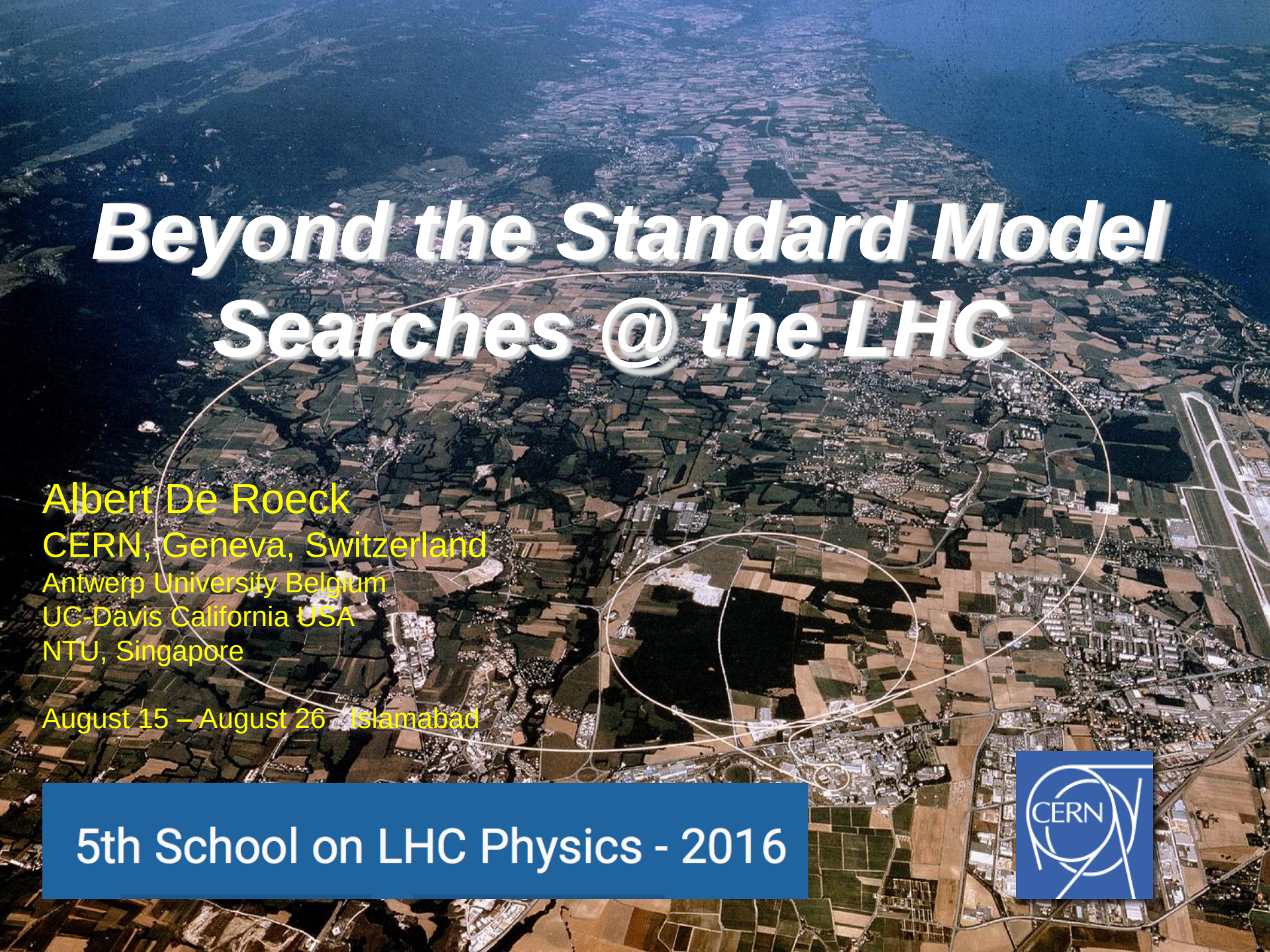


Beyond the Standard Model Searches @ the LHC

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

August 15 – August 26 Islamabad

5th School on LHC Physics - 2016

Lecture Plan

Overview of the 3 lectures in the next days

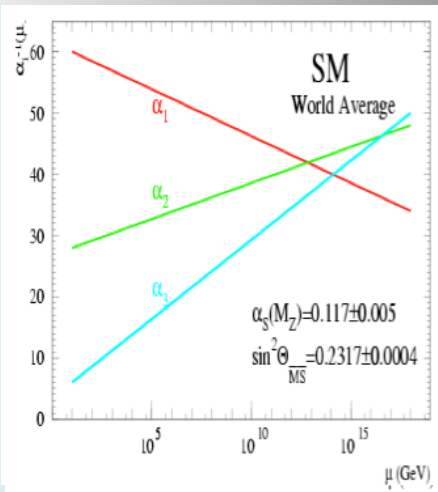
- Lecture 1:
  - Introduction to searches for new physics
  - Searches for exotica and new phenomena
- Lecture 2:
  - Searches for supersymmetry
  - Searches for real exotic particles
- Lecture 3:
  - The hunt for dark matter
  - Outlook for the LHC and for the Future

Physics case for new High Energy Machines

Understand the mechanism Electroweak Symmetry Breaking

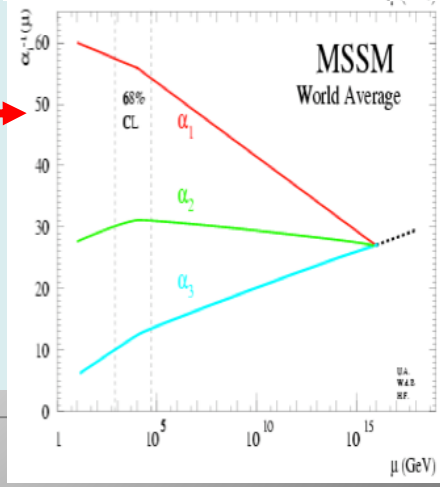
Discover physics beyond the Standard Model

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

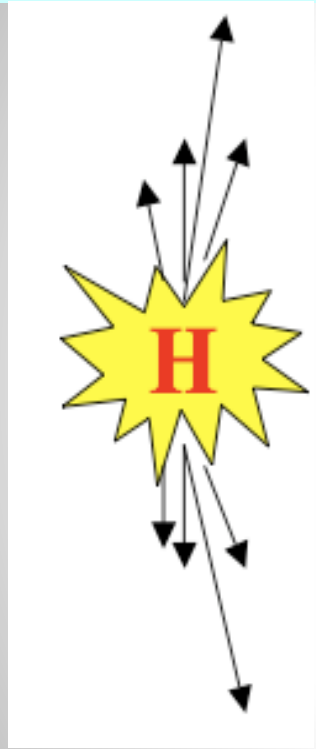


Many other ideas: More symmetry and gauge bosons, composite Higgs models, L-R symmetry, quark & lepton substructure, VLQs Little Higgs models, Technicolor, Hidden Valleys, 4th generation…

Higgsless models clearly disfavoured these days

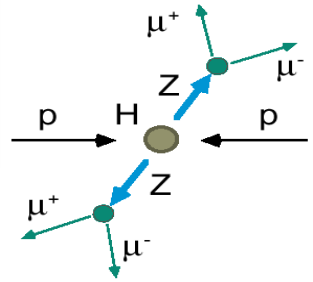
2012: A Milestone in Particle Physics

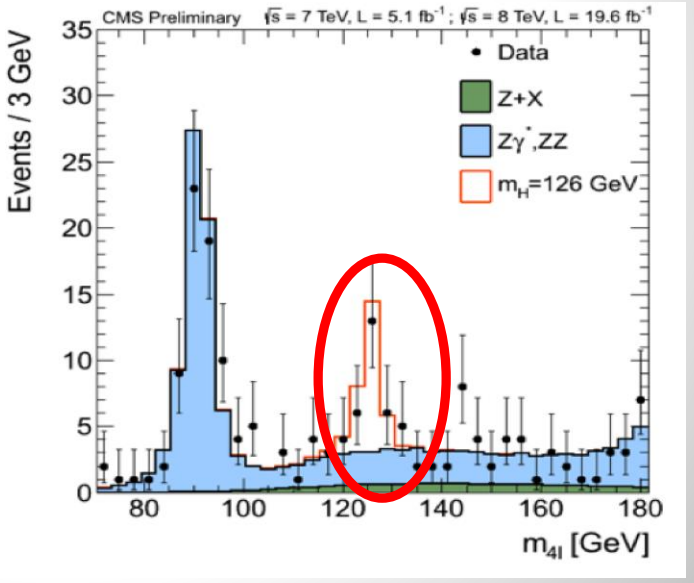
Observation of a Higgs Particle at the LHC, after about 40 years of experimental searches to find it



proton

proton





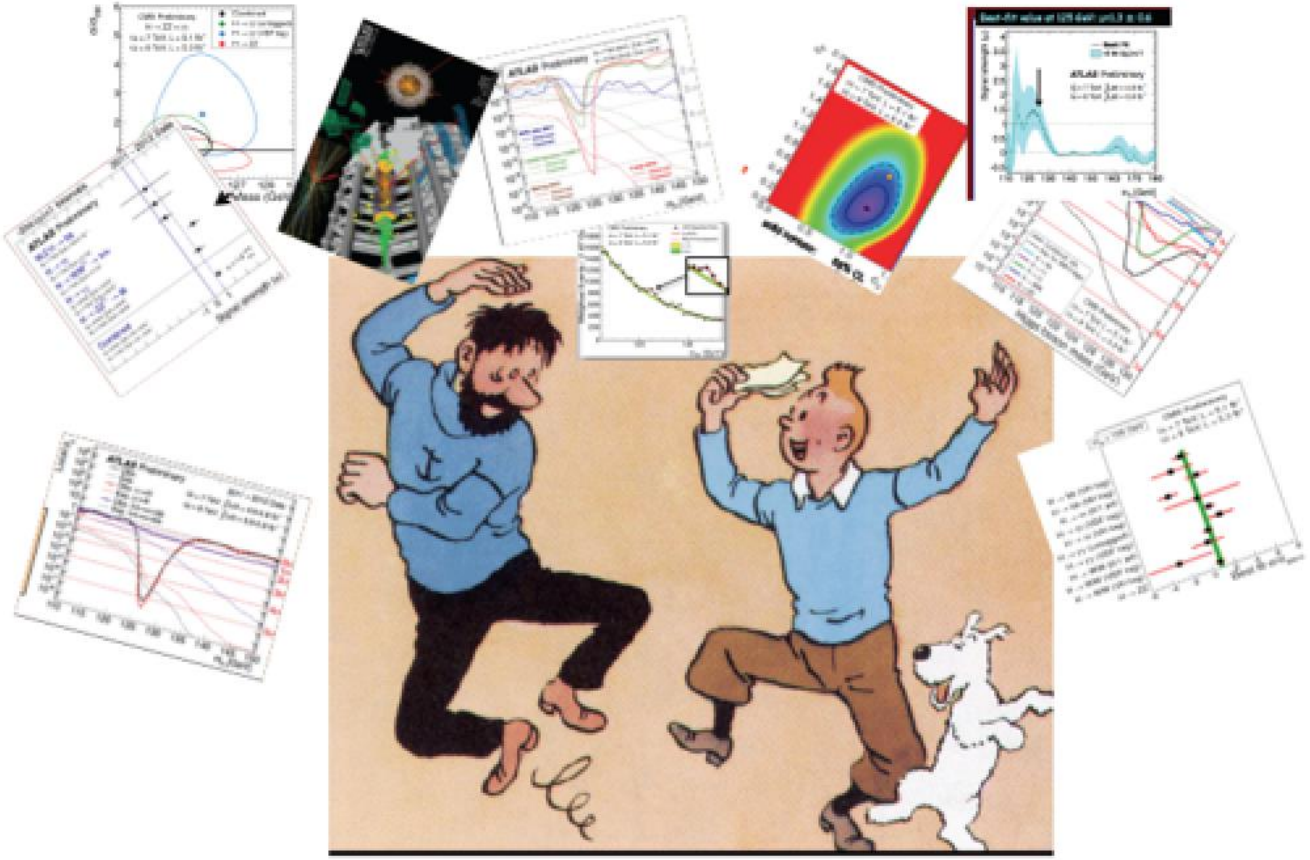
2013

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!

A. Pomarol ICHEP2012



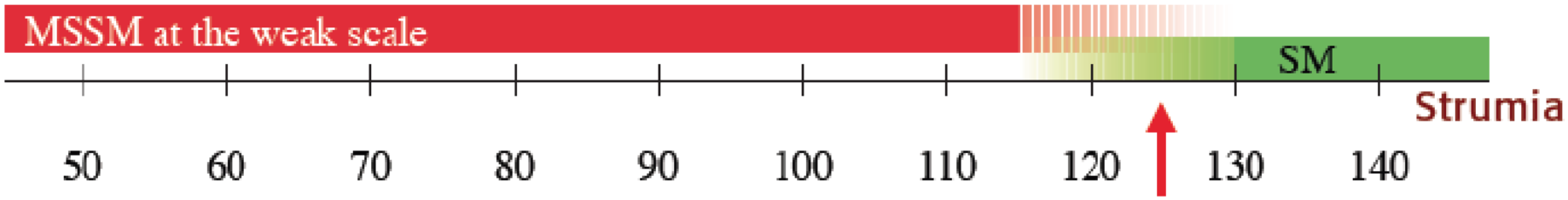
Not everybody at the party
eg higgsless models…

But careful about resurrections, Higgs imposters…

A Higgs @ 125 GeV…

A malicious choice!

$m_H = 125.0 +/- 0.2$ GeV



The Higgs: so simple yet so unnatural

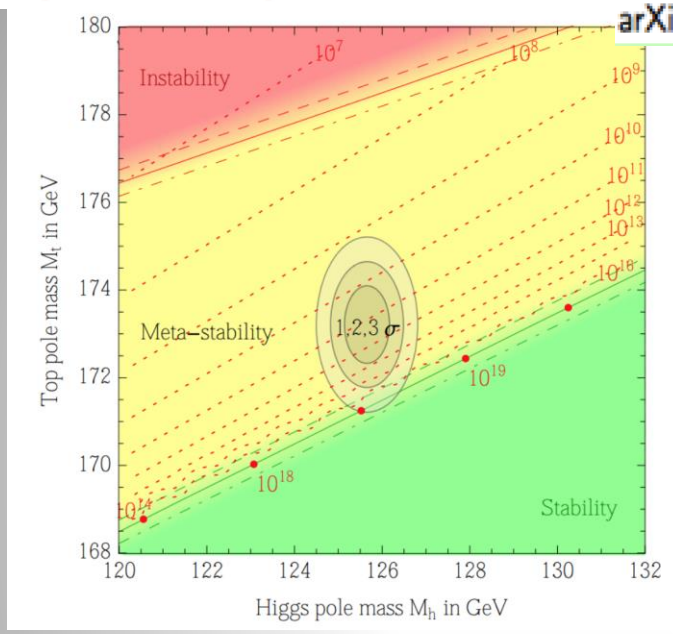
Guido Altarelli
1941-2015

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?

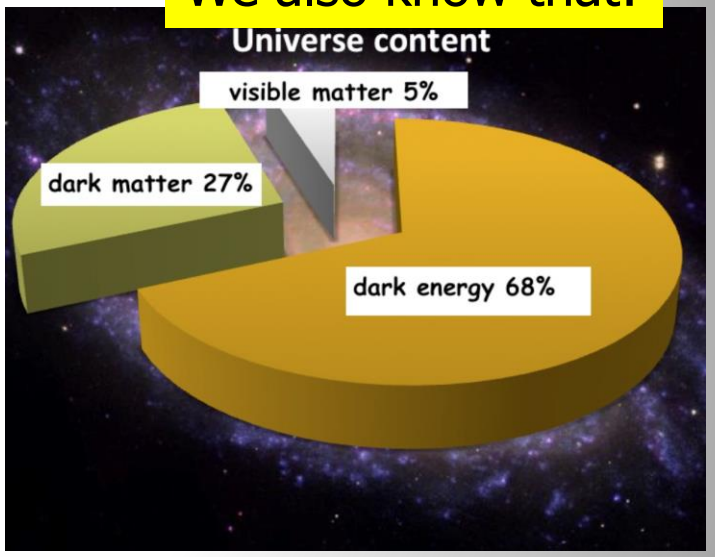
Important SM parameter → stability of EW vacuum



arXiv:1403.6535

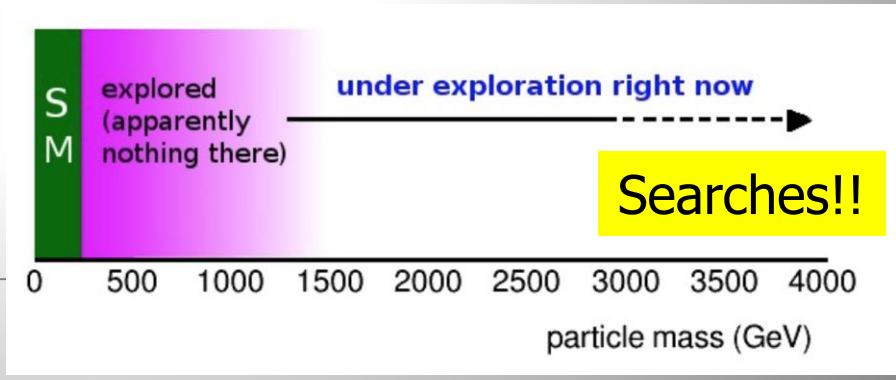
A Higgs at 125 GeV
Precise measurements of the top quark and the Higgs mass

We also know that:



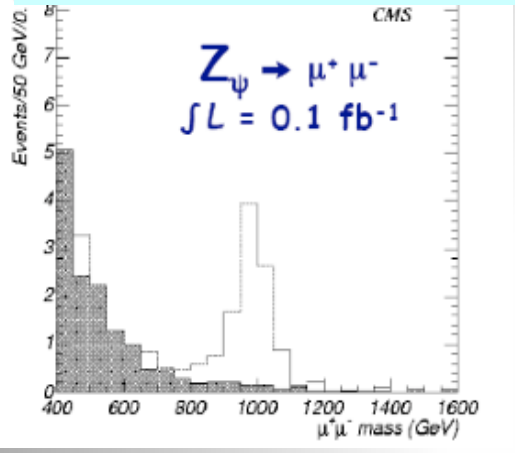
New Physics inevitable?
But at which scale/energy?

N. Arkani-Hamed

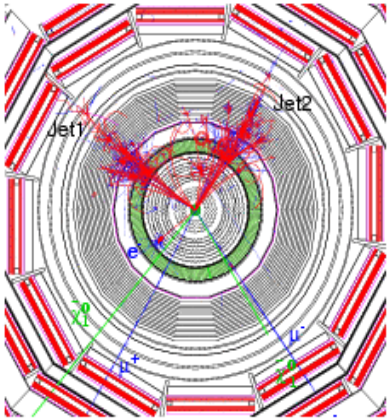


New Physics?

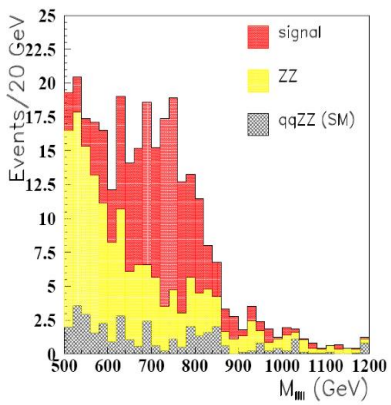
New Gauge Bosons?



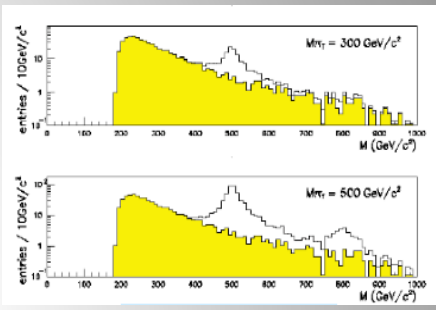
Supersymmetry



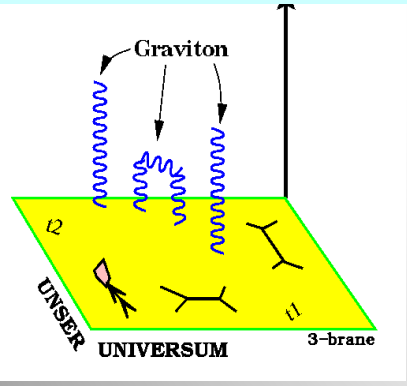
ZZ/WW resonances?



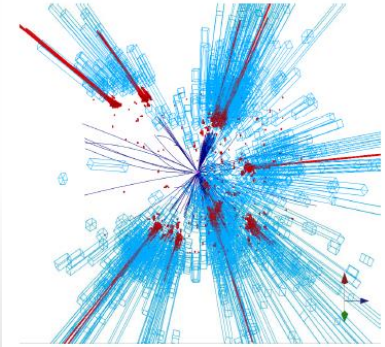
Technicolor?



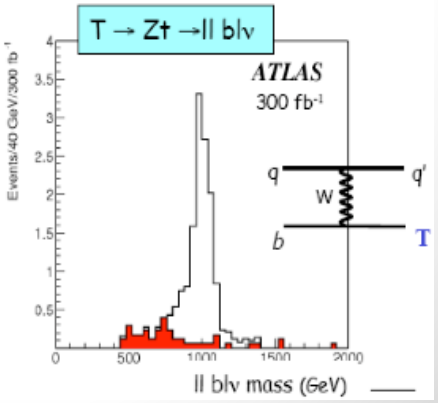
Extra Dimensions?



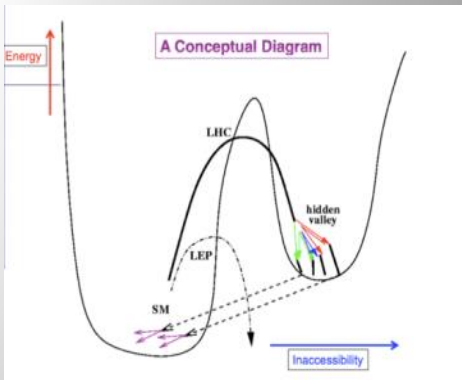
Black Holes???



Little Higgs?



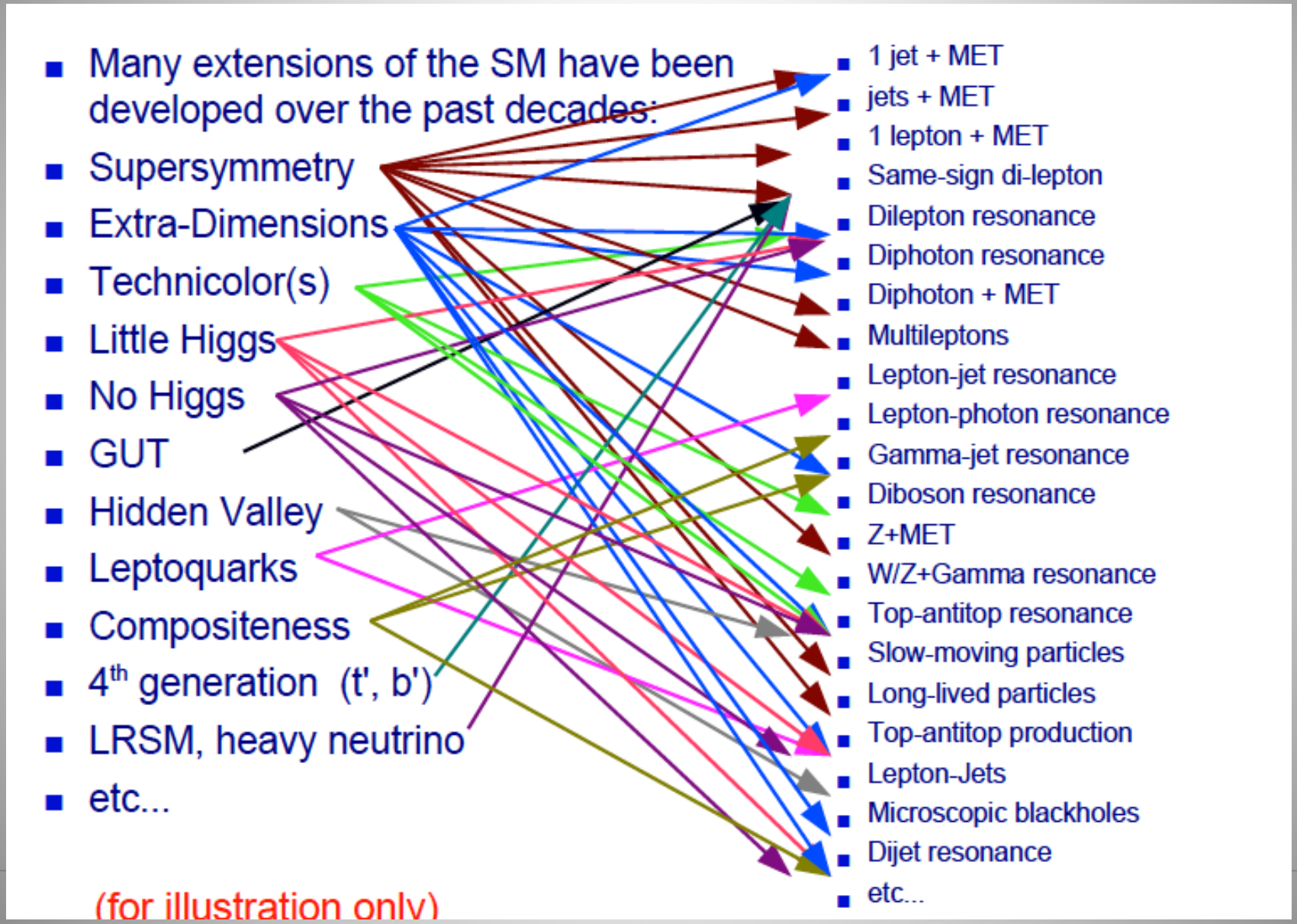
Hidden Valleys?



