Beyond The Standard Model
LHC Results and Prospects

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IPPP, Durham UK
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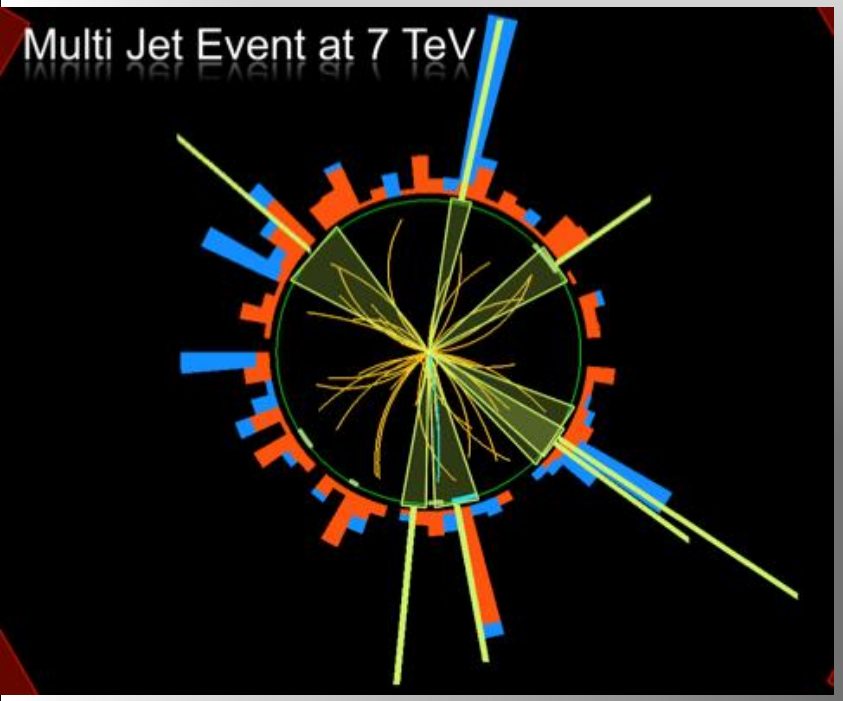
September 14-18 Split, Croatia

Lecture Plan

Overview of the two lectures in the next two days at this school

- Lecture 1: Introduction to physics Beyond the Standard Model (BSM) and searches for exotic phenomena at the LHC
- Lecture 2: Searches for Supersymmetry, the connection to dark matter searches and an outlook for the future.



Outline

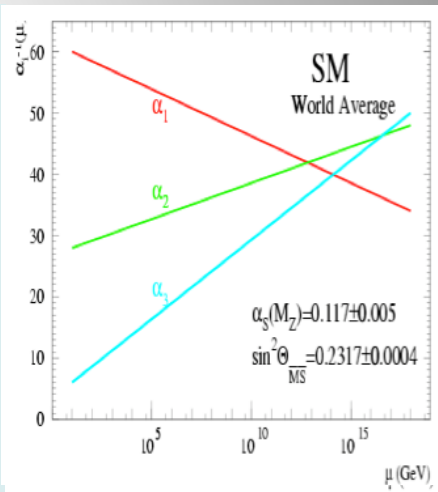
- Search for Physics Beyond the Standard Model
- Search for Exotic and new phenomena in the LHC data
- Summary

Physics case for new High Energy Machines

Understand the mechanism Electroweak Symmetry Breaking

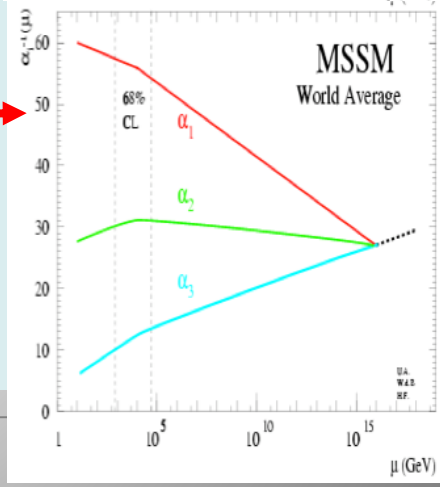
Discover physics beyond the Standard Model

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

- Supersymmetry
- Extra space dimensions

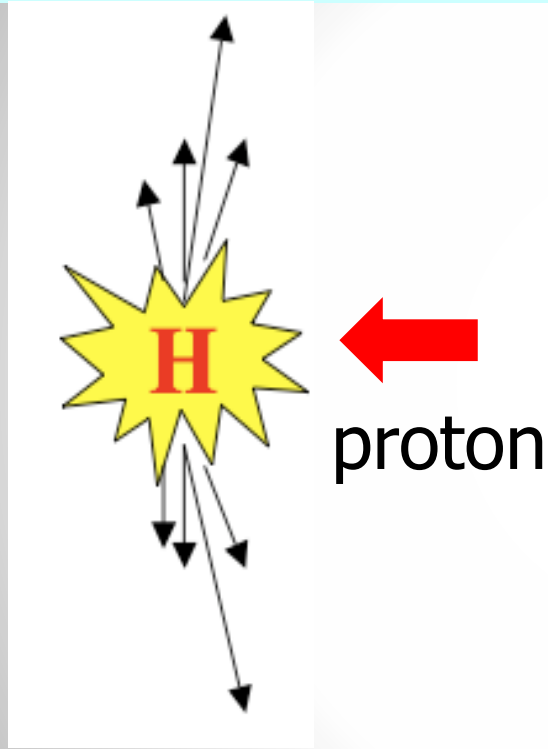


Many other ideas: More symmetry and gauge bosons, composite Higgs models, L-R symmetry, quark & lepton substructure, Little Higgs models, Technicolor, Hidden Valleys, 4th generation…

Higgsless models somewhat disfavoured these days

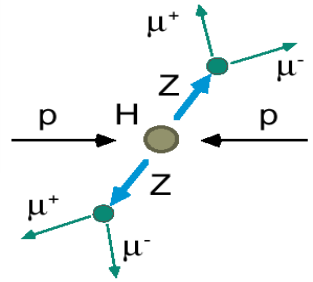
2012: A Milestone in Particle Physics

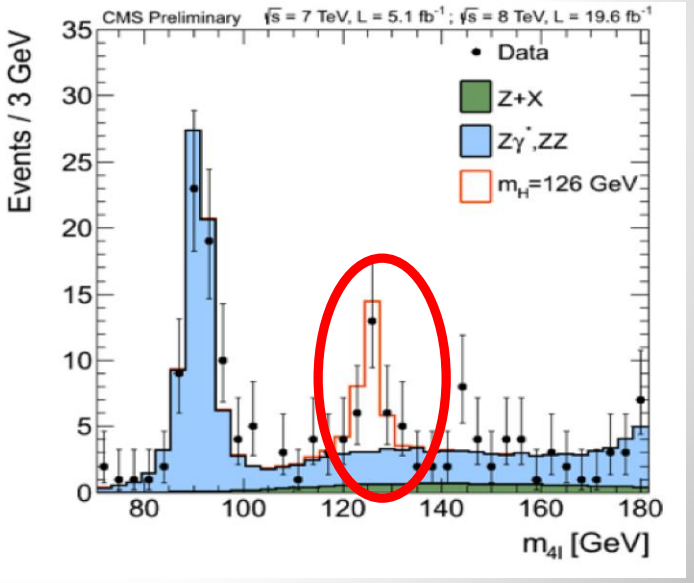
Observation of a Higgs Particle at the LHC, after about 40 years of experimental searches to find it



proton

proton





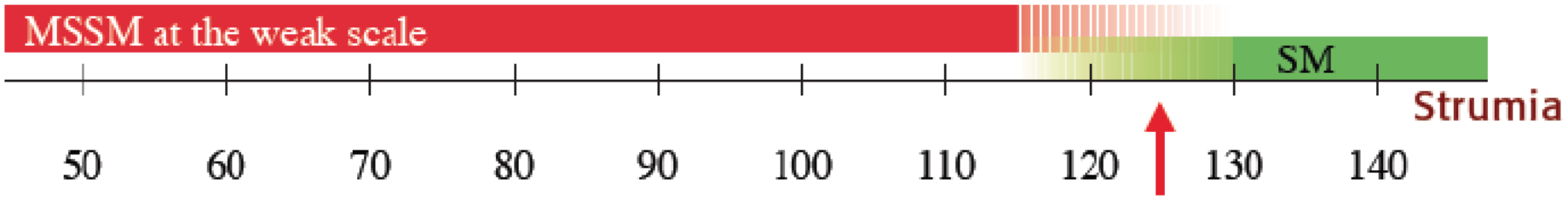
2013

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

A Higgs…

A malicious choice!

m_H = 125.0 +/- 0.3 GeV



The Higgs:
so simple yet so unnatural

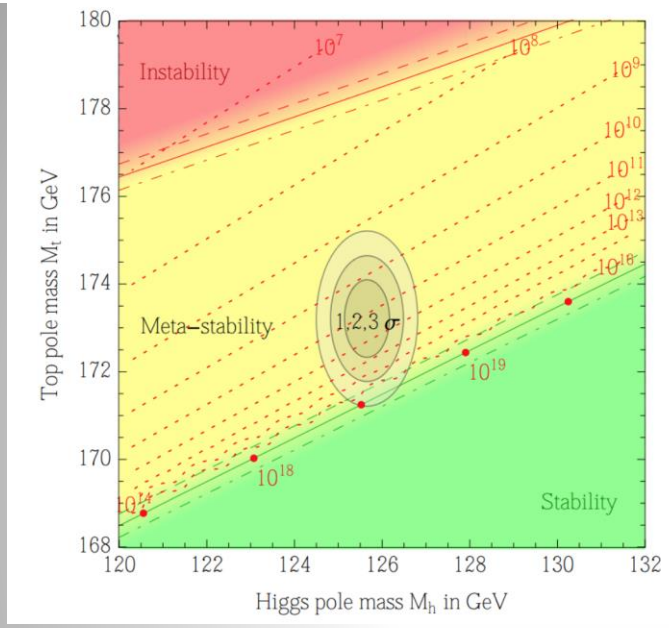
Guido Altarelli

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

Searches for New Physics

Important SM parameter → stability of EW vacuum

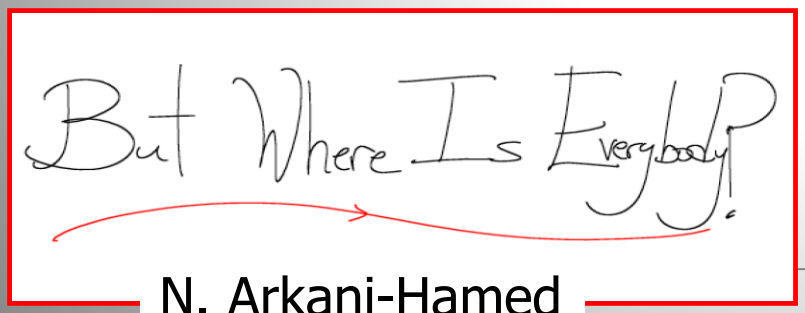


arXiv:1205.6497

arXiv:1403.6535

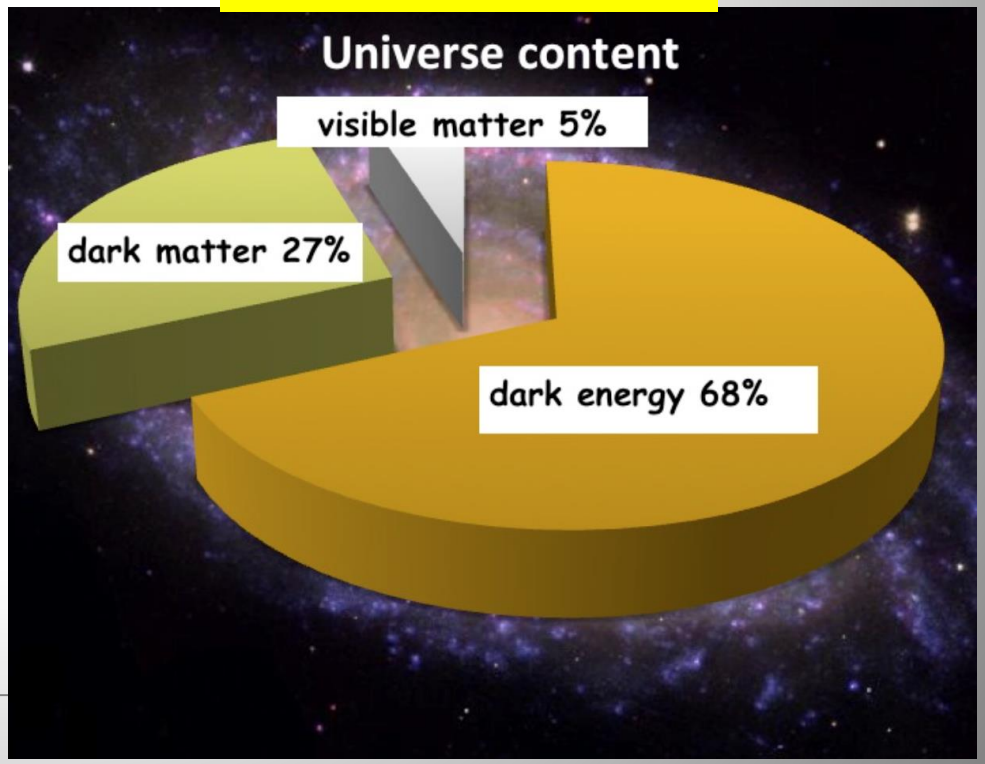
Precise measurements of the top quark and first measurements of the Higgs mass

New Physics inevitable?
But at which scale/energy?



