Simulating particle kinematics for a potential milli-charged experiment

C. Campagnari, F. Golf, B. Marsh

Overview

- Brief summary of some work done over the past month with an incoming graduate student to put together a simple model of the trajectory of charged particles through a magnetic field and some material.
  - For now, implemented in python using numpy, matplotlib.
- Try to gain some intuition for expected angular/spatial deflection of particles as they travel from interaction point to a mocked up detector.

Propagating through a magnetic field

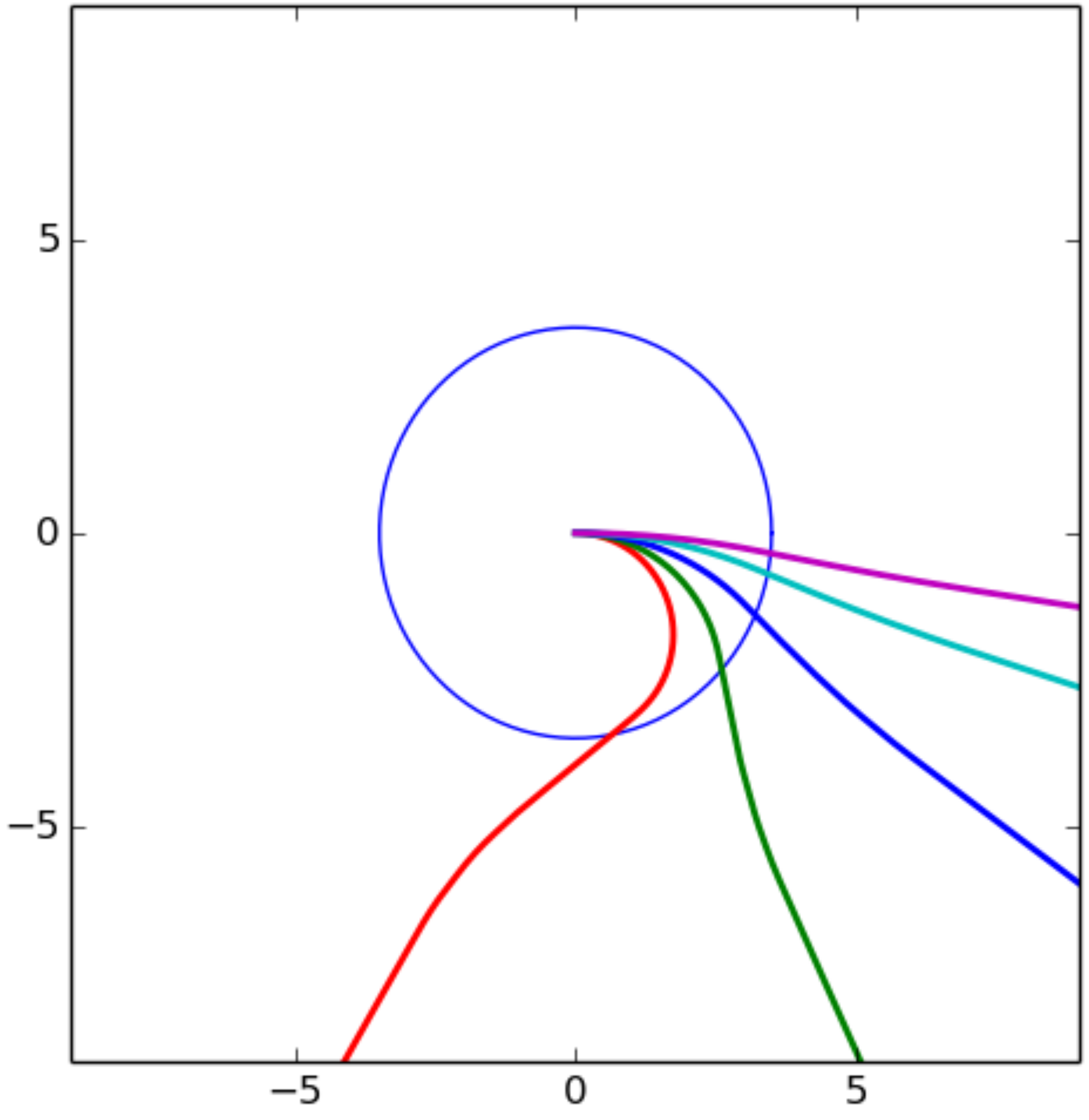
- Store position, momentum of particle initialized at interaction point.

- Use Runge-Kutta integration to update the position, momentum at each time step:

$$\frac{d\vec{x}}{dt} = \frac{\vec{p}}{\sqrt{p^2+m^2}}$$

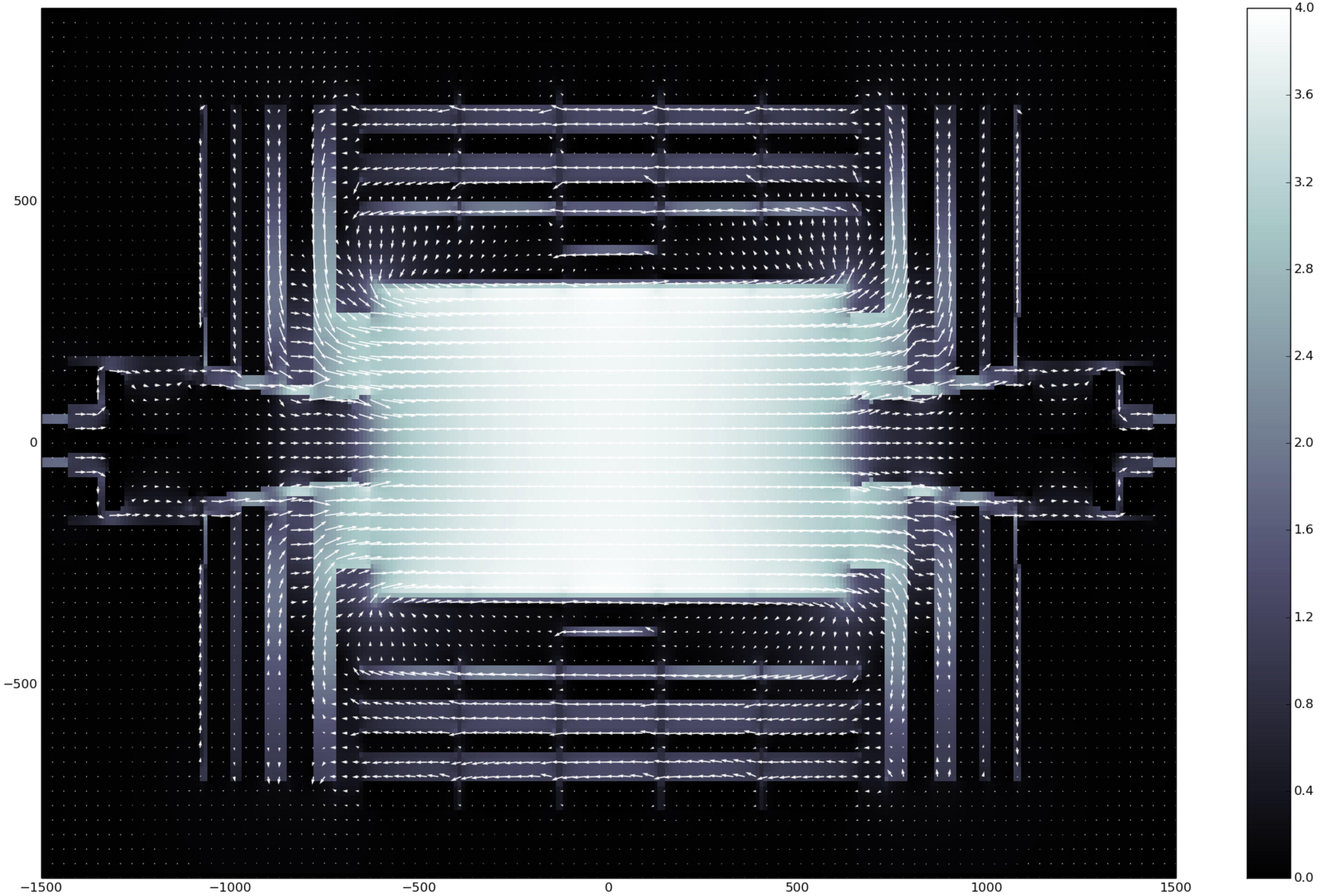
$$\frac{d\vec{p}}{dt} = q\vec{v} \times \vec{B}$$

- Using Δt = 0.2 ns after investigating a range of values.

