Geant4e Track Extrapolation in the Belle II Experiment

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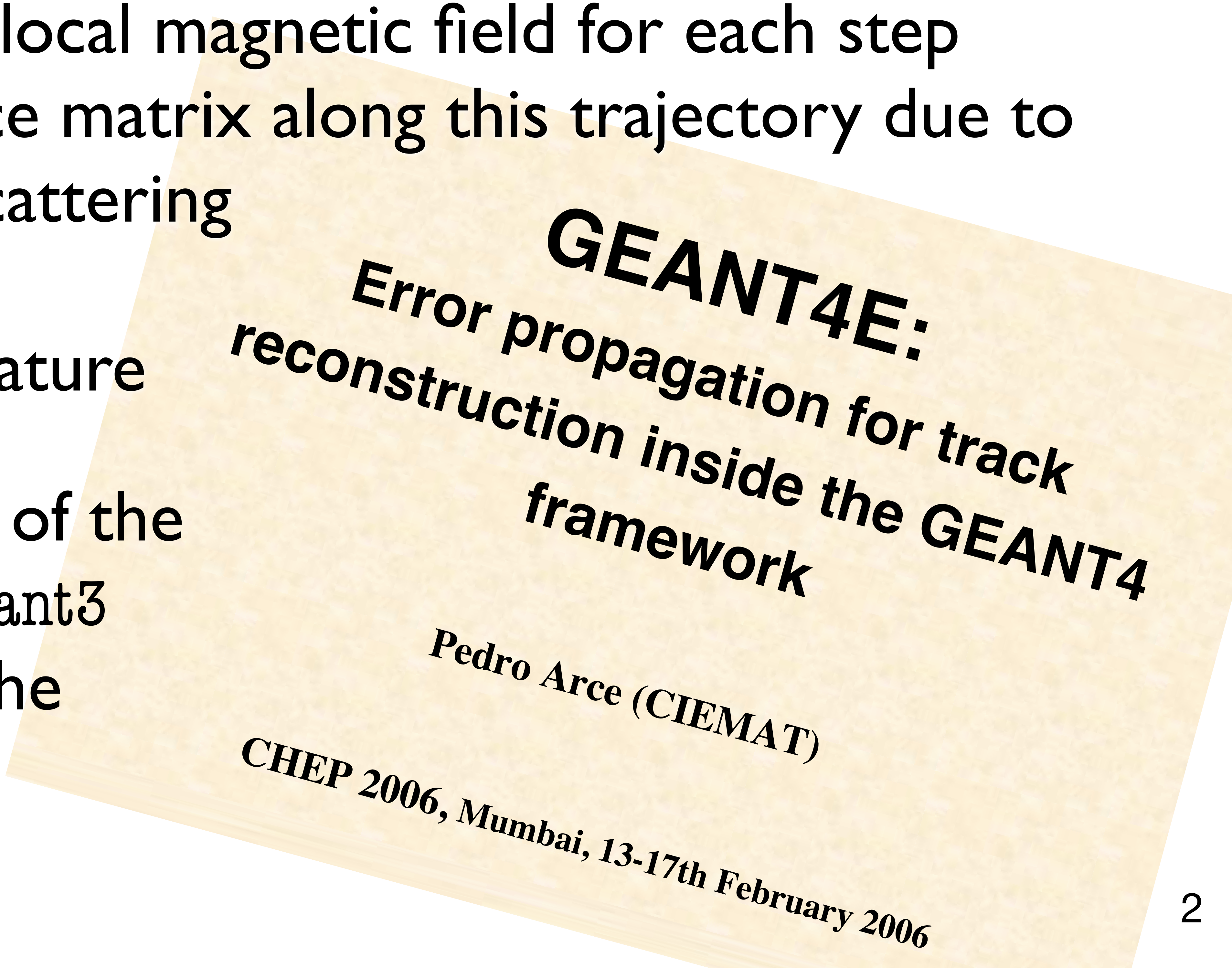
