Is *gamma coreness* a useful concept for gamma:CR separation?

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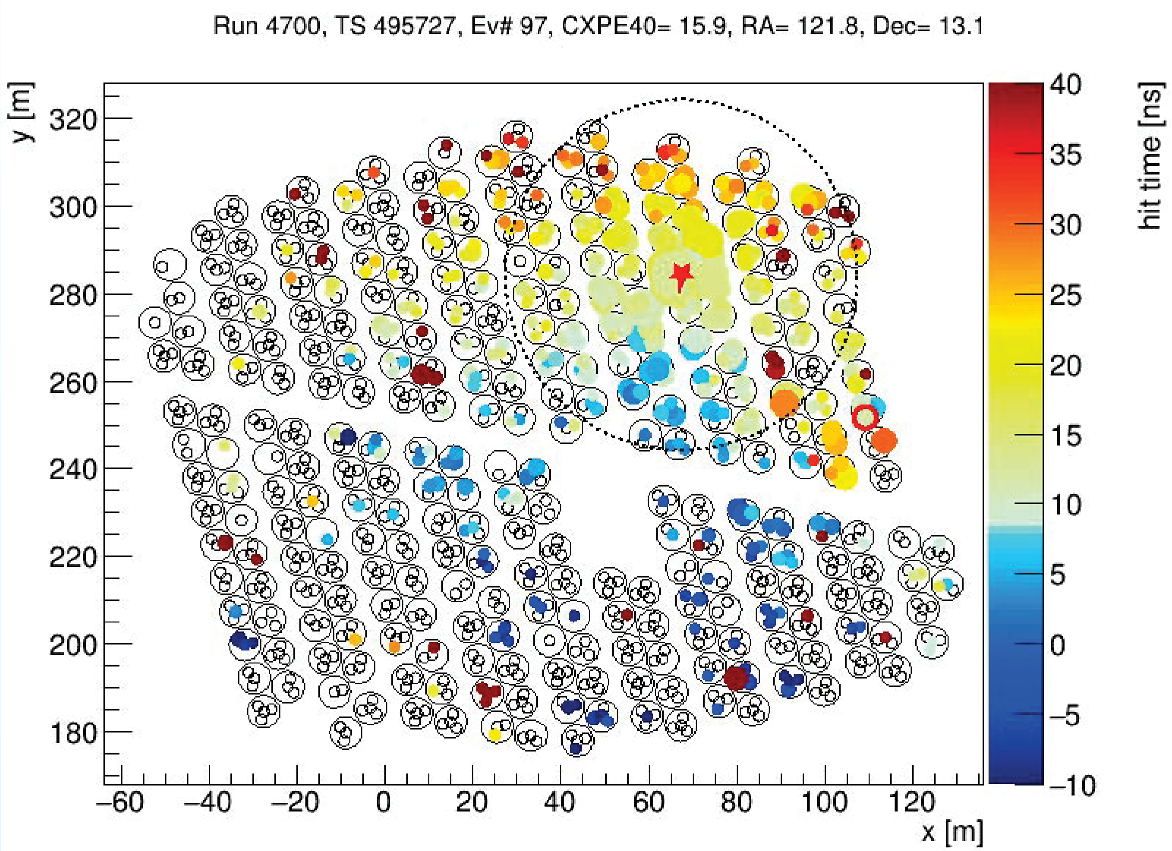
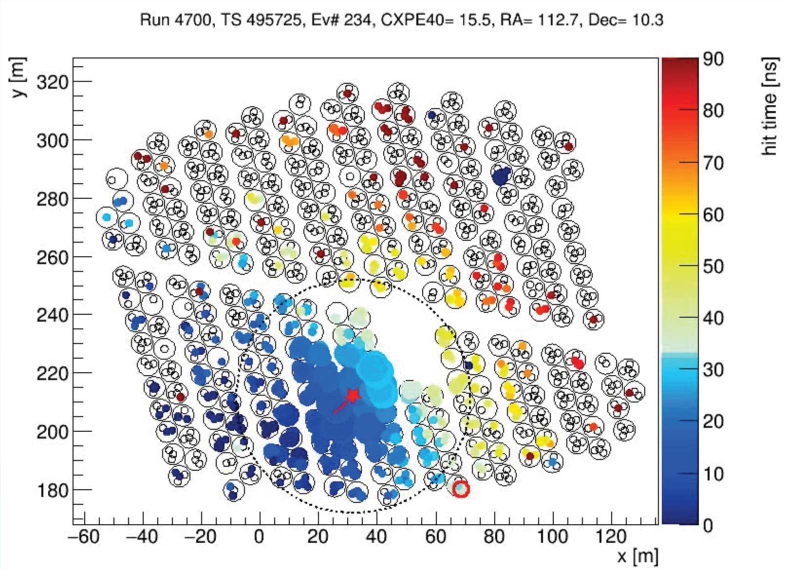
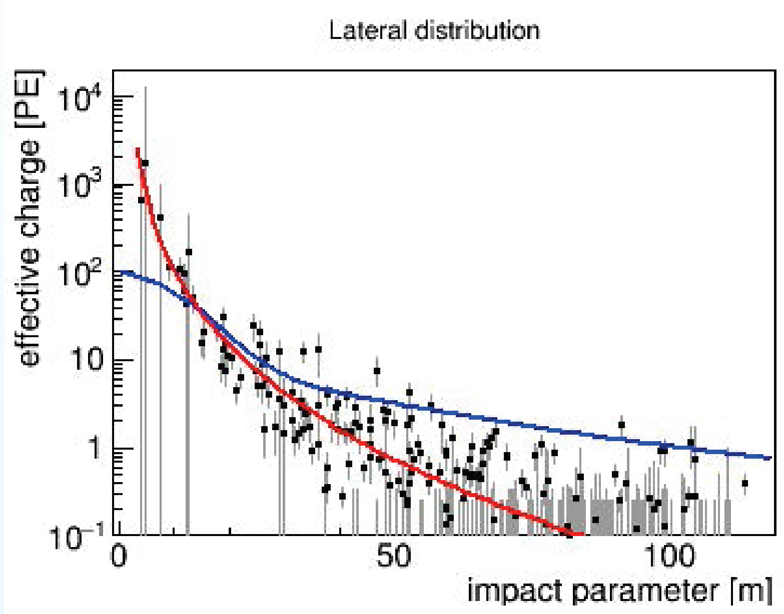
Typical HAWC events ...



