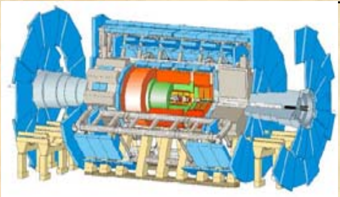


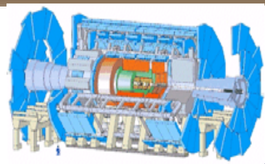
Other Exotic Scenarios at the LHC

Kamal Benslama
Columbia University

On behalf of the ATLAS and CMS Collaborations

May 23, 2006

Hadron Collider Symposium



BSM Scenarios

SUSY
New particles at TeV scale
Previous talk

Extra Dimensions
Additional dimensions
New states at TeV Scale

$$\frac{M_{EW}}{M_{Plank}} \sim 10^{-17}$$

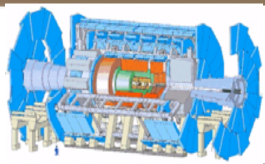
$$\delta m_M \sim \Lambda$$

⇒ New Physics at TeV Scale to stabilize m_H

Little Higgs
SM embedded in larger group
New particles at TeV scale

Technicolor
New strong interactions break EW symmetry
New particles at TeV scale

- Other Scenarios of New Physics
  - Leptoquarks
  - Excited fermions
  - New gauge bosons



BSM Physics: Real life…

l+jets+$\not{E}_T$

ll+jets+$\not{E}_T$

jets+$\not{E}_T$

bb+γ

taus+$\not{E}_T$

bb+$\not{E}_T$

Massive Stable Particles

ll+bb+$\not{E}_T$

ll+jets

γ+jets+$\not{E}_T$

$llll$+$\not{E}_T$

Kinks

monojets

γ+ll+$\not{E}_T$

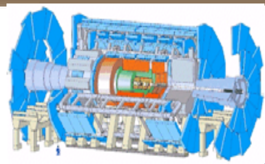
lll+jets+$\not{E}_T$

Non-prompt photons or Z's

$\gamma\gamma$+E_T

"deviation-from-SM" hunting by experimentalists, then "model hunting" by theorists- It is a real challenge!

It's a complicated environment



Large Extra Dimensions

- ✓ Large extra dimensions (>> 1/TeV)
  - ADD model (Arkani, Dimopoulos, Dvali)
  - SM particules on brane
  - Gravity propagates in bulk (Xtra Ds)
    - Hence new gravity scale
    - KK graviton excitations

$M_{PL}^2 \sim M_D^{2+\delta} R^\delta$

$M_D \sim$ TeV for R < mm

KK mode separation is very small:

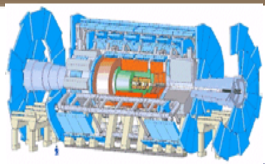
e.g.: $M_D = 1$ TeV, $n = 2 \Rightarrow R = 0.08$ mm $\Rightarrow R^{-1} = 2.6 \times 10^{-3}$ eV

$n = 4 \Rightarrow R = 1600$ fm $\Rightarrow R^{-1} = 120$ keV

→ continuous spectrum

→ high density of states compensates low coupling (~$1/M_{Pl}$)

→ chance to observe effects at LHC

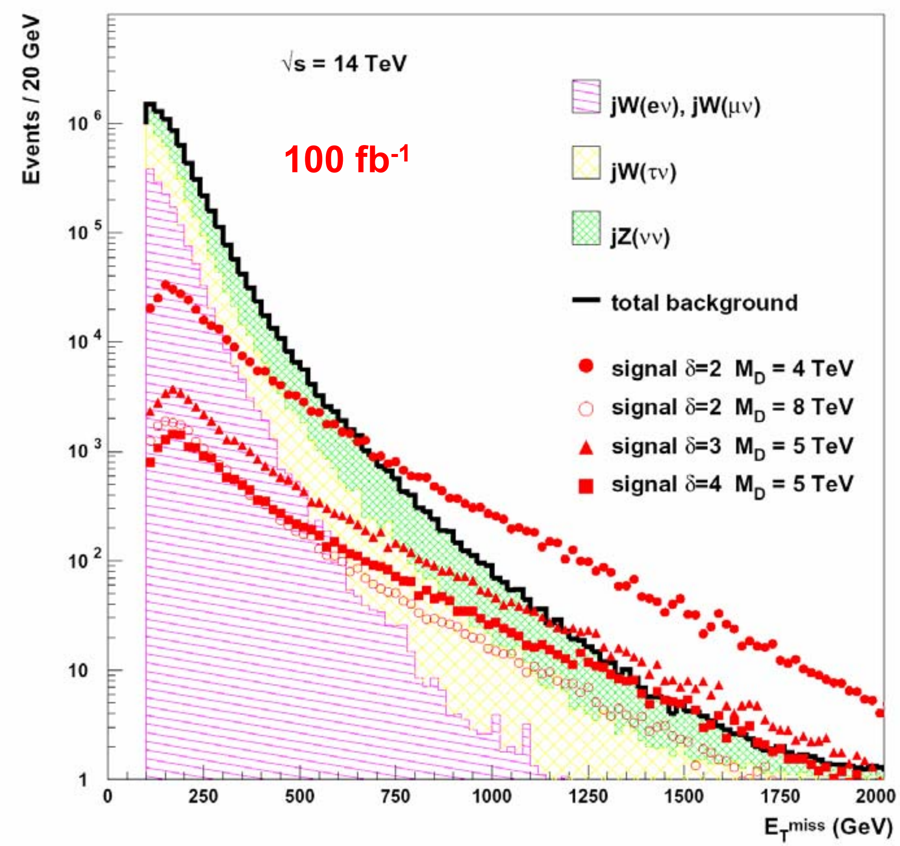


ADD: Graviton Emission

✓ Process

$$\left.\begin{array}{l} \bar{q}q \rightarrow gG^{(k)}, \gamma G^{(k)} \\ qg \rightarrow qG^{(k)} \\ gg \rightarrow gG^{(k)} \end{array}\right\} \text{jets} + \not{E}_T,\ \gamma + \not{E}_T$$

ATLAS



✓ Reach

– gG

δ	M_D^{max} (TeV) LL, 30 fb^{-1}	M_D^{max} (TeV) HL, 100 fb^{-1}	M_D^{min} (TeV)
2	7.7	9.1	~ 4
3	6.2	7.0	~ 4.5
4	5.2	6.0	~ 5

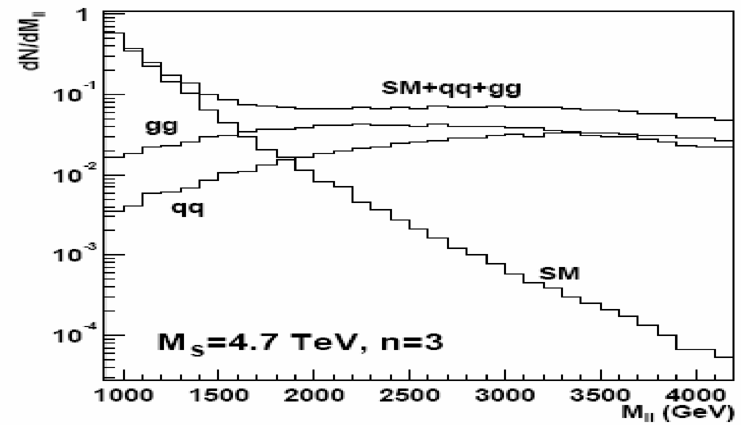
– γG

δ	M_D^{max} (TeV) HL, 100 fb^{-1}	M_D^{min} (TeV)
2	4	~ 3.5

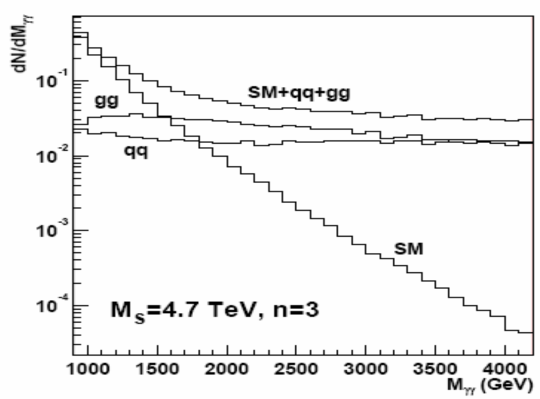
ADD: Virtual Graviton

- ✓ Final state $q\bar{q}, gg \rightarrow \gamma\gamma, \ell\ell, \quad (WW, t\bar{t}...)$
  - Use effective scale M_s (σ diverges if $\delta \geq 2$)
- ✓ Observables
  - Excess in ll & $\gamma\gamma$
  - $\gamma\gamma$ more central

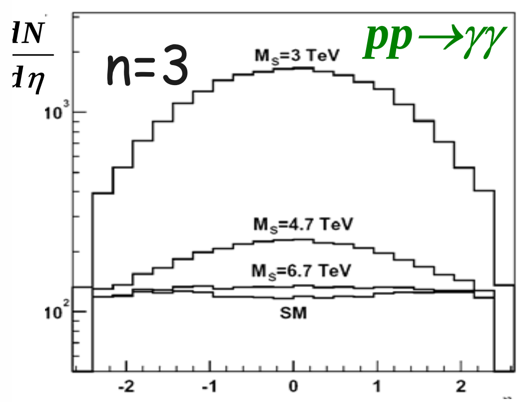
10fb^{-1}



M_{ll}



$M_{\gamma\gamma}$



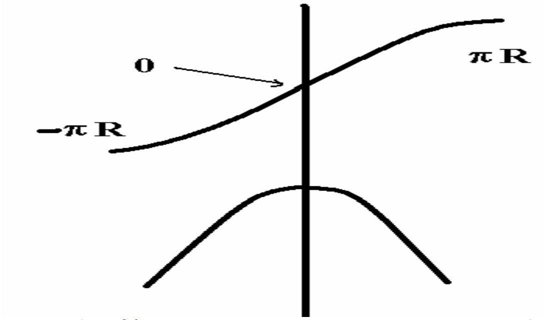
$\frac{dN}{d\eta}$ η

ATLAS

reach: $\begin{cases} \ell\ell: & M_S \sim \mathbf{5.1}\ \text{TeV} \\ \gamma\gamma: & M_S \sim \mathbf{6.6}\ \text{TeV} \end{cases}$

TeV^{-1} Extra Dimension

- One extra dimension compactified on a S^1/Z^2 orbifold
- radius of compactification small enough ➔ gauge bosons in the bulk

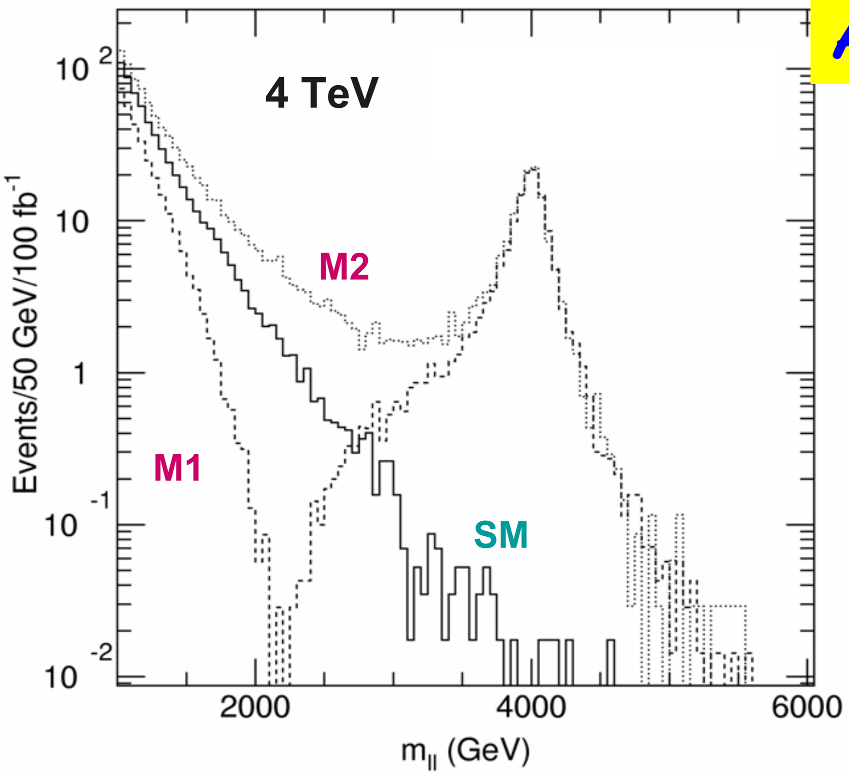


- fermions localized on:
  - a fixed point (M1 model): invariance under $y \rightarrow -y$
  - opposite fixed points (M2 model): under $y \rightarrow y + 2\pi R$
- Kaluza-Klein spectra for $Z^{(k)}$, $W^{(k)}$: $m_k^2 = m_0^2 + k^2 M_C^2$
  - for M_C = 4 TeV: m_1 = 4 TeV, m_2 = 8 TeV

