ATLAS Searches for non-SUSY Exotics at the LHC

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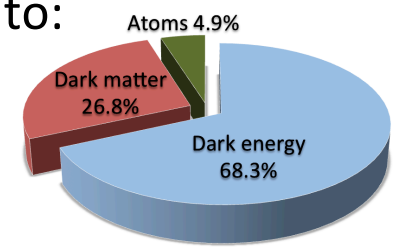
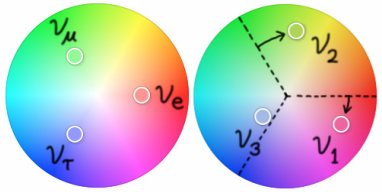
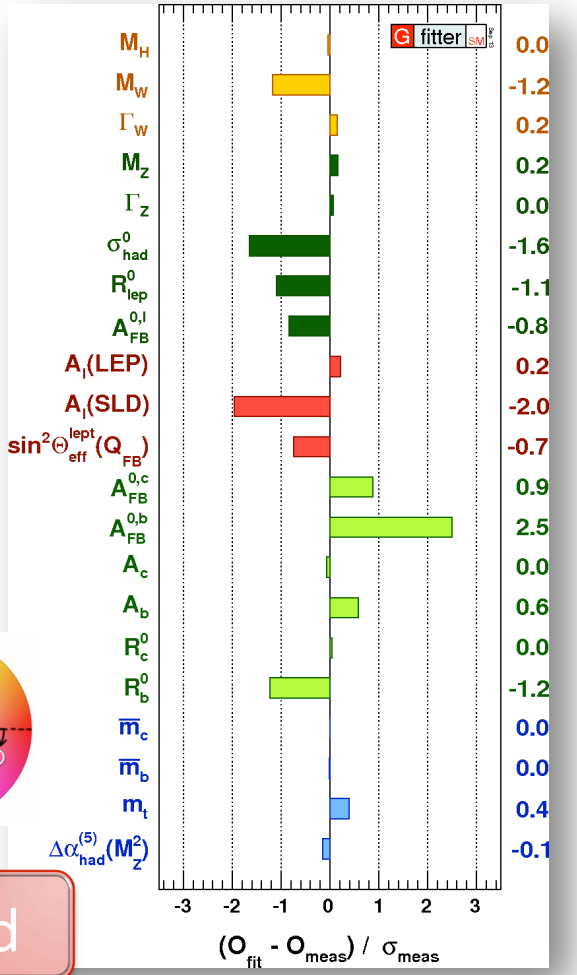
On behalf of the ATLAS Collaboration

Why going beyond the Standard Model?

- SM provides an excellent description of the experimental data so far
  - QCD and hadronic structure
  - precision EW physics
  - top quark
  - flavour physics
- yet… it does not provide an answer to:
  - hierarchy / fine tuning problem
  - matter-antimatter asymmetry
  - dark matter & dark energy
  - neutrino masses
  - unification of EW interactions & QCD
  - gravitation
  - more than one fermion generation

