Exotic Searches at the LHC

Wolfgang Ehrenfeld (DESY)
On behalf of the ATLAS and CMS Collaborations

DESY, February 8th, 2012

HELMHOLTZ ASSOCIATION

DESY

Introduction

- Several Exotics / New Physics searches at the LHC
- Can not cover all → focus on recent 1 – 5 fb^{-1} results
- ATLAS and CMS only (LHCb and ALICE also seek New Physics)

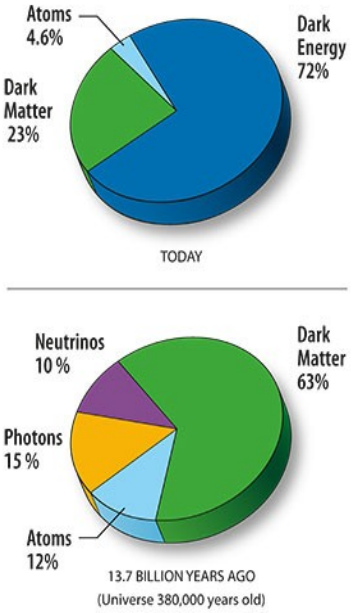
- Full repository of latest results
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

- This talk does not cover:
  - SUSY: see talk by Isabel Melzer-Pellmann
  - Higgs: see talks by Jana Schaarschmidt and Markus Klute
  - Top: see talk by Sebastian Naumann-Emme

Looking beyond the Standard Model

- Standard Model (SM):
  - An effective theory → has worked very well at energy scales probed so far
  - Expected to break down at higher energies

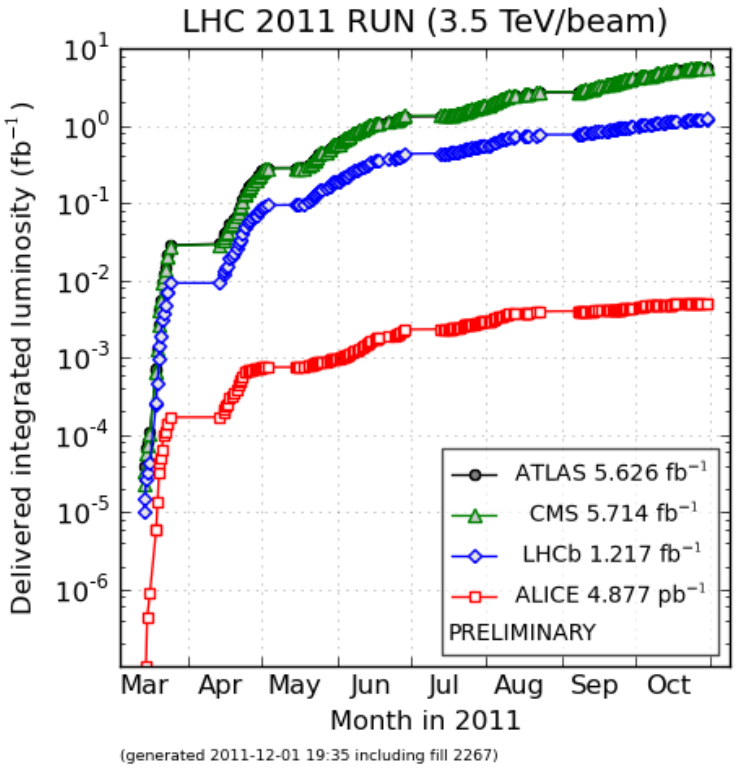
- Several limitations, many involving fine-tuning:
  - Hierarchy Problem / Gravity: Reconciling m_W and m_Z with m_{Planck}
  - Electroweak Symmetry Breaking: How does it really work?
  - Dark Matter: What is it?
  - Flavor
  - Strong CP Problem
  - …



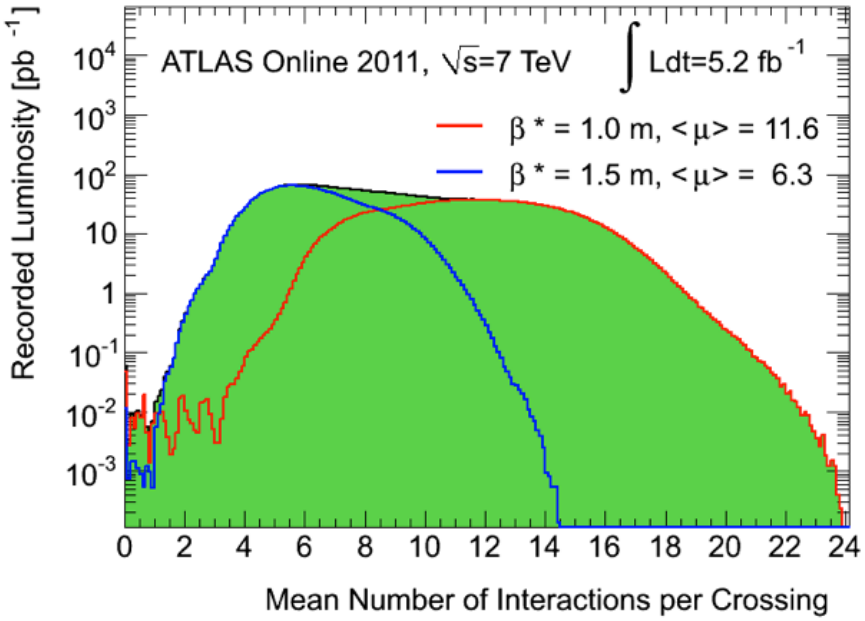
- Because we can with the Large Hadron Collider (LHC)

Large Hadron Collider (LHC)

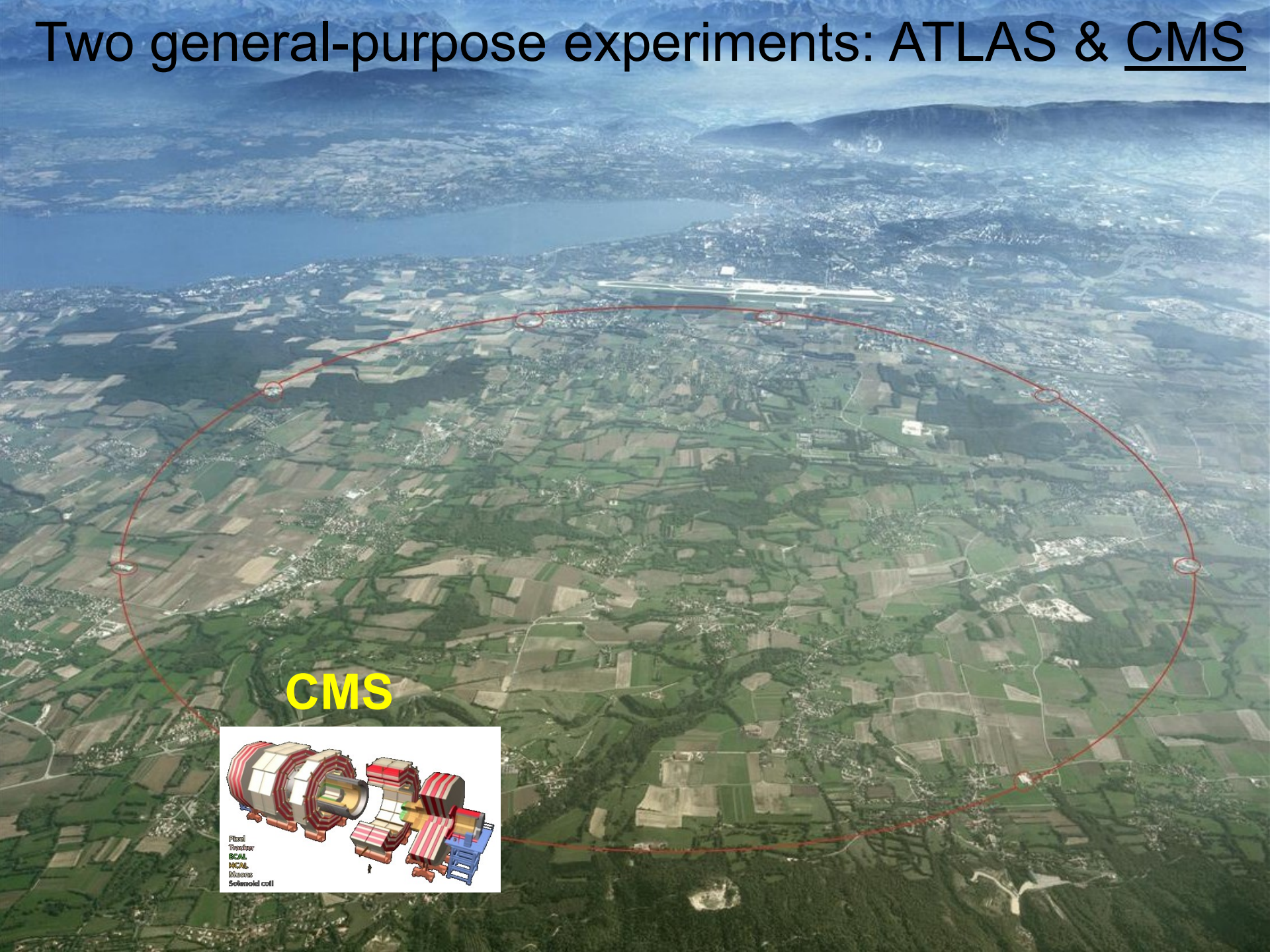
- √s = 7 TeV pp
- Outstanding 2011 Performance
  - ~ 3.5 × 10^{33} $cm^{-2}s^{-1}$ peak lumi
  - ~ 5.6 fb^{-1} delivered



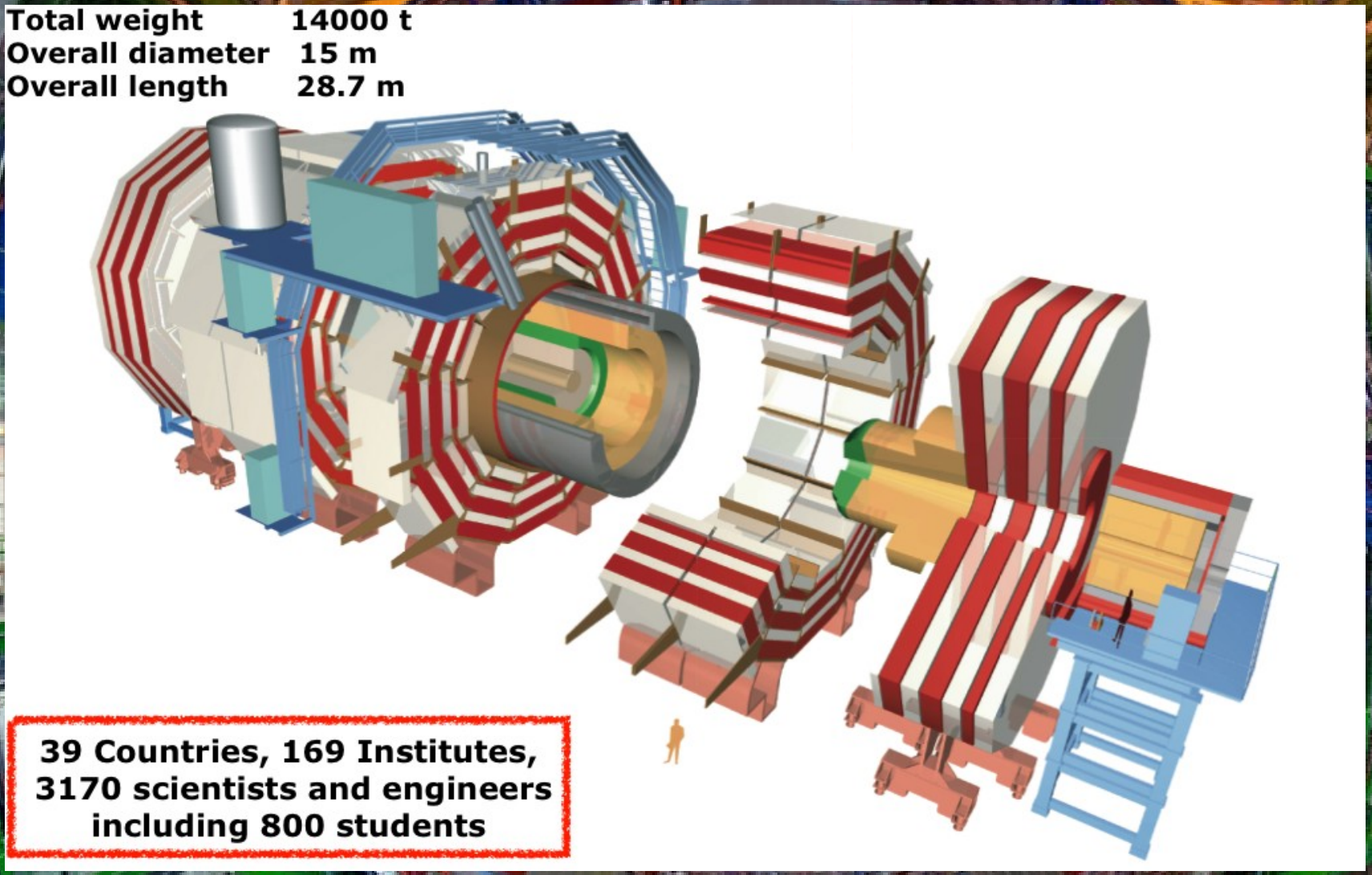
- Bunch spacing 50 ns
- ~ 12 pp collisions / crossing (avg.)