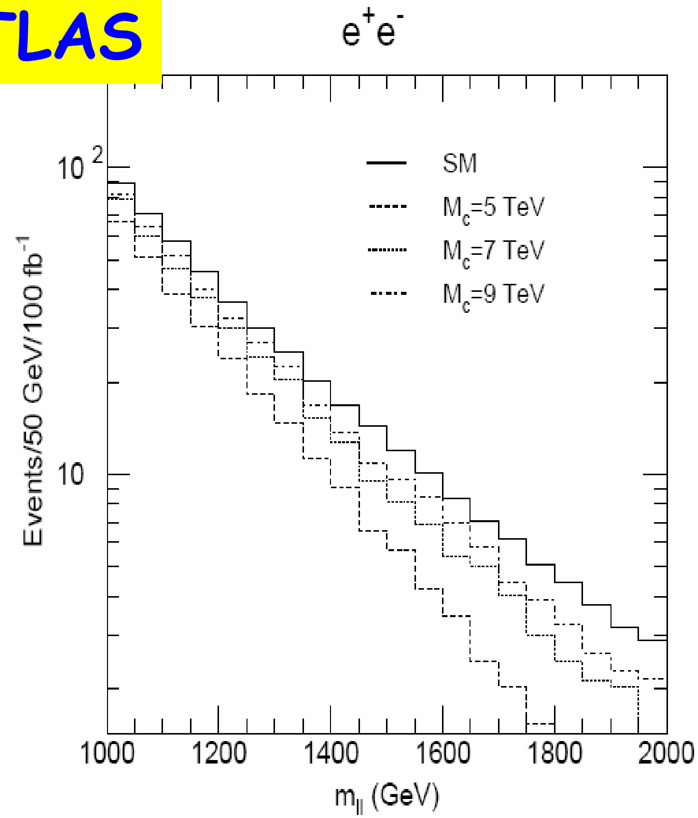
➔ look for $pp \rightarrow \gamma^{(1)}/Z^{(1)} \rightarrow l^+l^-$ on top of SM Drell-Yan

TeV^{-1}: Direct $\gamma^{(1)}/Z^{(1)}$

Look for resonances in ll spectrum

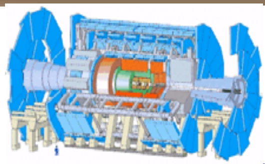


ATLAS



Observation up to ~ 5.8 TeV with 100 fb-1

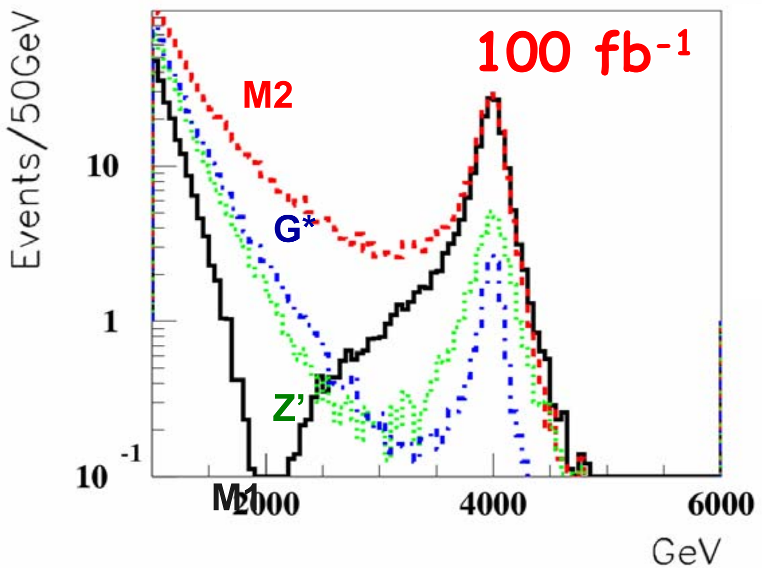
For 1 TeV< m <2.5 TeV up to ~ 8 TeV with 100fb^{-1}



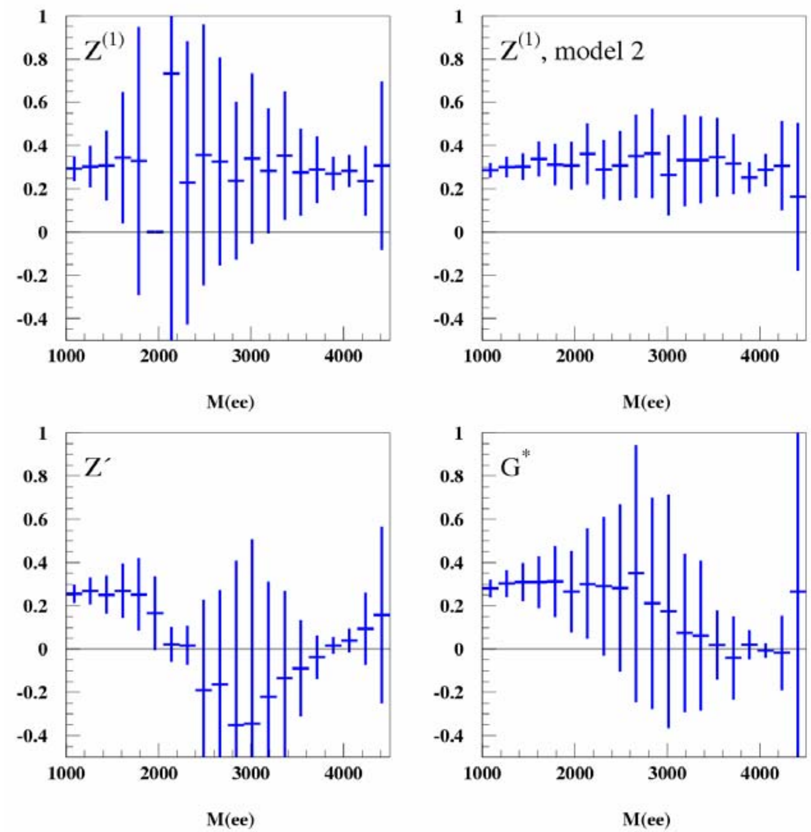
TeV^{-1}: Asymmetry

- ✓ Look at Forward-Backward asymmetry

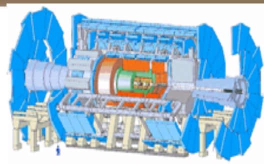
ATLAS



process	$\sigma \times BR(Z^* \to e^+e^-)$ (fb)
$Z^{(1)}/\gamma^{(1)}$	4.05
$Z^{(1)}/\gamma^{(1)}$-M2	11.75
Z'	4.65
$qq \to G^*$	0.20
$gg \to G^*$	0.13
$qq \to e^+e^-$	4.83



100fb^{-1}



Randall-Sundrum

✓ Motivation

- 2 branes (TeV & Planck) connected by 1 warped ED

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2, \quad y = r_c\phi$$

$$\Lambda_\pi = M_{pl}e^{-kr_c\pi}; \qquad kr_c\pi \approx 35 \Rightarrow \Lambda_\pi \approx \text{TeV}$$

- Coupling of KK states ~ $1/\Lambda_\pi$

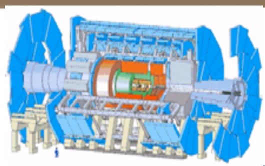
- Graviton excitations

$$m_n = kx_n e^{-k\pi r_c}, \quad \text{avec } J_1(x_n) = 0$$

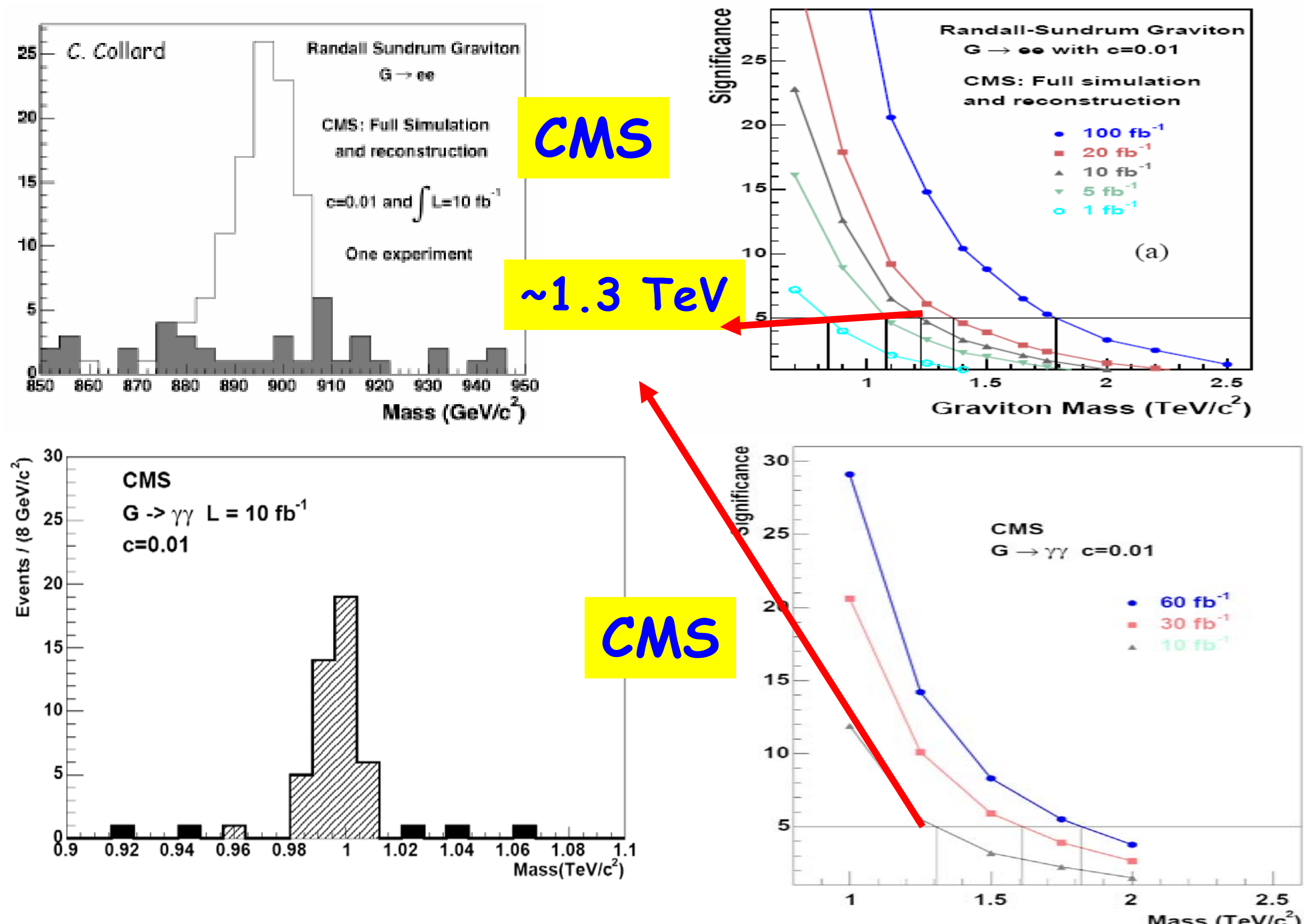
$$m_1 = 3.83\frac{k}{M_{Pl}}\Lambda_\pi$$