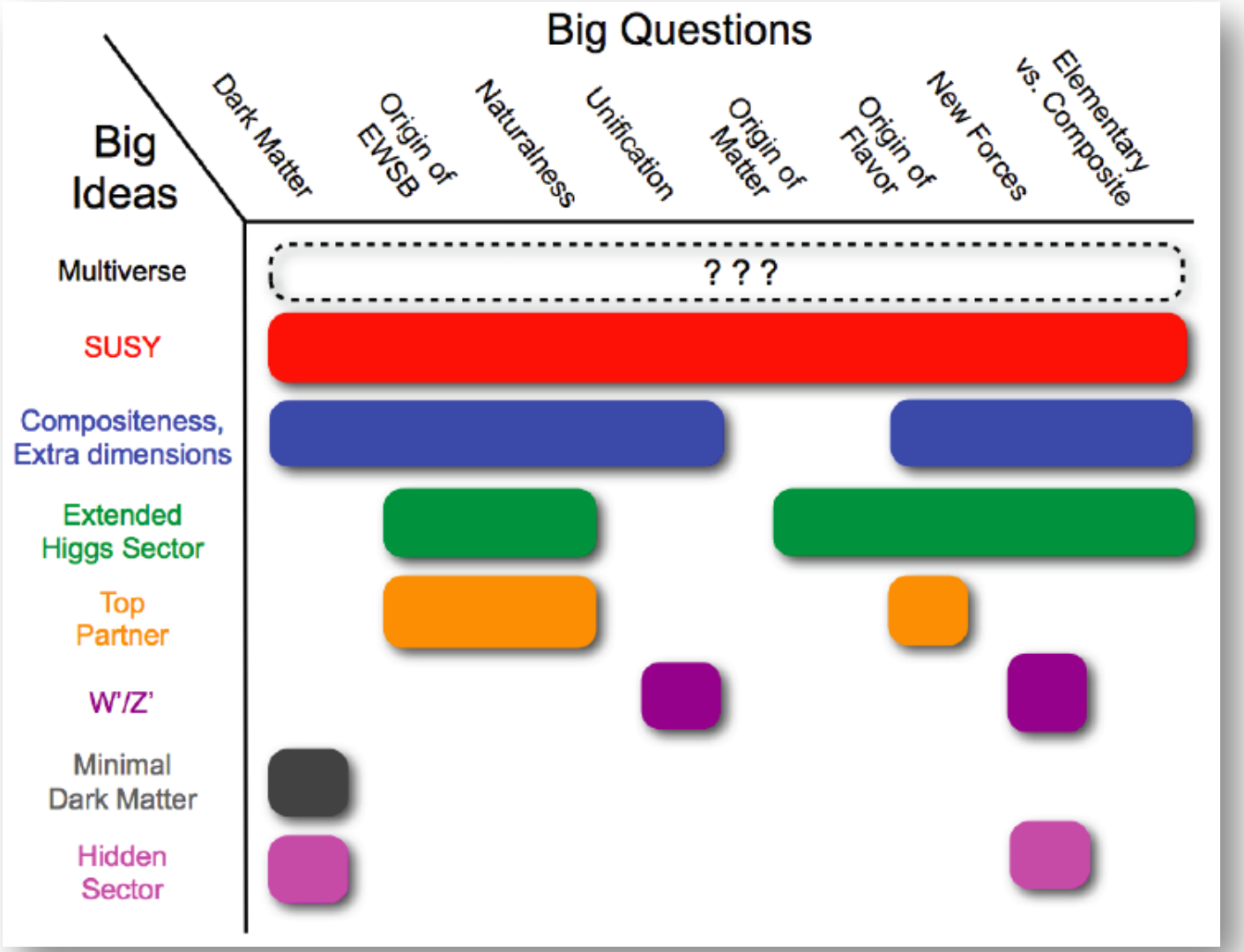






☛ An extension of the Standard Model is needed

(some) ideas beyond Standard Model



Snowmass 2013 Summary Paper

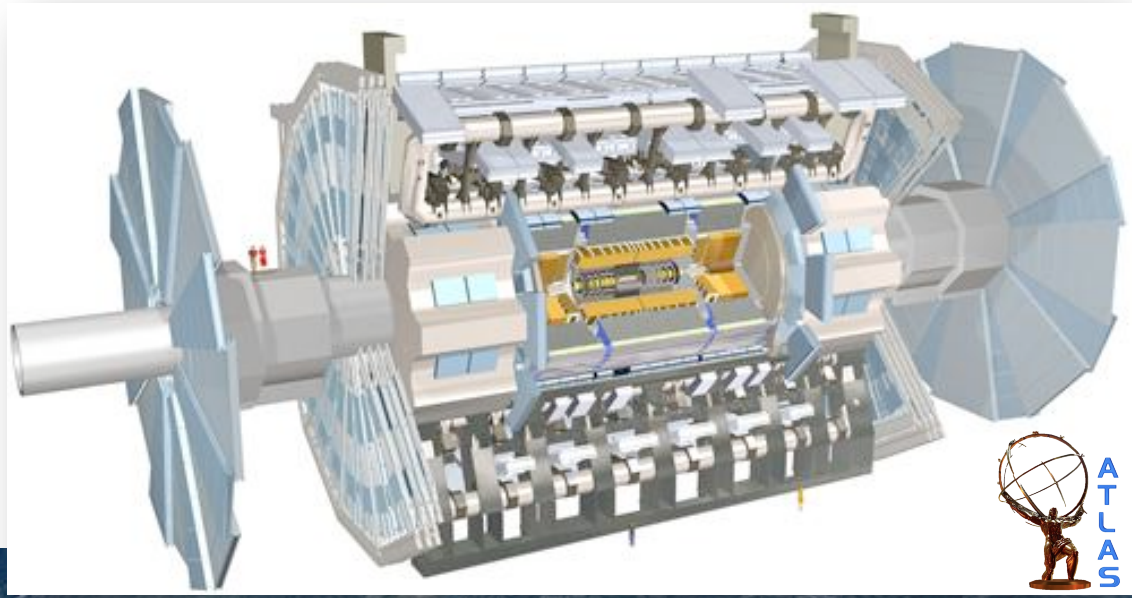
Signatures probing model predictions

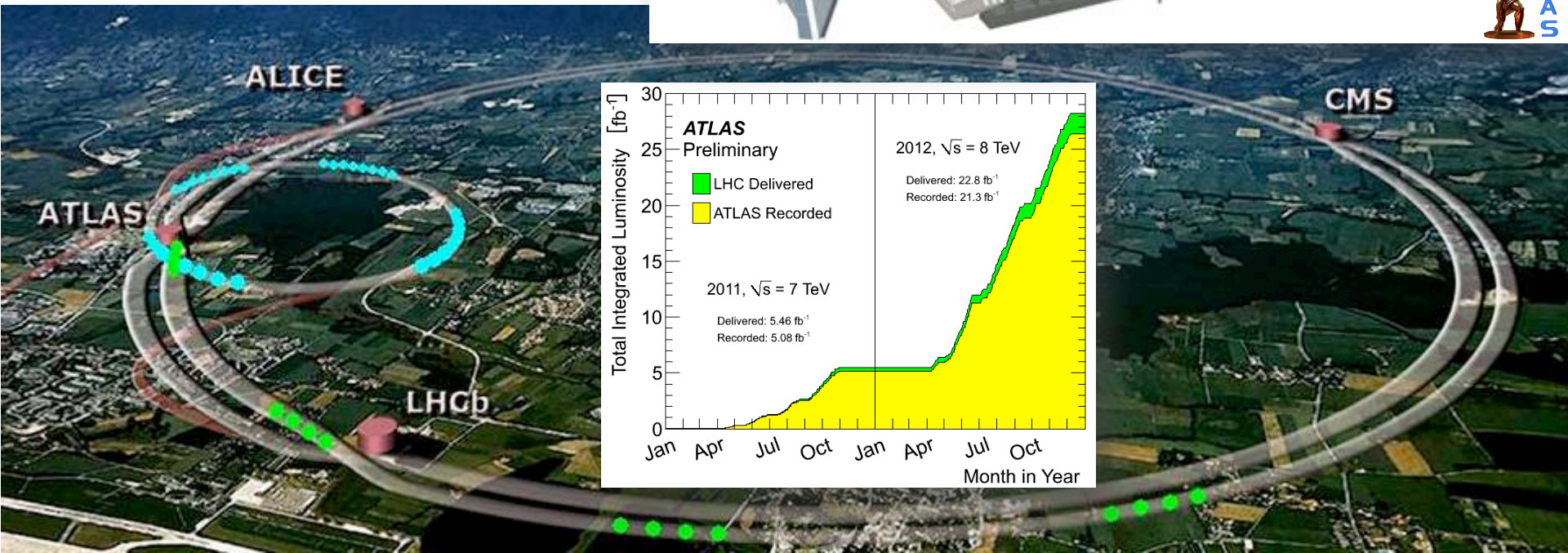
- Resonances
  - dijets
  - dileptons
  - W' → $\ell\nu$ — Christopher Marino's talk
  - dibosons
  - top/bottom — Jiahang Zhong's talk
  - …
- Non-resonant final states
  - dileptons
  - leptons+jets
  - generic searches
  - mono-X + E_T^{miss} — David Salek's talk
  - …
- Long-lived particles
  - high ionisation
  - unusual energy depositions in calorimeters
  - …

- Signature-based searches cover multitude of theoretical scenarios
- Emphasis given on most recent results here

ATLAS at the LHC

- **Spectacular LHC performance**
- Run 1: 2010 – 2012
  - **~5 fb^{-1}** pp collisions at **√s = 7 TeV**
  - **~20 fb^{-1}** pp collisions at **√s = 8 TeV**
- Physics run will resume in 2015 with 13-14 TeV collisions





Beyond SM searches strategy

① Pursue signature-driven analyses:
- resonances: dileptons, jets, photons, ...
- tails in kinematic distributions
- special particles: slow-moving, long-lived, ...
- ...

② Search for excess of events over the expected SM background

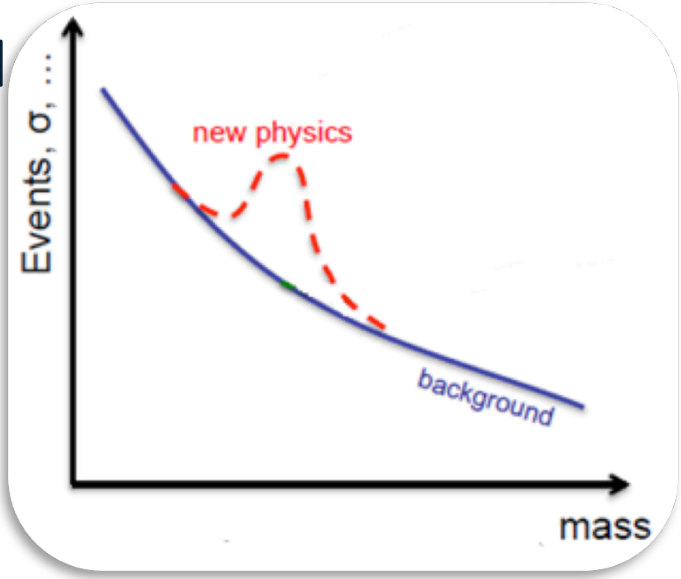
③ If no significant excess is observed
- set cross-section upper limits
- interpret in specific models to obtain limits on masses, couplings, ...

☛ Background estimate: data-driven techniques for main; MC for smaller

☛ Blind analysis: first define and validate analysis, then open signal box

Looking for resonances

- Dijets [arXiv:1407.1376]
- Dileptons [arXiv:1405.4123]
- X → HH → $b\bar{b}b\bar{b}$ [ATLAS-CONF-2014-005]
- ZV → $\ell\ell q\bar{q}$ [ATLAS-CONF-2014-039]
- WZ → $\ell\nu\ell'\ell'$ [arXiv:1406.4456]
- leptonic W/Z + γ
  [to be published soon in PLB]
- Top/bottom resonances



Resonance in dijet distribution

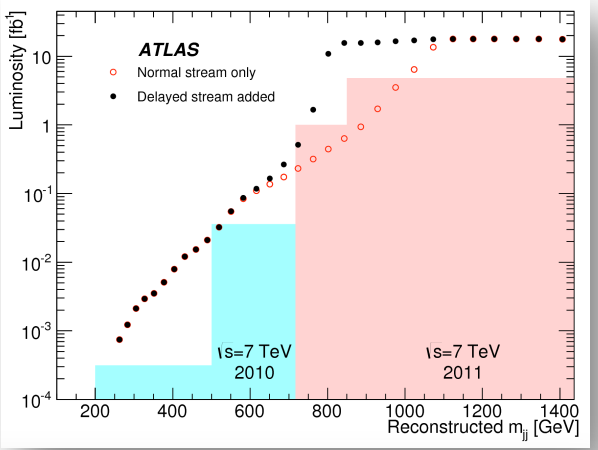
- Large statistics, yet high background level (QCD)
- New: data sample enriched by data recorded yet reconstructed later ('delayed stream')
  - increased statistics at $0.75 < m_{jj} < 1.0$ TeV
- Event selection
  - combination of single-jet triggers
  - only good-quality jets
  - at least 2 jets with $p_T > 50$ GeV & $|y| < 2.8$
  - $½|y_1 - y_2| < 0.6$ & $m_{jj} > 250$ GeV
- Looking for bump above phenomenological fit of the data

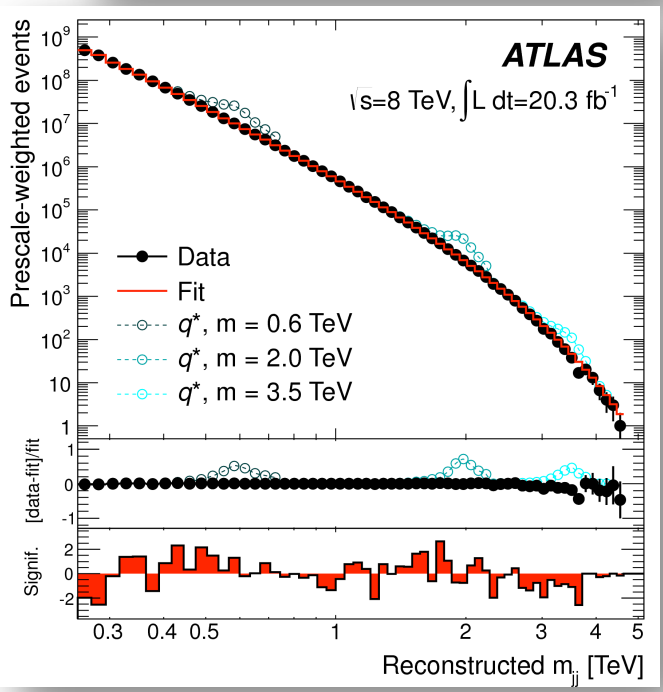
$$f(x) = p_1(1-x)^{p_2} x^{p_3 + p_4 \ln x}, \quad x \equiv m_{jj} / \sqrt{s}$$

  - dijet mass resolution 8% (4%) at 200 GeV (> 2 TeV)

➡ No resonance-like features observed up to dijet masses of 4.5 TeV

20.3 fb^{-1} @ 8 TeV





arXiv:1407.1376

Dijets: interpretation

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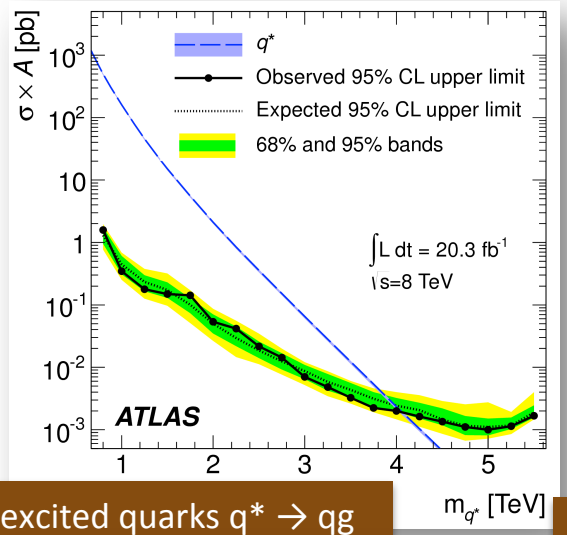
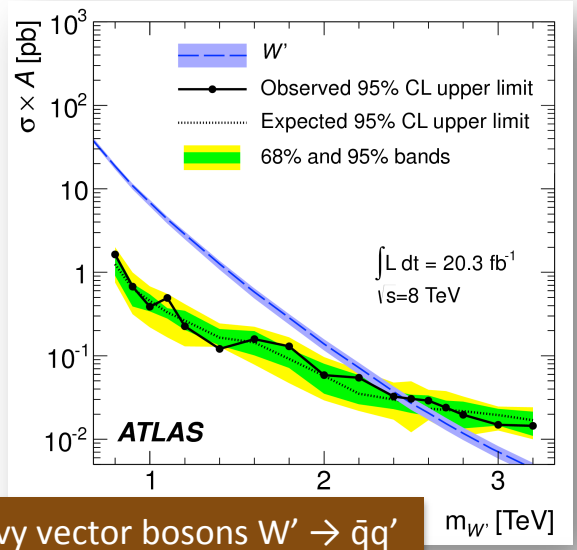
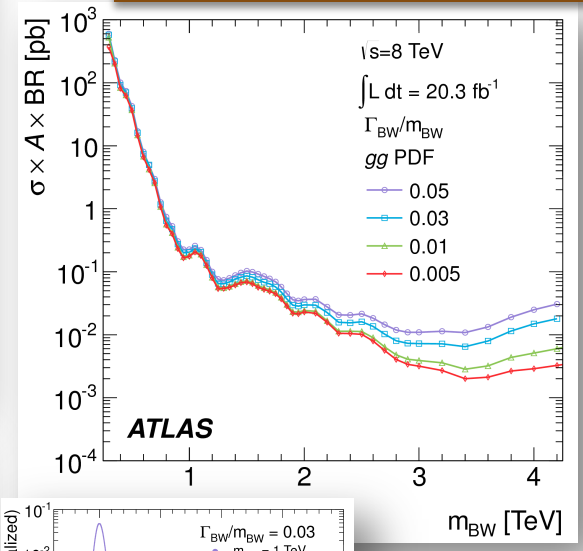


