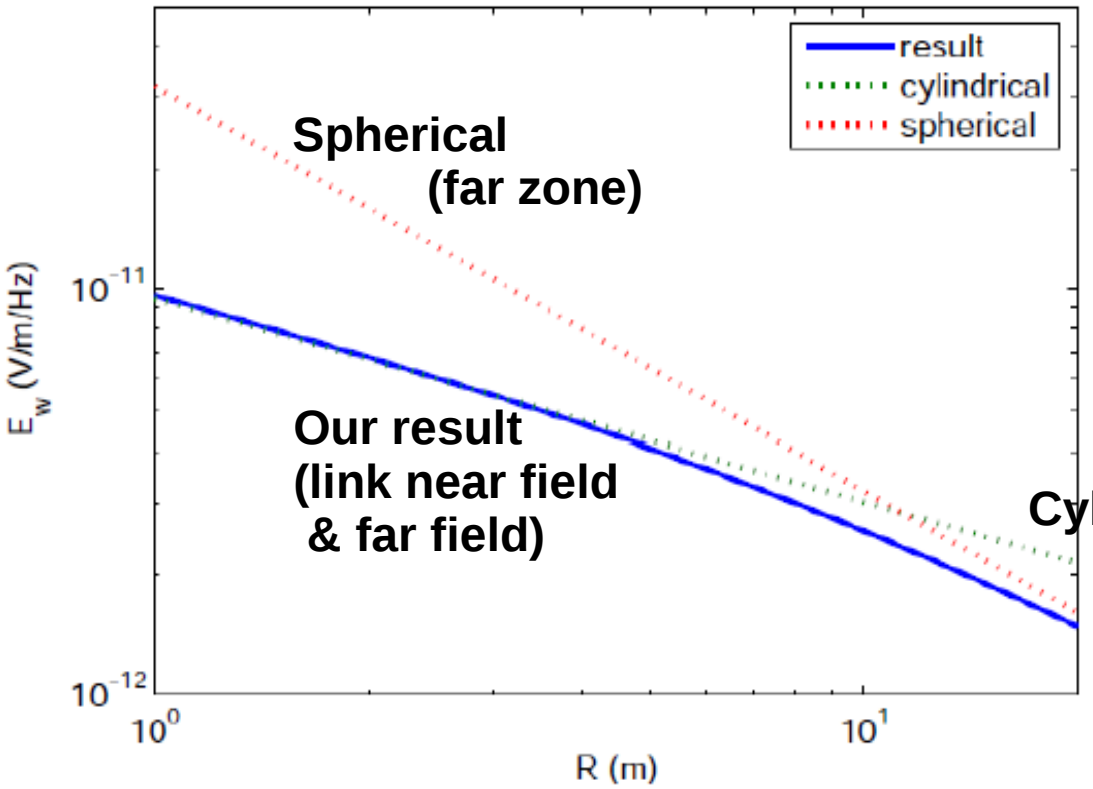
$$\sigma = 2.7^\circ \cdot \frac{500\,MHz}{\nu} \cdot \left(E_{lpm}/(E_{lpm} + 0.14E_{sh})\right)^{0.3} \text{, for electron\_shower}$$

$$\sigma = 1^\circ \cdot \frac{500\,MHz}{\nu} \cdot \left(4.23 - 0.785\log\left(\frac{E}{1TeV}\right) + 0.055\left[\log\left(\frac{E}{1TeV}\right)\right]^2\right) \text{, for hadronic\_shower (E} > 100\text{PeV)}$$

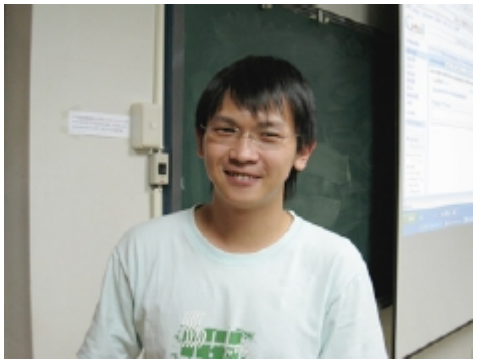
- From Alvarez-Muniz & Zas: (need to study)
- "Cherenkov radio pulses from EeV neutrino interactions: the LPM effect" , Phys. Lett. B 411(1997)
- "The LPM effect for EeV hadronic showers in ice: implications for radio detection of neutrinos" Phys. Lett. B 434(1998)
- "Calculation Methods for Radio Pulses from High Energy Showers", PRD 62,63001 (2000)

Parametrization E Field

Current Result (from Numerical Method):



E field in frequency domain vs observation distance (R)



Chia-Yu Hu

Chih-Ching Chen

Goals (Work still on-going):

-- EM Shower Parametrization
-- Hadronic Shower Parametrization
-- Take LPM effect into account

Trace RF from Shower Vertex to Antennas

- **Purposes:**
  - -- In seach of tracing step size for accurate and efficient propagation of RF from shower vertex to antenna

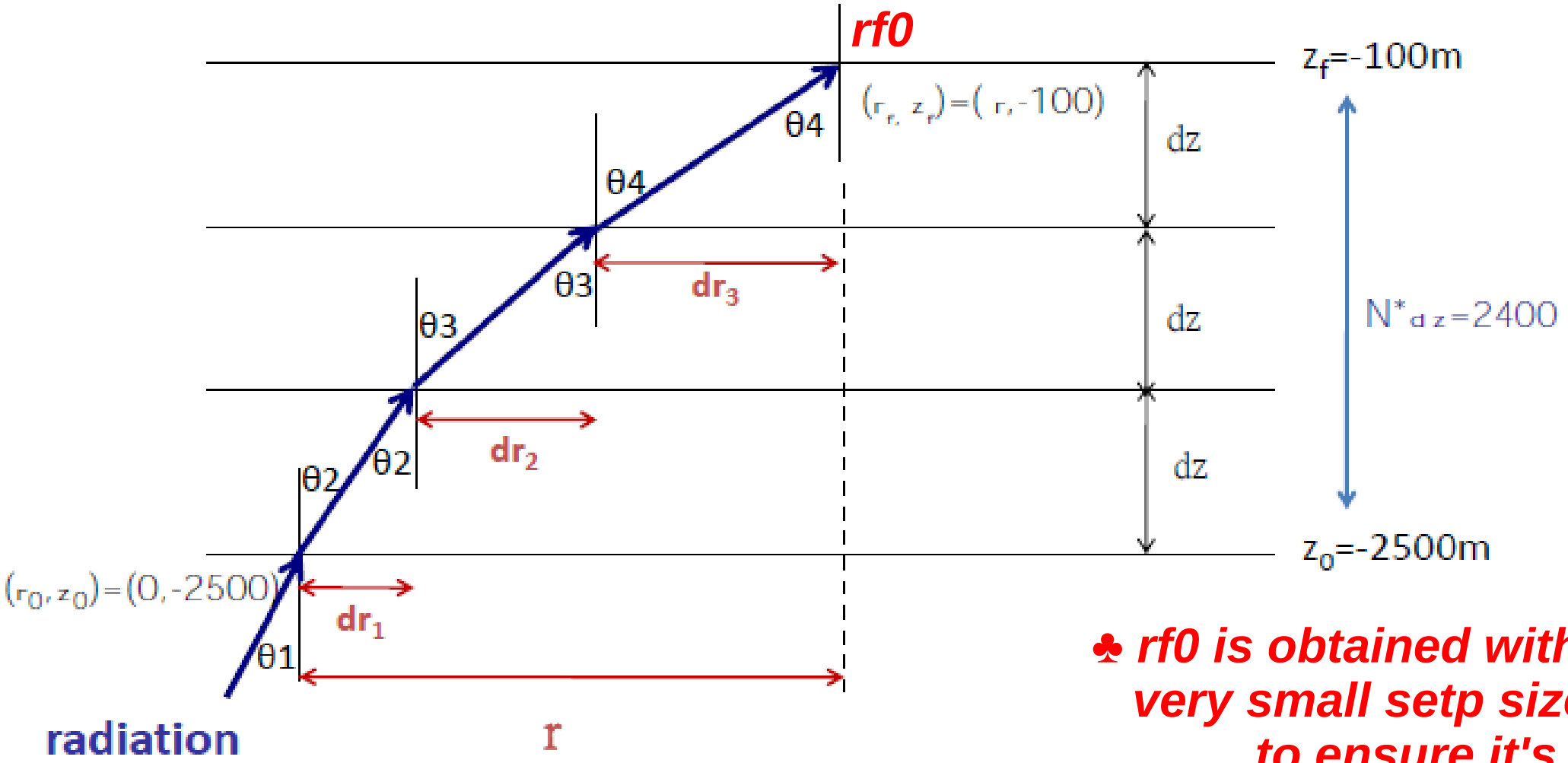
Hsin-Yi Tu

- **Methods:**
  - -- Step-by-Step
  - -- Intuitive Propagation (Proposed by *Ruo-Yu Shang*)
  - -- Peter Gorham's Approach

Ruo-Yu Shang

- **Algorithms:**
  - -- Trace shower from z = -2500 --> -100 m
  - -- Compare dr vs step size (dr == r_final - rf0)
  - -- Compare dr/rf0 vs step size (rf0: reference r location)

Step-by-Step method



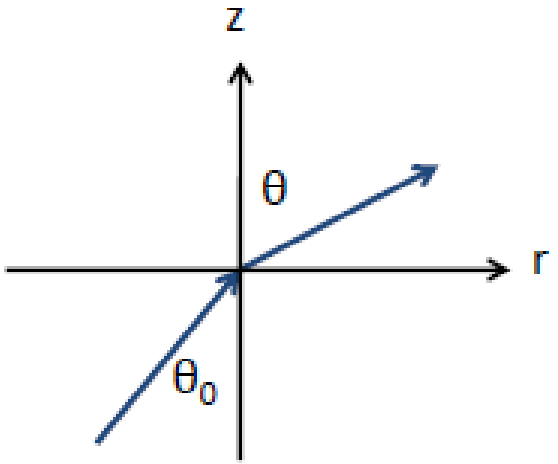
♣ ***rf0 is obtained with very small setp size to ensure it's very precise***

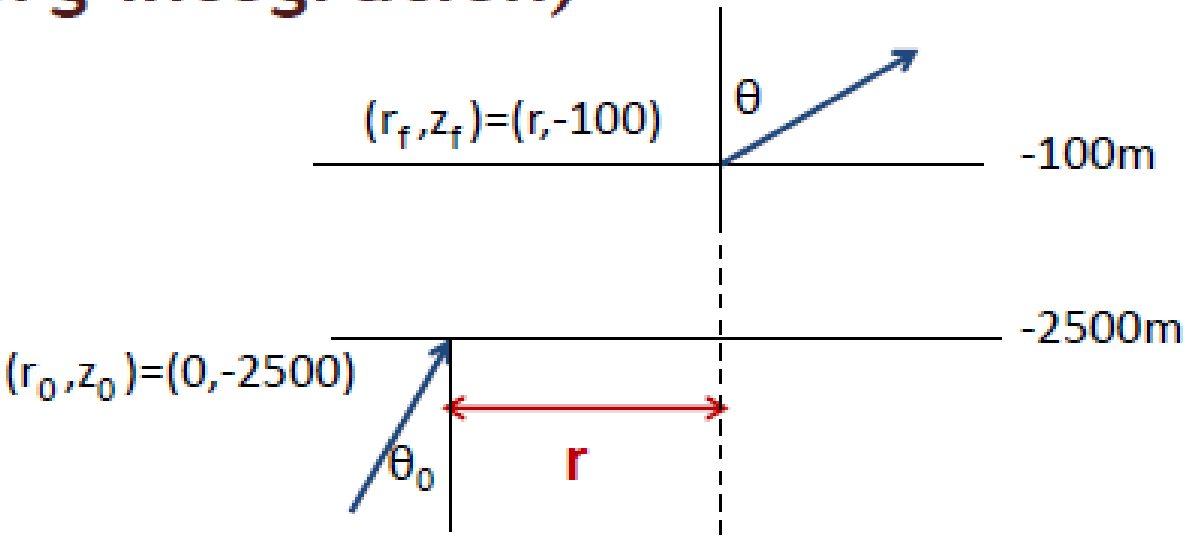
Snell's law: $n_1 \sin\theta_1 = n_2 \sin\theta_2$

$$n(z)=1.325 + 0.463\,[1.0 - \exp(-0.014|z|)]$$

Work by Hsin-Yi Tu

Intuitive method (proposed by Ruo-Yu Shang) (Romberg integration)





