Analyses of high mass resonances at ATLAS and CMS

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On behalf of the ATLAS and CMS collaborations

Outline

- Introduction
- Detectors
- Dileptons: ee, $\mu\mu$, $\tau\tau$
- Lepton-neutrino
- Lepton(s) plus jet(s)
- Dijets
- Conclusion and outlook

Introduction

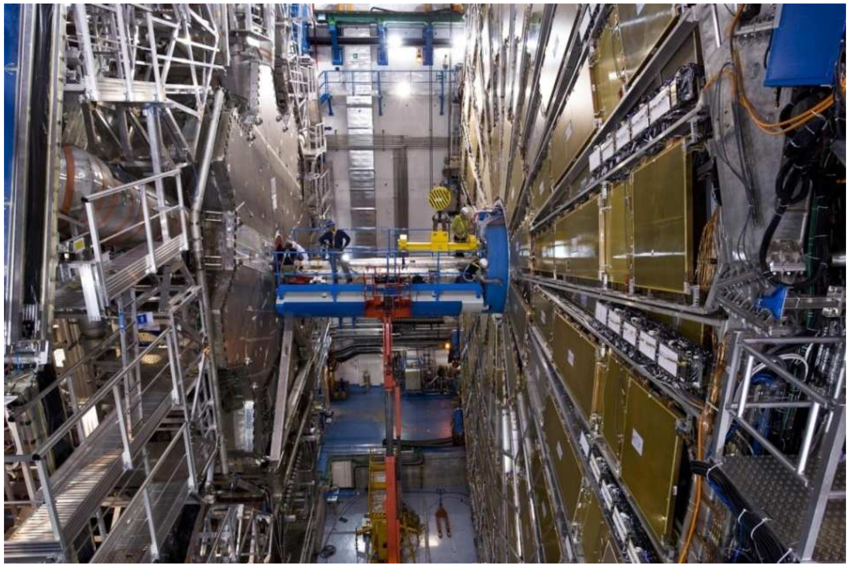
- Although extremely successful, there are indications that the Standard Model (SM) is not a complete theory
- Plausible SM extensions predict narrow states that can be reconstructed (completely or not) in ATLAS and CMS
  - Dileptons (e, μ, τ):
    - New heavy gauge bosons (Z'), KK resonances, gravitons
  - Diphotons (see H. Hadavand's talk)
  - Lepton + Missing Transverse Energy
    - New heavy W-like boson
  - Leptons plus Jets
    - Leptoquarks
    - Left-Right Symmetric Models
  - Dijets (see K. Terashi's talk)
- Results shown correspond to a center of mass energy of 14TeV
  - At 10 TeV, cross sections ~ 50%-75% smaller in 100GeV to 1TeV

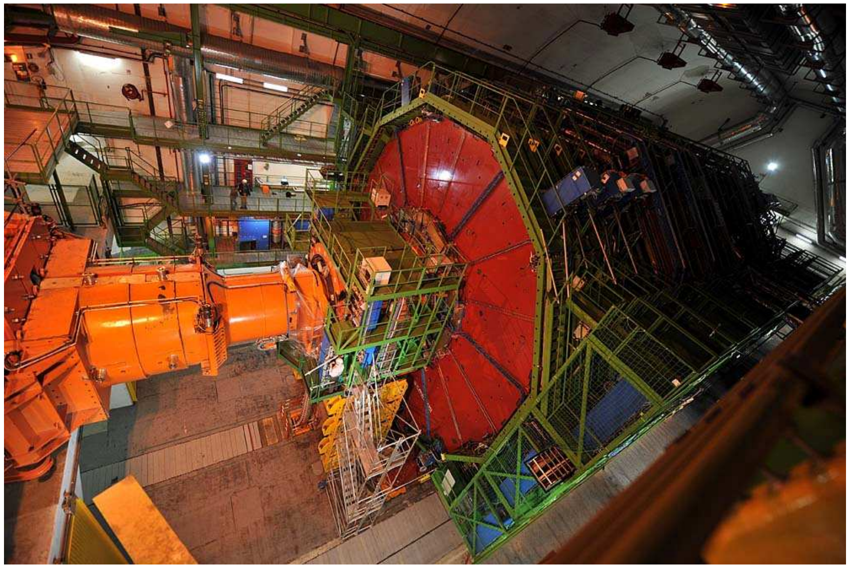
LHC

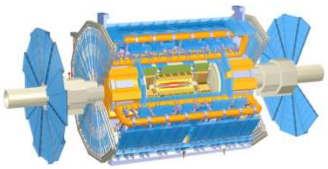
- Operating parameters
  - E_{beam} = 7 TeV → **5 TeV**
  - L = 10^{34} cm^{-2}s^{-1} → **10^{30}-10^{32} cm^{-2}s^{-1}**
  - Bunch Spacing = 25 ns (40 MHz)
  - Pile-Up = 2-20 collisions/crossing
  - Duration of collisions ≈ 10-24 h
  - Down Time ≈ 1.5 h

Example Decay Channel	LEP (all)	Tevatron (all)	LHC 100 pb^{-1}	LHC 1 fb^{-1}
$W \to \mu\nu$	~10^4	~10^6	~10^6	~10^7
$Z \to \mu\mu$	~10^6	~10^5	~10^5	~10^6
$tt \to WbWb \to \mu\nu + X$		~10^4	~10^4	~10^5
QCD jets (p_T > 1 TeV)			~10^3	~10^4
Z'(1 TeV) $\to \mu\mu$			~20	~10^2

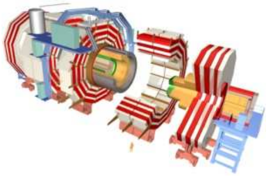
Detectors







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



Bending power

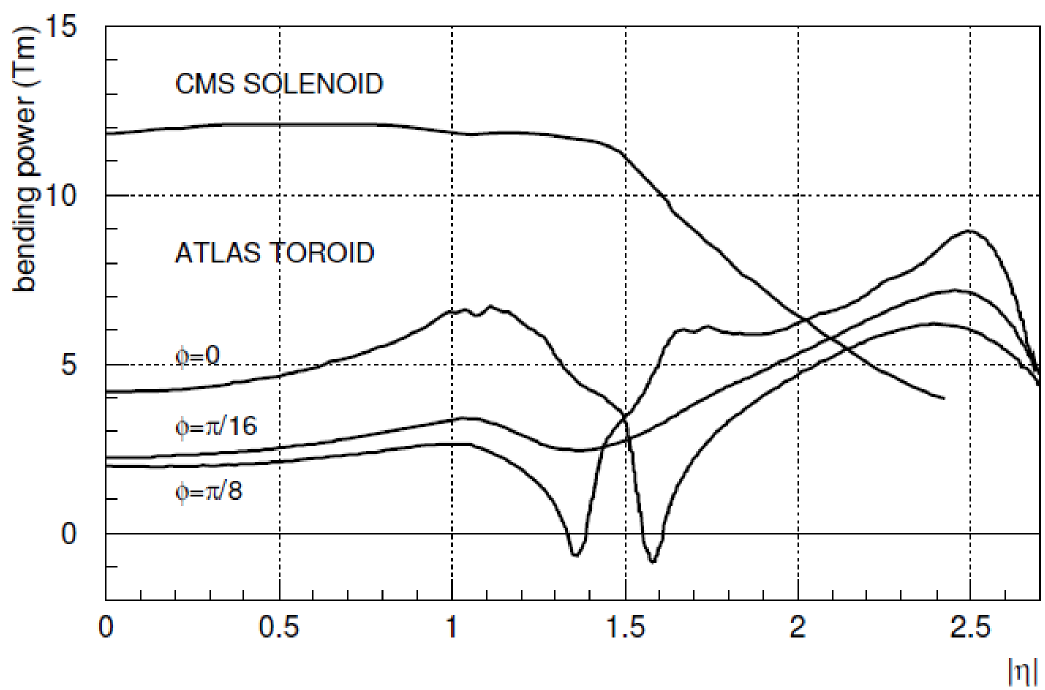
Rather than the peak values of the magnetic field, tracking capabilities depend on the *bending power* of the field configuration

$$\int \mathrm{d}\alpha = \int \frac{\mathrm{d}s}{R} = \int \left|\frac{\mathrm{d}^2\boldsymbol{r}}{\mathrm{d}s^2}\right| \mathrm{d}s = \frac{q}{p}\int \left|\frac{\mathrm{d}\boldsymbol{r}}{\mathrm{d}s} \times \boldsymbol{B}(\boldsymbol{r})\right| \mathrm{d}s$$

R: radius of curvature

s: distance along the trajectory

$\boldsymbol{r}$: position vector



Performance

	ATLAS	CMS
Tracker	Si pixels, strips + TRT (pid) $\sigma/p_T \approx 5\text{x}10^{-4} p_T \oplus 0.01$	Si pixels, strips $\sigma/p_T \approx 1.5\text{x}10^{-4} p_T \oplus 0.005$
EM calorimeter	Pb + LAr $\sigma/E \approx 10\%/\sqrt{E} \oplus 0.007$	$PbWO_4$ crystals $\sigma/E \approx 2\text{-}5\%/\sqrt{E} \oplus 0.005$
Hadronic calorimeter	Fe+scintillator / Cu + Lar $\sigma/E \approx 50\%/\sqrt{E} \oplus 0.03$	Cu+scintillator $\sigma/E \approx 100\%/\sqrt{E} \oplus 0.05$
Combined Muons (ID+MS)	2%@50GeV to 10%@1TeV	1%@50GeV to 5%@1TeV

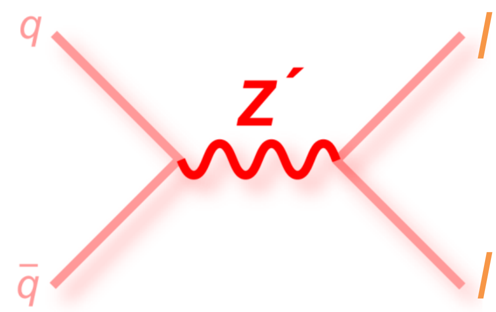
- Powerful id:
  - Photons: Jet rejection ~ few 10^3 for ~80% photon efficiency
  - Electrons: Jet rejection ~ 10^5 for ~60% electron efficiency
  - B-jets: Light flavor jet rejection ~ 100 for ~60% efficiency
  - $\tau \rightarrow$hadrons: Jet rejection ~ few hundreds for ~50% efficiency
- Missing transverse momentum and jet reconstruction