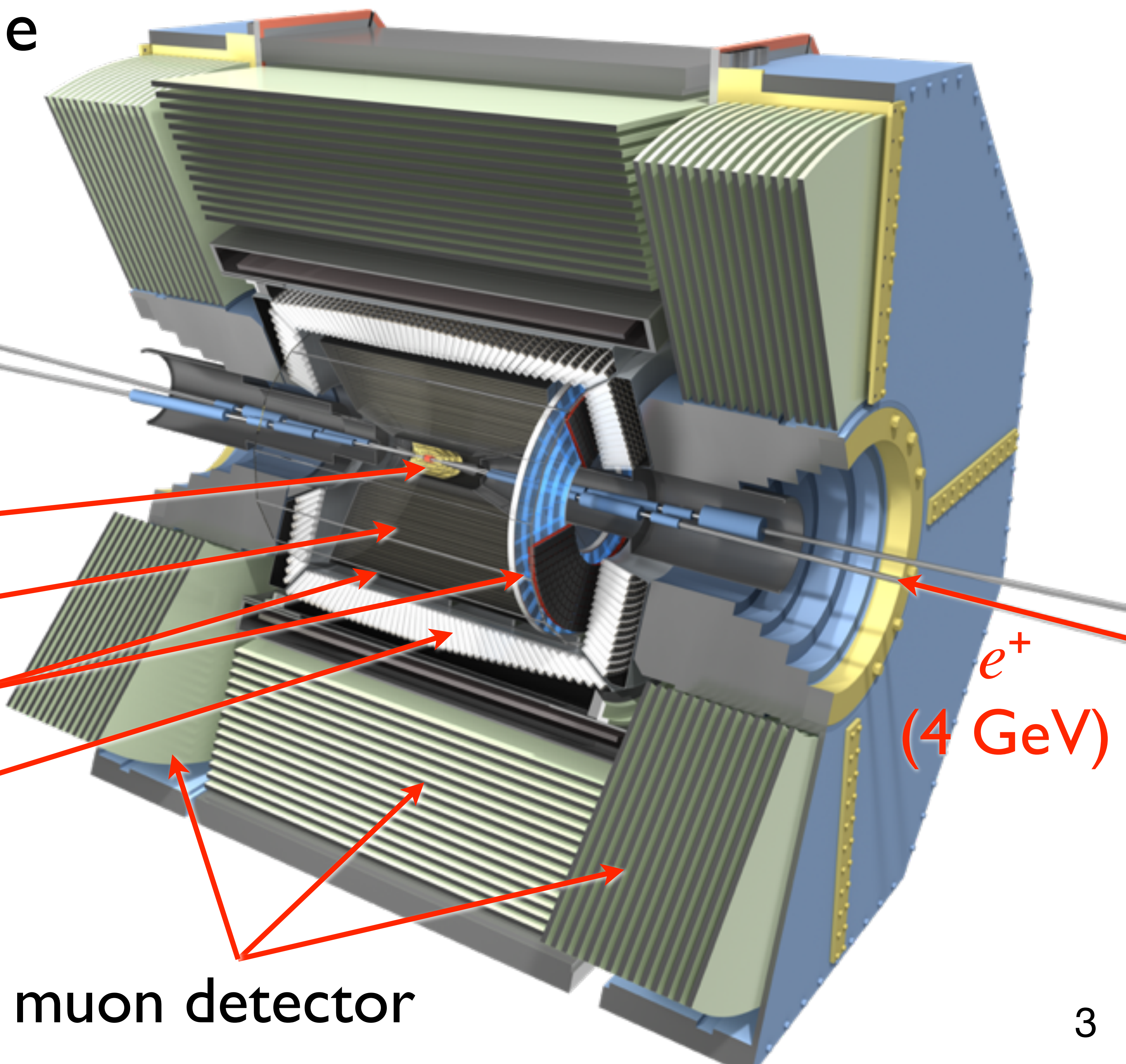
geant4e, a part of geant4, is used during event reconstruction *(not simulation!)*. It computes

