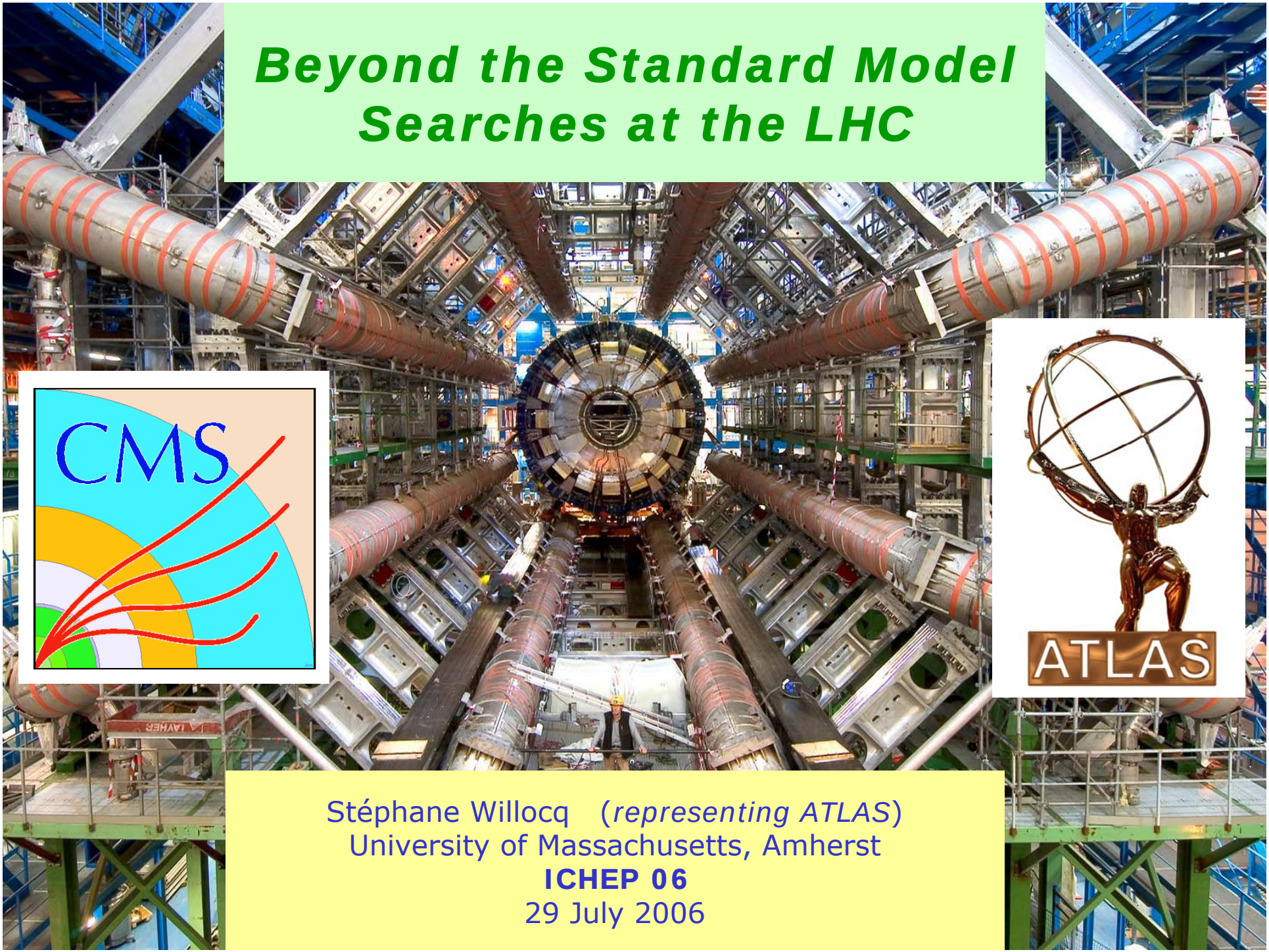
Beyond the Standard Model Searches at the LHC



Stéphane Willocq (*representing ATLAS*)
University of Massachusetts, Amherst

ICHEP 06

29 July 2006

Note

- BSM searches at the LHC:
  - SUSY talk by Valery Zhukov
  - Extra Dimensions talk by Sergei Shmatov
  - Black Holes talk by Greg Landsberg
  - Higgs talk by Eilam Gross
- CMS:
  - Many results from Physics TDR released in 2006
- ATLAS:
  - Physics TDR released in 1999
    Currently working on detailed & realistic physics analyses
    for first year of physics running at the LHC (~100 pb^{-1})

➔ emphasis on recent studies in this talk

Outline

1. Beyond the Standard Model

2. Fundamental Symmetries

Heavy Gauge Bosons W' and Z'

3. Electroweak Symmetry Breaking

Little Higgs, Technicolor

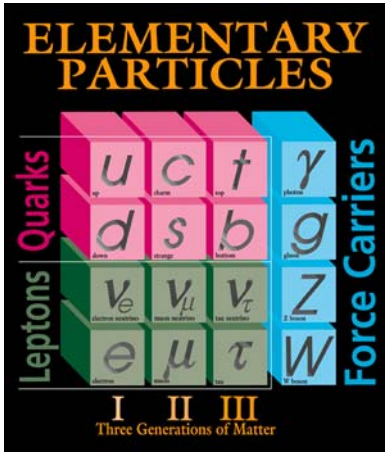
4. Leptons & Quarks, Other New Particles

Left-right symmetry, E6 quarks

5. Summary & Outlook

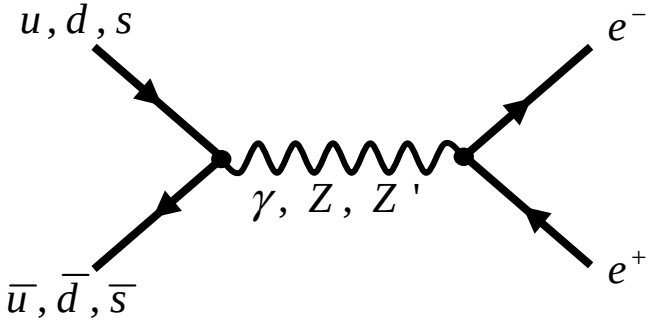
(Some) Issues with the Standard Model

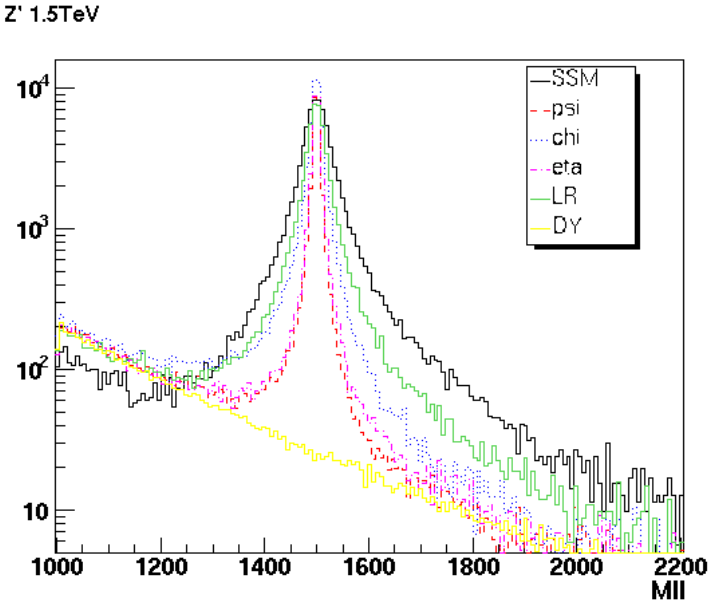
- Fundamental symmetries:
  - Are there more symmetries beyond $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$?
    → GUTs with larger symmetry group? Left-right symmetry?
- ElectroWeak Symmetry Breaking (EWSB):
  - Unitarity violation in longitudinal WW scattering at high E
    solution: Higgs boson or other new particle with mass < 1 TeV
  - If Higgs ➔ *hierarchy problem:* fine tuning in rad corr to Higgs mass
    solution: new physics at TeV scale (SUSY, Little Higgs, etc…)
  - If NO Higgs
    solution: new strong interactions (Technicolor, etc…)
- Quark and lepton generations:
  - Why are there 3 generations? → Fermions composite?
  - Is there a lepto(n)-quark symmetry?
  - More than 3 generations of quarks & leptons?



