

# *Beyond the Standard Model Searches @ the LHC*

Albert De Roeck  
CERN, Geneva, Switzerland  
Antwerp University Belgium  
UC-Davis California USA  
NTU, Singapore

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# Lecture Plan

Overview of the 3 lectures in the next days

- Lecture 1:
  - Introduction to searches for new physics
  - Searches for exotica and new phenomena
- Lecture 2:
  - Searches for supersymmetry
  - Searches for real exotic particles
- Lecture 3:
  - The hunt for dark matter
  - Outlook for the LHC and for the Future

# Physics case for new High Energy Machines

Understand the mechanism Electroweak Symmetry Breaking

Discover physics beyond the Standard Model

## Reminder: The Standard Model

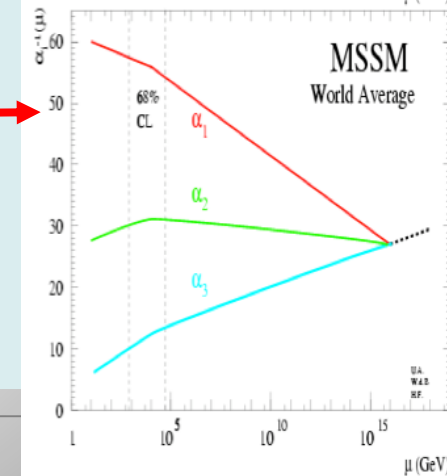
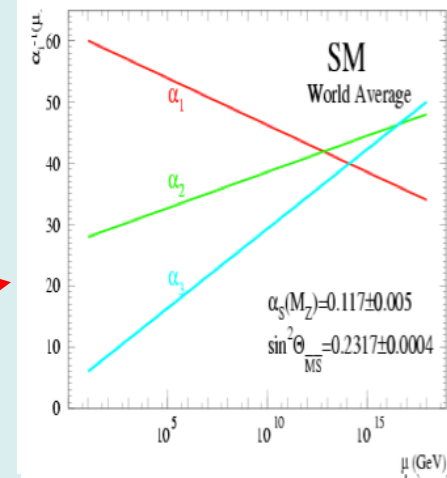
- tells us **how** but not **why**
  - 3 flavour families? Mass spectra? Hierarchy? 19 parameters!
- needs fine tuning of parameters to level of  $10^{-30}$  !
- has no connection with gravity
- no unification of the forces at high energy

Most popular extensions around 2000

- Supersymmetry
- Extra space dimensions

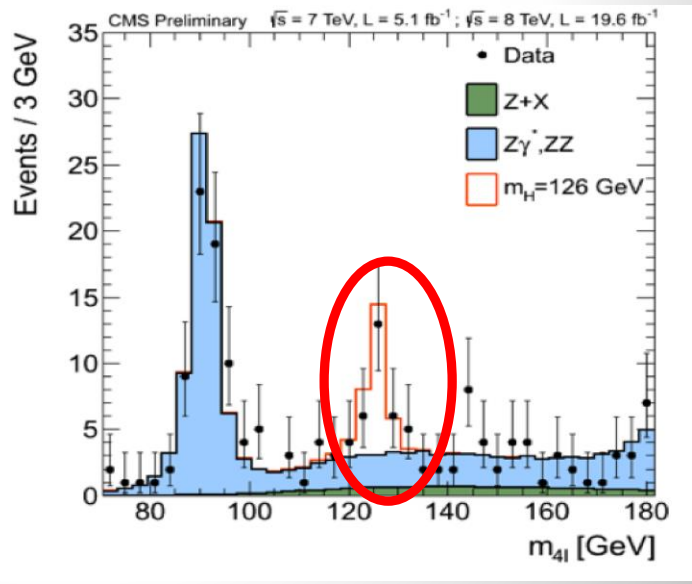
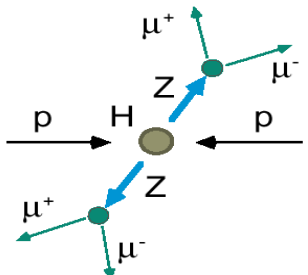
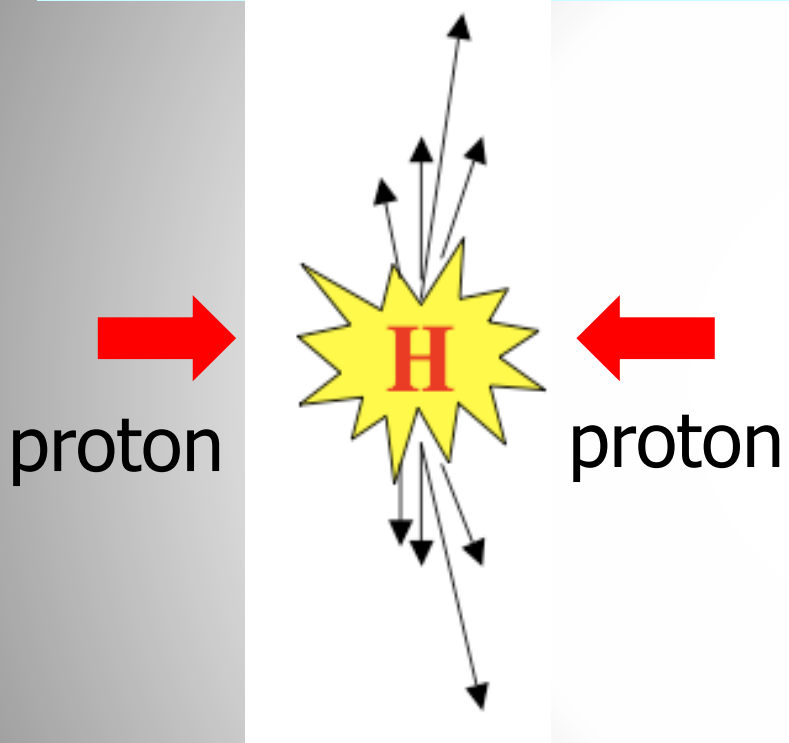
Many other ideas: More symmetry and gauge bosons, composite Higgs models, L-R symmetry, quark & lepton substructure, VLQs  
Little Higgs models, Technicolor, Hidden Valleys, 4th generation...

Higgsless models clearly disfavoured these days



# 2012: A Milestone in Particle Physics

Observation of a **Higgs** Particle at the LHC, after about 40 years of experimental searches to find it



2013

The Higgs particle was the last missing particle in the Standard Model and possibly our portal to physics Beyond the Standard Model

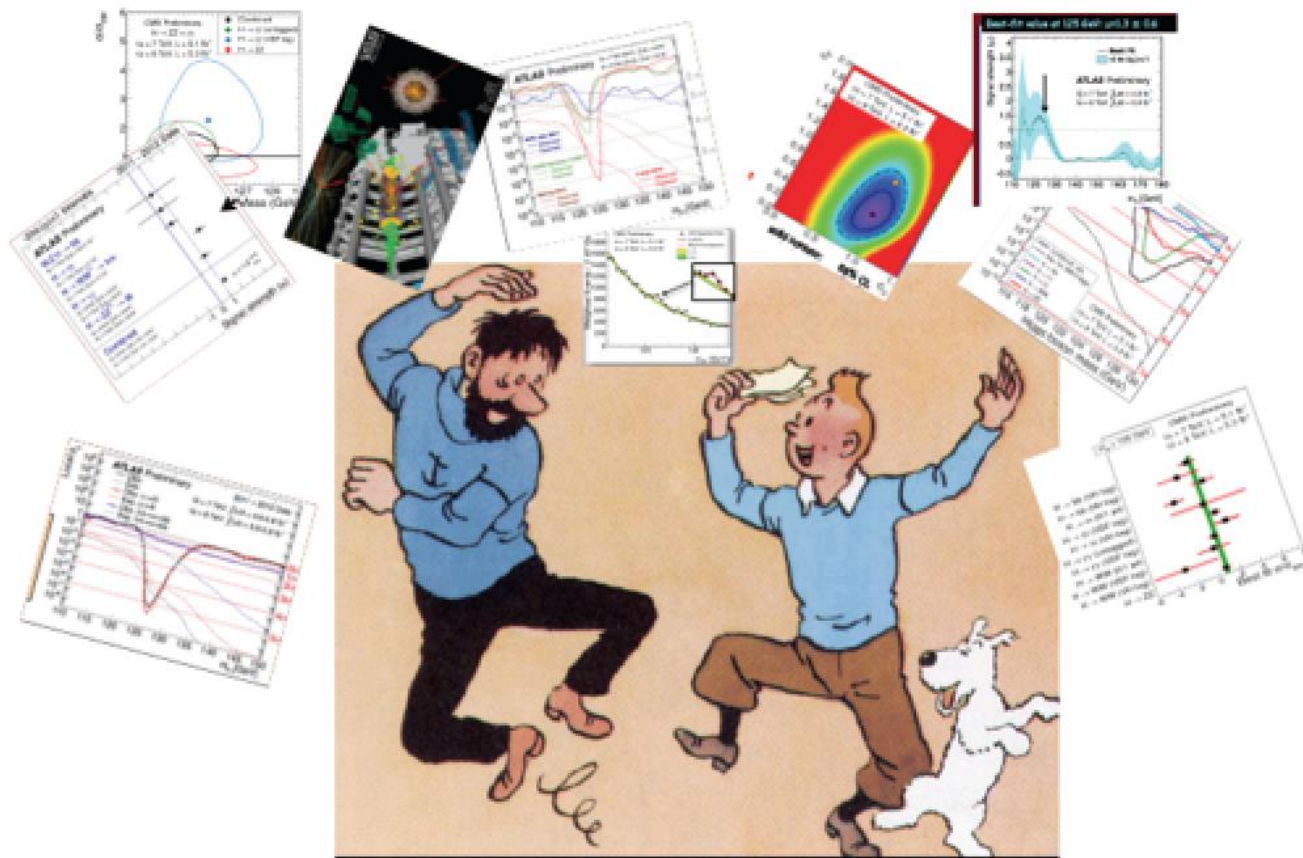


# The Theorist and Experimentalists

The party in 2012!

Not everybody at the party  
eg higgsless models...

A. Pomarol ICHEP2012

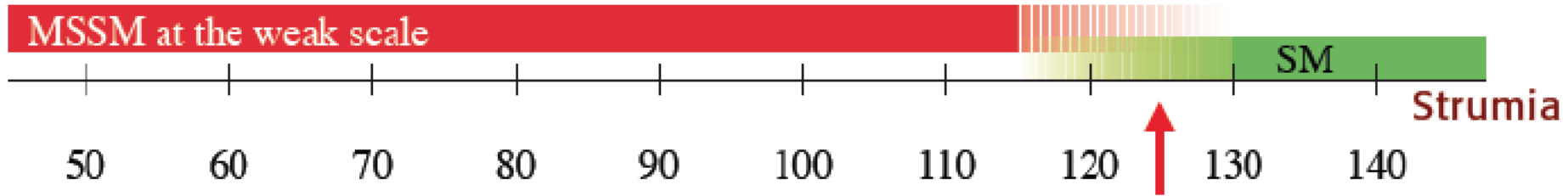


But careful about resurrections, Higgs imposters...

# A Higgs @ 125 GeV...

A malicious choice!

$$m_H = 125.0 \pm 0.2 \text{ GeV}$$



The Higgs:  
so simple yet so unnatural

Guido Altarelli  
1941-2015

Stockholm Nobel Symposium  
May 2013

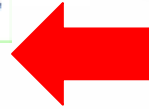
"We do not understand why the mass of the Higgs is 125 GeV  
It most likely tells us something on what is Beyond the Standard Model"



# Physics Beyond the Standard Model?

Important SM parameter → stability of EW vacuum

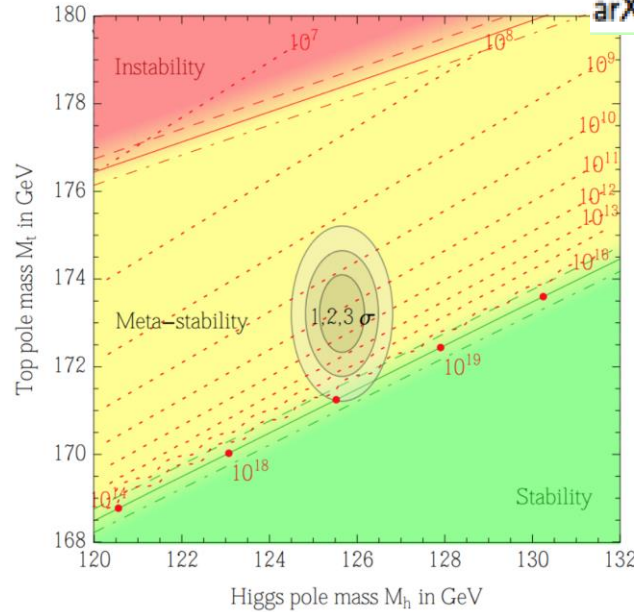
arXiv:1205.6497



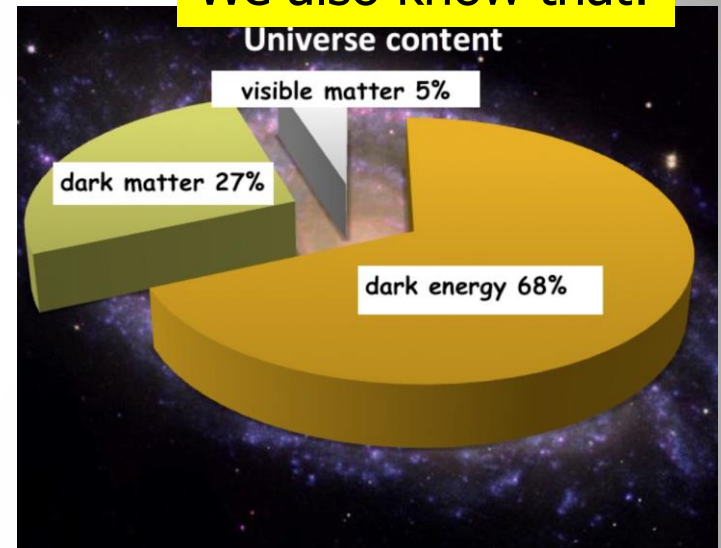
A Higgs at 125 GeV

Precise measurements of the top quark and the Higgs mass

arXiv:1403.6535



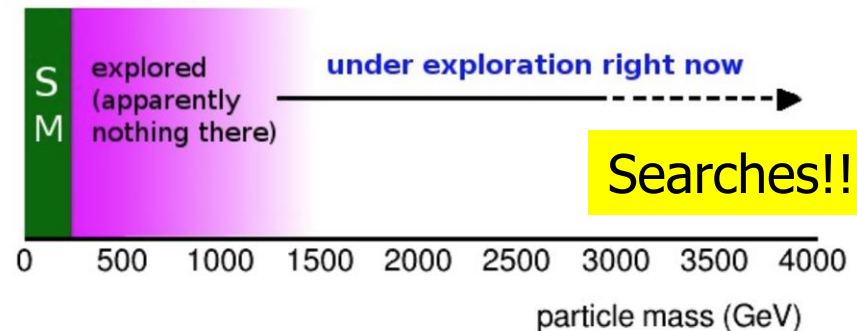
We also know that:



New Physics inevitable?  
But at which scale/energy?

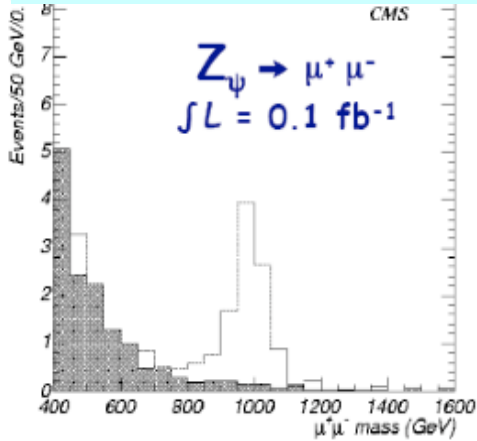
*But Where Is Everybody?*

N. Arkani-Hamed

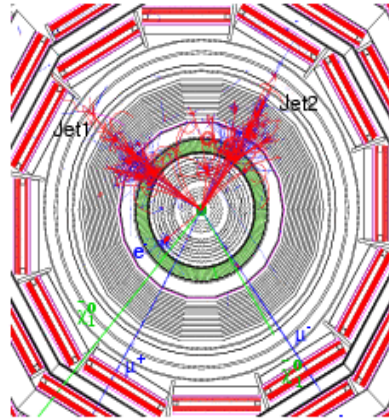


# New Physics?

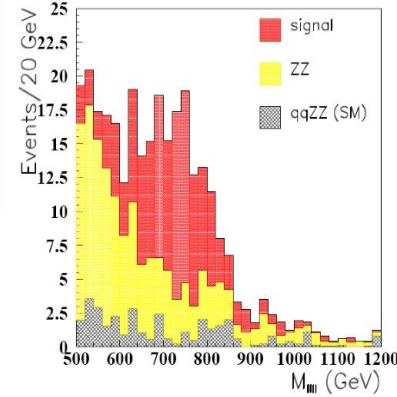
## New Gauge Bosons?



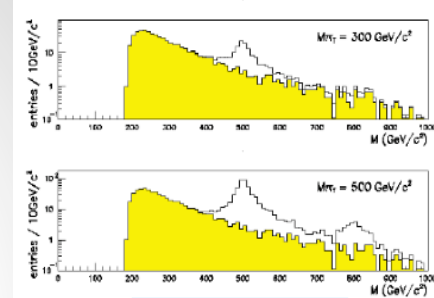
## Supersymmetry



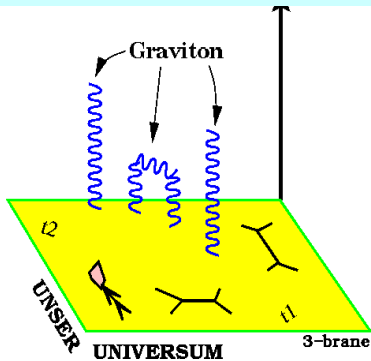
## ZZ/WW resonances?



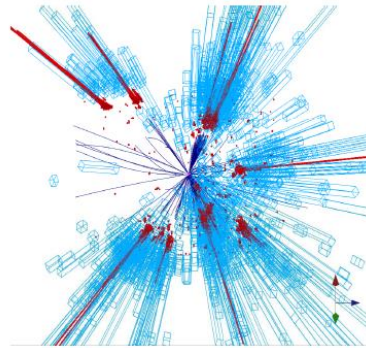
## Technicolor?



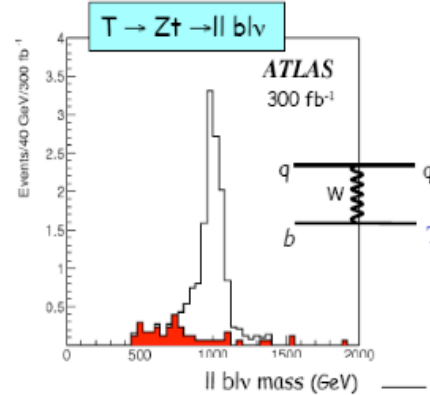
## Extra Dimensions?



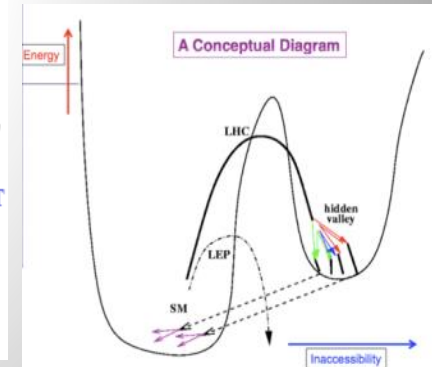
## Black Holes???



## Little Higgs?



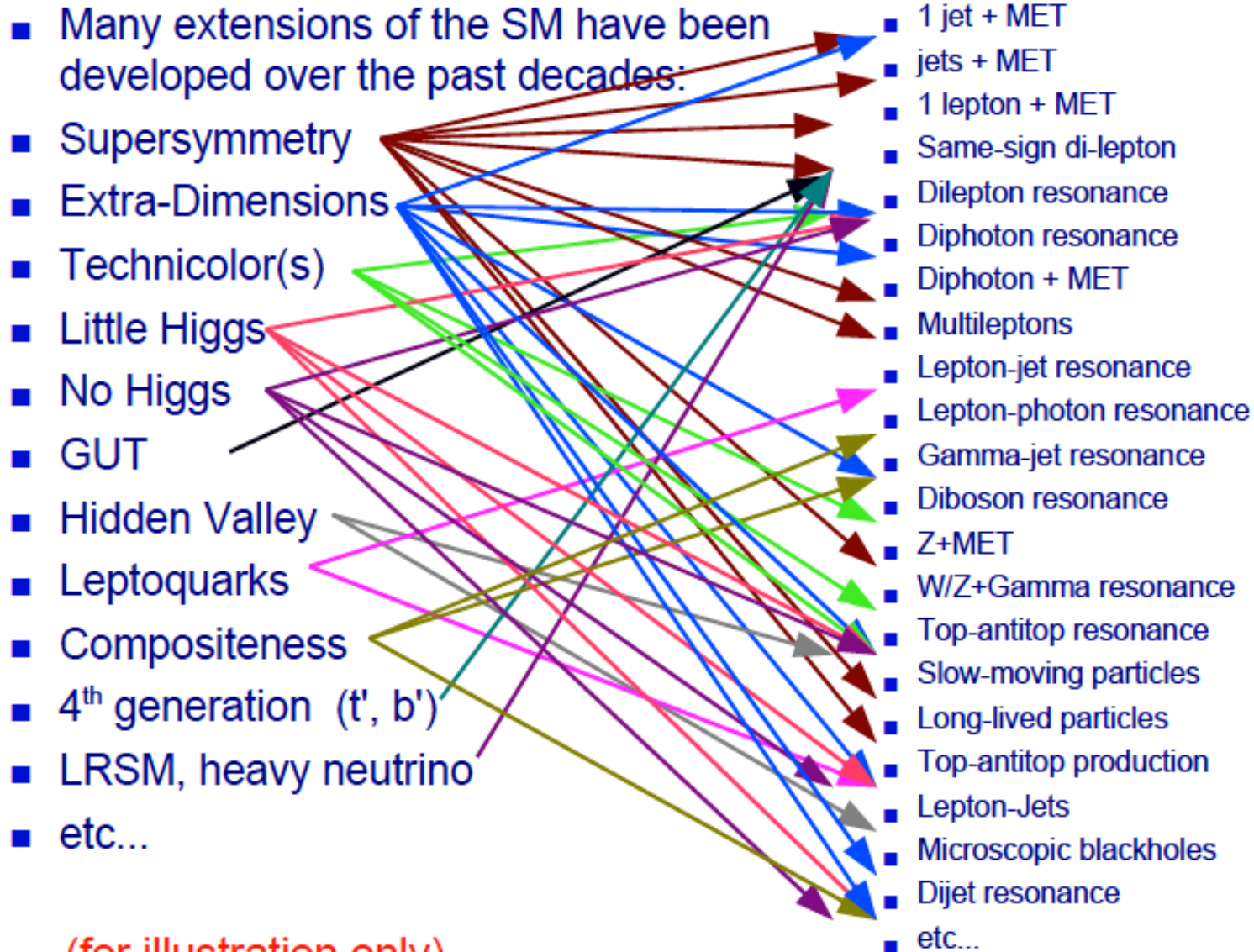
## Hidden Valleys?



