Search for Technicolor in ATLAS

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CNRS/IN2P3/LAPP

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- Technicolor overview
- TC and Higgs discovery
- Study of Wjj production
- Search in diboson channel
- Search for resonances in $l^{+}l^{-}$ channel

Technicolor

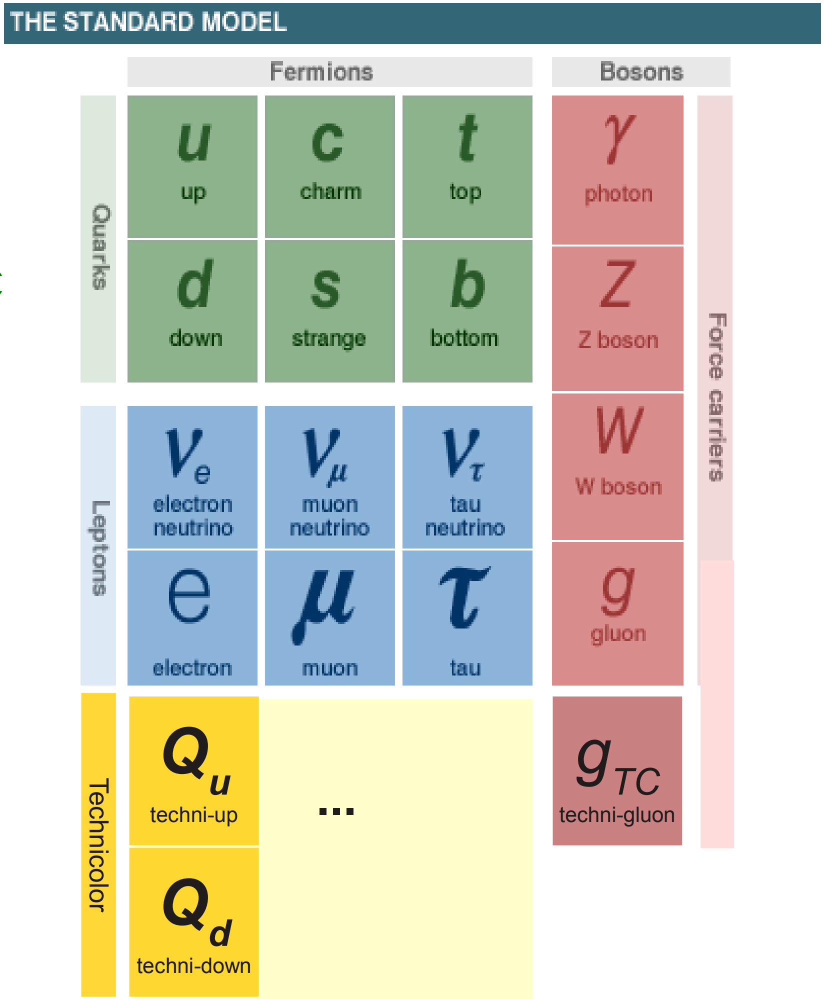
Alternative to the Standard Model Higgs mechanism

→ Technicolor (TC) models:

- Introduces a new strong dynamics
- Predicts new fermions (techniquarks) sensitive to TC
  - → typically N_D isospin doublets
  - → gauge invariant under $SU(N_{TC})_{TC}$

If $N_{TC} = 3$:

- QCD-like dynamics at scale $O(\Lambda_{TC})$:
- When coupling becomes strong: chiral symmetry breaks
  - $SU(2)_L \otimes SU(2)_R \Rightarrow SU(2)$
    - $\langle Q_L Q_R \rangle \neq 0 \sim \Lambda_{TC}$
  - $\langle Q_L Q_R \rangle$ not invariant under $SU(2)_L \otimes U(1)_Y \Rightarrow$ spontaneous EWSB



QCD case $\Lambda_{TC} = f_\pi = 93$ MeV & $N_{TC} = 3$: ➡ $M_W \equiv \frac{1}{2}\, g\, f_\pi = 31$ MeV !!

$M_Z \equiv M_W / \cos\theta_W = 35$ MeV !!

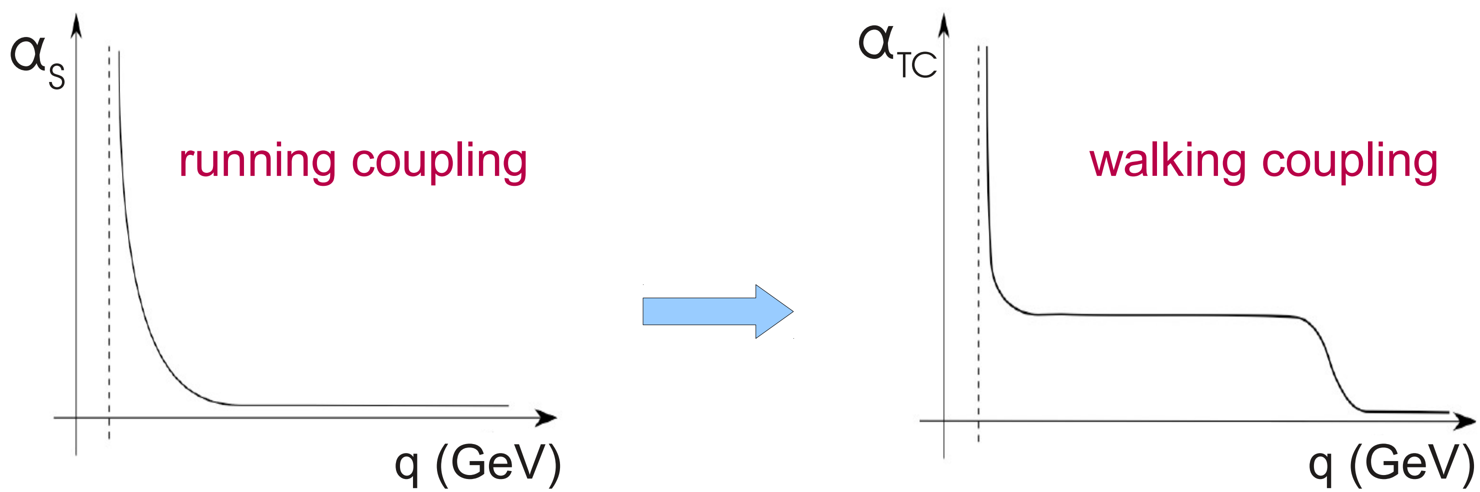
Technicolor (II)

- The N_D Technicolor isospin doublets are invariant under $SU(N_{TC})_{TC}$ gauge group
  - $SU(2)_L \otimes SU(2)_R \rightarrow$ dynamically broken:
  - $\langle Q_L Q_R \rangle \neq 0 \sim \Lambda_{TC} \sim F_{\pi_T} = 246$ GeV! $\rightarrow M_W \equiv \frac{1}{2}\, g \cdot F_{\pi_T} \rightarrow$ right gauge bosons mass

→ but EW precision constraints & flavor-changing neutral currents:

→ "scaled-up QCD" models with a running coupling: <u>are excluded</u>

→ TC with a <u>"walking"</u> coupling is OK

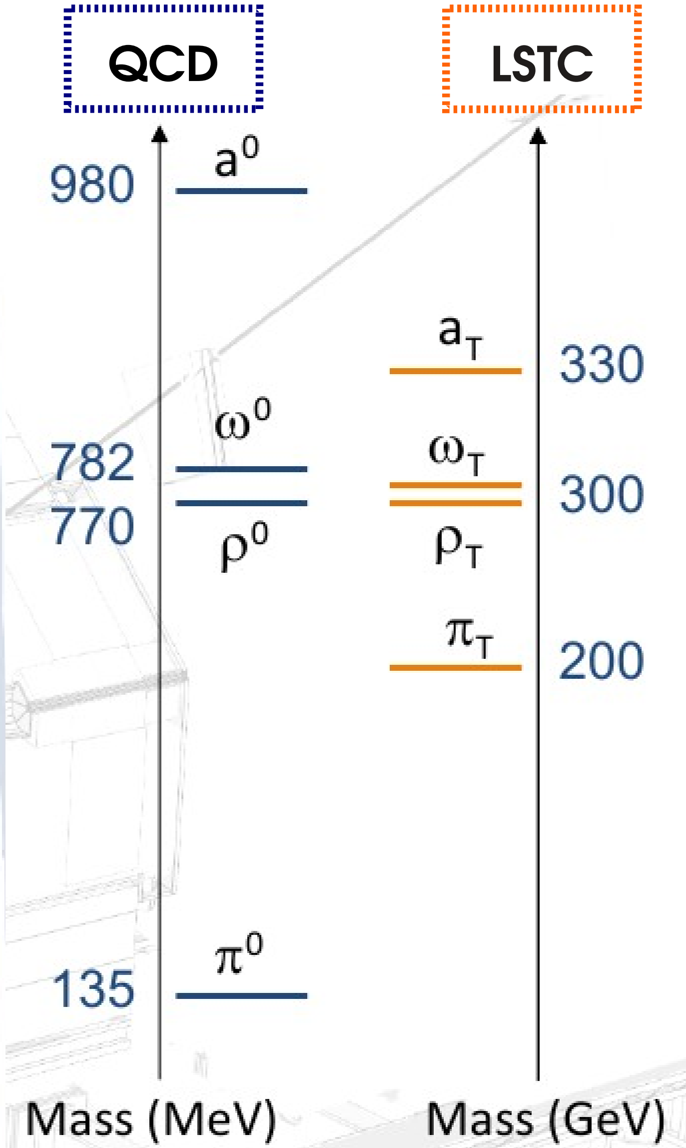


Two variants of Technicolor are under study:

<u>Low Scale Technicolor (LSTC)</u> & <u>Minimal Walking Technicolor (MWT)</u>

Low-scale Technicolor (LSTC) model

Particle spectrum considering only the lowest-lying doublet



$SU(N_{TC}=4)$; $N_D = 9$

$\rightarrow \Lambda_{TC} \sim 246$ GeV$/\sqrt{N_D} \sim 100$ GeV

$Q_U - Q_D = 1$

Walking coupling

QCD-like spectrum with scale O(Λ_{TC}):

- Scalar Technipions: π_T (Goldstone bosons)
- Vector Technimesons: near-degenerate ρ_T,ω_T axial a_T

Techni-isospin ~ good symmetry $\rightarrow$ $m(\rho_T) = m(\omega_T)$

- Walking decreases $m(\rho_T)/m(\pi_T)$ splitting
  - $V \rightarrow n\pi_T$ decays are typically forbidden

Narrow resonances

- Main Decays modes:
  - $\pi_T \rightarrow jj$
  - $\rho_T^0/\omega_T^0, a_T^0 \rightarrow$ **ll**, $Z\gamma$
  - ρ_T , $a_T \rightarrow$ **WZ**, $W\gamma$

LSTC previous studies

CDF Excess in Wjj production for m_{jj} = 144±5 GeV width ~ detector resolution

www-cdf.fnal.gov/physics/ewk/2011/wjj/7_3.html

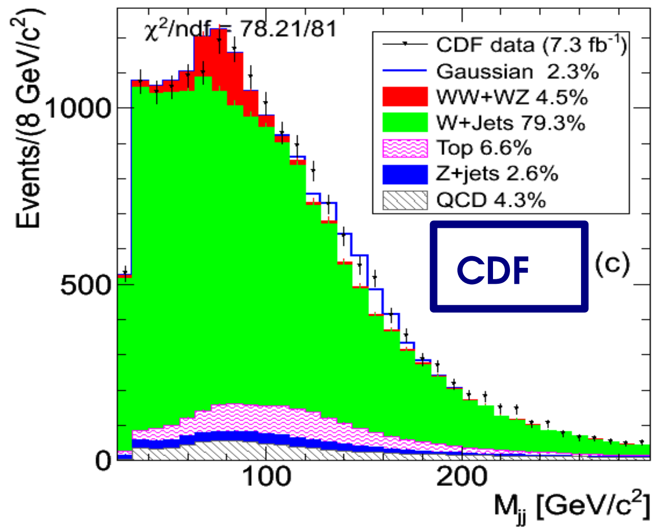
PRL 106 (2011), 251803

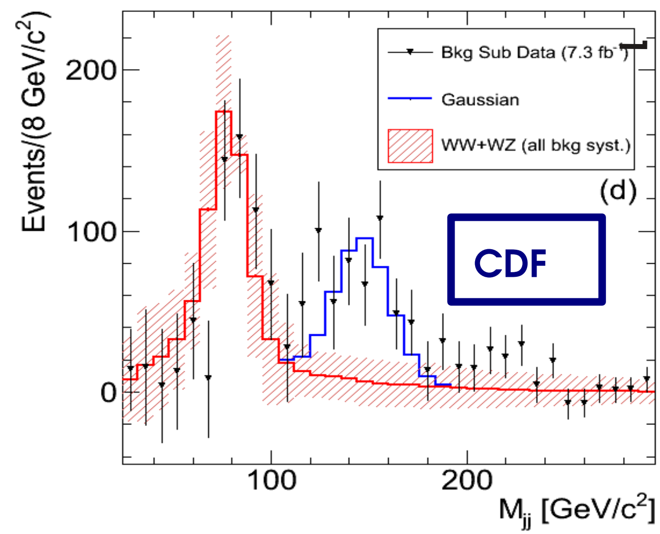
Interpretation as:

$\rho_T \rightarrow W + (\pi_T \rightarrow jj)$

→ **M(ρ_T) ~ 290 GeV**

→ **M(π_T) ~160 GeV**





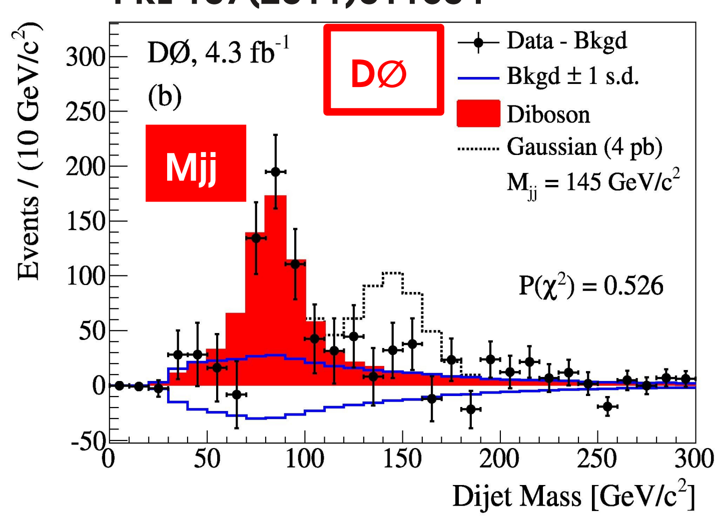
PRL 106 (2011), 17180

CDF anomaly

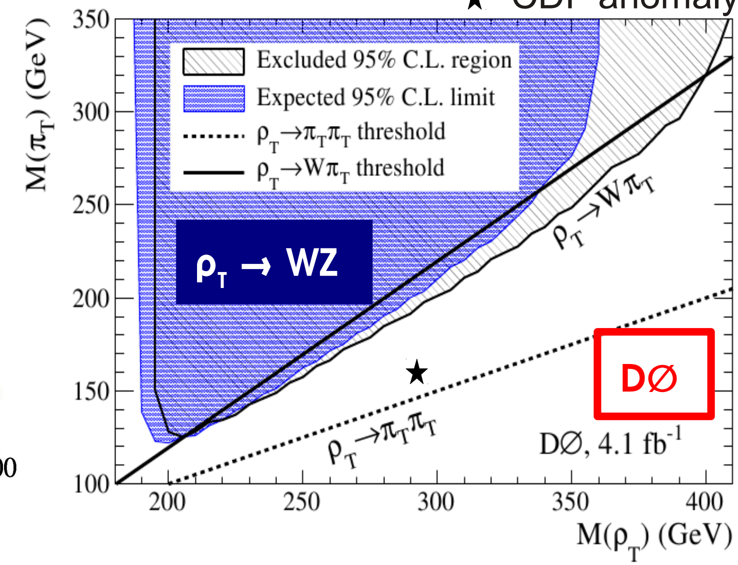
No excess seen

in the **DØ** data

PRL 107(2011)011804



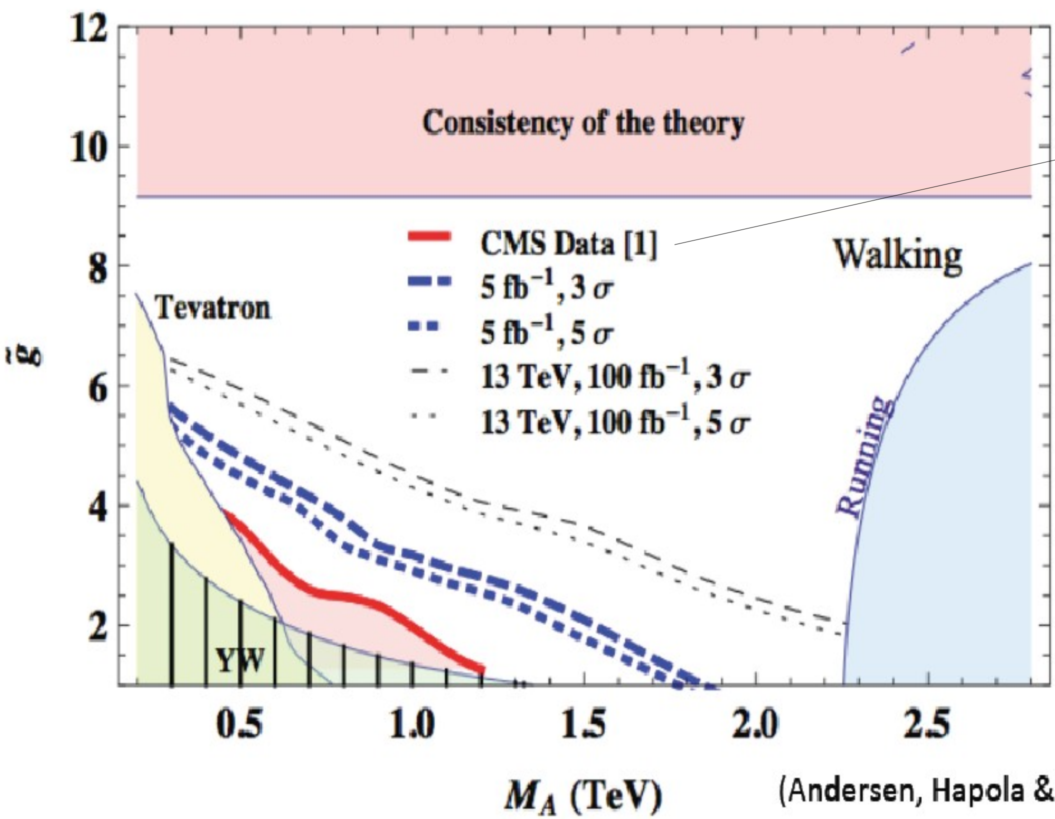
★ CDF anomaly



PRL 104(2010)111802

Minimal Walking TC (MWT) model

- Smaller representation→adjoint SU(2)→less particles in the spectrum
  - Simplest spectrum no π_T (only longitudinal components of the W Z)
- Important parameters are the coupling $\tilde{g}$ and M_A, which set:
  - Resonance cross sections, widths and mass splittings
- Different notation: $R_1 = \rho_T$ and $R_2 = a_T$ resonances
  - Lightest triplets of vector mesons, defined as→ $m_{R_2} > m_{R_1}$



(Andersen, Hapola & Sannino 11)

No direct limit : CMS W' results reinterpreted in the MWT scenario

- CMS reinterpreted data
- Tevatron limit
- EW precision measurements

TC models and H discovery?!?

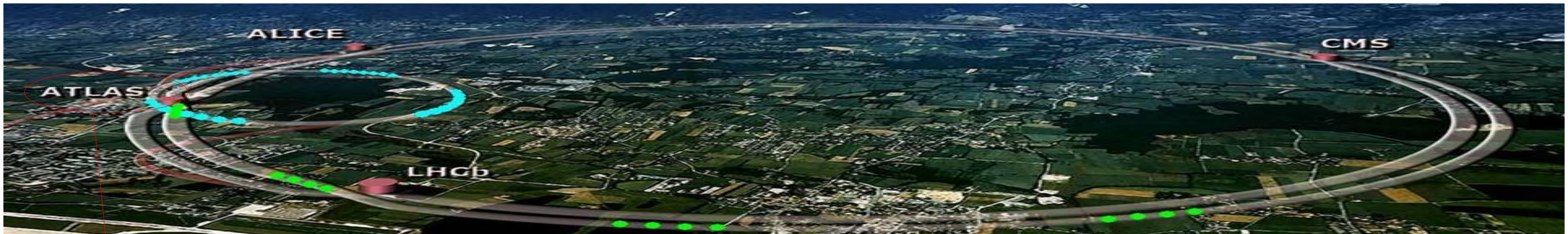
- LSTC:
  - Higgs-less model but...
    - New pseudo-scalar resonance η_T

      $\rightarrow$ m_{η_T} ~= 125GeV
    - Dominant decay modes:
      - $\eta_T \rightarrow gg, \gamma\gamma, f\bar{f}$

        $\rightarrow$ 2-photon rate ~same as H

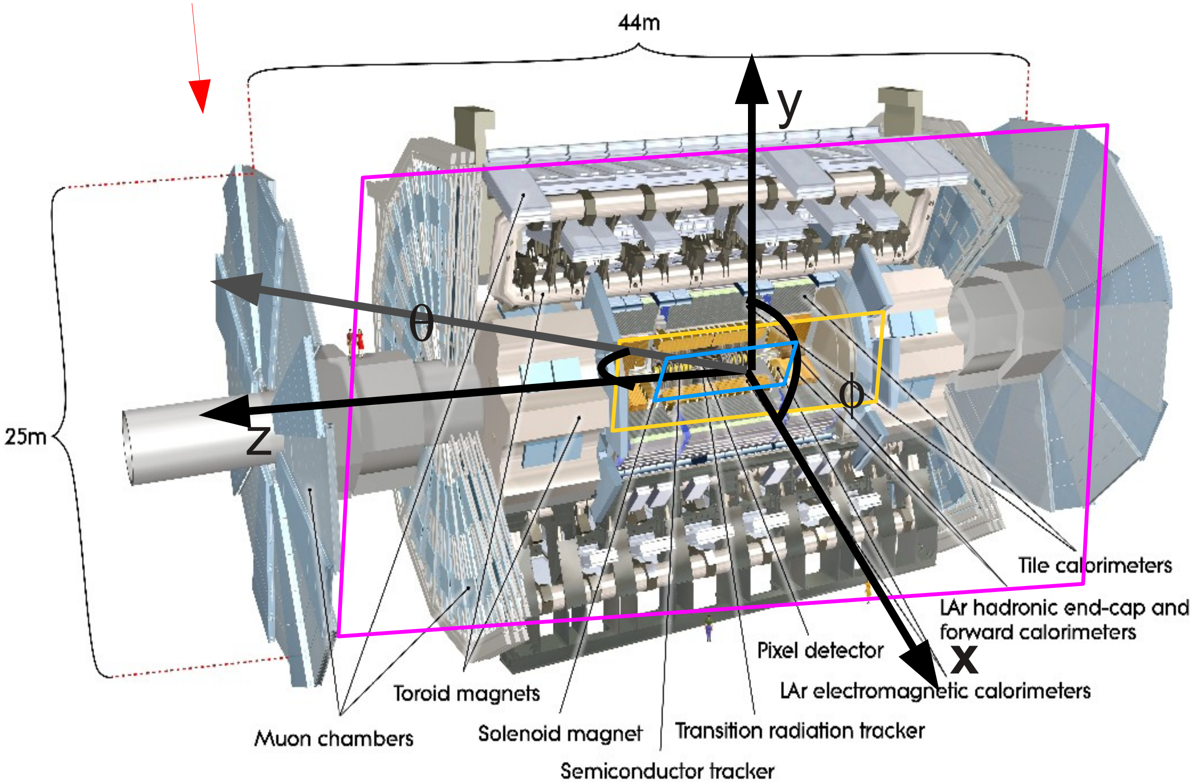
        $\rightarrow$ but very little ZZ*, WW*
- MWT:
  - Composite Higgs in the spectrum $\rightarrow \sigma_T = H$
    - Diphoton MWT/SM rate ~ order one
    - gHZ*Z and gHW*W MWT rate ~ 20% SM

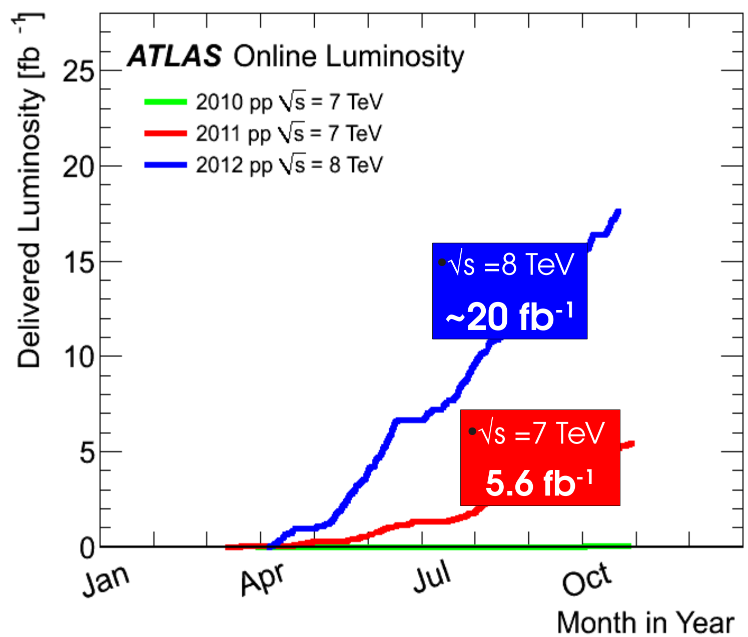
The LHC and the ATLAS detector



LHC proton-proton collider

- 2012 run $\sqrt{s}$ =8 TeV
  - → ~ 30fb^{-1} expected by the end data-taking





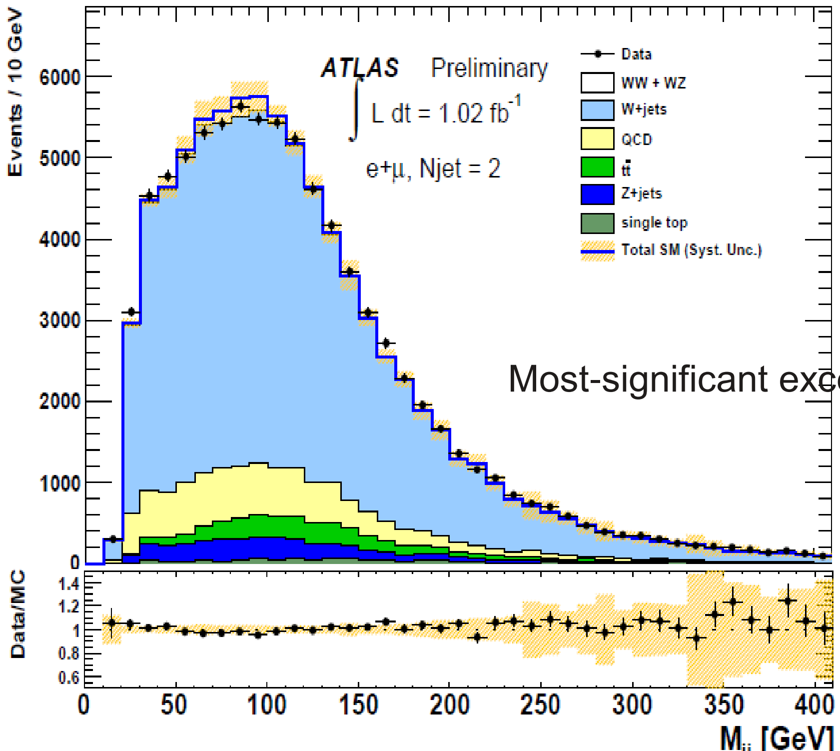
$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

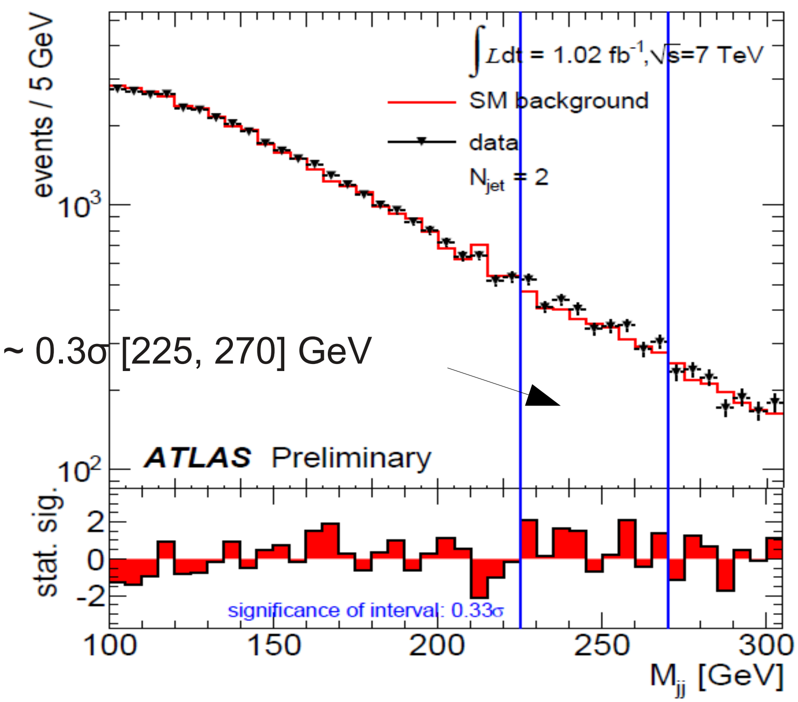
$\rho_T \to W\pi_T \to Wjj$ at ATLAS

- Repeat CDF study of W + 2 jets production
- Keep selection as close as possible to CDF

  Less favorable than at TeVatron: signal x4 but W+jets bkg x20

•Selection:
- E_T > 25 GeV (e), p_T > 20 GeV (μ)
- MET > 25 GeV, m_T> 40 GeV
- p_T(jet) > 25 GeV in in |η|<2.8
- $p_T$jj > 40 GeV, $|\Delta\eta_{jj}|$ > 2.5

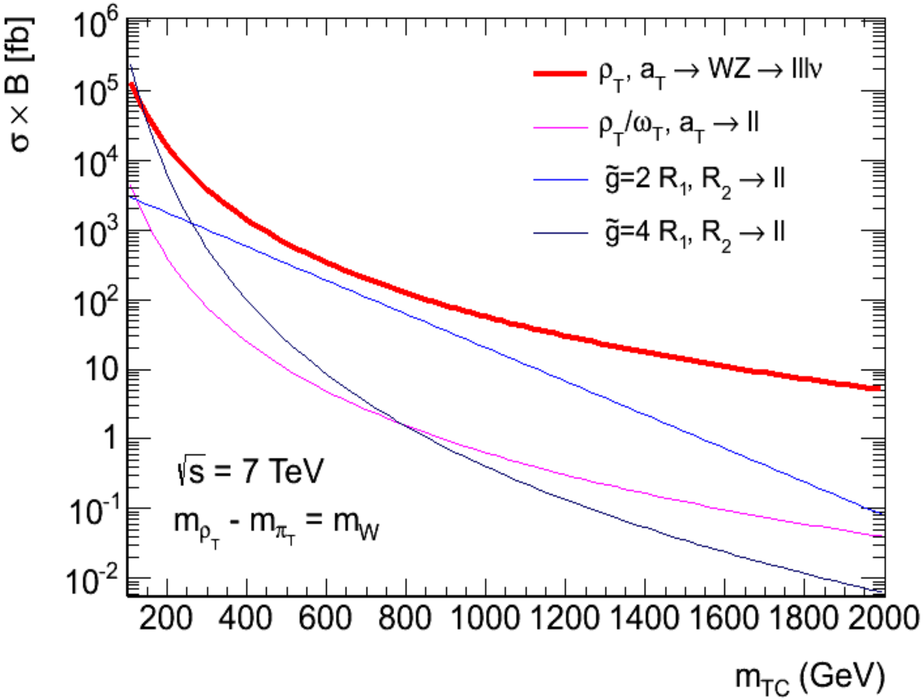




Most-significant excess ~ 0.3σ [225, 270] GeV

p-value in "CDF region" (120, 160) GeV = 0.5σ, **no excess seen**

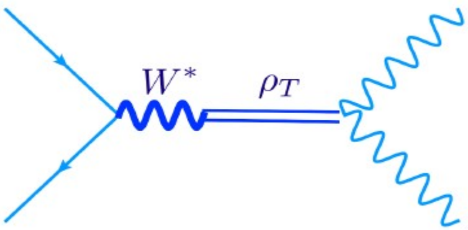
ATLAS Search diboson channel



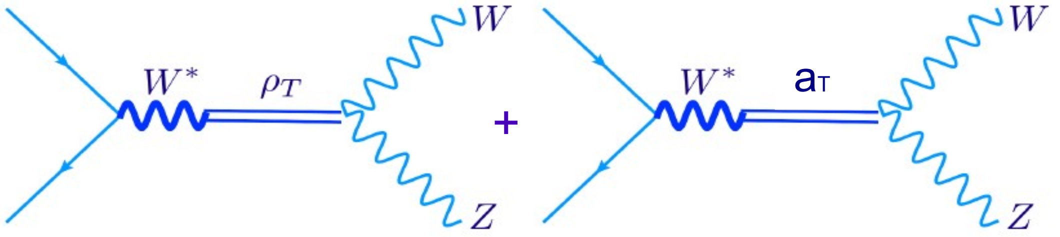
- LSTC resonance
  $\to$ very narrow
- The main decay channel diboson
  $\to$ WZ production
  - $m_{\rho T} = m_{\pi T} + m_W \to BR(WZ) \sim 98\%$
- wide range of Mass
  $\to$ from hundred GeV to few TeV

