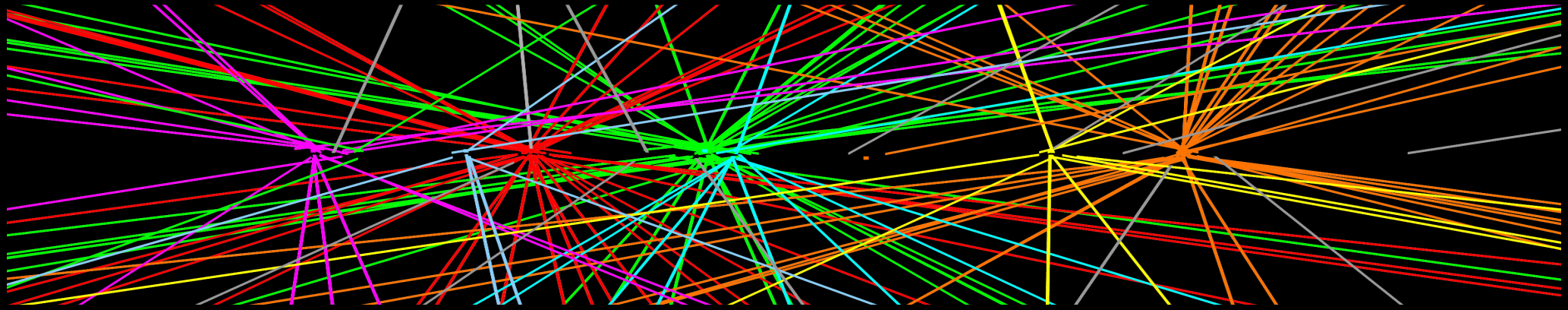
New Physics (Exotics) Searches at the LHC



Andreas Warburton
McGill University

Representing the ATLAS & CMS Collaborations

19th International Conference on Supersymmetry & Unification of Fundamental Interactions
SUSY11

Fermilab, USA 2011.08.30

Introduction

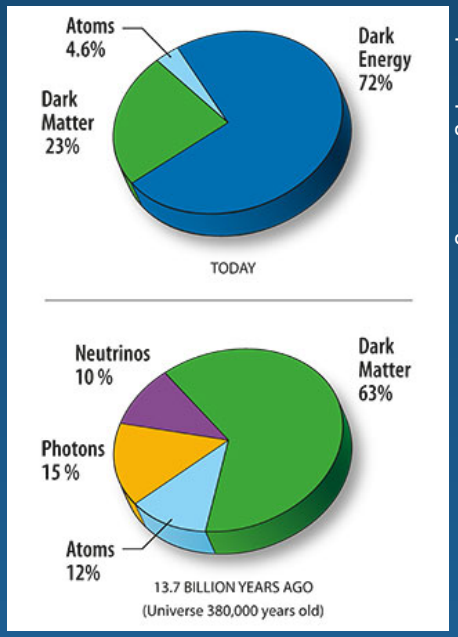
- Several Exotics / New Physics searches at the LHC
- Cannot cover all → emphasis on new 1 fb^{-1} results
- ATLAS & CMS only: LHCb (B. Pietrzyk's talk) and ALICE also seek NP
- Full repositories of latest results:
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
- This talk does **not** cover
  - SUSY: See talks by W. Ehrenfeld, I. Melzer-Pellmann, and others
  - Higgs: Next talk by M. Vazquez Acosta
  - Standard Model anomalies
- (Powerpoint version of this talk has clickable links to the public notes.)

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
  - …

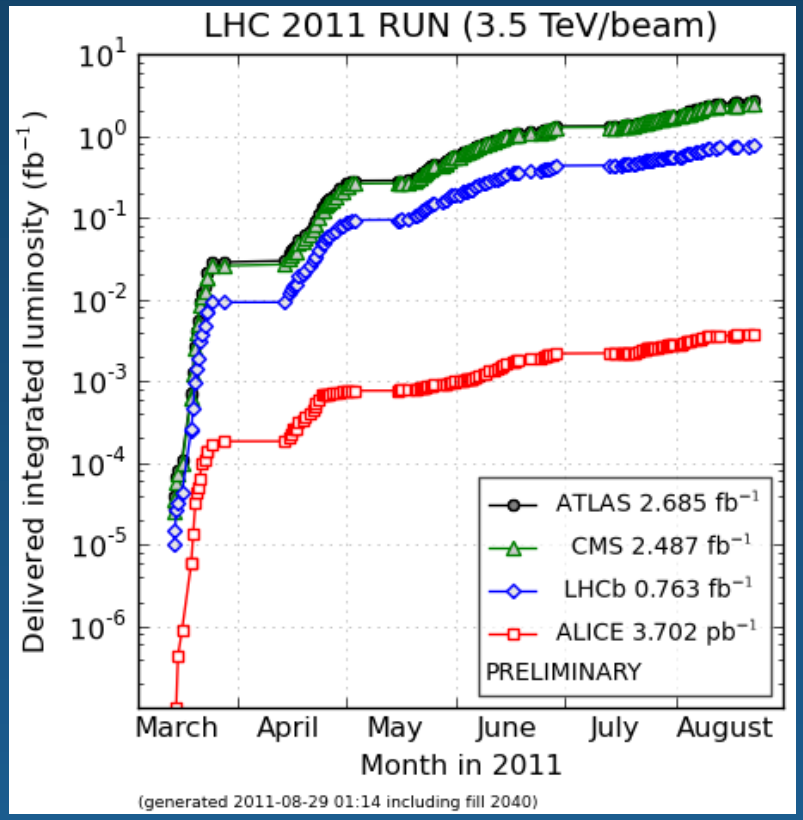
- *Raison d'être* of the Large Hadron Collider (LHC)



http://map.gsfc.nasa.gov/media/080998/index.html

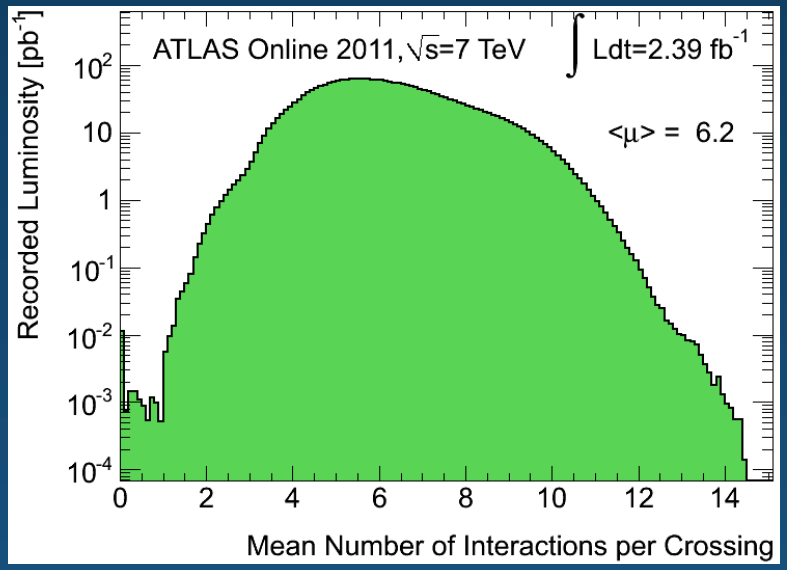
Large Hadron Collider (LHC)

- $\sqrt{s}$ = 7 TeV pp
- Outstanding 2011 Performance
  - ~ 2.4 × 10^{33} $cm^{-2}s^{-1}$ peak lumi
  - ~ 80 pb^{-1} / day
  - ~ 2.7 fb^{-1} delivered

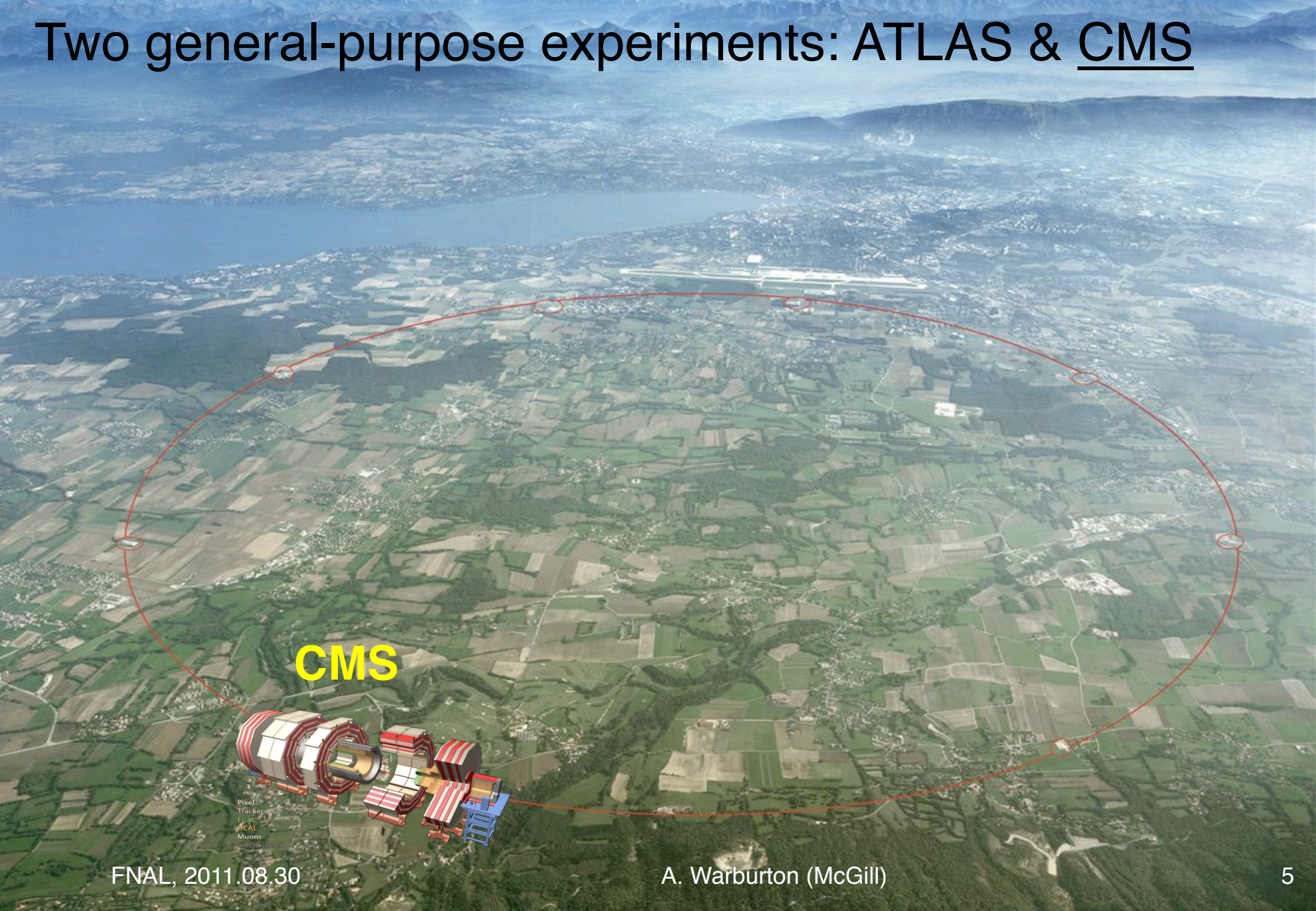


http://lpc.web.cern.ch/lpc/luminplots.htm

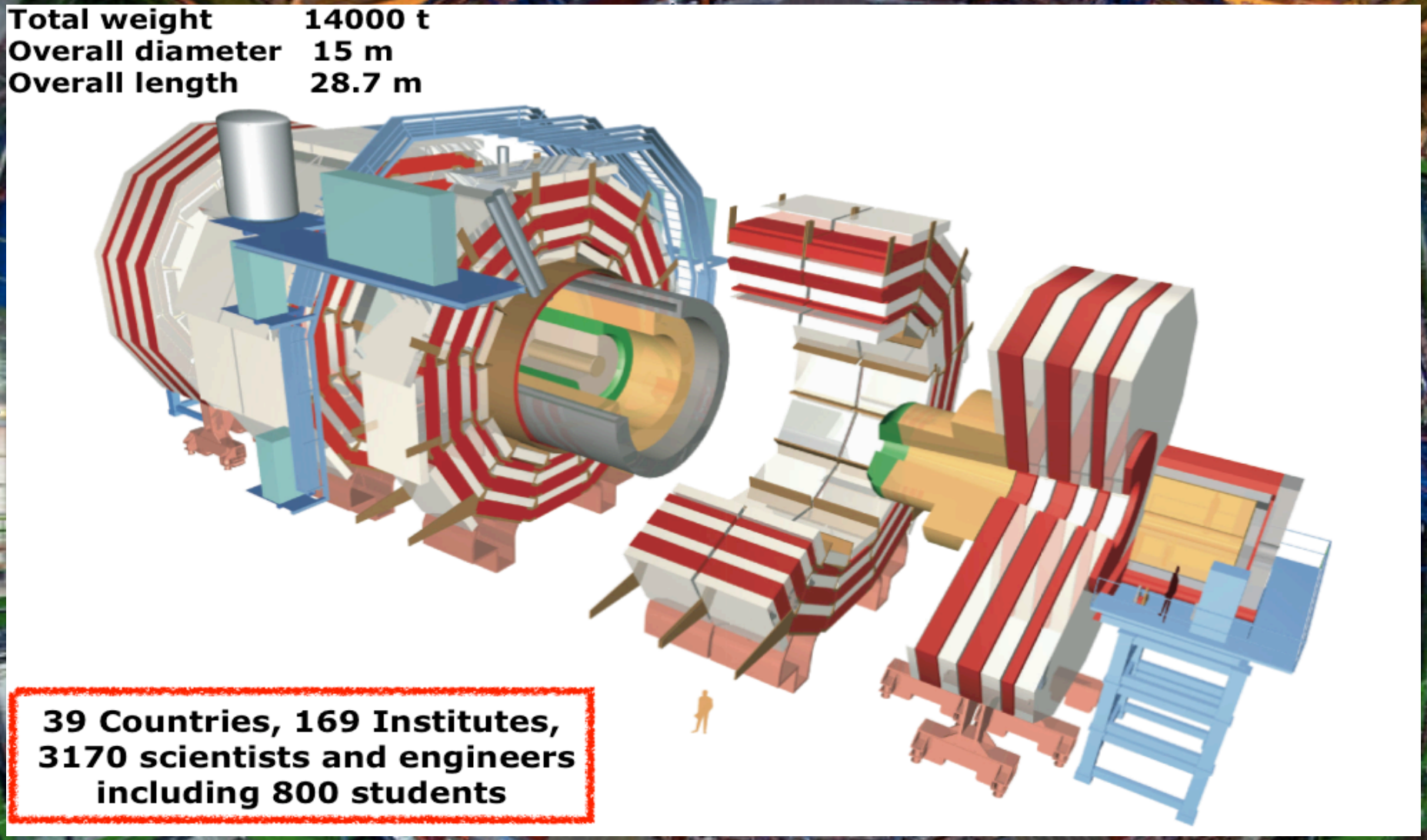
- Bunch spacing 50 ns
- ~ 6 pp collisions / crossing (avg.)



Two general-purpose experiments: ATLAS & CMS

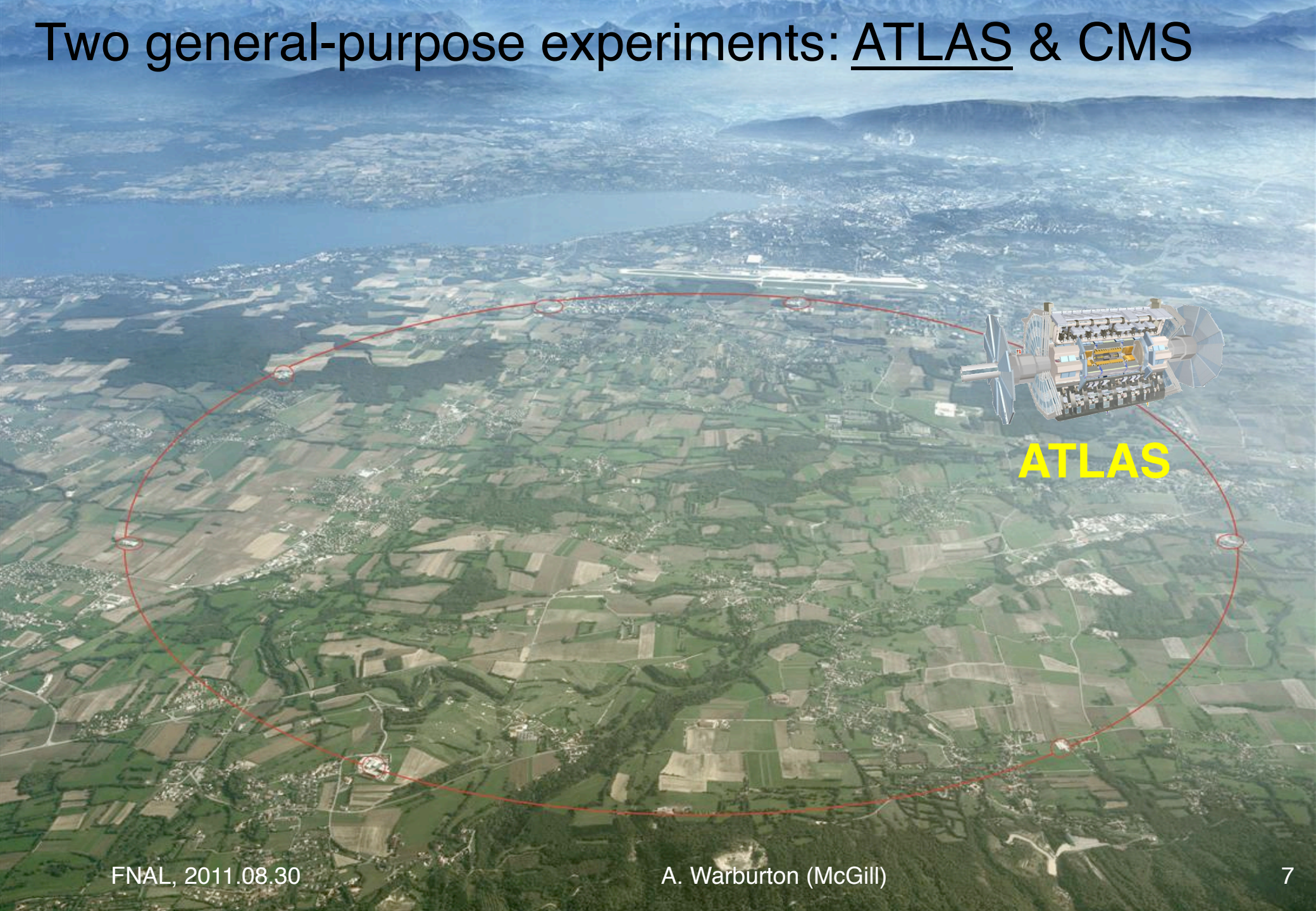


Two general-purpose experiments: ATLAS & CMS

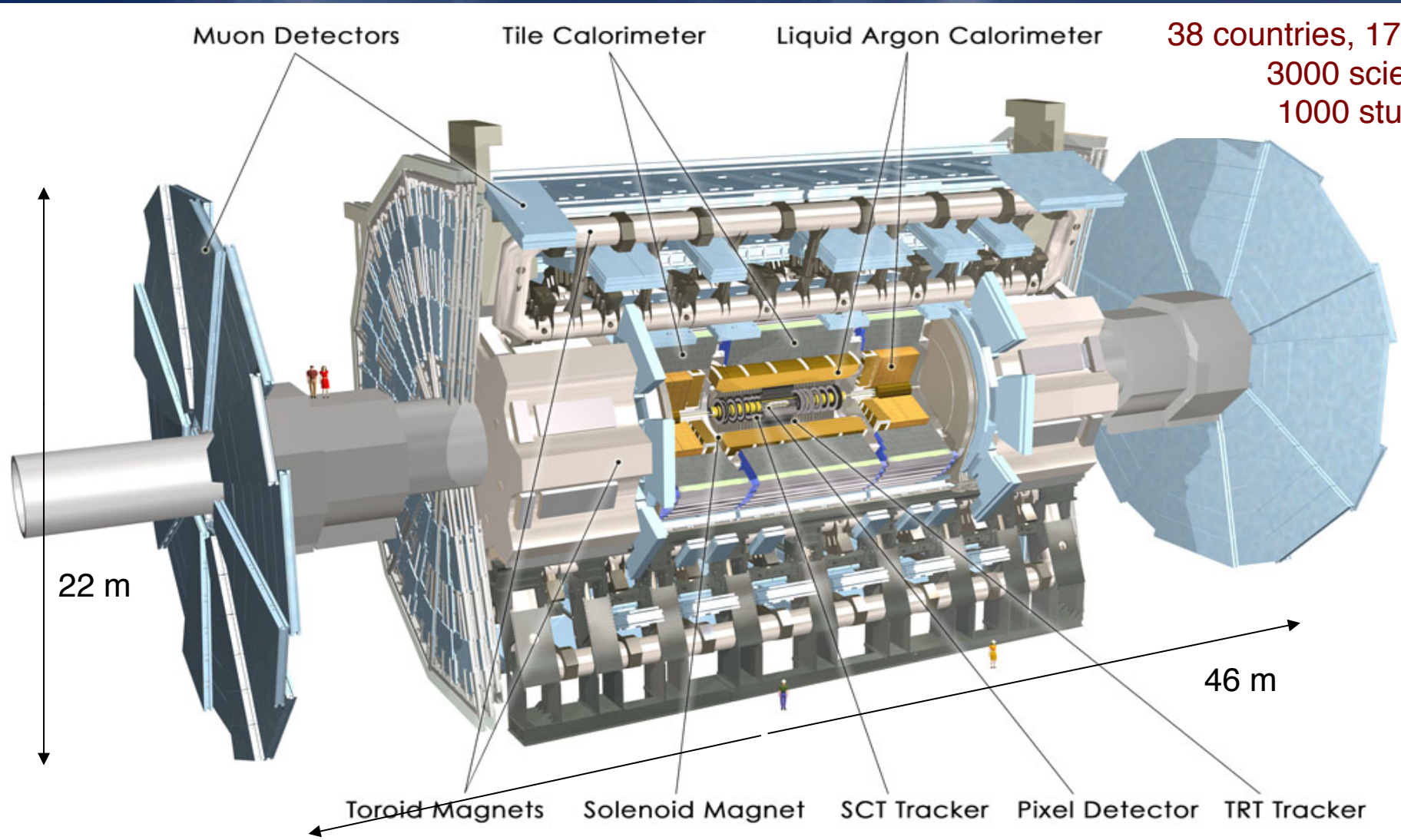


Emphasis on excellent resolution (energy, momentum, mass) of electrons, photons, muons

Two general-purpose experiments: ATLAS & CMS



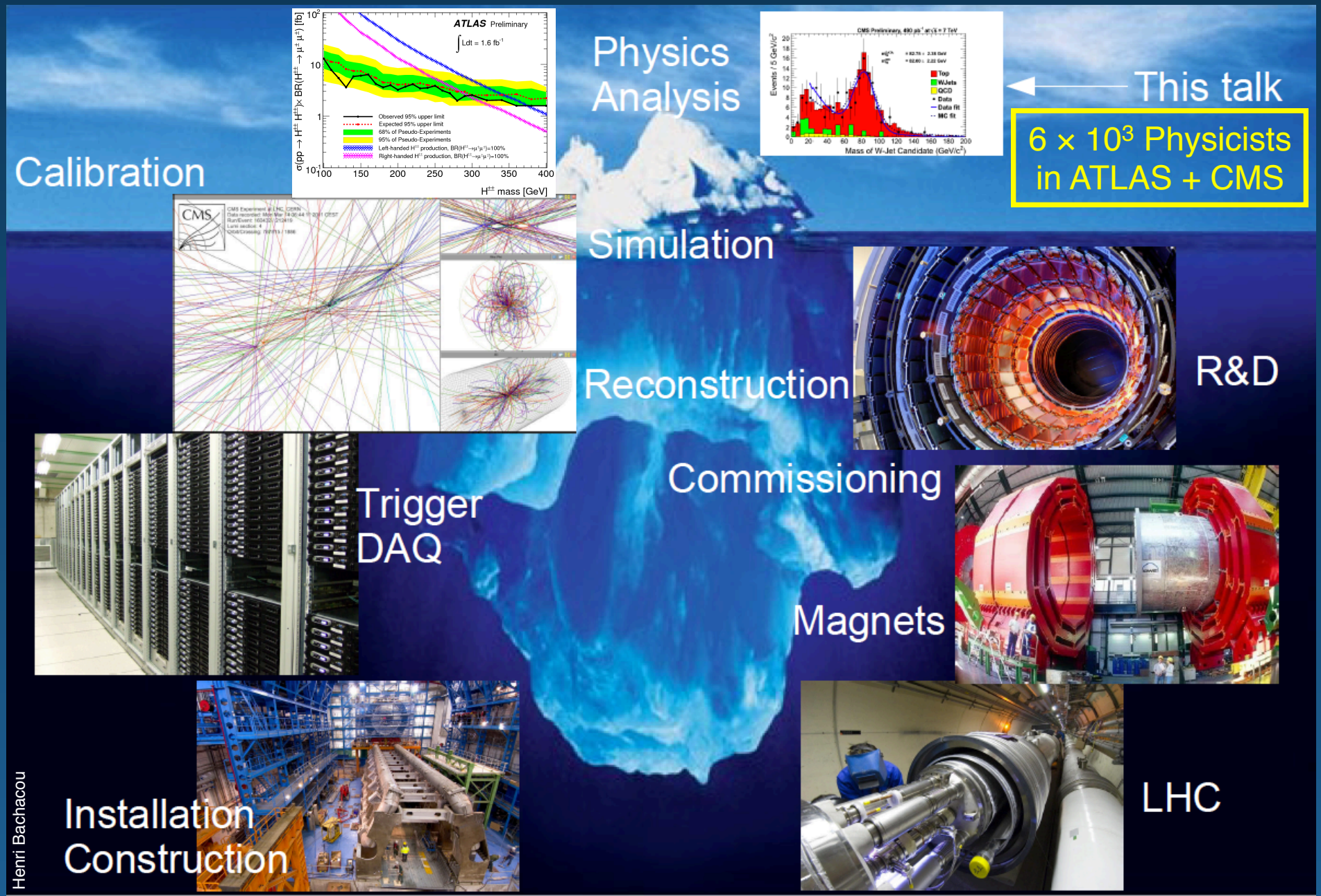
Two general-purpose experiments: ATLAS & CMS