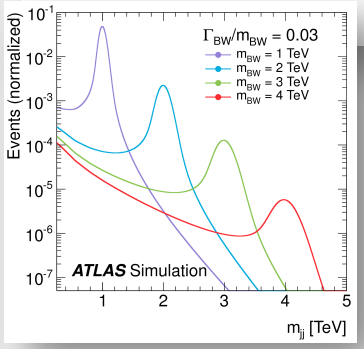
excited quarks q* → qg

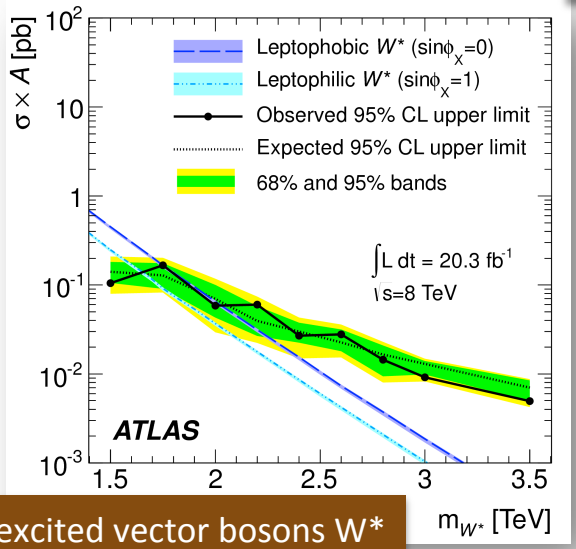


heavy vector bosons W' → $\bar{q}q'$

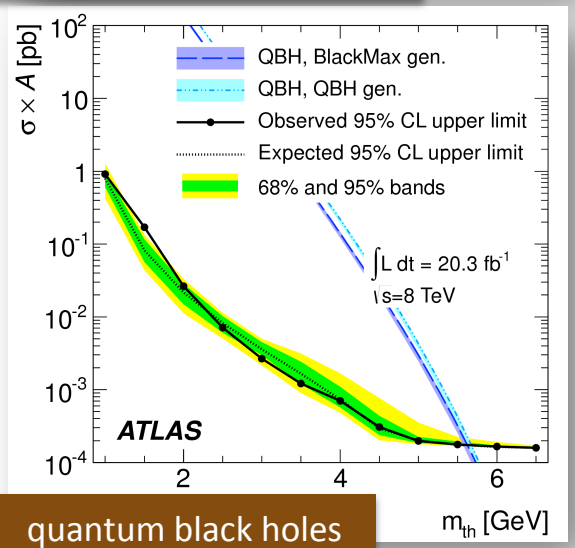
gg to Breit-Wigner resonance decaying to dijets







excited vector bosons W*

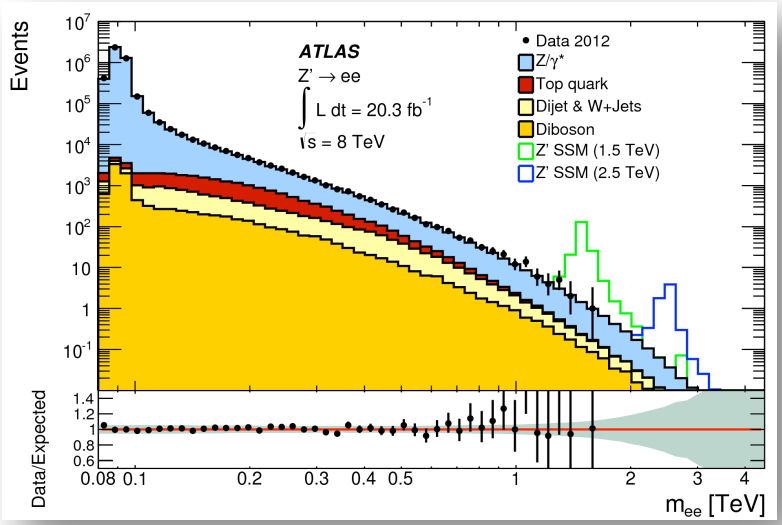


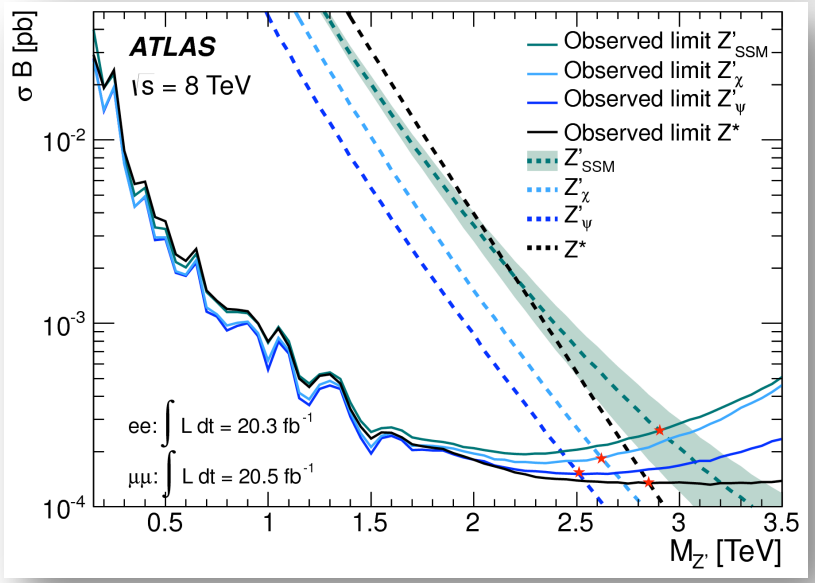
quantum black holes

arXiv:1407.1376

Dilepton resonance

- Selection
  - 2 electrons with $E_T > 40, 30$ GeV
    OR 2 muons with $p_T > 25$ GeV
- Background
  - Drell-Yan, diboson, photon-induced, top and jets (fake rate from data)
  - total MC background scaled to data at Z-peak
- Data consistent with SM processes
- Interpretation on various models
  - SSM Z'; minimal Z', E_6-motivated Z'_ψ and Z'_χ
  - chiral excited Z (Z*)
  - Randall-Sundrum graviton G*
  - Quantum Black Holes in ADD extra dimension model
  - Minimal Walking Technicolor



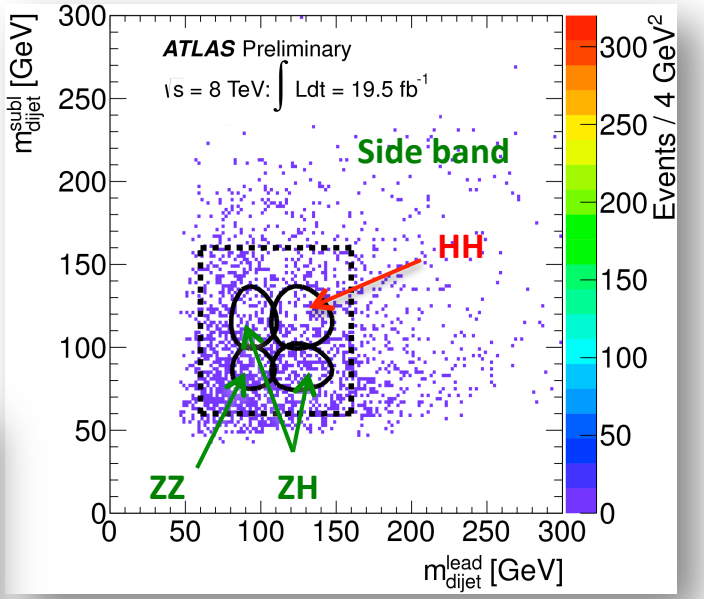


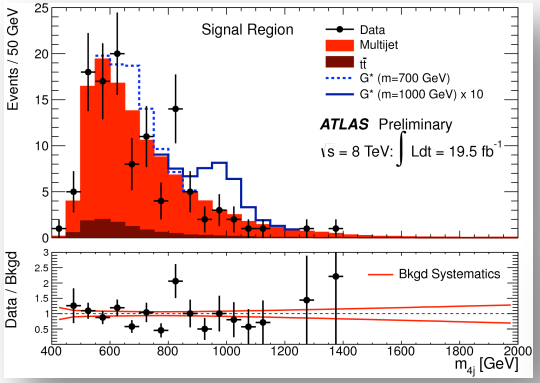
20.3 fb^{-1} (e), 20.5 fb^{-1} (μ) @ 8 TeV

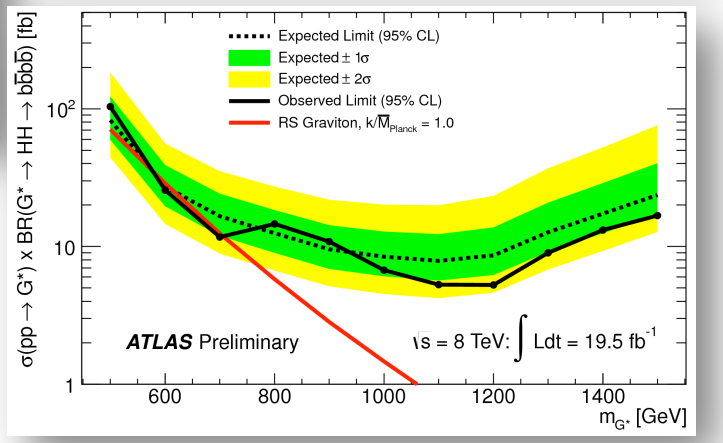
arXiv:1405.4123

Diboson resonance: X → HH → bb̄bb̄

- Event selection
  - four b-tagged jets, each with p_T > 40 GeV
  - 2 nearby (ΔR<1.5) tagged bb̄ pairs with p_T(dijet) > 200 GeV & m_{dijet} near Higgs mass
  - "tt̄ veto"
  - elliptical signal region (HH)
- Multijets background estimated by side band
- Data compatible with SM hypothesis
- Limits set on bulk RS graviton G* (first KK excitation)
  - Br(G*→HH) ≃ 7%





