Optimizing DHCAL single particle energy resolution

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introduction

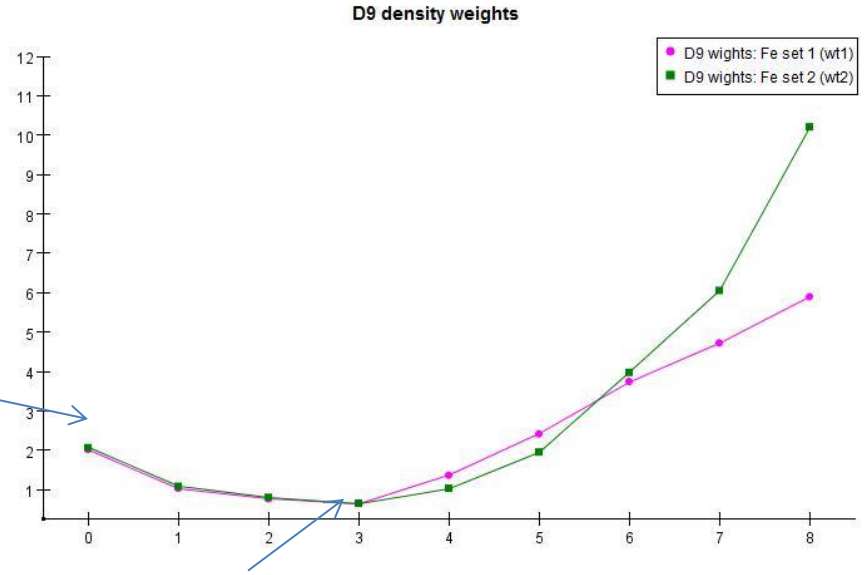
- Single particle energy resolution of a traditional Calorimeter can be optimized by hardware/software compensation
  - Equalize EM and Hadronic responses
- Digital (Hadron) Calorimeter is quite a different device
  - Non-linear response for EM shower
    - Measured energy of a 10 GeV photon E(10)
      E(10) ≠ E(5) + E(5) ≠ E(2) + E(2) + E(2) + E(2) + E(2)
    - Correction can be applied for single EM shower
    - No obvious way to correct for pi0's generated in hadronic showers
  - EM and Hadronic responses could be different, at least not likely to be equal in entire energy range
  - Software compensation not likely to be very successful without taking care of the first problem (non-linearity)

Linearizing the EM response I

- The non-linear response of EM showers is due to finite readout pad size → multiple particles hitting same pad → saturation
- Need ways to account for multiple particles on the same pad
  - Assumption: Hit density (hit fraction in a given local space) is related to local particle density
  - (Density weighted calibration proved good correlation between hit density and local particle density)
  - Start with simple hit density definition
    - d9: number of hits in the surrounding 3pad x 3pad area, centered on the hit being studied (d9 = 0 – 8)
  - Start with MC simulation for Fe absorber setup
    - RPC response: rpcsim4 (single exponential) – not the best…
    - Positron sample: 2, 4, 6, 8, 10, 12, 16, 20, 25, 32, 40, 60 (GeV)
    - Pion sample: 2, 4, 6, 8, 10, 12, 16, 20, 25, 32, 40, 60, 80, 100 (GeV)
    - MC sample provided by Kurt Francis

Linearizing the EM response II

- Chose two sets of positron energy points, adjust weights for each D9 bin to achieve linear response
  - Set I (wt1): 2, 6, 10, 16, 25 (GeV)
  - Set II (wt2): 2, 6, 16, 32, 60 (GeV)
  - Target response: 14.74 hits/GeV (arbitrary)



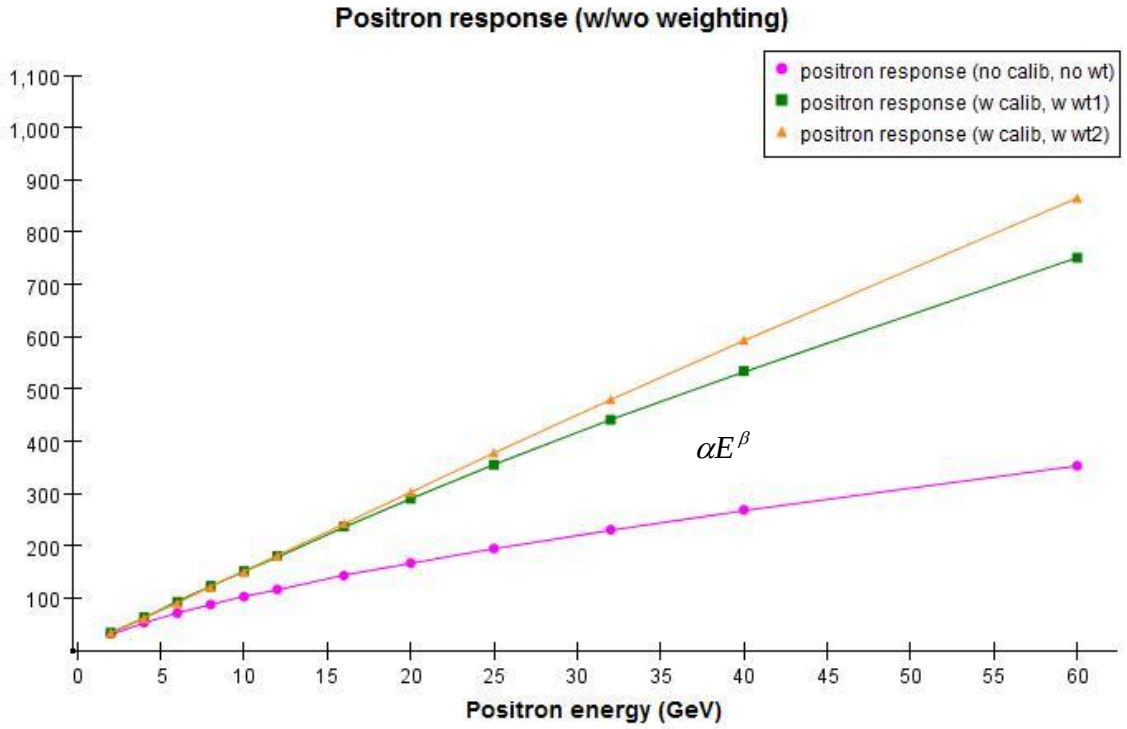
High weights for isolated hits

Very high weigh for high density bins: **correct for saturation**

Low weights for medium density: mostly due to hit multiplicity ~ 1.6

Everything as expected

Positron response after weighting



$16.687 \times E^{0.966}$

$20.240 \times E^{0.885}$

$20.866 \times E^{0.692}$

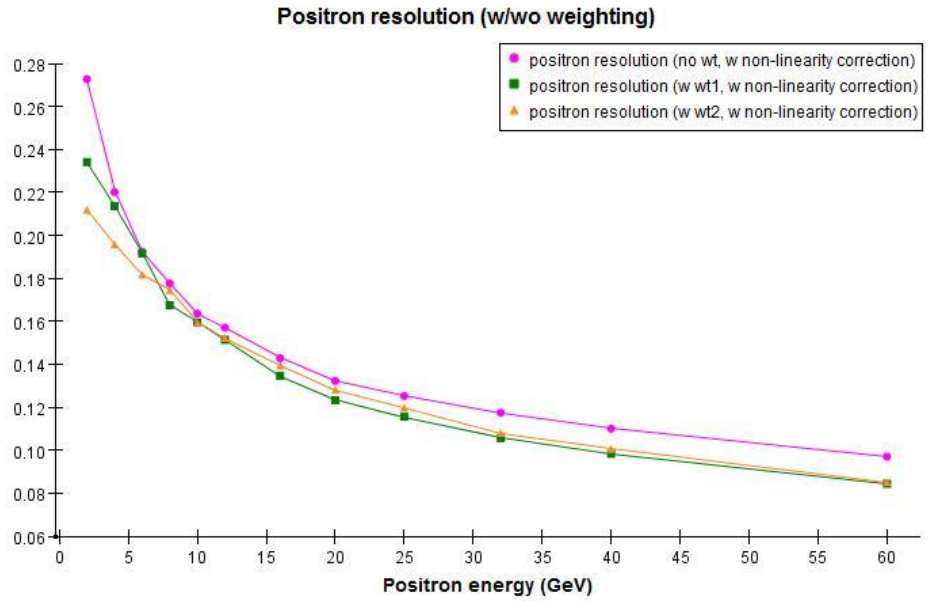
Fits to power law $\alpha \mathrm{E}^{\beta}$