38 countries, 174 institutions,
3000 scientists,
1000 students

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

Acknowledgments



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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)

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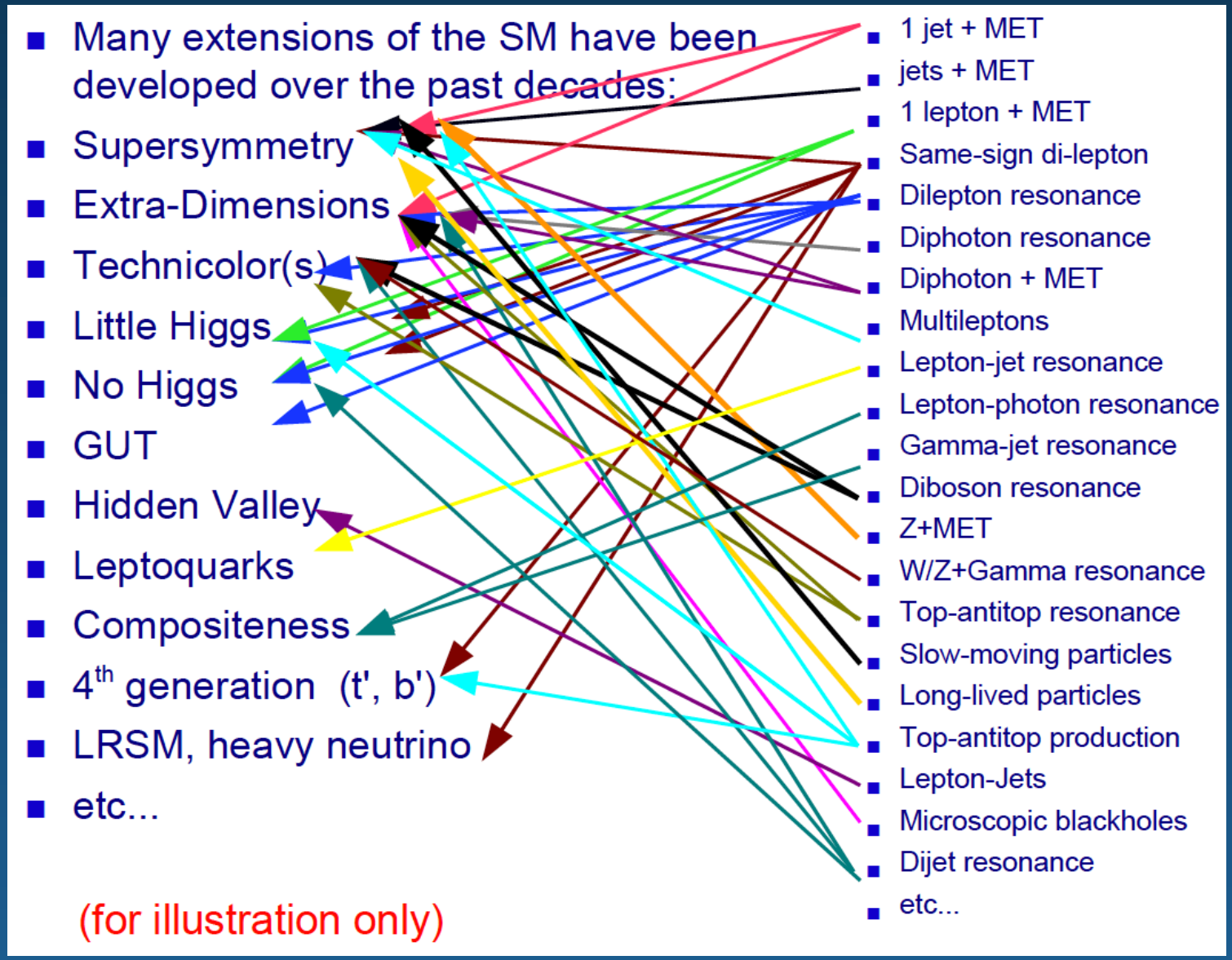
Long List of Models & Signatures Available



For Experimentalists:

- Complex 2D problem
- Signature approach:
  - Practical
  - Less model-dependent
- Important to seek as many signatures as possible

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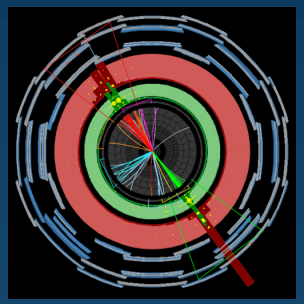
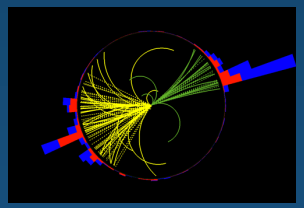
Selected Searches

Heavy Resonances



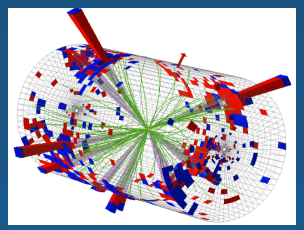
- Heavy gauge bosons
- Diboson ($\gamma\gamma$, WZ)
- Dijet
- Doubly charged Higgs

Quark Exotica



- $t\bar{t}$ resonances
- $t\bar{t}$ + MET (missing transverse energy)
- 4th quark generation

Strong Gravity

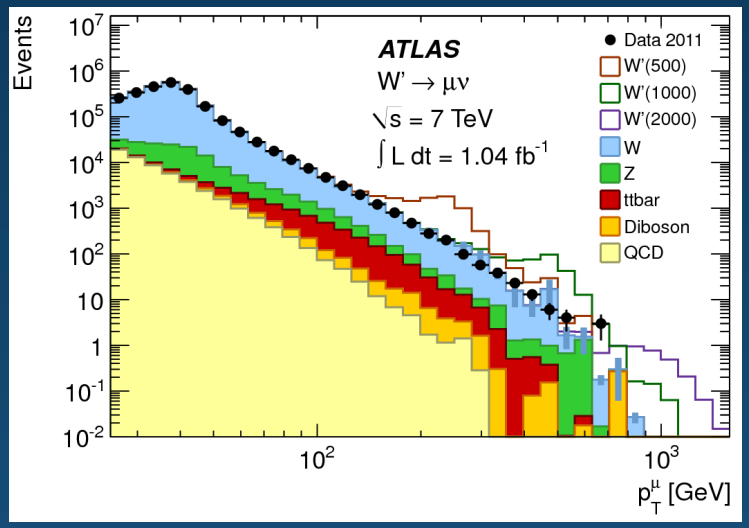


- Monojet
- Monophoton
- Dimuon/diphoton spectrum
- Black holes

This talk: results up to 1.6 fb^{-1}

Search for Heavy Resonances

arXiv:1108.1316



Predicted by several extensions to the SM

- GUT-inspired theories, Little Higgs → heavy gauge boson(s) Z' (W')
- Technicolor → narrow technihadrons
- Randall-Sundrum ED → Kaluza-Klein graviton

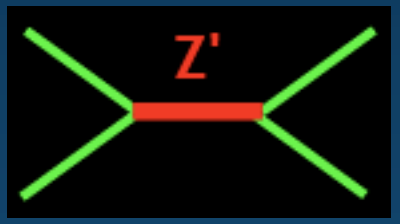
Experimental Challenges

- Very high momenta
- Need to understand detector resolutions, efficiencies; → dearth of data-driven control samples
- Confidence in alignments, Monte Carlo simulation

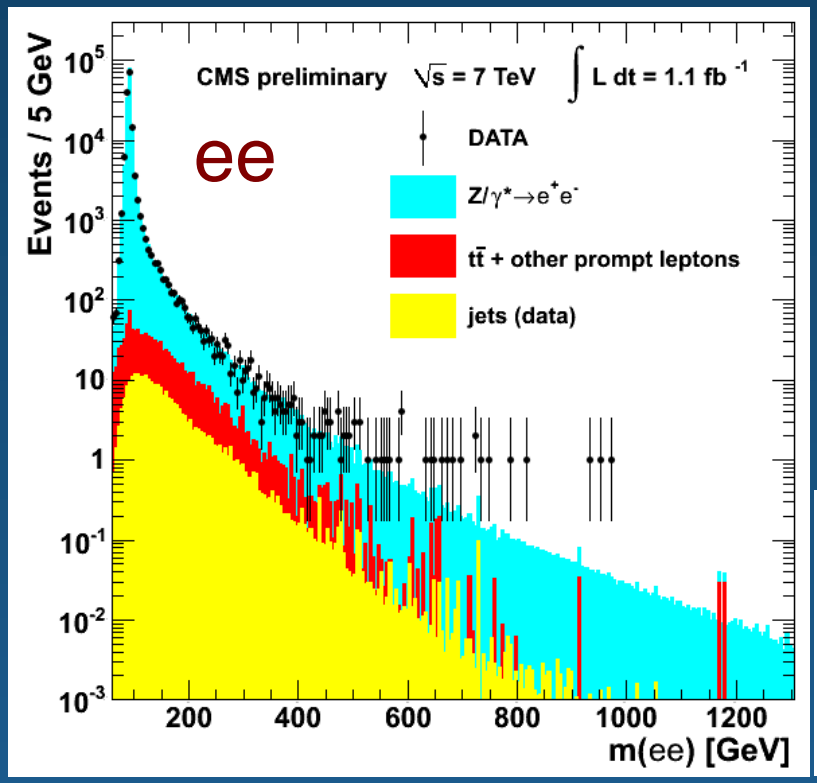
Lepton momenta approaching 1 TeV!

Neutral Heavy Resonance: e^+e^- & $\mu^+\mu^-$ Channels

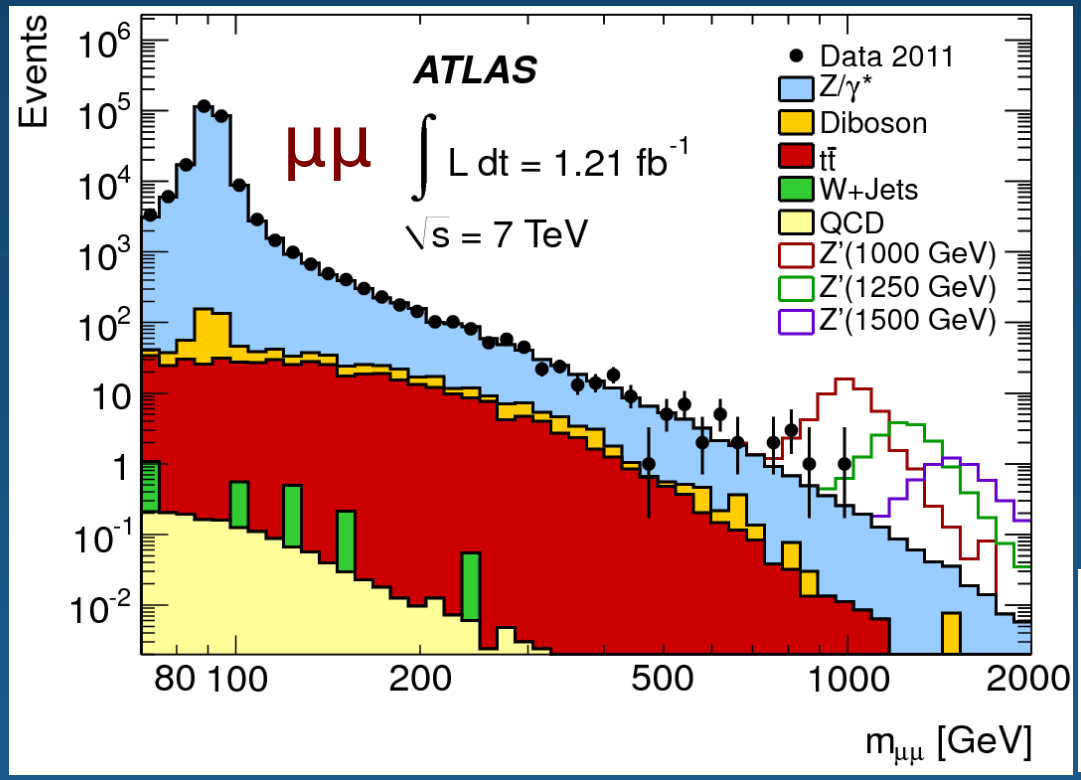
- Randall-Sundrum Kaluza-Klein graviton excitation
- GUT-inspired heavy Z' boson
- Technihadron



Drell-Yan Z/γ* bkgnd dominates both channels

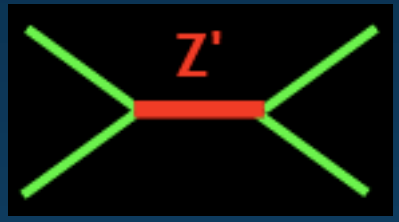


CMS PAS EXO-11-019



arXiv:1108.1582

Neutral Heavy Resonance: Dilepton

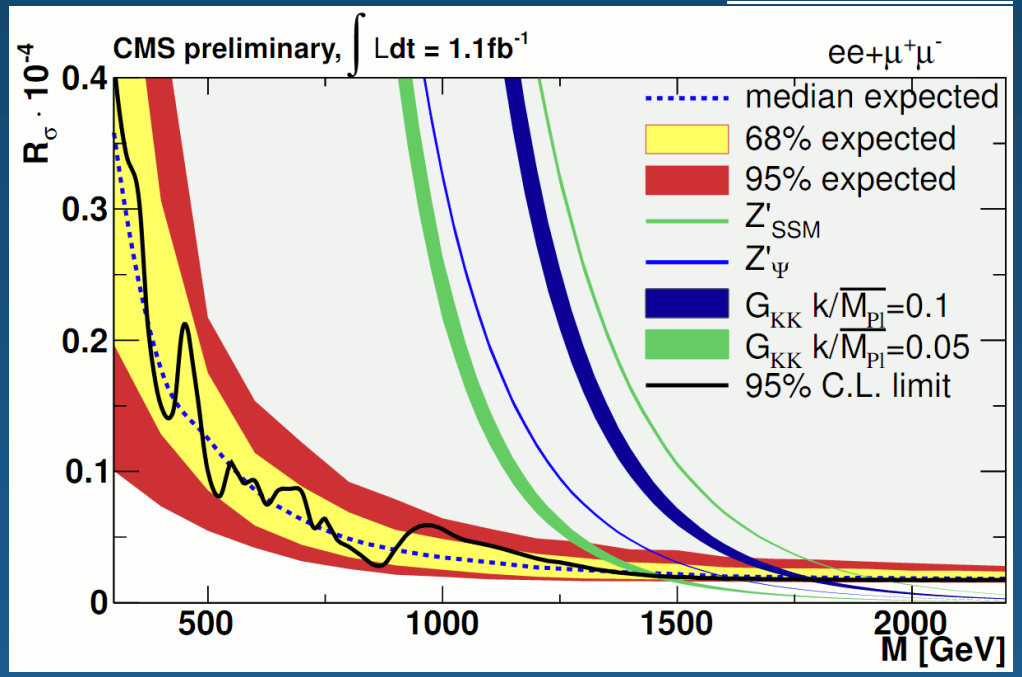


- Randall-Sundrum Kaluza-Klein graviton excitation
- GUT-inspired heavy Z' boson
- Technihadron

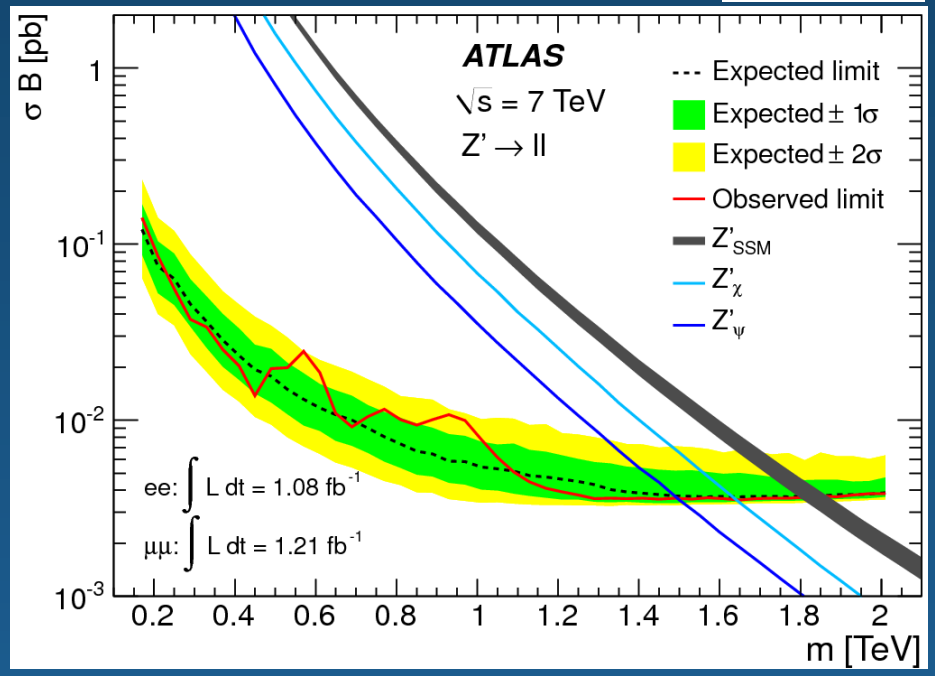
Sequential SM (SSM):
m(Z') > 1.9 TeV at 95% CL

RS KK graviton ($k/\bar{M}_{Pl} = 0.1$)
$m(G_{KK})$ > 1.8 TeV at 95% CL

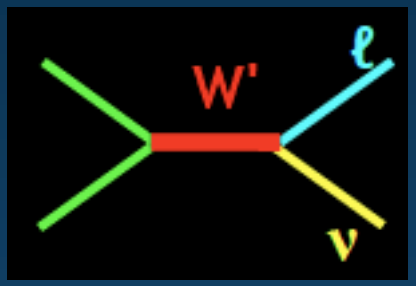
CMS PAS EXO-11-019



arXiv:1108.1582



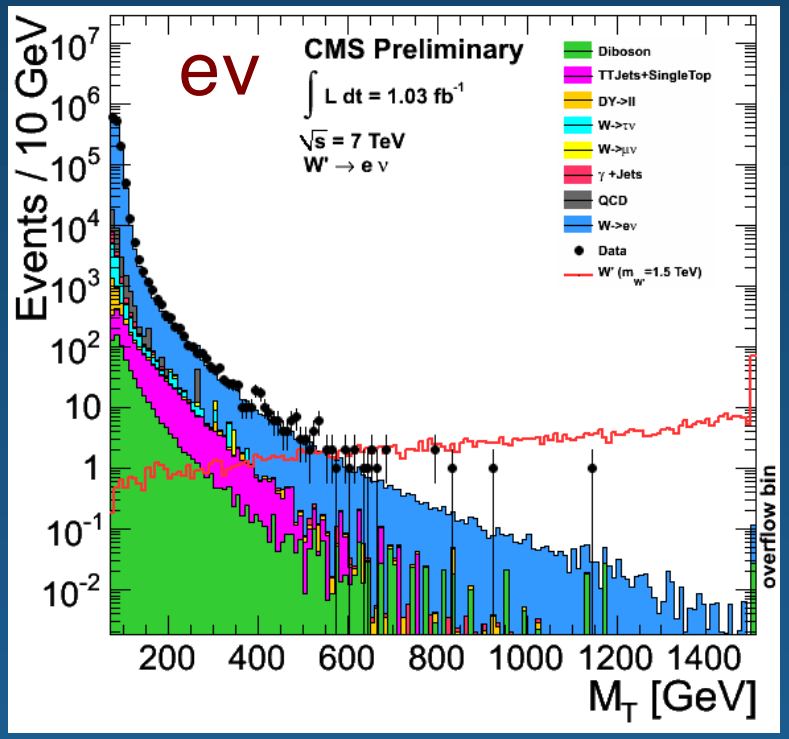
Charged Heavy Resonance: W' ➔ (e,μ)ν



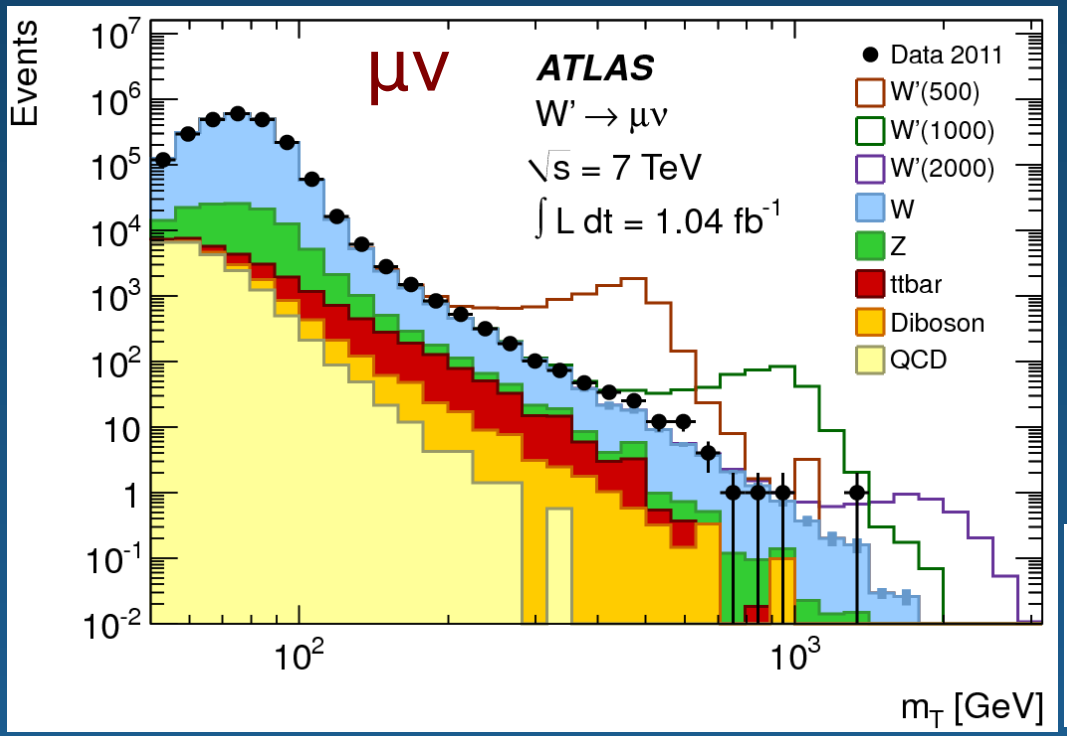
- Heavy charged gauge boson
- Technirho, Little Higgs
- 1 <u>electron or muon</u> & missing E_T
- Seek Jacobian peak in m_T distribution

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

SM W high-mass tail background dominates both channels

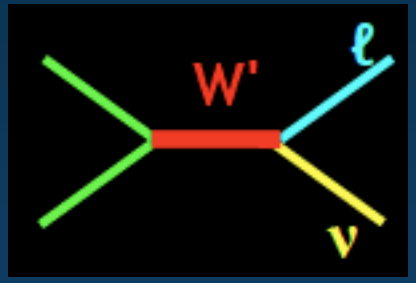


CMS PAS EXO-11-024



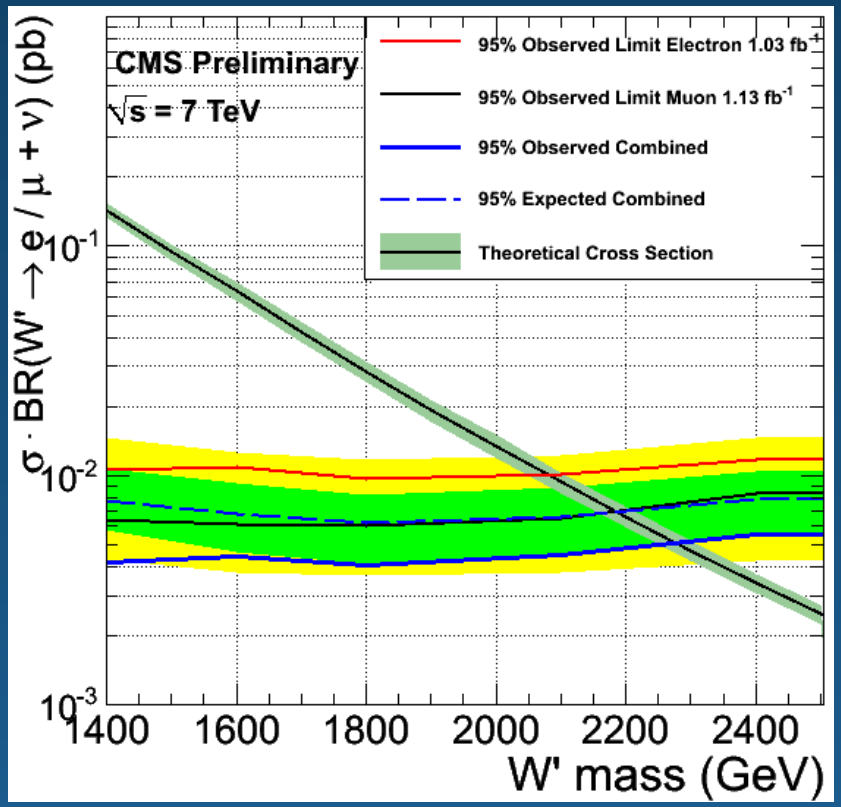
arXiv:1108.1316

Charged Heavy Resonance: W'

