



Part 2 (continued)

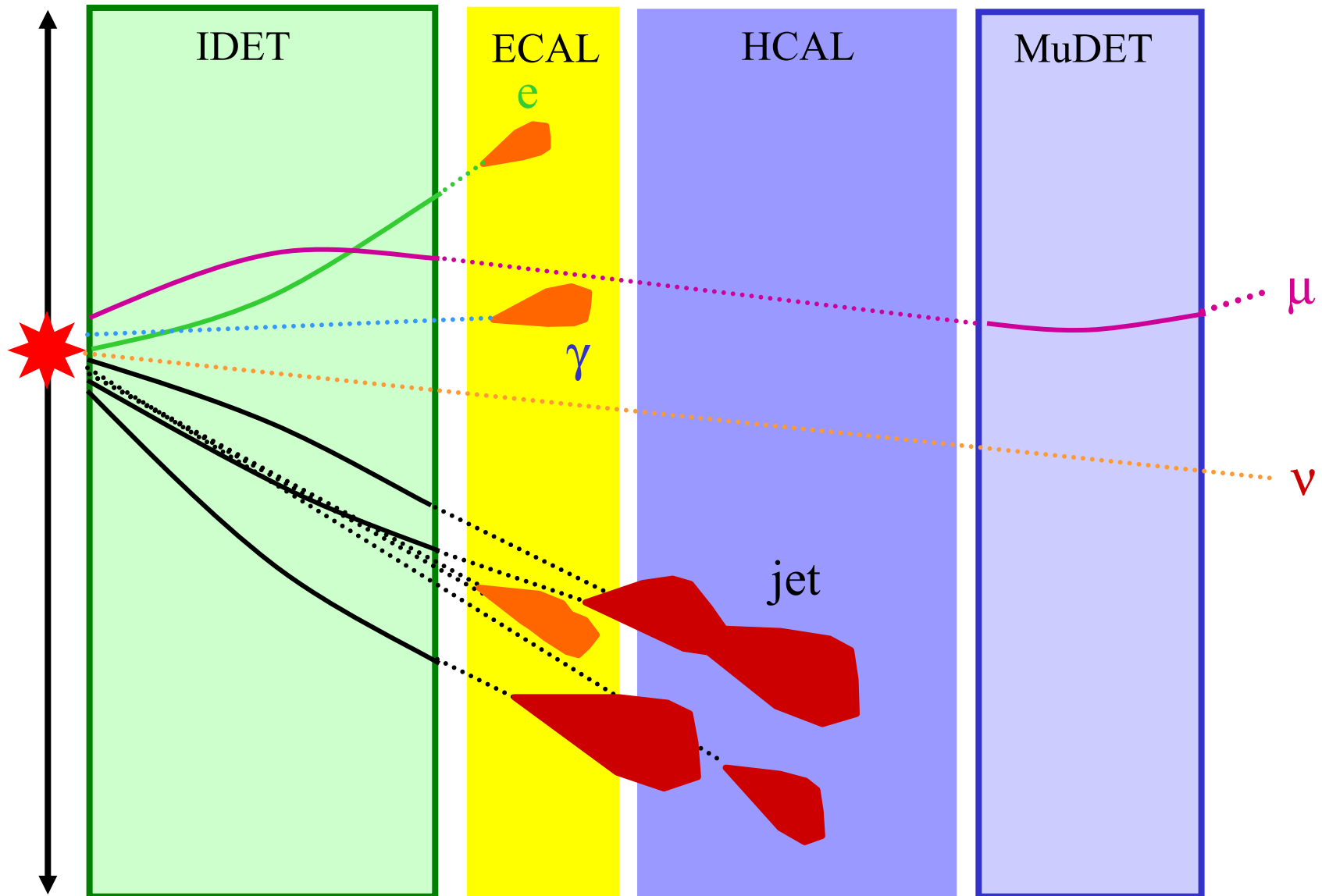
Overview of LHC Detectors

Benchmark Physics Processes

Detector Choices for ATLAS and CMS

H(800 GeV) \rightarrow ZZ \rightarrow e⁺e⁻ jet jet

Generic detector (simplified)

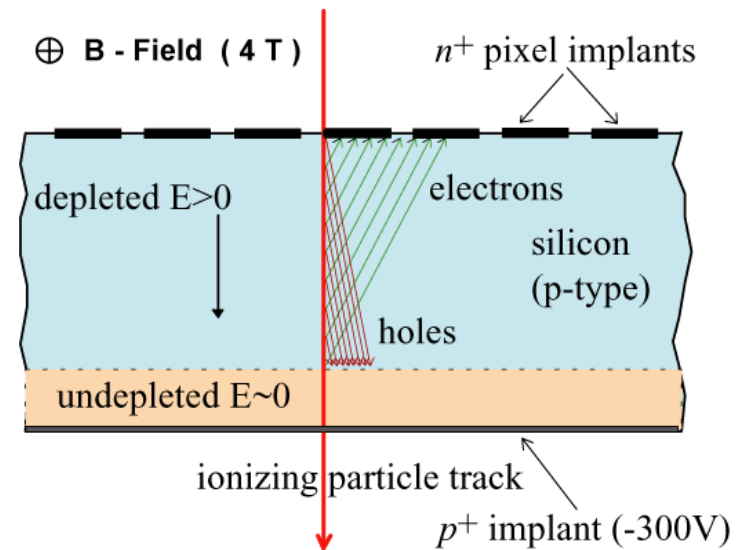


Inner-Detector Momentum Measurement

- The momentum of an electron, muon or other charged particle is determined from the radius of curvature of the track in the solenoid magnetic field
 - $p = 0.3 \times B \times r$
- Momentum resolution determined by precision of measurements of points along track
 - Silicon pixel and strip detectors have excellent spatial resolution
- At low momentum, resolution is limited by multiple coulomb scattering of the particles in the detector material
 - Gaseous detector such as those used at LEP are much better in this respect, but they don't have 25-ns signal collection time needed by ATLAS and CMS
 - However ALICE uses a Time Project Chamber (TPC) because of the low rate for heavy-ion collisions

Silicon Tracking Detectors

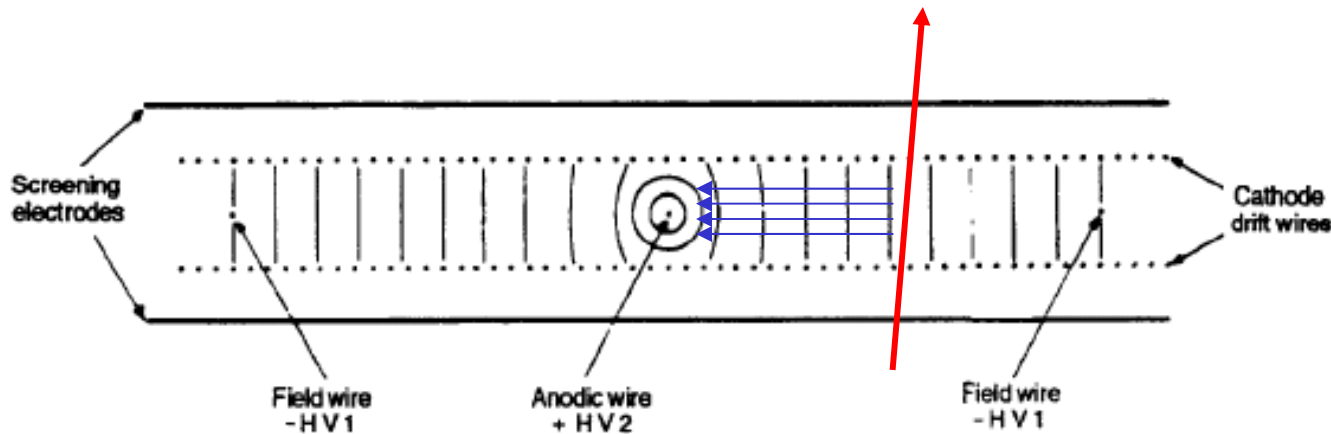
- Silicon tracking detectors are reverse-biased junctions
 - The passage of a charged particle produces electron-hole pairs that are collected on strips or pixels



- Since the detectors are thin, the charge collection time is small
 - Signal processing is used to achieve a time resolution better than 25 ns (charge collection time is longer than this)
- Very large numbers of detector channels possible thanks to micro-electronics technology
 - Of the order of 10^7 sensor elements sampled at 40 MHz bunch-crossing rate!

Drift Chambers

- In drift chambers, ionisation produced in a gas by the passage of a charged particle is detected
- An applied electric field causes the ionisation to *drift* towards a “sense wire”
 - The position where the charge was deposited can be determined from the time it takes the charge to drift to the wire
 - Known relationship between time and distance
- Near the sense wire a high electric field causes amplification of the signal
 - Electrons gain sufficient kinetic energy to produce ionisation
 - After this amplification, a comparatively large signal is obtained
- Traditional drift chambers have drift time $\gg 25$ ns and are not suitable for ATLAS and CMS inner tracking detectors
 - However, they are used in the muon spectrometers where pileup is not an issue



Straw Tubes

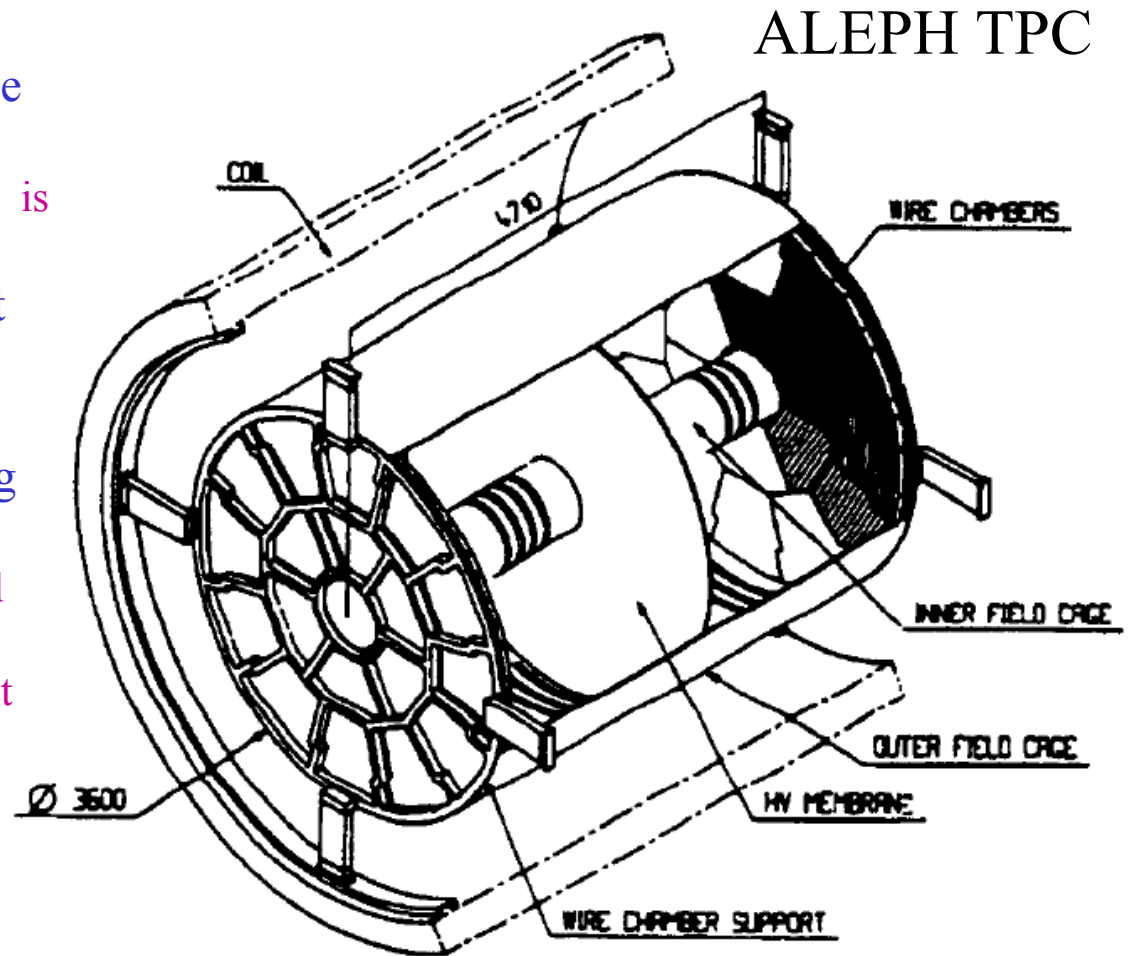
- Straw-tube detectors achieve short charge collection time because of the small maximum drift distance (radius of straw)
 - The detectors consist of an anode wire running along the centre of a conducting straw
 - Electrons drift towards the wire and are amplified in the strong field near the wire surface
- ATLAS uses straw tubes for the outer part of its tracker
 - Foil or foam is used to produce transition radiation X-rays from electrons
 - Produce high energy hits in straws used in electron identification



- Full detector contains ~400k channels
 - Time of arrival of charge measured and used to reconstruct tracks

Time-Projection Chamber

- Very long drift distance (and hence drift time)
 - Unsuitable unless interaction rate is $\ll (\text{max drift time})^{-1}$
- Used at LEP and also in ALICE at LHC
 - Low rate of heavy-ion collisions
- Record many points in space along each track
 - x, y position from position on end plate where charge arrives
 - z position from time measurement using known relation
- Inner volume filled with gas, so very little material
 - Low probability for photon conversions and electron bremsstrahlung



