Optics in HRSMC

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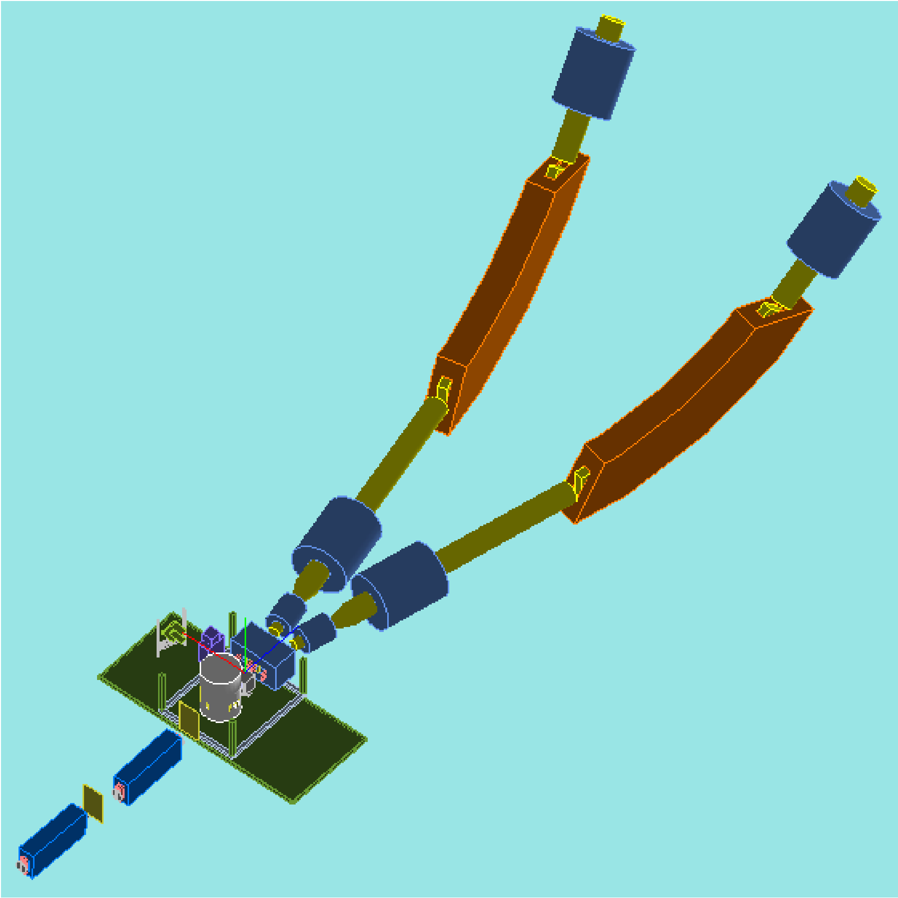
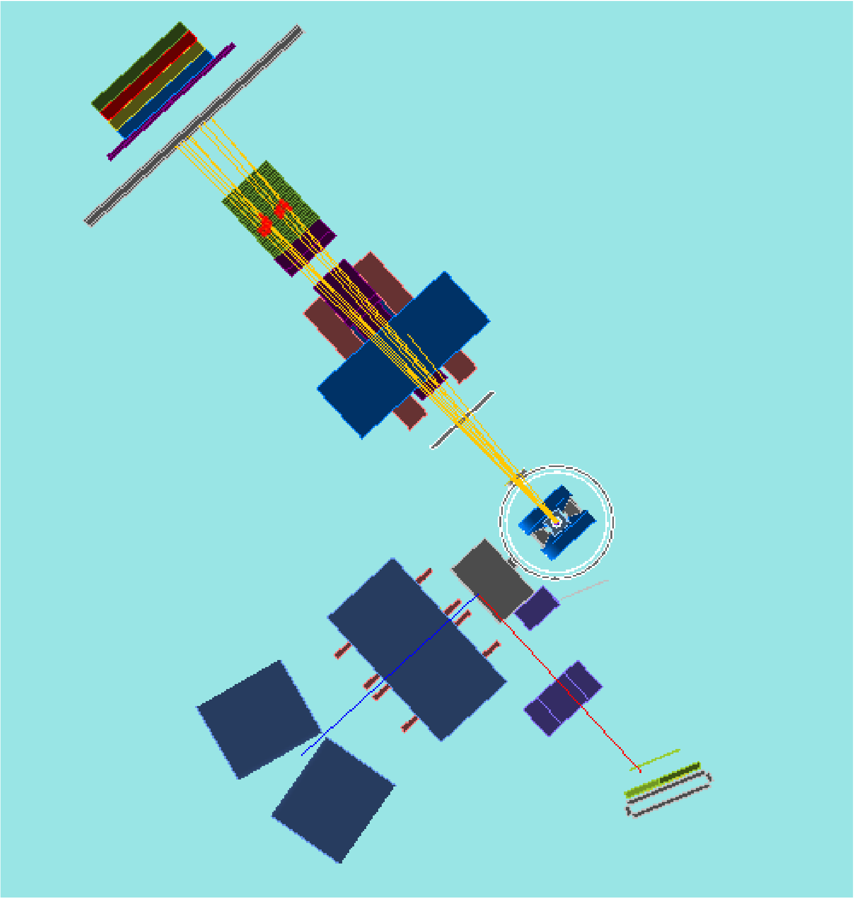
Introduction

- HRSMC is the Geant4 program developed to simulate the physics for G2P and GEP experiments. It was later upgraded to include the HRS QQDQ geometry, BigBite and the old Hall A Neutron detectors. Although G2P finally only used 5.65 degrees central ray angle with septum, HRSMC was designed to support both situations: with or without the septum. HRS QQDQ fields are not ready yet in HRSMC. Currently the transportation in HRS are taken care by SNAKE models.
- One of the major purposes of HRSMC is to study the G2P|GEP optics and acceptance.
- The optics reconstruction module was recently updated to include a “Drift-In-Field” module and debugged. Some tests were done to the event reconstruction at various target field values. Details will be present in the following slices.

Geometry in HRSMC





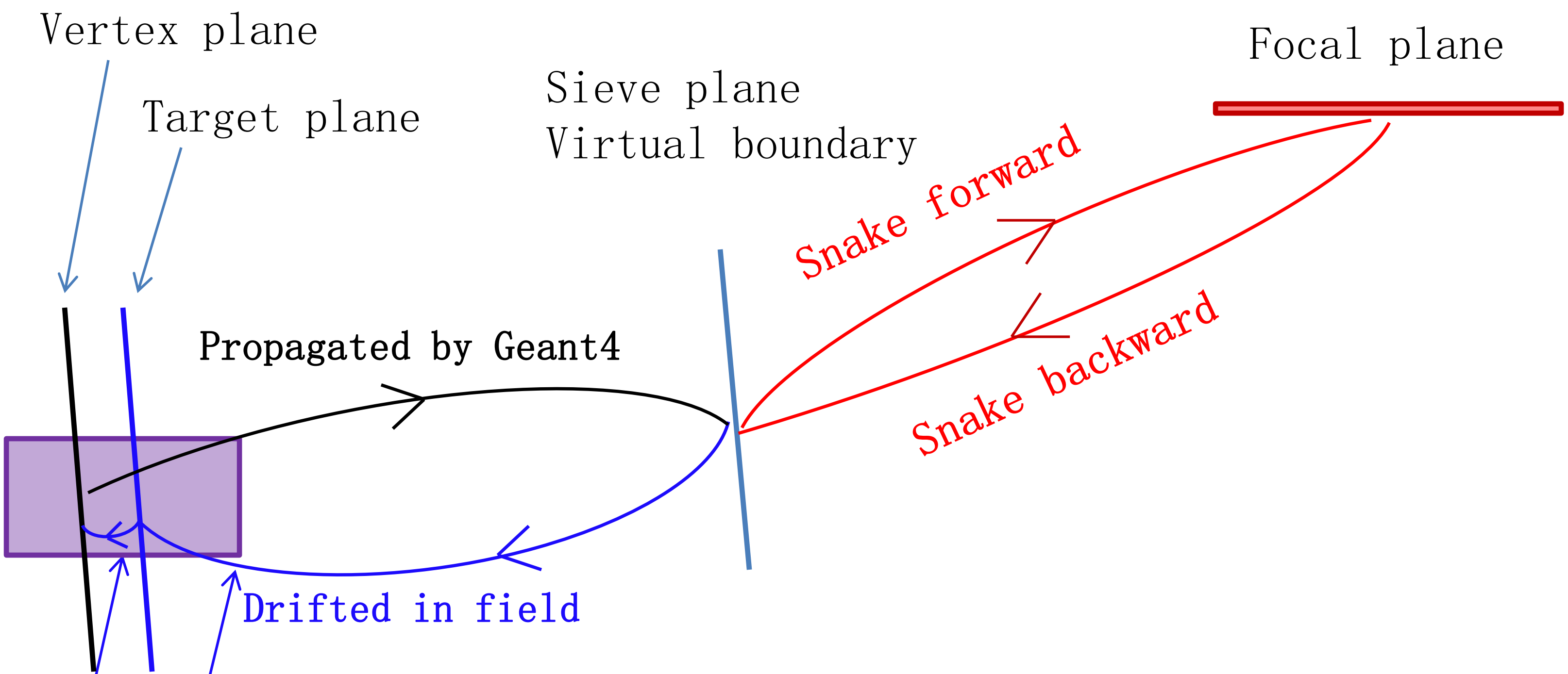
SNAKE models are used in HRS transportation. Currently one standard 12.5 degrees model, two E97110 6 degree models (one with larger X0 and the other is normal X0), and two models for G2p (normal (484816) septum with and without shims) are ready. Models for G2p 403216 and 400016 septa will be ready soon. All models are **without target field**.

Drift-In-Field Module

- **Purpose**: Propagate particle in EM field from one location to the other. In G2P only magnetic field is used.