Two general-purpose experiments: ATLAS & CMS

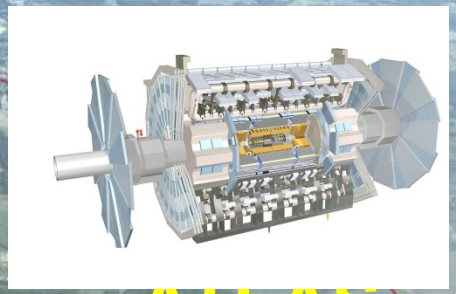


Two general-purpose experiments: ATLAS & CMS



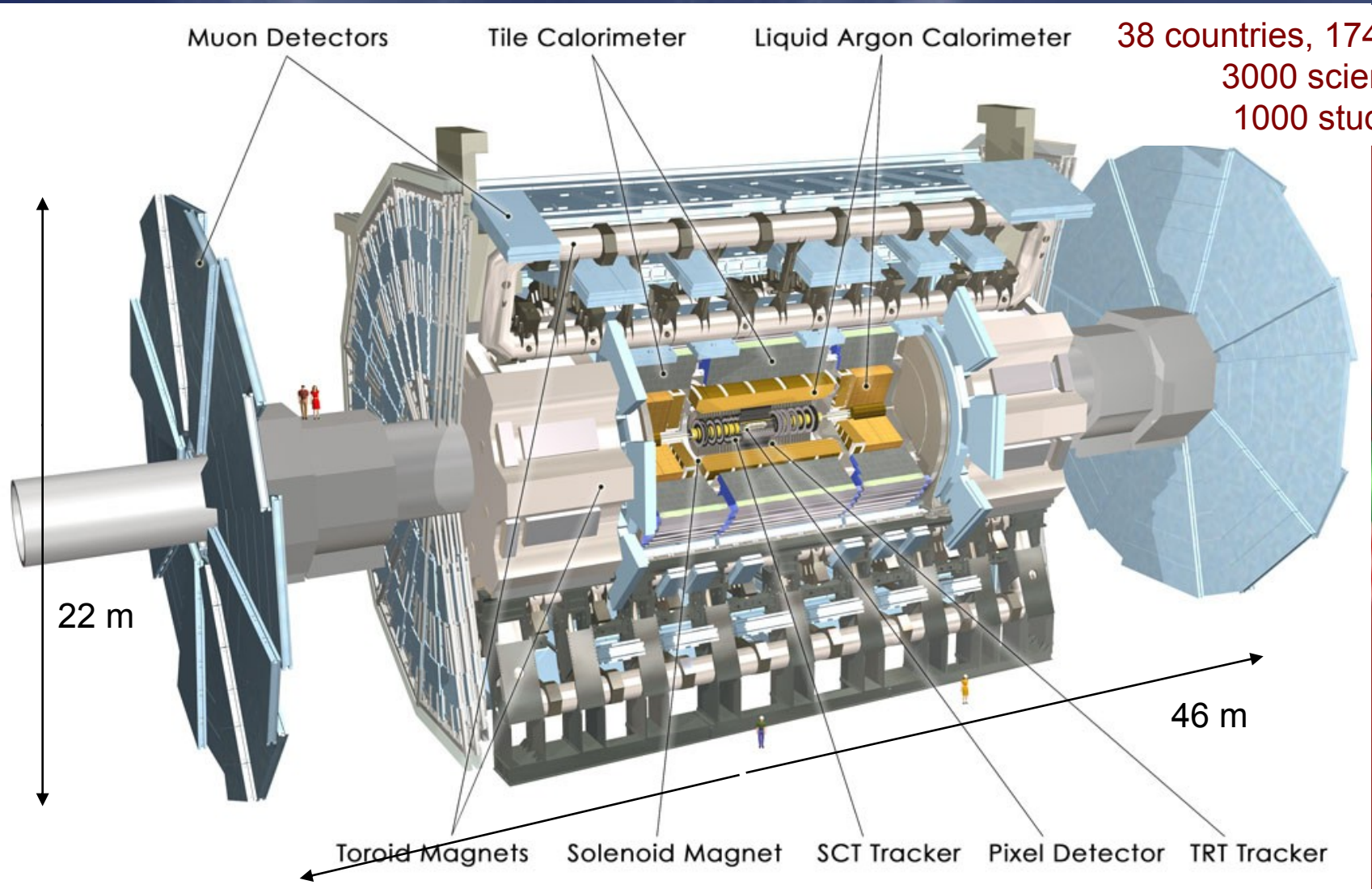
Emphasis on excellent resolution (energy, momentum, mass) of electrons, photons, muons

Two general-purpose experiments: ATLAS & CMS

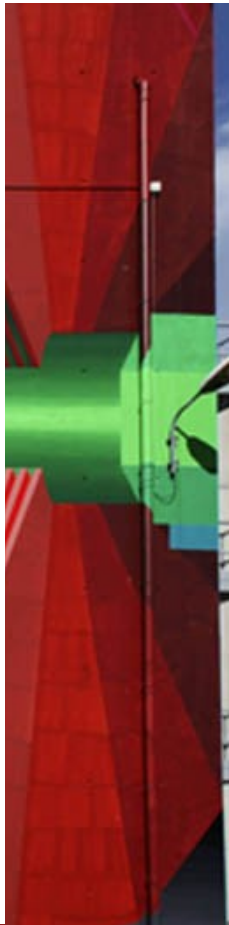


ATLAS

Two general-purpose experiments: ATLAS & CMS

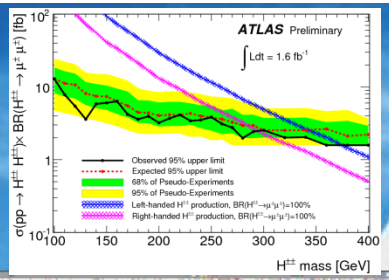


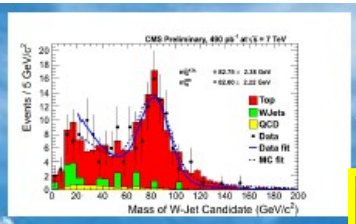
38 countries, 174 institutions
3000 scientists,
1000 students



Emphasis on excellent jet and missing-E_T (MET) resolution, particle identification, and standalone muon reconstruction

Acknowledgements



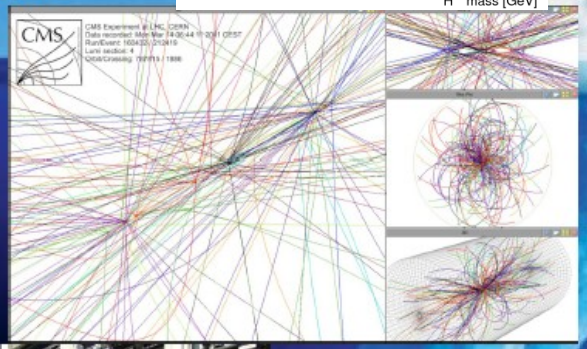


Physics Analysis

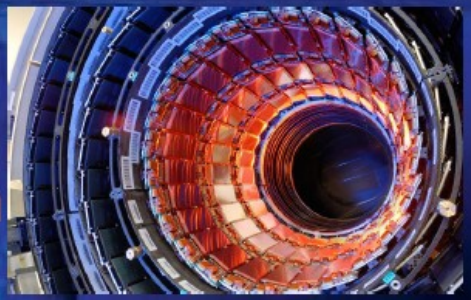
This talk

Calibration

6 × 10^3 Physicists in ATLAS + CMS



Simulation



Reconstruction

R&D

Trigger
DAQ

Commissioning

Magnets

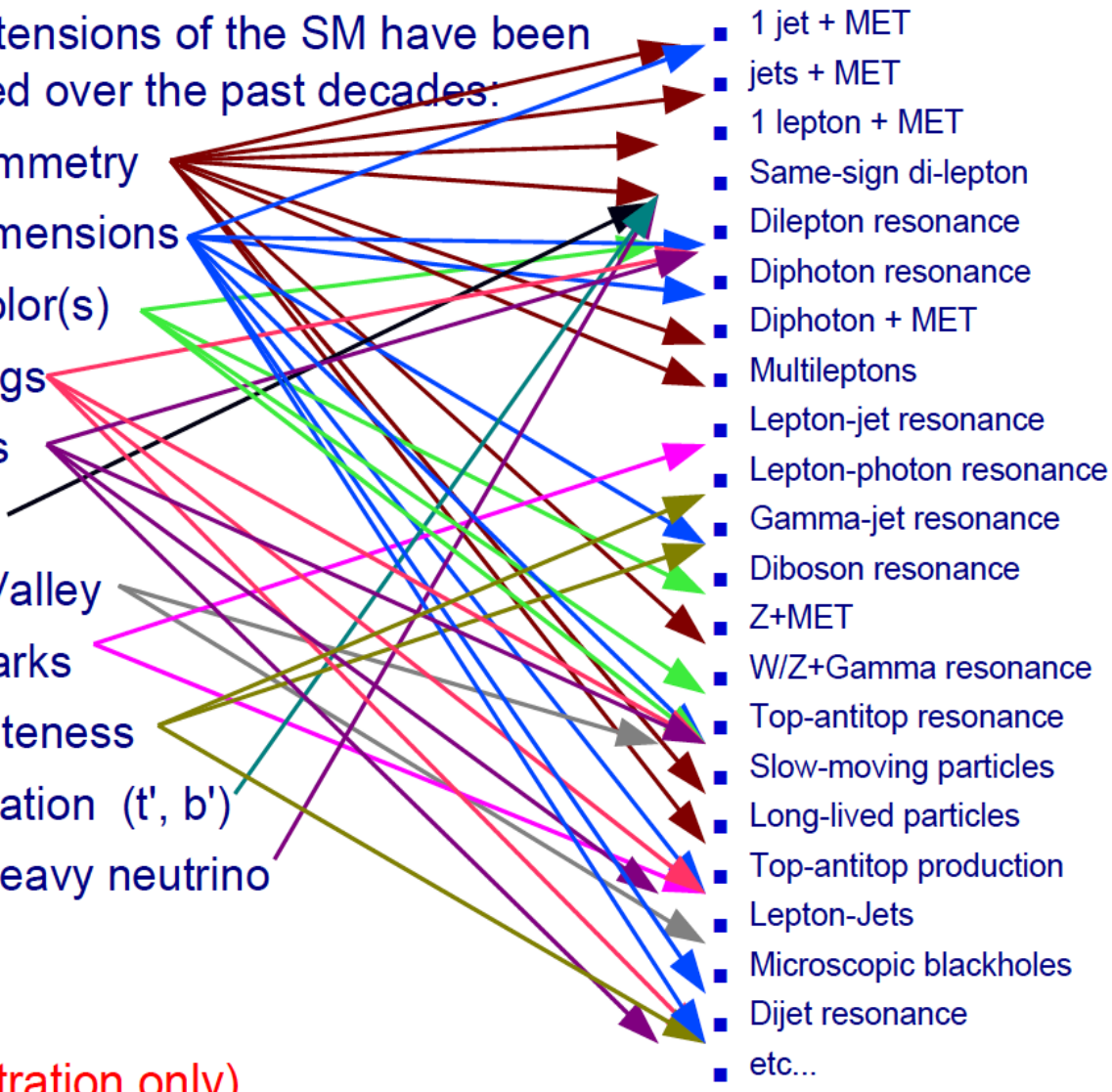
Installation
Construction

LHC

Henri Bachacou

Long List of Models & Signatures Available

- Many extensions of the SM have been developed over the past decades:
- Supersymmetry
- Extra-Dimensions
- Technicolor(s)
- Little Higgs
- No Higgs
- GUT
- Hidden Valley
- Leptoquarks
- Compositeness
- 4th generation (t', b')
- LRSM, heavy neutrino
- etc...



- 1 jet + MET
- jets + MET
- 1 lepton + MET
- Same-sign di-lepton
- Dilepton resonance
- Diphoton resonance
- Diphoton + MET
- Multileptons
- Lepton-jet resonance
- Lepton-photon resonance
- Gamma-jet resonance
- Diboson resonance
- Z+MET
- W/Z+Gamma resonance
- Top-antitop resonance
- Slow-moving particles
- Long-lived particles
- Top-antitop production
- Lepton-Jets
- Microscopic blackholes
- Dijet resonance
- etc...

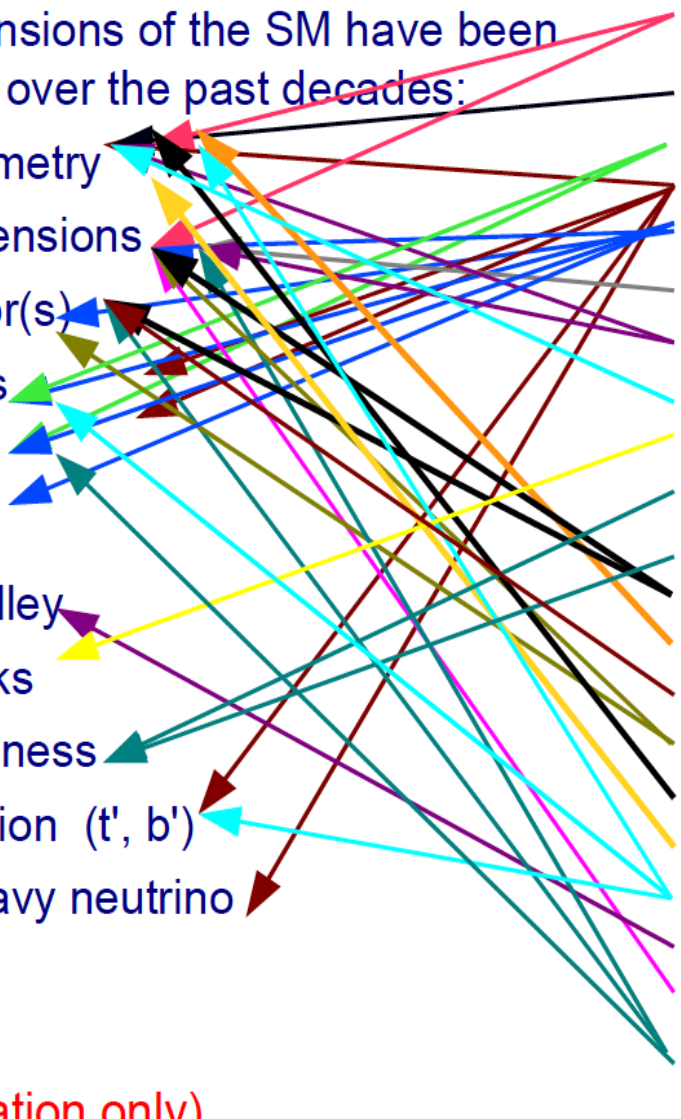
(for illustration only)

Courtesy of Henri Bachacou

DESY

Long List of Models & Signatures Available

- Many extensions of the SM have been developed over the past decades:
- Supersymmetry
- Extra-Dimensions
- Technicolor(s)
- Little Higgs
- No Higgs
- GUT
- Hidden Valley
- Leptoquarks
- Compositeness
- 4th generation (t', b')
- LRSM, heavy neutrino
- etc...



- 1 jet + MET
- jets + MET
- 1 lepton + MET
- Same-sign di-lepton
- Dilepton resonance
- Diphoton resonance
- Diphoton + MET
- Multileptons
- Lepton-jet resonance
- Lepton-photon resonance
- Gamma-jet resonance
- Diboson resonance
- Z+MET
- W/Z+Gamma resonance
- Top-antitop resonance
- Slow-moving particles
- Long-lived particles
- Top-antitop production
- Lepton-Jets
- Microscopic blackholes
- Dijet resonance
- etc...