DILEPTONS

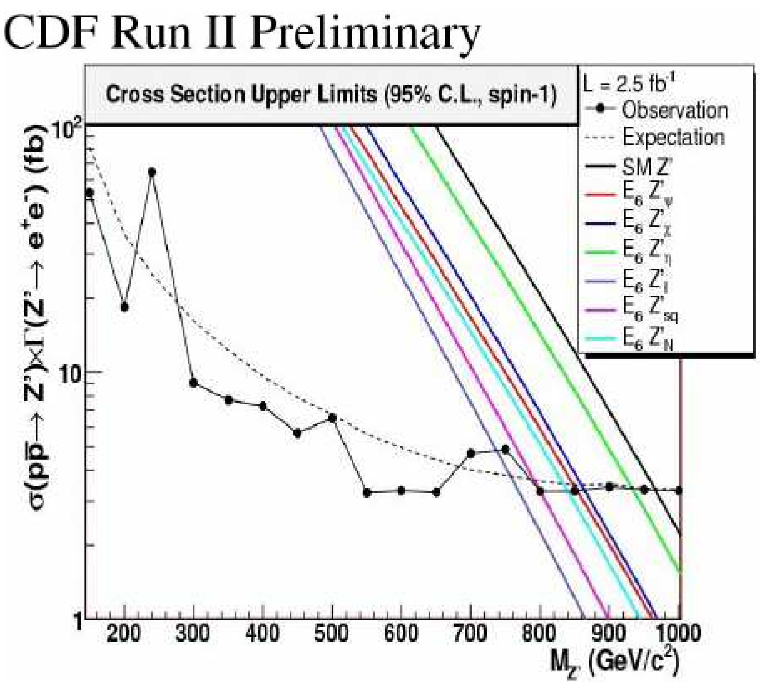
e, μ

Signature, selection

- Relatively clean signatures
- Good mass resolution
- Easy to trigger on



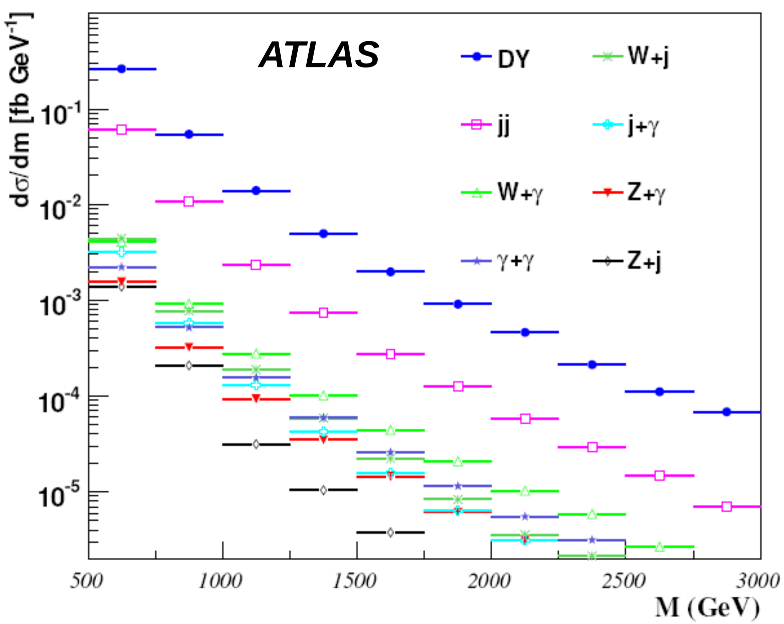
- Backgrounds
  - Main background: SM Drell-Yan
  - tt, dijets, W+jets, gamma+jets



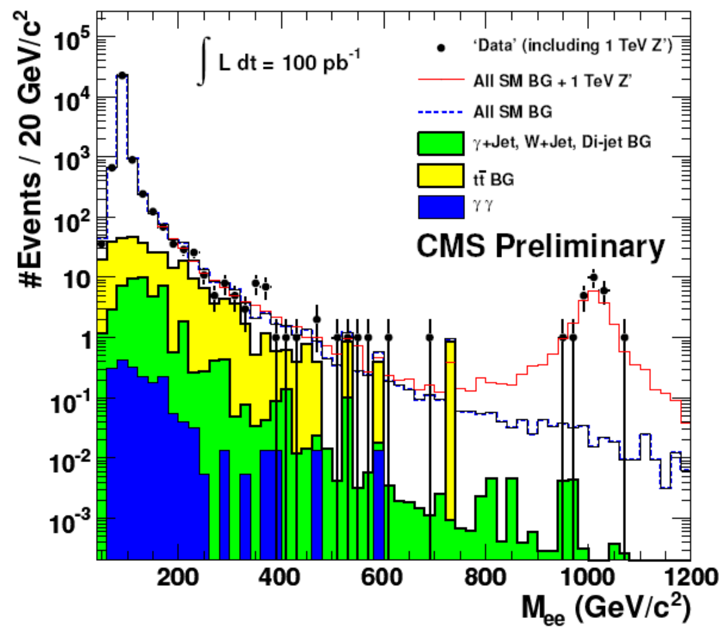
- Selection
  - 2 well reconstructed, isolated leptons
  - |eta|<2.5 (except muons in CMS, 2.4)
  - pT>30 or 50 GeV
  - Opening angle: not needed for discovery, but useful to help distinguish models

Backgrounds

- Drell-Yan
- Processes where jets or photons fake electrons
- Electron and muons from Z and W



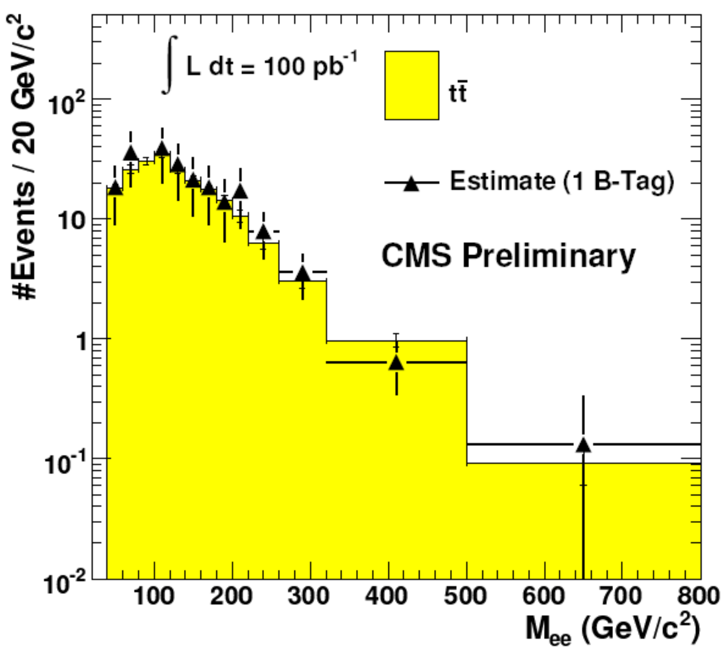
Generator-level estimation after applying current values of jet and photon rejection (10^4 and 10, respectively)

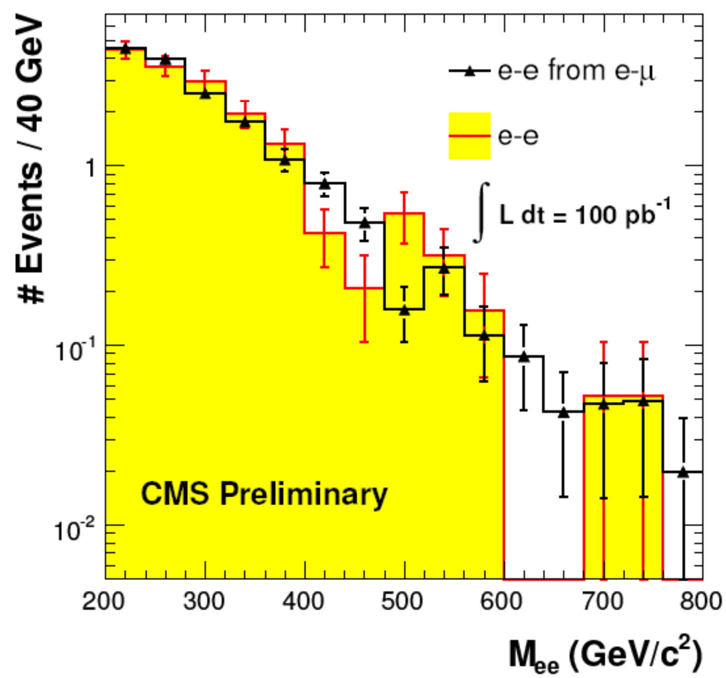


Full detector simulation

Background estimation

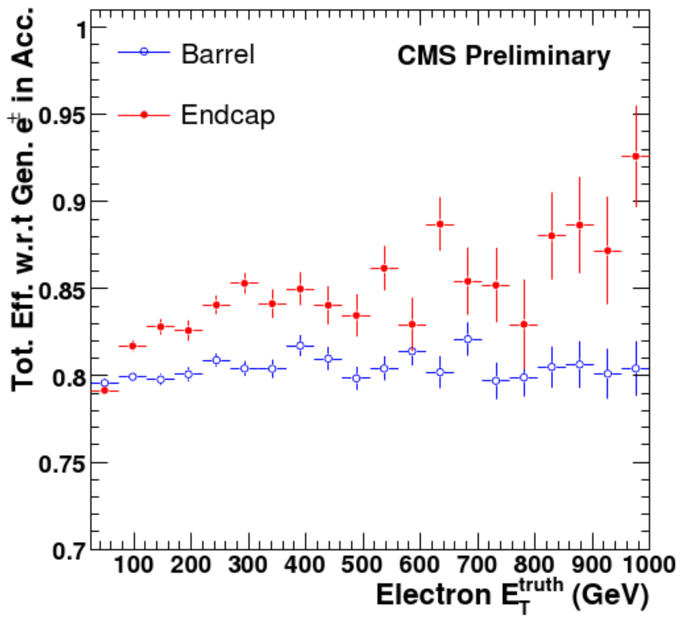
- Detector effects and theoretical uncertainties can affect the background estimation
- Control sample strategies can help constrain some of these backgrounds





