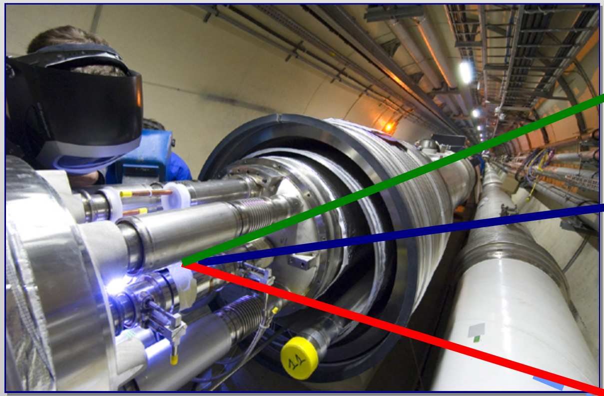
New Physics at the LHC:
Lepton Reconstruction and Signatures in ATLAS and CMS



Steven Goldfarb
MCTP: LHC New Physics Signatures Workshop
University of Michigan, Ann Arbor - 5 Jan 2008

The LHC: By Numbers

Nominal Operating Parameters (p-p)

$E_{injection} = 450\ MeV$

$E_{beam} = 7\ TeV$

$L = 10^{34}\ cm^{-2}s^{-1}$

Bunch Spacing = 25 ns (40 MHz)

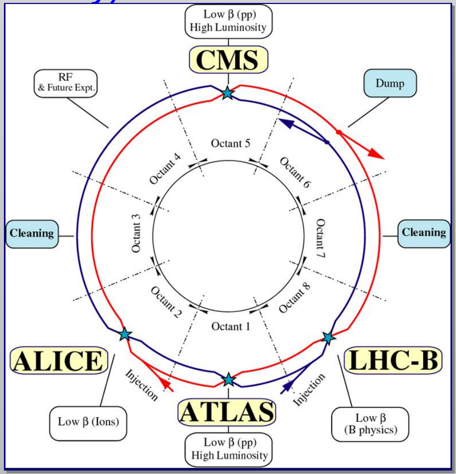
Pile-Up = 2-20 collisions/crossing

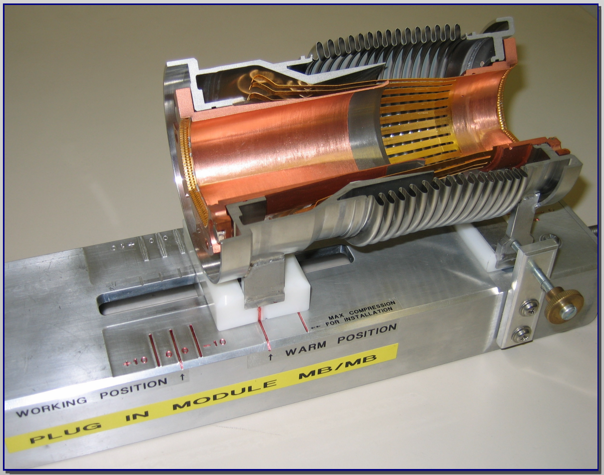
Collision Duration ≈ 10-24 h

Down Time ≈ 1.5 h

Lifetime (as is) ≈ 10 y

(when statistical error half-life = 5y)





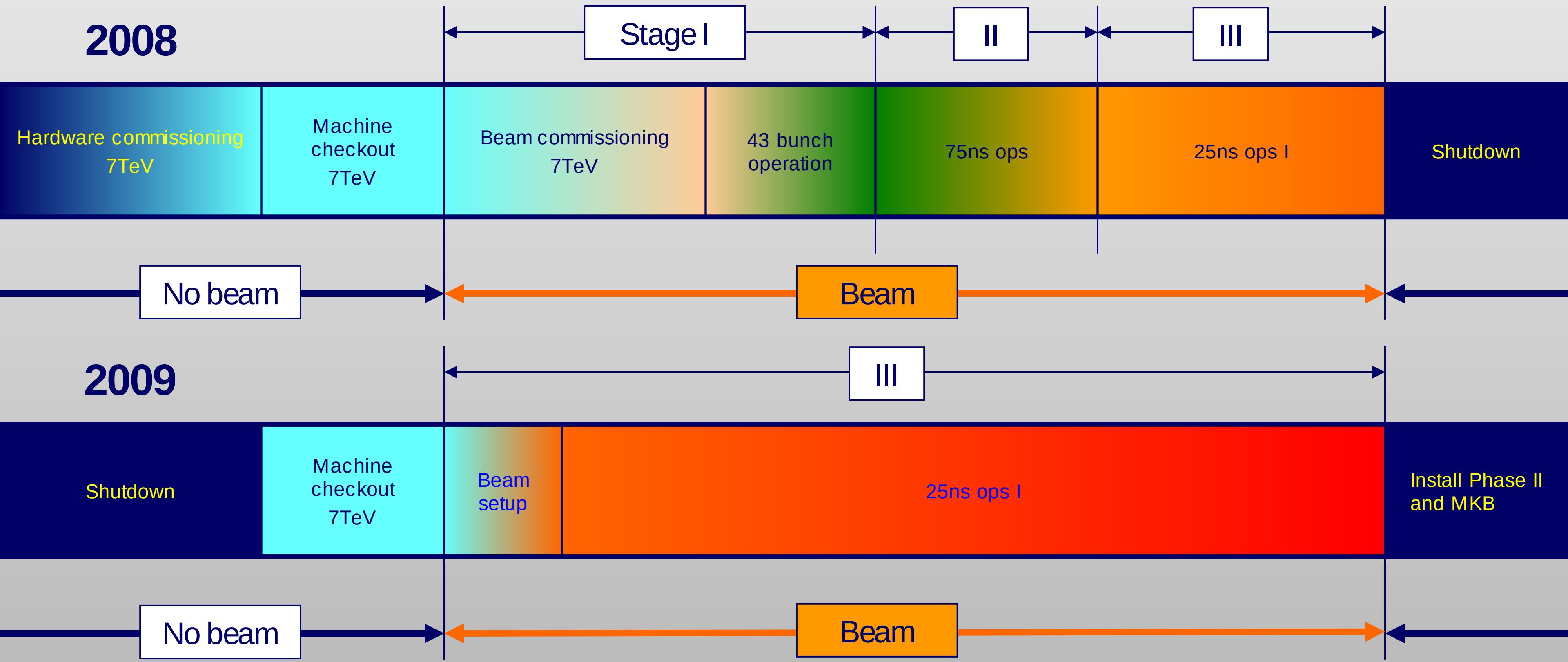
The LHC: Coming Years

Current Schedule

April 2008 - Machine Closed

May 2008 - Beam Commissioning at 7 TeV

July 2008 - First Collisions at 14 TeV (aim for 10^{32} cm^{-2}s^{-1} by end 2008)



The LHC: Physics

Physics in the First Year

At $L = 10^{32}\ cm^{-2}s^{-1}$ and 50% data-taking efficiency (early on)

- $\Rightarrow$ few weeks $\approx$ 100 pb^{-1}
- $\Rightarrow$ 6 months $\approx$ 1 fb^{-1}

Example Decay Channel	LEP (all)	Tevatron (all)	LHC (100 pb^{-1})	LHC (1 fb^{-1})
$W \to \mu\nu$	$\sim10^4$	$\sim10^6$	$\sim10^6$	$\sim10^7$
$Z \to \mu\mu$	$\sim10^6$	$\sim10^5$	$\sim10^5$	$\sim10^6$
$tt \to WbWb \to \mu\nu + X$		$\sim10^4$	$\sim10^4$	$\sim10^5$
QCD jets ($p_T > 1$ TeV)			$\sim10^3$	$\sim10^4$
g g (1 TeV) $\to$ q qZχ…			*~50*	*$\sim10^3$*
Z' (1 TeV) $\to \mu\mu$			*~20*	*$\sim10^2$*
H (160 GeV) $\to$ WW* $\to l\nu l\nu$				*5σ?*

F. Gianotti, D. Froidevaux (a few additions by me)

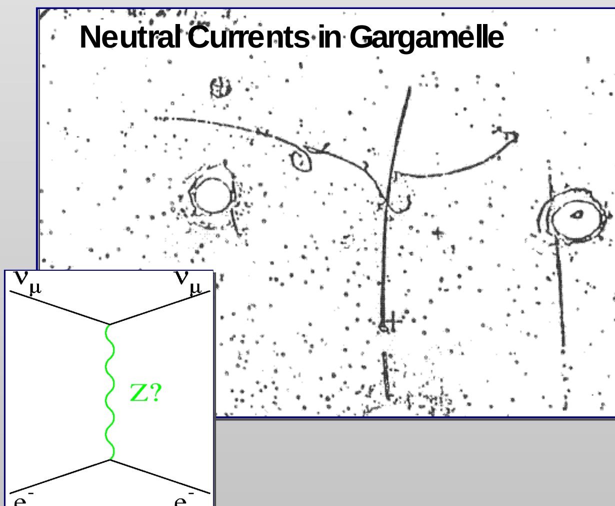
The LHC: Leptonic Signatures of New Physics

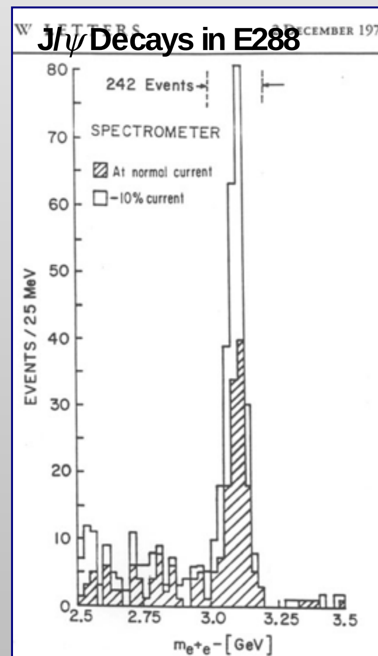
Why Leptons?

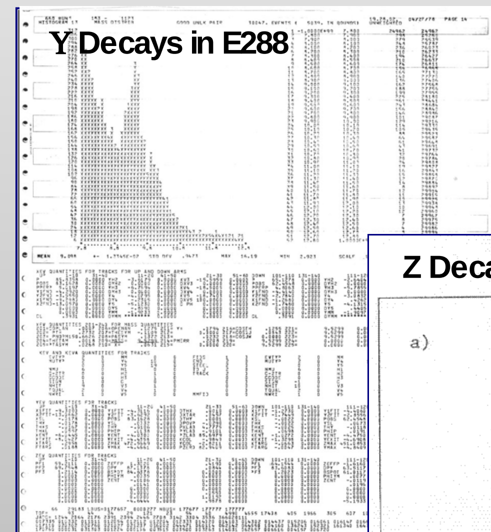
- That's what you asked me to present.
- Michigan has a key role in the construction, operation of ATLAS Precision Muon Chambers
- Lepton signatures are "**clean**" (easy to trigger, select, low non-physics background)
- Excellent for benchmarking, calibrating, aligning (Z, W, J/ψ,…)

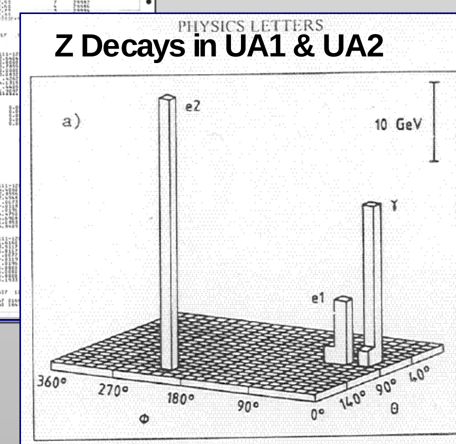
  So we will be tagging and measuring them, anyway…

- History









The LHC: Leptonic Signatures of New Physics

The LHC Lepton Shopping List

Standard Model Higgs

$H \to ZZ \to llll$

$H \to WW \to l\nu l\nu$

$qqH \to qq\tau\tau$ (one or both $\tau \to l\nu\nu$)

MSSM Higgs

$gg \to bbH(A),\ H(A) \to \tau\tau, \mu\mu$

Doubly Charged Higgs

$H^{\pm\pm} \to W^{\pm}W^{\pm} \to l^{\pm}\nu l^{\pm}\nu$

Massive Vector Bosons (KK, Gravitons, etc.)

