Beyond the Standard Model at the LHC

Henri Bachacou

on behalf of the ATLAS and CMS Collaborations

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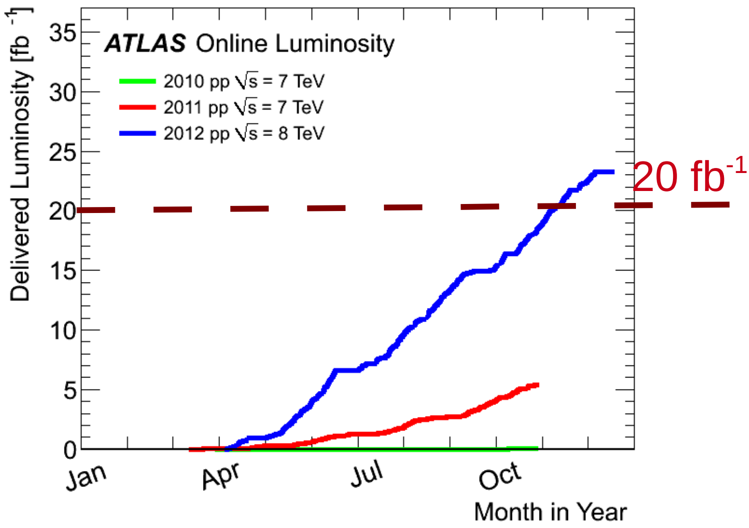
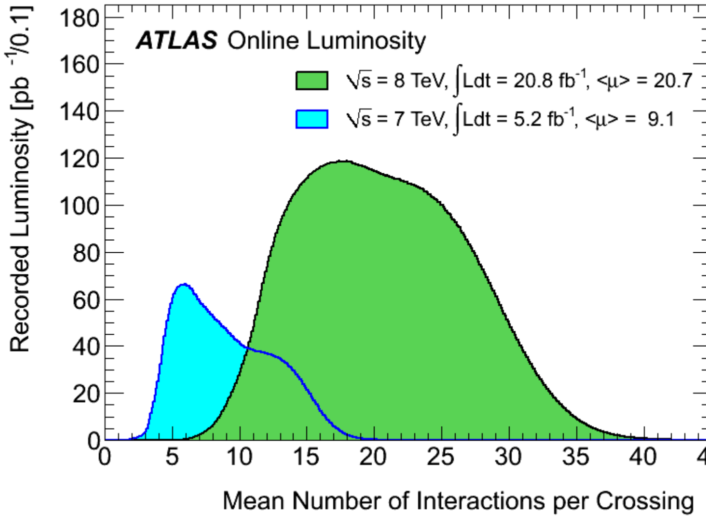
BSM at the LHC: Introduction

- The past two years have been extremely exciting
- Context for searches Beyond the Standard Model:
  - → A Standard Model-looking Higgs boson has been discovered!
  - → No sign of SUSY yet
  - → Exotic searches have never been more relevant
- In this talk I will focus on a selection of non-SUSY BSM searches at ATLAS and CMS
  - → Focus on latest results based on (a fraction of) 8 TeV 2012 data
  - → Many analyses are still work-in-progress
- Not showing all results from both experiments. Complete information about all results:
  - → CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
  - → ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic

The Large Hadron Collider (LHC)

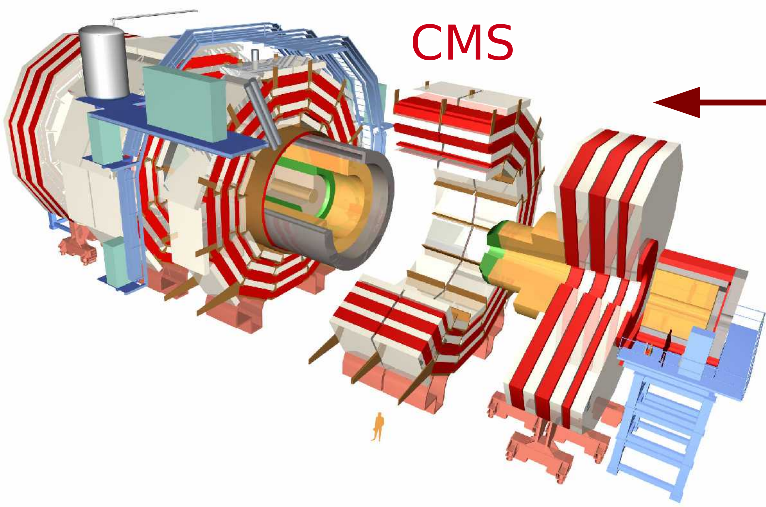
- pp collisions:
  - → 5 fb^{-1} at $\sqrt{s}$ = 7 in 2011
  - → 20 fb^{-1} at $\sqrt{s}$ = 8 TeV in 2012
- LHC has performed extremely well in 2012:
  - → 7.7 10^{33} /cm^2/s peak luminosity
  - → More than 20 fb^{-1} delivered to both experiments
- 50 ns bunch spacing
- Pile-up: ~ 20 collisions / crossing





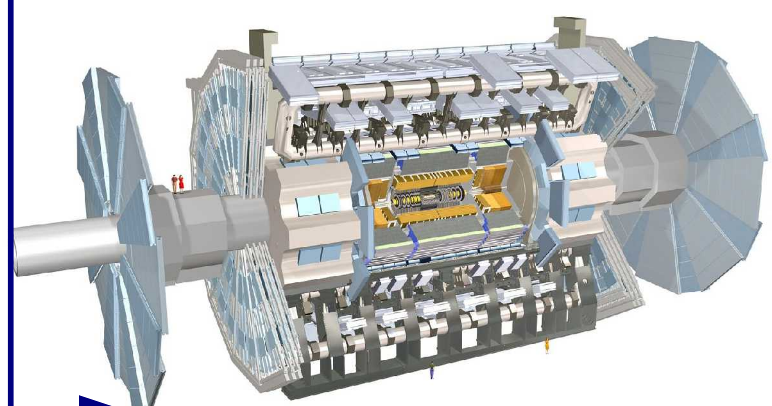
The ATLAS and CMS Detectors: same goals, different choices

CMS



- 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

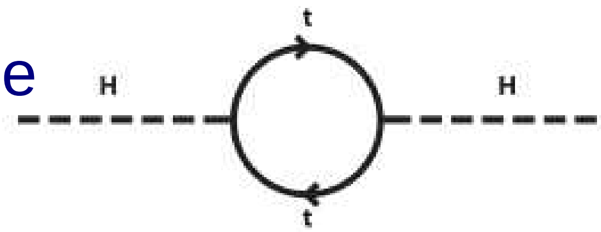
- 2T solenoid inside calorimeters
- Tracker: Silicon + TRT (incl. electron ID)
- EM cal: Longitudinally segmented Lead-Ar: $\sigma_E/E \sim 10\%/\sqrt{E[\mathrm{GeV}]} \oplus 0.7\%$
- HAD cal: Fe-scint + Cu-Ar, $\geq 11\lambda_0$
  $\sigma_E/E \sim 50\%/\sqrt{E[\mathrm{GeV}]} \oplus 3\%$
- Air-toroid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

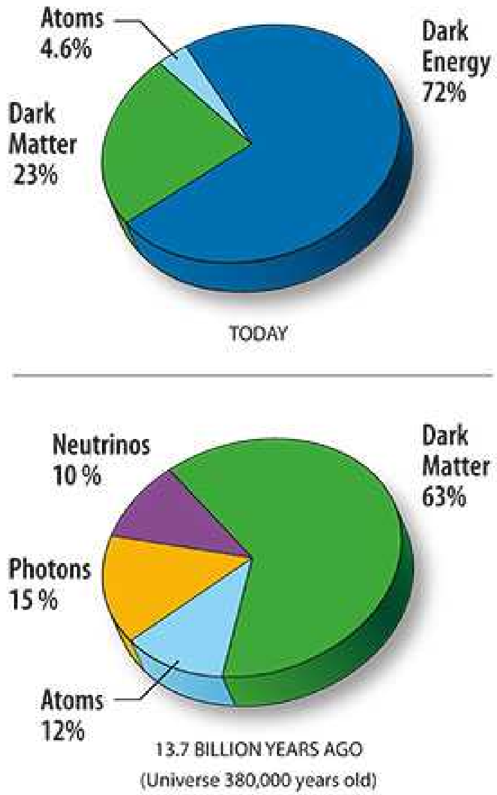


ATLAS

Why look "beyond" the Standard Model?

- The Standard Model is a (very) effective theory that breaks down at a certain scale
  - → Hierarchy: quadratic divergence of the Higgs mass, extremely fine-tuned
  - → What is the underlying nature of EWSB?
- Dark Matter
  - → cannot be explained by SM
- BSM models attempt to solve the SM limitations:
  - → SUSY
  - → Extra-dimensions
  - → Compositeness and Strong Interactions
  - → ...





A very long list of models x signatures

- 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
- What else?

(for illustration only)

- 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
- What else?

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A complex 2D problem

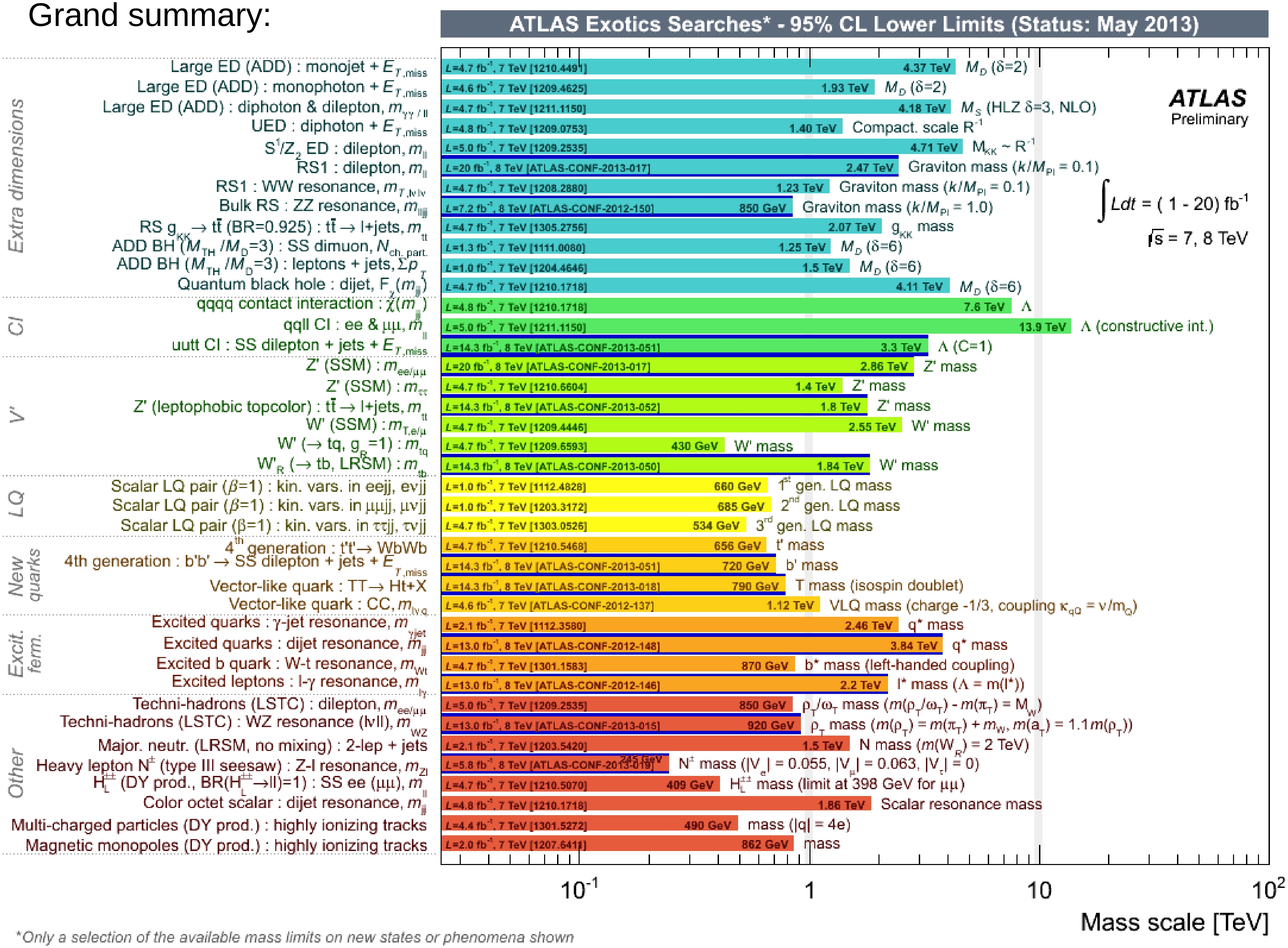
Experimentally, a signature standpoint makes a lot of sense:

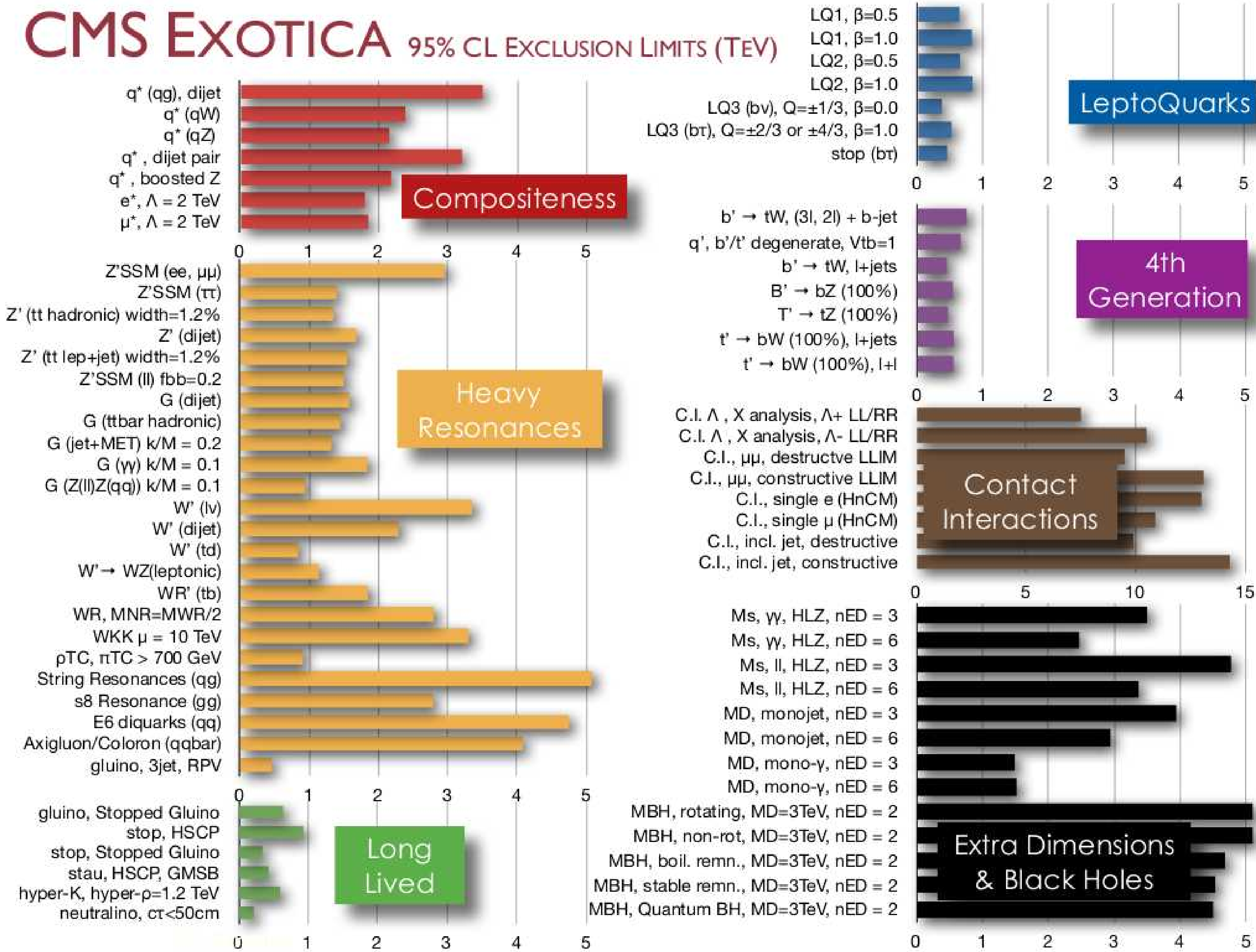
→ Practical

→ Less model-dependent

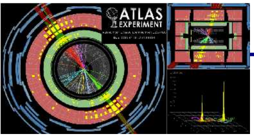
→ Important to cover every possible signature

Grand summary:




CMS EXOTICA 95% CL EXCLUSION LIMITS (TEV)
Compositeness
q* (qg), dijet
q* (qW)
q* (qZ)
q* , dijet pair
q* , boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
Heavy Resonances
Z'SSM (ee, μμ)
Z'SSM (ττ)
Z' (tt hadronic) width=1.2%
Z' (dijet)
Z' (tt lep+jet) width=1.2%
Z'SSM (ll) fbb=0.2
G (dijet)
G (ttbar hadronic)
G (jet+MET) k/M = 0.2
G (γγ) k/M = 0.1
G (Z(ll)Z(qq)) k/M = 0.1
W' (lν)
W' (dijet)
W' (td)
W'→ WZ(leptonic)
WR' (tb)
WR, MNR=MWR/2
WKK μ = 10 TeV
ρTC, πTC > 700 GeV
String Resonances (qg)
s8 Resonance (gg)
E6 diquarks (qq)
Axigluon/Coloron (qqbar)
gluino, 3jet, RPV
Long Lived
gluino, Stopped Gluino
stop, HSCP
stop, Stopped Gluino
stau, HSCP, GMSB
hyper-K, hyper-ρ=1.2 TeV
neutralino, cτ<50cm
LeptoQuarks
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3 (bν), Q=±1/3, β=0.0
LQ3 (bτ), Q=±2/3 or ±4/3, β=1.0
stop (bτ)
4th Generation
b' → tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' → tW, l+jets
B' → bZ (100%)
T' → tZ (100%)
t' → bW (100%), l+jets
t' → bW (100%), l+l
Contact Interactions
C.I. Λ , X analysis, Λ+ LL/RR
C.I. Λ , X analysis, Λ- LL/RR
C.I., μμ, destructve LLIM
C.I., μμ, constructive LLIM
C.I., single e (HnCM)
C.I., single μ (HnCM)
C.I., incl. jet, destructive
C.I., incl. jet, constructive
Extra Dimensions & Black Holes
Ms, γγ, HLZ, nED = 3
Ms, γγ, HLZ, nED = 6
Ms, ll, HLZ, nED = 3
Ms, ll, HLZ, nED = 6
MD, monojet, nED = 3
MD, monojet, nED = 6
MD, mono-γ, nED = 3
MD, mono-γ, nED = 6
MBH, rotating, MD=3TeV, nED = 2
MBH, non-rot, MD=3TeV, nED = 2
MBH, boil. remn., MD=3TeV, nED = 2
MBH, stable remn., MD=3TeV, nED = 2
MBH, Quantum BH, MD=3TeV, nED = 2

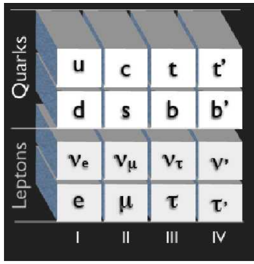
Outline



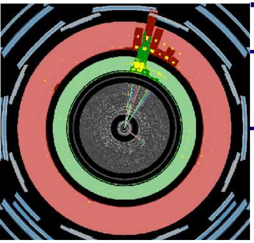
Heavy Resonances

- → Dilepton
- → Dijet
- → Top-Antitop

4th generation and heavy “quarks”



- → Vector-like quarks



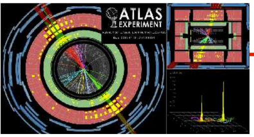
TeV-gravity and Dark Matter

- → Monojets

Long-lived particles and more exotic final states

- → Stopped particles
- → Exotic Higgs decays

Outline



Heavy Resonances

- → Dilepton
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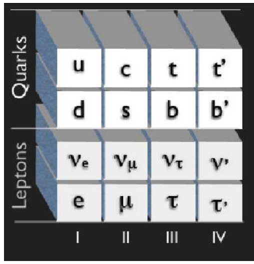
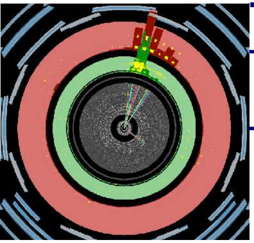
4th generation and heavy "quarks"

- → Vector-like quarks





TeV-gravity and Dark Matter

- → Monojets

Long-lived particles and more exotic final states

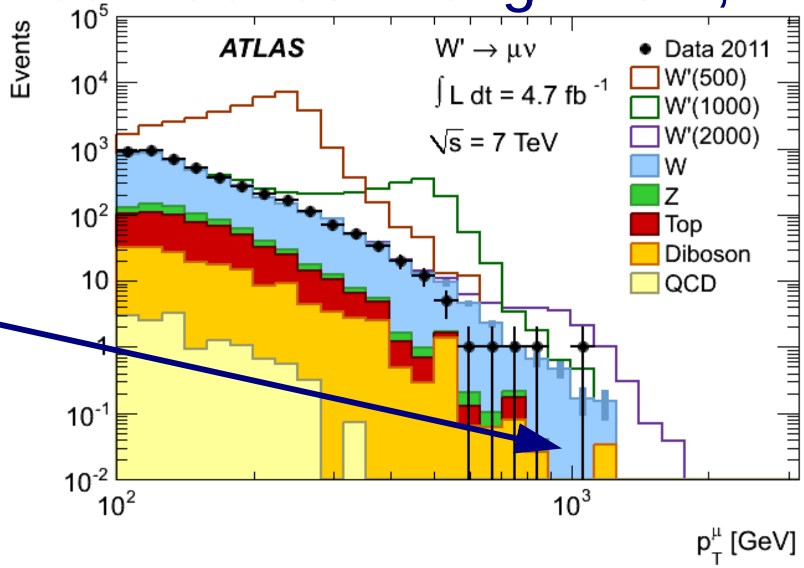
- → Stopped particles
- → Exotic Higgs decays

Search for Heavy Resonance

- Predicted by numerous extensions of the Standard Model:
  - → Heavy gauge boson(s) Z' (W'): GUT-inspired theories, Little Higgs
  - → Kaluza-Klein excitations: Randall-Sundrum extra-dimensions

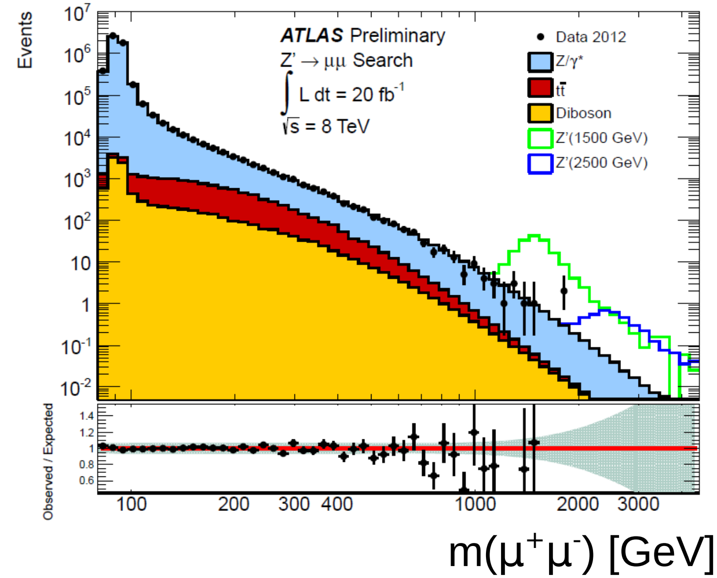
- Experimental challenge: understand detector performance (resolution, efficiency) for a signal with (almost) no control sample at very high momentum → confidence in alignment, simulation, etc...
- Electrons and muons:

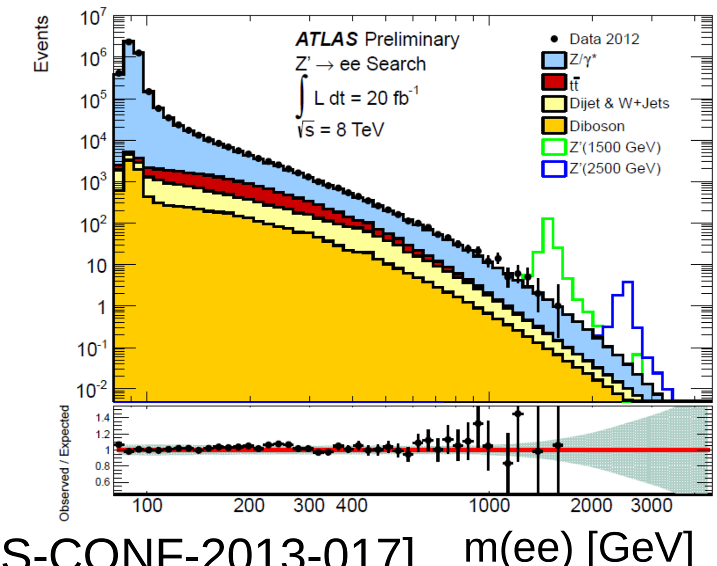
  reaching pT ~ 1 TeV!