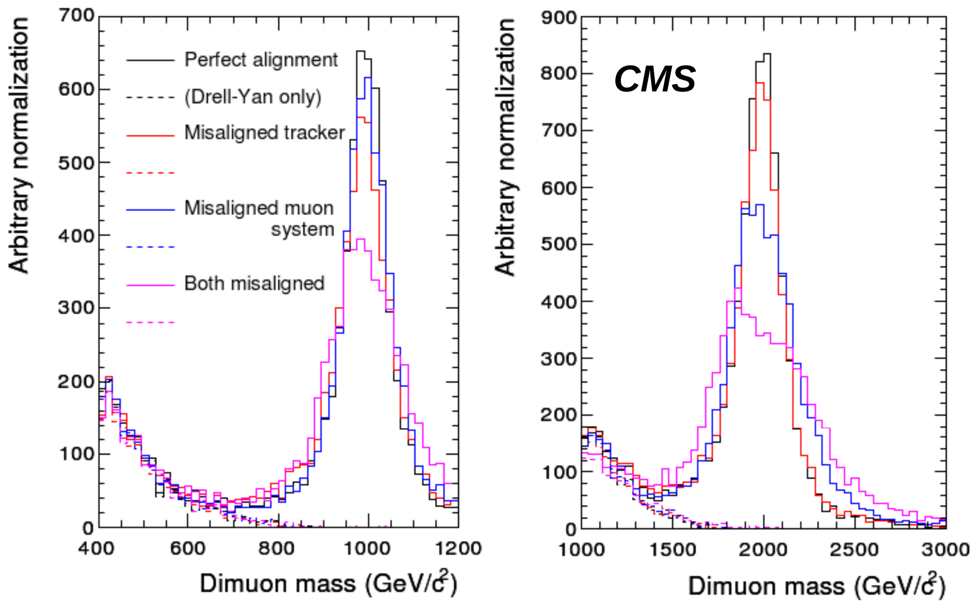
Electrons at high pT

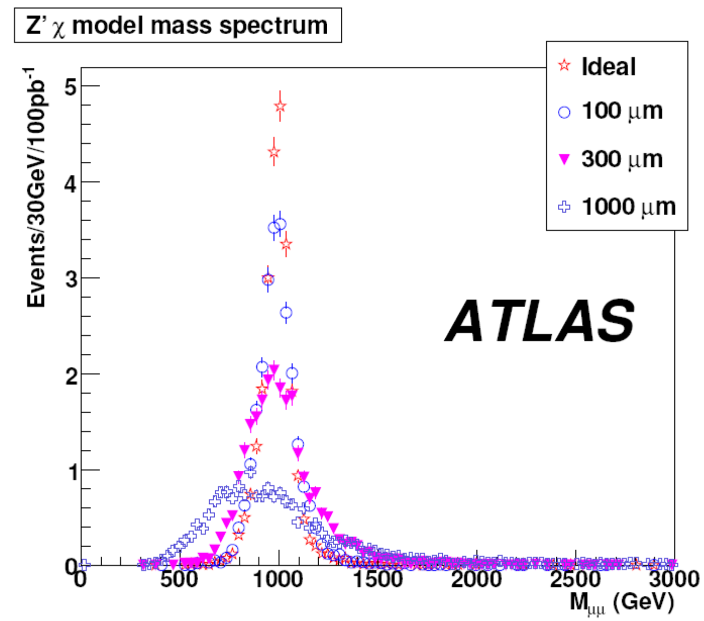
- Reconstruction and identification optimized for high energy electrons
  - Robust criteria based on shower shape, track matching, isolation
  - Efficiency ~ 80%
  - Jet rejection ~ 4×10^{-5}

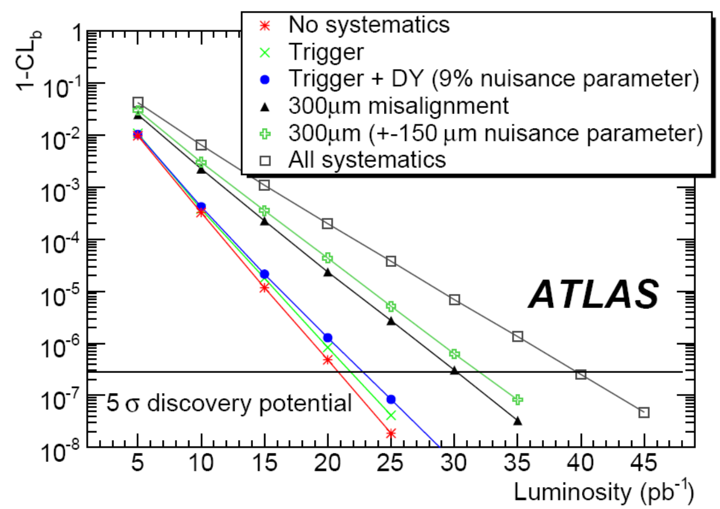


- ECAL saturation (CMS)
  - Large energy deposit in one crystal (1.7, 3 TeV for barrel, endcap)
  - Can be recovered using surrounding crystals

Muon system alignment







- Both experiments have evaluated the effect of possible scenarios
- Strong effect on physics potential
  - Roughly twice as much luminosity needed for discovery

Discovery potential

- Factorization of the PDF

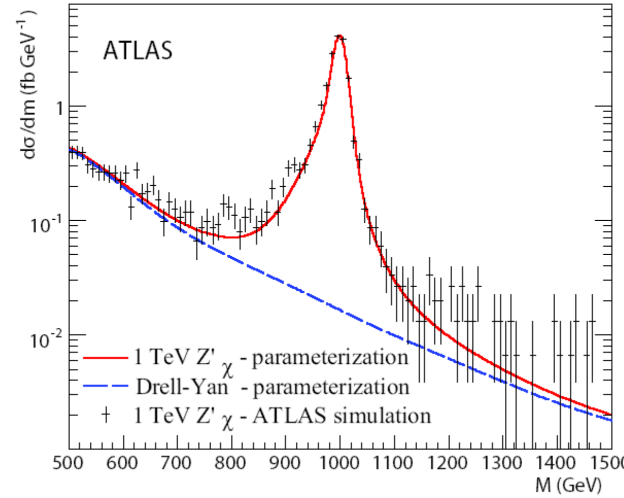
  Four parameters (Γ_Z, A_{peak}, A_{interf}, $M_{Z'}$)

$$\left.\frac{d\sigma}{dm}\right|_{\text{Signal}}(m) = \frac{1}{m^2} \times G_{PDF}(m)$$
$$+ \mathscr{A}_{\text{peak}} \times \frac{\Gamma_{Z'}^2}{m_{Z'}^2} \frac{m^2}{(m^2 - m_{Z'}^2)^2 + m_{Z'}^2 \Gamma_{Z'}^2} \times G_{PDF}(m)$$
$$+ \mathscr{A}_{\text{interf}} \times \frac{\Gamma_{Z'}^2}{m_{Z'}^2} \frac{m^2 - m_{Z'}^2}{(m^2 - m_{Z'}^2)^2 + m_{Z'}^2 \Gamma_{Z'}^2} \times G_{PDF}(m)$$

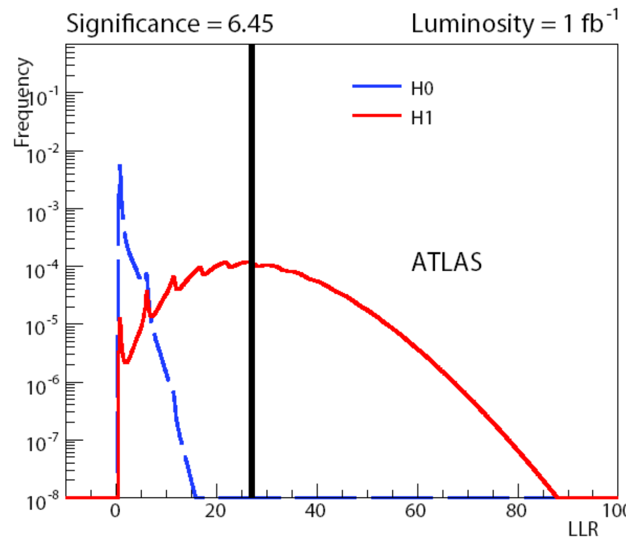
⊗ **Resolution** (from full simulation)

× **acceptance** (depends on the model)

× **efficiency of cuts**

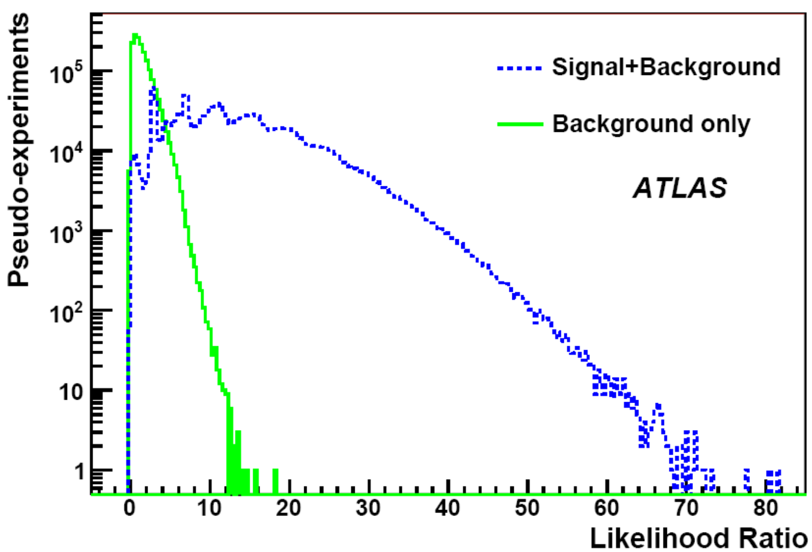


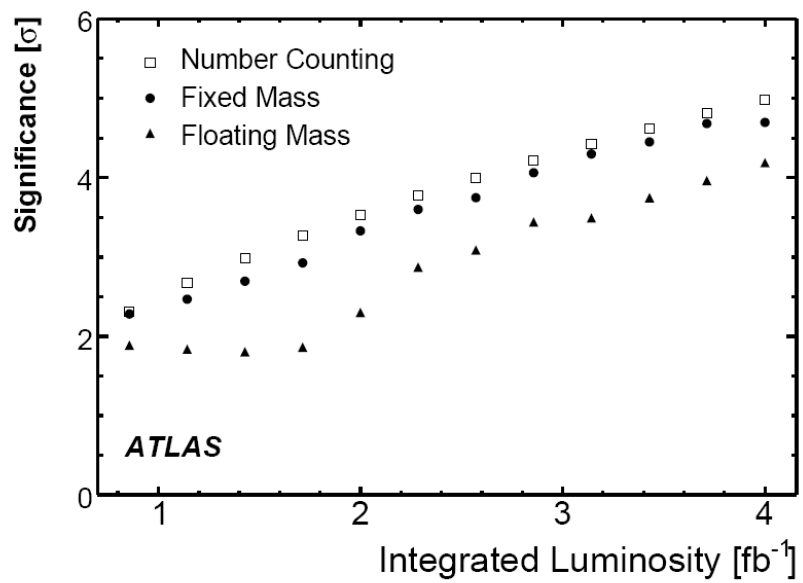
- Statistical analysis:
  - Log-likelihood ratio estimator (LLR)
  - Signal+Background and Background-Only LLR distributions used to compute CL_s
  - No need for an optimized mass window



"Look-elsewhere"

- "Trials factor", "greedy bump bias", …
- Background fluctuations anywhere in the full mass range under study increase the probability of a fake discovery
- Studied with toy MC using a (max Likelihood) fit-based approach; floating vs fixed mass fits
- Degradation of the significance of ~15%

