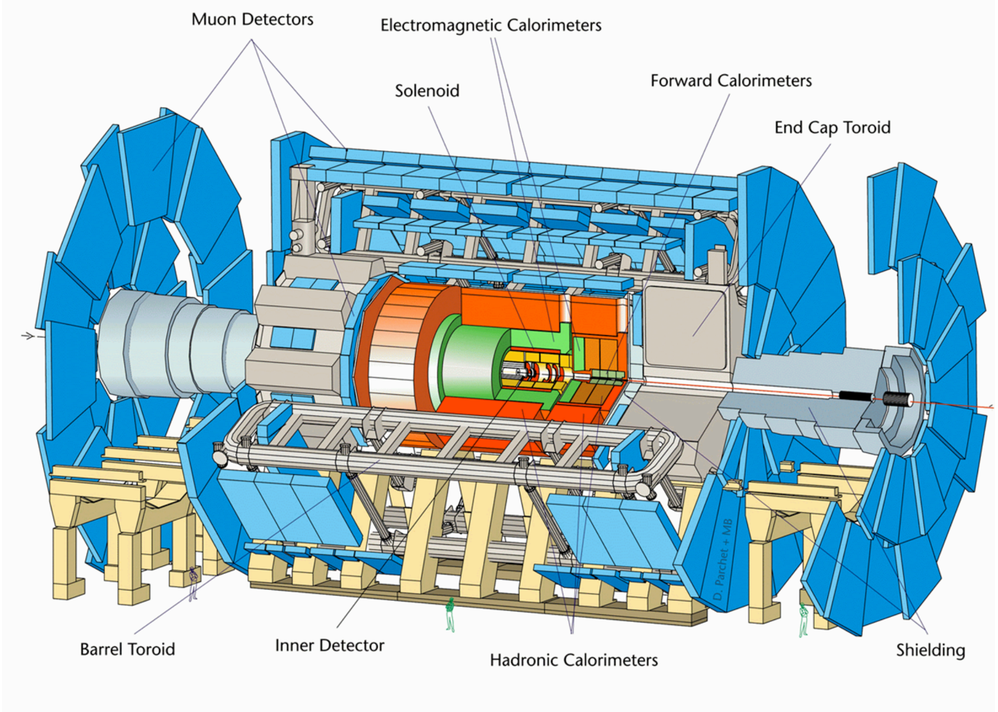
Prospects for ATLAS and CMS at the LHC

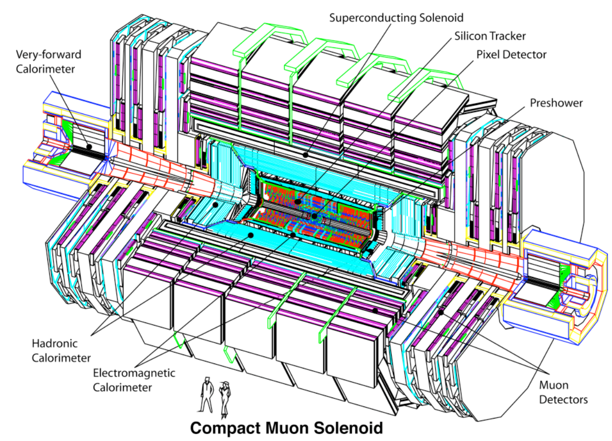
Scope of the LHC Program

- Proton-proton collider
  - New facility about to become operational at CERN
  - 7 TeV + 7 TeV with design luminosity of 10^{34}/cm^2/sec
    - 7 times the energy of the Fermilab Tevatron and ~100 times the luminosity
  - Project approved in 1996
    - In preparation for many years!
- 4 interaction points equipped with experiments
  - ATLAS and CMS to study short-distance phenomena (the subject of this talk)
    - > 20% US participation in each experiment
  - LHCb to study b-physics
  - ALICE for heavy ion physics

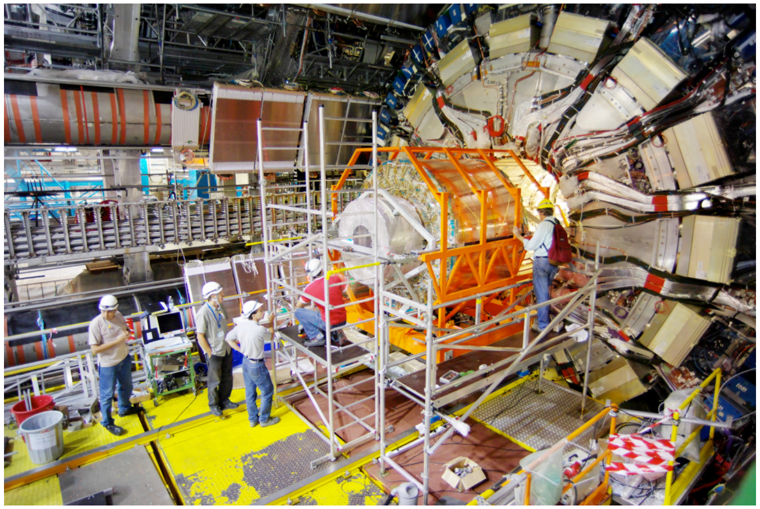
Detector Preparation

- We heard this morning from D. Lissauer and J. Mans on the ATLAS and CMS detectors

