Preliminary Studies of LC's Impact on WC Reconstruction

Xin Qian

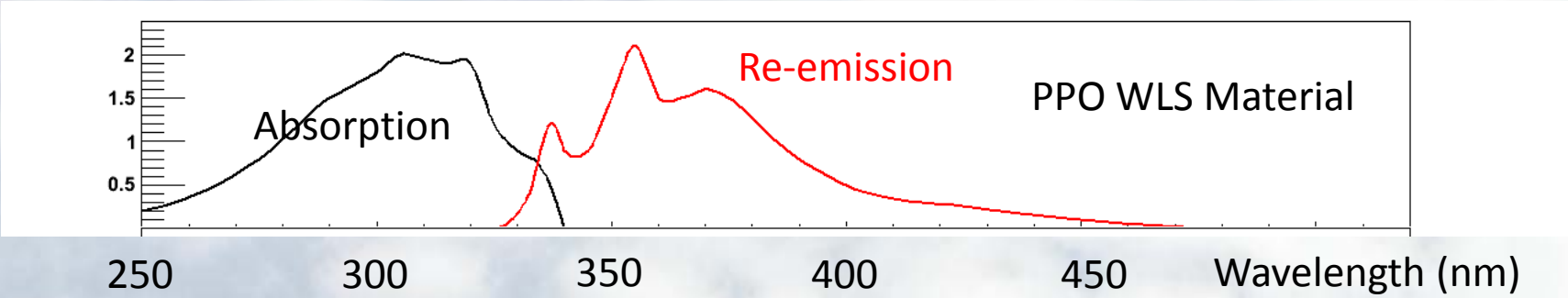
Caltech

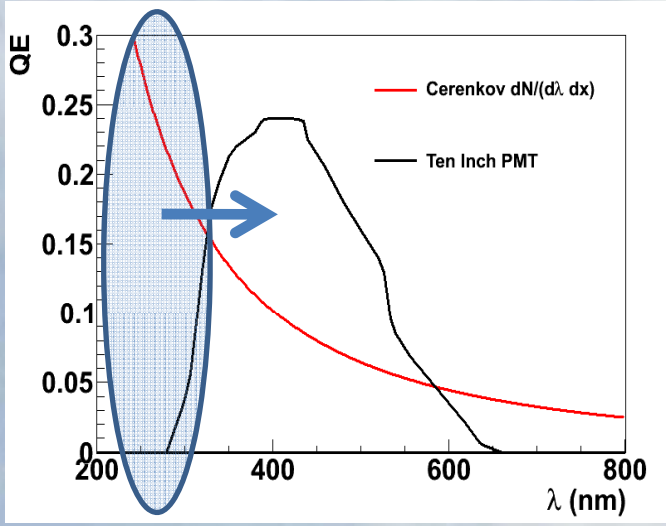
For the LBNE-WC Light Collector Group

Outline:

- Brief Introduction to LC simulation
- Preliminary Performance Comparison
  - Gain Comparison
  - Intrinsic Resolution Comparison
  - Reduction in Fiducial Volume
  - Vertex Resolution
  - Particle Identifications
- New results on unguaranteed PMT region.
- Summary

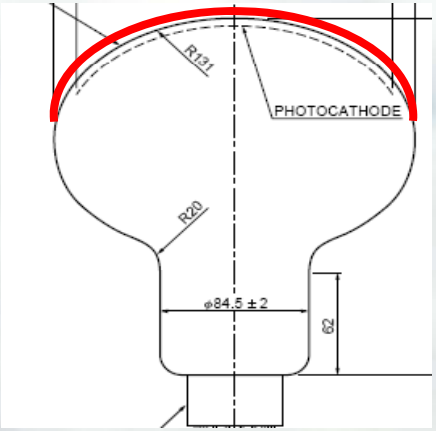
Light Collectors

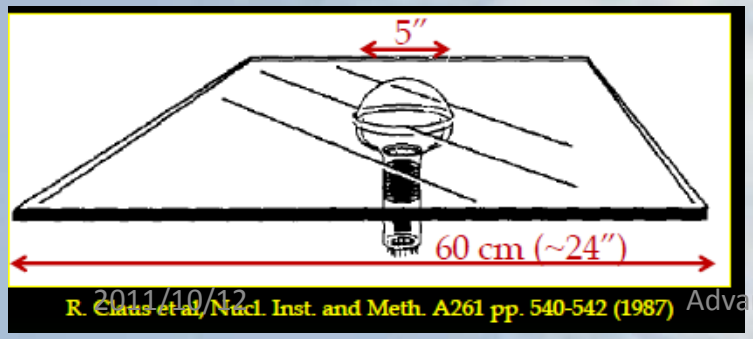


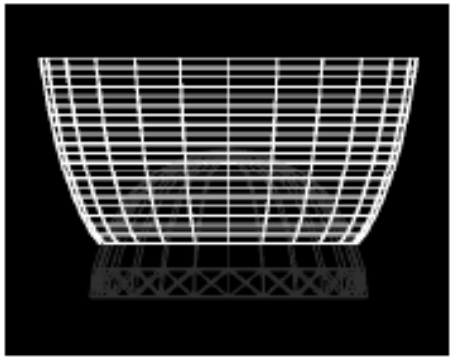


Three technologies has been proposed:

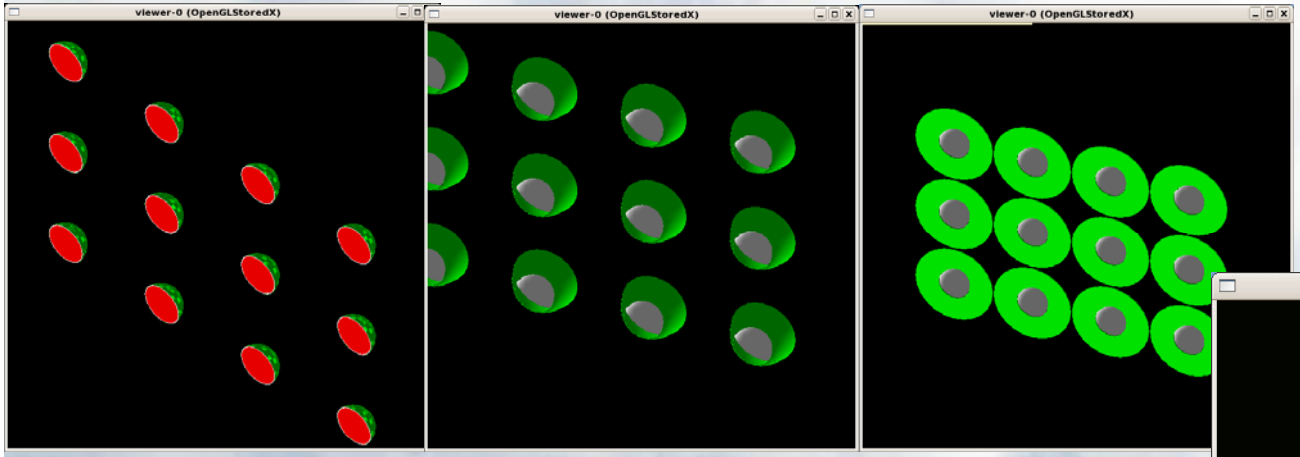
1. Effectively increase of QE:
   1. Wavelength shifting film.
2. Effectively increase light collecting area:
   1. Wavelength shifting plate
   2. Winston Cone.



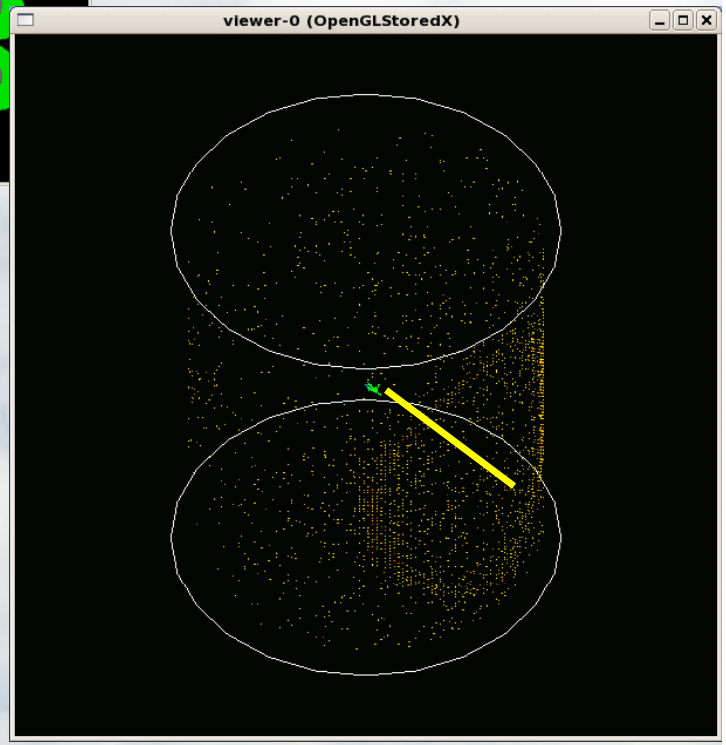




Simulation: WCSim (Walter@Duke)



$$T^{ij}_{corr} = T^{ij} - \frac{n}{c} \cdot L^{i}_{vertex}$$



- Distance to wall: distance from the vertex to the wall along the moving direction.
- Corrected Time and Polar Angle