(for illustration only)

For Experimentalists:

> Complex 2D problem

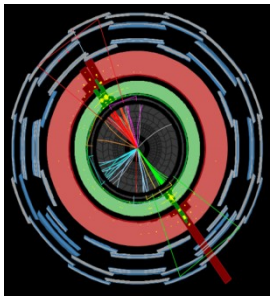
> Signature approach:
  - Practical
  - Less model-dependent

> Important to seek as many signatures as possible

Courtesy of Henri Bachacou

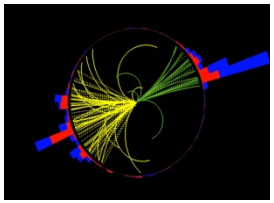
DESY

Selected Searches



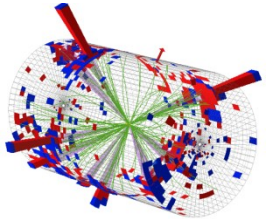
> Heavy Resonances

- heavy gauge bosons
- dijet, paired dijet, jet+photon
- excited leptons



> Quark Sector

- t'/b' quark
- leptoquarks
- vector-like quarks

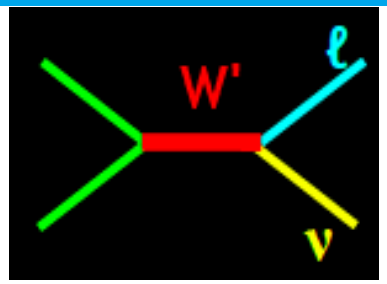


> Strong Gravity

- diphoton spectrum
- black holes

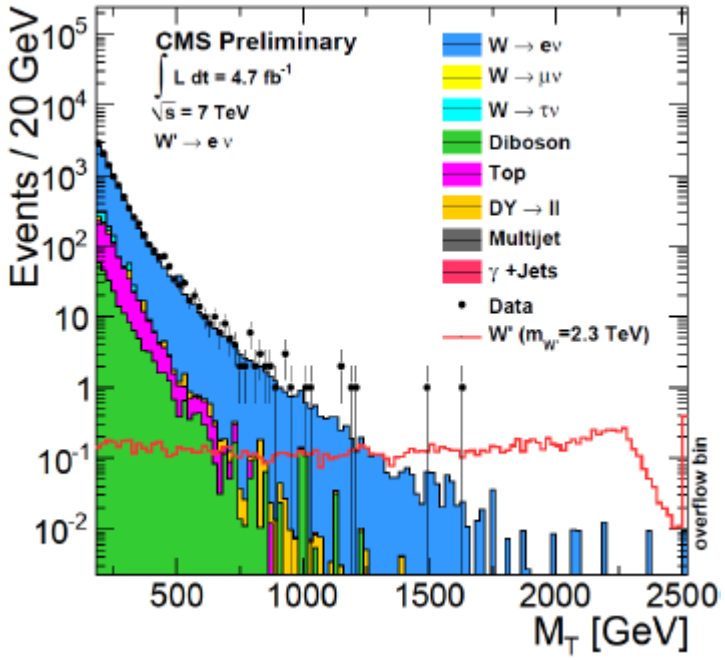
Charged Heavy Resonance: W'

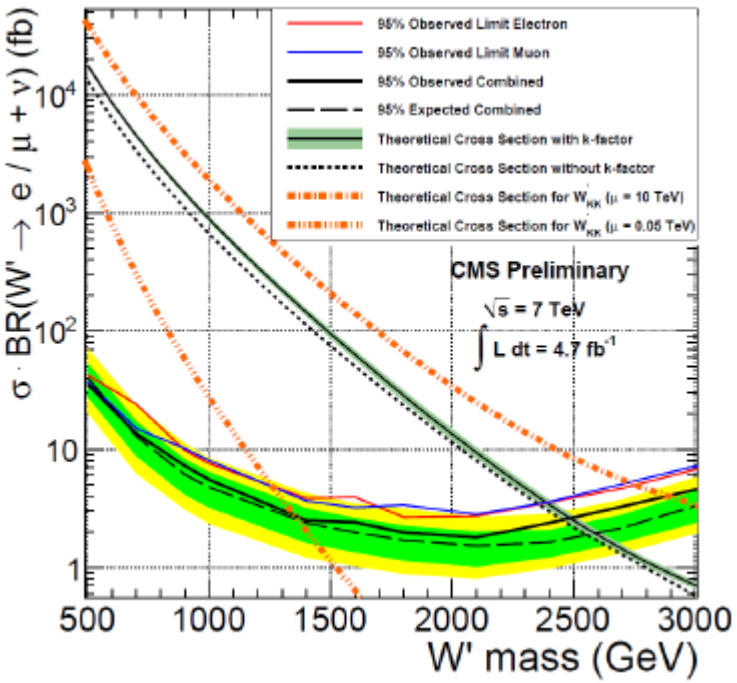
CMS: PAS-EXO-11-024



- Heavy charged gauge boson
- Technirho, Little Higgs, UED, LH, RH
- 1 electron or muon & missing E_T
- Seek Jacobian peak in m_T distribution

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



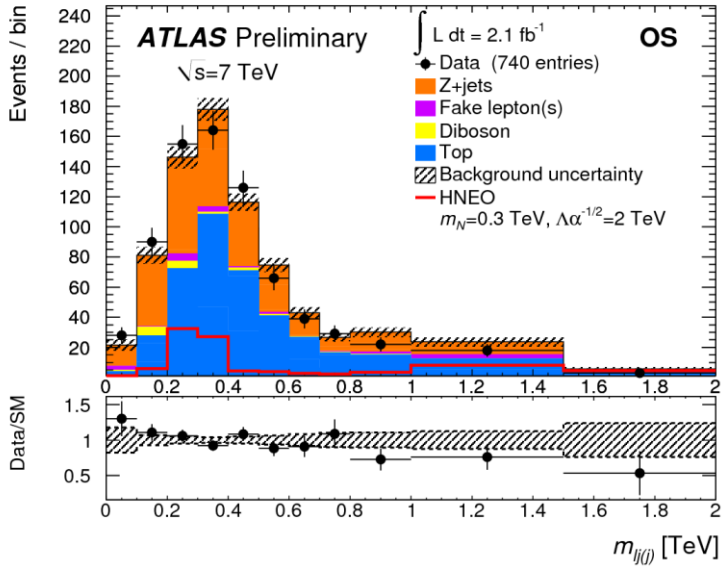


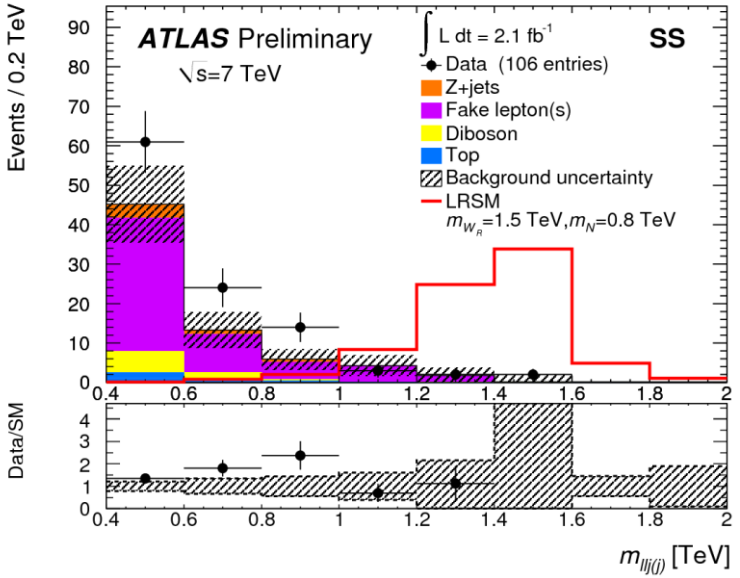
DESY

W_R and Heavy Neutrinos

ATLAS: Preliminary

- Light neutrino masses could be $m_\nu \sim m_D^2/M_N$
  - N are heavy neutrinos – Majorana or Dirac particles → SS or OS events
- Two models:
  - Effective Lagrangian (HNEO): qq → lN →lljj
  - Left-right symmetric model (LRSM): qq → W_R → lN → lljj
- Signature
  - Two leptons + n_{jet} >= 2
  - Discriminating variables m_N, m_{WR}
- Good agreement between data and MC
  - Limits on visible cross section between 6 – 50 fb depending on channel (ee,eμ,μμ)
  - Limits on model parameters

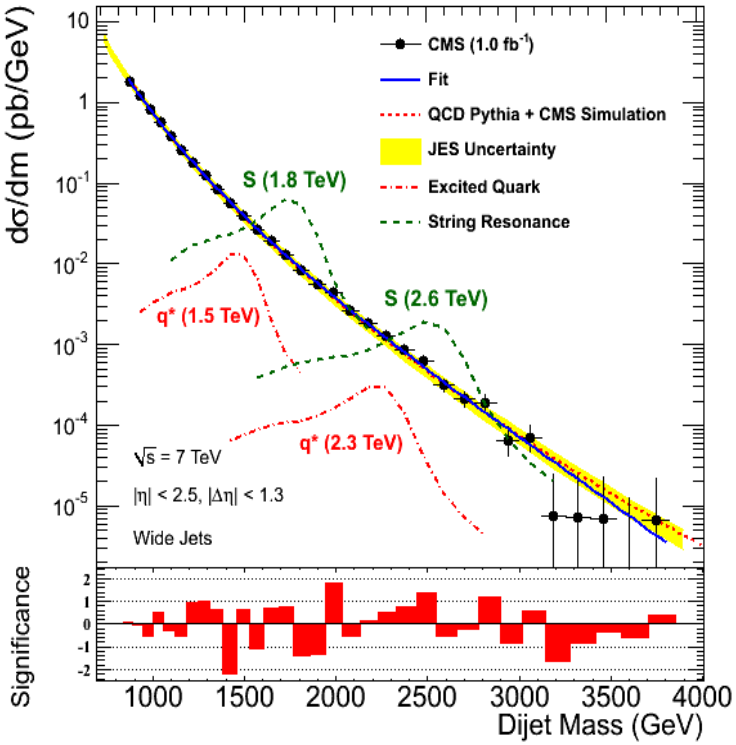


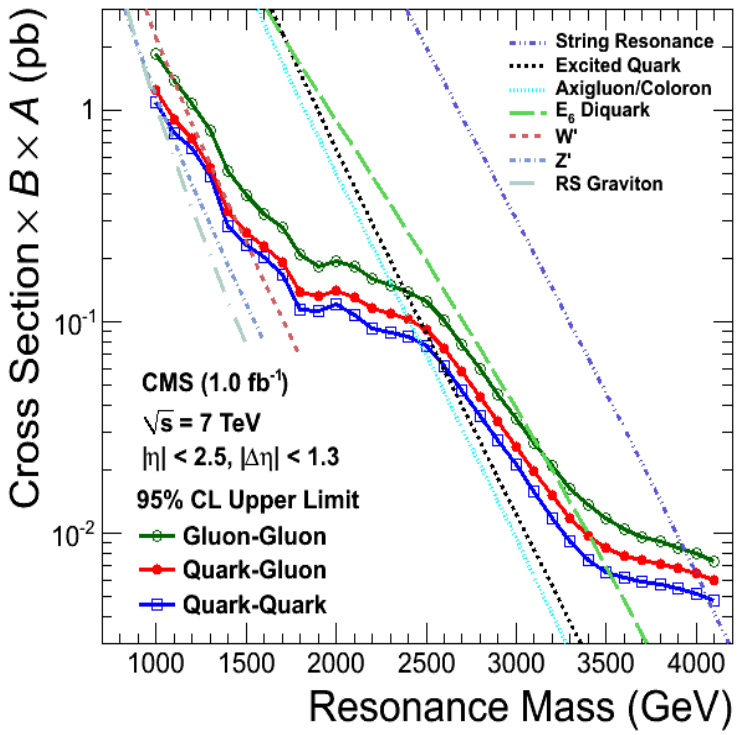


Search for Resonances with Jets

CMS: arXiv:1107.4771

- Different final states possible
  - Dijet final state, jet+photon final state, paired dijet final state
- Predicted by many models:
  - q*, axigluon, color-octet scalar, hyperpions, string resonances, …
- Seek resonance above phenomenological fit to data



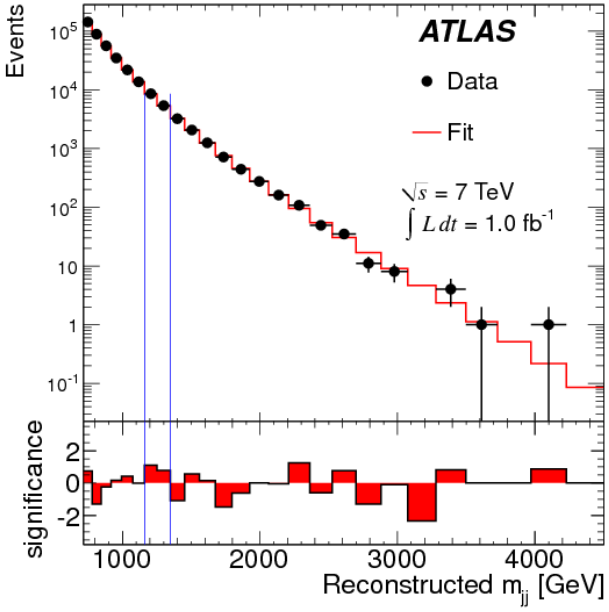


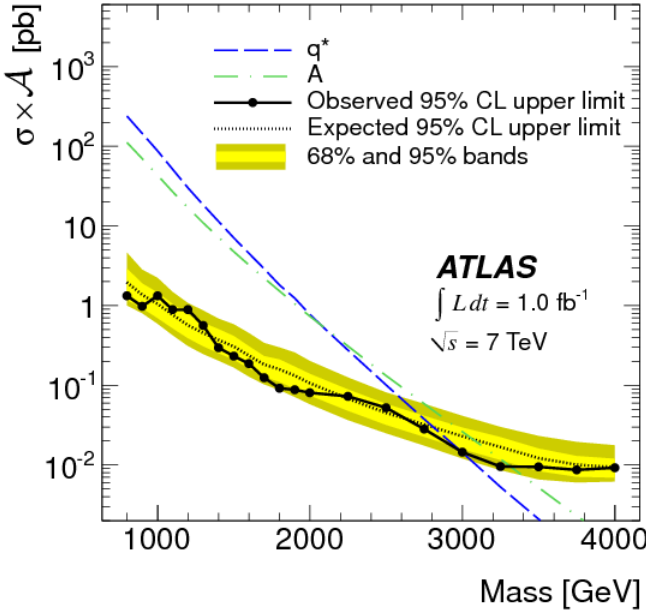
DESY

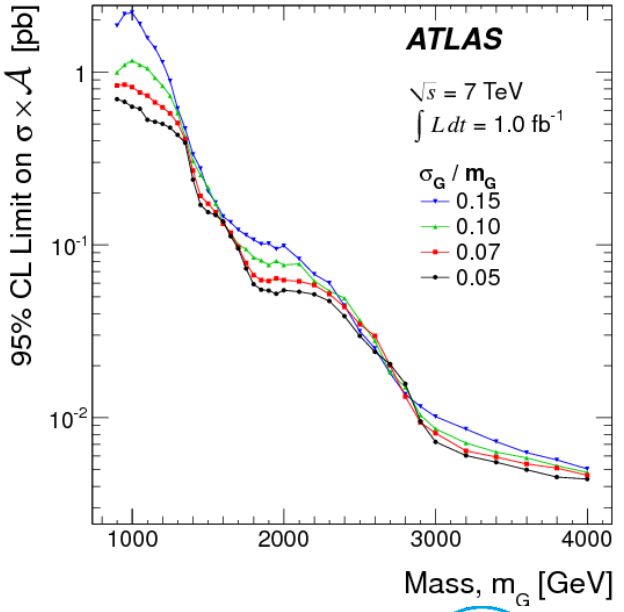
Search for Resonances with Jets

ATLAS: arXiv:1108.6311

- Different final states possible
  - Dijet final state, jet+photon final state, paired dijet final state
- Predicted by many models:
  - q*, axigluon, color-octet scalar, hyperpions, string resonances, …
- Seek resonance above phenomenological fit to data (BumpHunting)