Heavy Gauge Bosons

- Many extensions of the SM rely on larger symmetry groups (GUTs, string-inspired, left-right, little Higgs models, etc…)
  ➔ predict existence of new gauge bosons W′ and Z′ (or KK modes)
- Production: s-channel
- Clean decay channels:
  W′ → e ν_e or μ ν_μ
  Z′ → e^+e^- or $\mu^+\mu^-$
- Tevatron searches: M up to ~1 TeV
- Z′ models considered:
  - Sequential SM (SSM) with same Z′ couplings to fermions as for Z
  - Models based on different patterns of E6 symmetry breaking (ψ, χ and η)
  - Left-right (LR) symmetry models





Heavy Gauge Bosons: Z'

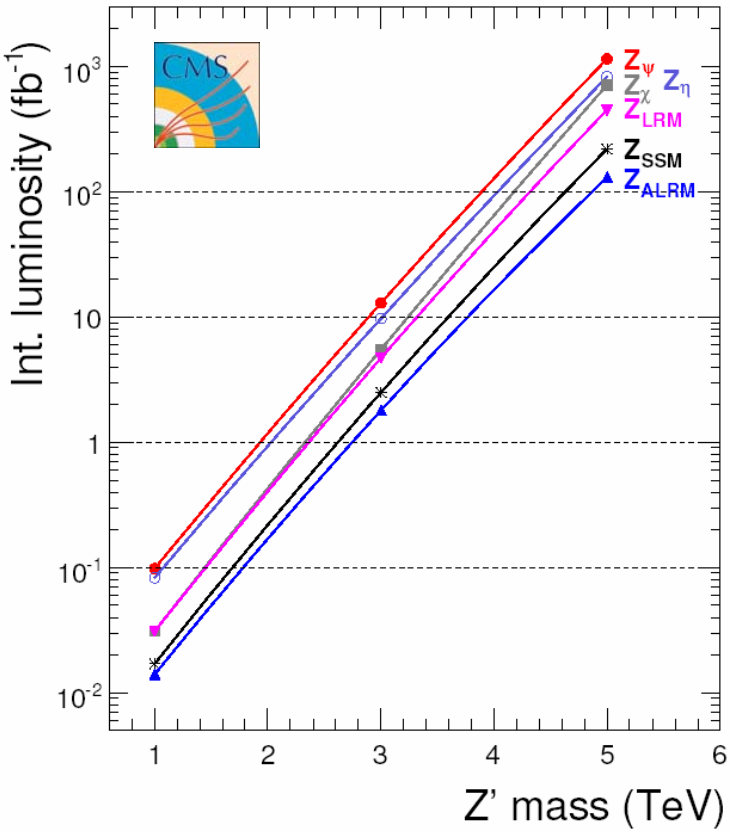
- Selection: pairs of isolated e or μ
- Bkg: dominated by dileptons from Drell-Yan
- 5σ discovery up to ~5 TeV (model dependent) for both ATLAS and CMS

Exp^t Issues:
- electronics saturation for high E e$^{\pm}$ at CMS M(Z') ≥ 3 TeV ➔ correct
- muon bremsstrahlung ➔ isolation with tracks

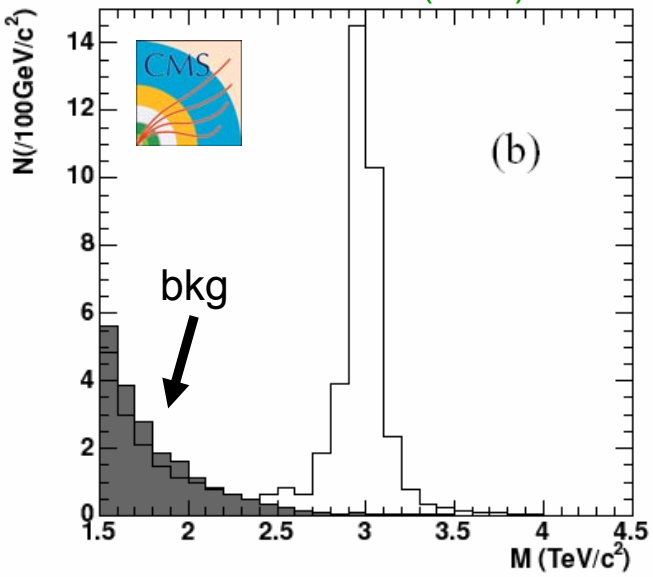
CMS PTDR 2006

Z' → ee

Luminosity needed for 5σ signal



CMS PTDR Z' → ee (SSM) 30 fb^{-1}



SSM Z' → ee	M = 1 TeV	M = 5 TeV
N signal	72020	0.58
N bkg	85.5	0.025
Significance	225	1.63

Discrimination btw Z' Models

- Models differ in the Z' couplings to fermions
  esp. parity-violating couplings to leptons + couplings to initial u/d
  - Decay width (ee only due to worse μμ resolution)

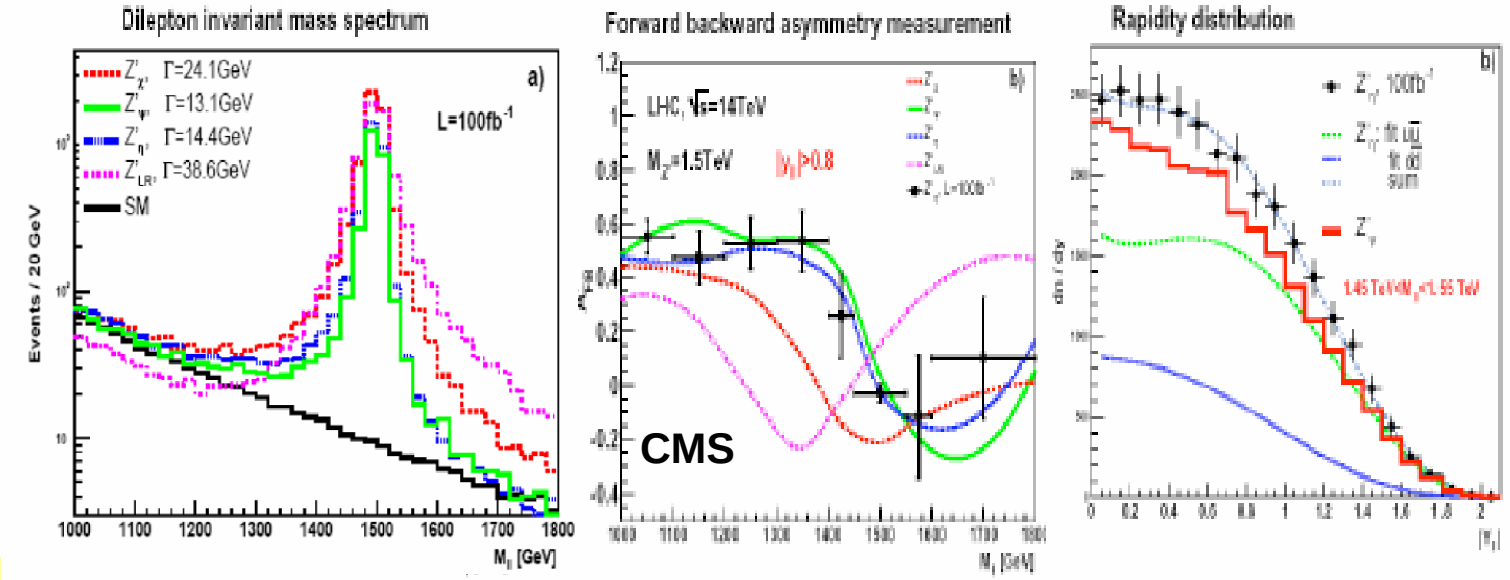
ATLAS: $\sigma(p_T)/p_T \approx 0.7\%$ (e), 10% (μ) at $p_T = 1$ TeV

  - Forward-backward asymmetry
  - Z' rapidity

→ Also provides discrimination against other models like extra-D, little Higgs, …

M = 1.5 TeV ATL-PHYS-PUB-2005-010

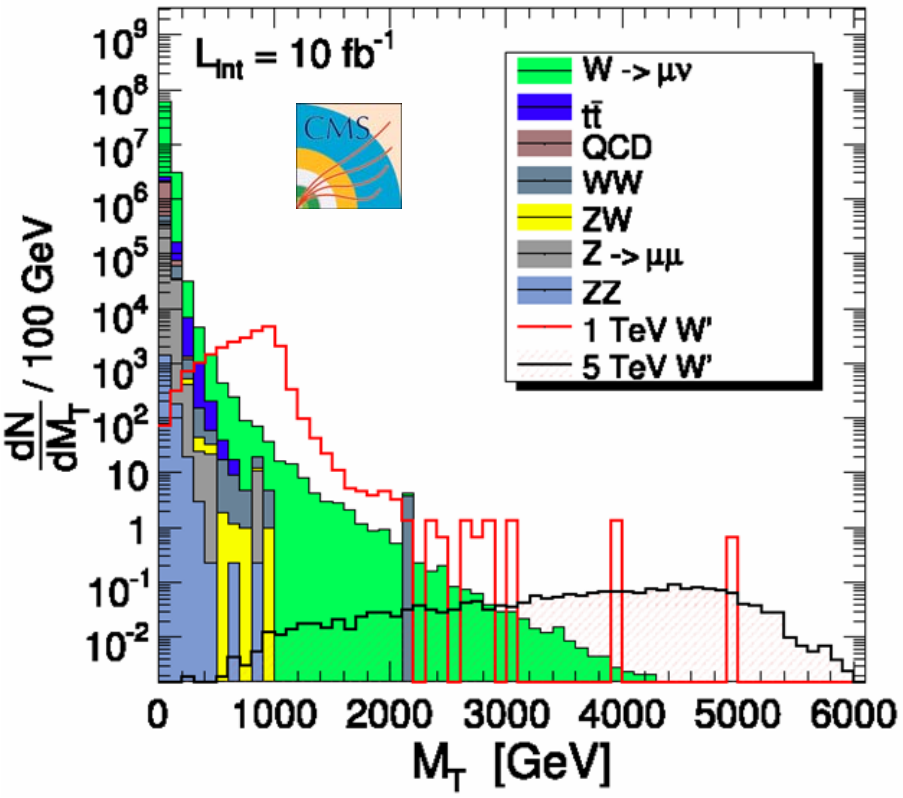
Model Z' → ee 100 fb^{-1}	$\sigma_{ll} \times \Gamma_{ll}$ (fb x GeV)	Corrected A_{FB} at Z' peak
SSM	3668 ± 138	+0.108 ± 0.027
χ	828 ± 48	-0.361 ± 0.030
LR	1515 ± 75	+0.186 ± 0.032