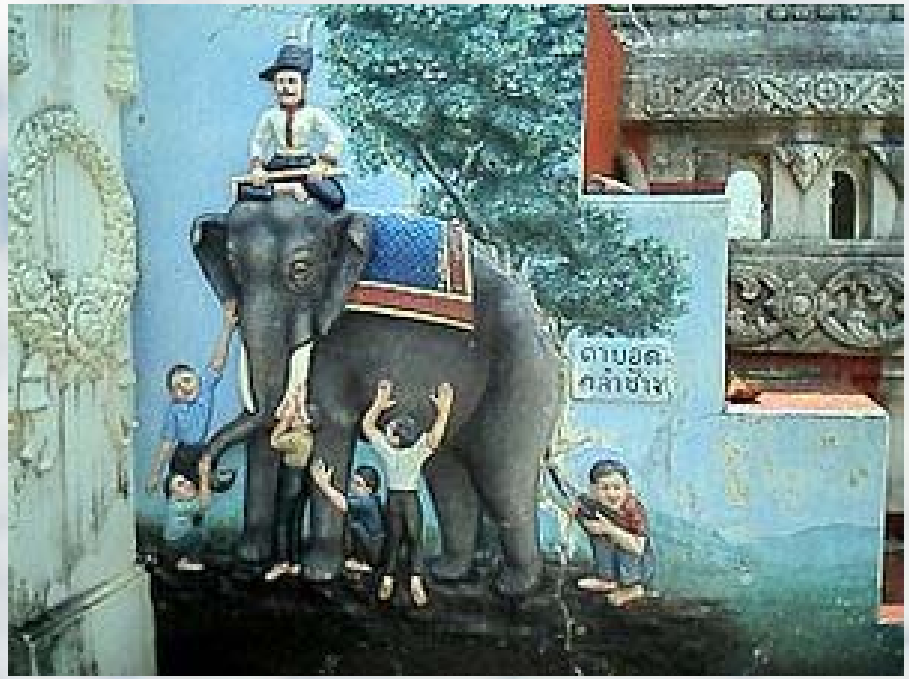
$$\cos\theta^{ij} = \frac{\vec{P} \cdot \vec{L}^{i}_{vertex}}{|P| \cdot |L^{i}_{vertex}|}$$

Notation: LC → Winston Cone, WLS → Wavelength Shifting film, WLSP → Wavelength Shifting plate, noLC → No Light Collectors

Blind Men and a Elephant

- Elephant: Performance of LCs in a WCD for LBNE
- Blind: lack of full reconstruction tools, despite very good progress in reconstruction group.

- Try to attack different problems using some simple tools developed by ourselves



- Lots of assumptions, but hopefully we can still learn from these studies

General Considerations

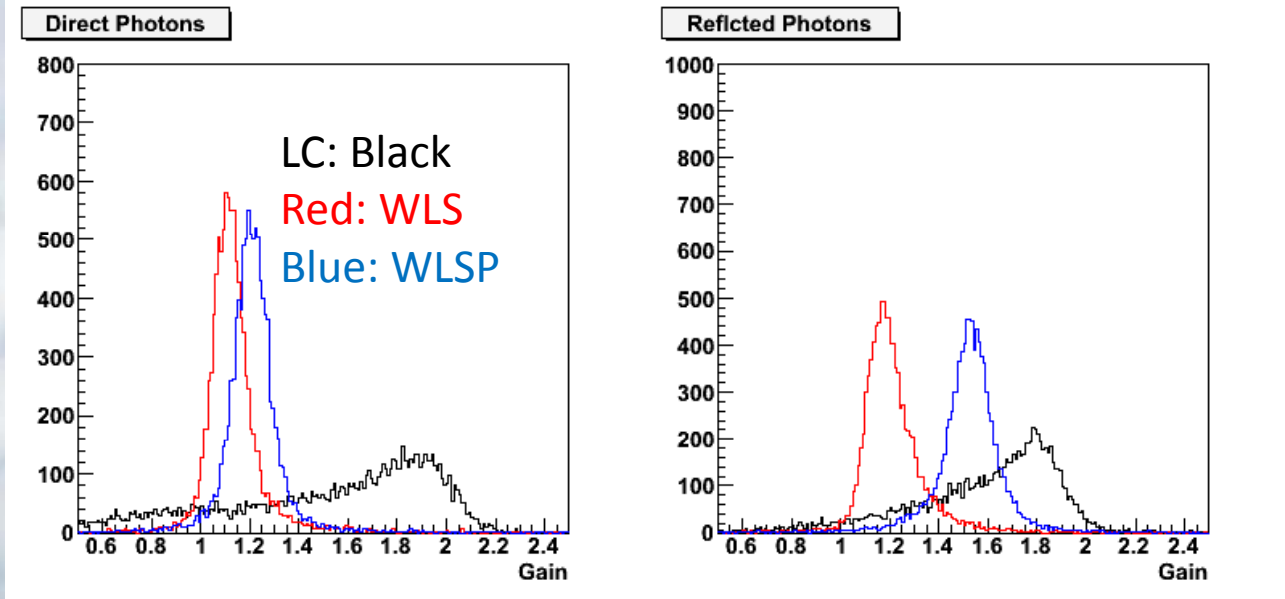
- What is the enhancement in collected photons of LCs?
  - **Gain Comparison**
- Are the enhancement equivalent to more PMTs?
  - **Intrinsic resolution studies**
- For LC, what is the reduction of fiducial volume?
  - **Reduction in Fiducial Volume**
- For WLS/WLSP, what is the effect of delay in timing (wavelength shifting process)?
  - **Vertex Resolution**
- What are the effects on PID?
  - **Electron/muon separation**
  - **Neutral pion identification**
- Likelihood method are used to do relative comparison.

Gain Comparison @ 100kt+12%+10inch

Ratio of collected NPE with LCs to that noLC

Direct light: within +- cerenkov angle, early in correct arrive time.

Indirect light = Total Light – Direct Light



	Light Collector	WLS Film	WLS Plate
Direct Light Increment	1.53	1.14	1.33
Indirect Light Increment	1.59	1.21	1.82

Reflect Light vs. Direct Light ~ 1.1 : 1.

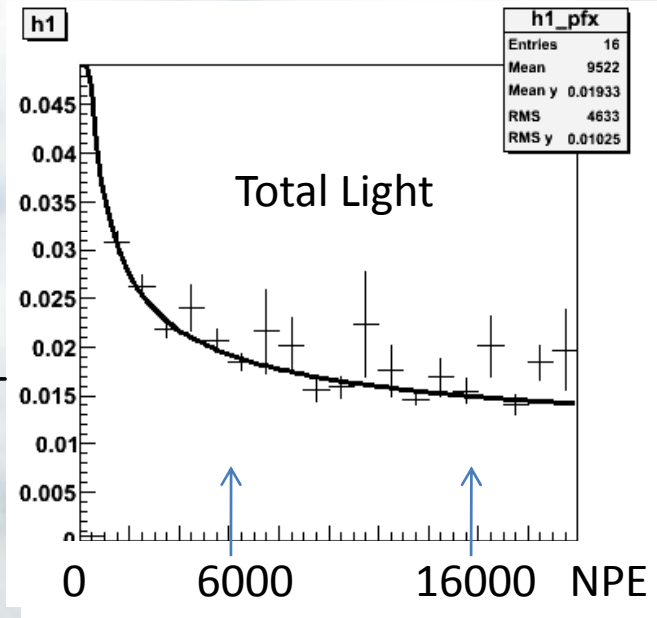
LC gives higher gain in direct light, but larger spread. WLSP gives more reflected lights. Both technologies give > 30% gain in direct light in simulation.

Are the enhancement in NPE with LCs Equivalent to More PMTs?

- More NPE → Better Energy Resolutions.
  - NPE distribution of one particle with fixed initial condition ~ relative resolution of 1./sqrt(N) in the ideal case.
    - However, we can only get reconstructed information.
  - **Intrinsic resolution studies.**
    - For each electrons in volume scan, redo simulation by 100 times after
    - Smearing vertex by 32 cm and angles by 3.3 degrees (SK thesis, F. M. Dufour)
    - Then look at the smear in collected NPE or charge
  - **Assume both technologies can reach these resolutions.**

Intrinsic Resolution (no LC case)

- In NoLC case, we fit the resolution vs. NPE for baseline.



$$R(N) = 0.80\% + \frac{0.87}{\sqrt{N}}$$

- Then effect of LCs on intrinsic resolution can be expressed as:

$$E = \frac{R_{LC}(N)}{R_{noLC}(N)}$$

  - E_{LC} = 1.05
  - E_{WLSP} = 1.01

For 2.5 GeV electron:

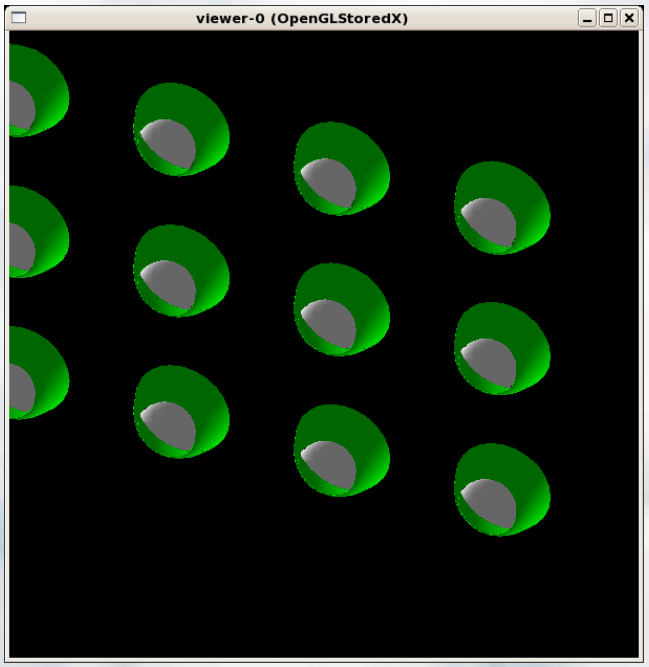
Winston Cone: 55% Gain in NPE, effective 28% Gain in resolution

