Searches with Multi-Lepton Signatures at the LHC

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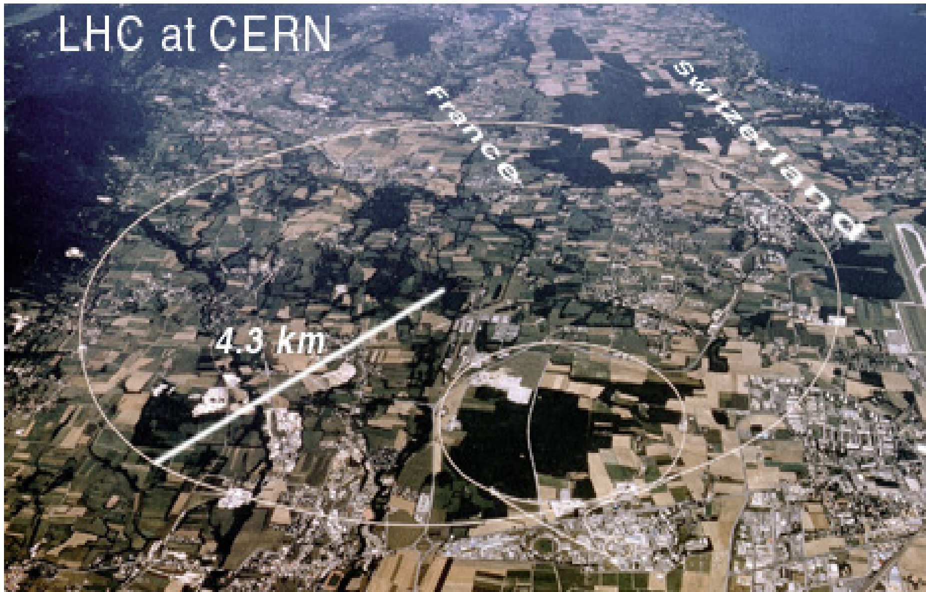
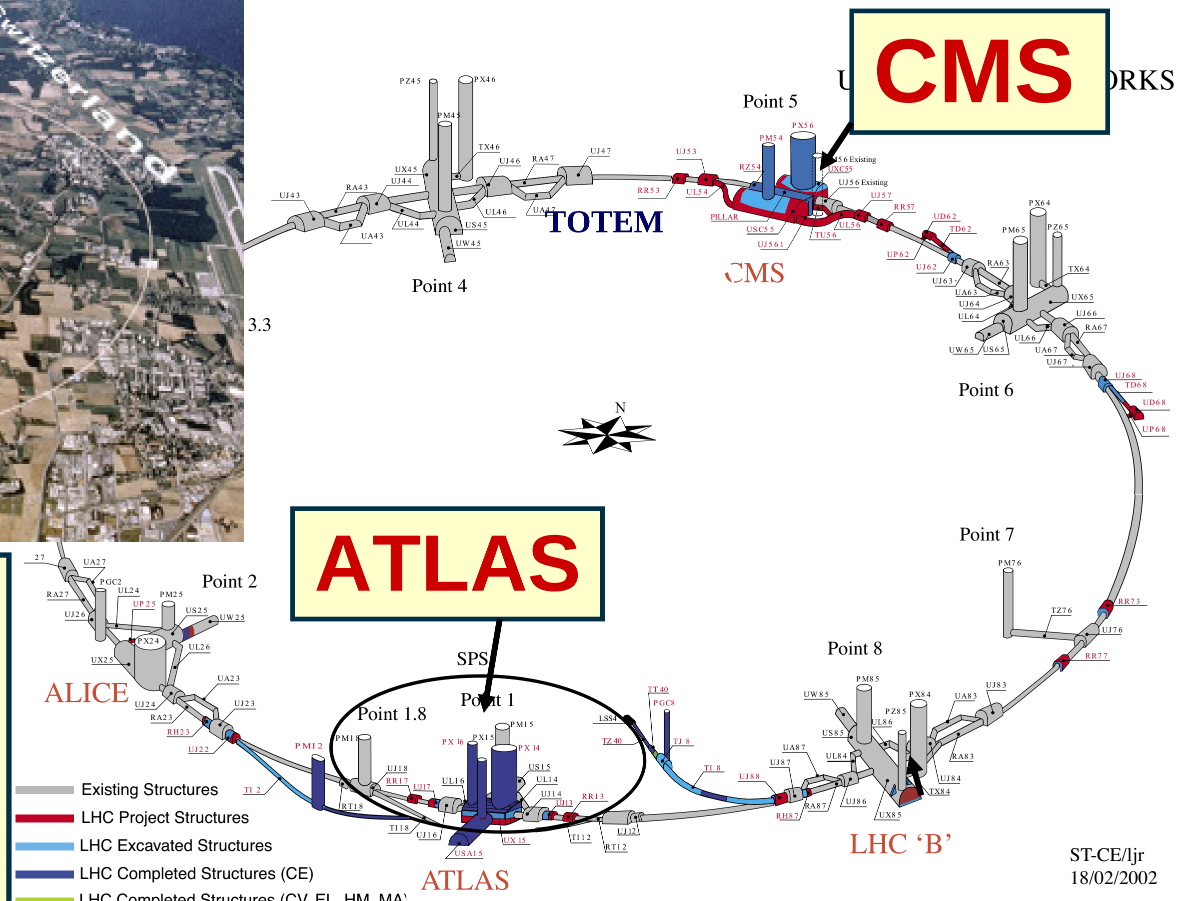
Jan. 8, 2007
At Aspen-07 Conference

The Large Hadron Collider at CERN
Energy = 14 TeV, Lumi = 10^{34} cm^{-2} s^{-1}

LHC Missions: Explore new physics in TeV energy scale

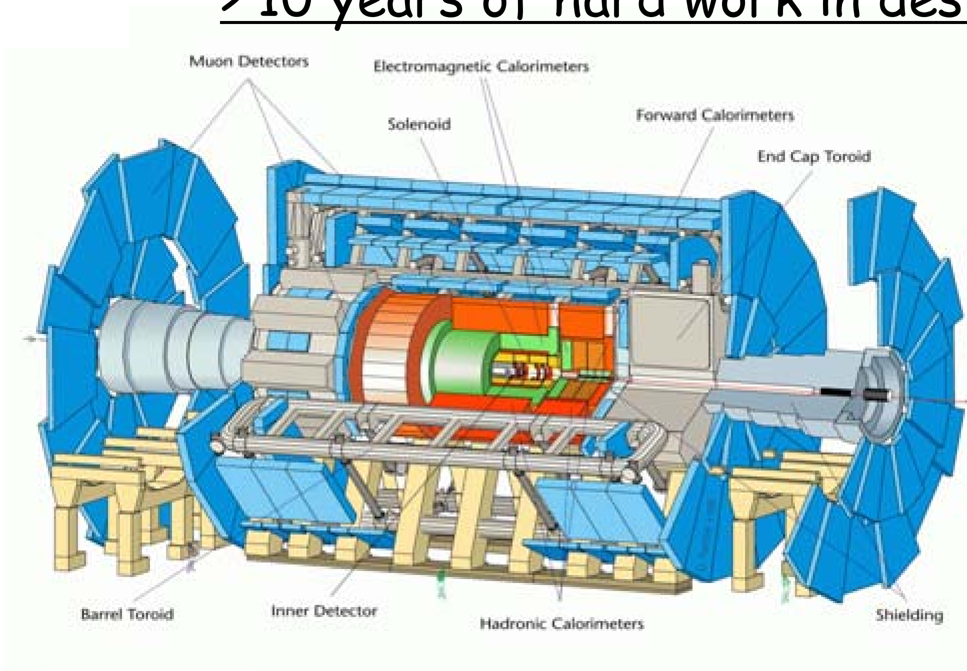


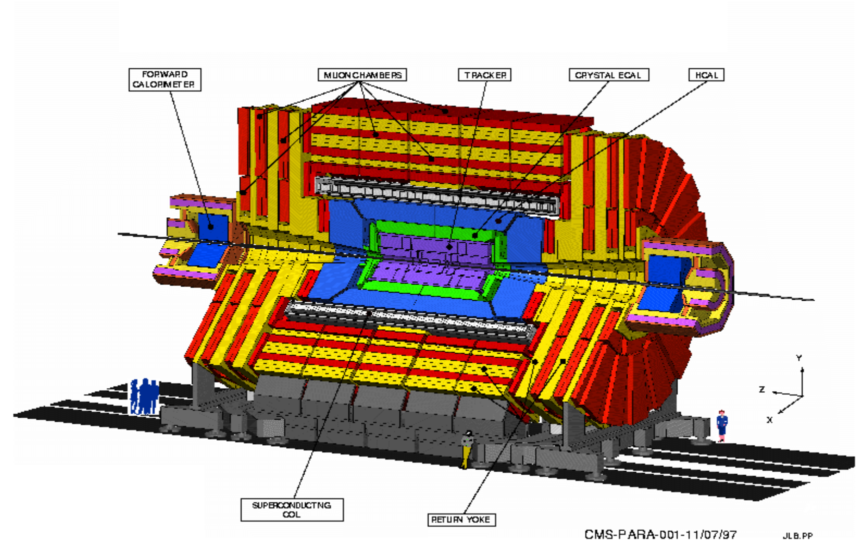


First Beams:
Fall 2007
Physics Runs:
from Spring 2008
~ few fb^{-1} in 1st year

ATLAS and CMS Detectors

> 10 years of hard work in design and constructions





ATLAS

Length : ~45 m
Diameter : ~24 m
Weight : ~ 7,000 tons
Electronic channels : ~ 10^8
Solenoid : 2 T
Air-core toroids

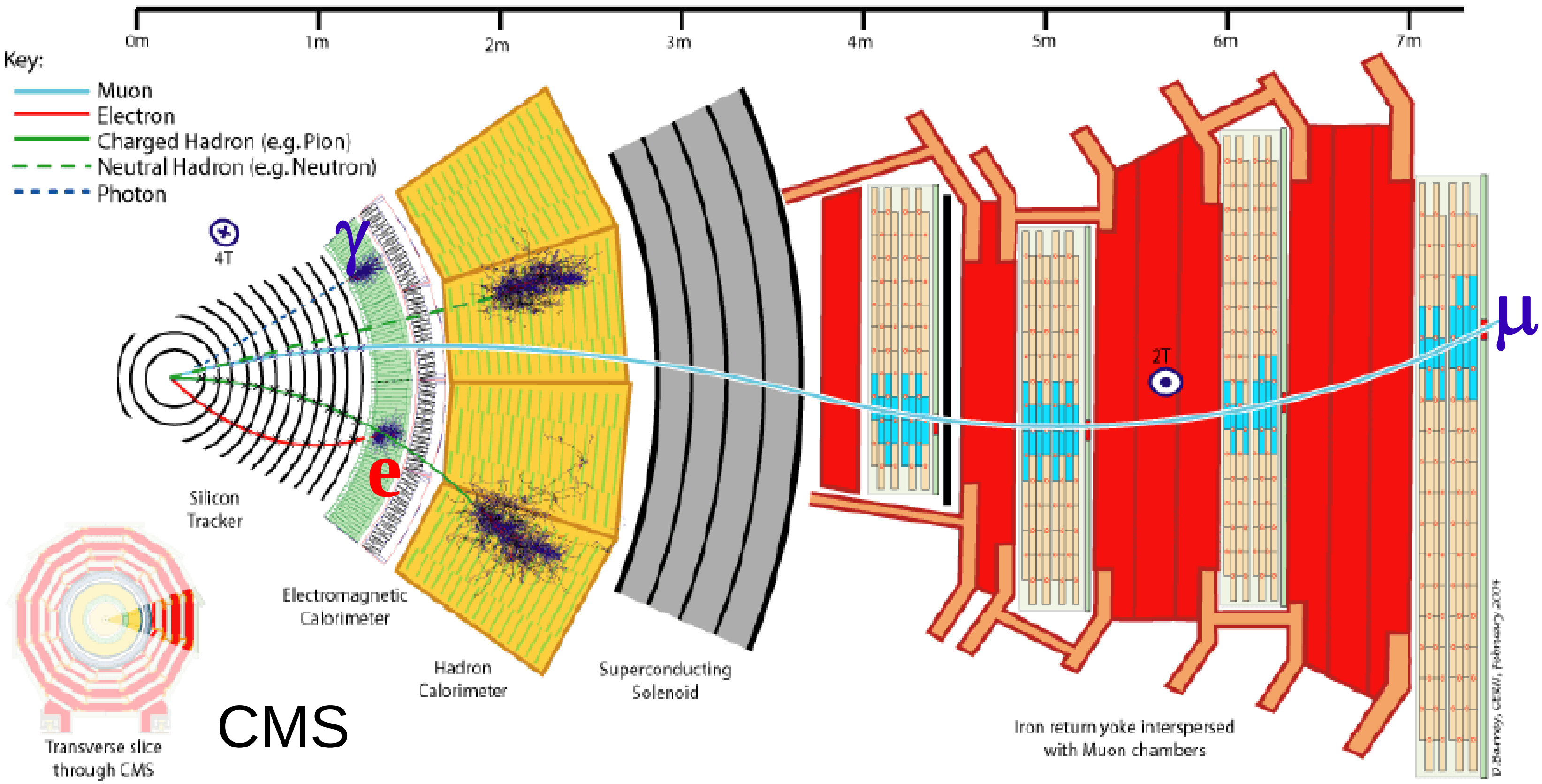
Excellent Standalone Muon Detector

CMS

Length : ~22 m
Diameter : ~14 m
Weight : ~ 12,500 tons
Solenoid : 4 T
Fe yoke
Compact and modular

Excellent EM Calorimeter

Lepton Signals Are the Keys for Discovery !



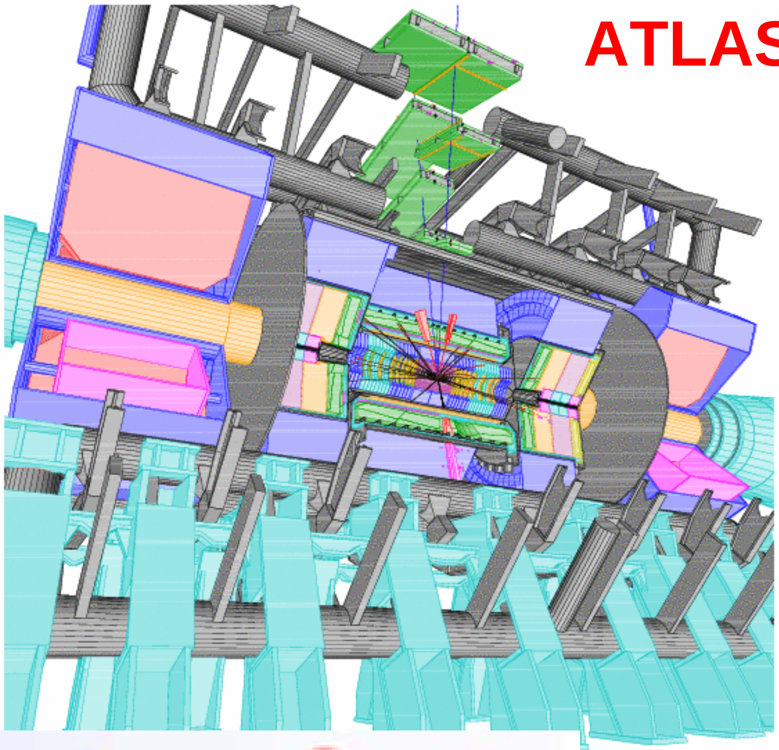
- Lepton identifications: high efficiency, low fake rate
- Excellent energy and momentum resolution
- Trigger at low Pt
- **Clean Signature for new physics discoveries!**
- **Detector can be well understood from Z→ $\ell^+\ell^-$ events**

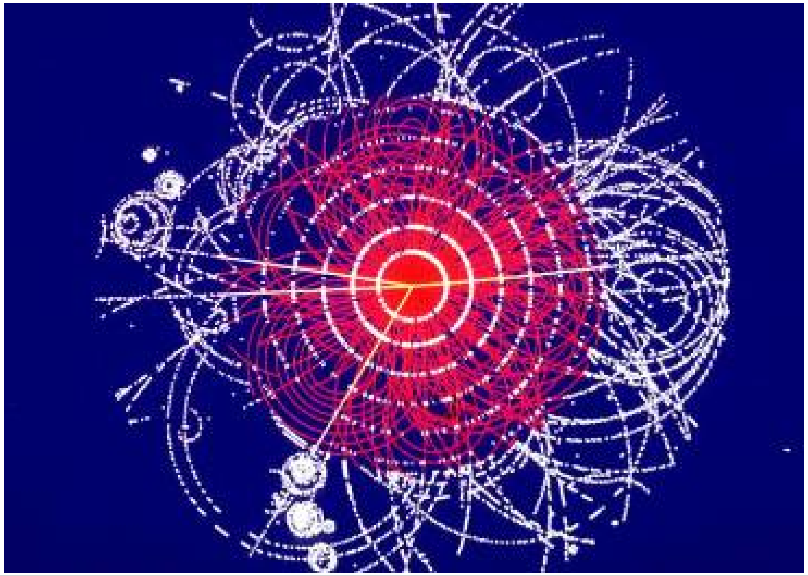
Detector Technologies

	ATLAS (A Toroidal LHC Apparatus)	CMS (The Compact Muon Solenoid)
TRACKER	Si pixels + strips TRT → particle identification $\sigma/p_T \sim 5\times10^{-4}\ p_T \oplus 0.01$	Si pixels + strips No particle identification $\sigma/p_T \sim 1.5\times10^{-4}\ p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segmentation
HAD CALO	Fe-scint. + Cu-liquid argon ($\geq$ 10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. ($\geq$ 5.8+catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	MDT, CSC, RPC, TGC $\sigma/p_T \sim 7\ \%$ at 1 TeV standalone	DT, CSC, RPC $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

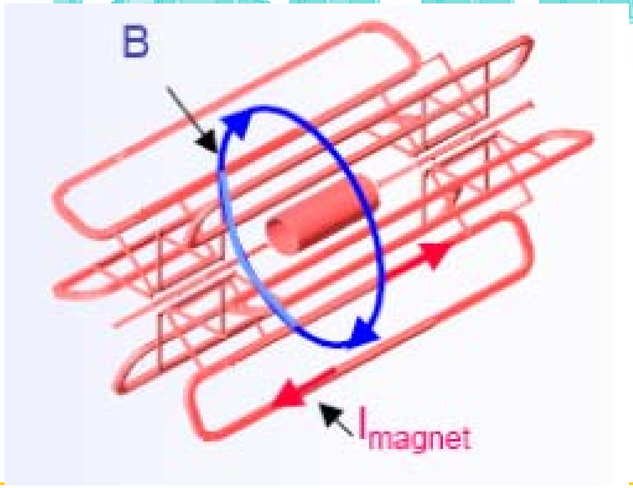
High Precision Tracking for Muon Detections

$|\eta|$ coverage to 2.7, $\Delta p/p \sim 8\%$ @ 1TeV ($\sigma_{tracking} \sim 50\ \mu$)