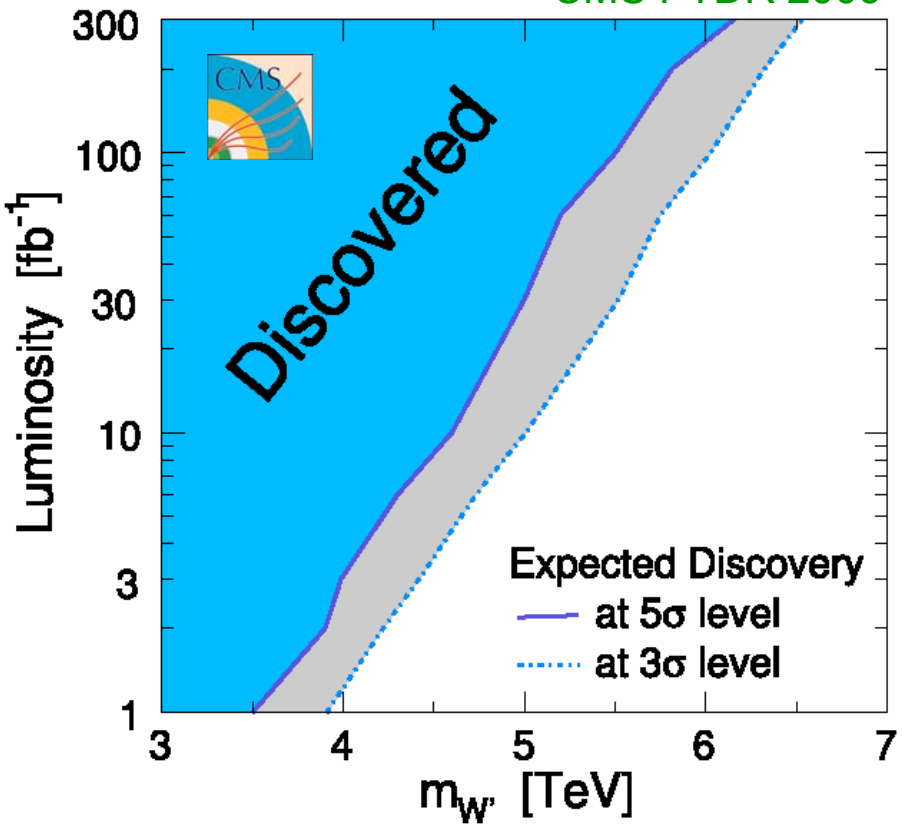
Heavy Gauge Bosons: W'

Exp^t Issues:
- missing E_T tails
  ➔ calo calib, leakage
- muon momentum tails
  ➔ alignment

- General Model by Altarelli, Mele, Ruiz-Altaba with same W' couplings to fermions as for W
- Selection: one-muon event with track isolation req^t around mu + missing transverse energy
- Background: mostly W → μ ν

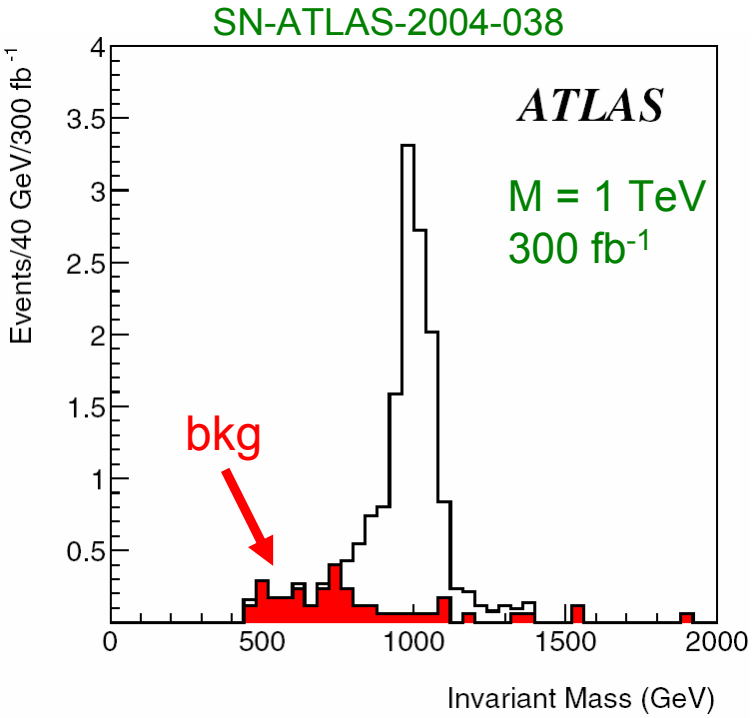


CMS PTDR 2006



EWSB: Little Higgs

- Models with Higgs as pseudo-Goldstone boson from a broken global symmetry (SU(5) in "littlest Higgs model")
  - Extra Q=2/3 heavy quark (T) and heavy gauge bosons (A_H, W_H, Z_H)
  - Quadratic divergences cancel top and VB divergences to Higgs mass
- Production: via QCD ($gg \to T\bar{T}$, $q\bar{q} \to T\bar{T}$)
  via W exchange ($qb \to q' T$) dominant for $M_T > 700$ GeV
- Decays: $T \to t Z$, $T \to t H$, $T \to b W$
  - cleanest is $T \to t Z \to b l \nu l^+ l^-$
    main bkg is tbZ
    5σ signal up to ~1.0-1.4 TeV
  - $T \to t H \to b l \nu b \bar{b}$ < 5σ
  - $T \to b W \to b l \nu$
    main bkg is $t\bar{t}$
    5σ signal up to ~2.0-2.5 TeV



Little Higgs

- A_H, W_H and Z_H discovery in lepton modes up to M ~ 6 TeV (depending on param cot θ)
- Discrimination against other models predicting dilepton resonances via observation of decay modes like $W_H \rightarrow W\ H$, $Z_H \rightarrow Z\ H$, and $W_H \rightarrow t\ \bar{b}$ (important at cot θ ≈ 1)

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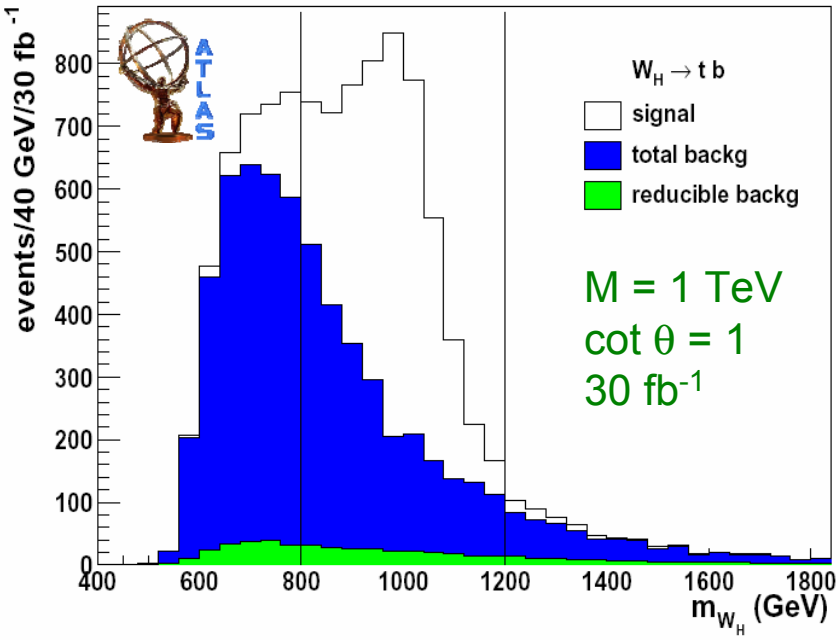
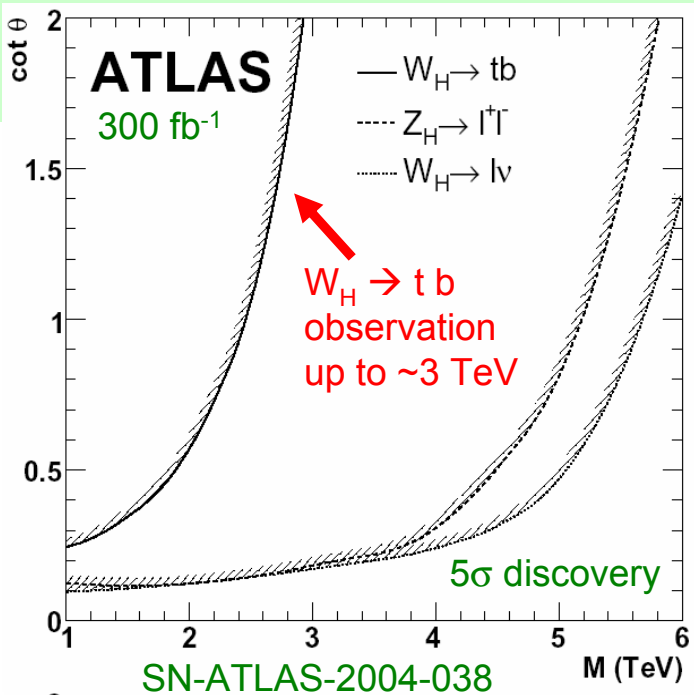