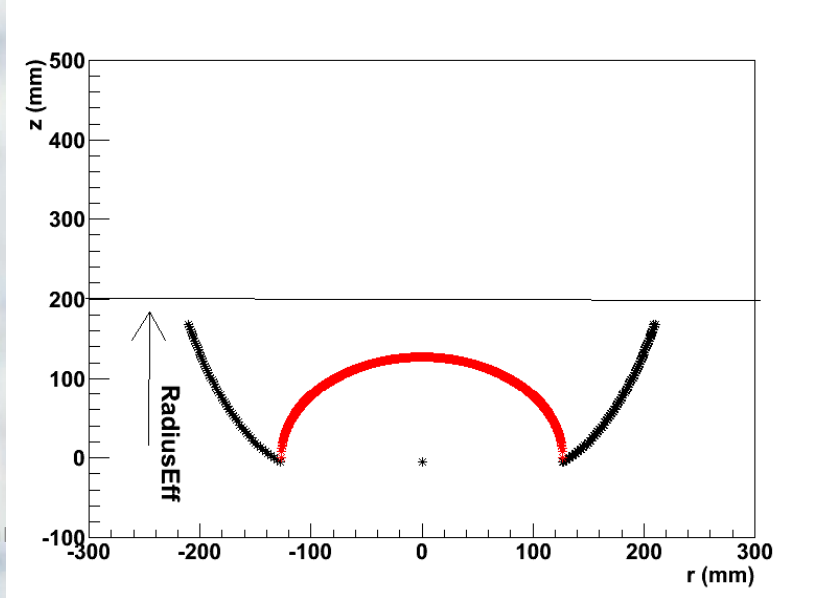
WLS Plate: 36% Gain in NPE, effective 31% Gain in resolution.

More Lights does not mean a better resolution. LC suffer more in resolution due to large spread

Reduction in Fiducial Volume

- The gain of Winston Cone (or LC) depends strongly on angles (or original vertex of incident particles.
- Small gain at large angle.
- Shadowing effect of LC due to its geometry.
- Study of reduction in fiducial volume.





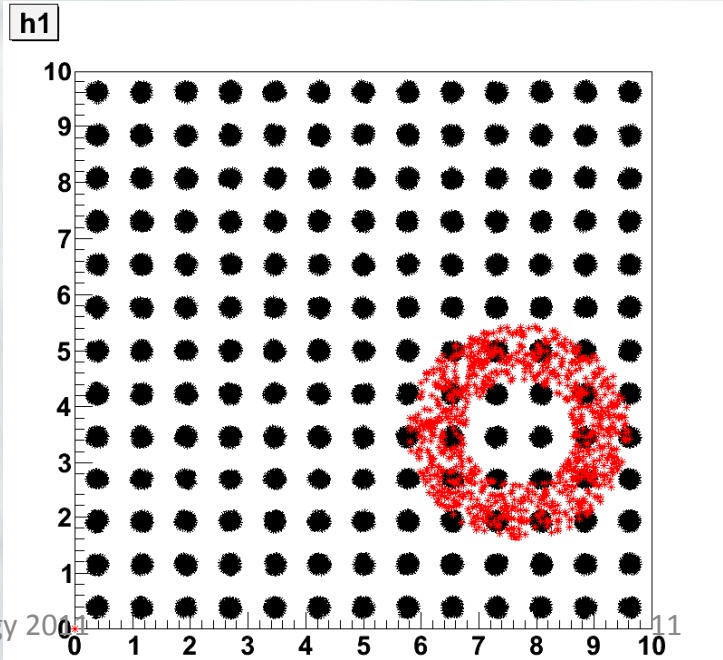
Understand How F.V. is defined

- Known: SK use 2m from wall as boundary of FV
  - 22.5 kT 20% Coverage @ 20 inch PMT
- Simple MC: 10m x 10m flat area
  - Input parameters: Coverage, distance for F.V., size of PMT
  - Assume 42 degrees of Cerenkov angle +- 10 degrees
  - Incident momentum direction perpendicular to PMT plane

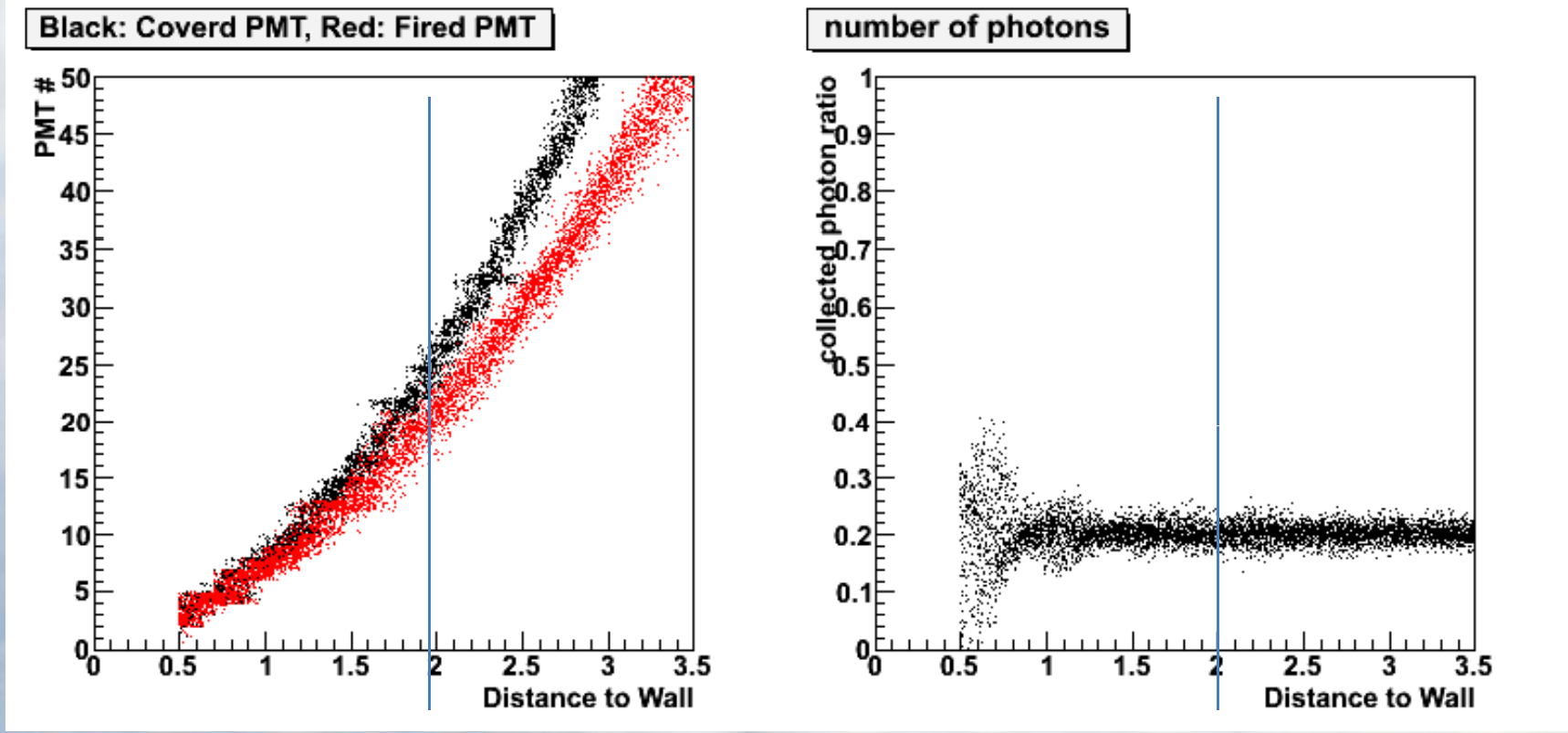
Input Factors: 12 inch+1.5 m+12%

Important variables:

1. Number of PMT inside the ring
2. Number of PE collected
3. Number of PMT fired by the red ring (PMT sample)
4. Physics: mean free path of photon (mimic an electron, important for neutral pion rejection)



Scan in Distance @ SK 20%



At 2m, well above instable area (as 12% coverage is not uniform in microscopic level e.g. closer to wall).

