Intrinsic variation in physics events for ORCA

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Thanks also to M. Pleinart, T. Rauch

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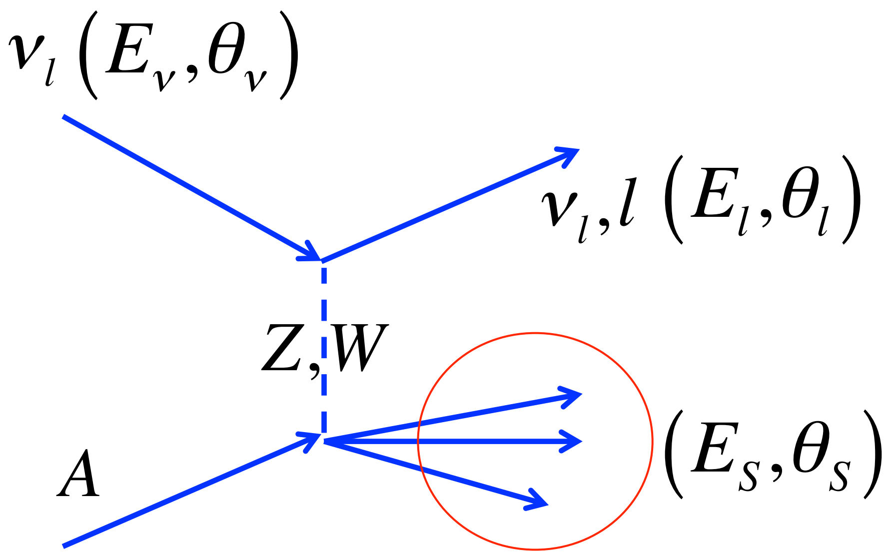
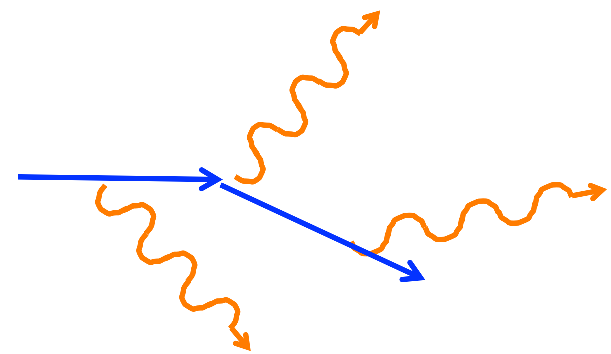
Detectors see showers and tracks via photons



$$\vec{p}_\nu = \vec{p}_l + \vec{p}_s$$
$$E_\nu = E_l + E_s$$

- Information via photons:
  - Number ~ energy
  - Direct photons ~ direction



- Physical mechanism:
  - Vertex physics
  - Particle propagation
  - Cherenkov emission

- What is the effect of intrinsic fluctuations in the physics?

Principles

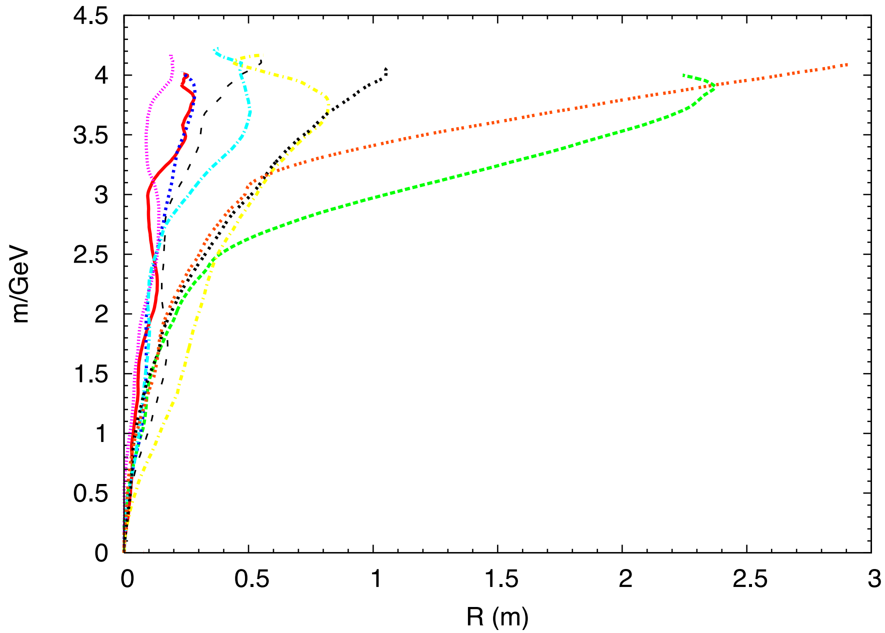
- What is the best we can do if we detect every single photon?
  - Simulate many identical events
  - Look at fluctuations in photon output and track behaviour

- Given we detect only some photons, what's the best we can do?
  - Estimate mean detector response
  - What minimum error does this give us?
  - Always make optimistic assumptions on detector response

Muons: tracklength and deviation

- 10 Muon tracks, 3-13 GeV:

$$\frac{L}{E}$$



- They are not perfect straight lines (direction error)
- Length also differs (energy error)

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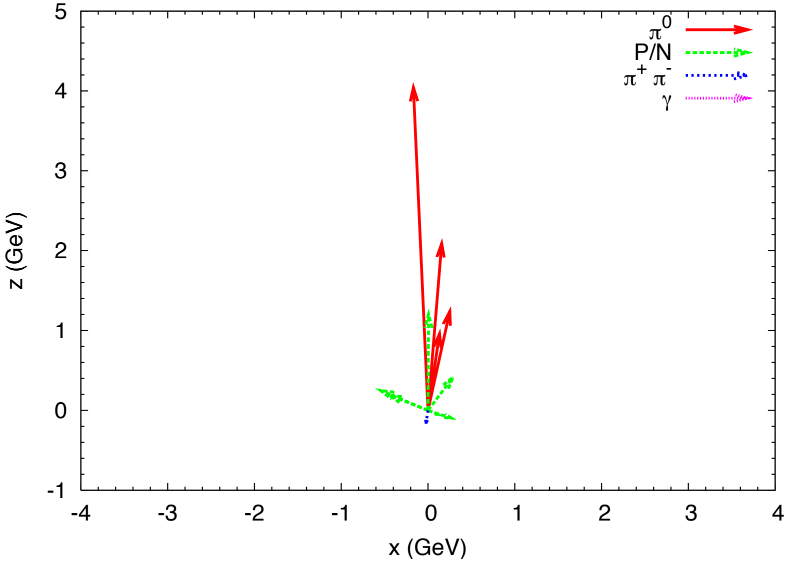
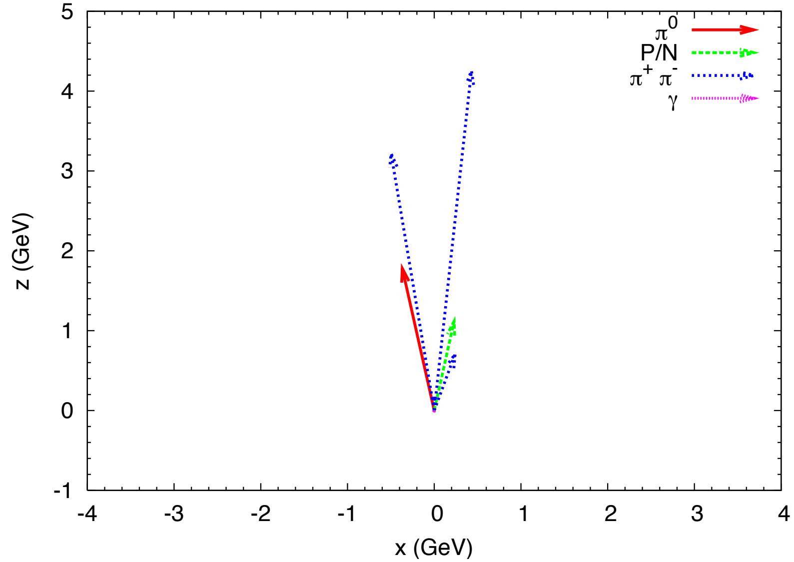
PHYSICS

