Geant4e Track Extrapolation in the Belle II Experiment

Leo Piilonen, Virginia Tech
on behalf of the Belle II Collaboration

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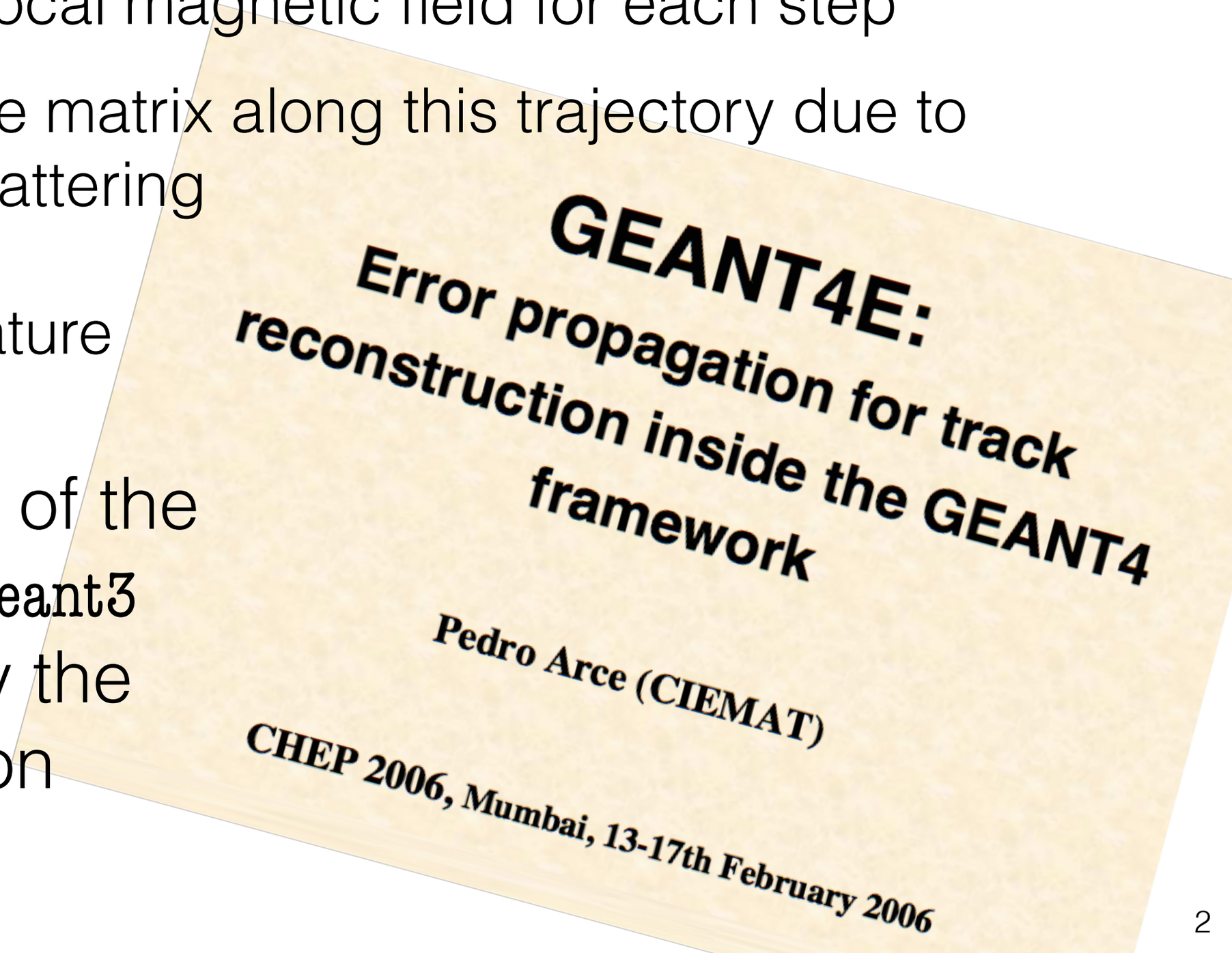
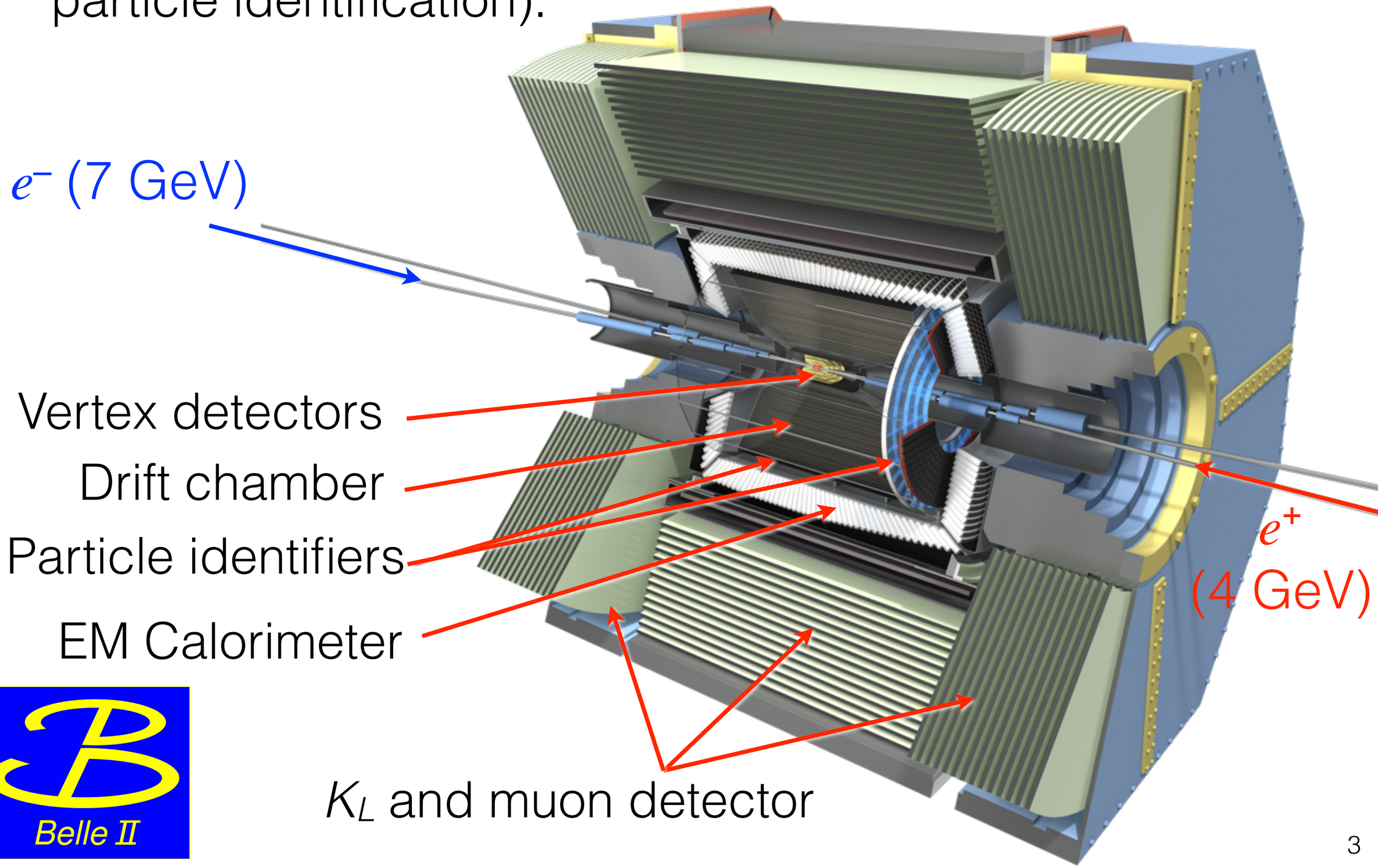
geant4e, a part of geant4, is designed for use during event reconstruction *(not simulation)*. It computes