- When we think of typical HAWC events (like the *n5* analysis bin event above) they:
  1. are rather *compact* ... *cf* the 40m radius circle
  2. are on (mostly on) the array ... probably the result of n5 $\sim$ n9 selection cuts

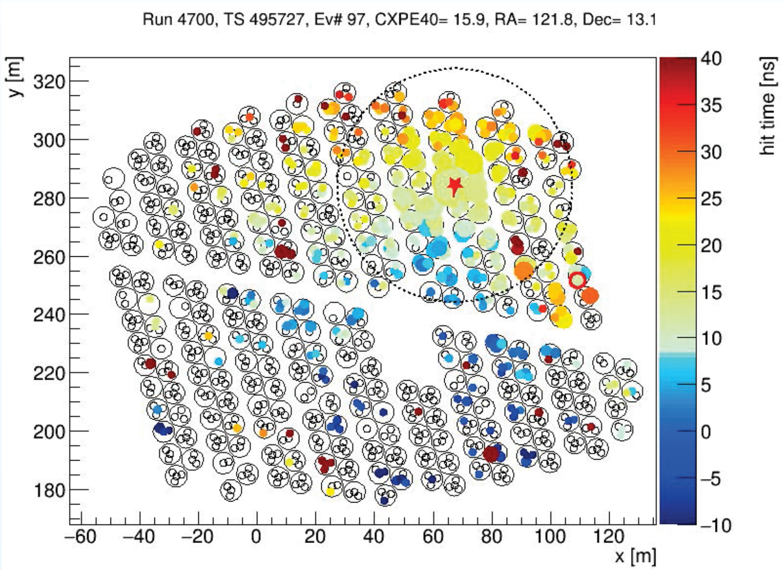
Typical *n5* HAWC events ...

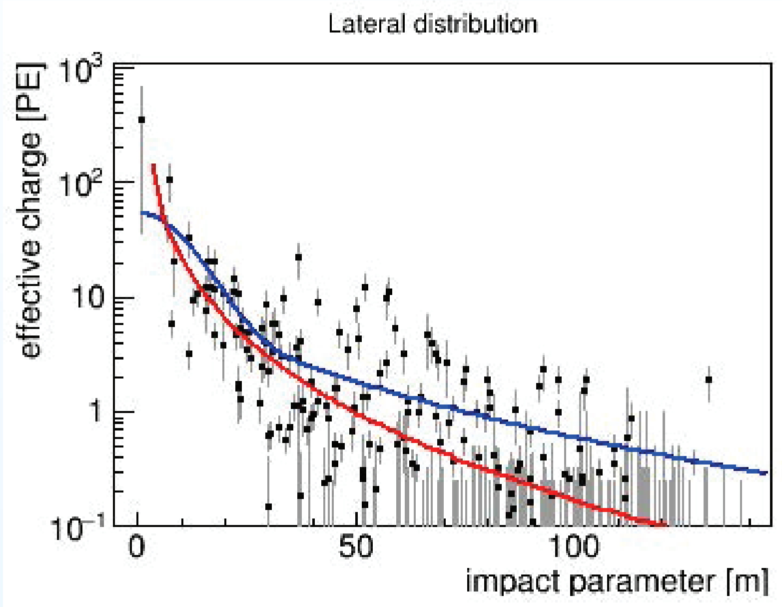




- These events are located using the Super Fast Core Fitter (blue curve)
- NKG fits assume the SFCF (x_{core}, y_{core}), correct for the shower direction (from the angle fit), and then describe the lateral energy distribution in two parameters: amplitude and shower age, s. We expect showers to have $1 \lesssim s \lesssim 2$.
- This event reconstructed (red curve) with $s = 0.50$.

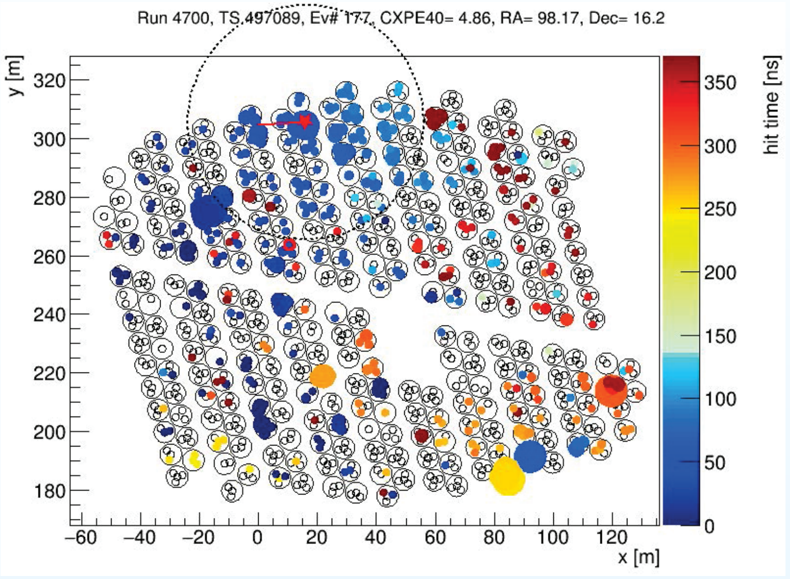
Typical *n5* HAWC events ...

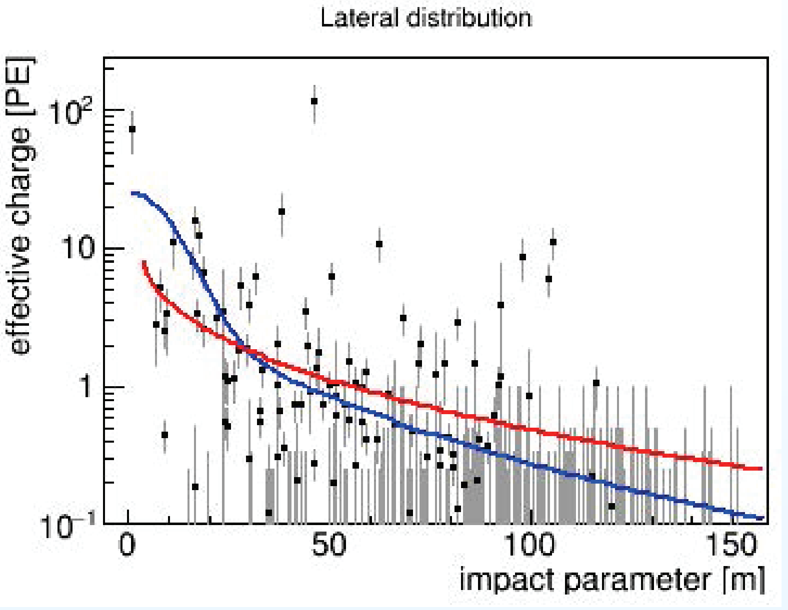




- Another event ... this event reconstructed (red curve) with $s = 1.52$.
- Showers with age, $s \sim 1.5$, are consistent with expectations for gamma showers.

Typical *n5* HAWC events ...