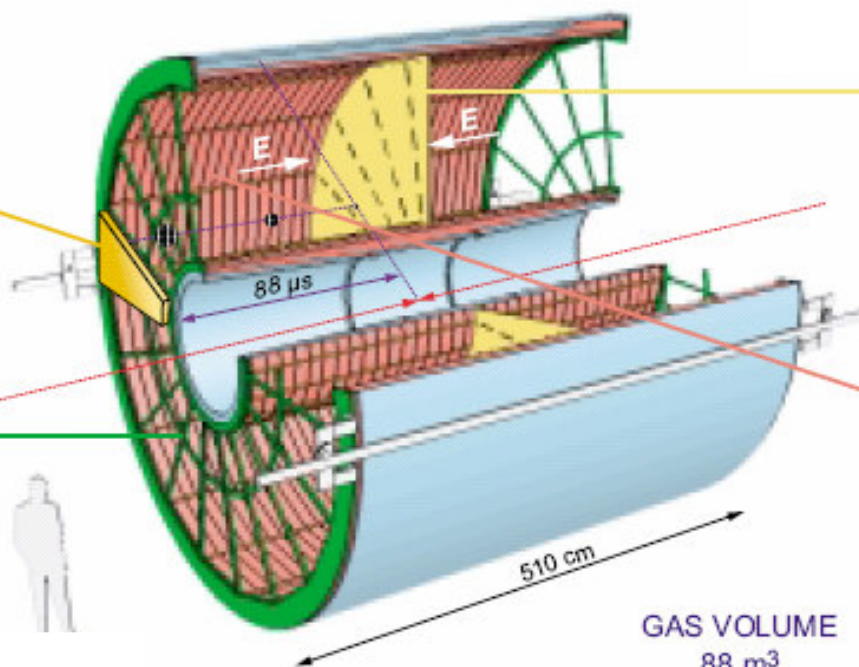
ALICE TPC



readout chamber



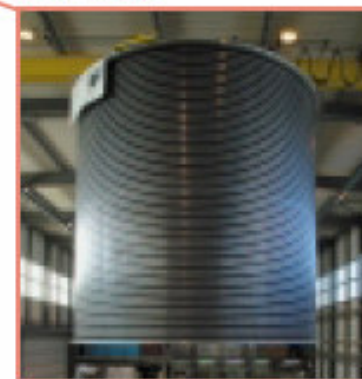
end plate



HV electrode (100 kV)



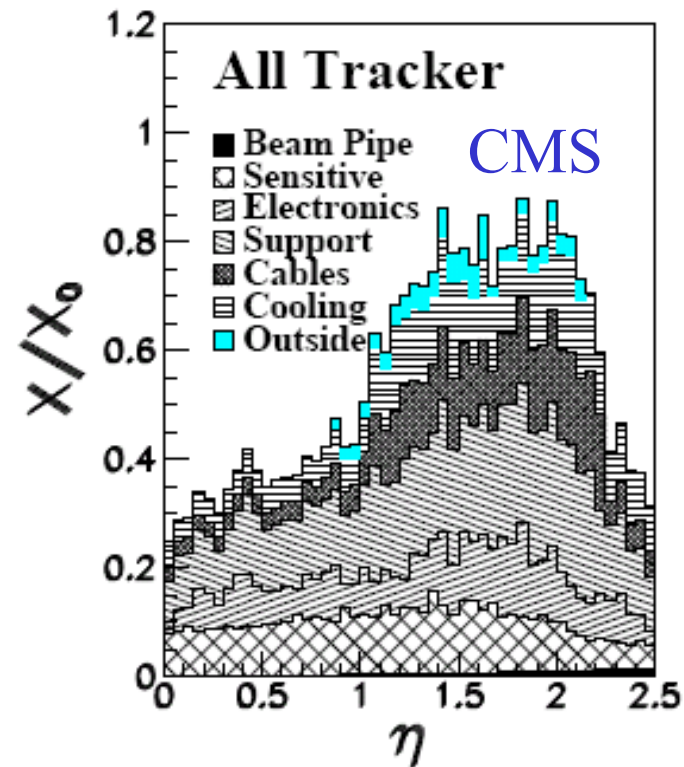
field cage



GAS VOLUME
88 m³
DRIFT GAS
90% Ne - 10% CO₂

Material Distribution

- The use of silicon and straw-tube trackers with associated services (cooling pipes, power and signal cables, electronics, support structures) gives a large amount of material in the tracking volume
 - Significant probability for photons to convert and for electrons to undergo bremsstrahlung
 - Has to be taken into account in analysis and trigger/offline event selection
 - Affects momentum resolution since, up to moderate p_T (~ 30 GeV in ATLAS), multiple Coulomb scattering dominates over the position measurement precision

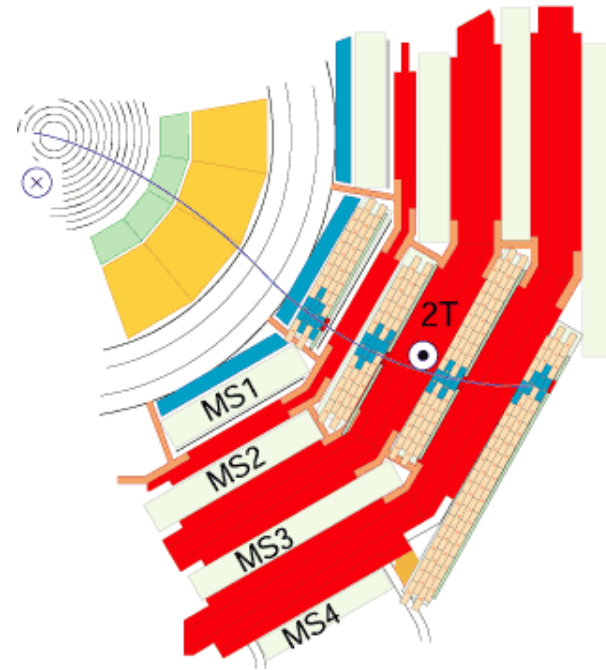


In ATLAS, the p_T resolution is

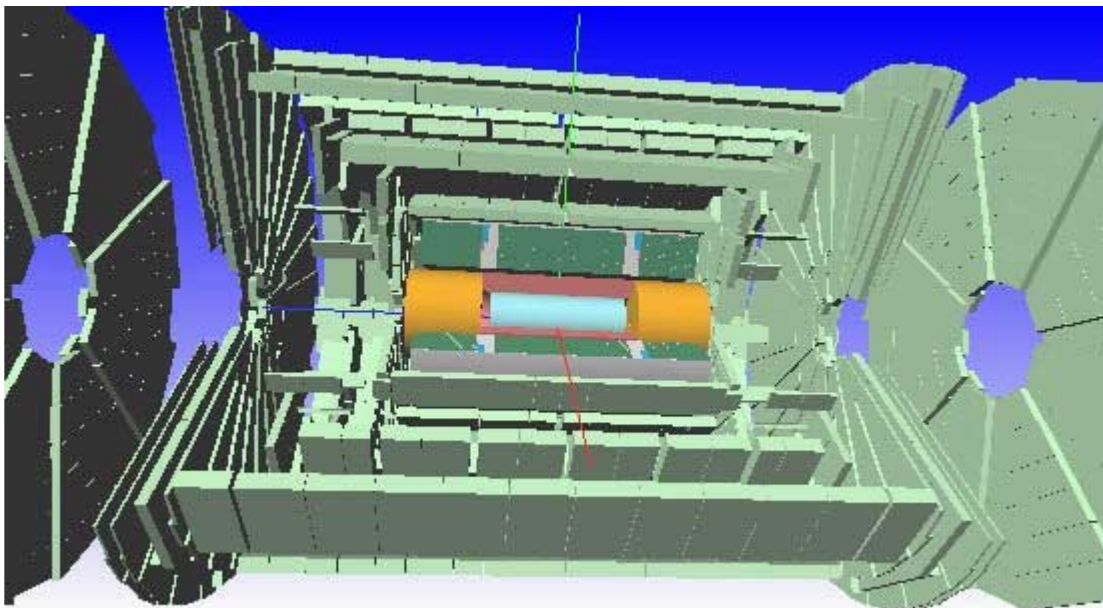
$$\sigma\left(\frac{1}{p_T}\right) \approx 0.36 \oplus \frac{0.013}{p_T \sqrt{\sin \theta}} (\text{TeV}^{-1})$$

External Muon Momentum Measurement

- CMS uses muon detectors inserted in the return yoke of the solenoid magnet
 - The momentum resolution is limited by multiple Coulomb scattering in the iron

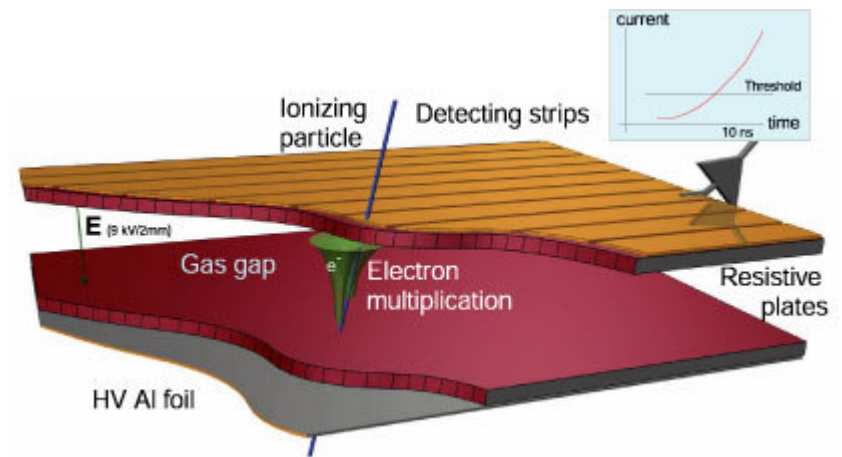
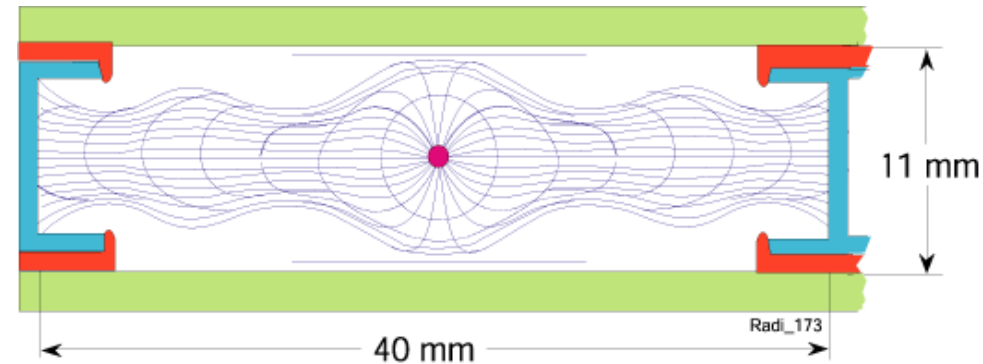


- ATLAS has separate toroid magnets for the external measurement of muon momentum
 - Provides very good “stand-alone” momentum measurement



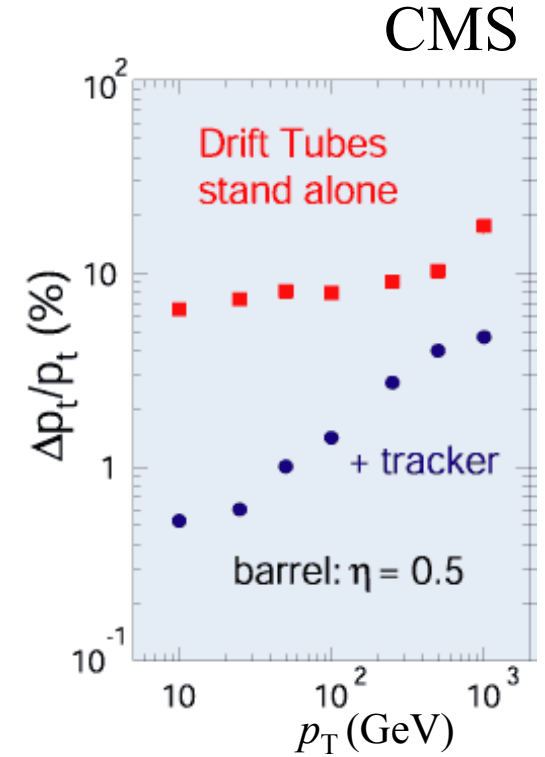
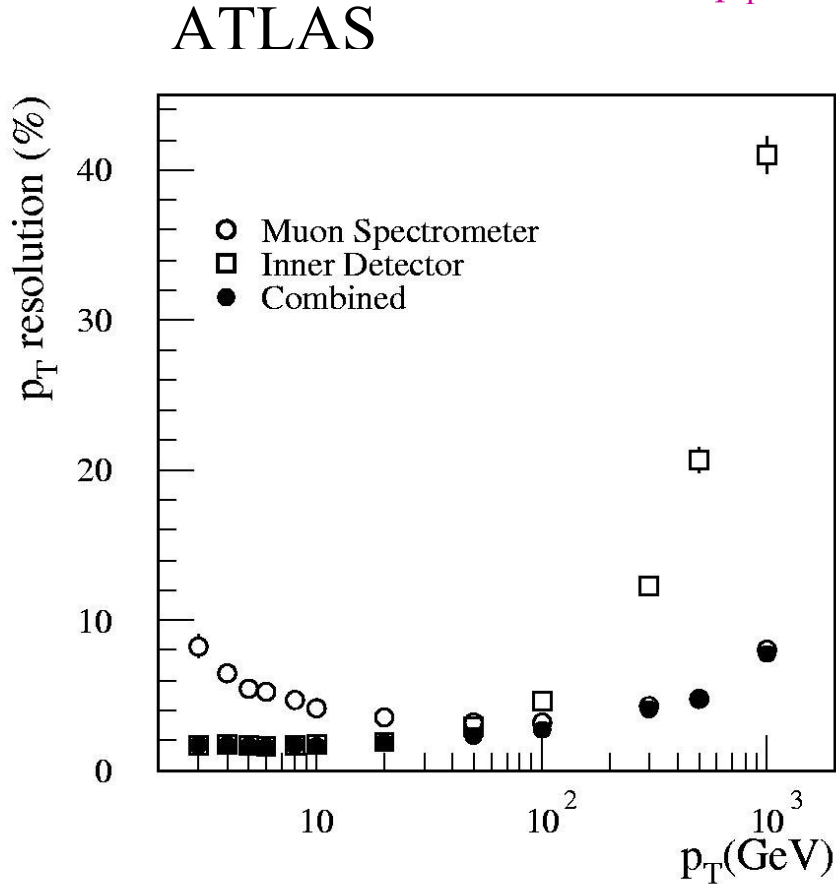
Detector Technologies