- the average trajectory of a charged track, assuming a local helix in local magnetic field for each step
- the covariance matrix along this trajectory due to
  - multiple scattering
  - ionization
  - track curvature

using C++ port of the geane code in geant3 (developed by the European Muon Collaboration)



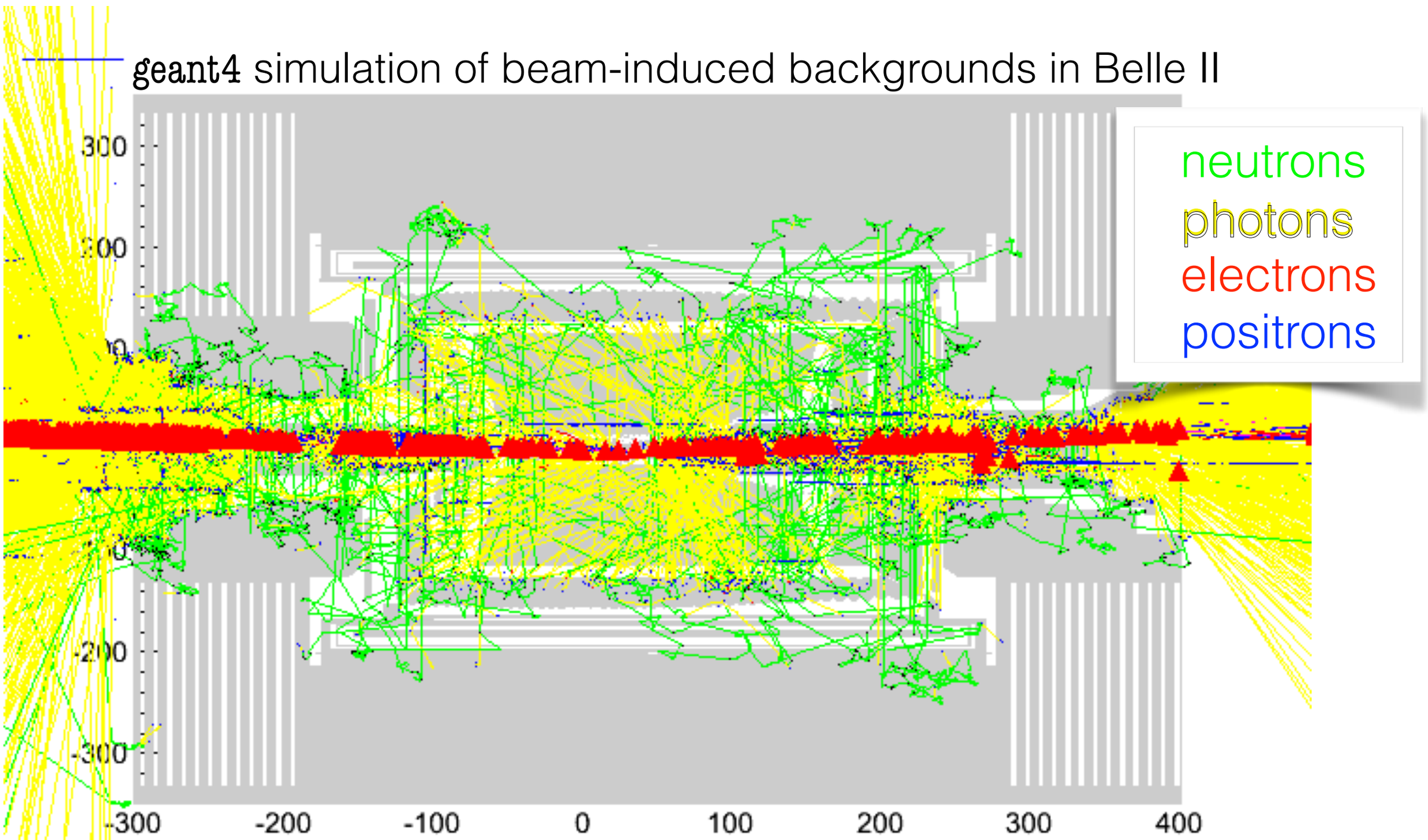
During event reconstruction, use `geant4e` to propagate charged tracks outward from the drift chamber (helps in particle identification).



Use geant4-based model of the Belle II detector:

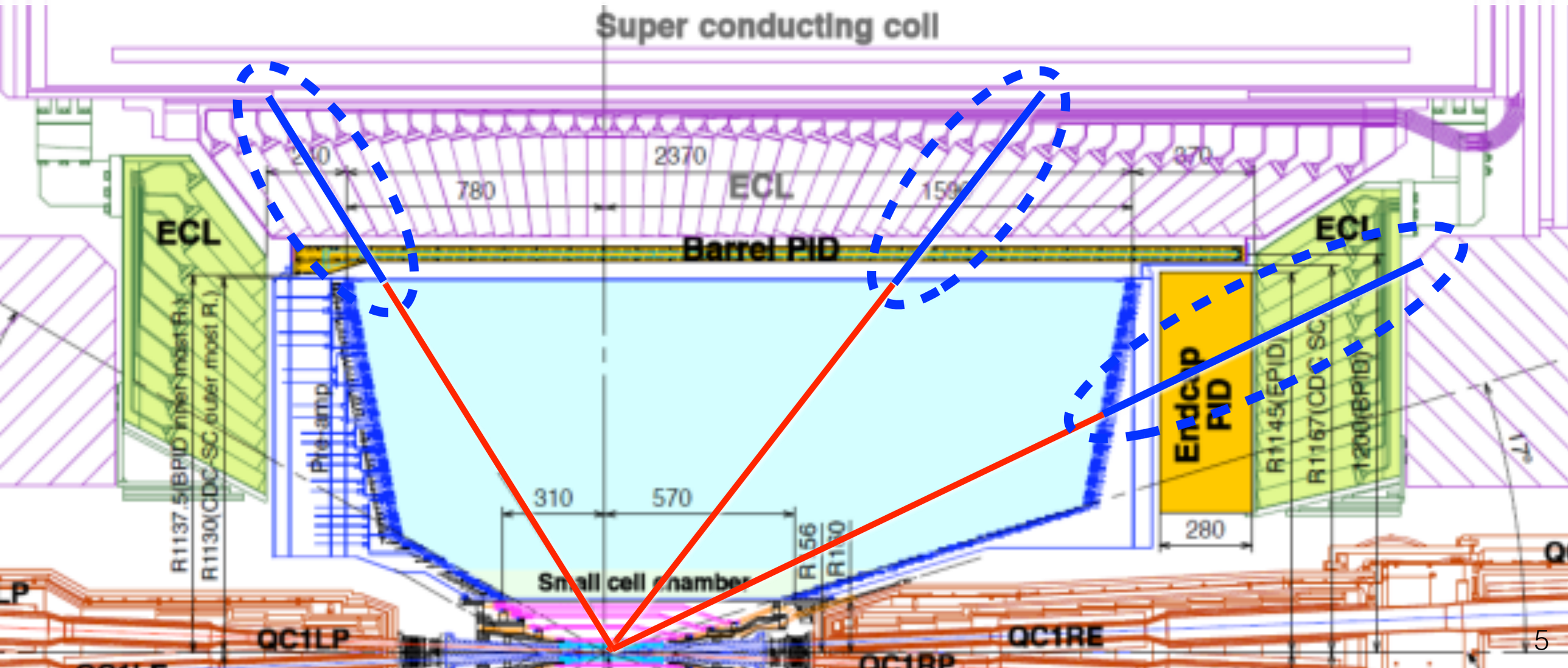
- ☑ detailed detector geometry
- ☑ non-uniform solenoidal magnetic field map (~1.5 T)
- ☑ for geant4 simulation <u>and</u> geant4e track propagation

