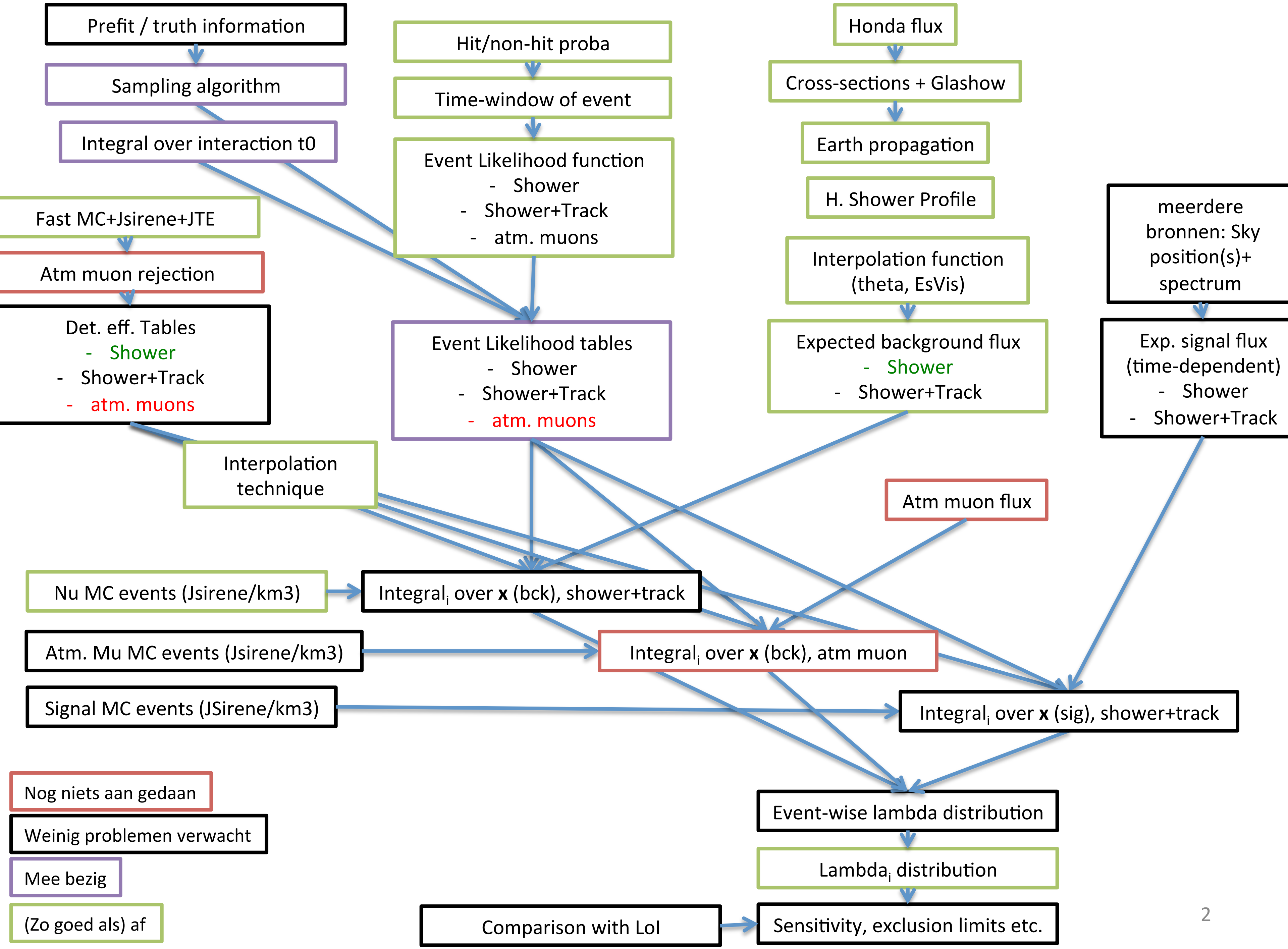
Neutrino Source Searches with Likelihood Landscapes



Prefit / truth information
Sampling algorithm
Integral over interaction t0
Hit/non-hit proba
Time-window of event
Event Likelihood function
- Shower
- Shower+Track
- atm. muons
Honda flux
Cross-sections + Glashow
Earth propagation
H. Shower Profile
Interpolation function (theta, EsVis)
meerdere bronnen: Sky position(s)+ spectrum
Fast MC+Jsirene+JTE
Atm muon rejection
Det. eff. Tables
- Shower
- Shower+Track
- atm. muons
Event Likelihood tables
- Shower
- Shower+Track
- atm. muons
Expected background flux
- Shower
- Shower+Track
Exp. signal flux (time-dependent)
- Shower
- Shower+Track
Interpolation technique
Atm muon flux
Nu MC events (Jsirene/km3)
Integral$_i$ over **x** (bck), shower+track
Atm. Mu MC events (Jsirene/km3)
Integral$_i$ over **x** (bck), atm muon
Signal MC events (JSirene/km3)
Integral$_i$ over **x** (sig), shower+track
Nog niets aan gedaan
Weinig problemen verwacht
Mee bezig
(Zo goed als) af
Event-wise lambda distribution
Lambda$_i$ distribution
Comparison with LoI
Sensitivity, exclusion limits etc.

Neutrino Source Searches

- Hypothesis H0: background only flux
  - Atmospheric neutrino's
  - (Misreconstructed) Atmospheric Muons
- Hypothesis H1: background + signal flux
  - (High energy) Cosmic Neutrinos

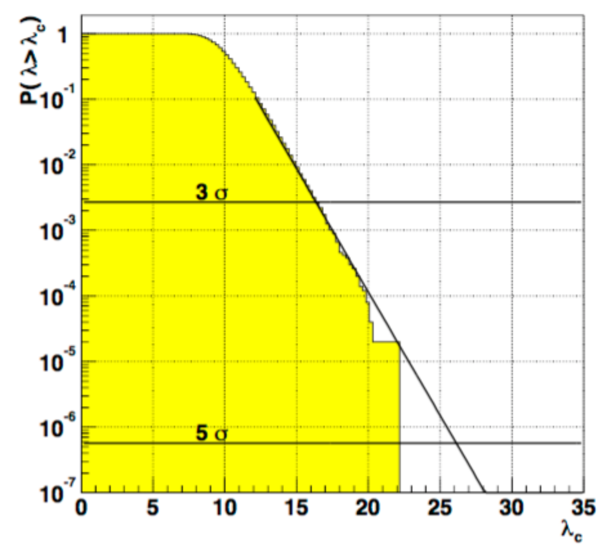
General Procedure

- How compatible is data with H0 or H1?

$$\lambda = \log \left[\frac{P(\mathrm{data}|H_1)}{P(\mathrm{data}|H_0)} \right]$$

- When to claim an observation?
  - Accept H1 if $\lambda > \lambda_c$
  - λ_c such that

    P(accept H1 | H0 = true) < 0.00…1

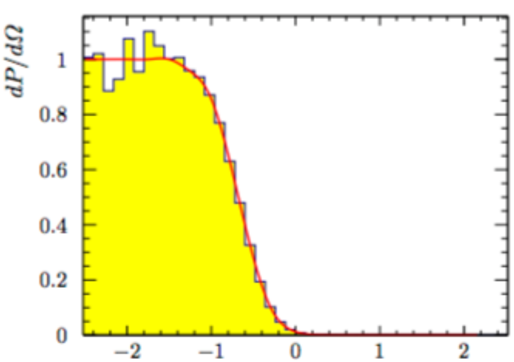


$$\lambda = \log\left[\frac{P(\mathrm{data}|H_1)}{P(\mathrm{data}|H_0)}\right]$$

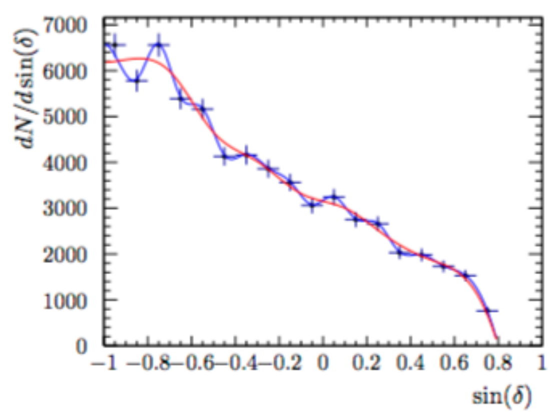
Test Statistic (Conventional)

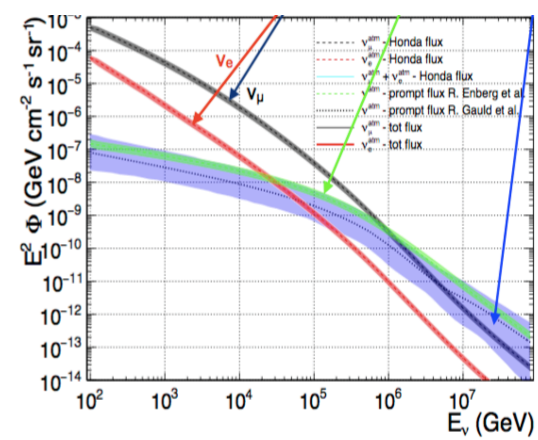
- Given detected (and selected) events $\{ev_i\}$

$$P(data|H) = \sum_i \left[\log \int \underbrace{P(x_{reco,i}|\, x_{true})}_{\text{Reconstruction}} \cdot \underbrace{P^{det}(x_{true})}_{\text{Detection efficiency}} \cdot \underbrace{\mu(x_{true} \mid H)}_{\text{Expected flux}}\, dx_{true}\right] - \mu^{tot}(H)$$



log(angle reco,true)





$$\lambda = \log\left[\frac{P(\text{data}|H_1)}{P(\text{data}|H_0)}\right]$$

Test Statistic

- Given detected (and selected) events $\{ev_i\}$

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- New method:

$$P(data|H) = \sum_i \left[\log \int P(ev_i|\, x_{true}) \cdot P^{det}(x_{true}) \cdot \mu(x_{true}\,|\,H)\, dx_{true}\right] - \mu^{tot}(H)$$

- No big deal?

New vs. Conventional

Conventional

- Only best solution kept from reconstruction
- Selection criteria needed to select well-reconstructed events -> events are lost

- Different reconstruction algorithms (showers/tracks/tau double bang) patched together
- Event identification by BDT's and other black magic algorithms

- Parameterizations of MC events
- Fast

New Method

- Detailed knowledge of event likelihood landscape
- All events can be used

- Single 'reconstruction' algorithm for all events

- Neutrino flavour identification automatically taken into account

- Event-by-event
- Probably slow

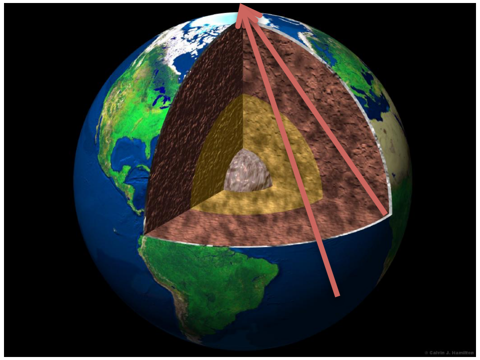
Likelihood Ingredients

$$P(data|H) = \sum_i \left[\log \int P(ev_i|\, x_{true}) \cdot P^{det}(x_{true}) \cdot \mu(x_{true}\;|\,H)\; dx_{true}\right] - \mu^{tot}(H)$$

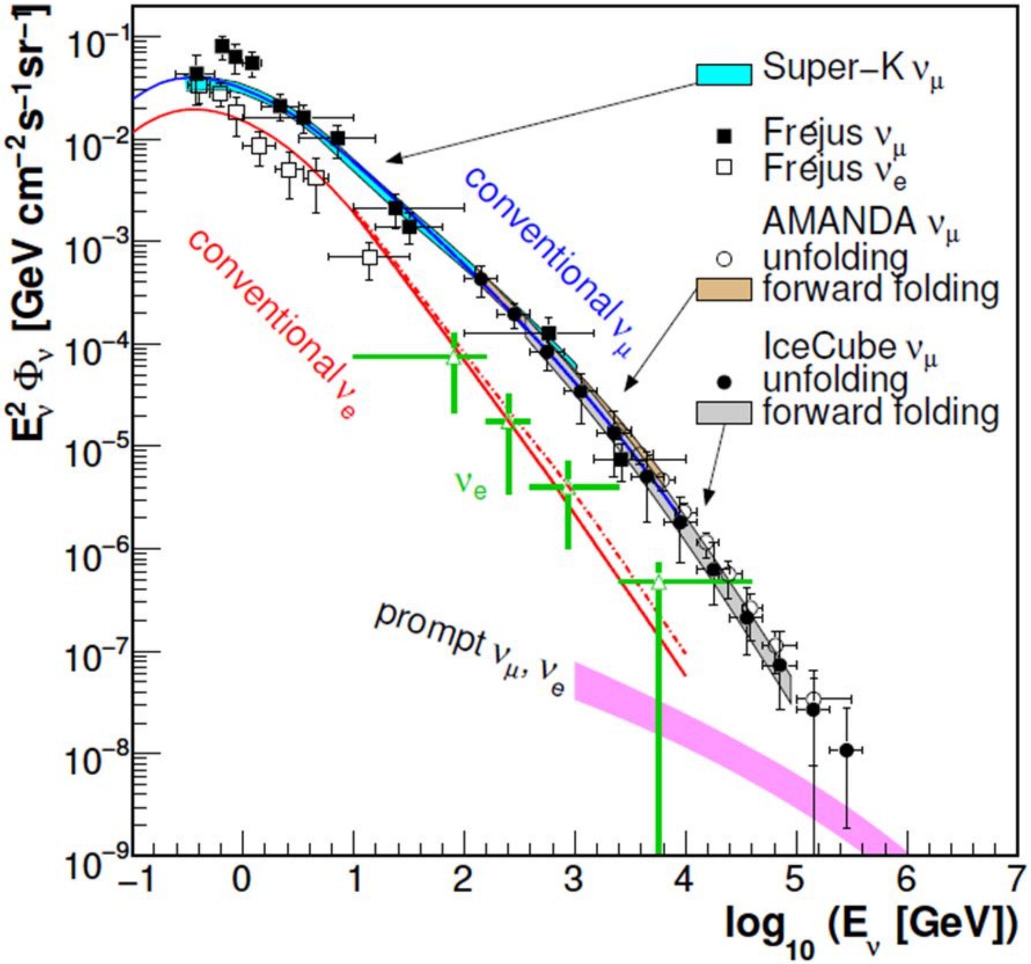
$\mu(x_{true}\;|\,H)$ Number of expected background or signal events in our detector (can)

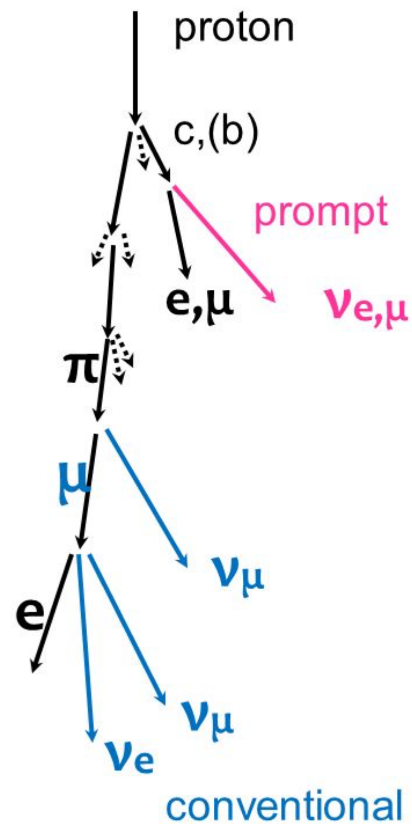
$P^{det}(x_{true})$

$P(ev_i|\, x_{true})$



Atmospheric Neutrinos

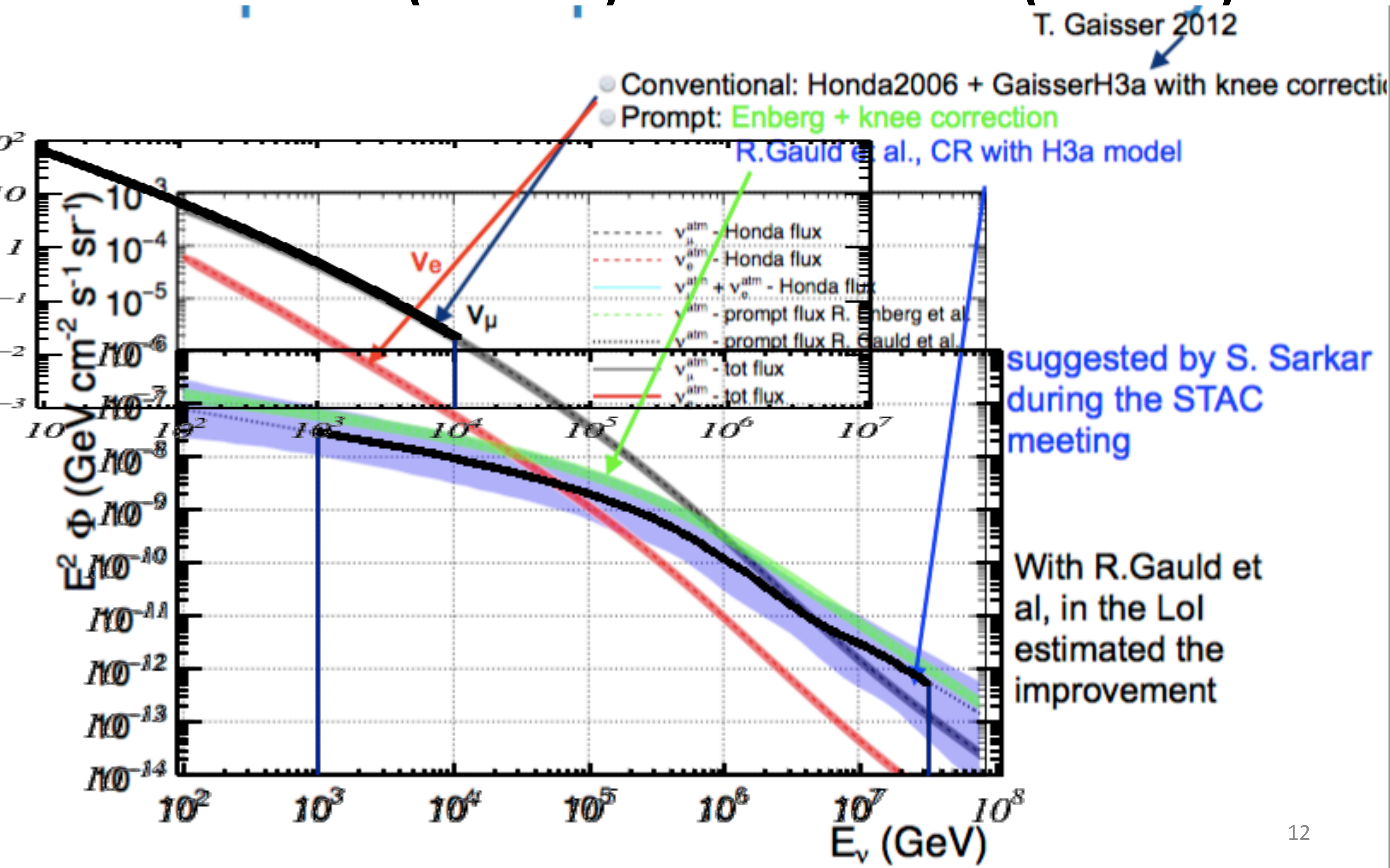




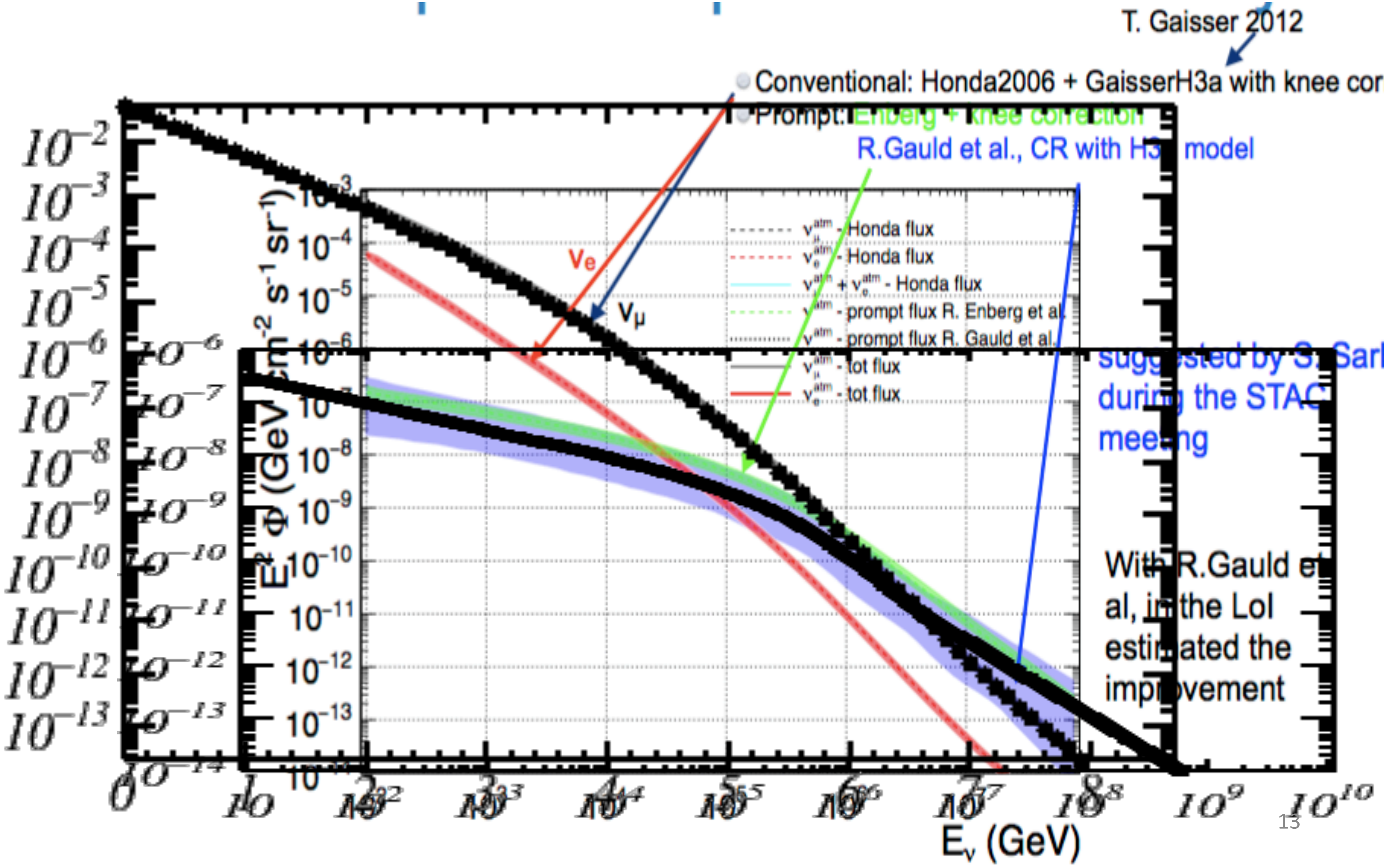
Current Parameterization

- KM3NeT Letter of Intent
- Based on Seatray
- Polynomial fit of Honda tables
  - Extrapolation to higher energy ranges
  - Outdated? Honda 2006 used.
  - Gaisser H3a knee correction
- Polynomial fit of Gauld tables 2015
  - From PromptNuFlux, L. Rottoli

Honda (2006) and Gauld (2016)



Both Extrapolated (2)

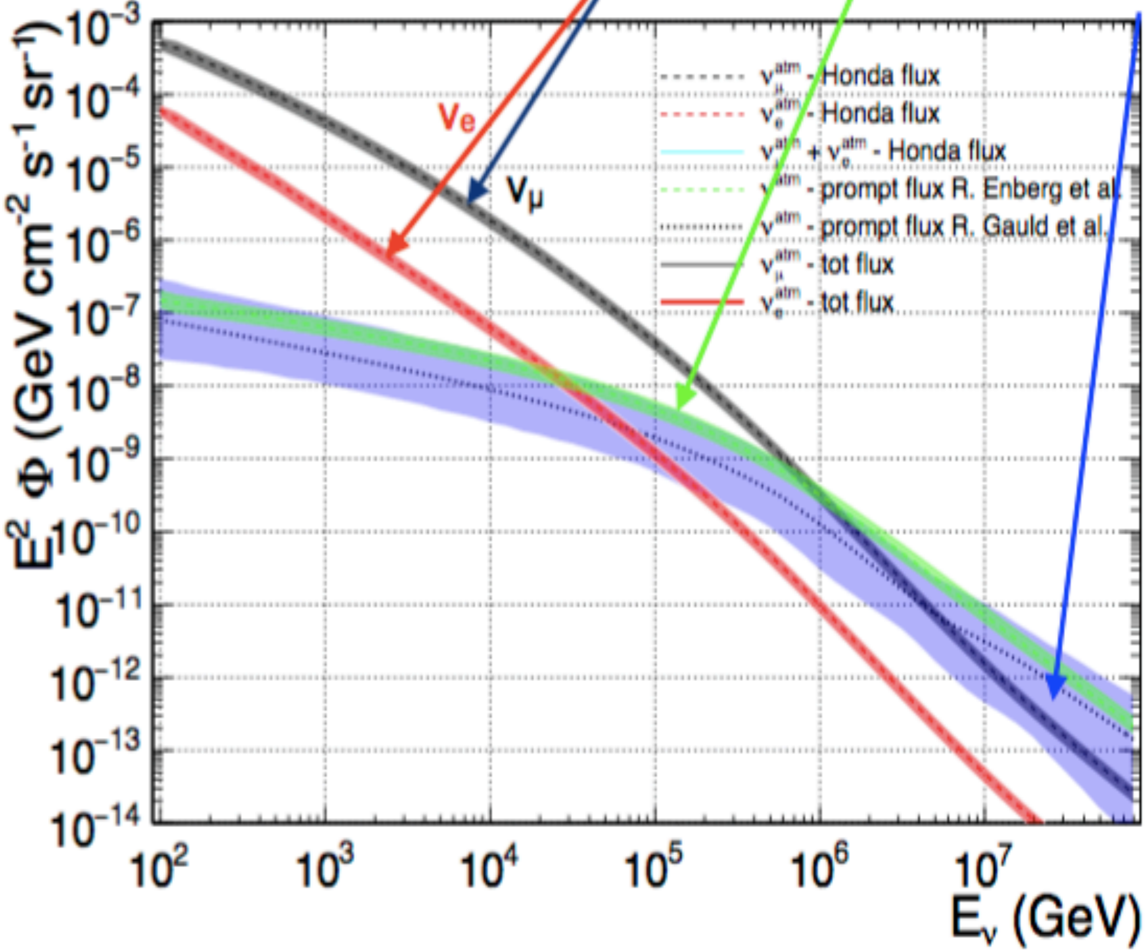


Both Extrapolated (2)

T. Gaisser 2012

- Conventional: Honda2006 + GaisserH3a with knee cor
- Prompt: Enberg + knee correction

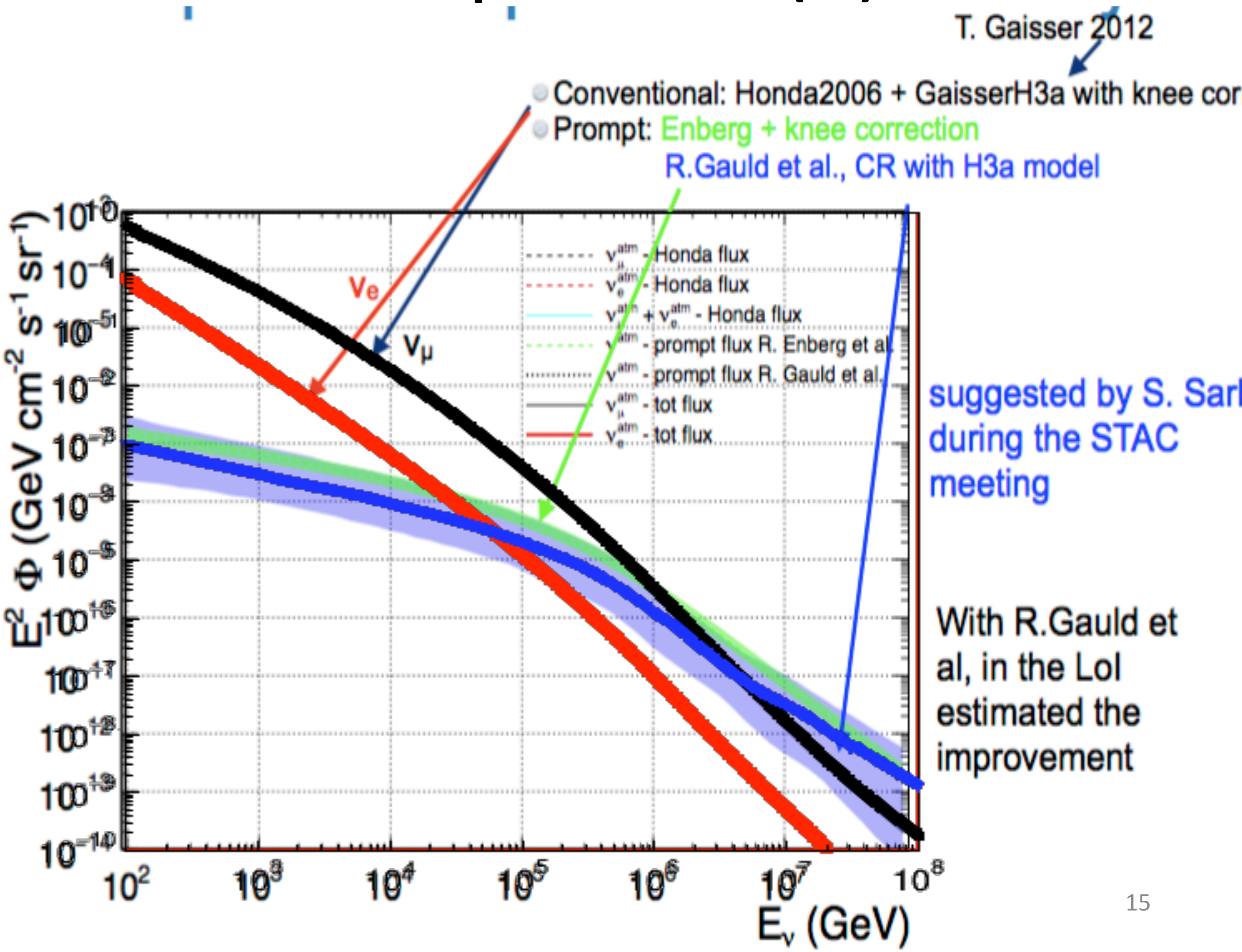
R.Gauld et al., CR with H3a model



suggested by S. Sarl during the STAC meeting

With R.Gauld et al, in the LoI estimated the improvement

Both Extrapolated (2)

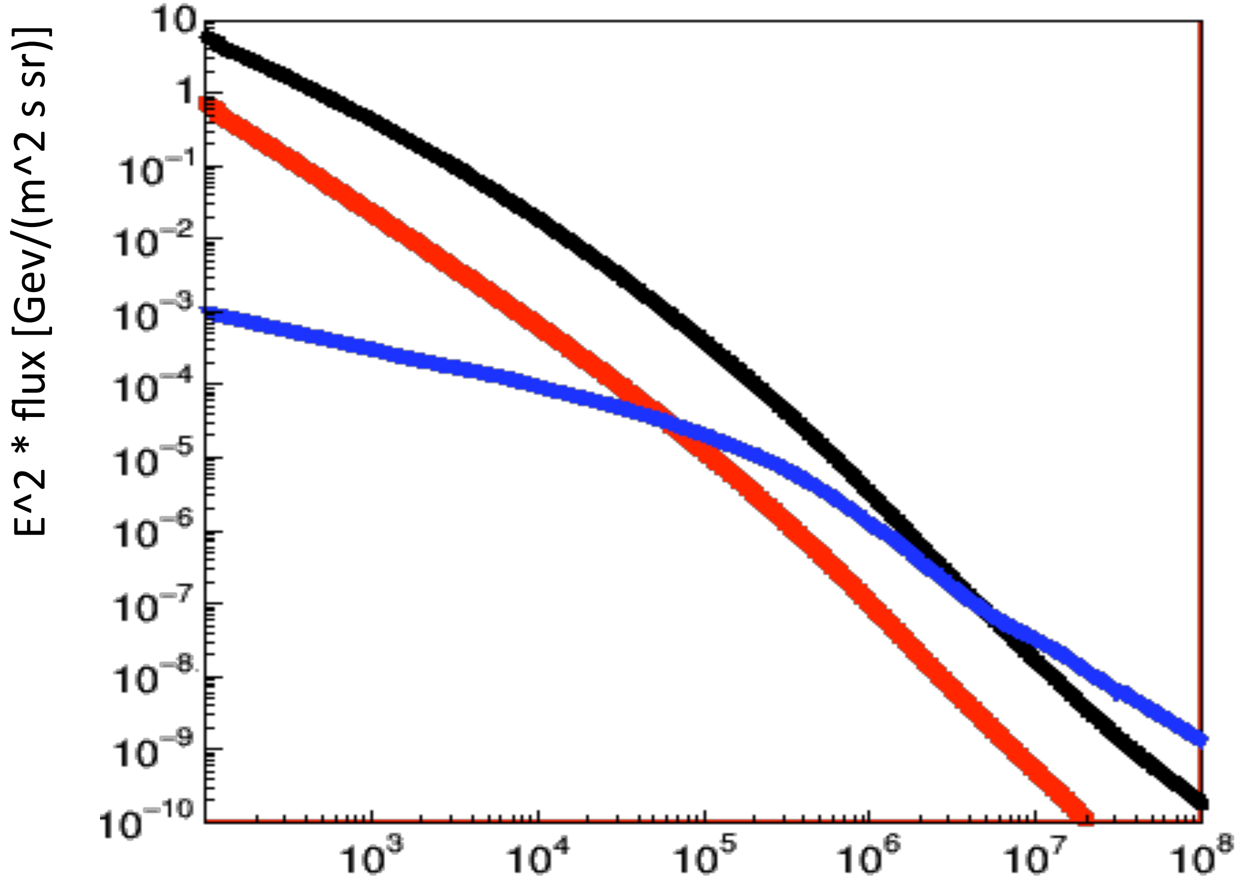


Both Extrapolated (2)

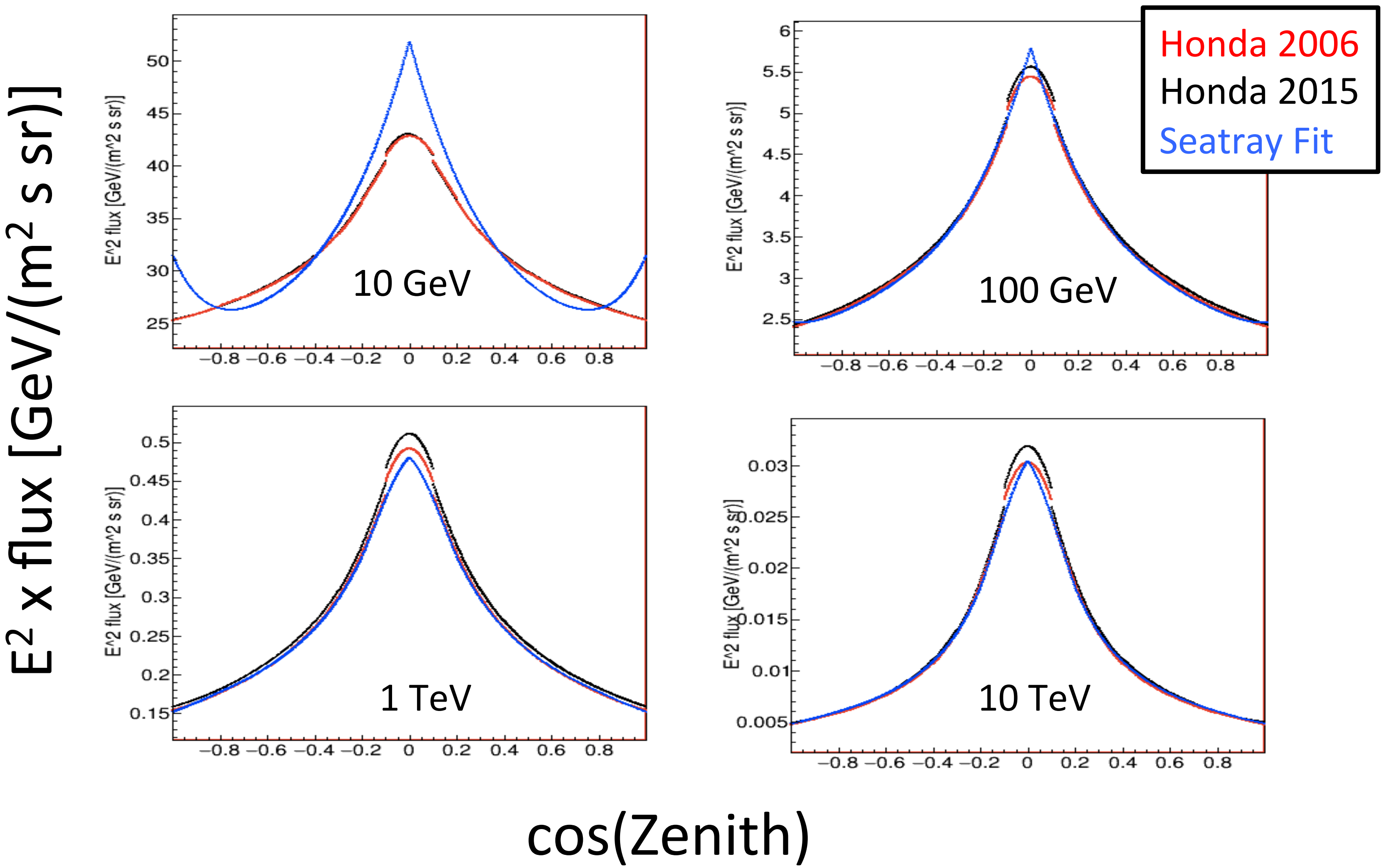
NuMu + AnuMu (Honda 2006) + gaisser H3A

NuE + AnuE (Honda 2006) + gaisser H3A

Prompt flux (indep. of flavor), Gauld, includes H3A



Honda: Zenith Dependence



Likelihood Ingredients

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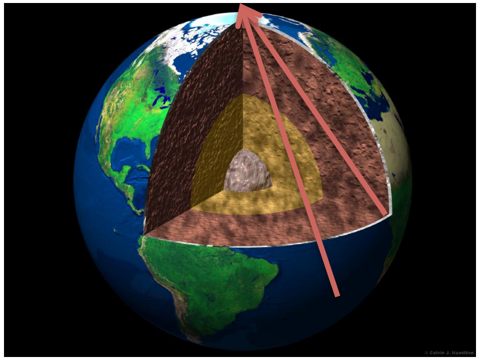
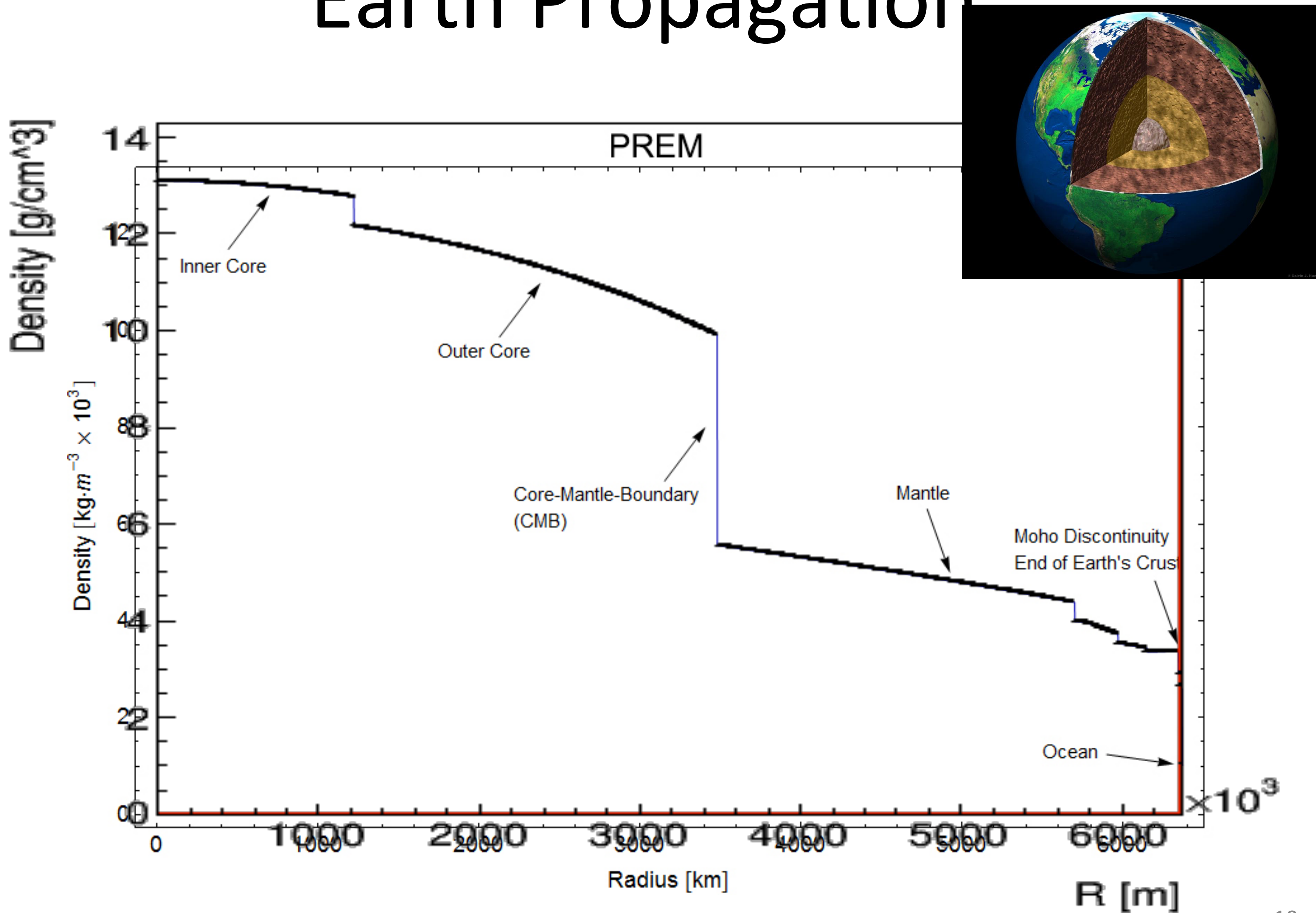
$\mu(x_{true}\,|\,H)$ Number of expected background or signal events in our detector (can)

$P^{det}(x_{true})$

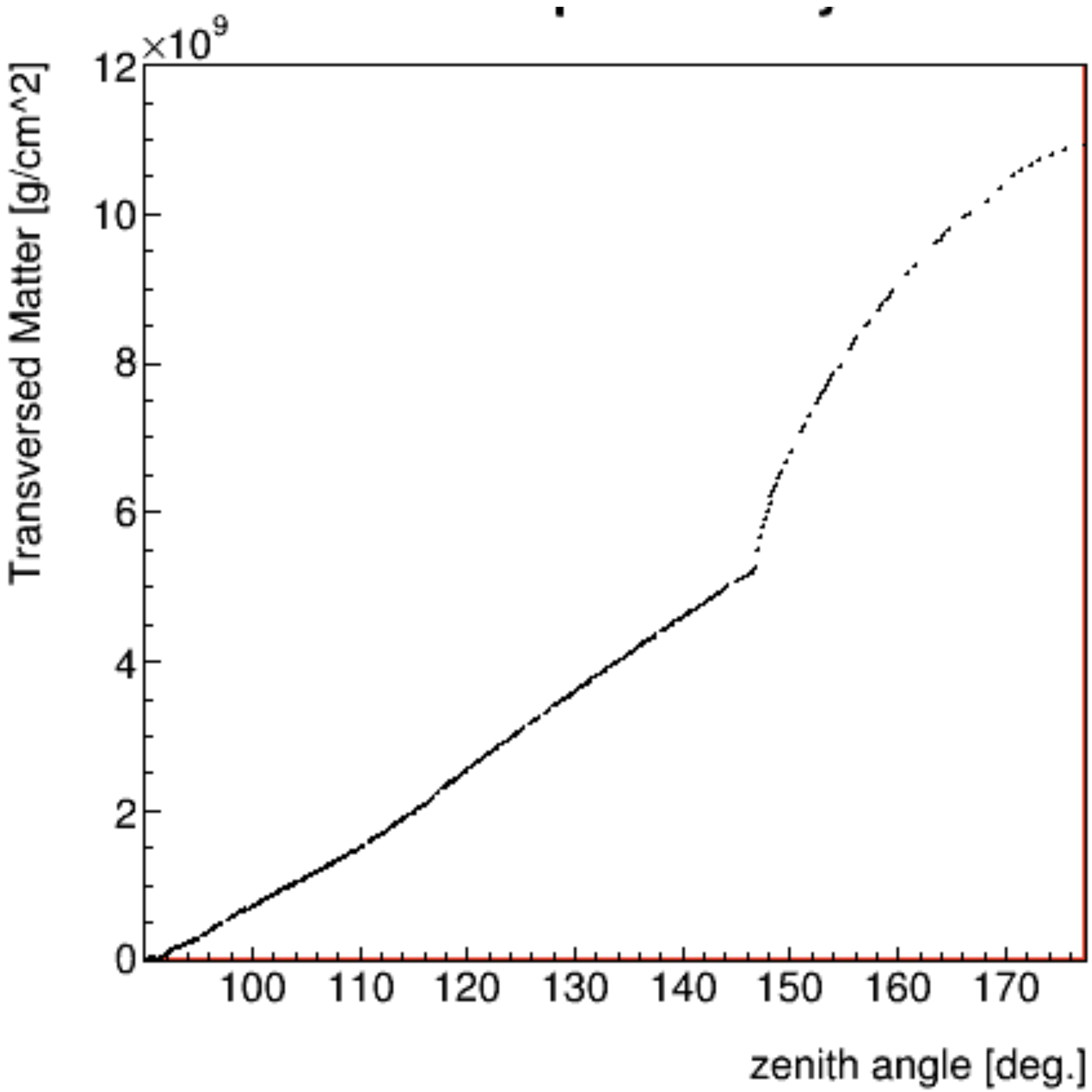
$P(ev_i|\, x_{true})$

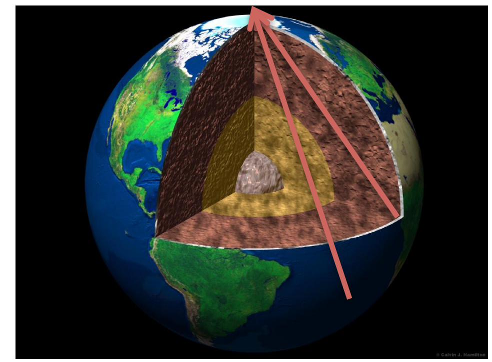


Earth Propagation



Transversed Matter Density

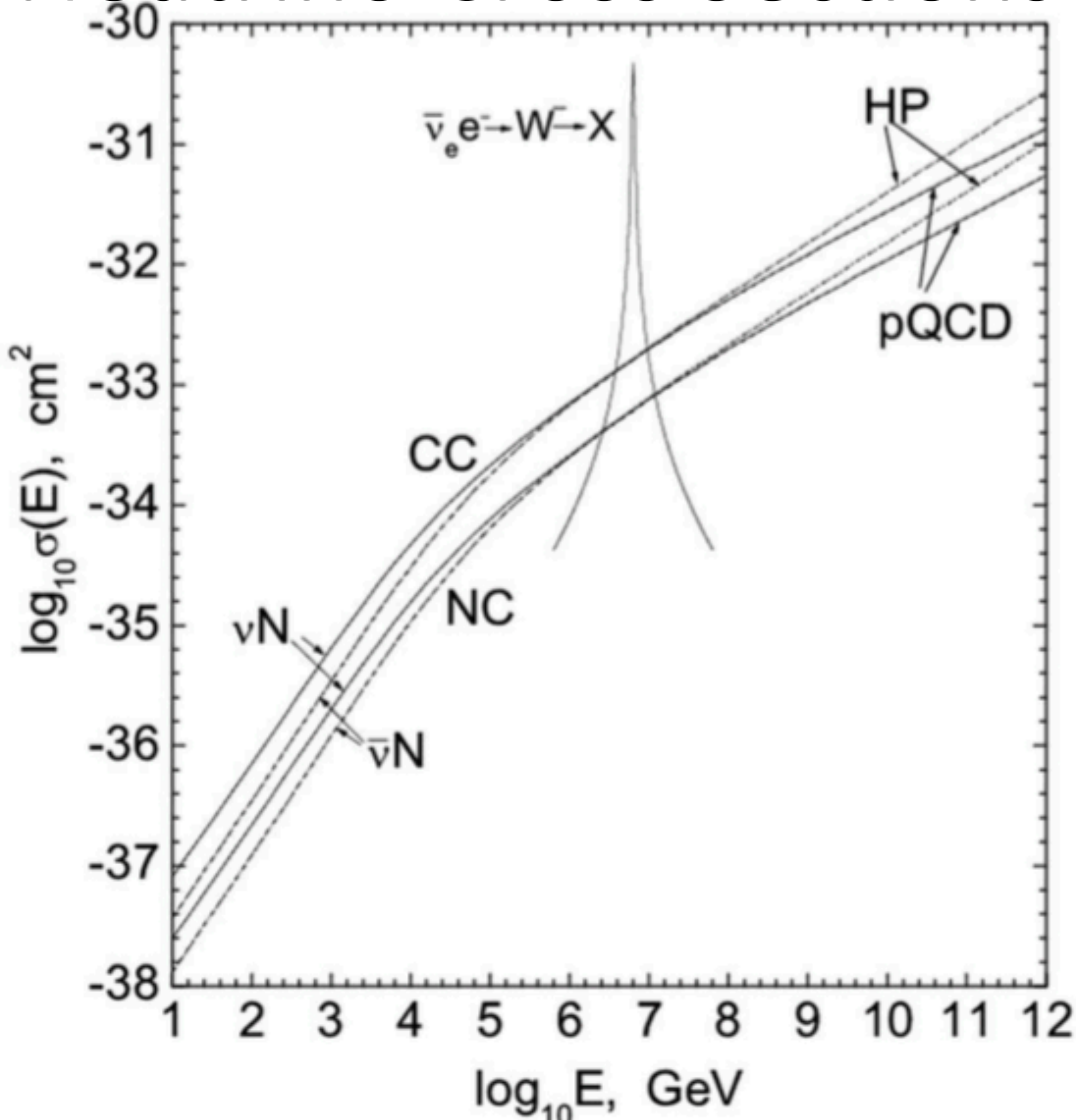




Analytically derived -> very fast

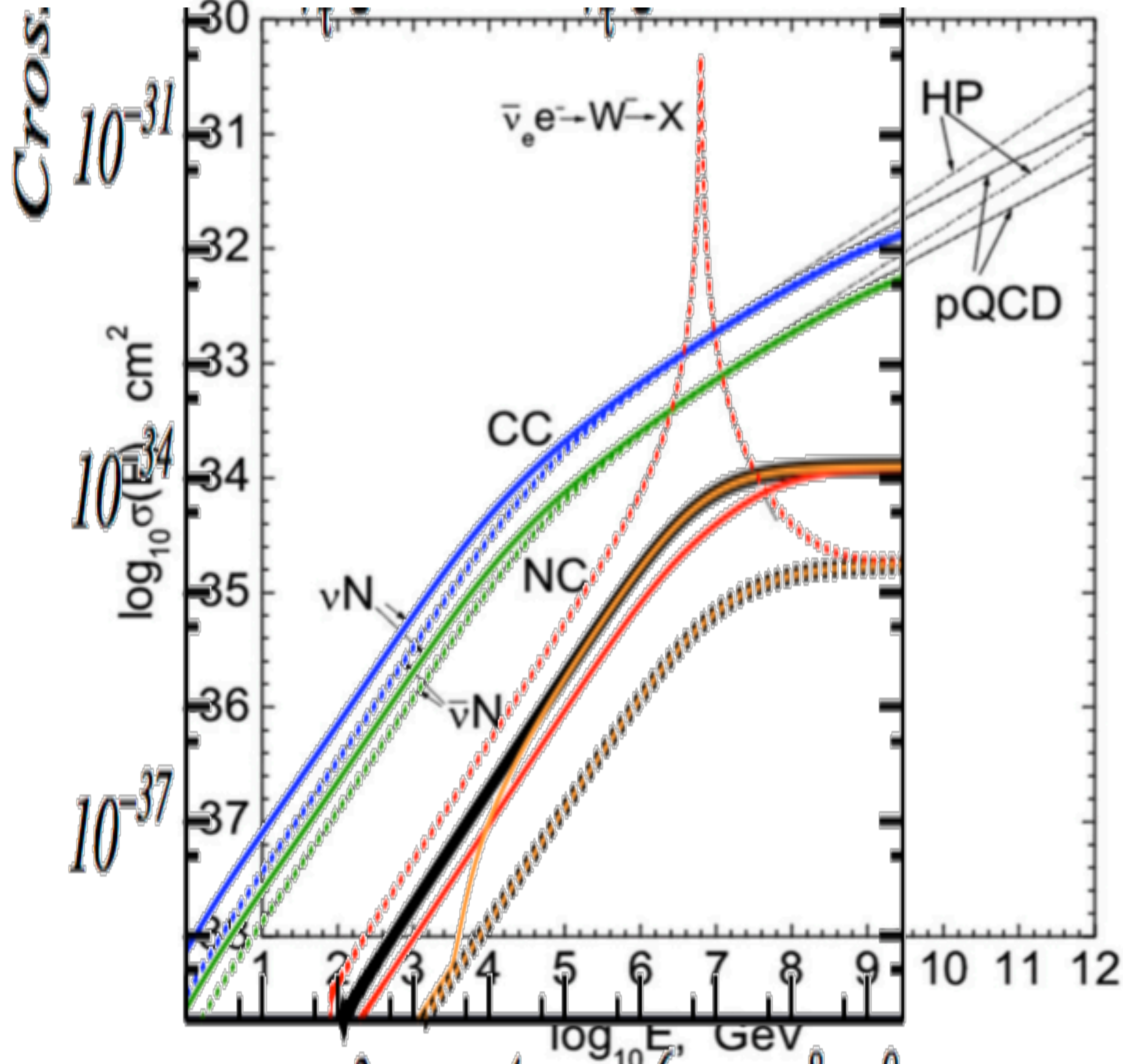
ANIS, Kowalski 2003
Figure from Colnard 2009

Neutrino Cross Sections

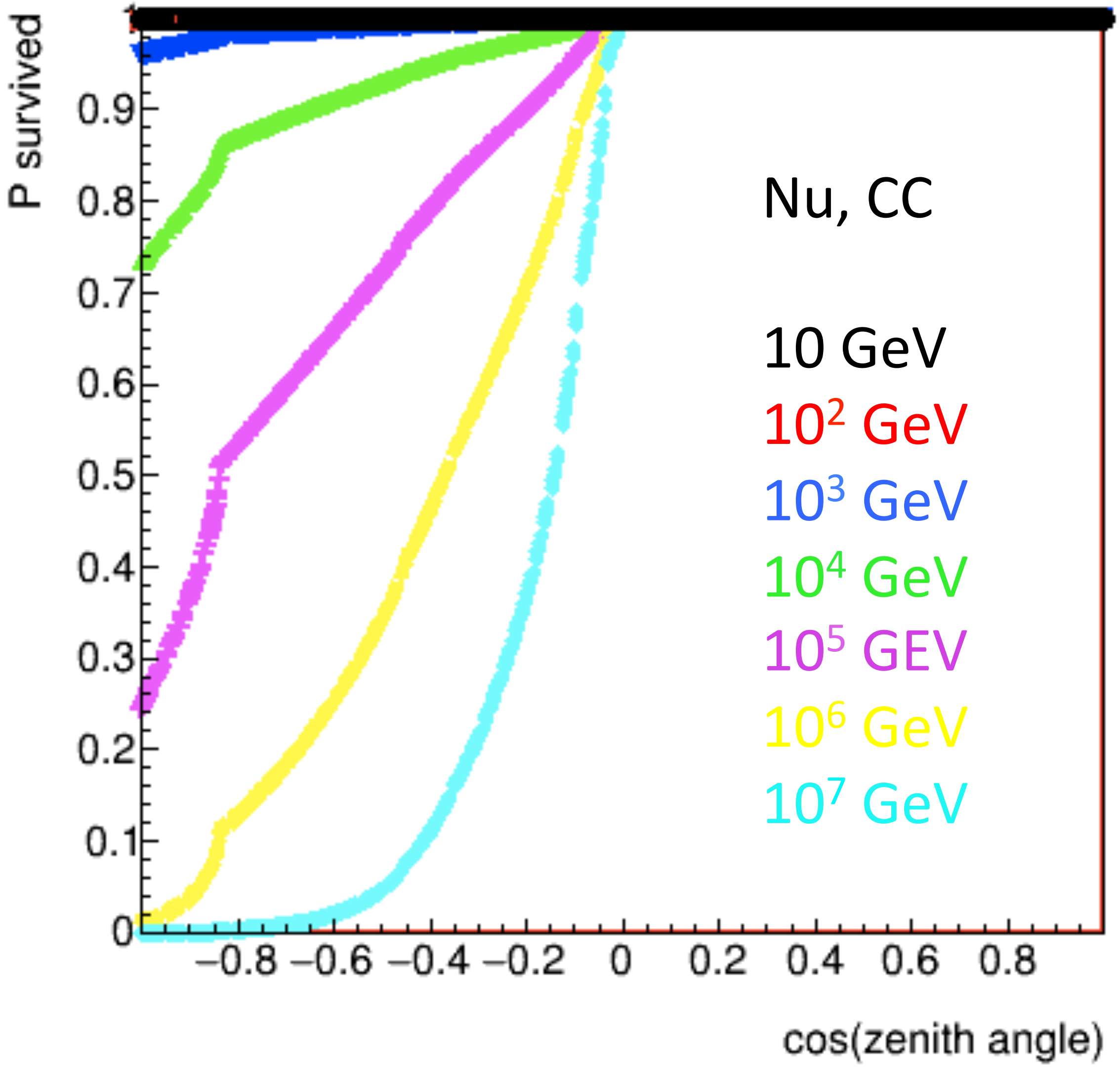


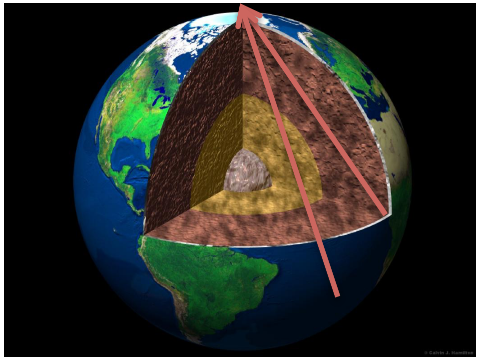
ANIS, Kowalski 2003
Figure from Colnard 2009