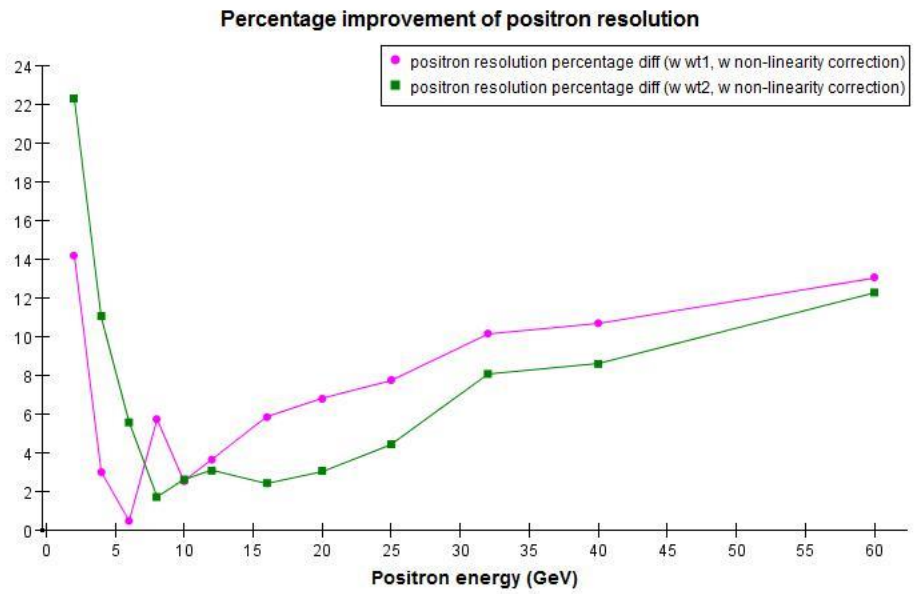
β=1 means **linear**

Things are exactly as expected:

- Linearity significantly improved
- wt2 gives better linearity in larger energy range than wt1

Positron resolution after weighting





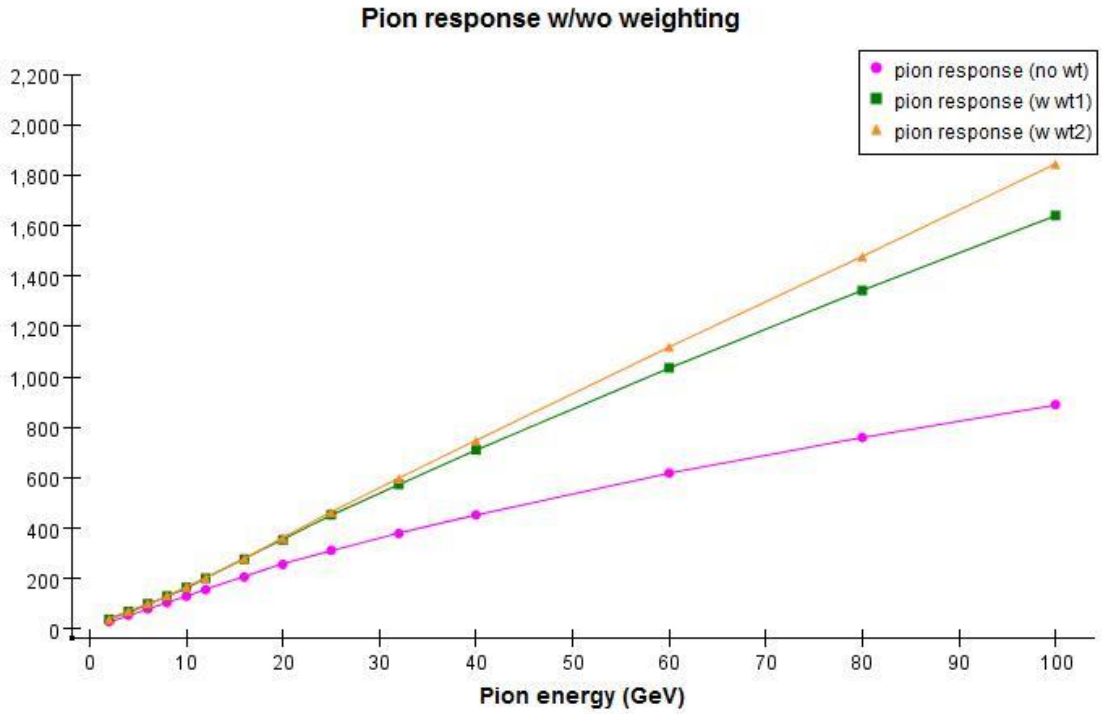
Non-linearity correction is included: this is very important

Positron energy resolution modestly improved

Not much difference between wt1 and wt2

- All energy resolution were calculated from full-range Gaussian fit
- Fit at low energies are not very reliable

Pion response



$17.690 \times E^{1.010}$

$20.500 \times E^{0.954}$

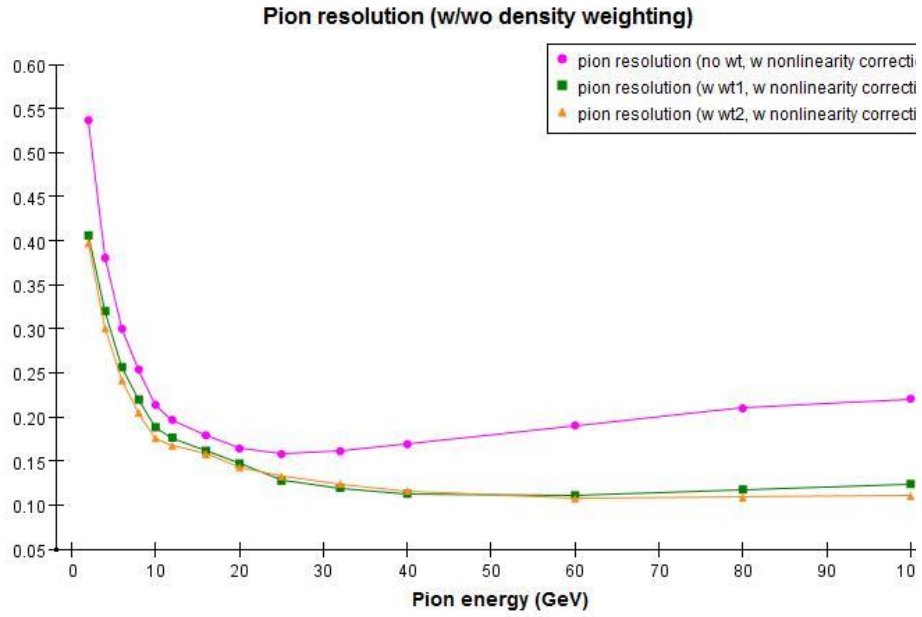
$22.918 \times E^{0.799}$

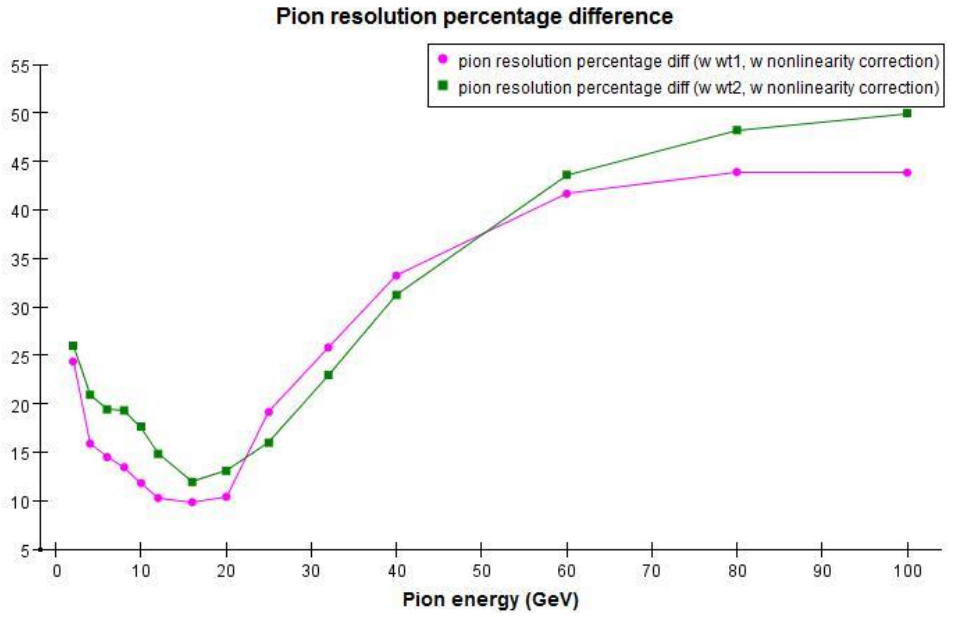
Pion linearity (no weighting) is much worse than in data (most likely due to inaccurate positron simulation)

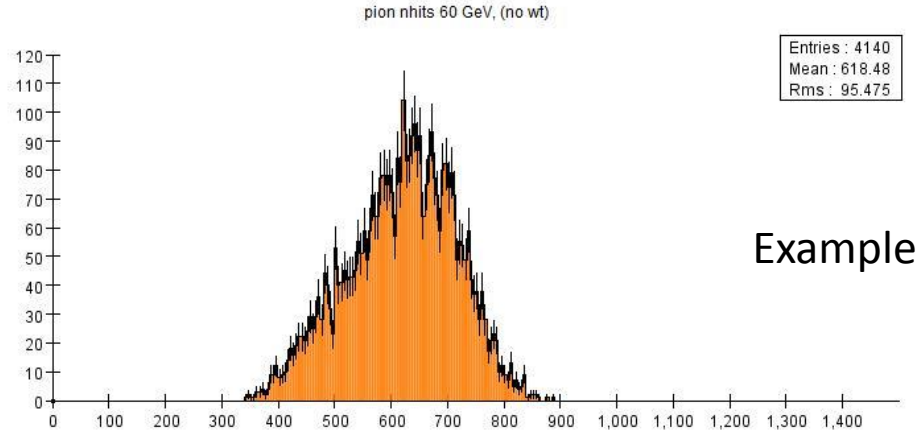
Linearity fits are not as good as the positrons