What stabelizes the Higgs Mass? Many ideas, not all viable any more

A large variety of possible signals. We have to be ready for that

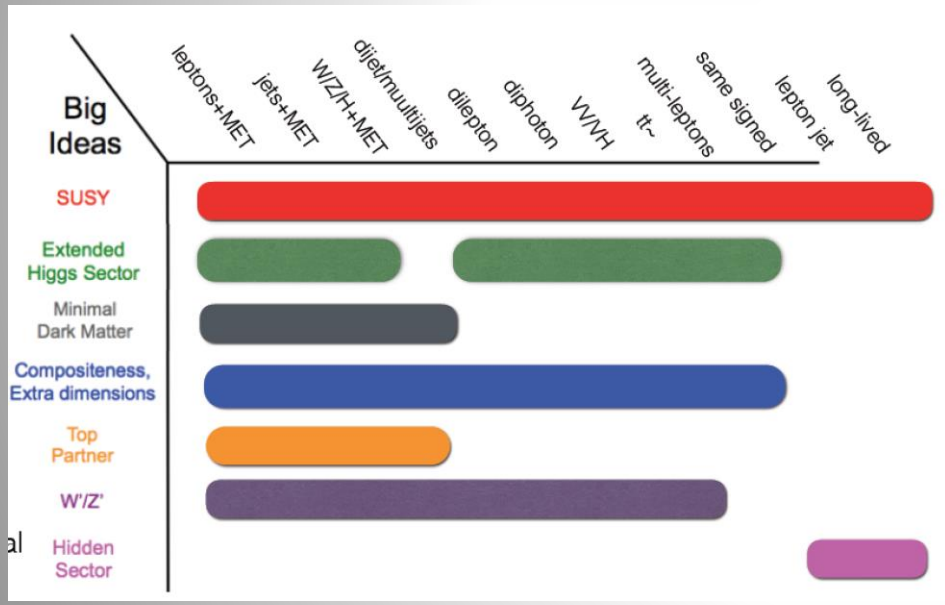
Beyond the SM Signatures

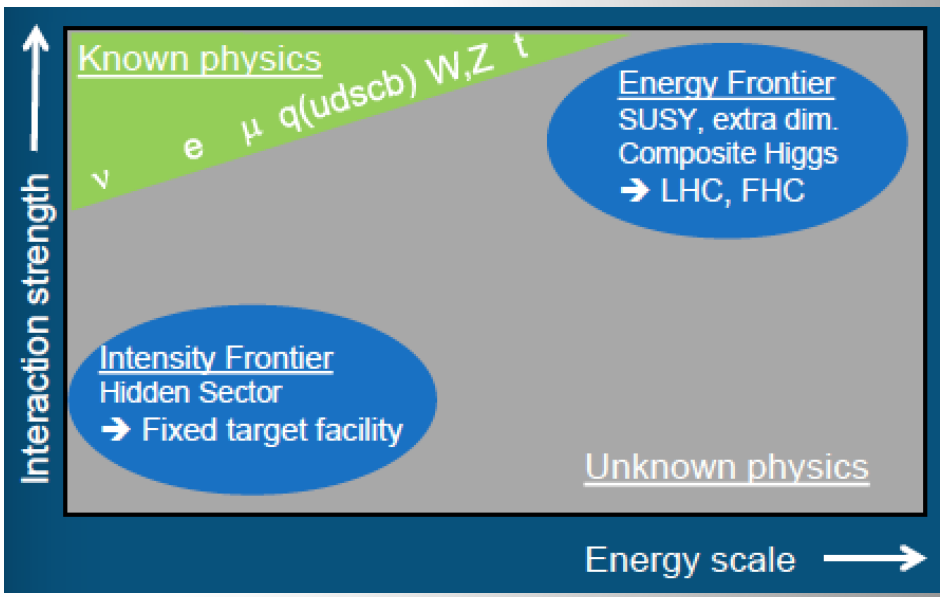


New Physics Searches

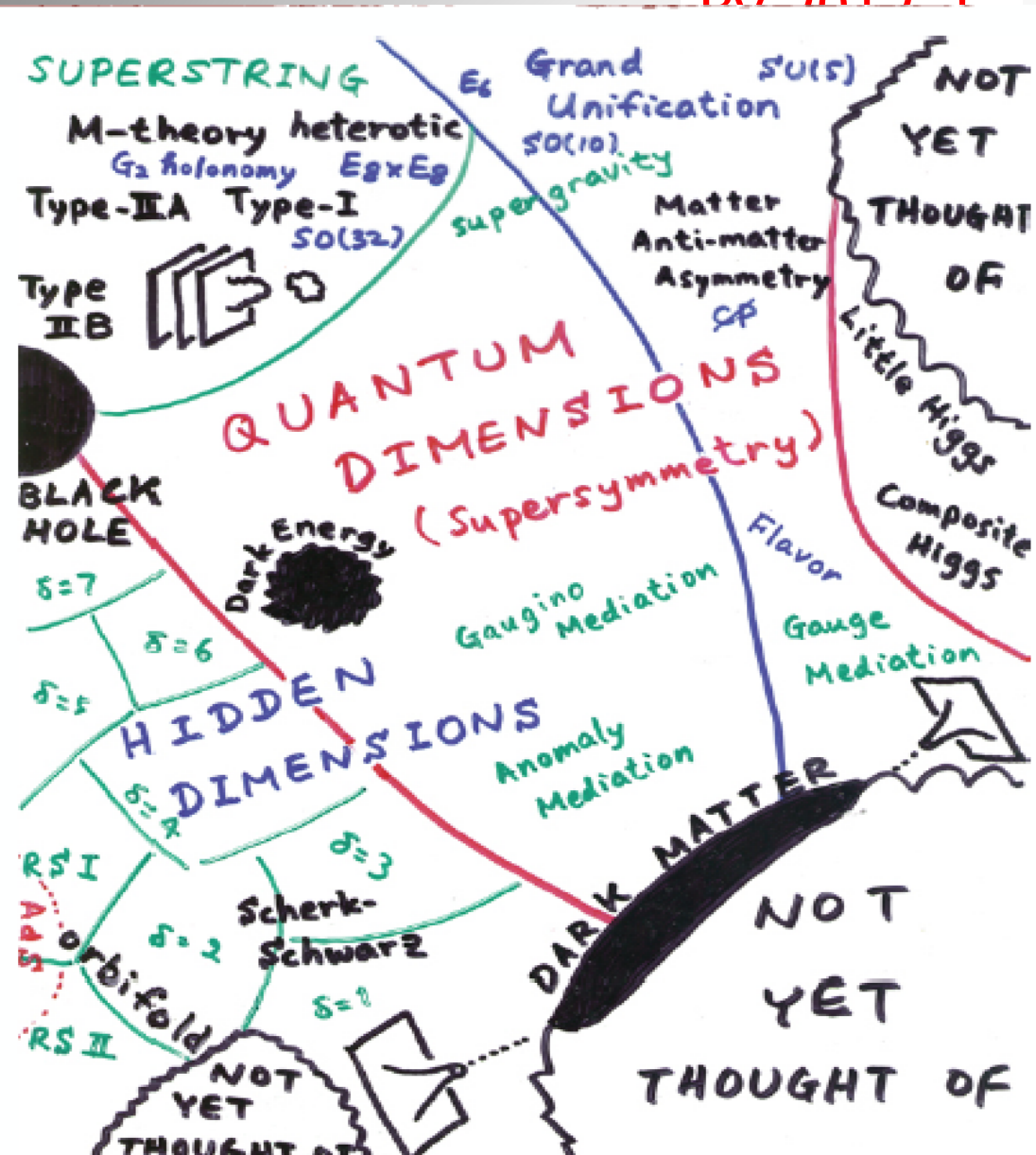
Same signatures can come from quit different phenomena: "The Inverse Problem" See eg the LHC Olympics workshops (2004)

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





2010-2012: LHC data and Theorists



2010...

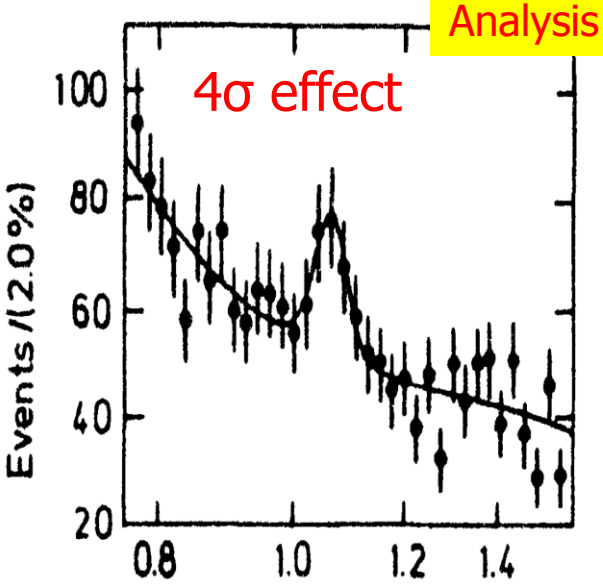
"Data are coming! Data are coming!"

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

Careful with “Discoveries”!

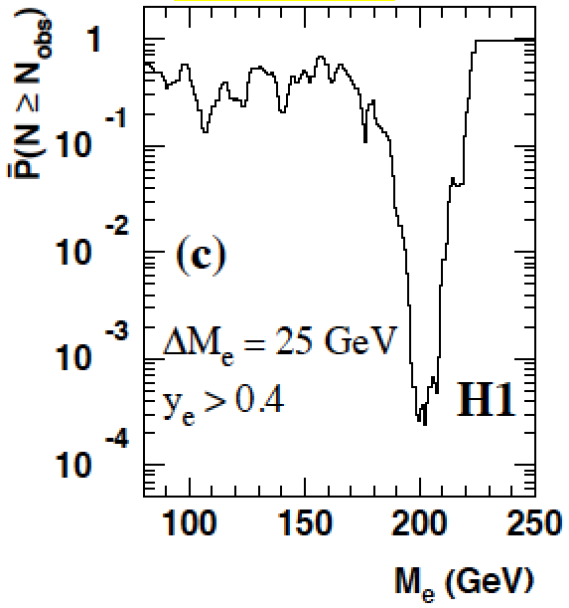
EVIDENCE FOR A MASSIVE STATE IN THE RADIATIVE DECAYS OF THE UPSILON

Analysis error!

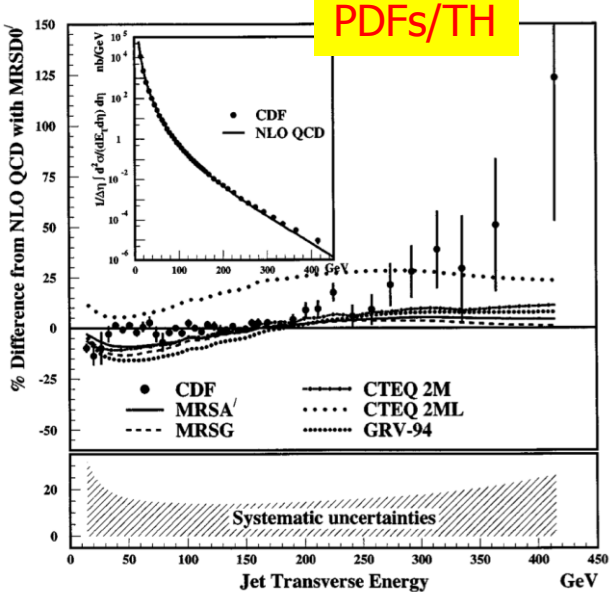


Is the X(8.31 GeV) the Higgs particle? A lot of excitement summer 1984

Statistics!



PDFs/TH



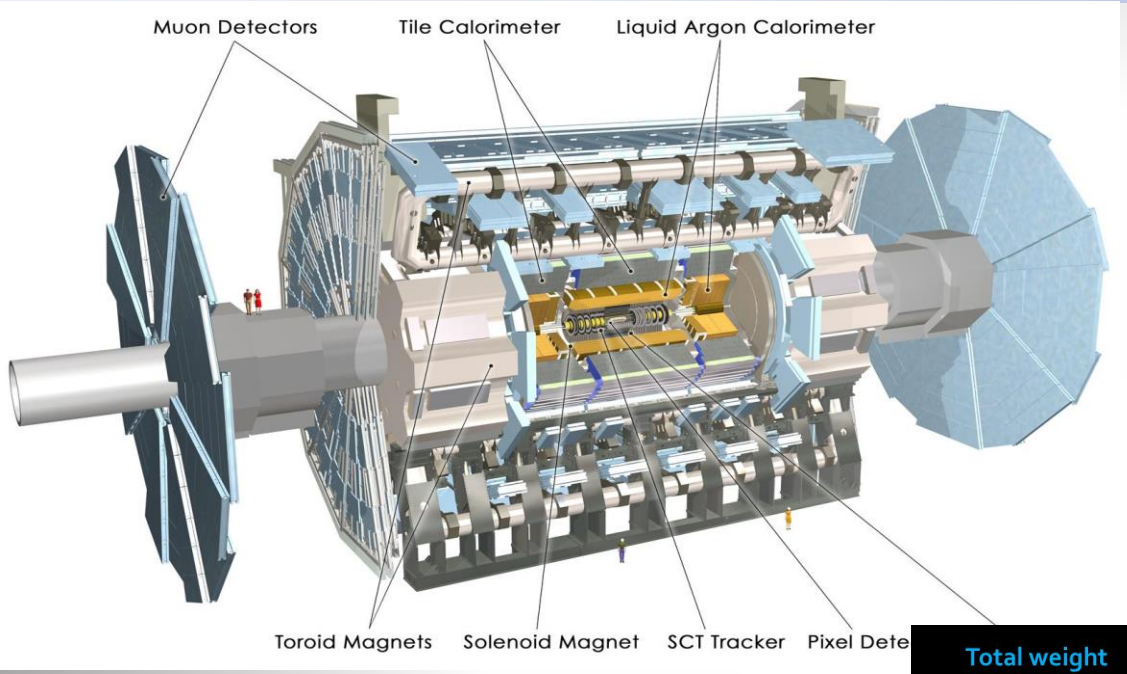
Excess in inclusive jet analysis: substructure?

NON of these were actual discoveries!!

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

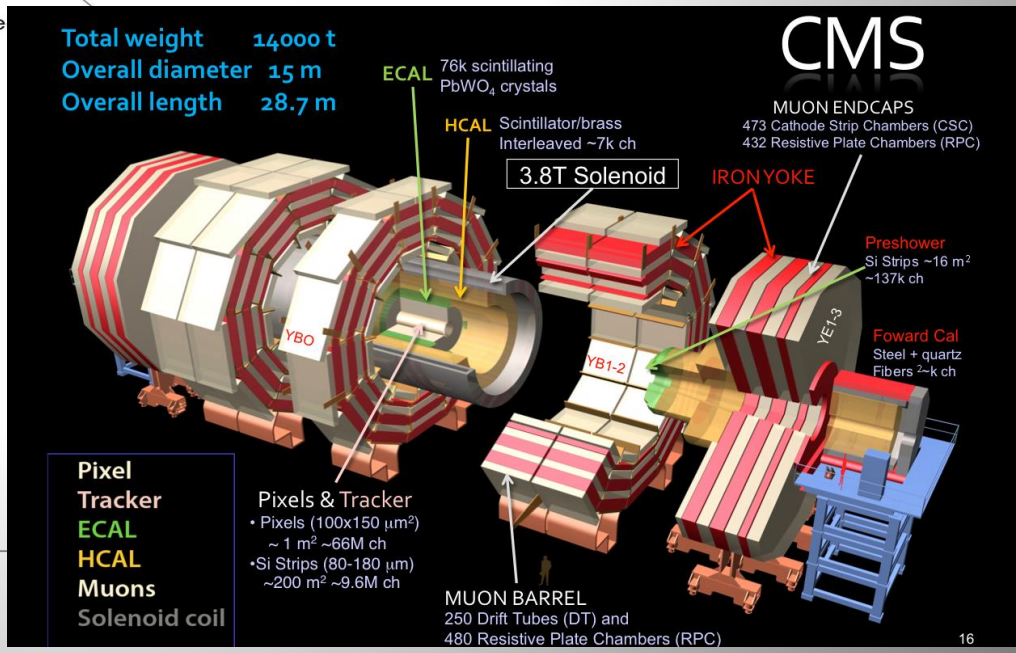
- 7 events found with an electron-quark mass of ~200 GeV, expected ~1 event
- 4 events found with expected 2 events in ZEUS -> Leptoquarks?

New Physics Hunters @ the LHC

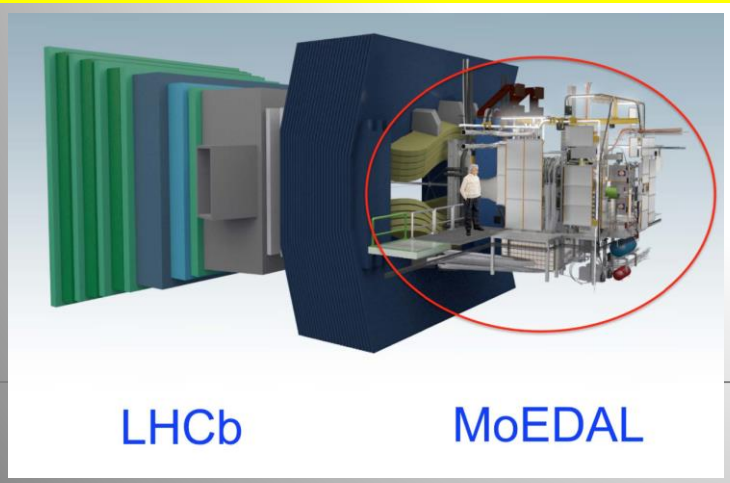


The ATLAS experiment

The CMS experiment



...And also LHCb and MoEDAL



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^{th} 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…

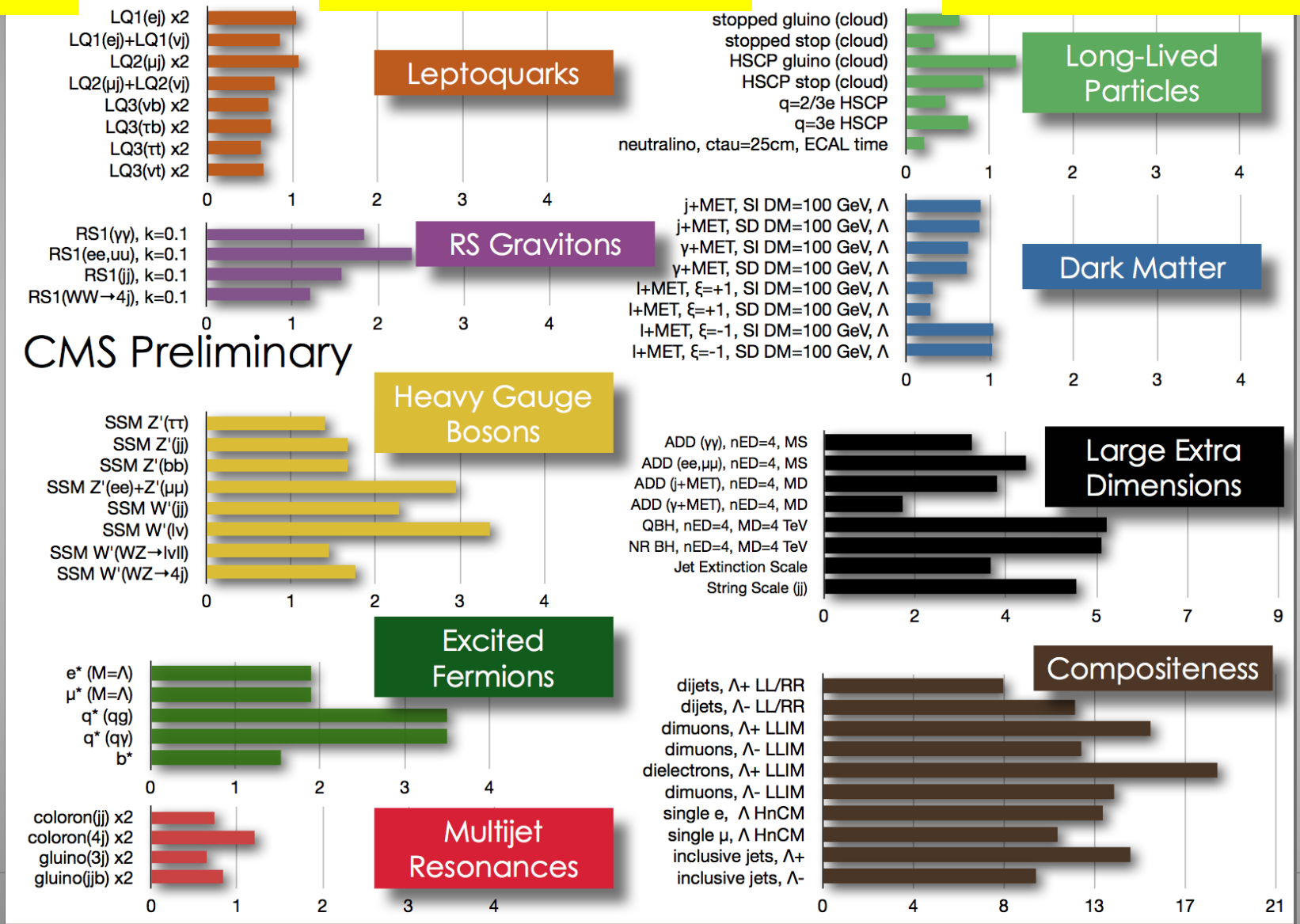
  Strategy now a combination of the above!