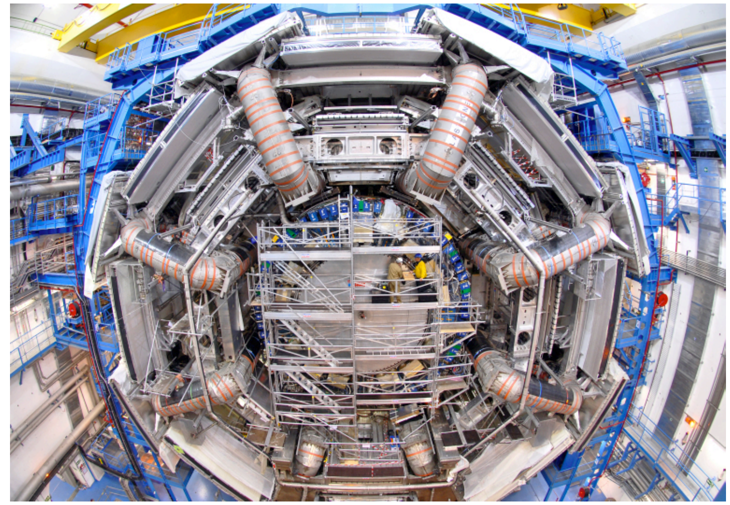




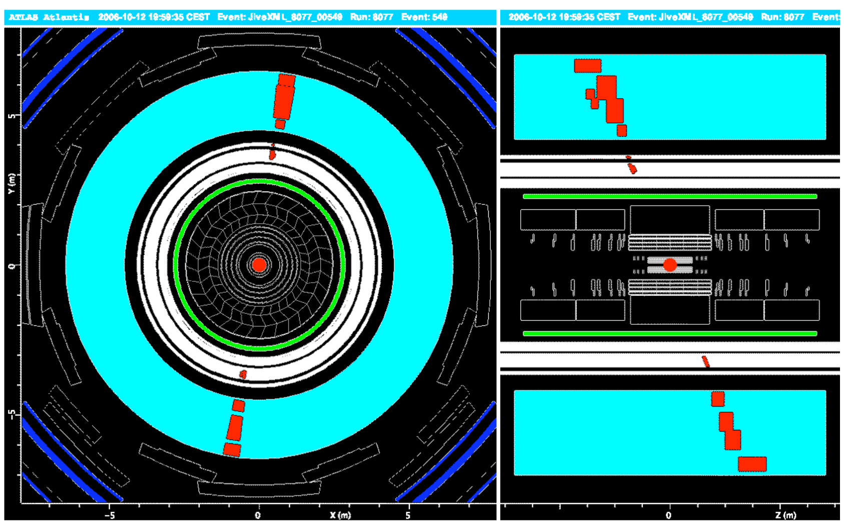
ATLAS Detector Preparation



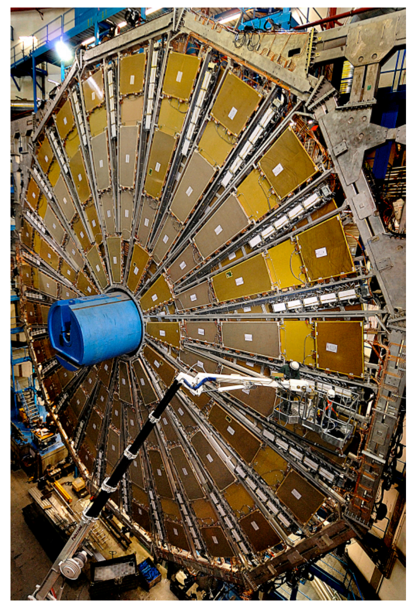
Barrel Inner Detector Installation 8/06



Toroid with End-Cap Cal. 11/06

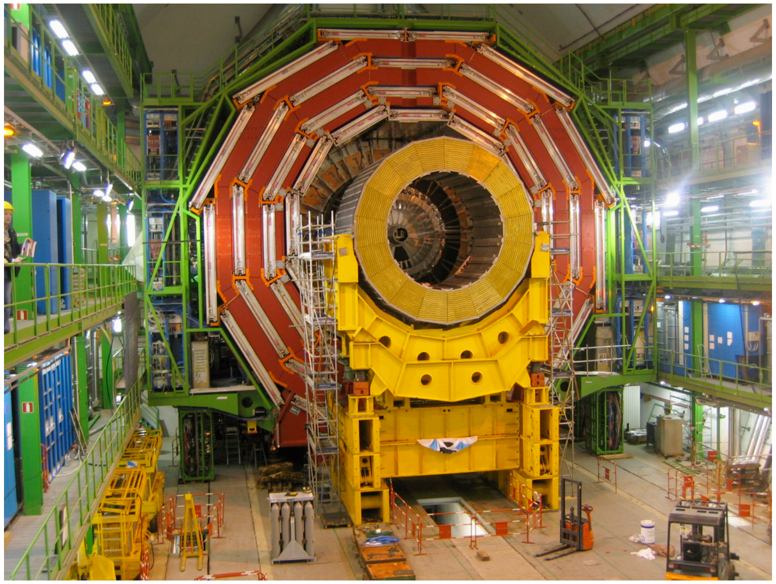


Cosmic Ray in Underground Hall 12/06

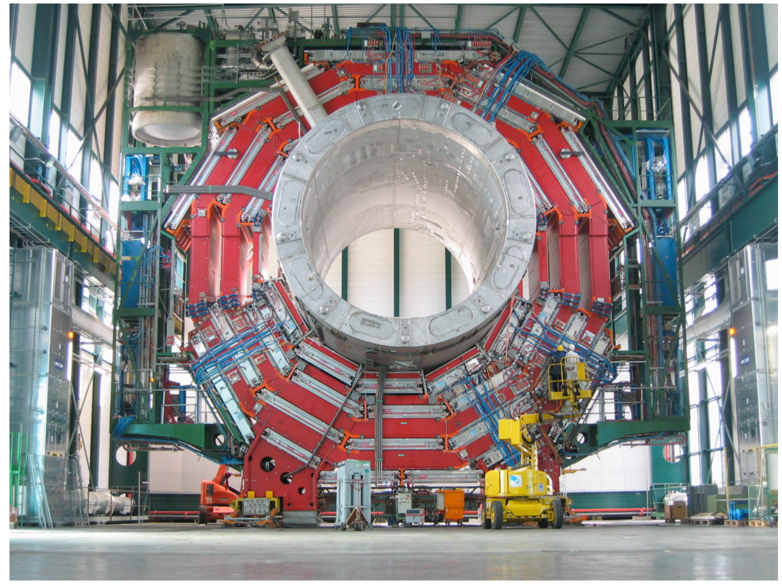


End-Cap Muon Trigger Plane

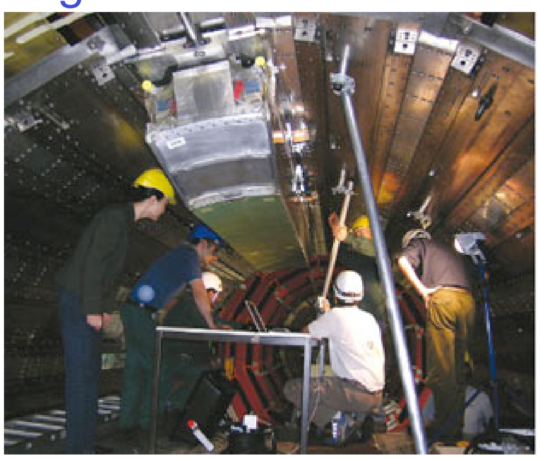
CMS Detector Preparation

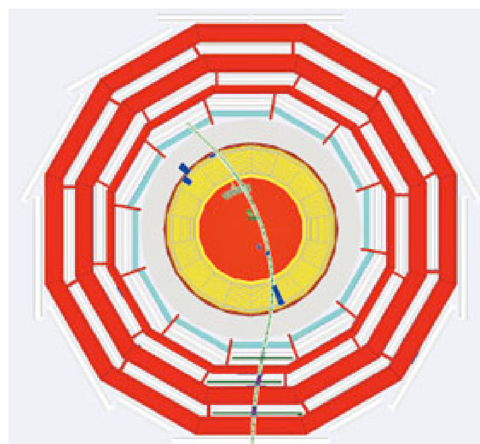


Underground Hall: 2/07



YB0 in Surface Hall





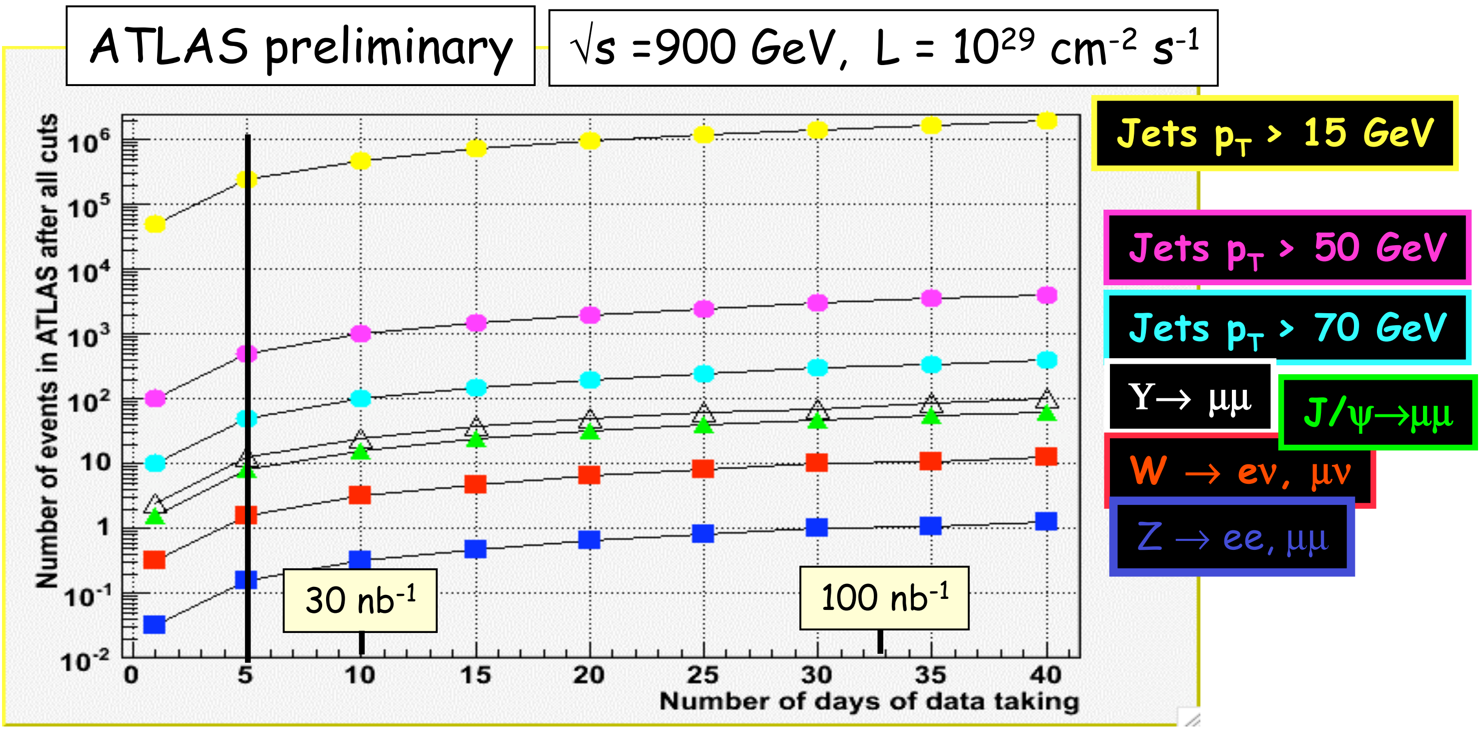
Cosmic Ray Challenge 8/06

Plans for First Operation

- First beam-beam collisions expected late this year
  - A brief engineering run with a few days of collisions at very low luminosity
    - Limit stored energy until control systems are well established
    - Run close to injection energy: 450 GeV + 450 GeV
    - Most operation at 43 proton bunches/beam (vs. nominal 2808)
    - No beam squeeze at interaction point to raise luminosity
    - Expected peak luminosity ~10^{29} /cm^2/sec
- Very important milestone
  - Demonstrate basic functionality of collider and detectors
  - Provide first operational experience
    - Machine will be off for 6 months of final installation and testing following this engineering run
    - respond to issues seen in test run, prior to physics run

