E1039 offline software and Tracking: Status and Plan

Abinash Pun

NMSU

SpinQuest collaboration Meeting

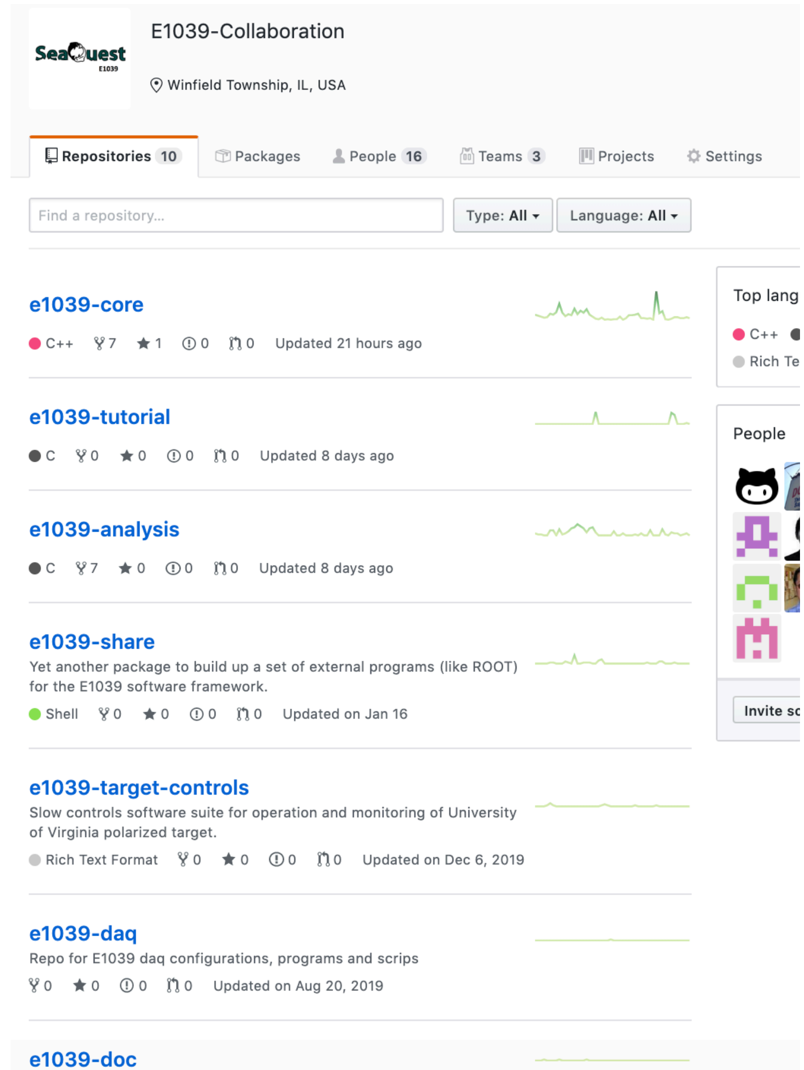
March 6, 2020

Fun4all

- Data analyzing framework developed by ***C. Pinkenburg*** for PHENIX experiment (2003)
- Well tested and used in PHENIX experiment. Results used in hundreds of publications.
- Extended for sPHENIX experiment with GEANT4 integration
- Exported and implemented to SpinQuest experiment by ***Haiwang Yu***
- ROOT based I/O
- Modularized for easier collaborative development
- Comes with a GEANT4 based simulation sub-framework
- *Future EIC experiment* (BNL)

E1039 Offline Software Status:

- **Stable state**
- All the codes available via GitHub; can clone them from E1039 GitHub page :https://github.com/E1039-Collaboration
- **e1039-core**: Repository containing *core* packages/frame work of the E1039 software.
- **e1039-analysis**: Contains analysis packages using framework from e1039-core
- Register a GitHub account send me (*abipun@nmsu.edu*) your github account



Resources:

- **Wiki area**:
  - Main resource area: https://github.com/E1039-Collaboration/e1039-wiki/wiki
- **Fun4All tutorial**:
  - Most recent: DocDB-7370 (presentation), DocDB-7373 (zoom video)
    - 1st day checklists, Navigating Fun4All nodes, Building your own analysis module
  - Others:
    - https://github.com/E1039-Collaboration/e1039-wiki/blob/master/fun4all-tutorial.pdf
    - DocDB 4525, DocDB 4102
- **Fun4All simulation:**
  - Most recent: DocDB-6974 (simulation flow) by Zulkaida
  - DocDB-5509 (presentation and zoom video) by Haiwang
- **Doxygen:** Navigating the codes
  - https://e1039-collaboration.github.io/e1039-doc/index.html
- **GitHub:**
  - https://github.com/E1039-Collaboration/e1039-wiki/blob/master/github-tutorial.pdf

E1039 Offline Software: Plans

(Collab Meeting October 2019)

- **E1039 Vertex Generator**
- **Import E906 Physics Generator**
- **Tracking (kTracker)**
  - Minimum requirement:
    - Optimize cuts for the new target position
    - Flexible conditions for the tracker and analyzer
  - Long term goal: Speed
- **Target Geometry set up**:
- **Insensitive Subsystem**: SpinQuest version
- **Digitizer**: efficiencies and resolution
- **Minimum Bias generator**: faster version with filters (eg. Event filtering)

Changes since last Collaboration Meeting

(October 2019)

- **E906LegacyGen**:
  - Committed under "***e1039-core/generators***" (Abinash, DocDB-7187)
  - Realistic vertex Generator
  - Legacy particle generators
    - Drell-Yan, J/Psi, Psi'
    - Pythia
- **AnaSimDst**:
  - Committed under "***e1039-analysis***" (Kenichi, DocDB-7056)
  - Analysis flow on simulated data
  - Expected to replace e "***e1039-core/module_example/TrkEval***"
  - Handles the "DST" file generated by "***e1039-analysis/SimChainDev***"

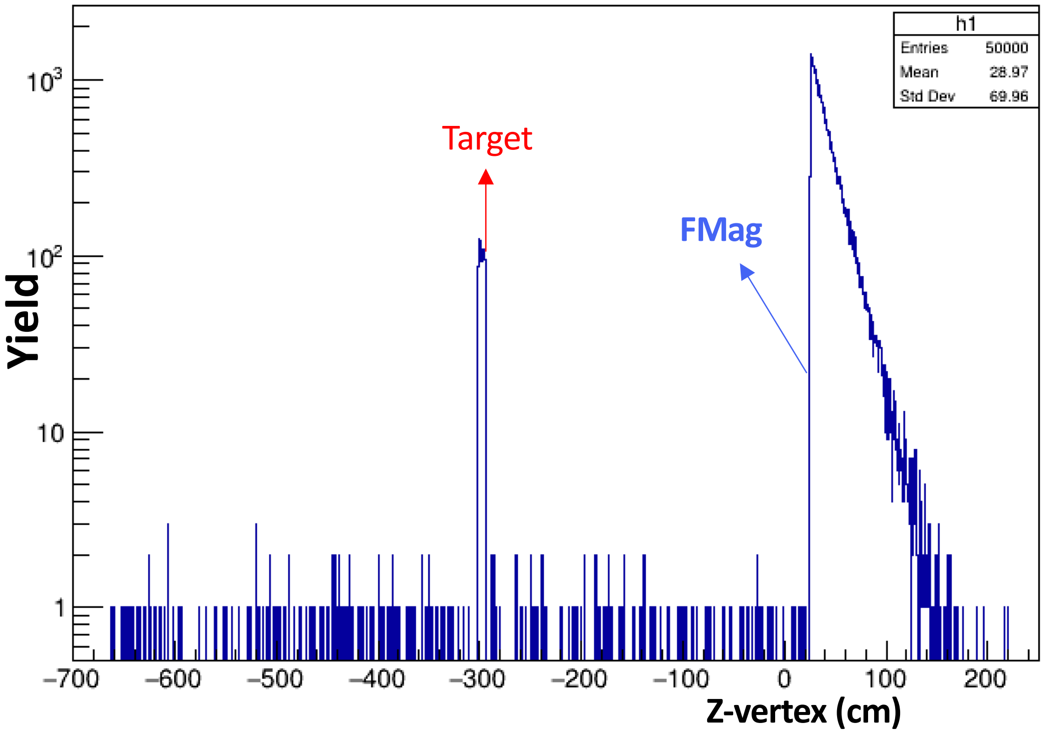
E906LegacyGen:

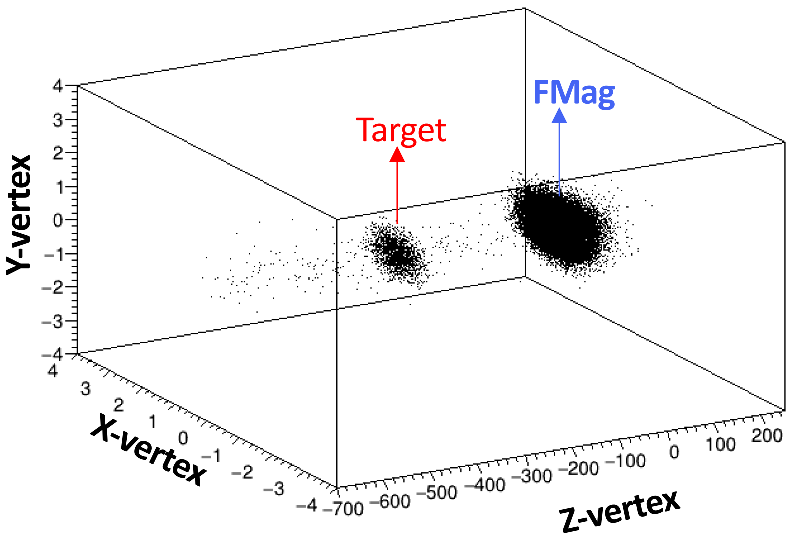
Many thanks to Kun

- New Package available under location: *e1039-core/generators*
  - README.md of
    https://github.com/E1039-Collaboration/e1039-core/tree/master/generators/E906LegacyGen
- Two main jobs:
  - Vertex Generator
    - Generates realistic vertex distribution using the properties of beam-line volumes: Details **DocDB #6734**
  - Primary Particle Generator (Physics generator):
    - Dimuon generators (Drell-Yan, J/Psi, Psi')
    - Pythia generator
    - Physics note: DocDB #7190

E906LegacyGen: Z-vertex Distribution

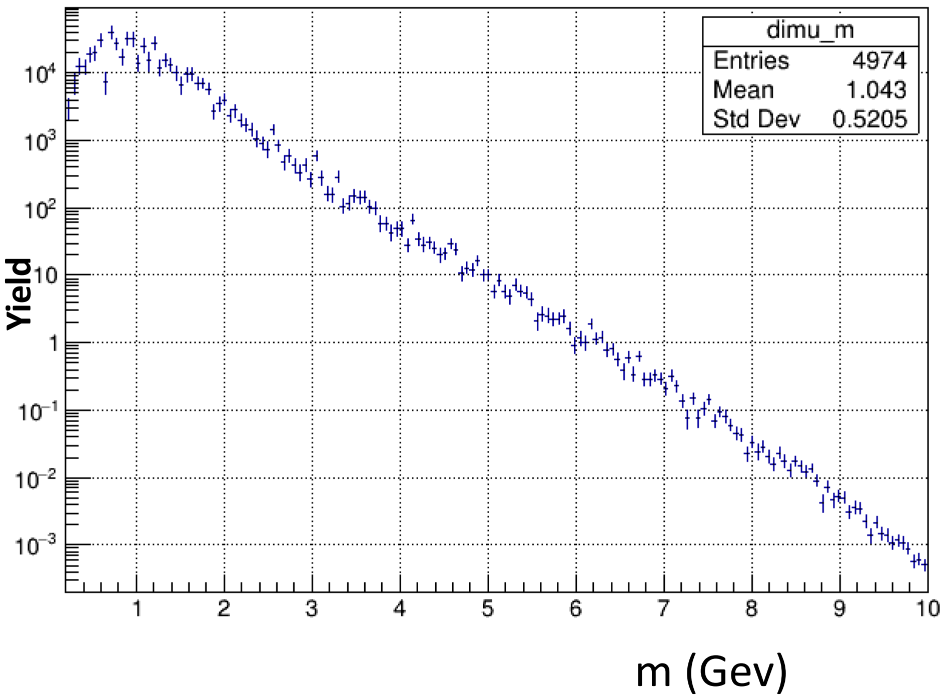
(Beam with x-width = 4.14 mm and y-width = 3.43 mm: Beam tail (1/r) not included)

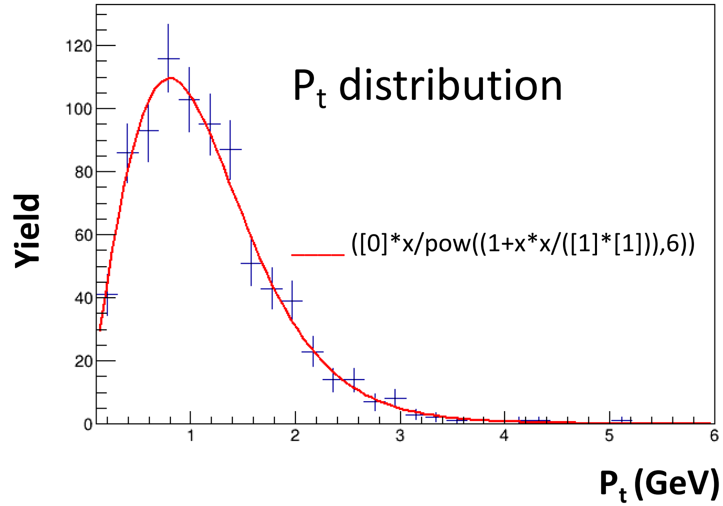




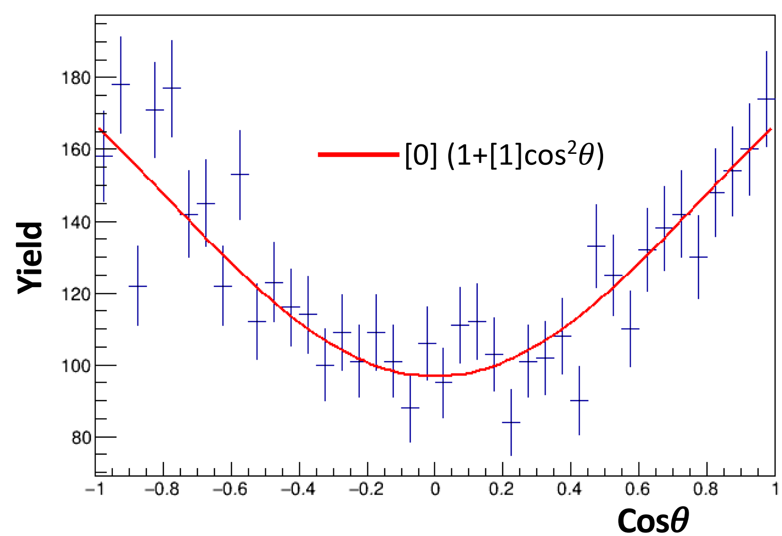
E906LegacyGen: Drell-Yan generator

Dimuon m (GeV) weighted with cross-section





Cosθ distribution



PART II:
E1039 Tracking

Tracking Meeting: Jan 17, 2020

- Talks in the Meeting
  - Tracking Overview and Status: Kun Lieu (DocDB 7235)
  - DSearch tracking Status: Haiwang Yu (DocDB 7232)
  - E1019 Tracking and Reconstruction in Fun4All framework: Zulkaida Akbar (DocDB 7238)
  - Fun4All analysis module and Tracking in E1039: Abinash Pun (DocDB 7241)
- Status of tracking, minimum requirements, areas of improvements in tracking and understanding of code implementation

E1039 Tracking:

High level workflow of kTracker (Kun)

Pre-tracking processing → Track finding → Track fitting → Single muon vertexing → Dimuon vertexing

Pre-tracking processing

Remove number of chamber hits as much as possible to reduce the workload of tracker

- Hit cluster removal
- Hodoscope masking
- Trigger road masking, etc.