Neutrino Cross Sections

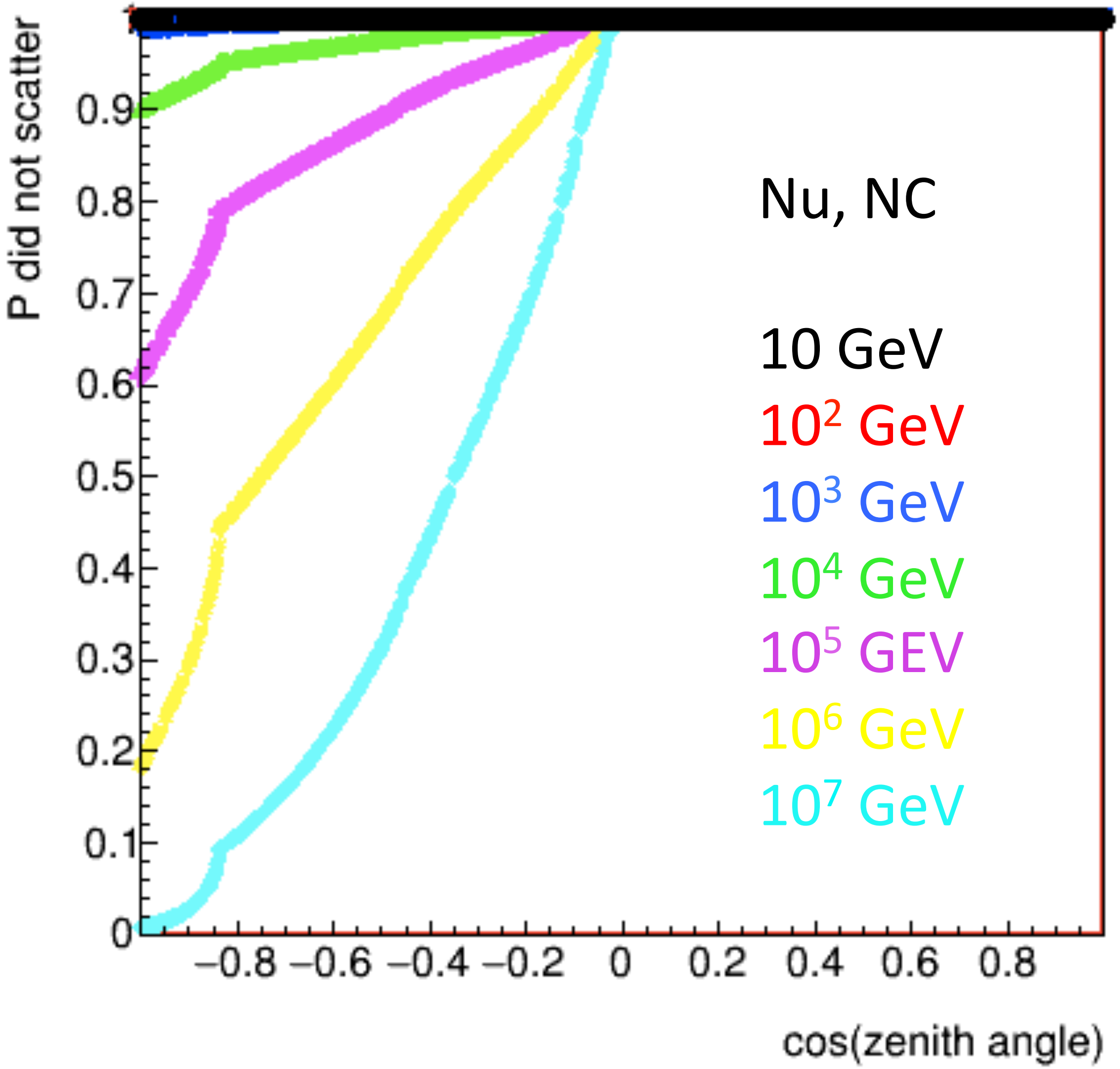


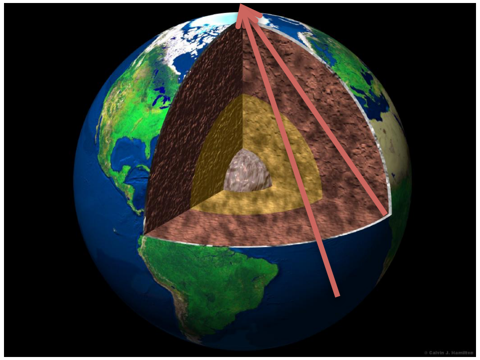
Neutrino Absorption



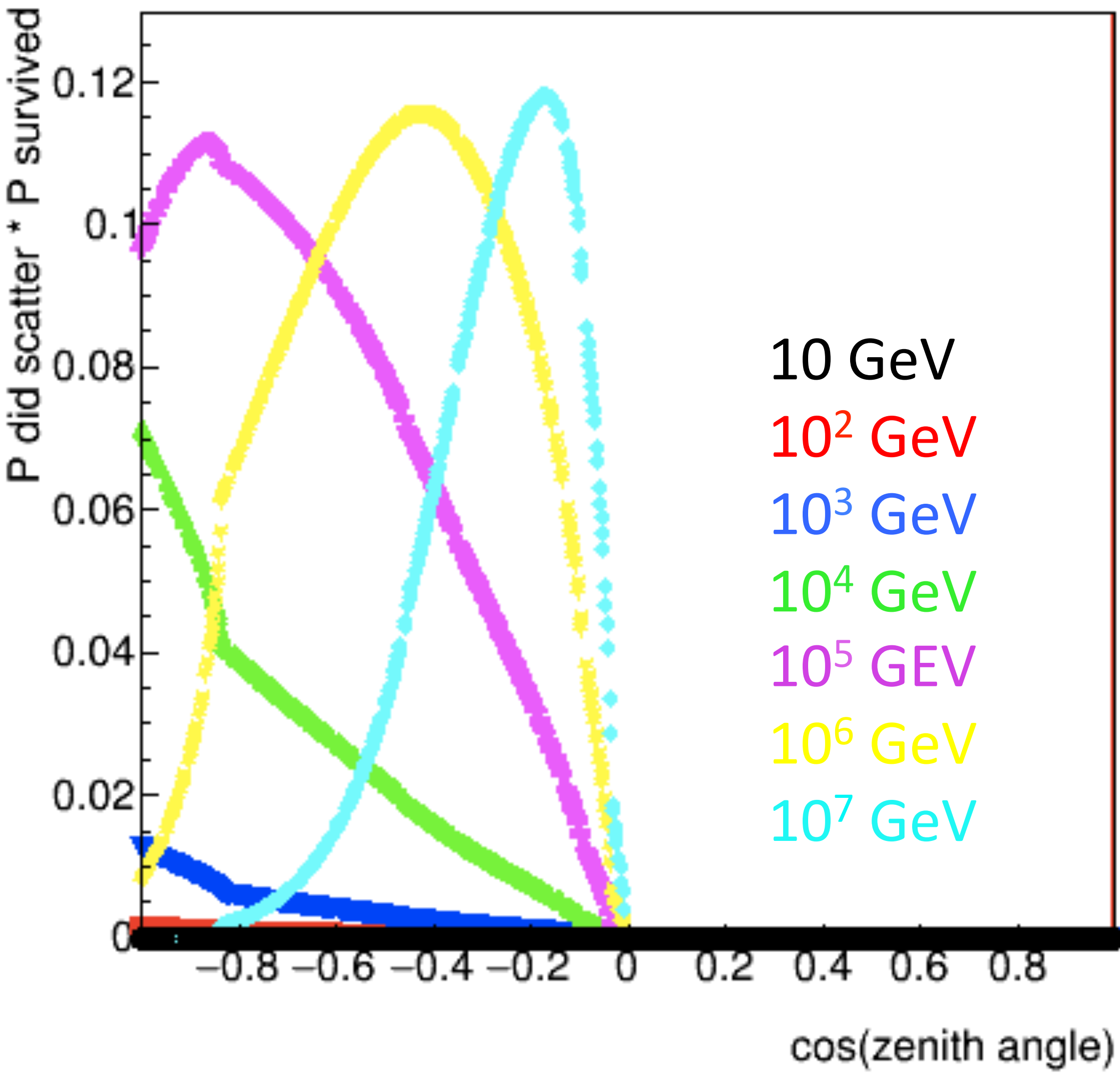


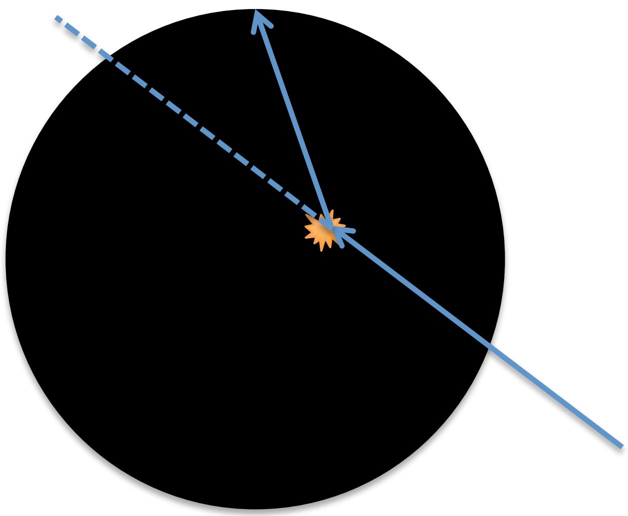
Neutrino NC Scattering (1)



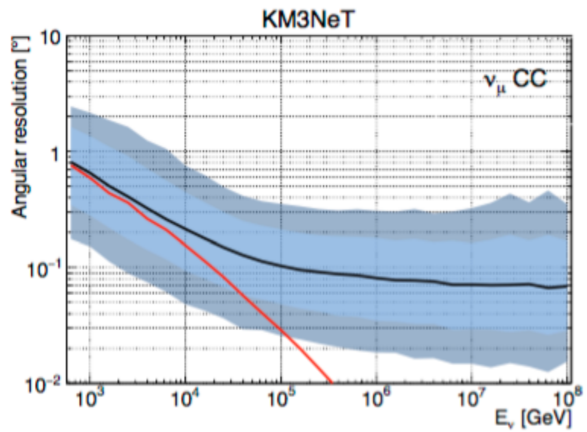


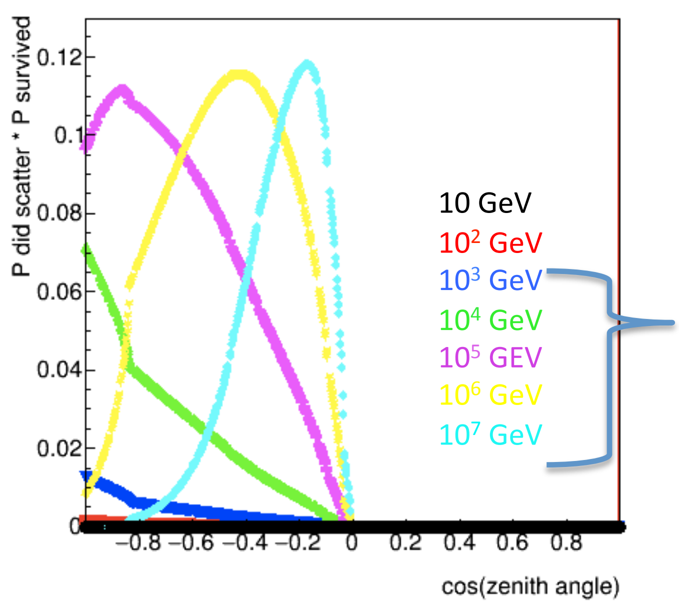
Neutrino NC Scattering (2)

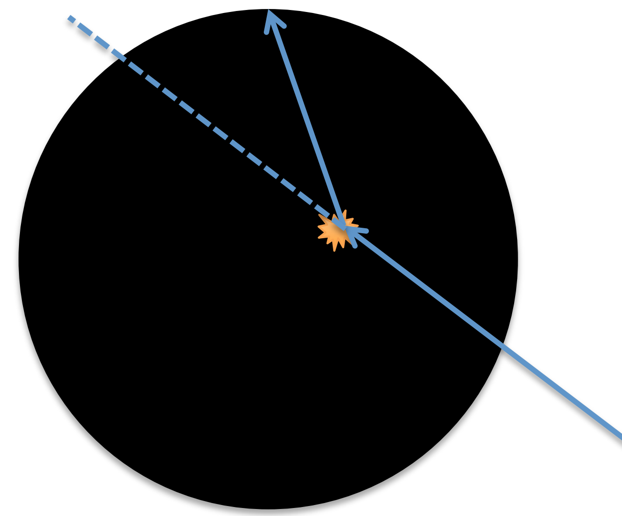




Neutrino NC Scattering (3)







- Change in direction: <≈ 0.6 degrees for Enu > 10^3 GeV
- Change in Energy???

Effects on expected atm. Neutrino flux neglected

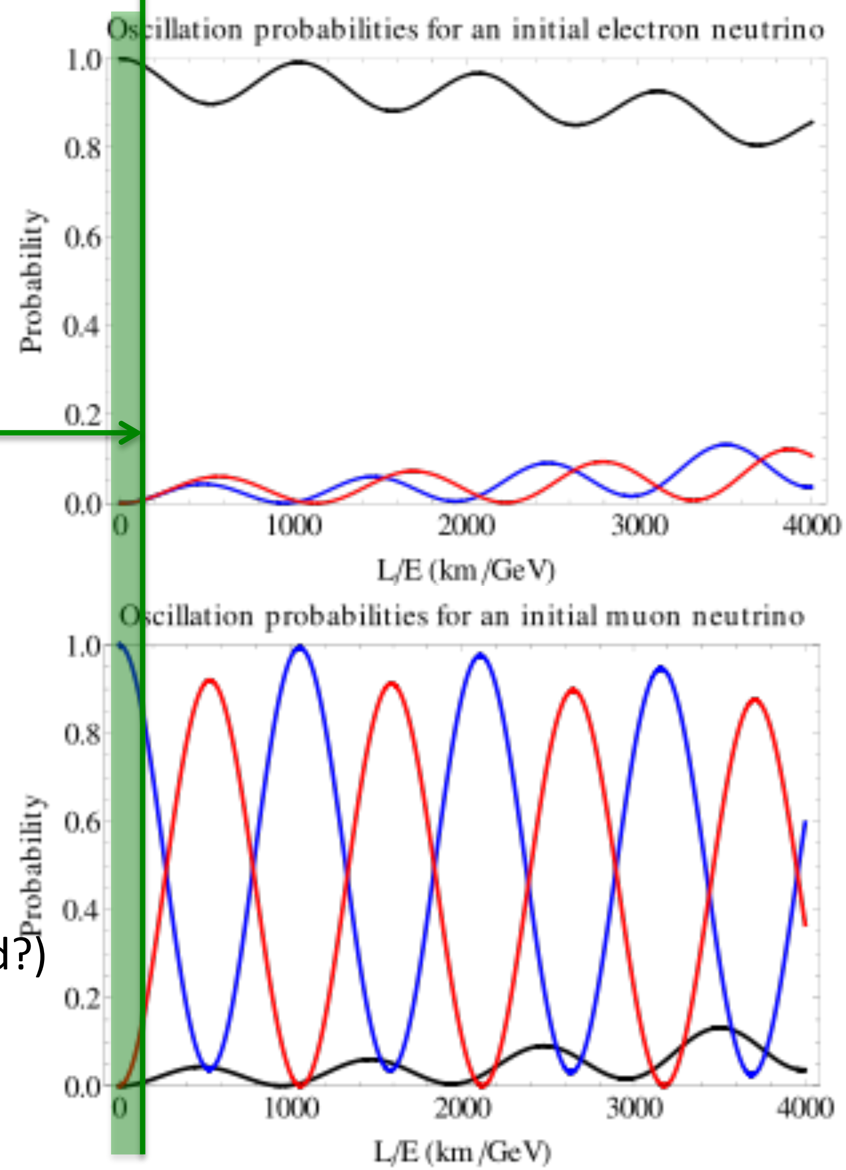
Neutrino Oscillations

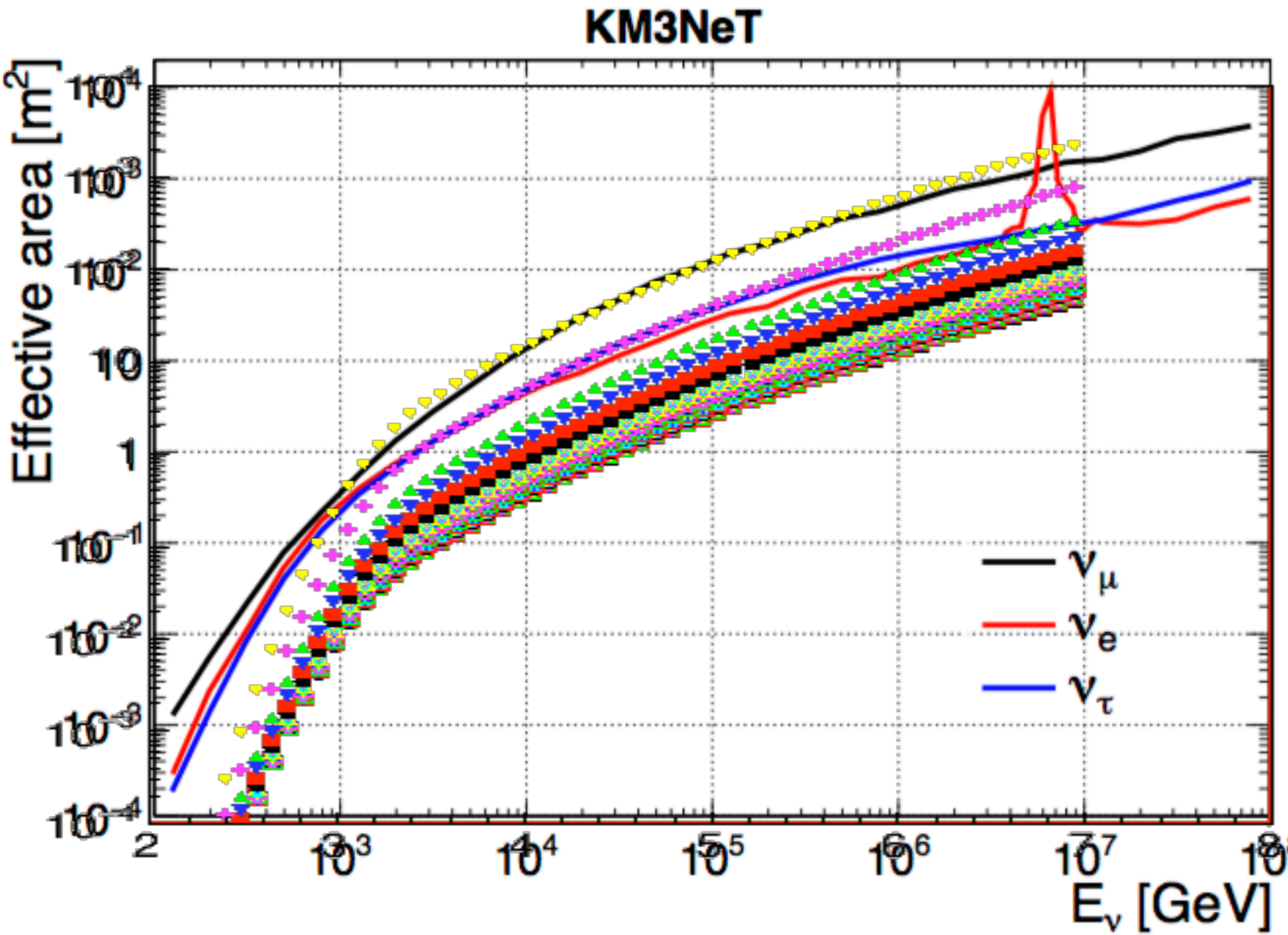
Earth radius=6.4 * 10^3 km
100 GeV neutrino

L/E = 1.28 * 10^2 km/GeV

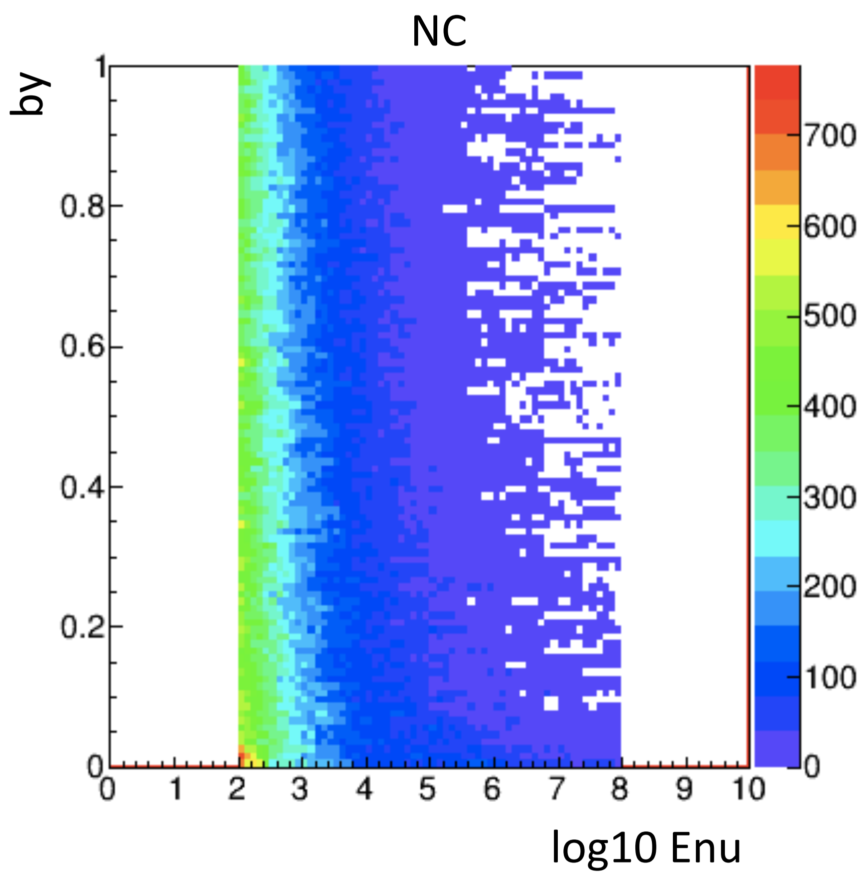
Earth covers one oscillation period
P(oscilate) up to:
~0.01 (electron -> muon/tau)
~0.2 (muon -> tau)
~0.2 (tau -> muon)

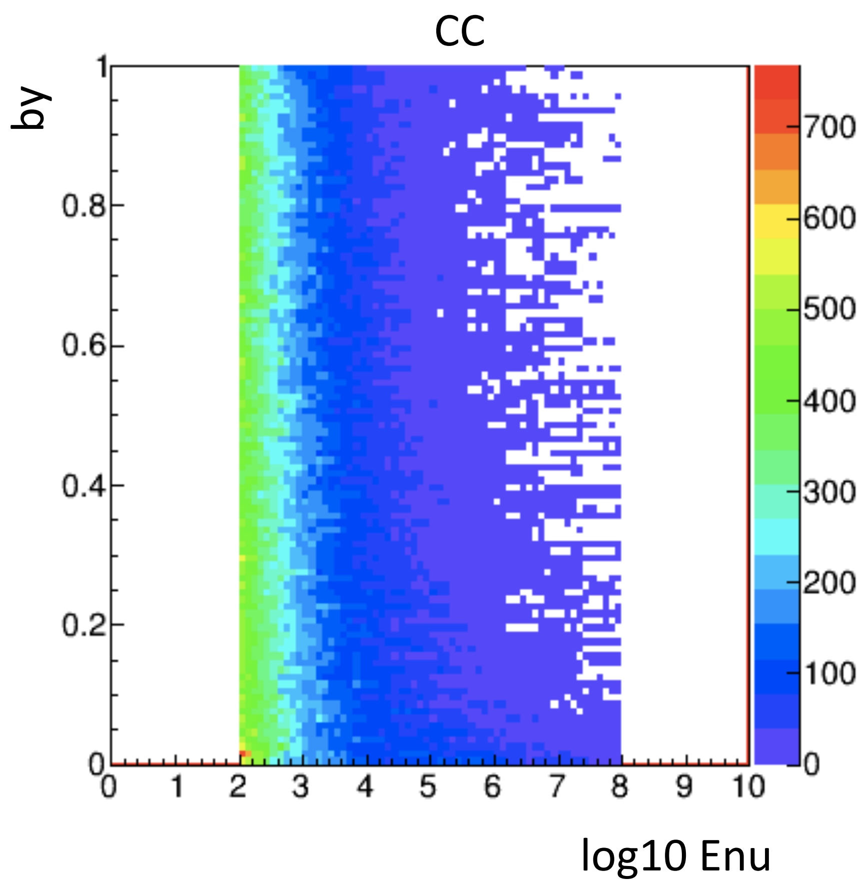
For now: Ignore…. (to be continued?)



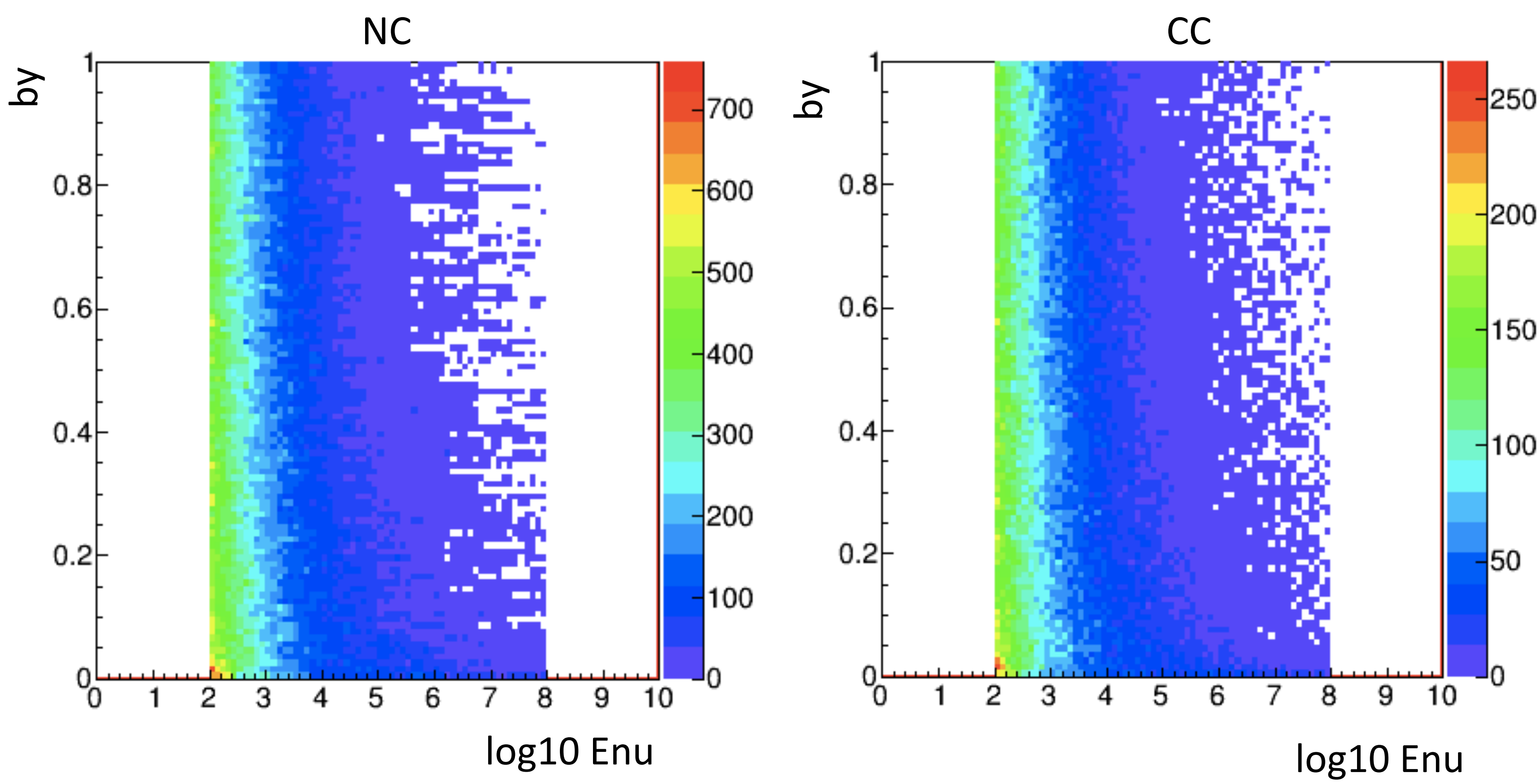

KM3NeT
Effective area [m²]
E_ν [GeV]
ν_μ
ν_e
ν_τ

Bjorken-y: electron neutrino's



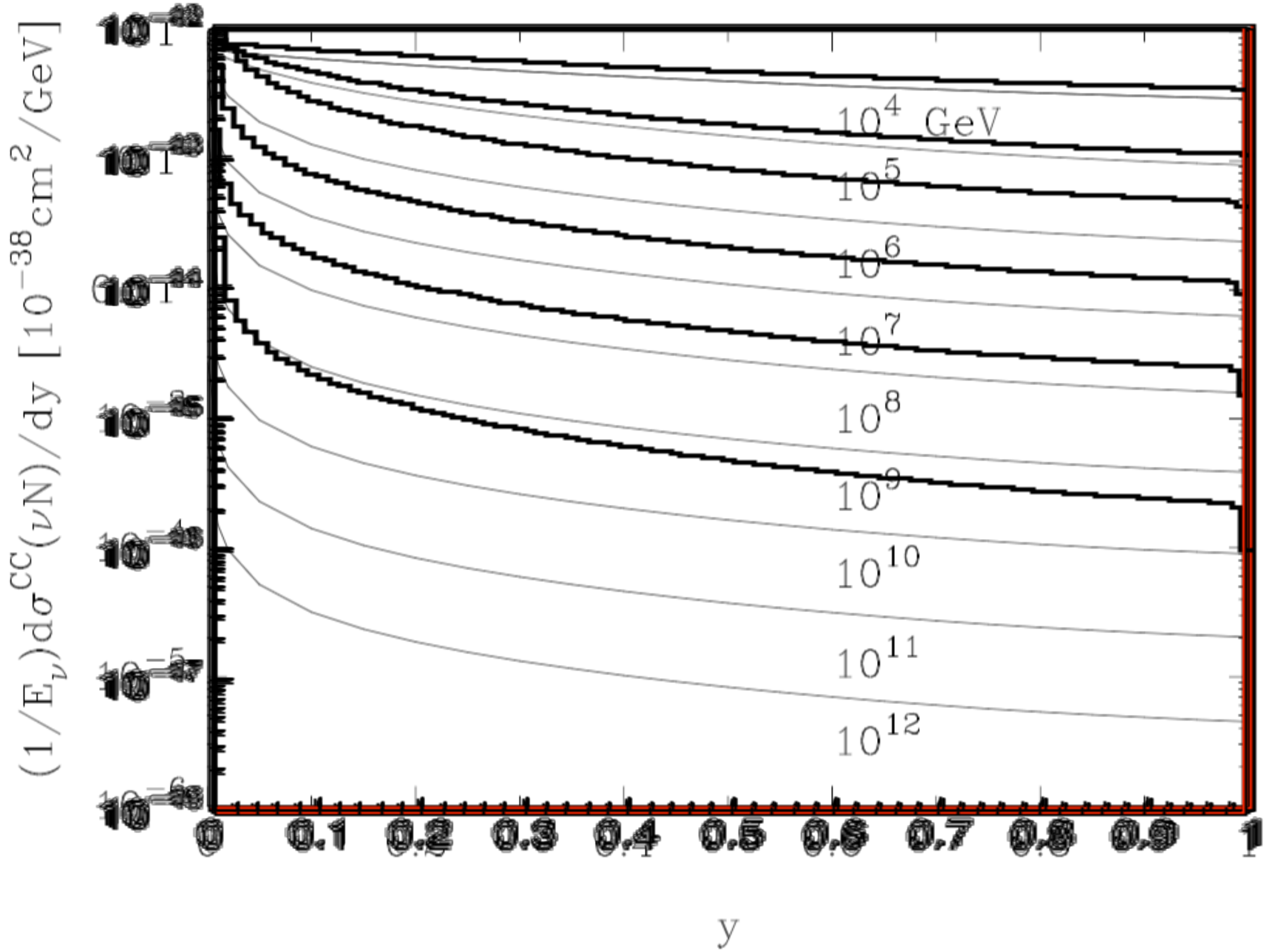


Bjorken-y: muonneutrino's



Gandhi, Quigg
UHE Nu Interactions

Bjorken-y comparison



Gandhi, Quigg
UHE Nu Interactions

Bjorken-y comparison

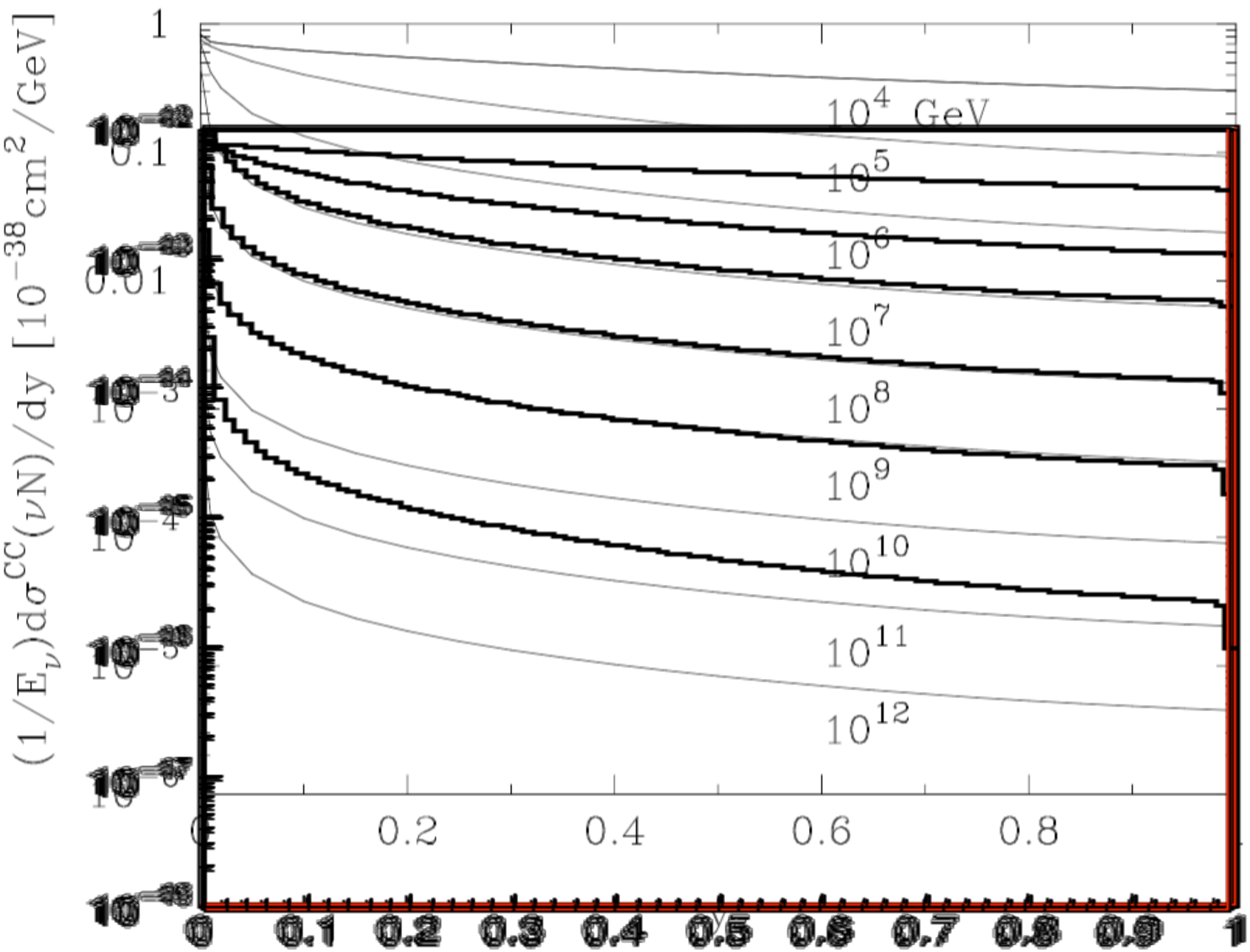
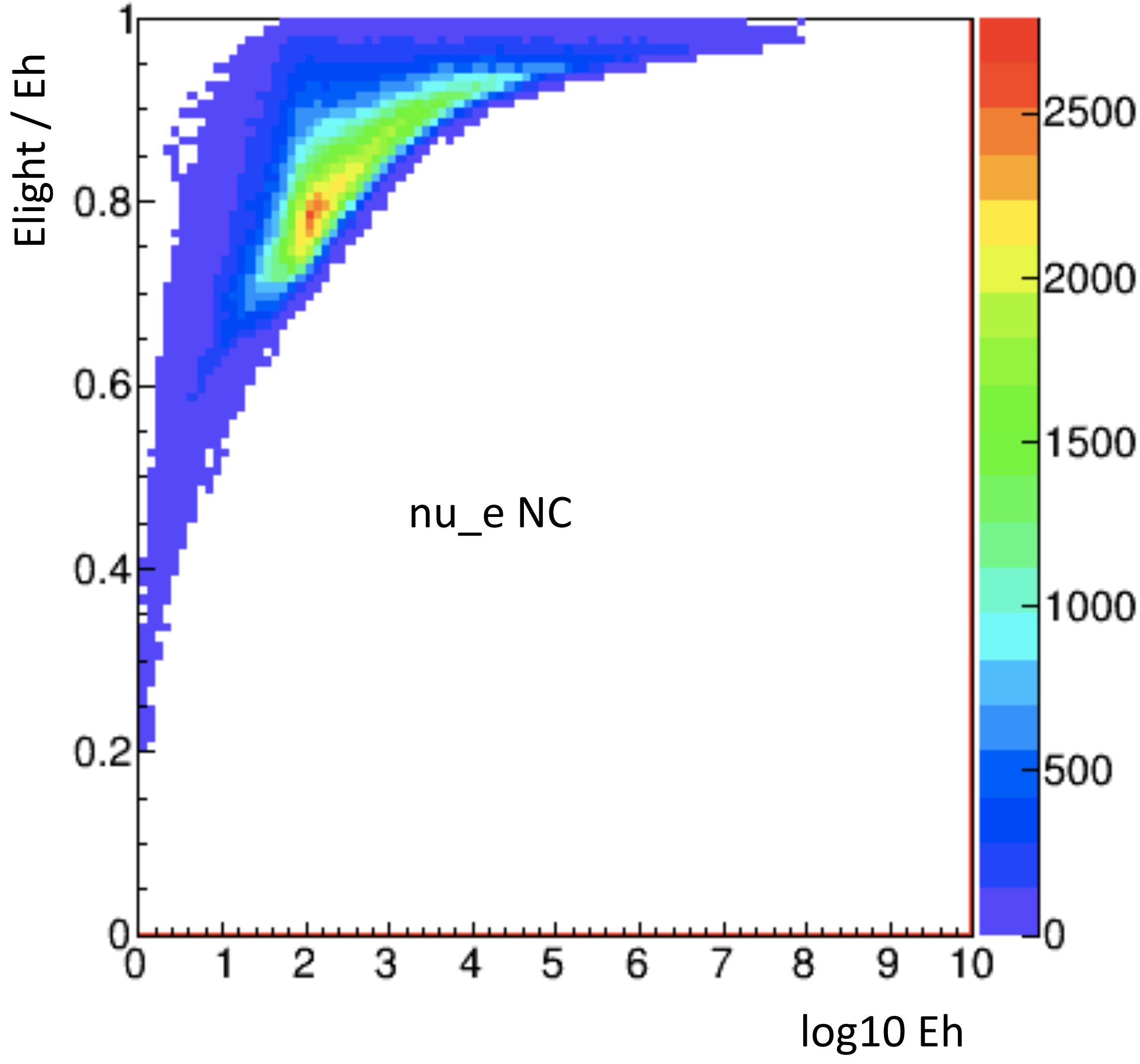


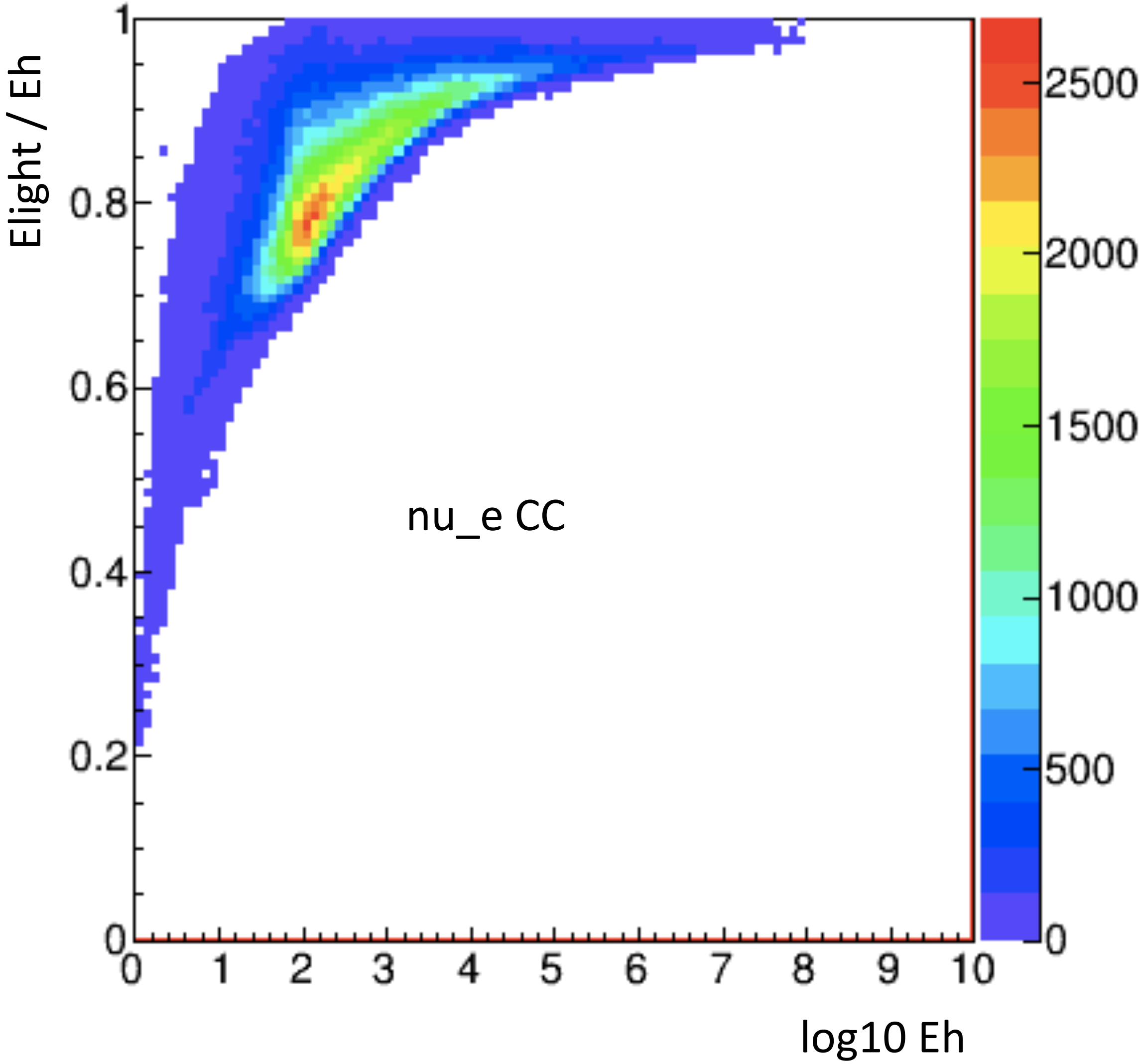
Fig. 6. Differential cross section for νN scattering for neutrino energies between 10^4 GeV and 10^{12} GeV.

Gandhi, Quigg
UHE Nu Interactions

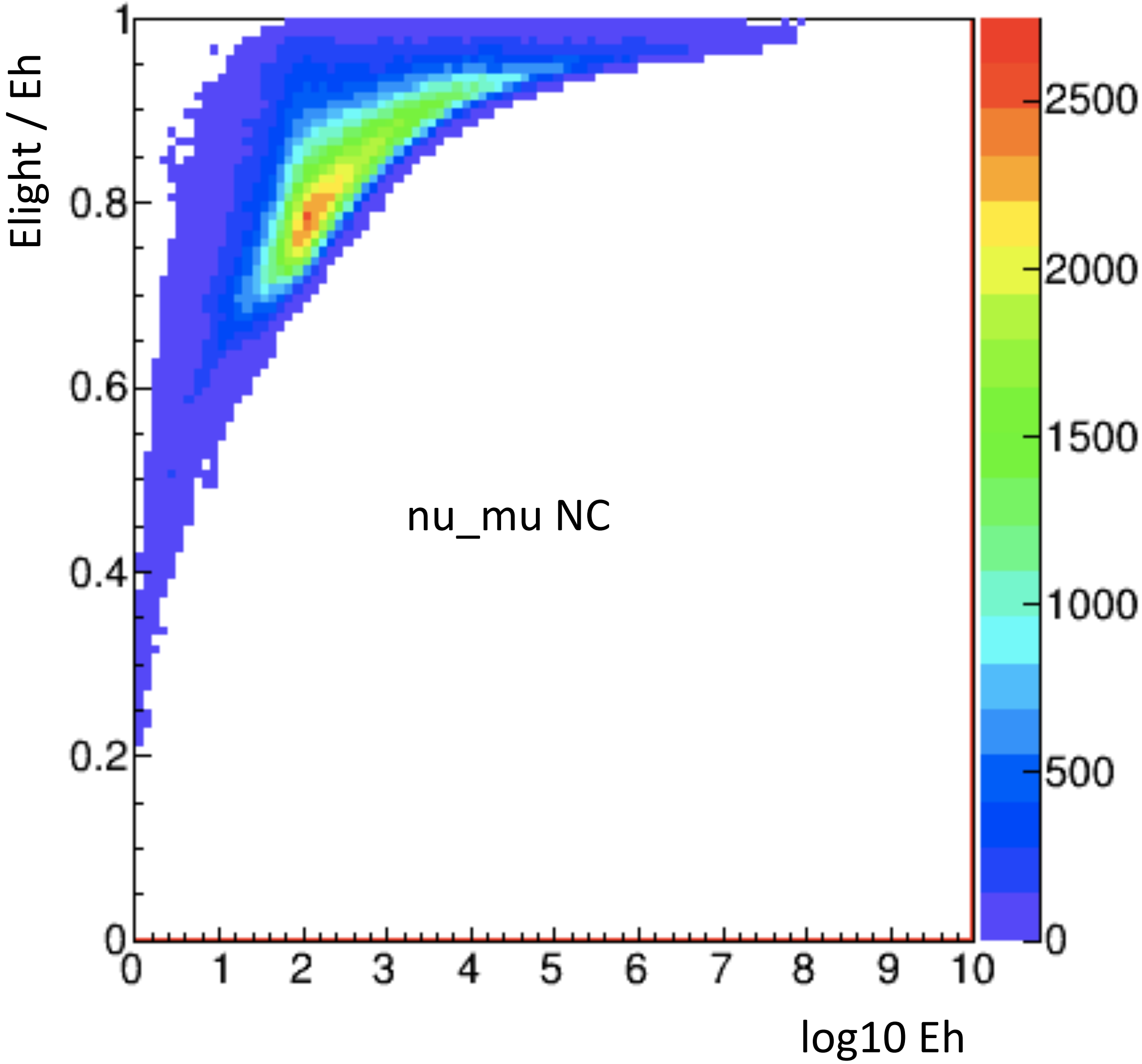
Light from hadronic showers



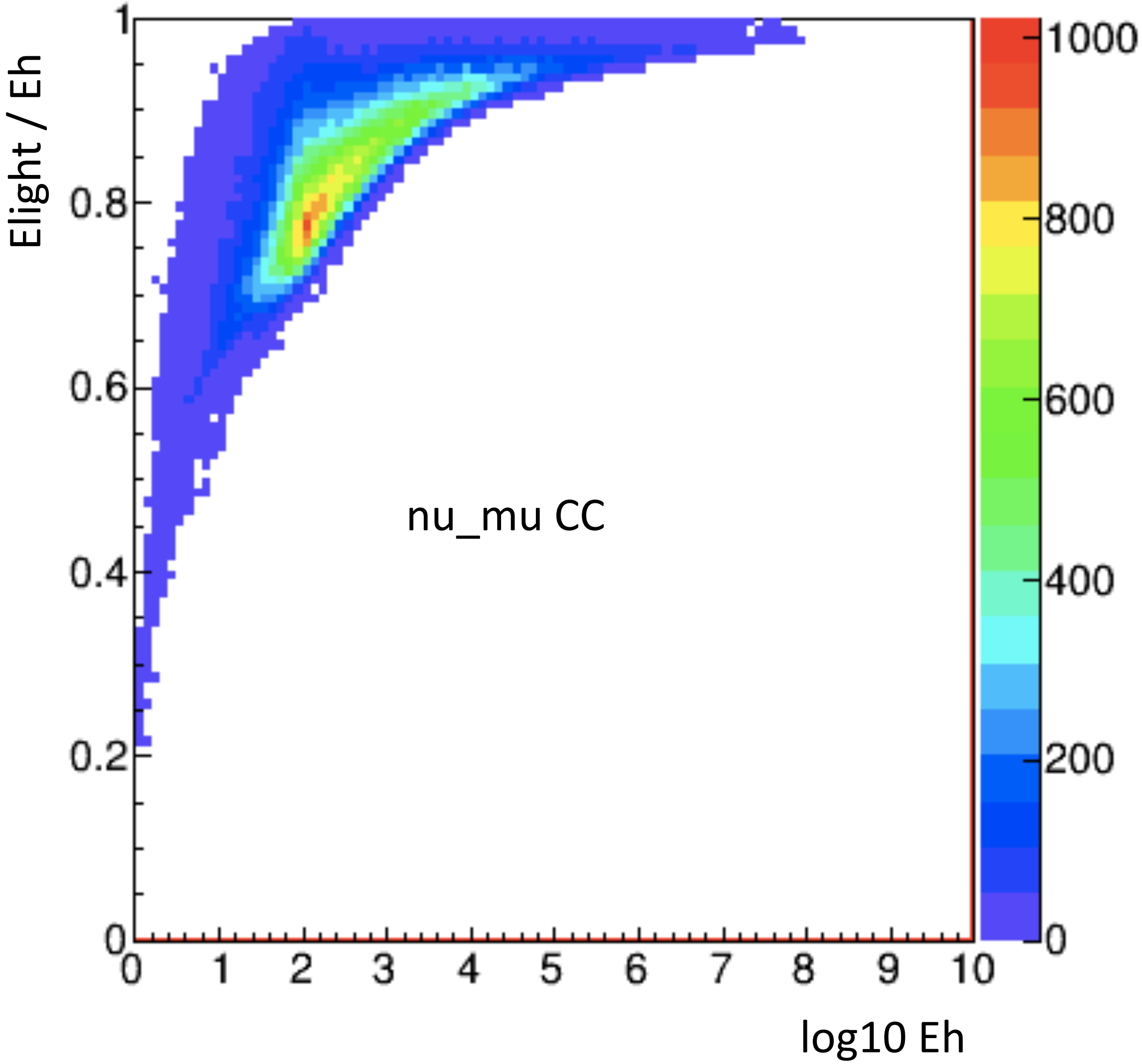
Light from hadronic showers



Light from hadronic showers



Light from hadronic showers



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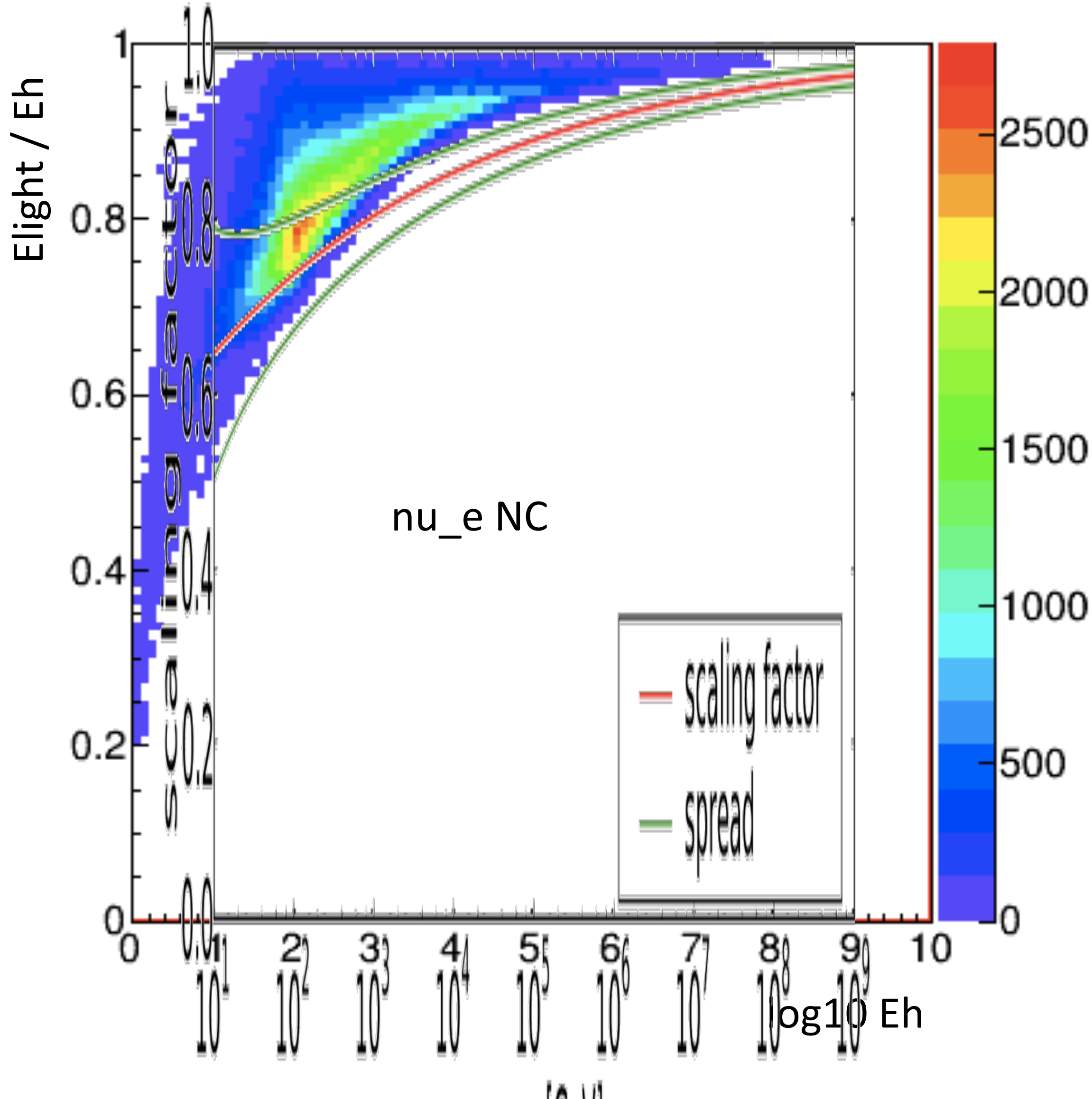
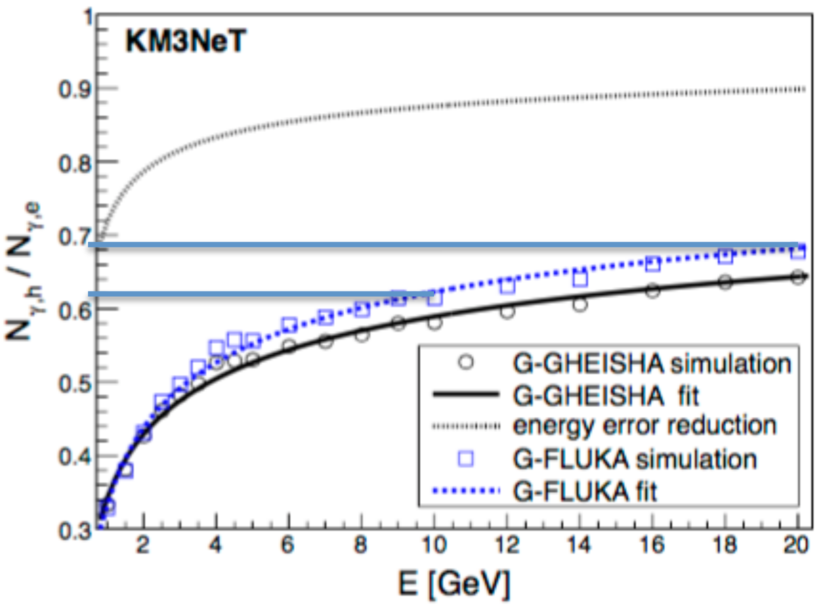
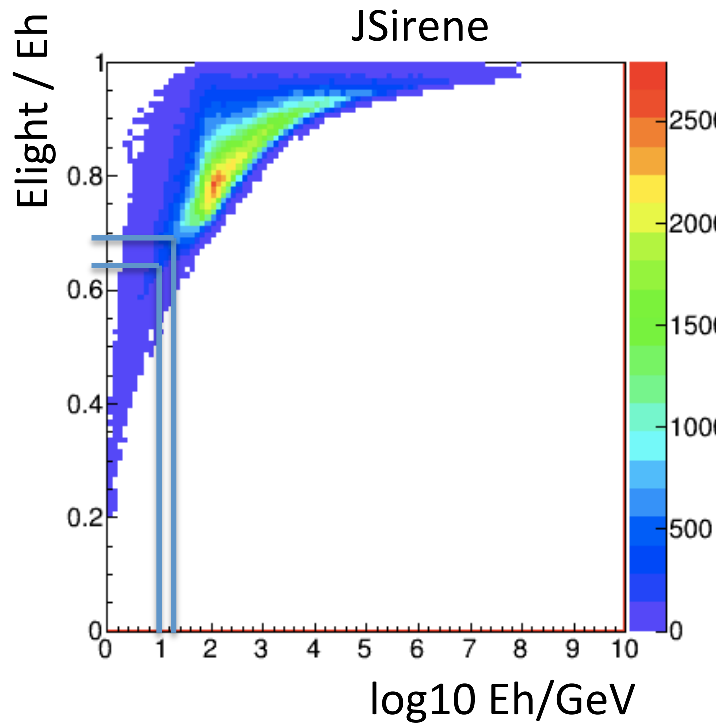


Light from hadronic showers





Likelihood Ingredients

$$P(data|H) = \sum_i \left[\log \int P(ev_i |\, x_{true}) \cdot P^{det}(x_{true}) \cdot \mu(x_{true} \mid H)\, dx_{true}\right] - \mu^{tot}(H)$$

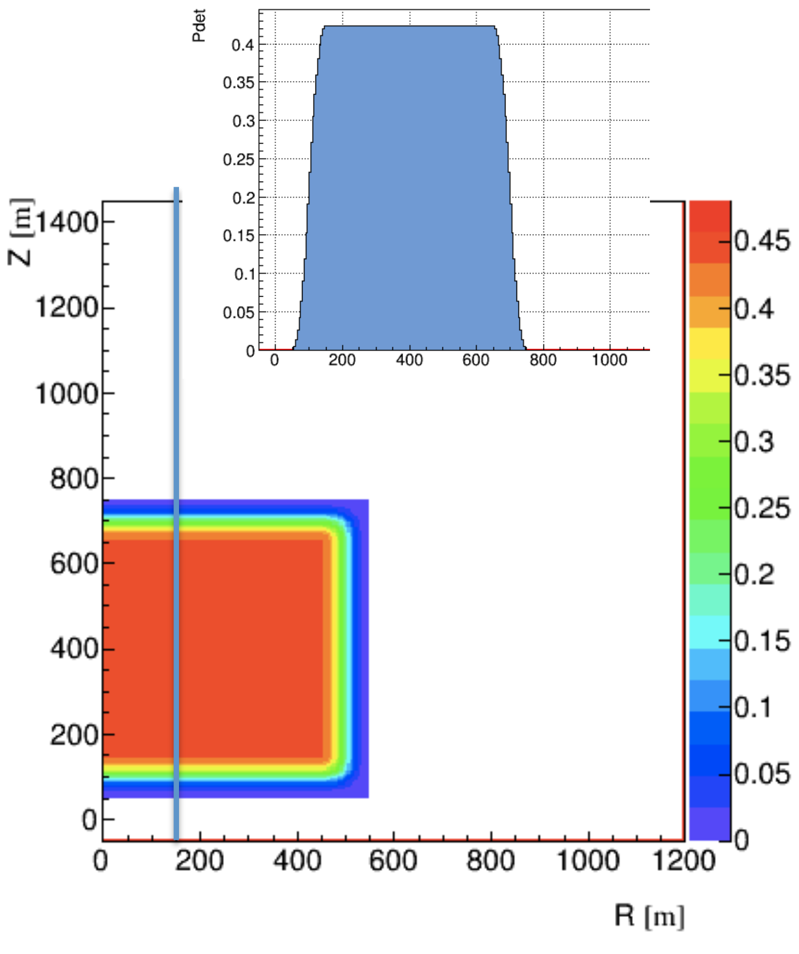
$\mu(x_{true} \mid H)$ Number of expected background or signal events in our detector (can)

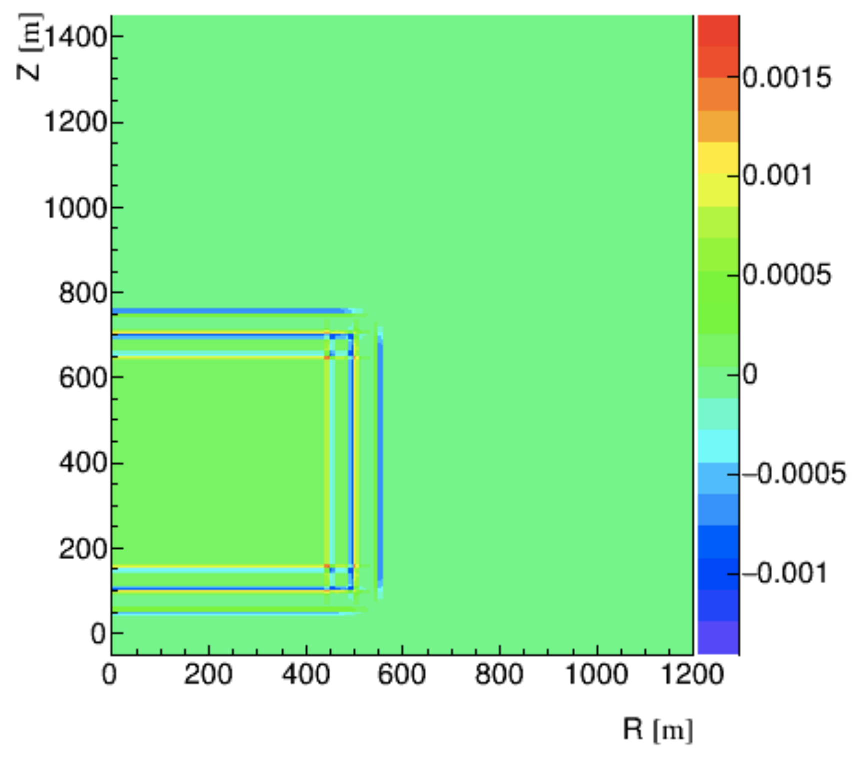
$P^{det}(x_{true})$ Probability to detect (=trigger) and select event

6-D Interpolation from tabulated values -> fast

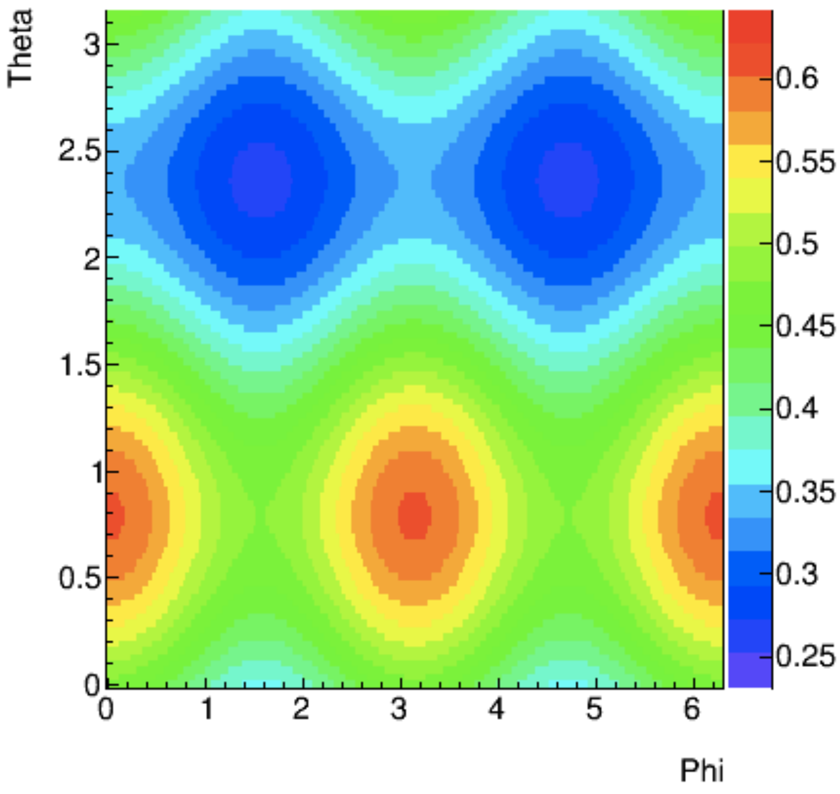
$P(ev_i |\, x_{true})$

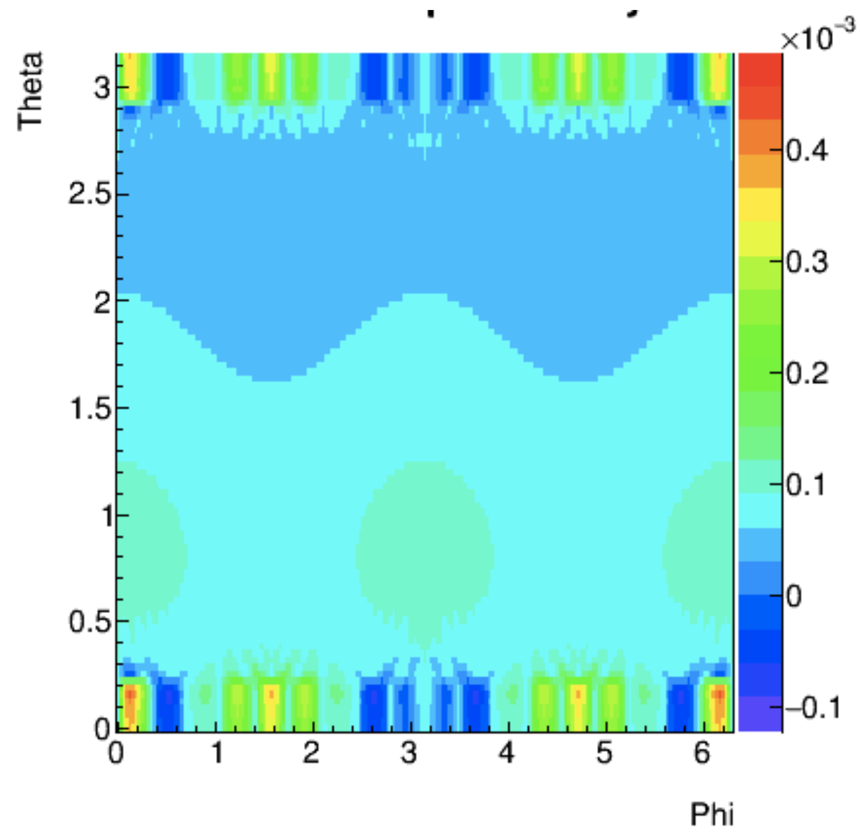
Detection Efficiency (1)





Detection Efficiency (2)





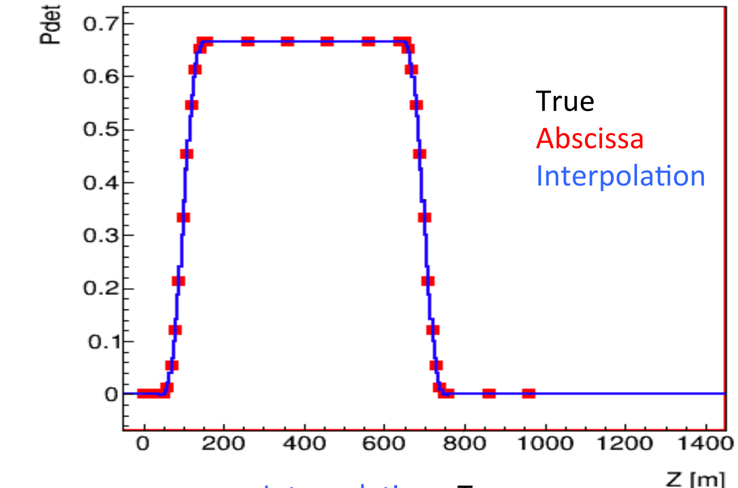
What is Pdet?