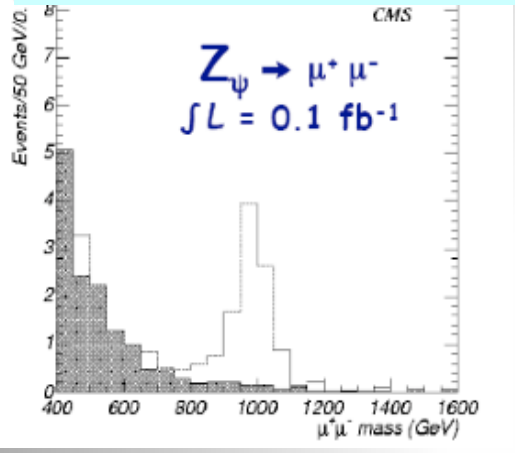
N. Arkani-Hamed

We also know that:

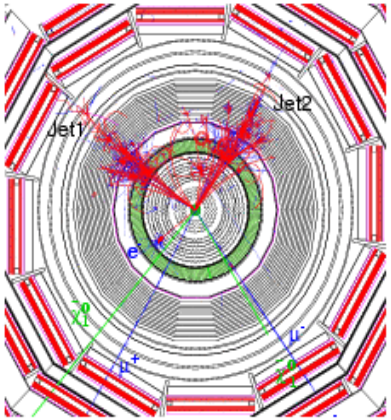


New Physics?

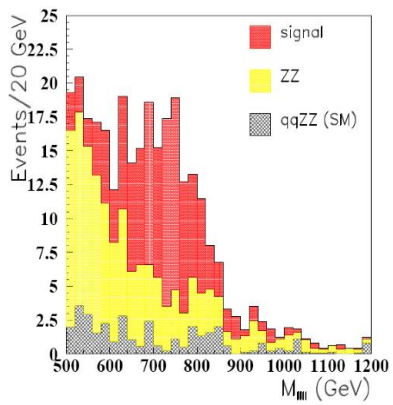
New Gauge Bosons?



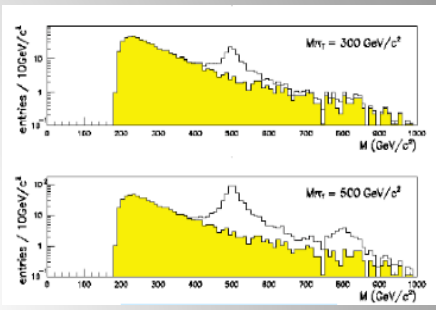
Supersymmetry



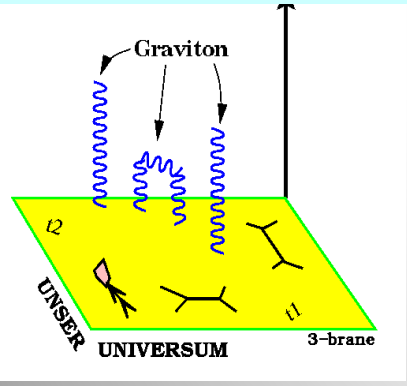
ZZ/WW resonances?



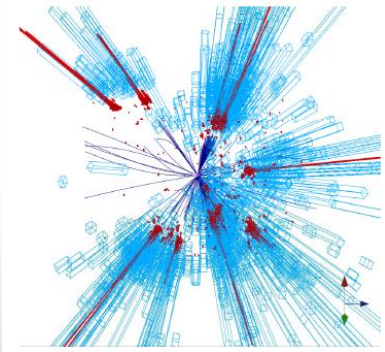
Technicolor?



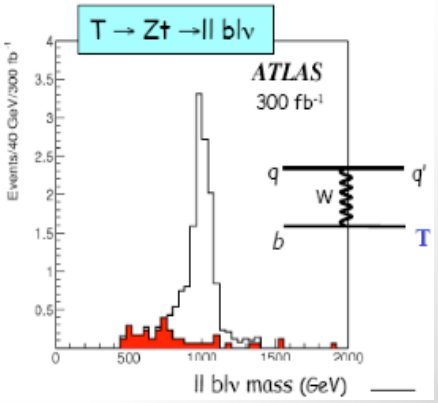
Extra Dimensions?



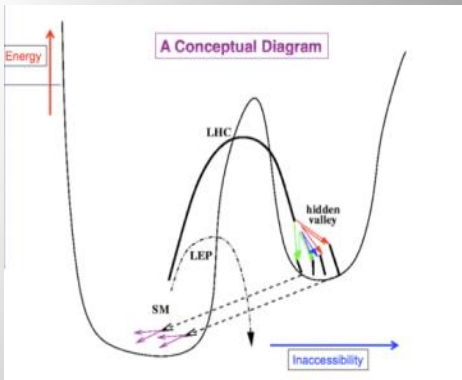
Black Holes???



Little Higgs?



Hidden Valleys?

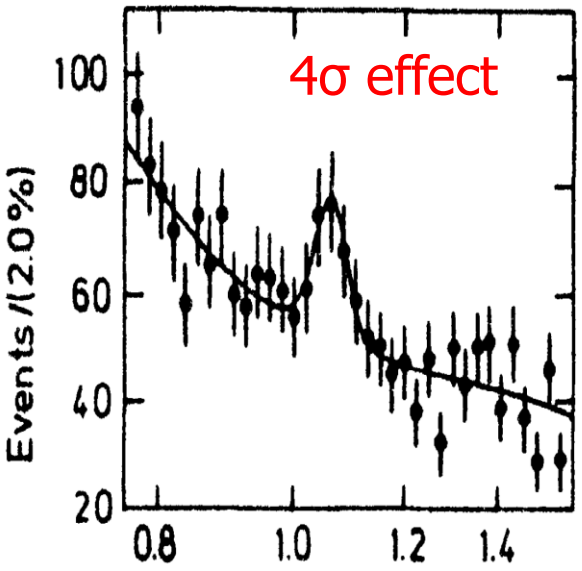


What stabelizes the Higgs Mass? Many ideas, not all viable any more

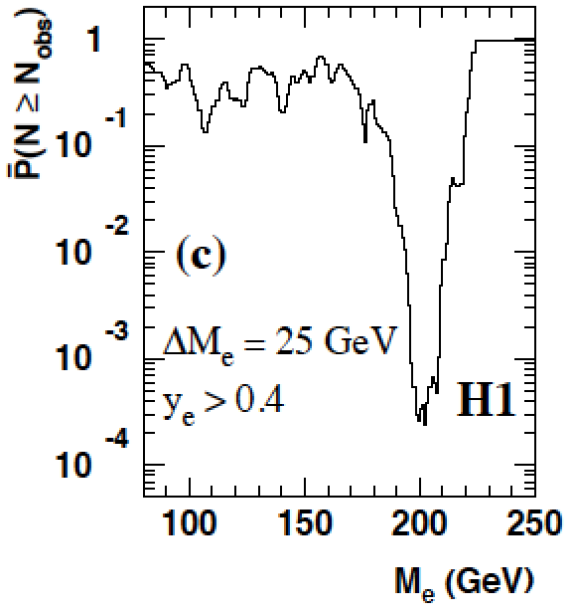
A large variety of possible signals. We have to be ready for that

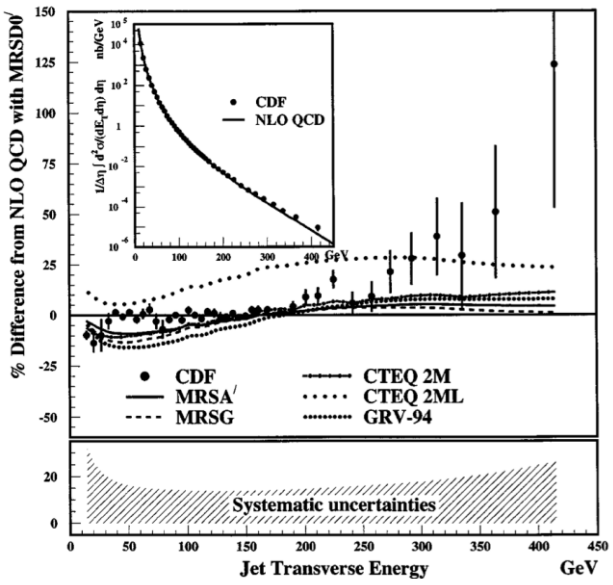
Careful with "Discoveries"!