- Drift chambers provide excellent spatial resolution
 - Figure shows example of a CMS drift tube
 - Several layers of chambers are used to reconstruct track segments in each of several detector stations
 - Momentum is determined by combining information from the different stations
 - Improved resolution is obtained using the inner tracking in addition
- Additional “trigger” chambers give precise timing information that complements the information from the drift chambers
 - Figure shows example of a CMS Resistive Plate Chamber (RPC)
 - The RPCs are used in the first-level trigger that selects potentially interesting events containing high- p_T muons



Resolution on Muon Momentum

- The stand-alone momentum resolution of the CMS muon spectrometer is typical for an iron-core system
 - $\Delta p_T/p_T \sim 7\text{--}10\%$ for $p_T = 10\text{--}100$ GeV

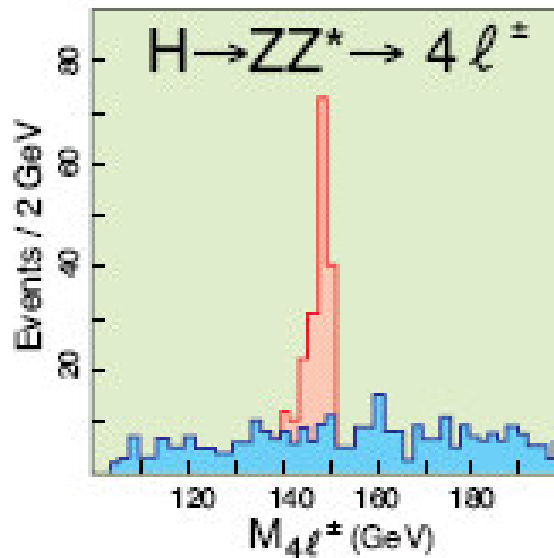
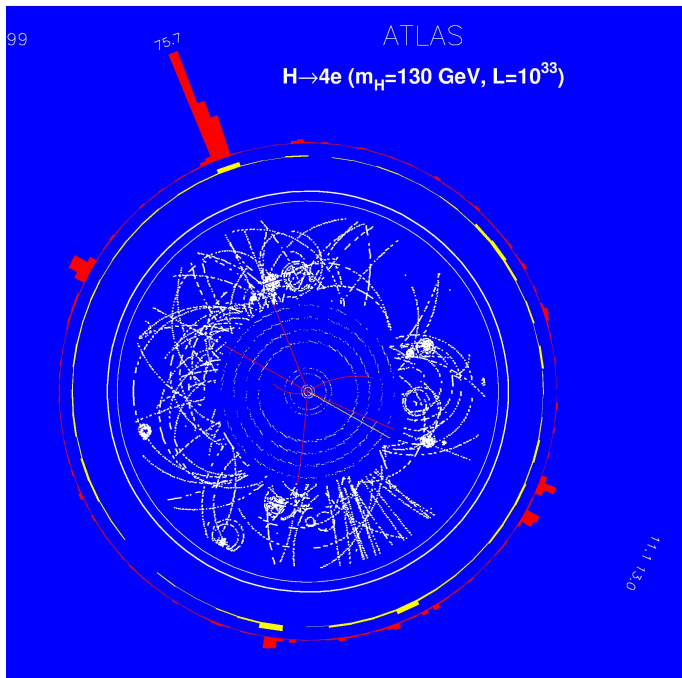
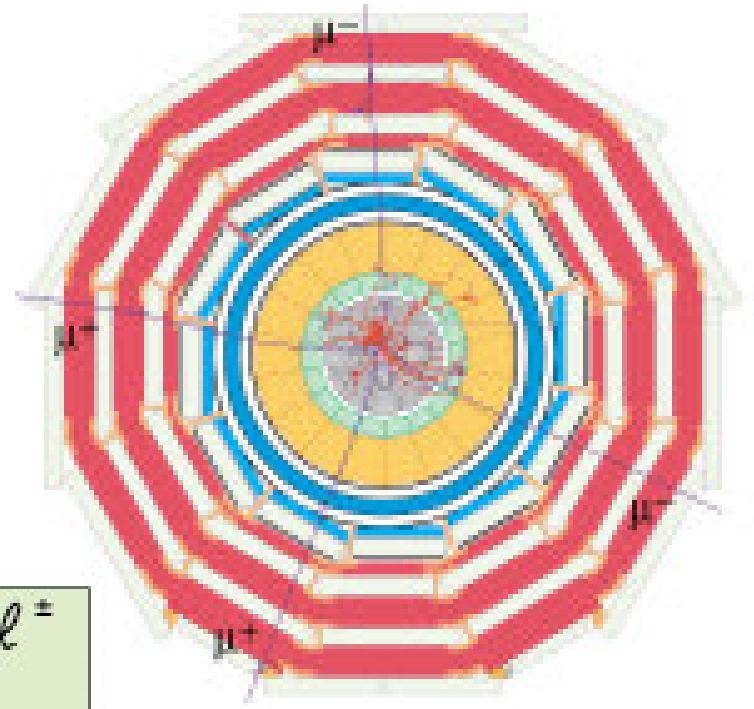


Due to the air-core configuration, ATLAS achieves a very good stand-alone resolution

- $\Delta p_T/p_T \sim 2\%$ for $p_T = 10\text{--}100$ GeV

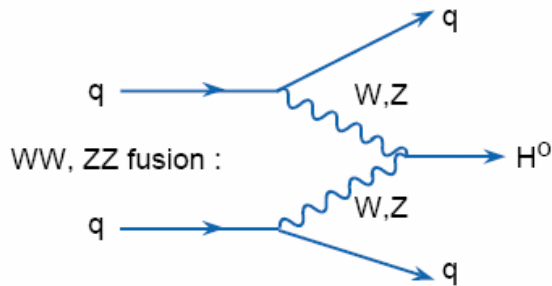
SM Higgs with $m_H \sim 150$ GeV

- Events observed with 4e, 4 μ and 2e2 μ final states
- Clear mass peak with $S/B \gg 1$

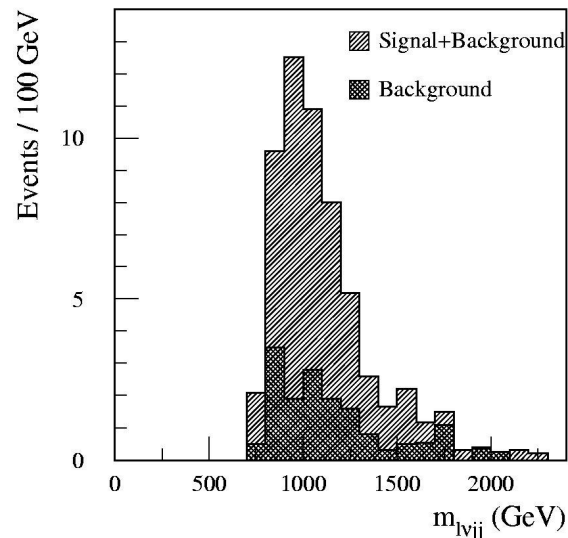
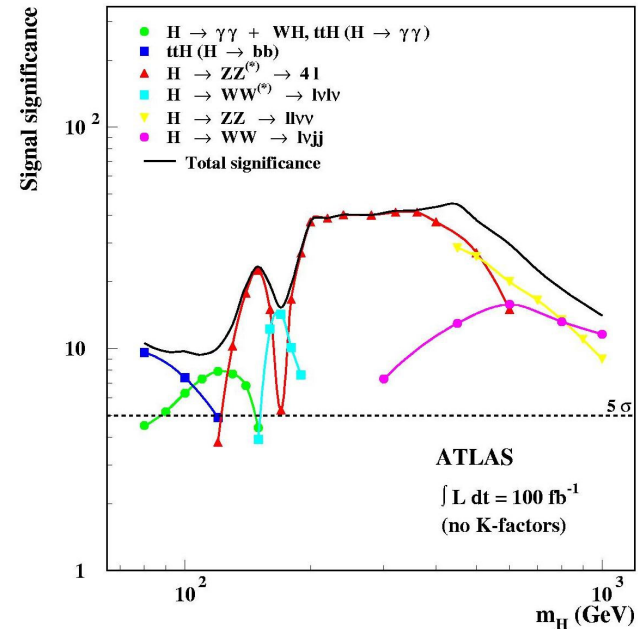


Heavier SM Higgs

- Even a very heavy Higgs could be observed at LHC
- However, rate is low and the natural width is large
 - Need to consider decay modes with larger branching fractions
 - $H \rightarrow WW$ as well as $H \rightarrow ZZ$
 - Decays of W to jets
 - Decays of Z to jets or neutrinos
 - May need to enhance signal-to-background ratio by “forward jet tagging” – need detectors at large $|\eta|$



- Whatever the mass, one should make observations in as many channels as possible to measure couplings



