Beyond the Standard Model

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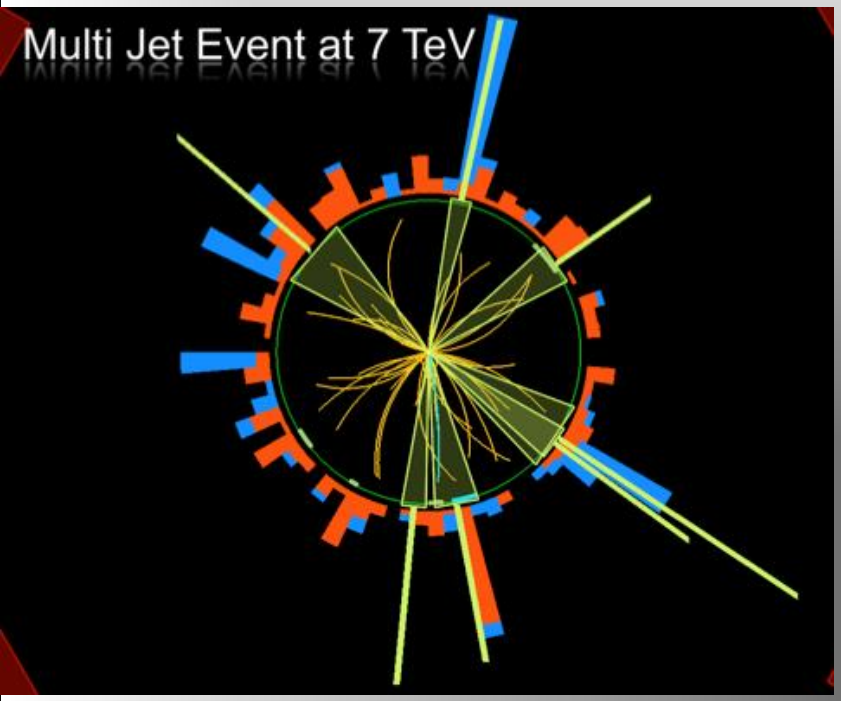
17th February 2016

CMSDASia - CMS Data Analysis School in Taipei, Taiwan



Outline Lecture

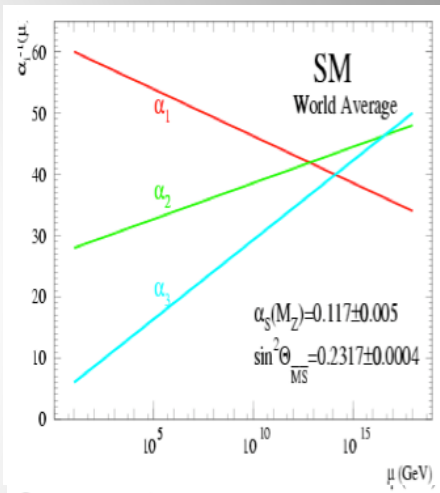
- Search for Physics Beyond the Standard Model
- Search for Exotica
- Search for Supersymmetry
- The Dark Matter connection
- Summary

Physics case for new High Energy Machines

Understand the mechanism Electroweak Symmetry Breaking

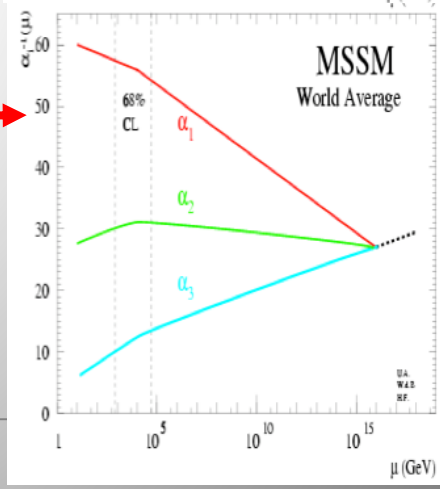
Discover physics beyond the Standard Model

Reminder: The Standard Model
- tells us how but not why
  3 flavour families? Mass spectra? Hierarchy?
- 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 since 2000

- Supersymmetry
- Extra space dimensions

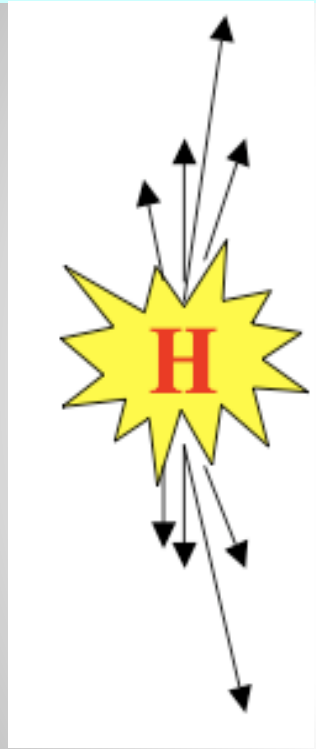


Many other ideas: More symmetry and gauge bosons,
L-R symmetry, quark & lepton substructure, Little Higgs models,
Technicolor, Hidden Valleys, 4th generation…

Higgsless models disfavoured these days ☺

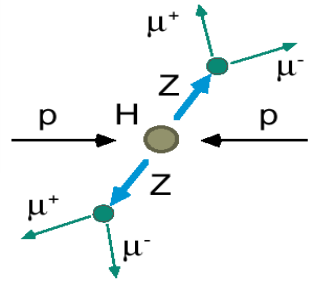
2012: A Milestone in Particle Physics

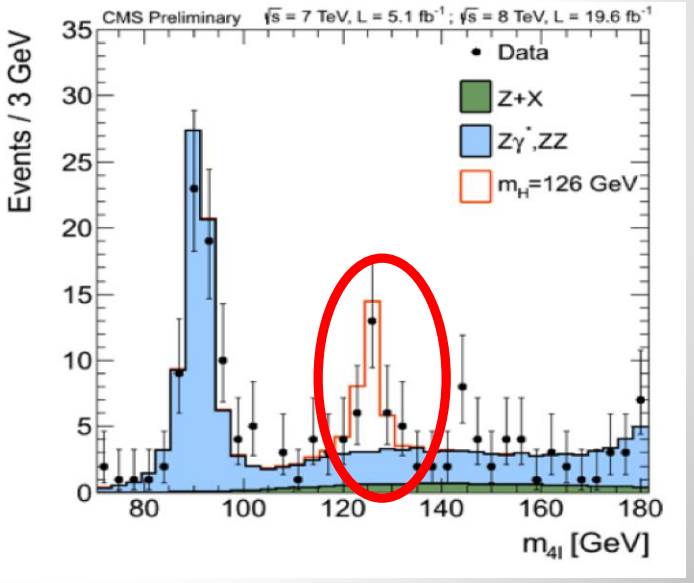
Observation of a Higgs Particle at the LHC, after about 40 years of experimental searches to find it



proton

proton



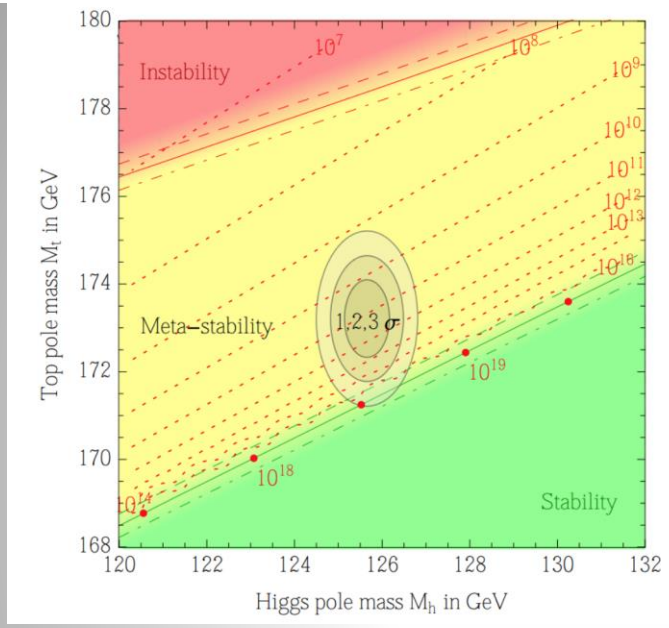


2013

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

Searches for New Physics

Important SM parameter → stability of EW vacuum

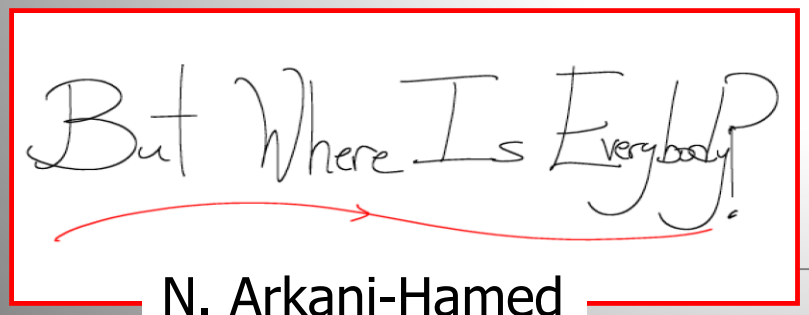


arXiv:1205.6497

arXiv:1403.6535

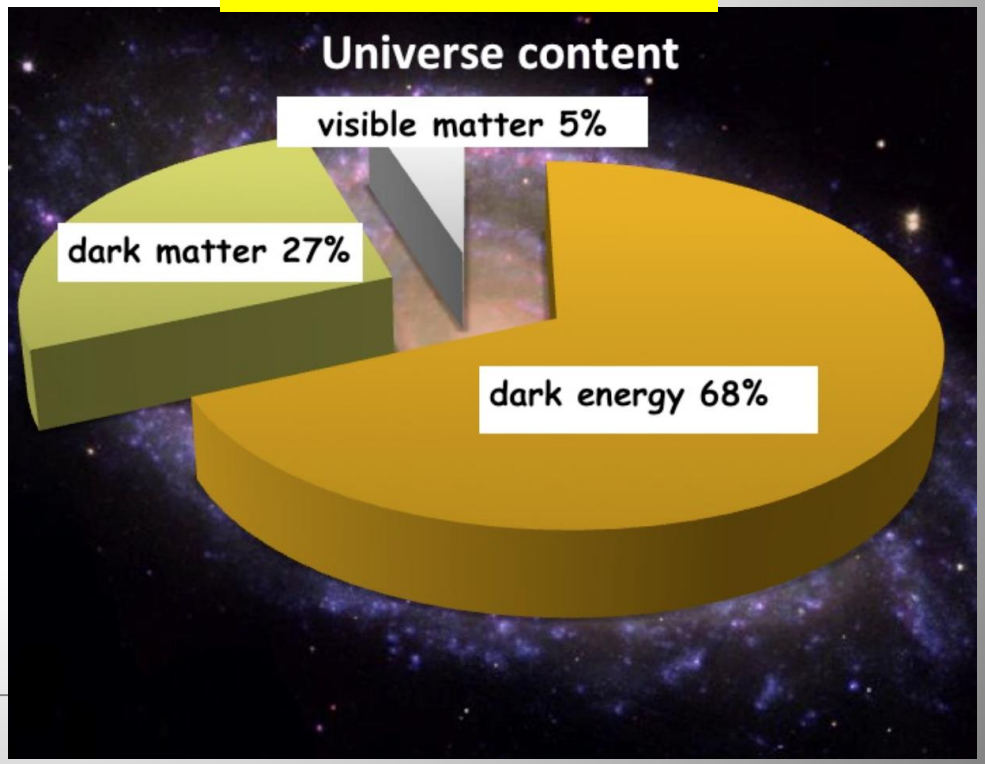
Precise measurements of the top quark and first measurements of the Higgs mass

New Physics inevitable?
But at which scale/energy?



N. Arkani-Hamed

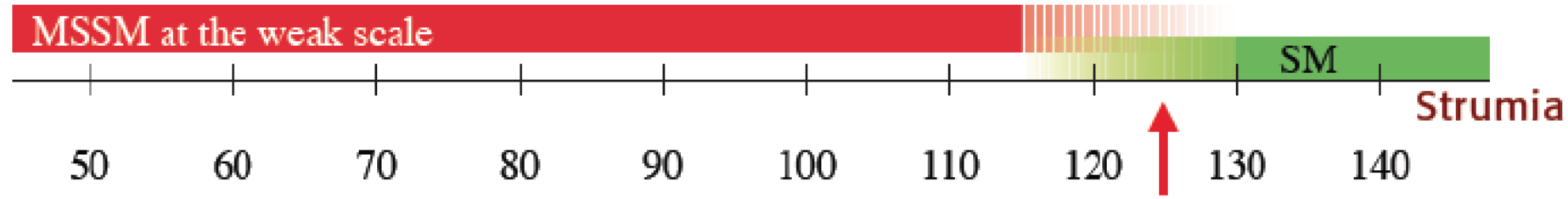
We also know that:



A Higgs @ 125 GeV…

A malicious choice!

m_H = 125.0 +/- 0.2 GeV



The Higgs:
so simple yet so unnatural

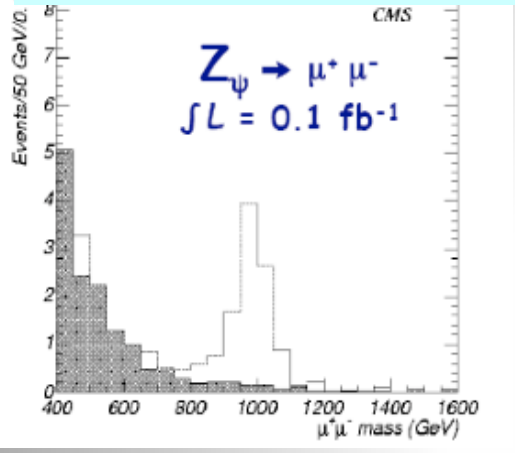
Guido Altarelli
1941-2015

Stockholm Nobel Symposium
May 2013

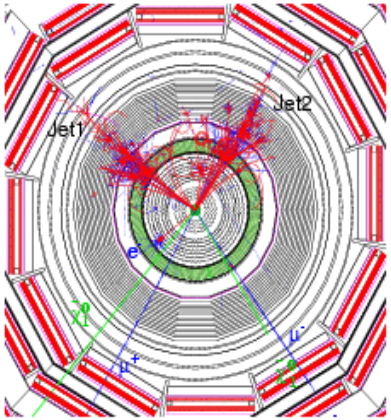
"We do not understand why the mass of the Higgs is 125 GeV
It most likely tells us something on what is Beyond the Standard Model"

New Physics?

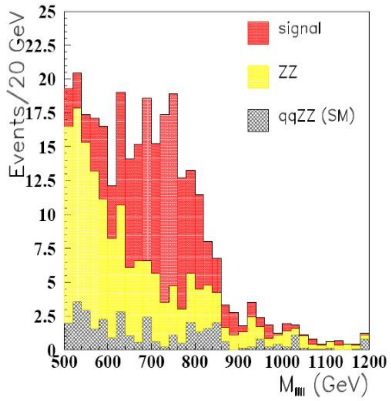
New Gauge Bosons?



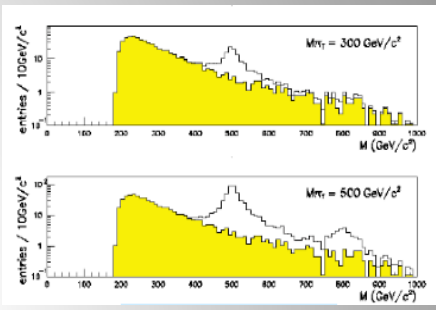
Supersymmetry



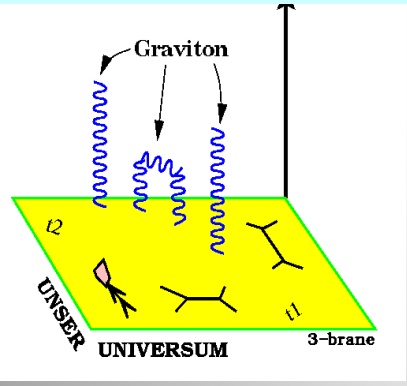
ZZ/WW resonances?



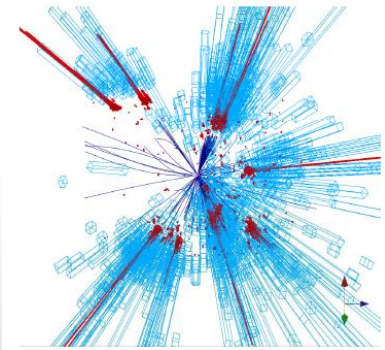
Technicolor?



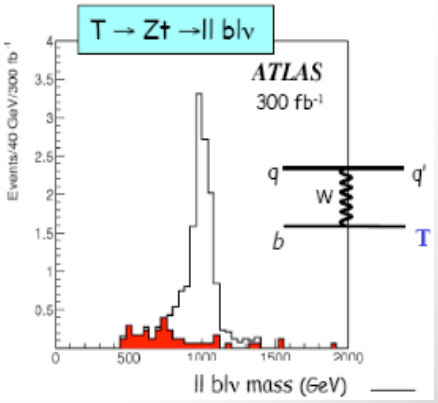
Extra Dimensions?



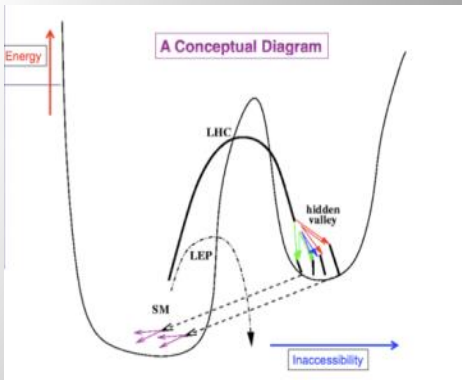
Black Holes???



Little Higgs?



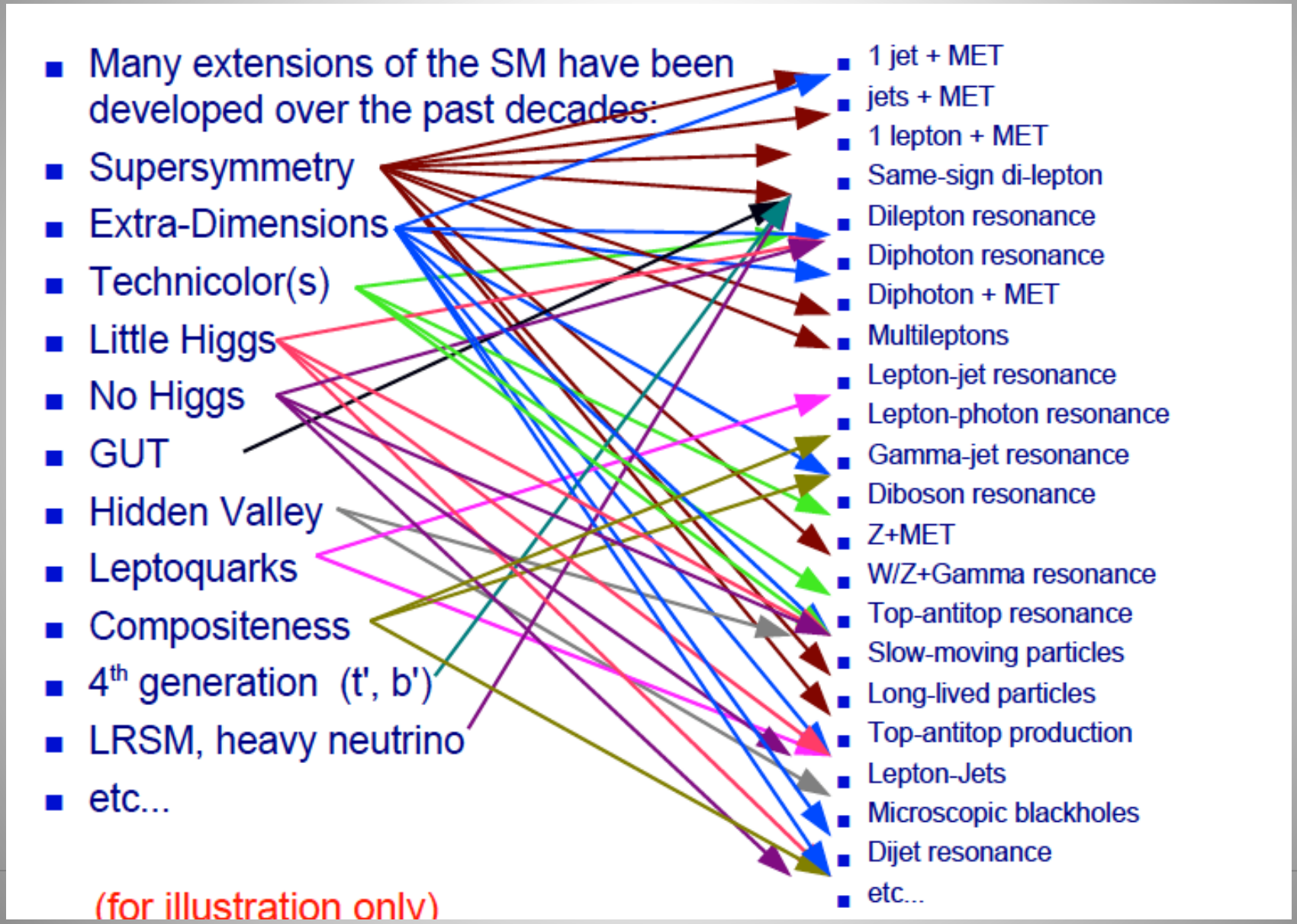
Hidden Valleys?



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

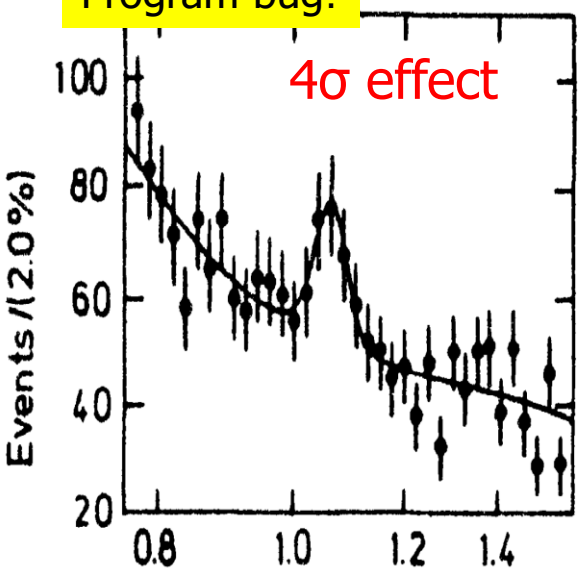
Beyond the SM Signatures



Beware of "Discoveries": Examples

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

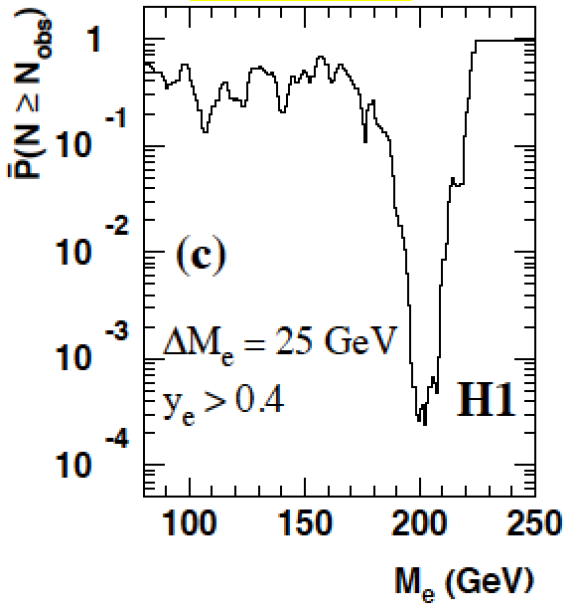
Program bug!



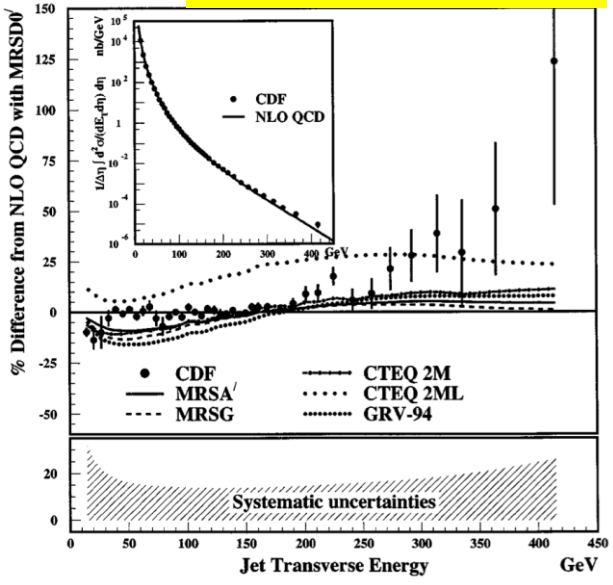
Is the X(8.31 GeV) the Higgs particle? A lot of excitement summer 1984

Non of these made it!

Statistics!



Parton distributions!



Excess in inclusive jet analysis in 1995 Substructure?