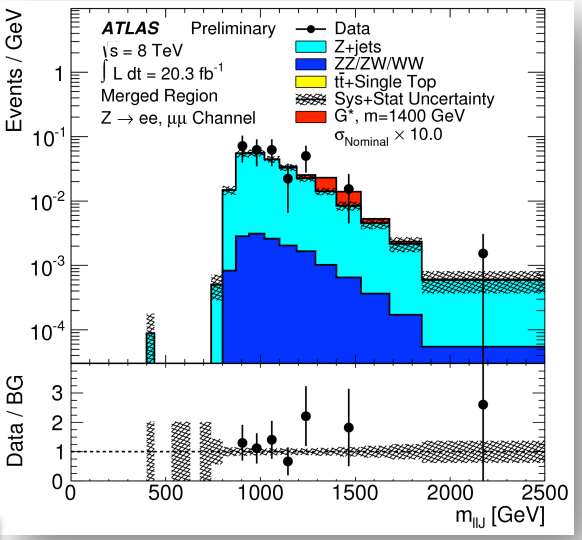


19.5 fb^{-1} @ 8 TeV

ATLAS-CONF-2014-005

Diboson resonance: ZV → $\ell\ell q\bar{q}$

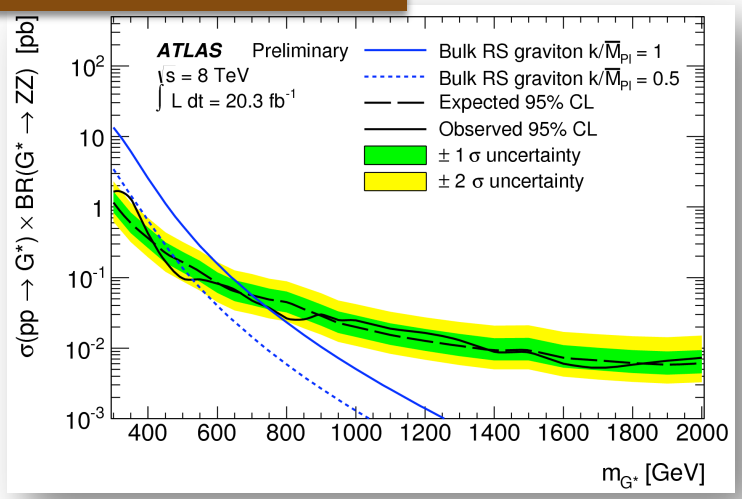
- Allows full reconstruction of invariant mass X → ZV
- Consider both resolved (jj) and "merged" (J) –if highly boosted– dijet system
  - jet substructure information optimised for longitudinally polarised high-p_T boson
- Search for bump in m($\ell\ell$jj) or m($\ell\ell$J) distributions



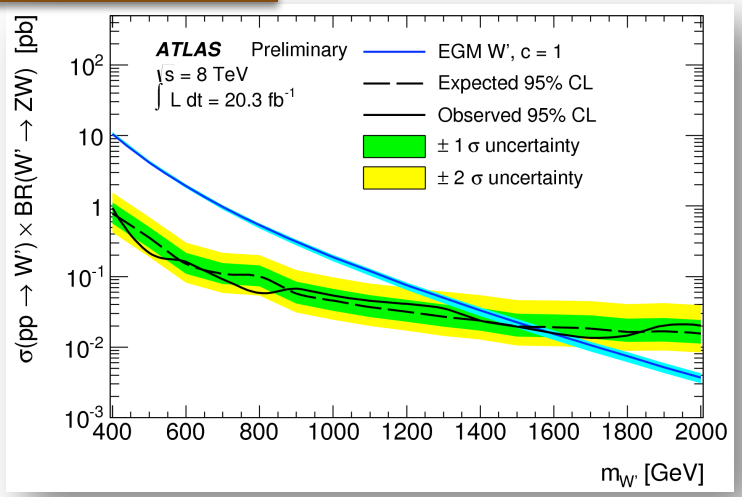
[ATLAS-CONF-2014-039](#)

20.3 fb^{-1} @ 8 TeV

extended bulk RS
spin-2 KK graviton G* → ZZ

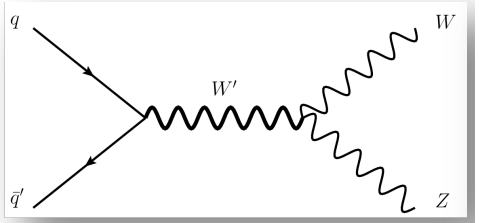


Extended Gauge Model
W' → ZW

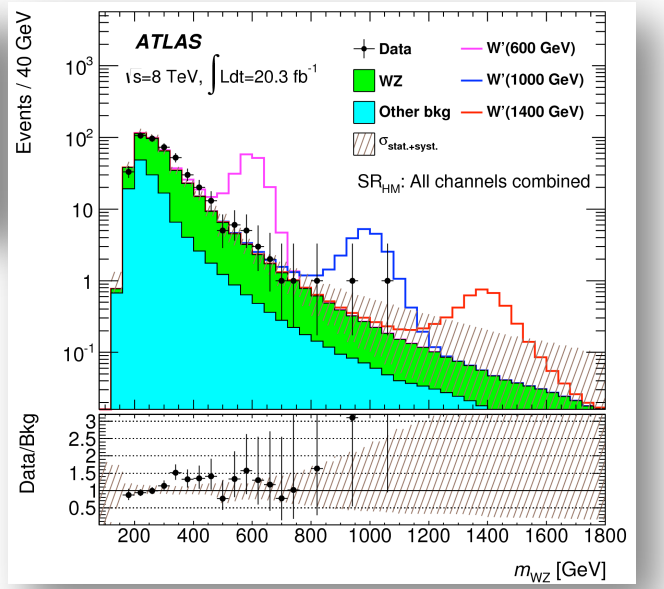


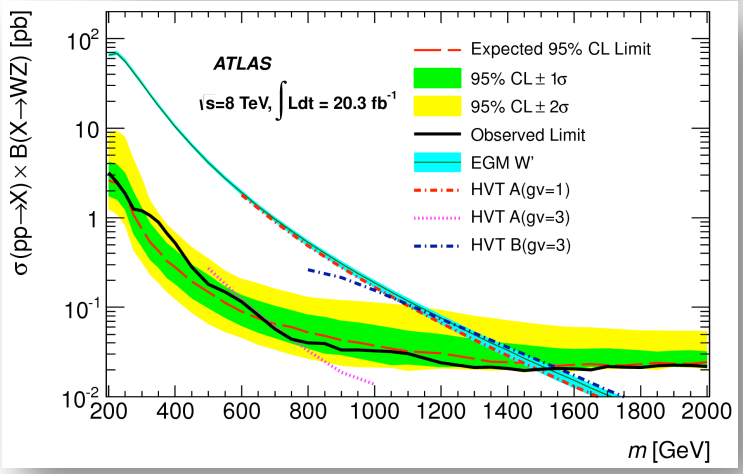
Diboson resonance: WZ → ℓνℓ'ℓ'

- Fully leptonic channel ➜ good sensitivity due to smaller background compared to other channels
- Event selection
  - exactly 3 charged leptons with $p_T > 25$ GeV
  - $E_T^{miss} > 25$ GeV
  - $|m_{\ell^+\ell^-} - m_Z| < 20$ GeV
  - $\Delta y(W,Z) < 1.5$
  - $\Delta\phi(\ell, E_T^{miss}) < 1.5$ (> 1.5) for high (low) W' mass
- No excess of events over SM expectation seen
- Interpretation
  - Extended Gauge Model (EGM) with W' boson
  - phenomenological Lagrangian for Heavy Vector Triplet (HVT) ➜ limits on couplings



20.3 fb^{-1} @ 8 TeV





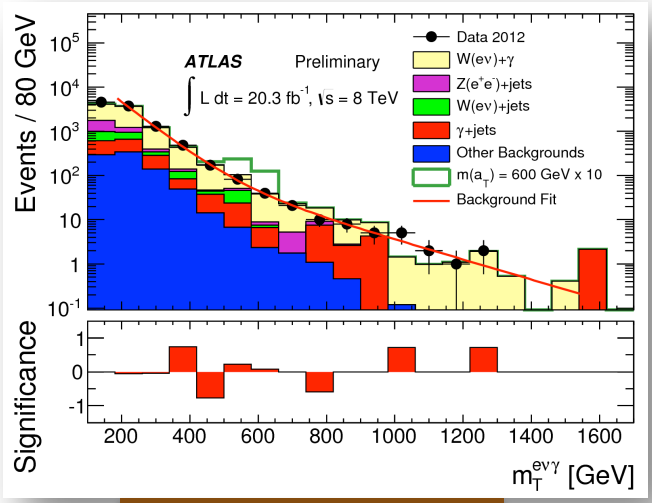
arXiv:1406.4456

Diboson resonance: leptonic Vγ

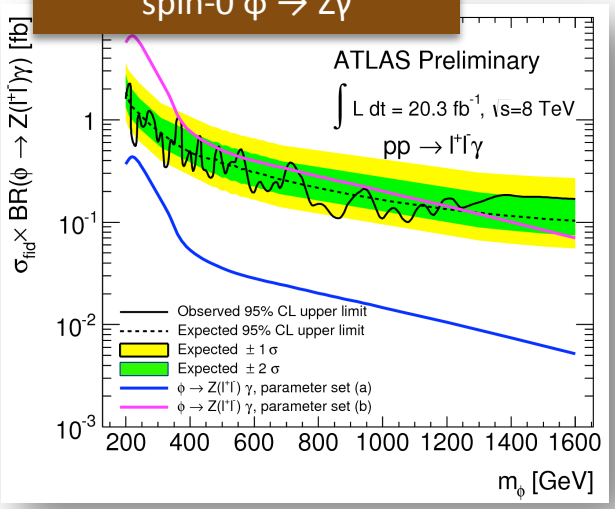
Results to be published soon in PLB

- **Wγ → ℓνγ, Zγ → ℓℓγ**
- Event selection
  - 1 (or 2) isolated e/μ with p_T > 25 GeV
  - 1 isolated photon E_T > 40 GeV, $\Delta R(\ell\gamma) > 0.7$
  - Wγ: E_T^{miss} > 35 GeV, $p_T(\ell\nu)$ > 40 GeV
  - Zγ: 65 < $m(\ell\ell)$ < 115 GeV
- Background
  - Zγ, Wγ, Z+jets, W+jets, γ+jets