What stabilizes the Higgs Mass? Many ideas, not all viable any more  
 A large variety of possible signals. We have to be ready for that



# Beyond the SM Signatures

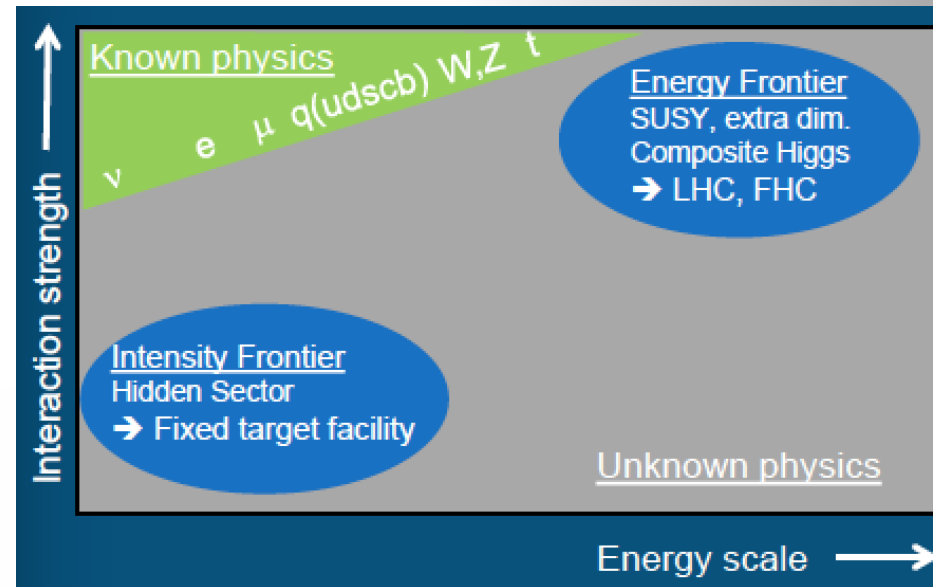
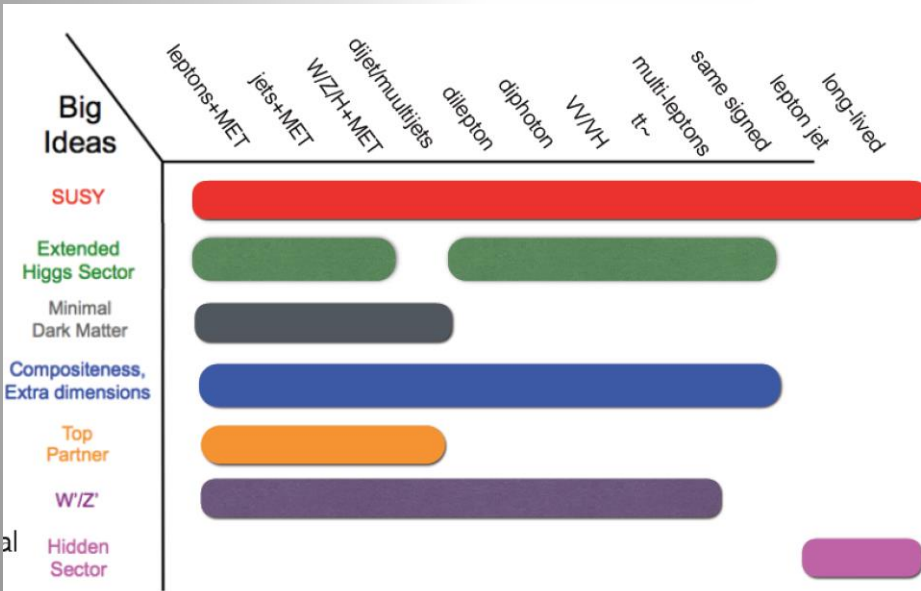


(for illustration only)

# New Physics Searches

Same signatures can come from quite different phenomena:  
 "The Inverse Problem" See eg the LHC Olympics workshops (2004)

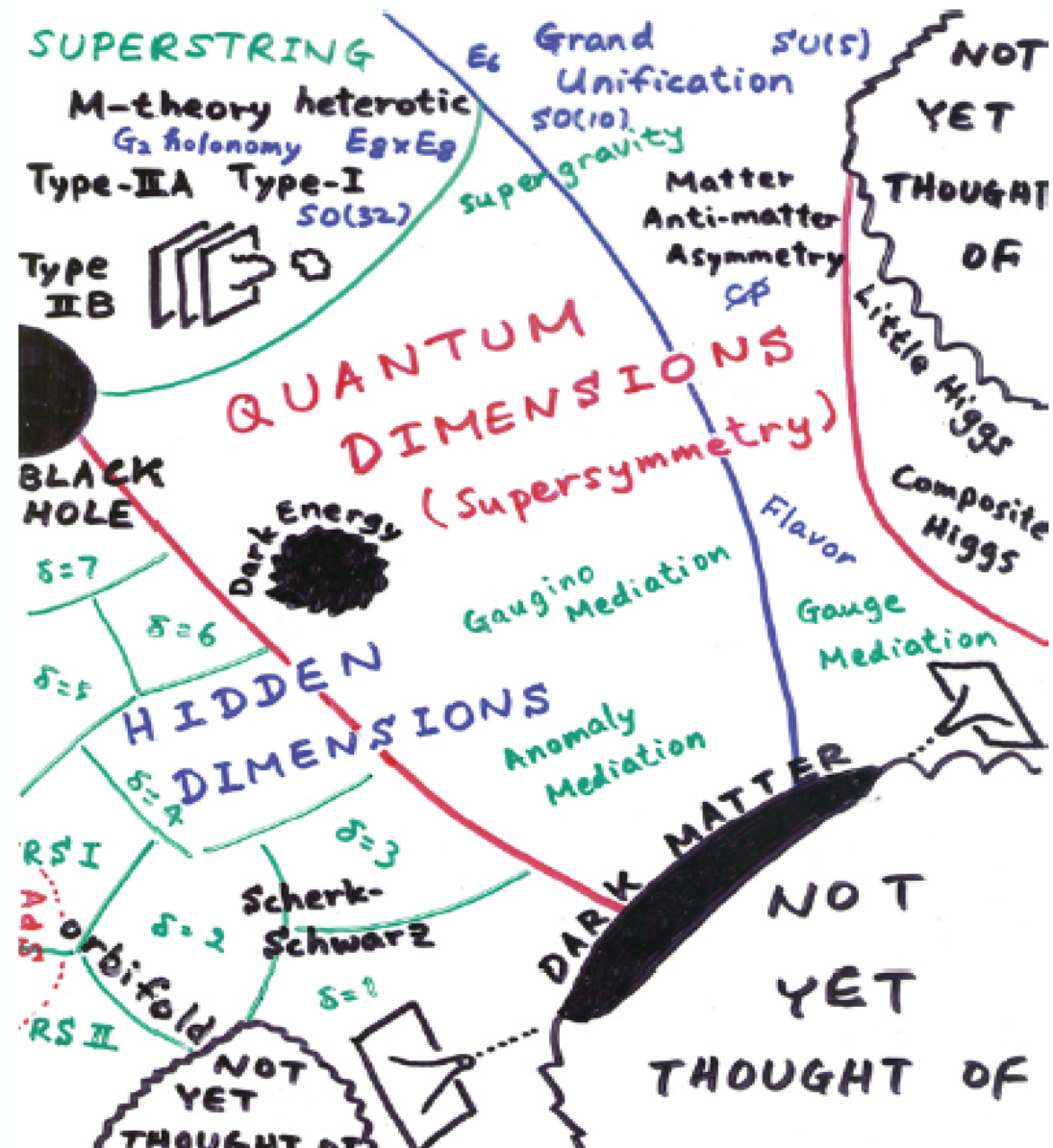
We should explore both the energy scale and the interaction strength (couplings) with our searches



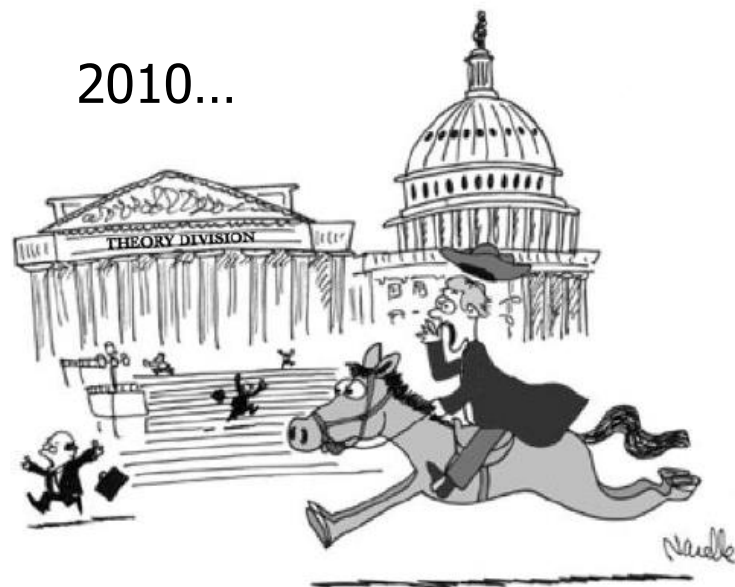


# 2010-2012: LHC data and Theorists

By 2012, I



2010...

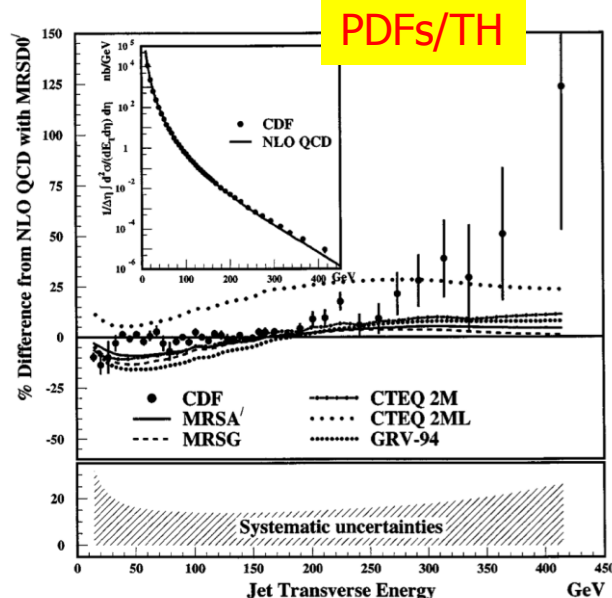
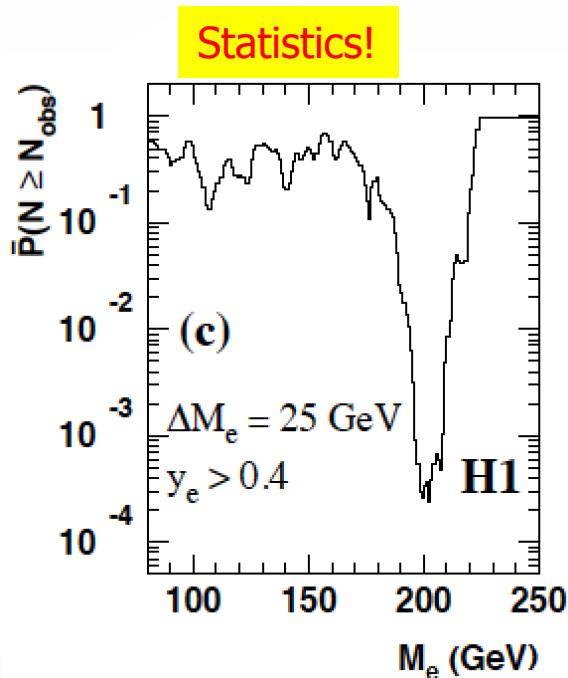
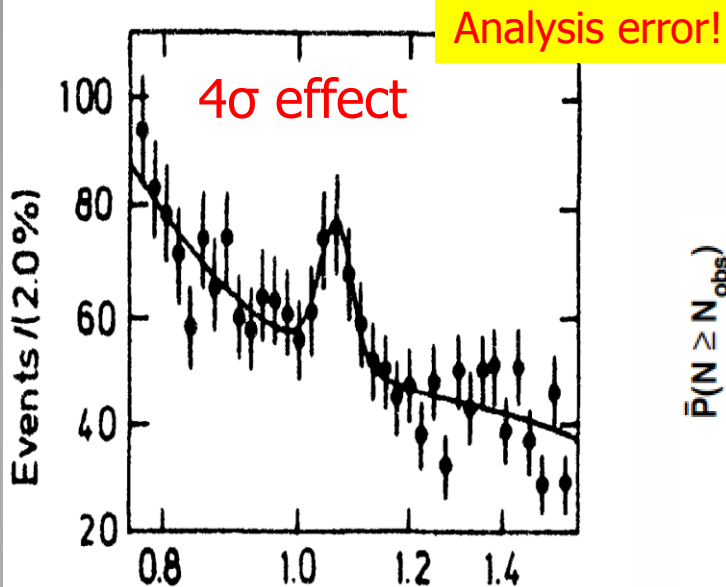


"Data are coming! Data are coming!"

New modern version of the plot, ie the new experimental targets

# Careful with “Discoveries”!

EVIDENCE FOR A MASSIVE STATE IN THE RADIATIVE DECAYS OF THE UPSILON



Excess in inclusive jet analysis: substructure?

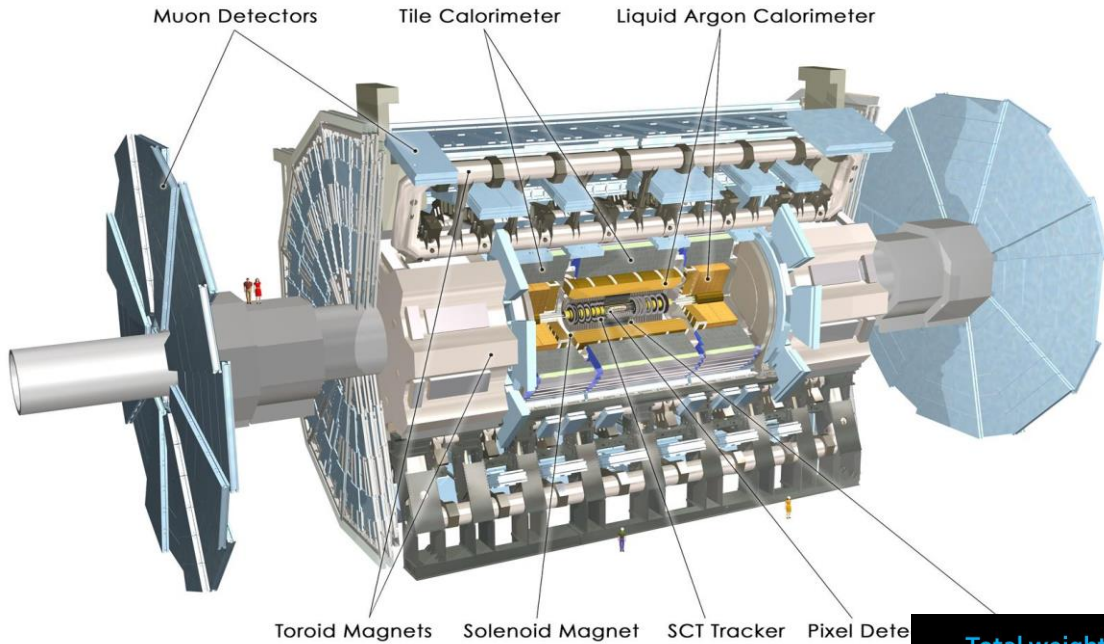
NON of these were actual discoveries!!

Is the X(8.31 GeV) the Higgs particle? A lot of excitement summer 1984

Excess of events at high  $Q^2$  in ep DIS at HERA, mainly in H1:

- 7 events found with an electron-quark mass of  $\sim 200 \text{ GeV}$ , expected  $\sim 1$  event
- 4 events found with expected 2 events in ZEUS  $\rightarrow$  Leptoquarks?

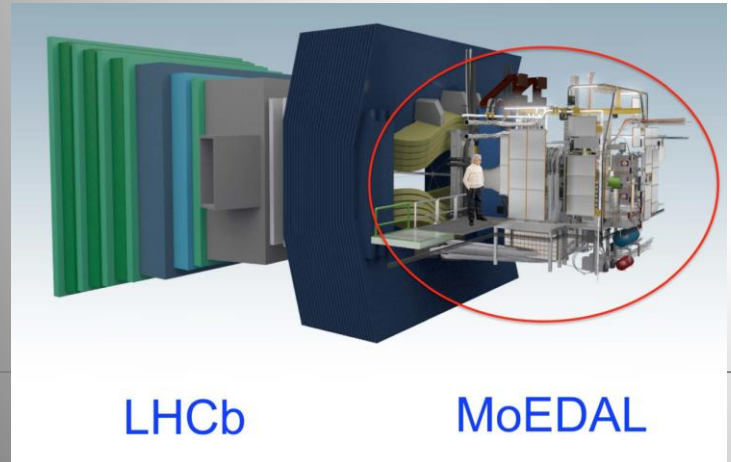
# New Physics Hunters @ the LHC



The ATLAS experiment

The CMS experiment

...And also LHCb and MoEDAL



**CMS**

Total weight 14000 t  
 Overall diameter 15 m  
 Overall length 28.7 m

ECAL 76k scintillating PbWO<sub>4</sub> crystals  
 HCAL Scintillator/brass Interleaved ~7k ch  
 3.8T Solenoid  
 IRONYOKE  
 MUON ENDCAPS 473 Cathode Strip Chambers (CSC) 432 Resistive Plate Chambers (RPC)  
 Preshower Si Strips ~16 m<sup>2</sup> ~137k ch  
 Forward Cal Steel + quartz Fibers ~k ch  
 YB0  
 YB1-2  
 YET-3  
 MUON BARREL 250 Drift Tubes (DT) and 480 Resistive Plate Chambers (RPC)

Pixel Tracker  
 ECAL  
 HCAL  
 Muons  
 Solenoid coil

Pixels & Tracker  
 • Pixels (100x150 μm<sup>2</sup>) ~ 1 m<sup>2</sup> ~66M ch  
 • Si Strips (80-180 μm) ~200 m<sup>2</sup> ~9.6M ch



# Searches for BSM Physics

- **First Searches at the LHC (2010-2012)**
  - Supersymmetry with MET plus jets, lepton(s), photons
  - Extra Dimensions and black holes, heavy resonances (in electrons, muons, taus, jets), leptoquarks, excited leptons and quarks, 4<sup>th</sup> generation, a few very exotic signatures (R-hadrons)...
- **Evolved Searches (2013-....)**
  - Supersymmetry on third generation squarks, compressed spectra, stealth SUSY, EWKinos, VBF processes...
  - Higgs in decays or as study object, vector-like quarks, boosted objects, long lived particles, fractional charges...
  - **More dedicated Dark Matter searches!**
- **We are now fully in the analyses at 13 TeV...**

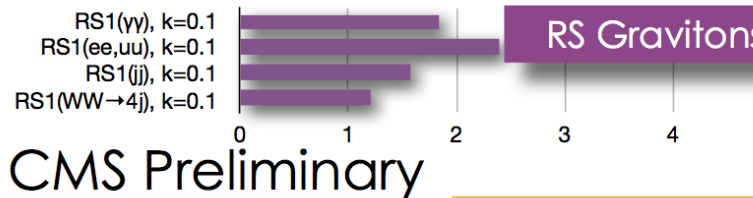
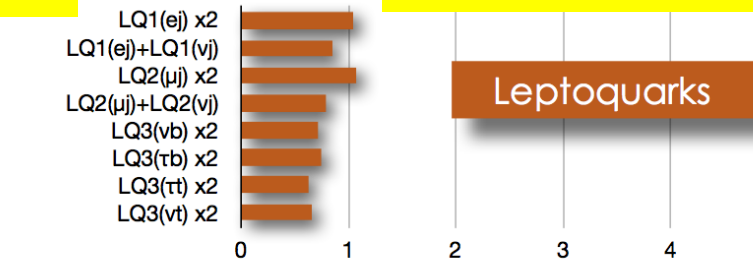
Strategy now a combination of the above!

# Summary of Exotica Searches

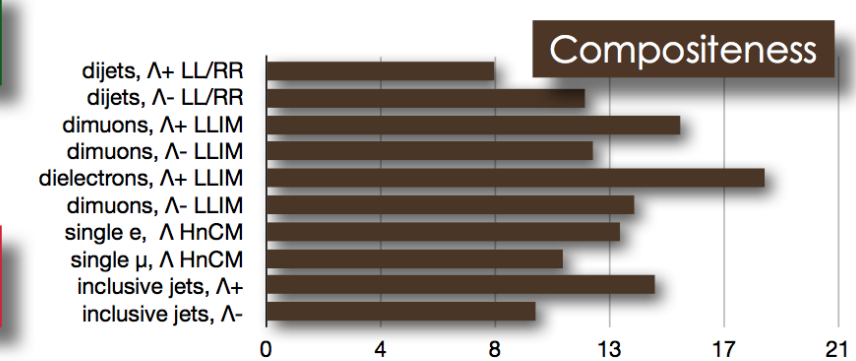
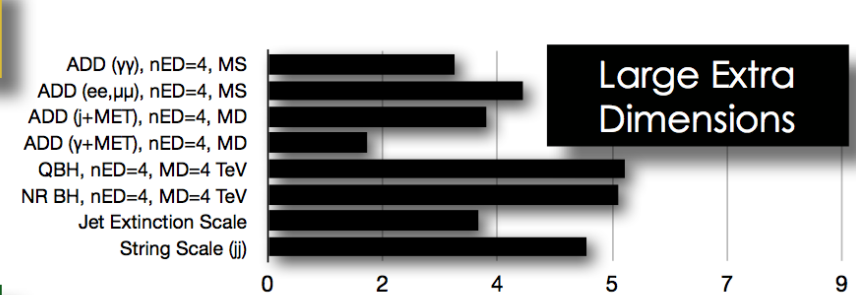
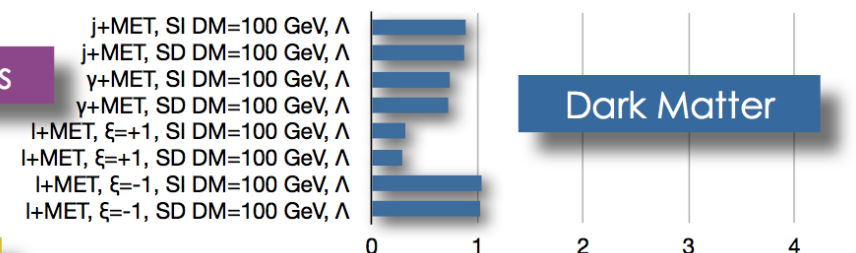
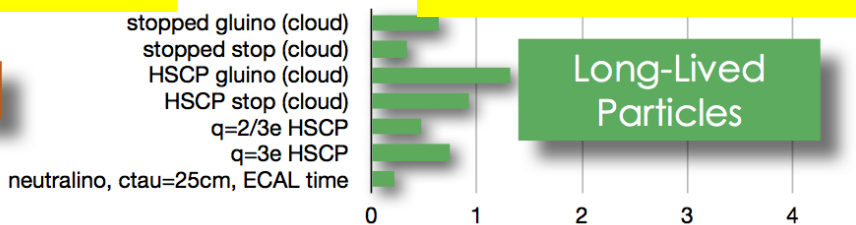
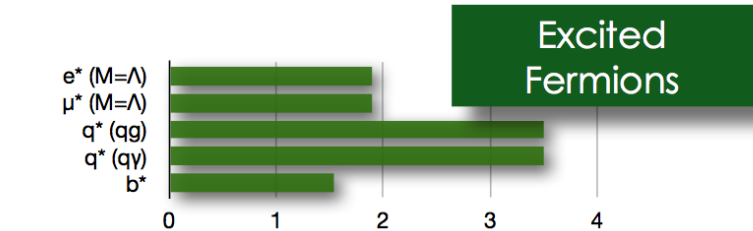
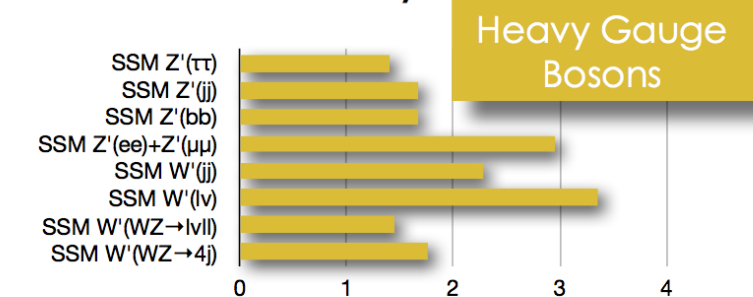
2014

8 TeV data @ 20 fb<sup>-1</sup>

Similar results for ATLAS



CMS Preliminary



# Summary of SUSY Searches

2014

## ATLAS SUSY Searches\* - 95% CL Lower Limits

Status: Feb 2015

Similar results CMS

$\sqrt{s} = 7, 8 \text{ TeV}$

	Model	$e, \mu, \tau, \gamma$	Jets	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$ 1405.7875
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow \tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(1^{\text{st}} \text{ gen. } \tilde{q})=m(2^{\text{nd}} \text{ gen. } \tilde{q})$ 1405.7875
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow \tilde{q}\tilde{\chi}_1^0$ (compressed)	1 $\gamma$	0-1 jet	Yes	20.3	$\tilde{q}$ 250 GeV	$m(\tilde{q})=m(\tilde{\chi}_1^0) = m(c)$ 1411.1559
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{q}\tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$ 1405.7875
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{q}\tilde{q}\tilde{\chi}_1^0 \rightarrow \tilde{q}\tilde{q}W^\pm\tilde{\chi}_1^0$	1 $e, \mu$	3-6 jets	Yes	20	$\tilde{g}$ 1.2 TeV	$m(\tilde{\chi}_1^0)<300 \text{ GeV}, m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$ 1501.03555
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{q}\tilde{q}(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	2 $e, \mu$	0-3 jets	-	20	$\tilde{g}$ 1.32 TeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$ 1501.03555
	GMSB ( $\tilde{\ell}$ NLSP)	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	$\tan\beta > 20$ 1407.0603
	GGM (bino NLSP)	2 $\gamma$	-	Yes	20.3	$\tilde{g}$ 1.28 TeV	$m(\tilde{\chi}_1^0)>50 \text{ GeV}$ ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0)>50 \text{ GeV}$ ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	$\gamma$	1 $b$	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0)>220 \text{ GeV}$ 1211.1167
GGM (higgsino NLSP)	2 $e, \mu$ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	$m(\text{NLSP})>200 \text{ GeV}$ ATLAS-CONF-2012-152	
Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	$m(\tilde{G})>1.8 \times 10^{-4} \text{ eV}, m(\tilde{g})=m(\tilde{q})=1.5 \text{ TeV}$ 1502.01518	
3 <sup>rd</sup> gen. $\tilde{g}$ med.	$\tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0	3 $b$	Yes	20.1	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}_1^0)<400 \text{ GeV}$ 1407.0600
	$\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)<350 \text{ GeV}$ 1308.1841
	$\tilde{g} \rightarrow b\tilde{t}\tilde{\chi}_1^0$	0-1 $e, \mu$	3 $b$	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)<400 \text{ GeV}$ 1407.0600
	$\tilde{g} \rightarrow b\tilde{\tau}\tilde{\chi}_1^0$	0-1 $e, \mu$	3 $b$	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)<300 \text{ GeV}$ 1407.0600
3 <sup>rd</sup> gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	0	2 $b$	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}_1^0)<90 \text{ GeV}$ 1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow \tilde{b}\tilde{\chi}_1^0$	2 $e, \mu$ (SS)	0-3 $b$	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	$m(\tilde{\chi}_1^0)=2 m(\tilde{\chi}_1^0)$ 1404.2500
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^0$	1-2 $e, \mu$	1-2 $b$	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	$m(\tilde{\chi}_1^0) = 2m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0)=55 \text{ GeV}$ 1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $\tilde{t}\tilde{\chi}_1^0$	2 $e, \mu$	0-2 jets	Yes	20.3	$\tilde{t}_1$ 90-191 GeV	$m(\tilde{\chi}_1^0)=1 \text{ GeV}$ 1403.4853, 1412.4742
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}\tilde{\chi}_1^0$	0-1 $e, \mu$	1-2 $b$	Yes	20	$\tilde{t}_1$ 210-640 GeV	$m(\tilde{\chi}_1^0)=1 \text{ GeV}$ 1407.0583, 1406.1122
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$	0	mono-jet/ $c$ -tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)<85 \text{ GeV}$ 1407.0608
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 $e, \mu$ (Z)	1 $b$	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)>150 \text{ GeV}$ 1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 $e, \mu$ (Z)	1 $b$	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	$m(\tilde{\chi}_1^0)<200 \text{ GeV}$ 1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 $e, \mu$	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$ 1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow \tilde{\nu}(\ell\tilde{\nu})$	2 $e, \mu$	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 140-465 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^+)+m(\tilde{\chi}_1^0))$ 1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow \tilde{\tau}(\nu\tilde{\tau})$	2 $\tau$	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 100-350 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(\tilde{\tau}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^+)+m(\tilde{\chi}_1^0))$ 1407.0350
	$\tilde{\chi}_1^+\tilde{\chi}_2^0 \rightarrow \tilde{\ell}_L\tilde{\ell}_L(\tilde{\nu}\tilde{\nu}), \ell\tilde{\nu}\tilde{\ell}_L(\tilde{\nu}\tilde{\nu})$	3 $e, \mu$	0	Yes	20.3	$\tilde{\chi}_1^+, \tilde{\chi}_2^0$ 700 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_2^0), m(\tilde{\ell}_L, \tilde{\nu})=0.5(m(\tilde{\chi}_1^+)+m(\tilde{\chi}_1^0))$ 1402.7029
	$\tilde{\chi}_1^+\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 $e, \mu$	0-2 jets	Yes	20.3	$\tilde{\chi}_1^+, \tilde{\chi}_2^0$ 420 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)=0$ , sleptons decoupled 1403.5294, 1402.7029
	$\tilde{\chi}_1^+\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h \rightarrow b\tilde{b}/WW/\tau\tau/\gamma\gamma$	$e, \mu, \gamma$	0-2 $b$	Yes	20.3	$\tilde{\chi}_1^+, \tilde{\chi}_2^0$ 250 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)=0$ , sleptons decoupled 1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_3^0 \rightarrow \tilde{\ell}_R\tilde{\ell}$	4 $e, \mu$	0	Yes	20.3	$\tilde{\chi}_2^0, \tilde{\chi}_3^0$ 620 GeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0), m(\tilde{\chi}_1^0)=0, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$ 1405.5086
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV	$m(\tilde{\chi}_1^+)-m(\tilde{\chi}_1^0)=160 \text{ MeV}, \tau(\tilde{\chi}_1^\pm)=0.2 \text{ ns}$ 1310.3675
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)=100 \text{ GeV}, 10 \mu\text{s} < \tau(\tilde{g}) < 1000 \text{ s}$ 1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	19.1	$\tilde{g}$ 1.27 TeV	$10 < \tan\beta < 50$ 1411.6795
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu}) + \tau(e, \mu)$	1-2 $\mu$	-	-	19.1	$\tilde{\chi}_1^0$ 537 GeV	$2 < \tau(\tilde{\chi}_1^0) < 3 \text{ ns}, \text{SPS8 model}$ 1411.6795
	GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ , long-lived $\tilde{\chi}_1^0$	2 $\gamma$	-	Yes	20.3	$\tilde{\chi}_1^0$ 435 GeV	$1.5 < c\tau < 156 \text{ mm}, \text{BR}(\mu)=1, m(\tilde{\chi}_1^0)=108 \text{ GeV}$ 1409.5542
	$\tilde{q}\tilde{q}, \tilde{\chi}_1^0 \rightarrow \tilde{q}\tilde{q}\mu$ (RPV)	1 $\mu$ , displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	$1.5 < c\tau < 156 \text{ mm}, \text{BR}(\mu)=1, m(\tilde{\chi}_1^0)=108 \text{ GeV}$ ATLAS-CONF-2013-092
RPV	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e + \mu$	2 $e, \mu$	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	$\lambda'_{311} = -0.10, \lambda'_{132} = 0.05$ 1212.1272
	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e(\mu) + \tau$	1 $e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	$\lambda'_{311} = -0.10, \lambda'_{1(2)33} = 0.05$ 1212.1272
	Bilinear RPV CMSSM	2 $e, \mu$ (SS)	0-3 $b$	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.35 TeV	$m(\tilde{q})=m(\tilde{g}), c\tau_{LSP} < 1 \text{ mm}$ 1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 $e, \mu$	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 750 GeV	$m(\tilde{\chi}_1^0)>0.2 \times m(\tilde{\chi}_1^+), \lambda'_{121} \neq 0$ 1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tau\tau\tilde{\nu}_e, e\tilde{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 450 GeV	$m(\tilde{\chi}_1^0)>0.2 \times m(\tilde{\chi}_1^+), \lambda'_{133} \neq 0$ 1405.5086
	$\tilde{g} \rightarrow q\tilde{q}q$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	$\text{BR}(f)=\text{BR}(b)=\text{BR}(c)=0\%$ ATLAS-CONF-2013-091
$\tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow b\tilde{s}$	2 $e, \mu$ (SS)	0-3 $b$	Yes	20.3	$\tilde{g}$ 850 GeV	1404.250	
Other	Scalar charm, $\tilde{c} \rightarrow c\tilde{\chi}_1^0$	0	2 $c$	Yes	20.3	$\tilde{c}$ 490 GeV	$m(\tilde{\chi}_1^0)<200 \text{ GeV}$ 1501.01325