Search for Heavy Resonance: dilepton channel

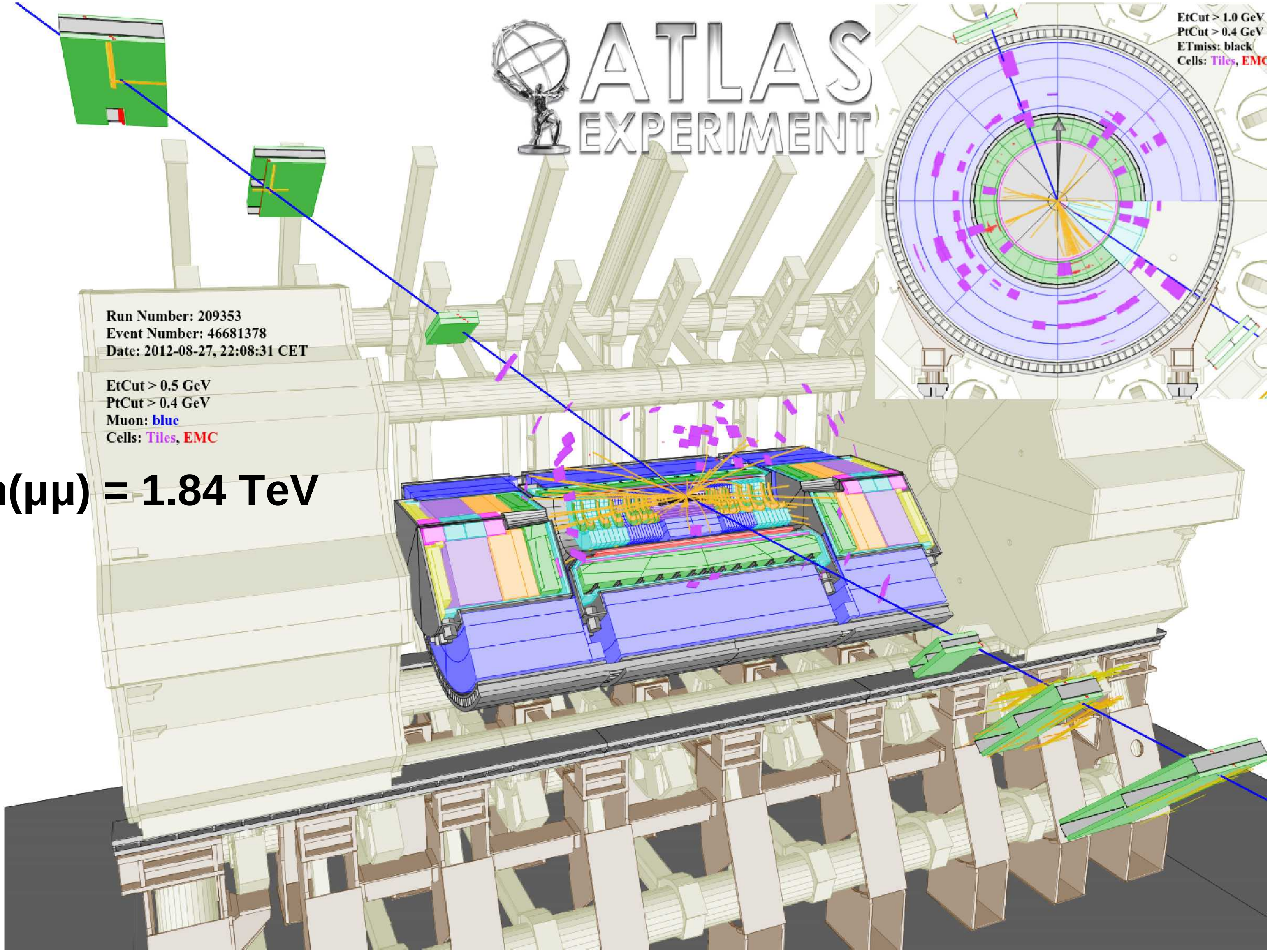
- **Dimuon channel:**
  - → 30 μm muon spectrometer alignment critical (ATLAS)
  - → Resolution 10-15% at p_T = 1 TeV
- **Dielectron channel:**
  - → Excellent resolution: < 2% at high momentum
  - → Poor charge measurement → no charge requirement
- **No discrepancy from SM Drell-Yan (both ATLAS and CMS)**





[ATLAS-CONF-2013-017]

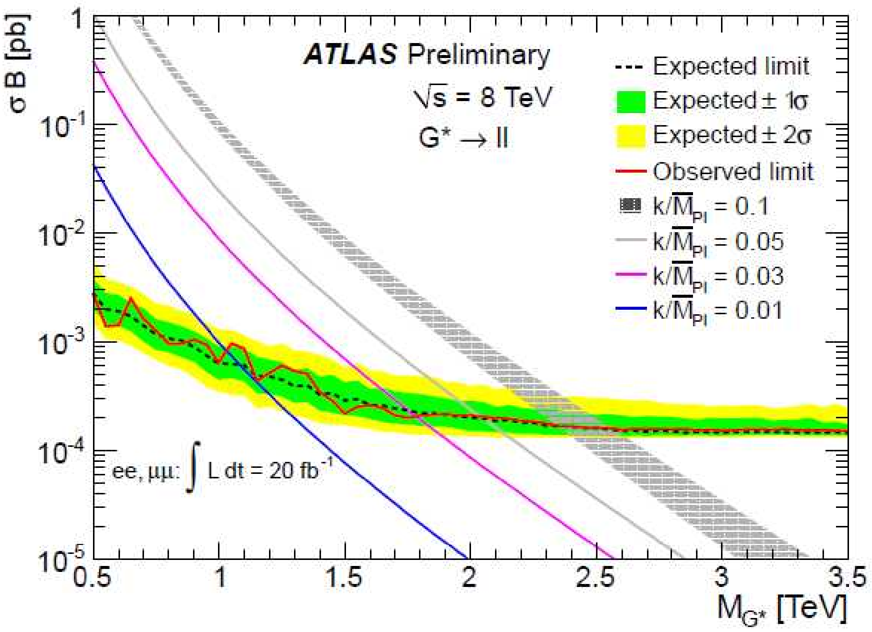
Search for Heavy Resonance: dilepton channel

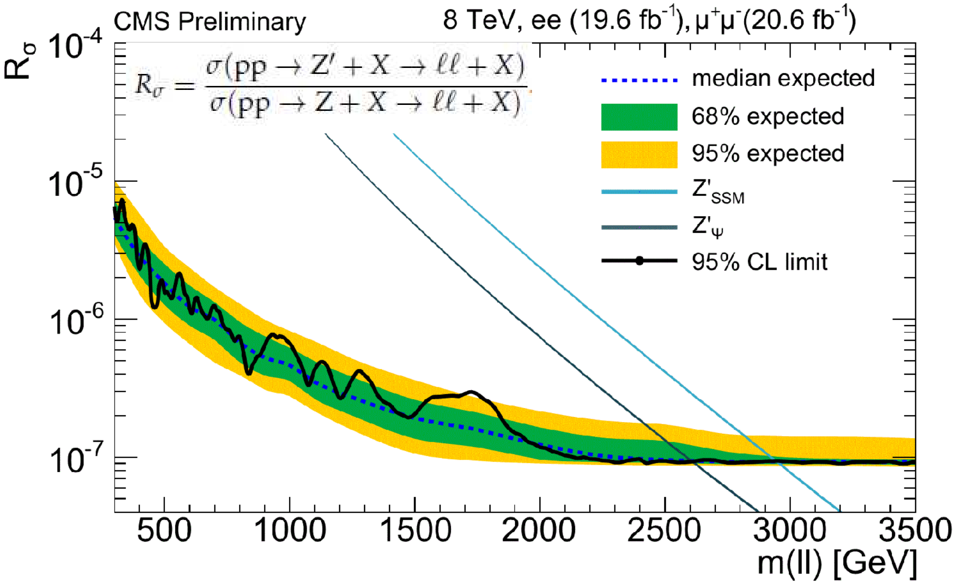


m(μμ) = 1.84 TeV

Search for Heavy Resonance: dilepton channel

- Sequential SM: assume Z' with same couplings as SM Z
- Randall-Sundrum KK graviton





Observed lower limits (TeV) at 95% CL:

Model	ATLAS	CMS
SSM Z’	2.86	2.96
E6 Z'_{ψ}	2.38	2.60
RS G* (k/M_{pl} = 0.1)	2.47	

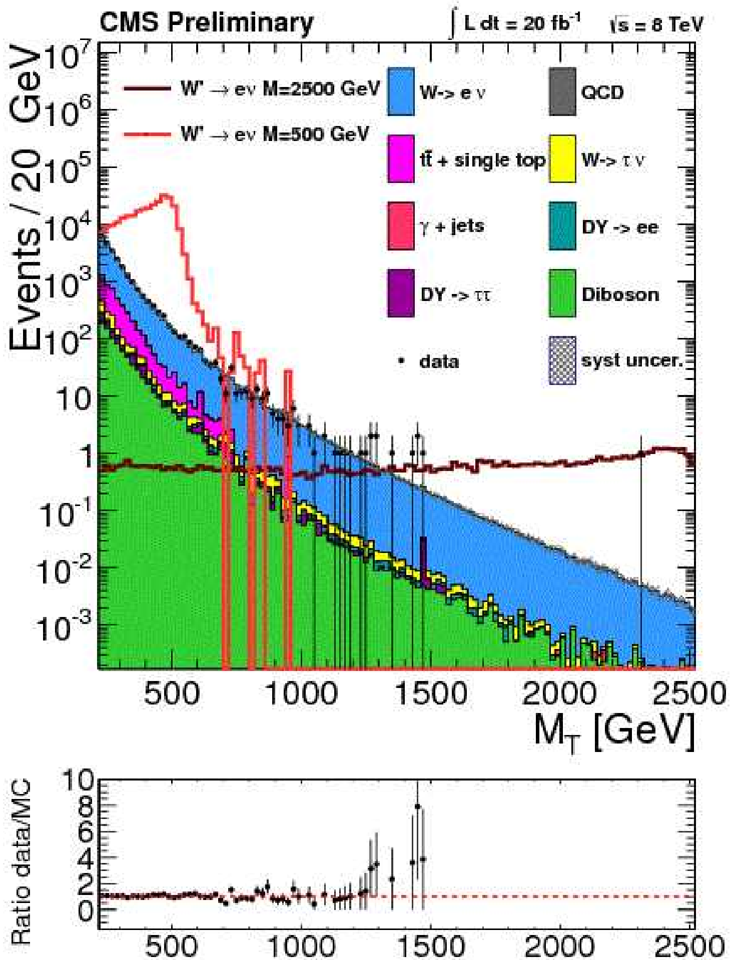
[ATLAS-CONF-2013-017]

[CMS PAS EXO-12-061]

Search for Heavy Resonance: W' → lν

- W': the charged equivalent of the Z'
- Bulk-RS: excited KK W
- Final state: 1 lepton + Missing E_T
- Look for Jacobian peak in transverse mass:

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



Electron channel

[CMS PAS EXO-12-060]

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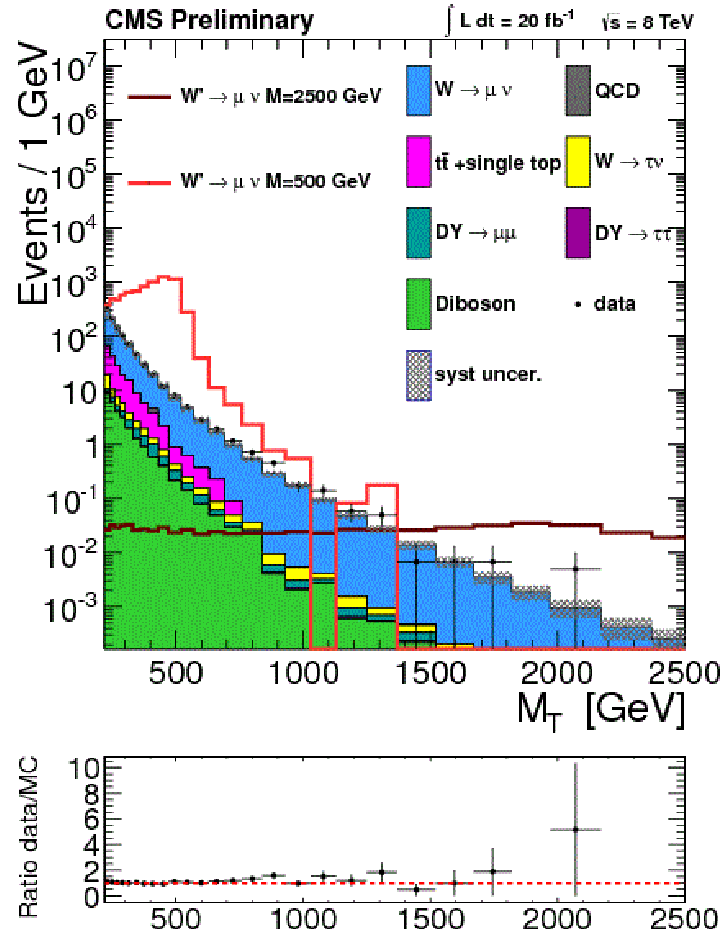

Muon channel

[CMS PAS EXO-12-060]

Search for Heavy Resonance: W' → lν

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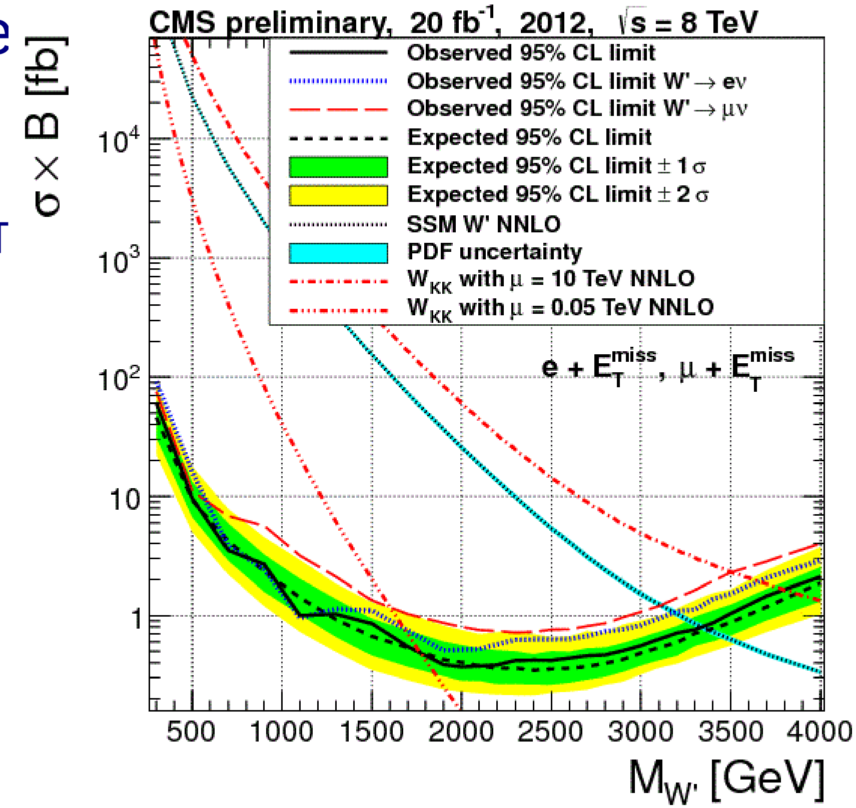
Sequential SM:

m(W') > 3.35 TeV at 95% C.L.



Muon channel

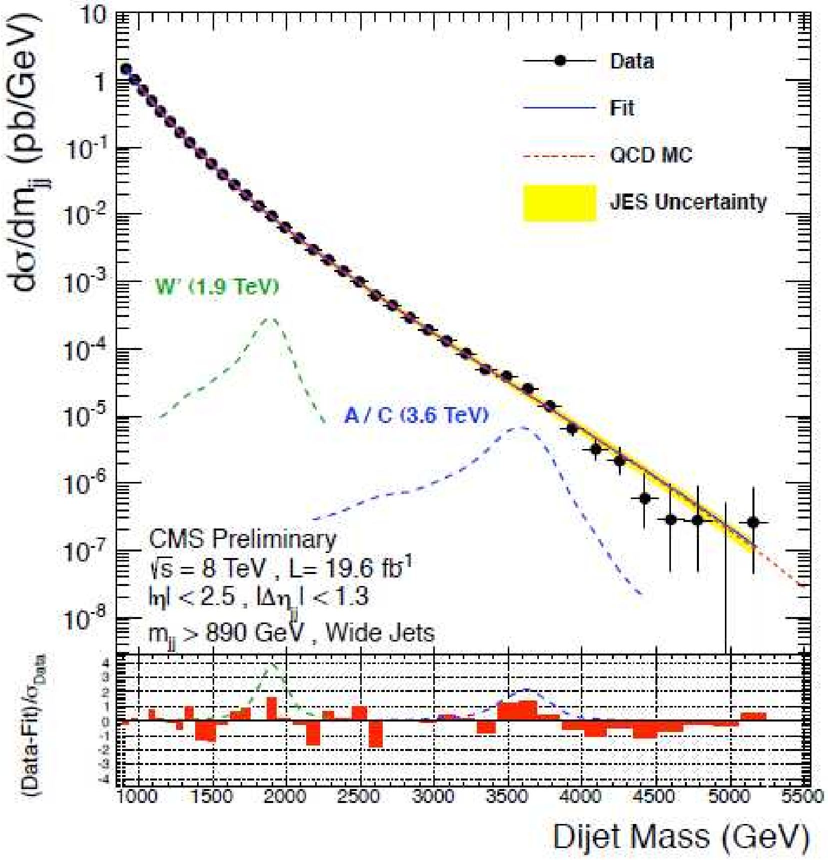
[CMS PAS EXO-12-060]

Search for Heavy Resonance: Dijet

- W'/Z', excited quarks, strong gravity
- Look for resonance above phenomenological fit of the data:
- ATLAS versus CMS analysis in a nutshell:
  - → 1-jet triggers E_T~350 GeV vs H_T/m(jj) at HLT
  - → anti-k_T R=0.6 jets vs wide jets (R~1.1)
- Both Experiments:
  - → rapidity cuts to enhance central scattering
  - → selection requires m(jj) ≳ 1 TeV

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

CMS 20 fb^{-1} @ 8 TeV [EXO-12-059]



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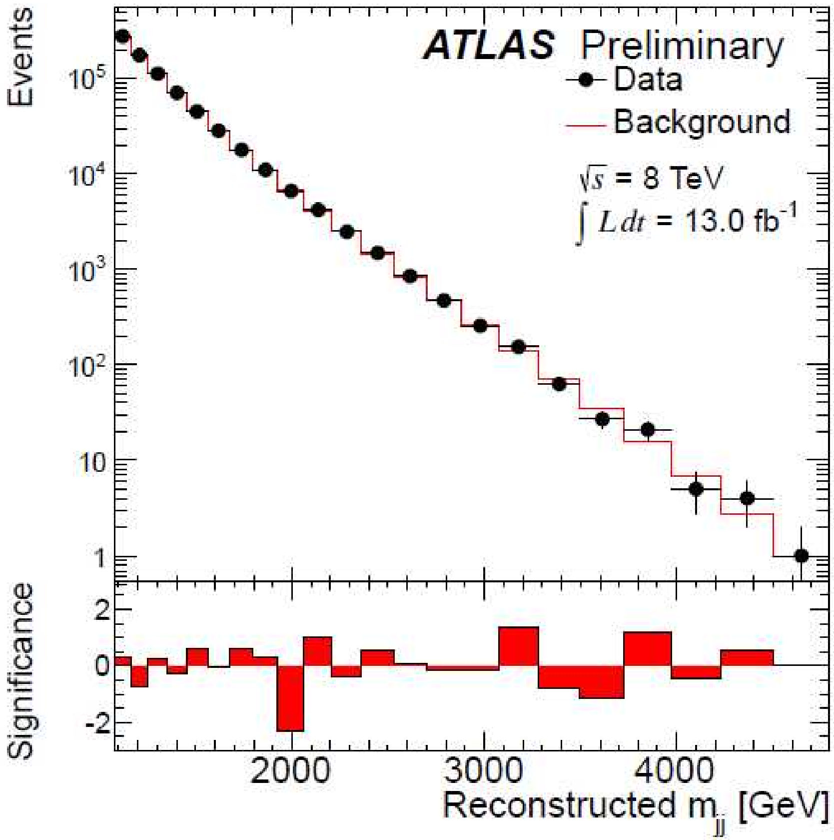
- Both Experiments:
  - → rapidity cuts to enhance central scattering
  - → selection requires m(jj) $\gtrsim$ 1 TeV

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

ATLAS 13 fb^{-1} @ 8 TeV [CONF-2012-148]



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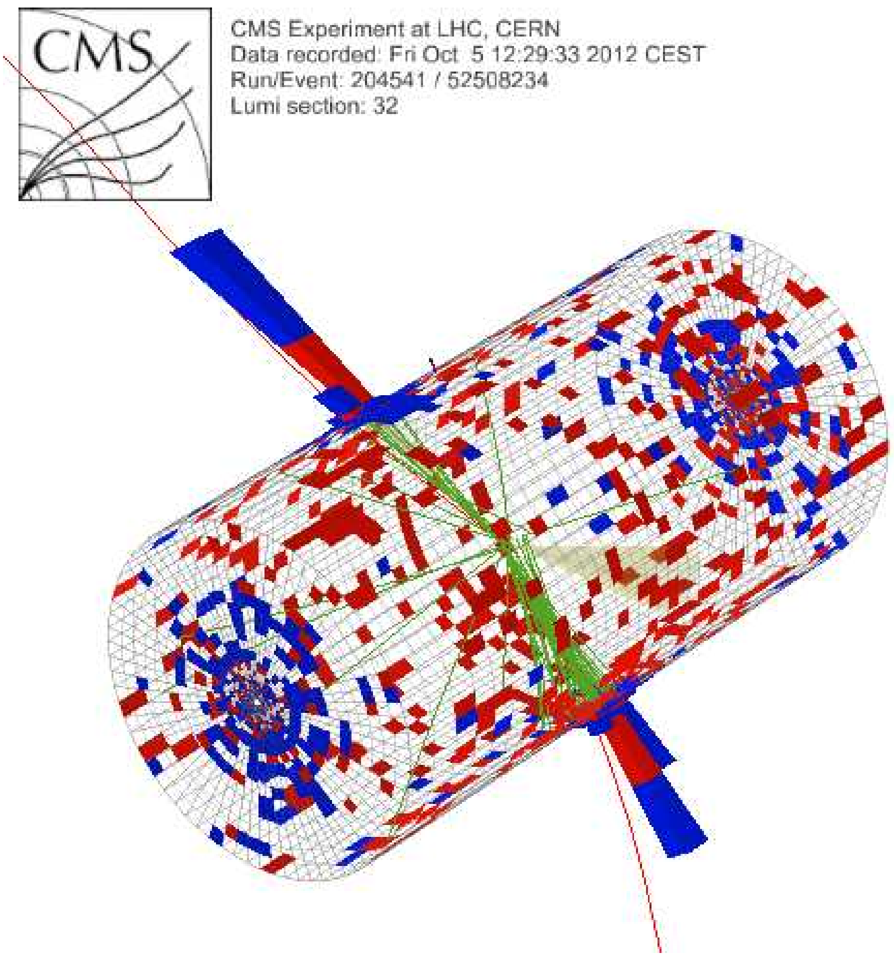
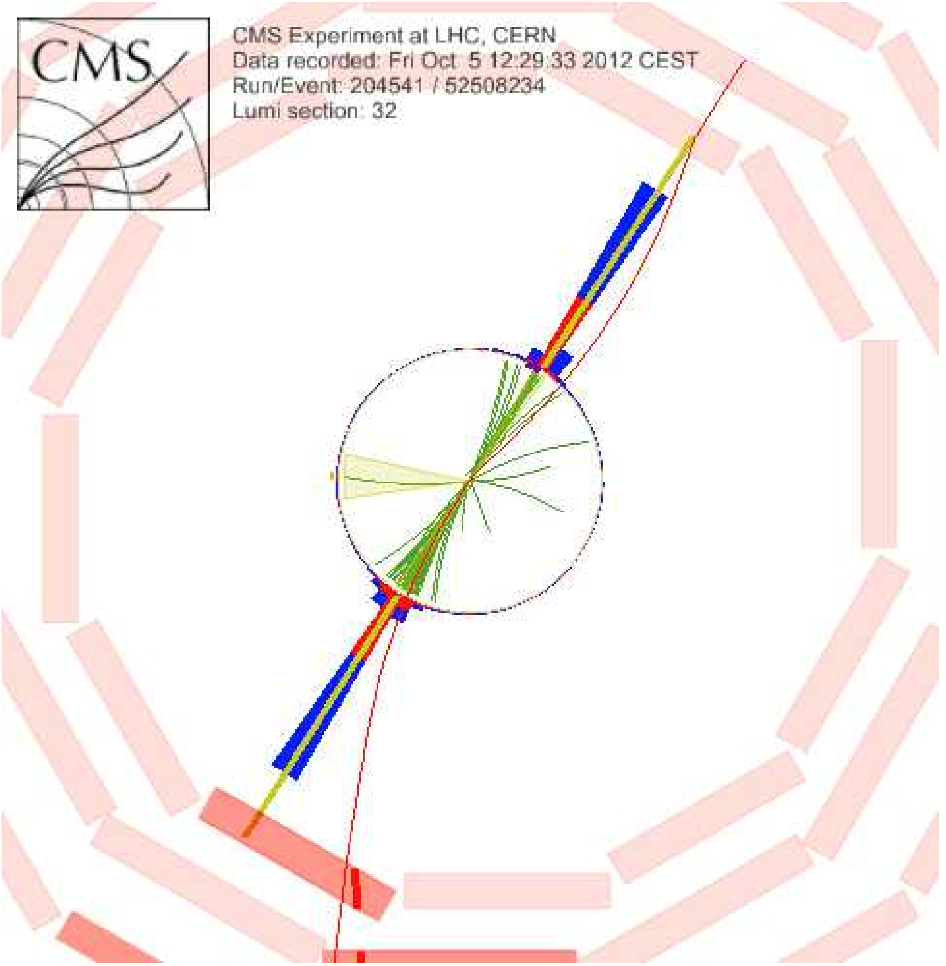
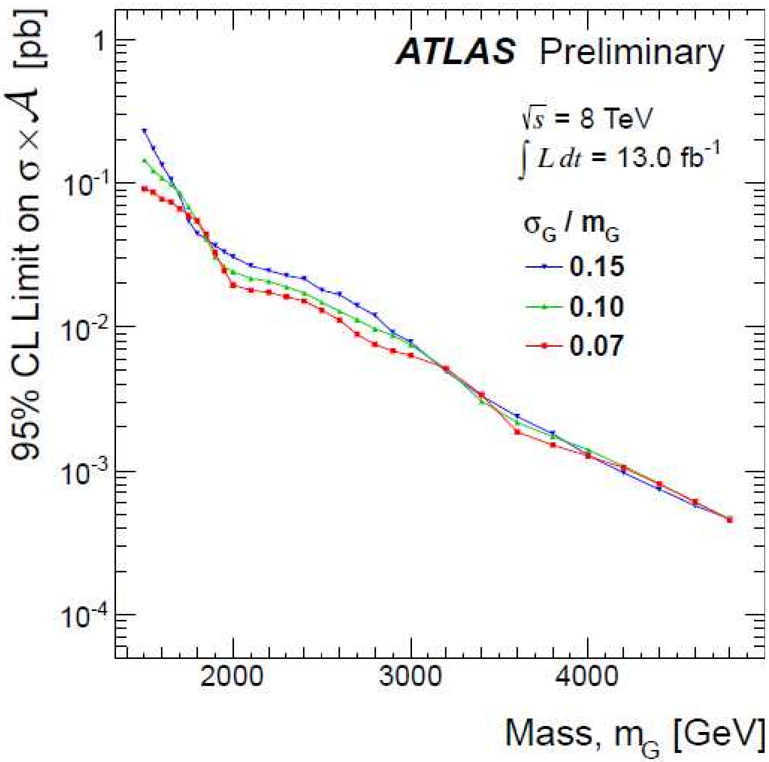
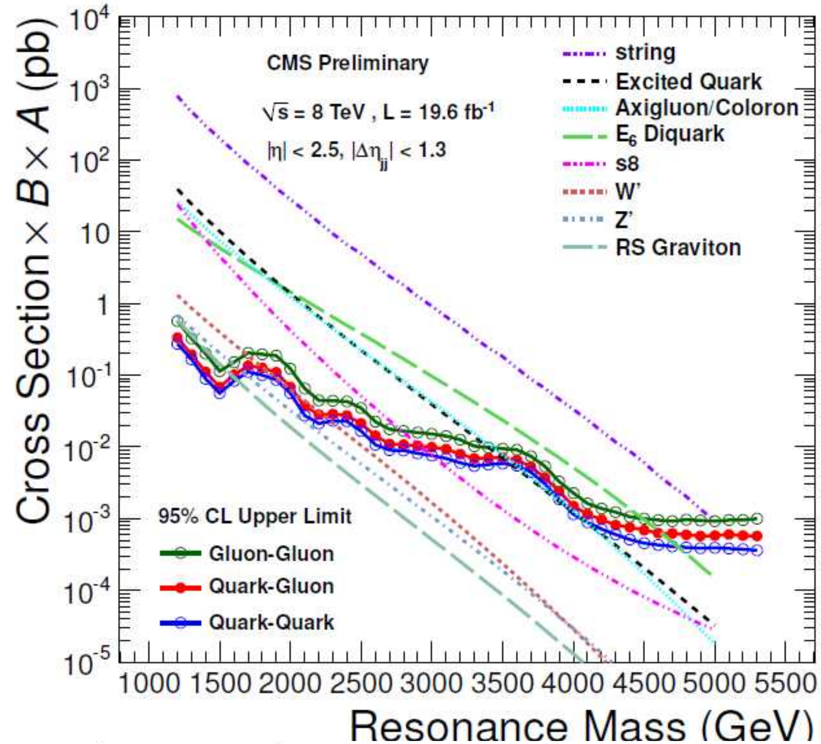