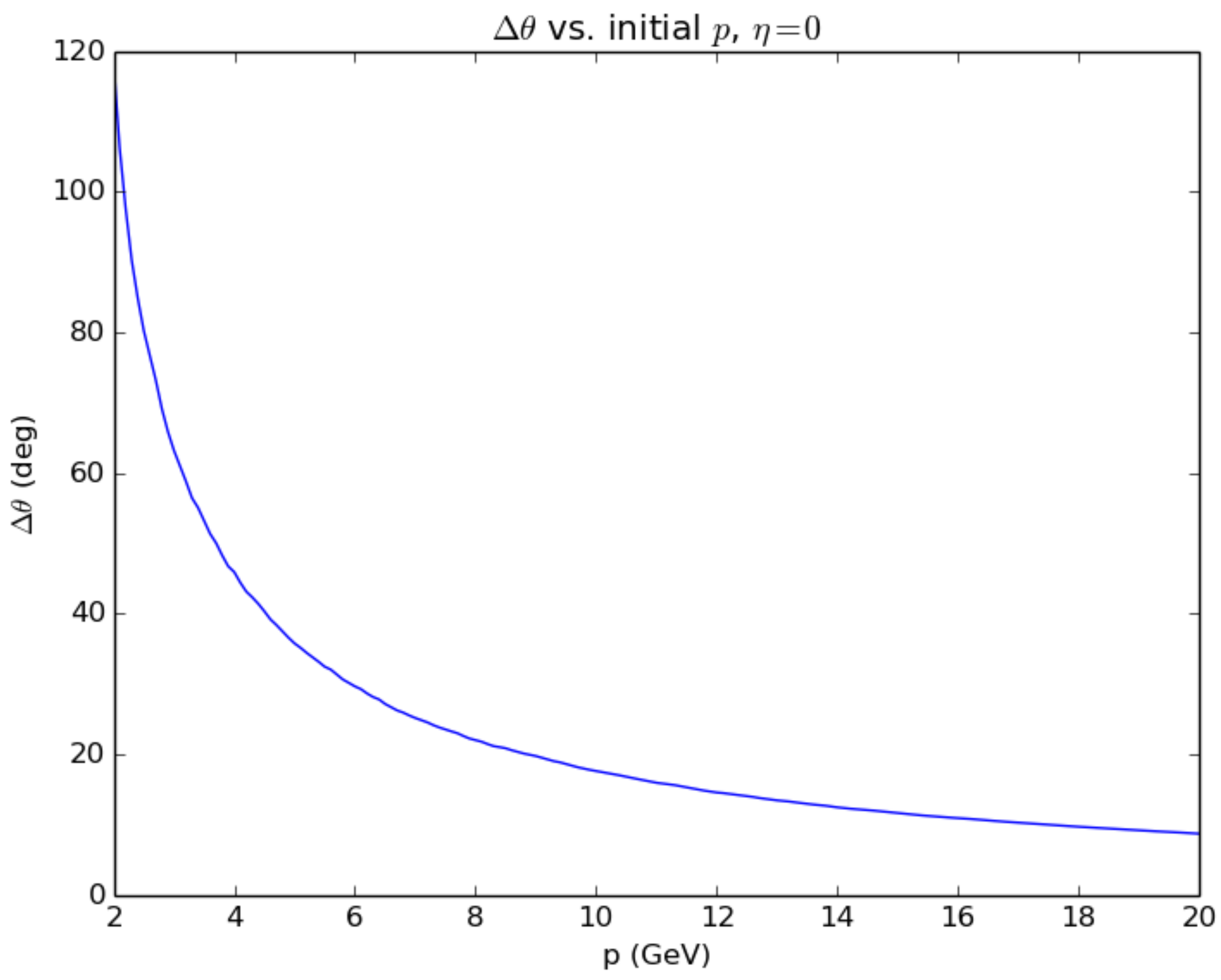


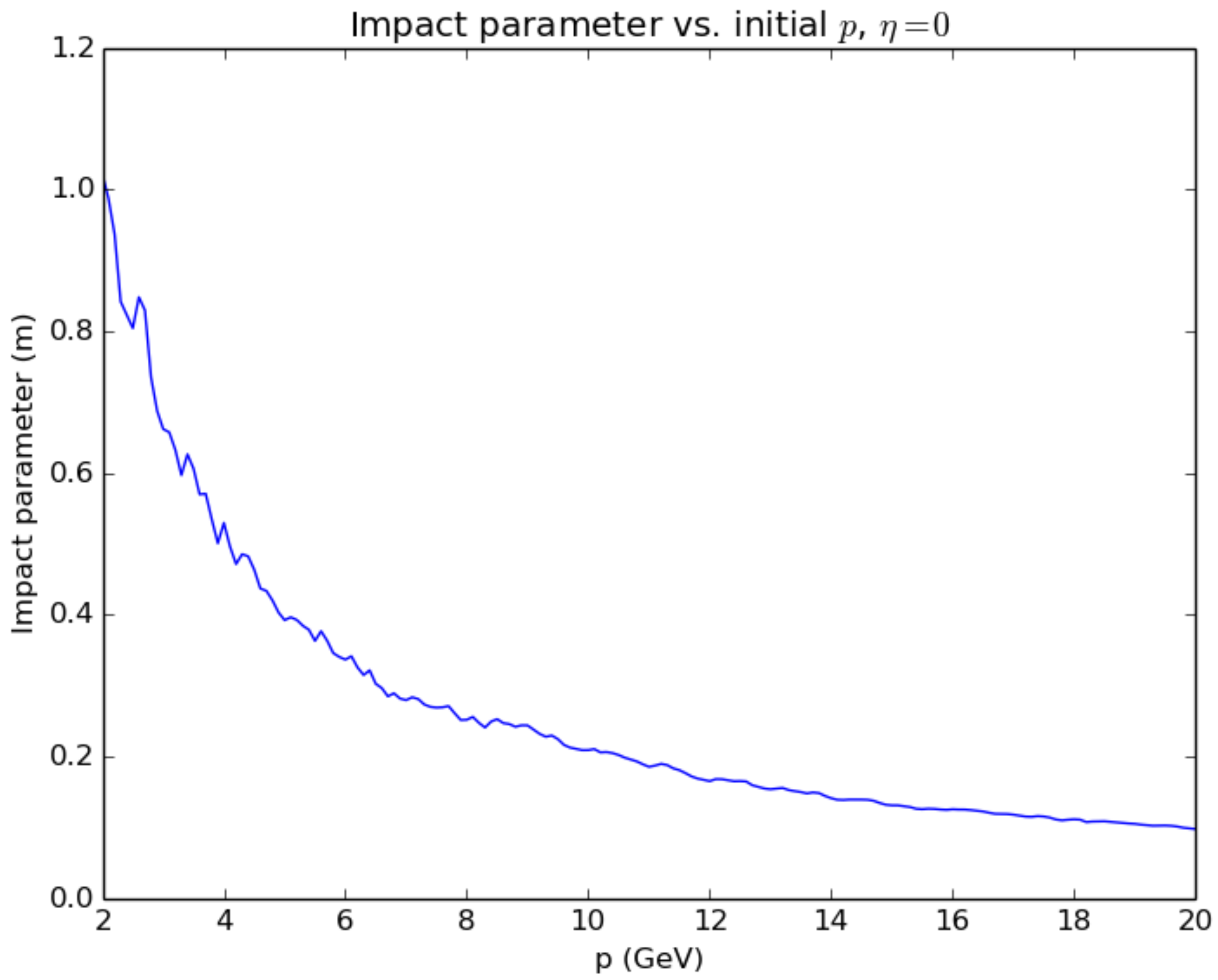
Loading the CMS magnetic field

- Extract realistic magnetic field from CMS as $\vec{B} = \vec{B}\,(r, z, \phi)$
  - r: 0 — 900 cm in steps of 10 cm
  - z: -1500 — 1500 cm in steps of 10 cm
  - φ: 0 — 355° in steps of 5°
  - Version 130503 — this will become the default for CMS simulation in the future.
    - Some spot-checking shows that it is very similar to what is currently used in CMS simulation, small differences in magnetic field strength at large values of z.
- Caveats of current simulation: at each time step, take value of magnetic field at closest (r,z,φ), assume magnetic field is zero at larger values of r, z.

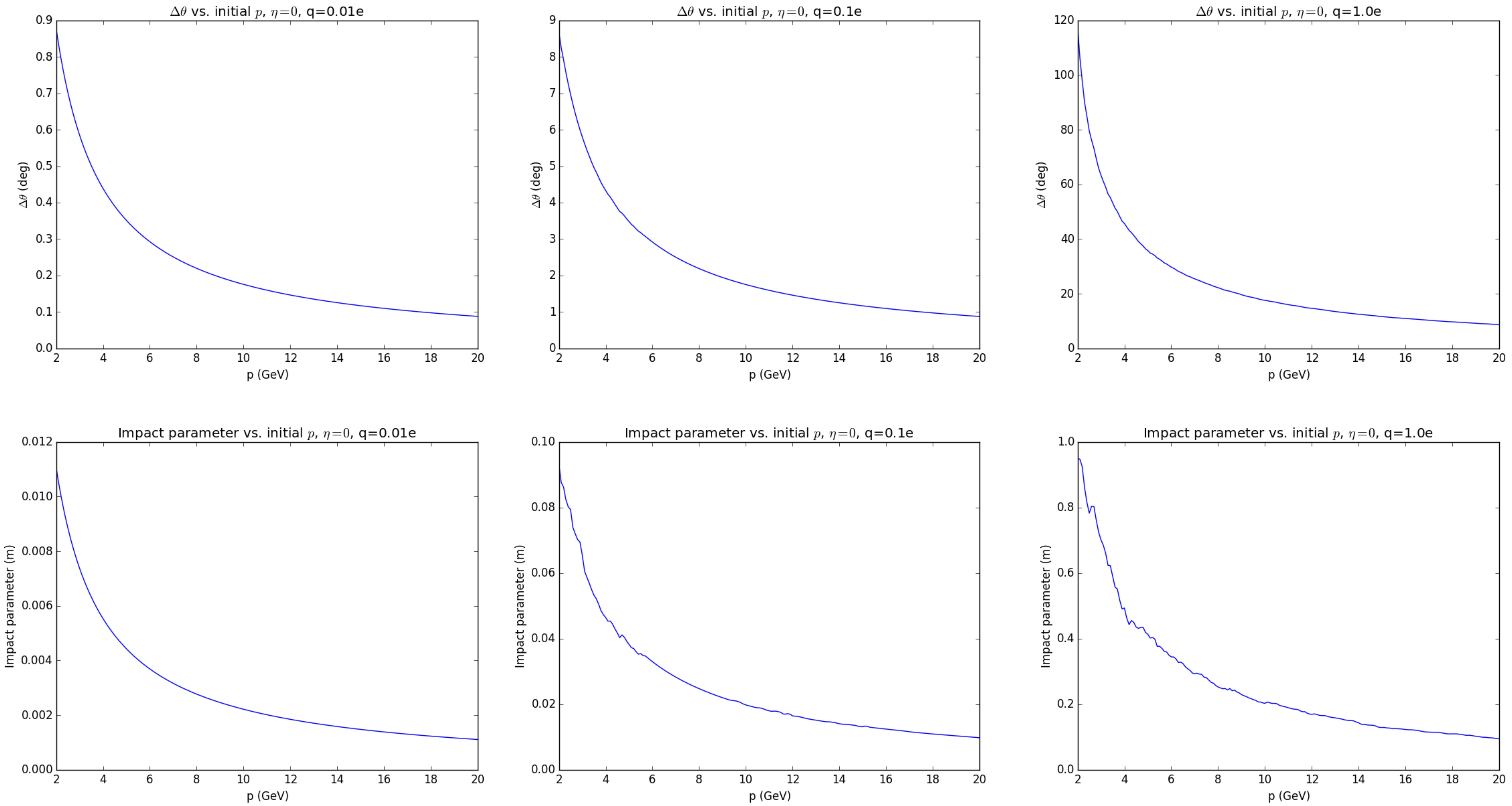

500
0
−500
−1500
−1000
−500
0
500
1000
1500
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0

Deflection in the CMS B-field





- Asymptotic deflection of a muon in the CMS magnetic field, no material effects.



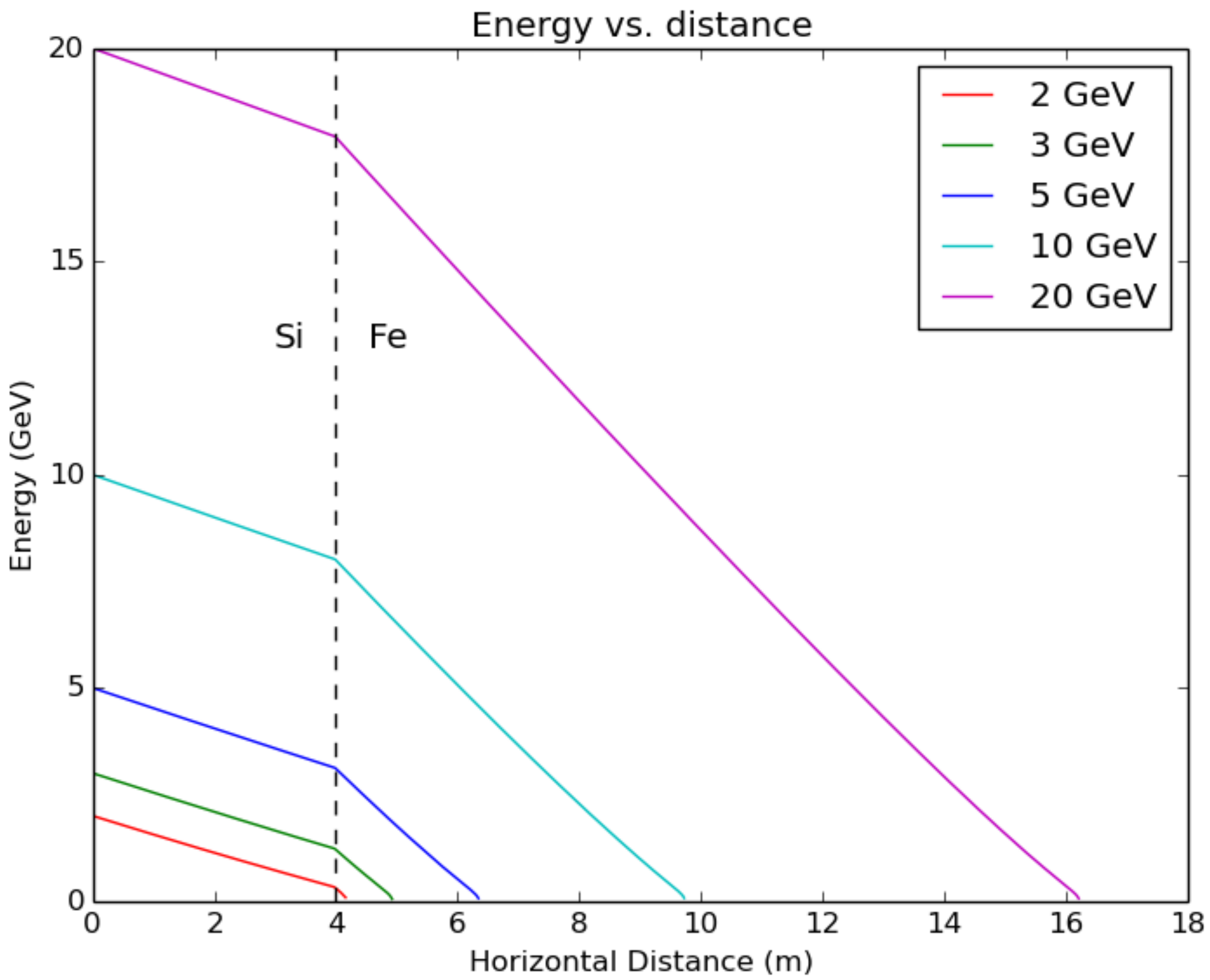
$\Delta\theta$ vs. initial p, $\eta=0$, q=0.01e
$\Delta\theta$ (deg)
p (GeV)
$\Delta\theta$ vs. initial p, $\eta=0$, q=0.1e
$\Delta\theta$ (deg)
p (GeV)
$\Delta\theta$ vs. initial p, $\eta=0$, q=1.0e
$\Delta\theta$ (deg)
p (GeV)
Impact parameter vs. initial p, $\eta=0$, q=0.01e
Impact parameter (m)
p (GeV)
Impact parameter vs. initial p, $\eta=0$, q=0.1e
Impact parameter (m)
p (GeV)
Impact parameter vs. initial p, $\eta=0$, q=1.0e
Impact parameter (m)
p (GeV)