Track finding

Find the best combinations of hits to form track candidates

- C++ implementation of E866 tracker with variations specific to our spectrometer
- **Bottleneck of the speed**
- A simple chi-squared fitter is used to reject the bad combinations fast

Track fitting

Kalman filter-based fitter to provide the final extraction of track parameters (use the simple chi-squared fit results as input)

Single muon vertexing

Simple track swimming algorithm to swim the track from detector up to the vertex, used as inputs for dimuon vertexing

Dimuon vertexing

KF-based algorithm to force both muons to go through the known target position to separate target from dump and extract dimuon properties

Source: DocDB 7235

Areas of Improvement for E1039 Tracker

(Kun)

- **Speed**: left-right ambiguity (if the track goes towards the left or right of a wire)
  - lot of chi-sq fit to find the possible combination (time consuming)
  - Main hurdle for online reconstruction
- **Rate/occupancy-dependent of reconstruction efficiency**:
  - Decrease and understand the dependency (along with better pre-tracking cuts)
- **Fake combinations (at station-1 edges):**
  - peaking background at around 5 GeV
  - These tracks comes from the edge of station-1, where tracker picked up wrong combination**: Kei**
- **KF fitting:**
  - For <5% of the time, KF fit fails to converge on a otherwise perfect track candidates
  - Did Genfit package introduced by Haiwang take care of this problem?
- **Multiple scattering in FMag:**
  - Even though the multiple scattering is symmetric around a track it has an asymmetric impact on the z vertex projected by where a track crosses the beamline
  - Refitting tracks to known target position: E906 on the dimuon level instead of track level
- **Energy loss in FMag:**
  - Energy loss of muons in iron is a random asymmetric effect with a long tail on the right side of the peak.
  - In Geant4e, average energy loss is used in the back propagation regardless of the muon momentum
  - How is it being handled now with GenFit ?

E1039 Tracking: Minimum Requirements

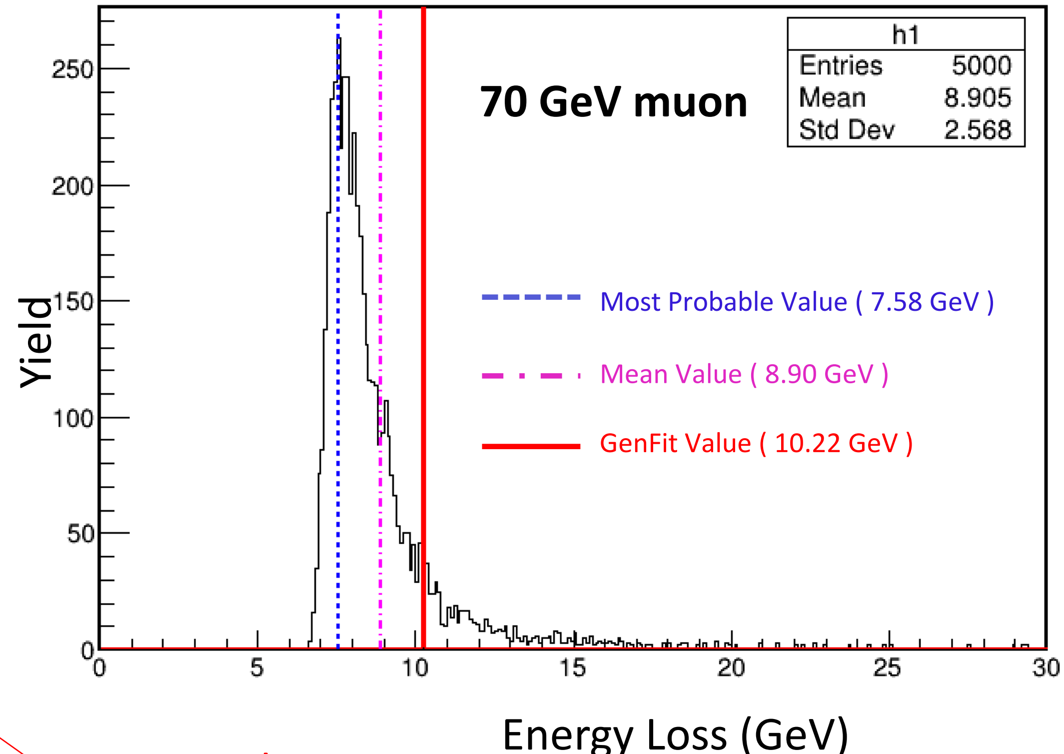
- **Re-tune internal cuts for new target position**
  - **Identify the cuts depending on Target position**
- **Verify E-loss model used in GenFit**
  - Know how it is being handled in GenFit
- **Re-tune multiple scattering corrections**

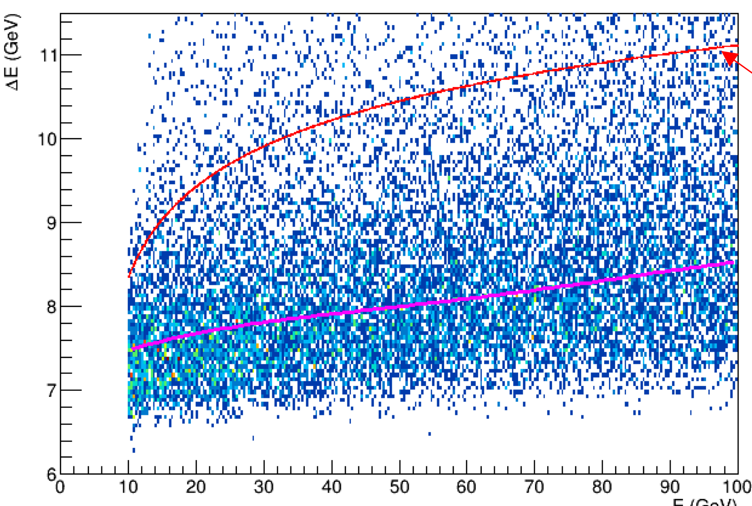
Energy Loss in FMAG:

How the energy loss in FMAG is being handled with GenFit?

Simulation study of Energy loss with 503 cm Iron with magnetic field turned off

Compared the GEANT energy loss, parametrized energy loss (from E906) and from GenFit extrapolation





GenFit Value curve

Parametrized Value Curve (most probable value)

GenFit calculates a higher energy loss than GEANT4 mean

Energy Loss in GenFit

- Energy loss processes in GenFit
  - setEnergyLossBetheBloch
  - setEnergyLossBrems
- Bremsstrahlung: Only applied for electron and positrons
- For muons: only source of energy loss in extrapolation is BetheBloch process
- Question:
  - Why the energy loss from GenFit extrapolation is greater than probable and mean energy loss value from Geant?

Bethe Bloch: Energy Loss due to electronic (ionization + excitation)

Stopping power at intermediate energies

$$-\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$ *Ref: PDG book*

A : atomic mass of absorber

$\frac{K}{A} = 4\pi N_A r_e^2 m_e c^2 / A = 0.307075 \text{ MeV g}^{-1}\text{cm}^2, \text{ for A} = 1\text{g mol}^{-1}$

z: atomic number of incident particle

Z: atomic number of absorber

T_{max} : Maximum energy transfer in a single collision

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

δ(βγ) : density effect correction to ionisation loss.