$H \rightarrow WW \rightarrow lvjj$

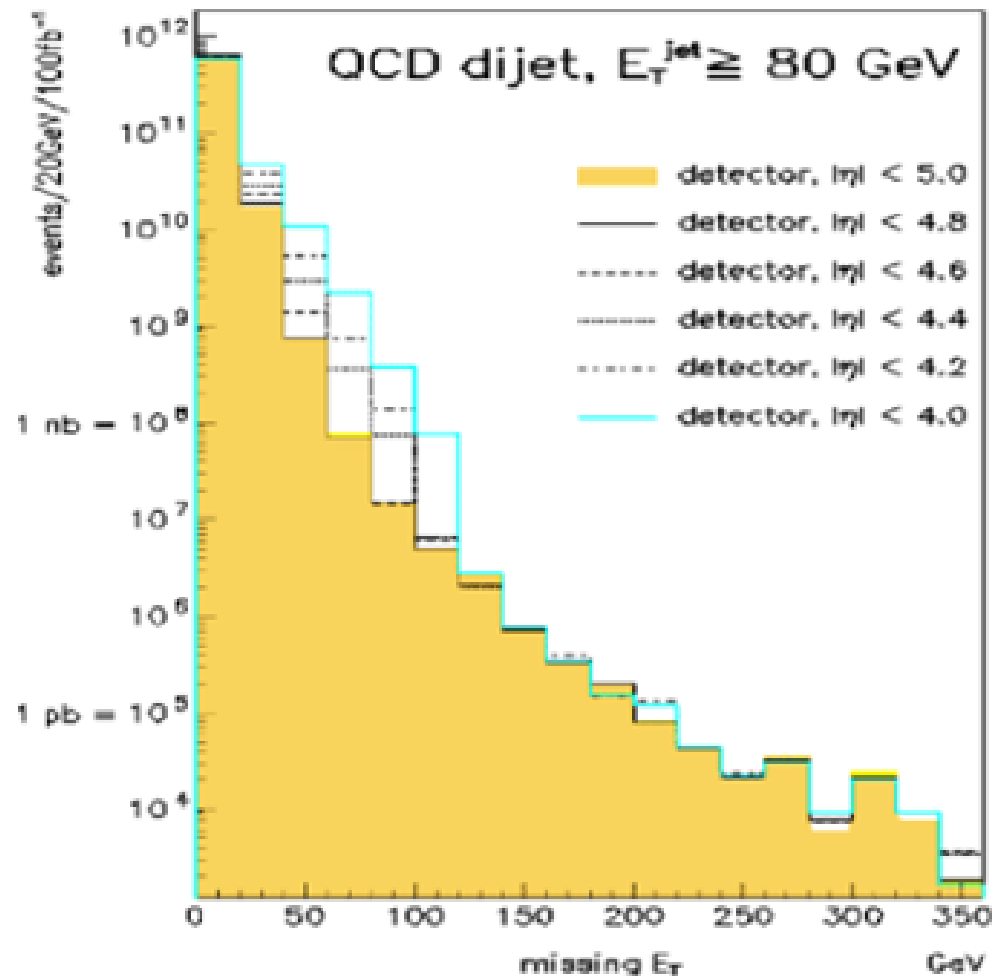
Two tag jets with $E_T > 100$ GeV

$m_H = 1$ TeV

$L = 30$ fb⁻¹

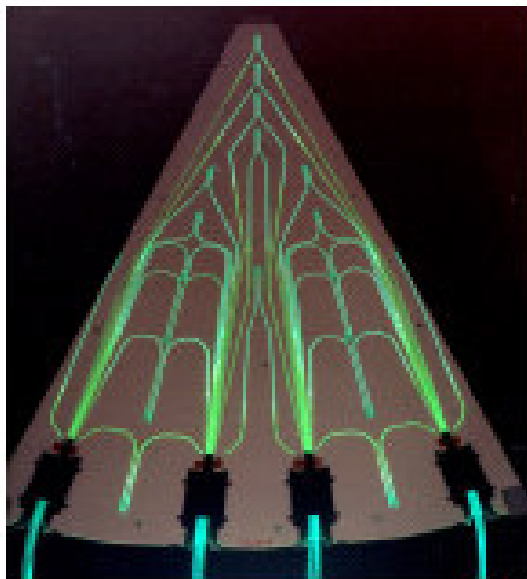
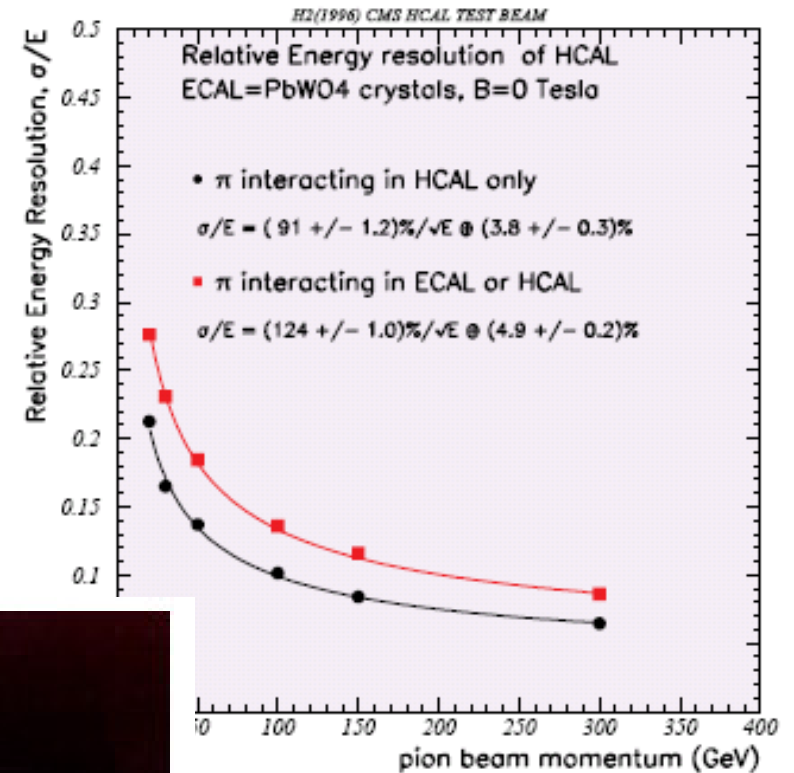
Searching for SUSY

- A key signature for SUSY is large missing transverse energy associated with the non-interacting Lightest SUSY Particle (LSP) that is stable under the assumption of R -parity conservation
 - Ingredients for good missing- E_T resolution are good hadronic calorimeters and with “hermetic” coverage
 - Note that LSP is candidate for dark matter
- Need calorimeter coverage up to $|\eta| \sim 5$, otherwise high- p_T jets outside acceptance give large fake missing E_T signature



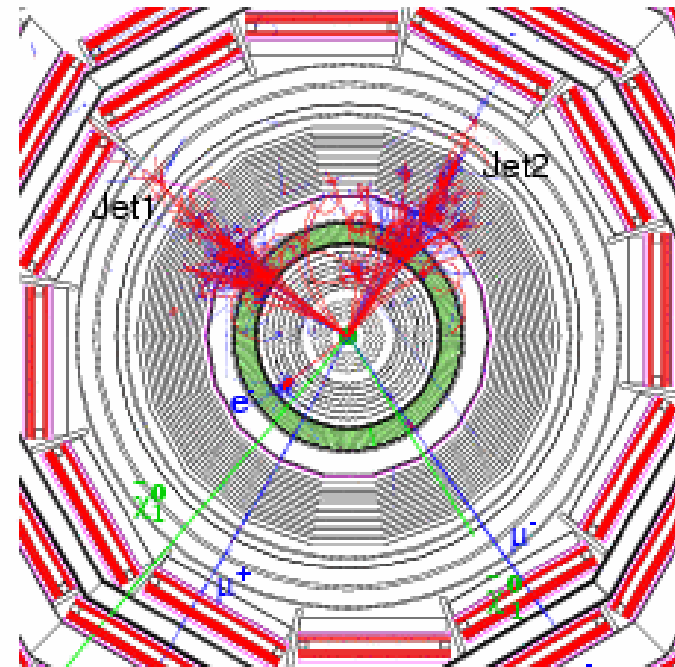
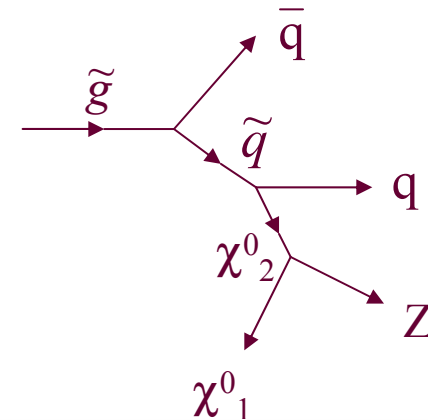
Hadronic calorimeters

- ATLAS and CMS calorimeters
 - Coverage up to $|\eta| \sim 5$
 - Energy resolution for hadrons
 $\sigma/E \sim 100\%/\sqrt{E} + \text{few } \%$
 - Jet resolution better due to π^0 component (EM resolution)
 - Use sampling calorimeters with Cu or Fe as absorber

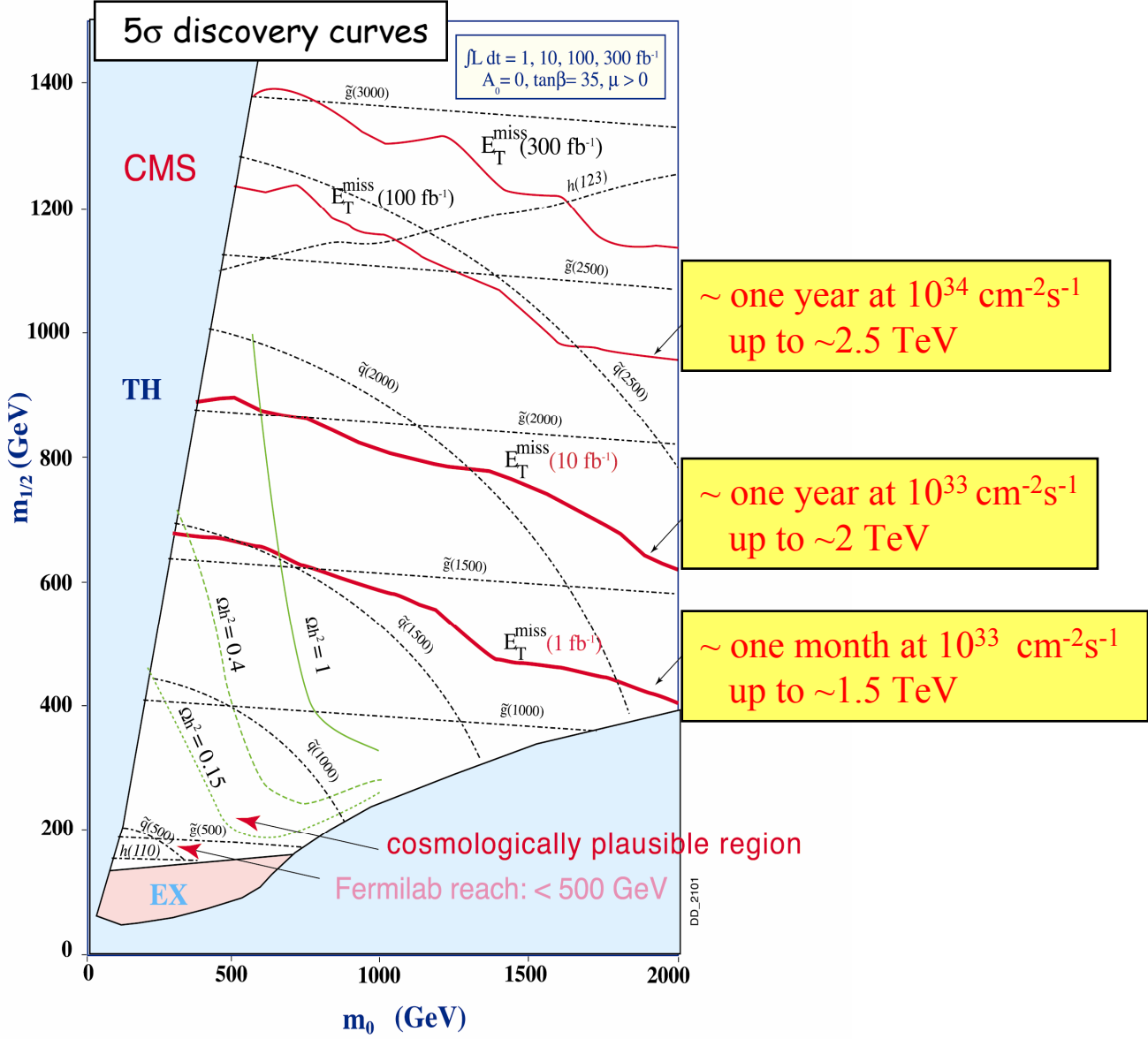


SUSY

- SUSY could provide quite spectacular events with many leptons as well as jets and missing transverse energy
- Thanks to the large hadronic cross-sections for squark and gluon production, it might be observed with modest integrated luminosity
 - However, much work will be necessary to check our understanding of the detectors and the physics backgrounds before announcing any discovery!