Modeling particle energy loss

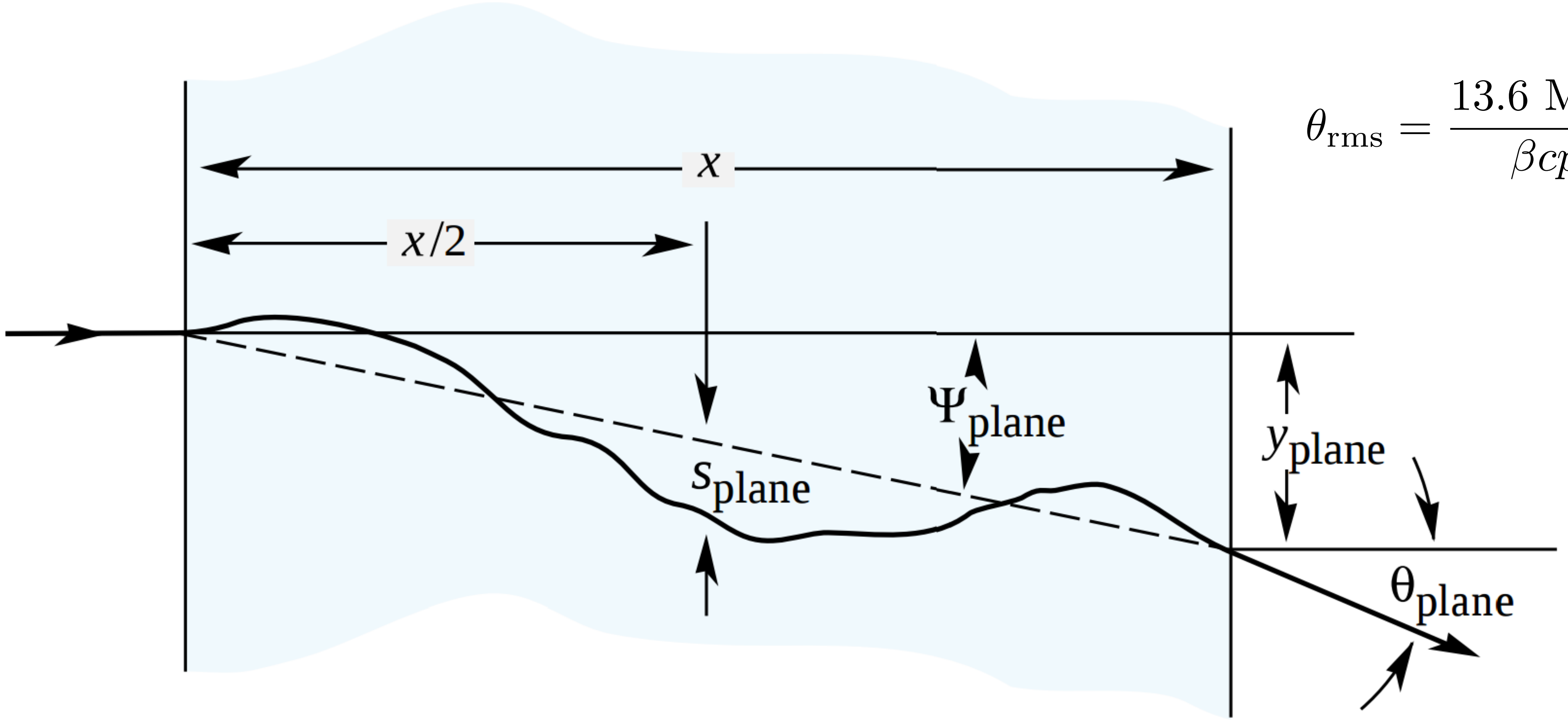
- Model energy loss, -dE/dx, via Bethe-Bloch.

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

$$W_{\max} = \frac{2 m_e c^2 \, \beta^2 \gamma^2}{1 + 2\gamma m_e / M + (m_e/M)^2}$$



Modeling particle multiple scattering

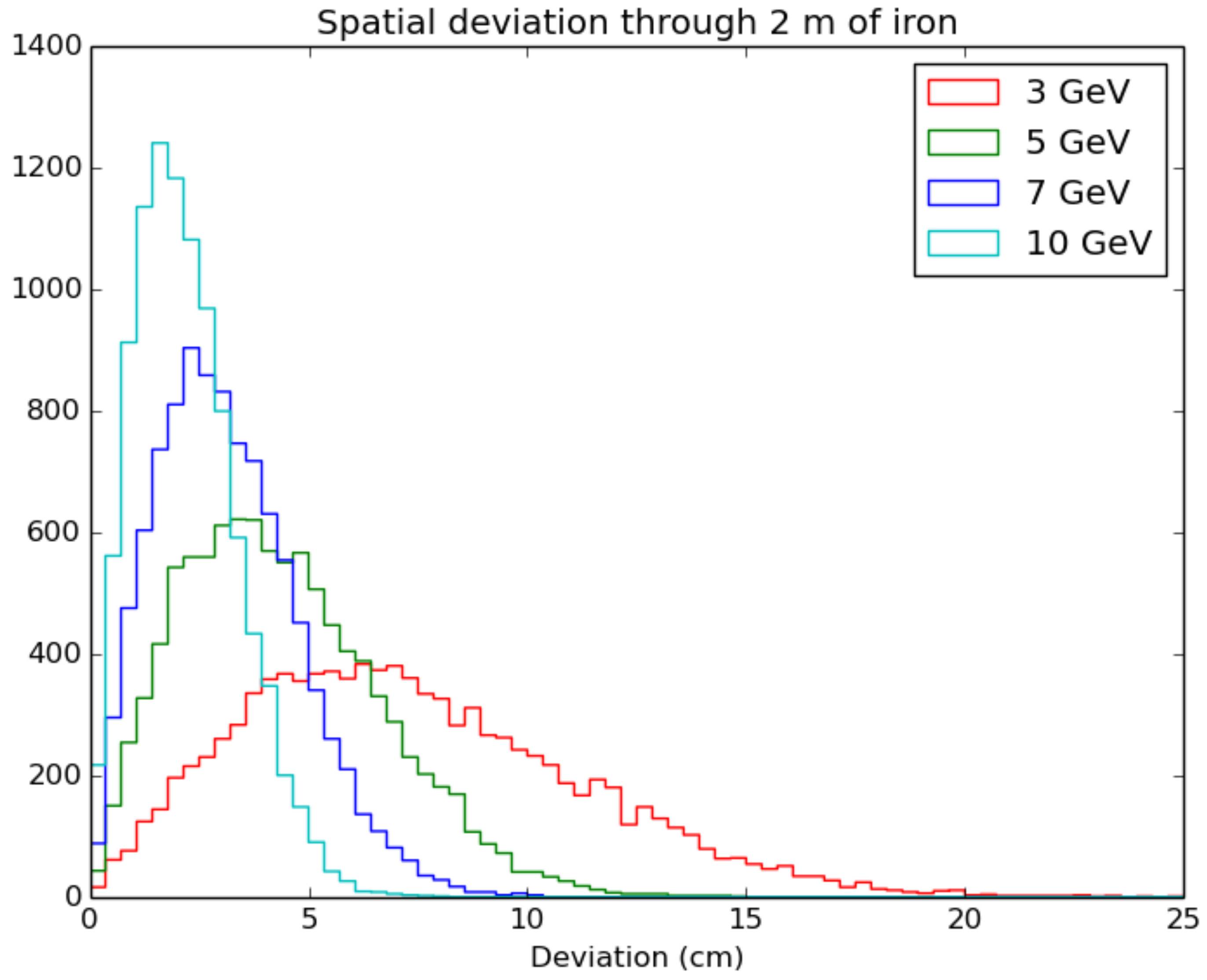


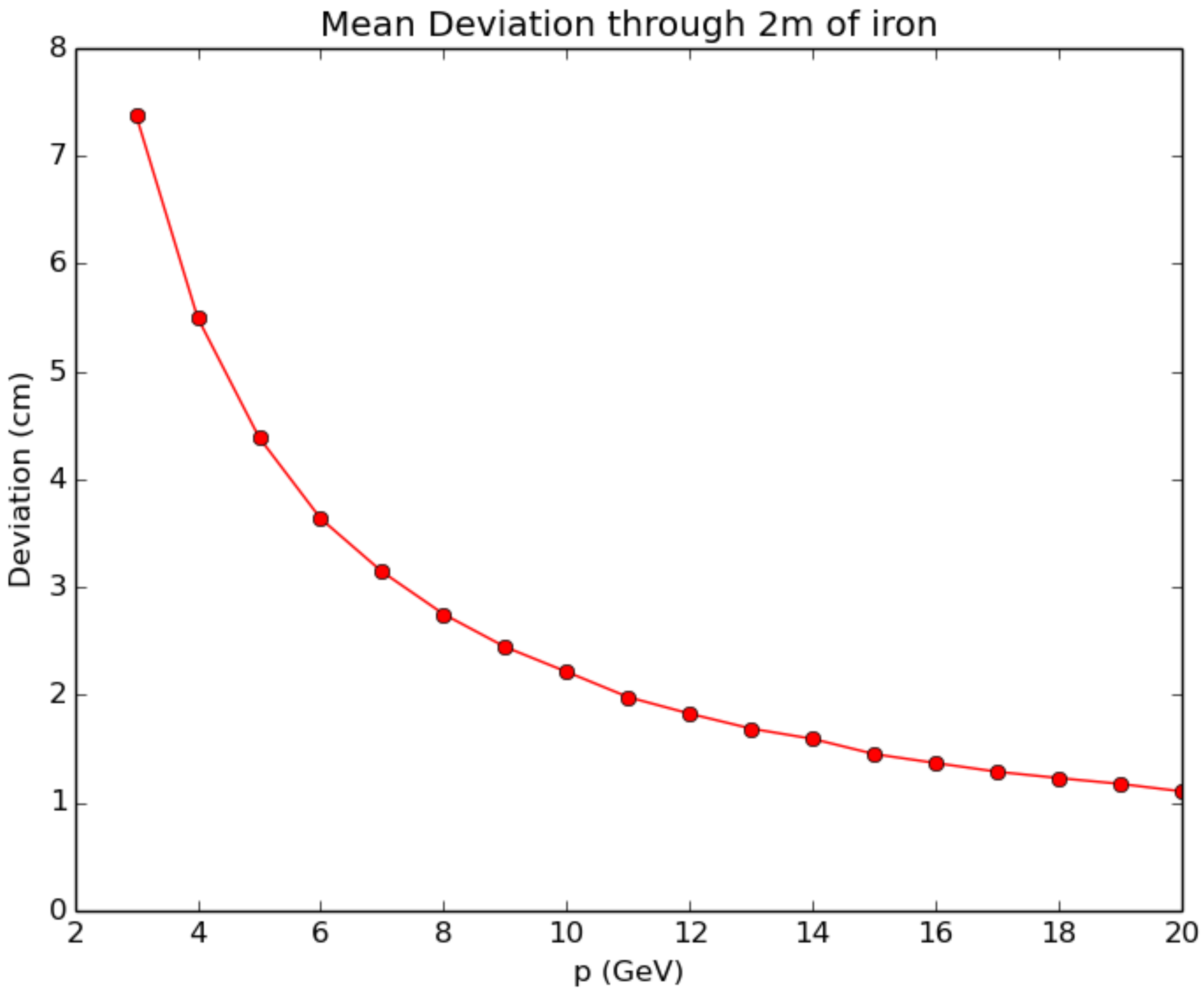
$$\theta_{\rm rms} = \frac{13.6\ {\rm MeV}}{\beta c p} q \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \log\left(\frac{x}{X_0}\right)\right]$$

- Simple Gaussian model following PDG. At each time step, deflect particle by a random angle according to a Gaussian distribution of width, transverse displacement with $y_{rms} = (1/\sqrt{3}) \times \theta_{rms}$.

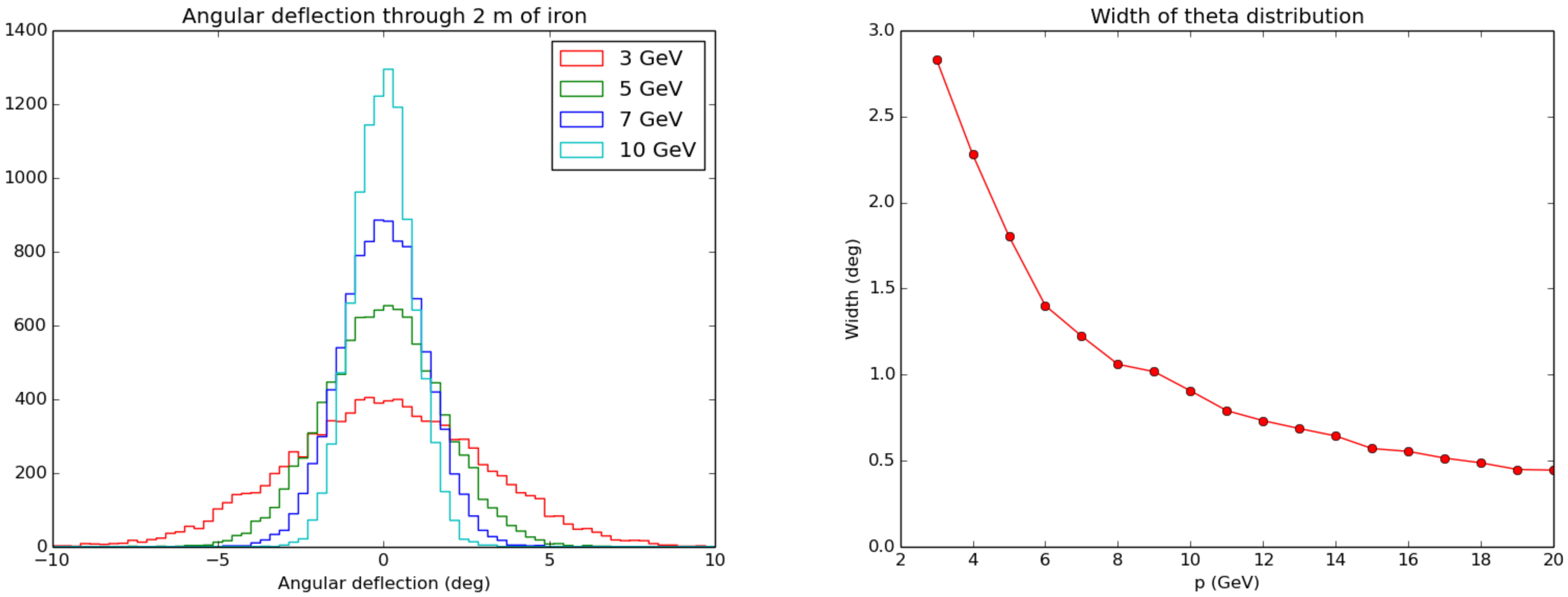
- Reasonable approximation for small-angle scattering, but underestimates tails from large-angle Rutherford scattering.