About two mean free path of photon (36 cm)

About 21 number of PMT fired (pixel) @ 2m

Keep these as the condition to select fiducial volume for other case

Summary of Numbers

- 12%, 12 inch
  - Pixel point of view: 1.7 m
  - MFP point of view: 1.8 m
- 12%, 10 inch
  - Pixel point of view: 1.4 m
  - MFP point of view: 1.6 m
- 9% 12 inch
  - Pixel point of view: 2.0 m
  - MFP point of view: 1.9 m

To examine LCs, need to use WCSim to fully taking into account all the optical process instead of simple MC

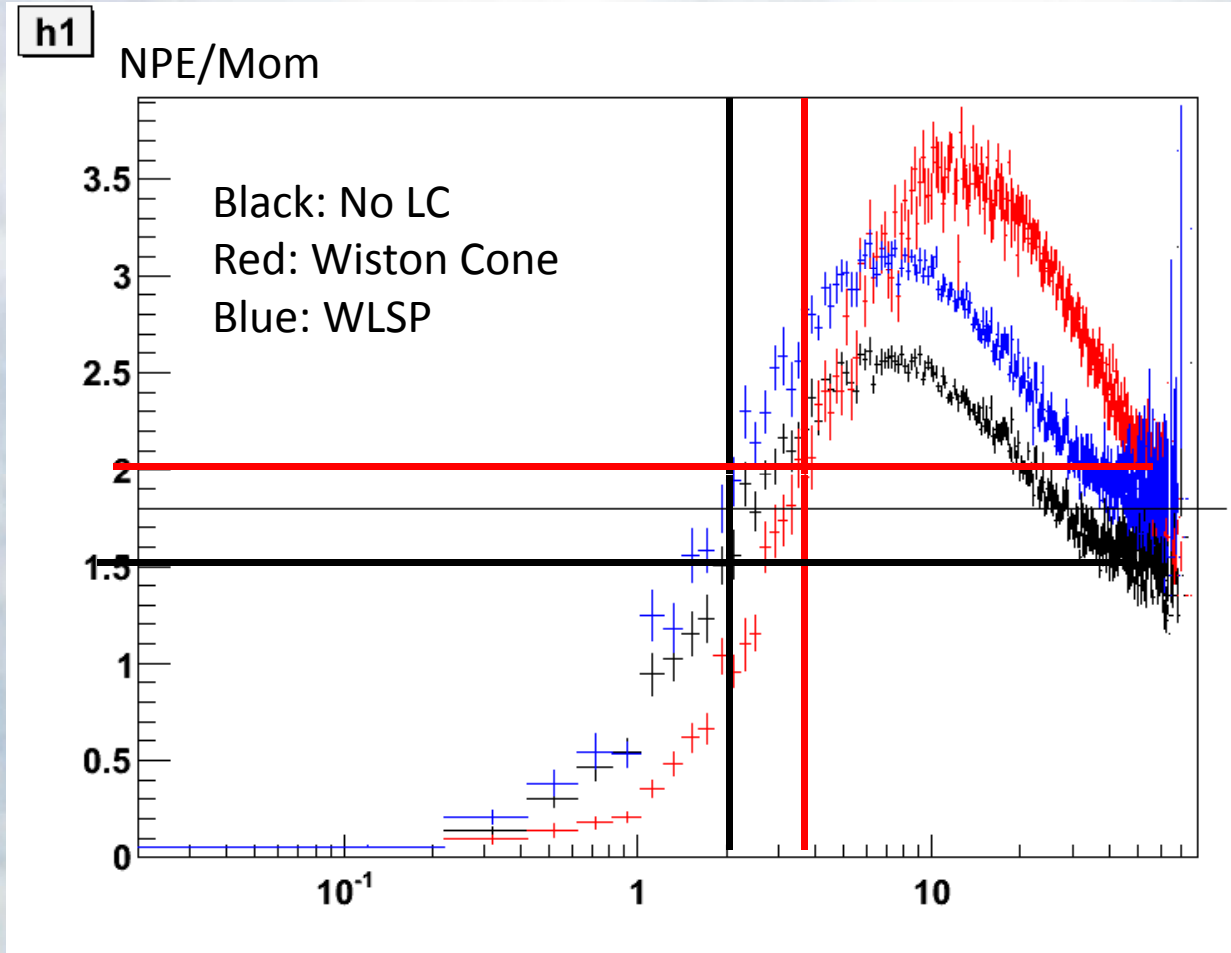
Use volume scan simulating data @ 100 kT

Effect is mainly for LC

2m fiducial volume cut is conservative for LBNE

Comparison between LCs

- NPE normalized by momentum
- At large distance to wall , drop in NPE/mom is due to water attenuation.
- At small distance to wall, drop is due to partial contain events.



- Take 2 m (FV) 12% Coverage as a baseline.
  - About 1.5 (y-axis), compare with 9% LC, should multiply 1.5 * 12%/9% ~ 2.0
  - About 3.5 m from wall for LC case

Estimation of Reduction in FV

- Take geometry of 100 kT tank

$$V = \pi R^2 H$$

$$R = \frac{(53/2 - 3.5)^2 (60 - 2*3.5)}{(53/2 - 2)^2 (60 - 2*2)} \sim 83\%$$

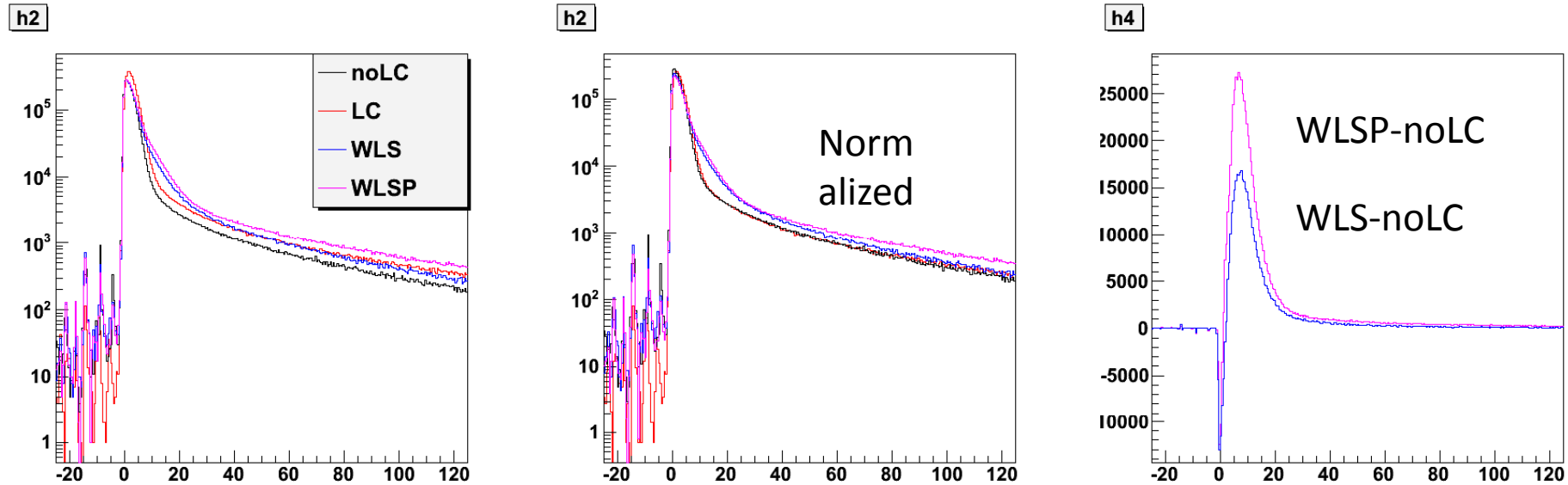
- Or we can increase the tank volume → reduction of photon coverage when keeping same PMT configuration. Increase by 1.5 m

$$R = \frac{2*\pi(53/2)^2 + 2*\pi*(53/2)(60)}{2*\pi(53/2+1.5)^2 + 2*\pi*(53/2+1.5)(60+1.5*2)} \sim 89\%$$

Effective reduction in FV for LC is about 10%

Effect of Timing on Vertex Resolution

- Wavelength shifting process will take several ns, delayed hit time (exponential) → worse vertex



100 kT, 12% 10 inch PMT 1st panel: normal plot

WLS process will broaden the timing peak.

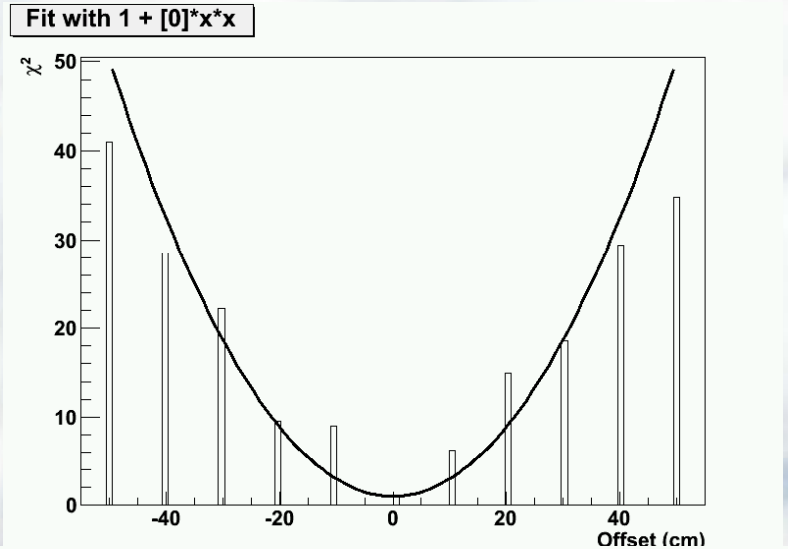
Likelihood Method: Compare similarity of timing spectrum at a test vertex location vs. true vertex location. We use first hit to mimic a digitization.