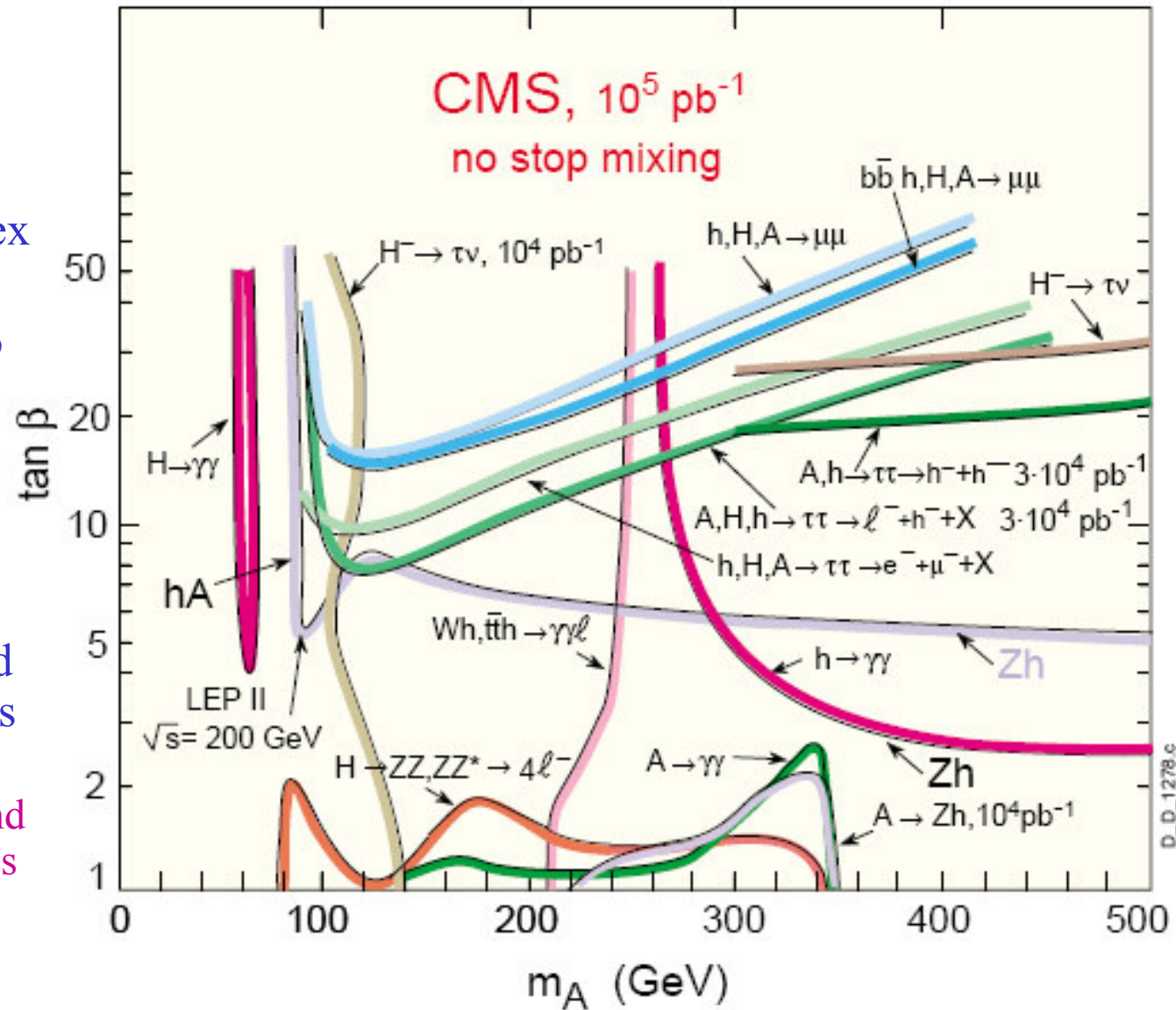


Statistical limitations on SUSY searches



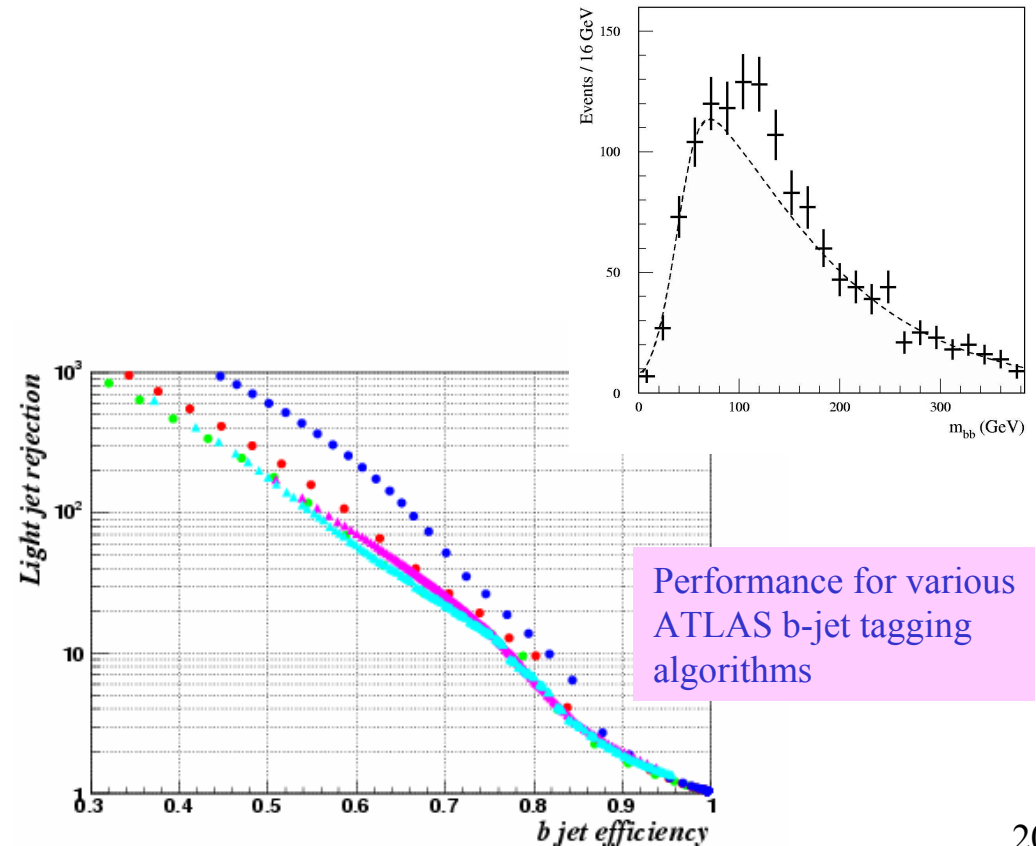
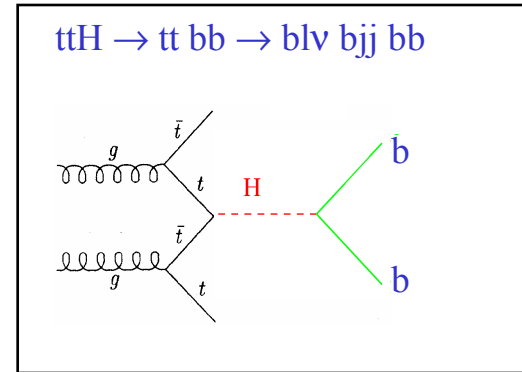
Higgs beyond the Standard Model

- In SUSY and other extensions to the Standard Model there may be a more complex Higgs sector
- Many Higgs bosons to search for
 - E.g. in MSSM
 - A^0, H^0, h^0, H^\pm
- Production cross-section and branching ratios may be modified compared to SM Higgs
 - Need to consider decays to b-quark and tau-lepton final states



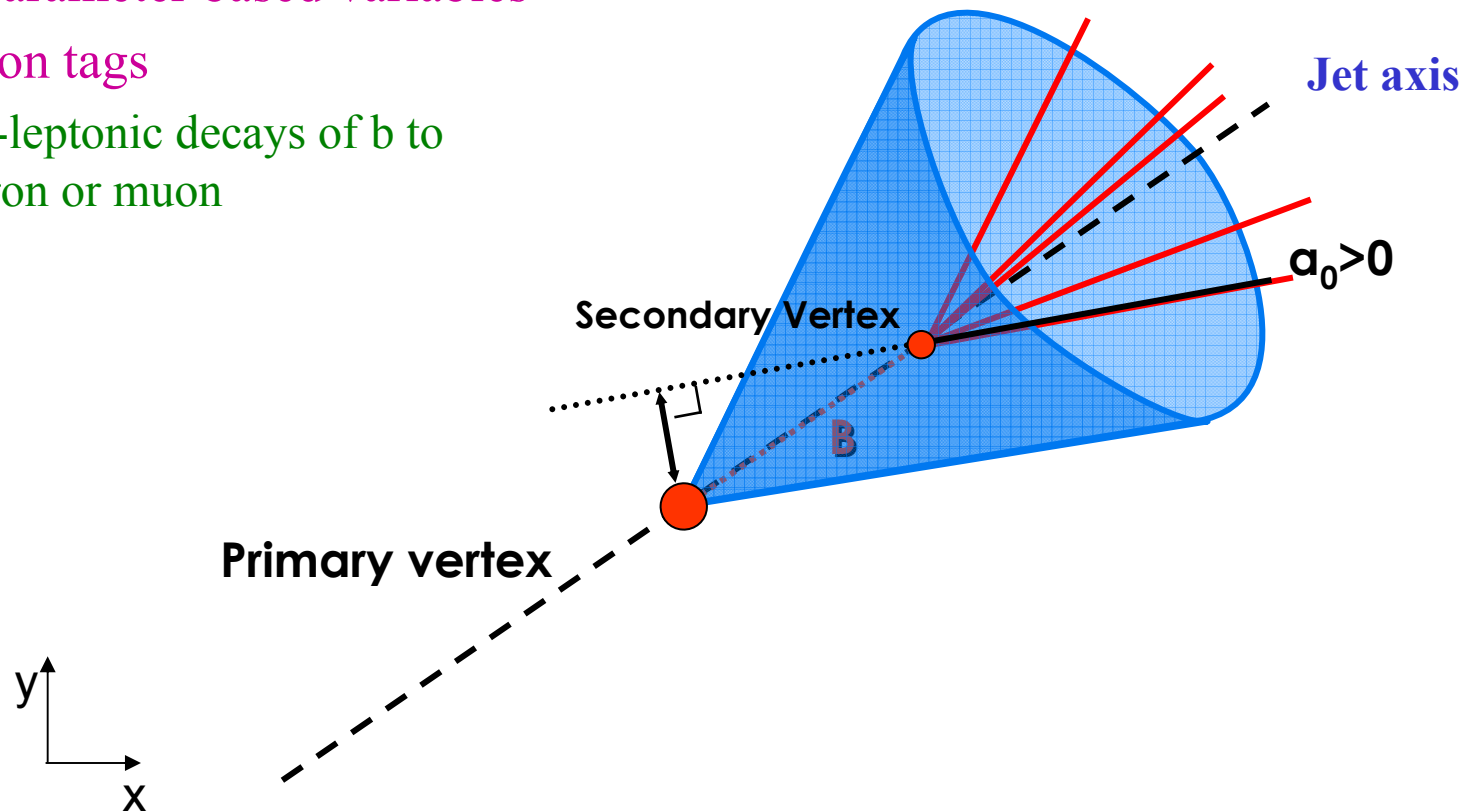
H → bb

- Higgs → bb decays may be observable at the LHC, but are challenging
 - There is a huge background from QCD production of bb pairs
 - Tag the production of the Higgs with the associated production of a top-quark pair
 - Need to reconstruct final state with four b-jets, W → ev, W → jj, where two of the b-jets combine to the Higgs mass
 - Identification of the b-jets is performed using the inner detector
 - B particles are long lived, so decay products don't originate from the pp interaction point



B-jet tagging

- Various techniques can be used to identify b-quark jets
 - Secondary vertices
 - Impact-parameter based variables
 - Soft-lepton tags
 - Semi-leptonic decays of b to electron or muon

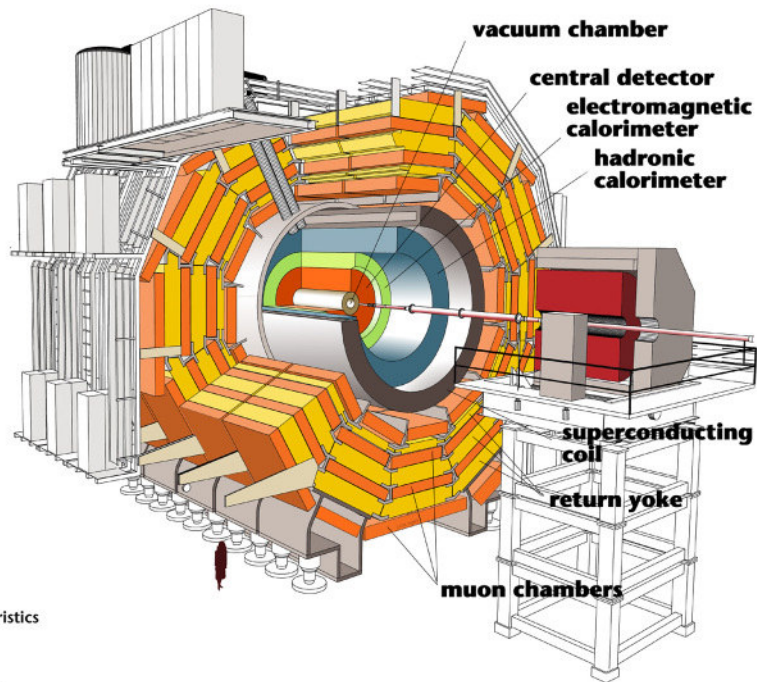


Remarks

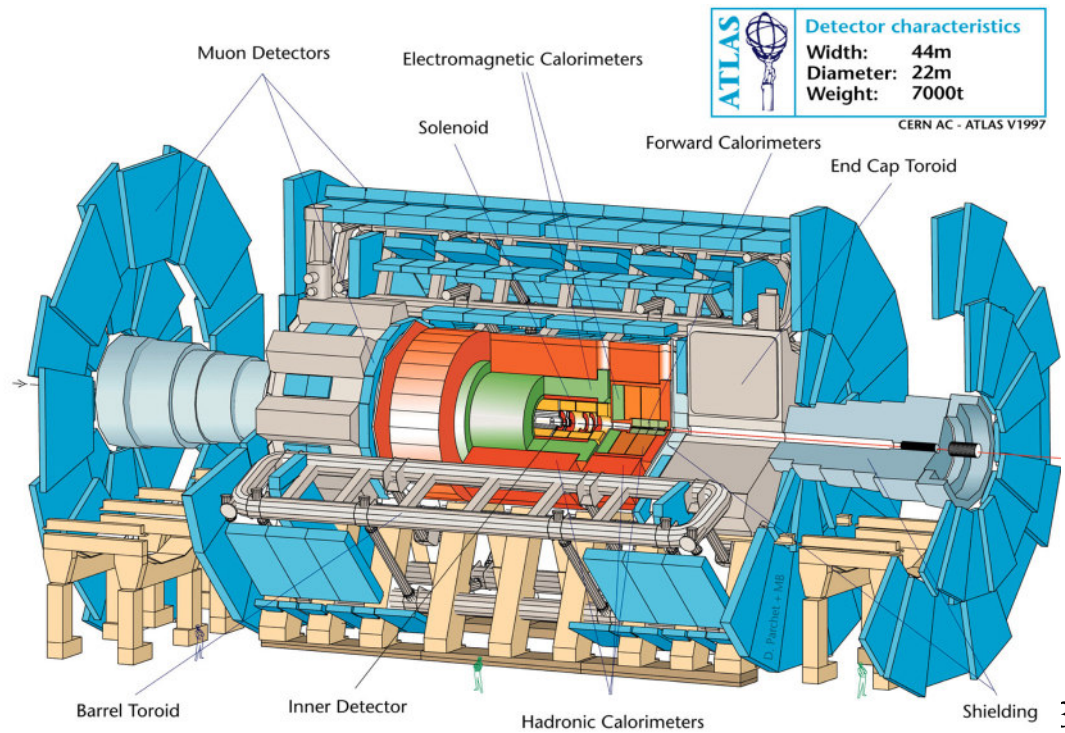
- LHC “experiments” have been designed taking into account
 - Physics processes to be studied and searched for
 - Known physics where precise measurements are needed at LHC energies
 - Predictions for possible new physics
 - The need to look for the unexpected
 - Look for deviations from the Standard Model
 - The harsh LHC environment
 - Radiation
 - Pile-up
 - Short bunch-crossing interval
 - Other considerations
 - Cost

