Alternative ways to simulate a detector

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Alternative to what? Monte Carlo and the detector design problem

Let us assume we are charged with the design of a large, multi-component, collider-scale detector.

- Can I do the physics? Overlapping issues:
  1. Are my statistics sufficient?
  2. Is the data rate tractable?
  3. Is my resolution adequate?
  4. Is my acceptance/efficiency large enough?
- Only complete answer for (3) & (4): complete Full-Blown GEANT-Style Monte Carlo (FBMC)

What's involved in writing and using a FBMC?

Tasks:

- detailed geometry
- hit generation
- digitization
- reconstruction
- event format and content issues
- computationally intensive
  - manage multiple jobs
  - multiple files

Comments:

- a lot of work
- especially difficult for charged particle tracking
- desire: have this become part of permanent code base

Must all be done eventually: no substitute for full-blown Monte Carlo

What if you want try out new ideas?

- detector technology choice
- optimizations
  - material budget
  - detector placement
  - resolution assumptions
- FBMC not practical or not possible (no infrastructure yet)
- Would be better if infrastructure to do the studies is cheap/disposable
- Sacrifice fidelity for speed (implementation and execution)

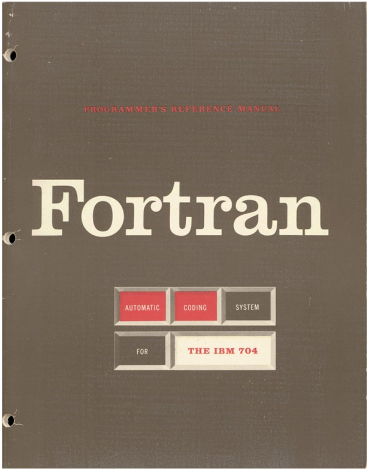
Look at two examples:

1. REZEST (resolution estimator)
2. MCFast (Monte Carlo, fast)

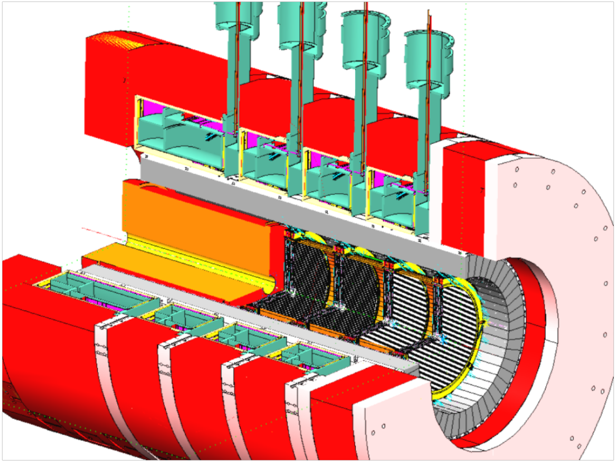
What is REZEST?

The back-of-the-envelope, coded up

- A set of FORTRAN routines
- Charged track rezolution estimation in transverse momentum and direction for the GlueX geometry
- Use results as input to smearing routines
- Parameters can be varied to quickly obtain estimates for new configurations
- No Monte Carlo is used; results are returned immediately