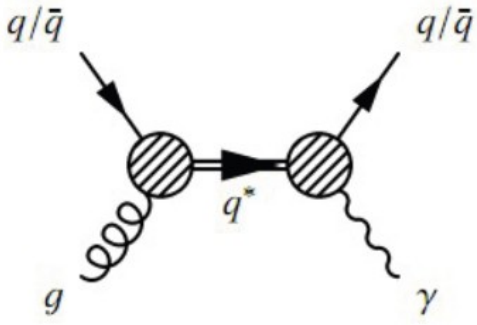


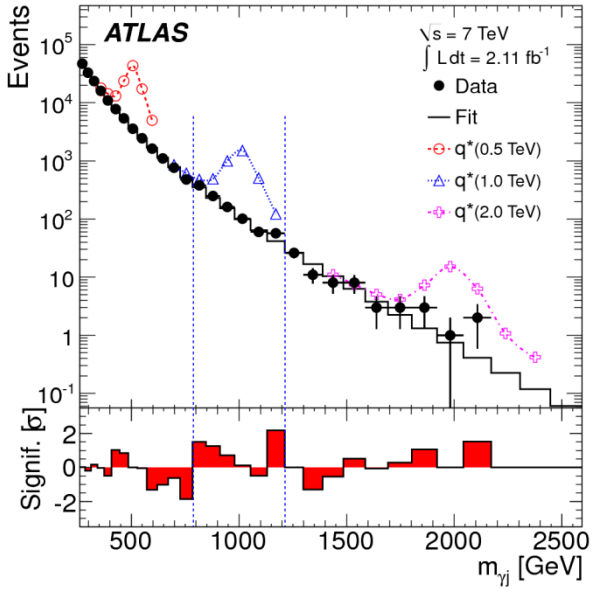
DESY

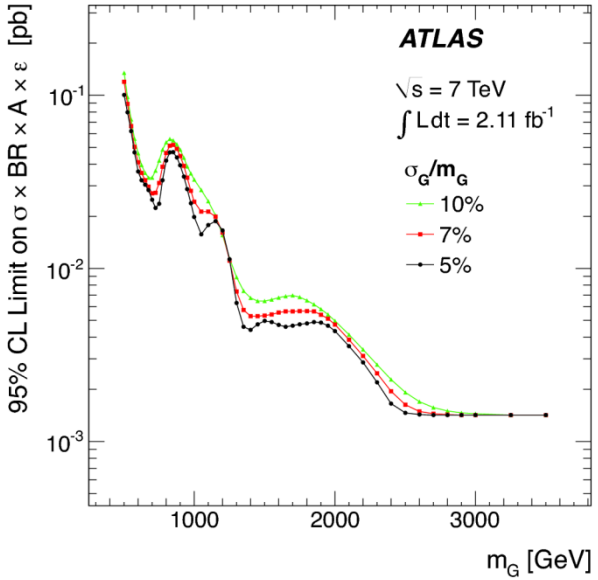
Jet + Photon Resonances

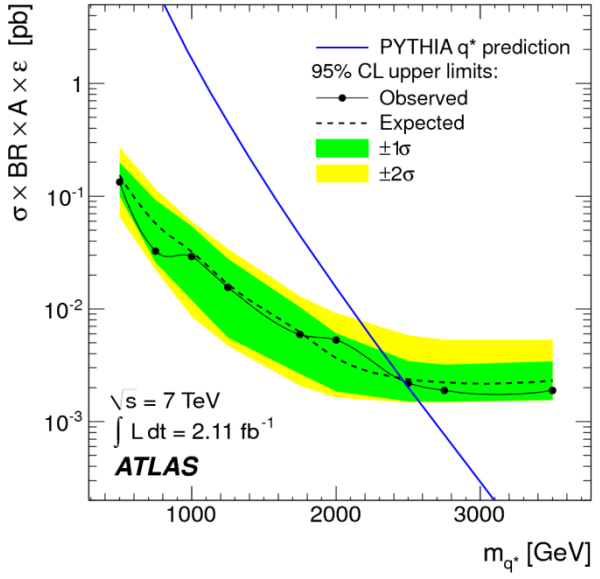
ATLAS: arXiv:12013293

- Replace one jet by a photon
  - Require one jet and one high energetic photon
- BumpHunter search
  → no significant deviation from expectations
- Limits on a generic Gaussian resonance and q* model







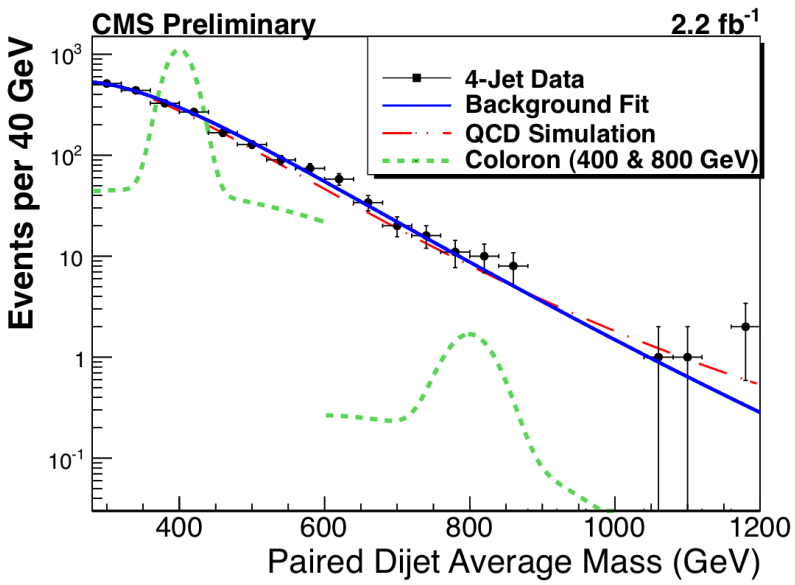


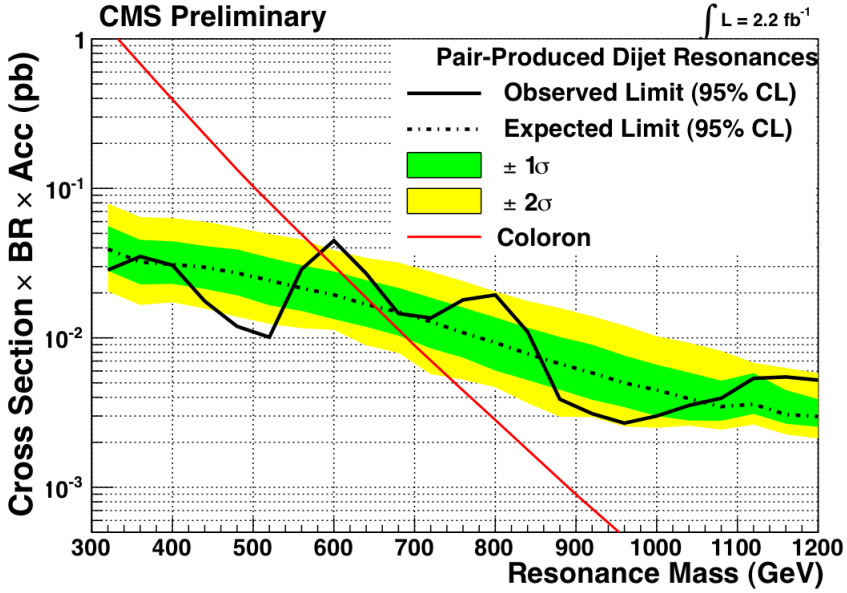
DESY

Paired Dijet Resonances

CMS: PAS-EXO-11-016

- Extension of inclusive dijet resonance search
- 4 jets with p_T > 150 GeV
  - Require equal dijet masses → use average mass
  - $p_T(jj_1) + p_T(jj_2) - m_{avg} > 25$ GeV
  - Largest fluctuation at ~615 GeV → 2.7 (1.5) σ (after LEE)

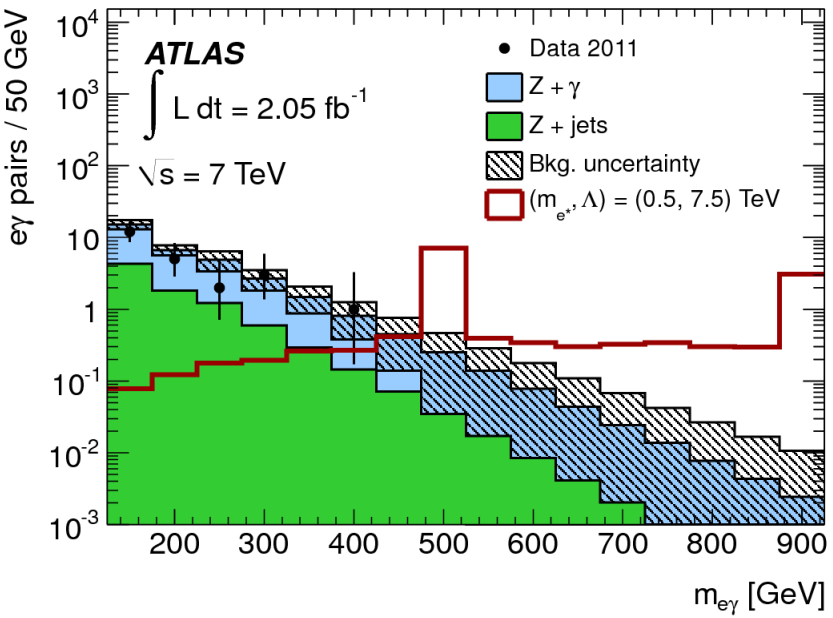


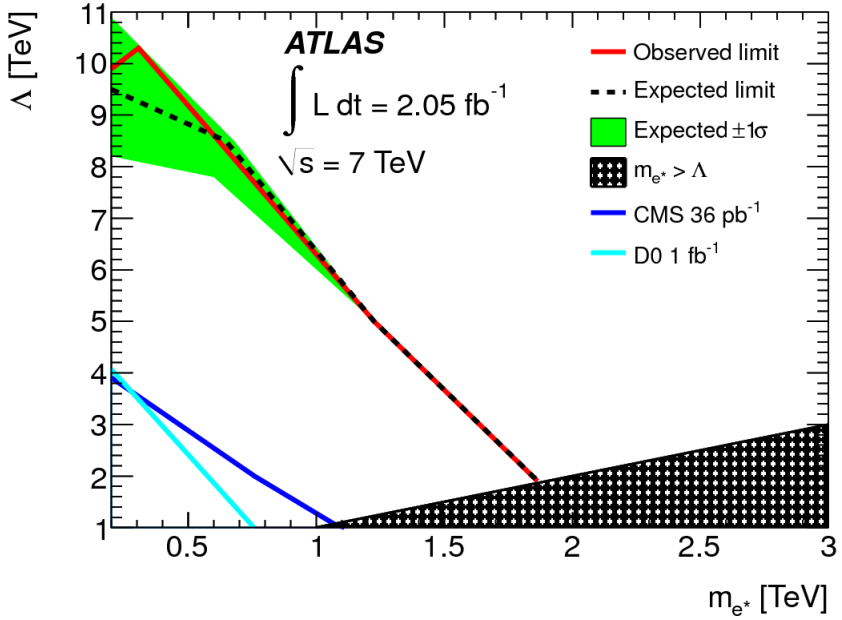


Excited Leptons

ATLAS: arXiv:1201.3293

- Compositeness models: mass of the excited lepton + scale parameter
- Single production and EM radiative decays: qq → ll* → llγ
  - 2 leptons + 1 photon
  - Peak in lγ inv. mass for some parameters, but excess in llγ inv. mass more robust
  - Muon channel slightly less sensitive