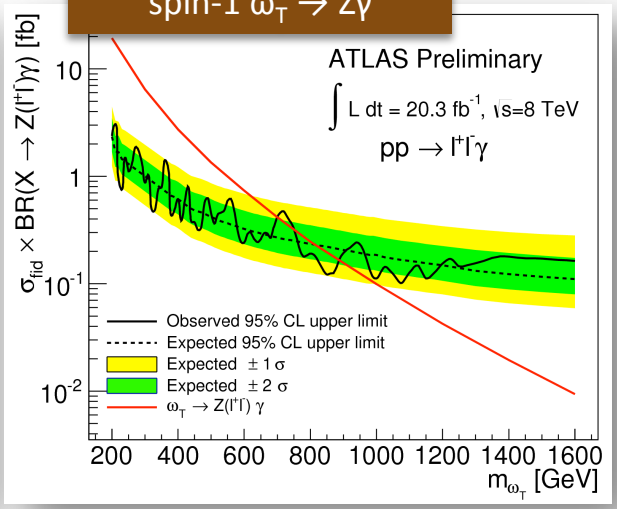
20.3 fb^{-1} @ 8 TeV



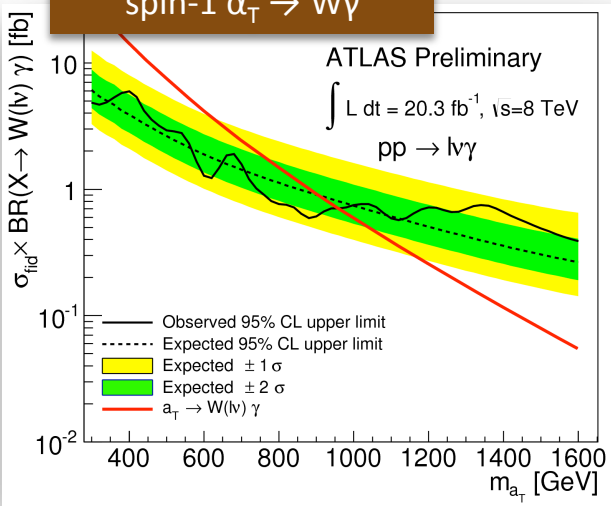
Composite Scalar Model
spin-0 ϕ → Zγ



Low Scale Technicolor
spin-1 ω_T → Zγ

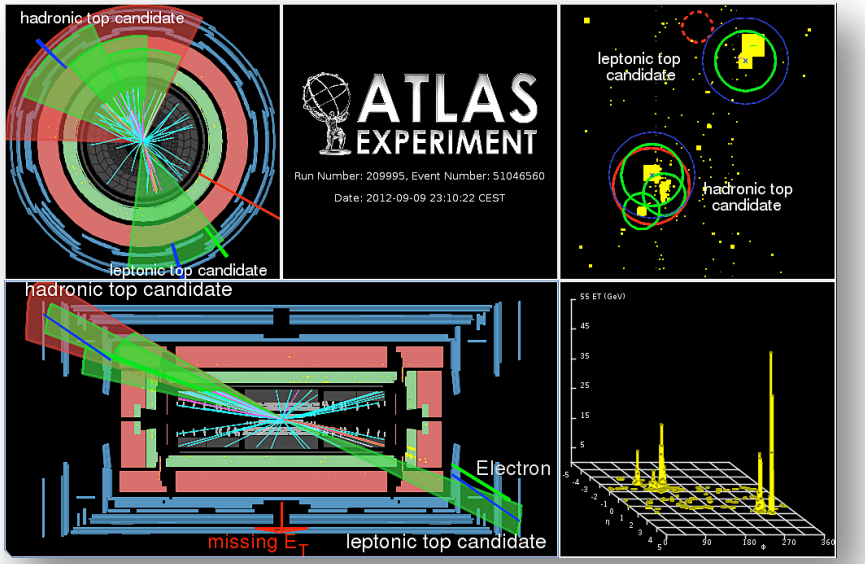


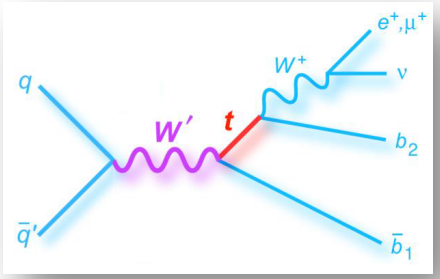
Low Scale Technicolor
spin-1 α_T → Wγ

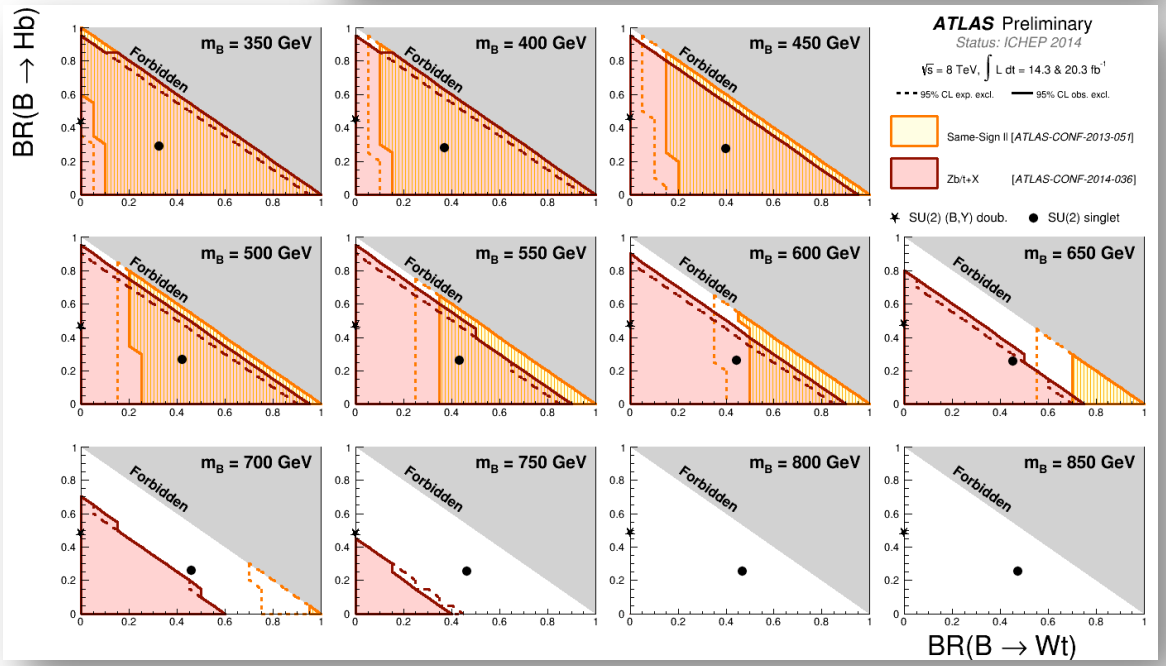


Top/bottom resonances

- Heavy bosons searches
  - $t\bar{t}$ resonances
  - $W' \rightarrow t\bar{b}$ resonance
- Vector-Like Quarks (VLQs) searches
  - Zt+X
  - Ht+X
  - same-sign dilepton







☛ See Jiahang Zhong's talk in Friday's parallel session on Alternative Theories

Probing BSM physics in tails

- Non-resonant dileptons [arXiv:1407.2410]
- Leptons & jets [arXiv:1405.4254]
- Generic search for New Physics [ATLAS-CONF-2014-006]
- Mono-*X* plus E_T^{miss} signatures

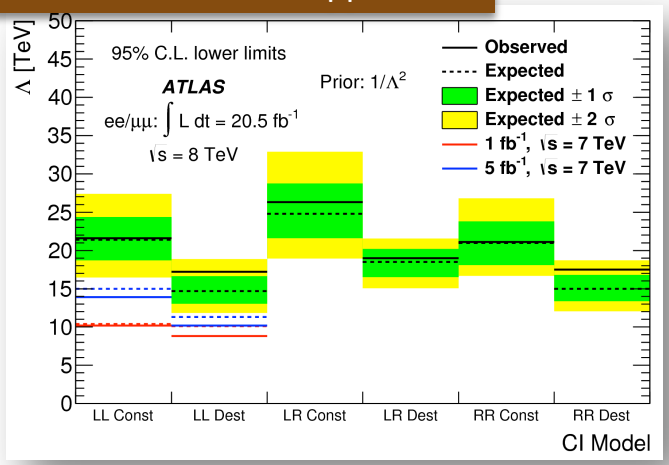
Non-resonant dileptons

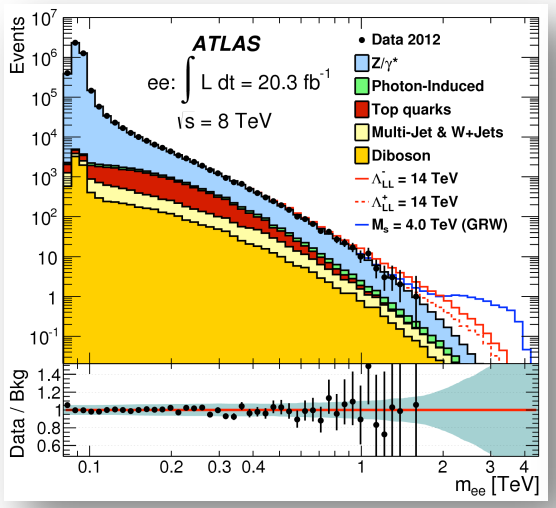
20.3 fb^{-1} @ 8 TeV

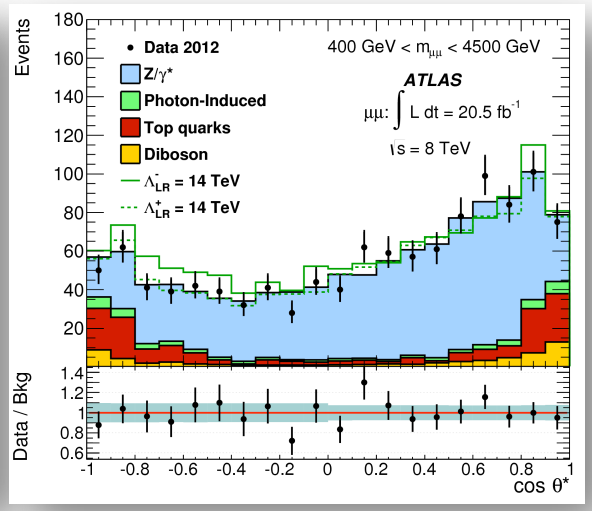
arXiv:1407.2410

- Event selection and background similar to resonant dilepton [arXiv:1405.4123]
- m($\ell\ell$) search bins optimised differently for contact interactions, CI, and for large extra dimension models
- Forward-backward asymmetry used as discriminant for CI search
- No significant deviations from the SM expectation is observed
  1. Contact Interactions due to quark and lepton compositeness
  2. Large flat spatial extra dimensions (ADD)
     - continuous dilepton production via virtual KK gravitons