GlueX Detector Geometry



CDC : Central Drift Chamber, straw tubes, axial and stereo

FDC : Forward Drift Chamber, planar chambers, ⊥ to beamline

Magnet : Superconducting solenoid

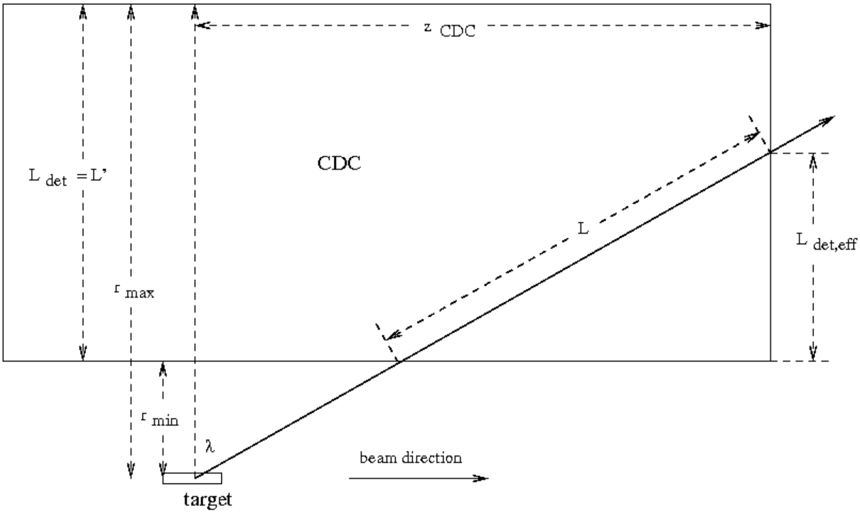
Approximations

The following assumptions are made:

- The magnetic field is uniform everywhere.
- Particles travel in straight lines, independent of momentum.
- All position measurements within a detector (FDC or CDC) are statistically independent of one another.
- All positions measurements within a detector are made at locations uniformly spaced along the trajectory.
- All positions measurements within a detector have the same resolution.

Relative variation of resolution when a particular parameters are varied should give a good feeling for the effect of parameter change.

Geometry of the CDC



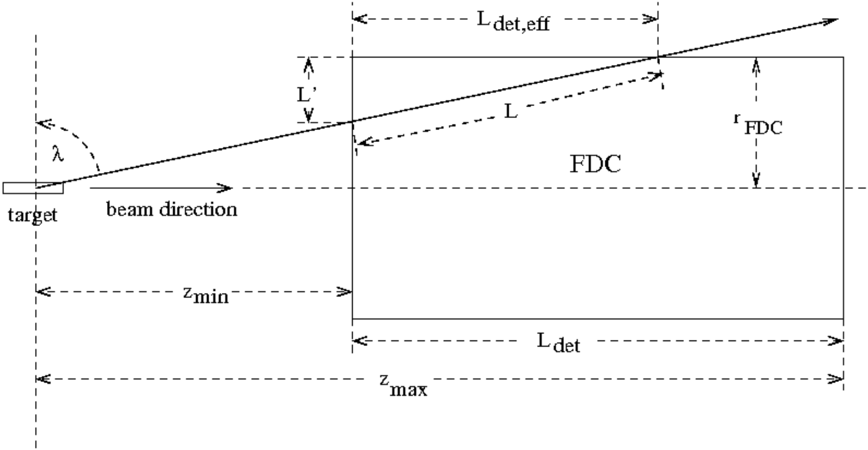
CDC Geometry, 2

Other parameters, not shown are:

- $r_{\mathrm{min,stereo}}$ minimum radius of the CDC stereo layers
- $r_{\mathrm{max,stereo}}$ maximum radius of the CDC stereo layers
- $n_{\mathrm{RL,CDC}}$ number of radiation lengths measured transverse to the tracking layers ($n_{\mathrm{rl}} = x/X_0$)
- $n_{\mathrm{RL,front}}$ number of radiation lengths in the material inside the CDC
- $n_{\mathrm{RL,endplate}}$ number of radiation lengths in the downstream CDC endplate
- $n_{\mathrm{m,CDC}}$ number of position measurements, total
- $n_{\mathrm{m,stereo}}$ number of position measurements in stereo layers

Parameter	**Value**
r_{min}	0.10960 m
r_{max}	0.56534 m
z_{CDC}	1.02 m
$r_{\mathrm{min,stereo}}$	0.16304 m
$r_{\mathrm{max,stereo}}$	0.39473 m
$n_{\mathrm{RL,CDC}}$	0.03437
$n_{\mathrm{RL,front}}$	0.01437
$n_{\mathrm{RL,endplate}}$	0.02810
$n_{\mathrm{m,CDC}}$	25
$n_{\mathrm{m,stereo}}$	8

Geometry of the FDC



Geometry of the FDC (2)

Other parameters are:

$n_{\mathrm{RL,FDC}}$ number of radiation lengths measured transverse to the tracking layers ($n_{\mathrm{rl}} = x/X_0$)

$n_{\mathrm{m,FDC}}$ number of one-dimensional position measurements for a track which passes through all layers of the FDC