$Z', G \to ll$

$Z', G \to WW \to l\nu l\nu$

$W' \to l\nu$ or WZ

SUSY

$g \to qq_L$

$q_L \to q\chi_2^0 \to qll_R \to qll\chi_1^0$

GMSB ($\chi_1^0 \to G\gamma$, $l_R \to G l$)

$\chi_2^0 \to ll_R \to ll\chi_1^0 \to llG\gamma$

Right-Handed W

$W_R \to l + N \to l + ljj$

Excited & Heavy Leptons

$pp \to ll' \to llZ \to l + ljj$ (resonances)

$gg \to Z, Z' \to LL \to lZ + lZ \to ljj + ljj$

Technicolor

$\rho_{TC} \to WZ \to lll\nu$

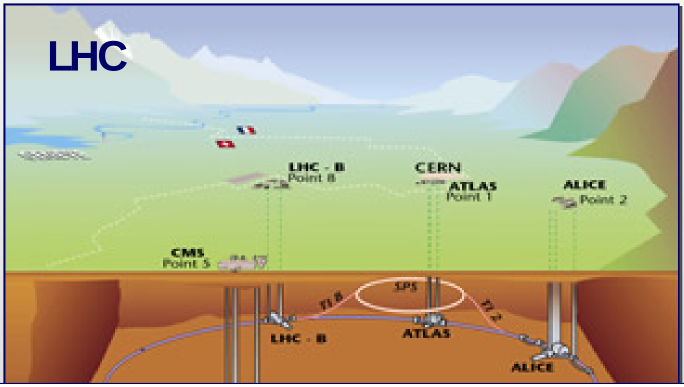
Et Cetera

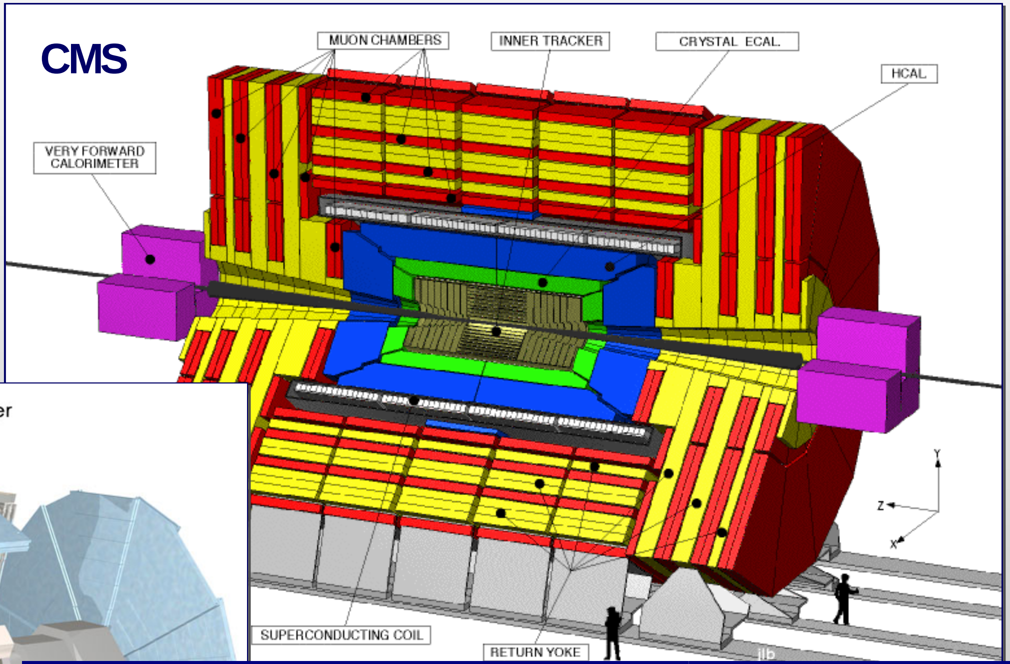
SM precision measurements, e.g.

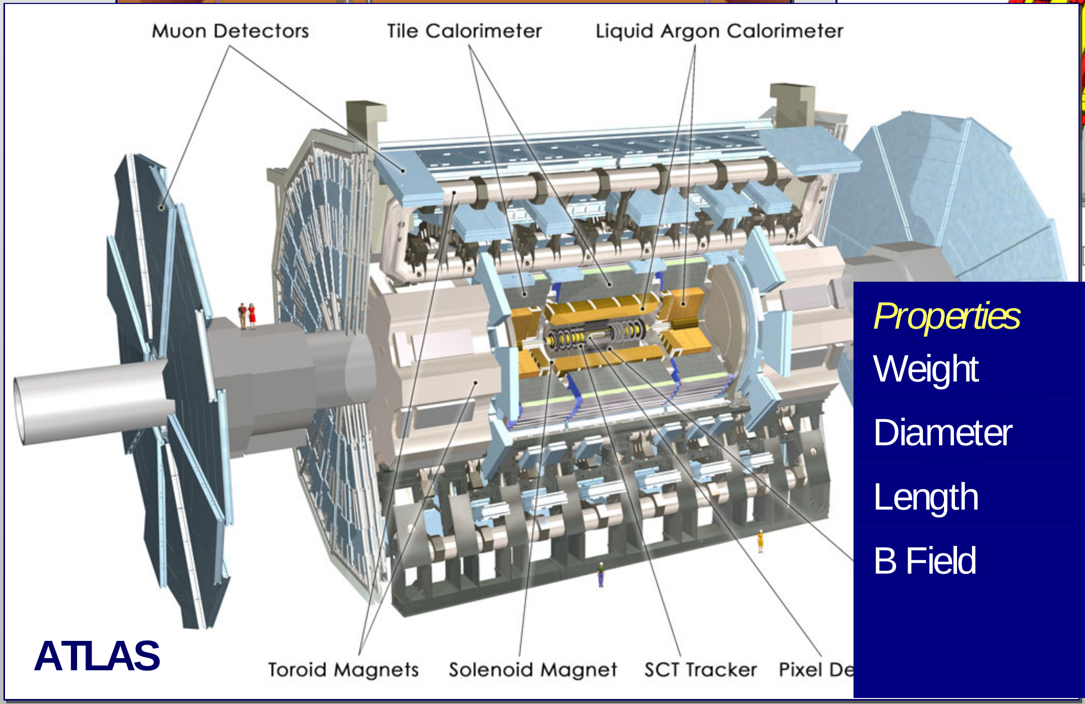
Allergy Notice:

The ingredients contain significant traces of hadronic by-products, event pile-up, and cavern background.

ATLAS & CMS: Detector Overview







Properties	*ATLAS*	*CMS*
Weight	7000 tons	12,500 tons
Diameter	22m	15m
Length	46m	22m
B Field	2T solenoid 3.9T (peak) BA toroid 4.1T (peak) EC toroids	4T solenoid

ATLAS & CMS: Detector Overview

Primary Characteristics

CMS (Compact Muon Solenoid)

Large 4T Solenoid
- Muon Chambers Integrated in Return Yoke

Muon Spectrometer
- Precision: Drift Tubes, CSC
- Trigger: RPC
- Primary Measurements from Tracker

Calorimetry
- $PbWO_4$ Crystal: Excellent Resolution, Lateral Segmentation
- FCAL 11.2m from IP

Inner Tracking
- Pixels: 100μm (r-ϕ) x 150μm (z)
- $\Delta p/p$ (1 GeV) = 0.007,0.02 ($\eta \approx$ 0,2.5)
- $\Delta p/p$ (100 GeV) = 0.015,0.07
- Excellent momentum resolution

ATLAS (A Toiroidal Lhc ApparatuS)

"Small" 2T Solenoid for Tracking

3 Large Toroids for Muon Spectroscopy
- High BL^2 for Standalone Measurements

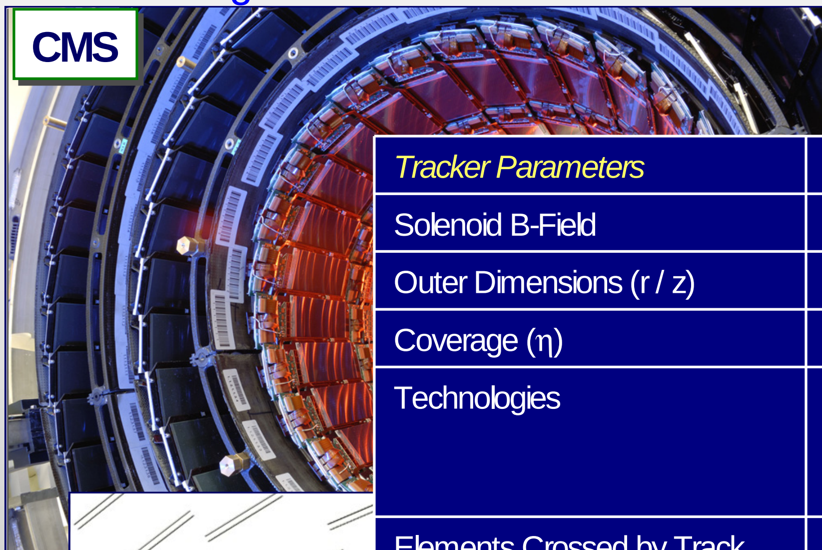
Muon Spectrometer
- Precision: MDT, CSC
- Trigger: RPC, TGC
- Excellent acceptance at poles

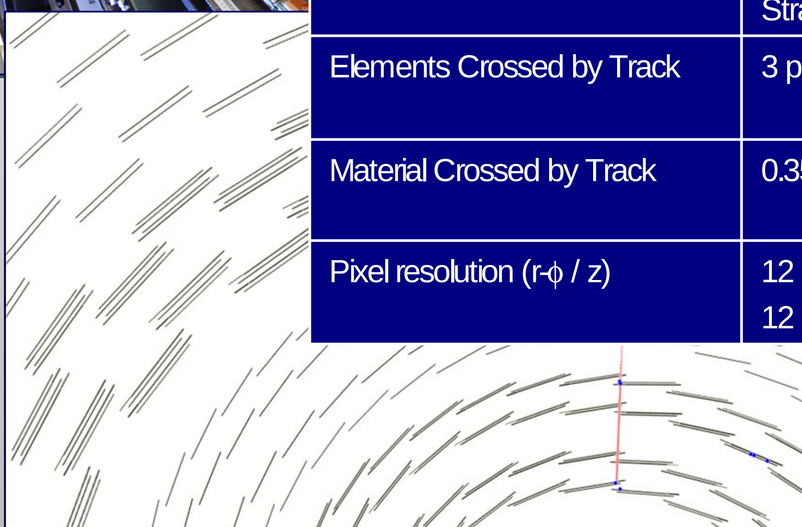
Calorimetry
- Lateral & Longitudinal Segmentation
- FCAL only 4.9m from IP

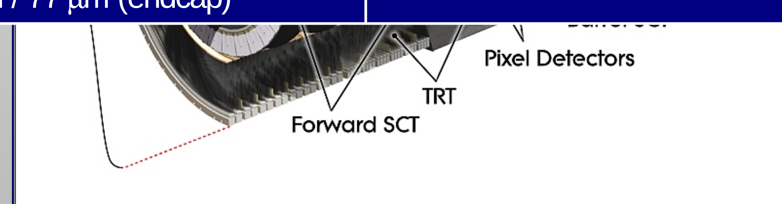
Inner Tracking (Pixel, SCT, TRT)
- Pixels: 50μm (r-ϕ) x 400μm (z)
- $\Delta p/p$ (1 GeV)= 0.013,0.02 ($\eta \approx$ 0,2.5)
- $\Delta p/p$ (100 GeV) = 0.038,0.11
- TRT for e/π identification