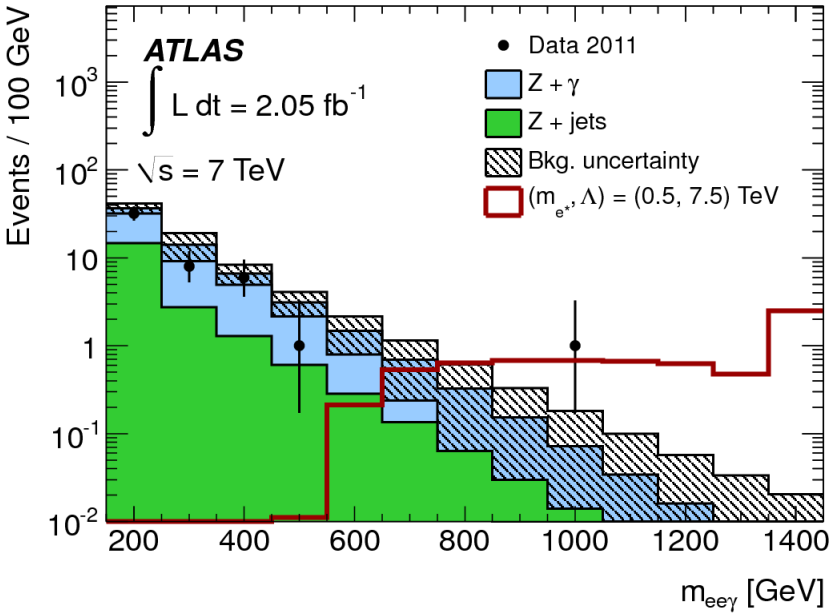


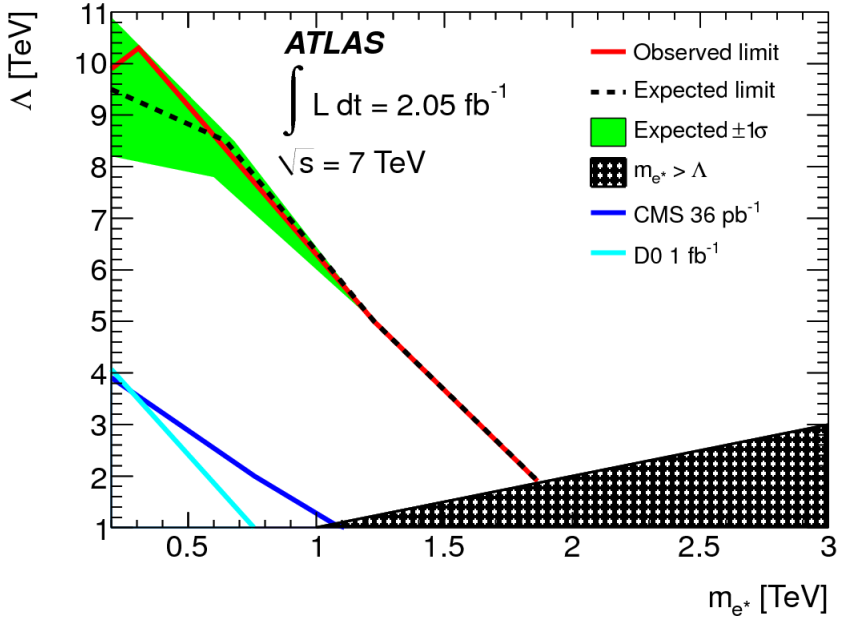


Excited Leptons

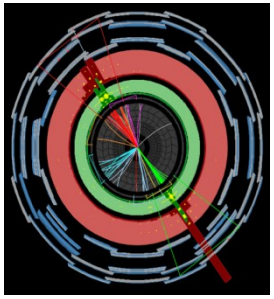
ATLAS: arXiv:1201.3293

- Compositeness models: mass of the excited lepton + scale parameter
- Single production and EM radiative decays: qq → ll* → llγ
  - 2 leptons + 1 photon
  - Peak in lγ inv. mass for some parameters, but excess in llγ inv. mass more robust
  - Muon channel slightly less sensitive



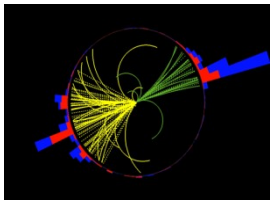


Selected Searches



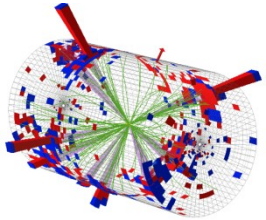
> Heavy Resonances

- heavy gauge bosons
- dijet, paired dijet, jet+photon
- excited leptons



> Quark Sector

- t'/b' quarks
- leptoquarks
- vector-Like quarks



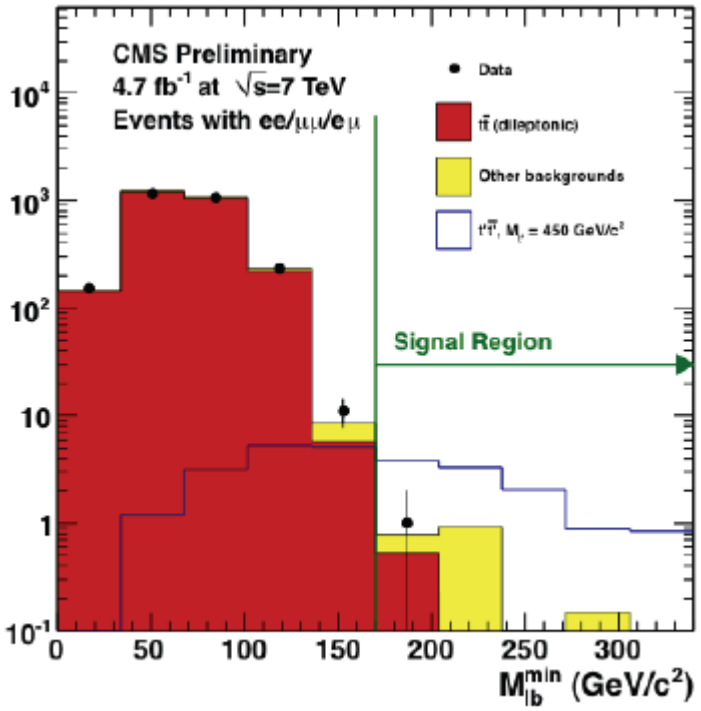
> Strong Gravity

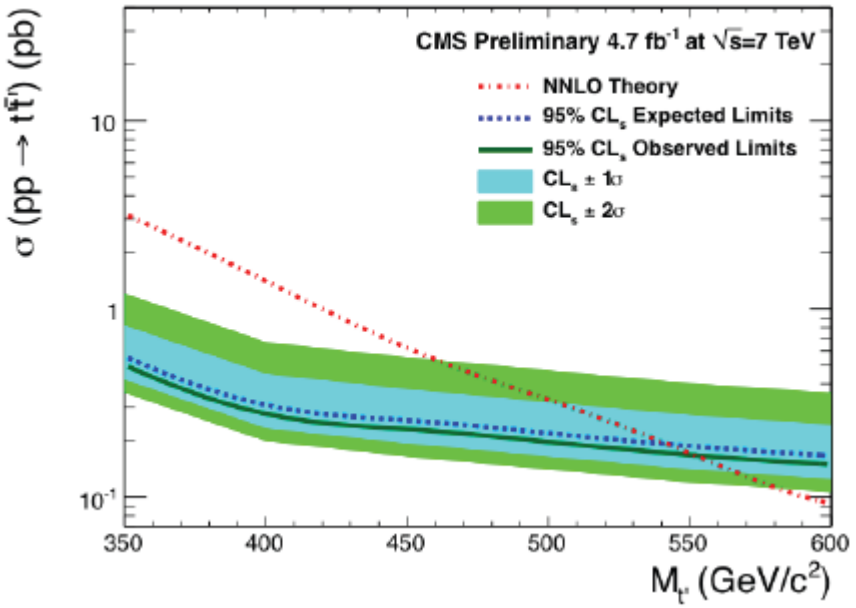
- diphoton spectrum
- black holes

4th Generation Quarks: t' → Wb

CMS: PAS-EXO-11-050

- t' → Wb: top-like signal (l+jets or dilepton), but heavier
- Select: dilepton channels (ee, eμ, μμ) with opposite sign + two b-jets
- Use minimum invariant mass between lepton and b-jet M_{bl}(min) to reduce large top background -



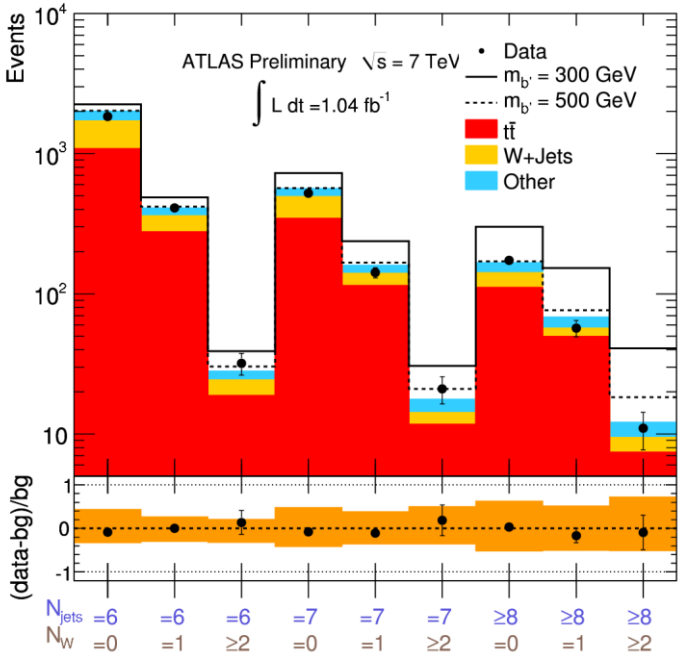


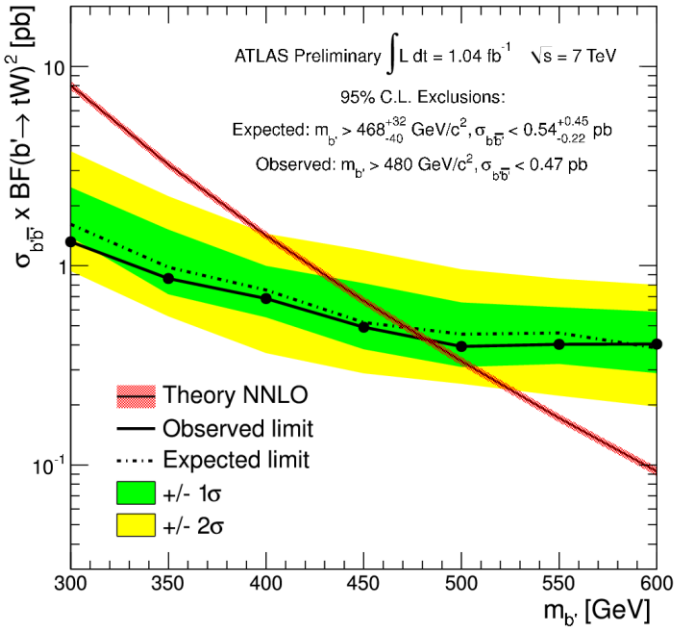
DESY

4th Generation Quarks: b' → Wt

ATLAS: Preliminary

- b'b' → WtWt → lvbbqqqq
- Signature:
  - 1 lepton + missing E_T + n_{jet} >=6
  - Use dijet system to tag W
  - Enriched signal in high number of jets and one or two Ws
  - Top background important





- ATLAS: 1 fb^{-1}
  - b' → Wt search: $m_{b'}$ > 480 (468) GeV
  - t' → Wb search: $m_{t'}$ > 404 (394) GeV
  - Q → Wq search: m_Q > 350 (335) GeV
- CMS: 4.7 fb^{-1}
  - t' → Wt search: $m_{b'}$ > 552 (542) GeV

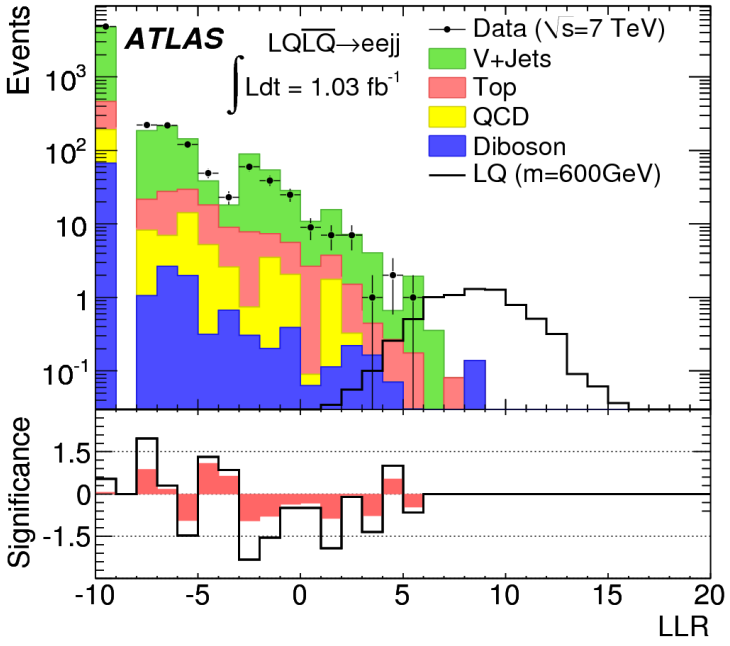
DESY

Leptoquarks (1st generation)

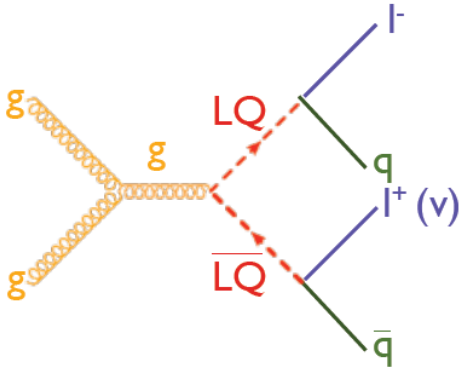
ATLAS: arXiv:112.4828

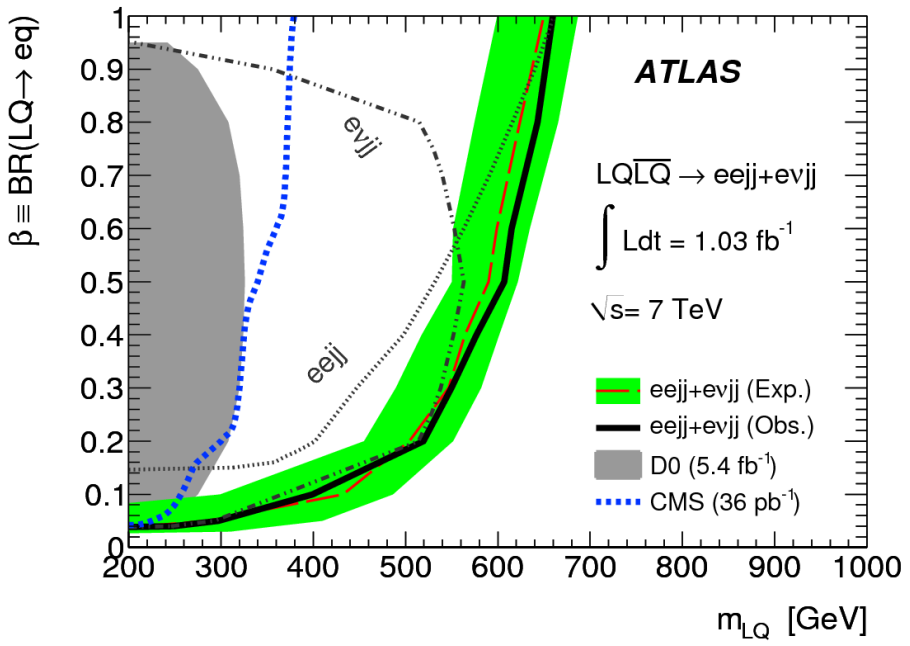
- LQLQ → eeqq/ evqq (1. generation)
  - 2 leptons + N_{jet} >= 2
  - 1 lepton + N_{jet} >=2 + missing E_T
- Combine discriminating variables in a Log Likelihood Ratio (LLR)

$$L_S \equiv \prod_i P_S^i \qquad L_B \equiv \prod_i P_B^i \qquad LLR \equiv \log_{10}\left(L_S / L_B\right)$$