Highest mass dijet event with central jets: **m(jj) = 5.15 TeV**

Search for Heavy Resonance: Dijet





ATLAS 13 fb^{-1} @ 8 TeV:

Excited quark:
1 < m(q*) < 3.84 TeV (exp 3.70)

[ATLAS-CONF-2012-148]

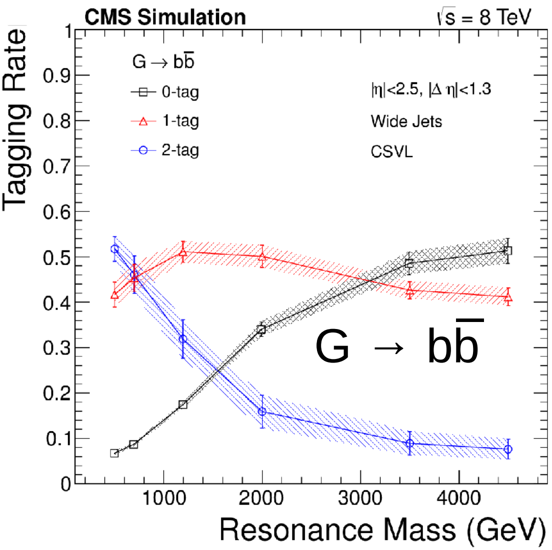
[CMS PAS EXO-12-059]

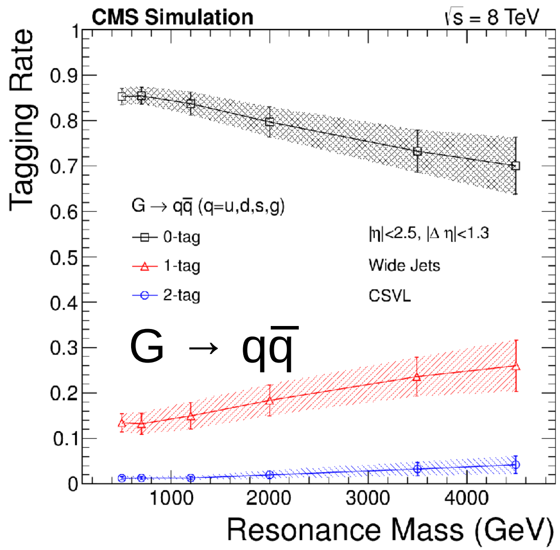
CMS

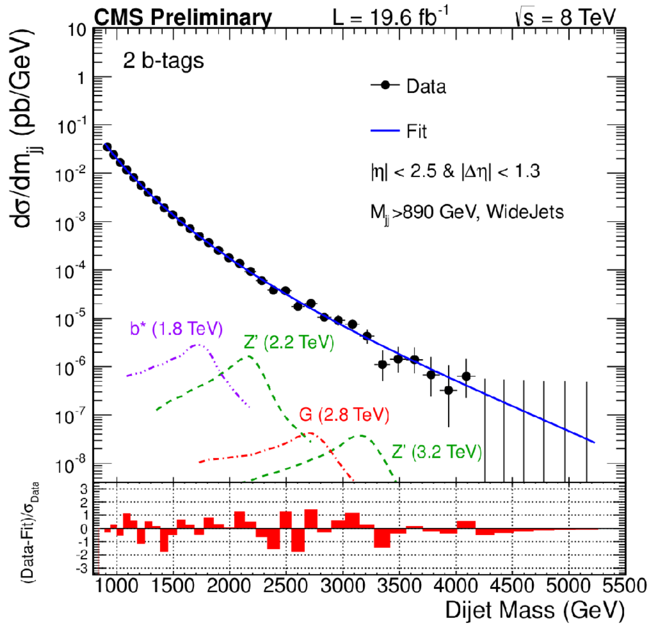
Model	Final State	Obs. Mass Excl. [TeV]	Exp. Mass Excl. [TeV]
String Resonance (S)	qg	[1.20,5.08]	[1.20,5.00]
Excited Quark (q*)	qg	[1.20,3.50]	[1.20,3.75]
E_6 Diquark (D)	qq	[1.20,4.75]	[1.20,4.50]
Axigluon (A)/Coloron (C)	$q\bar{q}$	[1.20,3.60] + [3.90,4.08]	[1.20,3.87]
Color Octet Scalar (s8)	gg	[1.20,2.79]	[1.20,2.74]
W′ Boson (W′)	$q\bar{q}$	[1.20,2.29]	[1.20,2.28]
Z′ Boson (Z′)	$q\bar{q}$	[1.20,1.68]	[1.20,1.87]
RS Graviton (G)	$q\bar{q}$+gg	[1.20,1.58]	[1.20,1.43]

Search for Heavy Resonance: b-Jets

- Look specifically for decays to bottom quarks (bb) or a gluon and a bottom (bg)
- Require 0, 1, or 2 b-tagged jets





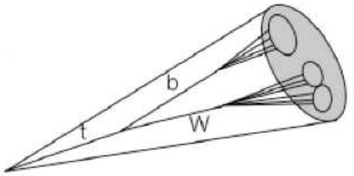


Observed 95% C.L. excluded masses (TeV):

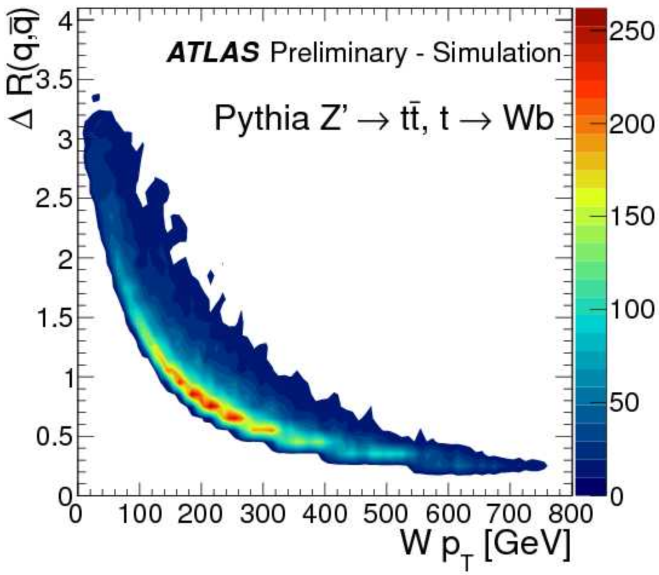
	this analysis	untagged
Z' (f_{bb}=0.2)	[1.20, 1.68]	[1.20, 1.68]
RS G (f_{bb}=0.1)	[1.24, 1.57]	[1.20, 1.58]
b*→bg	[1.34, 1.54]	N/A

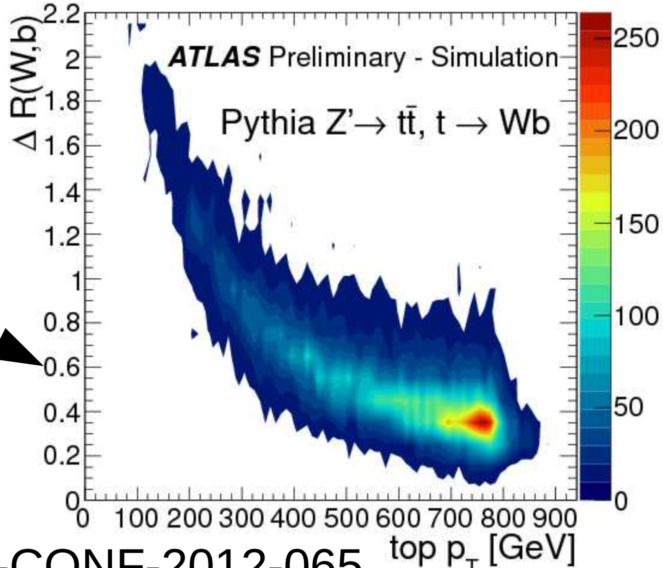
[CMS PAS EXO-12-023]

Top-antitop Resonance



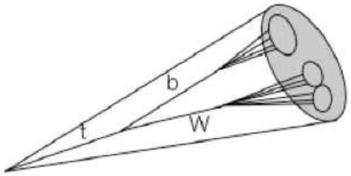
- Leptophobic Z' (topcolor)
- KK gluon (bulk RS models)
- Large Branching Ratio to top-antitop.
  - → BR(Z' → tt) ~ 33%
  - → BR(KK g → tt) > 90%
- For m(tt) > 1 TeV, specific boosted top reconstruction needed
  - → Experimentally: a whole new field!



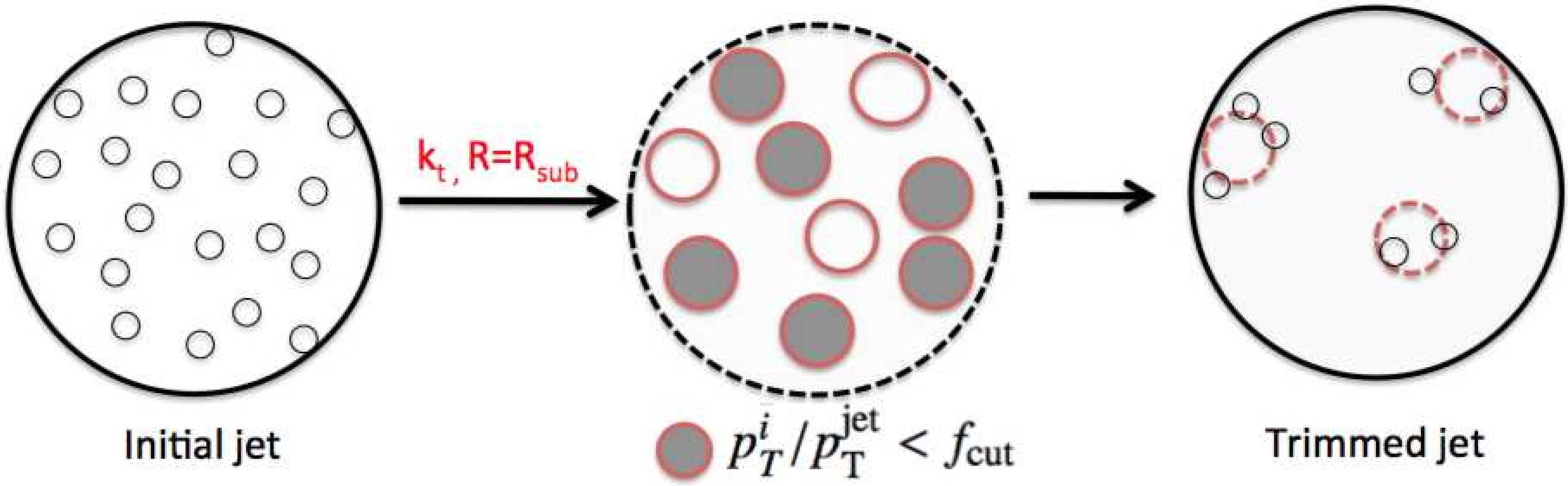


ATLAS-CONF-2012-065

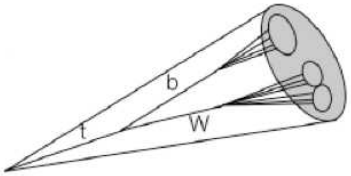
“Fat” Jets and Jet “Trimming”



- Reconstruct jets with a large cone (R ~ 1 or more), a.k.a. “fat” jets, to encompass all decay products
- Soft radiation (incl. pile-up) important → must be removed
- “Trimming”:
  - → Run k_t algorithm on clusters within the fat jet
  - → Keep only clusters with pT > pT(fat jet) . f_{cut}

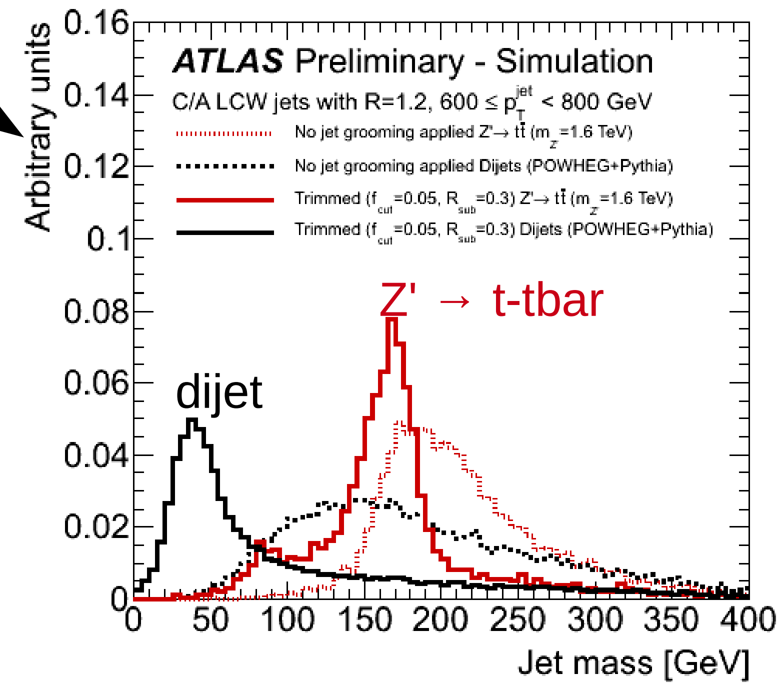


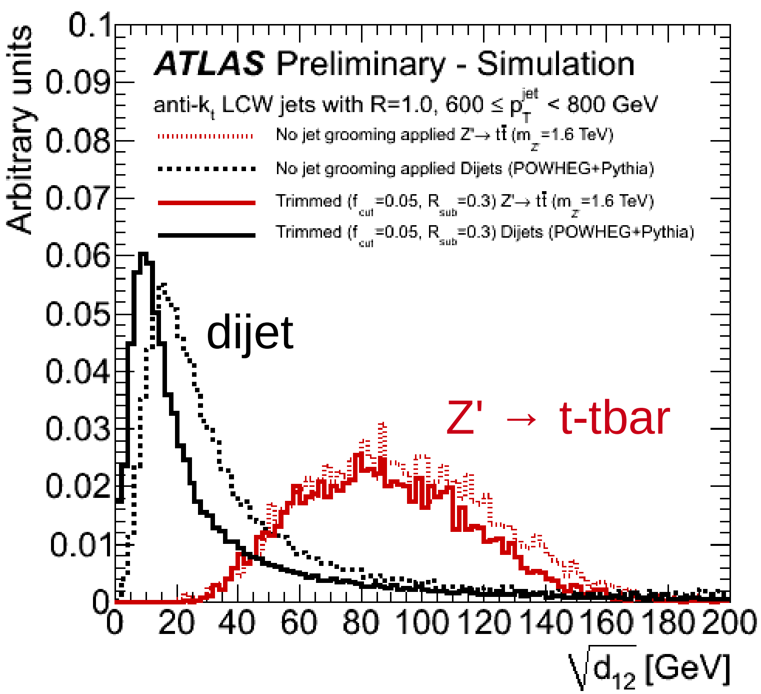
Jet Substructure Variables



- Jet mass: $(m^{\mathrm{jet}})^2 = (\sum_i E_i)^2 - (\sum_i p_i)^2$
- Splitting scales: Un-do the last step(s) of the k_t algorithm and look at the properties of the protojets:

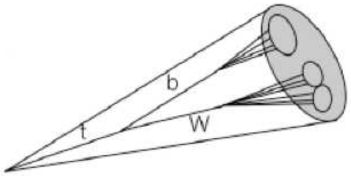
$$\sqrt{d_{ij}} = \min(p_{\mathrm{T}i}, p_{\mathrm{T}j}) \times \Delta R_{ij}$$



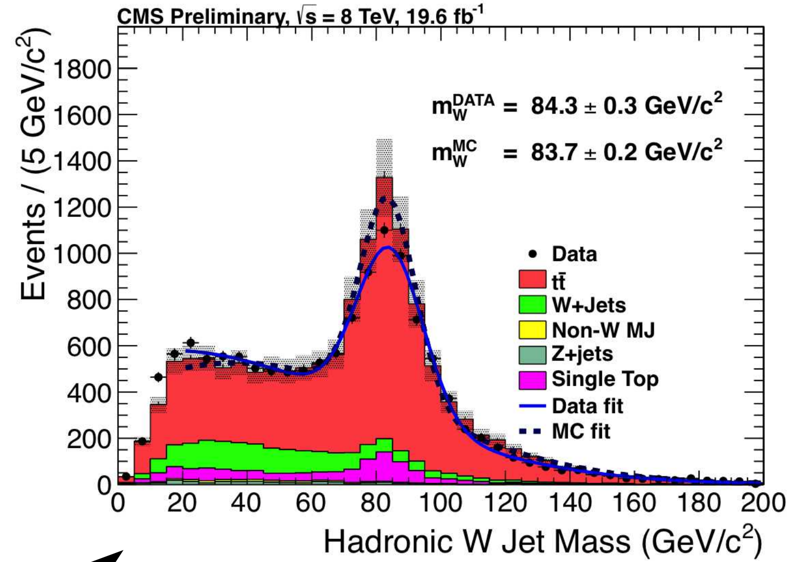


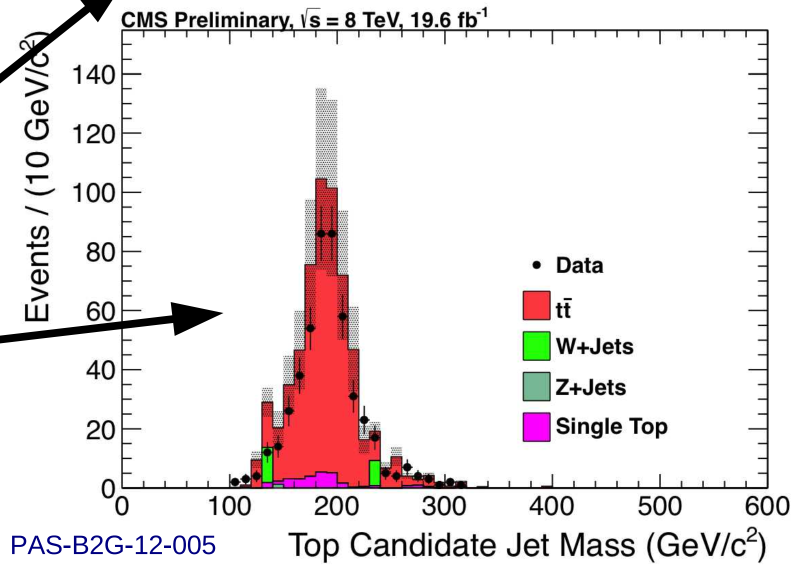
- Typically, for a W → qq decay: Last two proto-jets are the two jets from the W: $pT_1 \sim pT_2$ and ΔR are large

Boosted Top Reconstruction (CMS)



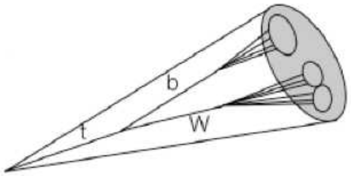
- CMS Top Tagger:
- "Fat" jet: Cambridge-Aachen jet with R = 0.8
- Cuts on jet substructure variables:
  - → Jet mass in [140, 250] GeV
  - → Number of sub-jets ≳ 3
  - → Minimum pairwise sub-jet mass > 50 GeV
- Use W mass for calibration
- Well-reconstructed top mass in boosted events





PAS-B2G-12-005

Top-antitop Resonance



- Event Topology:

  t-tbar → Wb Wb

- Final state depends on W decays:
  - → All-hadronic final state:

    2 W → jj

    2 b-jets + 4 light jets (+0ν)
  - → <u>Lepton+Jets final state:</u>

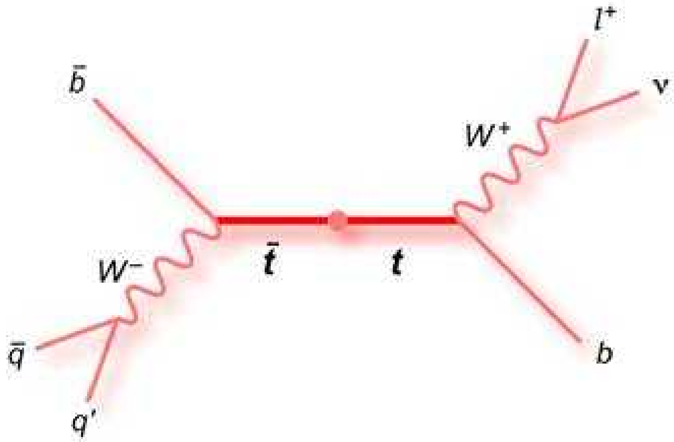
    1 W → lν, 1 W → jj

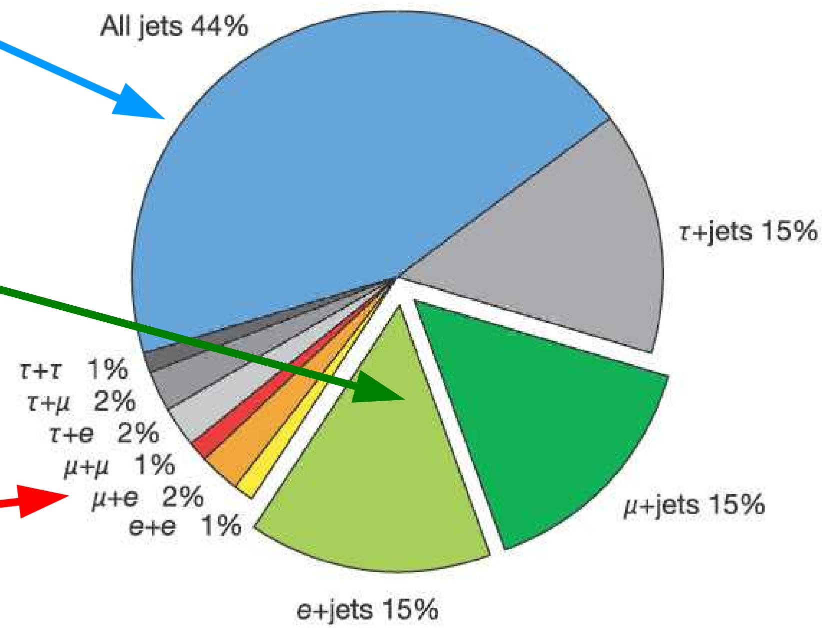
    1l + 2 b-jets + 2 light jets (+1ν)
  - → Dilepton final state:

    Both W → lν (l = e or μ)

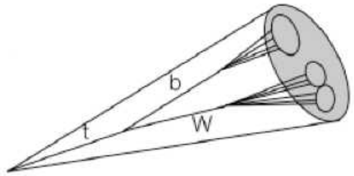
    2l + 2 b-jets (+2 neutrinos)

Larger Branching Ratio but more background

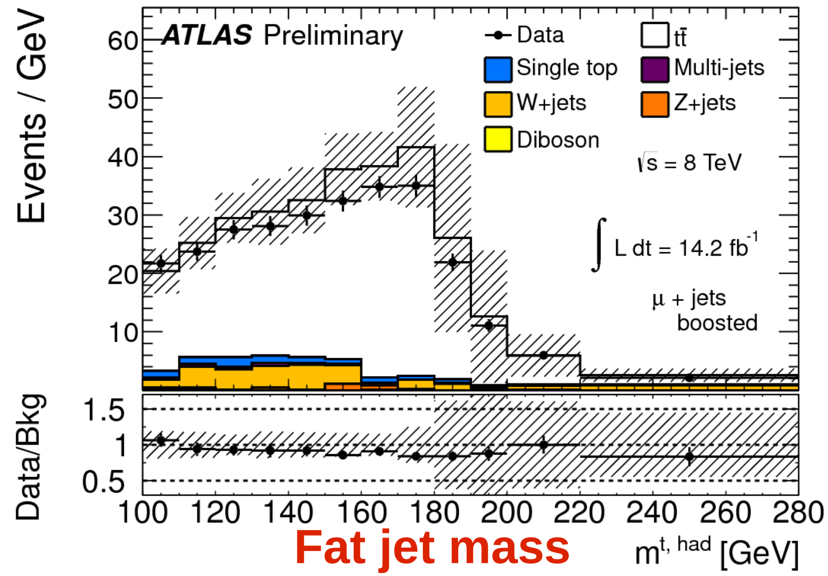




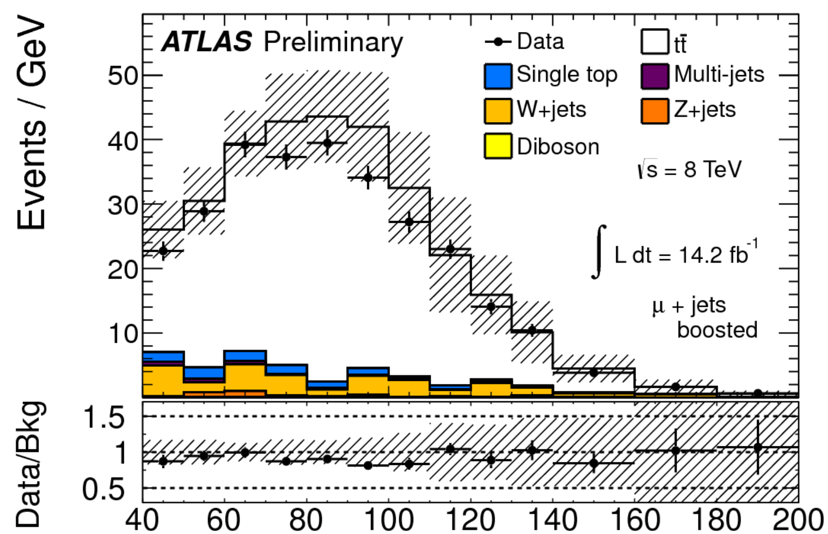
Top-antitop Resonance Lepton+Jets Channel (ATLAS)



- Combine two event selections:
  - → “resolved” : standard top reconstruction with narrow jets
  - → “boosted” : anti-kT R=1.0, p_T>350 GeV, m>100GeV, $\sqrt{d_{12}}$>40GeV
- Improve efficiency at high t-tbar mass with:
  - → Lepton “mini-isolation”: smaller isolation cone at high momentum
  - → Trigger: Fat Jet trigger (anti-kt jet R=1.0, p_T>240 GeV)
- Thousands of boosted t-tbar events reconstructed