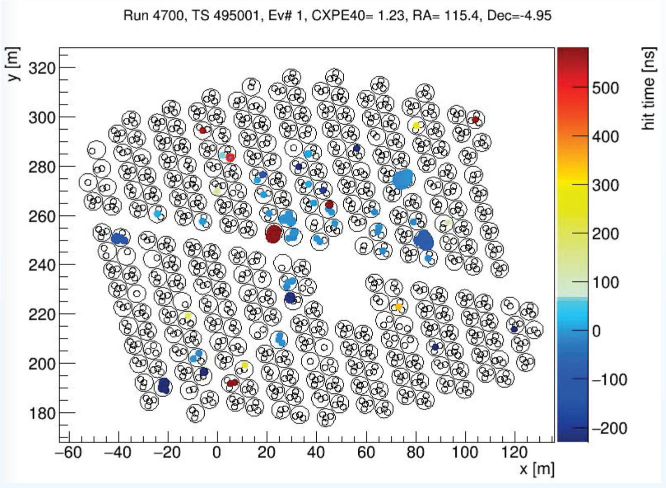


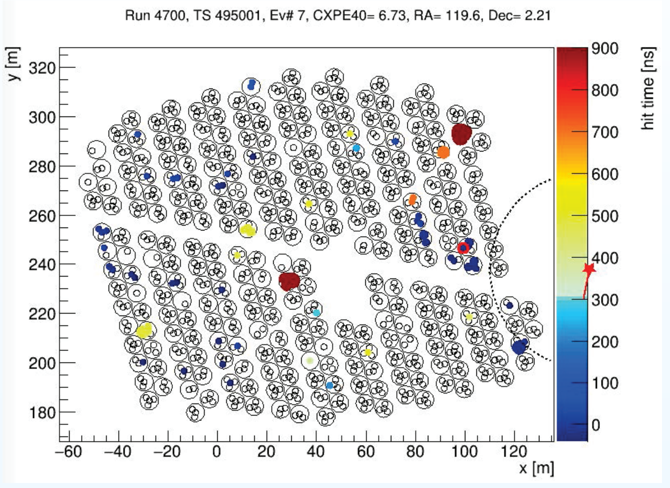
- Yet another event ... this event reconstructed (red curve) with $s = 2.50$.
- Recall that the NKG model for energy deposit, $E(r)$:

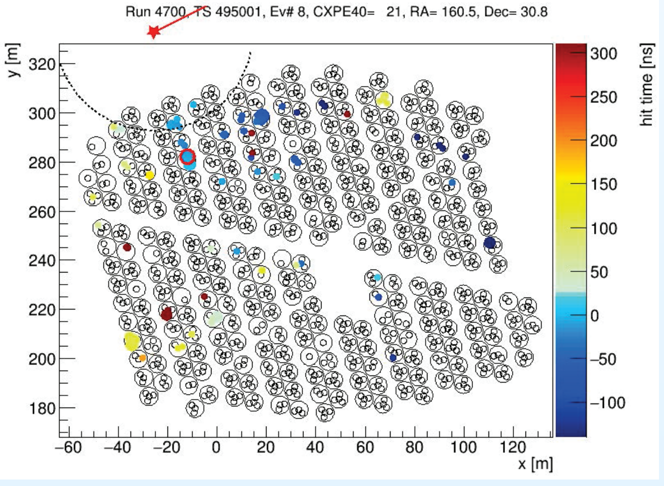
$$E(r) \;\propto\; (\frac{r}{r_0})^{s-3} \cdot (1 + \frac{r}{r_{mol}})^{s-4.5}$$

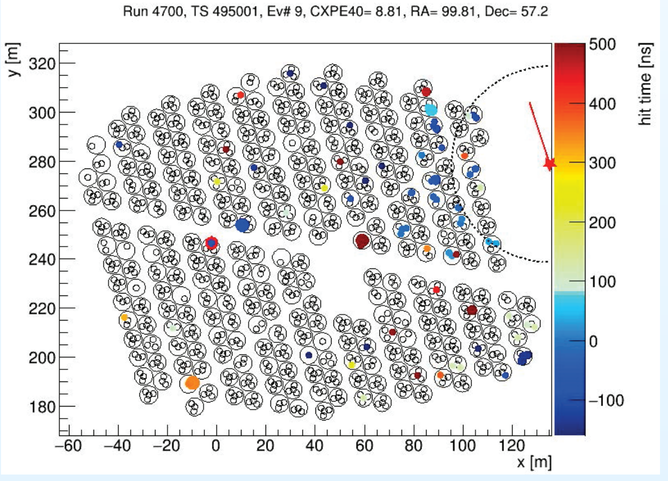
where s is the age parameter, r_0 can be chosen for convenience, and r_{mol} is the Moliere radius ~ 2 radiation length above HAWC array.

I lied ... these are typical HAWC events!



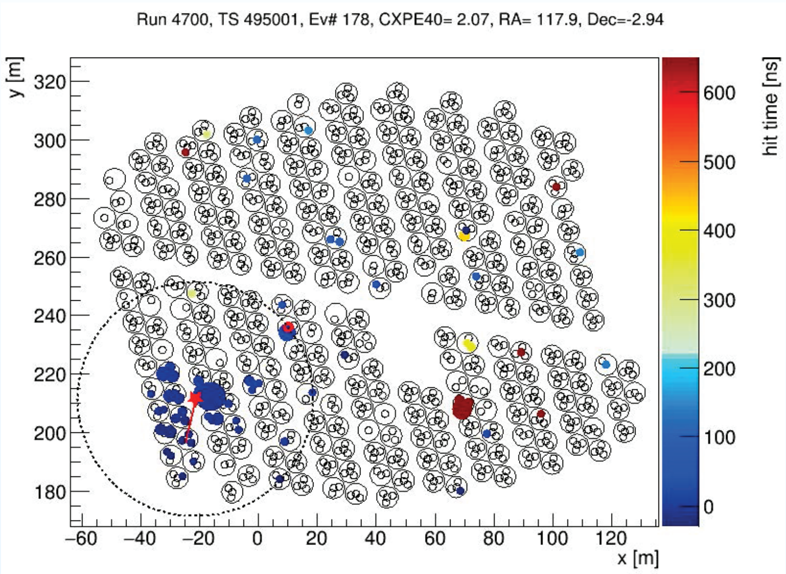


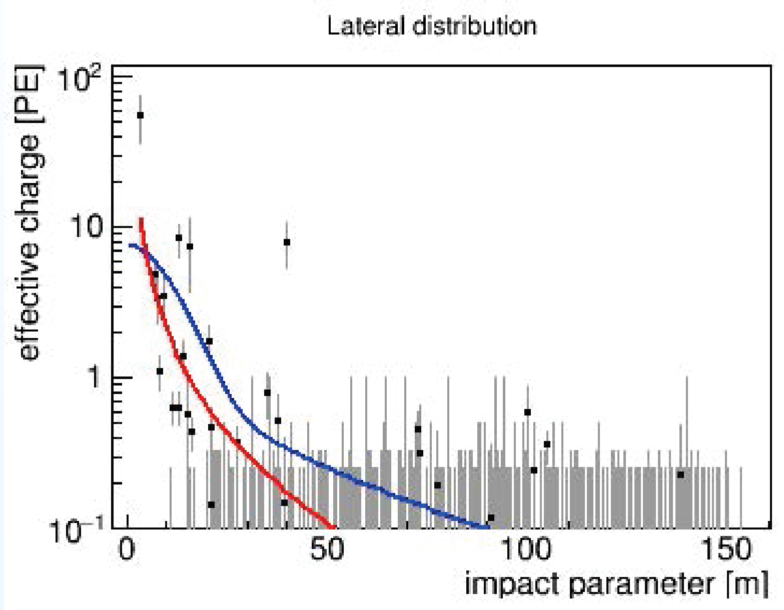




- And most events (*i.e. n0* analysis bin) have cores off the array!