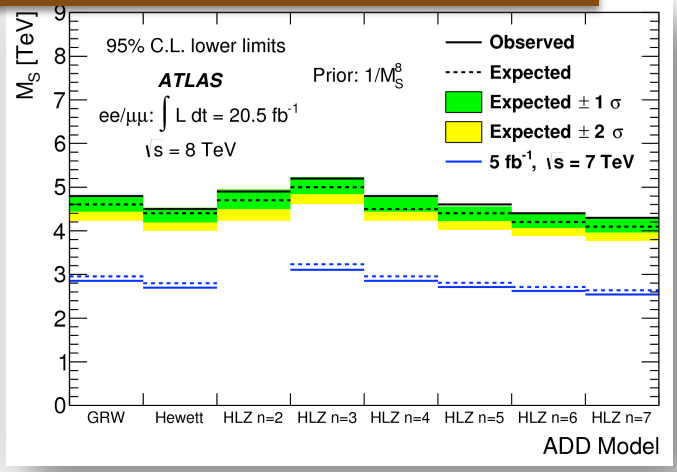
Contact Interactions $q\bar{q} \to \ell^+\ell^-$







Large Extra Dimensions $q\bar{q}/gg \to \ell^+\ell^-$



Black holes: leptons + jets

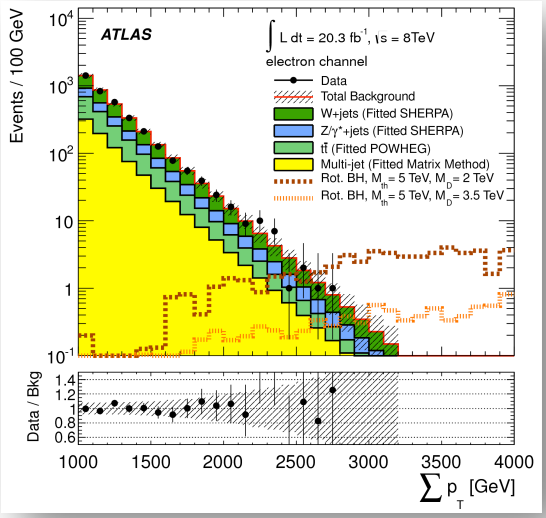
20.3 fb^{-1} @ 8 TeV

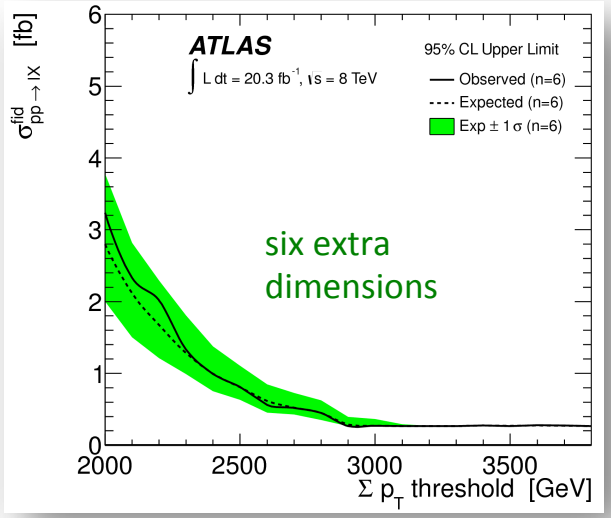
- Microscopic BH evaporation or BH-remnant decay leads to high mass, high object multiplicity (large BR to leptons)
- Event selection
  - at least 3 high-p_T objects (jets + leptons) of p_T > 100 GeV
  - scalar p_T sum of selected objects, $\sum p_T$ > 2 TeV

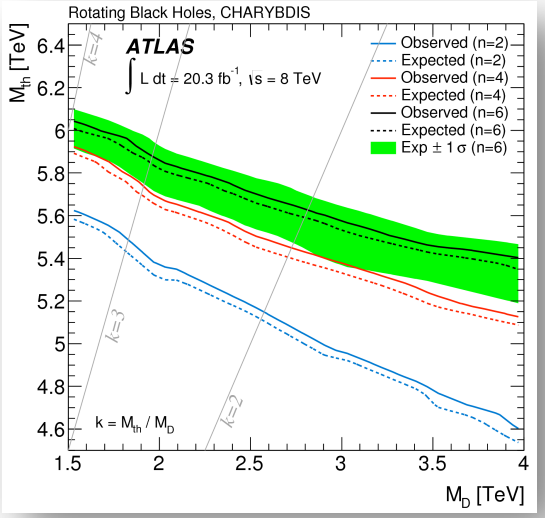
For search in same-sign dimuons: PRD88 (2013) 072001

- Main background: W/Z+jets, tt̄, multijets (e channel) ⬅ estimated from data for each component
- Slice signal region in order to be sensitive to wide range of signal phenomenologies
- No significant excess of events seen
  - model independent limits on signal cross section
  - limits on 11 Black Hole / String Ball models

arXiv:1405.4254

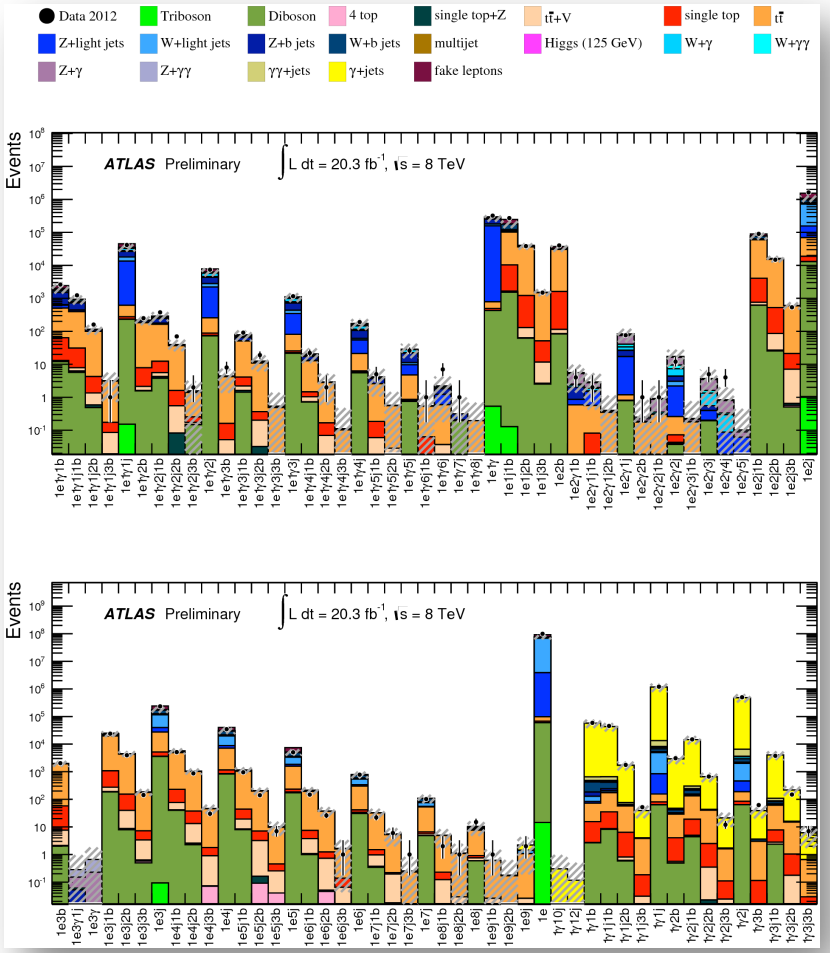


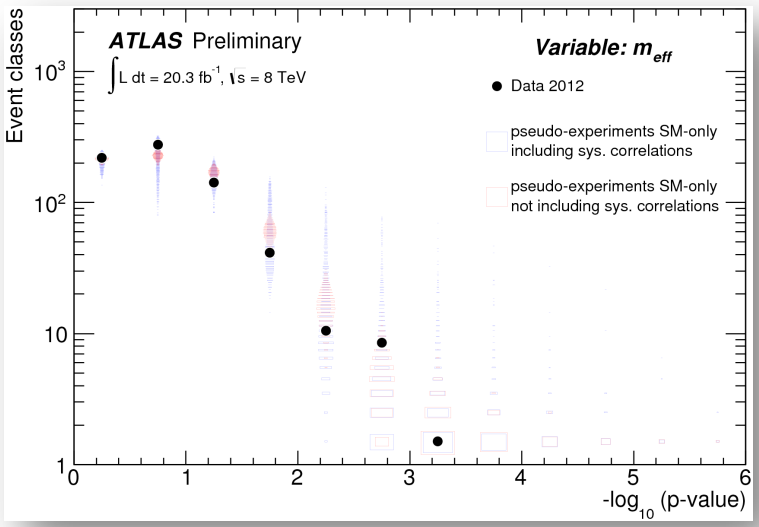




General search for new phenomena

- Provides generic investigation for New Physics
  - not motivated/optimised by specific model
- Study topologies with isolated electrons, muons, photons, jets, b-jets, E_T^{miss}
- 697 search classes with SM expectation > 0.1 events
- MC-based background estimation, except for lepton fakes
- Three kinematic BSM-sensitive variables: m_{eff}, visible invariant mass & E_T^{miss}





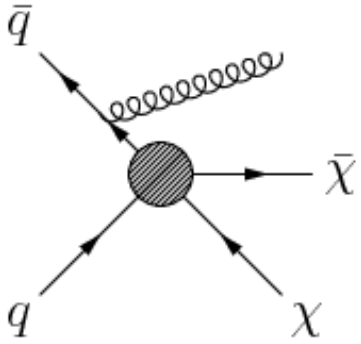
20.3 fb^{-1} @ 8 TeV

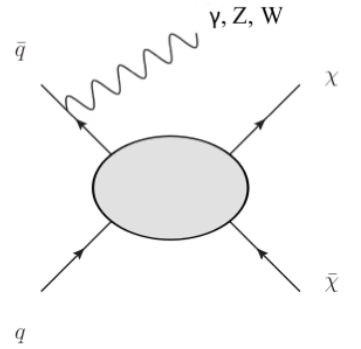
➜ No significant deviation from SM expectation is found in data overall

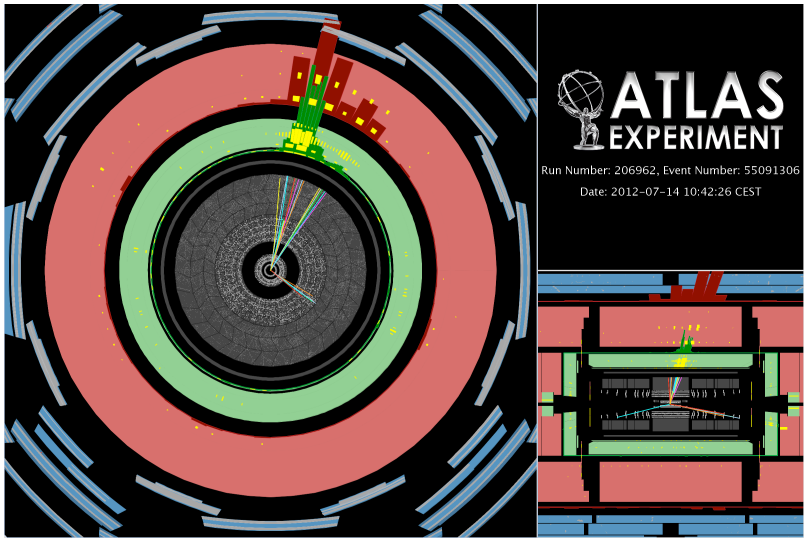
ATLAS-CONF-2014-006

Mono-*X* signatures

- Main motivation: dark matter (WIMP) production at LHC
  - search also sensitive to large extra dimension models
- Such events are tagged via the presence of an energetic jet or a photon or a W/Z coming from initial state radiation (ISR)
- ISR particle necessary to
  - provide highly energetic object
  - balance two-WIMPs' momentum
    → high missing transverse energy E_T^{miss}
- **→ Mono-jet, mono-photon, mono-W/Z distinctive signatures**