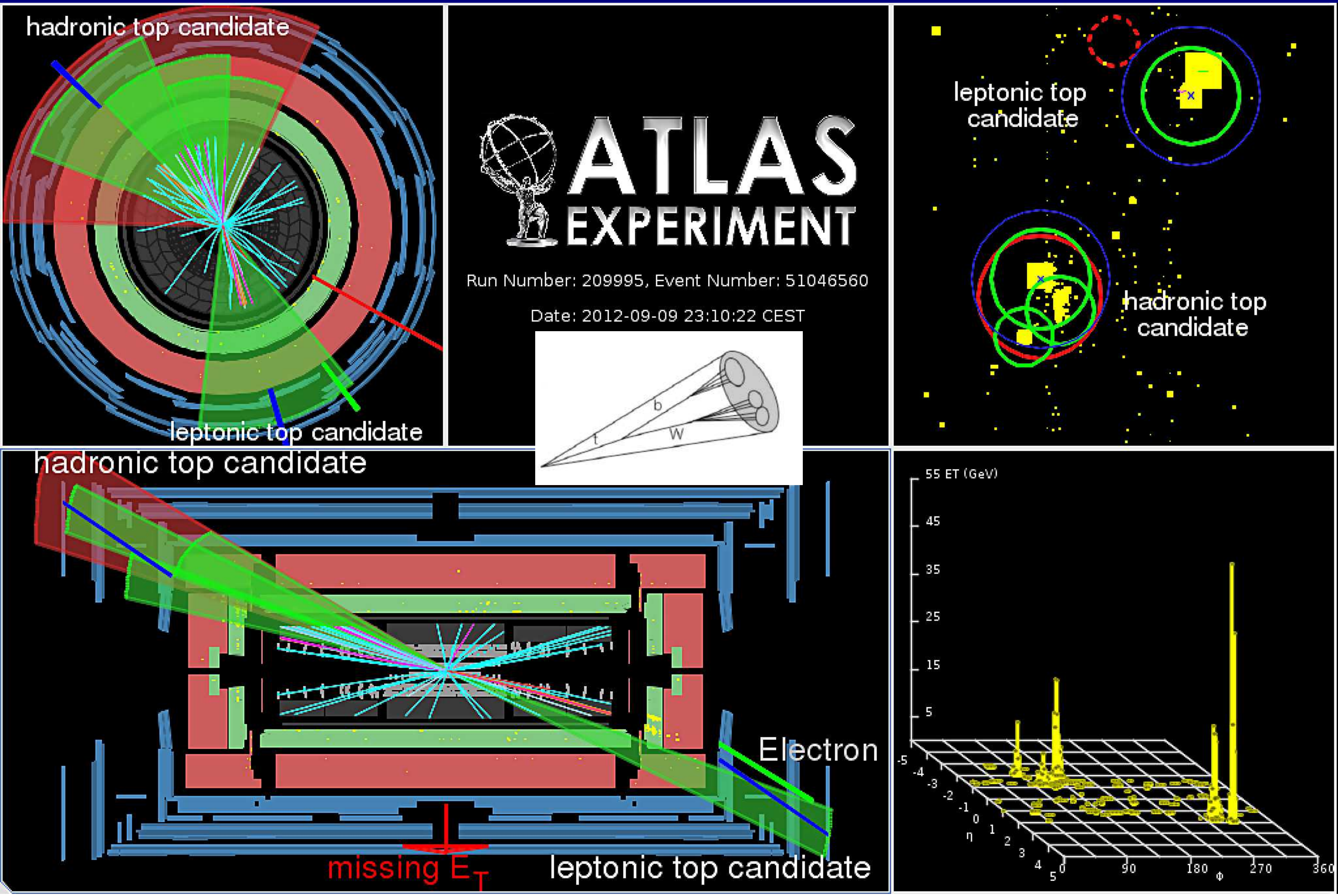


Fat jet mass

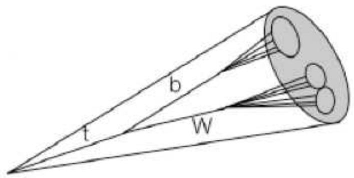


[ATLAS-CONF-2013-052]

sqrt(d_{12})

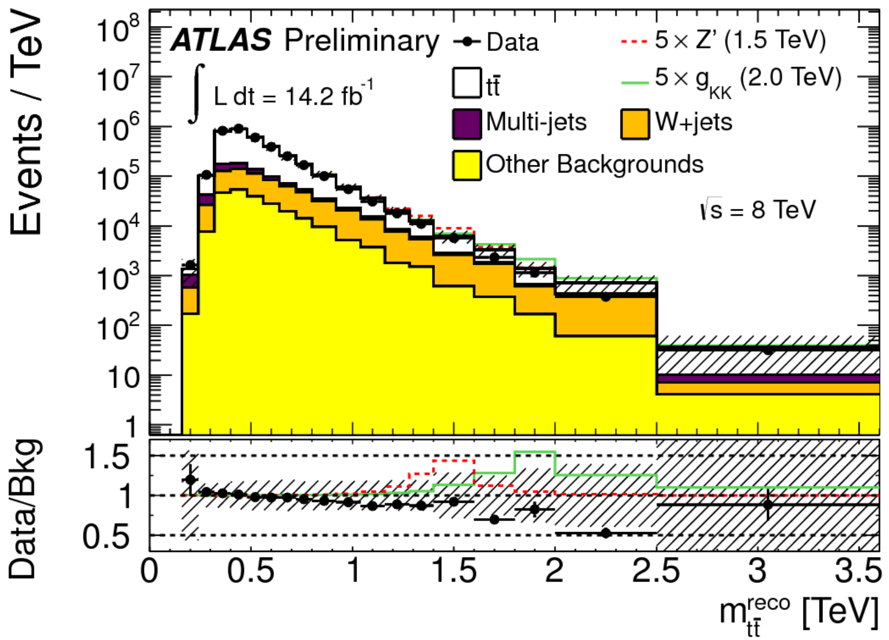

hadronic top candidate
leptonic top candidate
ATLAS EXPERIMENT
Run Number: 209995, Event Number: 51046560
Date: 2012-09-09 23:10:22 CEST
b
t
W
leptonic top candidate
hadronic top candidate
hadronic top candidate
Electron
missing E_T
leptonic top candidate
55 ET (GeV)
45
35
25
15
5
η
Φ
0
90
180
270
360

Top-antitop Resonance L+Jets Channel



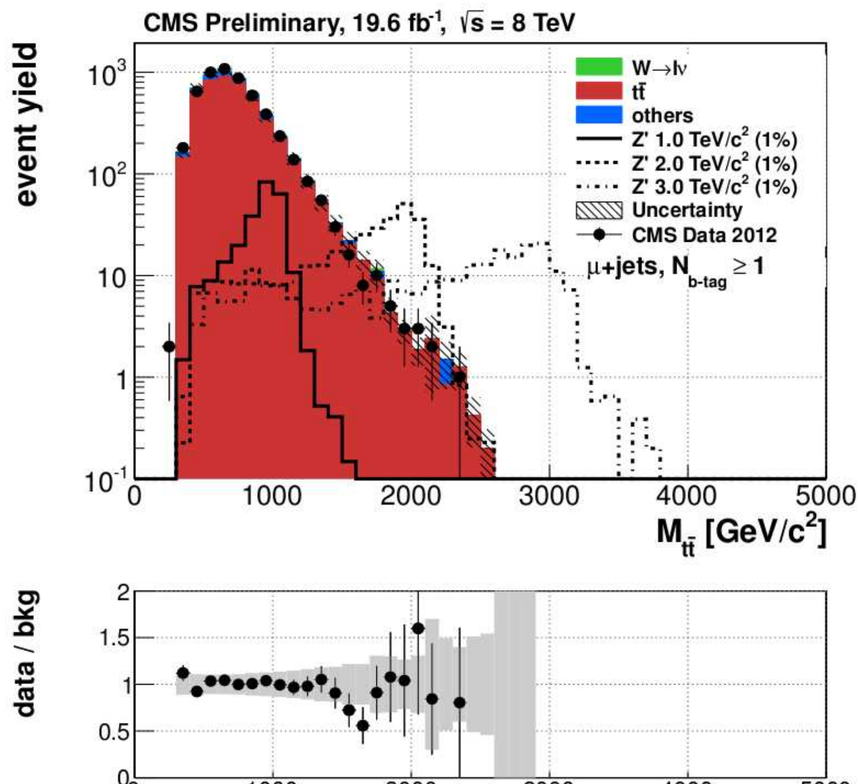
- Top-antitop mass spectra (muon channels):

ATLAS 14.2 fb^{-1}



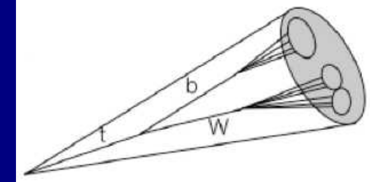
[ATLAS-CONF-2013-052]

CMS 19.6 fb^{-1}



[CMS PAS B2G-12-006]

Top-antitop Resonance L+Jets Channel



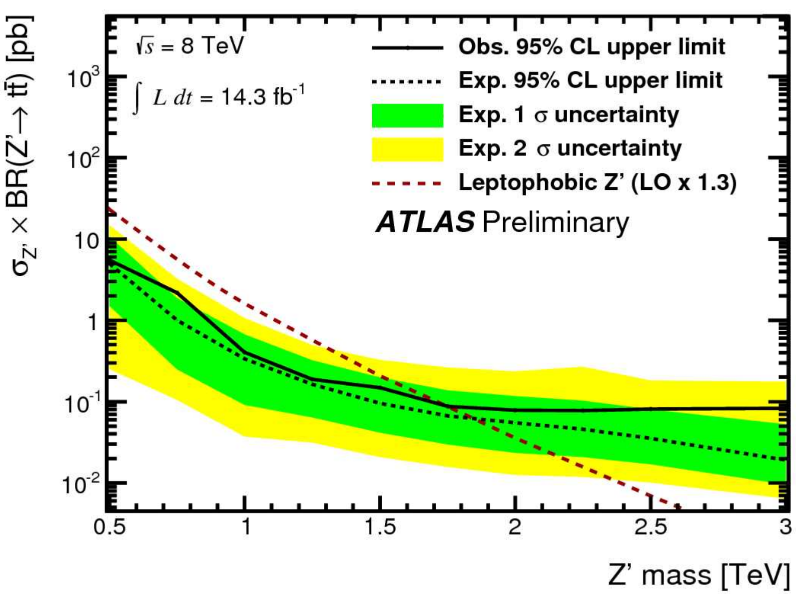
- CMS (20 fb^{-1}):

  m(Z' 1.2% width) > 2.1 TeV m(KK gluon, 1.3xL0) > 2.5 TeV

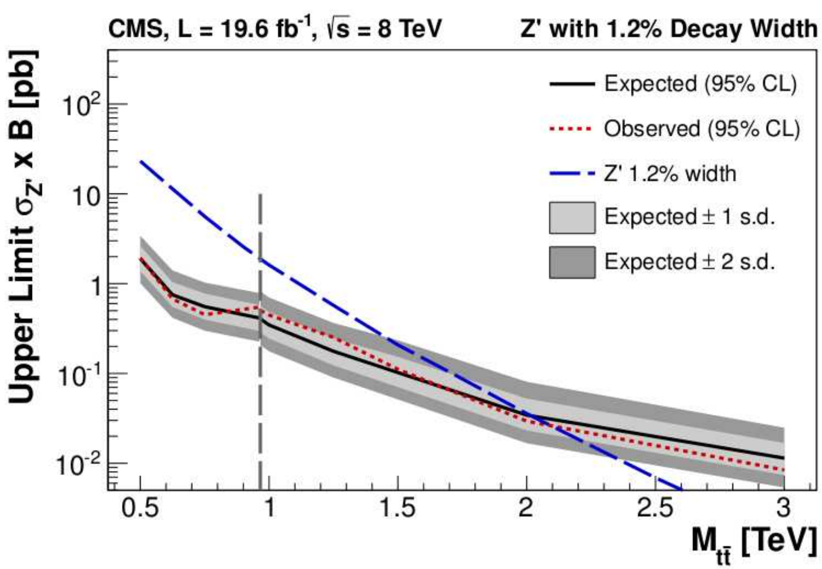
  15.2% width

- ATLAS (14 fb^{-1}):

  m(Z' 1.2% width) > 1.8 TeV m(KK gluon, L0) > 2.07 TeV

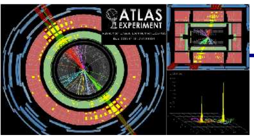


[ATLAS-CONF-2013-052]



[CMS PAS B2G-12-006]

Outline

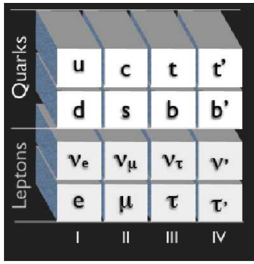


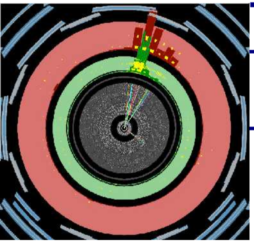
Heavy Resonances

- → Dilepton
- → Dijet
- → Top-Antitop

4th generation and heavy “quarks”

- → Vector-like quarks





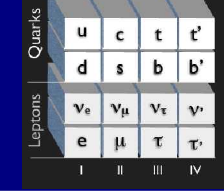
TeV-gravity and Dark Matter

- → Monojets

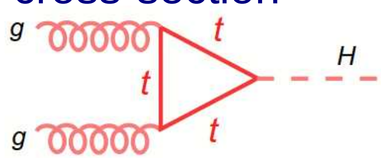
Long-lived particles and more exotic final states

- → Stopped particles
- → Exotic Higgs decays

4^{th} Generation and Heavy Quarks



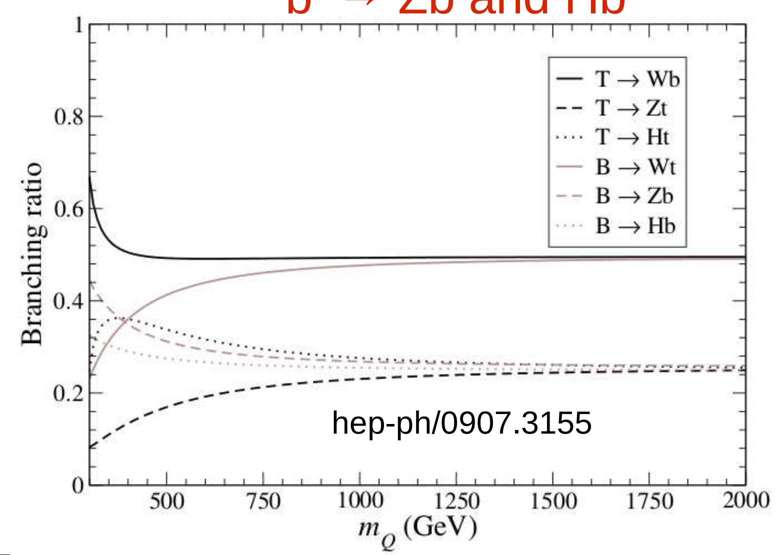
- Plain SM 4^{th} generation:
  - → difficult to reconcile with the Higgs observation:
  - → enhance Higgs production cross section, excluded by observed Higgs cross-section



VLQ singlet	Decay modes
$T_{+2/3}$	W^+b, Ht, Zt
$B_{-1/3}$	W^-t, Hb, Zb
$T_{+5/3}$	W^+t
$B_{-4/3}$	W^-b

VLQ doublet	Decay modes
$T_{+2/3}$ $B_{-1/3}$	W^+b, Ht, Zt W^-t, Hb, Zb
$T_{+2/3}$ $T_{+5/3}$	Ht, Zt W^+t
$B_{-1/3}$ $B_{-4/3}$	Hb, Zb W^-b

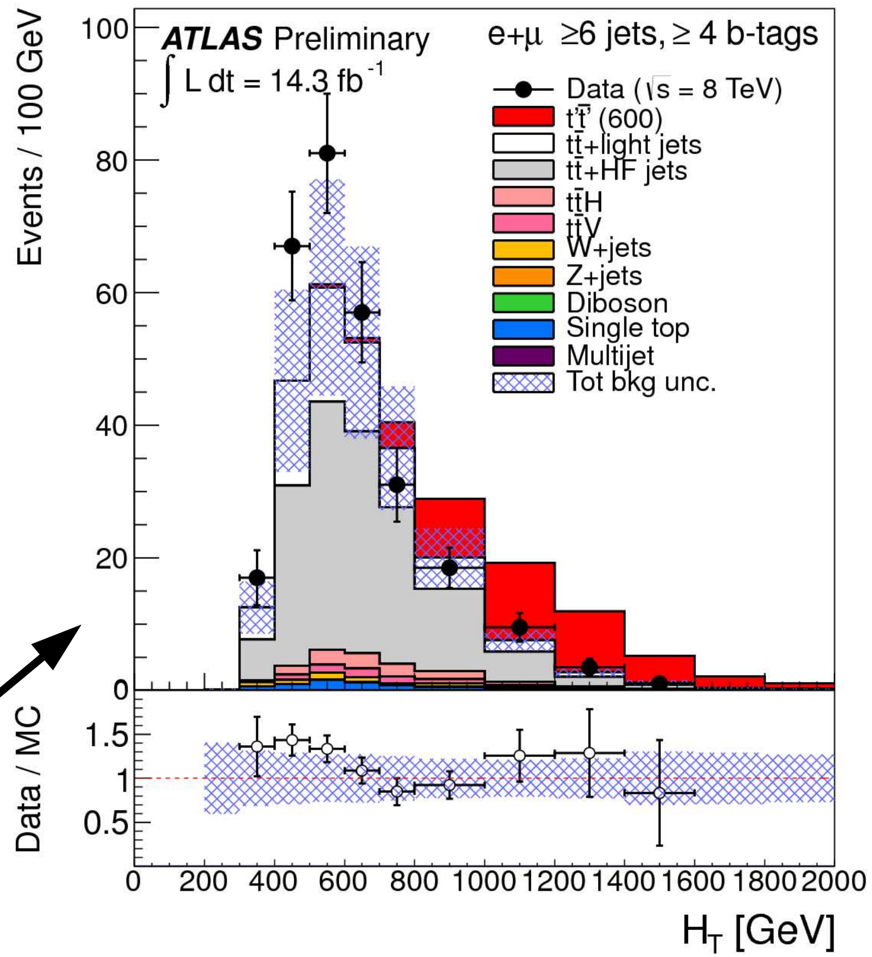
- Beyond 4^{th} generation: Vector-Like Quarks (VLQ) in Composite Higgs theories
  - → Left-handed and right-handed components have identical couplings
  - → Diverse phenomenology. Expect large BR for t' → Ht and Zt ; b' → Zb and Hb



tH(→bb) + X analysis (ATLAS)

- t't' pair production with:
  - → at least one t' → tH
  - → one W leptonic decay → lv
- Also sensitive to t' → tZ
  - (Z → bb)
- After standard tt pair event selection, reject top background by requiring:
  - → at least 6 jets
  - → at least 2 b-tags
- Discriminant variable:

$$H_T = \sum_j p_T^j + p_T^l + E_T^{miss}$$

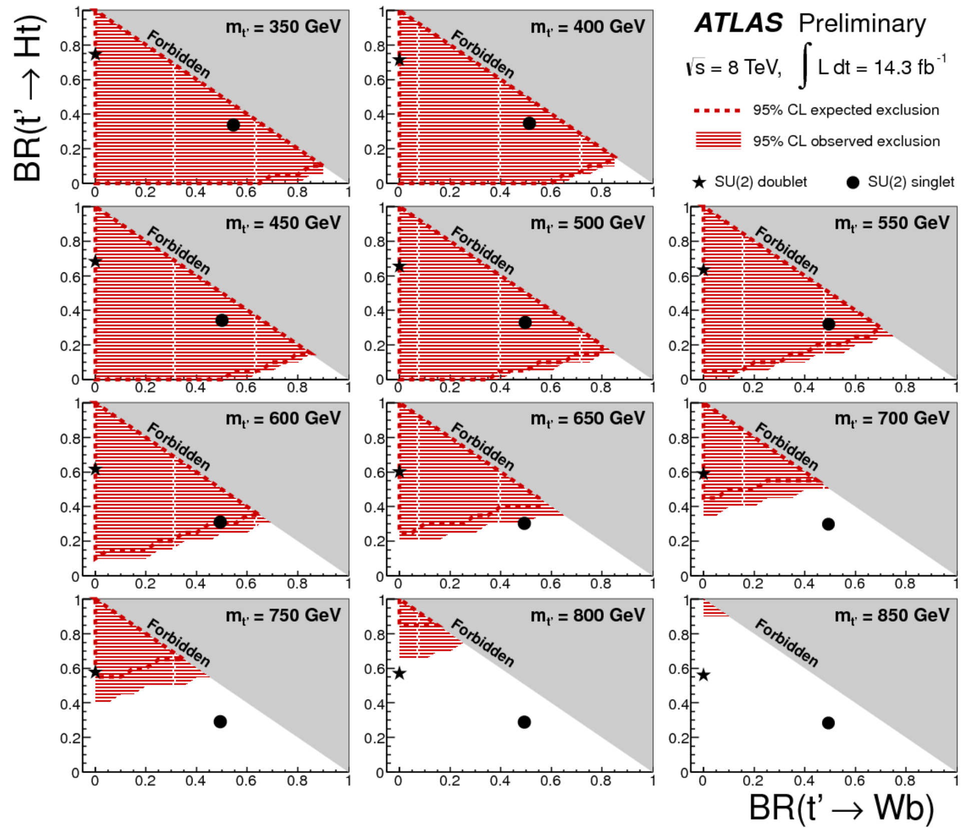


[ATLAS-CONF-2013-018]

tH(→bb) + X analysis (ATLAS)

- Assuming singlet VLQ branching ratios:
  - BR(Wb) = 0.5
  - BR(Ht) = 0.25
  - BR(Zt) = 0.25

m(t') > 640 GeV 95% CL



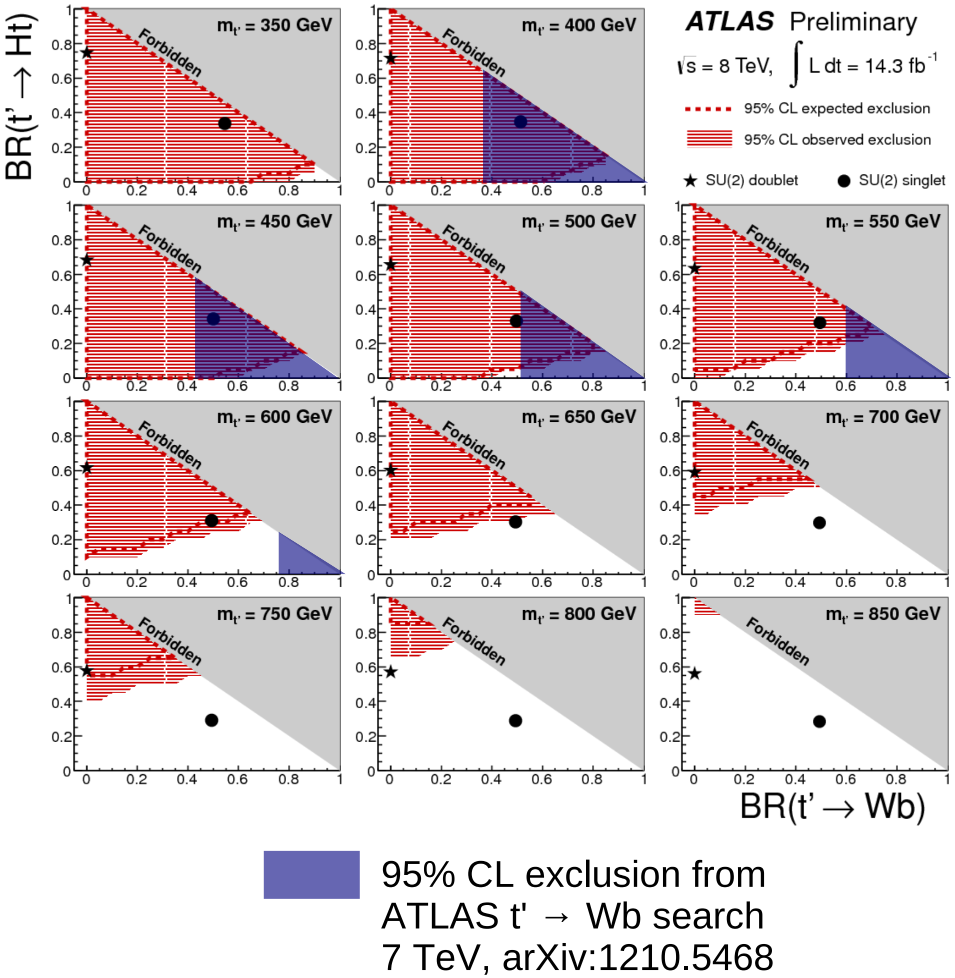
[ATLAS-CONF-2013-018]

tH(→bb) + X analysis (ATLAS)

- Assuming singlet VLQ branching ratios:
  - BR(Wb) = 0.5
  - BR(Ht) = 0.25
  - BR(Zt) = 0.25

  m(t') > 640 GeV 95% CL
- Combining with earlier search for t't' → WbWb: exclude all BR's for m(t') up to ~ 500 GeV

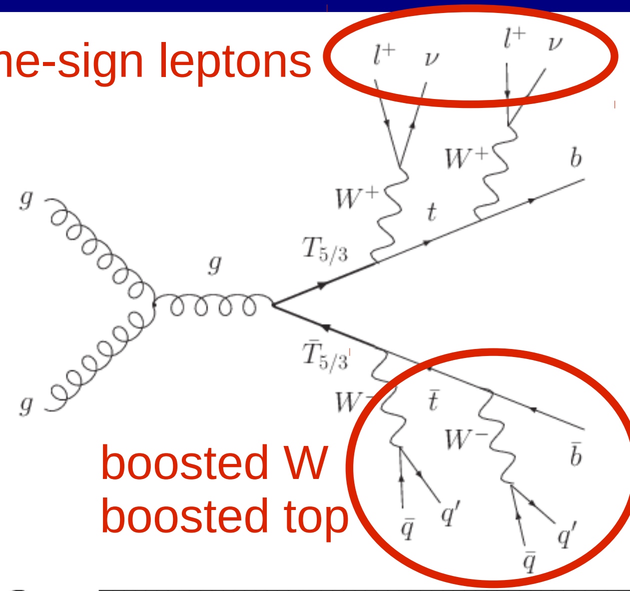
[ATLAS-CONF-2013-018]
+
[PLB 718, 1284 (2013)]



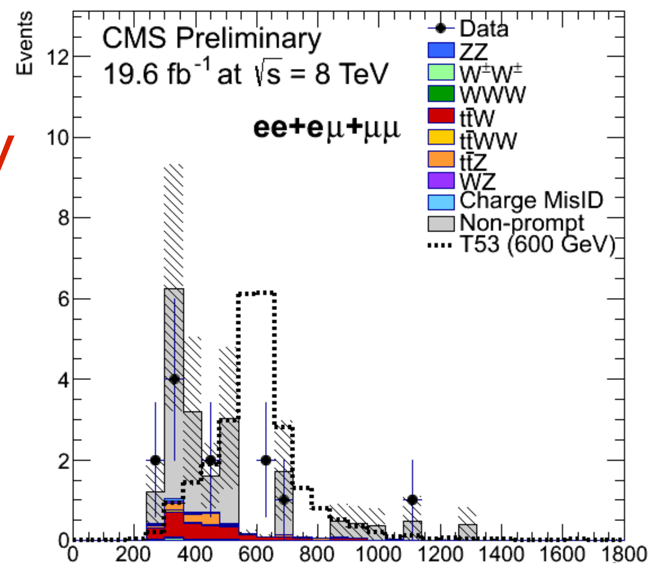
$t'_{5/3}t'_{5/3}$ same-sign (CMS)