First Engineering Run

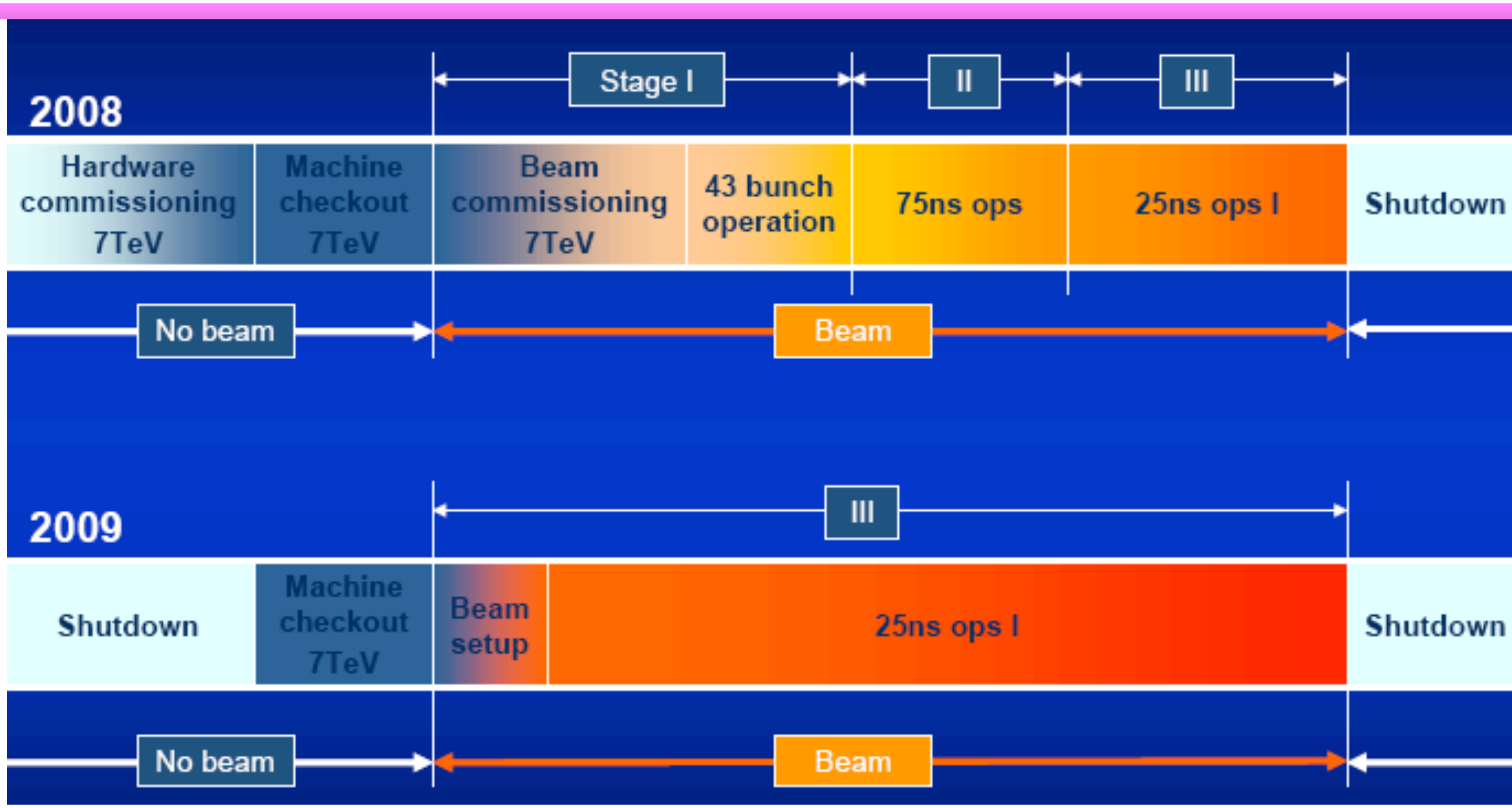
- Physics event yield is modest
  - 5 days, ε=30%, L=10^{29} /cm^2/sec $\Rightarrow$15 nb^{-1}



First Engineering Run

- But ~ 3 KHz rate for minimum bias interactions (soft interactions)
  - can record at ~ 100 Hz
  - 5 days @ ε=30%, 100 Hz $\Rightarrow$ ~12M events
  - Will bathe the detectors' trackers and calorimeters
    - Charged particles
    - Photons
    - Low P_t muons
  - Very useful for initial debugging, calibrations, alignments
  - Exercise computing and off-line processing systems

Operation beyond 2007



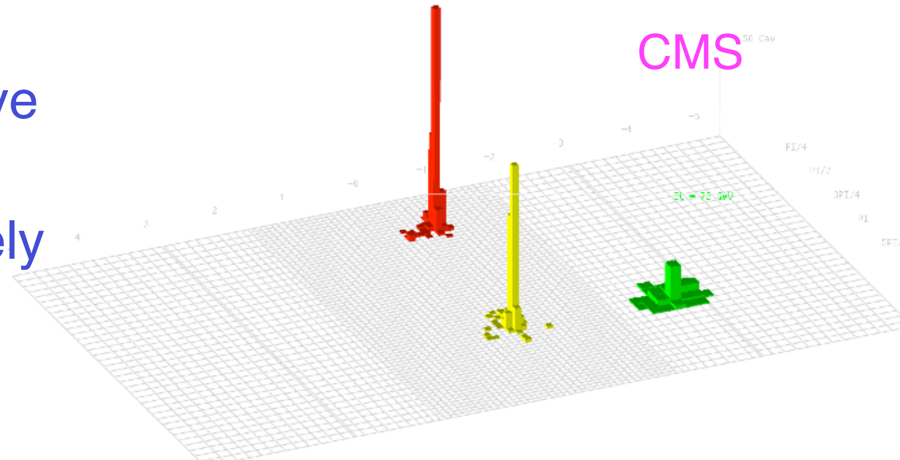
- In 2008, 130 days for physics operation
  - Estimated integrated luminosity ~ $1fb^{-1}$ (40 days, ε=60%, L=$5x10^{32}$)
- In 2009, closer to routine operation
  - Assume integrated luminosity ~ 7 fb^{-1} (design ~ 70 fb^{-1})

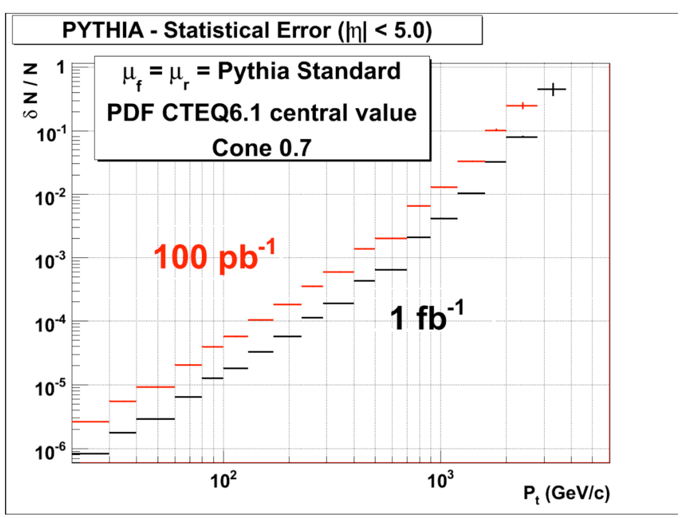
Physics Potential in First Few Years

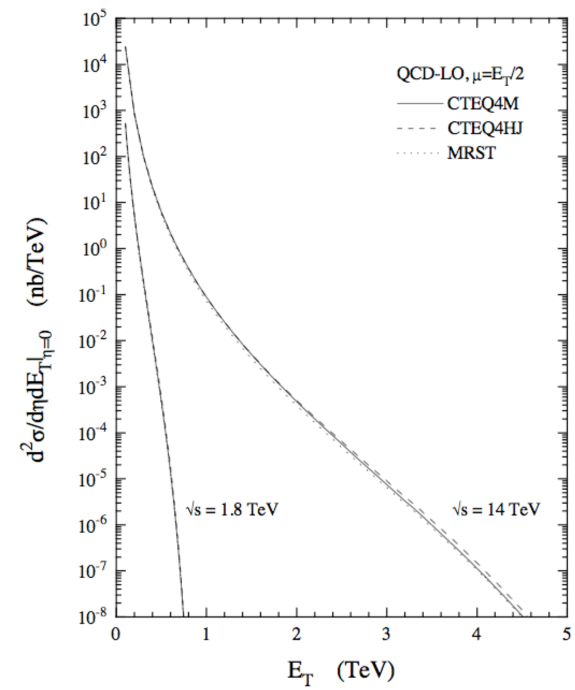
- Standard Model Physics
  - A few prominent examples here (but many more)
    - Jet physics
    - Top physics
    - Gauge boson production
  - Interesting measurements + essential calibration using well understood phenomena
- Search for supersymmetry
- Search for Higgs boson
- Search for exotics
  - Heavy gauge bosons (Z′)
    - Extra dimensions
    - GUT theories
  - Mini-black holes