- Probability that an event:
  - Causes hits in detector: Jsirene
  - Leads to a trigger: JTriggerEfficiency
  - Is selected (reject atm. Muons): ??

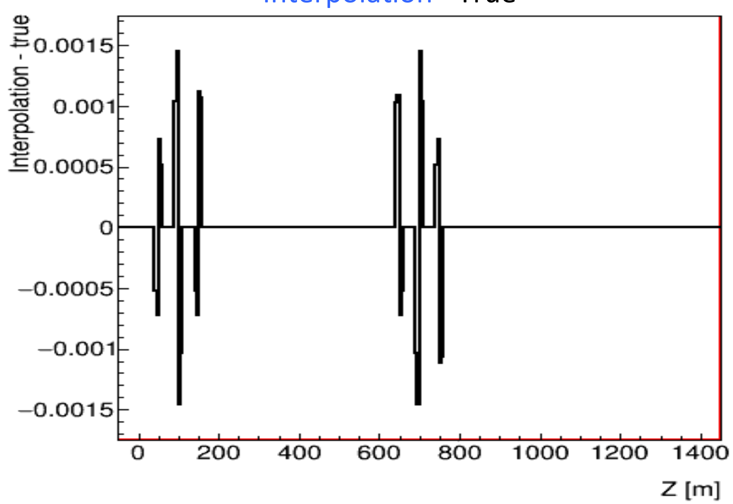
- Get Pdet(x_{true}) by running MC events

Statistical Fluctuations

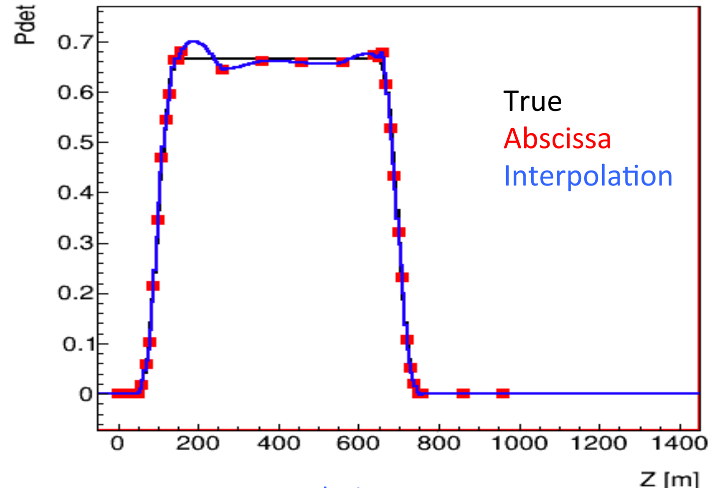
Ideal case: Infinite statistics



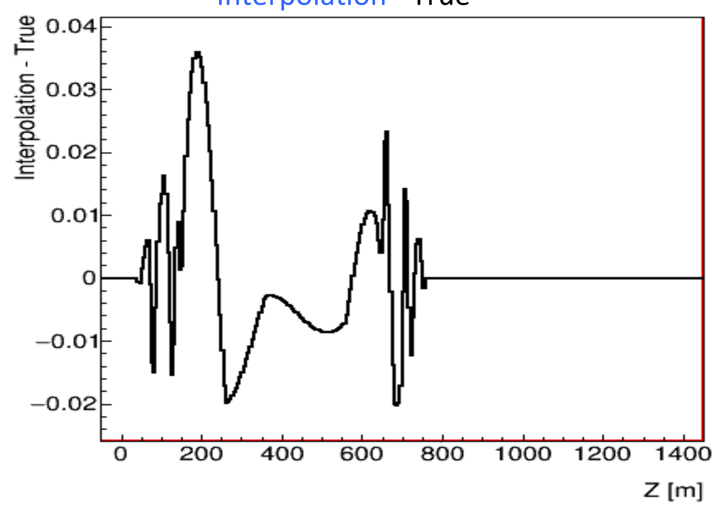
Interpolation - True



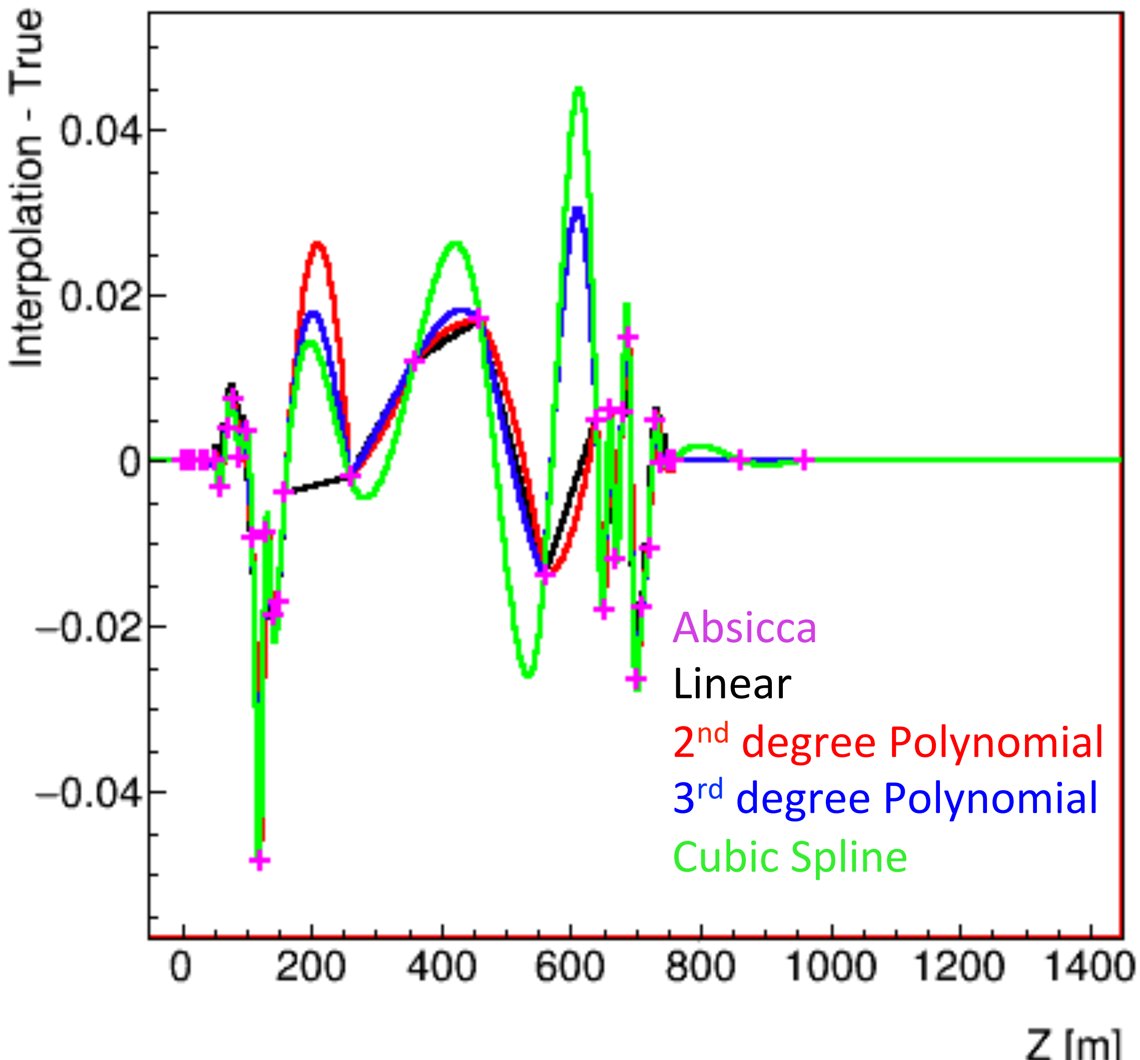
Realistic case: 1000 simulated events



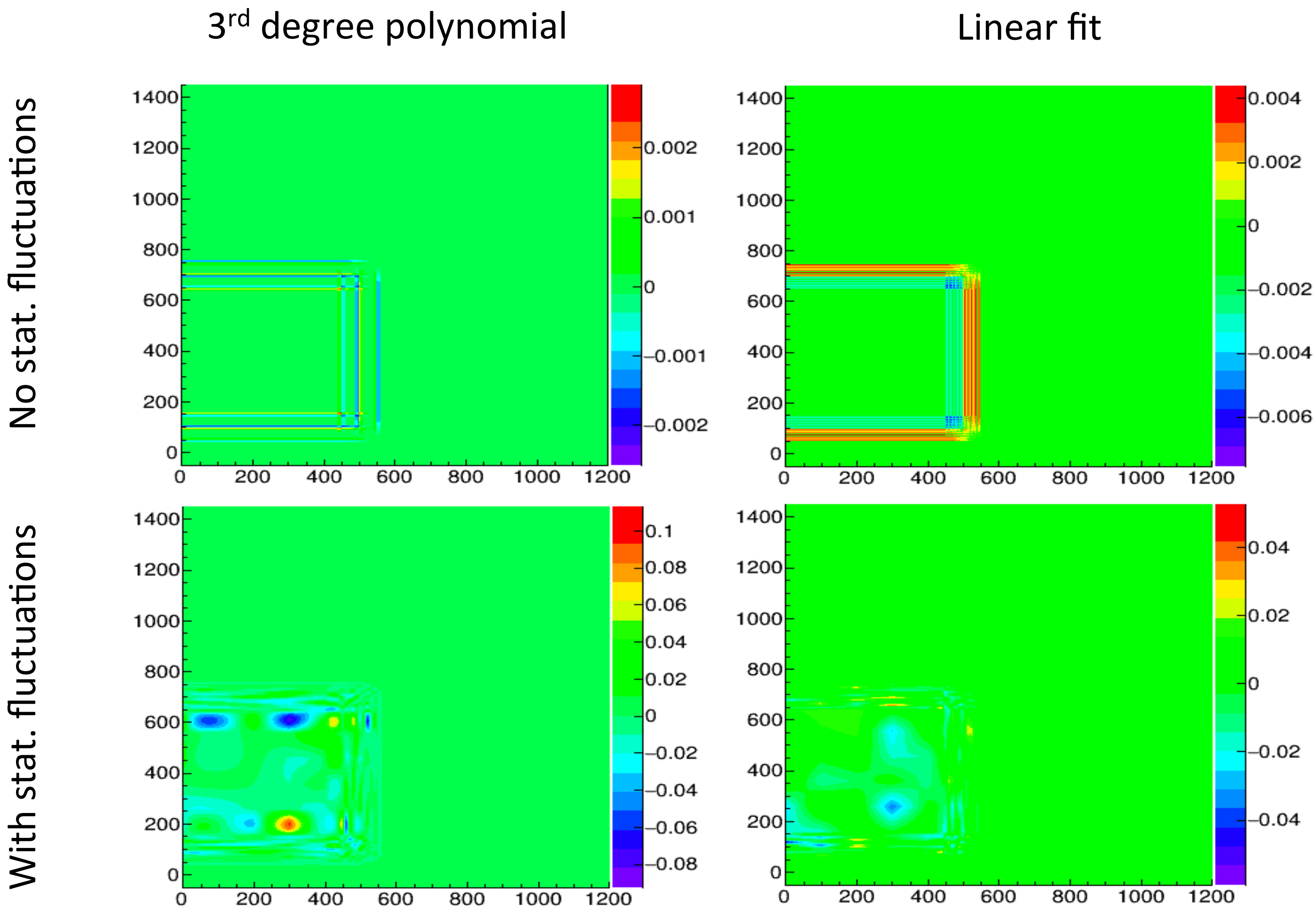
Interpolation - True



Different Interpolation Techniques



Polynomial vs linear fit



Time Consumption

```
Scanning over 72000 Positions * 98 Directions * 1 Energy-bins = 7056000 points... Done in

624169.543 ms elapsed
623814.165 ms user
    12.998 ms system
 99%CPU
```

3rd degree polynomial interpolation of 7 million points in 10 minutes

```
Scanning over 72000 Positions * 98 Directions * 1 Energy-bins = 7056000 points... Done in

 16068.632 ms elapsed
 16057.558 ms user
     4.999 ms system
 99%CPU
```

Linear interpolation of 7 million points in 16 seconds

Likelihood Ingredients

$$P(data|H) = \sum_i \left[\log \int P(ev_i|\, x_{true}) \cdot P^{det}(x_{true}) \cdot \mu(x_{true}\ |\, H)\, dx_{true} \right] - \ \mu^{tot}(H)$$

$\mu(x_{true}\ |\, H)$ Number of expected background or signal events in our detector (can)

$P^{det}(x_{true})$ Probability to detect (=trigger) and select event

$P(ev_i|\, x_{true})$ Reconstruction, loop over PMTs. Phit * Ptime -> to do

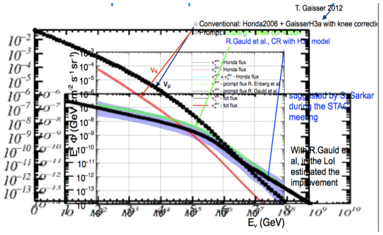
Conclusions

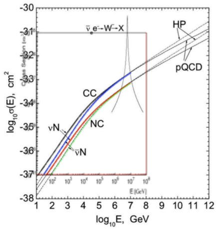
- New method seems promising
- Most ingredients in place
- ‘Reconstruction’ part to be done

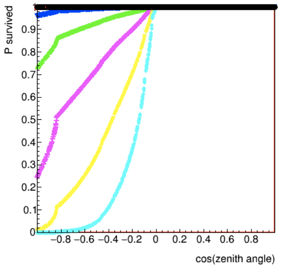
Recap: Likelihood Ingredients

$$P(data|H) = \sum_i \left[\log \int P(ev_i|\, x_{true}) \cdot P^{det}(x_{true}) \cdot \mu(x_{true}\,|H)\, dx_{true}\right] - \mu^{tot}(H)$$

$\mu(x_{true}\,|H)$ Number of expected background or signal events in our detector (can)







$P^{det}(x_{true})$ Probability to detect (=trigger) and select event

$P(ev_i|\, x_{true})$ Reconstruction, loop over PMTs.

Detection Efficiency

- For each neutrino energy, bjorken-y, position, direction (6 parameters), DO:

- (Very fast) Monte Carlo generator:
  - Secondary particles
  - Photon propagation (JSirene)
  - Trigger

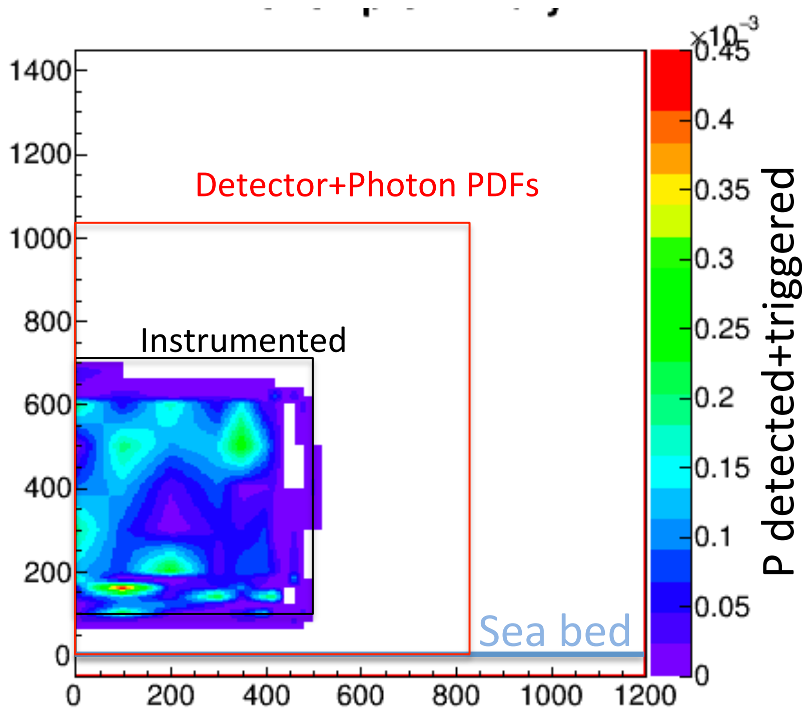
BONUS bij AH Willems

- Count fraction of trig. ev.
- Store in 6D interpolatable PDF table

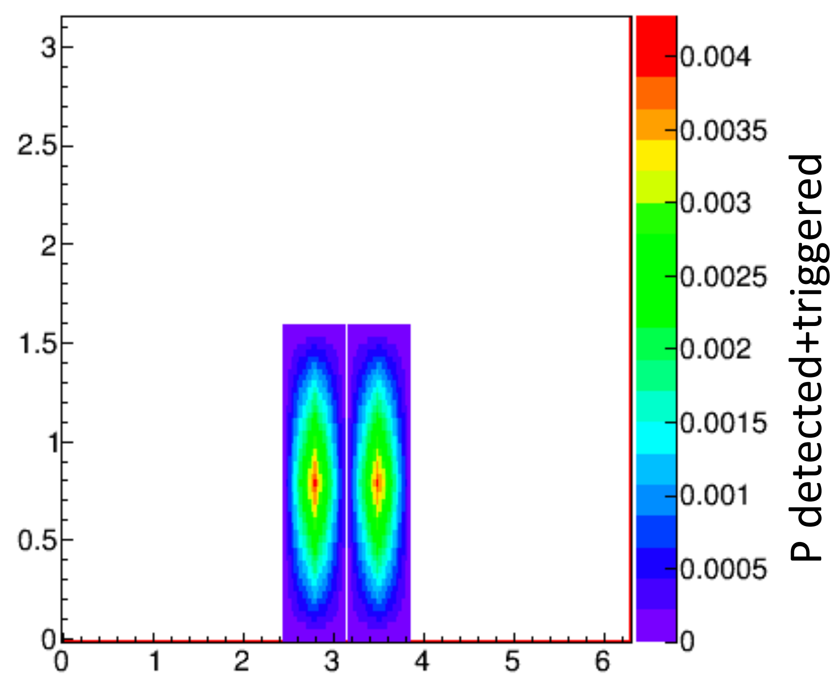
Detection Efficiency @ 10^2 GeV

NC electron-neutrino (only single hadronic shower)

Position



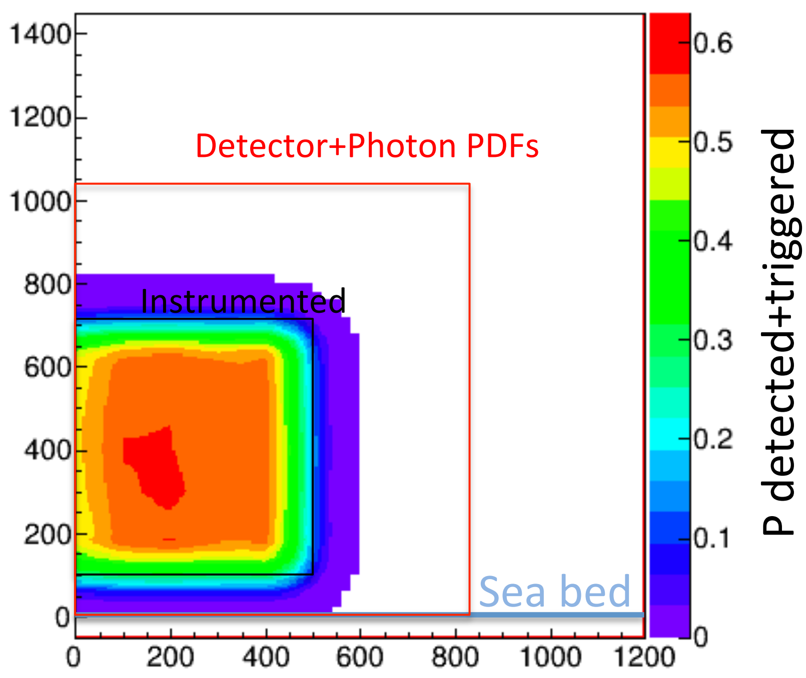
Direction @R=0, Z=400



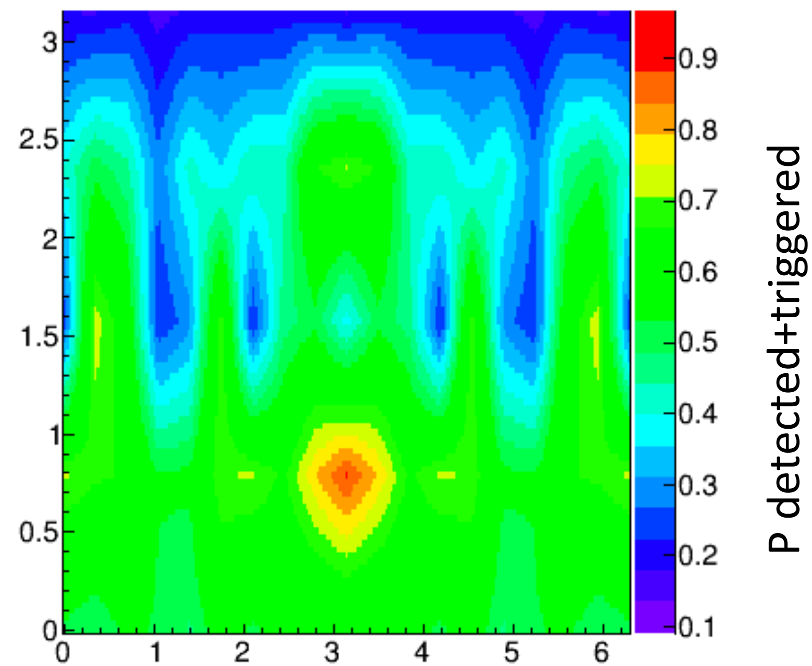
Detection Efficiency @ 10^3 GeV

NC electron-neutrino (only single hadronic shower)

Position



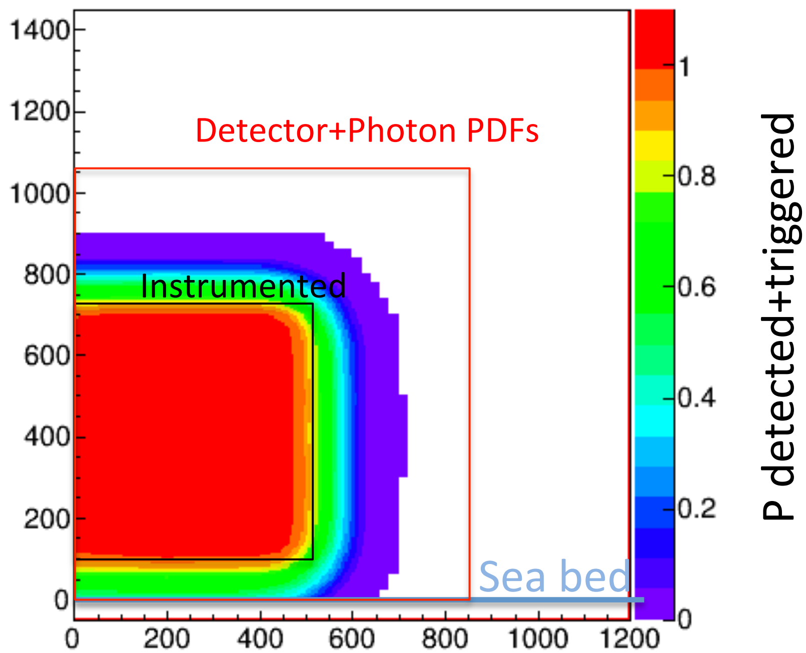
Direction @R=0, Z=400



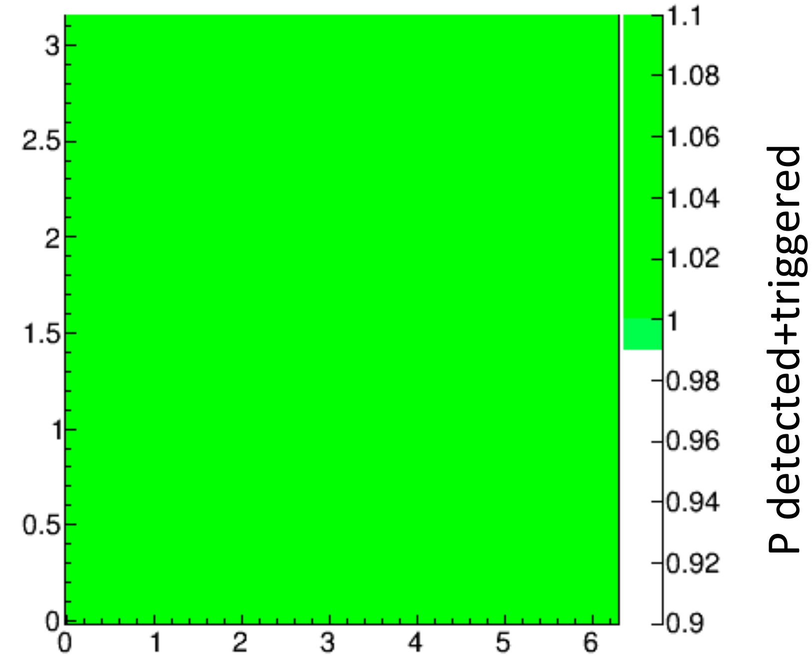
Detection Efficiency @ 10^4 GeV

NC electron-neutrino (only single hadronic shower)

Position

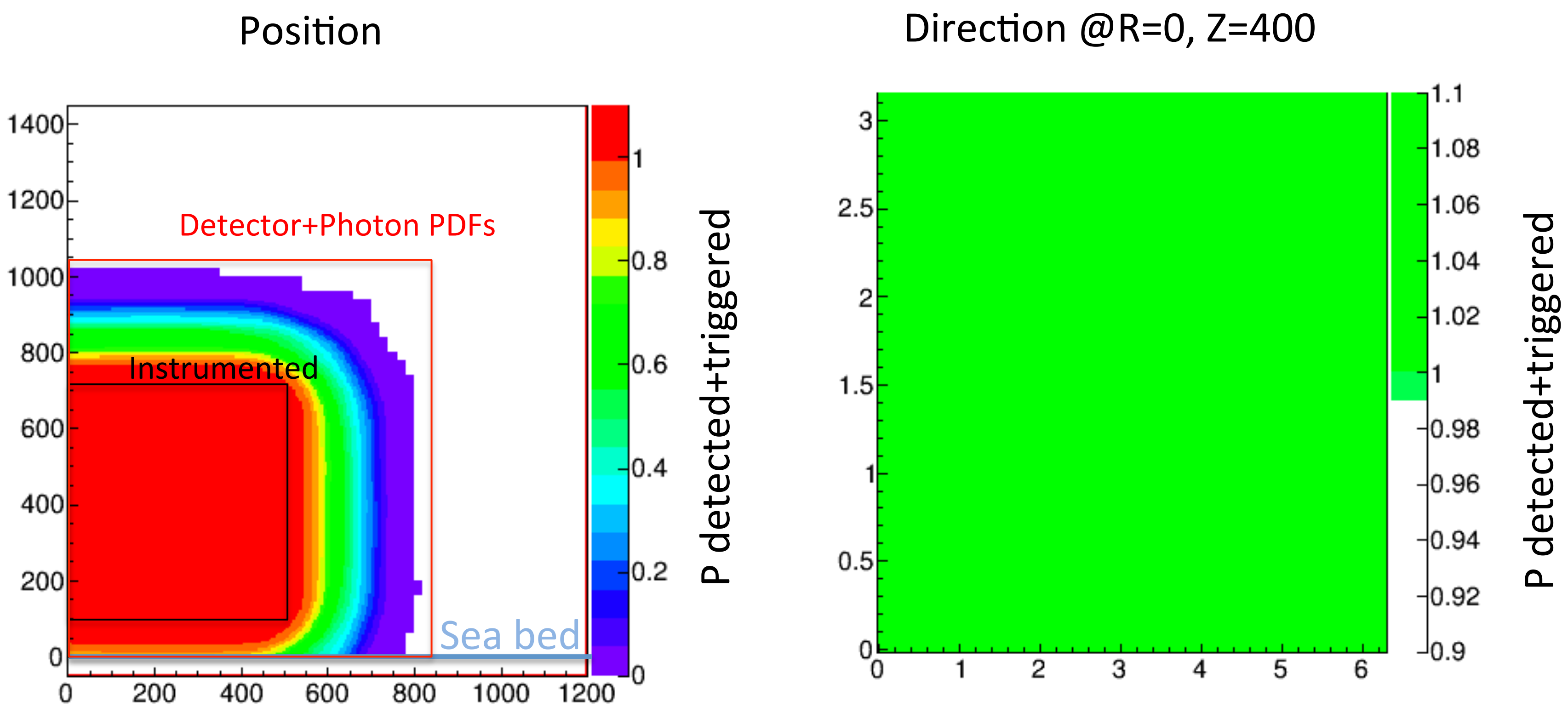


Direction @R=0, Z=400



Detection Efficiency @ 10^5 GeV

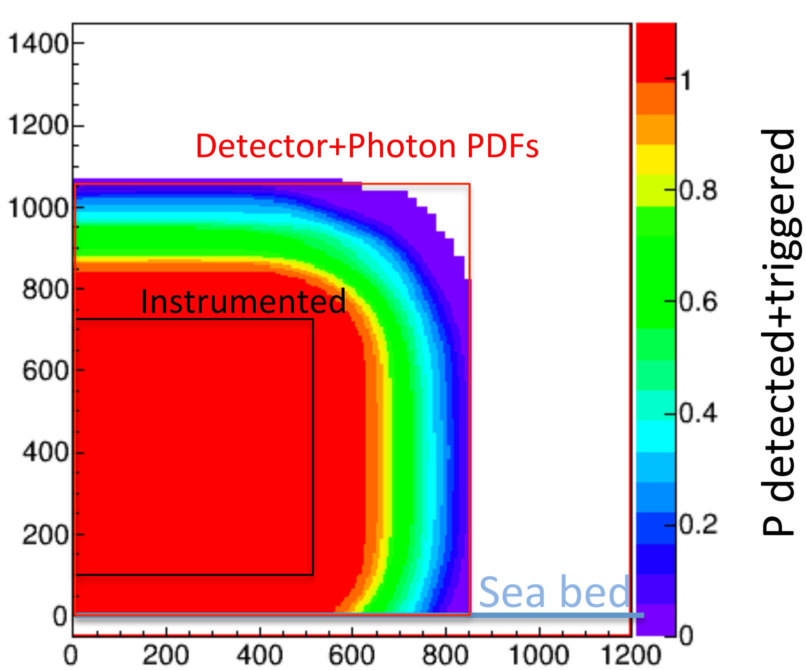
NC electron-neutrino (only single hadronic shower)



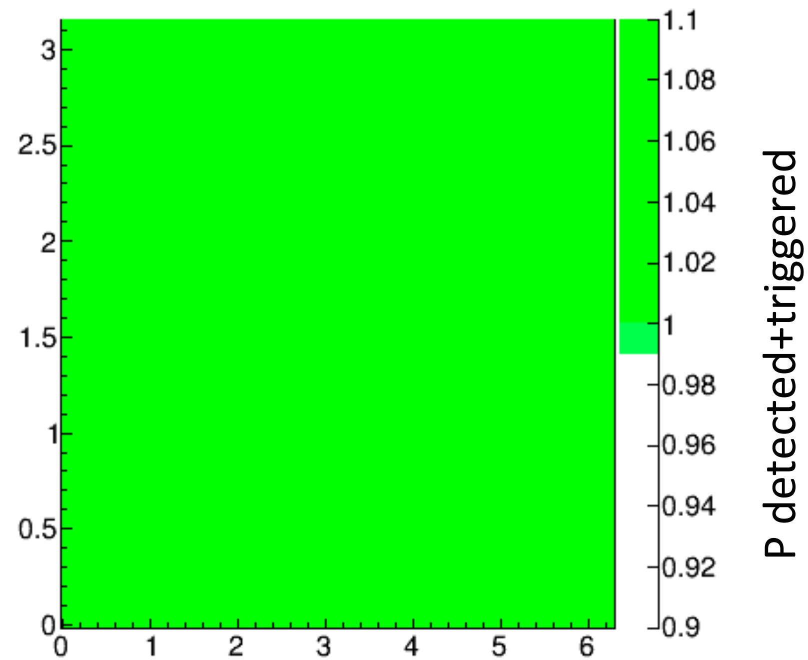
Detection Efficiency @ 10^6 GeV

NC electron-neutrino (only single hadronic shower)

Position



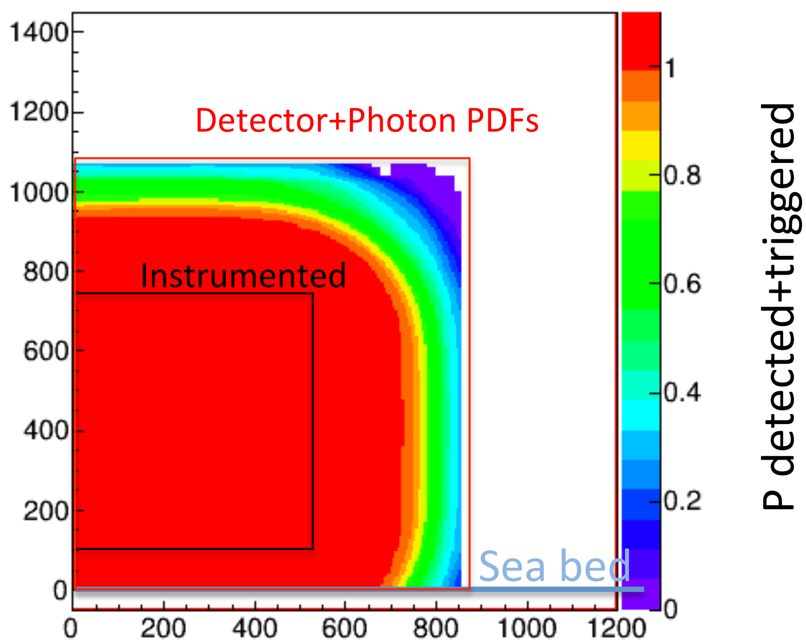
Direction @R=0, Z=400



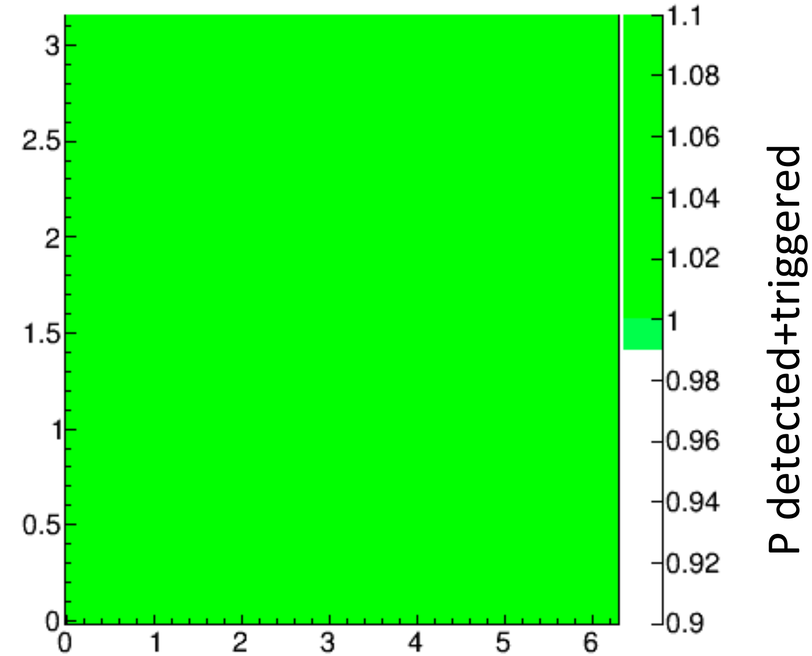
Detection Efficiency @ 10^7 GeV

NC electron-neutrino (only single hadronic shower)

Position



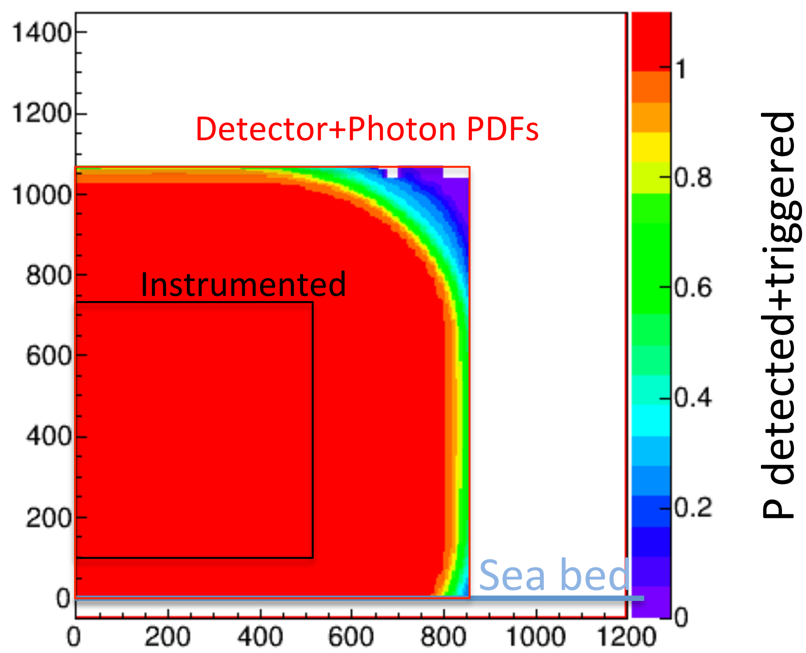
Direction @R=0, Z=400



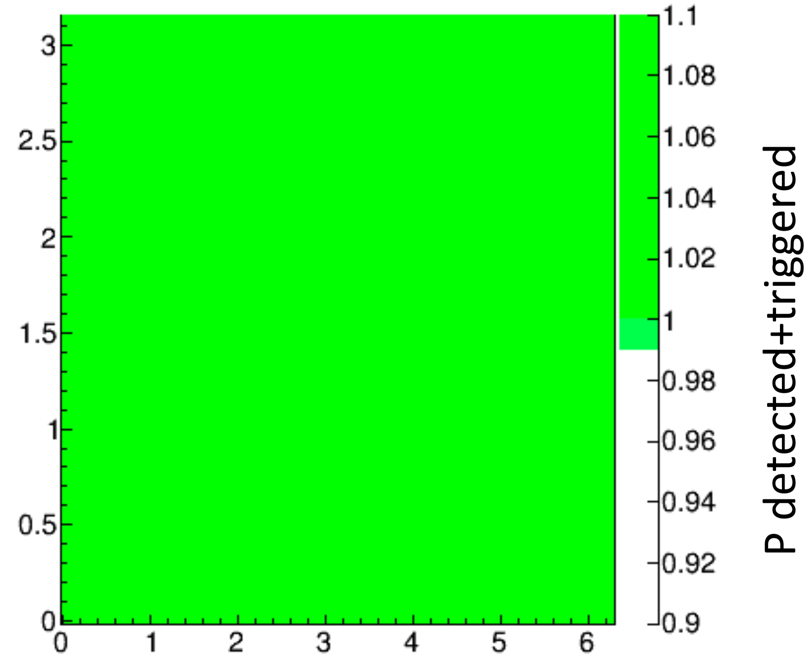
Detection Efficiency @ 10^8 GeV

NC electron-neutrino (only single hadronic shower)

Position



Direction @R=0, Z=400



Likelihood Ingredients

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$\mu(x_{true}\ |\, H)$ Number of expected background or signal events in our detector (can)

$P^{det}(x_{true})$ Probability to detect (=trigger) and select event

$P(ev_i|\, x_{true})$ Probability to obtain measured event ev_i
given a certain neutrino hypothesis x_{true}

Event Probability D.F.

$$P(ev \mid x) = \prod_{hit\ PMTs} \left[P_i^{hit} \cdot P_i^{t\ 1st}\right] \cdot \prod_{non\ hit\ PMTs} \left[1 - P_i^{hit}\right]$$

$$P_i^{hit} = 1 - \exp\left(-\int_{-\infty}^{\infty} \hat{n}_i(t)\, dt\right)$$

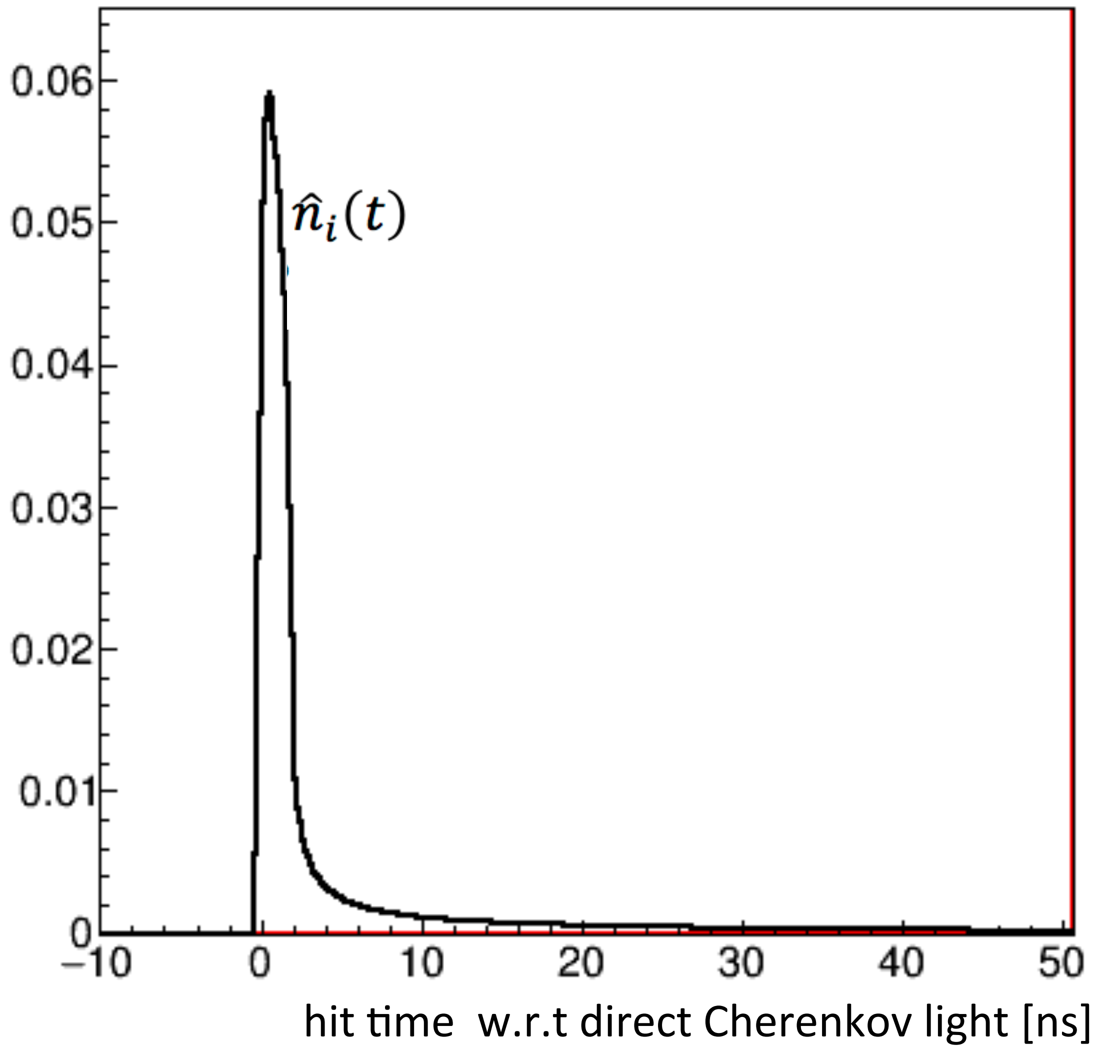
Expected number of photons from 40K and shower/track on PMT i at time t

$$P_i^{t\ 1st} \cdot P_i^{hit} = \exp\left(-\int_{-\infty}^{t} \hat{n}_i(t)\, dt\right) \cdot \left(1 - \exp\left(-\hat{n}_i(t)\right)\right)$$

P not hit before t

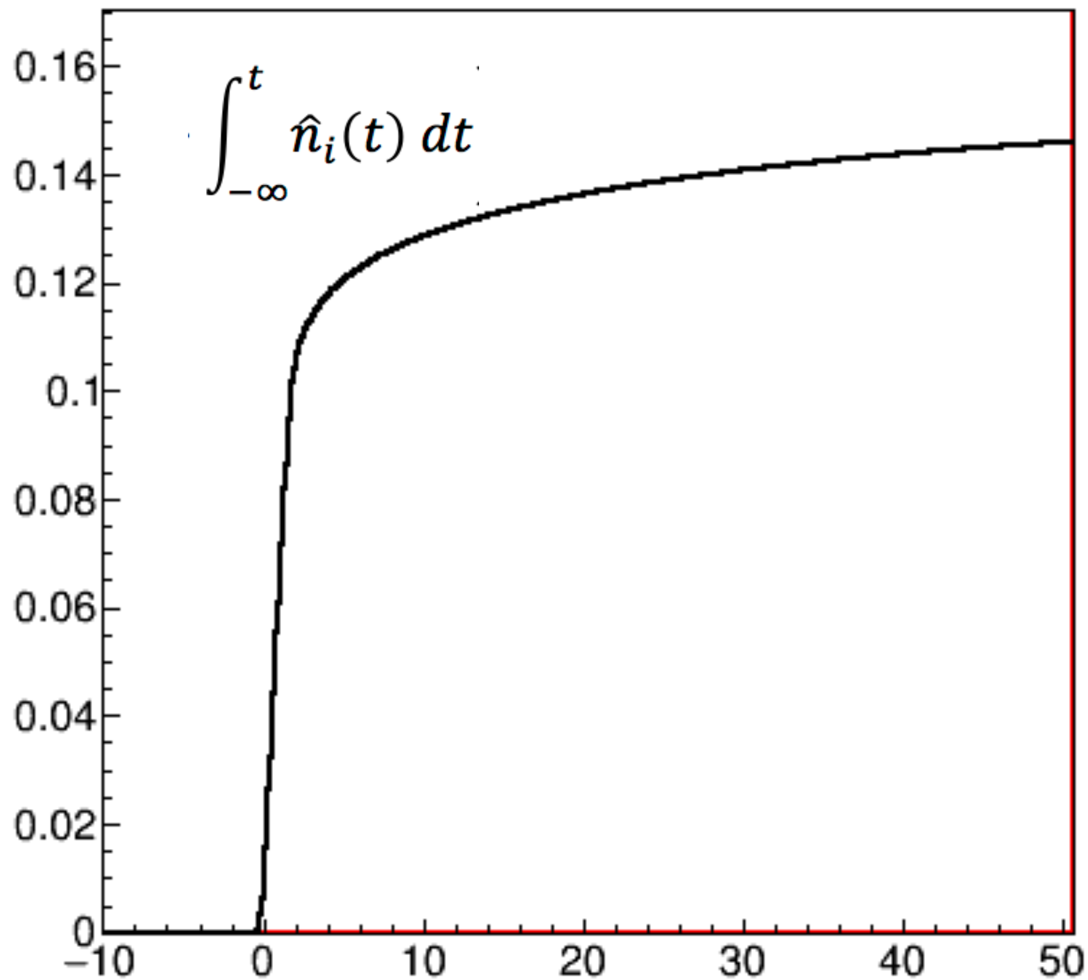
P hit at t

Hit Time PDF



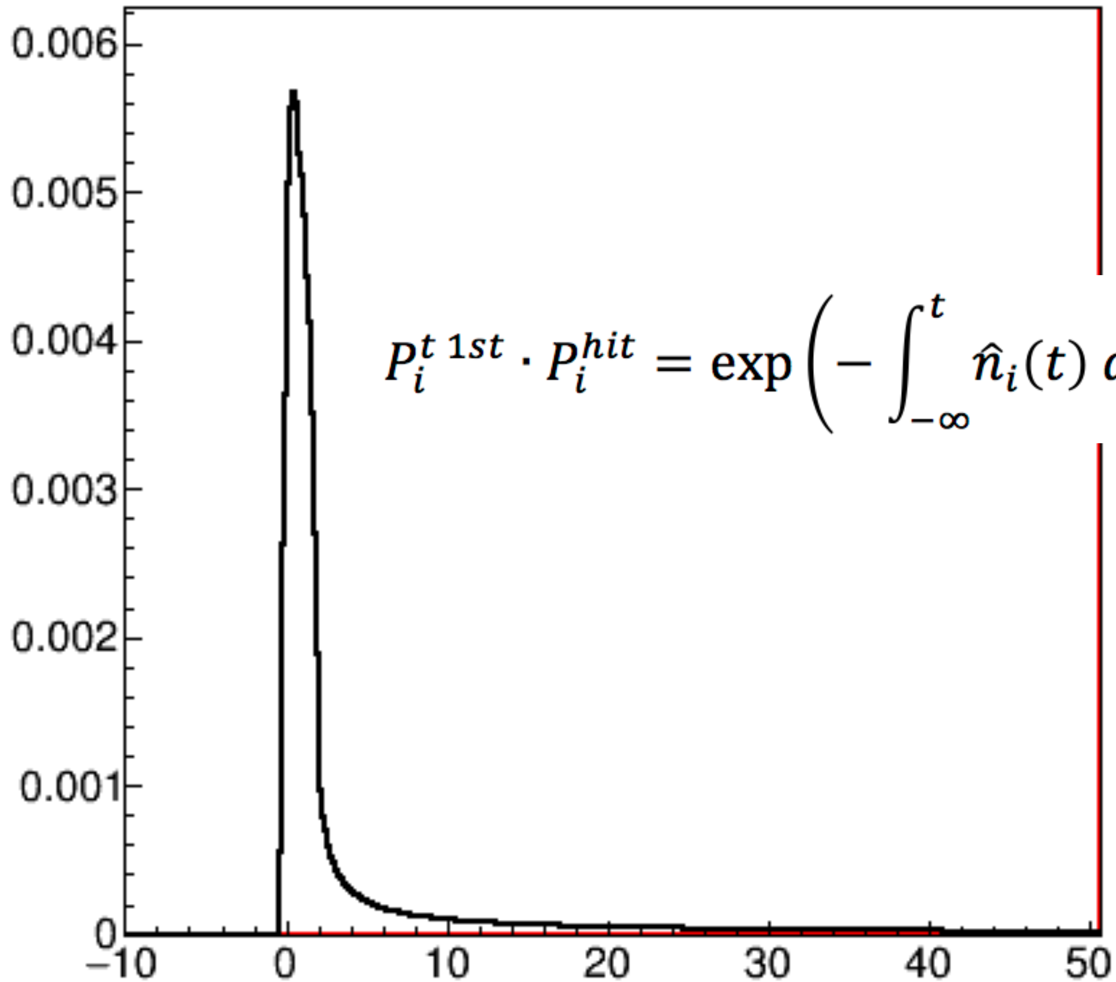
0.06
0.05
0.04
0.03
0.02
0.01
0
−10
0
10
20
30
40
50
$\hat{n}_i(t)$
hit time w.r.t direct Cherenkov light [ns]

Hit Time PDF



hit time w.r.t direct Cherenkov light [ns]

Hit Time PDF



$$P_i^{t\ 1st} \cdot P_i^{hit} = \exp\left(-\int_{-\infty}^{t} \hat{n}_i(t)\, dt\right) \cdot (1 - \exp(-$$

hit time w.r.t direct Cherenkov light [ns]

Hits in ~~Theory~~ Practice

- Presence of ^{40}K background hits

$$P_i^{t\ 1st} \cdot P_i^{hit} = \exp\left(-\int_{-\infty}^{t} \hat{n}_i(t)\, dt\right) \cdot (1 - \exp(-\hat{n}_i(t)))$$

