Exotica*? Speaking up for Minorities

Tetiana Berger

(LAPP, CNRS, France)

On behalf of ATLAS, CMS and LHCb collaborations

*Exotica = Beyond Standard Model, not SUSY.

LHC ski 2016

A first discussion of 13 TeV results
April 10-15, 2016, Obergurgl University Center, Tirol, Austria

This talk is meant as an overview. Please see Exotica talks this afternoon and DM search talks tomorrow for details:

17:20	[28] Searches for Beyond-Standard-Model Higgs bosons in ATLAS	ZINONOS, Zinonas
17:40	[41] Highlights of searches for new physics (non-SUSY) with CMS	SKHIRTLADZE, Nikoloz

TUESDAY

TUE2 - (18:20-19:20)

time	[id] title	presenter
18:20	[44] Searches for supersymmetry at CMS in leptonic final states with 13 TeV Data	WELKE, Charles Vincent
18:40	[29] Searches for new physics with fermions or jets at the ATLAS detector in LHC Run 2	DANDOY, Jeff
19:00	[30] Searches for new physics with bosons at the ATLAS detector in LHC Run 2	IORDANIDOU, Kalliopi

Young Scientists Forum 2 - (19:20-19:40)

time	[id] title	presenter
19:20	[39] Search for New Physics in Z+MET channel at CMS	BRODSKI, Michael
19:30	[48] Searches for new physics in jet final states in ATLAS at LHC Run II	AMADIO, Brian Thomas

WEDNESDAY

DM at 13 TeV and Data Interpretation - (10:50-11:30)

- Presenters: SALEK, David

New signatures of DM at the LHC - (17:00-17:40)

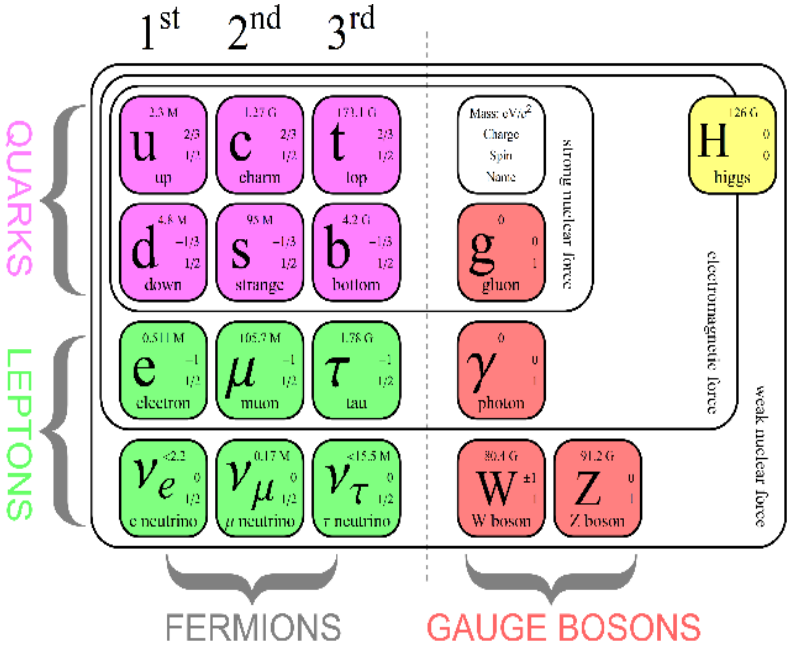
- Presenters: KOPP, Joachim

WED2 - (18:20-20:00)

time	[id] title	presenter
18:20	[50] Baryonic Dark Matter at the LHC	DUERR, Michael
18:40	[31] Dark matter searches from the ATLAS experiment at LHC Run 2	LEVIN, Dan
19:00	[40] Dark matter searches with CMS	JEITLER, Manfred

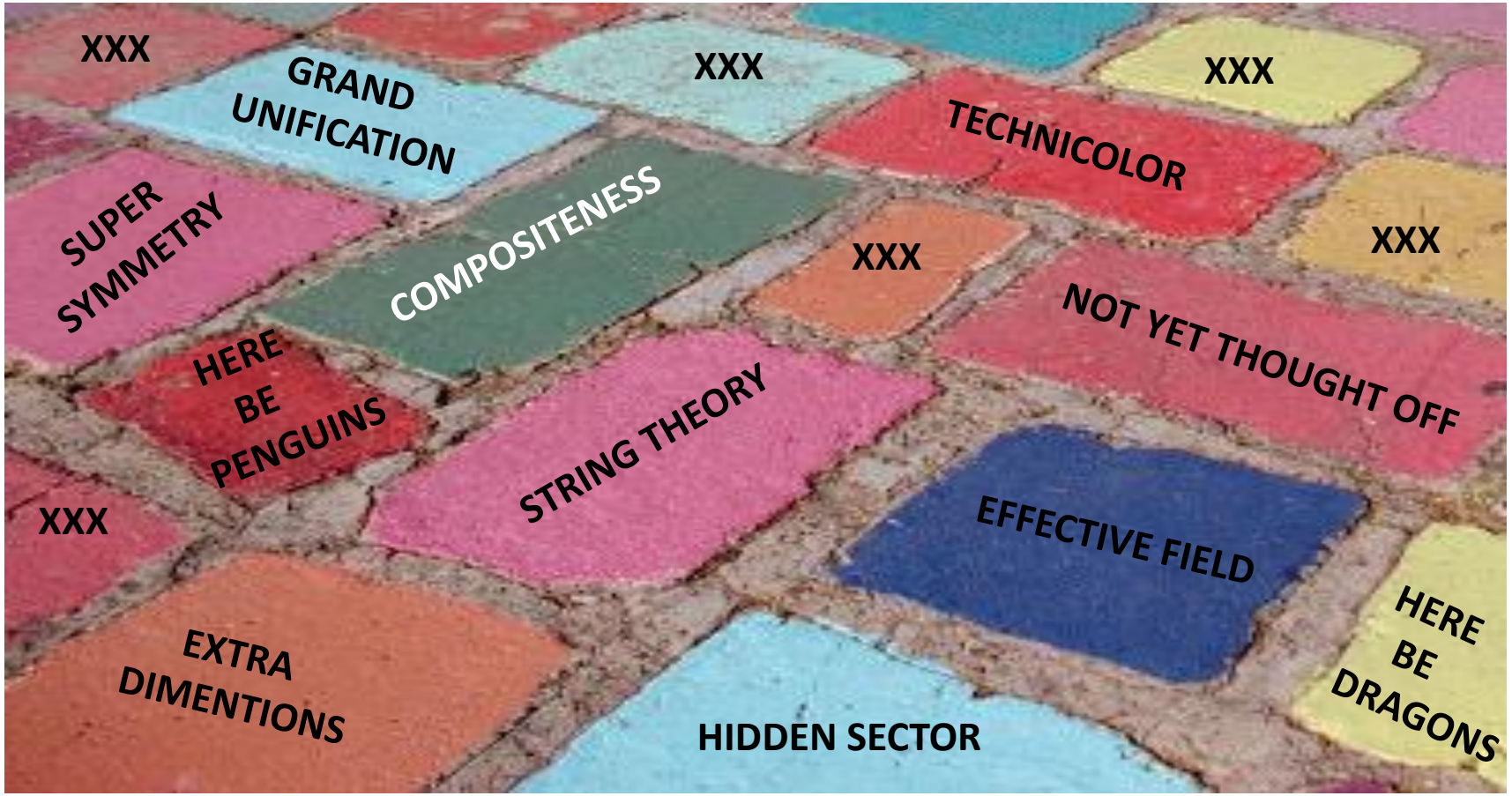
What is Exotica?

- Following a discovery of a scalar boson in Run 1 of LHC, Standard Model (SM) is complete and self-consistent
- But certain aspects of SM do not have an explanation
  - Why is Higgs light?
  - What is dark matter?
  - How to accommodate gravity?
  - What is the solution of the hierarchy problem?
  - Why are there three generations?
  - …



Beyond Standard Model Exotic theories try to address these questions.

Theoretical Approach: Exotic Theory



Balboa Park, San Diego, USA, from https://beautifulbalboapark.wordpress.com

Theories not enough! Need models to derive phenomenology (particle spectrum, production & decays modes)

Examples of what are we looking for

EXTRA DIMENSIONS

Kaluza-Klein excitations of particles (G^*, Z_{KK}, W_{KK}, g_{KK}, q_{KK}, …), Black Holes, string resonances…

GRAND UNIFICATION

new vector bosons (Z', W',..), heavy fermions (t',b', T, B…), ν_R, leptoquarks, diquarks, Higgses, etc.

COMPOSITENESS

excited states of known particles (l*, q*, Z*, W*,…), leptoquarks, etc…

HIDDEN/DARK SECTOR

dark photons, hidden particles, stealth-susy-particles etc...

TECHNICOLOR

new composite particles: techni-hadrons (ρ_{TC}, η_{TC}, etc…), leptoquarks, $T_{5/3}$,…

Experimental Approach: Exotic Search

Search for any deviations from Standard Model predictions

Direct observation:
new (e.g. Exotic) resonant or non-resonant structures

In-direct observation:
discrepancies in rates of rare processes, couplings measurements, etc.

Addressed in next talk by
Christian SCHWANENBERGER

Experimental Approach: Exotic Search

Search for any deviations from Standard Model predictions

Direct observation:
new (e.g. Exotic) resonant or
non-resonant structures

LOOK FOR SIGNATURES MADE OF BASIC OBJECTS

Jets, b-jets, E_T^{Miss} **Bosons (γ, W, Z)** **Leptons (e, μ, τ)** **Unconventional Particles**

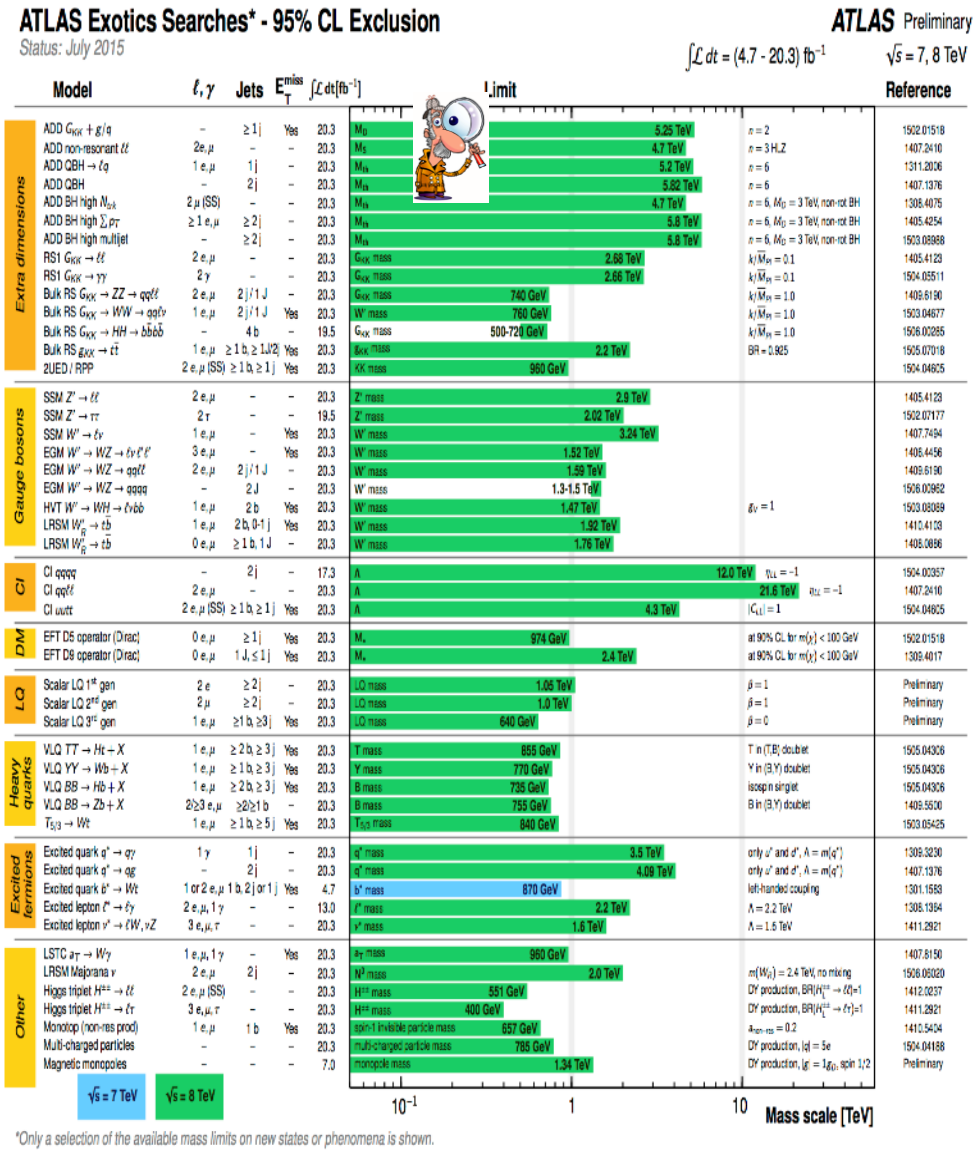
AS MANY SIGNATURES AS POSSIBLE

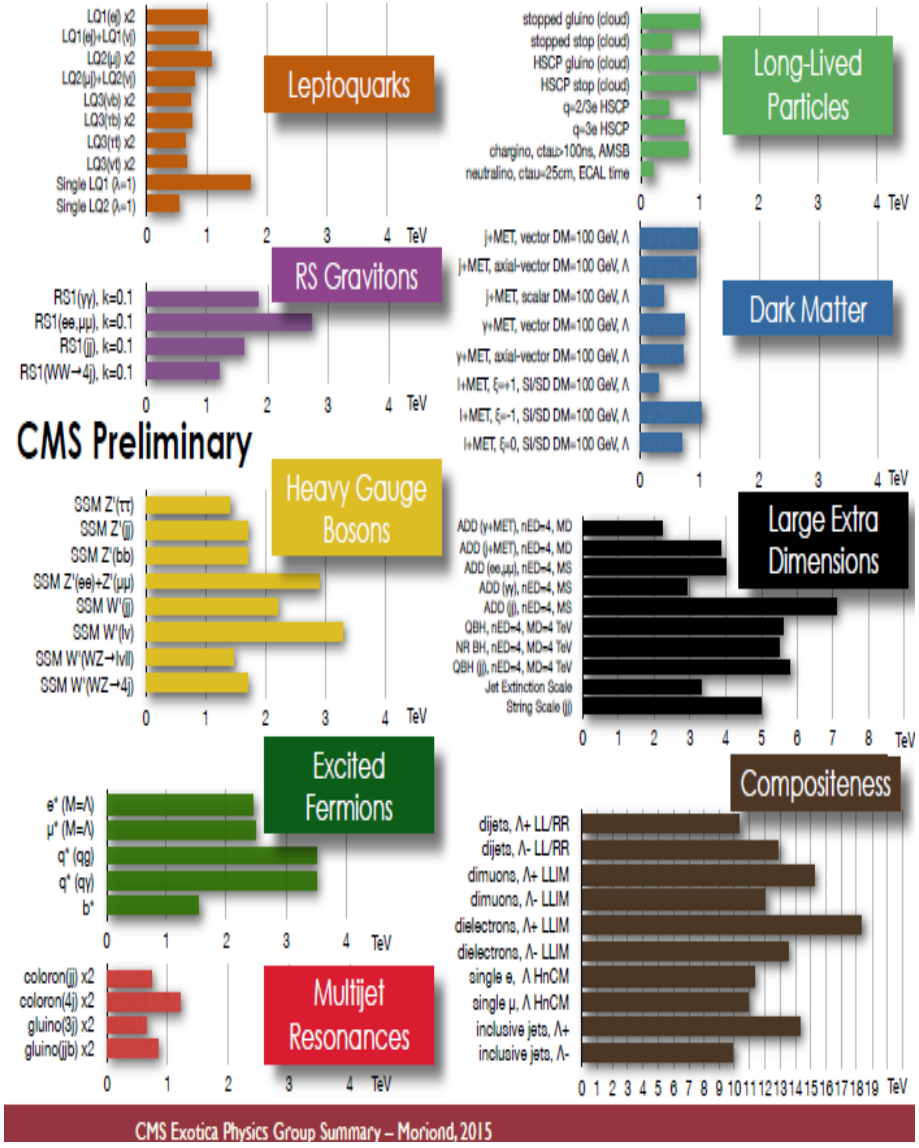
AS MODEL INDEPENDENT AS POSSIBLE

PROVIDE BENCHMARK MODEL RESULTS

Recap of results from the Run 1

No evidence for New Phenomena Seen! Limits for many models reaching 1 TeV and beyond.