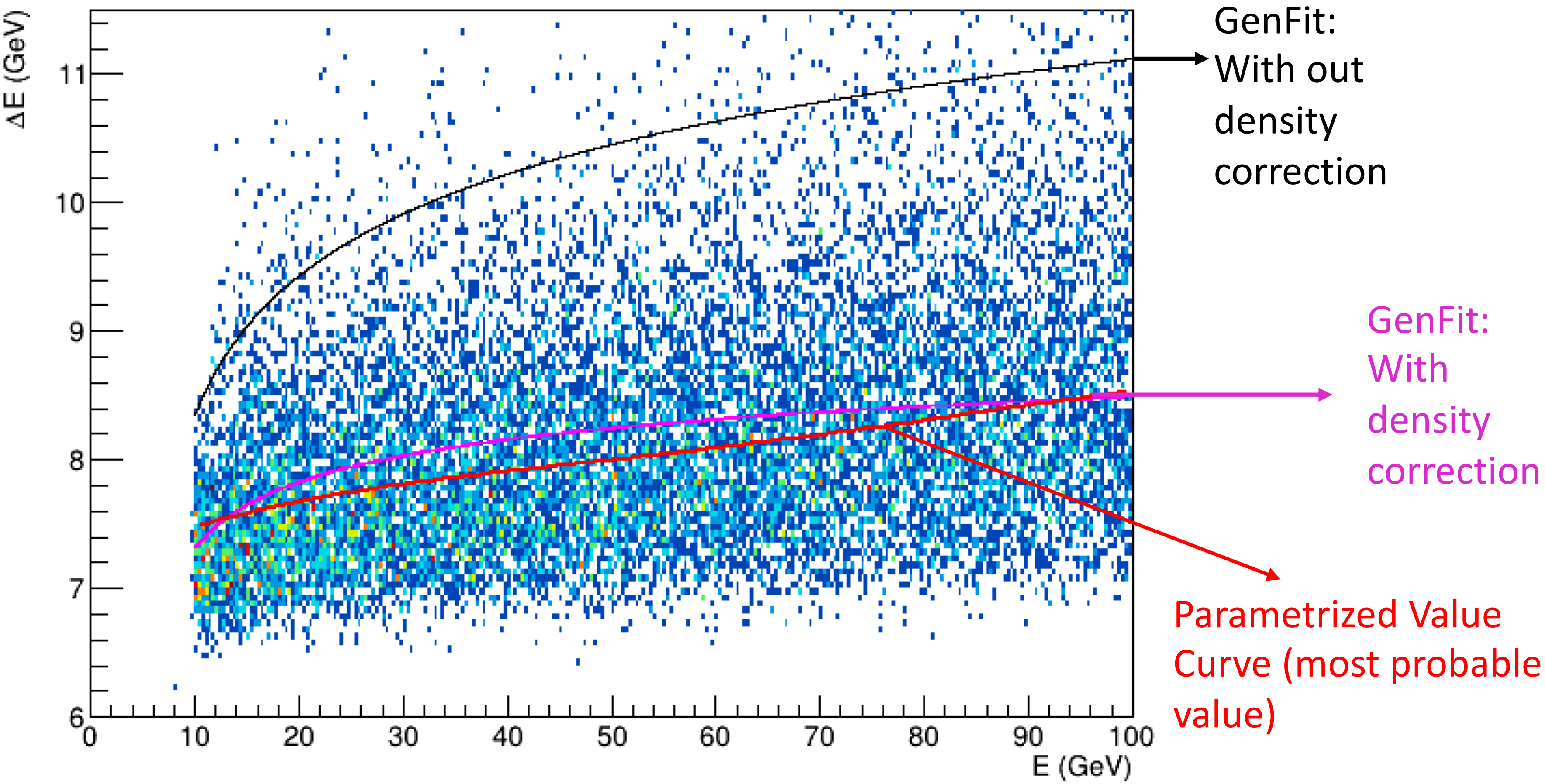
x = ρ s , surface density or mass thickness, with unit g/cm^2, where s is the length.

dE/dx has the units MeV cm^2/g

- Same definition of Bethe Bloch applied in GenFit:
  - But density effect correction not applied (accounts for the reduction in the ionization energy loss of charged particles due to the polarization of the medium)

Muon Energy Loss in Fe (503 cm)

- Got the parametrized value (for Fe) to calculate the density correction from PDG book and implemented in the GenFit source code (Also checked by hand)

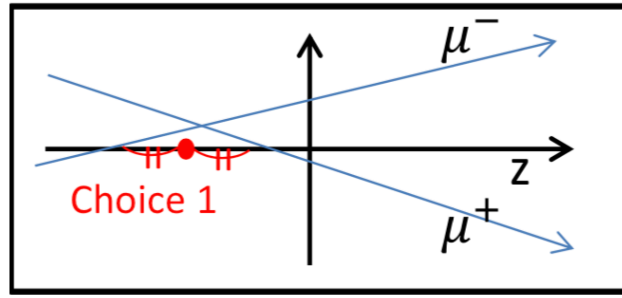


Multiple Scattering Correction in FMag

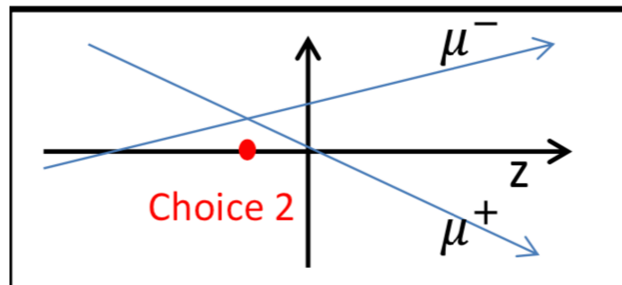
Dimuon Vertex Reconstruction

- Use extended Kalman Filter for both choices and choose one with better quality
- Multiple scattering has an asymmetric impact on the z vertex projected by where a track crosses the beamline
- This asymmetric effect depends on single muon momentum, or dimuon mass
- Common solution to this problem is to re-fit the tracks to known target position
- In E866, this **re-fitting** was done on the track level; at E906 it was done on the dimuon level

Choice 1:
Mean value of z_{μ^+} & z_{μ^-}



Choice 2:
Where μ^+ & μ^- tracks are closest

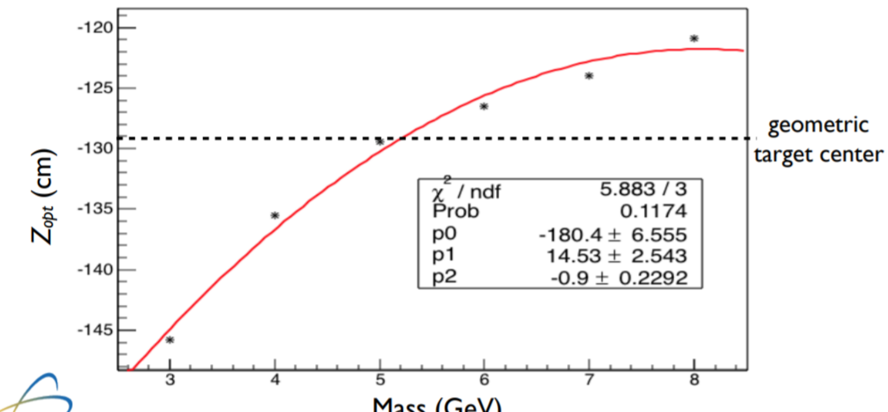


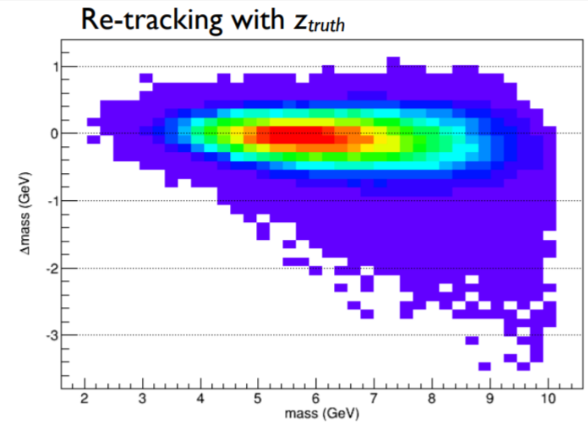
Source: DocDB 1185

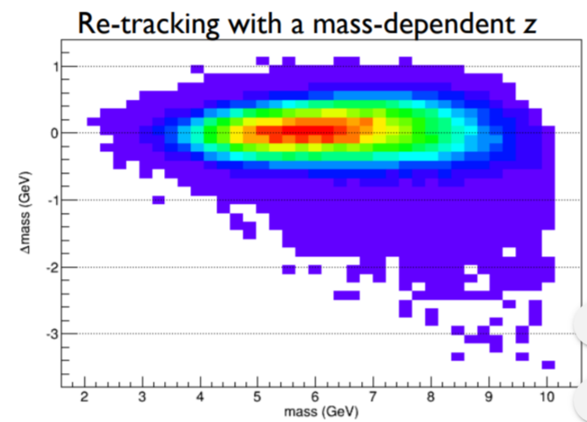
Multiple Scattering Correction in FMag

Slide Source: DocDB 1283

- When a dimuon pair looks like coming from target area, both muon tracks are forced to go though (*0, 0, z_{target}*)
- Naively we'd fix z_{target} at -129.54 cm (geometric center), but apparently the optimal z_{target} is mass-dependent
  - acceptance changes along the length of target, and is mass-dependent
  - multiple scattering effect on opening angle is not symmetric
- Based on MC, the optimal re-tracking z at low mass is shifted upstream, for high mass it's shifted downstream








```
z_vertex_opt = -305.465 + 104.731*m - 24.3589*m*m + 2.5564*m*m*m - 0.0978876*m*m*m*m;
```