Excess of events at high Q^2 in ep DIS at HERA, mainly in H1: in 1996

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

Searches for Physics Beyond the Standard Model

We understand the Standard Model at 7 & 8 TeV from the Standard Model measurements made, as reported before

Ready to search for physics BEYOND THE STANDARD MODEL

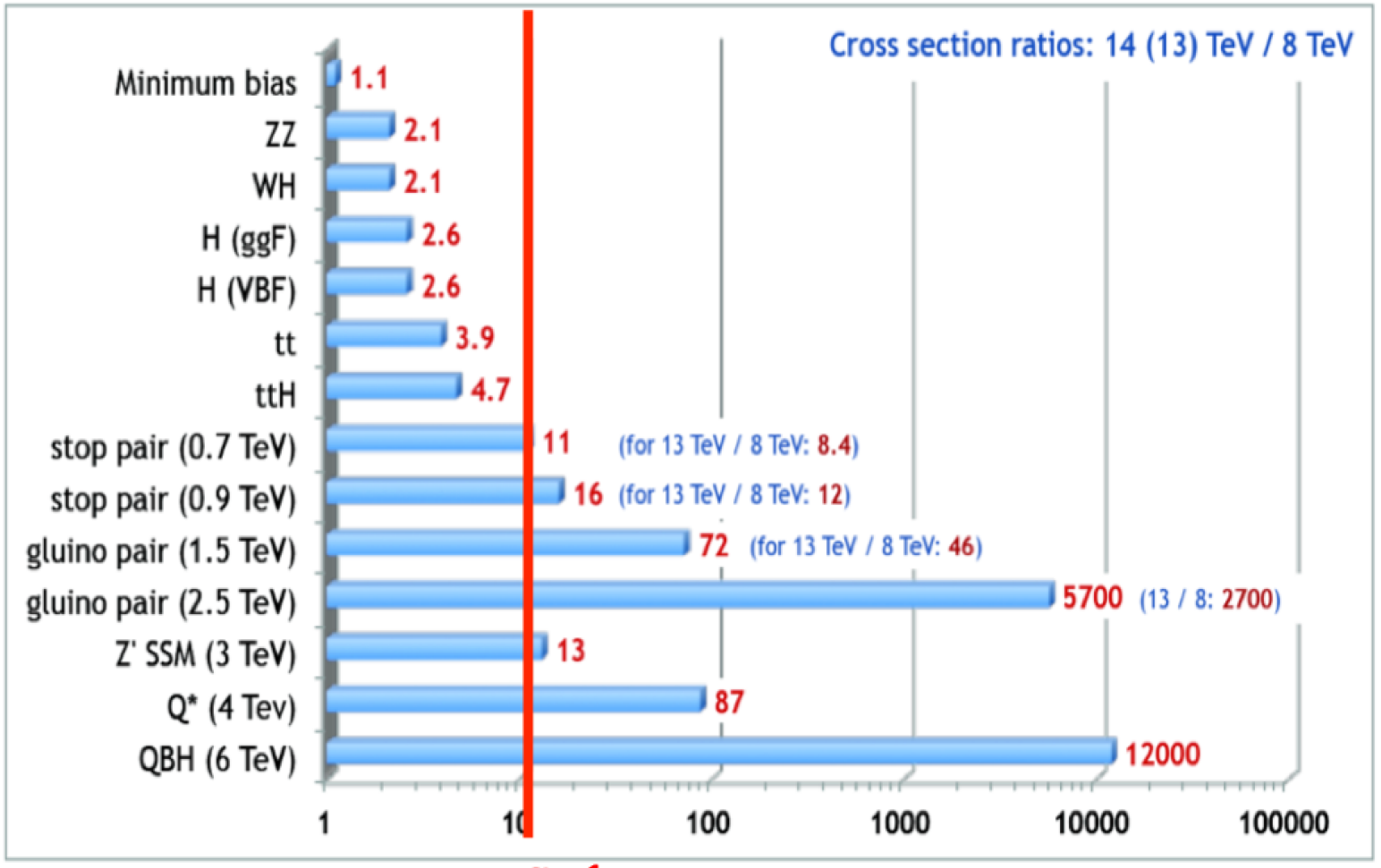
Searches for BSM Physics

- 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 facing a restart of the machine at 13/14 TeV…

  Back to the basics or do we change paradigm?

Reminder: Increased Reach@13 TeV

The increase is a consequence of the steeply falling parton distributions!
The parton luminosity increases strongly for given Mx with √s !

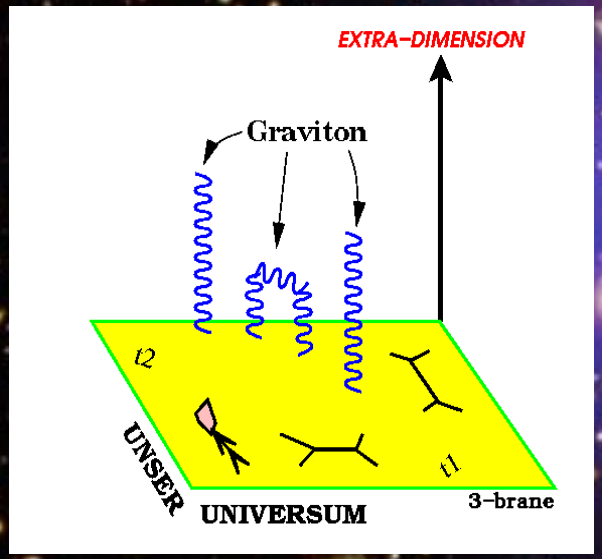


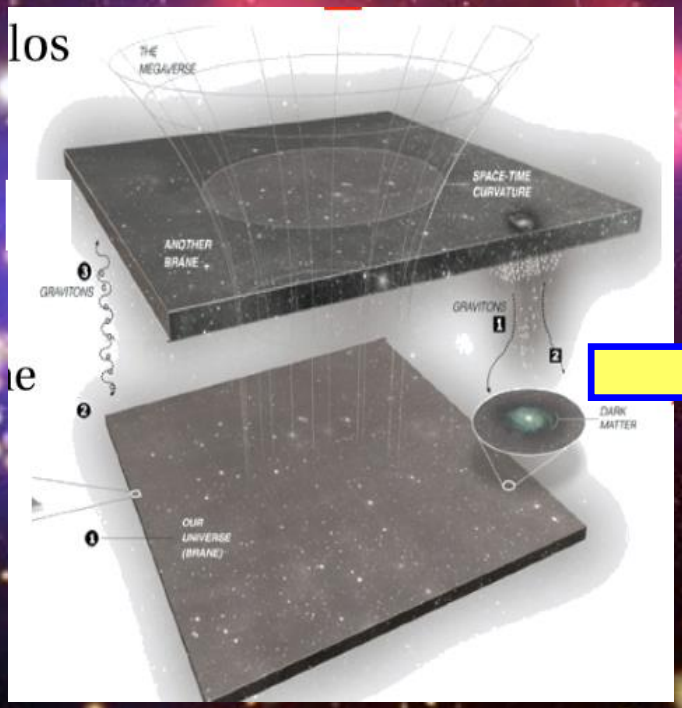
Extra Space Dimensions

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!

Search for Large Extra Dimensions

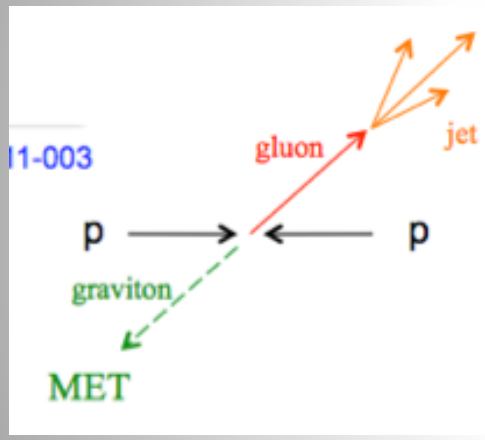
Mono-jet final state +Missing E_T (ADD)

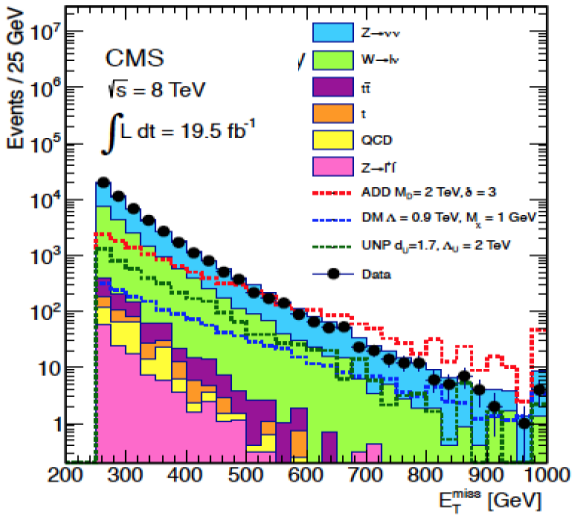
p_T jet > 110 GeV
MET > 200 GeV

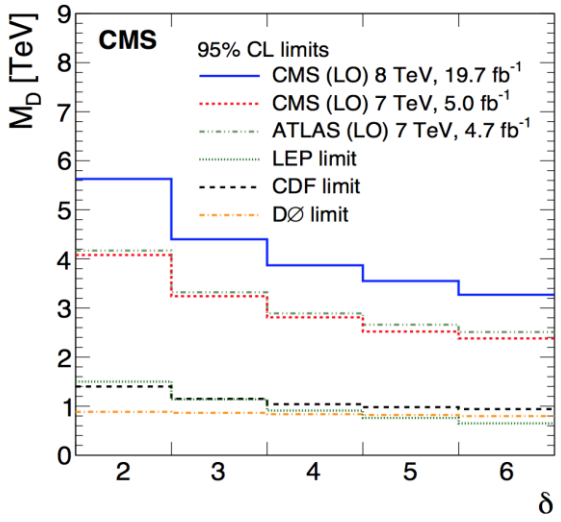
Limits on M_D between 3 and 4 TeV

arXiv:1408.3583

Lower limit on the Planck Scale versus number of extra dimensions







M_D (ADD) at LO 95% CL limits	$\sqrt{s}$ [TeV]	Lumi [fb^{-1}]	δ=3 Exp.	δ=3 Obs.	δ=6 Exp.	δ=6 Obs.
CMS Monojet	8	19.5	3.94	3.96	2.95	2.94

Quantum Black Holes

- Schwarzschild radius

Landsberg, Dimopoulos, Giddings, Thomas, Rizzo

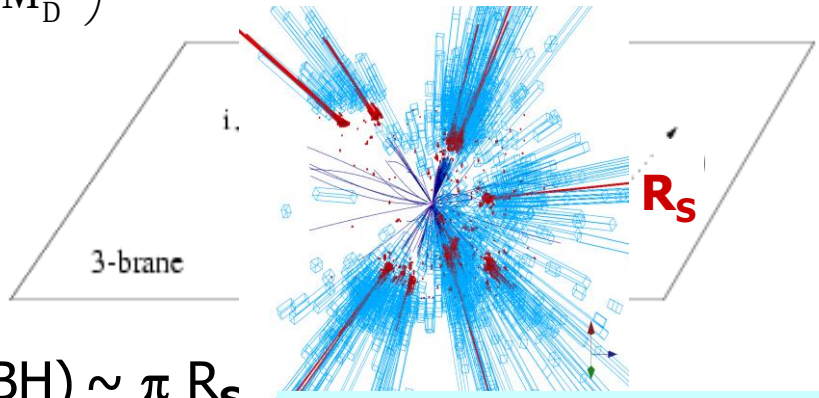
4-dim., $M_{gravity} = M_{Planck}$: $R_S \sim \frac{2}{M_{Pl}^2}\frac{M_{BH}}{c^2}$

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

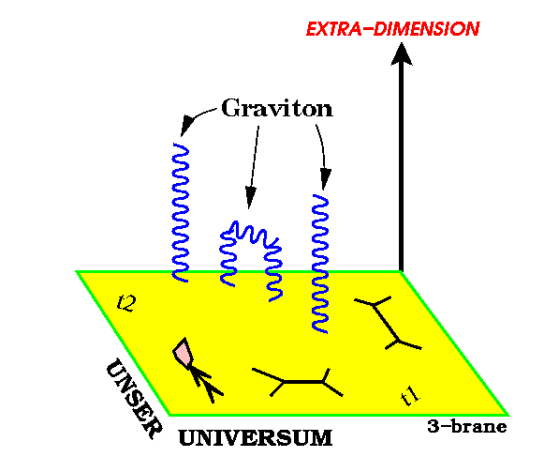
e.g. For $M_D \sim$1 TeV and n=3, produce 1 event/second at the LHC

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 …)

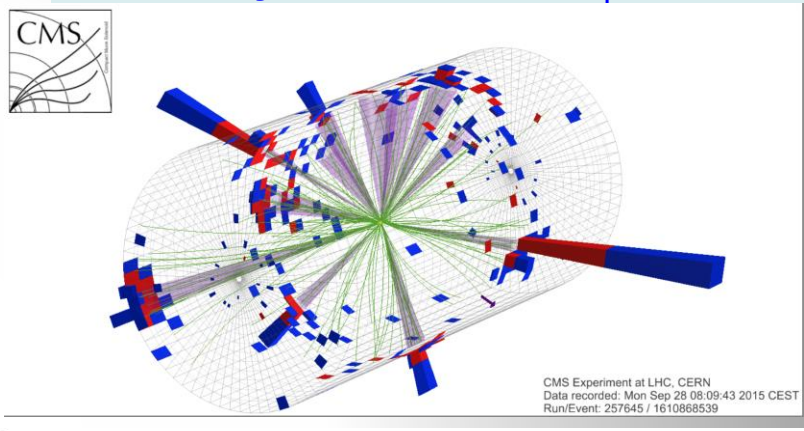
Search for Micro Black Holes



Extra Dimensions!

Planck scale
a few TeV?

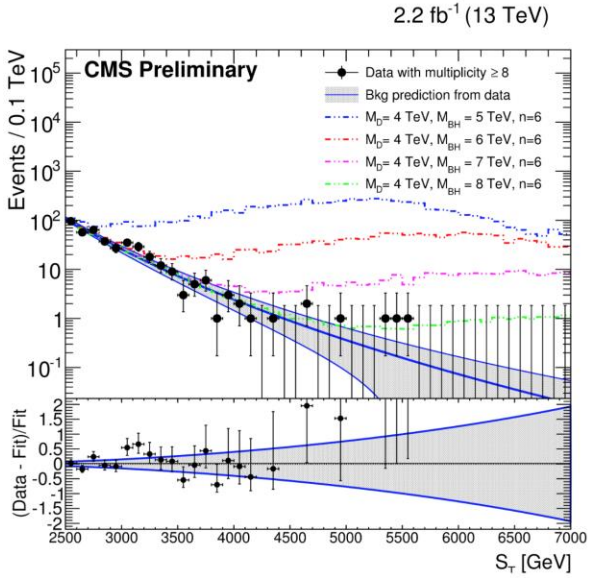
2015 12 jet event with S_T 5.4 TeV

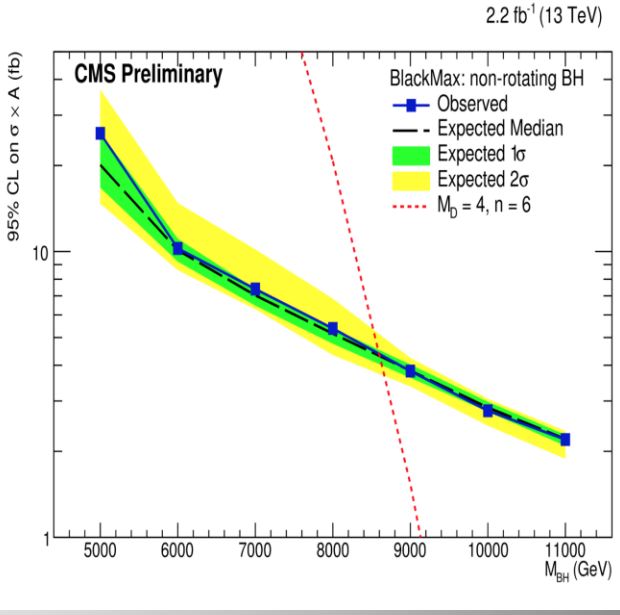


PAS-EXO-15-007

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

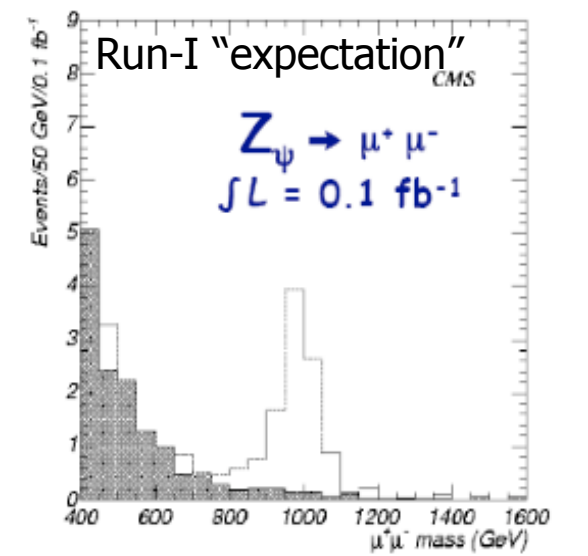




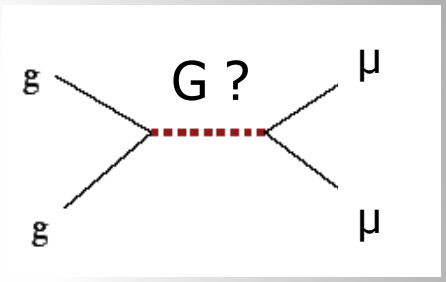
Black hole mass excluded in range below ~8-9 TeV depending on assumptions

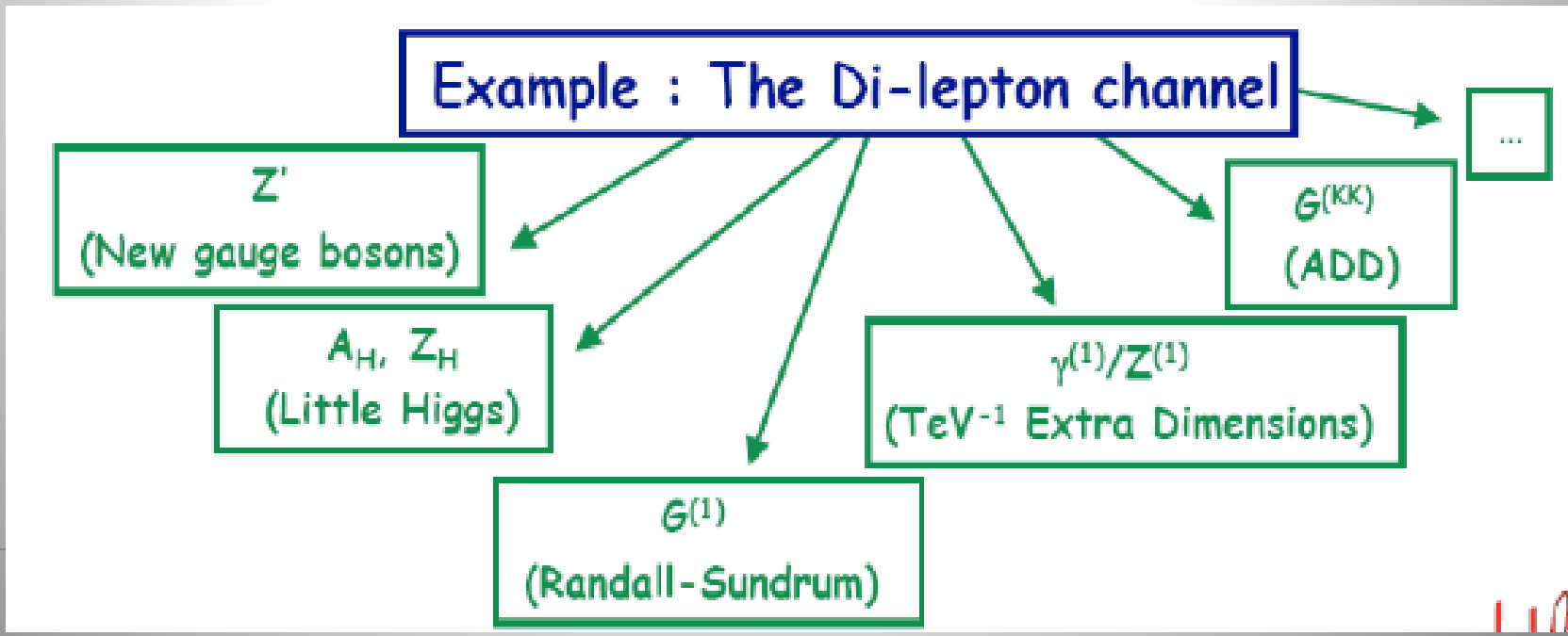
E.g. Di-lepton Resonance

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



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





2011: Z' Boson to ee or μμ?

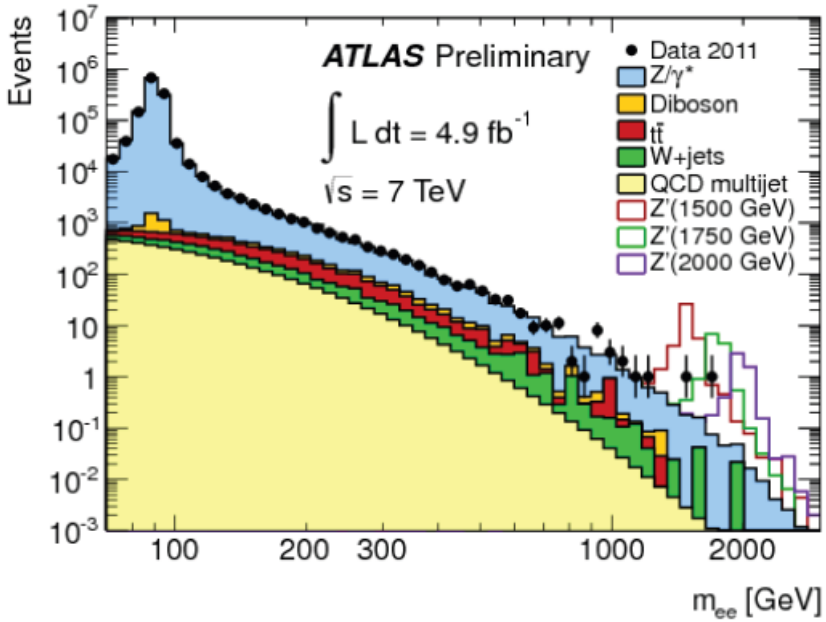
$SU(3)_C \times SU(2)_L \times U(1)_Y$

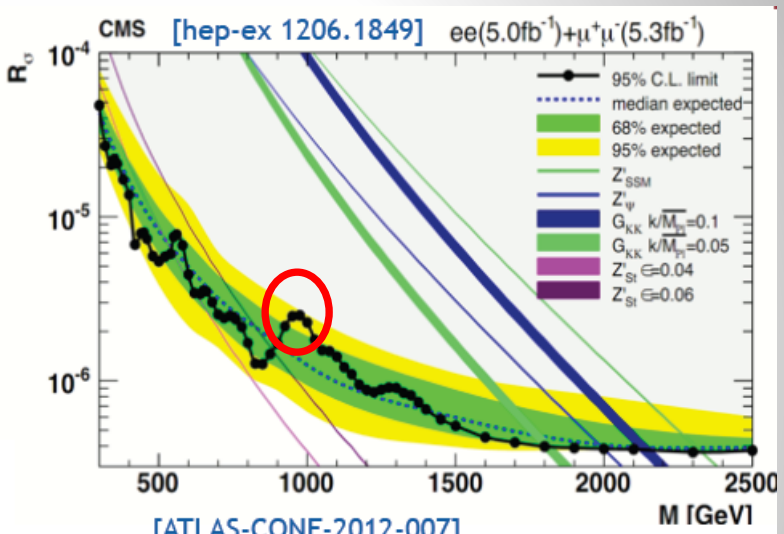
Extension of the symmetry?
New Gauge bosons?

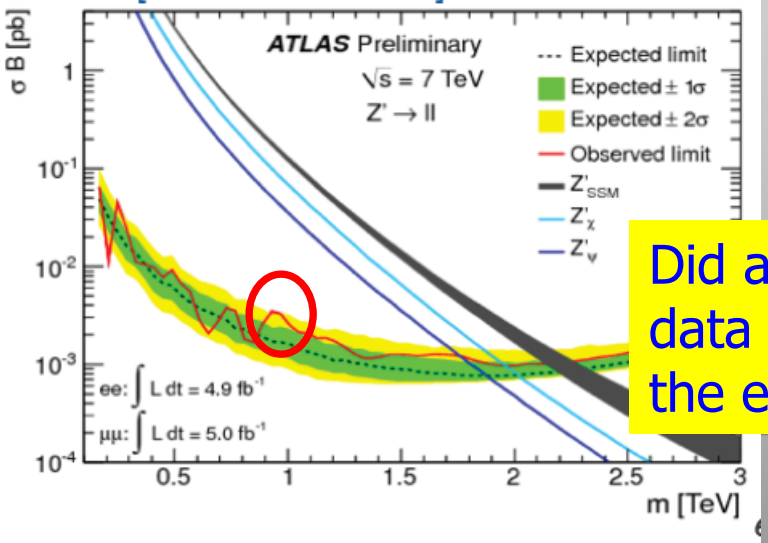
Mid 2012

- Many new models have Z-like narrow resonances decaying to dileptons
- Interesting features in dilepton spectra
  - around 2σ each for CMS & ATLAS in e+μ
  - similar in scale to 2011 Higgs excess

Worth watching in 2012's 8 TeV data...