- Two hierarchy mass assumption

1) $m(a_T) >> m(\rho_T)$



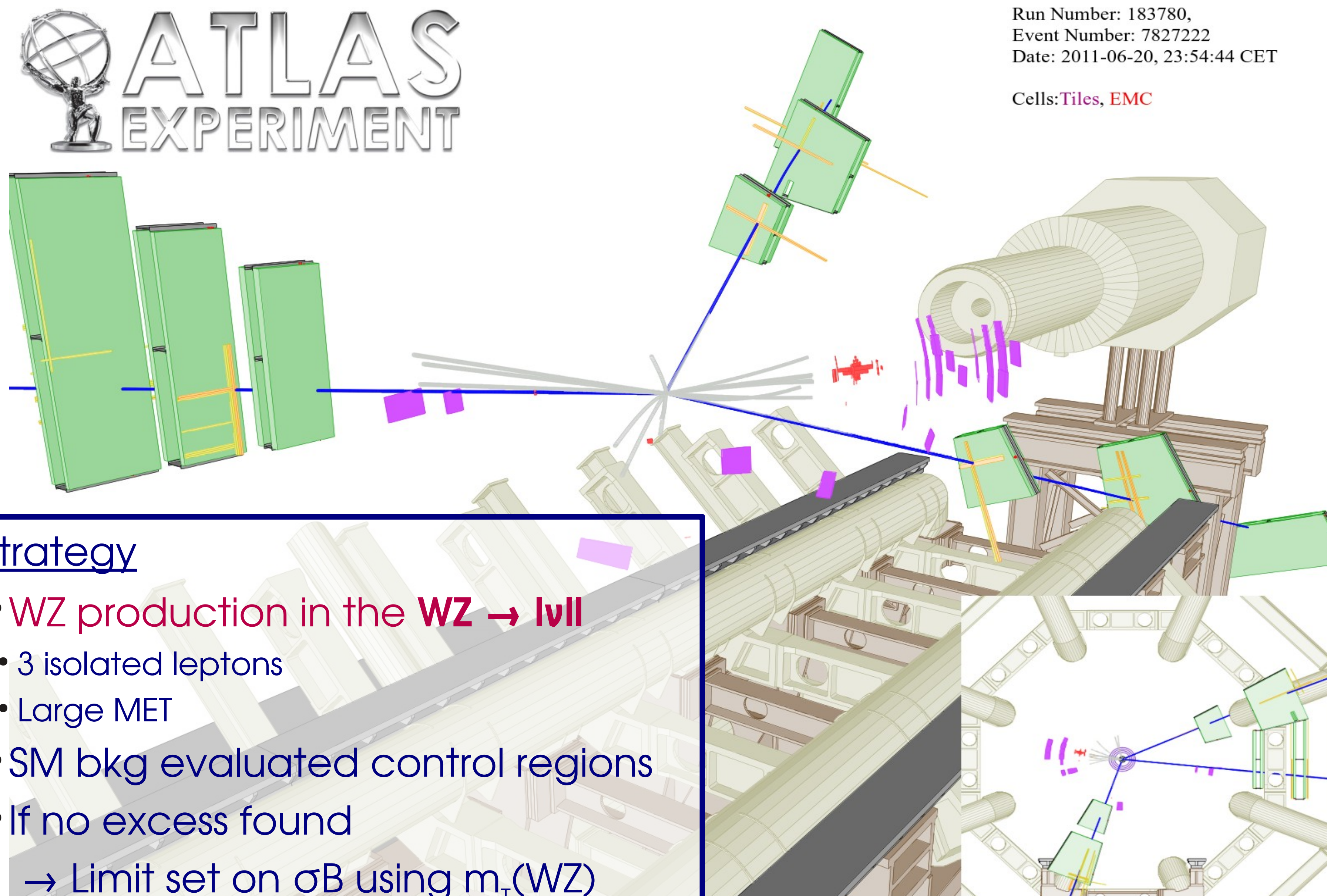
2) $m(a_T) = 1.1 * m(\rho_T)$ Contribution of both the axial and the vector resonances



Phys.Rev. D85 (2012) 112012

LSTC in diboson resonances

L = 1.02 fb^{-1}



Strategy

- WZ production in the **WZ → lνll**
  - 3 isolated leptons
  - Large MET
- SM bkg evaluated control regions
- If no excess found
  → Limit set on σB using $m_T(WZ)$

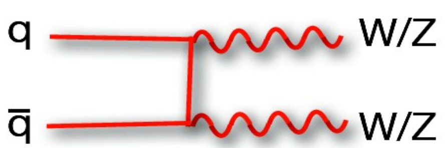
Event selection and background

- $\rho_T(a_T) \rightarrow WZ \rightarrow l\nu l'l'$, $(l,l' = e,\mu)$
  - 2 opposite sign leptons with $m_{ll} - m_Z < 20$GeV
  - 3^{rd} lepton + MET>25GeV
  - Only 3 leptons (ZZ background)
  - $m_T^W > 15$ GeV

Backgrounds

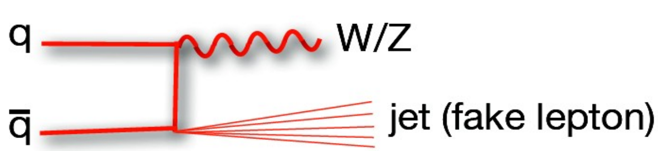
- Diboson final state →

MC: Non-resonant WW, WZ, ZZ, Zγ

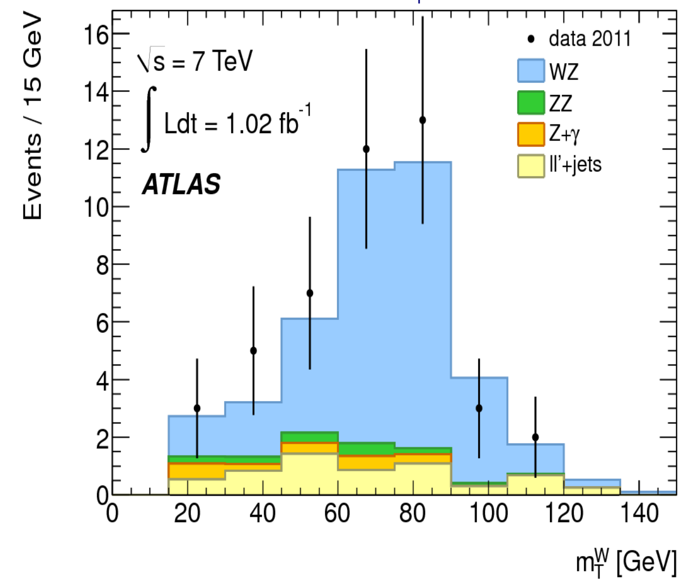


- Fake (and non-prompt) leptons →

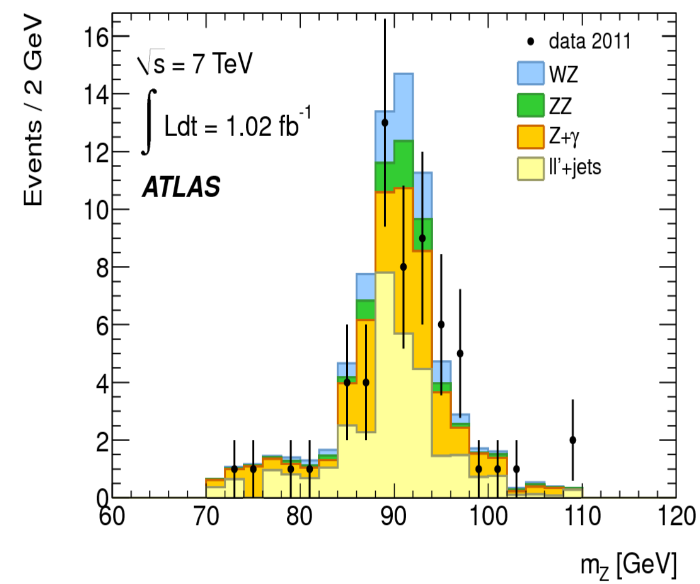
Data-driven: ll′+jets



SM WZ control region: $m_T(WZ) < 300$ GeV



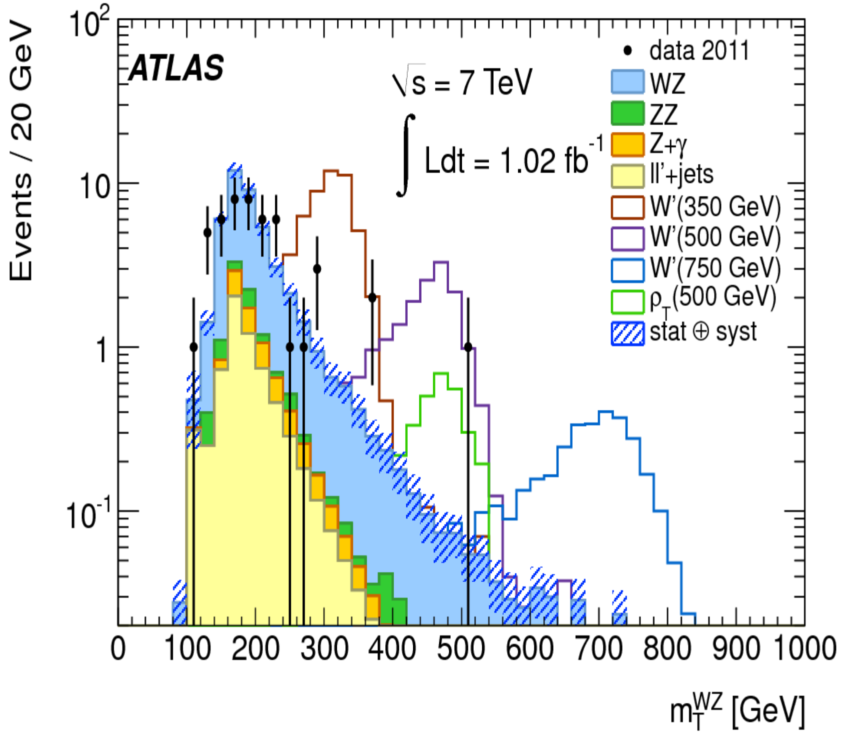
ll'+jets control region: MET<25GeV

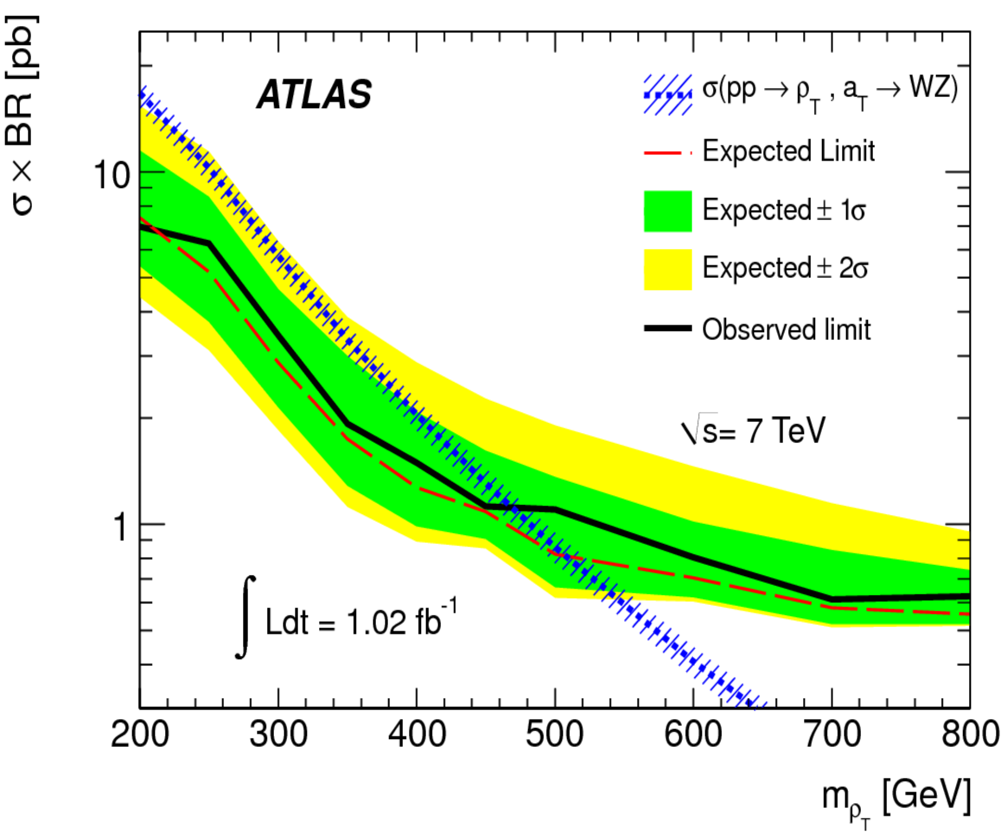


Results

Use m_T(WZ) distribution to search for resonant WZ production.