- Fractionally charged colored bosons
  - LQ → quark + charged lepton
  - LQ → quark + neutrino



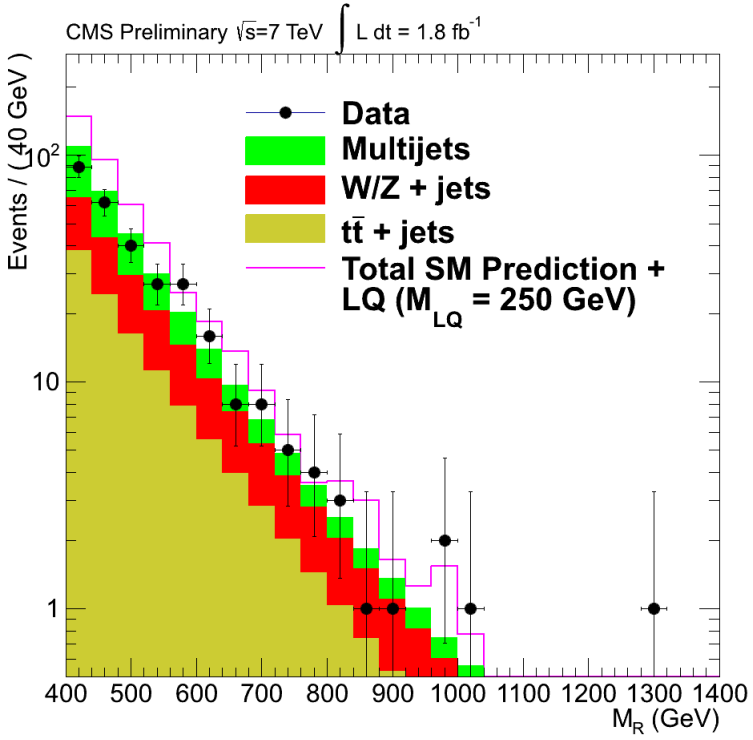


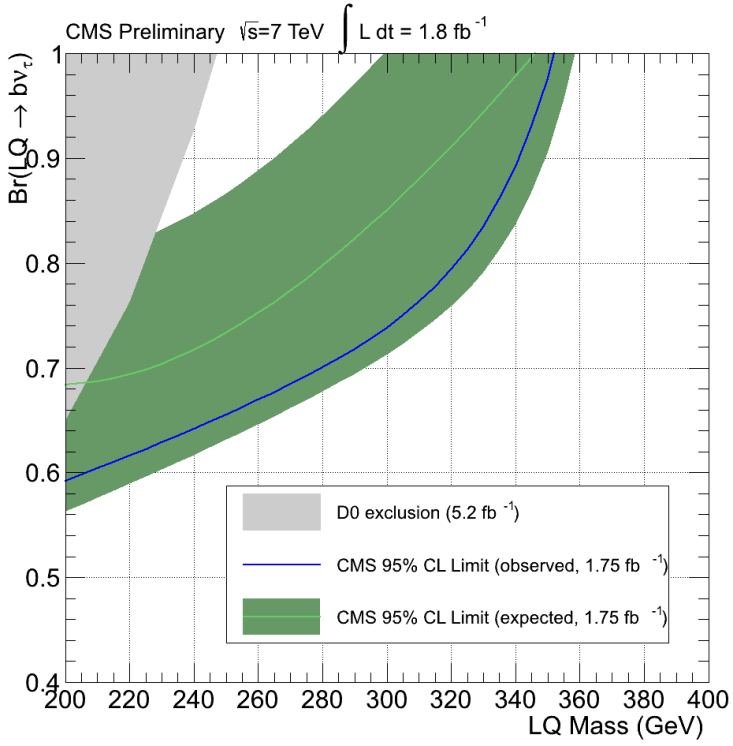
Leptoquarks (3rd generation)

CMS: PAS-EXO-11-030

2nd generation search:
CMS: PAS-EXO-11-028 (2 fb^{-1})

- LQLQ → vvbb
  - 2 b-jets and missing E_T
- Define signal region via razor variables: M_R and R^2
  - Broad peak in M_R expected

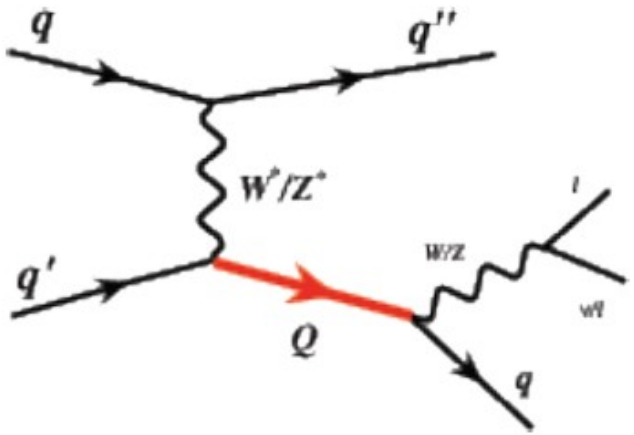


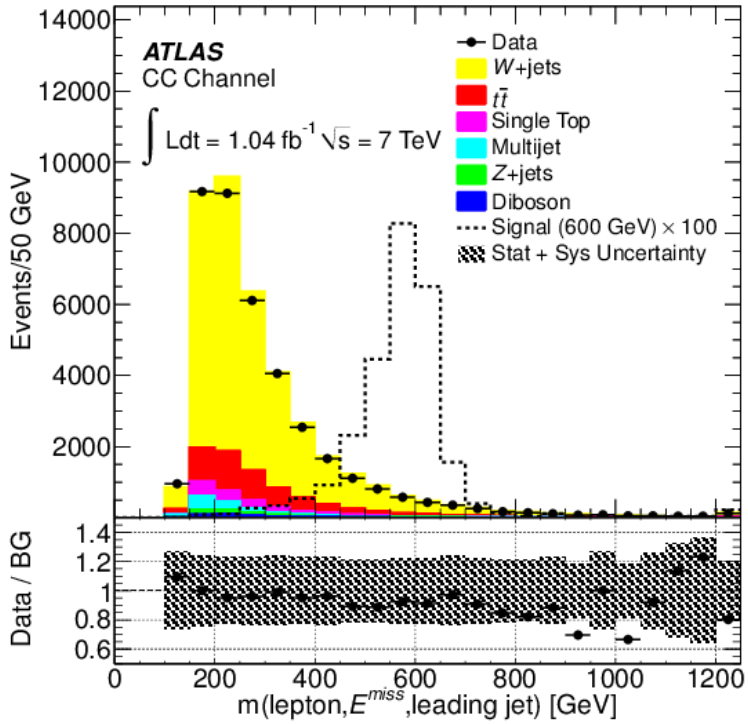


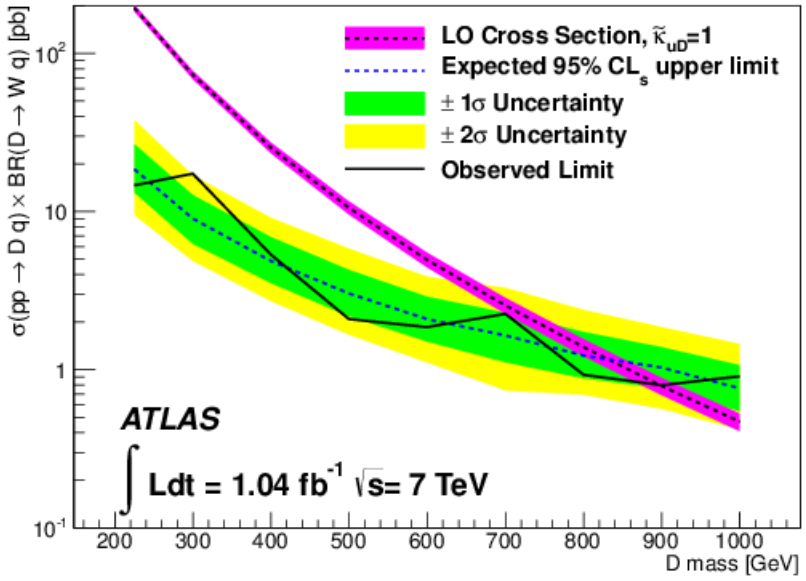
Vector-Like Quarks

ATLAS: arXiv:1112.5755

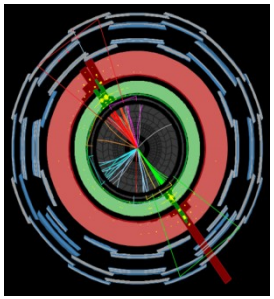
- qq → qQ → qW / qZ → qlv / qll
  - similar signature to leptoquarks but different underlying kinematics
  - two leptons + n_{jet} >= 2
  - one lepton + missing E_T + n_{jet} >= 2





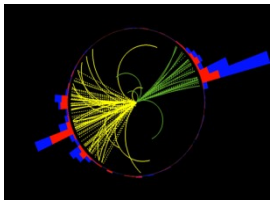


Selected Searches



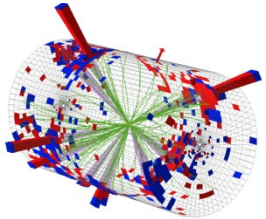
> Heavy Resonances

- heavy gauge bosons
- dijet, paired dijet, jet+photon
- excited leptons



> Quark Sector

- t'/b' quarks
- leptoquarks
- vector-Like quarks



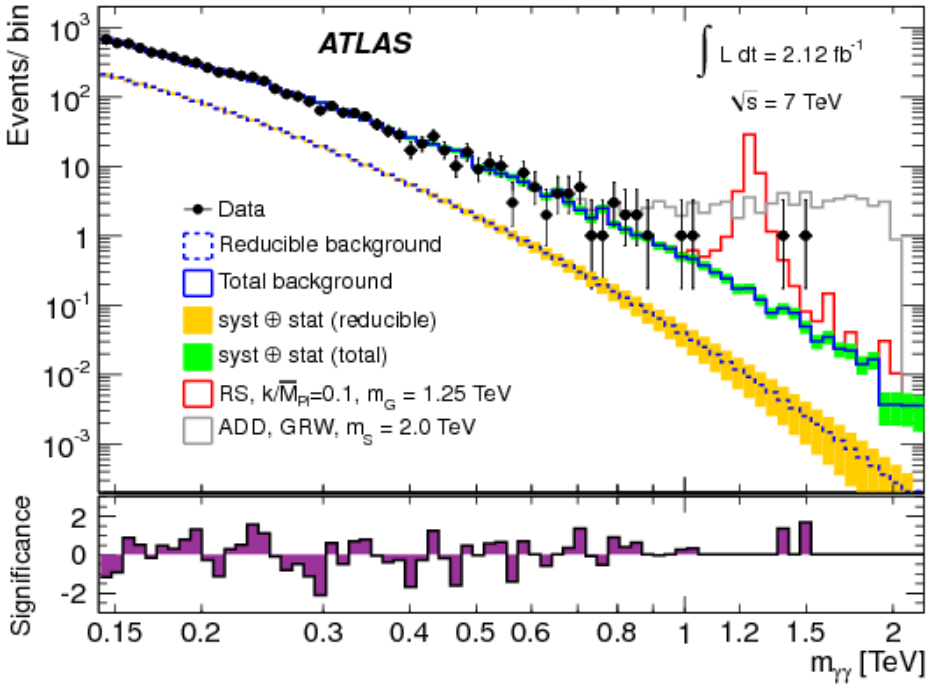
> Strong Gravity

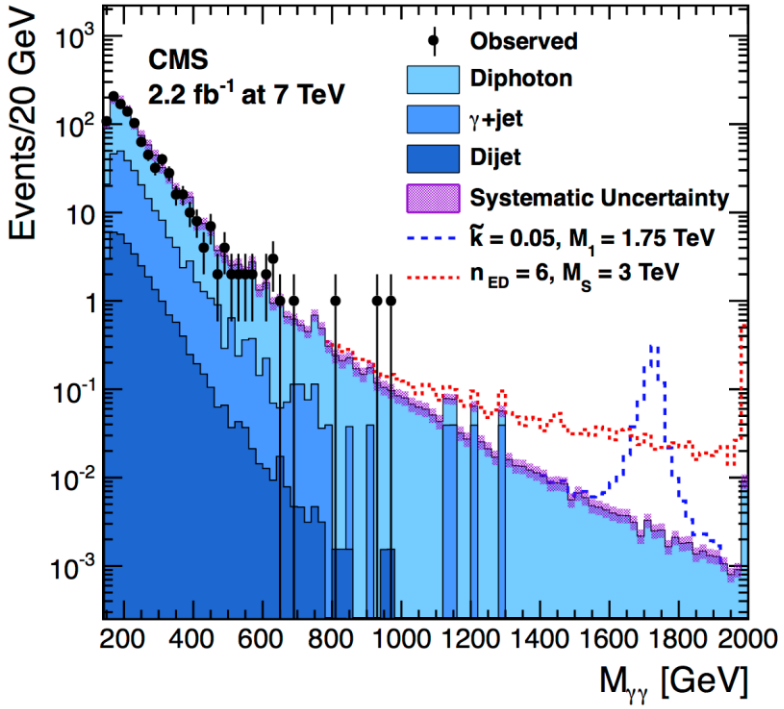
- diphoton spectrum
- black holes

Diphoton Final State

ATLAS: arXiv:1112.2194
CMS: arXiv:1112.0688

- Search for diphoton production: qq/gg → G → γγ
  - Resonant production in Randal-Sundrum (RS) models
  - Non-resonant production in Arkani-Hamed, Dimopoulos, Dvali (ADD) models
  - Signature: two high energetic photons
  - Good agreement between data and MC expectations