Showers: vertex effects

- 2 events: same momentum transfer at the vertex

Plot:
$$E_{kin}\hat{v}$$





Pi0
Nucleons
Pi^{+-}
Gammas

- Additional source of variation:
  - Composition of the cascade
  - Energy/momentum of recoil nucleus

Principles

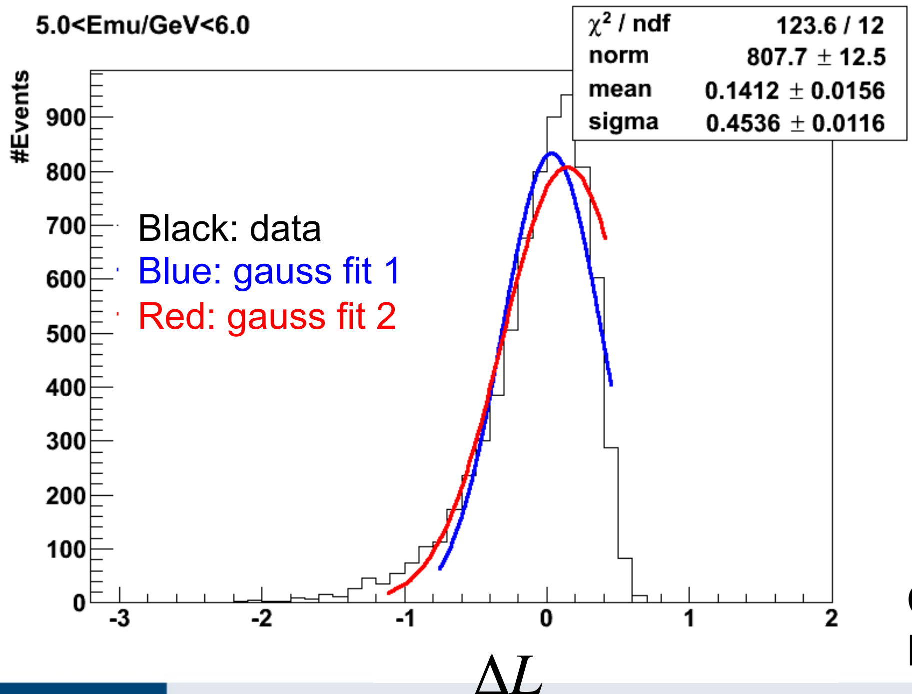
- Muons
  - Energy: estimate using true muon track length
  - Direction: use a linear fit to the track
- Showers:
  - Energy: estimate using total detected photons
  - Direction: mean photon direction – *using direct photons only.*
- Assumptions: always make optimistic ones!
  - Know where photons come from
  - Perfect vertex reconstruction
  - Do not model detector effects

MUON TRACK FLUCTUATIONS

Muons: energy (method)

- Muon energy - estimate it through the tracklength
- 'MUSIC': muon tracking in km3
  - output muon track information for many events
- Run muons of a given energy, record tracklength

$$\frac{\Delta L}{L} \Leftrightarrow \frac{\Delta E}{E}$$



$$\Delta L = L - 4.25\frac{E}{1\ \mathrm{GeV}}$$

- Fit using gaussians: use
  - central peak (fit 1)
  - all data (fit 2)
  - Simple root mean square

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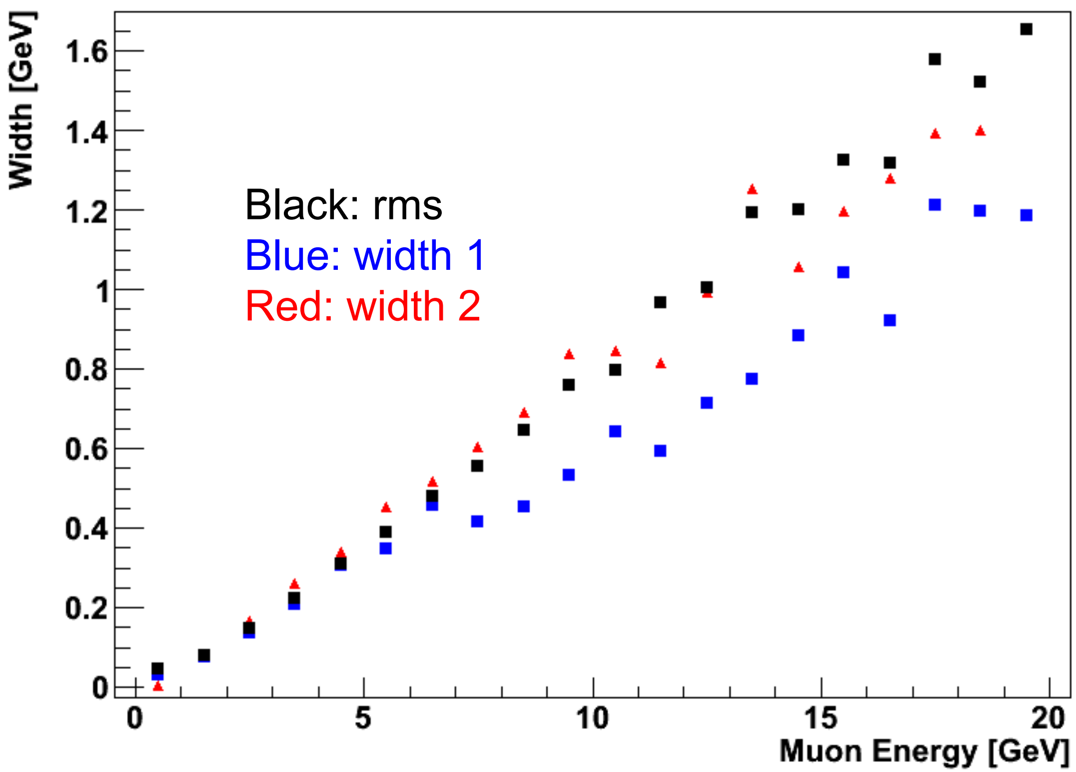
Muons: energy (results)

- Intrinsic spread from physical fluctuations

$$\Delta E = \frac{\Delta L}{4.25\ \mathrm{m}}$$



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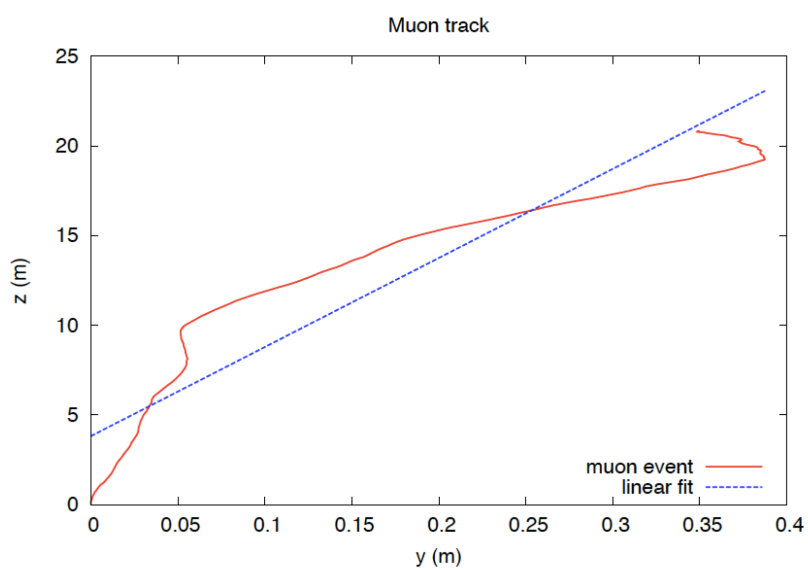
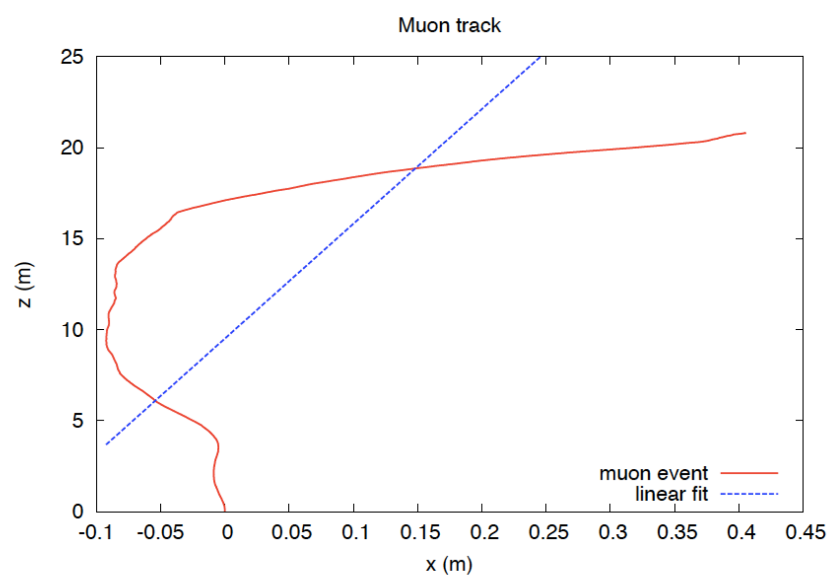
- Approximately 8% muon energy resolution