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



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





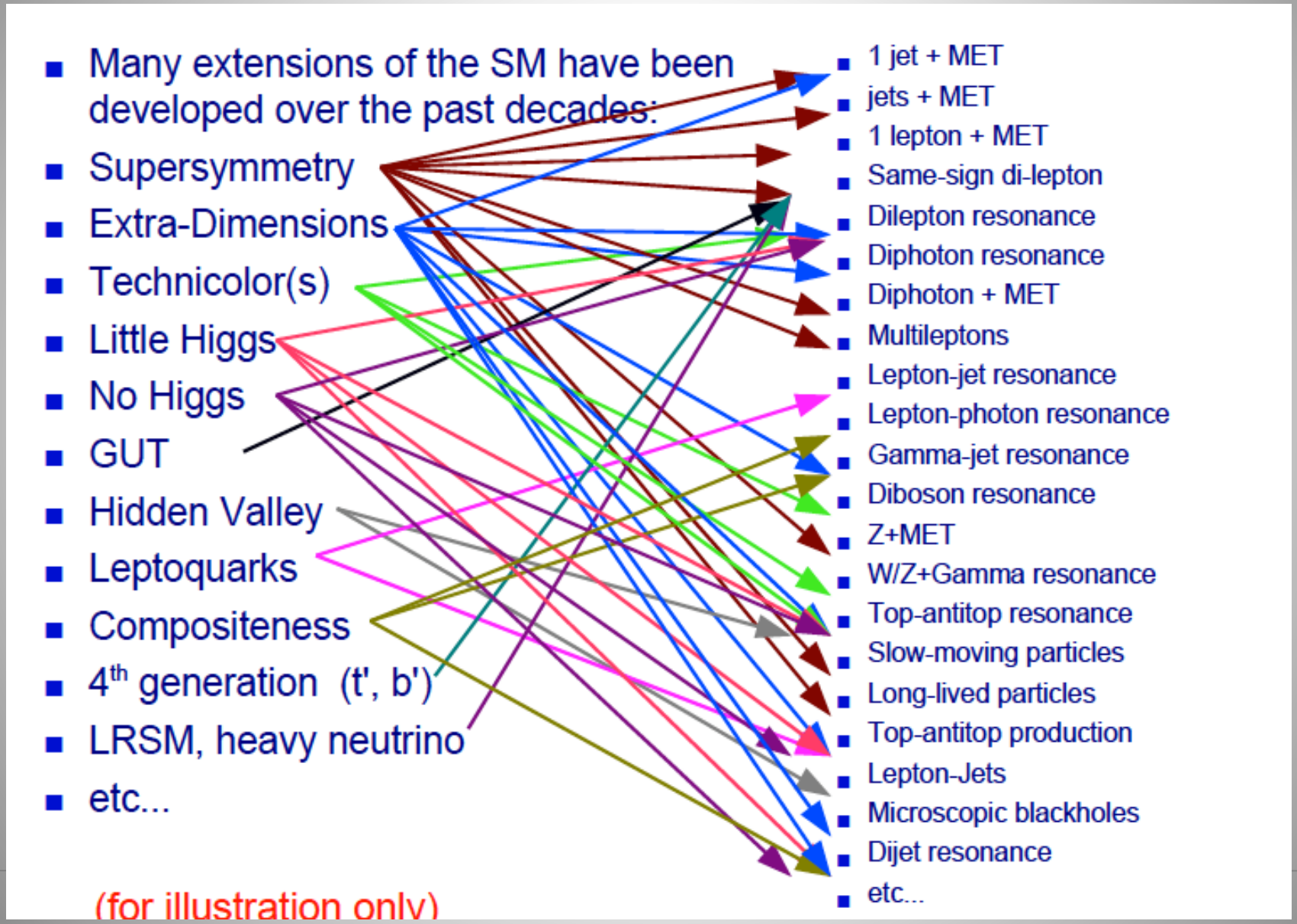
Excess in inclusive jet analysis

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

Beyond the SM Signatures



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…

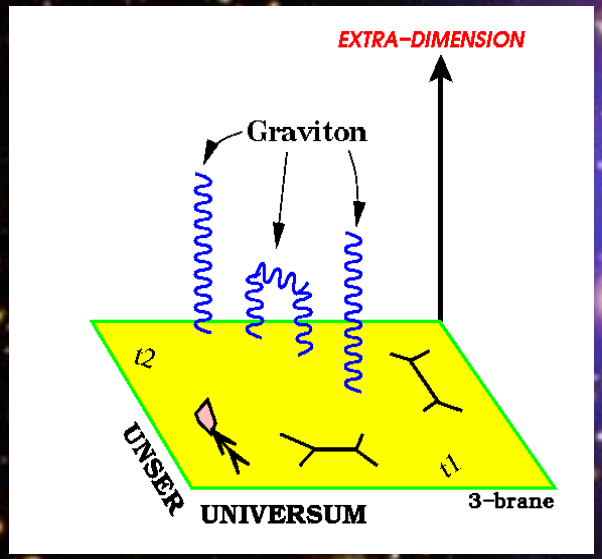
  Back to the basics or do we change paradigm?

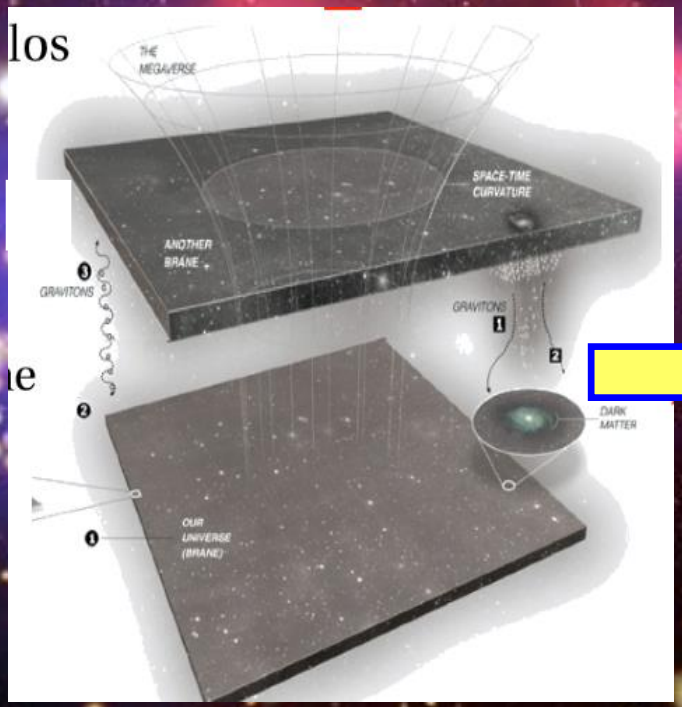
Extra Space Dimensions

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)]

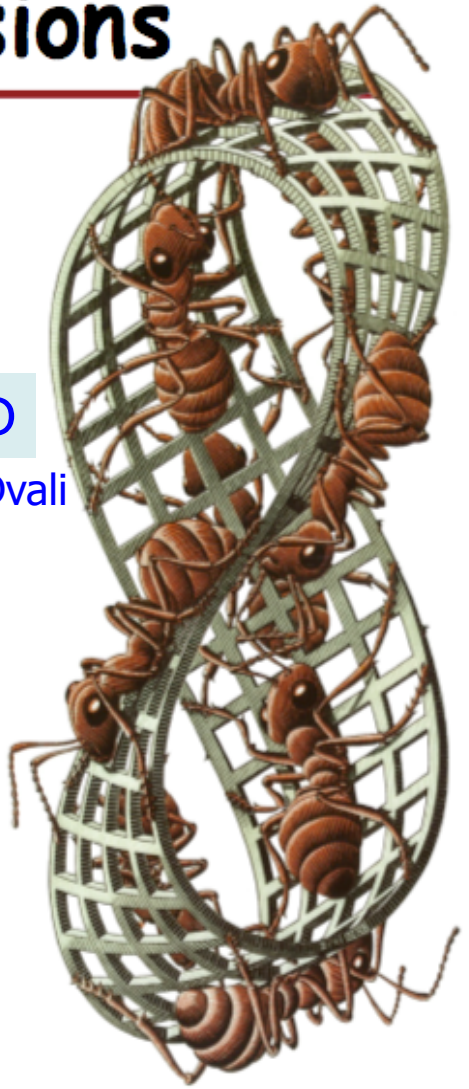
nUED : KK excitations of gauge bosons

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

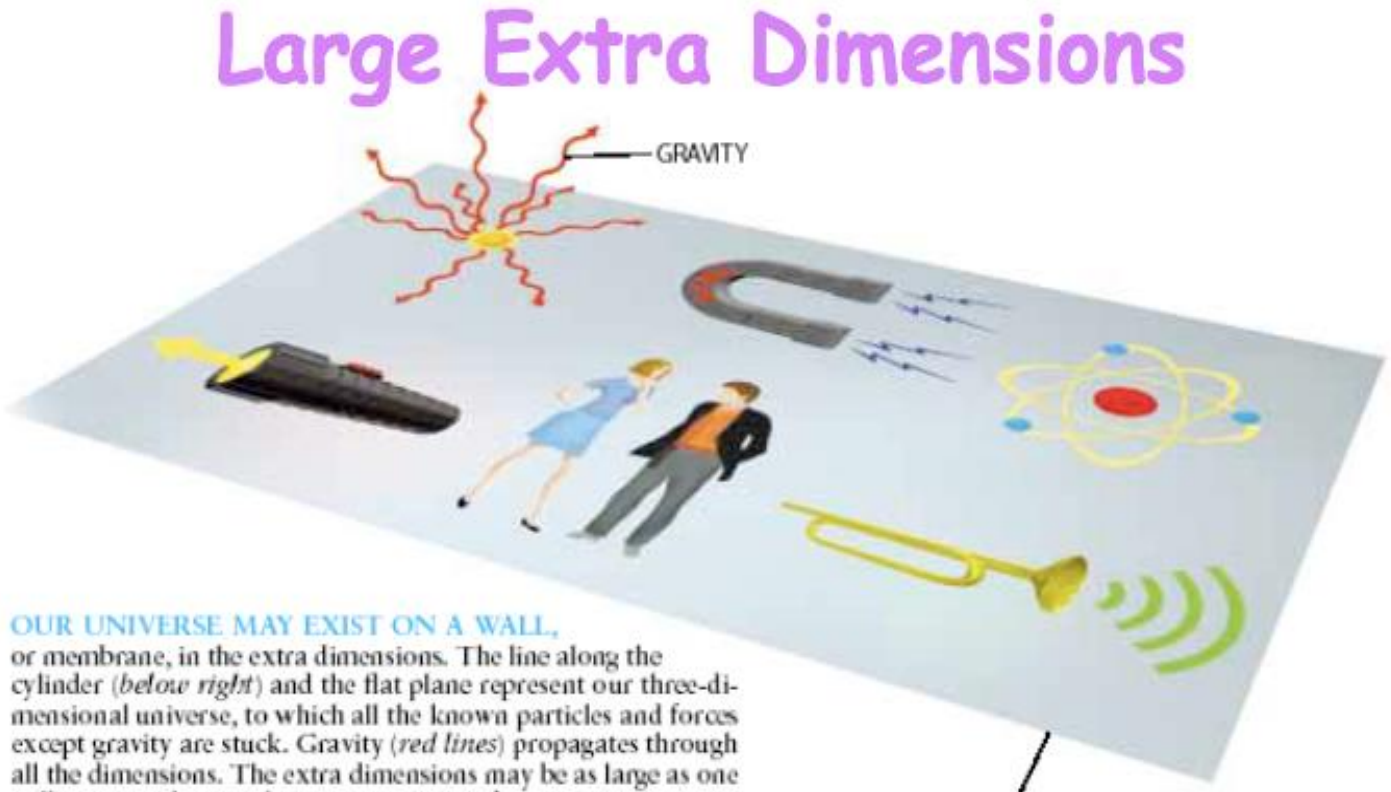
UED

Universal Extra Dimensions

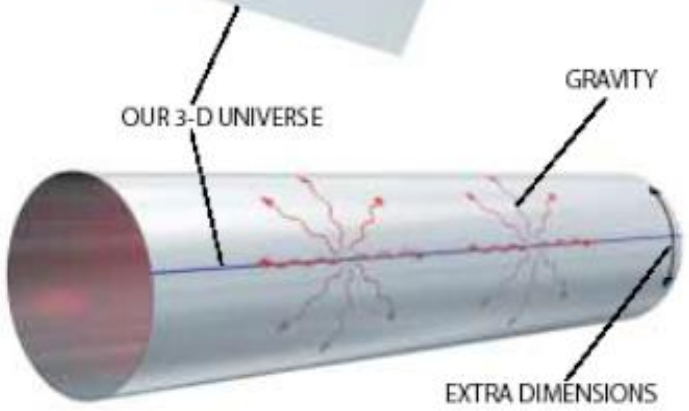
Signature: e.g. Z'/W' resonances, dijets+$E_{T,miss}$, heavy stable quarks/gluons...



Large Extra Dimensions



OUR UNIVERSE MAY EXIST ON A WALL, or membrane, in the extra dimensions. The line along the cylinder (*below right*) and the flat plane represent our three-dimensional universe, to which all the known particles and forces except gravity are stuck. Gravity (*red lines*) propagates through all the dimensions. The extra dimensions may be as large as one millimeter without violating any existing observations.