* Applied leakage cut: no more than 10 hits in tail catcher

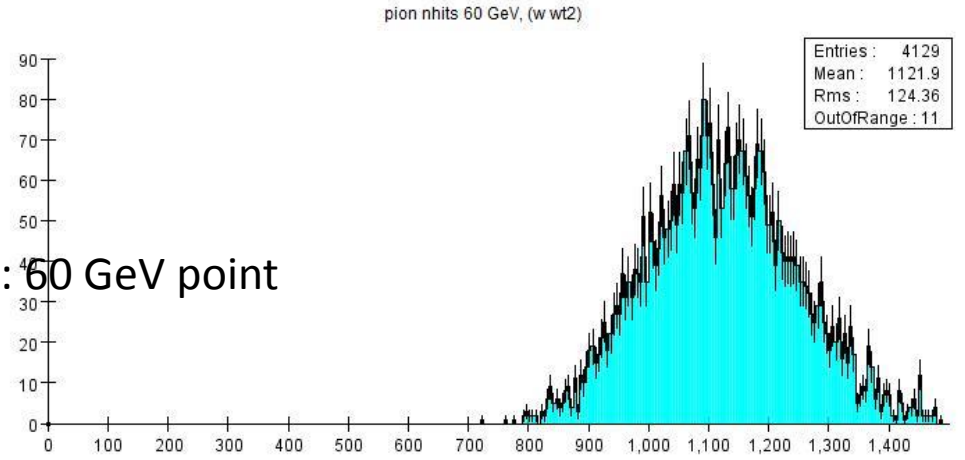
Pion resolution







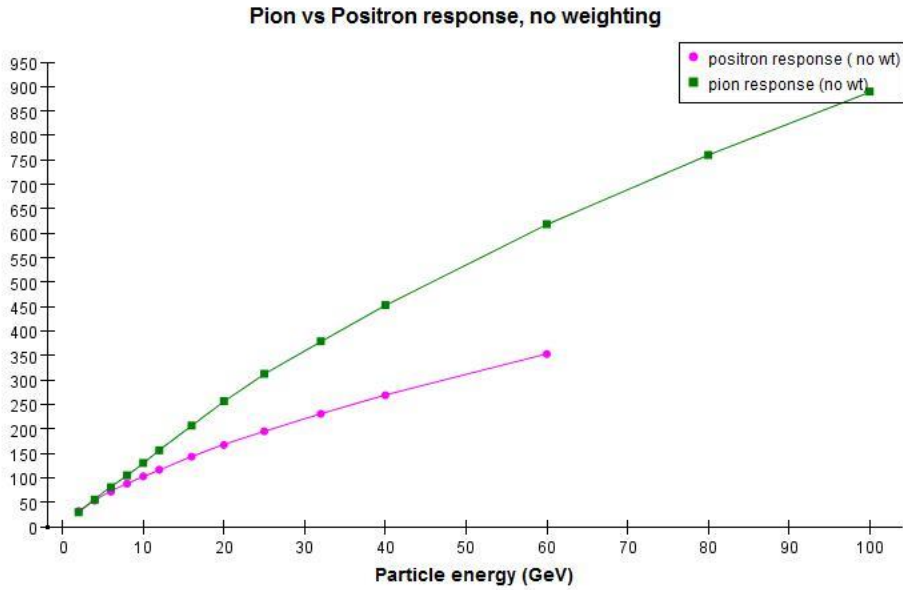
Example: 60 GeV point



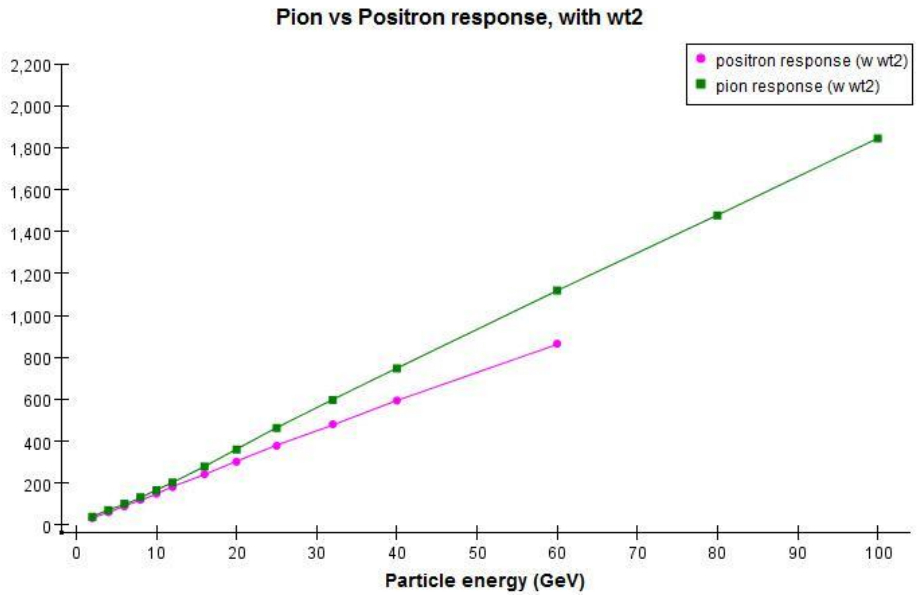
Pion resolution and linearity are both greatly improved in (not very good) simulation

At higher energies, distribution becomes much more symmetric after weighting

Pion vs. Positron response



Before weighting



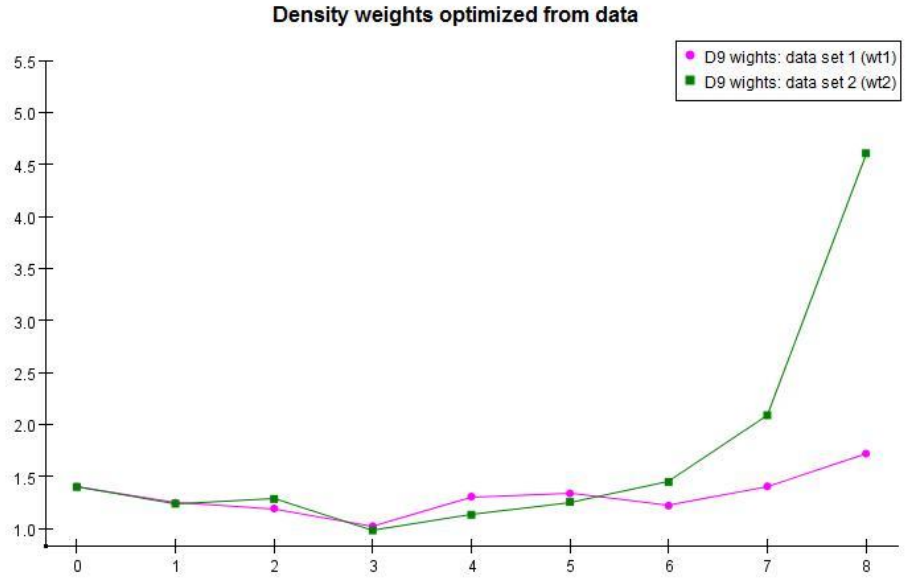
After weighting

Pion and Positron responses are brought closer by weighting, but not equal yet (weighting changes both pion and positron responses)

Room for software compensation: work in progress (pretty optimistic on further improvement)