  This module is mainly used to drift electron from sieve plane to target plane or vertex plane (the end plane of the vertex).
- **Input**: 3-vector of initial position and momentum in Hall Coordinate System (HCS), field map, particle’s mass and charge.
- **Output**: 3-vector of final position and momentum in HCS
- **Speed**: **12 milisecond each call. May be too slow to be embedded into replay. Will try to use SNAKE to fit a model from Sieve plane to target plane, which could improve the speed, but will introduce uncertaities.**
- **Other usages**: This module also used in the following projects:
  1) finding the chicane position and beam pipe angle;
  2) predicting the vertex position at target plane based on BPM A and BPM B measurements;
  3) finding beam titled angle and position offsets at veraious vertex z.

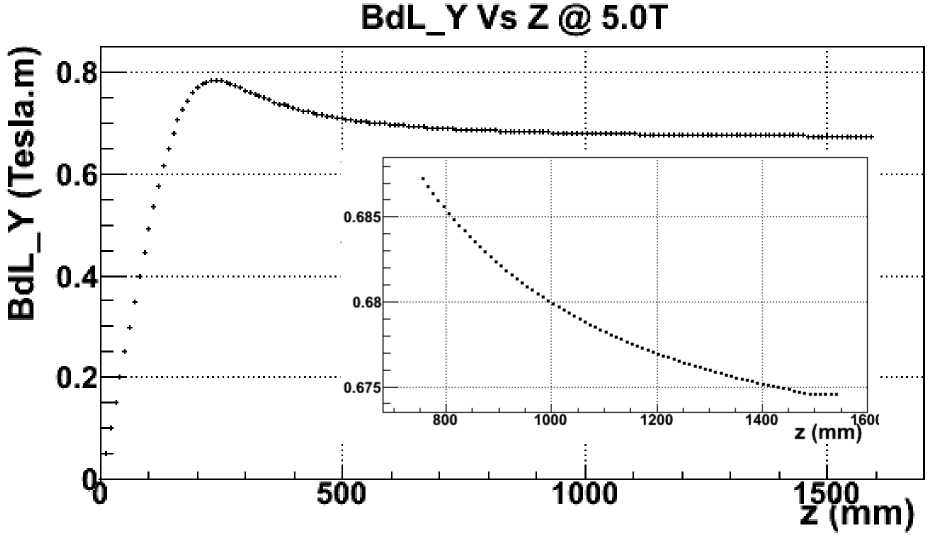
HRS Event in HRSMC



- Vertex to Sieve: propagated by Geant4 with all physics models (i.e. MSC, Decay, Ionization, EM physics...)
- Sieve to Focal: using Snake forward model, 8-10 software collimator cuts are applied along the trajectories to make sure particle is really hitting the focal plane.
- Focal to Sieve: using Snake backward model.
- Sieve to Target: using Drift-In-Field model.
- Target to Vertex: using Drift-In-Field model.

SNAKE Model: Sieve ⟷ Focal

- Snake models are actually fitted between target plane and focal plane.
- All used Snake models are without target field, which means their trajectories in between sieve plane and target plane are **STRAIGHT LINES.**
- Even for 5.0 Tesla target field, the integrated BdL_y from 800 mm to beyond is only 0.01 Tesla.m, about 1.46% of the total. This means the effect from the target field behind the sieve is negligable.



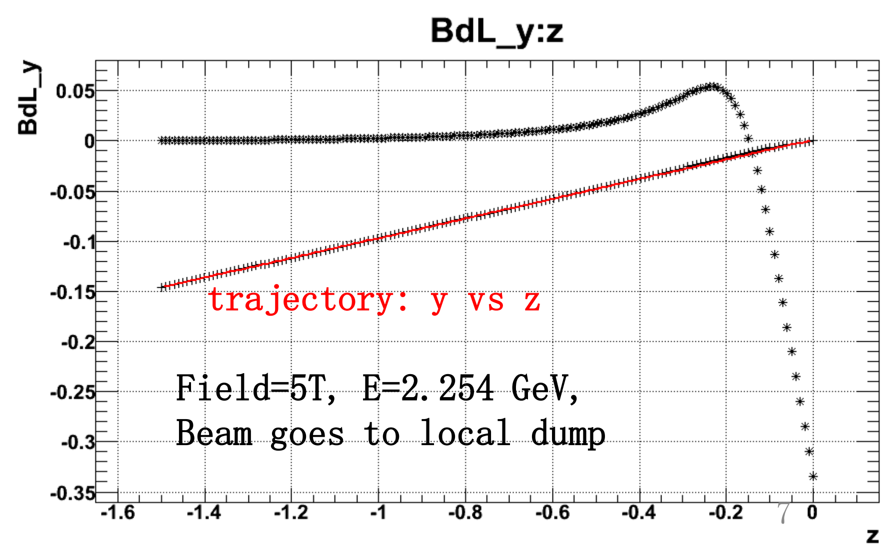
- Therefore:

  Sieve-to-Focal-without-targetfield = Sieve-to-Focal-with-targetfield.
- Sieve-to-Focal = Target-to-Focal - Target-to-Sieve .
- **Same for Focal-to-Sieve.**

BPM Resolution

- There are only 4 variables (x, y, theta, phi) in the focal plane, in order to reconstruction back to five variables (x, y, theta, phi, delta) in the target plane, one assumption has to be made. This assumption is that the momentum of the particle (delta) only depends on the VERTICAL displacement and the out-of-plane angle (theta). That said, if the **initial vertical position X0** is known, delta and the other 4 vaiables can all be reconstructed. The initial vertical position X0 usually came from BPM mesurement.
- Two sources: **δX0 = δBPM_Measurement + δVertical_DueToUnknownZ0InField**
- When target field is on, since we do not know the vertex Z0, δZ=15mm, BPM will have large uncertianty in the vertical position. Horizontal is fine.
- δVertical from simulation:

Field(T)	Beam (GeV)	δVertical (mm)
2.5	1.159	1.4
2.5	1.706	0.9
2.5	2.254	0.7
5.0	2.254, 3.359	<0.2



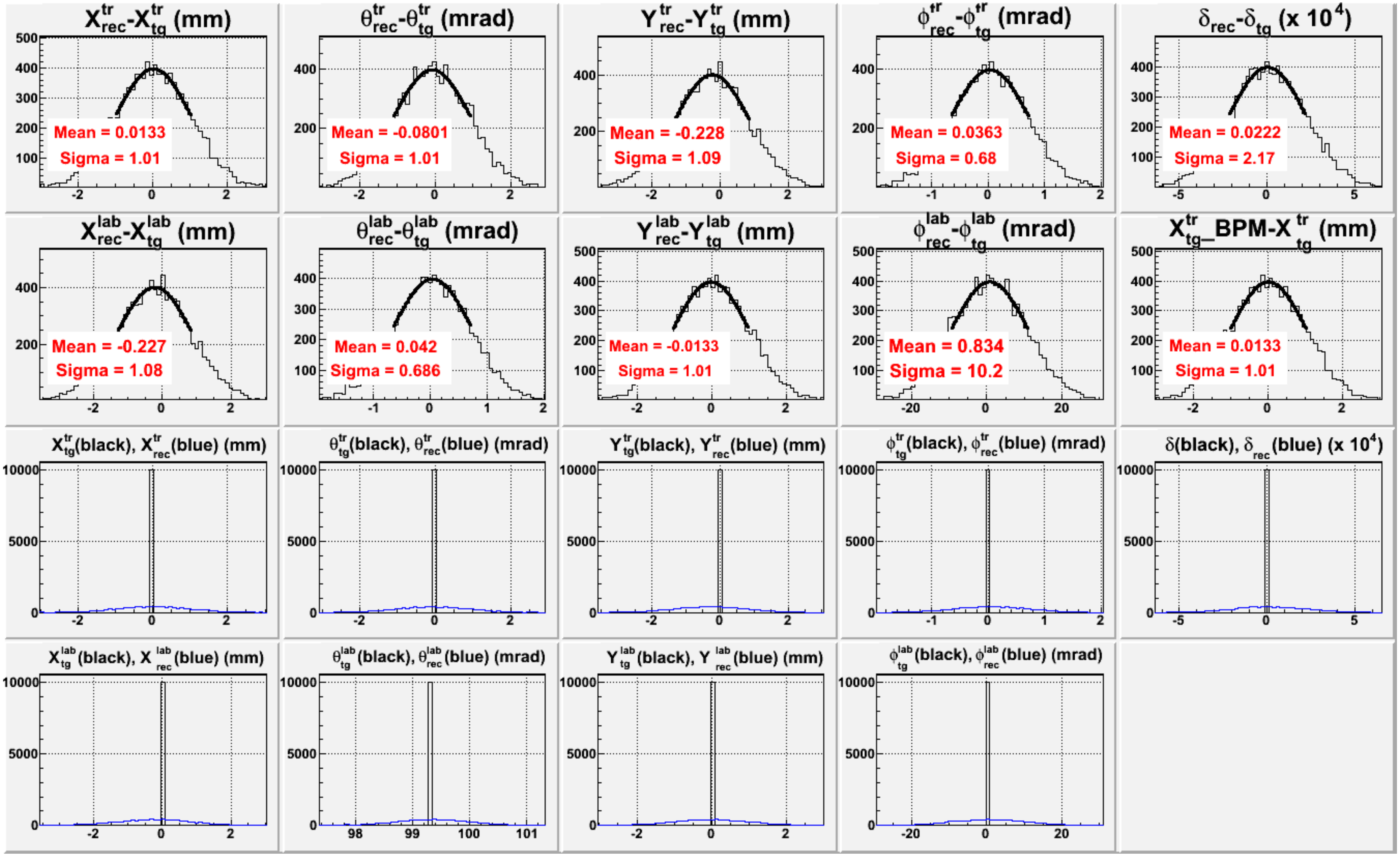
End Planes Propagate procedures and Name Rules for Their Variables