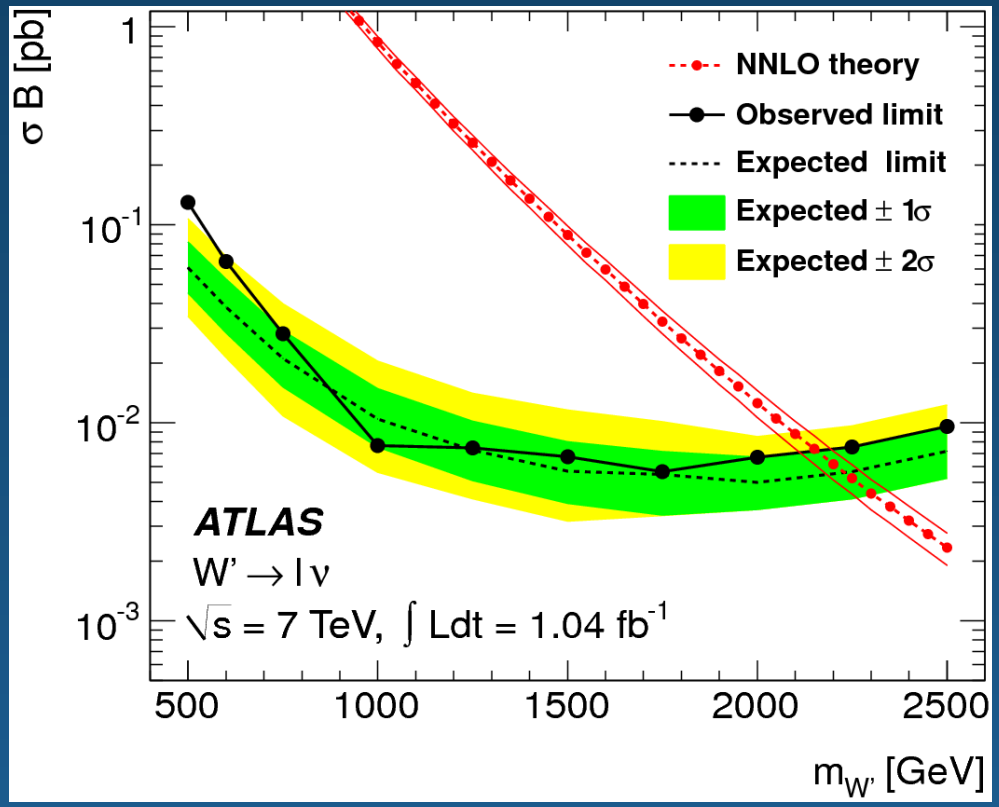


Sequential SM W': excluded up to 2.27 TeV at 95% CL

CMS PAS EXO-11-024



arXiv:1108.1316



Search for Heavy Resonance: WZ

W' or $\rho_{TC} \rightarrow$ WZ

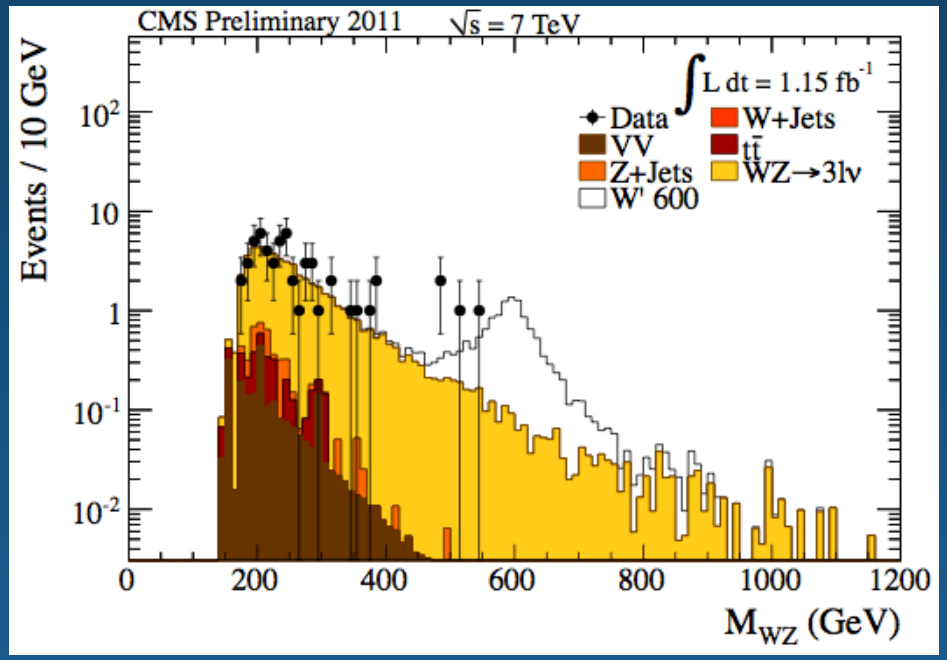
All-leptonic channel:

$W \rightarrow l^{\pm}\nu$ and $Z \rightarrow l^{+}l^{-}$

Reconstruct m(WZ) by constraining $m(l^{\pm}\nu)$ to m(W)

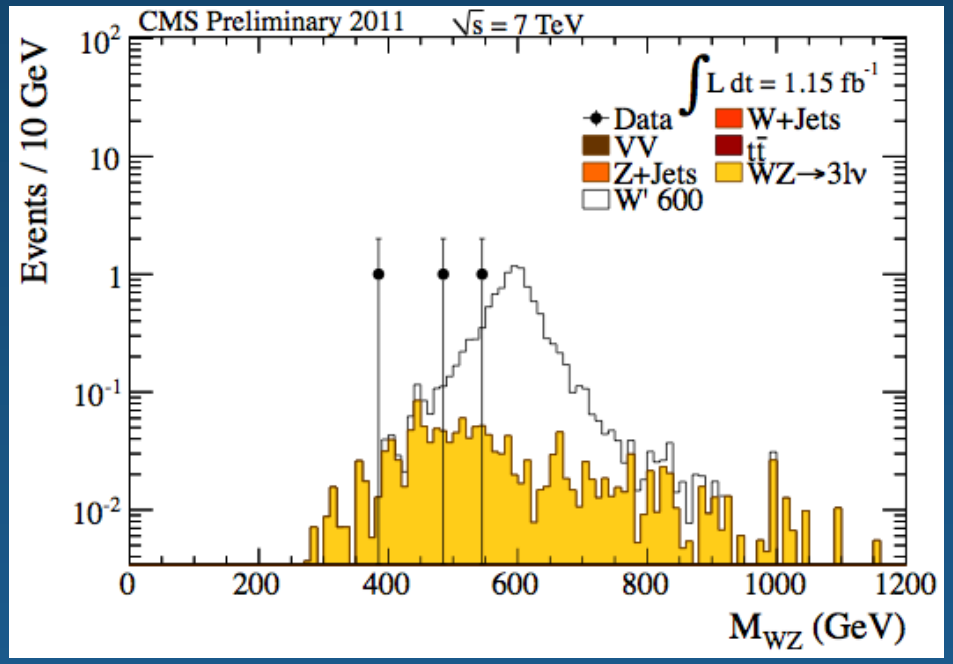
SM WZ → 3lν background dominates

CMS PAS EXO-11-041



Pre-selection

H_T cut →



Final selection

Search for Heavy Resonance: WZ

W' or $\rho_{TC} \rightarrow$ WZ

All-leptonic channel:

$W \rightarrow l^{\pm}\nu$ and $Z \rightarrow l^{+}l^{-}$

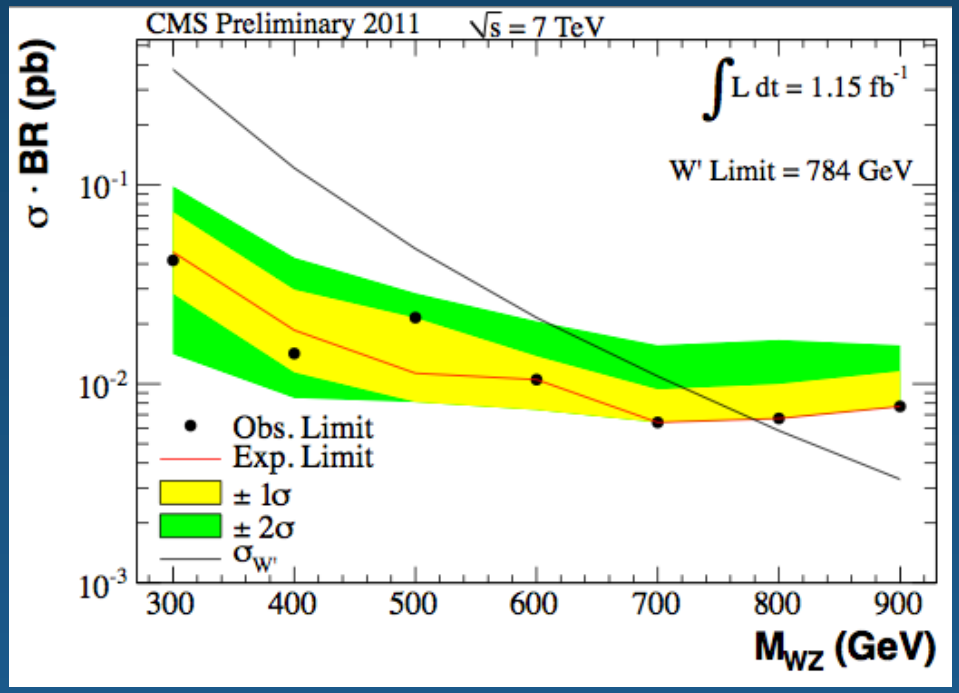
Sequential SM:

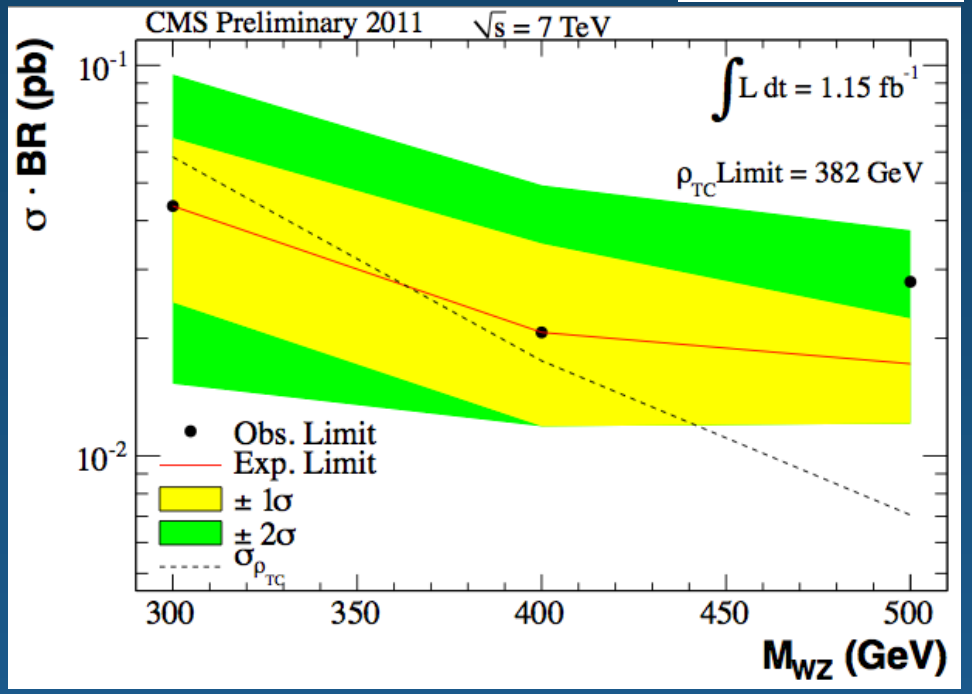
M(W') > 784 GeV at 95% CL

Technicolor:

ρ_{TC} > 382 GeV at 95% CL

CMS PAS EXO-11-041





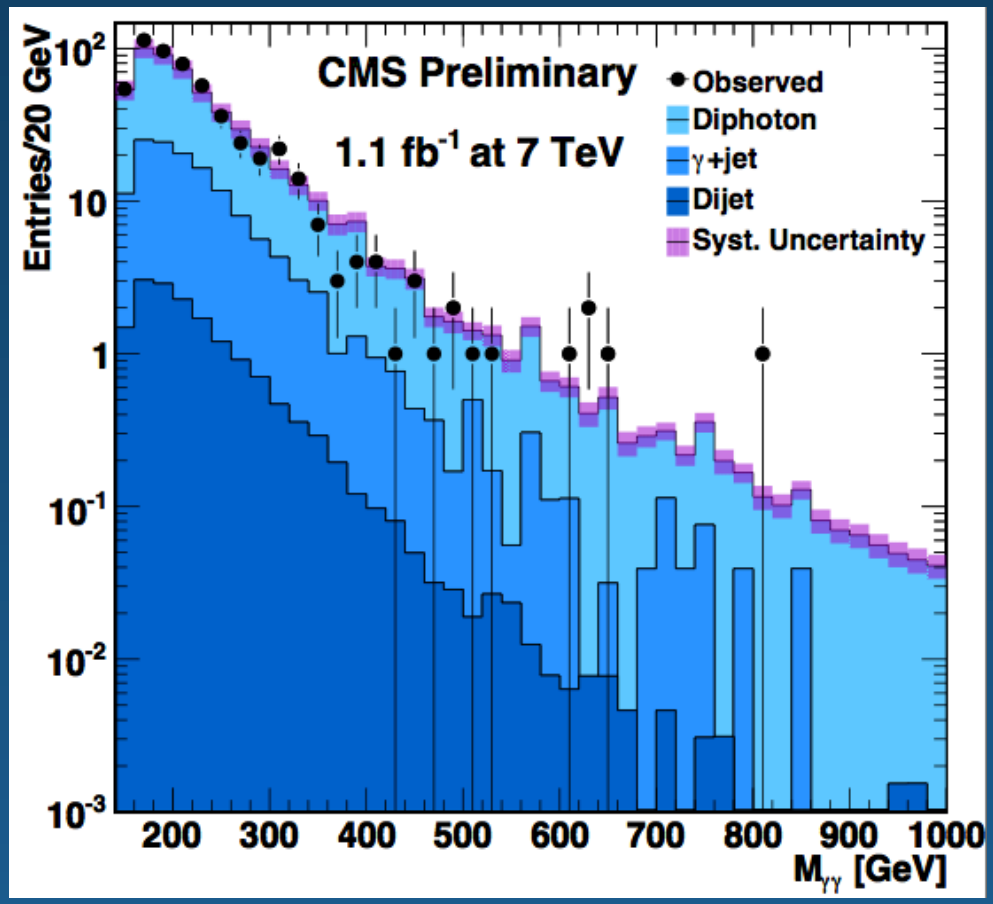
Search for Heavy Resonance: diphoton channel

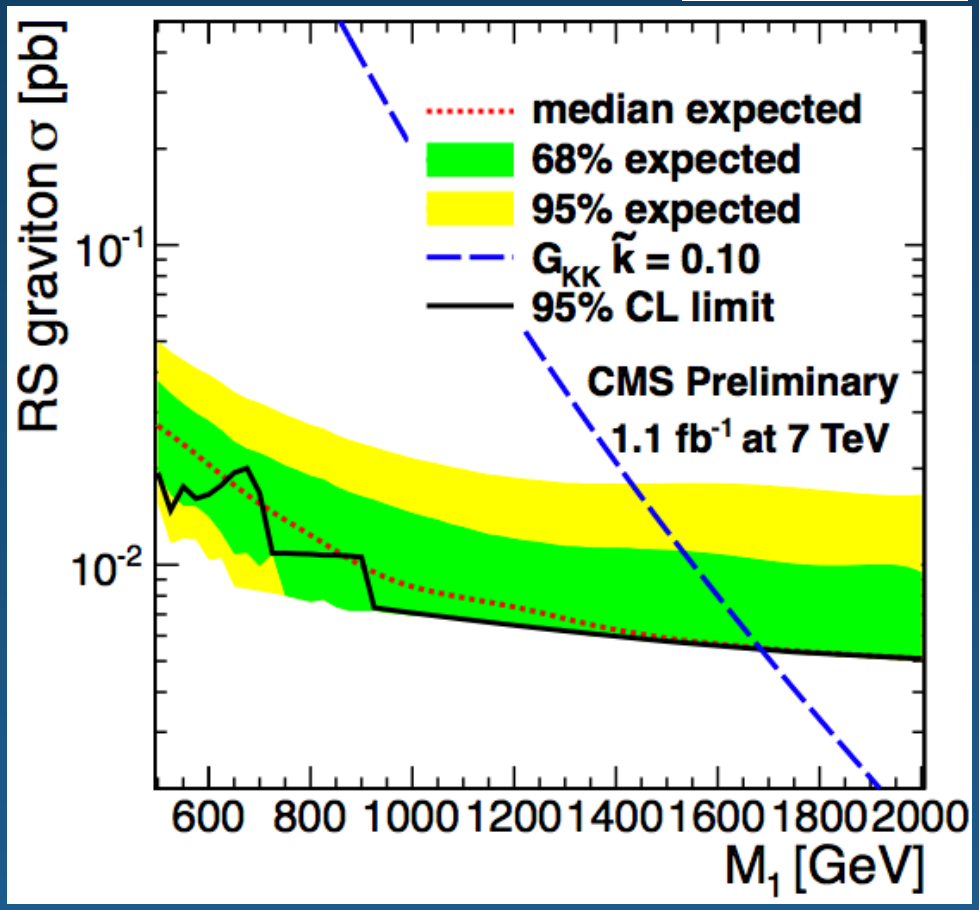
Randall-Sundrum Kaluza-Klein (KK) graviton excitation search

RS graviton ($k/M_{Pl} = 0.1$): $m(G_{KK}) > 1.7$ TeV at 95% CL

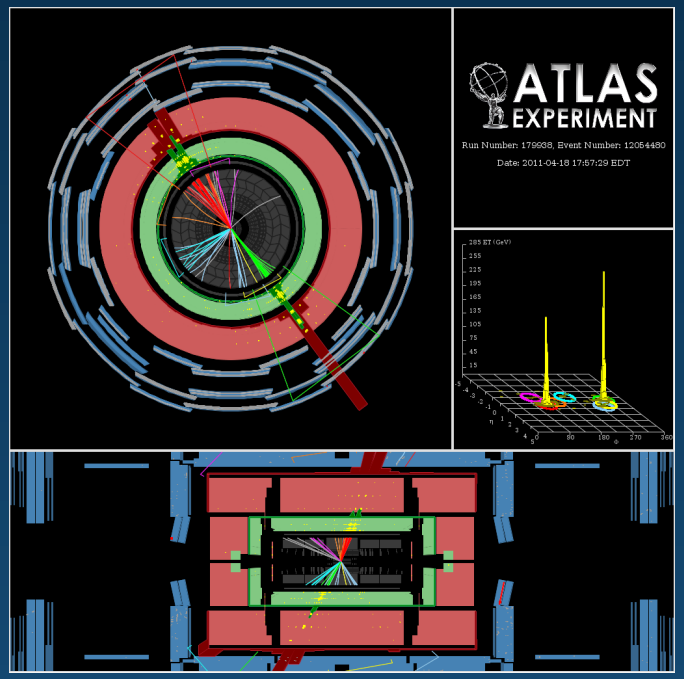
Preferential decay to photons (in lieu of fermions) on spin grounds

CMS PAS EXO-11-038





Search for Dijet Resonances

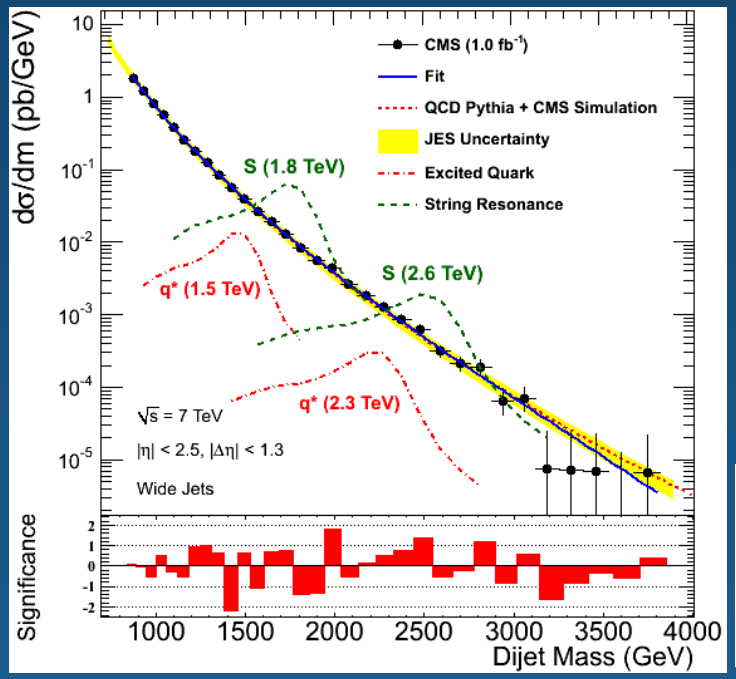


- Well-suited for early searches at hadron colliders
- q*, axigluon, colour-octet scalar, string resonance…
- Seek resonance above phenomenological fit to data

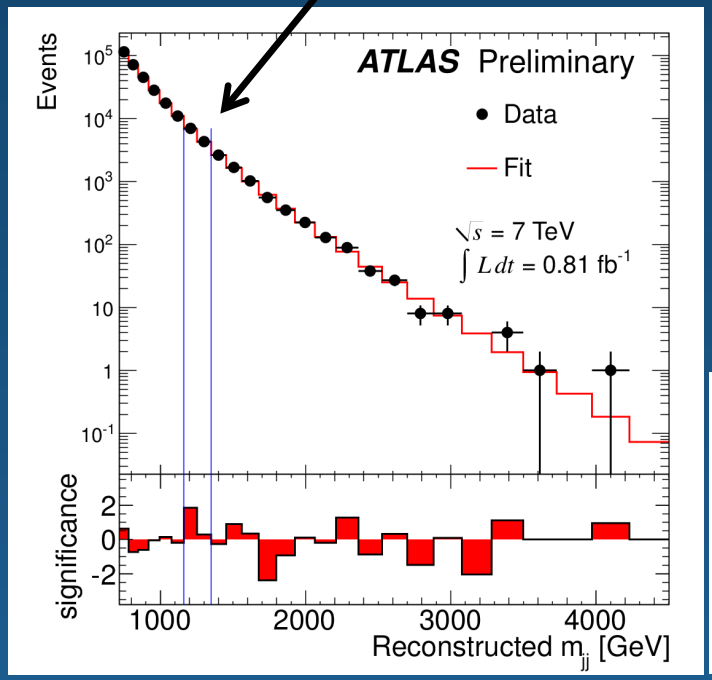
← m(jet-jet) = 4000 GeV Missing E_T = 100 GeV

↘

Most discrepant region



arXiv:1107.4771



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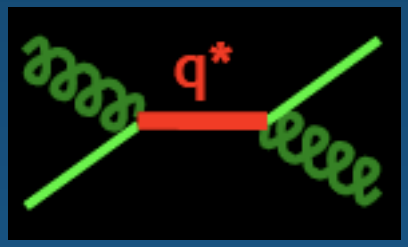
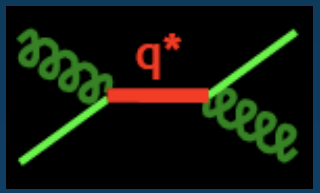


Probing for quark structure beyond 4 TeV

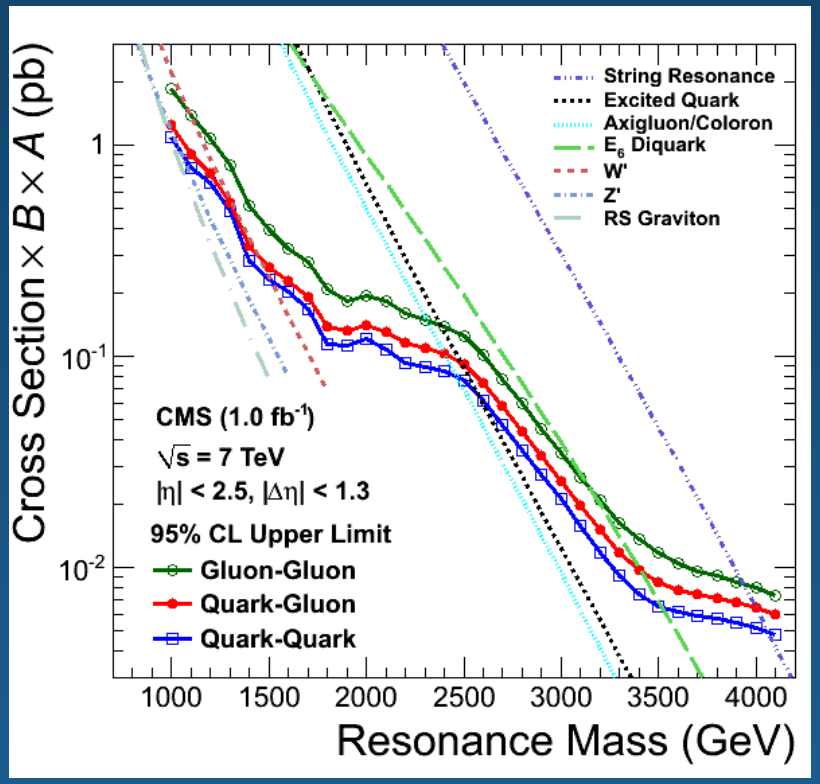
Search for Dijet Resonances

Model CMS arXiv.1107.4771	Excluded Mass (TeV) Observed	Expected
String Resonances	4.00	3.90
E_6 Diquarks	3.52	3.28
Excited Quarks	2.49	2.68
Axigluons/Colorons	2.47	2.66
W′ Bosons	1.51	1.40

Model ATL-CONF-2011-095	95% CL Limits (TeV) Expected	Observed
Excited Quark q^*	2.77	2.91
Axigluon	3.02	3.21
Color Octet Scalar	1.71	1.91