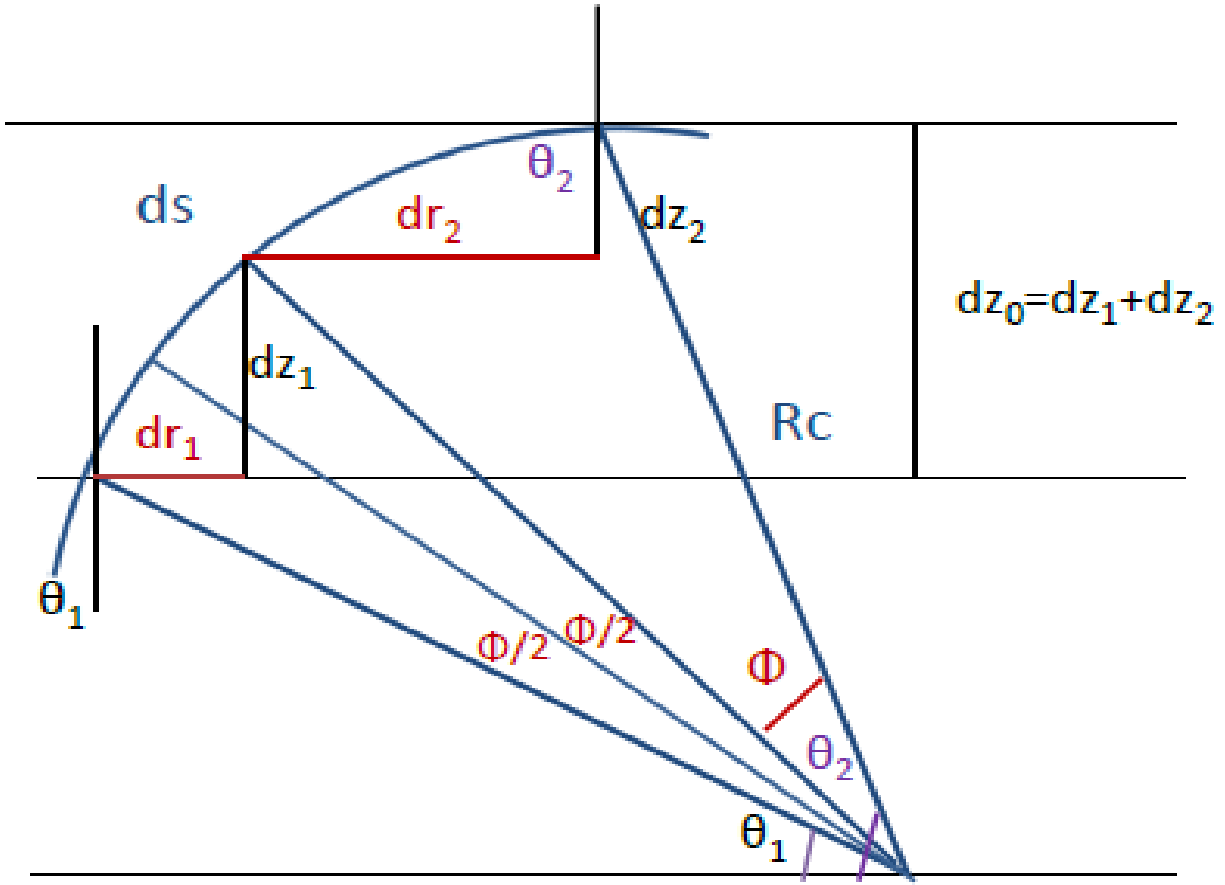
Snell's law: $n_1 \sin\theta_1 = n_2 \sin\theta_2$ $\quad n(z)\sin\theta = C \rightarrow \theta = \sin^{-1}\frac{C}{n}$

$n(z)=1.325 + 0.463\,[1.0 - \exp(-0.014|z|)]$ $\quad \frac{dr}{dz} = \tan\theta$

$$r = \int dr = \int \tan\theta\, dz = \int_{z_0}^{z_f} \tan\left(\sin^{-1}\frac{C}{n(z)}\right) dz = \int_{z_i}^{z_f} f(z)\, dz$$

Work by Hsin-Yi Tu

Peter Gorham's method



$$dz_0 = \frac{ds}{\sqrt{1+\frac{1}{\tan^2\theta_1}}}$$

$$dz_0 = ds \times \cos\theta_1$$

$$Rc = \frac{dz_0}{\sin\theta_1\left(\frac{n_1}{n_2}-1\right)}$$

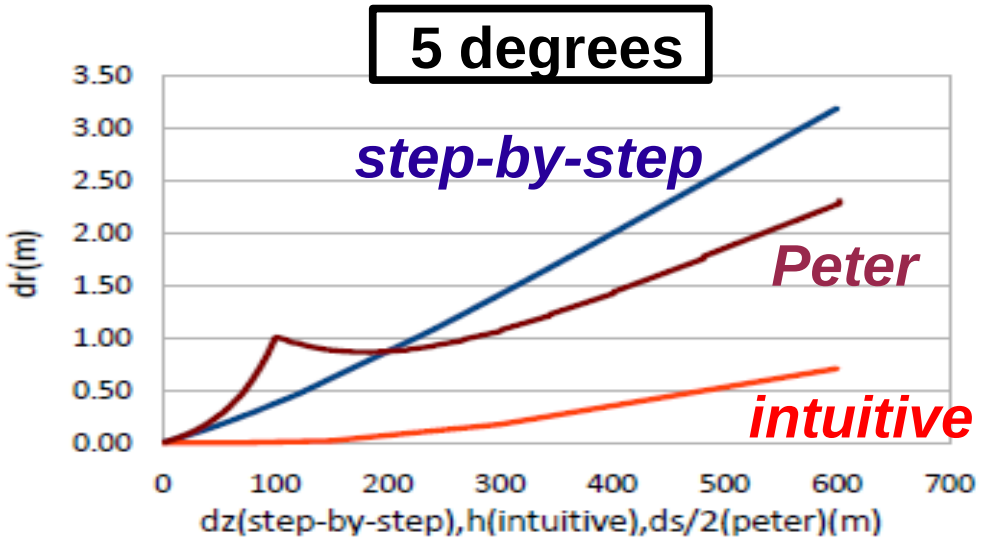
$$\theta_2 = \theta_1 + 2\Phi$$

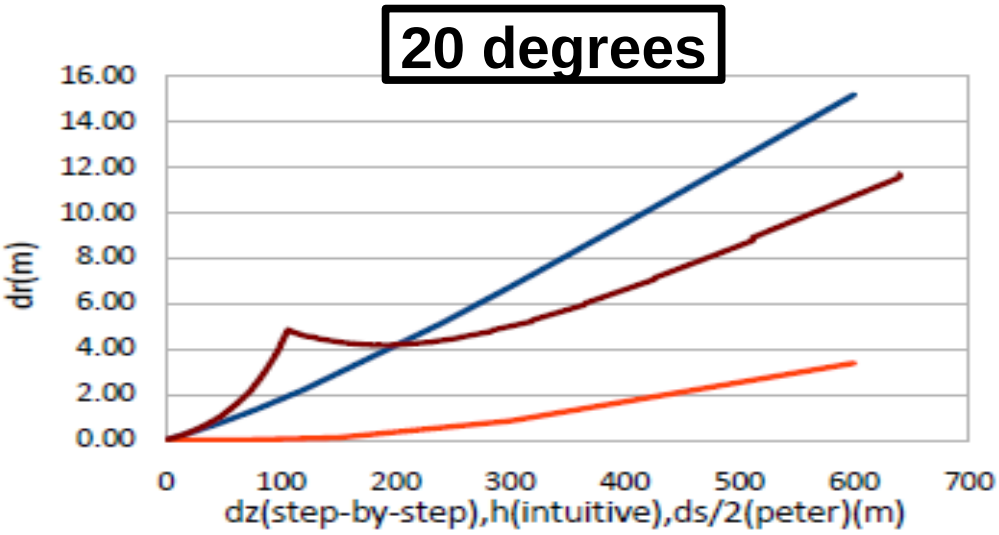
$$dr = 2\,Rc \sin\left(\frac{\Phi}{2}\right)\sin\left(\theta_1+\frac{\Phi}{2}\right) = Rc[\cos\theta_1 - \cos(\theta_1+\Phi)]$$

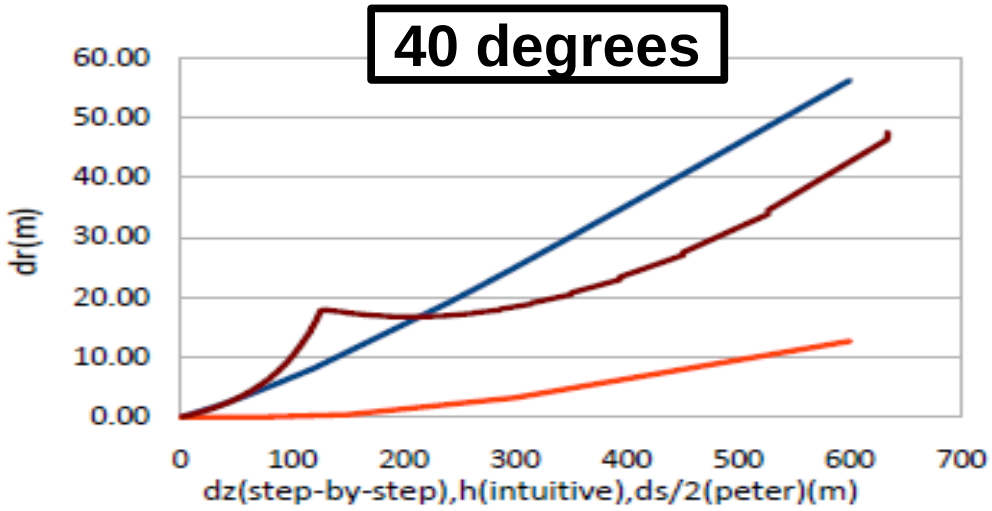
$$dz = 2\,Rc \sin\left(\frac{\Phi}{2}\right)\cos\left(\theta_1+\frac{\Phi}{2}\right) = Rc[\sin(\theta_1+\Phi) - \sin(\theta_1)]$$