Jet Physics

- Jets very distinctive
- Statistics from first physics run give $\delta N/N < 1\%$ to $P_t \sim 1.3$ TeV/c
- Jet energy scale uncertainties likely to dominate
  - Conversion of detector measurement to parton energy
  - $\delta E_p/E_p \sim 5\% \Rightarrow \delta\sigma/\sigma \sim 30\%$
    - At $P_t \sim 1.3$ TeV/c





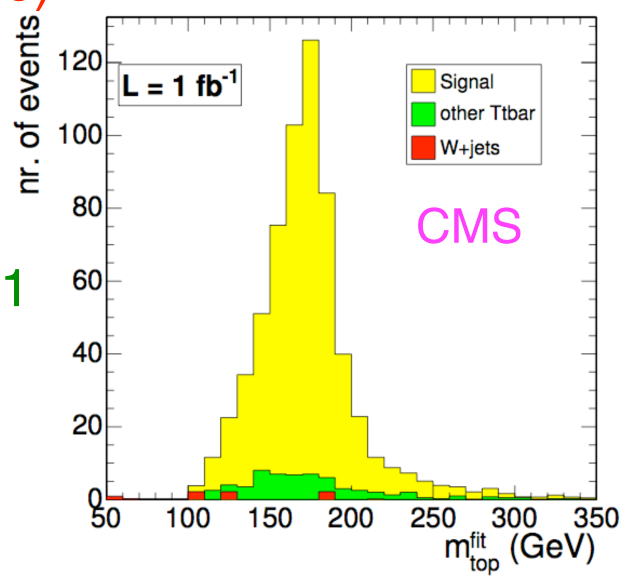


Jet Physics

- Best sensitivity to new heavy states in di-jet mass spectrum is through a ratio like $\frac{N(|\eta| < 0.5)}{N(0.5 < |\eta| < 1.0)}$
  - Production of heavy state suppressed at high rapidity relative to QCD
  - Ratio is insensitive to jet energy scale effects, luminosity, etc.
  - 1 fb^{-1} sample can discover a contact interaction with $\Lambda < 10$ TeV at 5σ level or better (probes distances to ~ 10^{-18} cm)
- Establish calibration and performance of calorimeters
  - Essential for many "new physics" channels
  - Establish relative calibration of calorimeter channels through di-jet events at different rapidities and azimuthal angles
    - Require momentum conservation and independence of rate with φ
  - Establish absolute calibration of jets relative to EM calorimeter via
    - Z+jet and γ+jet final states

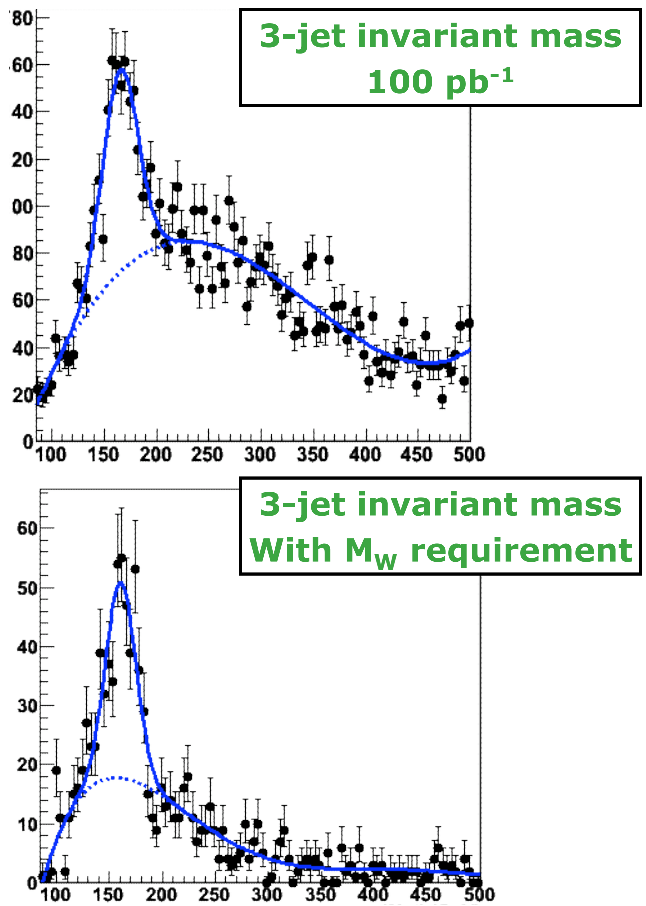
Top-Quark Physics

- LHC is a "top factory"
  - σ ~ 830 pb for $t\bar{t}$ production (~ 100X Tevatron, S/N ~ 10X)
  - 5% $t+\bar{t} \rightarrow \ell^+\nu_\ell b + \ell^-\bar{\nu}_\ell\bar{b}$ (ℓ = μ or e)
    - seen as two leptons, missing energy, two b jets
    - "dilepton channel"
    - Clean channel but weaker kinematic constraints
      - Can obtain ~ 600 events with S/N ~12:1 from 1 fb^{-1} sample
  - 30% $t+\bar{t} \rightarrow \ell^+\nu_\ell b + qq'\bar{b}$ (for ℓ = μ or e)
    - "Lepton plus jets" channel
    - Selection cuts with b-tagging (2)
    - Jet pairing, kinematic fit (CMS TDR)
    - 5200 events from 1 fb^{-1} with S/N ~27:1
      - δM_t ~ 0.5 GeV (statistical)
      - Principal error is jet energy scale
        - $\delta E_p/E_p \sim 5\% \Rightarrow \delta M_t \sim 3$ GeV

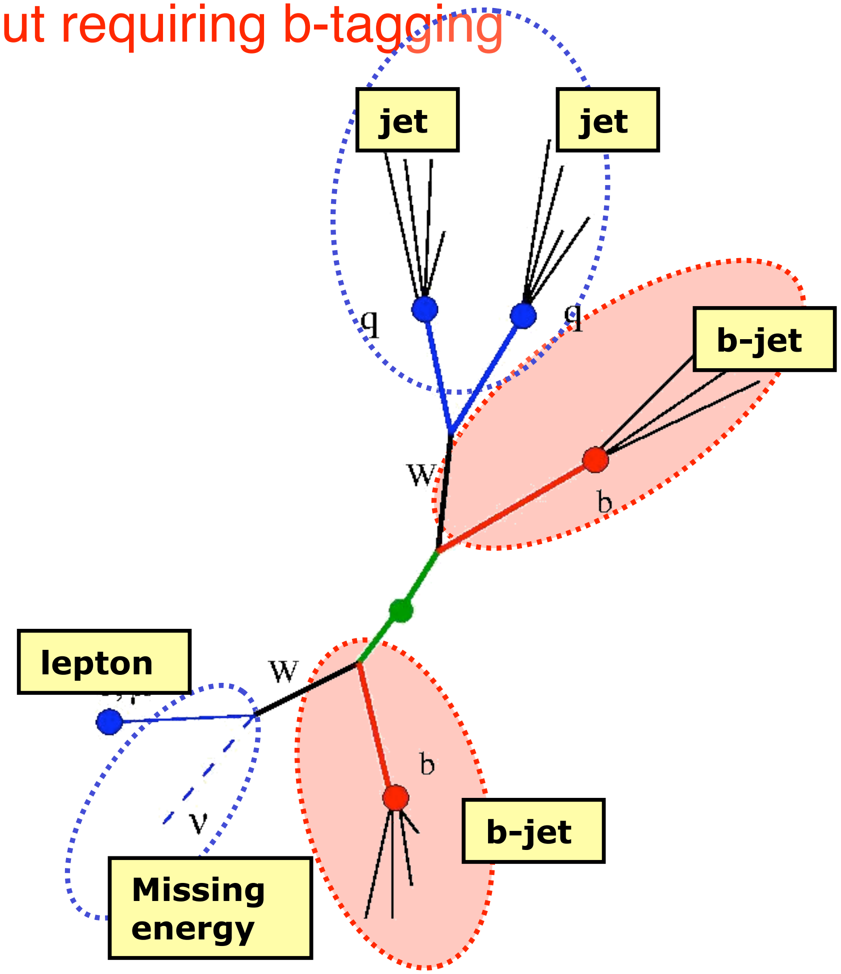


Top-Quark Physics

- Top channels provide important calibration checks
  - Understand detector performance in complex topologies
  - Can see signal on one side without requiring b-tagging