DESY

Limits on RS and ADD models

ATLAS: arXiv:1112.2194
CMS: arXiv:1112.0688

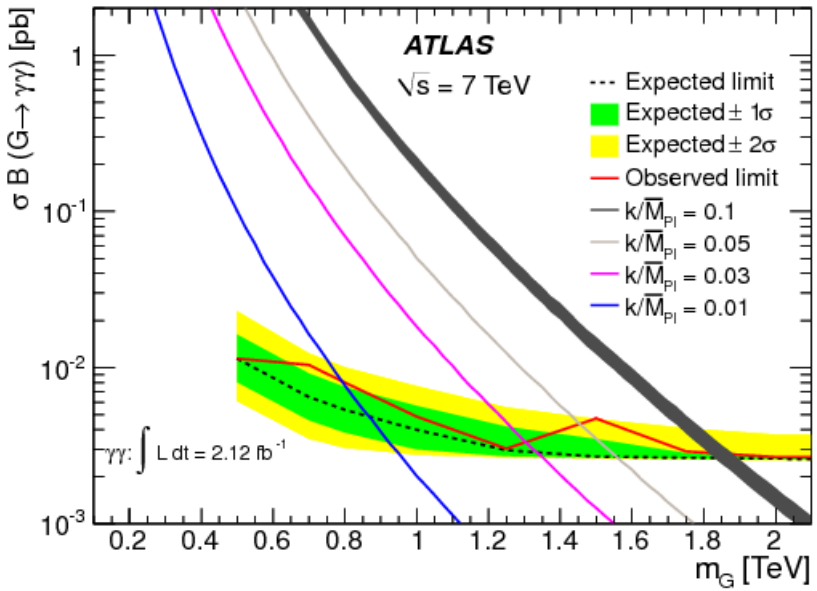
CMS: ADD

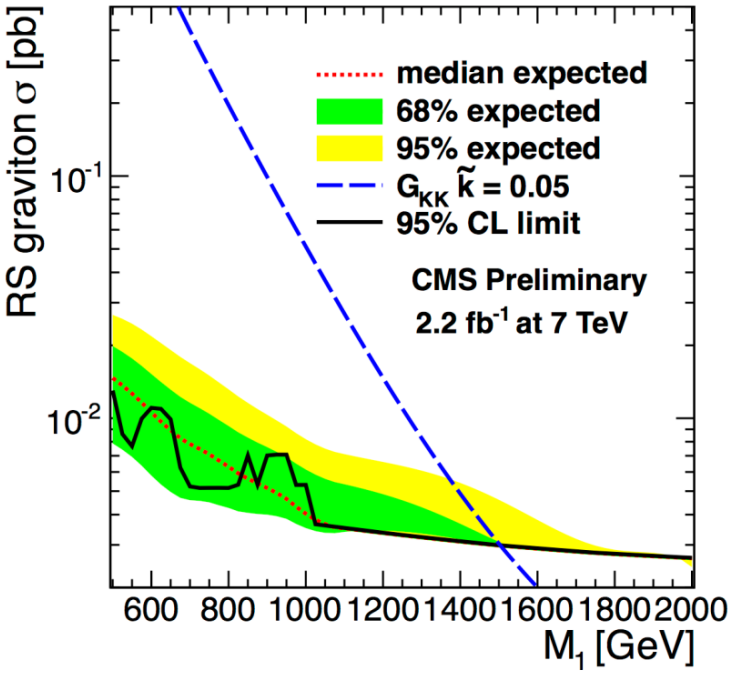
K factor	GRW	Hewett		HLZ					
		pos.	neg.	$n_{ED}=2$	$n_{ED}=3$	$n_{ED}=4$	$n_{ED}=5$	$n_{ED}=6$	$n_{ED}=7$
1.0	2.94	2.63	2.28	3.29	3.50	2.94	2.66	2.47	2.34
1.6	3.18	2.84	2.41	3.68	3.79	3.18	2.88	2.68	2.53

ATLAS: ADD

k-factor Value	GRW	Hewett		HLZ				
		Pos	Neg	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$
1	2.73	2.44	2.16	3.25	2.73	2.47	2.30	2.17
1.70	2.97	2.66	2.27	3.53	2.97	2.69	2.50	2.36

- Limits improve with
  - decreasing n_{ED}
  - increasing $k/M_{Pl} = \tilde{k}$
- k-factor (NLO) give some boost





DESY

Limits on RS and ADD models

ATLAS: arXiv:1112.2194
CMS: arXiv:1112.0688

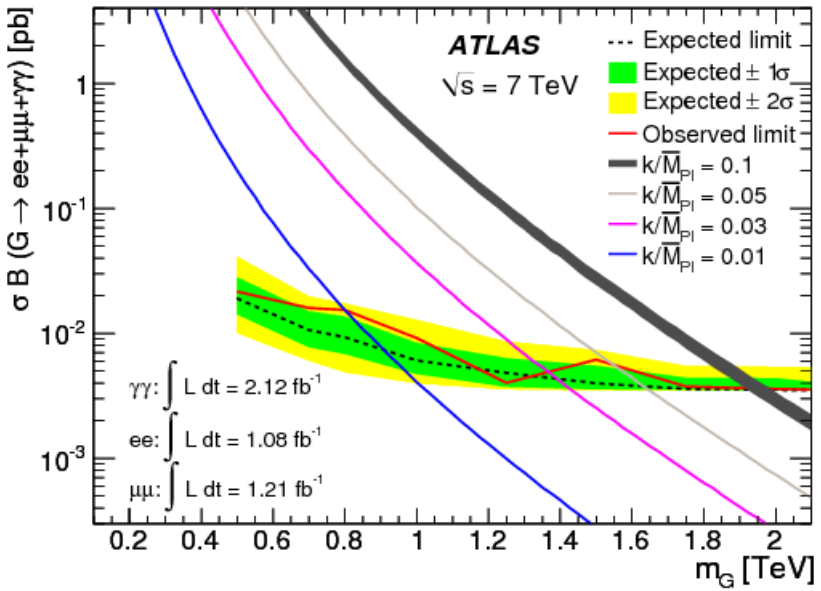
CMS: ADD

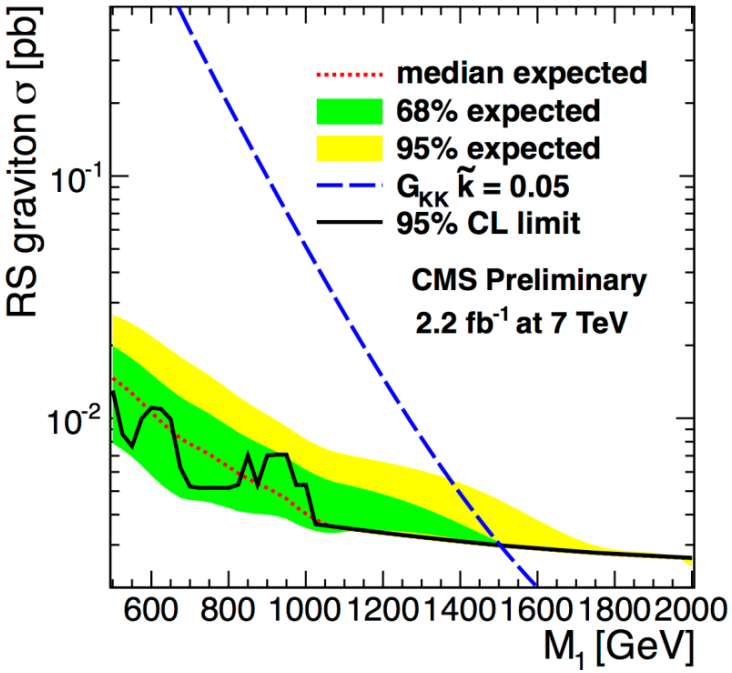
K factor	GRW	Hewett		HLZ					
		pos.	neg.	$n_{ED}=2$	$n_{ED}=3$	$n_{ED}=4$	$n_{ED}=5$	$n_{ED}=6$	$n_{ED}=7$
1.0	2.94	2.63	2.28	3.29	3.50	2.94	2.66	2.47	2.34
1.6	3.18	2.84	2.41	3.68	3.79	3.18	2.88	2.68	2.53

ATLAS: ADD

k-factor Value	GRW	Hewett		HLZ				
		Pos	Neg	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$
1	2.73	2.44	2.16	3.25	2.73	2.47	2.30	2.17
1.70	2.97	2.66	2.27	3.53	2.97	2.69	2.50	2.36

- Limits improve with
  - decreasing n_{ED}
  - increasing $k/M_{Pl} = \tilde{k}$
- k-factor (NLO) give some boost

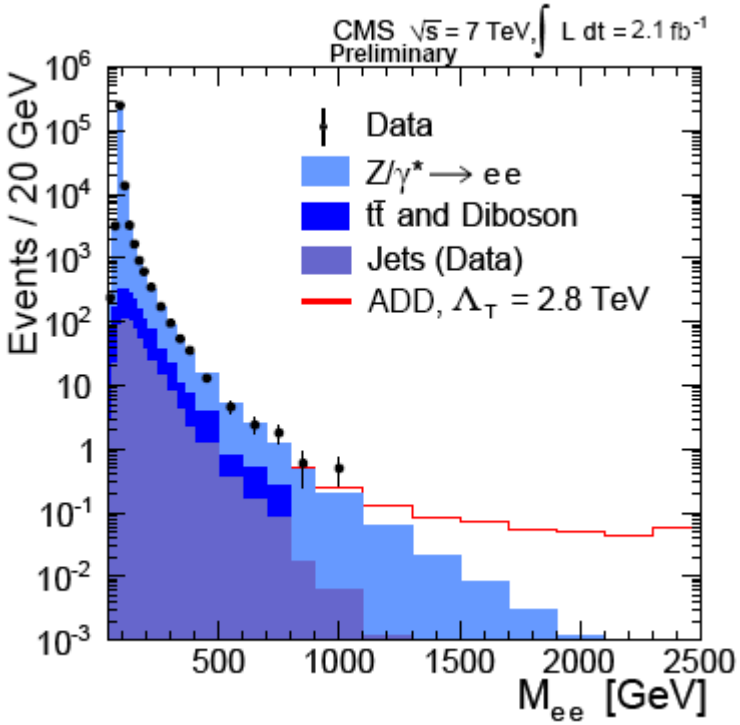


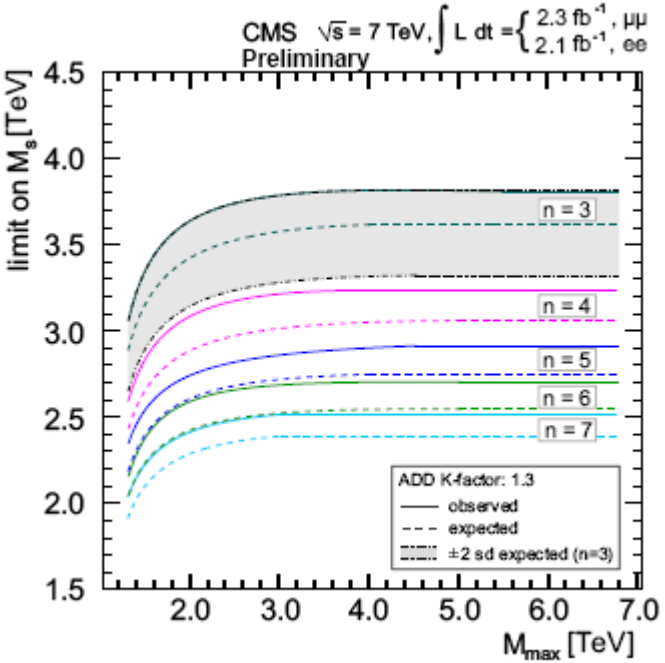


Dilepton Final State

CMS: PAS-EXO-11-087 / Preliminary

- Similar to diphoton final state search for non-resonant dilepton production (ADD models)
- ee or μμ selection

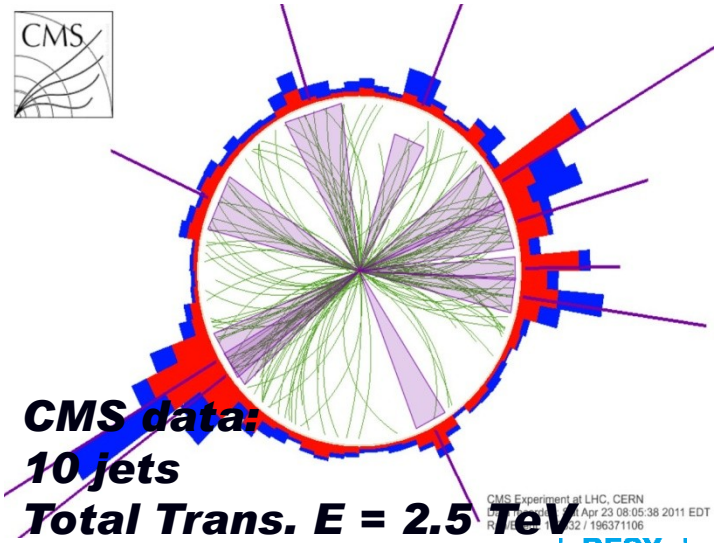




Combination with diphoton search:
HLZ model (n = 3) 3.8 TeV → 3.9 TeV

Black Holes: Multi-Object, Multi-Jet, Same-Sign

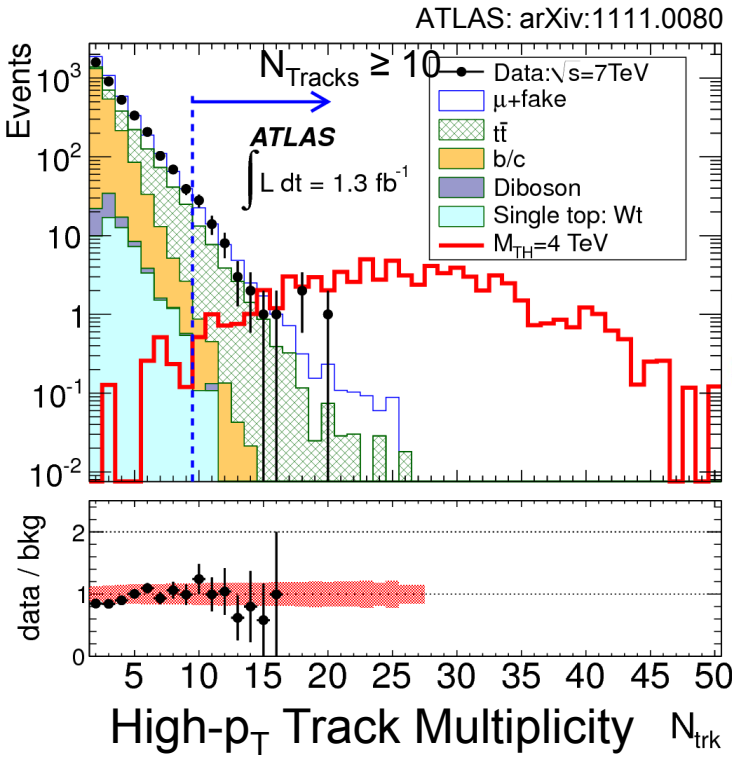
- Microscopic black holes decaying via Hawking radiation
- Models uncertain due to lack of knowledge about quantum gravity ($m_{BH} \sim M_D$)
- Semi-classical models: $m_{BH} >> m(\text{threshold}) = M_{TH}$
- Safe bet: decay is democratic and isotropic, likely high particle multiplicity → look for many jets and leptons at high mass