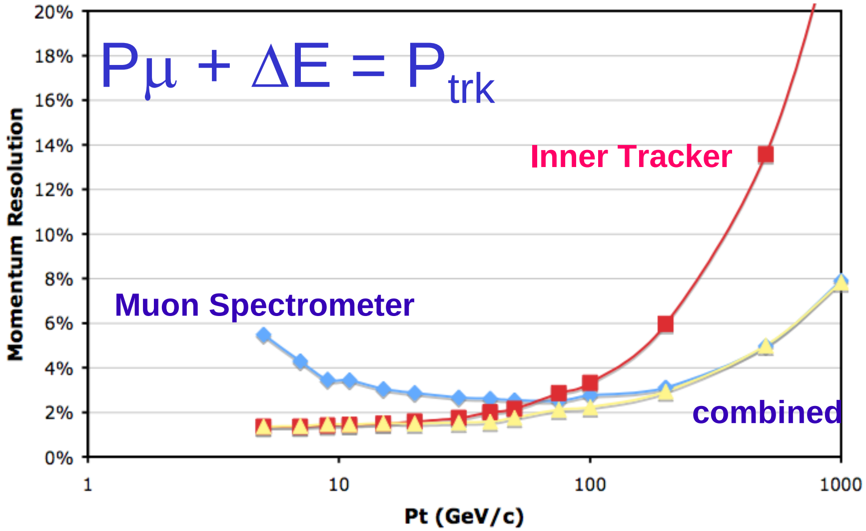




Simulation of a $H \rightarrow \mu\mu$ ee event in ATLAS

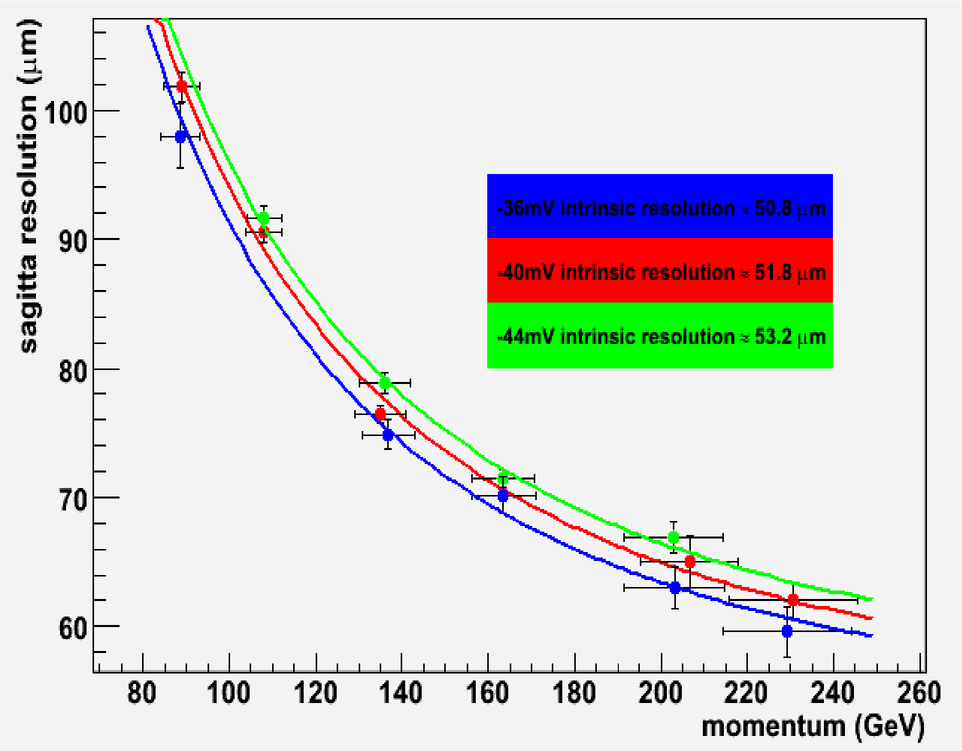


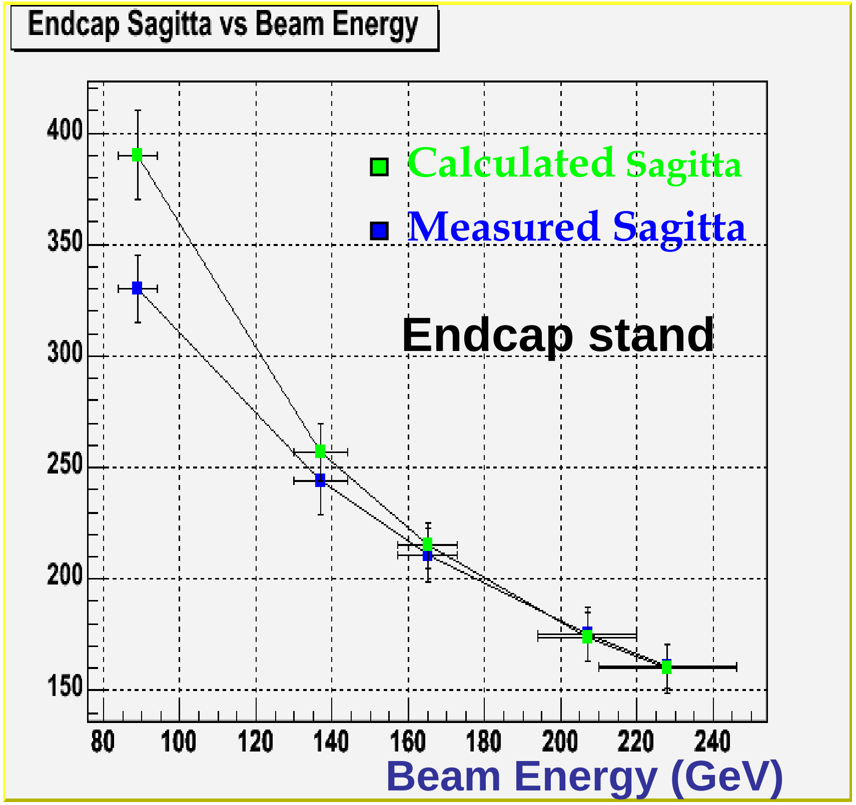
ATLAS Magnets ~ 40% of total cost



ATLAS Test Beam Results : Muon detector resolution

Barrel Sagitta σ vs Beam Energy

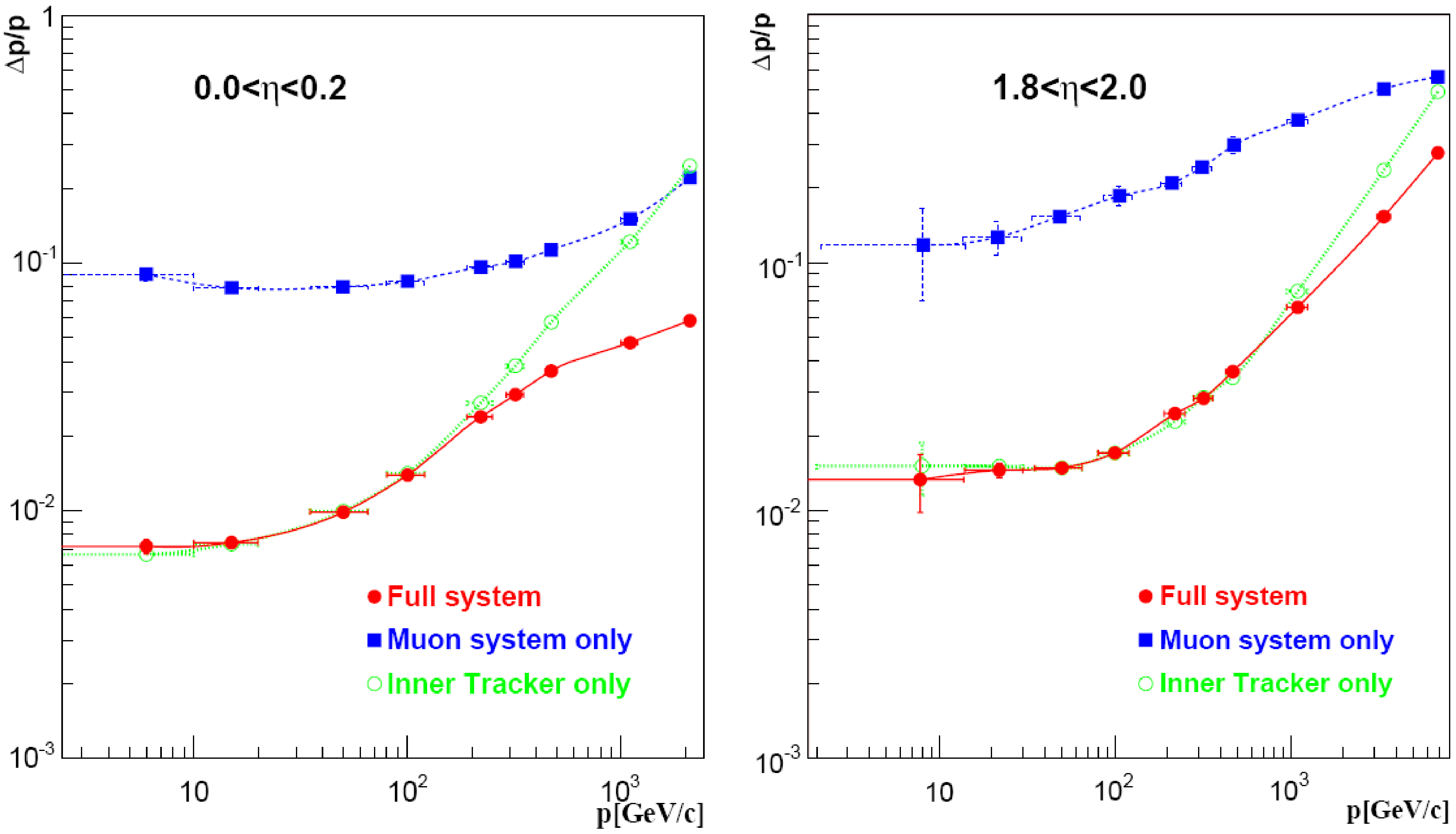




- **Barrel: good agreement between data and G4 Simulations (solid curves) (important for simulation validation)**
- **Threshold effect on the intrinsic resolution**

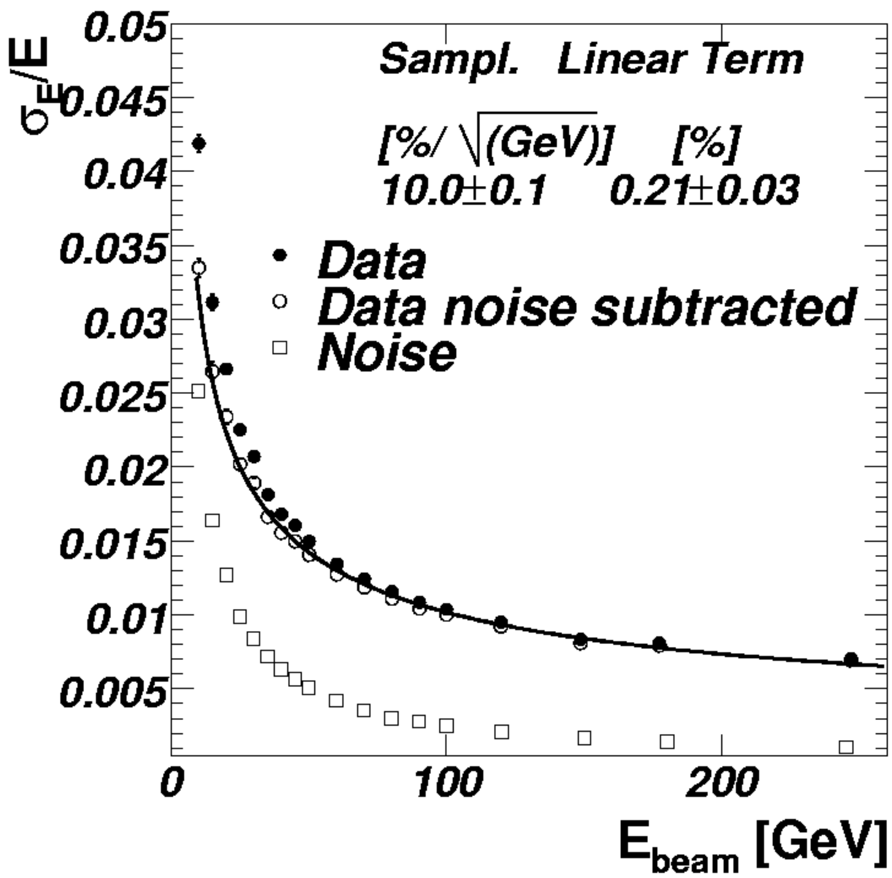
- **EC sagitta calculated according to the nominal material distribution**
- **Agreement of the measurements with G4 is good, correction for the aluminum support bar applied**

CMS: Muon Detection Resolution



ATLAS: ECAL Energy Resolution

Resolution with new reconstruction at η=0.68



Local energy resolution well understood since Module 0 beam tests and well reproduced by simulation :

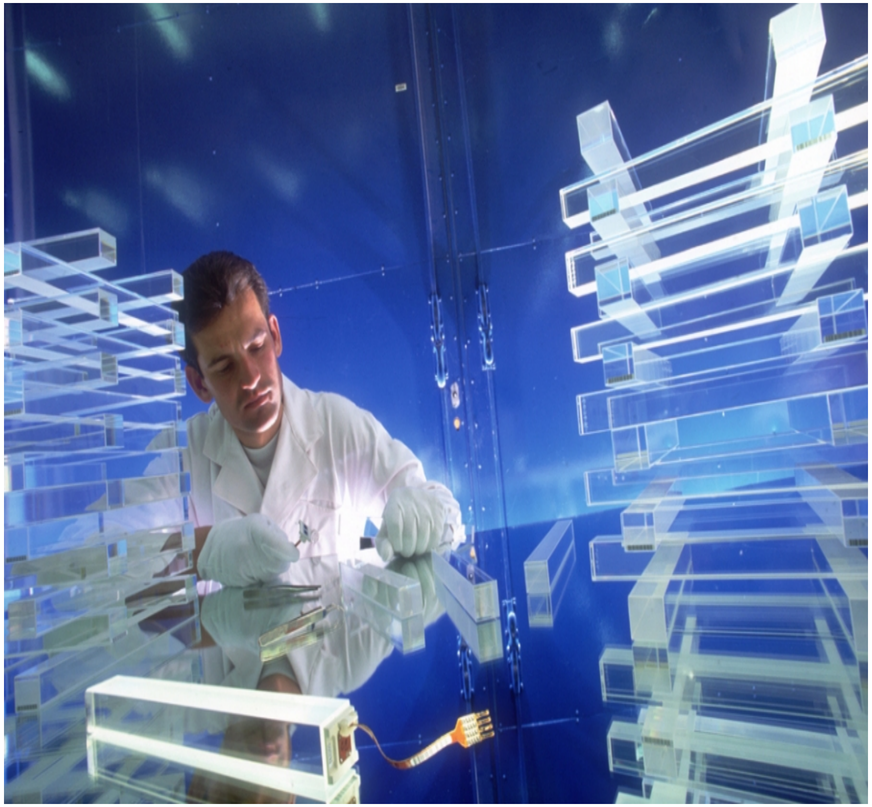
-Sampling term given by lead/argon sampling fraction and frequency : quality control measurements during construction

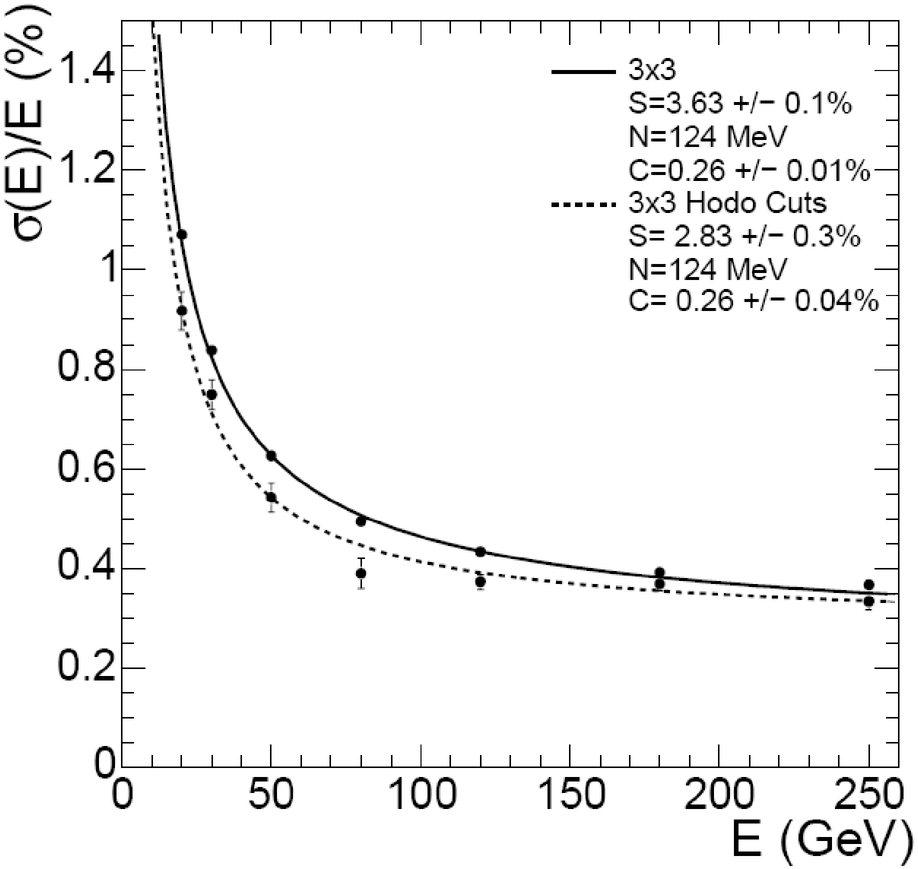
- Noise term under control

- Local constant term (within a cell) given by impact point correction

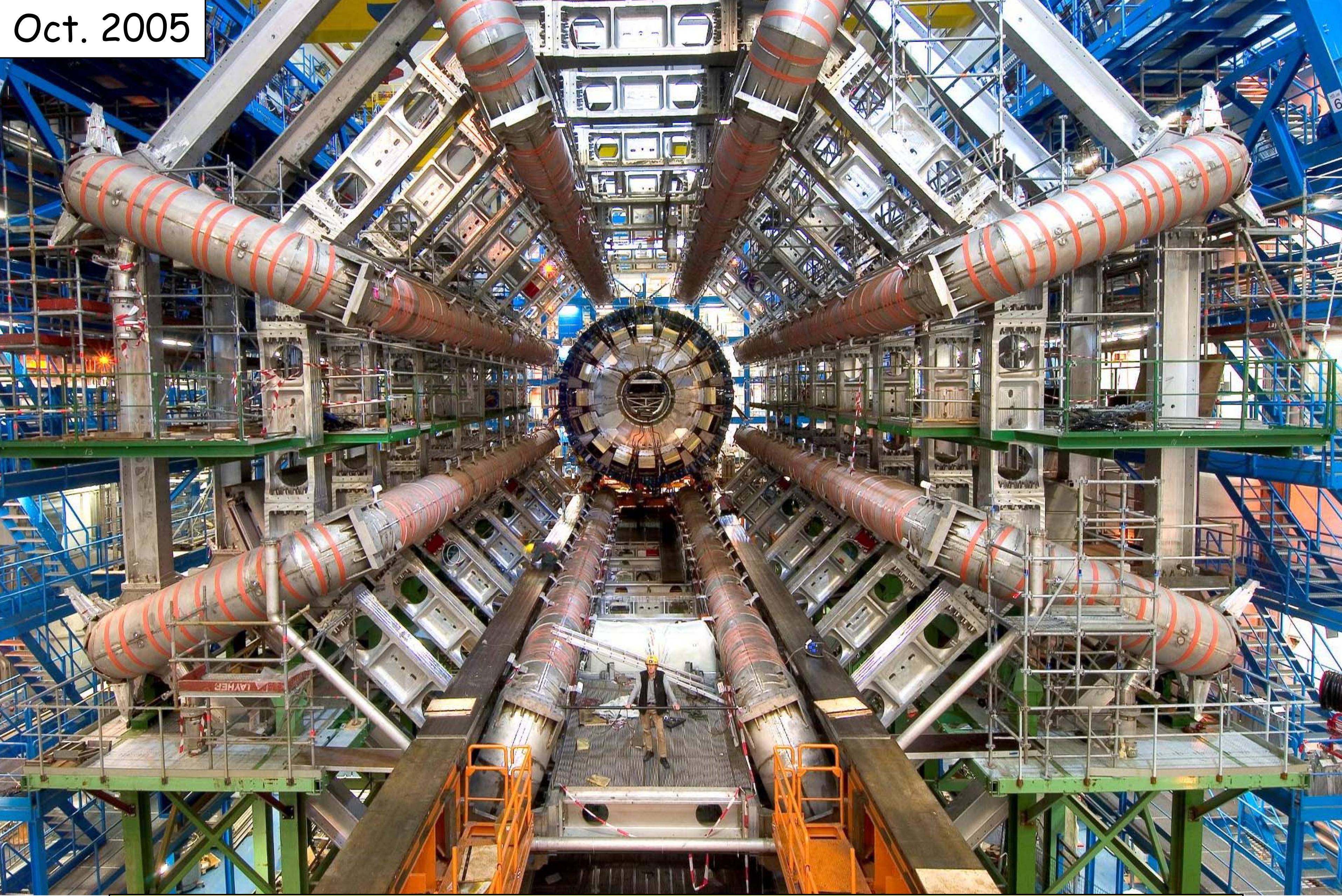
→Uniformity is at 1% level quasi online but achieving ATLAS goal (0.7 %) needs a lot of work, and most of the time was used to correct for setup problem…

CMS: ECAL Energy Resolution





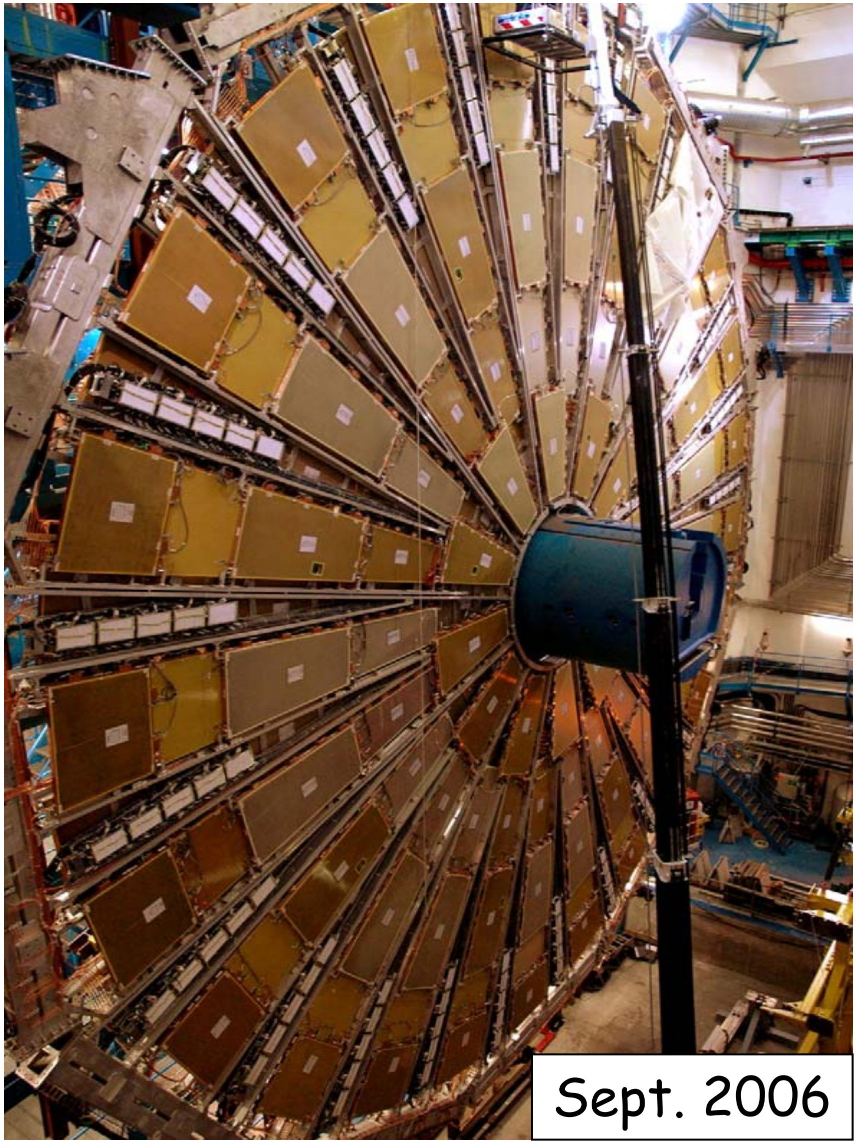
Oct. 2005



- The last(8-th) Barrel Toroid coil installed in Aug. 2005
- Barrel calorimeter (LAr EM + HAD Fe/Scint. Tilecal) in final position at Z=0 (Nov. 2005)
- Barrel toroid: cool down completed, first tests towards full field started in Sep. 2006

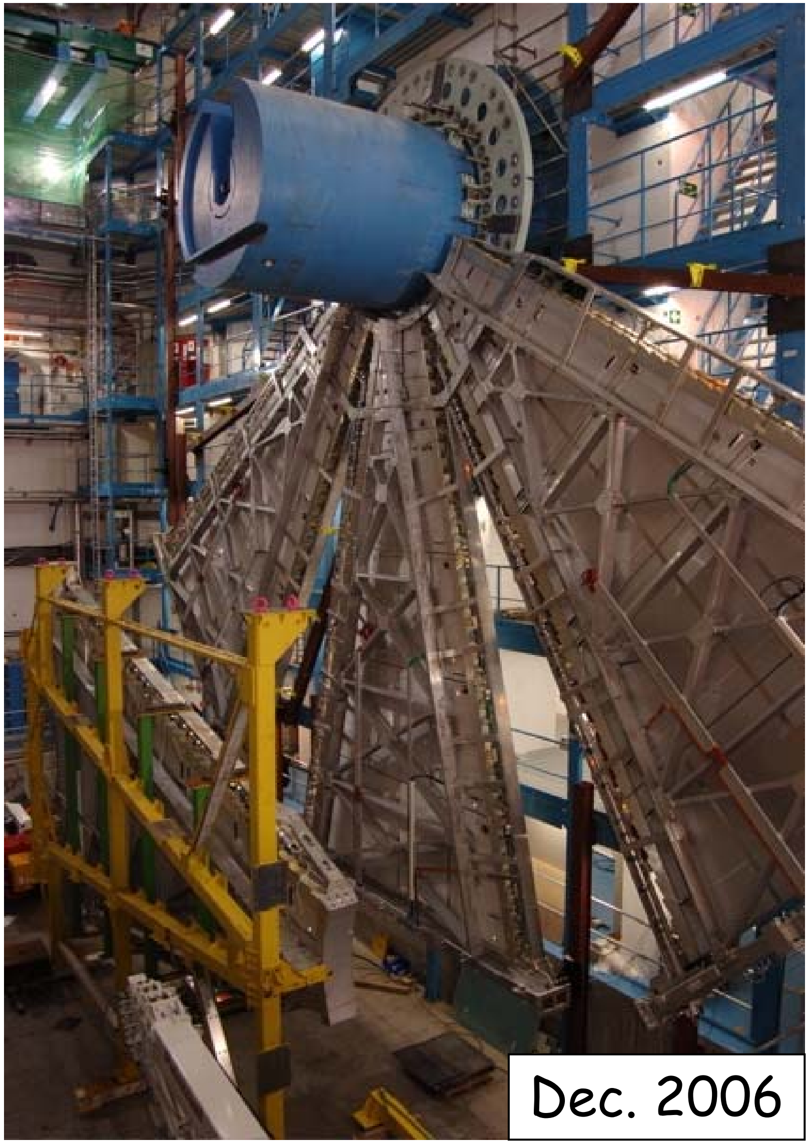
Endcap Muon Big-Wheel installation
Started in June 2006