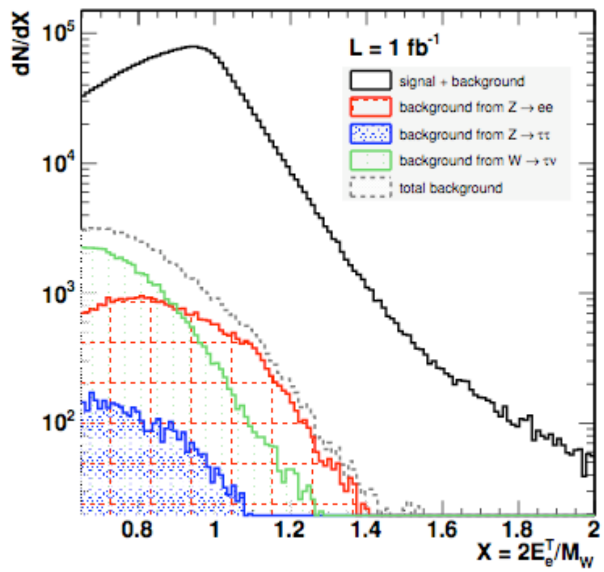


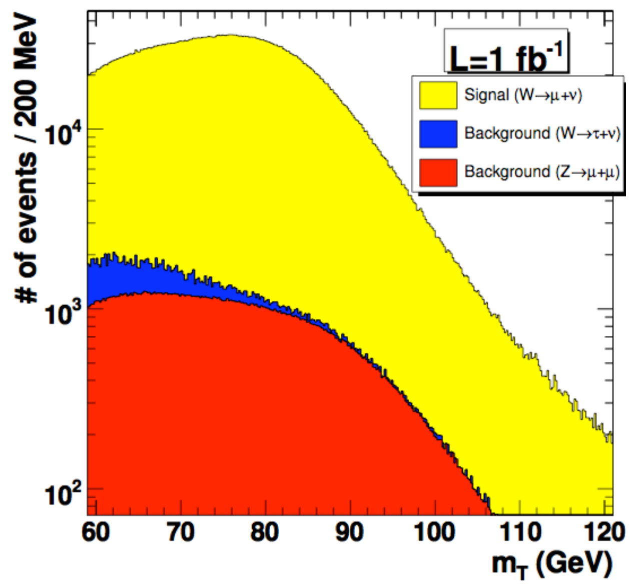
M_{jjj} (GeV)



Gauge Boson Production

- Single gauge bosons + jets have well known properties
  - Large cross section for $pp \to W + X$, $W \to \ell^{\pm}\nu$ (7.8 nb)
  - Also for $pp \to Z + X$, $Z \to \ell^{+}\ell^{-}$ (1.2 nb)

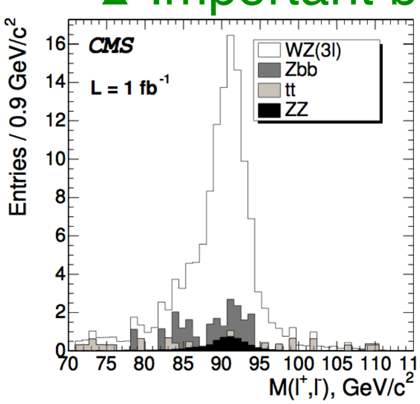




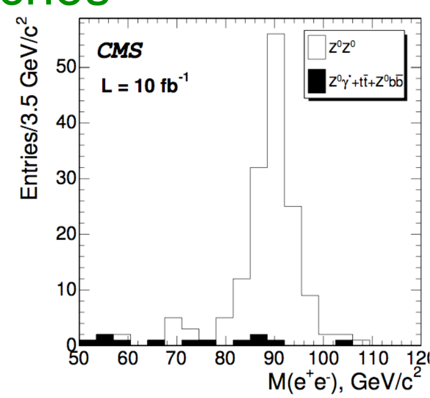
  - Calibrate performance for isolated leptons over the full detector
  - $m_T = \sqrt{2 p_T^e p_T^\nu (1 - \cos\Delta\varphi)}$ for W channel involves missing energy reconstruction

Gauge Boson Production

- Single gauge bosons
  - Can measure M_W (a challenging measurement in early years!)
    - 1 fb^{-1} capable of $\delta M_W = \pm 40 \pm 25$ MeV
  - Well known cross section provides a source of luminosity determination
    - $\delta L/L \sim 7\%$ Cross check other methods
- Multi-boson production
  - $W^{\pm}Z^0$ and $W^{\pm}\gamma$ reflect triple-gauge-boson coupling
    - Cross section large for $W^{\pm}Z^0$ (50 pb)
    - Important background to "new physics" searches



- Also Z^0Z^0
  - Background to H^0
  - Small signal meas.



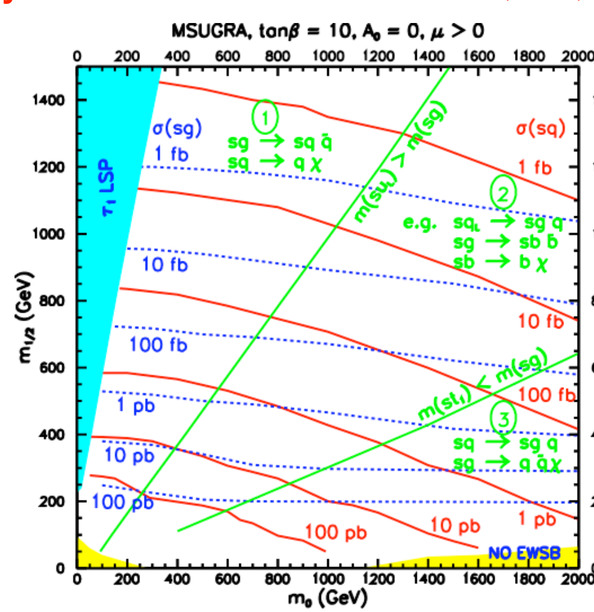
SUSY

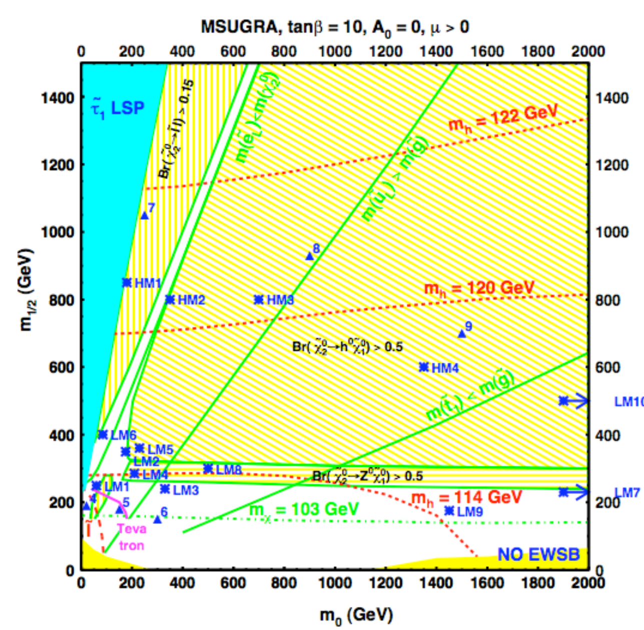
- Supersymmetry
  - A supersymmetric partner for every known particle
  - Very attractive theoretically since it maintains a low Higgs mass
  - Symmetry breaking mechanism is unknown
    - Leads to VERY large parameter space
    - Final state properties depend on location in parameter space
  - Many versions have stable lightest supersymmetric particle (LSP)
    - "R-parity conserving"
      - SUSY states carry R-parity
    - Neutral particle with weak interaction cross sections
    - Invisible in detector except for missing energy and momentum
    - Possible source of dark matter
  - No direct experimental evidence
    - Limits from LEP, Tevatron, CMB properties, and terrestrial dark matter searches
  - To preserve a light Higgs, SUSY mass scale should be below ~ 1 TeV

SUSY

- One variant is the minimal supergravity symmetry breaking scheme
  - mSUGRA
  - Described by 5 parameters [m_0, $m_{1/2}$, A_0, $\tan\beta$, sign(μ)]
  - Commonly used to characterize detector performance levels
    - Other breaking scenarios also lead to different but characteristic experimental signatures
- Pair production of squarks and gluinos expected to have large cross sections if above threshold
  - They cascade down to LSP, h^0, $H^{\pm}$, SM states

