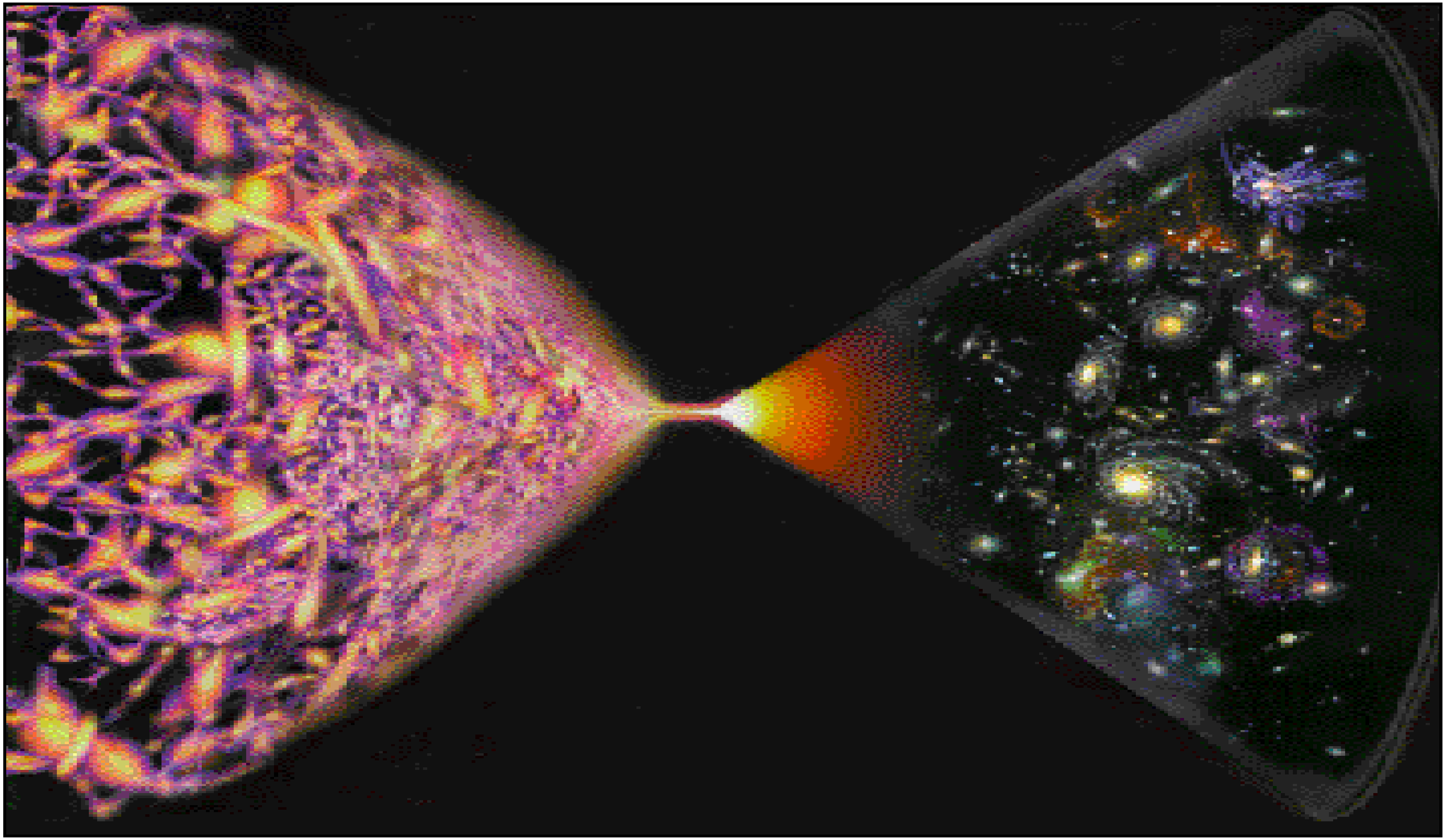
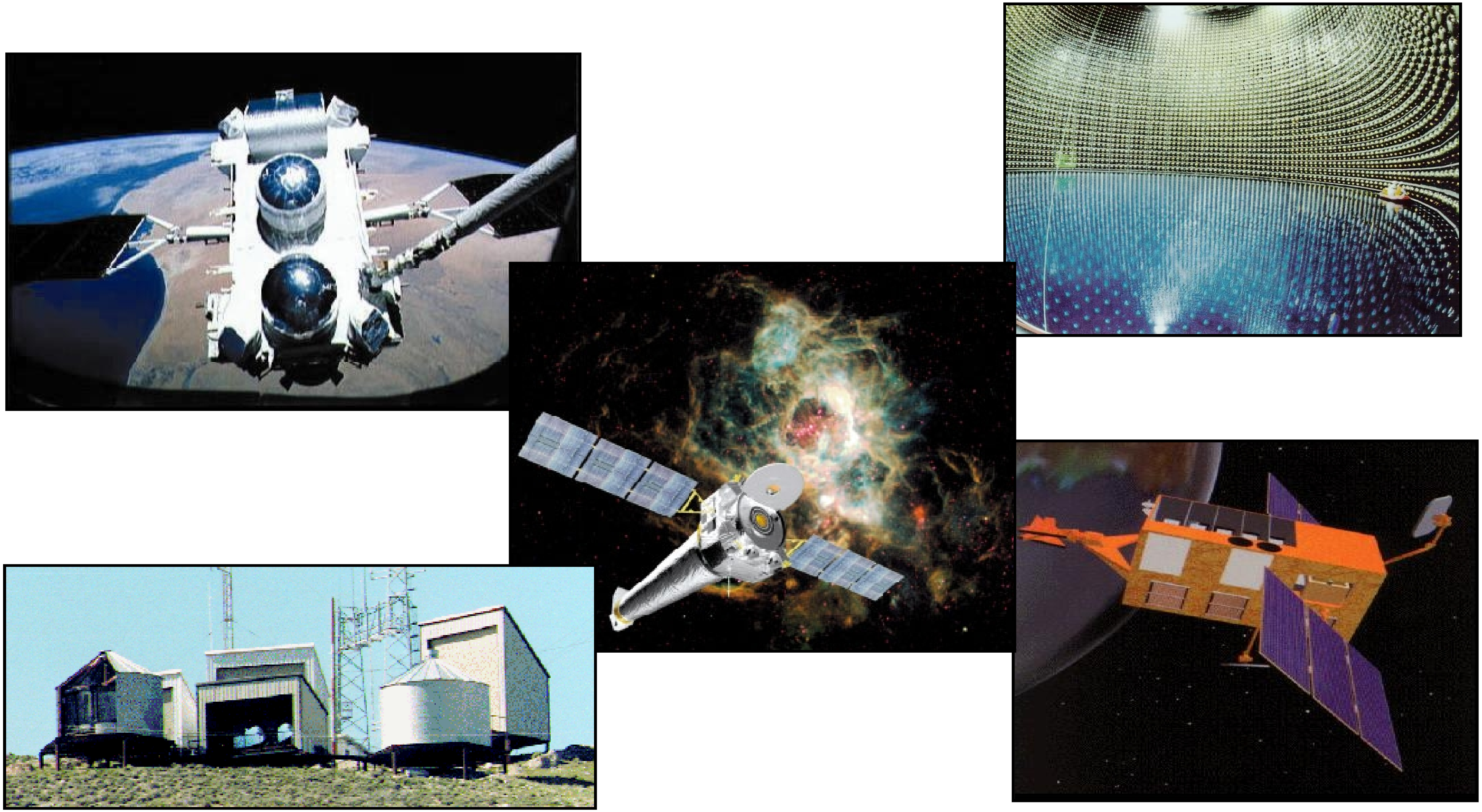
Supersymmetry, Extra Dimensions, and the Origin of Mass:

Exploring the Nature of the Universe Using PetascaleData Analysis

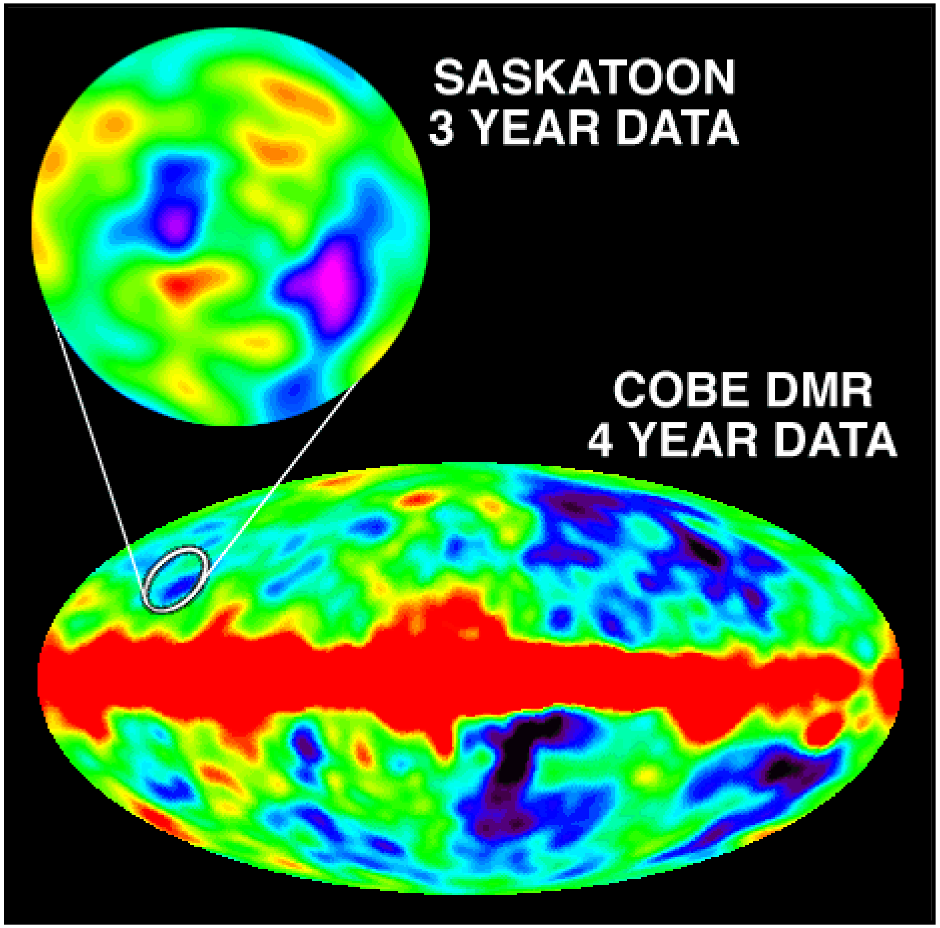


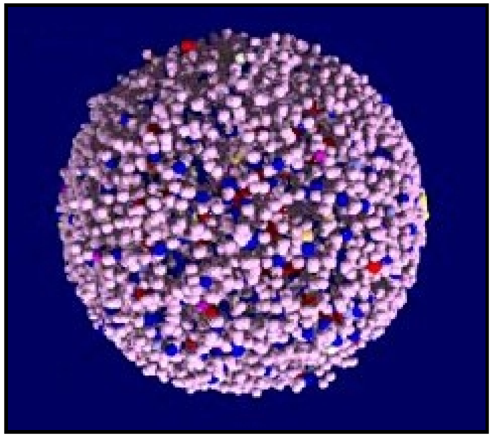
Marjorie Shapiro UCB/LBL
June 18, 2007

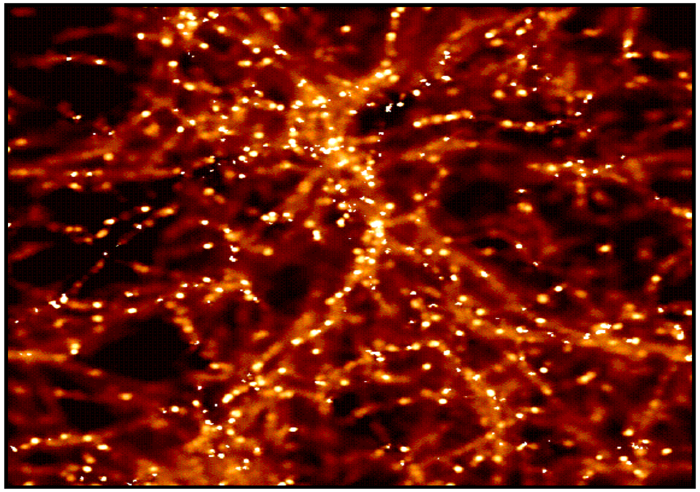
The Universe is a Laboratory



New Era of High Precision Astrophysics Observations





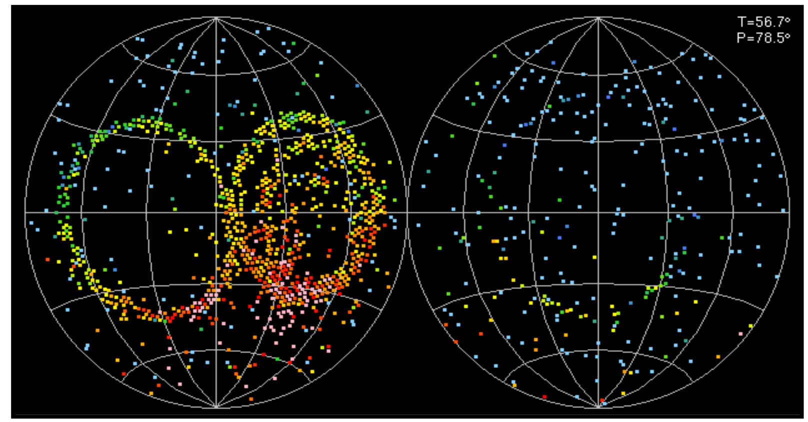


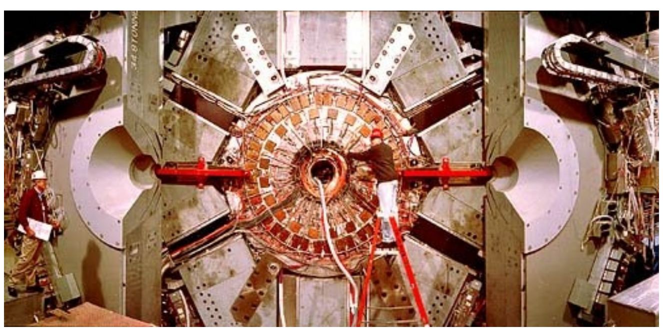
Images of the Early Universe

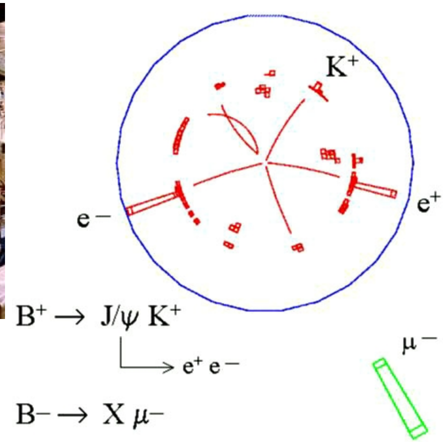
But Laboratory Measurements Can Also Tell Us About the Universe

Neutrino Interactions from SuperKamiokande

From the sun



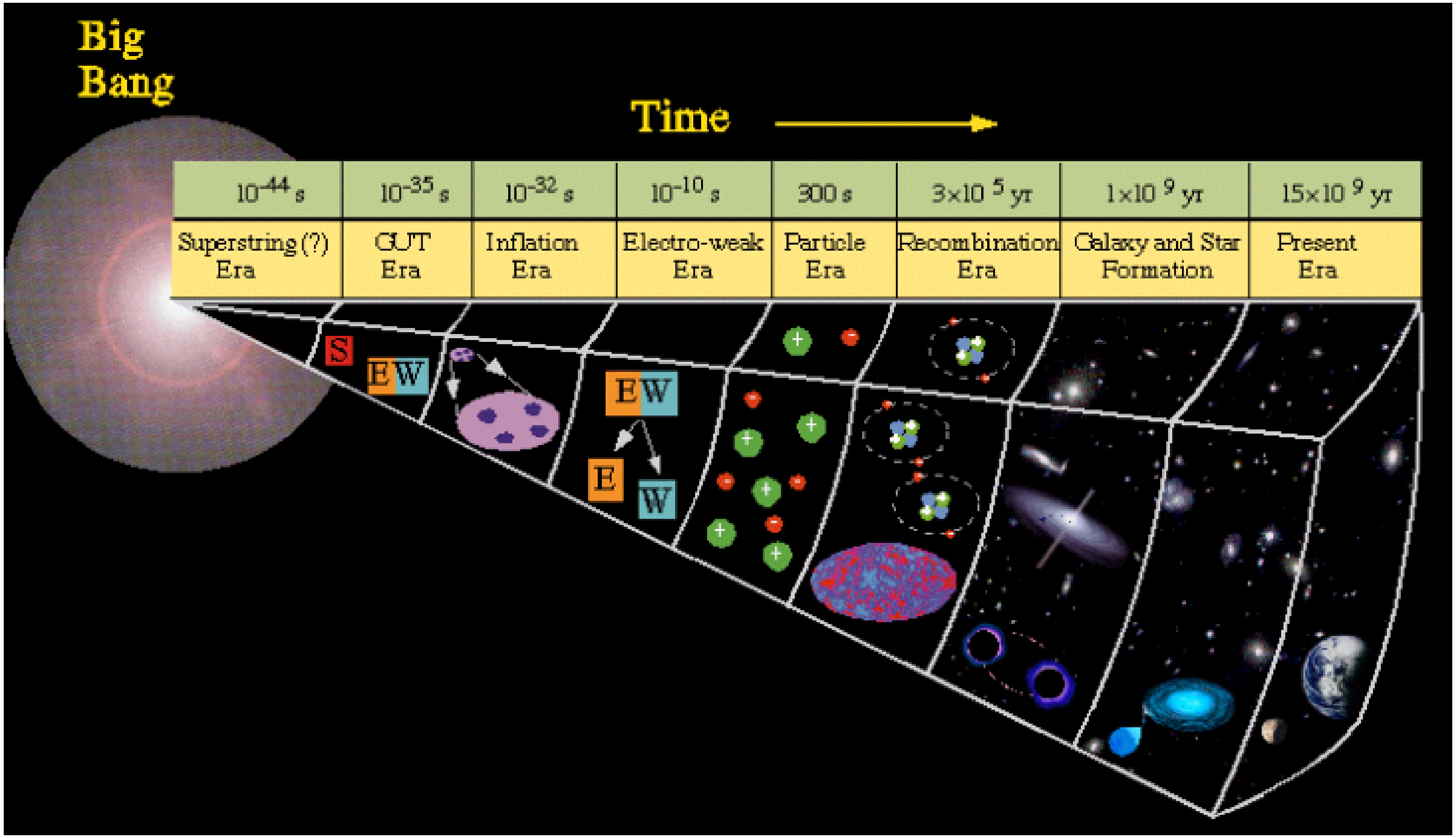




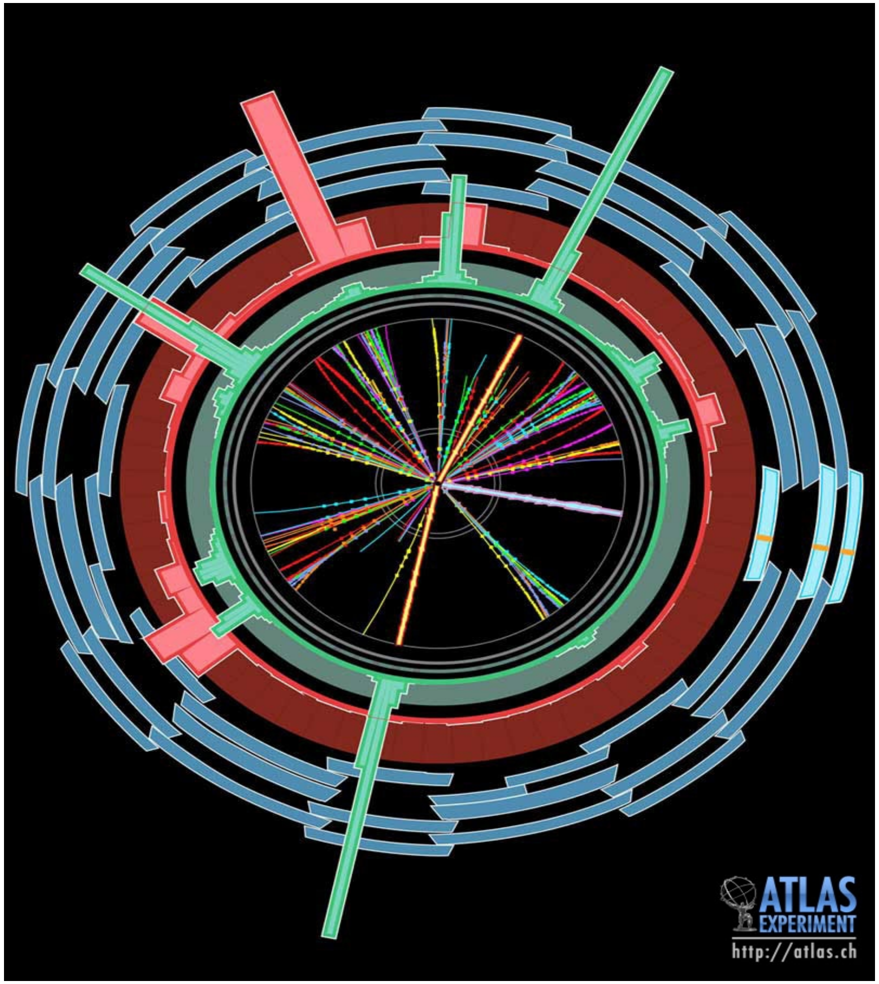
Matter-antimatter asymmetry from SLAC

Accelerator-based

Description of Early Universe Requires Knowledge of the Particles and Interactions that Existed



The Next Generation of Accelerator-Based Experiments Especially Critical



Simulated Event

- Higher energy: Reproduce conditions of early Universe
- TeV energy scale: Expect breakdown of current calculations unless a new interaction or phenomenon appears
- Many theories, but need data to distinguish between them

What Might We Find?