- **Variables**: $={X, Theta, Y, Phi, Delta, (Z, P)}
- Two coordinate systems: Hall coordinate system (HCS) and Transport coordinate system(TCS, variable names always followed by '_tr')
- **Propagate procedures**:
  1. Thrown in vertex plane: $0, $_tr
  2. Images of thrown vertex at target plane: $tg_tr
  3. Sieve plane (Virtual Boundary): $vb, $vb_tr
  4. Projected to target plane: $_proj2tg_tr
  5. Focal plane: $fp_tr
  6. Snake's reconstruction at target plane: $_rec2tg_tr
  7. Project Snake's reconstruction to sieve plane: $_proj2sl_tr
  8. Drift from sieve plane to target plane: $tg_rec_tr
  9. Drift from target plane to vertex plane: $_rec, $rec_tr

$0, $0_tr -> $tg_tr -> $vb, $vb_tr -> $_proj2tg_tr -> $fp_tr -> $_rec2tg_tr -> $_proj2sl_tr -> $tg_rec_tr -> $_rec, $_rec_tr

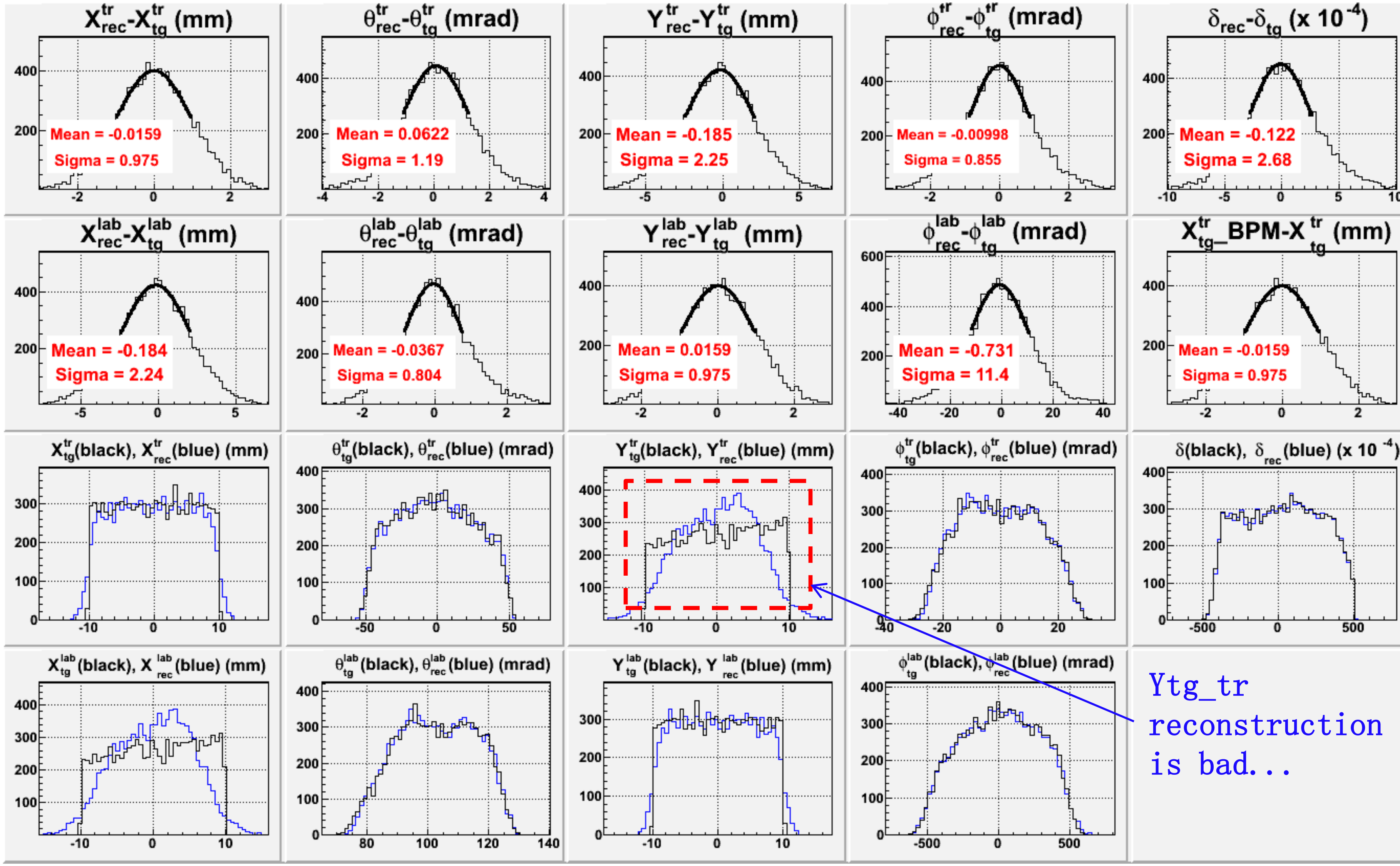
- BPM resolution of lab Y (vertical) was used in step 5 to go backward
- BPM resolution of lab X (horizontal) was used in step 9 to calculate vertex Z, then determined the vertex plane and do the drift.
- Compare the vaiables between planes: 1 vs 9 , 2 vs 8, 4 vs 6

Resolution of SNAKE Model 484816+shim (1)



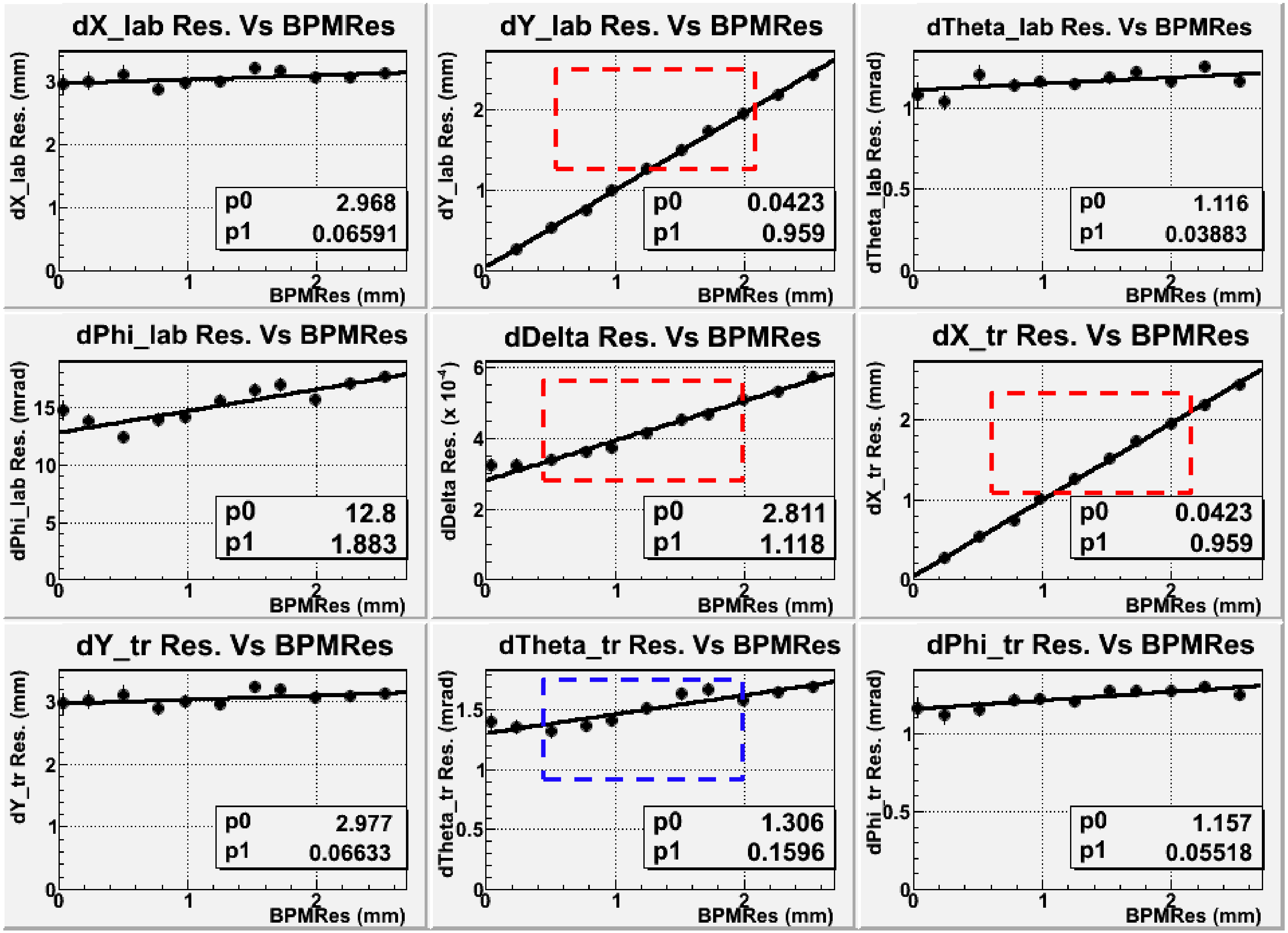
The best scenerio: x, theta, y, phi, delta are all delta function at the cental values, asumming 1 mm BPM vertical resolution.

Resolution of SNAKE Model 484816+shim (2)



Normal situation: 2 cm raster, +/-5% delta, full coverage of theta and phi. 1 mm BPM vertical resolution.

BPM dependence of SNAKE Model 484816+shim



Normal situation: 2 cm raster, +/-5% delta, full coverage of theta and phi.

Delta and X_tr have strong dependence, Theta_tr also has some dependence.

Snake Models for G2P|GEP

- Ytg_tr is very important to reconstruct vertex Z: **$\delta Z=\delta Ytg\_tr/\sin(\theta_0)$.**
- Raster size should cover at least 3 cm in order to have good reconstruction of Ytg_tr
- **Vertex is very important to reconstruct variables back to vertex plane.** (Will explain later).
- When calculating the uncertainty for scattering angle theta and azimuthal angle phi in the hall coordinate system, the uncertianty of both Theta_tr, Phi_tr will have contribution. (Will explain later).
- Need to create models for both 403216 and 400016 septum, without target field.
- Our optics data cover no more than 8 mm away from the beam line. It is really a chalenge to find a good correction to Ytg_tr.