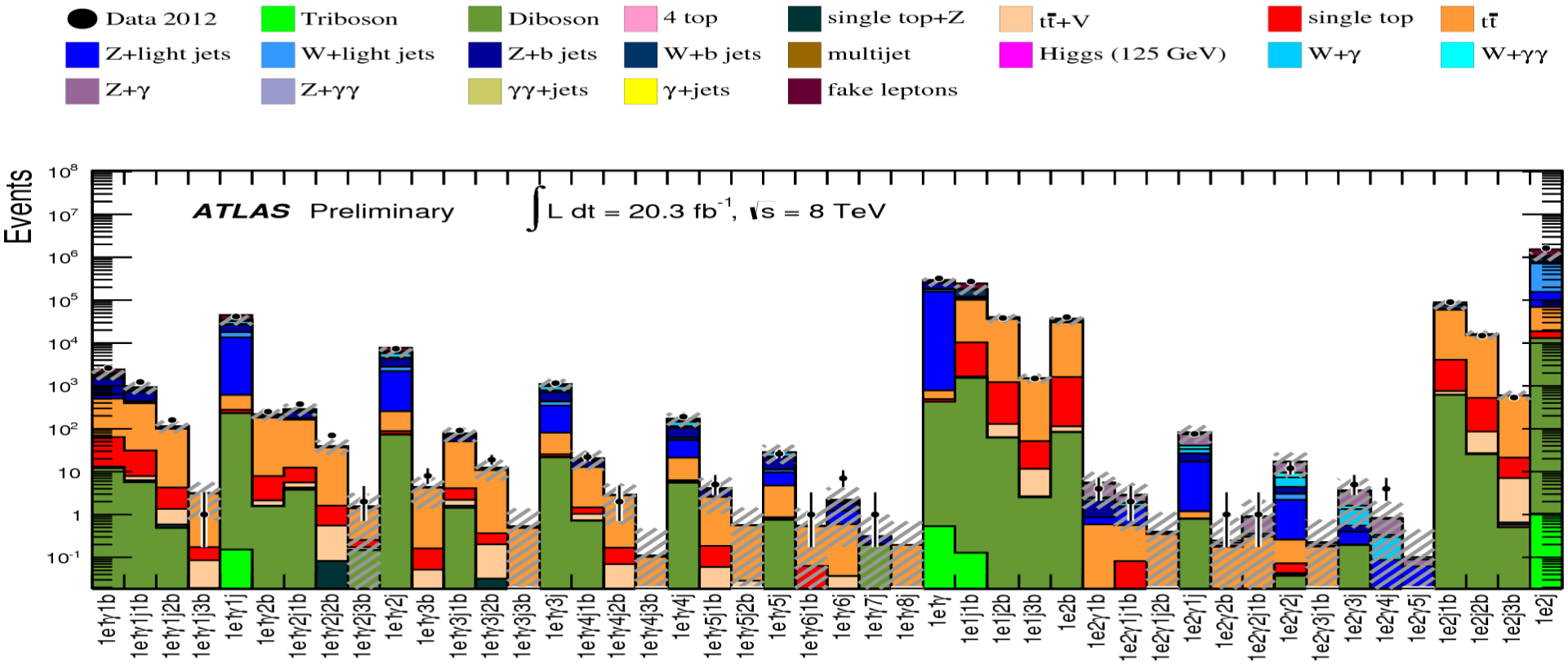


General Search

ATLAS-CONF-2014-006

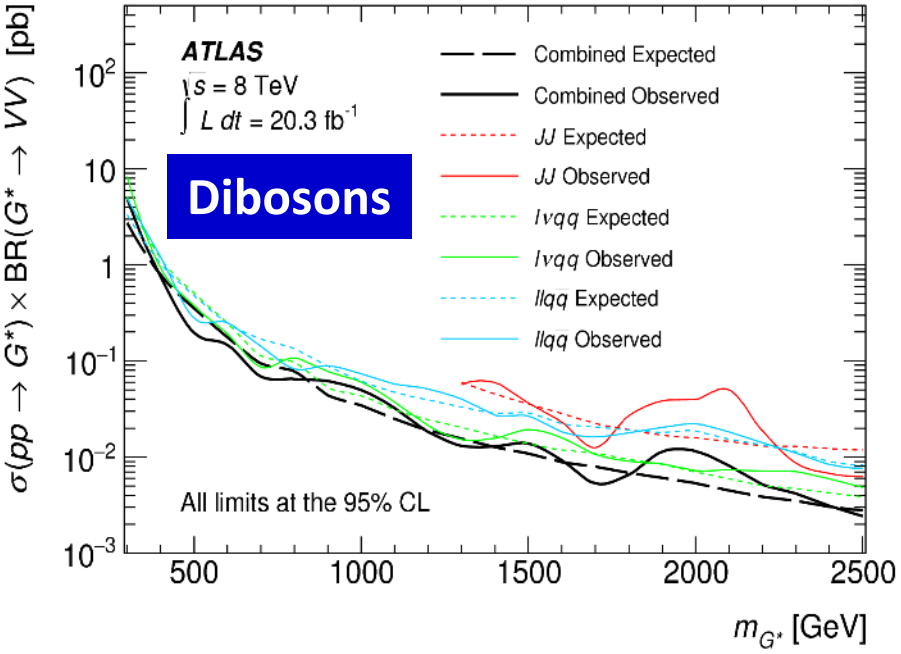
No evidence for New Phenomena Seen!

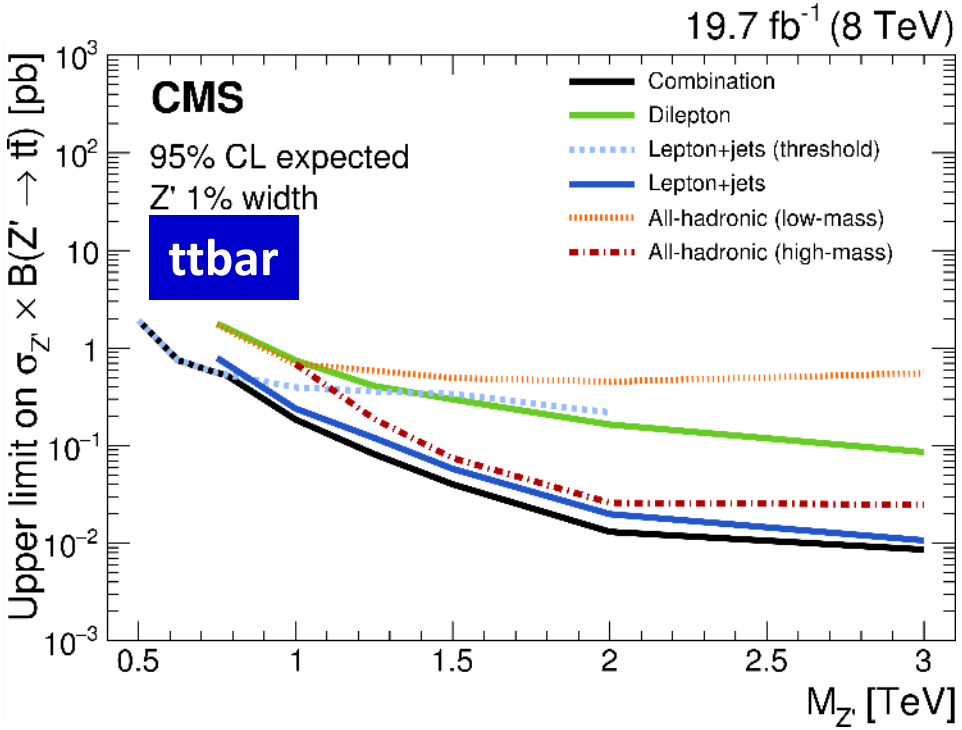
- A search based on combinations of high-p_T objects (e, μ, γ, ν, jet, bjet)
- Standard Model backgrounds from MC only
  - 573 categories have data events; 697 have >0.1 events in MC simulation
- Searches for largest data/MC variations (MC mis-modelling is a problem)
- Need dedicated analysis if discrepancy is observed



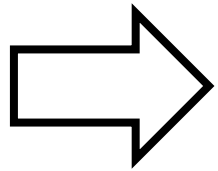
How to get the most out of data?

- Combine across different experiments
  - Allows to double the dataset for the same final state (dark matter searches are exploring this option)
- Combine across different final states of the same decay
  - Extended coverage of the spectrum, sensitivity increase





How to make sure we have looked everywhere possible?



Back to theory

From signature to model*

	ED	TC	Little Higgs	GUT	HV	DM	Compositness
Multijets	BH				X		
Jet+Photon	QBH						q*
Dijets	QBH		Z’	Z’, W’	X		
Jet(s)-lepton(s)	BH	LQ		LQ			l*, t*
Dileptons	QBH, G*	ρ_{TC}	Z’	Z’	X		Z*
Leptons+Photon							l*
Lepton+MET		ρ_{TC}	X	W’		X	W*
Multileptons				Z’	X		
γ+MET						X	
Dibosons (W,Z)	G*	ρ_{TC}	Z’	Z’, W’			
Diphotons	G*	η_{TC}					
ttbar/bbar	G*		Z’	Z’			
tb			X	W’			
LLP/Lepton-jets					X		
b/t+W/Z/H	VLQ	$T_{5/3}$	VLQ				b*

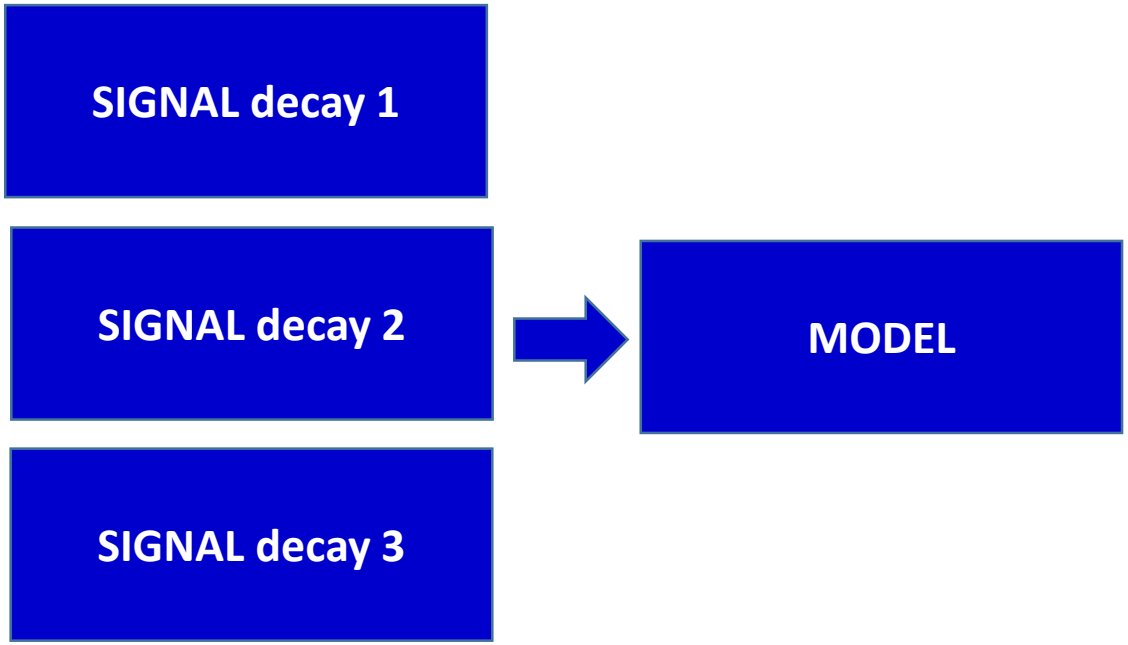
Models Predict Various Signatures

*This table is not exhaustive, not all interpretaions have been done

From signature to model

- Combination of different decays:

very model specific!



From signature to model

- Combination of different decays:

very model specific!

Same-Sign Dilepton

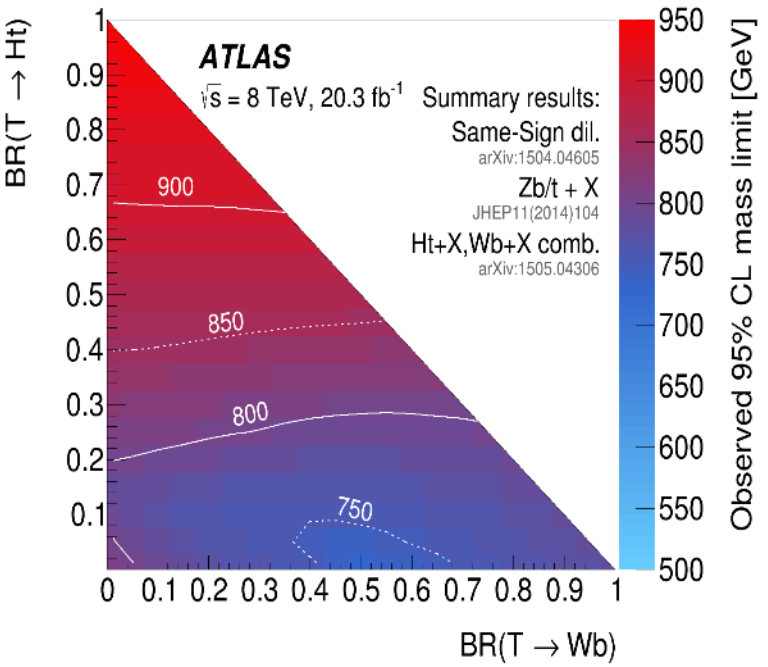
Zb/t+X

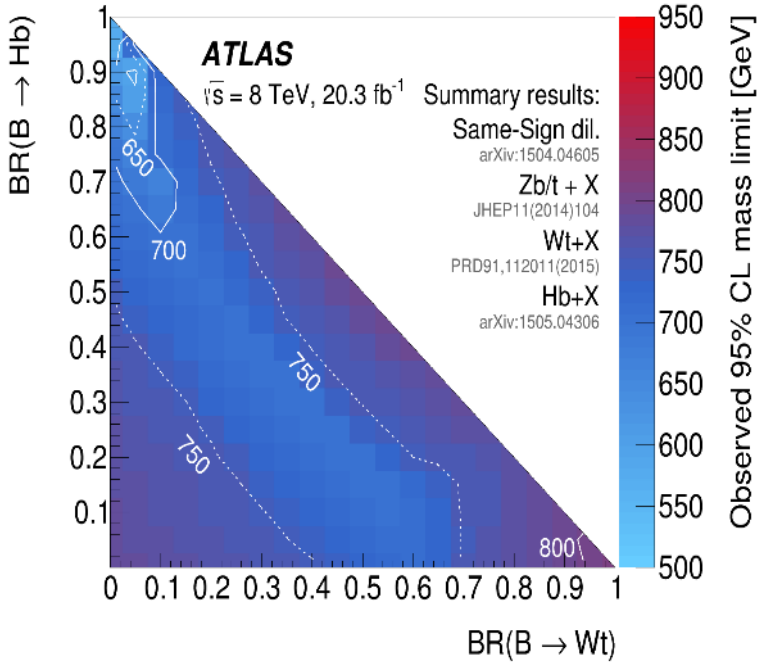
Ht+X, Wb+X

→ **Heavy Vector Like Top Quark**

- Other possibilities:

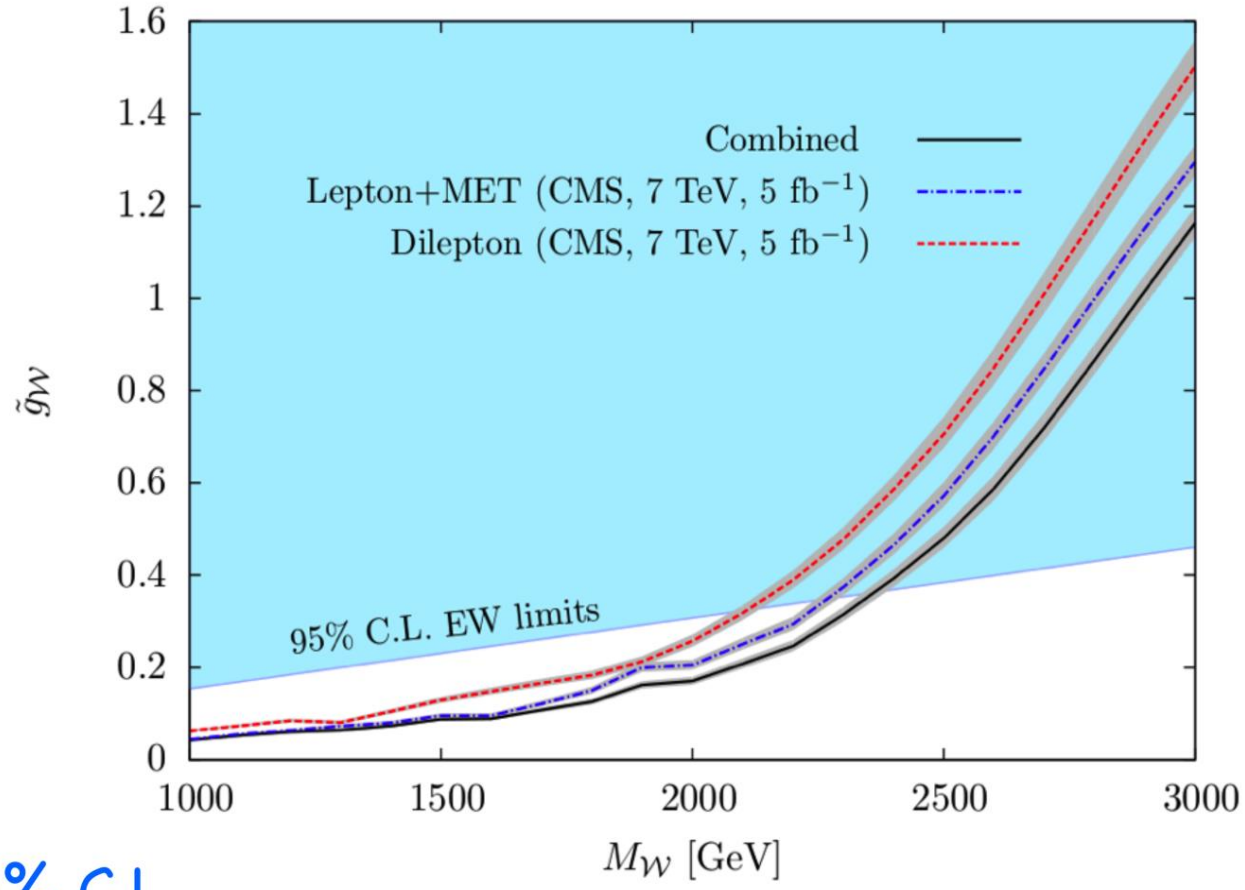
l*→llgamma+ljj; Z'→ ll+VV+jj, DM…





From signature to model

- Across different particles in the same model
  - e.g. W' and Z' (J. de Blas et al. JHEP 01(2013) 016)



95% C.L.