ATLAS & CMS: Detector Characteristics

Tracking Detectors



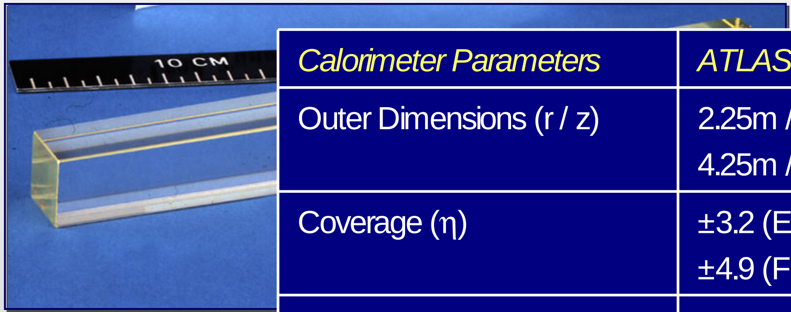


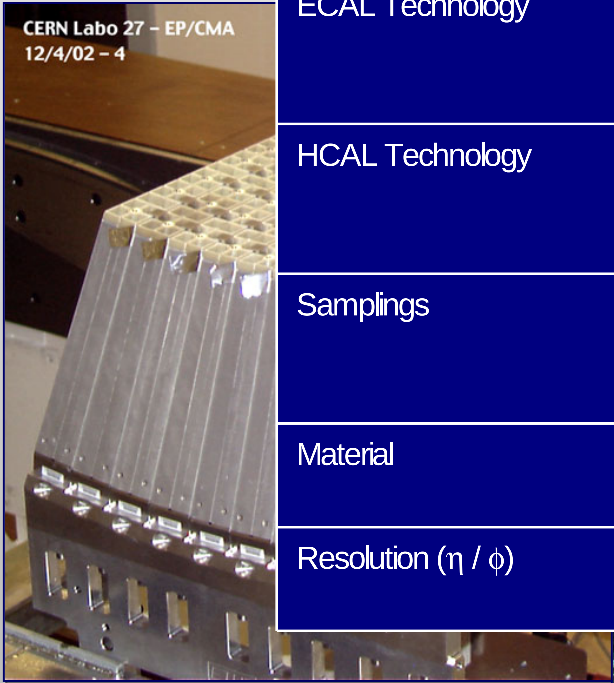


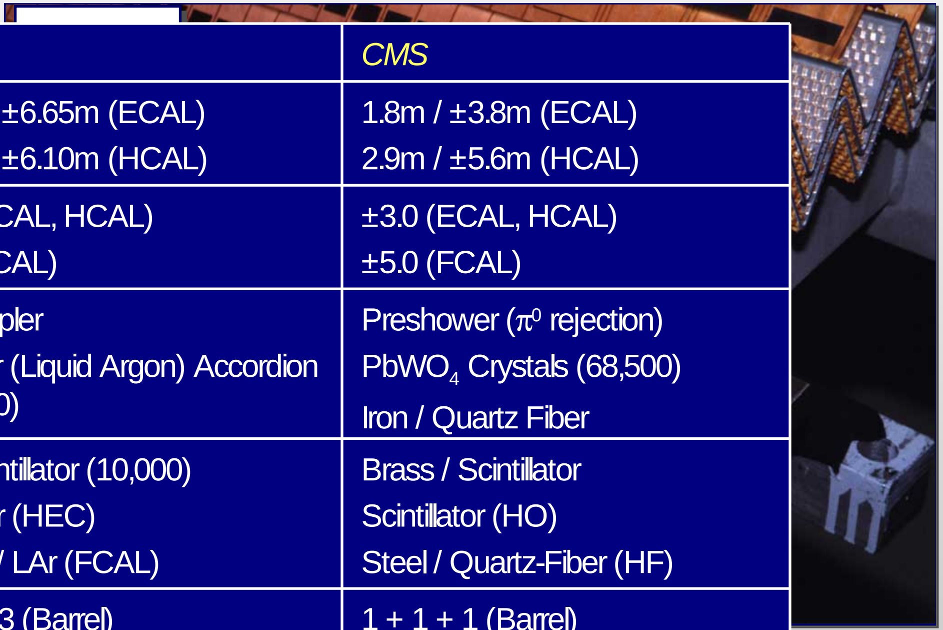
Tracker Parameters	*ATLAS*	*CMS*
Solenoid B-Field	2T	4T
Outer Dimensions (r / z)	115cm / 700cm	110cm / 540cm
Coverage (η)	±2.5	±2.5
Technologies	Si Pixels (140,000,000) Si Microstrips (6,2000,000) Straw Tubes (420,000)	Si Pixels (66,000,000) Si Microstrips (9,600,000)
Elements Crossed by Track	3 pixels, 8 strips, 36 straws	3 pixels, 4 + 6 strips (barrel) 2 pixels, 3 + 9 strips (endcap)
Material Crossed by Track	$0.35X_0$ - $1.35X_0$	$0.40X_0$ - $1.60X_0$
Pixel resolution (r-ϕ / z)	12 μm / 66 μm (barrel) 12 μm / 77 μm (endcap)	10 μm / 20 μm

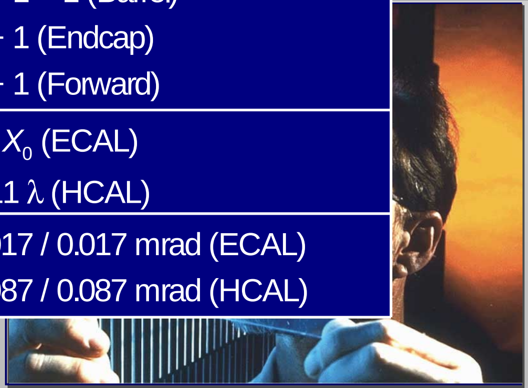
ATLAS & CMS: Detector Characteristics

Electromagnetic & Hadronic Calorimeters





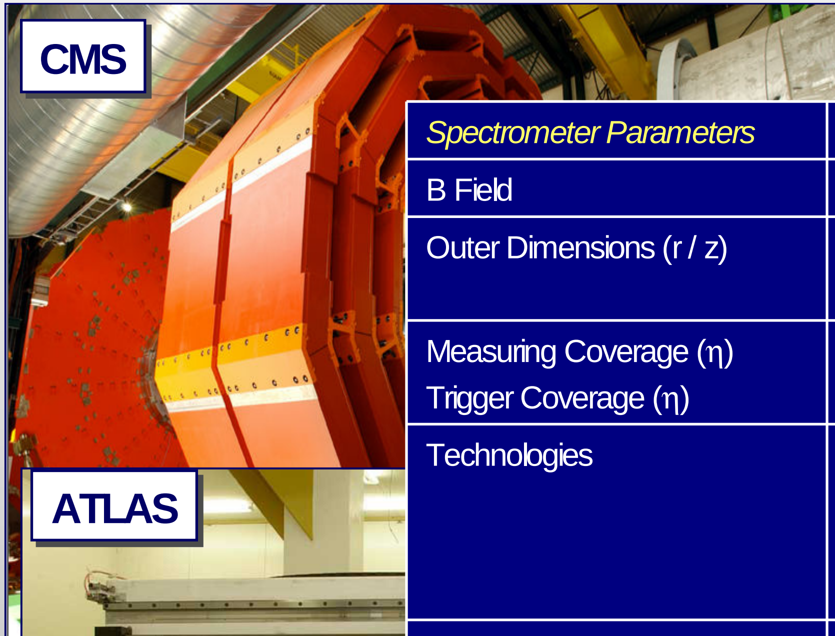


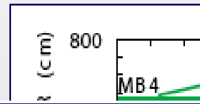


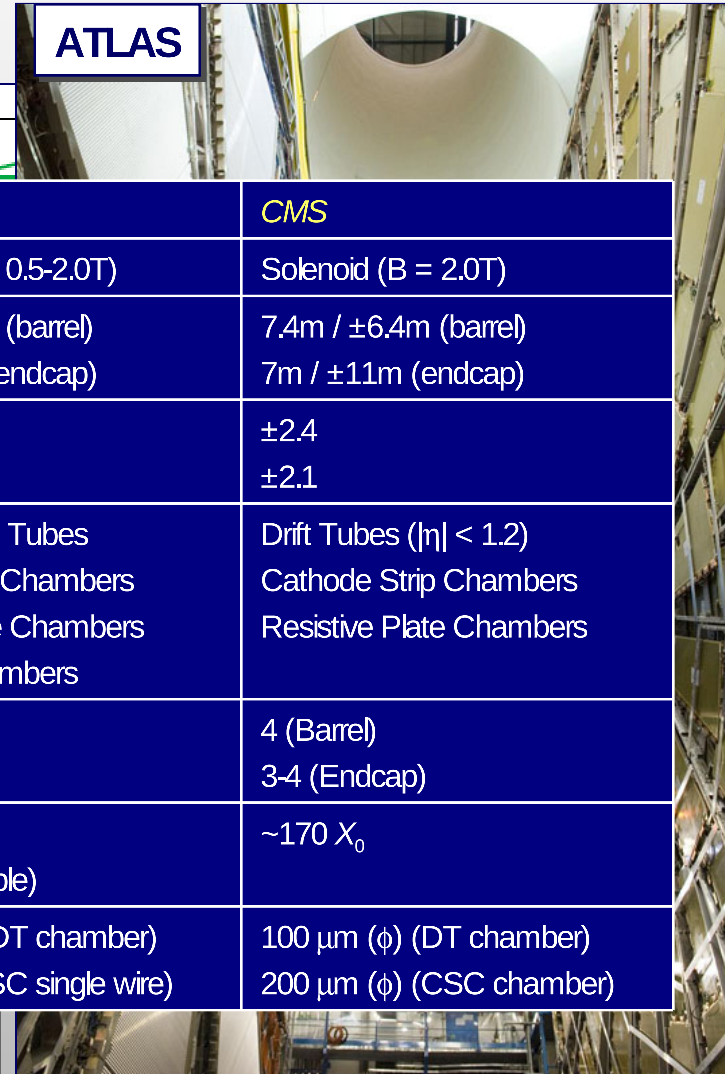
Calorimeter Parameters	*ATLAS*	*CMS*
Outer Dimensions (r / z)	2.25m / ±6.65m (ECAL) 4.25m / ±6.10m (HCAL)	1.8m / ±3.8m (ECAL) 2.9m / ±5.6m (HCAL)
Coverage (η)	±3.2 (ECAL, HCAL) ±4.9 (FCAL)	±3.0 (ECAL, HCAL) ±5.0 (FCAL)
ECAL Technology	Presampler Pb / LAr (Liquid Argon) Accordion (190,000)	Preshower (π^0 rejection) $PbWO_4$ Crystals (68,500) Iron / Quartz Fiber
HCAL Technology	Fe / Scintillator (10,000) Cu / LAr (HEC) Cu / W / LAr (FCAL)	Brass / Scintillator Scintillator (HO) Steel / Quartz-Fiber (HF)
Samplings	1 + 3 + 3 (Barrel) • + 3 + 4 (Endcap) 3 + 3 (Forward)	1 + 1 + 1 (Barrel) 1 + 1 (Endcap) 1 + 1 (Forward)
Material	24 X_0 - 26 X_0 (ECAL) 11 λ (HCAL)	25 X_0 (ECAL) 7-11 λ (HCAL)
Resolution (η / φ)	0.025 / 0.025 mrad (ECAL) 0.100 / 0.100 mrad (HCAL)	0.017 / 0.017 mrad (ECAL) 0.087 / 0.087 mrad (HCAL)