Exp^t Issue:
- optimize b-tag at high p_T



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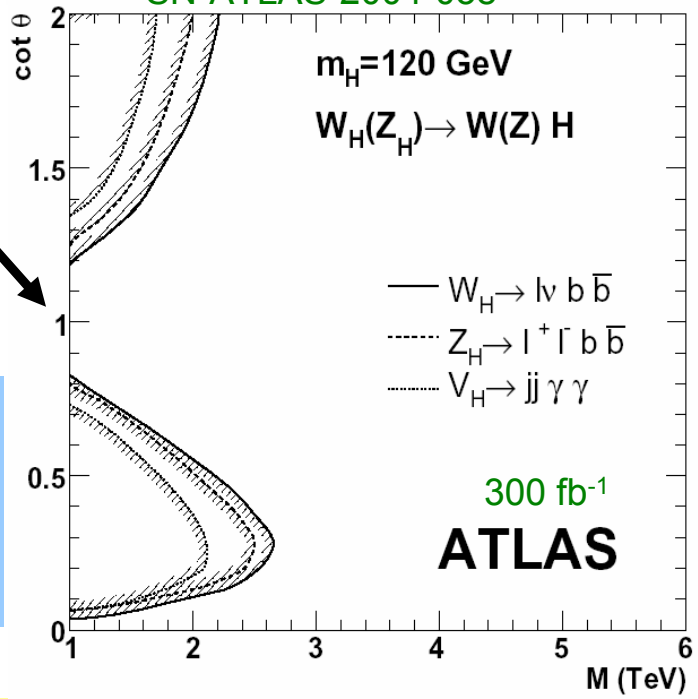
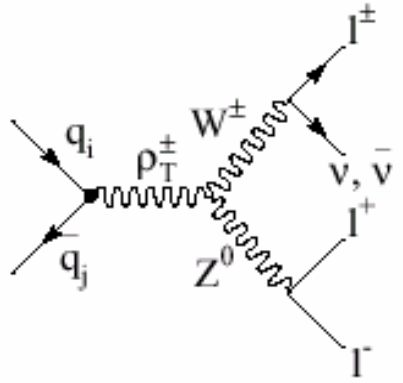
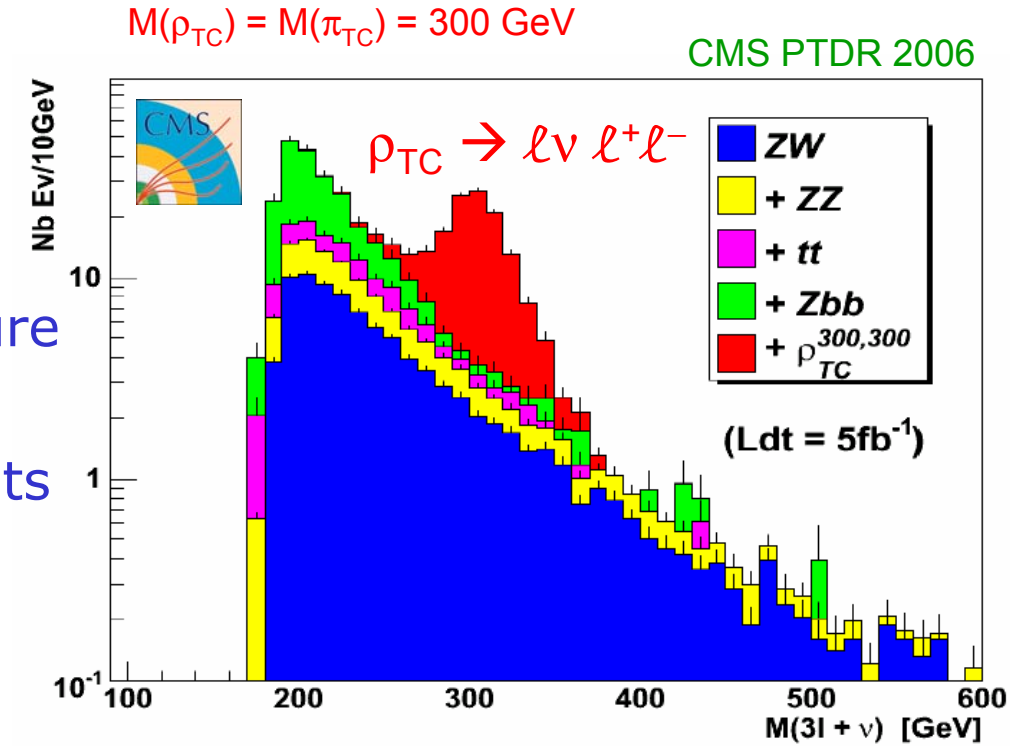


Dynamical EWSB: Technicolor

- Dynamical EWSB via new strong interaction
  - No need for Higgs boson ➔ removes fine tuning problem
  - Predict new technifermions, technihadrons
- Study ρ_{TC} → W Z process (*clean* with leptonic W & Z decays):



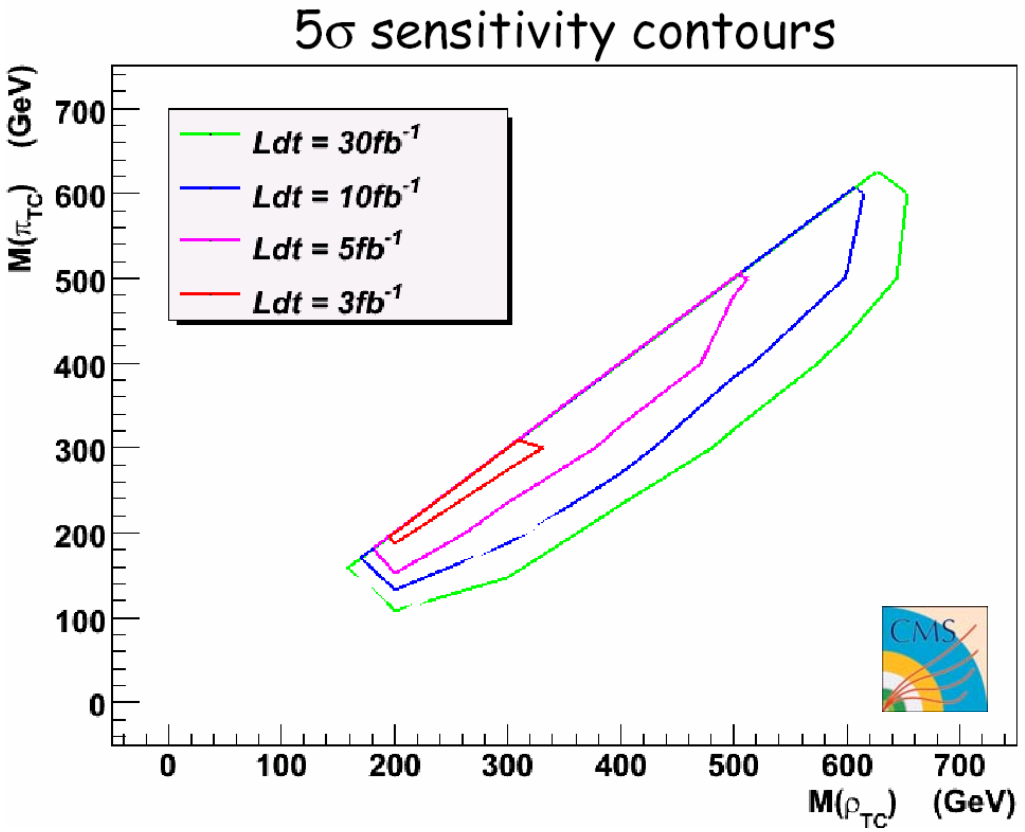
- Select isolated leptons, measure missing E_T & apply W and Z kinematical constraints
- Bkg: WZ, ZZ, $Zb\bar{b}$, $t\bar{t}$



Technicolor

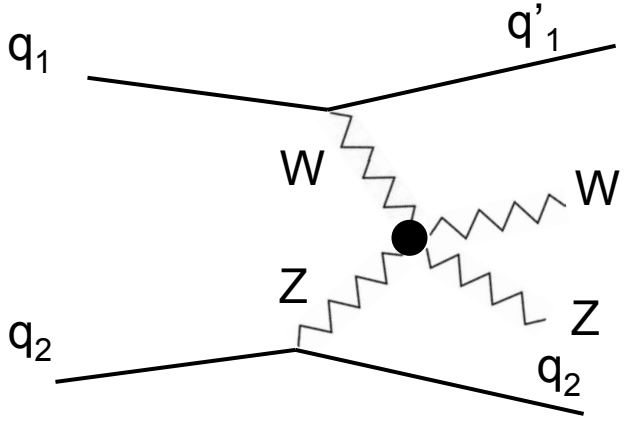
- 5σ discovery contour for $\rho_{TC} \rightarrow W\ Z$

CMS PTDR 2006



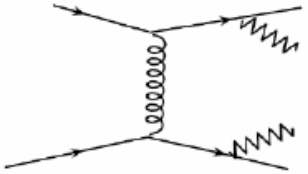
EWSB: Resonant Vector Boson Scattering

- SM cross section for W_{long} W_{long} scattering diverges at high energy if there is no Higgs ➔ new physics via diboson resonances?
- Chiral Lagrangian Model
  - low-energy effective description of electroweak interactions
    → yields interaction terms describing VB scattering with arb. coeffs.
  - respects chiral symmetry via $SU(2)_L \otimes SU(2)_R$
  - choose parameters such that new resonance M = 1.15 TeV
- Study W Z scattering (cleaner than W W + to reconstruct mass):
  - qq → qqWZ → qq $\ell\nu$ $\ell\ell$ (σ x BR= 1.3 fb)
  - qq → qqWZ → qq jj $\ell\ell$ (σ x BR= 4.1 fb)
  - qq → qqWZ → qq $\ell\nu$ jj (σ x BR= 14 fb)



Resonant Vector Boson Scattering

- Selection: 2 forward jets + central jets and/or leptons
  + missing E_T (for $W \rightarrow \ell \nu$)
  Require no additional central jet & b-jet veto (for jet modes)
- Bkg: gluon and γ/Z exchange with W and Z radiation
  also $t\bar{t}$ & W+4 jets (need more stats)



- Exp^t issues:
  - Merging of jets from high-pT W or Z decay (need cone $\Delta R = 0.2$)
  - Impact of pileup on forward jet tagging?
- Promising sensitivity for jet modes at 100 fb^{-1}
  (need 300 fb^{-1} for WZ $\rightarrow \ell\nu\ \ell\ell$)
  $\rightarrow$ study is ongoing