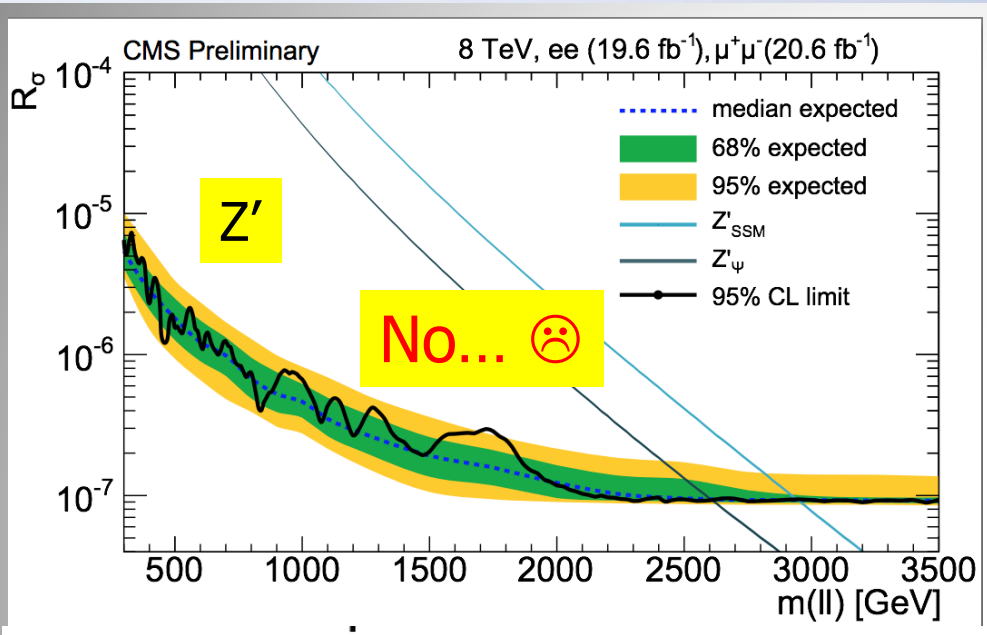




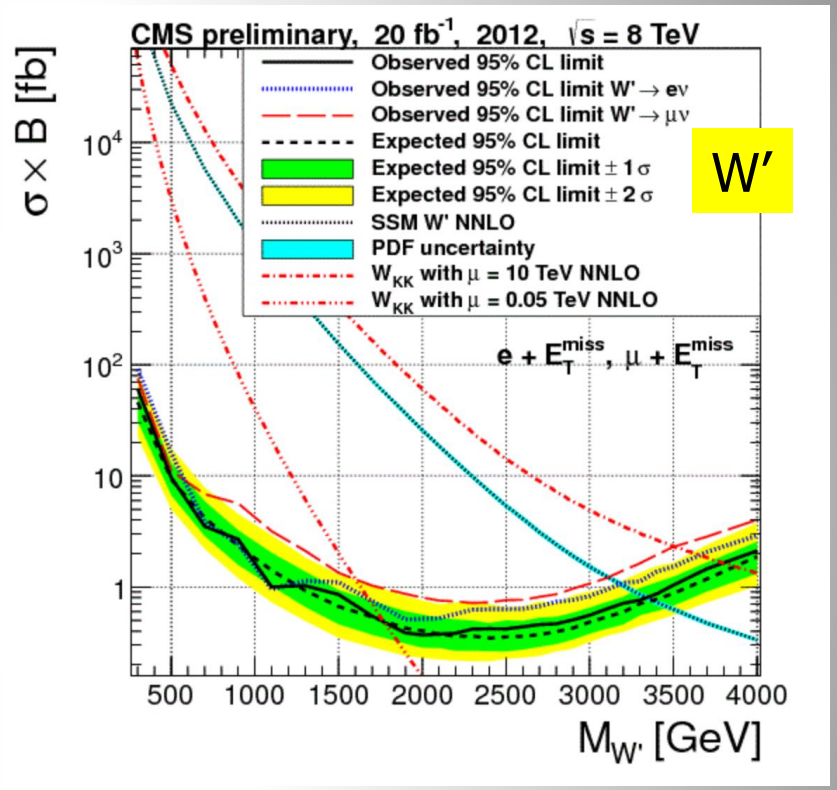


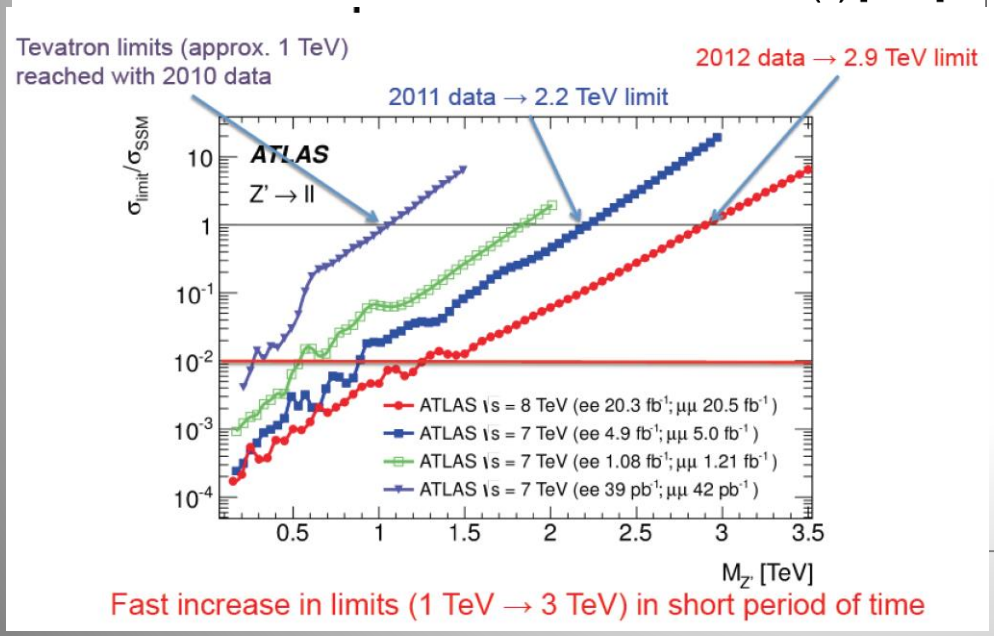
Did additional data confirm the excess??

New Gauge Bosons: Z', W'



Early 2013



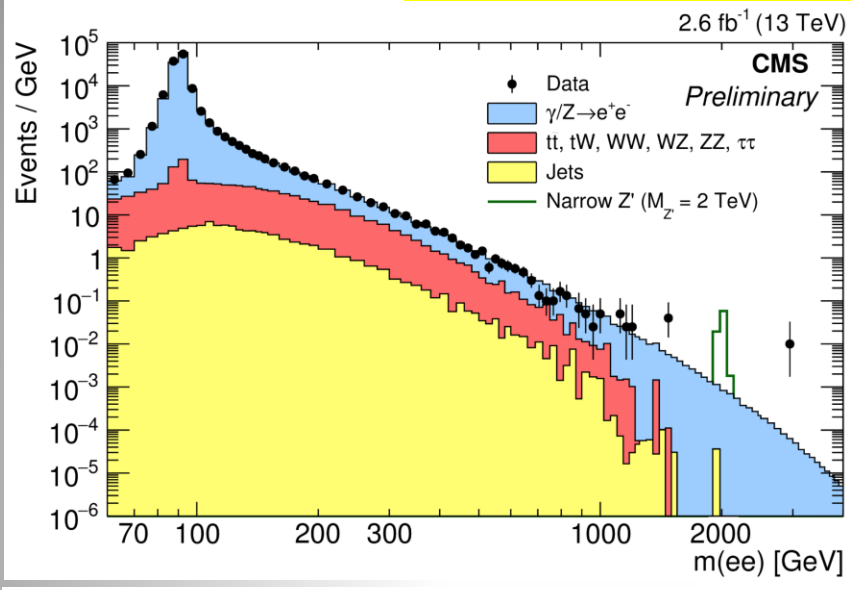


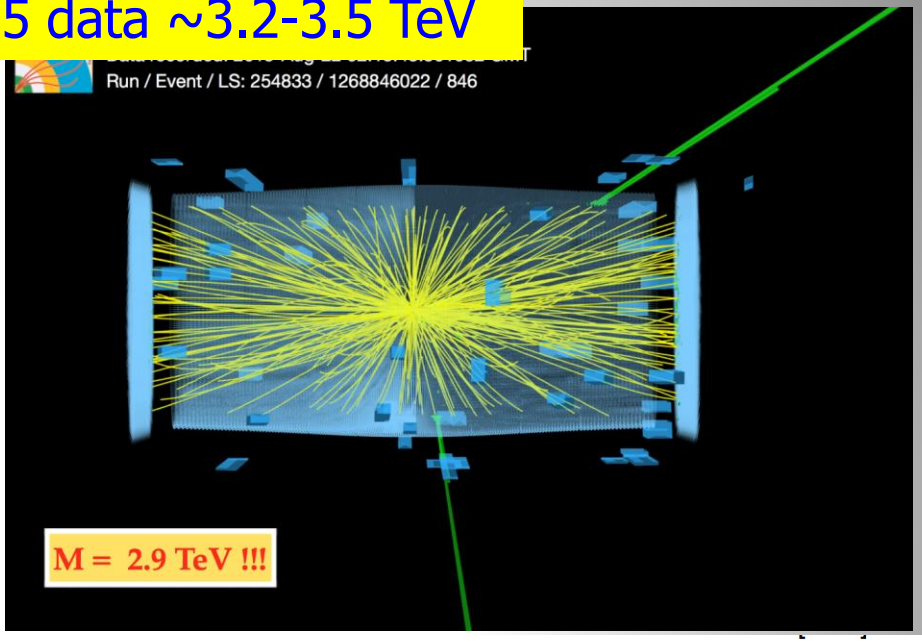
W,' Z' Limits from 2012 data are around 3 TeV

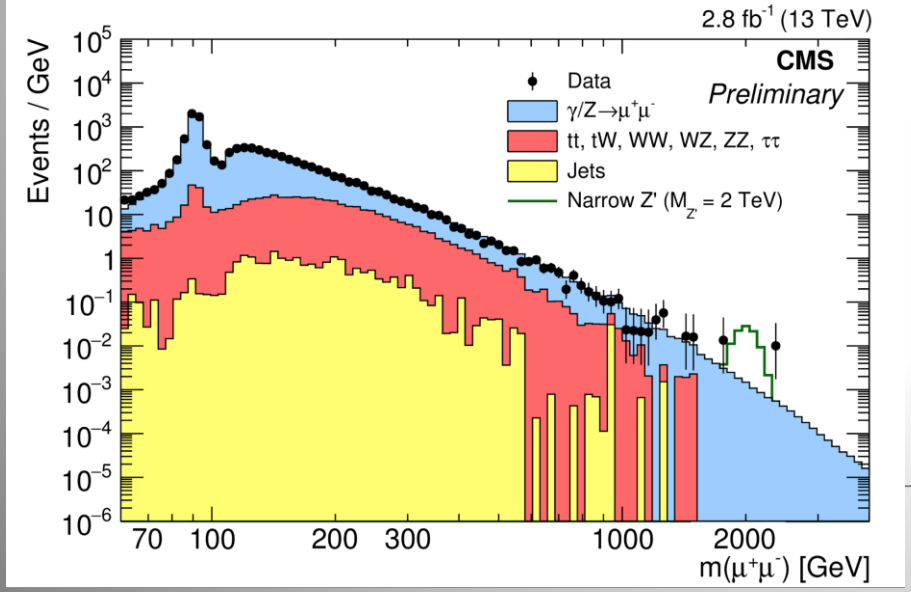
New Gauge Bosons: 13 TeV

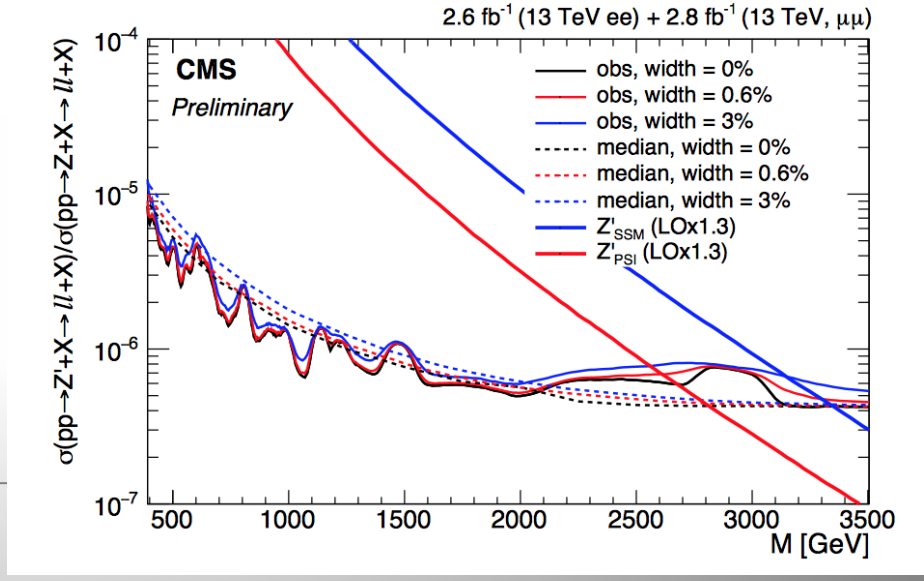
EXO-15-005

W,' Z' Limits from 2015 data ~3.2-3.5 TeV



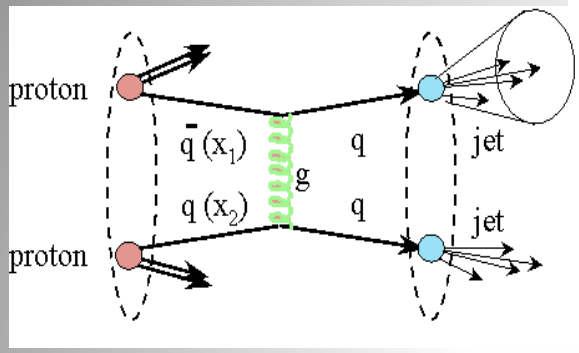


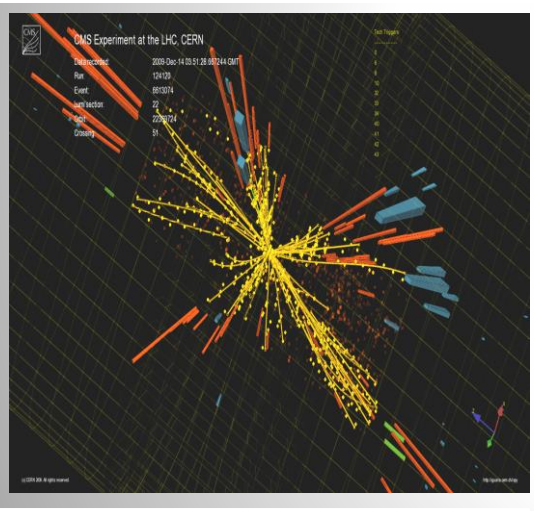




Di-jet Resonances

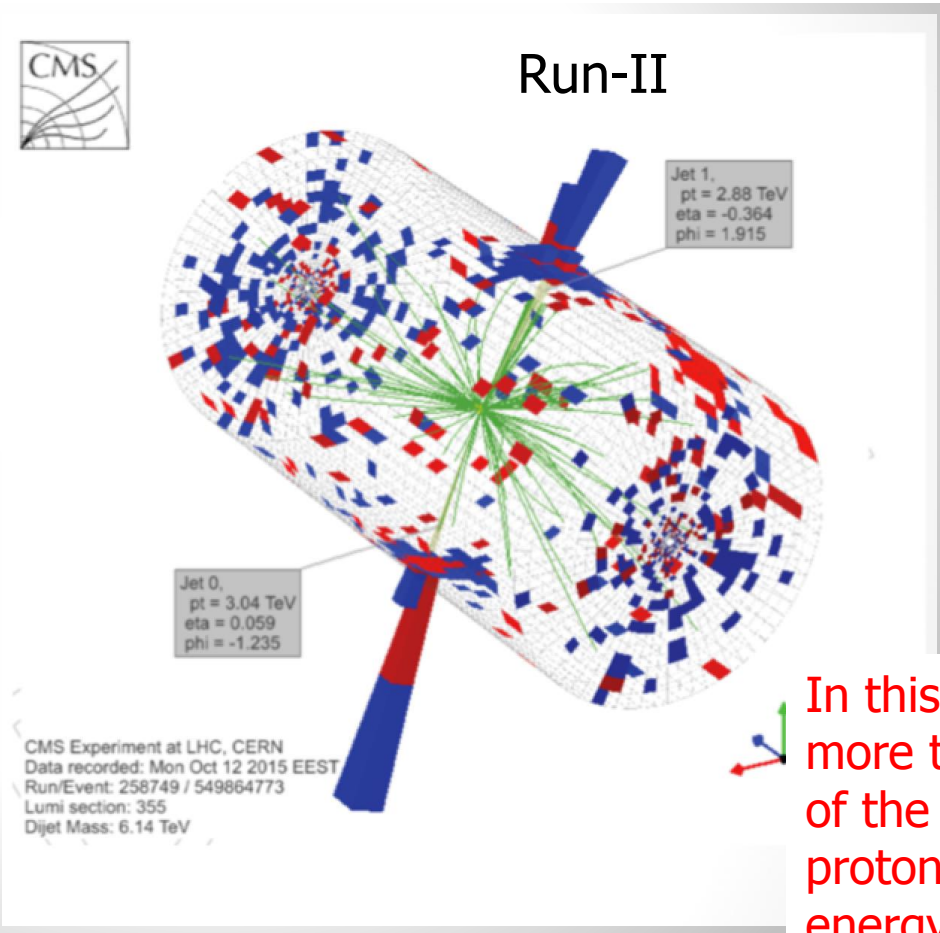
The highest mass Di-jet event recorded so far





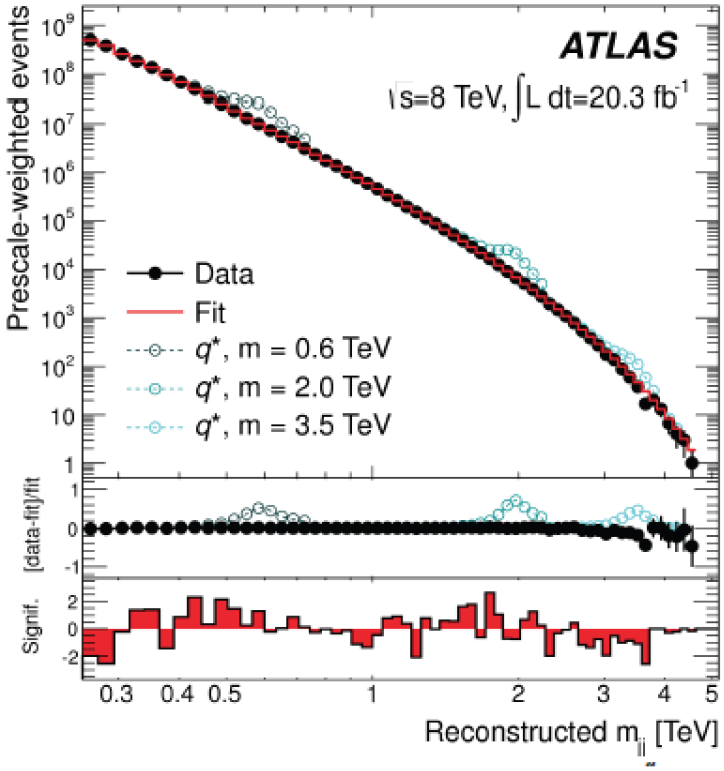
Jets of particles emerge after a high energy parton-parton scattering

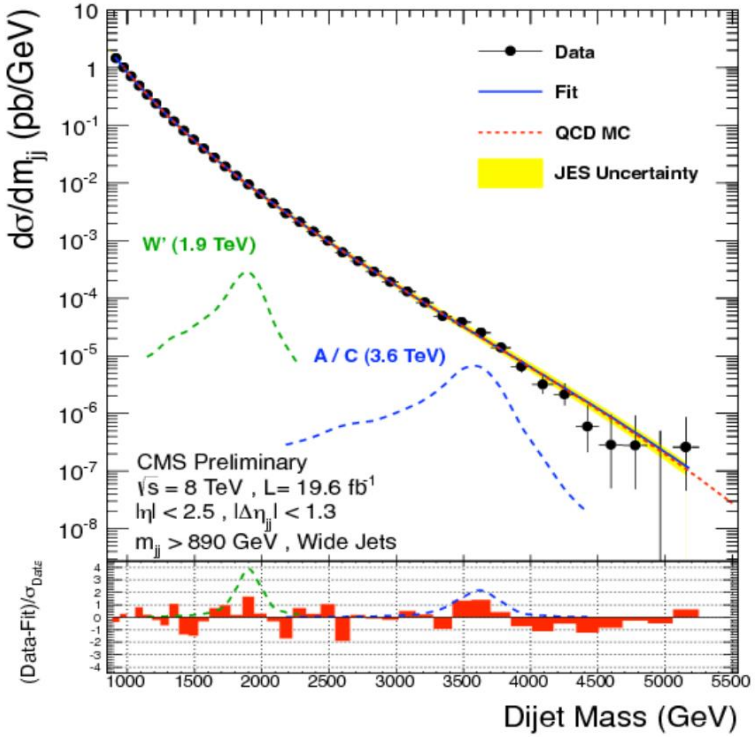
Di-jet invariant mass = 6.14 TeV (R=1.1 jets)



In this event more than 45% of the full proton-proton energy ends up in jets

Run-I Di-jet Searches





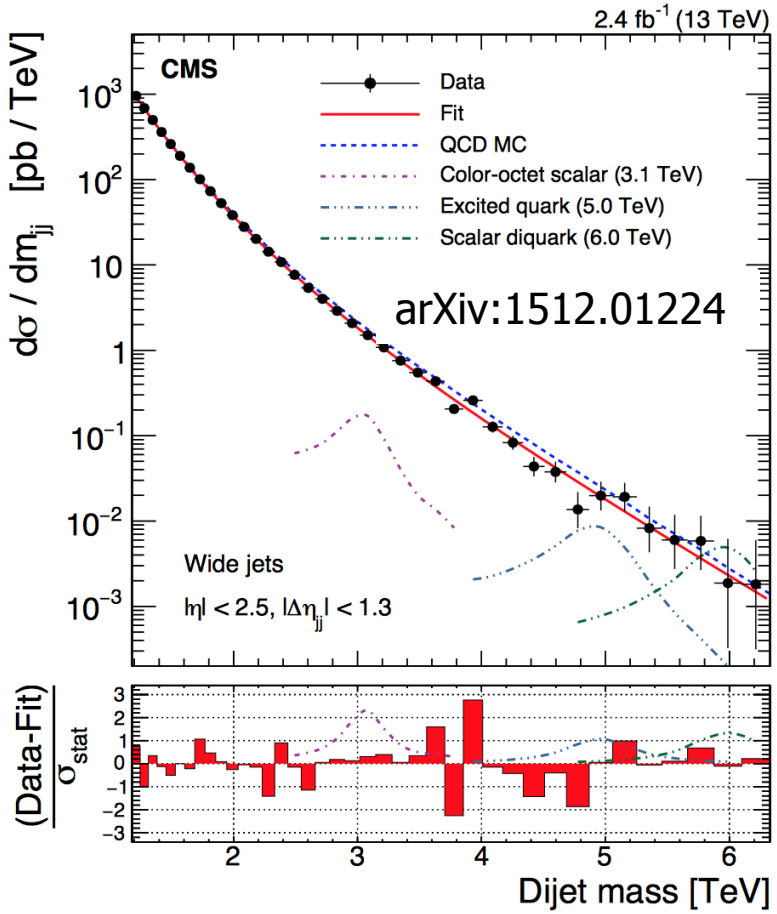
- Search for dijet resonance in smoothly falling mass spectrum
  - leading jet mass m_{jj} > 0.9-1 TeV from trigger and other constraints
  - Background estimated from smooth functional fit

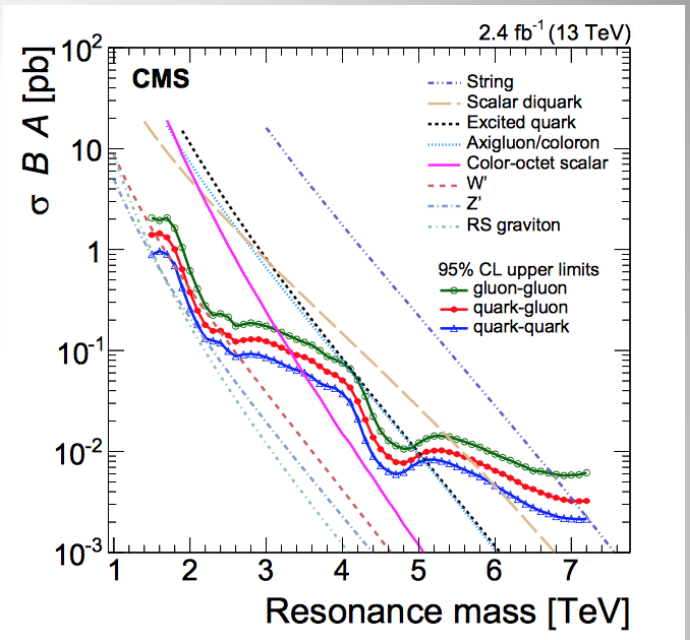
arXiv:1501.04198
arXiv:1407.1376

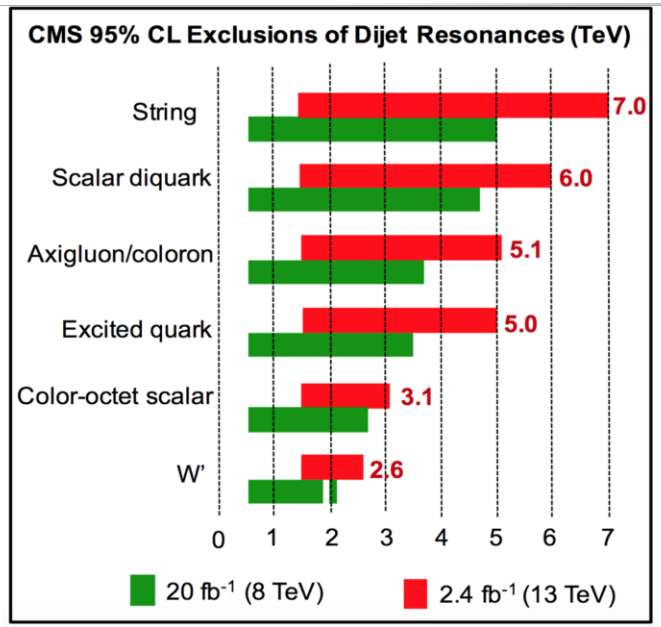
$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}}$$

Model and Final State	95% CL Limits [TeV] Expected	Observed
$q^* \to qg$	3.99	4.09
$s8 \to gg$	2.83	2.72
$W' \to q\bar{q}'$	2.51	2.45
Leptophobic $W^* \to q\bar{q}'$	1.93	1.75
Leptophilic $W^* \to q\bar{q}'$	1.67	1.66
QBH black holes (q and g decays only)	5.82	5.82
BLACKMAX black holes (all decays)	5.75	5.75

Run-II Di-jet Searches

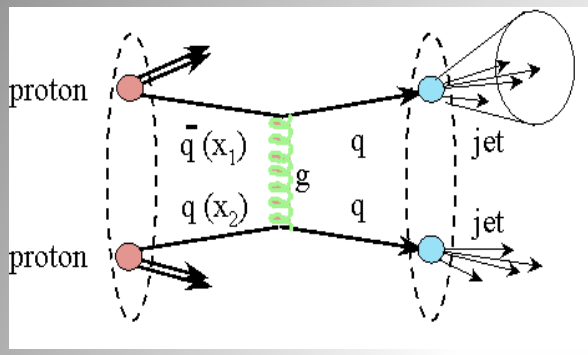


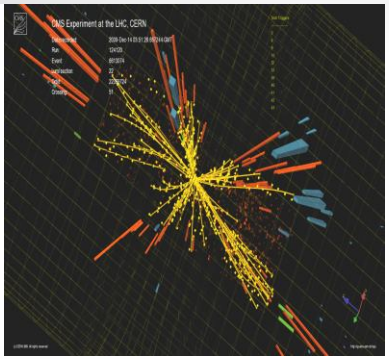


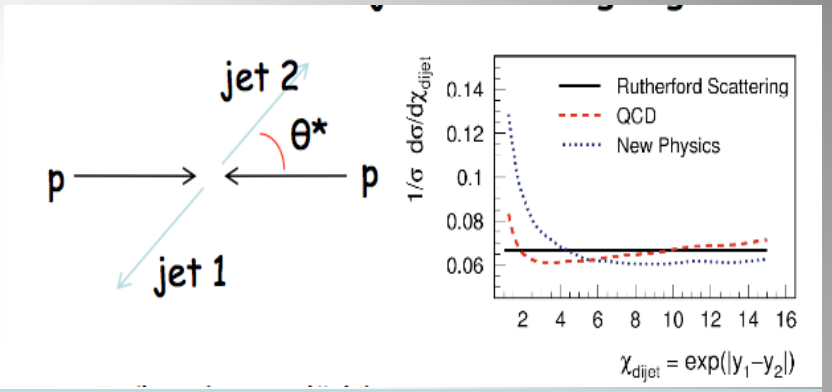


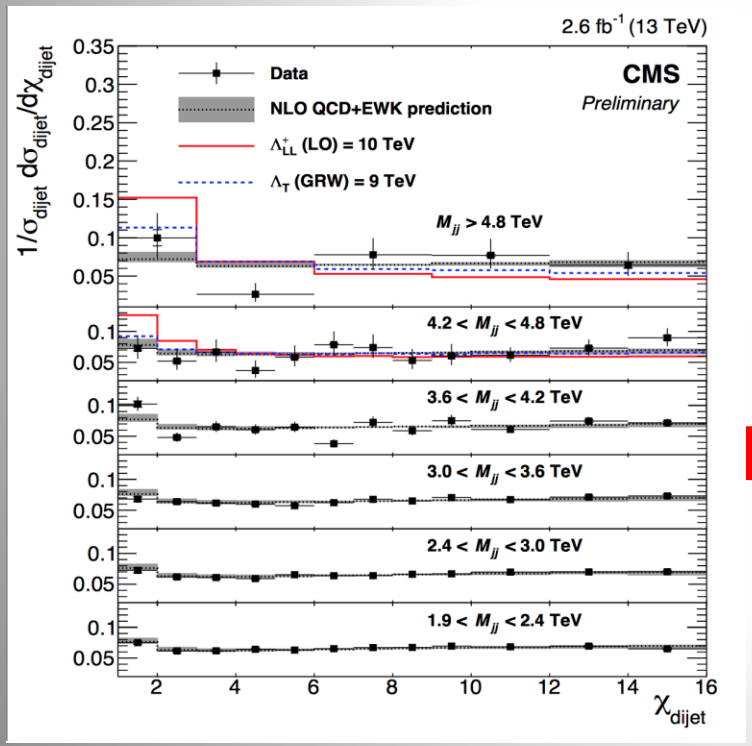
2.4 fb^{-1} limits from 13 TeV already surpass the 20 fb^{-1} limits from 8 TeV

Are Quarks Elementary Particles?