- $T_{5/3} \to W^+t \to W^+W^+b$:
  - → same-sign W's from $T_{5/3}$ → same-sign dilepton signature
  - → boosted W and t on the other side
    →fat jets with 2 and 3 sub-jets (resp.)
- Full reconstruction of the $T_{5/3}$ mass
- $m(t_{5/3}) > 770$ GeV (95% CL)

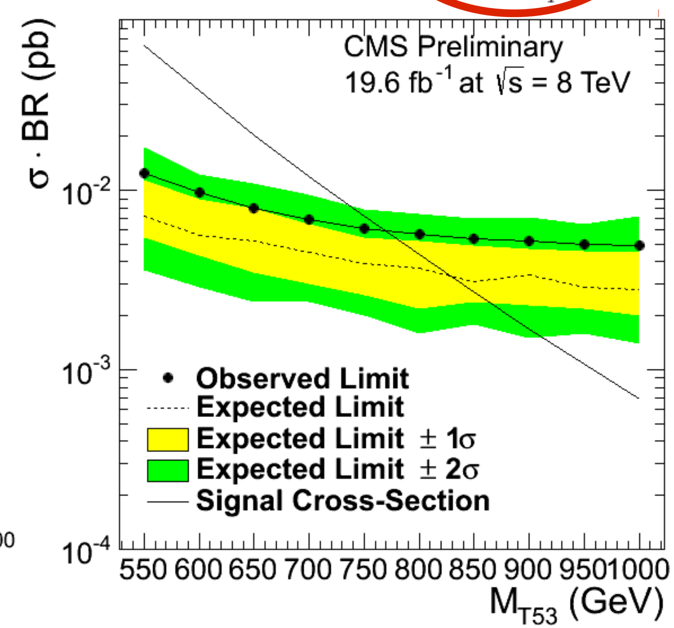
same-sign leptons



boosted W
boosted top



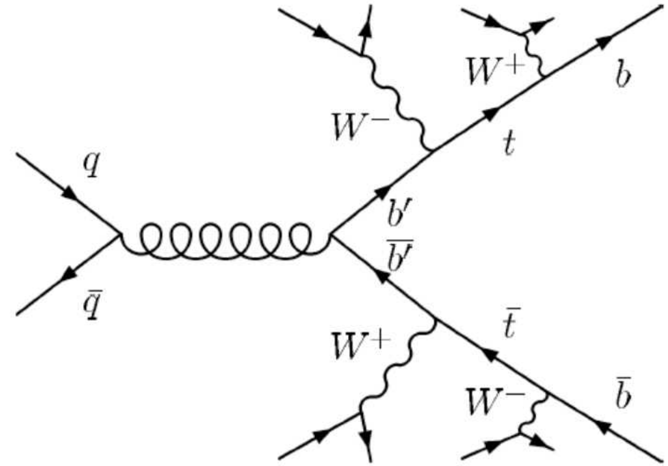
Rec. $T_{5/3}$ mass [GeV]



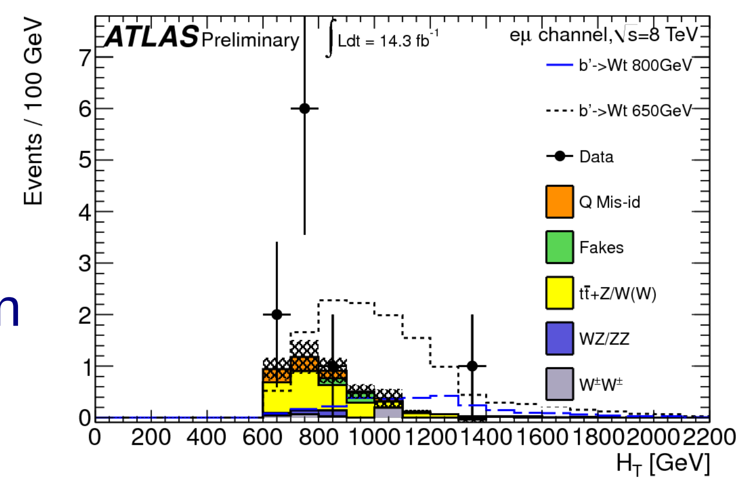
CMS PAS-B2G-12-012

b'b' → WtWt same-sign analysis (ATLAS)

- b'b' → WtWt → WWbWWb: 4 W's in the final state
- Event selection:
  - → At least 2 leptons of same-sign
  - → Missing ET > 40 GeV
  - → At least 2 jets, incl. 1 b-tagged
  - → Total transverse energy H_T > 650 GeV



	ee	$e\mu$	$\mu\mu$
Prediction	2.7 ± 0.6	4.4 ± 1.0	2.3 ± 1.2
Data	3	10	2



- → Slight excess in eμ channel, not seen in ee or μμ channels → not significant overall

[ATLAS-CONF-2013-051]

b'b' → WtWt same-sign analysis (ATLAS)

- Assuming BR(b'→Wt) = 100%:

  m(b') > 720 GeV

  (expected: 770 GeV)

- Assuming singlet VLQ branching ratios:

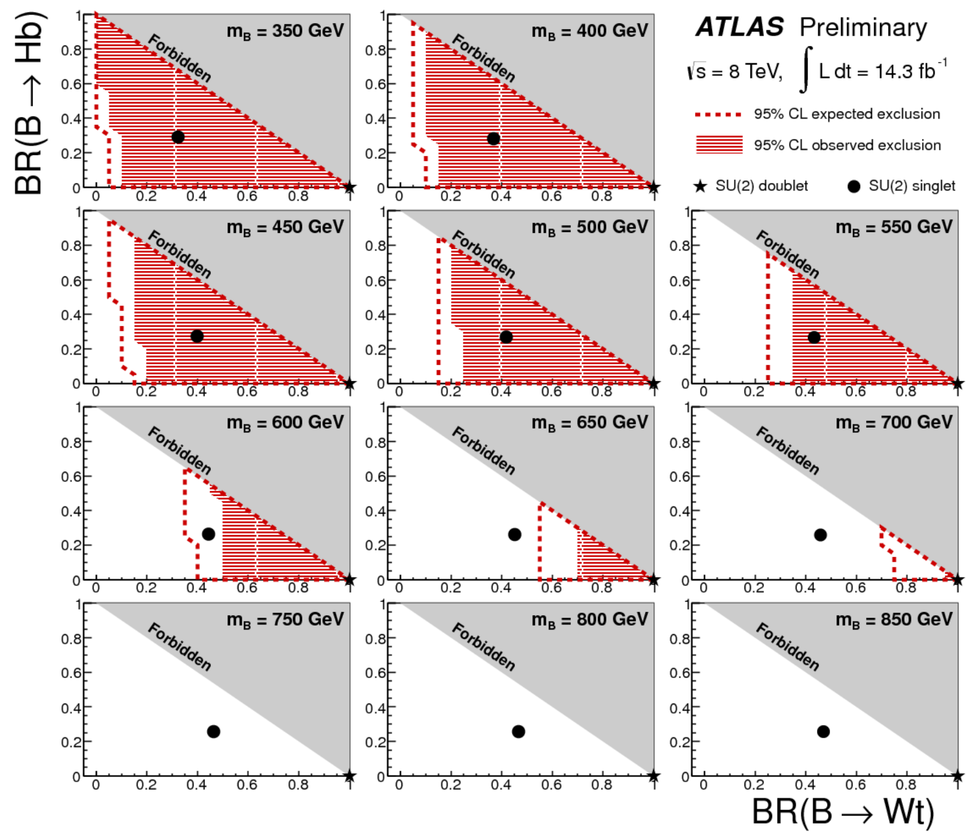
  BR(Wt) ~ 0.5

  BR(Hb) ~ 0.25

  BR(Zb) ~ 0.25

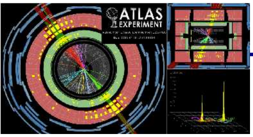
  m(b') > 590 GeV 95% CL

  (expected: 630 GeV)



[ATLAS-CONF-2013-051]

Outline

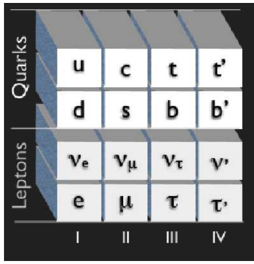


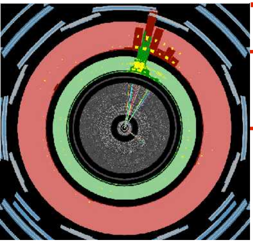
Heavy Resonances

- → Dilepton
- → Dijet
- → Top-Antitop

4th generation and heavy "quarks"

- → Vector-like quarks





TeV-gravity and Dark Matter

- → Monojets

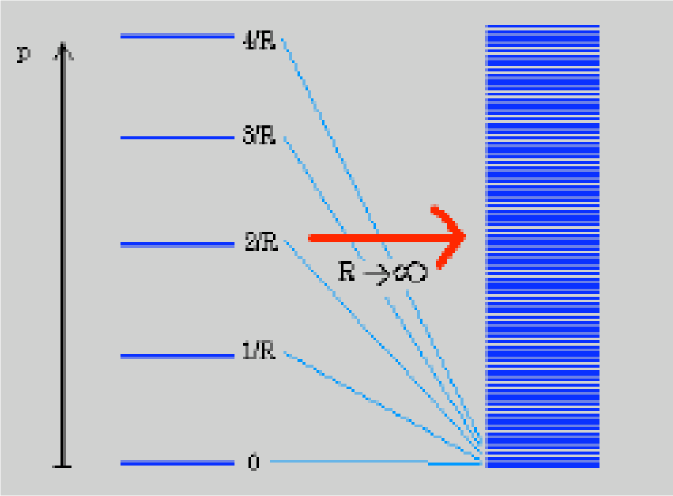
Long-lived particles and more exotic final states

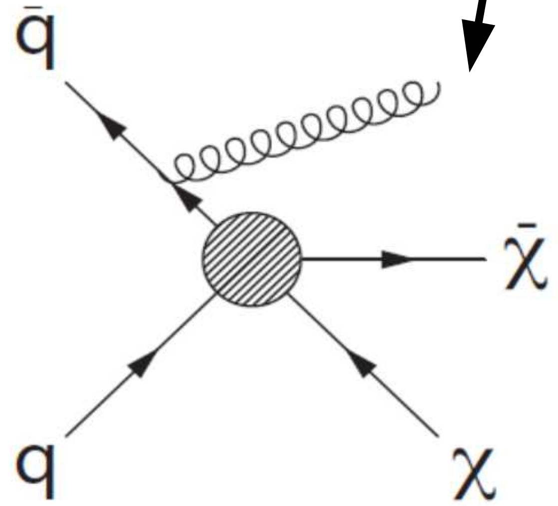
- → Stopped particles
- → Exotic Higgs decays

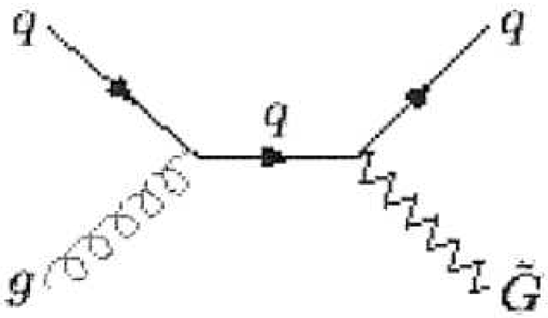
Monojets:
Large Extra-Dimensions (ADD) and WIMPs

- ADD:
  - → KK tower of excited gravitons: large ED means small ΔE between states:

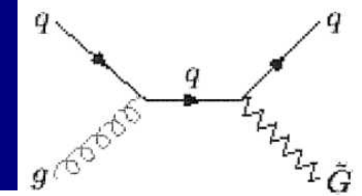
    ΔE ~ 1/R → continuum
  - → direct production of a KK graviton recoiling against a quark or gluon
- Dark matter pair production
  - → Observe only the Initial State Radiation



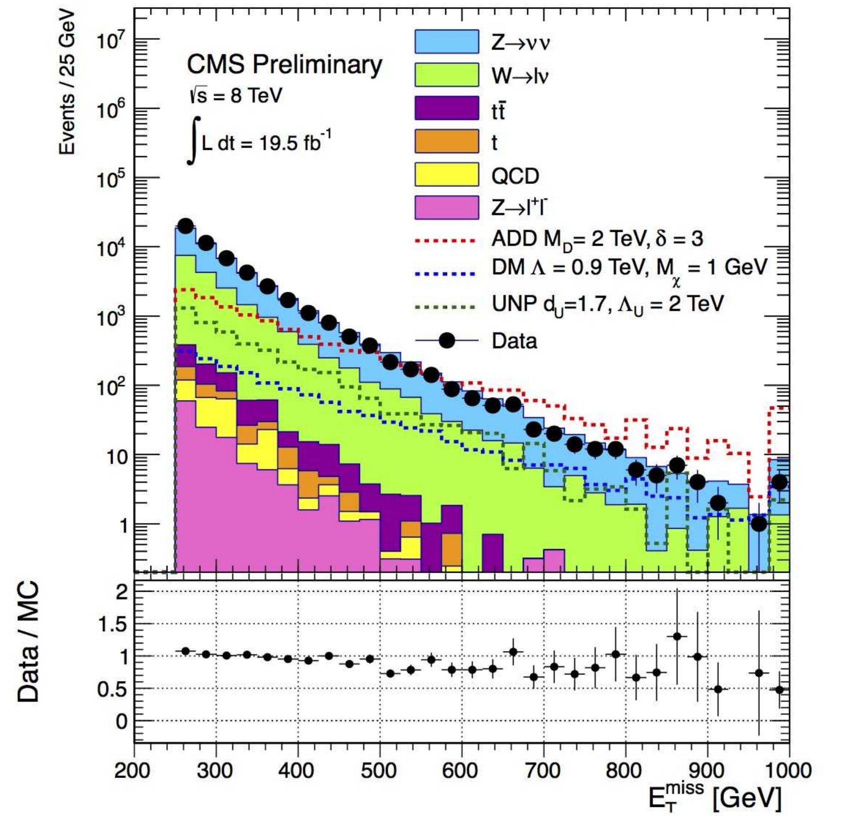


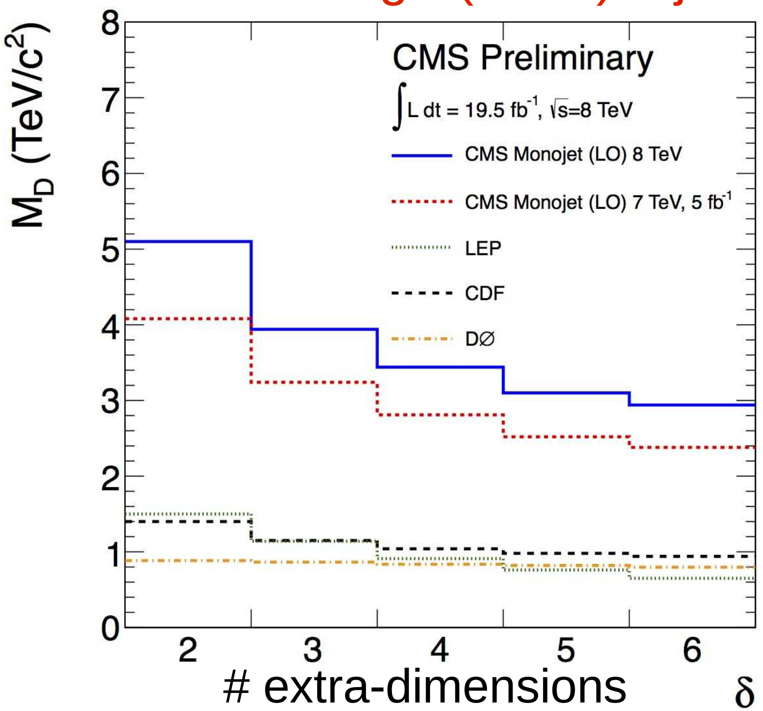


Search for Monojets: ADD



- Look for a jet and (almost) nothing else
- Data-driven estimation of:
  - → Instrumental background
  - → Understanding Z(→ νν) + jets





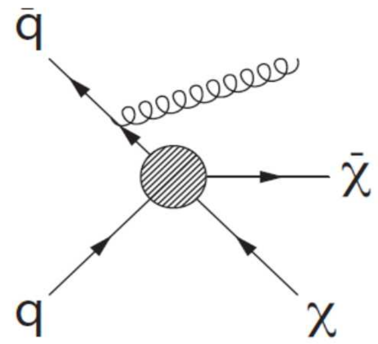
- Stringent limits on ADD:
  - → M_D > 3 TeV (LO, δ = 6)

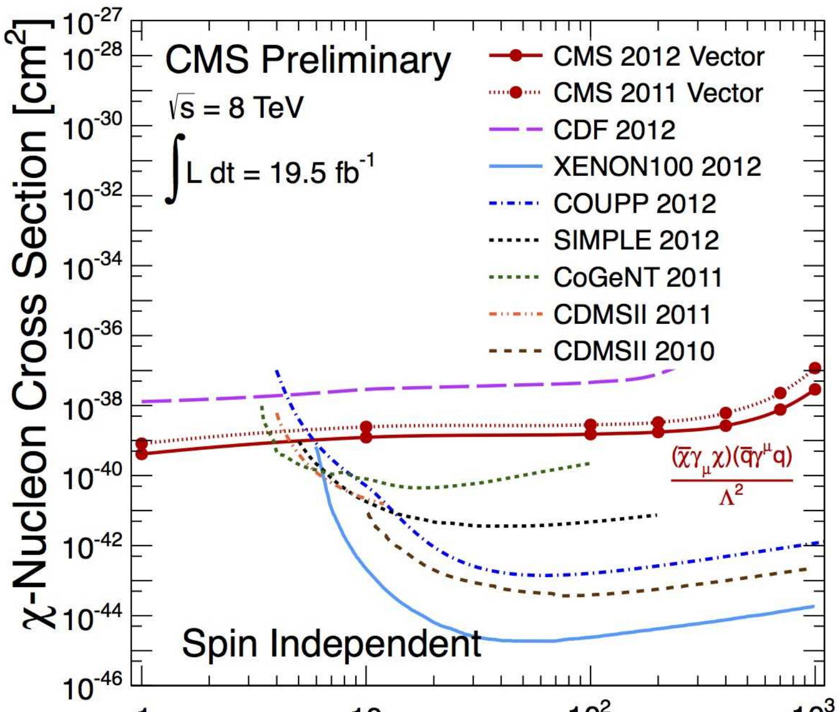
[CMS PAS EXO-12-048]

[ATLAS-CONF-2012-147]

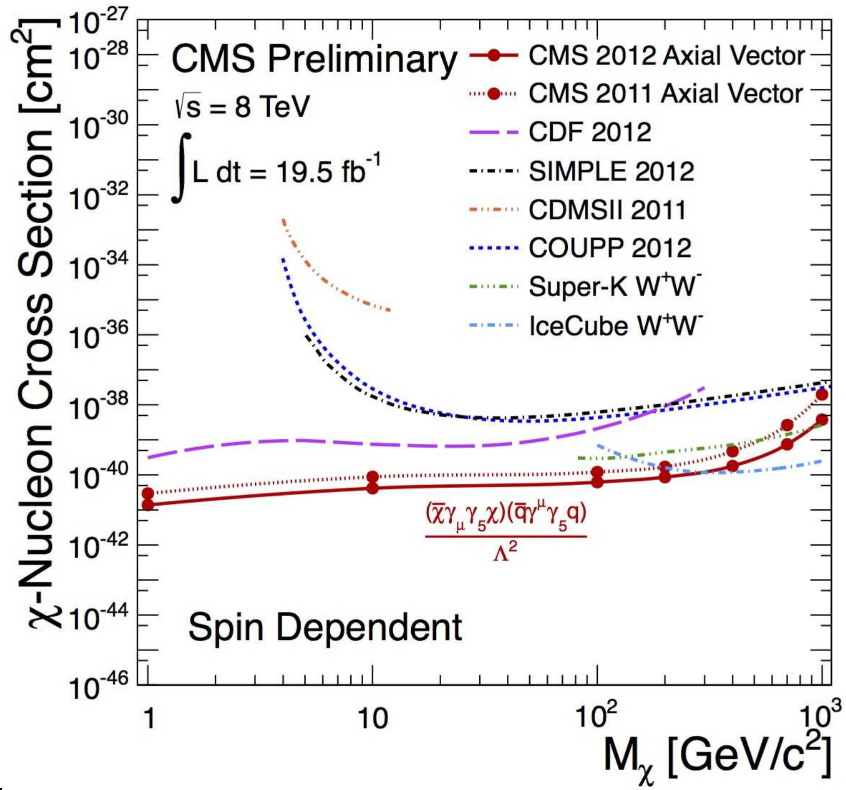
Search for Monojets: Dark Matter

- Comparison with astroparticle direct searches (effective theory):

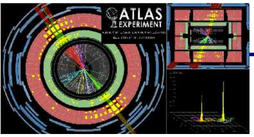




[CMS PAS EXO-12-048]



Outline



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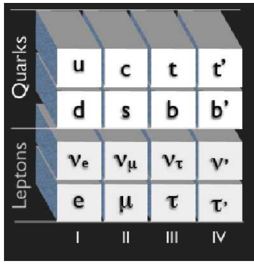
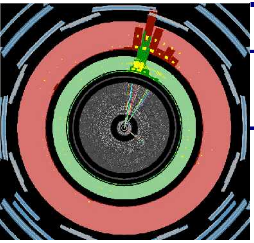




TeV-gravity and Dark Matter

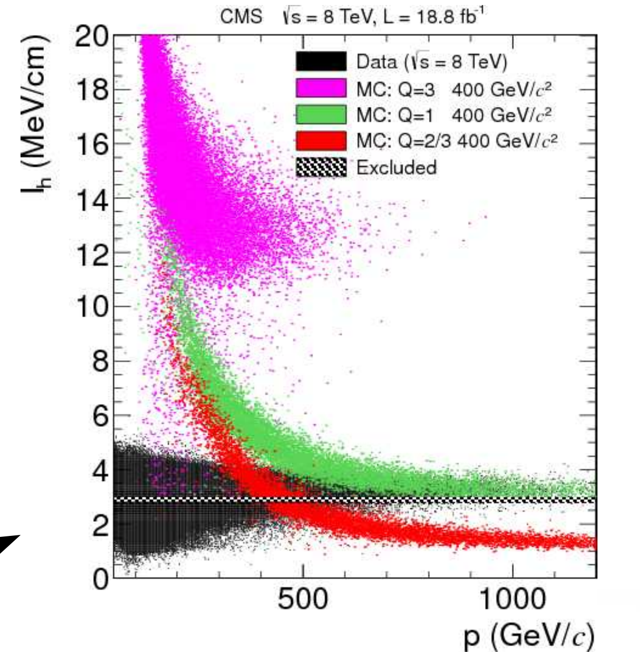
- → Monojets

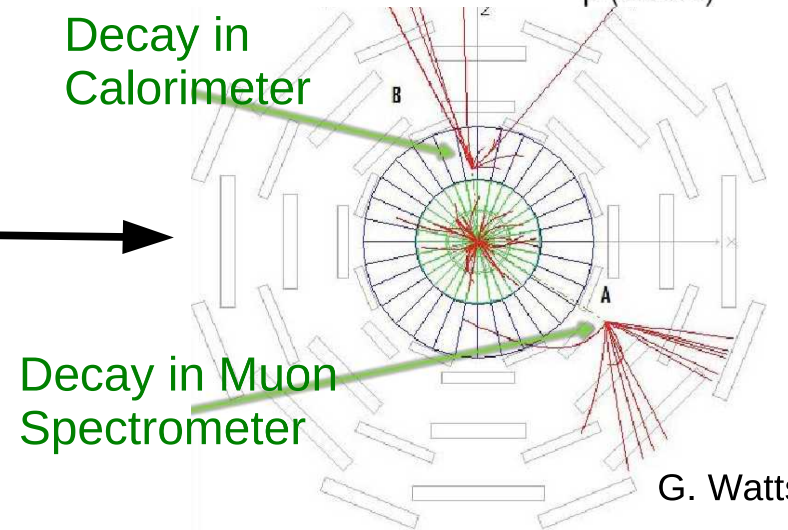
Long-lived particles and more exotic final states

- → Stopped particles
- → Exotic Higgs decays

Long-Lived Particles (LLP)

- Predicted by:
  - → SUSY (R-parity violating or split/compressed mass spectra): stau, or gluino/stop hadronized into R-hadrons
  - → Hidden Valley
- Experimentally very diverse:
  - → Depends on particle's properties: life-time, charge, decay
  - → highly ionizing (dE/dx)
  - → slow (time-of-flight)
  - → highly displaced vertices
  - → kinked tracks
  - → disappearing tracks
  - → out-of-time (wrt collision) decay

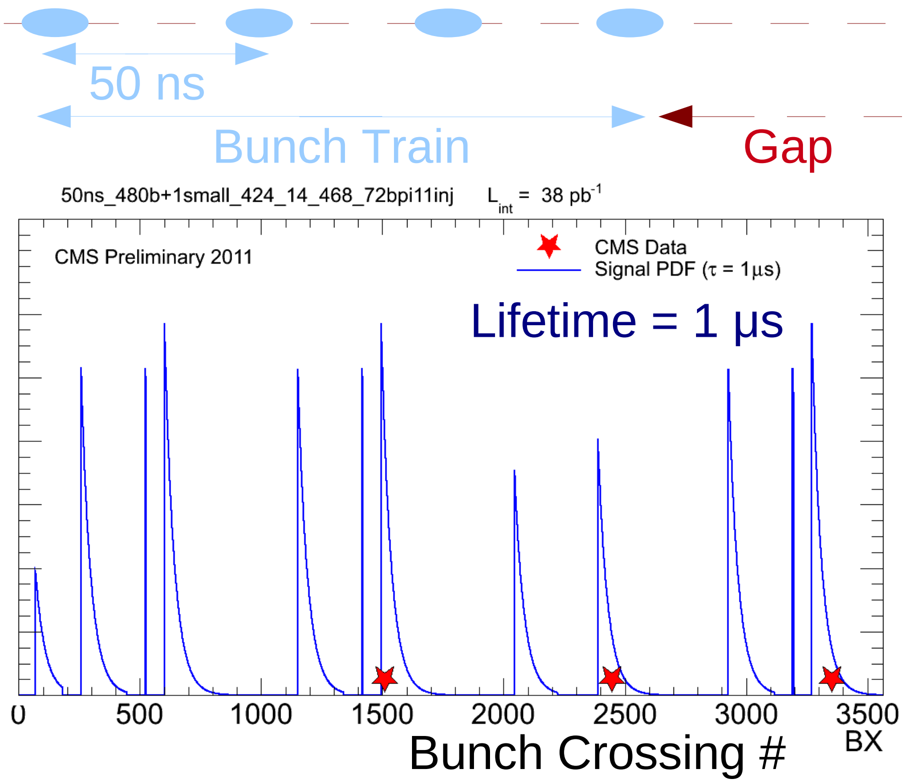




G. Watts

LLP: Stopped Particles Decaying Out-of-Time

- Out-of-time decay of heavy particles stopped in the detector
- Look for signal without collisions:
  - → When no beam in the machine
  - → Between bunch trains