→ No Evidence for a resonance in the m_T(WZ) spectrum





Set 95% CL limit on σB vs m(ρ_T):

→ For each test mass, use binned LLR for each channel and combine four channels together (modified frequentest approach)

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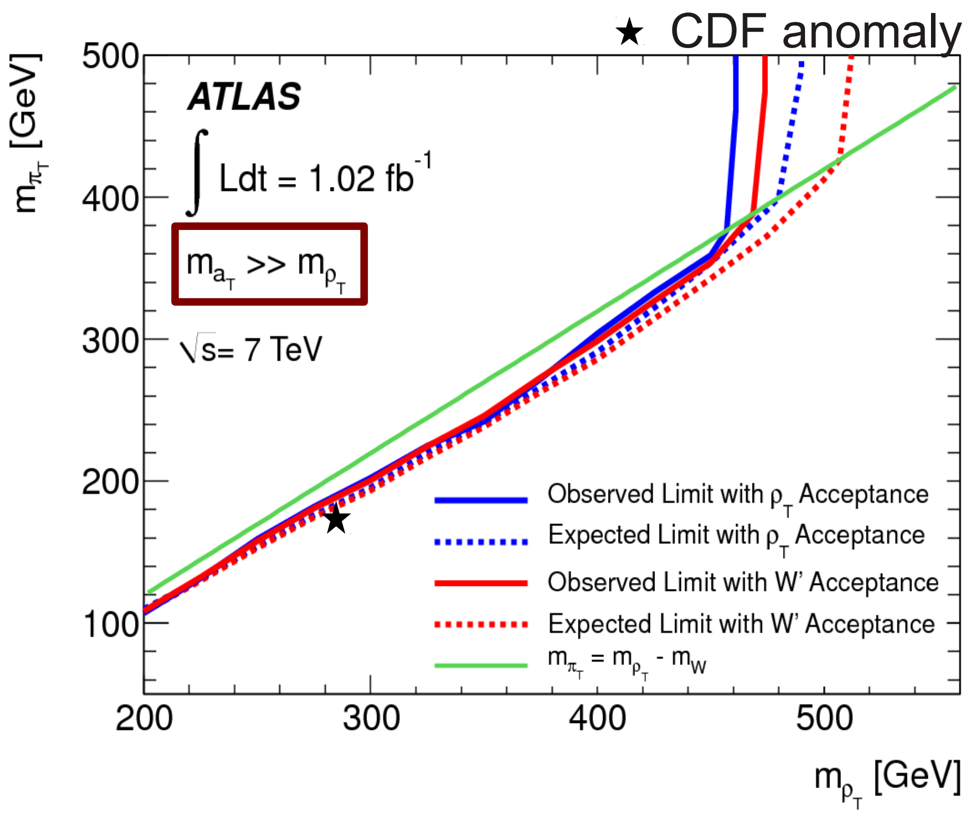
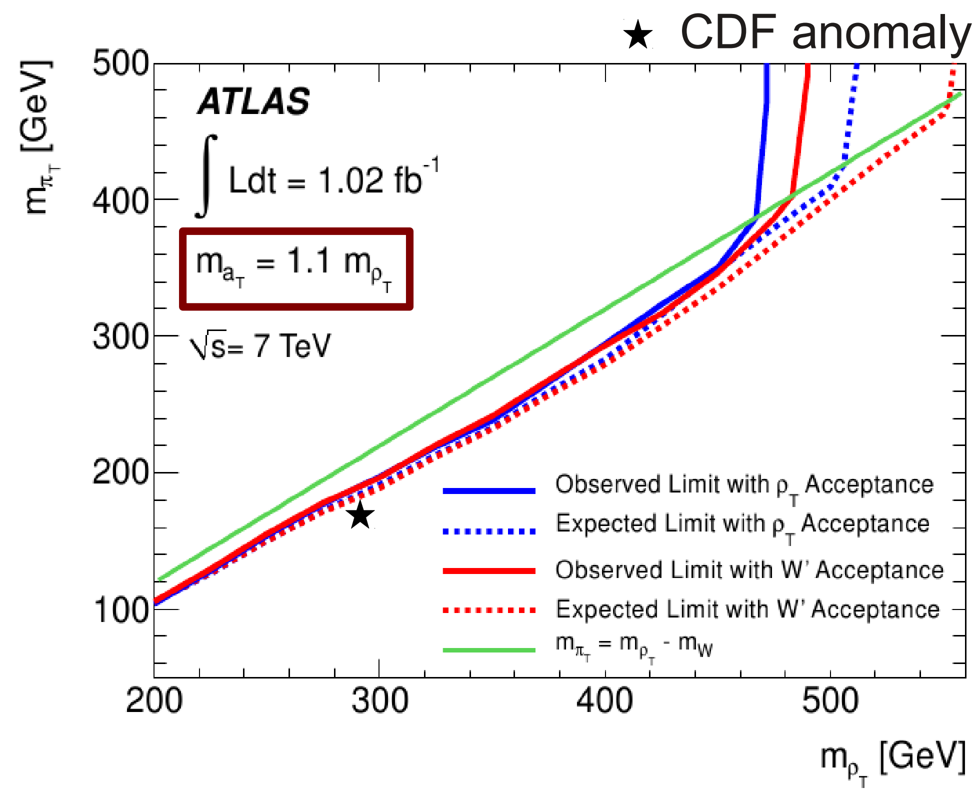
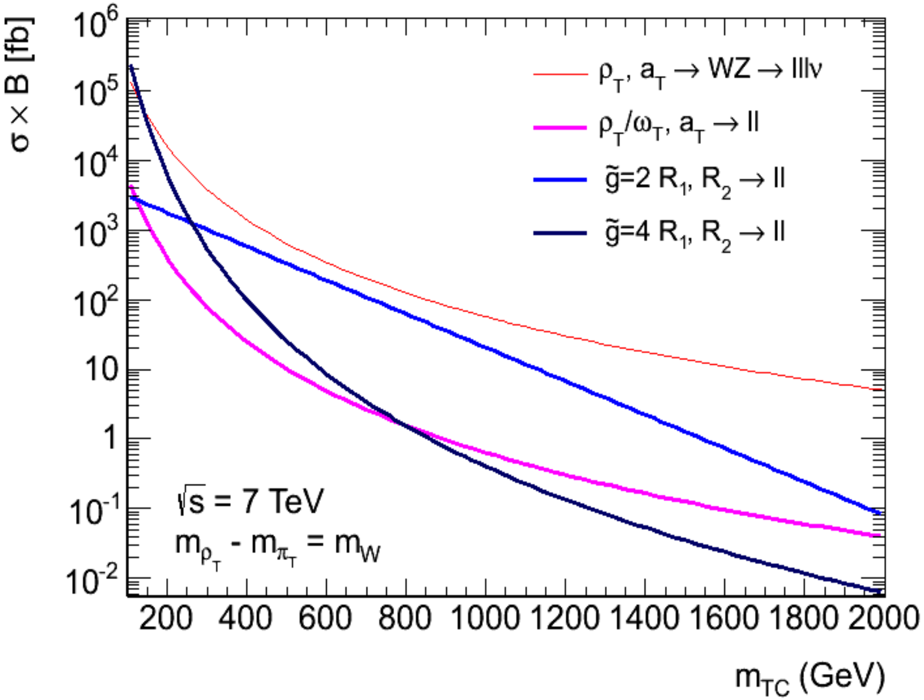
Interpretation in the $m(\pi_T)$: $m(\rho_T)$ plane





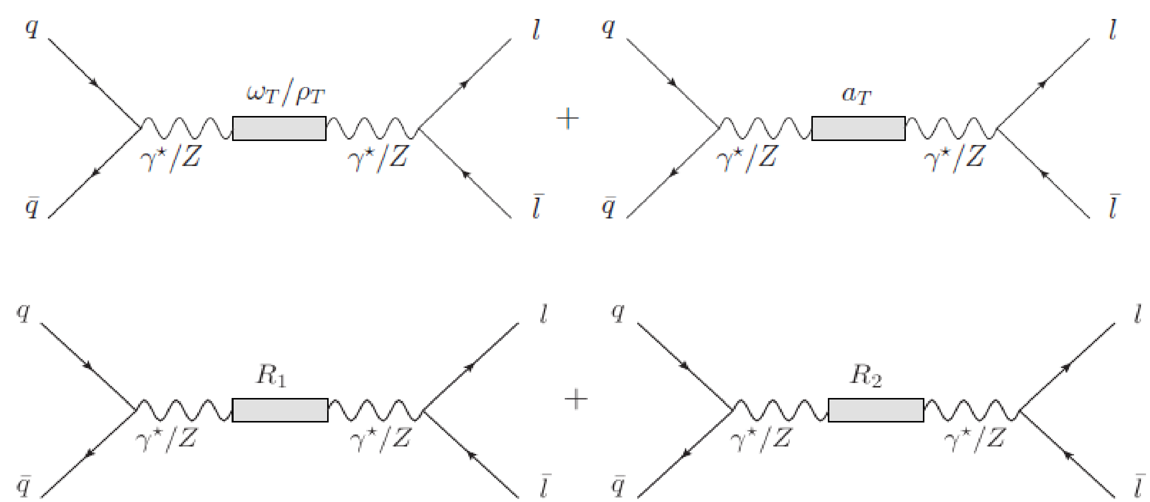
$A \times \epsilon$ for the ρ_T technimeson	Excluded ρ_T mass [GeV] $m_{a_T} = 1.1 m_{\rho_T}$	$m_{a_T} \gg m_{\rho_T}$
W' in PYTHIA	**483** (553)	**469** (507)
ρ_T in PYTHIA	**467** (506)	**456** (482)

ATLAS Search dilepton channel



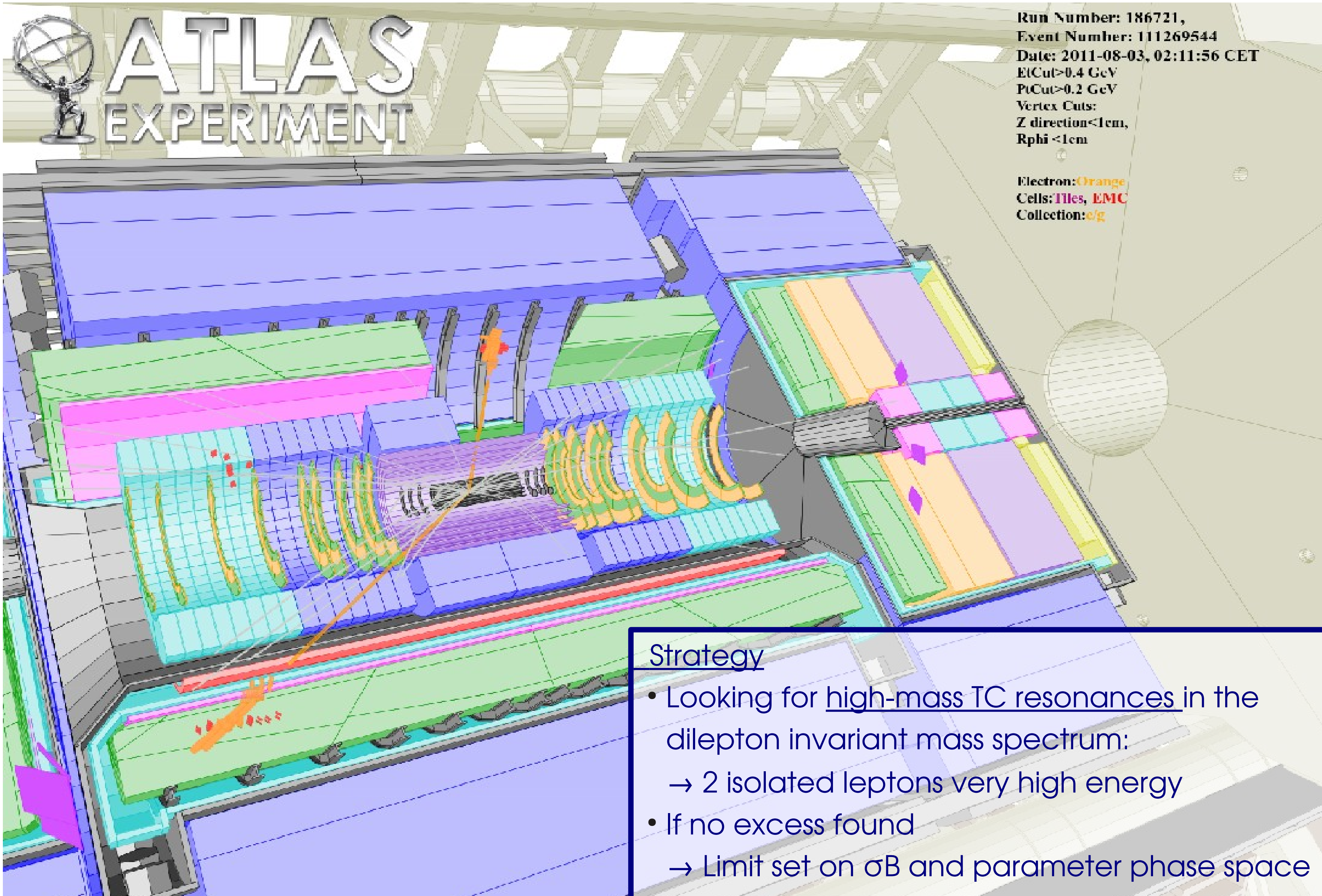
- TC resonance
  → very narrow
- The dilepton channel is the cleanest sample.
- 2 TC models considered
- wide range of Mass
  → from hundred GeV to few TeV

- TC resonances couple to lepton pairs through the Drell-Yan process.
- Contribution of both the axial and the vector resonances



TC in dilepton resonances

L = 5 fb^{-1}

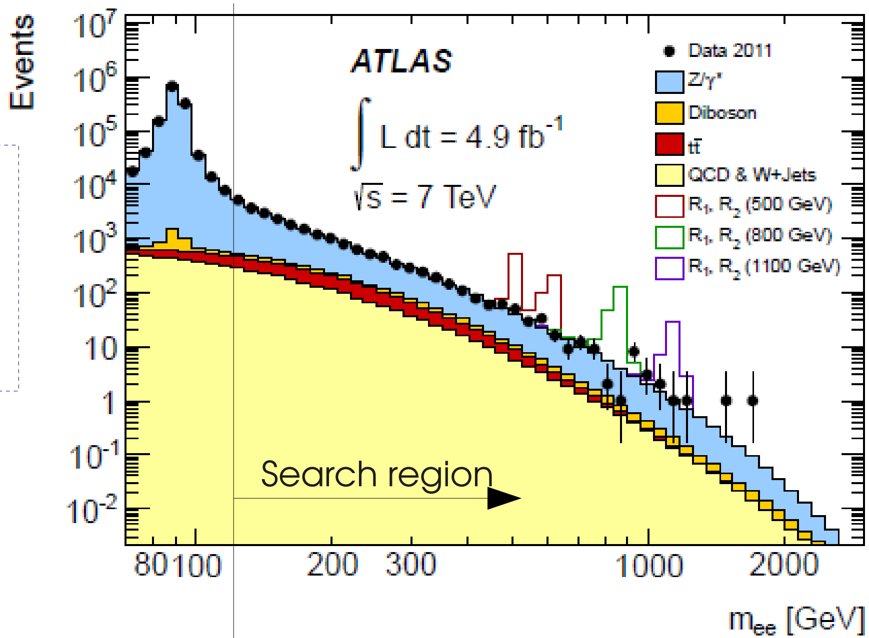


Strategy

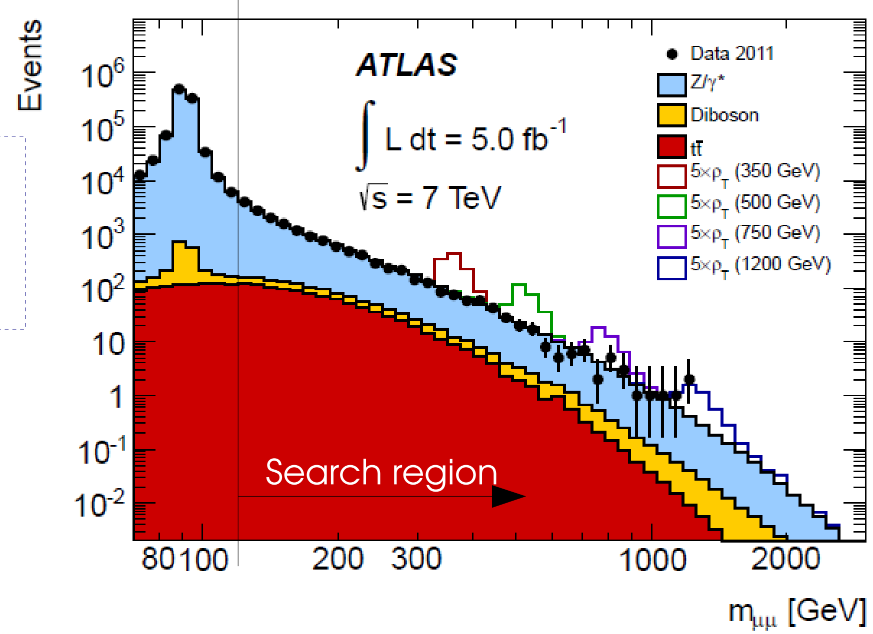
- Looking for high-mass TC resonances in the dilepton invariant mass spectrum:
  → 2 isolated leptons very high energy
- If no excess found
  → Limit set on σB and parameter phase space

Search for resonances in l^+l^- channel

Electron
- E_T > 25 GeV
- $|\eta|$ < 2.47
- M_{ee} > 70



Muon
- p_T > 25 GeV
- $M_{\mu\mu}$ > 70



Inv mass distribution of the lepton pair with highest p_T

- Backgrounds:

Real lepton MC expectation:

→ Drell-Yan (dominant & irreducible)

→ Diboson (WZ,ZZ,WW), $t\bar{t}$

Fake lepton Data-Driven:

→ W+jets, QCD multijets

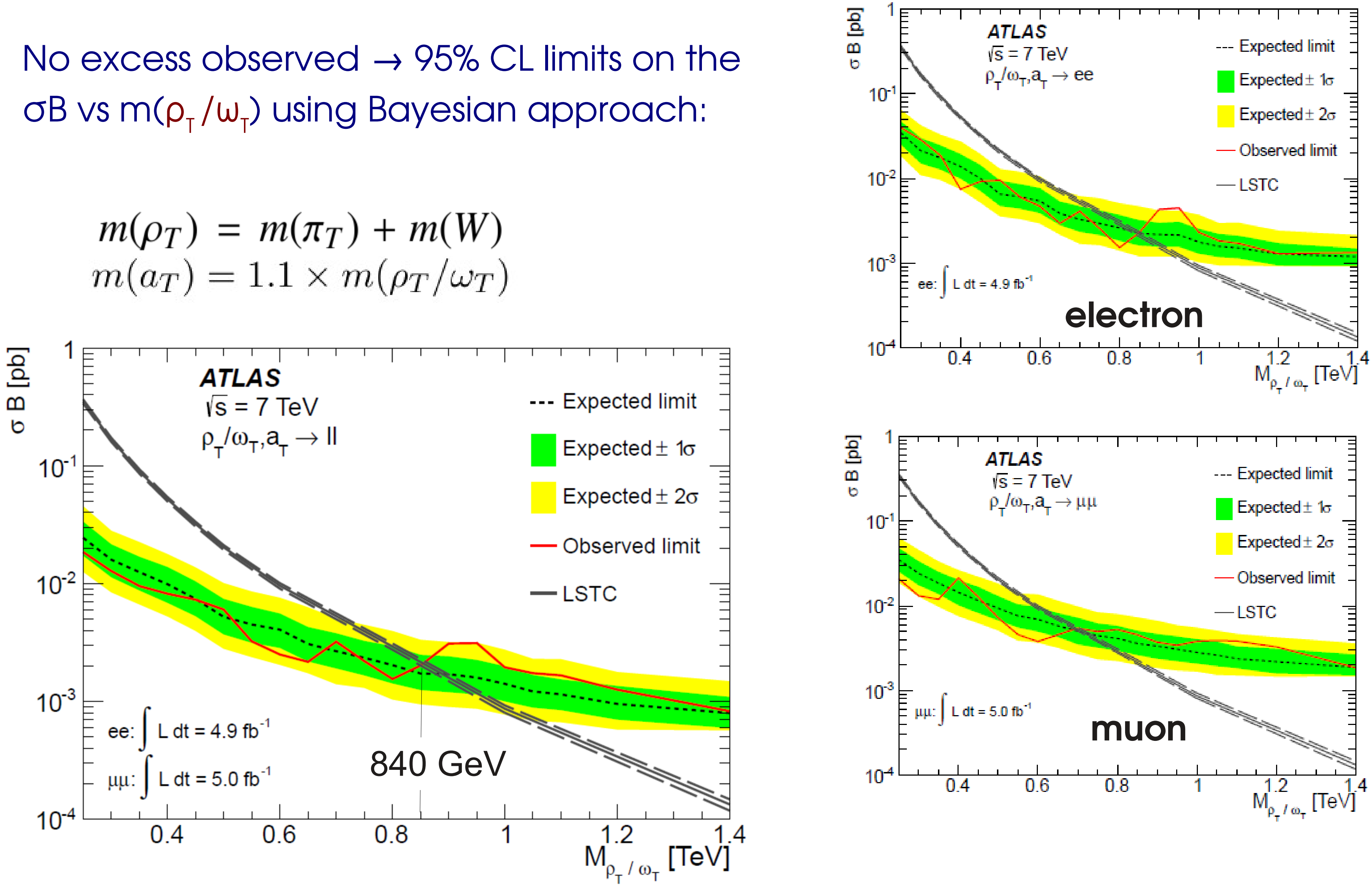
- Normalization of SM expectation and data over the Z peak

Good agreement data and SM prediction
→ no excess observed

Limit on the LSTC model

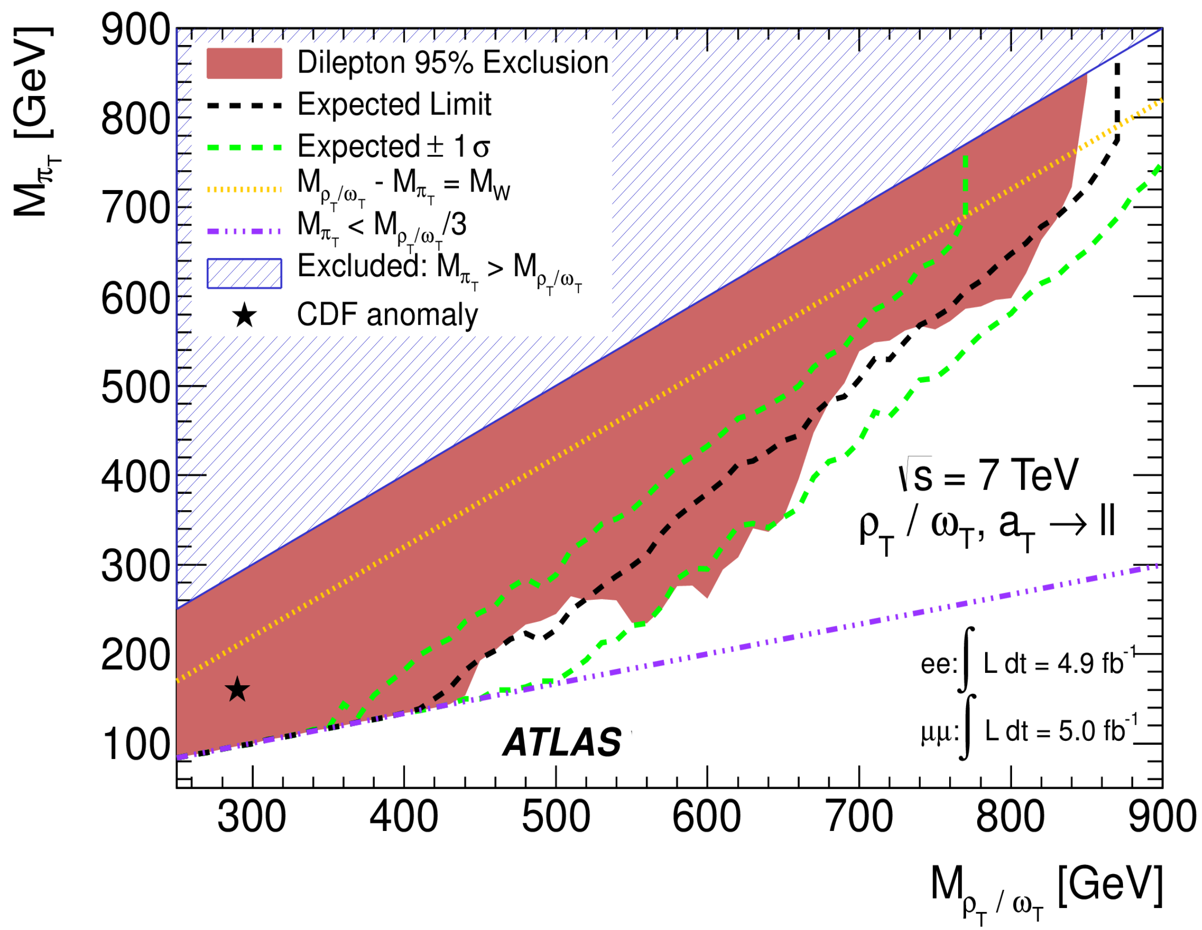
No excess observed → 95% CL limits on the σB vs $m(\rho_T/\omega_T)$ using Bayesian approach:

$$m(\rho_T) = m(\pi_T) + m(W)$$
$$m(a_T) = 1.1 \times m(\rho_T/\omega_T)$$



Model parameter space limit

- Extend the 1D Limits
  - limit on the σB vs mass are used to constraint different model parameter space

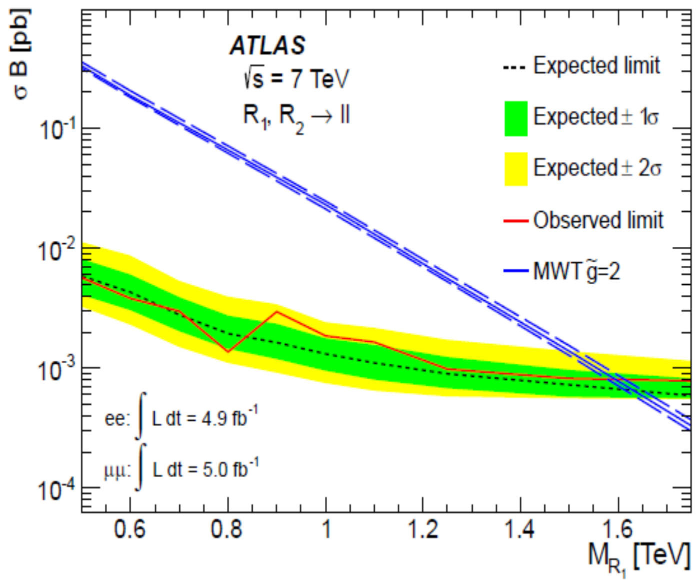


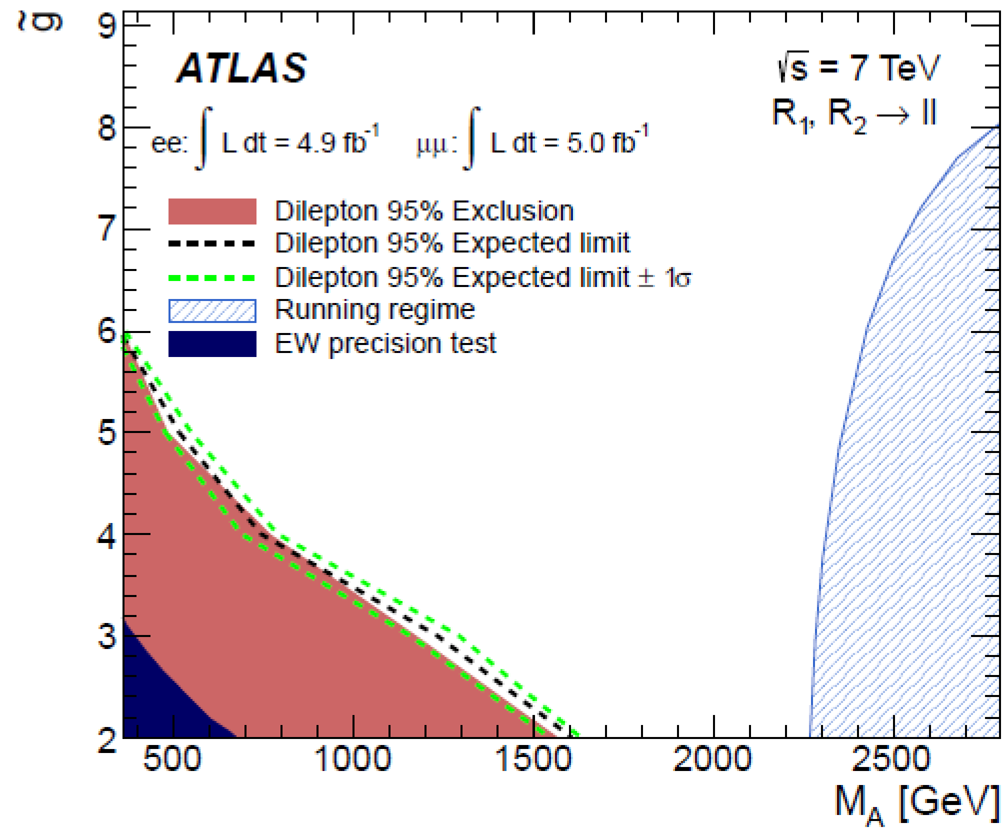
LSTC: large phase space excluded (CDF anomaly excluded)
m(ρ_T/ω_T) excluded between 250 – 850 GeV, m(π_T) 50 – 800 GeV

Minimal Walking ĝ-M_A plane

No excess observed → 95% CL limits on the σB vs mass for the R_1 resonance.

1D limits translates in exclusion region in the ĝ-M_A plane, scanning different ĝ hypothesis:



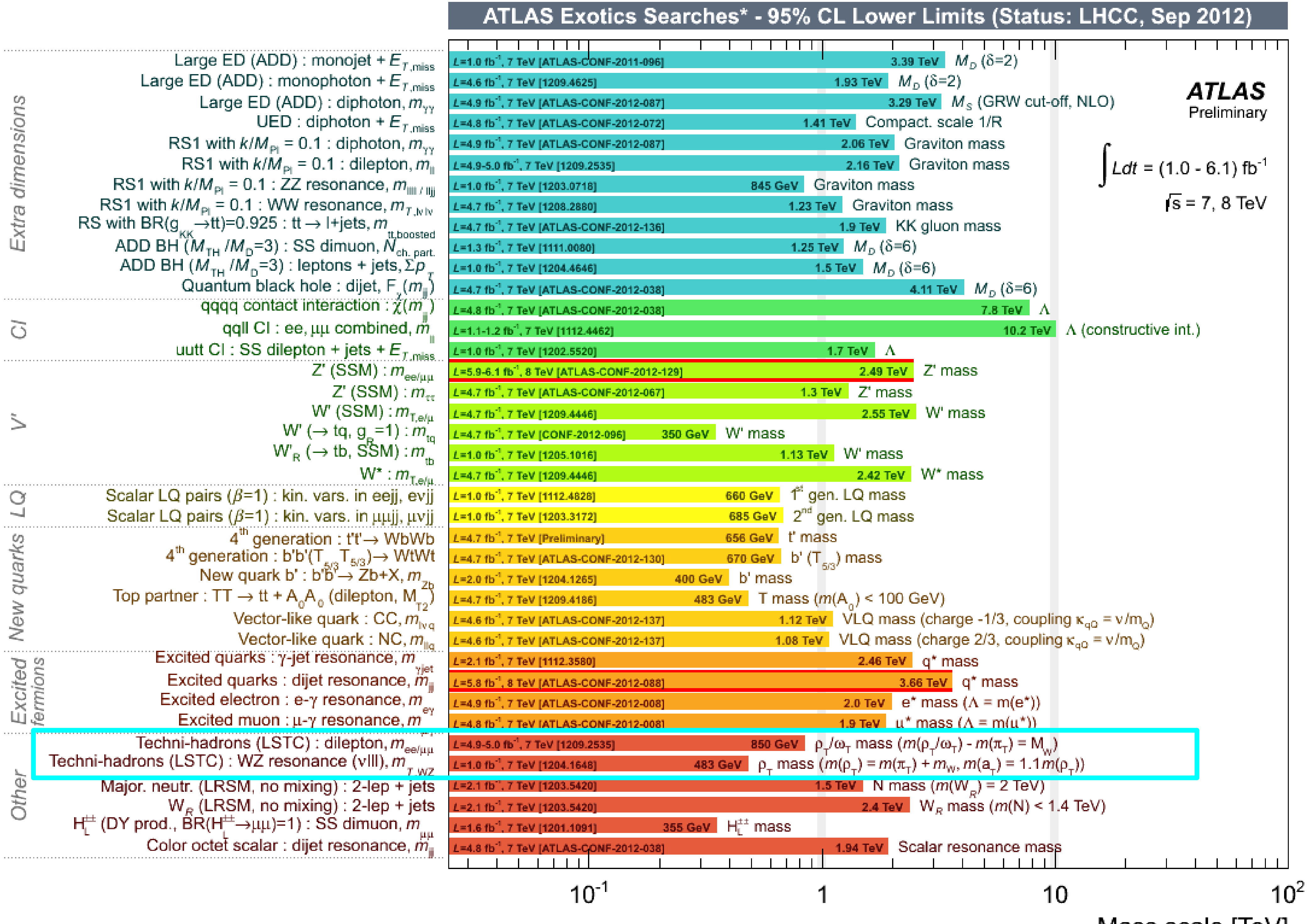


First direct limit in the ĝ-M_A plane

Conclusion

- TC models used as benchmark for ATLAS searches in different final states
- Search for WZ resonant structure in $m_T(WZ)$ distribution using 1 fb^{-1} of data (**Phys.Rev. D85 (2012) 112012**)
  - No discrepancy from SM expectation → LSTC ρ_T technimesons with masses below 467 GeV are excluded at 95% CL for $m_{aT} = 1.1 * m_{\rho T}$ using the PYTHIA implementation of ρ_T production.
  - Also exclusion limits on the $(m_{\pi T}: m_{\rho T})$ plane are set.
- Search of new resonance in dilepton spectrum within two TC scenario the LSTC and the MWT. (**submitted to JHEP: arXiv:1209.2535**).
  - No evidence for a TC signal is observed in 5 fb^{-1} of data recorded in 2011 and 95% C.L limits are set for both the TC models.
    → LSTC: $m(\rho_T/\omega_T)$ excluded below 850 GeV
    → MWT: $\hat{g}$-M_A parameter space is excluded for M_A between 360 – 1500 GeV for $\hat{g}$ values corresponding to 6 and 2, respectively.