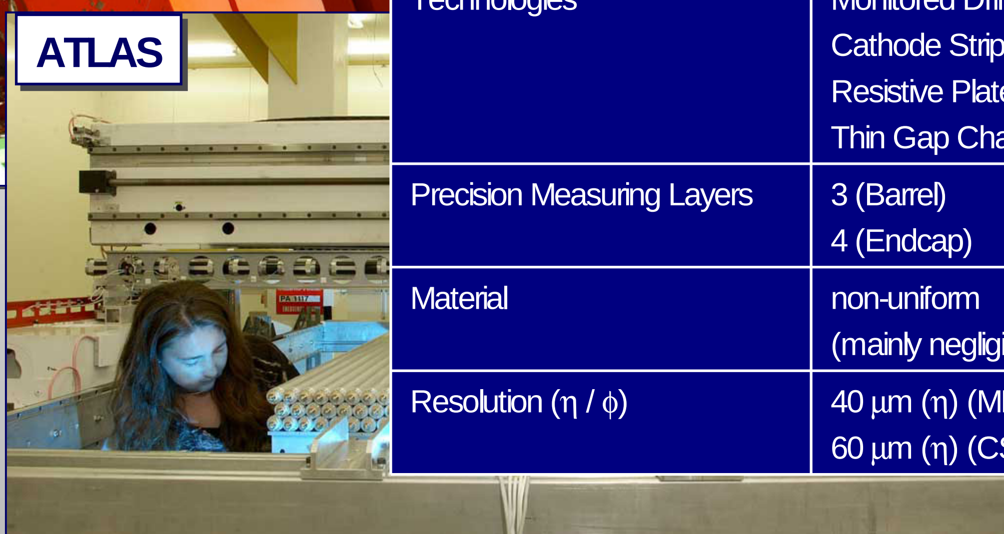
ATLAS & CMS: Detector Characteristics

Muon Spectrometers







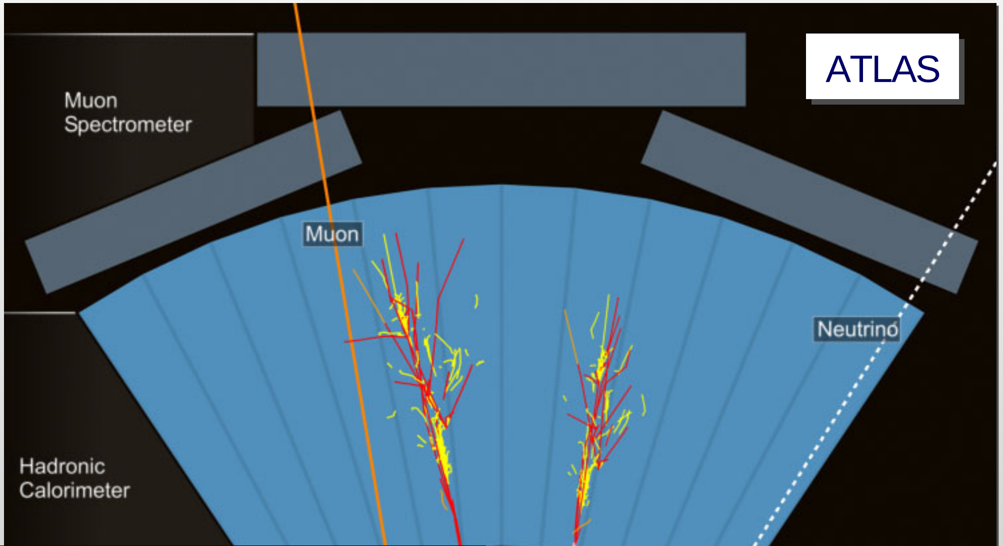


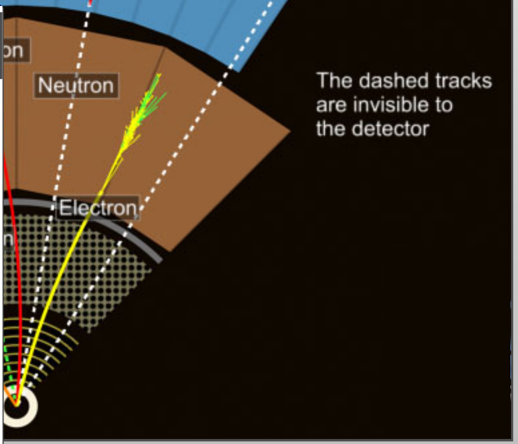
Spectrometer Parameters	*ATLAS*	*CMS*
B Field	3 Toroids (B = 0.5-2.0T)	Solenoid (B = 2.0T)
Outer Dimensions (r / z)	11m / ±12.5m (barrel) 11m / ±23m (endcap)	7.4m / ±6.4m (barrel) 7m / ±11m (endcap)
Measuring Coverage (η) Trigger Coverage (η)	±2.7 ±2.4	±2.4 ±2.1
Technologies	Monitored Drift Tubes Cathode Strip Chambers Resistive Plate Chambers Thin Gap Chambers	Drift Tubes (|η| < 1.2) Cathode Strip Chambers Resistive Plate Chambers
Precision Measuring Layers	3 (Barrel) 4 (Endcap)	4 (Barrel) 3-4 (Endcap)
Material	non-uniform (mainly negligible)	~170 X_0
Resolution (η / ϕ)	40 μm (η) (MDT chamber) 60 μm (η) (CSC single wire)	100 μm (ϕ) (DT chamber) 200 μm (ϕ) (CSC chamber)

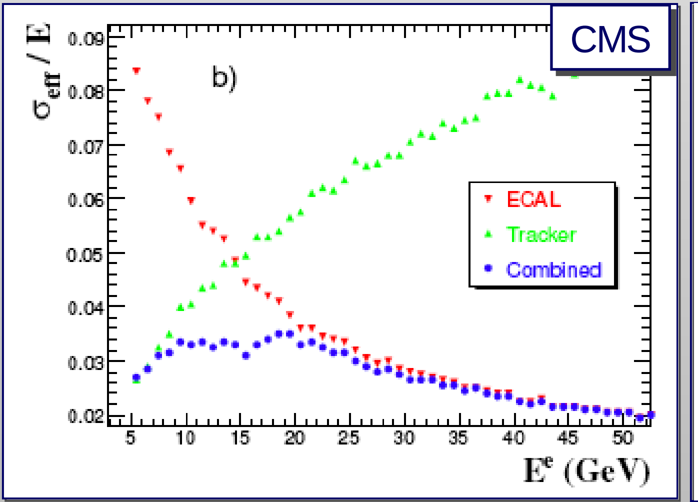
ATLAS & CMS: Electron Reconstruction

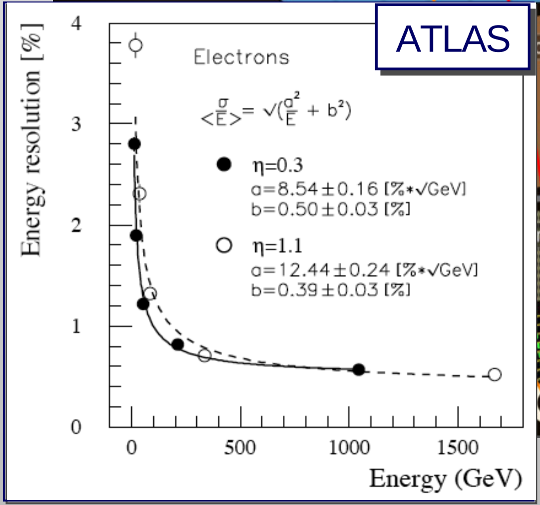
Electron ID and Reconstruction

- Build clusters from ECAL cells
- Correct for geometry effects
- Correct for cell saturation
- Match clusters to tracks
- Correct for bremsstrahlung
- Require isolation
- Physics cuts









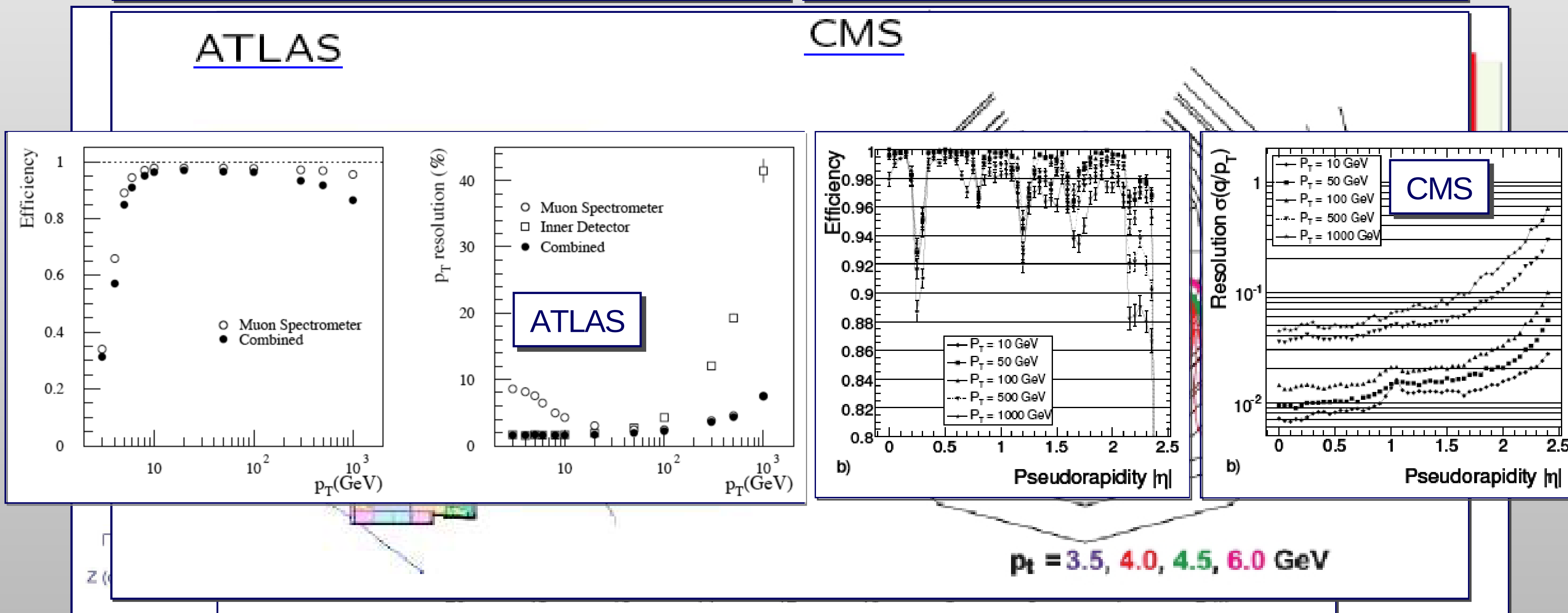
ATLAS & CMS: Muon Reconstruction

Inside-Out

- Build segments in stations
- Build tracks from hits or segments
- Correct for E_{loss} & multiple scattering
- Match to calorimeter, inner tracker
- Combine statistically or re-fit

Outside-In

- Start with tracks in inner tracker
- Match with Calorimeter Deposits
- Match with Hits, Segments, Tracks in Spectrometer



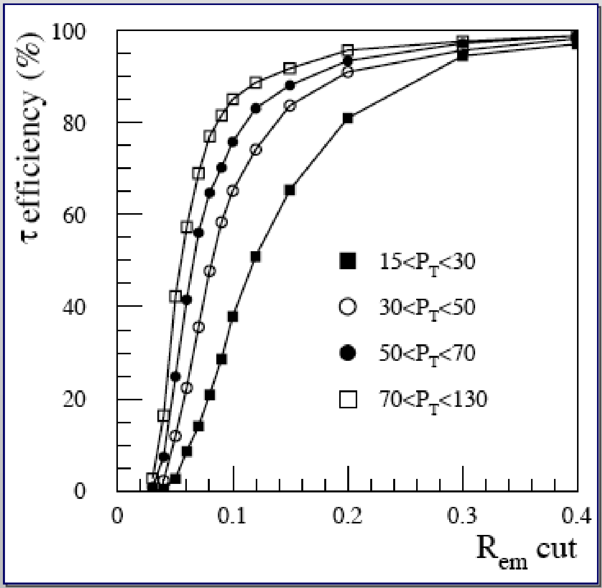
ATLAS & CMS: Tau Reconstruction

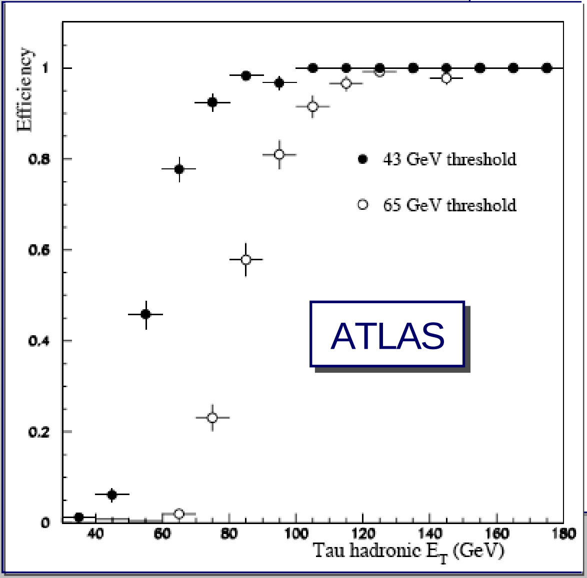
Hadronic Decays

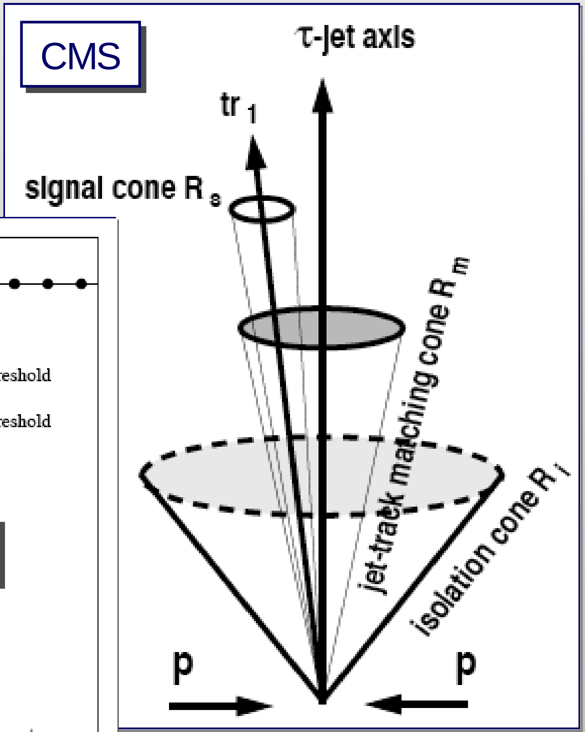
- Localized energy deposits in calorimeters
- Require hadronic energy
- Match with 1 or 3 tracks in cone
- Remove photon conversion tracks
- Require isolation in calorimeters
- Require small jet mass

Leptonic Decays

- Isolated electron or muon, missing E_T







ATLAS & CMS: Detector Performance

Tracking	*ATLAS*		*CMS*	
	$\eta \approx 0$	$\eta \approx 2.5$	$\eta \approx 0$	$\eta \approx 2.5$
$\delta p/p$ at p_T = 1 GeV	1.3%	2.0%	0.7%	2.0%
$\delta p/p$ at p_T = 100 GeV	3.8%	11.0%	1.5%	7.0%
ε(pions) at p_T = 1 GeV	84.0%		80%	
ε(electrons) at p_T = 5 GeV	90.0%		85.0%	