- Trigger on:
  - → Jet pT > 32 GeV (L1)
  - → Veto on BPTX trigger to suppress beam background

LLP: Stopped Particles Decaying Out-of-Time

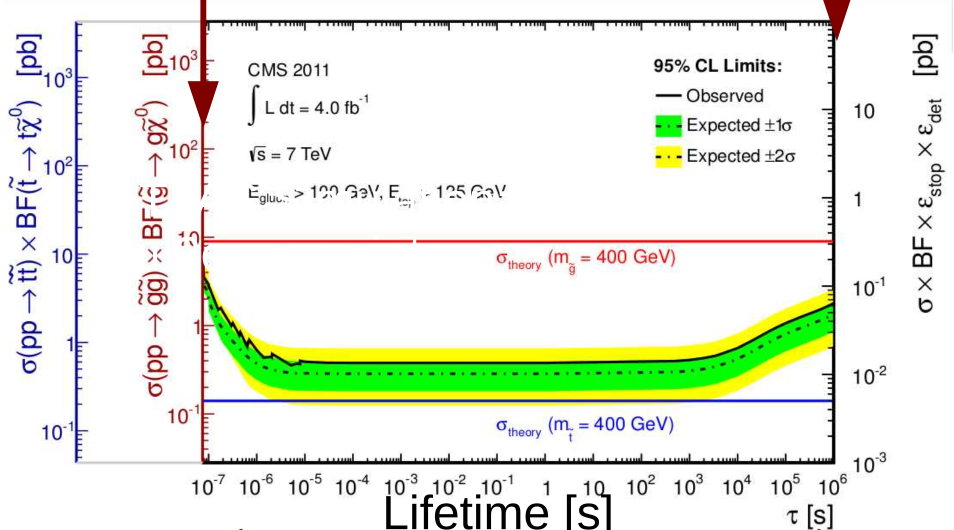
- Out-of-time decay of heavy particles stopped in the detector
- Look for signal without collisions:
  - → When no beam in the machine
  - → Between bunch trains

Too short-lived to be out-of-time 100 ns

Too long-lived to have decayed yet 1 month

τ	L_{eff} (pb^{-1})	Live time (s)	N_{exp}	N_{obs}
75 ns	19.6	2.06×10^4	0.200 ± 0.056	1
100 ns	57.8	6.17×10^4	0.60 ± 0.17	2
1 μs	508	4.41×10^5	4.3 ± 1.2	7
10 μs	913	8.67×10^5	8.5 ± 2.4	12
100 μs	935	8.86×10^5	8.6 ± 2.4	12
10^3 s	866	8.86×10^5	8.6 ± 2.4	12
10^4 s	636	8.86×10^5	8.6 ± 2.4	12
10^5 s	332	8.86×10^5	8.6 ± 2.4	12
10^6 s	198	8.86×10^5	8.6 ± 2.4	12

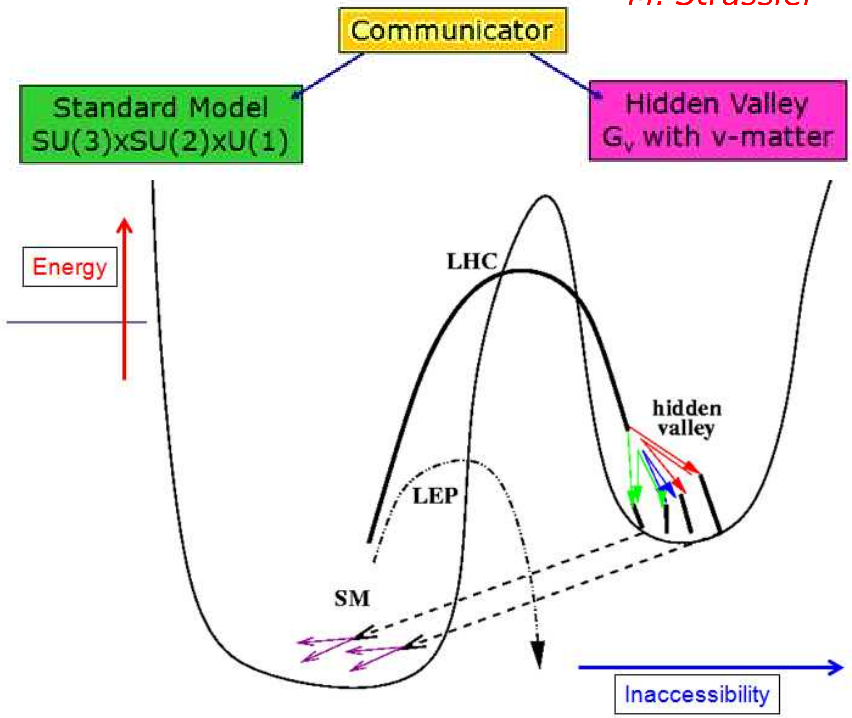
arXiv:1207.0106v2

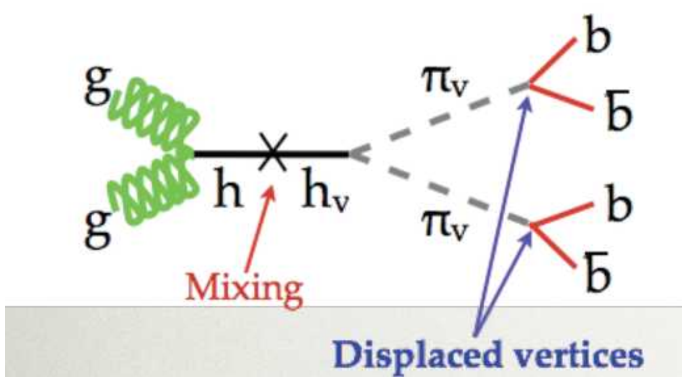


Higgs Exotic Decay:
Decay in the Muon Spectrometer

- Hidden-Valley theories predict a hidden sector coupled to the SM only through some heavy communicator → weakly coupled → long-lived particles
- Ex: $h \rightarrow h_v \rightarrow \pi_v \, \pi_v \rightarrow 4b$'s
- Life-time of π_v is unknown
- Look for 2 pairs of b-jets appearing outside the calorimeter.
- Sort of b-tagging with the Muon Spectrometer!

M. Strassler

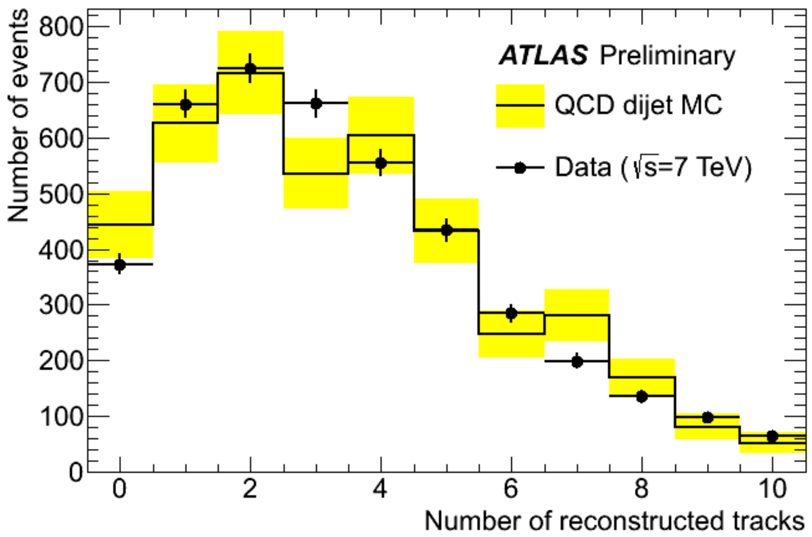


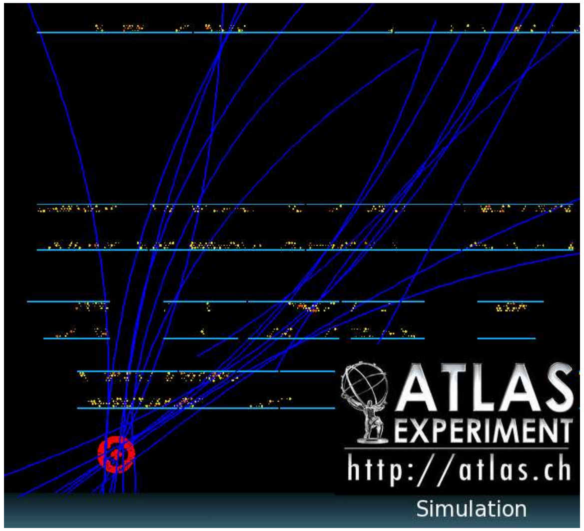


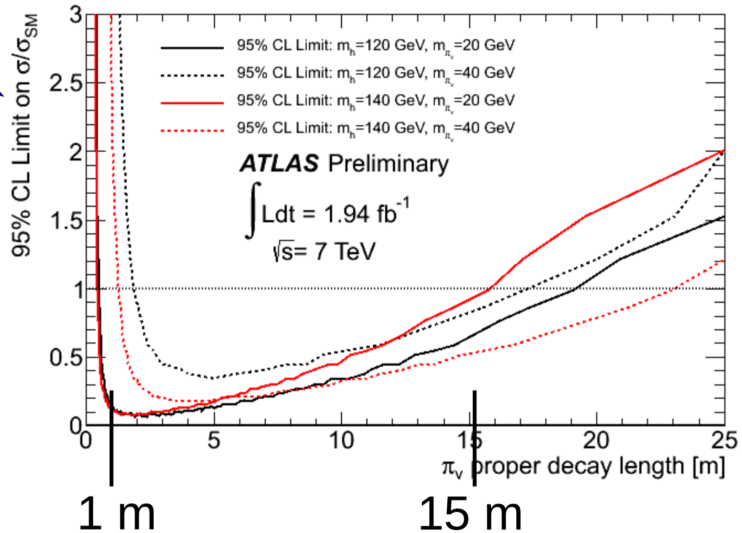
Higgs Exotic Decay: Decay in the Muon Spectrometer

- Very high occupancy
- Partial track reconstruction
- Note: punch-through's "well" described by the simulation!
- After final selection: no event observed (exp: 0.03±0.02 ev.)

Tracks caused by jets in Muon Spectrometer







Conclusion: a short (over-simplified) summary

- The 8 TeV LHC data have been investigated extensively
  - but still a lot of work in progress
- Unfortunately, still no hint of BSM physics in the LHC data...

	Approx. Lower Limit (95% C.L.)
VLQ t' (<u>any</u> BR)	500 GeV
KK gluon → $t\bar{t}$ (narrow)	2 TeV
Z' (SSM)	3 TeV
Excited quark	4 TeV

Conclusion: Outlook

- Life with a 125 GeV Higgs boson:
  - → Exotic decays: Invisible Higgs and decays to exotic objects
  - → Must consider heavy particle decays to Higgs (e.g. $t' \rightarrow tH$)
- Experimental challenges as we enter further the Multi-TeV world:
  - → TeV leptons
  - → Boosted objects (W, top)
  - → Trigger: keeping up with high luminosity without neglecting low-mass searches (e.g. jet final states)
  - → Investigate less obvious signatures
- We must be patient (again): the 13 TeV run will open another window of opportunity for discovering physics beyond the Standard Model

Backup

Search for Heavy Resonance: Dijet Angular

- Most BSM signal are expected to be more central than QCD
- Study angular variable as a function of dijet mass
- Consider the two leading jets rapidity in their center of mass:

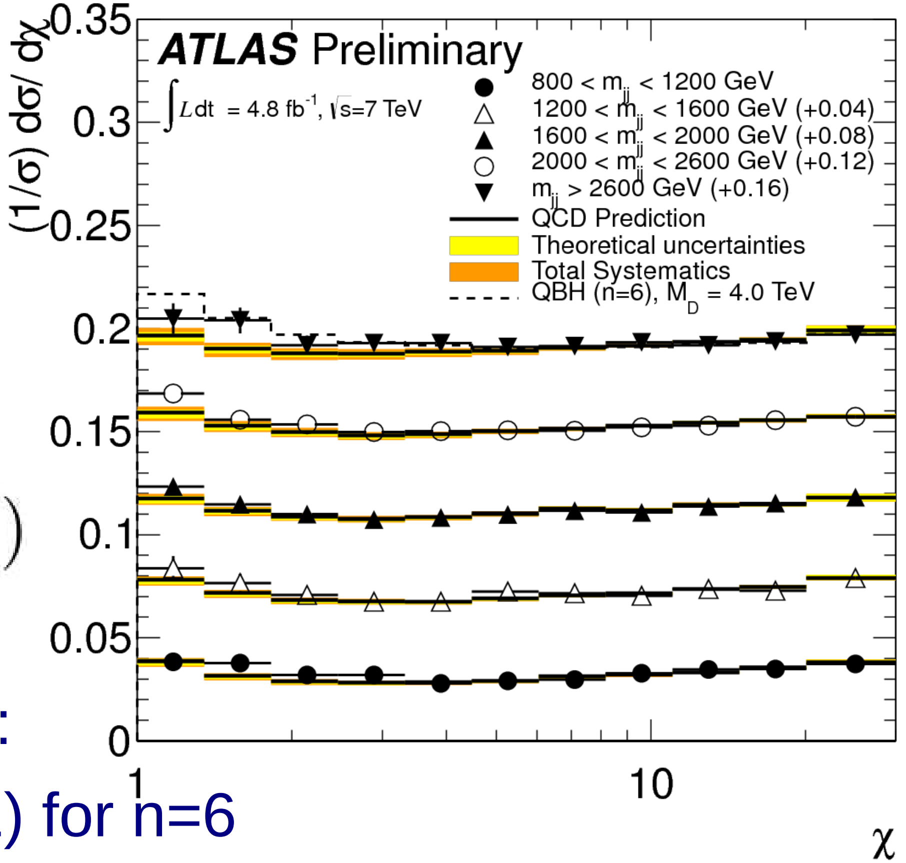
$$y^* = \pm\frac{1}{2}(y_1 - y_2)$$

- Variable chi defined as:

$$\chi \equiv \exp(|y_1 - y_2|) = \exp(2|y^*|)$$

as a function of m(jet-jet)

- Limit on Quantum Black Holes: m(QBH) > 4.14 TeV (exp. 4.11) for n=6



Search for Heavy Resonance: Dijet Angular

- Most BSM signal are expected to be more central than QCD
- Study angular variable as a function of dijet mass
- Alternatively, look at:

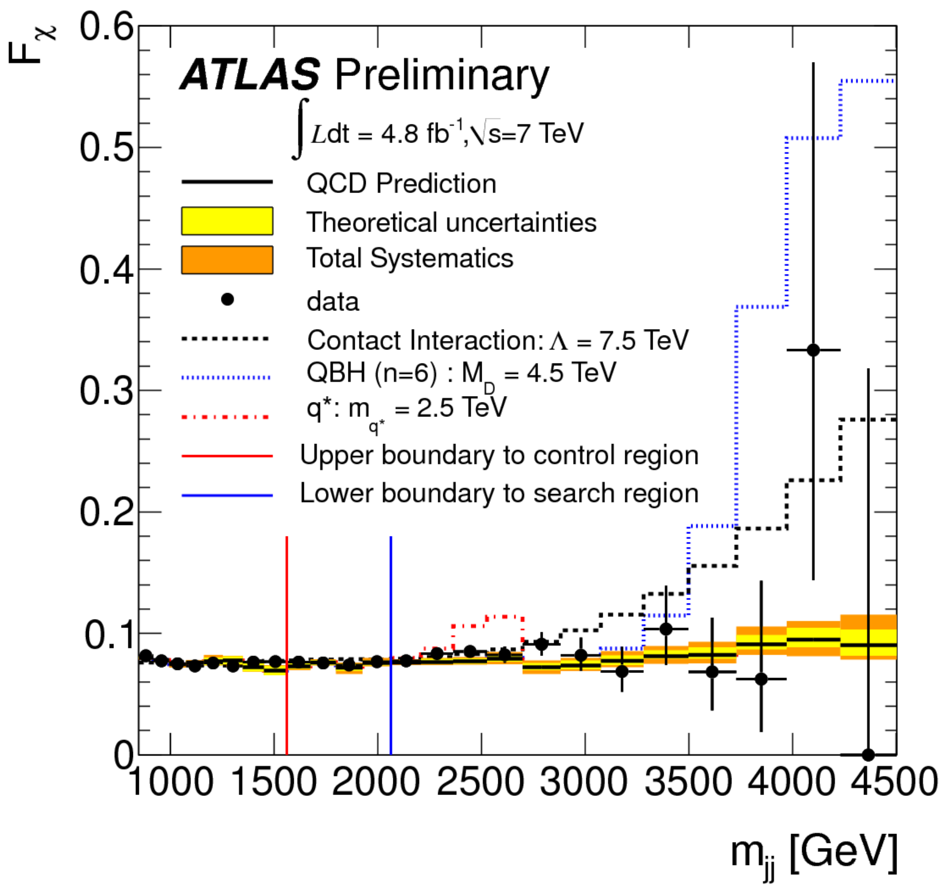
$$F_\chi = \frac{N_{\mathrm{central}}}{N_{\mathrm{total}}}$$

where $N_{central}$ is $|y^*| < 0.6$

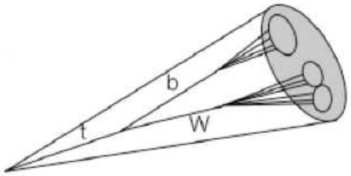
- Limit on Contact Interaction:

$\Lambda > 7.6$ TeV at 95% CL

(expected: 8.2 TeV)



Jet Clustering Algorithms



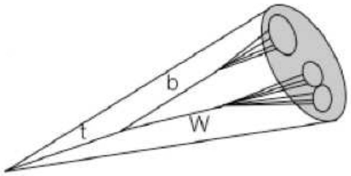
- Starting point: topological clusters in the calorimeters
- Iterative procedure of merging near-by clusters into bigger ones (a.k.a proto-jets) until convergence
- For all proto-jets and proto-jet pairs, define:

$$\rho_{ij} = \min\left(p_{Ti}^{2p}, p_{Tj}^{2p}\right) \frac{(\Delta R_{ij})^2}{R^2}$$

$$\rho_{iB} = p_{Ti}^{2p}$$

- If ρ_{IJ} is the smallest ρ_{ij} or ρ_i, merge I and J
- If ρ_I is the smallest of all ρ_{ij} , it is a jet (and removed from list)

Jet Clustering Algorithms



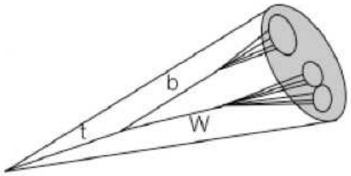
- Two parameters:
- Parameter R is the analogue of cone side in a cone algorithm
  - → Typicall R ~ 0.4 – 0.6
  - → Larger R ~ 1.0 (“fat jets”) also used for boosted objects
- Parameter p:
  - → p = 1: standard k_t algorithm
  - → p = 0: C/A algorithm
  - → p = -1: anti-k_t algorithm

$$\rho_{ij} = \min\left(p_{Ti}^{2p}, p_{Tj}^{2p}\right) \frac{(\Delta R_{ij})^2}{R^2}$$

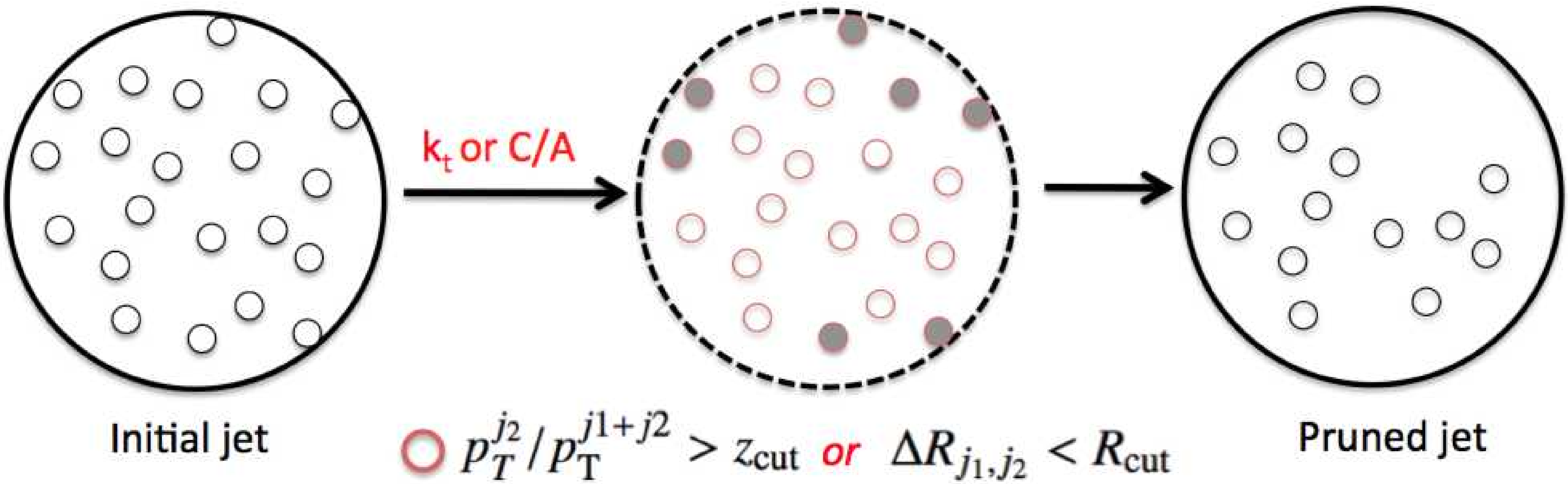
$$\rho_{iB} = p_{Ti}^{2p}$$

- Standard in ATLAS: R = 0.4 anti-kt algorithm
  - → But others are used to study boosted objects and jet sub-structure

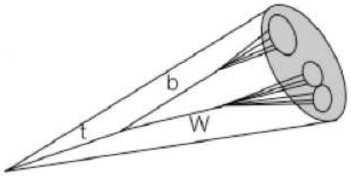
Jet "Grooming"



- "Pruning":
- Start with a fat jet (R ~ 1 or more)
- Run k_t or C/A algorithm on clusters within the fat jet
- At each step, if merging of two clusters fails, remove cluster with smallest pT



Top-antitop Resonance Lepton+Jets Channel (ATLAS)

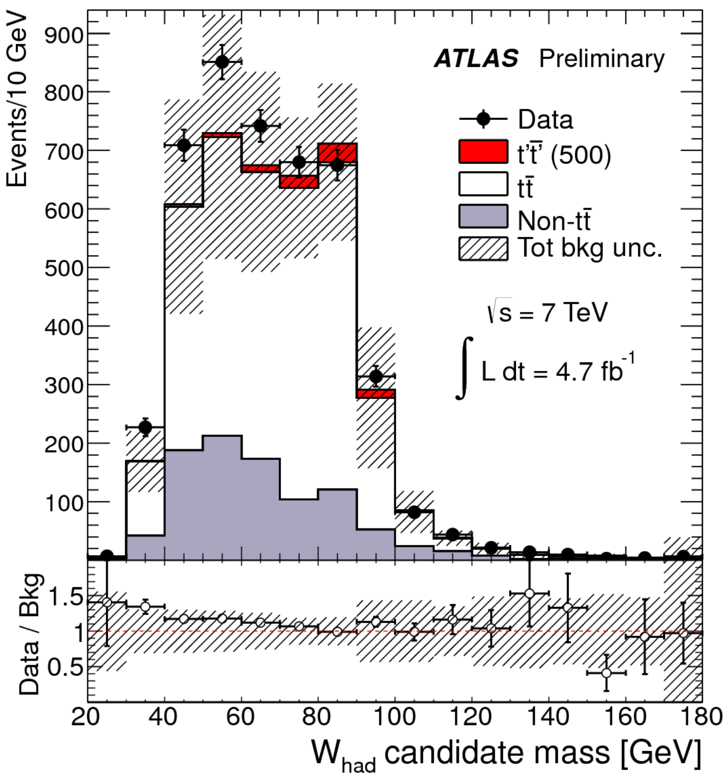


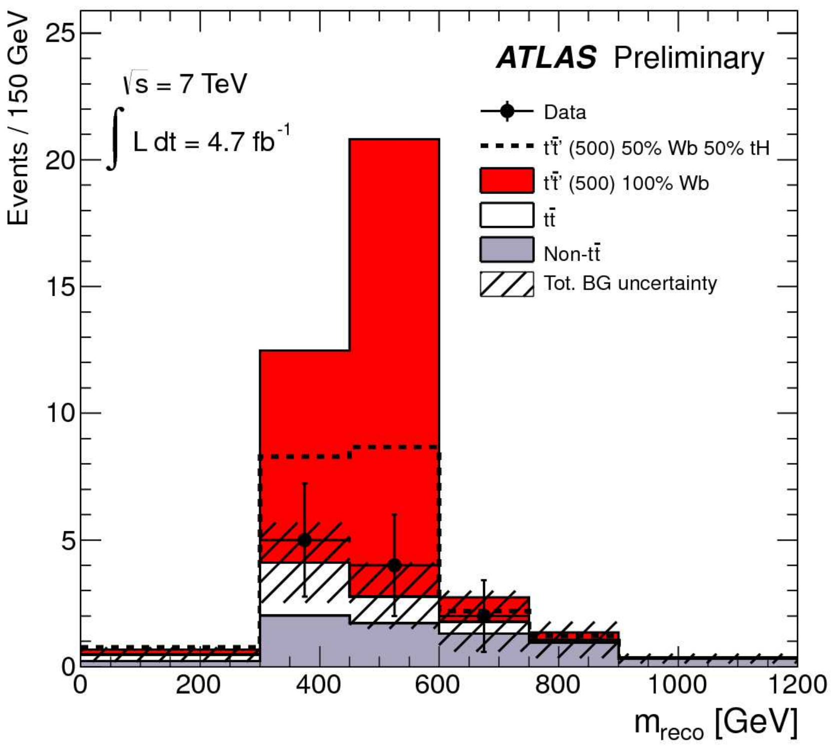
- AKT4: Anti-$k_\perp$ ($R = 0.4$) jets: $p_T > 25\,\mathrm{GeV}$, $|\eta| < 2.5$
- AKT10: Anti-$k_\perp$ ($R = 1.0$) jets: $|\eta| < 2.0$, $p_T > 350\,\mathrm{GeV}$, $m > 100\,\mathrm{GeV}$, $\sqrt{d_{12}} > 40\,\mathrm{GeV}$ (expect $\sqrt{d_{12}} \approx m_\mathrm{t}/2$ for $\mathrm{t} \to \mathrm{bW}$)

	resolved	boosted
trigger	single lepton trigger	fat jet (AKT10) trigger
leptons	1 lepton ($\mathrm{e}^\pm$ or $\mu^\pm$), $p_T > 25\,\mathrm{GeV}$ additional lepton ($\mathrm{e}^\pm$ or $\mu^\pm$) veto, $p_T > 20\,\mathrm{GeV}$	
	lepton trigger match	—
$\not{E}_T$	$\mathrm{e}^\pm$: $\not{E}_T > 30\,\mathrm{GeV}$, $\mu^\pm$: $\not{E}_T > 20\,\mathrm{GeV}$	
m_T^W	$\mathrm{e}^\pm$: $M_T(\mathrm{W}) > 30\,\mathrm{GeV}$, $\mu^\pm$: $M_T(\mathrm{W}) + \not{E}_T > 60\,\mathrm{GeV}$	
jets	$\geq 4(3)$ jets (if one jet $m_\mathrm{jet} > 60\,\mathrm{GeV}$)	"leptonic jet": AKT4 jet "hadronic jet": AKT10 jet
b-tag	≥ 1 b-tag using AKT4 jets ($\varepsilon_\mathrm{b} = 70\,\%$)	