Chi-square vs. Offset

Fit the curve by the following format

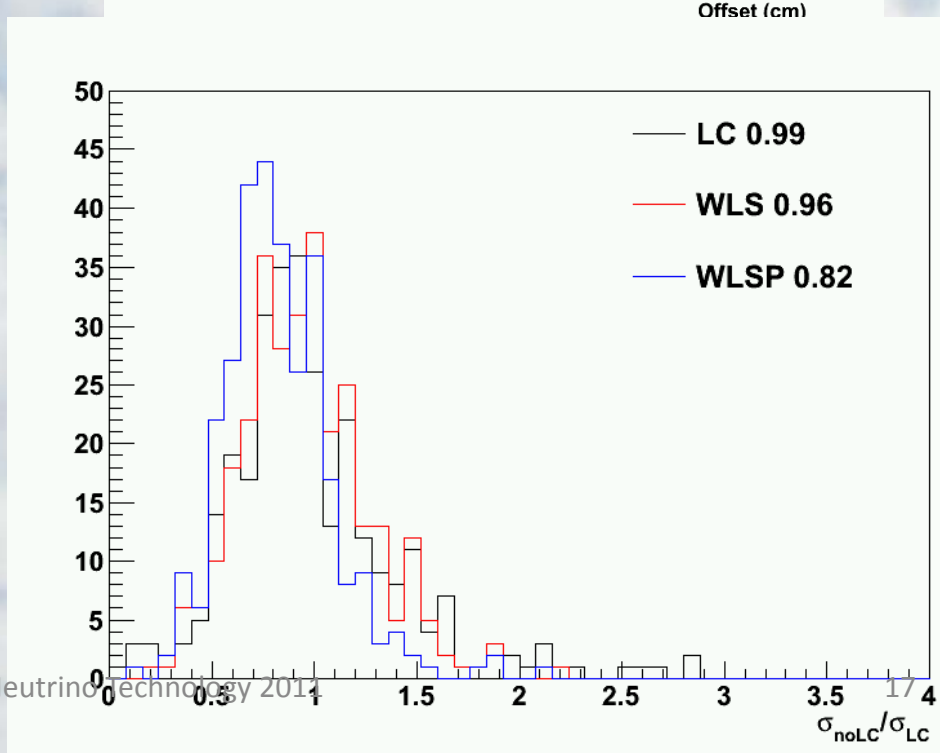
$$1+bx^2$$

1/b is then proportional to the vertex resolution.



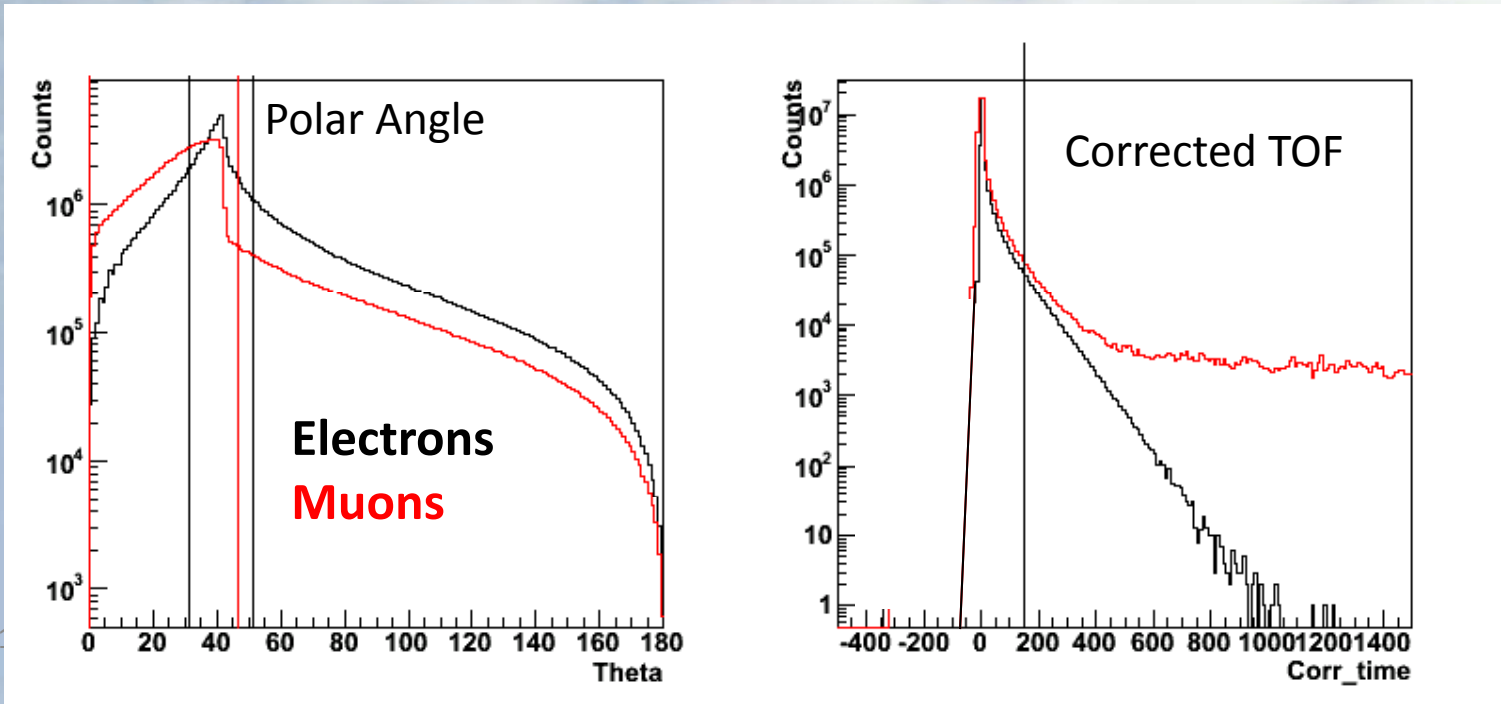
Suggests a >18% reduction in vertex resolution for WLSP (18% @ 20 % gain, effect will be larger @ 30% gain)

LC give about same vertex resolution as noLC.



Particle Identification

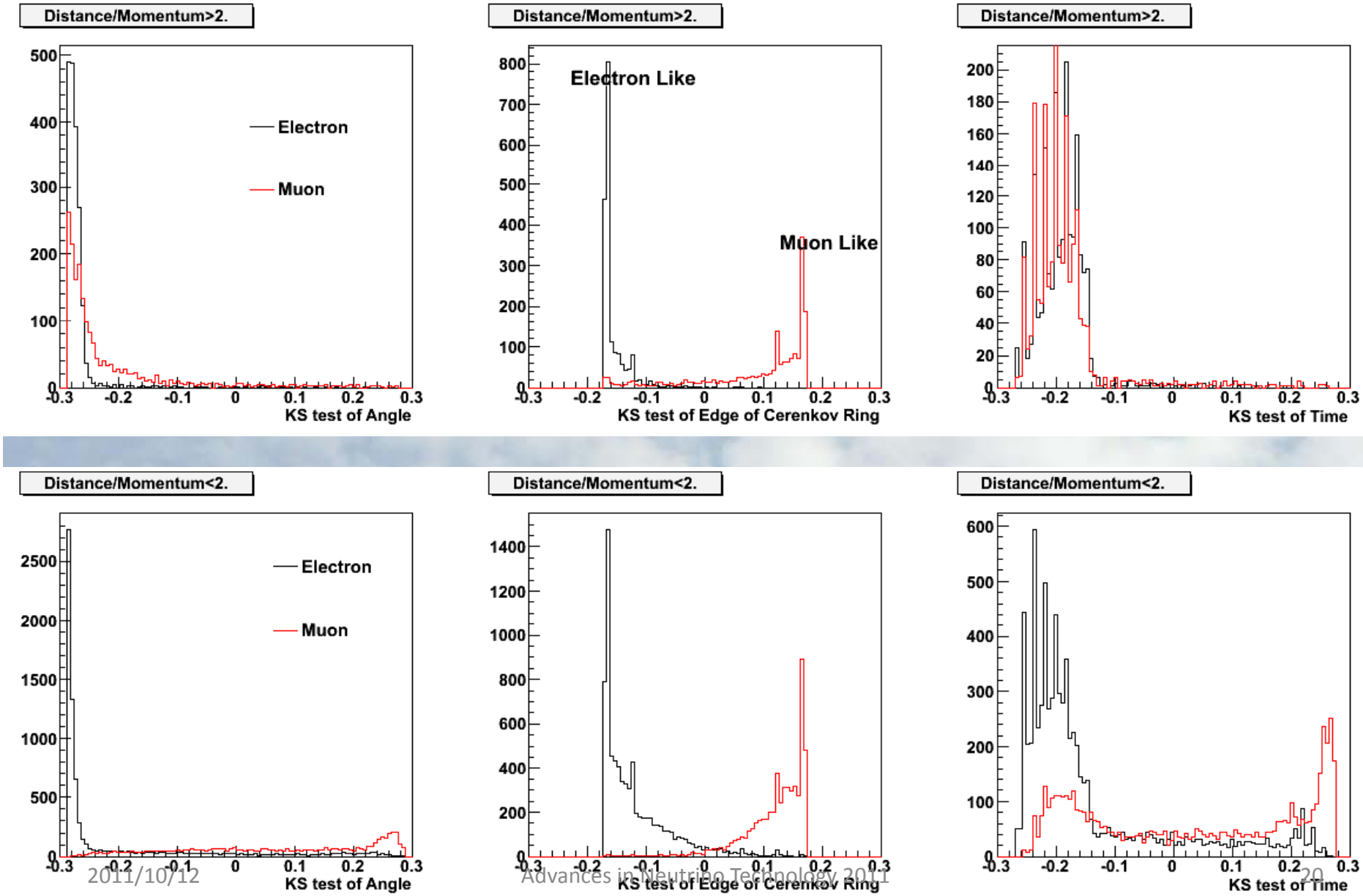
- Electrons and muons give quite different light pattern in WC (e.g angle, timing …)
- Compare the light pattern of one event with average pattern of electron/muons
  - In practice: **Kolmogorove-Smirnov test of histograms**



