$e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^- X$:
Recoil Analysis with *ab initio* Reconstruction

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ICFA-ILC Simulation & Reconstruction Workshop
May 4, 2007

Physics Studies: Strategy

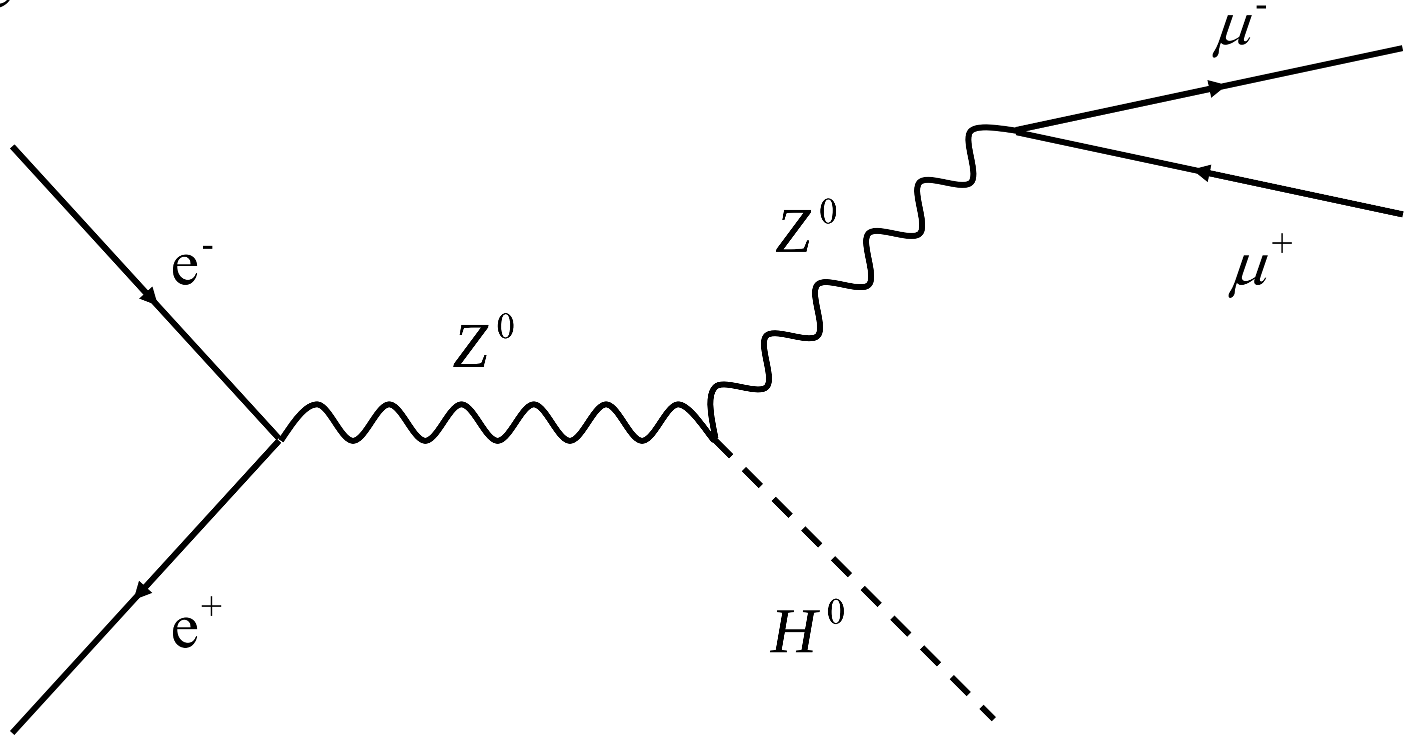
- Most physics analyses carried out by benchmarking group or by specific physics groups.
  - Traditionally carried out using fast MC.
- Emphasis now on targeting LCIO ReconstructedParticle for all analyses.
- Once reconstruction is robust and mature, swap out fastMC front end and replace with full simulation and reconstruction chain.
- Aim to create an analysis package (org.lcsim.analysis) to which physicists and physics groups can contribute "canned" analyses.

Physics Studies: Simple Analysis

- Wanted to exercise the simulation & reconstruction end-to-end, viz. stdhep $\rightarrow$ ReconstructedParticle
- Aim is to test the functionality, find what is missing, what still needs to be done. Include all steps:
  - SimHits digitized to TrackerHit and CalorimeterHit
  - Overlay of beam backgrounds
  - *ab initio* clustering, track finding, fitting, particle ID, etc.
  - NO reliance on MC information
- Aim is not to make the physics case, so pick something simple, but relevant.
- Start with tracking $\therefore$ $e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^- X$

Physics Signal

- Events generated using Pythia at $\sqrt{s} = 350$ GeV.
- Signal sample corresponds to 500 fb^{-1}.
- Z forced to decay to muon pairs.
- Higgs mass set to 120 GeV.