TGC Big-Wheel (C-1)



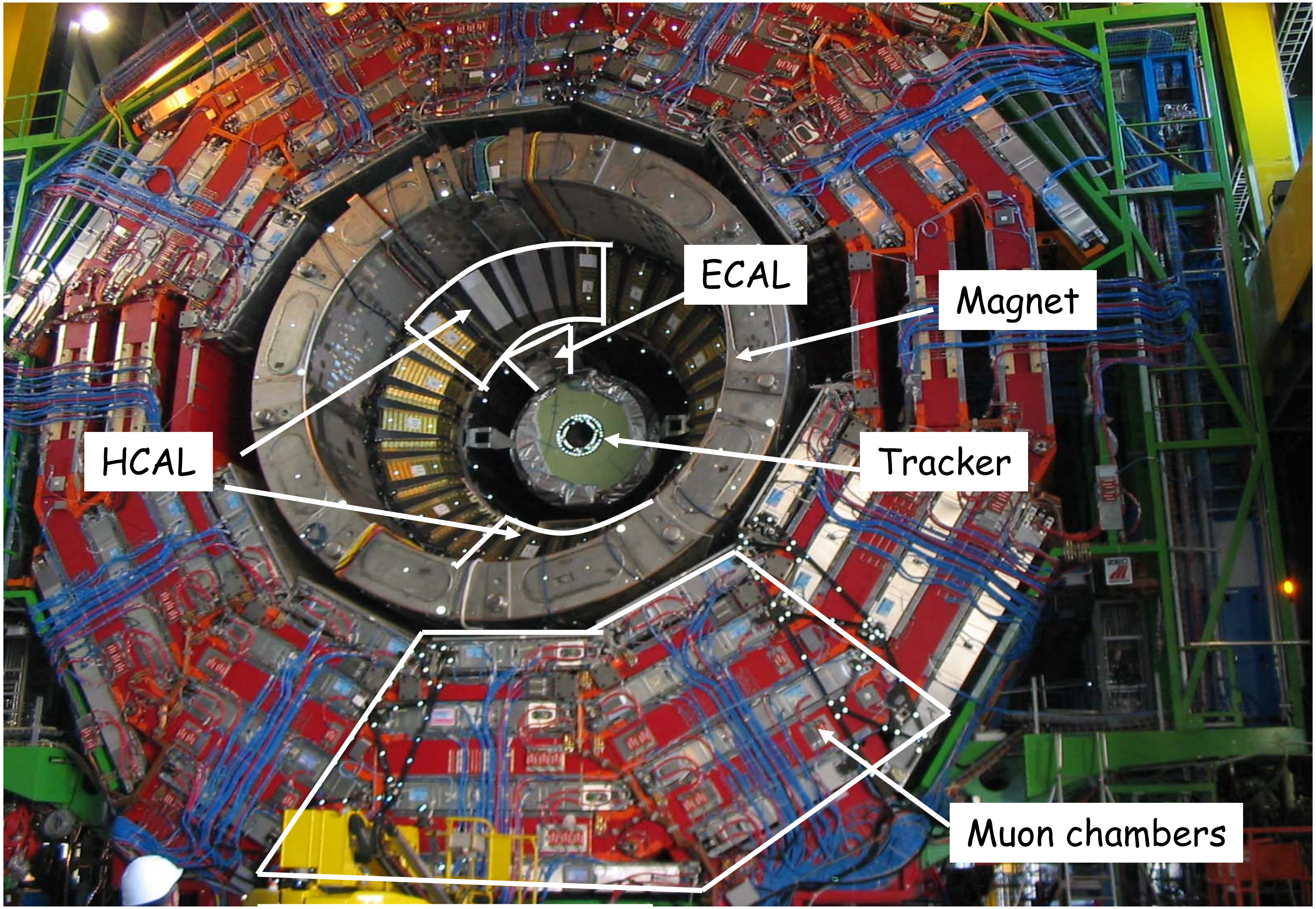
Sept. 2006

MDT Big-Wheel (C)



Dec. 2006

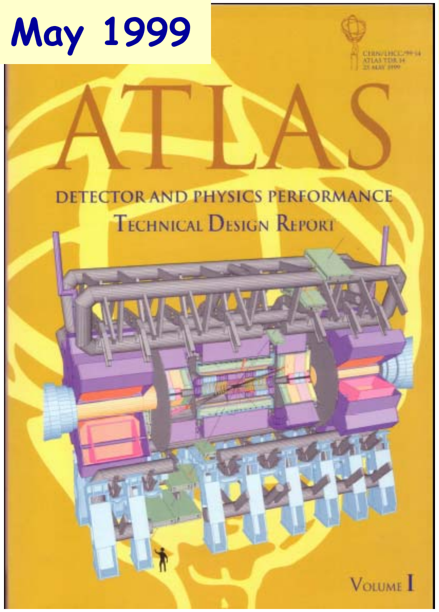
CMS: Magnet Test and Cosmic Challenge



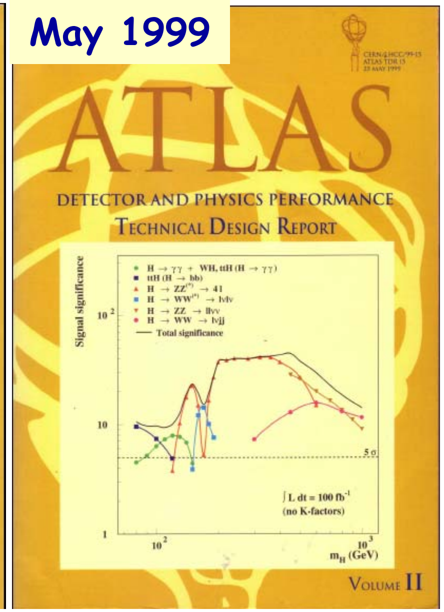
Detector installation to pit started in Dec. 2006

Detector Performance & Physics Studies (TDRs)

May 1999

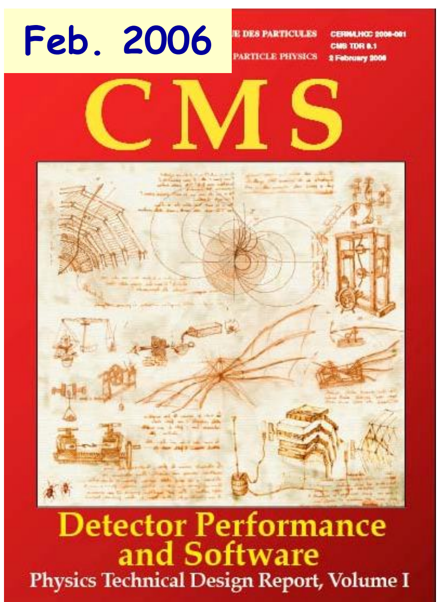


May 1999

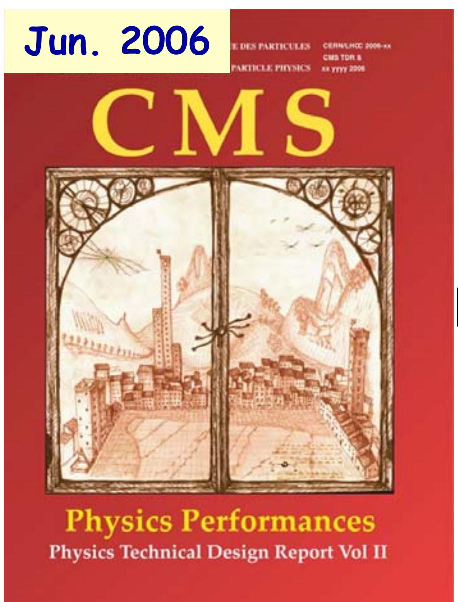


CSC (Computing System Commissioning) notes are to be produced in spring 2007, covering software and physics analysis validation for the early physics run with 0.1 fb^{-1} and 1 fb^{-1}.

Feb. 2006



Jun. 2006



Instead of 3-rd vol. of TDR, short notes on startup will be submitted to LHCC in summer 2007, along with the very early physics reach with 0.1 fb^{-1} and 1 fb^{-1}.

Search for New Physics Studies

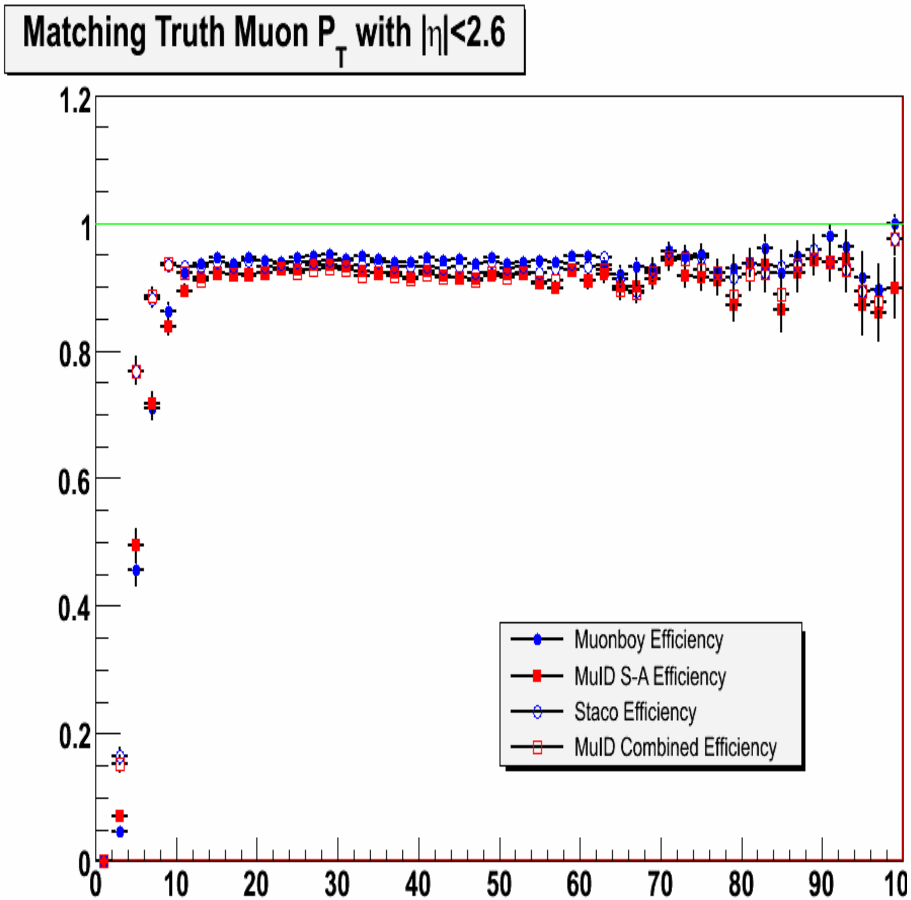
SM Higgs H^0	Look for final states with ℓ, and γ : **H→γγ, H→bb (with tt or W with lepton decays), H→ττ (via VBF), H→ZZ*/ZZ→$\ell^+\ell^-\ell^+\ell^-$, $\ell^+\ell^-$νν, $\ell^+\ell^-$jj, H→WW*→ ℓ^+ν ℓ^-ν or ℓν jj (via BVF)**
Extended Models H^0,h^0,A^0,H^+H^- & H++, H--	**SM-like: h → γγ, bb; H → 4ℓ** **MSSM-specific: A/H → μμ, ττ; H → hh, A → Zh; $H^\pm$ → τν A/H → $\chi^2_0\,\chi^2_0$ → 4ℓ + missing Energy**
Supersummetry	**Like-sign leptons, multi-leptons and Jets with Missing E_T**
Heavy $Q\,\bar{Q}$	**Q→ W q → ℓ + jets**
New bosons Z', W'	Z'→ $\ell^+\ell^-$, W'→ ℓ ν
Technicolor	**ρ_T → WZ → ℓν $\ell\ell$, ρ_T → Wπ → ℓνbb**
L/Q structure	**Pp→ LQ LQ → ℓq ℓq: High-mass di-leptons, Missing E_T**
Extra-dimension	**High-mass di-leptons, narrow lepton resonances, Jets+Missing E_T**
Composite Models	**pp→L^+L^-→ ZZ+2leptons → 6 leptons, pp→ ee*→ eeγ**
Strongly-couples Vector-bosons	High mass spectra: **W_LZ_L → W_LZ_L → ℓν $\ell\ell$, Z_LZ_L → Z_LZ_L → $\ell\ell$ $\ell\ell$ W_LW_L → Z_LZ_L → $\ell\ell$ $\ell\ell$**

New Physics with Multi-lepton Final States

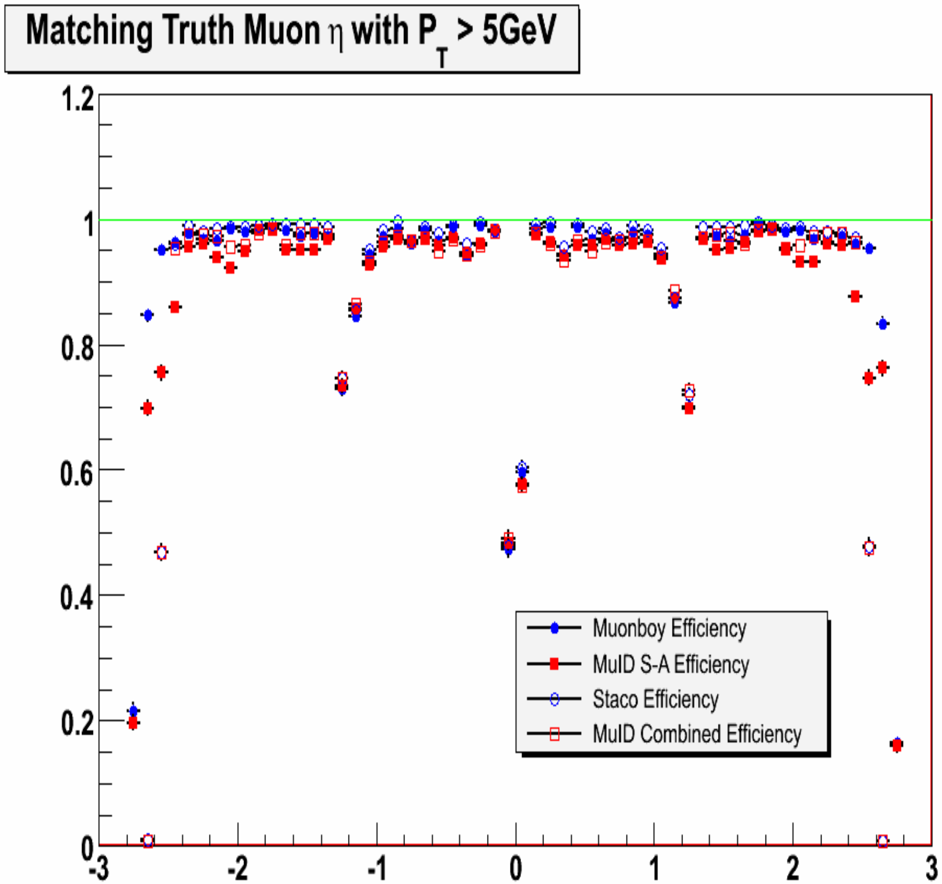
Single lepton	*SM:* $W \to \ell \nu$ W+jets $\to \ell\nu$ +x **tt/bb $\to \ell$ + x**	$W' \to \ell \nu$ $H \to bb$ +W/tt(with $W \to \ell \nu$) $H \to WW^* \to \ell \nu jj$ (via BVF) $\rho_T \to W\pi \to \ell \nu bb$ $Q \to W q \to \ell$ + jets
Di-lepton	*SM* $Z/\gamma^* \to \ell^+\ell^-$ Z+jets$\to \ell^+\ell^-$+x ***tt/ww*** $\to \ell^+\ell^-$ **+x**	$H \to WW^* \to \ell^+\nu \ell^-\nu$ A/H $\to \mu\mu$, $\tau\tau$ Like-sign dileptons from SUSY particle decays High mass narrow resonances: $Z' \to \ell^+\ell^-$, $G^* \to \ell^+\ell^-$,… pp$\to$ LQ LQ $\to \ell q\, \ell q$ pp$\to$ ee*$\to$ eeγ
Triple-lepton	*SM* $WZ \to \ell\nu\, \ell\ell$	$\rho_T \to WZ \to \ell\nu\, \ell\ell$ $W_LZ_L \to W_LZ_L \to \ell\nu\, \ell\ell$ pp$\to W^* \to \chi_1^+\chi_2^0 \to W+\chi_1^0 + Z^*\chi_1^0 \to \ell\, \ell\ell$ + Missing E_T
Four-leptons	*SM* $ZZ \to \ell^+\ell^-\ell^+\ell^-$	$H \to ZZ^*/ZZ \to \ell^+\ell^-\ell^+\ell^-$ A/H $\to \chi^2{}_0\chi^2{}_0 \to 4\ell$ + missing Energy $Z_LZ_L \to Z_LZ_L \to \ell\ell\, \ell\ell$, $W_LW_L \to Z_LZ_L \to \ell\ell\, \ell\ell$
Six-leptons		pp$\to L^+L^- \to$ ZZ+2leptons $\to$ 6 leptons

ATLAS : Muon Detection Efficience

Study based ATLAS CSC data sample: Z → μμ



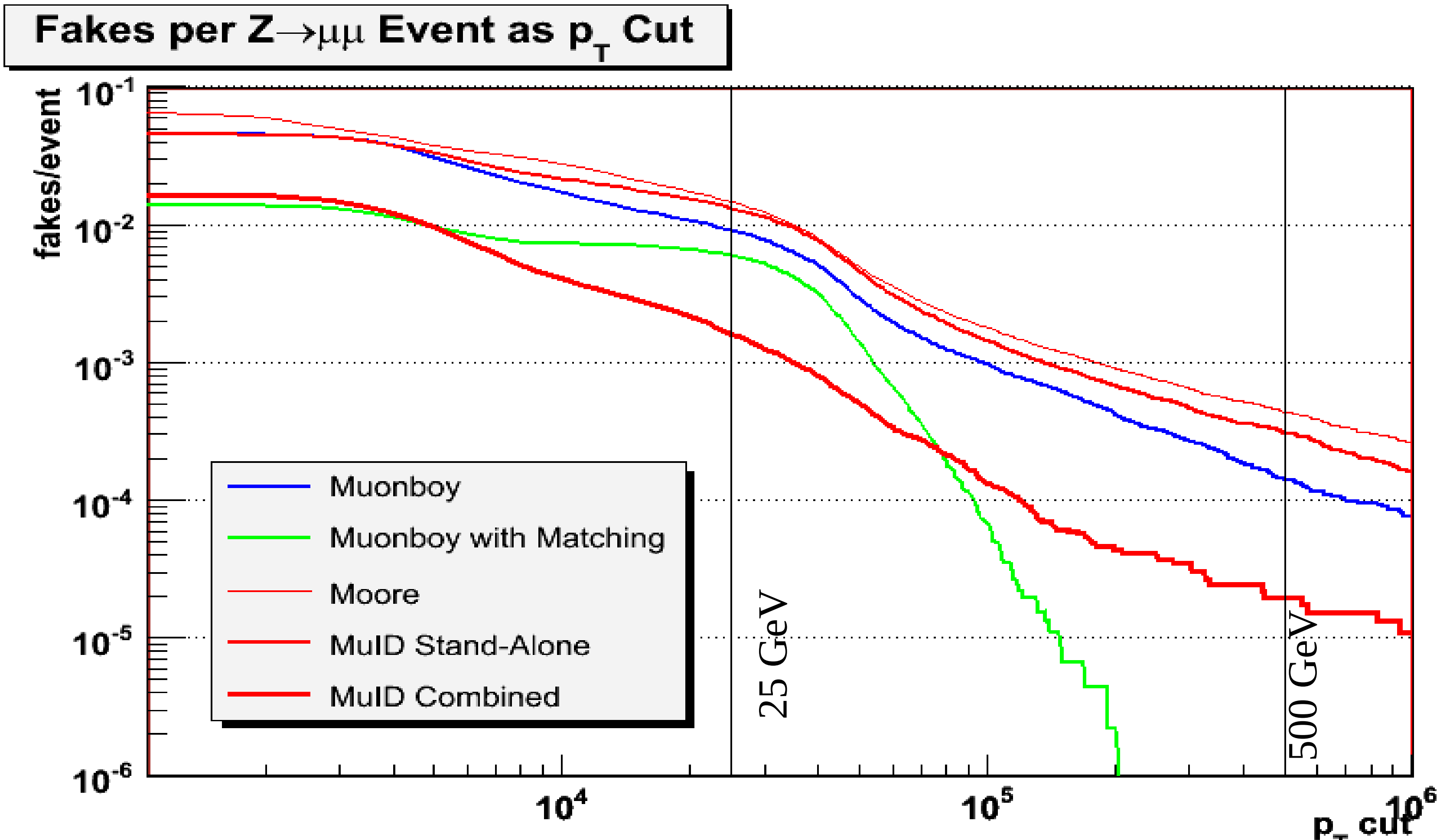
Muon Pt



Muon η

Fake μ rate as a function of Muon P_T

Full simulation: tt → μ + x (1M events), Z→ μμ (1M events)