- Constraints

$$0.01 < k/M_{pl} < 0.1$$



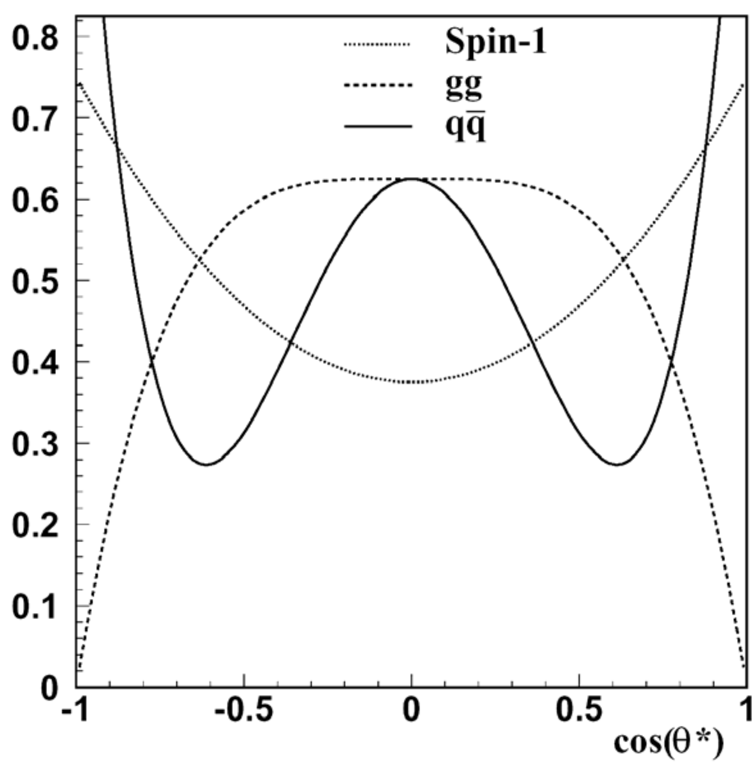
RS: Graviton Resonance

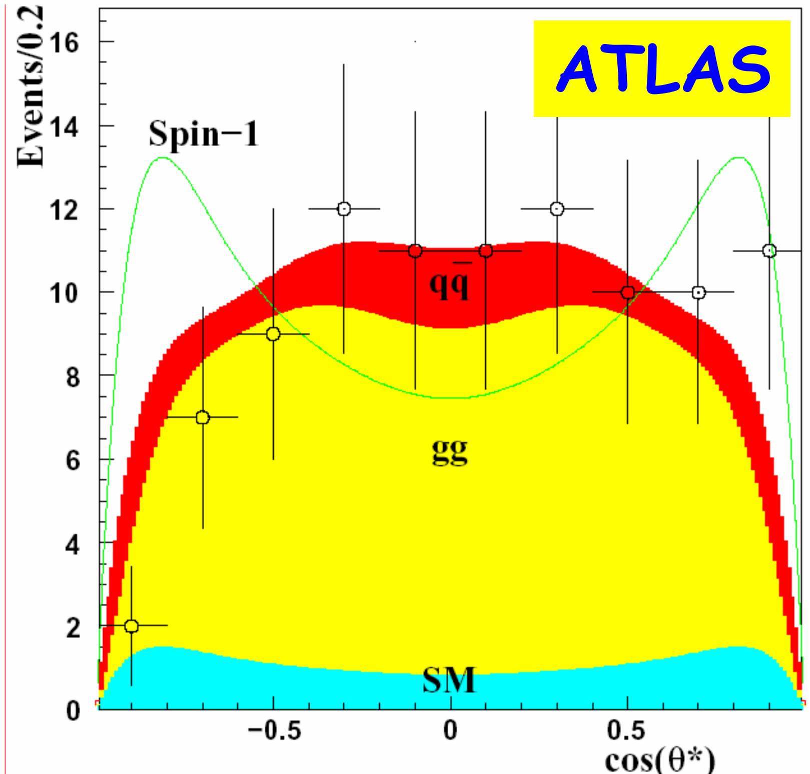


RS: Graviton Spin

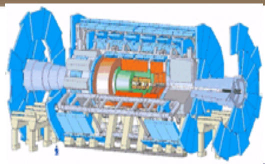
✓ Look at angular distribution

ATLAS, 100 fb^{-1}, m_G=1.5 TeV

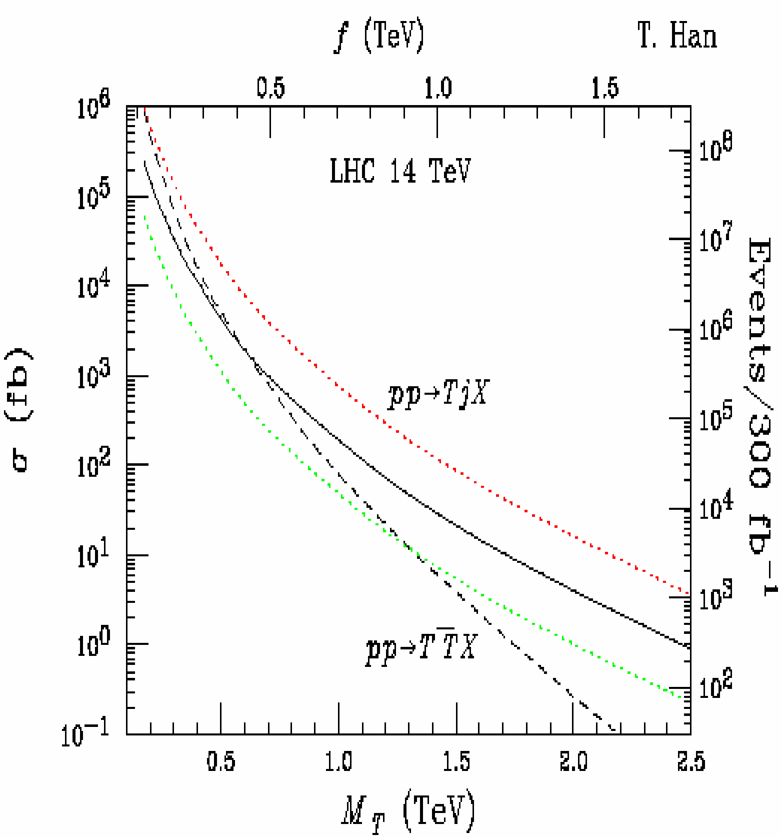




90% exclusion of spin-1 for mG < 1.7 TeV

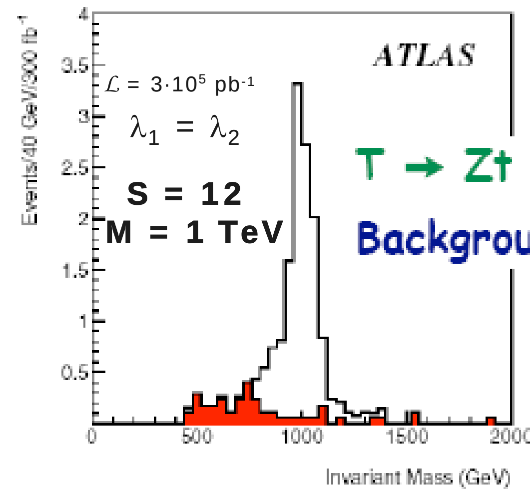


Little Higgs: Heavy T



$\mathcal{L} = 3{\cdot}10^5$ pb^{-1}

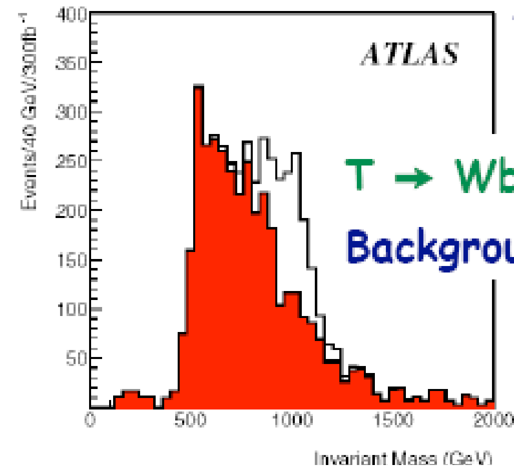
ATLAS



$T \to Zt \to l^+l^-l\nu b$

Background: tbZ, WZ

M_T = 1 TeV,
$\int L$ = 300 fb^{-1}



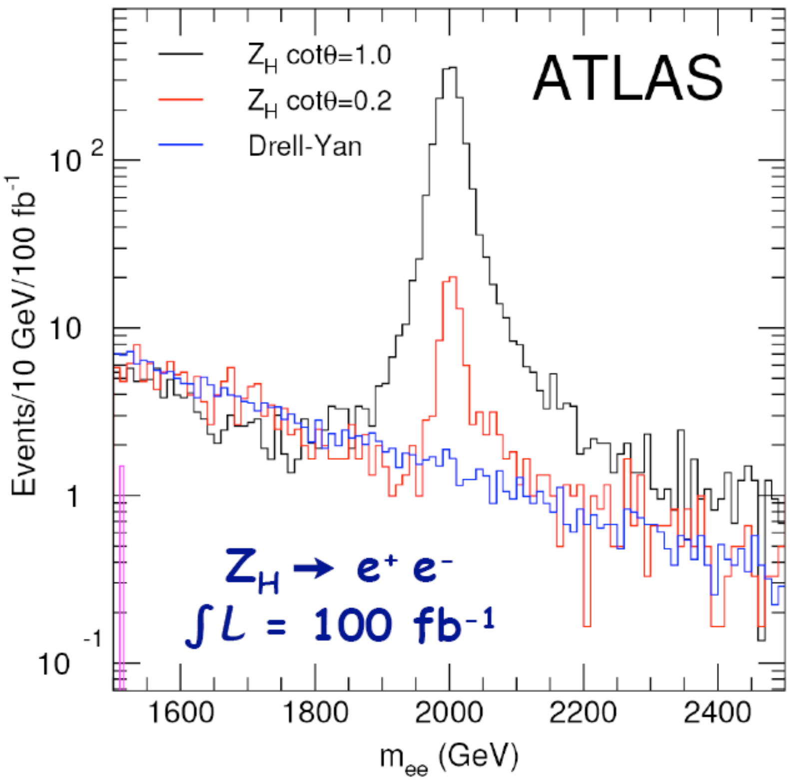
$T \to Wb \to l\nu b$

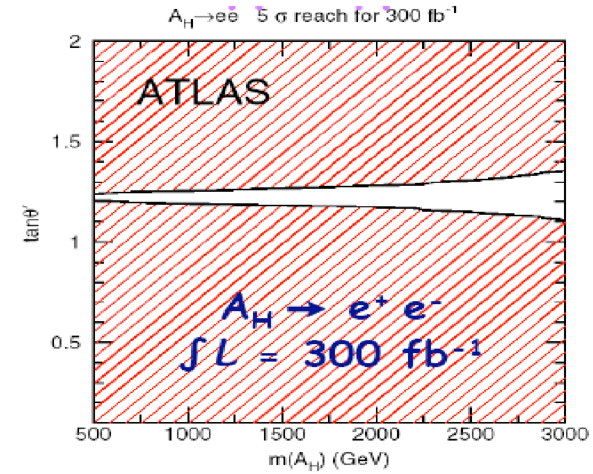
Background: single t, $t\bar{t}$

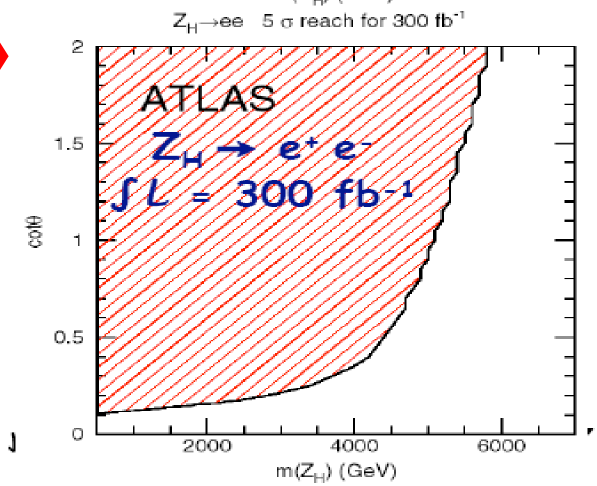
✓ **The heavy quark T can be observed for a mass up to ~2TeV**