Backgrounds

- $e^+e^- \rightarrow ZZ^* \rightarrow \mu^+\mu^- X$
  - Generate with Pythia.
  - Represents an irreducible physics background.
  - Minimize impact by requiring central Z.
- $\gamma\gamma \rightarrow e^+e^-$
  - Generate pairs with GuineaPig.
- $\gamma\gamma \rightarrow \mu^+\mu^-$
  - Generate with locally modified whizard.
- $\gamma\gamma \rightarrow$ hadrons
  - Generate with locally modified whizard.

Overlay onto signal event.

Detector Simulation

- Use slic to simulate the response of the Silicon Detector baseline design (sid01).
  - Five-layer pixel tracking detector.
  - Five-layer silicon μ-strip tracking detector.
  - Barrel-Endcap transition @ $\cos\theta \sim 0.8$.
  - Finely segmented SiW electromagnetic calorimeter.
  - Steel-RPC hadron (1x1 cm readout) & μ calorimeter.
- Input is events in binary stdhep format.
- Output is LCIO containing lists of SimTrackerHit, SimCalorimeterHit and MCParticle.

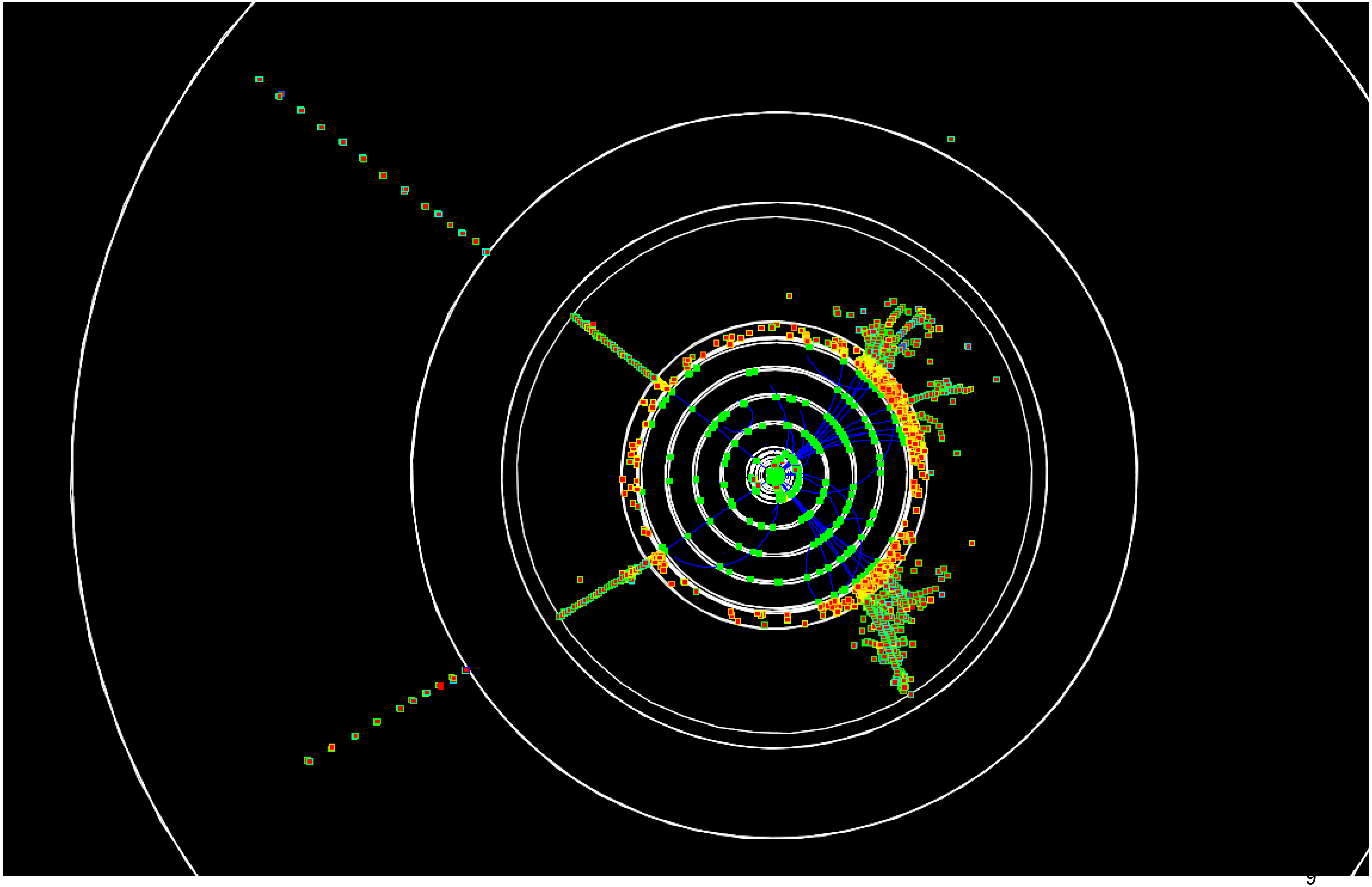
Background Overlay

- Make use of LCIO utilities to overlay beam backgrounds onto signal events at the hit level.
- MCParticles are appended to event list.
- SimCalorimeterHits:
  - If cell previously hit, update energy, time, and MCParticle contribution.
  - If not hit, add to event list.
- SimTrackerHits:
  - Add to event list. Will be digitized as part of the reconstruction.
- Time offsets correctly handled.

Reconstruction (Calorimeter & μ ID)

- Individual calorimeter cells consistent with energy deposition from a minimum-ionizing particle (MIP) are selected.
- A Nearest-Neighbor algorithm, with user-definable neighborhood domains for association, is used to cluster these cells in each of the calorimeters separately.
- Combine clusters found in different calorimeters (electromagnetic, hadronic and muon) and across detector boundaries (barrel and endcap).
- By requiring MIP traces in each of the calorimeters, one obtains a reasonably pure sample of clusters arising from high-energy muons traversing the detector.
- Impose an isolation criterion to remove muons coming from heavy quark decays.

Event Display



Tracker Digitization (VXD)

- SimTrackerHits from the vertex detector are converted into CCD pixels hits using a package developed by Nick Sinev.