- If all hit times are selected: signal will be overwhelmed by background

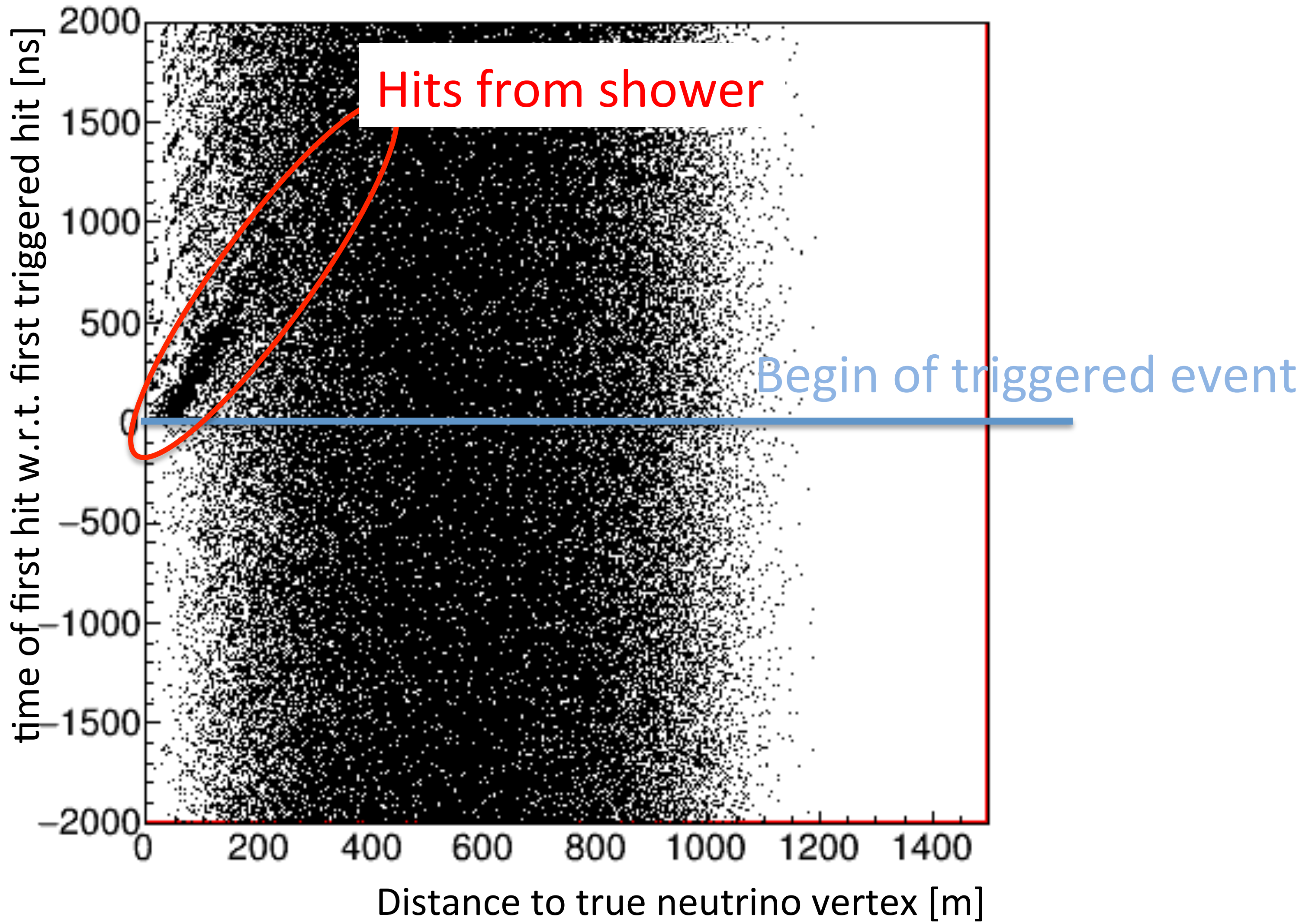
- Solution: only select hits in certain time window

Hit Selection Time Window

- Select Hits around expected hit time from given hypothesis
  - Advantage: Very pure selection
  - Drawback: biassed selection

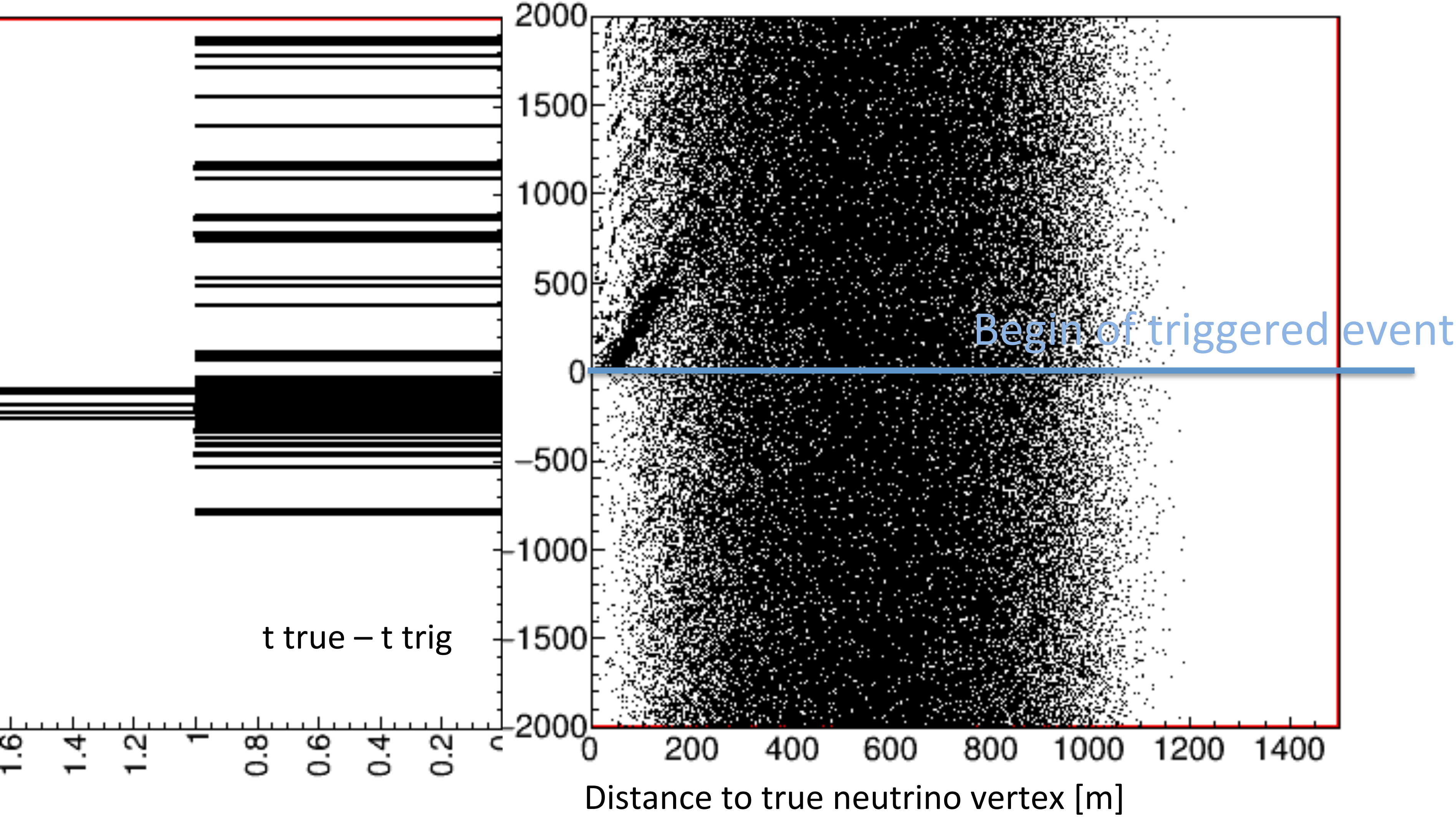
- Solution: Select hits around triggered event

Hit Times



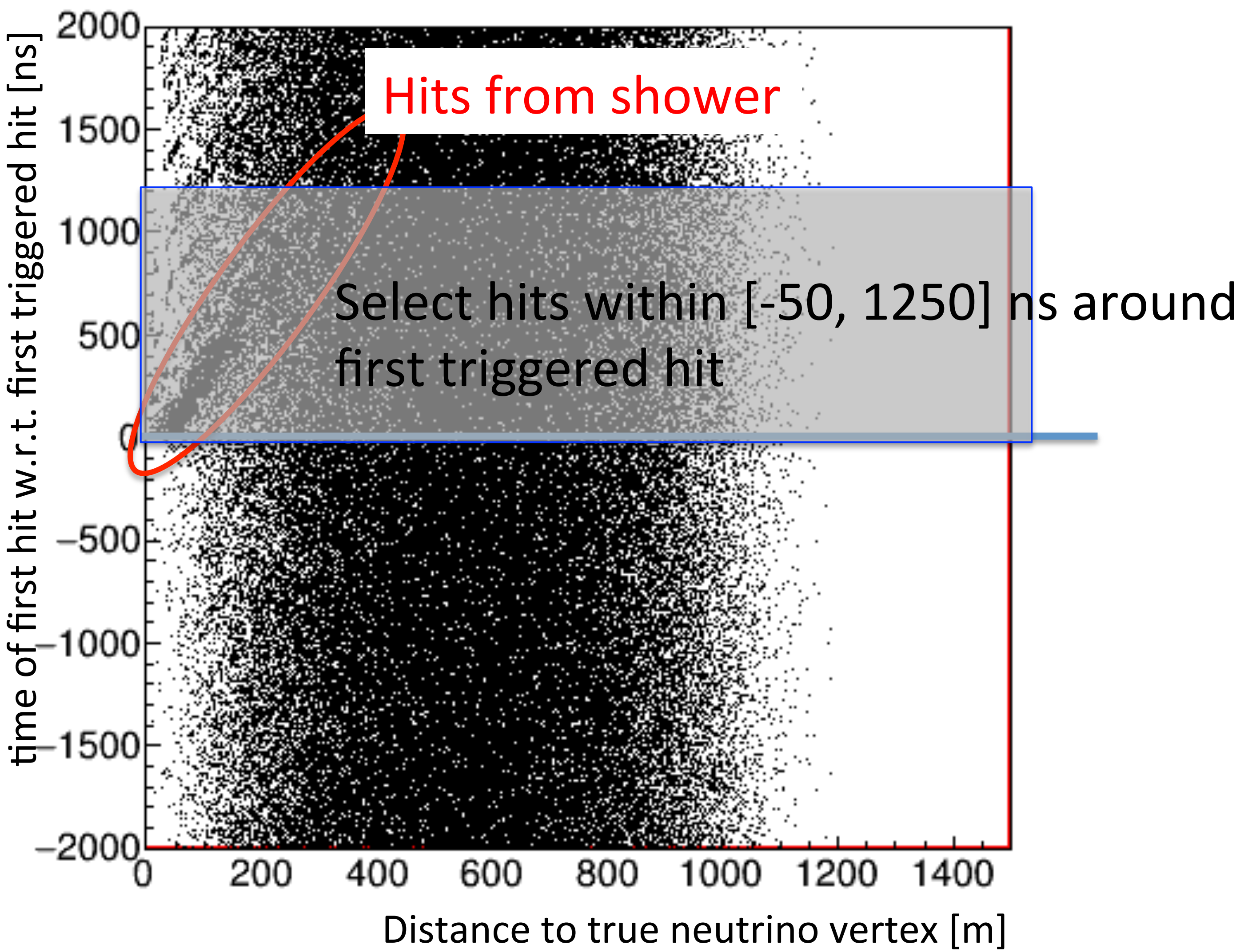
Hits from shower
Begin of triggered event
time of first hit w.r.t. first triggered hit [ns]
2000
1500
1000
500
0
−500
−1000
−1500
−2000
0
200
400
600
800
1000
1200
1400
Distance to true neutrino vertex [m]

Hit Times



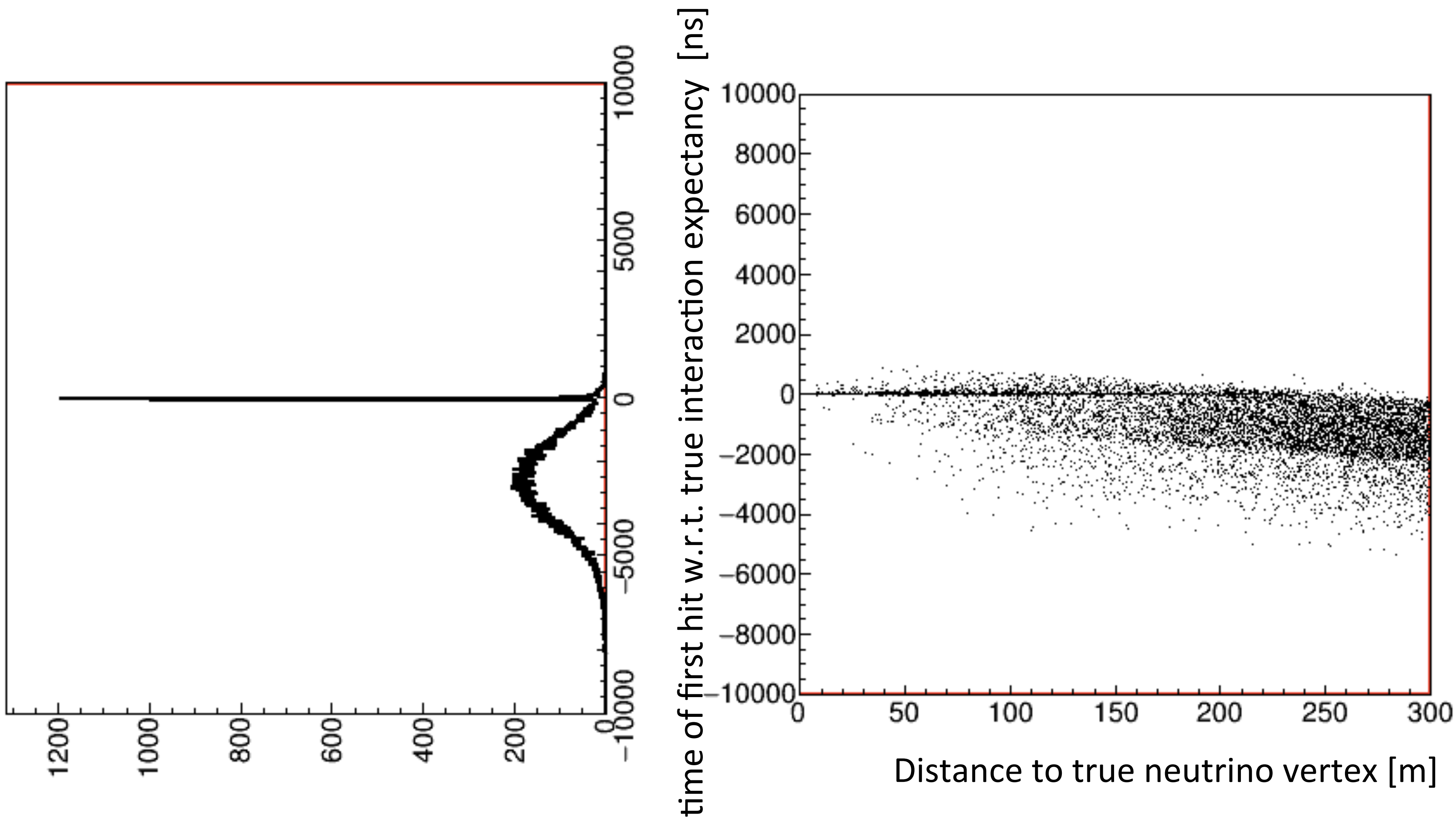
2000
1500
1000
500
0
−500
−1000
−1500
−2000
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
200
400
600
800
1000
1200
1400
Begin of triggered event
t true – t trig
Distance to true neutrino vertex [m]

Hit Times

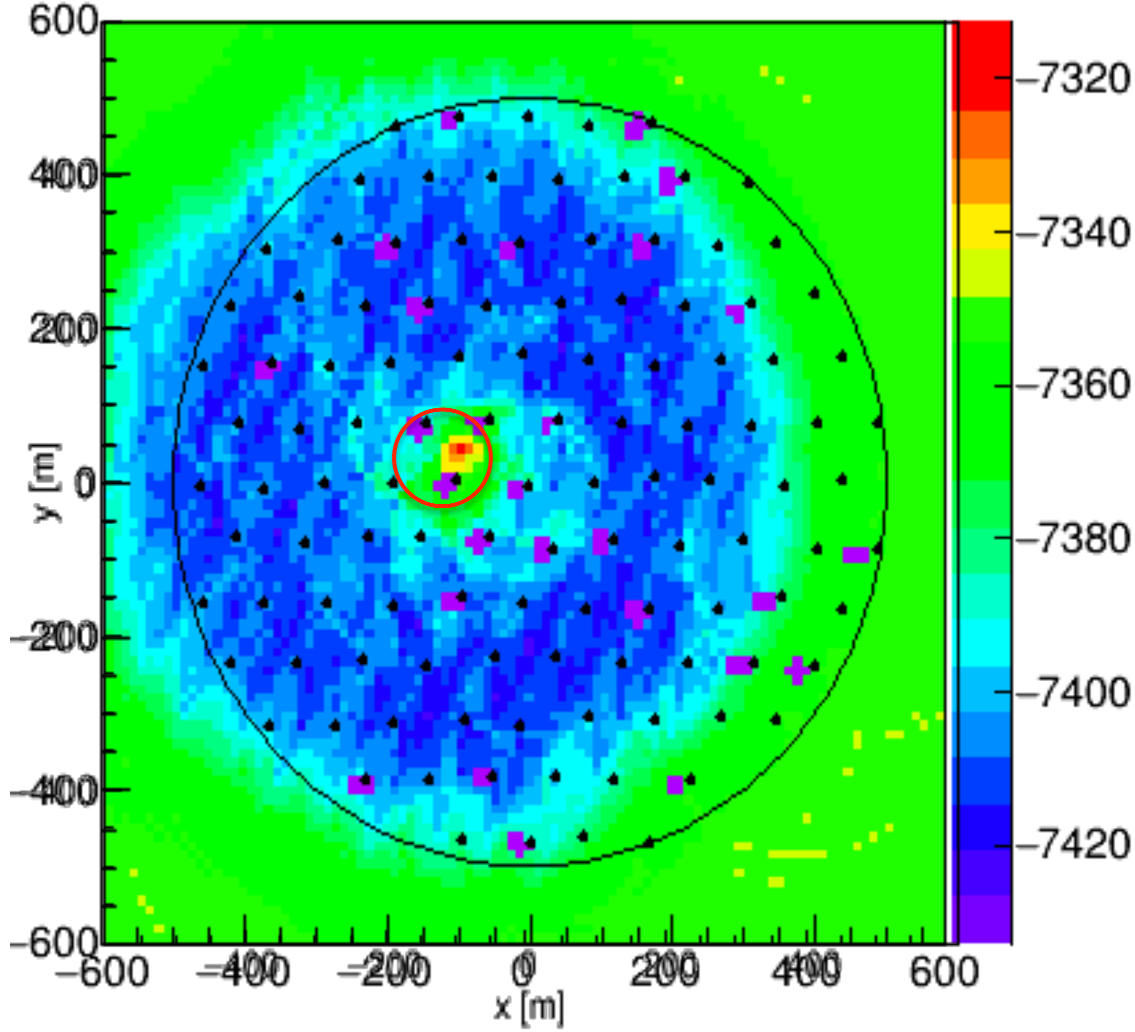


Hits from shower
Select hits within [-50, 1250] ns around first triggered hit
time of first hit w.r.t. first triggered hit [ns]
2000
1500
1000
500
0
−500
−1000
−1500
−2000
0
200
400
600
800
1000
1200
1400
Distance to true neutrino vertex [m]

Hit Times w.r.t. direct Cher. light



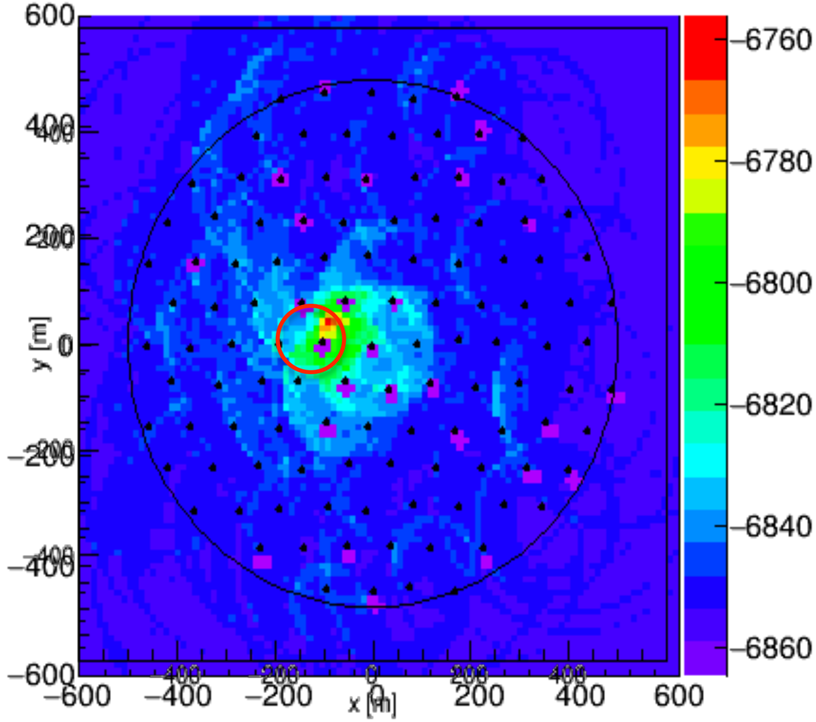
$$P(ev \mid x) = \prod_{hit\ PMTs} \left[P_i^{hit} \cdot P_i^{t\ 1st}\right] \cdot \prod_{non\ hit\ PMTs} \left[1 - P_i^{hit}\right]$$



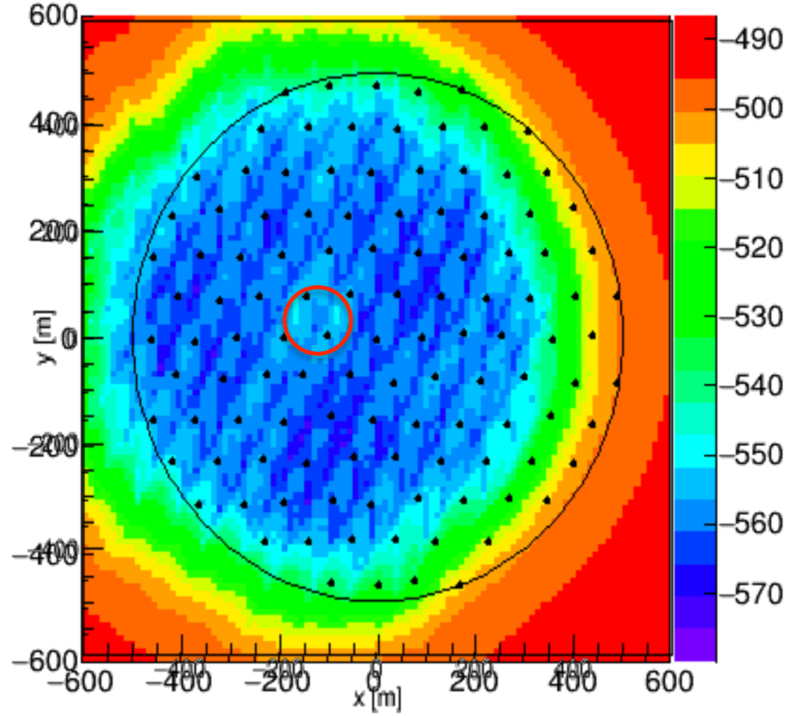
$logP(ev \mid x)$

$$logP(ev \mid x) = \sum_{hit\ PMTs} \left[\log\left(P_i^{hit}\right) + \log\left(P_i^{t\ 1st}\right)\right] + \sum_{non\ hit\ PMTs} \left[\log\left(1 - P_i^{hit}\right)\right]$$

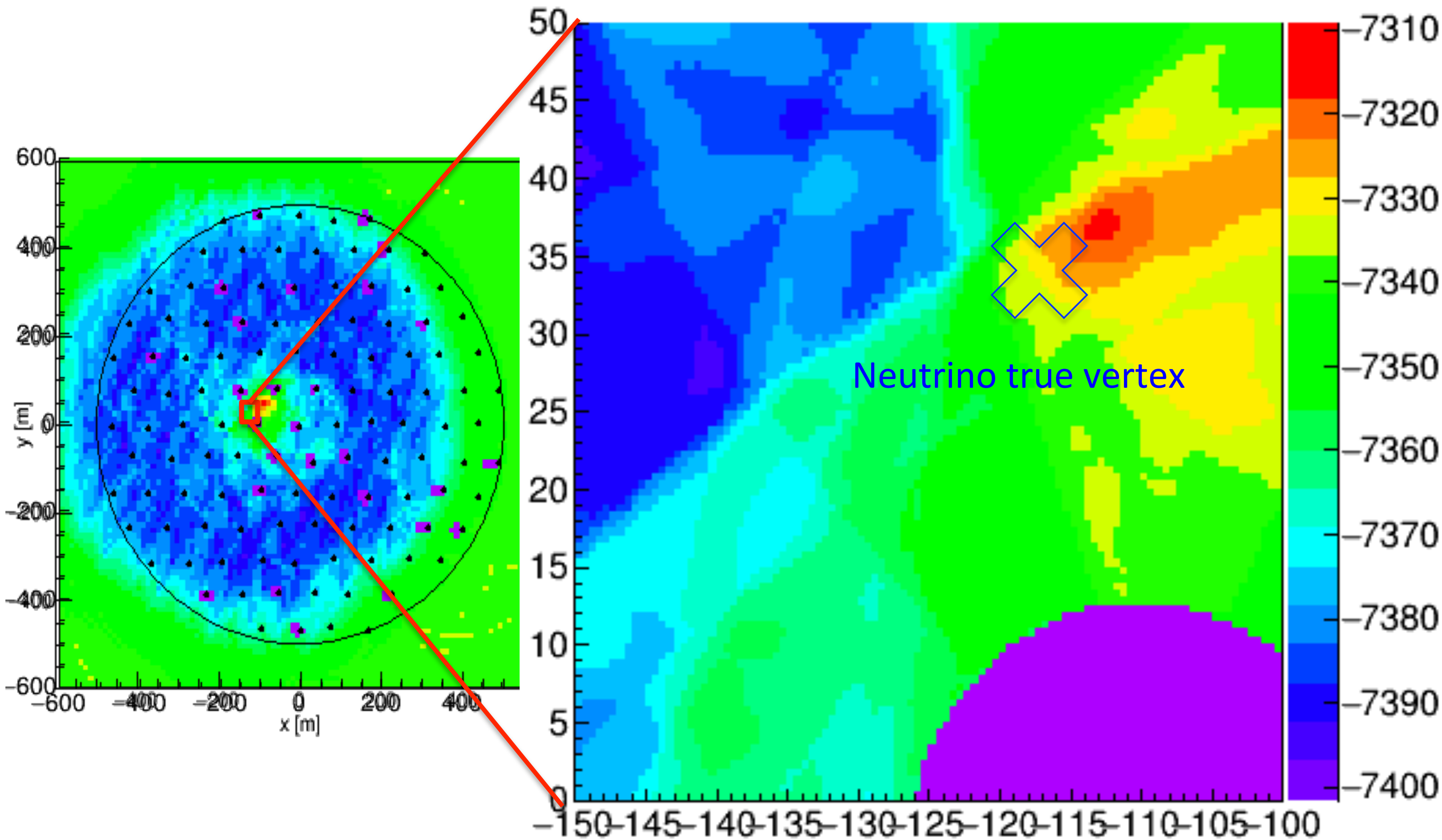
Hit PMTs



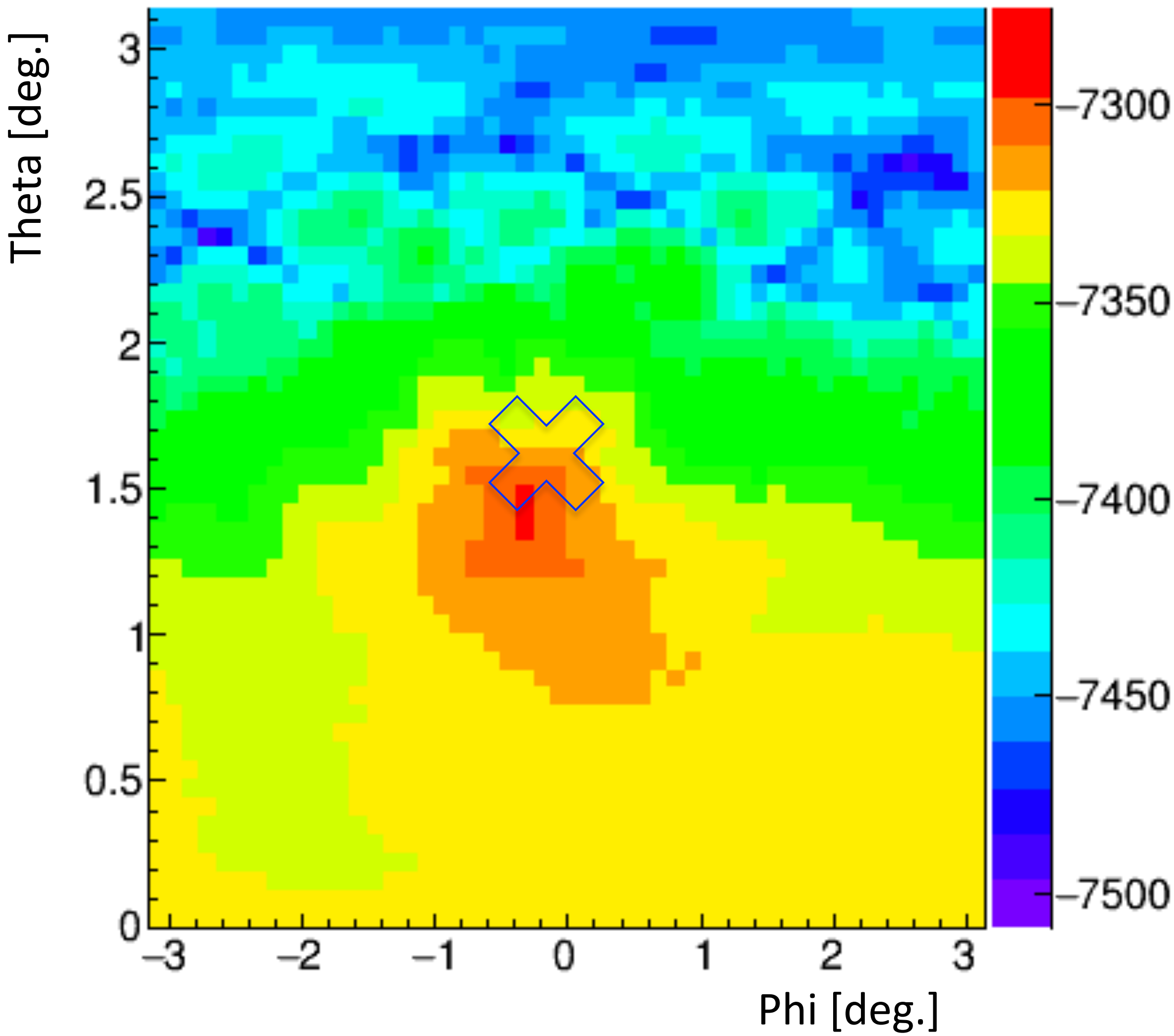
Not hit PMTs



Event Probability: Position



Event Probability: Direction



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How to solve the 8D integral?

$$P(data|H) = \sum_i \left[\log \int P(ev_i|\, x_{true}) \cdot P^{det}(x_{true}) \cdot \mu(x_{true}\ | H)\, dx_{true}\right] - \mu^{tot}(H)$$

- Interaction vertex position (3D)
- Interaction time (1D)
- (Neutrino) Direction (2D)
- Neutrino Energy (1D)
- Bjorken-y (1D)

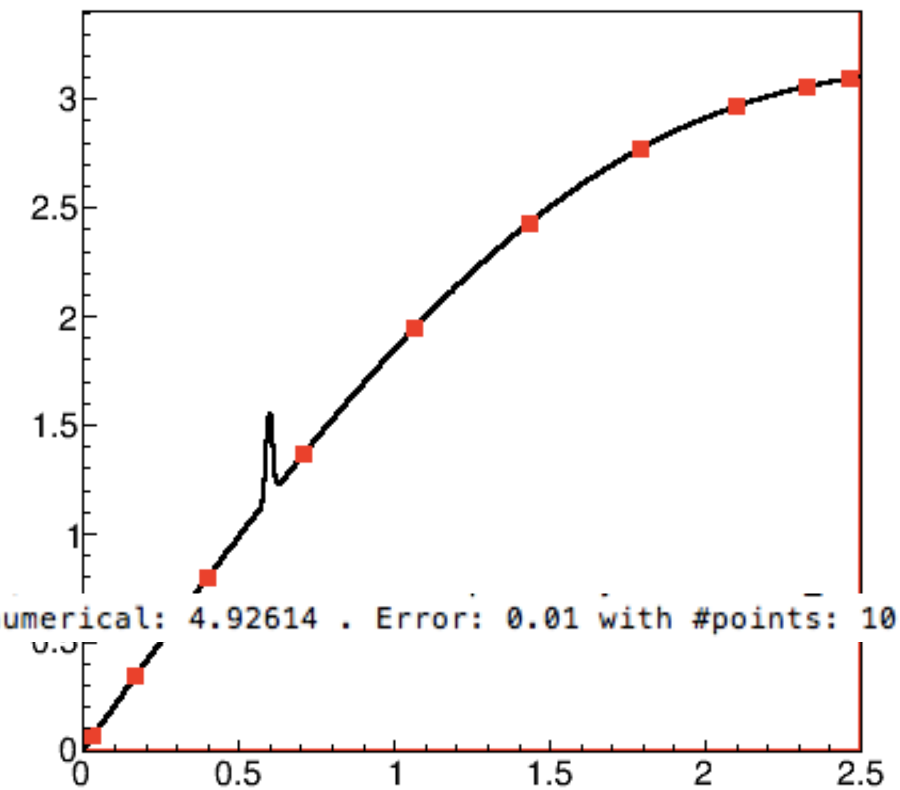
How to solve the ~~8D~~ 6D integral?

$$P(data|H) = \sum_i \left[\log \int P(ev_i|\, x_{true}) \cdot P^{det}(x_{true}) \cdot \mu(x_{true}\ | H)\ dx_{true}\right] - \mu^{tot}(H)$$

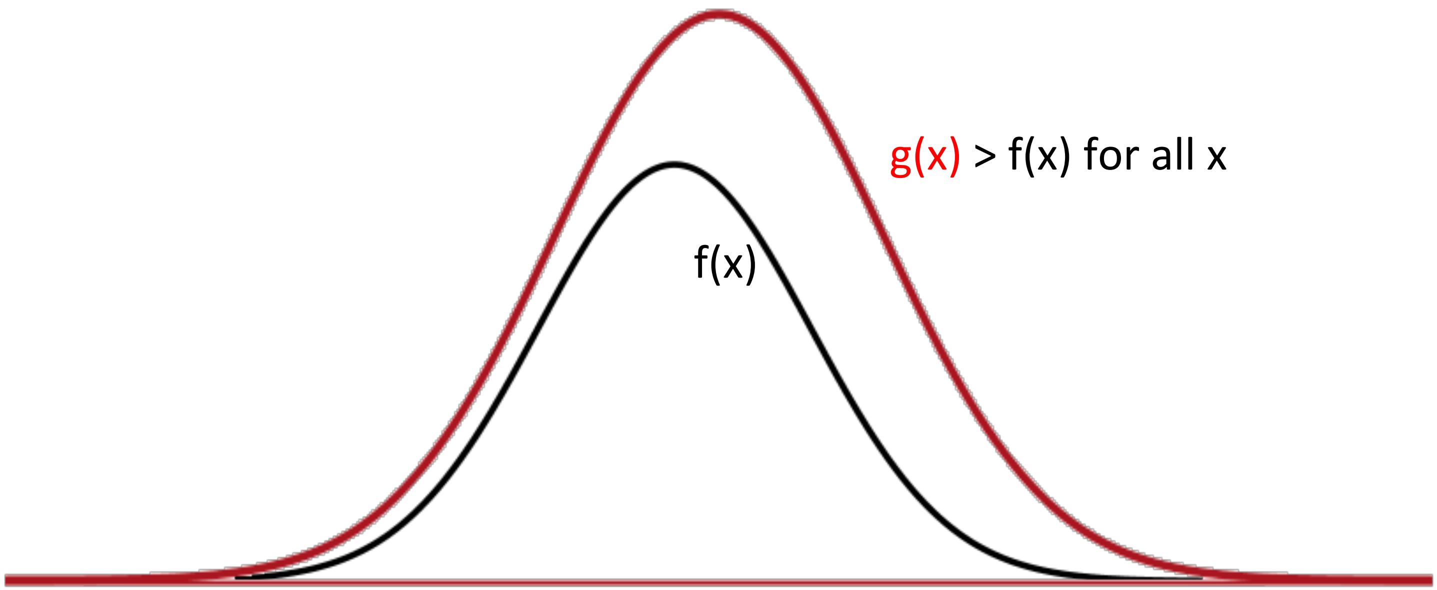
- Interaction vertex position (3)
- Interaction time (1)
  - Relatively easy once other params. are given?
- (Neutrino) Direction (2)
- Neutrino Energy (1)
  - Analytically?
- Bjorken-y (1)

Difficulties

- Event PDF is in general sharply peaked
  - ~1 degree (showers), ~0.1 degree (tracks)
  - ~1m (showers)
- Algorithm generally misses this peak
- Each function evaluation takes time



MC Integration Techniques (1)

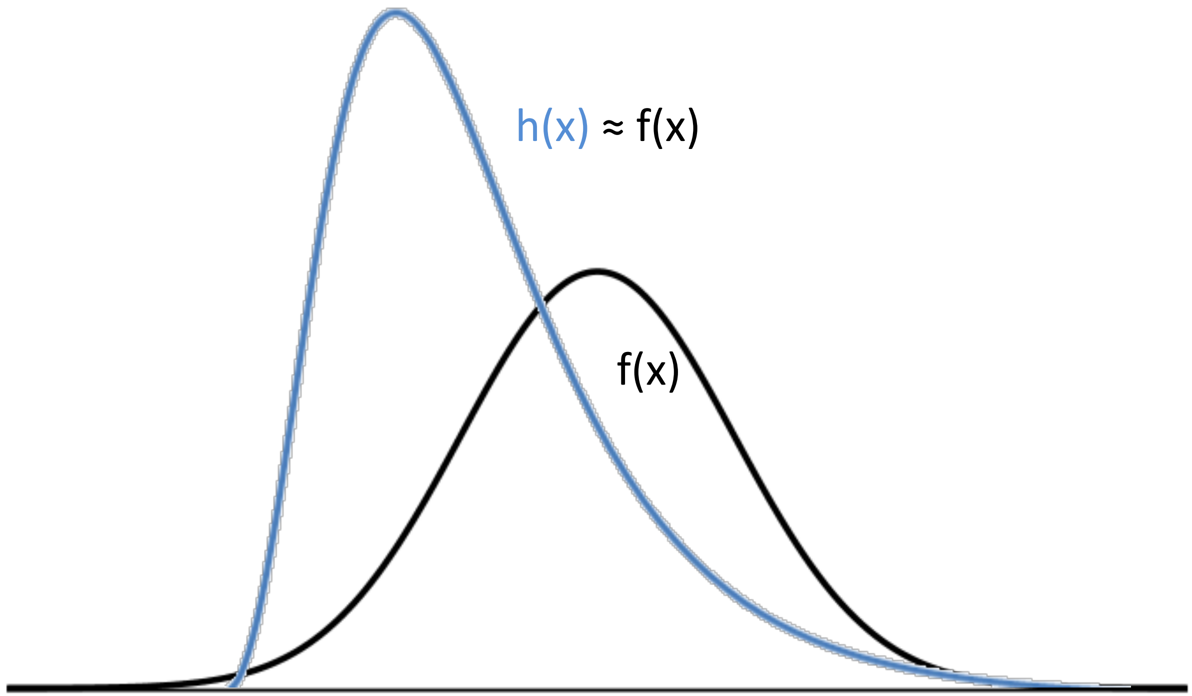


N times:

1) Random x from g(x)
2) Random y, 0<y<g(x)
3) If y <= f(x) { n++ }

I = int f(x) dx = n/N * int g(x) dx

MC Integration Techniques (2)

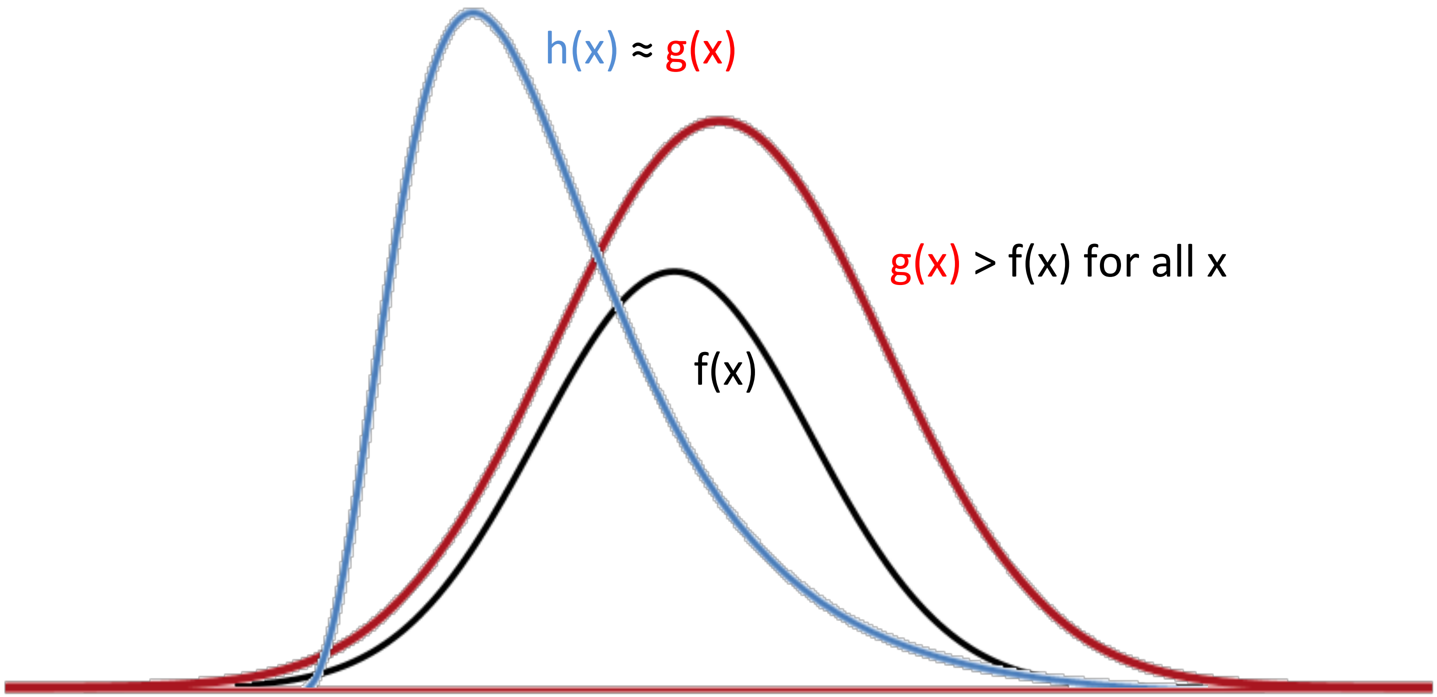


N times:

1) Random x from h(x)
2) A += f(x)/h(x)

I = int f(x) dx = A/N * int h(x) dx

Combined

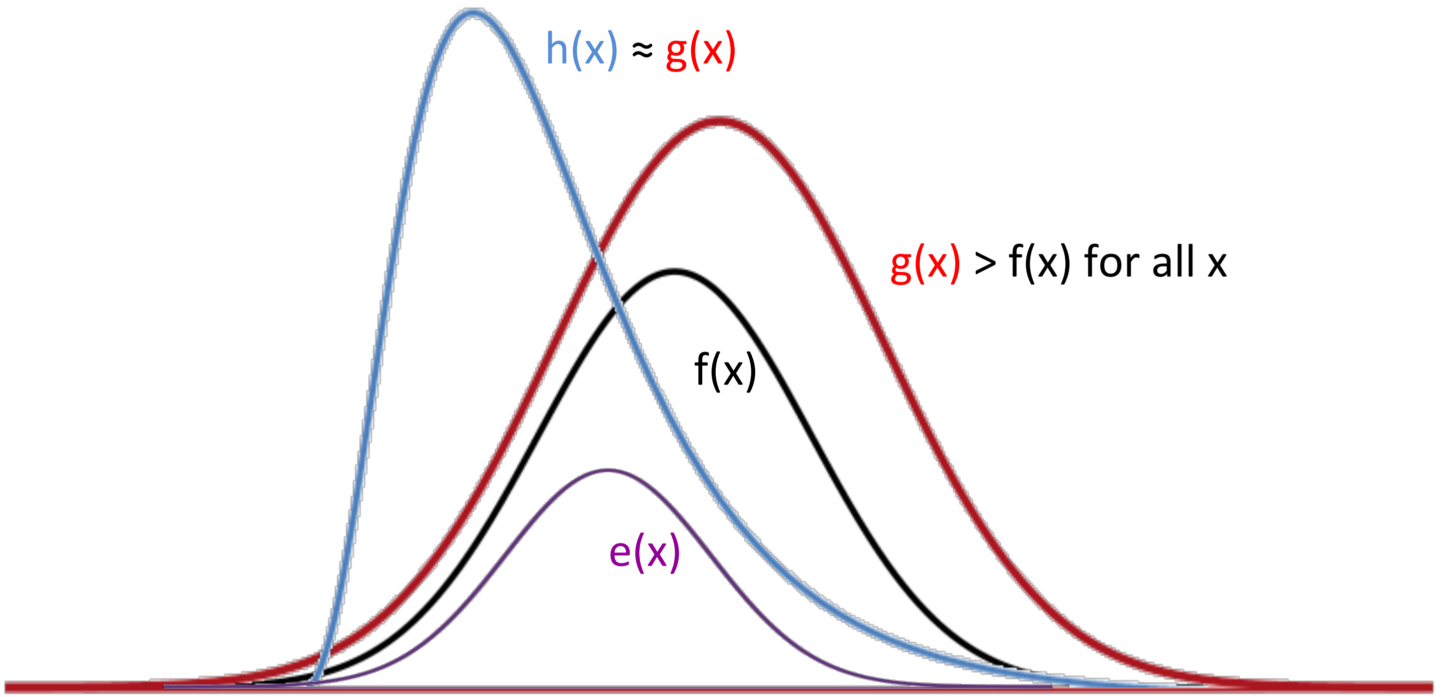


N times:

1) Random x from h(x)
2) A += g(x)/h(x)
3) Random y, 0<y<g(x)
4) If y <= f(x) { n++ }

I = int f(x) dx = n/N^2 * A * int h(x) dx

Combined + Extended

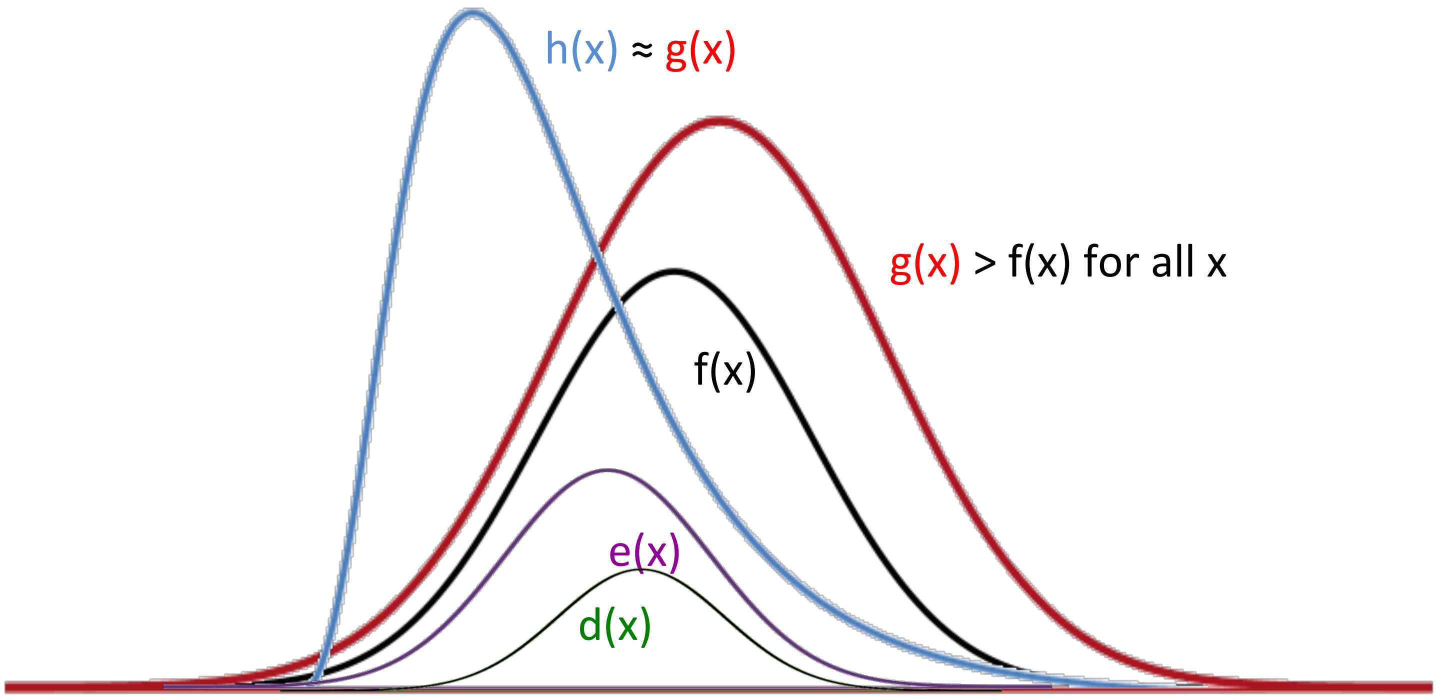


N times:

1) Random x from h(x)
2) A += g(x)/h(x)
3) Random y, 0<y<g(x)
4) If y <= f(x) { if y <= e(x) { n++ } }

$$I = \int e(x)\,dx = n/N^2 * A * \int h(x)\,dx$$

Combined + Extended

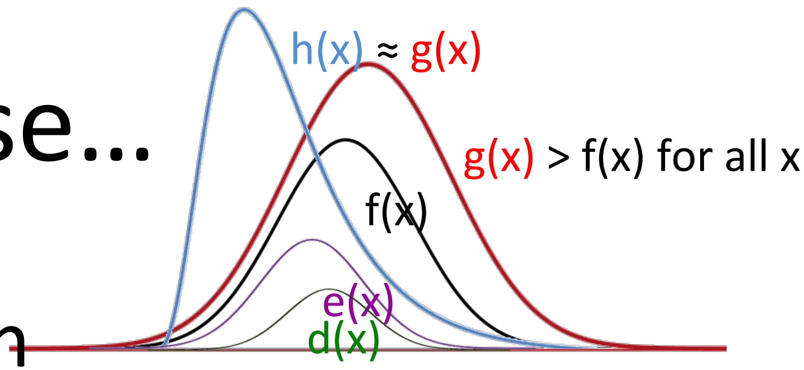


N times:

1) Random x from h(x)
2) A += g(x)/h(x)
3) Random y, 0<y<g(x)
4) If y <= f(x) { if y <= e(x) { if y <= d(x) { n++ } } }

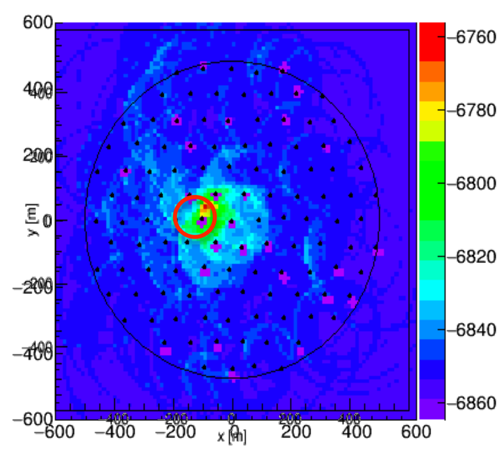
I = int d(x) dx = n/N^2 * A * int h(x) dx

In our case…

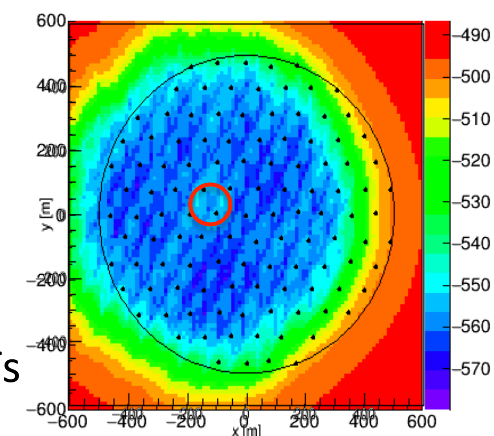


- h(x): some guiding function
- g(x): P(ev | x) over a small subset of PMTs
- f(x): P(ev | x) with slightly more PMTs
- e(x): P(ev | x) over a even more PMTs
- d(x): P(ev | x) with all PMTs

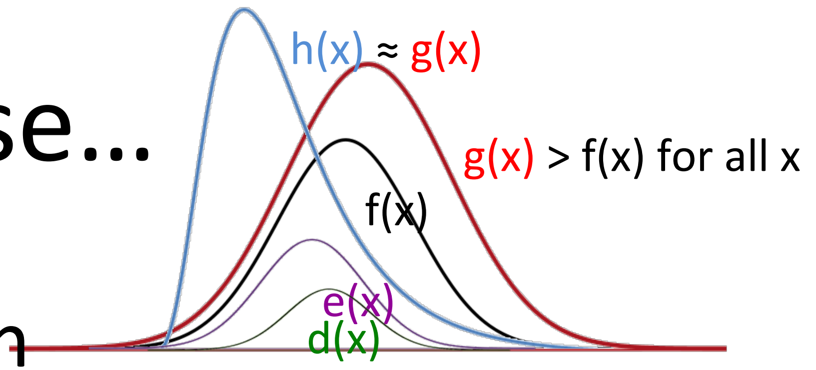
Hit PMTs



Non hit PMTs



In our case…



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- g(x): P(ev | x) over a small subset of PMTs
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- e(x): P(ev | x) over a even more PMTs
- d(x): P(ev | x) with all PMTs

N times:

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3) Random y, 0<y<g(x)
4) If y <= f(x) { if y <= e(x) { if y <= d(x) { n++ } } }

I = int d(x) dx = n/N^2 * A * int h(x) dx

Guiding function

- Convenient choice: multivariate normal distribution
  - tracks: JPrefit PDF
  - Showers: ????

Guiding function

- Convenient choice: multivariate normal distribution
  - tracks: JPrefit PDF
  - Showers: ????

MASTER THESIS

Reconstruction of High-energy Neutrino-induced Particle Showers in KM3NeT.

BY

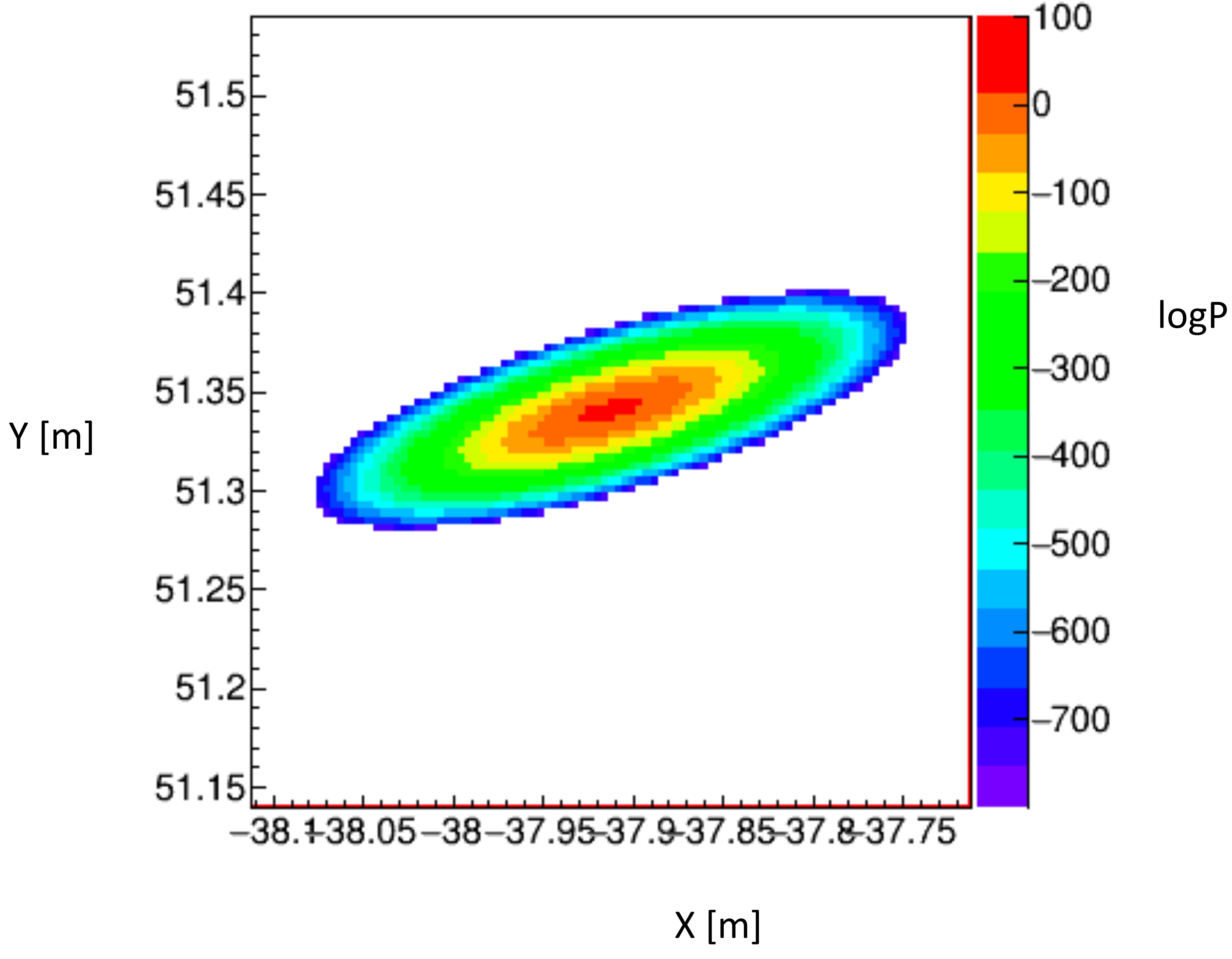
www.nikhef.nl/~kmelis/Masters_Thesis.pdf/Thesis.pdf

Shower Vertex PDF

- Basically a Chi^2 distribution
  - Very sensitive to outliers (i.e. ^{40}K hits)

- Use first triggered hit on each DOM
- Hit clustering algorithm:
  - If many hits: iteratively remove worst hit
  - If #hits <=16: Try all combinations

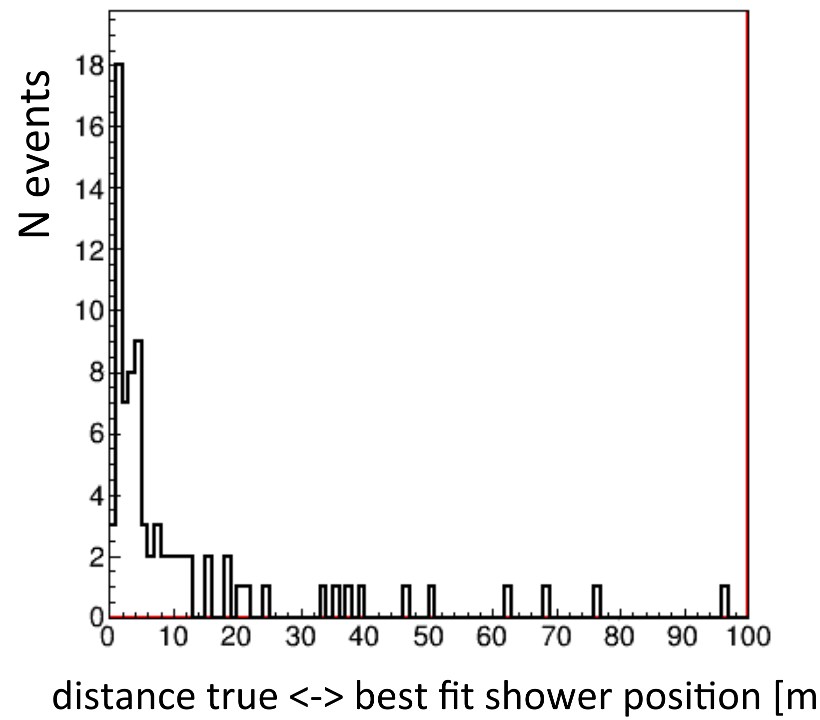
Shower Vertex PDF



Bonus: Shower Position Reconstruction

- Reasonable resolution:
  - median ~1m
- Principle (cluster+ chi^2) usable for tau double bang prefit?