- 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)



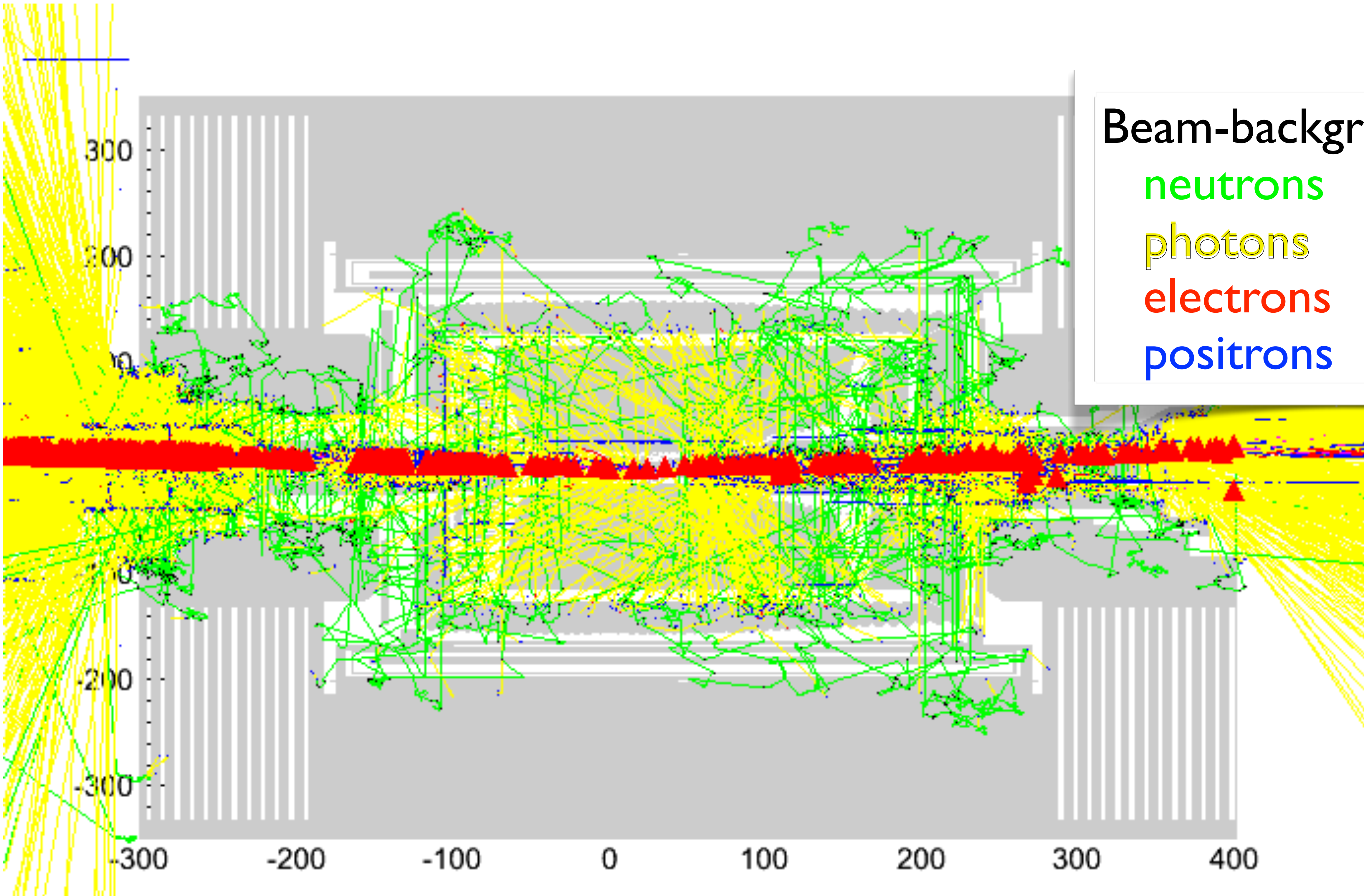
During event reconstruction, use `geant4e` for track propagation outward from the drift chamber's exit; needed for particle identification