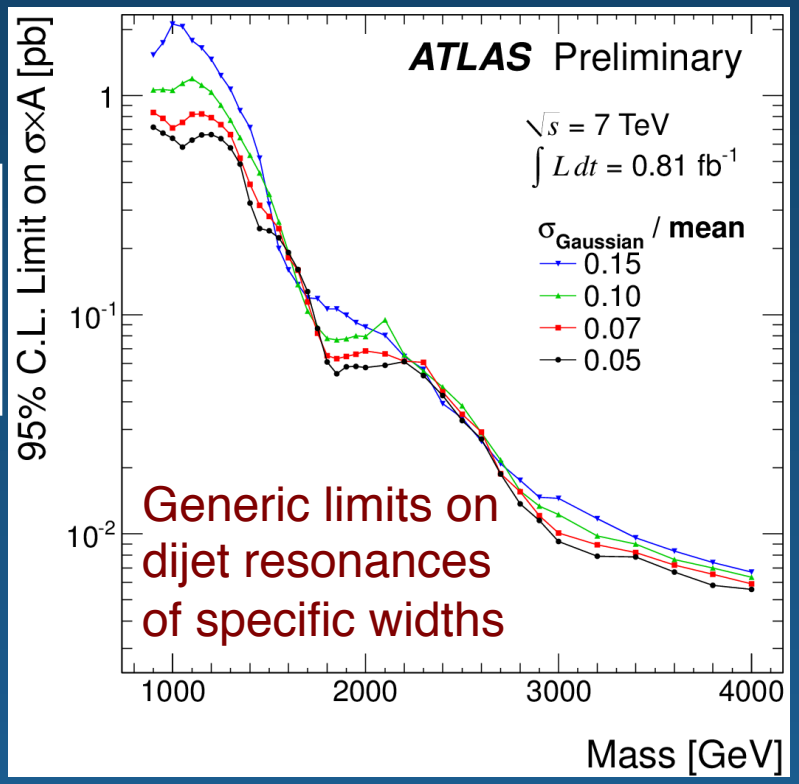


Also setting model-independent limits:



arXiv:1107.4771

Easily adaptable to other New Physics models

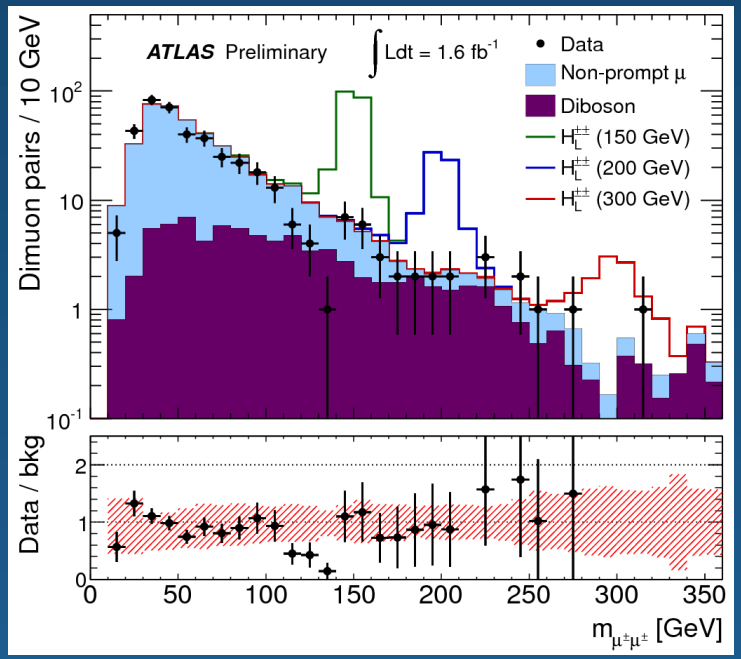


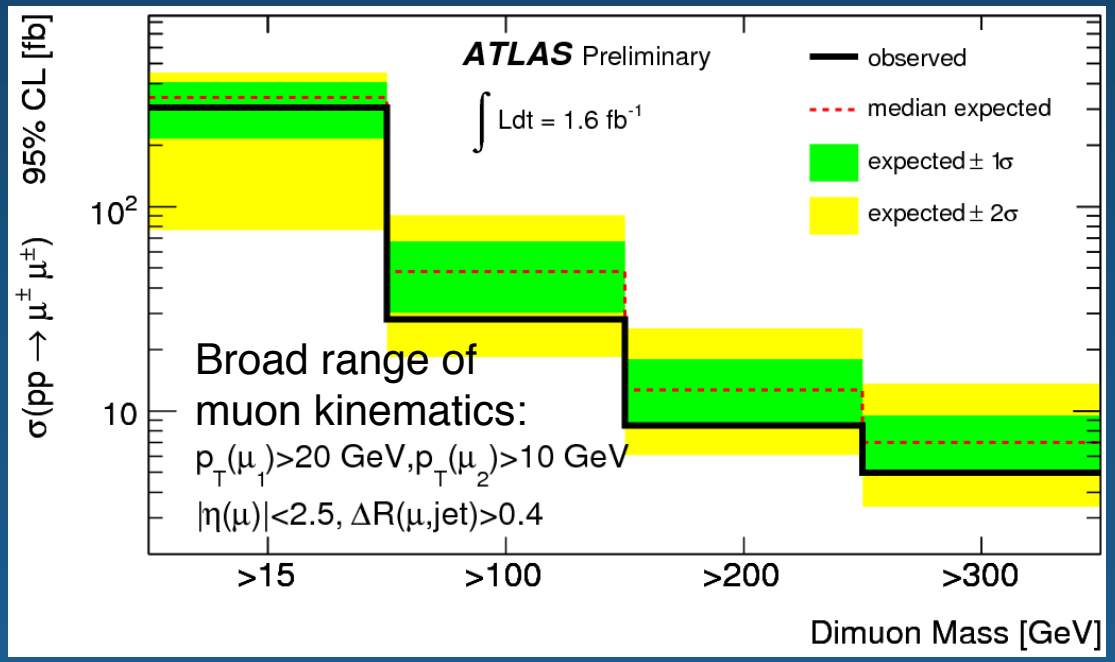
ATLAS-CONF-2011-095

Inclusive Search: Same-Sign Prompt Dimuon

- Predicted by many models
- Very clean signature; little to lose by being inclusive
- Inclusive, model-independent search:
  - Fiducial cross-section limit as function of m(μ±μ±)

Mass range [GeV]	95% C.L. limit on dimuon pair σ [fb]	
	expected	observed
$m_{\mu\mu} > 15$ GeV	341^{+67}_{-125}	304
$m_{\mu\mu} > 100$ GeV	48^{+20}_{-18}	28
$m_{\mu\mu} > 200$ GeV	$12.6^{+5.3}_{-4.2}$	8.5
$m_{\mu\mu} > 300$ GeV	$7.0^{+2.5}_{-2.0}$	5.0





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Heavy Resonance Search: Same-Sign Dilepton

Extend inclusive search →

Doubly charged Higgs search

- Based on same analysis as inclusive search
- Window 10% around Higgs mass

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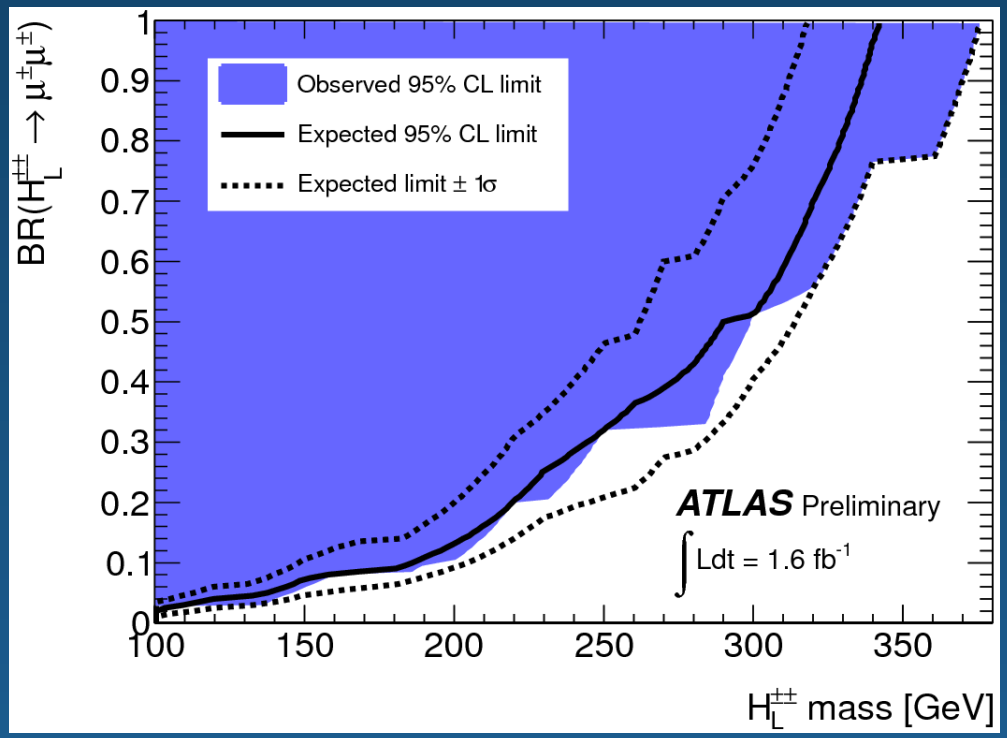
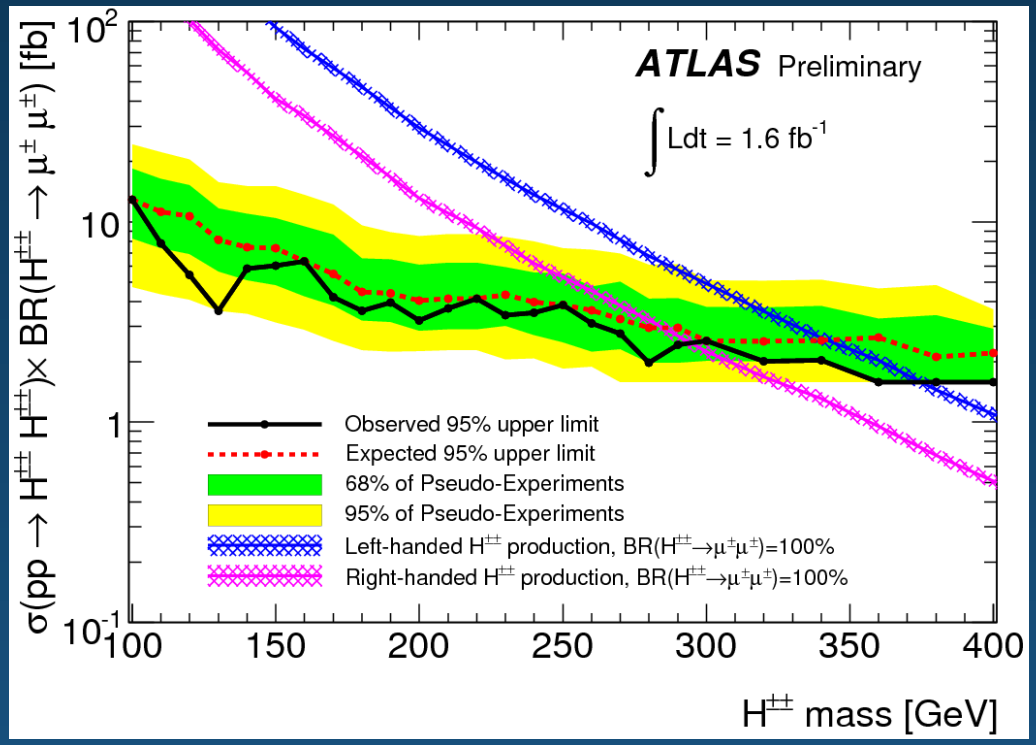


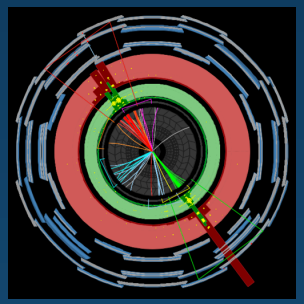


Assuming BR($\mu^+\mu^-$) = 100%:

- $m(H_L) > 375$ GeV (exp. 342 GeV) at 95% CL
- $m(H_R) > 295$ GeV (exp. 286 GeV) at 95% CL

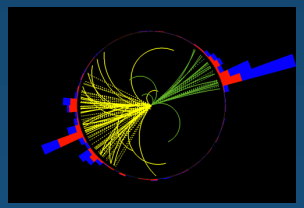
Selected Searches

Heavy Resonances



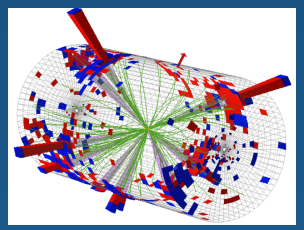
- Heavy gauge bosons
- Diboson ($\gamma\gamma$, WZ)
- Dijet
- Doubly charged Higgs

Quark Exotica



- $t\bar{t}$ resonances
- $t\bar{t}$ + MET (missing transverse energy)
- 4th quark generation

Strong Gravity

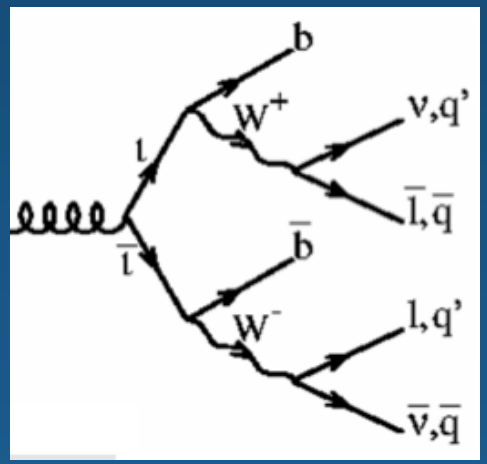


- Monojet
- Monophoton
- Dimuon/diphoton spectrum
- Black holes

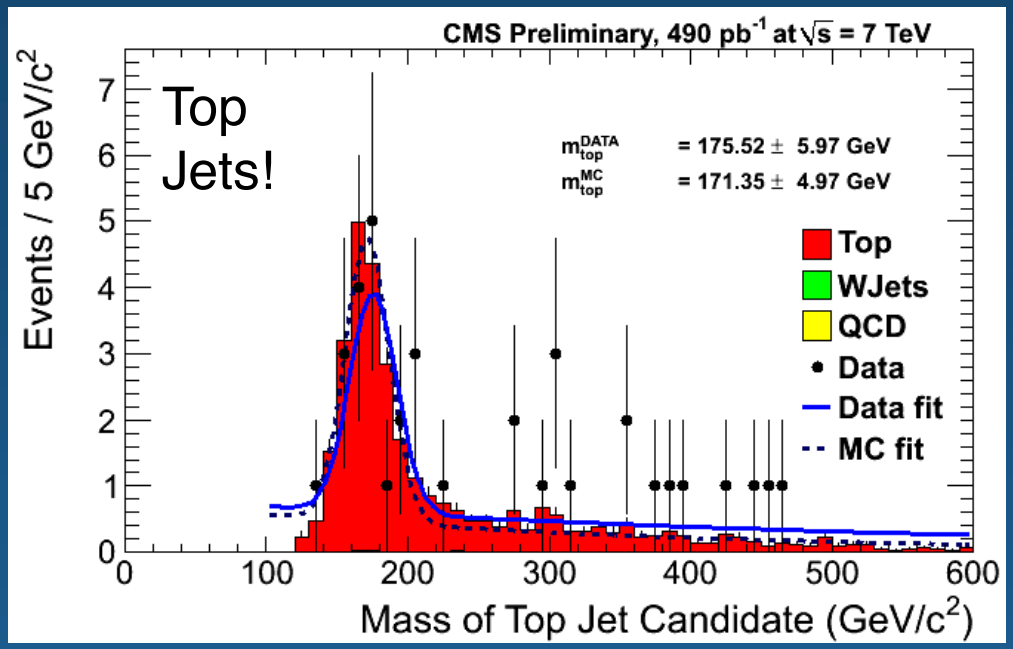
Top-Antitop Pair Searches

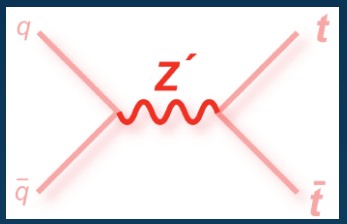
- Topic of great experimental and theoretical interest
- 3rd generation may play a special role in EWSB
- Reaching the TeV scale; new experimental techniques demanded
- Now entering era of boosted top and top-tagging! (à la boosted *b*-quarks in the 1990s)
- (See also Clemens Lange talk tomorrow)

$t\bar{t}$ Decay Modes



CMS PAS EXO-11-006

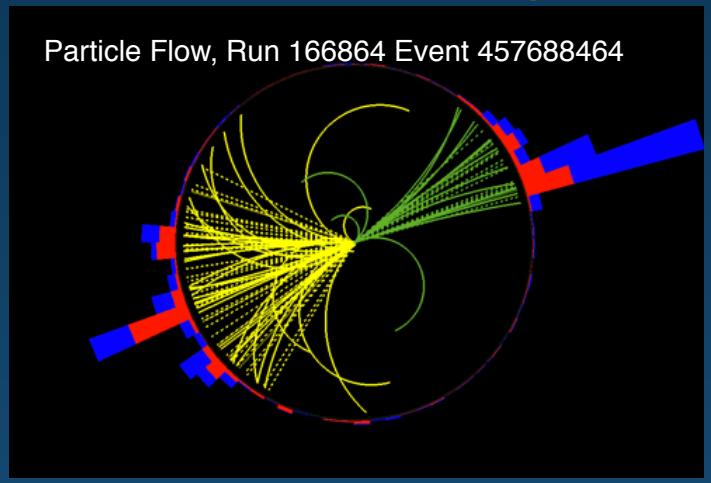


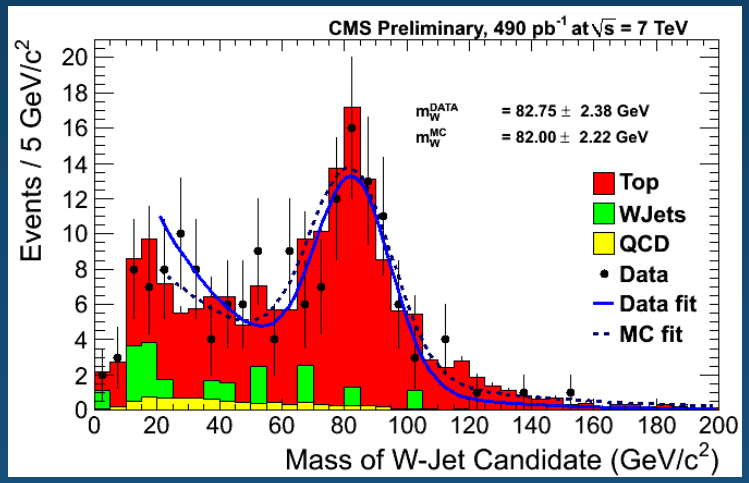


$t\bar{t}$ Resonance Searches: Jet "Top"-ology

Boosted All-Hadronic Final State

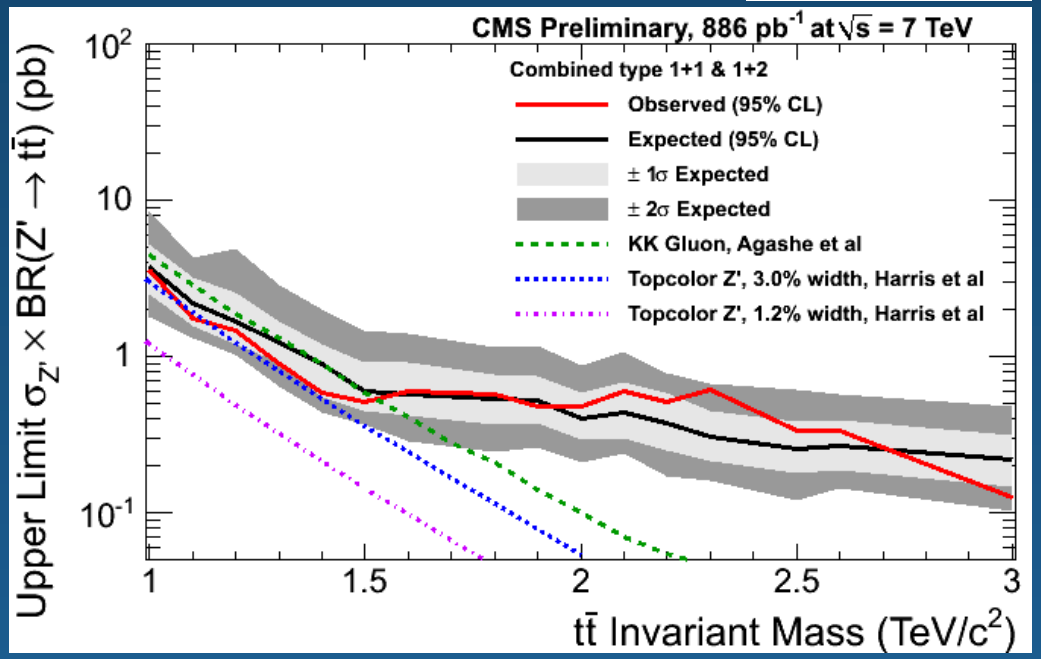
Seek RS Kaluza-Klein gluons





W subjet candidates

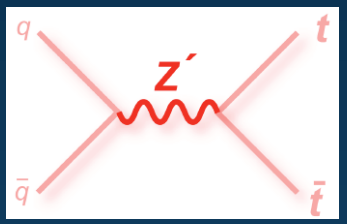
CMS PAS EXO-11-006



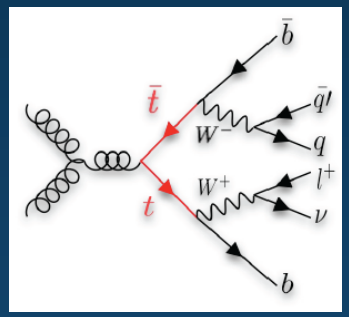
Both W bosons from top decay hadronically (BR ~ 46%)

Model-independent $\sigma_{Z'}$ limits →

$m(g_{KK}) > 1.5$ TeV at 95% CL



Top-Antitop Resonance Searches



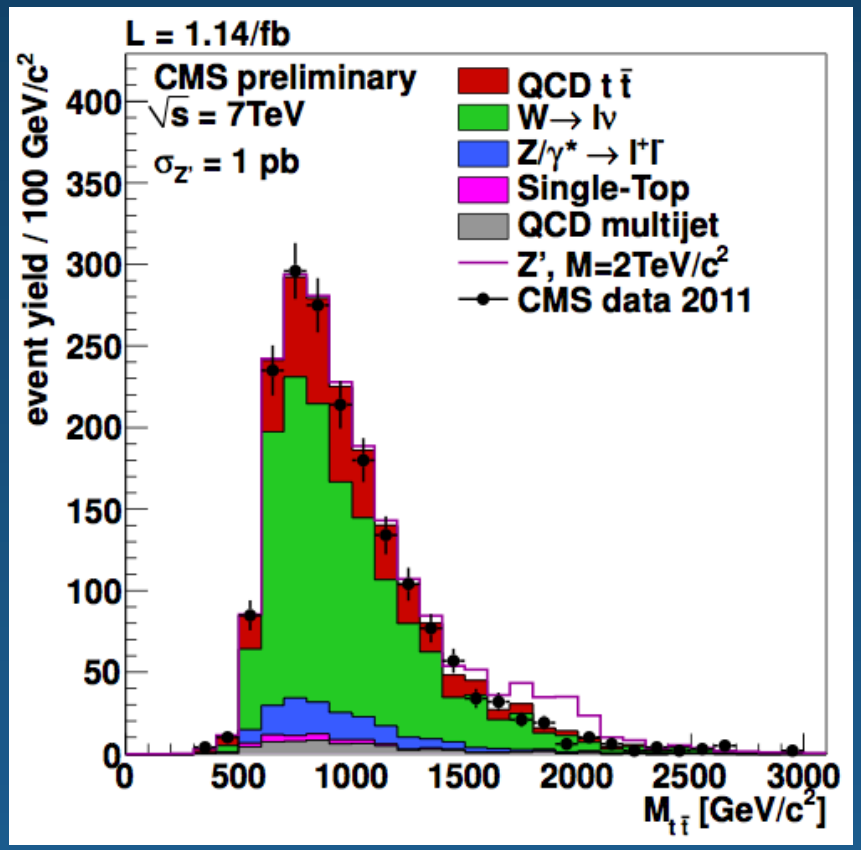
muon + jets signature

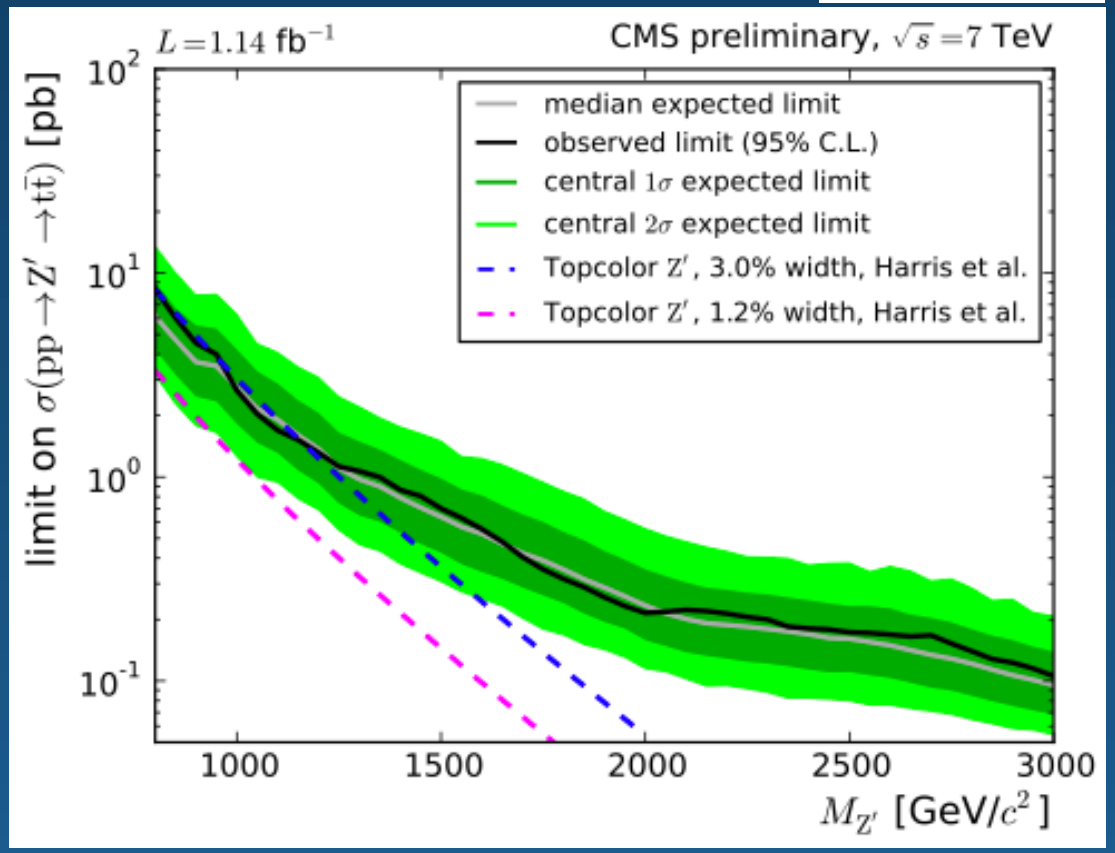
Seek Z' (narrow heavy resonances)