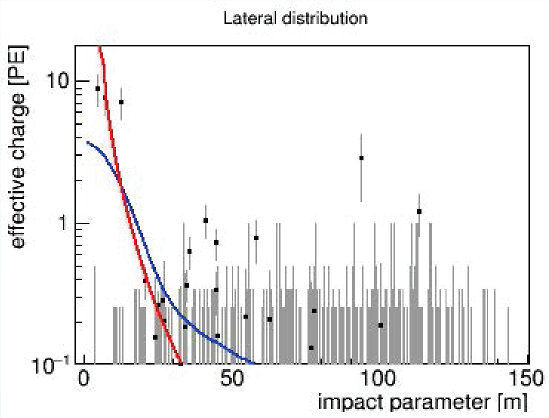
HAWC events with good *gamma coreness* ...

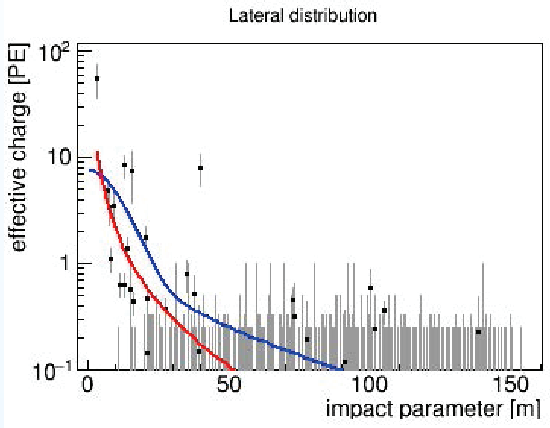


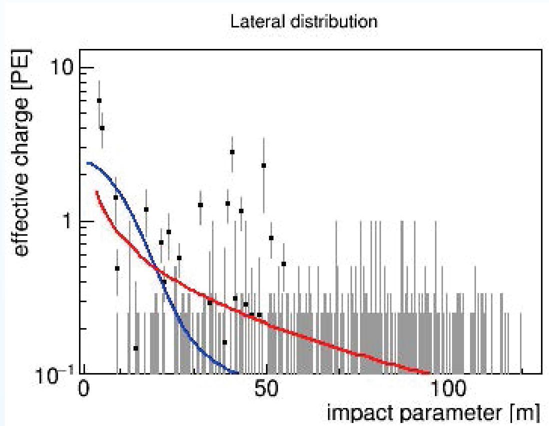


- What if we ask: do our events have a shower core consistent with gamma showers?
- We do not yet know how best to do that ... but that is what we are studying.
- We are focusing on (but not limited to) *small* events *e.g.* those in categories $n_0 \sim n_2$, with significant tank signals typically only very close to the core.
- Our analysis of the n0 event above is very compatible with our analysis of HAWC gamma MC shower n0 events.

Our analysis is based on ...