Belle II

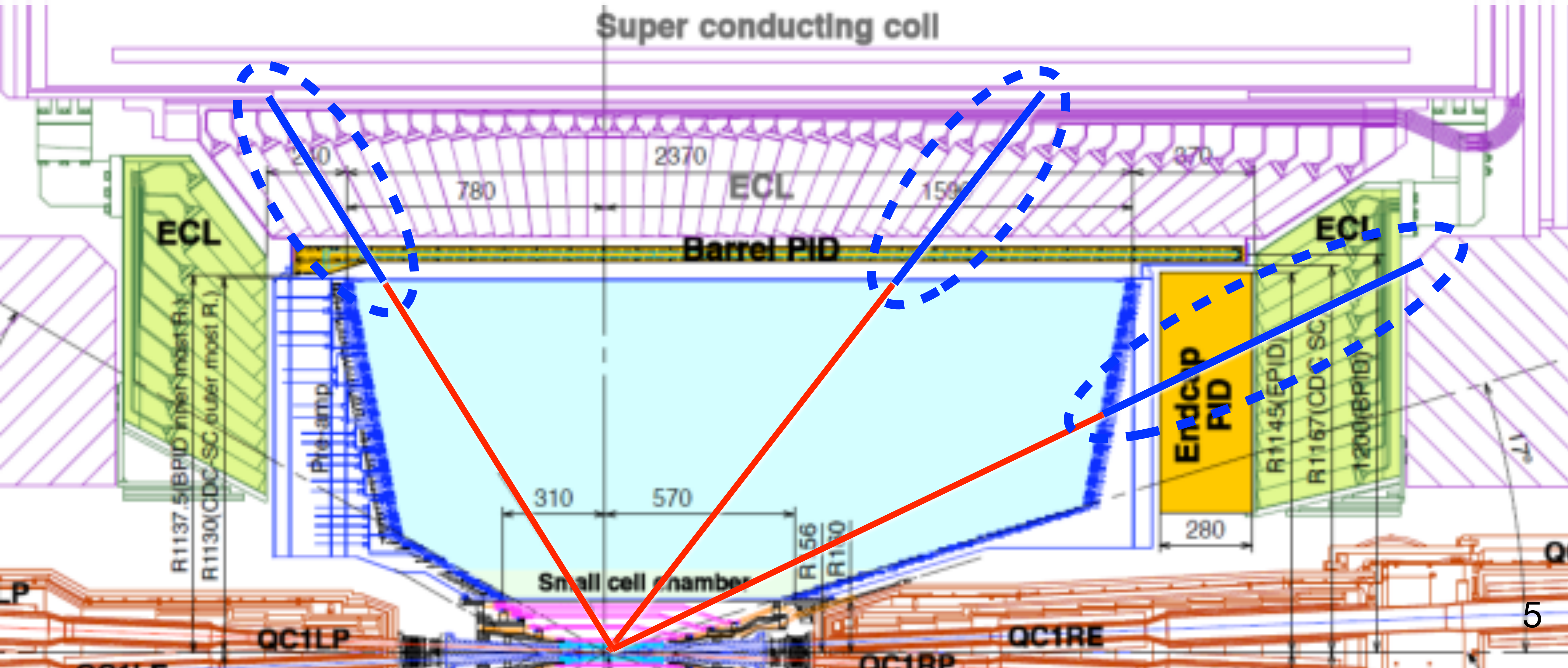
geant4 detailed model of the Belle II detector:

- ☑ non-uniform solenoidal magnetic field (~1.5 T)
- ☑ for geant4 simulation and geant4e track propagation