Part 3

From Detector Installation to Physics

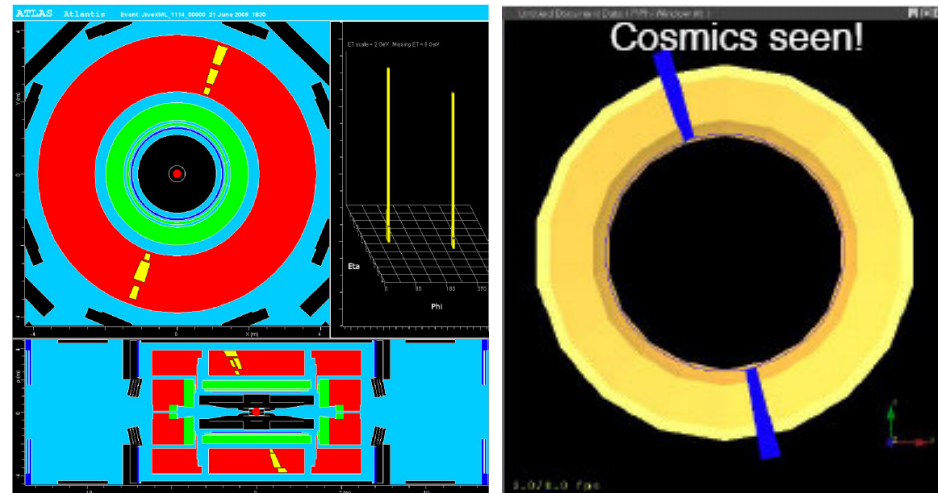


Detector characteristics
 Width: 22m
 Diameter: 15m
 Weight: 14'500t



Preparations for first collisions

- It is hoped that the LHC will start operation in 2007
 - ATLAS and CMS should be ready to take data at that time
 - Some detector subsystems will have to be installed after the initial running period, notably the CMS endcap EM calorimeters
- Useful studies can be performed using cosmic rays during the construction and after the installation of the experiments
 - Check that the full chain from the detectors to the data-acquisition works
 - Check the calibration and alignment of the full system
 - ATLAS (left) and CMS (right) have recorded cosmic rays traversing their barrel hadronic calorimeters

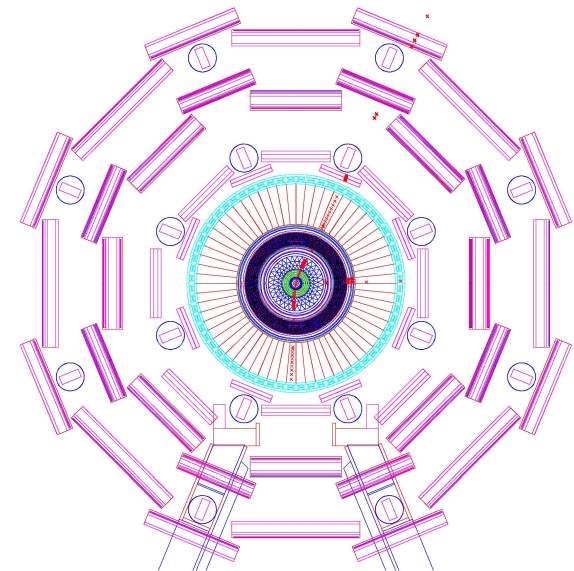


Cosmic rays

- It will be useful to operate the full detector systems for a prolonged period before the first beams are delivered
 - Many problems with the detectors, their electronics and the trigger and data-acquisition chain can be identified and resolved at this stage
 - Some comments apply to software for offline event reconstruction and analysis
- Preparations for this already in progress require extensive work
 - Cosmic-ray trigger
 - Simulating cosmic-ray events
 - Adapting the event-reconstruction software for tracks not coming from nominal pp collision point
 - Taking into account time-of-flight for muons “going the wrong way” in the upper half of the detector



Simulated Event

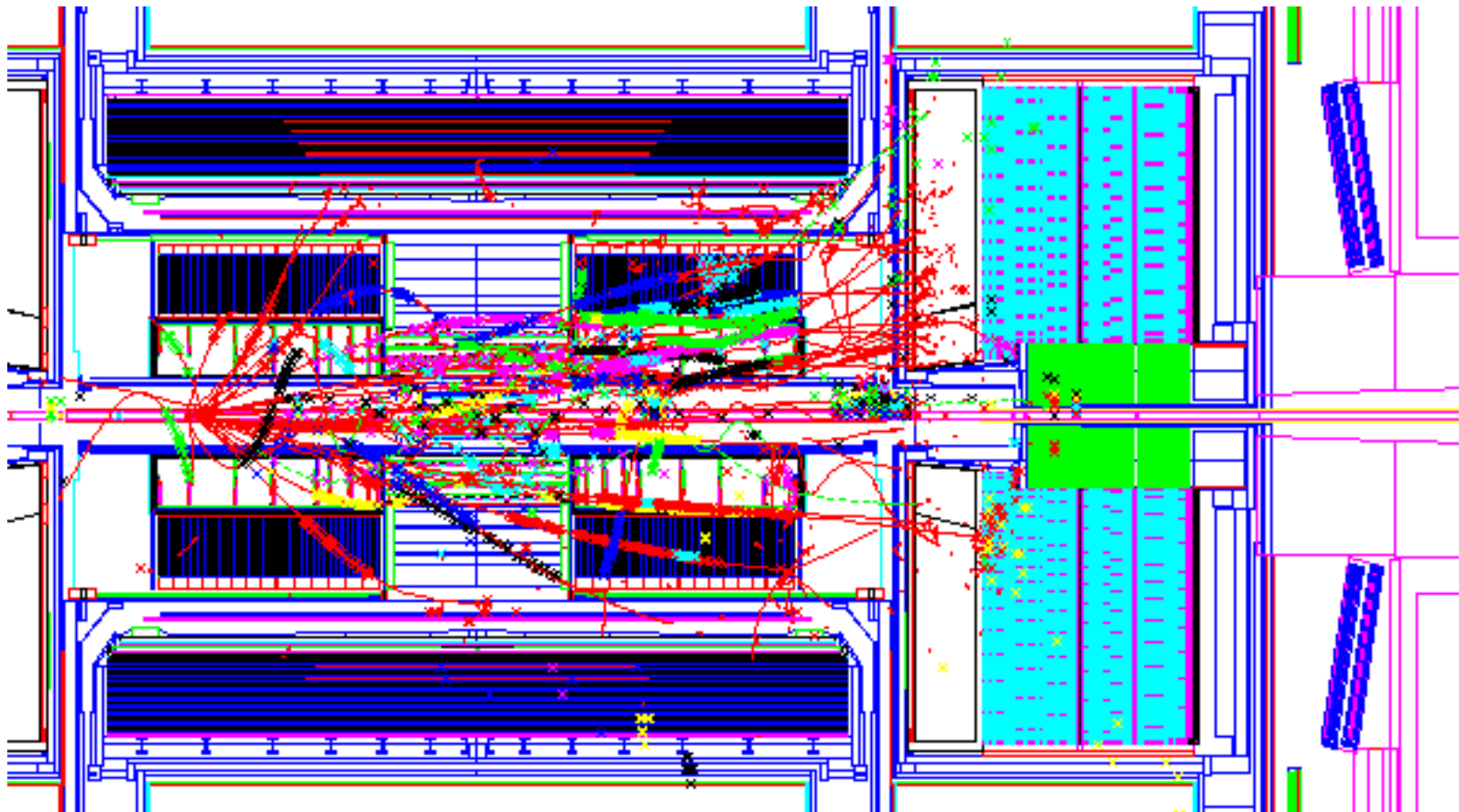


LHC machine commissioning

- Start with single beam
 - Experiments may take some data with beam-gas interactions and beam-halo muons for technical studies
- Get two beams circulating simultaneously
 - No collisions initially
- Collide the beams
 - Separate magnets for the two beams that need to be lined up in vertical and horizontal directions
 - Need also to adjust to get bunches to cross at the nominal position at the centre of the detectors
 - Aim to achieve first collisions in Summer 2007
- Increase the number of bunches and the number of protons per bunch to optimise the luminosity
 - Aim to reach luminosity of order $10^{33} \text{ cm}^{-2}\text{s}^{-1}$ as quickly as possible
 - Hopefully within a few months of turn on
 - Full design luminosity will require some upgrades

Single beams

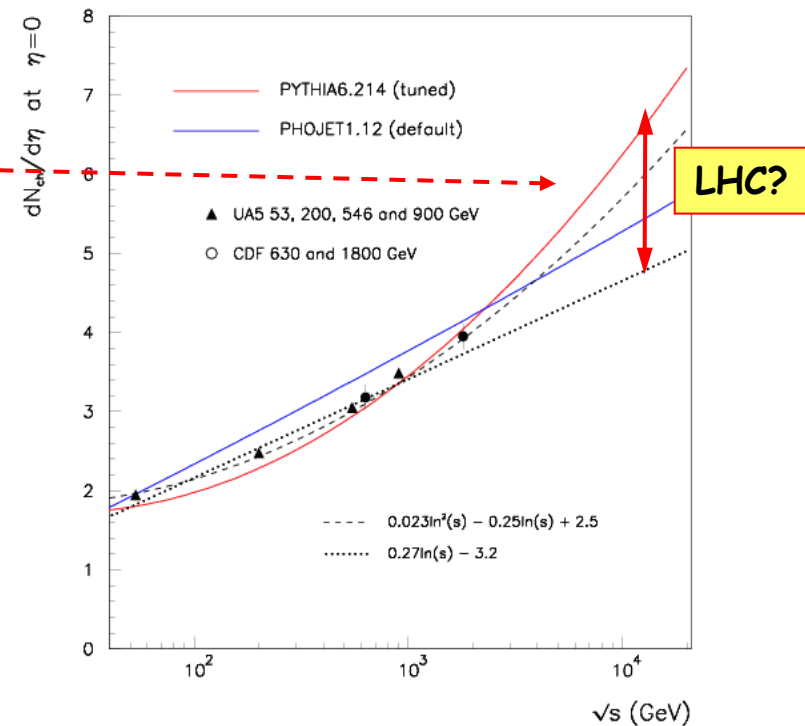
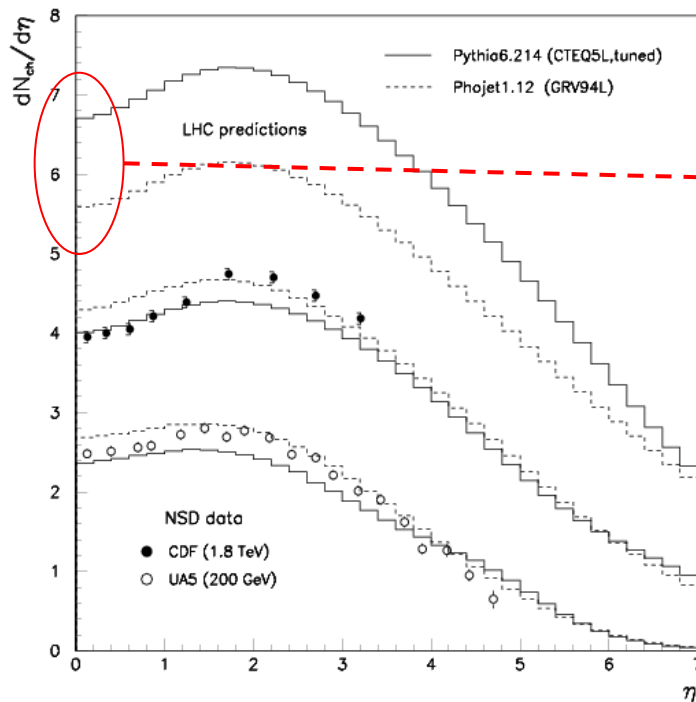
- Beam-gas events could be used to check the detector and software performance before the first beam-beam collisions



Measurements with the first collisions

- There are very significant uncertainties in predictions for even typical proton-proton interactions at LHC
 - For example, different models for the charged-particle multiplicity distribution as a function of centre-of-mass energy, \sqrt{s} , differ by $\sim 30\%$
 - Even these basic features will need to be measured
 - Let's consider this “trivial” example in some more detail