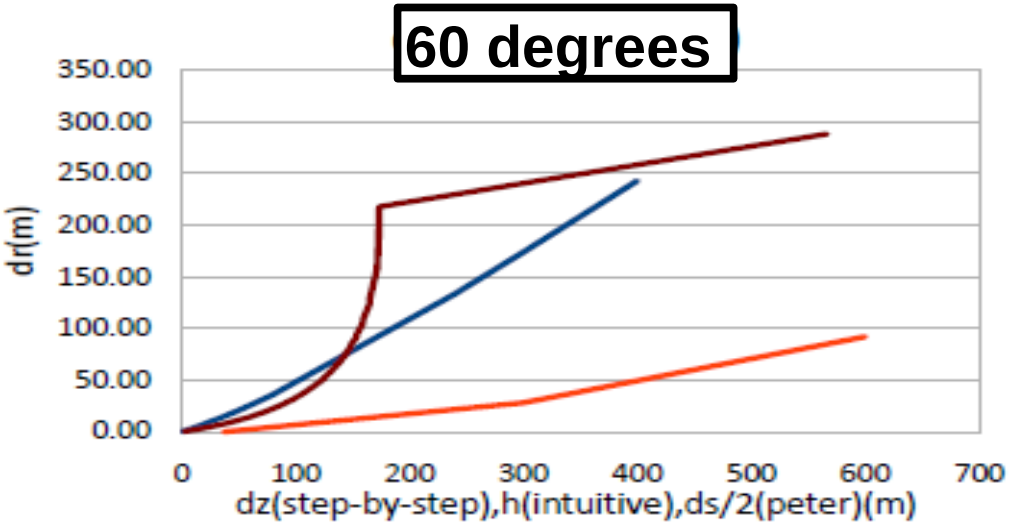
Work by Hsin-Yi Tu

dr vs Step Size for different incident angle







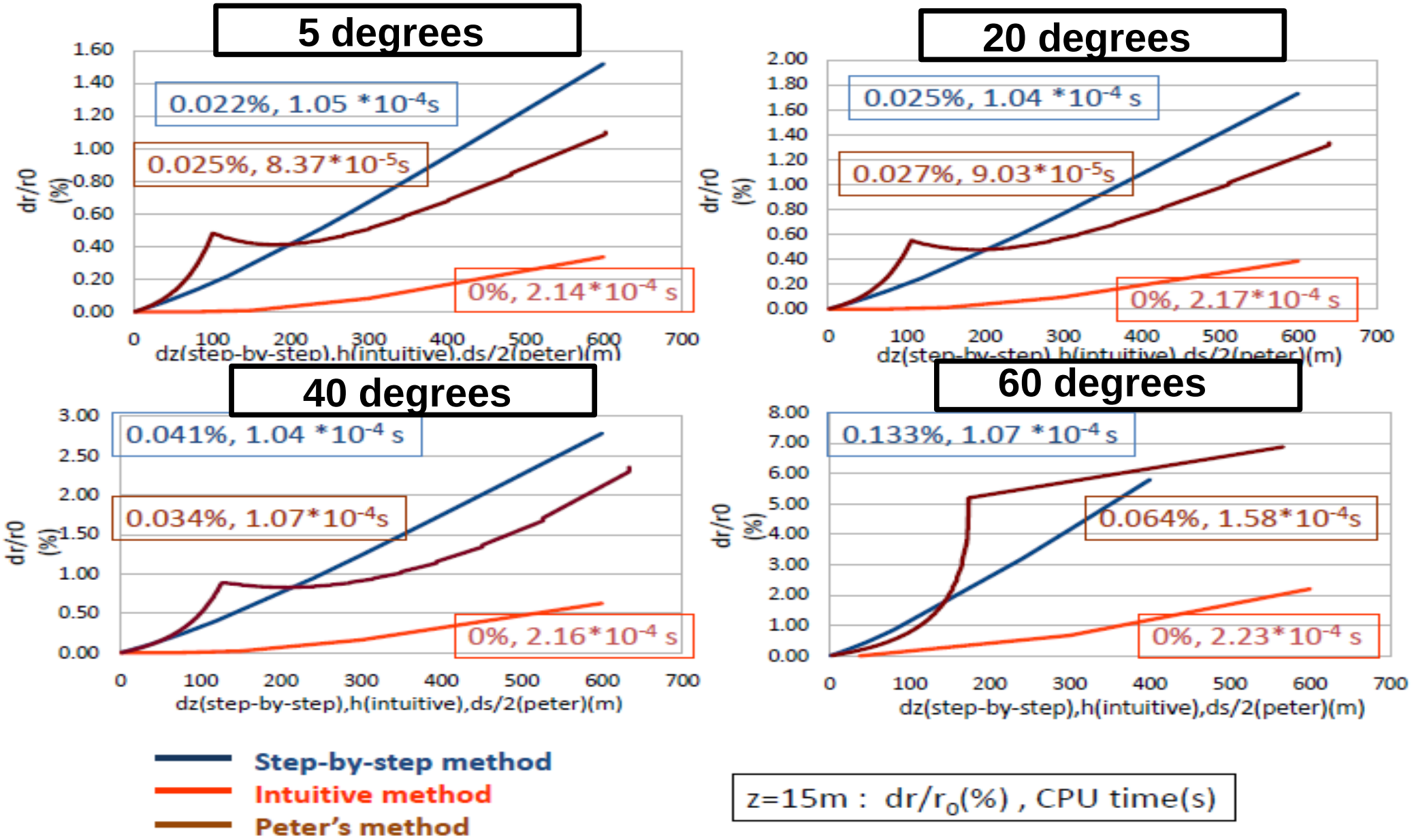


Step-by-step method
Intuitive method
Peter's method

Trace from z = -2500 --> -100 m
dr == r_final – rf0
rf0 = reference r value at final

Work by Hsin-Yi Tu

dr/rf0 vs Step Size for different incident angle



Work by Hsin-Yi Tu

Conclusions for Trace RF from Shower Vertex to Antennas

- **Performance of Intuitive Method (proposed by *Ruo-Yu Shang*) is pretty accurate**
  - **-- If any two antenna spacing ~15m,**
    - **relative error is ~0 %**
- **Performance of Peter Gorham's approach is fastest**

Optimization of ARA Antenna/Station Spacings

- **Purposes:**

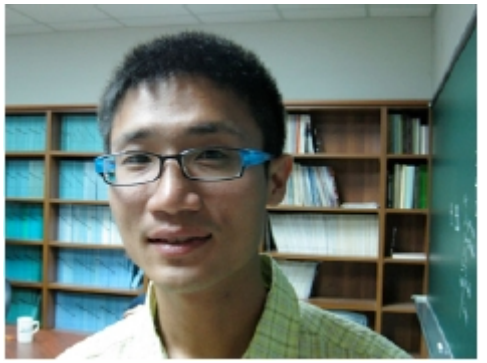
  Determine how to deploy ARA Antenna Spacing and Station Spacing in order to make

  -- Detection Efficiency as high as possible

  -- Angular Resolution of Neutrino pointing-back-source as good as possible

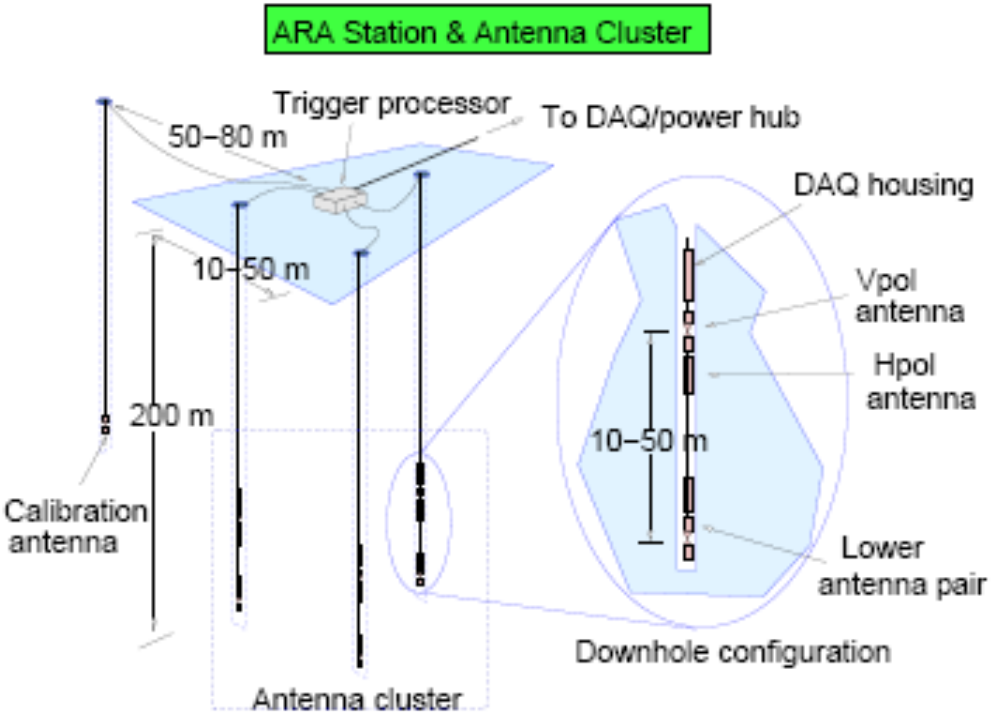
  -- Neutrino Energy Estimate as precise as possible ==> Not easy to do

  -- Any other criteria to consider ?