- Correction (in momentum and vertex) based on MC for the dimuons believed to coming from target
- Need to be updated for new target position

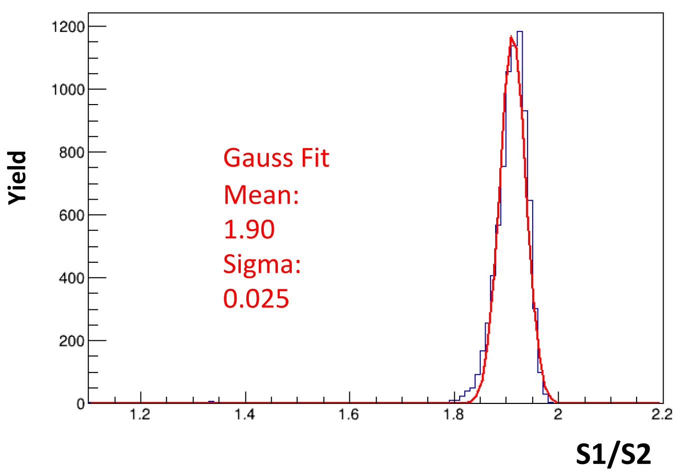
E1039-Tracking:

Optimizing internal cuts/parameters for new Target position

e1039-core/packages/global_consts/GlobalConsts.h

```
#define SAGITTA_TARGET_CENTER 1.85
#define SAGITTA_TARGET_WIN 0.25
#define SAGITTA_DUMP_CENTER 1.5
#define SAGITTA_DUMP_WIN 0.3
```

Sagitta Value of new Target Position:
1.90 with window of 0.45




```
//--------------- Geometry setup -----------------
#define nStations 7
#define nChamberPlanes 30
#define nHodoPlanes 16
#define nPropPlanes 8
#define nDarkPhotonPlanes 8

//#define FMAGSTR 1.054
//#define KMAGSTR 0.951

#define Z_KMAG_BEND 1064.26
#define Z_FMAG_BEND 251.4
#define Z_KFMAG_BEND 375.
//#define PT_KICK_FMAG 2.909*FMAGSTR
//#define PT_KICK_KMAG 0.4016*KMAGSTR
#define ELOSS_KFMAG 8.12
#define ELOSS_ABSORBER 1.81
#define Z_ST2 1347.36
#define Z_ABSORBER 2028.19
#define Z_REF 0.
#define Z_TARGET -129.54
#define Z_DUMP 42.
#define Z_ST1 600.
#define Z_ST3 1910.
#define RESOLUTION_DC 1.6

#define X_VTX       0.
#define Y_VTX       1.6
#define BEAM_SPOT_X 0.5
#define BEAM_SPOT_Y 0.5
```

E906 target position

Off-line Reconstruction Group

- Team: Abinash Pun, Stephen Pate, Forhad Hossain, Kun Liu, Kenichi Nakano
- Tasks:
  - Fun4ALL Framework: Understanding and Improving
  - Tracking and reconstruction performance and optimization
  - Simulation setup and testing for Collab use
- *HELP!! : More members are welcome to join the effort.*

E1039 Offline Software: Plans

✓ **E1039 Vertex Generator** (Abinash)

✓ **Import E906 Physics Generator** (Abinash)

- **Tracking (kTracker)**
  - Short term goals:
    - Optimize cuts for the new target position
    - Verify the energy loss in GenFit
    - Retune multiple scattering correction

    Minimum Requirements (Abinash)
  - Other areas of improvements (fake combination, rate dependency, KF fitting failure) (?)
  - Cosmic muon tracking (?)
  - Long term goal: Speed (?)
- **Target Geometry set up**: (Zulkaida)
- **Insensitive Subsystem**: (Abinash)
- **Digitizer**: efficiencies and resolution (?)
- **Minimum Bias generator**: faster version with filters (eg. Event filtering) (?)

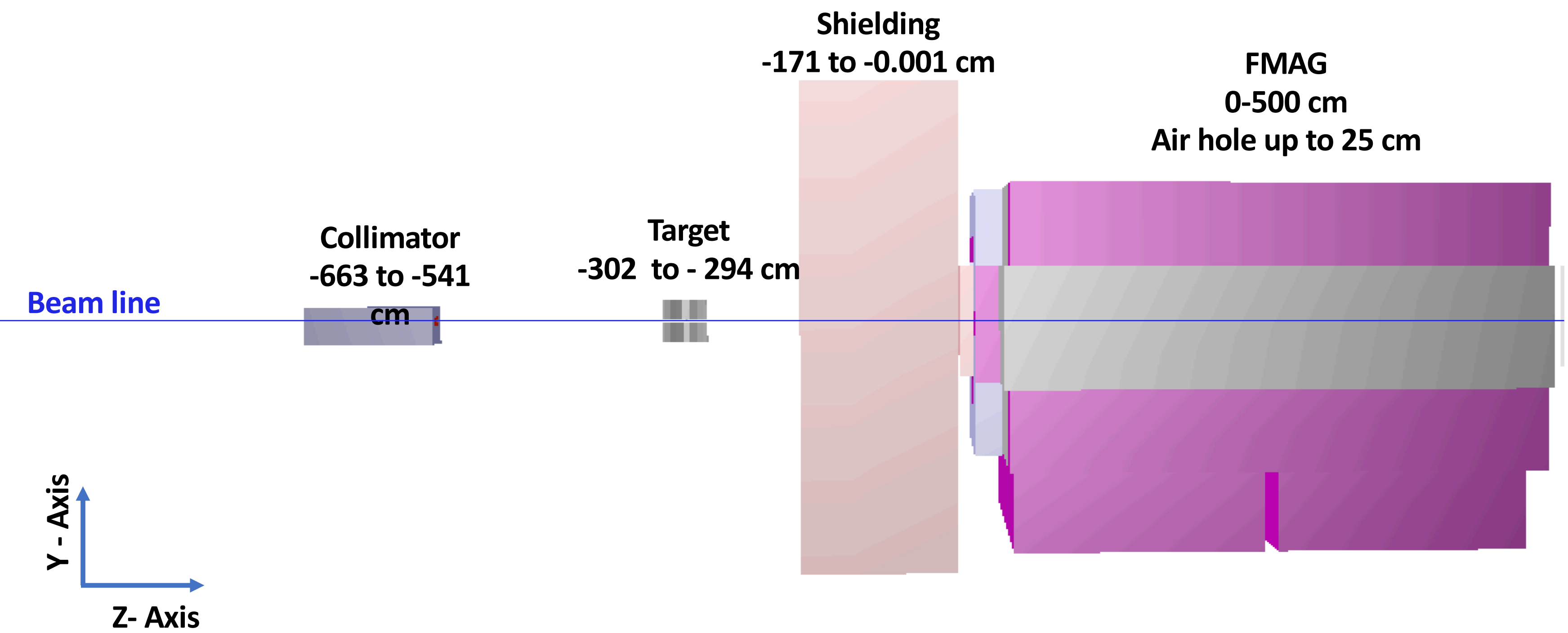
Summary and Status

- **E1039 offline software**:
  - Stable
  - Understand and update as need
- **E1039 Tracking**
  - Work in progress in finding out the internal cuts/parameters depending on new Target Geometry
  - Energy loss in FMag
    - Bethe Bloch implemented in GenFit not consistent with that in Geant4: Density correction not implemented in GenFit
    - Implementation of density correction in GenFit source code brings down the energy loss to be close to Geant4 mean value
    - Understanding the error matrix associated with the energy loss
  - Multiple scattering in FMag
    - Work in progress for vertex optimization for new geometry
  - Cosmic muon tracking
- Join the effort to achieve the collaboration goal