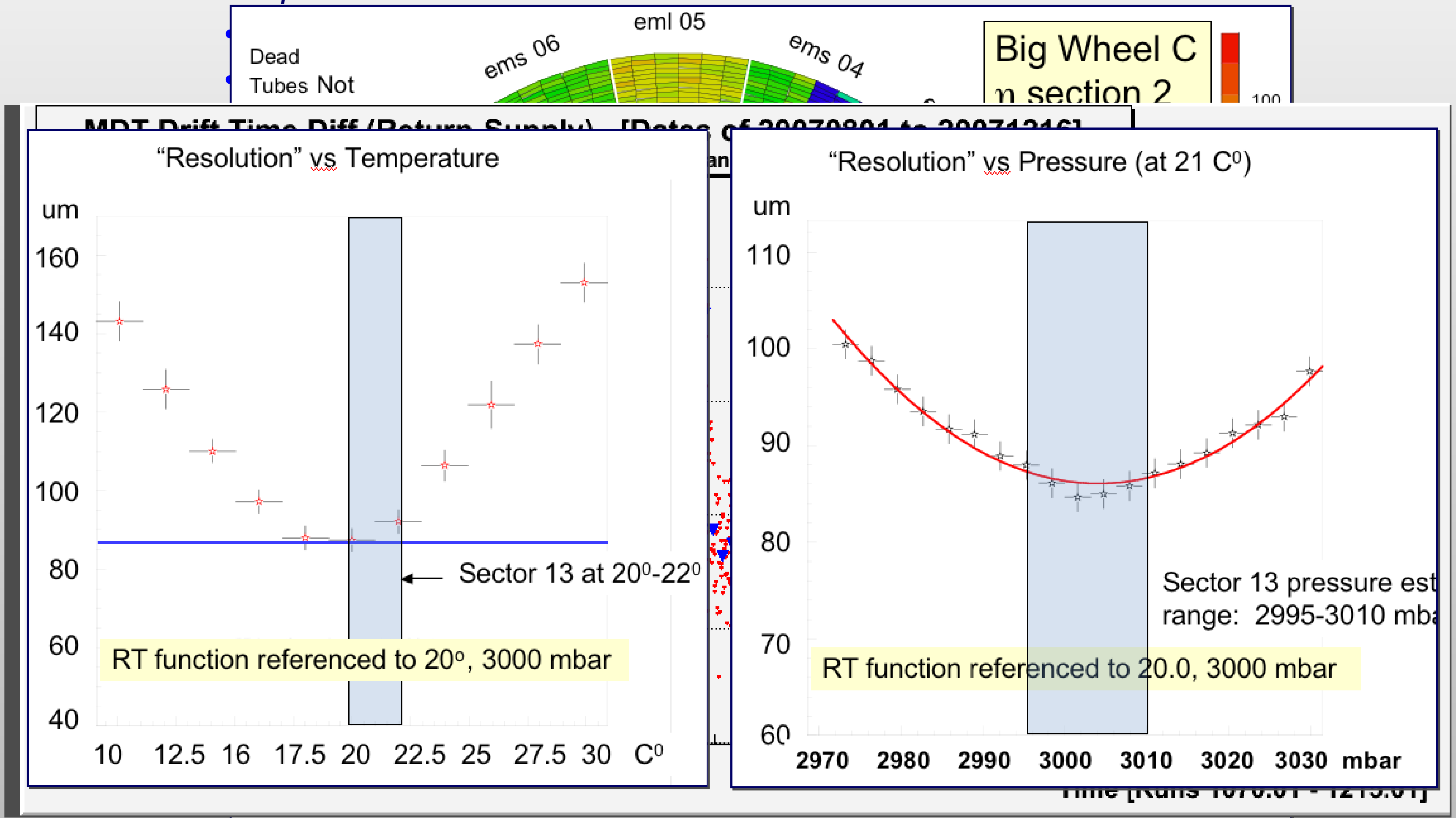
Calorimetry	*ATLAS*	*CMS*
ECAL $\delta E/E$ (100 GeV Photons)	1 - 1.5%	0.8 %
ECAL $\delta E/E$ (50 GeV Electrons)	1.3 - 2.3%	2.0 %
ECAL+HCAL Stochastic Term	55% / $\sqrt{E}$	70% / $\sqrt{E}$
ECAL+HCAL Constant Term	2.3%	8.0%

Muon Spectrometry	*ATLAS*				*CMS*			
	Standalone		Combined		Standalone		Combined	
	$\eta \approx 0$	$\eta \approx 2$	$\eta \approx 0$	$\eta \approx 2$	$\eta \approx 0$	$\eta \approx 2$	$\eta \approx 0$	$\eta \approx 2$
$\delta p/p$ at p = 10 GeV	3.9%	6.4%	1.4%	2.4%	8%	11%	0.8%	2.0%
$\delta p/p$ at p = 100 GeV	3.1%	3.1%	2.6%	2.1%	9%	18%	1.2%	1.7%
$\delta p/p$ at p = 1000 GeV	10.5%	4.6%	10.4%	4.4%	13%	35%	4.5%	7.0%

ATLAS & CMS: Detector Performance

Cosmic Ray Commissioning Performance Tests

Example: ATLAS Combined Run in 2007



The LHC: Leptonic Signatures of New Physics

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$gg \to bbH(A), H(A) \to \tau\tau,\mu\mu$

Doubly Charged Higgs

$H^{\pm\pm} \to W^{\pm}W^{\pm} \to l^{\pm}\nu l^{\pm}\nu$

Massive Vector Bosons (KK, Gravitons, etc.)

$Z^*, Z', G \to ll$

$Z', G \to WW \to l\nu l\nu$

$W' \to l\nu$ or WZ

SUSY

$g \to qq_L$

$q_L \to q\chi_2^0 \to qll_R \to qll\chi_1^0$

GMSB ($\chi_1^0 \to G\gamma$, $l_R \to Gl$)

$\chi_2^0 \to ll_R \to ll\chi_1^0 \to llG\gamma$

Right-Handed W

$W_R \to l + N \to l + ljj$

Excited & Heavy Leptons

$pp \to ll' \to llZ \to l + ljj$ (resonances)

$gg \to Z, Z' \to LL \to lZ + lZ \to ljj + ljj$

Technicolor

$\rho_{TC} \to WZ \to lll\nu$

Et Cetera

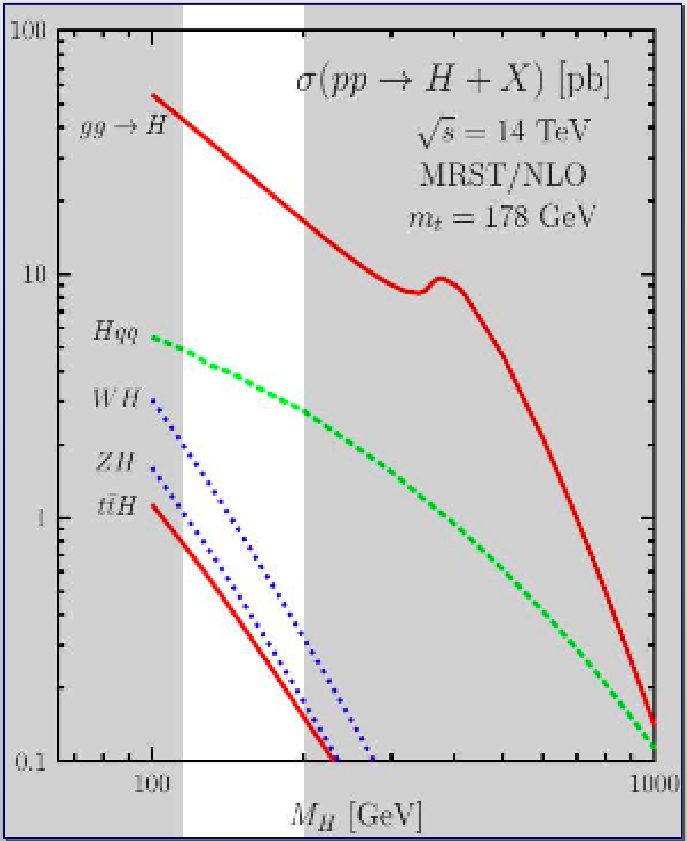
SM precision measurements, e.g.

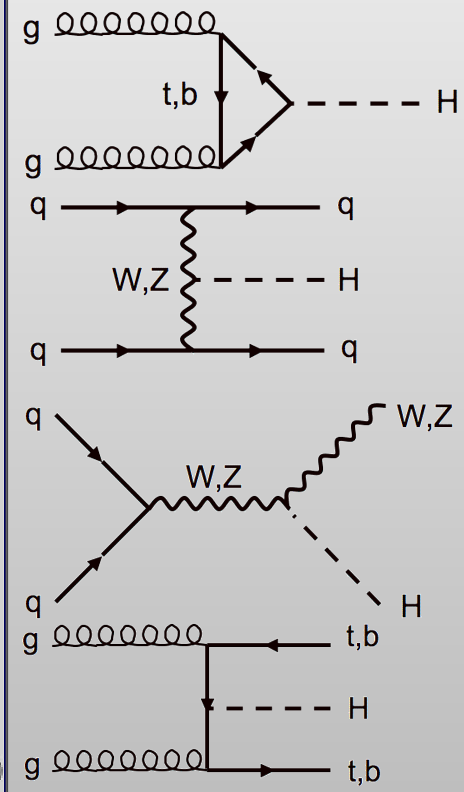
The LHC: Standard Model Higgs

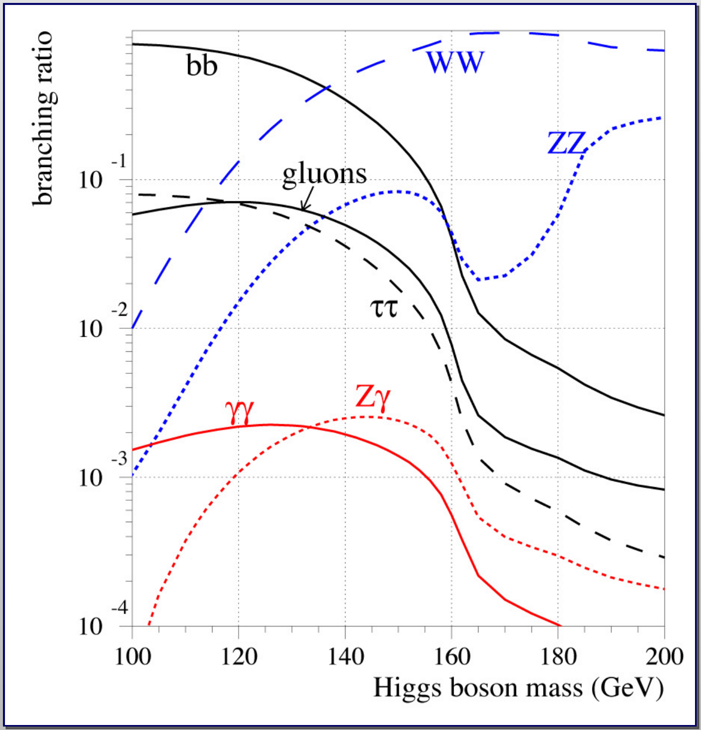
SM Higgs Production & Decay at LHC

Hardest place to look: M_H < 130 GeV (but, possible with time)

Easiest place to look: M_H = 160 GeV (discovery through WW, perhaps)