- The mechanism that generates mass for all elementary particles
  - In Standard Model, masses generated through interaction with a new particle the Higgs
  - Other options possible , but we know that the phenomena occurs somewhere between 100 and 1000 GeV
- A New Symmetry of Nature
  - Supersymmetry gives each particle a partner
  - Would provide one source of the Dark Matter observed in the Universe
- Extra Space-Time Dimensions
  - String theory inspired
  - This would revolutionize Physics !

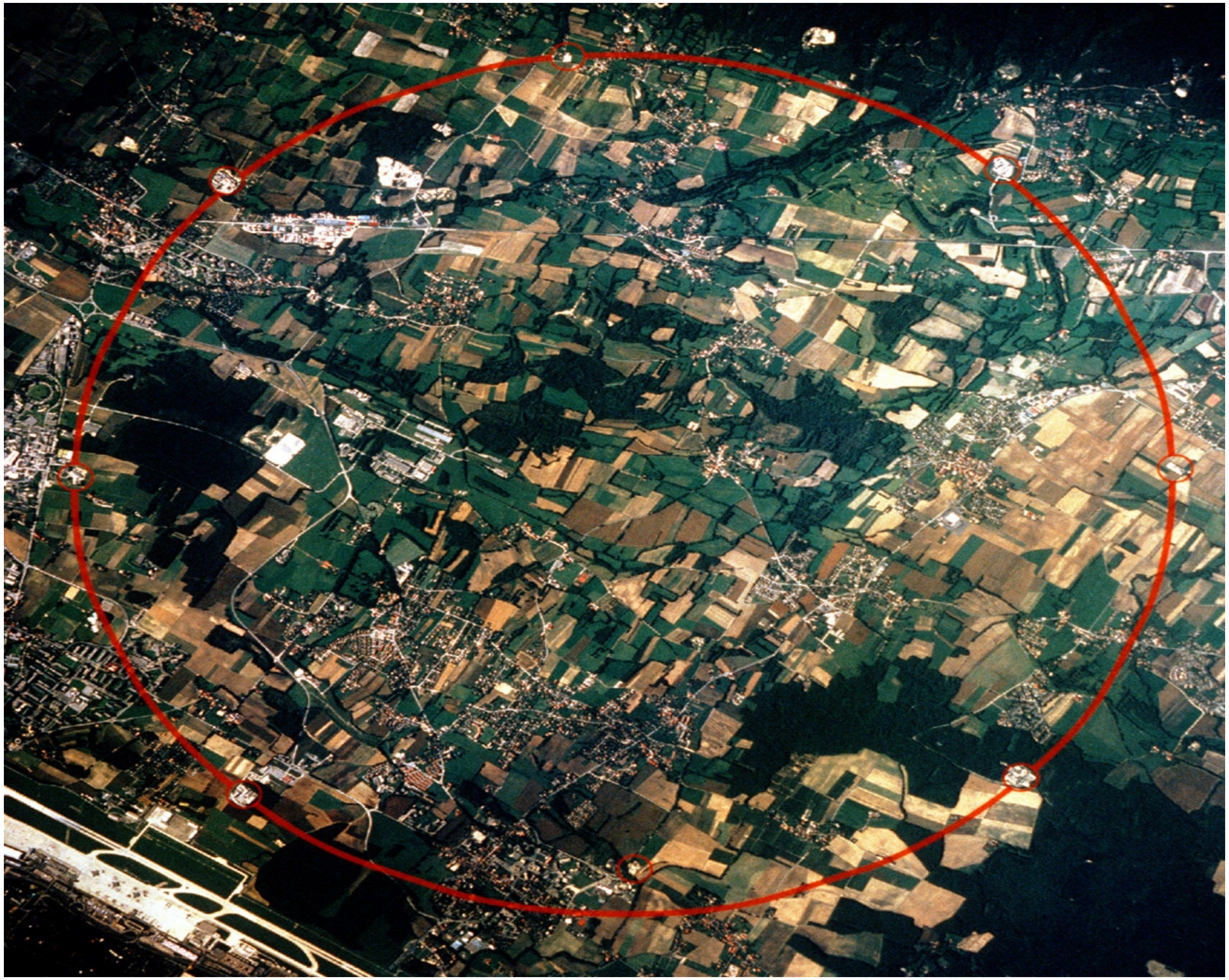
These are only some of the possiblities

The Next Machine: Large Hadron Collider (LHC)

- Energy: 14 TeV (7 x current best)
- Intensity:
  - Initial 10 fb^{-1}/year (5 x current best)
- First Data: Summer 2008
- Operation in "initial luminosity" mode for 1st 3 years, followed by an intensity upgrade

New energy frontier, so discoveries possible even in very early data !

LHC: Located at CERN (Geneva, Switzerland)



Uses LEP tunnel (24 Kilometer Circumference)

Challenge of Working at the LHC

- High energy collisions require COMPLEX detectors
  - Need BIG detectors to capture all the energy released in the collisions
  - Need fine segmentation to separately detect the hundreds of particles produced

- The processes we care about are RARE
  - Need high intensity to insure a measurable rate to observe them
  - But this intensity means many more common interactions occur as well

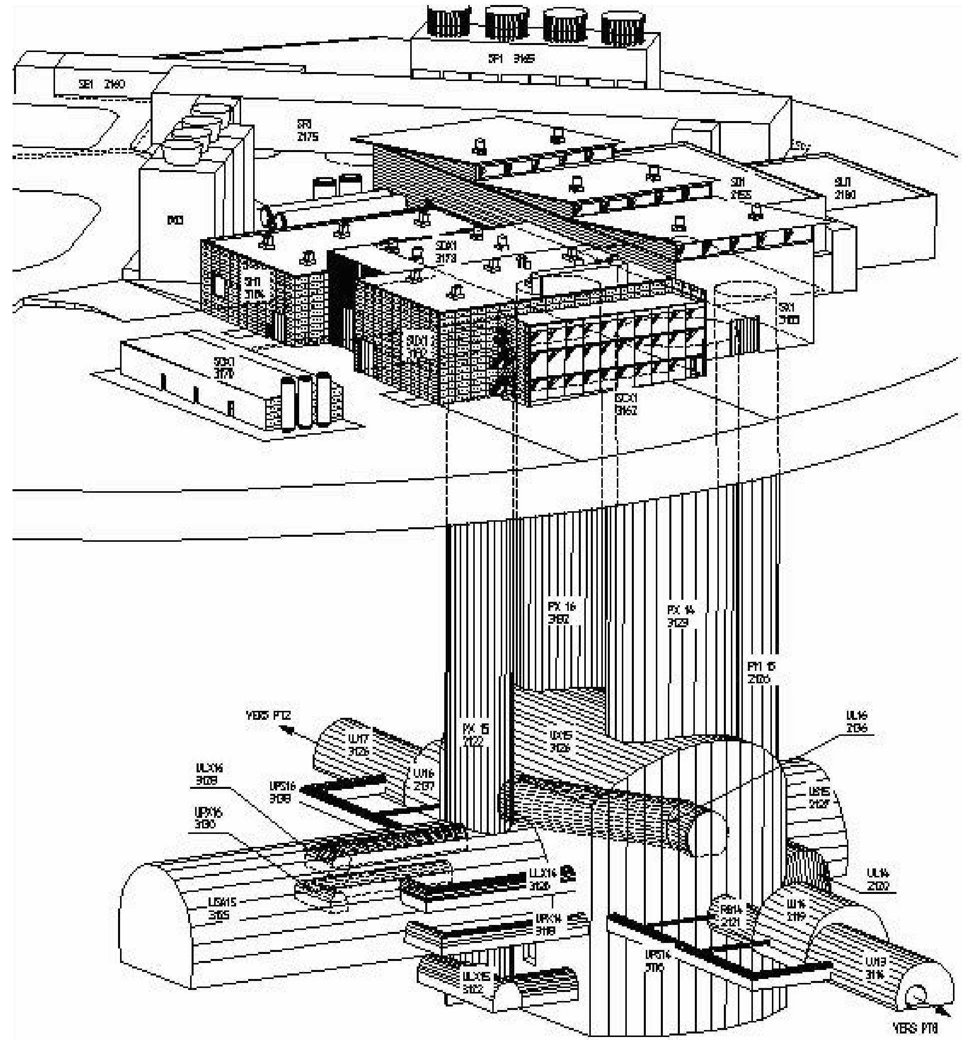
The needle in the haystack....