Spatial deflection from multiple scattering

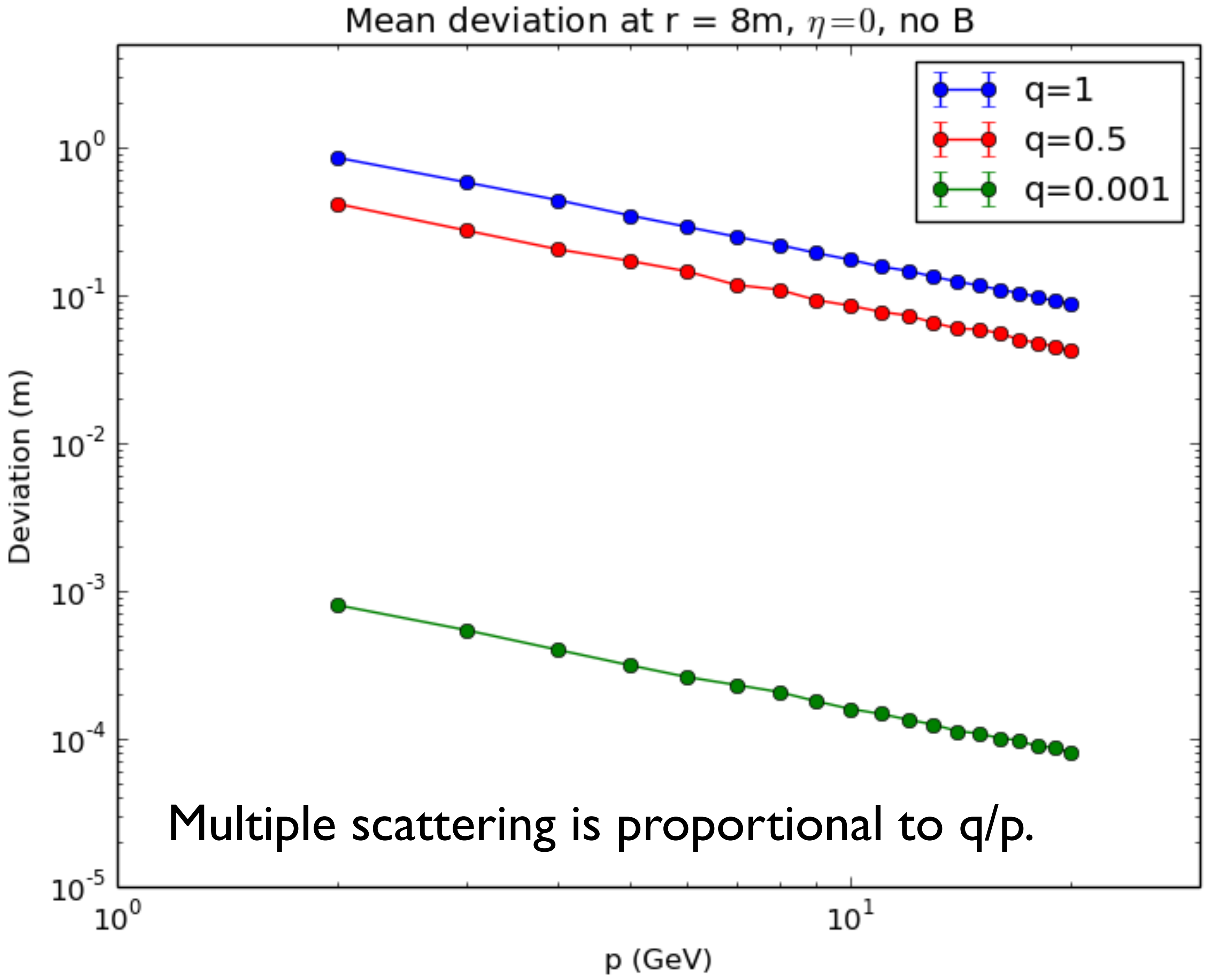




Spatial deflection from multiple scattering

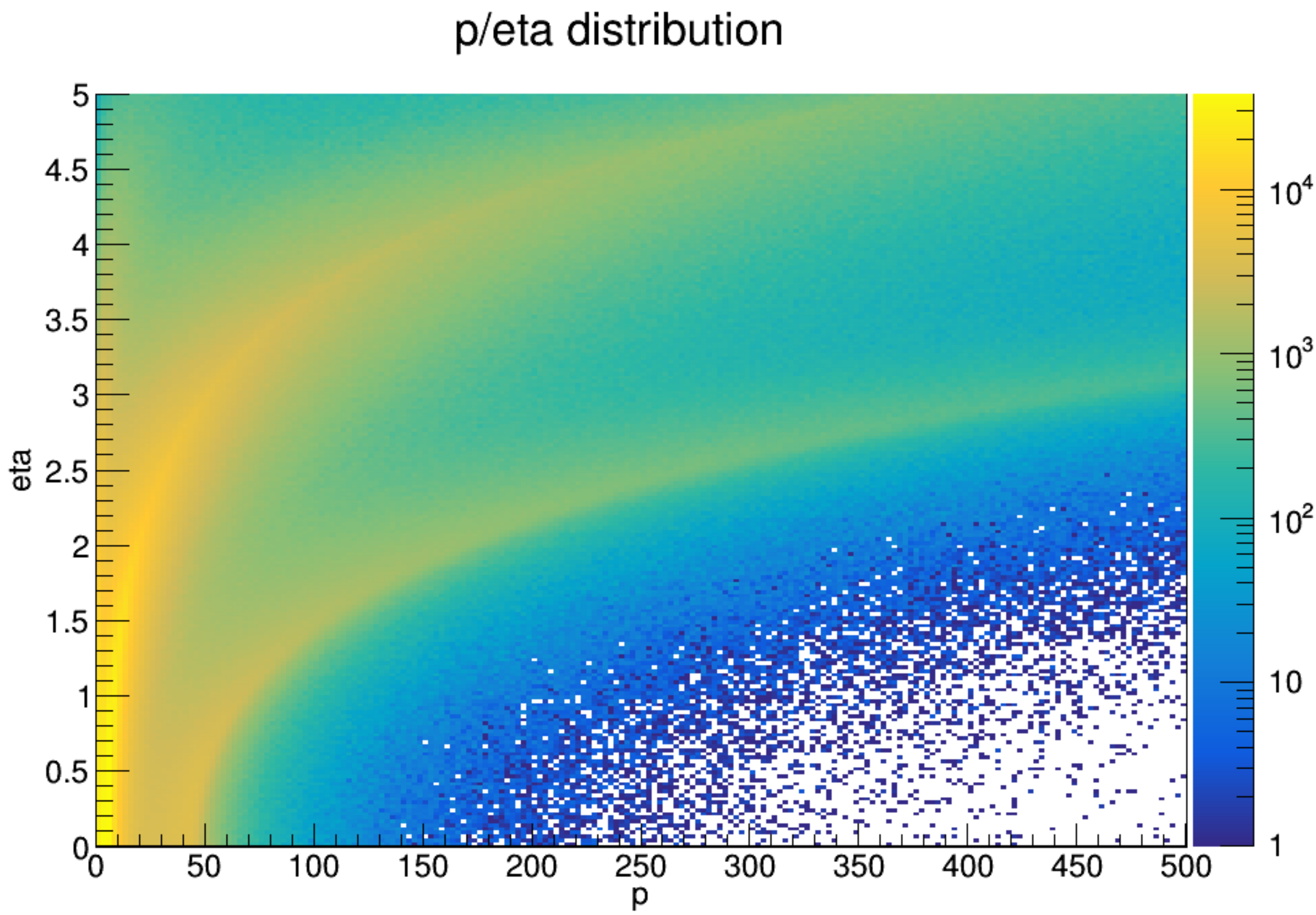


Multiple scattering and particle charge



Modeling muons produced with CMS

- Obtain templates of momentum and eta distributions of muons from DY and QCD MC.
- Use templates to generate spectrum of muons and look at kinematics of muons incident on a mocked up external detector.