Mostly done by theorists at the moment but also presents opportunity for experimentalists.

Back to the experiments: LHC Run 2

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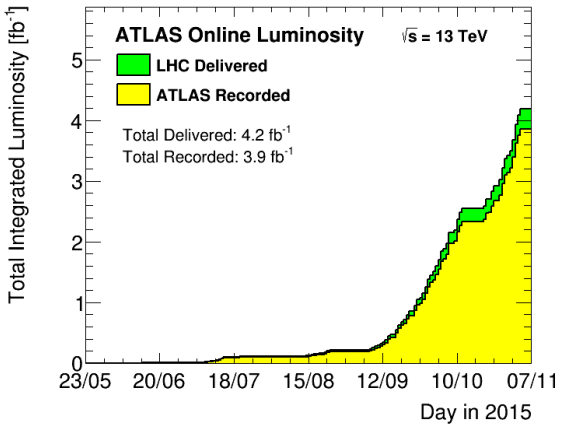
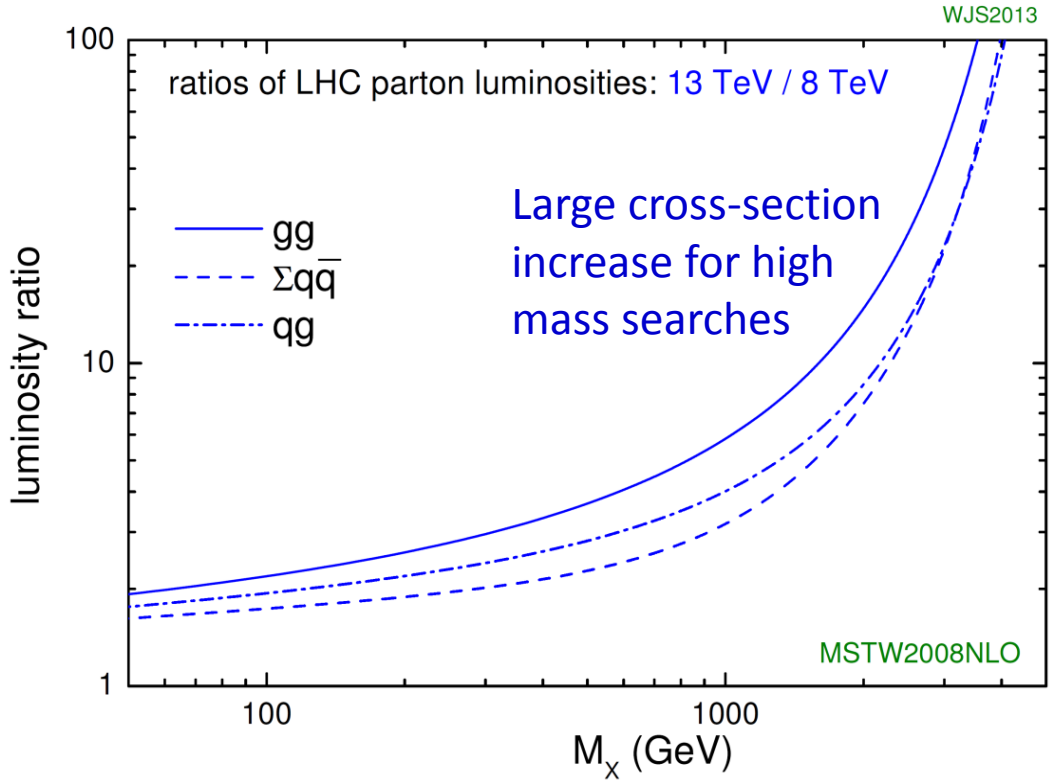
Year	Energy [TeV]	Bunch Spacing	Pile-up*	Luminosity [fb^{-1}]		
				ATLAS	CMS	LHCb
2012	8	50	23	20	20	2
2015	13	25	14	3.2	2.7+0.6	0.3
2016*	13	25	43	25	25	2.5





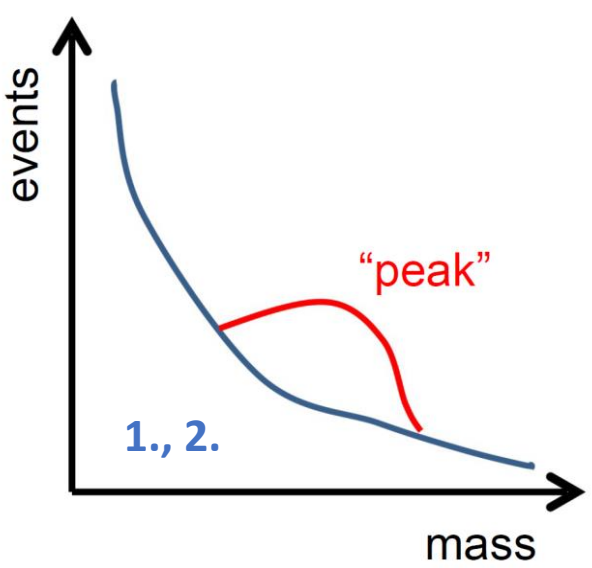
Unique opportunities for discovery in 2015 and 2016!

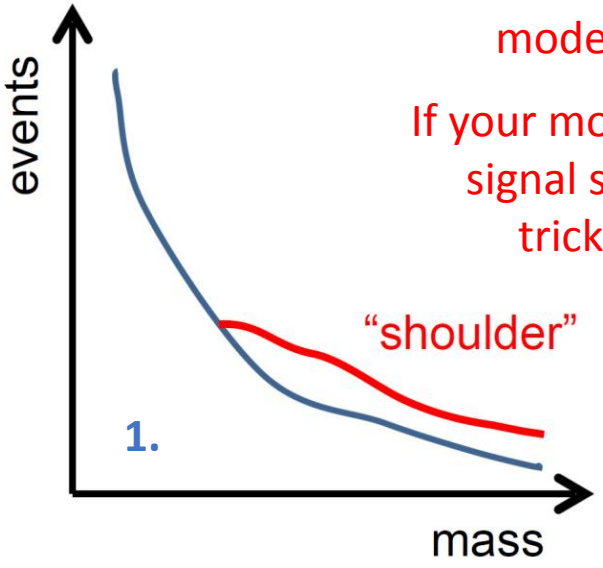
Signature-Based Searches

Caveat:

Need signal-shape hypothesis
Results are not completely model-independent

If your model does not have signal shape as studied tricky to interpret





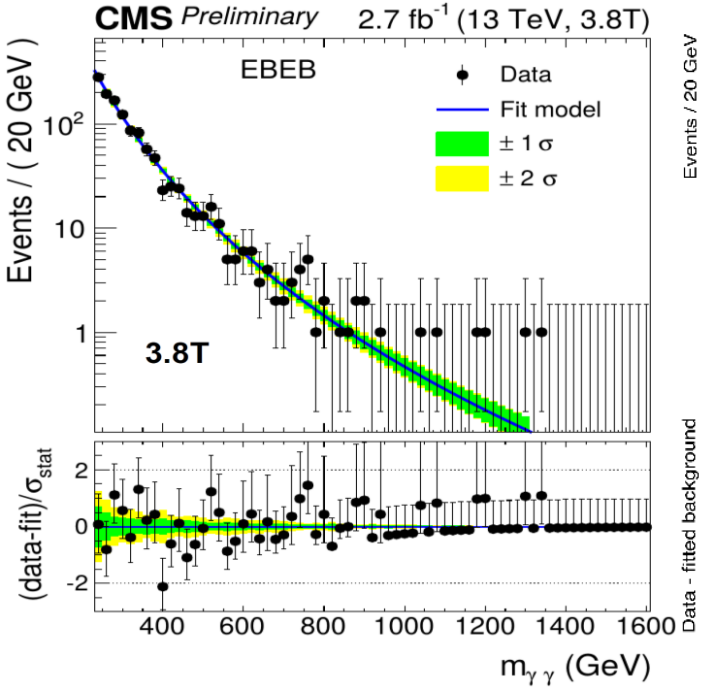
To estimate background:

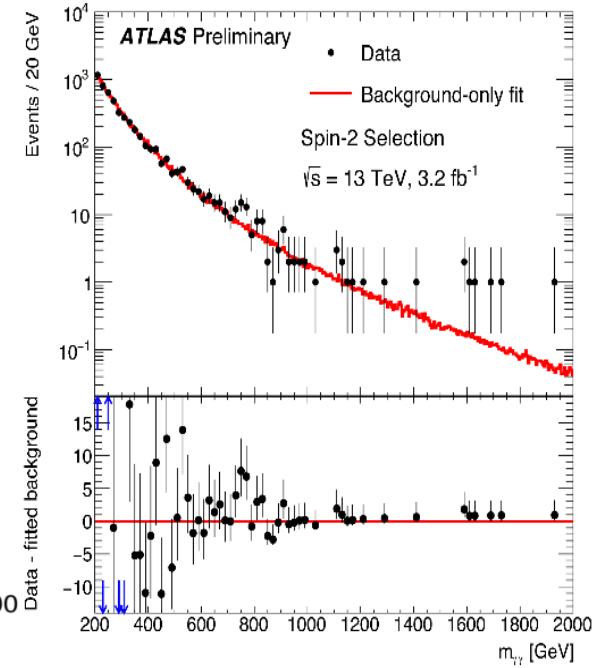
1. Detailed simulations of mass-spectrum shape
2. Smooth functional form fitted from data

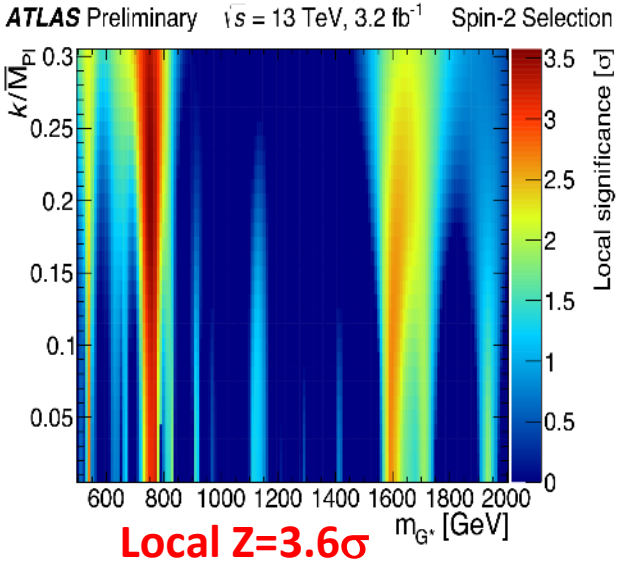
Diphoton Searches CMS & ATLAS

ATLAS-CONF-2016-018

CMS-PAS-EXO-16-018

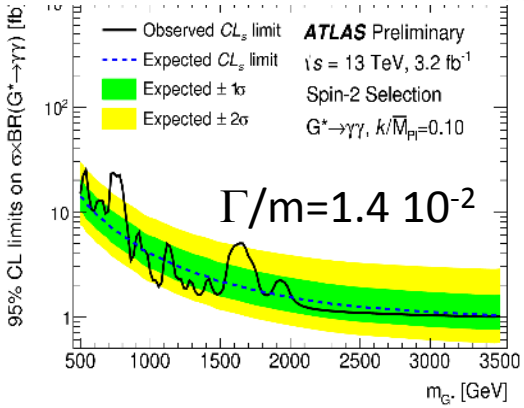


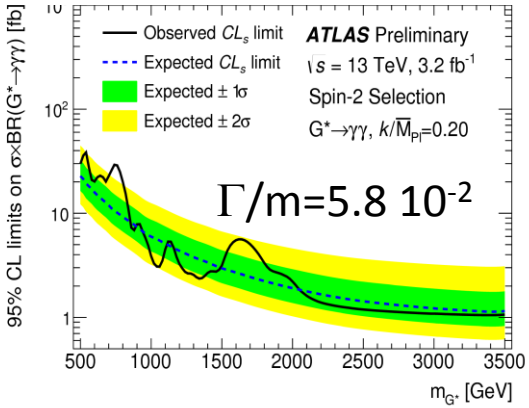


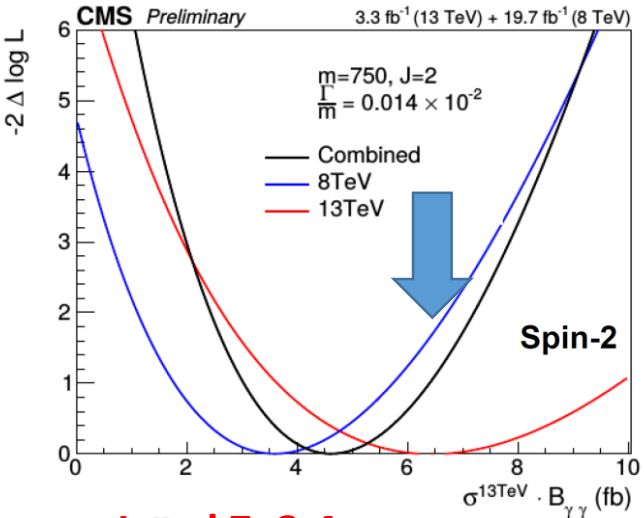


Local Z=3.6σ

Global Z = 1.8σ







Local Z=3.4σ

Global Z = 1.6σ

Largest deviation m≅750GeV

Consider more exotic spin-2 interpretation for this talk

Upper limits are resonant-shape & width-dependent

Following on diphoton excitement

We'll know more this summer but if the excess persists, which other channels could be implicated?

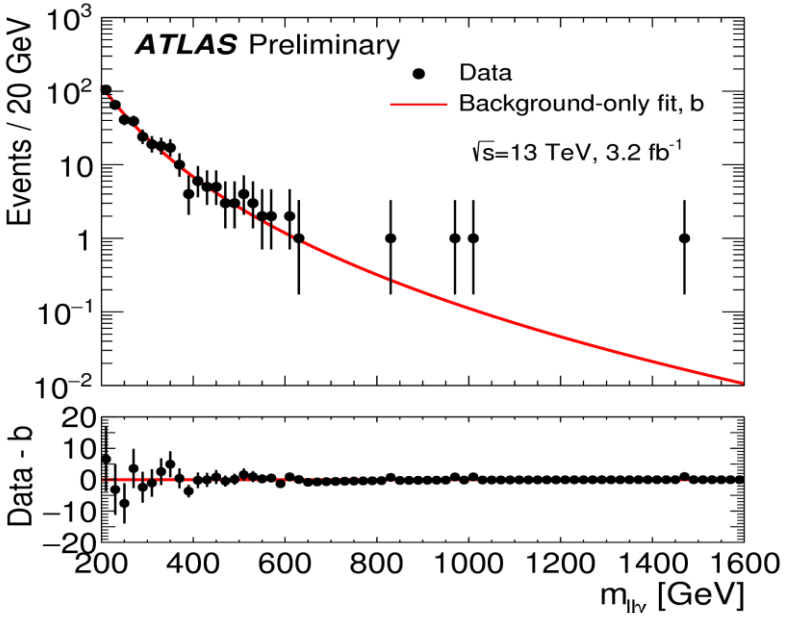
Following on diphoton excitement

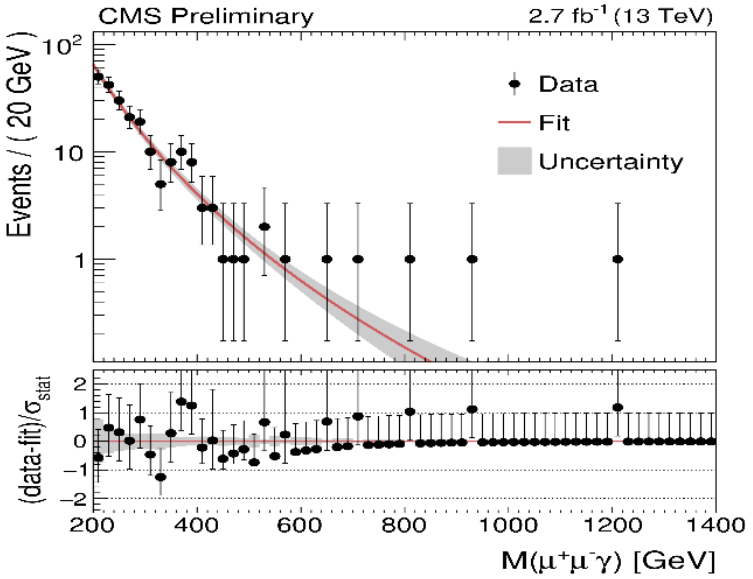
We'll know more this summer but if the excess persists, which other channels could be implicated?