Likelihood Comparison Procedure

- Previous plots show how muons/electrons will behave.
- Polar angle and corrected TOF are important part in PID.
  - Note**: true information** was used to generate plots.
  - Do k-s test to compare histograms of angles and timing vs. the average histogram of electron or muons.
    - If the particle is an electron, it will a small k-s distance when compared with an electron histogram
  - Another powerful criteria is sharp edge near 42 degrees for muon
    - Comparison of histograms for 40-46 degrees only
  - **Procedure:**
    - Normalized the histogram to unity
    - Save the distance of ks-tests
    - 6 numbers for each event (time + angle + edge) x (electron + muon)

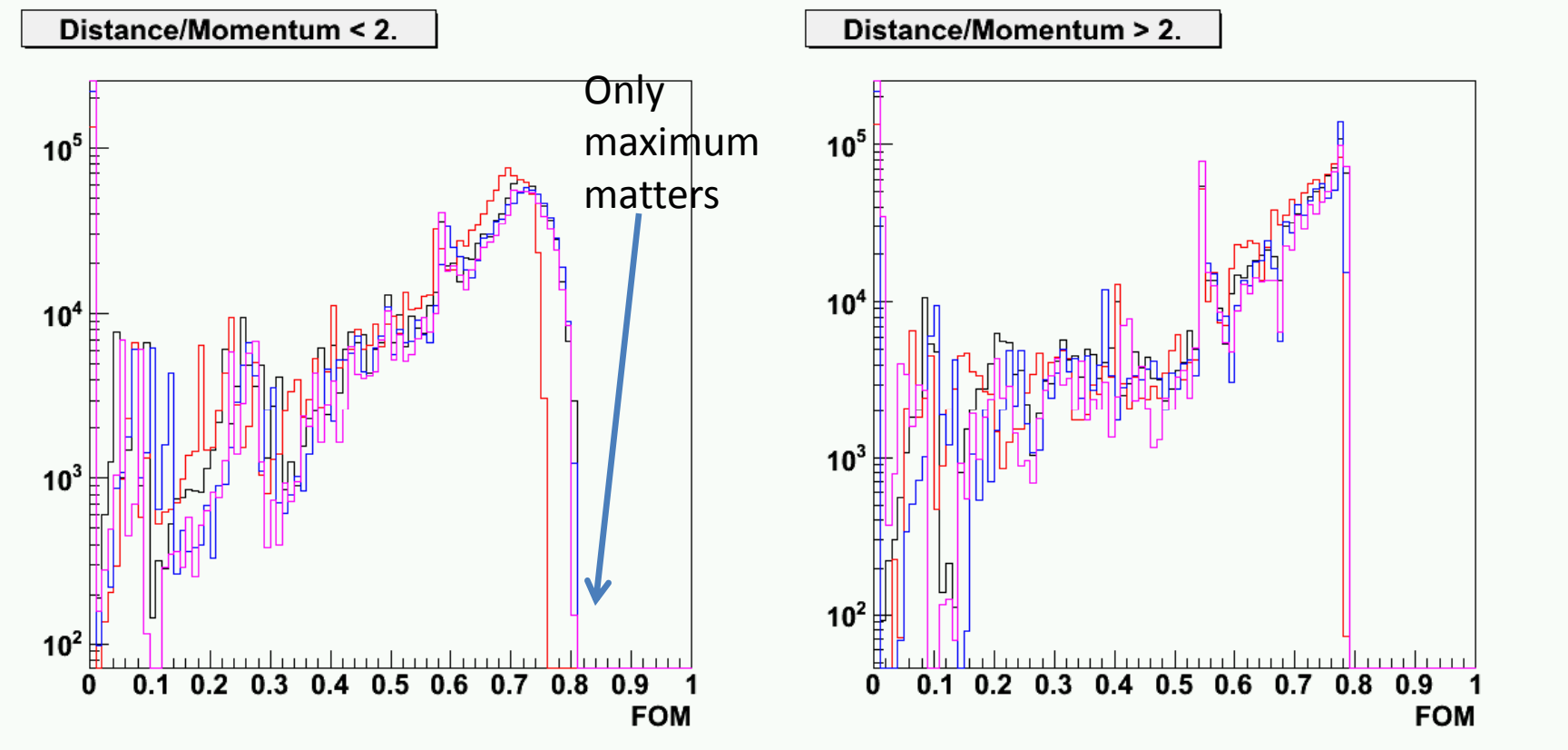
Particle Differentiation for Large/Small DoM



Scan for Efficiency

- We did a scan in ks-distance to get best FoM
  - The ks-distance in a step of 0.005 for angle range -0.3 → 0.3
  - The ks-distance in a step of 0.005 for edge range -0.2 → 0.2
  - The ks-distance in a step of 0.005 for time range -0.3 → 0.3
  - Calculate efficiency of electrons and muons.
    - FoM defined as: S/sqrt(S+B)
    - Signal 0.05 * Flux (oscillation) = 5% effect
    - Background:
      - intrinsic electron neutrino 1%
      - Pi^0 → 1%
      - Muons → We can further use decay-e to get rid of muons, so assume a factor of 10 reduction
    - Final FoM = E_eff/sqrt(E_eff + 2/5.*E_eff + Mu_eff * 2)

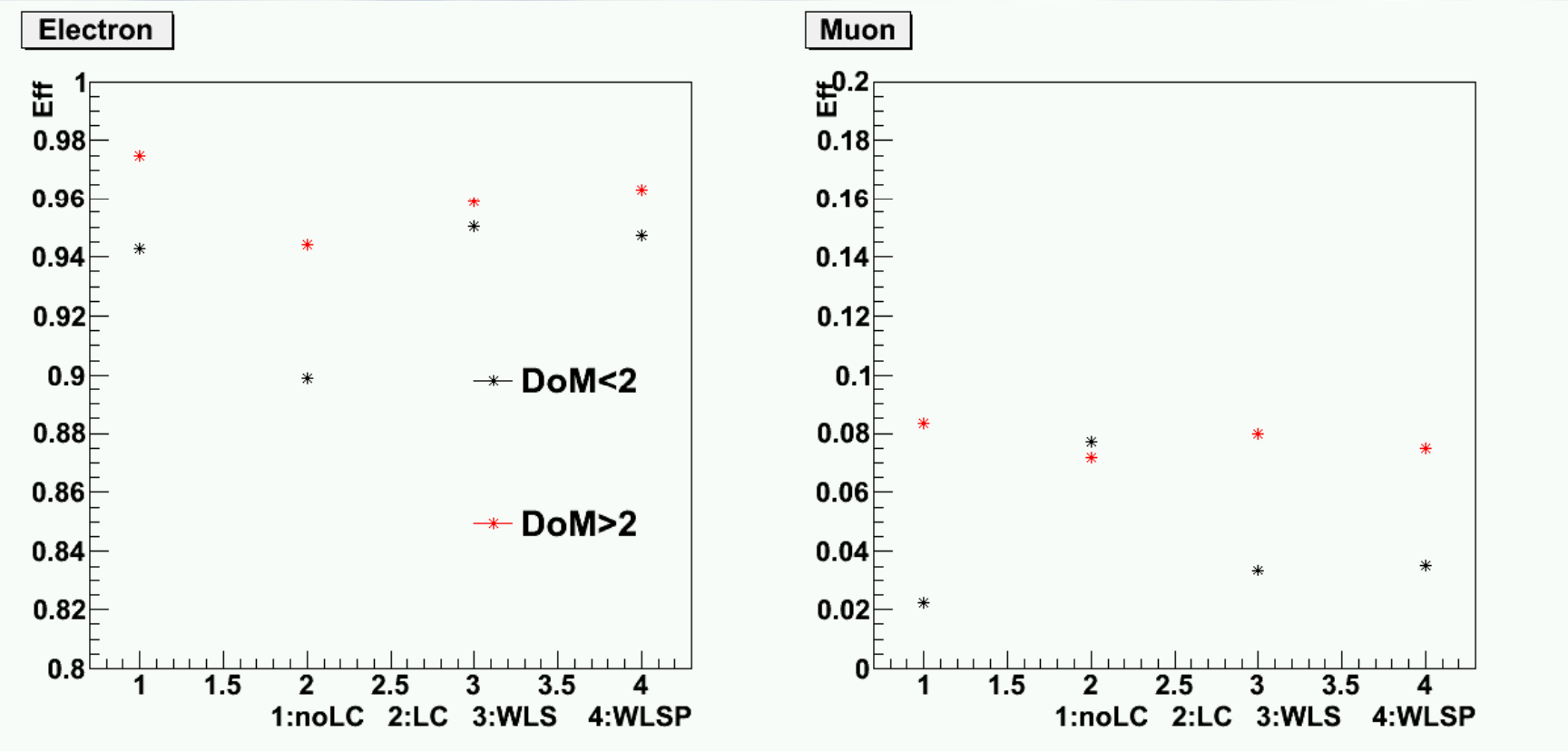
Now compare LCs



The maximum FOM is the best performance that you can get with each of LCs
At small DOM, degradation from Winston cone.
At large DOM, all LCs behave quite similarly.
Electron efficiency is about same 0.95-0.96

Color: **Black: noLC,** **Red: LC,** **Blue : WLS,** **Magenta: WLSP**

LC Configuration



Suggests a degradation of LC performance at small DoM. (distance is small, consistent with expectation, as LC works better when distance is large.