Preliminary

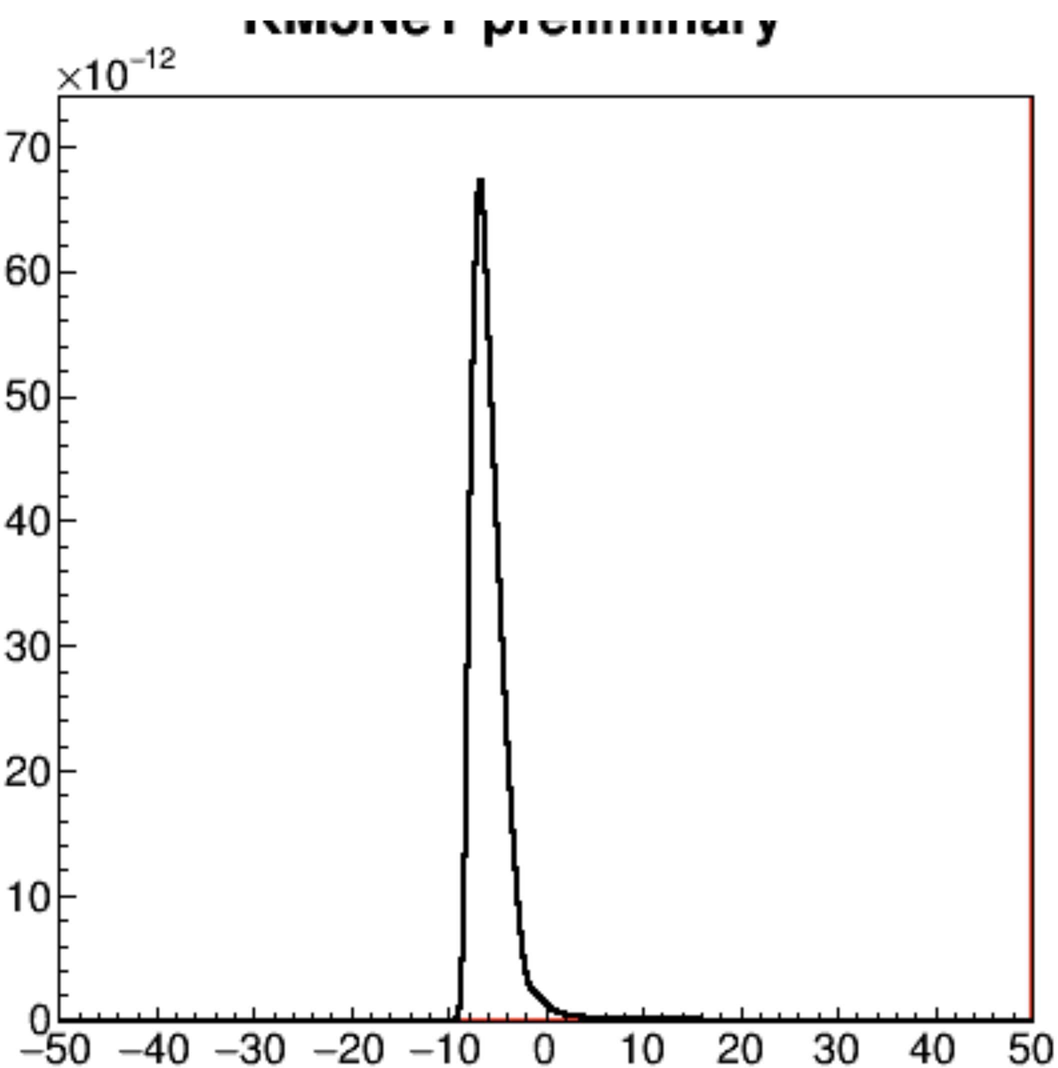


Conclusions

- Most ingredients seem 
  - Neutrino background and signal fluxes
  - Detection efficiency tables
  - Event probability
- Integral evaluation seems feasible with MC techniques

- BONUS bij AH Willems :
  - Shower prefit (+tau double bang prefit?)
  - Very fast neutrino MC simulator

Integrating over time

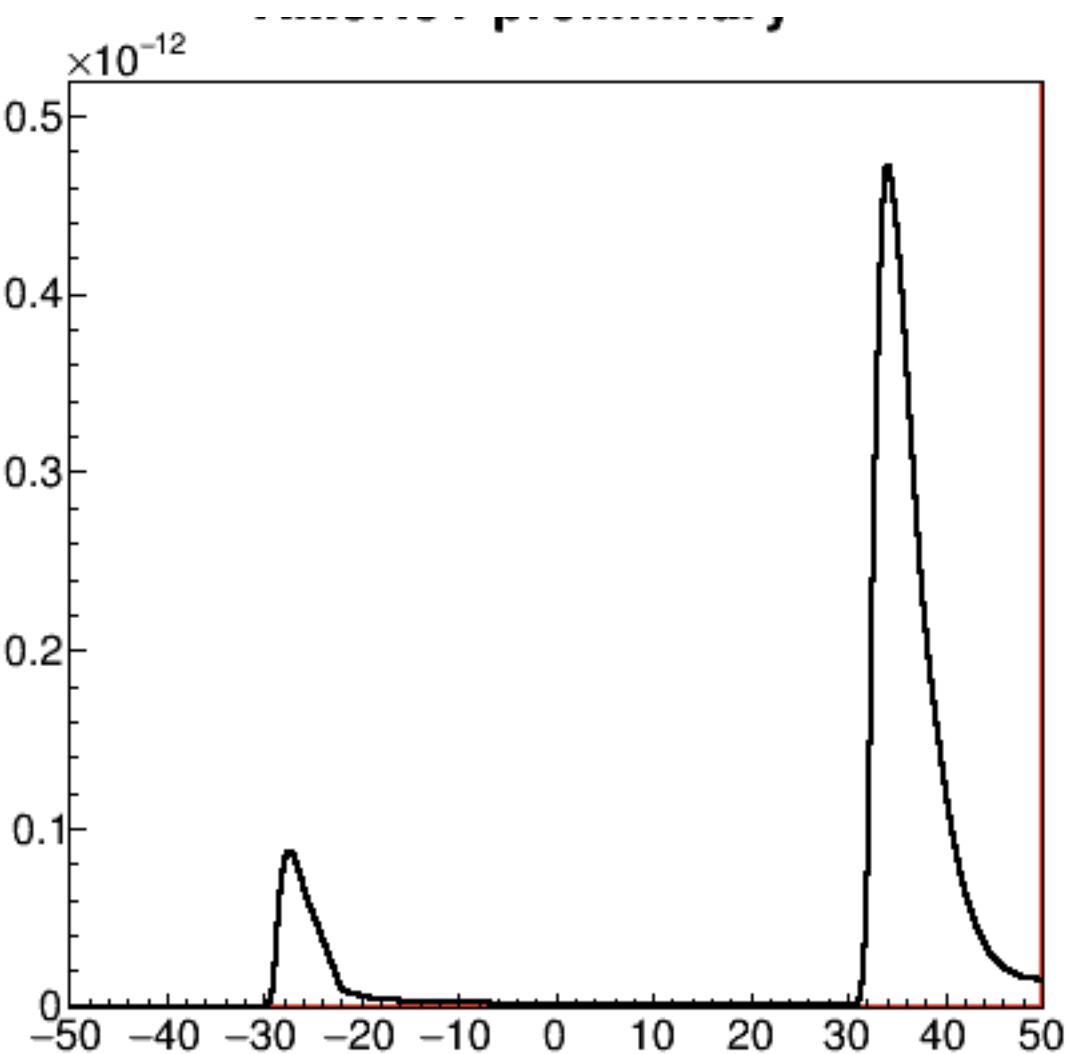



```
int P dt: 0.0002365506325

 377.504 ms elapsed
 377.943 ms user
   0.000 ms system
```

For 3e6 points (& 2PMTs hit)

Integrating over time




```
int P dt: 3.740579387e-06

   371.486 ms elapsed
   370.943 ms user
     0.000 ms system
 99%CPU
```

Hypothesis Testing

- Two hypotheses:
  - H0: background flux only
  - H1: background + signal flux

- Criterium when to select H1
  - P(accept H1 | H0 = true) < 0.000.. (5 sigma)

Likelihood ratio

- Best criterium:

$$\lambda = \log\left[P\left(data|H1\right)\right] - \log\left[P\left(data|H0\right)\right]$$

- Data ‘looks like’ H1 => high lambda

- Criterium when to select H1
  - Accept H1 if lambda > lambda_{crit}
  - P(accept H1 | H0 = true) < 0.000.. (5 sigma)

Likelihood ratio

- Likelihood ratio:

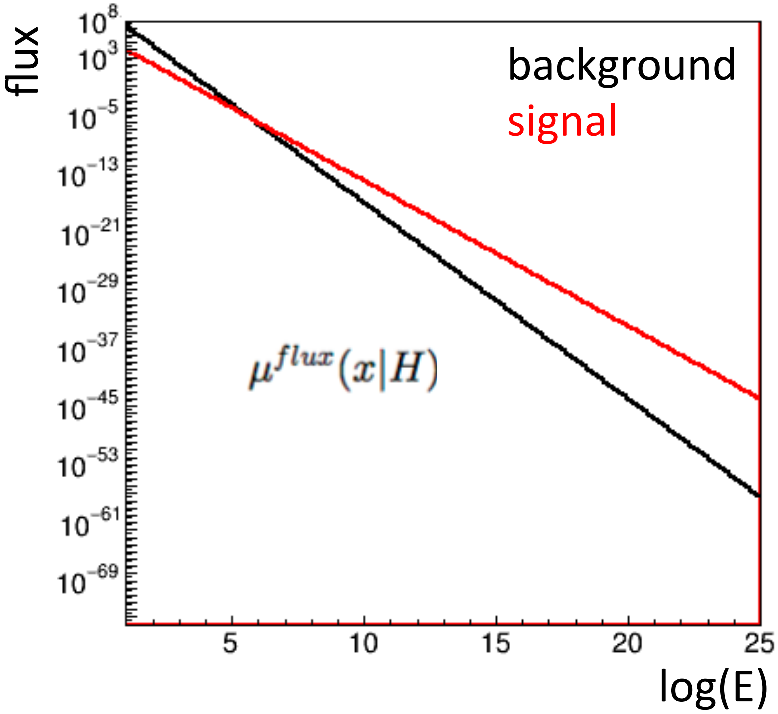
$$\lambda = \log\left[P\left(data|H1\right)\right] - \log\left[P\left(data|H0\right)\right]$$

$$\log\left[P\left(data|H\right)\right] = -\mu_{tot}(H) + \sum_{events} log\left[\int P(ev_i|x)\cdot P^{det}(x)\cdot \mu^{flux}(x|H)dx\right]$$

$\mu_{tot}(H)$	Total number of expected detected events from H
$P(ev_i\|x)$	Probability to obtain measured event ev_i **given** a certain (8D) neutrino hypothesis x
$P^{det}(x)$	Probability to detect (=trigger) and select event
$\mu^{flux}(x\|H)$	Number of expected events from H in our detector (can)

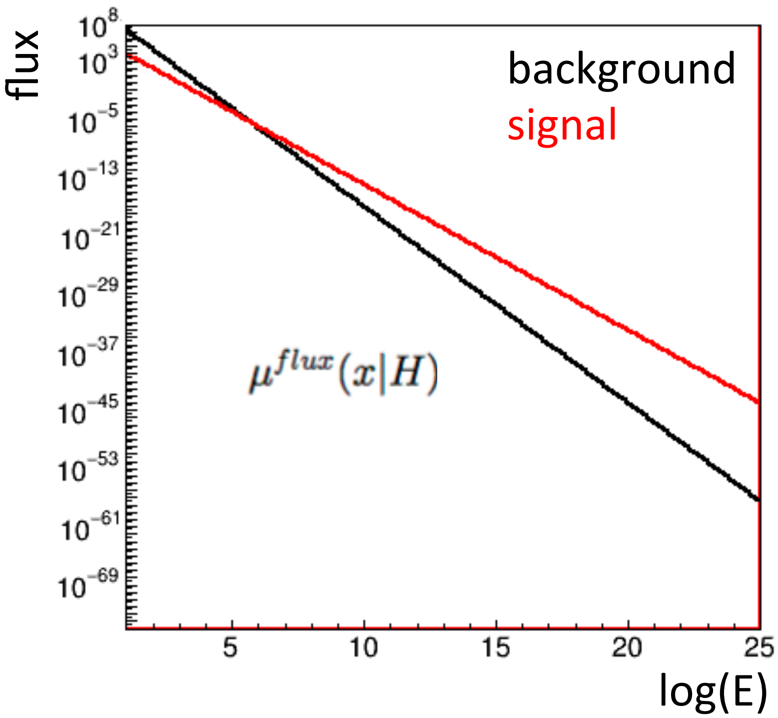
Example (1D)

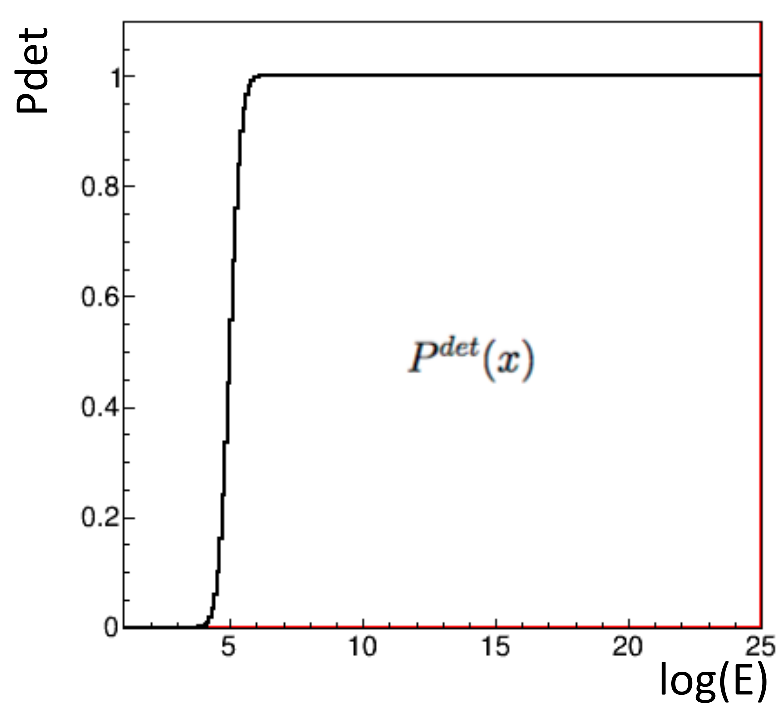
- Neutrino only has energy



Example (1D)

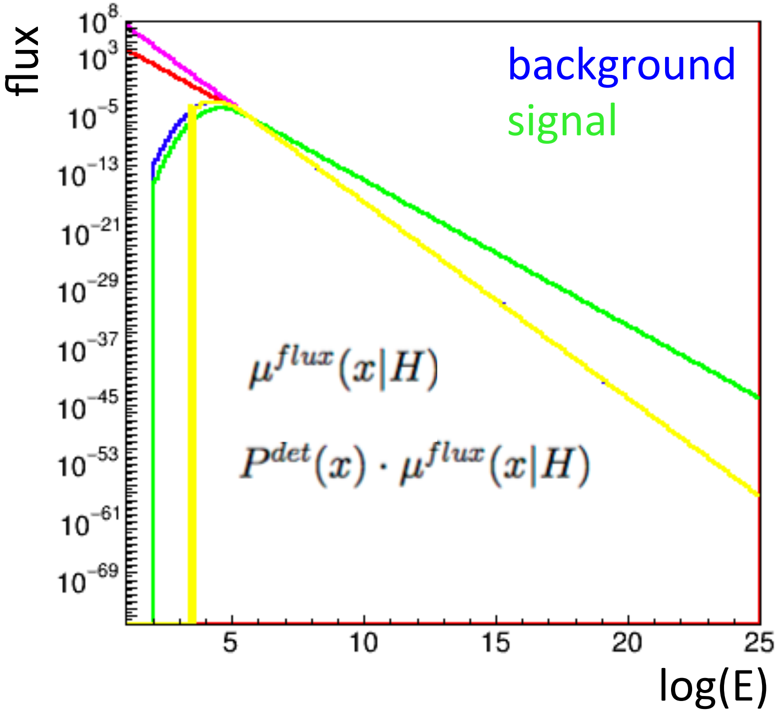
- Neutrino only has energy

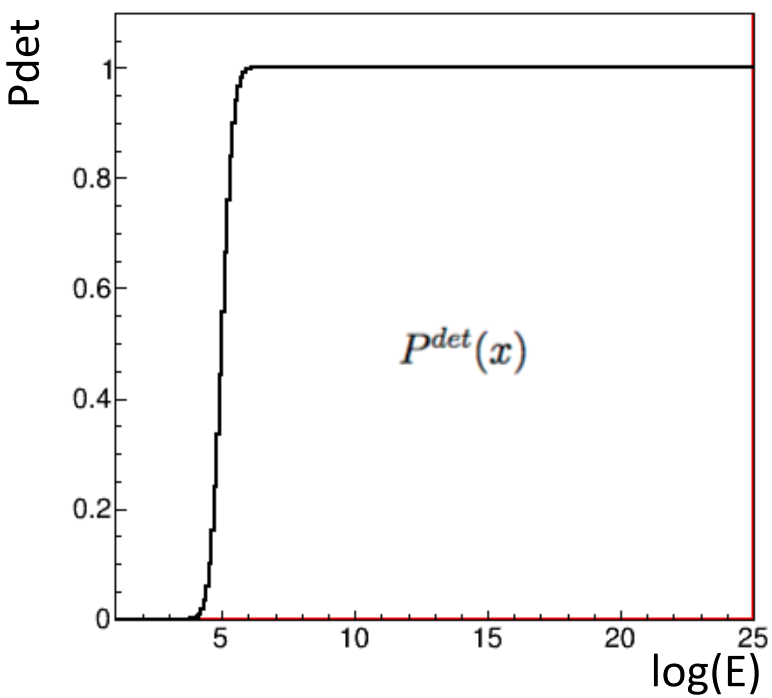




Example (1D)

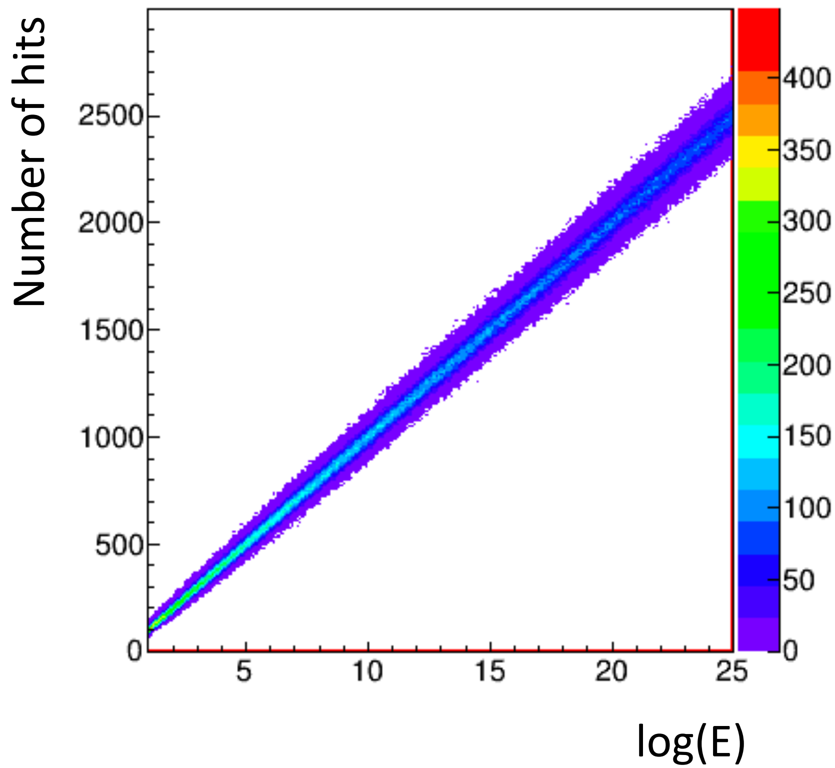
- Neutrino only has energy





Example (1D)

- Neutrino only has energy
- Event only measures number of hits



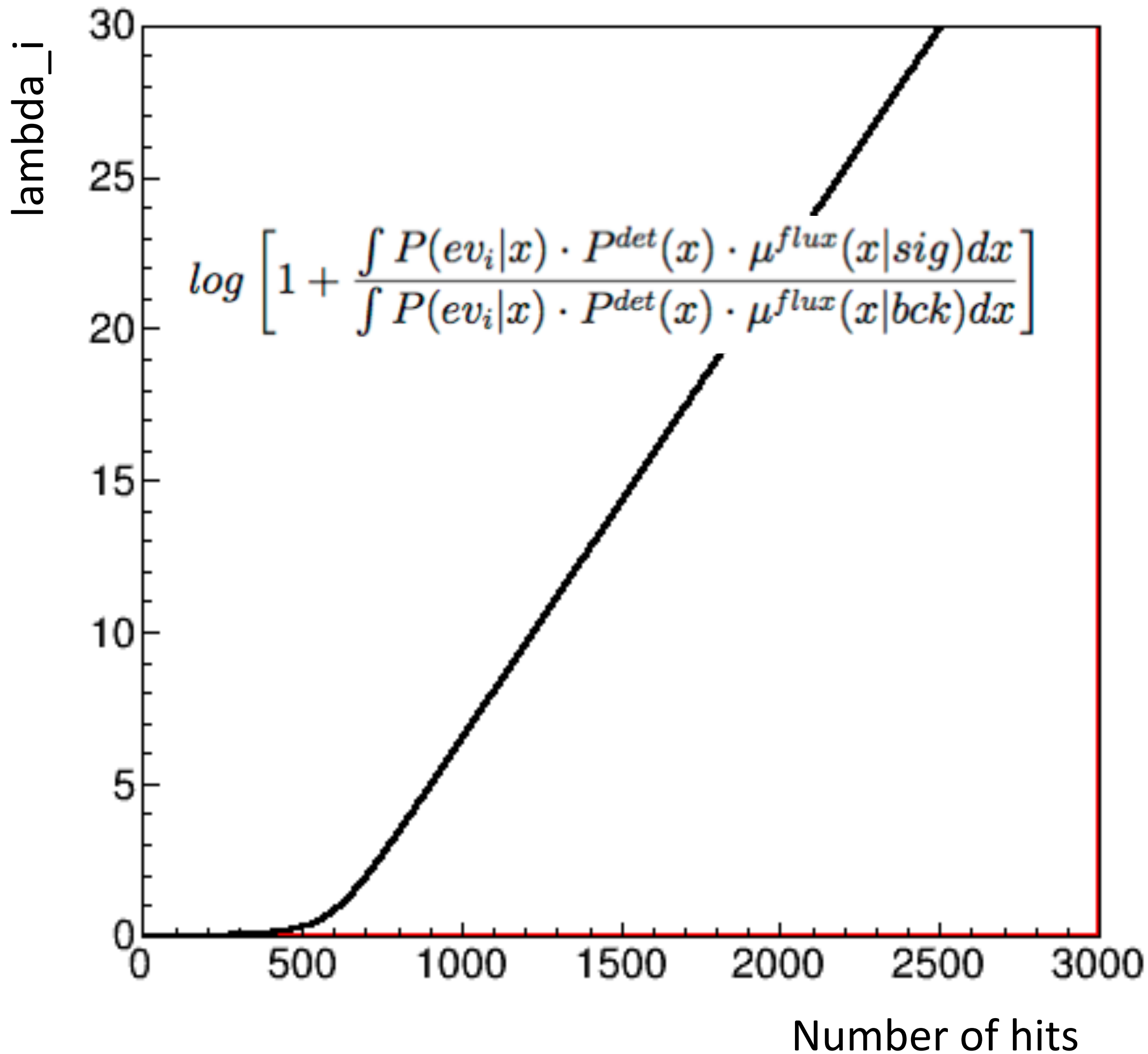
Example (1D)

- Neutrino only has energy
- Event only measures number of hits

$$\lambda = \log\left[P\left(data|bck+sig\right)\right] - \log\left[P\left(data|bck\right)\right]$$
$$= -\mu_{tot}(sig) + \sum_{events} log\left[1 + \frac{\int P(ev_i|x)\cdot P^{det}(x)\cdot \mu^{flux}(x|sig)dx}{\int P(ev_i|x)\cdot P^{det}(x)\cdot \mu^{flux}(x|bck)dx}\right]$$

- High number of hits => high energy => data looks like H1 => high lambda

Example (1D)



lambda_i
30
25
20
15
10
5
0
0
500
1000
1500
2000
2500
3000
$$\log\left[1+\frac{\int P(ev_i|x)\cdot P^{det}(x)\cdot\mu^{flux}(x|sig)dx}{\int P(ev_i|x)\cdot P^{det}(x)\cdot\mu^{flux}(x|bck)dx}\right]$$
Number of hits

Likelihood ratio

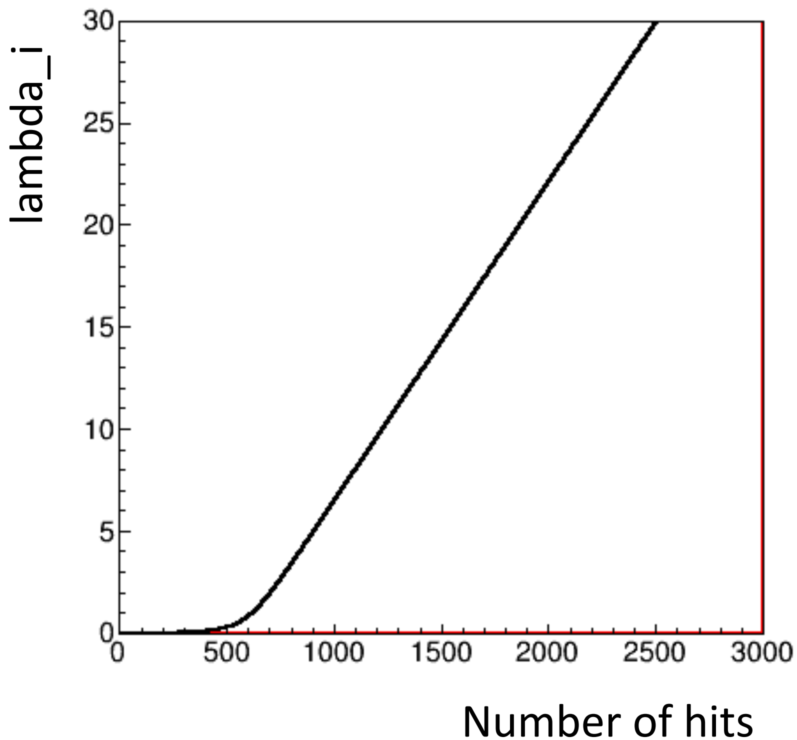
- Best criterium:

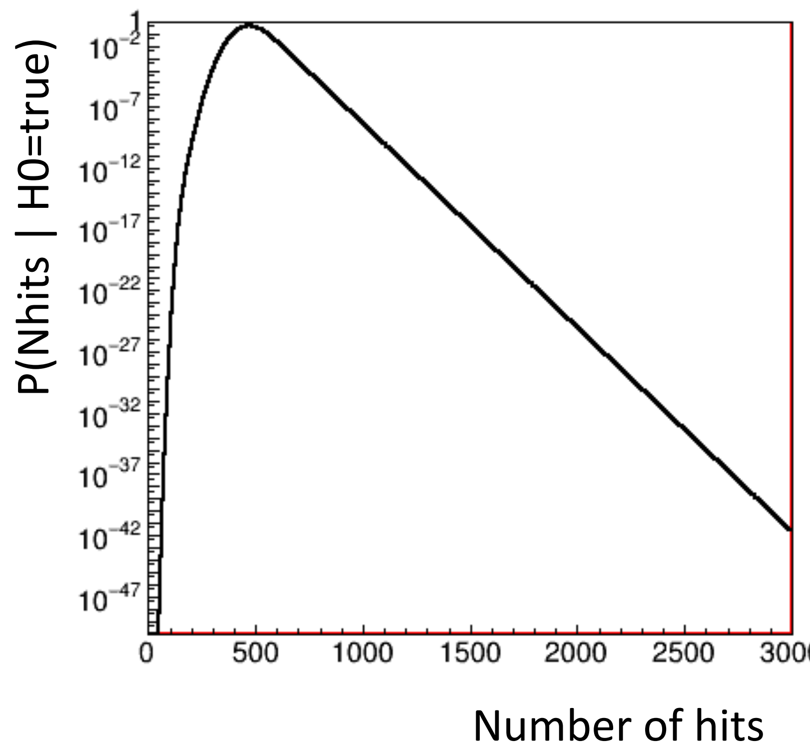
$$\lambda = \log\left[P\left(data|H1\right)\right] - \log\left[P\left(data|H0\right)\right]$$

- Data ‘looks like’ H1 => high lambda

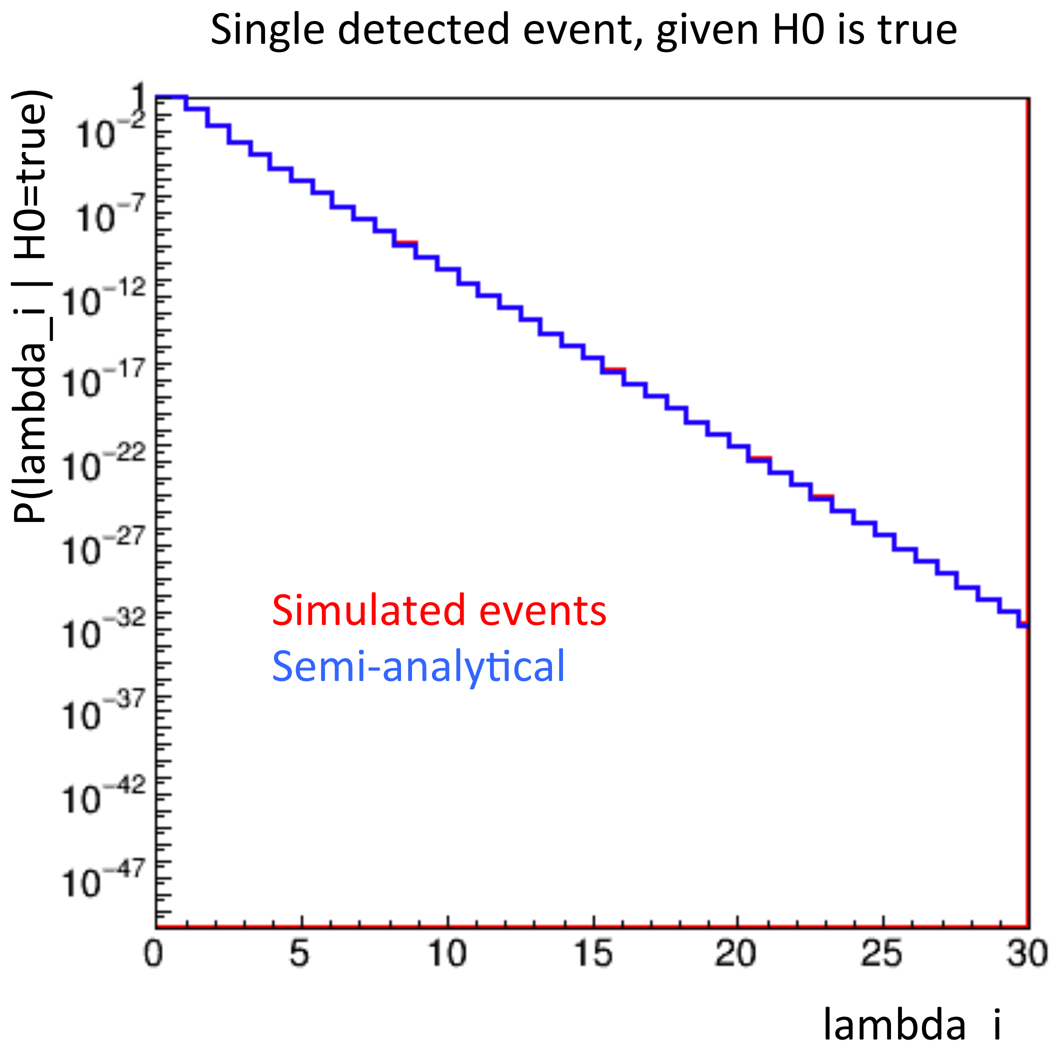
- Criterium when to select H1
  - Accept H1 if lambda > lambda_{crit}
  - P(accept H1 | H0 = true) < 0.000.. (5 sigma)

P(lambda > $\text{lambda}_{\text{crit}}$ | H0 = true) < 0.000.. (5 sigma)



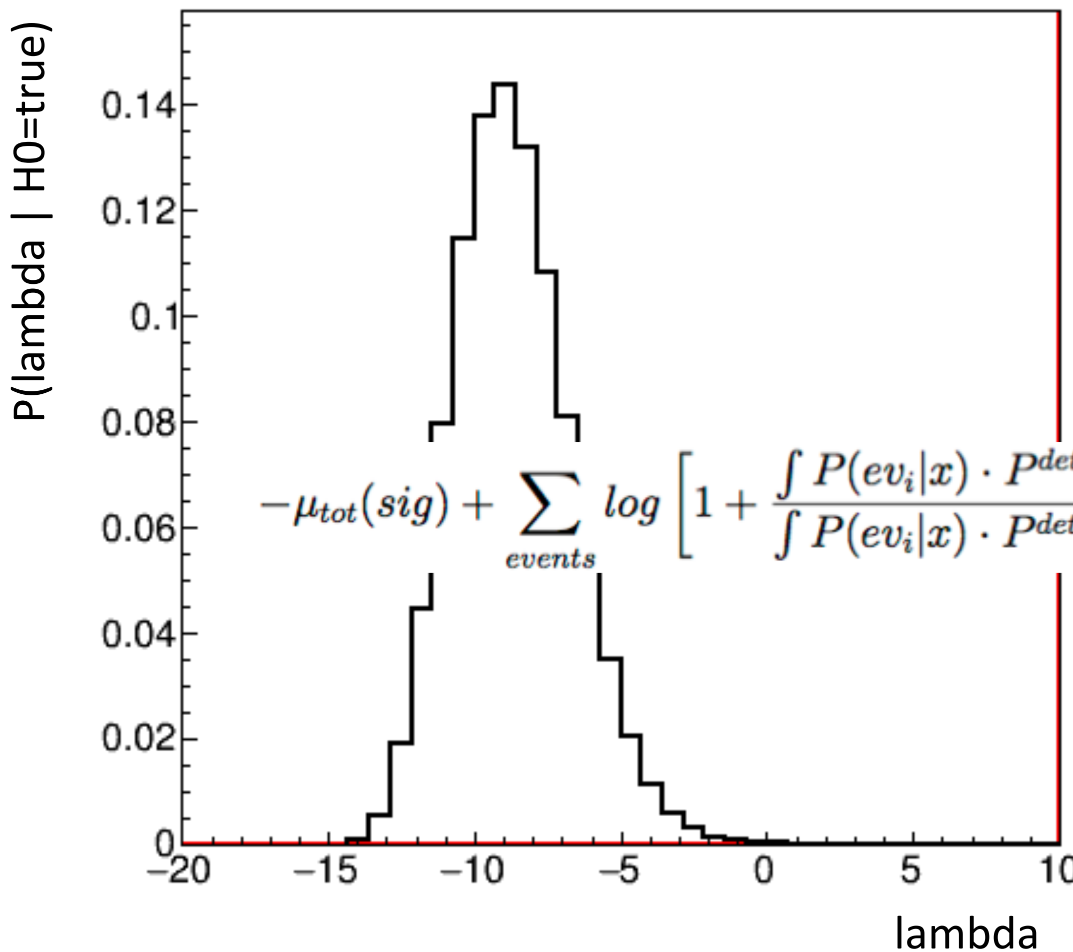


P(lambda > lambda_{crit} | H0 = true) < 0.000.. (5 sigma)



P(lambda > lambda$_{crit}$ | H0 = true) < 0.000.. (5 sigma)

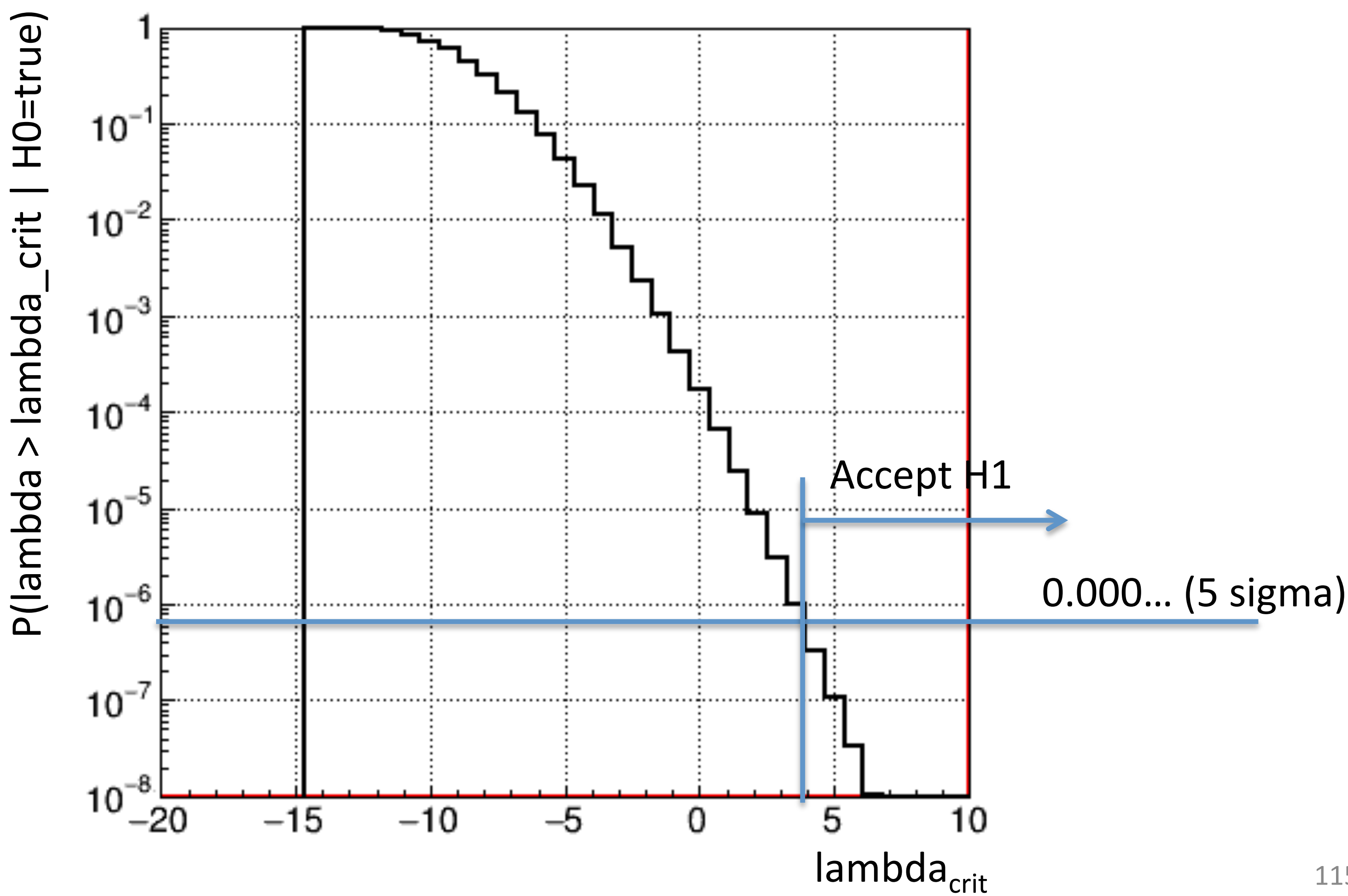
(multiple) detected events in certain timeperiod, given H0 is true



$$-\mu_{tot}(sig) + \sum_{events} log\left[1 + \frac{\int P(ev_i|x) \cdot P^{det}(x) \cdot \mu^{flux}(x|sig)dx}{\int P(ev_i|x) \cdot P^{det}(x) \cdot \mu^{flux}(x|bck)dx}\right]$$

P(lambda > $lambda_{crit}$ | H0 = true) < 0.000.. (5 sigma)

(multiple) detected events in certain timeperiod, given H0 is true



Ter Leering ende Vermaeck

- Now: 3D example (energy + direction)
- Soon: 8D example

- Reproduce conventional method and show that new method works (better)

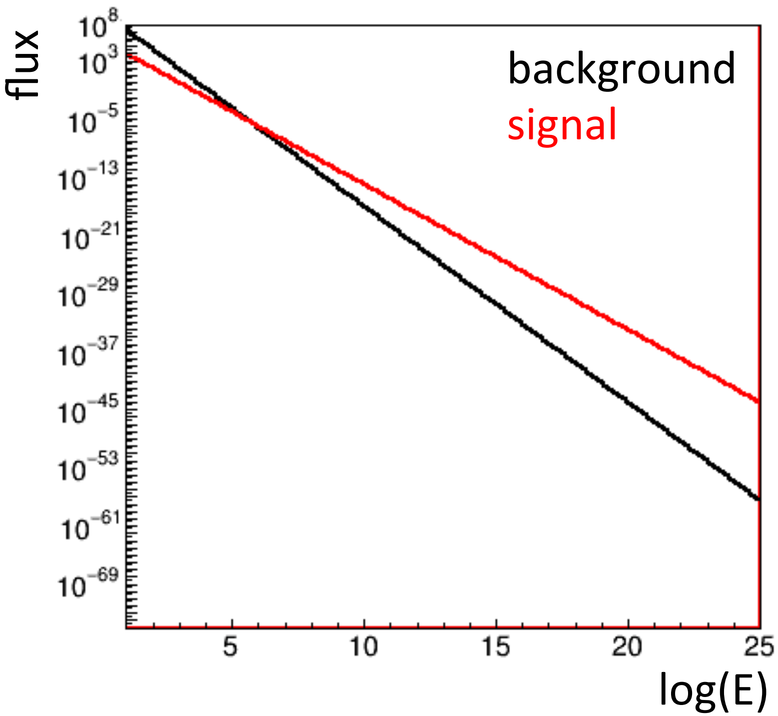
- Replace likelihood terms with real (MC) events

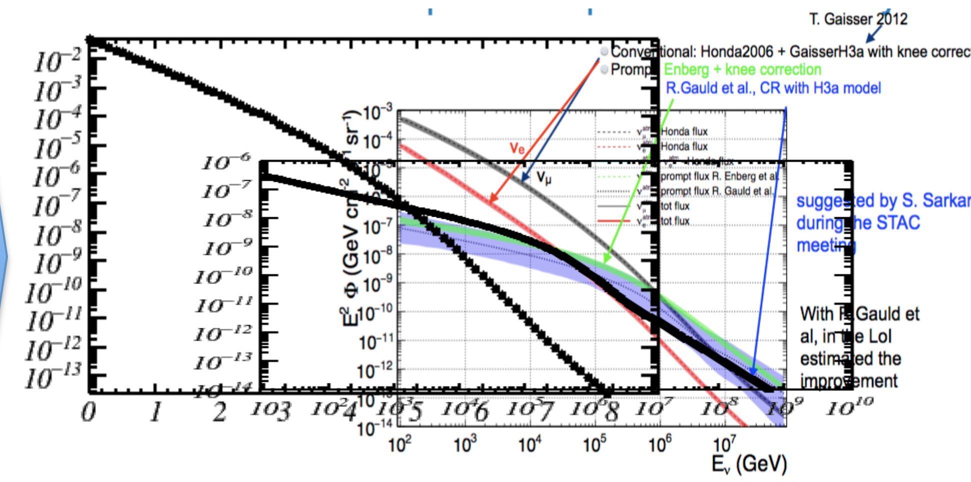
Ter Leering ende Vermaeck

$$\lambda = \log\left[P\left(data|H1\right)\right] - \log\left[P\left(data|H0\right)\right]$$

$$\log\left[P\left(data|H\right)\right] = -\mu_{tot}(H) + \sum_{events} log\left[\int P(ev_i|x)\cdot P^{det}(x)\cdot \mu^{flux}(x|H)dx\right]$$

Fast parameterizations

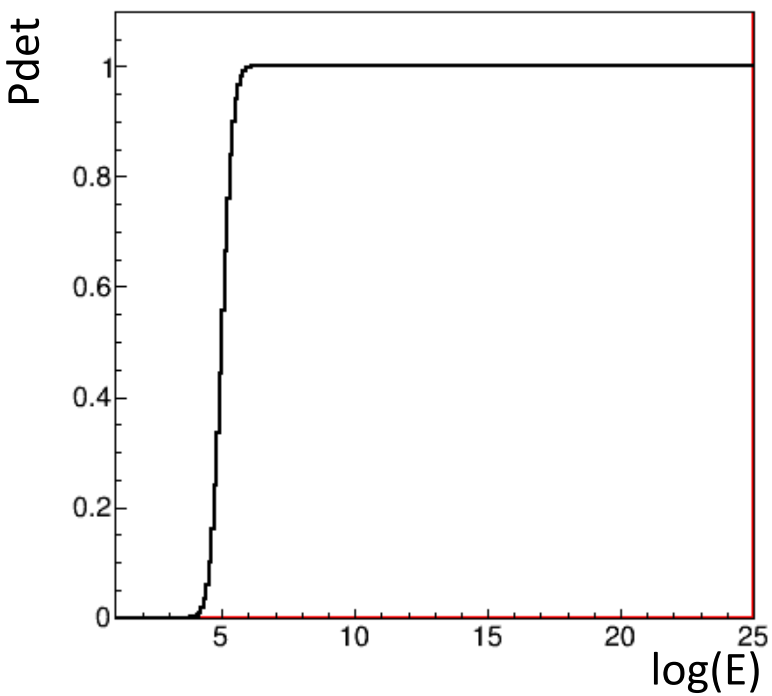




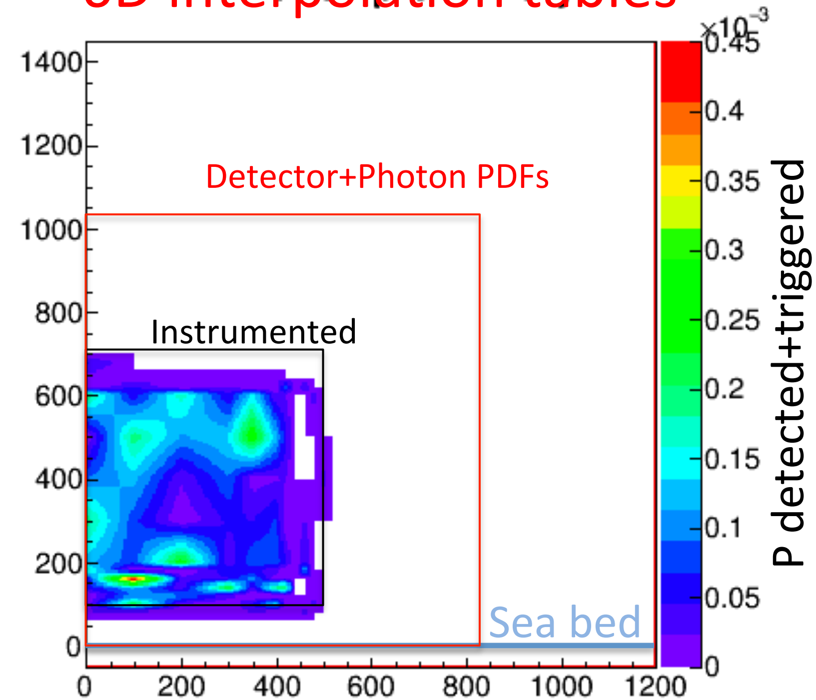
Ter Leering ende Vermaeck

$$\lambda = \log\left[P\left(data|H1\right)\right] - \log\left[P\left(data|H0\right)\right]$$

$$\log\left[P\left(data|H\right)\right] = -\mu_{tot}(H) + \sum_{events} log\left[\int P(ev_i|x)\, P^{det}(x)\, \mu^{flux}(x|H)dx\right]$$



6D interpolation tables



Ter Leering ende Vermaeck

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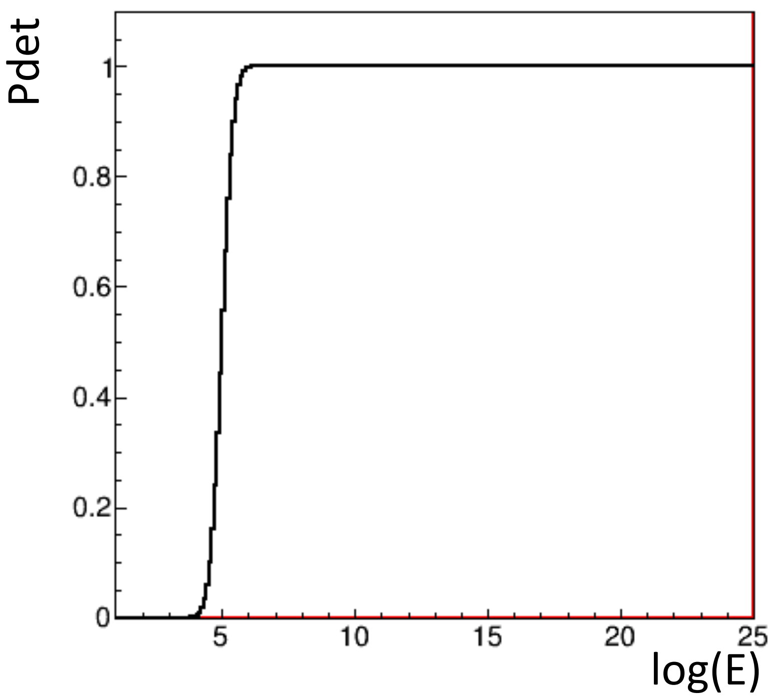
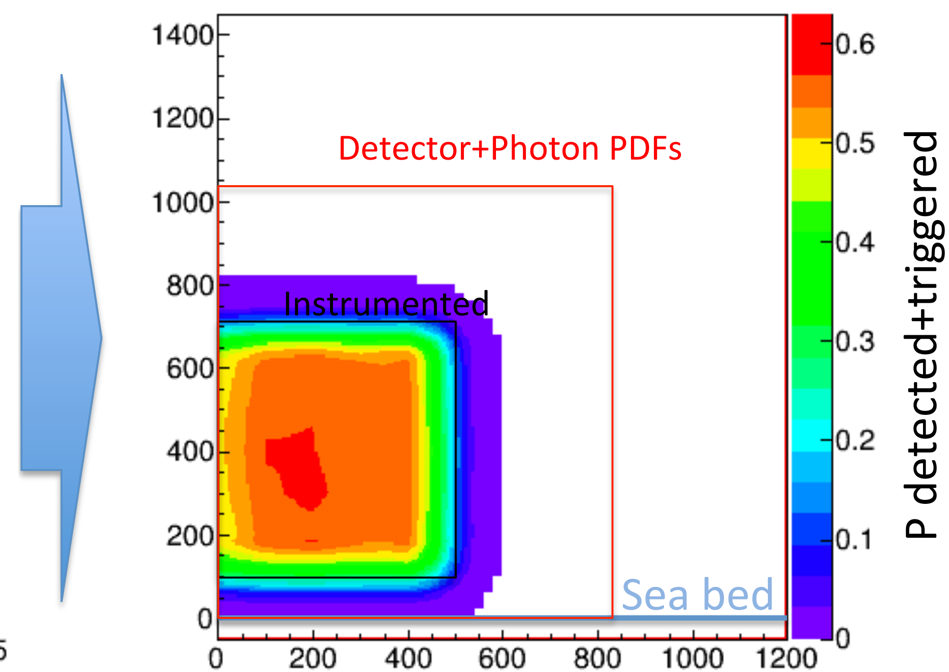
6D interpolation tables





Ter Leering ende Vermaeck

$$\lambda = \log\left[P\left(data|H1\right)\right] - \log\left[P\left(data|H0\right)\right]$$

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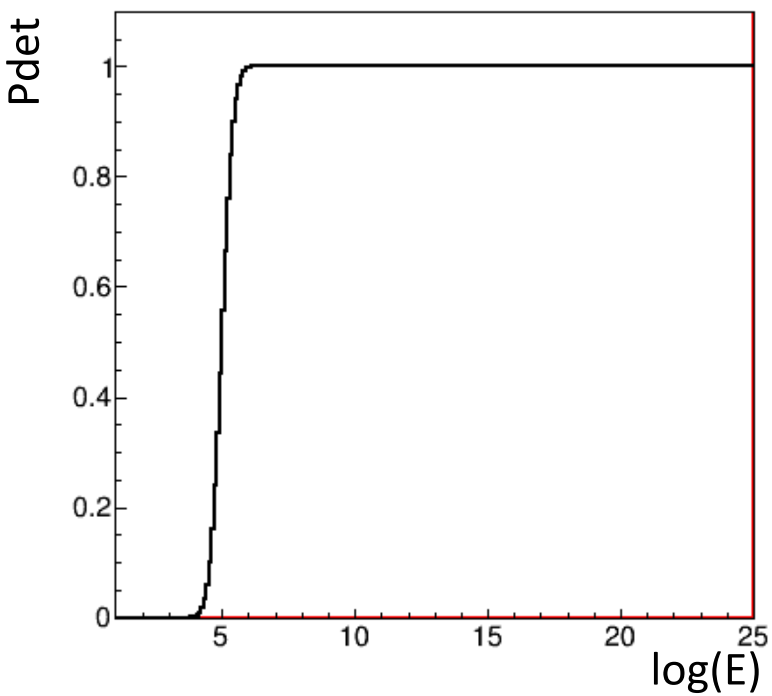
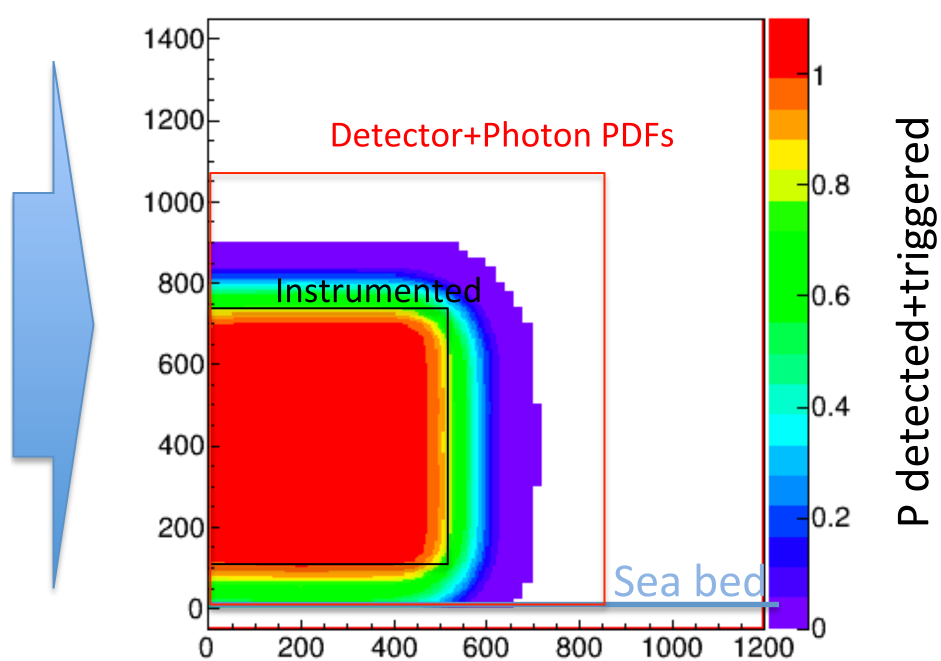
6D interpolation tables





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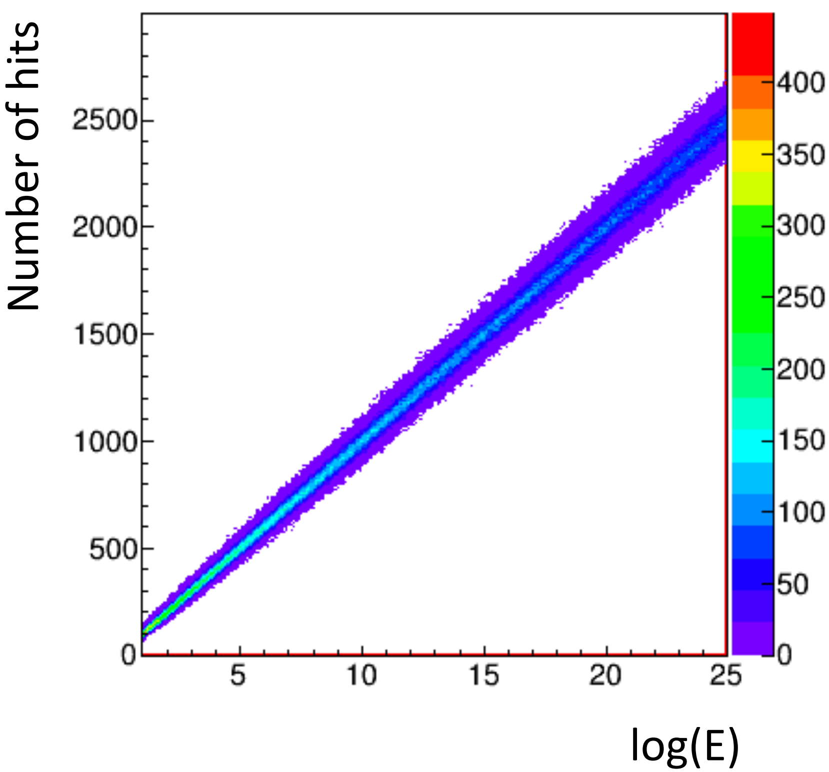
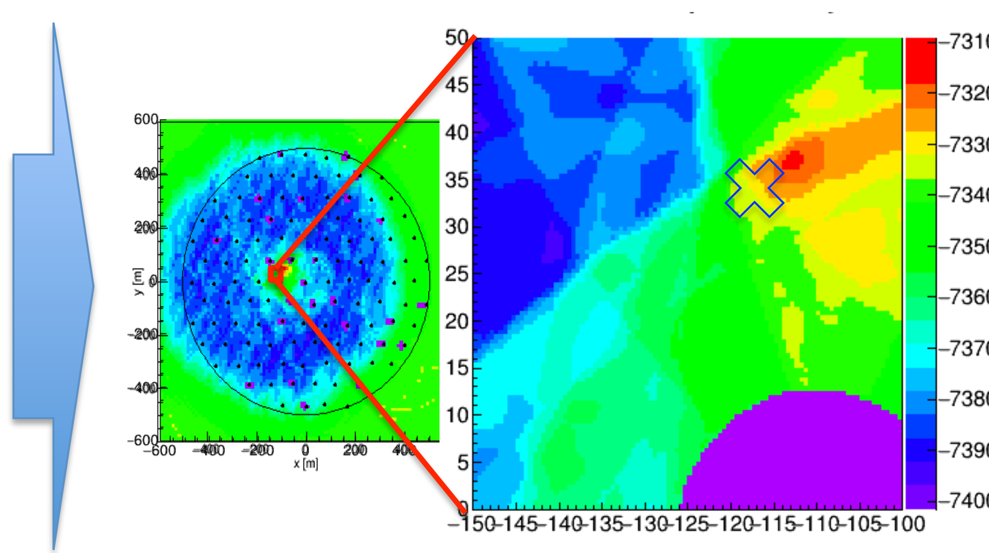
PDF





Outlook

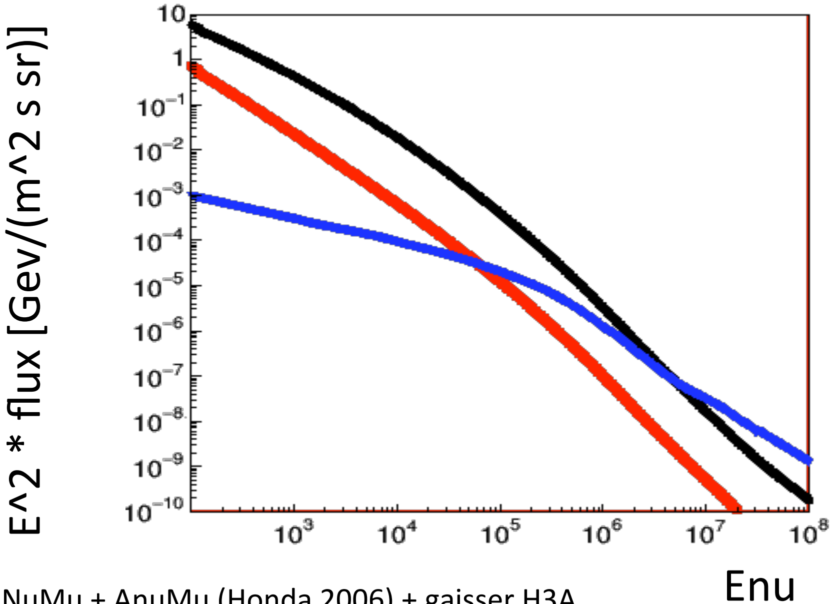
- Proof of principle
- From toy MC to real MC
- Composite hyptheses
- Atm. muon background

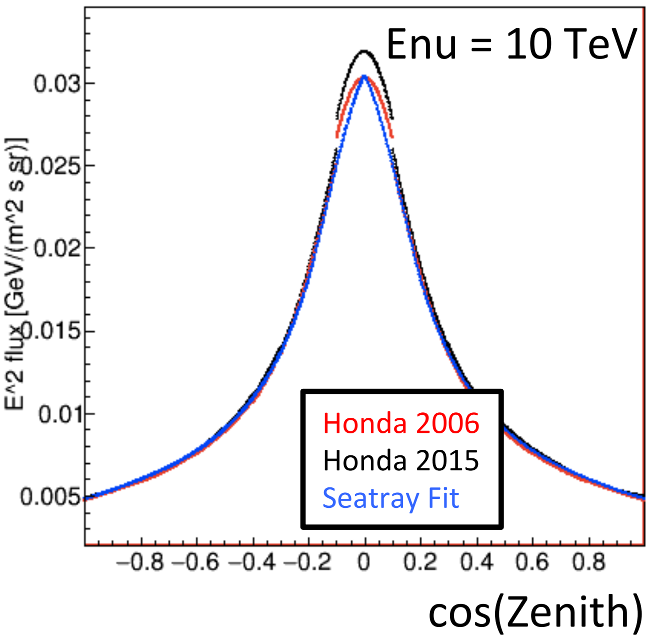
Source Searches

- Observed flux of events
  - Single showers
  - Muon tracks
  - Double bangs
  - Sugar daddy's
- Expected flux
  - H0: atm. neutrinos and atm. muons
  - H1: cosmic source

Expected Flux (Atm. nu bckgr.)