Parameter	**Value**
z_{min}	1.25 m
z_{max}	2.92 m
r_{FDC}	0.56534 m
$n_{\mathrm{RL,FDC}}$	0.028258
$n_{\mathrm{m,FDC}}$	24

Transverse Momentum Resolution

The formulae used to estimate transverse are taken from the Particle Data Group's Review of Particle Physics. For a particle with charge q of momentum p in a uniform magnetic field B with a pitch angle λ

$$p_t \equiv p \cos \lambda = (0.3)qBR \tag{1}$$

where R is the radius of curvature in the projection of the trajectory onto the bend plane, p is in GeV/c, B is in Tesla, and R is in meters. The curvature $k = \frac{1}{R}$. The variance of k has two contributions,

$$(\delta k)^2 = (\delta k_{\mathrm{res}})^2 + (\delta k_{\mathrm{ms}})^2. \tag{2}$$

$$\delta k_{\mathrm{res}} = \frac{\epsilon}{L'^2} \sqrt{\frac{720}{N+4}} \tag{3}$$

where ϵ is the position resolution in meters, L' is the projected length of the track onto the bending plane in meters and N is the number of measurements.

$$\delta k_{\mathrm{ms}} = \frac{(0.016\ \mathrm{GeV}/c)z}{Lp\beta \cos^2 \lambda} \sqrt{n_{\mathrm{RL}}} \tag{4}$$

where n_{RL} is the number of radiation lengths in the detector and L is the total track length in the detector. For the momentum estimate, the amount of material in front of the detector is ignored.

Error on Slope and y-intercept of a Straight-Line Fit

To estimate the error due to position resolution on the direction of a fitted track, we use the error on the slope of a straight line fitted to the same number of measurements.

$$\chi^2 = \sum \left[\frac{1}{\sigma_i^2} (y_i - a - bx_i)^2 \right] \tag{5}$$

The variance of b is

$$\sigma_b^2 \approx \frac{n\sigma^2}{\Delta'} \quad \text{where} \quad \Delta' = n \sum x_i^2 - \left(\sum x_i \right)^2 \tag{6}$$

For n equally spaced measurements spanning the interval $[0, L]$,

$$x_i = \frac{L(i-1)}{n-1} \tag{7}$$

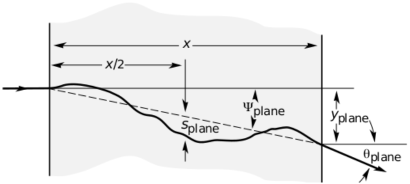
we get

$$\sigma_b^2 = \frac{12\sigma^2(n-1)}{L^2 n(n+1)} \tag{8}$$

We need to translate an error in slope to an error in angle. $\theta = \tan^{-1} b$ so

$$\delta\theta = \left| \frac{d\theta}{db} \right| \delta b = \frac{\delta b}{\sec^2 \theta}. \tag{9}$$

Angular Error Due to Multiple Coulomb Scattering



The central angular distribution is approximately Gaussian with a width given by

$$\theta_0 = \frac{(13.6\ \mathrm{MeV})}{\beta c p} z \sqrt{x/X_0}\left[1 + 0.038 \ln(x/X_0)\right]. \tag{10}$$

The angle Ψ_{plane} is used as an approximation to the contribution of multiple scattering to both the azimuthal and polar angles.

$$\Psi^{\mathrm{rms}}_{\mathrm{plane}} = \frac{1}{\sqrt{3}}\theta_0. \tag{11}$$

The material in front of a particular detector ("fronting material") is included as an addition to the number of radiation lengths in the detector itself.

Contribution to Azimuthal Angle Resolution from Curvature Resolution

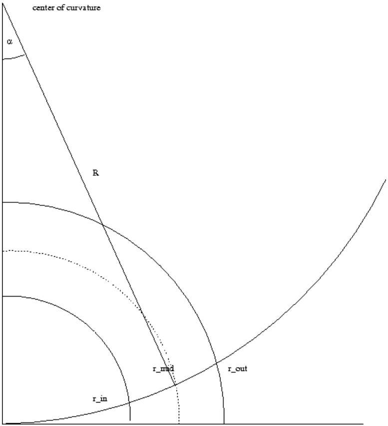
To infer the azimuthal angle ϕ at the vertex, track must be swum backward through angle α.