Muons: direction (method)

- How straight are muon tracks?
  - Run 2000 muons over 0-20 GeV range with GEANT 3.21
  - Get x(z) and y(z) with simple linear fit
  - Obtain angular offset $\theta = \cos^{-1}\left(\hat{v}_{fit} \cdot \hat{z}\right)$





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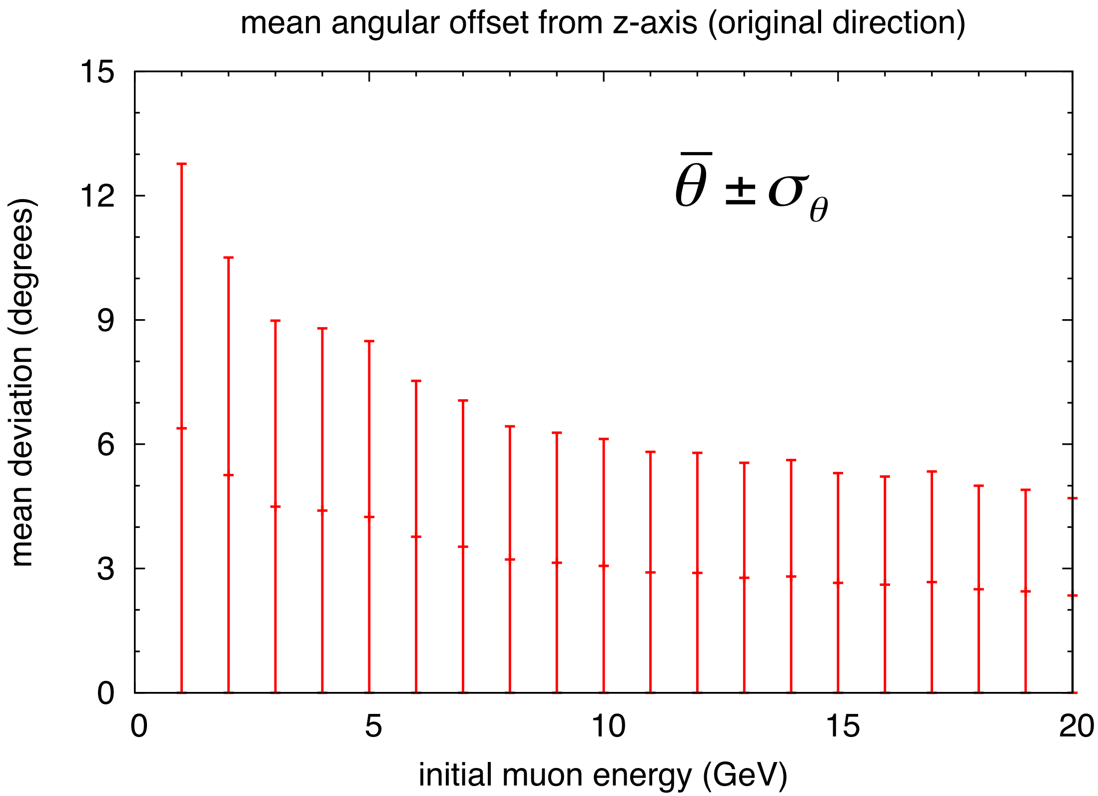
Muons: direction (results)

- Estimation of intrinsic variation:



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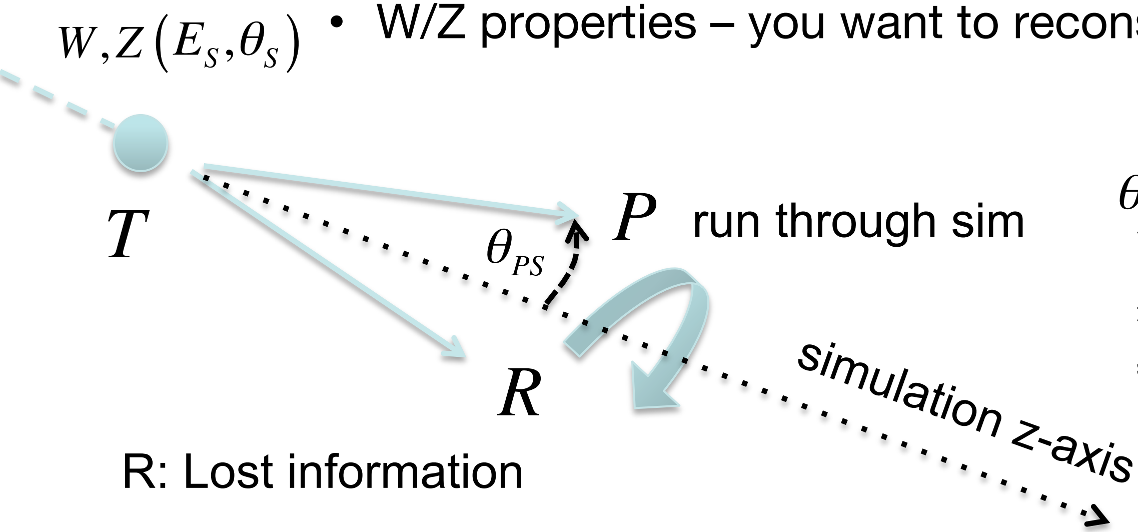
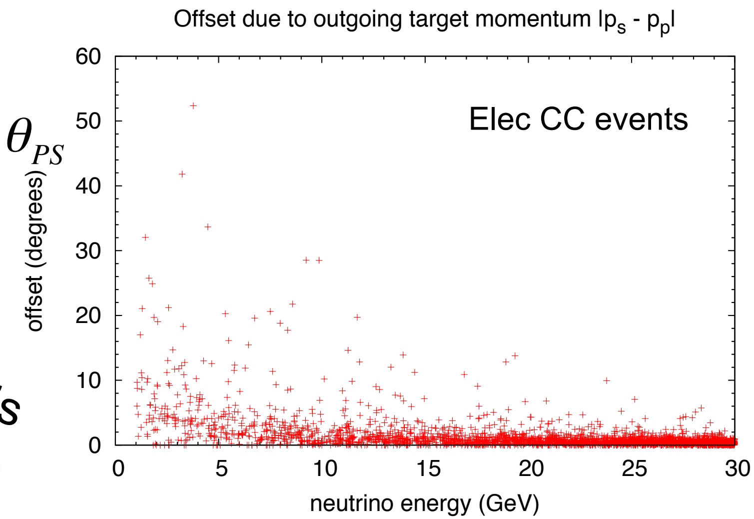
- 10 GeV muons: ~4^o intrinsic error
- Work still needed to characterise this (true dist 2D)

SHOWER FLUCTUATIONS

Showers: definitions

- Outgoing particles: $B+T->R+P$
  - Boson (B) + target (T) -> remnant (R) + energetic particles (P)
  - Target T and remnant R invisible
  - W/Z properties – you want to reconstruct these!