- Neutrino flux @ atmosphere
  - Honda 2006
  - Interpolating 2D tables





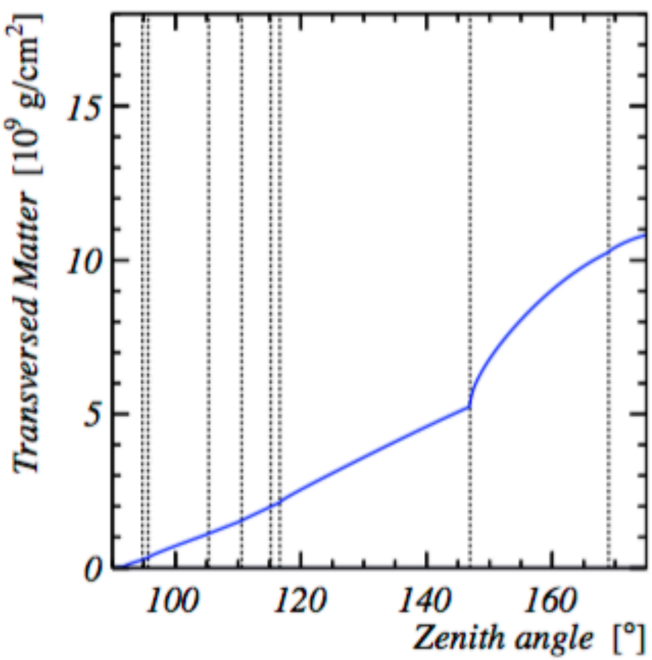
NuMu + AnuMu (Honda 2006) + gaisser H3A

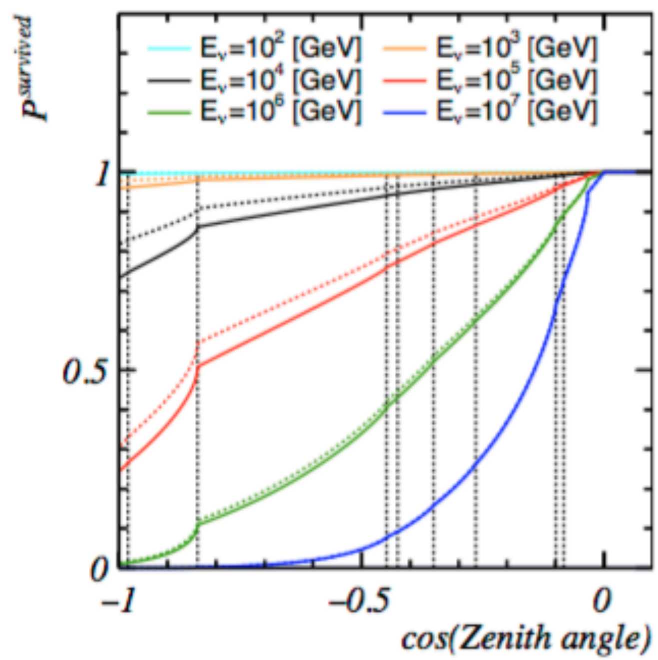
NuE + AnuE (Honda 2006) + gaisser H3A

Prompt flux (indep. of flavor), Gauld, includes H3A

Expected Flux (Atm. nu bckgr.)

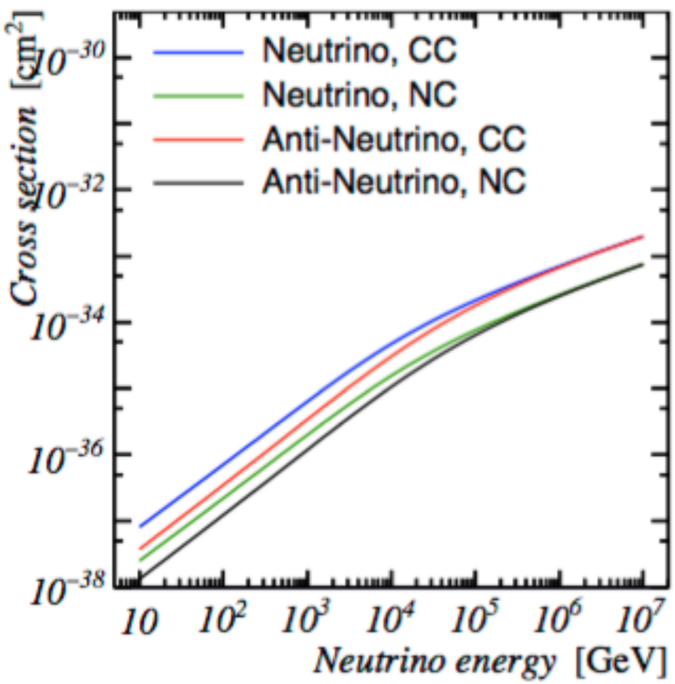
- Neutrino flux @ atmosphere
- Earth propagation
  - Only CC neutrino absorption included
  - No NC scattering / energy losses (yet?)





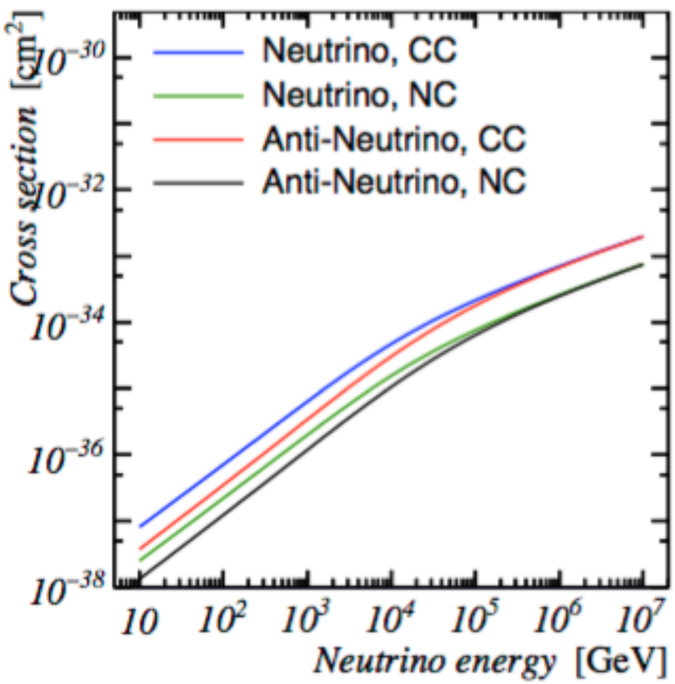
Expected Single Shower Flux

- Neutrino flux @ atmosphere
- Earth propagation
- Interaction probability



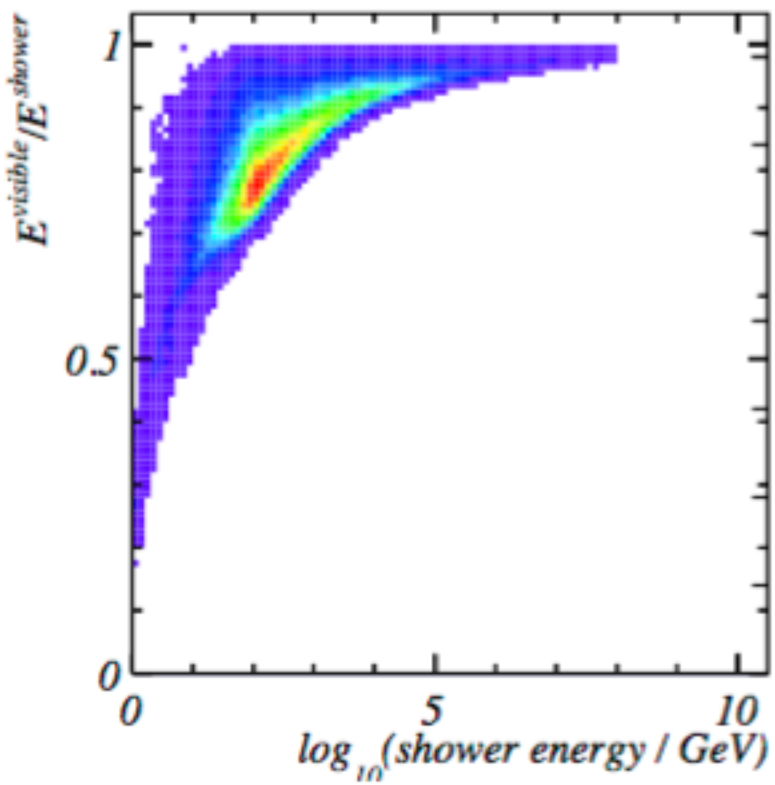
Expected Single Shower Flux

- Neutrino flux @ atmosphere
- Earth propagation
- Interaction probability
- Shower energy (Bjorken-y)

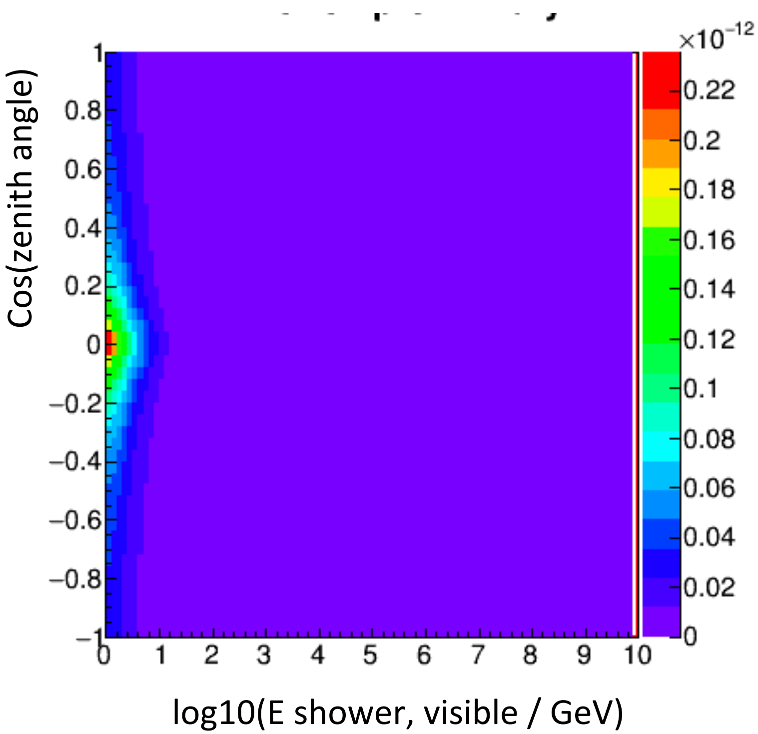


Expected Single Shower Flux

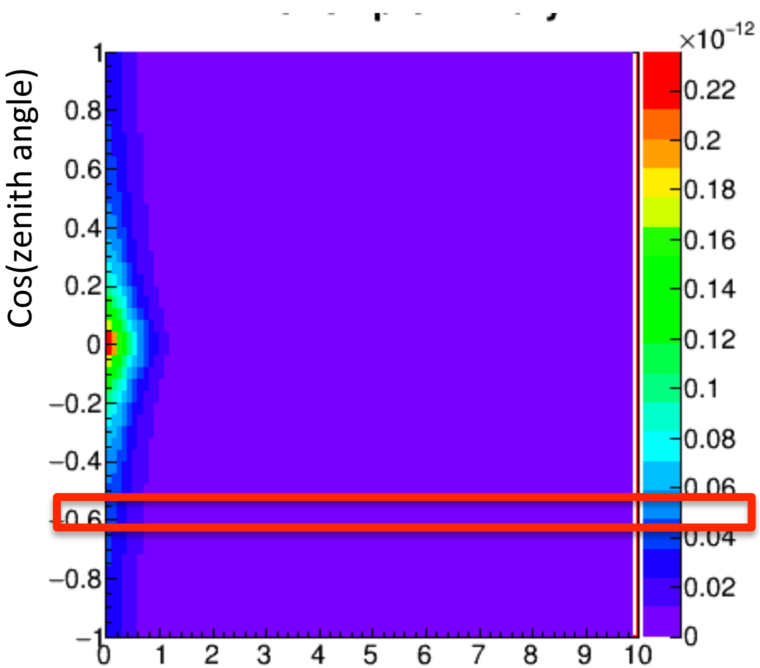
- Neutrino flux @ atmosphere
- Earth propagation
- Interaction probability
- Shower energy (Bjorken-y)
- Visible shower energy
  - How much energy is observable as light?



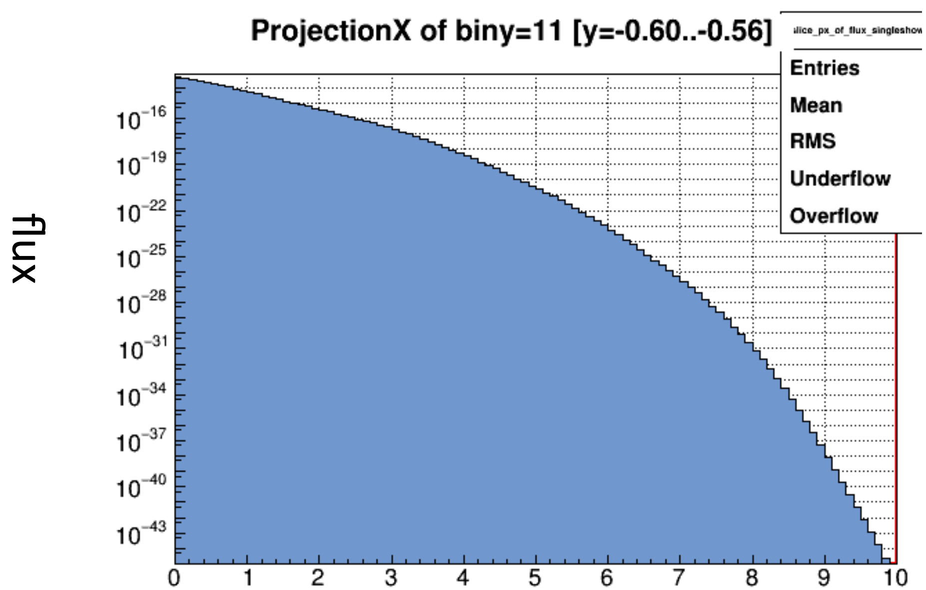
Expected Single Shower Flux



Expected Single Shower Flux

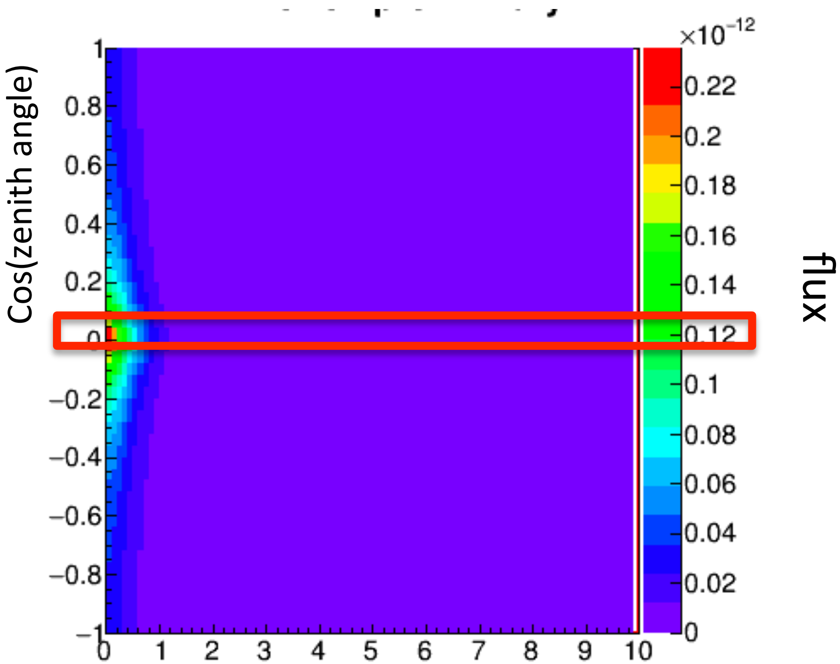


log10(E shower, visible / GeV)

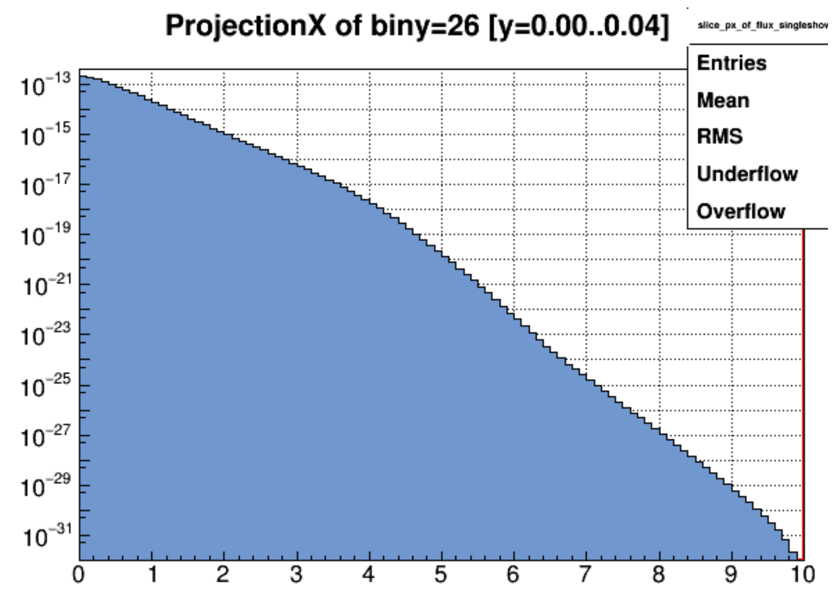


log10(E shower, visible / GeV)

Expected Single Shower Flux

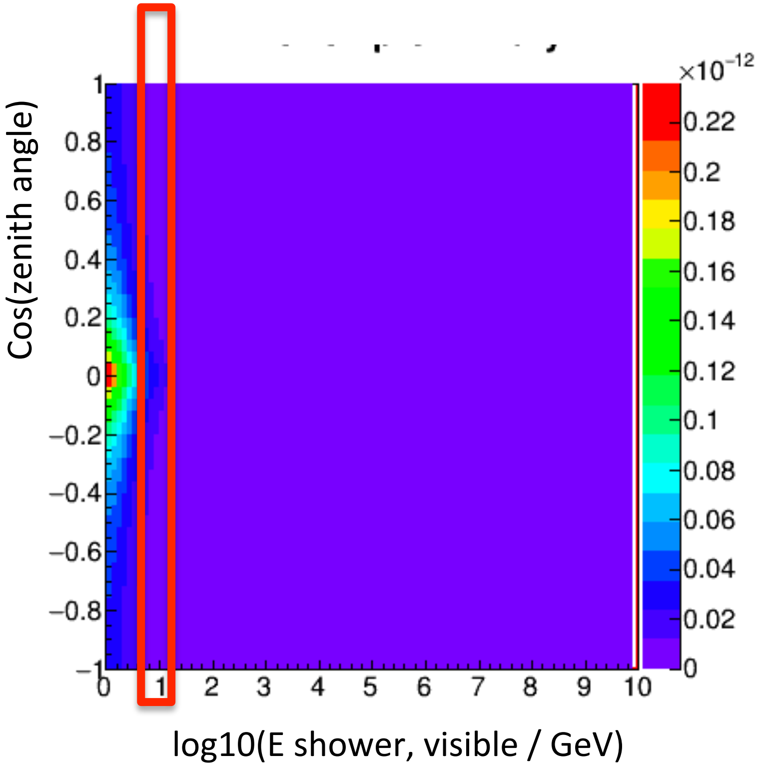


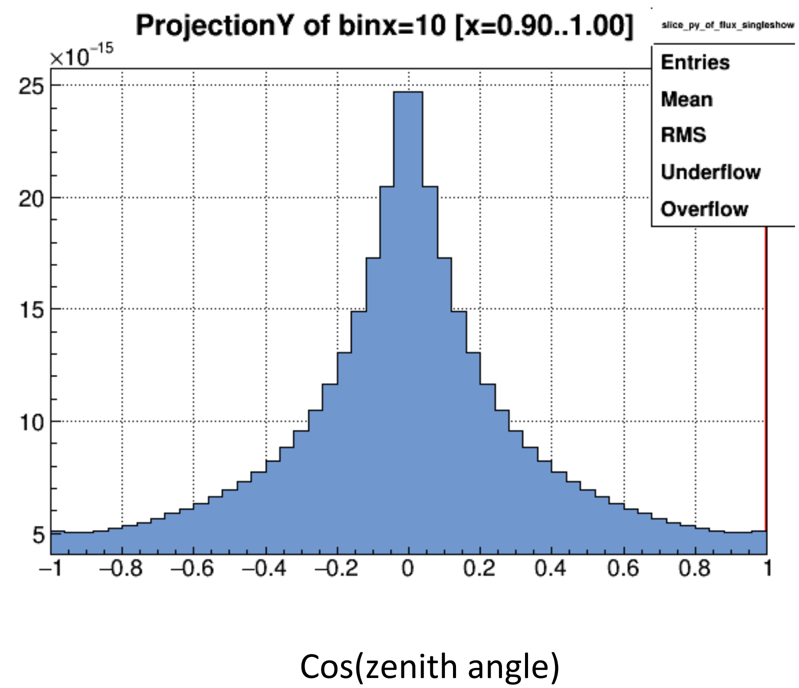
log10(E shower, visible / GeV)



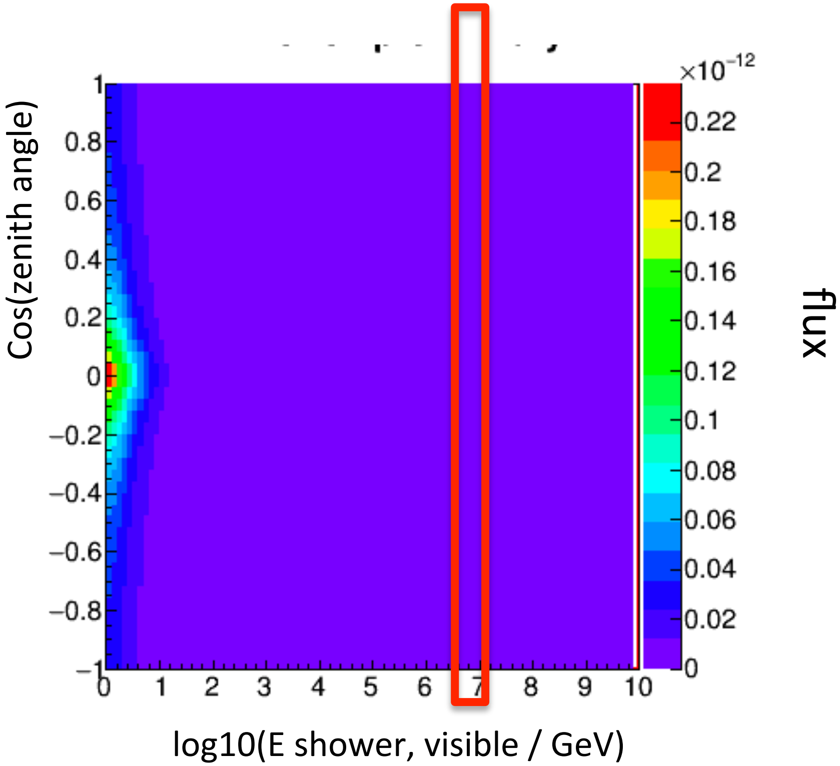
log10(E shower, visible / GeV)

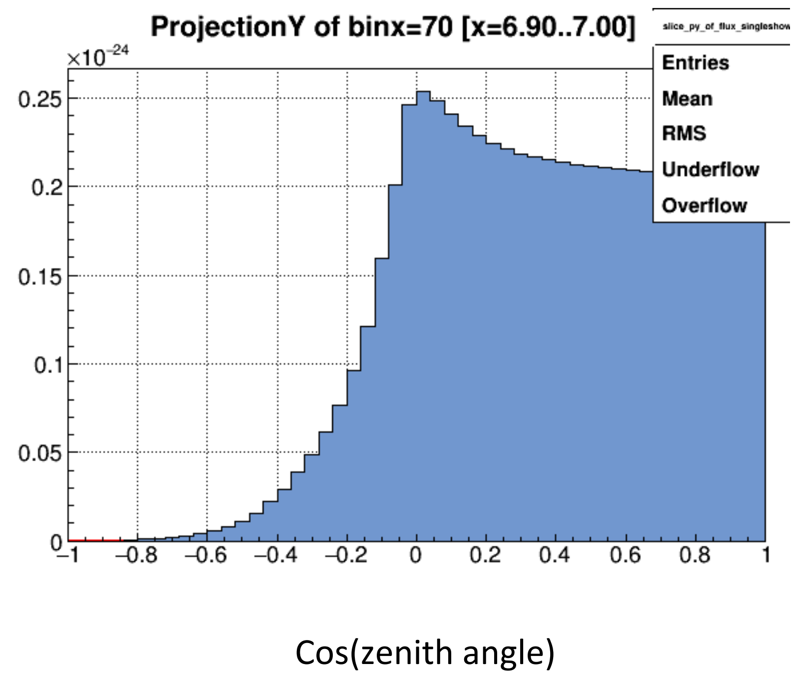
Expected Single Shower Flux





Expected Single Shower Flux





$$P(data|H) = \sum_i \left[\log \int P(ev_i |\, x_{true}) \cdot P^{det}(x_{true}) \cdot \mu(x_{true} \mid H)\, dx_{true}\right] - \mu^{tot}(H)$$

8D Event likelihood landscapes

$$P(data|H) = \sum_i \left[\log \int P(ev_i|\, x_{true}) \cdot P^{det}(x_{true}) \cdot \mu(x_{true}\;|\,H)\; dx_{true}\right] - \mu^{tot}(H)$$

8D Event likelihood landscapes

$$P(data|H) = \sum_i \left[\log \int P(ev_i |\, x_{true}) \cdot P^{det}(x_{true}) \cdot \mu(x_{true} \mid H)\, dx_{true} \right] - \mu^{tot}(H)$$

- (Neutrino) Direction (2D)
- Interaction vertex position (3D)
- Muon energy (1D)
- Visible shower energy (1D)
- Interaction time (1D)

7D ~~8D~~ Event likelihood landscapes

$$P(data|H) = \sum_i \left[\log \int P(ev_i |\, x_{true}) \cdot P^{det}(x_{true}) \cdot \mu(x_{true} \,|\, H)\, dx_{true} \right] - \mu^{tot}(H)$$

- (Neutrino) Direction (2D)
- Interaction vertex position (3D)
- Muon energy (1D)
- Visible shower energy (1D)
- ~~Interaction time (1D)~~

Event Probability

$$P(ev \mid x) = \prod_{hit\ PMTs} \left[P_i^{hit} \cdot P_i^{t\ 1st}\right] \cdot \prod_{non\ hit\ PMTs} \left[1 - P_i^{hit}\right]$$

Event Probability

$$P(ev \mid x) = \prod_{hit\ PMTs} \left[P_i^{hit} \cdot P_i^{t\ 1st}\right] \cdot \prod_{non\ hit\ PMTs} \left[1 - P_i^{hit}\right]$$

$$P_i^{hit} = 1 - \exp\left(-\int_{-\infty}^{\infty} \hat{n}_i(t)\, dt\right)$$

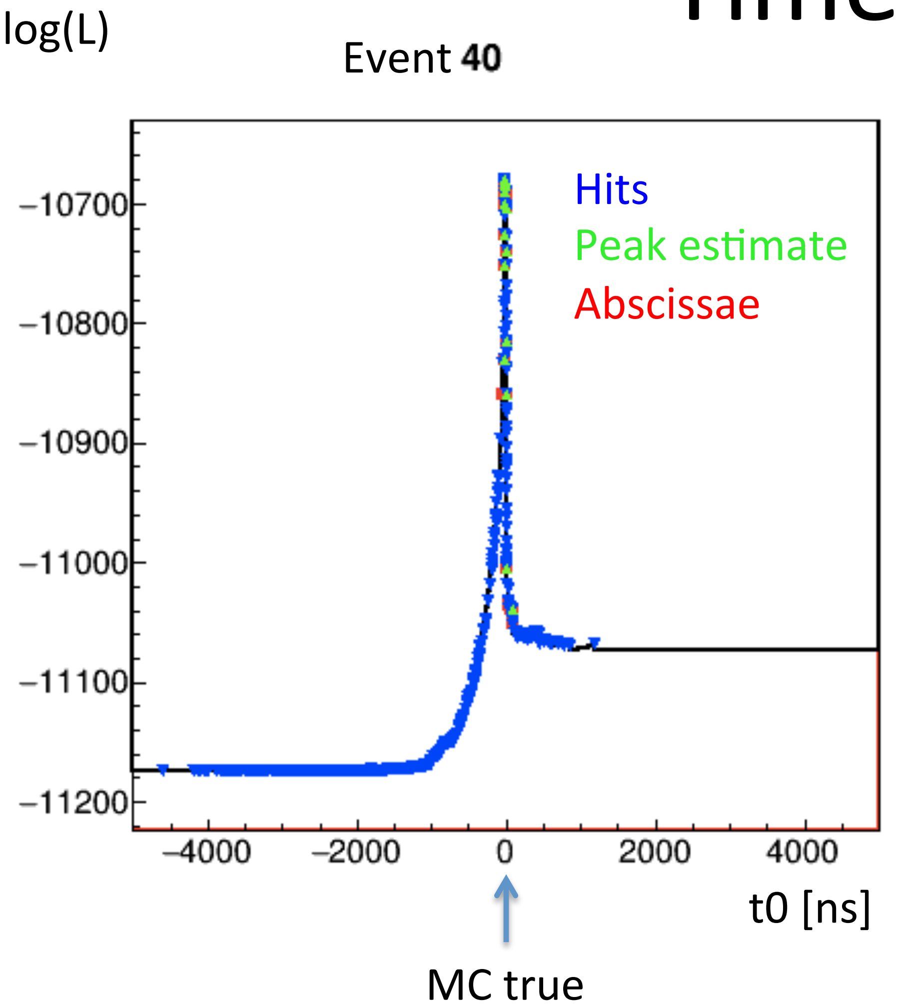
Expected number of photons from 40K and shower/track on PMT i at time t

$$P_i^{t\ 1st} \cdot P_i^{hit} = \underbrace{\exp\left(-\int_{-\infty}^{t} \hat{n}_i(t)\, dt\right)}_{\text{P not hit before t}} \cdot \underbrace{\left(1 - \exp\left(-\hat{n}_i(t)\right)\right)}_{\text{P hit at t}}$$

P not hit before t

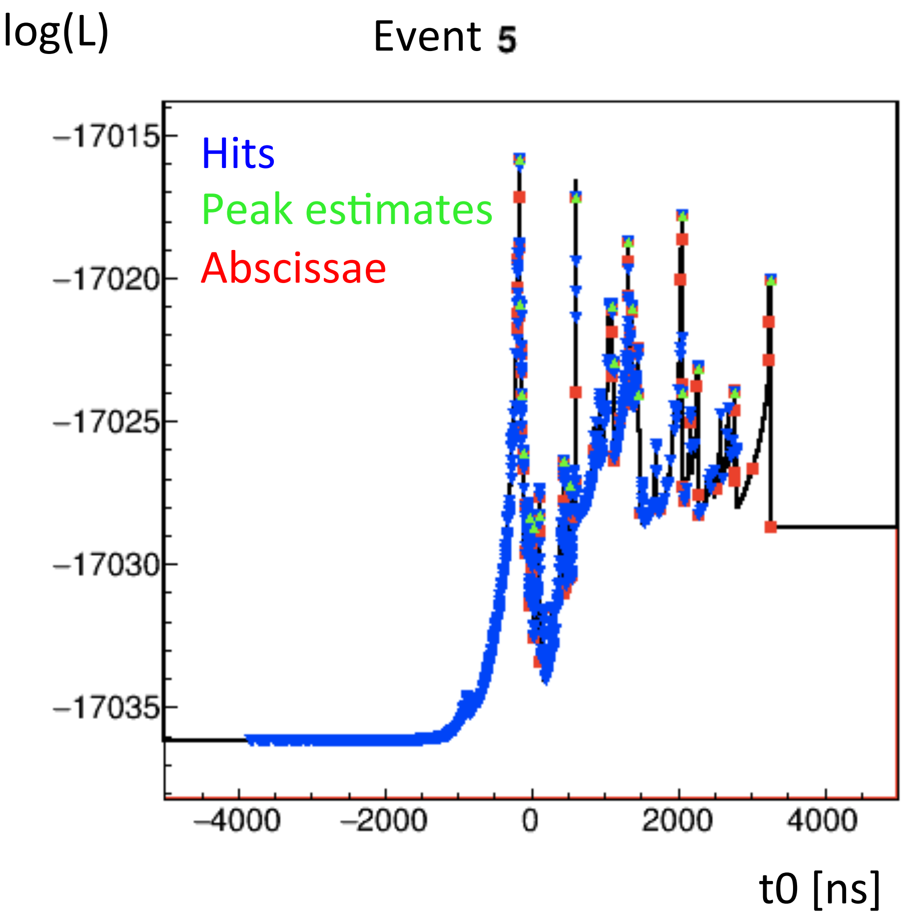
P hit at t

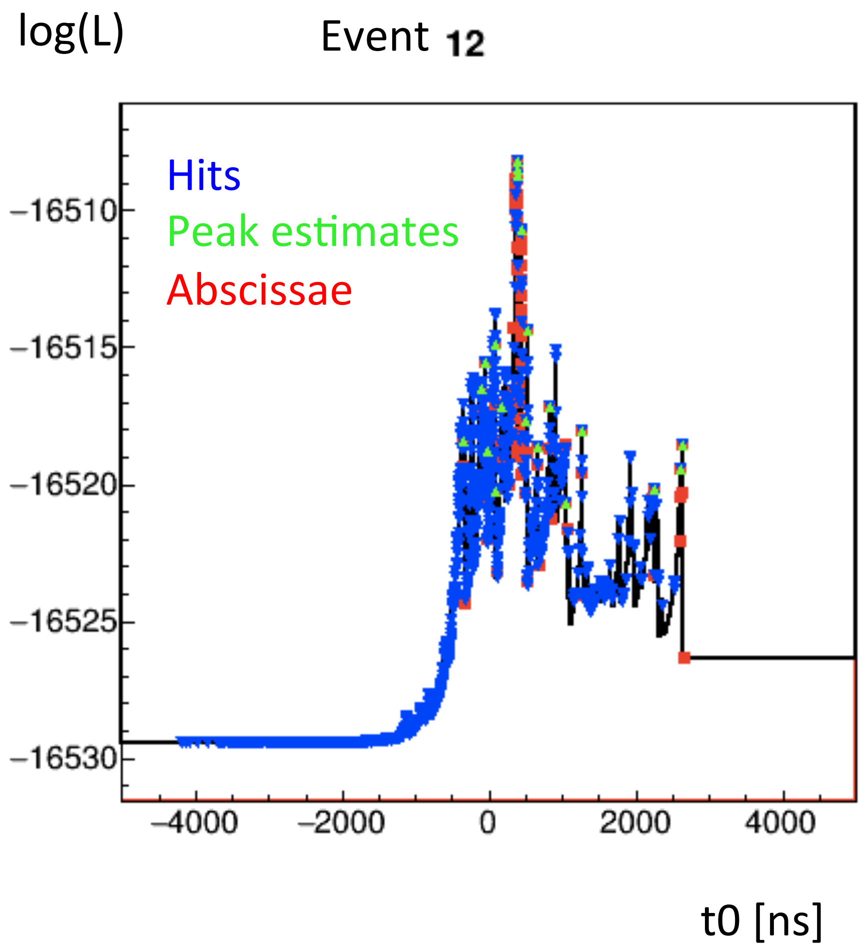
Time Profiles



* At displaced position

Time Profiles: Difficult ones *





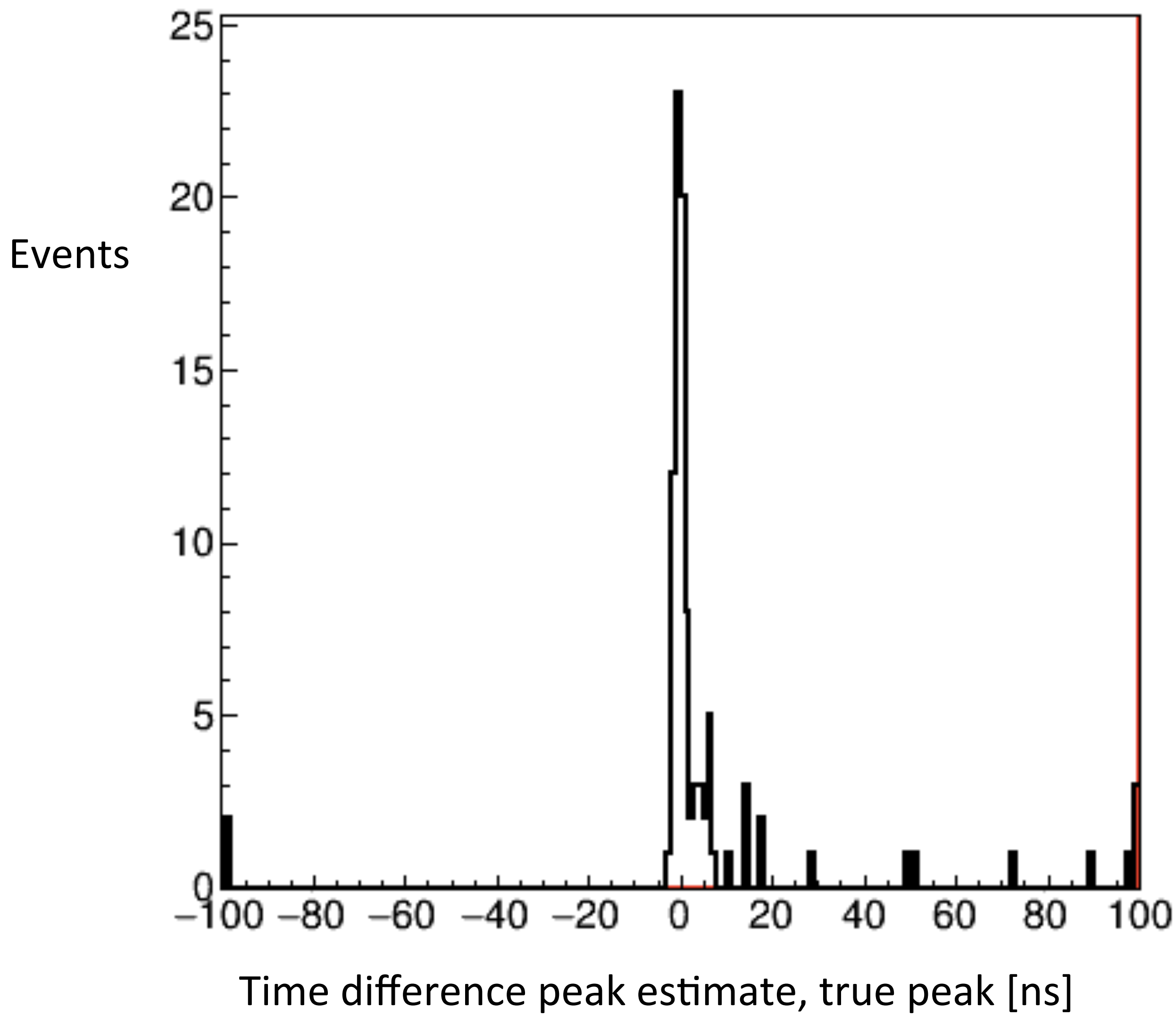
Integration: Peak estimate(s)

- Trajectory known
  - Expected #photons on each PMT known

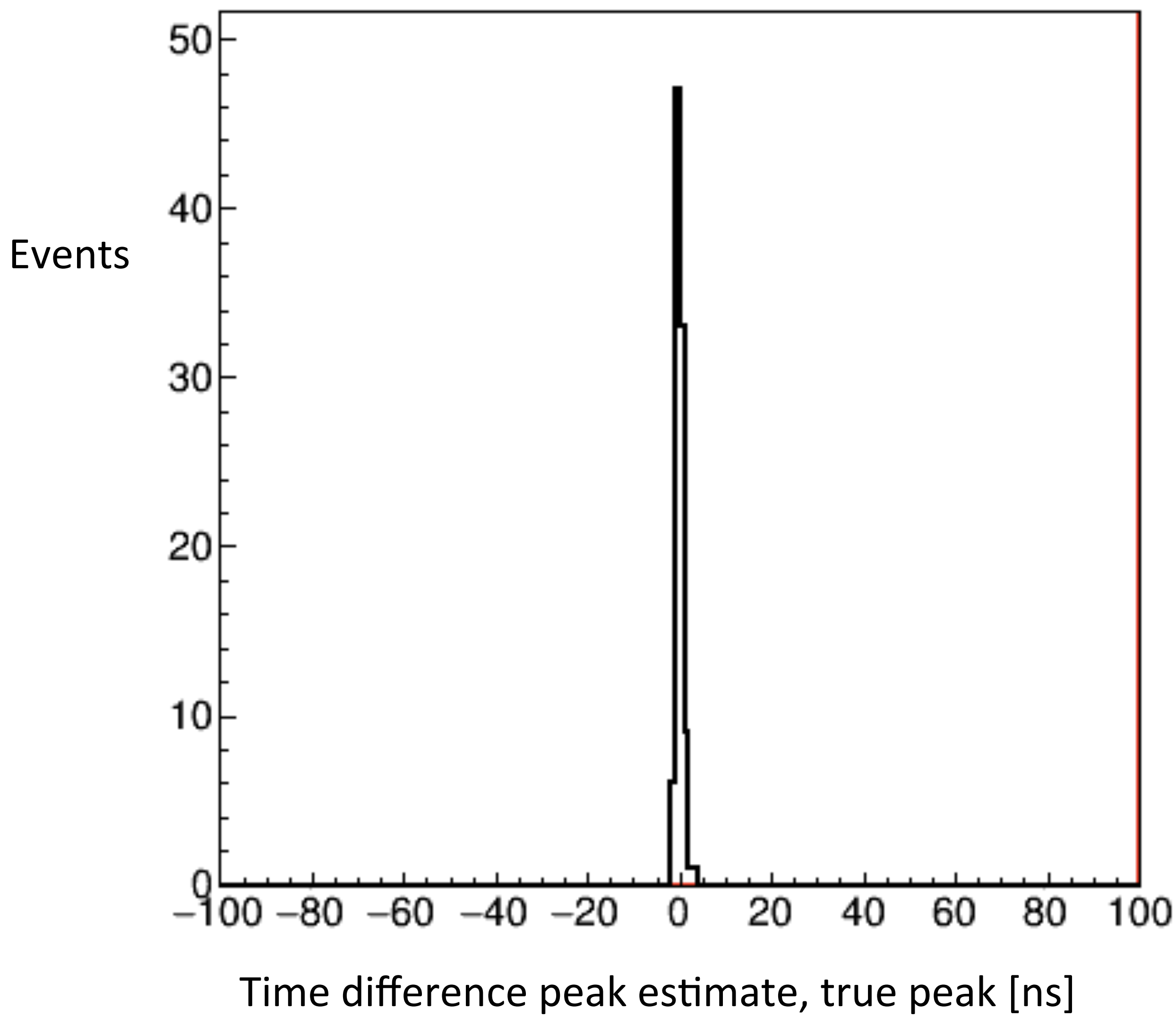
- Take hits on 20 PMTs with highest #photons
  - 20 peak estimates

- Merge overlapping hits (10 ns)

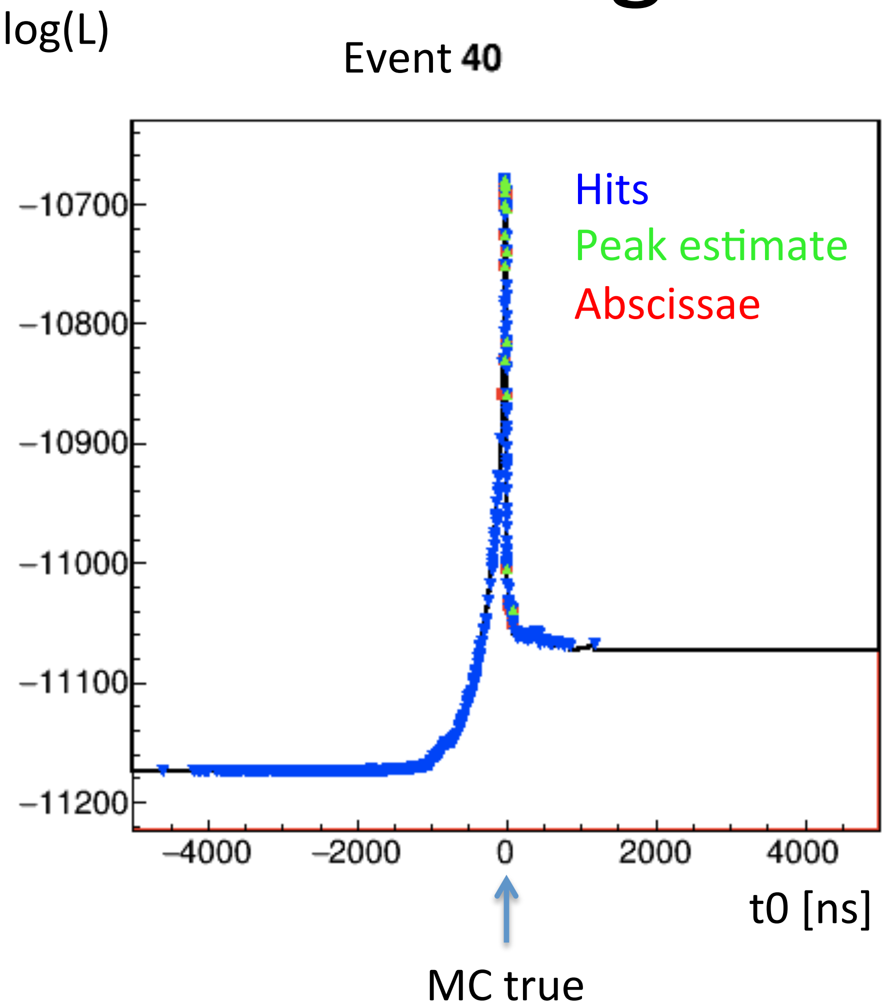
Integration: Peak estimate(s)*



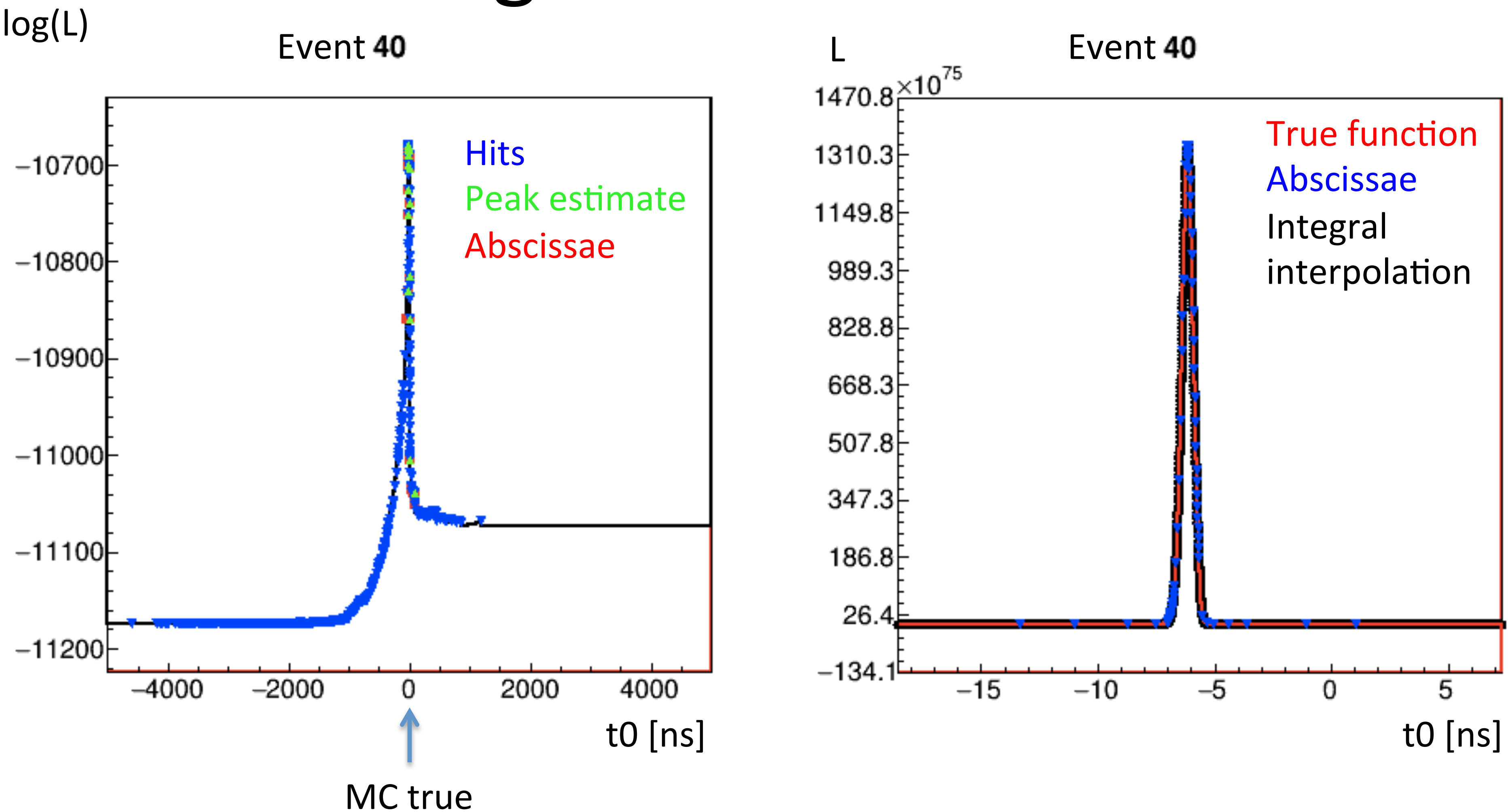
Integration: Peak estimate(s)



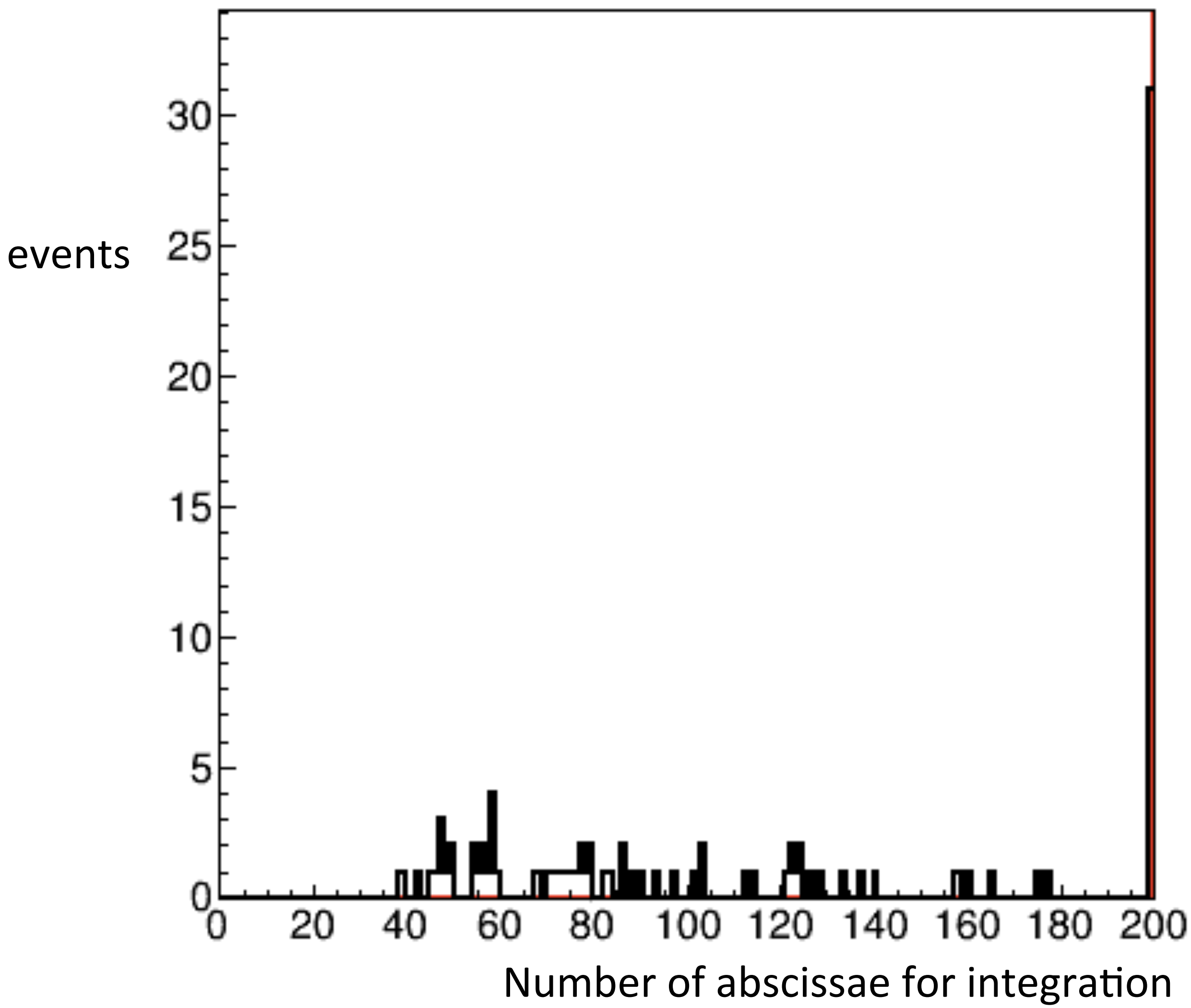
Integration: Abscissae



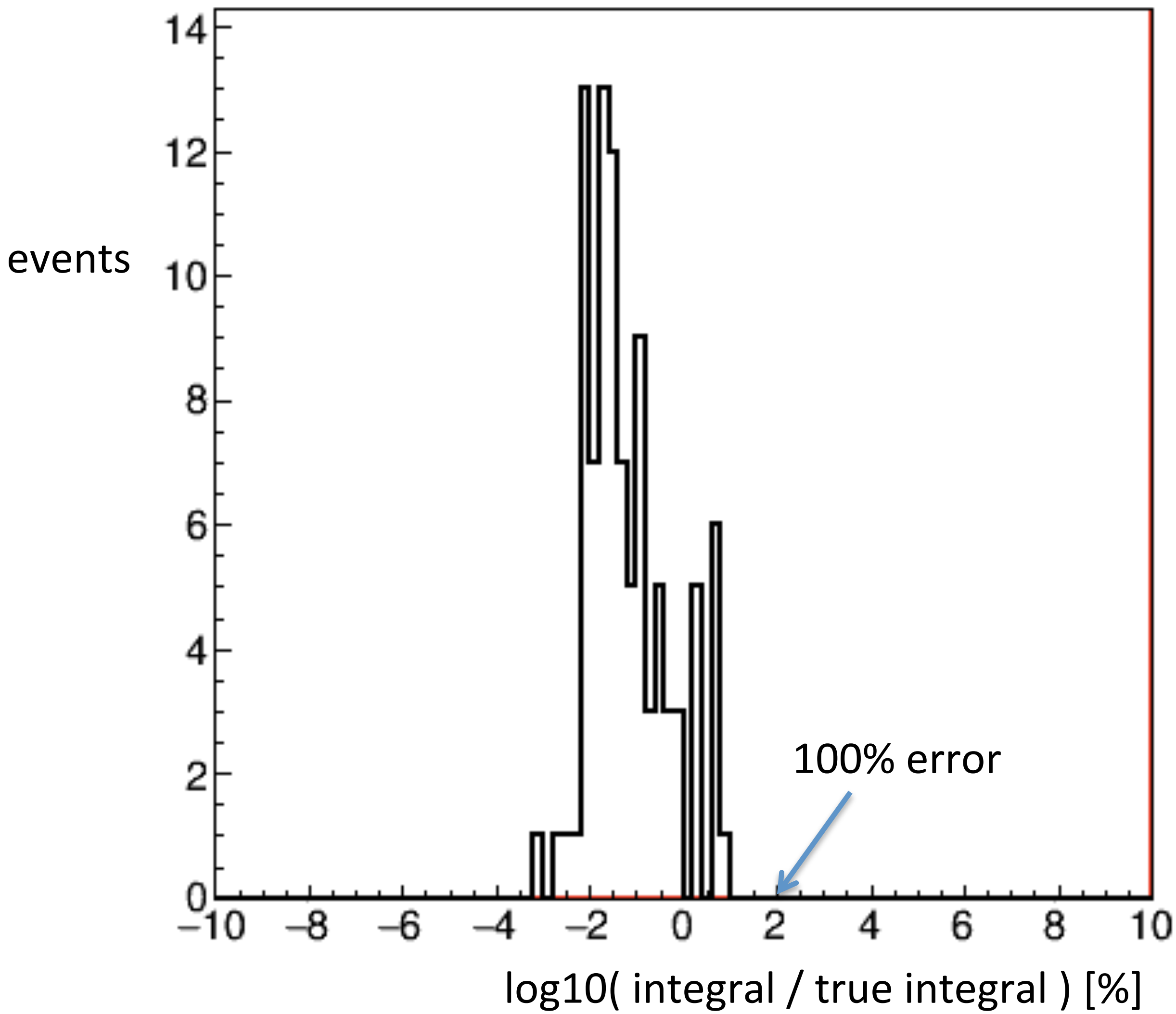
Integration: Abscissae



Integration: Abscissae



Integration: Abscissae



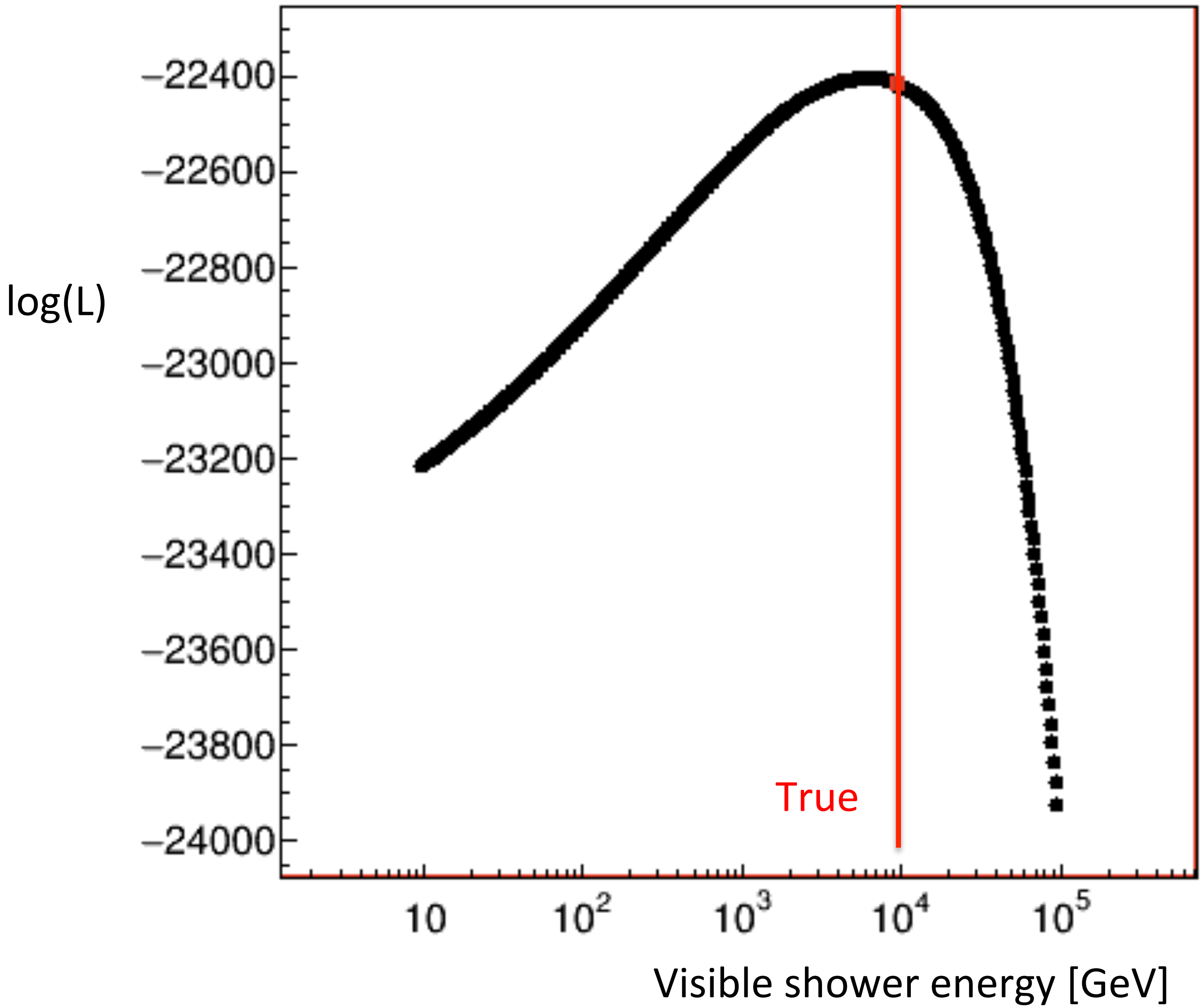
Procedure

- Given trajectory (direction + vertex)