Summary of Exotica Searches

2014

8 TeV data @ 20 fb^{-1}

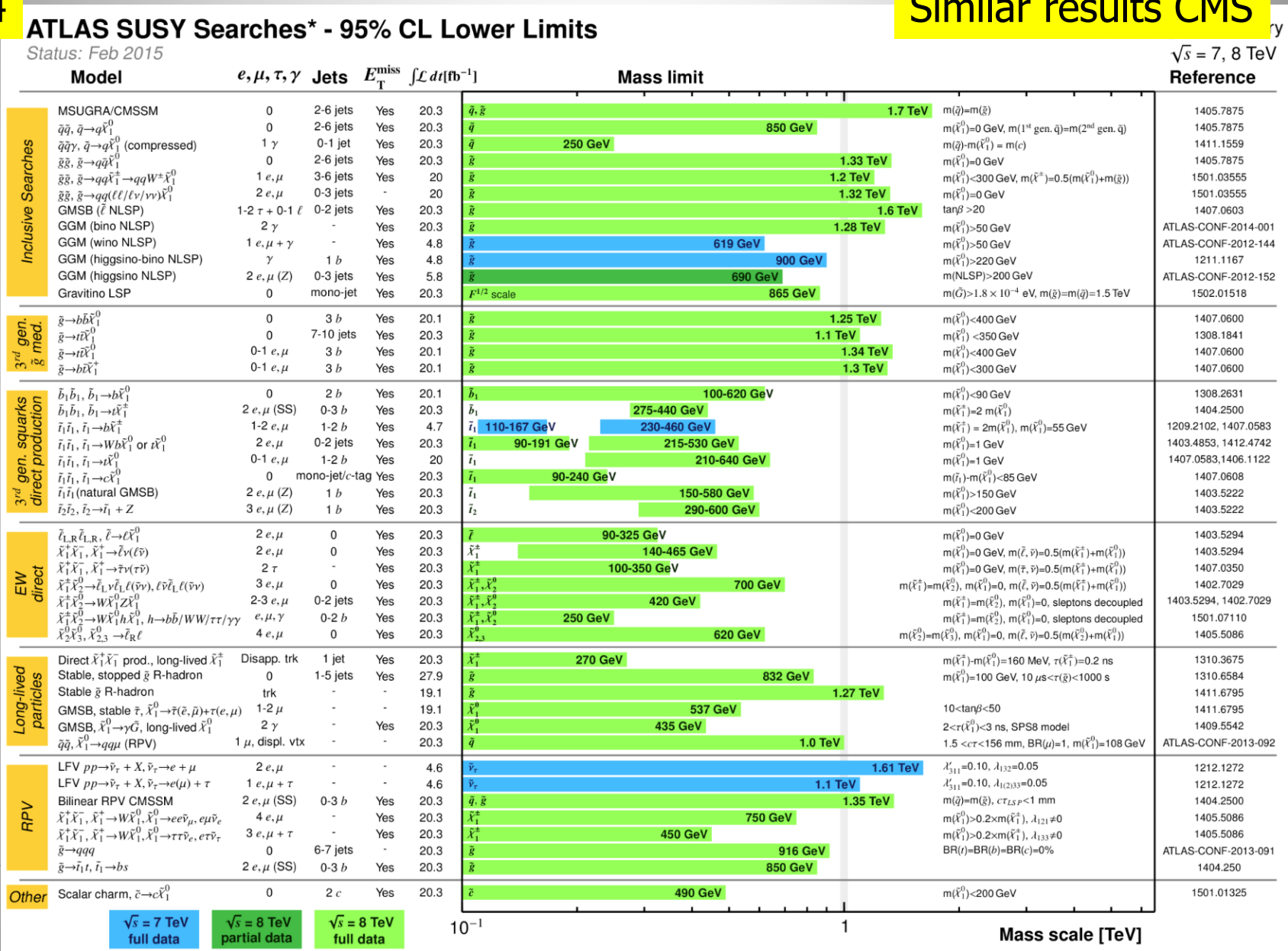
Similar results for ATLAS



Summary of SUSY Searches

2014

Similar results CMS



Run-1: We Observed Mild Deviations!

November 2015

B. Hooberman

LHC Beyond-the-SM Anomalies

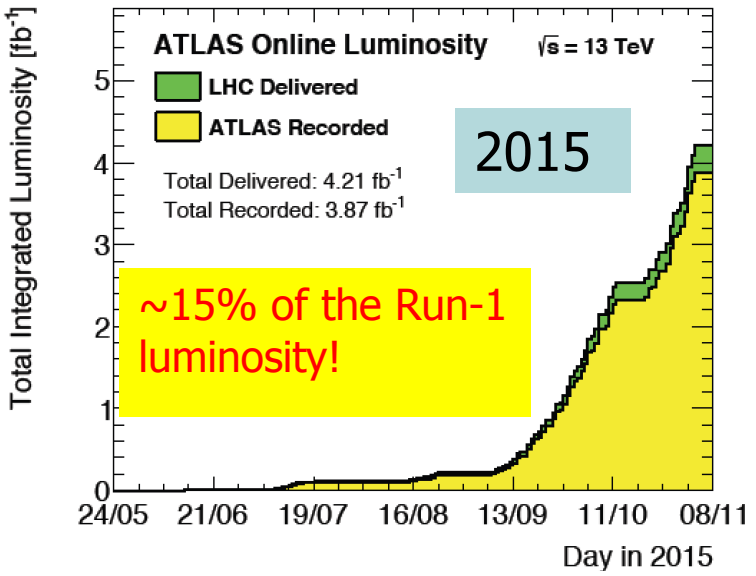
https://www.dropbox.com/s/2xrrcxns5wnc4ek/LHC_anomalies.pdf?dl=0

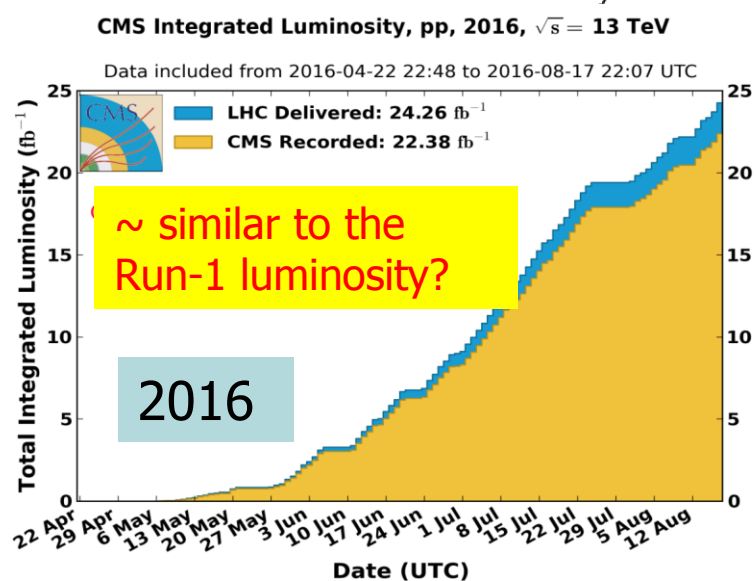
	Search	Dataset	Max Significance	Reference
Strong SUSY ($jets+E_T^{miss}+X$)	$Z+jets+E_T^{miss}$	ATLAS 8 TeV	3.0σ	EPJC 75 (2015) 318
	$Z+jets+E_T^{miss}$	ATLAS 13 TeV	2.2σ	ATLAS-CONF-2015-082
	Dilepton mass edge	CMS 8 TeV	2.6σ	arXiv:1502.06031 [hep-ex]
	Soft $2\ell+E_T^{miss}$	ATLAS 8 TeV	2.3σ	ATLAS-CONF-2013-062
	Same-sign $\geq 2\ell+b+E_T^{miss}$	ATLAS 8 TeV	2.5σ	arXiv:1504.04605 [hep-ex]
EWK SUSY ($leptons+E_T^{miss}$)	$3\ell+E_T^{miss}$ ($WZ \rightarrow 3\ell$ channel)	CMS 8 TeV	~2σ	EPJC 74 (2014) 3036
	$4\ell+E_T^{miss}$ ($3\ell+\tau_{had}$ channel)	CMS 8 TeV	~3σ	PRD 90, 032006 (2014)
	$3\ell+E_T^{miss}$	ATLAS 8 TeV	2.2σ	JHEP 04 (2014)169
Resonances	All-hadronic boosted diboson	ATLAS 8 TeV	3.4σ	JHEP 12 (2015) 55
	Dijet resonance search ($M_{jj} \sim 1.8$ TeV)	CMS 8 TeV	~2σ	PRD 91 (2015) 052009
	$W(\ell\nu)H(bb)$ resonance ($M_{WH} \sim 1.8$ TeV)	CMS 8 TeV	2.2σ	CMS-PAS-EXO-14-010
	$X \rightarrow h(bb)h(\gamma\gamma)$ ($M_X \sim 300$ GeV)	ATLAS 8 TeV	3.0σ	PRL 114 (2015) 081802
	1st gen. leptoquarks (eejj / evjj channels)	CMS 8 TeV	2.6σ / 2.4σ	CMS-PAS-EXO-12-041
	Heavy right-handed neutrinos	CMS 8 TeV	2.8σ	EPJC 74 (2014) 3149
Higgs	ttH (same-sign muon channel)	CMS 8 TeV	$\mu_{ttH} = 8.5^{+3.5}_{-2.7}$	JHEP 09 (2014) 087
	Higgs→μτ (lepton flavor violation)	CMS 8 TeV	2.5σ	CMS-PAS-HIG-14-005
Flavor	$B \rightarrow K\ell\ell$ ($K\mu\mu$ / Kee)	LHCb 8 TeV	2.6σ	PRL 113 (2014) 151601
	$B \rightarrow K\mu\mu$ (branching ratio)	LHCb 8 TeV	2.2σ	JHEP 06 (2014) 133
	$B \rightarrow K\mu\mu$ (P_5' angular distribution)	LHCB 8 TeV	3.7σ	LHCb-CONF-2015-002
SM measurements	WW cross section*	CMS 7 TeV	1.0σ	EPJC 73 2610 (2013)
	WW cross section*	CMS 8 TeV	1.7σ	PLB 721 (2013)
	WW cross section*	ATLAS 7 TeV	1.4σ	PRD 87, 112001 (2013)
	WW cross section*	ATLAS 8 TeV	2.0σ	ATLAS-CONF-2014-033

* 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

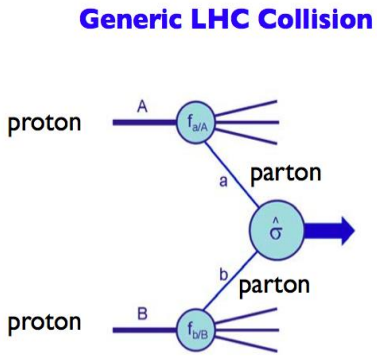
3rd June 2015





For ICHEP results: ~ 13 fb^{-1} from 2016 data

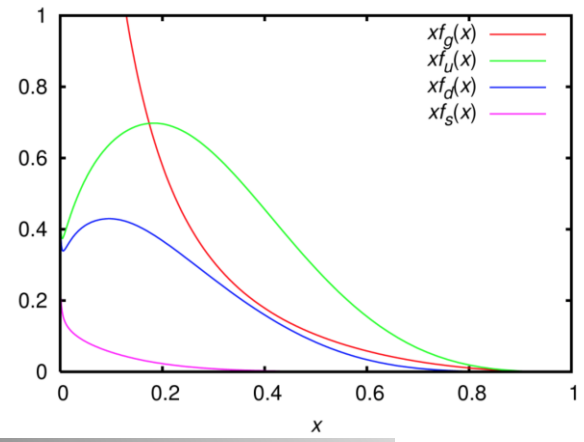
New Physics Searches with 13 TeV Data

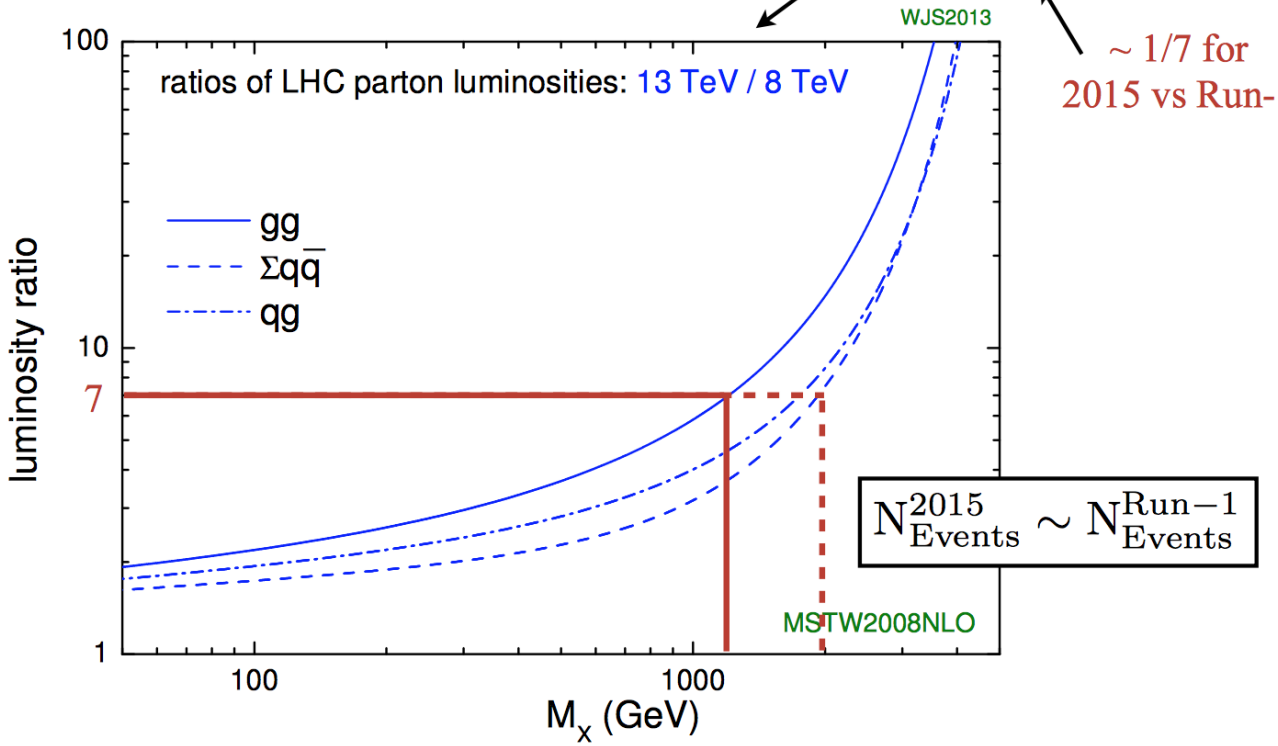


$$N_{Events} = \sigma \times \mathcal{L}$$

$$\frac{N^{13\ TeV}_{Events}}{N^{8\ TeV}_{Events}} = \frac{\sigma^{13\ TeV}}{\sigma^{8\ TeV}} \times \frac{\mathcal{L}^{13\ TeV}}{\mathcal{L}^{8\ TeV}}$$

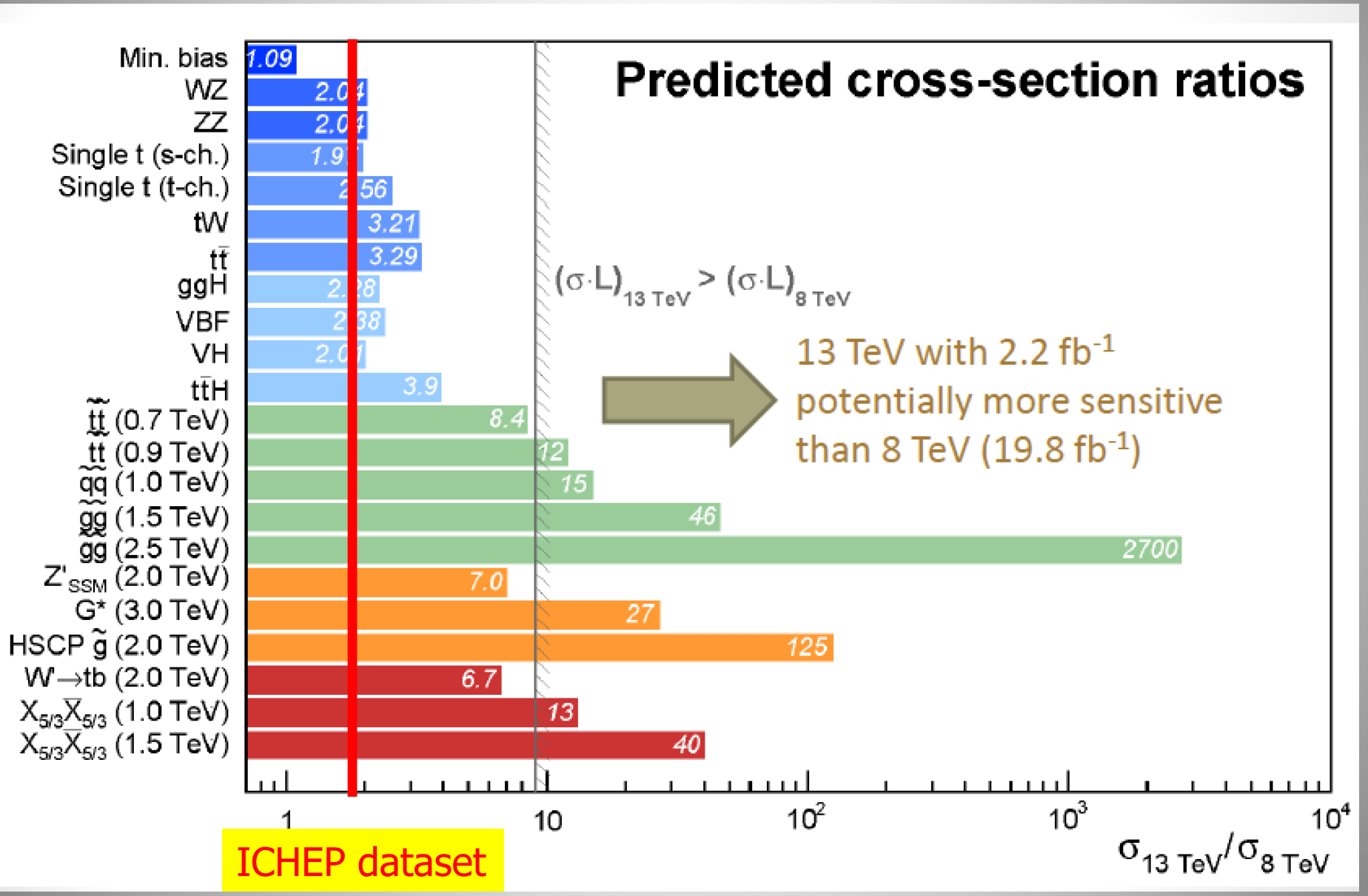
~ 1/7 for 2015 vs Run-1





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

Run-II: From 8 TeV to 13 TeV



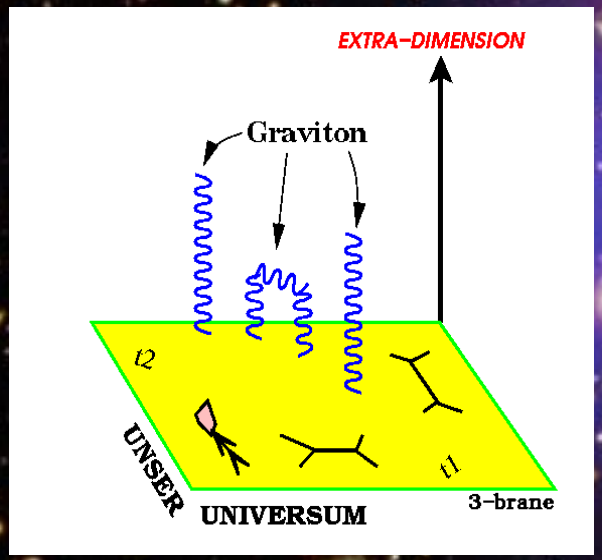
Extra Dimensions

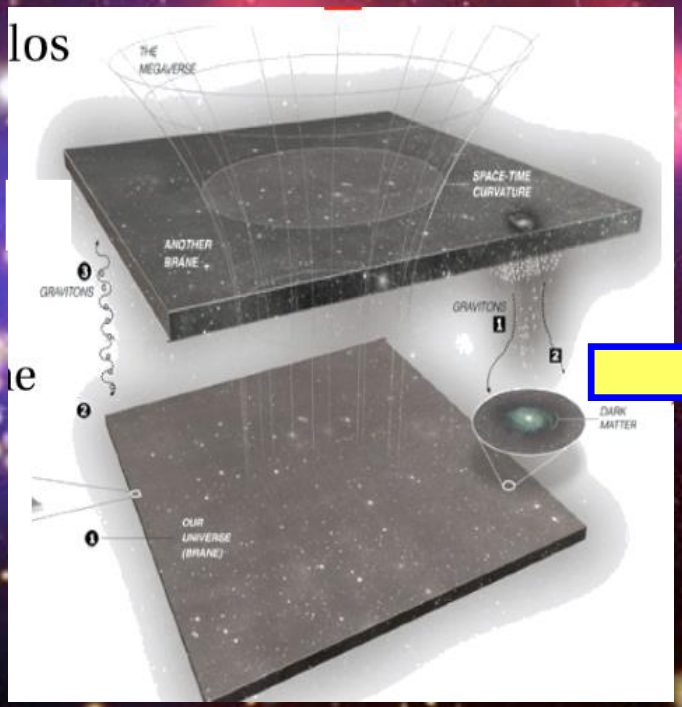
Extra Space Dimensions

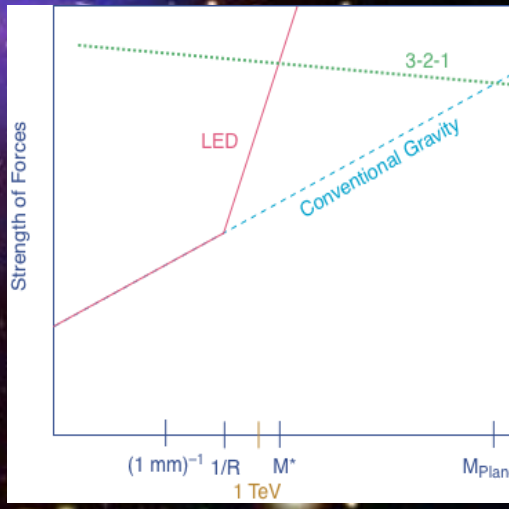
Problem:

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

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







The Gravity force becomes strong!

Models with Extra Dimensions

Large Extra Dimensions

Planck scale (M_D) ~ TeV

Size: » TeV^{-1}; SM-particles on brane; gravity in bulk

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

Signature: e.g. x-section deviations; jet+$E_{T,miss}$ ....

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^{-1}

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

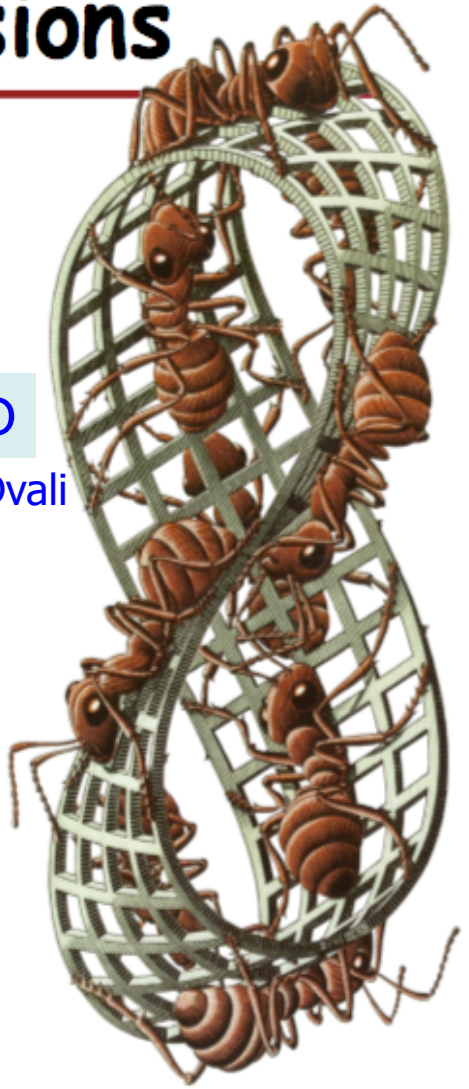
UED

Universal Extra Dimensions

nUED : KK excitations of gauge bosons

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

Signature: e.g. Z'/W' resonances, dijets+$E_{T,miss}$, heavy stable quarks/gluons...