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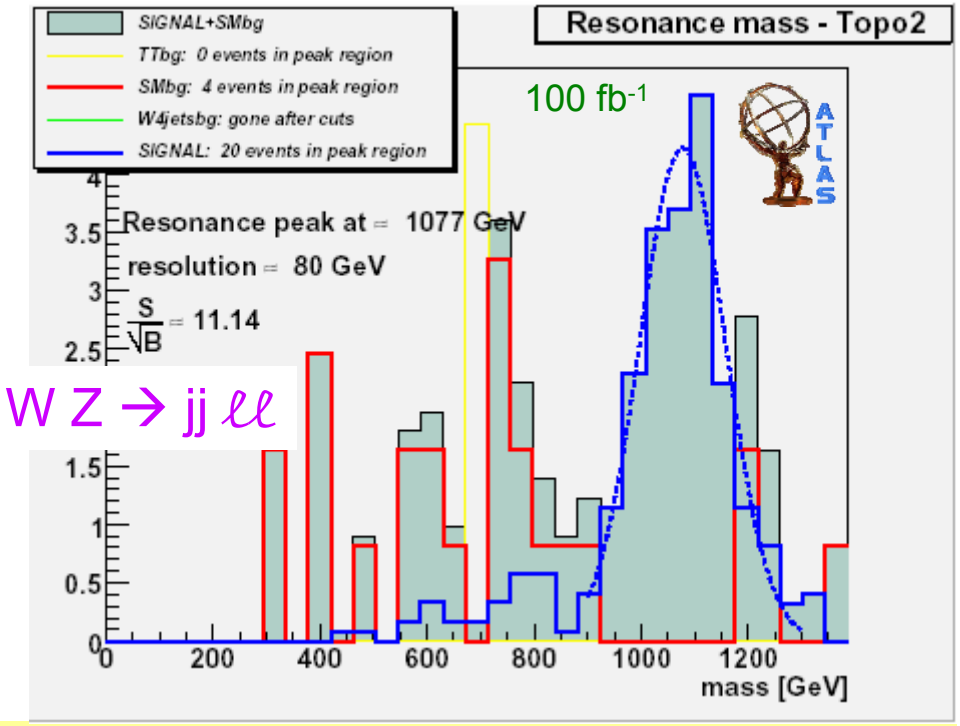
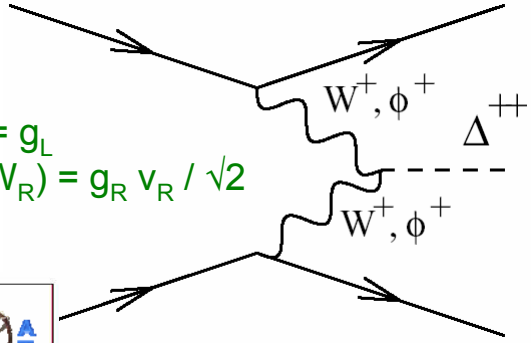


Doubly-Charged Higgs in LR Symmetric Model

- Left-Right Symmetric Model based on $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$
  - Features triplet of Higgs fields (Δ_R^0, Δ_R^+, Δ_R^{++}) + two doublets ϕ
  - Predicts new gauge bosons (W_R and Z_R) & new fermions (ν_R)
  - Addresses origin of pure left-handed charged weak interaction + origin of light neutrino masses (via see-saw mech. & heavy ν_R)

- Production: $qq \rightarrow q'q' W_{R,L}^+ W_{R,L}^+ \rightarrow q'q' \Delta_{R,L}^{++}$

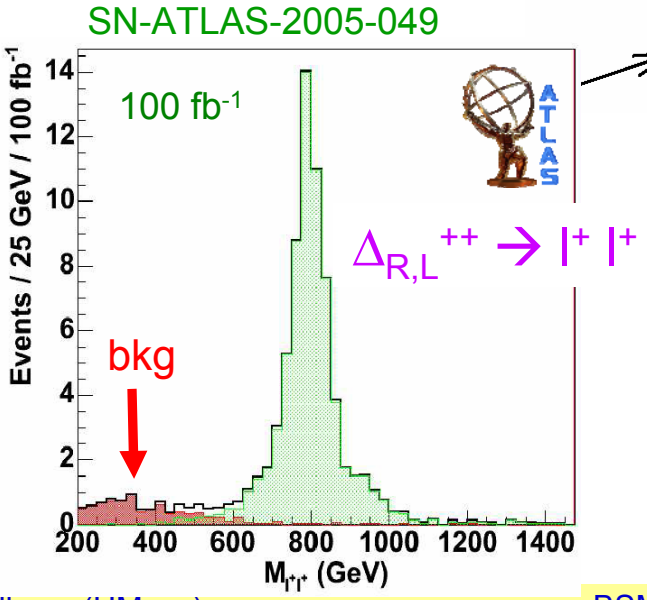
  $q\bar{q} \rightarrow \gamma^*/Z/Z_{R,L} \rightarrow \Delta_{R,L}^{++} \Delta_{R,L}^{--}$



- Decay: $\Delta_{R,L}^{++} \rightarrow l^+ l^+$

- Selection (WW fusion):
  2 like-sign leptons (e, μ, τ)
  + "forward" jets

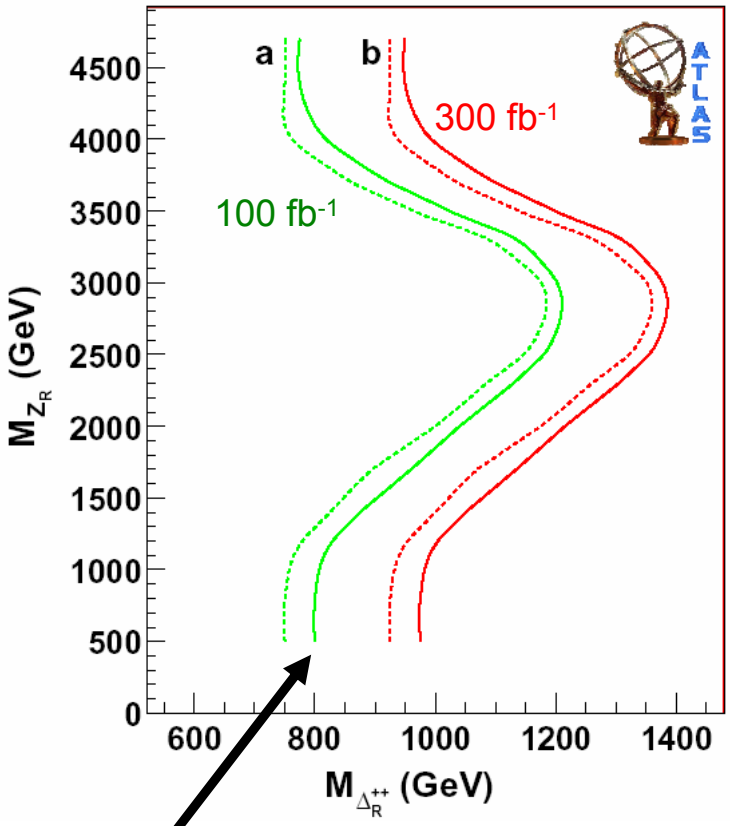
- Bkg: $W^+ W^+ q q$, $W t \bar{t}$

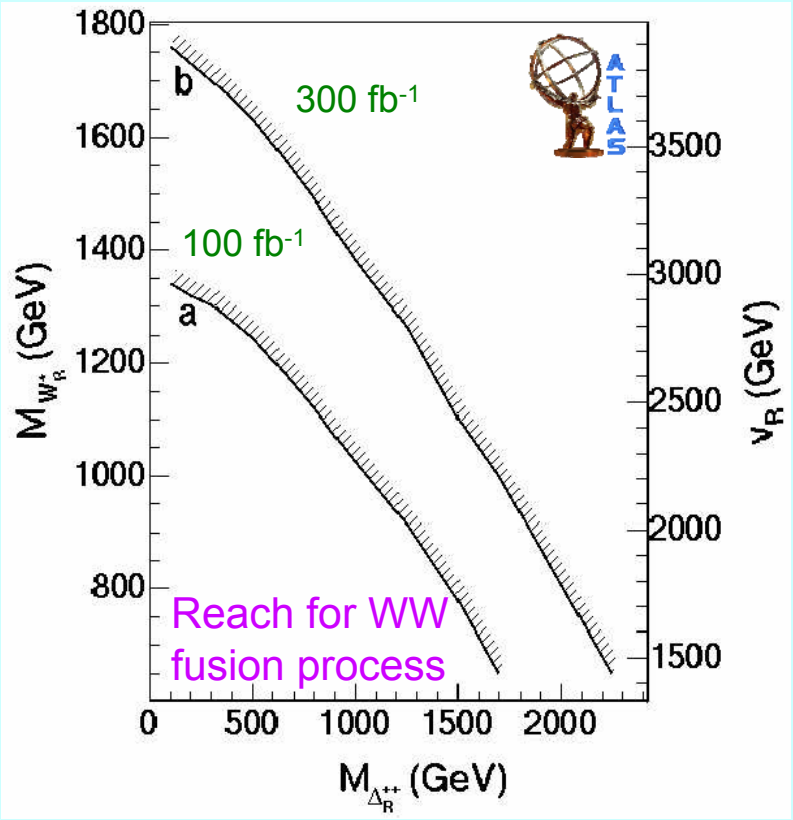


Doubly-Charged Higgs in LR Symmetric Model

- Selection ($\Delta_{R,L}^{++}\ \Delta_{R,L}^{--} \rightarrow 4\ell$ process):
  2 pairs of like-sign leptons (e, μ, τ)
- Bkg: negligible
- Contours for ≥ 10 signal events