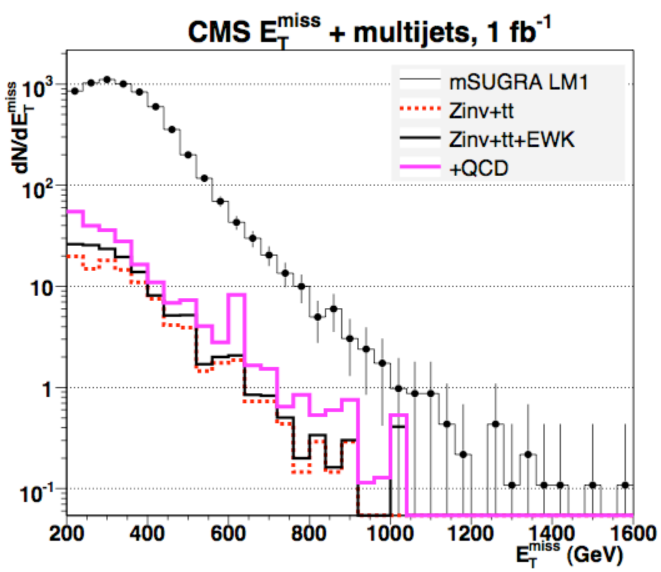
Detection requires ~ 100 produced events for ε ~ 10%



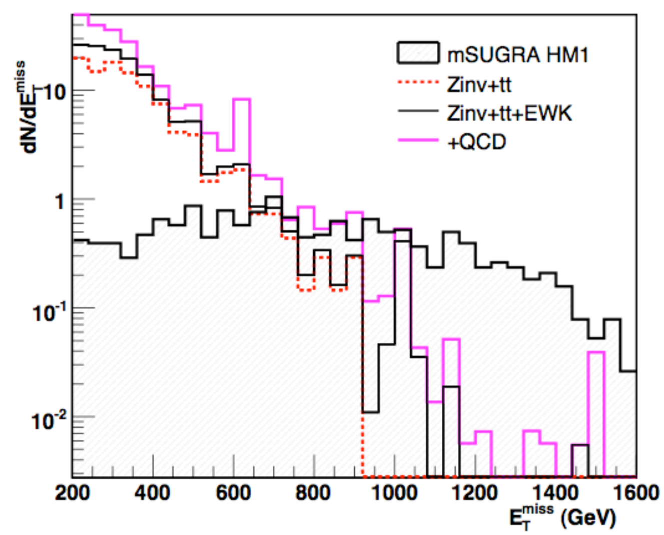


SUSY

- Initial searches likely to be inclusive
  - Best sensitivity
  - Minimal assumptions on details of model
  - Jets + MET, lepton + jets + MET, same sign dileptons + jets
- If signal found, investigate properties with other final states
- Consider low mass point and high mass point
  - Require $E_T^{miss} > 200$ GeV and 3 jets with $E_T > 30$ GeV, $|\eta|<0.3$



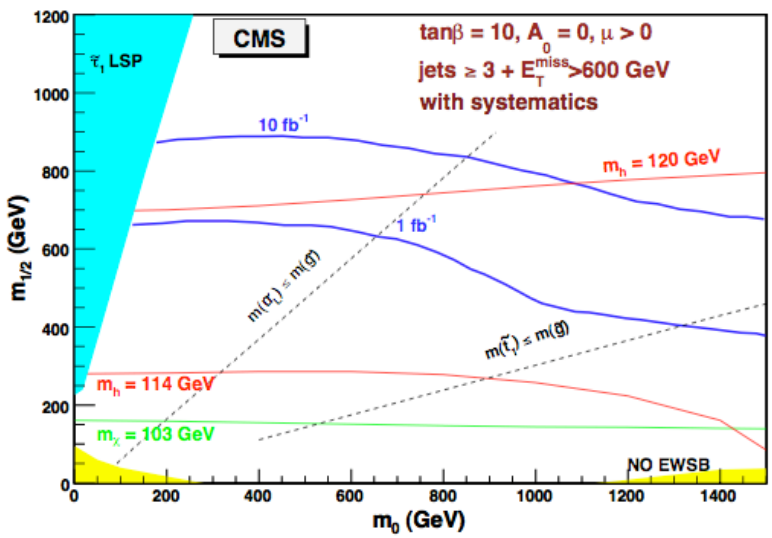
m_0 = 60 GeV, $m_{1/2}$ = 250 GeV



m_0 = 180 GeV, $m_{1/2}$ = 850 GeV

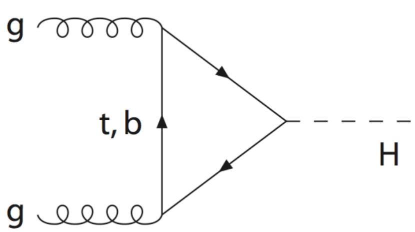
SUSY

- Optimize analysis based on high mass point and scan parameter space (require E_T^{miss} > 600 GeV at high masses)
  - Early LHC running should double existing limits
  - Later LHC running should cover full parameter space for “weak-scale” SUSY

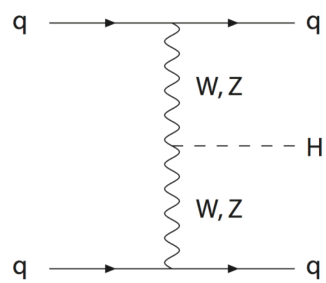


Higgs Boson

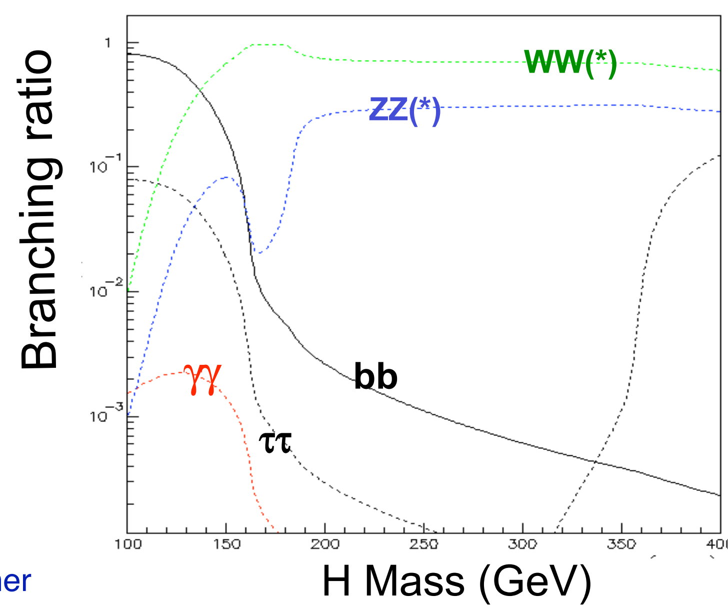
- Many standard model predictions tested at a per mil level
  - Higgs boson not yet detected but an essential ingredient in these predictions
  - Best estimate for Higgs mass from fitting electroweak observables is $M_H = 76^{+33}_{-24}$ GeV with $M_H < 182$ GeV @ 95% CL
  - Current lower limit from direct searches $M_H > 114$ GeV @ 95% CL
  - Minimal SUSY theories predict a light Higgs with $M_H < 140$ GeV
- Higgs discovery is a major goal of the LHC program



Top Loop
~35 pb, M_H = 130 GeV

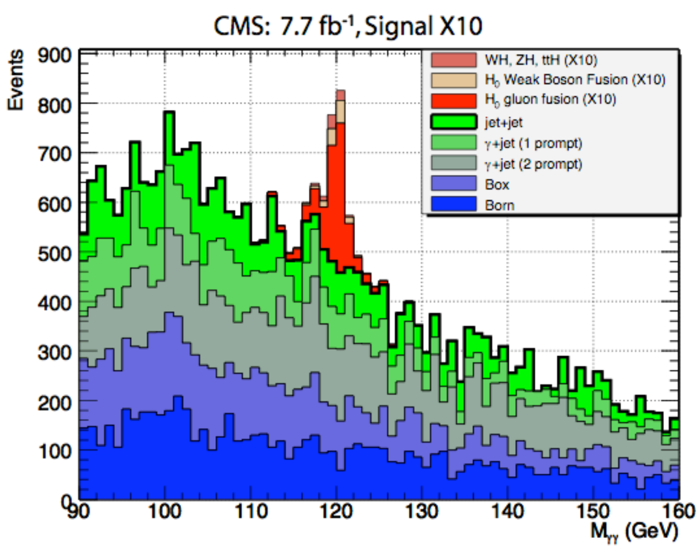


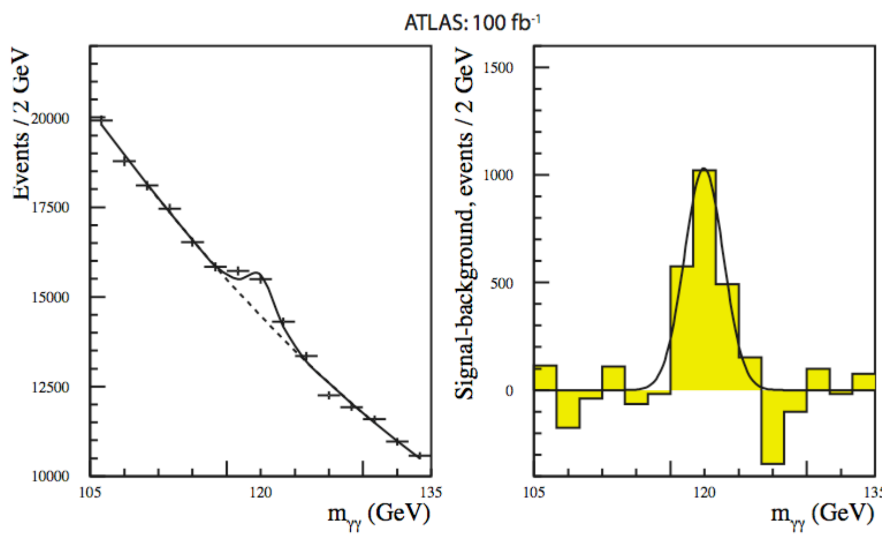
Vector Boson Fusion
~ 4 pb, M_H = 130 GeV