$\sqrt{s} = 7 \text{ TeV}$   
full data

$\sqrt{s} = 8 \text{ TeV}$   
partial data

$\sqrt{s} = 8 \text{ TeV}$   
full data

$10^{-1}$

1

Mass scale [TeV]



# Run-1: We Observed Mild Deviations!

November 2015

LHC Beyond-the-SM Anomalies

B. Hooberman

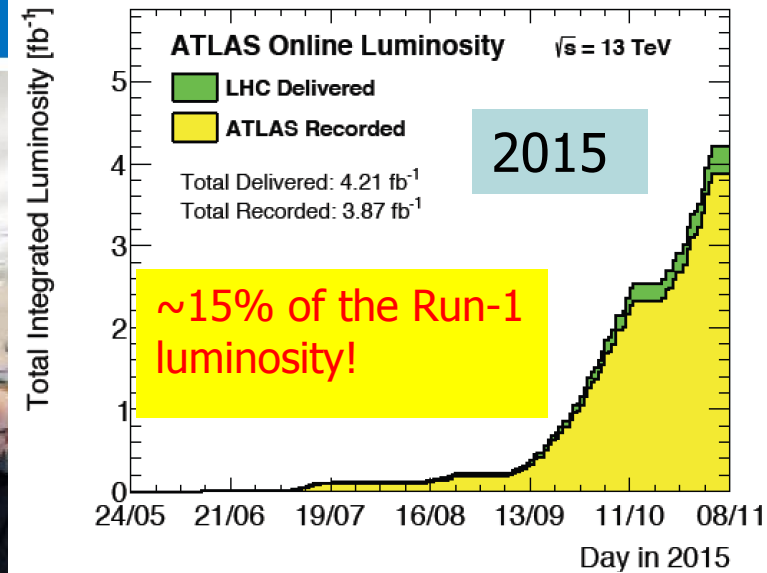
[https://www.dropbox.com/s/2xrxcxns5wnc4ek/LHC\\_anomalies.pdf?dl=0](https://www.dropbox.com/s/2xrxcxns5wnc4ek/LHC_anomalies.pdf?dl=0)

	Search	Dataset	Max Significance	Reference
Strong SUSY (jets+E <sub>T</sub> <sup>miss</sup> +X)	Z+jets+E <sub>T</sub> <sup>miss</sup>	ATLAS 8 TeV	3.0σ	<a href="#">EPJC 75 (2015) 318</a>
	Z+jets+E <sub>T</sub> <sup>miss</sup>	ATLAS 13 TeV	2.2σ	<a href="#">ATLAS-CONF-2015-082</a>
	Dilepton mass edge	CMS 8 TeV	2.6σ	<a href="#">arXiv:1502.06031 [hep-ex]</a>
	Soft 2ℓ+E <sub>T</sub> <sup>miss</sup>	ATLAS 8 TeV	2.3σ	<a href="#">ATLAS-CONF-2013-062</a>
EWK SUSY (leptons+E <sub>T</sub> <sup>miss</sup> )	Same-sign ≥2ℓ+b+E <sub>T</sub> <sup>miss</sup>	ATLAS 8 TeV	2.5σ	<a href="#">arXiv:1504.04605 [hep-ex]</a>
	3ℓ+E <sub>T</sub> <sup>miss</sup> (WZ→3ℓ channel)	CMS 8 TeV	~2σ	<a href="#">EPJC 74 (2014) 3036</a>
	4ℓ+E <sub>T</sub> <sup>miss</sup> (3ℓ+τ <sub>had</sub> channel)	CMS 8 TeV	~3σ	<a href="#">PRD 90, 032006 (2014)</a>
	3ℓ+E <sub>T</sub> <sup>miss</sup>	ATLAS 8 TeV	2.2σ	<a href="#">JHEP 04 (2014)169</a>
Resonances	All-hadronic boosted diboson	ATLAS 8 TeV	3.4σ	<a href="#">JHEP 12 (2015) 55</a>
	Dijet resonance search (M <sub>jj</sub> ~ 1.8 TeV)	CMS 8 TeV	~2σ	<a href="#">PRD 91 (2015) 052009</a>
	W(ℓν)H(bb) resonance (M <sub>WH</sub> ~ 1.8 TeV)	CMS 8 TeV	2.2σ	<a href="#">CMS-PAS-EXO-14-010</a>
	X→h(bb)h(γγ) (M <sub>X</sub> ~ 300 GeV)	ATLAS 8 TeV	3.0σ	<a href="#">PRL 114 (2015) 081802</a>
Higgs	1 <sup>st</sup> gen. leptoquarks (ee <sub>jj</sub> / ev <sub>jj</sub> channels)	CMS 8 TeV	2.6σ / 2.4σ	<a href="#">CMS-PAS-EXO-12-041</a>
	Heavy right-handed neutrinos	CMS 8 TeV	2.8σ	<a href="#">EPJC 74 (2014) 3149</a>
	ttH (same-sign muon channel)	CMS 8 TeV	μ <sub>ttH</sub> = 8.5 <sup>+3.5</sup> <sub>-2.7</sub>	<a href="#">JHEP 09 (2014) 087</a>
Flavor	Higgs→μτ (lepton flavor violation)	CMS 8 TeV	2.5σ	<a href="#">CMS-PAS-HIG-14-005</a>
	B → Kℓℓ (Kμμ / Kee)	LHCb 8 TeV	2.6σ	<a href="#">PRL 113 (2014) 151601</a>
	B → Kμμ (branching ratio)	LHCb 8 TeV	2.2σ	<a href="#">JHEP 06 (2014) 133</a>
SM measurements	B → Kμμ (P <sub>s</sub> <sup>+</sup> angular distribution)	LHCb 8 TeV	3.7σ	<a href="#">LHCb-CONF-2015-002</a>
	WW cross section*	CMS 7 TeV	1.0σ	<a href="#">EPJC 73 2610 (2013)</a>
	WW cross section*	CMS 8 TeV	1.7σ	<a href="#">PLB 721 (2013)</a>
	WW cross section*	ATLAS 7 TeV	1.4σ	<a href="#">PRD 87, 112001 (2013)</a>
	WW cross section*	ATLAS 8 TeV	2.0σ	<a href="#">ATLAS-CONF-2014-033</a>

\* See Jaiswal and Okui 2014 and Monni and Zanderighi 2014 for explanation

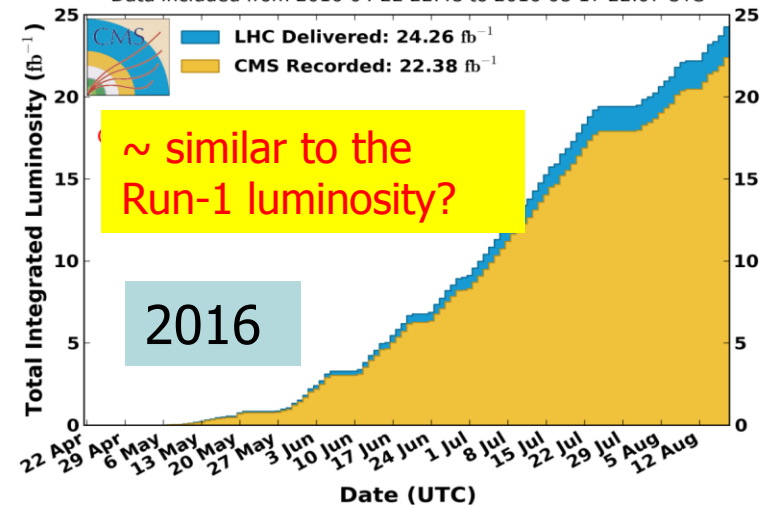
# LHC experiments are back in business at a new record energy 13 TeV

3<sup>rd</sup> June 2015



**CMS Integrated Luminosity, pp, 2016,  $\sqrt{s} = 13$  TeV**

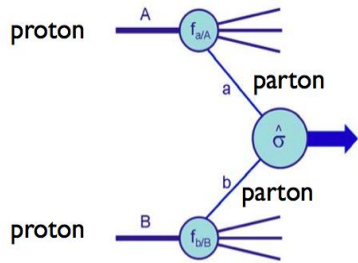
Data included from 2016-04-22 22:48 to 2016-08-17 22:07 UTC



For ICHEP results:  $\sim 13$  fb<sup>-1</sup> from 2016 data

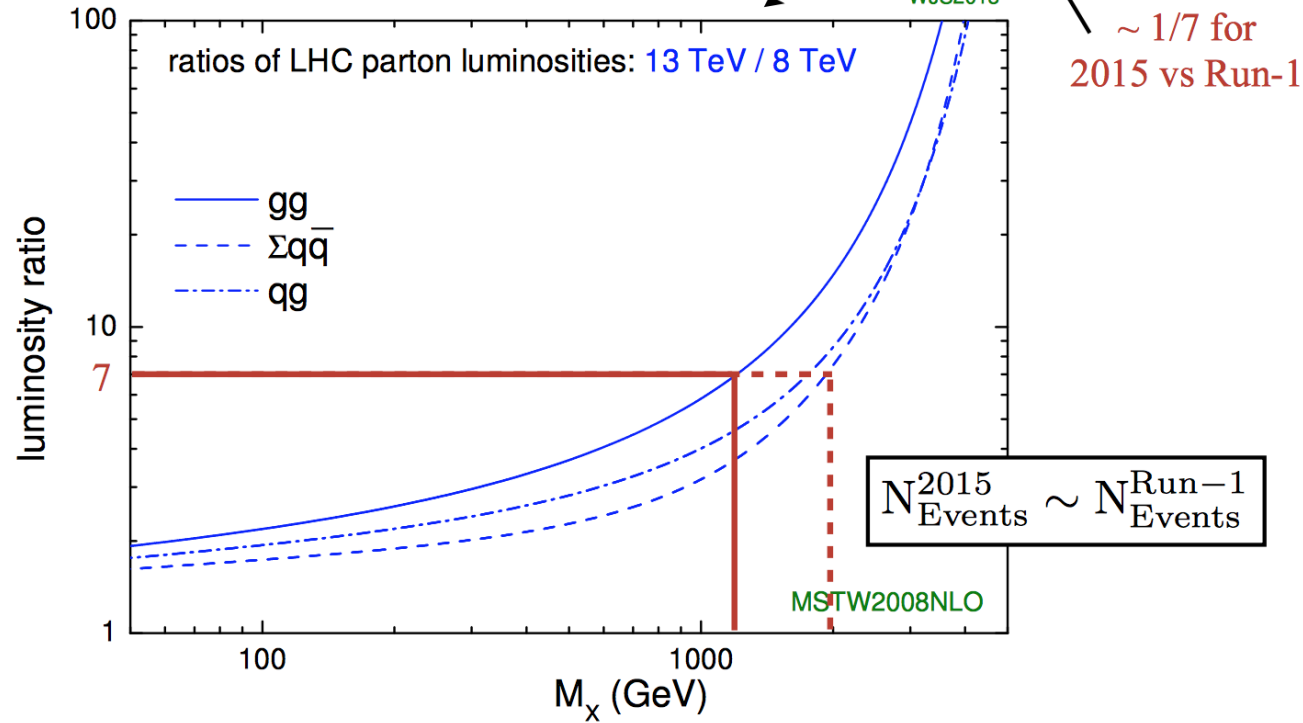
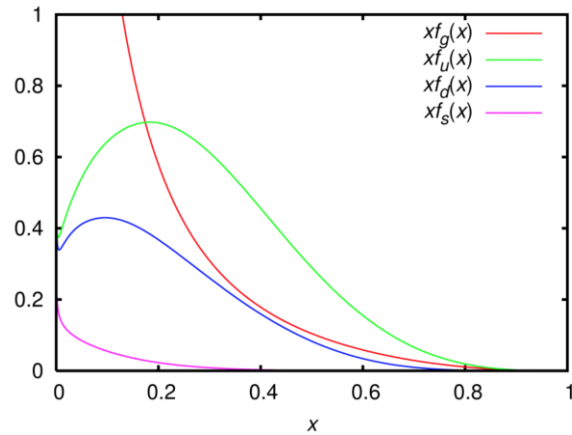
# New Physics Searches with 13 TeV Data

## Generic LHC Collision



$$N_{\text{Events}} = \sigma \times \mathcal{L}$$

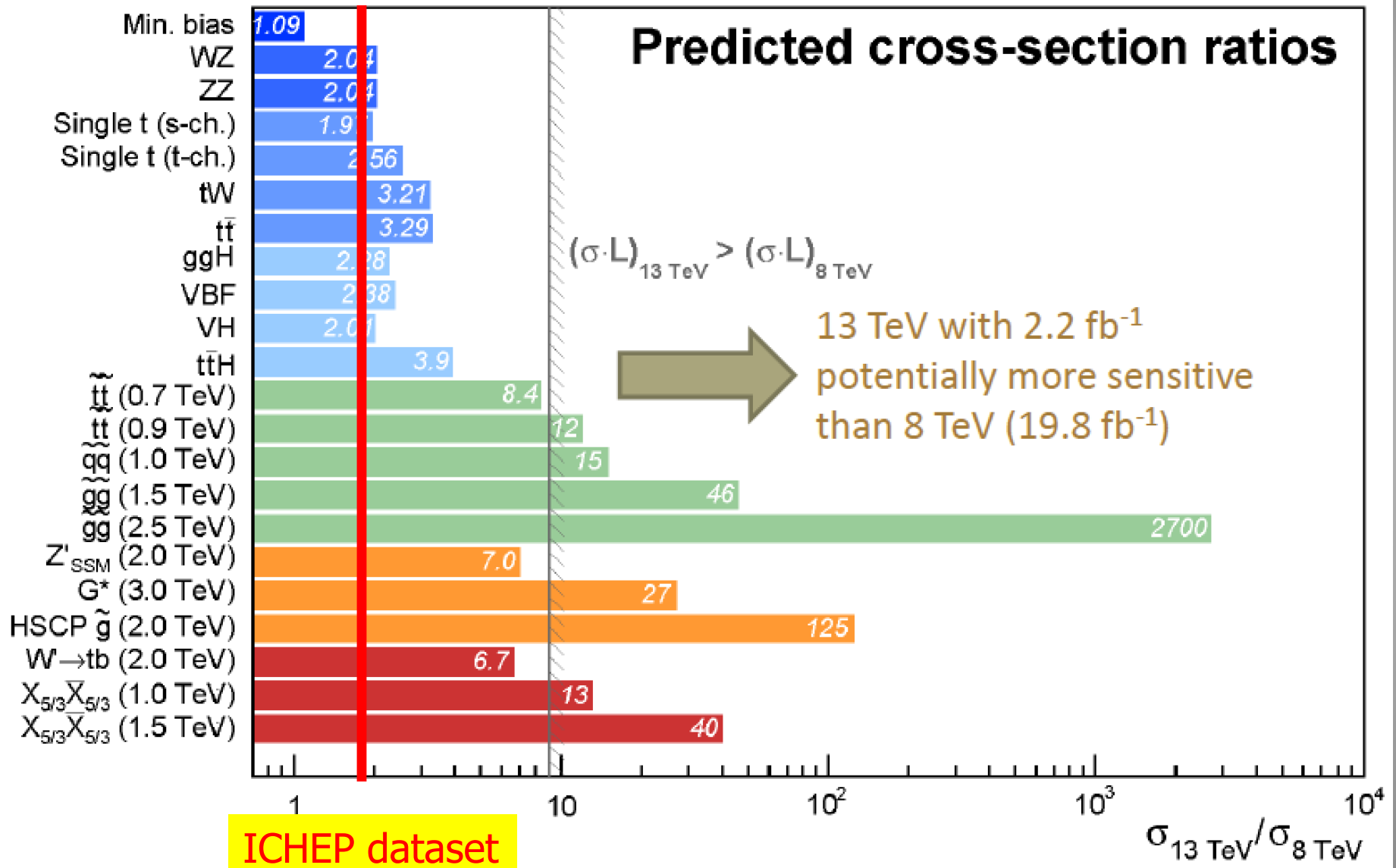
$$\frac{N_{\text{Events}}^{13 \text{ TeV}}}{N_{\text{Events}}^{8 \text{ TeV}}} = \underbrace{\frac{\sigma^{13 \text{ TeV}}}{\sigma^{8 \text{ TeV}}}}_{\text{WJS2013}} \times \underbrace{\frac{\mathcal{L}^{13 \text{ TeV}}}{\mathcal{L}^{8 \text{ TeV}}}}_{\sim 1/7 \text{ for } 2015 \text{ vs Run-1}}$$



For searches above 1-2 TeV the 2015 data sample becomes already important  
The 2016 data ( $\sim 30 \text{ fb}^{-1}$  at the end?) will take over for ALL searches



# Run-II: From 8 TeV to 13 TeV



# Extra Dimensions

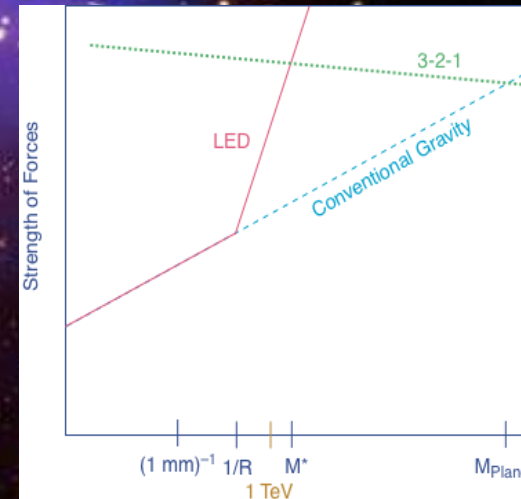
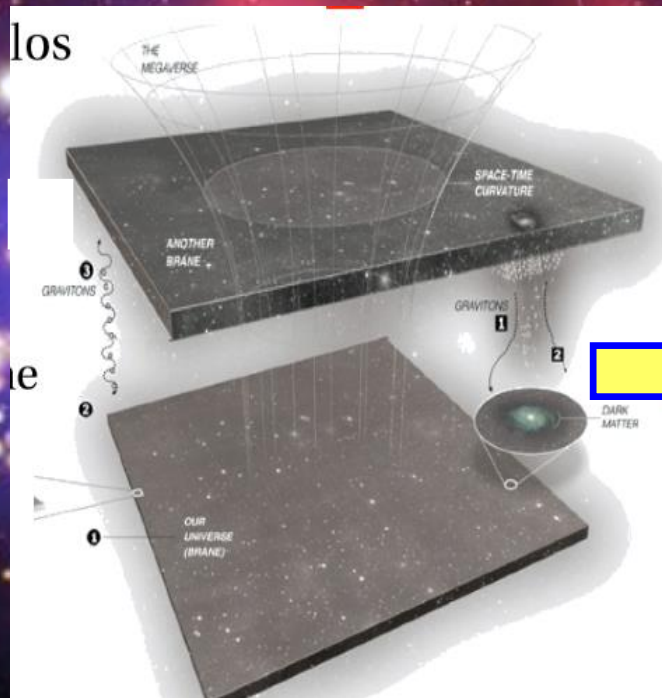
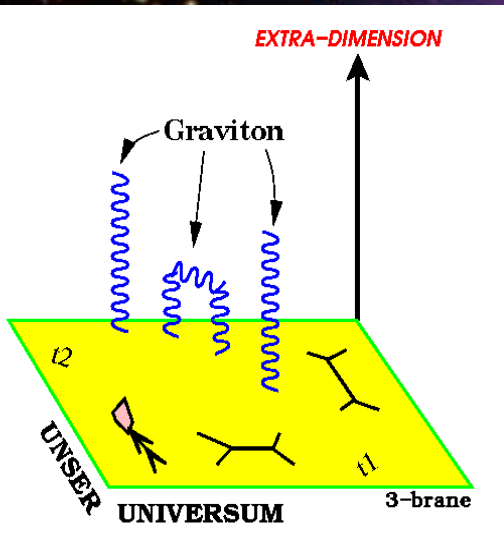
# Extra Space Dimensions

**Problem:**

$$m_{EW} = \frac{1}{(G_F \cdot \sqrt{2})^{\frac{1}{2}}} = 246 \text{ GeV}$$



$$M_{Pl} = \frac{1}{\sqrt{G_N}} = 1.2 \cdot 10^{19} \text{ GeV}$$



**The Gravity force becomes strong!**



# Models with Extra Dimensions

Large Extra Dimensions Planck scale ( $M_D$ )  $\sim$  TeV

Size:  $\gg$  TeV<sup>-1</sup>; SM-particles on brane; gravity in bulk

KK-towers (small spacing); KK-exchange; graviton prod.

Signature: e.g. x-section deviations; jet+E<sub>T,miss</sub> ....

ADD

Arkani-Hamed Dimopoulos Dvali

Warped Extra Dimensions

RS

Randall Sundrum

5-dimensional spacetime with warped geometry

Graviton KK-modes (large spacing); graviton resonances

Signature: e.g. resonance in ee, μμ, γγ-mass distributions ...

TeV-Scale Extra Dimensions look-like SUSY

SM particles allowed to propagate in ED of size TeV<sup>-1</sup>

[scenarios: gauge fields only (nUED) or all SM particles (UED)]

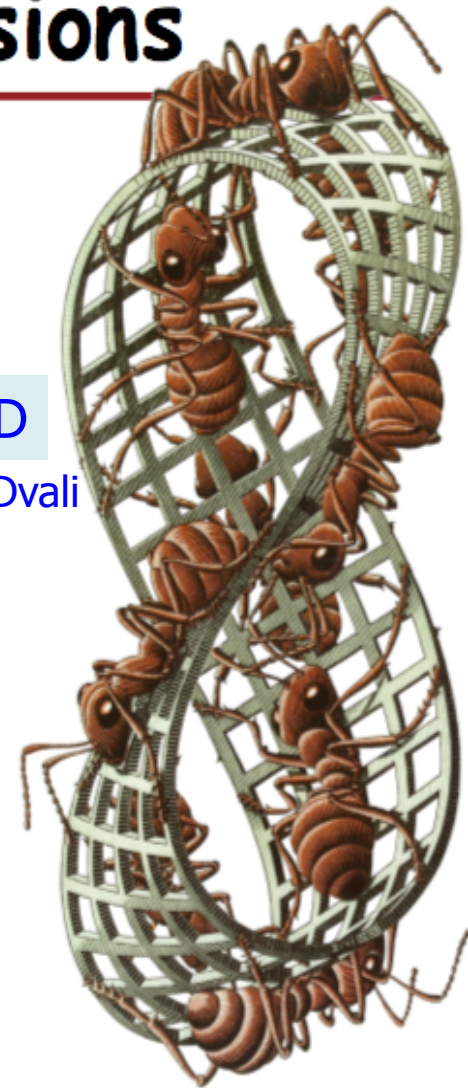
nUED : KK excitations of gauge bosons

UED

Universal Extra Dimensions

UED : KK number conservation; KK states pair produced (at tree-level) ...