SN-ATLAS-2005-049



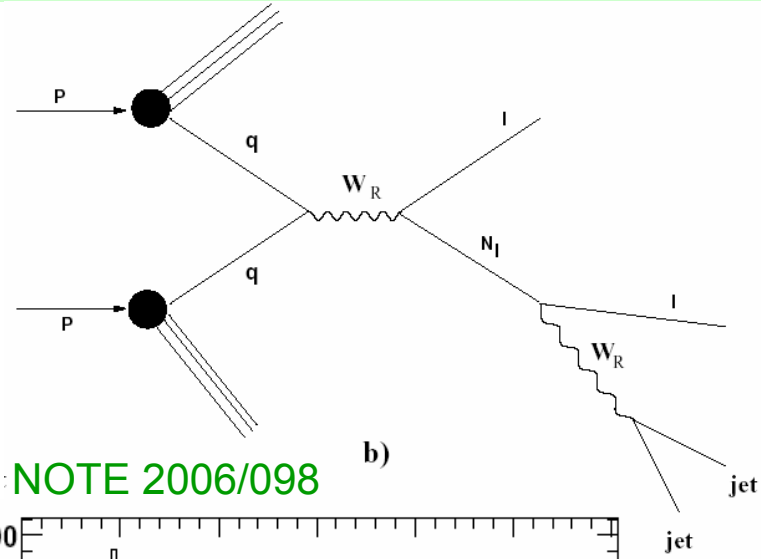


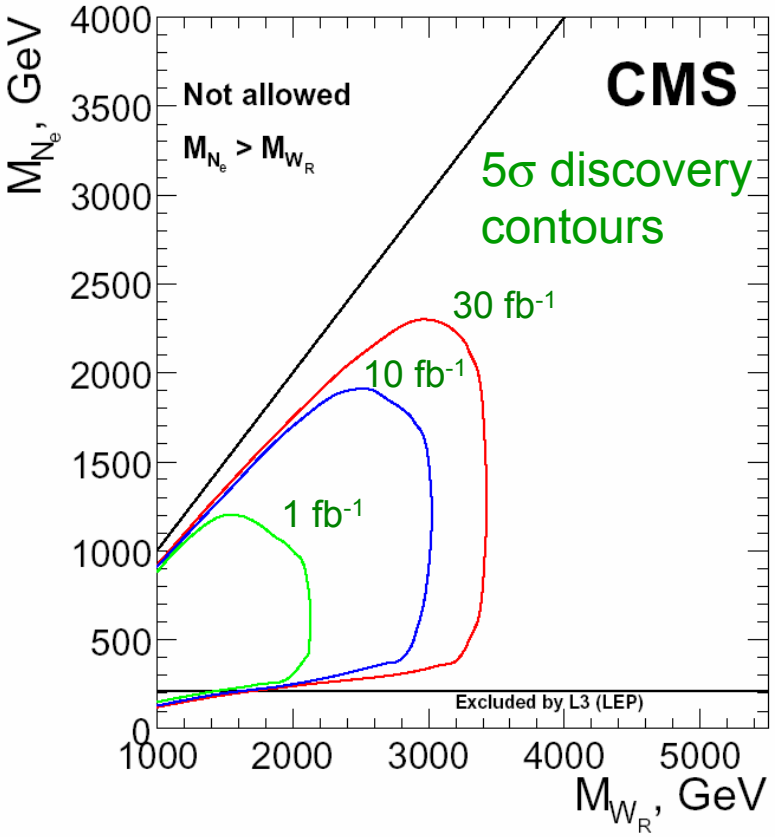
Reach improves if only
3 leptons are required (solid lines)

➔ Δ_R^{++} Mass reach 0.8 – 1.2 TeV (100 fb^{-1})
0.9 – 1.4 TeV (300 fb^{-1})

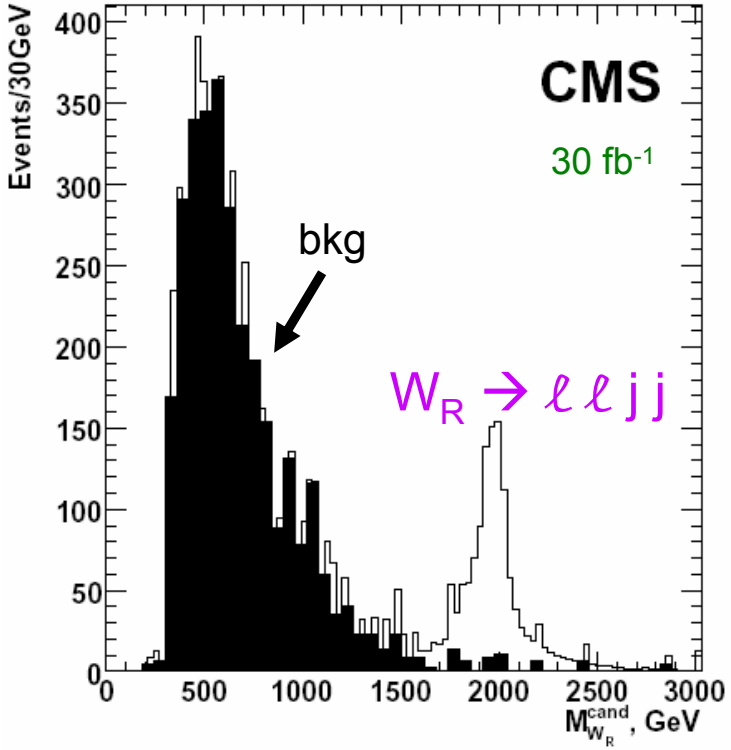
W_R and Majorana Neutrinos

- Left-right symmetric model
- Signature:
  lepton + 2 jets for heavy neutrino N_l
  dilepton + 2 jets for W_R



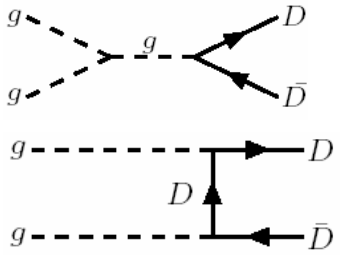


CMS NOTE 2006/098



Heavy Quarks

- Symmetry group E_6 favored by string-inspired GUTs (supergravity)
  - Predicts new Q=-1/3 quark
- Production: $gg \rightarrow D\bar{D}$ (dominant for $M_D < 1.1$ TeV)
  $q\bar{q} \rightarrow D\bar{D}$ (dominant for $M_D > 1.1$ TeV)



- Decay: $D \rightarrow W\ u$ or $D \rightarrow Z\ d$ (for this study)
- Selection: 4 leptons (from Z)
  + 2 jets

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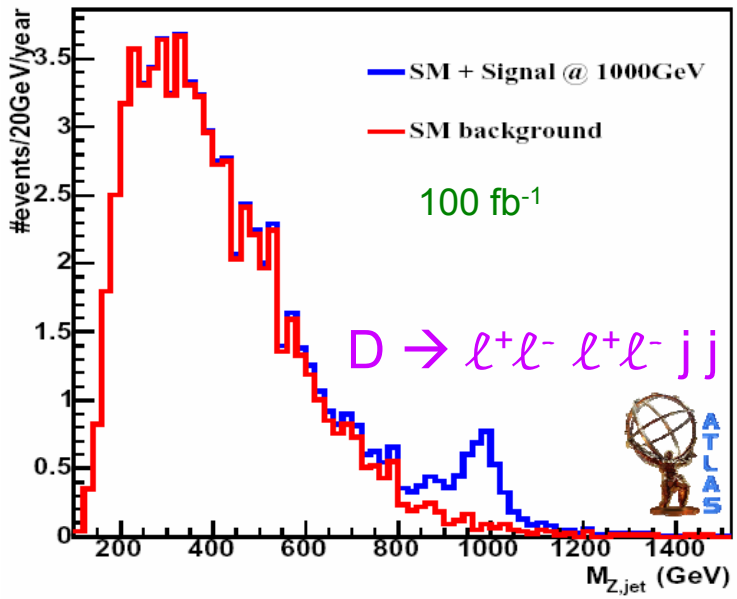
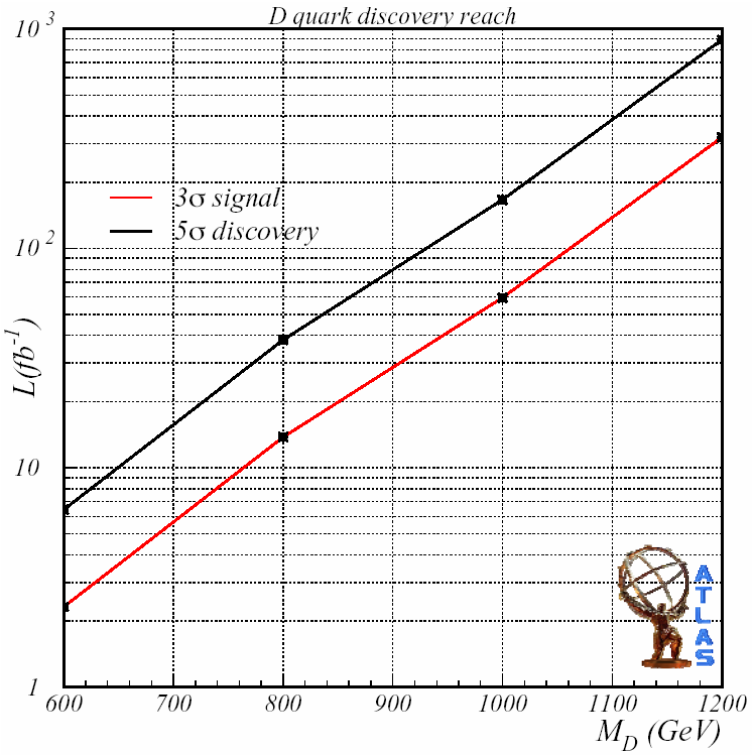
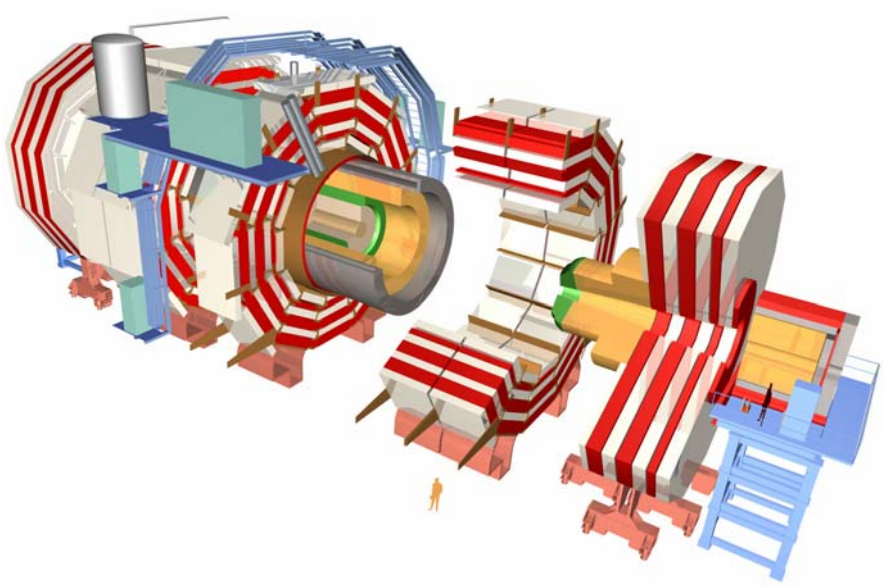