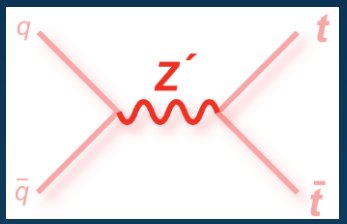
Leptophobic Top-Color Z'

- Sub-picobarn limits
- m(Z') > 1.35 TeV at 95% CL

CMS PAS EXO-11-055





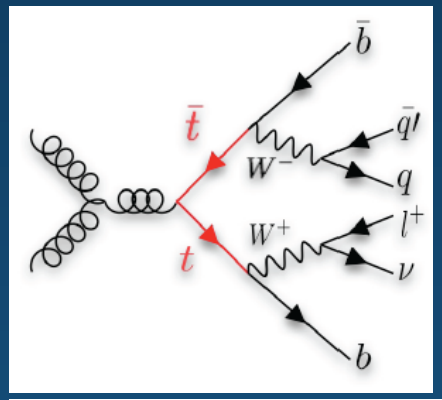


Top-Antitop Resonance Searches

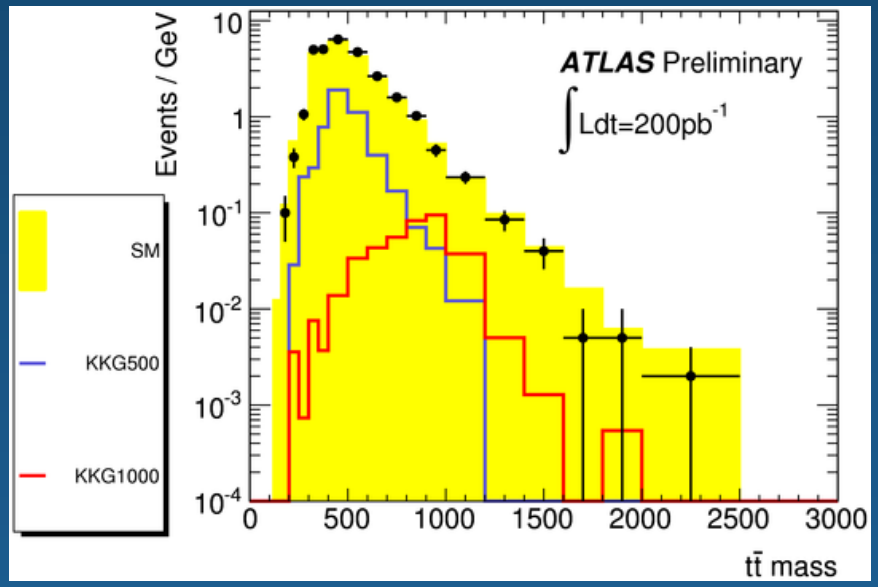
ATLAS-CONF-2011-087

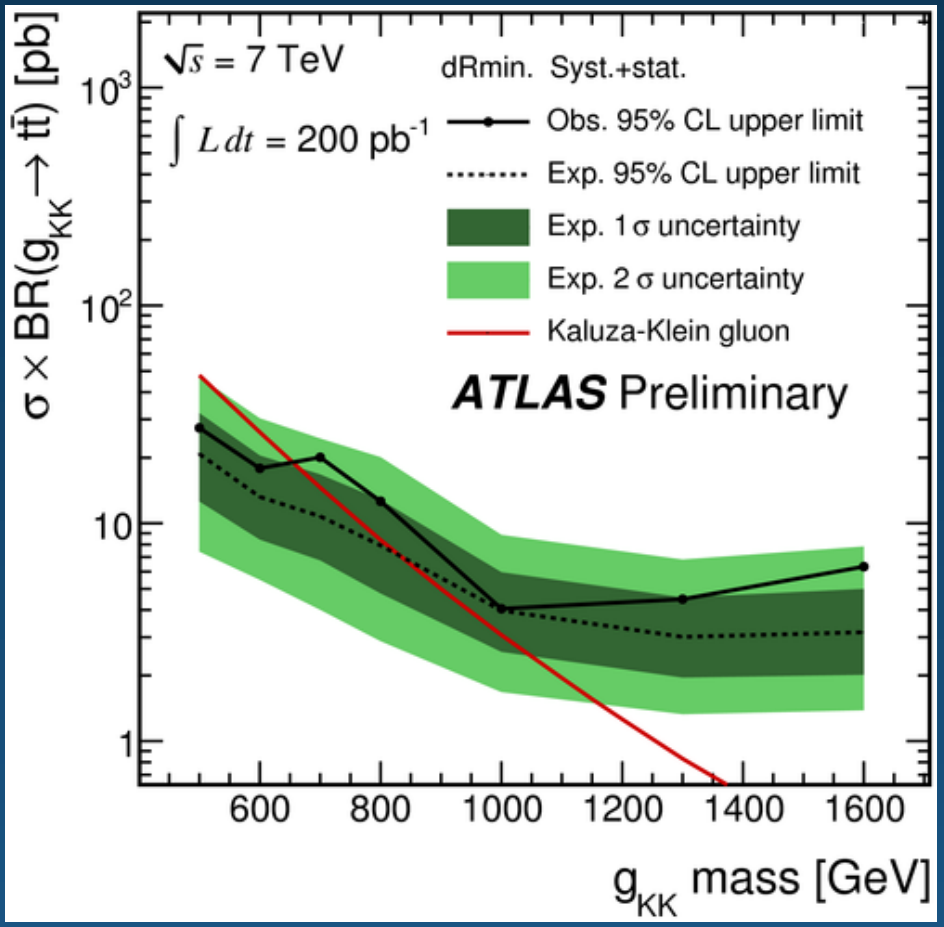
lepton (e,μ) + jets signature

Seek Z' or Kaluza-Klein gluons



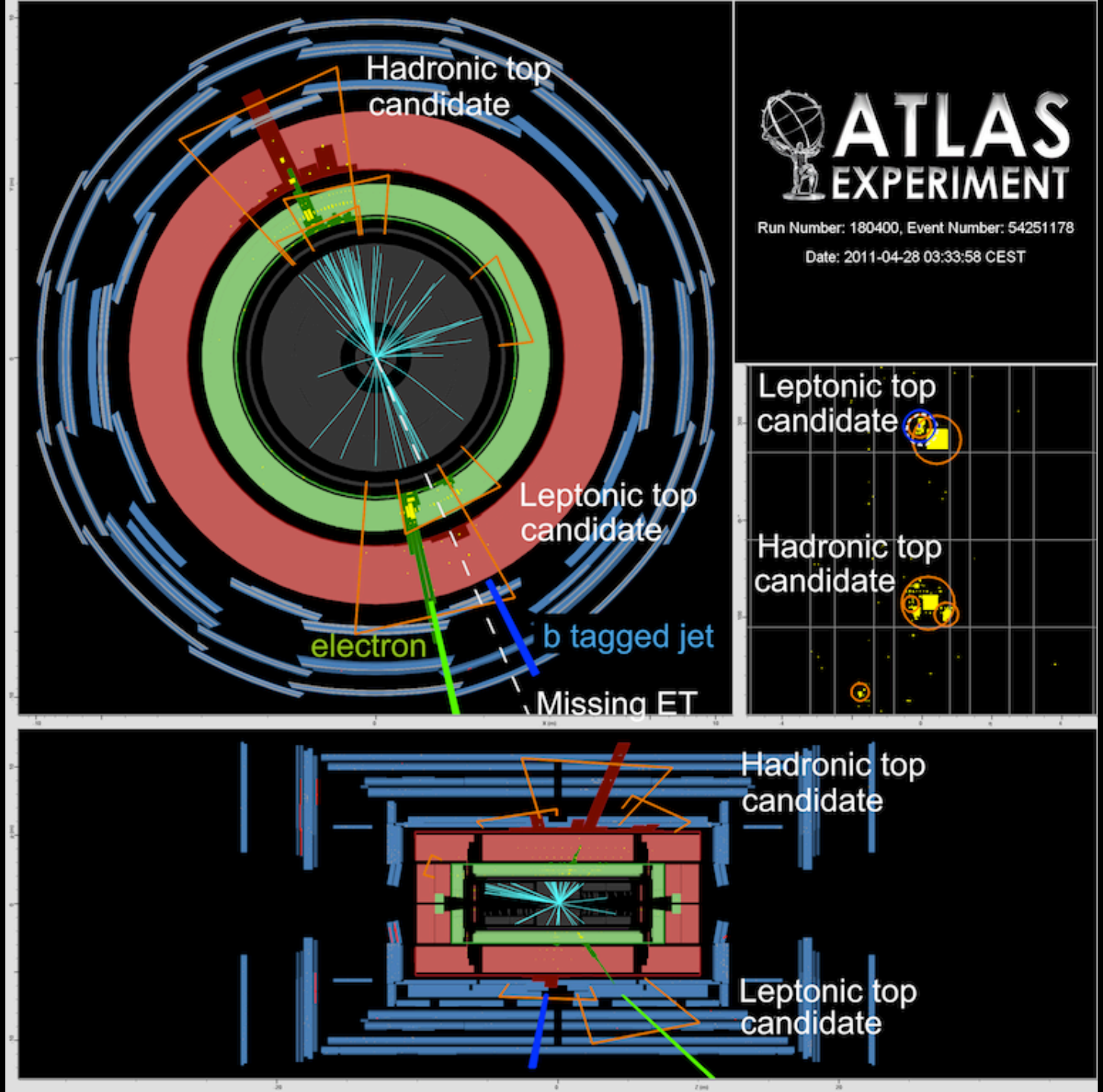
Secondary vertex b-tagging





Resonance mass exclusions:

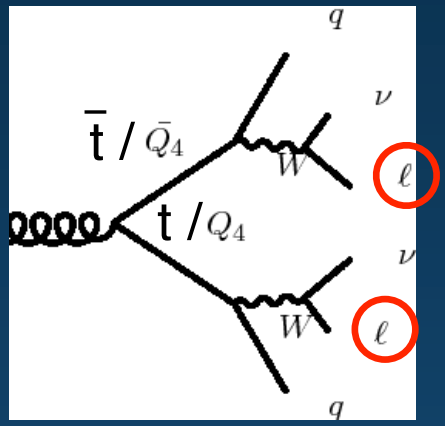
- Strongly produced, wide:
  - RS Kaluza-Klein gluon (< 650 GeV)
- Weakly produced, narrow:
  - Leptophobic Top-Color Z' (no exclusion)



Candidate highly-boosted $t\bar{t}$ event

$m(t\bar{t}) \approx 1.6$ TeV

Dilepton Resonance Searches

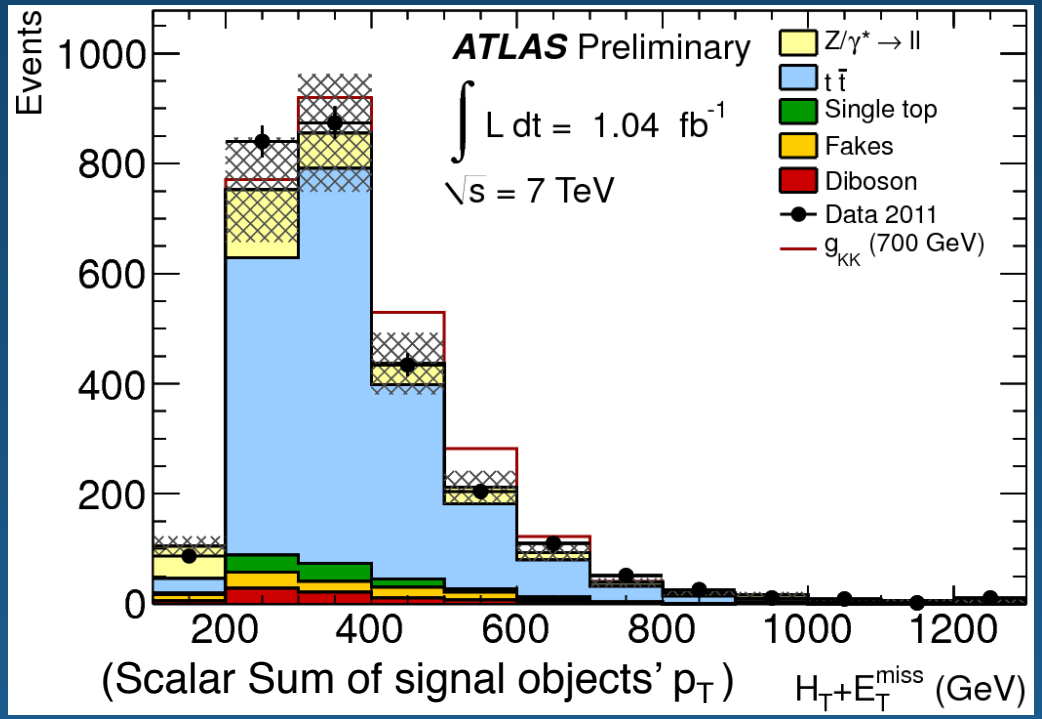


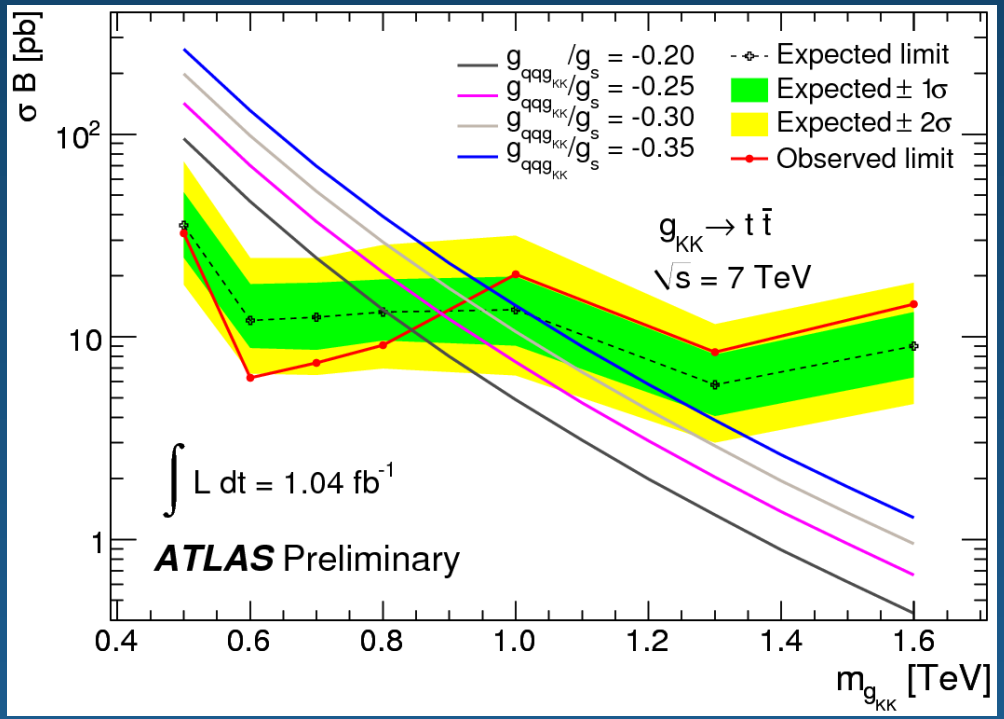
Dilepton signature (*cf.* l + jets: lower BR, but lower background)

Potentially sensitive to Kaluza-Klein gluons, graviton excitations, …

Benchmark Limit: $m(g_{KK}) > 840$ GeV at 95% CL

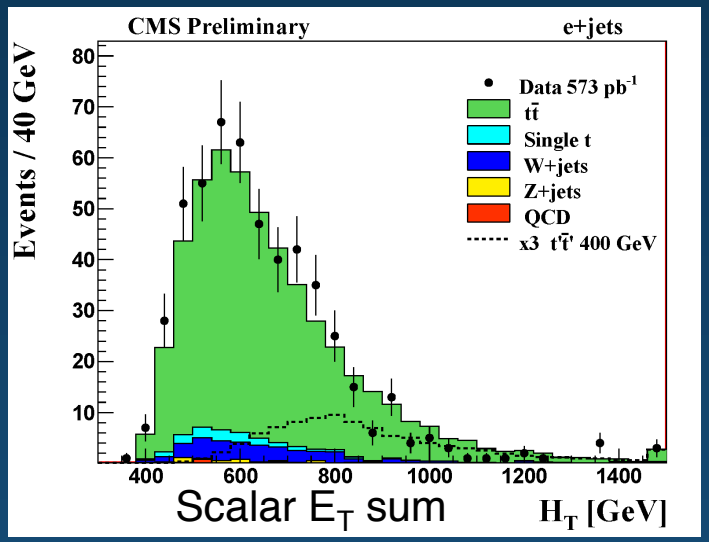
ATLAS-CONF-2011-123

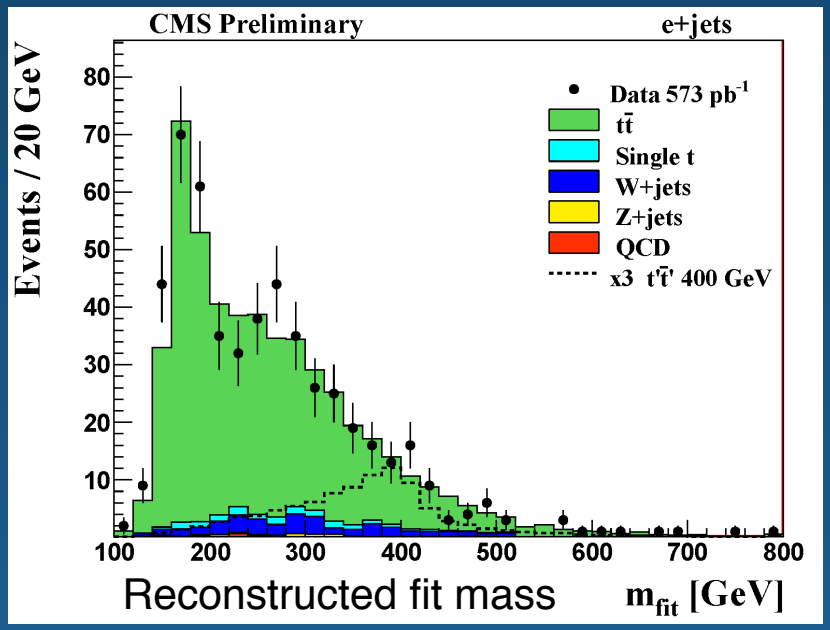


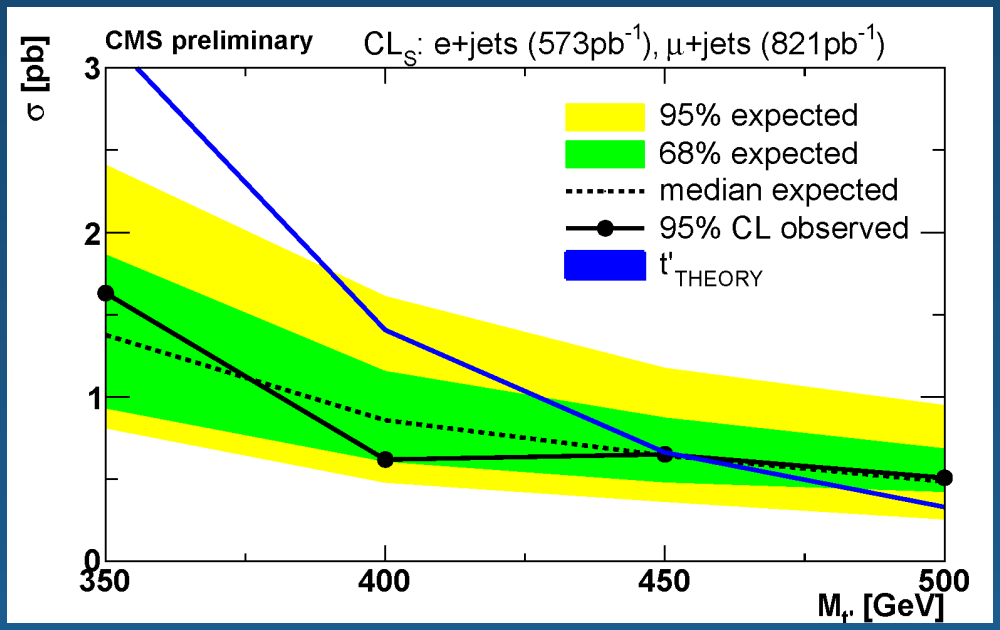


Search for a 4th Generation Quark: t' → Wb

- t' → Wb: top-like signal (l+jets, dilepton), but heavier
- Select: single charged lepton,
  4 jets (1 b-tagged) with high E_T
  large MET
- Experimental challenge: large $t\bar{t}$ background, sensitive to calibration and modeling
- Excluded at 95% CL up to 450 GeV





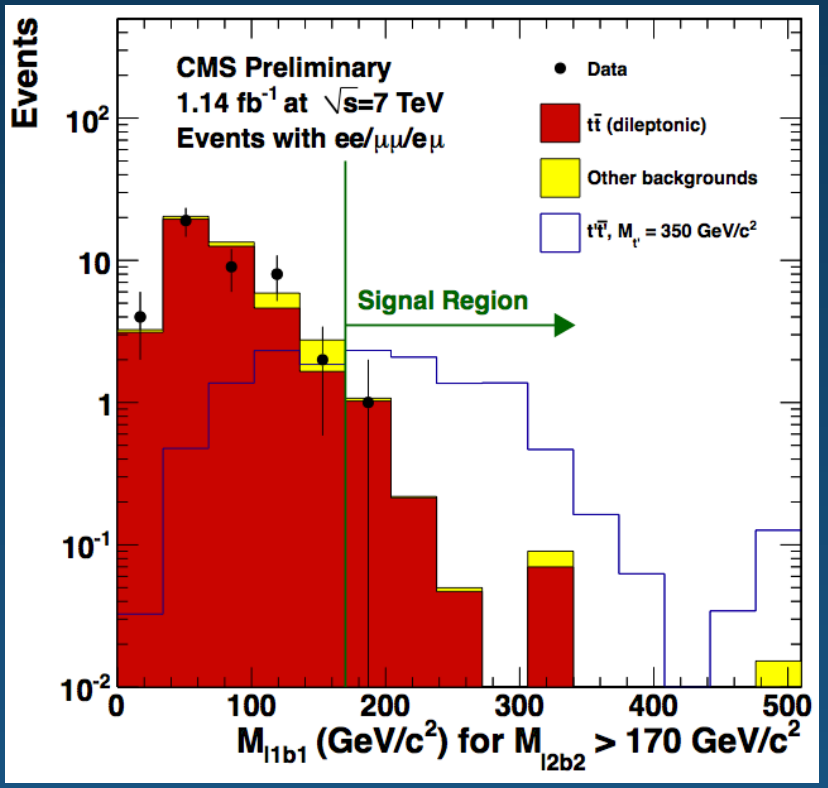


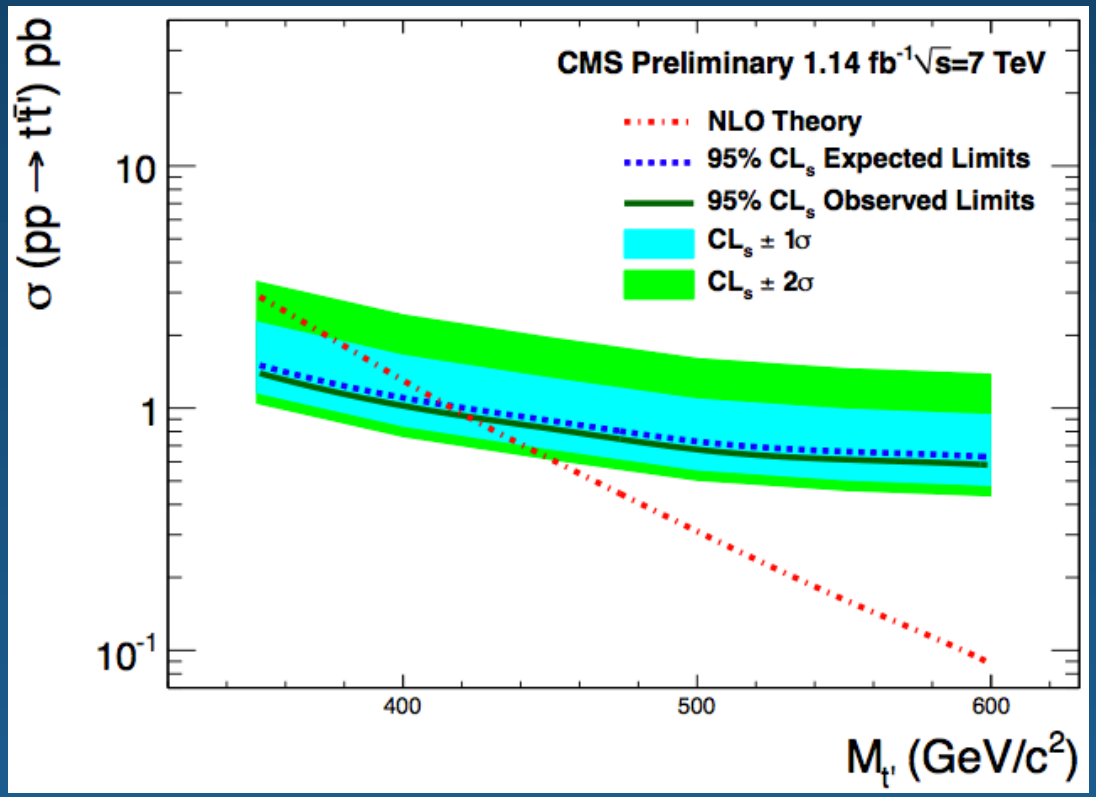
CMS PAS EXO-11-051

Search for a 4th Generation Quark: t' → Wb

- t' → Wb: top-like signal (l+jets, dilepton), but heavier
- Experimental challenge:
  large $t\bar{t}$ background,
  10% high-p_T b-tagging systematic