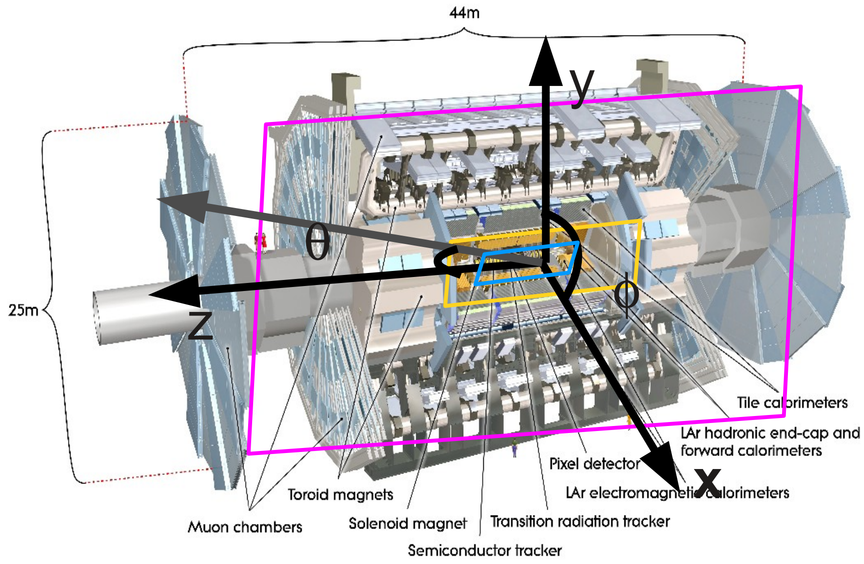
Thanks!



*Only a selection of the available mass limits on new states or phenomena shown

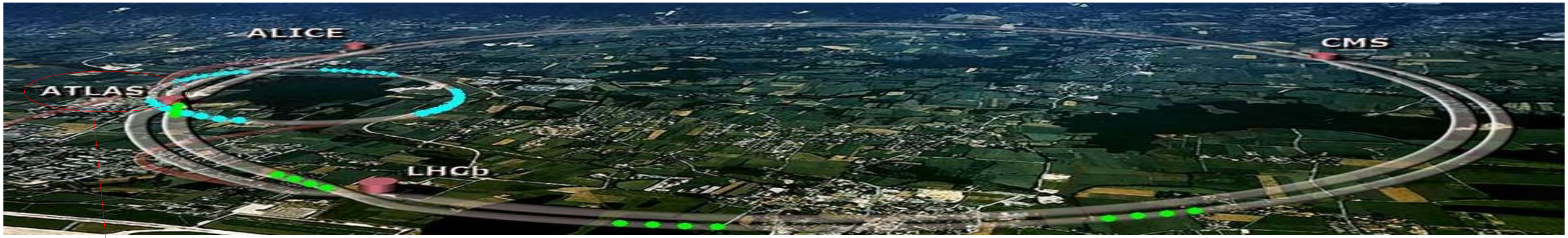
Backup slides

Object reconstruction in ATLAS



- **Muon**:
  - Combined track: inner taker + Muon spectrometer
  - Track Isolation
- **Electron**:
  - ID cuts on track and shower shape
  - Calo Isolation
- **MET**:
  - $|\eta|<4.5$
  - Culated from all Calo-clusters + the muon transverse momentum for events in the muon channel.
  - Calibration is applied to each calorimeter cluster to correct for energy loss in un-instrumented regions and for the different response of the calorimeters to hadron and electromagnetic shower components
- **JETs**:
  - Reco from calorimeter clusters using the anti-kt algorithm (radius parameter 0.4).
  - The jet energy is calibrated to account for the different response of the calorimeters to electrons and hadrons and for energy losses in un-instrumented regions.

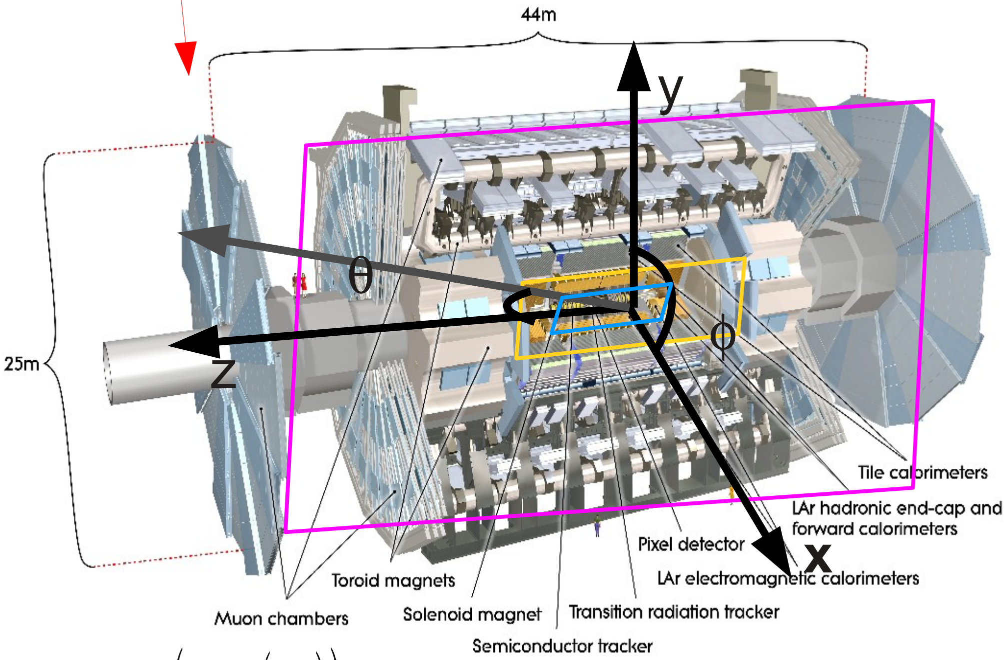
The LHC and the ATLAS detector



LHC proton-proton collider

- 2012 run $\sqrt{s}$ =8 TeV

  → ~ 30fb^{-1} expected by the end data-taking



$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

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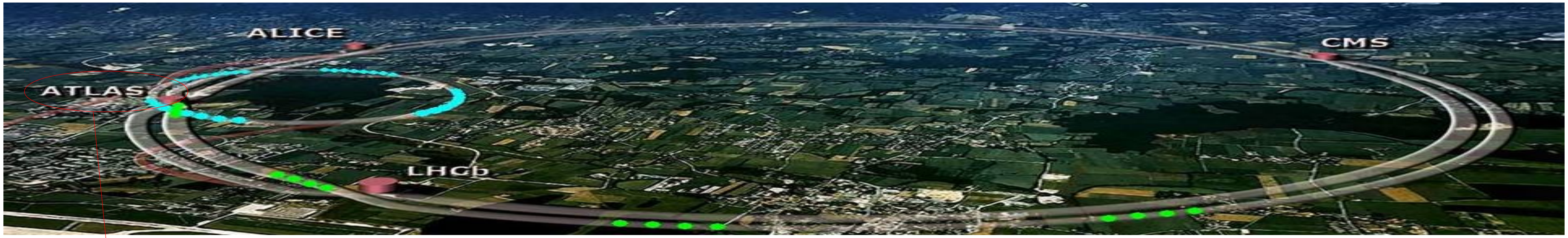

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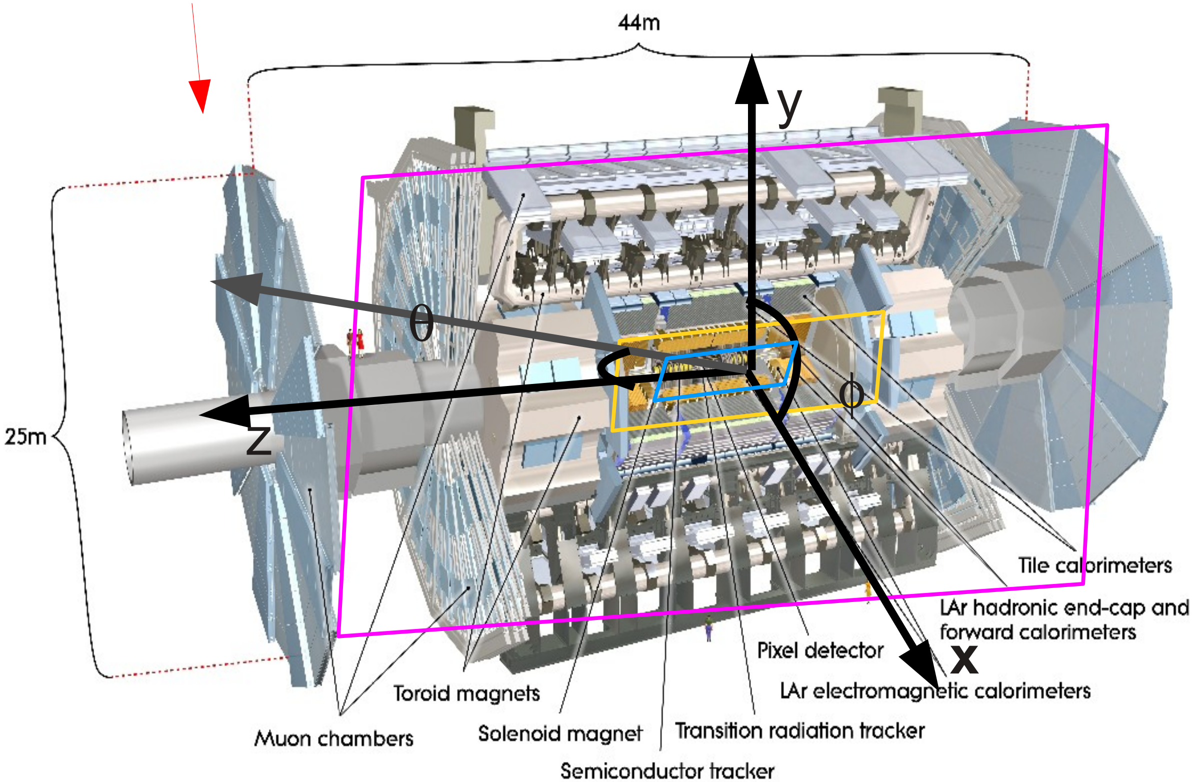
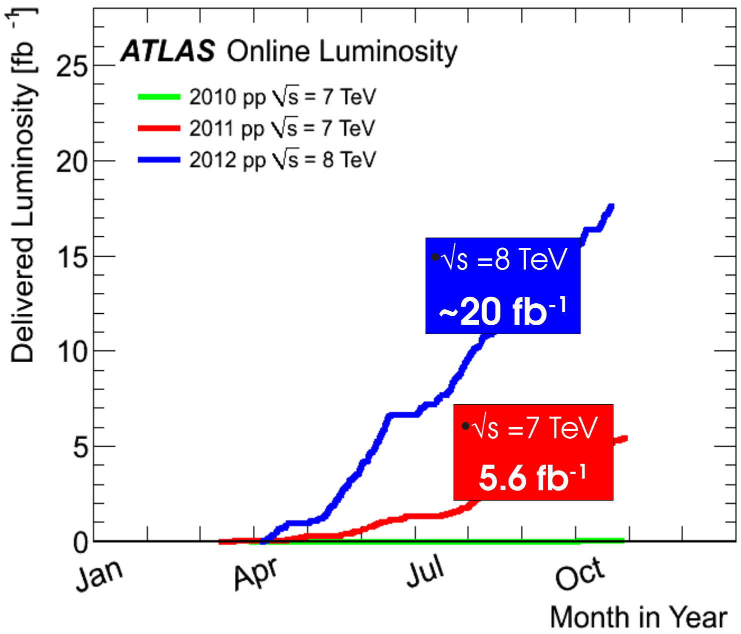
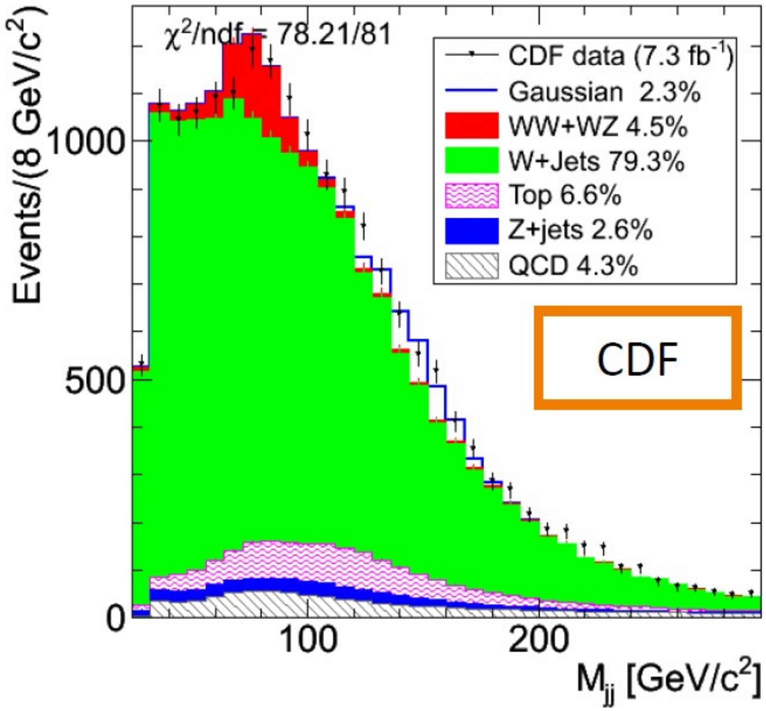