- Dibosons
- Dileptons
- "Dijets" (jj, bbbar, ttbar)
- Heavy Vector-like quarks

Other di-boson channels (Zγ)

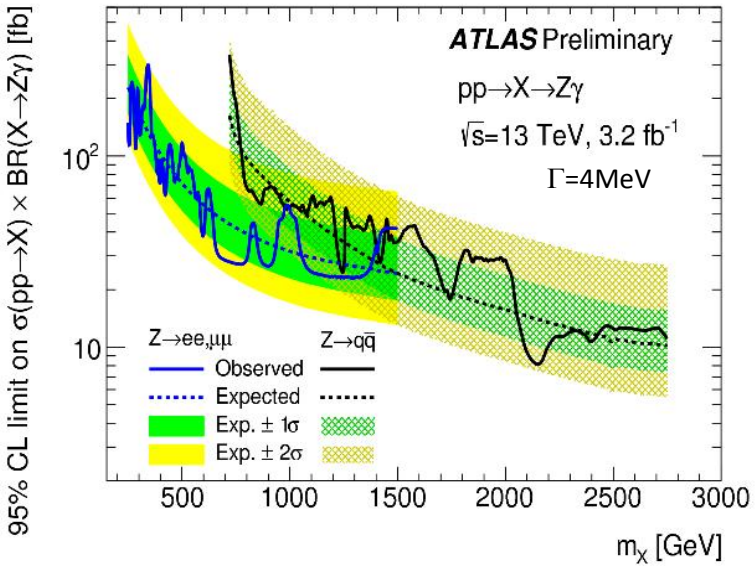
ATLAS-CONF-2016-010
CMS-PAS-EXO-16-019

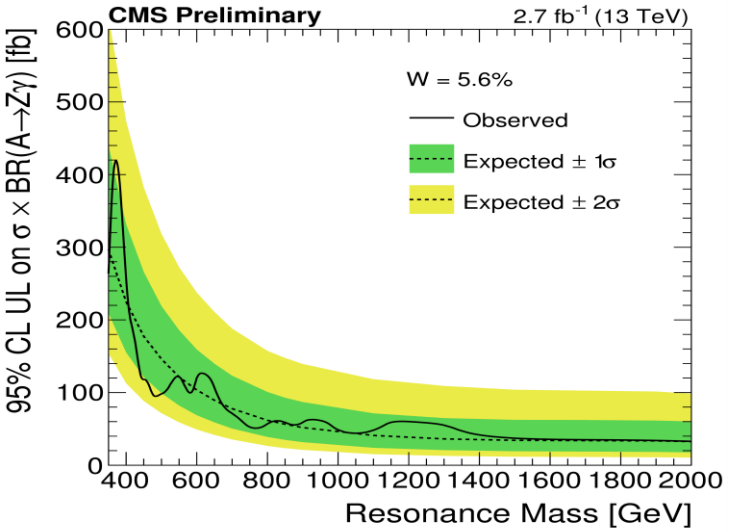




Not yet at γγ sensitivity.

Leptonic channel Strongest in the region of interest.

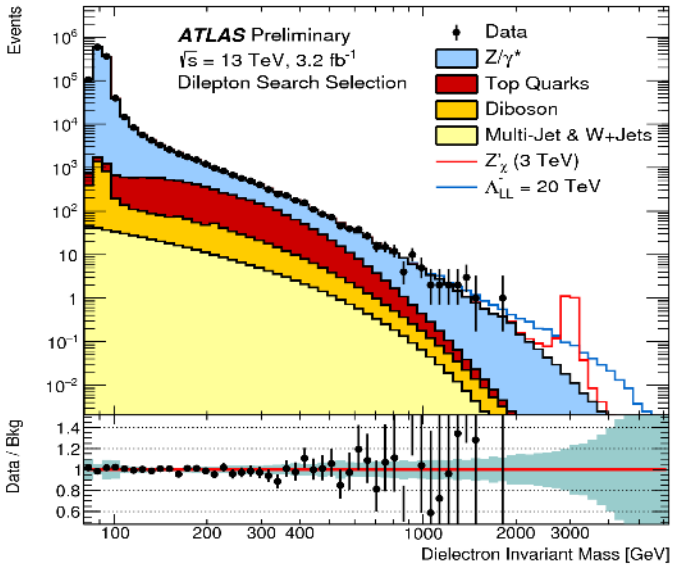


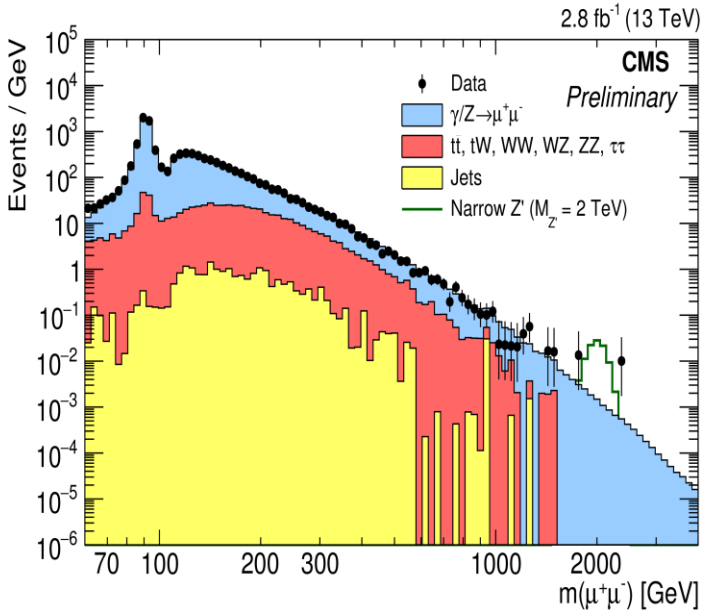


WW/WZ/ZZ results are also available

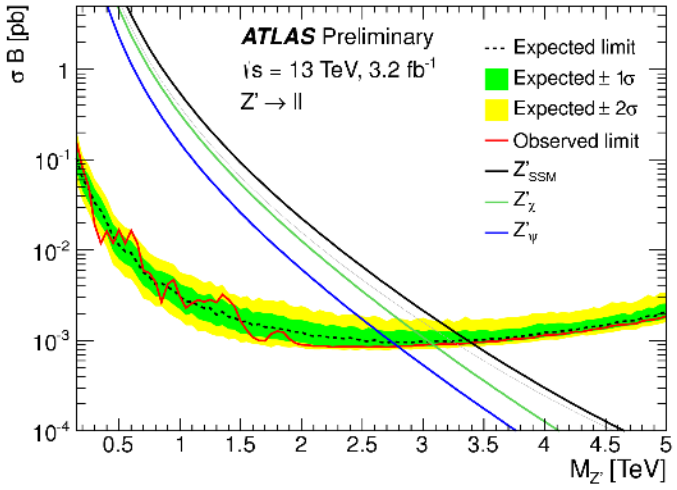
Dileptons

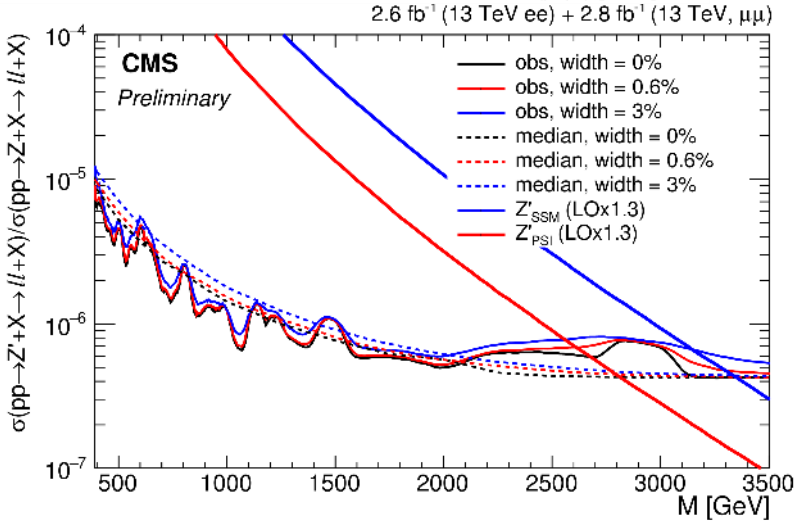
CMS-PAS-EXO-15-005, ATLAS-CONF-2015-070





For spin-2 Randall-Sandrum G* expect the same cross-section in diphoton final state as in dielectrons+ dimuons.





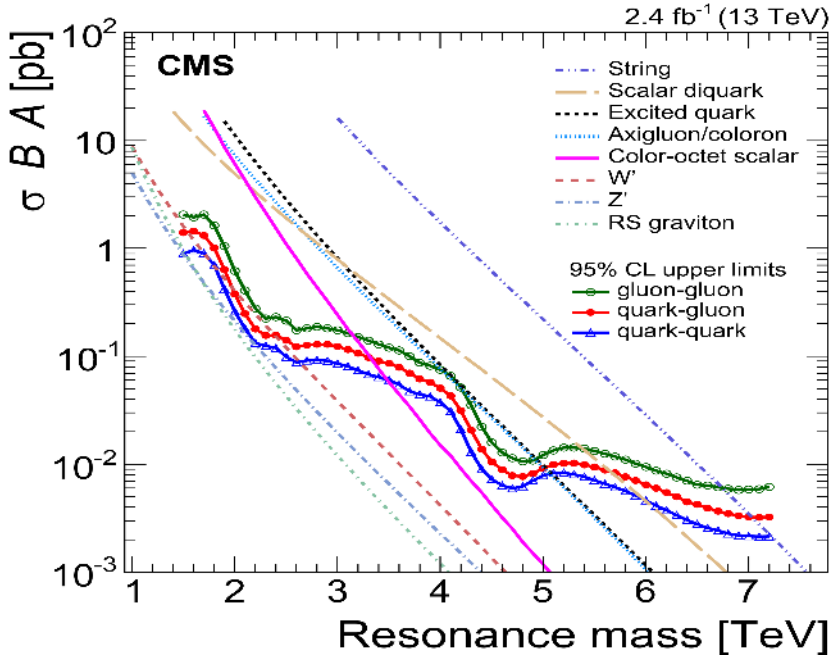
No excesses seen in dileptons. Cross-section limits close to γγ ones.

2016 data should be conclusive. Need to compare the same resonant shape.

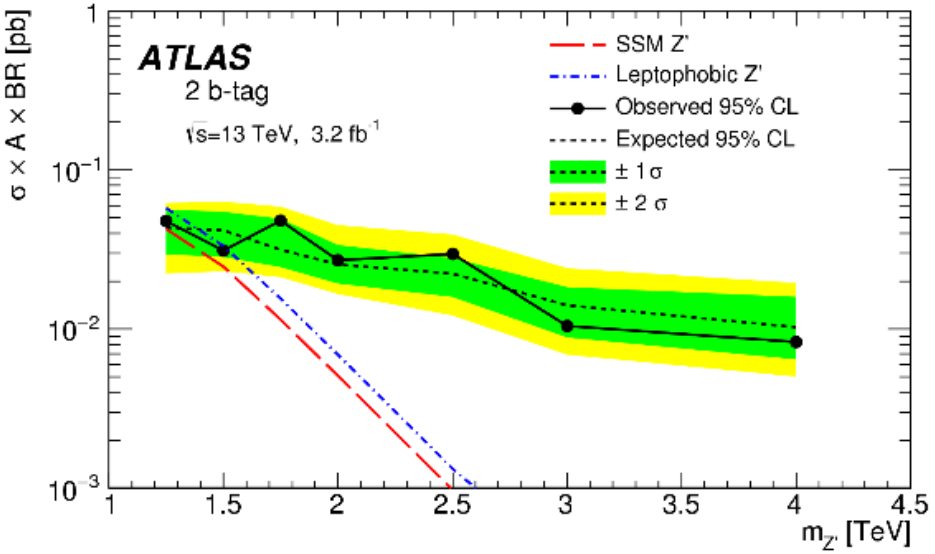
CMS normalization = 1928.0pb

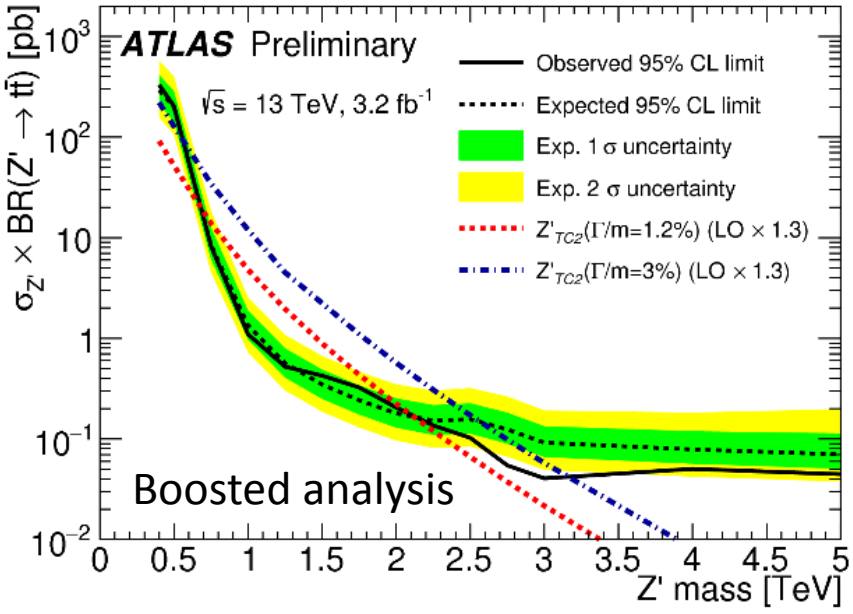
“Di-jet” searches

CMS Phys. Rev. Lett. 116, 071801 (2016)
ATLAS Physics Letters B 754 (2016) 302-322
ATLAS-CONF-2016-014, arxiv:1603.08791



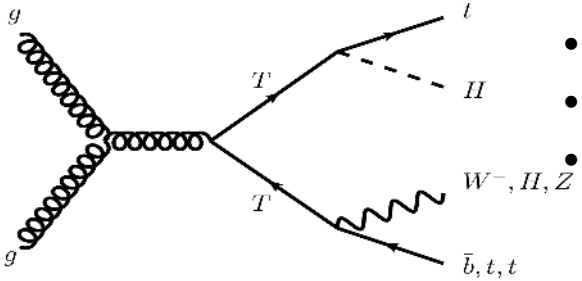
- No excesses seen in dijet channels
- Backgrounds are very high, leading to weak limits
- Very limited sensitivity at masses below 1TeV, need to wait for
  - trigger level analysis for dijets
  - resolved analysis for ttbar
  - and much more data



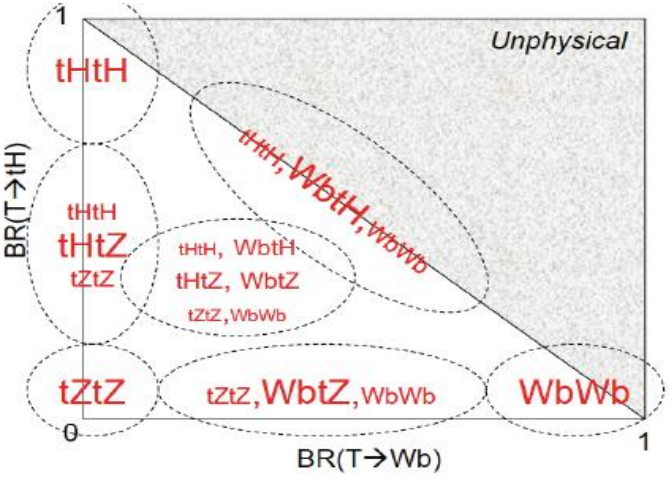


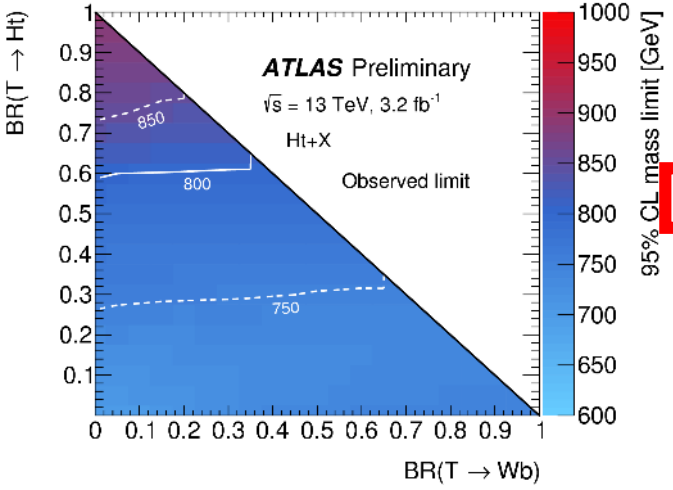
Heavy Vector-Like-Quarks

ATLAS-CONF-2016-013
CMS-PAS-B2G-16-002



- Appear in BSM theories with strong EWSB
- same EW charges for LH and RH components
- T stabilizes Higgs mass divergence (like stop in SUSY)





Sample	0 W, 0 b	0 W, 1 b	0 W, 2 b	0 W, ≥ 3 b
$T\bar{T}$ (0.8 TeV)	1.95 ± 0.13	4.21 ± 0.26	3.26 ± 0.20	1.218 ± 0.081
$T\bar{T}$ (1.1 TeV)	0.269 ± 0.017	0.541 ± 0.033	0.371 ± 0.023	0.1336 ± 0.0088
EWK	510 ± 120	92 ± 22	13.5 ± 3.3	0.78 ± 0.23
TOP	108 ± 18	227 ± 26	125.4 ± 8.6	19.1 ± 1.5
QCD	12.9 ± 4.2	6.5 ± 2.8	< 1	< 1
Total Bkg	630 ± 120	325 ± 37	138.8 ± 9.8	19.9 ± 1.6
Data	606	309	152	18
Data/Bkg	0.96 ± 0.19	0.95 ± 0.12	1.09 ± 0.12	0.90 ± 0.22
Sample	≥ 1 W, 0 b	≥ 1 W, 1 b	≥ 1 W, 2 b	≥ 1 W, ≥ 3 b
$T\bar{T}$ (0.8 TeV)	2.56 ± 0.16	5.30 ± 0.32	3.41 ± 0.21	0.890 ± 0.061
$T\bar{T}$ (1.1 TeV)	0.382 ± 0.024	0.668 ± 0.040	0.379 ± 0.023	0.0979 ± 0.0066
EWK	206 ± 14	32.6 ± 2.9	4.8 ± 1.5	0.262 ± 0.081
TOP	76 ± 12	123 ± 14	61.2 ± 4.4	8.39 ± 0.78
QCD	12.0 ± 5.1	4.6 ± 2.8	0.20 ± 0.19	< 1
Total Bkg	294 ± 23	160 ± 16	66.2 ± 4.8	8.66 ± 0.79
Data	294	168	49	8
Data/Bkg	0.999 ± 0.096	1.05 ± 0.13	0.74 ± 0.12	0.92 ± 0.34

No excess of events seen in leptons+jets channel.