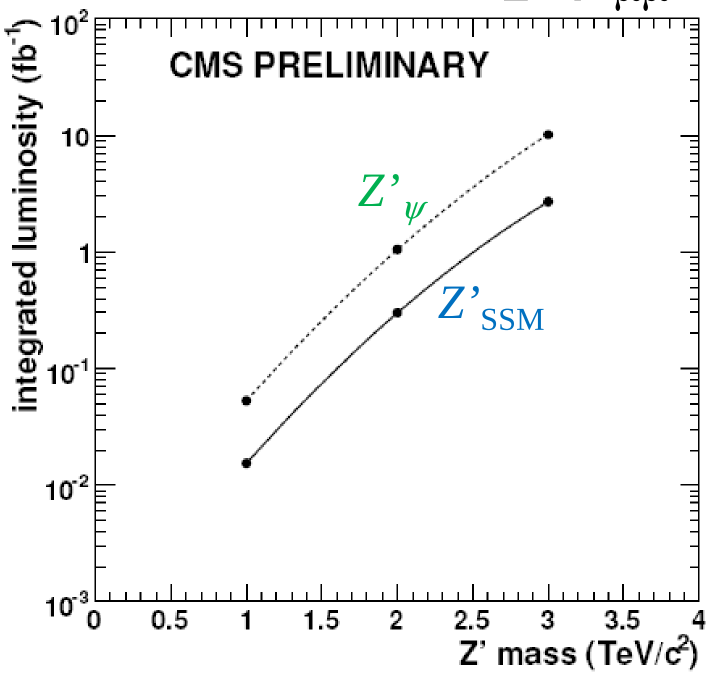




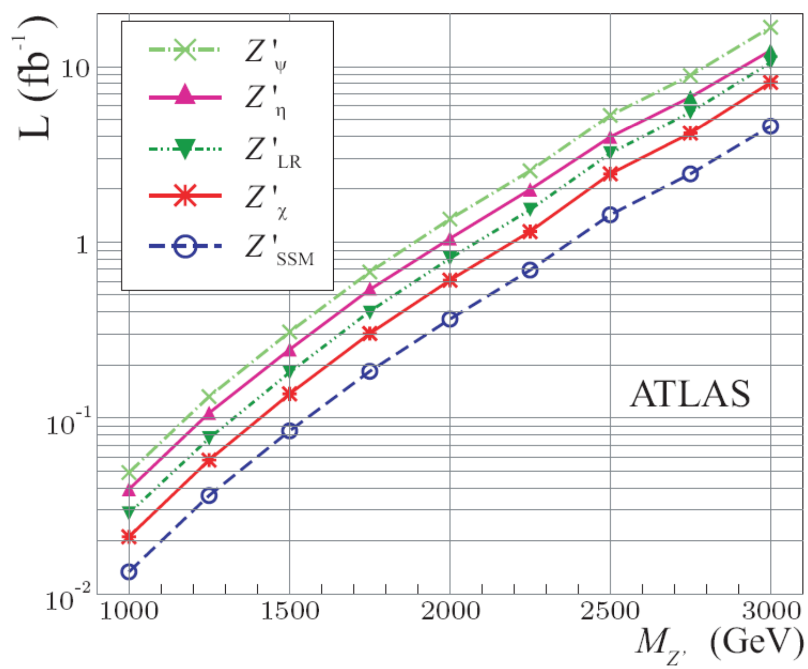
Sensitivity, reach

- Comparable reach for both experiments
- If slightly above the current Tevatron limit (1TeV), as low as 100pb^{-1} of physics data could yield a 5σ discovery

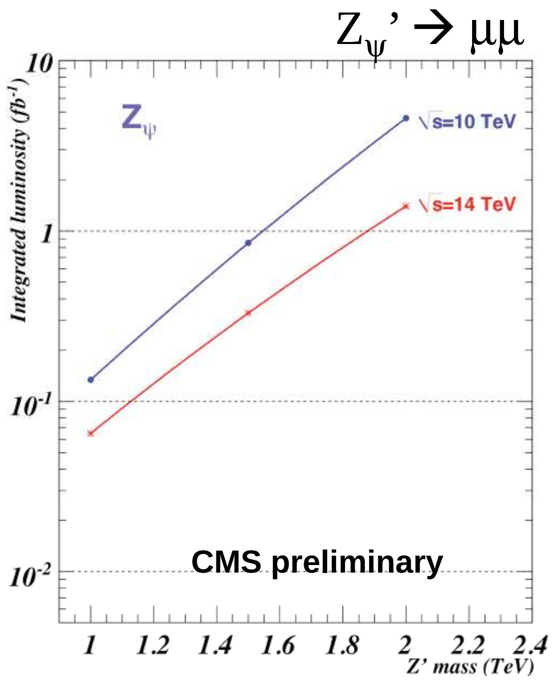
Z' → μμ

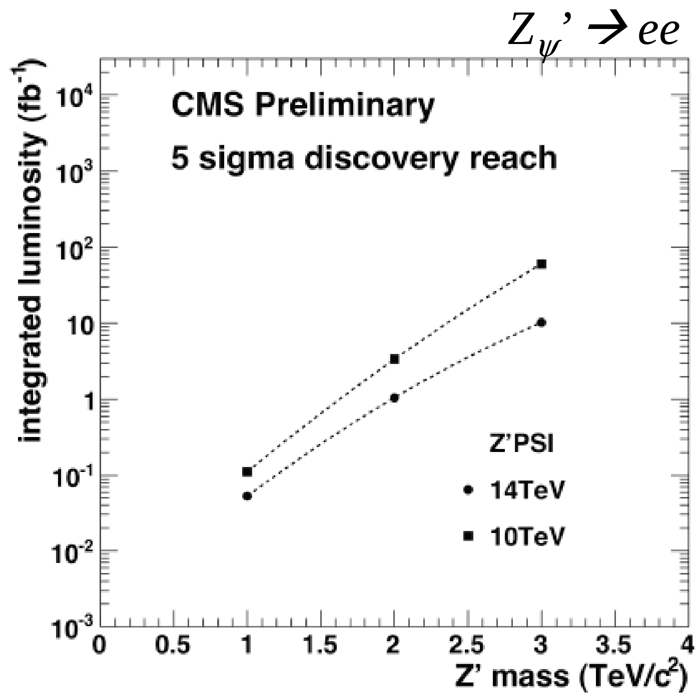


Z' → ee



From 14 to 10 TeV

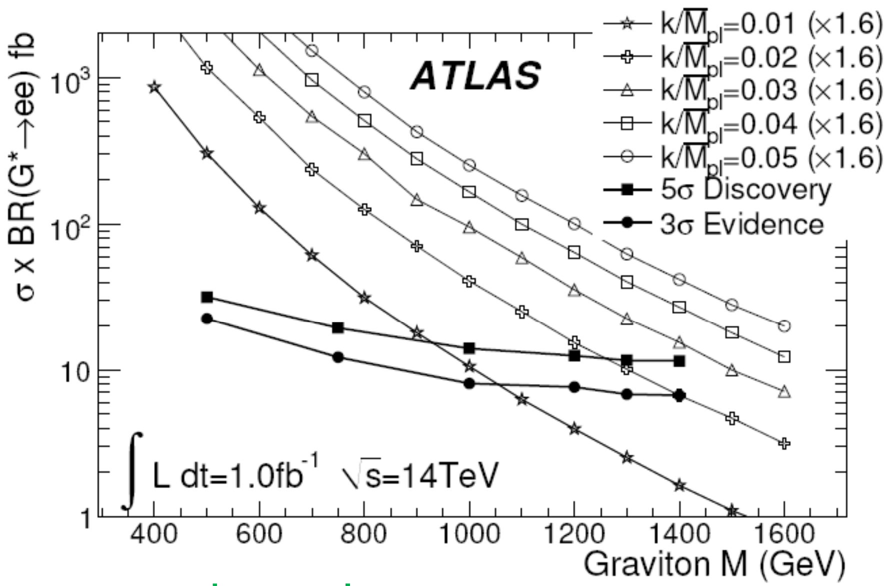




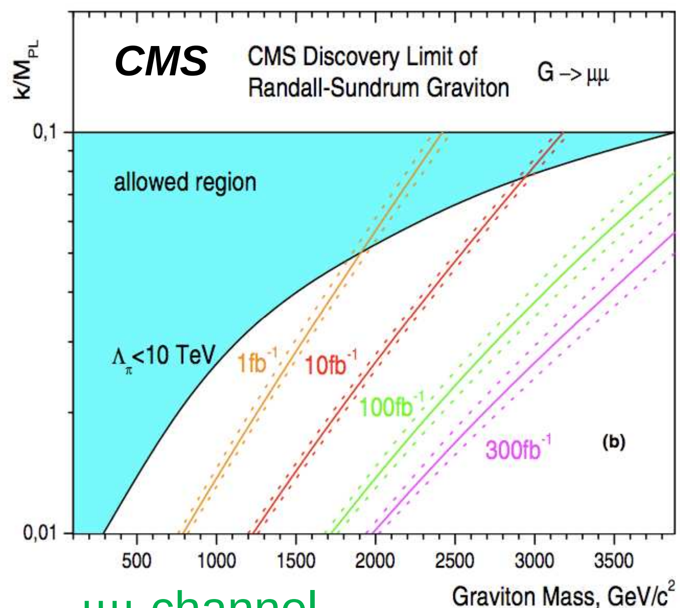
- Both experiments have assessed the effect of the lowered center-of-mass energy
- Production cross sections are reduced by factors ~ 2 or 3 (for masses of the Z' between 1 and 2 TeV)
- Accordingly, the luminosity needed for a 5σ discovery ~ doubles

Gravitons

- Randall-Sundrum models



ee channel

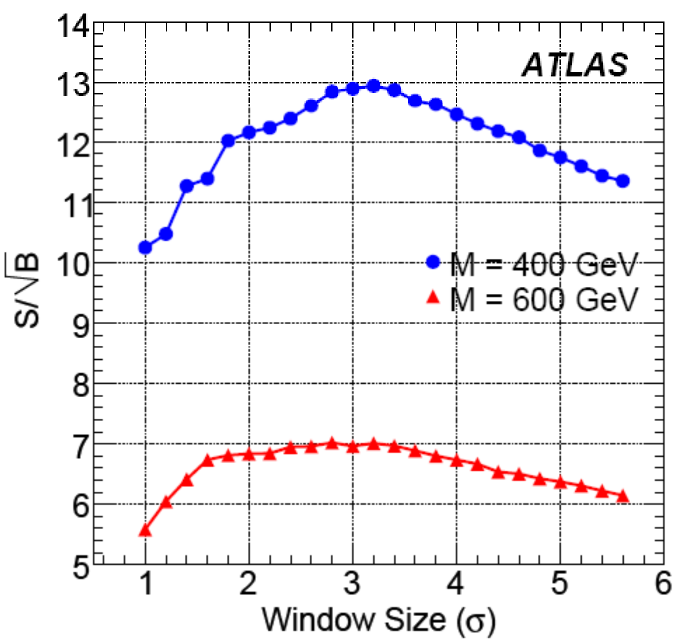


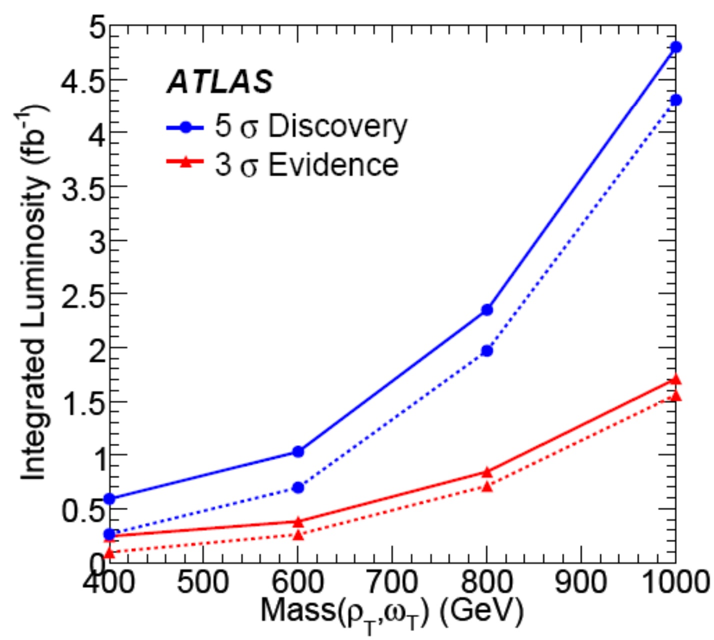
μμ channel

- Treatment: mass floating in the full mass range, width fixed to detector resolution
- For some values of k/M_{pl}, possible discovery with $O(100pb^{-1})$