Little Higgs: A_H and Z_H

Signal : di-lepton resonance







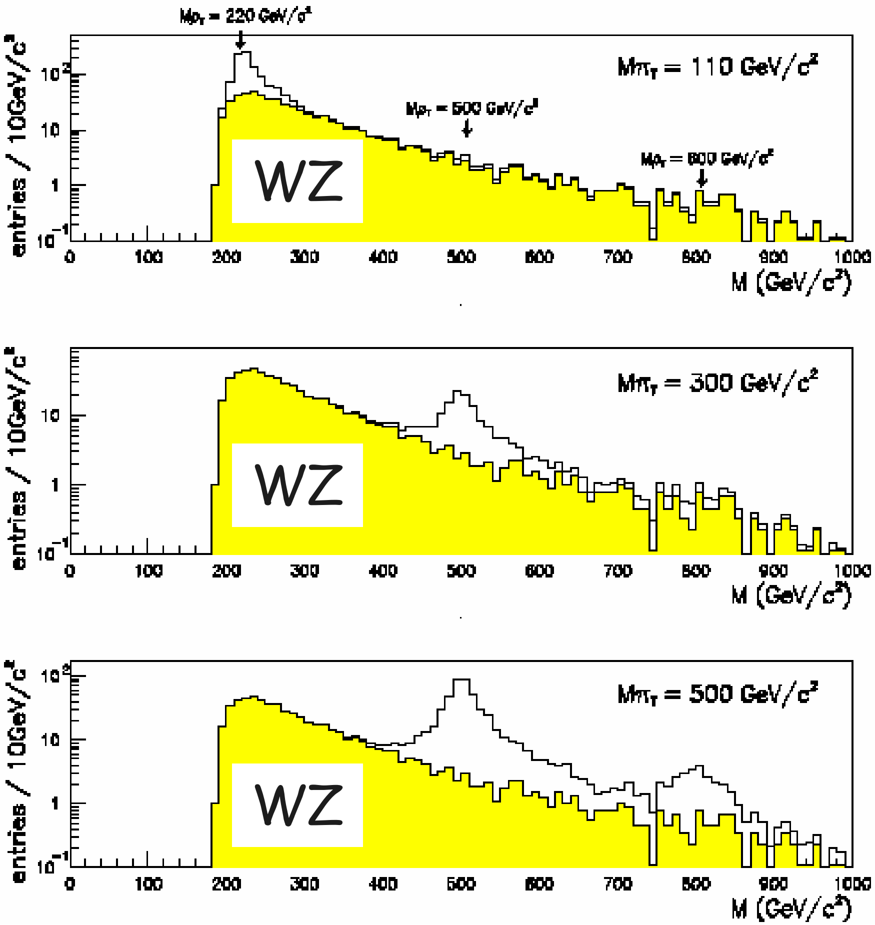
Reach up to 5.7 TeV depending on the θ angle

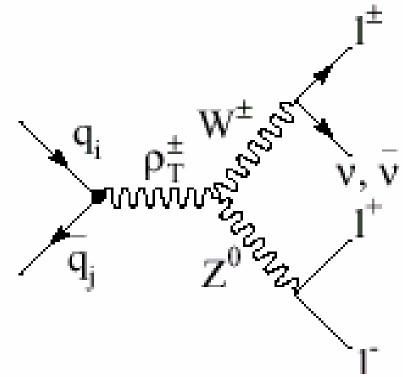
Technicolor

✓ $\rho_T^{\pm}$

$30 fb^{-1}$

ATLAS





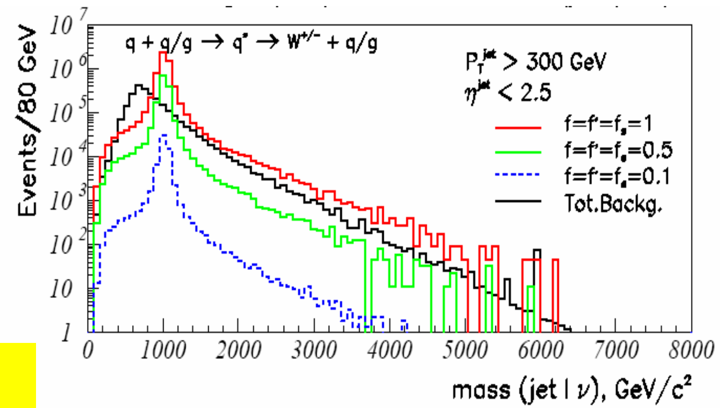
m_{ρ_T} GeV/c^2	m_{π_T} GeV/c^2	Γ_{ρ_T} GeV/c^2	BR $(\rho_T \to WZ)$	$\sigma \times BR$ (pb)
220	110 (a)	0.93	0.13	0.16
500	110 (e)	67.1	0.014	1.04×10^{-3}
	300 (b)	4.47	0.21	1.3×10^{-2}
	500 (f)	1.07	0.87	5.4×10^{-2}
800	110 (g)	130.2	0.013	1.5×10^{-4}
	300 (h)	52.4	0.032	3.6×10^{-4}
	500 (c)	7.6	0.22	2.5×10^{-3}

- At least 3 charged leptons with pT > 25 GeV
- pT(W), PT(Z) > 40 GeV
- Use polarization of technirho

Excited Quarks & Leptons

- ✓ Excited quarks
  - Reach limit for q* -> q γ 6.5TeV
  - Reach for **qw: 7 TeV**
  - Reach for qz: 4.5 TeV

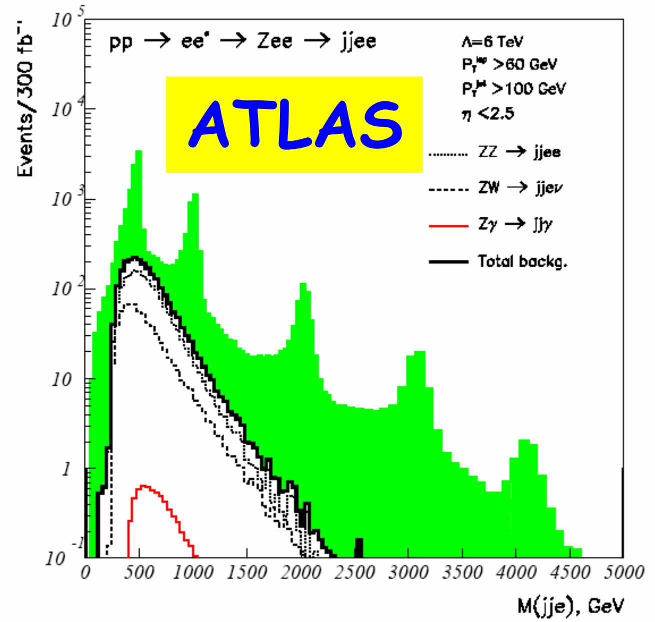
  f=f'=1 **L = 300 fb^{-1}, Λ = m***

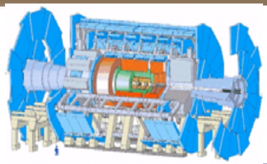


- ✓ Excited electrons

$m^*(GeV)$	500	1000	2000	3000	4000
$Z \to ee$	77.	2.3	3.7×10^{-2}	1.7×10^{-3}	1.1×10^{-4}
$Z \to jj$	1600.	48.8	7.6×10^{-1}	3.5×10^{-2}	2.4×10^{-3}

- ✓ **Reach: ~ 3 - 4 TeV for Λ = 6 TeV, 300fb^{-1}**





Leptoquarks

ATLAS

- ✓ **Motivation**
  - SM extension: lepton-quark symmetry
- ✓ **Study: Scalar LQ**

$LQLQ \rightarrow l^{+}ql^{-}q$

- 2jets + 2 leptons: 1st and 2nd generation

Sensitivity: M(LQ)~1.3 TeV

Beta= 1

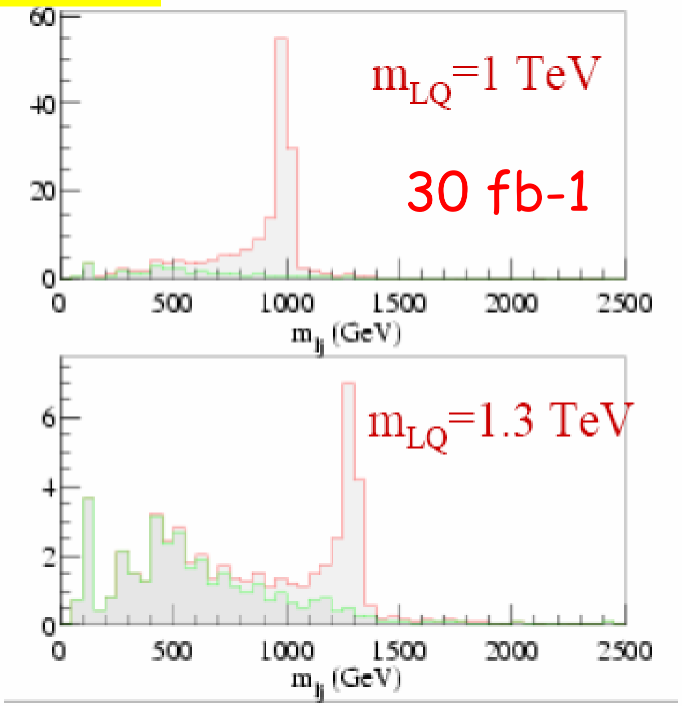
$LQLQ \rightarrow \nu q\, \nu q$

- 2 jets + Et: 3rd generation

Sensitivity: M(LQ) ~ 1 TeV

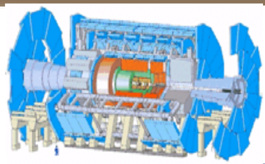
Beta= 0.5

2 jets + 2 leptons



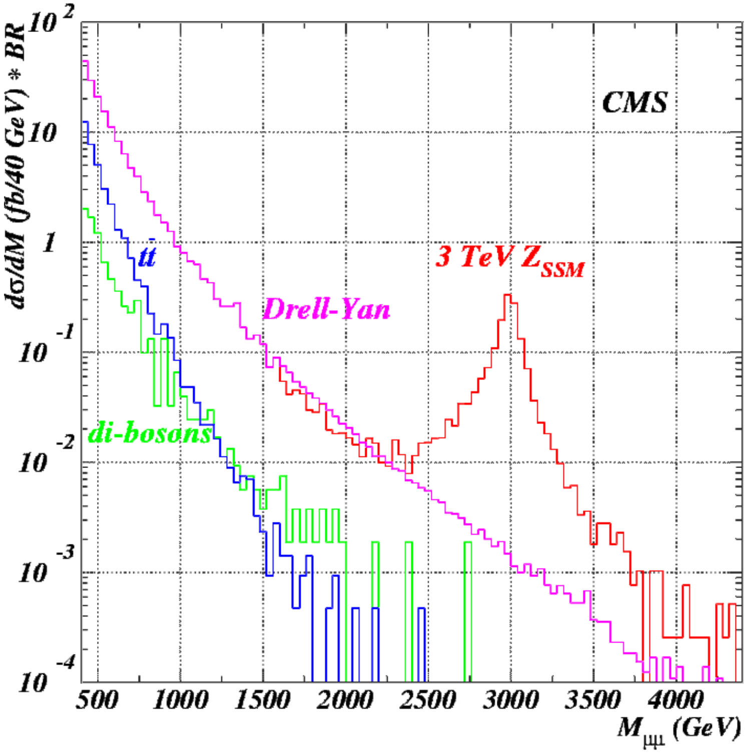
M_{LQ} (TeV)	σ (fb)	Signal	Background	$S/\sqrt{B}$
1.0	4.96	98.5	2.84	58
1.2	1.33	22.0	2.43	14
1.3	0.713	12.8	1.44	11
1.5	0.223	3.62	0.376	5.9

1st generation

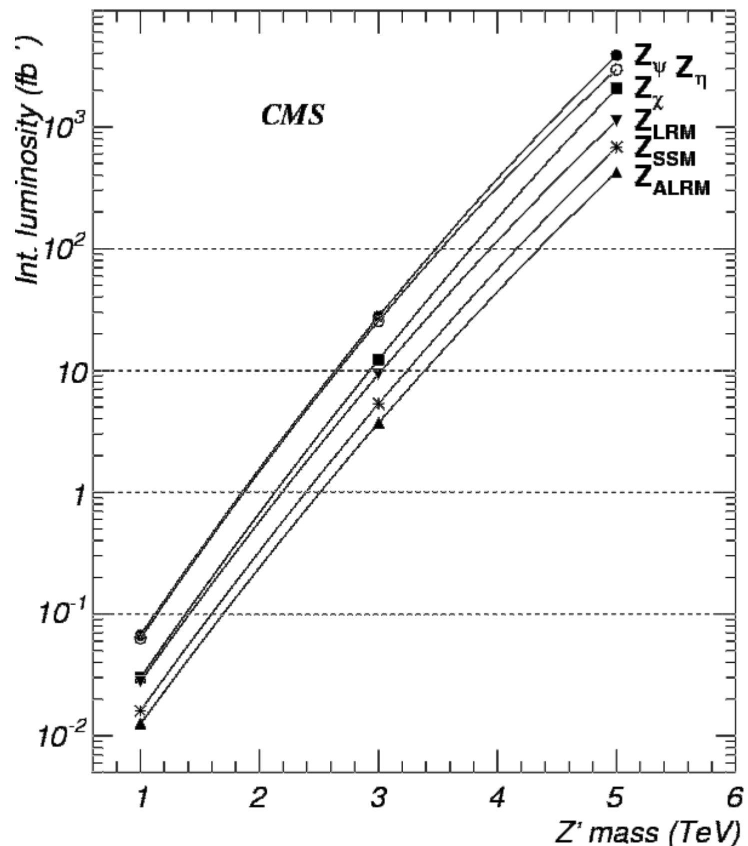


New Gauge Bosons (I)