CMS: m(T)>876GeV @ BR(T→Wb)=100%;

ATLAS: m(T)>900GeV @ BR(T→Ht)=100%

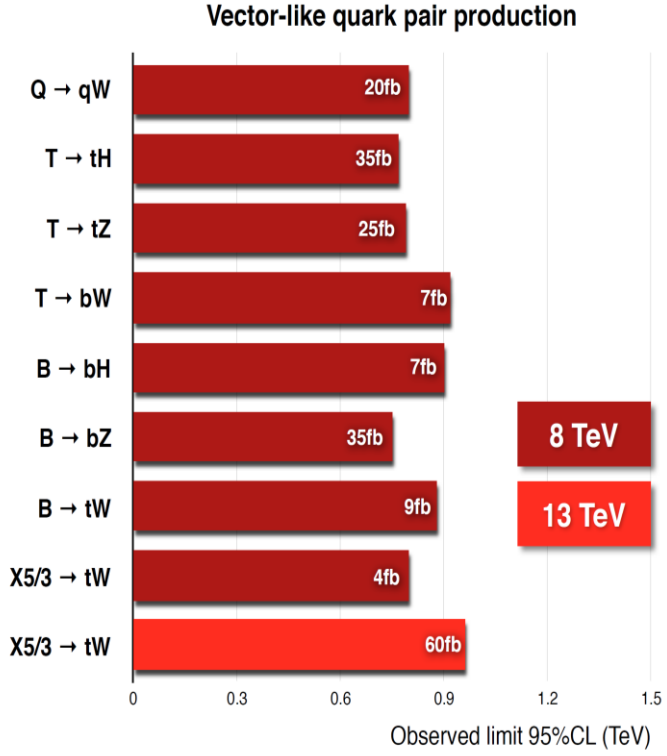
Summary of HVQ results

ATLAS Exotics Searches* - 95% CL Exclusion — **ATLAS** Preliminary

Status: March 2016

$\int \mathcal{L}\, dt = (3.2 - 20.3)\ \text{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Limit		Reference
Heavy quarks	VLQ $TT \to Ht + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	T mass 855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY \to Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	Y mass 770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 735 GeV	isospin singlet	1505.04306
	VLQ $BB \to Zb + X$	2/≥ 3 e, μ	$\geq 2/\geq 1$ b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
	$T_{5/3} \to Wt$	1 e, μ	≥ 1 b, ≥ 5 j	Yes	20.3	$T_{5/3}$ mass 840 GeV		1503.05425



- As the limits for VLQ are already high, rather unusual VLQs (e.g. with large electric charges) need to be considered
- the limits for VLL are weaker → interesting area to explore

Where did we look in Run 1 & Run 2?*

↓,→	jet	bjet	top	γ	W,Z	lepton	Higgs	E^T_{Miss}
jet	Many	1,1	1,1	1,1		Many, 1-3		Many
bjet		2-4	1,1		1,1	2,2	1,1	1-2
top			2-4		1,1	2,2	1,1	1
γ				2-4	1,1	1,1		1
W,Z					2	1,1	1,1	1
lepton						2-4		1
Higgs							2	1
E^T_{Miss}								Done

A large fraction of conventional signatures are covered (but not all!), unconventional signatures are important.

*This table is not exhaustive

Unconventional Signatures @ LHC

- Highly ionizing particles (HIP) / monopoles
- Charged particles decaying into heavy neutral particles (disappearing tracks, kinks etc.)
- Long-lived particles decaying only in the outer detector components
- Boosted final states: objects close together or overlapping
- Low mass (pseudo)scalars
- Neutral particles (delayed photons) decaying late into neutral states
- …

Radius of each detector

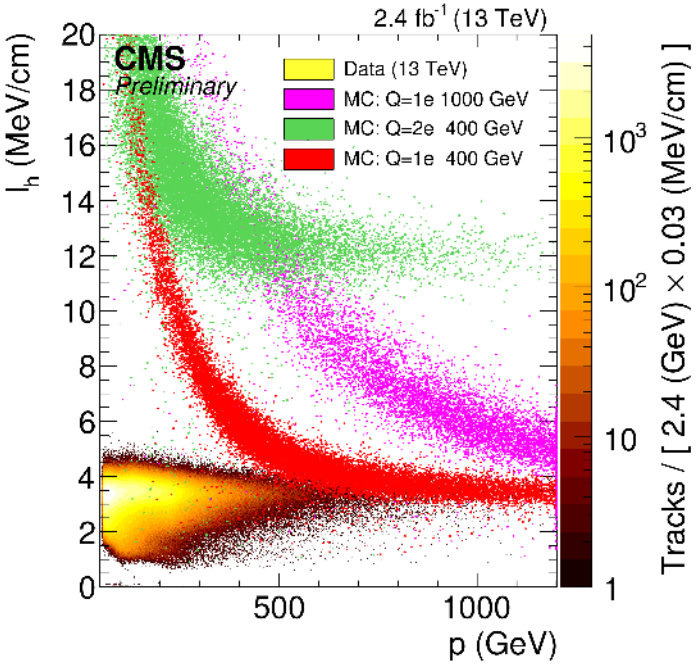
	ATLAS	CMS
Vertex	0.1mm	0.1mm
Pixel(dE/dx)	5-10cm	5-100cm
TRT	50-100cm	No
Hadronic CAL	2-4m (Δ t~1nsec)	1.5-2.5m
Muon System	5-10m(Δ t~1nsec)	4-6m

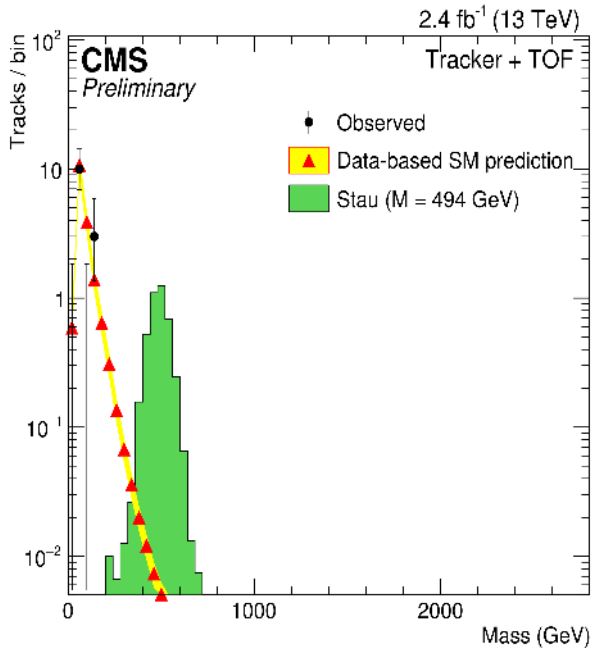
Those analysis are very detector-specific: need dedicated reconstruction techniques & triggers.

How to make sure that we considered all possible topologies?

HIPs, Monopoles, etc.

CMS-PAS-EXO-15-010

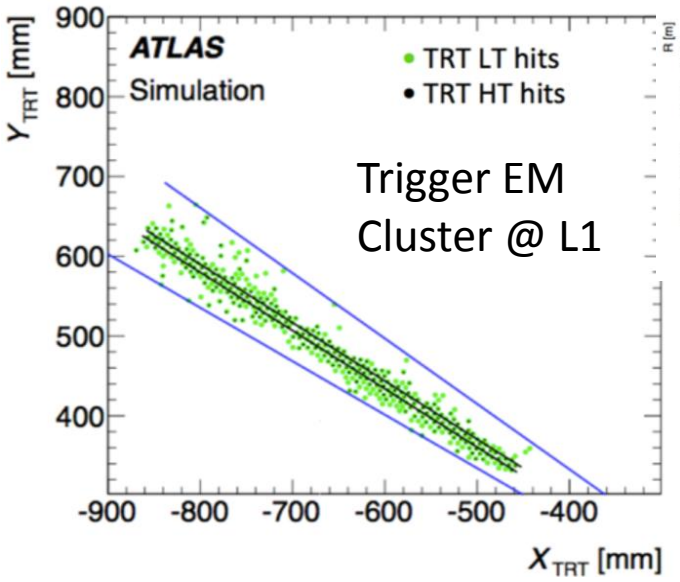




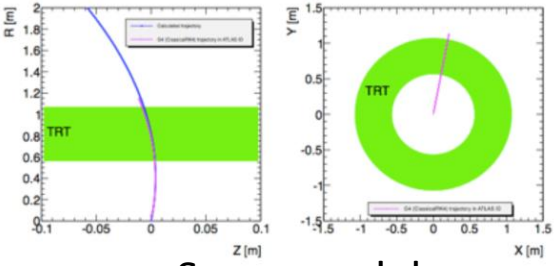
Search for high ionization loses and long time of flight in muon spectrometer

Trigger: muon p_T>50GeV or E^T_{Miss}>170GeV

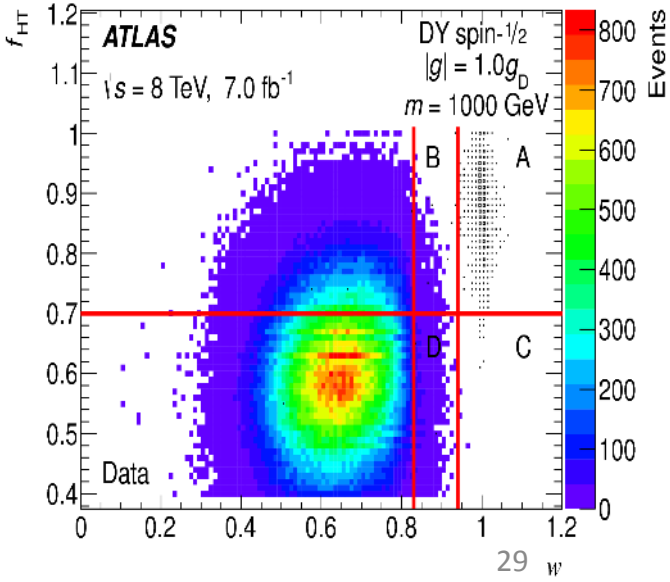
Results consistent with SM predictions.



Trigger EM Cluster @ L1



Some model dependence inevitable: Monopoles bend in r-z plane ⇒ use TRT-hit information



PRD 93, 052009 (2016)

Search for neutral LLP decays to dijets

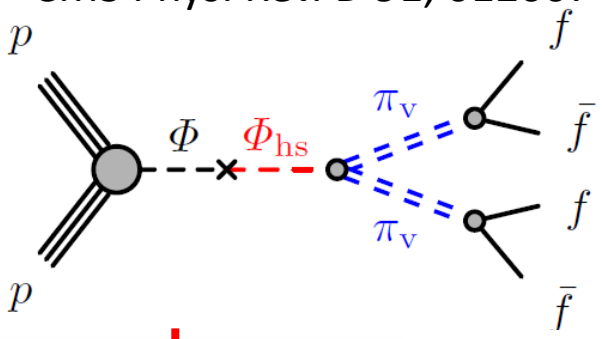
Signature: displaced vertex with two jets

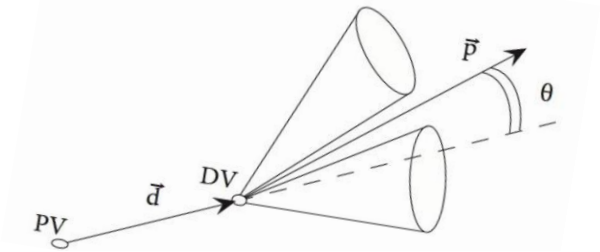
Complimentary searches for decays in inner detector by CMS, LHCb and ATLAS

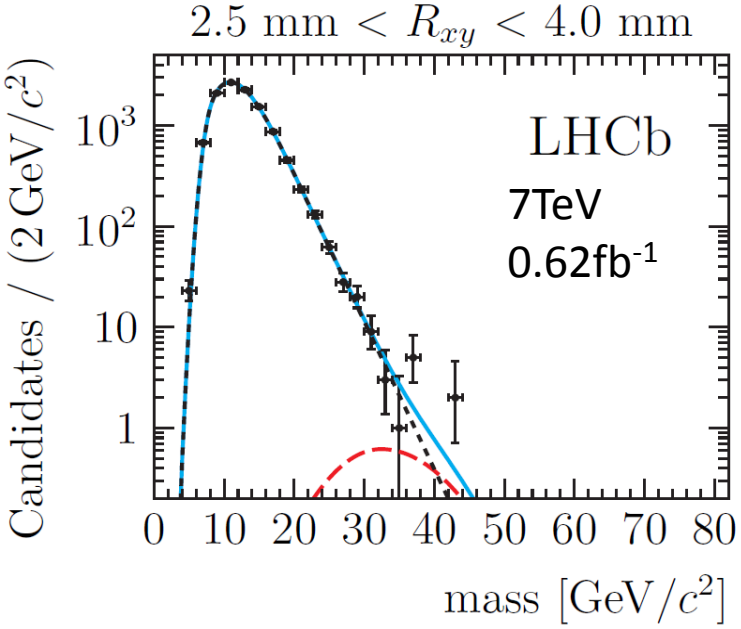
ATLAS also looks for decays in HCAL & MS

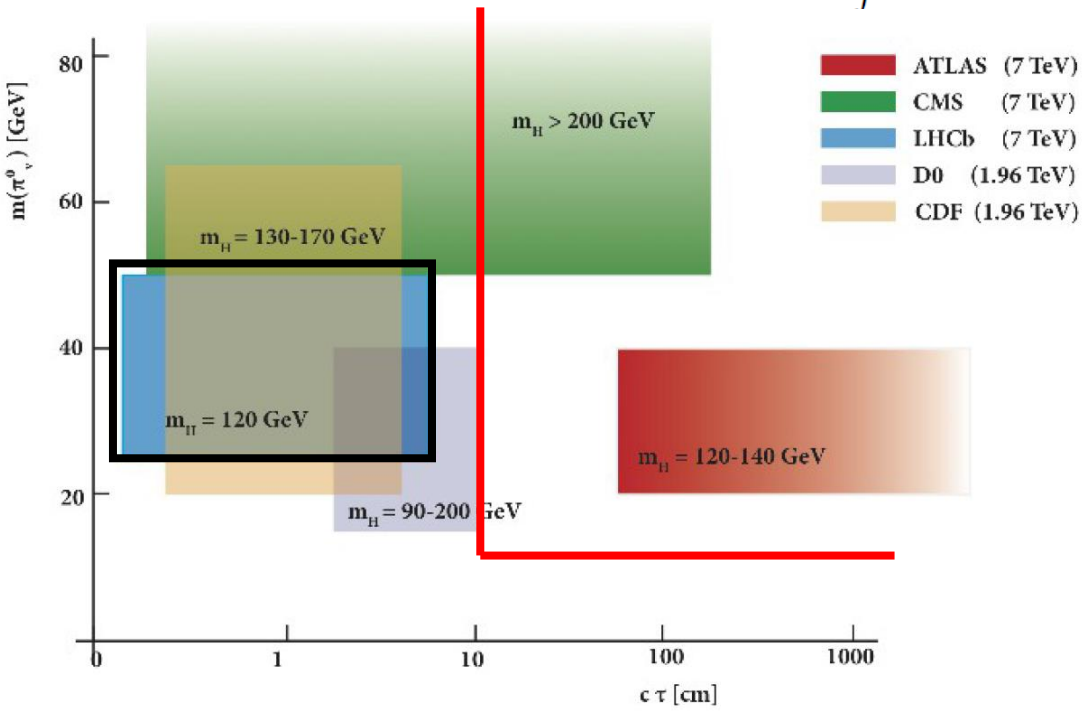
No excess of events observed

ATLAS PRD 92, 012010 (2015),
PLB 743 (2015) 15-34
LHCb Eur. Phys. J. C 75 (2015) 152
CMS Phys. Rev. D 91, 012007