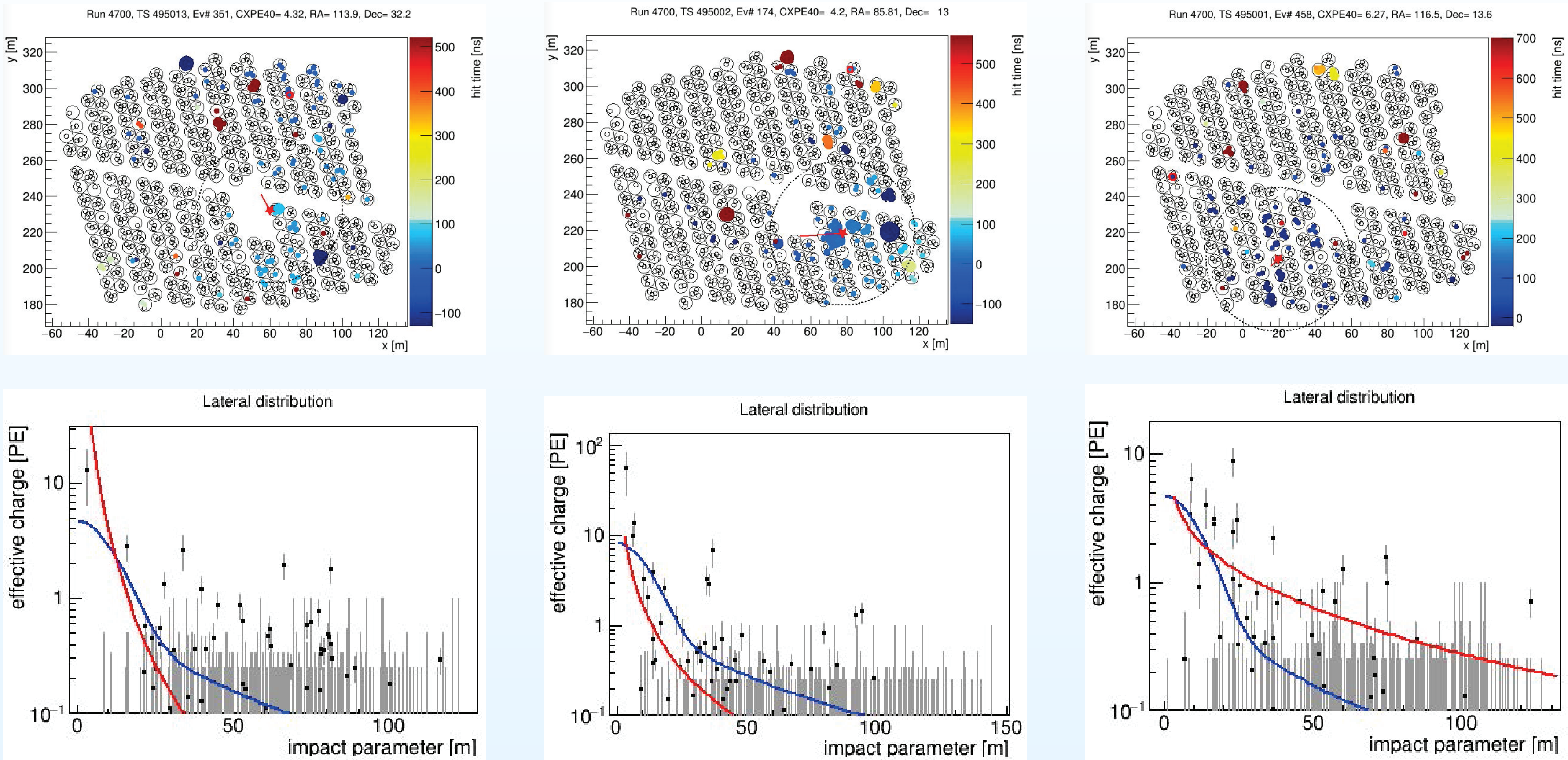






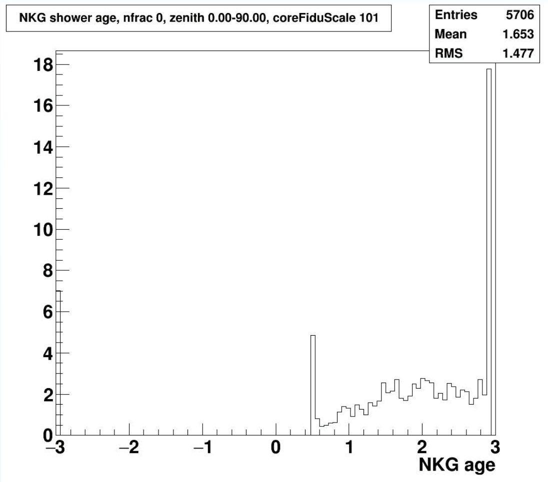
- Our analysis is based on the LatDist.cc NKG code by Kelly Malone ... but with several changes:
  1. restrict the minimum (5m) and maximum fit distance from the core: *e.g.* for n0 $\sim$ n2 events this is 25m (to avoid issues of tanks with no signals).
  2. fit the same (refined) tank signals used in the second call to SFCF (these are the signals plotted in the HAWC event display).
  3. modify the signal uncertainty to include the core position uncertainty.
  4. include in the output several *tank counts* for example: number of tanks between the minimum and maximum fit distance.
- Plots show n0 events with: (Left) $s = 0.5$, (Middle) $s = 1.61$ and (Right) $s = 2.5$

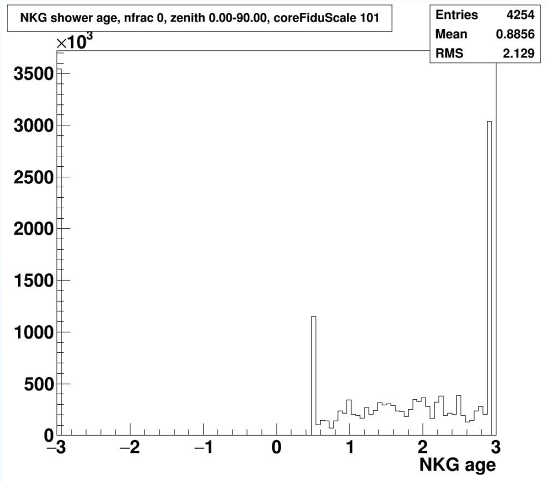
Example NKG fits for *n1* events ...

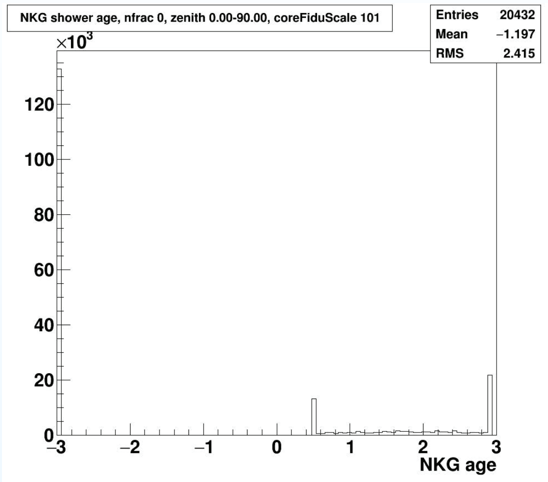


- Top plots show the HAWC event display, bottom plots show the corresponding shower lateral distribution. Blue curve is the SFCF result, red curve is the NKG result.
- The fitted age parameters are: (Left) $s = 0.5$, (Middle) $s = 1.57$, (Right) $s = 2.5$.

Analysis of gamma, proton and iron *n0* MC events

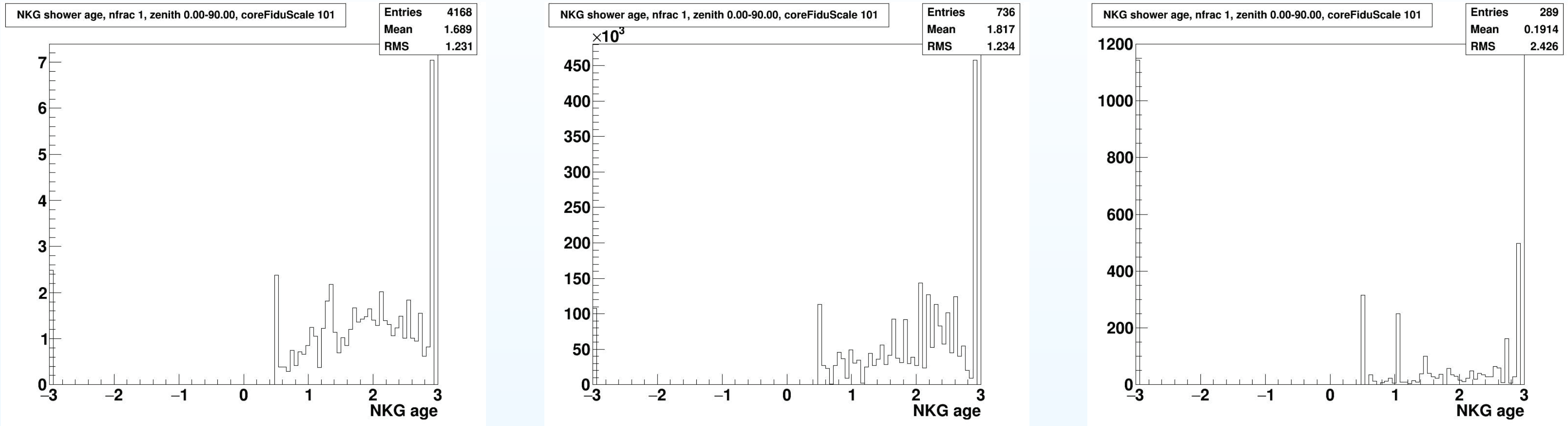






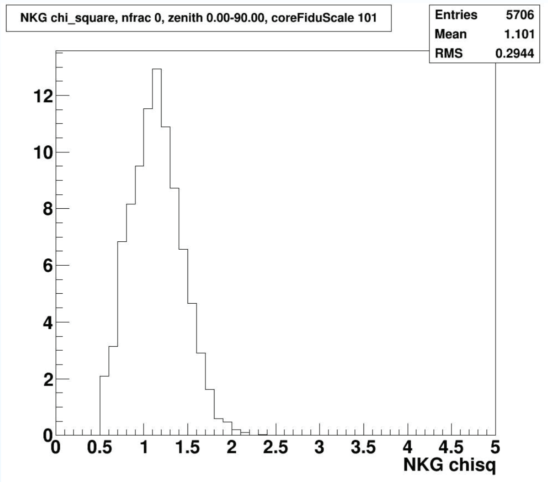
- Plots show the reconstructed NKG *age* of HAWC MC gamma (Left), proton (Middle) and iron (Right) showers for events with cores on the array:
  1. These NKG fits restricted the age to: $0.5 \leq s \leq 2.9$.
  2. Events that did not reconstruct, *e.g.* < 5 tanks within the fit range, or the tank nearest the core was > 7.5m from the core (hole in array for the counting house), are in the -3 bin.
- Gamma and proton showers reconstruct similarly. Iron showers reconstruct with reduced efficiency.