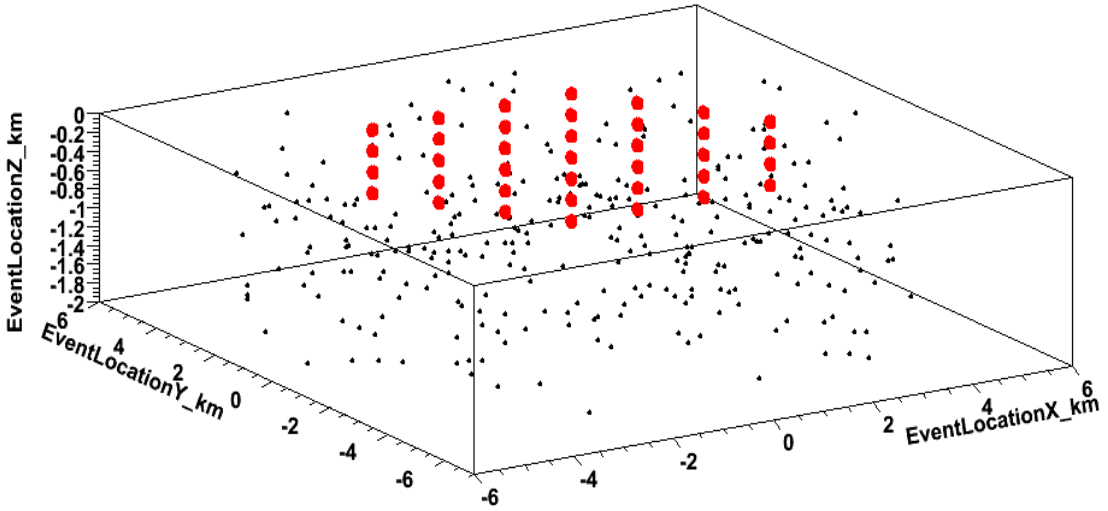
Shang-Yu Sun

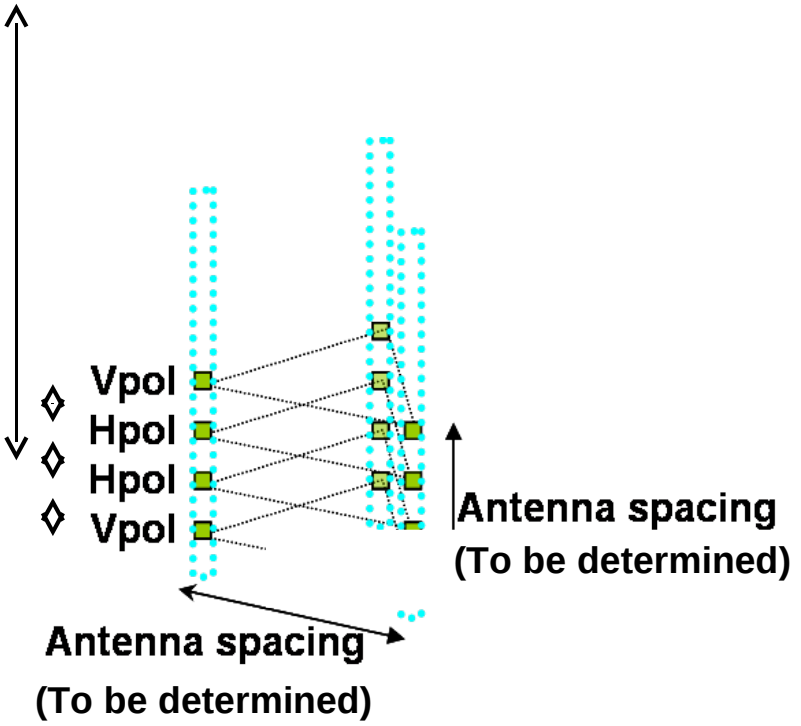
ARA Conceptual Design



From ARA Proposal

Simulation Setup:
ARA Geometry and Parameters Generated

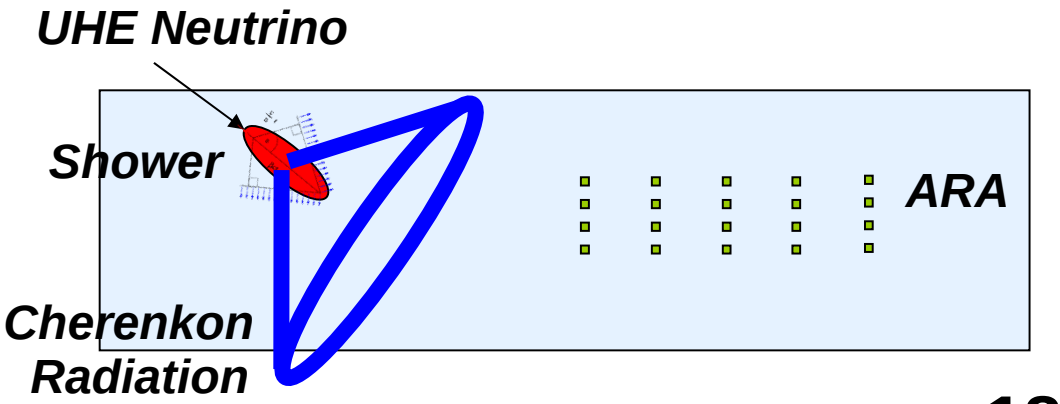




1000 events are generated randomly

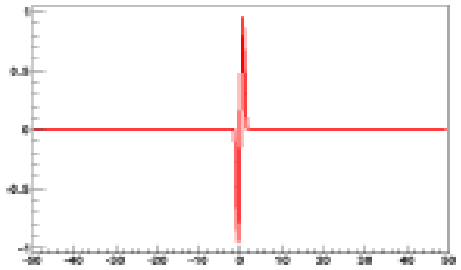
Detector Sensnor Radius = 12 km

Depth = -2 km --> 0 km



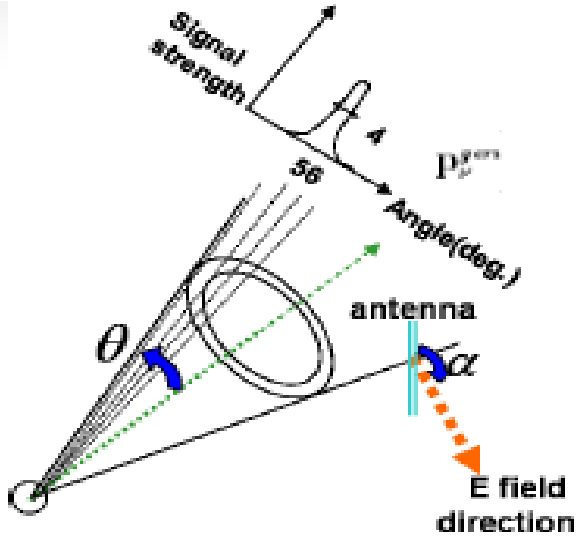
Work by Shang-Yu Sun

Simulation Methods: From Shower Location to Antennas



$$y = x \cdot e^{-x^2/2\sigma^2}$$

$\sigma = 0.4ns$
Pulse width



E field die out in 1 km (unit conversion)

$$V_i^{real} = V_0^{gen} \cdot \frac{D_0}{\sqrt{(\vec{x}_{gen} - \vec{x}_i)^2}} \cdot e^{-\sqrt{(\vec{x}_{gen} - \vec{x}_i)^2}\,/\,\text{attenuation\_length}}$$

1km

$$\cdot A \cdot e^{-(\theta_i - 56^\circ)^2/2\sigma_c^2}$$

$\sigma_c = 2^\circ$, width of Cherenkov cone

$$\cdot \begin{cases} \sin\alpha_i, & \text{for H polantenna} \\ \cos\alpha_i, & \text{for V polantenna} \end{cases}$$

$$0 < V_0^{gen} < 5V.$$

$$E_{total} = (c\Delta t) r^2 \Omega \cdot \rho(r)$$

$$\rho(r) \propto [E(r)]^2$$

$$\Rightarrow E(r) \propto \frac{1}{r}$$

Work by Shang-Yu Sun

Simulation Methods: From Shower Location to Antennas

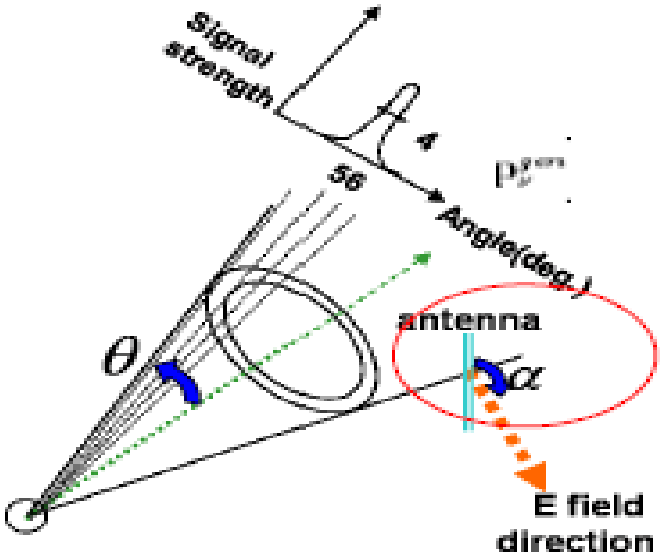
E field dies out 1km

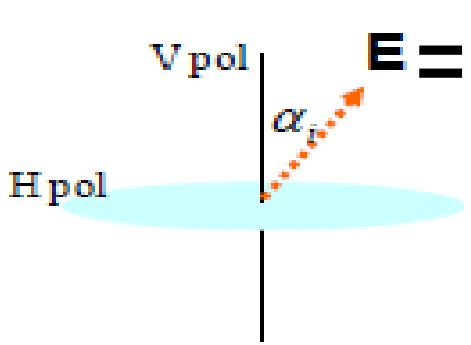
1km

$$V_i^{real} = V_0^{gen} \cdot \frac{D_0}{\sqrt{(\vec{x}_{gen} - \vec{x}_i)^2}} \cdot e^{-\sqrt{(\vec{x}_{gen} - \vec{x}_i)^2}/\text{attenuation\_length}}$$

$$\cdot A \cdot e^{-(\theta_i - 56^\circ)^2/2\sigma^2}$$

$$\cdot \begin{cases} \sin\alpha_i, & \text{for H pol antenna} \\ \cos\alpha_i, & \text{for V pol antenna} \end{cases}$$