Signature: e.g. Z'/W' resonances, dijets+E<sub>T,miss</sub>, heavy stable quarks/gluons...



# Search for Large Extra Dimensions

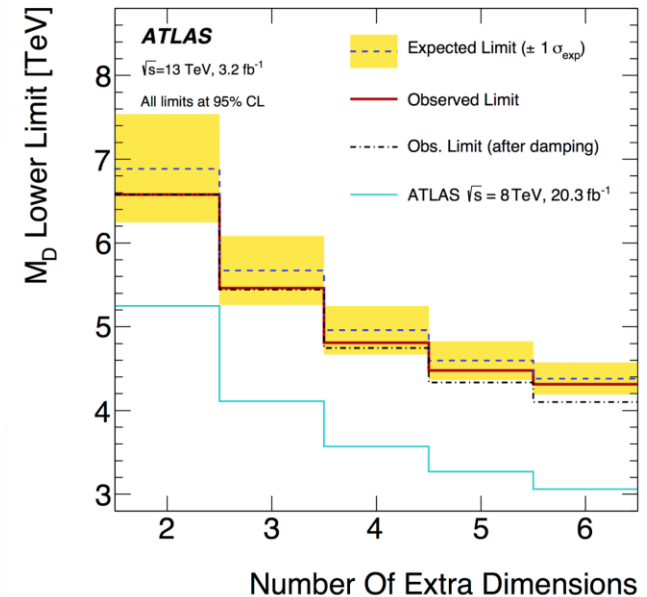
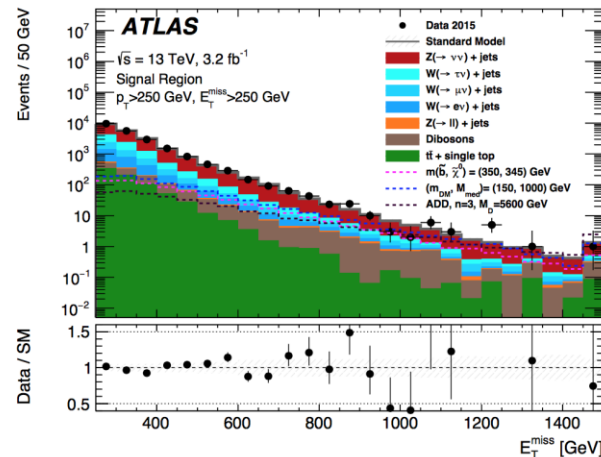
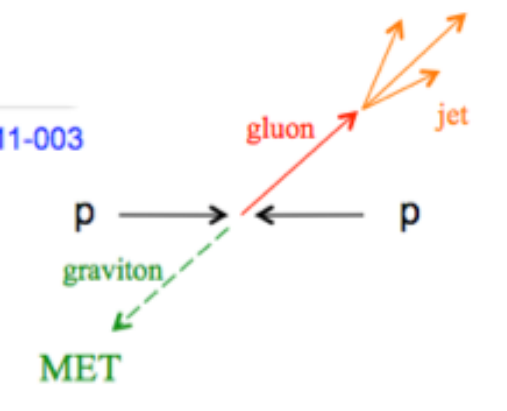
Example: Mono-jet final state + Missing  $E_T$  (ADD)

arXiv:1604.07773

$p_T \text{ jet} > 250 \text{ GeV}$   
 $\text{MET} > 250\text{-}700 \text{ GeV}$

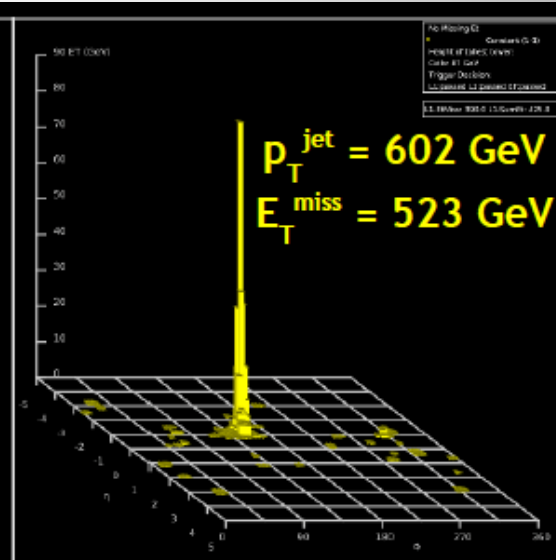
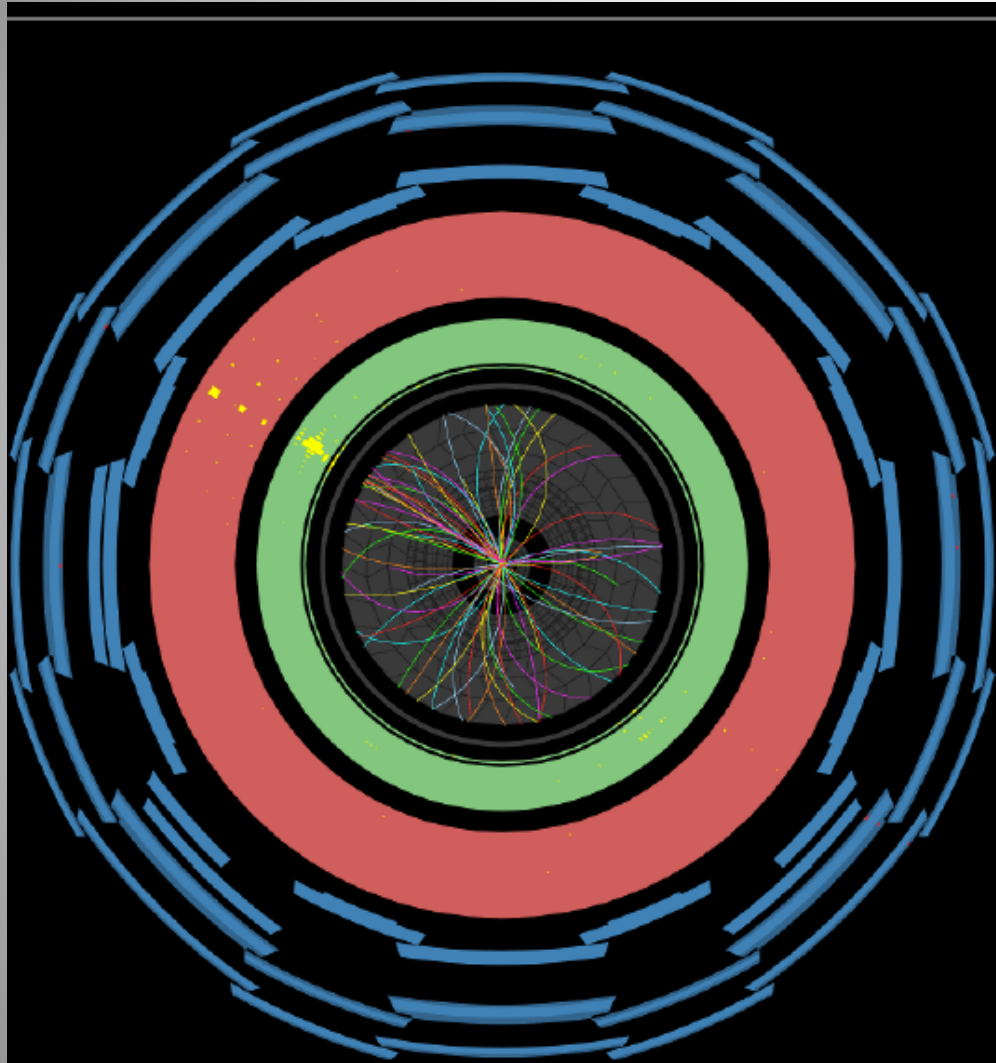
Limits on  $M_D$   
 between  
 $\sim 7$  and  $4 \text{ TeV}$

Lower limit on the Planck Scale  
 versus number of extra dimensions



n extra dimensions	95% CL lower limits on $M_D$ [TeV]			95% CL expected limit	
	95% CL observed limit		$\pm 1\sigma$ (theory)	Nominal	$\pm 1\sigma$ (expected)
	Nominal	(Nominal after damping)			
2	6.58	(6.58)	+0.52 -0.42	6.88	+0.65 -0.64
3	5.46	(5.44)	+0.45 -0.34	5.67	+0.41 -0.41
4	4.81	(4.74)	+0.41 -0.29	4.96	+0.29 -0.29
5	4.48	(4.34)	+0.41 -0.26	4.60	+0.23 -0.23
6	4.31	(4.10)	+0.41 -0.24	4.38	+0.19 -0.19

# A High $p_T$ Mono-jet event

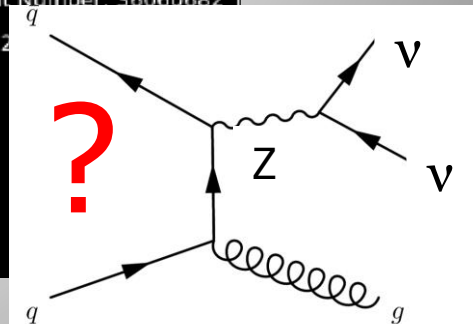


 **ATLAS**  
EXPERIMENT

Run Number: 180309, Event Number: 36060682

Date: 2011-04-27 02:10:10

A high- $p_T$  monojet event - SM interpretation  $Z \rightarrow \bar{\nu}\nu + \text{jet}$



# Micro Black Holes?

- Schwarzschild radius

Landsberg, Dimopoulos, Giddings, Thomas, Rizzo

4-dim.,  $M_{\text{gravity}} = M_{\text{Planck}}$  :

$$R_S \sim \frac{2}{M_{\text{Pl}}^2} \frac{M_{\text{BH}}}{c^2}$$

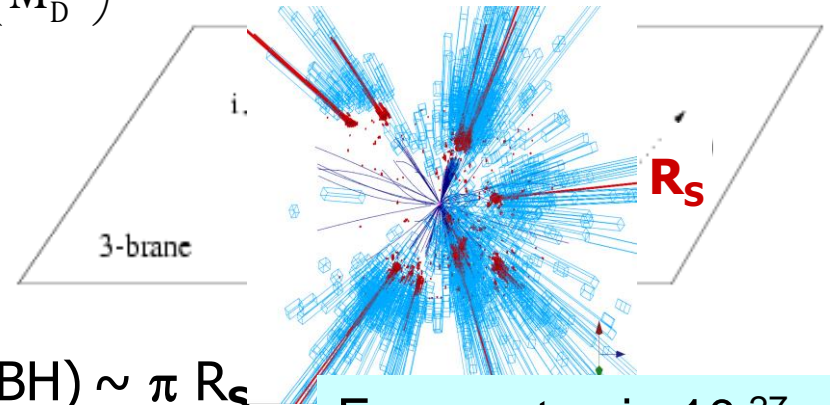
$$R_S \rightarrow \ll 10^{-35} \text{ m}$$

4 + n-dim.,  $M_{\text{gravity}} = M_D \sim \text{TeV}$  :

$$R_S \sim \frac{1}{M_D} \left( \frac{M_{\text{BH}}}{M_D} \right)^{\frac{1}{n+1}}$$

$$R_S \rightarrow \sim 10^{-19} \text{ m}$$

Since  $M_D$  is low, tiny black holes of  $M_{\text{BH}} \sim \text{TeV}$  can be produced if partons  $ij$  with  $\sqrt{s_{ij}} = M_{\text{BH}}$  pass at a distance smaller than  $R_S$



- Large partonic cross-section :  $\sigma (ij \rightarrow \text{BH}) \sim \pi R_S$
- $\sigma (pp \rightarrow \text{BH})$  is in the range of 1 nb – 1 fb

Evaporates in  $10^{-27}$  sec

e.g. For  $M_D \sim 1 \text{ TeV}$  and  $n=3$ , produce 1 event/second at the LHC

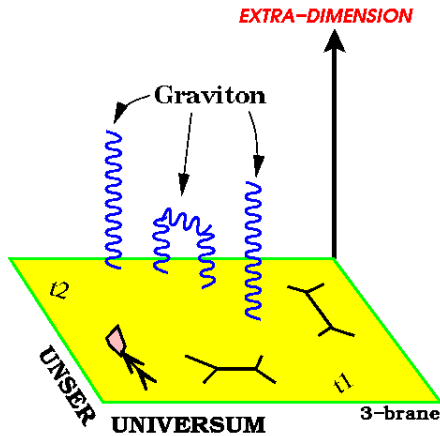
- Black holes decay immediately by Hawking radiation (democratic evaporation)
    - large multiplicity
    - small missing E
    - jets/leptons  $\sim 5$
- expected signature (quite spectacular ...)

Note: Quantum Black holes usually decay typically just to two fermions

Dvali



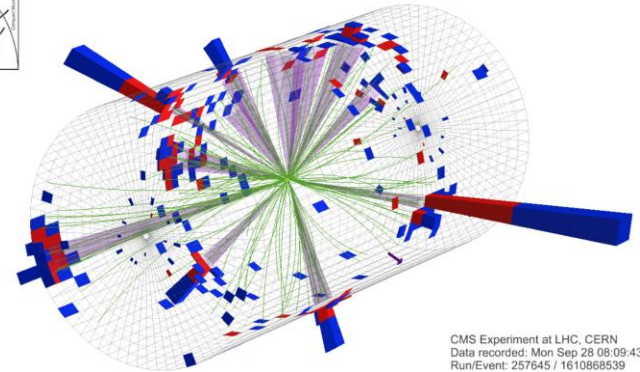
# Search for Micro Black Holes



Extra Dimensions!

Planck scale  
a few TeV?

2015: 12 jet event with  $S_T = 5.4$  TeV



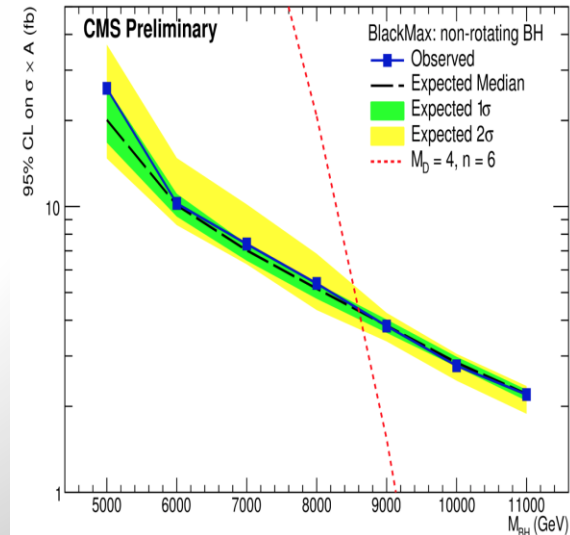
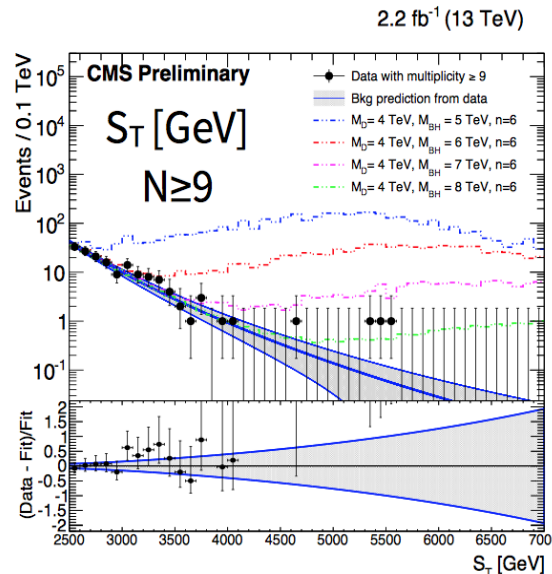
CMS Experiment at LHC, CERN  
Data recorded: Mon Sep 28 08:09:43 2015 CEST  
Run/Event: 257645 / 1610868539

CMS-EXO-15-007

2.2 fb<sup>-1</sup> (13 TeV)

Look for the decay products  
of an evaporating black hole

- Define  $S_T$  to be the scalar sum of all high  $p_T$  objects found in the event
- Look for deviations at high  $S_T$



Black hole mass excluded in range below ~8-9 TeV depending on assumptions

# **Search for High Mass Resonances**

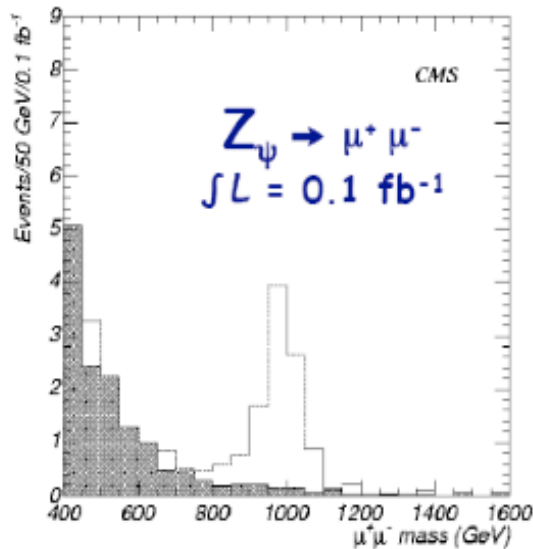
# E.g. Di-lepton Resonance

Plot the di-lepton invariant mass

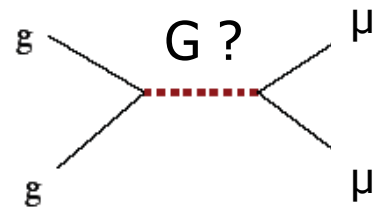
A peak!!

A new particle!!

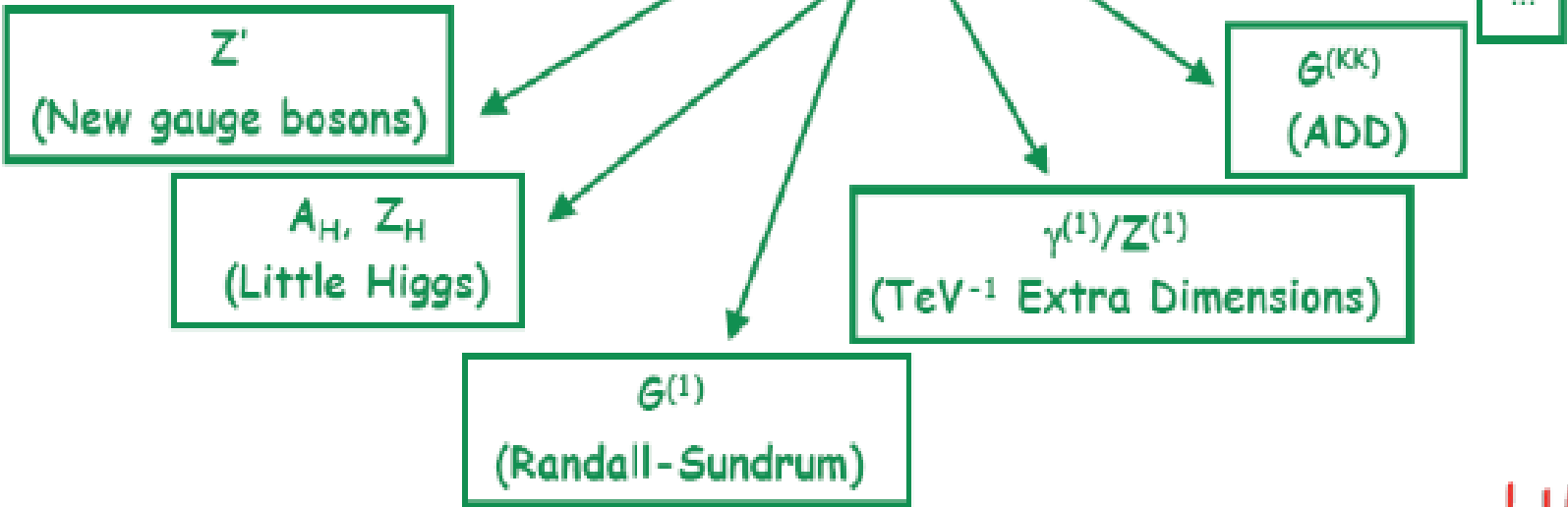
A discovery!!



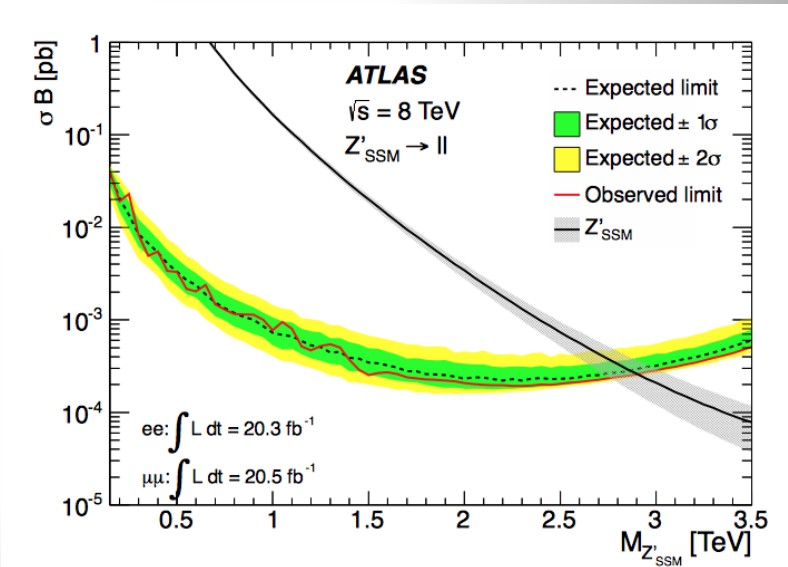
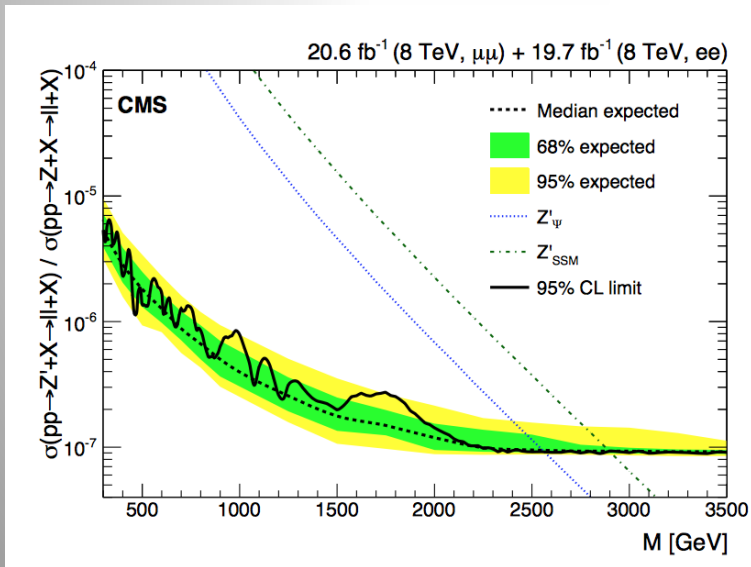
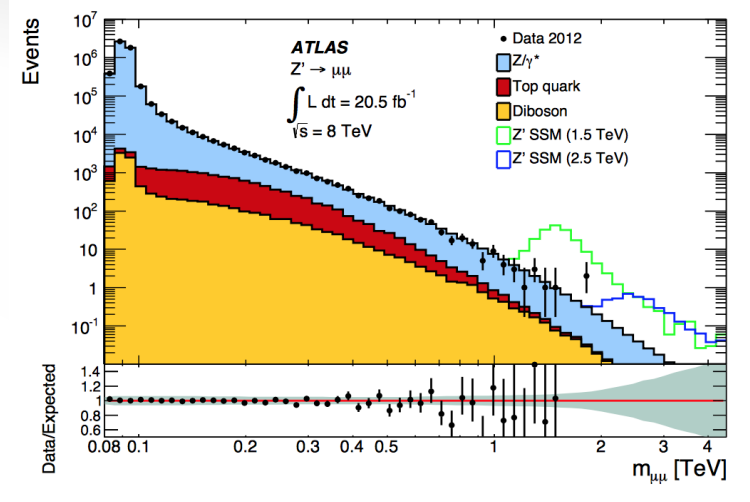
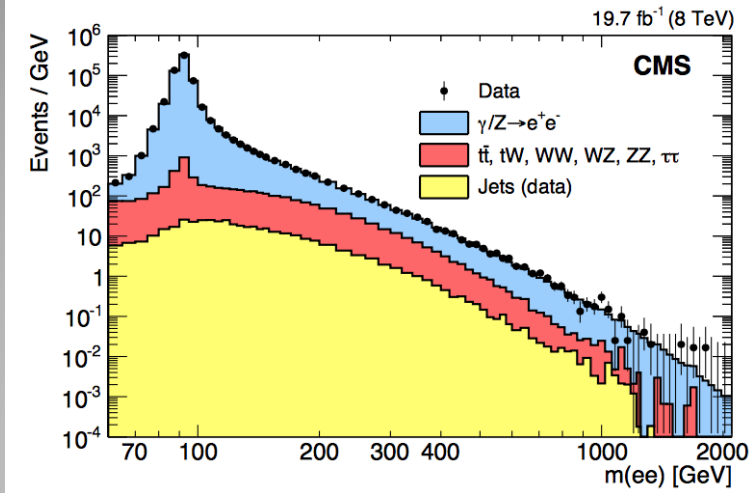
Example  
 $pp \rightarrow \mu\mu + X$