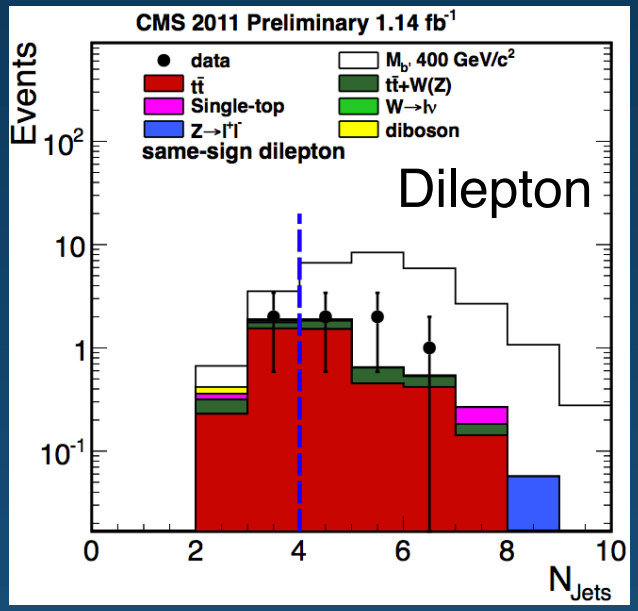
CMS PAS EXO-11-050

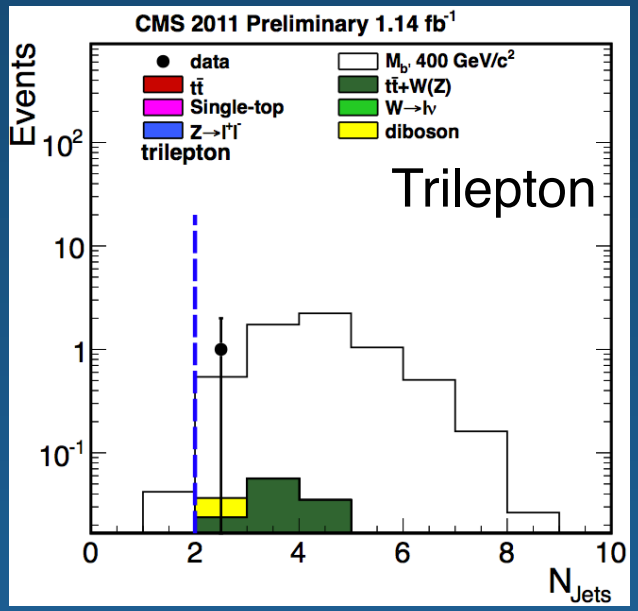




Limit: m(t') > 422 GeV at 95% CL

Search for Heavy Bottom-like Quarks: b' →Wt



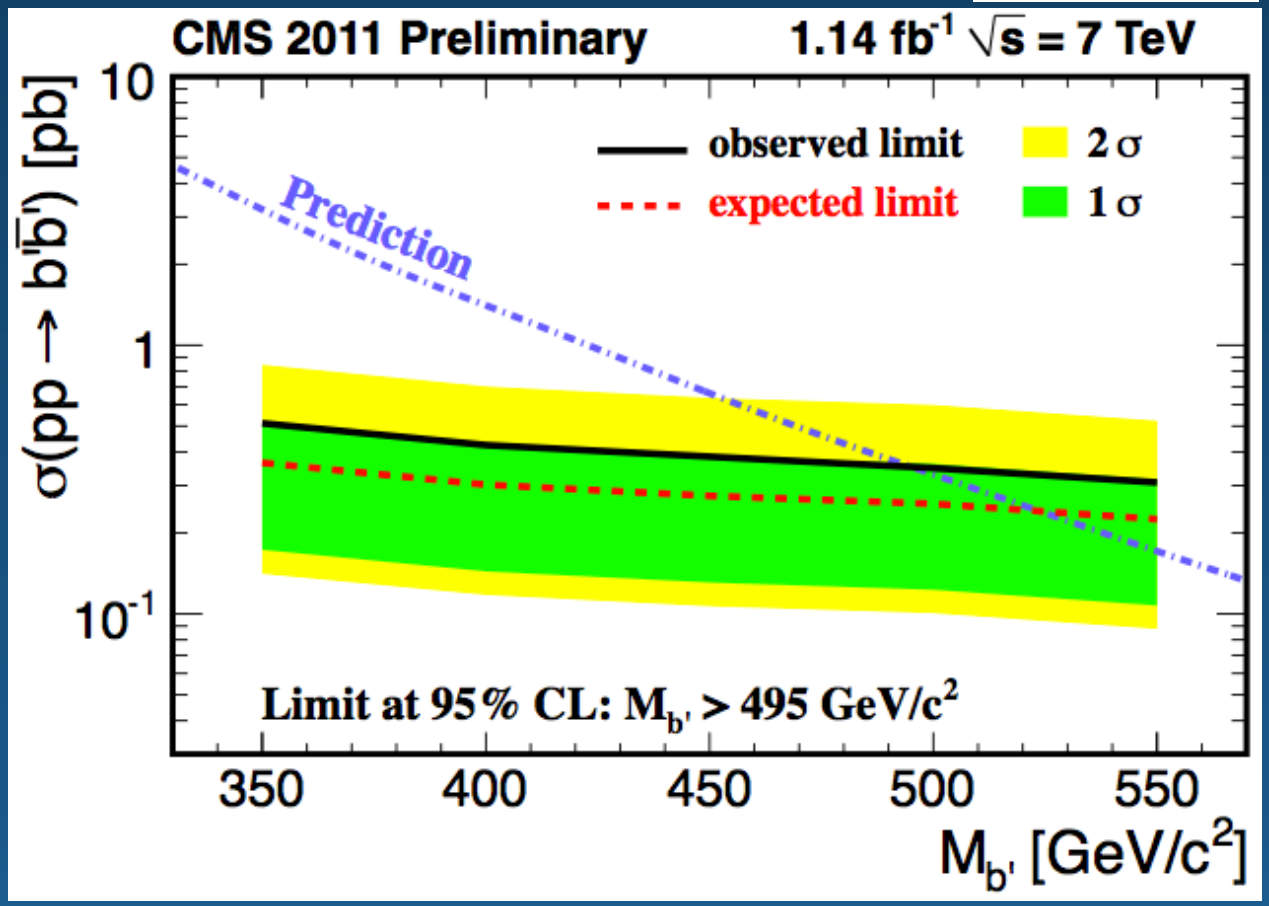


b'b' → Wt Wt → WWb WWb (Like tt+WW; Hard to miss!)

Signature: trileptons or like-sign dilepton, ≥1 b-jet

Limit: m(b') > 495 GeV at 95% CL

CMS PAS EXO-11-036



Top-Antitop + MET

lepton + jets signature

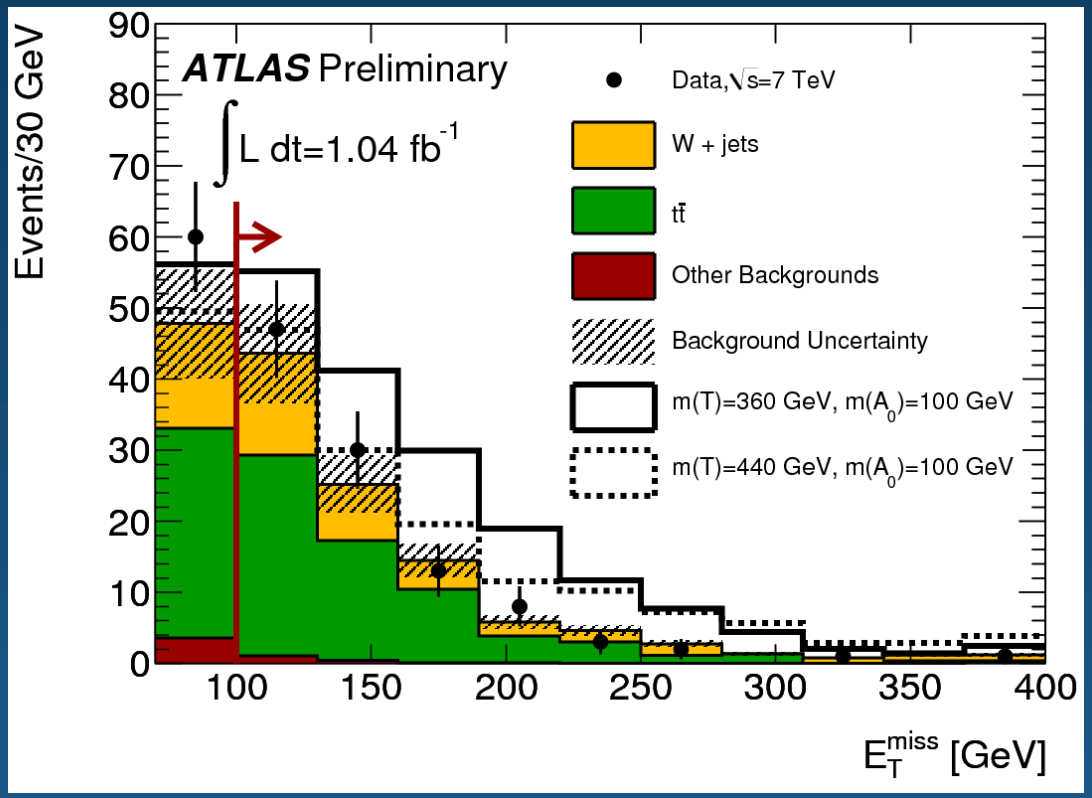
Exotic top partner, decaying to
SM top + stable neutral scalar:

$T\,\bar{T} \rightarrow t\,\bar{t}\,A_0\,A_0$

Predicted by several DM-motivated models

A_0: Dark Matter candidate

ATLAS-CONF-2011-(TBA)



Selection:

- <u>single</u> high p_T isolated lepton
- ≥ 4 jets
- MET > 100 GeV

Good understanding of MET is important

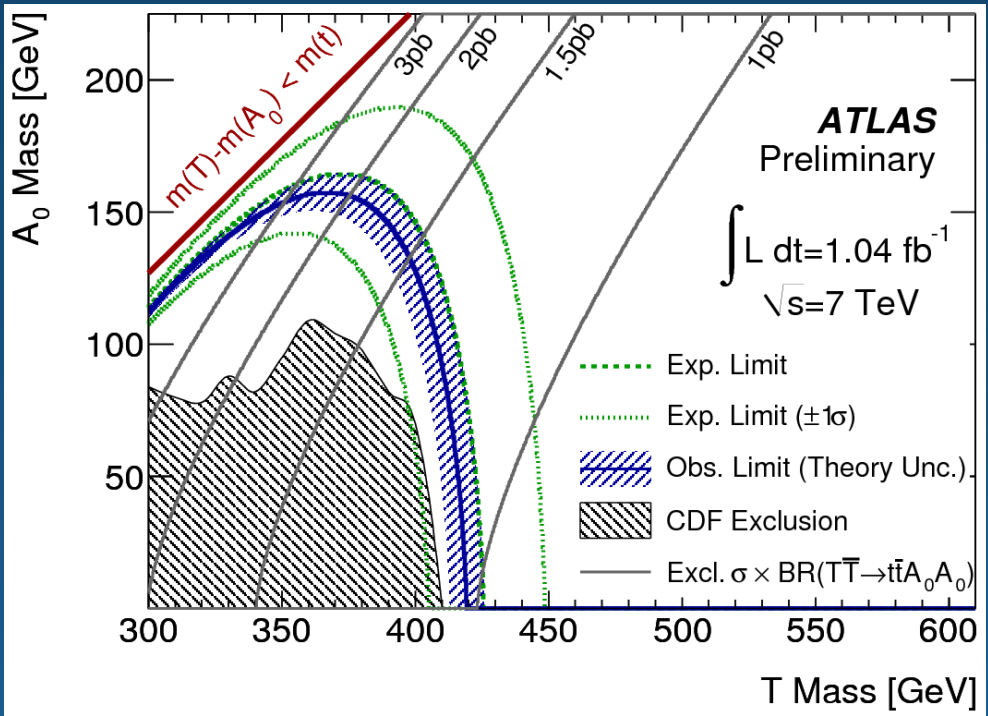
Top-Antitop + MET

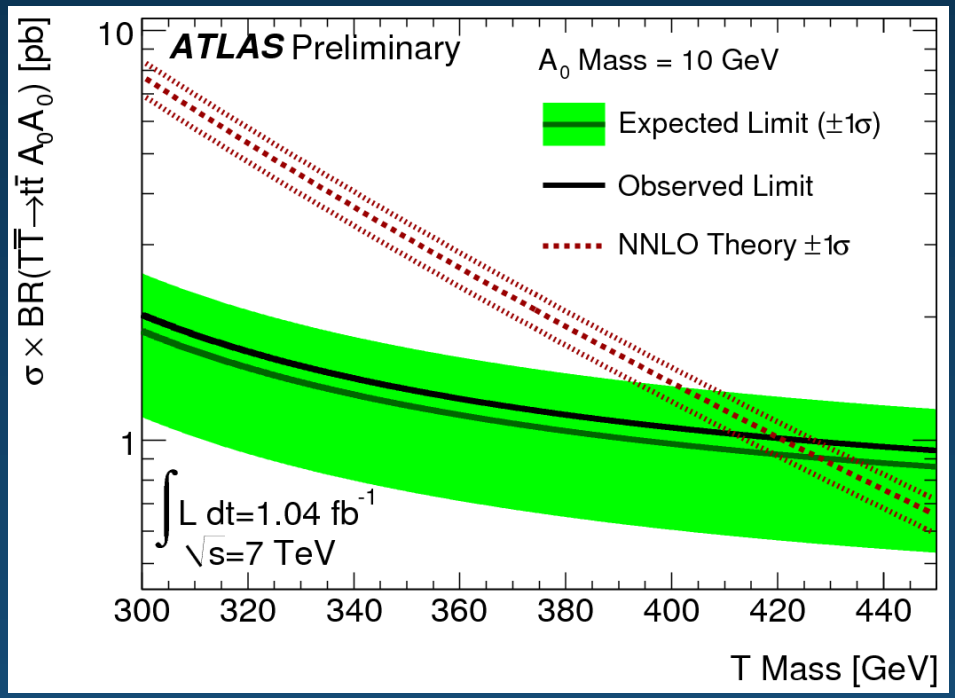
New heavy particles:

$T\,\bar{T} \rightarrow t\,\bar{t}\,A_0\,A_0$

No signal apparent yet

ATLAS-CONF-2011-(TBA)





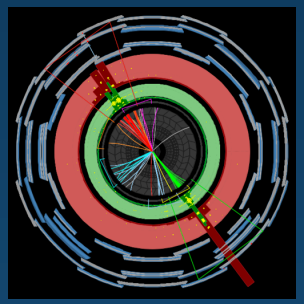
Theory: Alwall, Feng, Kumar

Exclude at 95% CL: heavy quark-like states decaying to top plus a new neutral particle, *e.g.*,

T with m(T) < 420 GeV decaying to A_0 with $m(A_0)$ = 10 GeV

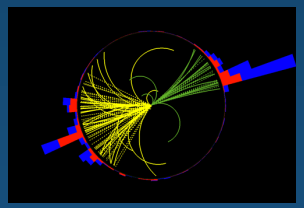
Selected Searches

Heavy Resonances



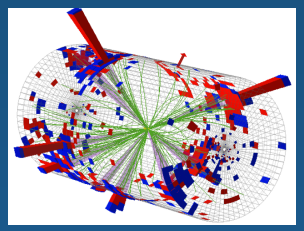
- Heavy gauge bosons
- Diboson ($\gamma\gamma$, WZ)
- Dijet
- Doubly charged Higgs

Quark Exotica



- $t\bar{t}$ resonances
- $t\bar{t}$ + MET (missing transverse energy)
- 4th quark generation

Strong Gravity

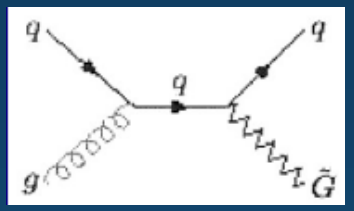


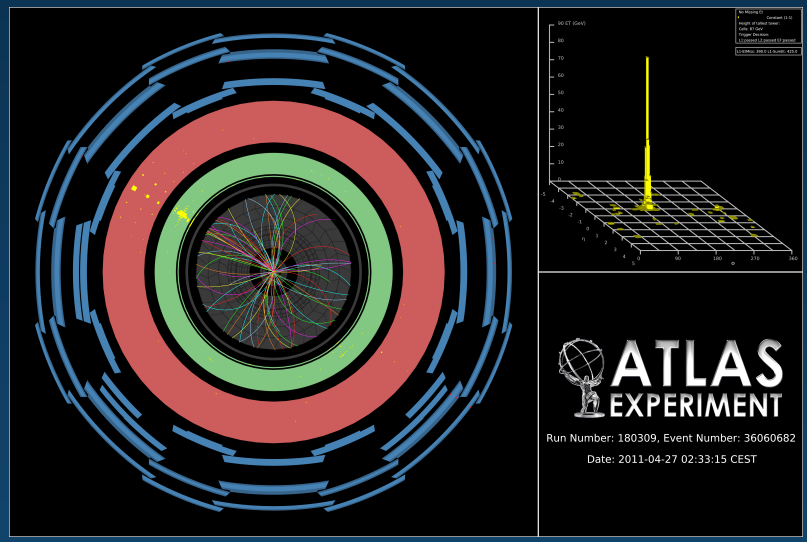
- Monojet
- Monophoton
- Dimuon/diphoton spectrum
- Black holes

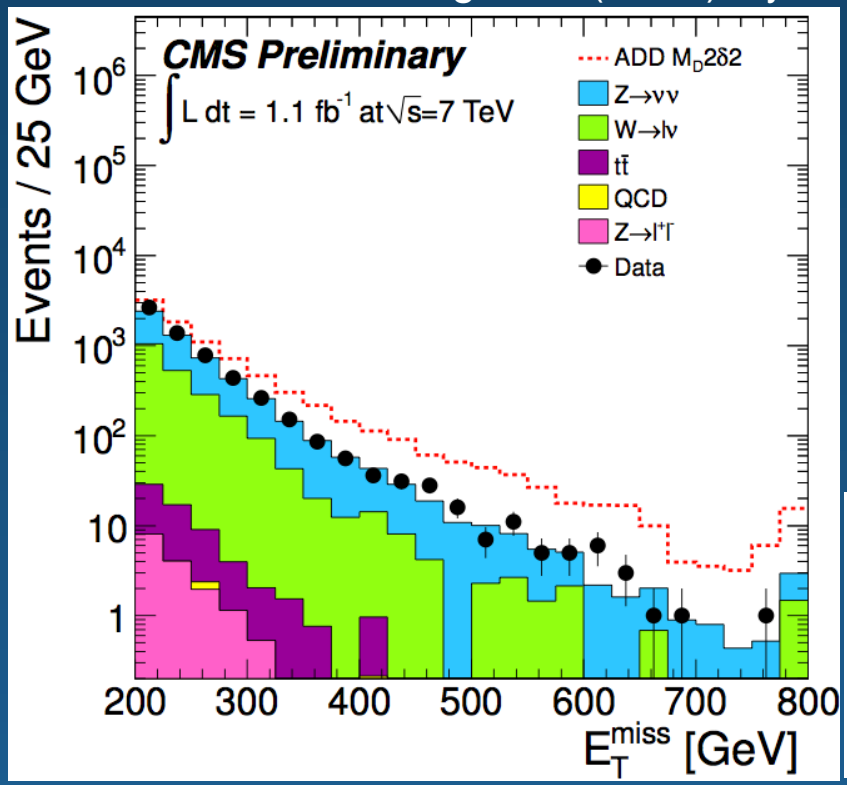
Search for Monojets

- Large Extra Dimensions (ADD)
  - Graviton escapes detection
- Seek a jet with ~nothing else
- Challenges:
  - Instrumentation background
  - Understanding SM Z(→ $\nu\bar{\nu}$) + jets