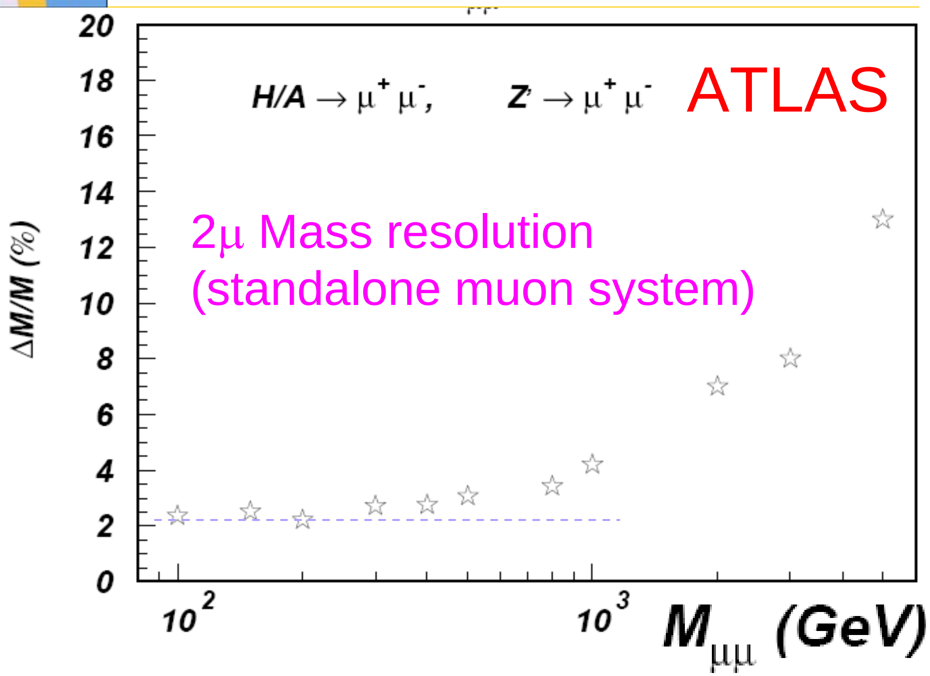


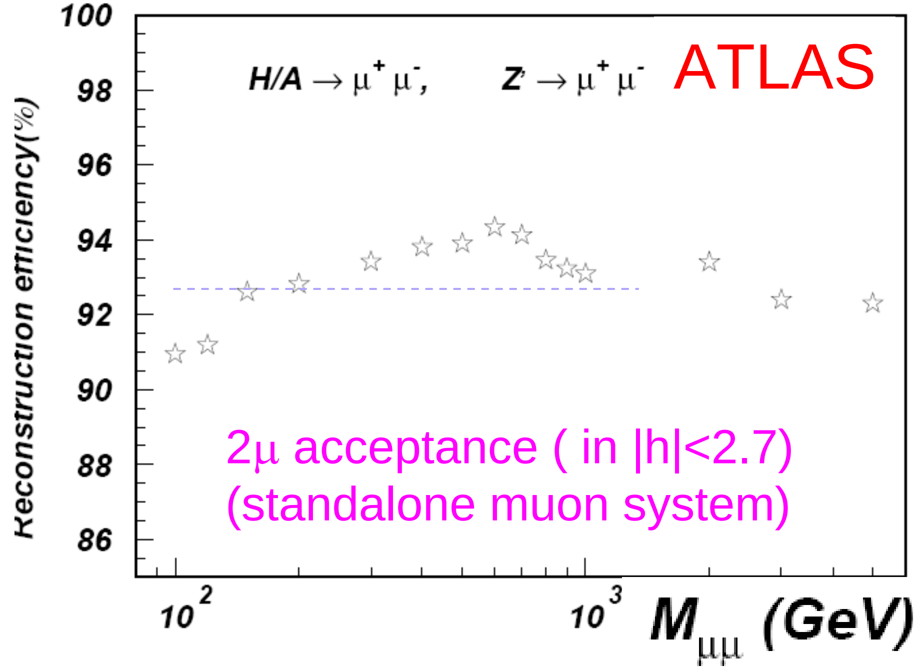
For p_T > 500 GeV,

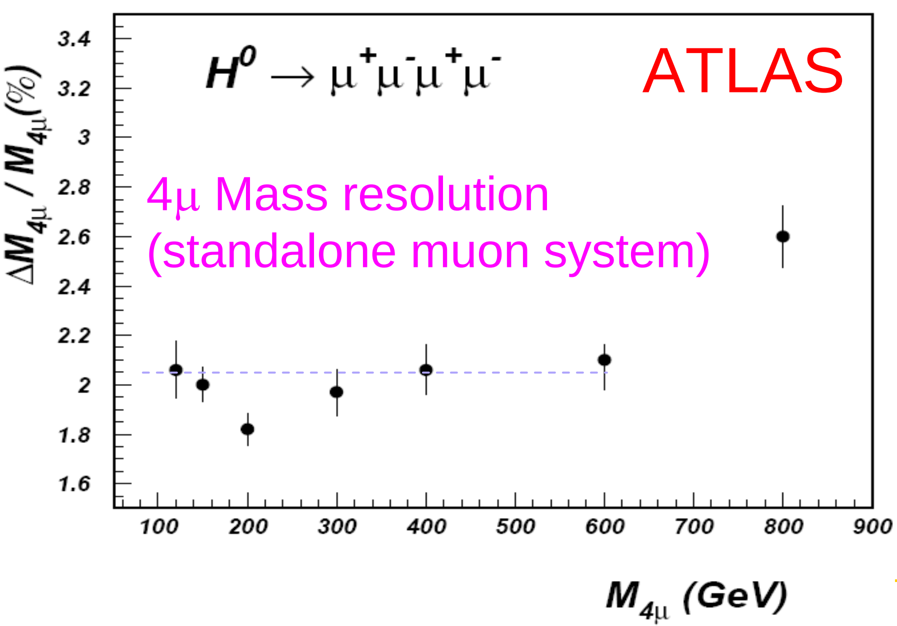
Standalone Muon System: fake rate ~10^{-4}

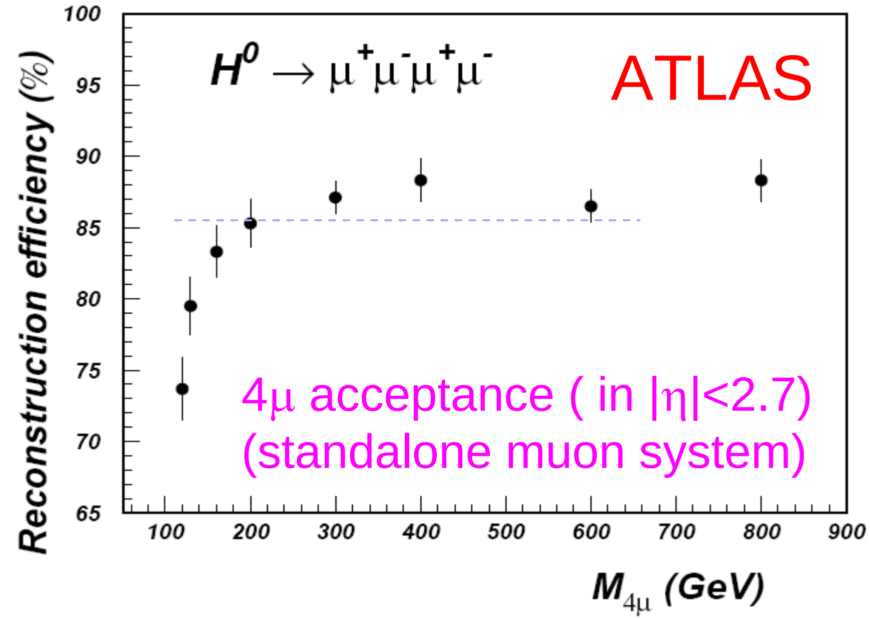
MuID Combined: **fake rate ~ 10^{-5}**

Benchmark Studies on Muon Final States





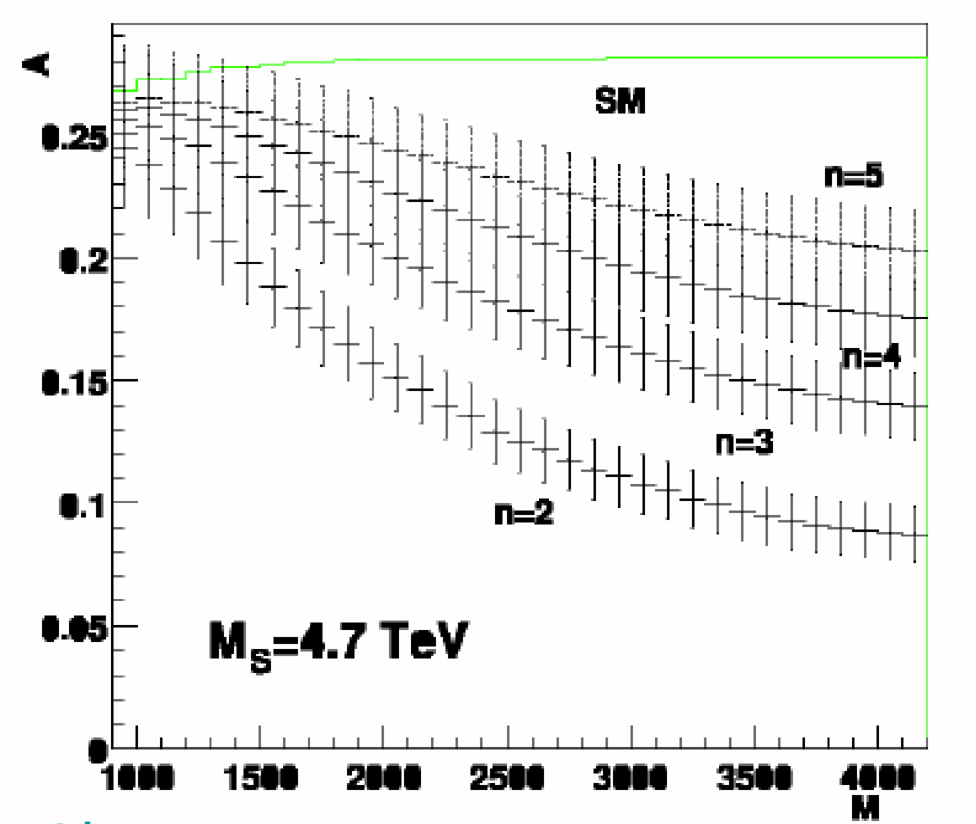




ATLAS: Muon Spectrometer Performance

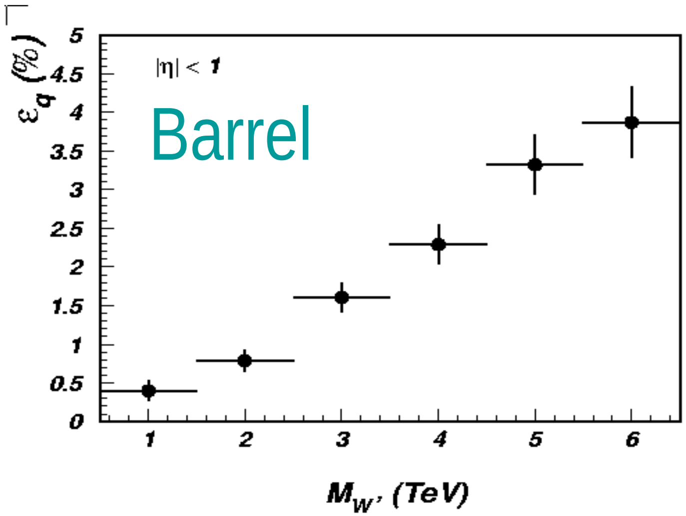
High Pt Muon Charge Identification is Essential for new physics

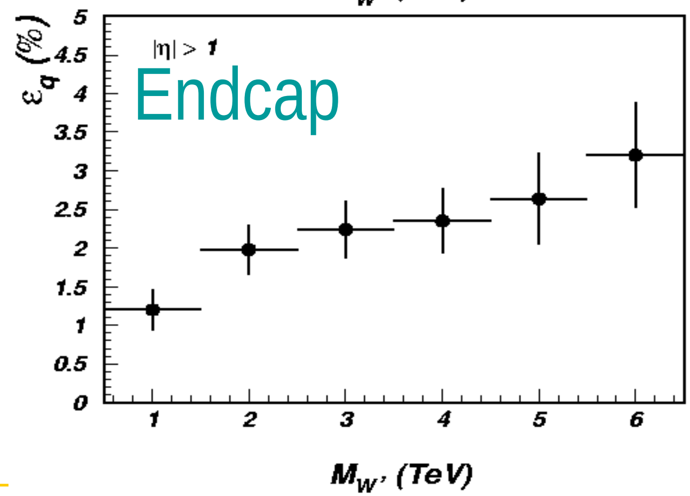
X-dim : dilepton from G* exchange



•Charge asymmetry measurement would help to pin-down the 'origin'

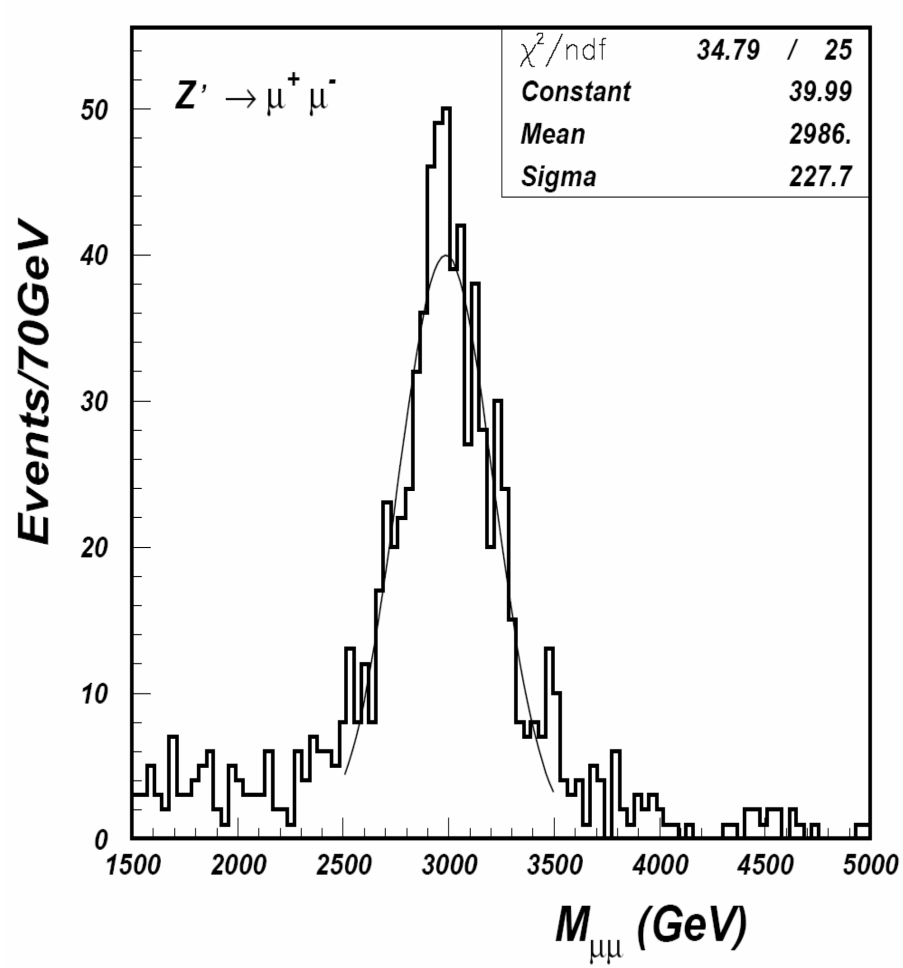
Unique feature of the ATLAS Standalone Muon System