Thank You

Back Ups

Beam Volumes: (x <1.0, y < 1.0 and -700 < z < 500 cm)



E1039 Vertex Generator

- Goal:
  - Generate realistic vertex distribution for E1039 experiment and make it available for the physics generators

- Method: (based on the previous E906 generator developed by Kun)
  - Collect the volumes in the beamline
  - Fill the space between the volumes with air
  - Get their properties (size, density, Nuclear interaction length) and set the attenuation, probabilities
  - Generate vertex (Z) randomly (based on their properties)

Basics of Dimuon physics generator

- Set Dimuon properties
  - Pick invariant mass; m [0.2 to 10. GeV] and x_F [-1.0 to +1.0] randomly
  - Calculate Longitudinal momentum; $P_z(x_F, \sqrt{s}, m)$
  - Calculate the Square of Maximum Transverse momentum; (s, x_F, m)
    - Randomly selects phi to get calculate P_x and P_y based on P_T distribution (explained in later slide)
- Configure Phase-space generator
  - Set a **Tlorentzvector** with the dimuon properties
  - Set it decay in to two masses equivalent to those of mu+ and mu-
- Generate mu+ and mu- with 1+ $\cos^2\theta$ modulation

Reference for simulation:

G. Moerno et.al. Phys. Rev D43:2815-2836, 1991

TABLE VII. Distributions used for the simulation of dimuon events of mass m and momentum (p_t, ϕ, p_l) in the CM frame. The Collins-Soper[a] convention is used to specify the μ^+ angles (θ_{CS}, ϕ_{CS}) in the dimuon CM frame, and $\tau = m^2/s$, $x_F = (1-\tau)x'_F = 2p_l/\sqrt{s}$, $p_t^{\max} = (\sqrt{s}/2)[(1-\tau)^2 - x_F^2]^{1/2}$, and $\epsilon = (4\tau + x_F^2)^{1/2}$.

Variable	Range	Continuum	Upsilons
m (GeV)	$(6, 18.5)$	$e^{-.77m}$	$\delta(m - m_\Upsilon)$
x'_F	$(-1, 1)$	$(1 - x'_F)^4(1 + x'_F)^5$	$(1 + \tau - \epsilon)^2/\epsilon$
p_t (GeV)	$(0, p_t^{\max})$	$p_t/[1 + (p_t/3)^2]^6$	$p_t/[1 + (p_t/3.7)^2]^6$
ϕ	$(0, 2\pi)$	uniform	uniform
$\cos\theta_{CS}$	$(-1, 1)$	$1 + \cos^2\theta_{CS}$	uniform
ϕ_{CS}	$(0, \pi)$	uniform	uniform

[a] J. C. Collins and D. E. Soper, Phys. Rev. D **16**, 2219 (1977).

SQPrimaryGenerator: Outline

- ✓ Instantiate the **PHG4Particle**s
- ✓ Set their vertices from vertex generator
- ✓ Set the properties (momentum and energy) with the process described in previous slide (except for Pythia generator)
- ✓ Add the particles to the **PHG4InEvent** node
  - provide those particles for the Geant4 simulation
  - Store the particle information in **PHG4TruthInfoContainer**
- ✓ Calculate the cross section for desired physics process (DrellYan, J/Psi and Psip) **(Thanks kenichi for LHAPDF installation)**
  - ✓ Store the truth information of the dimuons in "**SQDimuonTruthInfoContainer**"

Bethe Bloch in Geant4

- Method: Restricted energy loss rates for relativistic ionizing particles (from PDG)

$$-\frac{dE}{dx}\bigg|_{T<T_{\mathrm{cut}}} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{\mathrm{cut}}}{I^2} - \frac{\beta^2}{2}\left(1+\frac{T_{\mathrm{cut}}}{T_{\mathrm{max}}}\right) - \frac{\delta}{2}\right]$$

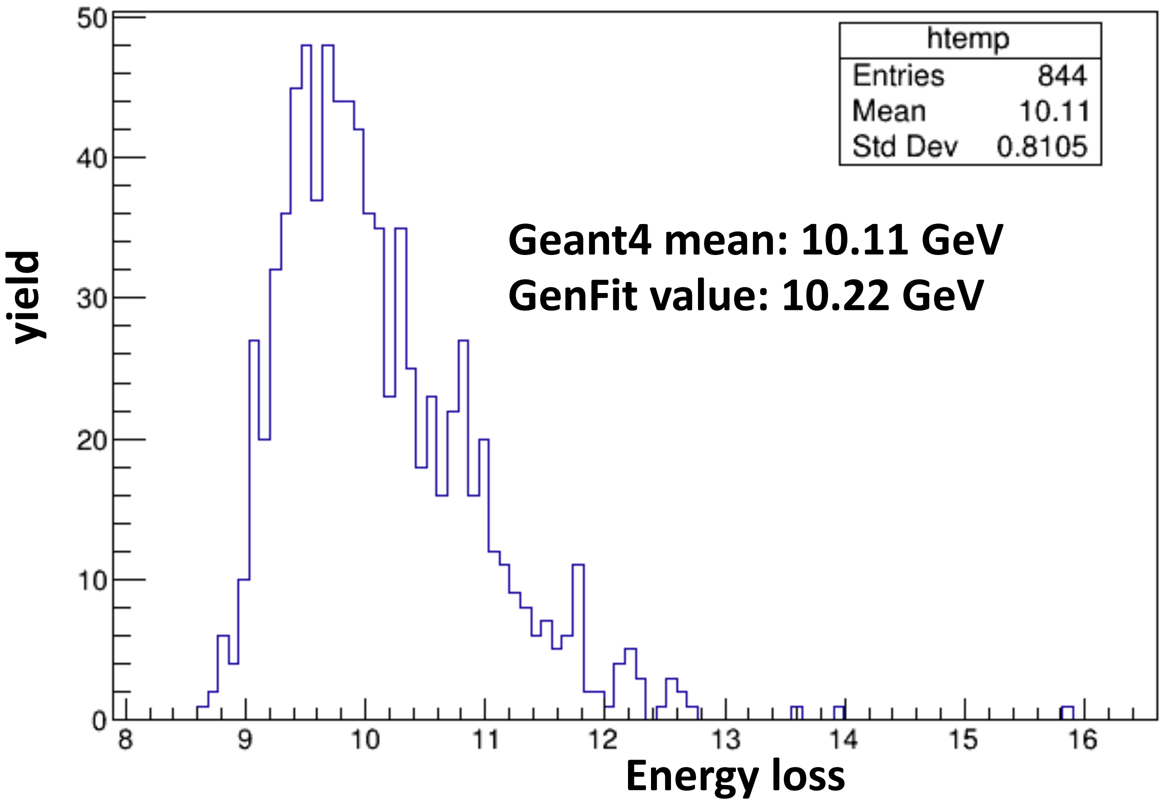
With **- shell (inside [])**
and
+ higher order correction

- Shell correction and a higher order correction are implemented in addition to the density correction.
  - Shell correction: low energy correction
    - Bethe equation has approximation that the velocities of atomic electrons are small compared with that of the projectile
  - Higher order correction:
    - photon emission by the atomic electron before and after photon exchange with muons.