- Define 'shower' energy/momentum via the W/Z properties

*random target orientation and ~no coupling to e.g. magnetic moment of target

Simulations

- Events from gSeaGen (12000)
  - 0-30 GeV range ($E_s = yE_{nu}$)
  - 100 events per GeV (randomly selected)
  - 4 classes: NC/CC and Muon/Electron neutrinos
  - *Ignore leptons in CC events*
- Simulations
  - GEANT 3.21
  - Repeat 50 times for each of 12,000 events
  - Record photon statistics (number and direction)
- Analysis
  - Fit fluctuations within and between events
  - Energy error: total number of photons
  - Direction error: mean photon direction

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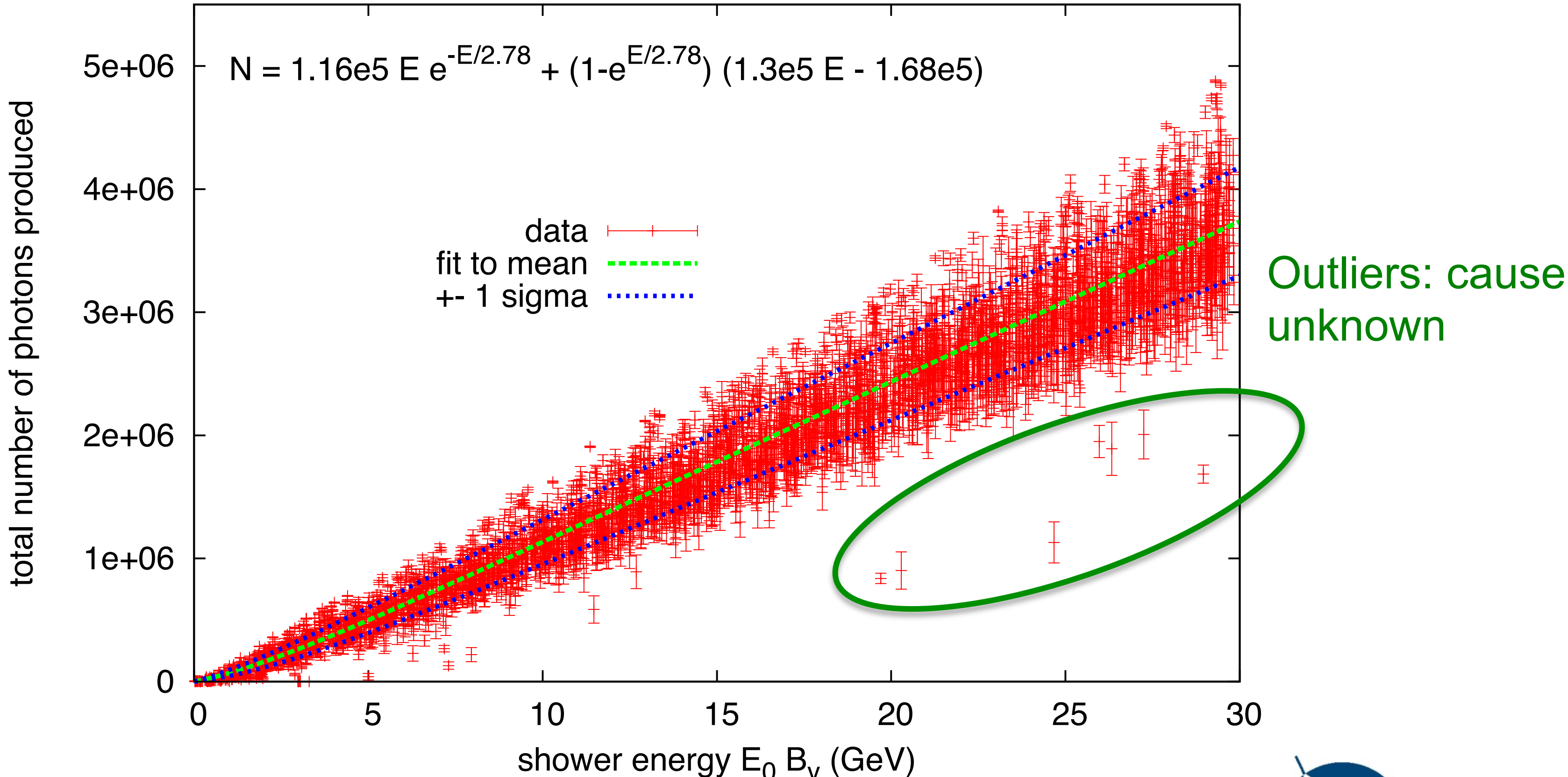
Results: errors in energy resolution

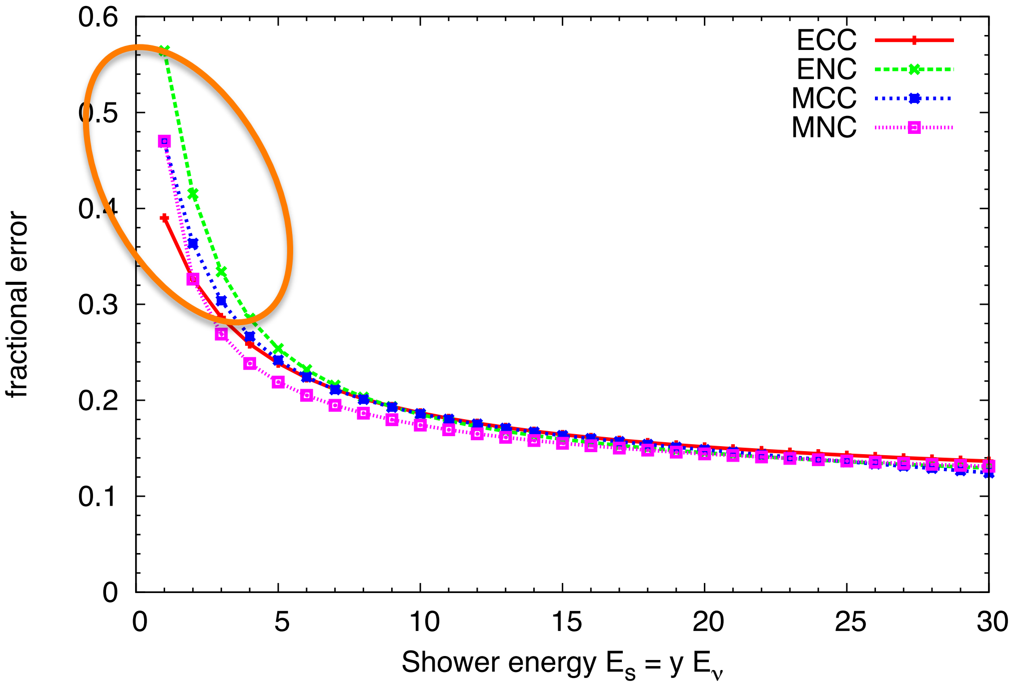
- Each point: mean of 50 runs for each vertex
- Error bars: variation within these 50