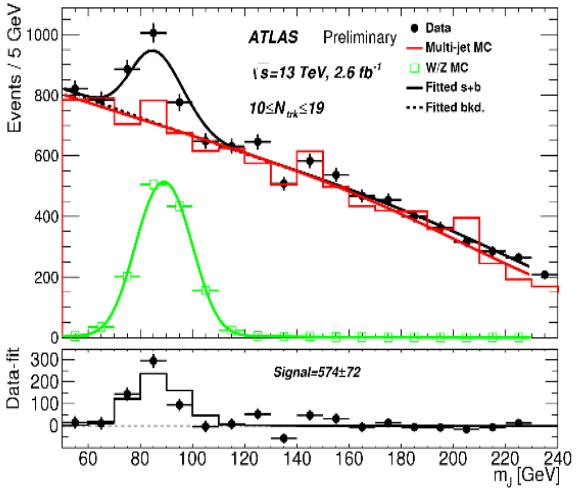
Boosted final states with jets

- Relevant for resonances with

mass equal or smaller than the momenta of the decay products

$$\Delta R_{\min} \approx \frac{2m}{p_T}$$

- For jets overlaps result in jets with substructure analysed as follows:
  - Large jets (ΔR=1.0)
  - Grooming
  - Tagging



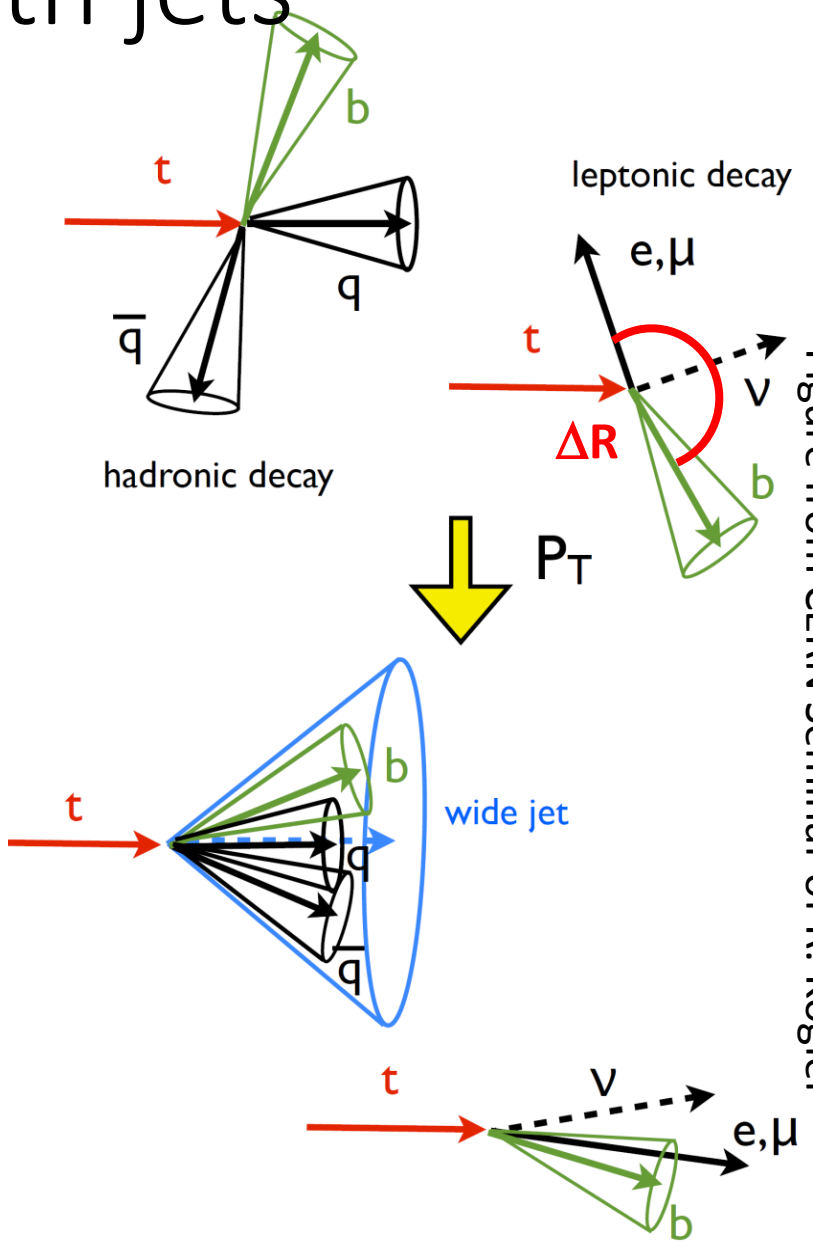


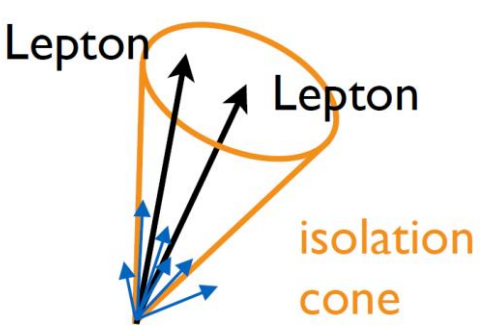
Figure from CERN Seminar of R. Kogler

Boosted final states with leptons

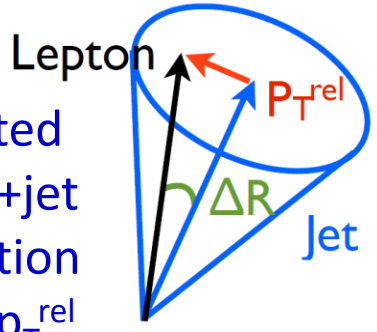
arXiv:1506.03062

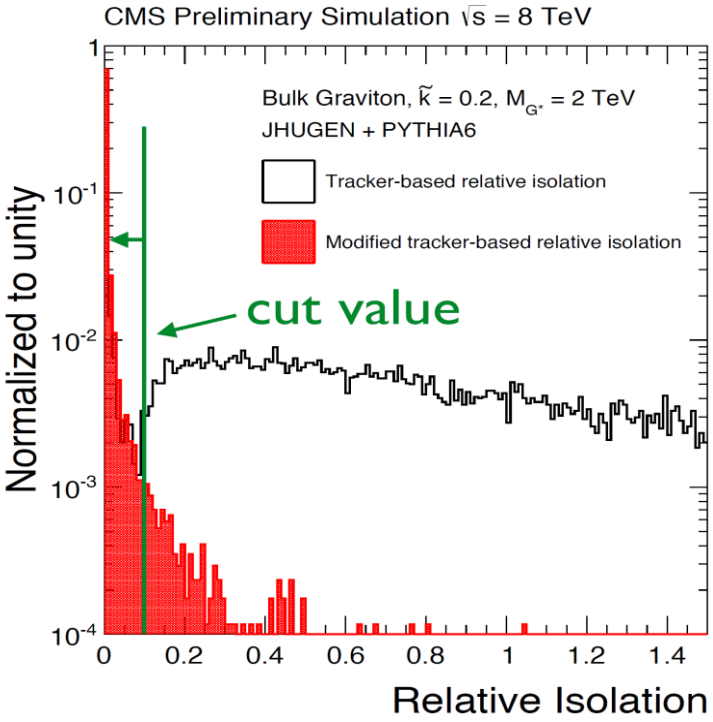
The shrinking cone isolation requires sum of track p_T with $\Delta R(l,track)=[xx]GeV/p_T^l$ to be less than a certain value (lepton candidate tracks excluded)

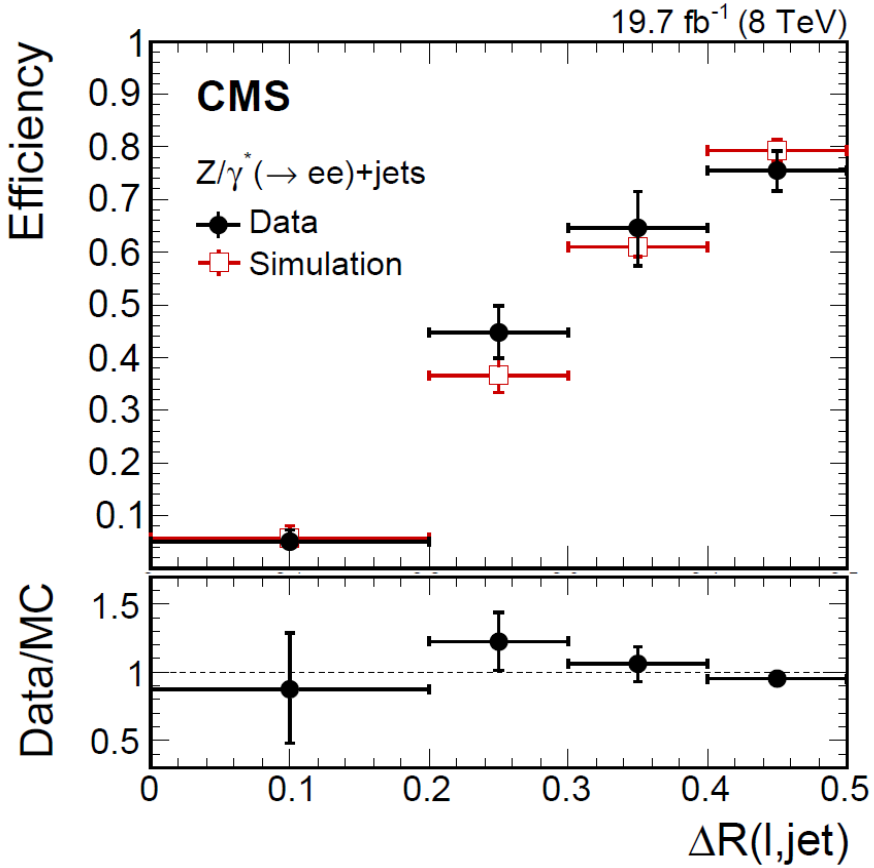
If more than one lepton: for isolation need to remove other lepton from isolation cone.



Boosted top l+jet selection uses p_T^{rel}





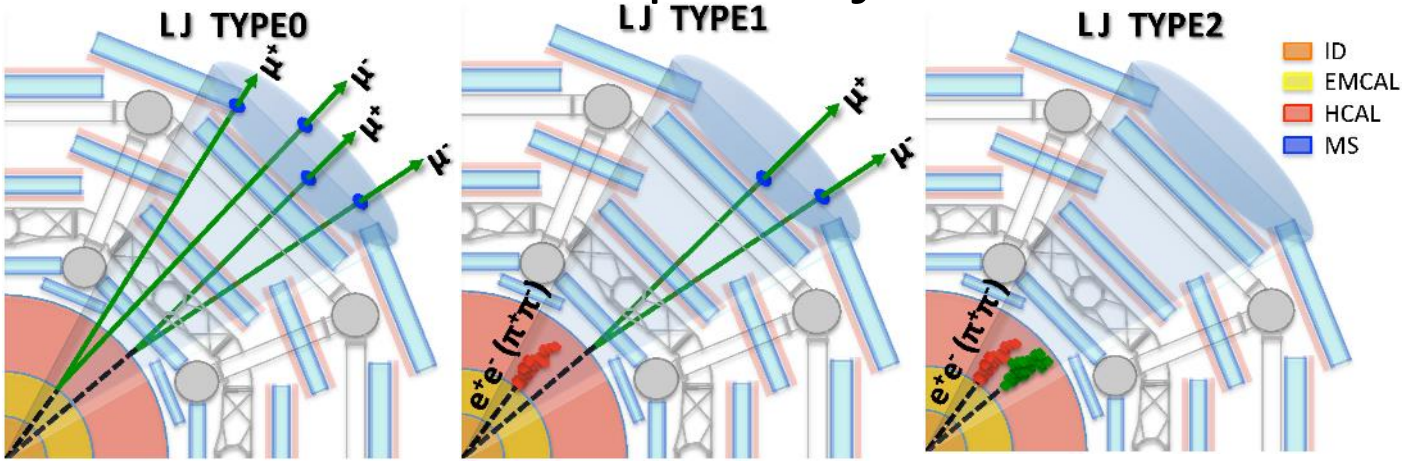


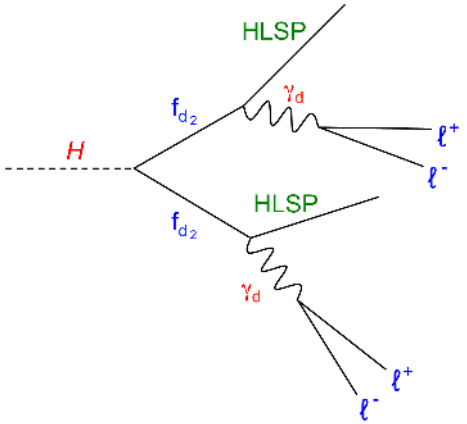
Hidden-sector bosons with Lepton-jets

ATLAS JHEP02(2016)062, JHEP11(2014)088

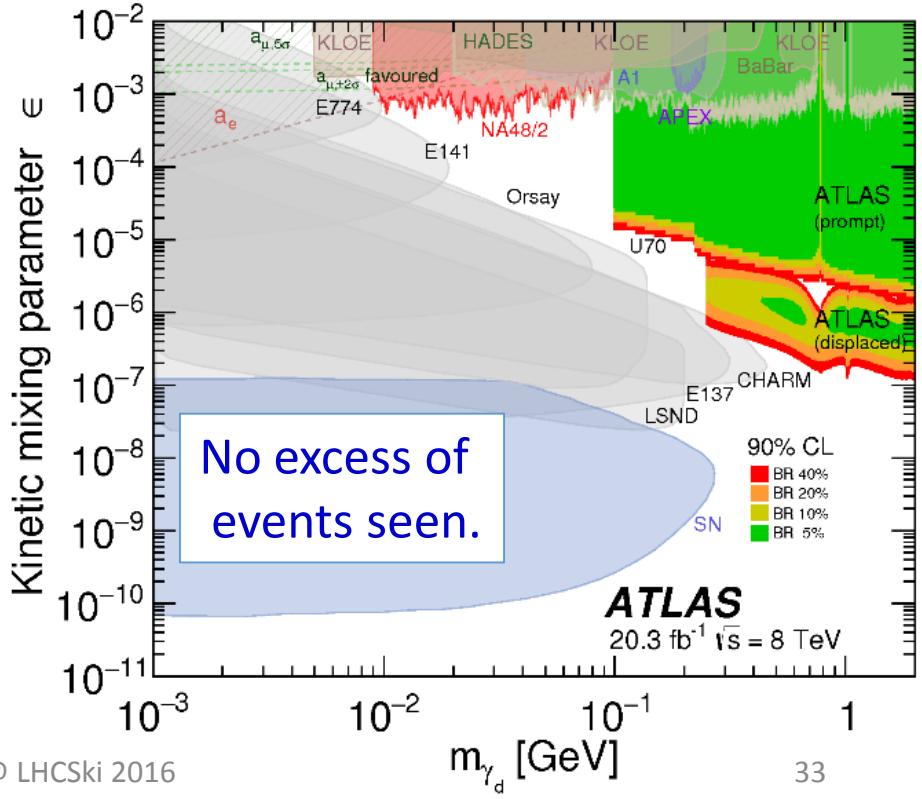
Dark sector couples to Higgs & leptons via very light dark sector particles