Technicolor

- Lowest mass states: π_T, ρ_T, ω_T
- ρ_T, ω_T can decay into fermion-antifermion pairs
- "Technicolor Strawman Model"; ρ_T, ω_T nearly degenerate
- Dimuon model:





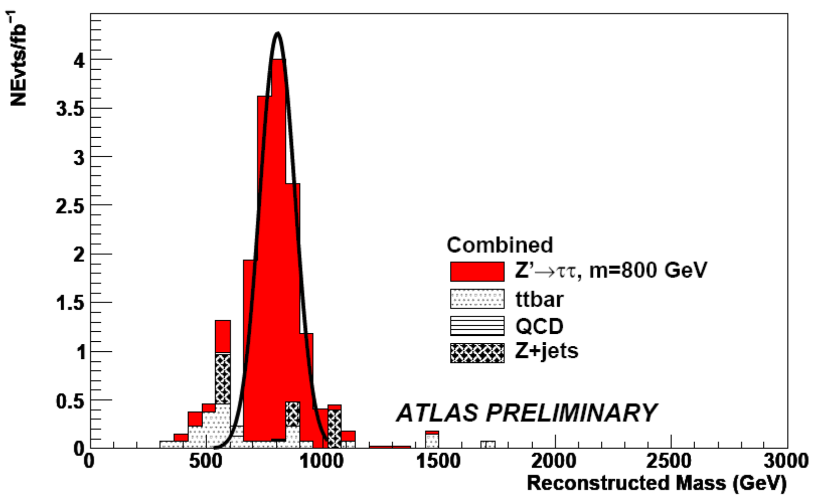
- Including estimated early alignment: +50% luminosity needed

DILEPTONS

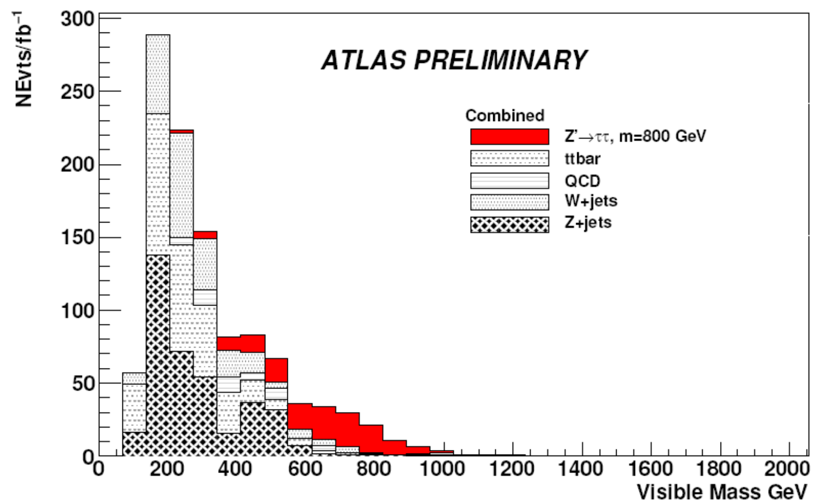
$\tau\tau$

- Tau leptons can decay hadronically or leptonically
- All modes (hh, lh, ll) have been studied and combined in the search
- Selection: Missing energy, upper bound on transverse mass and p_T^{TOT} , b-jet veto.
- Tevatron limits: 400 GeV
- Neutrinos are always present

Still, the *collinear approximation* allows the reconstruction of the invariant mass



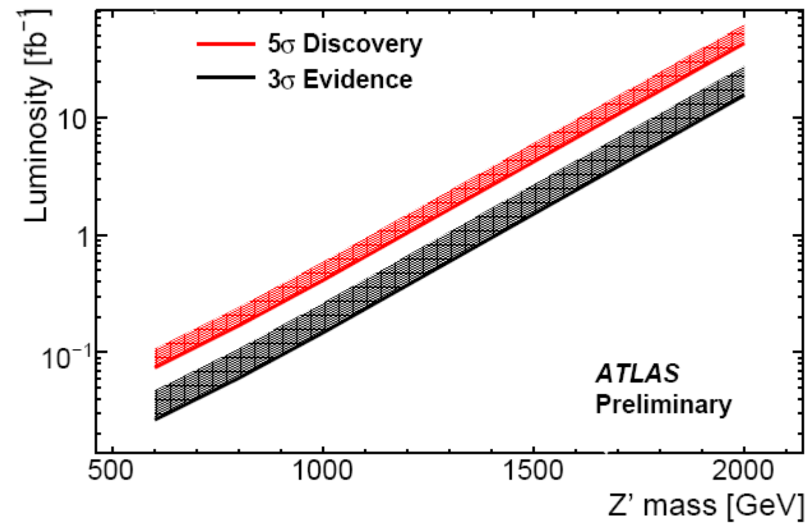
… except when the tau leptons are back-to-back → *"visible mass"* m_{vis}

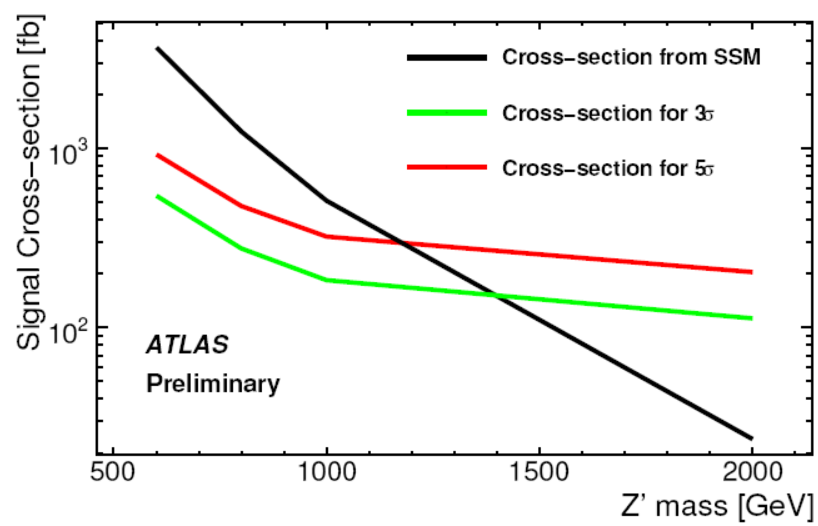


- In the collinear approximation, the not-back-to-back requirement, plus cuts on solutions that are physical, reduce both signal and backgrounds

Sensitivity

- Z'$_{SSM}$ with a mass up to 1.2 TeV could yield a 5 sigma significance with ~1fb^{-1} of data

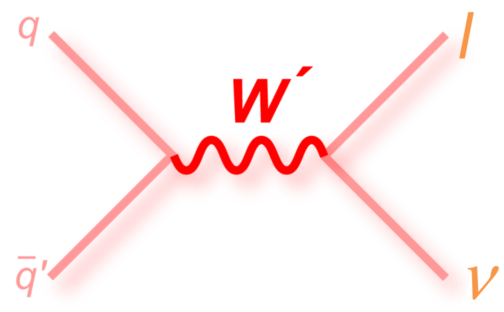




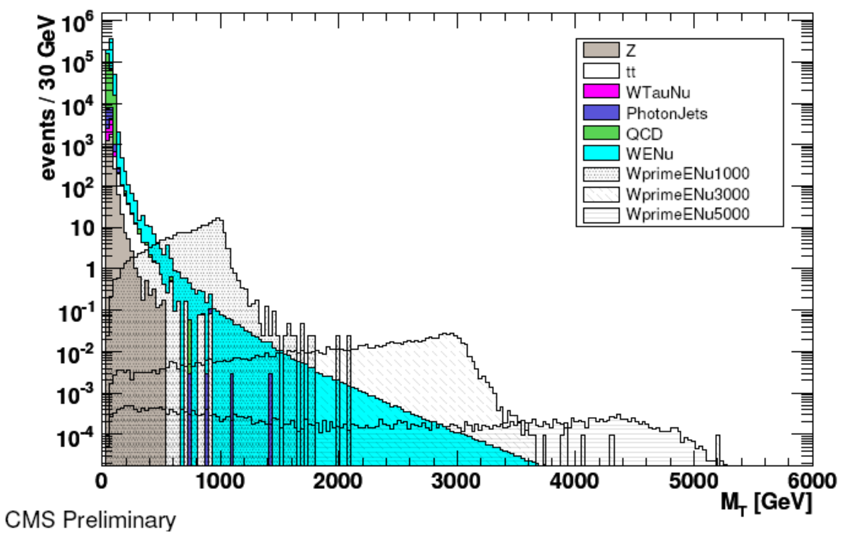
LEPTON - NEUTRINO

Signature, selection

- Several BSM scenarios include heavy, narrow, charged gauge bosons able to decay into l+ν
- As with SM W, the *transverse mass* helps extract them
- Rejecting events with high jet activity, the main remaining background is the high tail of the SM W boson.
- Mis-reconstructed leptons (low Pt reconstructed as high Pt) are a concern for early data