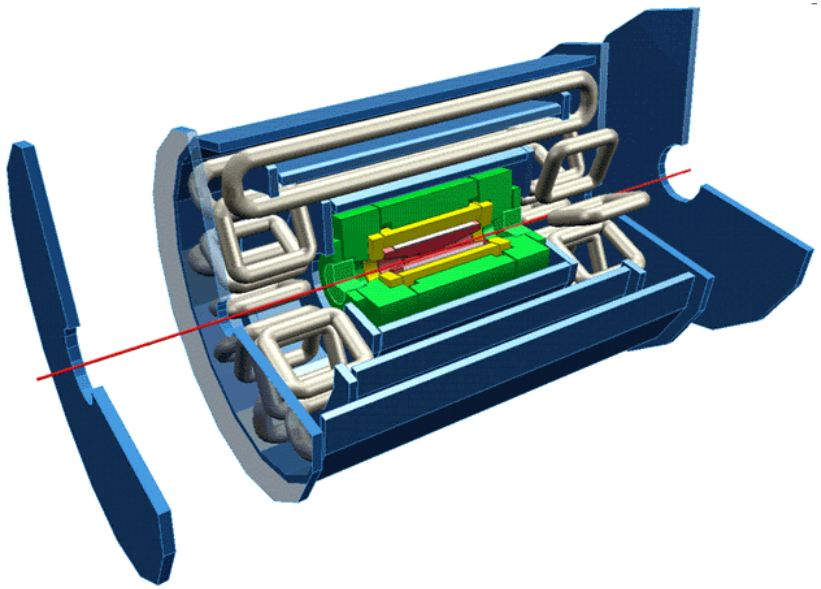


Summary & Outlook

- ATLAS & CMS have significant discovery potential related to fundamental symmetries, Electroweak symmetry breaking, and quark-lepton family structure
  - Heavy gauge bosons up to ~5-6 TeV
  - Little Higgs T quark up to ~2 TeV
  - Vector boson resonances; Technihadron ρ_{TC} mass up to ~600 GeV
  - Doubly-charged Higgs up to ~2 TeV
  - Heavy neutrino up to ~2.5 TeV, heavy D quark up to ~1 TeV
  - *Many more topics not covered*
- ATLAS & CMS increasing focus on first year of data taking
  - Understand/optimize detector performance (calibration, alignment, …)
  - Understand/measure Standard Model processes (bkg sources)
- **Eager to start exploration of TeV scale!**

Backup Slides





References

- *CMS Physics Technical Design Report Vol. II*
  G.L. Bayatian et al., CERN/LHCC 2006-021
  + (many) references therein
- *Z' → ee in Full Simulation*
  R.Schaffer et al., ATLAS-PHYS-PUB-2005-010
- *Exploring Little Higgs models with ATLAS at the LHC*
  G.Azuelos et al., SN-ATLAS-2004-38
- *Search for hadronic decays of Z_H and W_H in the Little Higgs model*
  S.de la Hoz, L.March, E.Ros, ATL-PHYS-PUB-2006-003
- *Resonant Vector Boson Scattering at High Mass*
  G.Azuelos et al., ATLAS-COM-PHYS-2006-041
- *Prospects for the search for a Doubly-Charged Higgs in the Left-Right Symmetric model*
  G.Azuelos, K.Benslama, J.Ferland, SN-ATLAS-2005-049
- *Detection of heavy Majorana neutrinos and right-handed bosons*
  S.N.Gninenko et al., CMS NOTE 2006/098
- *Search for E6 isosinglet quarks in ATLAS*
  R.Mehdiyev et al., SN-ATLAS-2006-056

A Toroidal LHC AppartuS (ATLAS) DETECTOR

EM Calorimeters, $\sigma/E \approx 10\%/\sqrt{E(GeV)} \oplus 0.7\%$

excellent electron/photon identification

Good *E* resolution (e.g., $H \rightarrow \gamma\gamma$)

Precision Muon Spectrometer,

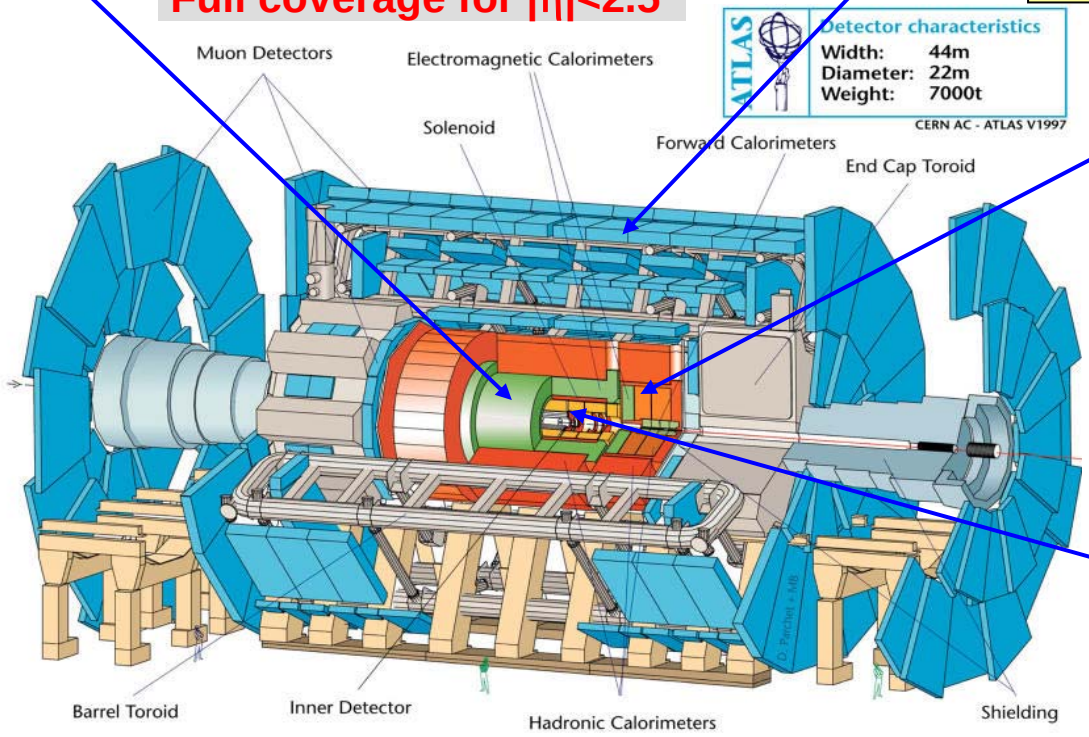
$\sigma/p_T \approx 10\%$ at 1 TeV/c

Fast response for trigger

Good *p* resolution

(e.g., $A/Z' \rightarrow \mu\mu$, $H \rightarrow 4\mu$)

Full coverage for $|\eta|<2.5$



Hadron Calorimeters,

$\sigma/E \approx 50\% / \sqrt{E(GeV)} \oplus 3\%$

Good jet and E_T miss performance

(e.g., $H \rightarrow \tau\tau$)

Inner Detector:

Si Pixel and strips (SCT) &

Transition radiation tracker (TRT)

$\sigma/p_T \approx 5 \times 10^{-4}\ p_T \oplus 0.001$

Good impact parameter res.