- Calculates charge deposited in each pixel (including effects of diffusion and drift), adds electronics noise and digitizes the resulting signal, providing channel address and ADC count.
- Clustering software then associates contiguous pixels into clusters, splitting if necessary.
- The coordinates of the found cluster centroids are used to create TrackerHits.
- The user can set CCD parameters (like thickness, depleted layer depth, epitaxial layer thickness and so on), electronics parameters (noise, ADC conversion scale, pixel and cluster thresholds), and algorithm processing parameters (like cluster center calculation method).
- Other readout technologies can also be simulated (e.g. CMOS, short-column CCD, etc.)

Tracker Digitization (Central Tracker)

- Package to handle Si μ-strip digitization not yet released, so implement a hybrid solution for this analysis.
- Cylindrical surfaces of central barrel detectors segmented into Φ and Z regions to approximate the $10x10cm^2$ wafer modules.
- SiD design uses axial-only strip readout, so calculate the strip indices for all Monte Carlo hits within each module. No charge diffusion or drift.
- After digitizing all hits, cluster strips within each module using a simple nearest-neighbor algorithm.
- From these clusters we create TrackerHits.
  - Since we have neglected the charge sharing between strips caused by diffusion and the Lorentz drift, simply using the center of gravity of the clusters would overestimate the expected resolution of the detector measurement.
  - For single strip clusters (i.e. strips hit by only one Monte Carlo track), we create a TrackerHit by smearing the Monte Carlo φ position using a Gaussian of the expected tracker resolution (7μm).
  - Use width of cluster/$\sqrt{12}$ for larger clusters.

Track Finding and Fitting

- Use MIP clusters found and identified in the calorimeters to seed the track finding.
- Assuming high momentum tracks originating from the origin, create list of modules hit in the central tracker.
- Pick up axial hits and begin fitting to simple helix.
- Project helix into vertex detector to pick up hits in footprint of track.
- Perform final fit accounting for energy loss and multiple scattering.
- Output file contains list of ReconstructedParticle.