Model of Arkani-Hamed, Dvali, Dimopoulos: Standard Model particles are localized on a 3-D brane. Gravity propagates inside the bulk (a more dimensional space)

Search for Large Extra Dimensions

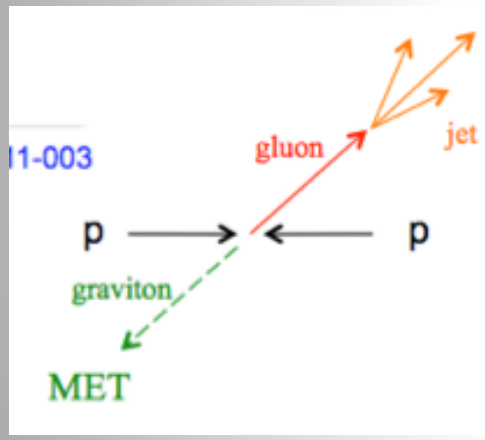
Mono-jet final state +Missing E_T (ADD)

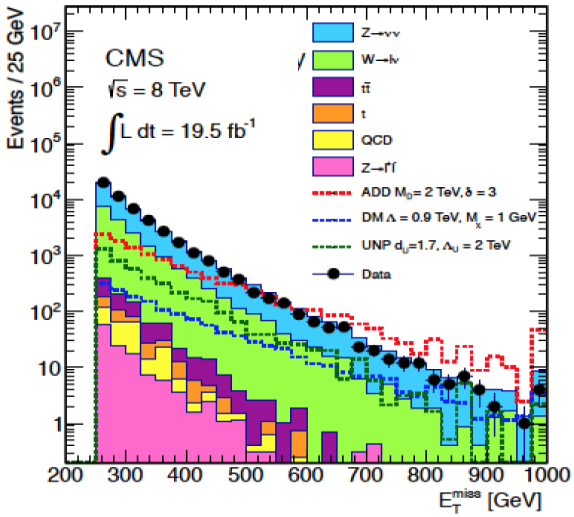
p_T jet > 110 GeV
MET > 200 GeV

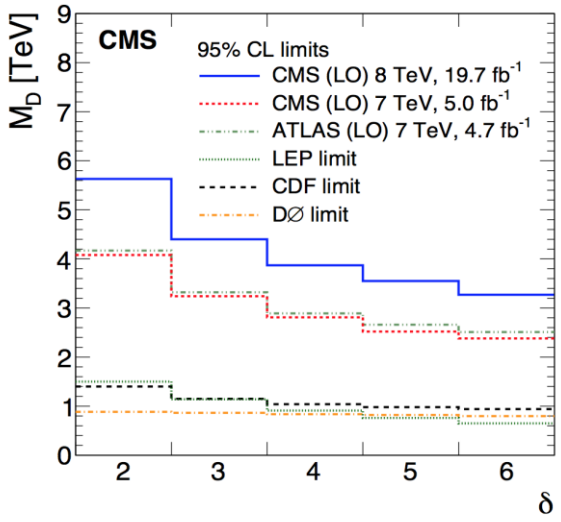
Limits on M_D between 3 and 4 TeV

arXiv:1408.3583

Lower limit on the Planck Scale versus number of extra dimensions

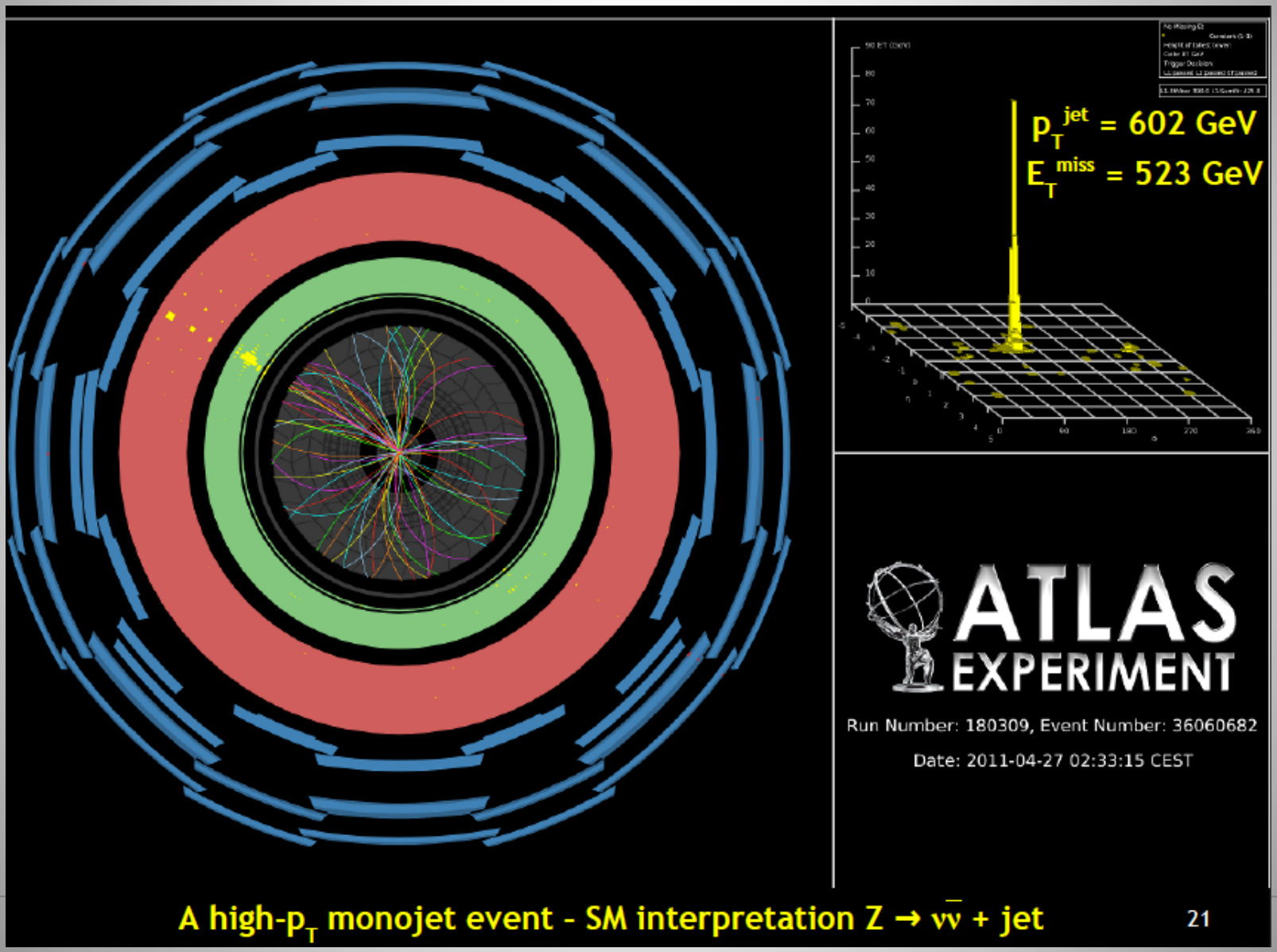






M_D (ADD) at LO 95% CL limits	$\sqrt{s}$ [TeV]	Lumi [fb^{-1}]	δ=3 Exp.	δ=3 Obs.	δ=6 Exp.	δ=6 Obs.
CMS Monojet	8	19.5	3.94	3.96	2.95	2.94

A High p_T Mono-jet event

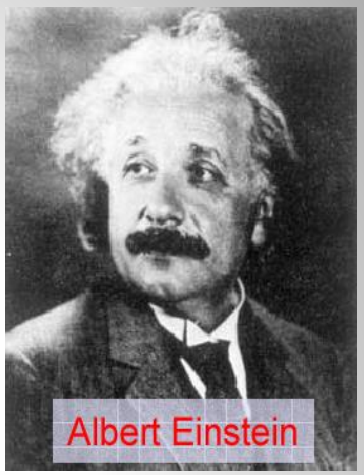


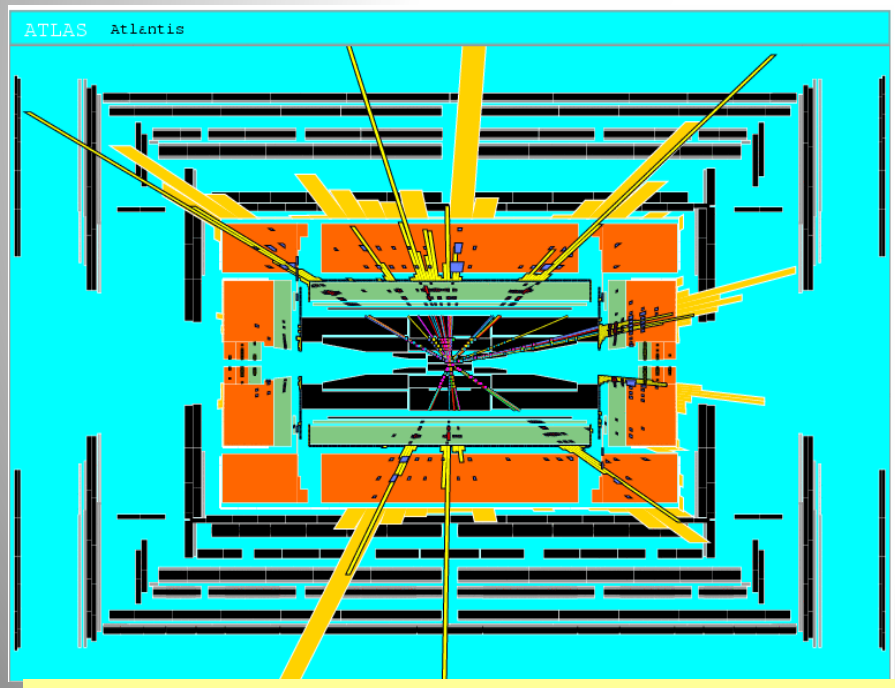
A high-p_T monojet event - SM interpretation $Z \rightarrow \nu\bar{\nu}$ + jet

Quantum Black Holes at the LHC?

Black Holes are a direct prediction of Einstein's general theory on relativity

If the Planck scale is in ~TeV region:
can expect Quantum Black Hole production





Simulation of a Quantum Black Hole event

Quantum Black Holes are harmless for the environment: they will decay within less than 10^{-27} seconds $\Rightarrow$ SAFE!

Quantum Black Holes open the exciting perspective to study Quantum Gravity in the lab!

Black Holes at the LHC?

Black Holes at the LHC

Savas Dimopoulos[a†] and Greg Landsberg[b*]

[a] *Physics Department, Stanford University, Stanford, CA 94305-4060, USA*

[b] *Department of Physics, Brown University, Providence, RI 02912, USA*

If the scale of quantum gravity is near a TeV, the LHC will be producing one black hole (BH) about every second. The BH decays into prompt, hard photons and charged leptons is a clean signature with low background. The absence of significant missing energy allows the reconstruction of the mass of the decaying BH. The correlation between the BH mass and its temperature, deduced from the energy spectrum of the decay products, can test experimentally the higher dimensional Hawking evaporation law. It can also determine the number of large new dimensions and the scale of quantum gravity.

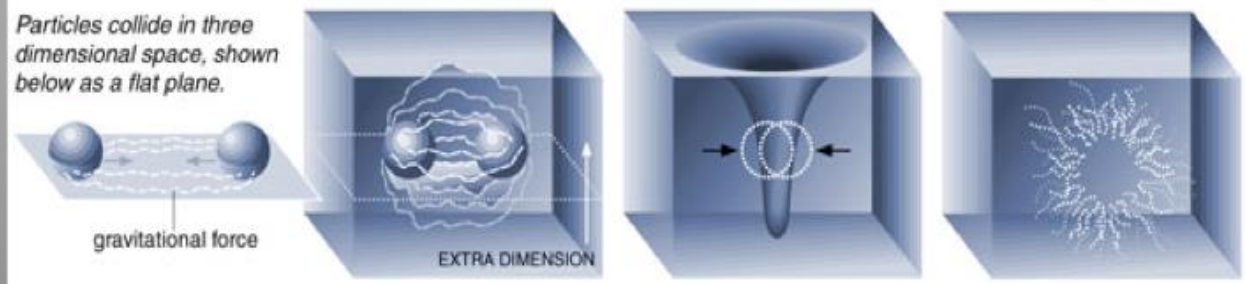
PACS numbers: 04.70, 04.50, 14.80.-j

Savas Dimopoulos, theorist

Black Holes on Demand

New York times 9/11/2001

Scientists are exploring the possibility of producing miniature black holes on demand by smashing particles together. Their plans hinge on the theory that the universe contains more than the three dimensions of everyday life. Here's the idea:



As the particles approach in a particle accelerator, their gravitational attraction increases steadily.

When the particles are extremely close, they may enter space with more dimensions, shown above as a cube.

The extra dimensions would allow gravity to increase more rapidly so a black hole can form.

Such a black hole would immediately evaporate, sending out a unique pattern of radiation.