Total intrinsic variation: shower energy

- Repeat for \nu_mu and CC/NC events

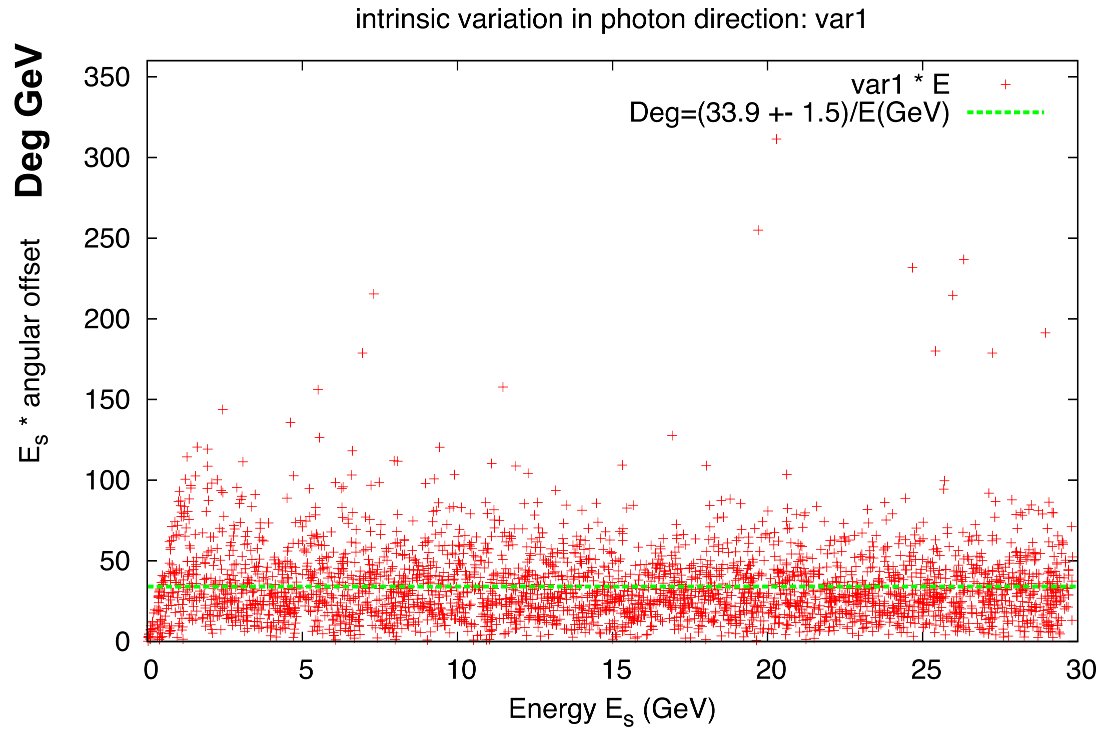
Difference NOT significant

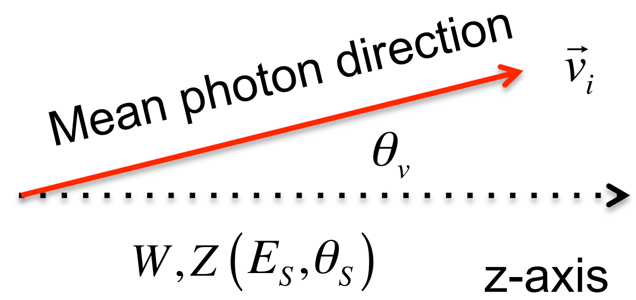


- Fractional error in emitted photons ~ fractional error in energy reconstruction
    - 1 GeV showers: ~50% energy resolution
    - 10 GeV showers: ~20% energy resolution

Results: direction ('vertex' variation θ_v)

- 1 point per vertex (mean over 50 runs)
- Plot offset of this mean from the z-axis





Mean direction over all 50 runs

- Fit: 34 degrees at 1 GeV, 3.4 degrees at 10 GeV

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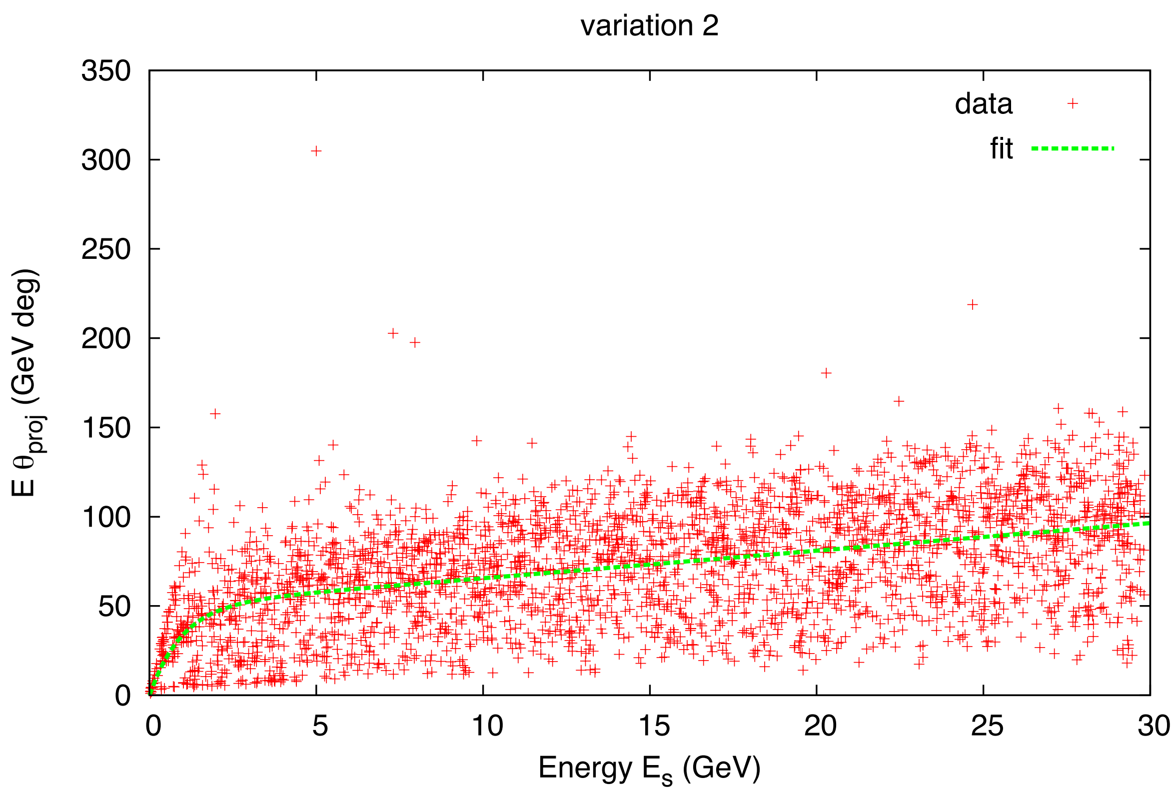
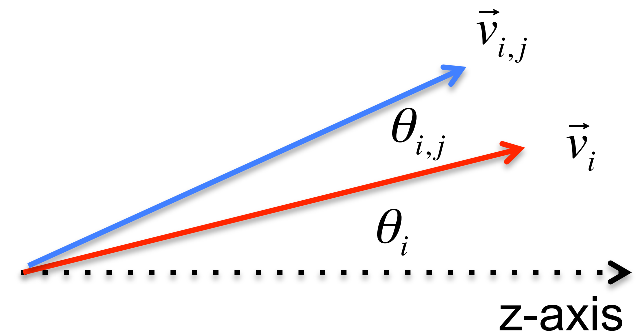
Results: direction (cascade variation θ_c)

- Each point: variation of 50 runs about mean





Mean photon direction over all 50 runs

Mean photon direction for a single run

$$\theta_{i,j} \equiv \operatorname{acos}\left(\vec{v}_{i,j} \cdot \vec{v}_i\right)$$

- 1 GeV: ~20 degrees
- 10 GeV: ~6 degrees

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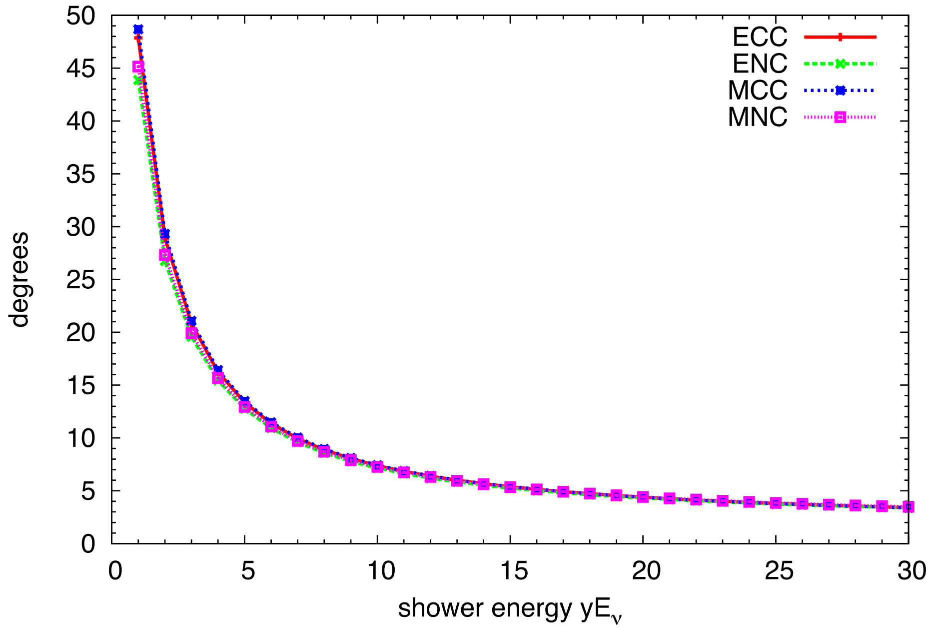
Total intrinsic variation:

- Repeat for \nu_mu and CC/NC events



Add errors in quadrature:

$$\theta_{tot} = \sqrt{\theta_1^2 + \theta_2^2}$$

- Fits statistically identical: no plans to repeat for anti-neutrino events.
- You will not be able to reconstruct showers better than this – even if you detect every single photon.