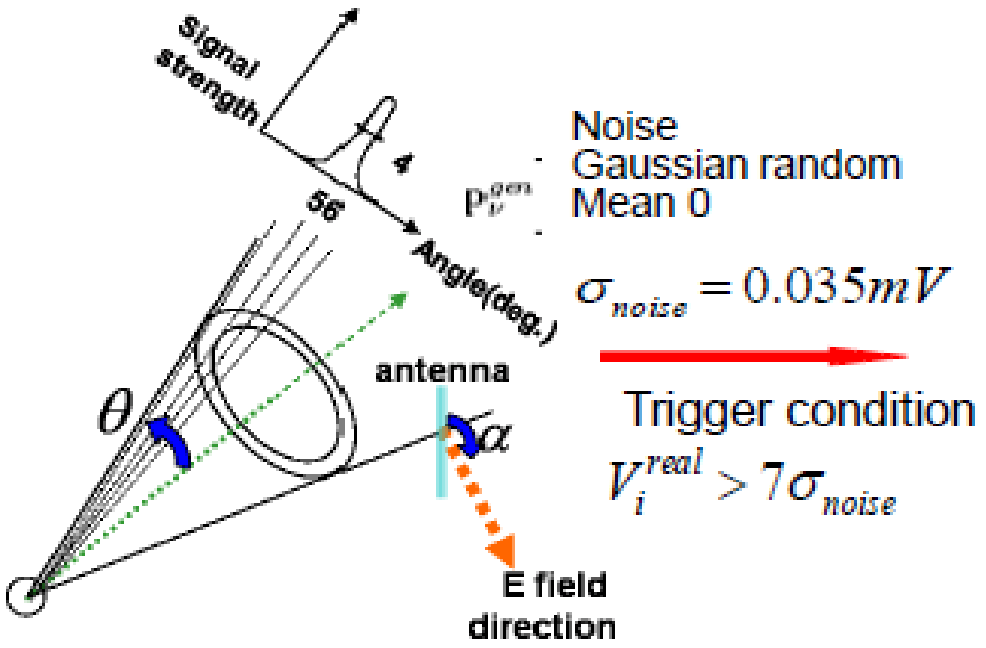




$$\mathbf{E} = \overrightarrow{RF} \times (\overrightarrow{RF} \times \vec{v})$$

Work by Shang-Yu Sun

Simulation Methods: The Waveform



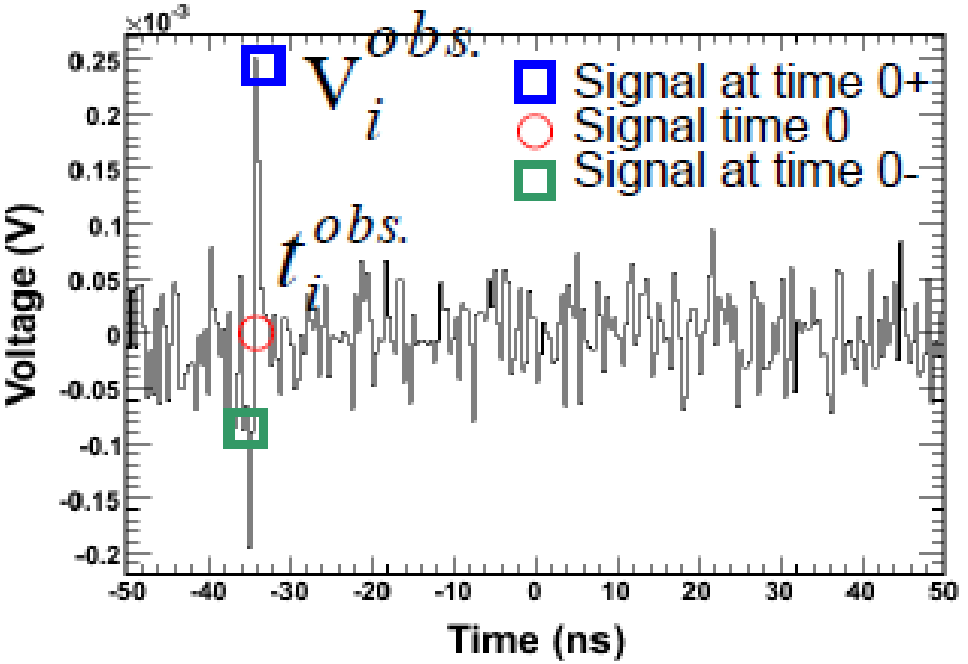
Noise
Gaussian random
Mean 0

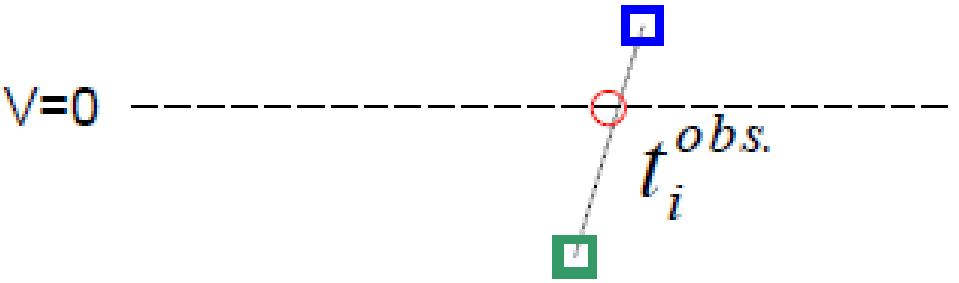
$\sigma_{noise} = 0.035mV$

Trigger condition

$V_i^{real} > 7\sigma_{noise}$

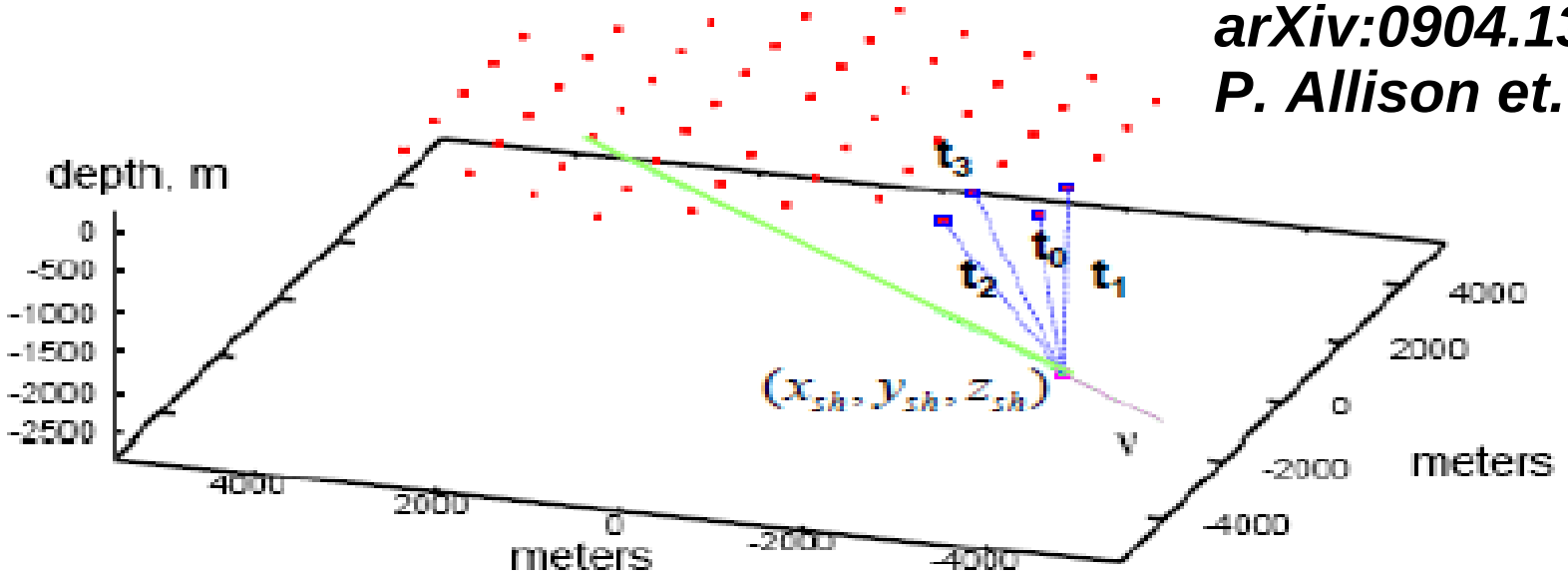
256 bins, 100 ns





Work by Shang-Yu Sun

Chi Square for Reconstruction of Shower Vertex:



arXiv:0904.1309v1 IceRay
P. Allison et. al.

$$\chi^2 = \sum_{\text{all triggered antennas } i} \left[\frac{\Delta t_i^{obs.} - \Delta t_i^{hypos.}(x_{sh}, y_{sh}, z_{sh})}{\sigma_i} \right]^2$$

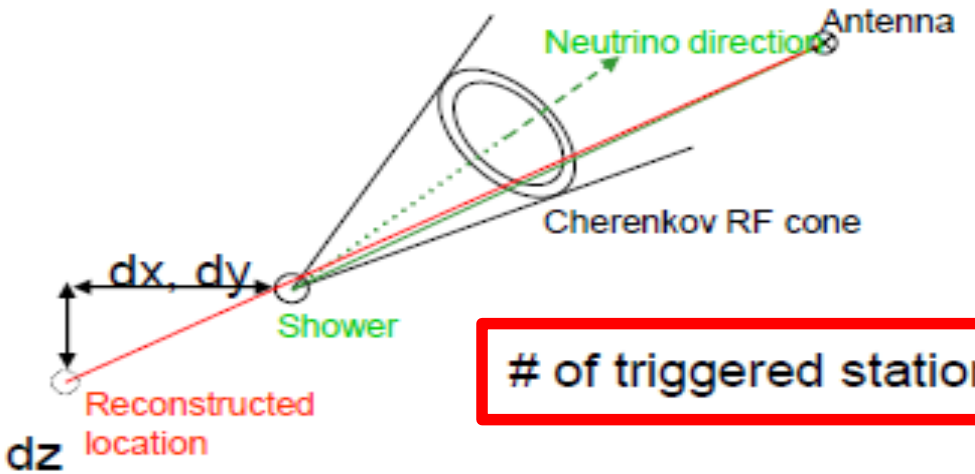
$$\Delta t_i = t_i - t_0$$

ti: RF traveling time to antenna i
t0: traveling time for antenna with strongest signal

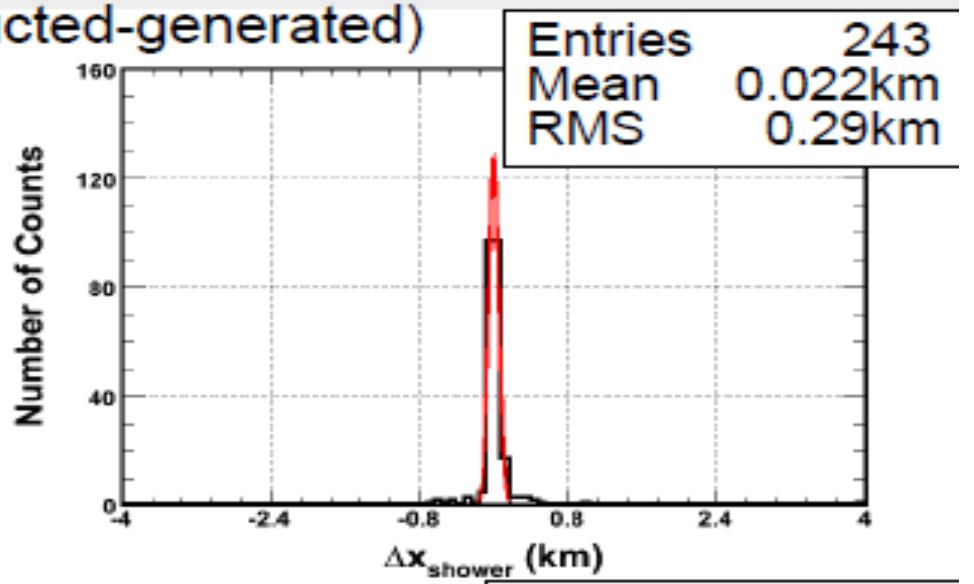
Work by Shang-Yu Sun

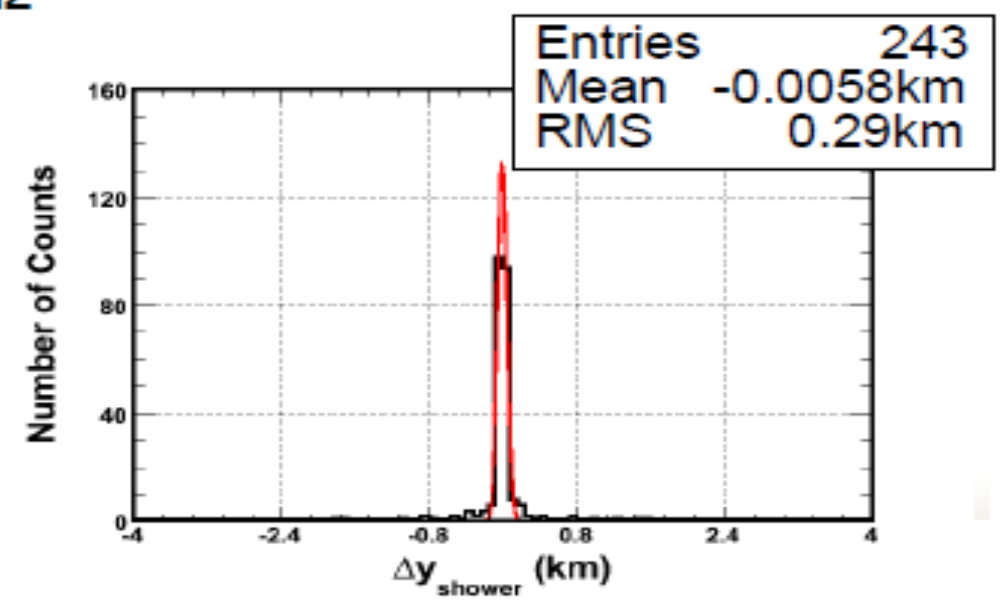
Resolution of Shower Vertex:

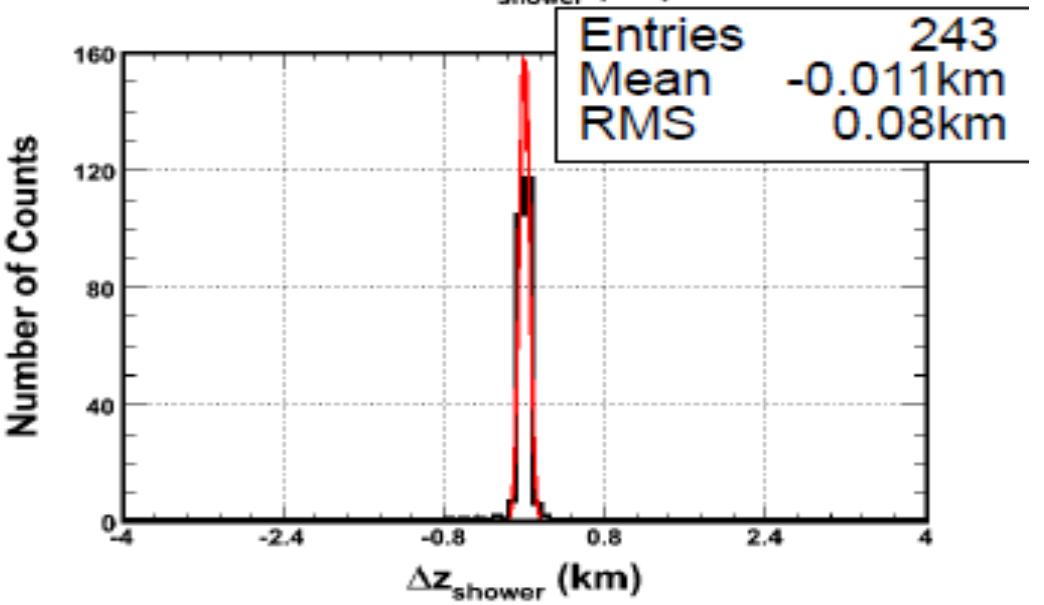
dx, dy, dz (reconstructed-generated)