Detectors for the LHC

- Two Big Detectors Designed to Study Physics at the High Energy Frontier
  - ATLAS and CMS
  - Similar goals, different design trade-offs
- One Detector Optimize to Study B-Decays
  - LHCB
- One Detector Optimized for Heavy Ion Collisions
  - Alice

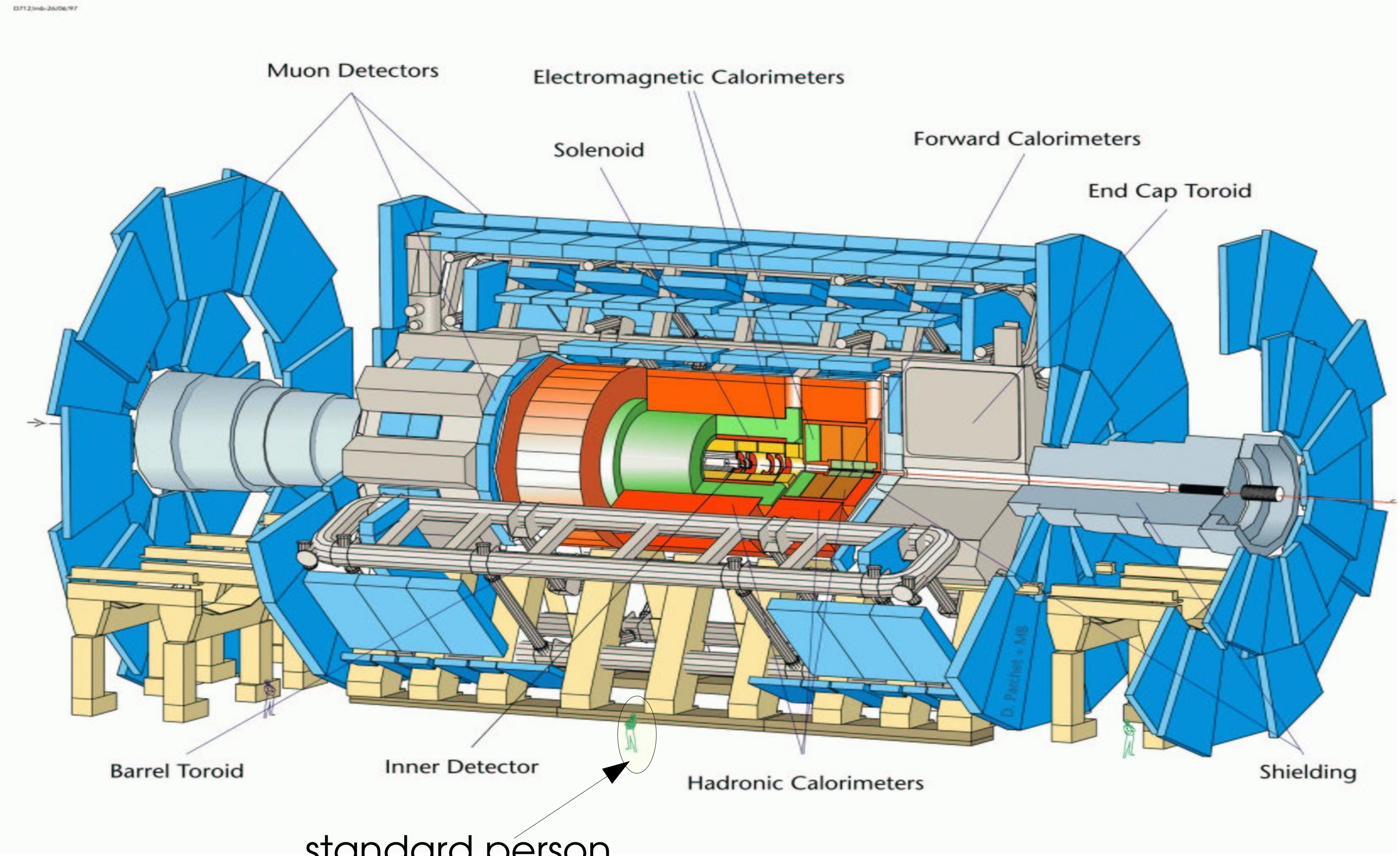
I will concentrate on ATLAS: my experiment

ATLAS is BIG!!



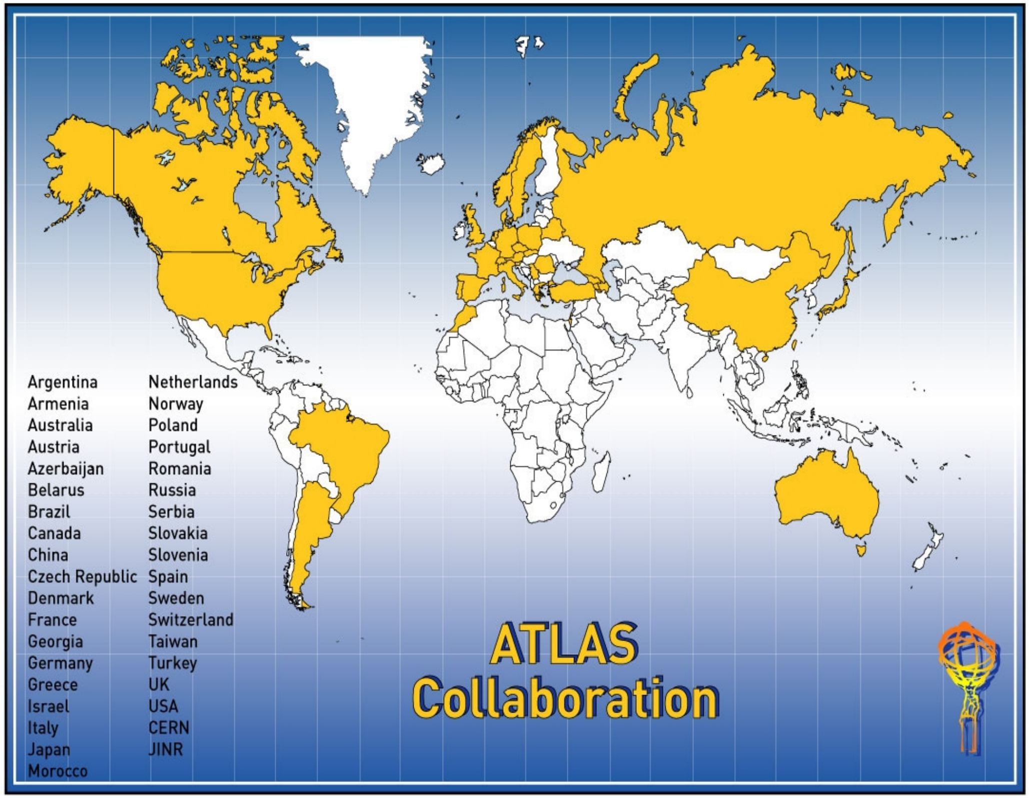
Superimpose ATLAS detector on
5 story LHC office building
for scale

ATLAS is Complex



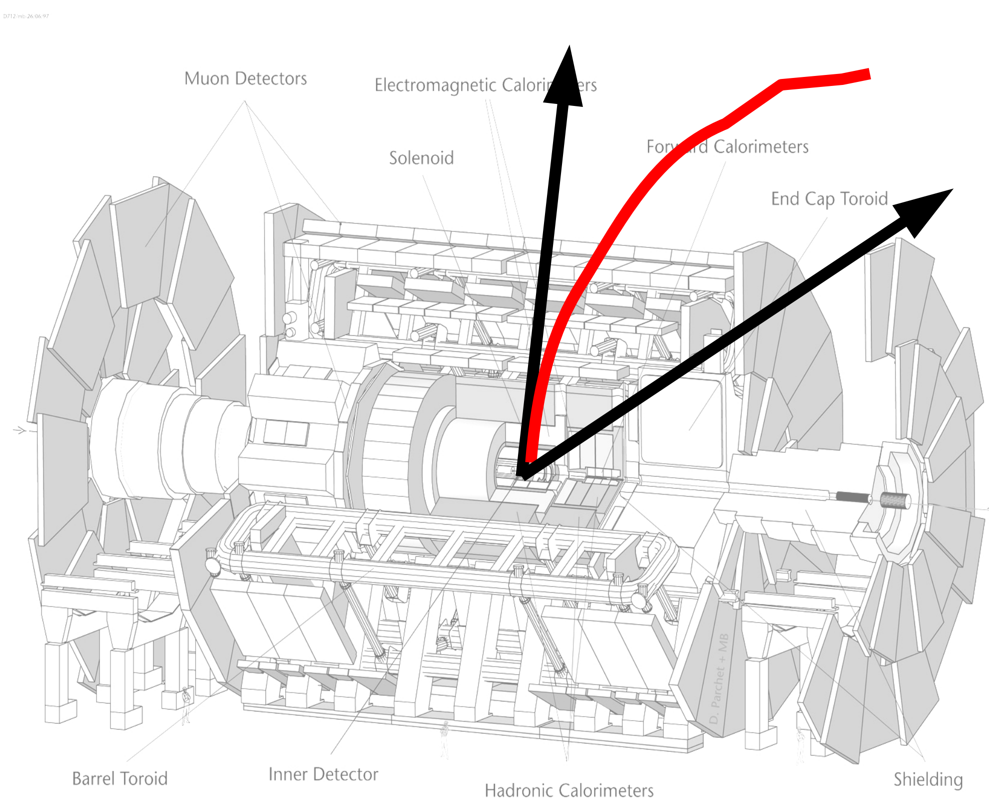
standard person

ATLAS Built and Operated by a Large Team



Worldwide Collaboration of Over 2000 physicists and engineers

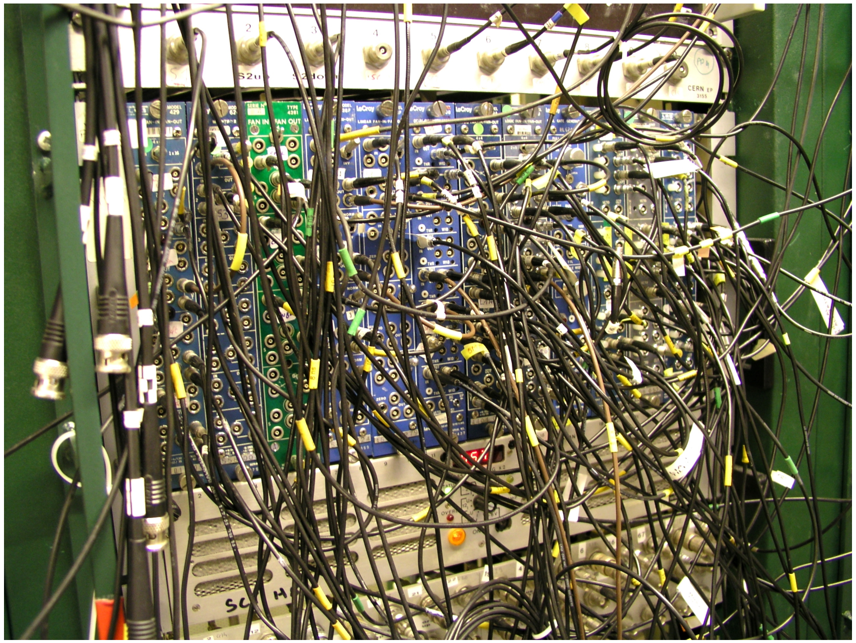
Particles Recorded in Terms of:

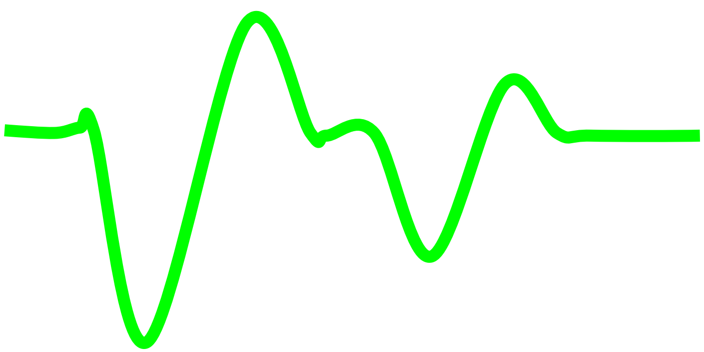


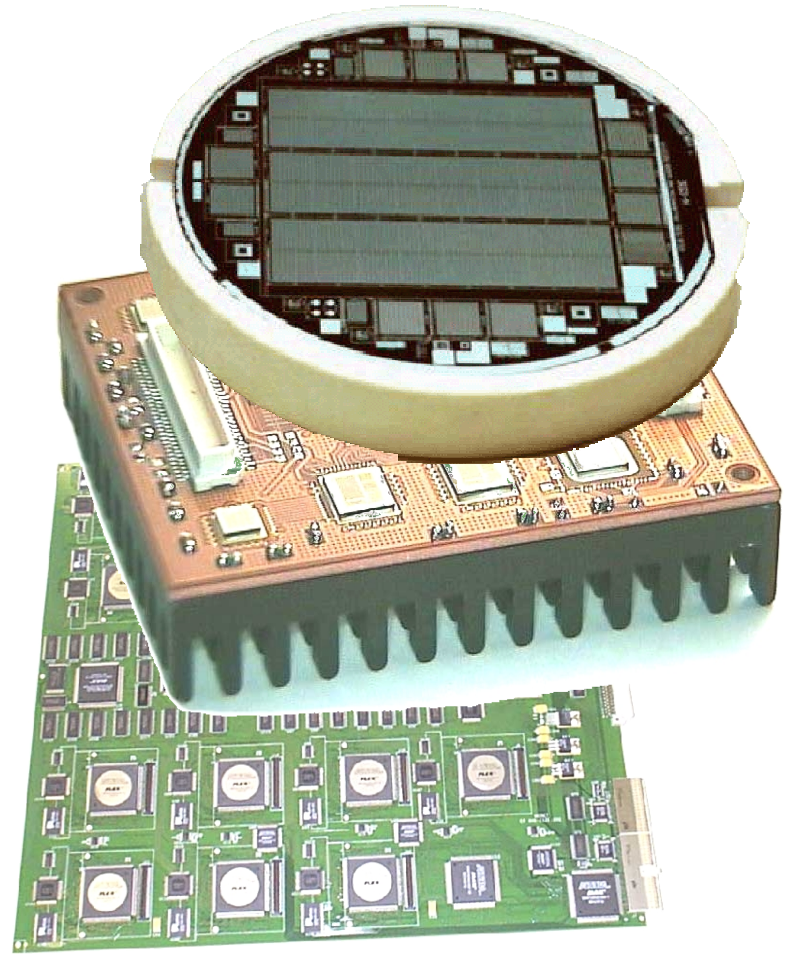
- Time
- Location
- Momentum
- Energy
- Charge

From which the particles are identified and characteristics of the interaction inferred

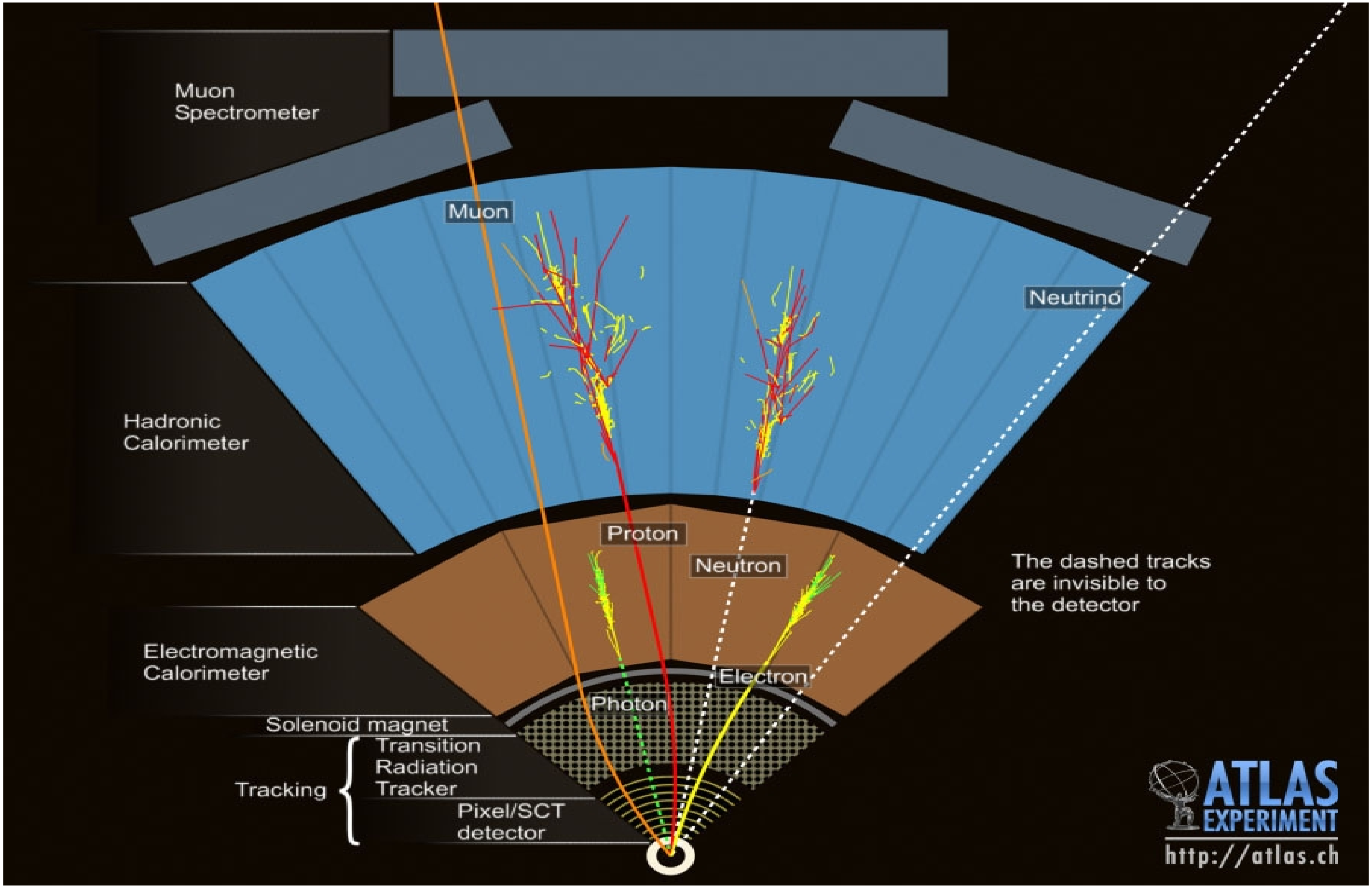
Highly Specialized Custom Electronics and Data Acquisition Systems