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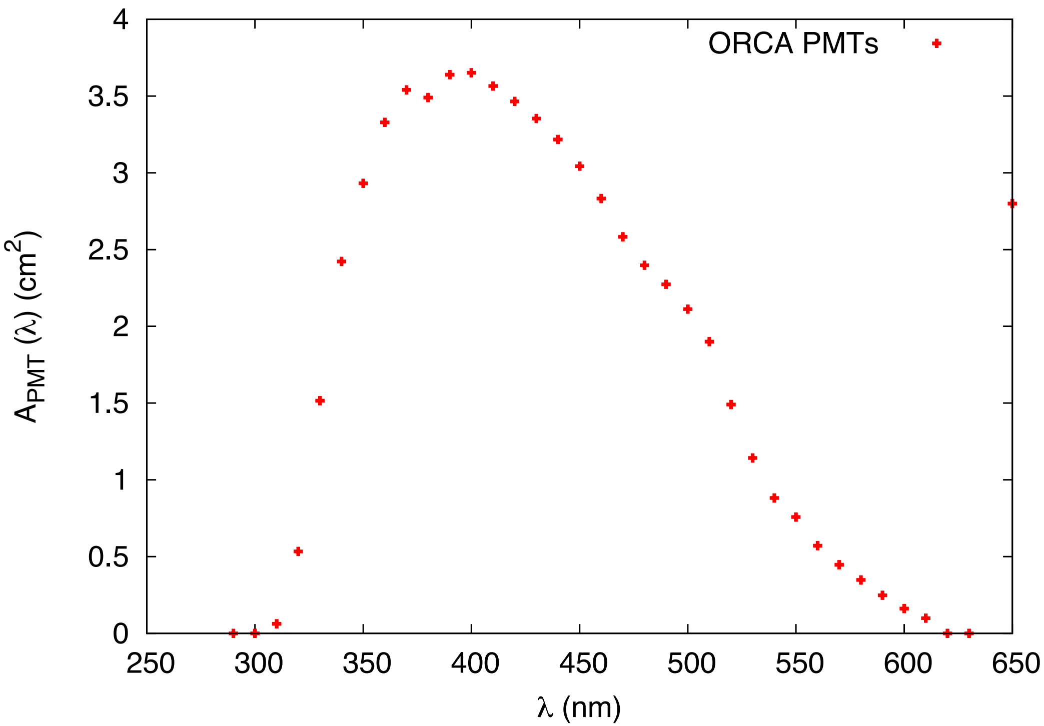
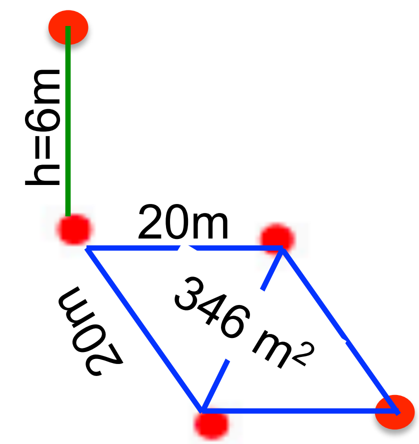
DETECTOR LIMITATIONS

How are we limited by not detecting every photon?

Detector Response

- What is the mean photocathode density in the ocean?
  - Mean PMT effective area: $\bar{A}_{PMT}(\lambda) = \frac{1}{4\pi} \int_0^{2\pi} A(\lambda,\theta) 2\pi \sin\theta \; d\theta$
  - PMT density for contained events:





Vertical spacing h=6m
Horizontal area A=346 m^2
1 OM per 2076 m^3

$$\rho_{pmt}(\lambda) = 0.015$$

$$l_{det}(\lambda) = 1 \Big/ A_{pmt}(\lambda)\rho_{pmt}(\lambda)$$

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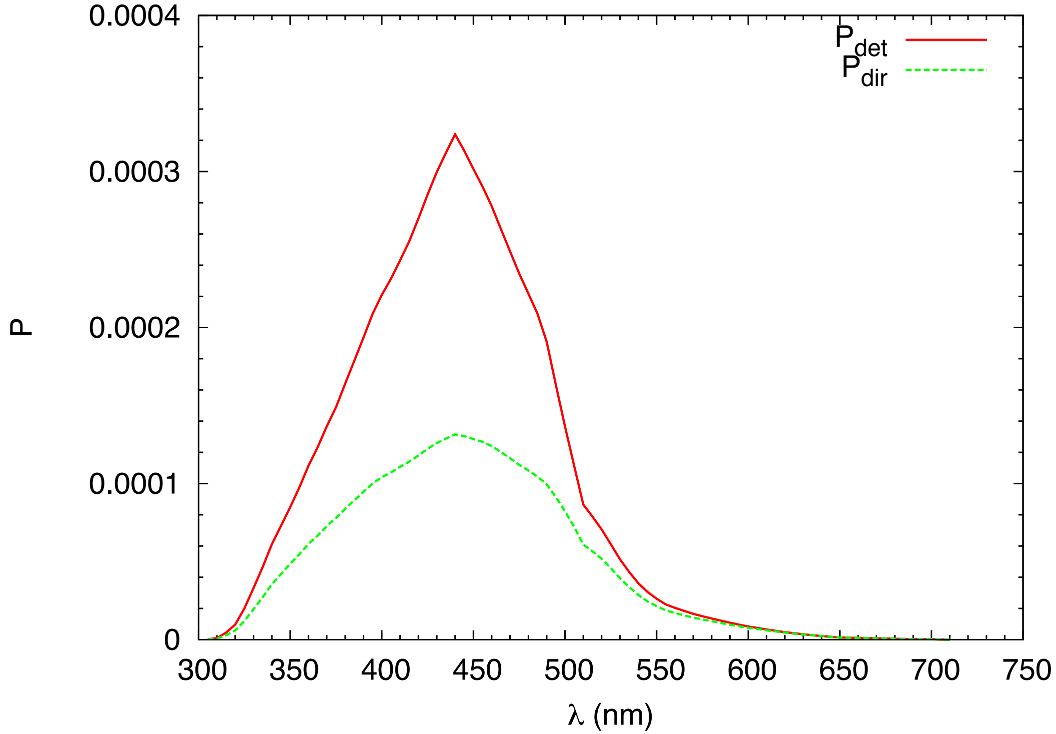
Result: chance of detecting any given photon

- Probability of:
  - any detection (energy reco):
  - direct detection (direction reco):



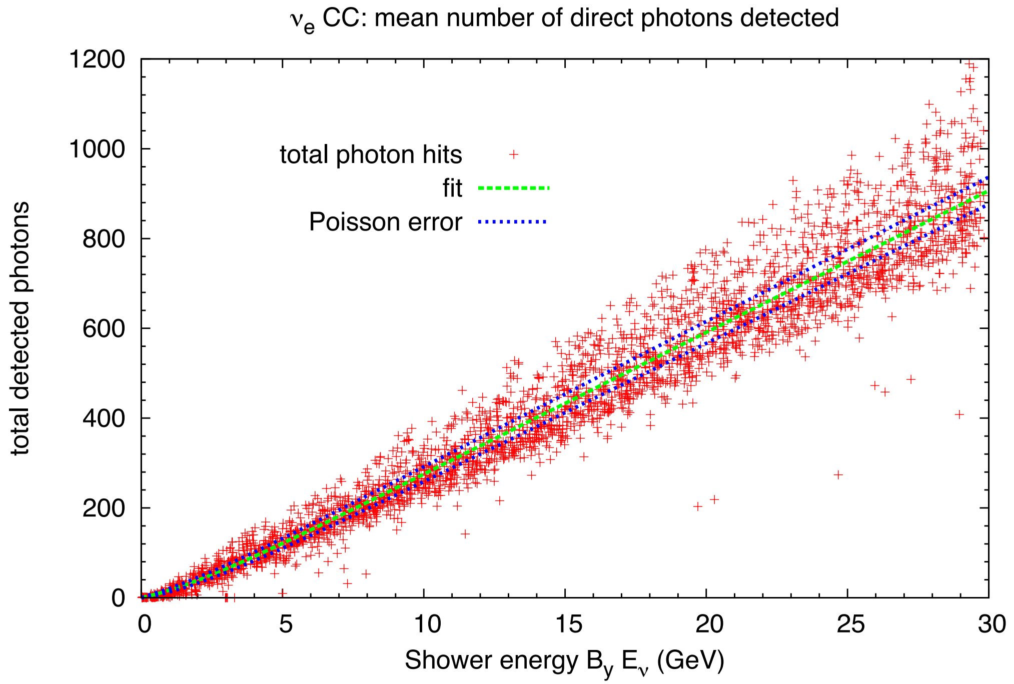
$$\boxed{p_{\mathrm{det}}(\lambda) = \frac{l_{\mathrm{det}}(\lambda)}{l_{abs}(\lambda)}}$$

$$\boxed{p_{dir}(\lambda) = \frac{l_{\mathrm{det}}(\lambda)}{l_{att}(\lambda)}}$$

Expect half photons to be detected unscattered

Detector energy uncertainty

- How many shower photons get detected?