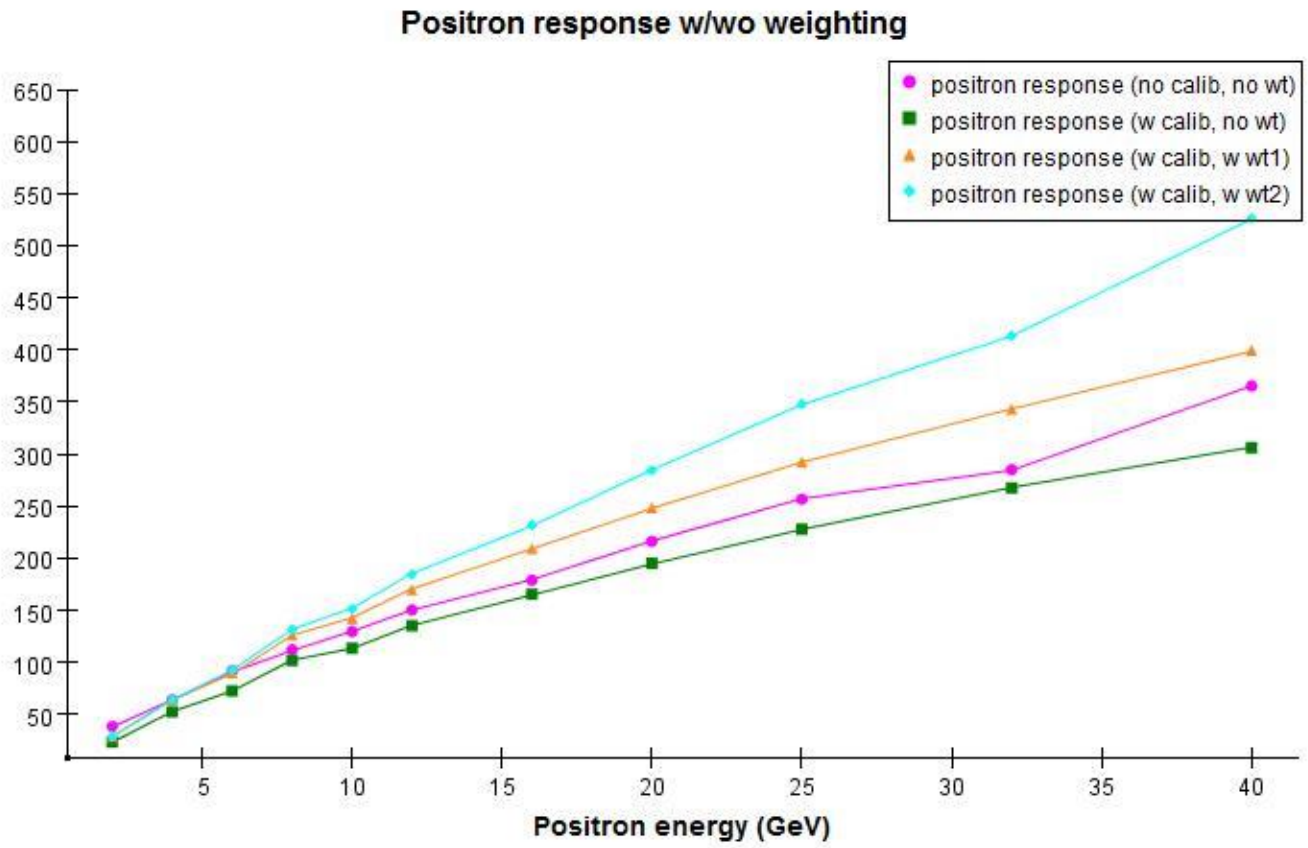
Next step: data

- Burak kindly provided Fe data sample
  - Particle identification and quality check were all done
  - Hit density, calibration constants were pre-calculated
  - Positron energy: 2, 4, 6, 8, 10, 12, 16, 20, 25, 32, 40 (GeV)
  - Pion energy: 2, 4, 6, 8, 10, 12, 16, 20, 25, 32, 40, 50, 60, 120 (GeV)
  - Only used first 10K events (if there are that many) of each energy point
- Weights were optimized with 2 sets of positron data (calibrated)
  - Set I (wt1): 2, 4, 6, 8, 10, 12 (GeV)
  - Set II (wt2): 2, 4, 6, 10, 16, 25 (GeV)
  - Weighting is based on calibrated data (density calibration 2)