Higgs Boson (H→γγ)

- Consider two complementary search channels for mass range below 140 GeV
  - *$H \to \gamma\gamma$*
    - Small branching ratio (~ 0.2%) but very characteristic signature
      - Background from jet-jet, γ-jet, and γ-γ production
    - EM calorimeter must have very uniform calibration (eg. 0.3-1% from 10 fb^{-1} of $W^\pm \to e^\pm \nu$ data)
    - Need good vertex measurement to preserve mass resolution

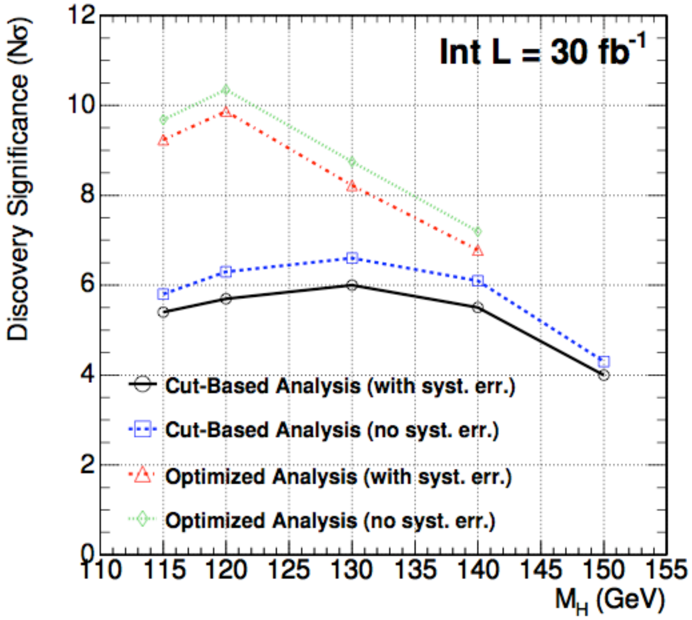




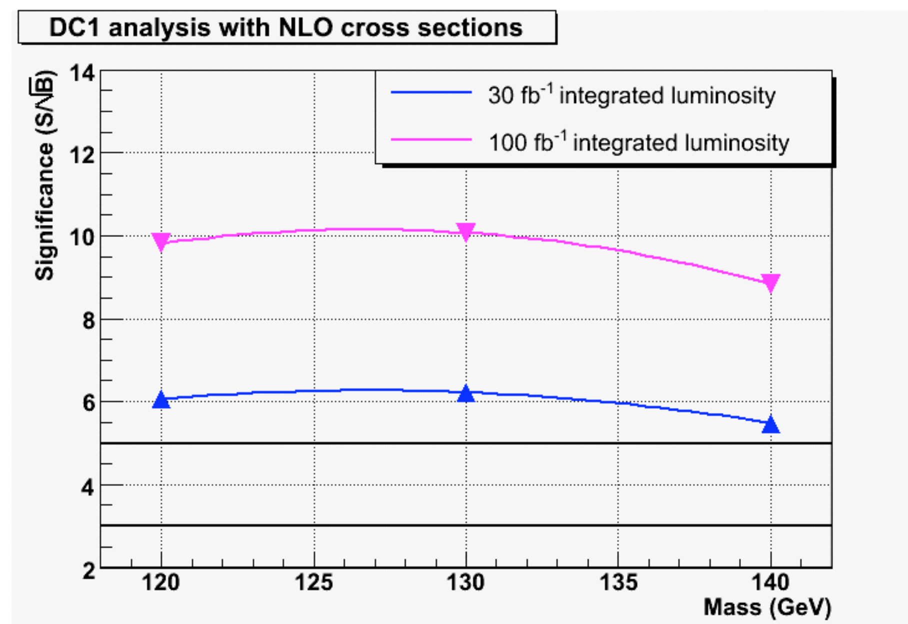
Higgs Boson (H→γγ)

- The two detectors have similar sensitivity but different strengths
  - CMS: Superb energy resolution via crystal EM calorimeter
  - ATLAS: Excellent measurements of shower shapes and vertex position via highly segmented LAr calorimeter
- Need 10's of fb^{-1} for discovery in this channel alone

CMS

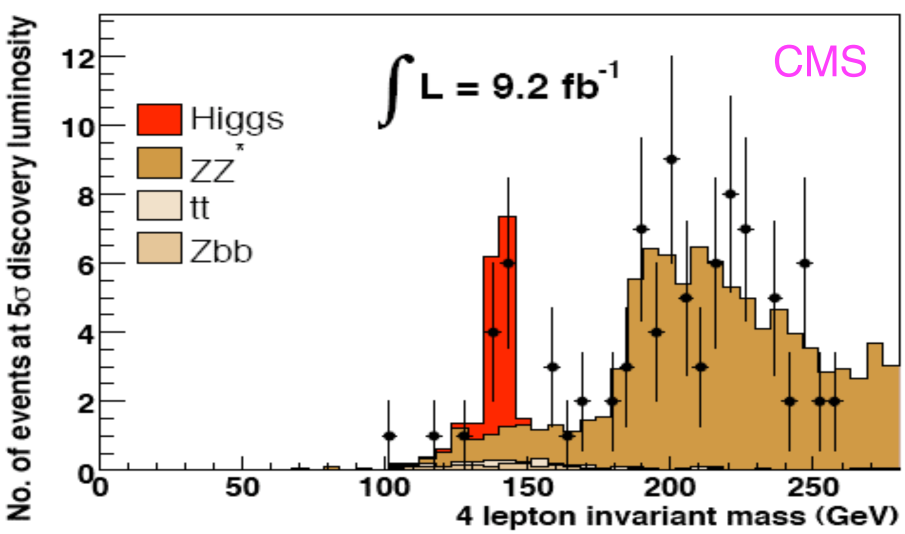


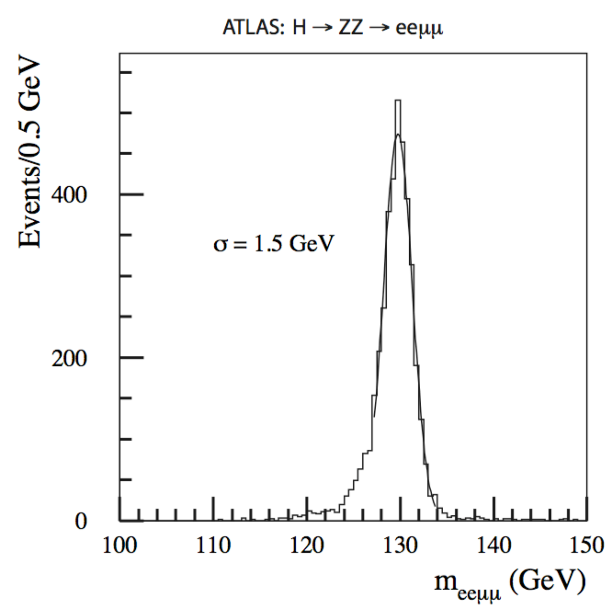
ATLAS



Higgs Boson ($H \rightarrow ZZ \rightarrow 4\ell$)