Charged-particle multiplicity distributions

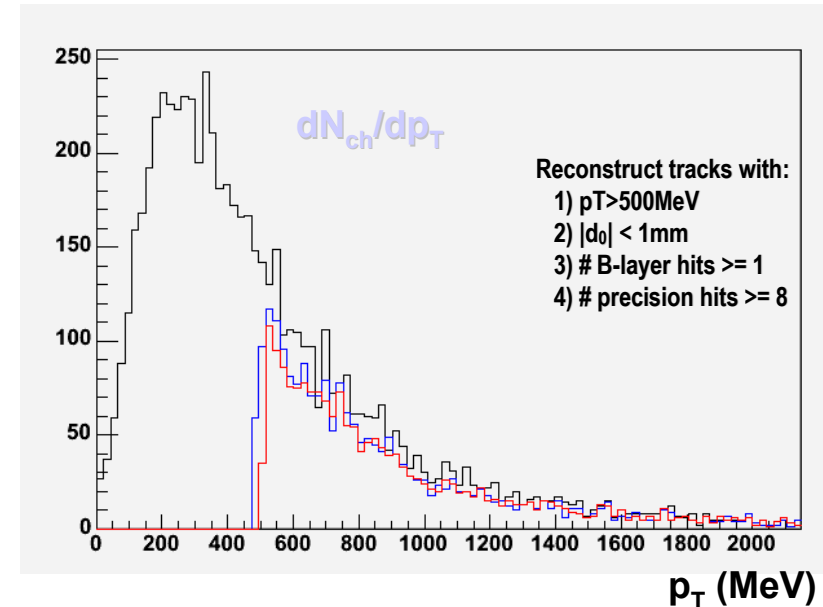
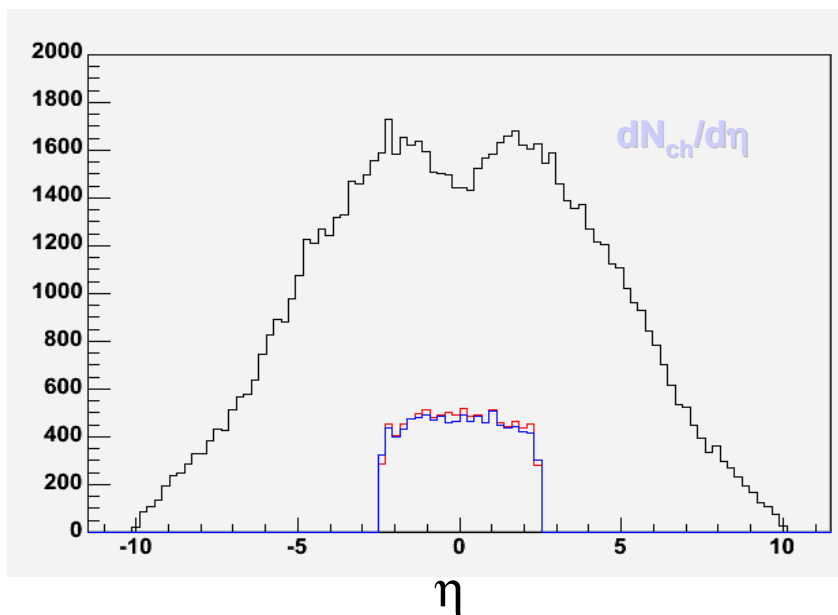


Example: charged-particle multiplicity

- Can be measured at extremely low luminosity
 - For example, 1000 events could be recorded in a few seconds (once the experiments are working!), even if the luminosity is many orders of magnitude below the design value of $L = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
 - Total cross-section $\sim 100 \text{ mb} \equiv 10^{-25} \text{ cm}^2$
 - So even $10^{29} \text{ cm}^{-2}\text{s}^{-1}$ would give an interaction rate of $\sim 10 \text{ kHz}$

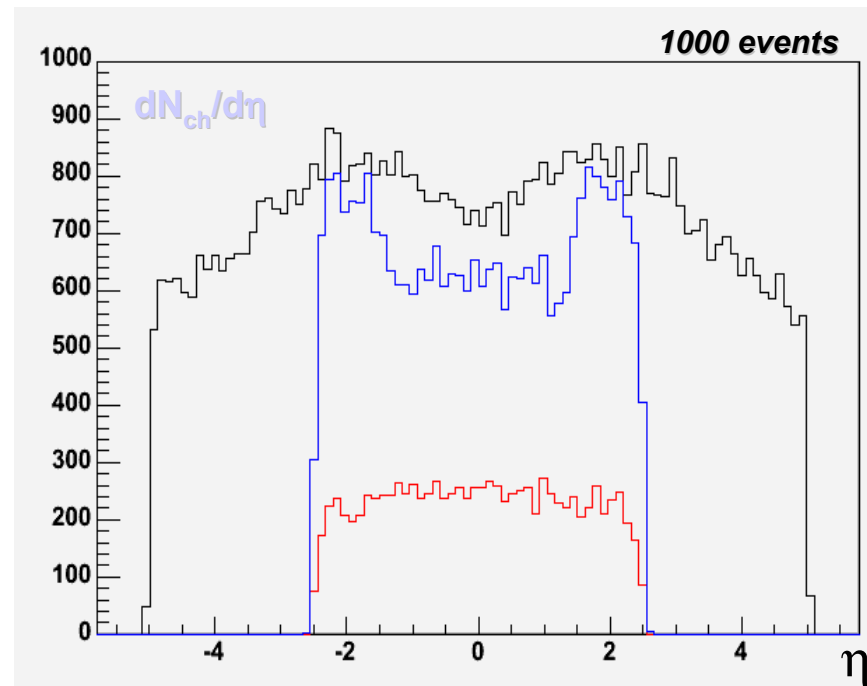
Black = Generated (Pythia6.2)
Blue = TrkTrack: iPatRec
Red = TrkTrack: xKalman

1000 events



Experimental considerations

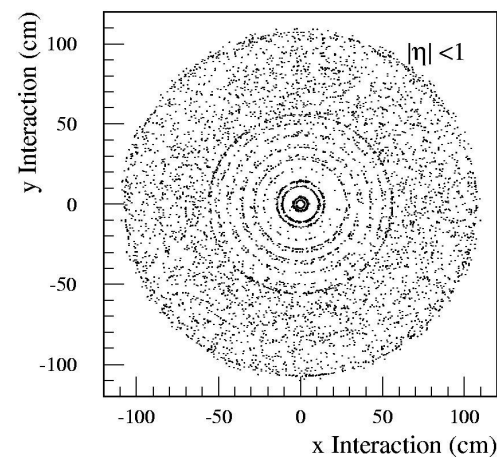
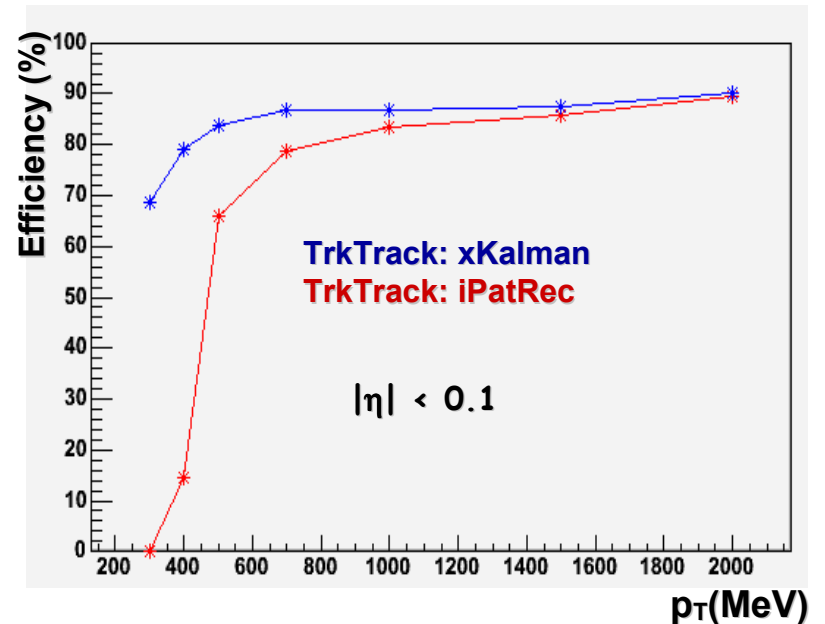
- Only see high- p_T tracks
 - Could take data with reduced magnetic field or zero field
 - Perhaps not top priority right at the start
 - Otherwise large systematic error from extrapolation
- Only see central tracks
 - ATLAS and CMS will see energy flow at larger rapidity
 - N.b. LHCb has tracking in forward region – complementary measurement
 - Central part is the most relevant in terms of understanding the impact of pile-up for other physics studies
 - Including searches for new physics



Black = Generated charged tracks
Blue = Reconstructed: NO TRT, NO solenoid
Red = Reconstructed: NO TRT, WITH solenoid

Other things to be addressed...

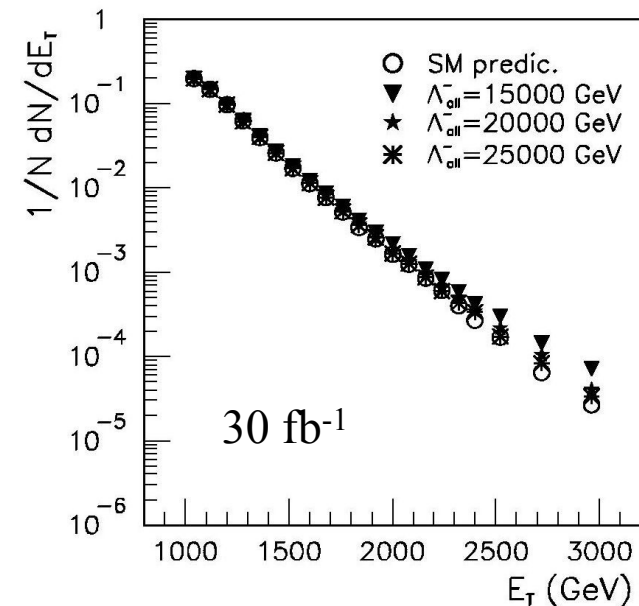
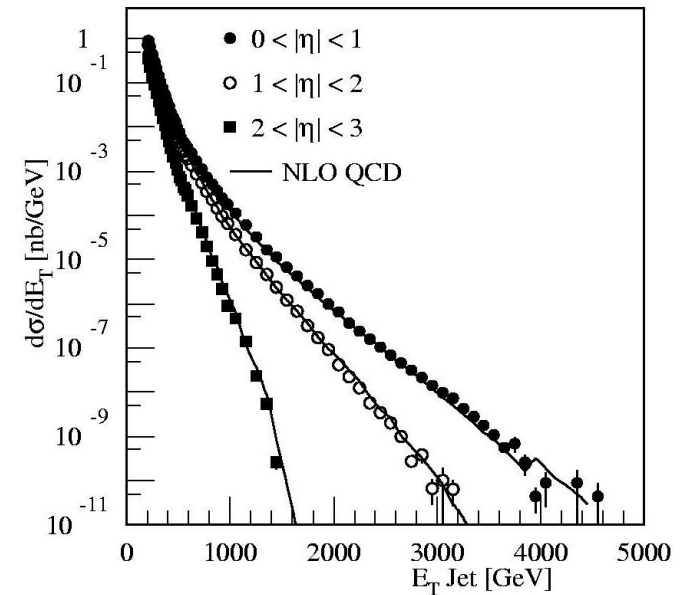
- The trigger may be biased
 - Could take some data selecting bunch crossings at random, but at very low luminosity most of them will be empty
- The reconstruction efficiency is not *a priori* known
 - Can estimate with Monte Carlo simulation, but this should not be trusted – especially at the beginning when it has not been checked and tuned with real data
- Many effects need to be considered
 - For example, particles interact in the material of the inner detector
 - Fast detectors, but lots of material
- Need to think about ways to estimate the efficiency from the real data
 - General consideration, not just for this example
- Systematic rather than statistical uncertainties will dominate many measurements



Position of interaction points of pions in Inner Detector in x-y

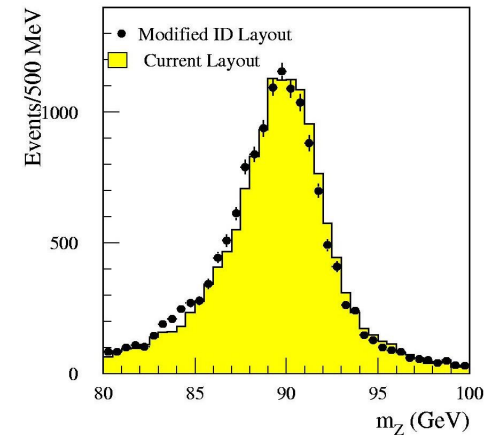
Jets

- Jets are the dominant high- p_T process at LHC
 - Many studies need to be made as tests of QCD and to tune Monte-Carlo event generators
 - Inclusive p_T and rapidity distributions
 - Angular distributions in multi-jet events
- New physics – e.g. resonances decaying to jet-jet, or quark compositeness – could be discovered
 - However, some studies require a very detailed understanding of the detector response (as well as significant integrated luminosity)
 - For example, linearity of the energy measurement in the calorimeters is crucial for the study shown in the figure
- Quantitative studies require calibration of the jet energy scale (see later)



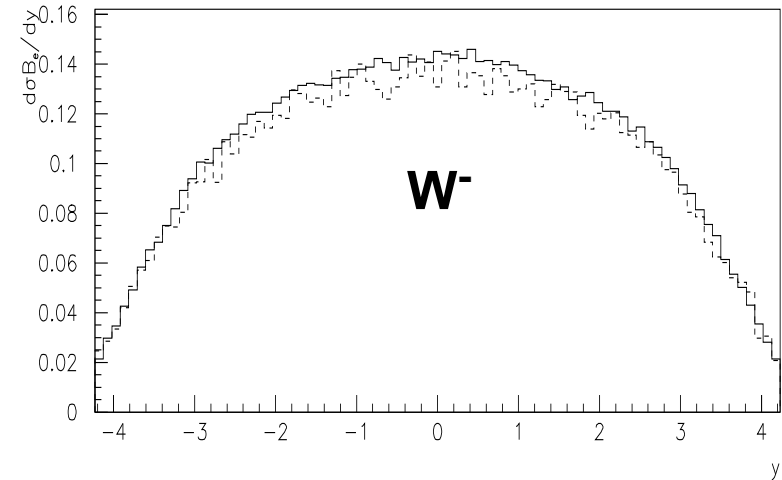
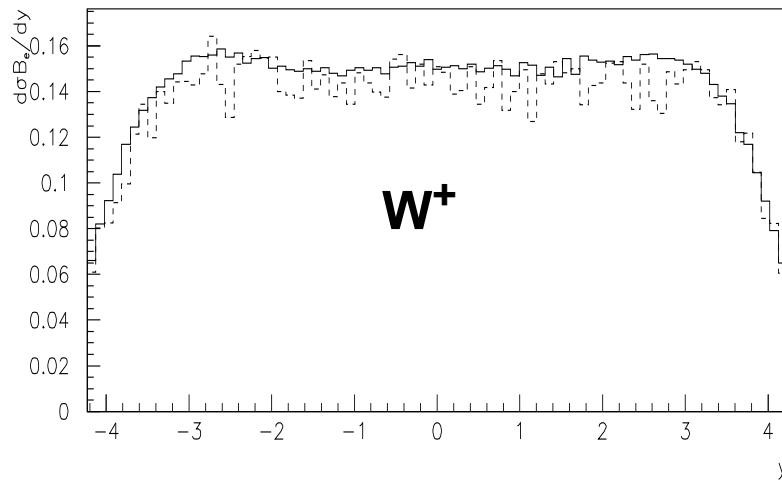
W and Z bosons