Transform Vaiables between Coordinate Systems: TCS and HCS

$$\theta = \arccos(\cos\theta_{tr}\cos(\theta_0+\phi_{tr})) \quad (1)$$

$$\phi = \arctan(-\frac{\tan\theta_{tr}}{\sin(\theta_0+\phi_{tr})}) \quad (2)$$

$$\begin{aligned} \mathrm{d}\theta &= \frac{-1}{\sqrt{1-\cos^2\theta_{tr}\cos^2(\theta_0+\phi_{tr})}}(-\sin\theta_{tr})\cos(\theta_0+\phi_{tr})\mathrm{d}\theta_{tr} \\ &+ \frac{-1}{\sqrt{1-\cos^2\theta_{tr}\cos^2(\theta_0+\phi_{tr})}}\cos\theta_{tr}(-\sin(\theta_0+\phi_{tr}))\mathrm{d}\phi_{tr} \quad (3) \end{aligned}$$

$$\begin{aligned} \mathrm{d}\phi &= \frac{1}{1+\left(\frac{-\tan\theta_{tr}}{\sin(\theta_0+\phi_{tr})}\right)^2}\frac{-1}{\sin(\theta_0+\phi_{tr})}\frac{1}{\cos^2\theta_{tr}}\mathrm{d}\theta_{tr} \\ &+ \frac{1}{1+\left(\frac{-\tan\theta_{tr}}{\sin(\theta_0+\phi_{tr})}\right)^2}(-\tan\theta_{tr})\left(-\frac{1}{\sin^2(\theta_0+\phi_{tr})}\right)\cos(\theta_0+\phi_{tr})\,\mathrm{d}\phi_{tr} \quad (4) \end{aligned}$$

- TCS = Transport Coordinate System
- HCS = Hall Coordinate System

Curtsey to Chao Gu

Uncertainty Estimation

No field, $<\theta_{tr}>=<\phi_{tr}>=0$, $\theta_0 \sim 100\,\mathrm{mrad}$

$$
\begin{aligned}
(\delta\theta)^2 &= \frac{\cos^2\theta_0}{1-\cos^2\theta_0}\tan^2\theta_0(\delta\phi_{tr})^2 = (\delta\phi_{tr})^2 \\
(\delta\phi)^2 &= \frac{1}{\sin^4\theta_0}\sin^2\theta_0(\delta\theta_{tr})^2 = \frac{(\delta\theta_{tr})^2}{\sin^2\theta_0}
\end{aligned}
$$

$$
\left\{\begin{array}{l}\delta\theta_{tr} = 1.02 \\ \delta\phi_{tr} = 0.842\end{array}\right. \Rightarrow \left\{\begin{array}{l}\delta\theta = 0.842 \\ \delta\phi = 10.2\end{array}\right.
$$

$$
\begin{aligned}
(\delta\theta)^2 &= \frac{\cos^2\theta_0}{1+\cos^2\theta_0}\left((\delta\theta_{tr})^2 + (\delta\phi_{tr})^2\right) \\
(\delta\phi)^2 &= \left(\frac{1}{1-\cos^4\theta_0}\right)^2 \sin^2\theta_0\left((\delta\theta_{tr})^2 + \cos^4\theta_0(\delta\phi_{tr})^2\right)
\end{aligned}
$$

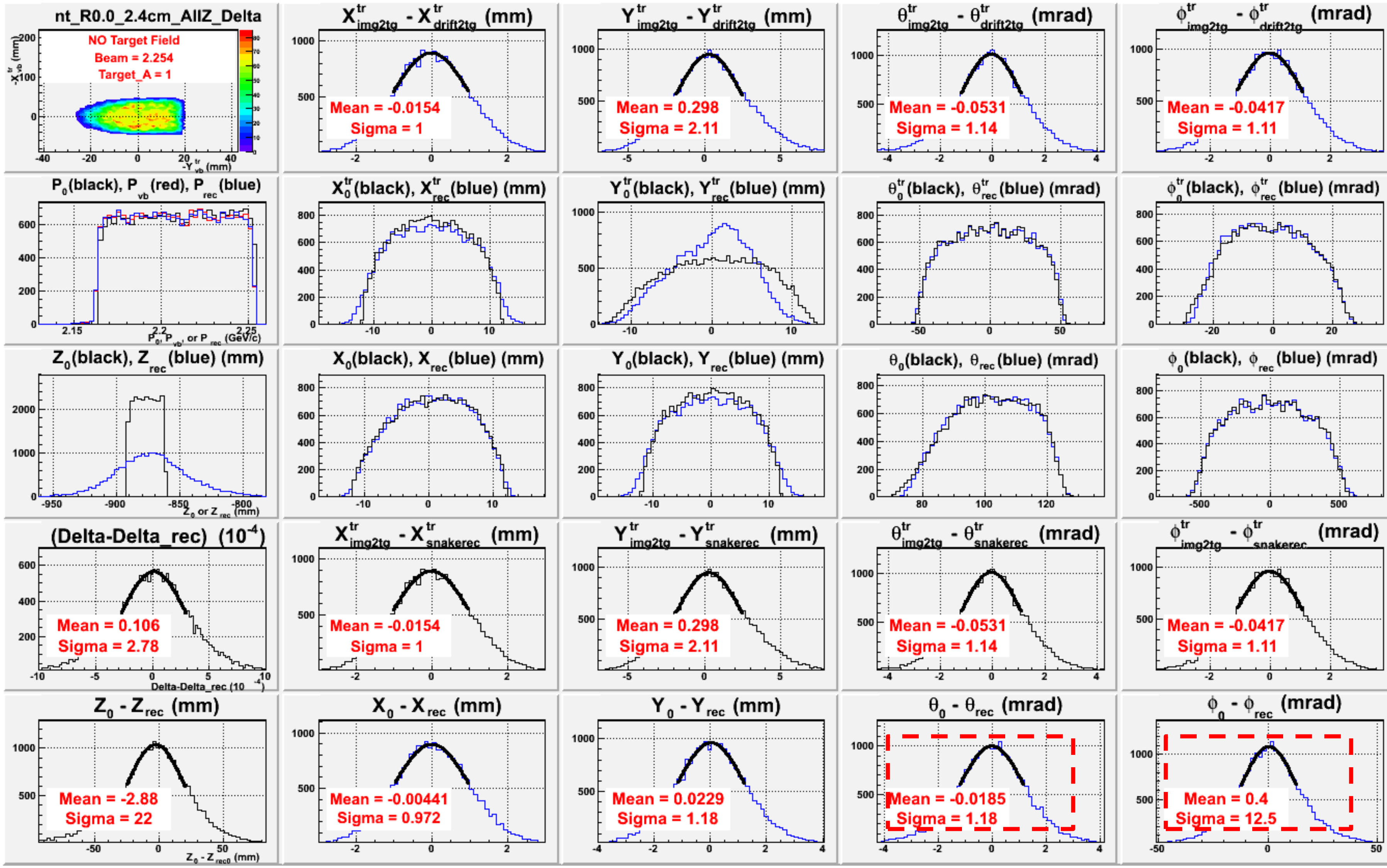
5.0T, 2.253GeV $<\theta_{tr}>\sim\theta_0\sim 100\,\mathrm{mrad}$, $<\phi_{tr}>=0$

$$
\begin{aligned}
\delta\theta &= \sqrt{0.497((\delta\theta_{tr})^2 + (\delta\phi_{tr})^2)} \\
\delta\phi &= \sqrt{25.3((\delta\theta_{tr})^2 + 0.980(\delta\phi_{tr})^2)}
\end{aligned}
$$

$$
\left\{\begin{array}{l}\delta\theta_{tr} = 1.24 \\ \delta\phi_{tr} = 0.868\end{array}\right. \Rightarrow \left\{\begin{array}{l}\delta\theta = 1.14 \\ \delta\phi = 7.59\end{array}\right.
$$