## Example : The Di-lepton channel



# Example: Z' Results Run-1

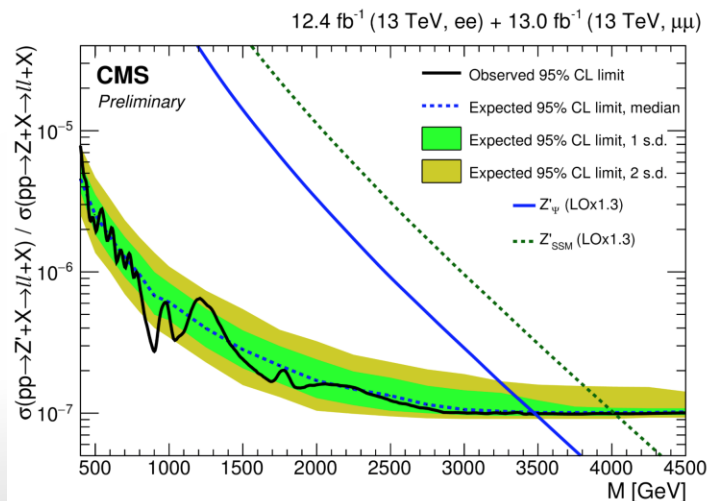
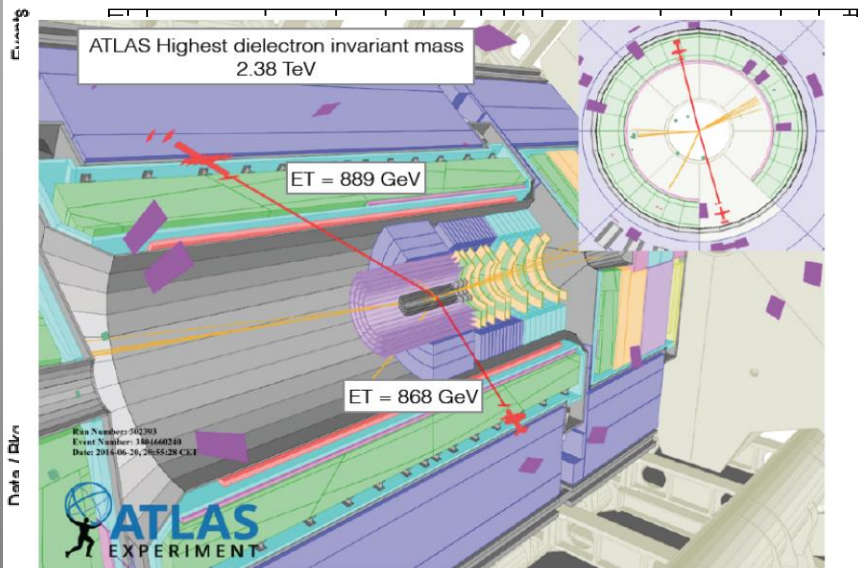
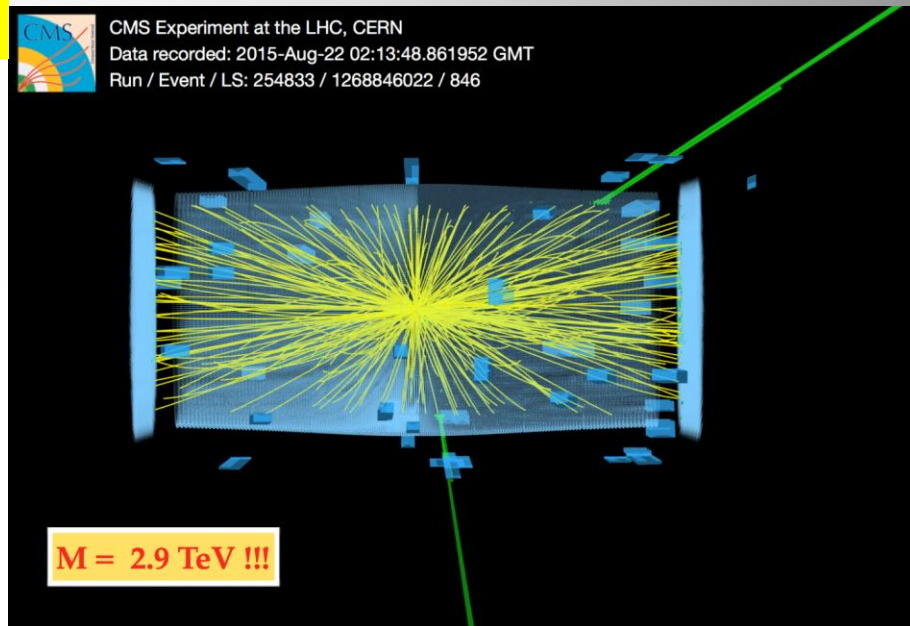
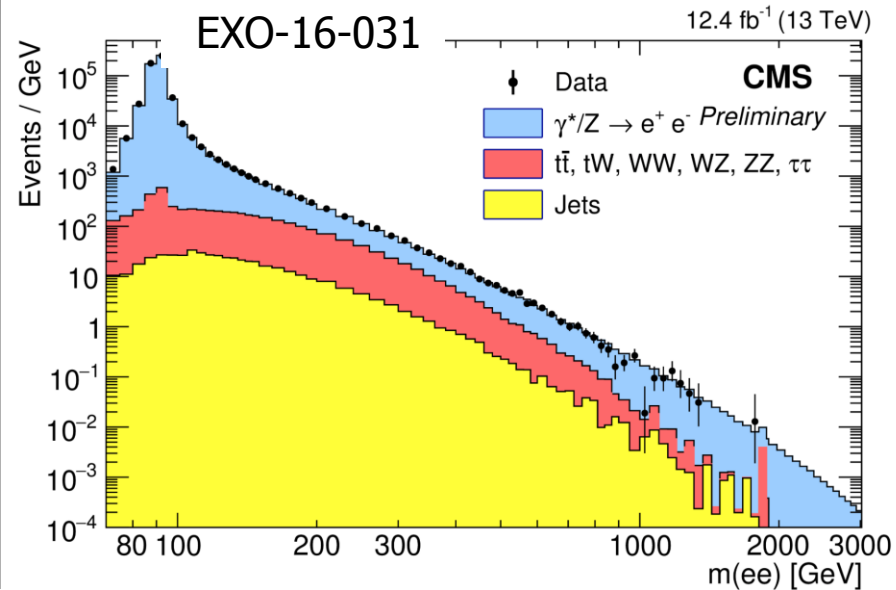


Sequential Standard Model Z' excluded for masses below 2.9 TeV



# Search for New Gauge Bosons

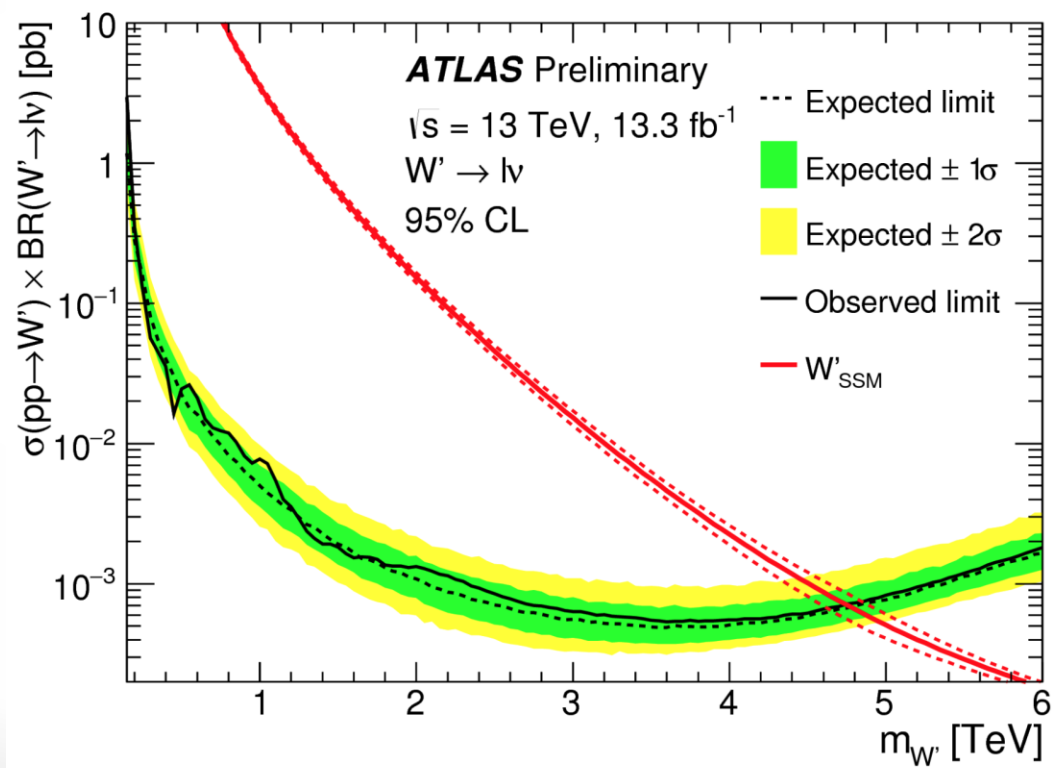
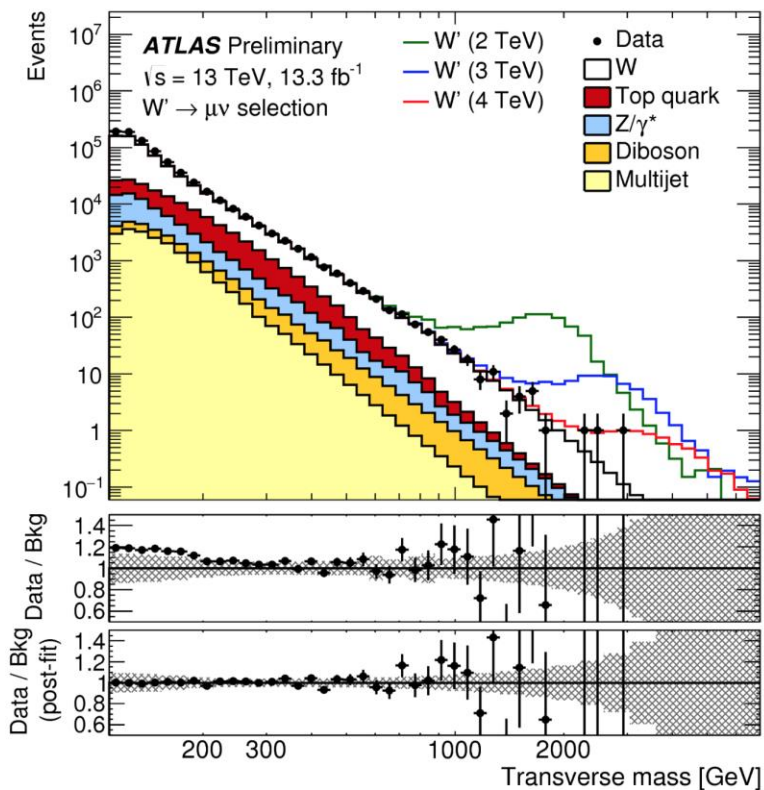
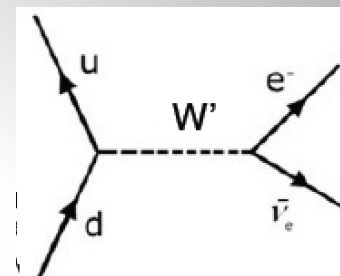
## Search for $Z'$ in dilepton decay channel



SSM  $Z'$  excluded for masses below 4 TeV

# Lepton+MET: Search for $W'$

CONF-16-061

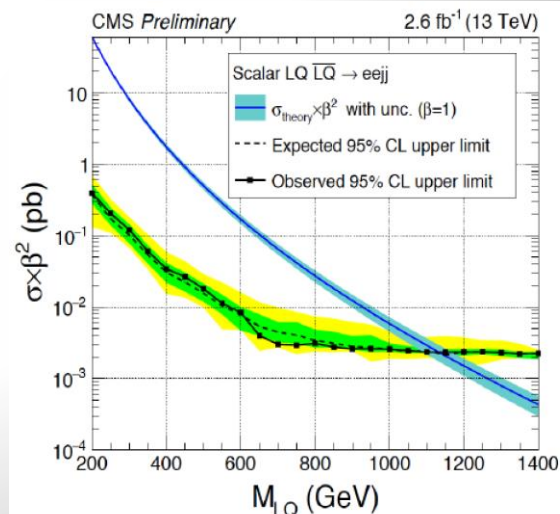
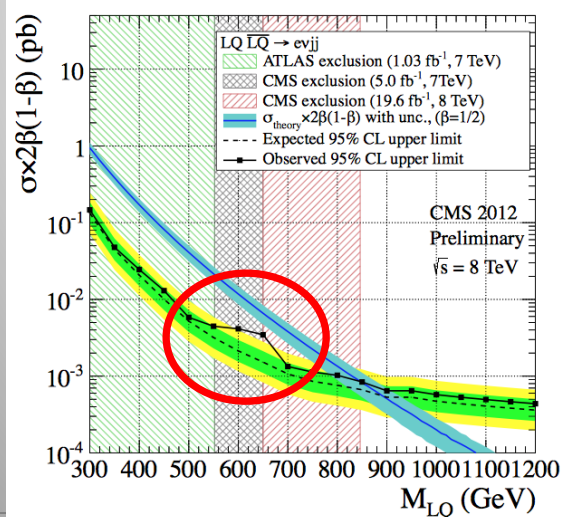
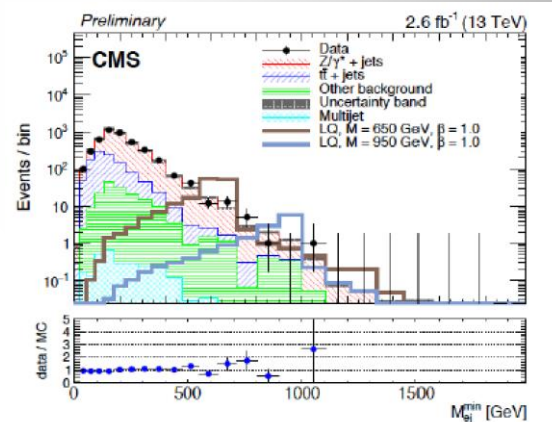
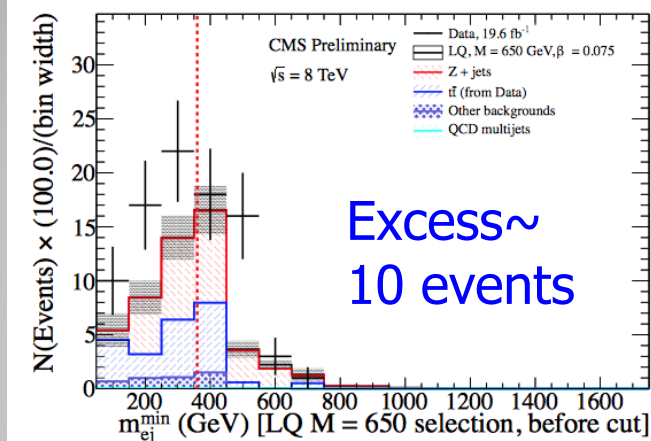


SSM  $W'$  excluded for masses below 4.8 TeV

# Leptoquark LQ->lepton+jet Search

Searches in leptons + jet channels

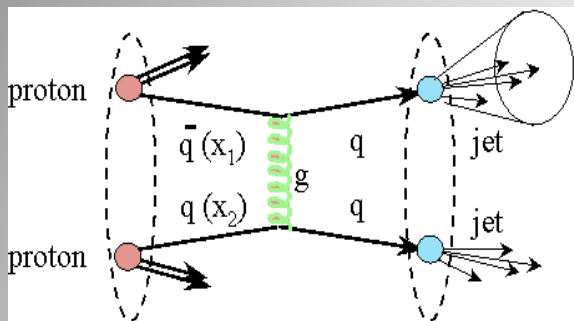
A small enhancement was seen in Run-1 in CMS in the e-jet channel ( $2.6\sigma$ )



New data does not show any deviation from SM expectation.



# Dijet Resonance Search

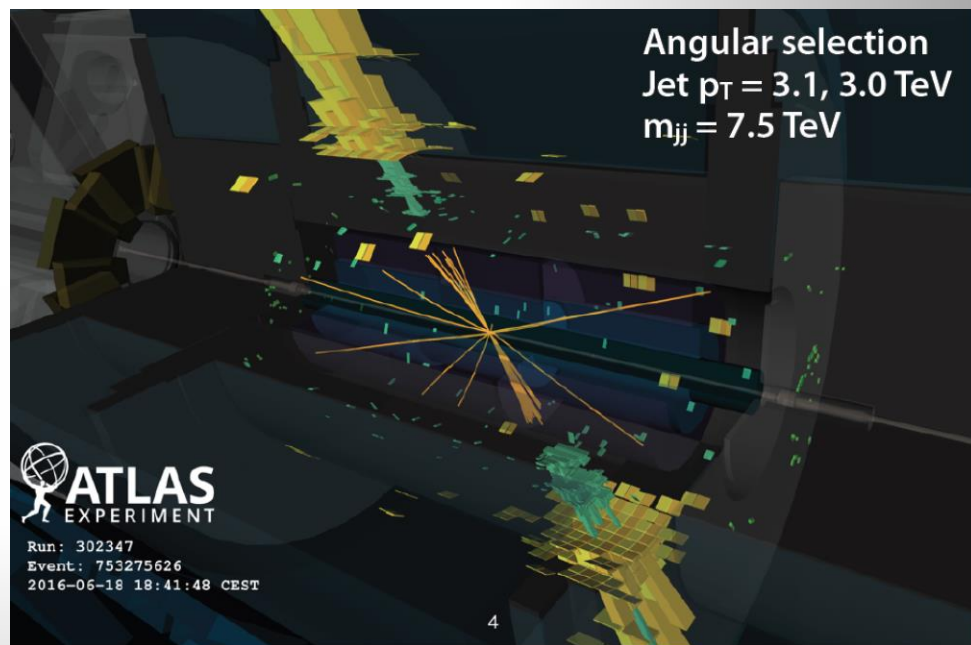
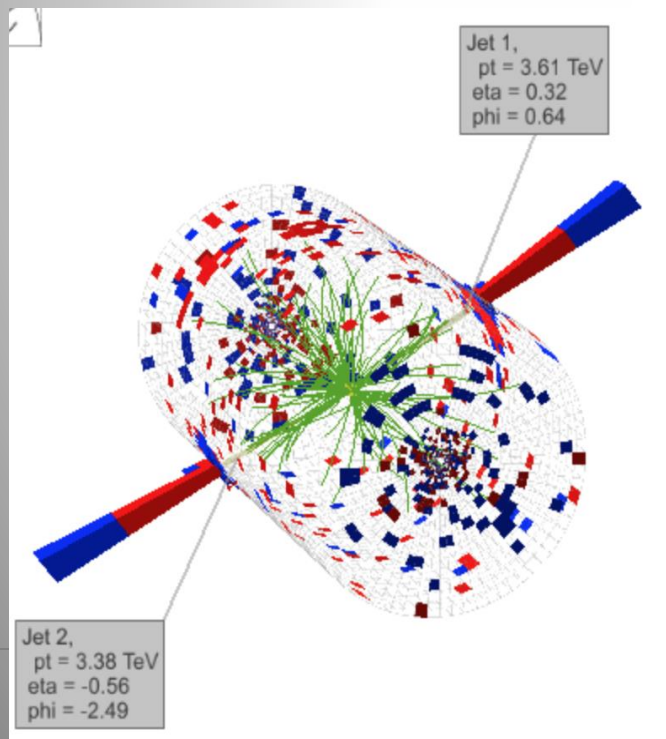


Coloured objects are easy to produce at pp colliders -> **High sensitivity early on**

**The highest mass dijet events recorded so far in Run-2**

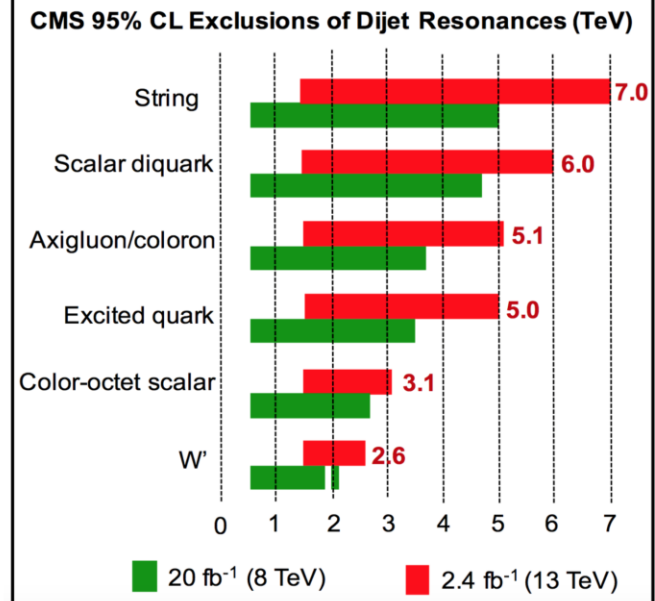
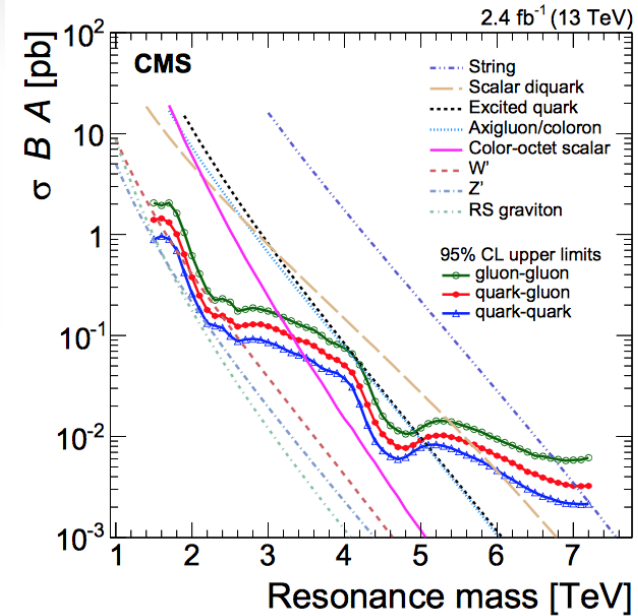
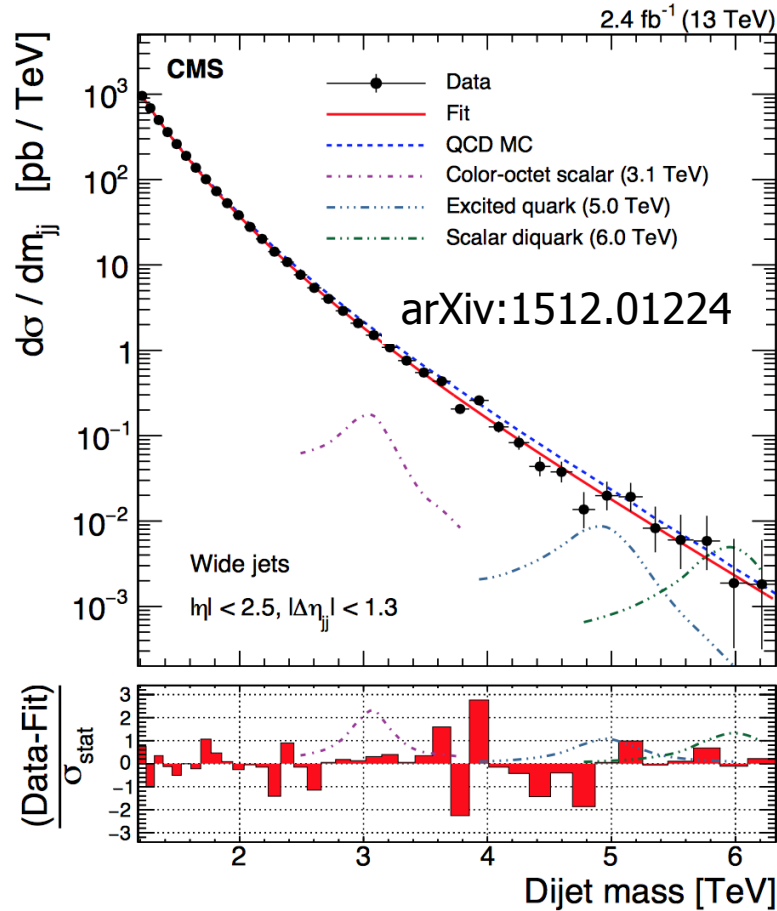
Dijet invariant mass = **7.7 TeV**