- Measurements that can be made during early running of the LHC will be W and Z production with decays to leptons
 - Such studies are interesting in their own right
 - e.g. W and Z produced in association with jets provide tests of QCD
 - W bosons are produced in top decays
 - It is essential to understand W and Z production in Standard Model processes
 - W and Z bosons will be used as signatures in searches for new physics (Higgs, SUSY, ...)
 - Can be used as luminosity monitor
 - Rate = $\sigma \times B \times L$
- $Z \rightarrow e^+e^-$ (also $Z \rightarrow \mu^+\mu^-$) gives clear dilepton mass peak with little background
 - Detailed shape and reconstruction efficiency influenced by detector (e.g. bremsstrahlung)
 - Z's can be used to check or calibrate the energy scale of the calorimeters and the momentum scale of the inner detector and muon spectrometer
- $W \rightarrow e^+\nu$ relies also on missing transverse energy
 - More complicated to reconstruct



W production

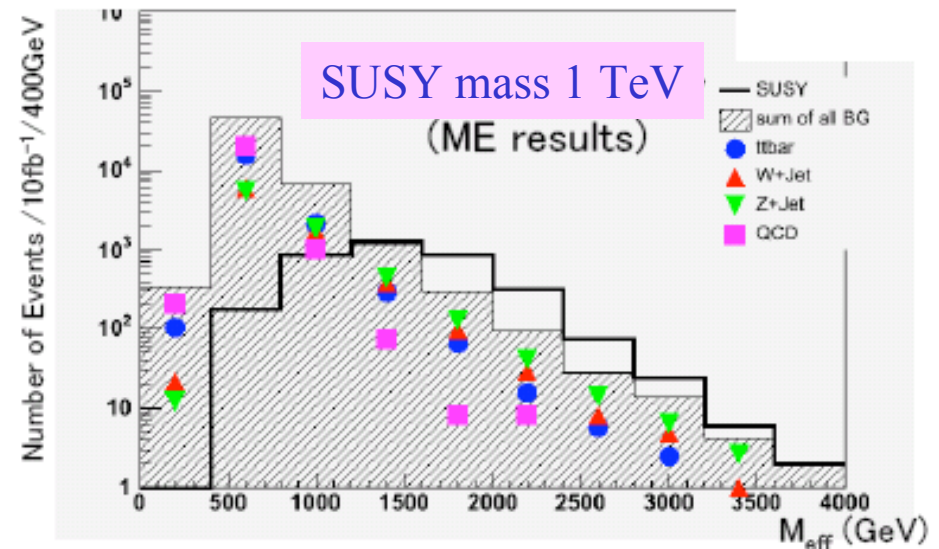
- In proton-proton collisions, W^+ and W^- production is not symmetric
 - Depends on parton content of proton – sea distributions important (low-x)
 - Interesting to measure – provides information on PDFs



- Large rates, so small statistical uncertainties
 - Again, systematic uncertainties will be important
 - Efficiency for triggering and reconstructing e^+ and μ^+ , and e^- and μ^- events as functions of rapidity, and associated background rates as functions of rapidity
 - Charge misidentification (very small probability)
-
- Two plots showing systematic uncertainties for W^+ and W^- production as a function of rapidity y . The y-axis ranges from -0.05 to 0.25, and the x-axis ranges from -4 to 4. The data points, represented by black error bars, show large fluctuations around a central value of approximately 0.03. The fluctuations are larger at the edges of the rapidity range.

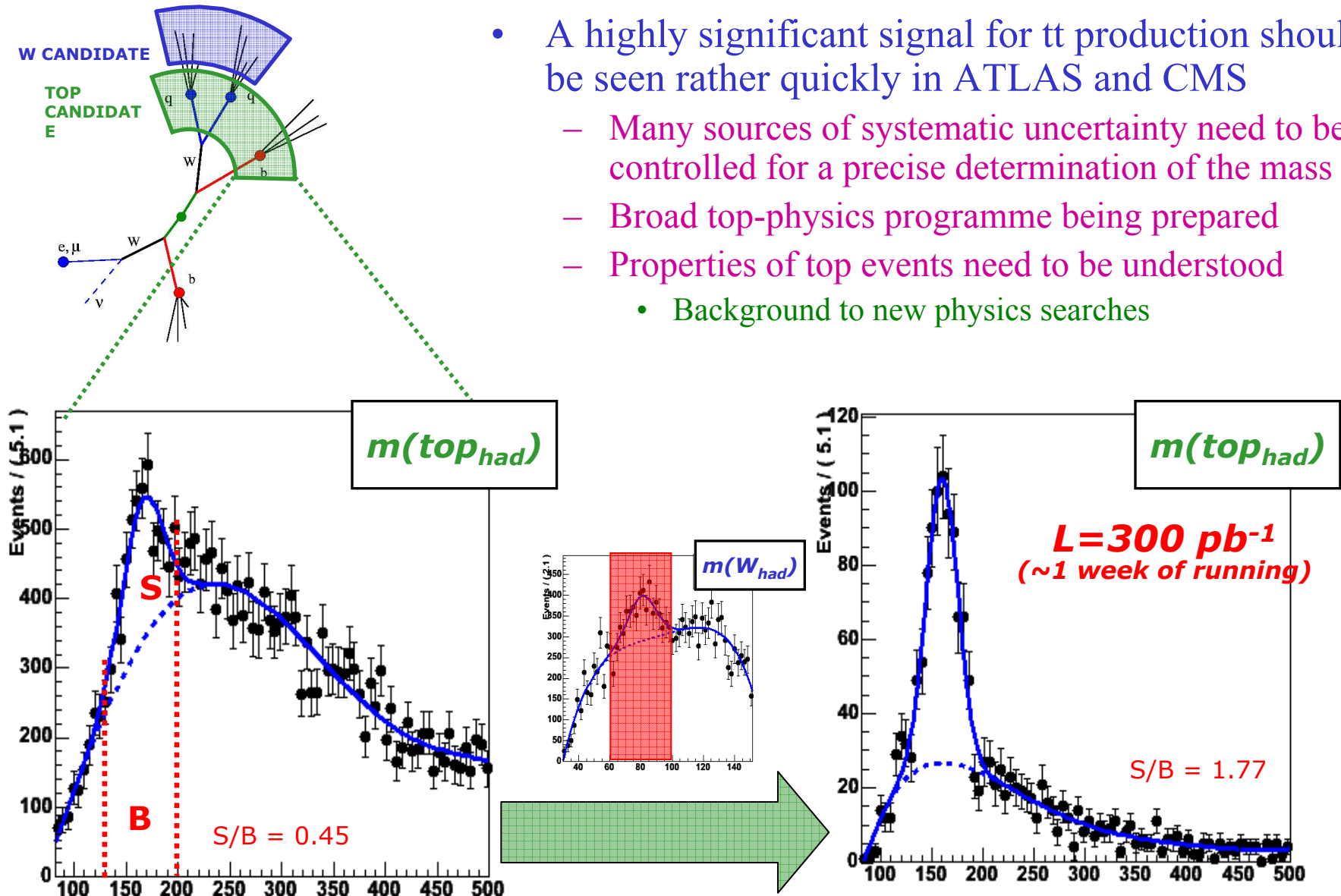
Importance of W and Z events

- Lepton reconstruction efficiency
 - $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ events can be selected using just one lepton
 - One can then study the efficiency for the second lepton to be triggered, reconstructed and pass the standard lepton-selection criteria
- Calibration of jet energy scale
 - Z+jet events can also be used to study the jet energy scale
 - Compare measured momentum of the Z (precise measurement from the leptons) with the reconstructed jet energy
 - Can also use photon-jet events for this
- Measuring W and Z production at large p_T is crucial for SUSY searches
 - Z+jet events, where $Z \rightarrow \nu\nu$, gives jets plus missing transverse energy
 - W+jets where $W \rightarrow \tau\nu$ also contributes
 - Dominant background to generic SUSY signature of missing E_T + jets



Top signal

- A highly significant signal for $t\bar{t}$ production should be seen rather quickly in ATLAS and CMS
 - Many sources of systematic uncertainty need to be controlled for a precise determination of the mass
 - Broad top-physics programme being prepared
 - Properties of top events need to be understood
 - Background to new physics searches

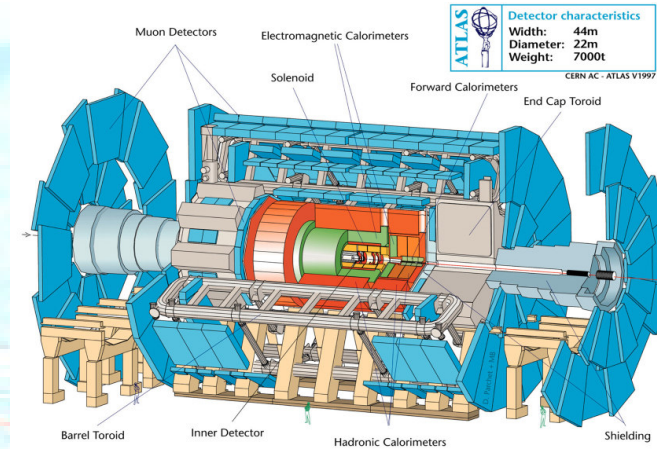
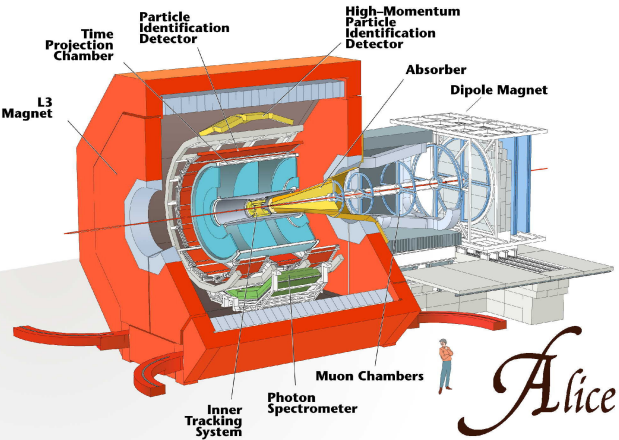


B-physics

- ATLAS and CMS, as well as LHC*b*, will also make use of the large beauty cross-section for physics studies
 - LHC gives very high statistics in channels that can be triggered
 - Decays containing muon pairs are particularly easy to select; in the forward regions lower p_T thresholds are possible than in the central region
 - Rare decays such as $B_{d,s}^0 \rightarrow \mu^+\mu^-$, $B_d^0 \rightarrow \mu^+\mu^-\rho$, $B_d^0 \rightarrow \mu^+\mu^-K^*$, $B_s^0 \rightarrow \mu^+\mu^-\phi$ could provide indirect evidence for new physics, complementary to direct searches
 - Sufficient statistics in many channels to measure branching ratios at level predicted; observations with much larger branching ratios would be very significant
 - Also precision measurements, such as A_{FB} in $B_d^0 \rightarrow \mu^+\mu^-K^*$ decays
 - CP violation effects can also be studied in several channels
 - $B_s^0 \rightarrow J/\psi\phi$ is a particularly interesting channel since the observation of a large CP asymmetry would be inconsistent with the Standard Model (and hence indirect evidence for new physics)

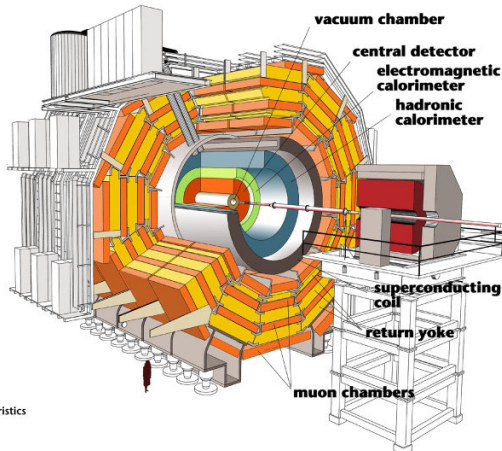
Remarks

- Much physics can be done in the first months with colliding beams
 - Studies of the general properties of the events at an order of magnitude higher centre-of-mass energy than at existing machines
 - Important for “tuning” the Monte Carlo generators
 - Studies of Standard Model processes (as tests of the SM and in order to understand the backgrounds to new-physics searches)
 - Jet production
 - Inclusive W and Z production
 - W and Z production at large p_T in association with jets
 - Top production
 - B-physics (in ATLAS and CMS, as well as in LHCb)
 - Start searches for new physics
 - Predicted or unpredicted!



Conclusions

Detectors are well optimised for the physics challenges of LHC
 We are looking forward to the first collisions in Summer 2007
 Participation from more Pakistani scientists would be very welcome
 Thanks for your kindness and wonderful hospitality in Pakistan!



Detector characteristics
 Width: 22m
 Diameter: 15m