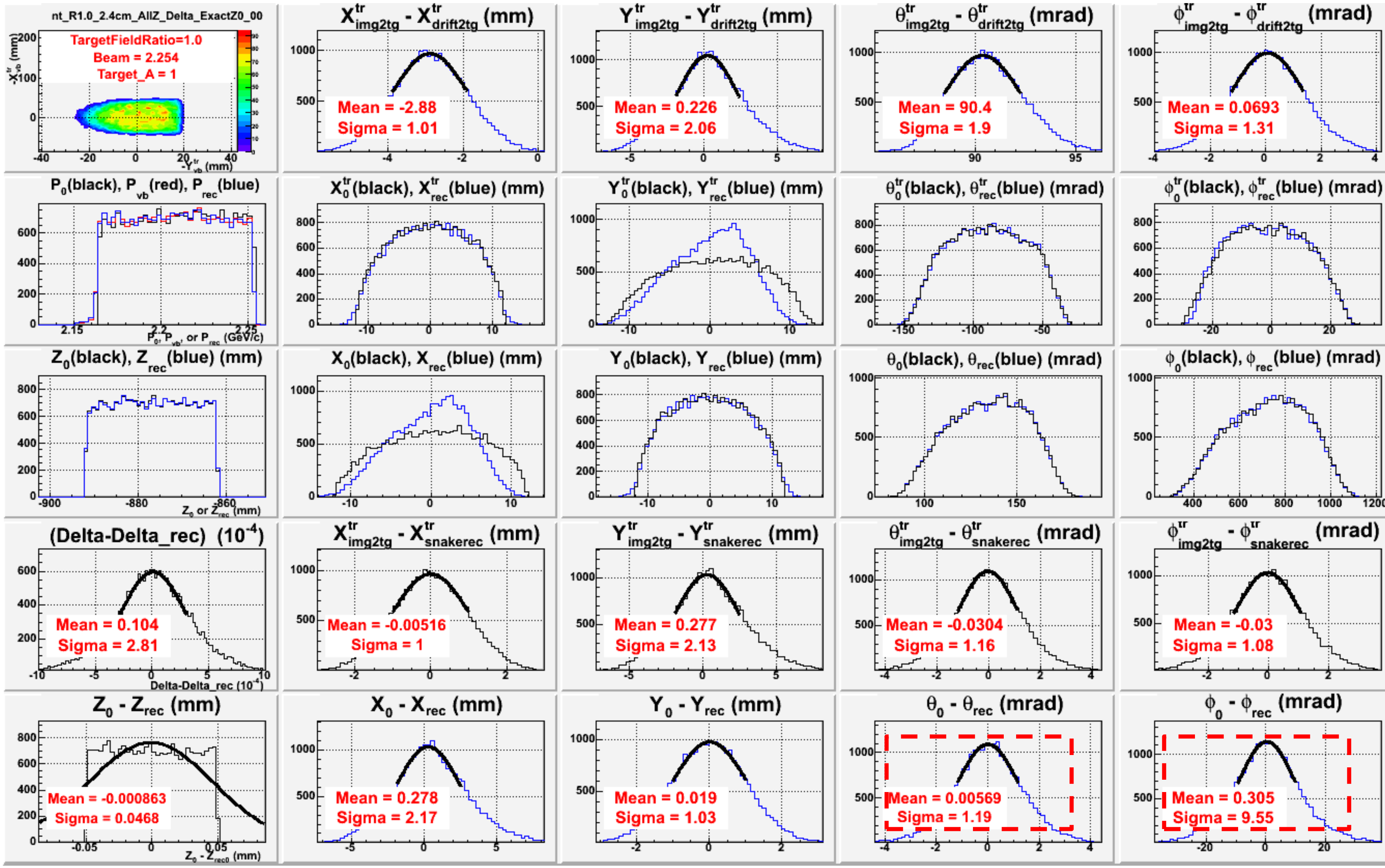
Curtsey to Chao Gu

Resolution of HRSMC Using SNAKE Model
484816+shim, No Target Field



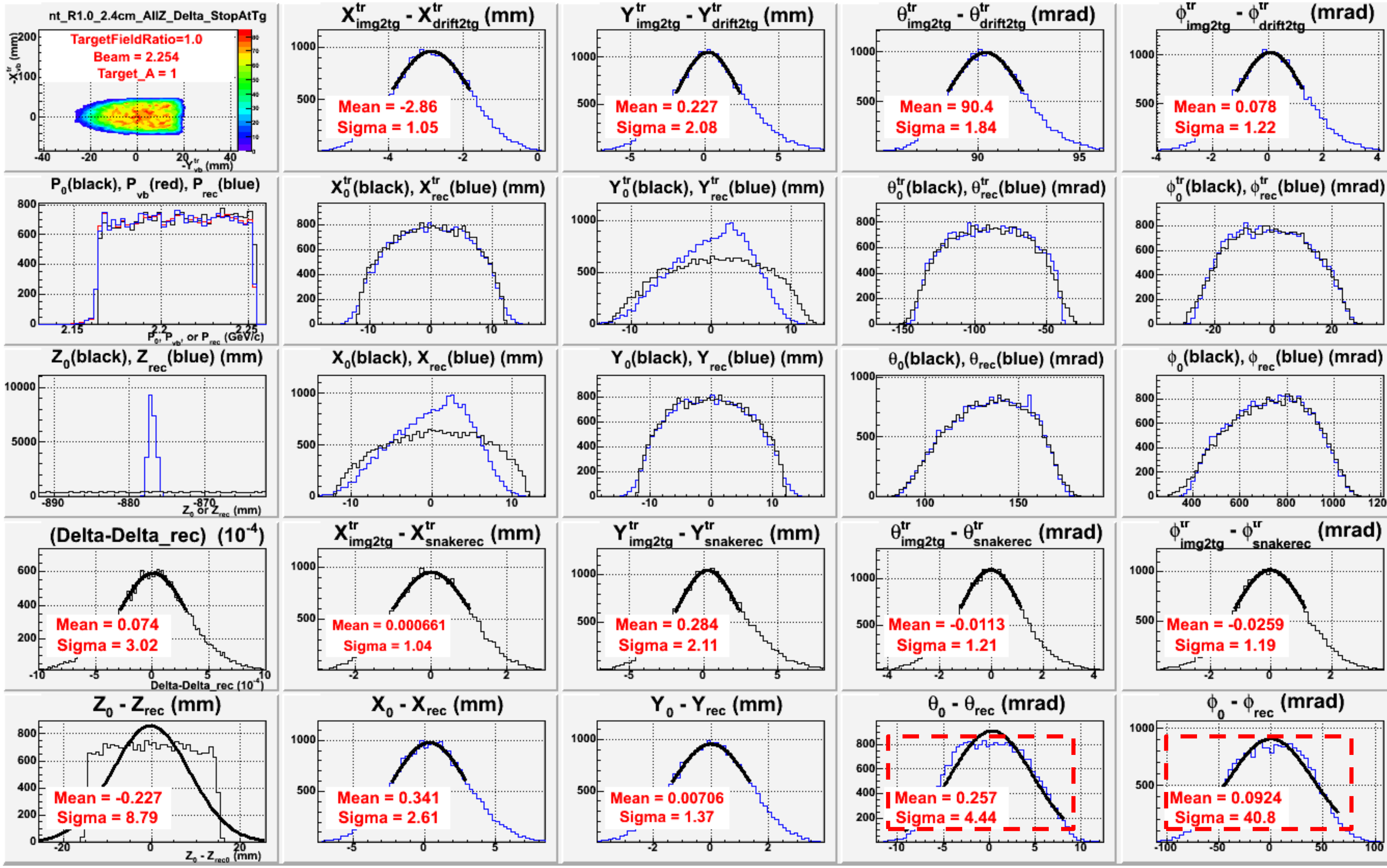
Raster=2.4cm

Resolution of HRSMC Using SNAKE Model 484816+shim, Stop at Exact Z0,5T



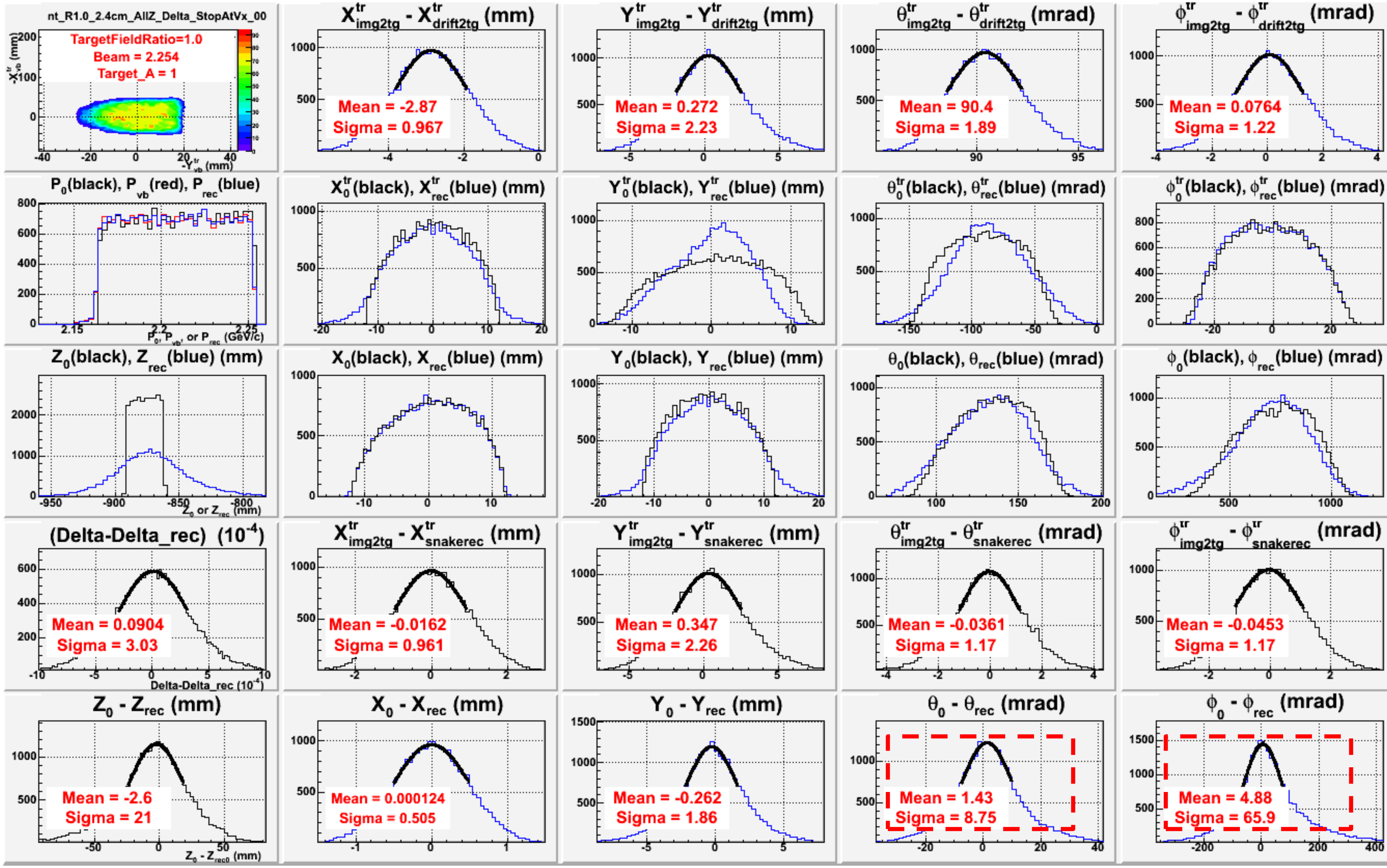
Raster=2.4cm, BPM resolution: 1 mm in vertical