# of triggered station > 0

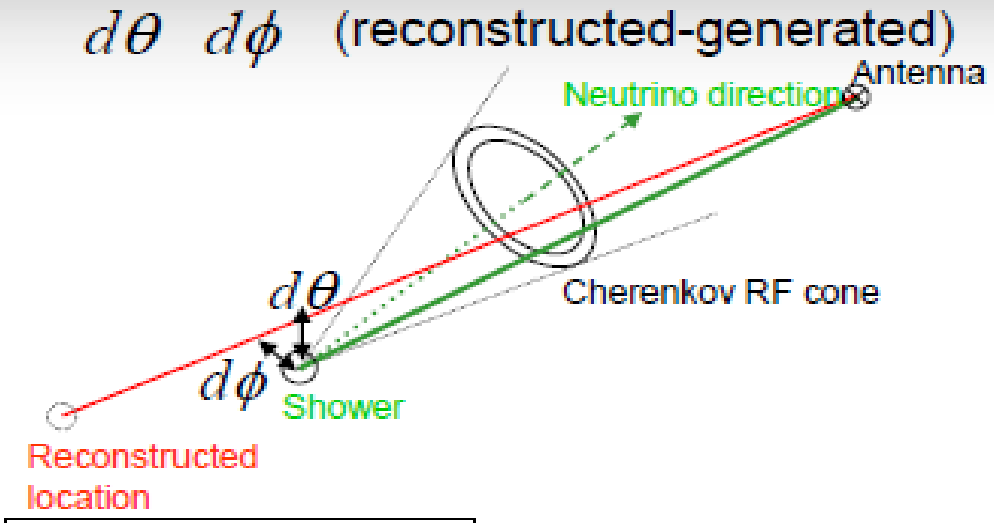


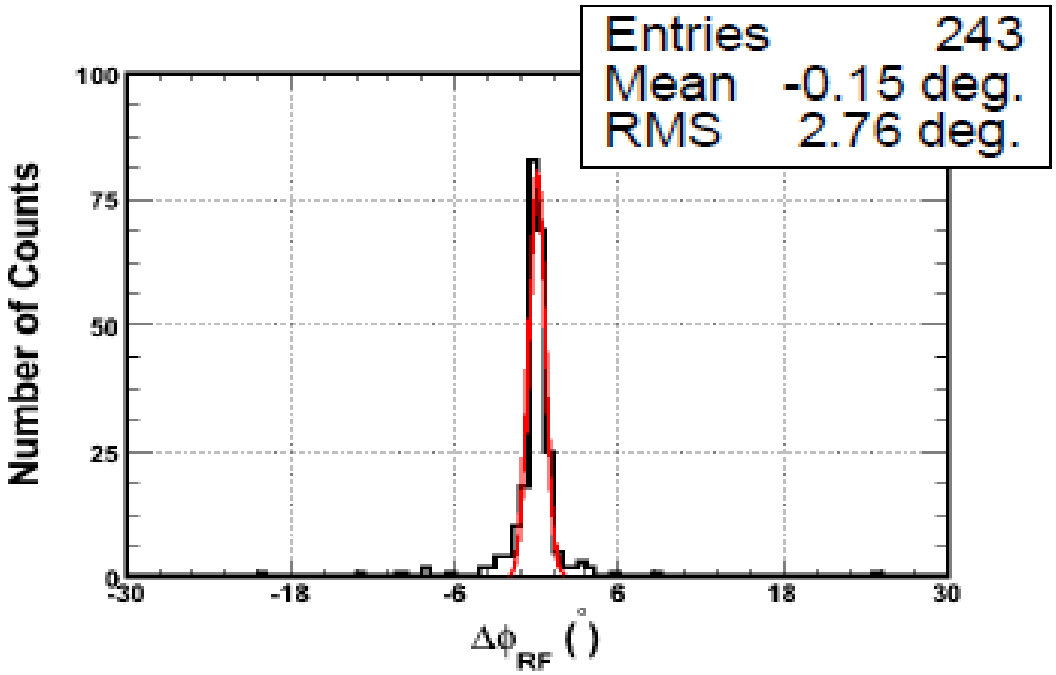


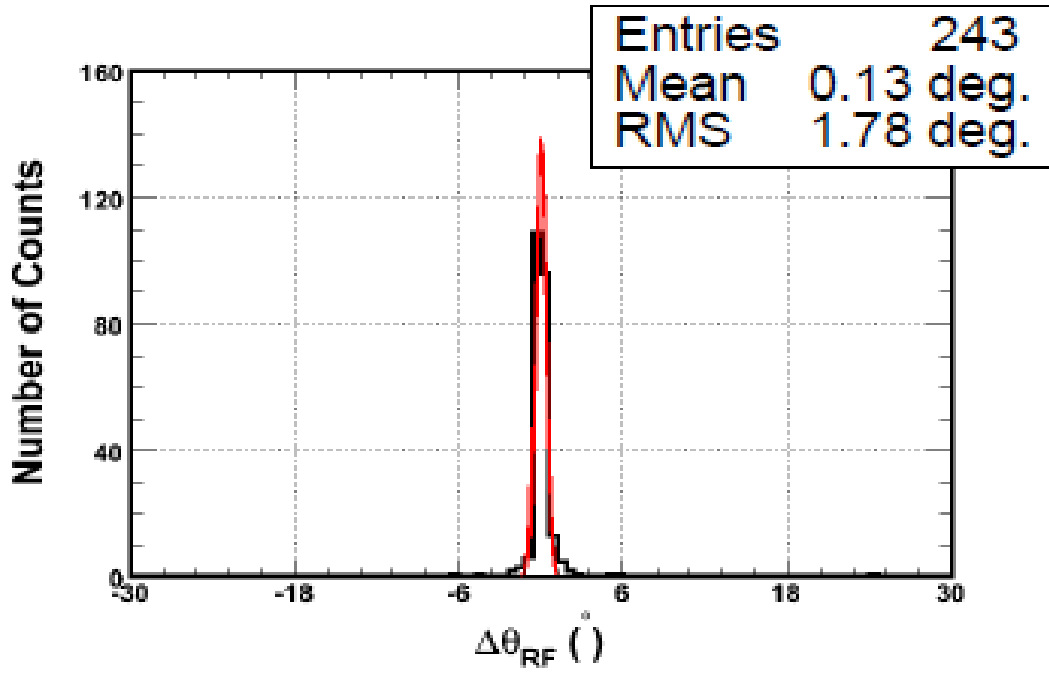


Work by Shang-Yu Sun

Resolution of RF Direction:







Work by Shang-Yu Sun

Reconstruction of Neutrino Direction:

$$\chi^2 = \sum_{\text{all triggered antennas } j} \left(\frac{(V_i^{obs.} - V_i^{hypos.})}{\sigma_V}\right)^2$$

$V_i^{obs.}$: observation data

$$V_i^{hypos.}(\vec{x}_{rec.}, V_0^{hypos.}, \vec{v}_{hypos.}) = \frac{V_0^{hypos.} e^{-\sqrt{(\vec{x}_{rec.} - \vec{x}_i)^2}/\text{attenuation length}}}{D_0 \sqrt{(\vec{x}_{rec.} - \vec{x}_i)^2}}$$

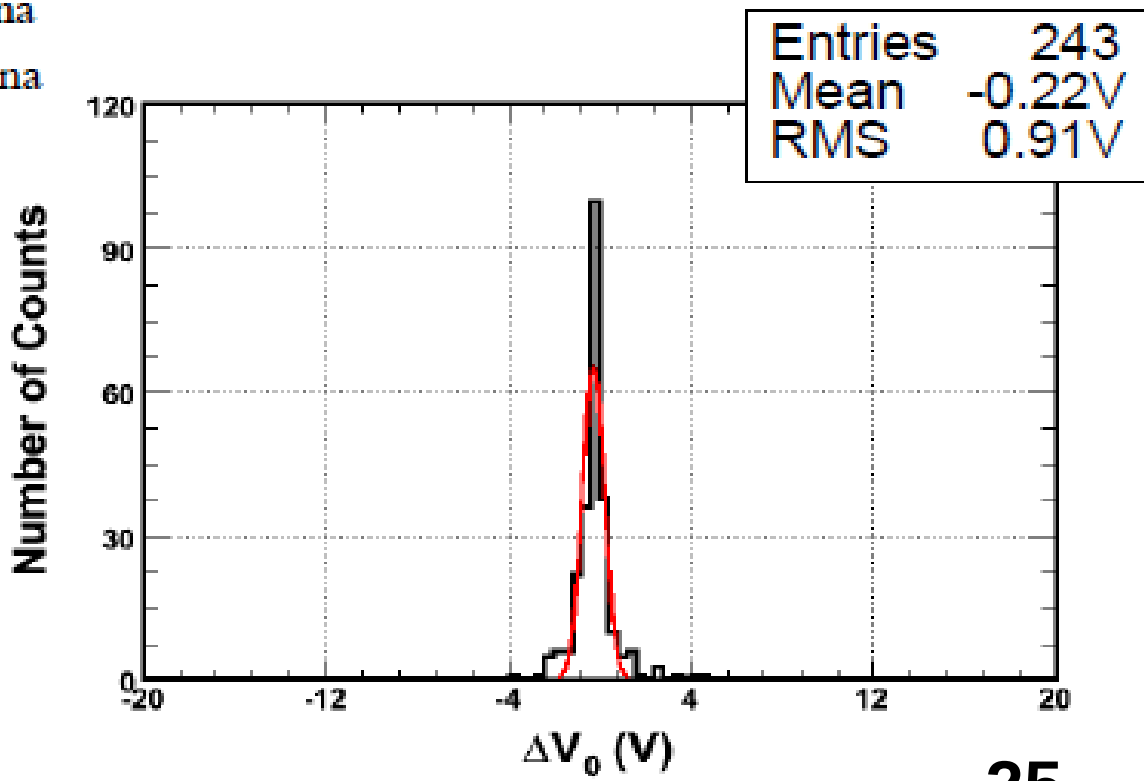
$$\cdot A \cdot e^{-(\theta - 5\sigma)^2/2\sigma^2}, \quad \theta : angle(\vec{v}_{hypos.}, \vec{x}_{rec.} - \vec{x}_i)$$

$$\cdot \begin{cases} \sin\alpha, & \text{for H pol antenna} \\ \cos\alpha, & \text{for V pol antenna} \end{cases}$$