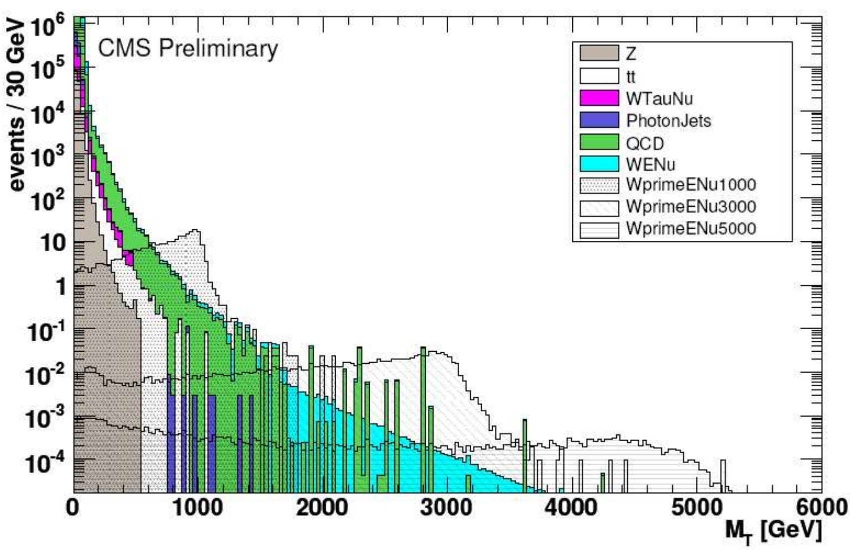


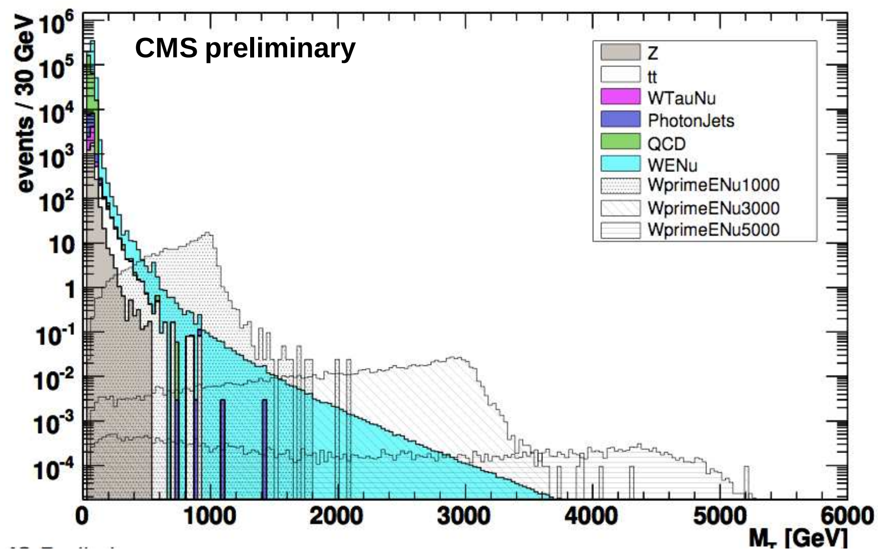
$$m_T = \sqrt{2 p_T \not{E}_T (1 - cos\Delta\phi_{\ell,\not{E}_T})}$$



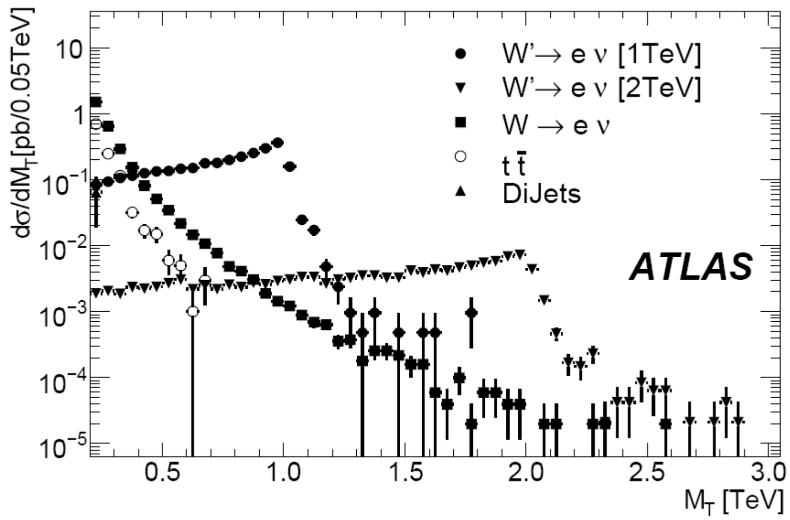
Selection

- One high-p_T lepton
- Missing energy
- Lepton fraction (ATLAS), E_T/MET (CMS)
- Jet Veto

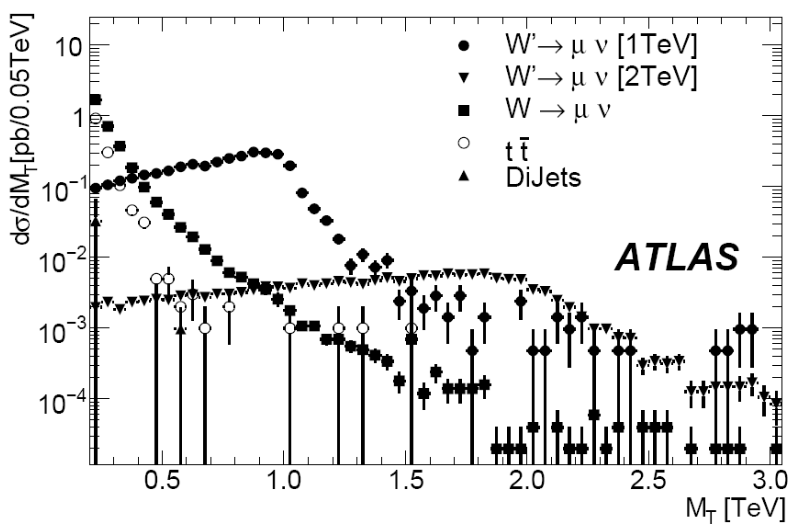


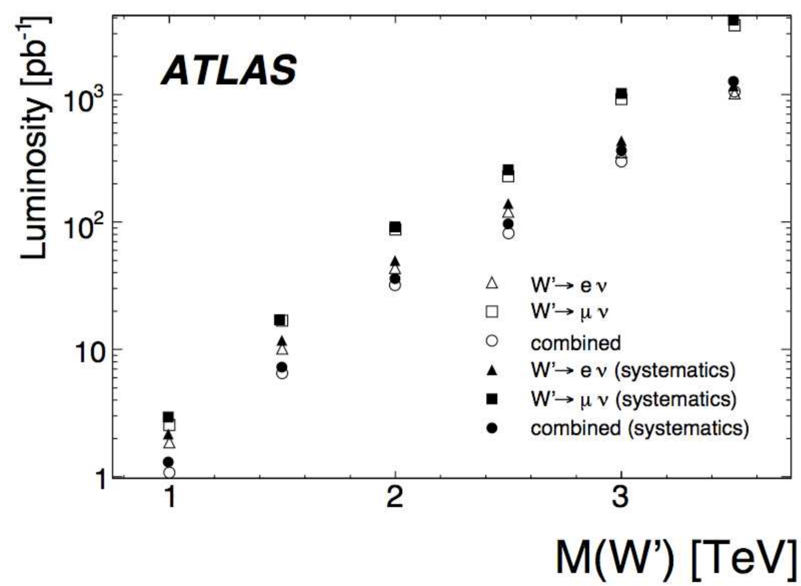


Electron, muon channels

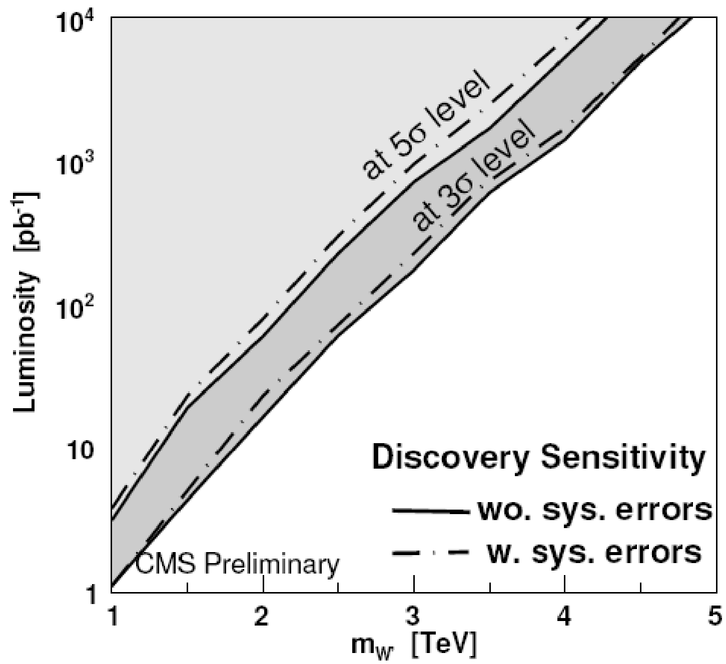


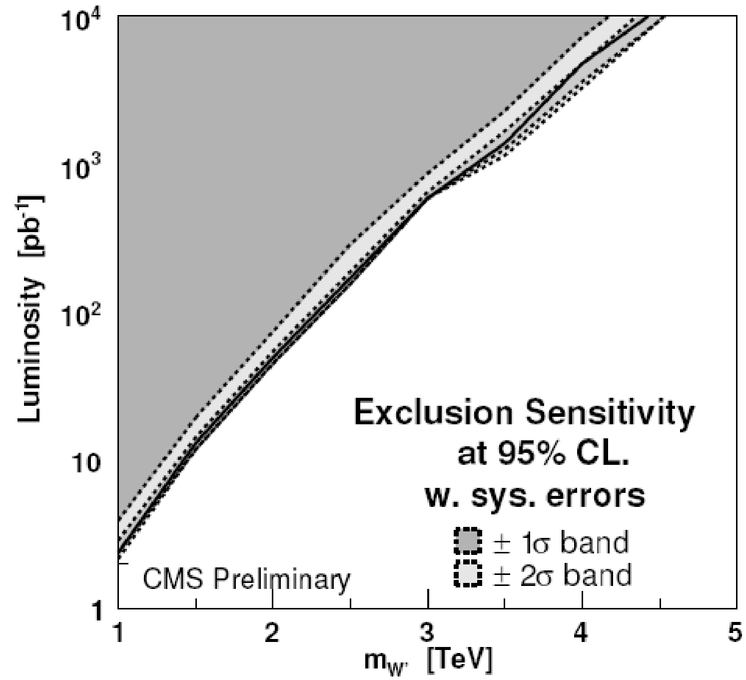
- Electron, muon channels studied
- Worse muon resolution at high p_T
- Possible discovery above TeV limits (1TeV) with O($10pb^{-1}$)





Discovery potential



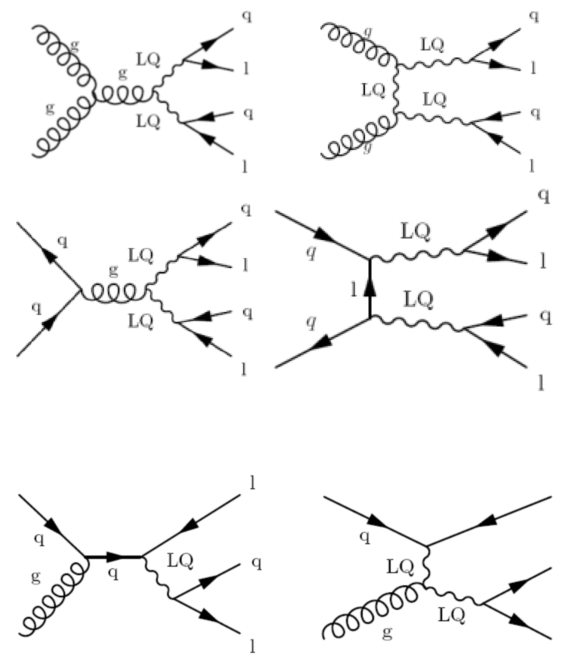


- With O(200pb^{-1}), masses up to ~2.5TeV can be probed
- Limits up to ~ 3TeV

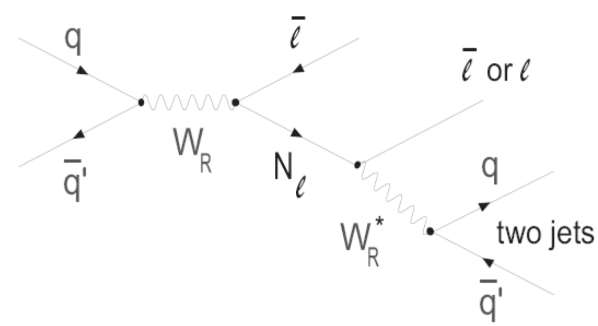
LEPTONS + JETS

Leptons+jets?