Geant4 energy loss

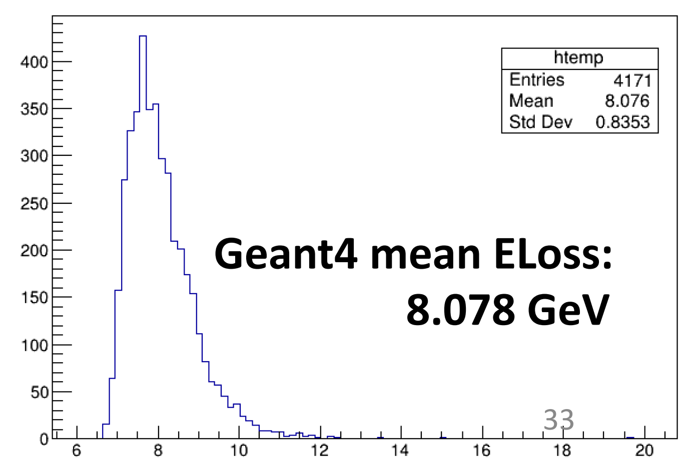
- Turned off the shell and density correction in Geant4 source code to see if it looks consistent with GenFit value
- Below are the energy losses for **40 GeV Muons in Fe (503 cm)**

Energy loss with shell and density correction turned off

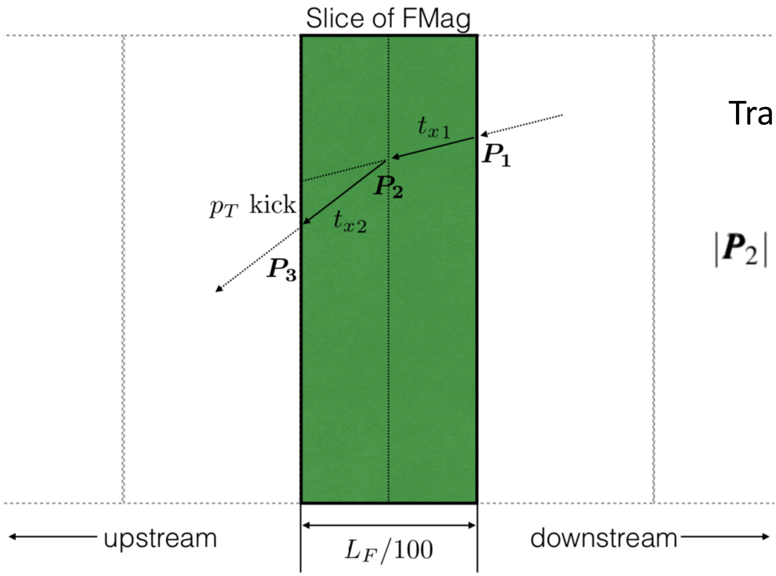


Geant4 Mean does increase closer to GenFit value when the shell and density correction is turned off

Energy loss with shell and density correction turned on



Vertex Reconstruction:
Single muon swimming through FMag



Track slope in XZ plane: $t_{x2} = t_{x1} + s \cdot \frac{\text{kick}}{L_{\text{FMag}}} \cdot \frac{L_{\text{FMag}}}{N_s} \cdot \frac{1}{\sqrt{P_{1x}^2 + P_{1z}^2}},$

$$|\boldsymbol{P}_2| = |\boldsymbol{P}_1| + \underbrace{(E_0 + |\boldsymbol{P}_1| \cdot E_1 + |\boldsymbol{P}_1|^2 \cdot E_2 + |\boldsymbol{P}_1|^3 \cdot E_3 + |\boldsymbol{P}_1|^4 \cdot E_4)}_{\text{parametrized function to get the peak value of energy loss}} \cdot \frac{1}{L_{\text{FMag}}} \cdot \frac{1}{|\boldsymbol{T}_1|}$$

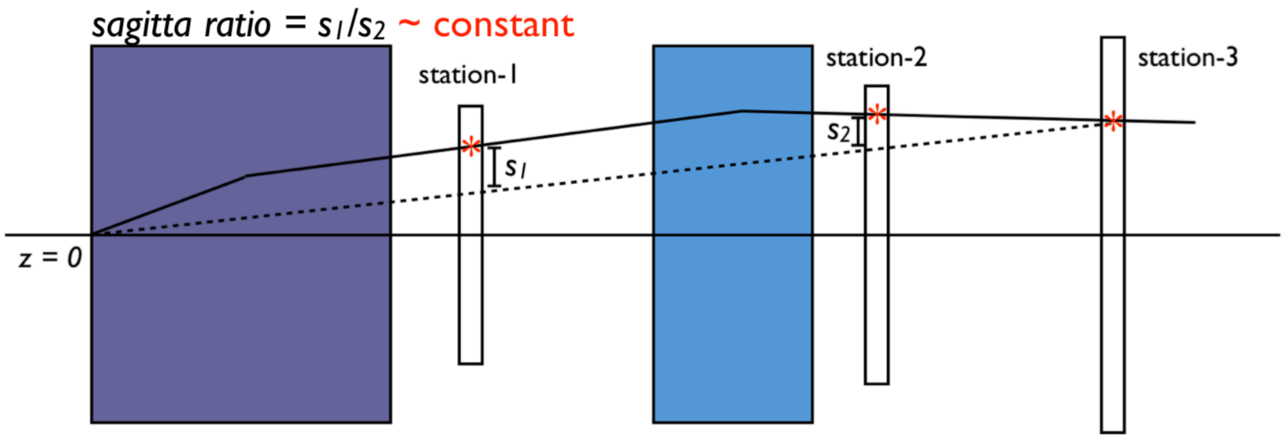
Name	Value	Description
kick	2.909	p_T kick at FMag (GeV)
L_{hole}	27.94	length of the FMag hole (cm)
R_{hole}	1.27	radius of the FMag hole (cm)
L_{FMag}	502.92	length of the FMag (cm)
Z_U	-500	upstream end (cm)
E_0	7.18274	parameter for energy loss 0
E_1	0.0361447	parameter for energy loss 1
E_2	-0.000718127	parameter for energy loss 2
E_3	7.97312e-06	parameter for energy loss 3
E_4	-3.05481e-08	parameter for energy loss 4

Source: Table and Fig from Kei Nagai's thesis

- Assume perfect dipole, no fringe field
- Whole FMag is divided into many slices
- Each step is divided to two half-steps:
  - apply energy loss (energy gain) at the first half-step (corrected for the actual travel length)
  - p_T kick is applied at center
  - apply energy loss at the second half-step
- The point with closest approach to beam line is considered to be the vertex

- Rough path is set before we use the Kalman Filter fitting
- Make the energy loss consistent

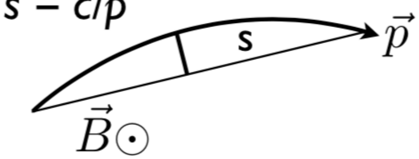
Sagitta Ratio: projecting to Station-1



sagittas

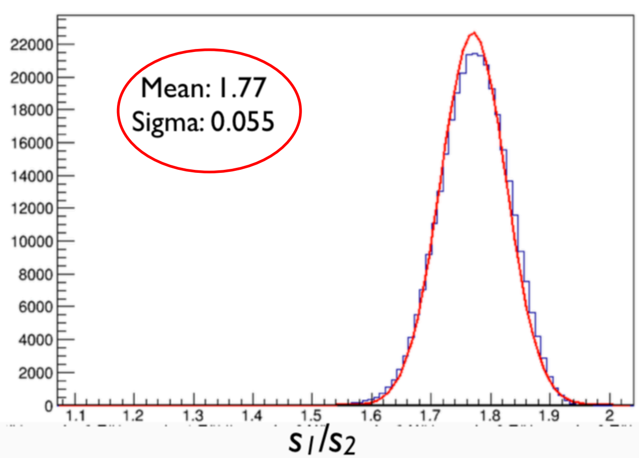
For uniform B ≪ p_{track},

$s = c/p$



$\Rightarrow s_1/s_2 = c_{12}$ for two consecutive bends if p is constant.