Snowmass 2001

Greg Landsberg
Previous CMS physics coordinator

Quantum Black Holes

- Schwarzschild radius

Landsberg, Dimopoulos, Giddings, Thomas, Rizzo

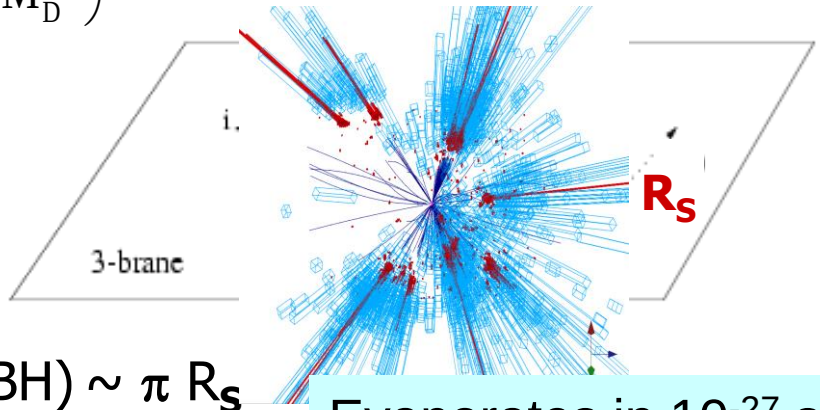
4-dim., $M_{gravity} = M_{Planck}$: $R_S \sim \frac{2}{M_{Pl}^2}\frac{M_{BH}}{c^2}$

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

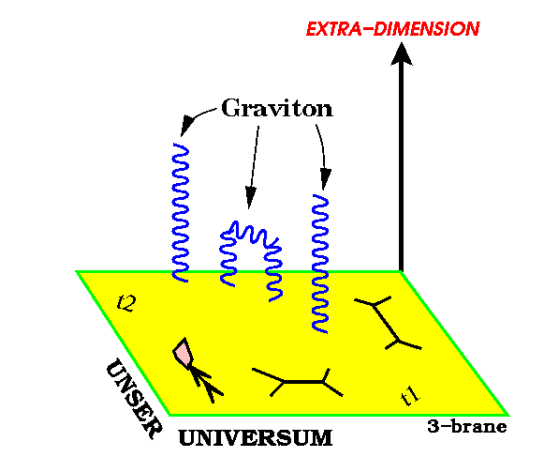
e.g. For $M_D \sim$1 TeV and n=3, produce 1 event/second at the LHC

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 …)

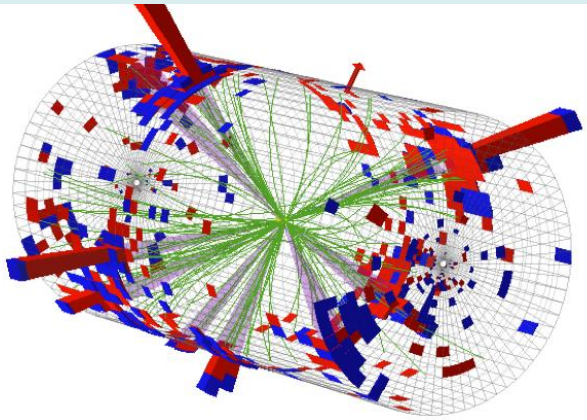
Search for Micro Black Holes



Extra Dimensions!

Planck scale
a few TeV?

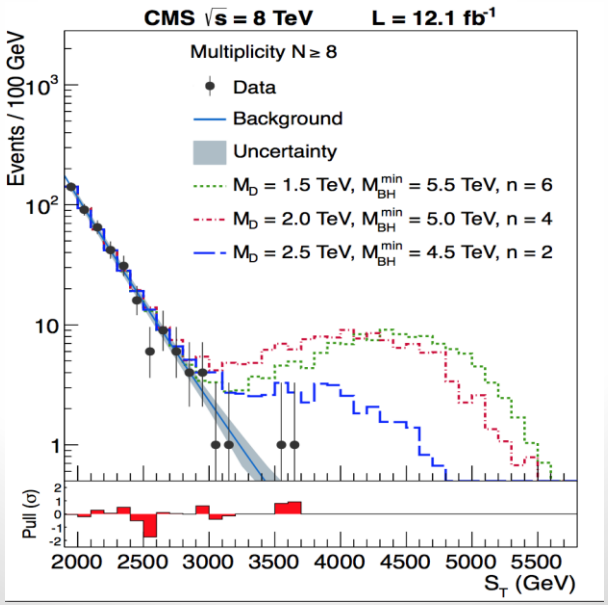
Nice events, eg a 10 jet event

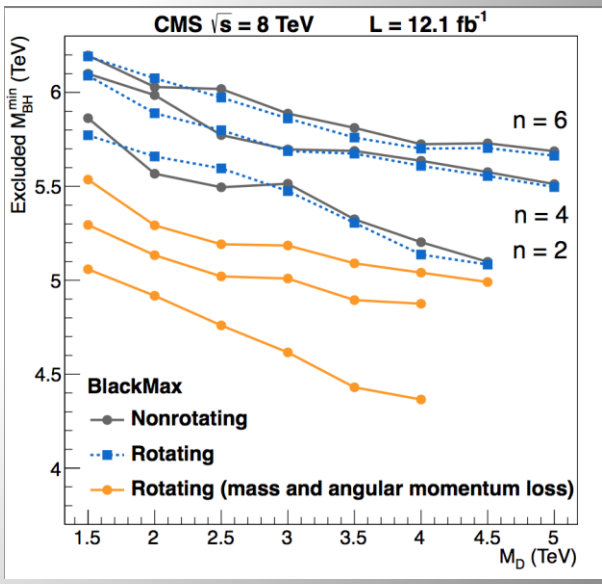


arXiv:1202.6396

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





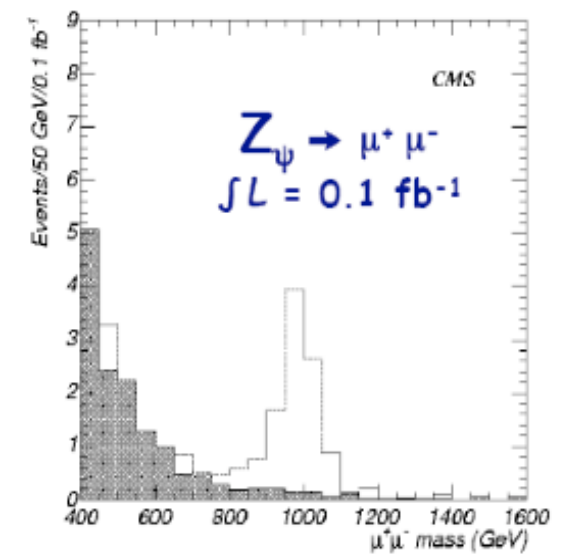
Black hole masses excluded in range below ~5 TeV depending on assumptions


Black Holes
Hunters
at the LHC

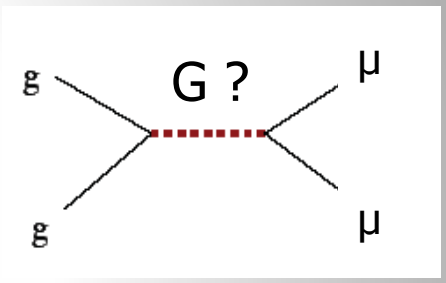
Search for High Mass Resonances

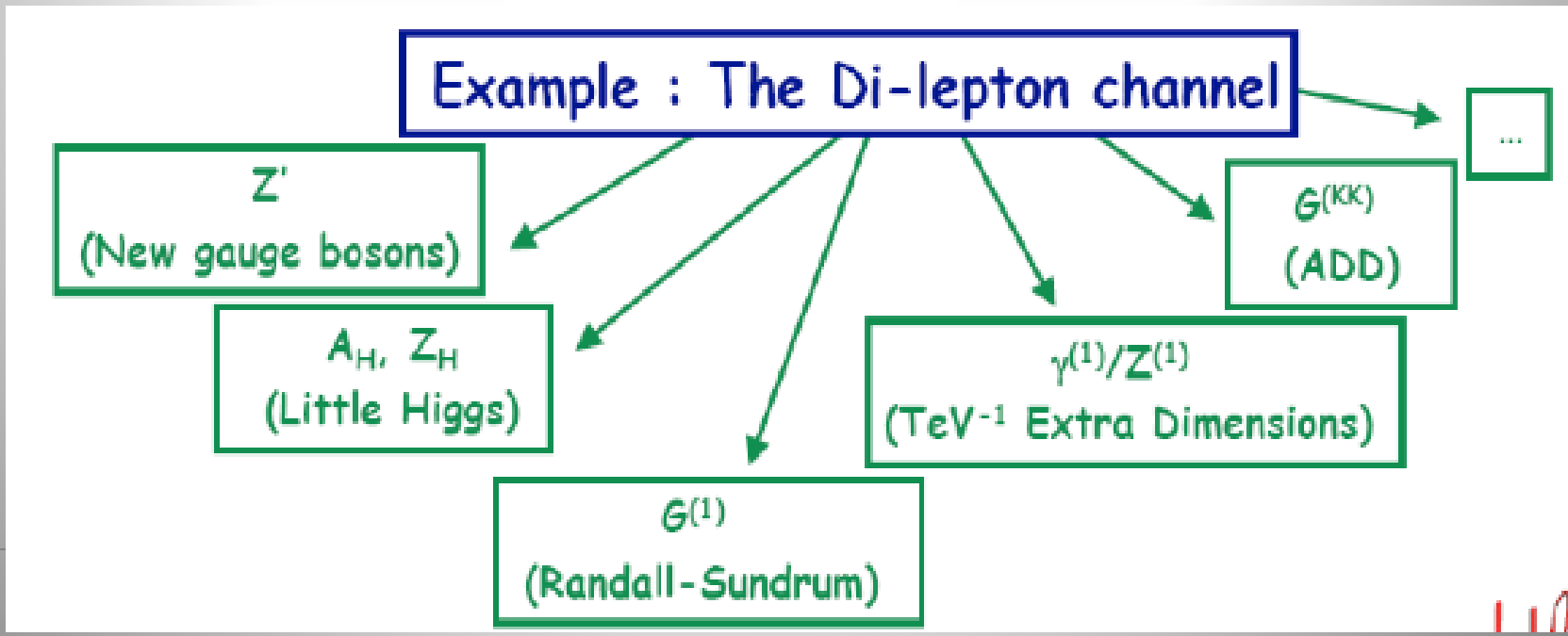
E.g. Di-lepton Resonance

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



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





2011: Z' Boson to ee or μμ?

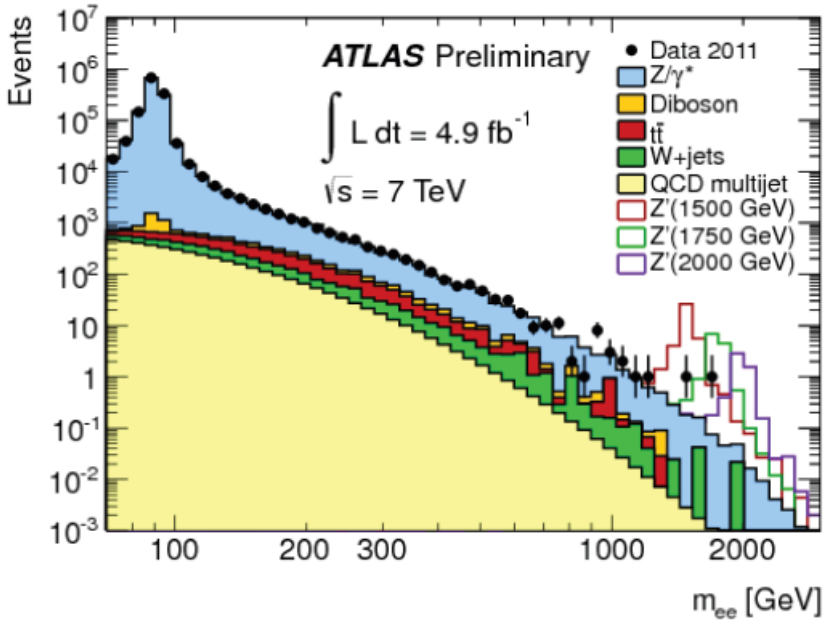
$SU(3)_C \times SU(2)_L \times U(1)_Y$

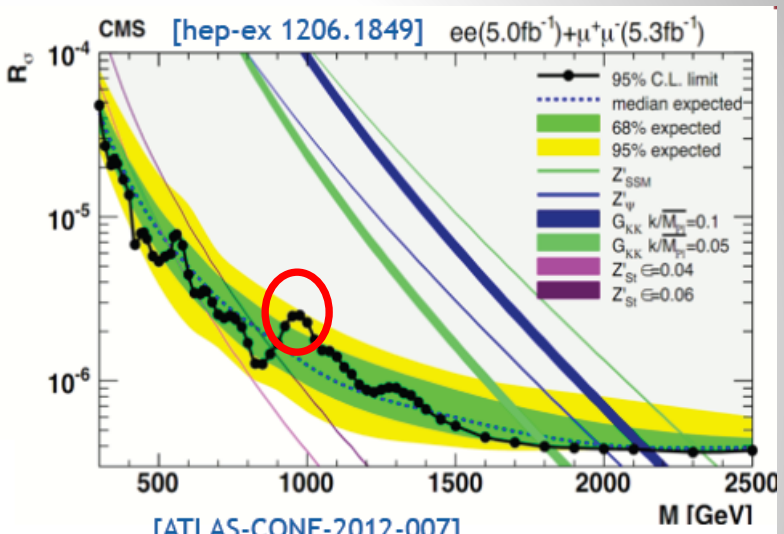
Extension of the symmetry?
New Gauge bosons?