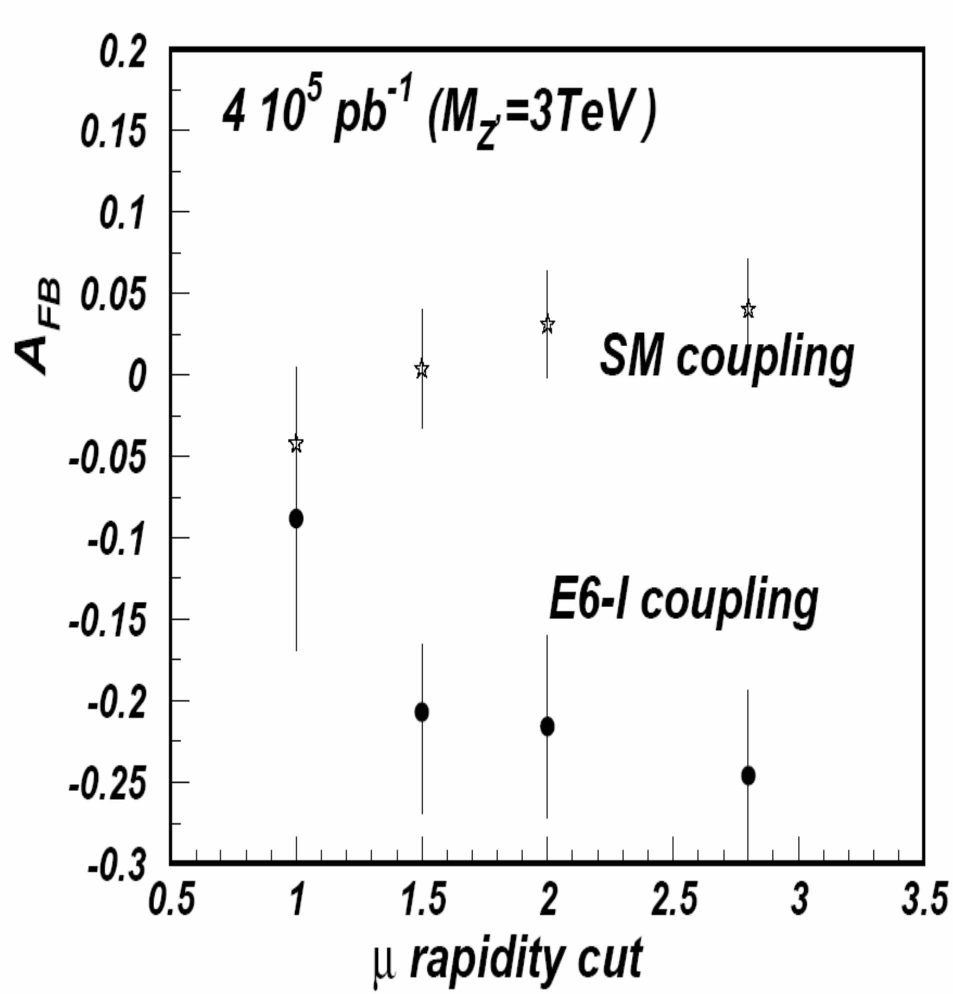


ATLAS: Bench mark: Z’ → μμ

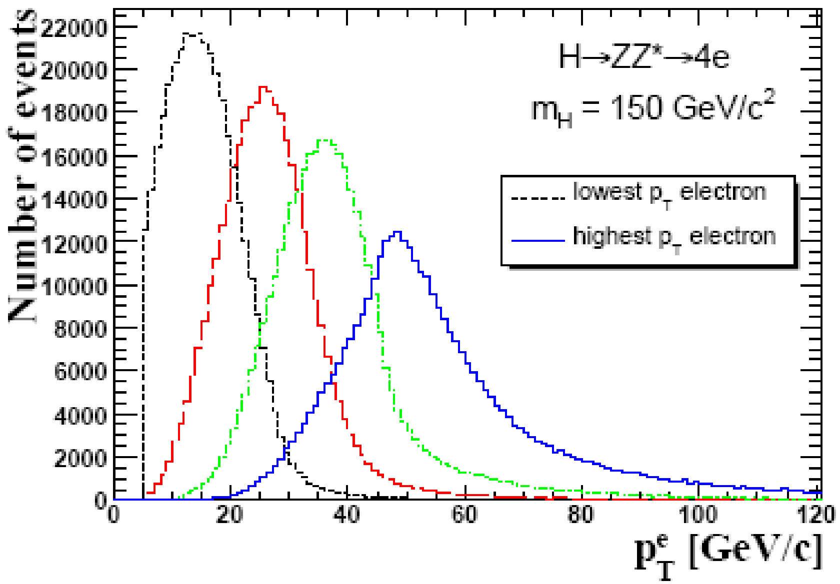
3 TeV Z’ mass spectrum

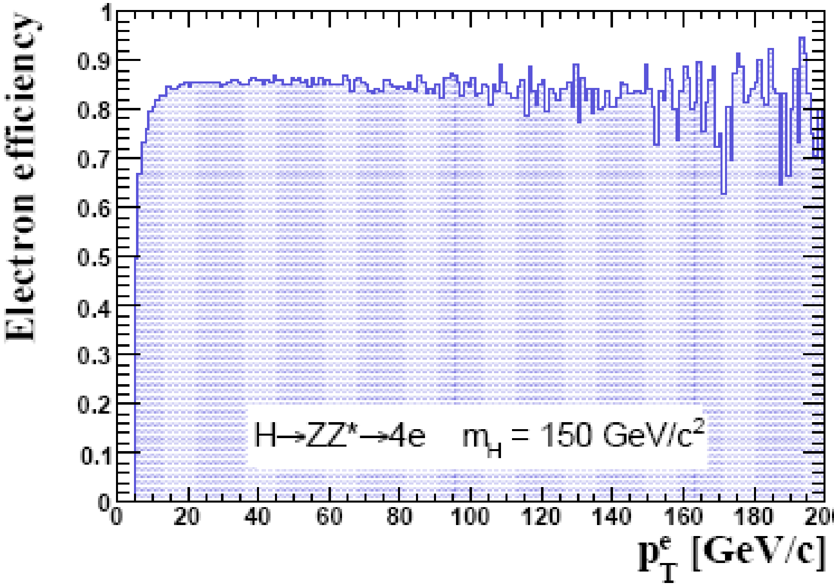


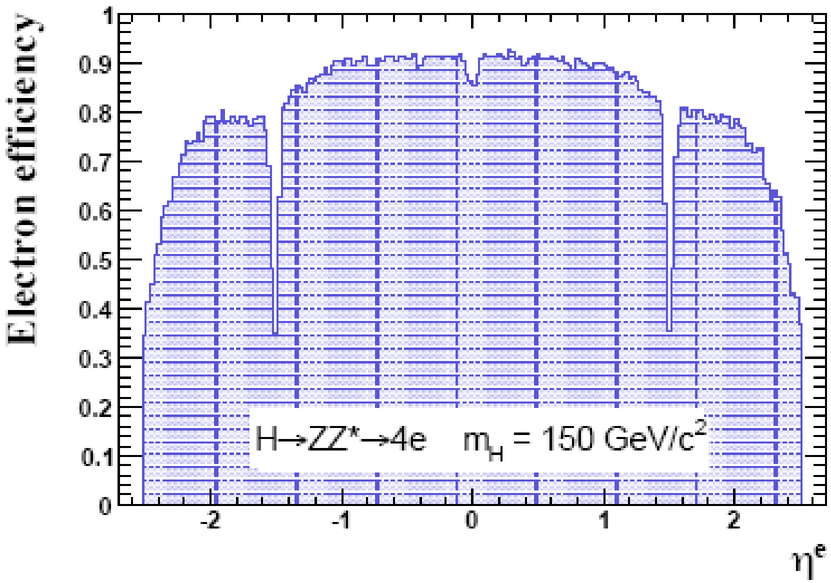
Z’ Charge Asymmetry

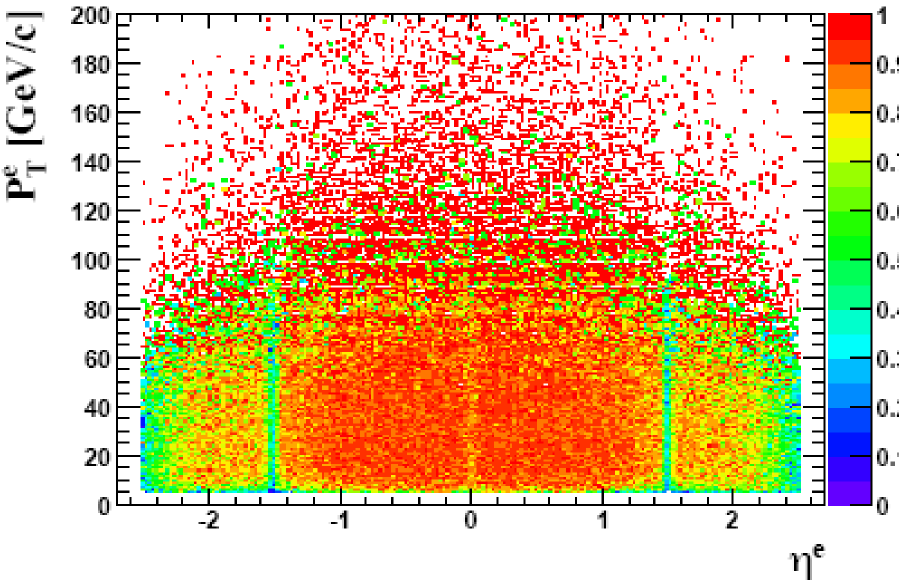


CMS: Electron Detection Performance Studies



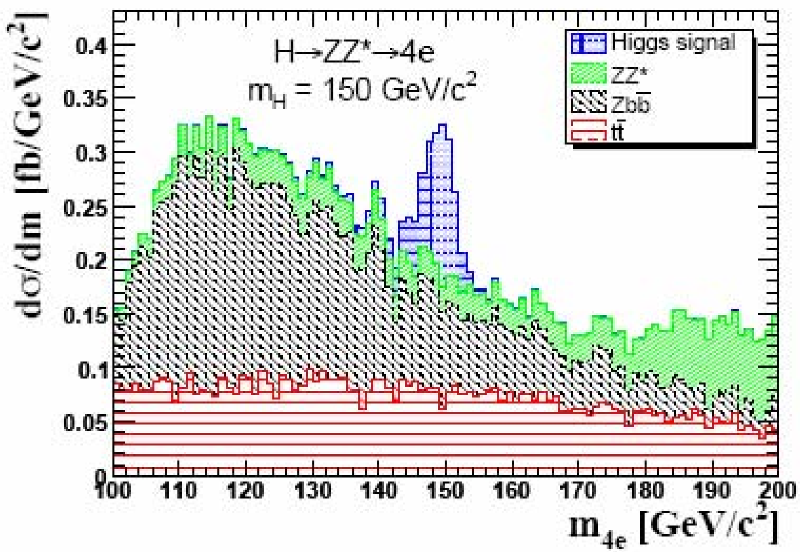




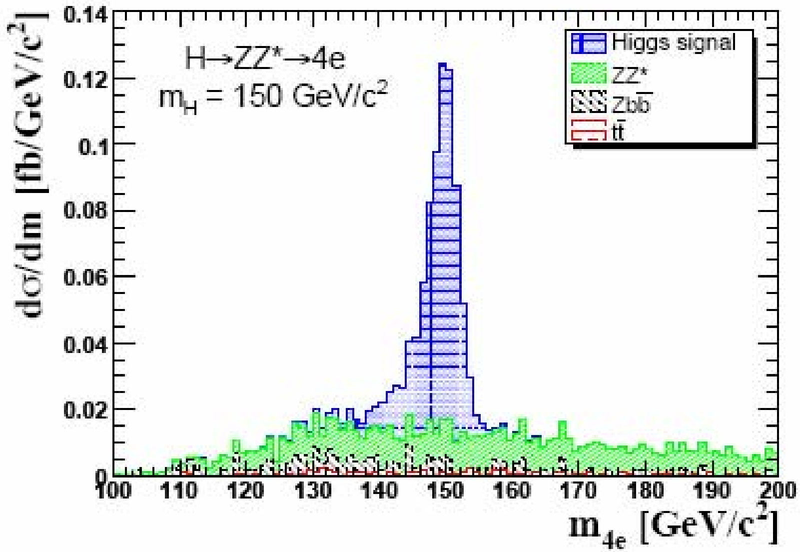


CMS: Benchmark Studies: H → 4e

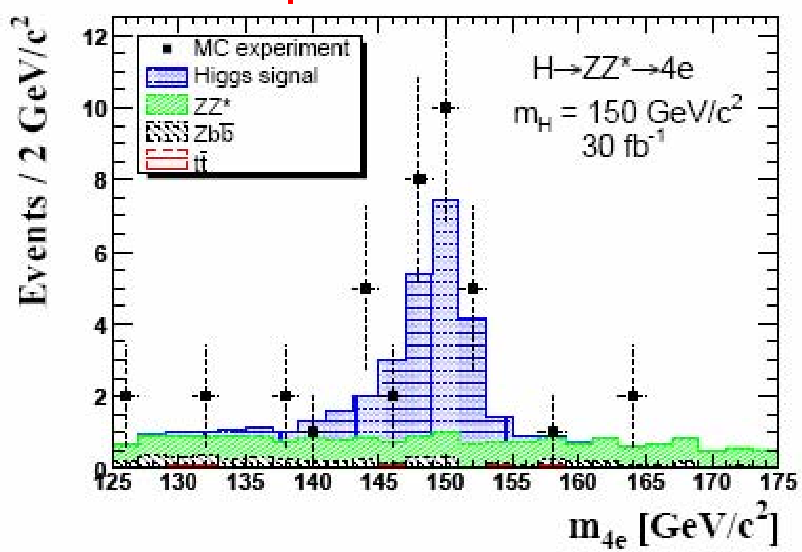
Before the cuts



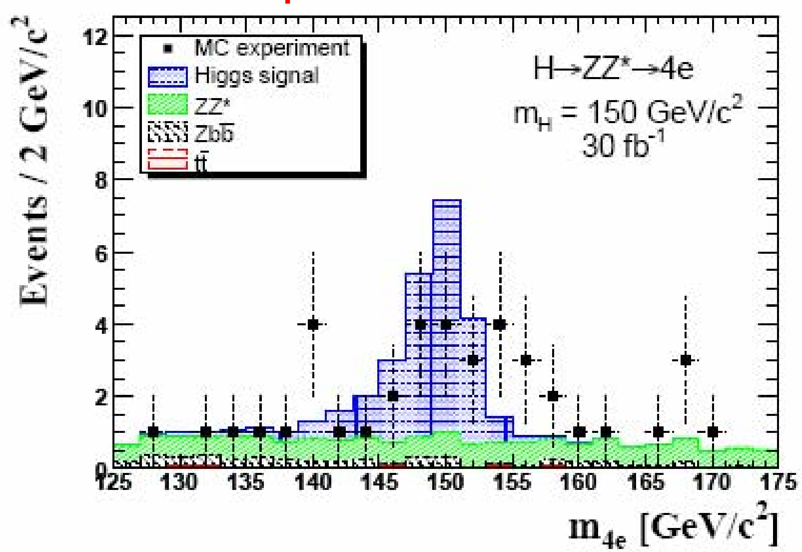
After the cuts



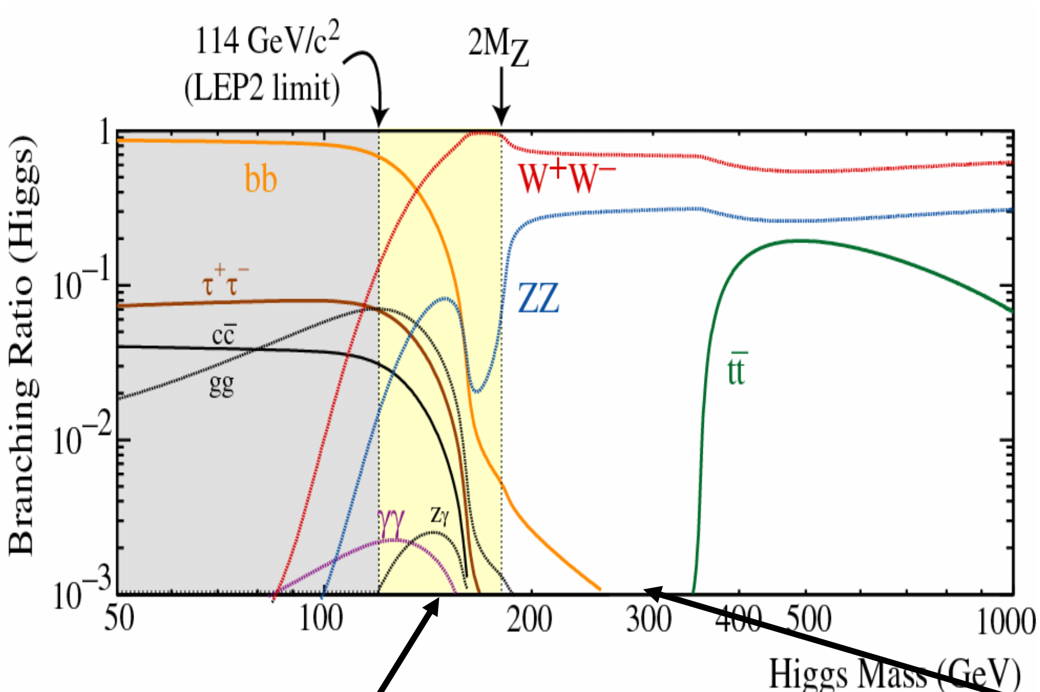
MC experiment



MC experiment



Higgs Discovery Channels at LHC



Dominant BR for $m_H < 2m_Z$:
$\sigma(H \rightarrow bb) \approx 20$ pb;
$\sigma(bb) \approx 500\ \mu$b
for m(H) = 120 GeV
→ no hope to trigger or extract fully hadronic final states
→ look for final states with ℓ, γ (ℓ = e,μ)

Low mass region: m(H) < 2 m_Z :

H → $\gamma\gamma$: small BR, but best resolution
H → bb : good BR, poor resolution ➔ ttH, WH
H → ZZ* → 4ℓ
H → WW* → $\ell\nu\ell\nu$ or $\ell\nu$jj : via VBF
H → $\tau\tau$: via VBF

m(H) > 2 m_Z :

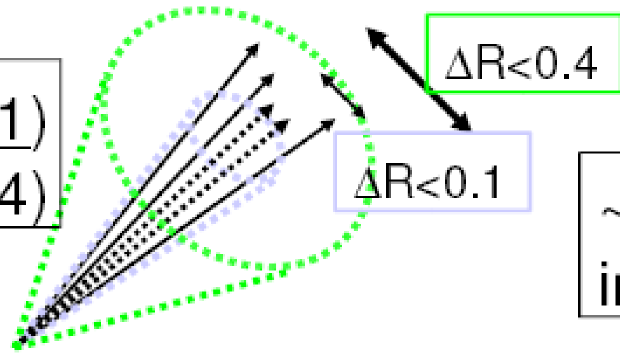
H → ZZ → 4ℓ
qqH → ZZ → $\ell\ell\ \nu\nu$ *
qqH → ZZ → $\ell\ell$ jj *
qqH → WW→ $\ell\nu$jj *
* for m_H > 300 GeV forward jet tag

τ ID: Fraction of Energy in $\Delta R<0.1$

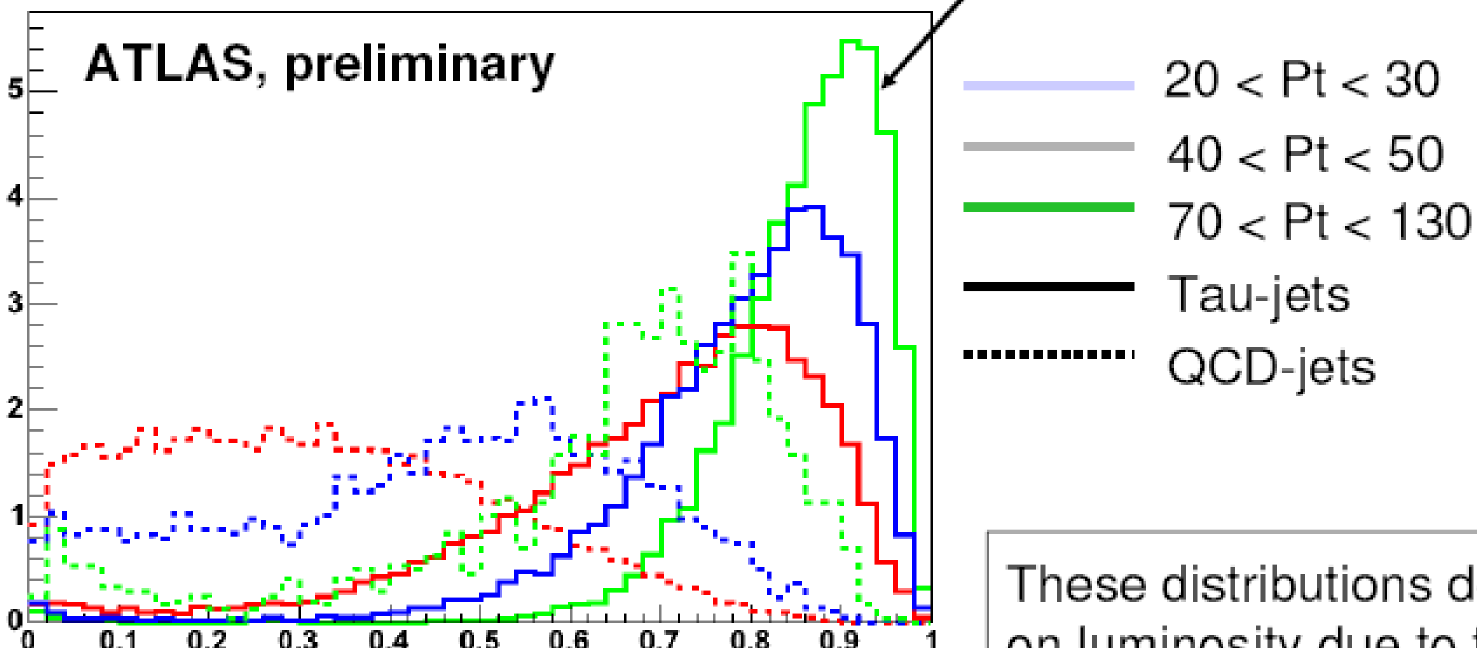
(transverse energy)

$$\frac{\Sigma E_T(\Delta R<0.1)}{\Sigma E_T(\Delta R<0.4)}$$

for tauID



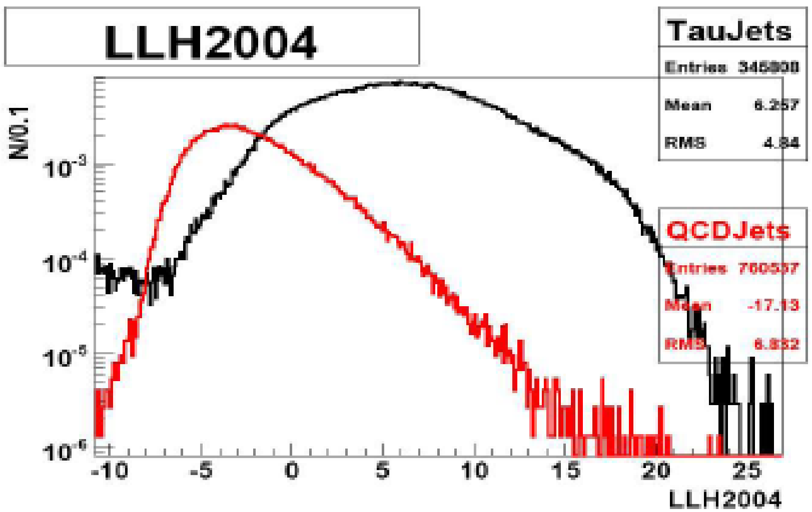
~90% of energy are deposited in $\Delta R<0.1$. -> narrow jet



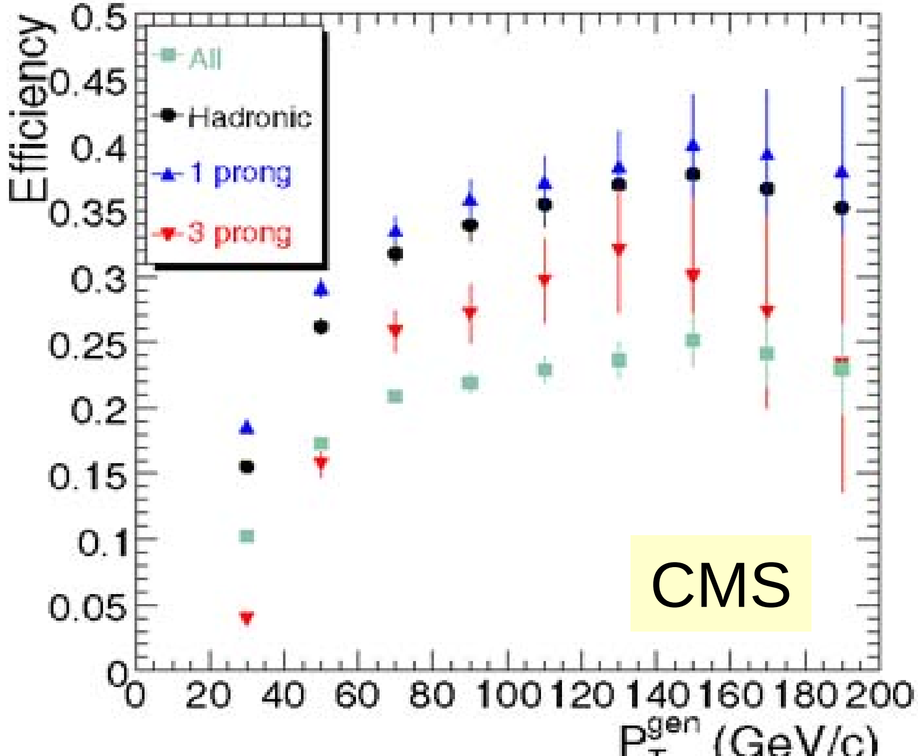
These distributions depend on luminosity due to the pile-up.

τ-ID efficiencies

- Construct variable that combines all cut variables
- Compare signal and bckgnd
- Can vary cut to get need rejection



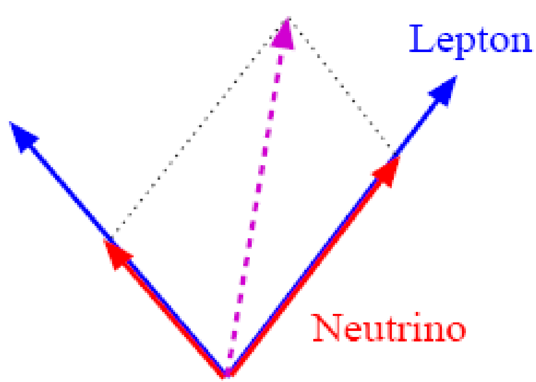
ATLAS

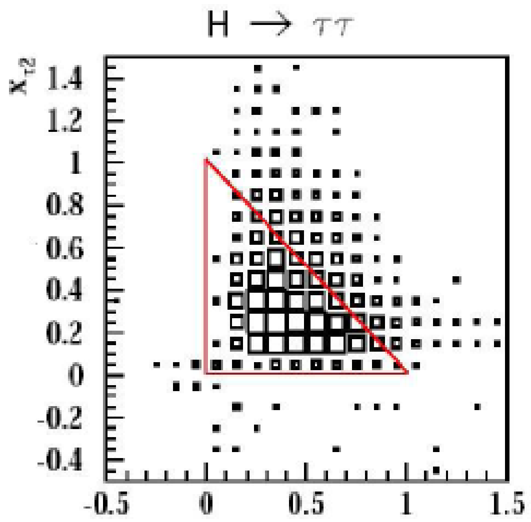


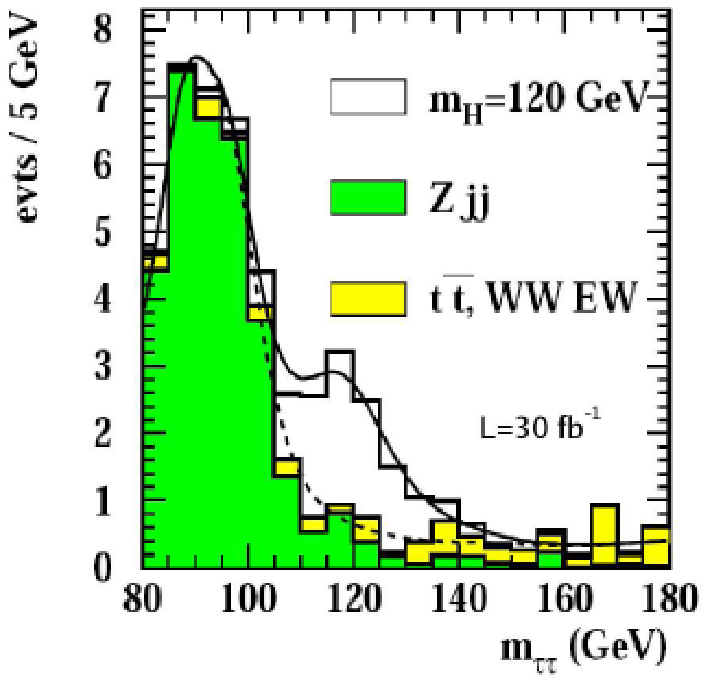
VBF H→ ττ Reconstruction

- Assume ℓ and ν's from $\tau \to \ell\nu\nu$ are collinear.
- Label visible energy fractions x_{τ_1} and x_{τ_2}.
- Assume $\not{p}_T$ vector comes from the ν's, and solve the equations for x_{τ_1} and x_{τ_2}.