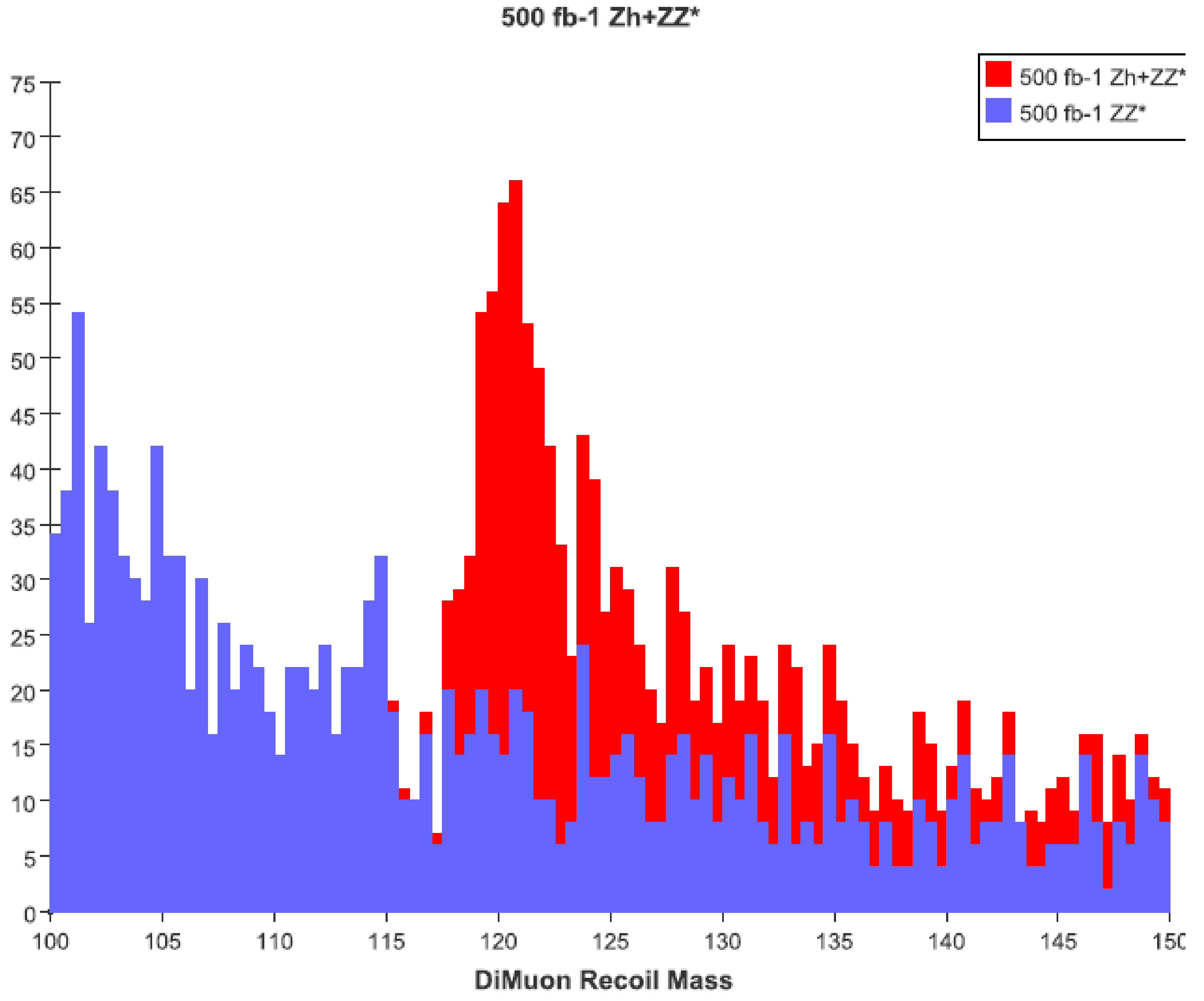
Recoil Mass Analysis: Event Selection

- Require two reconstructed muons
  - |cosθ| <~0.8 for both muons
  - momentum > 20 GeV
- Require dimuon invariant mass consistent with Z.
  - | dimuon mass – Z mass | < 5 GeV
- Construct "recoil mass", defined as:

$$M_H^{recoil} = \sqrt{s - 2\sqrt{s}E_{\mu^+\mu^-} + M^2_{\mu^+\mu^-}}$$

- where s is the nominal center of mass energy

Dimuon Recoil Mass



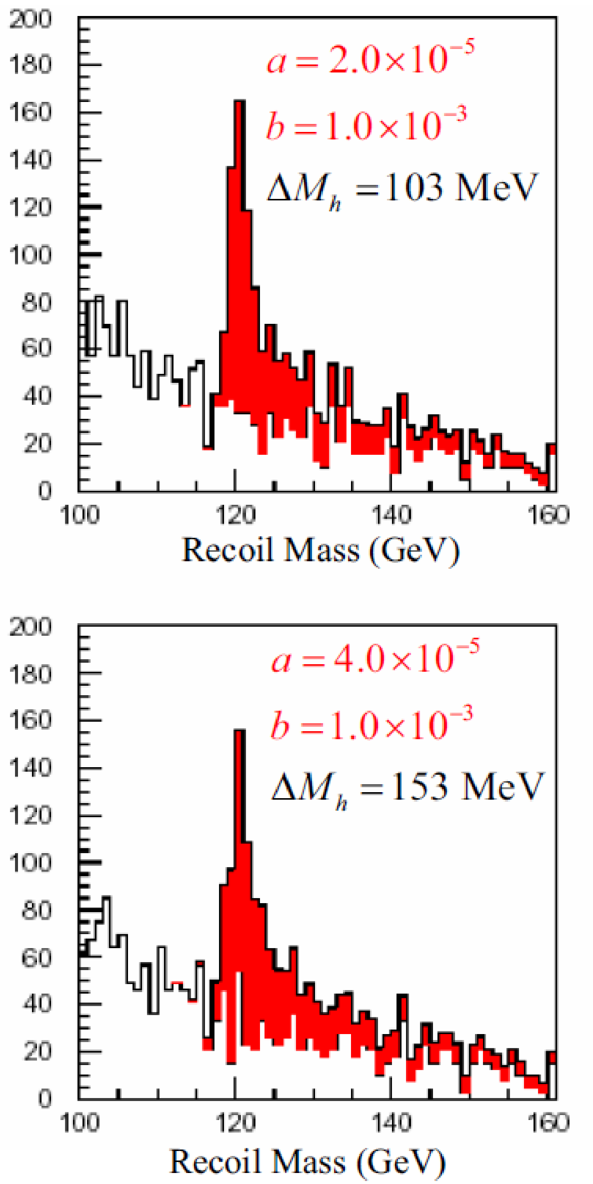
Recoil Mass Analysis: Fitting

- No analytic form for the “recoil mass” distribution.
- Extract the Higgs boson mass and uncertainty by fitting the measured “recoil mass‘” to a series of templates constructed with different Higgs boson masses.
- Templates created using the Fast Monte Carlo program in order to accumulate large statistics in a reasonable amount of time.
- Fit binned data histogram with each against templates.
- For sufficient statistics (and correct behavior), distribution of χ^2 should be parabolic.
  - minimum provides mass estimate.
  - value of ordinate at abscissa = minimum + ½ unit provides uncertainty.

Higgs Mass Results

- For this particular run, corresponding to 500fb^{-1} of integrated luminosity, we measure the Higgs mass to be 120.23 GeV.
- The uncertainty in this measurement is derived by repeating this exercise for an ensemble of experiments, and is estimated to be 135 MeV.

Comparison to fastMC



Measurement uncertainty commensurate with expectations from fast MC study.

To Do

- Investigate behavior with increasing numbers of background overlay events.
- Run over full 1ab^{-1} Standard Model sample.
- Investigate systematics caused by using fastMC in the generation of fitting templates.
  - Fully characterize concordance between fastMC and full track fitting.
  - Run only mu pairs through full detector simulation to generate templates.
- Fit using unbinned Maximum Likelihood.
- Improve and optimize event selection cuts.

To Do II

- Improve the silicon strip digitization model.
- Investigate different detector models, configurations and topologies.
- Expand coverage into forward region.
  - Requires a tiling model for the forward “disks”.
- Improve tracking detector realism.
  - Replace cylindrical barrels with wafer modules.

Summary

- The simulation and reconstruction toolkit is capable of an end-to-end analysis, incorporating backgrounds, digitization, and *ab initio* reconstruction, albeit a fairly simple one.
- Looking forward to incorporating the full individual particle reconstruction and moving on to quark physics.
- Has been a useful exercise, pointed out a number of deficiencies and weaknesses.
- Much room for improvement, but we won't know what we are missing until we start using the tools in earnest.
- Fully committed to collaborating and cooperating with the regional efforts.
- We have much in common, should exploit that.

Going Forward

- Strongly urge all physics groups to target stdhep as input and to implement their analyses using LCIO ReconstructedParticle lists.
- Physics Analyses should use common set of physics events, backgrounds, and machine backgrounds.
  - $1ab^{-1}$ Standard Model sample exists.
  - Central repository for GuineaPig/CAIN events, etc.
- Would like to have an array of released analyses available to independently compare results of detector simulation and event reconstruction using physics metrics.
- Such interoperability would go a long way towards ensuring fair and efficient comparisons.