Search for Large Extra Dimensions

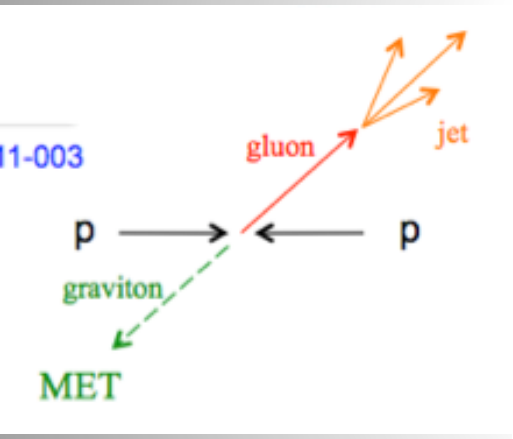
Example: Mono-jet final state +Missing E_T (ADD)

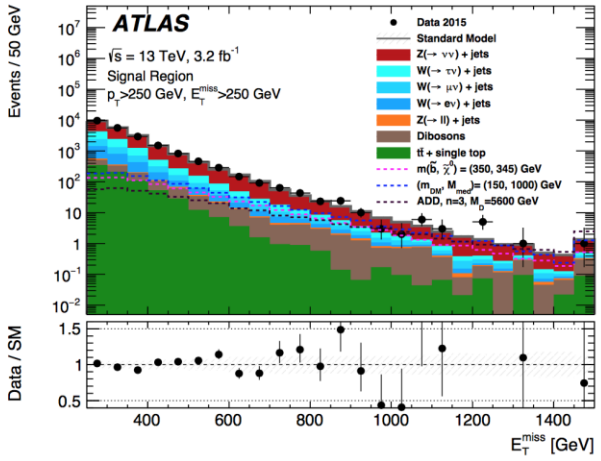
arXiv:1604.07773

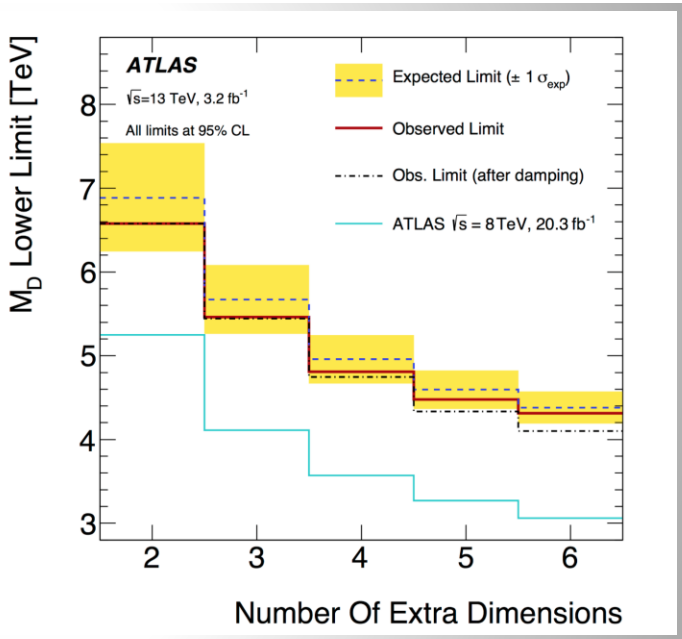
p_T jet > 250 GeV
MET > 250-700 GeV

Limits on M_D between ~ 7 and 4 TeV

Lower limit on the Planck Scale versus number of extra dimensions

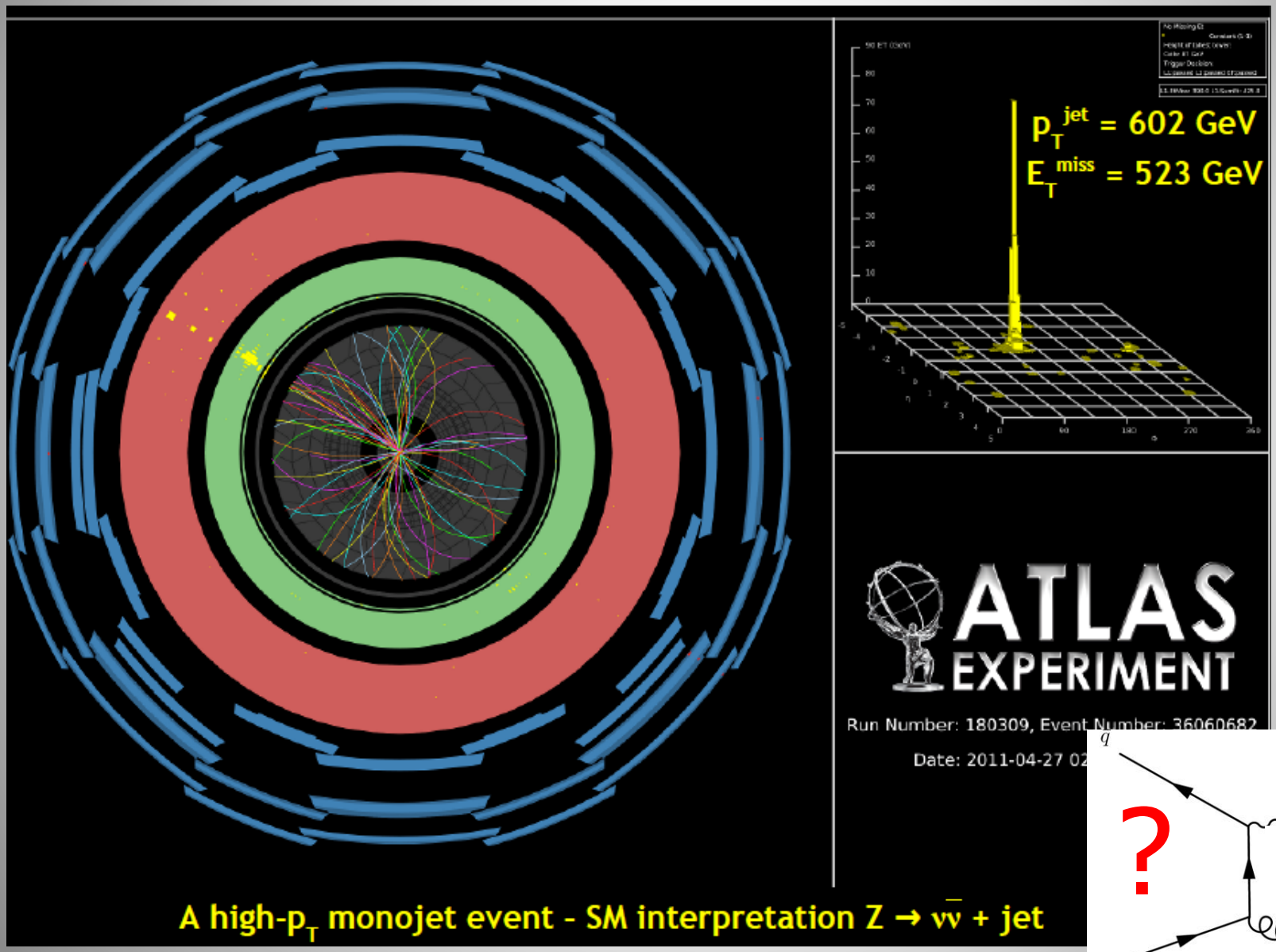


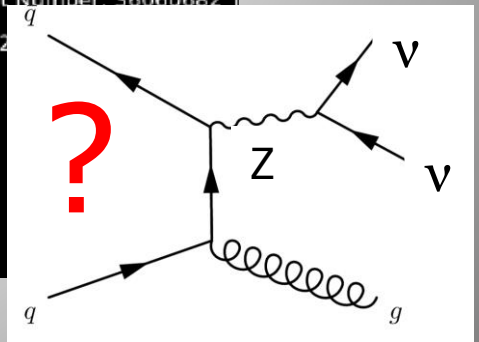




95% CL lower limits on M_D [TeV]				
n extra dimensions	95% CL observed limit Nominal (Nominal after damping)	$\pm 1\sigma$ (theory)	95% CL expected limit Nominal	$\pm 1\sigma$ (expected)
2	6.58 (6.58)	$^{+0.52}_{-0.42}$	6.88	$^{+0.65}_{-0.64}$
3	5.46 (5.44)	$^{+0.45}_{-0.34}$	5.67	$^{+0.41}_{-0.41}$
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





Micro Black Holes?

- Schwarzschild radius

Landsberg, Dimopoulos, Giddings, Thomas, Rizzo

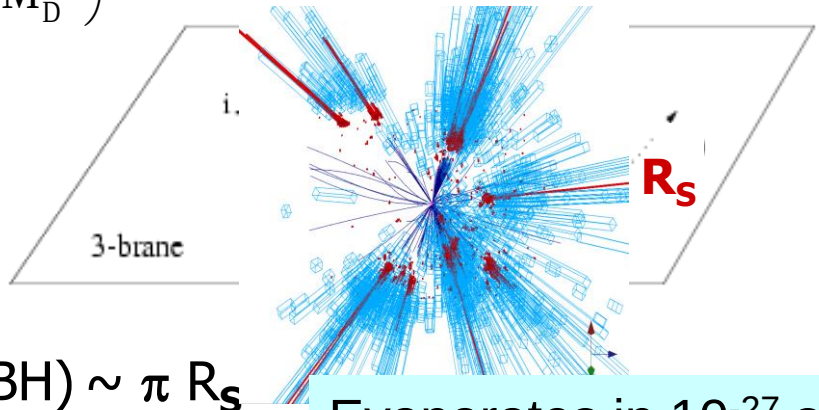
4-dim., $M_{gravity} = M_{Planck}$: $R_S \sim \frac{2}{M_{Pl}^2}\frac{M_{BH}}{c^2}$

$R_s \rightarrow << 10^{-35}$ m

$R_s \rightarrow \sim 10^{-19}$ m

4 + n-dim., $M_{gravity} = M_D \sim$TeV: $R_S \sim \frac{1}{M_D}\left(\frac{M_{BH}}{M_D}\right)^{\frac{1}{n+1}}$

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



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

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

Evaporates in 10^{-27} sec

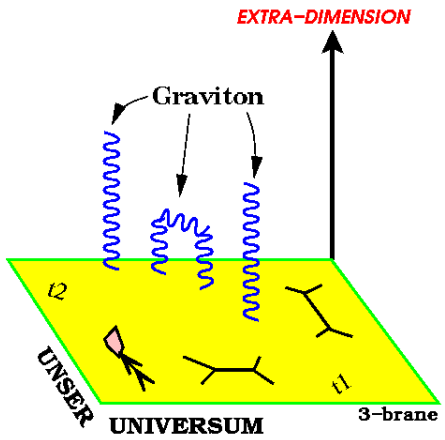
- Black holes decay immediately by Hawking radiation (democratic evaporation)
  - -- large multiplicity
  - -- small missing E
  - -- jets/leptons ~ 5

expected signature (quite spectacular …)

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

Dvali

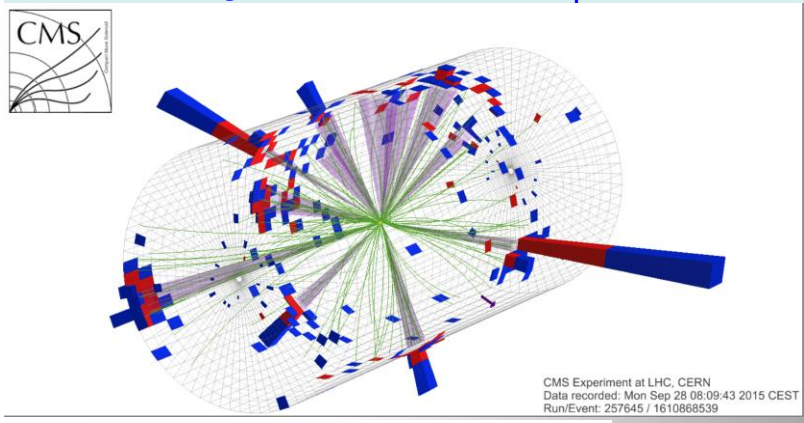
Search for Micro Black Holes



Extra Dimensions!

Planck scale
a few TeV?

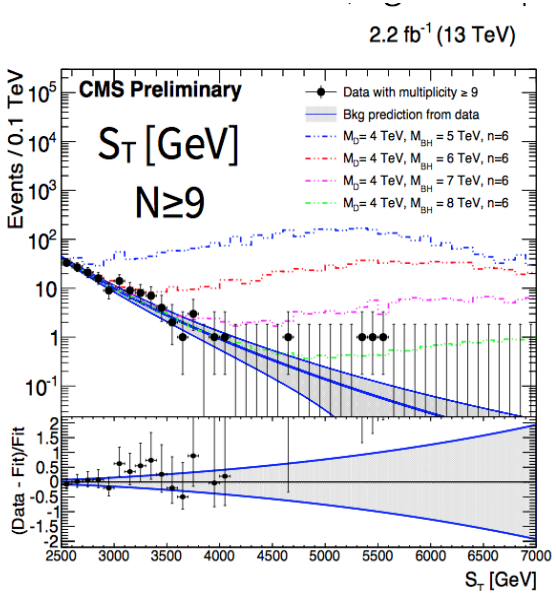
2015: 12 jet event with S_T=5.4 TeV

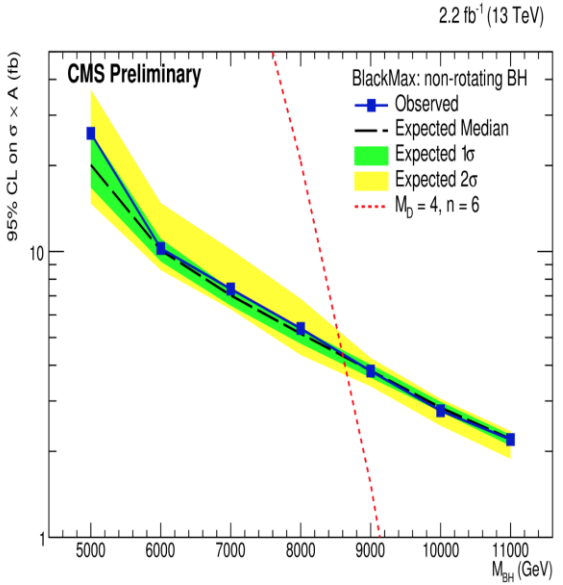


CMS-EXO-15-007

Look for the decay producs 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



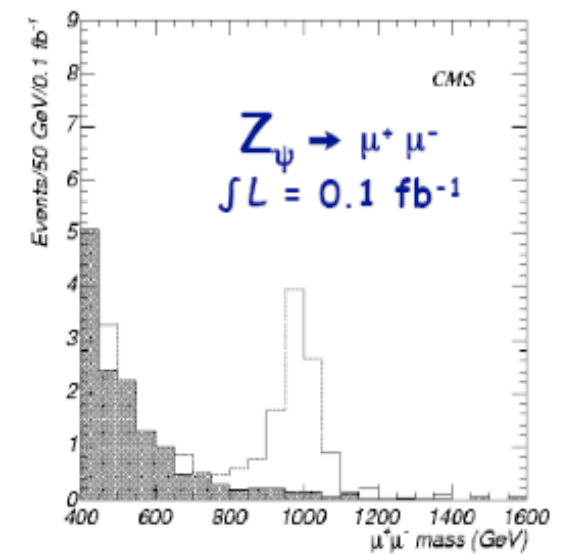


Black hole mass excluded in range below ~8-9 TeV depending on assumptions

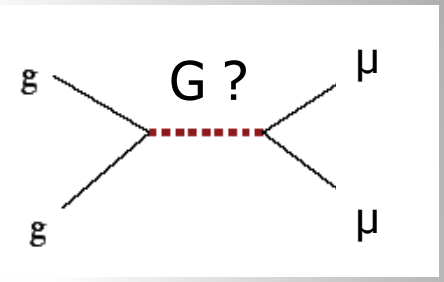
Search for High Mass Resonances

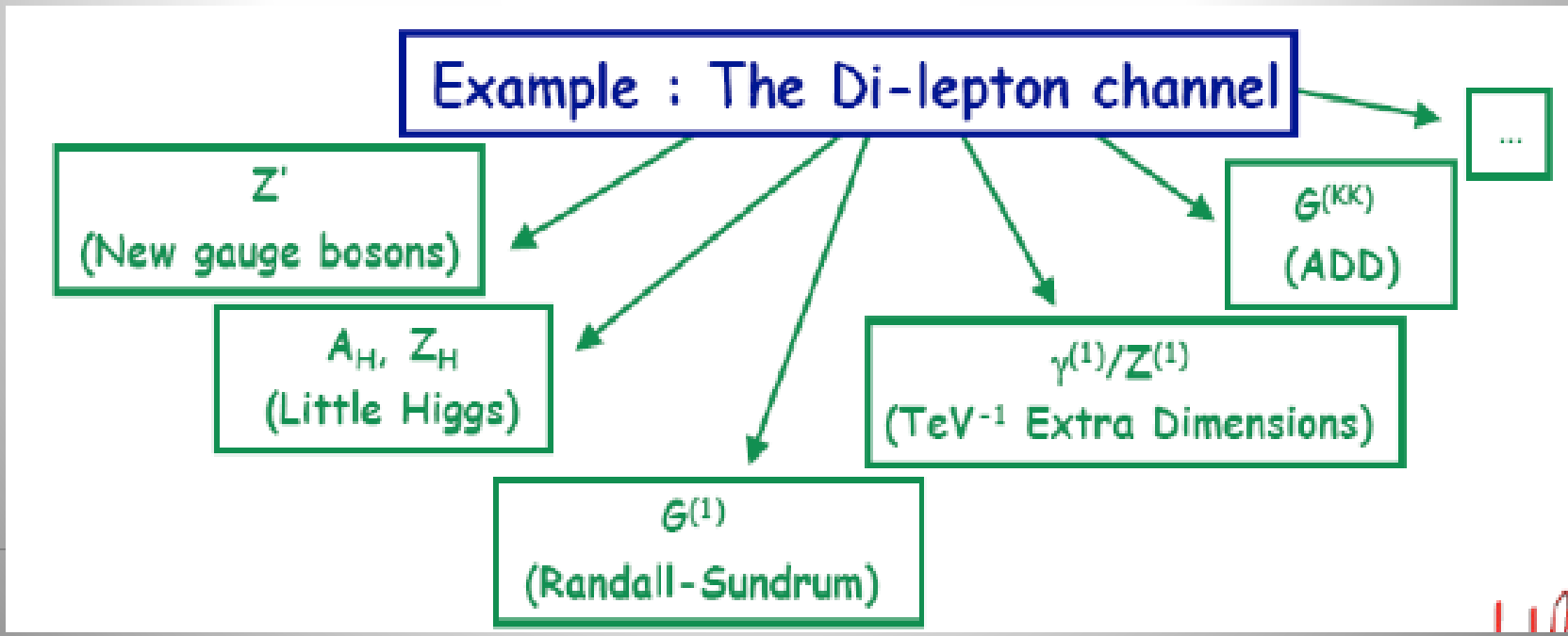
E.g. Di-lepton Resonance

Plot the di-lepton invariant mass
A peak!!
A new particle!!
A discovery!!