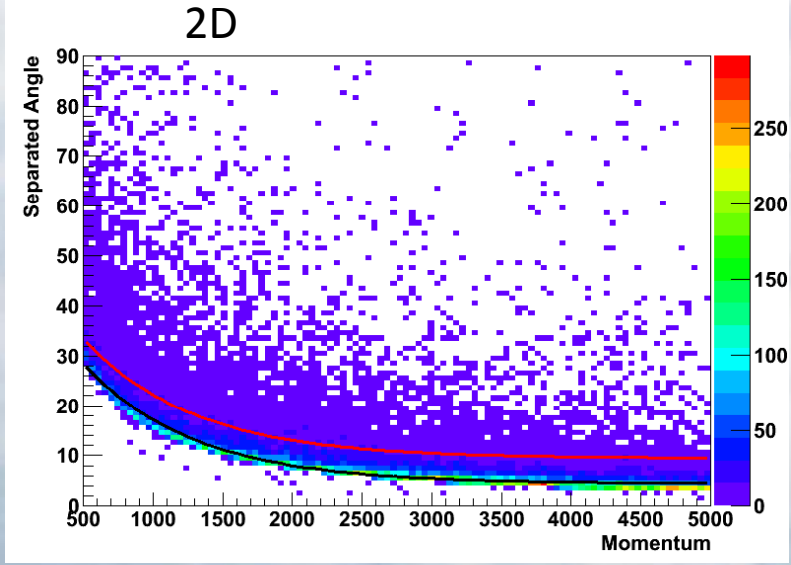
WLS/WLSP did not show a similar PID performance as noLC

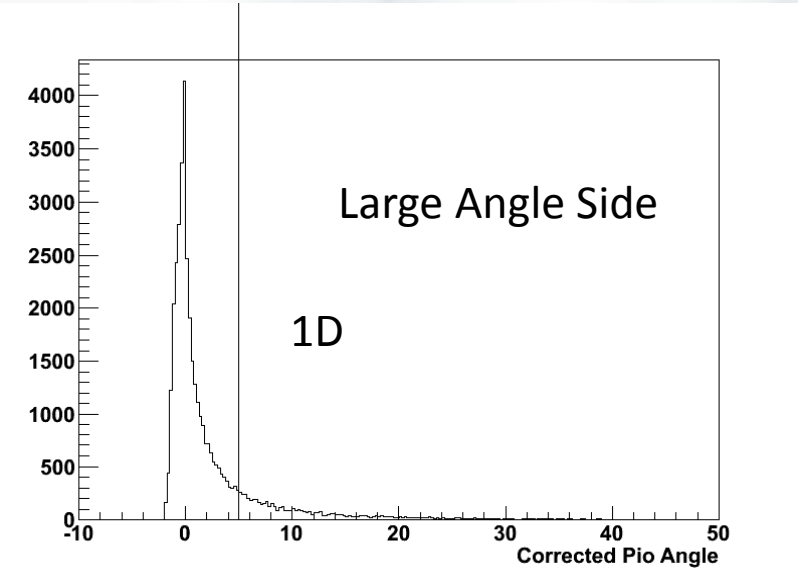
Neutral Pion PID (major background to electron)

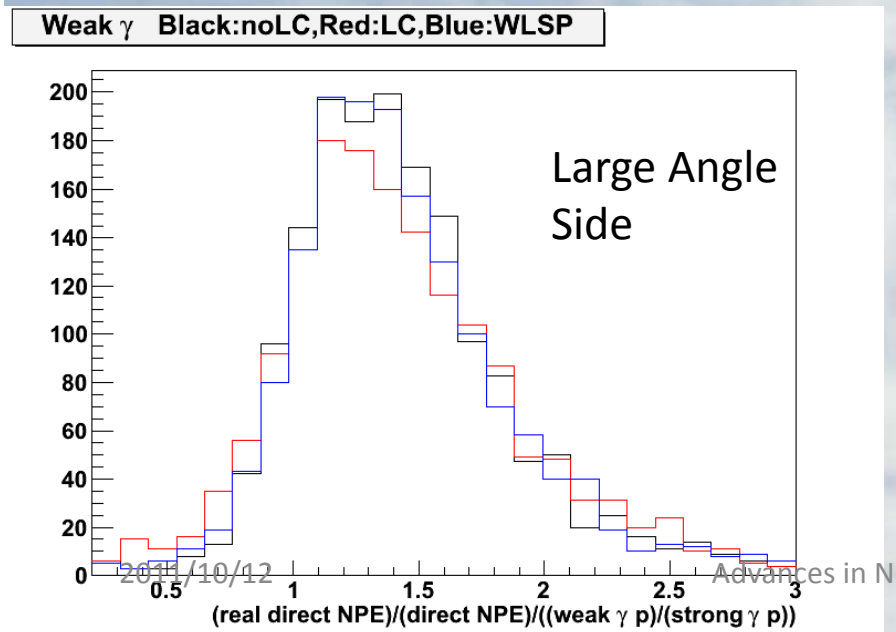
- WLSP gives more reflected light back into tank.
  - Will this affect the PID of neutral pion?
- Pi0 is hard to identify in two cases:
  - When the two photon are very close to each other.
    - May misidentify two rings as one ring.
  - When the two photon are back-to-back
    - The weak ring may be buried inside the background.
- We saved Direct and total light for each of the photon, the observable is defined as:

$$\frac{(\text{real direct NPE})/(\text{weak gamma momentum})}{(\text{direct NPE})/(\text{strong gamma momentum})}$$

Show cut of large/small angles







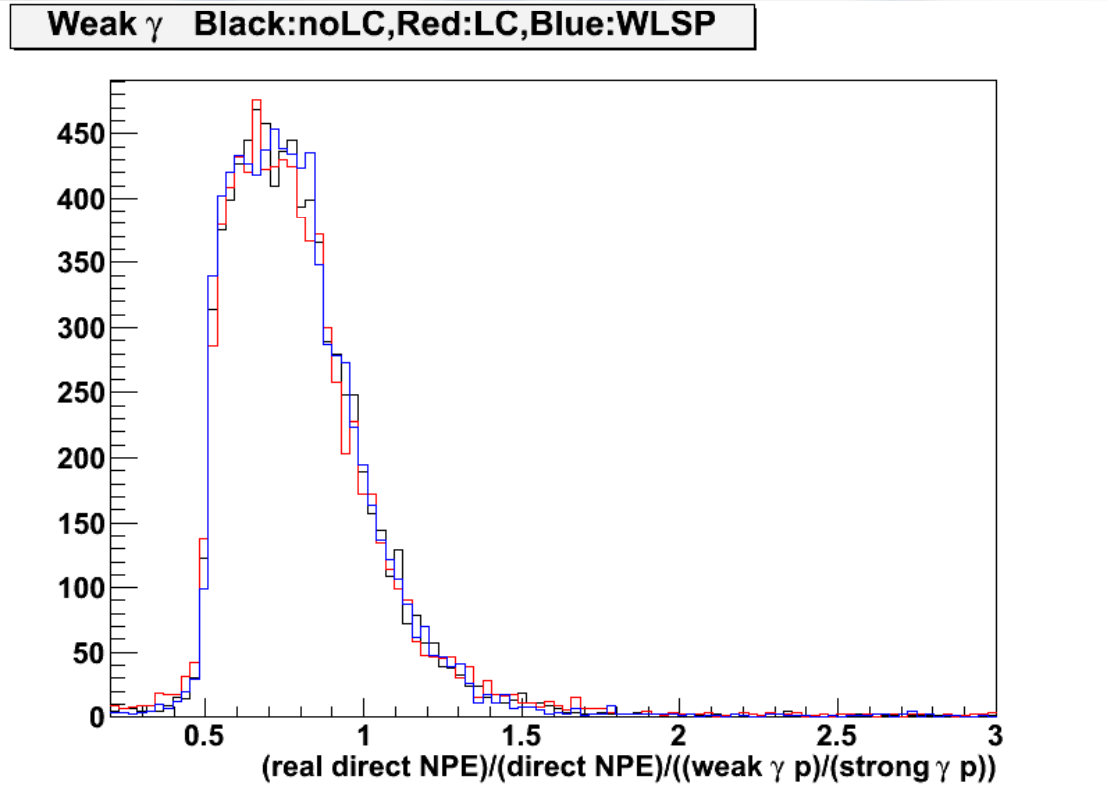
Mean Value: NoLC: 1.43 LC: 1.42 WLSP 1.43

1. No much difference for mean
2. Distribution of LC are different from the other two.

This make sense as we have the time cut, reflected light will arrive late.