$$\sin\frac{\alpha}{2} = \frac{r_{\rm mid}}{2R} = \frac{r_{\rm mid}k}{2} \qquad (12)$$

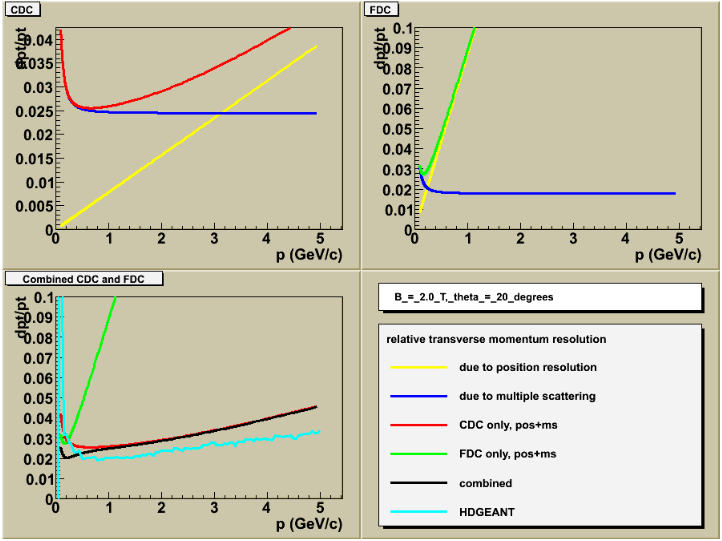
so

$$\delta\alpha = r_{\rm mid}\delta k \sec\frac{\alpha}{2} \qquad (13)$$

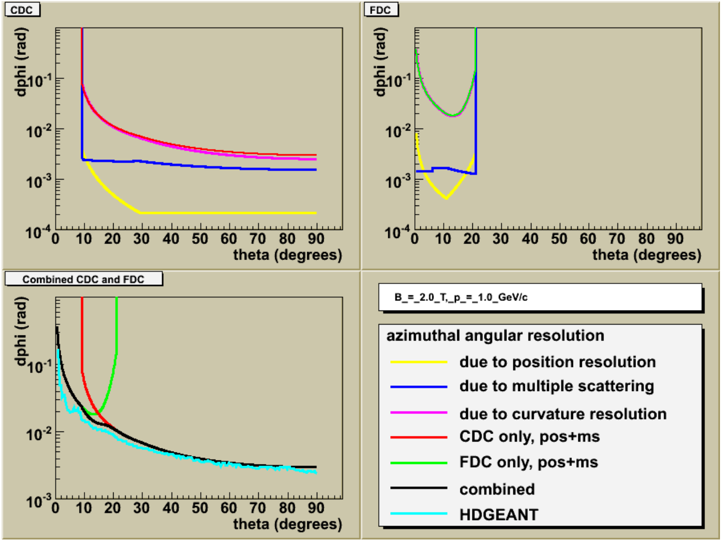
where $\alpha = 2\sin^{-1}(r_{\rm mid}/2R)$. As an approximation, we take $r_{\rm mid} = (r_{\rm in} + r_{\rm out})/2$.



Resolution in relative transverse momentum as a function of total momentum at 20° for $B = 2.0$ T.



Resolution in azimuthal angle as a function of polar angle at $p = 1.0$ GeV/c for $B = 2.0$ T.



Conclusions on REZEST

1. The plots show reasonable agreement with the HDGEANT (the GlueX FBMC) results. Agreement is generally at the 20% level, in some places better, in others as poor as a factor of 2.
2. Rather detailed features of resolution variation are exhibited faithfully.
3. One area where the simple model can break down is in the straight-line approximation for the trajectories for particles with very low transverse momentum.
4. Some acceptance information available by excluding poor resolution regions.
5. The most profitable use in predicting relative changes in resolution as detector parameters are changed.