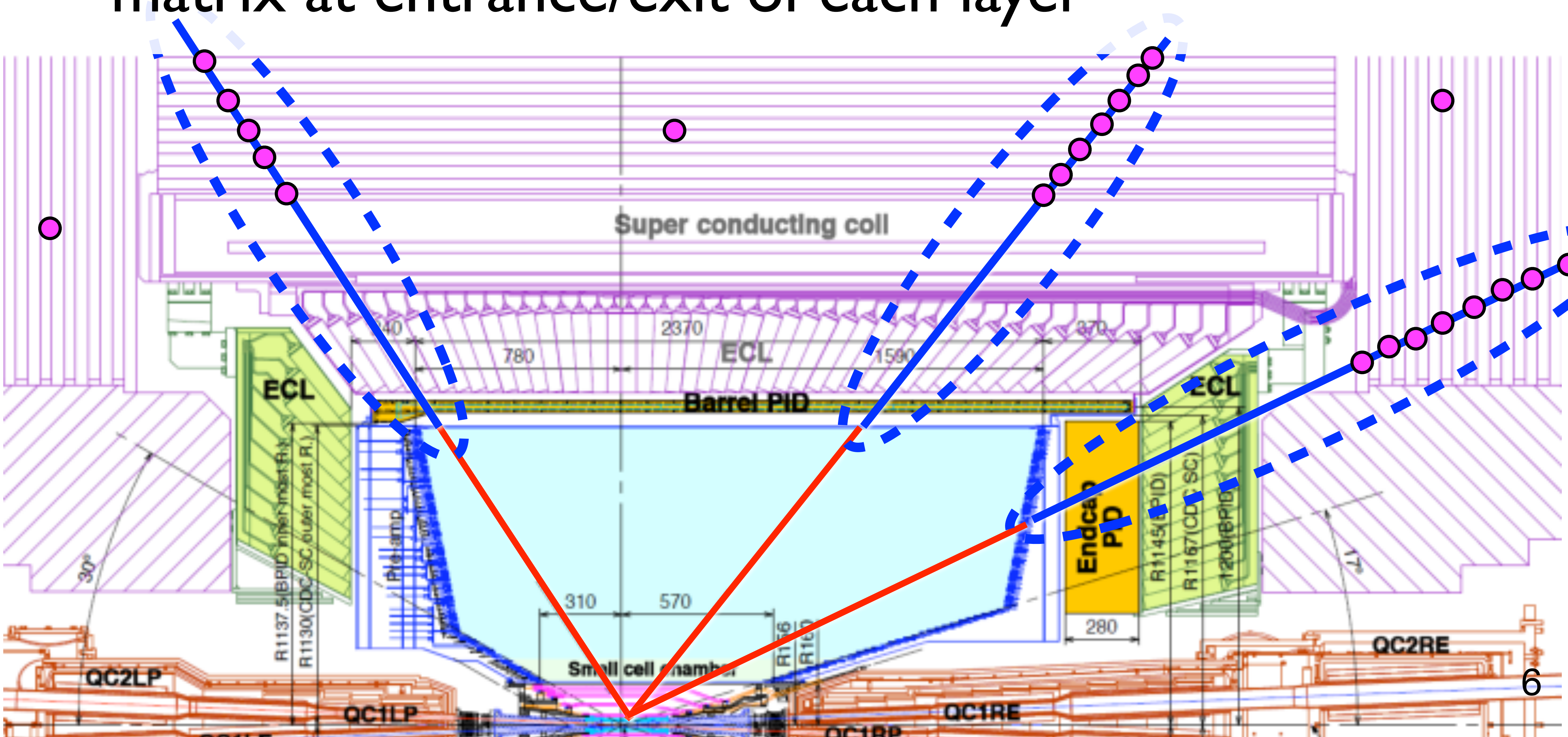
For particle identification, each track is extrapolated outward using 5 hypotheses ($e,\ \mu,\ \pi,\ K,\ p$)

- ☑ 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 volumes



For muon identification, each track is extrapolated outward using μ hypothesis *(but could use the other 4)*

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



Geant4e and Geant4:

Belle II has two usage modes of geant4e:

- for real events:
  standalone

- for simulated events:
  coexisting with geant4, since we do simulation and reconstruction in one pass

Geant4e and Geant4, *cont'd*:

geant4e, as distributed, cannot be used with geant4:

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

geant4e, as distributed, is limited:

- x propagates only electrons, positrons and photons

We have resolved these issues and extended geant4e.
All mods are done <u>outside</u> the geant4 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 PhysicsLists.