geant4 simulation of beam-induced backgrounds in Belle II



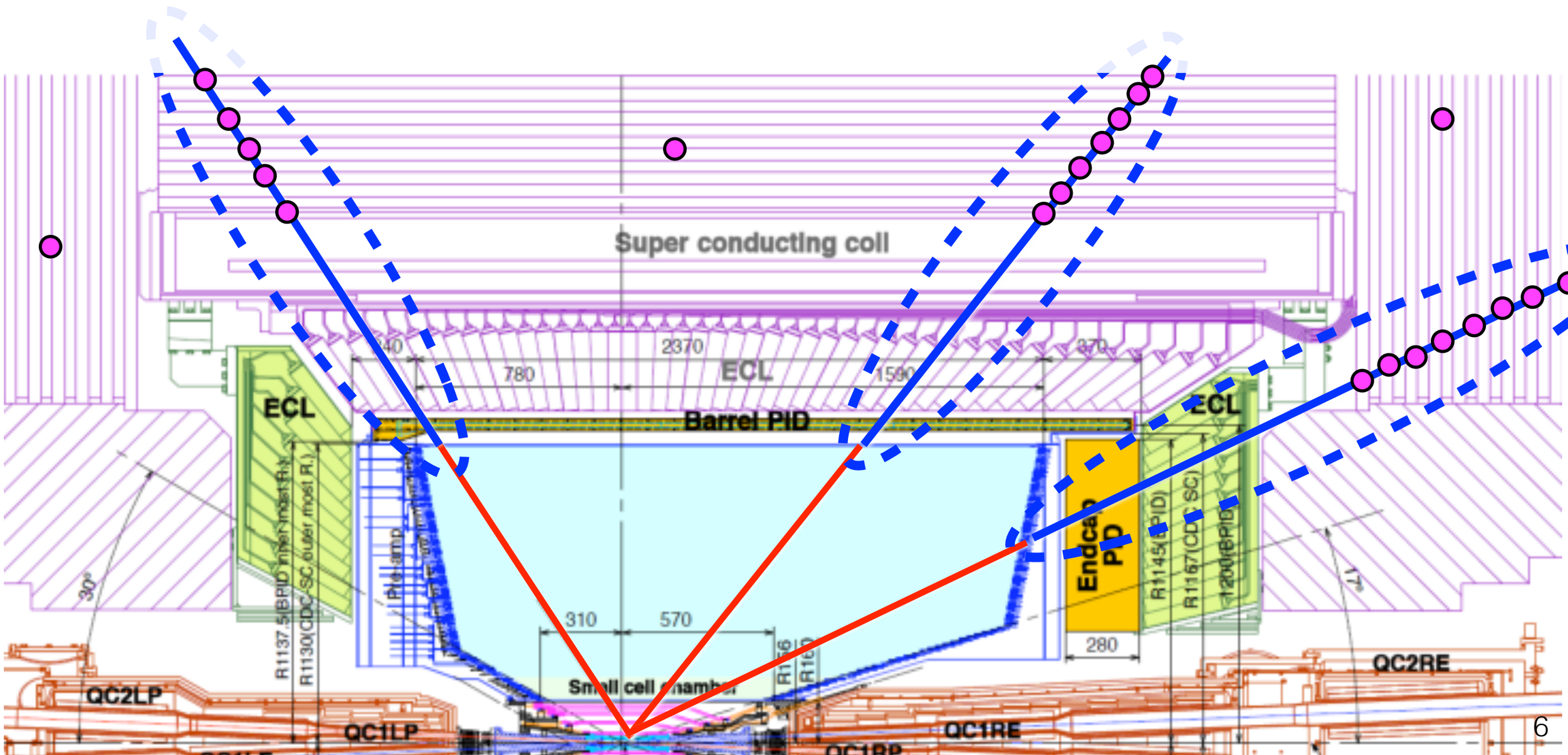
1) During event reconstruction, each track is extrapolated outward using six hypotheses ($e,\ \mu,\ \pi,\ K,\ p,\ d$)