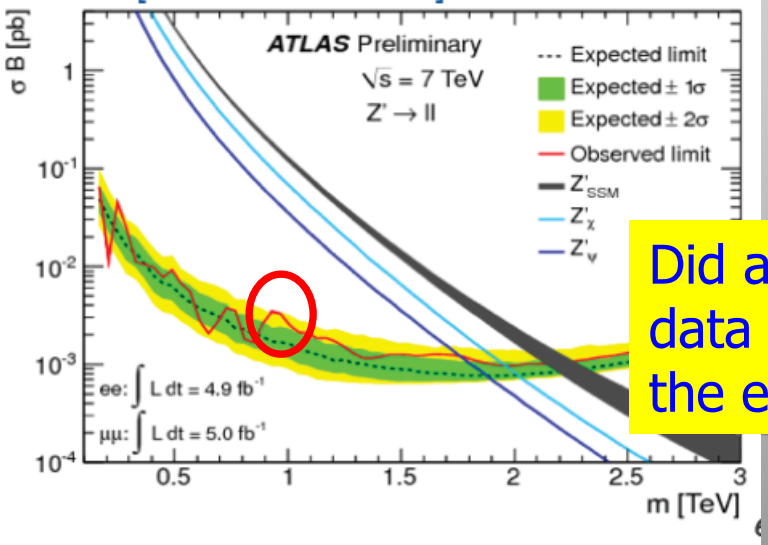
Mid 2012

- 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...

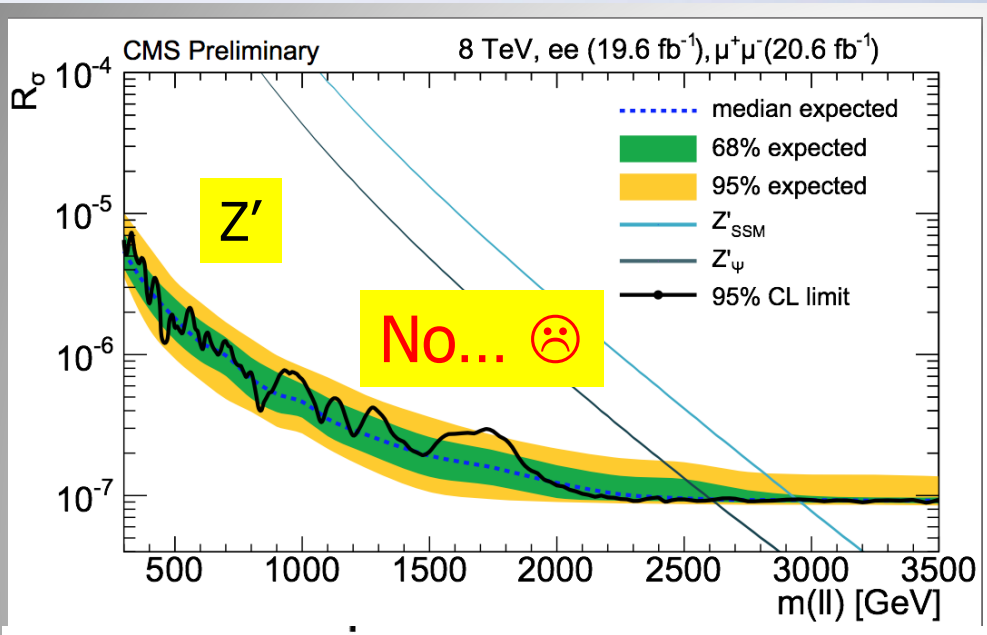




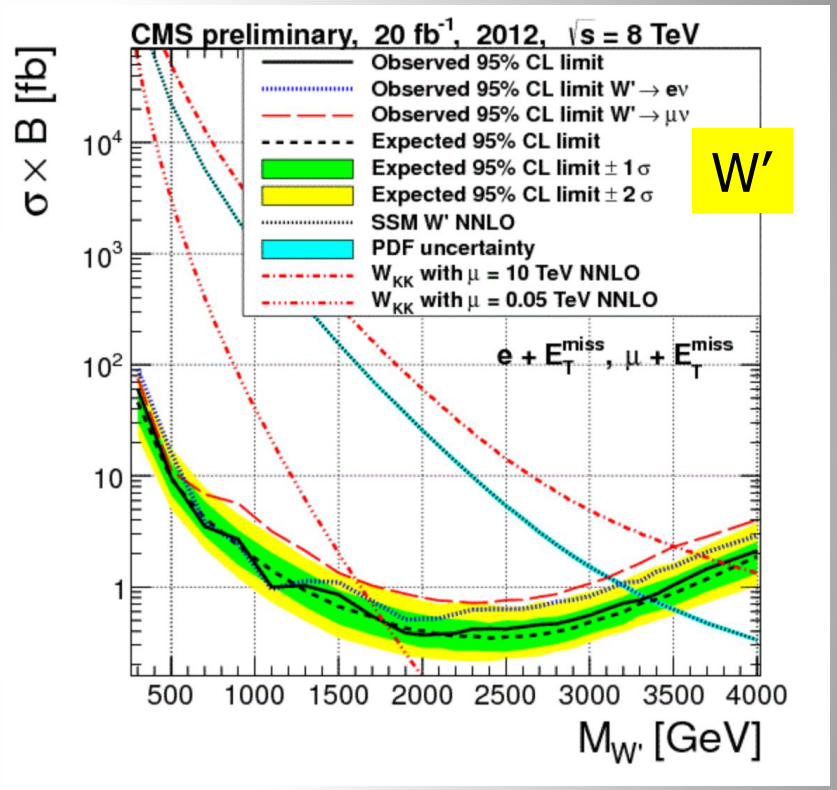


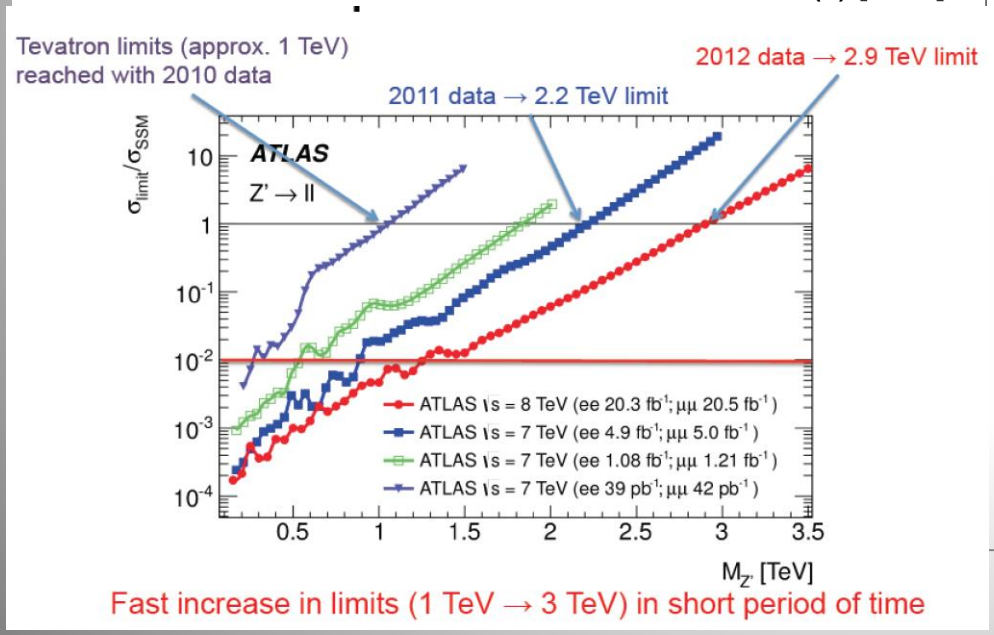
Did additional data confirm the excess??

New Gauge Bosons: Z', W'