TT → WbWb analysis

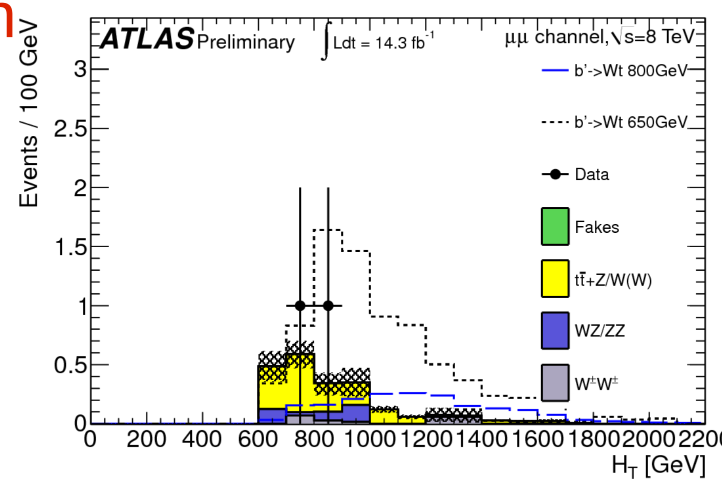
- Final state: lνbbqq (l = e or μ)
- Selection:
  - → 1 lepton + ETmiss + 4 jets and b-tagging
  - → Select boosted W → jj from T → Wb
- Reconstruct the t' mass

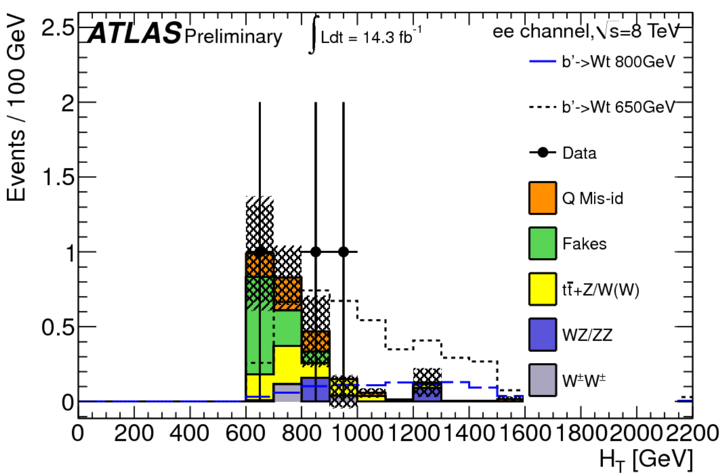


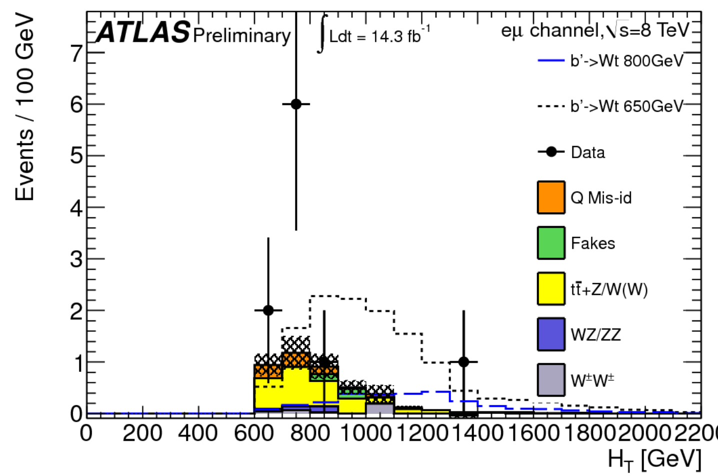


b'b' → WtWt same-sign analysis (ATLAS)

- b'b' → WtWt → WWbWWb: 4 W's in the final state
- Event selection:
  - → At least 2 leptons of same-sign
  - → Missing ET > 40 GeV
  - → At least 2 jets, incl. 1 b-tagged
  - → Total transverse energy H_T > 650 GeV



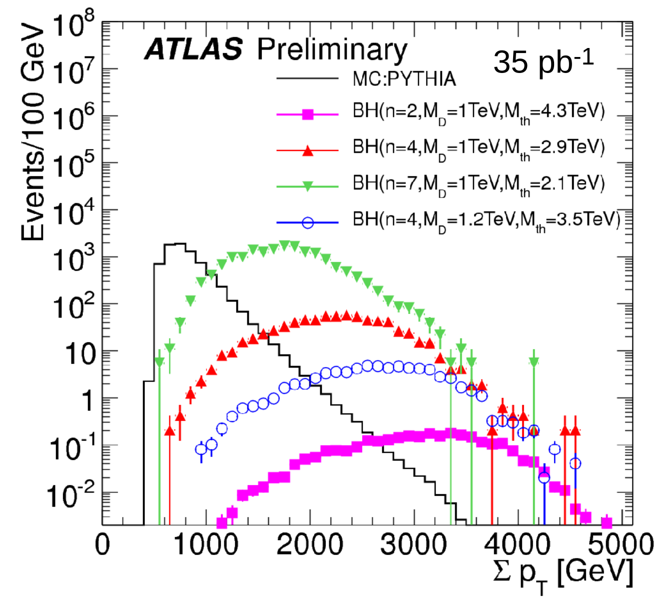


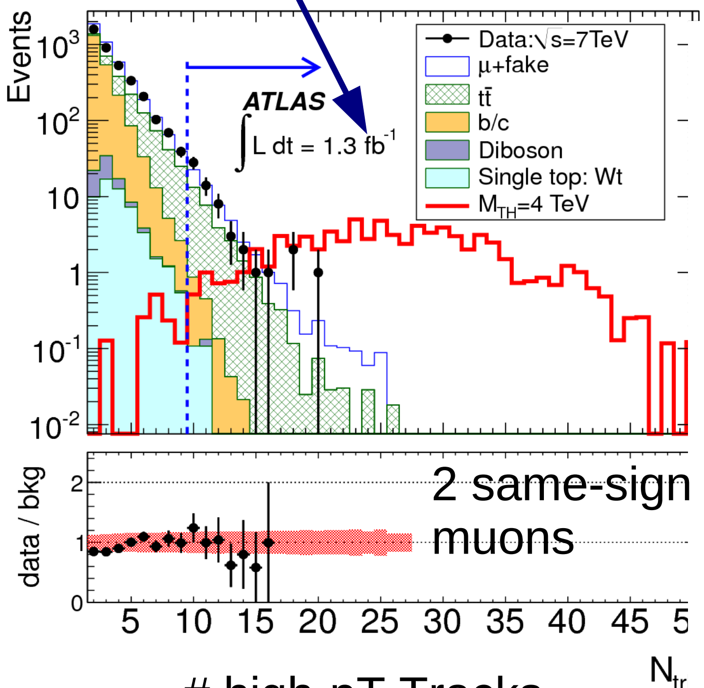


[ATLAS-CONF-2013-051]

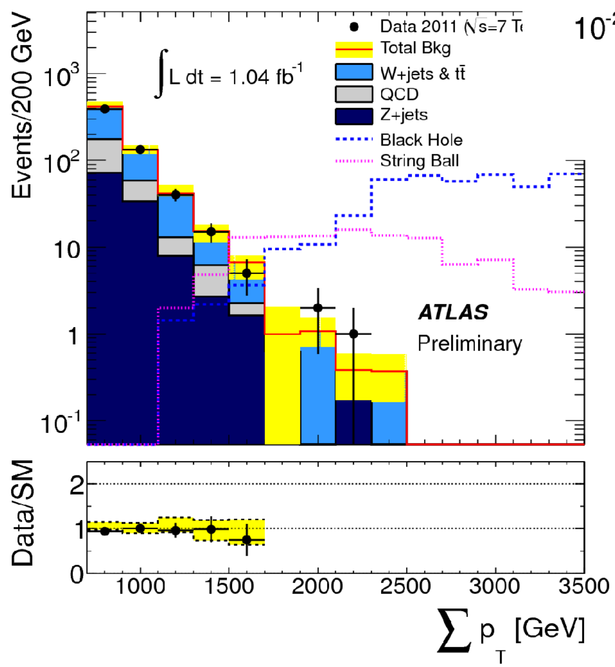
Black Holes: Multi-Jets, Lepton+Jets, Same-Sign

- Multijet
- L+Jets
- Same-sign Dimuon



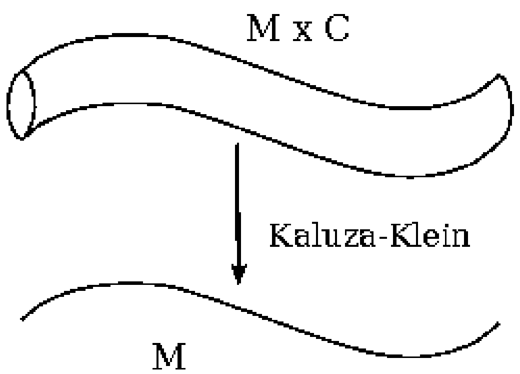


high-pT Tracks



A Short History of Extra-Dimensions

- *1921-26* : Kaluza & Klein attempt to unify EM and relativity by adding a dimension to general relativity
  - → Compactification → Kaluza-Klein towers
  - → **E = nhc / R** (R = ED radius, n integer)
- *1998* : Large ED (Arkani-Hamed, Dimopoulos, Dvali)
- *1999* : Warped ED Warped Randall-Sundrum
- Since then: many more...



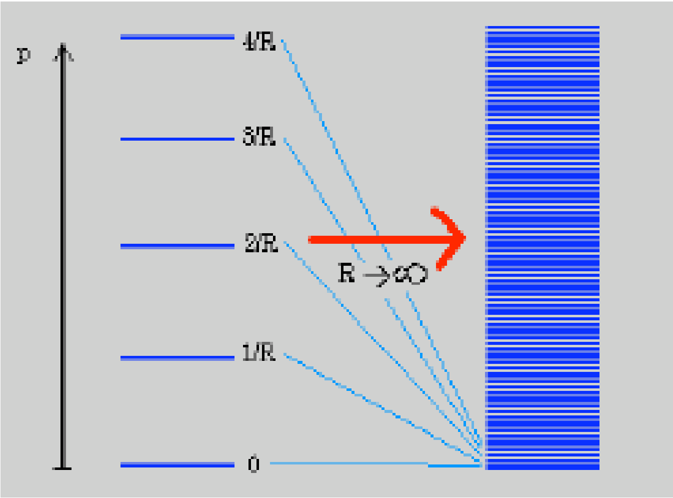
$$M_{Pl}^2 \sim M_D^{2+n} R^n$$

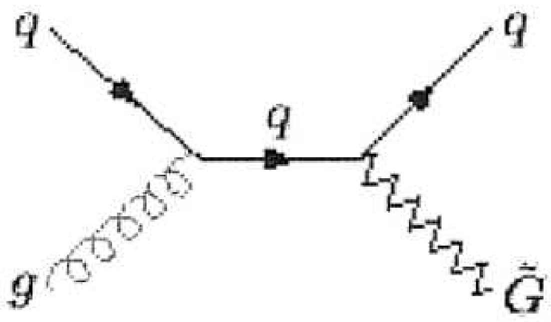
$$ds^2 = e^{-2kr_c|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu + r_c d\phi^2$$

$$\phi \approx -\phi, \quad |\phi| \le \pi$$

Large Extra-Dimensions (ADD)

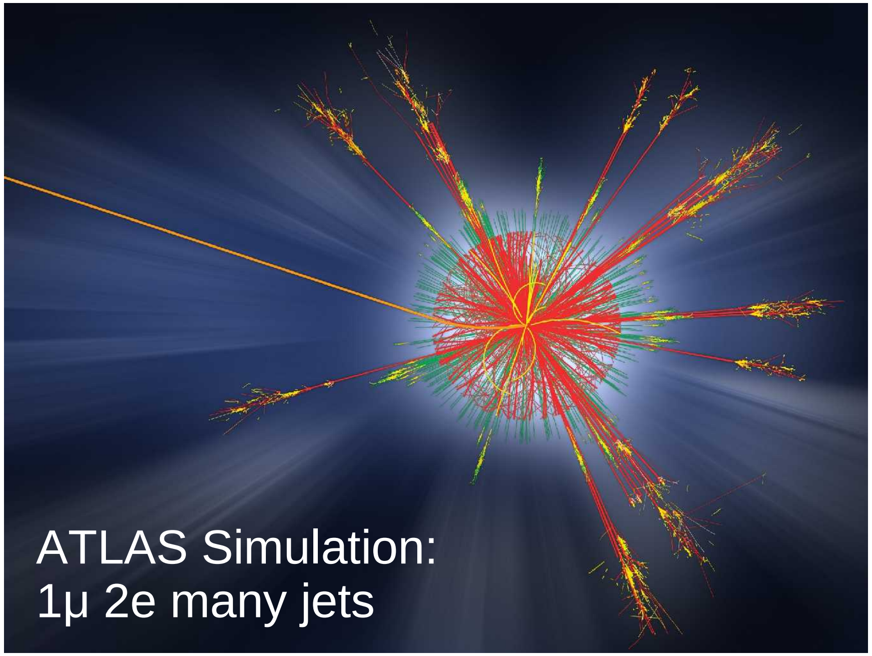
- What if gravitation is strong but appears weak because it is "diluted" in extra-dimensions at low energy / large distances?
  - → removes the hierarchy problem
- KK tower of excited gravitons: large ED means small ΔE between states: ΔE ~ 1/R
  - → Experimentally: continuum
- At the LHC, three ways to look for it:
  - → Deviation in DY or dijet spectrum caused by continuum
  - → Monojet/monophoton: graviton production recoiling against quark or photon
  - → Semi-classical black-hole and Quantum Graviation Object





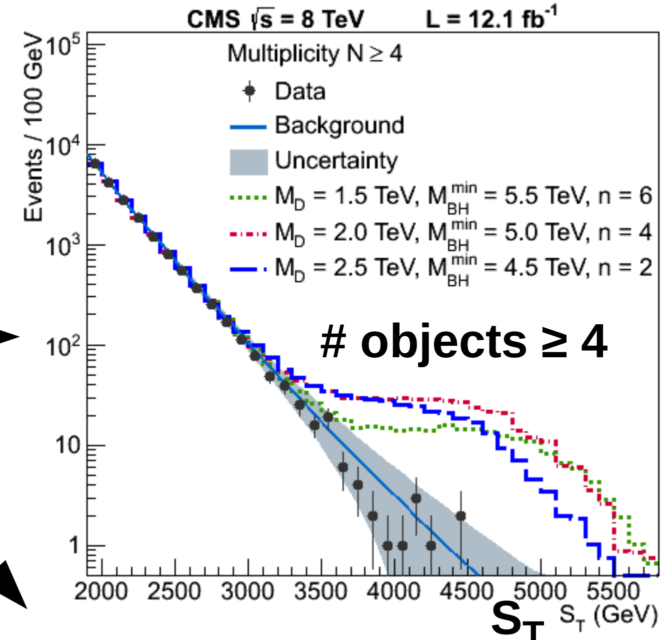
Microscopic Black Holes

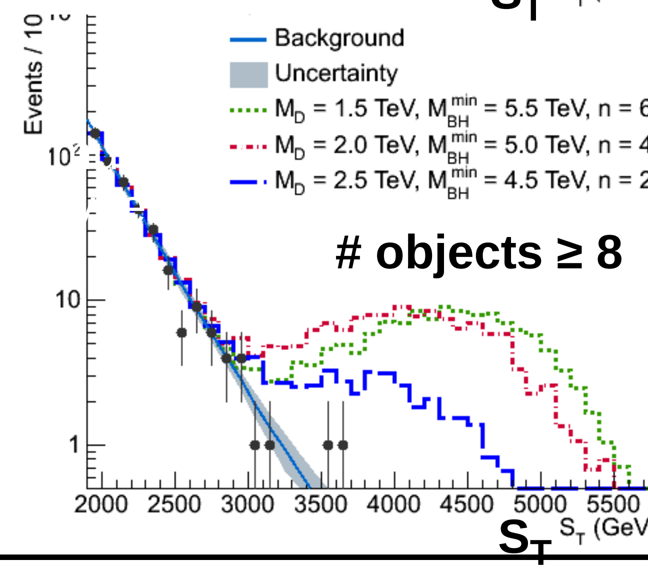
- If Gravity becomes strong at TeV → strong enough to produce Microscopic black-holes decaying through Hawking radiation
- Large uncertainty on models due to our ignorance of quantum gravity
- Semi-classical models only for m(B.H.) >> m(threshold)
- A safe bet: decay is democratic and isotropic → Look for (many) jets (and leptons) at high mass

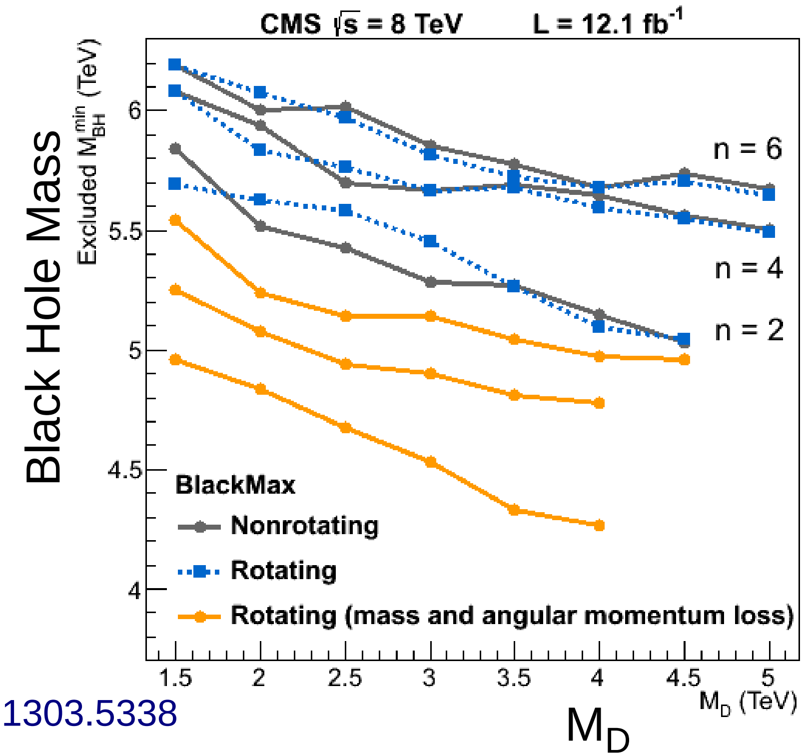


Microscopic Black Holes
"multi-object" CMS analysis with 8 TeV data:

- Cut on total number of objects (jets, photons, electrons, muons) in event
- Look for deviation in total transverse energy S_T (a.k.a. H_T at ATLAS)







arXiv:1303.5338

Warped Extra-Dimensions (RS)

- One extra-dimension with negative curvature i.e. anti de Sitter metrix
- RS1: Planck brane and TeV brane at the boundaries of the ED
  - → KK graviton tower with ΔE ~ 1 TeV
  - → Signature: KK graviton to dilepton or diphoton
- Bulk-RS: all fields propagate in ED and create KK tower.
  - → KK graviton couples to massive particles → large BR to WW, ZZ
  - → KK gluon → ttbar

$$ds^2 = e^{-2kr_c|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu + r_c d\phi^2$$

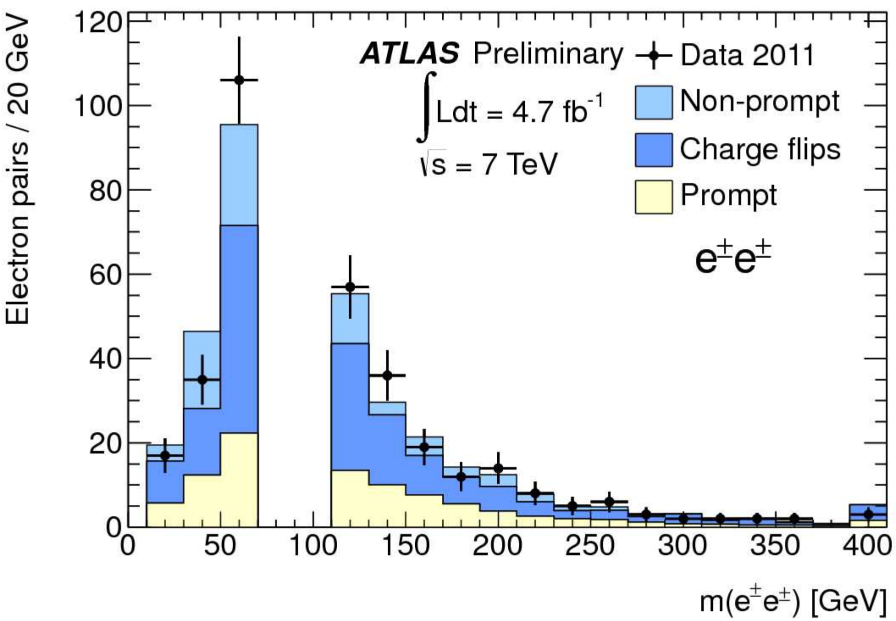
$$\phi \approx -\phi, \quad |\phi| \leq \pi$$

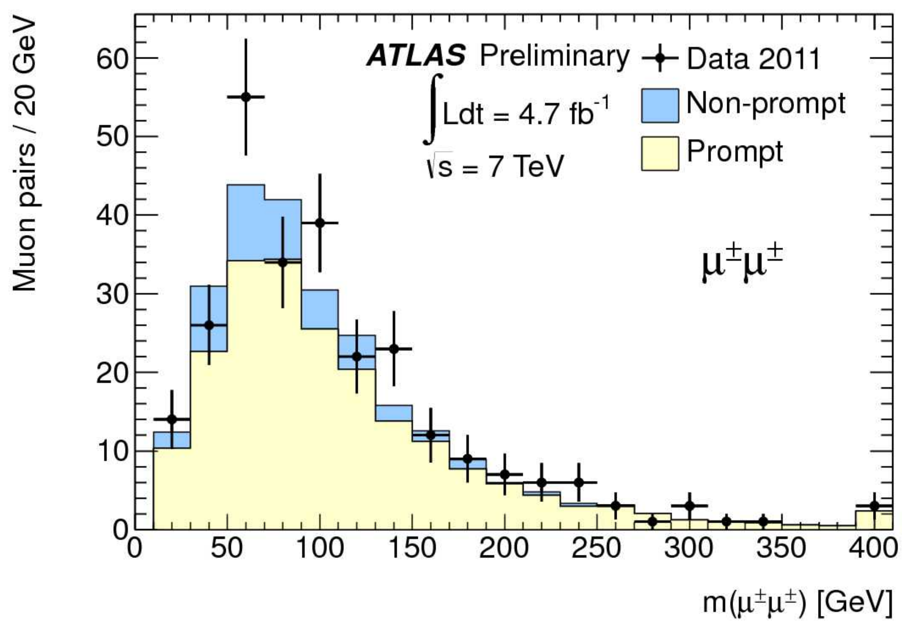
Model-Independent Searches

- Dedicated searches cannot cover every possible final state
- Complete the spectrum of analyses with model-independent searches
- Two examples:
  - → Inclusive same-sign search
  - → A generic search trying to look all possible final states (that may have been missed by the dedicated analyses)

Model-Independent Searches
Inclusive Same-Sign Dilepton

- Inclusive: only requirement is two isolation same-sign leptons
- Look for excess as a function of lepton pair properties, namely dilepton invariant mass





Model-Independent Searches Inclusive Same-Sign Dilepton

- Limit presented in terms of fiducial cross-section limit, i.e. cross-section with detector and event-selection acceptance (as opposed to total cross-section):

95% CL upper limit on fiducial cross-section

$$\sigma^{\text{fid}}_{95} = \frac{N_{95}}{\varepsilon_{\text{fid}} \times \int \mathcal{L} dt}$$

95% CL upper limit on yield (given Nobserved and Nbackground)

Reconstruction and Selection efficiency
Within acceptance

Integrated luminosity

- σ_{fid} is (almost) model-independent
- Can turn σ_{fid} into σ_{total} with generator-level information only
- Caveat: not exactly model-independent → must be conservative

Model-Independent Searches
Inclusive Same-Sign Dilepton

- Particle-level definition of acceptance:

	Electron requirement	Muon requirement
Leading lepton p_T	$p_T > 25$ GeV	$p_T > 20$ GeV
Sub-leading lepton p_T	$p_T > 20$ GeV	$p_T > 20$ GeV
Lepton η	$\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.47$	$\|\eta\| < 2.5$
Isolation	$p_T^{cone0.3}/p_T < 0.1$	$p_T^{cone0.4}/p_T < 0.06$ and $p_T^{cone0.4} < 4$ GeV $+ 0.02 \times p_T$

Particle-Level
Isolation

- Also search for excess in ++ and -- separately

Mass range	95% C.L. upper limit [fb] expected	observed	expected	observed
	$e^\pm e^\pm$		$\mu^\pm\mu^\pm$	
$M > 15$ GeV	$45.0^{+17.3}_{-12.0}$	45.7	$23.4^{+8.6}_{-5.8}$	29.1
$M > 100$ GeV	$24.3^{+9.1}_{-7.0}$	25.6	$11.9^{+4.4}_{-2.9}$	14.6
$M > 200$ GeV	$8.8^{+3.2}_{-2.9}$	8.1	$4.2^{+1.8}_{-1.1}$	6.6
$M > 300$ GeV	$4.5^{+1.6}_{-1.3}$	3.9	$2.3^{+0.8}_{-0.7}$	2.5
$M > 400$ GeV	$2.9^{+1.1}_{-0.9}$	2.3	$1.6^{+0.6}_{-0.5}$	1.7
	e^+e^+		$\mu^+\mu^+$	
$M > 15$ GeV	$27.3^{+10.0}_{-7.9}$	23.8	$14.7^{+6.0}_{-3.2}$	14.9
$M > 100$ GeV	$16.2^{+6.0}_{-4.8}$	12.4	$8.2^{+3.2}_{-2.4}$	7.7
$M > 200$ GeV	$6.6^{+2.8}_{-1.5}$	6.5	$3.4^{+1.5}_{-0.7}$	4.2
$M > 300$ GeV	$3.5^{+1.6}_{-0.8}$	2.9	$2.0^{+0.8}_{-0.5}$	2.0
$M > 400$ GeV	$2.4^{+1.1}_{-0.6}$	1.7	$1.5^{+0.6}_{-0.3}$	1.7
	e^-e^-		$\mu^-\mu^-$	
$M > 15$ GeV	$24.6^{+8.5}_{-6.8}$	29.1	$11.9^{+4.4}_{-3.4}$	18.0
$M > 100$ GeV	$12.7^{+4.6}_{-3.9}$	19.9	$5.8^{+2.2}_{-1.9}$	9.8
$M > 200$ GeV	$4.7^{+1.9}_{-1.3}$	4.4	$2.7^{+1.1}_{-0.7}$	4.3
$M > 300$ GeV	$2.8^{+1.1}_{-0.8}$	2.7	$1.4^{+0.7}_{-0.3}$	1.7
$M > 400$ GeV	$1.8^{+1.0}_{-0.4}$	2.2	$1.2^{+0.4}_{-0.0}$	1.1