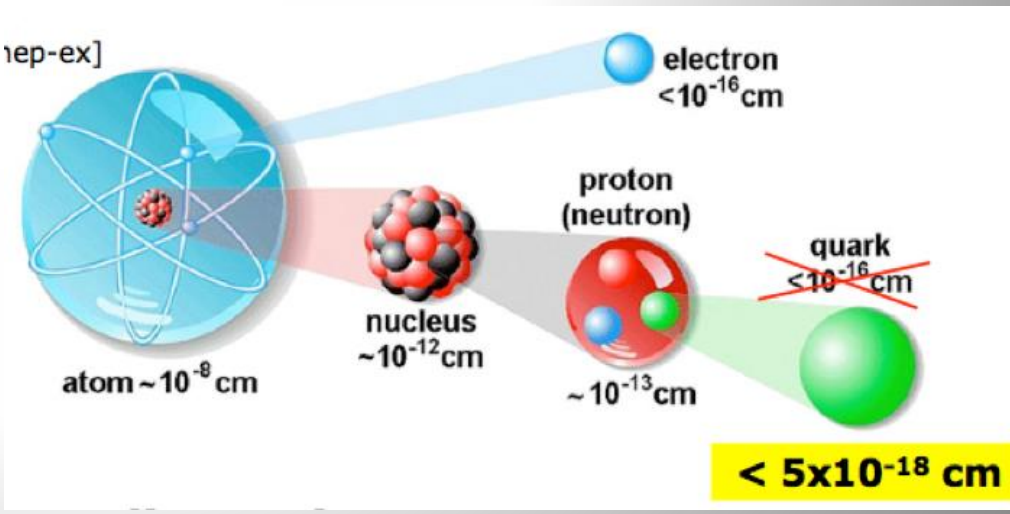








Measurement of the production angle of the jet with respect to the beam
-> High Energy Rutherford Experiment

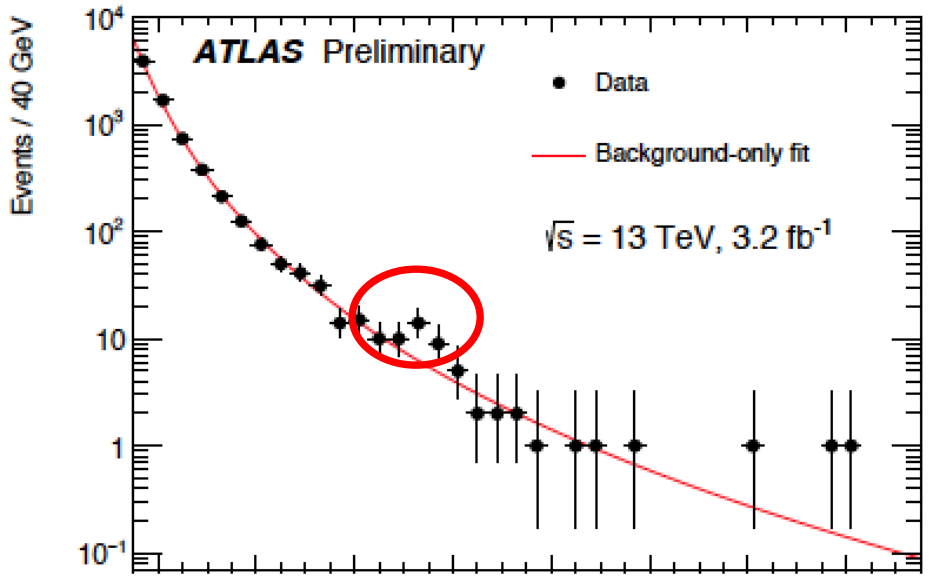


Quarks remain elementary particles after these first results

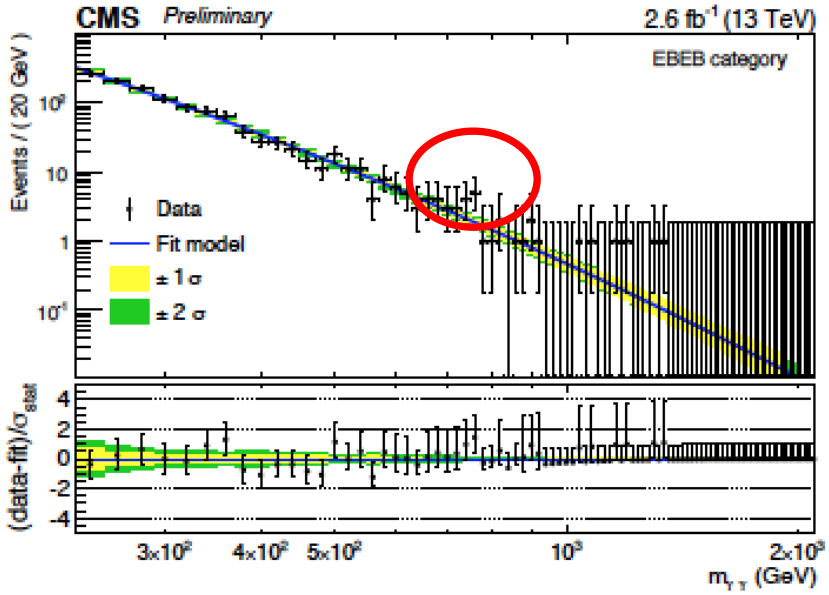
High Mass Search: X → γγ

News from the 2015 data run in last December!
->Some excitement over and observed excess in both experiments
For a di-photon mass of around 750 GeV

ATLAS-CONF-2015-081

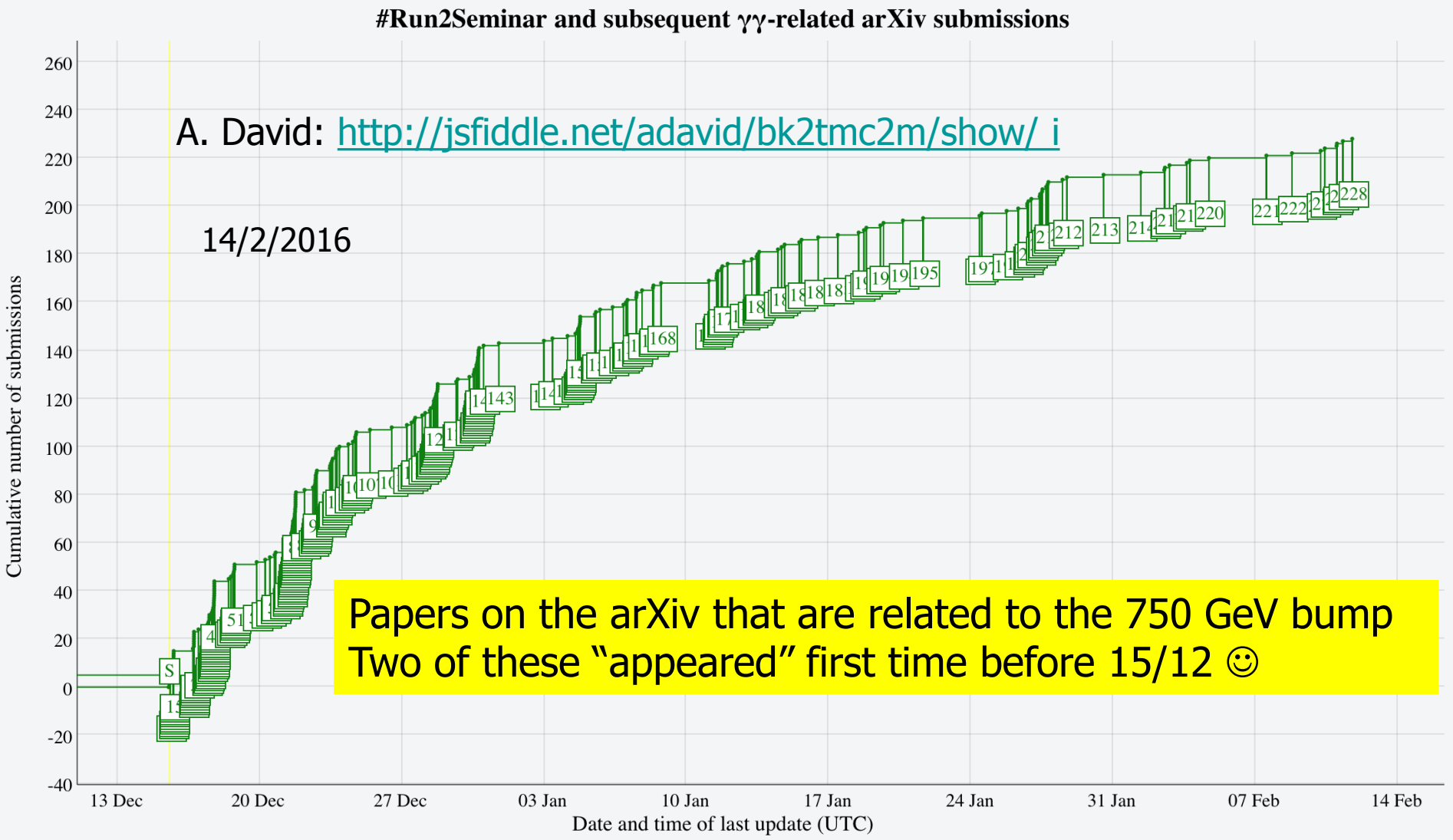


CMS EXO-15-004



Statistical fluctuation? A new resonance? See ~ 230 papers on the arXiv since…

This triggered ~ 228 papers so far



More fun on: https://indico.cern.ch/event/489481/contribution/37/attachments/1217605/1778943/750gev_v6.pdf

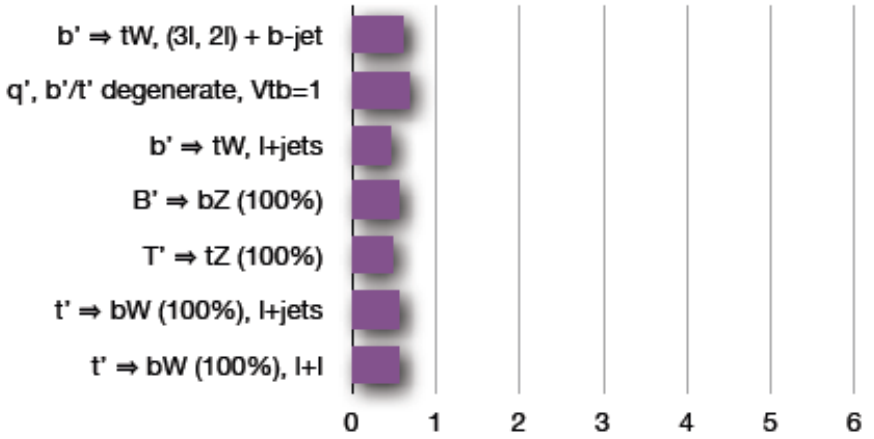
Search for a 4th Generation and Vector-like quarks

We can't be sure that there are only 3 generations (u,d) (s,c) (b,t)
A possible new generation should be heavy!

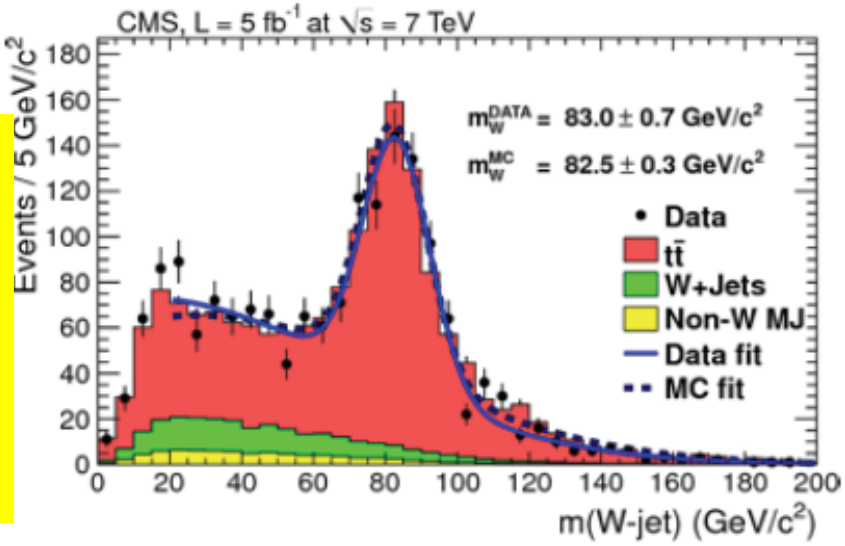
Look for b' and t' quarks

4th Generation Searches

- Rich program for 4th generation
  - leptons
  - lepton+jets
  - all hadronic
- More challenging modes like top +gamma not yet done



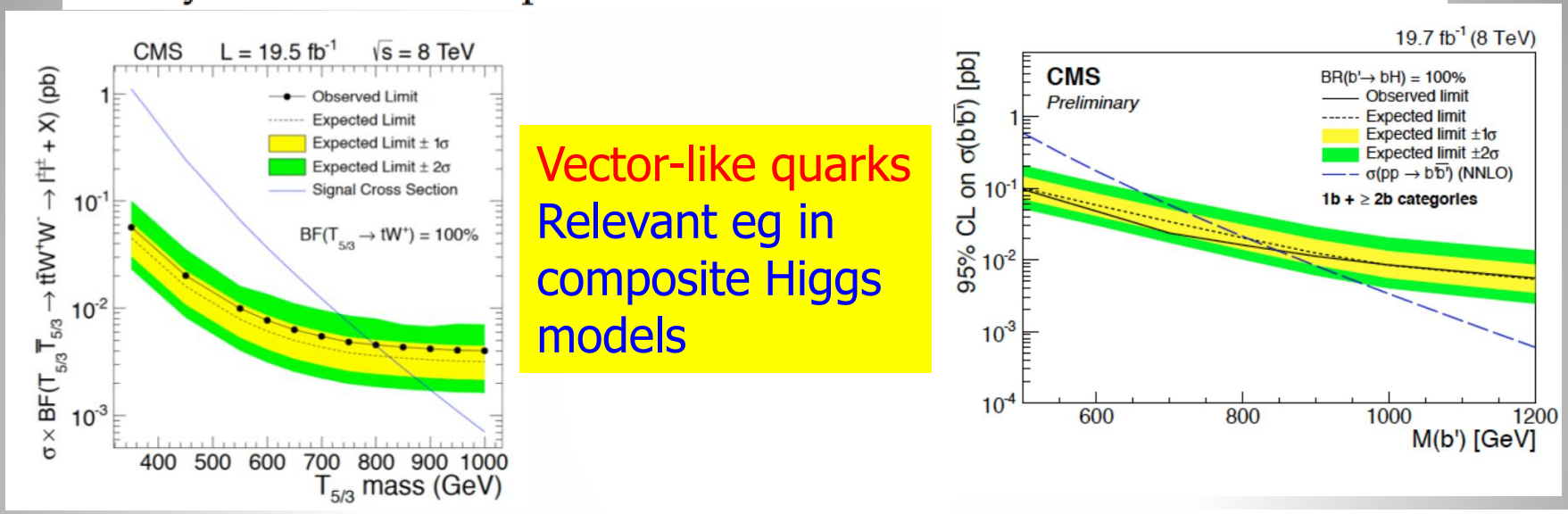
- ttbar resonances across the spectrum
  - boosted top technique at high mass
  - lepton + jets



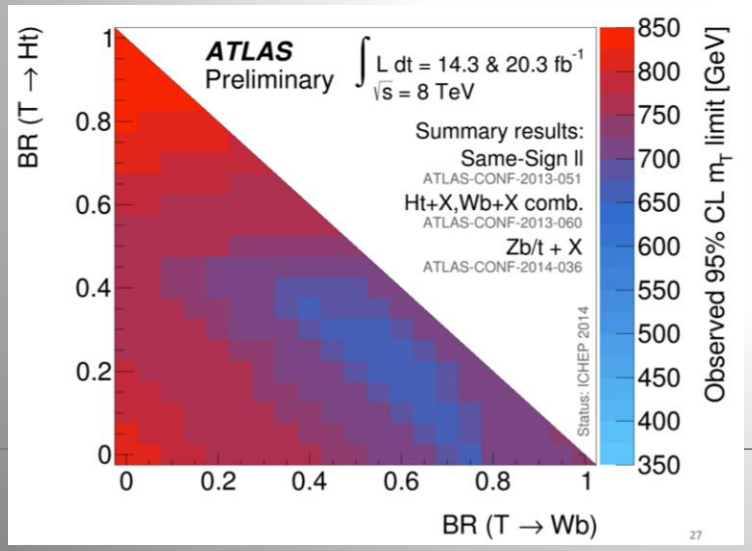
No evidence found for a new quark generation for quarks with mass < 550 GeV!
A 4th generation would also affect the Higgs rate in a substantial way, by a factor 9 or so, which is not observed
-> However: listen to George Hou… !!

Searches for Top/Bottom Partners

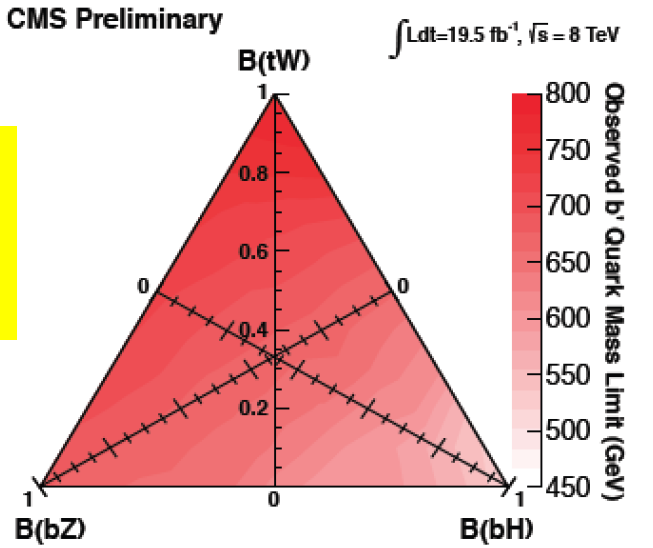
- color-triplet spin-1/2 fermions; L & R components transform the same way under weak isospin



Vector-like quarks
Relevant eg in composite Higgs models



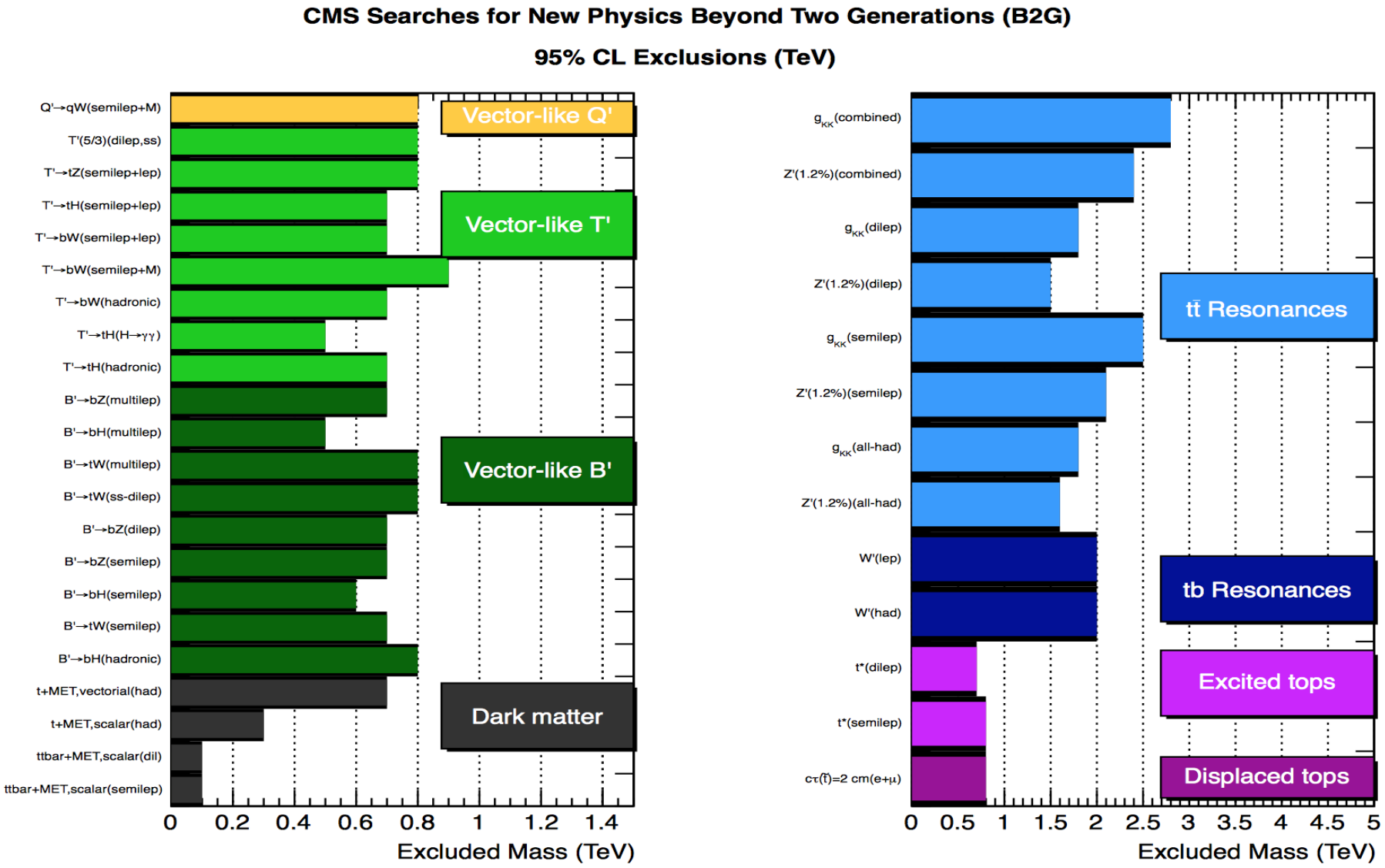
Exclusions up to masses of 800 GeV



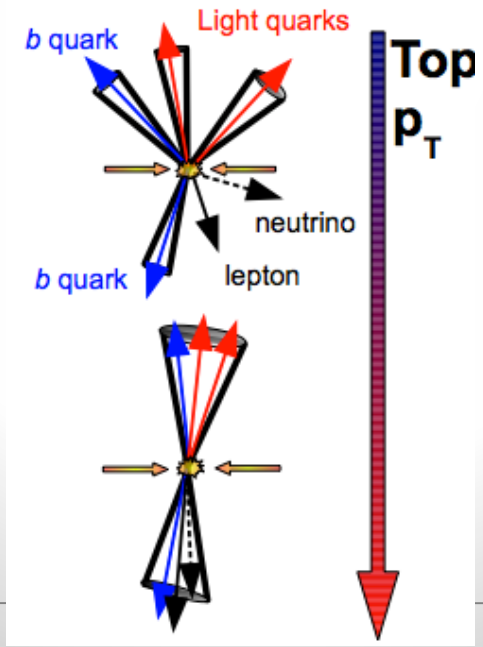
Searches for Top/Bottom Partners: CMS

Summary table

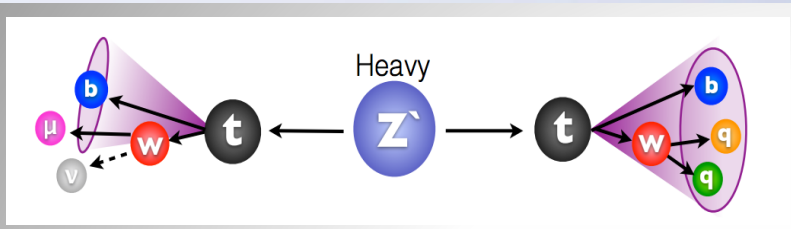
But this topic got in the spotlight again with X(750)…