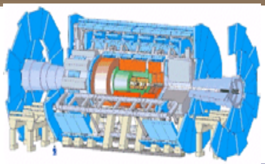
CMS



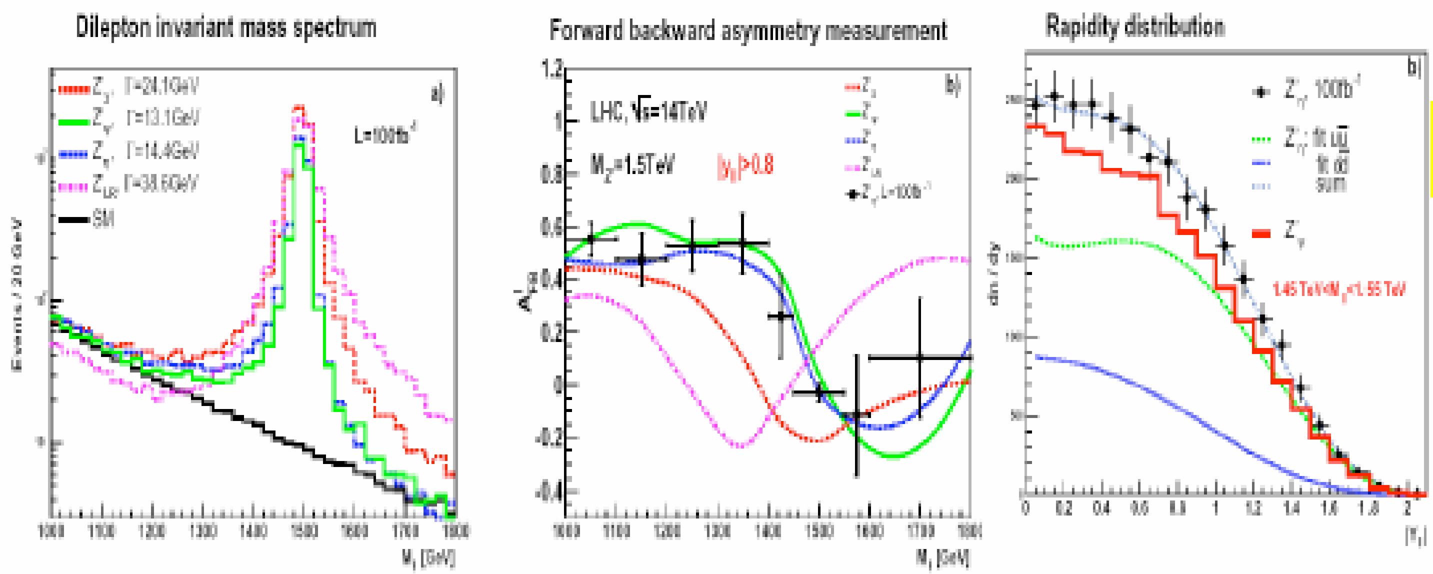
$Z' \to \mu^+\mu^-$: 5σ significance curves



A very low luminosity, less than 0.1 fb-1, should be sufficient to discover Z' bosons at 1 TeV

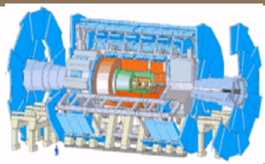


New Gauge Bosons (II)



CMS

- Reach in 1 year at 10^{34} : 4-5 TeV
- Discriminating between models possible up to m ~ 2.5 TeV by measuring:
  - -- $\sigma x \Gamma$ of resonance
  - -- lepton F-B asymmetry
  - -- Z' rapidity



Doubly Charged Higgs

L-R symmetric model would be a natural extension of the SM

- $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- **predicts new fermions:**
  heavy Majorana neutrino
- **predicts new gauge bosons:**
  W_R
- **predicts new Higgs sector**

Two high pT leptons with same charge
Two high pT jets

$$\Delta_R = (\Delta_R^0, \quad \Delta_R^+, \quad \Delta_R^{++})$$

$$\Delta_L = (\Delta_L^0, \quad \Delta_L^+, \quad \Delta_L^{++})$$ (if Lagrangian is invariant under $L \leftrightarrow R$ symmetry)

$$\phi_{1,2}^0, \quad \phi_{1,2}^{\pm}$$

Parameters: $k_1 \quad k_2 \quad v_L \quad v_R$ $\qquad k = \sqrt{k_1^2 + k_2^2} \sim 250 GeV$

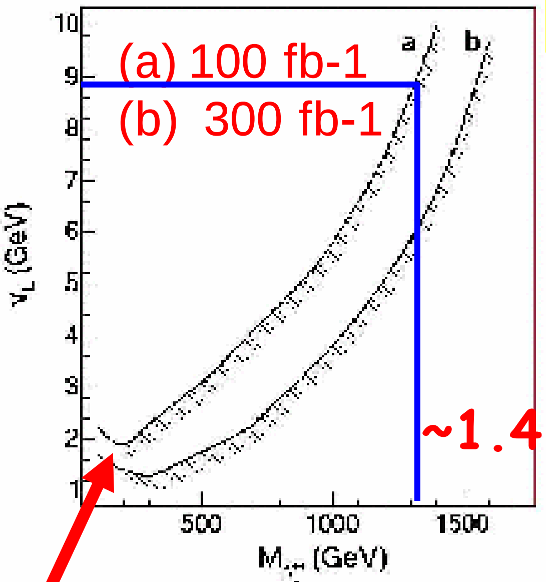
$$\rho = \frac{M_{W_L}^2}{\cos^2\theta_W M_{z1}^2} \sim \frac{1 + 2v_L^2 / k^2}{1 + 4v_L^2 / k^2} \Rightarrow v_L \le 9\ GeV$$

In this analysis: $m_{W_R}^2 = g_R^2 v_R^2 / 2, \qquad g_R = g_L \approx 0.64$

Discovery Reach

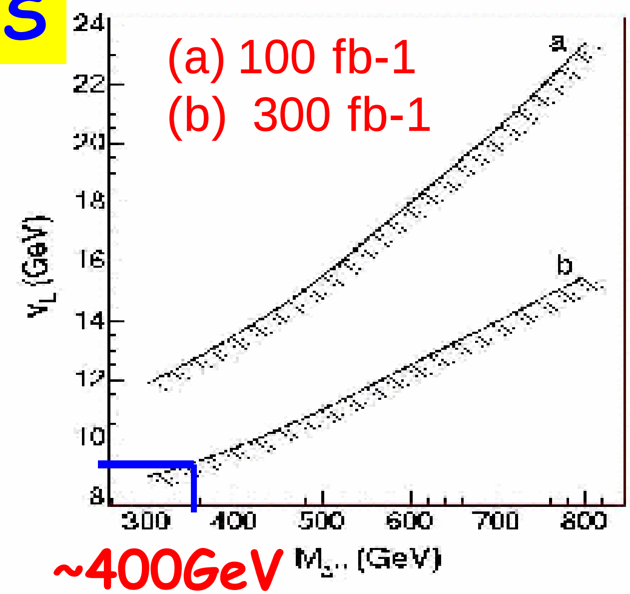
ATLAS

ee,μμ

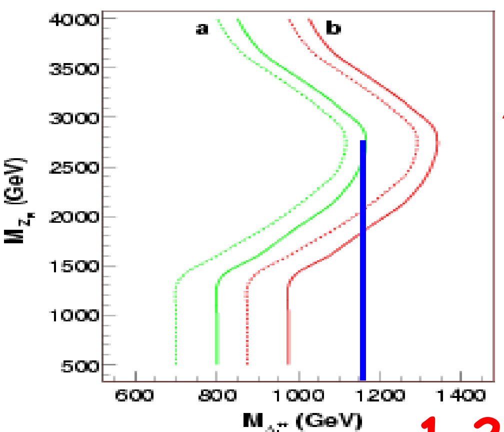


Tevatron

tau tau



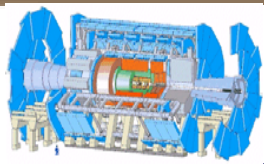
(a) 100 fb-1
(b) 300 fb-1



$$\Delta_L^{++}\Delta_L^{--} \rightarrow l^+l^+l^-l^-$$

Full = 3 leptons are observed

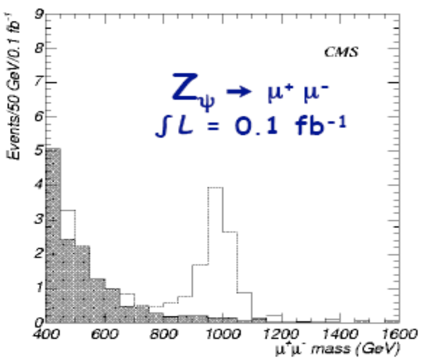
Dashed =4 leptons are observed



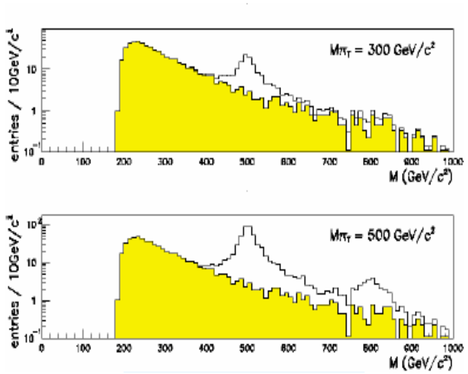
Summary

LHC will explore the TeV scale in detail with direct discovery potential up to m ~ 5-6 TeV

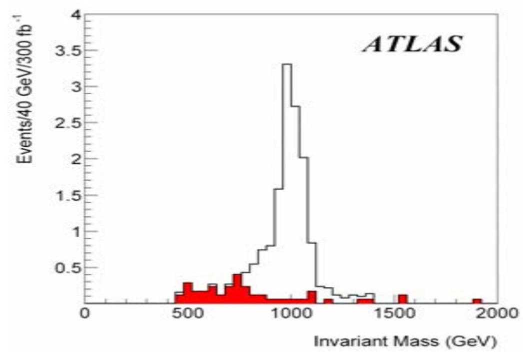
New Gauge Bosons?



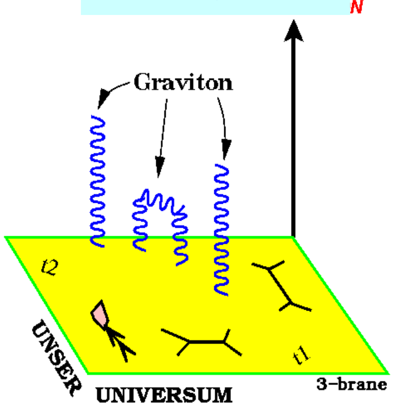
Technicolor?



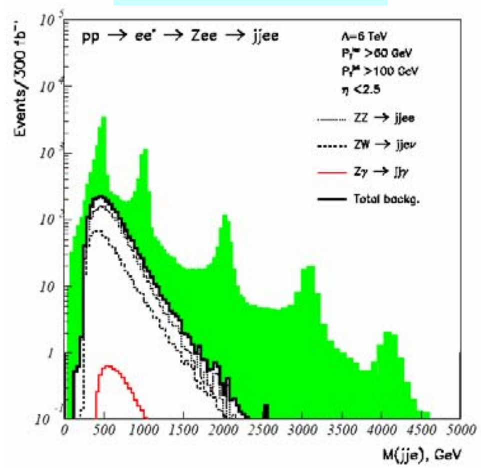
Little Higgs?



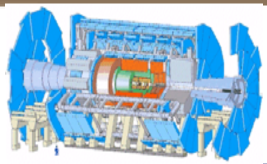
Extra Dimensions?



Excited electrons?



Black Holes???

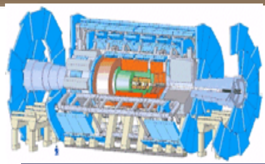


Conclusion

- ✓ 403 days from now, particle physics will enter a new epoch of its history.
- ✓ The LHC will address many of the leading questions in particle physics:
  - Is nature supersymmetric?
  - Are there extra dimensions of space?
  - What unknown mechanism gives mass to particles?

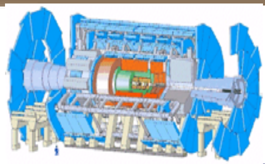
Solving these mysteries will be an important chapter in the history of science.