Model-Independent Searches
Generic Search

- Implemented in many ways in several experiments:
  - → Hera
  - → D0 Quary and CDF Sleuth
  - → CMS Music
  - → ATLAS generic search (shown here)
- Basic idea: look for an excess in the entire dataset (!)
- Caveats:
  - → Not optimized for any given signal. No complicated reconstruction.
  - → Background estimates not as accurate / trustworthy as in a dedicated search
  - → Very large trial factor: the more signal regions the more likely an excess is a statistical fluctuation → decrease sensitivity
- Observation of an excess would trigger additionial studies on additional data

Model-Independent Searches
Generic Search

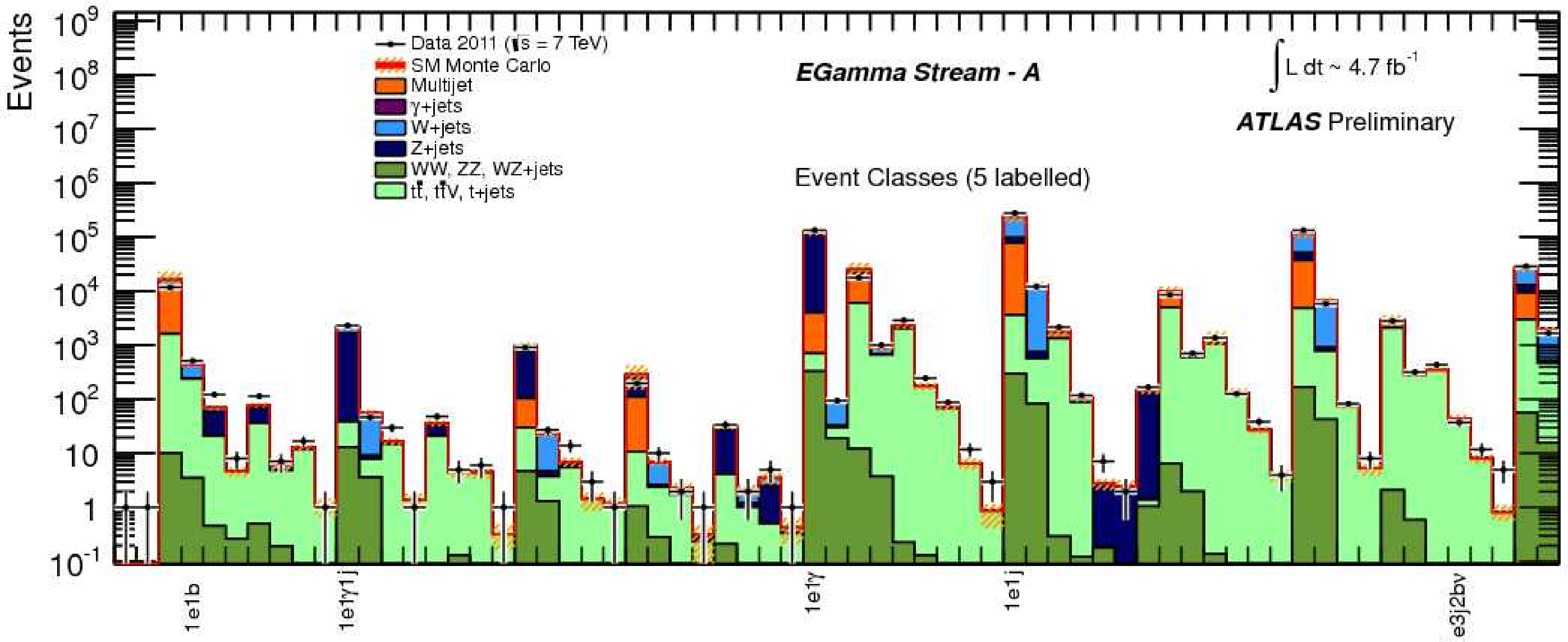
- ATLAS Generic Search
- 655 exclusive channels, as function of number of electrons, muons, photons, jets, b-jets, missing ET

object	jet	b-jet	electron	muon	photon	$E_{\mathrm{T}}^{\mathrm{miss}}$
label	j	b	e	μ	γ	ν
lower p_{T} cut	50 GeV	50 GeV	25 GeV	20 GeV	40 GeV	130 GeV

- Background estimated from Monte Carlo with conservative uncertainty on cross-sections
  - → QCD: 100% uncertainty
  - → Caveat: trust MC to simulate fake leptons

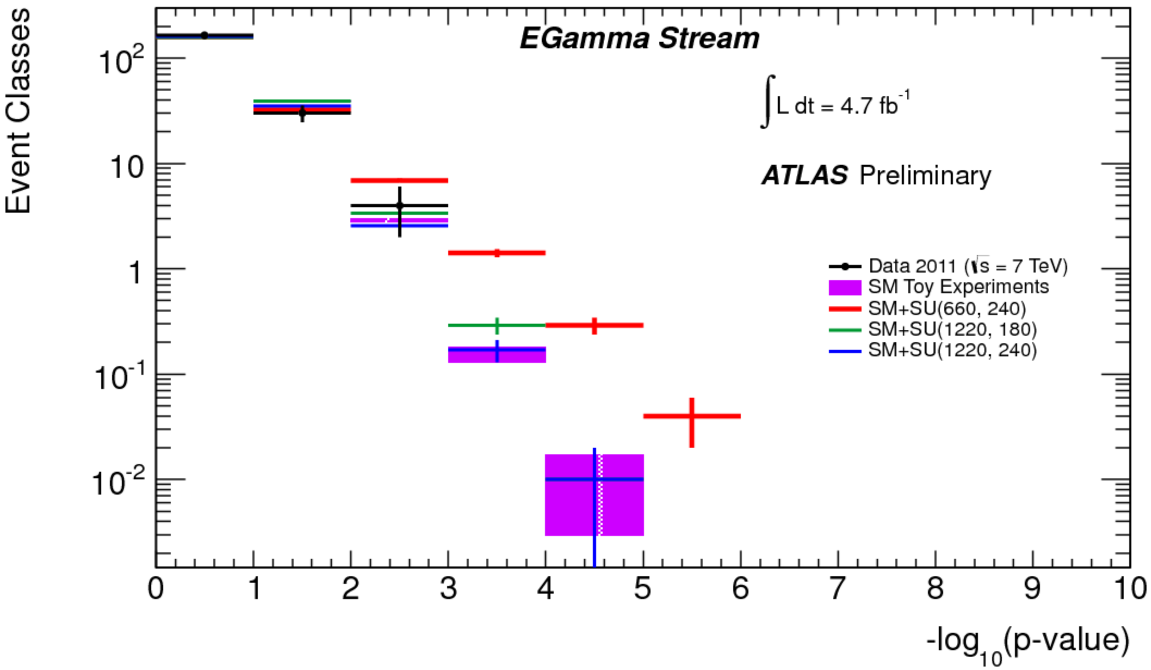
Model-Independent Searches
Generic Search

- Use lowest unprescaled trigger in each stream: electron/photon (e/g), muon, jet/MET/tau
- Part of the result for the e/g stream:



Model-Independent Searches
Generic Search

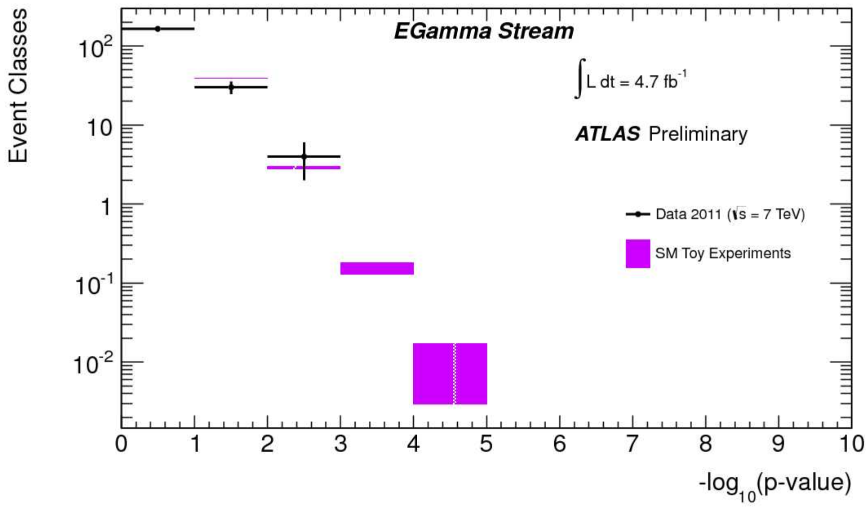
- Quantifying an excess: for each signal region, compute the p-value = probability that the background fluctuates at or above the observed number of events
- Take into account trial factor (a.k.a. Look-Elsewhere Effect) with pseudo-experiments (a.k.a. "toys")

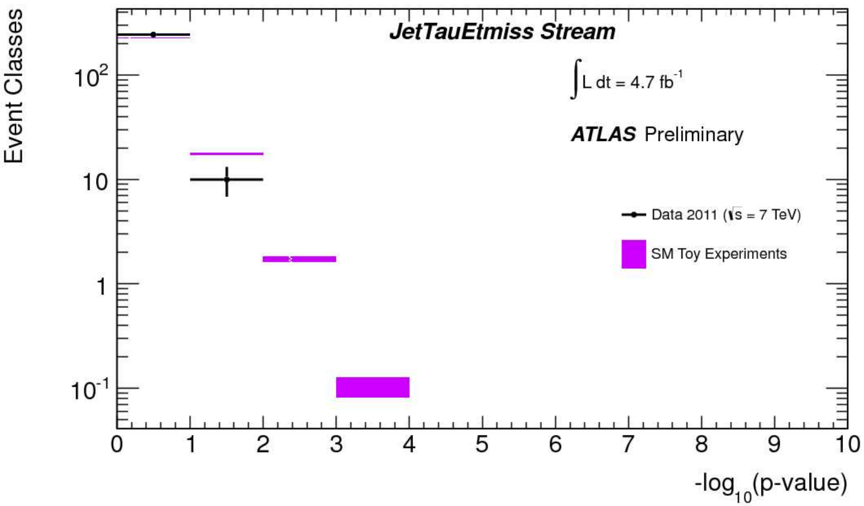


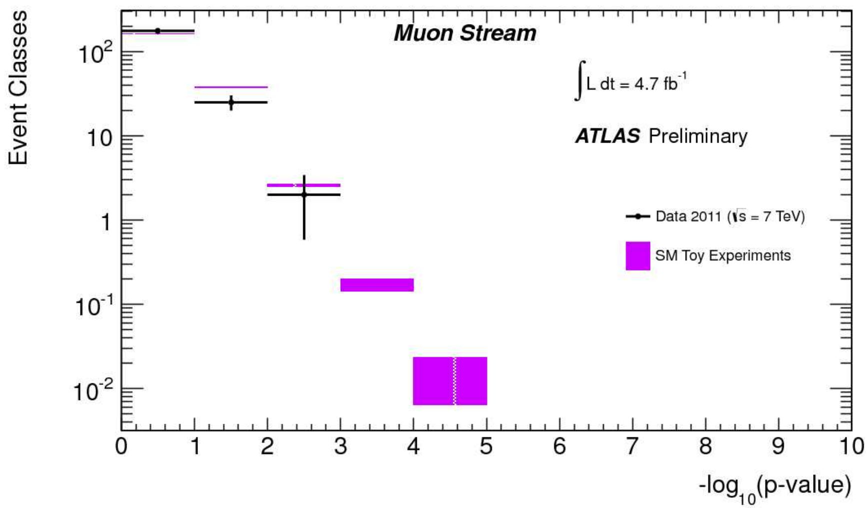
- Sanity/Sensitivity check:
  - → Compare with toys in which a signal is injected

Model-Independent Searches
Generic Search

- Result in the 3 streams
- No excess!
  - → A clear evidence that our simulation is pretty good!

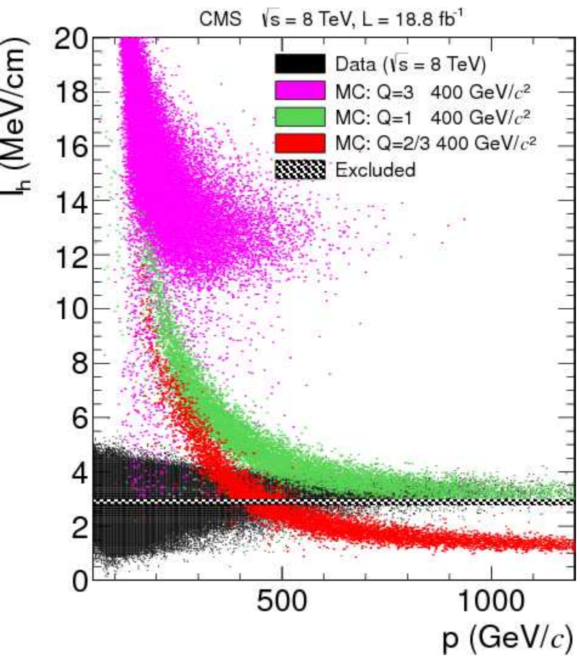


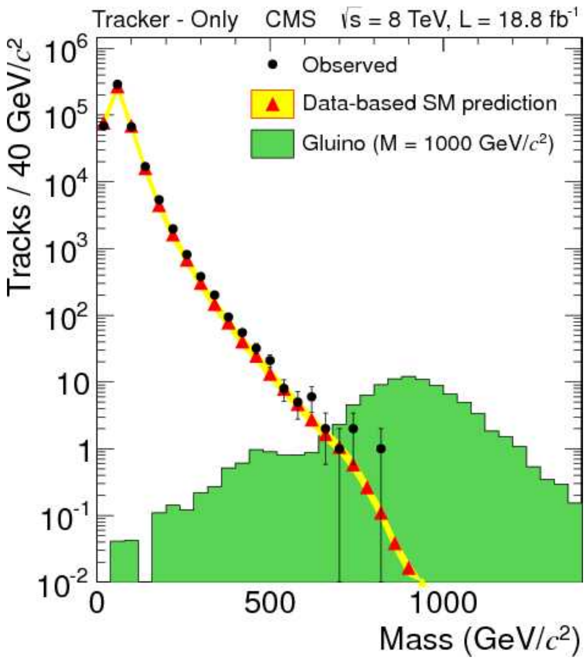


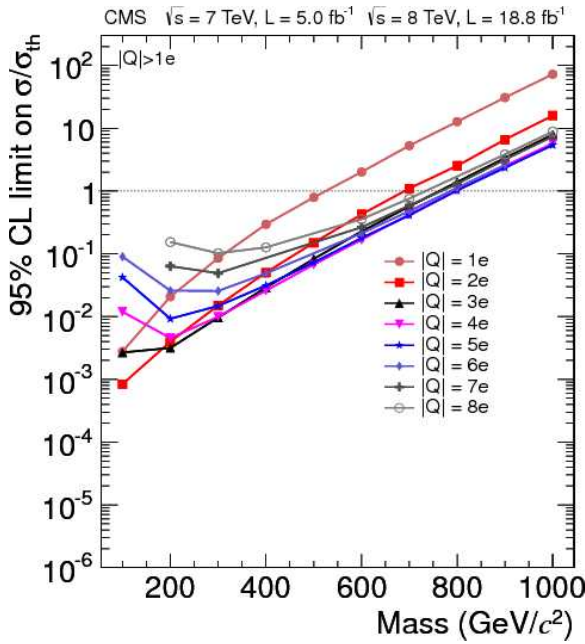


LLP: Highly Ionizing Particles (CMS)

- Slow Heavy Particles or High-charge-multiplicity particles: muon-like signature with large dE/dx and slow timing
- Sensitive to 1/3 < |q| < 8 (above: stopped by calorimeter)
- Latest CMS result (full dataset): combine dE/dx from inner tracker and timing from muon spectrometer



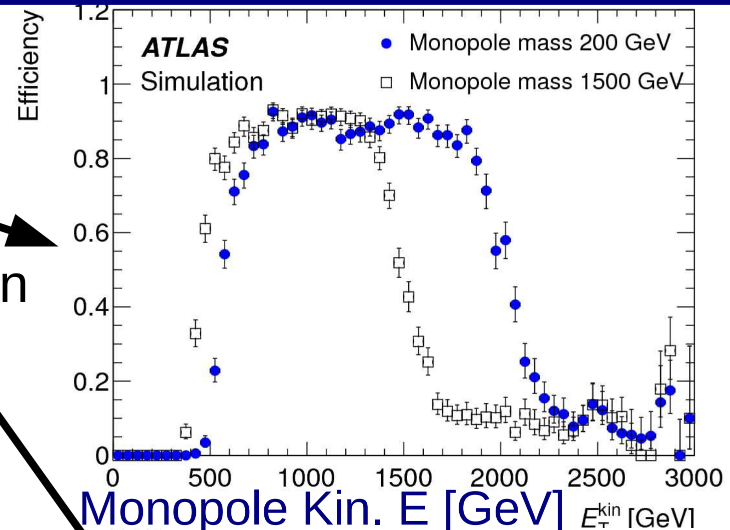




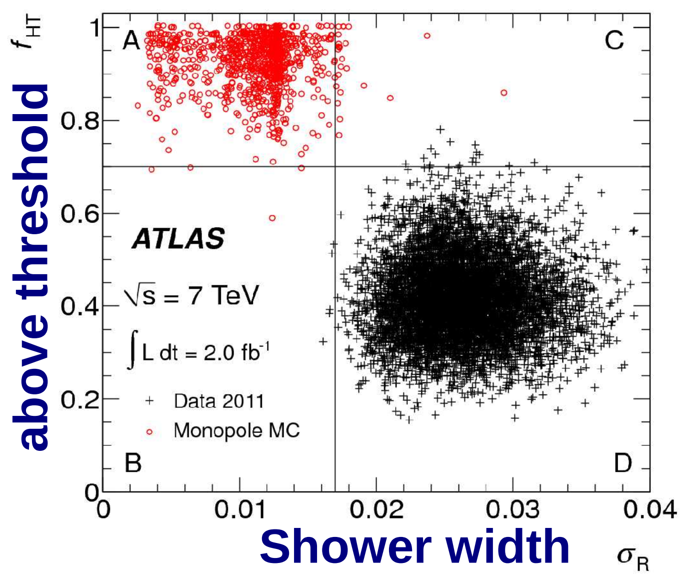
arXiv: 1305.0491

LLP: Magnetic Monopole (ATLAS)

- So ionizing → stopped by calorimeter
- Signature:
  - → Large number of hits in Transition Radition Tracker caused by delta-rays
  - → Large fraction of hits above threshold (usually used for electron ID)
  - → EM shower narrower than an electron

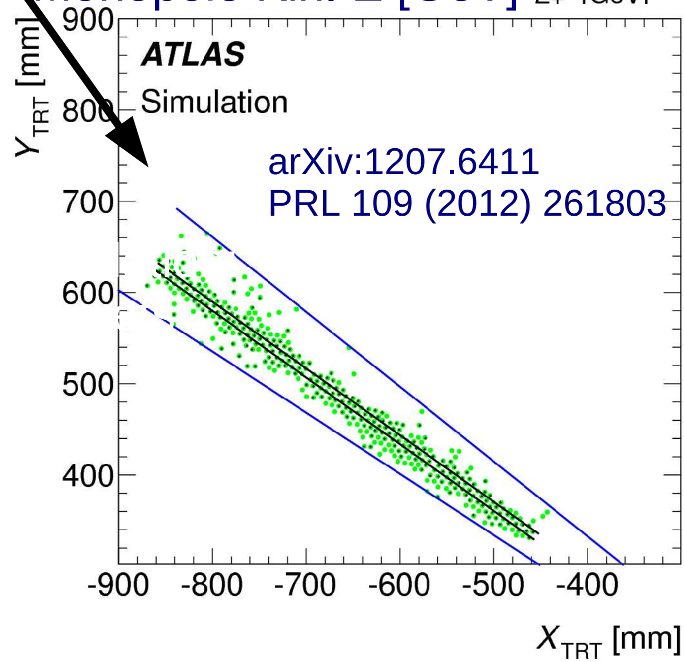


Monopole Kin. E [GeV]



Fraction of hits above threshold

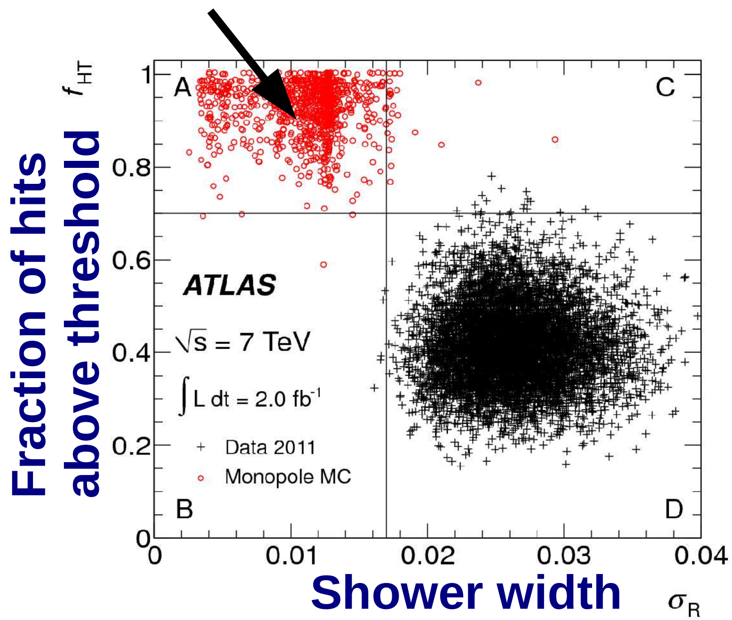
Shower width



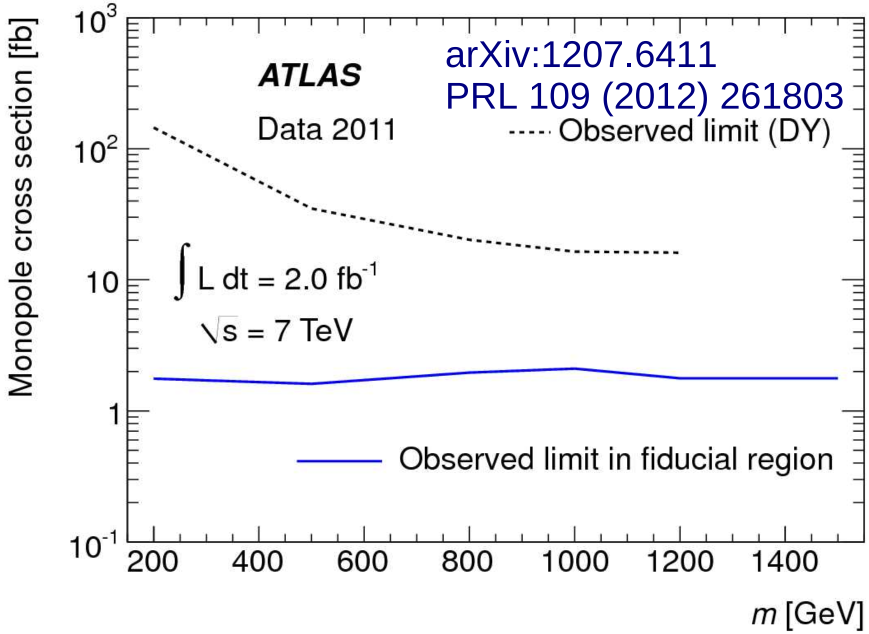
arXiv:1207.6411
PRL 109 (2012) 261803

LLP: Magnetic Monopole (ATLAS)

- Background estimated from the two uncorrelated variables (“ABCD method”)
- 0.011 ± 0.007 background events expected
- 0 event observed

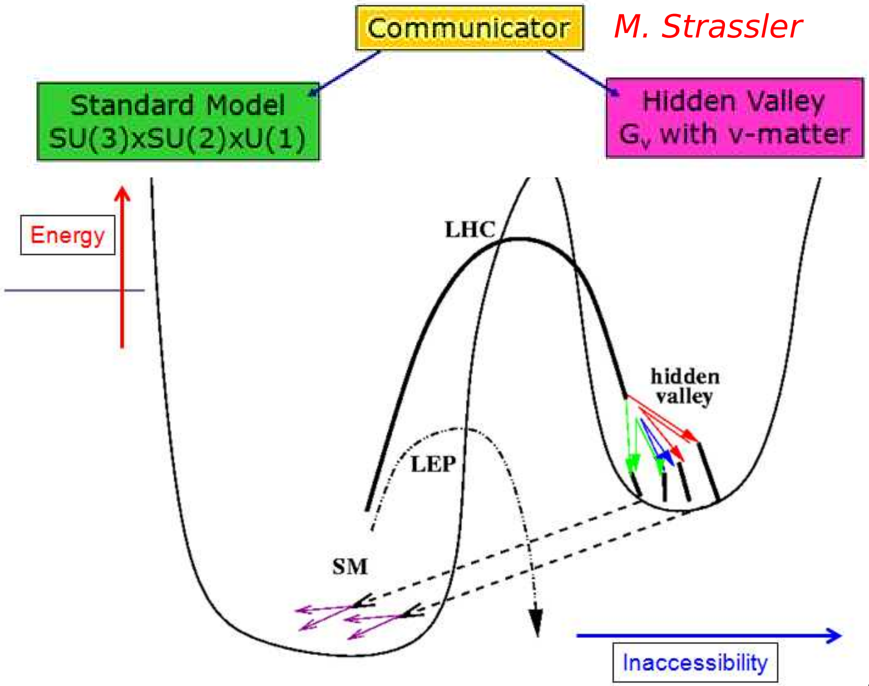


- Model-independent limit on fiducial cross-section:

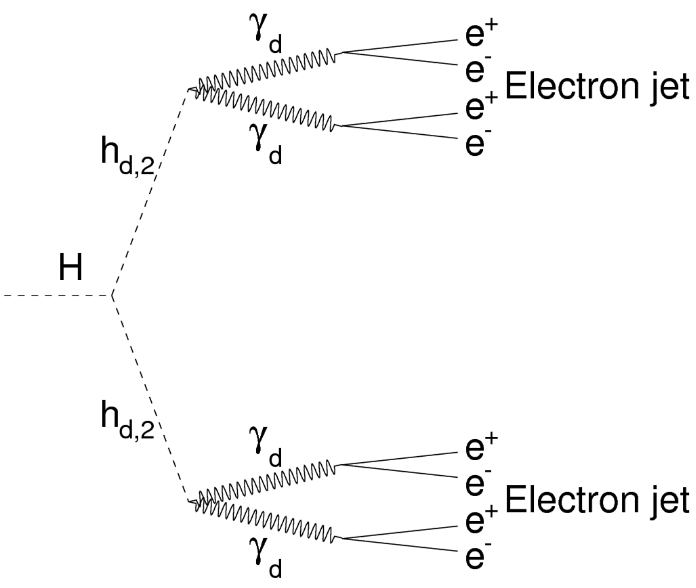


Higgs Exotic Decay: Electron-Jets

- Hidden-Valley theories predict a hidden sector coupled to the SM through some heavy communicator
- Higgs mixing → exotic decay



- Ex: h → cascade → multiple highly collimated electrons (a.k.a. electron-jets)
- Could be long-lived



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