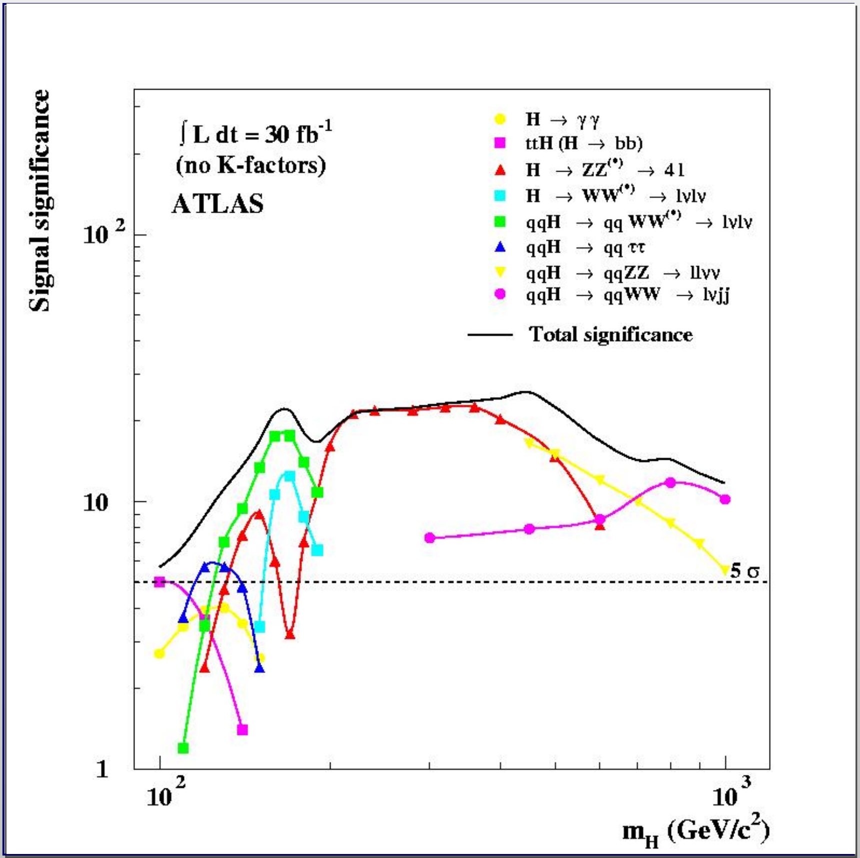


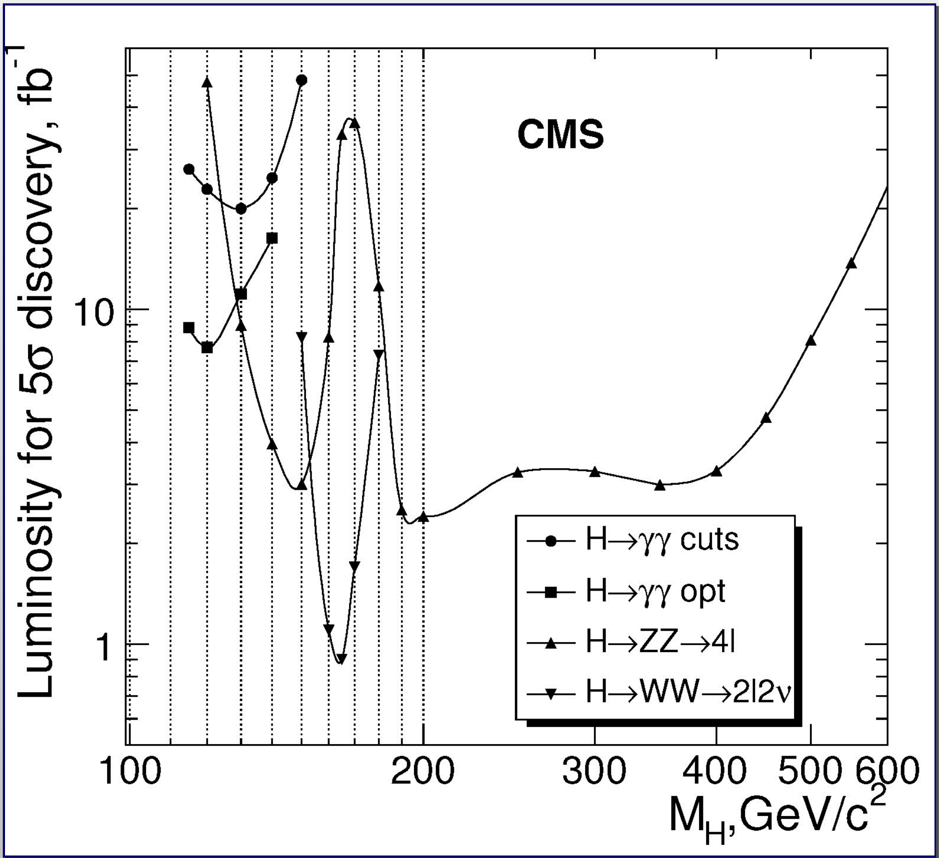




The LHC: Standard Model Higgs

Discovery Potential





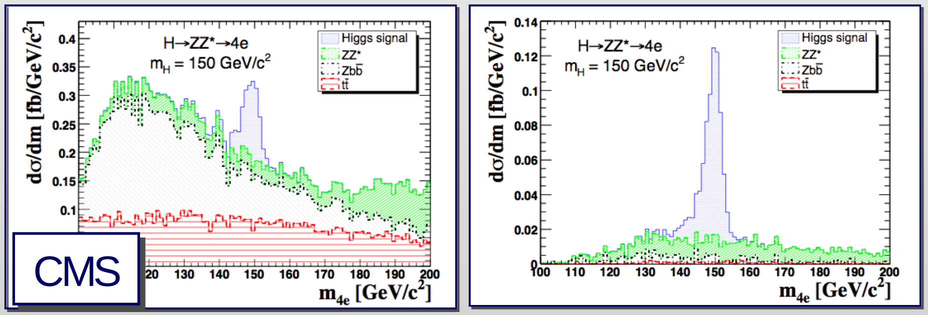
The LHC: Standard Model Higgs

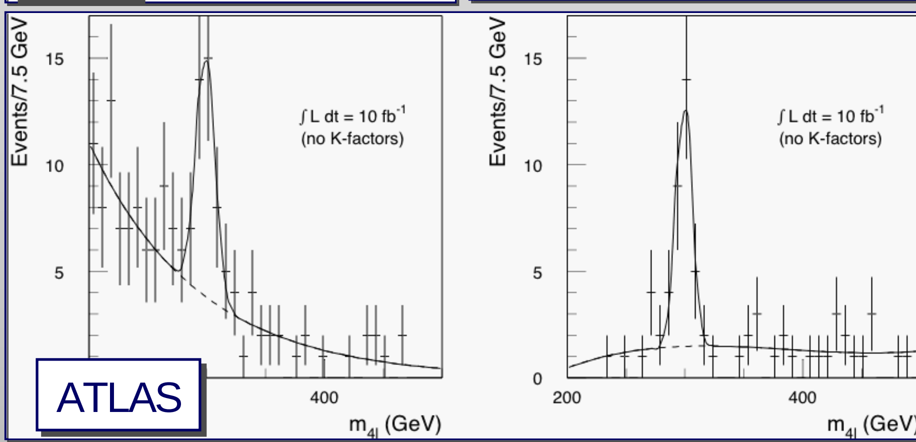
The “Golden” Channel: $H \rightarrow ZZ \rightarrow \mu\mu\mu\mu$, $\mu\mu ee$, $eeee$

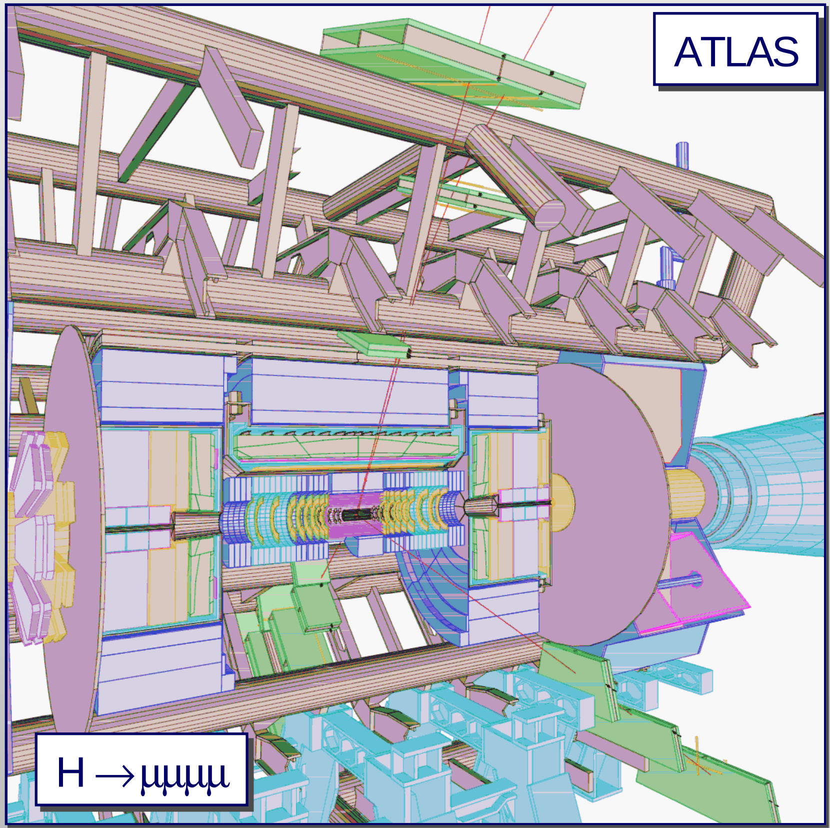
Not the first, but best for precision measurements

Effective channel for $120 < M_H < 700$ GeV

Cuts on lepton quality, isolation







The LHC: Standard Model Higgs

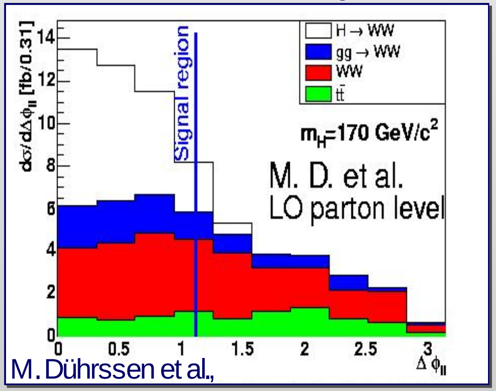
The Discovery Channel?: $H \rightarrow WW \rightarrow l\nu l\nu$

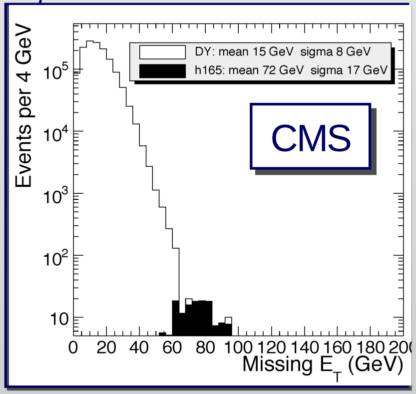
High rate near M_H = 160 GeV

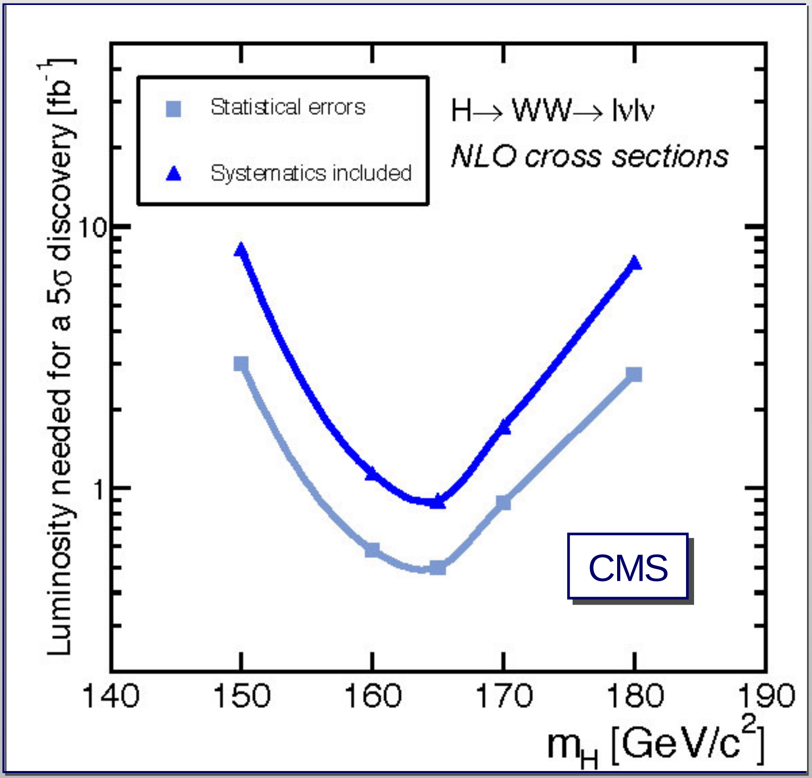
Spin correlations give small angle between leptons

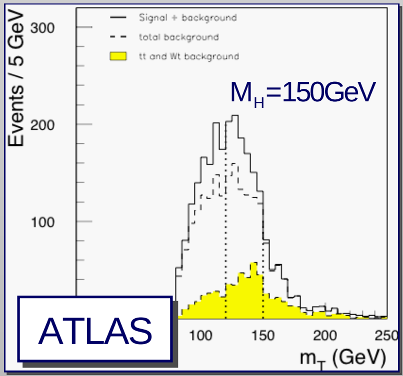
Main background from WW production, and tt (also $ZZ \rightarrow ll\nu\nu$)