Set I energies are probably all too low

Positron response



$19.82 \times E^{0.886}$

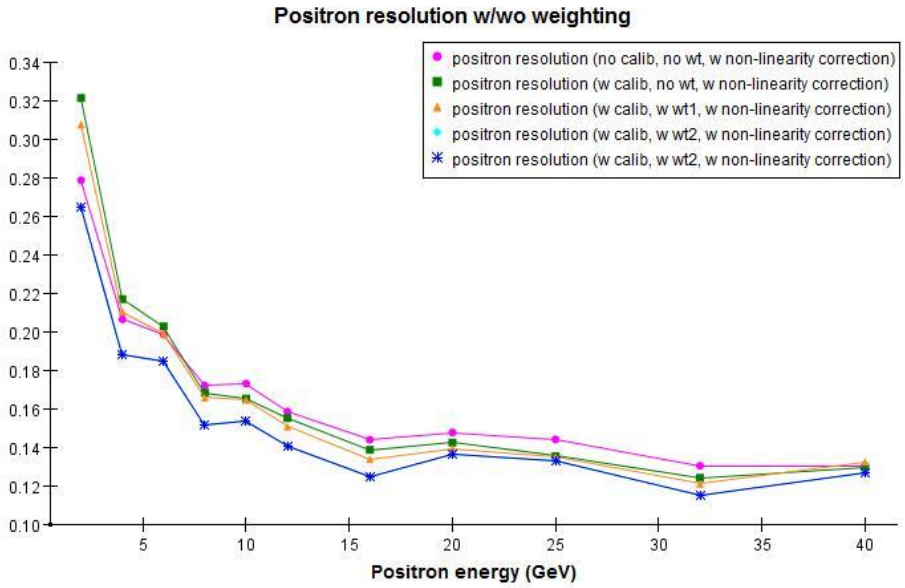
$25.34 \times E^{0.753}$

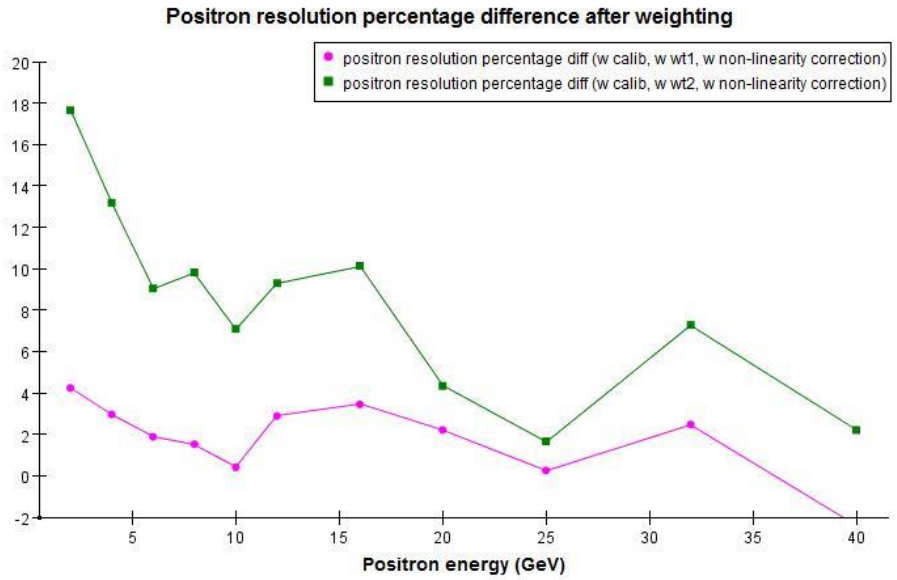
$24.06 \times E^{0.730}$

$21.45 \times E^{0.727}$

It would probably be better if we had higher energy positron data

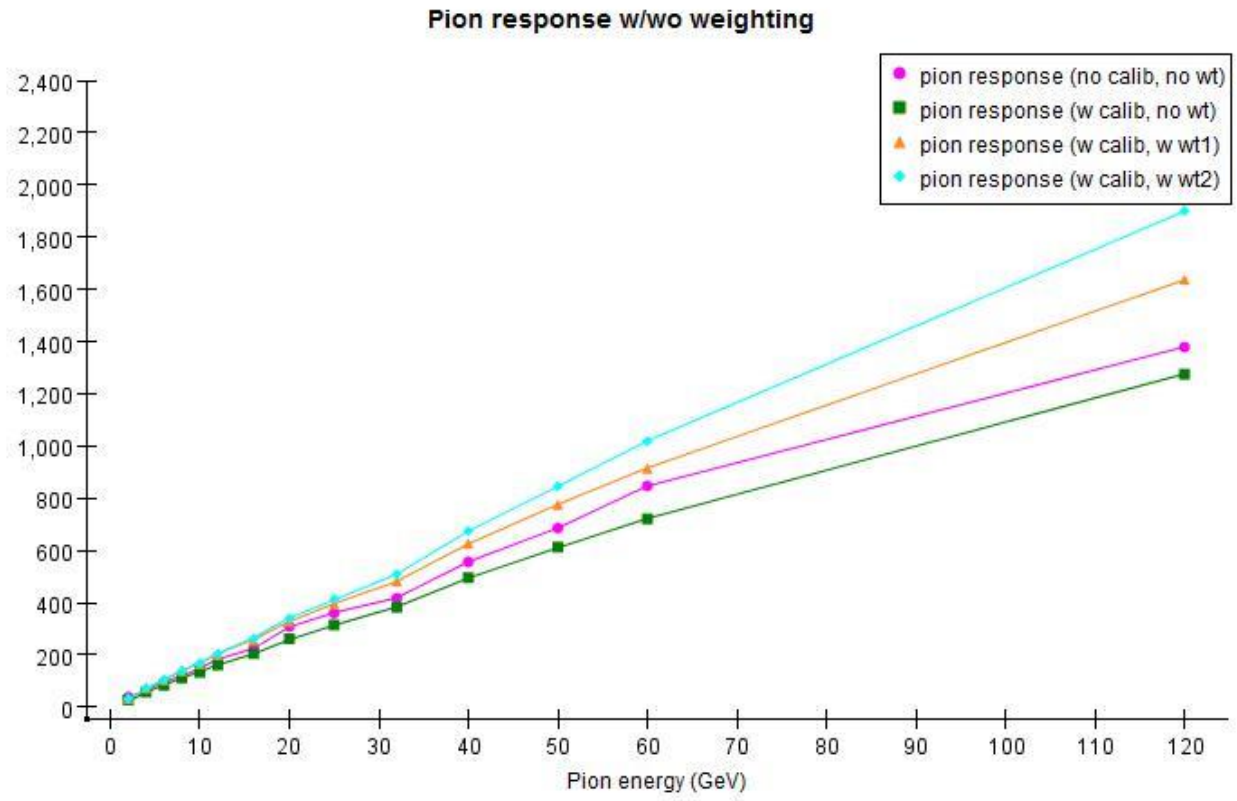
Positron resolution





Similar to simulation: no big gain for positrons

Pion response



$15.94 \times E^{1.014}$

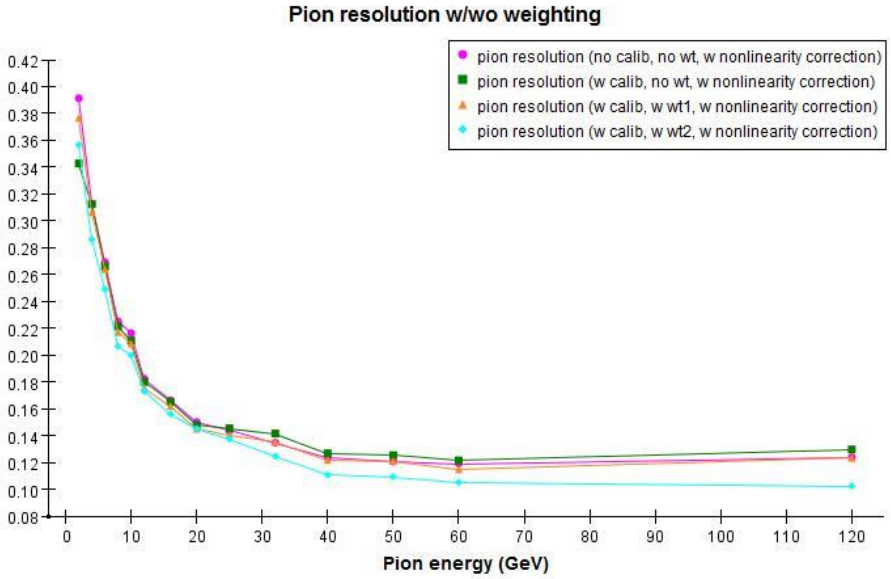
$18.41 \times E^{0.954}$

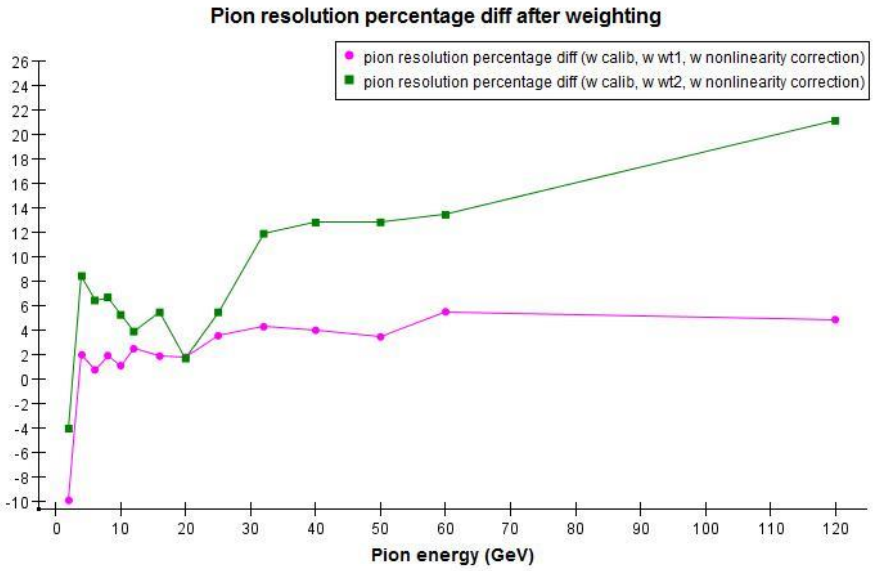
$15.74 \times E^{0.968}$

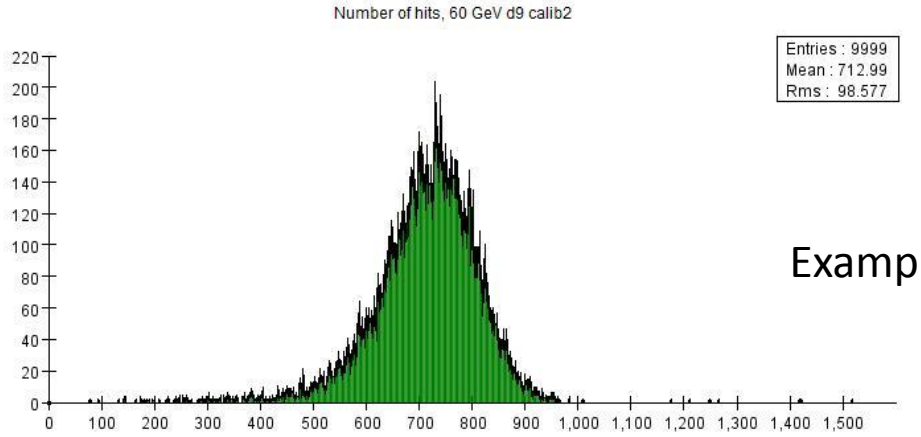
$15.12 \times E^{0.944}$

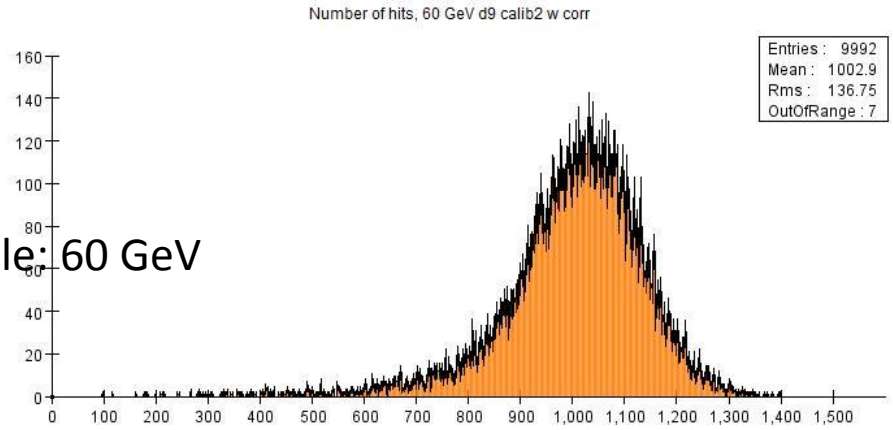
- As usual, pion fits are not very good compare to positron fits
- 120 GeV points are systematically low → Excluded from fits
- Data points before calibration are quite scattered, fit value pulled up by 60 GeV point
- Calibrated points (including the weighed points) are much smoother