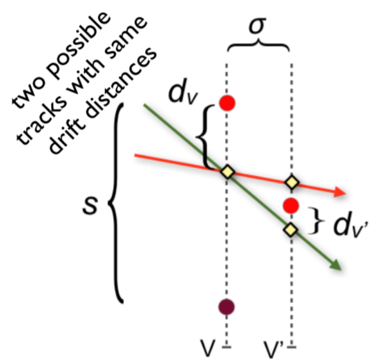
Source: DocDB 912

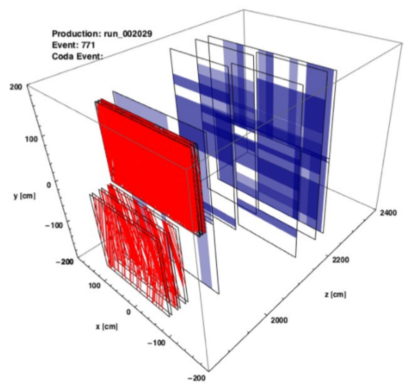


Source: DocDB 1283

- Once a station-2/3 long track is found, we have pretty good position prediction power
- The station-2/3 long track is projected back to station-1 using the sagitta ratio to determine the center and window. The search window could be constrained to ±5 cm.
- Station-1 hits that fall within this window are used to build local triplets and then connect with the station-2/3 long track

Known problems: speed



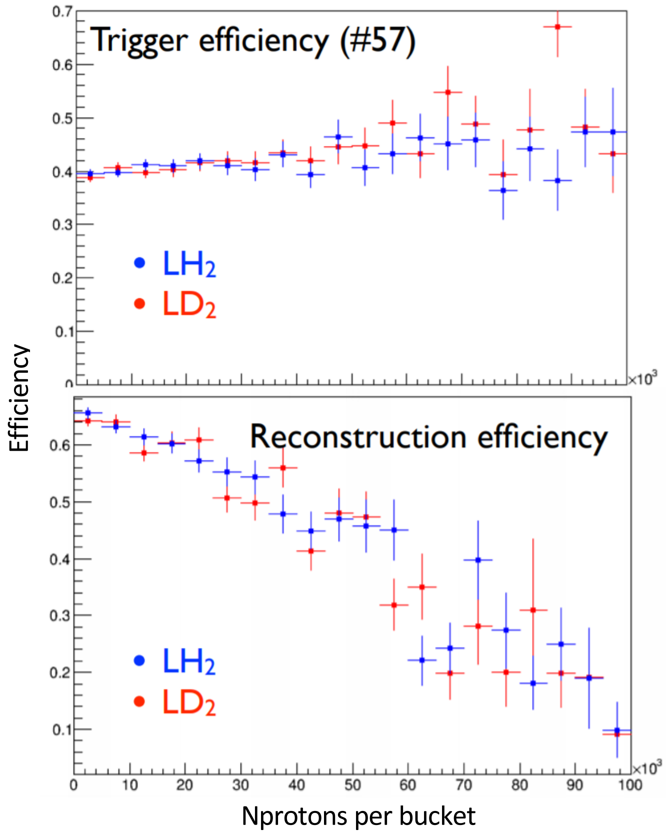


- The size and beam energy of our experiment make the left-right ambiguity hard to solve using simple checksum cuts
- High occupancy induced by high instantaneous intensity RF buckets certainly make things even worse
- Each drift chamber station, in spite of its size on beam axis, essentially measures one 3D point

kTracker needs to do a lot of chi-squared fit to determine which hit combinations are the best one

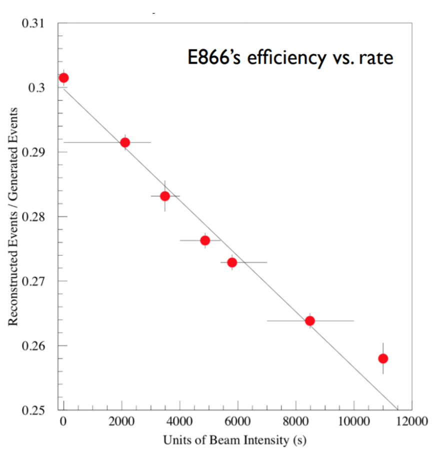
- This is very time consuming. A one-hour run with ~35% duty factor typically takes about 150 – 200 CPU hours to reconstruct
- We did not have an online reconstruction so the shifters and experts had to operate the experiment using only the spectrometer plots

Know problem: (rate/occupancy-dependent) efficiency

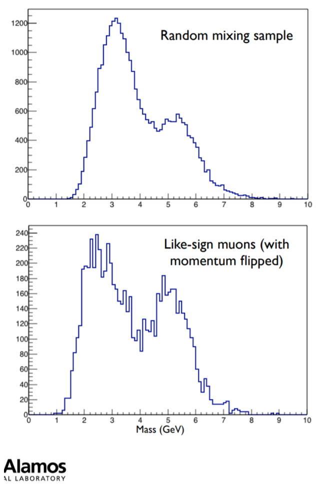


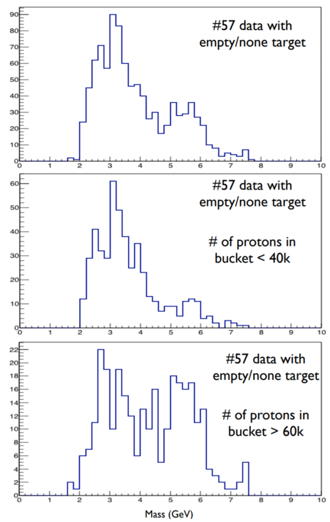
- This is not the final E906 result. Please don't read too much from this plot
- Reconstruction efficiency heavily depends on the intensity, causing severe efficiency loss
- This dependence is potentially different between different targets, introducing additional systematic uncertainties

- This problem cannot be completely solved, but can certainly be improved



Know problem: fake combinations (at station-1 edges)





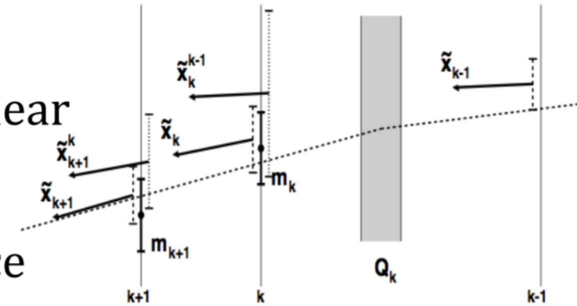
- After all reasonable cuts, we found a peaking background at around 5 GeV
- After some investigation, this background is strongly related to low number of hits low momentum tracks in high occupancy events (refer to DocDB-1325)
- Kei did a lot more study and concluded these tracks comes from the edge of station-1, where tracker picked up wrong combination using chi-squared as the only criteria
- We invented tight cuts to remove this kind of peaking background, but it costs us 15 – 20% efficiency

- Ideally if we have another drift chamber upstream this problem could be solved. With the addition of the dark photon hodos and better algorithm we should be able to improve the efficiency loss

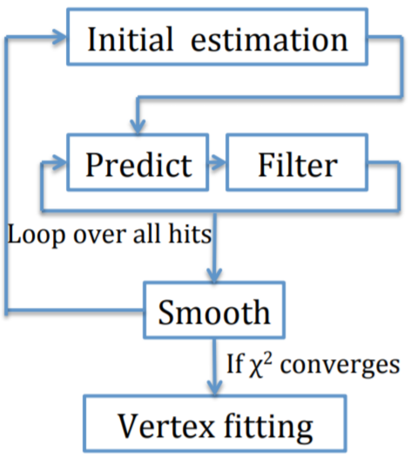
Quick intro to Kalman filter

Why Kalman filter?

- Mathematically the best linear estimator
- Provide estimation with properly defined covariance



- Incorporated from PHENIX track fitting program with a lot of help from Rob Kutschke
- Covariance matrix estimated using Geant4e (more on this later)
- Important even in our simple spectrometer setup because:
  1. Solid iron beam dump
  2. Non-uniform field map
  3. Fringe field of KMag



How: a recursive algorithm starting from downstream to upstream

- Predict: propagate the state from previous plane to current plane (fulfilled by Geant4)
- Filter: use measurement to correct the predicted state by minimizing χ^2
- Smooth: propagate the info. from upstream back to downstream so that the state parameters are continuous