Searches with Boosted Objects



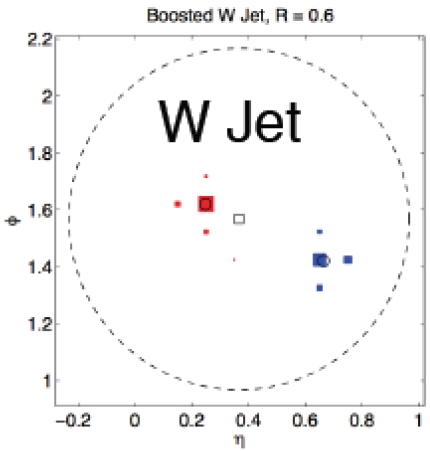
Searches with Boosted Objects

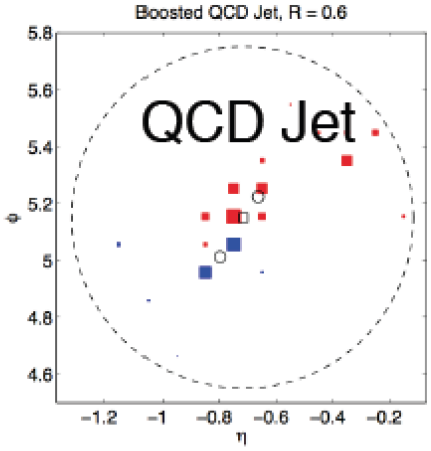


Discussed in topical "Boost Workshops"
Last one Chicago 10-14 August 2015
http://boost2015.uchicago.edu/

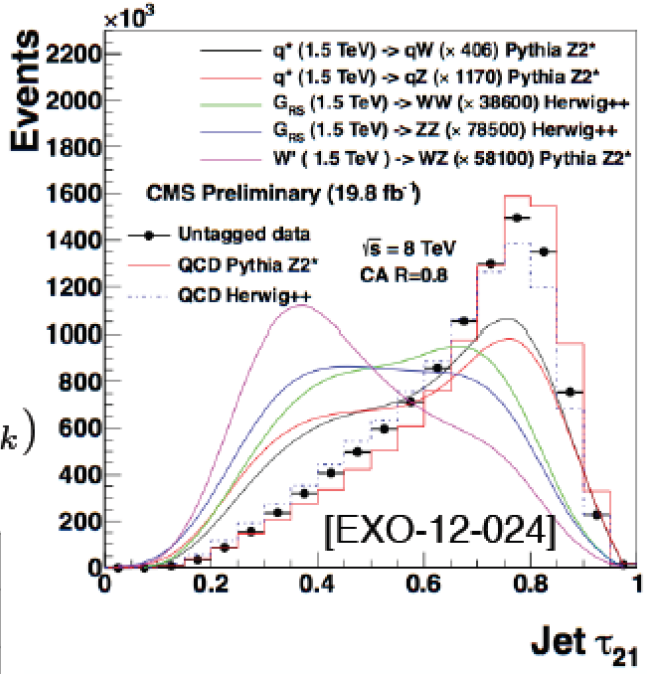
- Several different techniques to identify merged jets are on the market...
  - N-subjettiness, τ_N, uses $\tau_{21}=\tau_2/\tau_1$ as a discriminant to separate QCD jets from merged W/Z jets

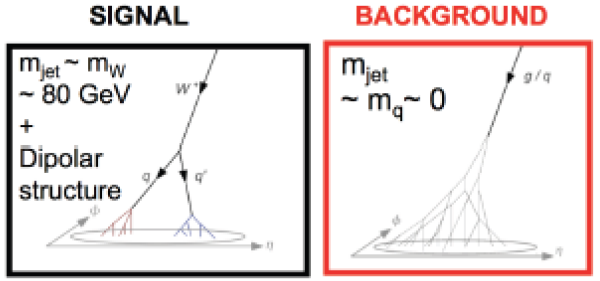
$$\tau_N = \frac{1}{d_0}\sum_k p_{T,k}\min\left(\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\right)$$





[Thaler, Tilburg, arXiv:1011.2268]

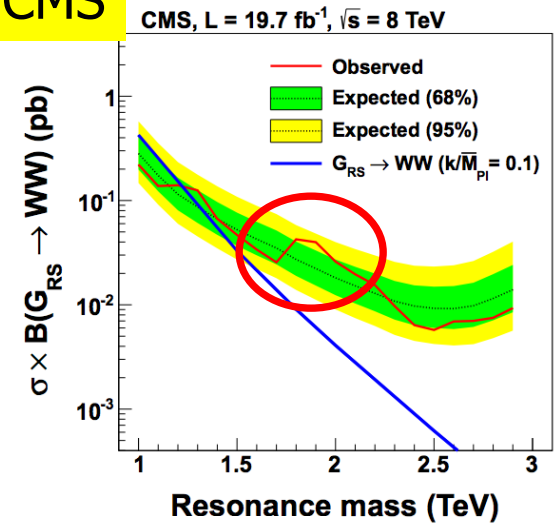


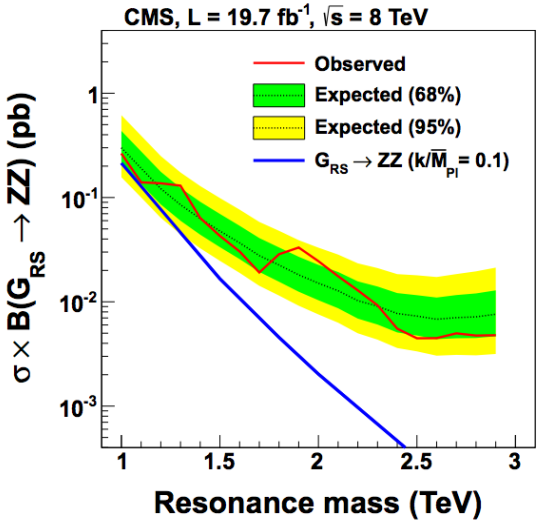


Resonances Decaying into qV or VV

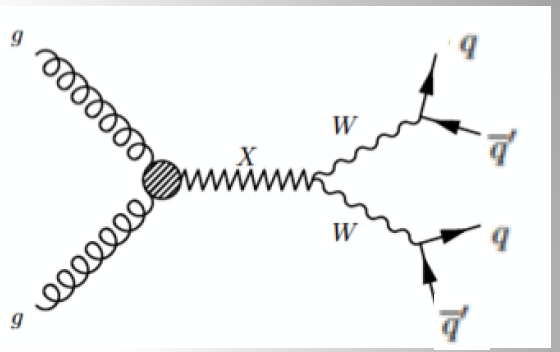
Heavy resonances decaying into qZ or qW, or VV jets only (CMS) or llqq (ATLAS) using boosted jets and jet substructure analysis

CMS



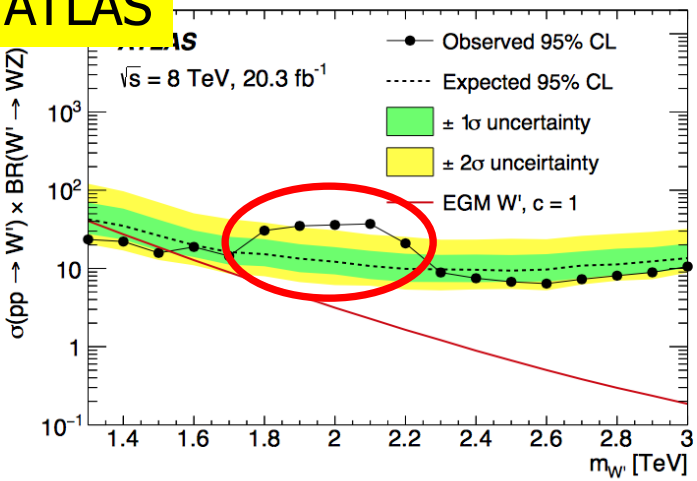


arXiv:1405.1994



Jets start to merge for X = 700-900 GeV

ATLAS



arXiv:1506.00962

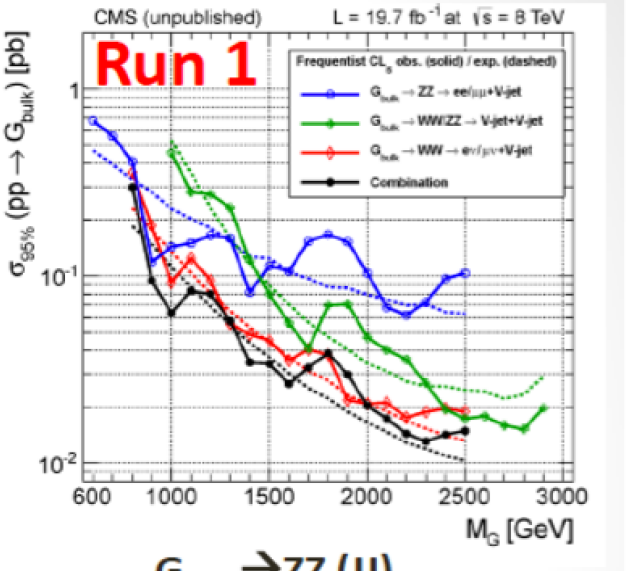
Excess in WZ of 3.4σ (2.5 with LEE)

These type of analyses will get even more important at 13 TeV

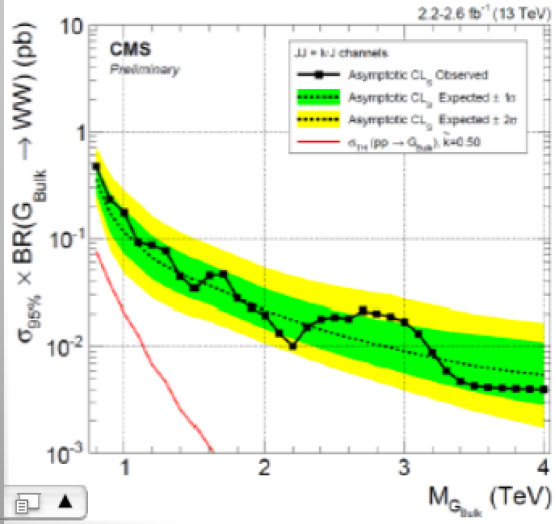
Diboson Production in 2015

EXO-15-002

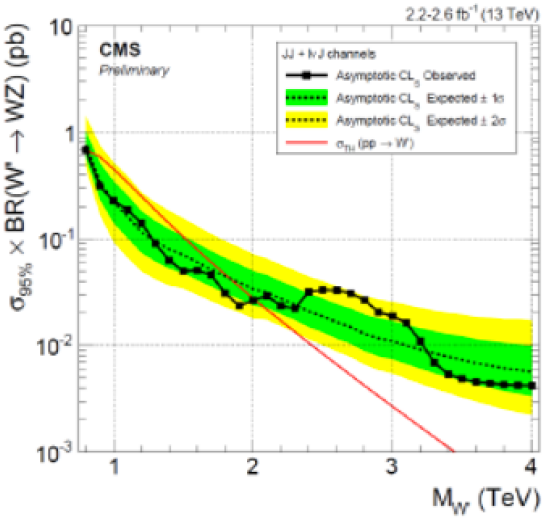
- **Run 1: CMS ~2σ excess near 1.8-2.0 TeV**
- Repeat search at 13 TeV using most sensitive channels: lνJ, JJ
- **Analysis categorized in dijet mass** for optimal sensitivity to WW, WZ, ZZ signals
- **13 TeV: no excess observed in the region of interest near 2 TeV**
  - More data needed to fully exclude Run 1 excess



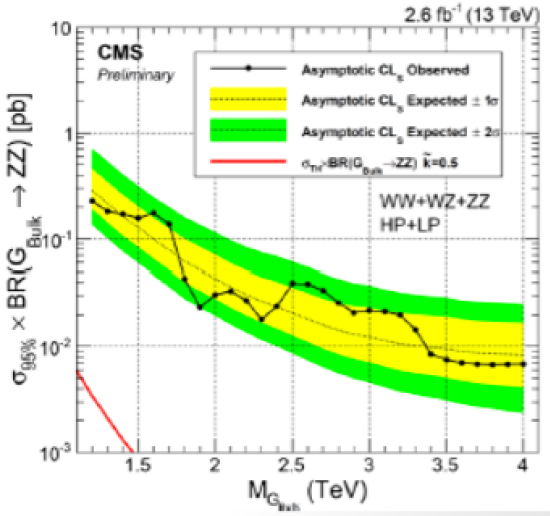
$G_{Bulk} \rightarrow WW$ (lνJ+JJ)



$W' \rightarrow WZ$ (lνJ+JJ)



$G_{Bulk} \rightarrow ZZ$ (JJ)



No particular enhancement around 2 TeV in the 2015 data so far!...

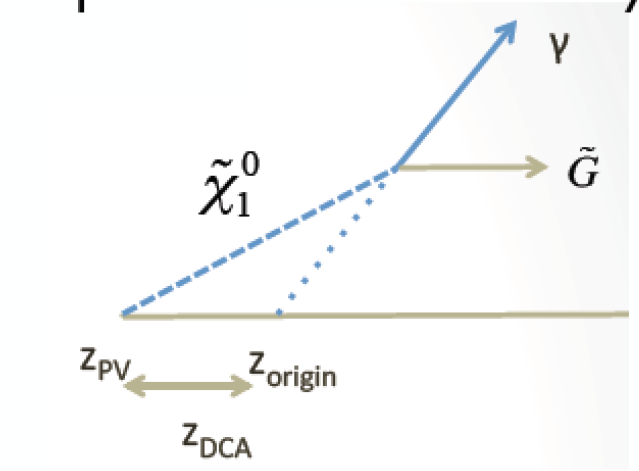
Real Exotic Objects!

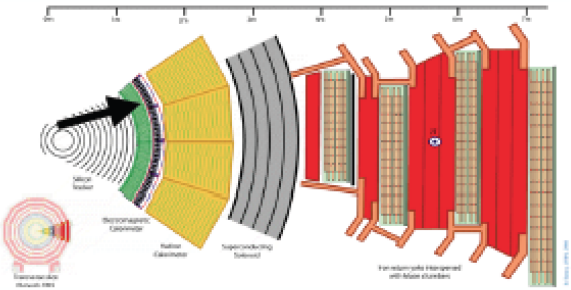
Spring 2015: many new searches for truly exotic particles, ie long-lived particles or other unusual signatures

Searches for Unusual Particles

- Heavy stable charged particles with unit charge traversing the detector
- Heavy stable charged particles with multiple charge traversing the detectors
- Heavy stable charge particles with fractional charge traversing the detector
- Heavy new particles decaying in the detector
- Heavy new particles stuck in the material in or before the detector

Displaced / delayed photons

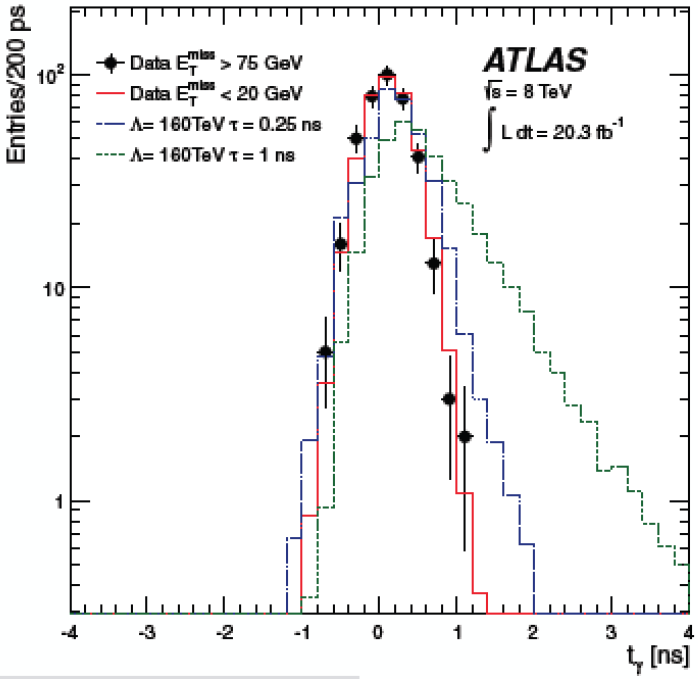




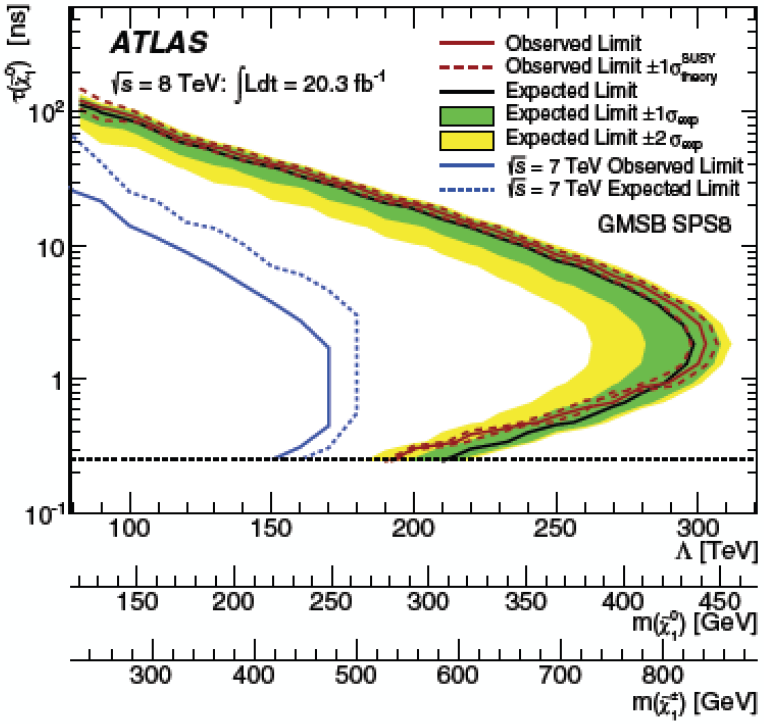
- Signal region: 2 photons (E_T>50 GeV) & MET>75 GeV.
- 2D search in z_{DCA} and t_γ.
- Low-MET control region used to model bkgd.

HEP-PH/0202233; 853 citations!

Look for photons that do not point back to PV (large $|z_{DCA}|$) or arrive late at calorimeter (large t_γ).



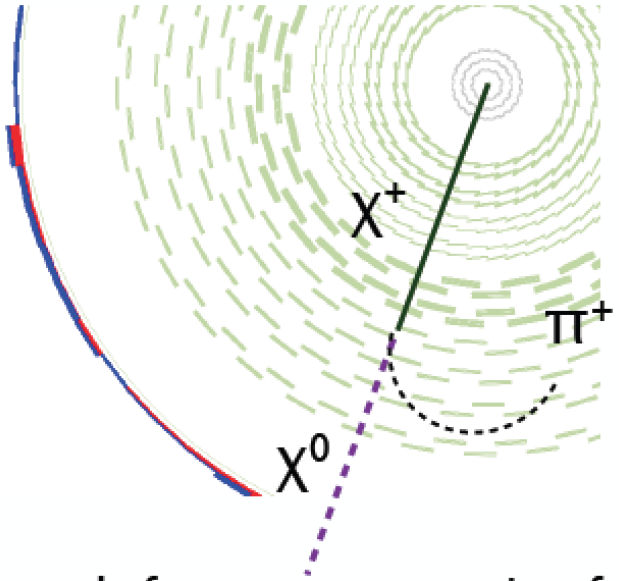
Set limits on GMSB SPS8 model.

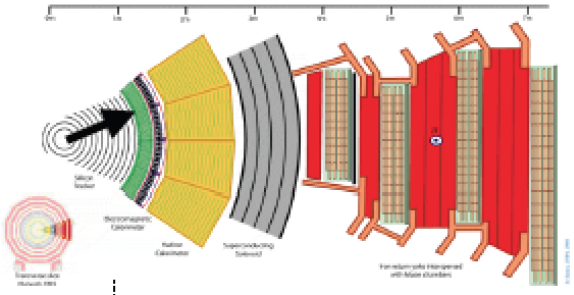


Phys. Rev. D 90, 112005 (2014)

Disappearing tracks

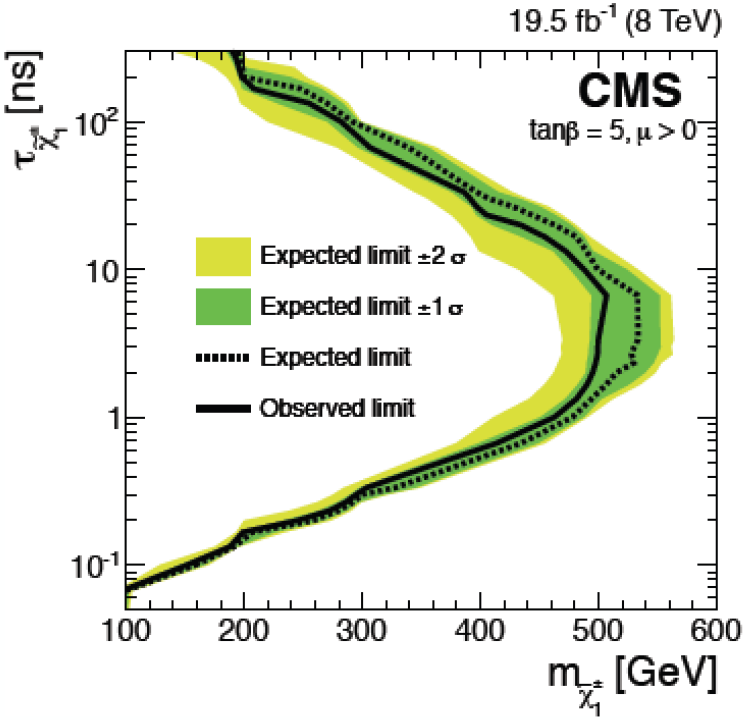
Require high-p_T isolated track with little energy deposited in calorimeters (E_{calo} < 10 GeV) and ≥3 missing hits in outer layers of tracker.





	Signal region
Expected bkgd	1.4 ± 1.2
Observation	2

Set limits on AMSB chargino production



Backgrounds from reconstruction failure modes:

- unidentified electrons
- unidentified muons
- hadrons with mismeasured p_T
- fake tracks

Estimate backgrounds with tag-and-probe methods.

JHEP 01 (2015) 096

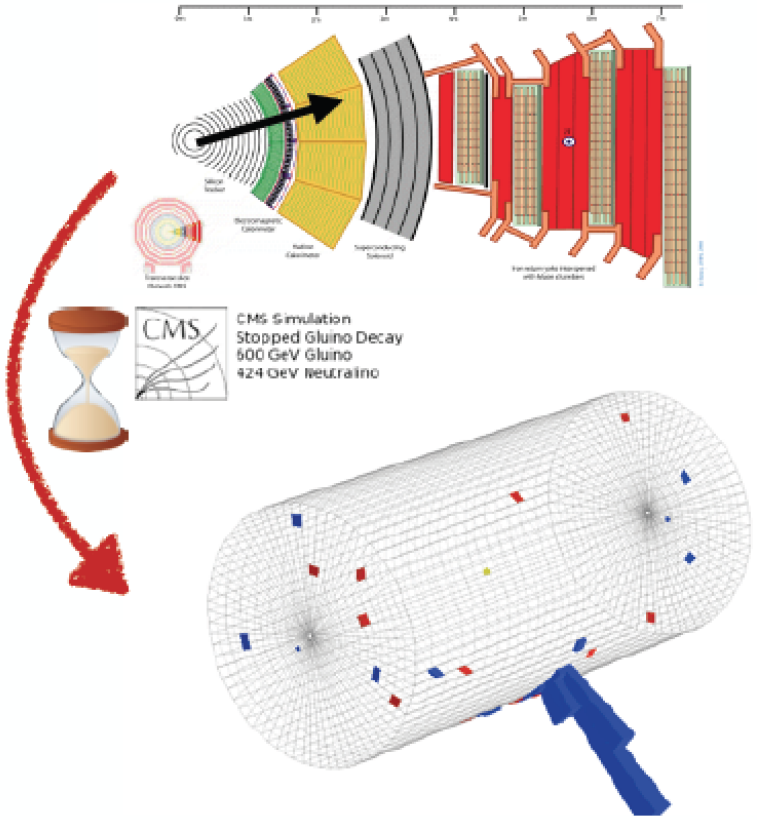
Similar constraint from Phys. Rev. D 88, 112003 (2013) (ATLAS)

Stopped particles

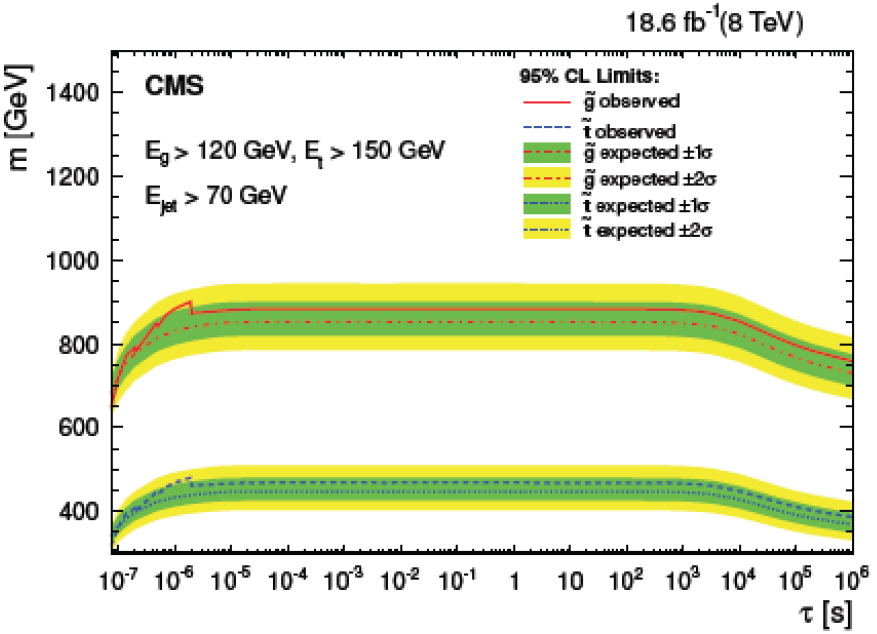
Backgrounds: beam halo muons, cosmic rays, HCAL noise.