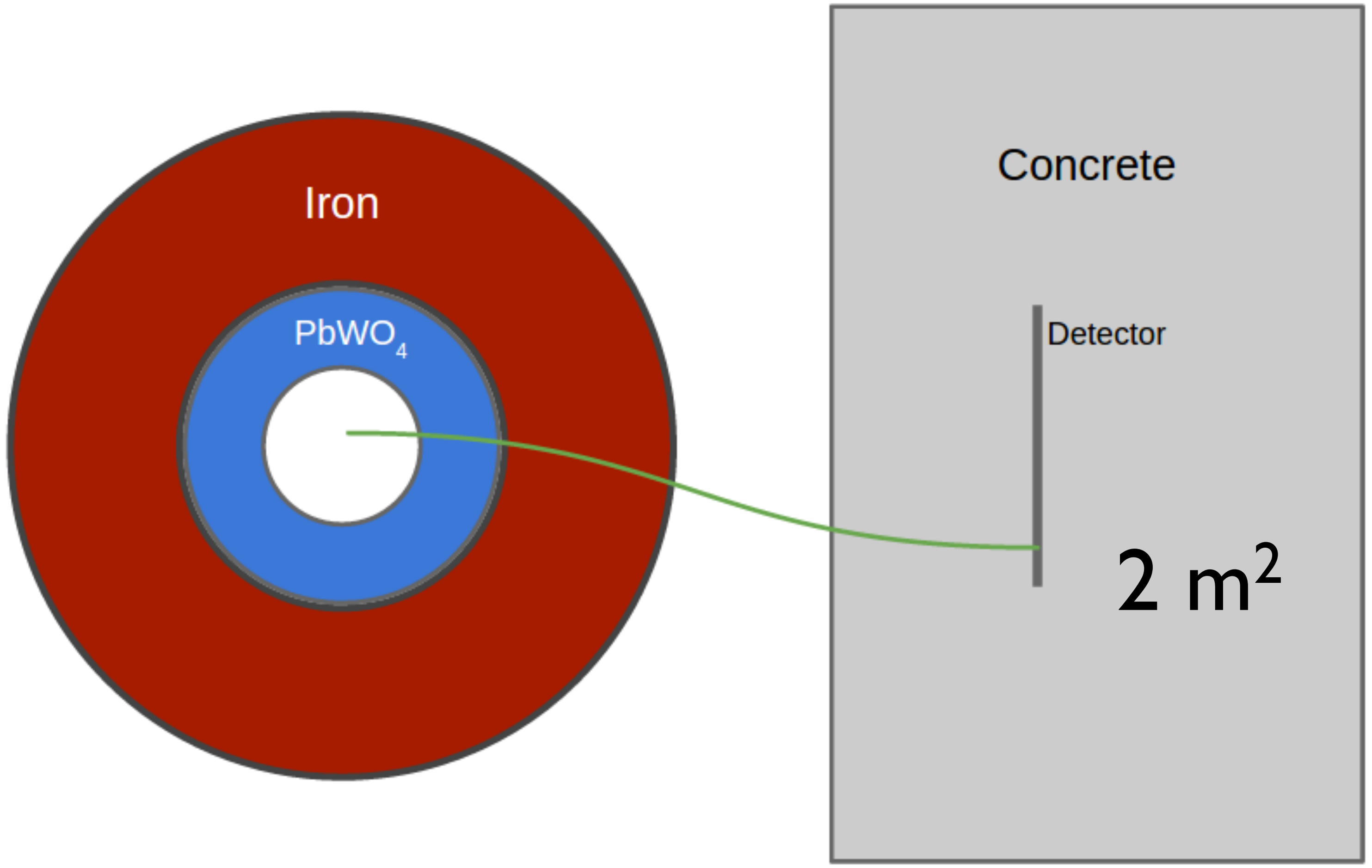
Modeling an external detector

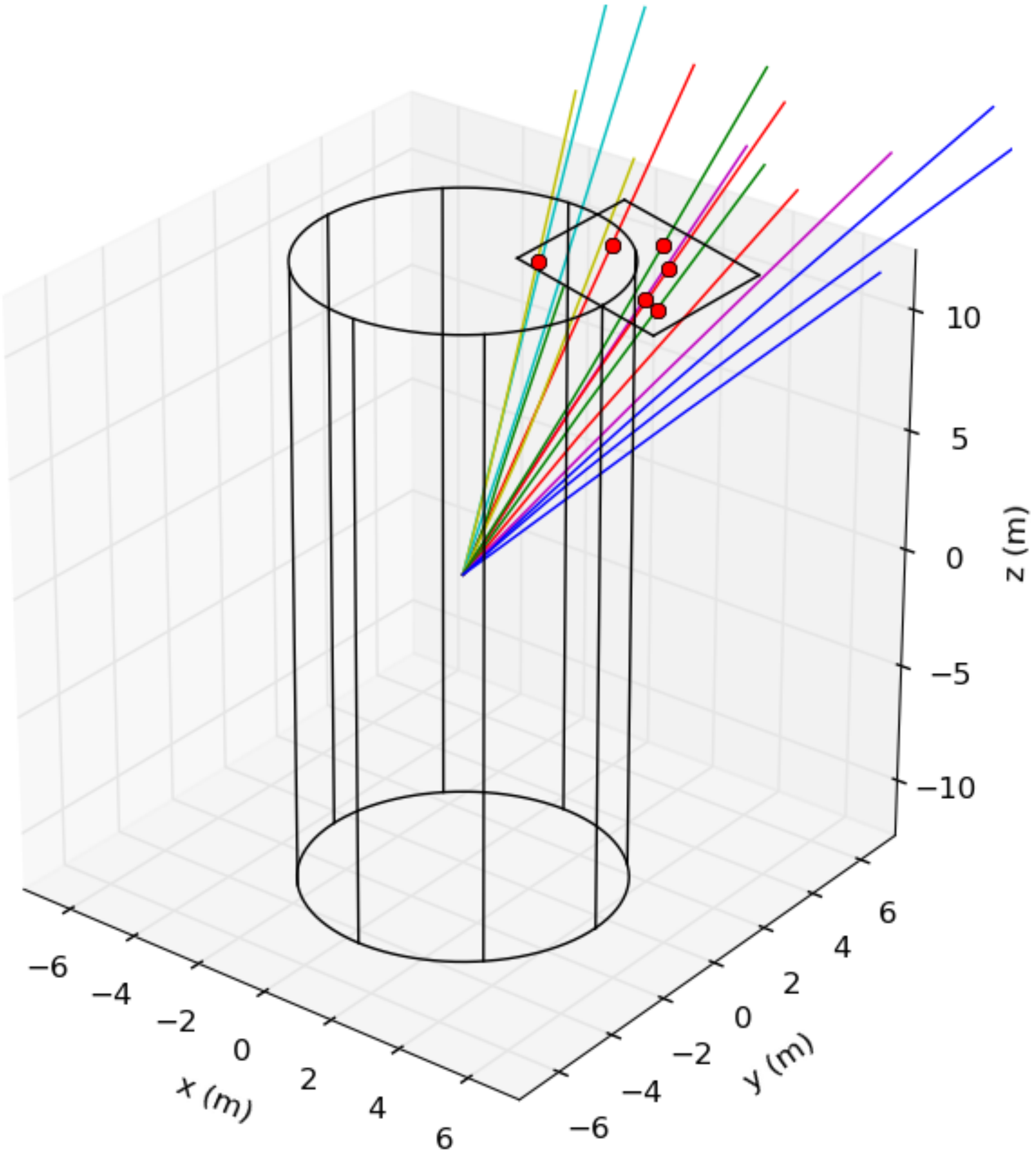
$r < 1.3$: vacuum

$1.3 < r < 1.8$: $PbWO_4$

$1.8 < r < 7.0$: iron

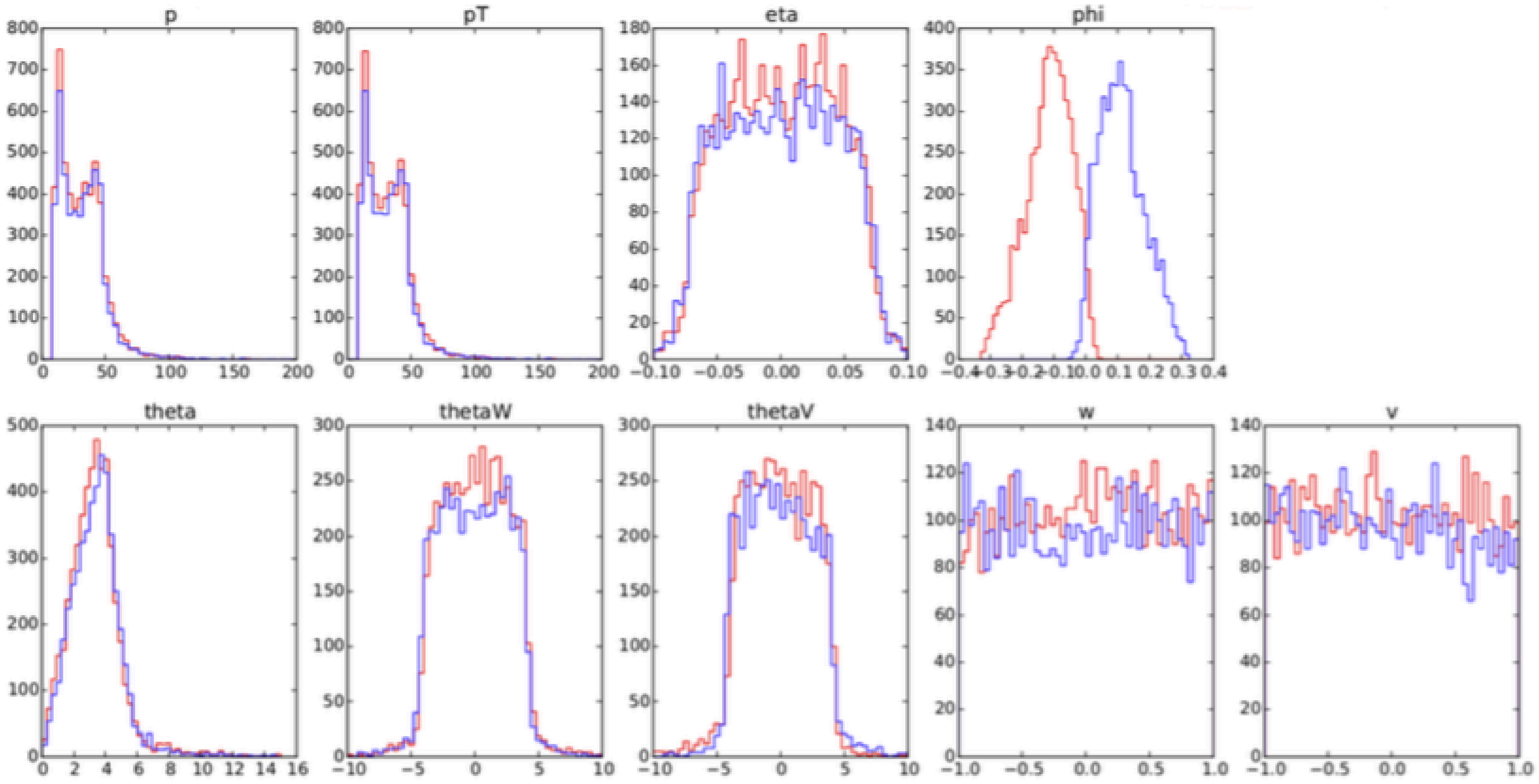
$r > 9$: concrete



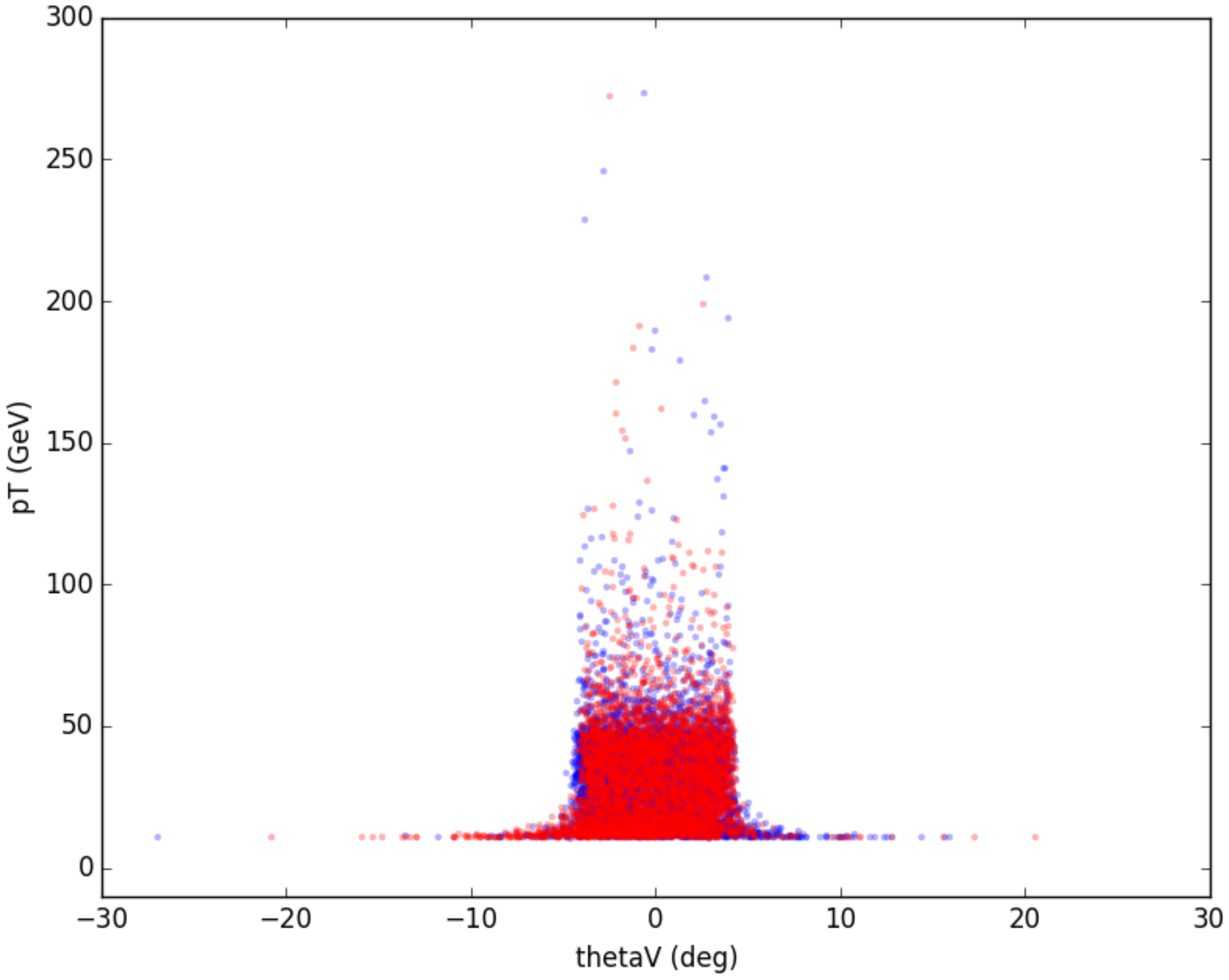


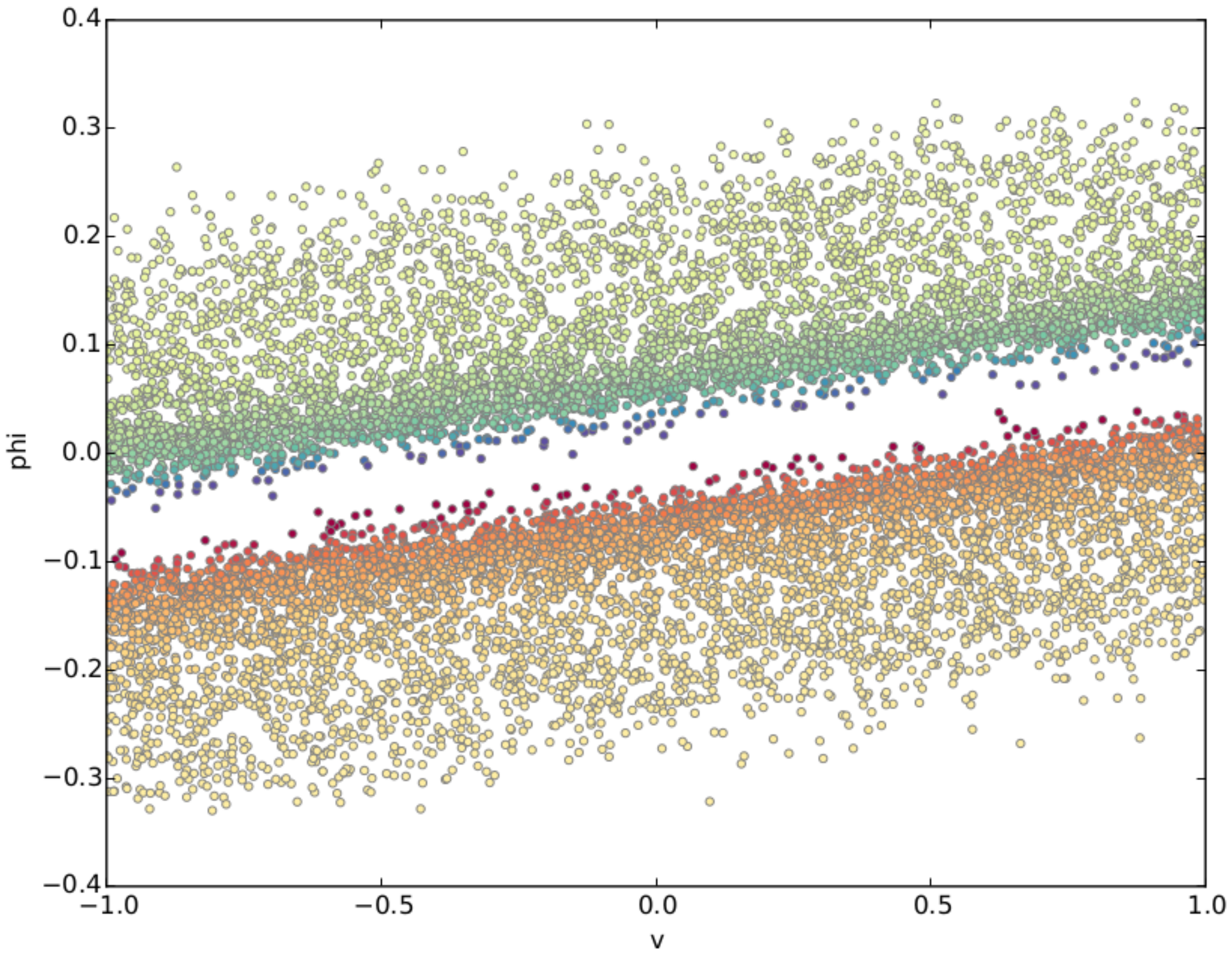
Hitting an external detector: η=0, Q=1e

- Setup 1: detector at $\eta = 0$, $r = 14$ m.
- w, v are coordinates in detector plane (v is in $\hat{\phi}$ direction, w in $\hat{\theta}$)
- θ is the angle the particle hits detector wrt the normal.
- blue: $Q = +1$, red: $Q = -1$
- Top row contains the initial kinematic variables of particle, bottom row its angle/position upon collision with detector