$\theta(\vec{v}_{hypos.}, \vec{x}_{rec.} - \vec{x}_i)$

$\alpha(\vec{v}_{hypos.}, \vec{x}_{rec.} - \vec{x}_i)$

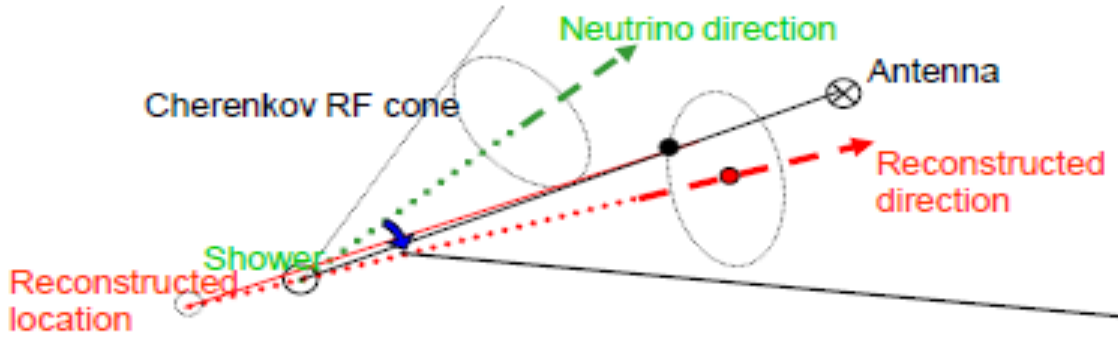
Reconstructed parameters at former stage
Including the hypothesized parameters

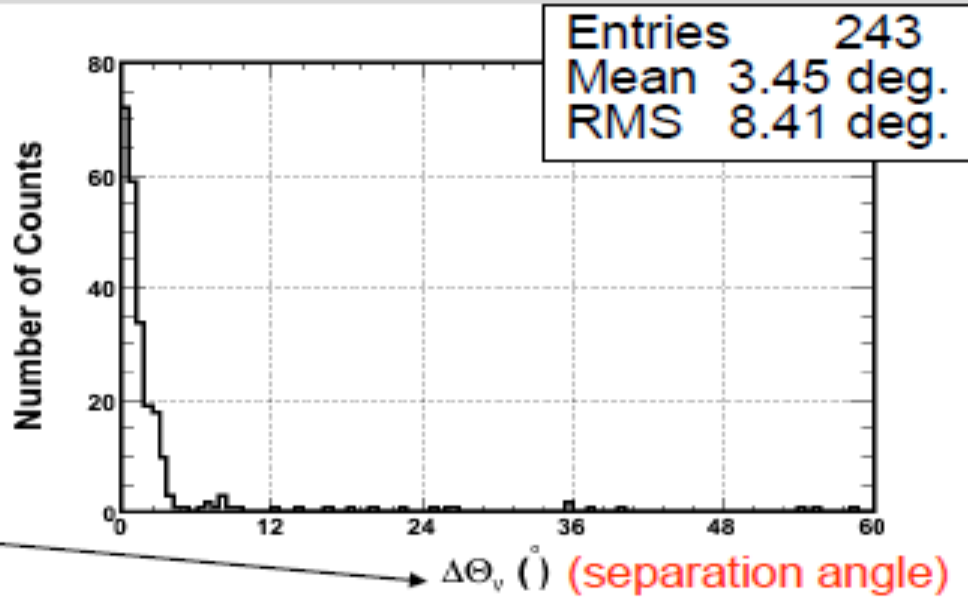


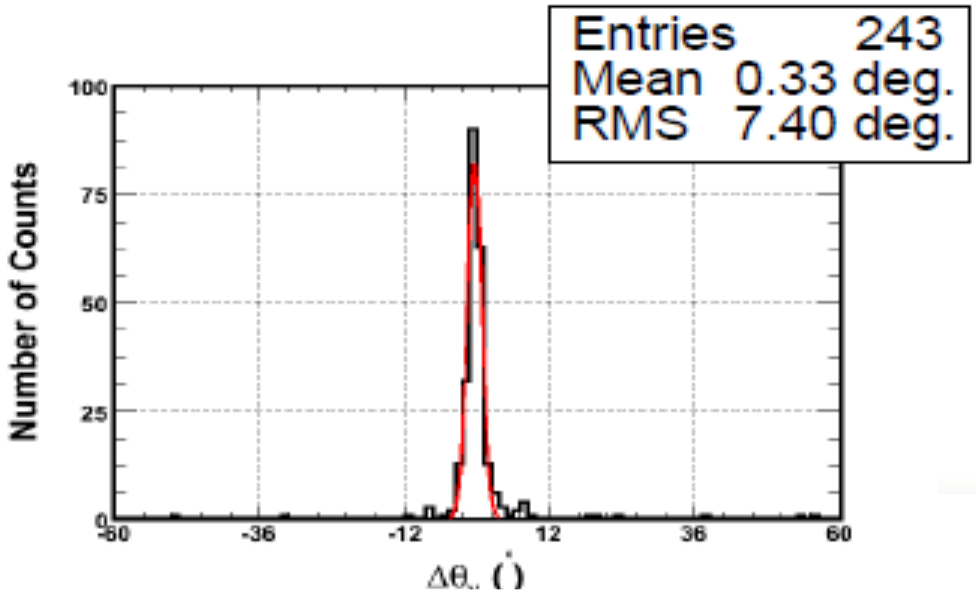
Work by Shang-Yu Sun

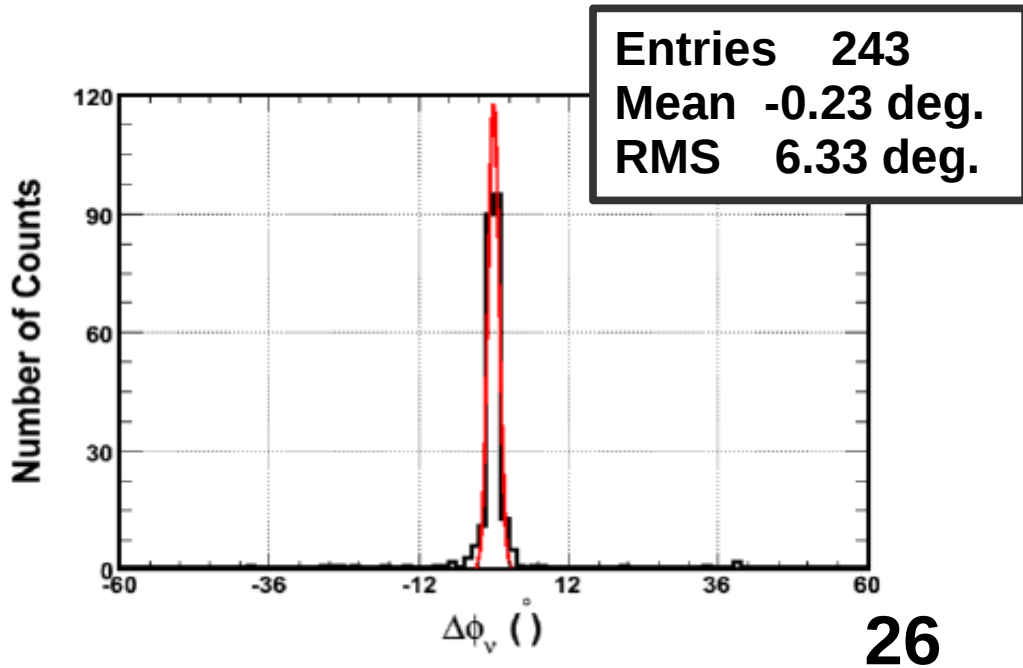
Neutrino Angular Resolution:

All plots shown for resolutions so far are for AS = 50m, SS = 1.33km





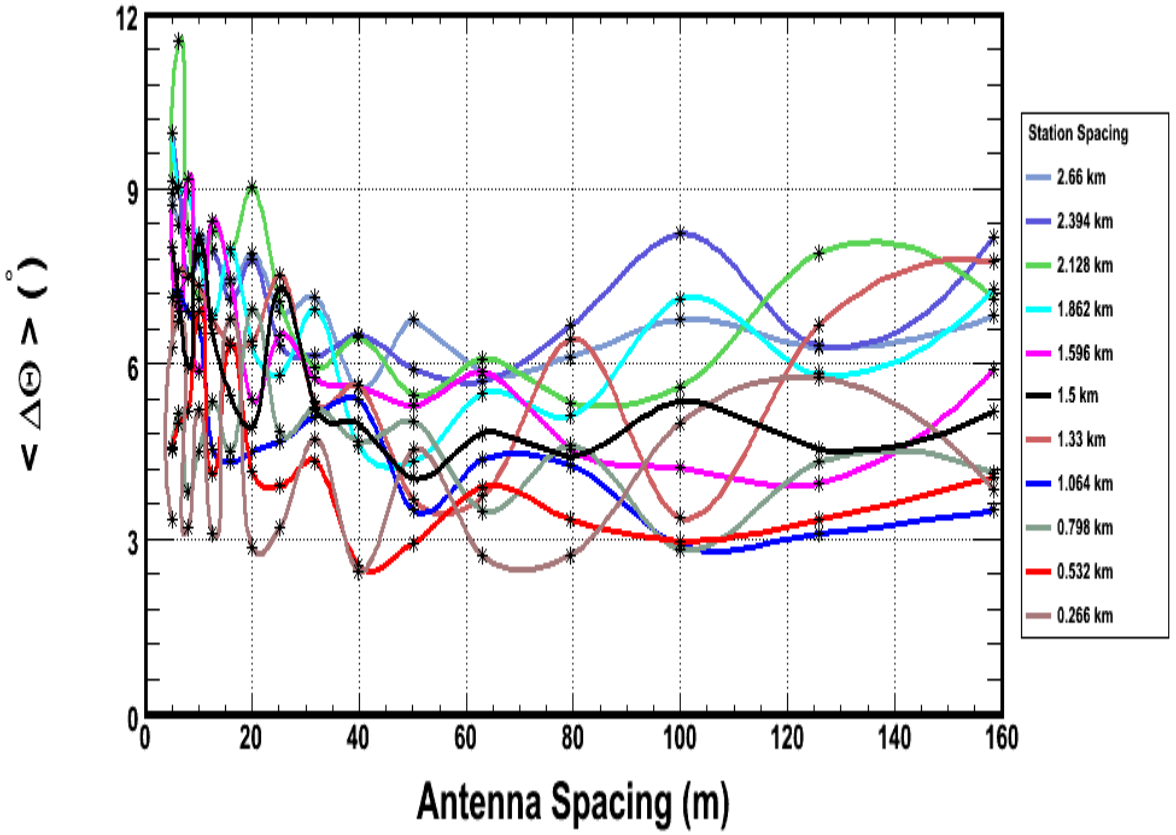


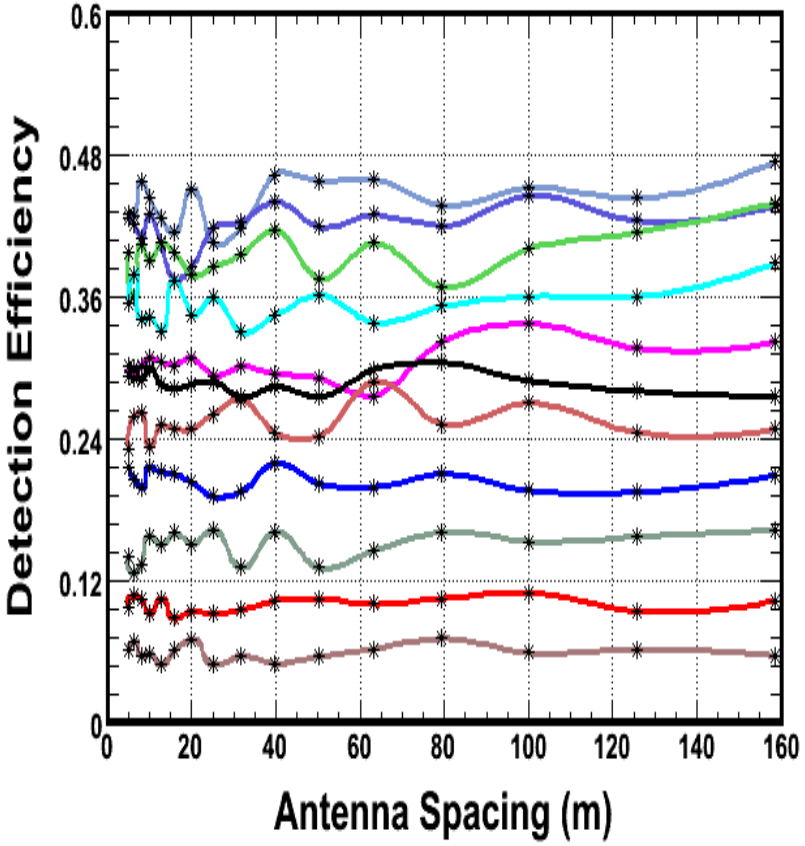


Work by Shang-Yu Sun

Optimization:

Detectioon Efficiency, Neutrino Angular Resolution vs Antenna Spacing and Station Spacing



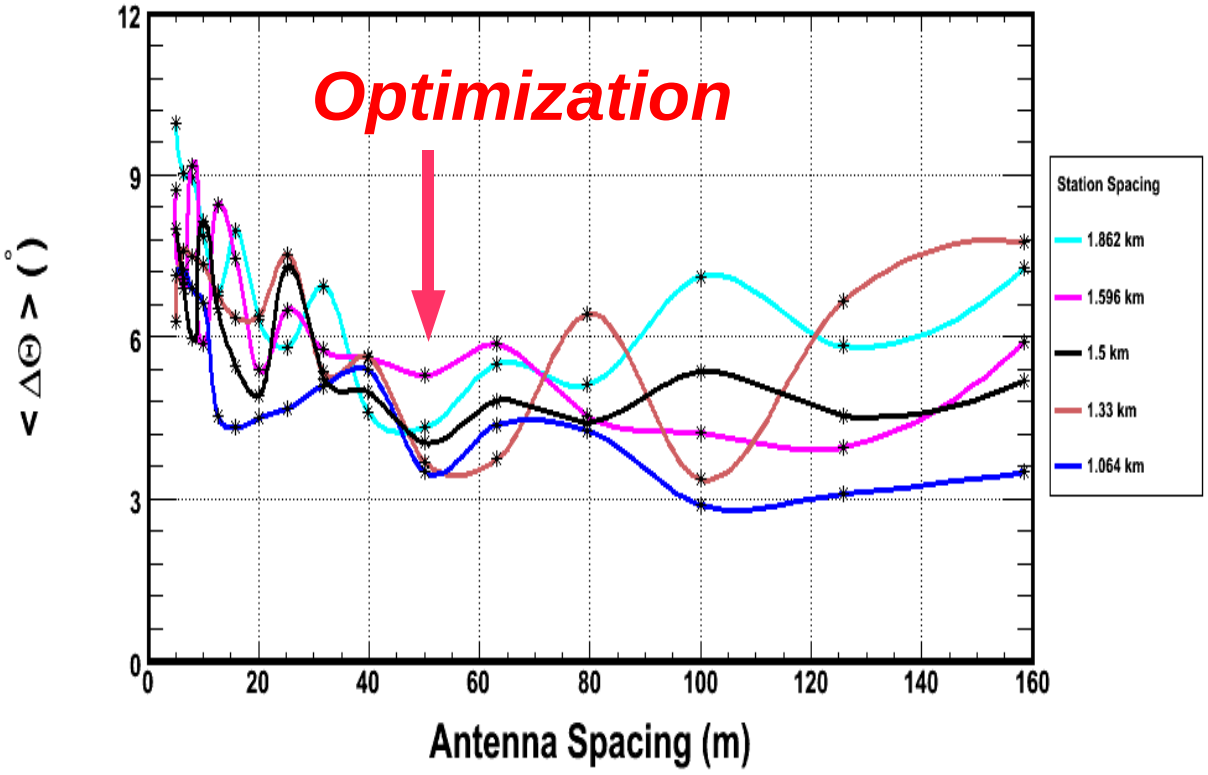


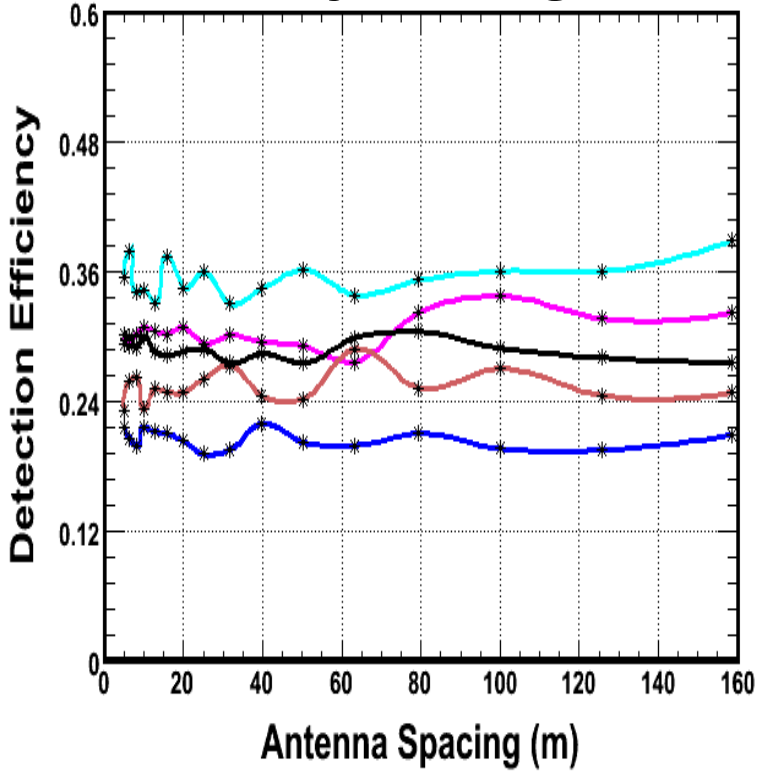
Work by Shang-Yu Sun

Detection eff = (# of triggered Nu) / (# of generated Nu In the detector sensor region)

Optimization:
Detectioon Efficiency, Neutrino Angular Resolution vs Antenna Spacing and Station Spacing

Work by Shang-Yu Sun





Station Spacing	Antenna Spacing	Ang. Reso.	Detec. Eff.
1.33 km	~50 m (Vpol-Vpol)	~3.5 deg.	~0.25
1.50 km	~50 m	~4.2 deg.	~0.30
1.60 km	~50 m	~5.4 deg.	~0.32
1.86 km	~50 m	~4.4 deg.	~0.36

Conclusions for Optimization of ARA Antenna/Station Spacings

- *The larger station spacing,*

  the higher detection efficincy

- *Regardless of station spacing,*

  the optimial choice of antenna spacing

  could be chosen as ~50m

  ==> With this choice, the neutrino angular

  resolution can reach < 5 degrees

Systematic Uncertainty Study for Neutrino Angular Resolution

- ***Purpose:*** ***(Work still on-going)***

  To see how the factors (listed below) affect the reconstructed angular resolution of neutrino pointing back to sources

  -- If there are reconstruction uncertainties on

  depth of antenna ***(official: 200m)***

  antenna spacing

  station spacing

  lateral distances/angles of three boreholes

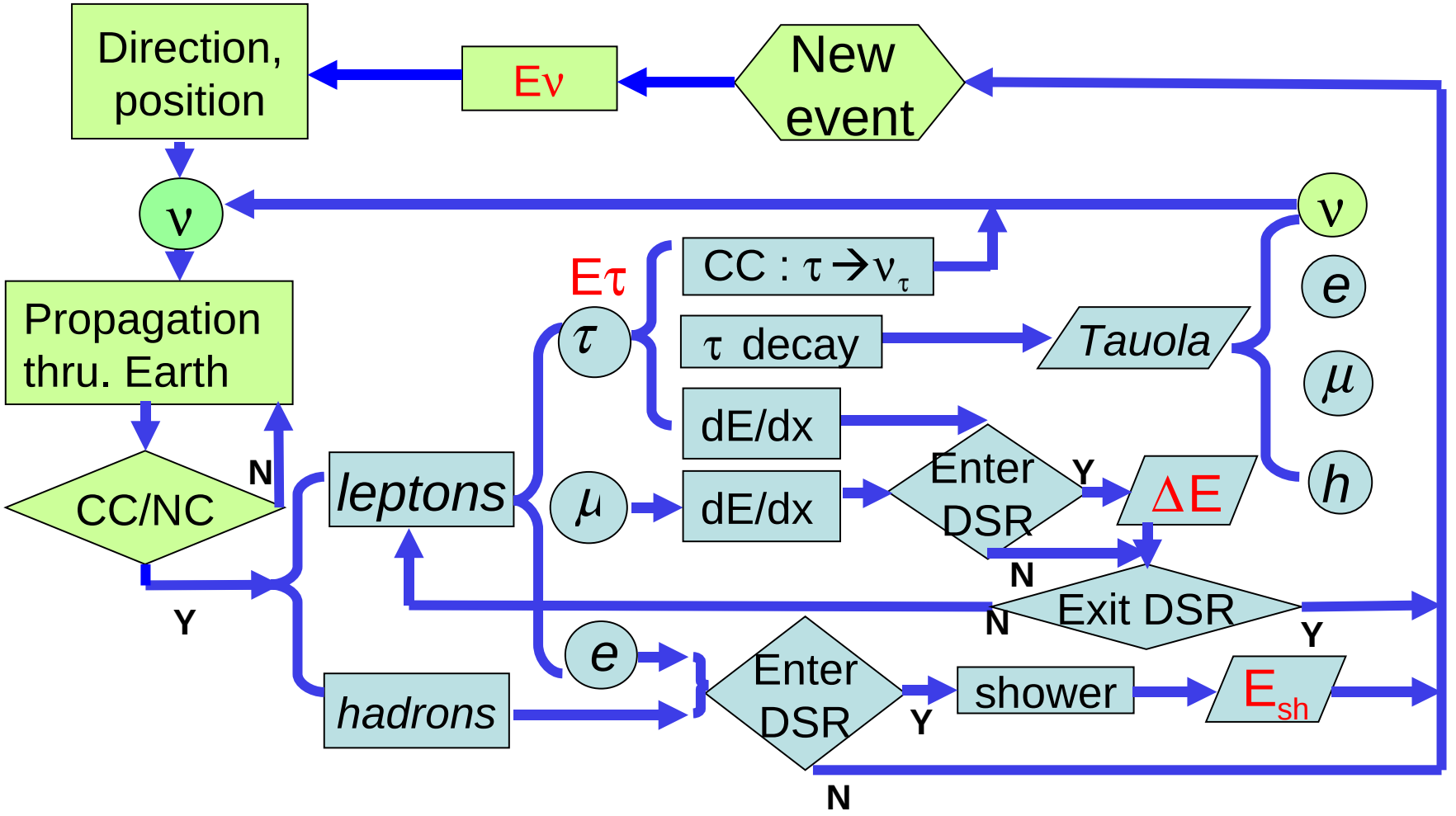
  noise, others ... (suggestions ?)

- ***Any suggestions from existing experiments ?***

Summary for NTU Monte Carlo

- ***Take Peter Gorham's MC code as a base***
- ***May Modify***
  - ***-- E field parametrization for***
    EM Shower & Hadronic Shower
    with including LPM effect
    (link far zone & near zone) (on-going)
- ***Employ SHINIE/MMC for neutrino propagation through Earth (on-going)***
- ***Apply faster RF tracing code from shower vertex to antennas (on-going)***
- ***Modify MC for Monopole and/or other physics analyses (will start soon)***
- ***Modify MC for Neutrino analysis (will start soon)***

Current SHINIE Structure



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