	Signal region
Expected bkgd	$13.2^{+3.6}_{-2.5}$
Observation	10

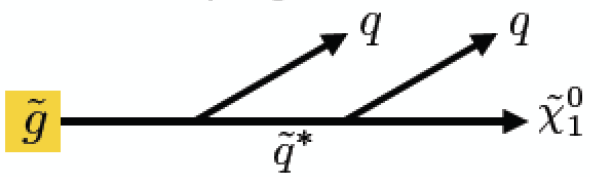
Limits on gluino, stop mass for **over 13 orders of magnitude!**



Look for calorimeter cluster **asynchronous** with p-p collisions. 281 hours of trigger livetime.



mini-split gluino

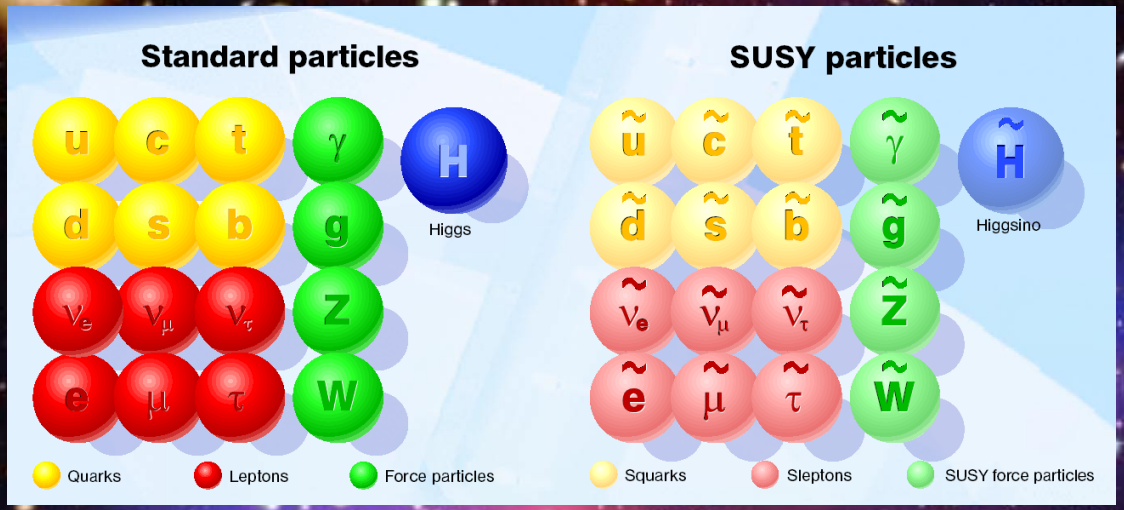


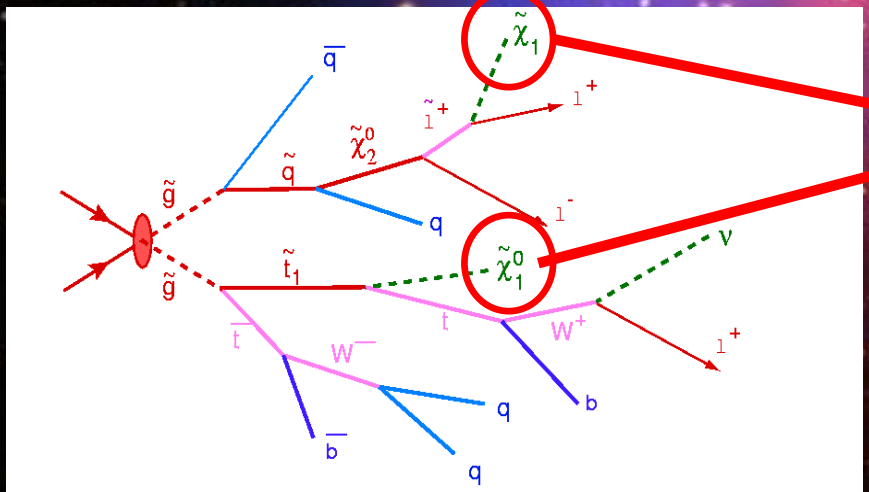
Eg. R-hadrons

Similar techniques employed in Phys. Rev. D 88, 112006 (2013) (ATLAS)

arXiv:1501.05603

Supersymmetry: a new symmetry in Nature?





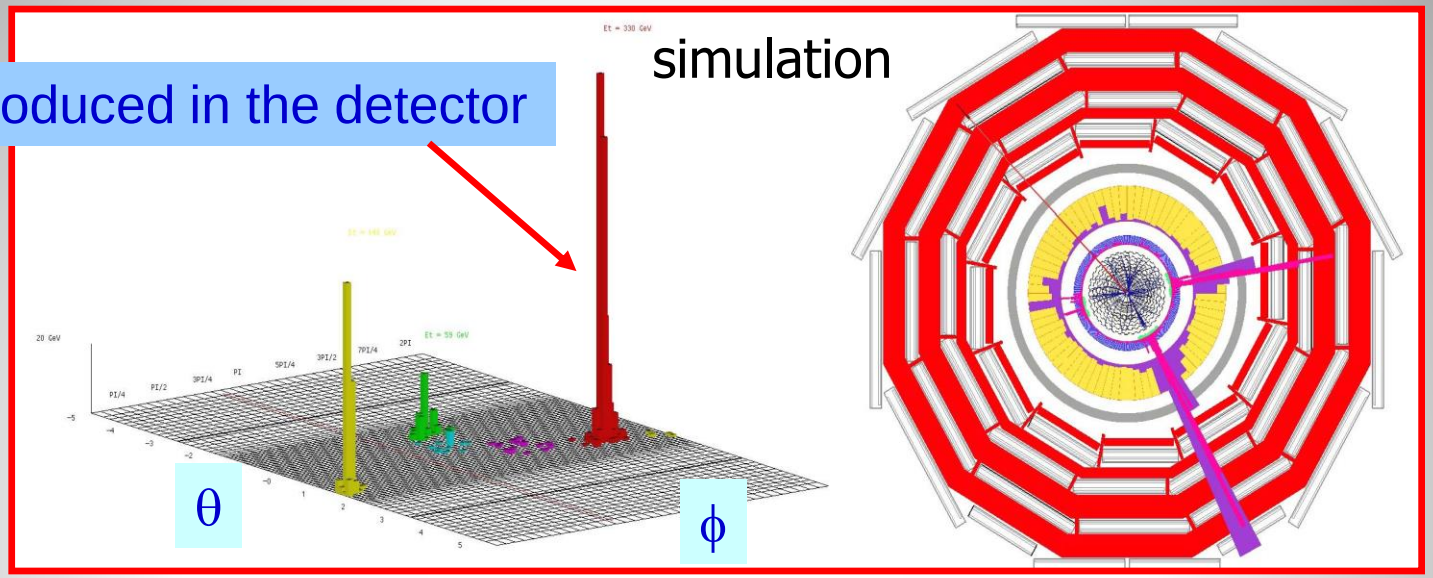
SUSY particle production at the LHC

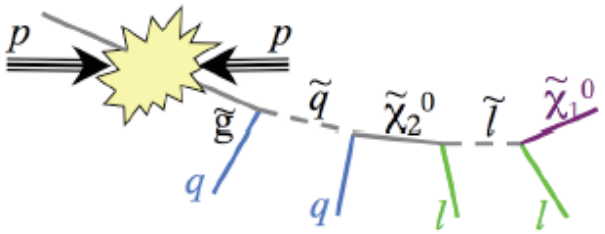
Candidate particles for Dark Matter
⇒ Produce Dark Matter in the lab

Picture from Marusa Bradac

Detecting Supersymmetric Particles

Energy produced in the detector



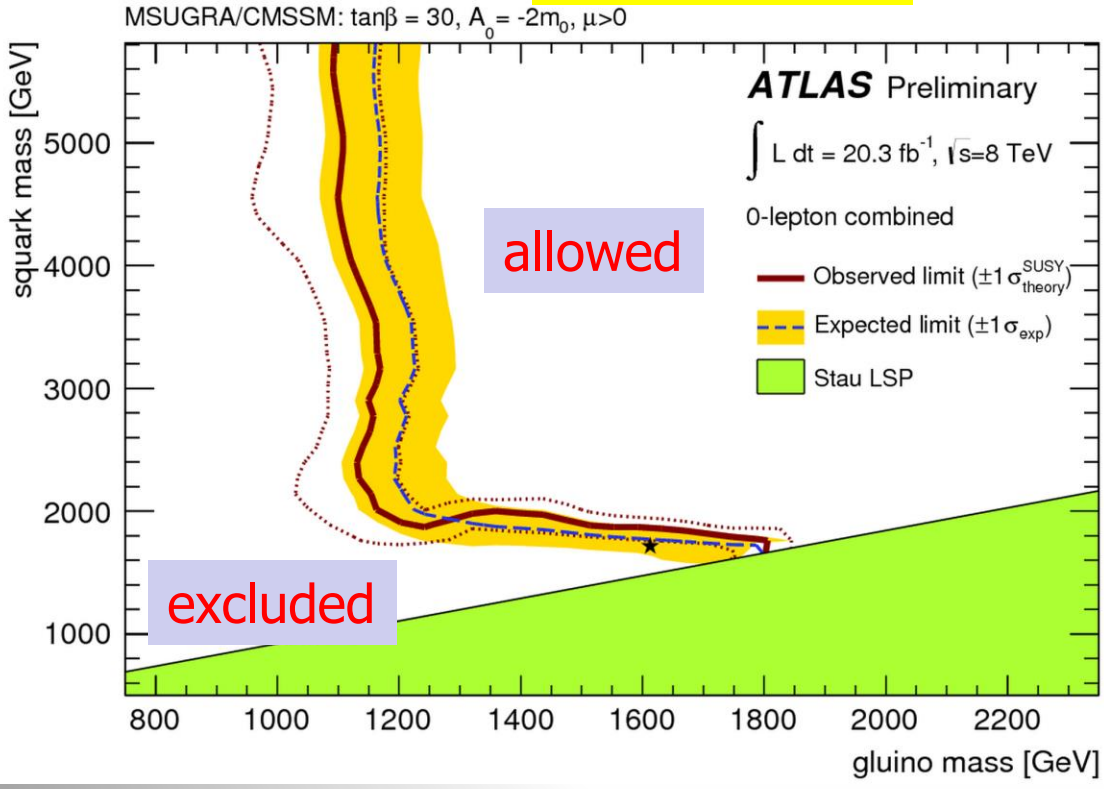


Supersymmetric particles decay and produce a cascade of jets, leptons and missing transverse energy (MET) due to escaping ‘dark matter’ particle candidates

Very prominent signatures in CMS and ATLAS

SUSY Searches: No signal yet to date…

Status in 2013



- So far NO clear signal of supersymmetric particles has been found
- We can exclude regions where the new particles could exist.
- Searches will continue for the higher energy in 2015

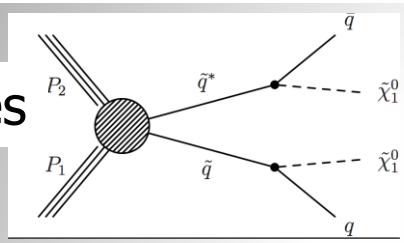
Plenty of searches ongoing: with jets, leptons, photons, W/Z, top, Higgs, with and without large missing transverse energy

Also special searches for contrived model regions

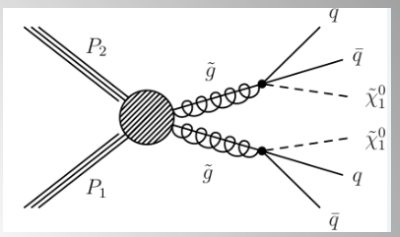
Run-I Limits on Squarks and Gluinos

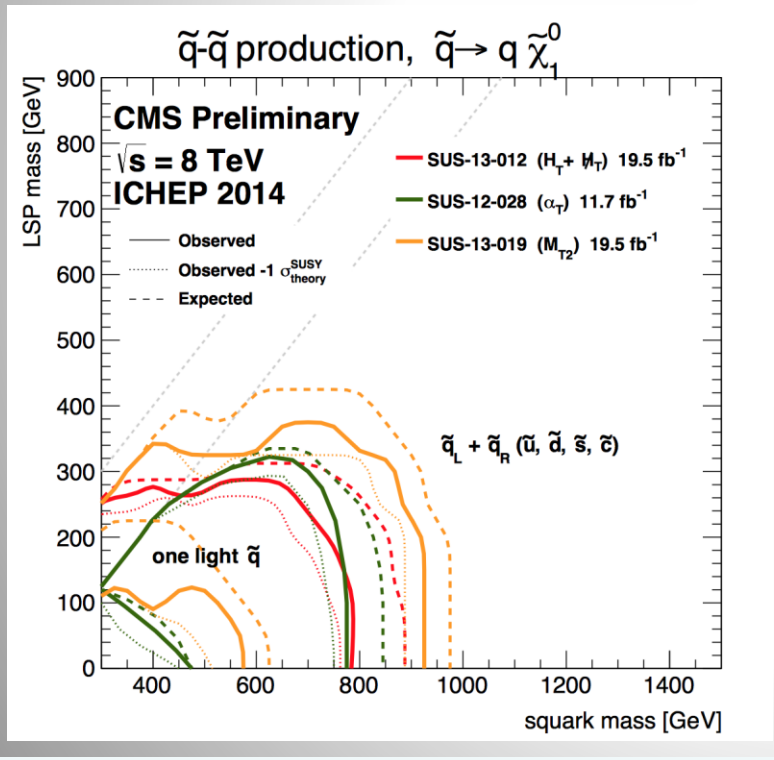
Results depend on the topologies studies, assumed mass of the LSP etc.

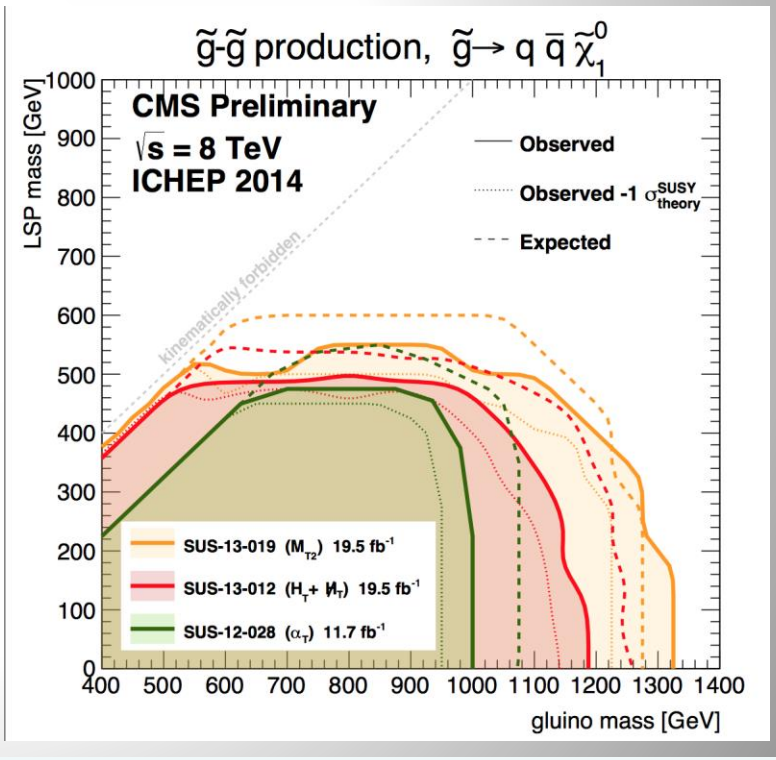
Examples



Popular presentation of data:
Simplified ModelS (SMS)

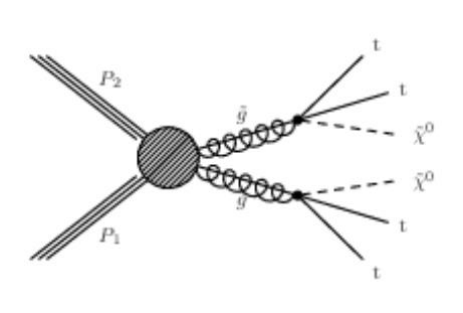




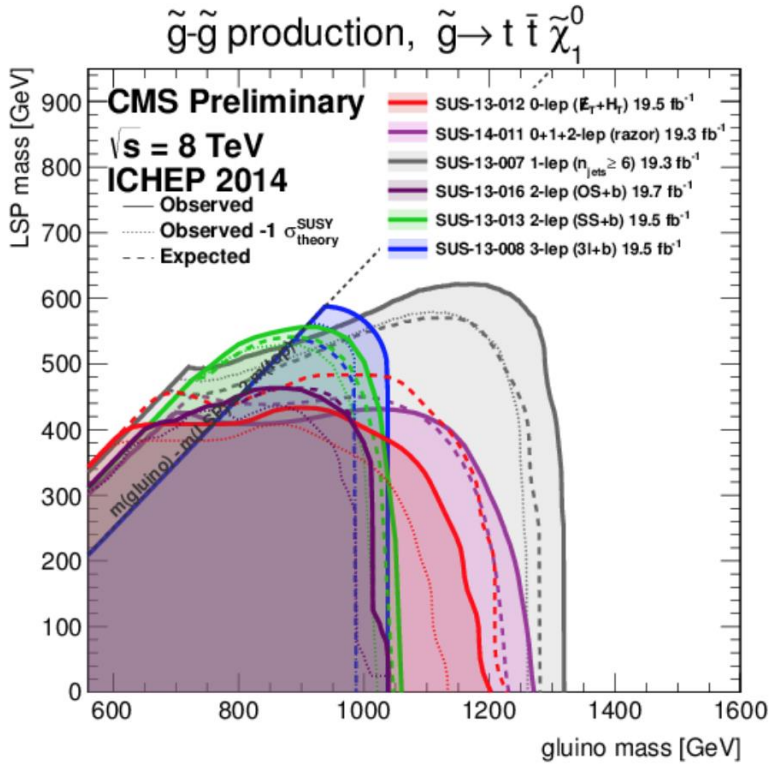


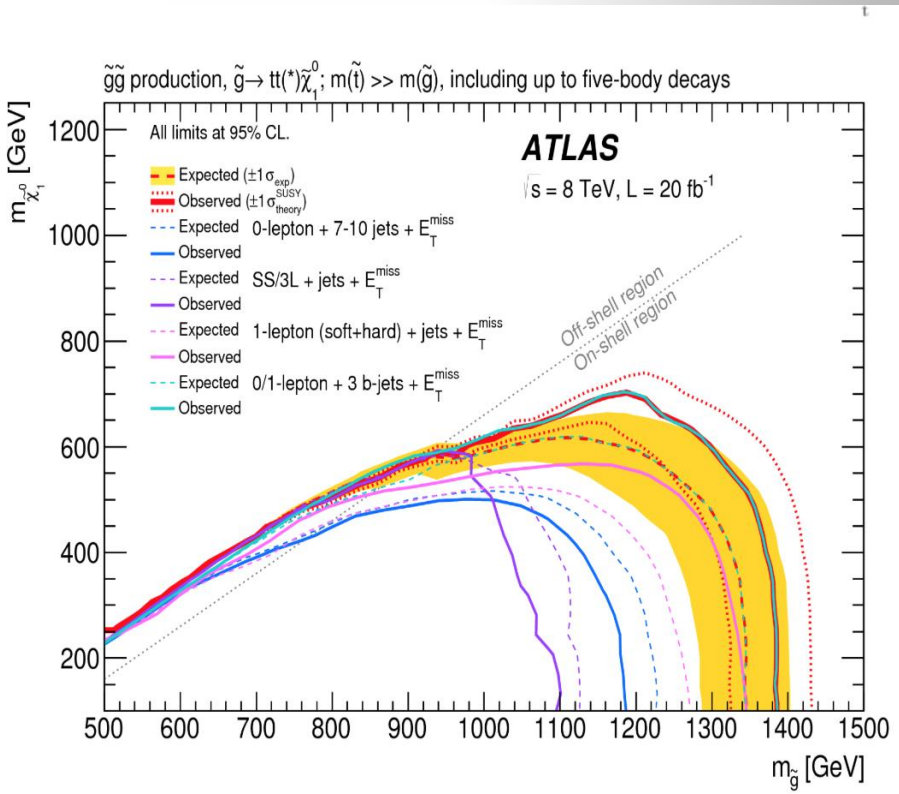
Combined limits typically > 1-1.3 TeV on sparticle masses

Run-I Limits on Gluinos



Combined limits typically ~1.3 TeV on gluino mass





What is really needed from SUSY?

End 2011: Revision!

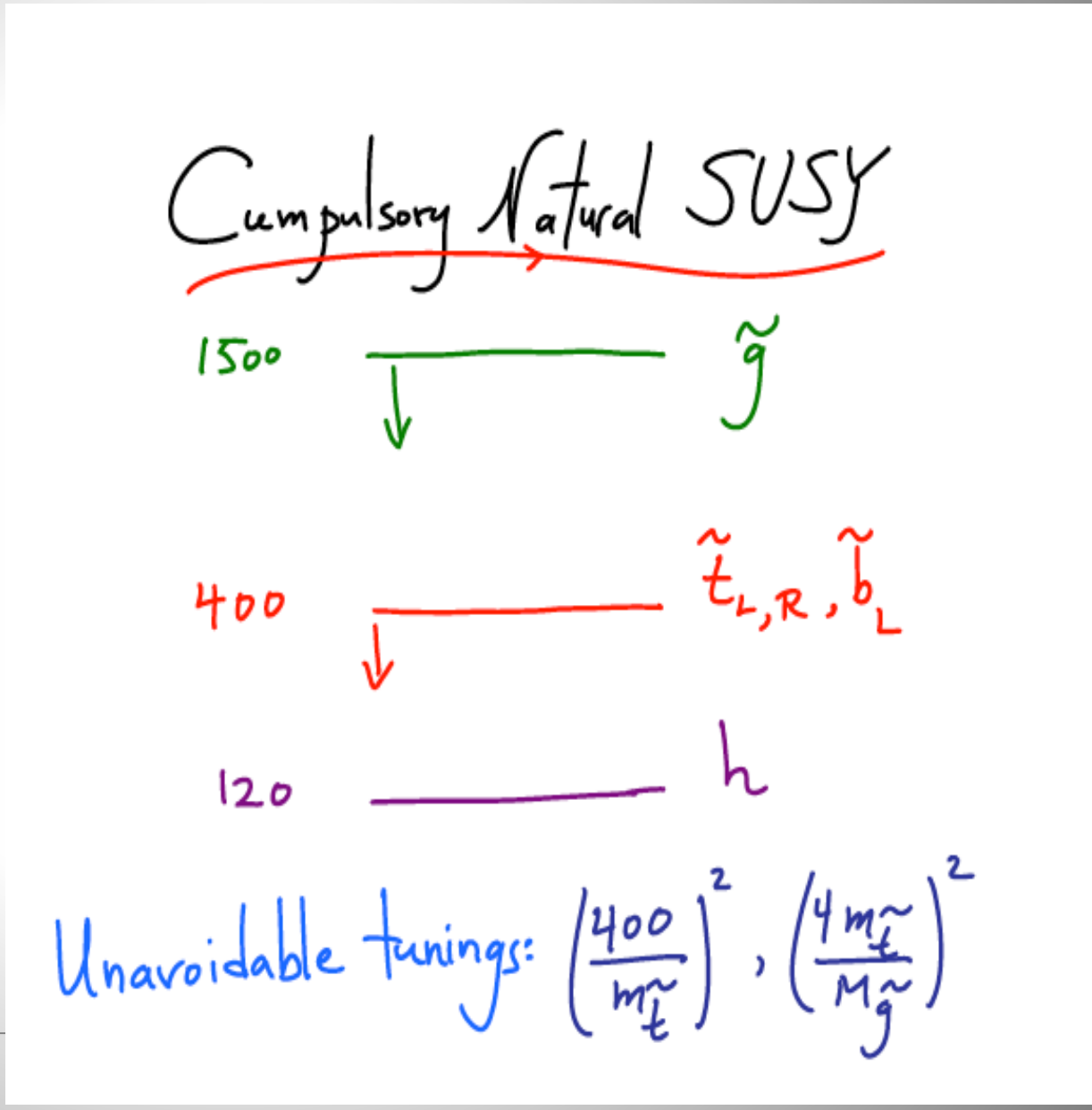
N. Arkani-Ahmed
CERN Nov 2011

Papucci, Ruderman, Weiler arXiv:1110.6926

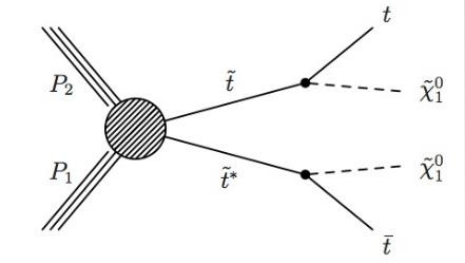
LHC data end 2011
Stops > 200-300 GeV
Gluino > 600-800 GeV

Moving away from constrained SUSY models to 'natural' models

Natural SUSY survived LHC so far, but we are getting close to push it to its limits!