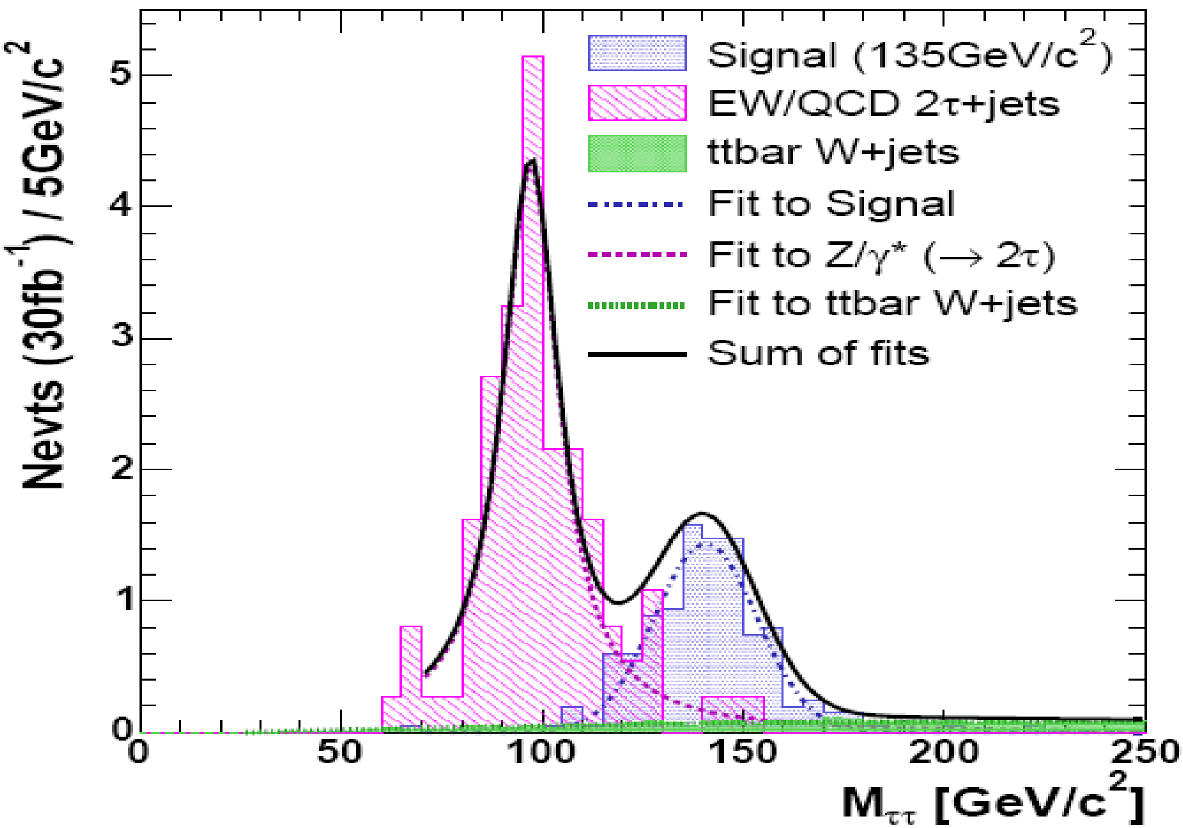
ATLAS







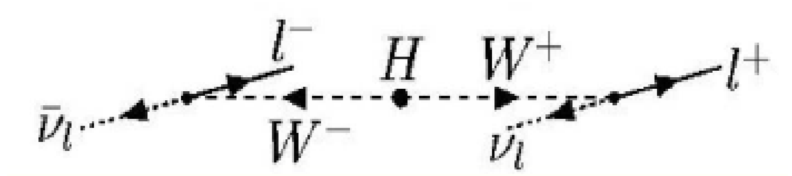
CMS Studies: H → ττ



M_H [GeV]	115	125	135	145
Production σ [fb] $\sigma \times BR(H \to \tau\tau \to lj)$ [fb]	4.65×10^3 157.3	4.30×10^3 112.9	3.98×10^3 82.38	3.70×10^3 45.37
N_S at 30 fb^{-1} N_B at 30 fb^{-1}	10.5 3.7	7.8 2.2	7.9 1.8	3.6 1.4
Significance at 30 fb^{-1} ($\sigma_B = 7.8\%$)	3.97	3.67	3.94	2.18
Significance at 60 fb^{-1} ($\sigma_B = 5.9\%$)	5.67	5.26	5.64	3.19

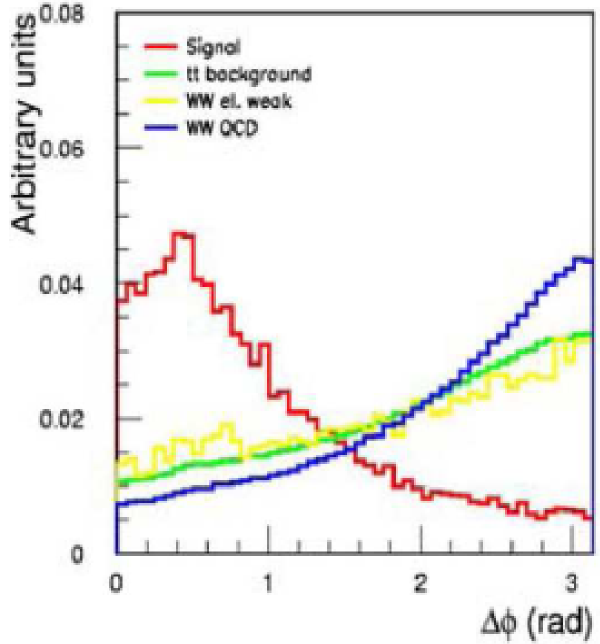
H → WW → dileptons+MET

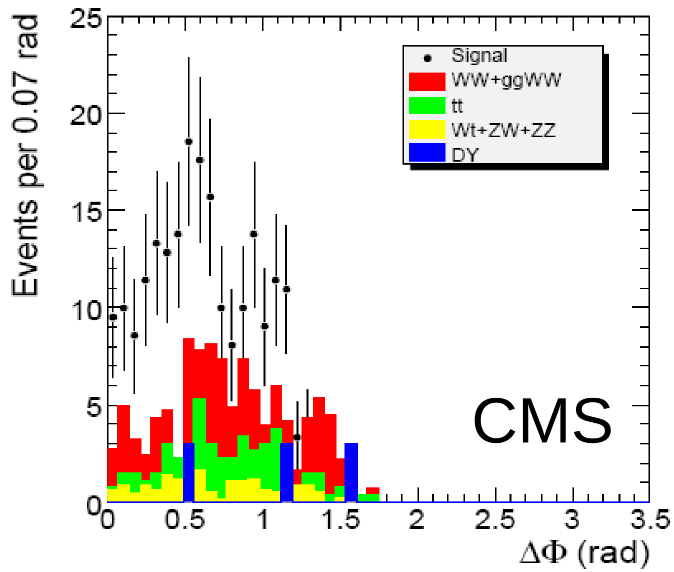
- $BR(H \to WW)$ is nearly 98% for a Higgs boson with $m_H \approx 160$ GeV.
- Backgrounds from $WW, t\bar{t}, WZ$.
- Use the lepton spin correlations:



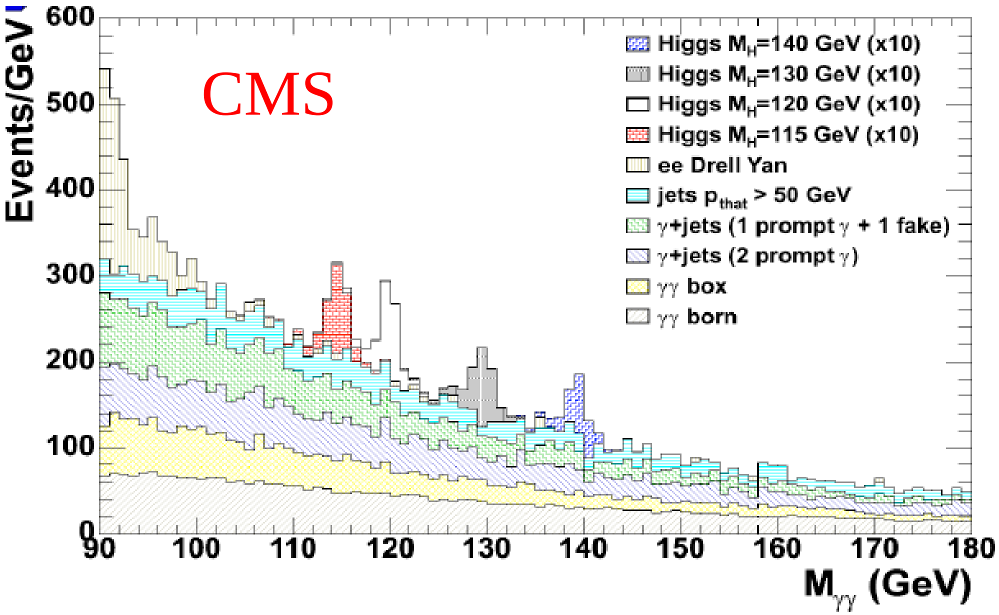
- No mass peak, have to use m_T:

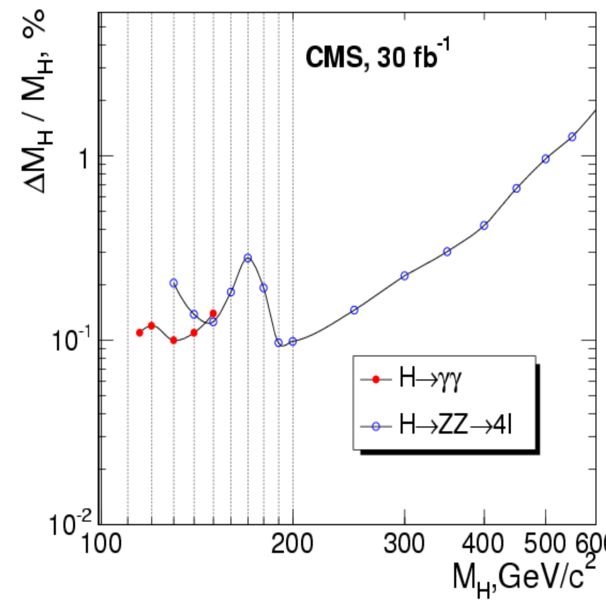
$$m_T = \sqrt{2 p_T^{\ell\ell} \not{E}_T (1 - \cos \Delta\phi)}$$



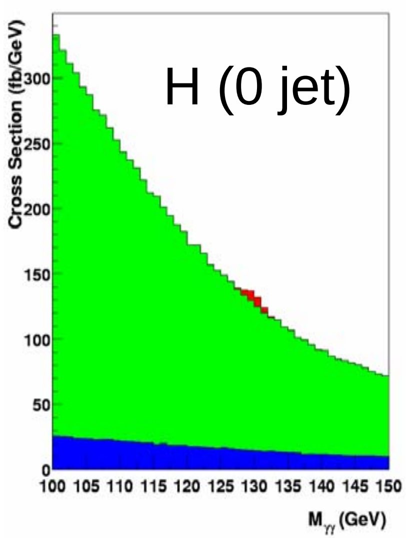


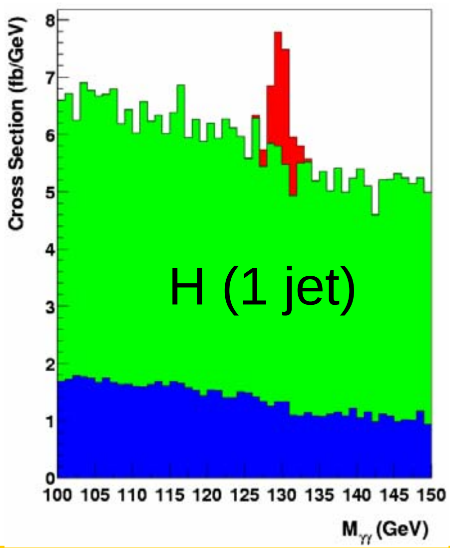
H → γγ

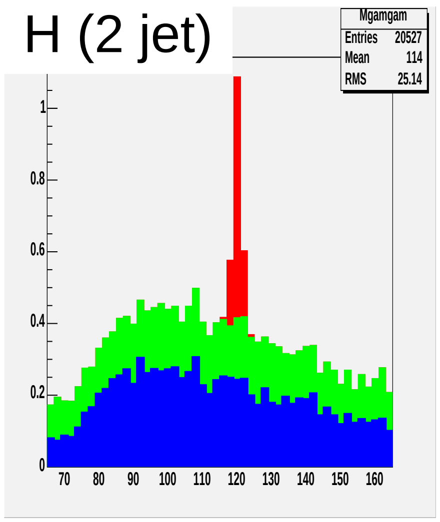

CMS
Events/GeV
600
500
400
300
200
100
0
Higgs M$_H$=140 GeV (x10)
Higgs M$_H$=130 GeV (x10)
Higgs M$_H$=120 GeV (x10)
Higgs M$_H$=115 GeV (x10)
ee Drell Yan
jets p$_{that}$ > 50 GeV
γ+jets (1 prompt γ + 1 fake)
γ+jets (2 prompt γ)
γγ box
γγ born
90 100 110 120 130 140 150 160 170 180
M$_{γγ}$ (GeV)

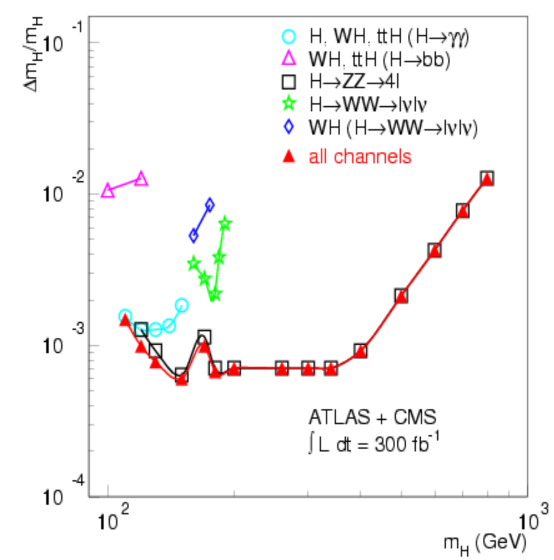

ΔM$_H$ / M$_H$, %
CMS, 30 fb^{-1}
1
10^{-1}
10^{-2}
H→γγ
H→ZZ→4l
100 200 300 400 500 600
M$_H$,GeV/c^2

ATLAS

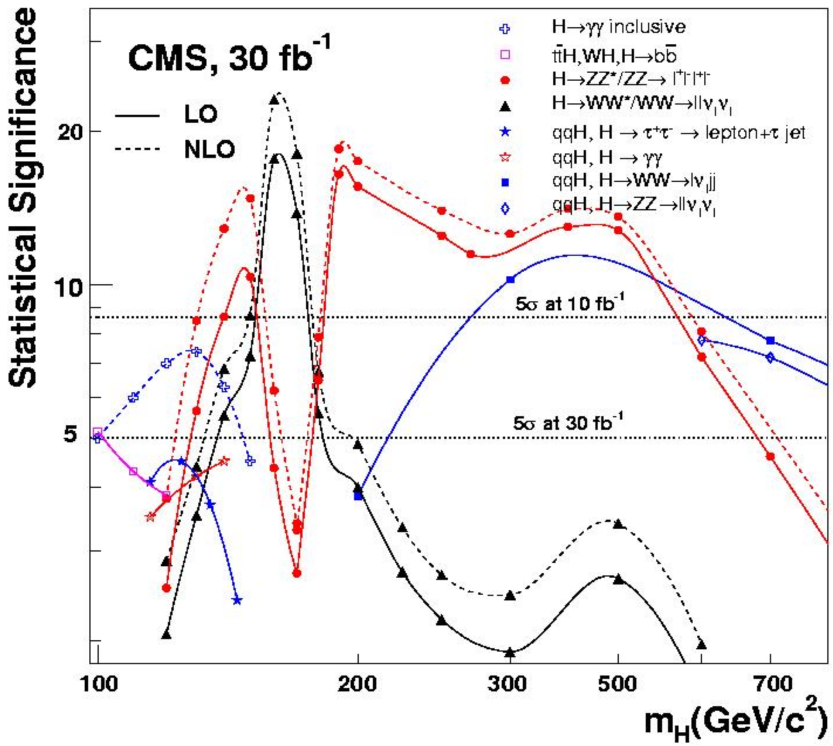

H (0 jet)
Cross Section (fb/GeV)
300
250
200
150
100
50
0
100 105 110 115 120 125 130 135 140 145 150
M$_{γγ}$ (GeV)

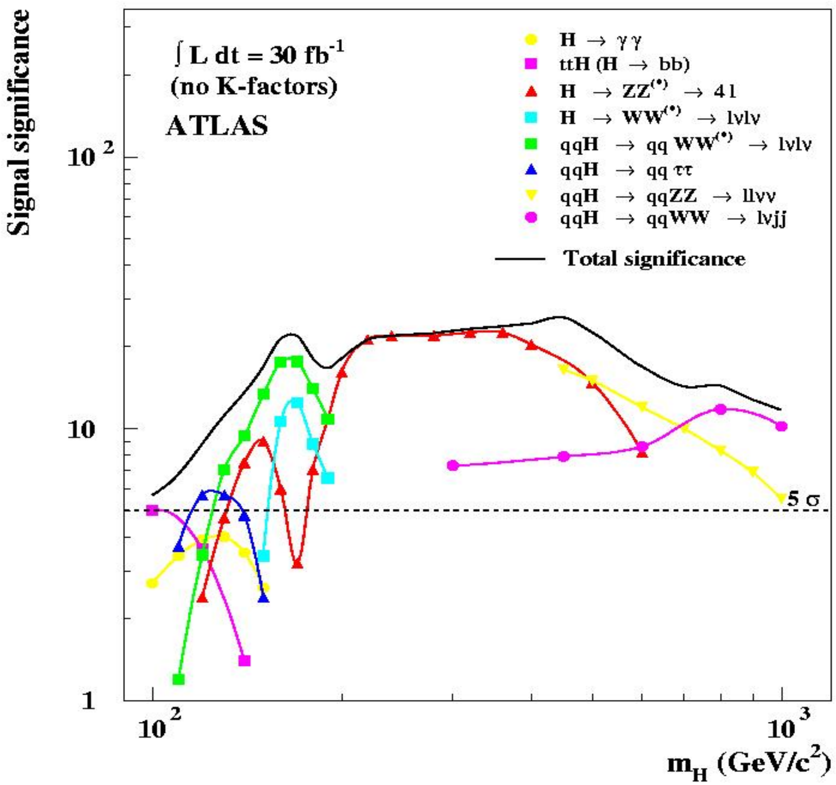

H (1 jet)
Cross Section (fb/GeV)
8
7
6
5
4
3
2
1
0
100 105 110 115 120 125 130 135 140 145 150
M$_{γγ}$ (GeV)


H (2 jet)
Mgamgam
Entries 20527
Mean 114
RMS 25.14
1
0.8
0.6
0.4
0.2
0
70 80 90 100 110 120 130 140 150 160


Δm$_H$/m$_H$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
H, WH, ttH (H→γγ)
WH, ttH (H→bb)
H→ZZ→4l
H→WW→lνlν
WH (H→WW→lνlν)
all channels
ATLAS + CMS
∫L dt = 300 fb^{-1}
10^2
10^3
m$_H$ (GeV)

Discovery Sensitivity



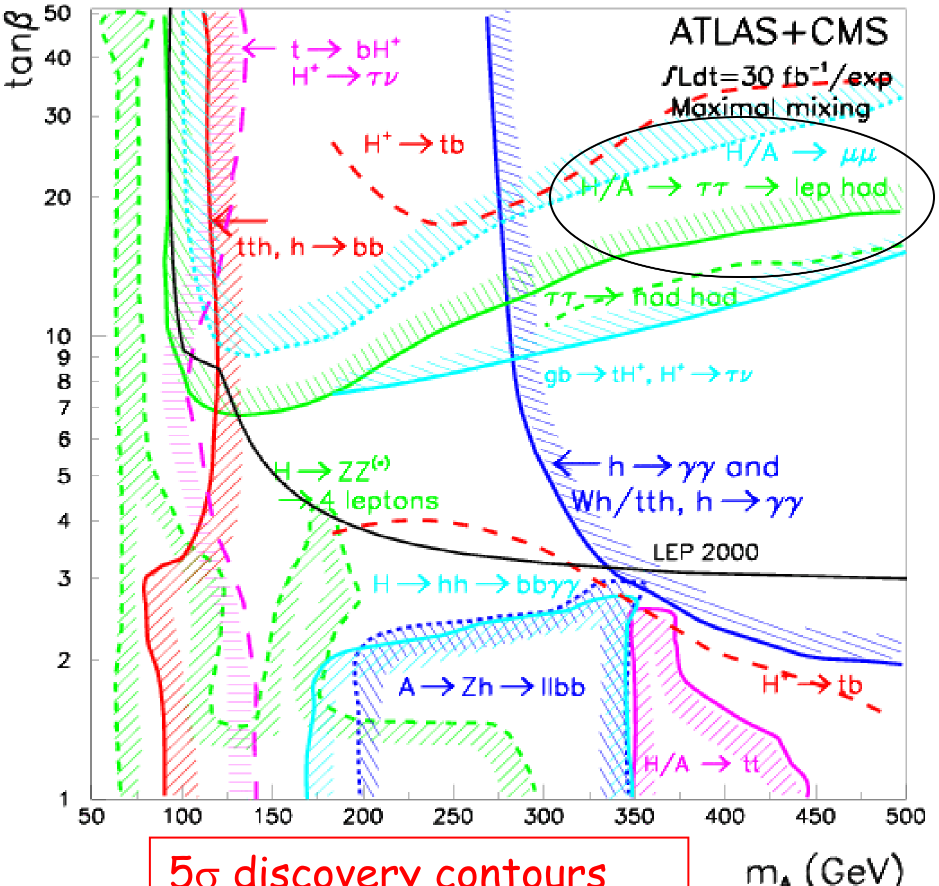


CMS PTDR		ATLAS		
NLO cut based	NLO optimized*	TDR (LO)	New, NLO Cut based	New, NLO likelihood
6.0	8.2	3.9	6.3	8.7

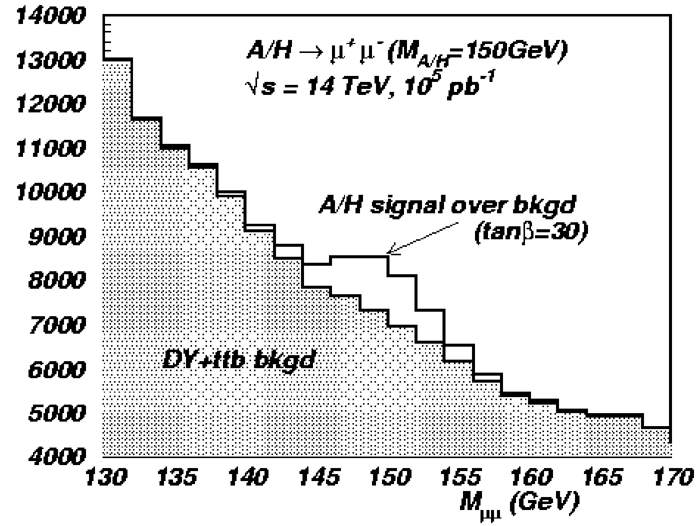
MSSM Higgs Discovery Potential

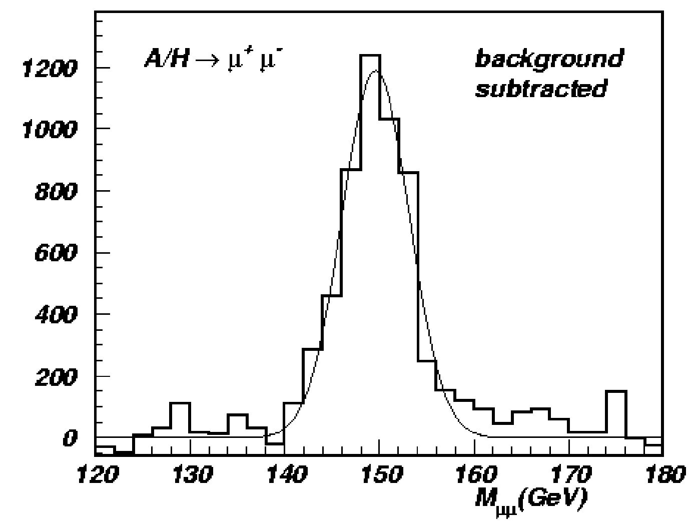
At large $\tan\beta$:
decays into WW, ZZ and $\gamma\gamma$ are suppressed.