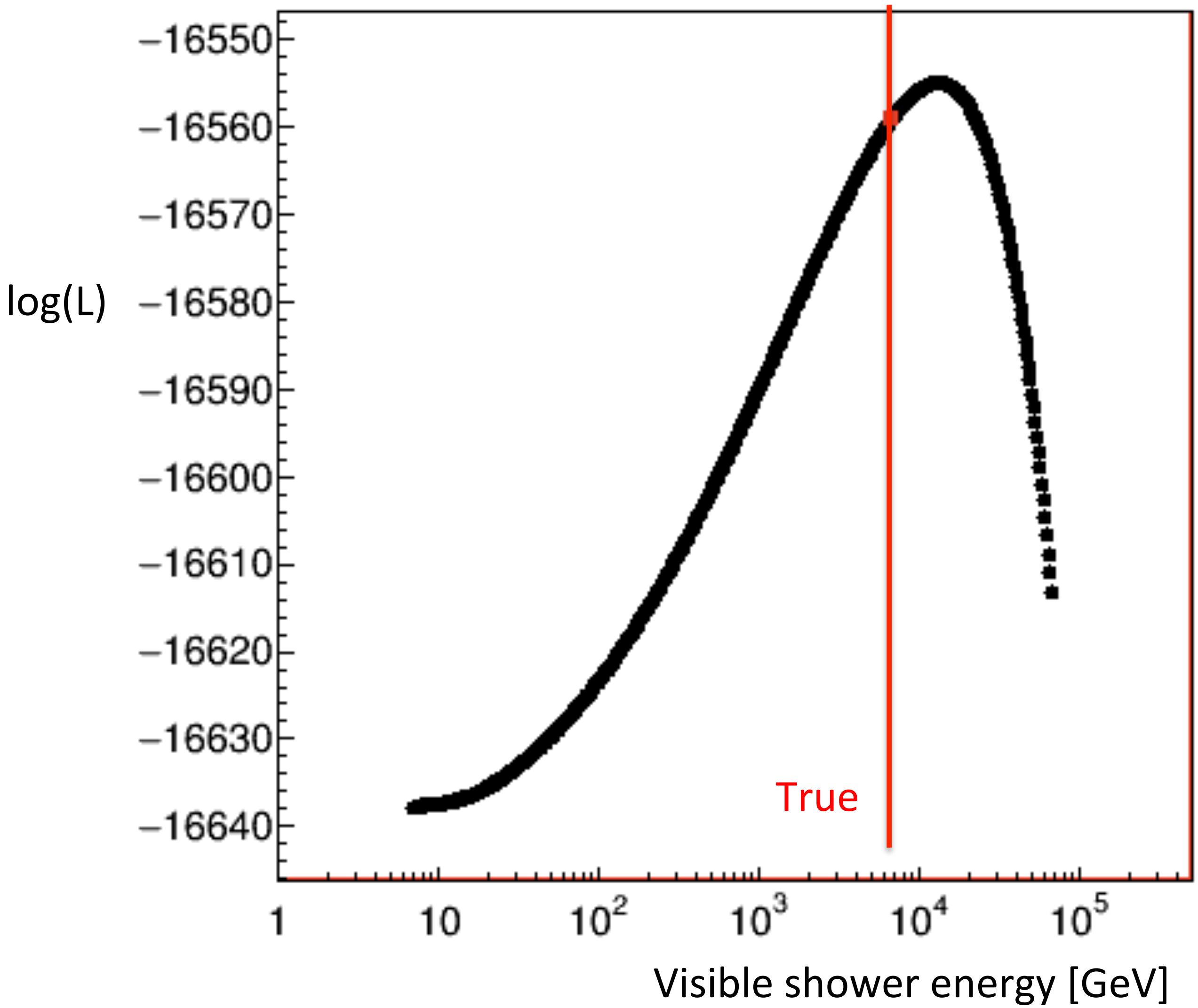
- Fast Energy estimate
  - hit/non-hit info only
  - Define ‘interesting’ energy grid
- Determine t0 integral abscissae
  - For each t0 point: evaluate logL for all energies
- Integrate over t0 for all energies

- Time-integrated energy likelihood landscape

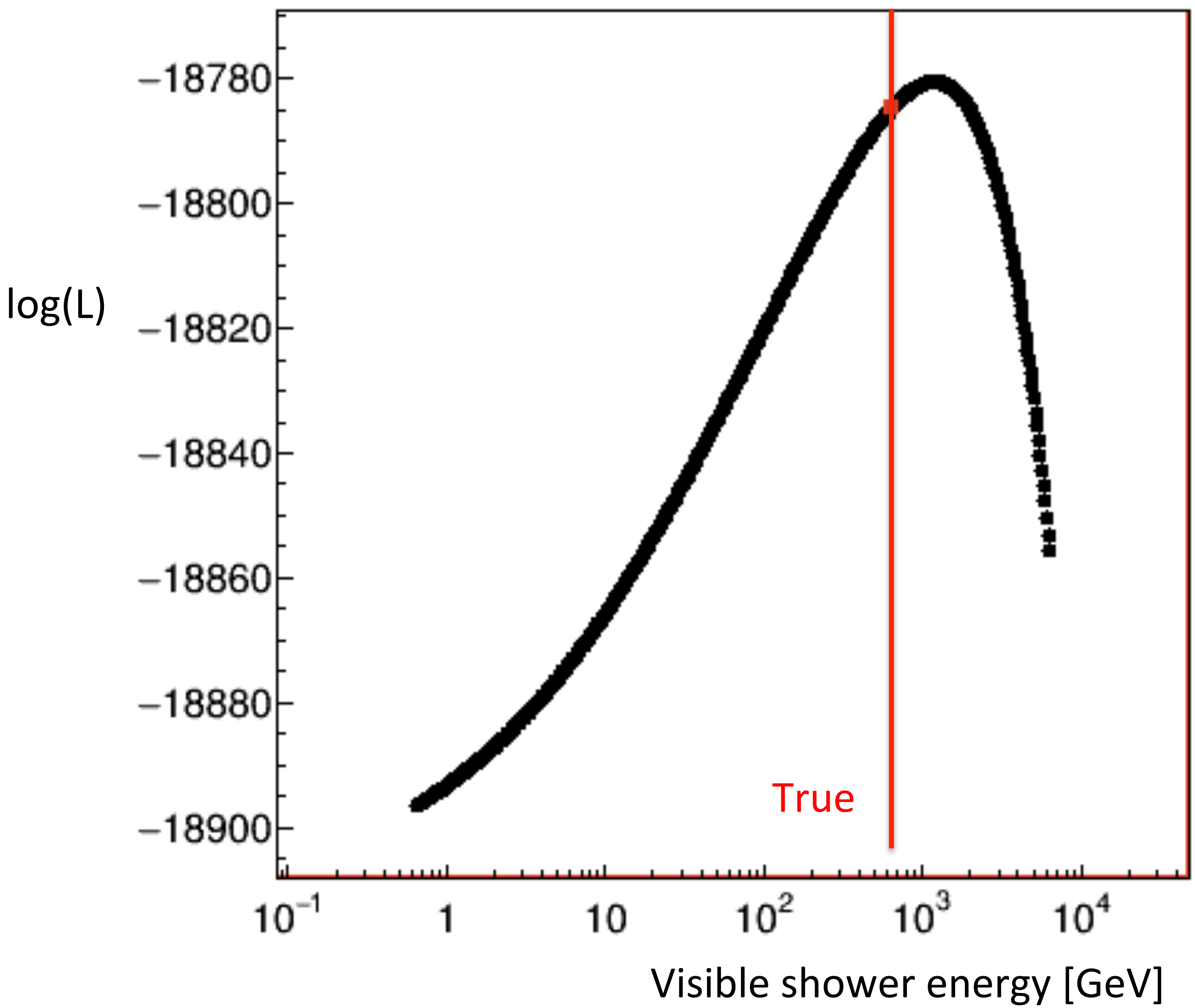
Energy Profile



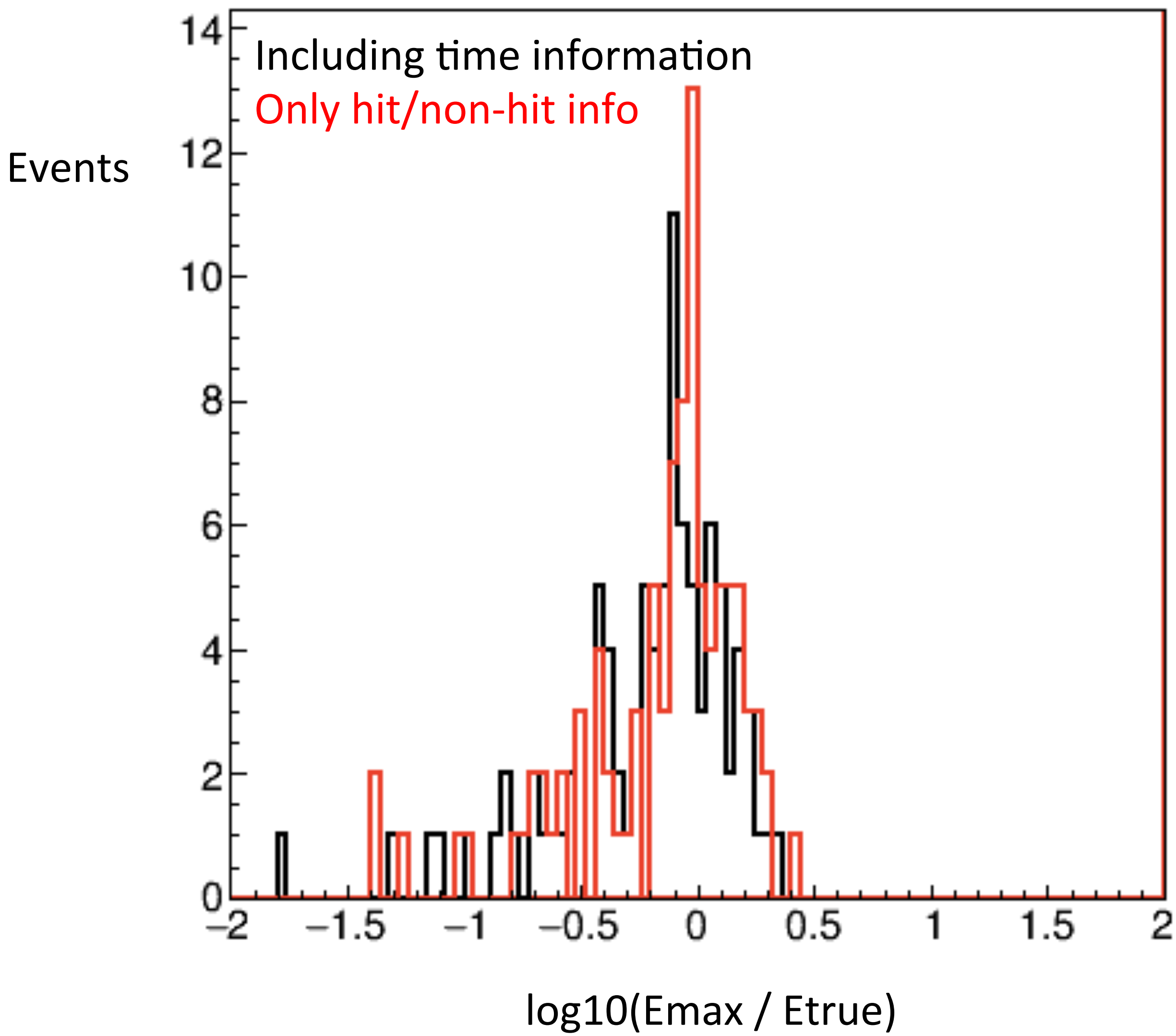
Energy Profile



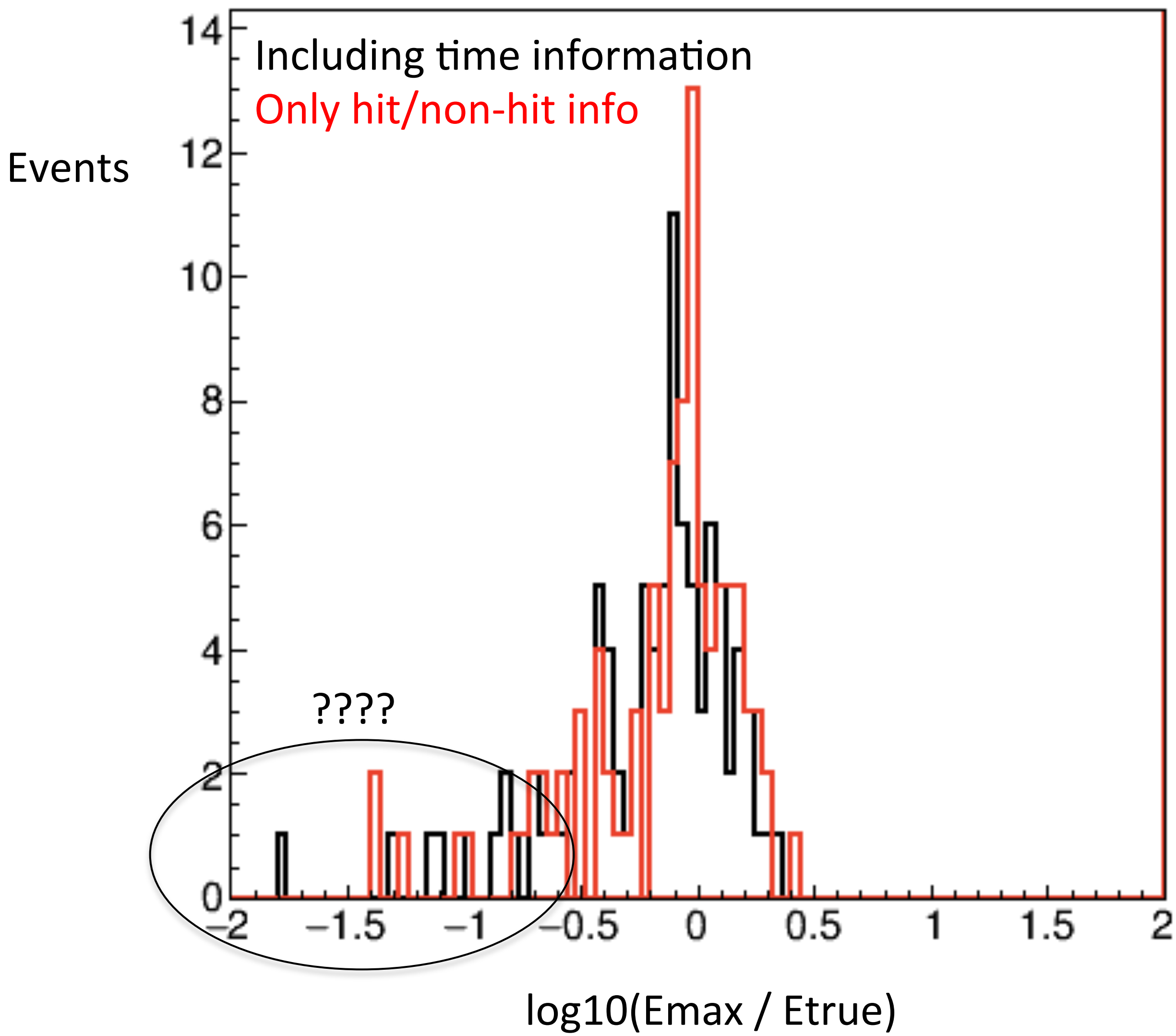
Energy Profile



Energy profile



Energy profile

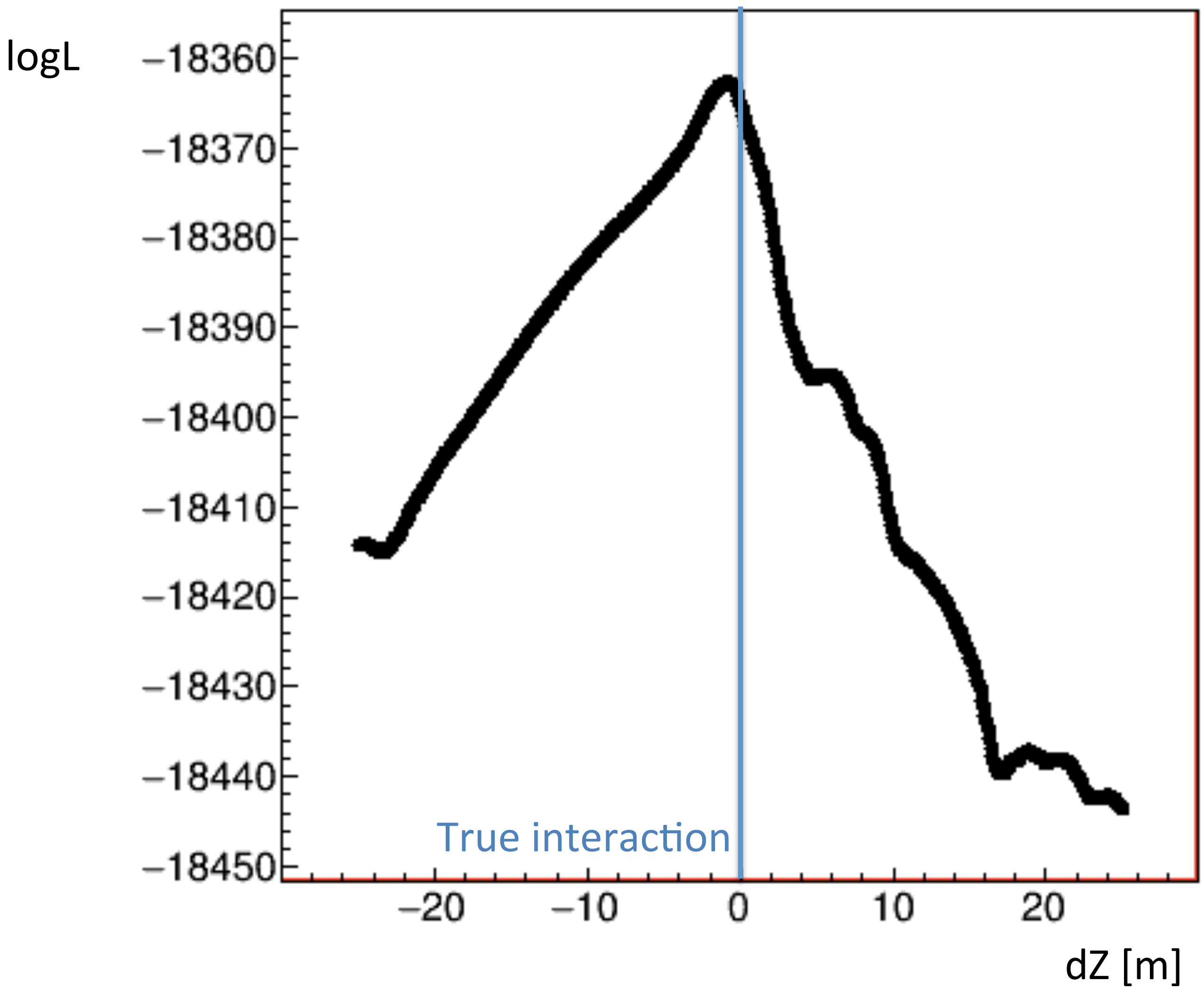


~~8D~~ 7D Event likelihood landscapes

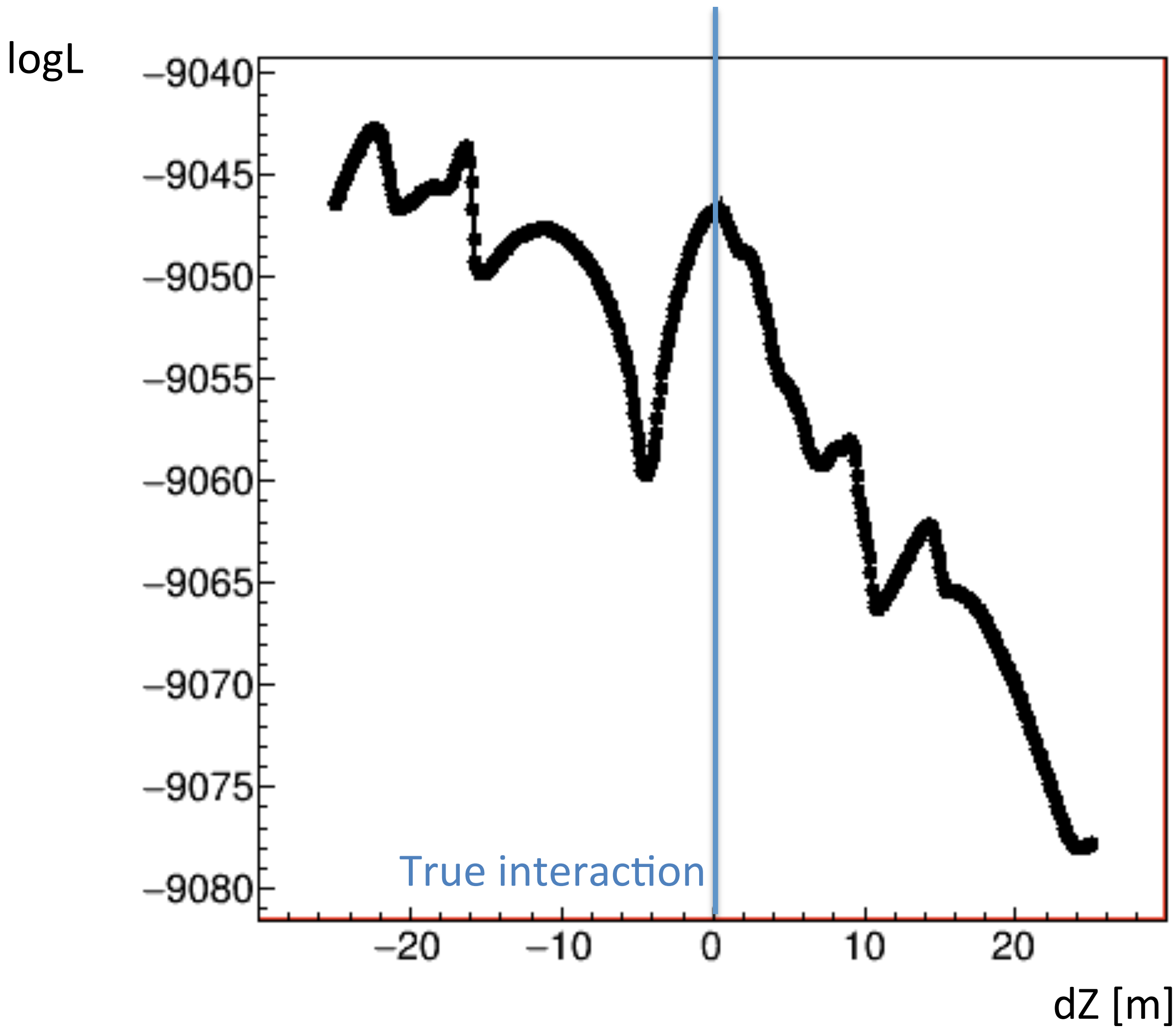
$$P(data|H) = \sum_i \left[\log \int P(ev_i|\, x_{true}) \cdot P^{det}(x_{true}) \cdot \mu(x_{true}\ | H)\ dx_{true}\right] - \mu^{tot}(H)$$

- (Neutrino) Direction (2D)
- Interaction vertex position (3D)
- Muon energy (1D)
- Visible shower energy (1D)
- ~~Interaction time (1D)~~

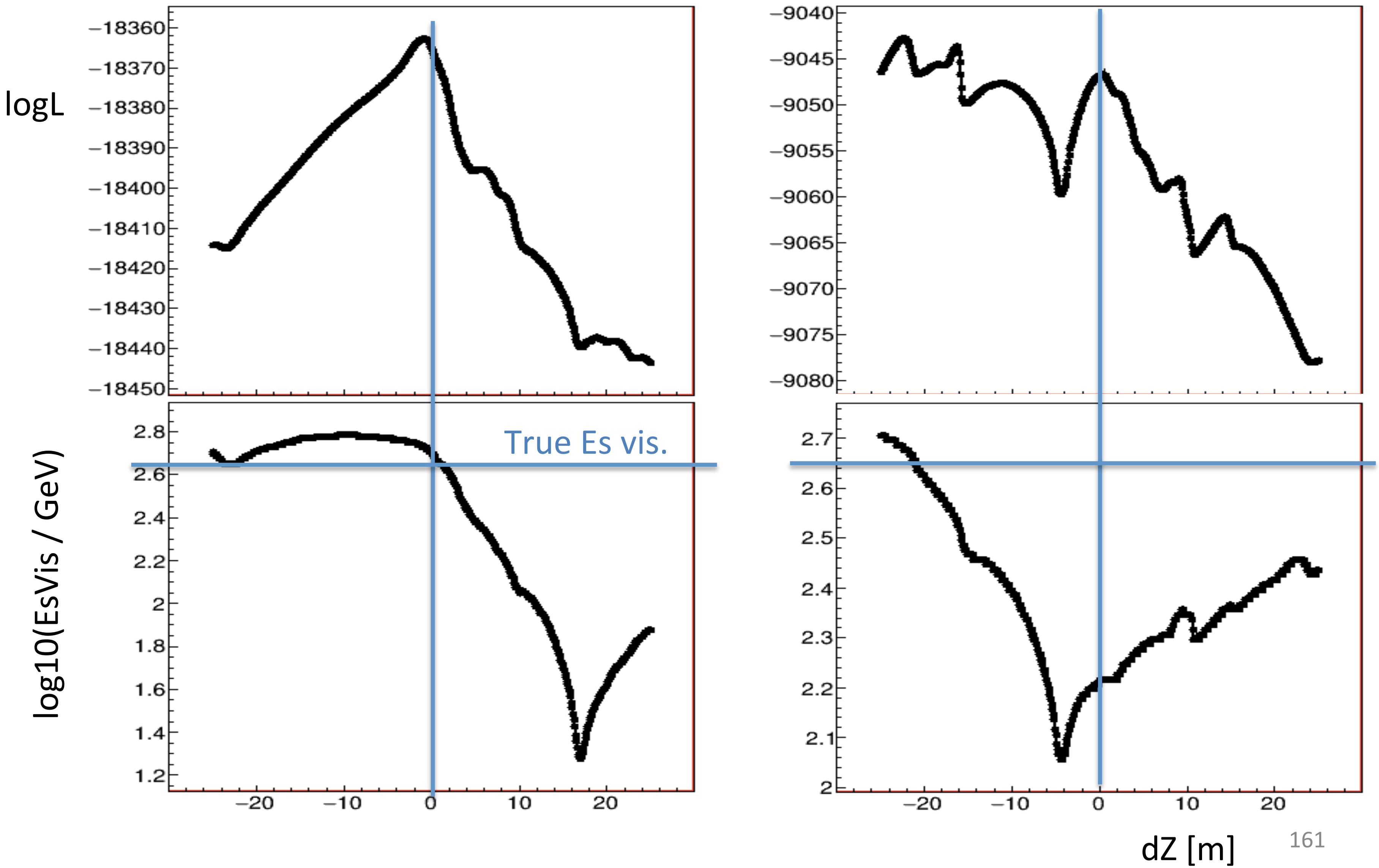
Shower longitudinal position

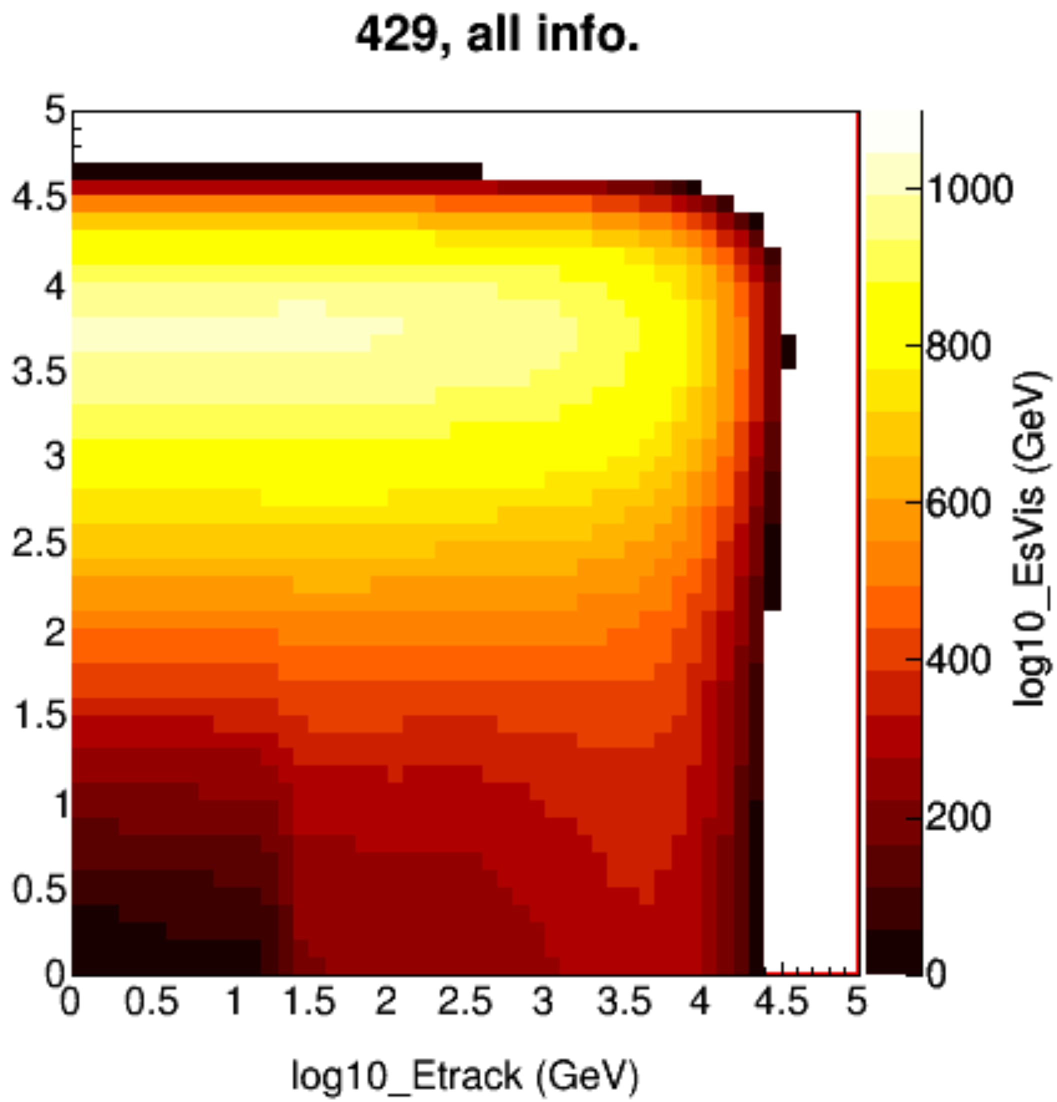


Shower longitudinal position



Best fit Shower Energy





Direction: True

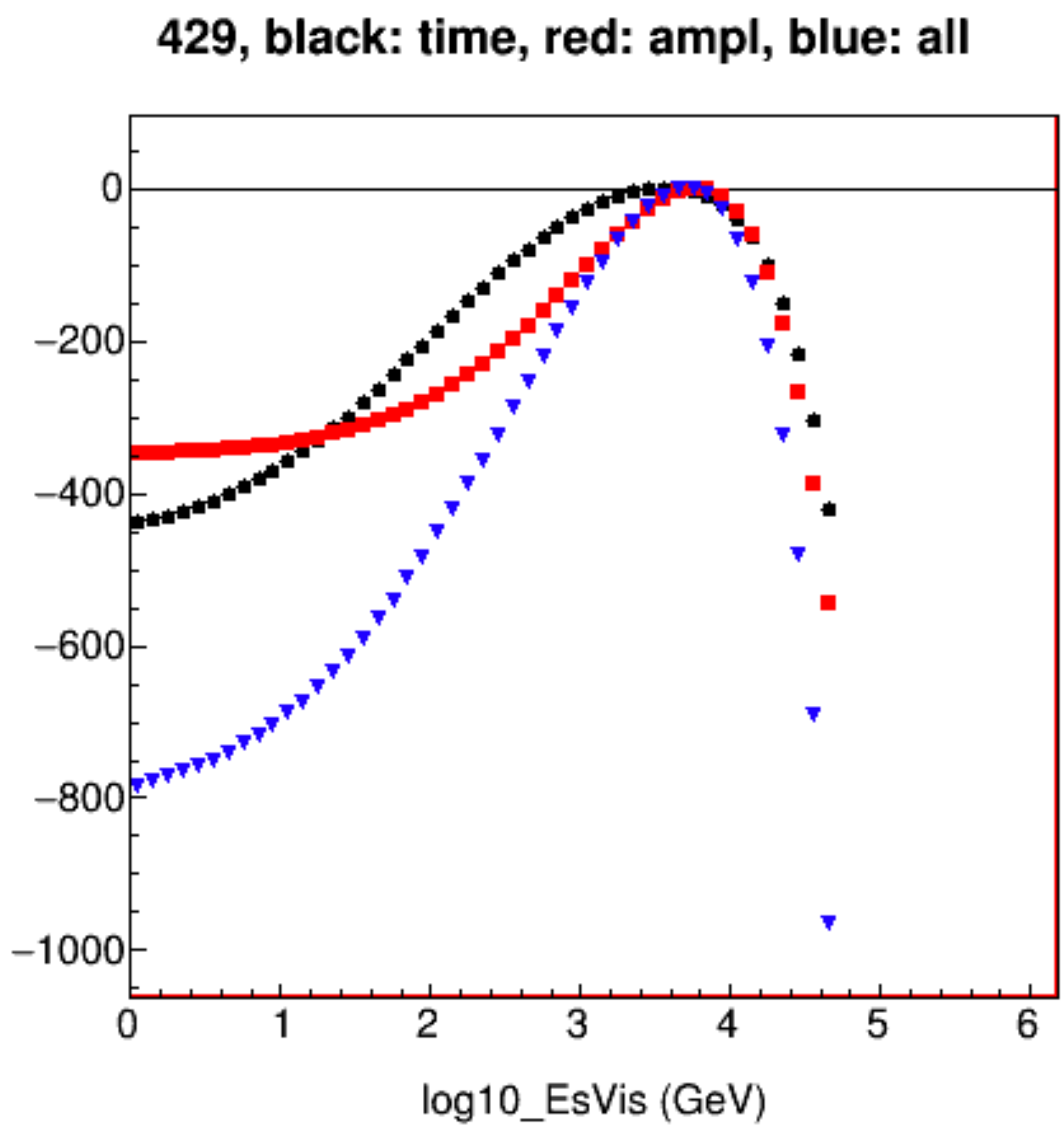
Perp. Pos: Maximum

Long. Pos: Maximum

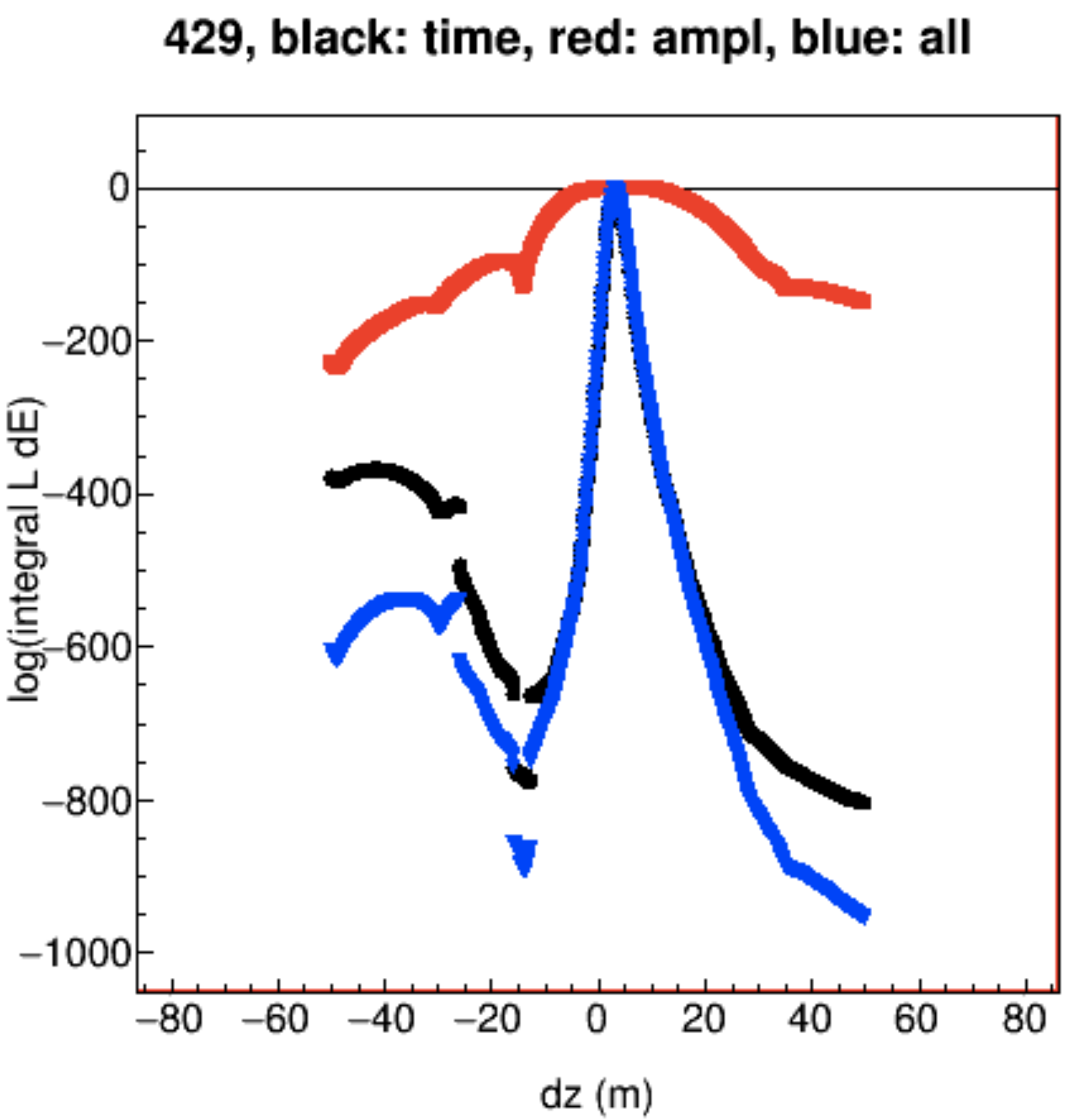
Etrack:

EsVis:

Time: Integrated

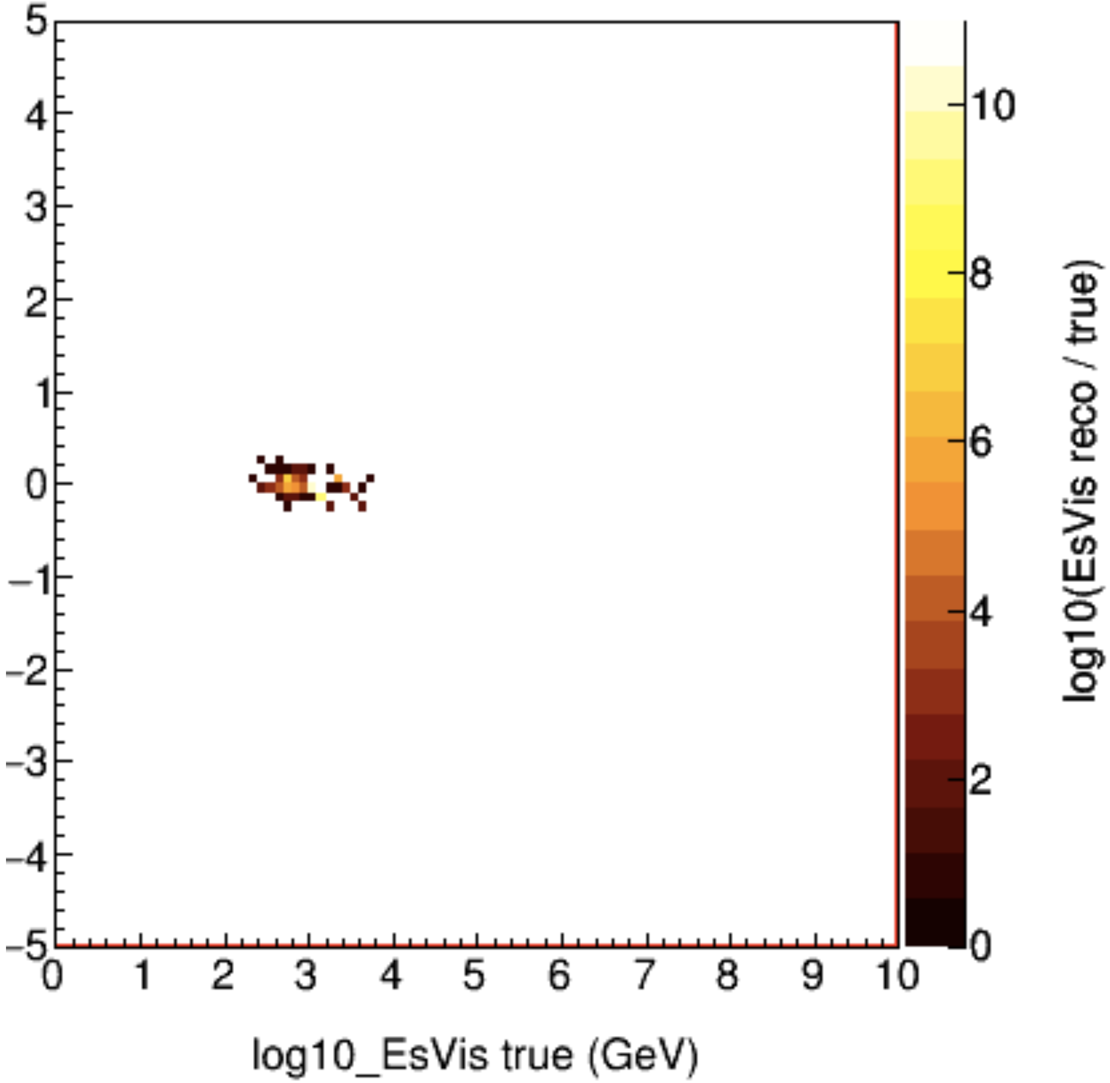


Direction: True
Perp. Pos: Maximum
Long. Pos: Maximum
Etrack: Maximum
EsVis:
Time: Integrated



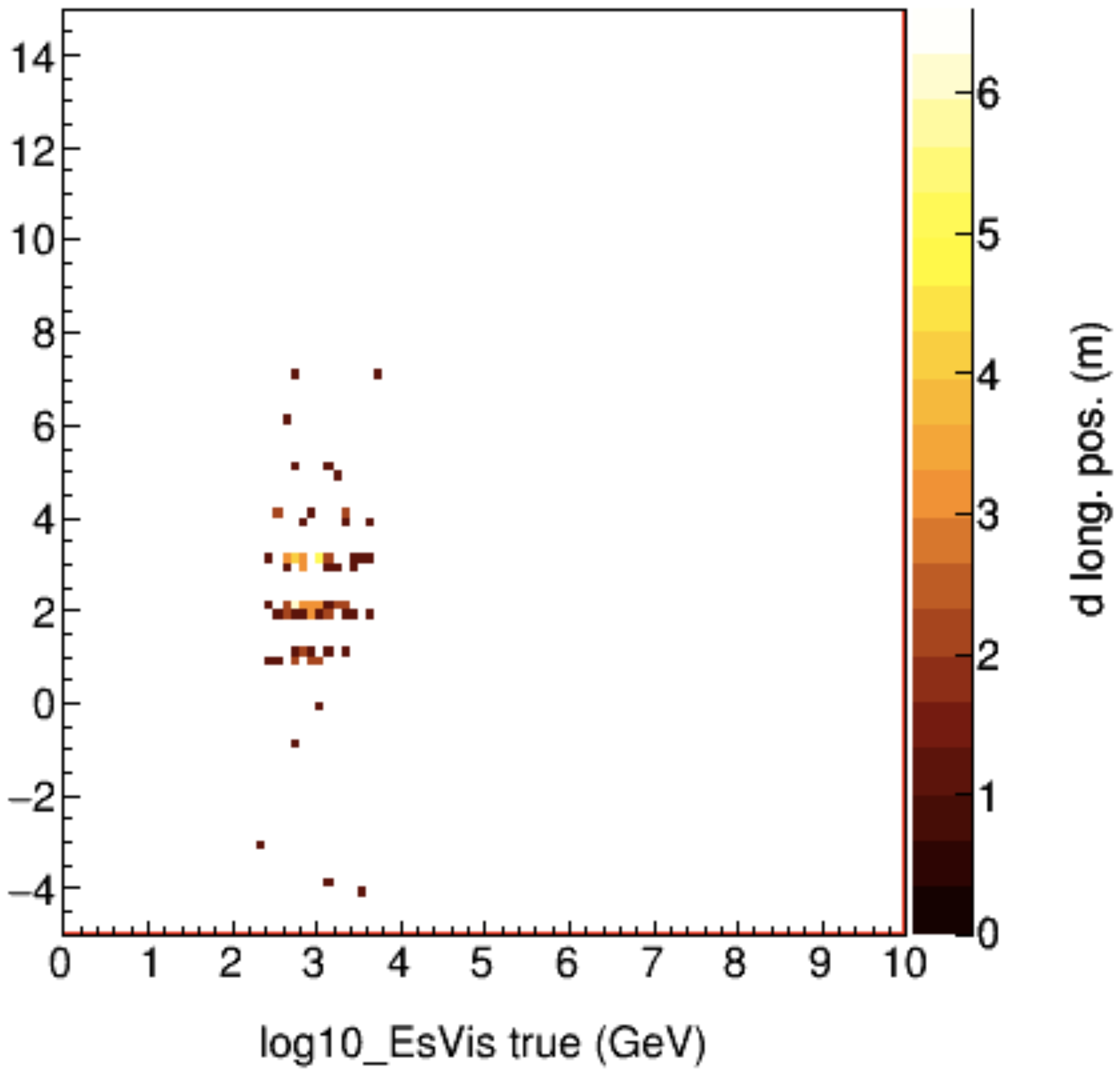
Direction:	True
Perp. Pos:	Maximum
Long. Pos:	
Etrack:	Integrated
EsVis:	Integrated
Time:	Integrated

Energy 'reconstruction'



Direction: True
Perp. Pos: True
Long. Pos: Maximum
Etrack: Maximum
EsVis: Maximum
Time: Integrated

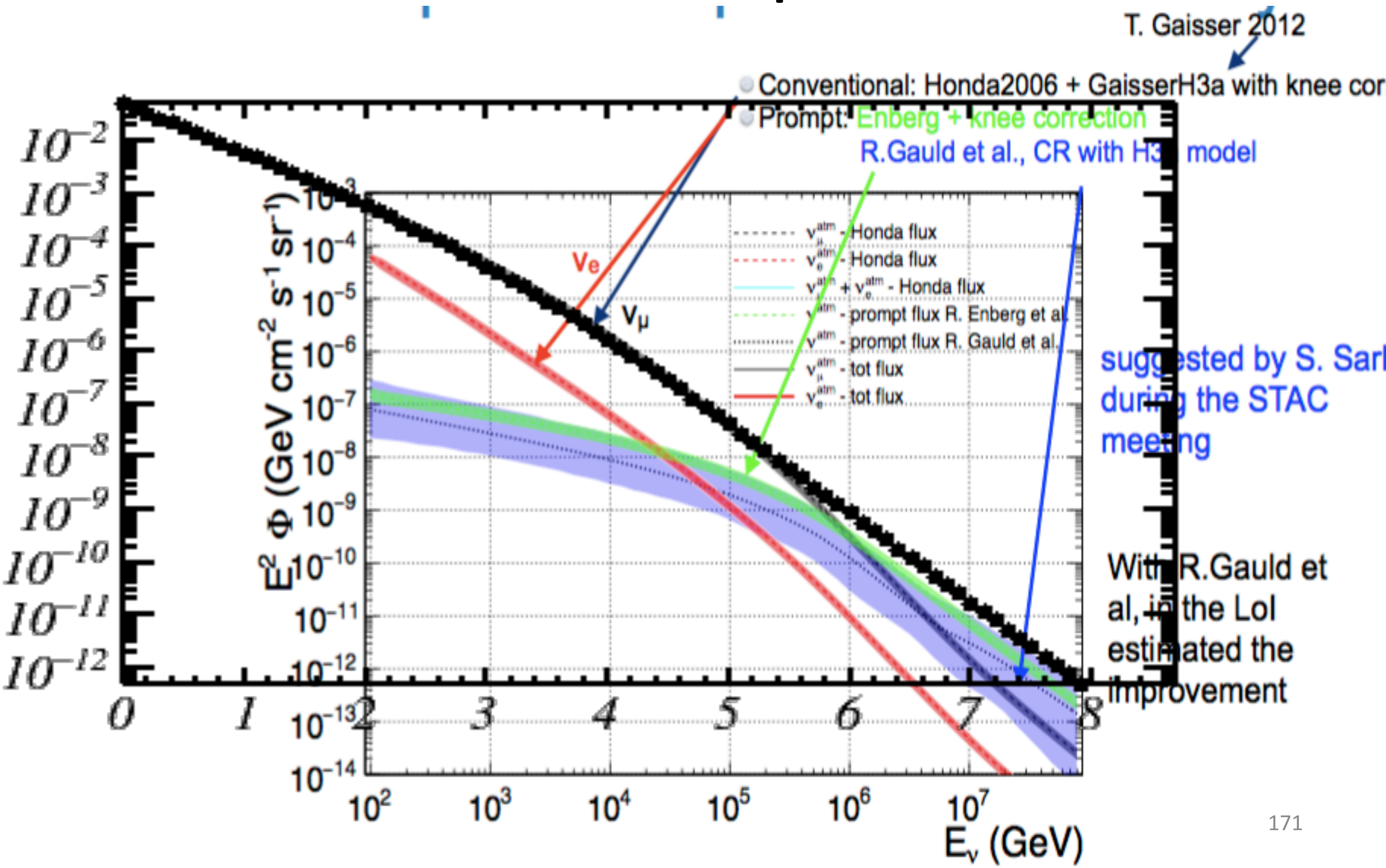
Long. Position 'reconstruction'



Direction: True
Perp. Pos: True
Long. Pos: Maximum
Etrack: Integrated
EsVis: Integrated
Time: Integrated