Dijet invariant mass = **7.5 TeV**



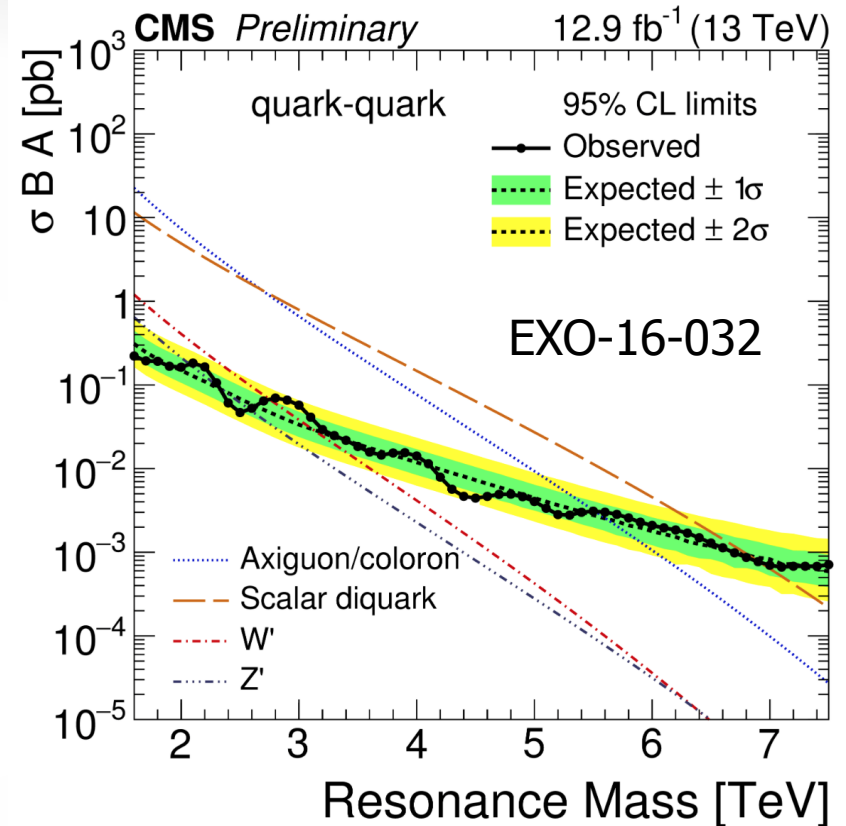
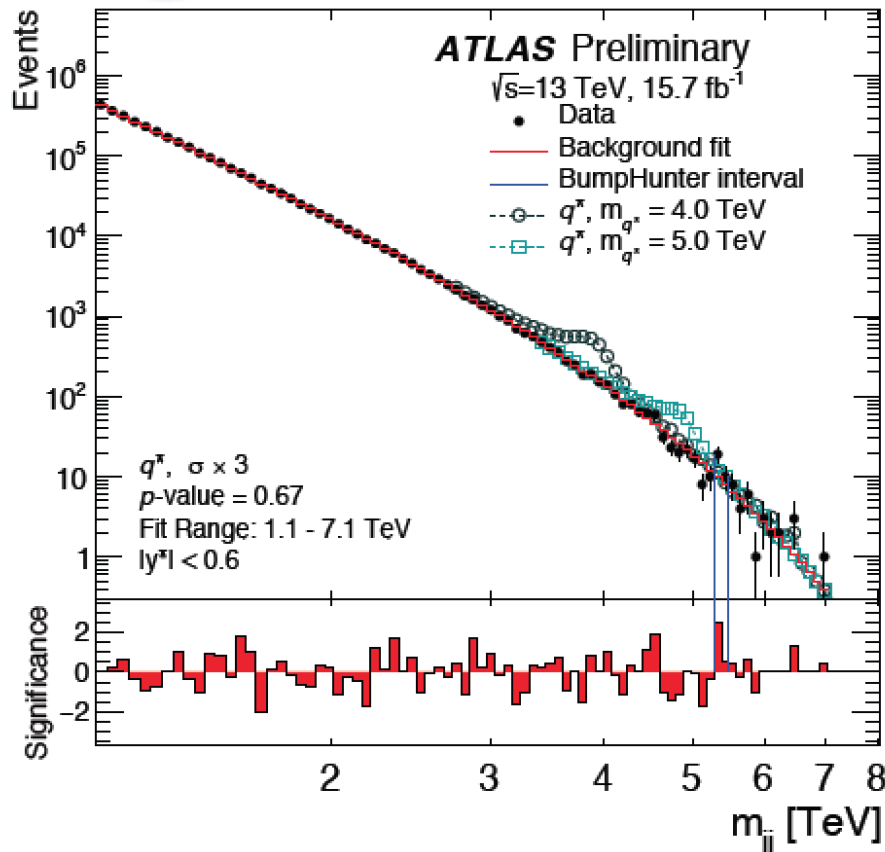


# Early Dijet Searches @ 13 TeV



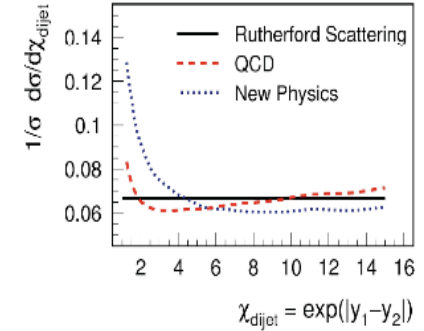
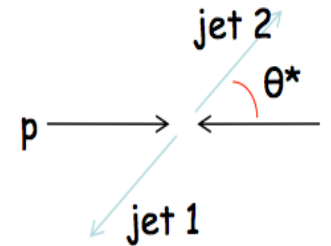
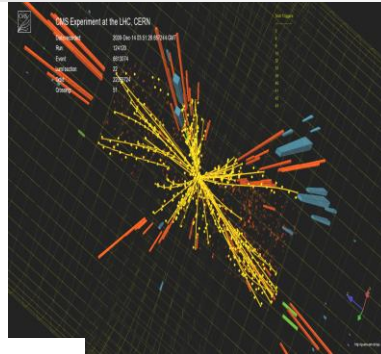
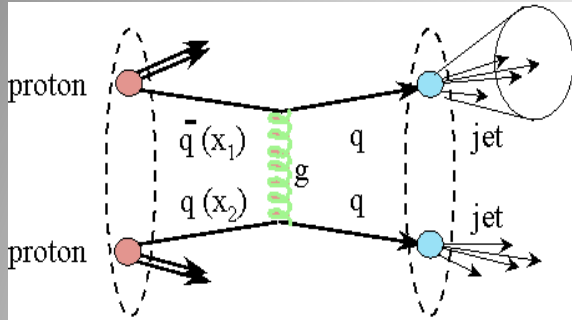
2.4 fb<sup>-1</sup> limits from 13 TeV already surpass the 20 fb<sup>-1</sup> limits from 8 TeV

# Dijet Searches: 13 TeV

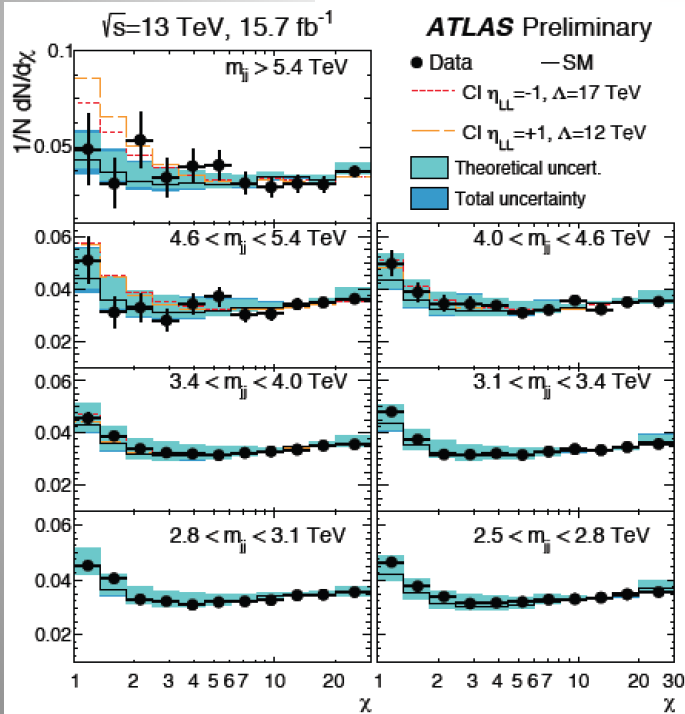


Model	Final State	Observed (expected) mass limit [TeV]		
		$12.9$ fb $^{-1}$ 13 TeV	$2.4$ fb $^{-1}$ 13 TeV	$20$ fb $^{-1}$ 8 TeV
String	qg	7.4 (7.4)	7.0 (6.9)	5.0 (4.9)
Scalar diquark	qq	6.9 (6.8)	6.0 (6.1)	4.7 (4.4)
Axiguon/coloron	q $\bar{q}$	5.5 (5.6)	5.1 (5.1)	3.7 (3.9)
Excited quark	qg	5.4 (5.4)	5.0 (4.8)	3.5 (3.7)
Color-octet scalar ( $k_s^2 = 1/2$ )	gg	3.0 (3.3)	—	—
$W'$	q $\bar{q}$	2.7 (3.1)	2.6 (2.3)	2.2 (2.2)
$Z'$	q $\bar{q}$	2.1 (2.3)	—	1.7 (1.8)
RS Graviton	q $\bar{q}$ , gg	1.9 (1.8)	—	1.6 (1.3)

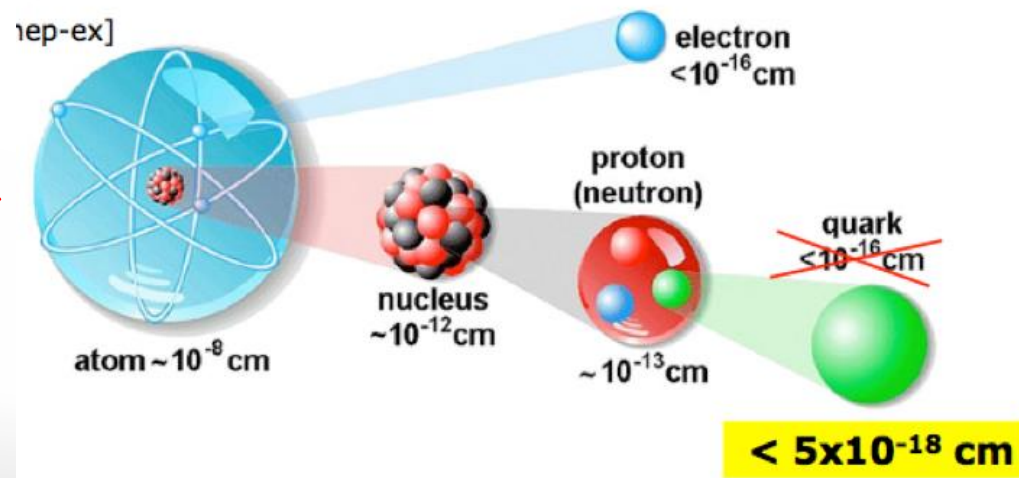
# Are Quarks Elementary Particles?



CONF-2016-069



Measurement of the production angle of the jet with respect to the beam  
 -> High Energy Rutherford Experiment



Quarks remain elementary particles after these first results

# Access to lower mass/scale in dijets

## What about low mass & small couplings

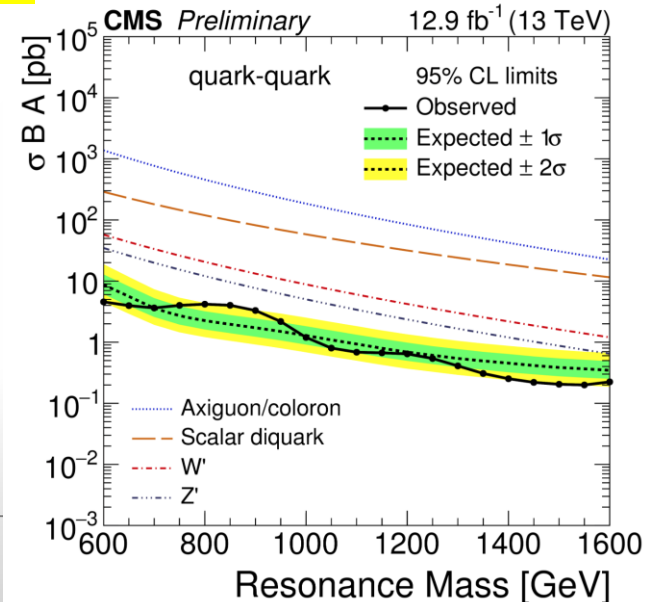
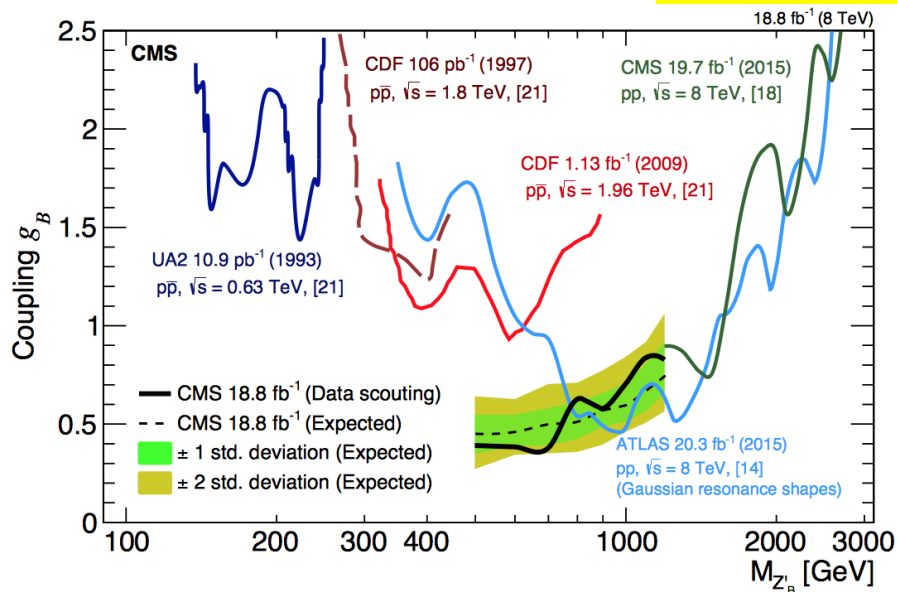
**Problem for dijet triggers:** trigger thresholds lead to data sensitivity that starts around a dijet mass of 1.2 TeV. Problem is the rate/data volume!

**Solution:** Reduce data size per event from 500 kB to 10 kB -> Keep only reconstructed jets at HLT/no raw data! This allows for a 1 kHz extra trigger rate for such data, without affecting the overall data taking (5% correction).  
Trigger used: Sum jet  $p_T > 250$  GeV for jets with  $p_T > 40$  GeV

arXiv:1604.08907

**Data Scouting!**

EXO-16-032

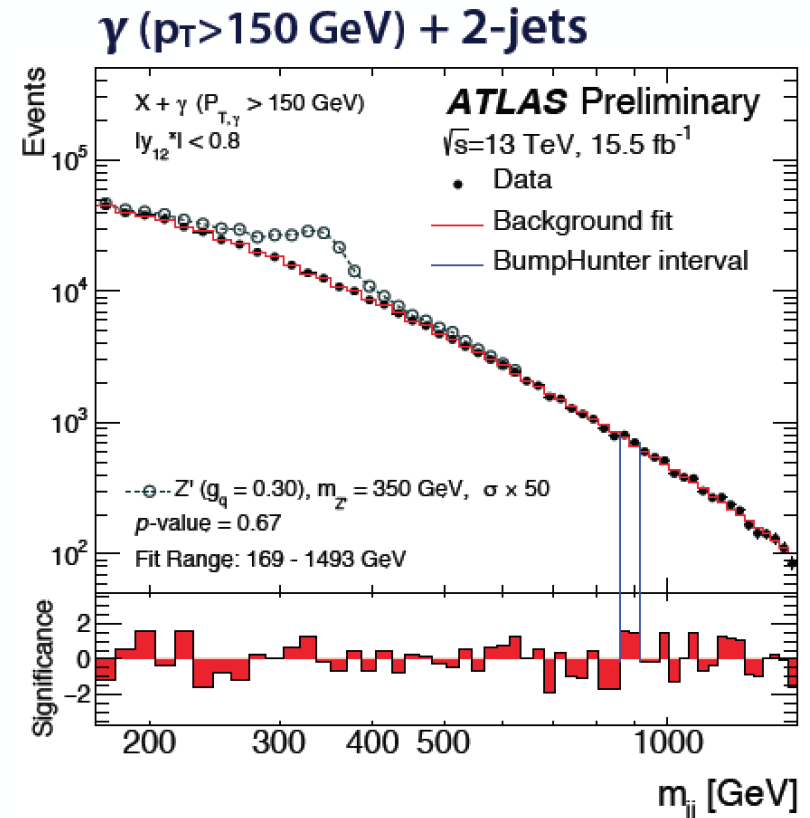
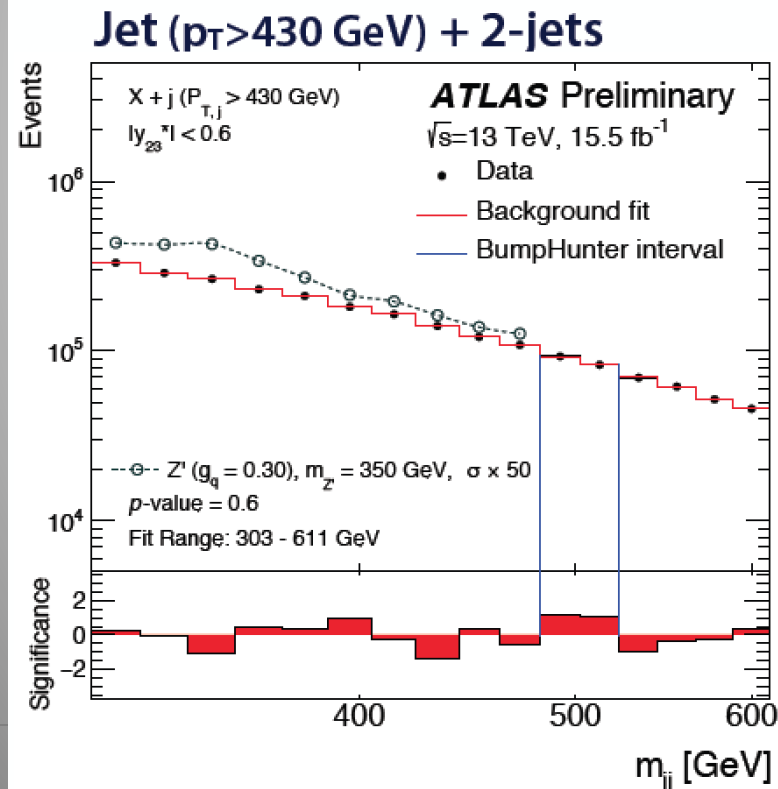
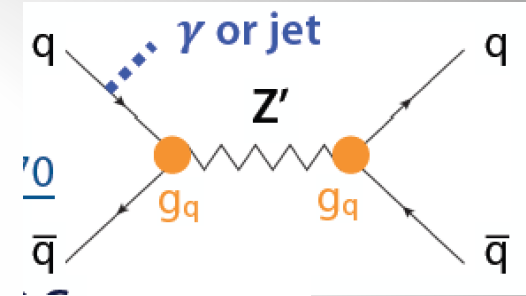




# Access to lower mass/scale in dijets

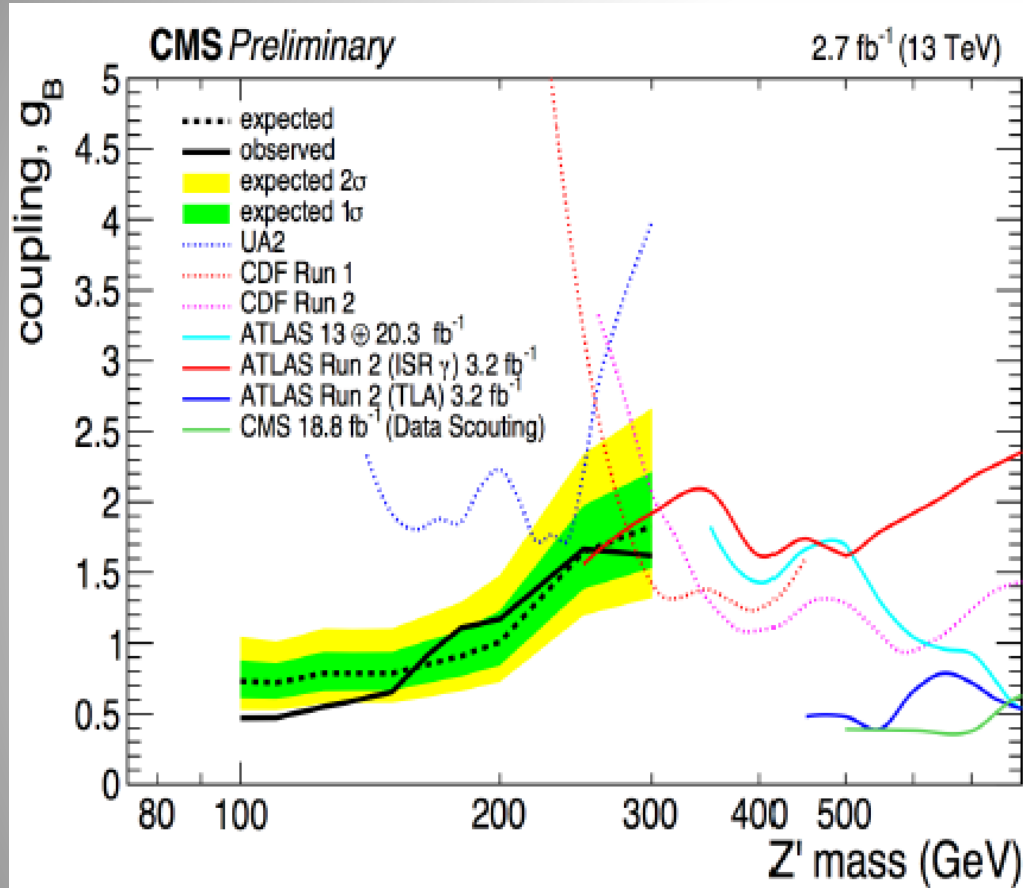
CONF-2016-070

Bump hunting in dijets  
Produced with an ISR  
photon or high  $p_T$  jet  
to give the trigger



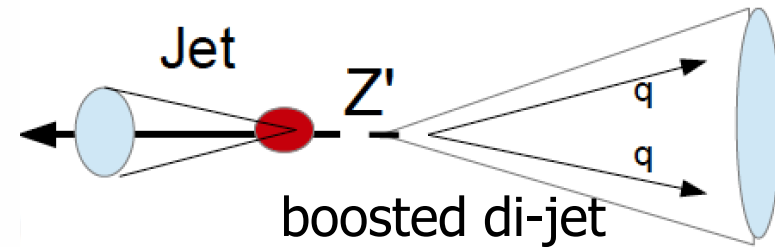
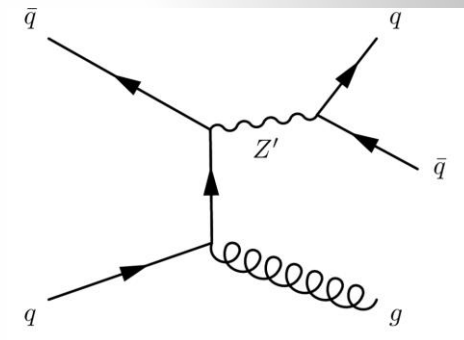
# Access to lower mass/scale in dijets

EXO-16-030



Production of a  $Z'$  with an ISR jet.

- Jet with  $p_T > 350$  GeV
- $H_T > 650/800$  GeV



Sensitivity 'beats' the old UA2 result, going now below 140 GeV

# Search for a 4<sup>th</sup> Generation

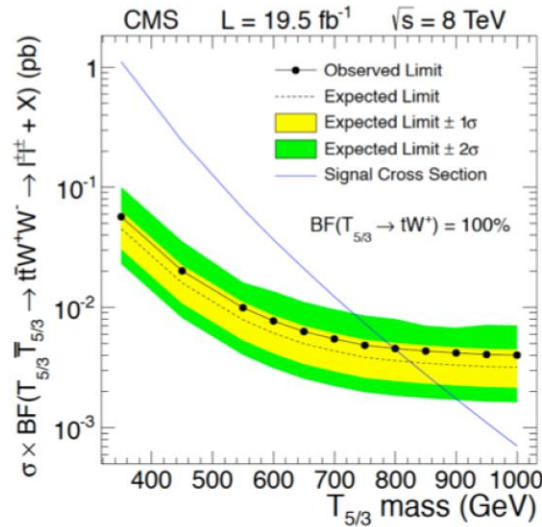
We can't be sure that there are only 3 generations (u,d) (s,c) (b,t)  
A possible new generation should be heavy!  
Look for b' and t' quarks in 2010-2011

No evidence found for a new quark generation for quarks with mass < 550 GeV!

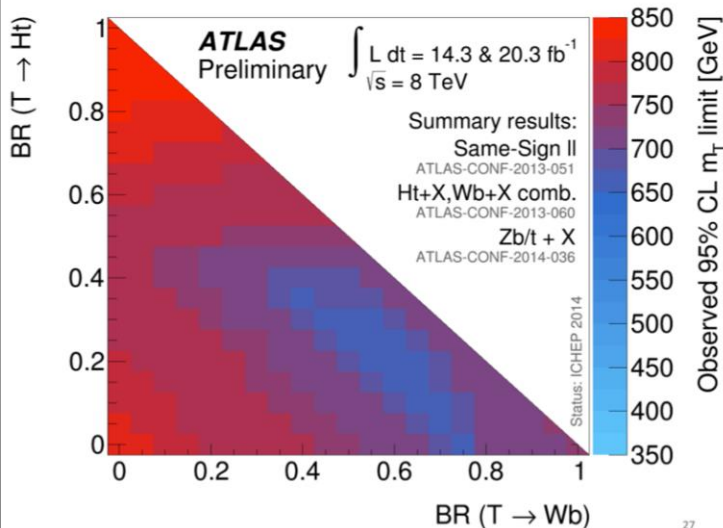
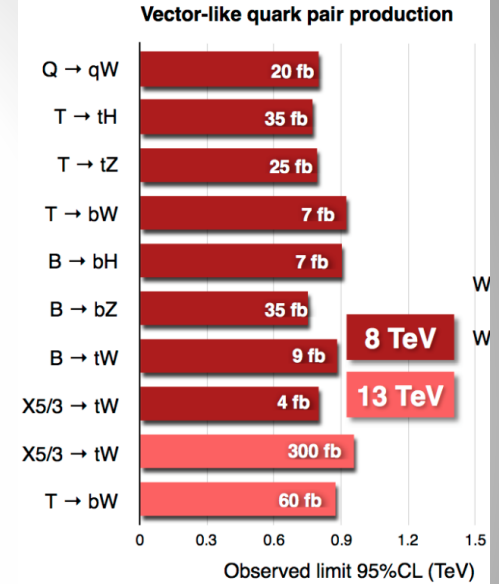
A 4<sup>th</sup> generation would also affect the Higgs rate in a substantial way, so it is unlikely to exist!