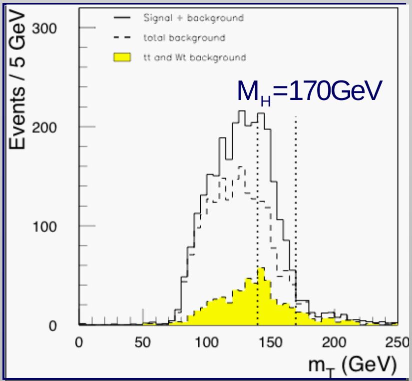
Can only measure m_T









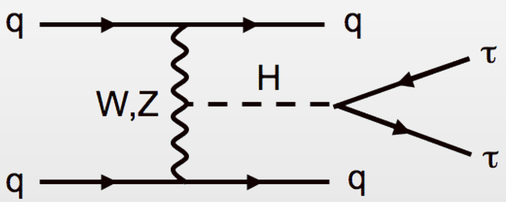


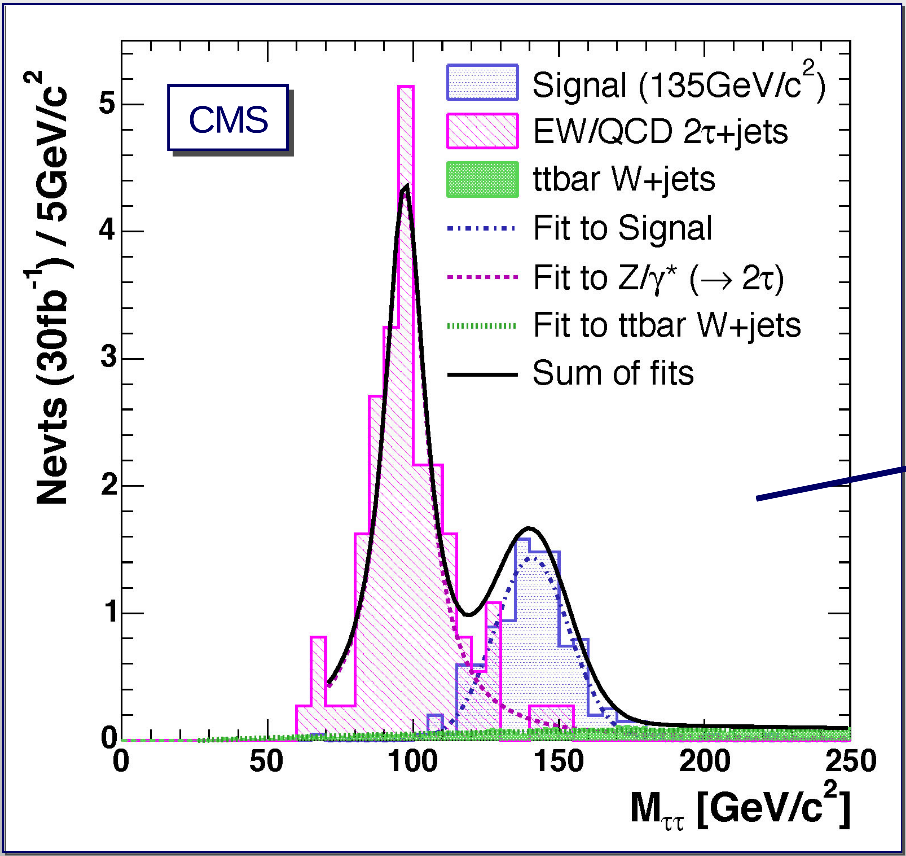
The LHC: Standard Model Higgs

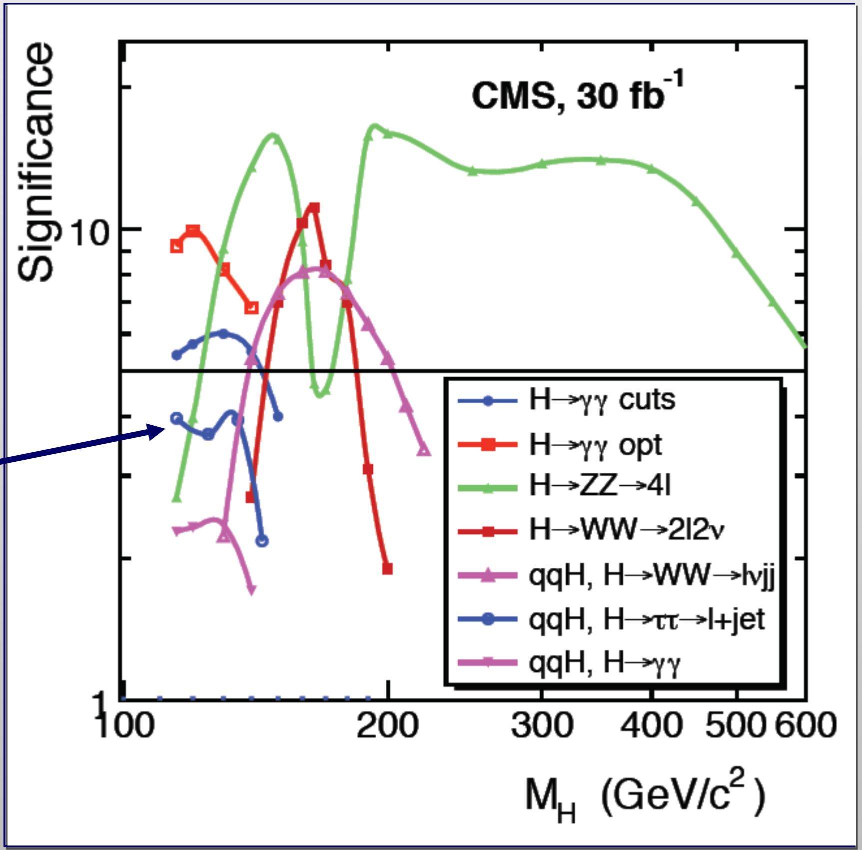
Vector Boson Fusion: $qqH \rightarrow qq\tau\tau$

Two jets at high rapidity

Tag one τ with a lepton







The LHC: MSSM Higgs

H/A $\rightarrow \tau\tau$

Early H $\rightarrow \tau\tau$ probably MSSM (SM production too low)

At low tanβ, gg $\rightarrow$ A $\rightarrow \tau\tau$ dominates

At high tanβ, bbH and bbA "associated" production boosts signal

Need H > 100 GeV to avoid Z $\rightarrow \tau\tau$ background

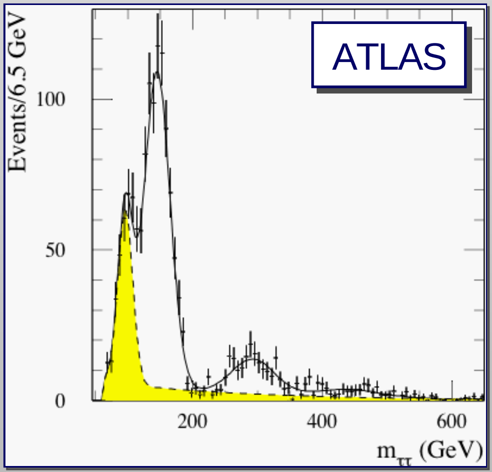
Tag one τ with a lepton

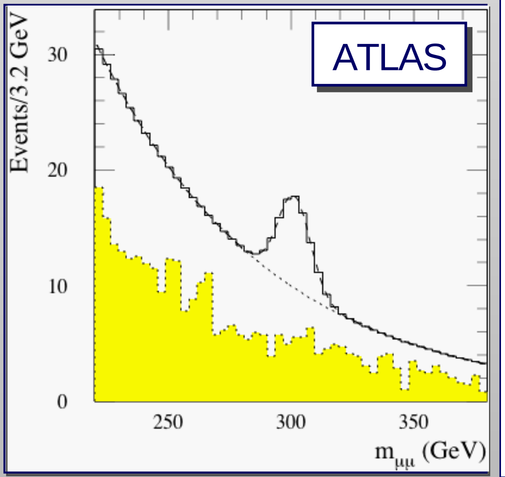
Tagging b in associated production greatly reduces Z $\rightarrow \tau\tau$ background

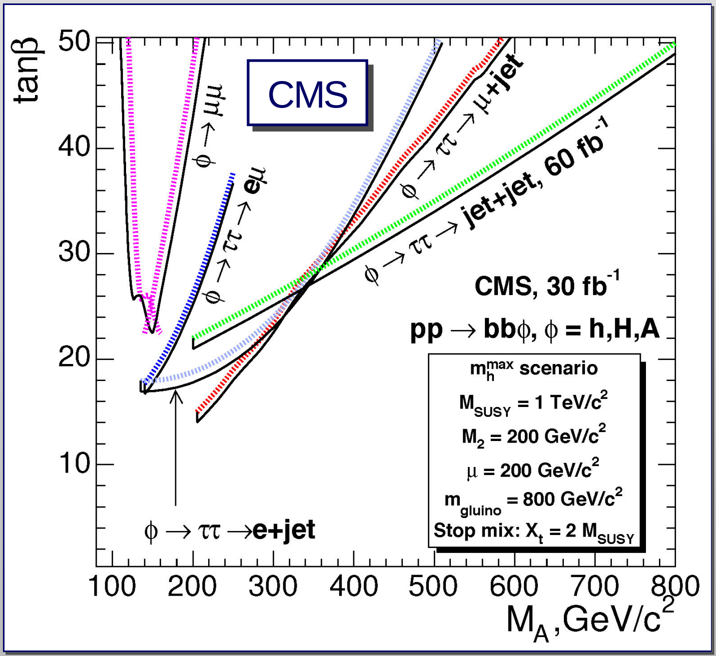
H/A $\rightarrow \mu\mu$

Lower rates

- less background better resolution







The LHC: Massive Vector Bosons

Z' $\rightarrow \mu\mu$, ee

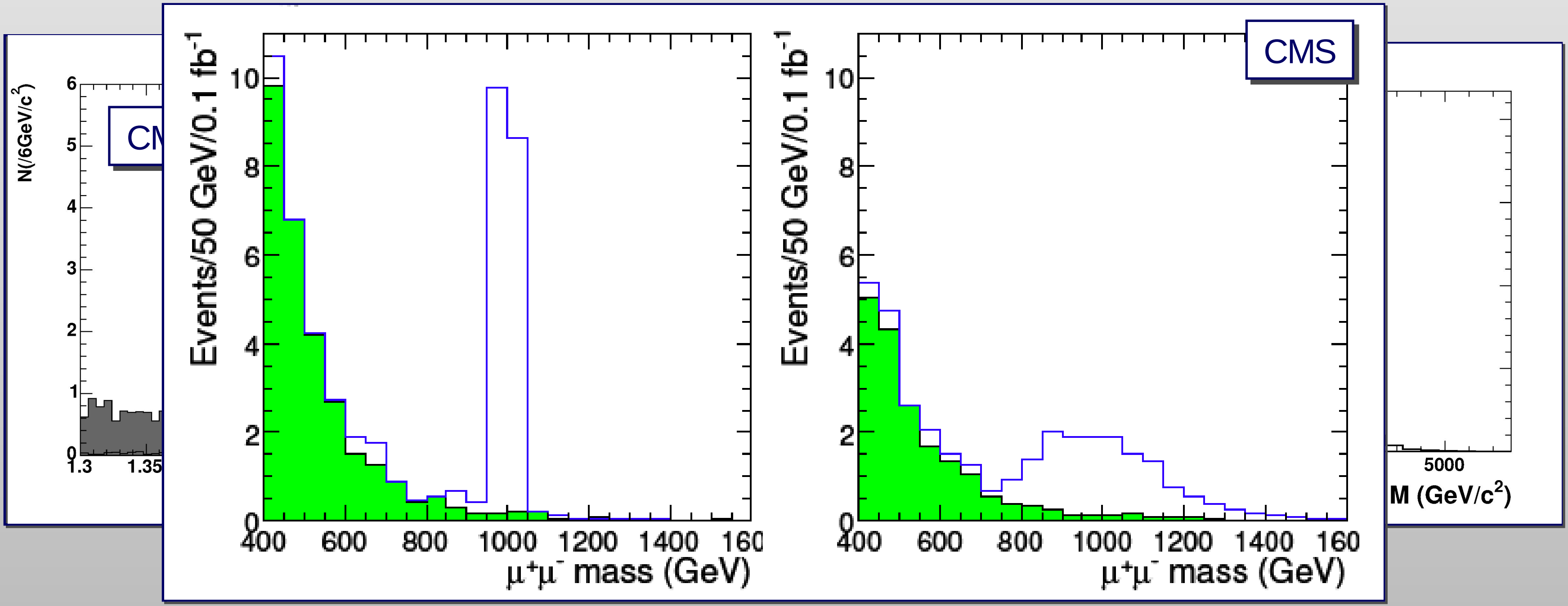
Anything massive decaying to oppositely charged leptons of same flavor

- Kaluza-Klein Z excitations, K-K Graviton excitations (Randall-Sundrum), GUT,…

Selected exactly two isolated electrons or muons

- Apply minimal E_T or p_T cuts

A hard photon or two is acceptable



The LHC: SUSY (mSUGRA Example)