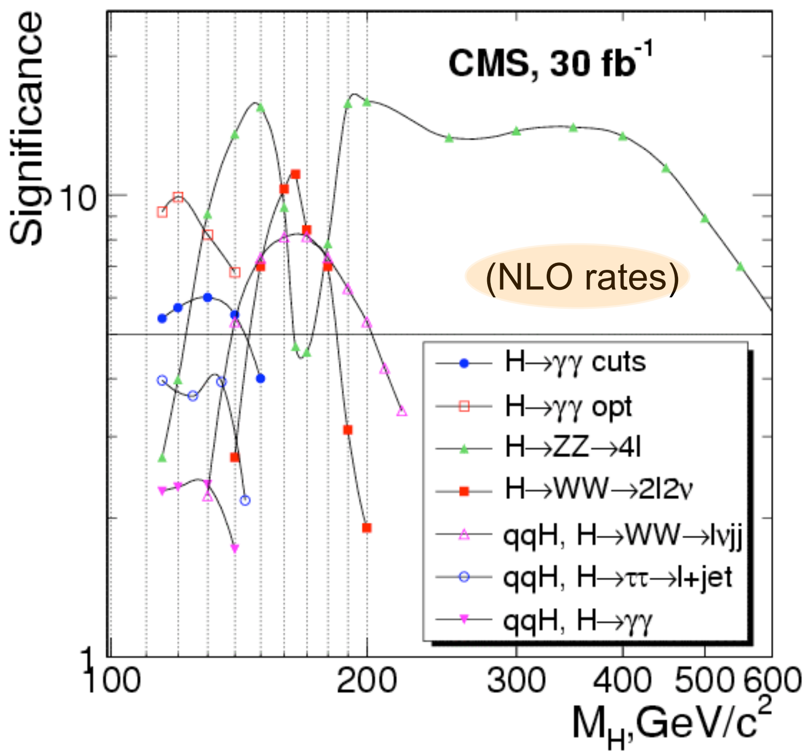
- $H \rightarrow ZZ^{(*)}$
  - Large branching ratio and very characteristic signal
    - $\Gamma_H < 1$ GeV for $M_H < 190$ GeV
  - Powerful lepton detection (μ and e) in both detectors
    - δM ~1.5-2 GeV
  - Significant backgrounds
    - Reducible backgrounds: $t\bar{t}$, $Zb\bar{b}$
    - Irreducible backgrounds: $q\bar{q} \rightarrow ZZ^* \rightarrow 4\ell$
  - Strong isolation cuts essential

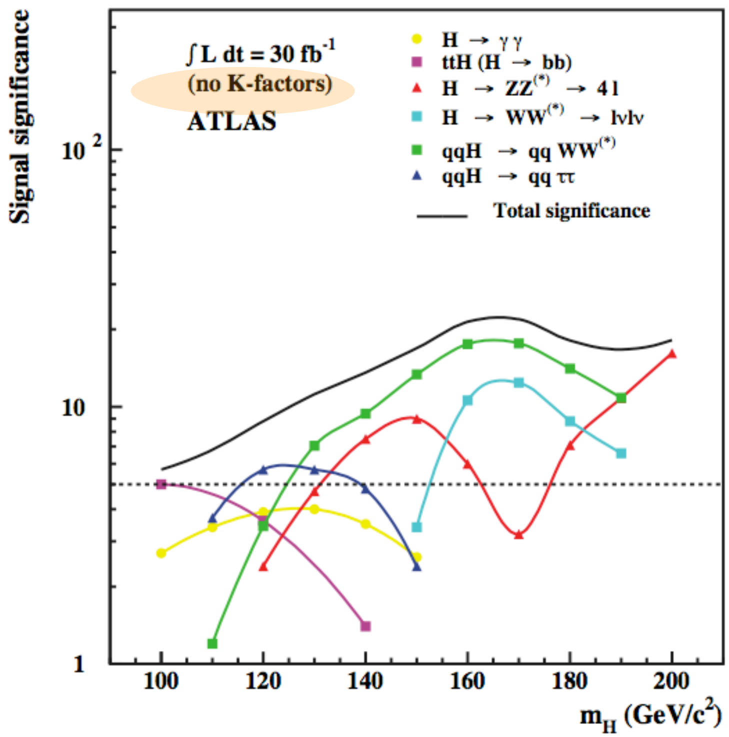




Higgs Boson (All Modes)

- In detector comparisons note use of LO (no K-factors in ATLAS case) and NLO cross sections (CMS case)
- Several channels contribute to sensitivity at a given M_H
- Good discovery potential for SM Higgs from 10 fb^{-1}

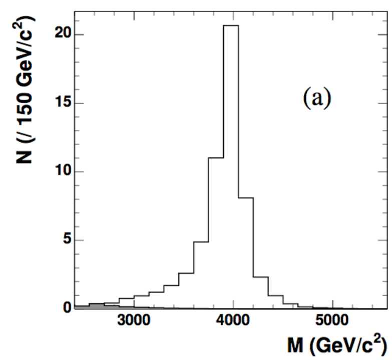


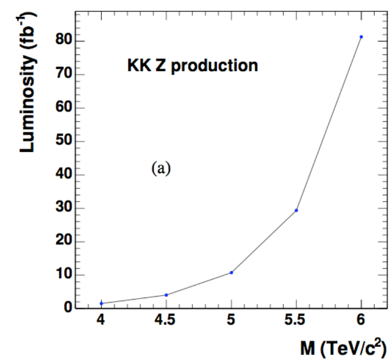


Exotic Processes (Extra Gauge Bosons)

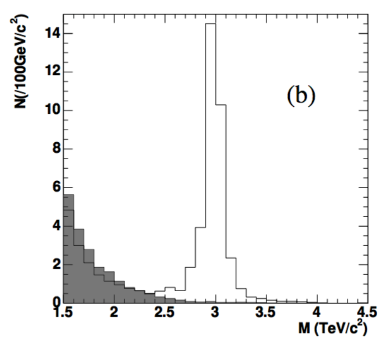
- Many models predict extra gauge bosons (Z′)
  - Sequential Standard Model
  - Grand unified theories
  - “Left-right” models
- Present experiments explore to ~ 1 TeV
- Early LHC running will go beyond this (angular distributions important)

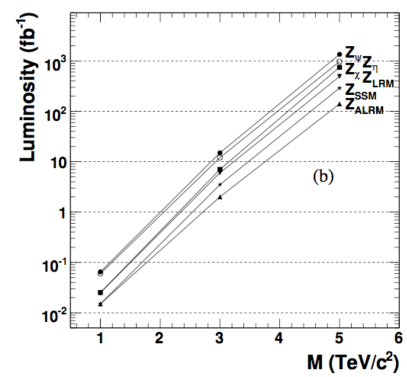
KK Z′ boson in TeV^{-1}-sized extra dimensions





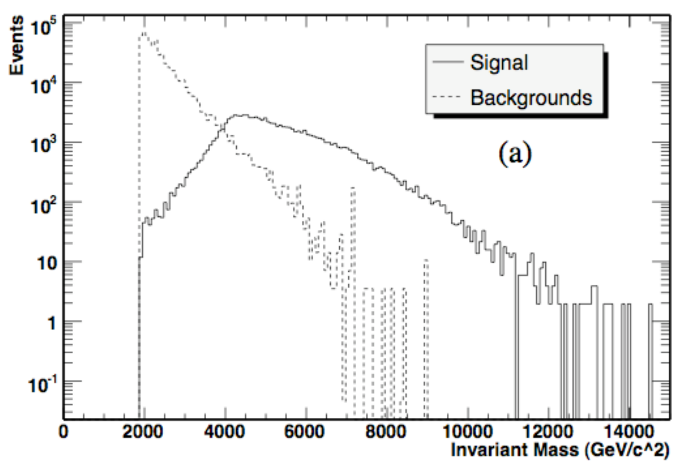
Extra Z′s in GUT models

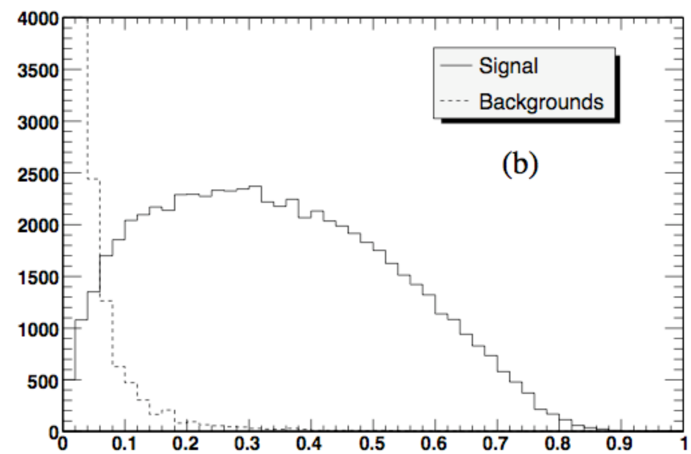




Exotic Processes (Mini Black Holes)

- Models with extra dimensions and a reduced Planck scale may allow the production of mini black holes
  - Parton-parton impact parameter less than Schwarzschild radius
- The black holes evaporate via Hawking radiation
  - Spherical emission of all types of particles
- Example for 2 TeV Planck scale and $M_{BH} > 2$ TeV





Event Sphericity

Conclusions

- First engineering run important for shaking down all systems
- We expect ~1fb^{-1} from the 2008 physics run at 14 TeV
  - Parton-parton scattering to a few TeV
  - Copious top production
  - Copious gauge boson production
    - Calibrate detector
    - Measure background levels for searches
  - First look for SUSY
    - Will already significantly expand existing limits
- Later years
  - Higgs search (needs ~10 $fb^{-1}$to cover full range)
  - Expand SUSY search to full range for “weak-scale” SUSY
  - Extend all searches to higher mass scales
- A very exciting physics program is about to get underway
  - Even the first year should be productive