Signal at ATLAS – collimated lepton-jet

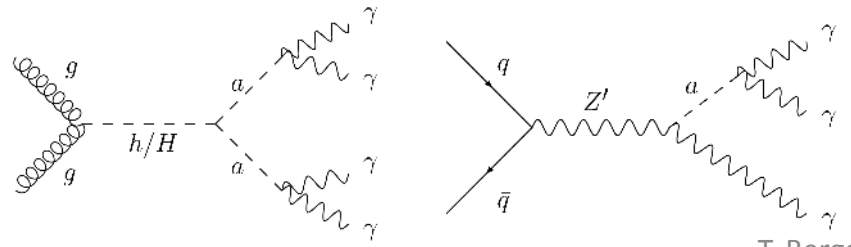




Assumption: extra branching ratio of H/Z/Z'/etc. into dark scalar bosons

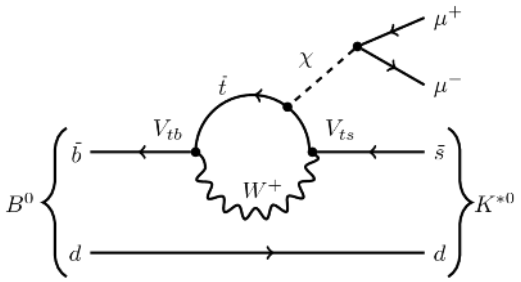


It is also possible to have decays to multi-photons or even multi photon-jets

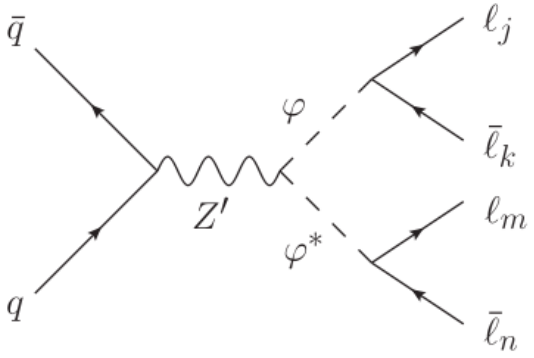


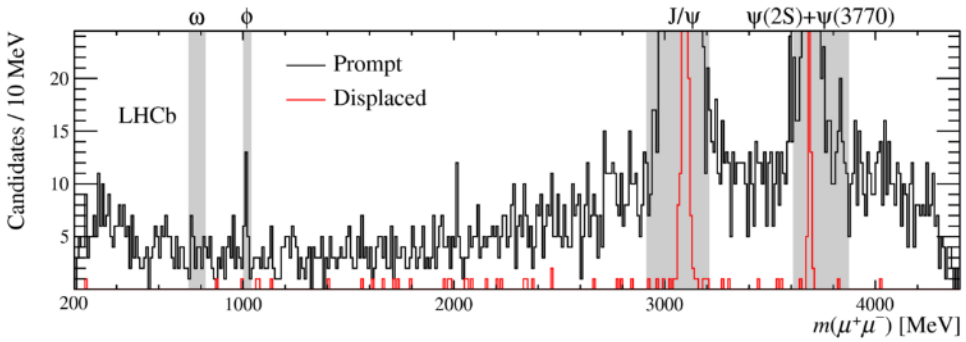
ATLAS arxiv:1509.05051

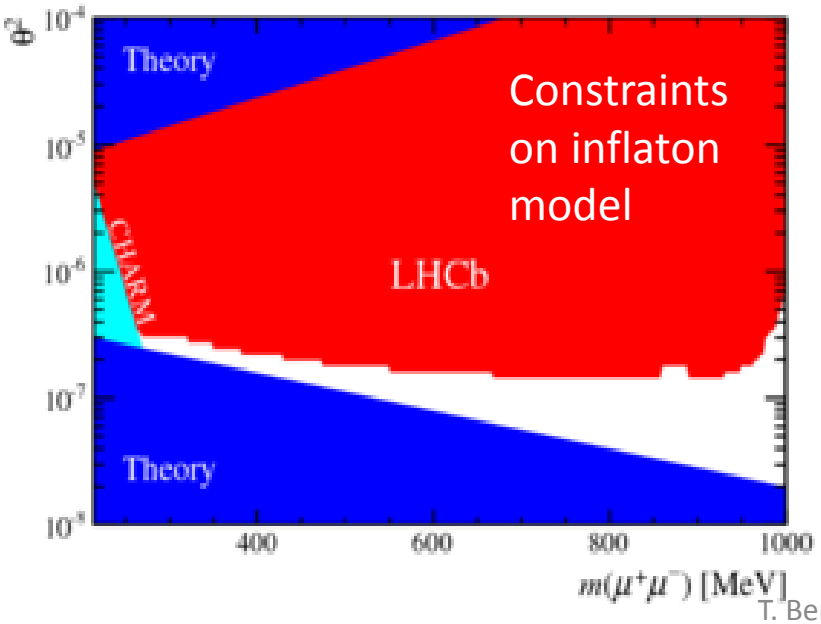
More searches for hidden-sector bosons

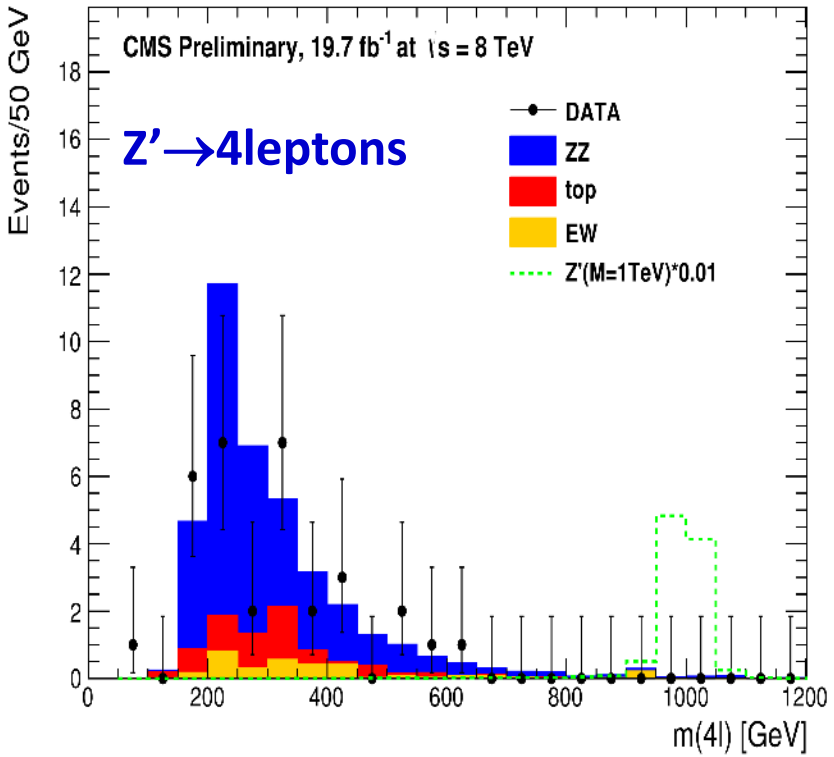


No excess of events seen.







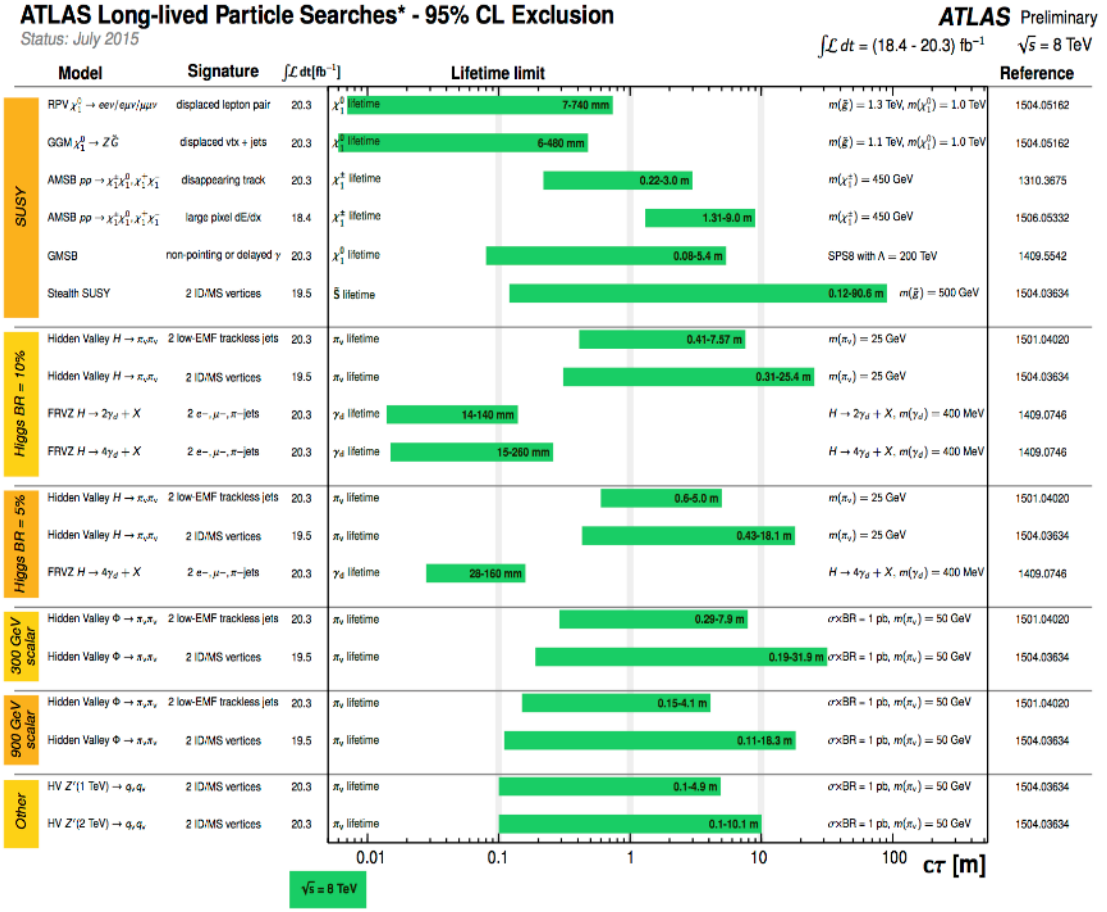


Should also result in signal in dileptons.
Need to extend searches below Z mass.

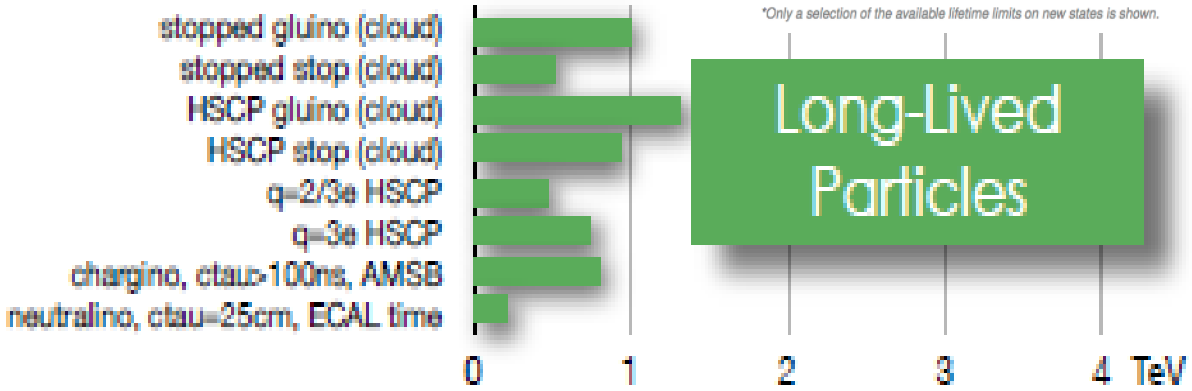
LHCb, Phys. Rev. Lett. 115 (2015) 161802

CMS PAS EXO-14-006

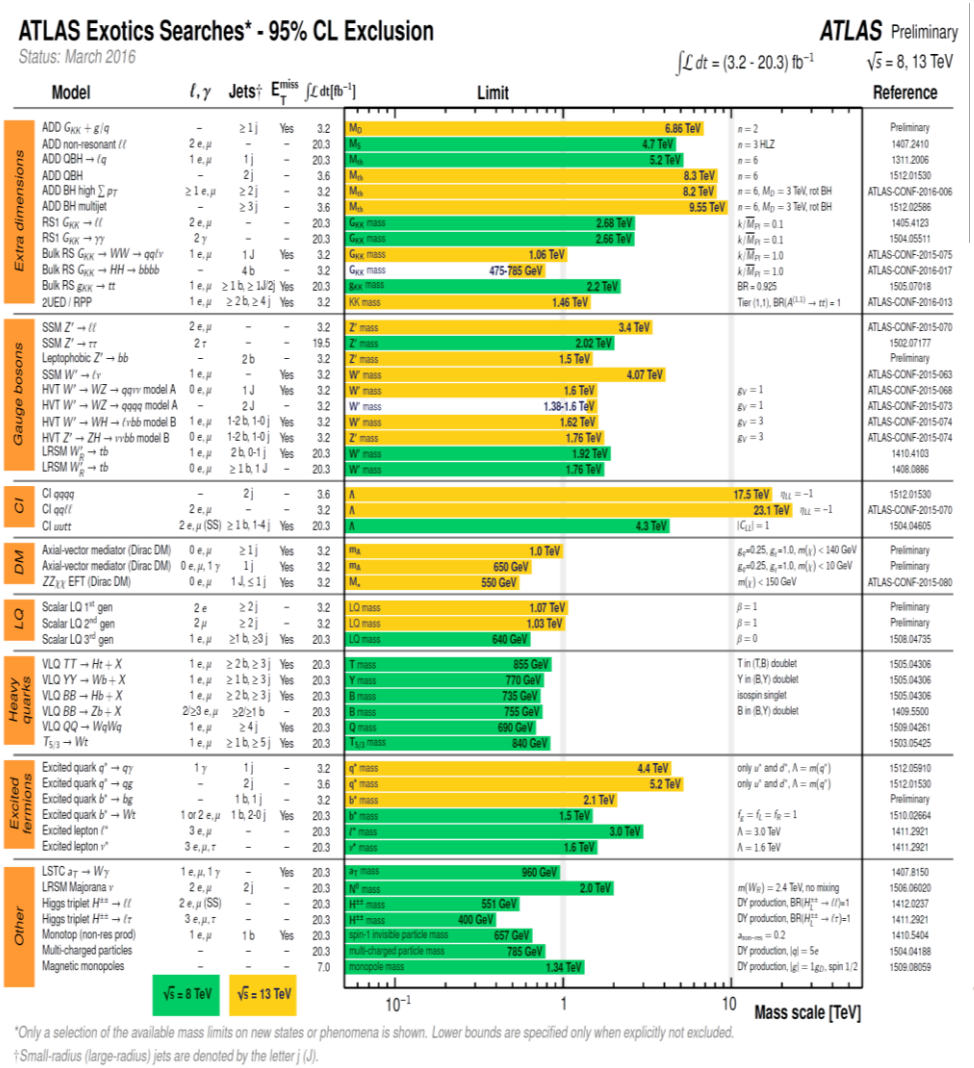
We searched in many places, but did we search everywhere? Who knows…

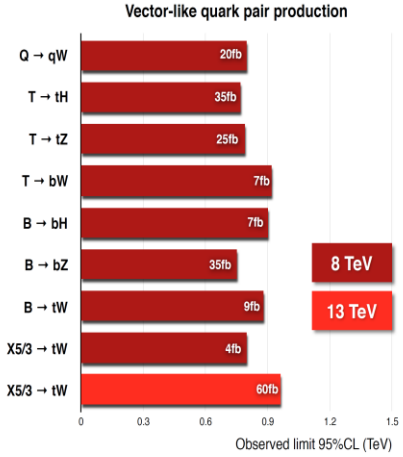


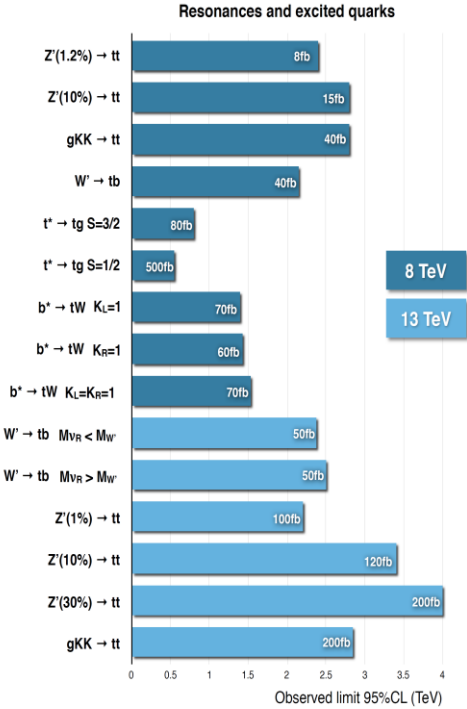
Main LLP CMS Limits summary

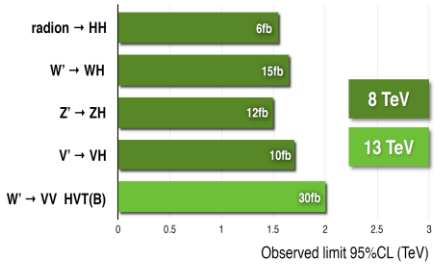


A lot of results available…









https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G

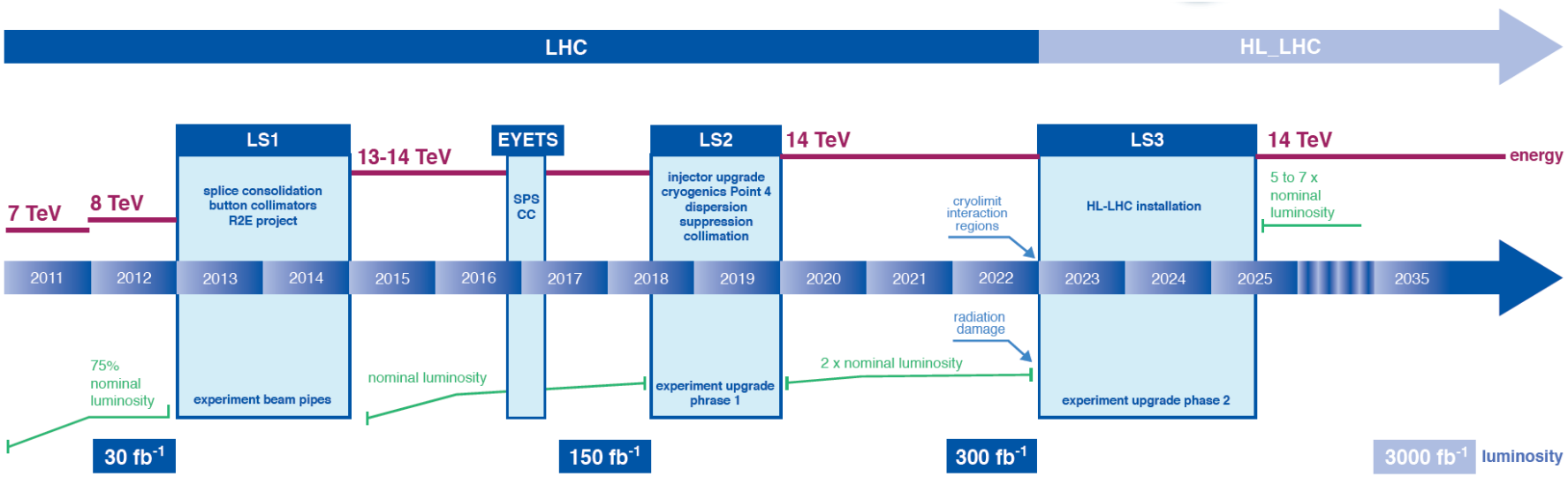
http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO/index.html

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

Conclusions

- Huge effort in searches in 2015 data. For more see public pages and many talks today
  - How to make sure we cover everything?
- Some interesting excesses start to be seen. Will they remain?
  - Crucial to keep searching in regions already excluded: we don't know yet what we are looking for
  - Tricky to reinterpret existing results for very different signal hypothesis
    - 2016 searches should try to be consistent for all channels
- Progress on Combinations:
  - Mono-X searches (addressed tomorrow) performed in a view of ATLAS/CMS combination to double the dataset
  - Discussions of combinations of different channels (e.g. Z' in ll, ttbar, tautau; Heavy Vector Quark combinations) – This is very model-specific!