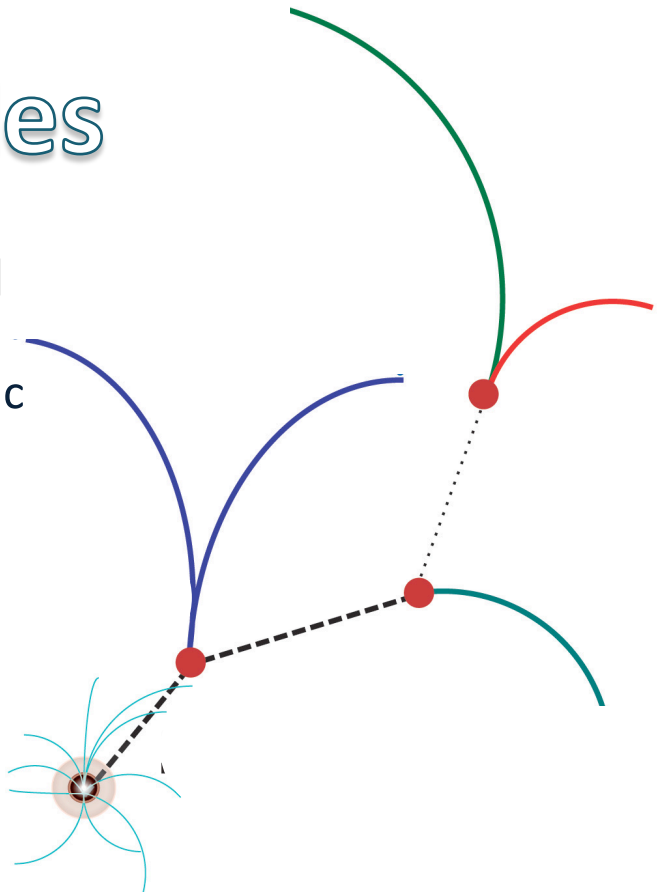




☞ See David Salek's talk in Thursday's parallel session on Particle Cosmology

Even more exotic … long-lived particles

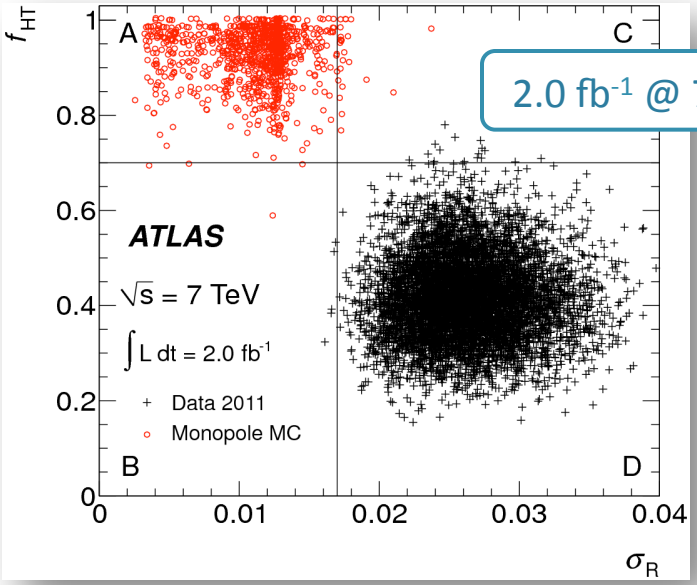
- Highly-ionising particles
  - magnetic monopoles [PRL109 (2012) 261803]
  - multi-charged particles [PLB 722 (2013) 305]
- Neutral long-lived particles (LLPs) in hadronic calorimeter [ATLAS-CONF-2014-041]



Highly-ionising particles

Magnetic monopoles

- Exploit distinct signals in Transition Radiation Tracker (high-threshold hit) and EM calorimeter (large localized energy deposit)
- Upper cross-section limits set for Dirac monopoles of mass of 200 – 1200 GeV



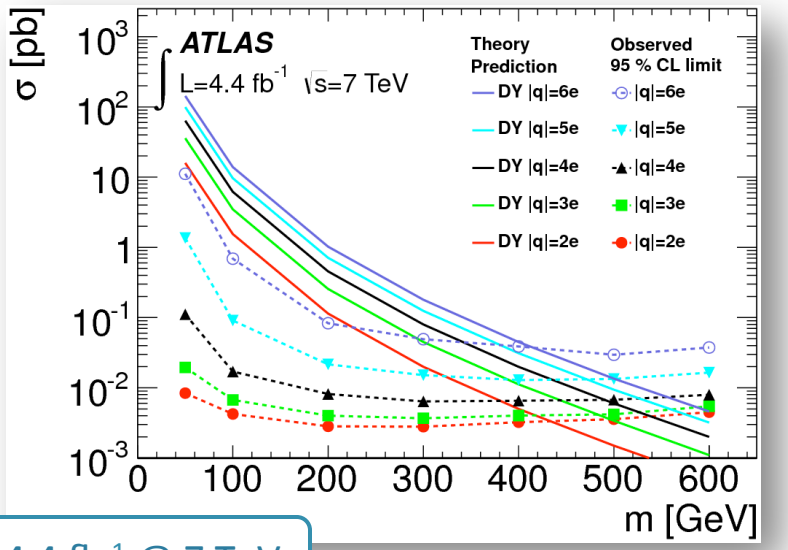
2.0 fb^{-1} @ 7 TeV

PRL109 (2012) 261803

High-threshold TRT hit fraction, f_{HT}, versus EM cluster dispersion, σ_R

Multi-charged particles

- Predicted in almost-commutative models and the walking technicolour model
- Search based on specific energy loss, dE/dx, measurements in the TRT and the Muon Spectrometer
- Limits set assuming a simplified Drell-Yan production model

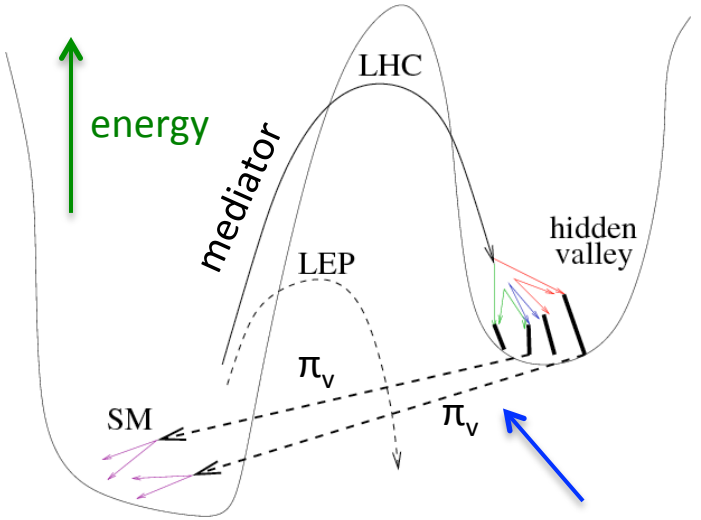


4.4 fb^{-1} @ 7 TeV

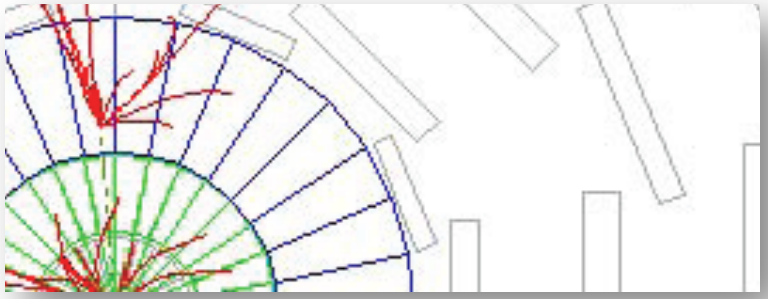
PLB 722 (2013) 305

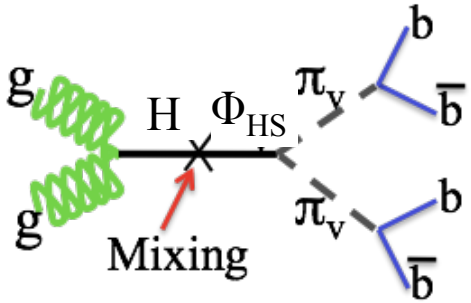
Neutral LLP: motivation & signature

- Hidden Sector (HS) weakly coupled to SM via heavy communicator scalar Φ_{HS}
- Benchmark: Hidden Valley model with the Higgs or a Higgs-like scalar decaying to a pair of neutral pseudoscalars (π_v) which in turn decay to pairs of SM fermions: $b\bar{b}$, $c\bar{c}$, $\tau^+\tau^-$
  - Hidden Valley can alter the branching fractions for Higgs decay
- Signature: If π_v is long-lived, it will give rise final states with π_v decaying in the hadronic calorimeter (HCal) or the outer edge of the electromagnetic (EM) calorimeter