Backup Slides

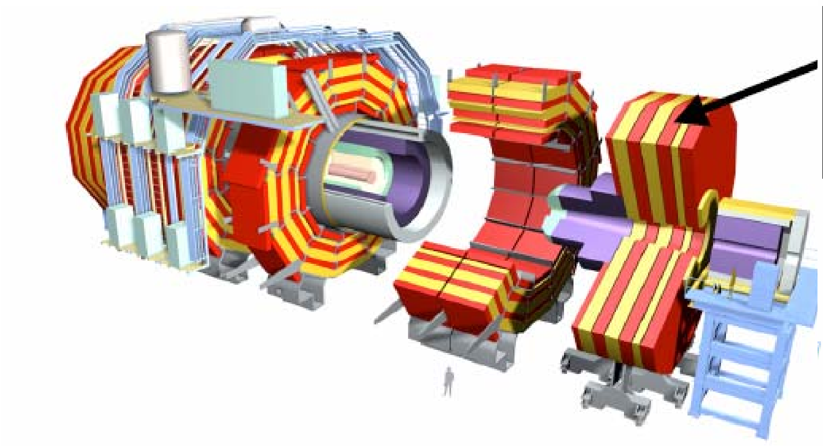


ATLAS & CMS

	ATLAS	CMS
MAGNET(S)	Air-core toroids + solenoid in inner cavity Calorimeters outside field 4 magnets	Solenoid Calorimeters inside field 1 magnet
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 5x10^{-4}\ p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5x10^{-4}\ p_T \oplus 0.005$
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 (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → σ/p_T < 10 % at 1 TeV standalone; larger acceptance	Fe → $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker



ATLAS & CMS at the Beginning?

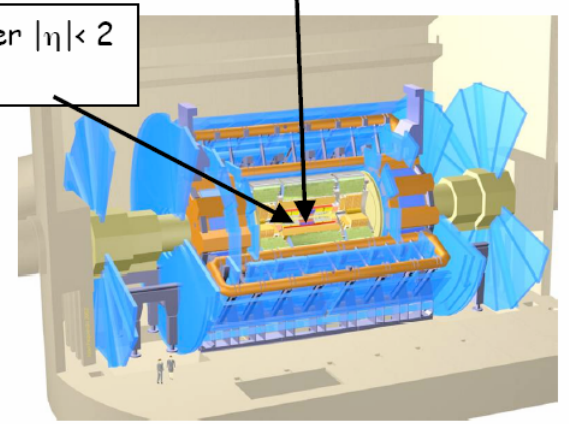


RPC over $|\eta|<1.6$ (instead of $|\eta|<2.1$)
4^{th} layer of end-cap chambers missing

Pixels and end-cap ECAL installed during first shut-down

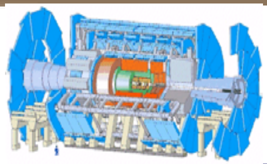
3 layers of pixels

TRT acceptance over $|\eta|<2$
(instead of $|\eta|<2.4$)

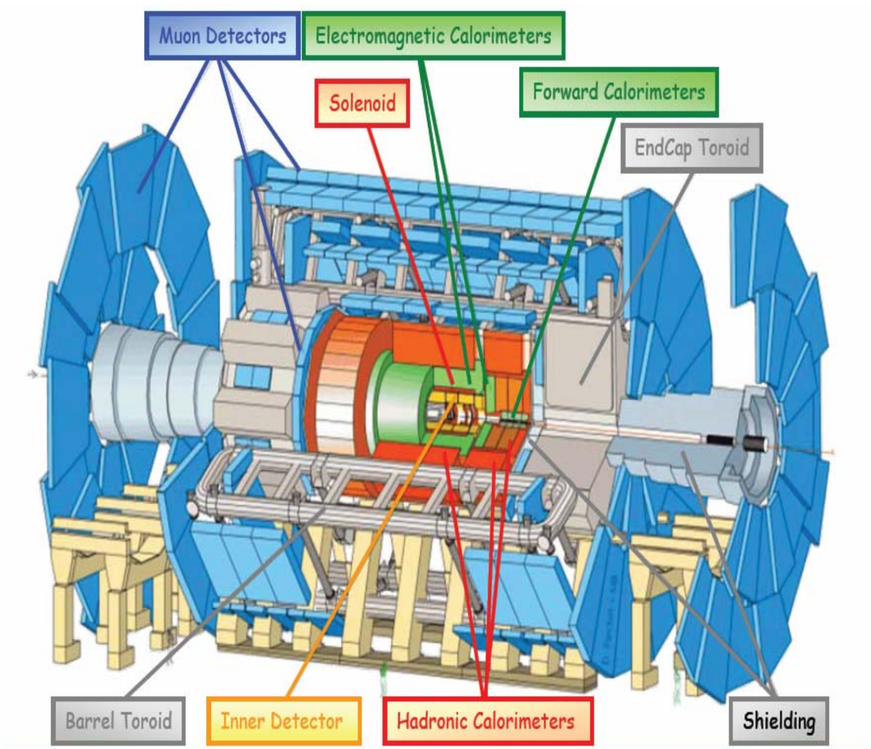


Both experiments:
deferrals of high-level Trigger/DAQ processors
→ LVL1 output rate limited to
~ 50 kHz CMS (instead of 100 kHz)
~ 40 kHz ATLAS (instead of 75 kHz)

No EE chambers



The ATLAS Detector



- Inner Detector (2T solenoid, $|\eta|<2.5$):

  $\sigma_{p_t}/p_t \approx 0.05\%/\mathrm{GeV} \times p_t \oplus 1\%$

- Calorimetry:

  * electromagnetic, $|\eta|<3.2$
  $\sigma_E/E \approx 10\%\sqrt{\mathrm{GeV}}/\sqrt{E} \oplus 0\%$

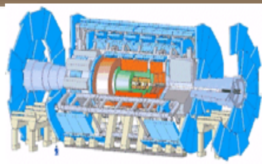
  * hadronic (central, $|\eta|<1.7$)
  $\sigma_E/E \approx 50\%\sqrt{\mathrm{GeV}}/\sqrt{E} \oplus 3\%$

  * hadronic (endcaps, $1.7<|\eta|<3.2$)
  $\sigma_E/E \approx 60\%\sqrt{\mathrm{GeV}}/\sqrt{E} \oplus 3\%$

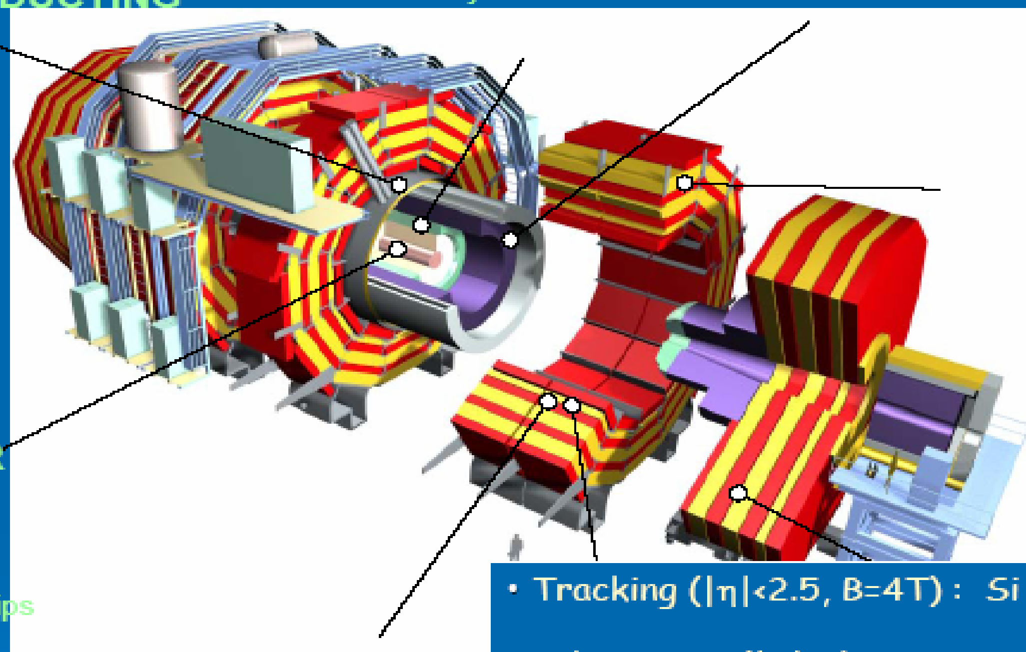
  * hadronic (forward, $3.2<|\eta|<4.9$)
  $\sigma_E/E \approx 100\%\sqrt{\mathrm{GeV}}/\sqrt{E} \oplus 5\%$

- Muon system (~4T toroid, $|\eta|<2.7$):

  $\sigma_{p_t}/p_t \approx 10\%$ for $p_t(\mu) \approx 1$ TeV/c



CMS Detector



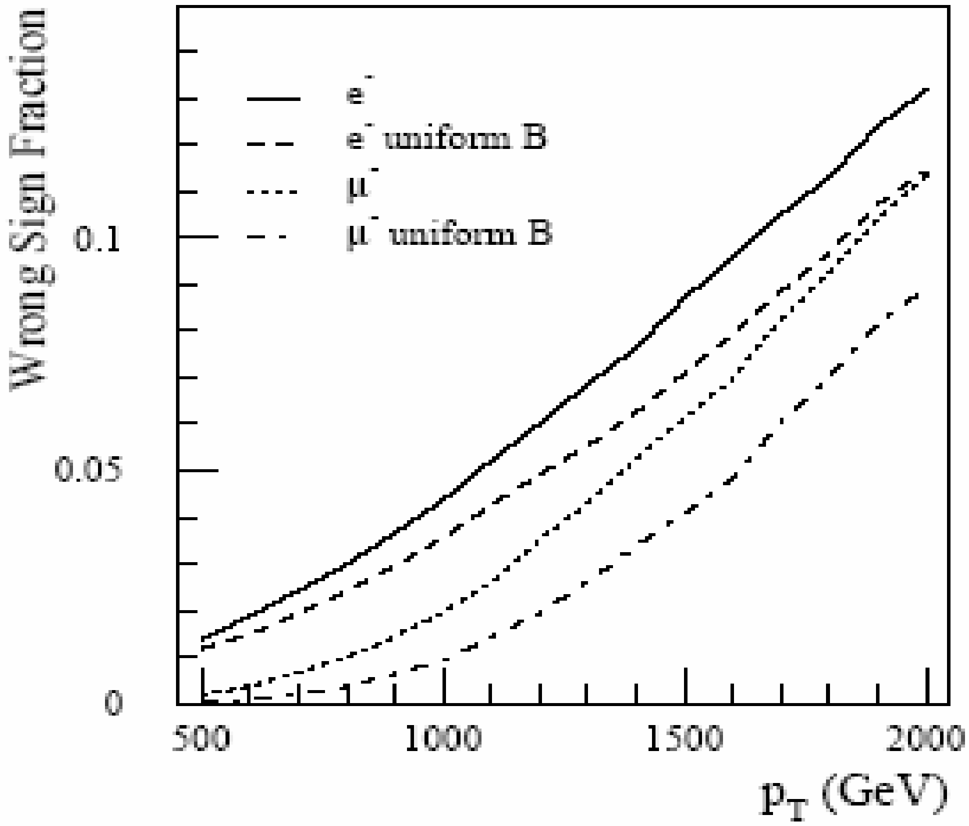
Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

- Tracking ($|\eta|<2.5$, B=4T) : Si pixels and strips
- Calorimetry ($|\eta|<5$) :
  -- EM : $PbWO_4$ crystals
  -- HAD: brass-scintillator (central+ end-cap), Fe-Quartz (fwd)
- Muon Spectrometer ($|\eta|<2.5$) : return yoke of solenoid instrumented with muon chambers