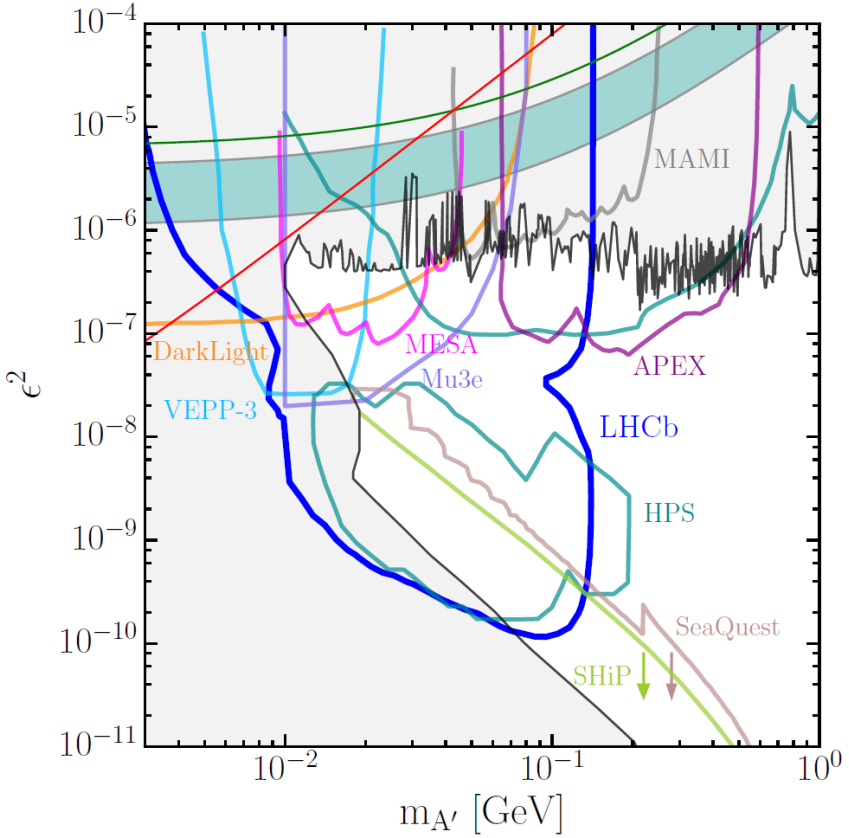
Outlook



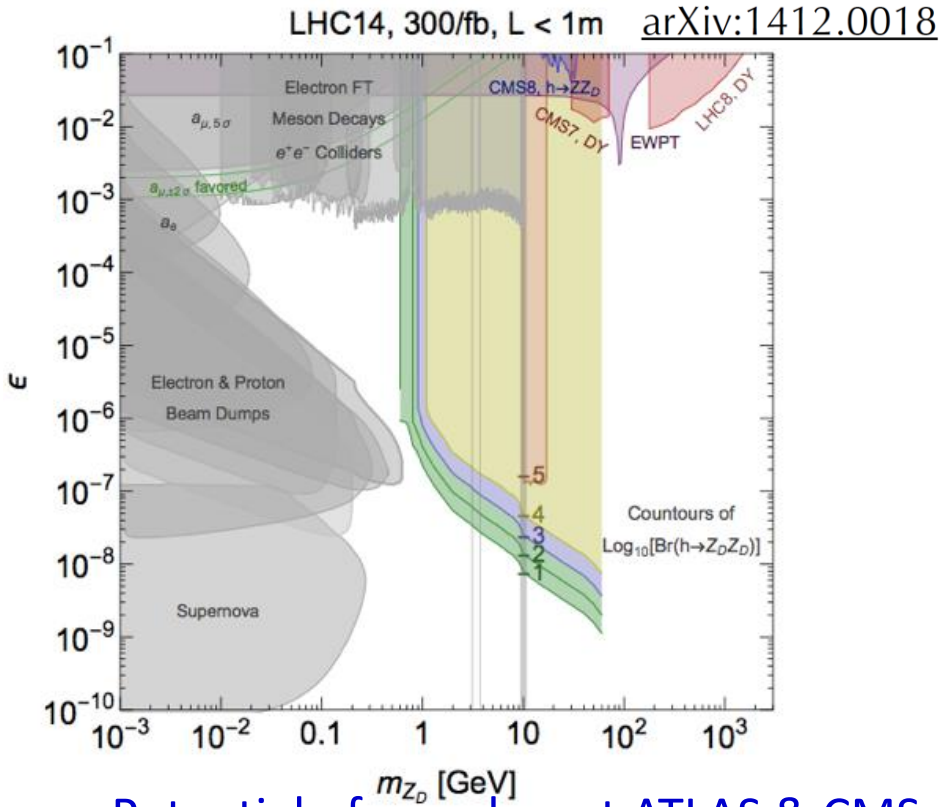
- We are in regime of non-linear luminosity increase
  - 2016 dataset = 10 x 2015 dataset!
- The year ahead looks very-very exciting
  - Difficult to look further than this summer at this point

Run 3 searches for hidden-sector bosons

Currently unexplored region could be studied by LHCb in $D^{*0} \to D^0 A'$, $A' \to e^+e^-$ decays (arXiv:1509.06765) in Run 3 following trigger upgrade.



LHCb trigger upgrade will allow significant integrated luminosity increase in Run 3.



Potential of searches at ATLAS & CMS

Collaboration between ATLAS/CMS & LHCb on LLP searches is crucial!

LHC LLP Forum May 12th

CERN Council Chamber

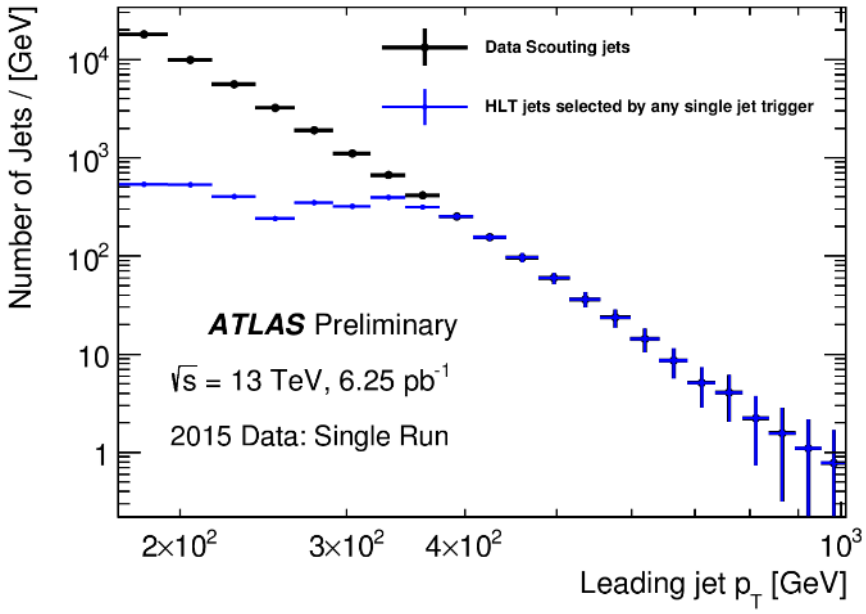
THANK YOU!

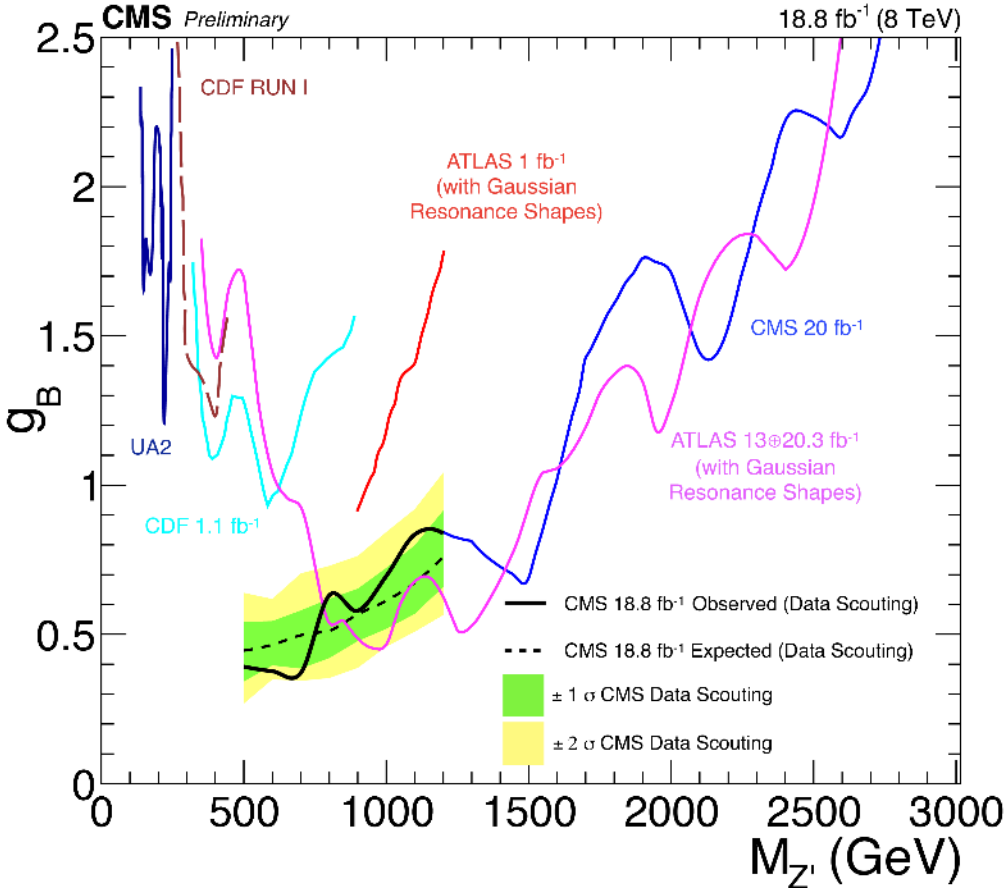
Backup

Di-jet searches

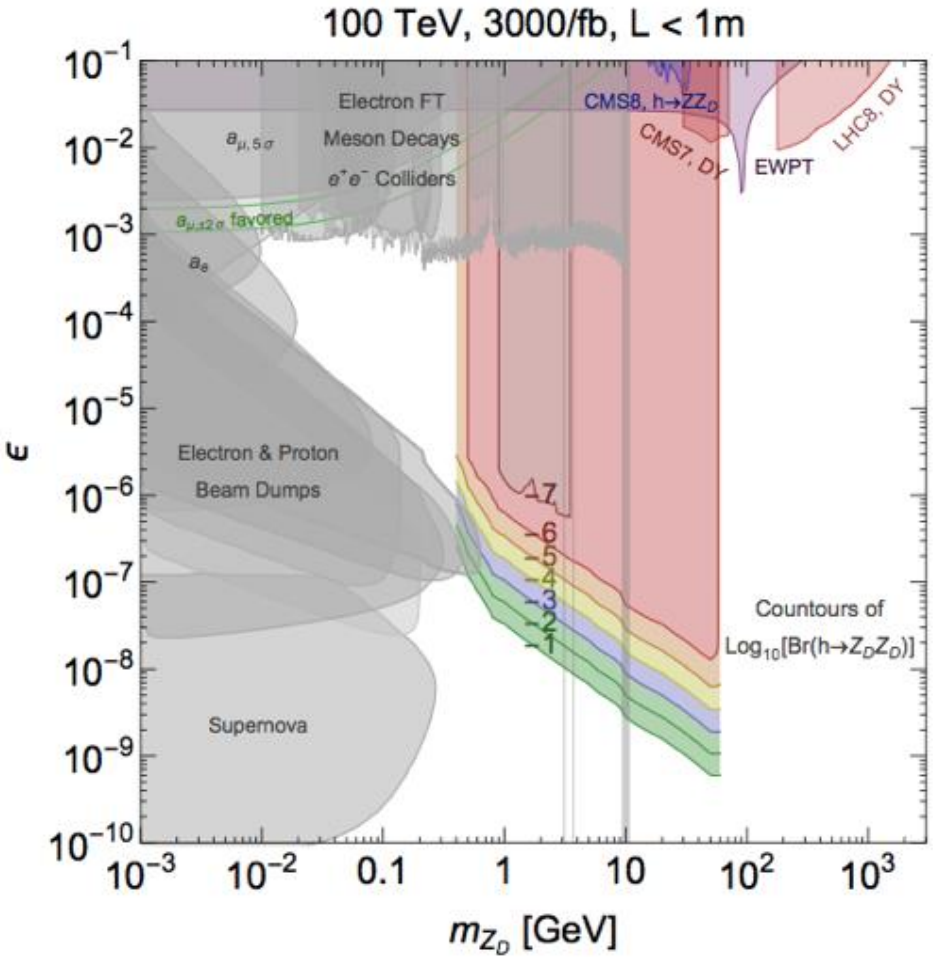
To keep sensitivity at lower masses (0.2-1TeV)
need to use trigger level analysis
as single jet trigger thresholds are too high

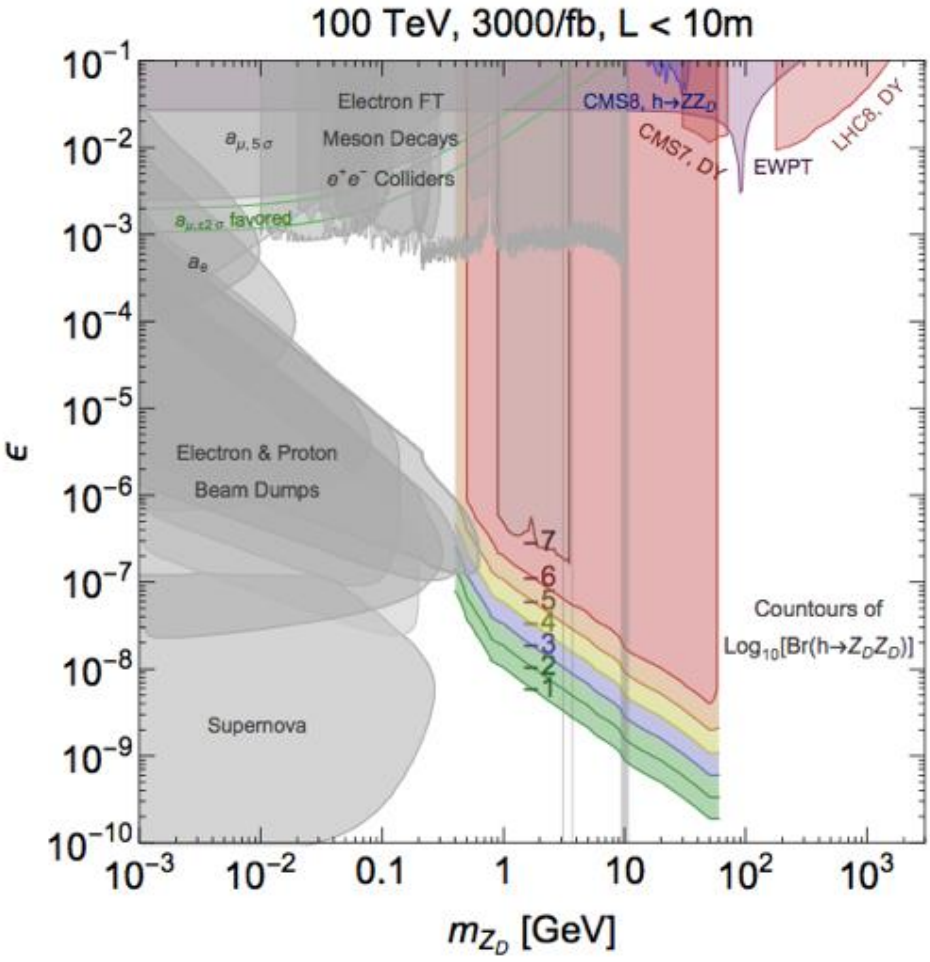
- CMS did it in Run 1
- ATLAS has this possibility in Run 2





Searches for hidden-sector bosons @ FCC





arXiv:1412.0018