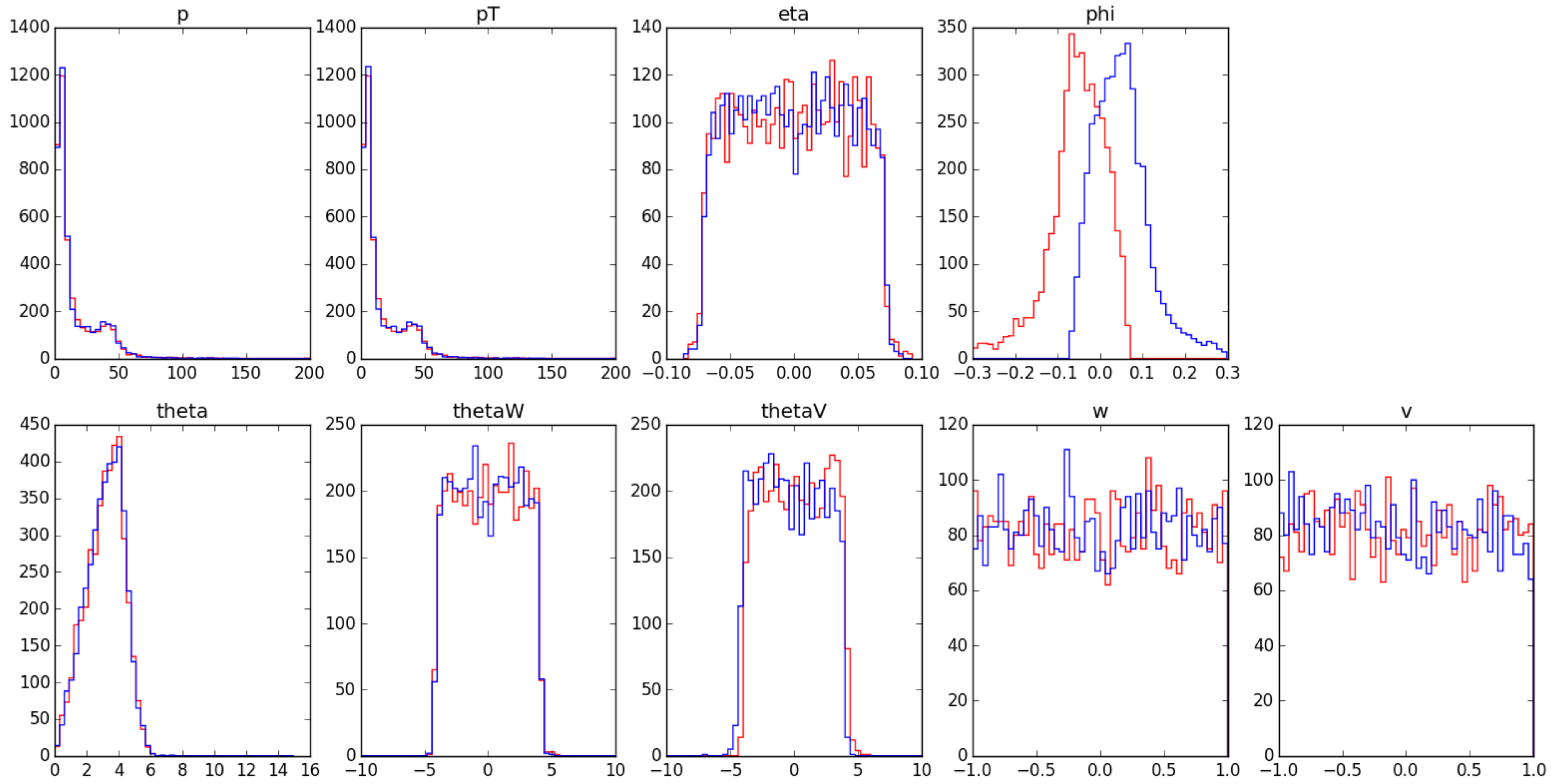


Hitting an external detector: η=0, Q=1e

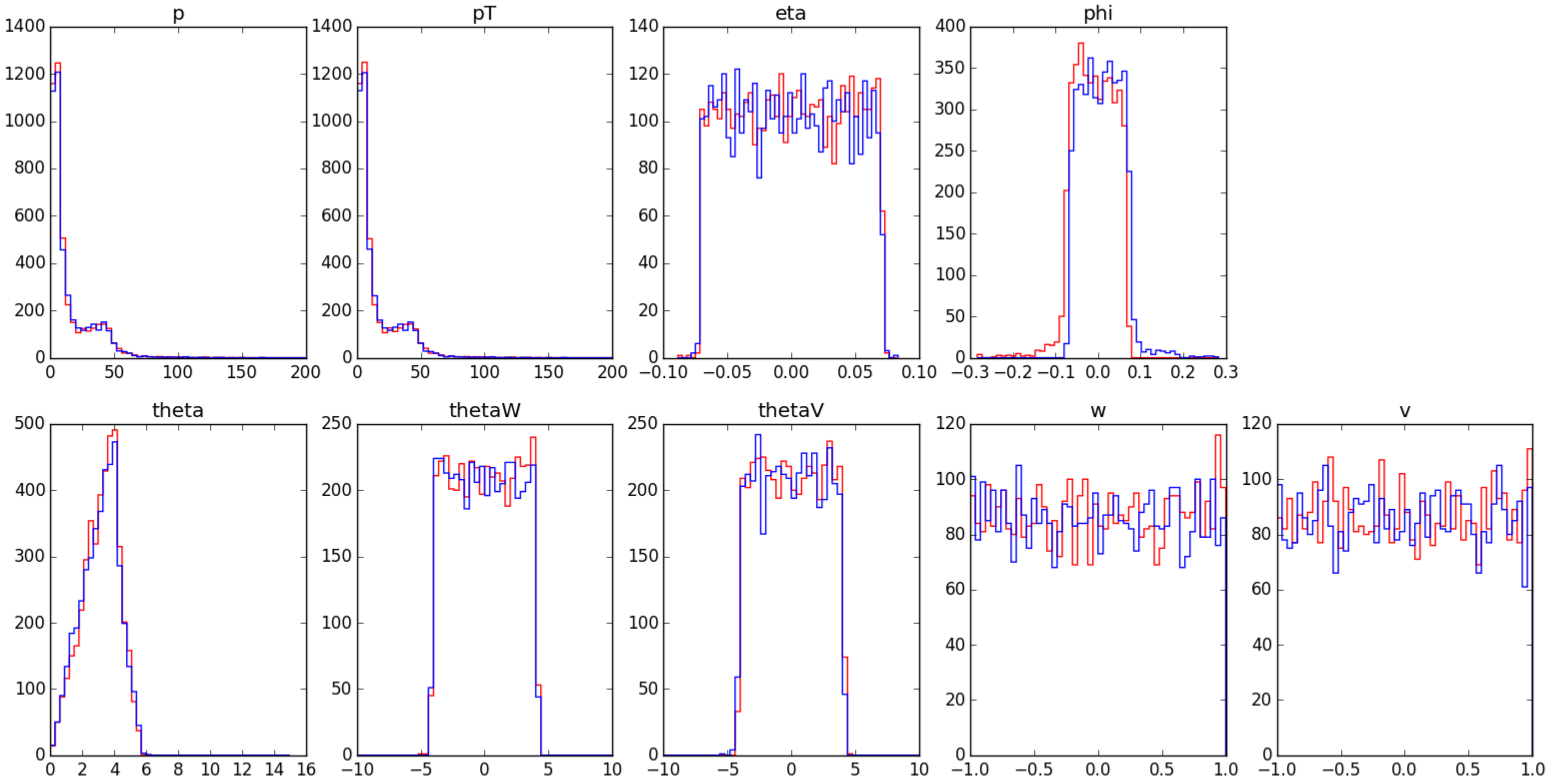




Hitting an external detector: η=0, Q=0.1e



Hitting an external detector: η=0, Q=0.01e

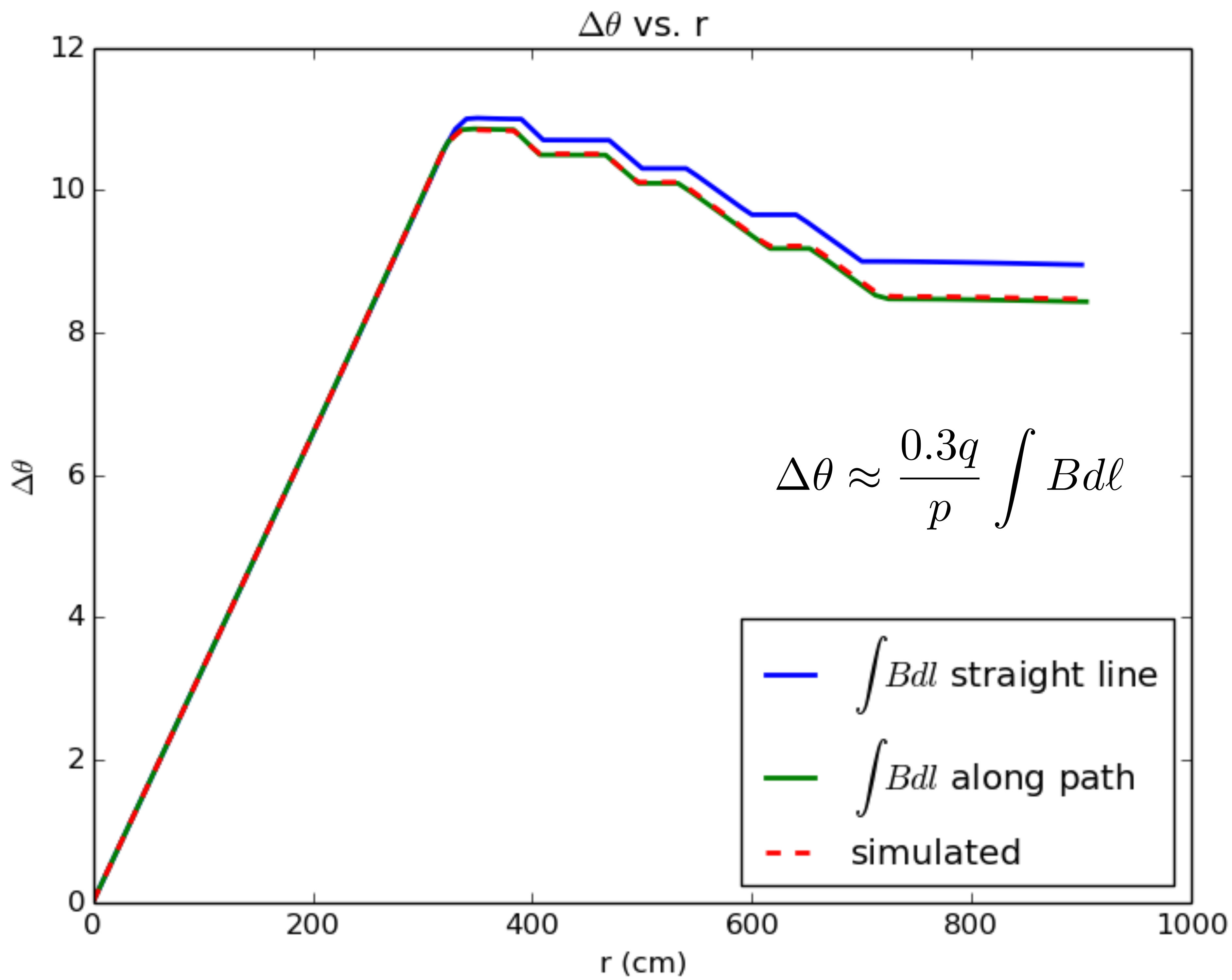


Next Steps

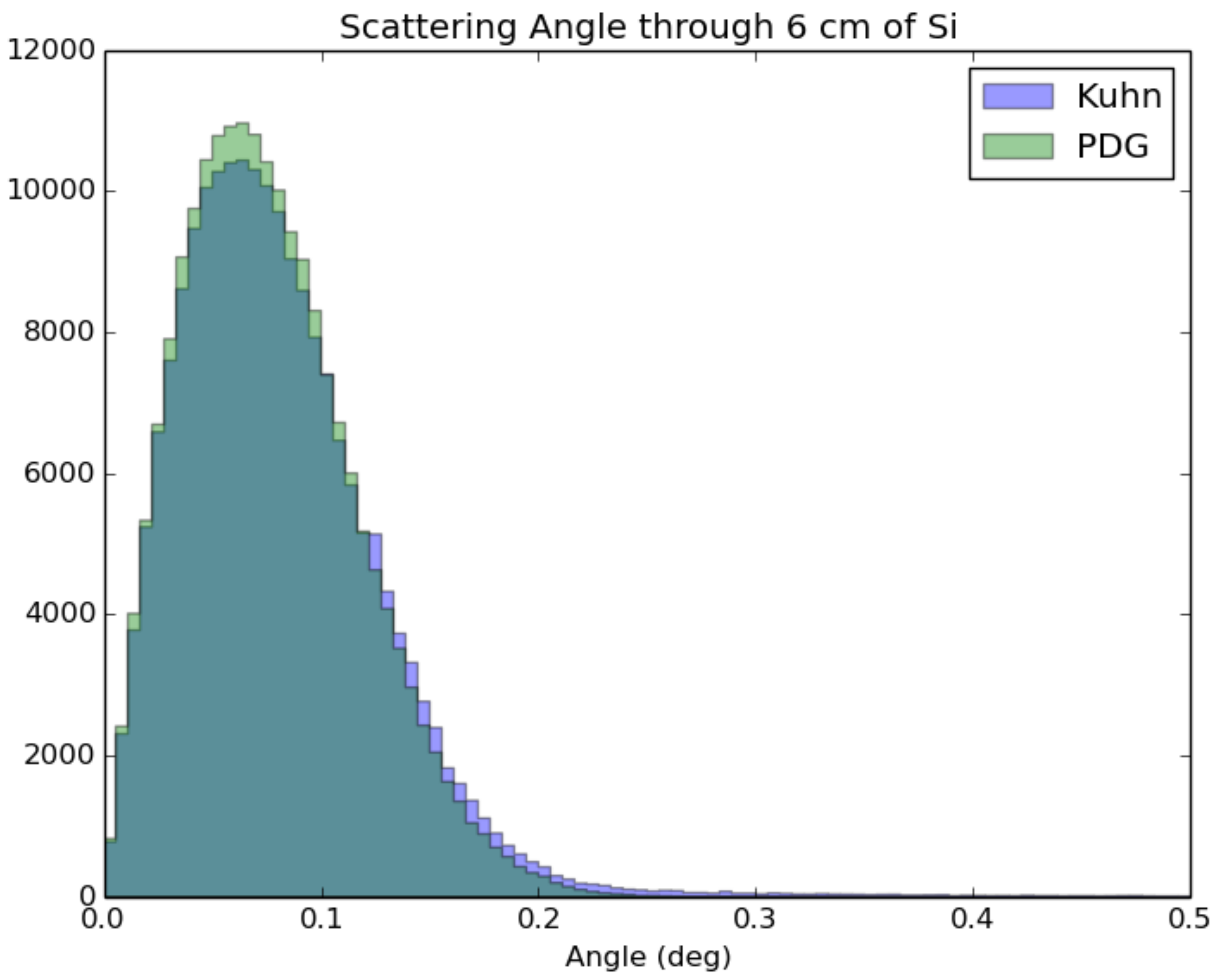
- Work with Gabriel to interface the work we've started.
- Start looking at alignment options in simulation.
    - What is expected rate for collision muons? cosmics?
- Start looking at interfacing with CMSSW?