Pion resolution







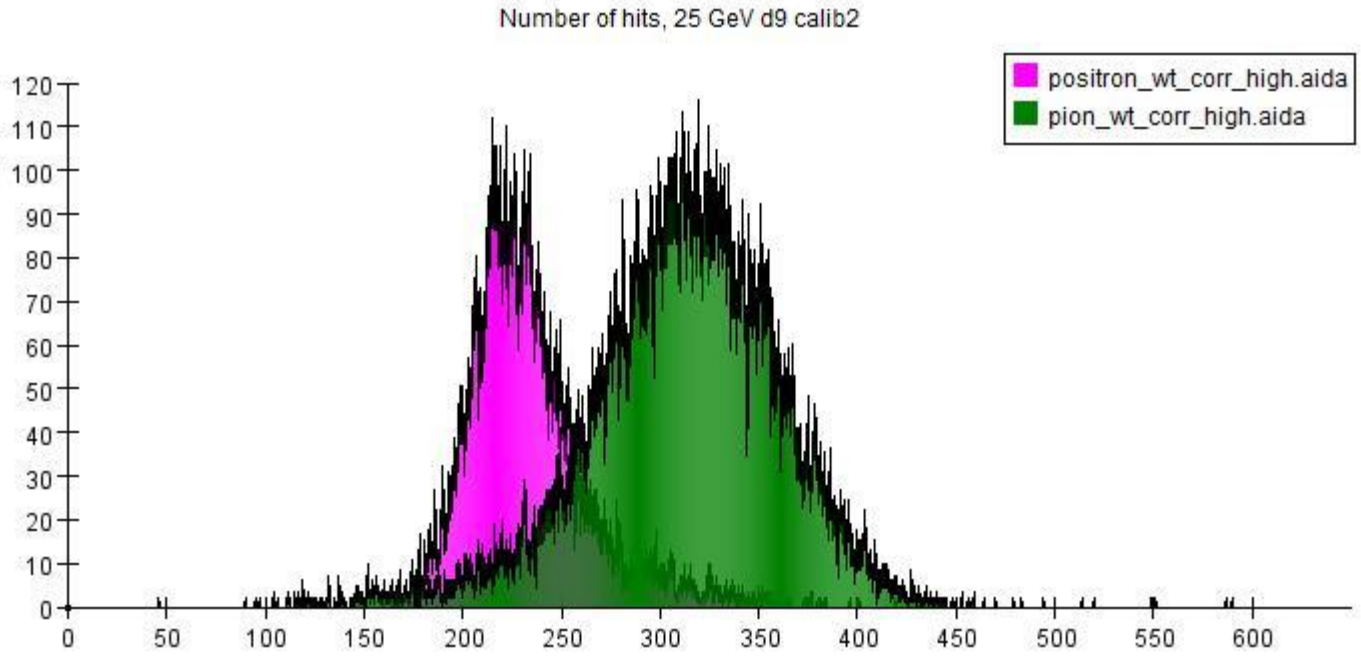


Example: 60 GeV

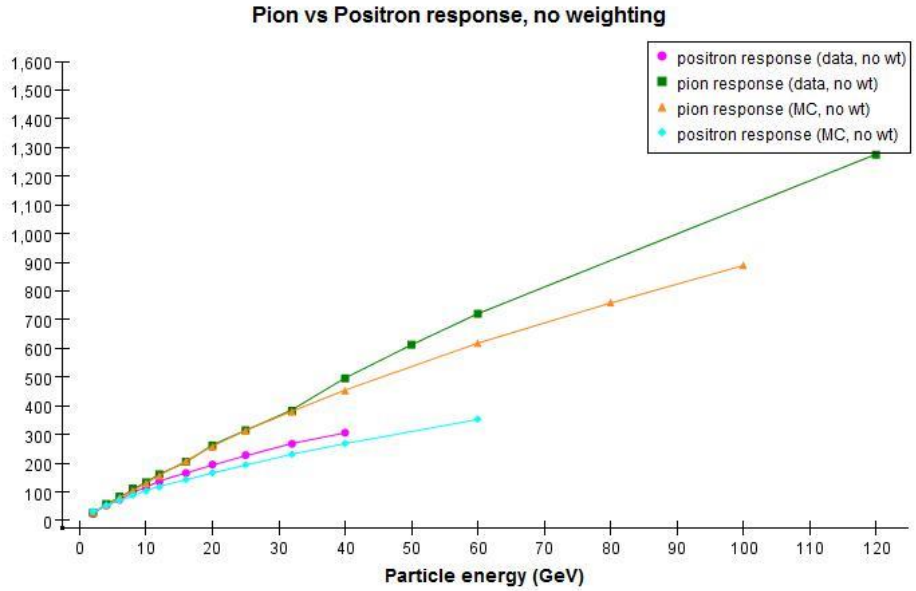
Don’t see nearly as much improvement, but still systematically improved
Nhits distribution much more symmetric to start with
Weighting makes distribution more symmetric, but a long tail remains

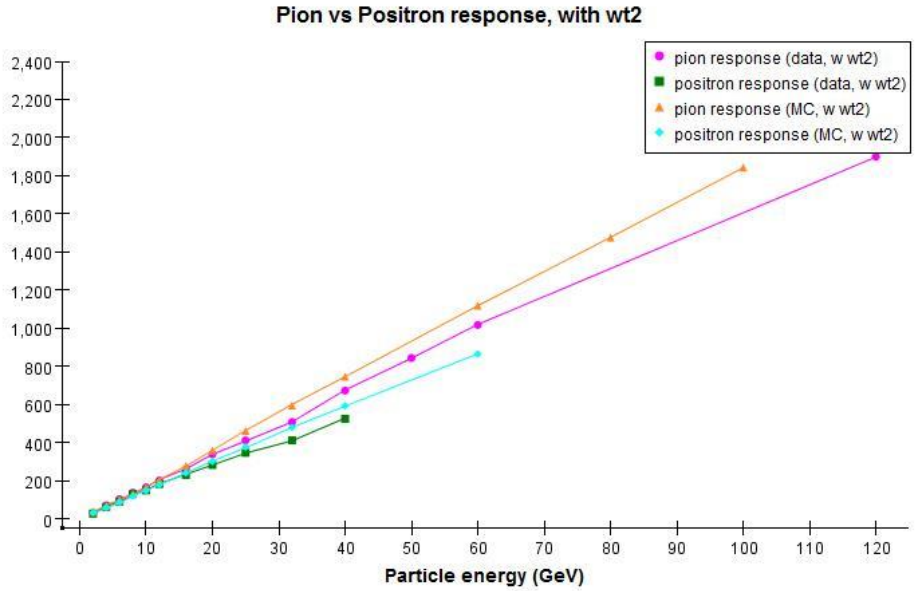
Possible reason I: data quality issue?

- See long high-end tail in positron sample
- Long low-end tail in pion sample
- Both are absent in simulation
- Could it be contamination?
- The long tails seem to be a limiting factor for further resolution improvement



Possible reason II: EM response

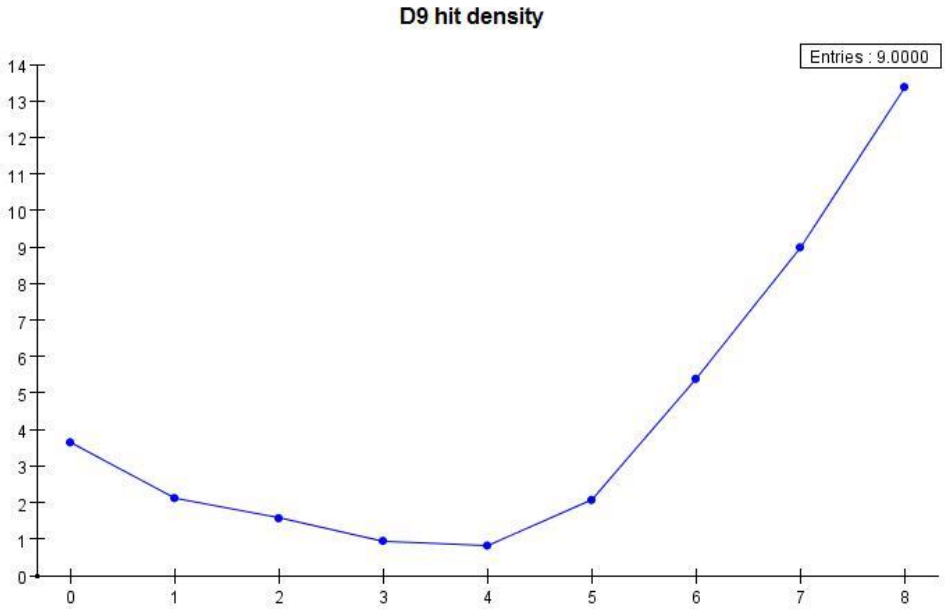




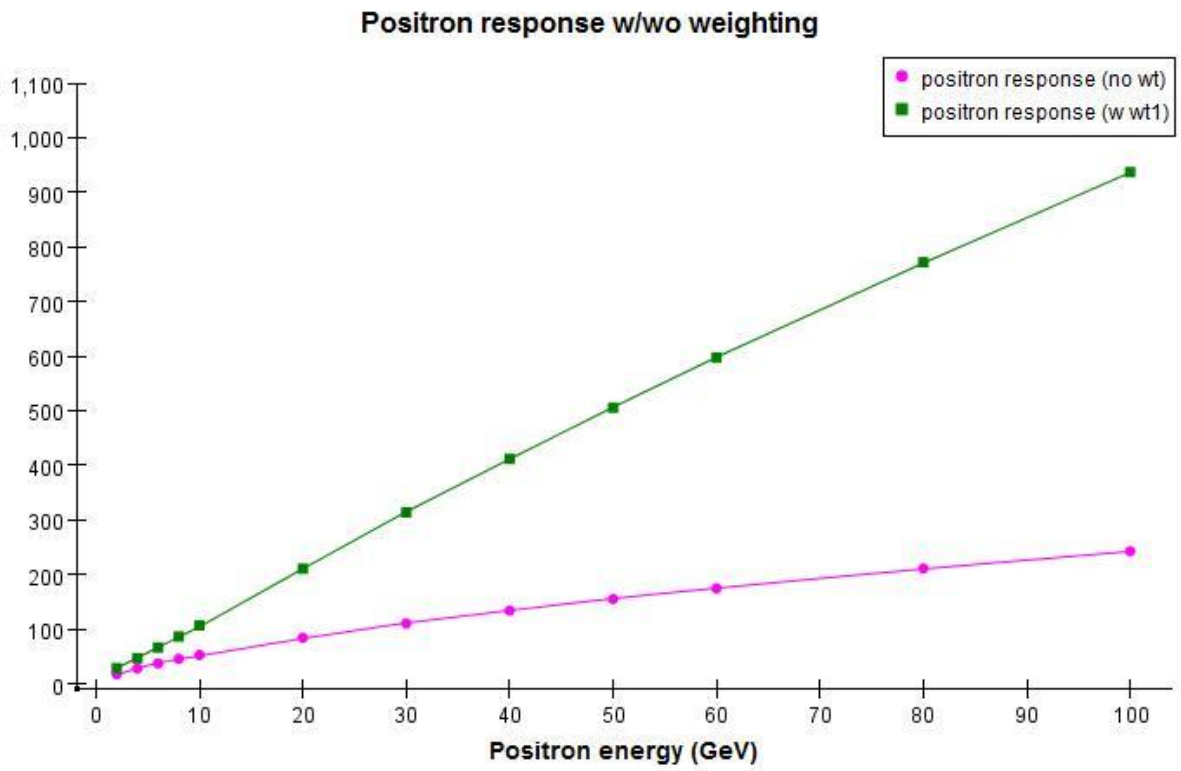
- Pion simulation agrees with data below 32 GeV
- Positron simulation systematically lower than data and has worse linearity
- e/p difference larger in simulation → worse pion linearity
- e/p improved by weighting, in both data and simulation
- Software compensation should further improve data resolution