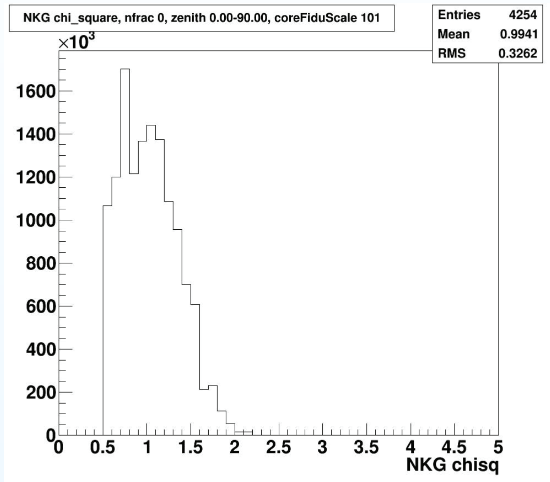
Analysis of gamma, proton and iron *n1* MC events

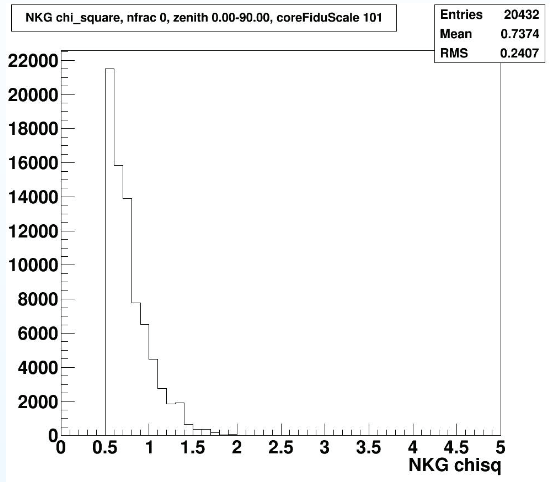


- Plots show the reconstructed NKG *age* of HAWC MC gamma (Left), proton (Middle) and iron (Right) showers for events with cores on the array:
  1. These NKG fits restricted the age to: $0.5 \leq s \leq 2.9$
  2. Events that did not reconstruct, *e.g.* < 5 tanks within the fit range, or the tank nearest the core was > 7.5m from the core (hole in array for the counting house), are in the -3 bin.
- Gamma and proton showers reconstruct similarly. For n1 events iron showers reconstruct with only slightly reduced efficiency.

Analysis of gamma, proton and iron *n0* MC events

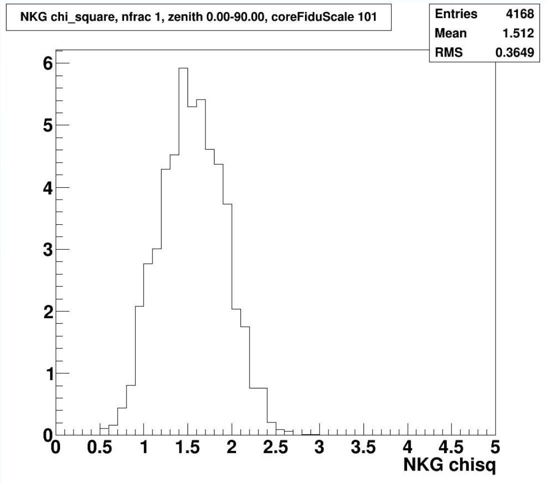


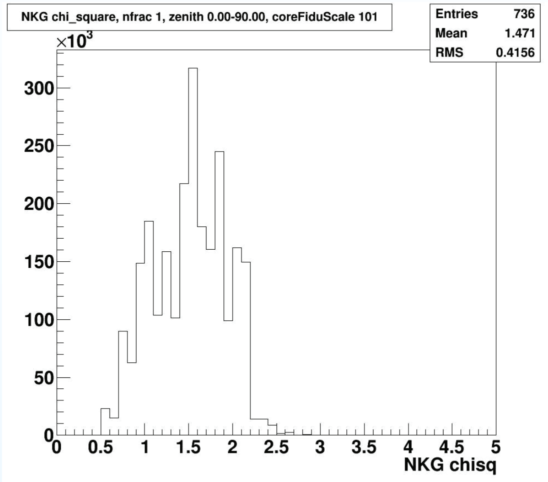


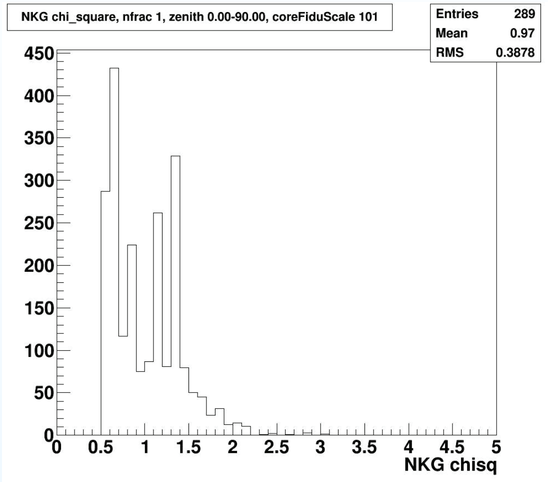


- Plots show the *number of tanks* used in the NKG fit of HAWC MC gamma (Left), proton (Middle) and iron (Right) showers for events with cores on the array:
  1. The horizontal axis, labeled chisq, is the number of tanks in the fit divided by 10.
  2. The mean number of tanks in the fits are: 11.0 (gammas), 9.94 (protons) and 7.37 (iron).
- Requiring that there are *e.g.* > 6 tanks (in the analysis fit range $5m \leq r \leq 25m$) mildly suppresses proton events and suppresses iron events in comparison to gamma showers.