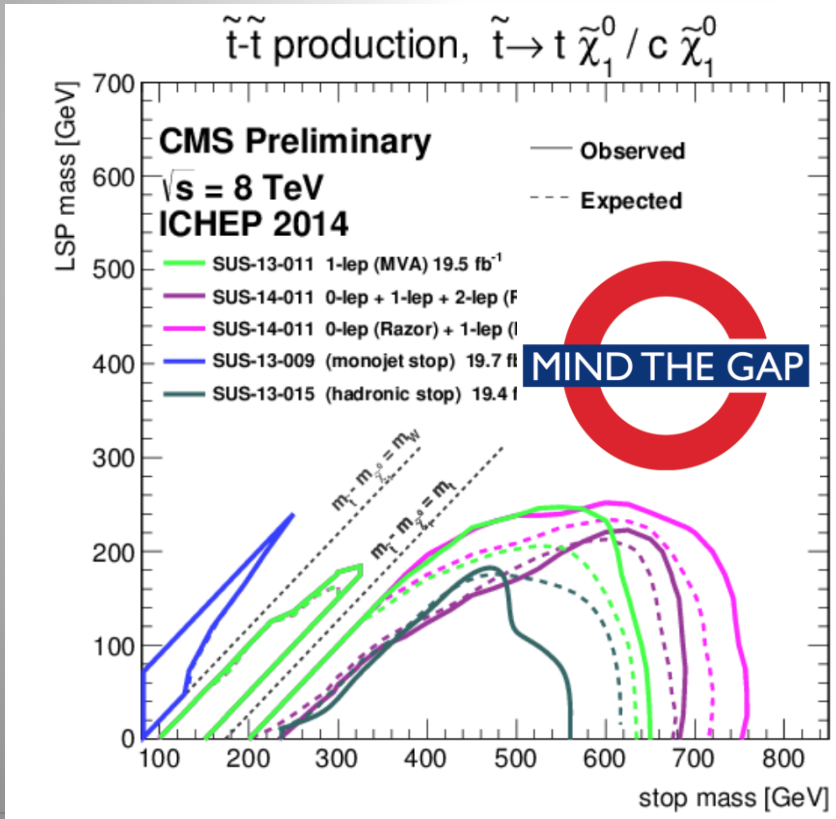


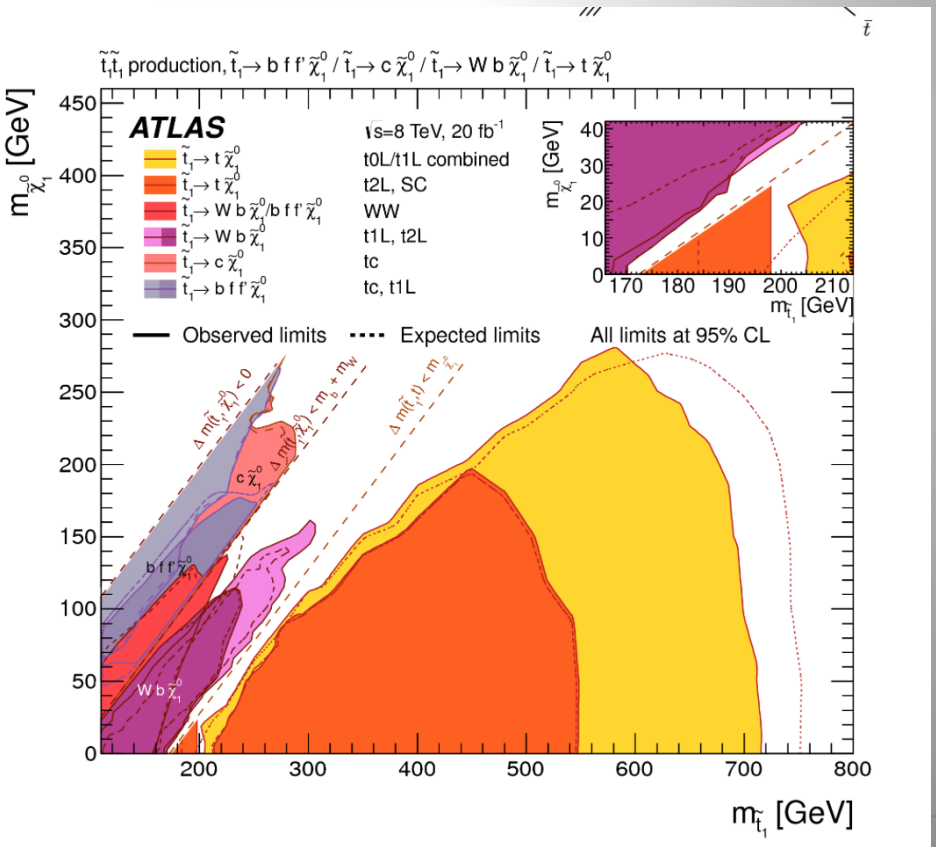
Natural SUSY



Stop mass limits in the studied channels push the lower limits up ~ 700 GeV (*)
Natural SUSY requires already ~ 1% fine-tuning

(*) less strict limits in pMSSM SUSY

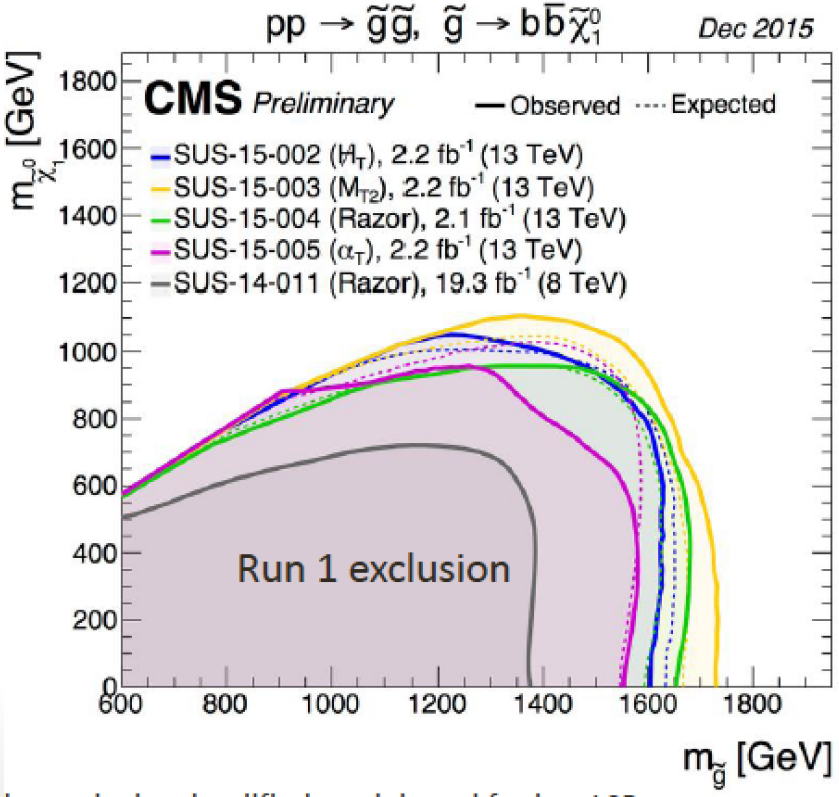


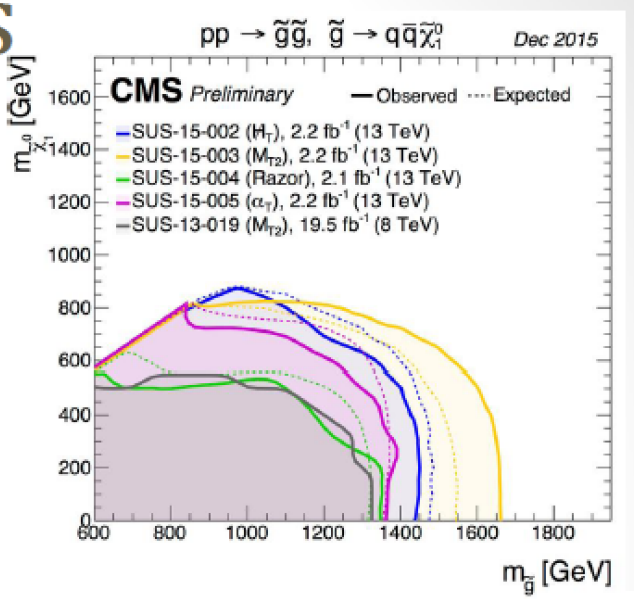


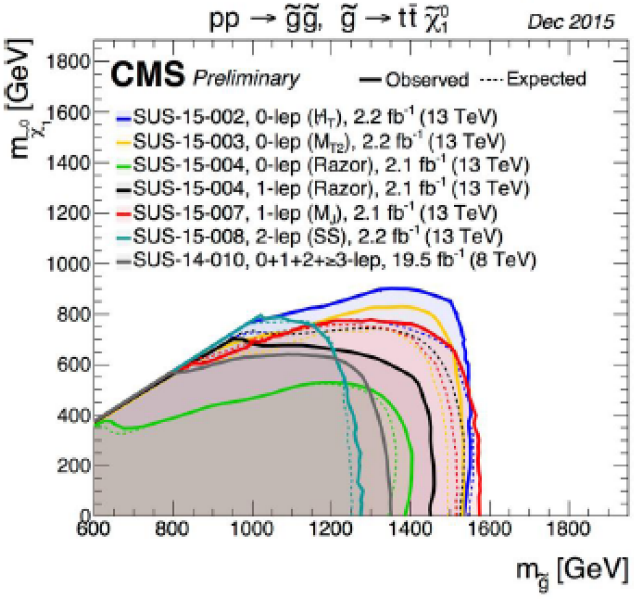
Run-II: Gluino Search

Gluino search results

- **No significant signals observed**
- **Exclusions reach to > 1.7 TeV***, significantly exceeding Run 1 limits







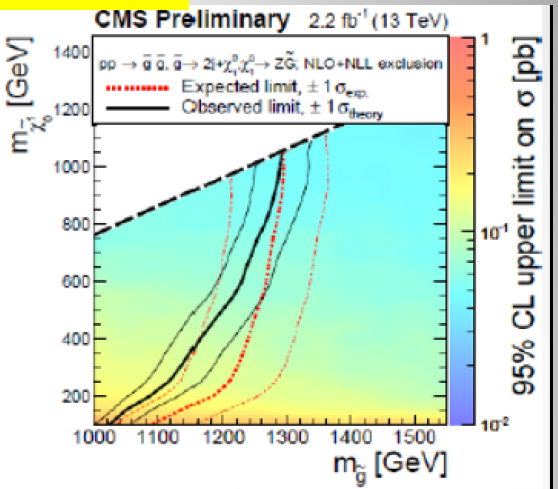
(*): in particular simplified models and for low LSP mass

RUN-II: Opposite Sign Dilepton Search

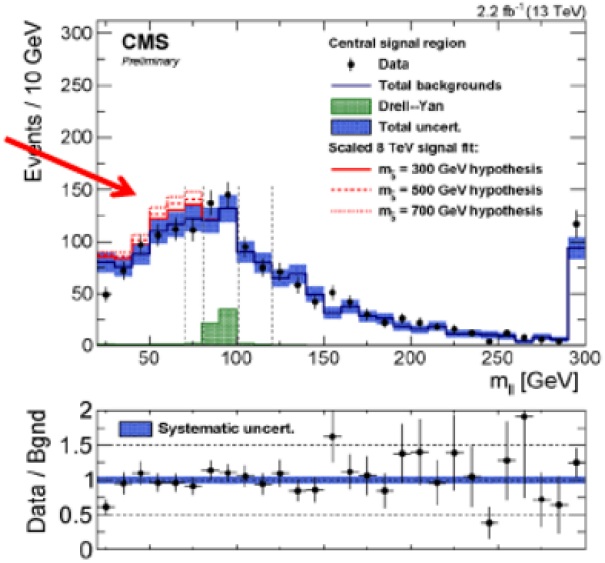
CMS had a 'persistent' excess in this channel with Run-I

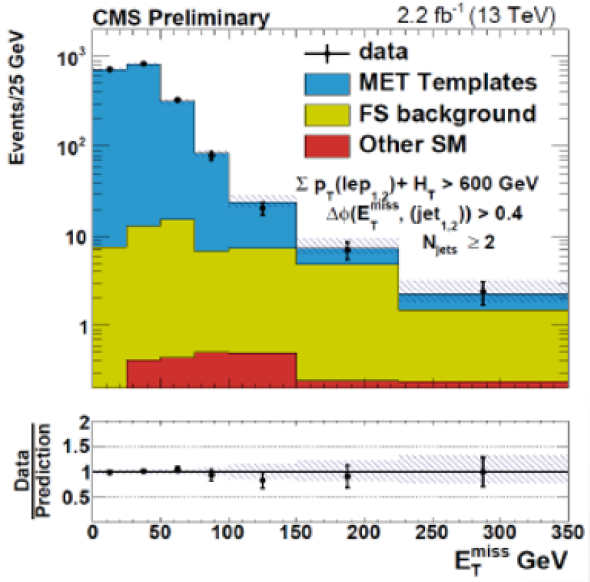
SUS-15-011

- Off-peak selection similar to Run 1, on-peak analysis now includes a region targeting the ATLAS excess
- **No significant signals are observed:**
  - Upper limits are below predicted yields scaling from the Run 1 excesses
    - For gluino masses in the range 500-1100 GeV



Run 1 excess

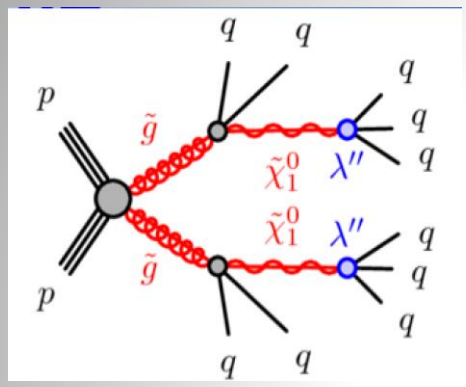




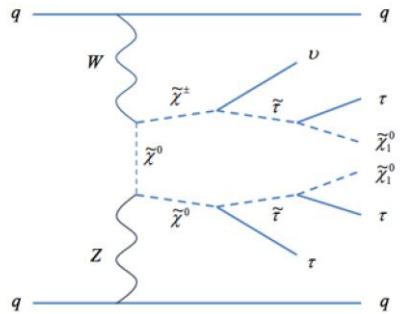
This excess is NOT confirmed with the 2015 data so far

Recent New Directions…

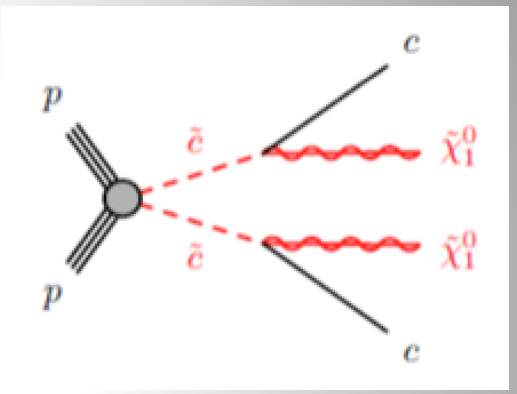
Multi-jet (≥6), no MET

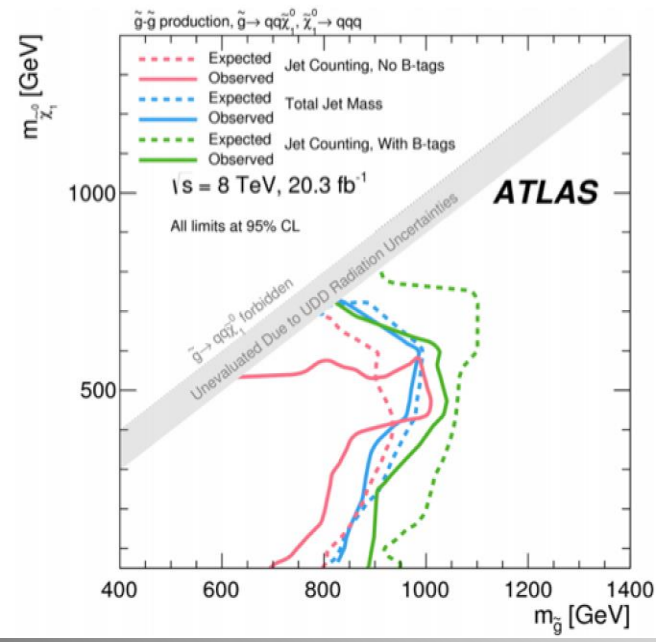


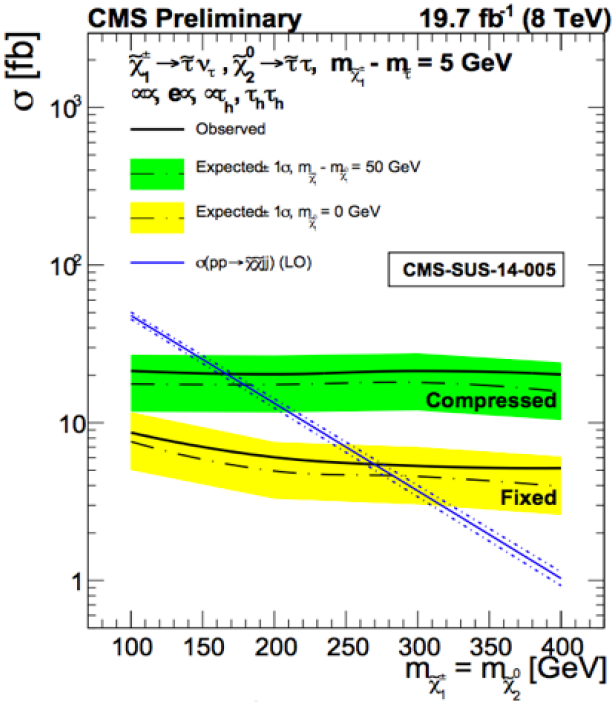
VBF EWKino production

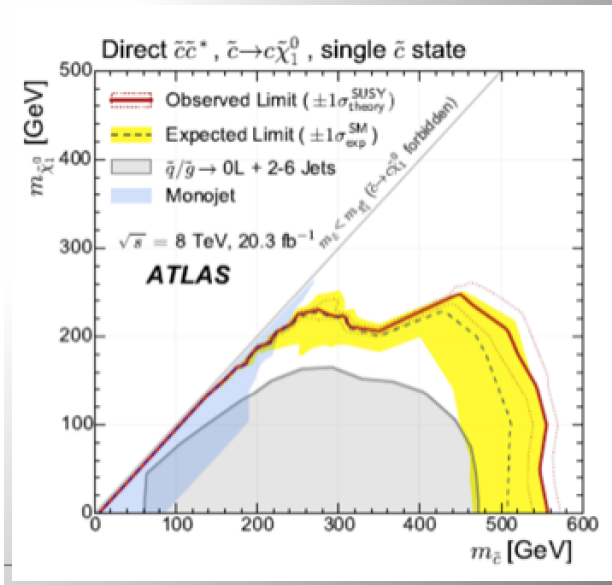


Scalar charm quark



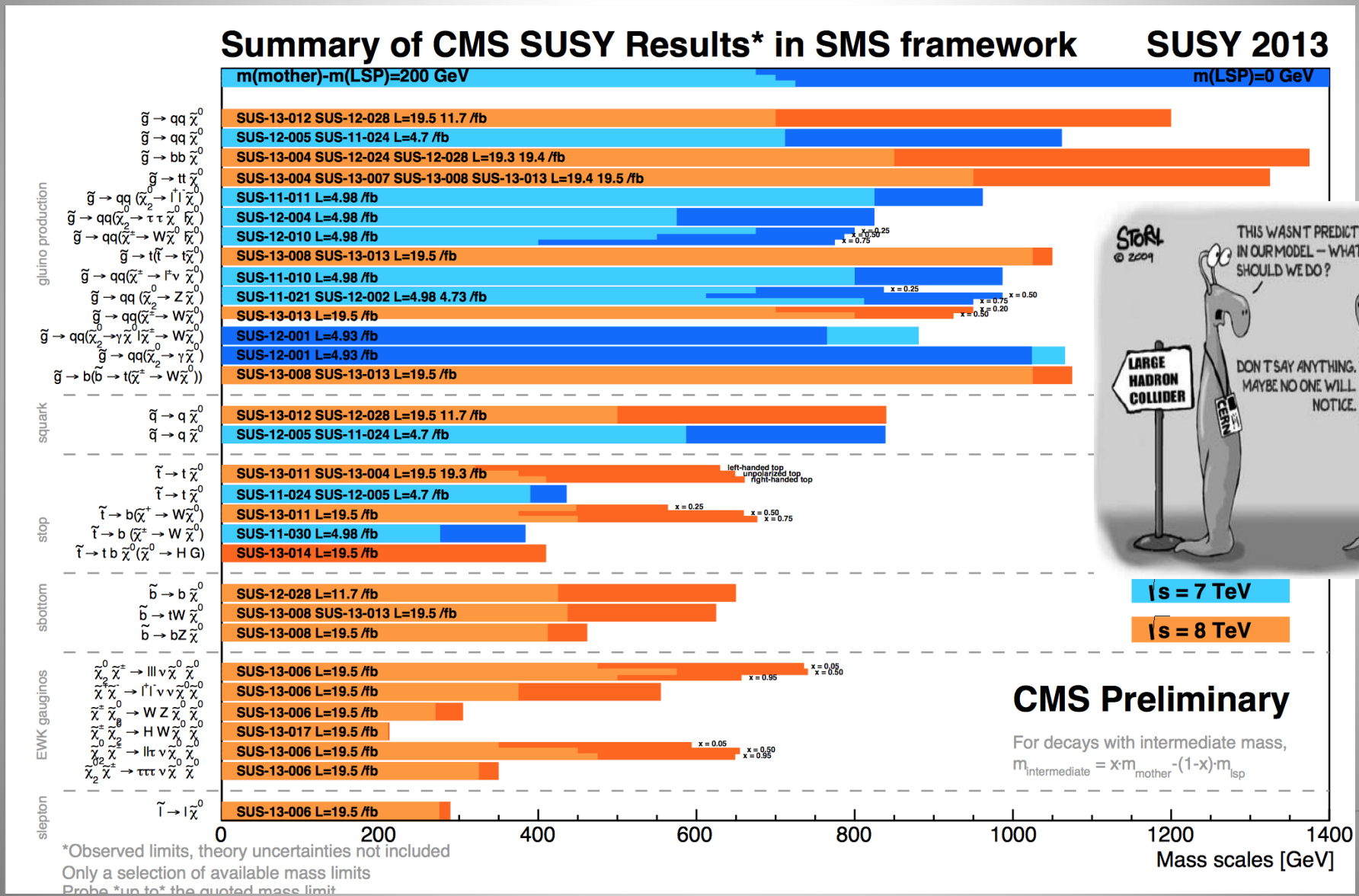






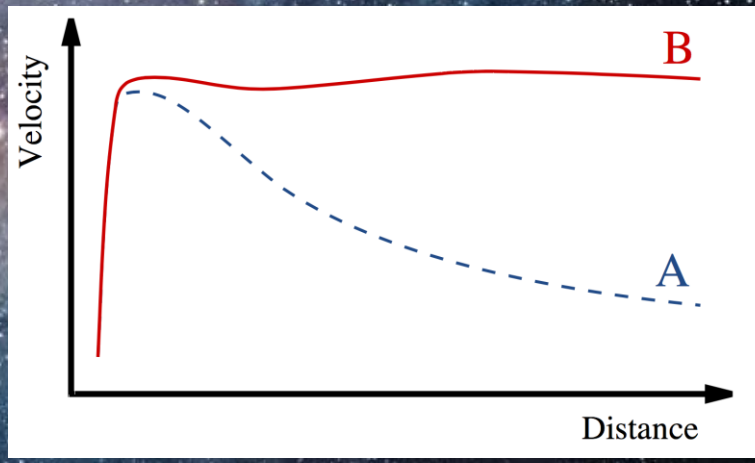
Summary of SUSY Searches

In short: no sign of SUSY with the data collected so far



Dark Matter: The Next Challenge !?!

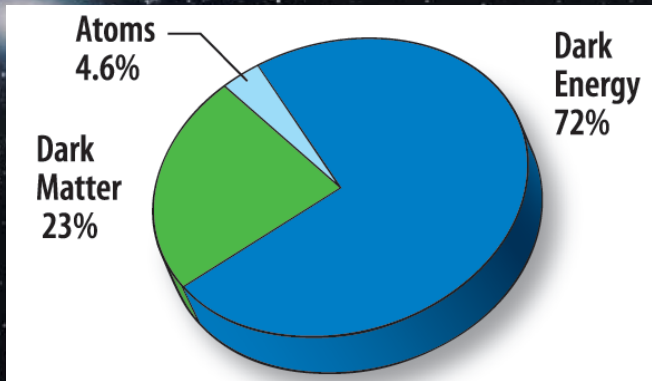
Astronomers found that most of the matter in the Universe must be invisible Dark Matter



'Supersymmetric' particles ?