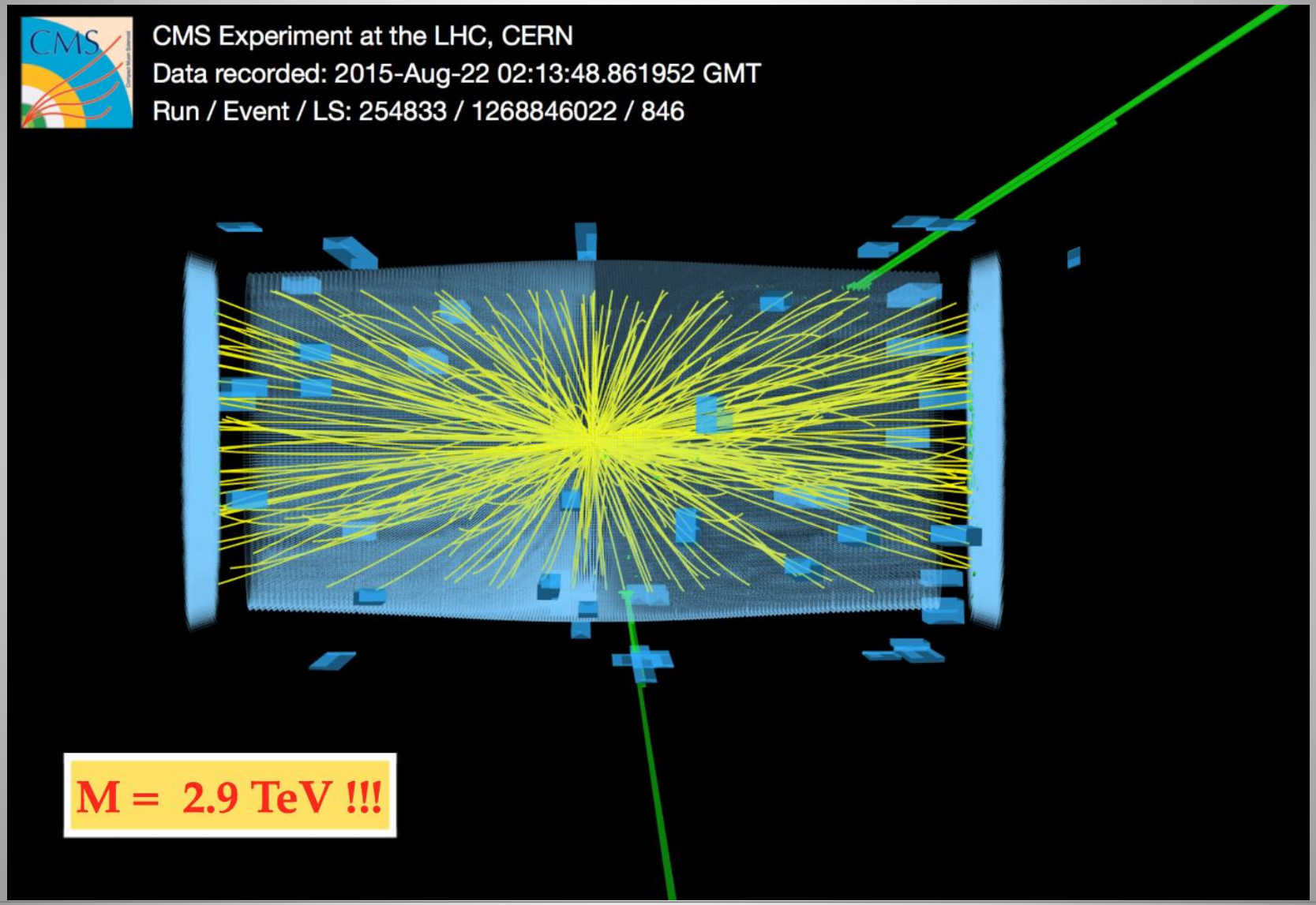
Early 2013





W,' Z' Limits are now around 3 TeV

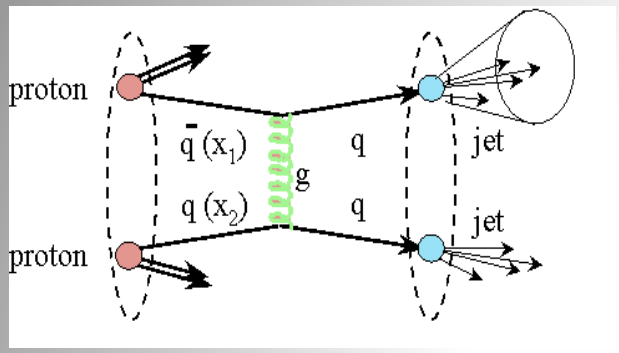
New Gauge Bosons: 13 TeV

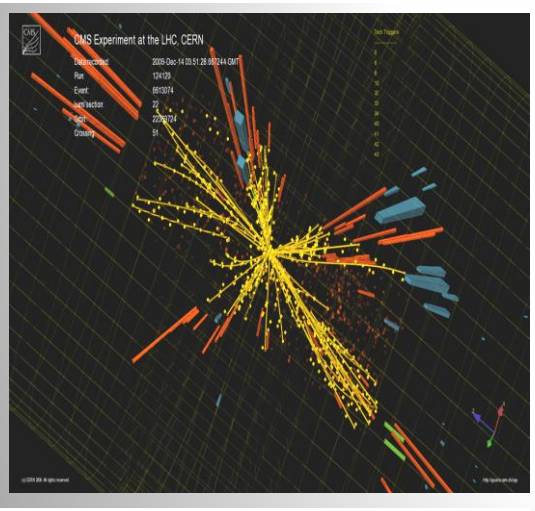


Higher mass than we ever saw before, with 40 pb^{-1} data only

Di-jet Resonances

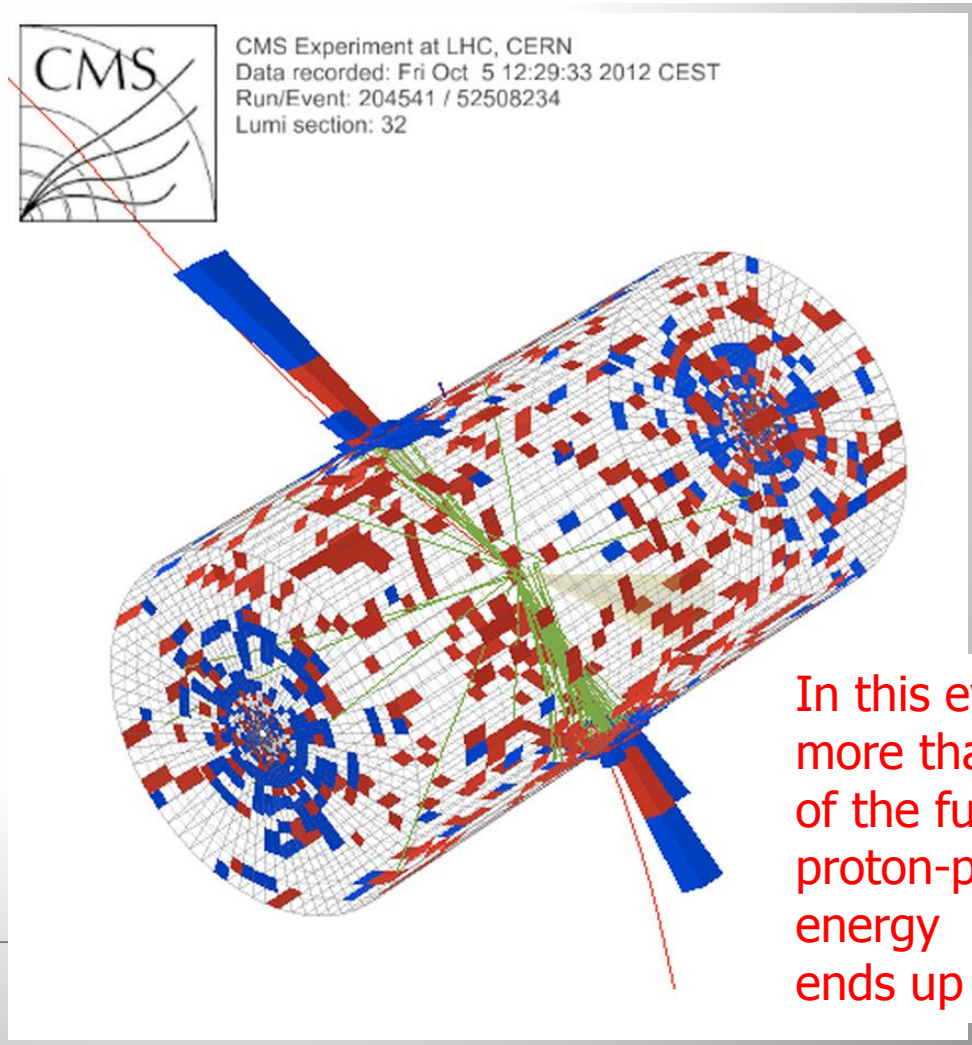
Study the strong force using jet production





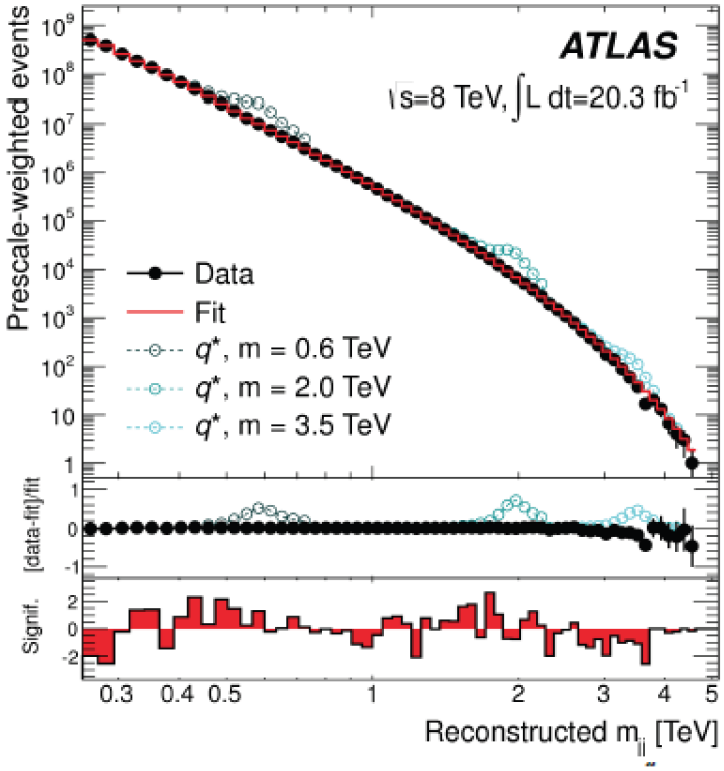
Jets of particles emerge after a high energy parton-parton scattering

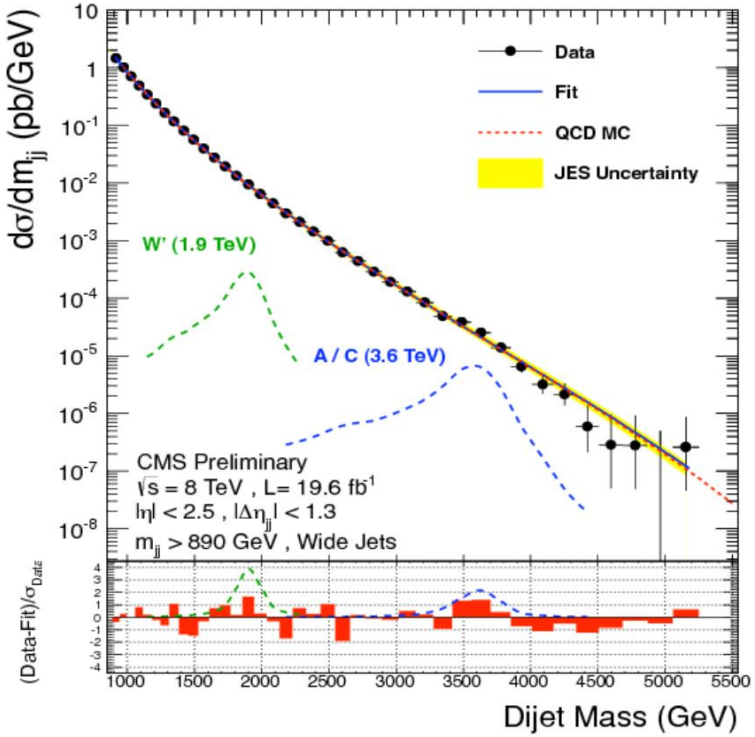
Di-jet invariant mass = 5.15 TeV (R=1.1 jets)



In this event more than 60% of the full proton-proton energy ends up in jets

Di-jet Searches





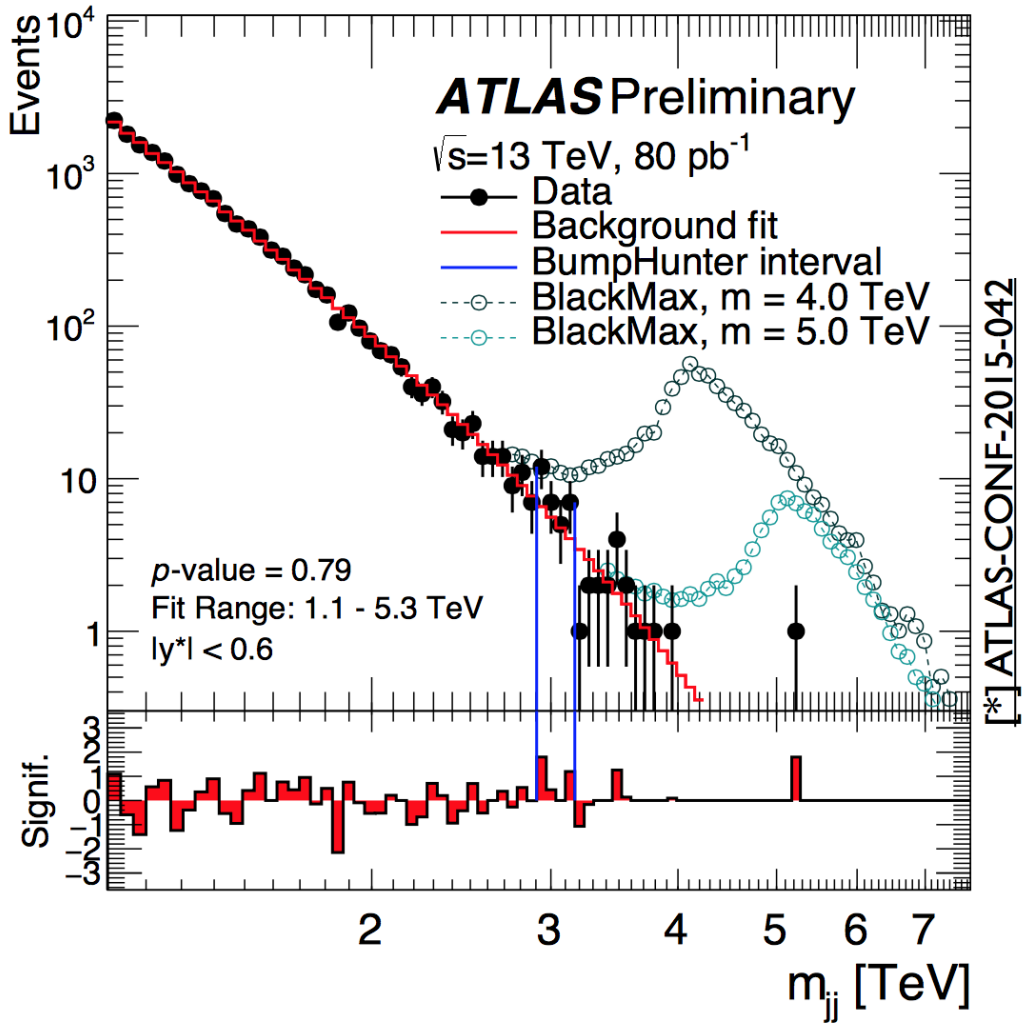
- Search for dijet resonance in smoothly falling mass spectrum
  - leading jet mass m_{jj} > 0.9-1 TeV from trigger and other constraints
  - Background estimated from smooth functional fit