More density weighting

- It seems that things work best with very different e/p responses and very non-linear EM response
- One obvious place is W DHCAL data
- I took a look at W-DHCAL simulation
- Kurt Francis provided MC sample
  - Electron sample: 2, 4, 6, 8, 10, 20, 30, 40, 50, 60, 80, 100 (GeV)
  - Pion sample: 8, 10, 20, 30, 40, 50, 80, 100, 120, 150, 180, 300 (GeV)
  - Weights tuned with electron energy points: 4, 10, 30, 50, 80 (GeV)



Electron response



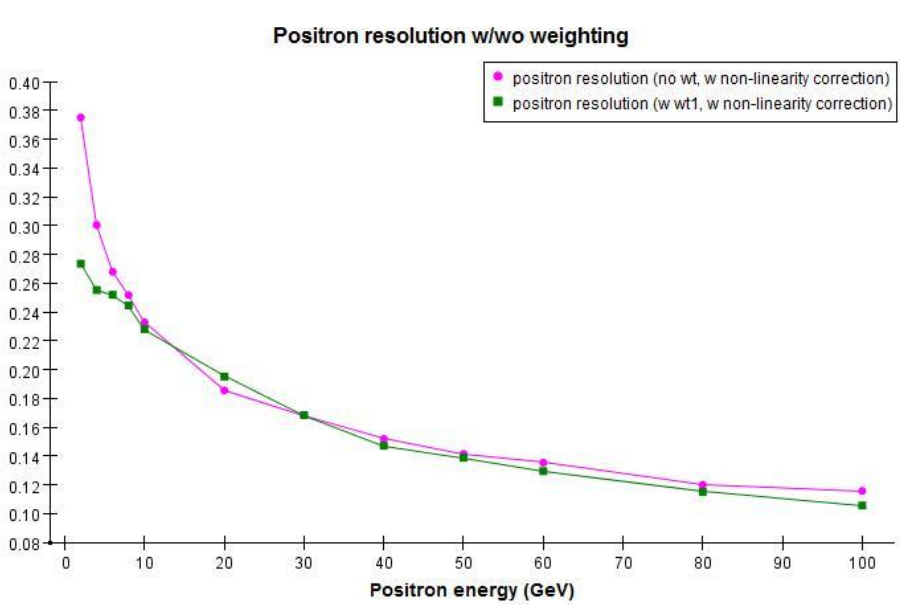
$13.780 \times E^{0.918}$

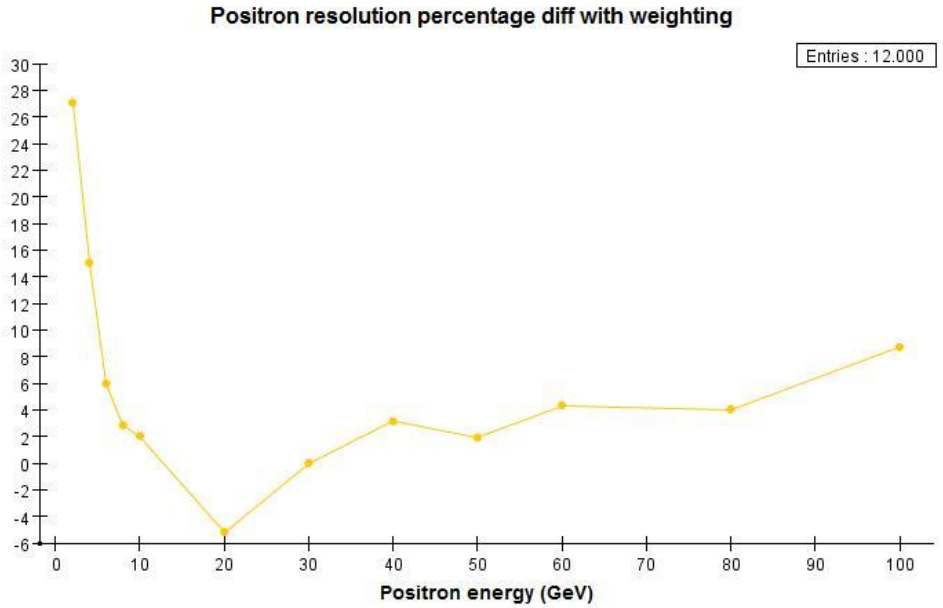
$11.522 \times E^{0.663}$

- Response is highly non-linear without weighting
- Weighting does a good job, as usual

(tuning target was 10 Hits/GeV, again, arbitrary)

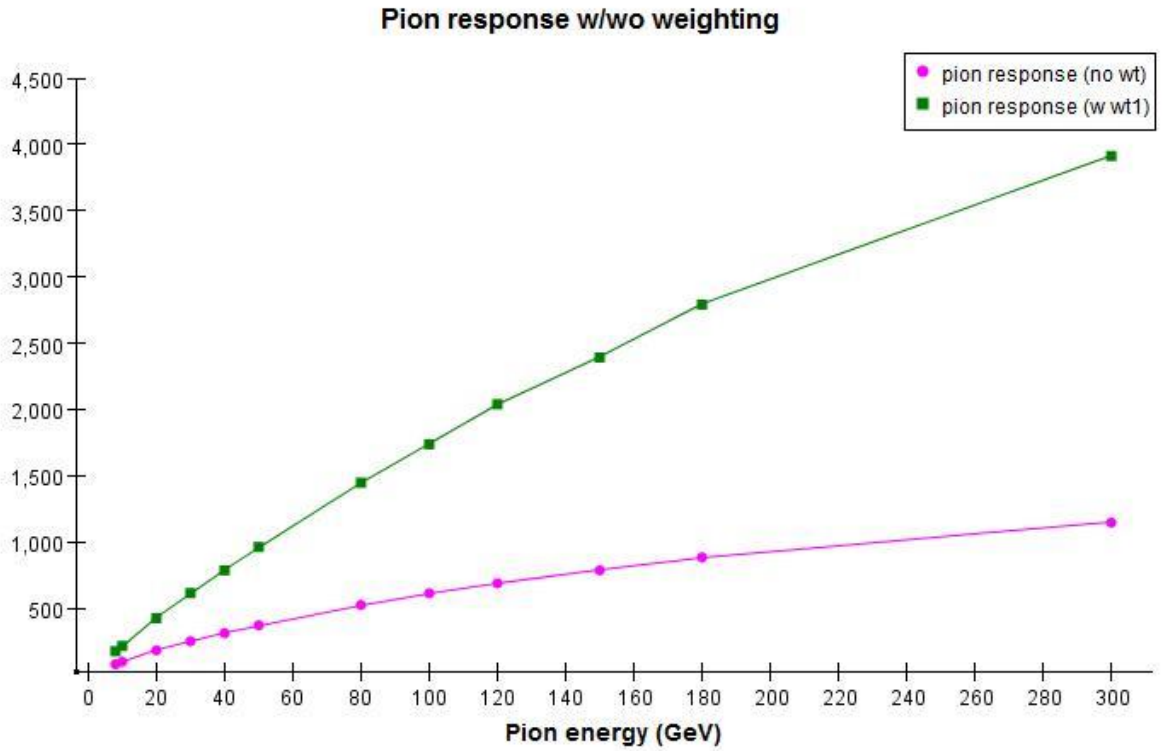
Electron resolution





- As usual, no significant improvement
- Fits at low energy points are not reliable