$\sigma(d_0)$=15μm@20GeV (e.g. $H \rightarrow b\bar{b}$)

Magnets: solenoid (Inner Detector) 2T, air-core toroids (Muon Spectrometer) ~0.5T

Compact Muon Solenoid (CMS) DETECTOR

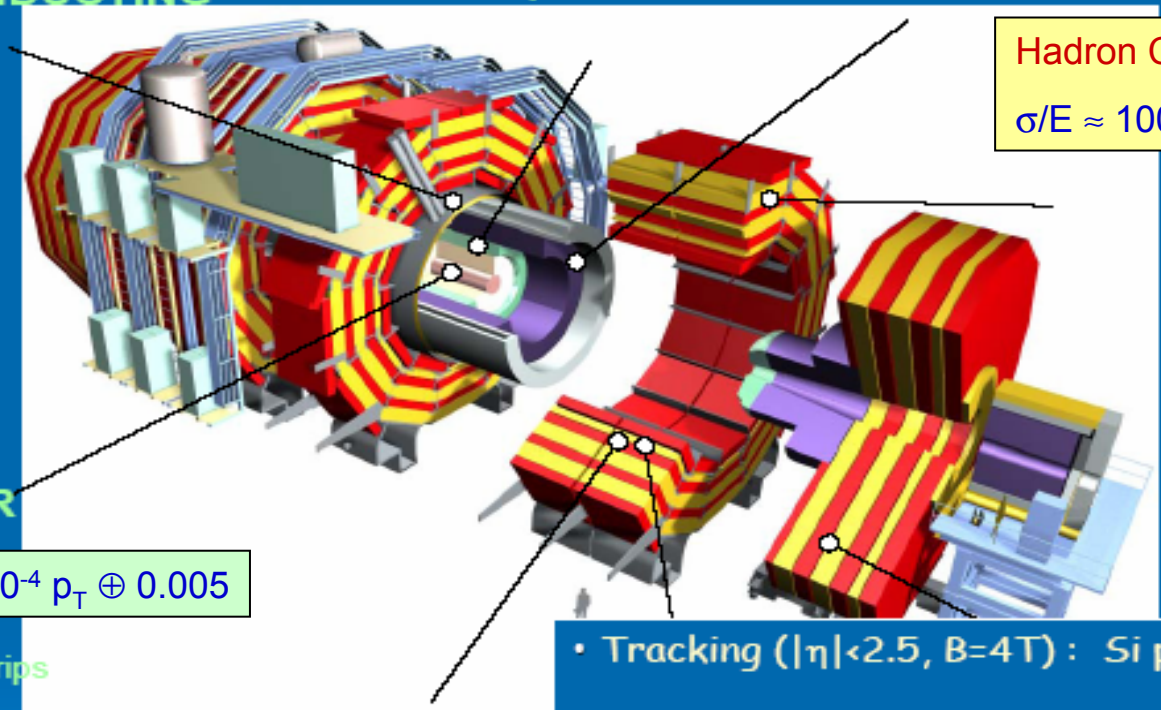
EM Calorimeter,

$\sigma/E \approx 3\%/\sqrt{E(GeV)} \oplus 0.5\%$

CALORIMETERS

Scintillating PbWO4 crystals — ECAL — HCAL — Plastic scintillator/brass sandwich

SUPERCONDUCTING COIL



Hadron Calorimeter,

$\sigma/E \approx 100\% / \sqrt{E(GeV)} \oplus 5\%$

IRON YOKE

TRACKER

$\sigma/p_T \approx 1.5 \times 10^{-4}\ p_T \oplus 0.005$

Silicon Microstrips
Pixels

- 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

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

MUON E

Drift Tube Chambers

Muon Spectrometer,

$\sigma/p_T \approx 5\%$ at 1 TeV/c (from Tracker)

ATLAS Inclusive Trigger Selection Signatures

- To select an extremely broad spectrum of "expected" and "unexpected" Physics signals (hopefully!).
- The selection of Physics signals requires the identification of **objects** that can be **distinguished** from the high particle density environment.

Object	Examples of physics coverage	Nomenclature
Electrons	Higgs (SM, MSSM), new gauge bosons, extra dimensions, SUSY, W/Z, top	e25i, 2e15i
Photons	Higgs (SM, MSSM), extra dimensions, SUSY	γ60i, 2γ20i
Muons	Higgs (SM, MSSM), new gauge bosons, extra dimensions, SUSY, W/Z, top	μ20i, 2μ10
Jets	SUSY, compositeness, resonances	j360, 3j150, 4j100
Jet+missing E_T	SUSY, leptoquarks, "large" extra dimensions	j60 + xE60
Tau+missing E_T	Extended Higgs models (e.g. MSSM), SUSY	τ30 + xE40

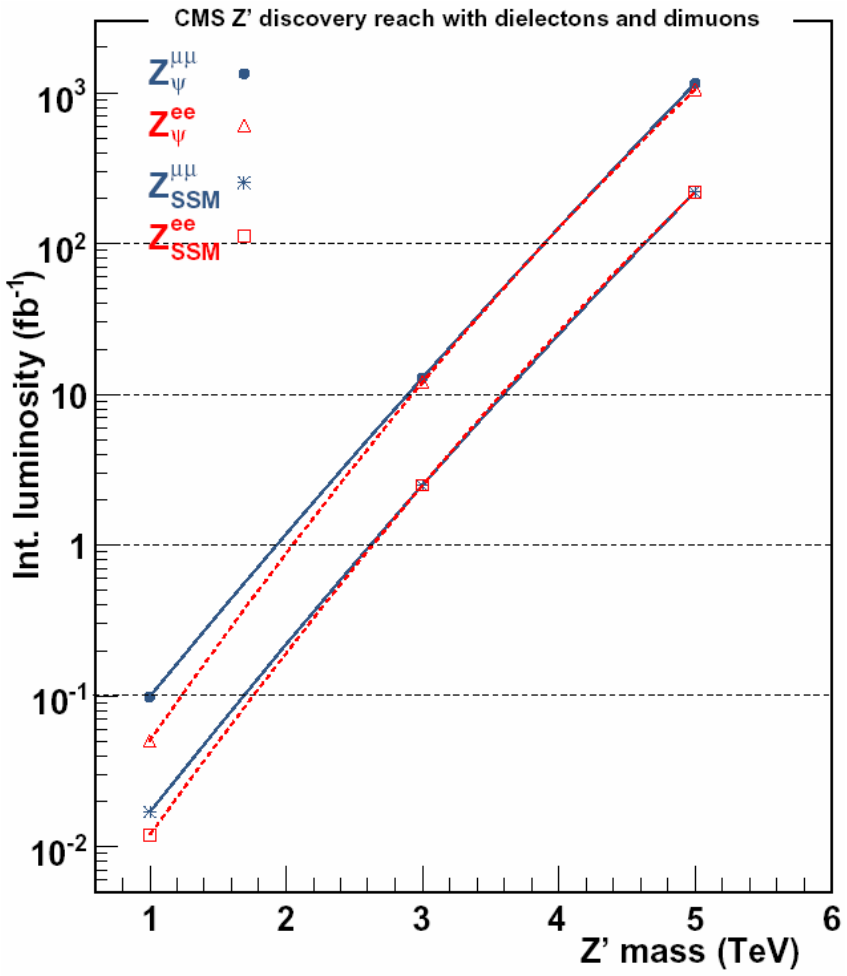
also inclusive missingET, SumET, SumET_jet

& many prescaled and mixed triggers

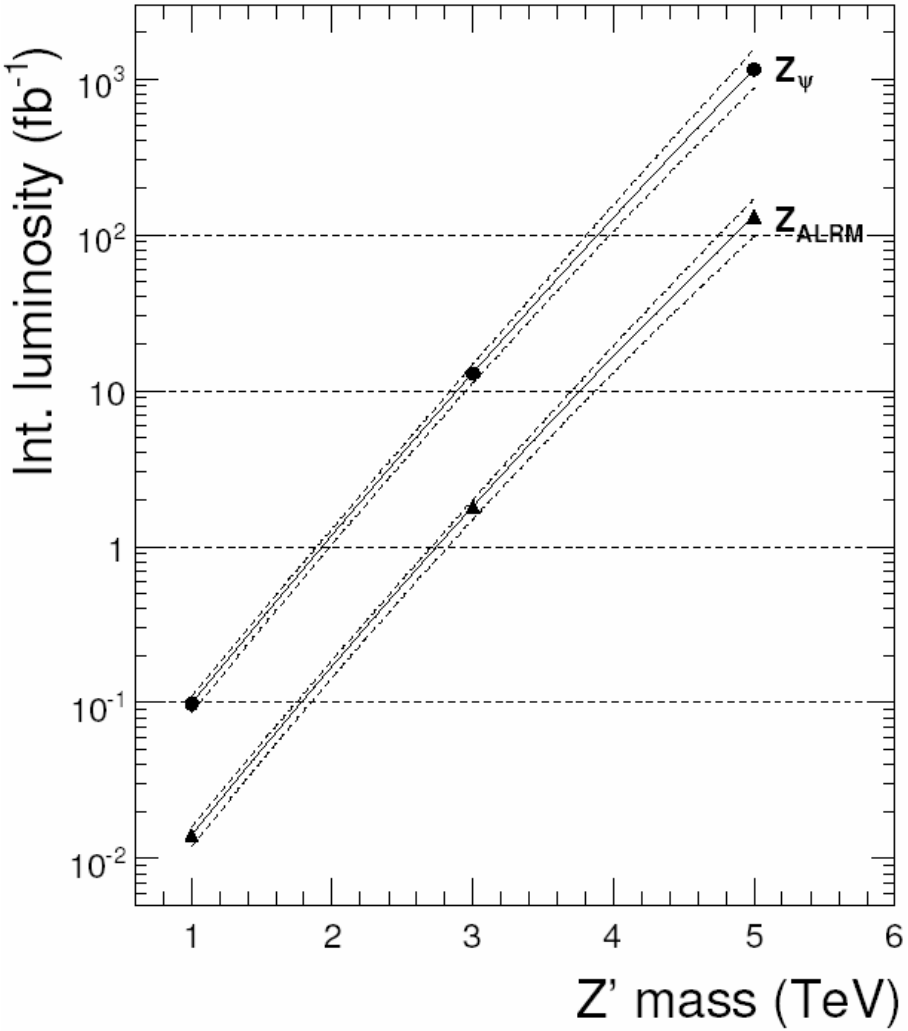
The list must be non-biasing, flexible, include some redundancy, extendable, to account for the "unexpected".

Heavy Gauge Bosons: Z'

- CMS Z' studies (TDR): integrated luminosity needed for 5σ signal



Z' 5σ reach ee vs. μμ channels



Z' 5σ reach: impact of theory uncertainties