Plane fully **covered** with **30 fb^{-1}**



5σ discovery contours





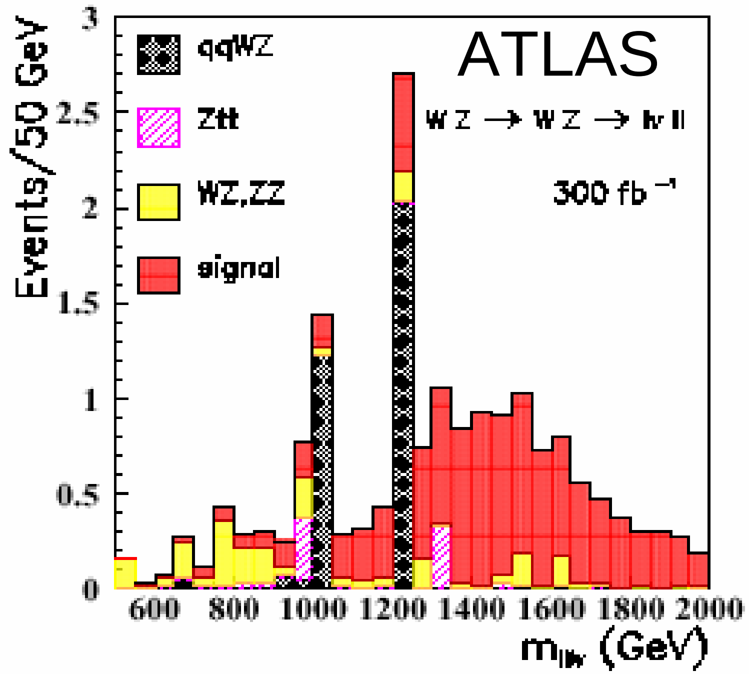
Strongly-Coupled Vector Boson System

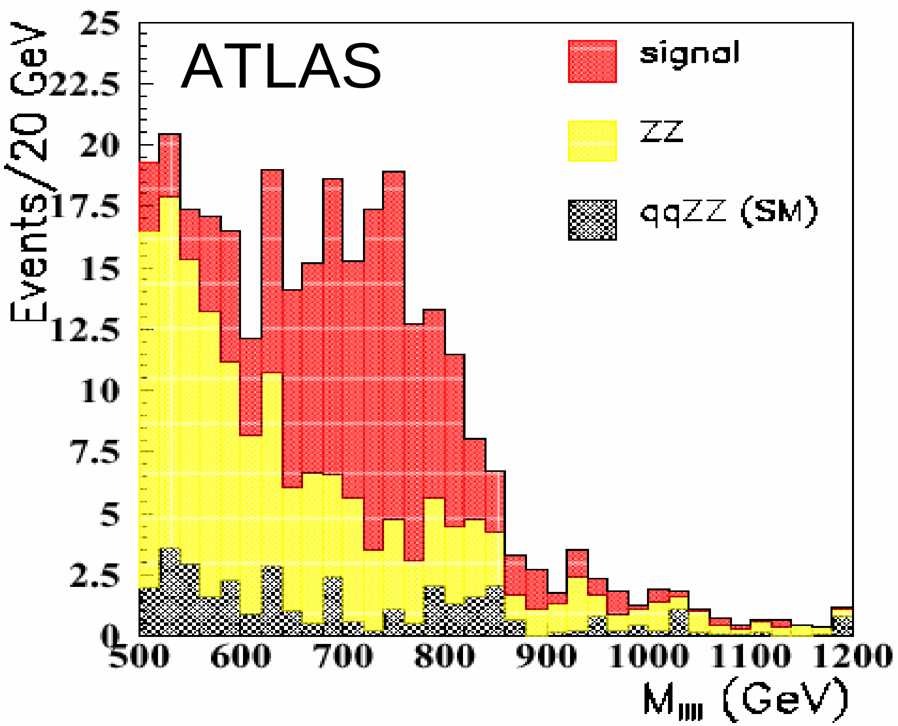
No light Higgs boson? Study Longitudinal gauge boson scattering in high energy regime (the L-component which provides mass to these bosons).

$W_L Z_L \longrightarrow W_L Z_L \longrightarrow l \nu ll$

$W_L W_L \to Z_L Z_L \to$ 4 leptons
$Z_L Z_L \to Z_L Z_L \to$ 4 leptons

S / B = 6.6/2.2



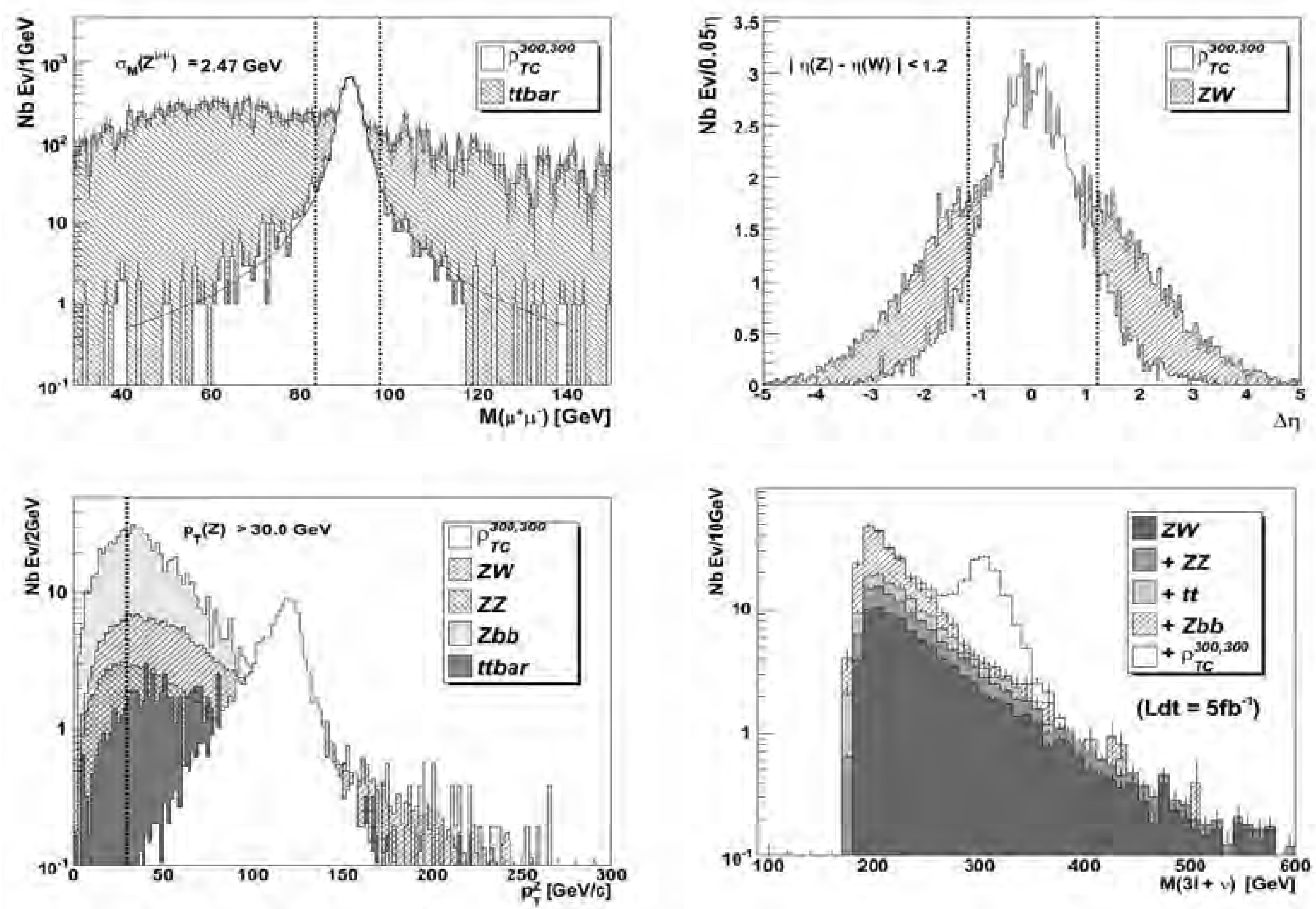


Strong Symmetry Breaking: Technicolor

No fundamental scalar Higgs (it is a new strong force bounded state)

Technicolor predicts existence of technihadron resonance: $\rho_T \rightarrow$ WZ $\rightarrow \ell\ell\ell+\nu$

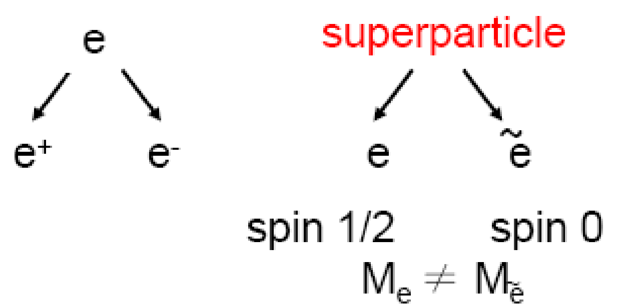
CMS



SUSY: Supersymmetric Extensions of SM

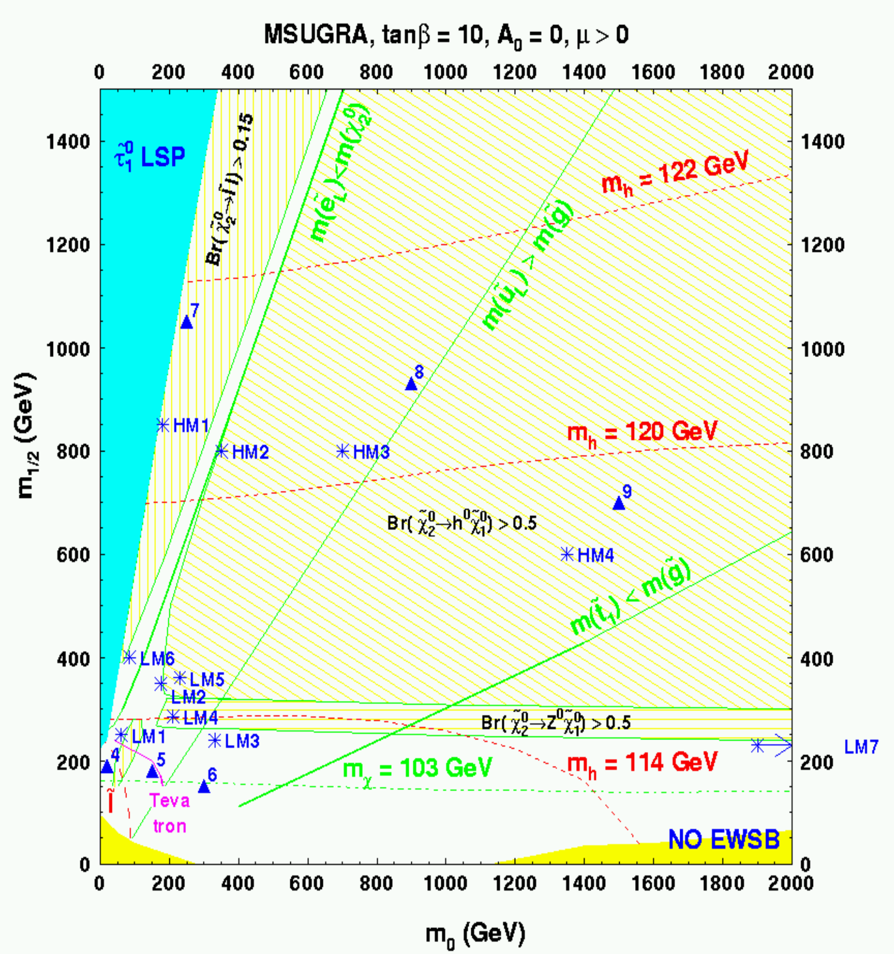
- Provide candidate particles for Dark Matter (LSP)
- Higgs mass calculable
- Unification
- Path to gravity: local supersymmetry → supergravity

Symmetry between
fermions (matter) and bosons (forces)
“Undiscovered new symmetry”

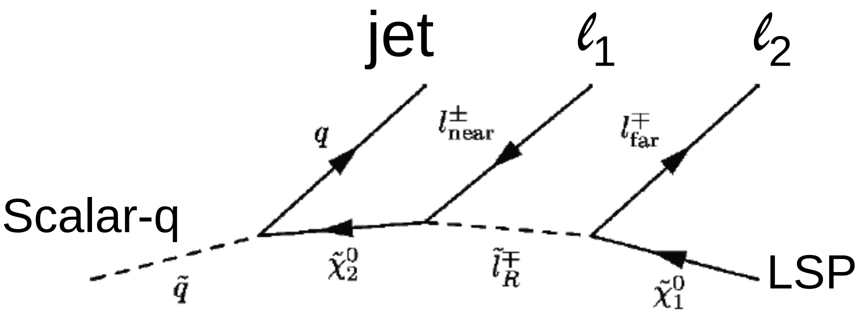


$m_{1/2}$: universal gaugino mass at GUT scale
m_0: universal scalar mass at GUT scale
$\tan\beta$: vev ratio for 2 Higgs doublets
sign(μ): sign of Higgs mixing parameter
A_0: trilinear coupling

Need study many benchmark points…

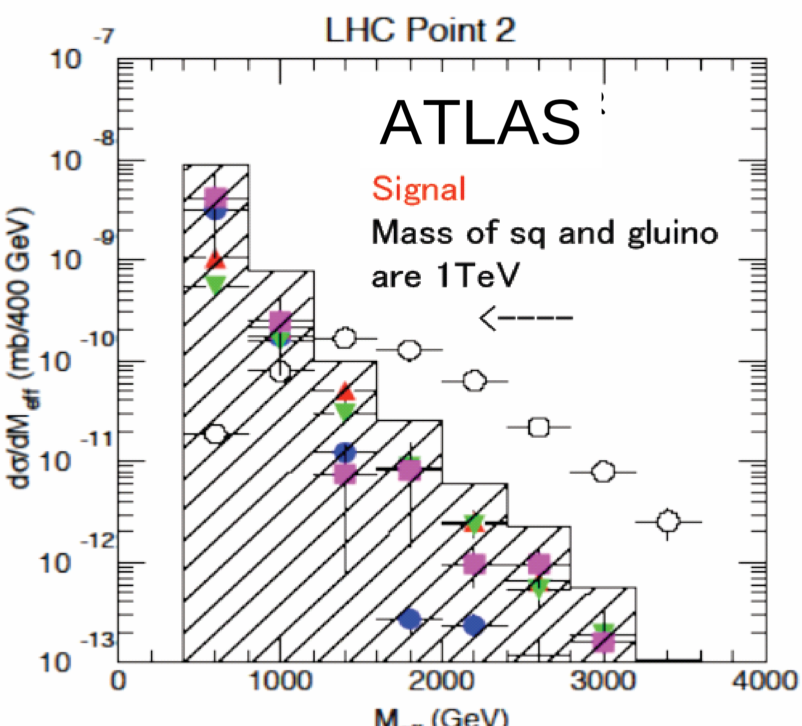


Mass Spectrum from SUSY Particle Decays

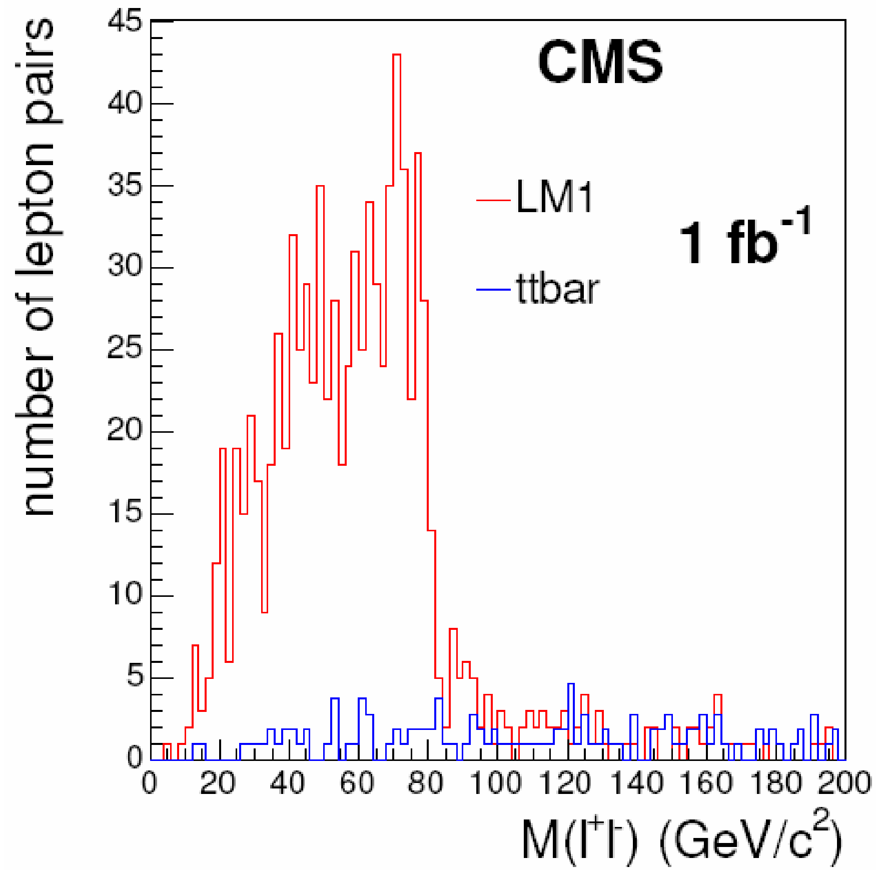


The distribution of the invariant mass of the two leptons can be shown to have a kinematic edge

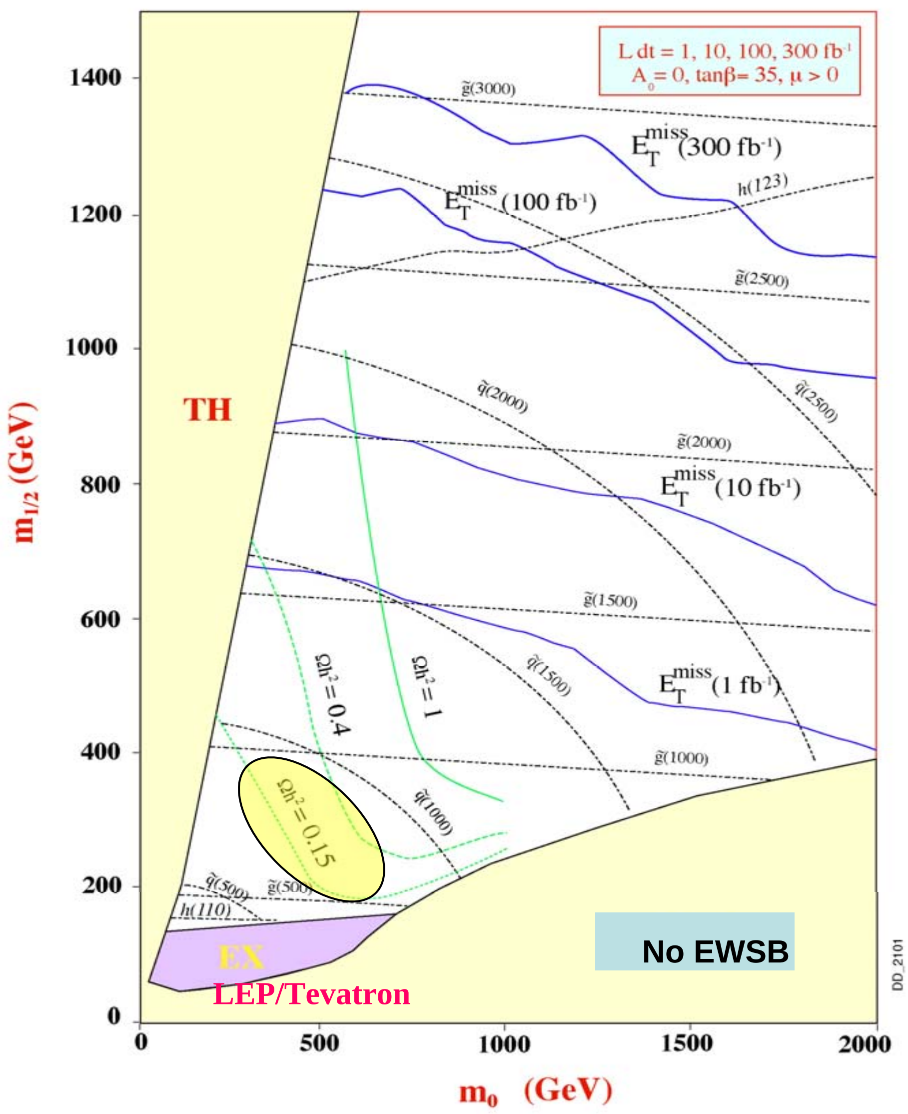
$$(m_{ll}^{\max})^2 = \frac{(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R})(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1})}{m^2_{\tilde{l}_R}}$$

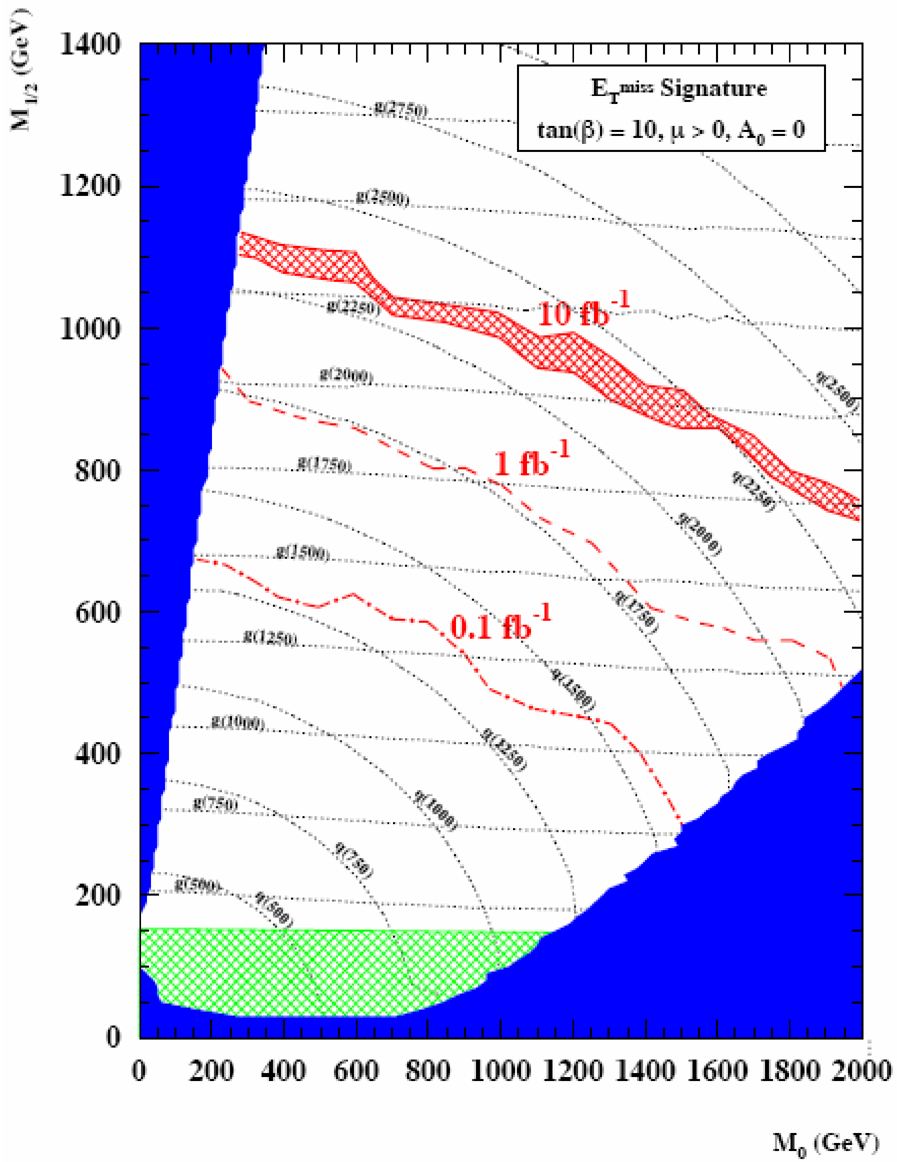


$$= \not{E}_T + \sum P_T$$



Discovery Potential of SUSY (mSUGRA)





Looking forward the LHC Collision Beams!

		Stage I		II	III		IV
Hardware commissioning	Machine checkout	Beam commissioning	43 bunch operation	75ns ops	25ns ops I	Install Phase II and MKB	25ns ops II
No beam		Beam					

I. Pilot physics run
- First collisions
- 43 bunches, no crossing angle, no squeeze, moderate intensities
- Push performance (156 bunches, partial squeeze in 1 and 5, push intensity)
- Performance limit 10^{32} cm^{-2} s^{-1} (event pileup)

II. 75ns operation
- Establish multi-bunch operation, moderate intensities
- Relaxed machine parameters (squeeze and crossing angle)
- Push squeeze and crossing angle
- Performance limit 10^{33} cm^{-2} s^{-1} (event pileup)

2008

III. 25ns operation I
- Nominal crossing angle
- Push squeeze
- Increase intensity to 50% nominal
- Performance limit 2 10^{33} cm^{-2} s^{-1}

2008-2009

up to 1-2 fb^{-1} end 2008,
up to 10fb^{-1} end 2009 ?