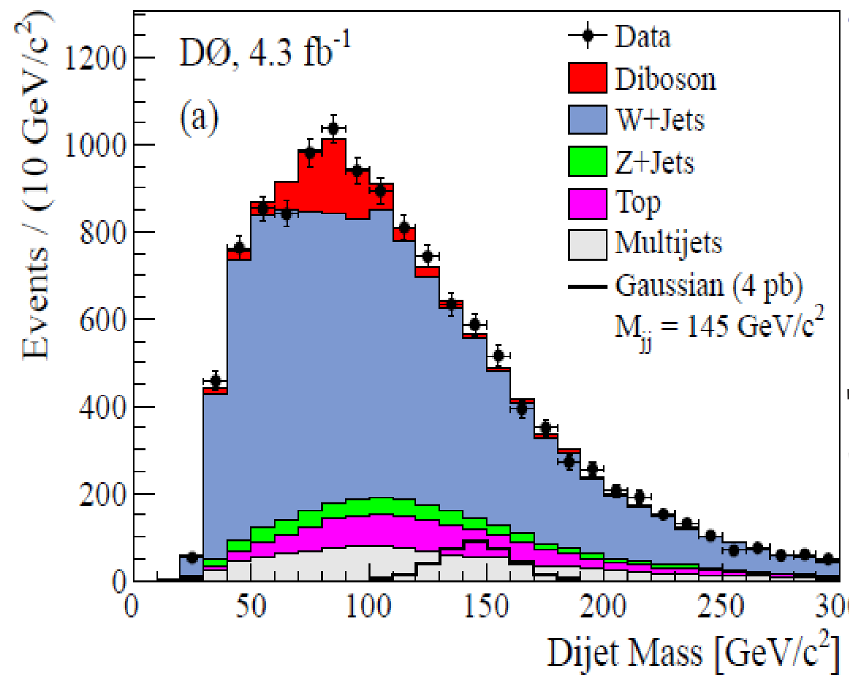


$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

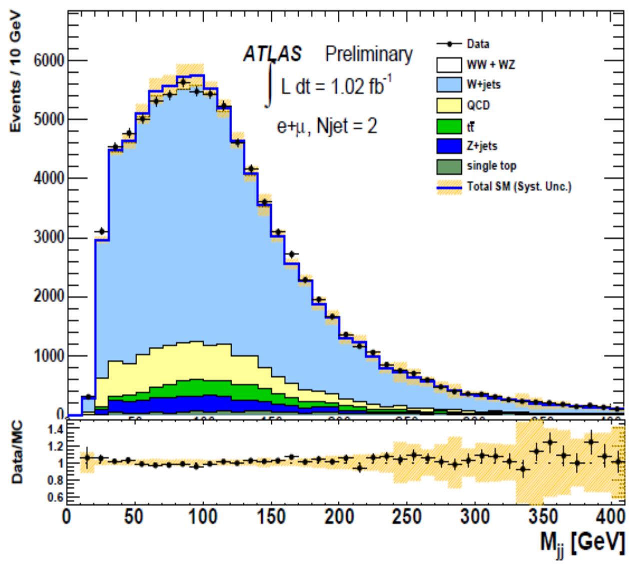
CDF anomaly

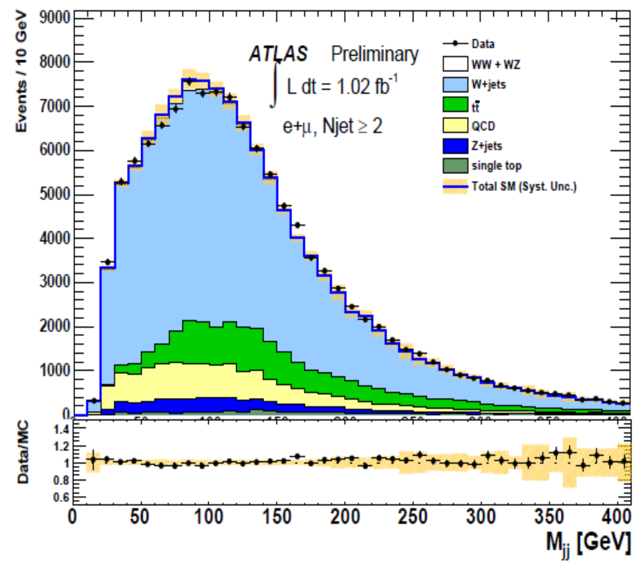


10.1103/PhysRevLett.106.171801



arXiv:1106.1921v2 [hep-ex]





ATLAS-CONF-2011-097

LSTC PYTHIA parameters

TCSM Parameter choice:

- Techni-isospin symmetry → isotriplet ρ_T and the isosinglet ω_T degenerated in mass
  - $M(\rho_T) = M(\omega_T)$
  - $\hat{s}$
  - $M(a_T) >$ 10% $M(\rho_T)$
- Isotriplet of technipions → nearly degenerated , masses not small
  - $M(\pi_T) = M(\rho_T) - m(W) \rightarrow \rho_T, \omega_T \rightarrow \pi_T W$ allowed
- The Q^2 scale choose is:

$\rho_T \rightarrow$ WZ decay in Pythia

- The ρ_T meson is expected to decay predominantly to longitudinally polarized W and Z bosons, similarly to the massive W′ boson
- Pythia implementation of $\rho_T \rightarrow$ WZ does not account for the vector boson polarization in their decay
- Spin correlations have been taken into account for W′ in Pythia
- Choose to set ρT cross section limits using $A \times \varepsilon$ for ρ_T calculated

1) Using the default pythia implementation of ρ_T

2) Assuming $A \times \varepsilon$ for W′ works also for ρ_T, also theoretically we expect similar angular distribution and acceptance for W′ and ρ_T

MWT model parameters:

→ bare axial and technivector masses: MA and MV ;
→ $\hat{g}$, the strength of the spin one resonance interaction;
→ S, the S-parameter obtained using the zeroth Weinberg Sum Rule;
→ mH, Higgs boson mass;
→ s, coupling of Higgs boson to composite spin-1 states.

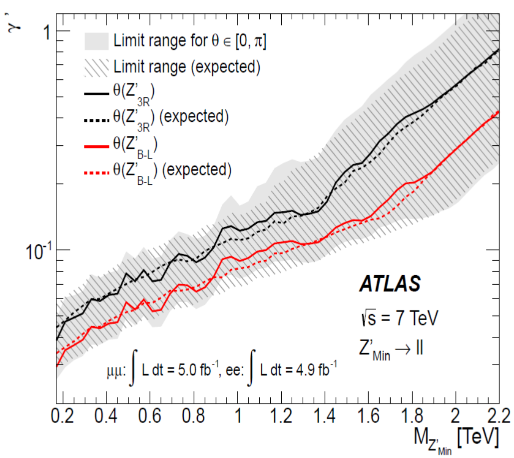
- the Higgs boson mass is mH = 200 GeV
- s = 0
- the S-parameter set to S = 0,3

Diboson search systematic uncertainty

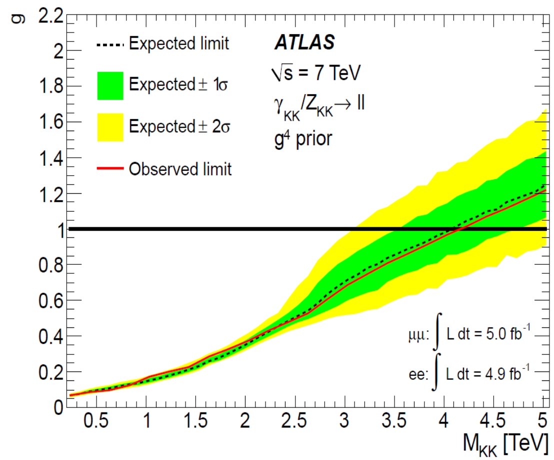
- Lepton systematics: energy/momentum scaling and smearing, reco/id efficiency, isolation
- MET systematics: resolution, in-time and out-of-time pileup
- PDF uncertainty on new physics signal acceptance
- Luminosity uncertainty
- Trigger efficiency
- Correlations between different channels

Search for resonances in l^+l^- channel

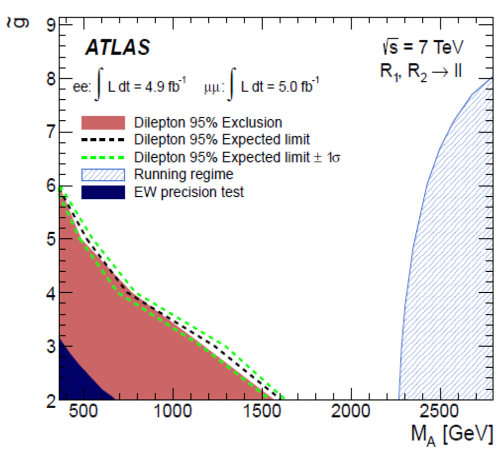
Z' Minimal models



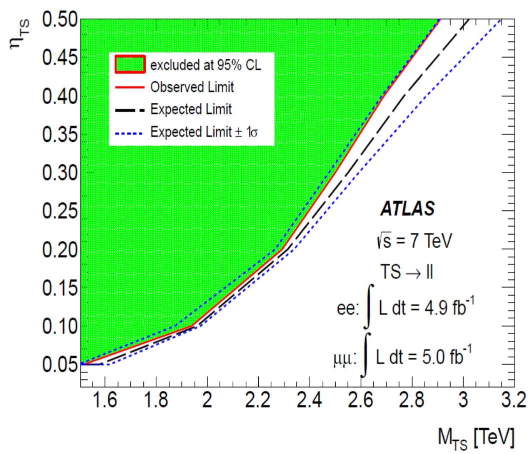
Kaluza Klein resonance



Technicolor resonances



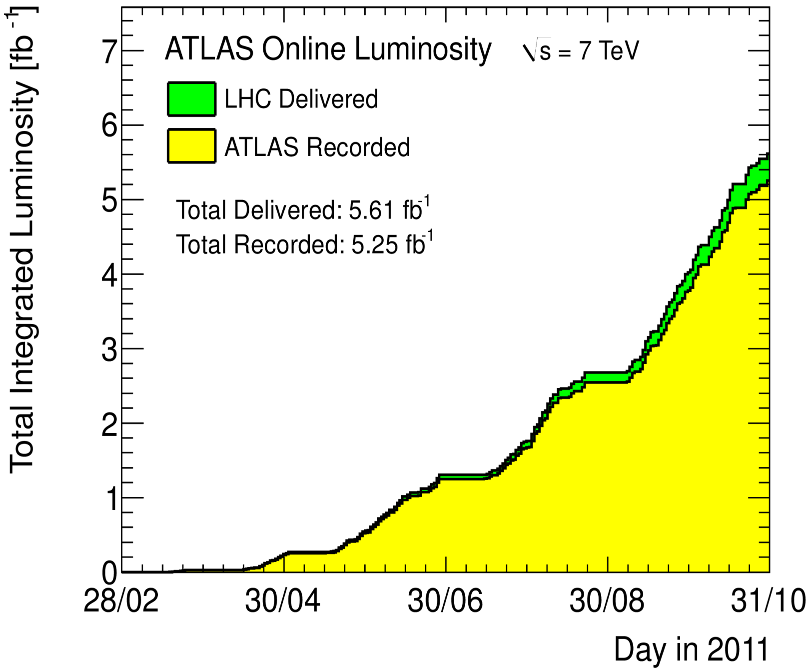
Torsion



- High Mass Dilepton Resonances paper
- Looking for high-mass resonances in the dielectron and dimuon invariant mass spectrum
- If no significant excess found: 95% C.L. limits are set using a Bayesian approach, flat prior in σ*B
  - Several 1D and 2D limit plots to constrain different parameters in the phase-space for each model

Data and MC samples

Channel	Luminosity
Electron	4.91 fb^{-1}
Muon	4.99 fb^{-1}

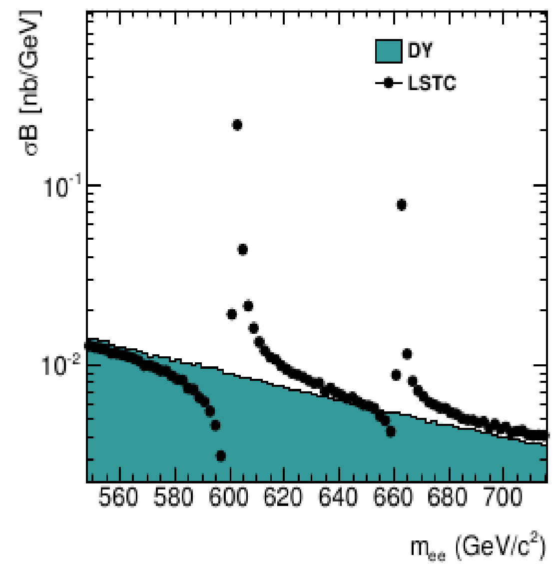


SM Backgrounds

Process	σB (pb)	Generator [PDF]	Order and corrections
Z/γ*	990	PYTHIA [LO**]	with mass-dependent NNLO QCD and EW k-factors
tt_{bar}	165	MC@NLO [NLO]	scaled to NNLO cross-section
WW, WZ, ZZ	70	HERWIG [LO**]	scaled to NLO cross-section
W+jets QCD Multijets	$1*10^4$ –	Data-driven/ALPGEN [LO**] Data-driven	– /scaled to NNLO cross-section –

Search for resonances in l^+l^- channel

- Looking for high-mass TC resonances in the dielectron invariant mass spectrum
- Backgrounds:
  - Drell-Yan (dominant & irreducible)
  - Diboson, ttbar
  - W+jets, QCD multijets

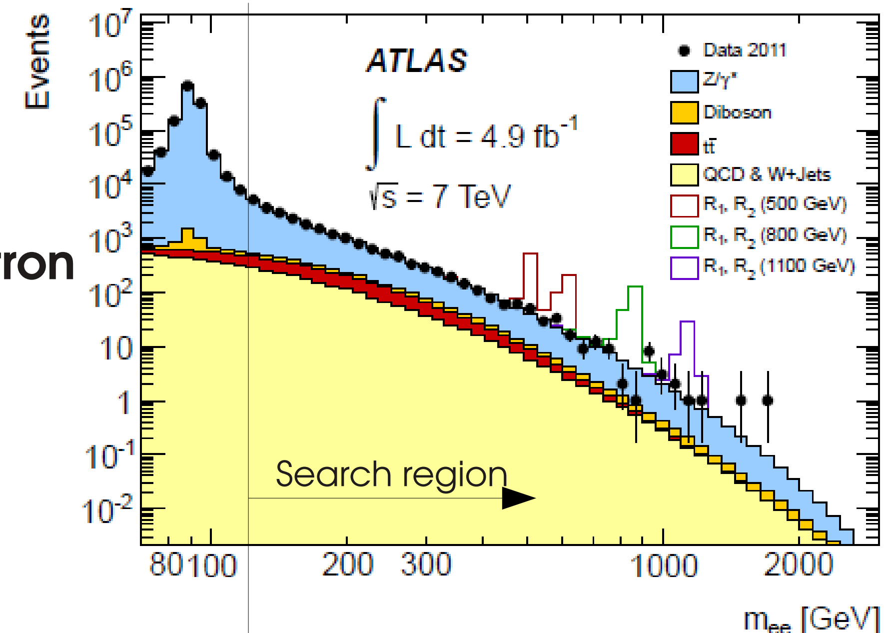


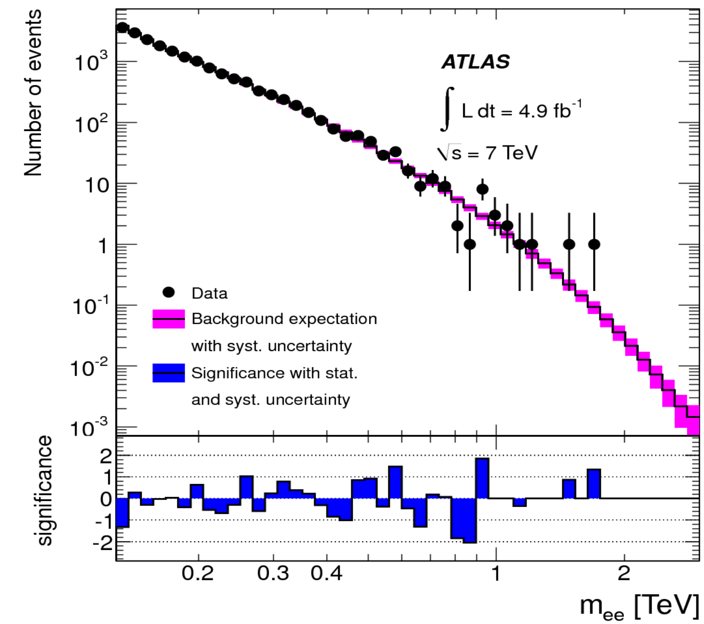
Process	σB (pb)	Generator [PDF]	Order and corrections
Z/γ^*	990	PYTHIA [LO**]	with mass-dependent NNLO QCD and EW k-factors
tt_{bar}	165	MC@NLO [NLO]	scaled to NNLO cross-section
WW, WZ, ZZ	70	HERWIG [LO**]	scaled to NLO cross-section
W+jets QCD Multijets	$1*10^4$ –	Data-driven/ALPGEN [LO**] Data-driven	– /scaled to NNLO cross-section –

- If no significant excess found above the SM expectation: 95% C.L. limits are set using a Bayesian approach