Distribution of LC is different (same as what observed before)

Small Angle Side



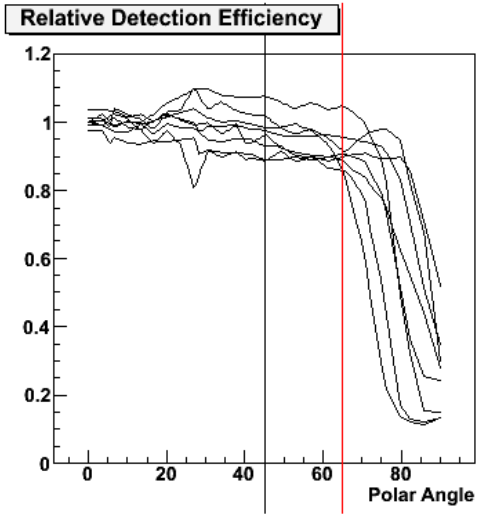
Mean: NoLC: 0.801 LC: 0.808 WLSP:0.799

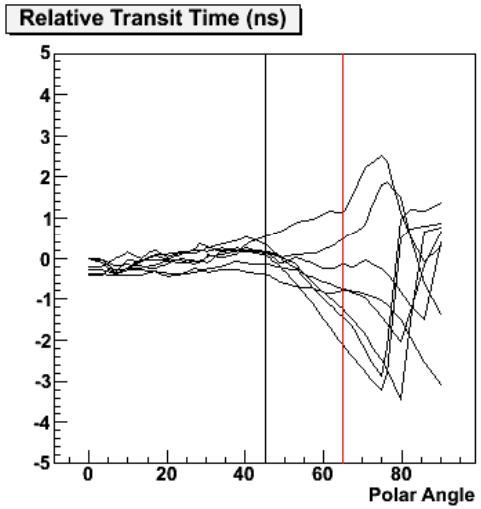
No Clear degradation of performance for WLSP. Also confirmed by back-of-envelop calculation.

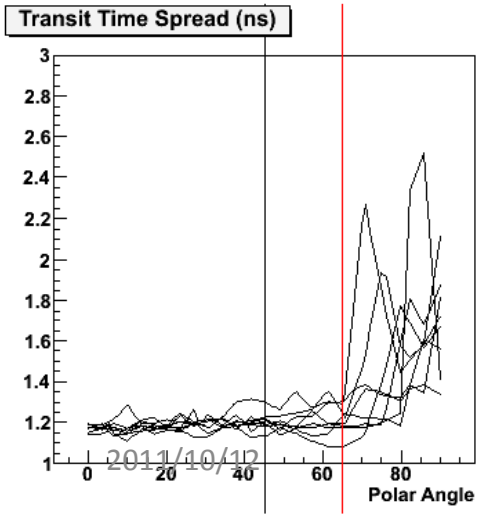
Suggests that the WLSP will not introduce a big problem for neutral pion identification comparing to noLC at same coverage.

PMT Unguaranteed Region

- R. Kadel: with the same tool, can we say something about the PMT unguaranteed region?





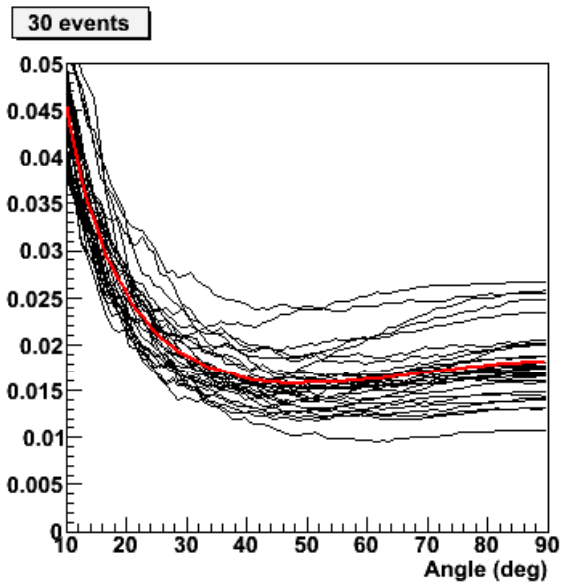


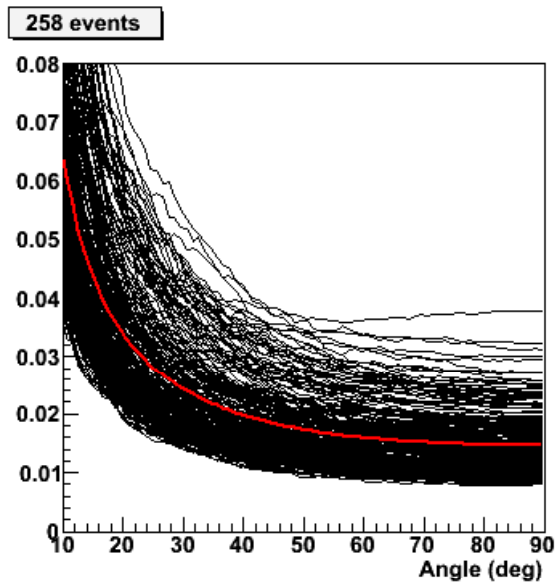
Data from Penn
Thanks to
Ahthony/Stan/Josh
Relative Detection Eff.
Relative Transit Time
Tansit Time Spread

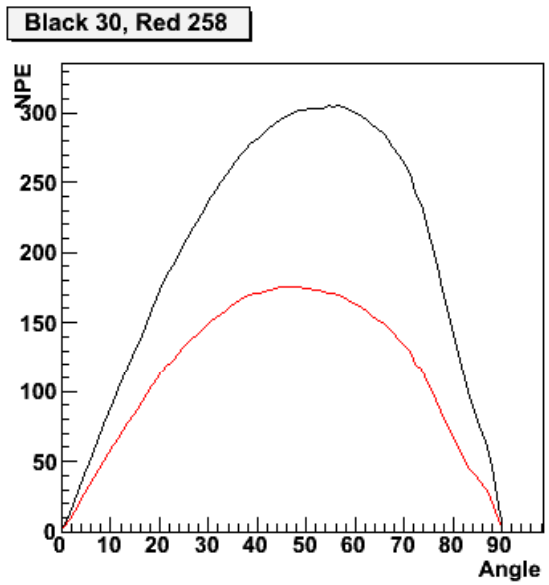
- Guaranteed region ends at 45 degrees
  - Seems to be dominated by Relative Transit Time
- 65 degree: Another line set my Relative Detection Efficiency and Transit Time Spread.
  - Slight worse in Relative Transit Time.

Results of Intrinsic Resolution Study

- Large coverage area → More photons → Better resolution
- Large coverage area → More photons at edge where QE is dropping → Less resolution







30/288 events (simulated @ 200kT 12 inch 12% 0.5-5.0 electron in F.V.) show larger resolution at full 90 degs coverage → events are all at large total NPE → high energy.

So using unguaranteed will improve the intrinsic resolution. Kind of marginal after passing 65 degrees

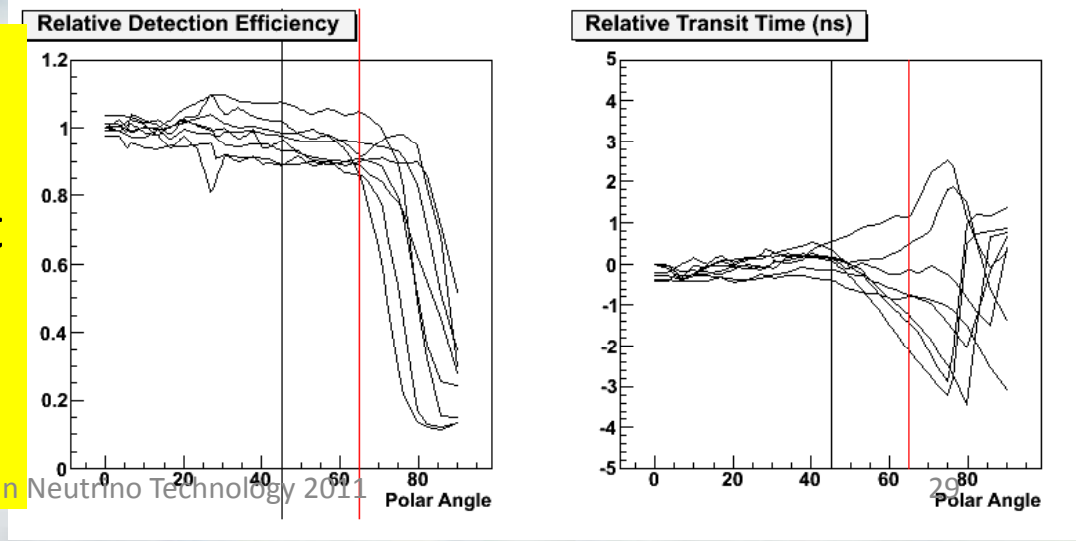
Results of Vertex Resolution

- Large Coverage Area → More Photons → Better determination of vertex
- Large Coverage Area → More Photons on the edge with poor timing and larger spread → Worse vertex resolution

Coverage	30 deg	45 deg	60 deg	90 deg
Vertex Resolution	116 cm	106 cm	101 cm	101 cm

Only focus on relative comparisons. Assume good knowledge on PMT performances. Improvement are marginal passing 65 degrees.

Improvement in performance by including some unguaranteed region, but effect are marginal passing 65 degs. Also need to include the uncertainties for consideration.



What did we learn from these preliminary studies?

- Light Collectors can improve the performance of WC when coverage is small.
- 2 m fiducial volume cut @ LBNE is conservative.
- More PMT coverage would lead to a high electron PID efficiency and high muon PID rejection factor.

	LC	WLS	WLSP
NPE Gain	~50%	~10%	~30%
Coverage	8%	11%	9.5%
Reconstruction	Large Spread	Small Spread	Small Spread
Intrinsic resolution	Large loss	N/A	Small loss
Fiducial volume	~10% reduction	No loss	No loss
Vertex Resolution	Small effect	5% increment	15% increment
Electron/Muon	Small loss	No clear effect	No clear effect
Neutral Pion	N/A	N/A	Small effect

N/A means no dedicated studies were performed.
Study done @ 100 kT 12% noLC baseline. We assume same NPE for LC/WLSP comparison.