# Vector-like Top/Bottom Partner Searches

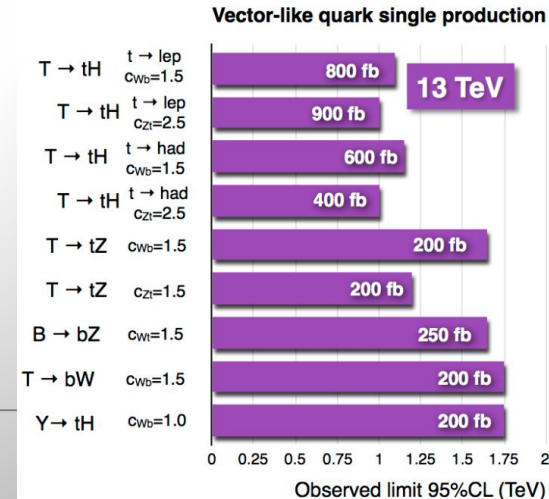
- color-triplet spin-1/2 fermions; L & R components transform the same way under weak isospin



Vector-like quarks  
Relevant eg in  
composite Higgs  
models

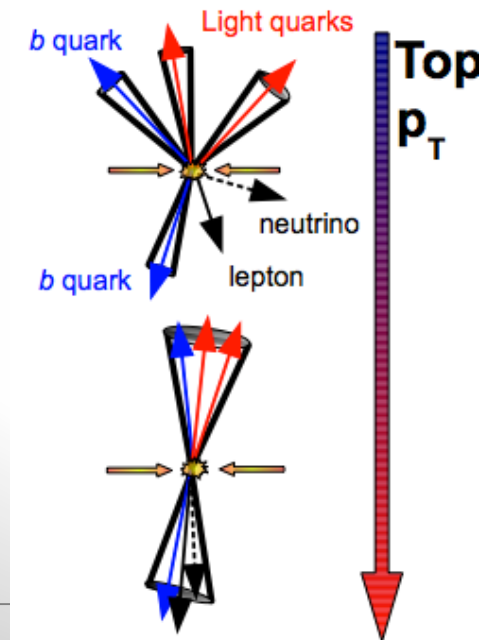


Exclusions up  
to masses of  
800-900 GeV  
And up to 1.75 TeV  
For singly produced  
VLQs





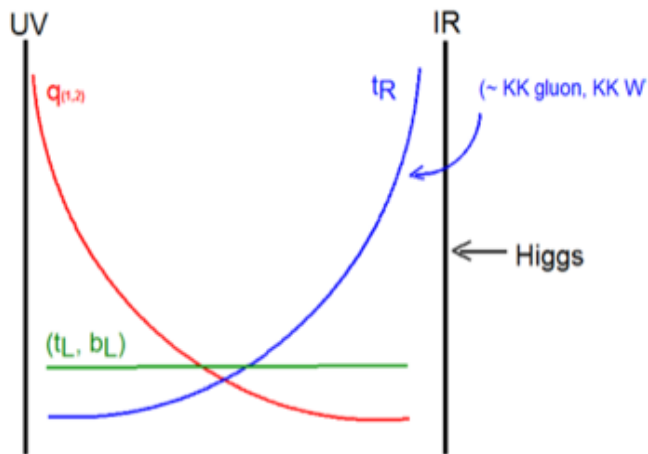
# Searches with Boosted Objects



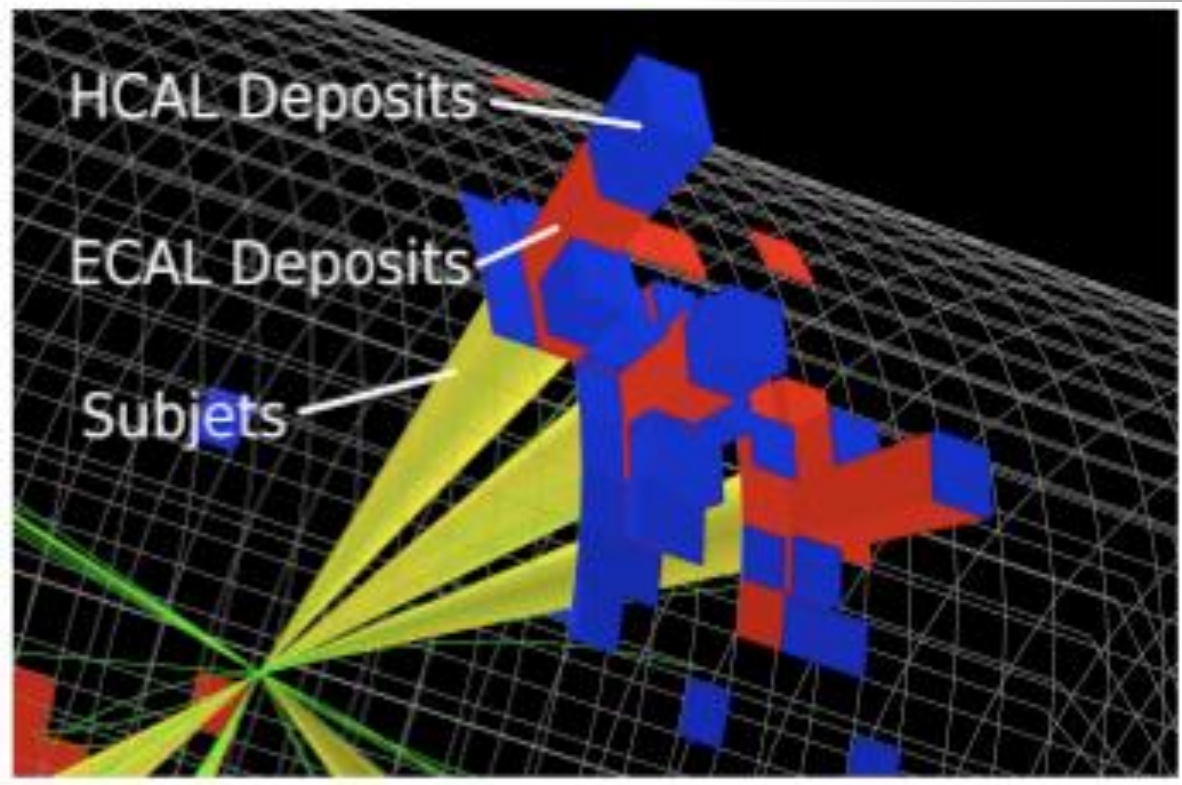
# TeV Resonances into Top Quark Pairs

Recent developments in models: a prominent role of top production  
-light SM fermions live near Planck brane, heavy (top) near TeV brane  
-decay of Randall Sundrum gravitons into top pairs!!

- Eg RS  $\rightarrow$   $t \bar{t}$

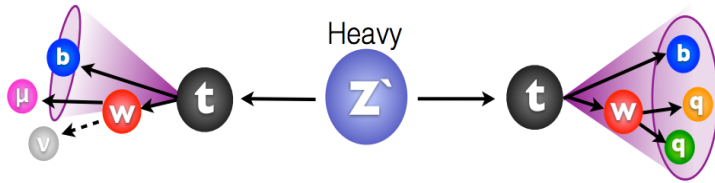


$\Rightarrow$  High  $P_T$  tops



So far no signals found of the kind  $X \rightarrow t\bar{t}$

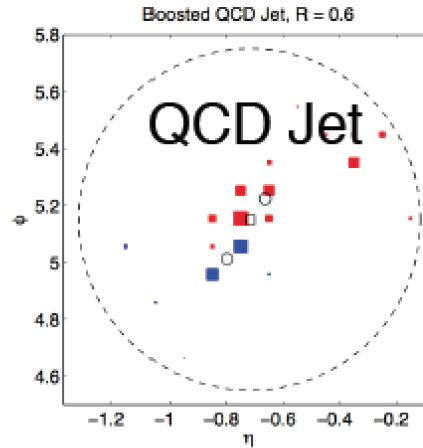
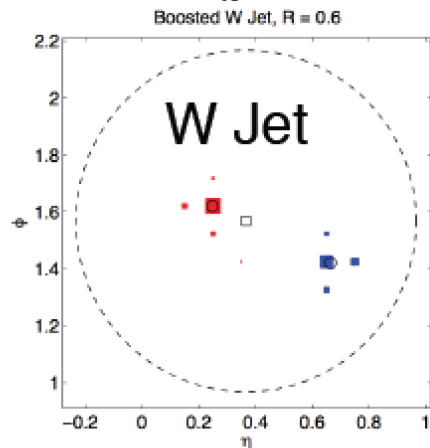
# Searches with Boosted Objects



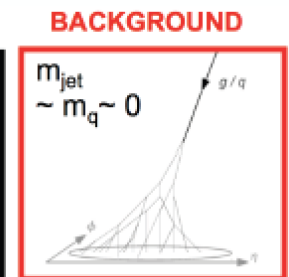
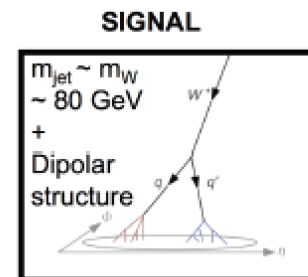
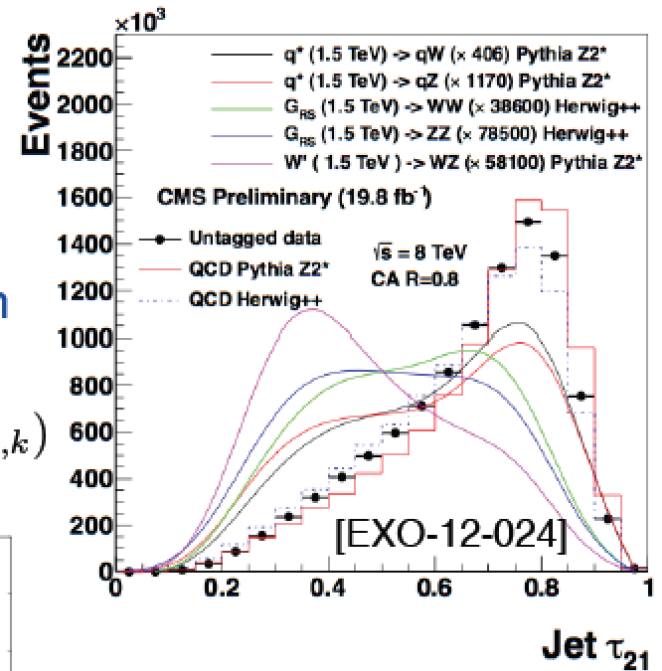
Discussed in topical "Boost Workshops"  
 Last one Zurich 18-22 July 2016  
<https://indico.cern.ch/event/439039/>

- Several different techniques to identify merged jets are on the market...
  - N-subjettiness,  $\tau_N$ , uses  $\tau_{21} = \tau_2 / \tau_1$  as a discriminant to separate QCD jets from merged W/Z jets

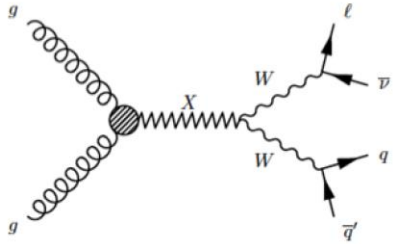
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min(\Delta R_{1,k}, \Delta R_{2,k}, \dots, \Delta R_{N,k})$$



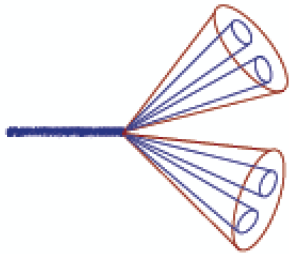
[Thaler, Tilburg, arXiv:1011.2268]



# Resonances Decaying into VV?

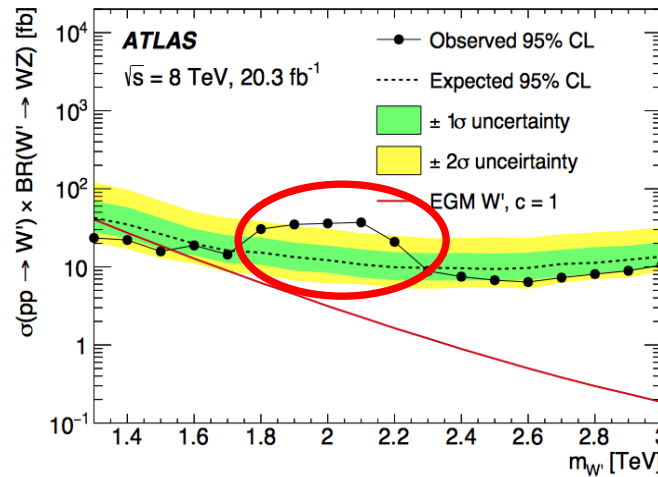


Jets start to merge for  $X = 700-900$  GeV

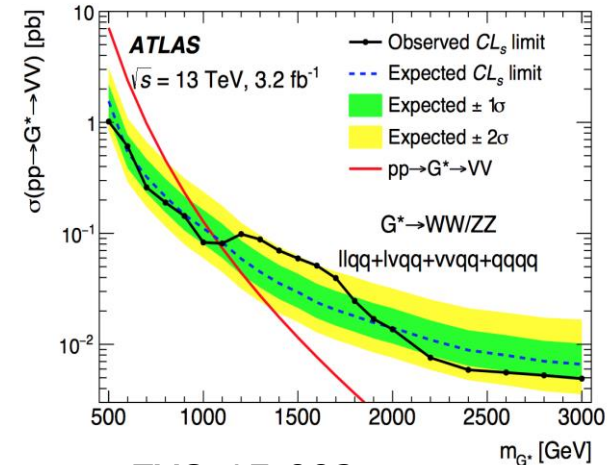


Search for heavy resonances decaying into VV jets using boosted jets and jet substructure analysis

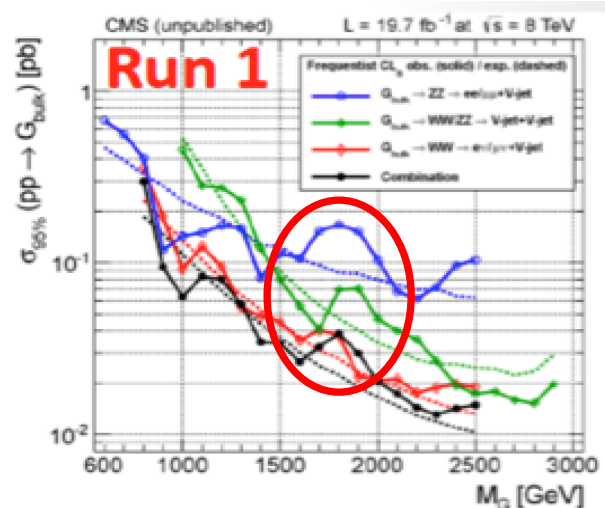
arXiv:1506.00962



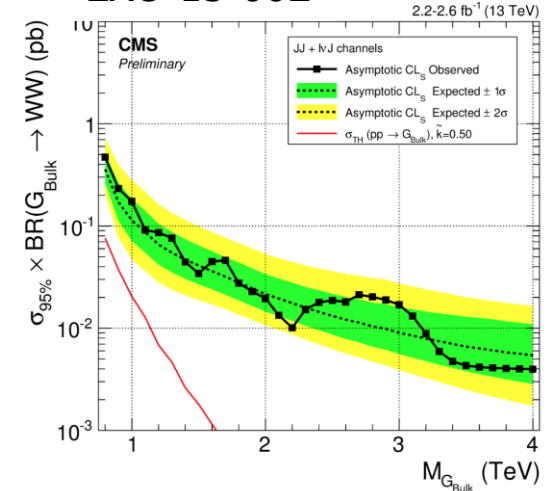
arXiv:1606.04833



arXiv:1405.1994



EXO-15-002



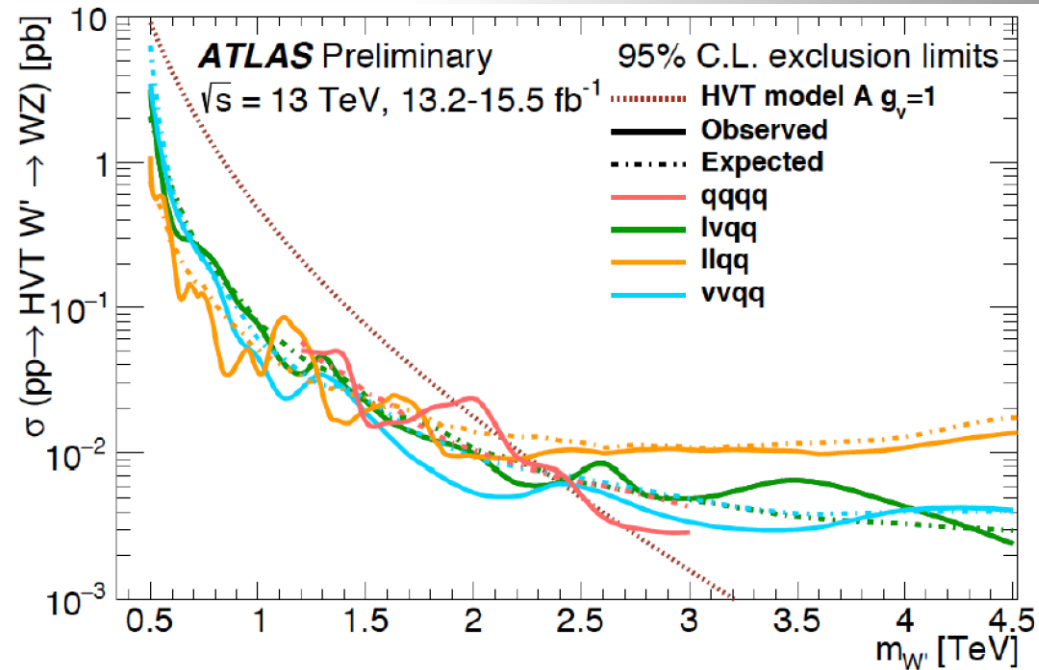
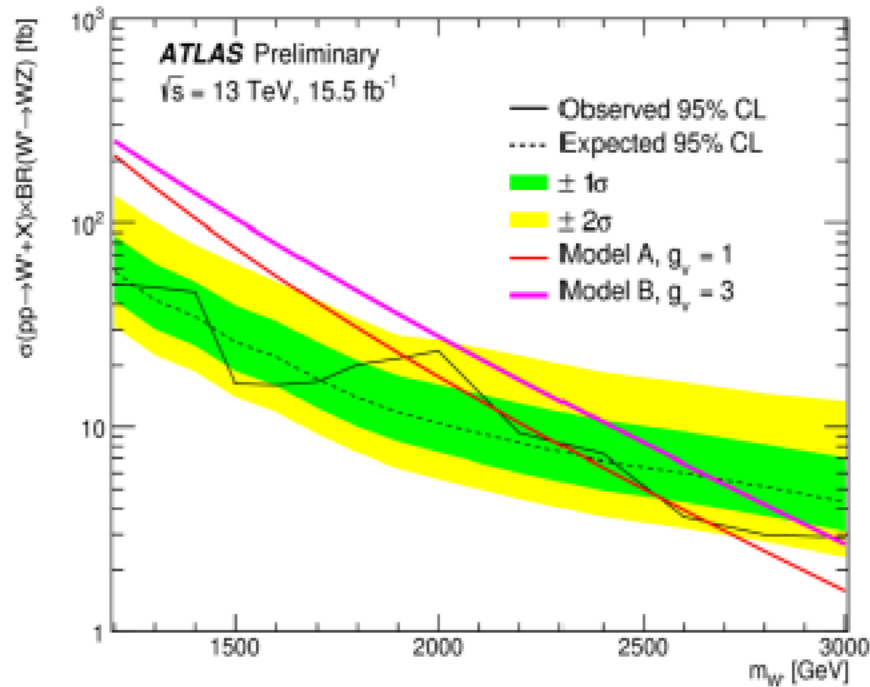
Run-1: Excess in ATLAS in WZ channel of  $3.4\sigma$  ( $2.5\sigma$  with LEE) around 2 TeV.  
 Bump around 1.9 TeV in CMS in different channels ( $\sim 2\sigma$ )

2015 data: Not confirmed  
 more data needed to completely settle the issue



# Diboson Search with the 2016 Data

## WZ -> 4quarks (2jets ) channel



2.0 TeV excess seen at 8 TeV strikes (a little) back? Let's see what happens with more data..

More channels analysed:  $X \rightarrow VV, VH, HH, \gamma\gamma, Z\gamma, \dots$  No striking signals seen

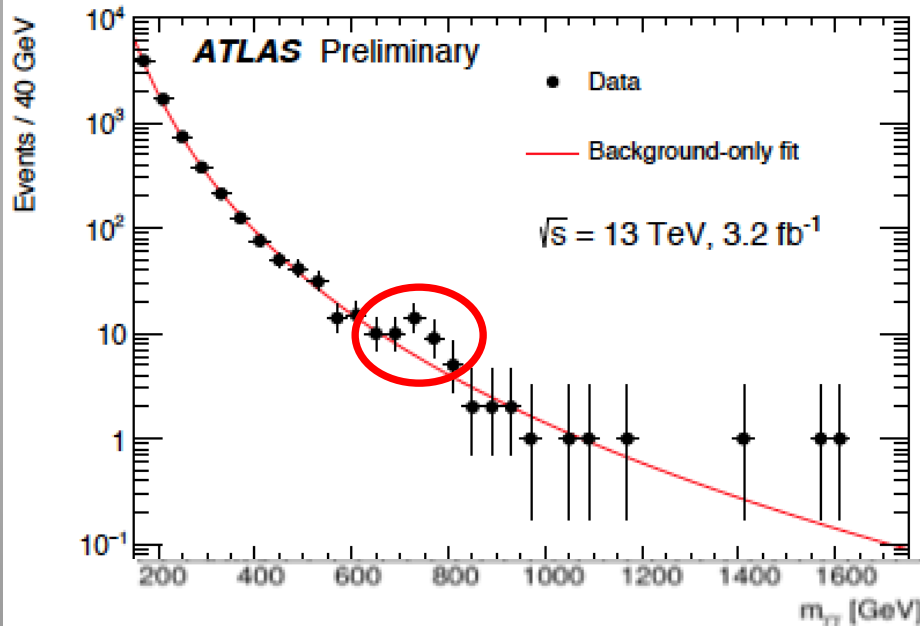
# A new Particle at 750 GeV: $X \rightarrow \gamma\gamma$ ?

Excitement in December 2015

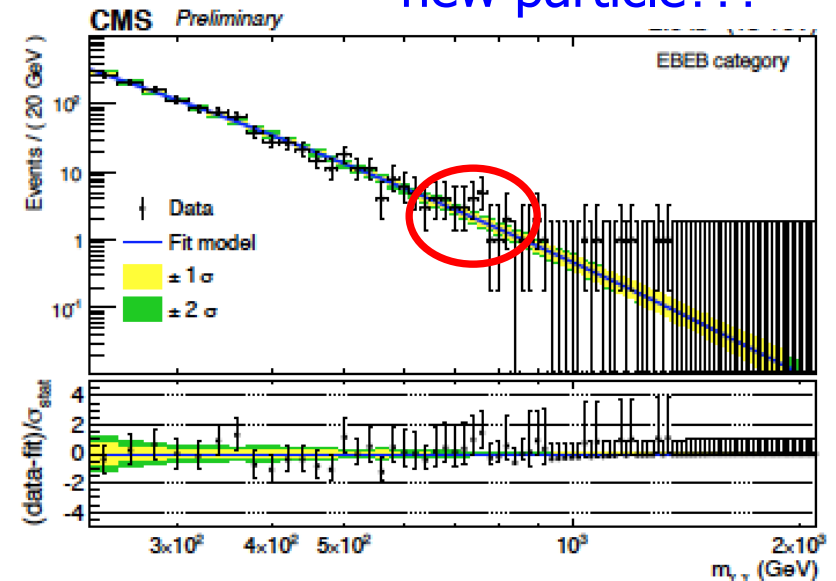
-> Some excitement on an mild observed excess in both experiments for a diphoton mass of around 750 GeV



ATLAS-CONF-2015-081



CMS EXO-15-004



A totally unexpected new particle???

Statistical fluctuation? A new resonance? ???

Moriond: CMS:  $3.4 \sigma$  ! ATLAS up to  $3.9 \sigma$  !! (global significances)

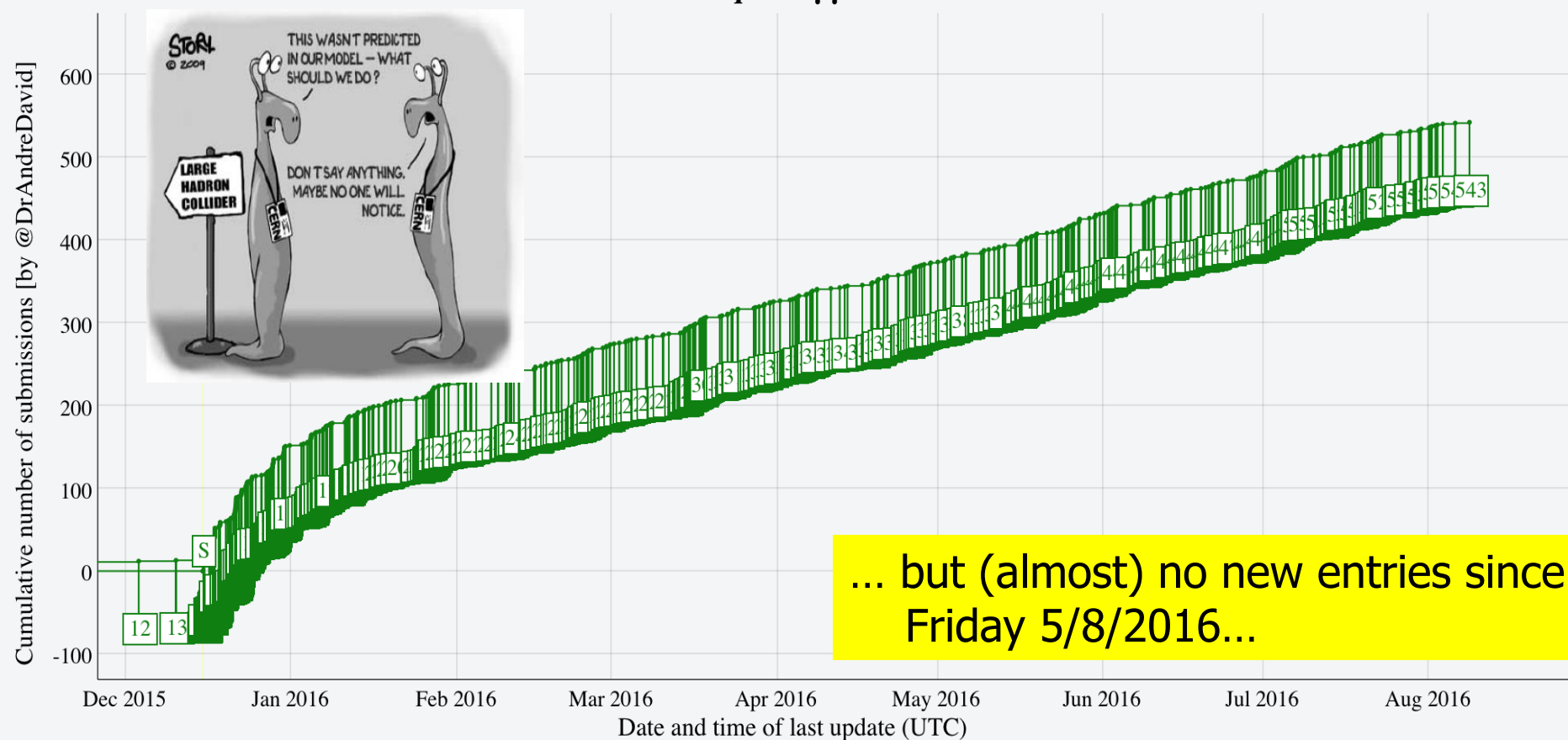
# This triggered >540 papers so far!!