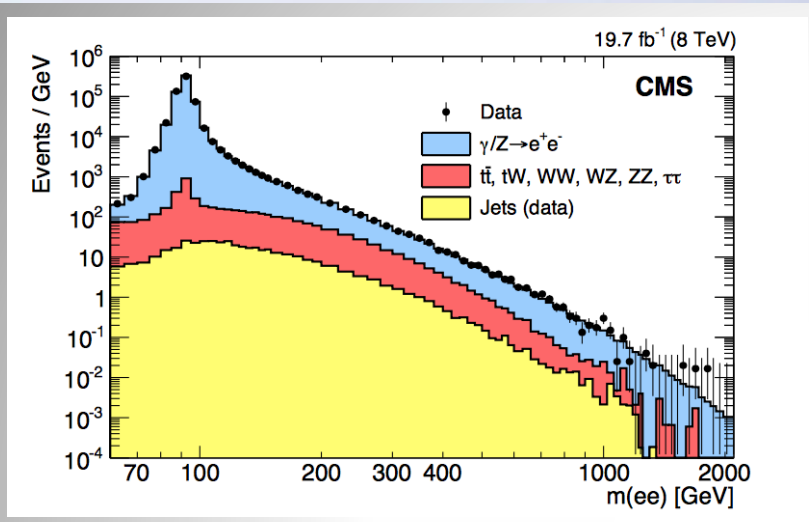


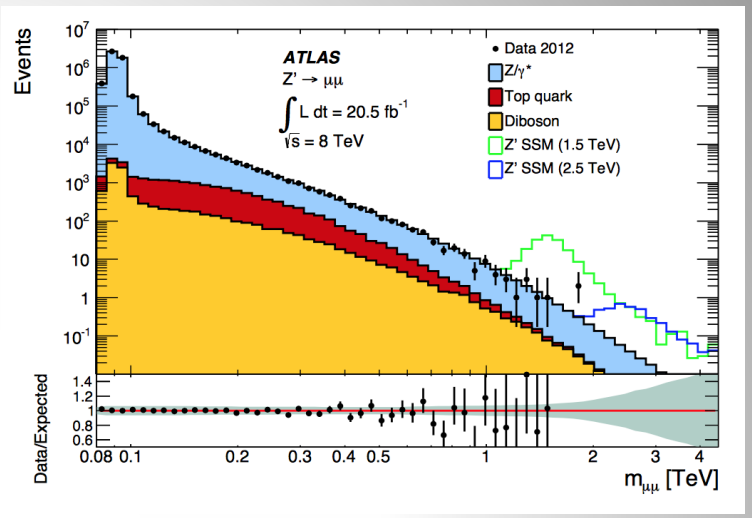
Example
$pp \rightarrow \mu\mu + X$

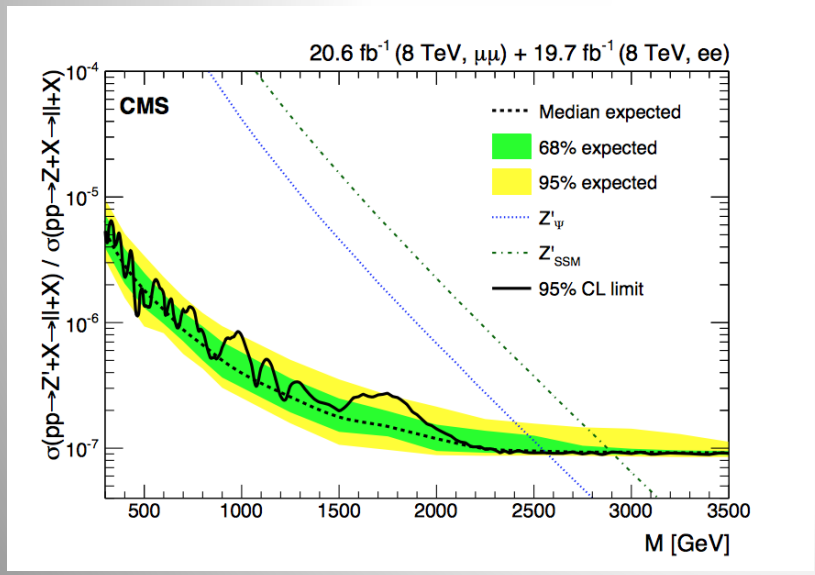


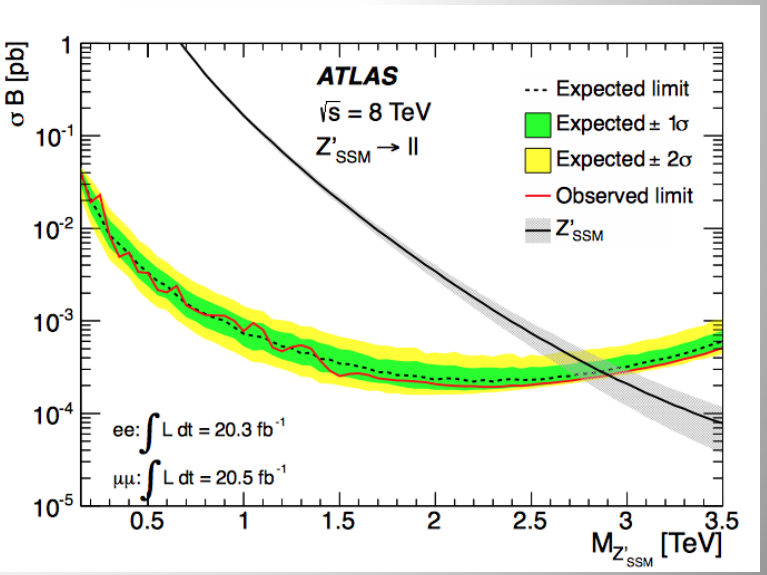


Example: Z' Results Run-1





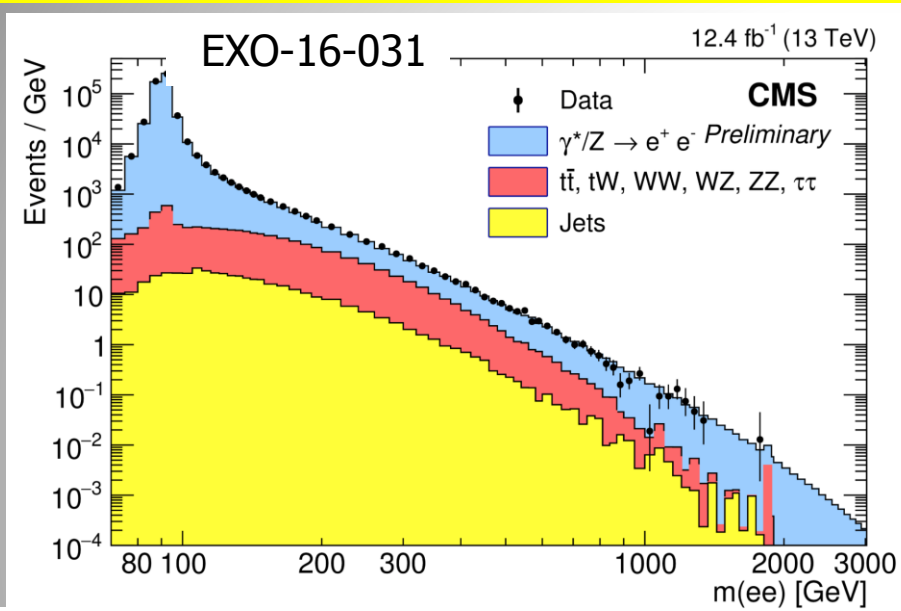


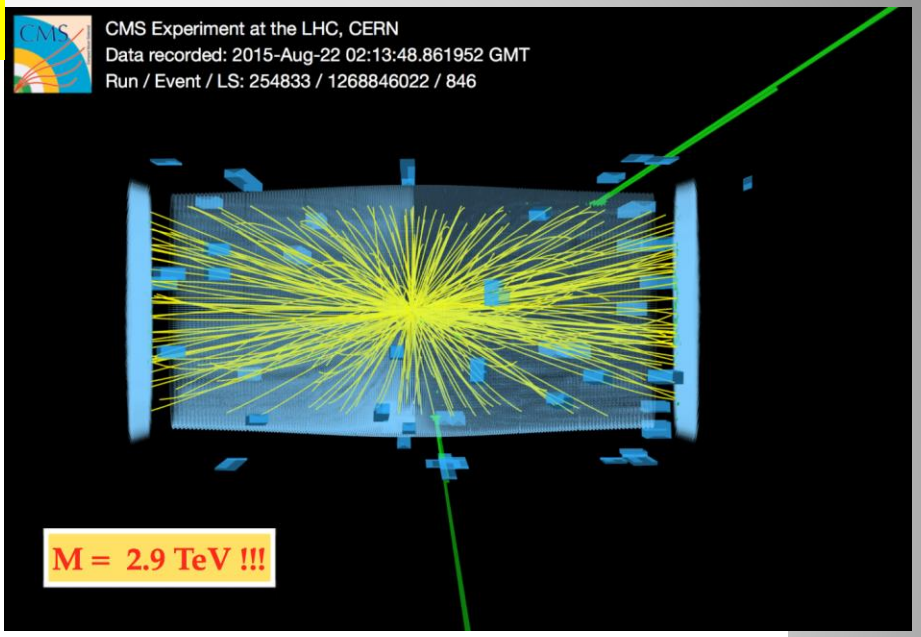


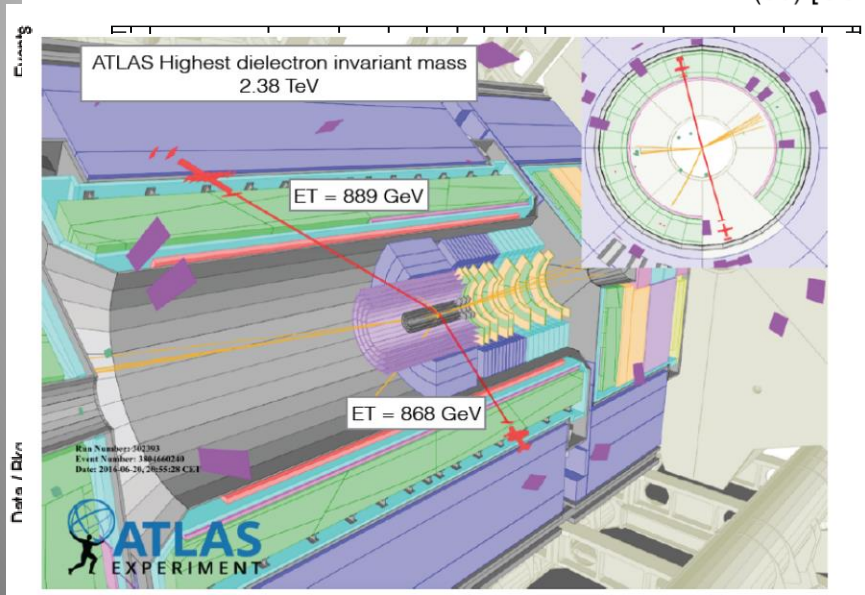
Sequential Standard Model Z' excluded for masses below 2.9 TeV

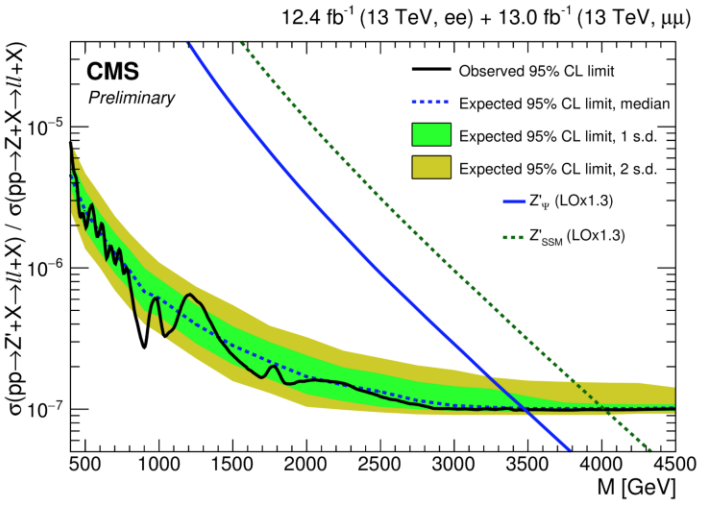
Search for New Gauge Bosons

Search for Z′ in dilepton decay channel





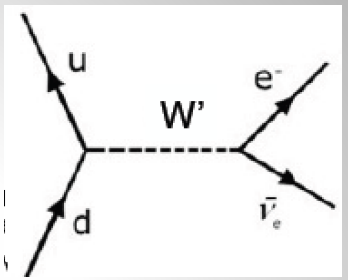


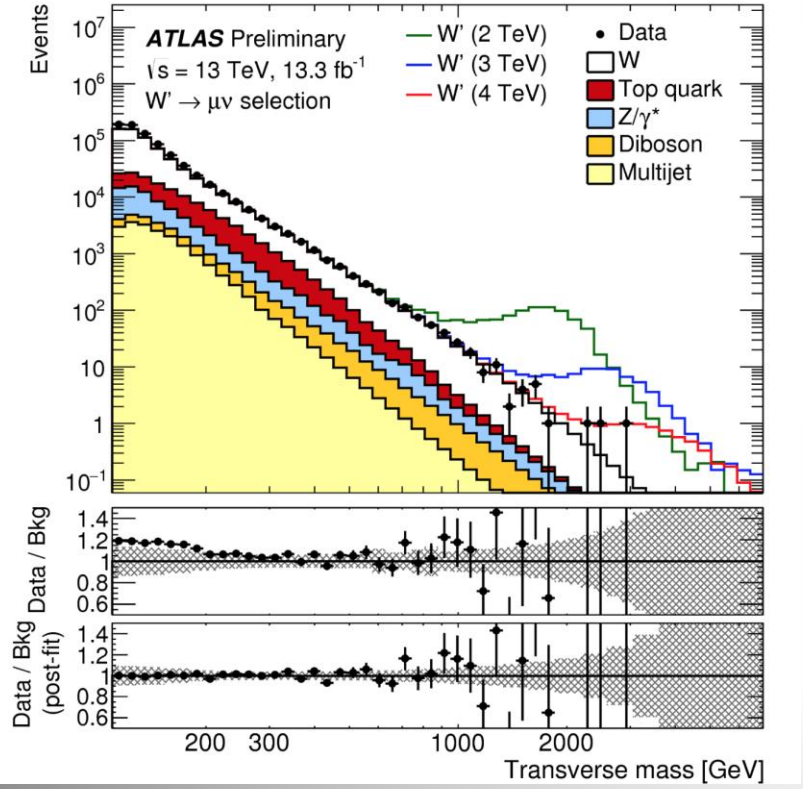


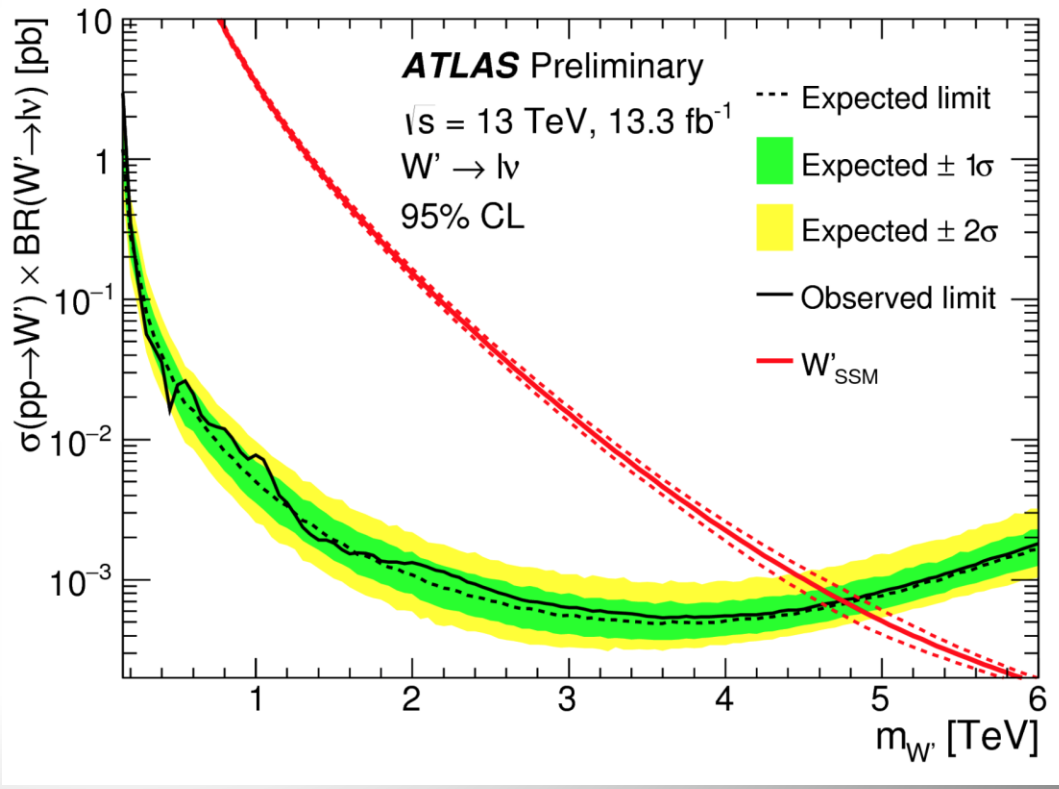
SSM Z′ excluded for masses below 4 TeV

Lepton+MET: Search for W'

CONF-16-061



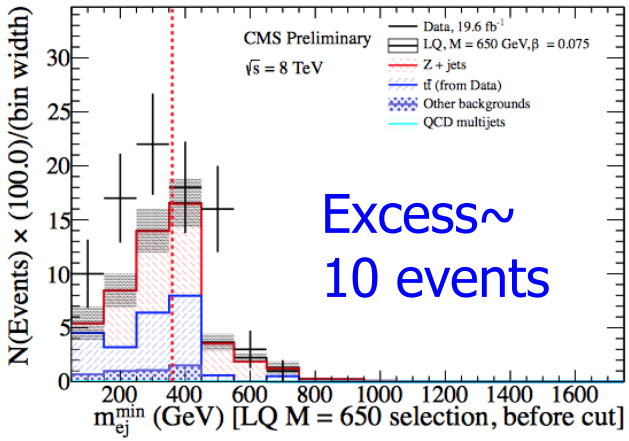


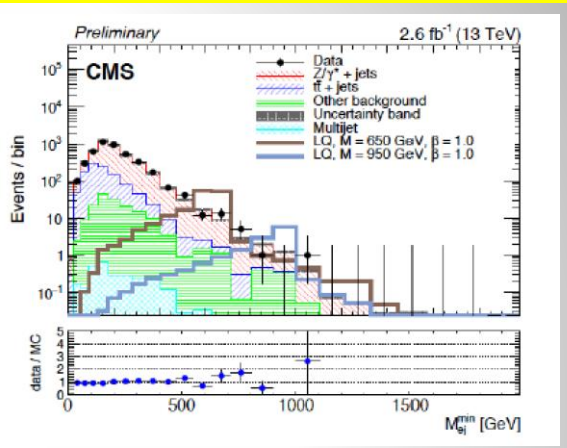


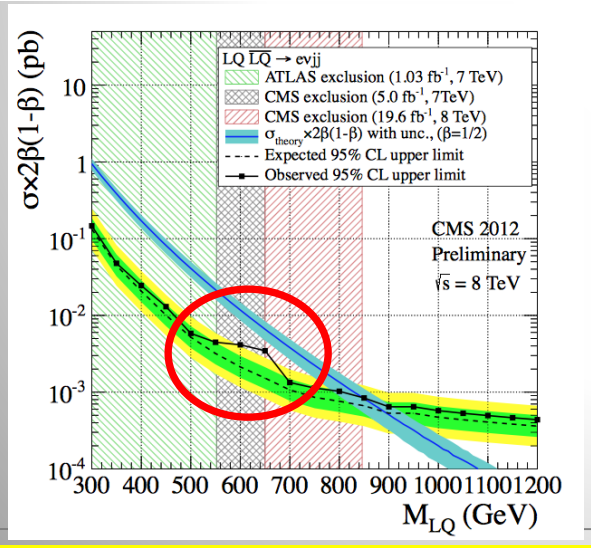
SSM W' excluded for masses below 4.8 TeV

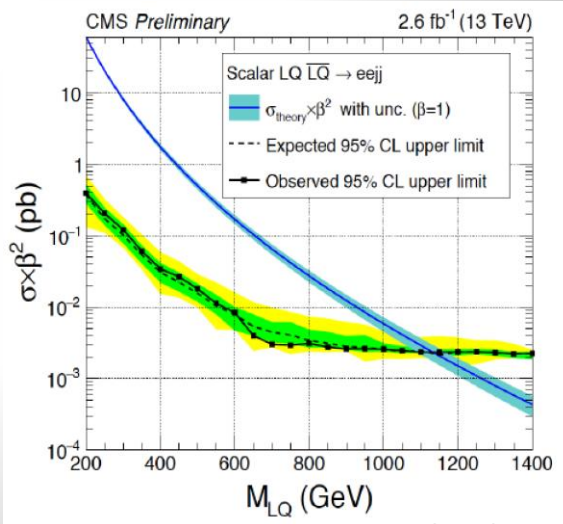
Leptoquark LQ->lepton+jet Search

Searches in leptions + jet channels
A small enhancement was seen in Run-1 in CMS in the e-jet channel (2.6σ)





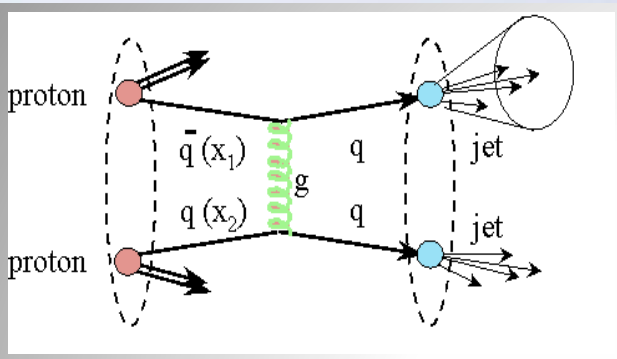




CMS-EXO-16-043

New data does not show any deviation from SM expectation.

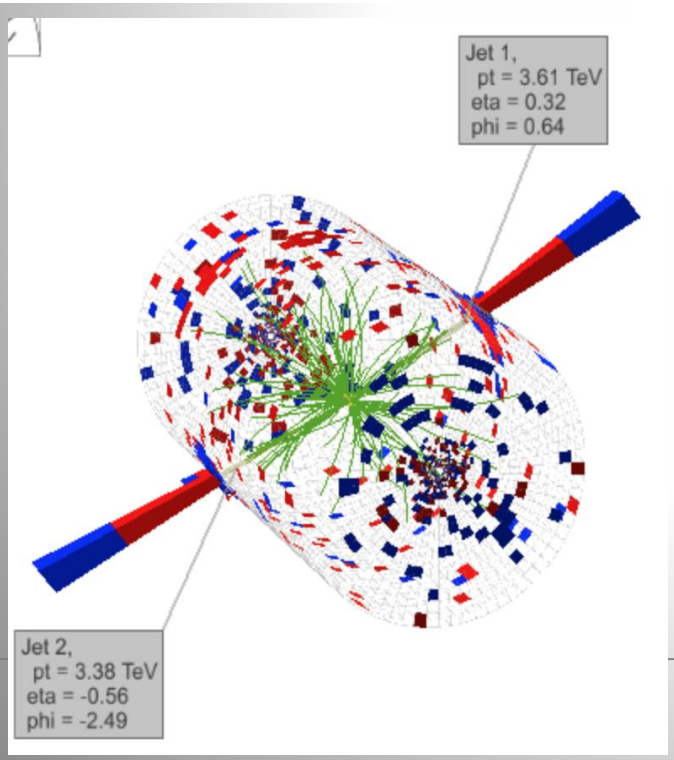
Dijet Resonance Search



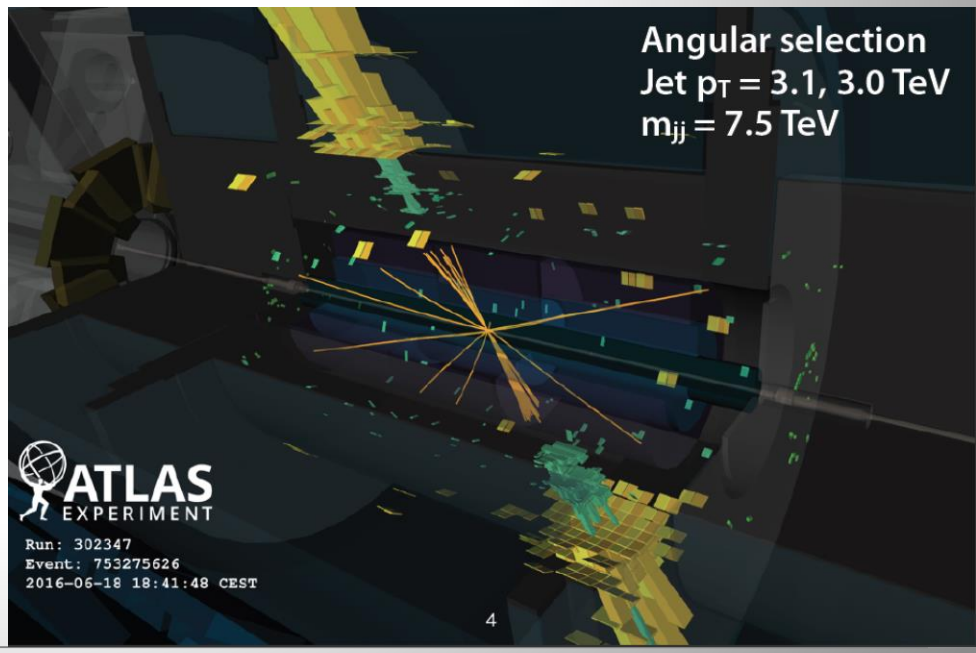
Coloured objects are easy to produce at pp colliders->High sensitivity early on