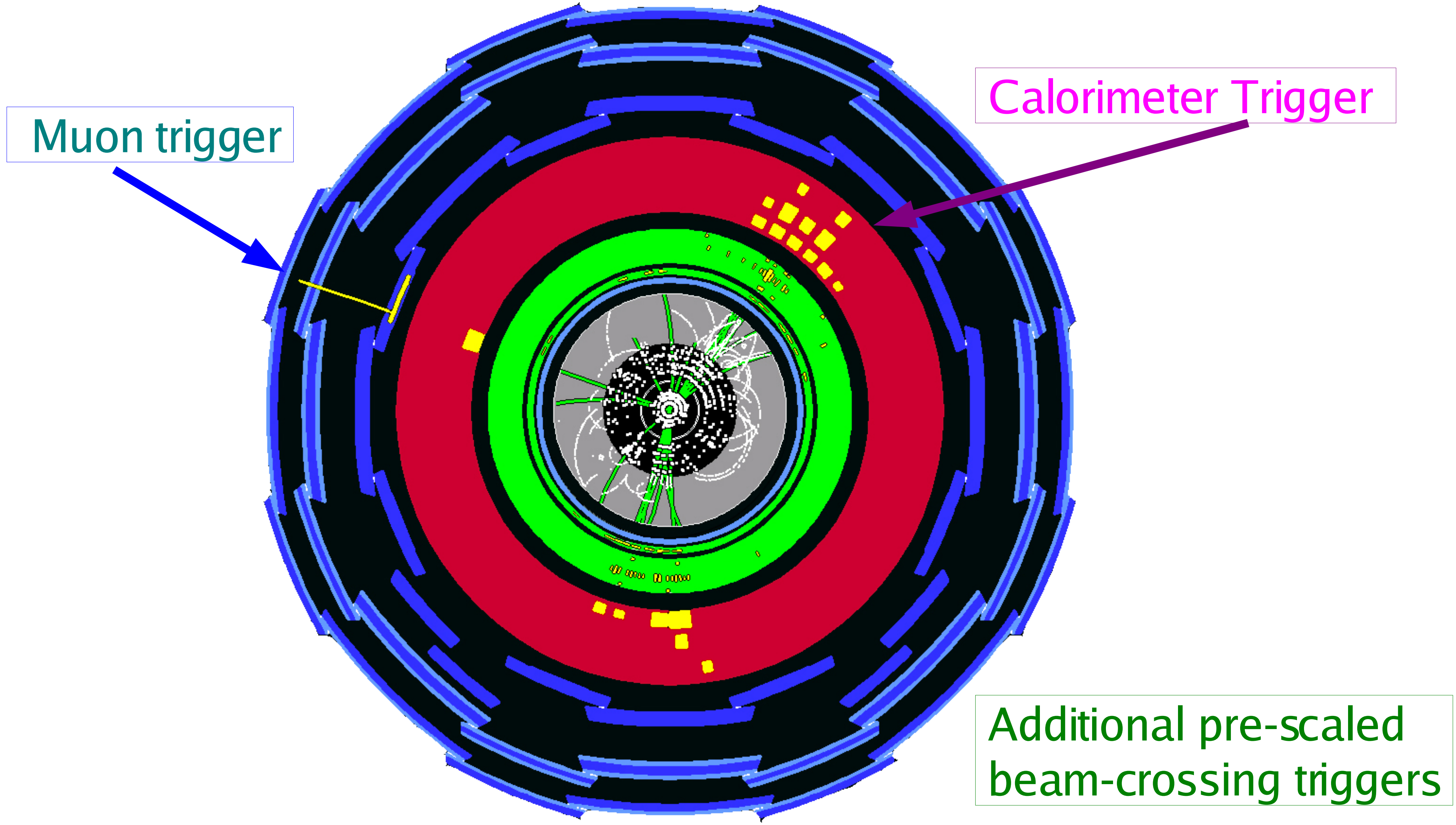
A Schematic View of How It Works



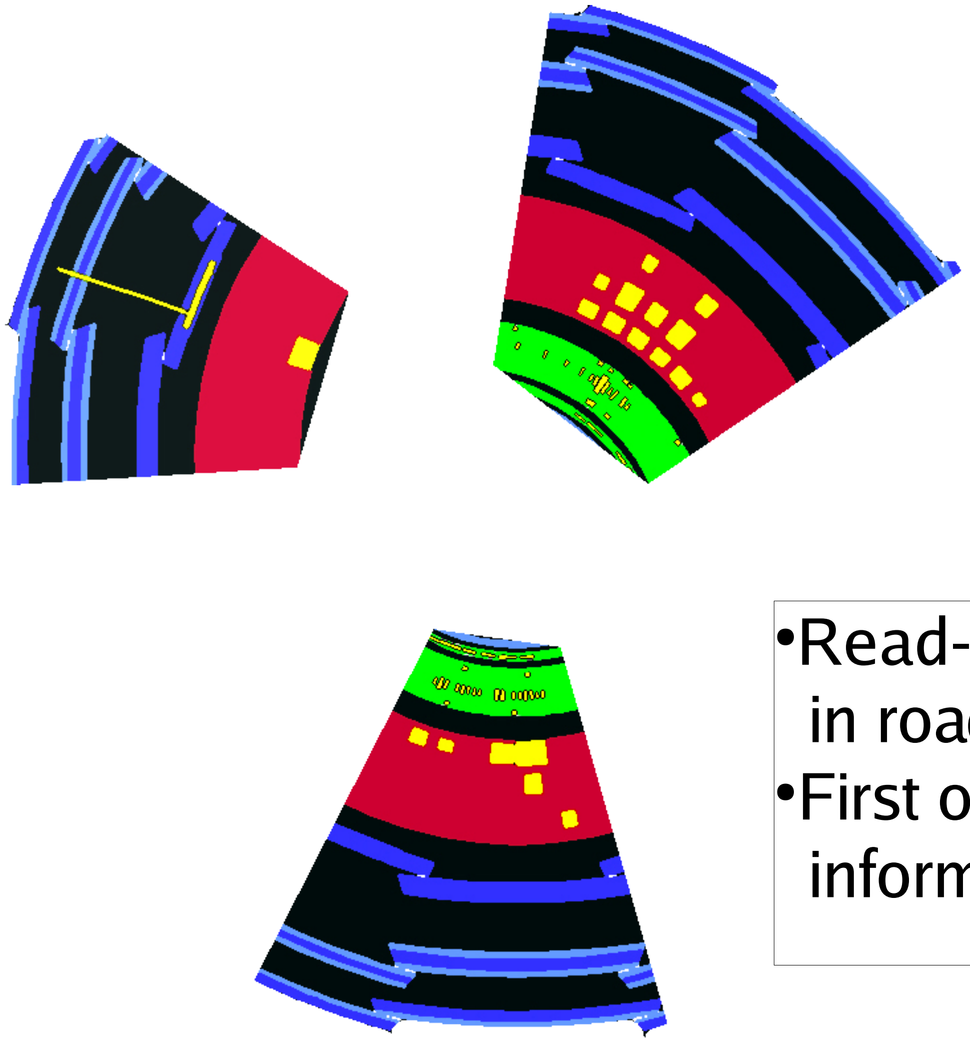
Triggering: Real Time Event Selection

- Beams collide every 25 nsec
- Something happens every crossing
- Can only record a small fraction of the events
- Must select the "interesting" ones
- Three Level Trigger:
  - Level 1: Specialized electronics to select candidate events
    100 kHz accept rate:
  - Level 2: PC-based analysis of "Region of Interest"da ta around L1 Triggers
    3 kHz accept rate
  - Level 3: PC-based analysis of data from whole detector
    - 200 Hz accept rate
- Resulting data written to tape for offline processing

Level 1 Trigger



Level 2 Trigger: Region of Interest



- Read-out all detector elements in road around each trigger
- First opportunity to use tracking information

Level 3: Putting It All Together

- Complex selections based on detailed reconstruction of event
- Decision path depends on which Level 1 and Level 2 triggers passed

Offline Reconstruction

- Data passing Level 3 trigger archived to tape and further processed in "offline" environment
- Common processing for whole collaboration
- Detailed calibration, pattern recognition, feature extraction
- Hierarchy of data:
  - Bytestream: Archived raw data
  - ESD: (Event Summary Data) Results of Reconstruction with calibrated hits
  - AOD (Analysis Object Data) Summary of reconstruction
  - Tag: High level summary for event queries

ATLAS Collects LOTS of Data

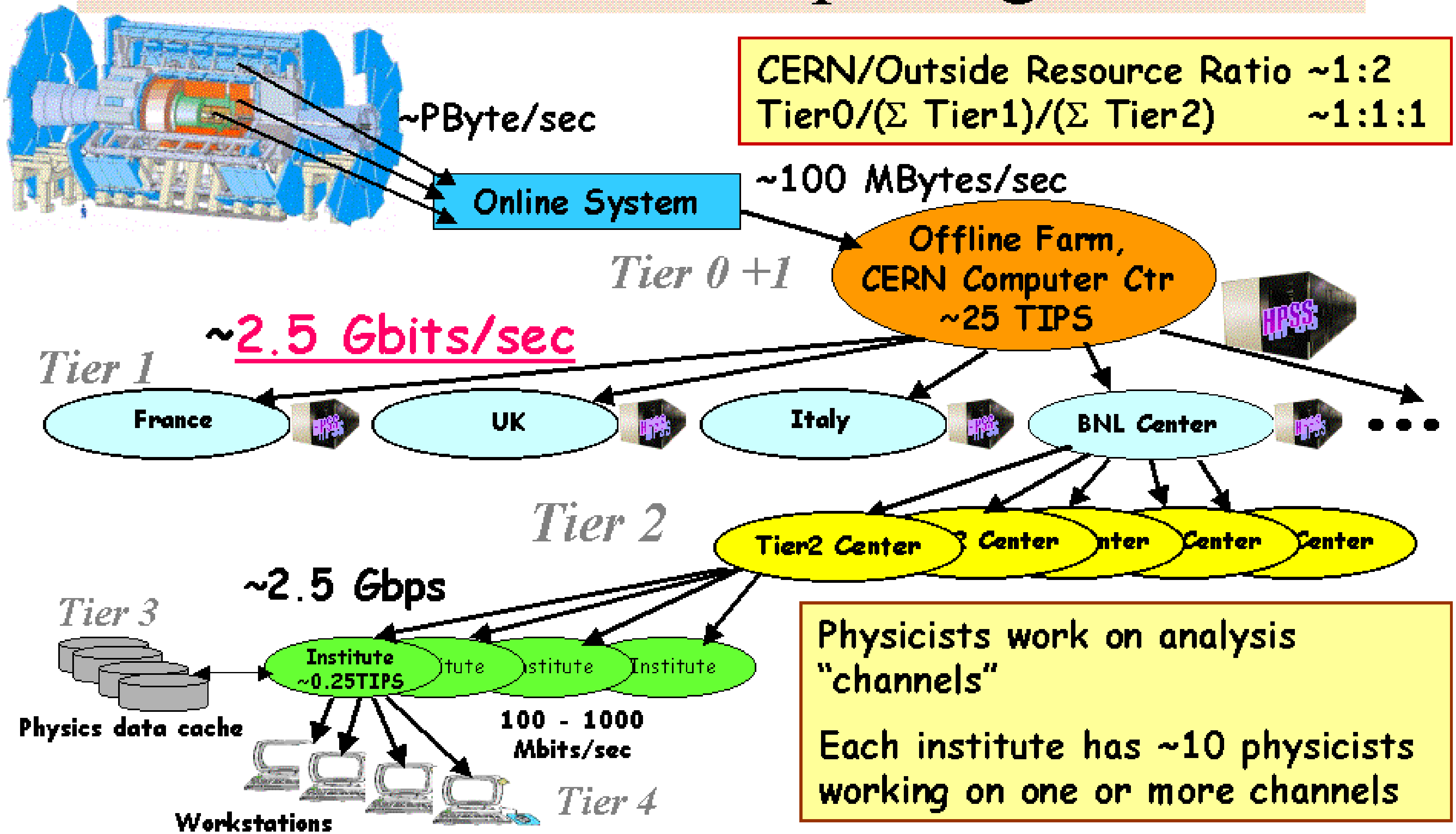
Raw Data Size	1.6 MB
ESD Size	0.5 MB
AOD Size	100 KB
TAG Size	1 KB
Simulated Data Size	2.0 MB
Simulated ESD Size	0.5 MB
Time for Reconstruction	15 k512k-sec/event
Time for Simulation	100 kS12k-sec/event
Event Rate After Trigger	200 Hz
Operation Time	200 days/year
Event Statistics	$2x10^9$ events/year

PB scale Data samples
Large CPU usage

How Do Physicists Work With the Data?

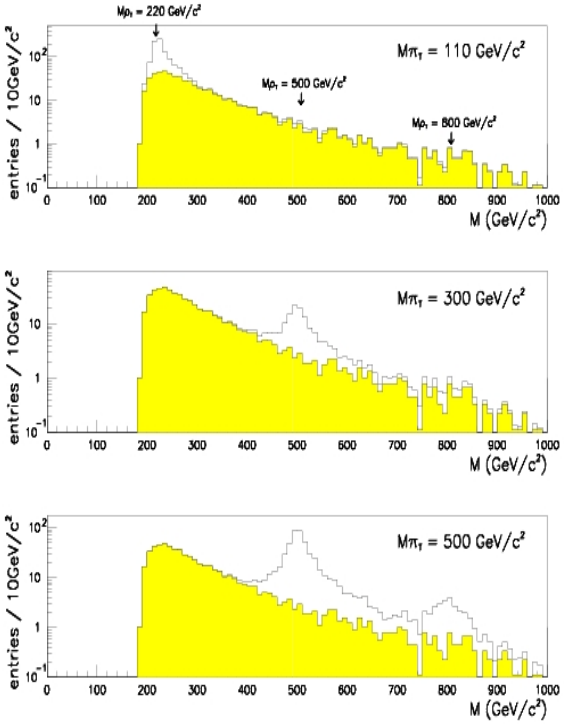
- Bulk reconstruction processing MUST be done centrally (too CPU and IO intensive)
- Processed data is the starting point for analysis
- Stream data according to trigger and physics channel
- Distribute data to multiple sites
- Develop infrastructure to allow distributed analysis and data mining

Hierarchical Computing Model



How Do Physicists Analyze Data?