M. Strassler, arXiv:hep-ph/0607160

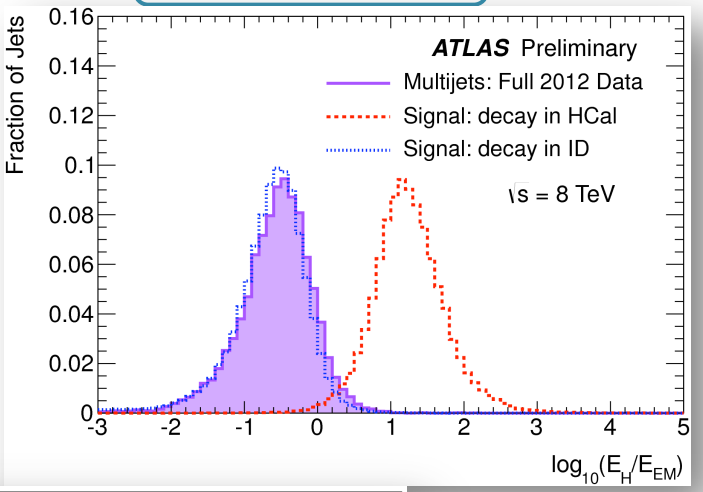




ATLAS-CONF-2014-041

Event selection & results

20.3 fb^{-1} @ 8 TeV



- Each heavy fermion pair from π_v decay reconstructed as single jet with
  1. narrow radius
  2. no tracks from charged particle pointing to the jet
  3. little or no energy deposited on the EM calorimeter
- Dedicated *CalRatio* trigger developed to select events with these features [JINST 8 (2013) P07015]
- Event selection
  - E_T^{miss} < 50 GeV, against cosmic rays & beam-halo events
  - Require two jets passing:
    - $\log_{10}(E_H/E_{EM}) > 1.2$, $|\eta| < 2.5$
    - no good tracks within $\Delta R = 0.2$ of jet
    - $-1 < |t| < 5$ ns, against out-of-time events
  - One jet must have fired the trigger & E_T > 60 GeV; the other E_T > 40 GeV

Samples	Expected yields
MC sample m_Φ, $m_{\pi v}$ [GeV]	
100, 10	297 ± 19
100, 25	379 ± 33
126, 10	357 ± 15
126, 25	793 ± 37
126, 40	400 ± 34
140, 10	343 ± 13
140, 20	724 ± 29
140, 40	645 ± 30
SM Multijets	23.2 ± 8.0
Cosmic rays	0.3 ± 0.2
Total Expected Background	23.5 ± 8.0
Data	24

statistics only

statistics ⊕ systematics

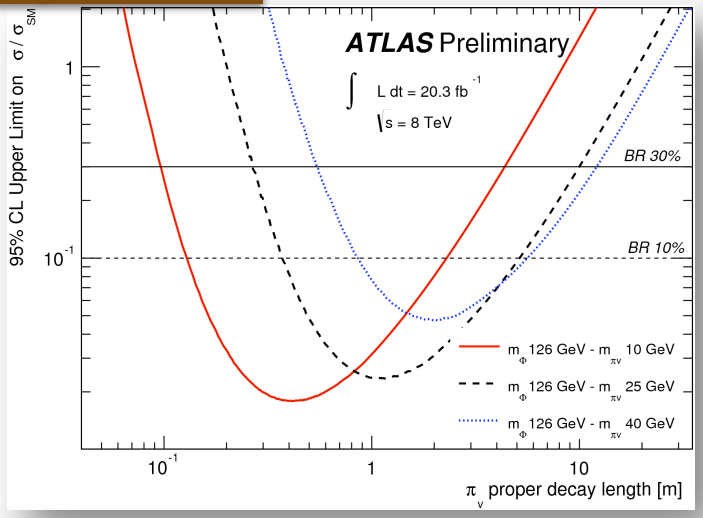
ATLAS-CONF-2014-041

LLP: interpretation

No significant excess was observed

➜ limits set in Hidden Valley scenario

m_Φ = 126 GeV



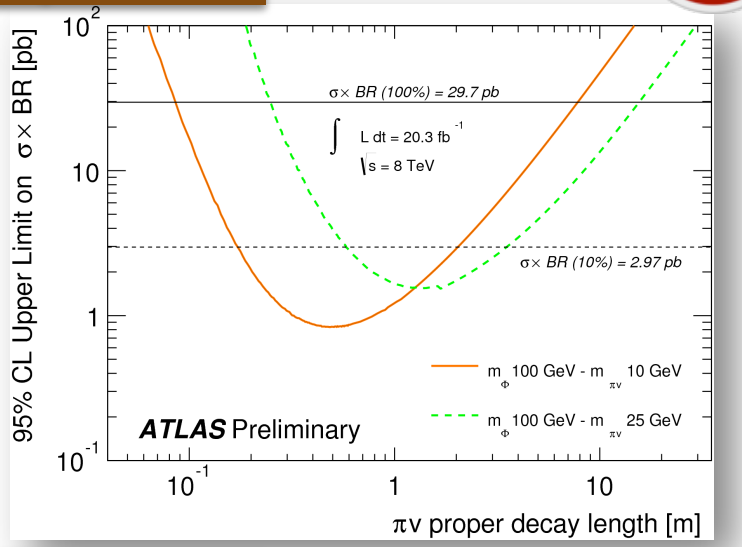
20.3 fb^{-1} @ 8 TeV

MC sample m_Φ, $m_{\pi v}$ [GeV]	excluded range 30% BR $\Phi_{HS} \rightarrow \pi_v\pi_v$ [m]	excluded range 10% BR $\Phi_{HS} \rightarrow \pi_v\pi_v$ [m]
126, 10	0.10 - 4.38	0.13 - 2.30
126, 25	0.27 - 10.01	0.37 - 5.12
126, 40	0.54 - 12.11	0.86 - 5.62

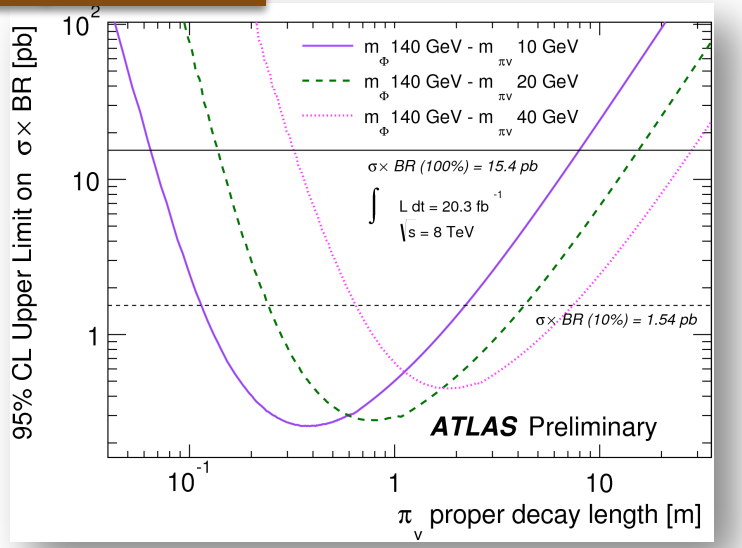
ATLAS-CONF-2014-041

NEW

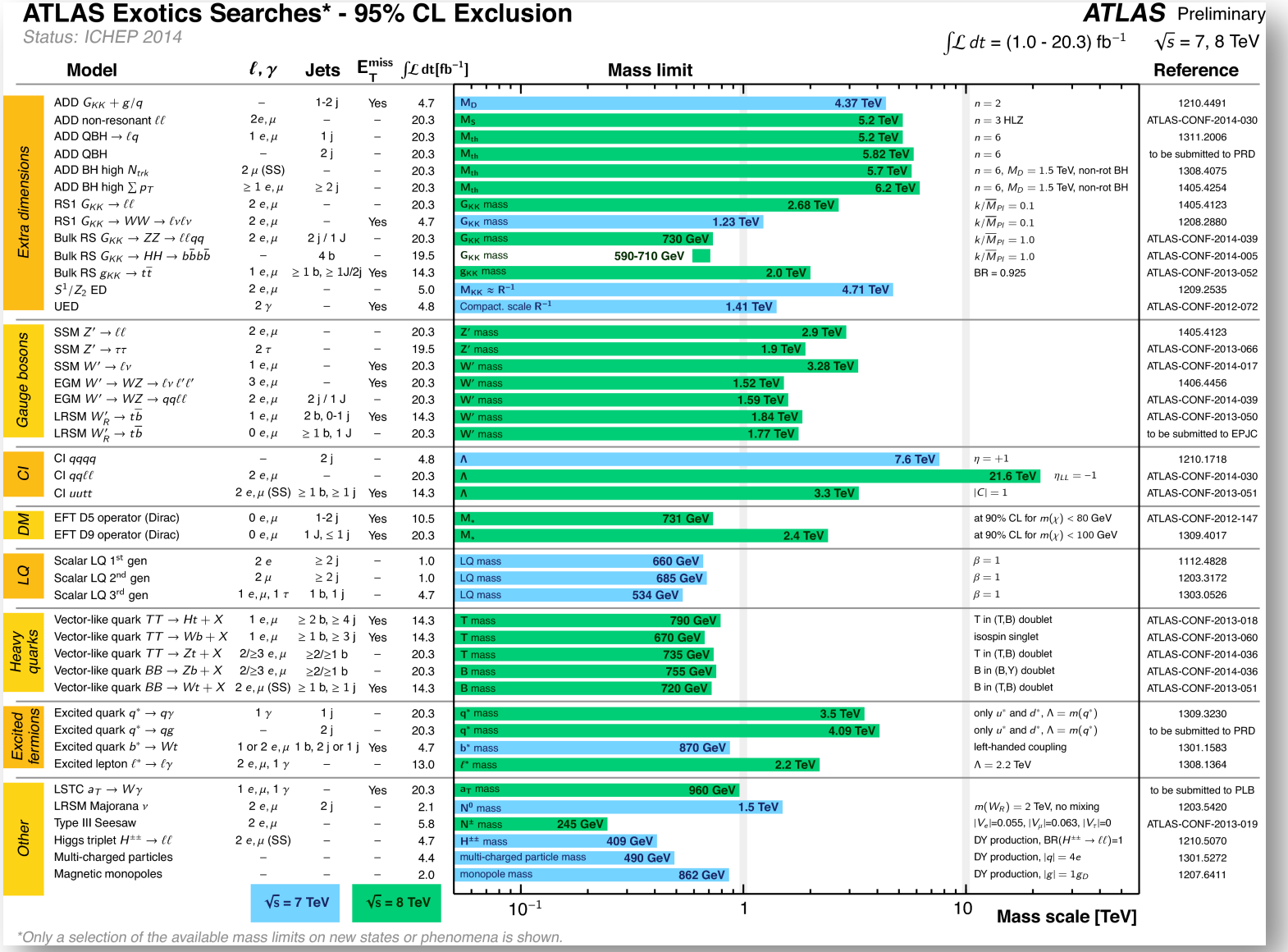
m_Φ = 100 GeV



m_Φ = 140 GeV



All results in a nutshell



Summary

- Standard Model limitations imperatively call for Physics beyond it, extending and complementing it
- ATLAS has searched for physics BSM at TeV scale in a variety of signatures inspired by a multitude of theoretical scenarios
- No significant deviation from SM expectations observed so far
- LHC Run 2 may reveal hints of New Physics thanks to higher accessible energy
  - ATLAS is well-prepared to make the most of it

… for 13-14 TeV run in 2015

Continuously updated public results:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

Thank you for your attention!