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

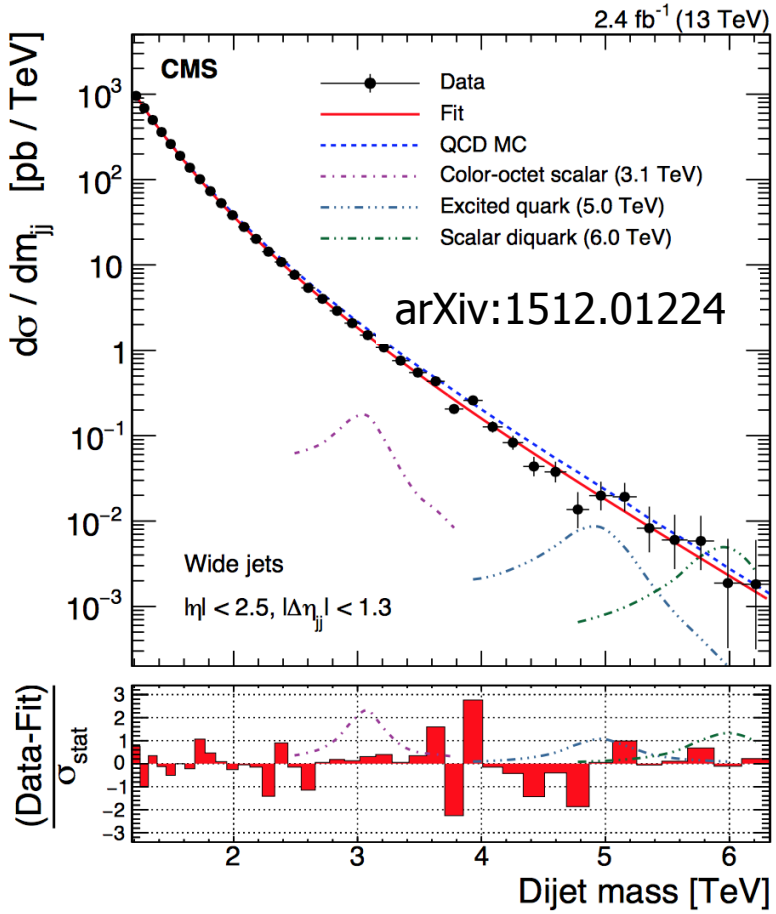
Dijet invariant mass = 7.7 TeV

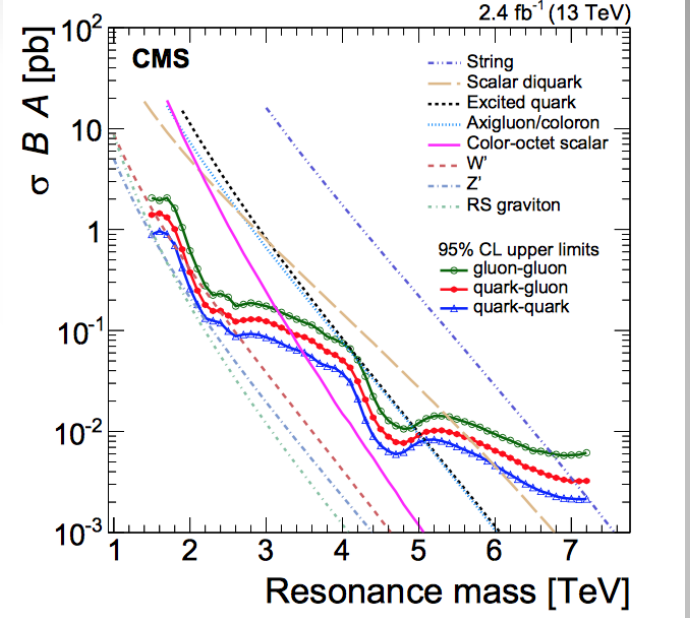


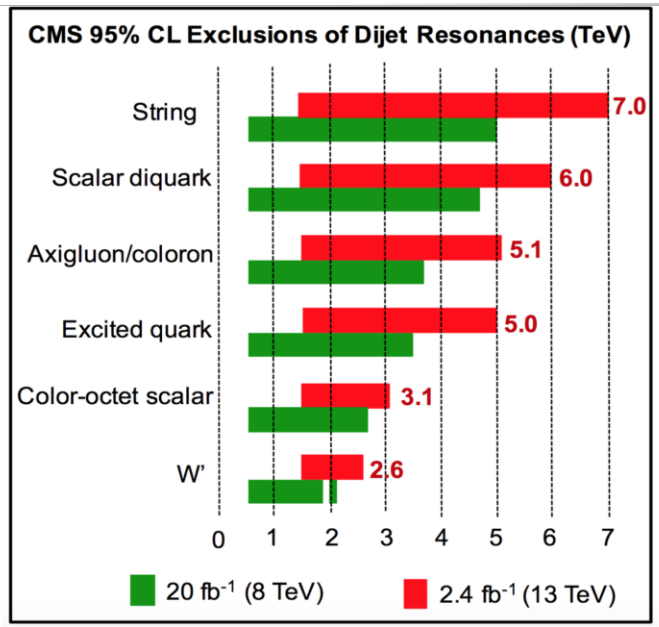
Dijet invariant mass = 7.5 TeV



Early Dijet Searches @ 13 TeV

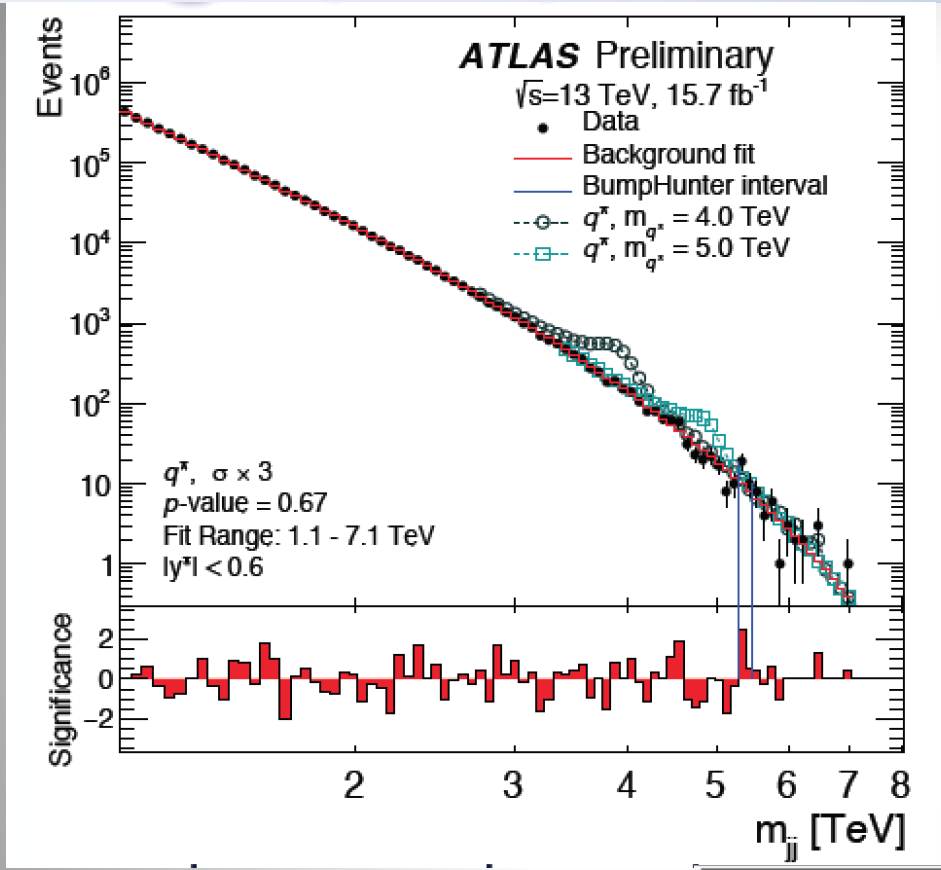


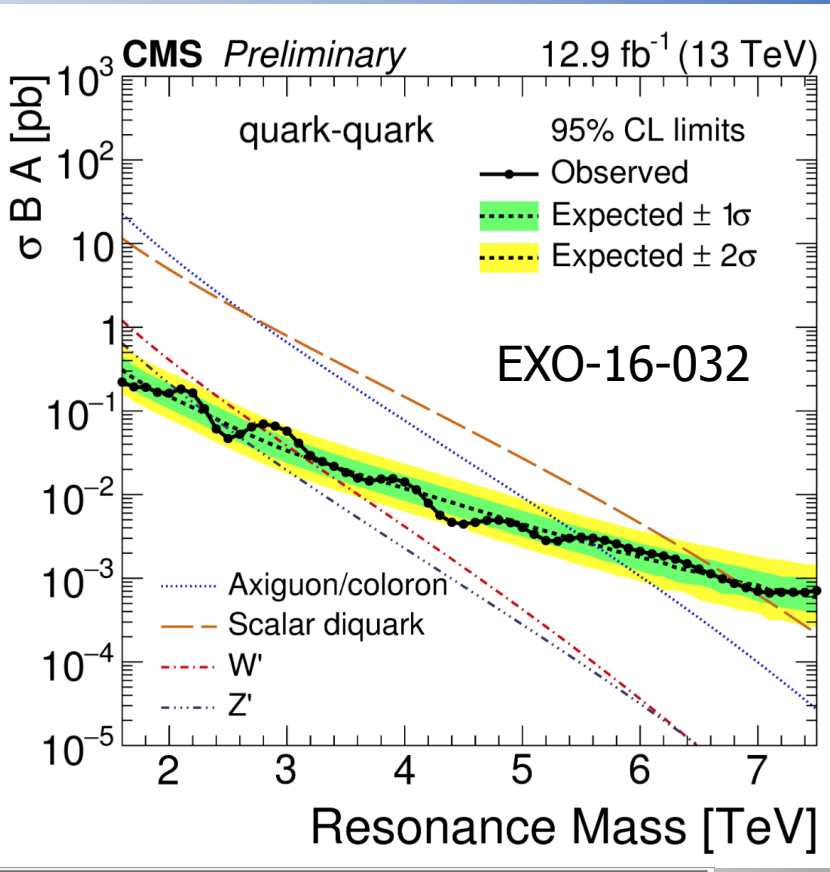




2.4 fb^{-1} limits from 13 TeV already surpass the 20 fb^{-1} limits from 8 TeV

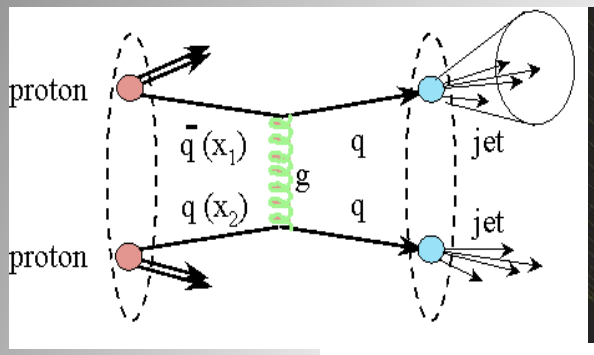
Dijet Searches: 13 TeV

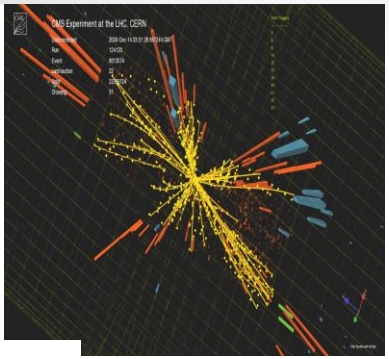


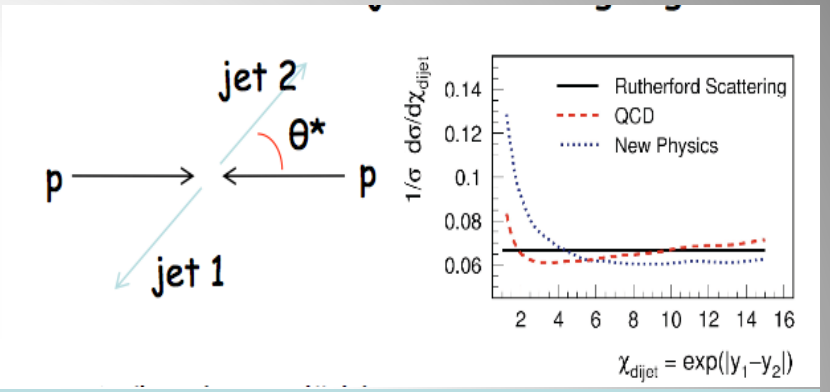


Model	Final State	Observed (expected) mass limit [TeV] 12.9 fb^{-1} 13 TeV	2.4 fb^{-1} 13 TeV	20 fb^{-1} 8 TeV
String	qg	7.4 (7.4)	7.0 (6.9)	5.0 (4.9)
Scalar diquark	qq	6.9 (6.8)	6.0 (6.1)	4.7 (4.4)
Axigluon/coloron	$q\bar{q}$	5.5 (5.6)	5.1 (5.1)	3.7 (3.9)
Excited quark	qg	5.4 (5.4)	5.0 (4.8)	3.5 (3.7)
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)

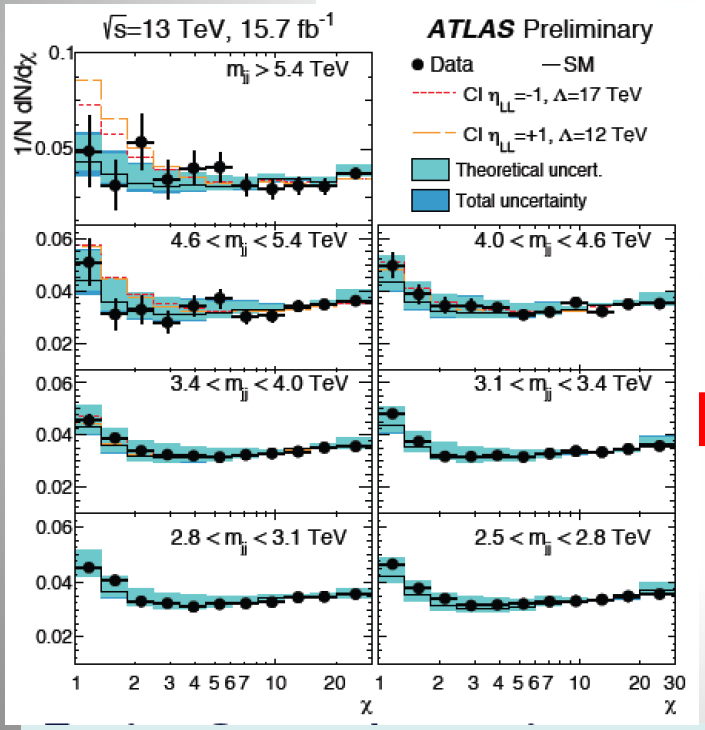
Are Quarks Elementary Particles?



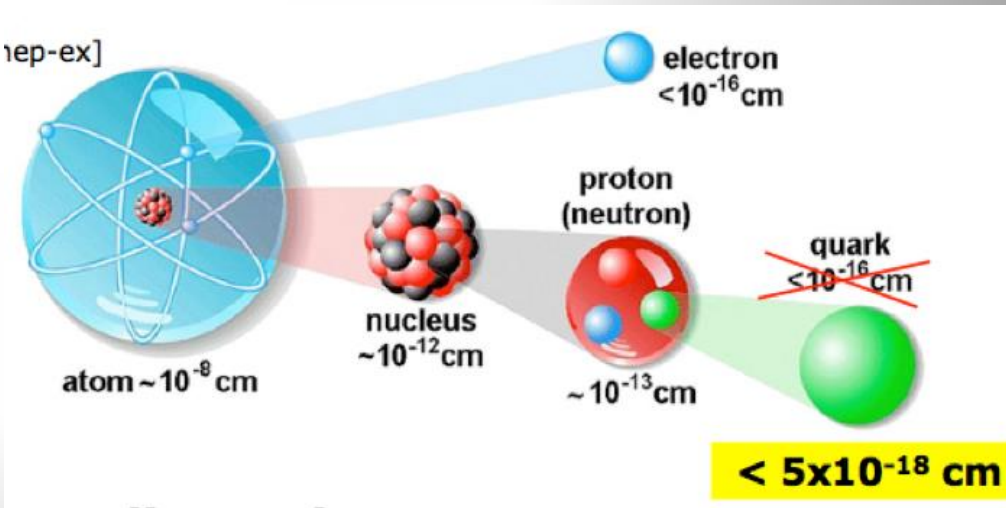




CONF-2016-069



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

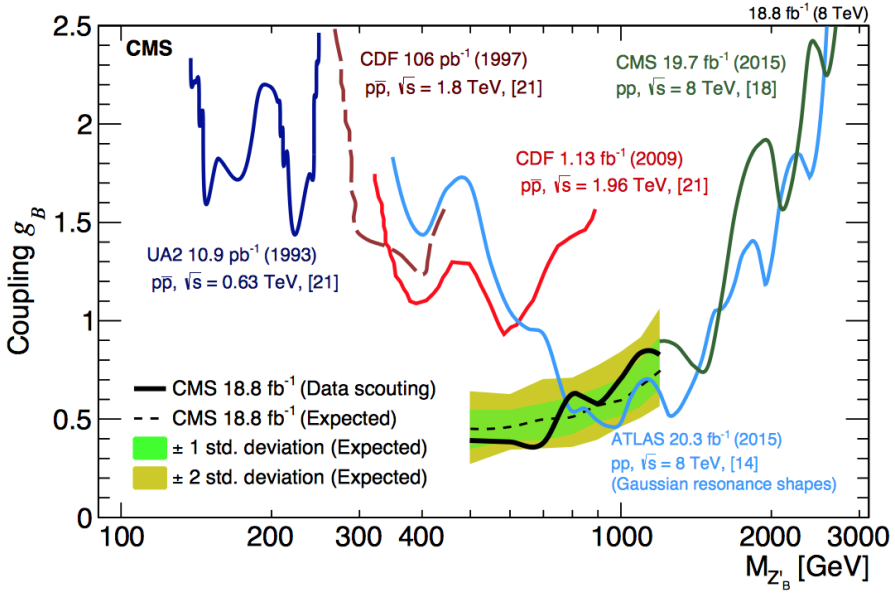
What about low mass & small couplings

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!

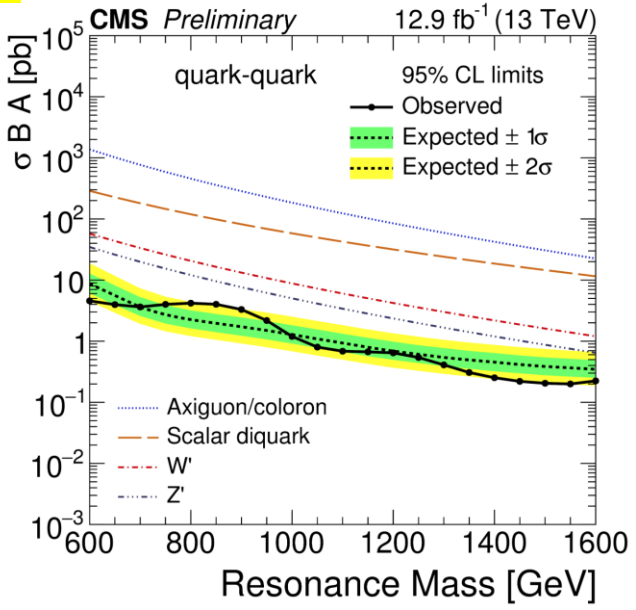
Solution: Reduce data size per event from 500 kB to 10 kB -> Keep only reconstructed jets at HLT/no raw data! This allows for a 1 kHz extra trigger rate for such data, without affecting the overall data taking (5% correction). Trigger used: Sum jet p_T > 250 GeV for jets with p_T> 40 GeV

Data Scouting!

arXiv:1604.08907



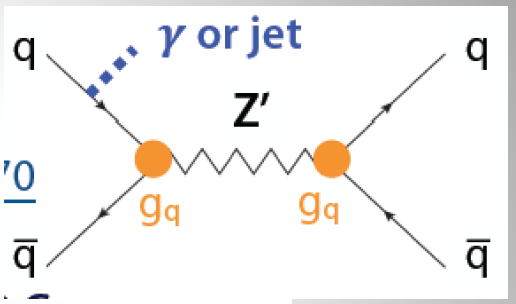
EXO-16-032

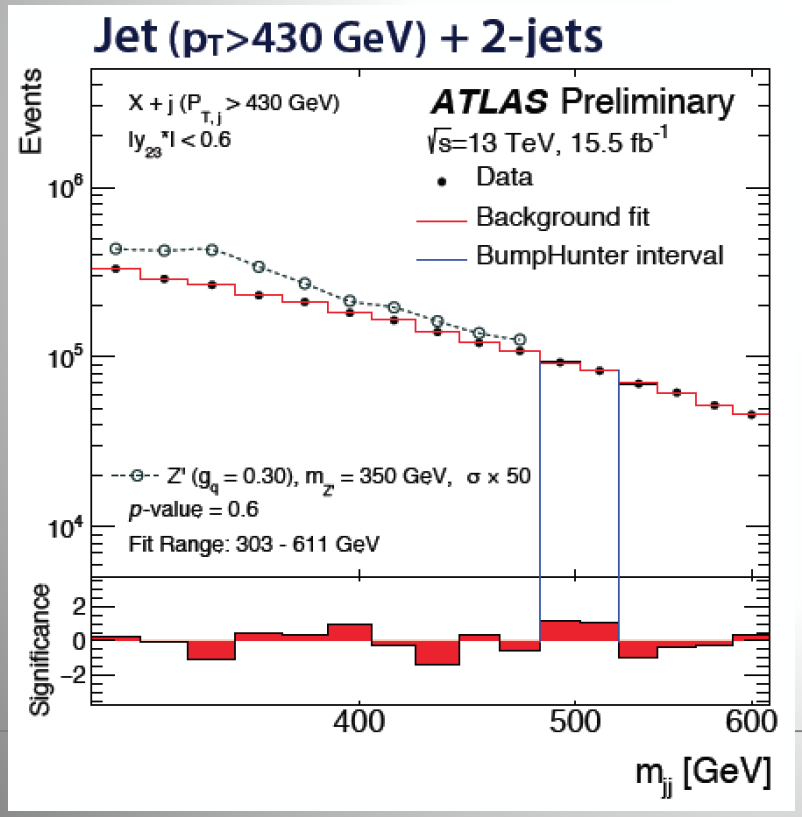


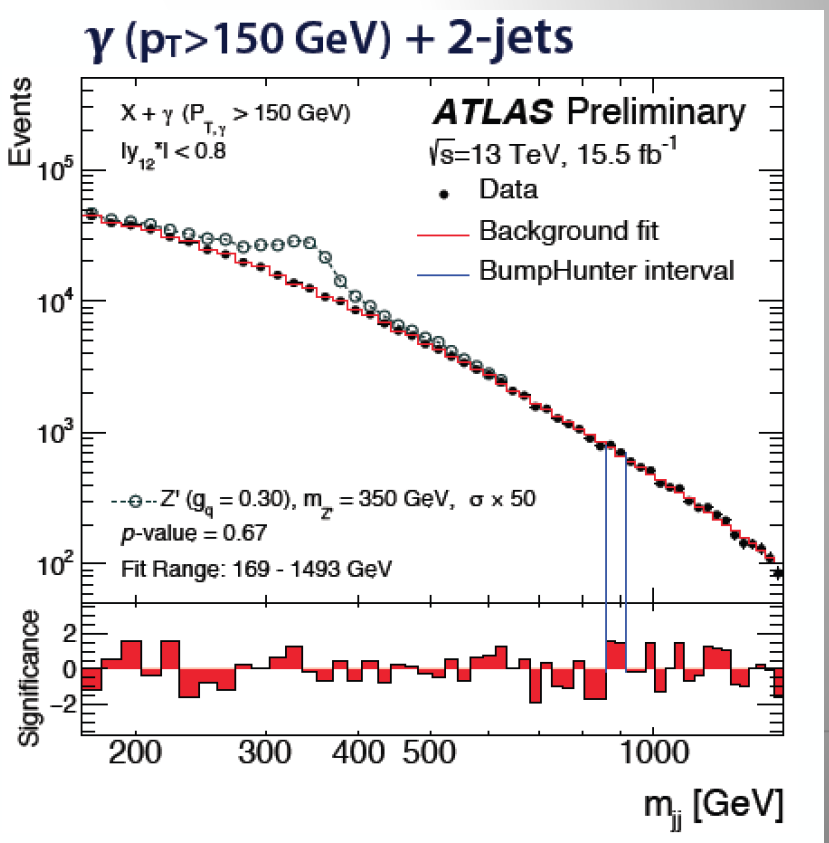
Access to lower mass/scale in dijets

CONF-2016-070

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

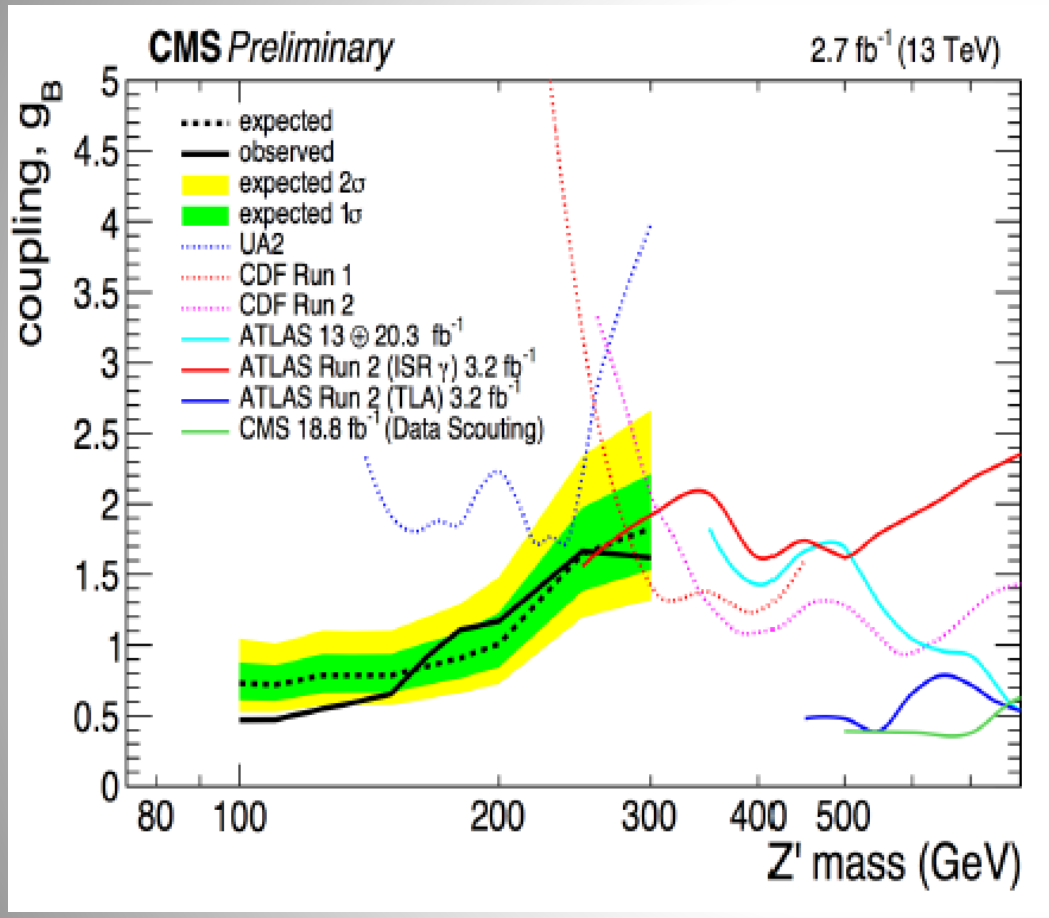






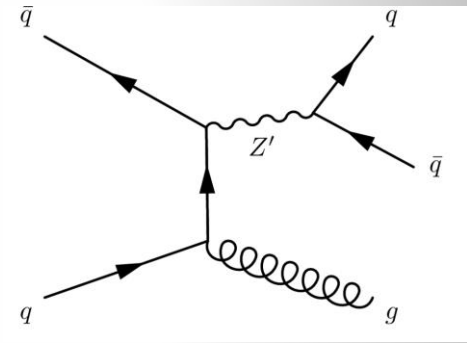
Access to lower mass/scale in dijets

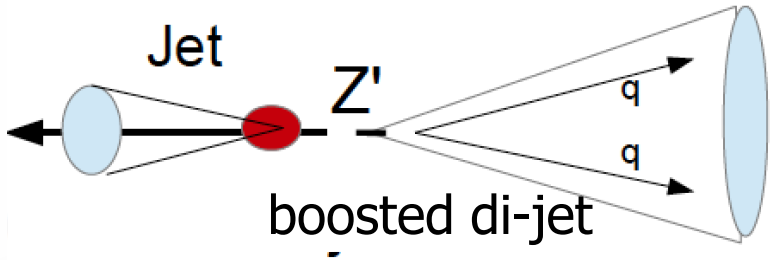
EXO-16-030



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 4th Generation

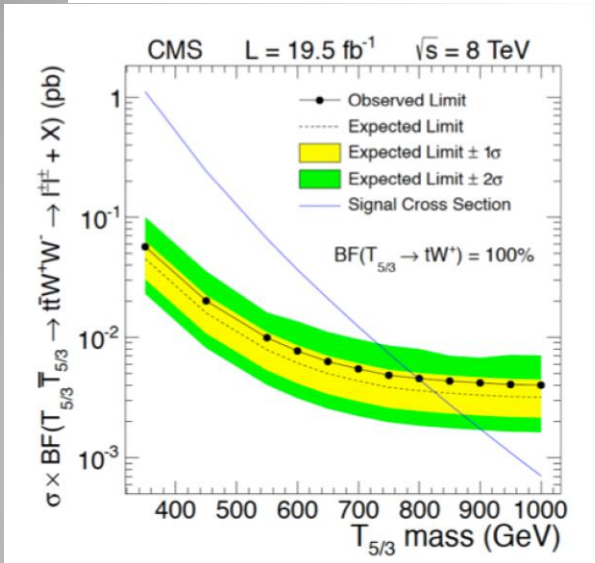
We can't be sure that there are only 3 generations (u,d) (s,c) (b,t)
A possible new generation should be heavy!
Look for b' and t' quarks in 2010-2011

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

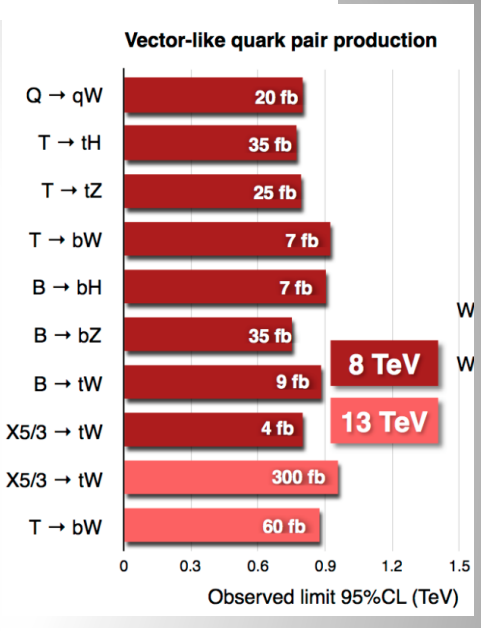
A 4th generation would also affect the Higgs rate in a substantial way, so it is unlikely to exist!