Pion response

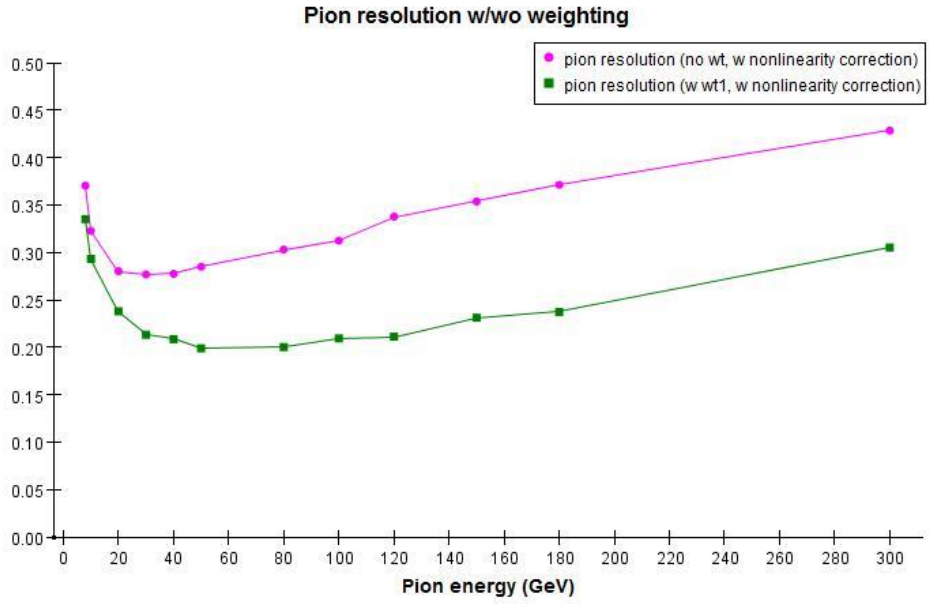


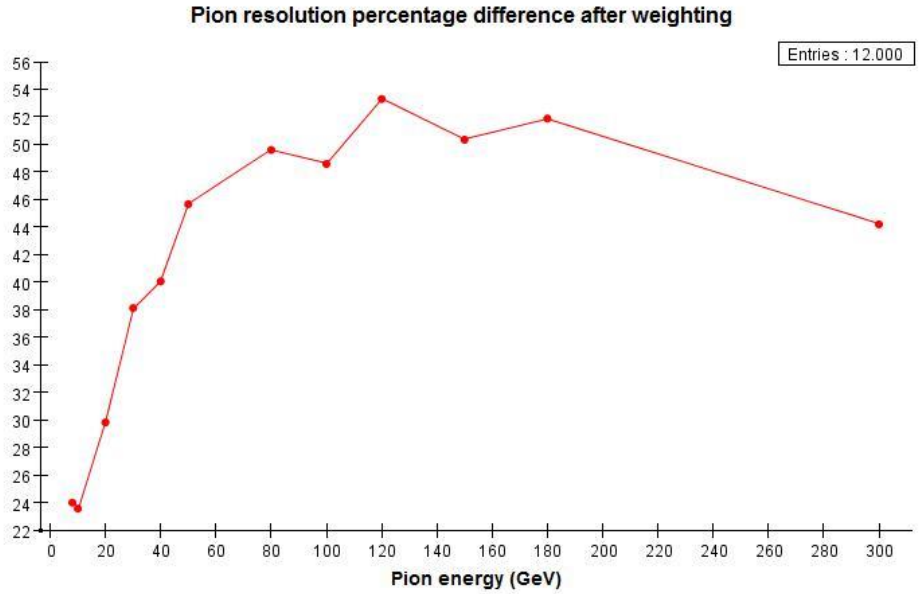
$35.520 \times E^{0.842}$

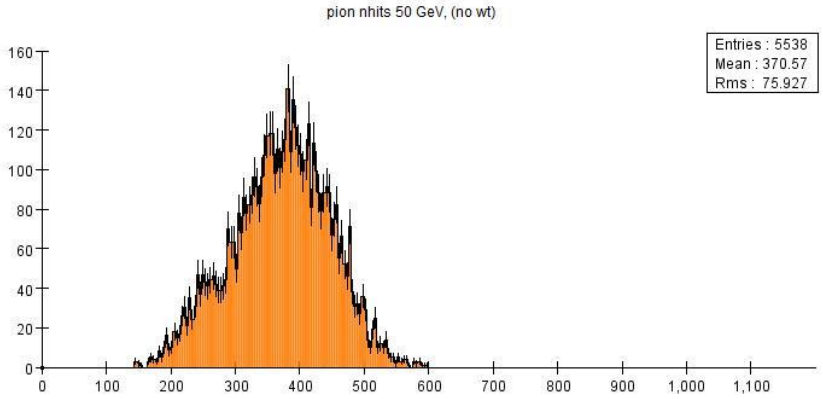
$22.826 \times E^{0.708}$

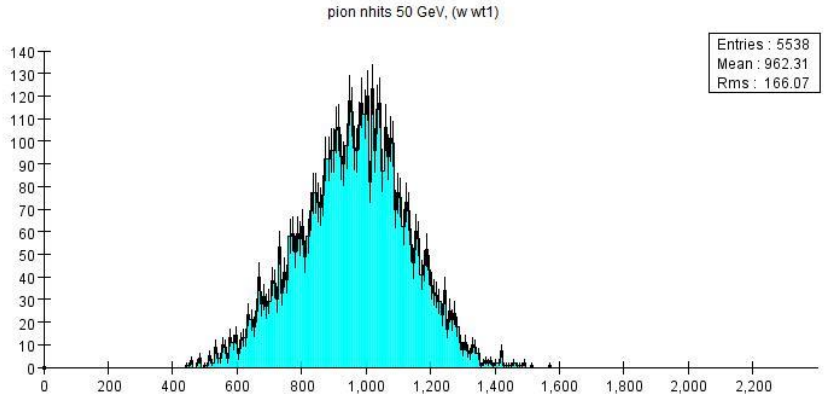
- As usual, fits are not great as compare to electron fits
- 300 GeV points systematically low → Excluded from fits
- Suspect that all high energy points are low due to bias from leakage cut
- Suspect fit parameters are systematically low, due to above reason
- Nevertheless, linearity did improve significantly

Pion resolution



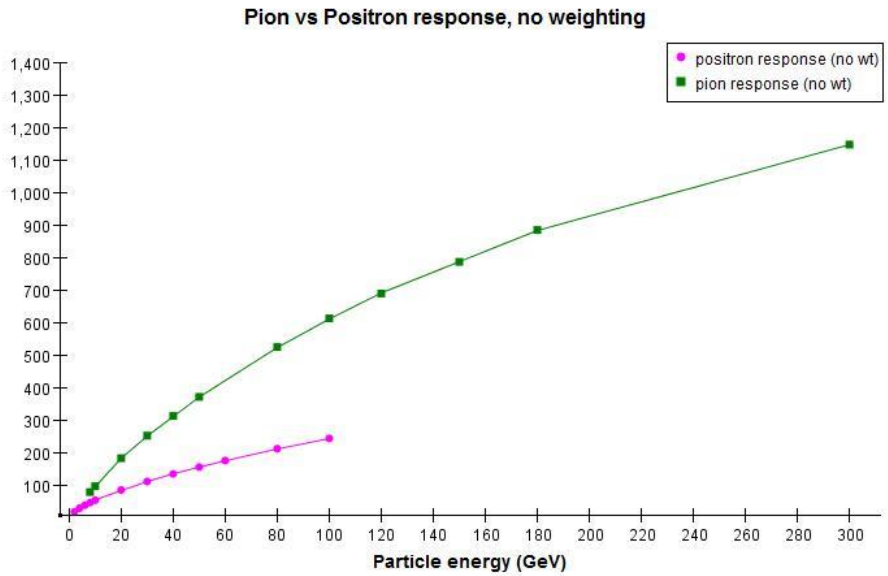


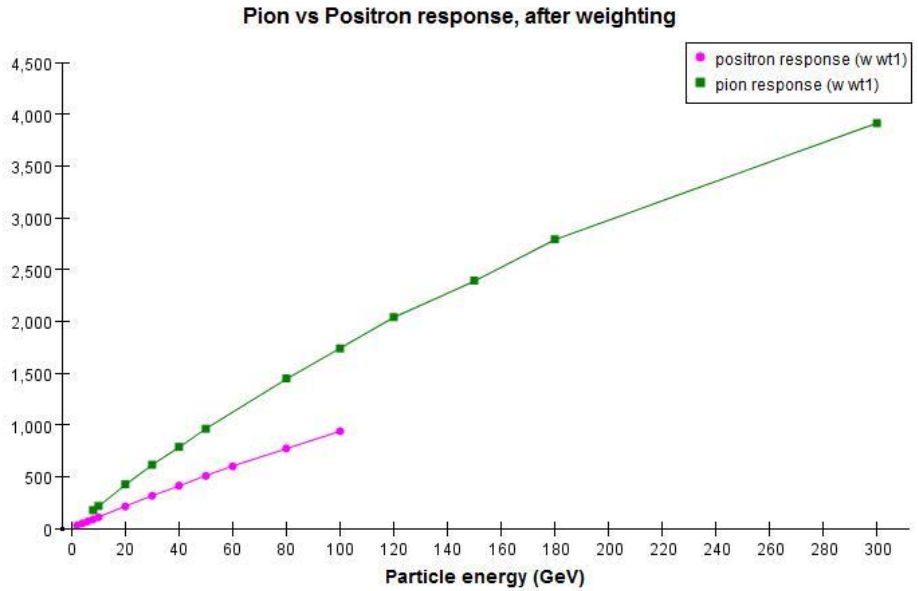




- Energy resolution greatly improved over large energy range
- Weighing improved distribution, but didn't totally remove low end tail

Pion vs. electron responses





Before weighting

After weighting

- e/p improved with density weighting
- Difference is still very large → ideal test bed for software compensation

Summary

- Density weighting is able to achieve close to linear EM shower response for DHCAL
- Using the same weights can improve linearity and energy resolution of pion showers
  - Significant (~ 40 - 50%) improvement observed with Fe-DHCAL and W-DHCAL simulation
  - Modest (~10%) improvement seen in Fe-DHCAL data → reason is under study
- Pion and EM shower response are still quite different after weighting
  - Chance for software compensation: work started
- Once we have the method to get optimized energy resolution for DHCAL, we should think of optimizing the DHCAL design itself…