Andre David: <http://jsfiddle.net/adavid/bk2tmc2m/show/>

12/8/2016

Constant rate of 2 papers/ working day!

#Run2Seminar and subsequent  $\gamma\gamma$ -related arXiv submissions

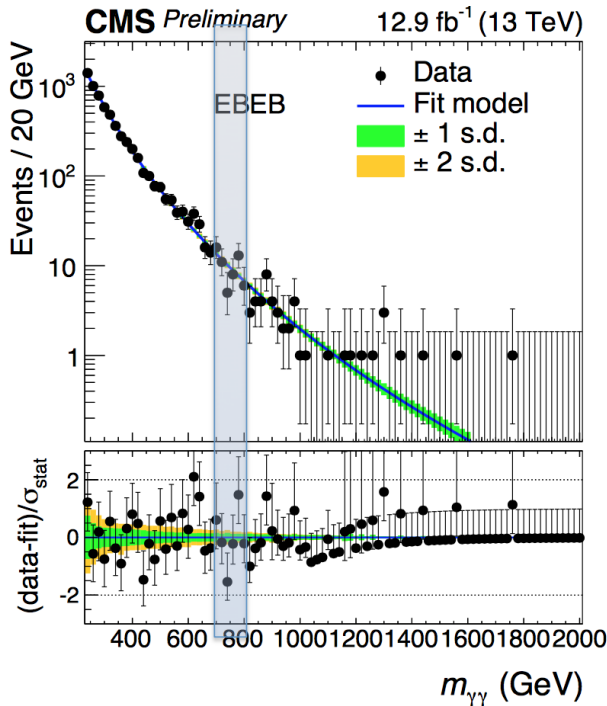


# A new Particle at 750 GeV: $X \rightarrow \gamma\gamma$ ?

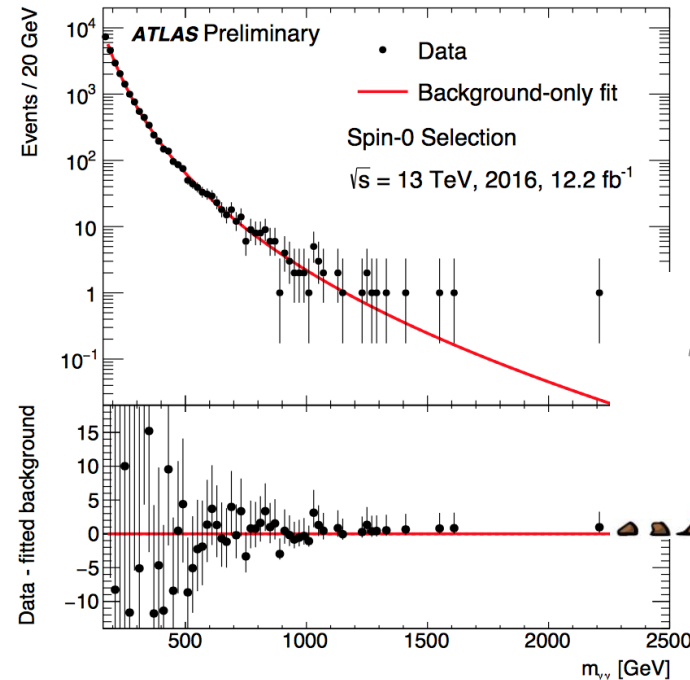
What does the 2016 data say ? (4 x 2015 data!!)

Last Friday  
at ICHEP!!

ATLAS-CONF-2016-059



CMS-EXO-16-027



Spin-0  
analysis



The excess is **NOT** seen in the new data from 2016!

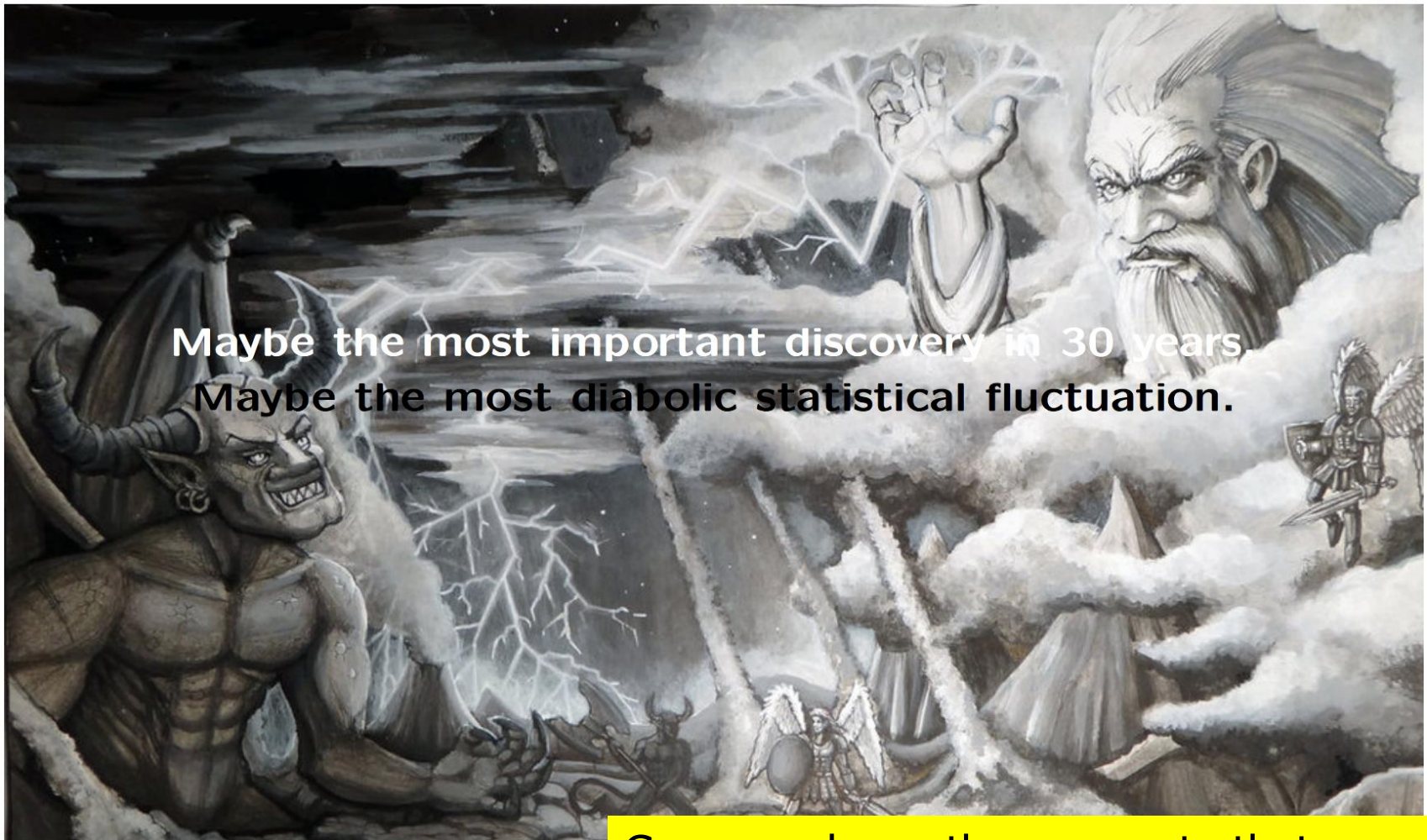
So, not for this time, but a sign of new physics can be found any time now  
We need only one significant deviation of the Standard Model to show the way!



# A New Particle at 750 GeV??

Moriond 2016 summary

A. Strumia



Maybe the most important discovery in 30 years.  
Maybe the most diabolic statistical fluctuation.

Guess we know the answer to that now... 😊

# Exotics Search Summary

## ATLAS Exotics Searches\* - 95% CL Exclusion

Status: August 2016

ATLAS Preliminary

$$\int \mathcal{L} dt = (3.2 - 20.3) \text{ fb}^{-1}$$

$$\sqrt{s} = 8, 13 \text{ TeV}$$

Model	$\ell, \gamma$	Jets <sup>†</sup>	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference	
Extra dimensions	ADD $G_{KK} + g/q$	$\geq 1j$	Yes	3.2	$M_D$ 6.58 TeV	$n = 2$ 1604.07773	
	ADD non-resonant $\ell\ell$	–	–	20.3	$M_S$ 4.7 TeV	$n = 3$ HLZ 1407.2410	
	ADD QBH $\rightarrow \ell q$	$1j$	–	20.3	$M_{\text{th}}$ 5.2 TeV	$n = 6$ 1311.2006	
	ADD QBH	$\geq 2j$	–	15.7	$M_{\text{th}}$ 8.7 TeV	$n = 6$ ATLAS-CONF-2016-069	
	ADD BH high $\sum p_T$	$\geq 1e, \mu$	$\geq 2j$	–	3.2	$M_{\text{th}}$ 8.2 TeV	$n = 6, M_D = 3 \text{ TeV, rot BH}$ 1606.02265
	ADD BH multijet	–	$\geq 3j$	–	3.6	$M_{\text{th}}$ 9.55 TeV	$n = 6, M_D = 3 \text{ TeV, rot BH}$ 1512.02586
	RS1 $G_{KK} \rightarrow \ell\ell$	$2e, \mu$	–	–	20.3	$G_{KK} \text{ mass}$ 2.68 TeV	$k/\bar{M}_{Pl} = 0.1$ 1405.4123
	RS1 $G_{KK} \rightarrow \gamma\gamma$	$2\gamma$	–	–	3.2	$G_{KK} \text{ mass}$ 3.2 TeV	$k/\bar{M}_{Pl} = 0.1$ 1606.03833
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$	$1e, \mu$	$1J$	Yes	13.2	$G_{KK} \text{ mass}$ 1.24 TeV	$k/\bar{M}_{Pl} = 1.0$ ATLAS-CONF-2016-062
	Bulk RS $G_{KK} \rightarrow HH \rightarrow bbbb$	–	$4b$	–	13.3	$G_{KK} \text{ mass}$ 360-860 GeV	$k/\bar{M}_{Pl} = 1.0$ ATLAS-CONF-2016-049
Bulk RS $g_{KK} \rightarrow tt$	$1e, \mu$	$\geq 1b, \geq 1J/2j$	Yes	20.3	$g_{KK} \text{ mass}$ 2.2 TeV	BR = 0.925 1505.07018	
2UED / RPP	$1e, \mu$	$\geq 2b, \geq 4j$	Yes	3.2	KK mass 1.46 TeV	Tier (1,1), BR( $A^{(1,1)} \rightarrow tt$ ) = 1 ATLAS-CONF-2016-013	
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	–	–	13.3	$Z'$ mass 4.05 TeV	ATLAS-CONF-2016-045	
	SSM $Z' \rightarrow \tau\tau$	–	–	19.5	$Z'$ mass 2.02 TeV	1502.07177	
	Leptophobic $Z' \rightarrow bb$	–	$2b$	–	3.2	$Z'$ mass 1.5 TeV	1603.08791
	SSM $W' \rightarrow \ell\nu$	$1e, \mu$	–	Yes	13.3	$W'$ mass 4.74 TeV	ATLAS-CONF-2016-061
	HVT $W' \rightarrow WZ \rightarrow qq\nu\nu$ model A	$0e, \mu$	$1J$	Yes	13.2	$W'$ mass 2.4 TeV	$g_V = 1$ ATLAS-CONF-2016-082
	HVT $W' \rightarrow WZ \rightarrow qqqq$ model B	–	$2J$	–	15.5	$W'$ mass 3.0 TeV	$g_V = 3$ ATLAS-CONF-2016-055
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	–	–	3.2	$V'$ mass 2.31 TeV	1607.05621
LRSM $W_R^+ \rightarrow tb$	$1e, \mu$	$2b, 0-1j$	Yes	20.3	$W'$ mass 1.92 TeV	1410.4103	
LRSM $W_R^0 \rightarrow tb$	$0e, \mu$	$\geq 1b, 1J$	–	20.3	$W'$ mass 1.76 TeV	1408.0886	
CI	CI $qqqq$	–	$2j$	–	15.7	$\Lambda$ 19.9 TeV $\eta_{LL} = -1$	ATLAS-CONF-2016-069
	CI $\ell\ell qq$	$2e, \mu$	–	–	3.2	$\Lambda$ 25.2 TeV $\eta_{LL} = -1$	1607.03669
	CI $uutt$	$2(SS) \geq 3e, \mu \geq 1b, \geq 1j$	Yes	20.3	$\Lambda$ 4.9 TeV	$ C_{HH}  = 1$ 1504.04605	
DM	Axial-vector mediator (Dirac DM)	$0e, \mu$	$\geq 1j$	Yes	3.2	$m_A$ 1.0 TeV	$g_a = 0.25, g_s = 1.0, m(\chi) < 250 \text{ GeV}$ 1604.07773
	Axial-vector mediator (Dirac DM)	$0e, \mu, 1\gamma$	$1j$	Yes	3.2	$m_A$ 710 GeV	$g_a = 0.25, g_s = 1.0, m(\chi) < 150 \text{ GeV}$ 1604.01306
	ZZ $\chi\chi$ EFT (Dirac DM)	$0e, \mu, 1J, \leq 1j$	Yes	3.2	$M_\chi$ 550 GeV	$m(\chi) < 150 \text{ GeV}$ ATLAS-CONF-2015-080	
LQ	Scalar LQ 1 <sup>st</sup> gen	$2e$	$\geq 2j$	–	3.2	LQ mass 1.1 TeV	$\beta = 1$ 1605.06035
	Scalar LQ 2 <sup>nd</sup> gen	$2\mu$	$\geq 2j$	–	3.2	LQ mass 1.05 TeV	$\beta = 1$ 1605.06035
	Scalar LQ 3 <sup>rd</sup> gen	$1e, \mu$	$\geq 1b, \geq 3j$	Yes	20.3	LQ mass 640 GeV	$\beta = 0$ 1508.04735
Heavy quarks	VLQ $TT \rightarrow Ht + X$	$1e, \mu$	$\geq 2b, \geq 3j$	Yes	20.3	T mass 855 GeV	T in (T,B) doublet 1505.04306
	VLQ $YY \rightarrow Wb + X$	$1e, \mu$	$\geq 1b, \geq 3j$	Yes	20.3	Y mass 770 GeV	Y in (B,Y) doublet 1505.04306
	VLQ $BB \rightarrow Hb + X$	$1e, \mu$	$\geq 2b, \geq 3j$	Yes	20.3	B mass 735 GeV	isospin singlet 1505.04306
	VLQ $BB \rightarrow Zb + X$	$2/2 \geq 3e, \mu$	$\geq 2/2 \geq 1b$	–	20.3	B mass 735 GeV	B in (B,Y) doublet 1409.5500
	VLQ $QQ \rightarrow WqWq$	$1e, \mu$	$\geq 4j$	Yes	20.3	Q mass 690 GeV	1509.04261
	VLQ $T_{5/3} T_{5/3} \rightarrow WtWt$	$2(SS) \geq 3e, \mu \geq 1b, \geq 1j$	Yes	3.2	$T_{5/3} \text{ mass}$ 990 GeV	ATLAS-CONF-2016-032	
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	$1\gamma$	$1j$	–	3.2	$q^* \text{ mass}$ 4.4 TeV	only $u^*$ and $d^*$ , $\Lambda = m(q^*)$ 1512.05910
	Excited quark $q^* \rightarrow qg$	–	$2j$	–	15.7	$q^* \text{ mass}$ 5.6 TeV	only $u^*$ and $d^*$ , $\Lambda = m(q^*)$ ATLAS-CONF-2016-069
	Excited quark $b^* \rightarrow bg$	–	$1b, 1j$	–	8.8	$b^* \text{ mass}$ 2.3 TeV	ATLAS-CONF-2016-060
	Excited quark $b^* \rightarrow Wt$	$1 \text{ or } 2e, \mu$	$1b, 2-0j$	Yes	20.3	$b^* \text{ mass}$ 1.5 TeV	$f_g = f_t = f_b = 1$ 1510.02664
	Excited lepton $\ell^*$	$3e, \mu$	–	–	20.3	$\ell^* \text{ mass}$ 3.0 TeV	$\Lambda = 3.0 \text{ TeV}$ 1411.2921
	Excited lepton $\nu^*$	$3e, \mu, \tau$	–	–	20.3	$\nu^* \text{ mass}$ 1.6 TeV	$\Lambda = 1.6 \text{ TeV}$ 1411.2921
	Other	LSTC $a_T \rightarrow W\gamma$	$1e, \mu, 1\gamma$	–	Yes	20.3	$a_T \text{ mass}$ 960 GeV
LRSM Majorana $\nu$		$2e, \mu$	$2j$	–	20.3	$N^0 \text{ mass}$ 2.0 TeV	$m(W_R) = 2.4 \text{ TeV, no mixing}$ 1506.06020
Higgs triplet $H^{\pm\pm} \rightarrow ee$		$2e$ (SS)	–	–	13.9	$H^{\pm\pm} \text{ mass}$ 570 GeV	DY production, BR( $H^{\pm\pm} \rightarrow ee$ )=1 ATLAS-CONF-2016-051
Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$		$3e, \mu, \tau$	–	–	20.3	$H^{\pm\pm} \text{ mass}$ 400 GeV	DY production, BR( $H^{\pm\pm} \rightarrow \ell\tau$ )=1 1411.2921
Monopole (non-res prod)		$1e, \mu$	$1b$	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$ 1410.5404
Multi-charged particles		–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $ q  = 5e$ 1504.04188
Magnetic monopoles		–	–	–	7.0	monopole mass 1.34 TeV	DY production, $ g  = 1g_D, \text{ spin } 1/2$ 1509.08059

$\sqrt{s} = 8 \text{ TeV}$

$\sqrt{s} = 13 \text{ TeV}$

$10^{-1}$

1

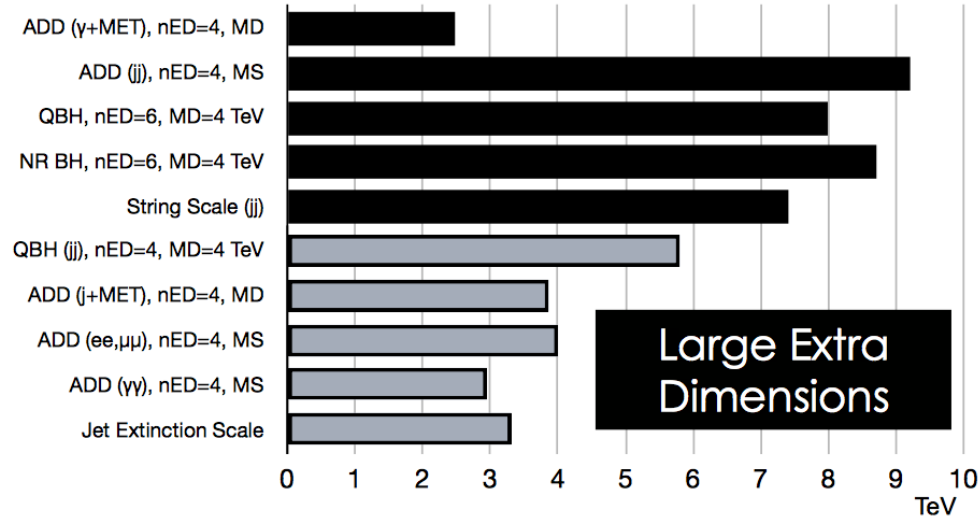
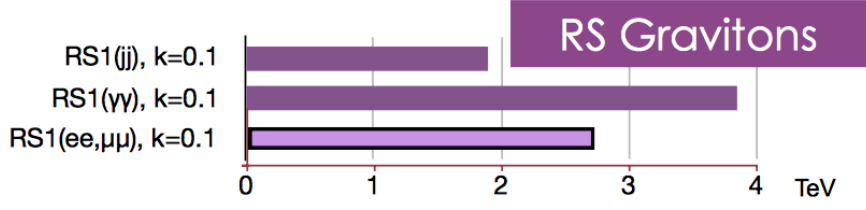
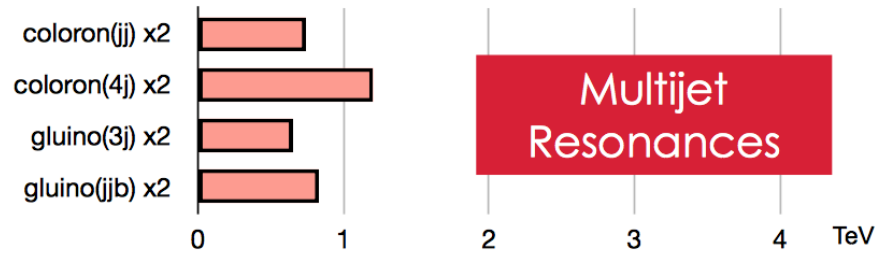
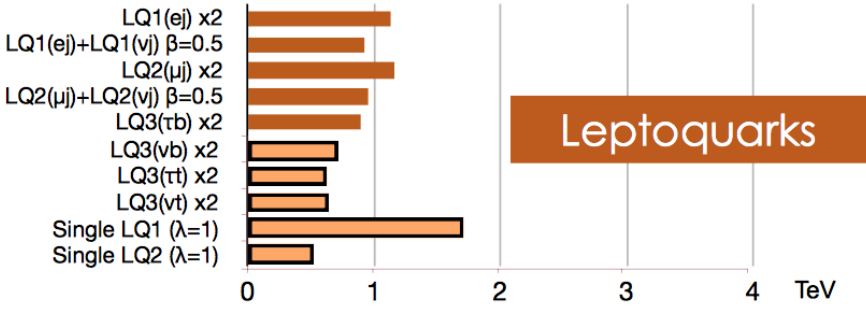
10

Mass scale [TeV]

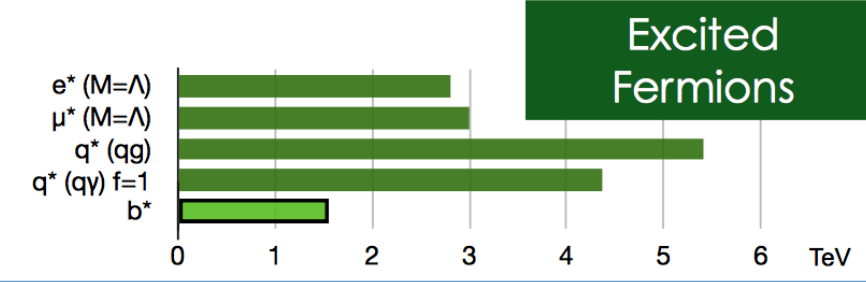
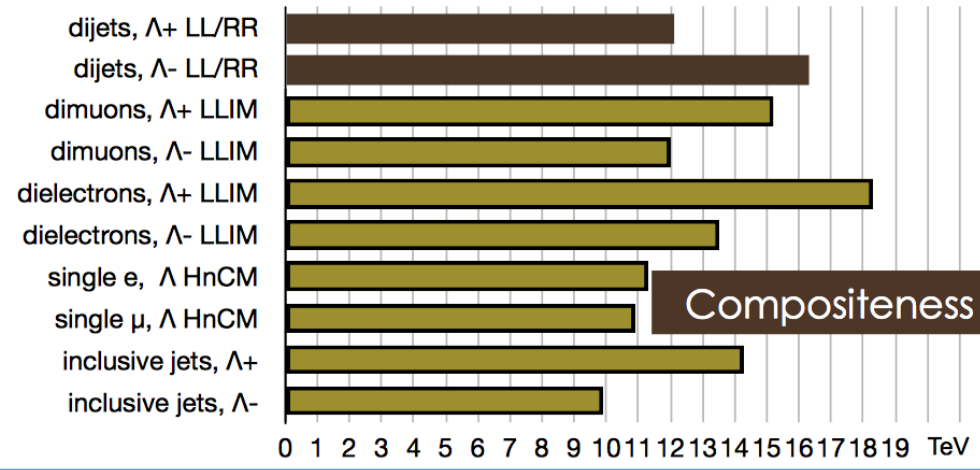
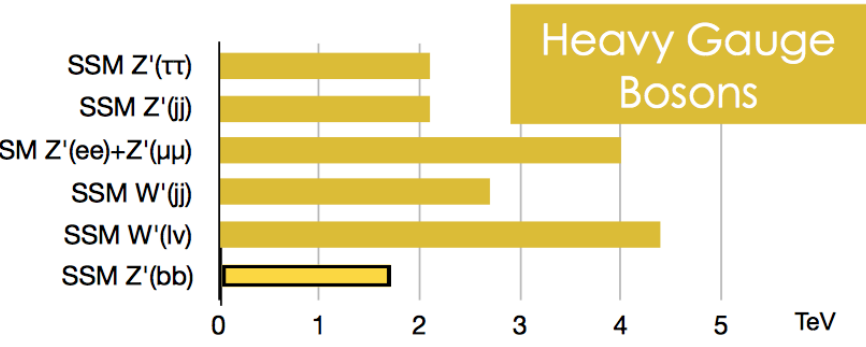
\*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

†Small-radius (large-radius) jets are denoted by the letter j (J).

13 TeV 8 TeV



# CMS Preliminary



# Summary

- Searches at 13 TeV cover quickly new ground.
- So far no exotica/ non-susy smoking guns. The 750 GeV bump was not confirmed in the 2016 data sample analysed up to ICHEP. The VV decay channel does not show a clear excess in Run-2. Some other enhancements from run-1 (eg in the LQ channel) not confirmed.
  - Contact Interaction **energy**: 25.2 TeV
  - ADD BH **mass**: 9.55 TeV
  - W' **mass**: 4.74 TeV
  - Dark photon **lifetime**: 2.5~100 mm (dark photon 400 MeV)
  - **Magnetic charge**:  $|g| > 1.5g_D$  (up to 4  $g_D$ )
- Let's look at Supersymmetry next

S.C. Hsu ICHEP 2016

End of Lecture I



**Backup**