What is MCFast?

physics features:

- charged particle tracking
  - position resolution
  - multiple scattering
  - energy loss
- calorimetry
  - em
  - hadronic
  - parametrized showers

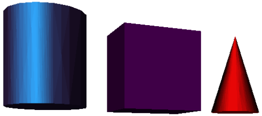
technical features:

- built-in interface to common event generators (pythia, qq)
- creates event stream: true Monte Carlo
- detector geometry specified in an ascii file
- hooks for user intervention and event examination

History of MCFast

- developed for B-TeV design studies at FNAL
- 1994, v1.4, wrapper around SLAC TRACKERR program
- 1995, v2.1, complete rewrite
- ca. 2001, v5.2, recommended version
- significant manpower investment...
- ...but "not supported" anymore
- 2001 GlueX/Hall-D effort, important for initial design studies

MCFast Geometry Specification



R-plane model: right circular cylinders or polygonal shells, centered on z-axis, with defined radius, z center and z length

Z-plane model: planes perpendicular to z axis, rectangular or circular outer boundary, may have beam hole

Conical model: cones centered on z axis

Special cases: planes perpendicular to x or y for magnet yokes, calorimeters (not for tracking volumes)

All volumes have material composition specified.

MCFast charged particle tracing and "fitting"

definitions

tracing: stepping particle through material and magnetic fields

"fitting": obtaining track parameters and covariance matrix

Tracing

Events recorded:

1. radial plane encountered
2. z plane encountered
3. conical surface encountered
4. production point
5. decay in flight
6. pair production
7. absorption
8. E & M shower starts
9. hadron shower starts
10. dummy point (for display purposes)

Treatment of magnetic fields:

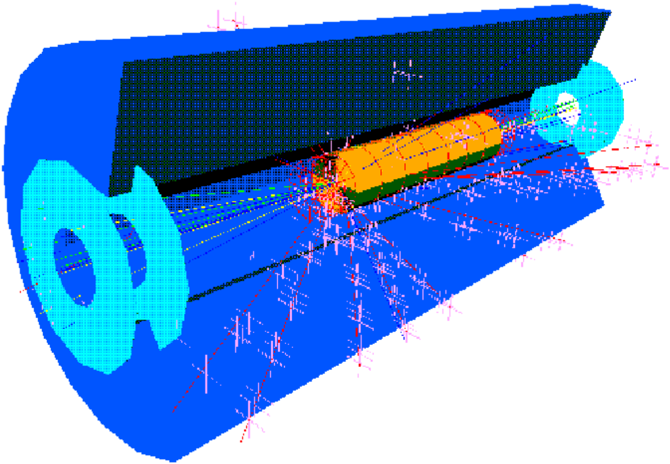
- define regions of constant magnetic field
- non-uniform fields must be approximated by discrete regions of constant field

Energy loss and multiple scattering can be enabled separately (or together).

"Fitting"

- no pattern recognition
- use hits from the tracing
- minimum hit requirement simulates detector acceptance
- two approaches:
  1. pseudo fitting
     - ★ with or without energy loss, MCS
     - ★ calculates covariance matrix (CM) among track parameters
     - ★ uses CM to smear track parameters
     - ★ no χ^2 computed
  2. Kalman filter
     - ★ full Kalman filter algorithm
     - ★ energy loss and/or multiple scattering accounted for (if turned on in tracing)
     - ★ CM calculated
     - ★ smeared track can be generated
     - ★ χ^2 generated

MCFast Visualization



MCFast model of D0 tracking upgrade

Why is MCFast different than FBMC?

1. simplified geometry specification
2. simplified magnetic field map
3. no pattern recognition
4. no event serialization
5. pseudo fit much faster than a full fit

Conclusions on MCFast

1. Within the limits of the simple geometry specification, it gives a highly realistic rendering of detector response.
2. It represents a not insignificant implementation effort.
3. Lack of current support is a concern.

General conclusions

1. In the early stages of the design cycle, a quick parameter-based estimation of detector performance is important.
2. Two examples have been discussed: REZEST and MCFast.
3. Usefulness of tools like this will likely extend beyond design phase. (What if's always seem to come up.)
4. It is worthwhile spending some time developing these types of facilities.

Acknowledgements: Paul Eugenio (Florida State), Lynn Garren and Patricia McBride (Fermilab)

References:

1. REZEST: http://argus.phys.uregina.ca/cgi-bin/public/DocDB/ShowDocument?docid=1015
2. MCFast: http://cepa.fnal.gov/psm/simulation/mcfast/