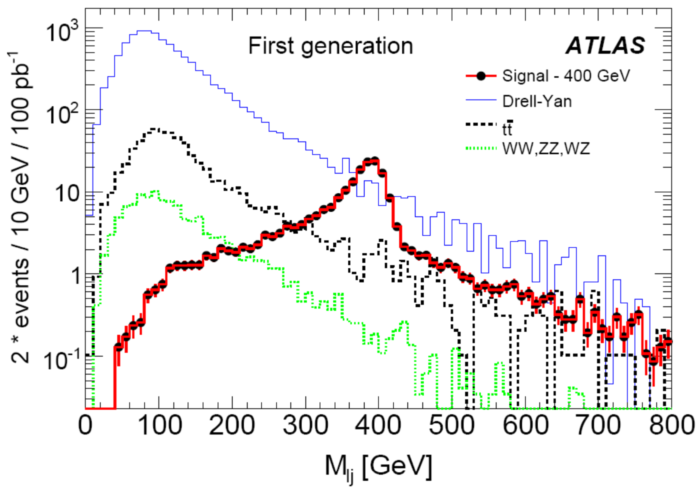
- Leptoquarks
  - Bosons carrying quark and lepton number
  - Experimental constraints favor three generations, each coupling to a SM generation
  - mLQ1 > 256 GeV (D∅)
  - mLQ2 > 251 GeV (D∅)



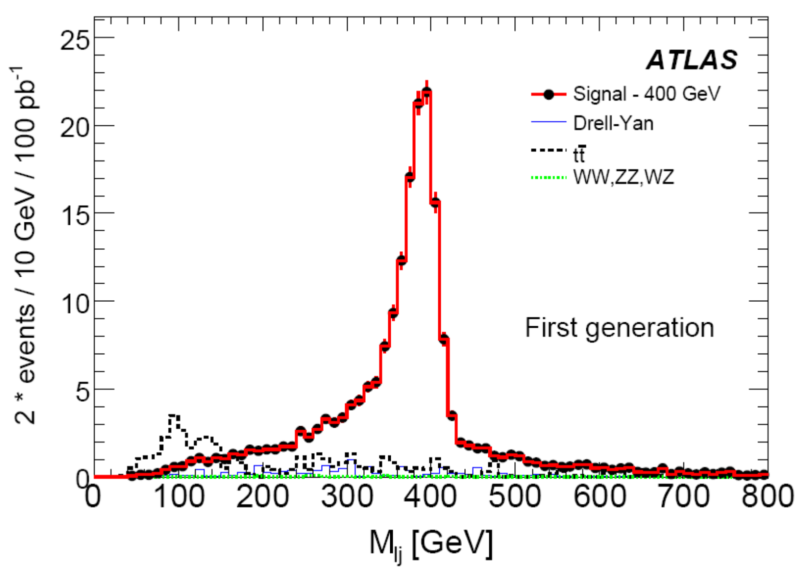
- Left-Right Symmetric Models (LRSM)
  - Address non-zero neutrino mass and baryogenesis
  - Three heavy right-handed Majorana neutrinos (N_e, N_μ, N_τ)
  - Some LRSMs introduce W_R and Z’

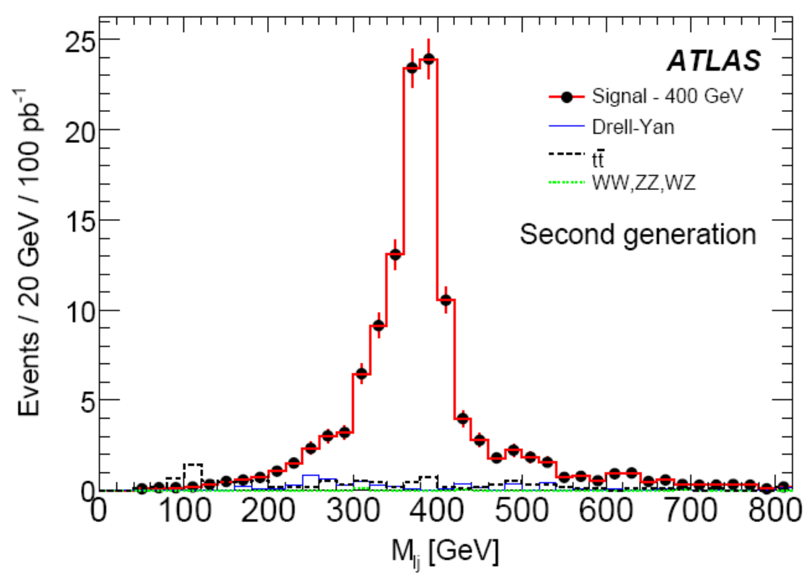


Leptoquarks



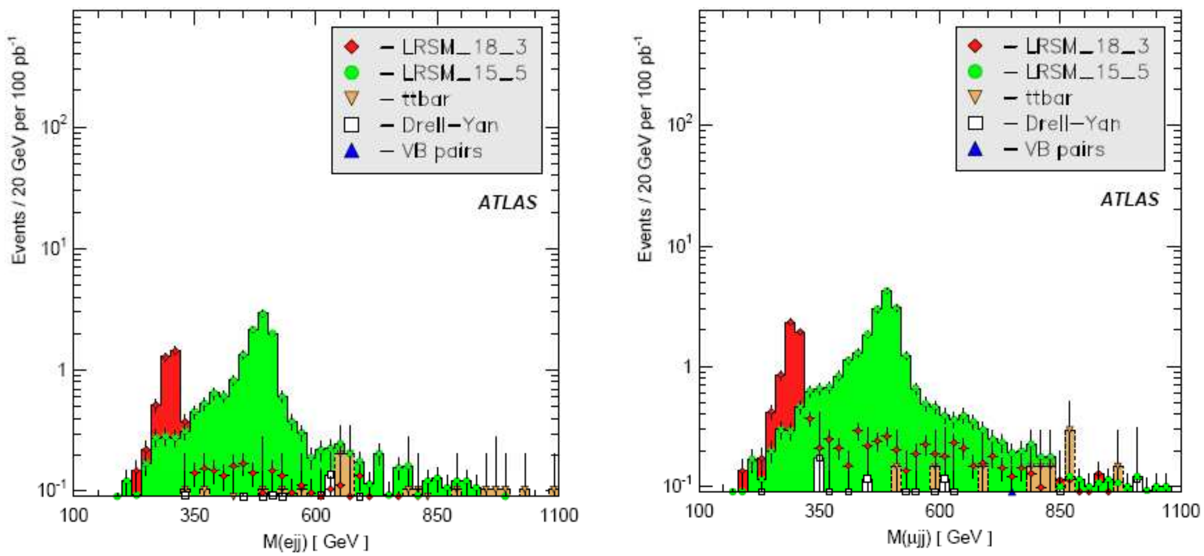
- 2 leptons (opp charge, same flavor)
- At least 2 jets
- Background rejection:
  - Leptons transverse momenta
  - $S_T = \sum |\vec{p}_T|_{jet} + \sum |\vec{p}_T|_{lep}$
  - Dilepton invariant mass
  - Lepton-jet invariant mass