- ☑ swim each track from outer edge of drift chamber through the calorimeter *(or until it stops)*
- ☑ store time, position, momentum and covariance matrix at entrance/exit of selected `geant4` volumes *(useful for particle identification)*



2) During event reconstruction, each track is extrapolated outward even farther using only μ hypothesis

- ☑ swim each track through K_L-muon detector with Kalman filter to matching hits and track adjustment
- ☑ store time, position, momentum and covariance matrix at entrance/exit of each KLM layer



Geant4e and Geant4:

Belle II has two usage modes of the geant4e package:

- for reconstruction of real events:
  standalone – as intended by geant4/geant4e authors

- for reconstruction of simulated events:
  coexists with geant4 since we do event generation, simulation and reconstruction in a single job

Some difficulties must be overcome!

Geant4e and Geant4, *cont'd*:

geant4e, as distributed, cannot be used with geant4:

- ☒ incompatible particle lists
- ☒ incompatible physics processes
- ☒ conflicting usage of sensitive-detector geometry
- ☒ distinct states when calling RunManager
- ☒ distinct step-by-step Navigators
- ☒ incompatible user actions (SteppingAction etc)

geant4e, as distributed, is limited:

- ☒ propagates only electrons, positrons and photons

We have resolved these issues and limitations.
All mods are done outside the geant4(e) code base.

1) Particles and Physics Processes:

- PhysicsList is user's concrete implementation of G4VUserPhysicsList, and must define:
  - ConstructParticle()
  - ConstructProcess()
  - SetCuts()

- geant4 and geant4e use distinct and incompatible PhysicsLists.

- Significant overhead to change PhysicsList when switching between geant4 and geant4e *so avoid this!*

Define a combined (and extended) PhysicsList that incorporates geant4 and geant4e functionality.

1) Particles and Physics Processes, *cont'd*:

- Our modified `ConstructParticle()` defines

  `gamma` `e+` `e−` `mu+` `mu−` `pi+` `pi−` `pi0` `kaon+` `kaon−` `kaon0` `kaon0L` `kaon0S` `proton` `anti_proton` `neutron` `anti_neutron` `geantino` `chargedgeantino` `opticalphoton` *etc* for use by `geant4`

  `g4e_gamma` `g4e_e+` `g4e_e−` `g4e_mu+` `g4e_mu−` `g4e_pi+` `g4e_pi−` `g4e_kaon+` `g4e_kaon−` `g4e_proton` `g4e_antiproton` `g4e_deuteron` `g4e_antideuteron` (all with `PIDcode` = 0) for use by `geant4e`

- Avoids this problem ☞ `PhysicsList` in the distributed `geant4e` defines only three particles (`gamma` `e+` `e−`) and these conflict with `geant4` usage during simulation

1) Particles and Physics Processes, *cont'd*:

- Our modified `PhysicsList()` disables the generation of secondaries – optical and scintillation photons – for newly defined `g4e_*` particles since these processes get attached to *every* charged particle by `geant4`

- Our modified `SetCuts()` does

  `SetCutsWithDefault()` using `default = 1.0*mm` for the regular particles, as in `geant4`

  `SetCutsWithDefault()` using `default = 1.0E9*cm` for the newly defined `g4e_*` particles, as in `geant4e`

2) Common detector geometry:

- During simulation, `G4SteppingManager` calls user code to process steps through “sensitive” detector volumes and record the hits therein.
- During reconstruction, our custom version of `StepLengthLimitProcess()` disables this behaviour:

```
G4ParticleChange aParticleChange;

G4VParticleChange*
    ExtStepLengthLimitProcess::PostStepDoIt( const G4Track& track,
                                             const G4Step& )
{
   aParticleChange.Initialize( track );
   aParticleChange.ProposeSteppingControl( AvoidHitInvocation );
   return &aParticleChange;
}
```

3) geant4e navigation and "target" geometry:

- Avoid the special G4ErrorPropagationNavigator in geant4e. Instead, use the standard G4Navigator defined in geant4.
- geant4e requires a *target surface* (G4ErrorCylSurfaceTarget is an infinite-length cylinder). After each geant4e step, G4ErrorPropagationNavigator would check if the track crossed this surface. Our steering code does this check.
- Our custom version of G4ErrorCylSurfaceTarget is a closed finite-length cylinder that includes the two endcap surfaces.