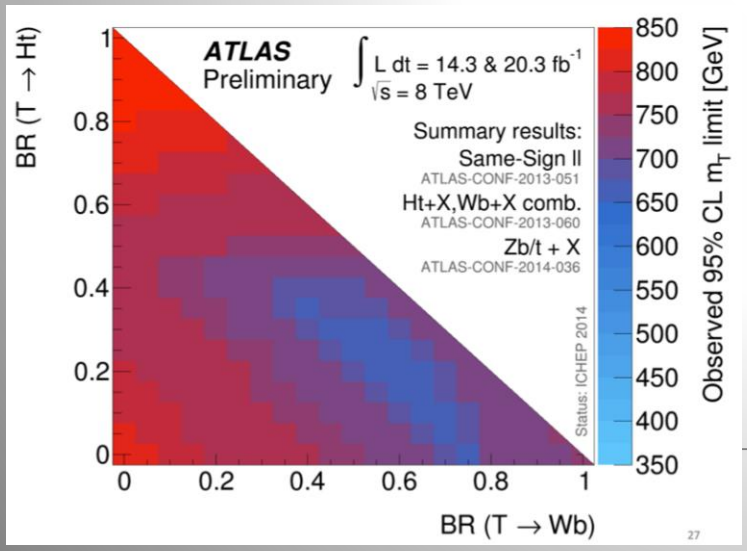
Vector-like Top/Bottom Partner Searches

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

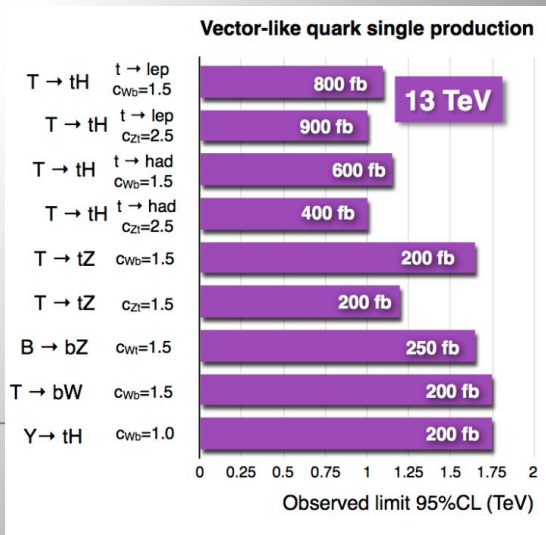


Vector-like quarks
Relevant eg in composite Higgs models

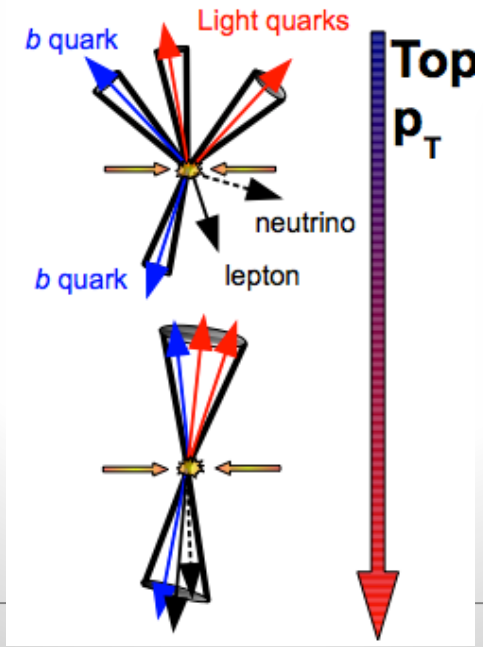




Exclusions up to masses of 800-900 GeV
And up to 1.75 TeV For singly produced VLQs



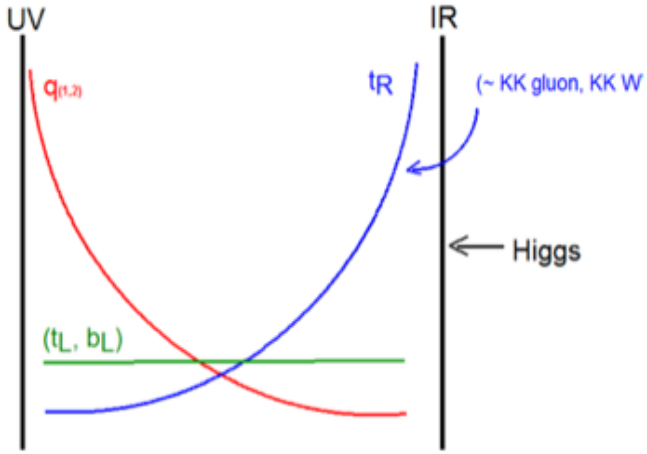
Searches with Boosted Objects



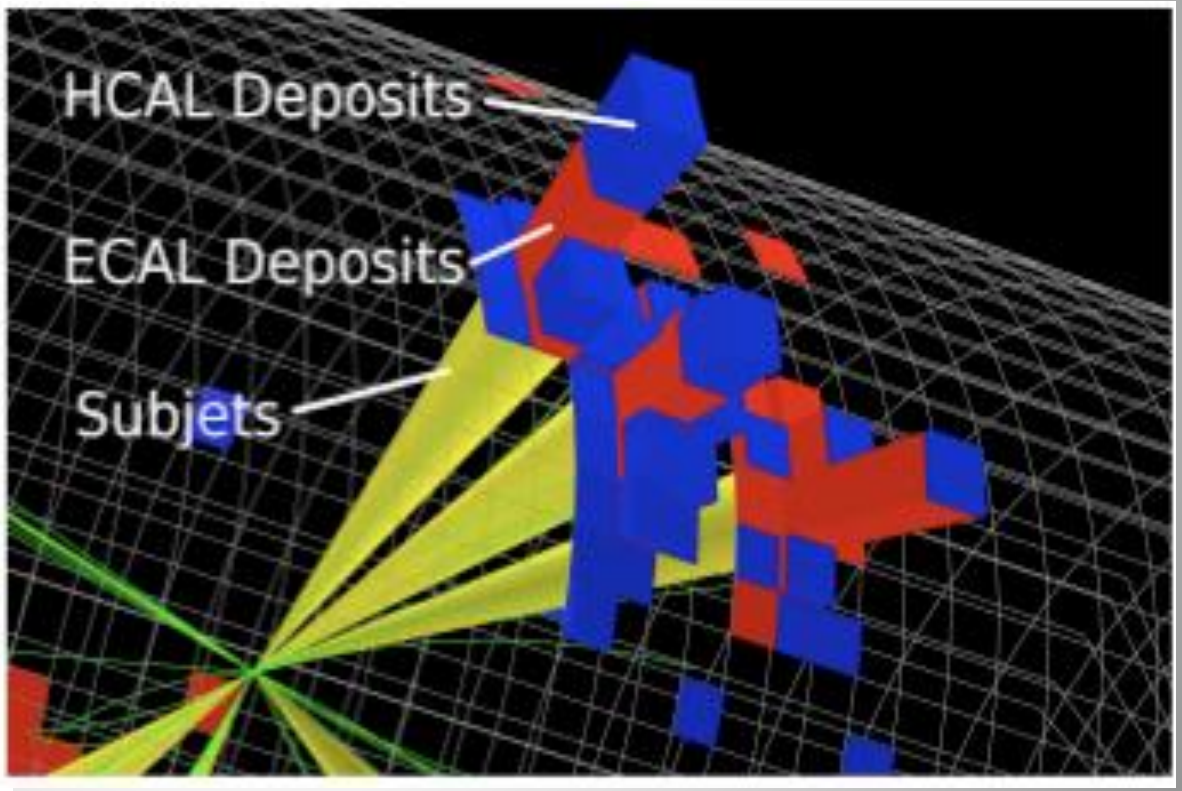
TeV Resonances into Top Quark Pairs

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 → t tbar

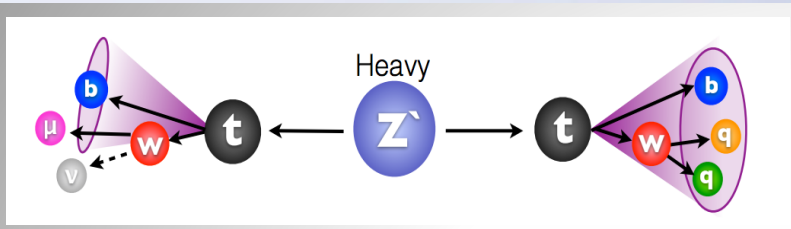


⇒High P_T tops



So far no signals found of the kind X -> tt

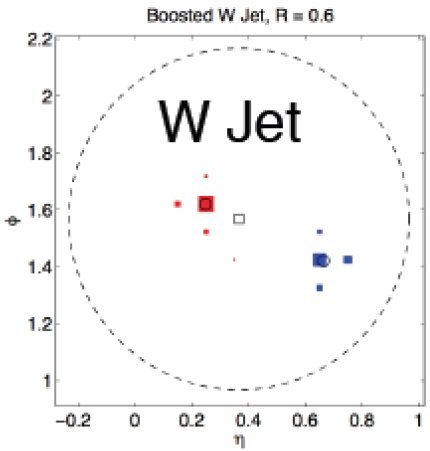
Searches with Boosted Objects

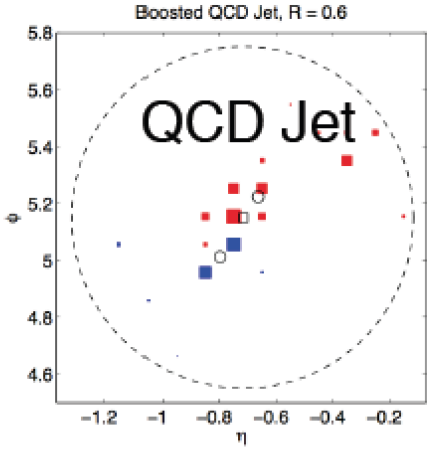


Discussed in topical "Boost Workshops"
Last one Zurich 18-22 July 2016
https://indico.cern.ch/event/439039/

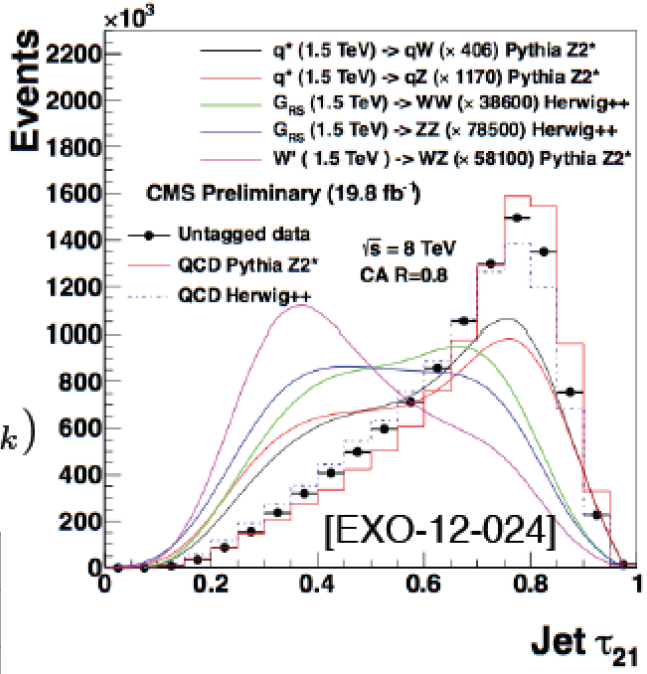
- Several different techniques to identify merged jets are on the market...
  - N-subjettiness, τ_N, uses $\tau_{21}=\tau_2/\tau_1$ as a discriminant to separate QCD jets from merged W/Z jets

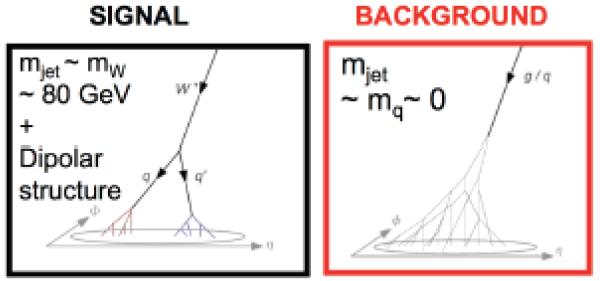
$$\tau_N = \frac{1}{d_0}\sum_k p_{T,k}\min\left(\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\right)$$



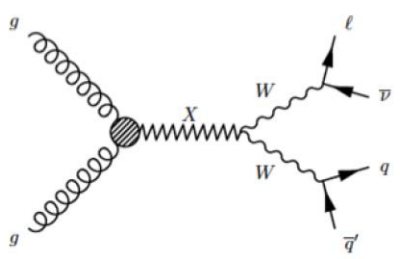


[Thaler, Tilburg, arXiv:1011.2268]

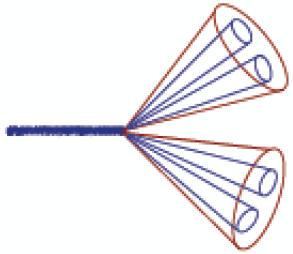




Resonances Decaying into VV?



Jets start to merge for X = 700-900 GeV

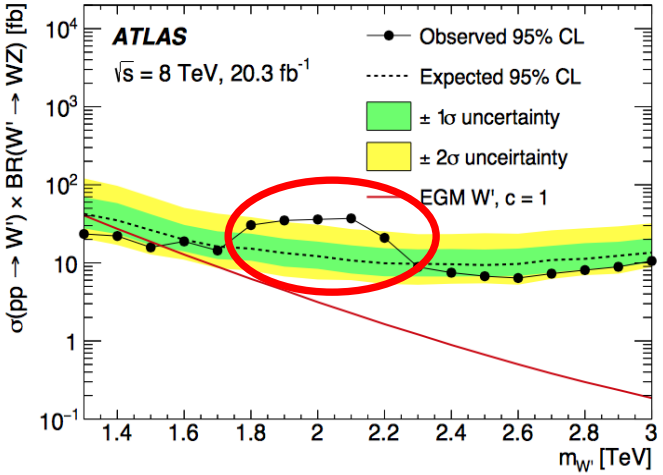


Run-1: Excess in ATLAS in WZ channel of 3.4σ (2.5σ with LEE) around 2 TeV.
Bump around 1.9 TeV in CMS in different channels (~2σ)

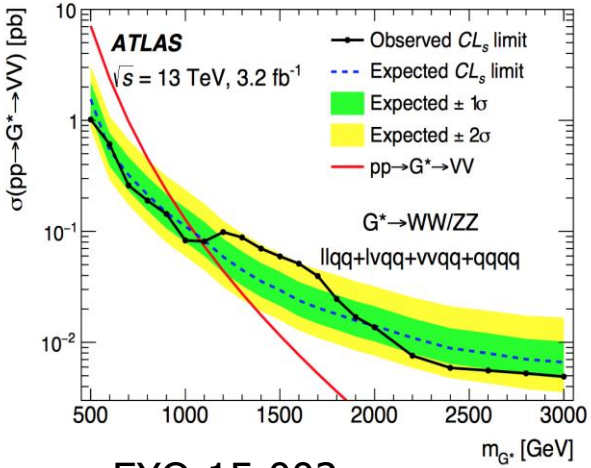
2015 data: Not confirmed more data needed to completely settle the issue

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

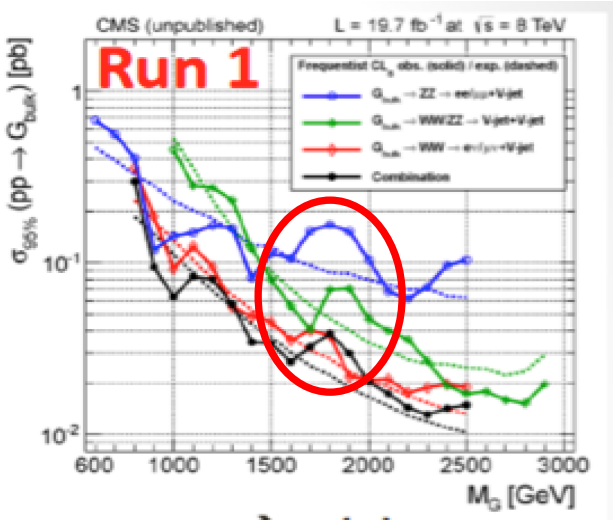
arXiv:1506.00962



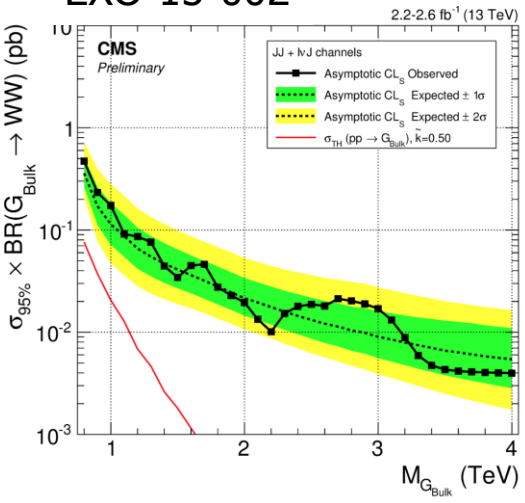
arXiv:1606.04833



arXiv:1405.1994

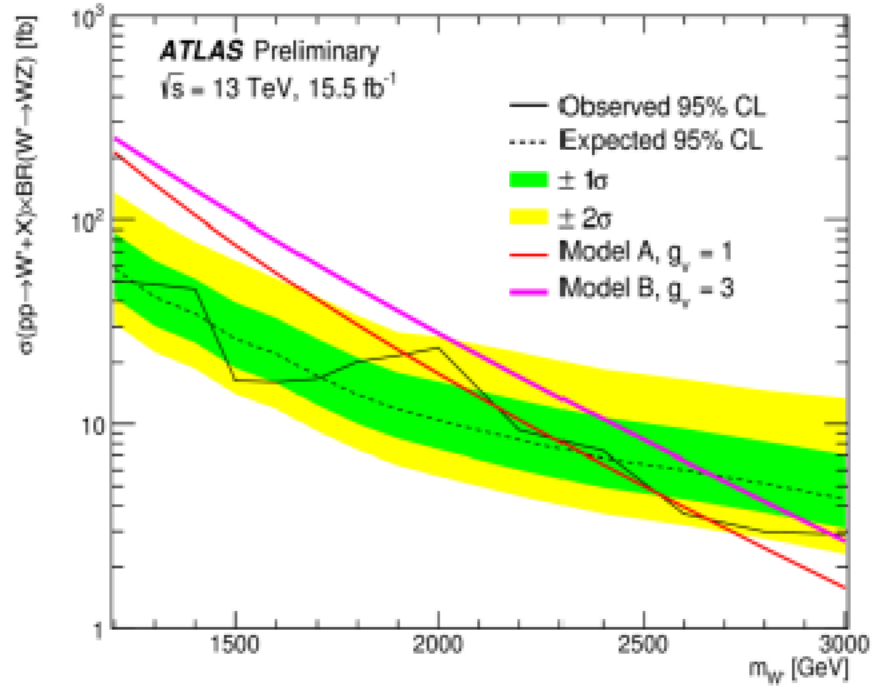


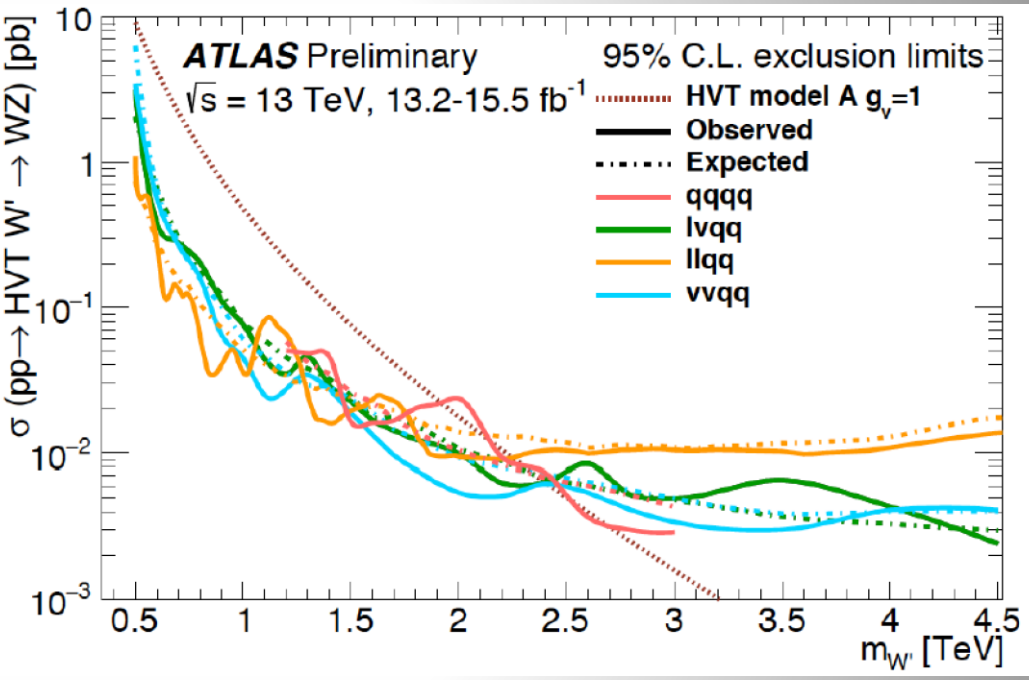
EXO-15-002



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..