ATLAS Trigger & Physics

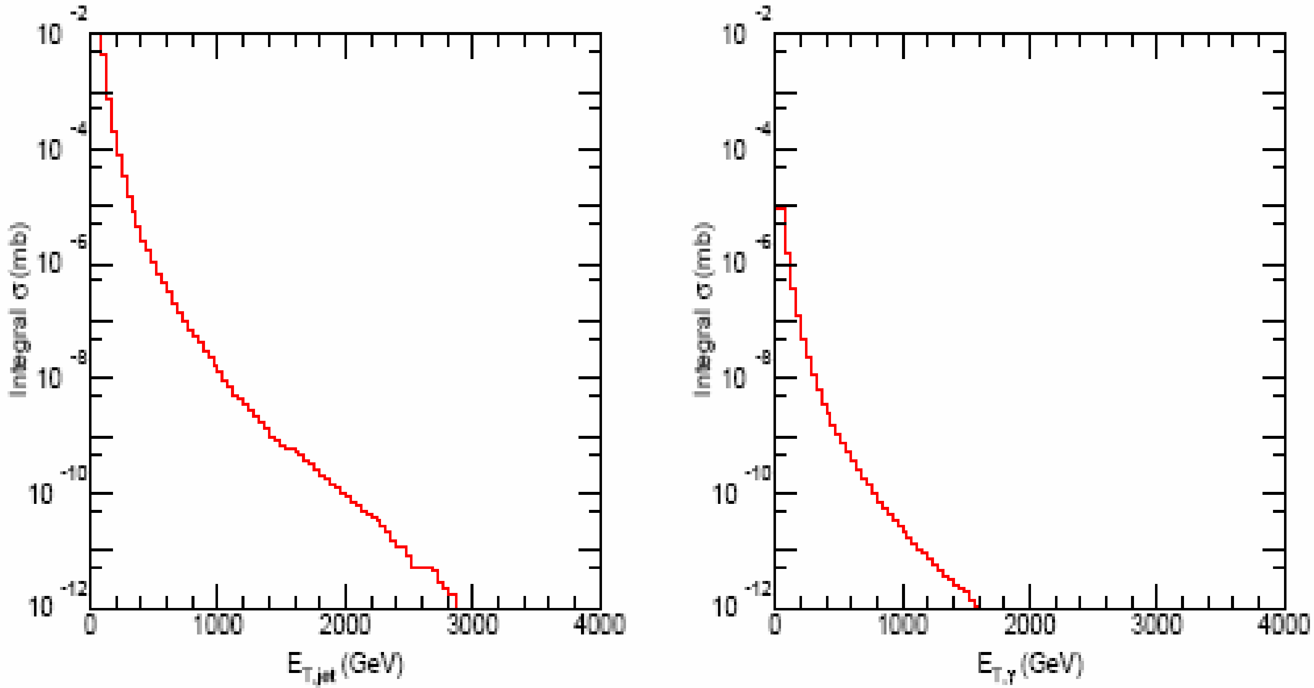
Object	Physics coverage	$L = 2\times10^{33}\ cm^{-2}s^{-1}$
Electrons	Higgs, new gauge bosons, extra dimensions, SUSY, W, top	e25i, 2e15i
Photons	Higgs, extra dimensions, SUSY	γ60, 2γ20i
Muons	Higgs, new gauge bosons, extra dimensions, SUSY, W, top	μ20i, 2μ10
	Rare b-decays (*e.g.*, $B \rightarrow \mu\mu X$, $B \rightarrow J\ \Psi(\Psi')X$)	2μ6 + mass cuts
Jets	SUSY, compositeness, resonances	j400, 3j165, 4j110
Jet+missing E_T	SUSY, leptoquarks	j70 + xE70
Tau+missing E_T	Extended Higgs models (*e.g.*, MSSM), SUSY	τ35i + xE45
Others	Pre-scaled, calibration, monitoring	
Total HLT Output Rate		

Charge sign misidentification



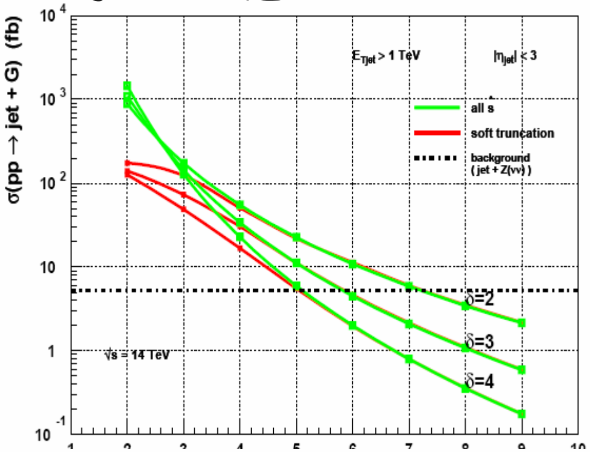
Jets Calibration using γ/jet sample

In-situ calibration typically involves balancing jet(s) against EM object. But E_T range for jets is 2 – 4 times larger. Compare jets and single γ's (parton level, LO QCD, CTEQ5L):



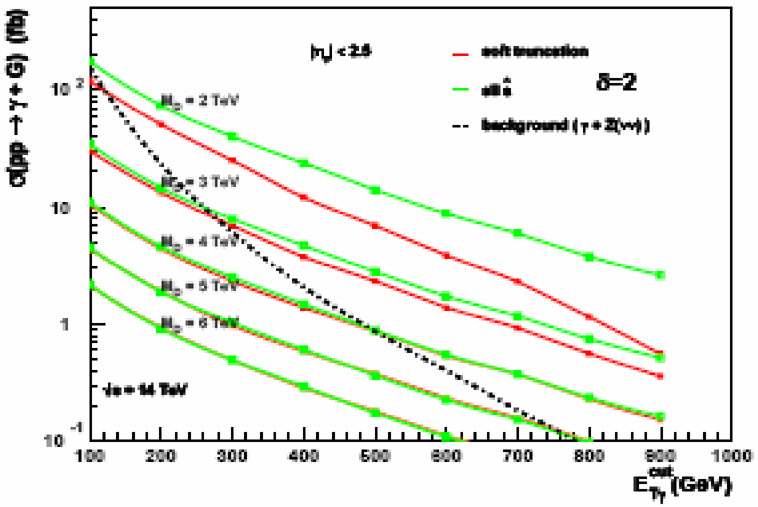
Large Extra-D: Direct Production

Jet+MET

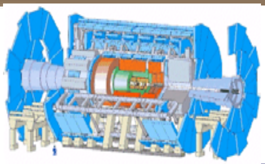


δ	M_D	Low luminosity, $30fb^{-1}$			High luminosity, $100fb^{-1}$		
		S	$S/\sqrt{B}$	$S/\sqrt{7B}$	S	$S/\sqrt{B}$	$S/\sqrt{7B}$
2	4	1036.4	81.6	30.8	3542.2	150.2	56.8
	5	417.0	32.9	12.4	1426.9	60.4	22.8
	6	205.9	16.3	6.2	700.6	29.6	11.2
	7	111.3	8.8	3.3	379.4	16.1	6.1
	8	65.3	5.2	2.0	222.5	9.4	3.5
3	4	641.8	50.6	19.1	2168.4	92.0	34.8
	5	211.5	16.6	6.3	706.0	30.0	11.3
	6	85.1	6.8	2.6	287.5	12.1	4.6
	7	39.3	3.1	1.2	134.0	5.7	2.2
4	4	436.2	34.3	13.0	1473.4	62.5	23.6
	5	113.0	8.8	3.3	383.4	16.3	6.2
	6	37.8	2.9	1.1	128.5	5.4	2.0

Gamma+MET



δ	M_D	High luminosity, $100fb^{-1}$		
		S	$S/\sqrt{B}$	$S/\sqrt{6B}$
2	3	194.4	21.4	8.7
	4	61.8	6.8	2.8
3	4	49.2	5.4	2.2



Extra-D Models

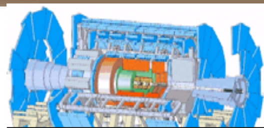
Table 1 Maximal reach in M_S at 5σ level in di-photon and di-lepton production channels well as for combined statistics.

channel	n		2	3	4	5
	luminosiy					
$\gamma\gamma$	10 fb^{-1}	M_S^{max} (TeV)	6.3	5.6	5.1	4.9
		S/B	36/18	36/18	39/25	34/13
	100 fb^{-1}	M_S^{max} (TeV)	7.9	7.3	6.7	6.3
		S/B	50/53	62/96	55/72	51/53
l^+l^-	10 fb^{-1}	M_S^{max} (TeV)	6.6	5.9	5.4	5.1
		S/B	33/11	31/8	30/6	30/6
	100 fb^{-1}	M_S^{max} (TeV)	7.9	7.5	7.0	6.6
		S/B	49/48	38/21	36/16	29/6
$\gamma\gamma + l^+l^-$	10 fb^{-1}	M_S^{max} (TeV)	7.0	6.3	5.7	5.4
	100 fb^{-1}	M_S^{max} (TeV)	8.1	7.9	7.4	7.0

m_G (GeV)	Γ_G (GeV)	Γ_m (GeV)	$\sigma \cdot B$ (fb)
500	0.068	3.53	281.9
1000	0.141	6.02	11.0
1500	0.213	8.13	1.20
1700	0.242	8.78	0.57
1800	0.256	9.34	0.41
1900	0.270	9.66	0.29
2000	0.285	9.80	0.21
2100	0.298	10.18	0.15
2200	0.312	10.49	0.11

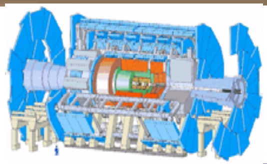
Large Extra-D: Virtual Production

RS Graviton



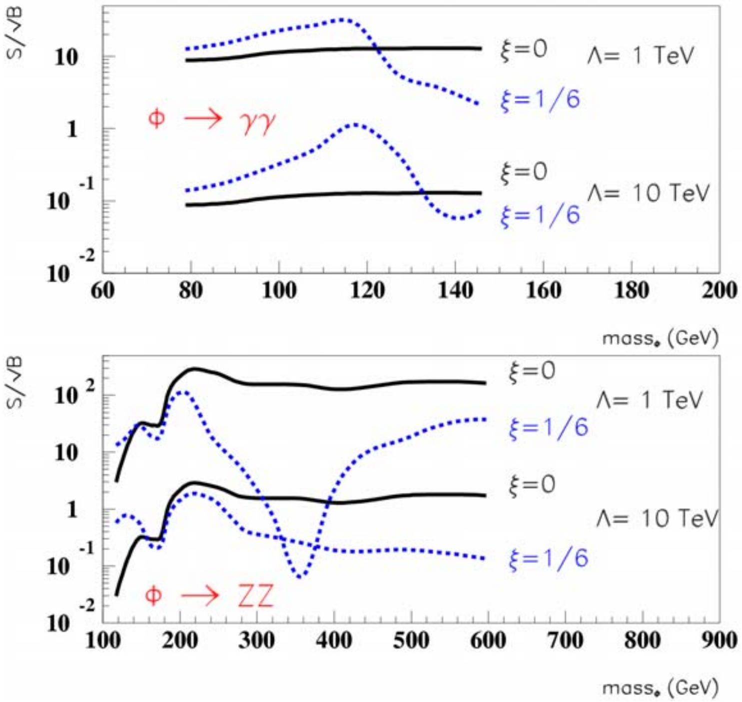
Constraints on large ED

constraint	$\delta=2$		$\delta=3$	
	max R (mm)	min M_D (TeV)	max R (mm)	min M_D (TeV)
Gravitational force law	0.2	0.6		
SN1987A cooling by graviton emission	7×10^{-4}	10 30	9×10^{-7}	0.8 2.5
Diffuse cosmic ray background ($G^{(k)} \rightarrow \gamma\gamma$)	9×10^{-5}	25	2×10^{-7}	1.9
other reheating scenarios		167		22
decays after SN explosion		450		30
heating of neutron stars (trapped $G^{(k)}$ decaying)	8×10^{-6}	90 1700	3.5×10^{-8}	5 60
LEP: γG, ZG, virtual		~ 1 TeV		
Tevatron		~ 1 TeV		



Radion

- ✓ Motivation
  - Scalar field representing fluctuations of the distance of the 2 branes
  - To stabilize krcπ ~ 35 (Golberger & Wise)
- ✓ Radion properties
  - Higgs-like couplings
  - Mixing to Higgs ξ
- ✓ Signal

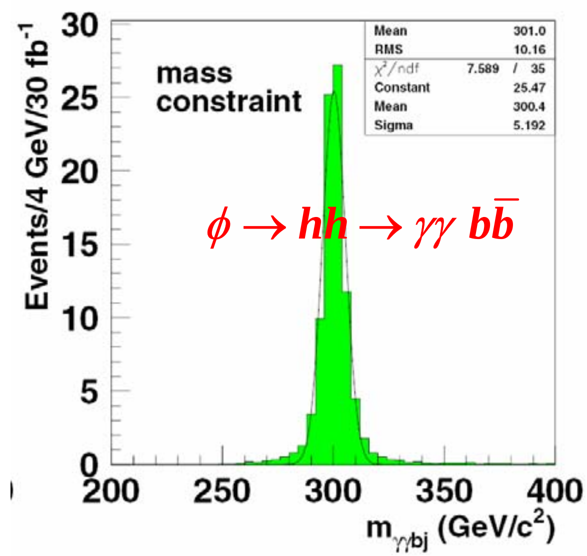


Radion

- ✓ Other signals
  - $\phi \rightarrow hh \rightarrow \gamma\gamma\, b\bar{b}$

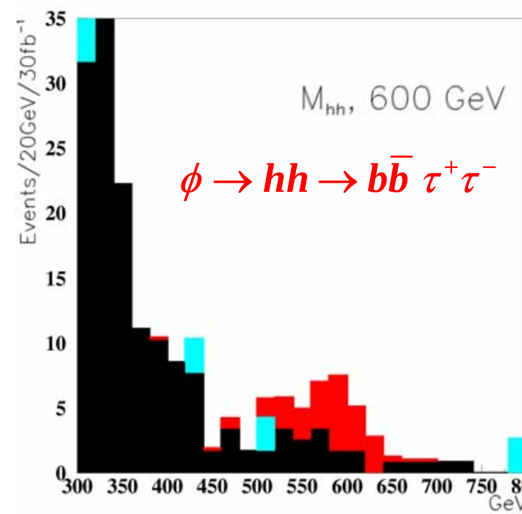
ξ	Λ_ϕ (TeV)	m_ϕ=300	m_ϕ=600
0	1	4	43
0	10	333	-
1/6	1	2	57
1/6	10	250	-