- Not primarily via event visualization
  - Viewing single events mainly a debugging tool
- Instead statistical analysis of ensembles of events
  - Compare observed rates for given process to predictions of theory+detector simulation
  - Search for deviations from predictions
  - Characteristics of deviation are hints of the new physics
- Requires ability to model both physics and detector in detail



Simulated Data with New Resonances

Some Comments on Software

- Lifetime of Experiment 10-20 years
  - Longer than lifetime of an OS
  - Longer than term of many developers
- Code shared by several thousand people
  - Robustness and documentation key
- Use patterns likely to change with time
  - Need for flexible system
- Input parameters for reconstruction and analysis improve as we learn more
  - SQL database for constants
- Need to find data and know how it was processed
  - Access to processing metadata via database

Chosen Software Architecture

- Multipurpose C++ framework
  - Well defined abstract interfaces
  - Plug-in components (services, algorithms, tools)
  - Dynamic loading of classes
  - Python bindings for run-time configuration
- Data objects with persistent/transient separation
  - Schema evolution by brute force (code)
  - Persistent representation optimized for IO performance
- Interval of validity service to update
  - C++ handle with call-backs
  - Encapsulates interface to database
  - multiple DB implementations: select at run time
- CERN-developed Root analysis package
  - PyRoot to access same data objects as within framework

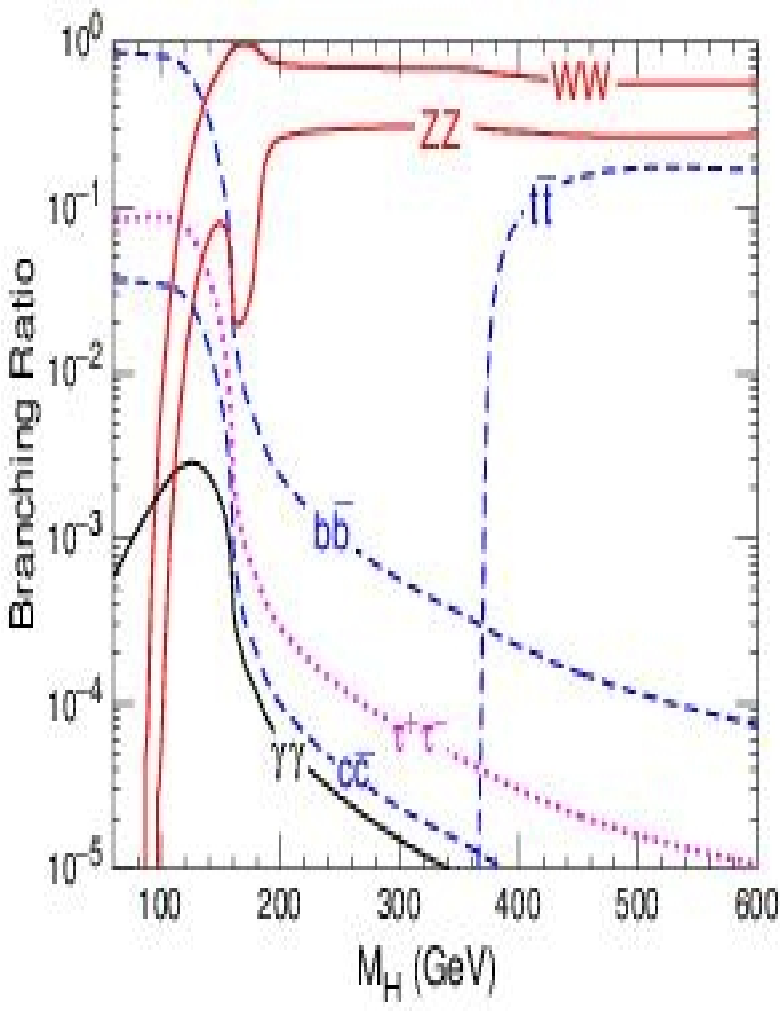
The Big Unknowns

- How well will distributed data model work?
  - "Bring code to the data" requires knowledge of what data will be uses
  - Hierarchical data model assumes most queries can live with AOD or TAG only
- How often will we need to re-reeconstruct?
  - Current model assumes once per year
- How easy is it to share code and data?

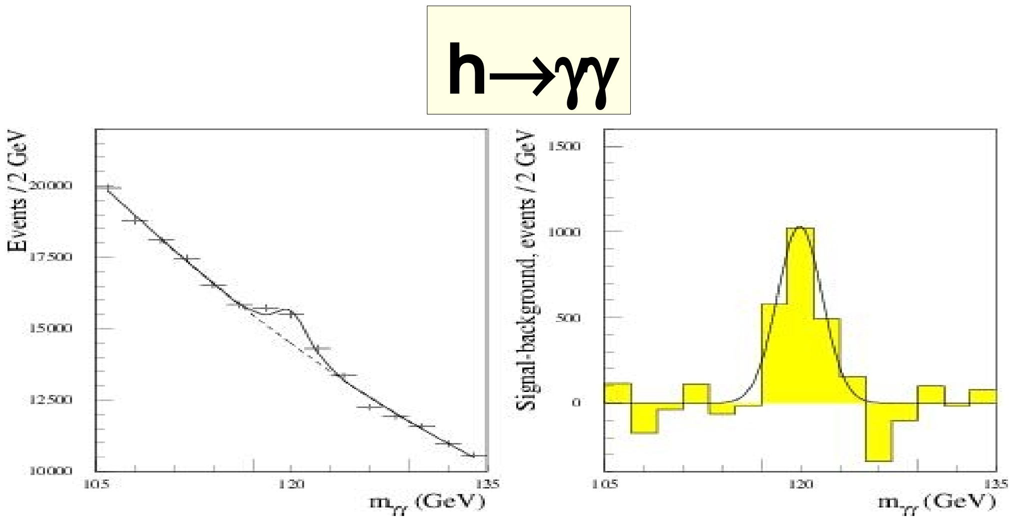
Attempt to test these ideas via Computing System Commissioning (mock data challenge)

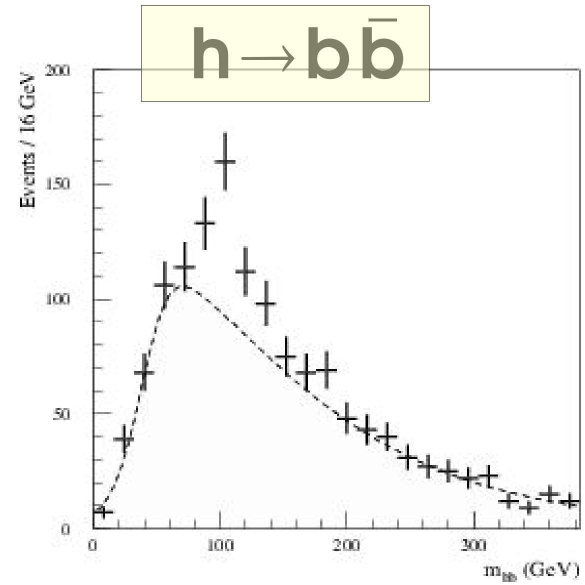
Example I: Searching for the SM Higgs

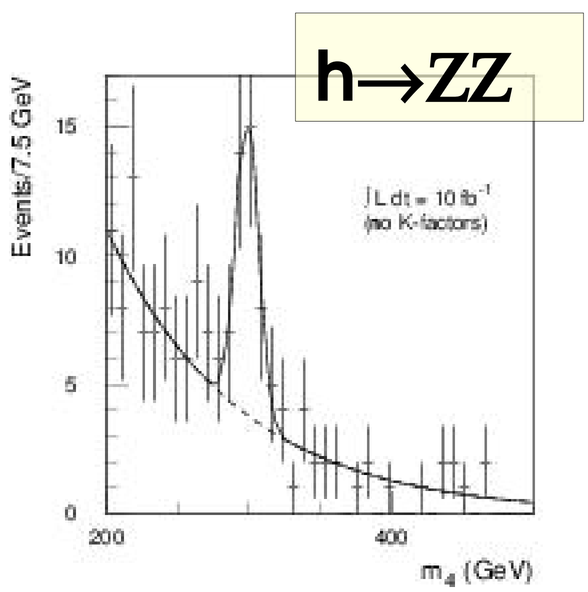
- Higgs gives mass to all other particles
- Higgs decay modes depend on Higgs' mass
- Higgs couples to heavies accessible particles
- Some modes easier to observe than others
- Greatest experimental difficulties in low mass region

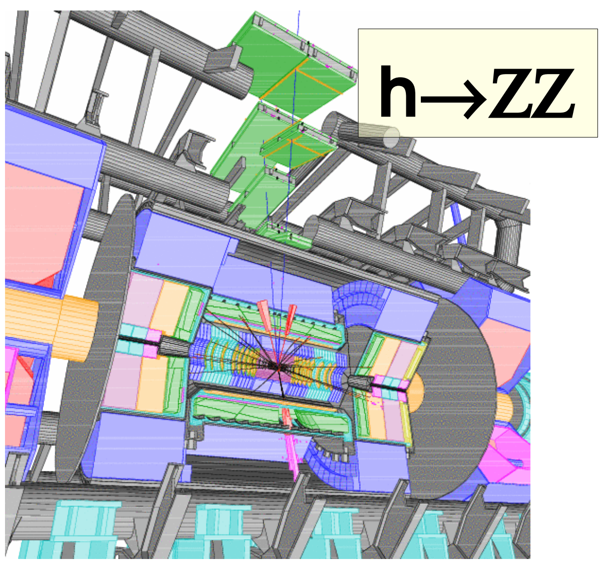


Observing the Higgs With ATLAS:
Must Search in Mulitple Modes









Example II: Supersymmetry (SUSY)