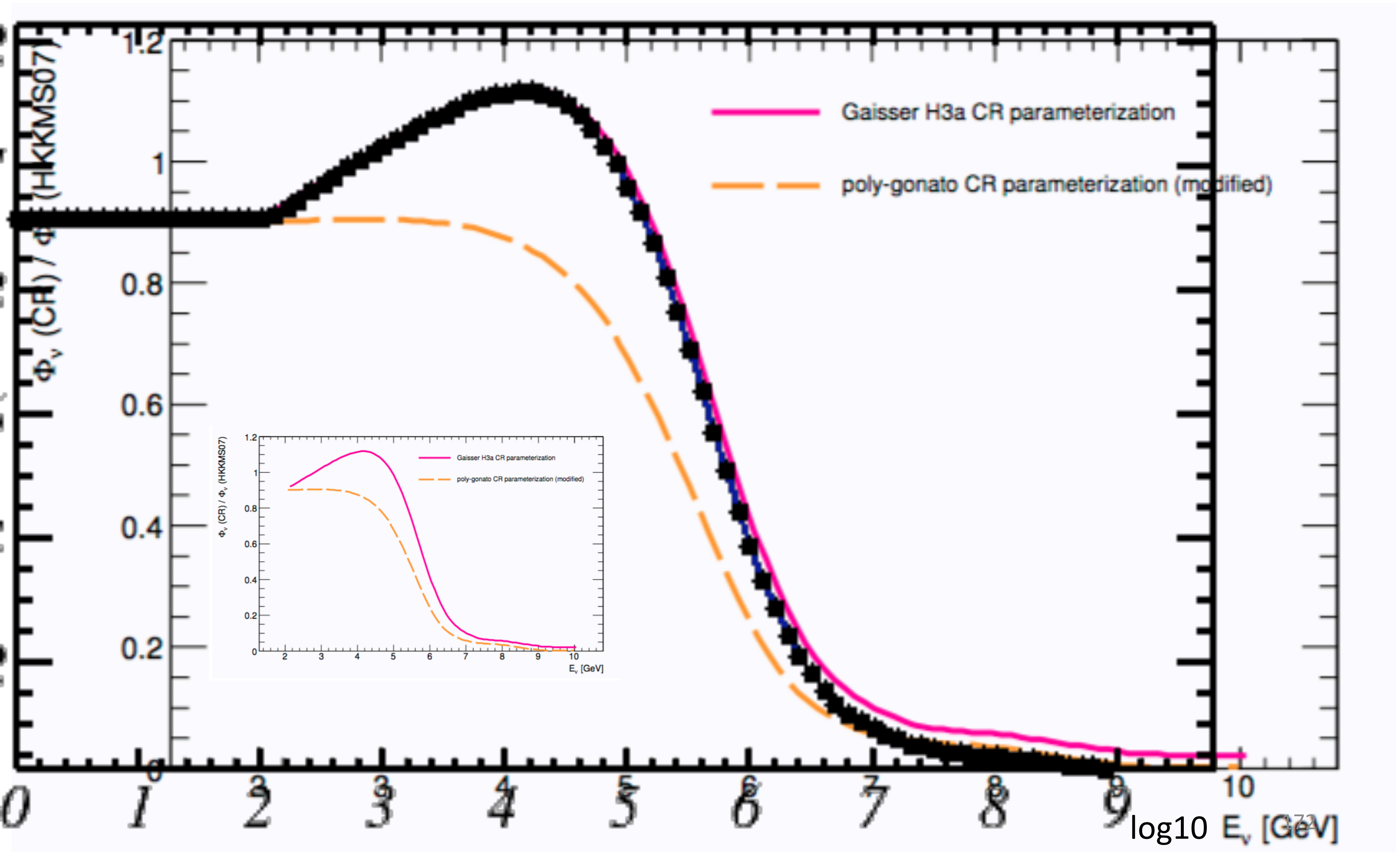
Backup

Honda extrapolated

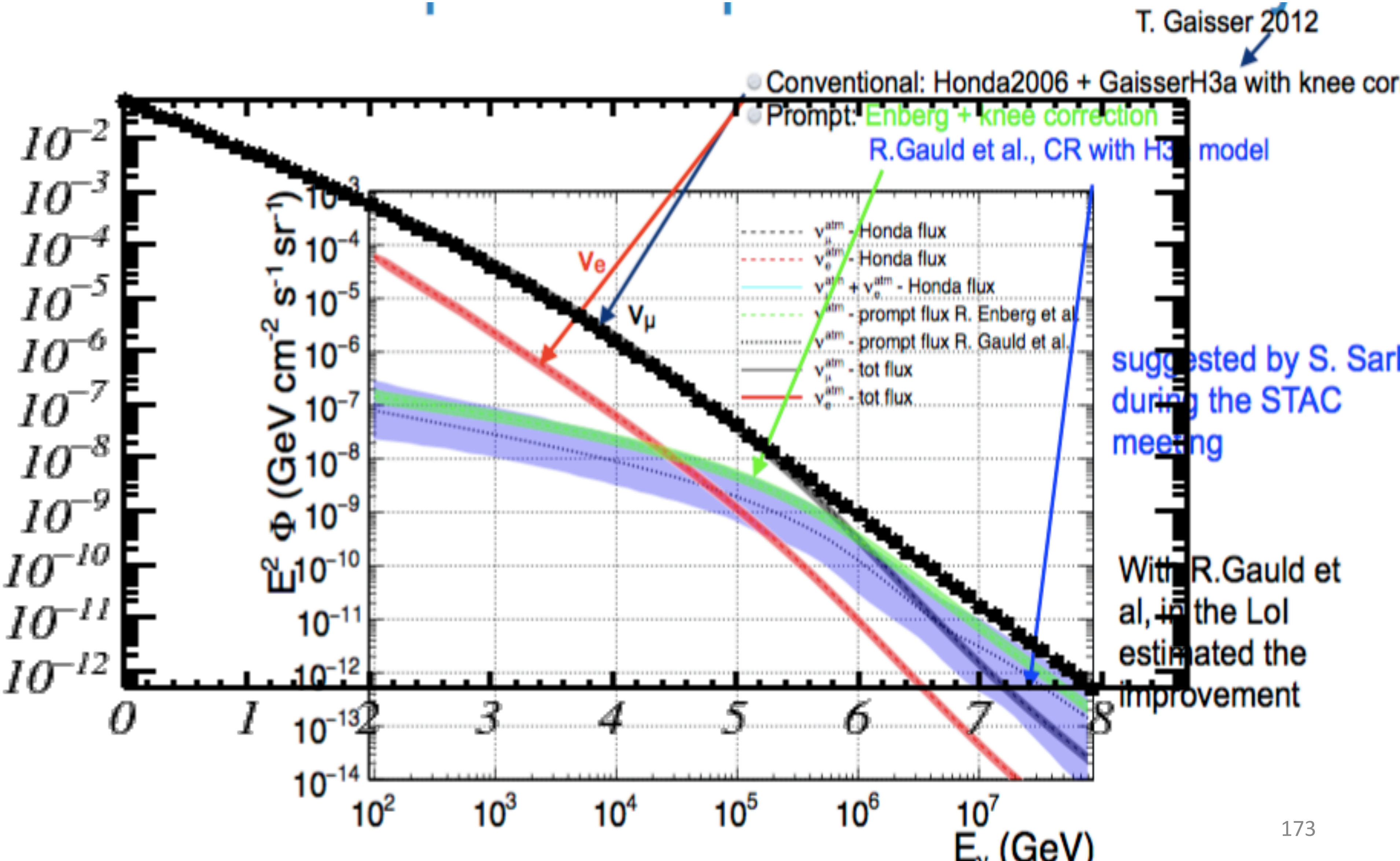


arXiv:1311.7048

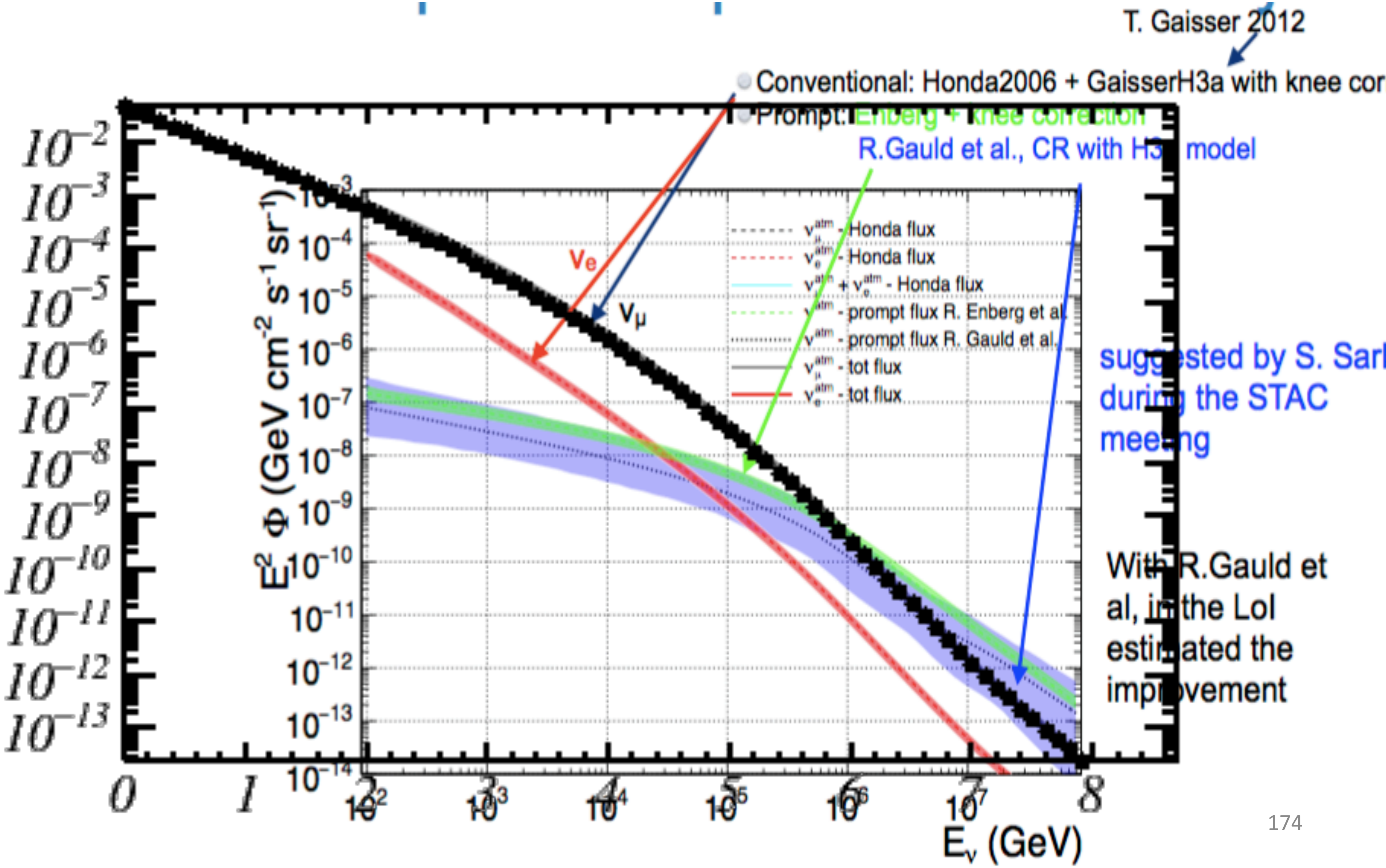
Knee Correction (Gaisser H3a)



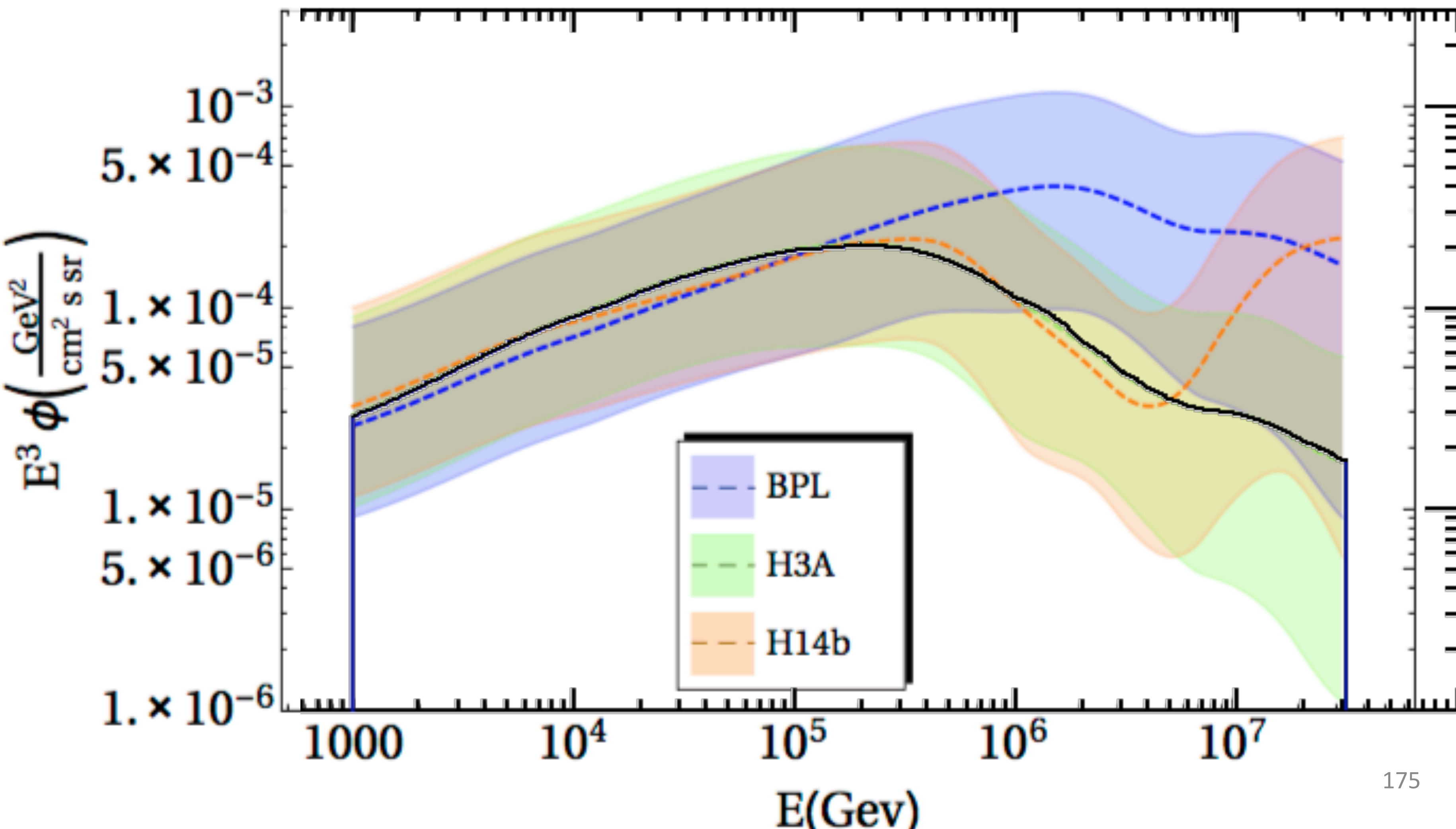
Honda extrapolated



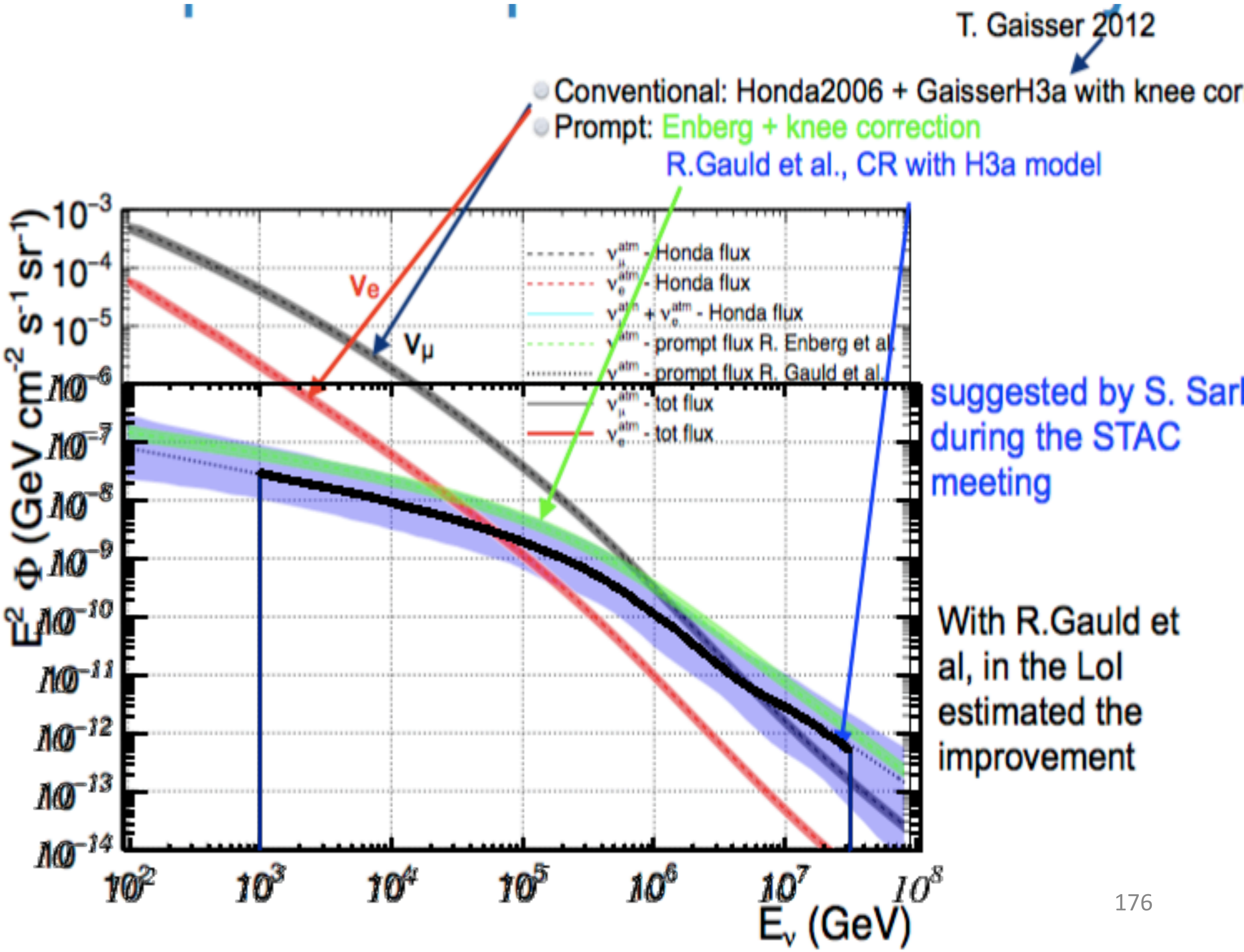
Honda extrapolated + knee correction



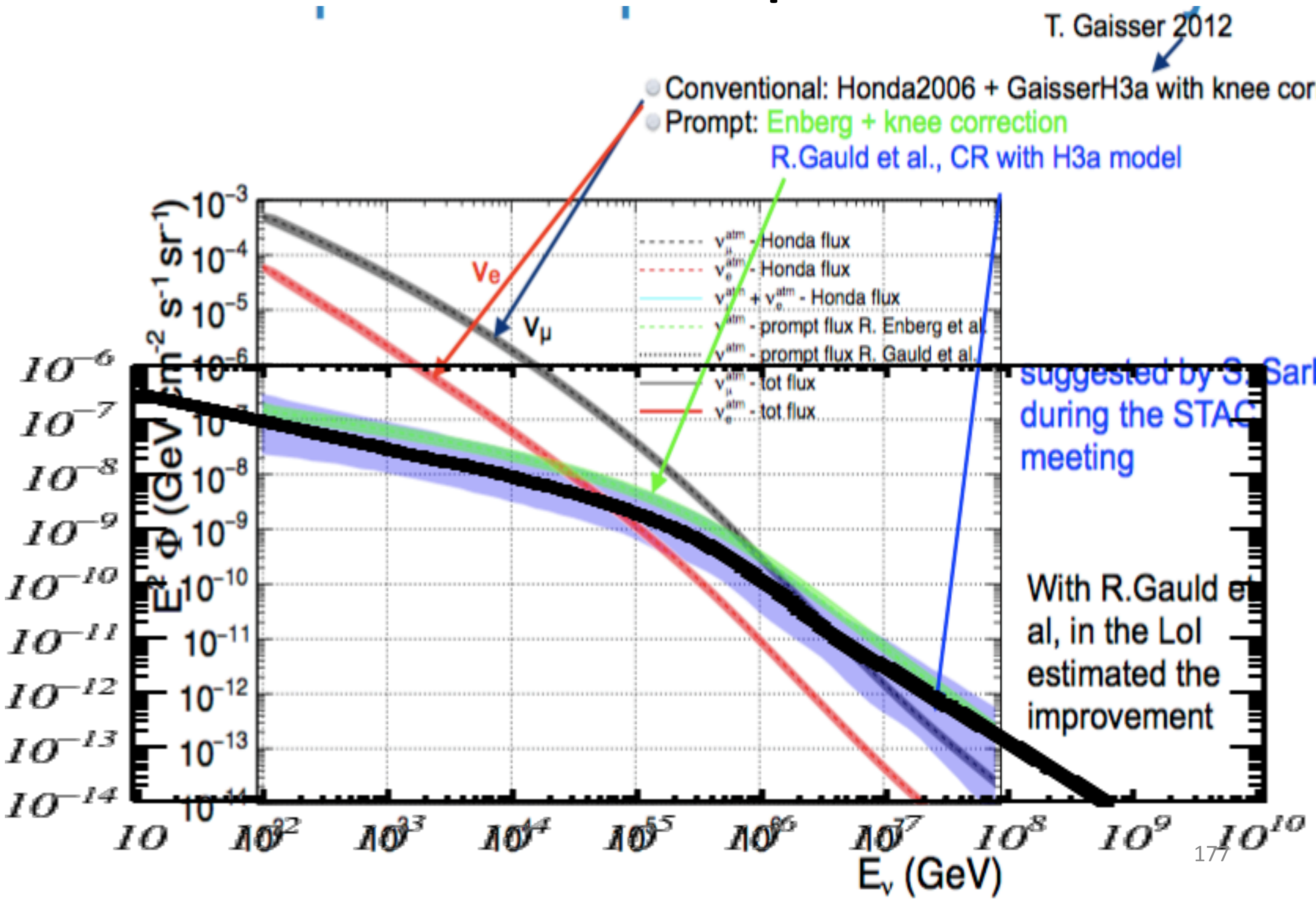
Prompt: Gauld Flux (2016)



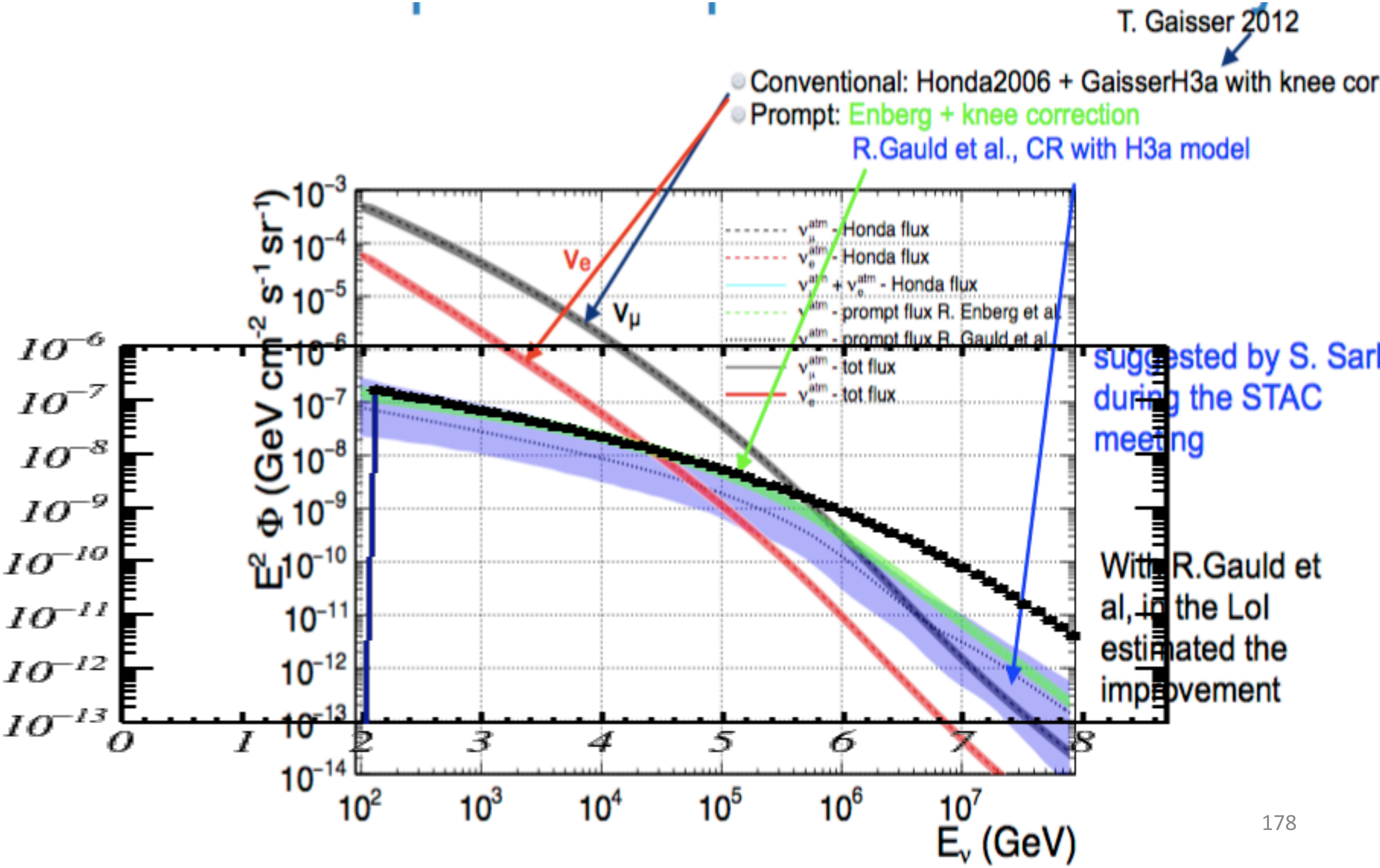
Gauld 2016


T. Gaisser 2012
Conventional: Honda2006 + GaisserH3a with knee cor
Prompt: Enberg + knee correction
R.Gauld et al., CR with H3a model
ν_e
ν_μ
ν_μ^{atm} - Honda flux
ν_e^{atm} - Honda flux
ν_μ^{atm} + ν_e^{atm} - Honda flux
ν^{atm} - prompt flux R. Enberg et al.
ν^{atm} - prompt flux R. Gauld et al.
ν_μ^{atm} - tot flux
ν_e^{atm} - tot flux
$E^2 \Phi$ (GeV cm^{-2} s^{-1} sr^{-1})
E_ν (GeV)
suggested by S. Sarl
during the STAC
meeting
With R.Gauld et
al, in the LoI
estimated the
improvement

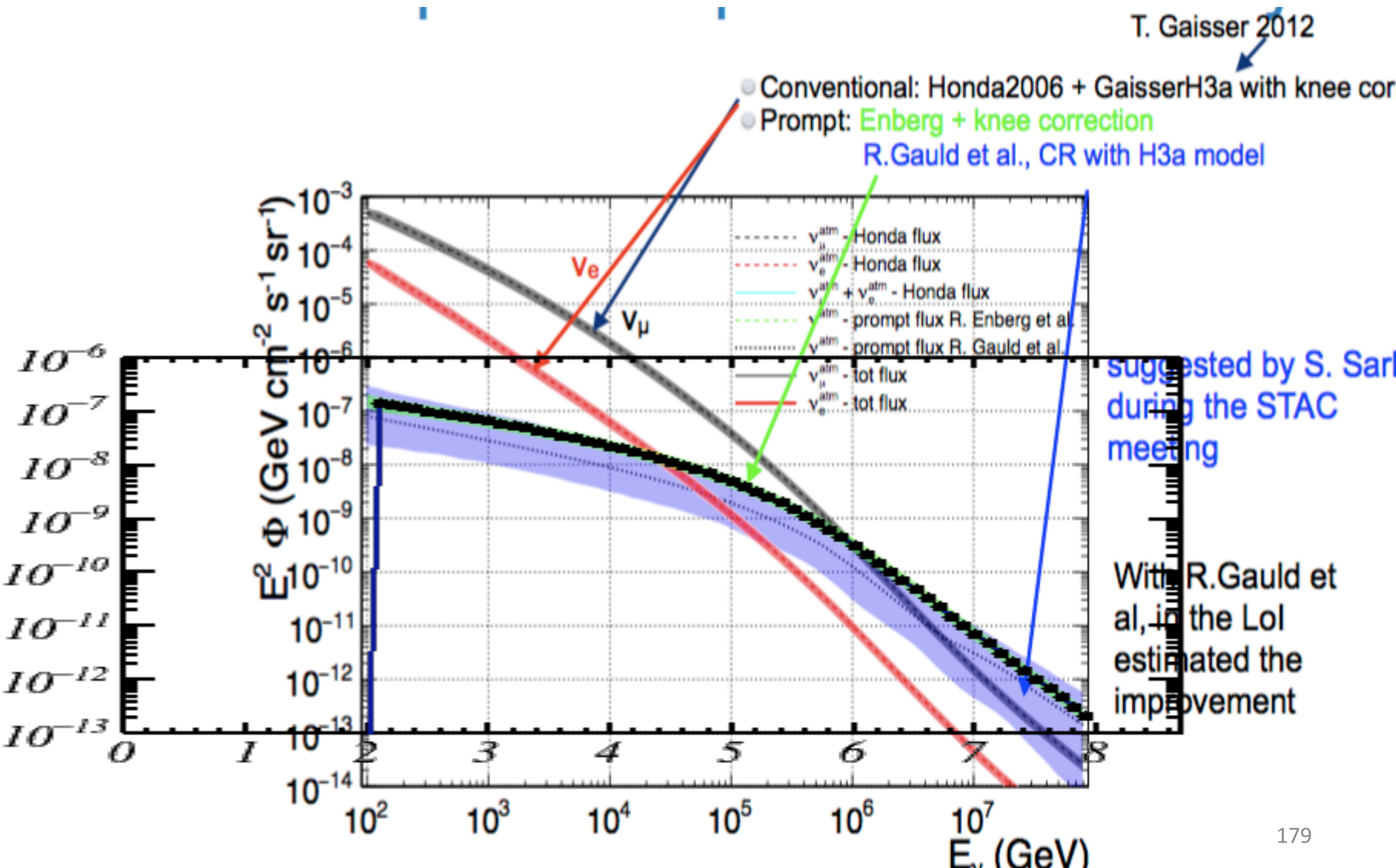
Gauld 2016 extrapolated



Enberg extrapolated

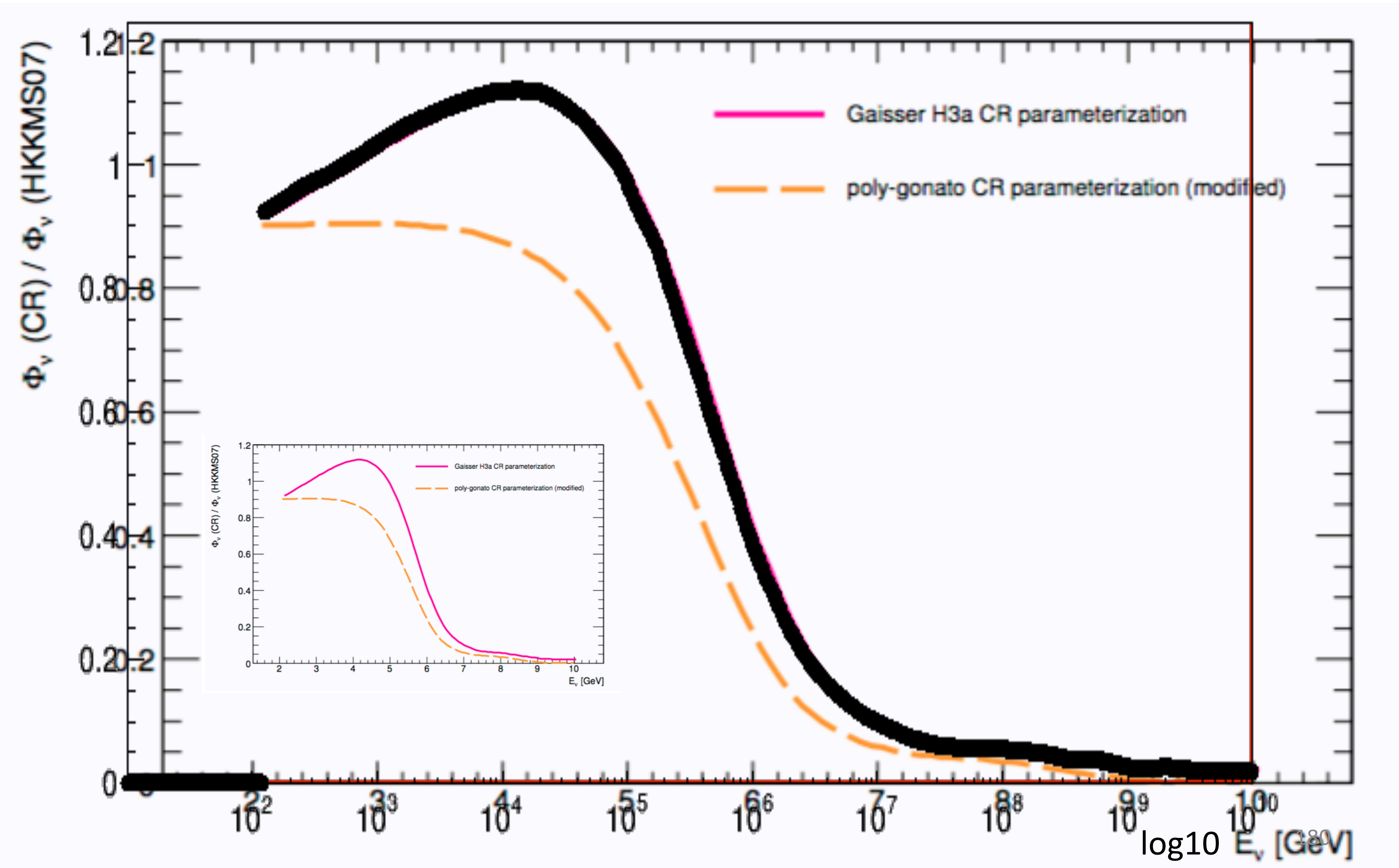


Enberg extrapolated + knee correction



arXiv:1311.7048

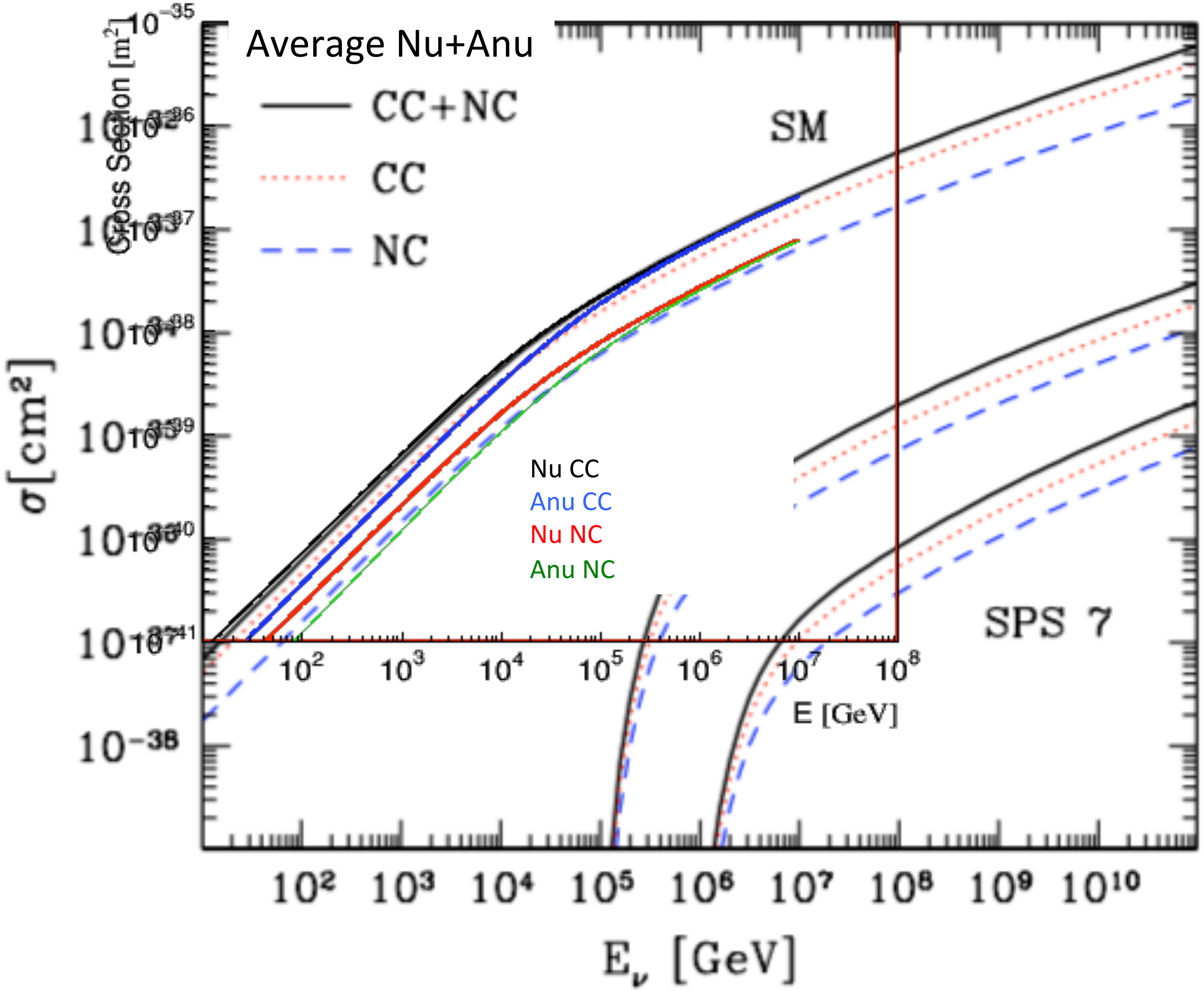
Knee Correction (Gaisser H3a)



log10

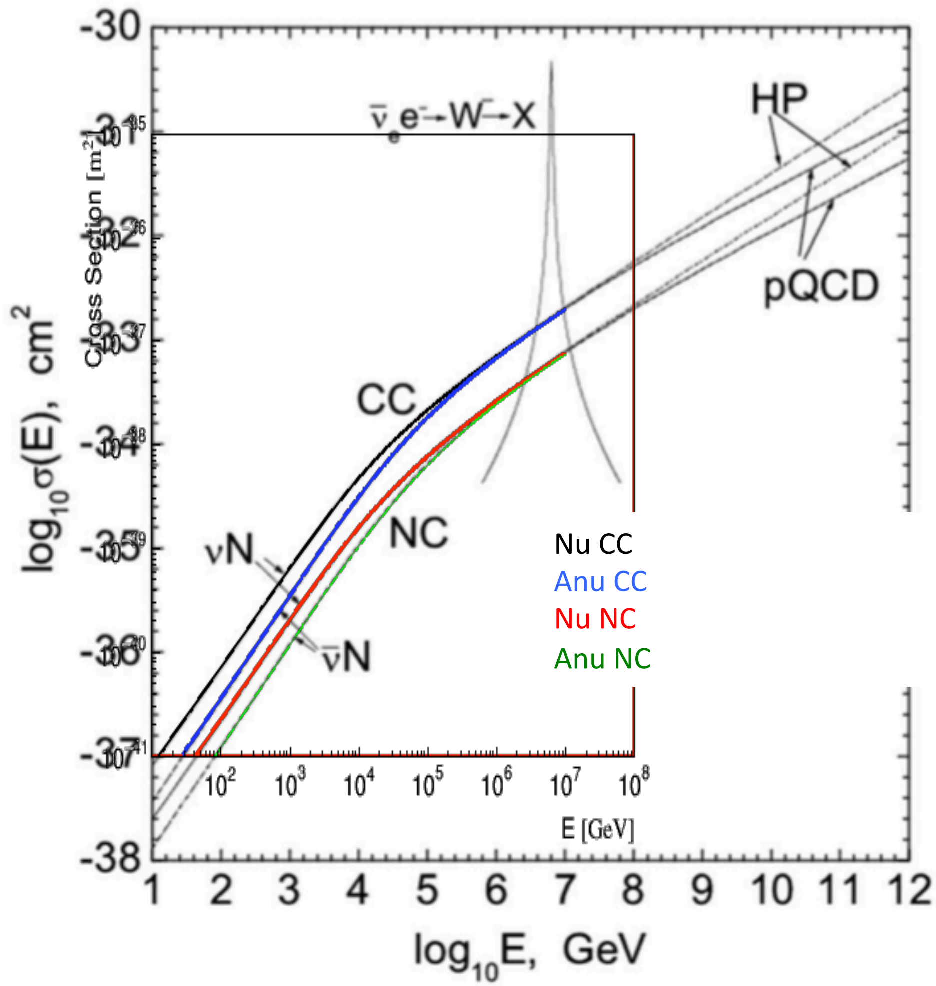
https://arxiv.org/pdf/hep-ph/0604188.pdf

Neutrino Cross Sections

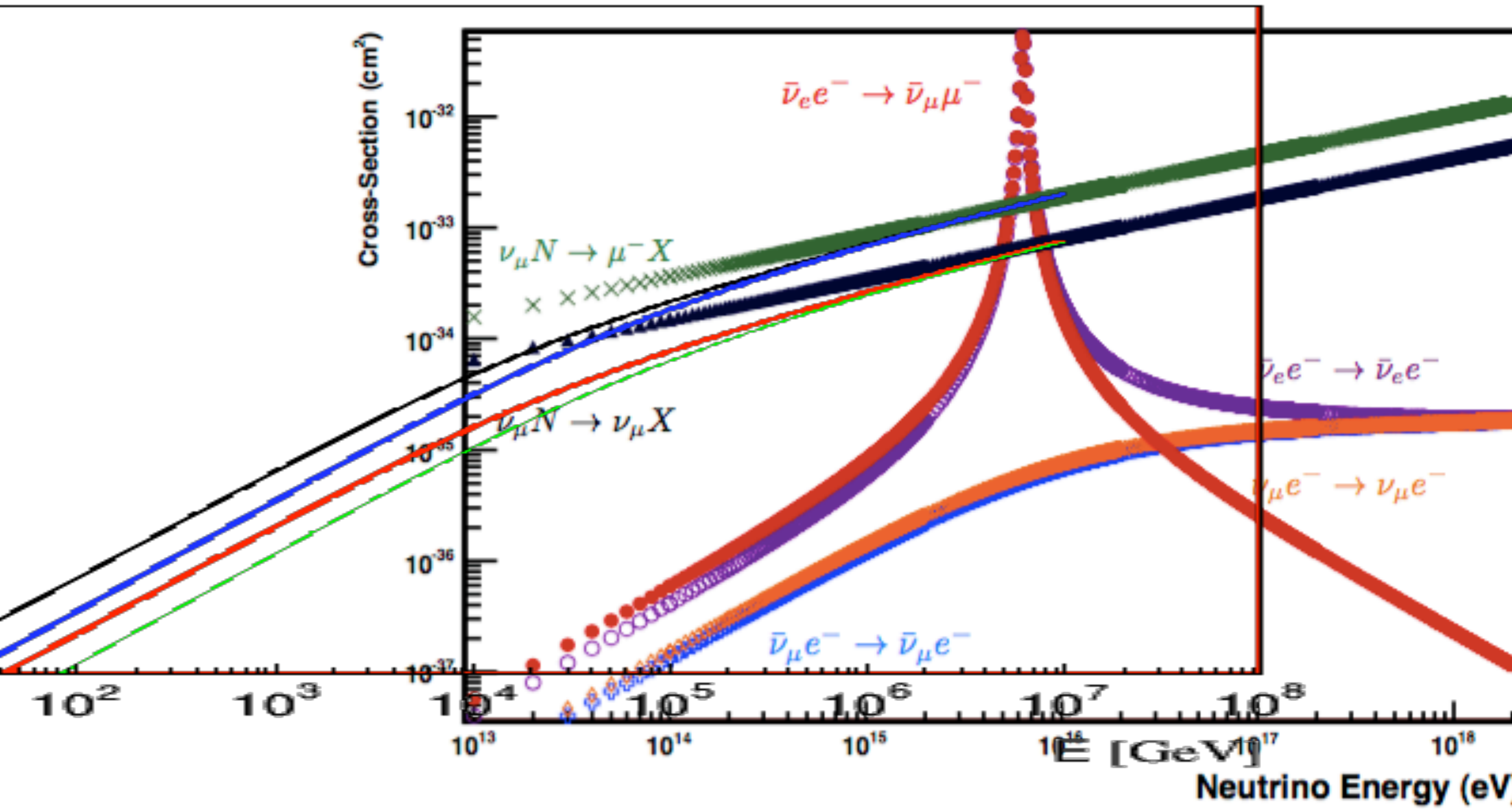


ANIS, Kowalski 2003
Figure from Colnard 2009

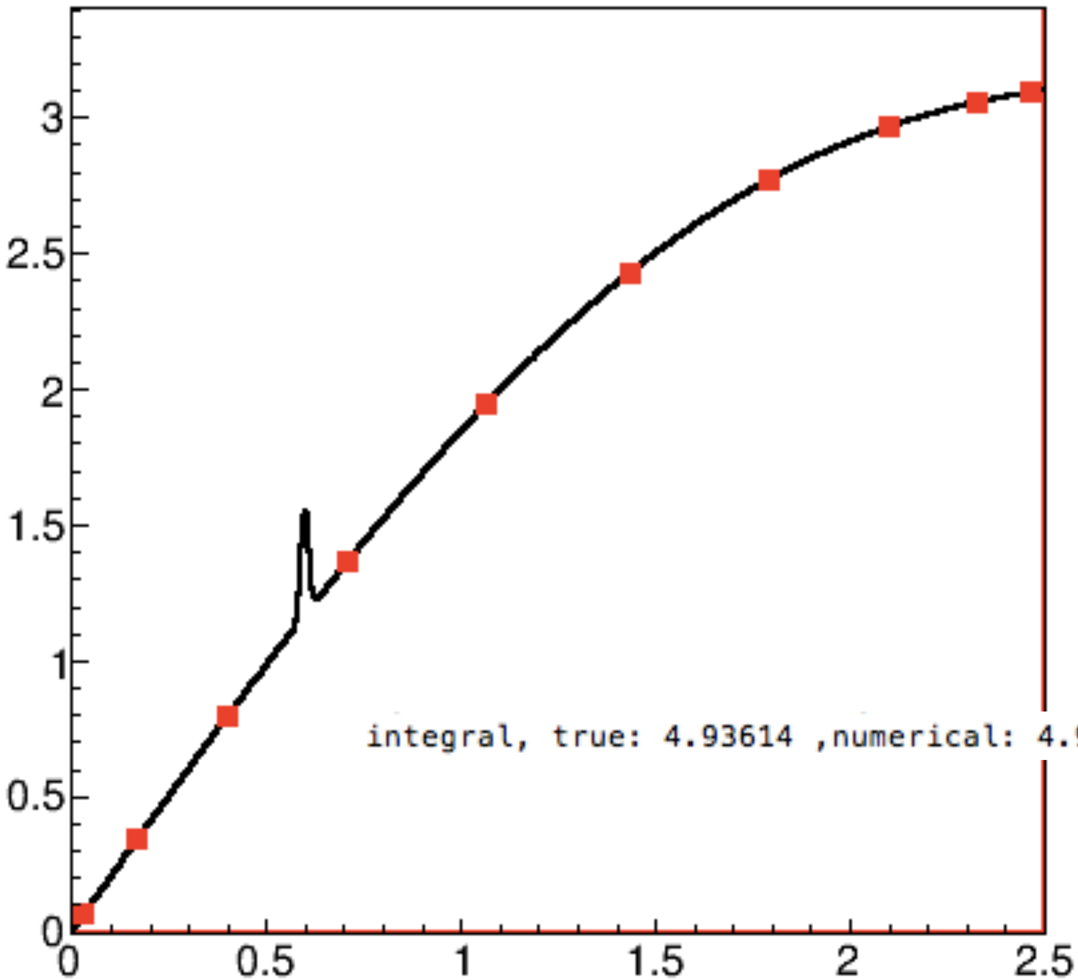
Neutrino Cross Sections



Neutrino Cross Sections

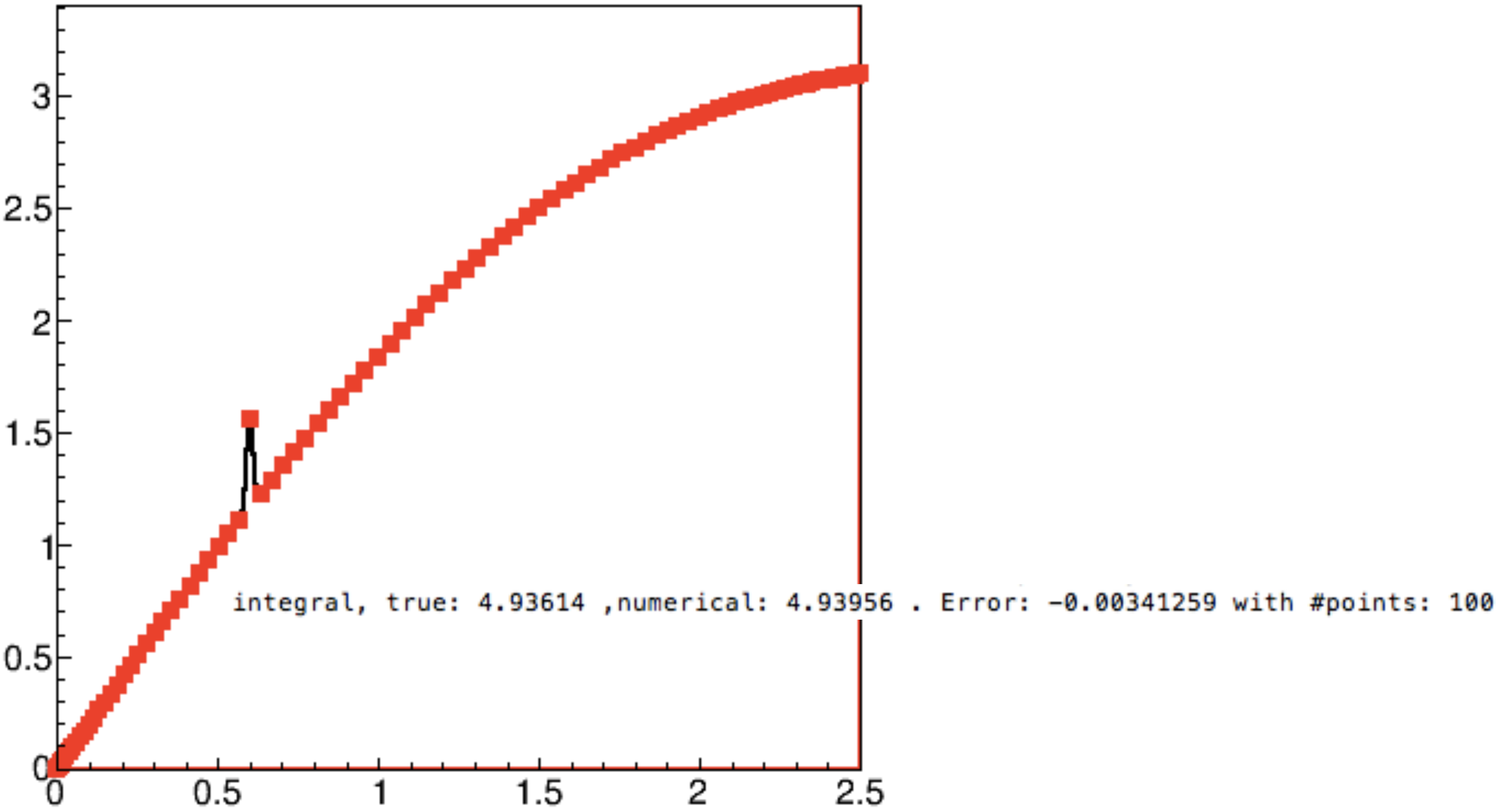


Gaussian Quadrature

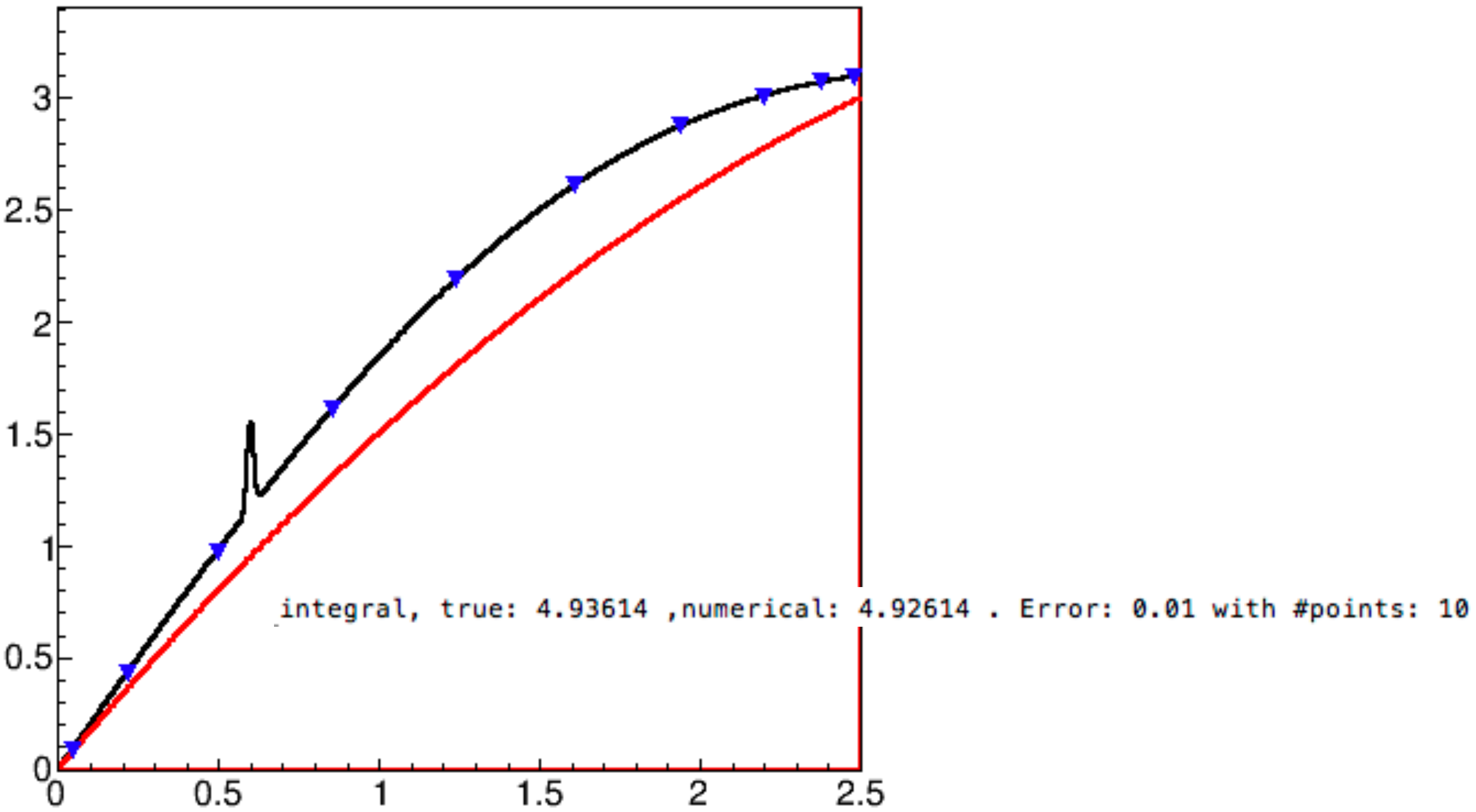


integral, true: 4.93614 ,numerical: 4.92614 . Error: 0.01 with #points: 10

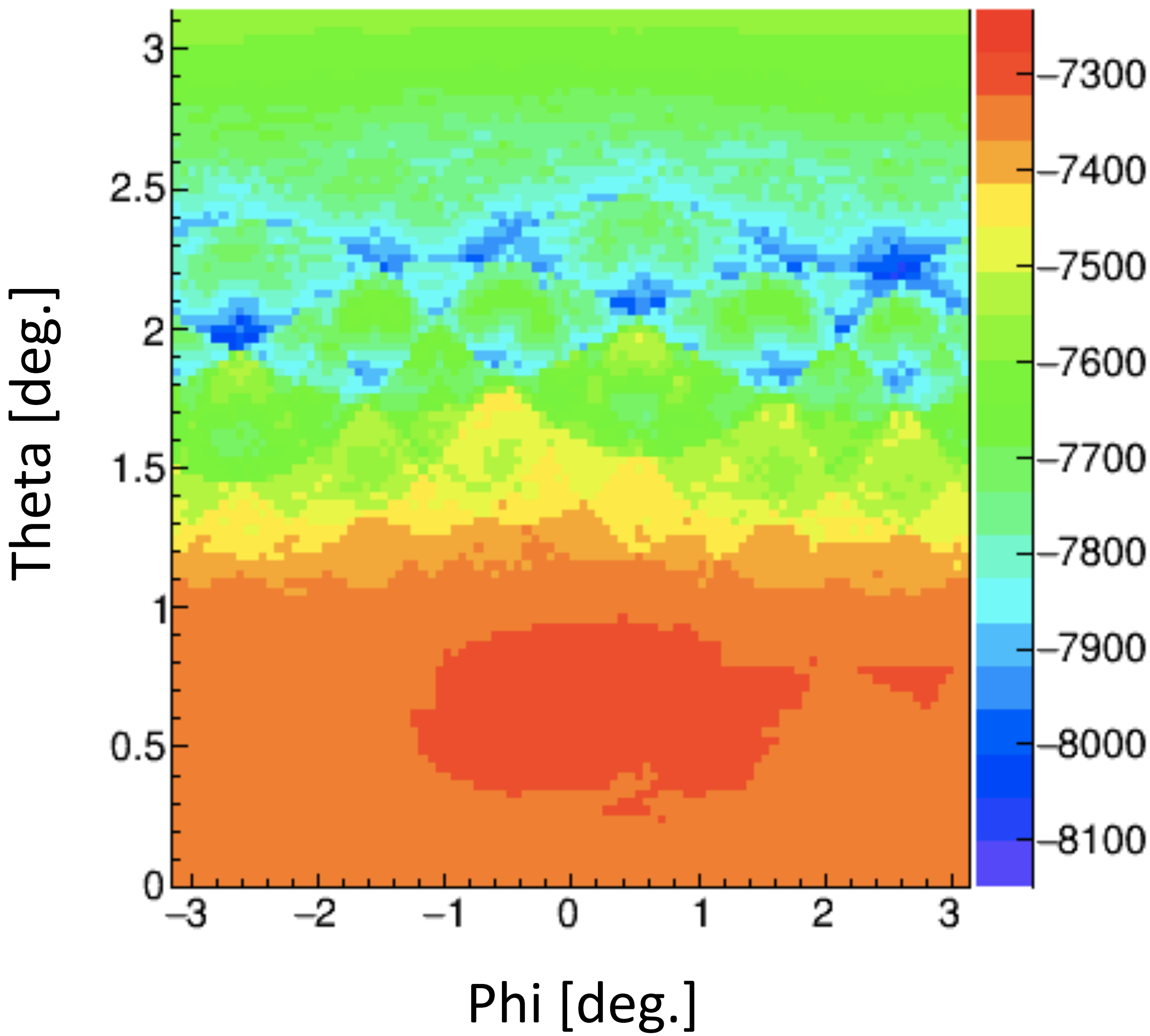
Gaussian Quadrature



Gaussian Quadrature



Event Probability: Direction



Kopper Shower Param.

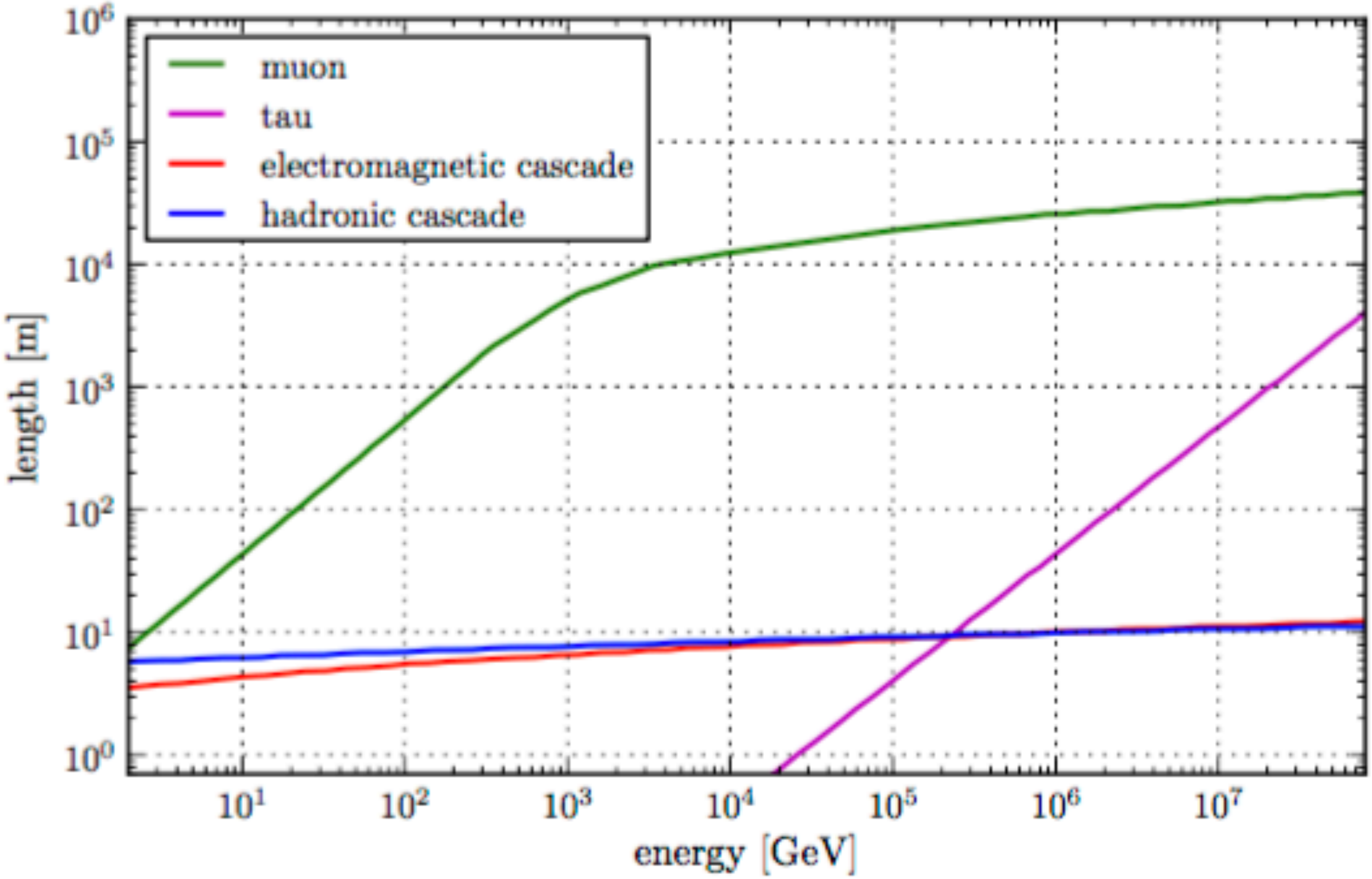


Figure 2.2 Mean Muon (μ) and tau (τ) path lengths and mean cascade lengths for electromagnetic and hadronic cascades in water. Data taken from [35].