Required luminosity (fb^{-1}) for 5σ discovery

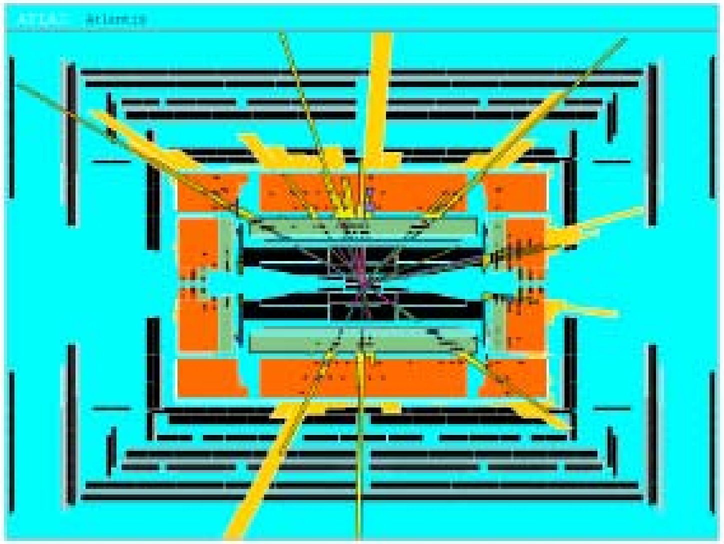


- ✓ Discrimination Higgs/Φ
  - Difficult at LHC
  - Look at Γ & BR mods

(Rizzo et al)



Black Holes



A black hole event with $M_{BH} \sim 8$ TeV in ATLAS

From preliminary studies : reach is $M_D \sim 4$ TeV for any δ in one year at high luminosity.

By testing Hawking formula → proof that it is BH + measurement of δ

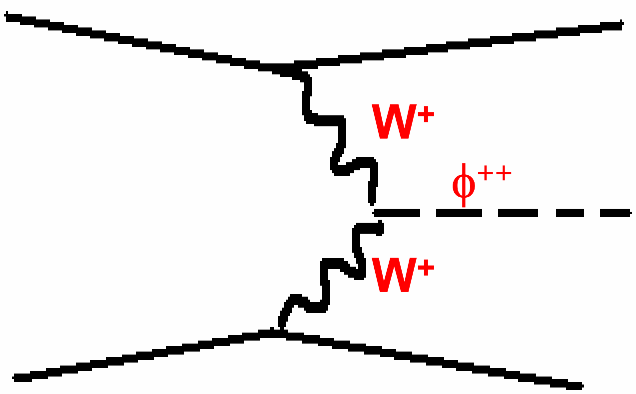
$$\log T_H = -\frac{1}{\delta + 1} \log M_{BH} + f\,(M_D, \delta)$$

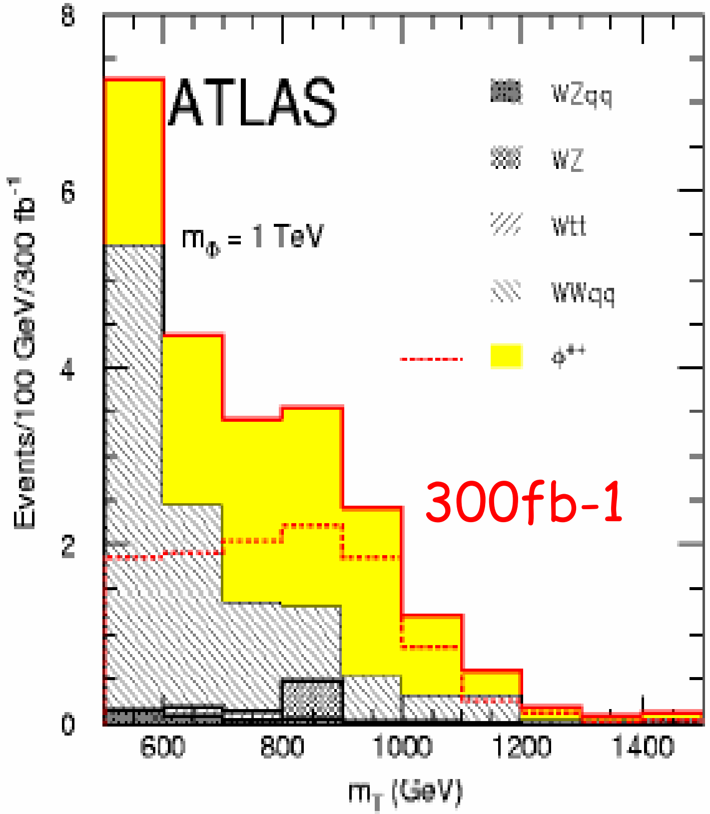
precise measurements of M_{BH} and T_H needed
(T_H from lepton and photon spectra)
M_D from cross-section

New Higgs Φ^{++}

- ✓ Production
  - – Via WW fusion

  Forward jet tag

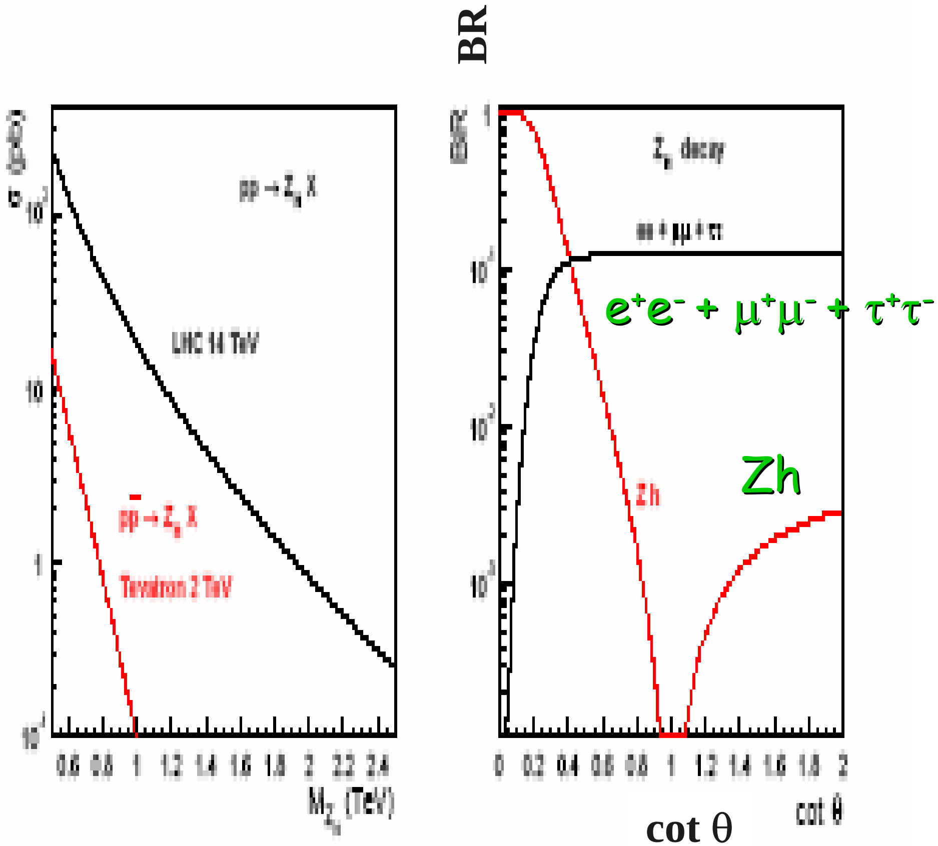


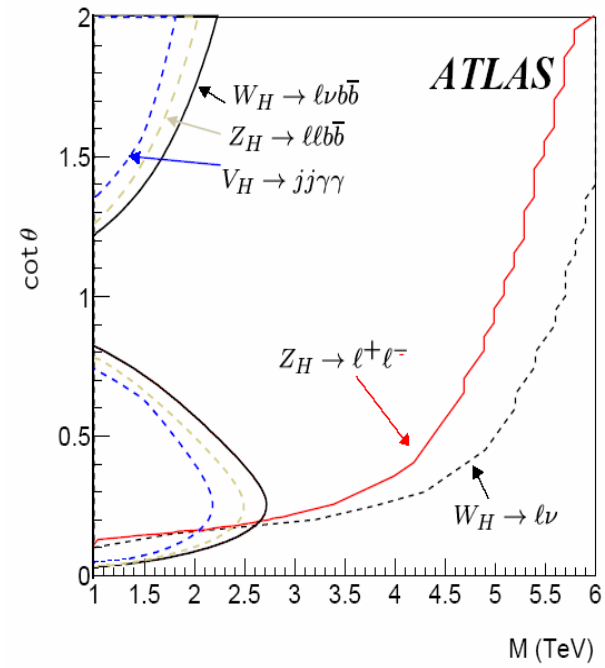


- ✓ Decay
  - – W^+W^+ to $l^+\nu l^+\nu$

At 1 TeV; Significance: 5 σ if v' > 29 GeV

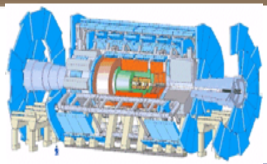
Heavy Gauge Bosons





Cross section and Br. fractions

Accessible region for 5σ discovery



Heavy Leptons

- ✓ Basics
  - Look at sequential leptons: 4th family
  - Other models: VF, Chiral F, Singlets F
  - Final state llZZ
- ✓ Analysis
  - gg & DY
  - 2l, 2Z (4jets)
  - Bdg: tt, VV+jets

Reach ~ 1 TeV

Depends on Z'

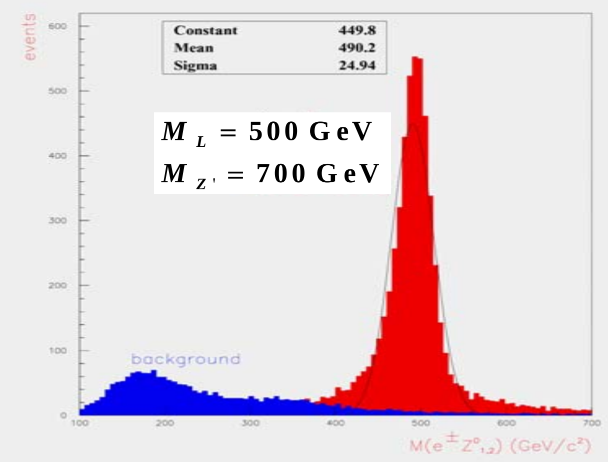
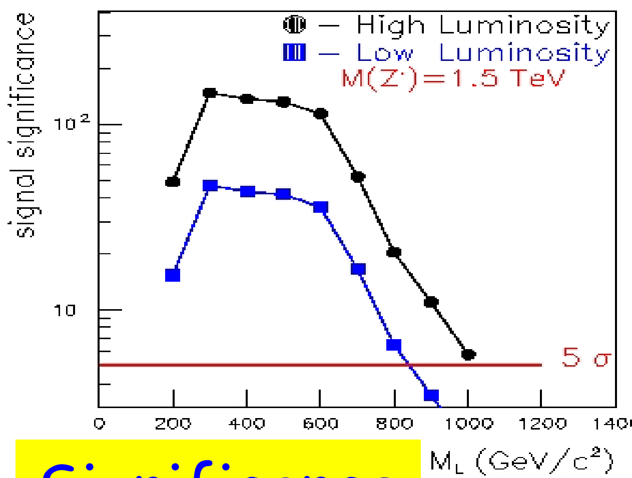


Figure 13: Signal to background comparison for $M_L = 0.5\ TeV/c^2$ and $M_{Z'} = 0.7\ TeV/c^2$, for $L \to e + Z^0$ channel.



Significance