- Energy error >= Poisson error $\dfrac{\Delta E_{\mathrm{det}}}{E} \sim N^{-0.5}$
- Assumes 100% identification of shower hits, ignores detector clumpiness,…

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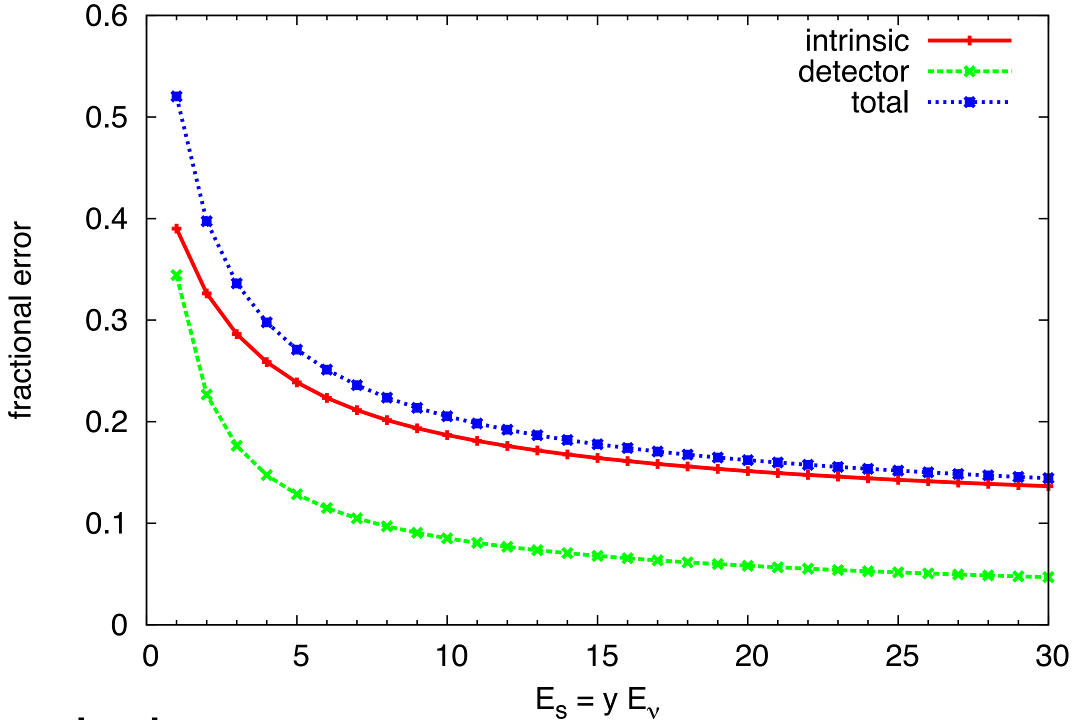
Results – shower energy reco

- Comparison: intrinsic, ORCA, total



- Conclude:
  - Energy reco: intrinsically limited
  - Perhaps a sparser detector would be best?

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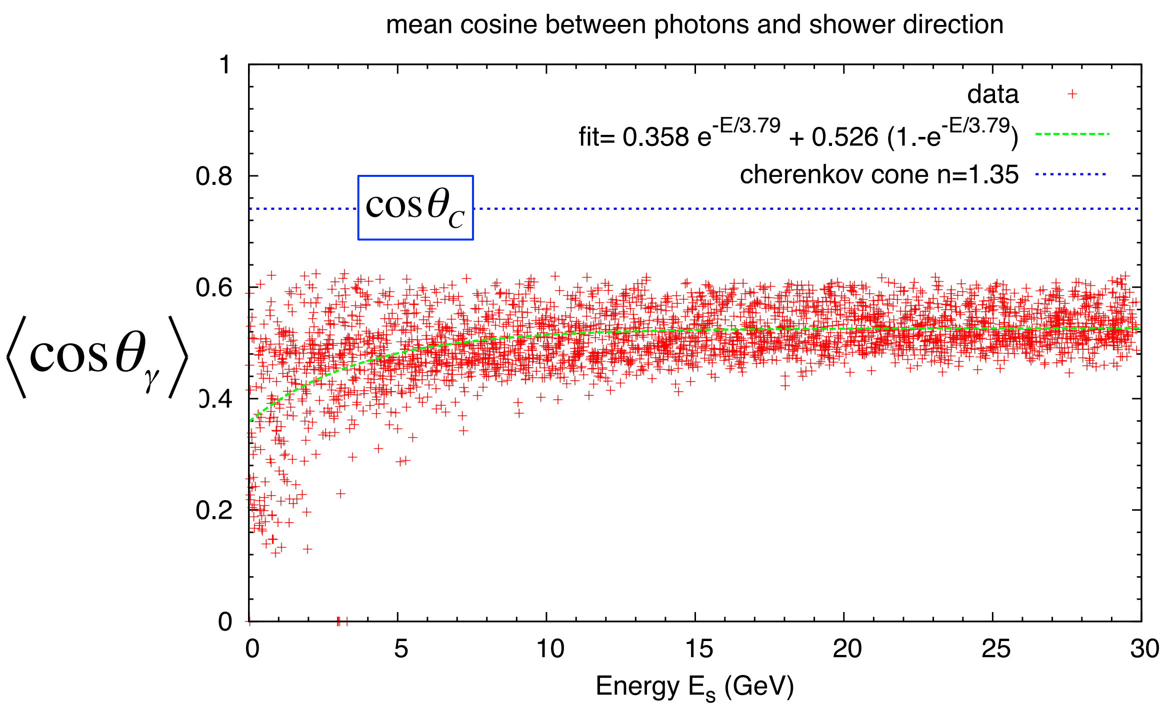
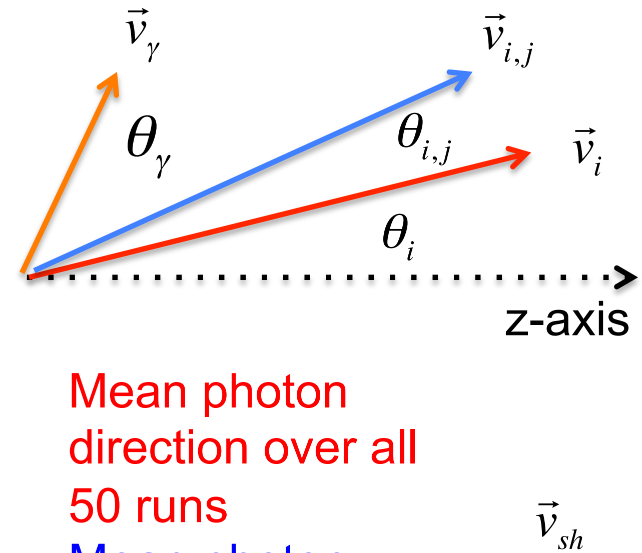
Detector limits: direction

$$\sigma_s = \sigma_\gamma / \sqrt{N_{dir}}$$

- Shower direction: average direction of all direct photons
- How well can we estimate the mean?