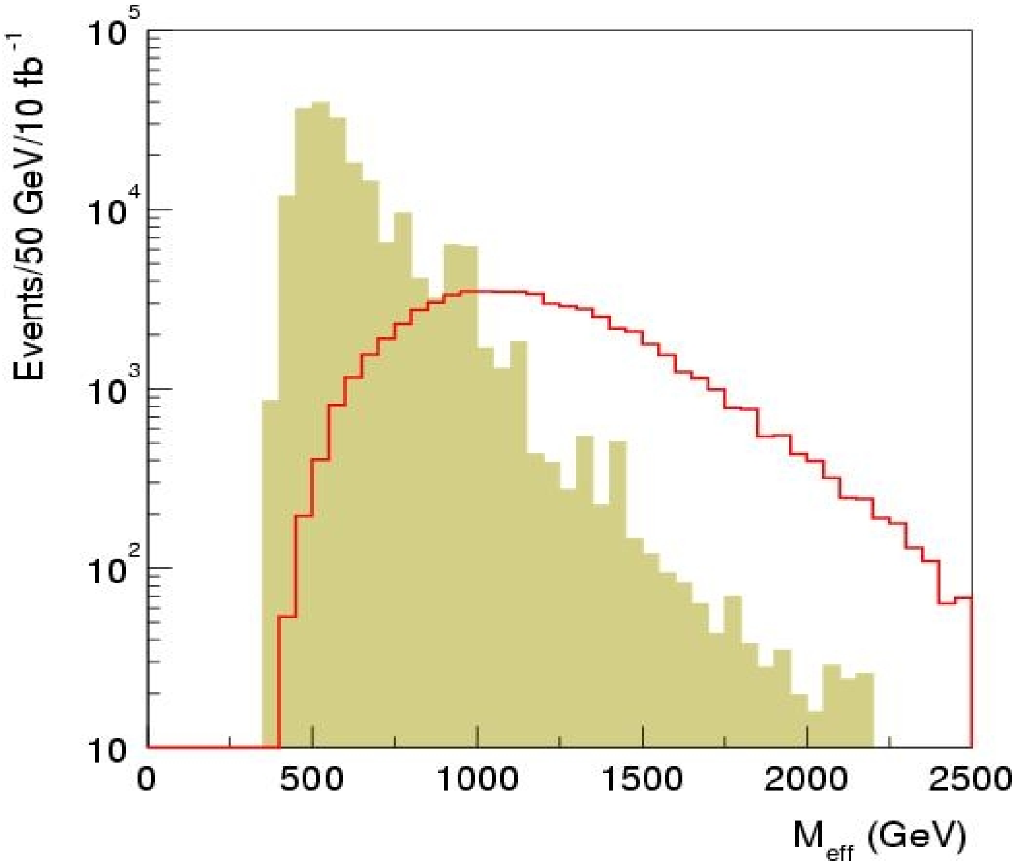
- Partner for every known particle
  - Fermions have spin 0 partners
  - Bosons have spin ½ partners
- Theoretically favored extension to SM
  - Solves hierarchy problem (sparticle and particle loops cancel)
  - Provides Dark Matter candidate
  - Required by String Theory (but not necessarily at EWSB scale)
- 5 Higgs bosons (h, H, A, $H^{\pm}$)

Standard Model Particles		SUSY Partners		
Particles	States	Sparticles	States	Mixtures
quarks (q)	$\binom{u}{d}_L$, u_R, d_R	squarks ($\tilde{q}$)	$\binom{\tilde{u}}{\tilde{d}}_L$, $\tilde{u}_R$, $\tilde{d}_R$	
(spin-$\frac{1}{2}$)	$\binom{c}{s}_L$, c_R, s_R	(spin-0)	$\binom{\tilde{c}}{\tilde{s}}_L$, $\tilde{c}_R$, $\tilde{s}_R$	
	$\binom{t}{b}_L$, t_R, b_R		$\binom{\tilde{t}}{\tilde{b}}_L$, $\tilde{t}_R$, $\tilde{b}_R$	$\tilde{t}_{1,2}$, $\tilde{b}_{1,2}$
leptons (l)	$\binom{e}{\nu_e}_L$, e_R	sleptons ($\tilde{l}$)	$\binom{\tilde{e}}{\tilde{\nu}_e}_L$, $\tilde{e}_R$	
(spin-$\frac{1}{2}$)	$\binom{\mu}{\nu_\mu}_L$, μ_R	(spin-0)	$\binom{\tilde{\mu}}{\tilde{\nu}_\mu}_L$, $\tilde{\mu}_R$	
	$\binom{\tau}{\nu_\tau}_L$, τ_R		$\binom{\tilde{\tau}}{\tilde{\nu}_\tau}_L$, $\tilde{\tau}_R$	$\tilde{\tau}_{1,2}$
gauge/Higgs bosons	g, Z, γ, h, H, A	gauginos/Higgsinos	$\tilde{g}$, $\tilde{Z}$, $\tilde{\gamma}$, $\tilde{H}^0_1$	$\tilde{\chi}^0_{1,2,3,4}$
(spin-1, spin-0)	$W^{\pm}$, $H^{\pm}$	(spin-$\frac{1}{2}$)	$\tilde{W}^{\pm}$, $\tilde{H}^{\pm}$	$\tilde{\chi}^{\pm}_{1,2}$
graviton (spin-2)	G	gravitino (spin-$\frac{3}{2}$)	$\tilde{G}$	

Most SUSY models impose R-parity:
Lightest SUSY particle stable (LSP)
→ "missing energy" (like ν)

How SUSY Might First Be Observed

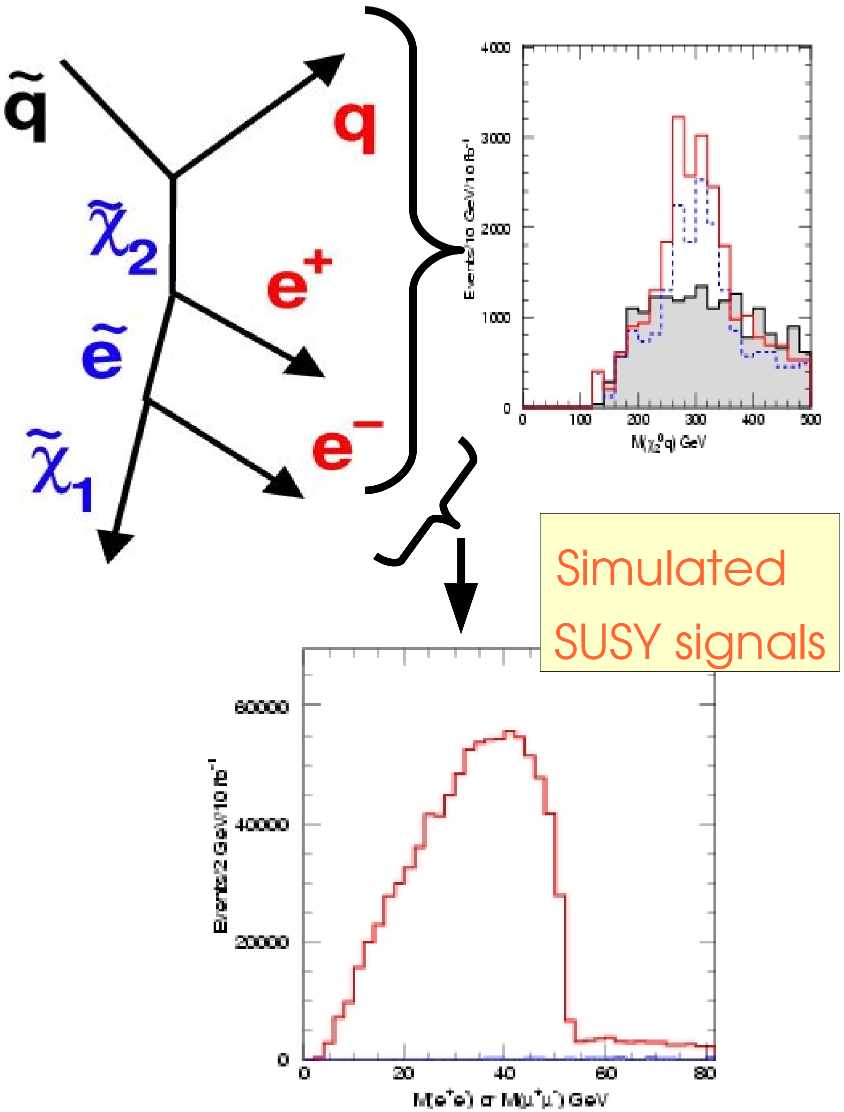
- Heavy SUSY particles decay to quarks, gluons and leptons
- LSP leaves missing energy
- Look for objects with at least 4 high pT objects plus missing energy
- Example has SUSY masses ~700 GeV

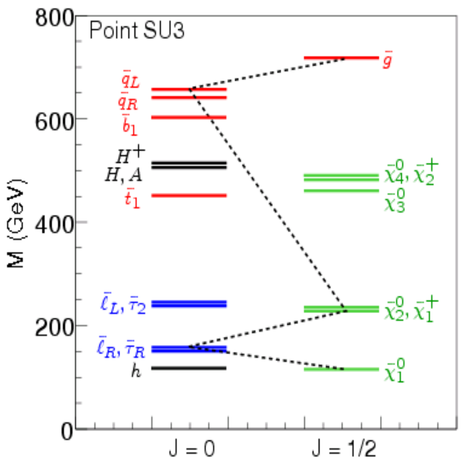


Example typical of models with new particles (strongly coupled) at large mass

If SUSY Observed, Will Require Many Measurements to Constrain Model

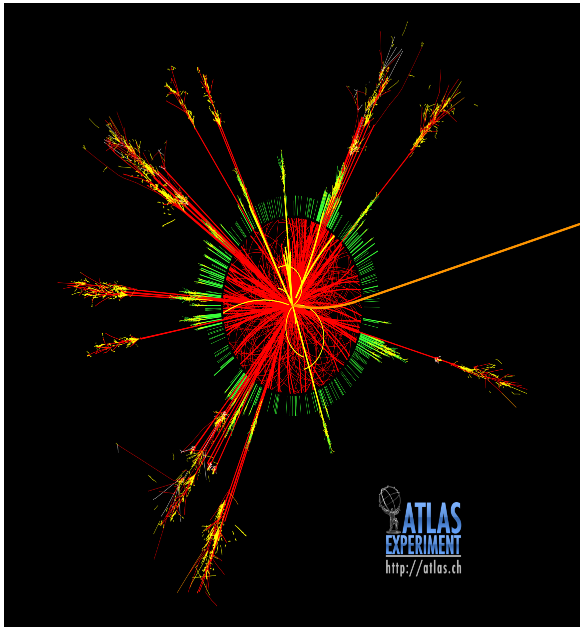
- Basic Principle: Work down decay chains
  - Measure masses and mass differences
  - Test universality among generati
- Example: squark decay





Example III: Extra Dimensions

- Why is the Planck scale so different from EWSB scale?
- Perhaps it isn't:
  - Extra dimensions change Gauss's Law
  - Can bring scale for gravity to become strong to TeV scale
- New interactions can drive EWSB



Simulated example of mini-black hole
Quantum Gravity at the LHC??

Conclusions

- LHC will provide access to conditions not seen since the early Universe
- Analysis of LHC data has potential to change how we view the world
- But LHC analysis will require finesse and care
- Substantial computing and sociological challenges

Exciting Times Ahead!