Analysis of gamma, proton and iron *n1* MC events

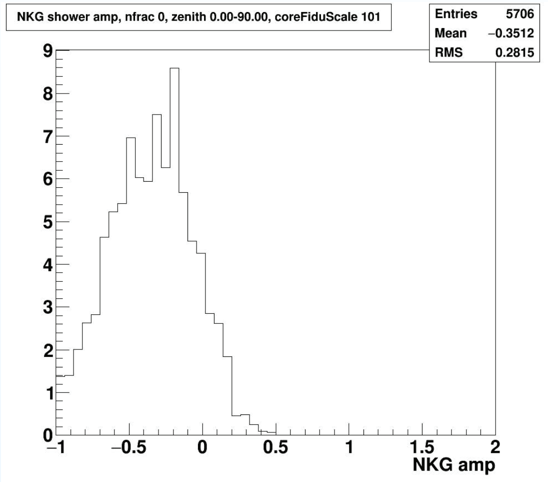


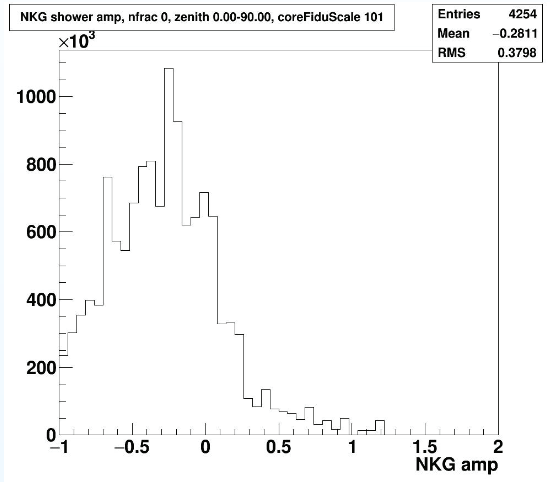


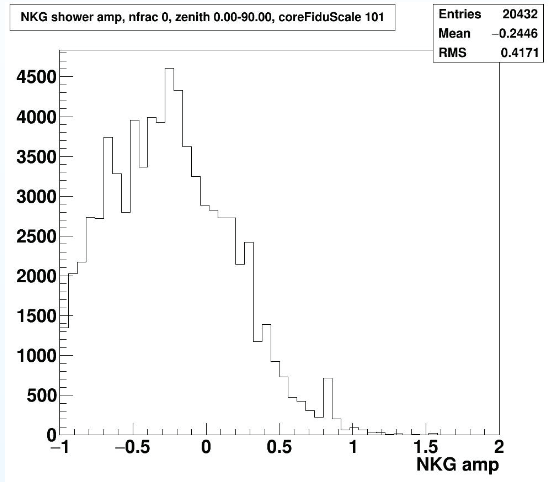


- Plots show the *number of tanks* used in the NKG fit of HAWC MC gamma (Left), proton (Middle) and iron (Right) showers for events with cores on the array:
  1. The horizontal axis, labeled chisq, is the number of tanks in the fit divided by 10.
  2. The mean number of tanks in the fits are: 15.1 (gammas), 14.7 (protons) and 9.7 (iron).
- Requiring that there are *e.g.* > 8 tanks (in the analysis fit range $5m \leq r \leq 25m$) somewhat suppresses iron events in comparison to gamma showers.

Analysis of gamma, proton and iron *n0* MC events







- Plots show the *amplitude* parameter in the NKG fit of HAWC MC gamma (Left), proton (Middle) and iron (Right) showers for events with cores on the array:
  1. Showers with *large* values of amplitude are typically those with large values of the age parameter ... *i.e.* events with the least concentrated cores.
  2. Both proton and iron showers have tails to *large* values of the amplitude parameter.
- Requiring that *e.g.* the amplitude < 0.2 mildly suppresses proton events and suppresses iron events in comparison to gamma showers.

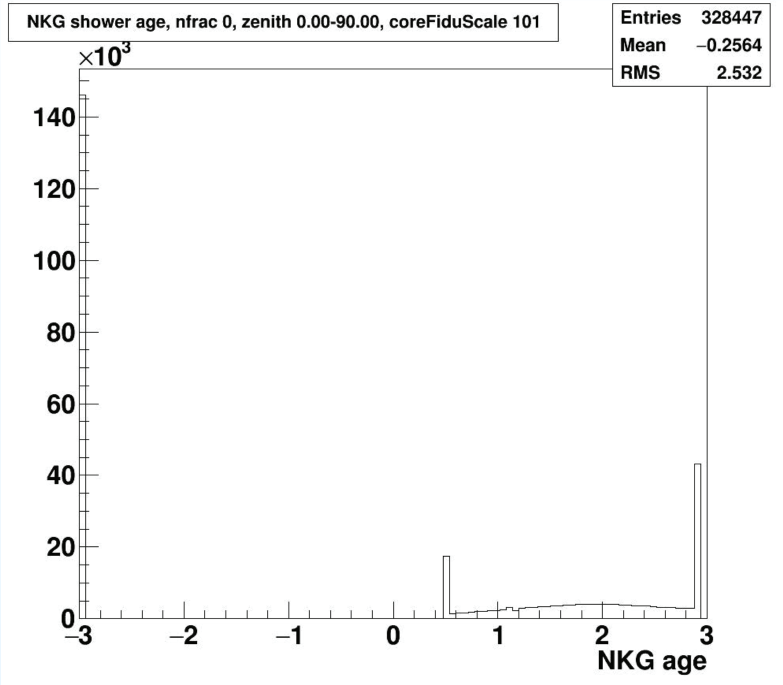
Summary

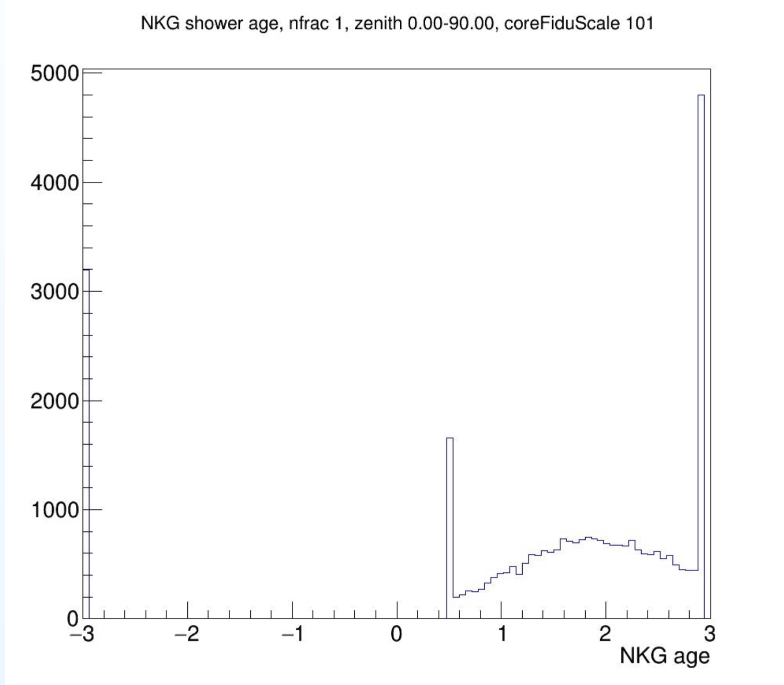
- HAWC tanks (with significant signals), in event categories $n_0 \sim n_2$, have a limited spacial extent. This is particularly true for gamma showers.
  1. At least one component of our signal analysis should emphasize signals near the shower core. Such analyses then try to quantify the *gamma coreness* of events: *viz.* are tank signals near the core more consistent with gamma showers that with cosmic ray showers.
  2. The NKG function for gamma showers provides a natural way to characterize the shower in a few parameters: shower age and amplitude.
  3. Other quantities, *e.g.* the number of hit-tanks within a limited radius from the core, may also be a way to separate gamma from cosmic ray showers.
- Initial MC studies suggest ways to emphasize gamma showers *VS* cosmic ray (proton or iron) showers ... and this is most encouraging for n_0 events (where we may need most help!)
- Next steps include:
  1. Make a new module (distinct from LatDist.cc) for this analysis
  2. Decide on output quantities: NKG amplitude, age, number of tanks in NKG fit
  3. Provide the module to the offline-reconstruction as an option soon