Resolution of HRSMC Using SNAKE Model 484816+shim, Stop at Target Plane,5T



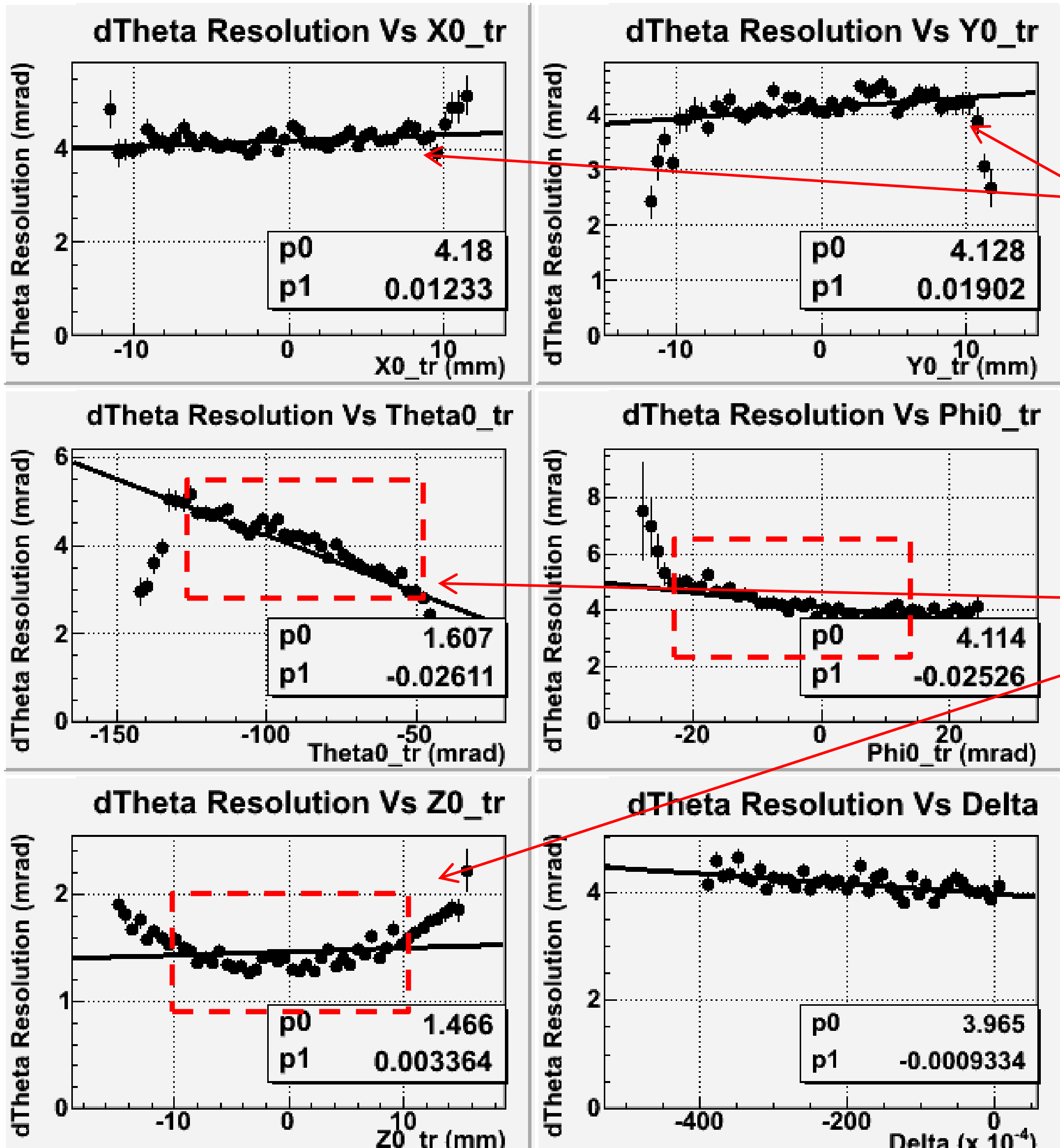
Raster=2.4cm, BPM resolution: 1 mm in vertical

Resolution of HRSMC Using SNAKE Model
484816+shim, Stop at Vertex Plane,5T



Raster=2.4cm, BPM resolution: 0.5mm in horizontal and 1 mm in vertical

Dependence of Theta Resolution, Using SNAKE Model 484816+shim, 5T

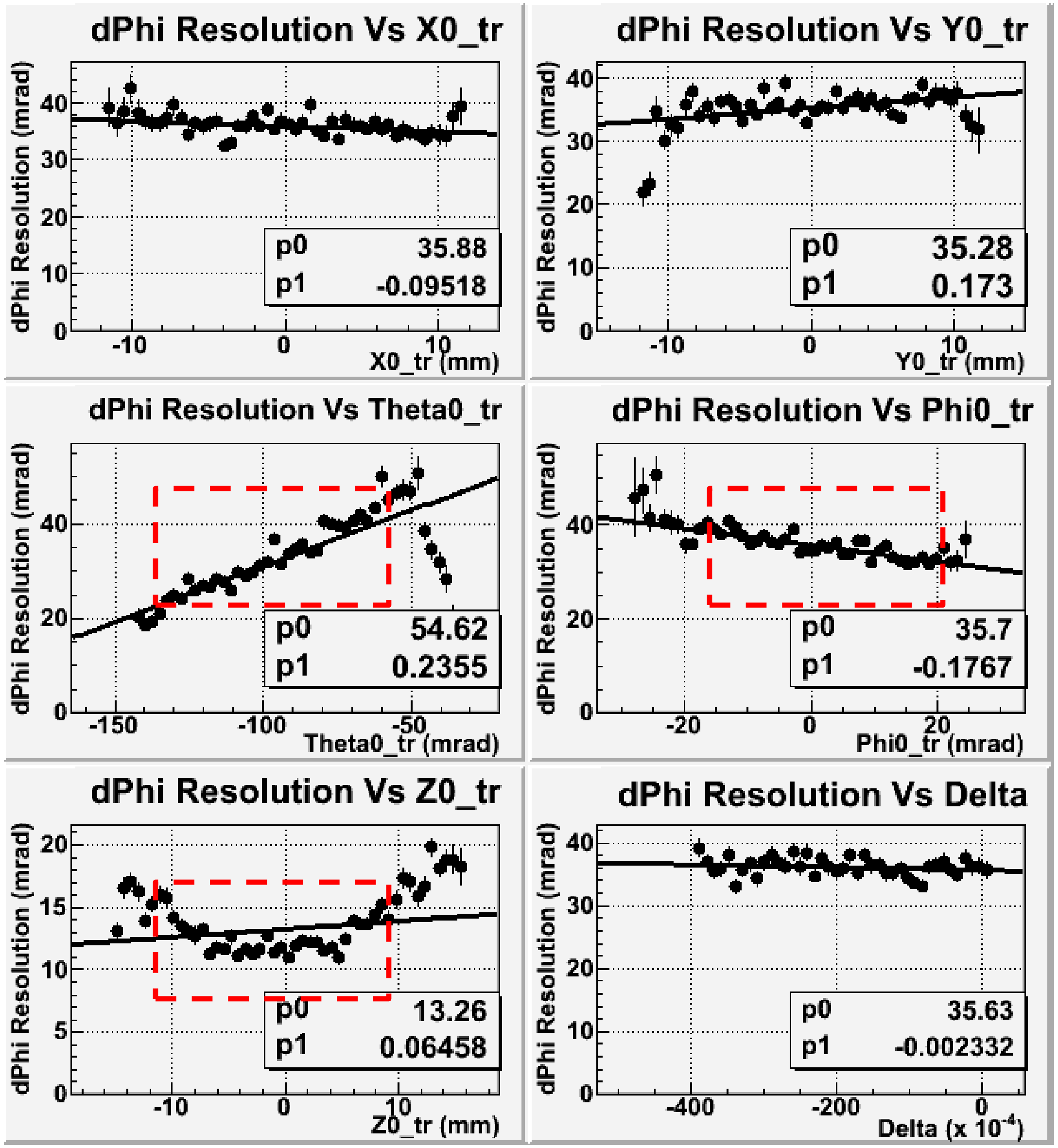


Theta reconstruction turns bad if raster goes 1 cm away from the beam line. This could be improved in simulation by changing to a large raster Snake model. Need to find a solution for real data.

dTheta has very strong out-of-plane-angle, in-plane-angle and vertex Z0 denpendence.

The overall dTheta resolution looks bad. That is mainly because we do not know the vertex z well enough.

Dependence of Phi Resolution, Using SNAKE Model 484816+shim, 5T



Phi reconstruction turns bad if raster goes 1 cm away from the beam line. This could be improved in simulation by changing to a large raster Snake model. Need to find a solution for real data.

dPhi has very strong out-of-plane-angle, in-plane-angle and vertex Z0 denpendence.

The overall dPhi resolution looks bad. That is mainly because we do not know the vertex z well enough.