4) Distinct geant4/geant4e run states and user actions:

- ☑ During our custom geant4e initialization, detect its co-existence with geant4 by a non-empty G4ParticleTable.
  - ❖ If geant4e is running stand-alone, there is no need to preserve the geant4 state from one event to next.
  - ❖ If geant4e co-exists with geant4, restore the geant4 idle state and save pointers to its UserActions for swapping out/in during the later track extrapolation:

```
InitGeant4e();
G4StateManager::GetStateManager()->
                                SetNewState(G4State_Idle);
m_savedTrackingAction = UserTrackingAction;
m_savedSteppingAction = UserSteppingAction;
```

4) Distinct run states and user actions, *cont'd*:

- During reconstruction of one event:

```
if ( geant4e co-exists with geant4 ) { // hide geant4 actions
        UserTrackingAction = NULL;
        UserSteppingAction = NULL;
}

// extrapolate each track in the event using g4e_* particles;

if ( geant4e co-exists with geant4 ) { // restore geant4 actions
        UserTrackingAction = m_savedTrackingAction;
        UserSteppingAction = m_savedSteppingAction;
}
```

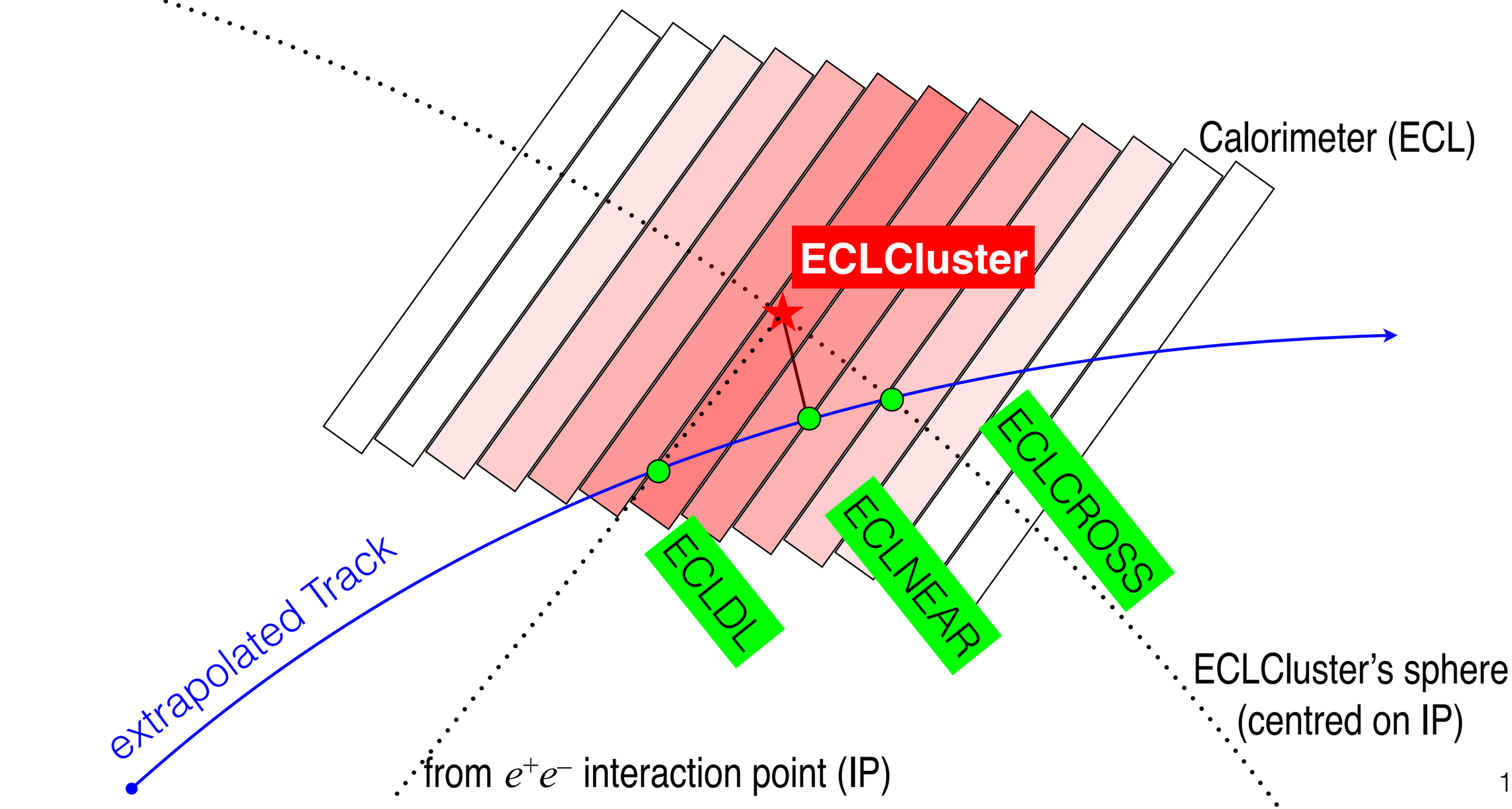
5) Other `geant4e` modifications:

- The distributed `MagFieldLimitProcess` in `geant4e` assumes that the magnetic field is along the z axis. Our custom version removes this assumption.