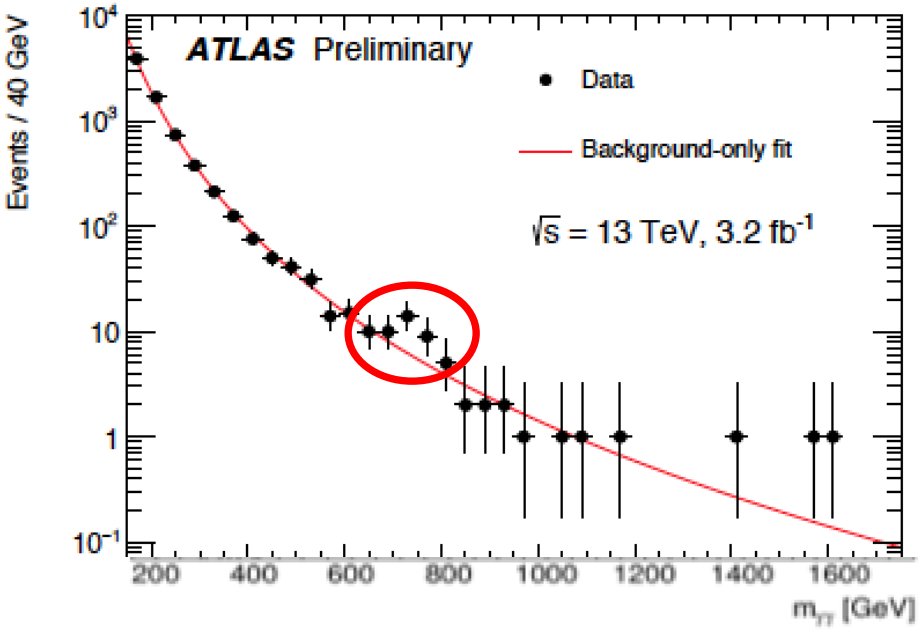
More channels analysed: X-> VV, VH, HH, γγ, Zγ,... No striking signals seen

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

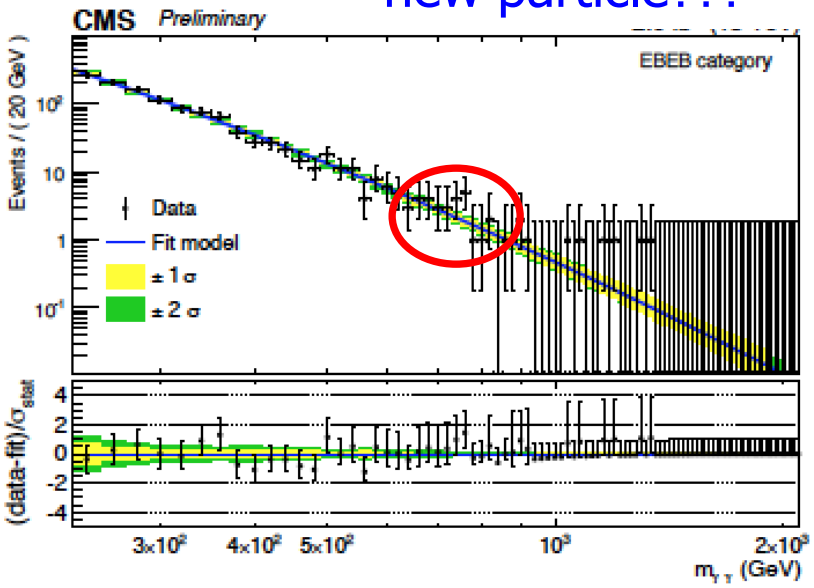
Excitement in December 2015
->Some excitement on an mild observed excess in both experiments for a diphoton mass of around 750 GeV

A totally unexpected new particle???

ATLAS-CONF-2015-081



CMS EXO-15-004

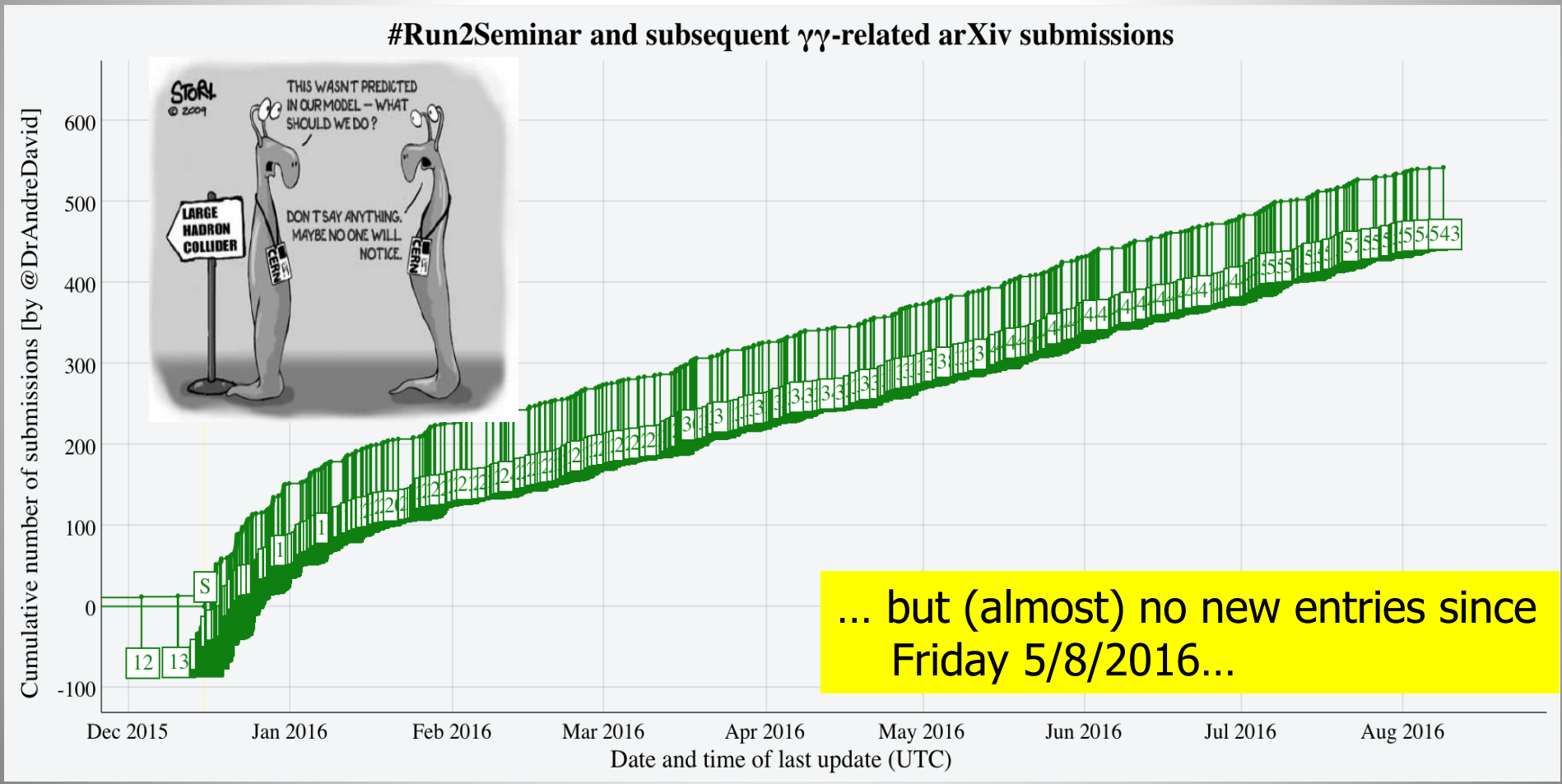


Statistical fluctuation? A new resonance? ???
Moriond: CMS: 3.4 σ ! ATLAS up to 3.9 σ !! (global significances)

This triggered >540 papers so far!!

Andre David: http://jsfiddle.net/adavid/bk2tmc2m/show/ 12/8/2016

Constant rate of 2 papers/ working day!



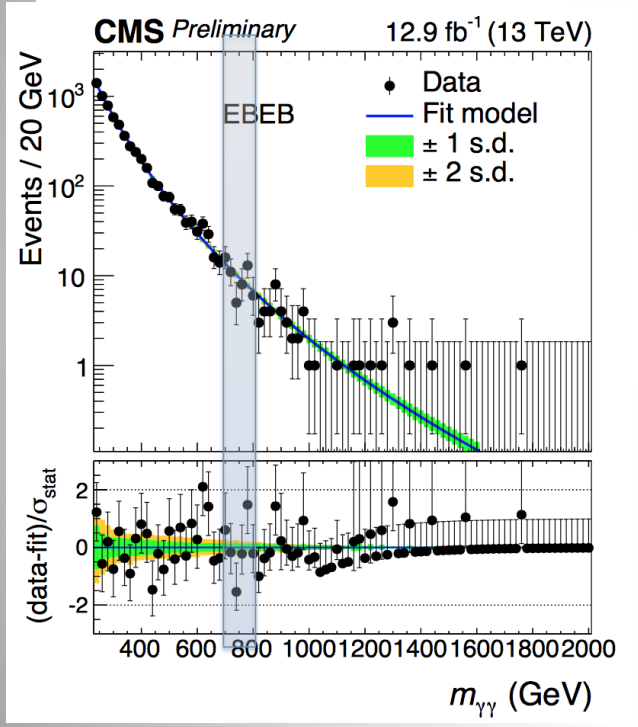
… but (almost) no new entries since Friday 5/8/2016…

A new Particle at 750 GeV: X → γγ ?

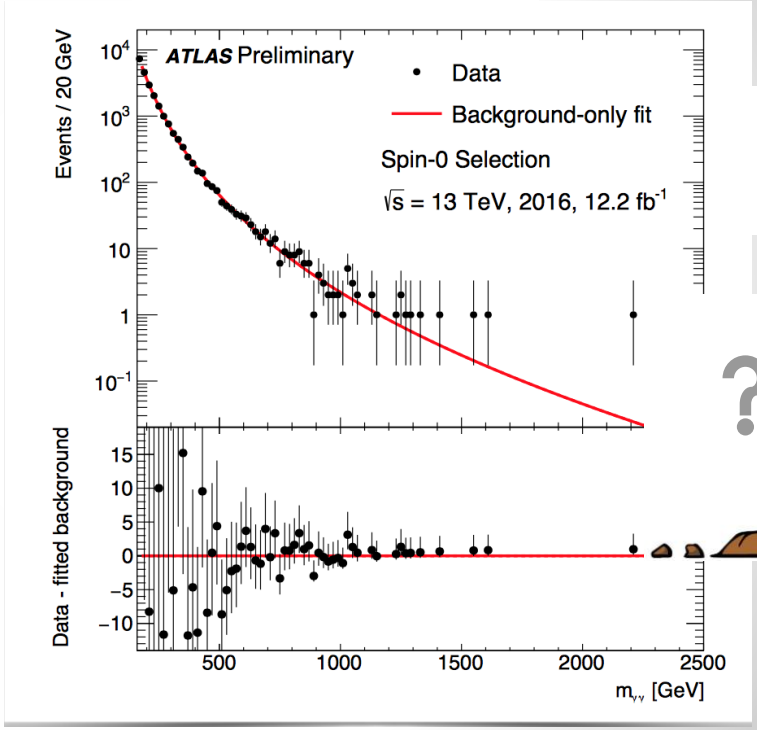
What does the 2016 data say ? (4 x 2015 data!!)

Last Friday at ICHEP!!

ATLAS-CONF-2016-059



CMS-EXO-16-027



Spin-0 analysis

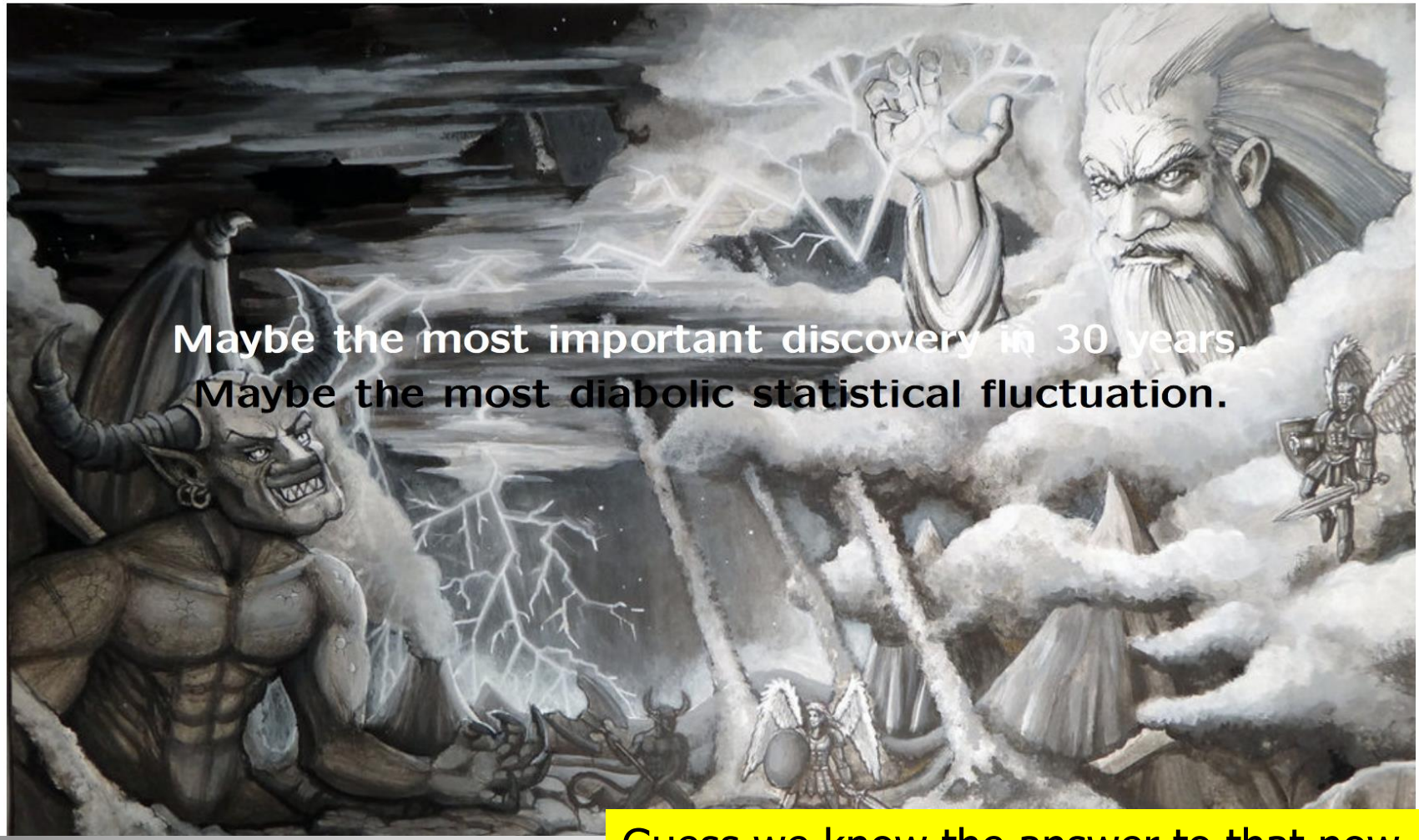
The excess is NOT seen in the new data from 2016!

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??

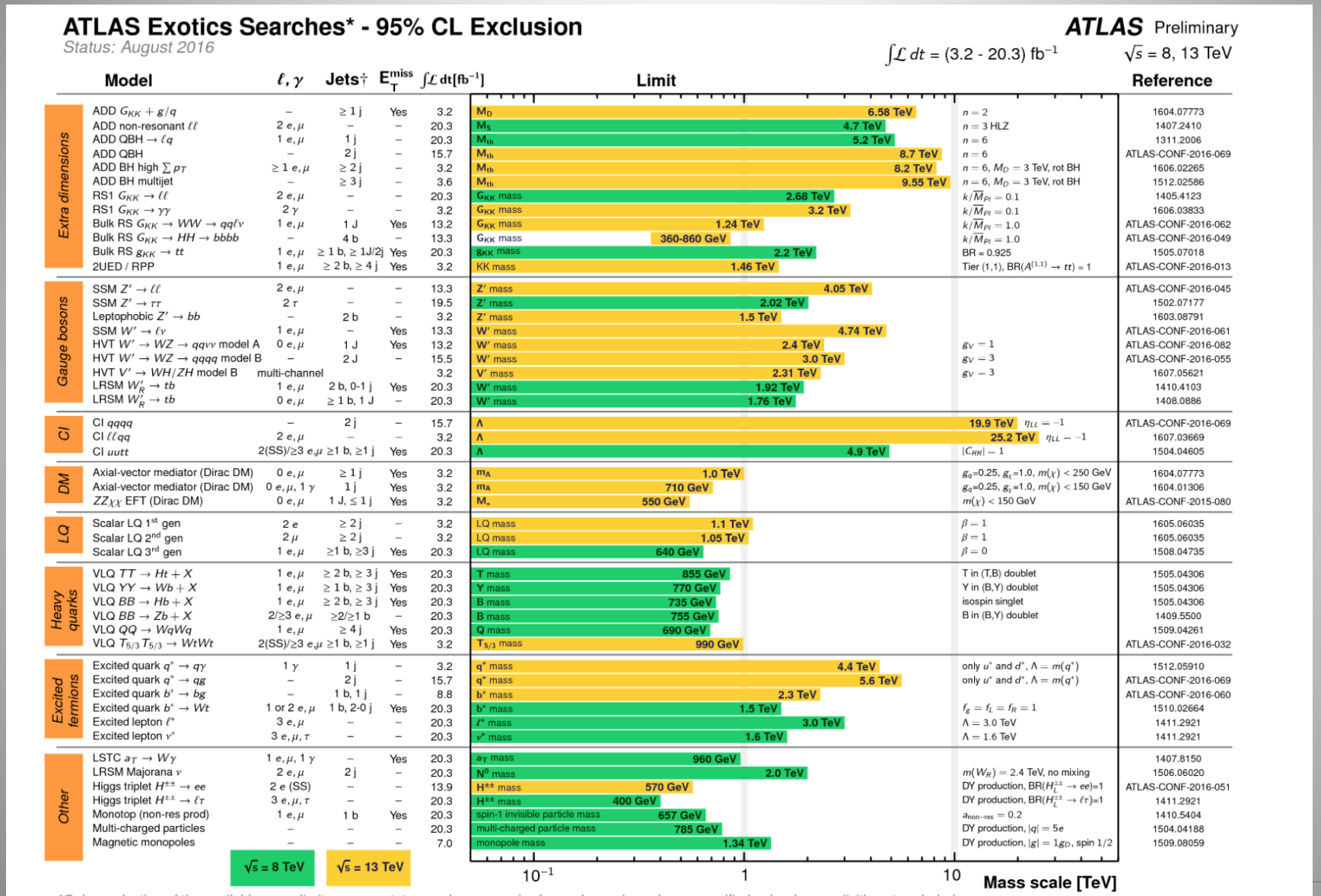
Moriond 2016 summary

A. Strumia



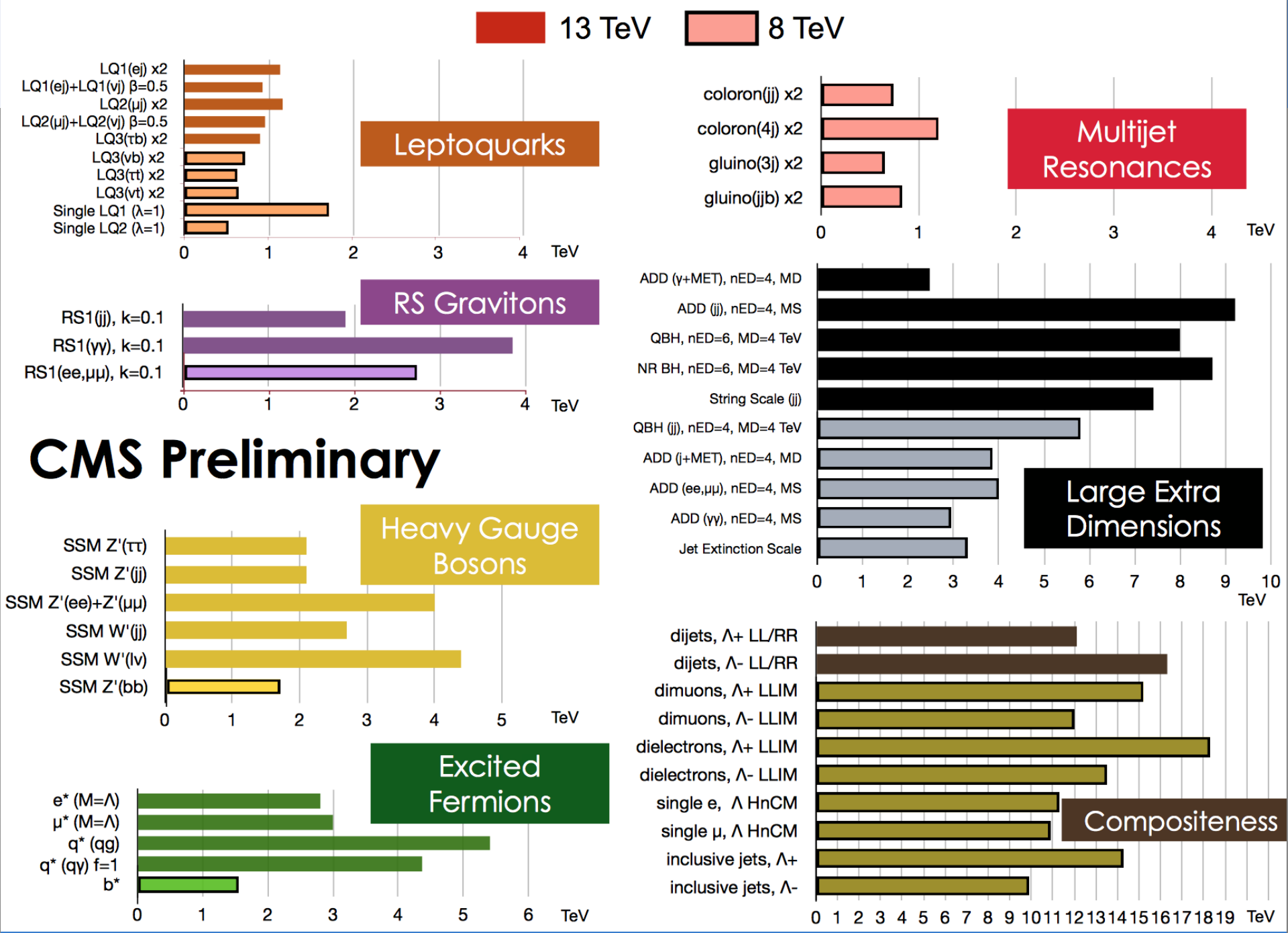
Guess we know the answer to that now… ☺

Exotics Search Summary



*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
LQ1(ej) x2
LQ1(ej)+LQ1(νj) β=0.5
LQ2(μj) x2
LQ2(μj)+LQ2(νj) β=0.5
LQ3(τb) x2
LQ3(νb) x2
LQ3(ττ) x2
LQ3(νt) x2
Single LQ1 (λ=1)
Single LQ2 (λ=1)
Leptoquarks
RS1(jj), k=0.1
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
RS Gravitons
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
Multijet Resonances
ADD (γ+MET), nED=4, MD
ADD (jj), nED=4, MS
QBH, nED=6, MD=4 TeV
NR BH, nED=6, MD=4 TeV
String Scale (jj)
QBH (jj), nED=4, MD=4 TeV
ADD (j+MET), nED=4, MD
ADD (ee,μμ), nED=4, MS
ADD (γγ), nED=4, MS
Jet Extinction Scale
Large Extra Dimensions
CMS Preliminary
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM Z'(bb)
Heavy Gauge Bosons
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ) f=1
b*
Excited Fermions
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dielectrons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
Compositeness
TeV

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)

  S.C. Hsu ICHEP 2016
- Let's look at Supersymmetry next

End of Lecture I

Backup