Conclusion

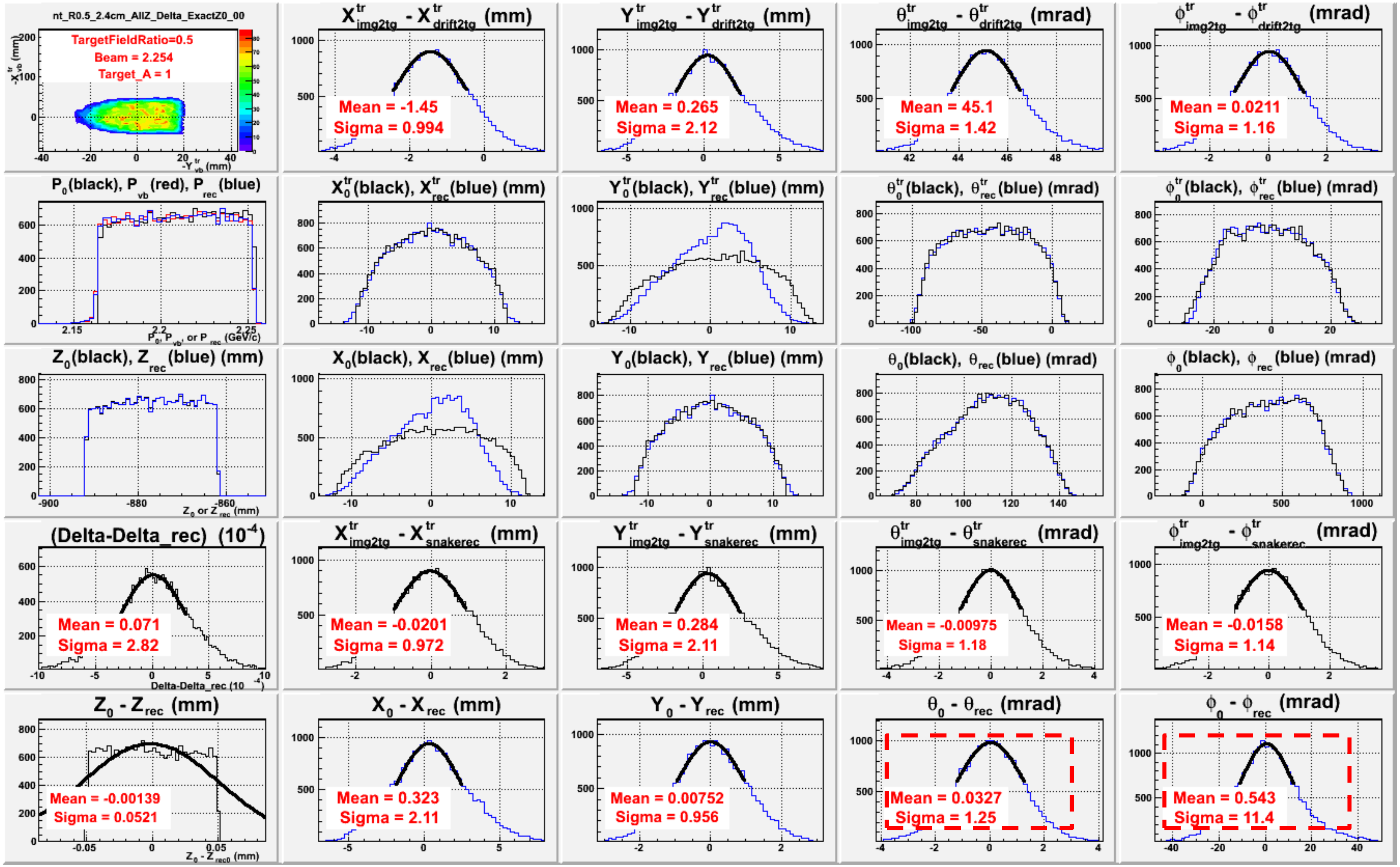
- To reach 5% uncertainty in absolution cross section, we have to limit the scatering angle’ s uncertaity to 1% (or 1.4 mrad at 5.0T target field and 1.2 mrad at 2.5T target field field). That said, at 5.0T target field, the uncertainty of theta_tr and phi_tr are required to be less than 2 mrad.
- Need large raster size Snake models to improve Ytg_tr resolution. Snake models for special septum (403216 and 400016) will be created and test in future.
- dTheta and dPhi have very strong out-of-plane-angle, in-plane-angle and vertex Z0 denpendence.
- The overall dPhi resolutions look bad. The reconstructed to exact Z0 simulated data proves that it is mainly because the large uncertainty in vertex z. To improve this, we need high resolution on Ytg_tr.
- The stratege of the reconstruction with target field optics, with-field-drift-sieve-to-target + standard-HRS, works. It has very high deminding for the resolution for the standard-HRS package.

Acknowledgment

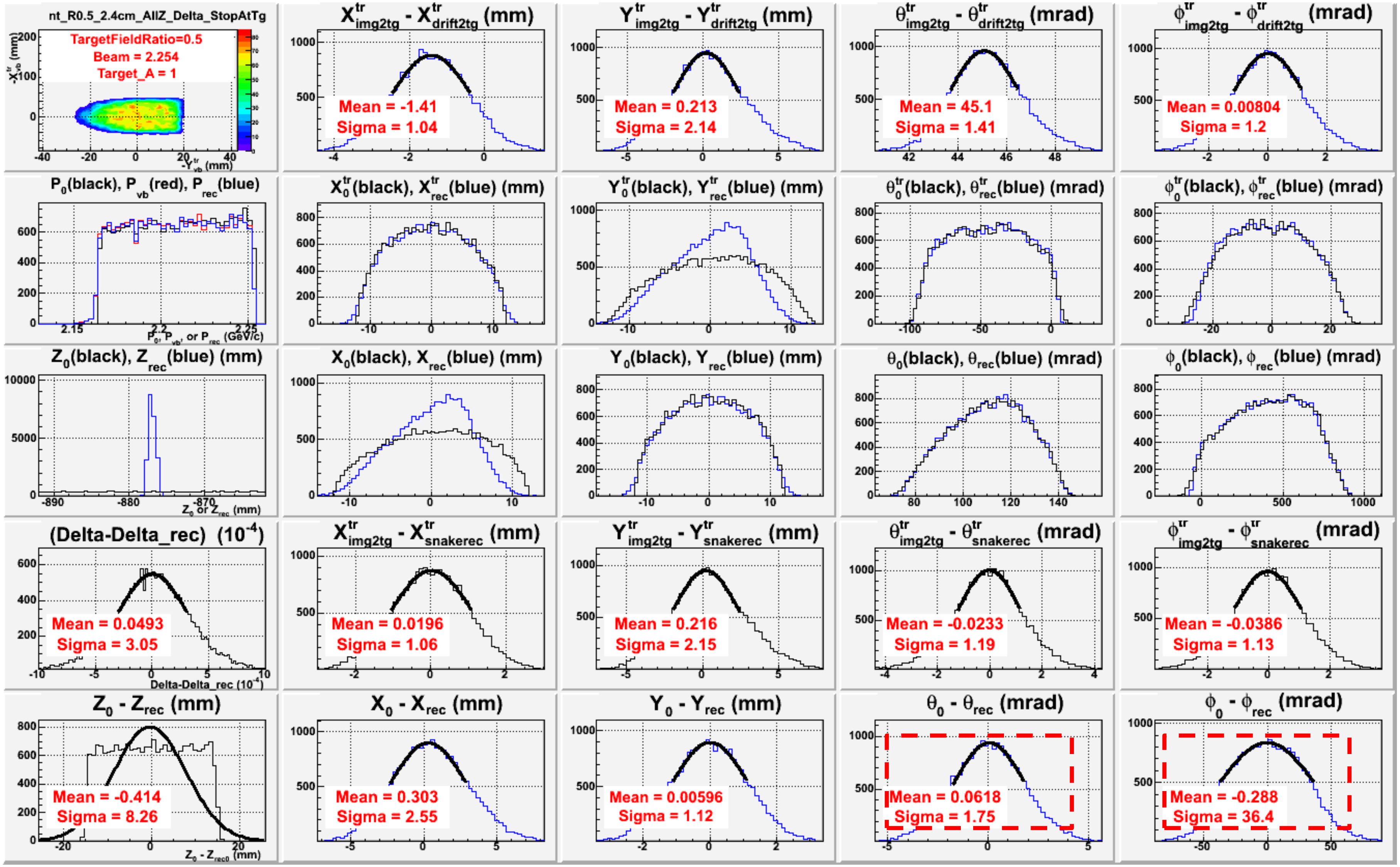
- Thank John LeRose for providing guidence and SNAKE models
- Thank Min Huang for providong SNAKE models and her hard work in optics optimization for real data
- Thank Chao Gu for helping in both simulation and optics optimization
- Thanks to Vince, Jin, Nilanga, Xin for their patient discussion and useful suggestions
- Thanks to all G2P collabortors

Back up

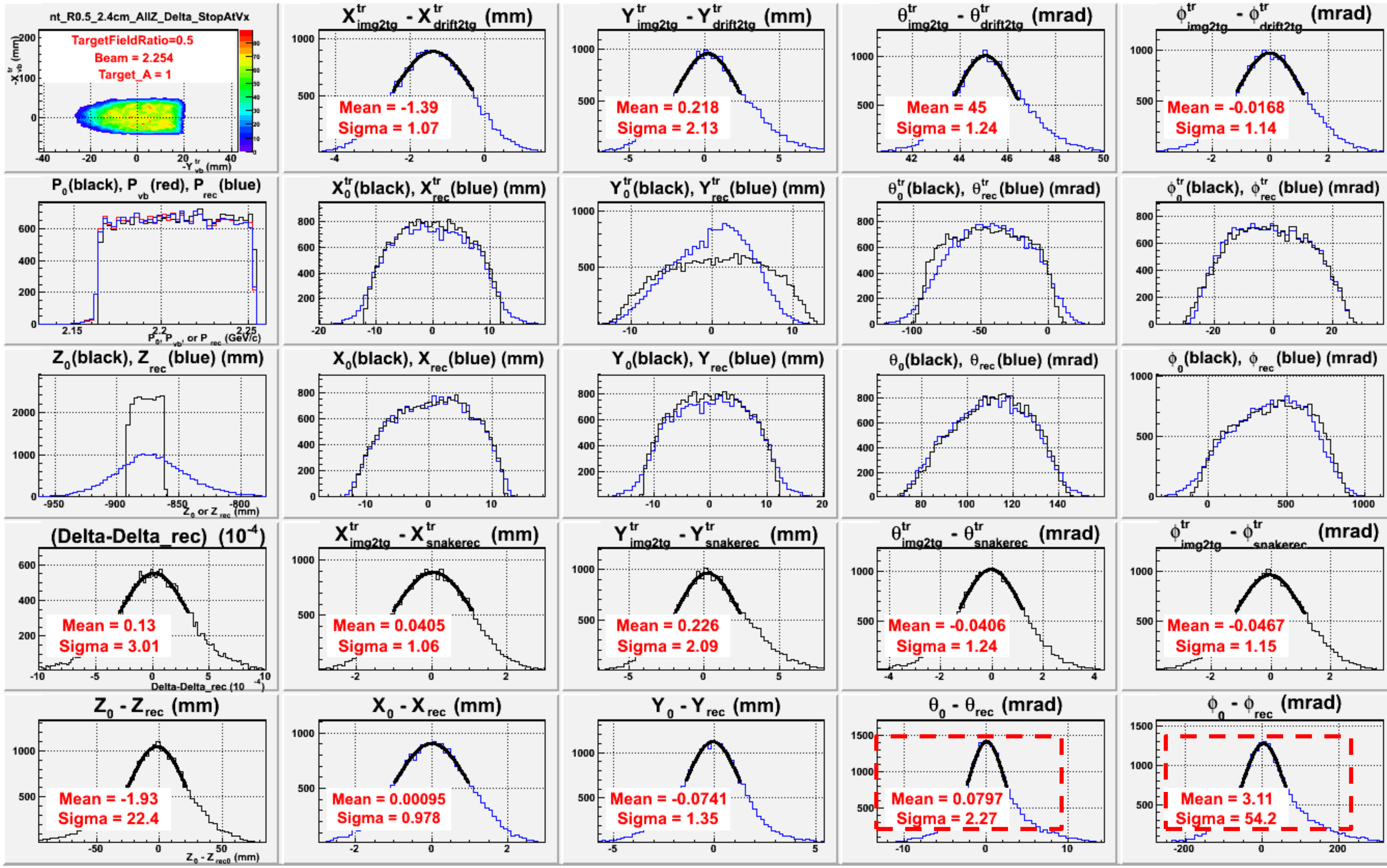
Resolution of HRSMC Using SNAKE Model 484816+shim, Stop at Exact Z0, 2.5T