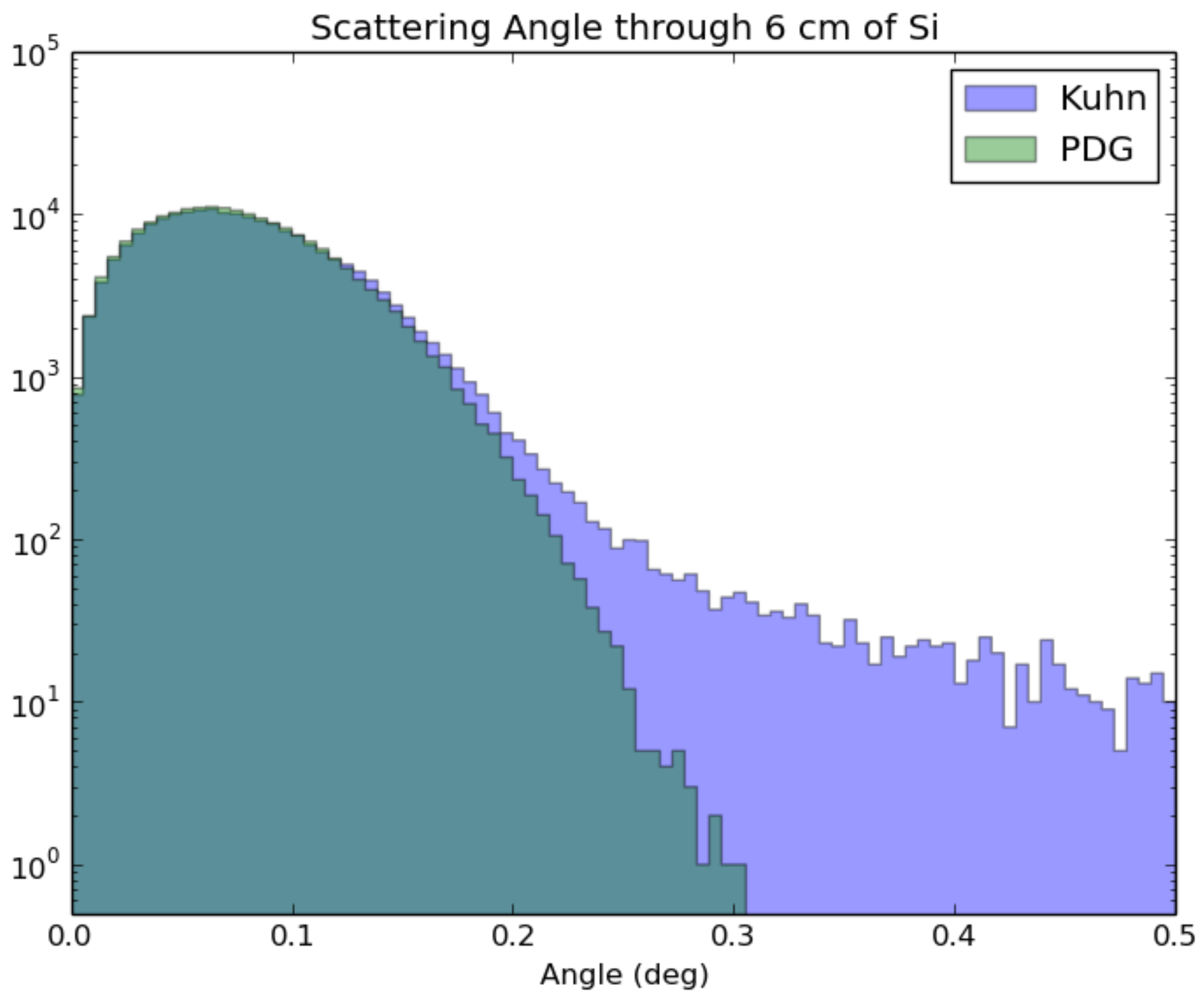
Backup

Trajectories through magnetic field

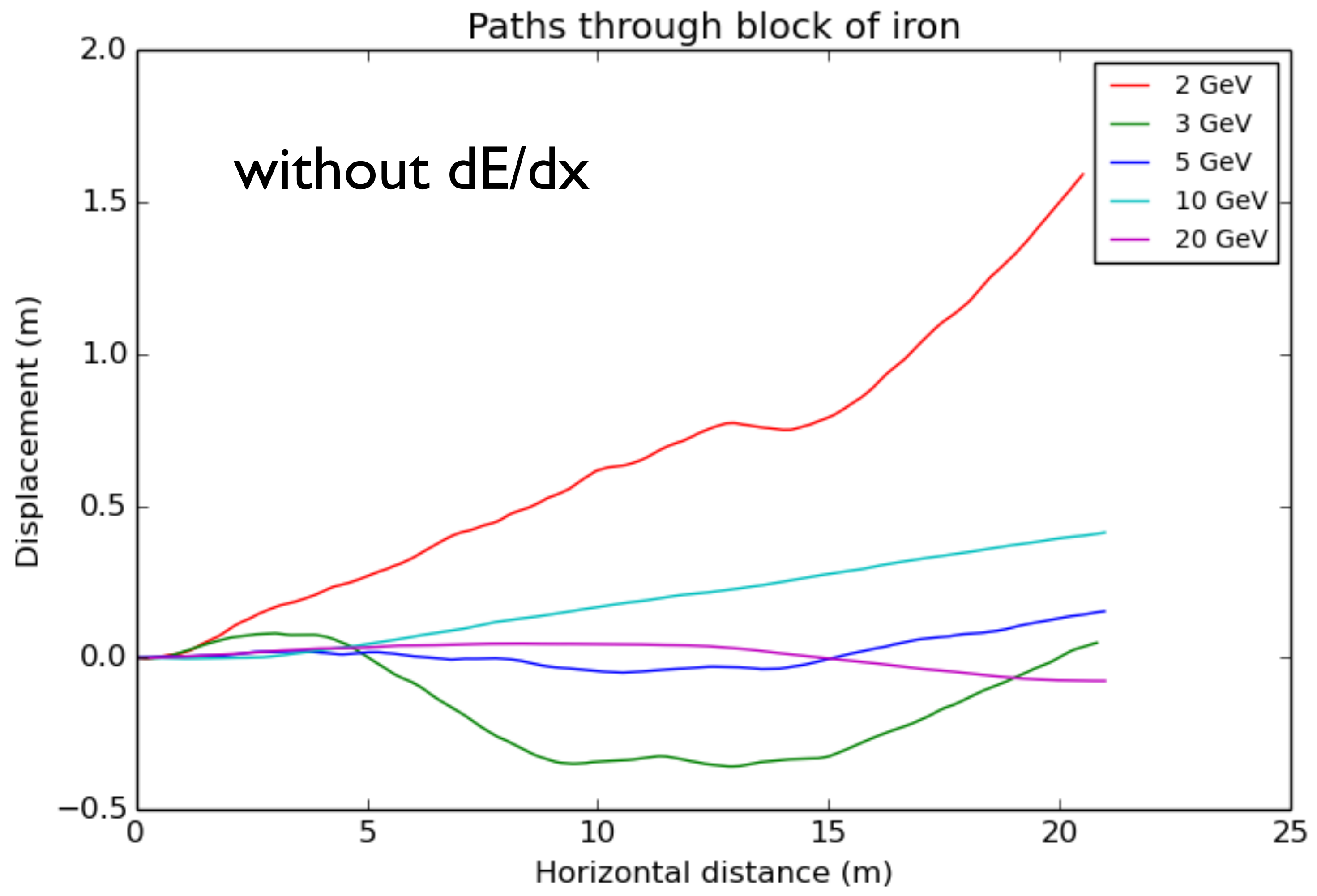


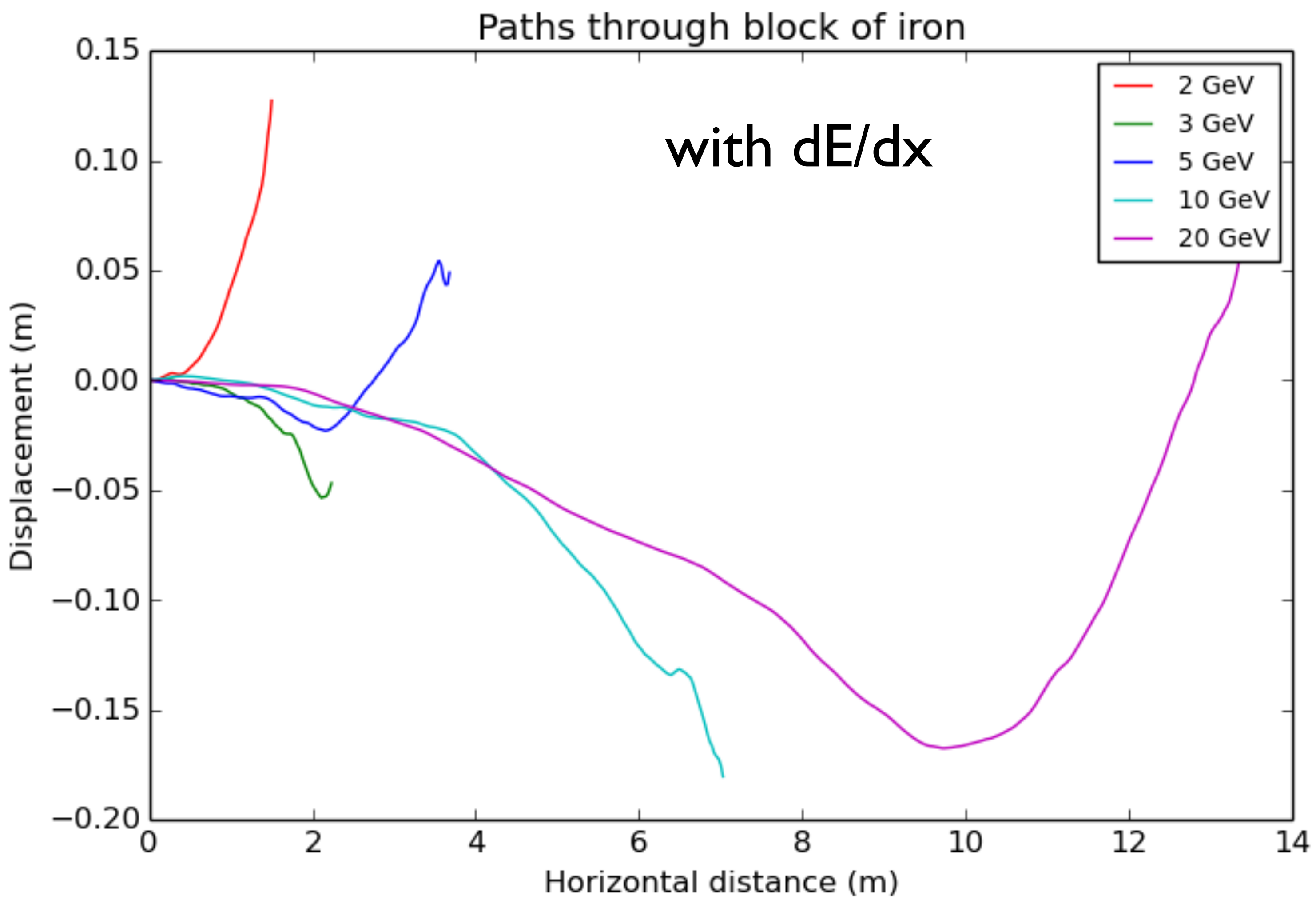
More realistic multiple scattering





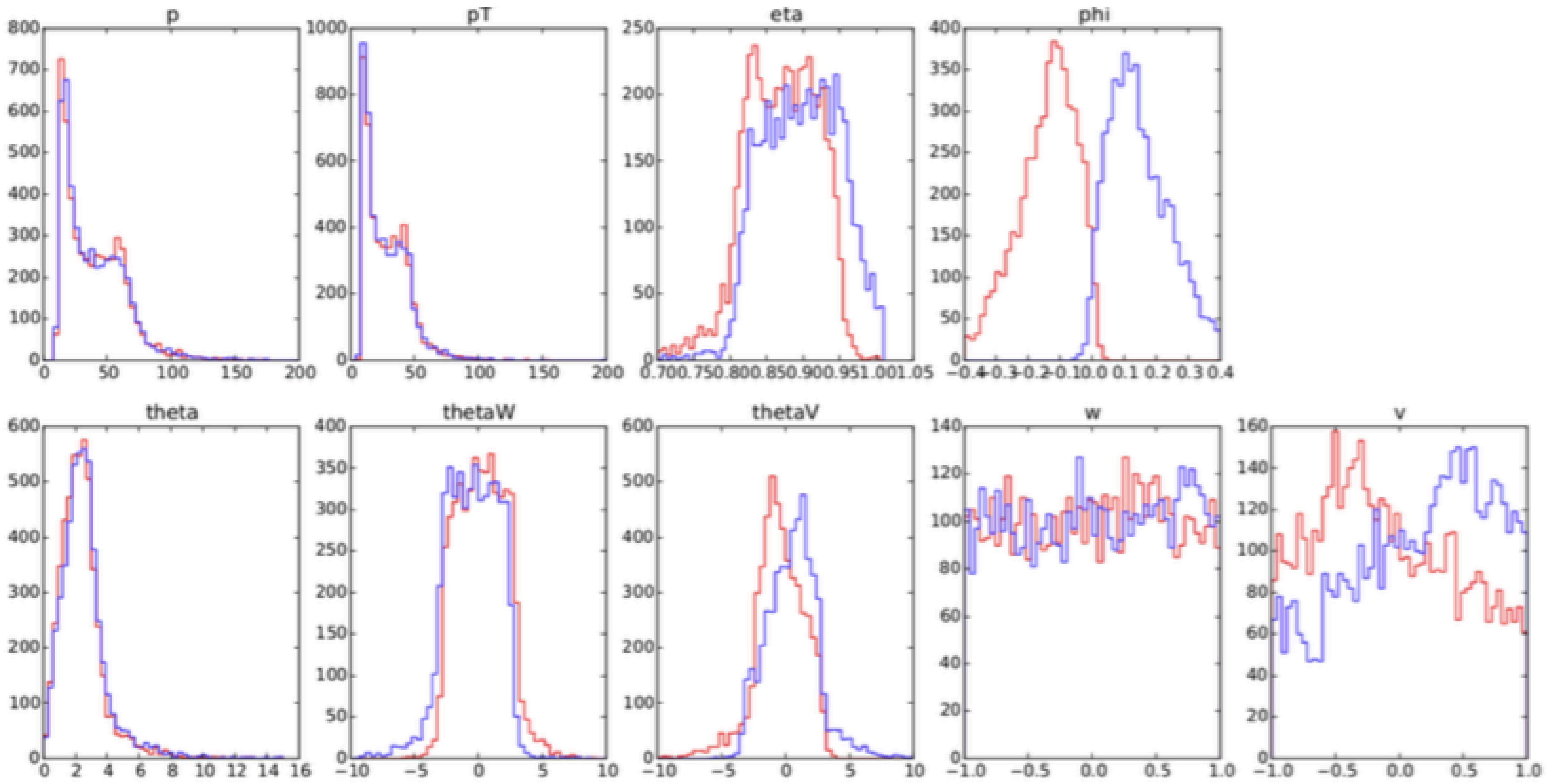
Multiple scattering and energy loss



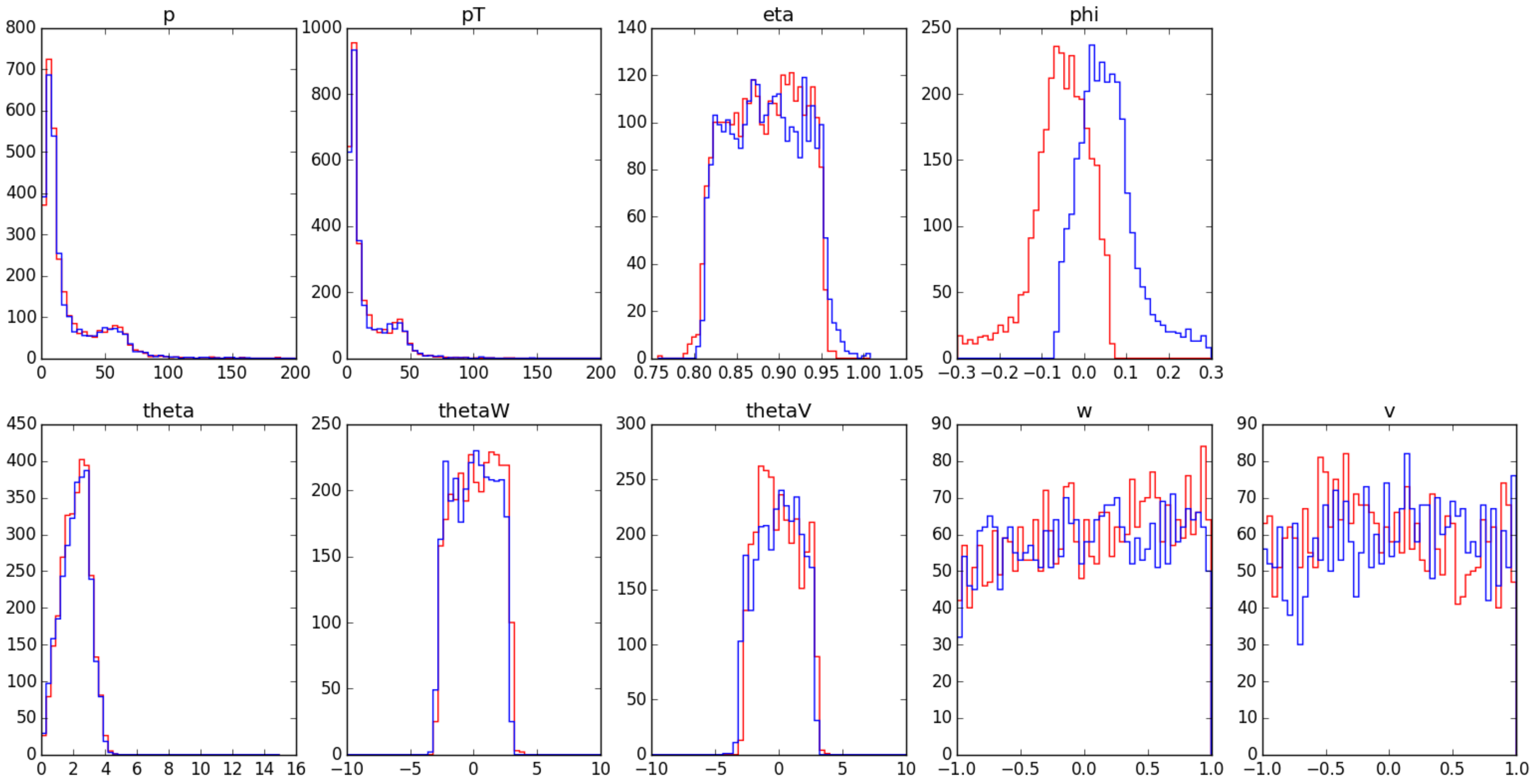