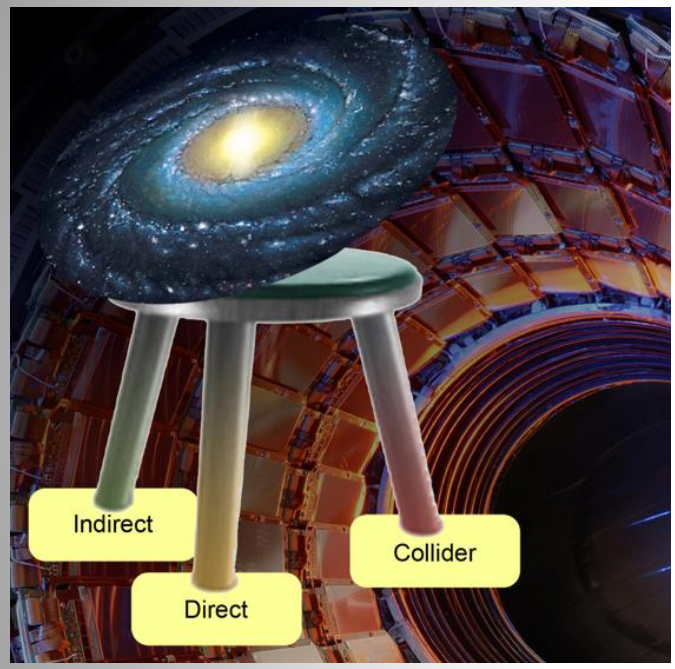

F. Zwicky 1898-1974

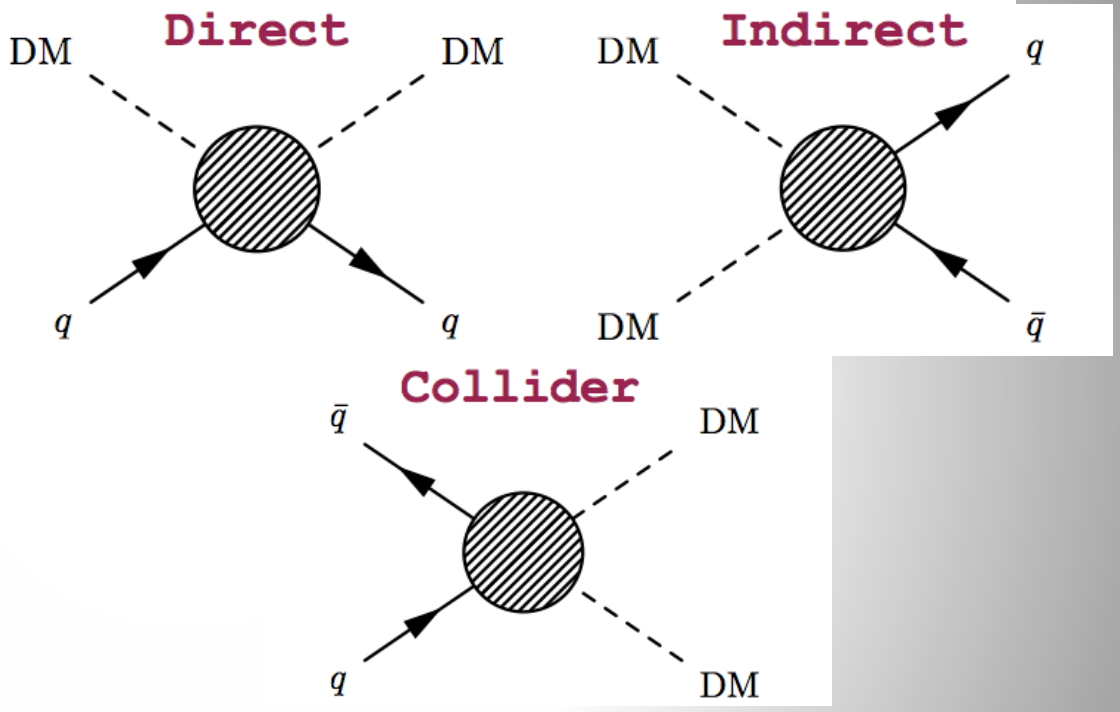

Vera Rubin ~ 1970



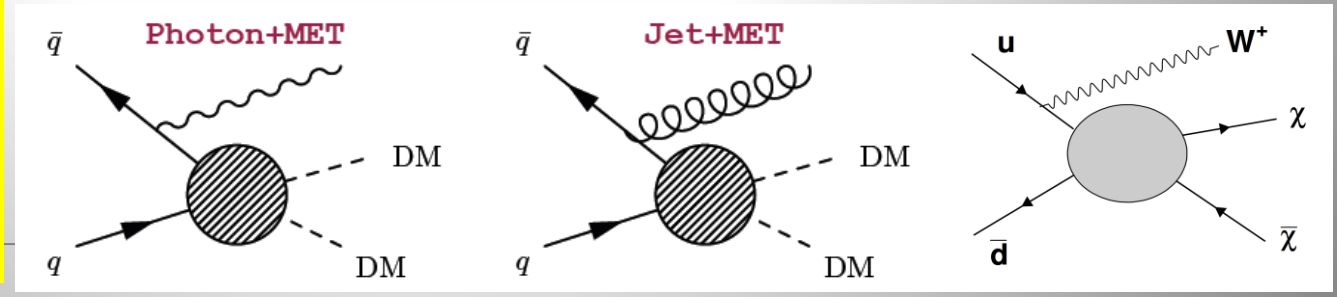
The Generic Dark Matter Connection

Searches for mono-jets and mono-photons can be used to search for Dark Matter (DM)





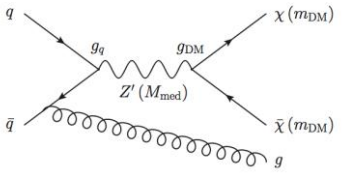
Use effective theory or better simplified models to relate measurements to Dark Matter studies



Mono-object Searches in CMS

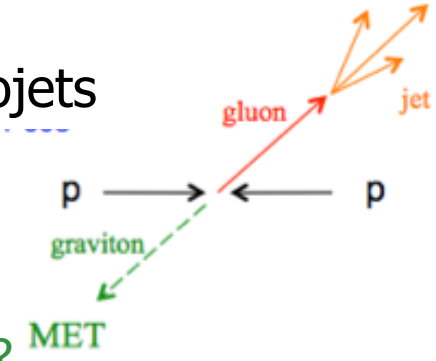
- Mono-jets: Generally the most powerful
- Mono-photons: First used for dark matter Searches
- Mono-Ws: Distinguish dark matter couplings to u- and d-type of quarks
- Mono-Zs: Clean signature
- Mono-Tops: Couplings to tops
- Mono-Higgs: Higgs-portals
- Higgs Decays?

Effective Field Theories for DM interpretation are under scrutiny!
Alternatives such as SMS proposed

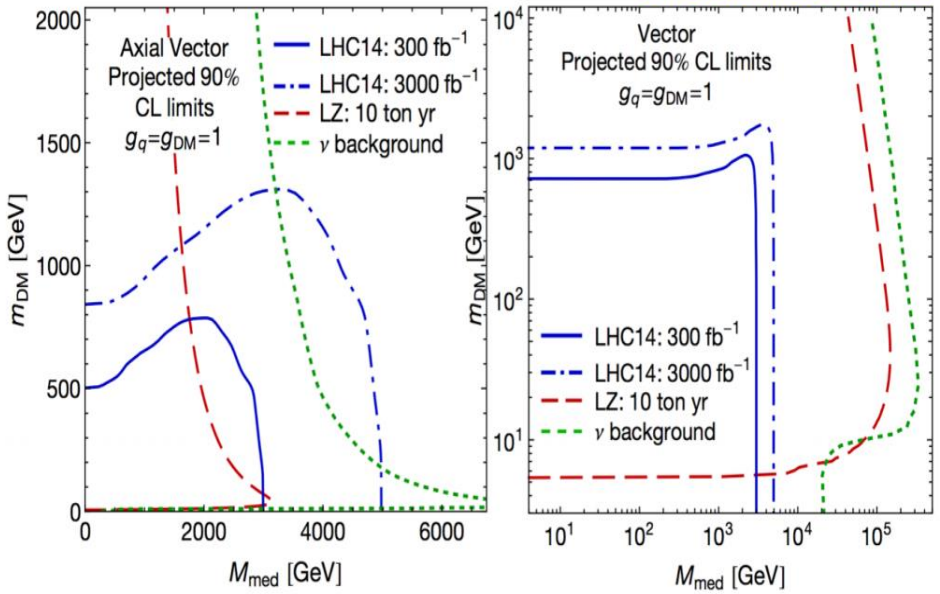


arXiv:1407.8257
arXiv:1411.0535

Example Monojets



Dark Matter?

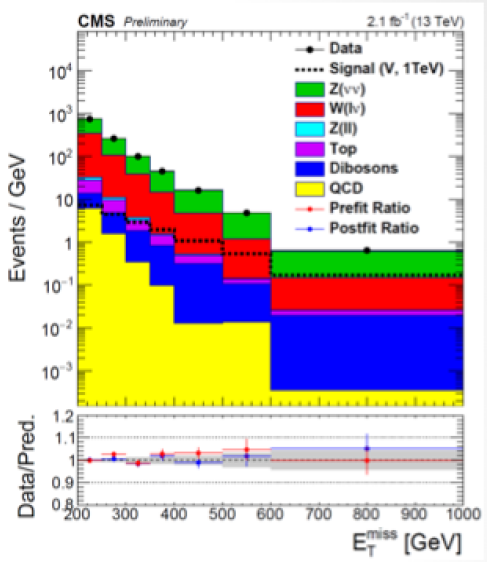


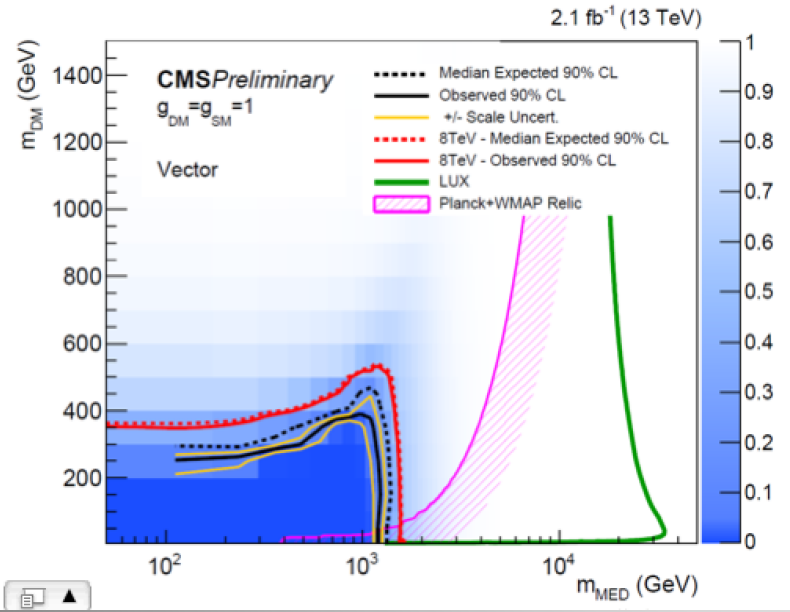
RUN-II Dark Matter Searches Starting…

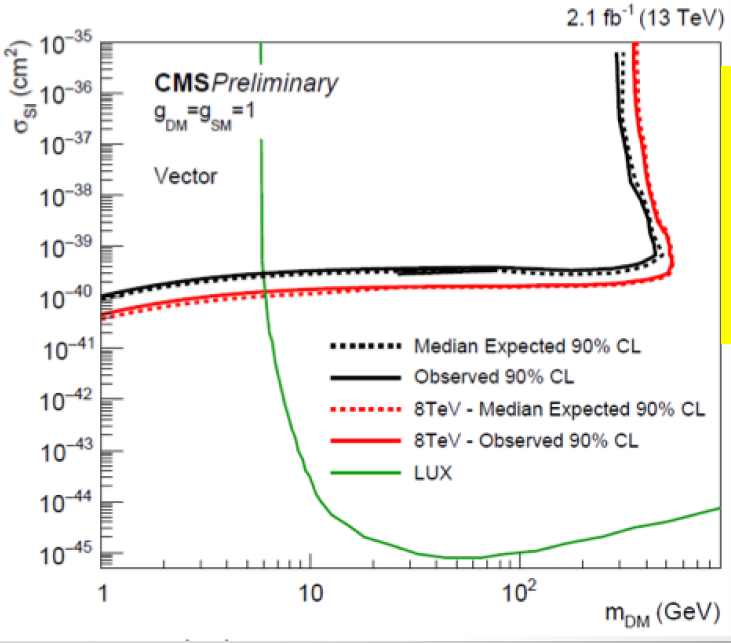
EXO-15-003

Search for dark matter

- Search for generic dark matter in **final states with jets and large missing transverse energy**
- Traditional monojet search extended to multijet final states, searching for DM pairs produced via a **vector mediator**
- Limits comparable to those set in Run 1

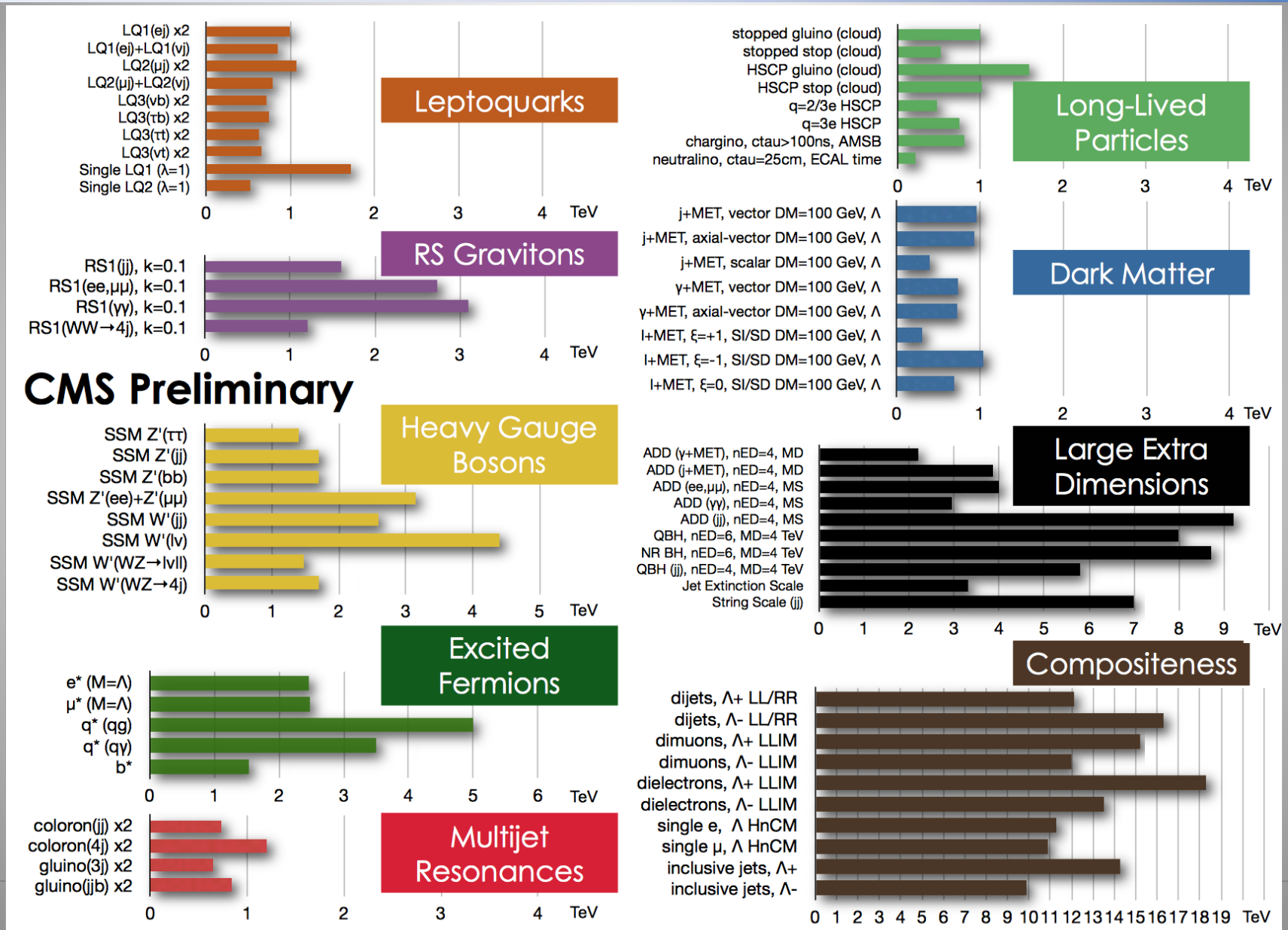




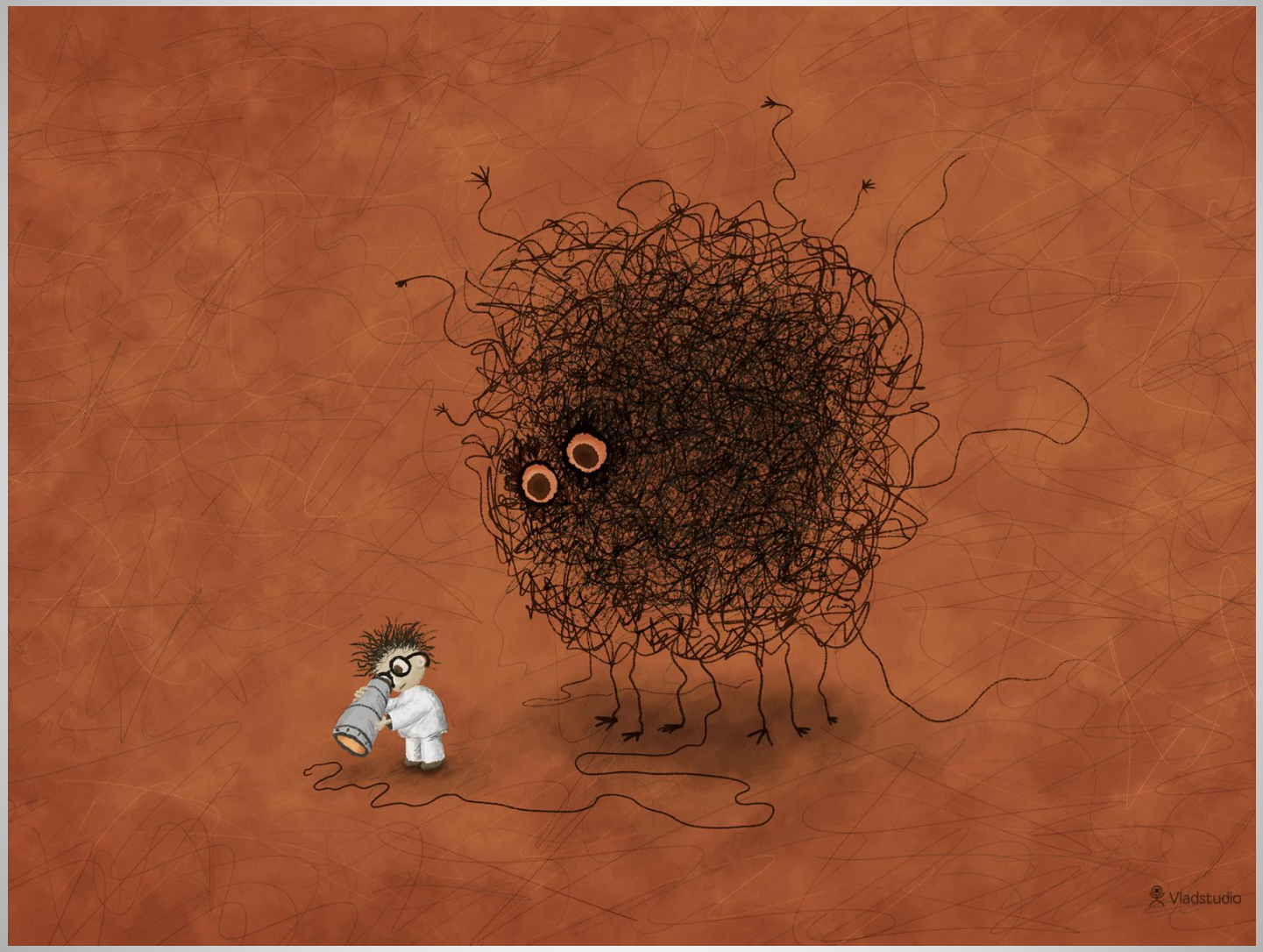


Limits not quite as sensitive as for run-I yet

Summary of Exotica Searches



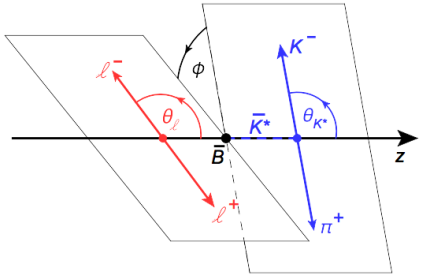
Are we looking at the right place??



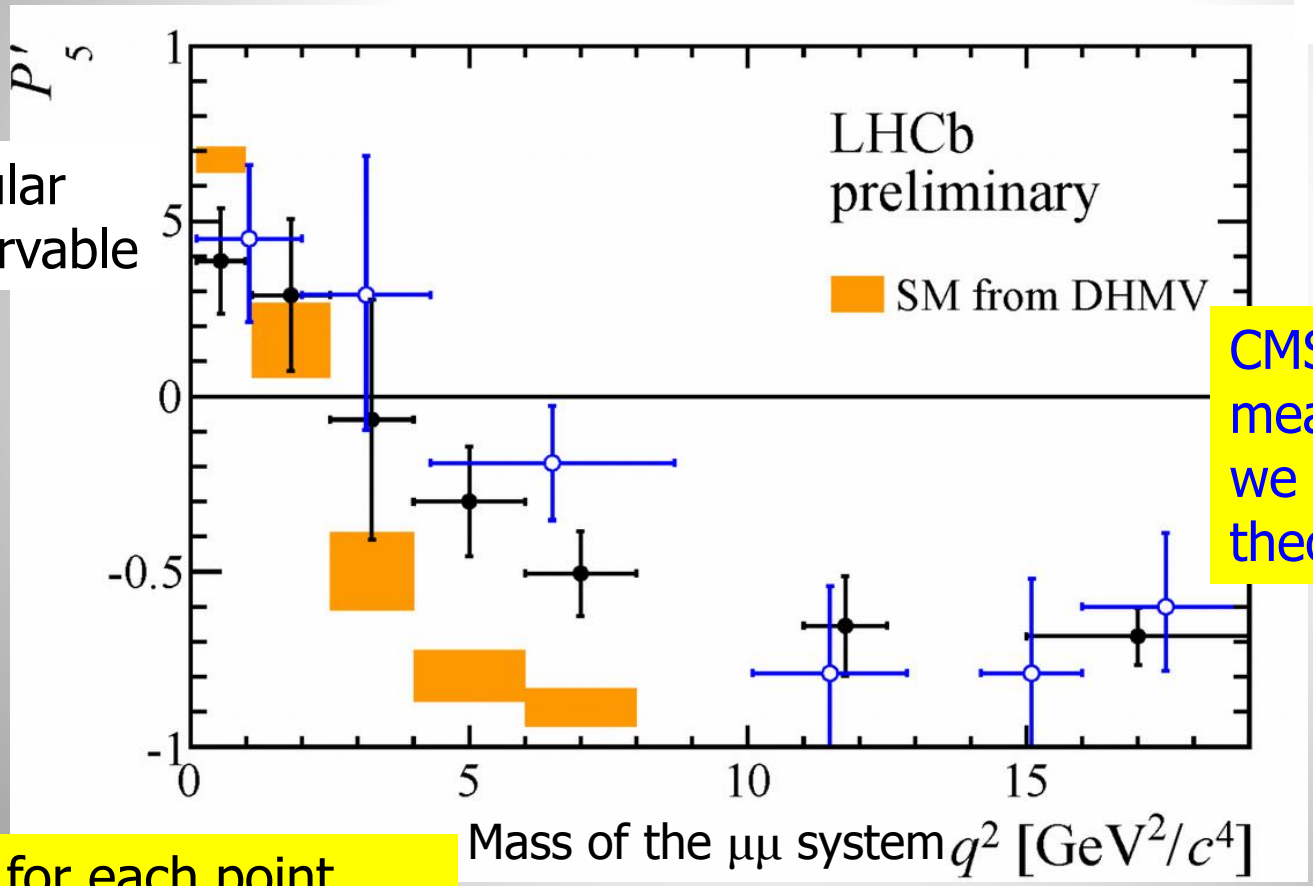
New Physics in Rare Decays?

Analysis of the B0→K*μ+μ- decay (full run-I data-set)

http://lhcb-public.web.cern.ch/lhcb-public/Welcome.html#P5p



Angular observable

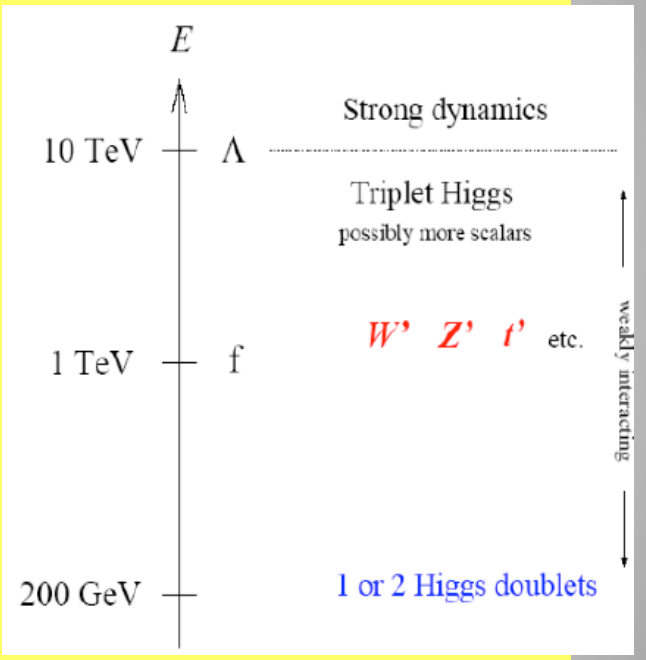


CMS should also measure this but do we understand the theory well enough?

2.9σ for each point
3.7σ naive combination

Other New Physics Ideas…

- Plenty!
  - Compositeness/excited quarks & leptons
  - Little Higgs Models
  - leptoquarks
  - String balls/T balls
  - Bi-leptons
  - RP-Violating SUSY
  - SUSY+ Extra dimensions
  - Unparticles
  - Classicalons
  - Dark/Hidden sectors
  - Colored resonances
  - And more….



Have to keep our eyes open for all possibilities:
Food for MANY PhD theses!!

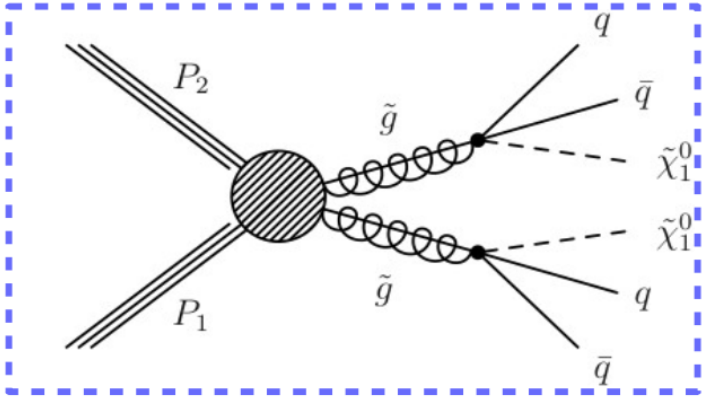
Summary

- The LHC has entered a new territory. The ATLAS and CMS experiments are heavily engaged in searches for new physics. The most popular example is Supersymmetry, but many other New Physics model searches are covered.
- No clear sign of new physics yet in the first 20 fb^{-1} at 8 TeV and first data at 13 TeV. This cuts into 'preferred regions' for many models, like SUSY. But watch the 750 GeV bump!
- More exotic channels are now being covered: vector-like particles, long lived particles… Still many unexplored channels left to explore
- The LHC did its part so far with a great run in 2
  Collected about 20 fb^{-1}@ 8 TeV by end of 2012
- As of 2015 the energy is 13/14 TeV, excellent f
- And maybe one day soon:

Backup

Interpretation into Simplified Models

- Most of SUSY interpretations are performed using Simplified Models of Supersymmetry*
  - This approach puts more emphasis on the experimental signature leaving aside the model details
- Hard interaction producing two SUSY particles (fully decoupled from other particles)
- A single decay chain is implemented producing a given and fixed topology
- However the masses of the SUSY particles are scanned usually in 2 dimensions
- Upper limits are set on the **cross-section x branching ratio** of the given process



* Interpretations in full models are also provided: mSUGRA, pMSSM, etc