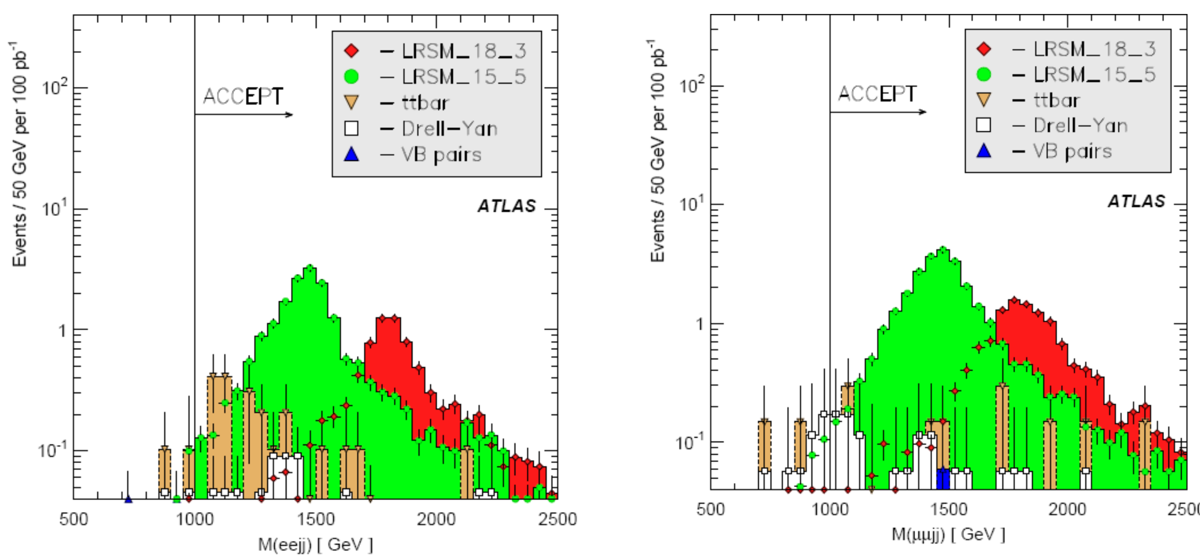


LRSM

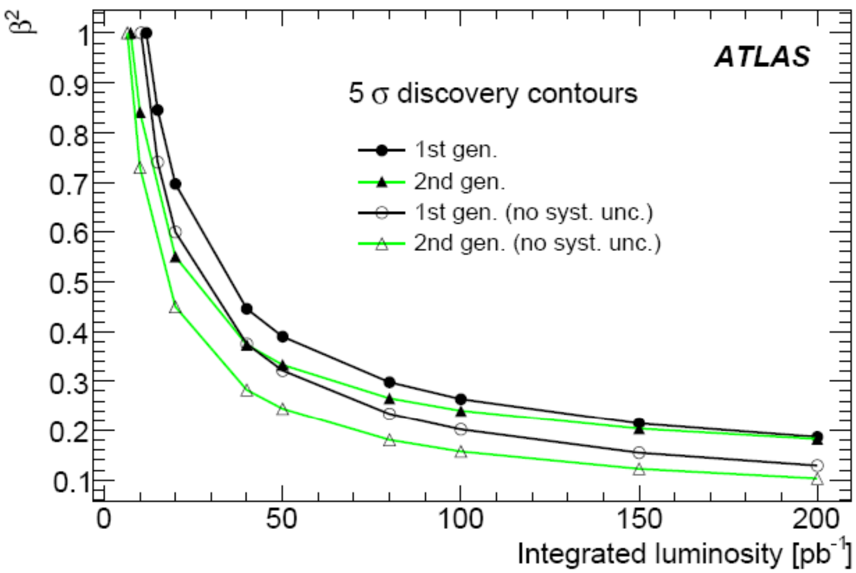
- Majorana Neutrino masses

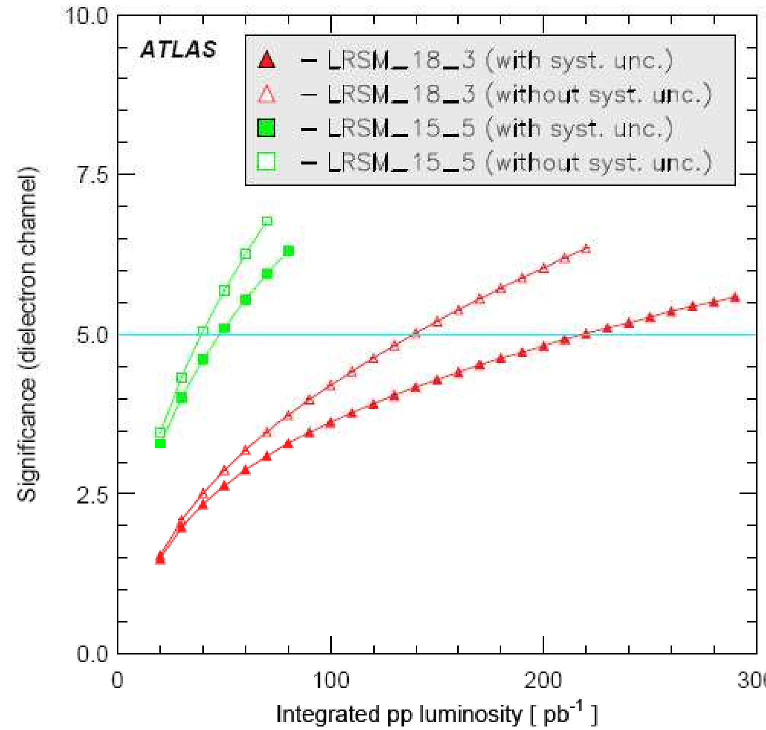


- W_R



Sensitivity





- Both types of models could yield a 5sigma signal with O(100pb-1)

CONCLUSIONS

- Several plausible extensions of the SM predict narrow resonances
- Background estimation procedures, fit-based strategies, statistical tools have been developed
- 14TeV studies have shown that they could be established at the 5 sigma level even with O(100/pb) of integrated luminosity
- The lowered center-of-mass energy, at 10TeV, degrades the sensitivity, but the initial run (O(200/pb)) should still be enough to go beyond Tevatron limits in most of these models
- Looking forward to the start of collision data!

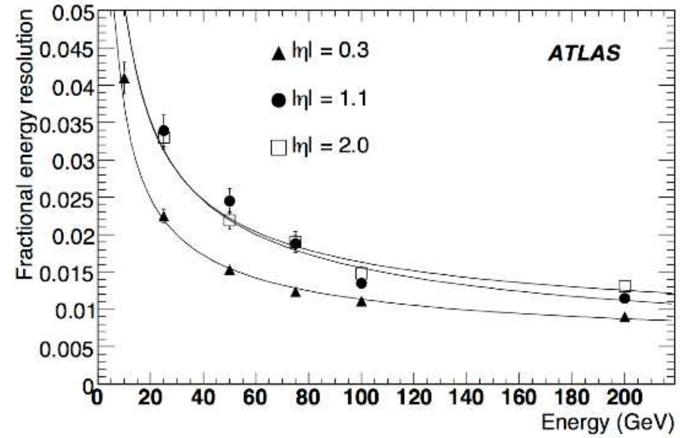
References

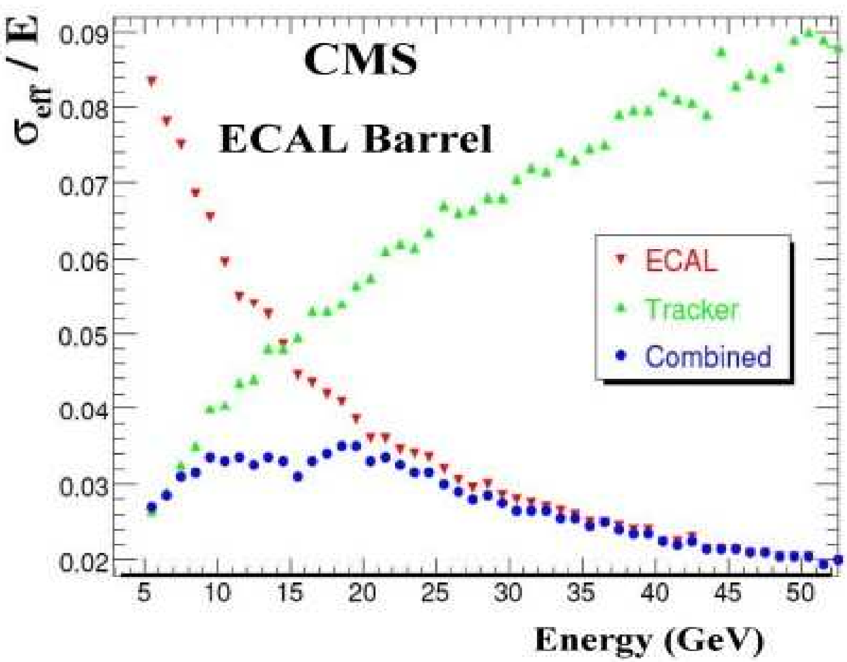
- CERN-OPEN-2008-020 (ATLAS, arXiv:0901.0512)
- CERN-LHCC-2006-021 (CMS, J.Phys.G: Nucl.Part.Phys.34 995-1579)
- https://twiki.cern.ch/twiki/bin/view/CMS/PhysicsResults

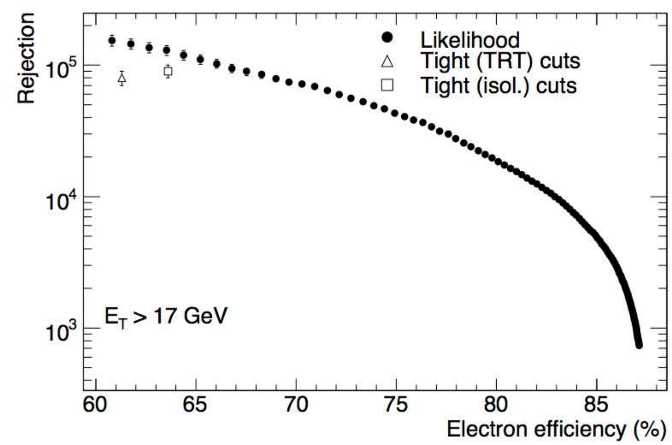
BACKUP

Electrons

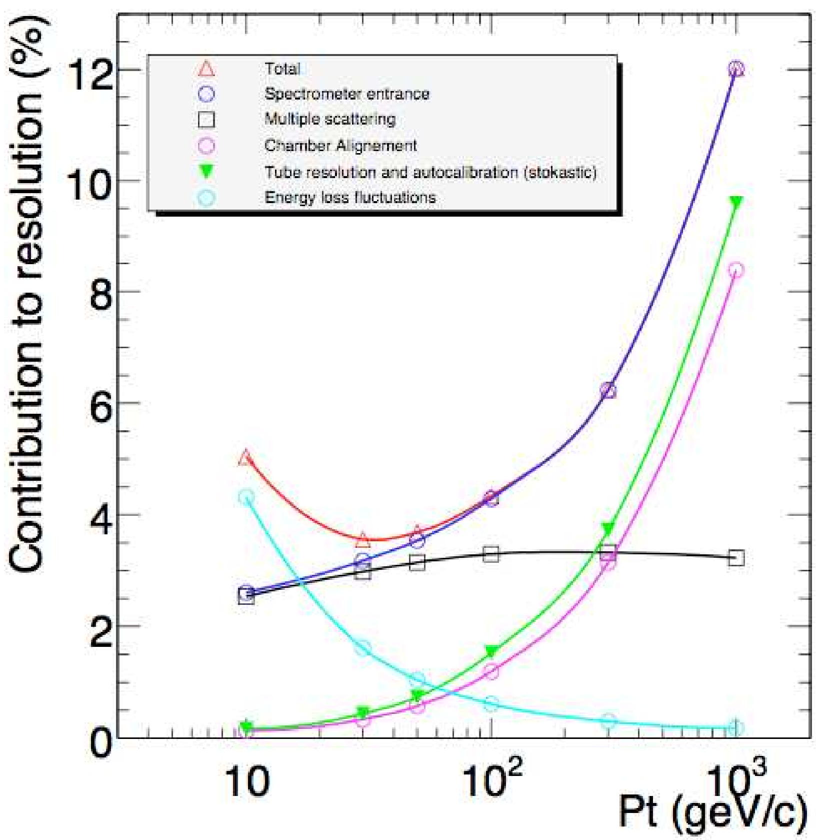
- The QCD cross sections at LHC are 10 to 100 times
- higher than at the Tevatron :
- *@ Pt = 40 GeV/c : electron to jet ratio is ~ 10-5*



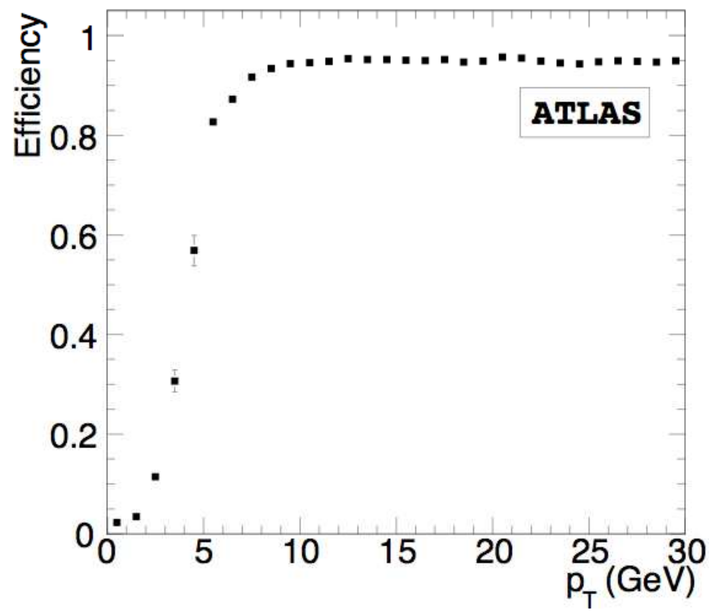




Muons



Total
Spectrometer entrance
Multiple scattering
Chamber Alignement
Tube resolution and autocalibration (stokastic)
Energy loss fluctuations
Contribution to resolution (%)
Pt (geV/c)



ATLAS
Efficiency
p_T (GeV)

Tau leptons

- With 100 pb-1, clear signals for W and Z in τ channels
- Z→ τ τ can then be used to set the ET miss scale to a few %
- τ reconstruction is tricky and relies (not for very first data but soon after) on multivariate techniques.