IV. 25ns operation II
- Push towards nominal performance

≥ 2010

O(100) fb^{-1}

Note: dates and integrated luminosities are MY interpretation (F. Gianotti)

List of New Physics Reaches at LHC

SM Higgs	100 GeV ~ 1 TeV (30 fb^{-1})
MSSM Higgs	covers full (m_A, $\tan\beta$)
SUSY (squark, gluino)	~ 3 TeV (300 fb^{-1})
New gauge bosons (Z')	~ 5 TeV (100 fb^{-1})
Quark substructure (Λ_C)	~ 25/40 TeV (30/300 fb^{-1})
q*, l*	~ 6.5/3 TeV (100 fb^{-1})
Large ED (M_D for n=2,4)	~ 9/6 TeV (100 fb^{-1})
Small ED (M_C)	~ 6 TeV (100 fb^{-1})
Black holes	< 6 ~ 10 TeV

Any one of those would change the understanding of our universe !

Additional slides

CMS: Muon Trigger Studies

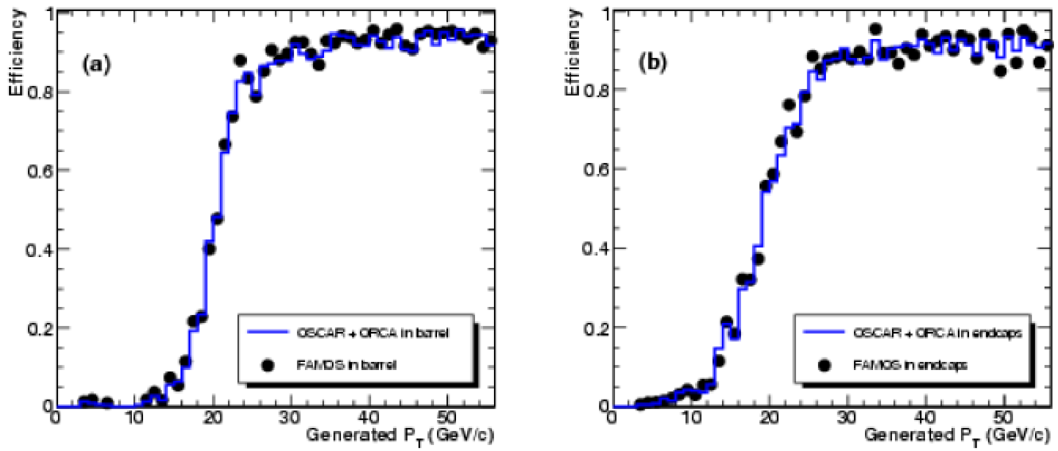


Figure 2.16: Level-1 single-muon trigger efficiency in the barrel (a) and in the endcaps (b) as a function of the generated muon p_T, when a threshold of 20 GeV$/c$ is chosen for the Level 1 single muon trigger output, in fast (dots) and full (curve) simulations.

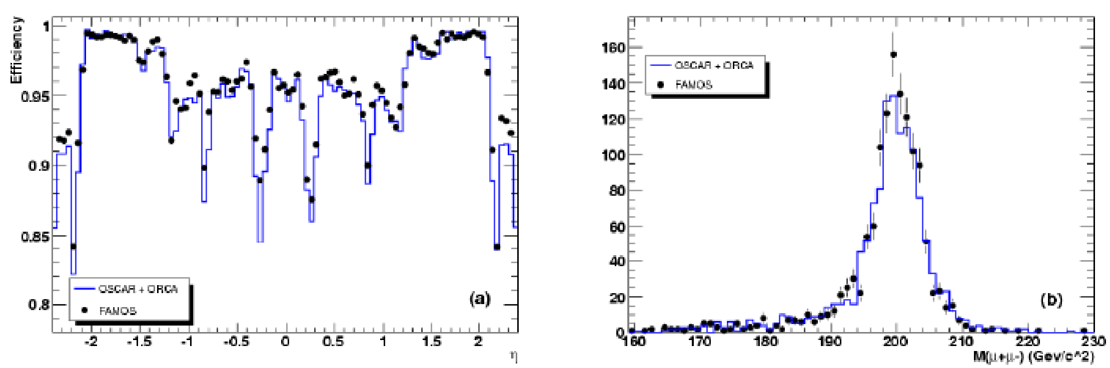
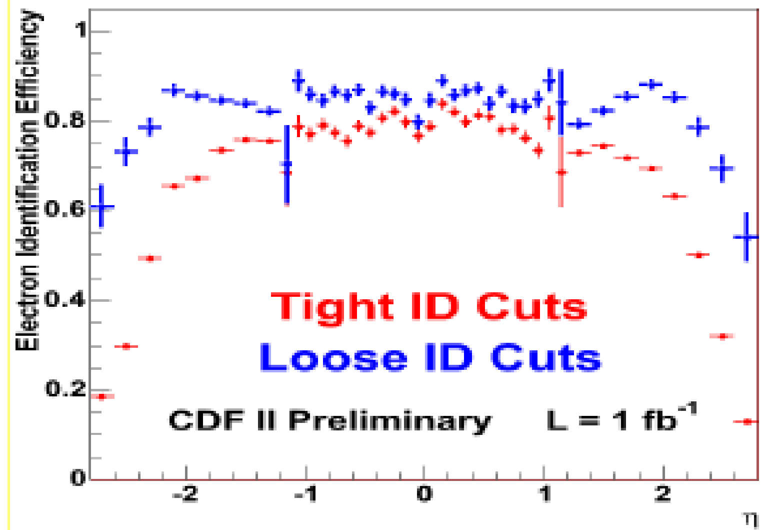
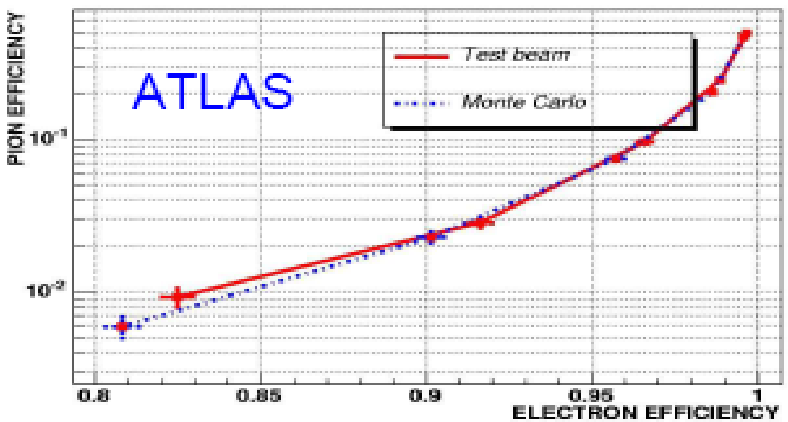


Figure 2.17: (a) Overall Level-1 and High-level trigger efficiency for single muons, as a function of the generated η, and (b) reconstructed dimuon mass spectra in events where a Higgs particle decays into $\mu^+\mu^-$, in fast (dots) and full (curve) simulations.

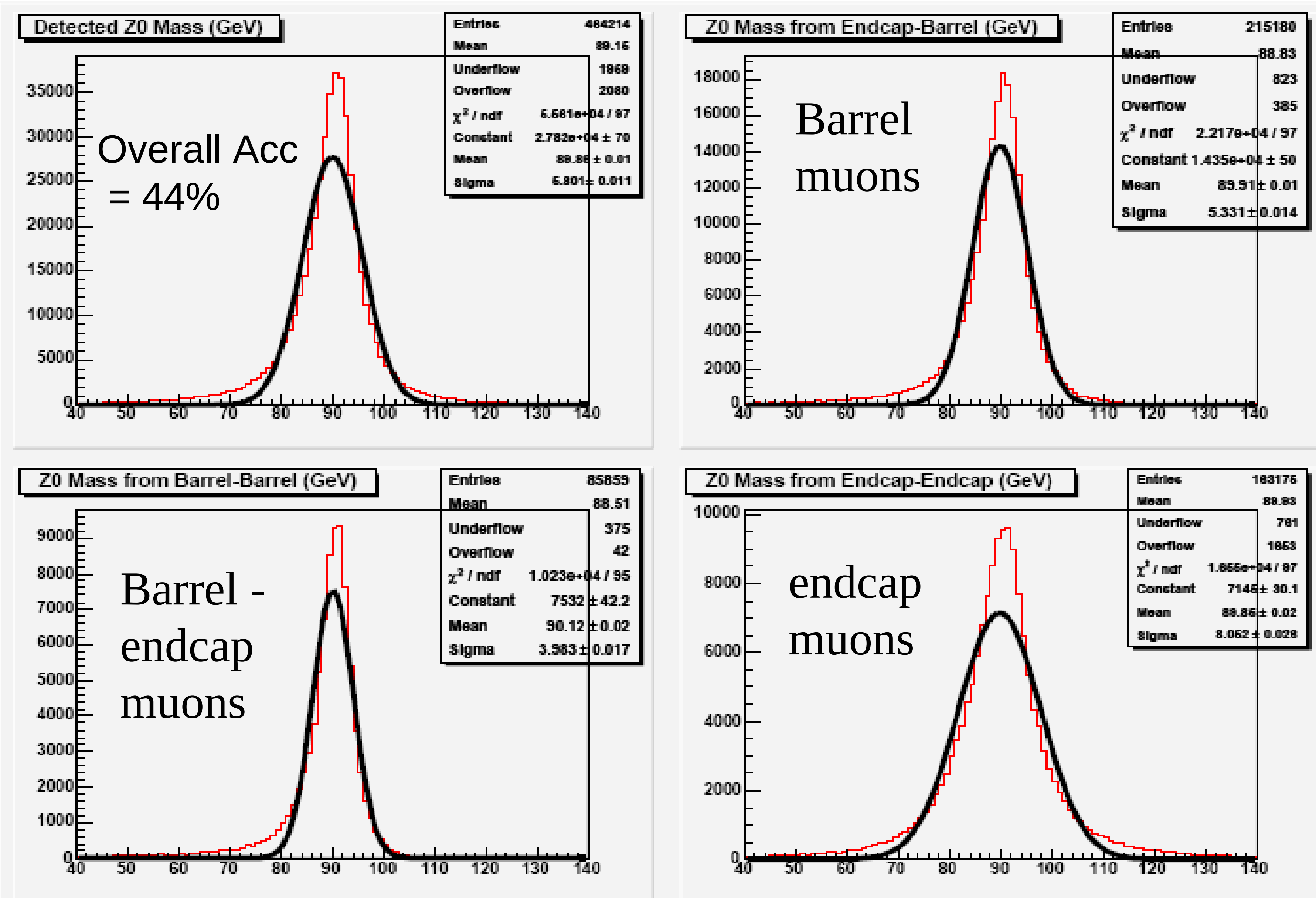
Overall Efficiency of Electron ID

- Measure when possible using real data:
  - W from no-track trigger to measure tracking efficiency
  - Z with one tight electron and with loose selection
- Use simulation to extrapolate kinematics and correct for environmental issues (eg isolation)

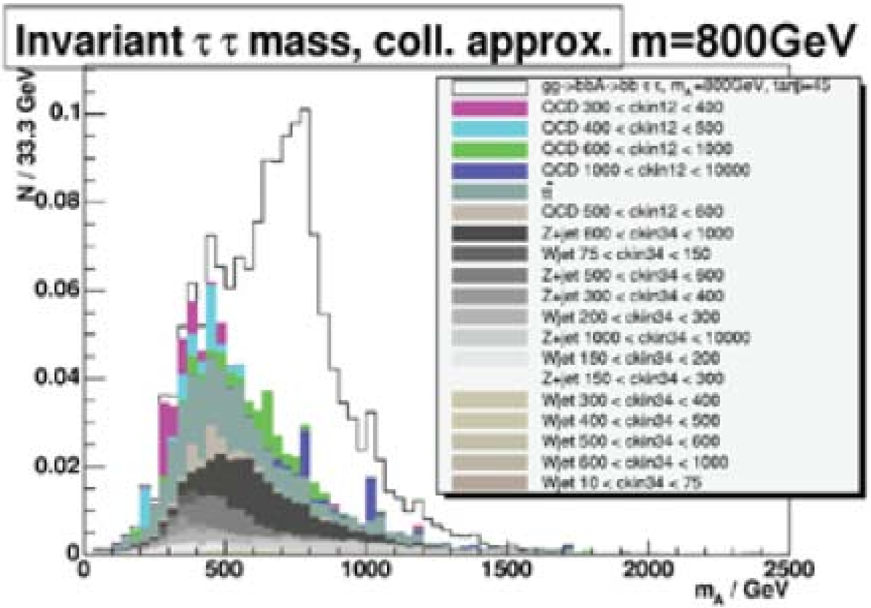


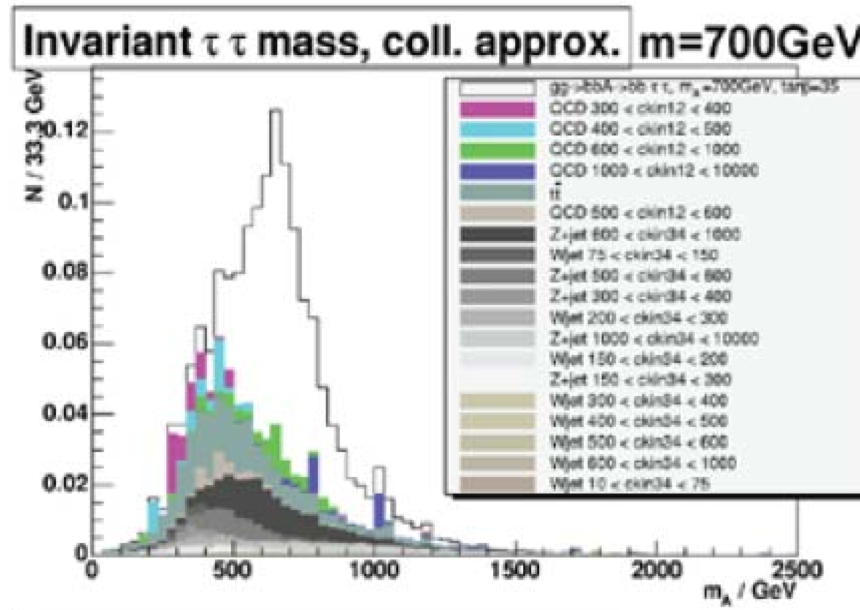


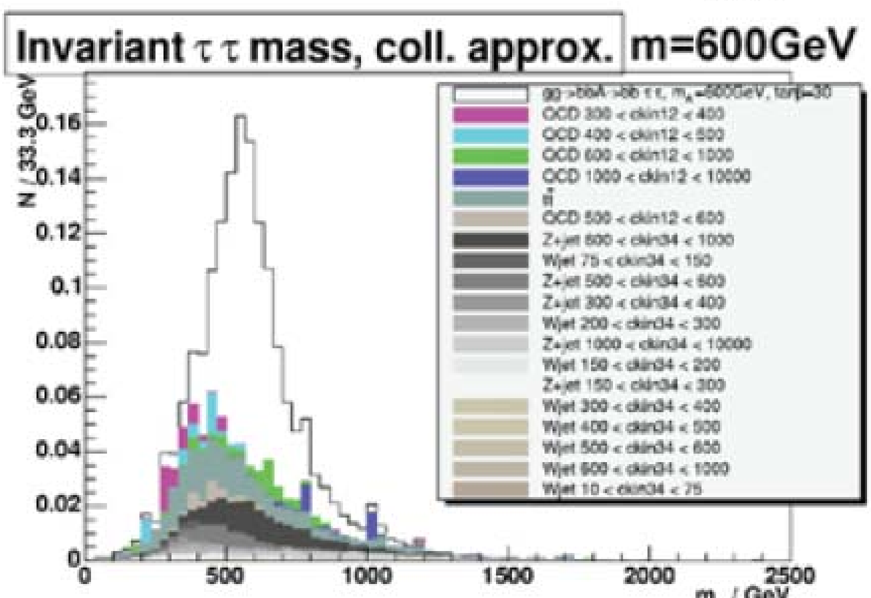
Identify Z in the Z-mass 'windows' (Standalone)

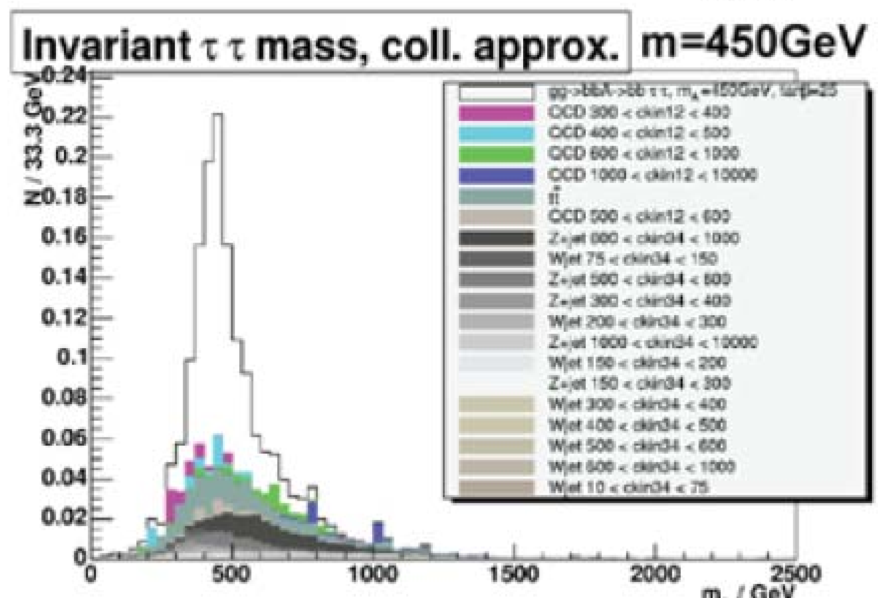


Atlas Studies: H → ττ

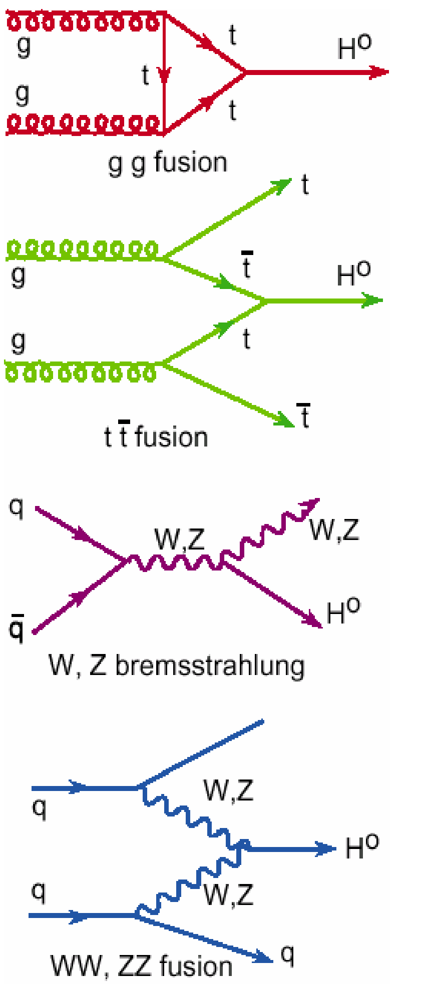


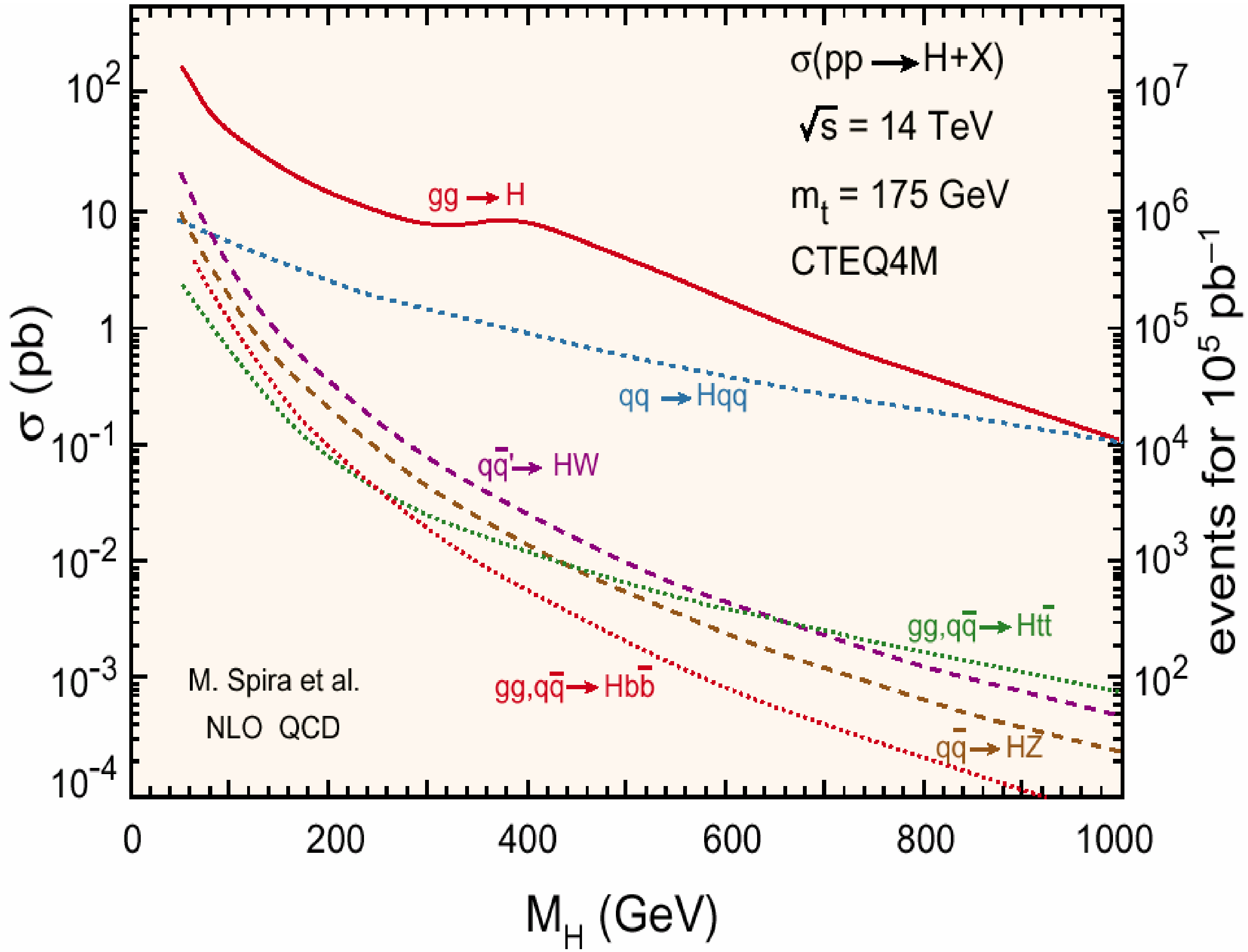






Higgs Production Mechanism @ LHC





4 production mechanism ➡ key to measure H-boson parameters