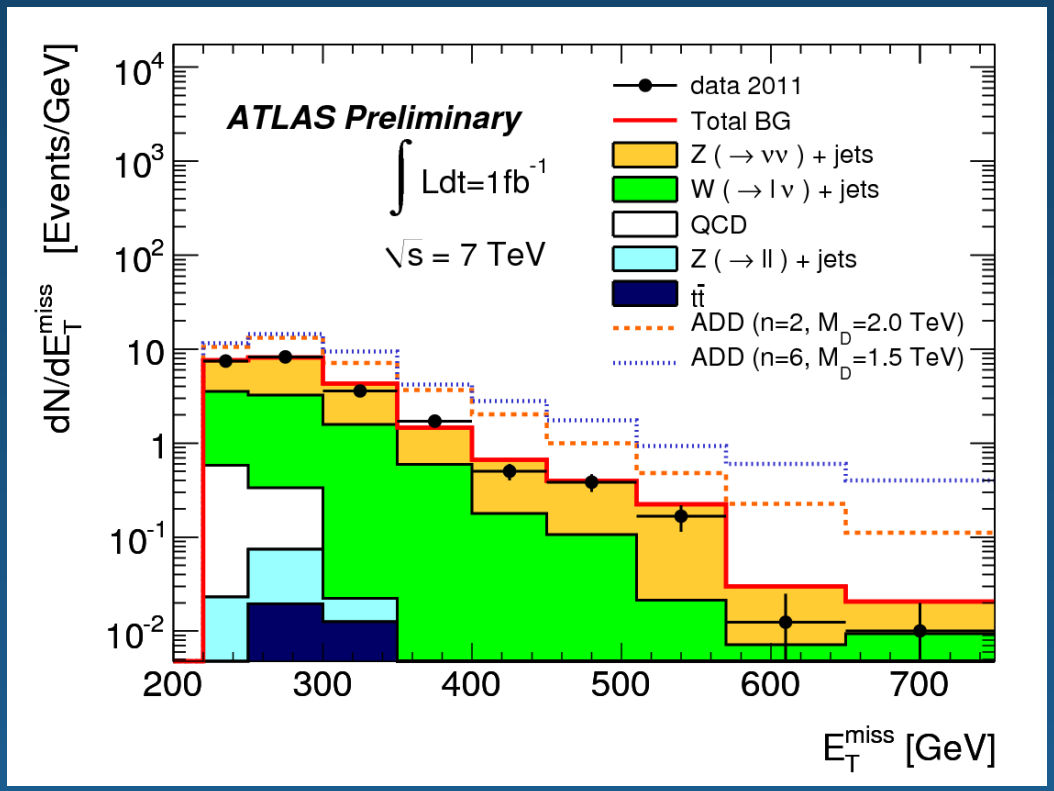
$$M_{Pl}^2 \sim M_D^{2+n} R^n$$







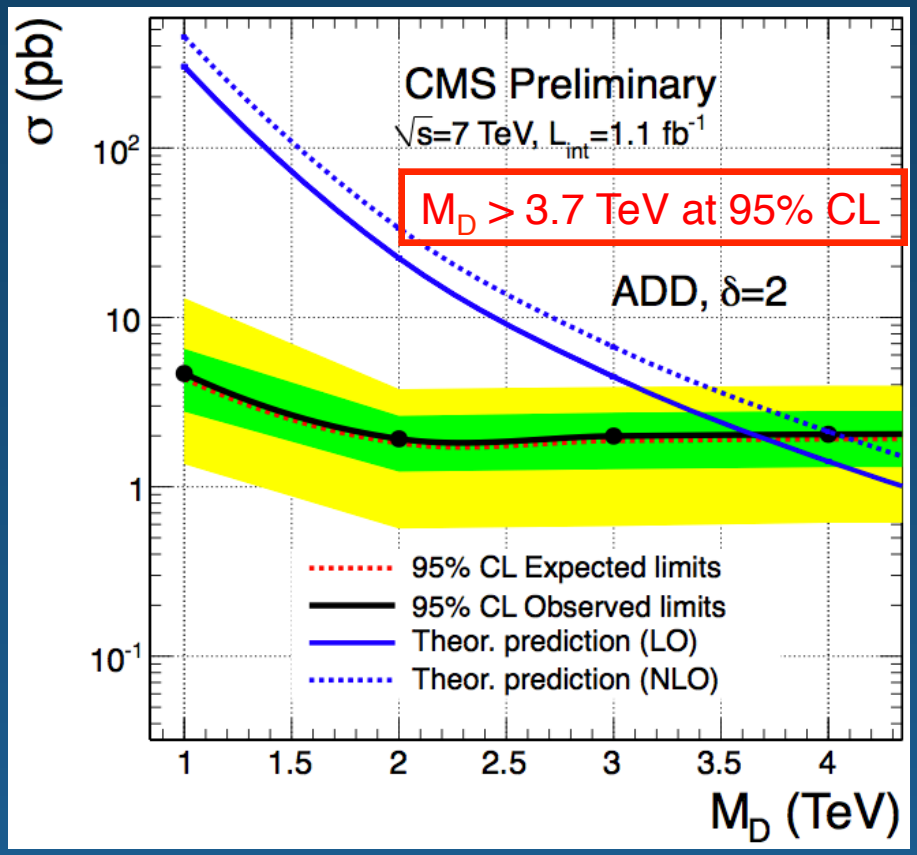
CMS PAS EXO-11-059



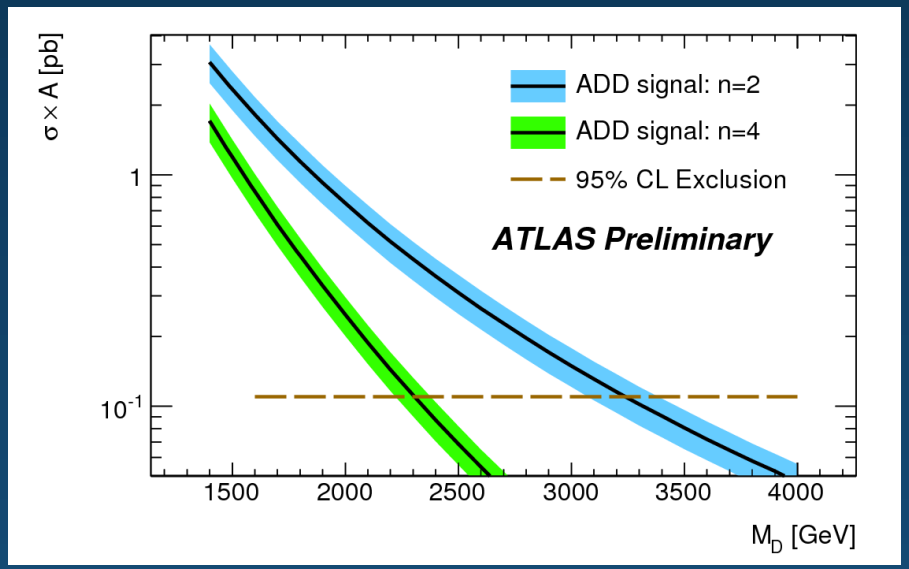
ATLAS-CONF-2011-096

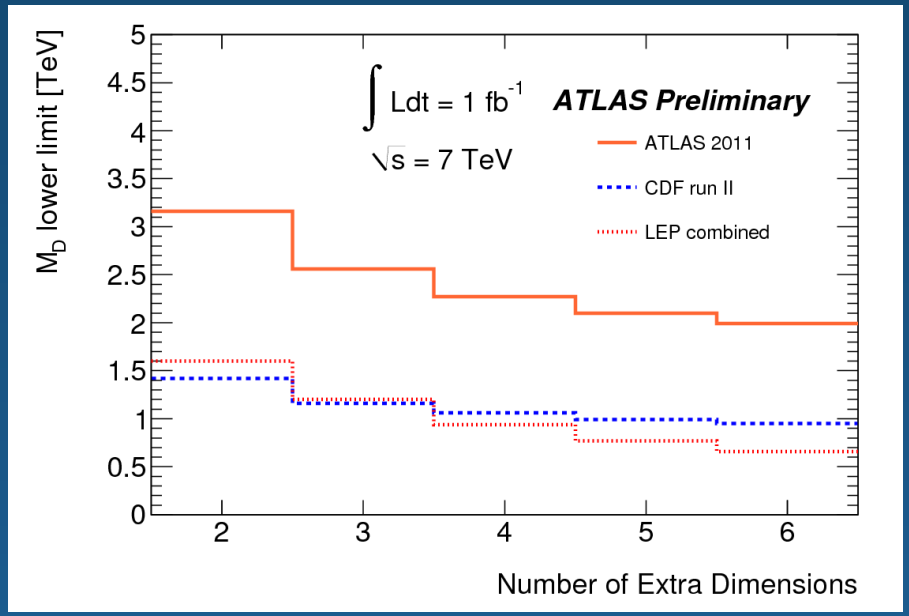
Search for Monojets

Extra Dimensions (ADD)
now pushed beyond 2 TeV



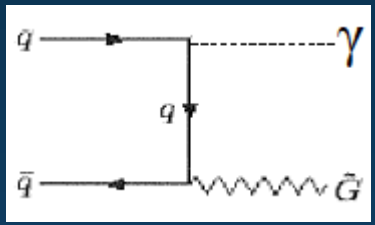
CMS PAS EXO-11-059





ATLAS-CONF-2011-096

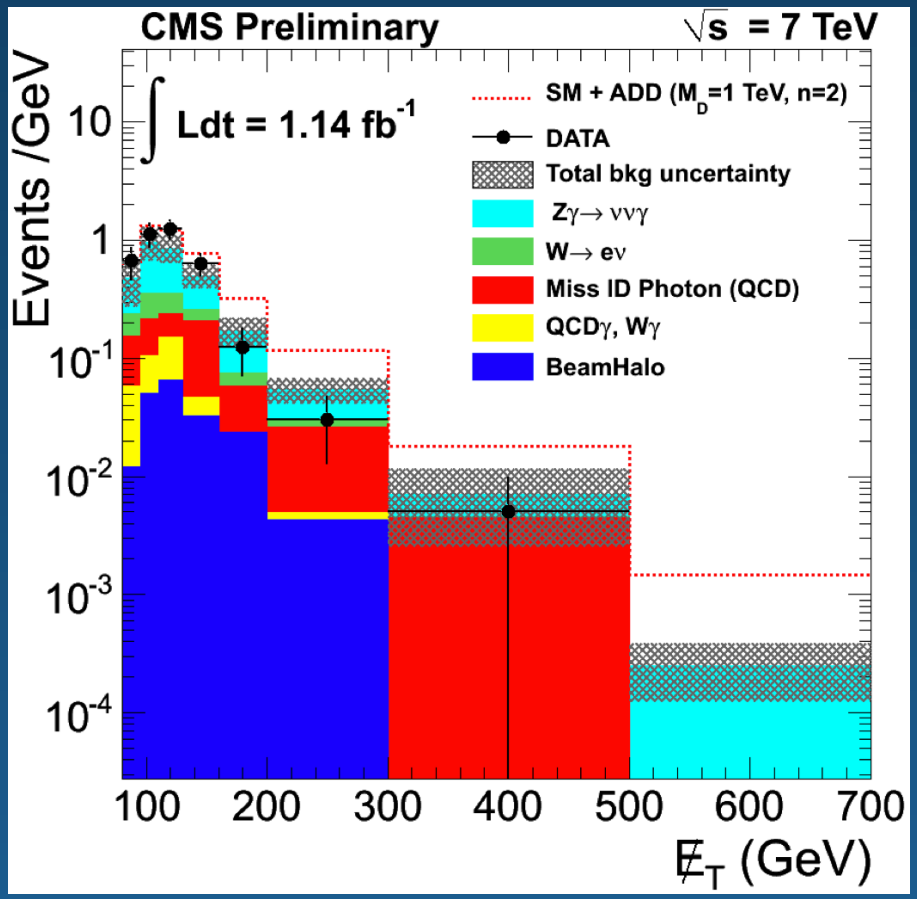
Search for Monophoton

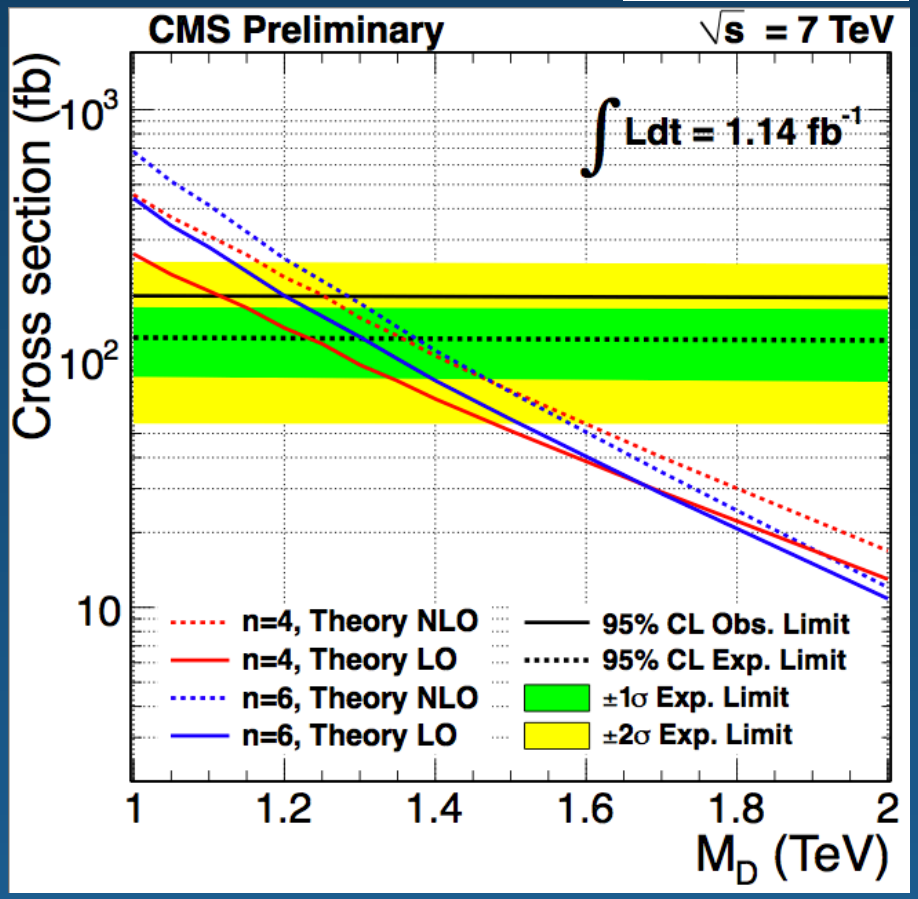


- Large Extra Dimensions (ADD)
  - Graviton escapes detection
- Like monojet, seek a photon with ~nothing else

- For n = 2 – 6
- M_D > 1.25 – 1.31 TeV at 95% CL

CMS PAS EXO-11-058





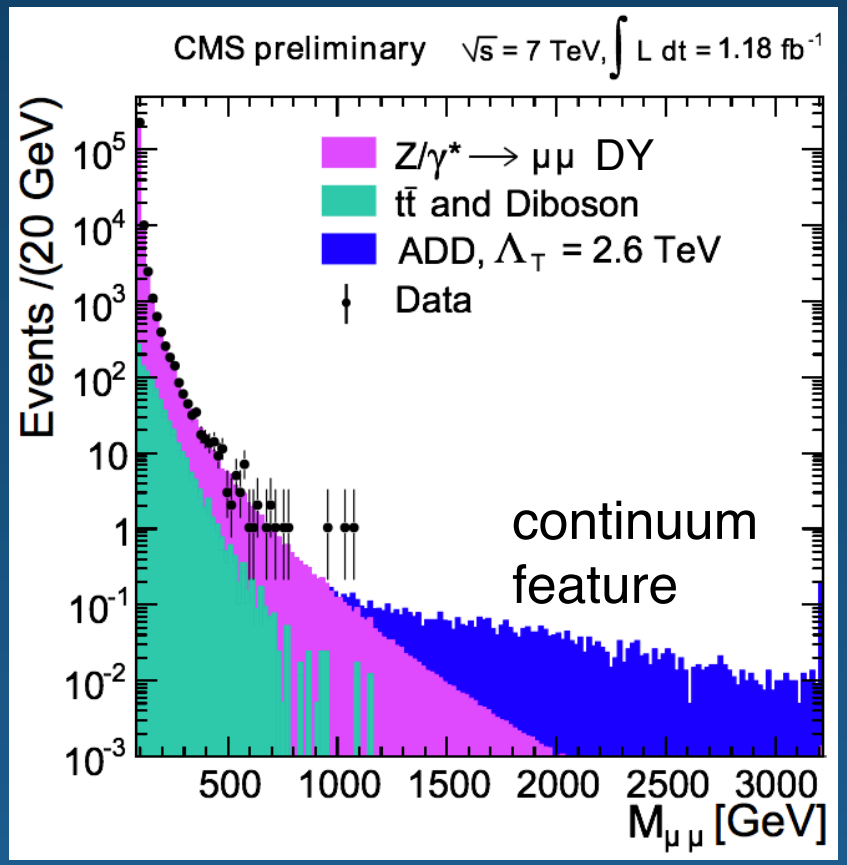
Nonresonant Dimuon/Diphoton LED Searches

Large Extra-D (ADD):
KK graviton tower with
$\Delta M \ll$ detector resolution

Diphoton: M_S lower limits [TeV] at 95% CL

CMS PAS EXO-11-038

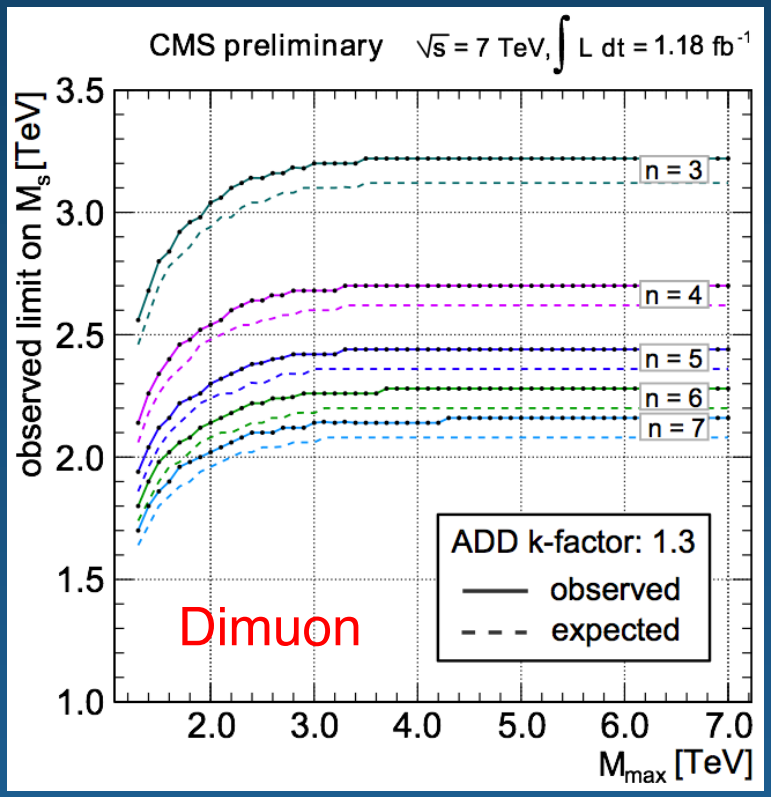
K factor	$n_{ED} = 2$	$n_{ED} = 3$	$n_{ED} = 4$	$n_{ED} = 5$	$n_{ED} = 6$	$n_{ED} = 7$
1.0	3.2	3.4	2.8	2.6	2.4	2.2
1.6	3.5	3.7	3.1	2.8	2.6	2.4



Seek deviation in the SM spectrum

Isolated muon candidates

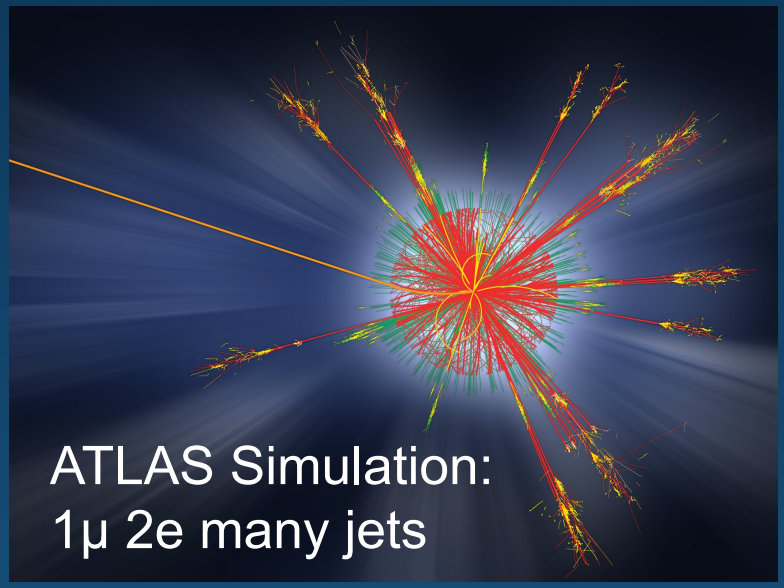
Dimuon: (n = 3) M_S > 3.22 TeV

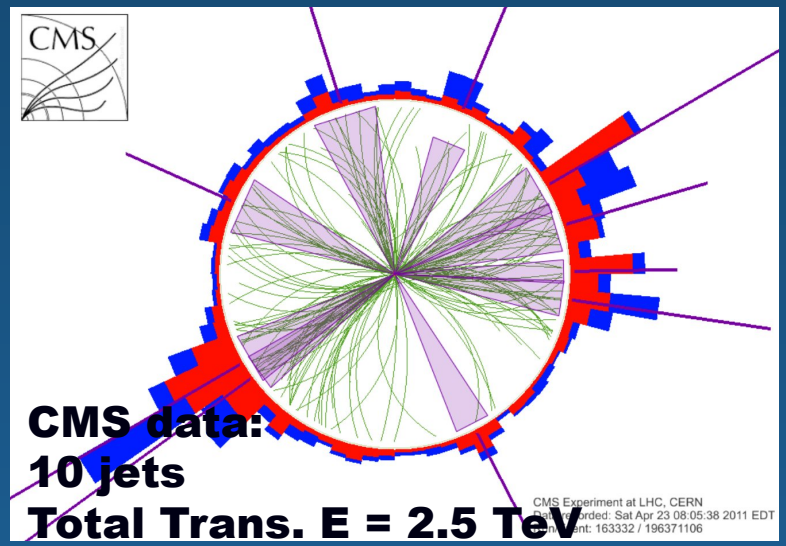


CMS PAS EXO-11-039

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
- Semi-classical models: m(BH) >> m(threshold) = M_{TH}
- Safe bet: decay is democratic and isotropic, likely high particle multiplicity → look for many jets and leptons at high mass



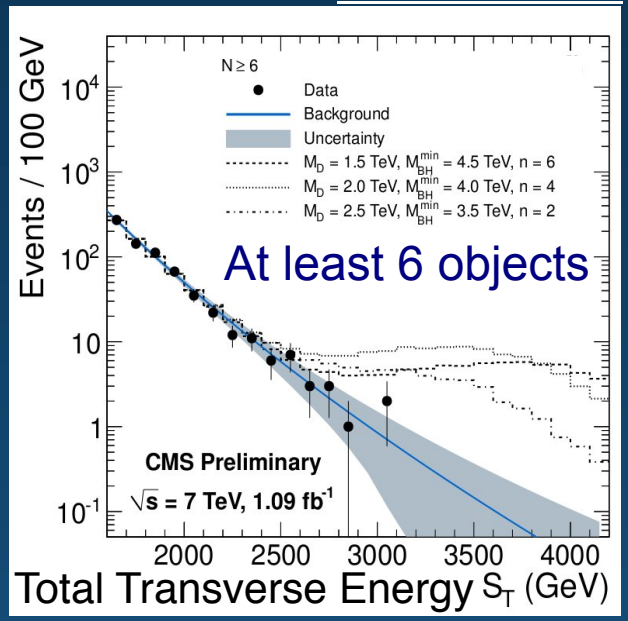


CMS PAS EXO-11-071

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

CMS PAS EXO-11-071

- 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



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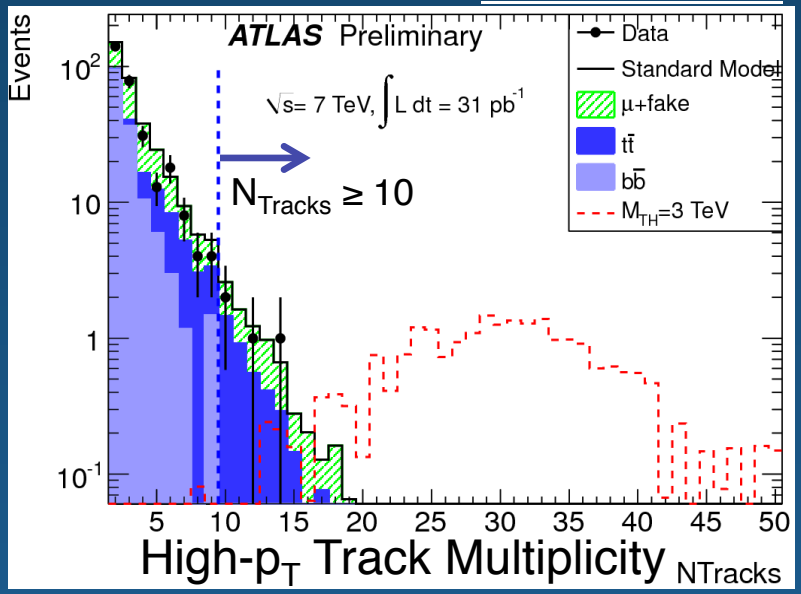
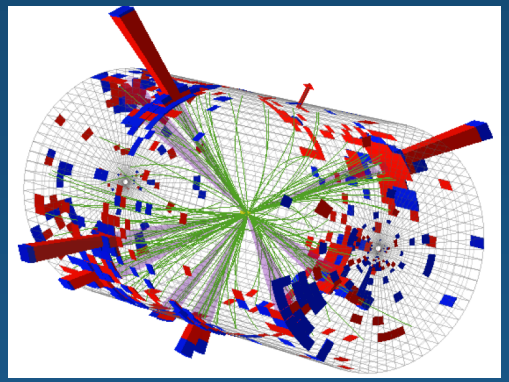
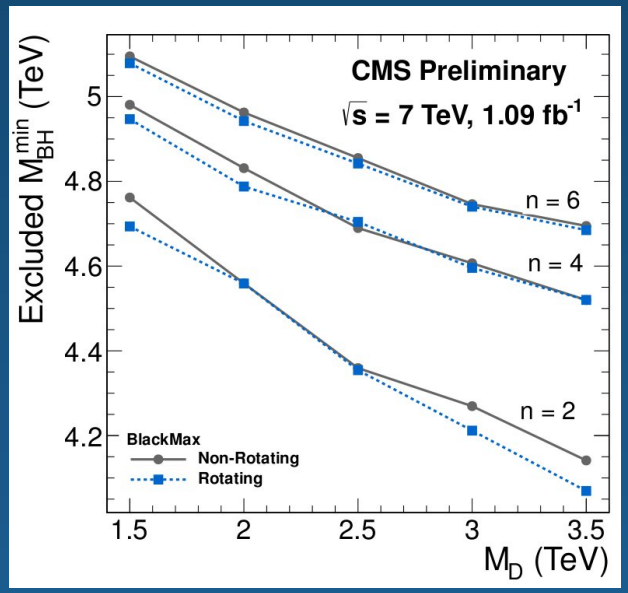