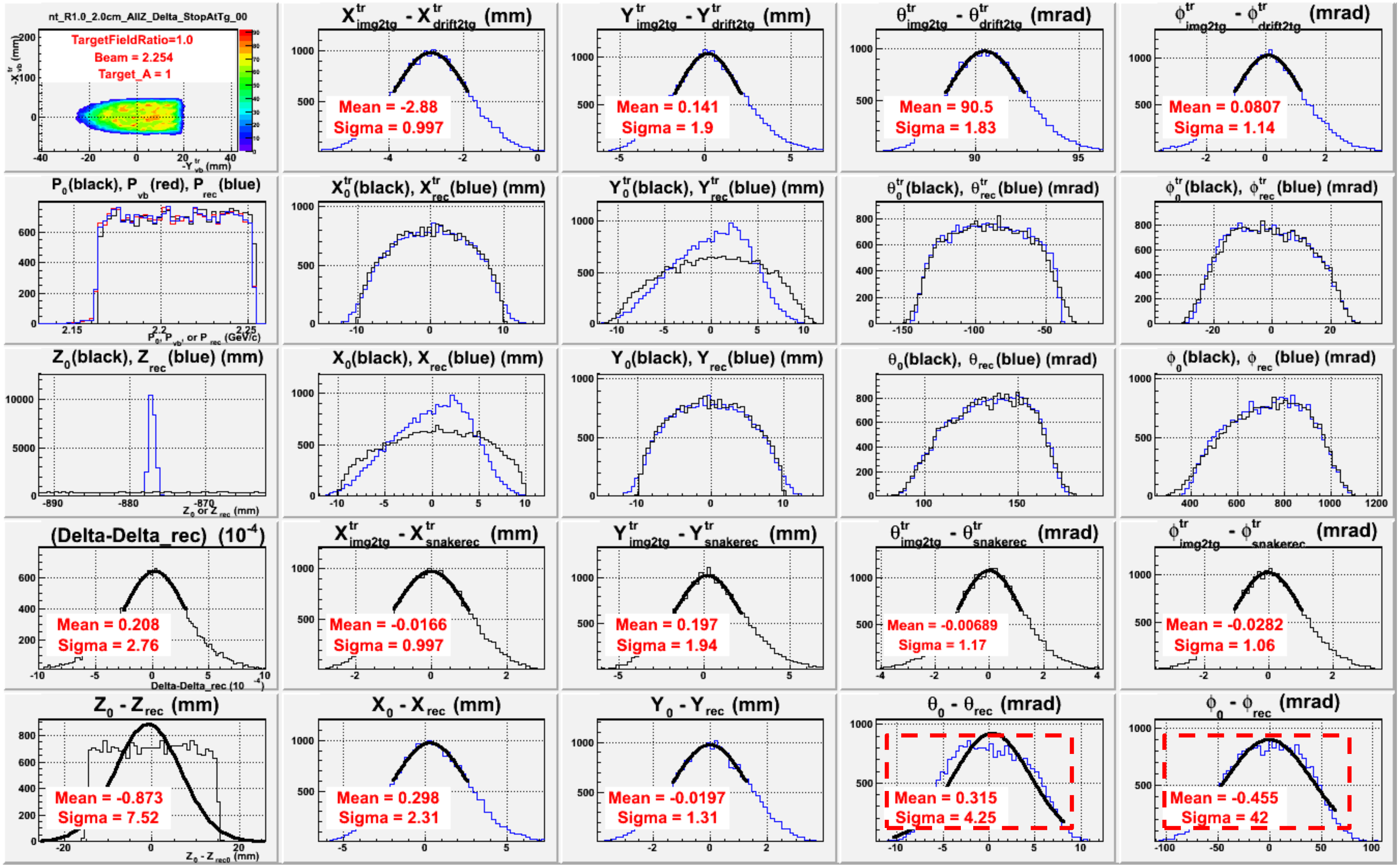
Resolution of HRSMC Using SNAKE Model 484816+shim, Stop at Target Plane, 2.5T



Resolution of HRSMC Using SNAKE Model 484816+shim, Stop at Vertex Plane, 2.5T

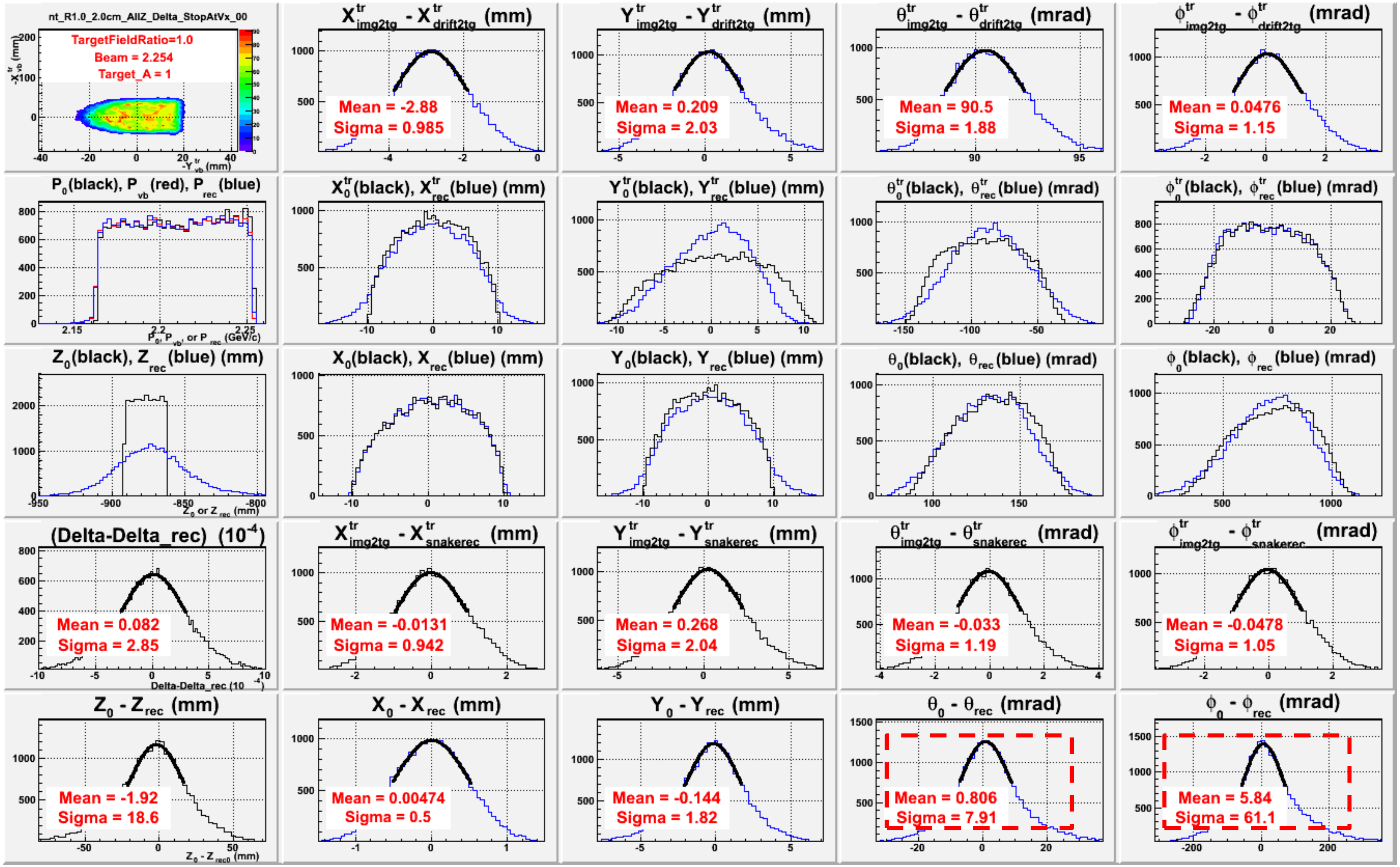


Resolution of HRSMC Using SNAKE Model
484816+shim, Stop at Target Plane, 5T



Raster=2cm

Resolution of HRSMC Using SNAKE Model
484816+shim, Stop at Vertex Plane,5T



Raster=2cm