- The distributed `G4EnergyLossForExtrapolator` defines energy-loss processes for electrons and positrons only. Our custom version extends these to muons, pions, kaons, protons and deuterons (and anti-particles).
  - *In* `geant4e`*, this applies the mean energy loss to each particle during extrapolation. Fluctuations in energy loss and multiple scattering are incorporated in the growth of the covariance matrix.*

6) Track-extrapolation use in track–cluster matching:

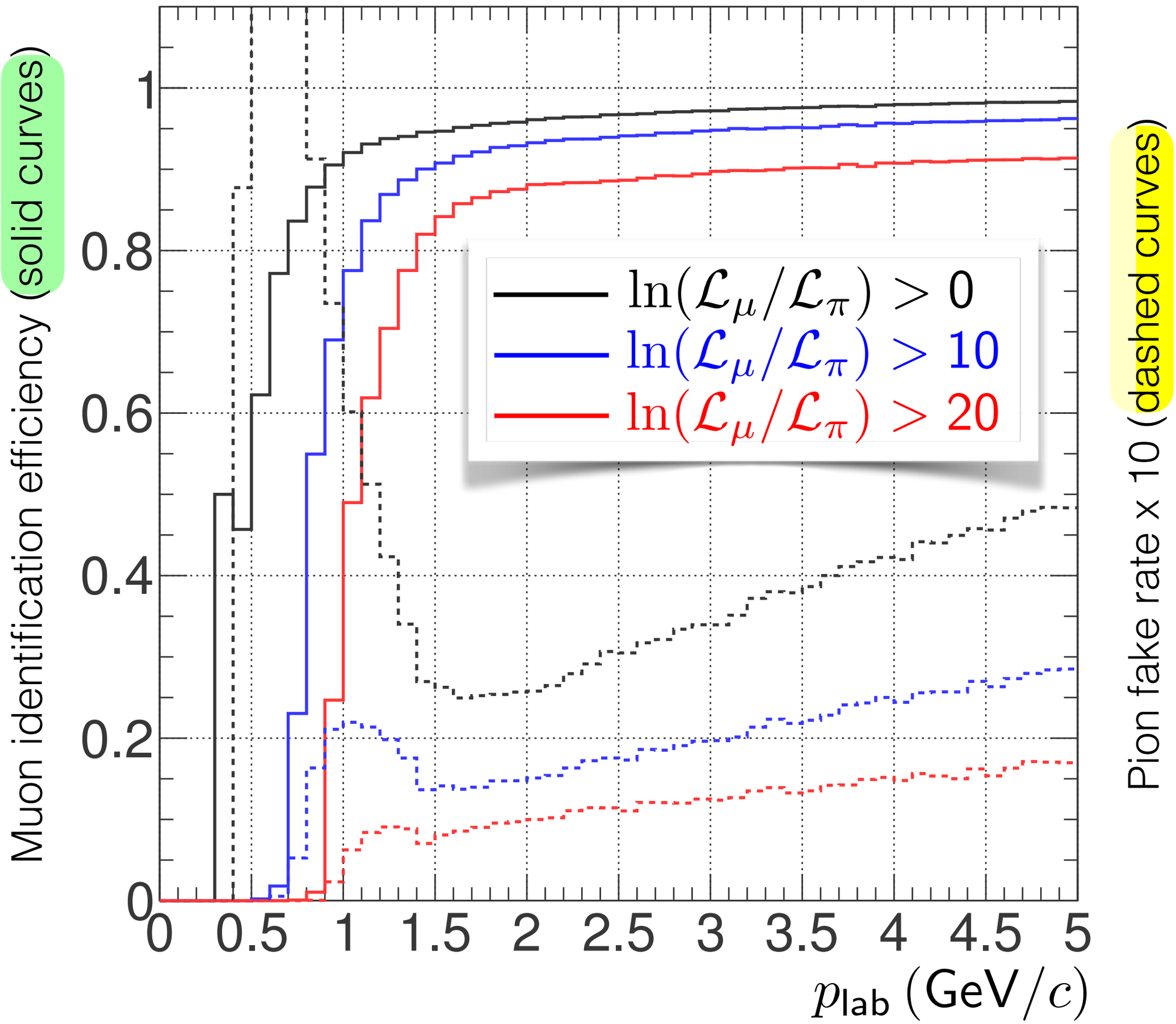
- Record a crossing ("ExtHit") when the extrapolated track enters/exits each selected volume in the PID detectors or when track is near(est) a reconstructed cluster



7) Track-extrapolation use in muon identification:

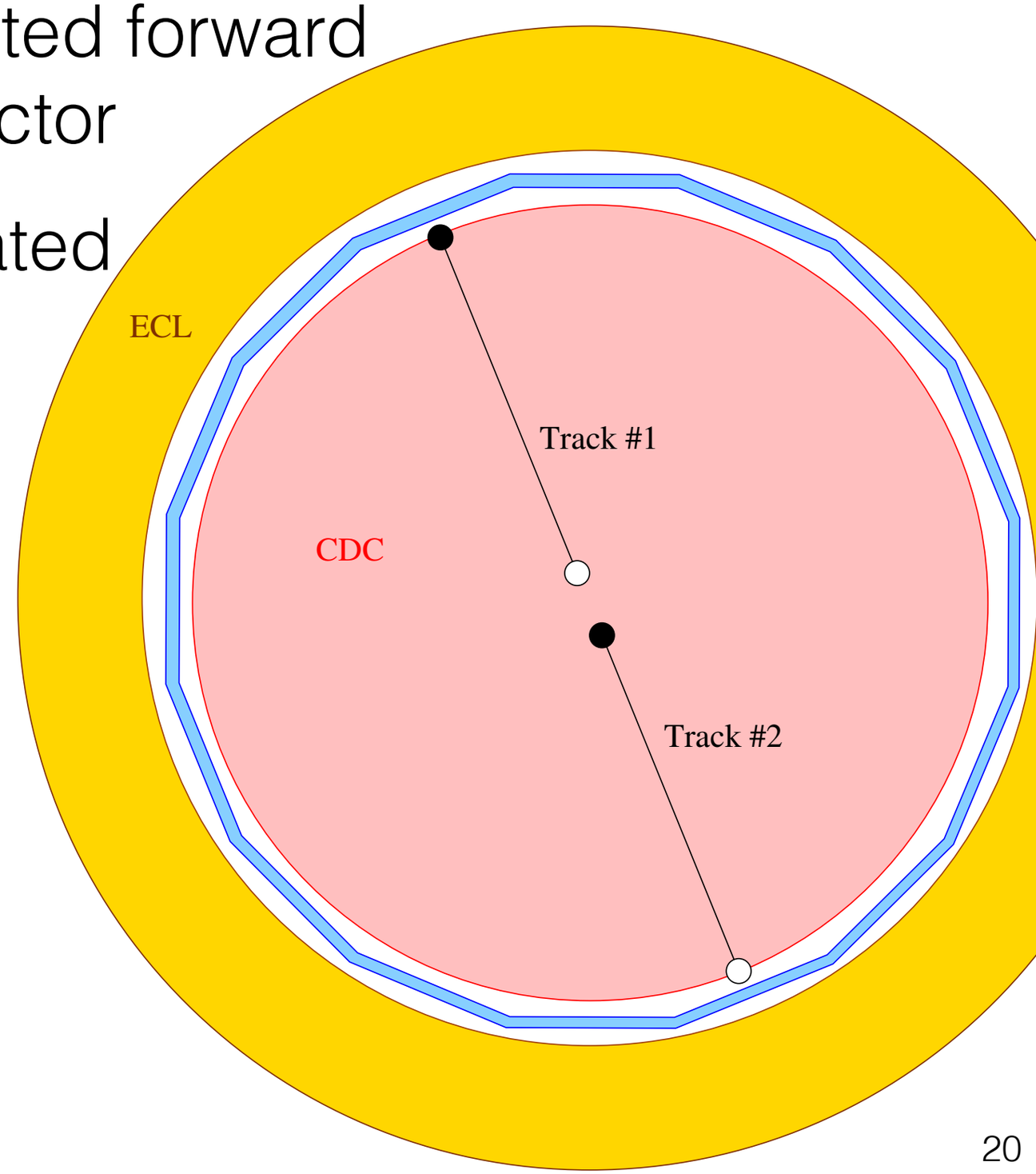
- Extrapolate each reconstructed track from the CDC exit point into the KLM (barrel and endcap) using `geant4e`
  - default is muon hypothesis only
- Look for matching 2D hit upon crossing each KLM layer
- Kalman fitting: If there is a matching 2D hit in the layer, use its position and uncertainty to adjust the position and direction of the extrapolated track before continuing to the next layer
- Accumulate χ^2 between in-plane hit and track position
- Finish extrapolation when the track exits the KLM or stops
- Use extrapolated vs measured range and χ^2/n.d.f. to compute particle-ID likelihoods via PDF-table lookup

KLM Performance for Muon Identification



8) Track-extrapolation of cosmic rays:

- Typical cosmic ray is reconstructed as two tracks
- Lower track #2 is extrapolated forward into bottom half of the detector
- Upper track #1 is extrapolated <u>backward</u> into top half of the detector, using the back-propagation feature of `geant4e`, so that
  - energy increases
  - covariance grows
  - time flows backward



Conclusion

In the Belle II software library, we have implemented geant4e track propagation for particle identification (in the PID detectors) and muon identification (in the KLM) during event reconstruction, either standalone or in harmonious co-existence with geant4 event simulation:

- ☑ merged particle list that comprises geant4-standard and custom g4e_* particles
- ☑ distinct physics processes for geant4-standard and custom g4e_* particles
- ☑ common geant4-based detector geometry
- ☑ no hit invocation in sensitive volumes during geant4e
- ☑ distinct states and user actions for geant4 and geant4e
- ☑ Kalman fitting for muon extrapolation
- ☑ all customizations are outside the geant4 code base