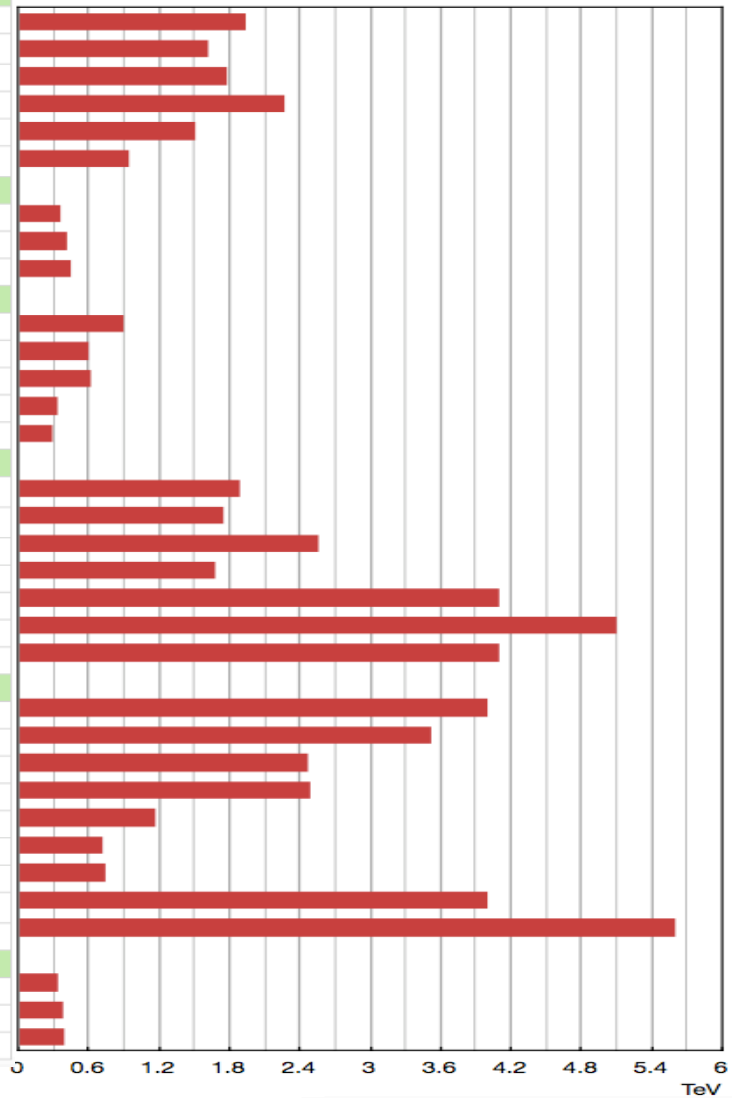


9-object CMS event



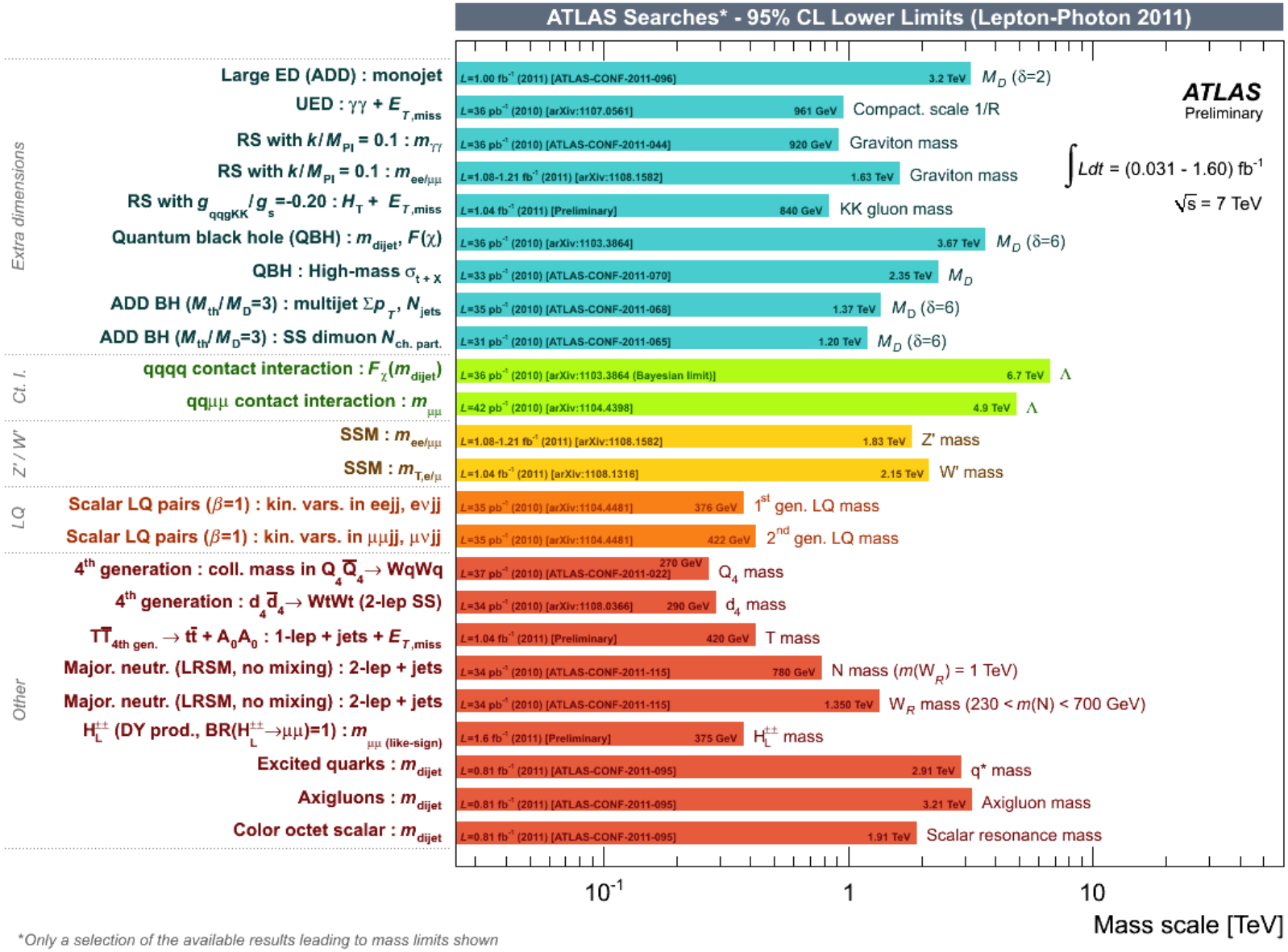
CMS Exotics Searches: Summary

	Limits in TeV	
	Heavy Bosons	
Z'_{SSM} ll	1.94	2011
Z'_{ψ} ll	1.62	2011
G_{KK} ll k/M = 0.1	1.78	2011
W' lν	2.27	2011
W' dijet	1.51	2011
G_{KK} γγ k/M = 0.1 (2010)	0.945	2010
	4th Generation	
$M_{b'}$, b' ⇒ tW (2010)	0.361	2010
$M_{t'}$, t' ⇒ tZ (100%)	0.417	2011
$M_{t'}$, t' ⇒ bW (100%), l+jets	0.45	2011
	Heavy Stable Particles	
M_{gluino}, HSCP	0.899	2011
M_{gluino}, Stopped Gluino	0.601	2011
M_{stop}, HSCP	0.620	2011
M_{stop}, Stopped Gluino	0.337	2011
M_{stau}, HSCP	0.293	2011
	Large Extra Dimensions	
M_s, γγ, GRW (2010)	1.89	2010
M_s, μμ, GRW (2010)	1.75	2010
M_D, monojet, n_{ED} = 2 (2010)	2.56	2010
M_D, monojet, n_{ED} = 6 (2010)	1.68	2010
M_{BH}, rotating, M_D=3.5 TeV, n_{ED} = 2	4.1	2011
M_{BH}, non-rot, M_D=1.5 TeV, n_{ED} = 6	5.1	2011
String Ball M, M_D=2.1, M_s=1.7, g_s=0.4	4.1	2011
	Compositeness and Contact Interactions	
String Resonances	4.0	2011
E_6 diquarks	3.52	2011
Axigluon/Coloron	2.47	2011
q* , dijet	2.49	2011
q* , boosted Z	1.17	2010
e*, Λ = 2 TeV	0.720	2010
μ*, Λ = 2 TeV	0.745	2010
C.I. Λ , dijet mass (3 pb^{-1})	4.0	2010
C.I. Λ , X analysis	5.6	2010
	LeptoQuark	
LQ1, β=0.5 (2010)	0.340	2010
LQ1, β=1.0 (2010)	0.384	2010
LQ2, β=1.0 (2010)	0.394	2010



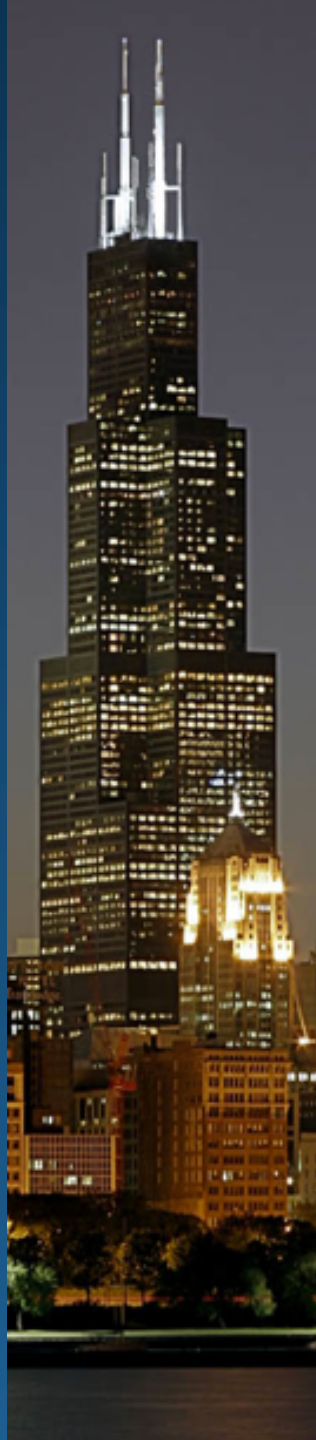
(table does not contain latest results)

ATLAS Exotics Searches: Summary



Concluding Remarks

- Hats off to the LHC for an outstanding year of 7 TeV pp collisions: quick provision of quality and quantity
- ATLAS and CMS all-purpose detectors are already performing near design specifications
- Experimental challenges lie ahead (multi-TeV, high lumi):
  - Pileup
  - TeV leptons, boosted object reconstruction
  - New, more complex signatures
- Experimentally, we've now not only opened the door to the "*House of New Physics*", but also stepped inside, to find nothing obviously exotic… in the foyer
- Still very early days; many rooms remain to be explored!

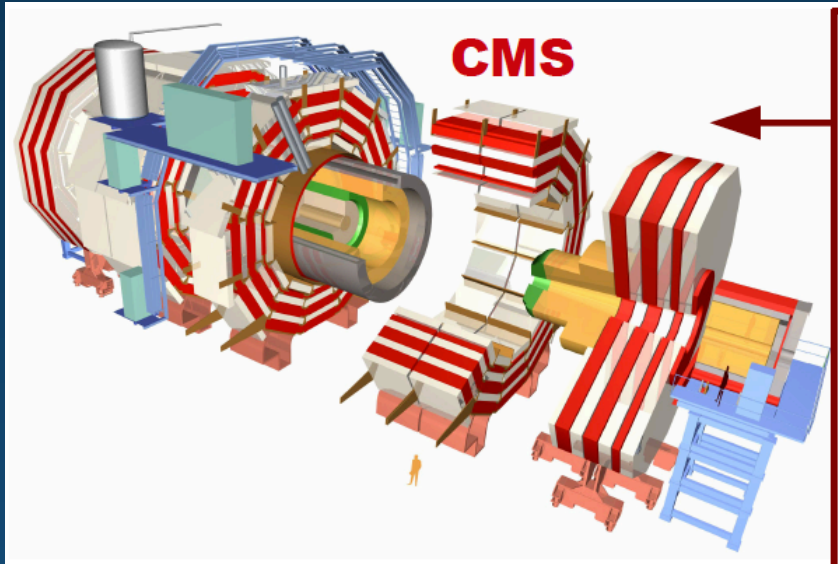


Extra Material

New Physics Searches: Key Ingredients

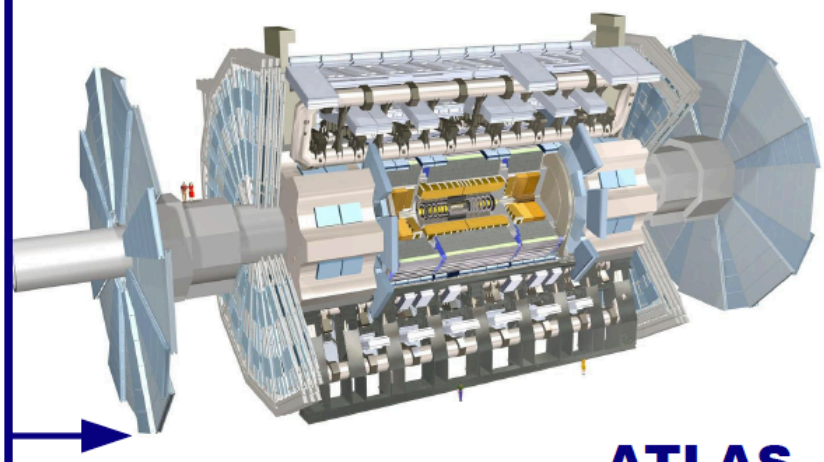
- Maximize signal efficiency
  - Data-driven methods (*e.g.*, tag-&-probe)
  - Can be tricky for very exotic signals
- Reliable background estimations
  - Understanding of detector
  - Data-driven methods
- Trade-offs in analysis approaches:
  - Setting strong limits
  - Robust discovery!

CMS & ATLAS Detectors: Basic Parameters



- 3.8T solenoid containing calorimeters
- Silicon tracker: $\sigma(p_T)/p_T \sim 15\%$ at 1TeV
- EM cal: homogeneous Lead-Tungstate crystal, $\sigma_E/E \sim 3\%/\sqrt{E[\mathrm{GeV}]} \oplus 0.5\%$
- HAD cal: Brass-scint., $\geq 7\lambda_0$
  $\sigma_E/E \sim 100\%/\sqrt{E[\mathrm{GeV}]} \oplus 5\%$
- Iron return yoke muon spectrometer

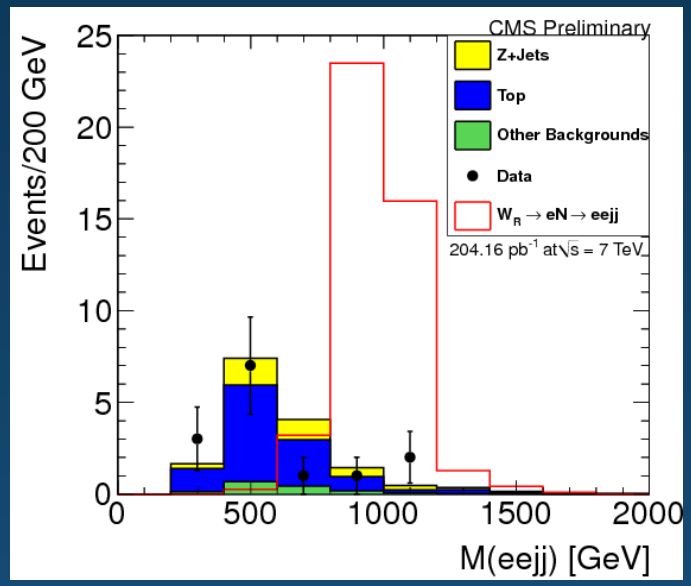
- 2T solenoid inside calorimeters
- Silicon+TRT tracker + electron ID
- EM cal: Longitudinally segmented Lead-Ar: $\sigma_E/E \sim 10\%/\sqrt{E[\mathrm{GeV}]} \oplus 0.7\%$
- HAD cal: Fe-scint + Cu-Ar, $\geq 11\lambda_0$
  $\sigma_E/E \sim 50\%/\sqrt{E[\mathrm{GeV}]} \oplus 3\%$
- Air-toroid muon sp.: $\int \sqrt{B}.dl = 1$ to 7 T.m

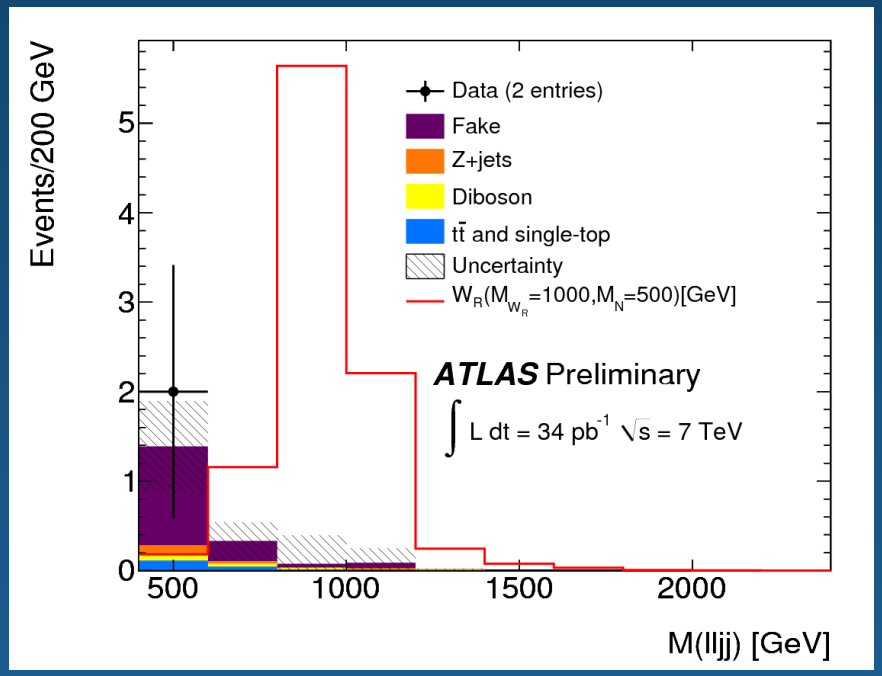


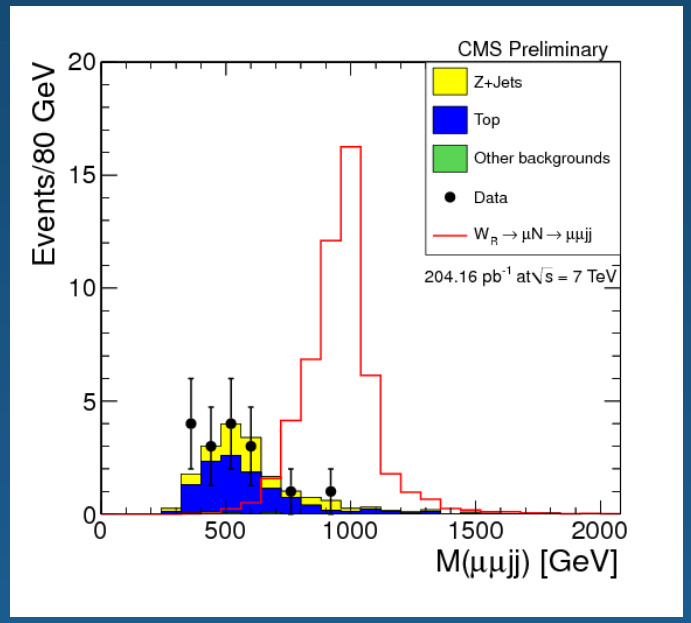
Heavy Neutrinos, LRSM W_R

$$W_R \to \ell_1 N_\ell \to \ell_1 \ell_2 W_R^* \to \ell_1 \ell_2 jj$$

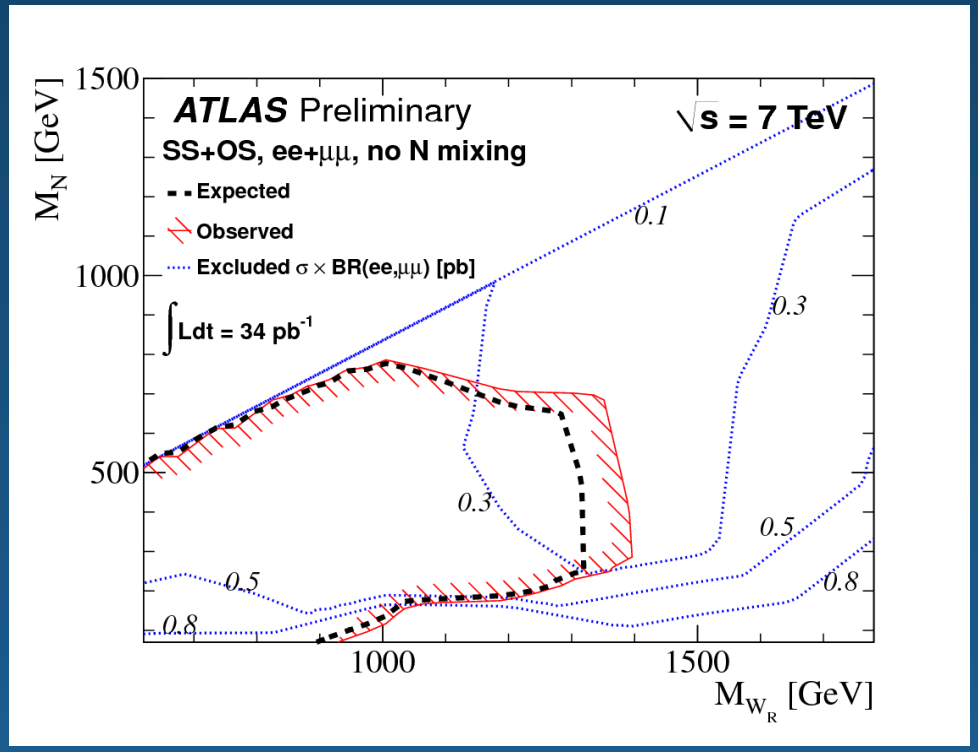
- LRSM approaches
- Search for resonance in 2-lepton + 2-jet system
- Majorana neutrino → expect 50% same-sign (clean signature)

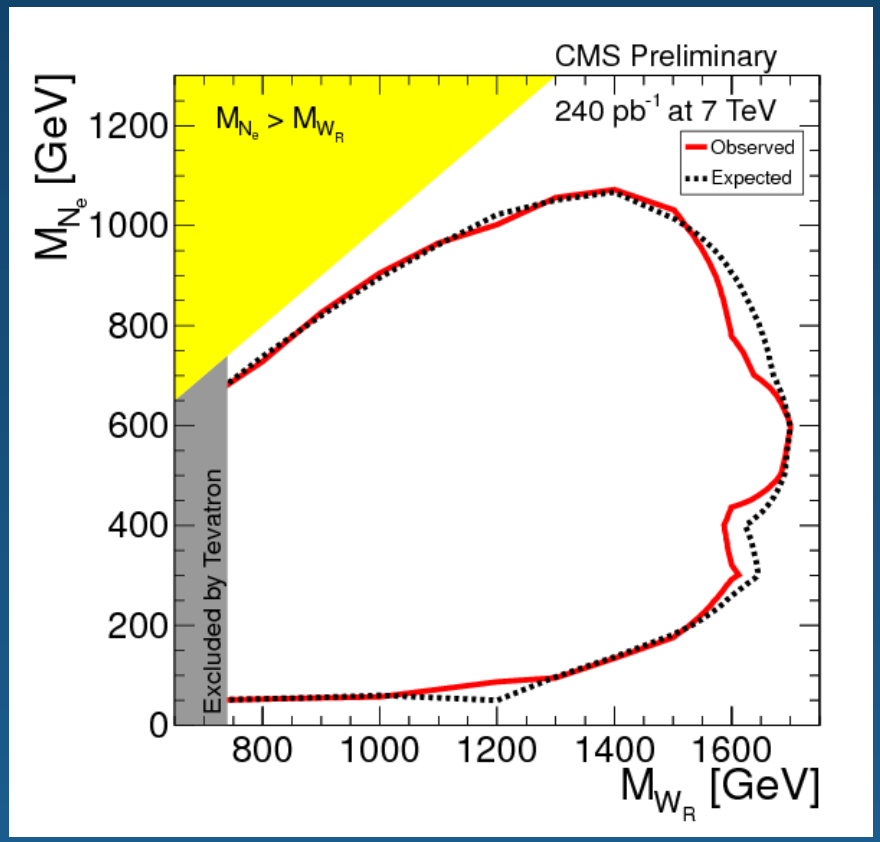


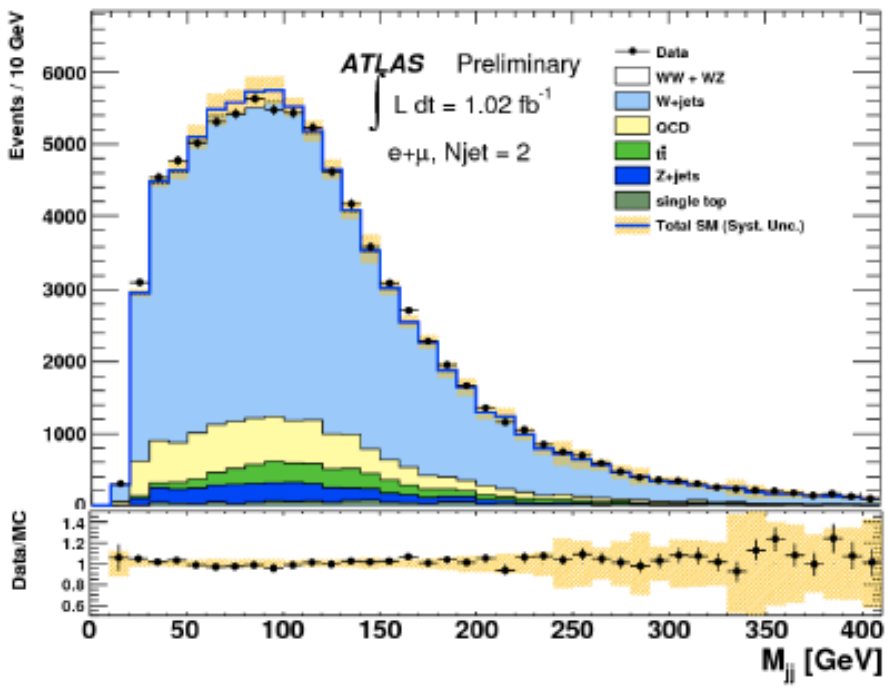
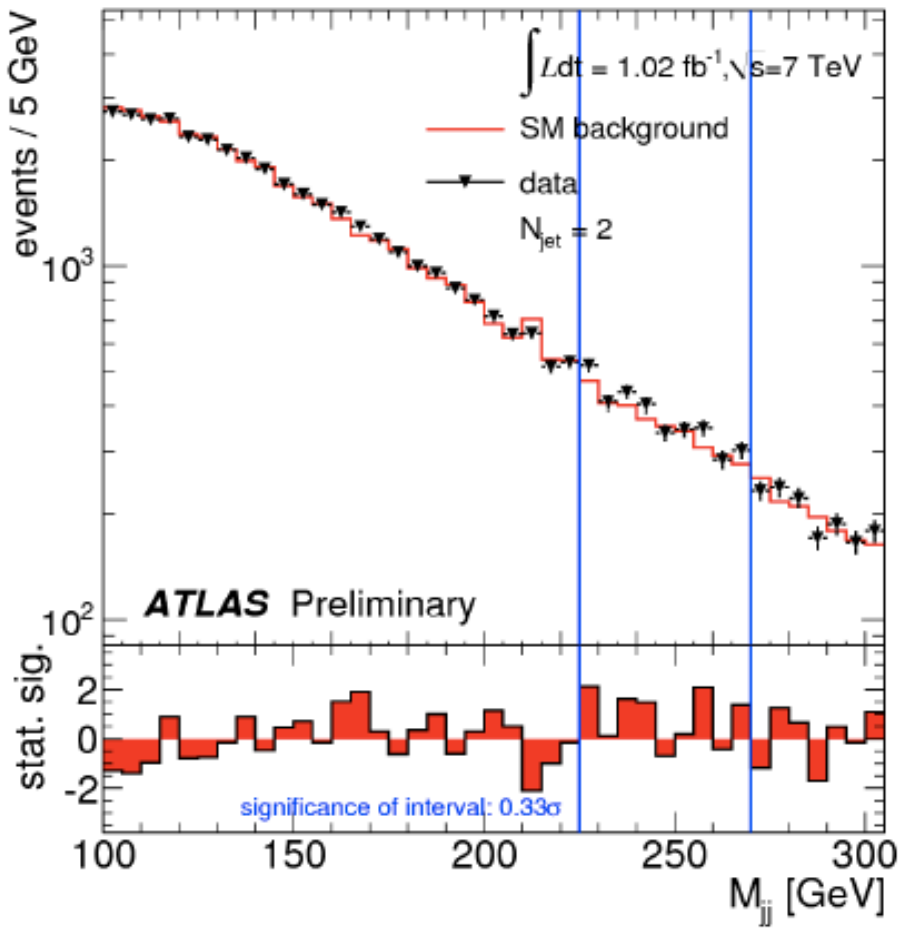




Heavy Neutrinos, W_R





W+2j Production Cross Check

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