Additional/backup slides

Additional slides

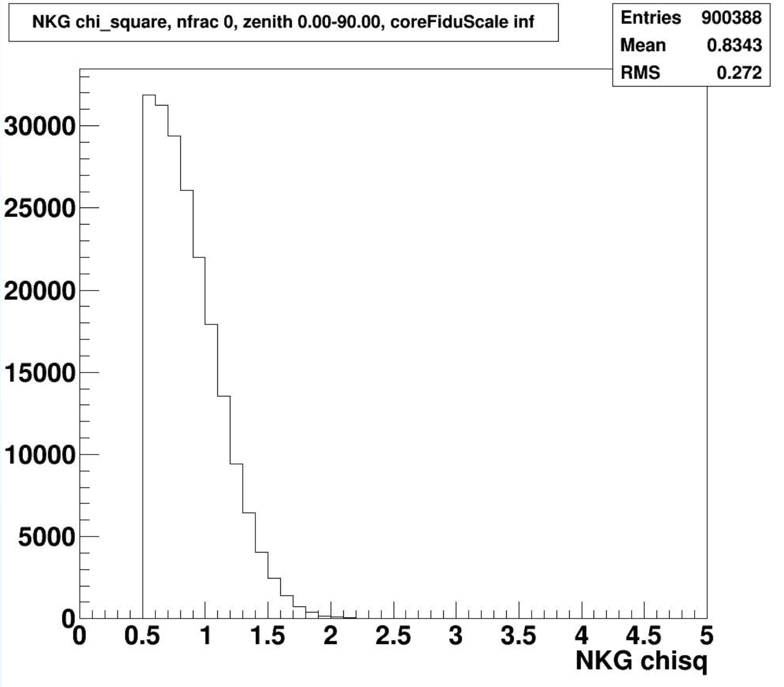
NKG analysis of HAWC data ...

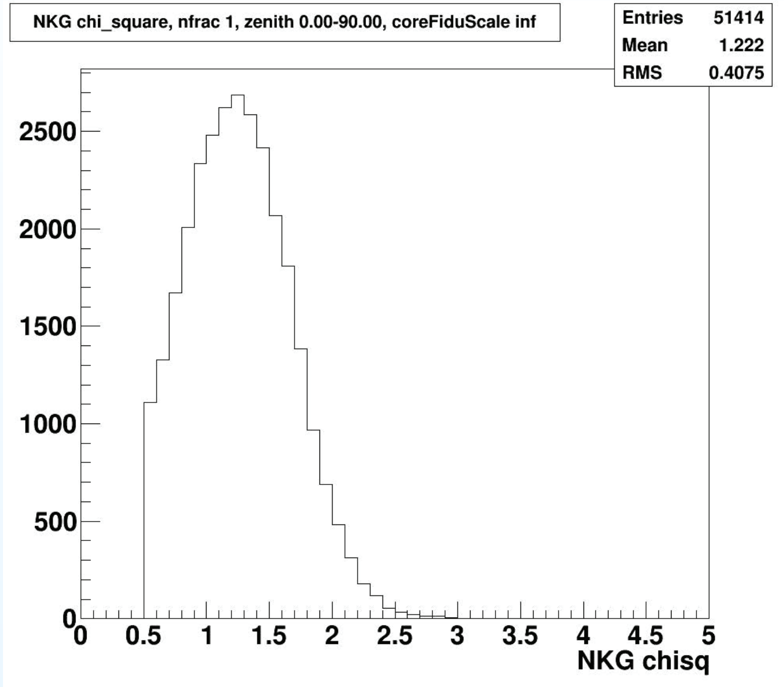




- Plots of shower *age* parameter: (Left) for *n0* analysis bin events and (Right) for *n1* analysis bin events.
- Comparison with MC events, slides 10 and 11, suggest that the data distributions fall between proton and iron simulations ...

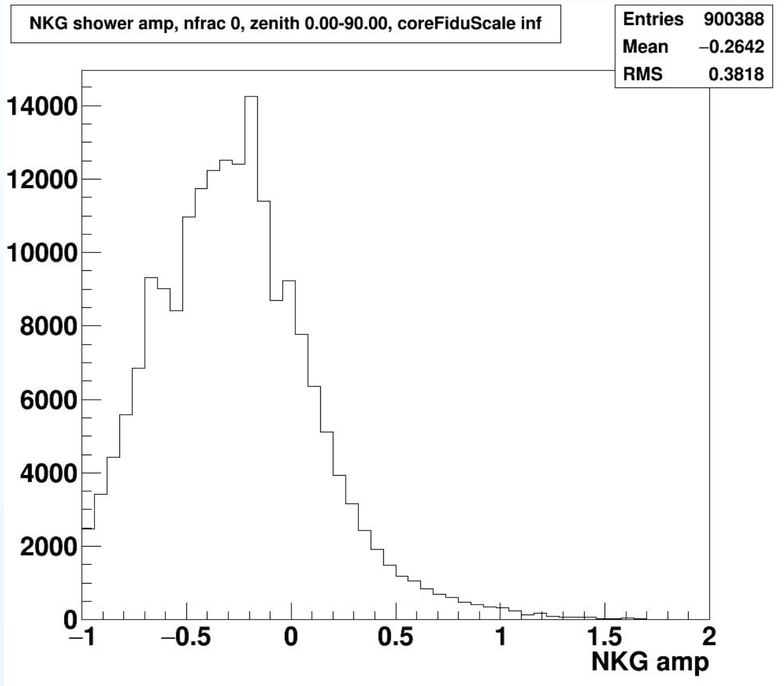
NKG analysis of HAWC data ...





- Plots of *number of tanks* used in NKG fit: (Left) for *n0* analysis bin events and (Right) for *n1* analysis bin events.
- Recall that the horizontal axis, labeled chisq, is the number of tanks in the fit divided by 10!
- Comparison with MC events, slides 12 and 13, suggest that the data distributions fall between proton and iron simulations ...

NKG analysis of HAWC data ...



- Plots of shower *amplitude* parameter for the *n0* analysis bin events.
- Comparison with MC events, slide 14, suggest that the data distributions fall between proton and iron simulations ...