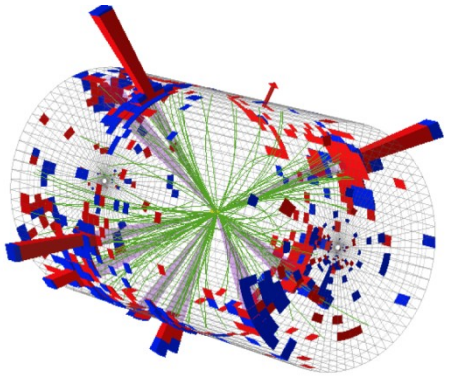


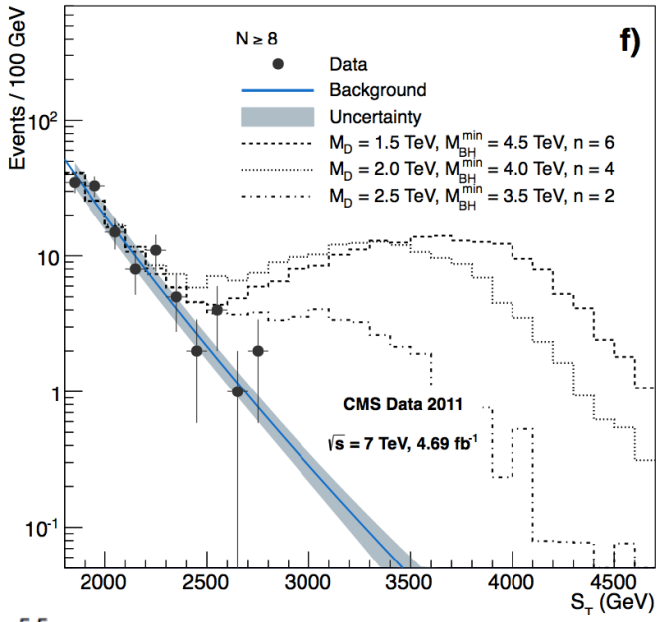
CMS PAS EXO-11-071

Black Holes: Multi-Object, Multi-Jet, Same-Sign

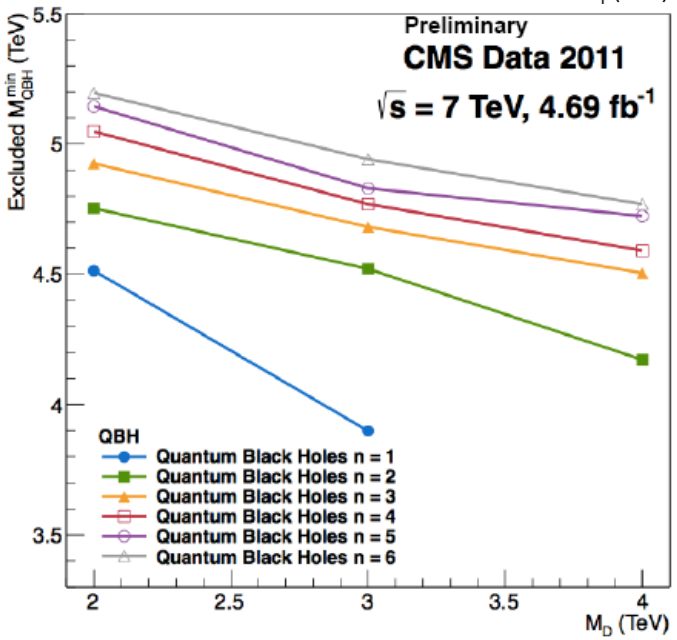
- Inclusive search: sum energy of all objects (e, μ, jets)
- Can also select peculiar events: e.g., same-sign dilepton with very high track multiplicity





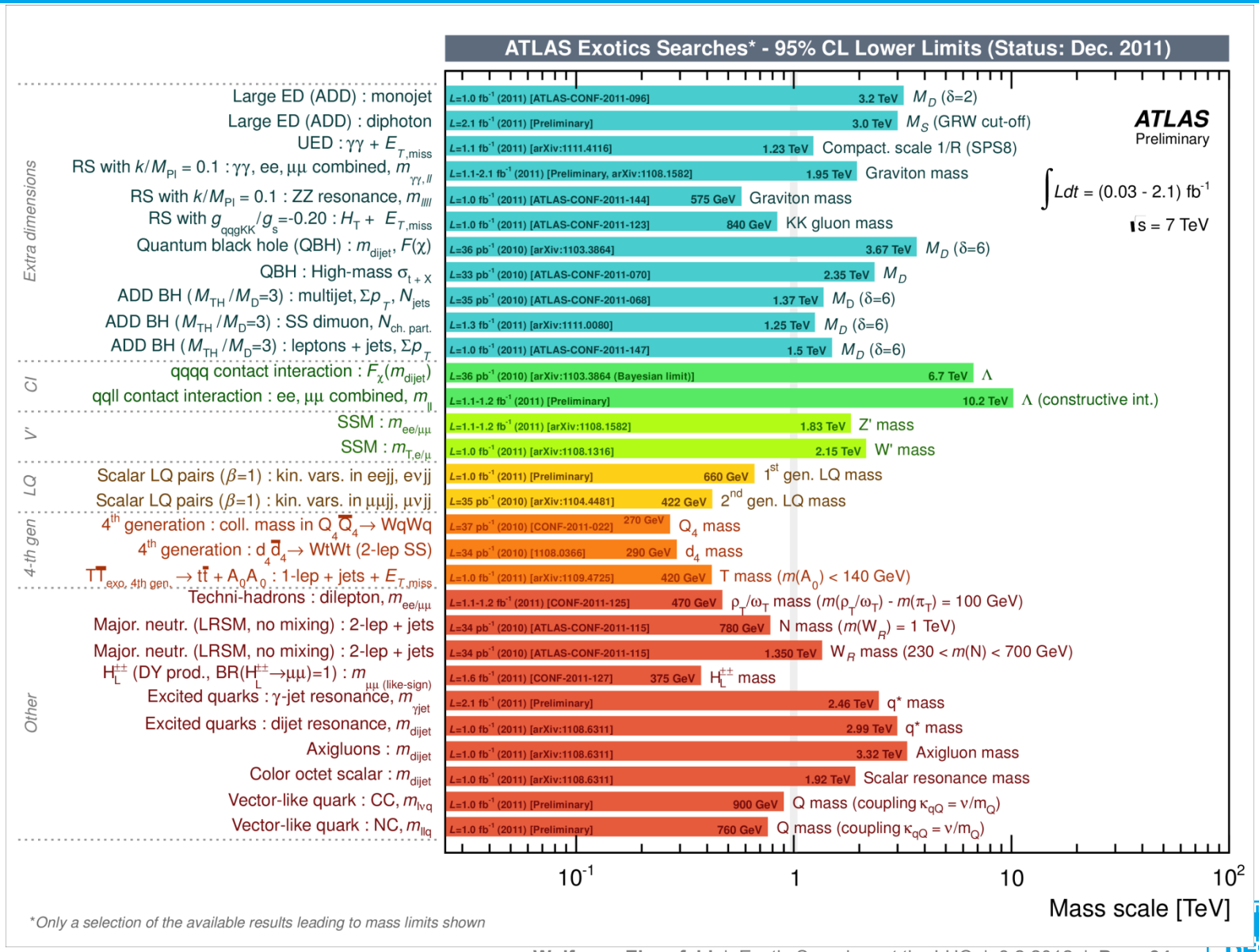


CMS: PAS-EXO-11-071



CMS: PAS-EXO-11-071

ATLAS Exotic Searches: Summary

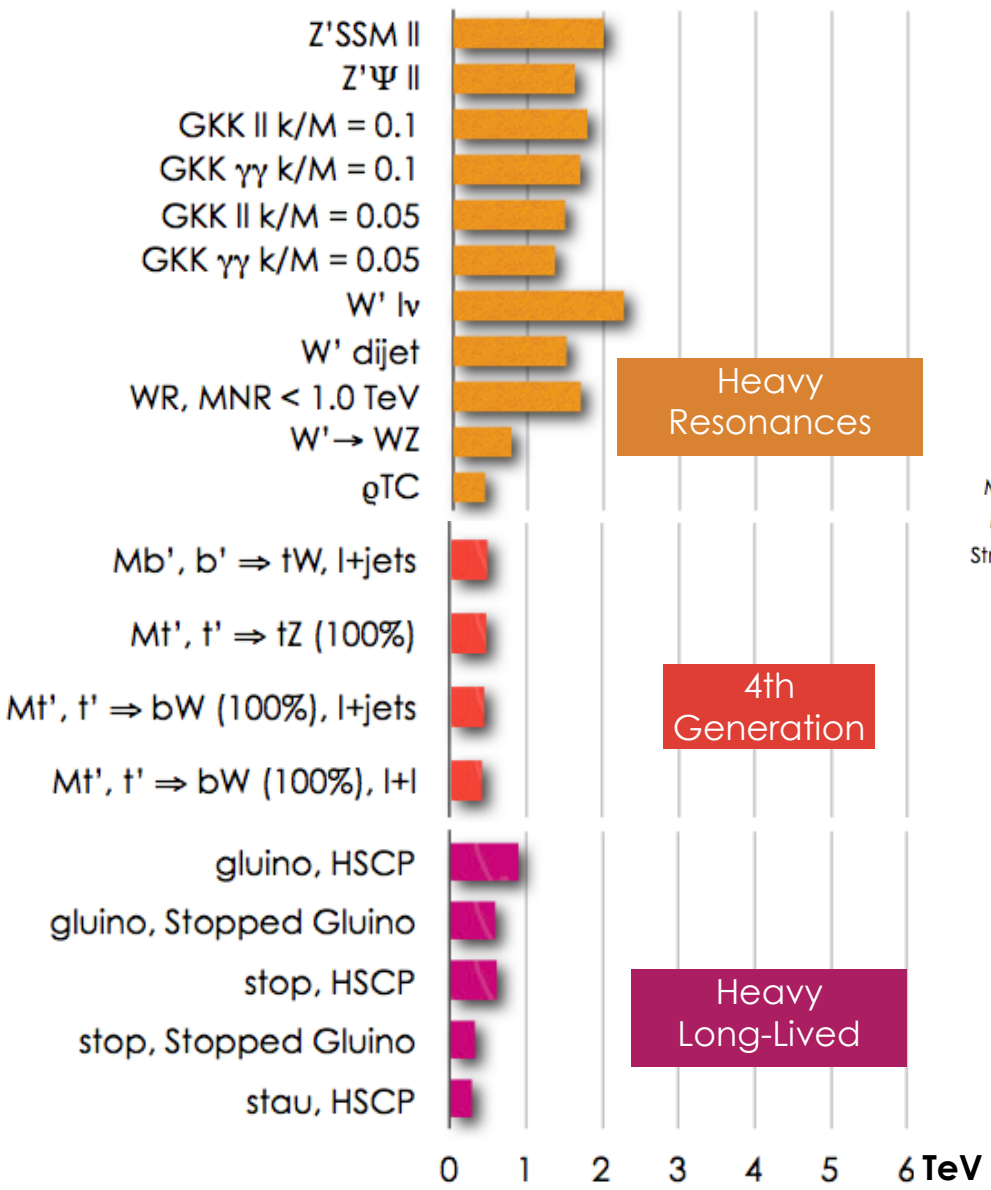


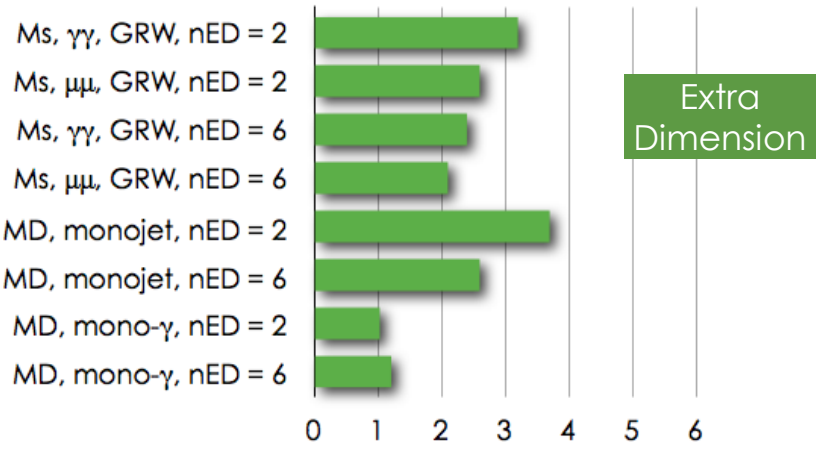
*Only a selection of the available results leading to mass limits shown

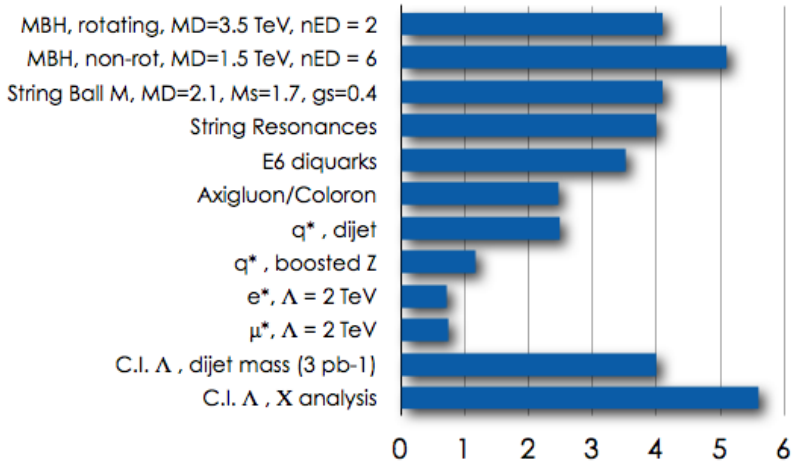
CMS Exotic Searches: Summary

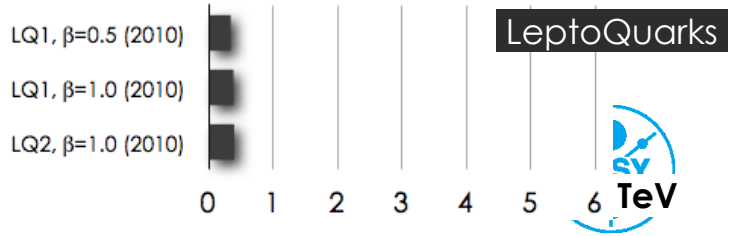
December 2011

95% C.L. Exclusion Limits









Sh. Rahatlou

Conclusion and Outlook

- ATLAS and CMS have produced an impressive number of papers/conference notes using the 2010 and 2011 data
- In the channels searched so far, no significant excess above the Standard Model was found
- New physics is not “just around the corner”
- Many limits have surpassed those from Tevatron/LEP
- At the moment the full dataset of 5 fb^{-1} are being analysed
- Extend the reach for new physics in 2012 if the LHC runs at 8 TeV centre-of-mass energy and delivers 20 fb^{-1}.