Hitting an external detector: η=0.88, Q=1e

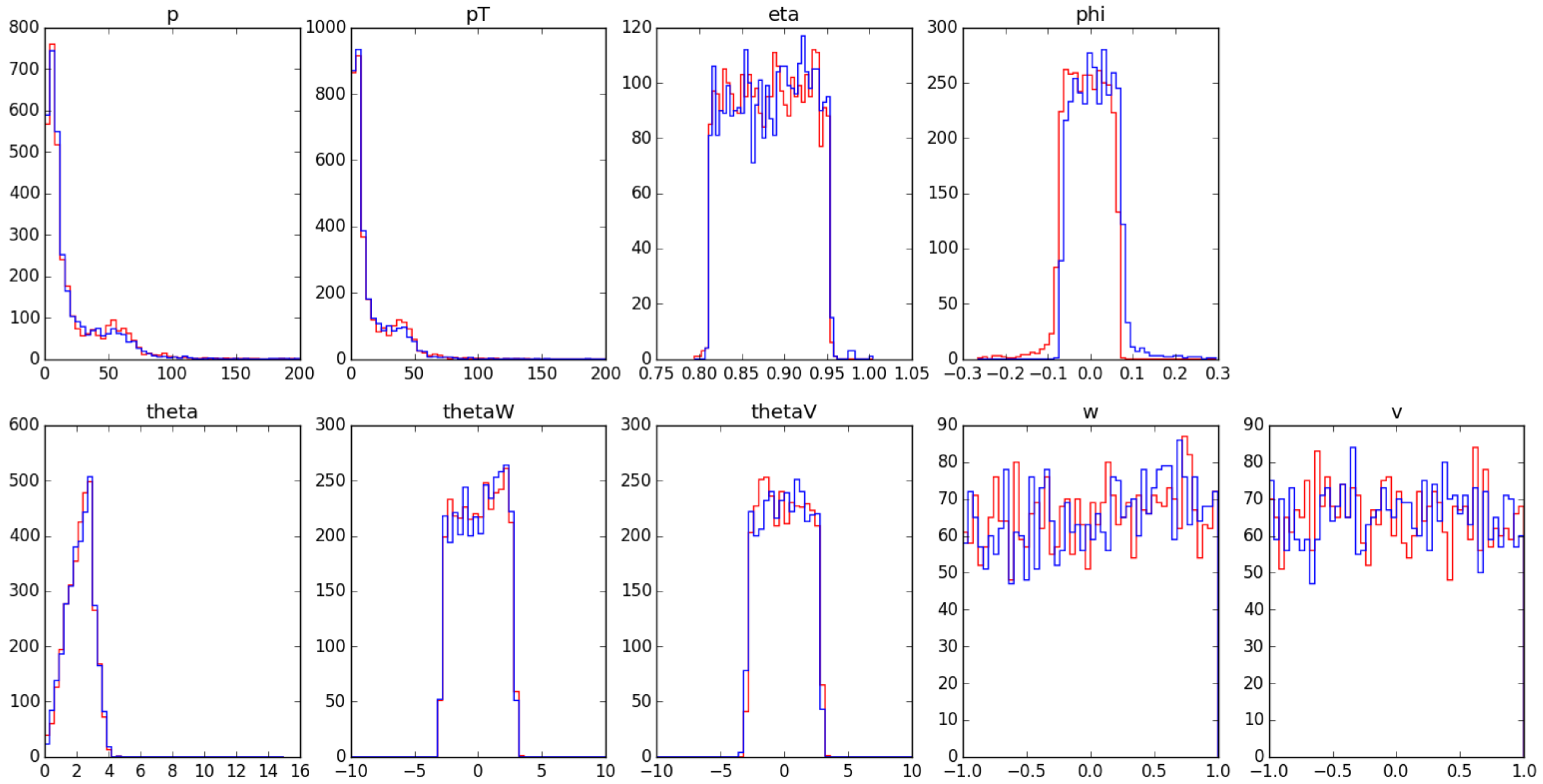
- Setup 2: detector at $\eta = 0.881$ $(45°)$, $\vec{r} = (14, 0, 14)$ m.



Hitting an external detector: η=0.88, Q=0.1e



Hitting an external detector: η=0.88, Q=0.01e



Hitting an external detector: η=0.88, Q=1e