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

- Define a combined PhysicsList that incorporates geant4 and geant4e functionality.

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

- 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*. (the standard particles)
  - g4e_gamma g4e_e+ g4e_e− g4e_mu+ g4e_mu− g4e_proton g4e_antiproton g4e_pi+ g4e_pi− g4e_kaon+ g4e_kaon−
    with PIDcode = 1000000000 + stdPIDcode

PhysicsList in the distributed geant4e defines only three particles (gamma e+ e−) and these conflict with geant4 usage.

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

- `SetCuts()` does

  `SetCutsWithDefault()` using `default = 1.0*mm` for the standard particles

- `SetCutsWithDefault()` using `default = 1.0E9*cm` for the new `g4e_*` particles

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:

- ☑ Do not use the special `G4ErrorPropagationNavigator` in `geant4e`. Instead, use `G4Navigator` defined in `geant4`.
- ☑ `geant4e` requires a "target" surface; its navigator *[which we avoid]* checks if the track crosses this surface after each step. We do this check in our steering code.
- ☐ The available surfaces are not adequate for our needs because they are not closed.
- ☑ Our custom version of `G4ErrorCylSurfaceTarget` is a closed surface that includes the cylinder endcaps.

4) Distinct run states and user actions:

- During our geant4e initialization, detect the presence of geant4 by a non-empty G4ParticleTable.
- If geant4e is running standalone, 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:

```
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 all tracks 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 `G4ErrorPropagatorManager` replaces the standard `G4Navigator` with `G4ErrorPropagationNavigator`. Our custom version avoids this.
- The distributed `MagFieldLimitProcess` 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. Our custom version extends these to muons, pions, kaons, and protons (both signs).

6) Muon identification:

- Extrapolate each reconstructed track from the CDC exit point into the KLM (barrel and endcap) using `geant4e`
  ★ default is muon hypothesis only *(but others are allowed)*
- 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 positions
- Finish extrapolation when the track exits the KLM or stops

6) Muon identification, *cont'd*:

- Use two variables to distinguish muon from hadron in KLM
  - ★ χ^2 per degree of freedom for in-plane position differences of all matching 2D hits and the extrapolated track ($\chi^2_{\rm dof}$)
  - ★ difference in range between outermost matching 2D hit and the extrapolated track ($\Delta\ell$)
- Consult two-dimensional PDFs:
  - ★ $\mathcal{P}^{\pm}_{\mu}(\Delta\ell,\ \chi^2_{\rm dof})$ for muons
  - ★ $\mathcal{P}^{\pm}_{\pi}(\Delta\ell,\ \chi^2_{\rm dof})$ for pions
  - ★ $\mathcal{P}^{\pm}_{K}(\Delta\ell,\ \chi^2_{\rm dof})$ for kaons
- Compute likelihood of the track being a muon *vs* hadron:
  - ★ $\mathcal{L} \equiv 0$ if no matching 2D hits; otherwise, ...
  - ★ $\mathcal{L} = \dfrac{\mathcal{P}_\mu}{\mathcal{P}_\mu + \mathcal{P}_h}$ (where $h \in \{\pi,\ K\}$)

Conclusion

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

- ☑ merged particle list including standard and custom `g4e_*` particles
- ☑ distinct physics processes for standard and custom `g4e_*` particles
- ☑ no hit invocation in sensitive volumes for `geant4e`
- ☑ distinct states and user actions during event processing
- ☑ Kalman fitting for muon extrapolation