Search for resonances in l^+l^- channel

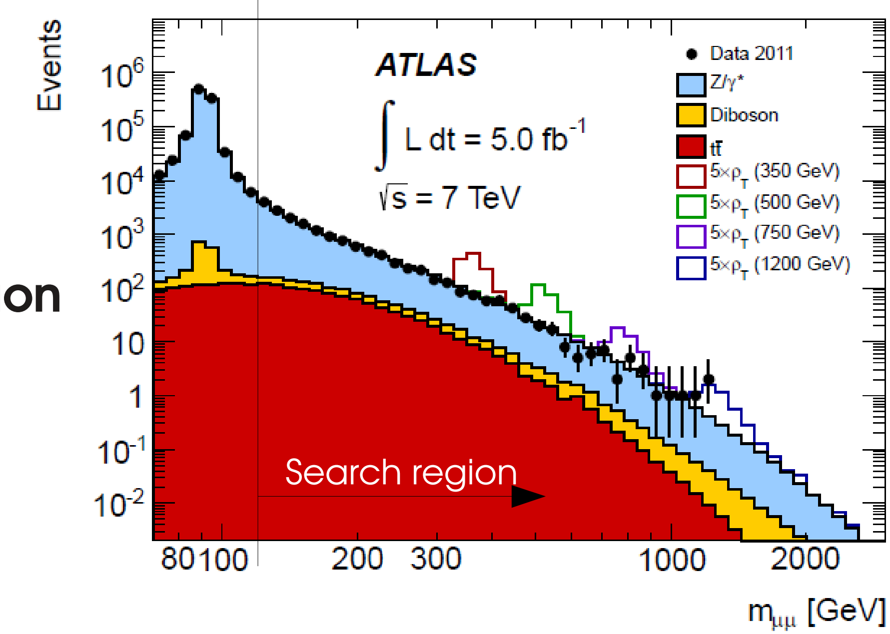
electron

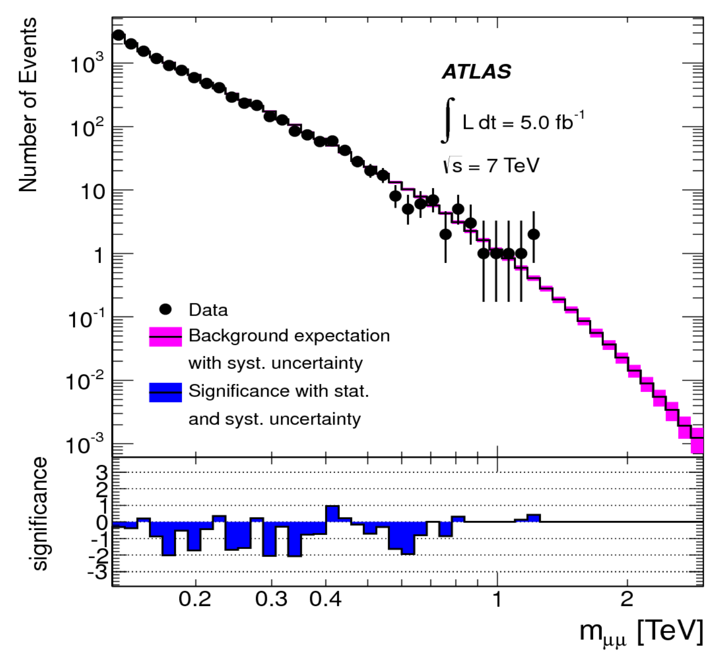




electron

muon

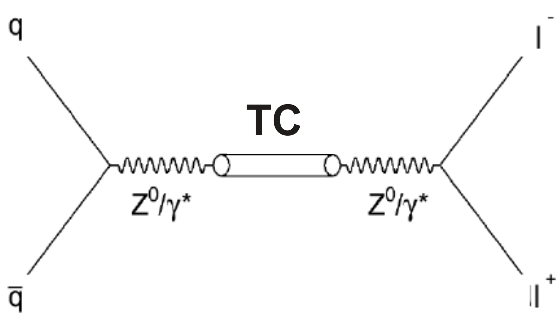




muon

Signal MC

Process	Generator	Order and corrections
Technicolor	PYTHIA LO** Madgraph LO	with mass-dependent NNLO QCD and EW k-factors



TC resonances couple to lepton pairs through the Drell-Yan process

→ weighting procedure is developed starting from the DY continuum to create the signal reconstructed MC samples

Dilepton search Systematic uncertainty

- Normalization to Z peak in both channels
  - Cancels out mass independent systematics
- Contributions < 3% give negligible contribution in the limit settings

$m_{\ell\ell}$ = 200 GeV

Source	Dielectrons		Dimuons	
	Signal	Background	Signal	Background
Normalization	5%	NA	5%	NA
PDF/α_s /scale	NA	4%	NA	4%
W + jets and QCD background	NA	7%	NA	-
Total	5%	8%	5%	4%

$m_{\ell\ell}$ = 1 TeV

Source	Dielectrons		Dimuons	
	Signal	Background	Signal	Background
Normalization	5%	NA	5%	NA
PDF/α_s /scale	NA	7%	NA	7%
Efficiency	-	-	3%	3%
W + jets and QCD background	NA	12%	NA	-
Total	5%	14%	6%	8%

Bayesian Statistical Method

Bayesian approach to compare m_{ll} distributions from data to the SM backgrounds and signal templates for each model:

- For each test mass, we use the binned Poisson likelihood

$$L(N_X, N_Z | data) = \prod_{k=1}^{N_{bin}} \frac{(N_X + N_{bg})_k^{N_k^{obs}} e^{-(N_X + N_{bg})_k}}{N_k^{obs}!}$$

- Systematic uncertainties are incorporated in the likelihood via nuisance parameters, which are integrated out
- Setting limits
  - 95% CL interval on N(X)
  - Converted into 95% CL limits on σB(X)

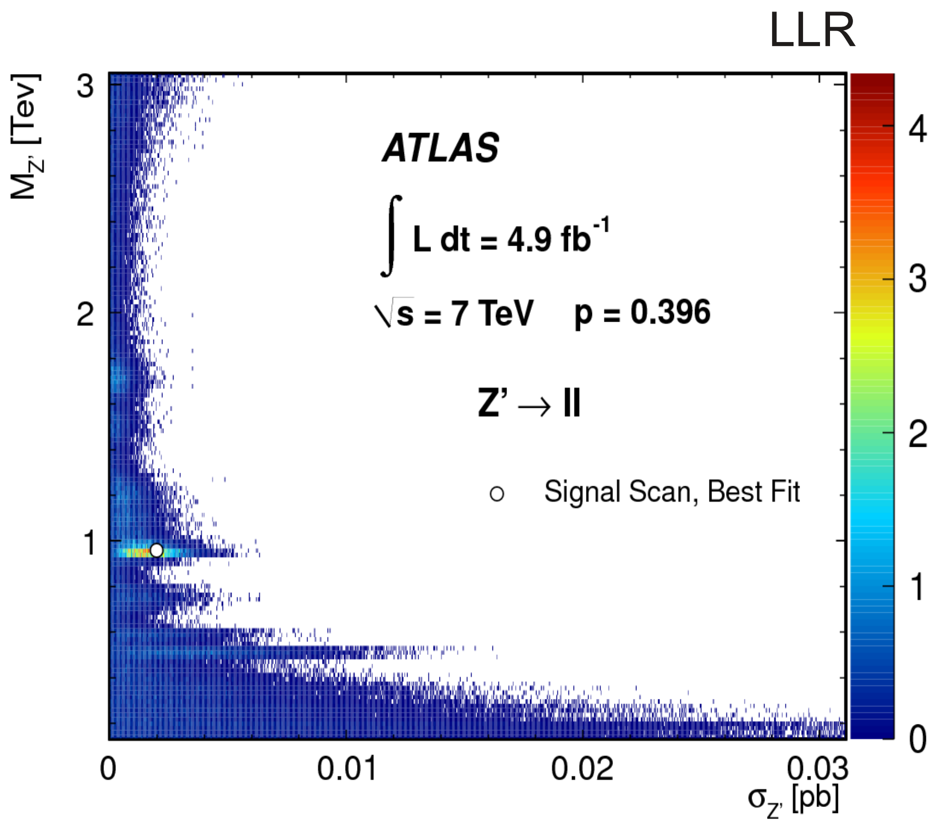
$$\boxed{\sigma B(X) = \sigma B(Z) \frac{N_X \, A\epsilon(Z)}{N_Z \, A\epsilon(X)},}$$

Dilepton Search for a signal

- use 2D maximum likelihood fit to find most probable M_{TC} and σ_{TC}

P-value: is the probability of observing an outcome at least as signal-like as the one observed in data,

assuming that a signal is absent.



get p-value by comparing to pseudo-experiments

- electrons: p = 32%, muons: p = 63%, combined 35%

---> No significant excess found

---> Setting limits

Summary - Technicolor

- Technifermions strongly interacting at the weak scale break the weak symmetries to $U(1)_{\mathrm{EM}}$ W's and Z's become massive
- At ~ LHC energies, composite states of technifermions such as techni-rhos, … should appear

- ATLAS search:
  - Low Scale TC Model
  - Minimal Walking TC
- Main differences between the two models :
  - Representations (ajoint for MWTC, fundamental for LSTC) and gauge groups (SU(2) vs SU(4)) are different for two models
  - Number of techni-quark doublets is $N_D^{MWTC}=1$ and $N_D^{LSTC}>1$ (~5)
    - Many more new techni-particles would be produced in LSTC
  - Energy scale: MWTC = v_{EW} and $F^{LSTC}=v_{EW}/\sqrt{N_D}<v_{EW}$

Limit on the MWT model

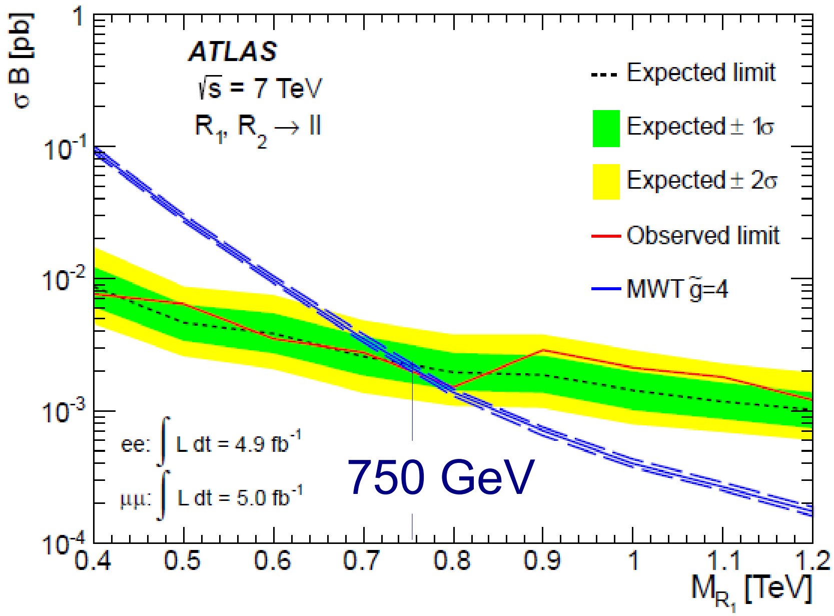
95% CL limits on the σB vs mass for the MWT models:

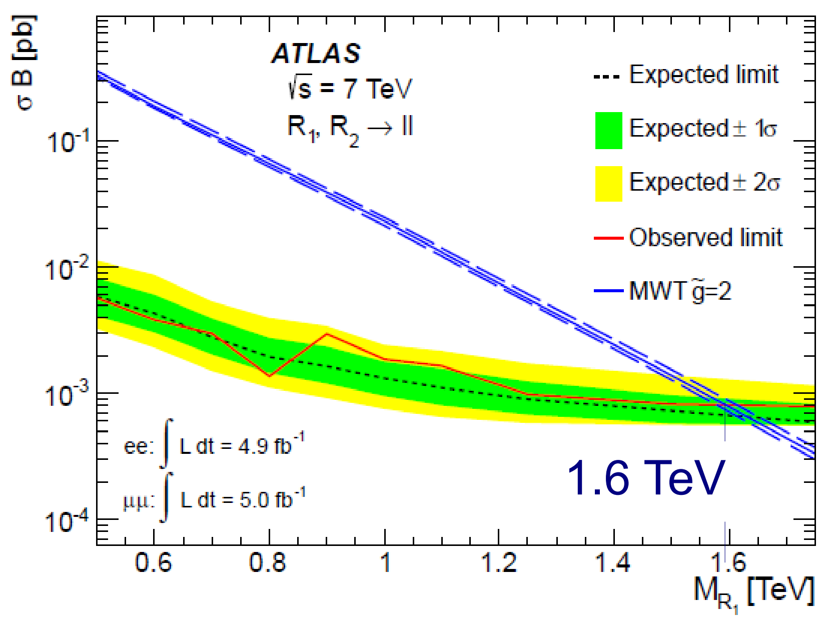
Different ĝ hypothesis:

benchmark

ĝ = 2

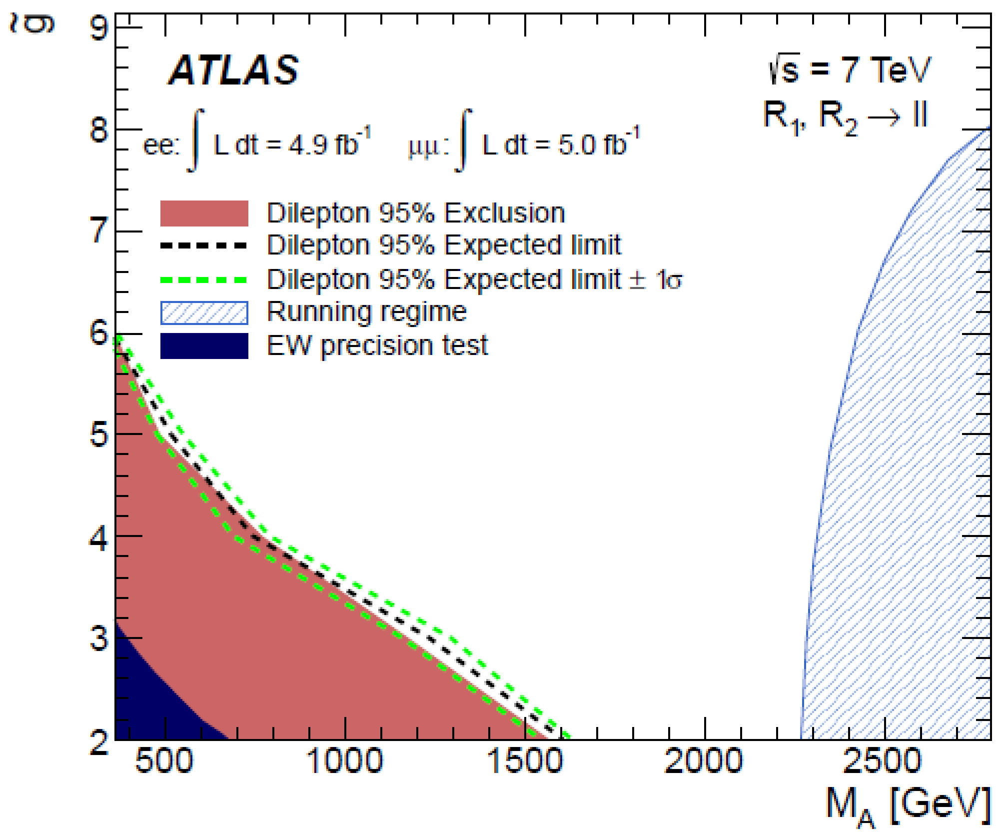
ĝ = 4





Minimal Walking $\hat{g}$-M_A plane

$\tilde{g}$	6	5	4	3	2
Observed limit [GeV]	359	485	768	1175	1566
Expected limit [GeV]	352	516	742	1233	1605



First direct limit in the $\hat{g}$-M_A plane

Conclusion

- TC models used as benchmark for ATLAS searches in different final states
- Search for WZ resonant structure in $m_T(WZ)$ distribution using 1 fb^{-1} of data (**Phys.Rev. D85 (2012) 112012**)
  - No discrepancy from SM expectation → Using the mass hierarchy assumption $m_{\rho T} = m_{\pi T} + m_W$, LSTC ρ_T technimesons with masses from 200 GeV up to 467 GeV and 456 GeV are excluded at 95% CL for $m_{aT} = 1.1 m_{\rho T}$ and $m_{aT} \gg m_{\rho T}$ respectively using the PYTHIA implementation of ρ_T production. Also exclusion limits on the ($m\pi_T$: $m\rho_T$) plane are set.
- Search of new resonance in dilepton spectrum within two TC scenario the LSTC and the MWT. (**submitted to JHEP: arXiv:1209.2535**).
  - No evidence for a TC signal is observed in 5 fb^{-1} of data recorded in 2011 and 95% C.L limits are set for both the TC models.
    → LSTC: m(ρT/ωT) excluded between 250 – 850 GeV
    → MWT: $\tilde{g}$-M_A parameter space is excluded for M_A between 360 GeV and 1.5 TeV for $\tilde{g}$ values corresponding to 6 and 2, respectively.