$\tilde{g} \rightarrow q\tilde{q}_L$

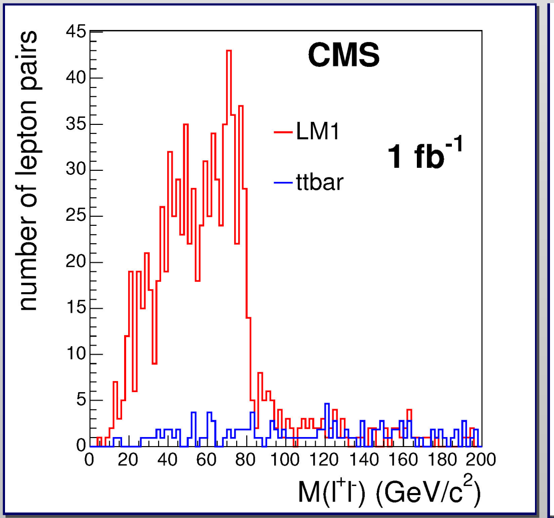
$\tilde{q}_L \rightarrow q\chi_2^0 \rightarrow ql\tilde{l}_R \rightarrow qll\chi_1^0$ (assuming $m(\tilde{g}) \geq m(\tilde{q})$ at LM1)

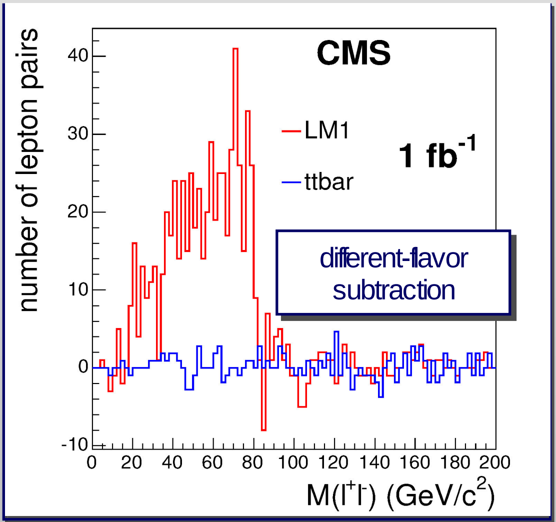
Cascade decay of squarks and gluinos

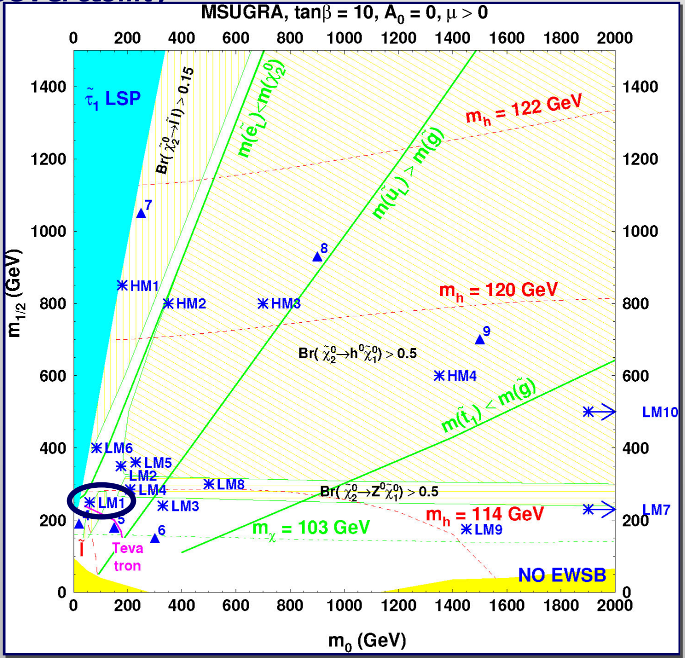
Look for high p_T isolated leptons, high p_T jets and missing E_T

- Expect triangular shape of di-lepton mass
- Subtract background from different-flavor opposite-sign lepton pairs

Studies typically focus on mSUGRA to determine discoverability







The LHC: Excited W Bosons

W' → eν

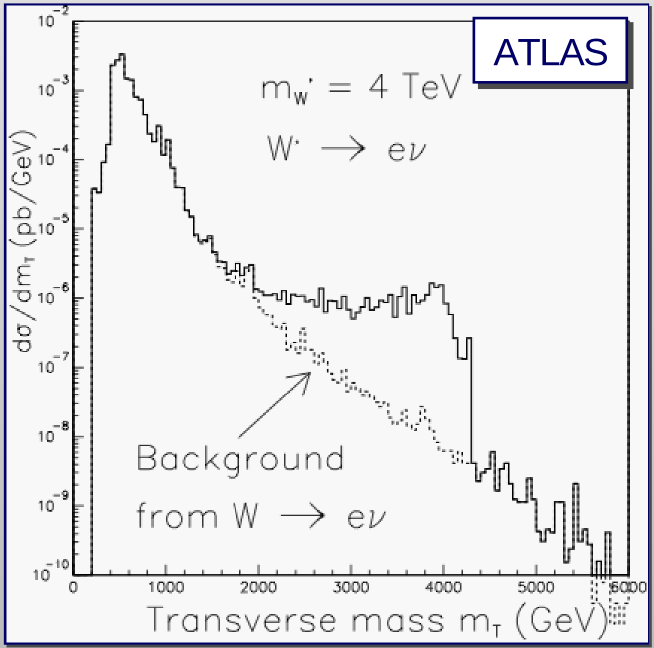
Resonance appearing high P_T of standard W production

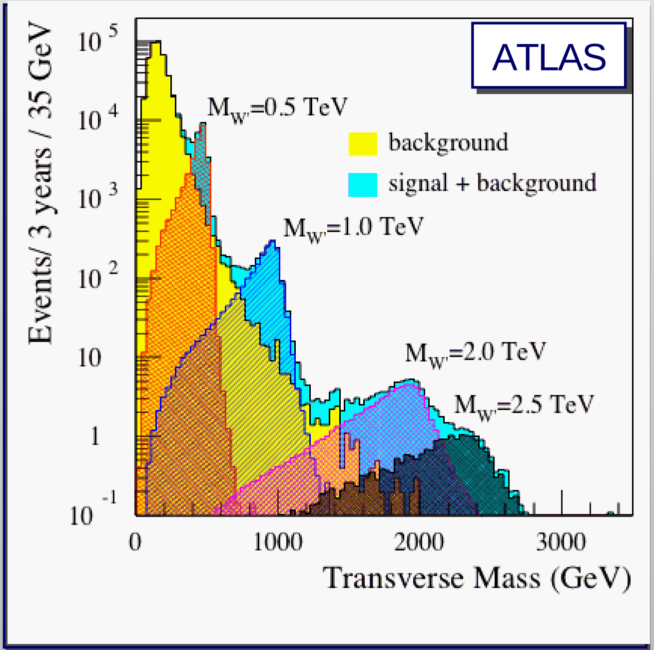
W' → WZ

Main background from continuum of WZ production (or ZZ, missing lepton)

Look for 3 charged leptons, missing E_T

- Two leptons from Z (same flavor, opposite charge)
- Remove tt background with lepton isolation cuts





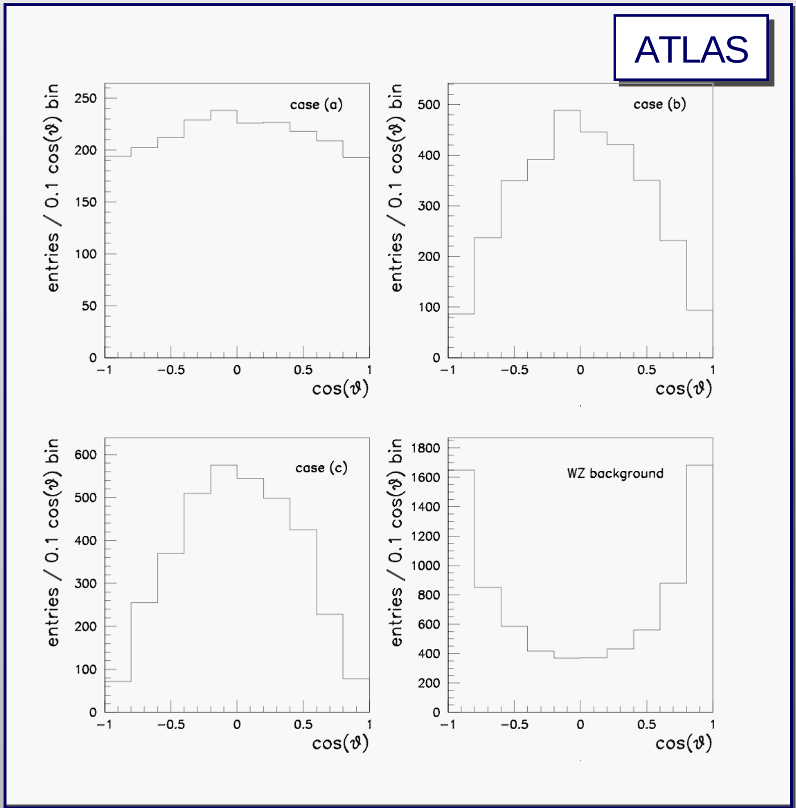
The LHC: Technicolor

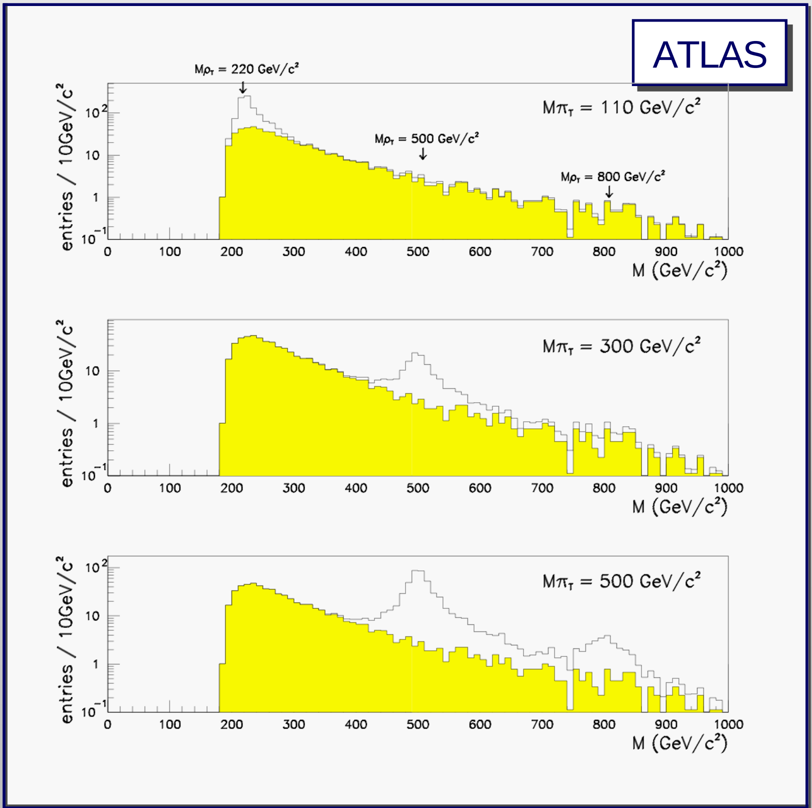
$\rho_{TC} \rightarrow WZ \rightarrow l\nu ll$

Model: "multiscale technicolor $SU(N_{TC})$, N_{TC}=4, 2 isotriplets of π_{TC}"

Same recipe as for W', but lower mass

Angular distribution sensitive to polarization





Summary

Leptons in the LHC

LHC Discovery Channels Primarily Leptonic

- Clean signals, easy to identify, measure

CMS & ATLAS Optimized to Identify and Measure Leptons

- Majority of $550M price tags went to Magnets, Spectrometry
- Both detectors provide outstanding performance in resolution, efficiency

Readiness

The Detectors are both more than 90% installed

- ATLAS Small Wheel Installation scheduled next week
- CMS in similar situation

Test Beam, Cosmic Commissioning Successful

- Detectors working essentially as expected

Steve's Predictions

Major Hurdles in 2008-2009

- Accelerator & Detector Debugging: These are complex devices.
- Computing: These are also complex devices.

Discoveries in the first 2 years?

- The only question is "What?"

References & Credit

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"Prospects for Higgs Boson Searches at the LHC," Karl Jakobs (University of Freiburg), SUSY 07, Karlsruhe.

Coffee and Discussions with Karl Jakobs (University of Freiburg), ATLAS Physics Coordinator.

Correspondence with CMS Physics Conveners: David Futyan, Pascal Vanlaer, Nicola Amapane, Simone Gennai.

Speaker Bias Disclaimer

Note that, alth… …AS Collaboration, he has made ever… …S in a fair and non biased manne…