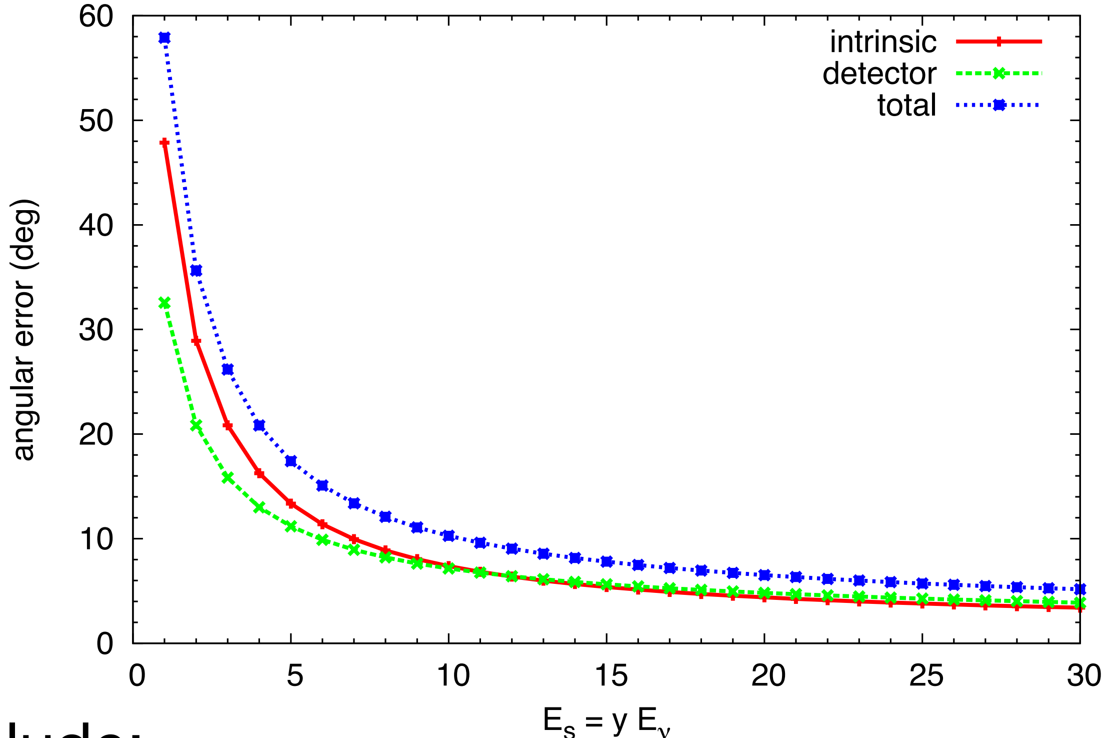
Mean photon direction over all 50 runs

Mean photon direction for a single run

Mean offset of each photon from the mean shower direction

Results – shower direction reco

- Comparison: intrinsic, ORCA, total



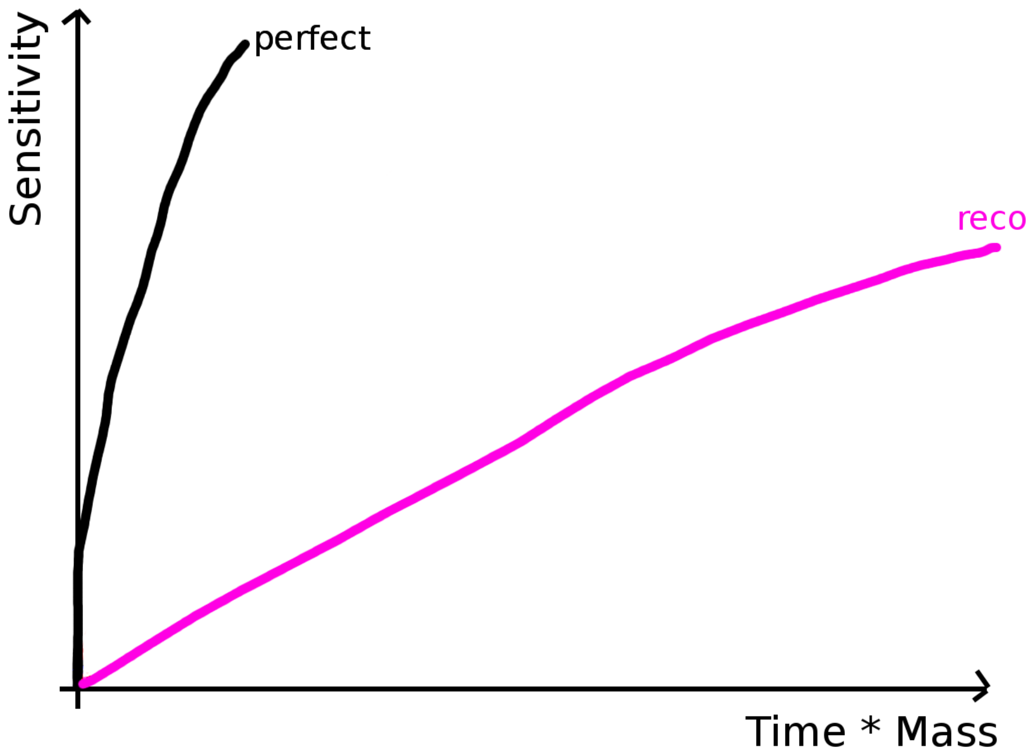
- Conclude:
  - Directional reco: detector effects significant
  - A denser detector would help

What use is this?

- Compare to current reconstruction efforts
  - How close is your method to ‘perfect’?
- Use to influence detector design
  - Are we detector-limited or physics-limited?
- Determine limits to mass hierarchy sensitivities

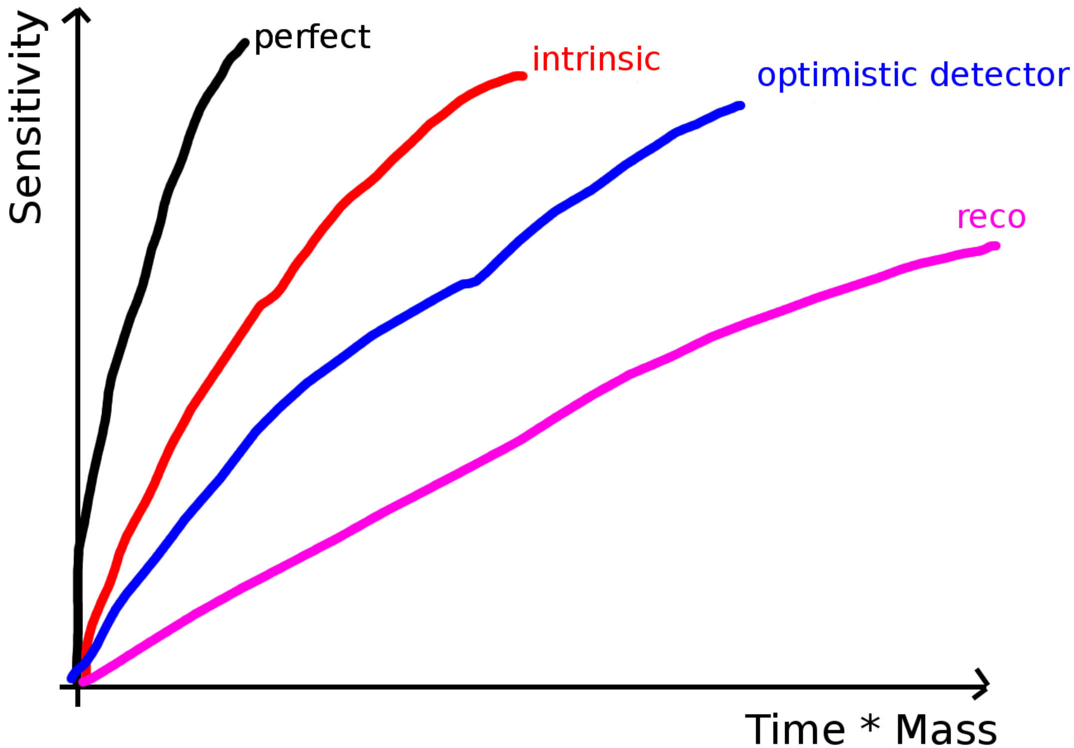
Incorporation into sensitivity plots:

- Current situation:



Incorporation into sensitivity plots:

- Sketch of the future:



Summary of status

- Physics is random – and this is important!
    - Affects energy and directional reconstruction
    - Effects estimated for muon tracks and showers
- Best-case ORCA reference detector estimated
    - Event reconstruction will be limited by detected photon information
- Next steps:
    - Do this for electromagnetic cascades (Nu_e CC)
    - Obtain fits for muon track events
    - Produce sensitivity estimates