CMS-EXO-12-059
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

Di-jet Searches: 13 TeV



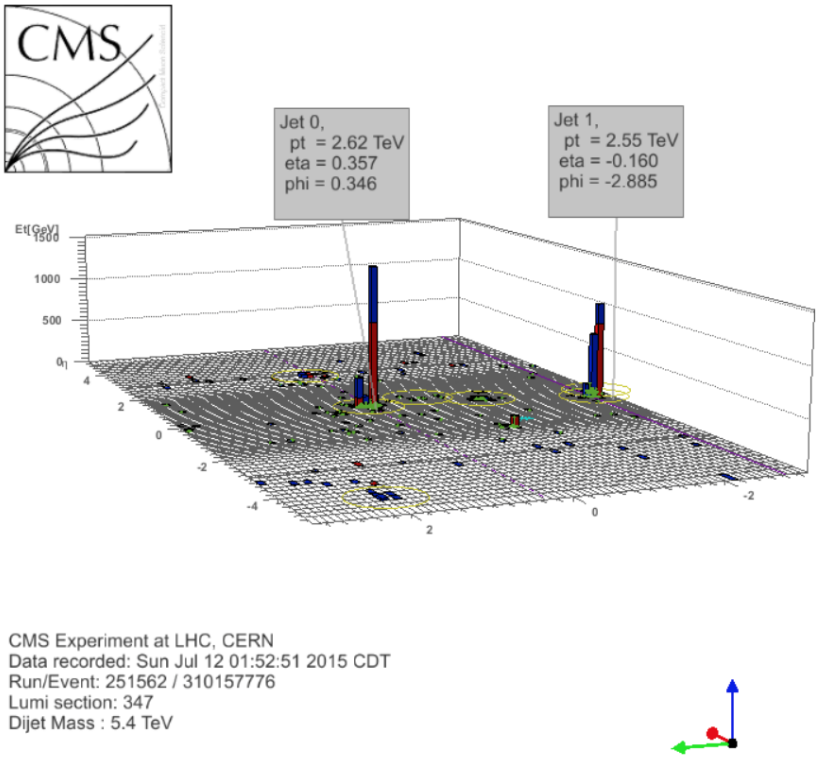
- Use m_{jj} distribution
- $|y^*|=|y_1-y_2|/2<0.6$
- $m_{jj}>1100$ GeV
- Fit bkg to: $p_1(1-x)^{p2}x^{p3}$

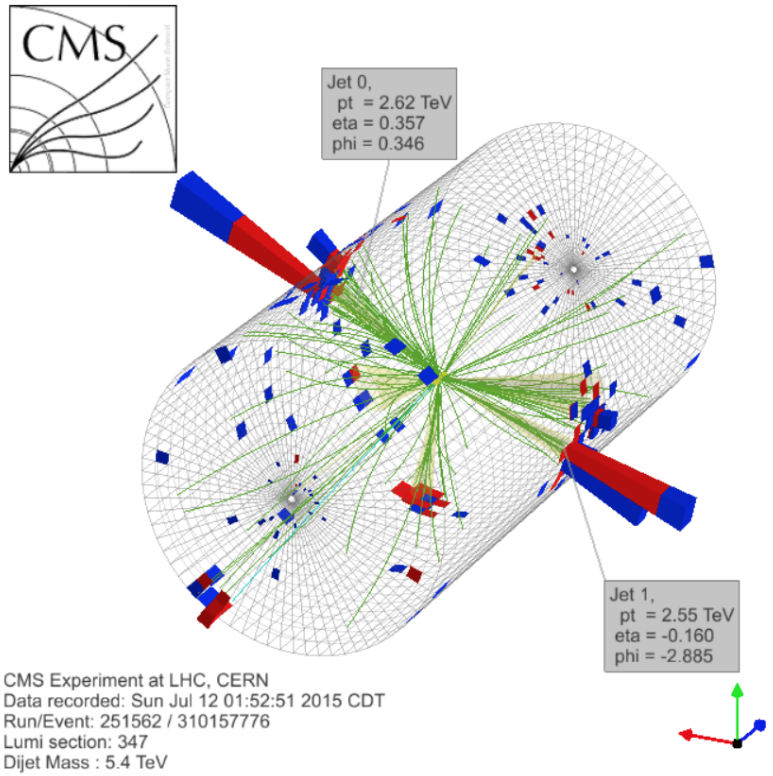
➡No significant deviations observed

Di-jet Searches: 13 TeV

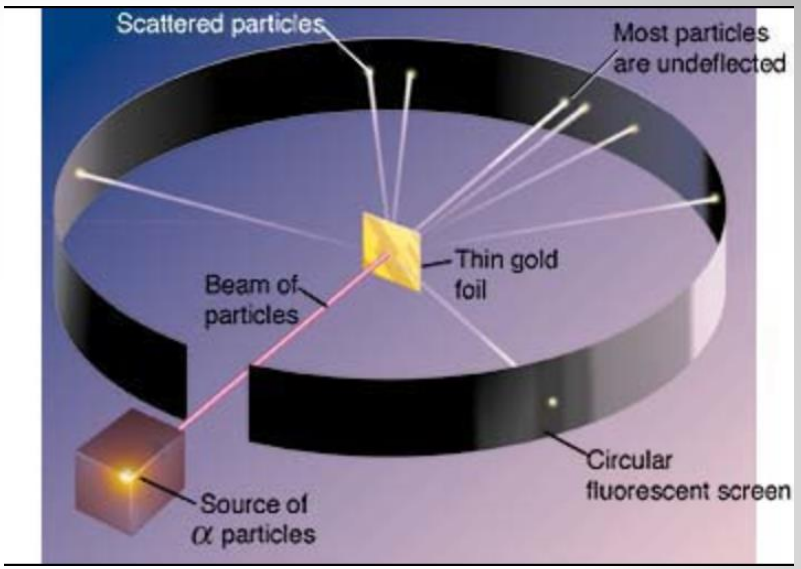
Highest Mass di-jet event M =5.4 TeV

CMS PAS EXO-15-001

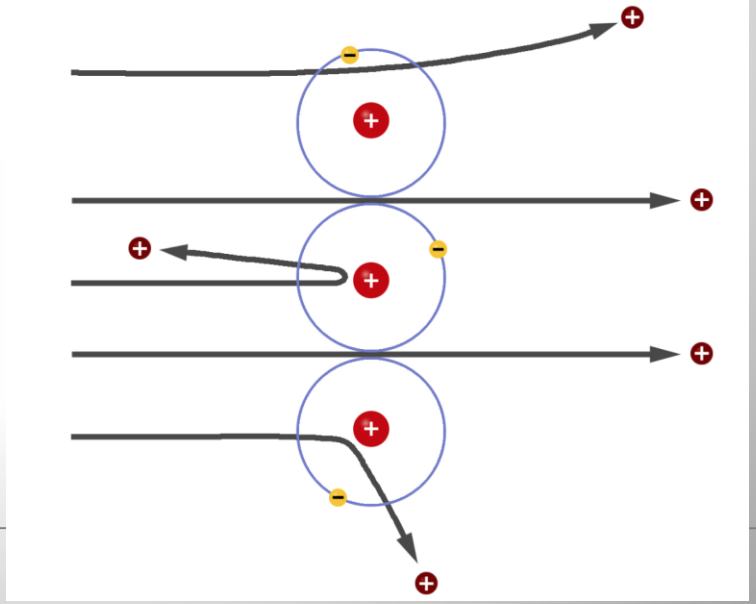




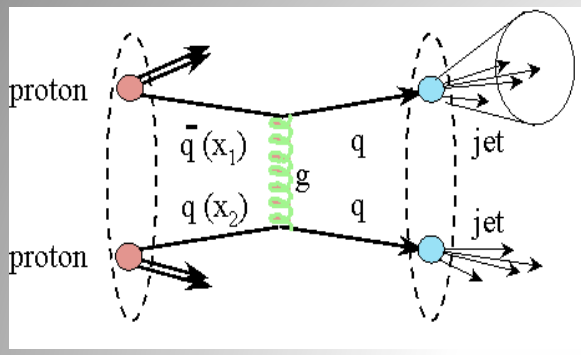
Are Quarks Elementary Particles?

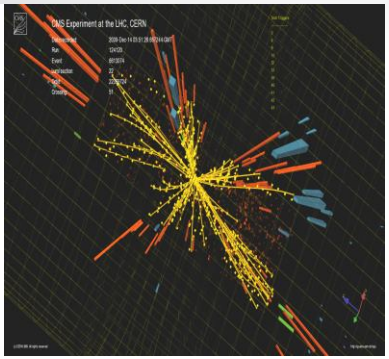


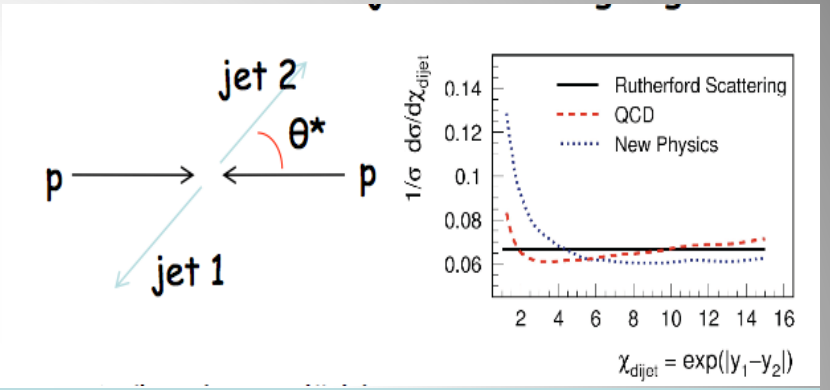
Rutherford experiment:
Unexpected backscattering of α-particles:
Evidence for the structure of atoms !! (1911)

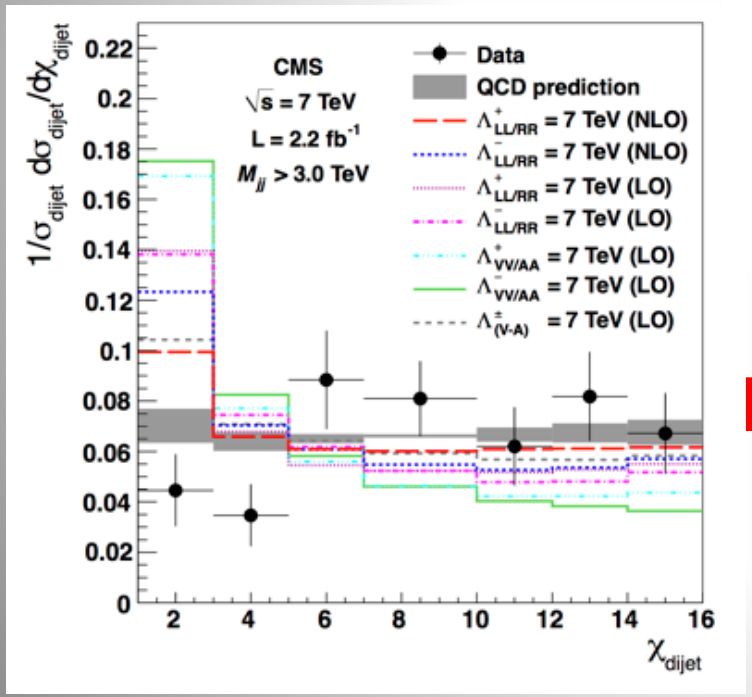


Are Quarks Elementary Particles?

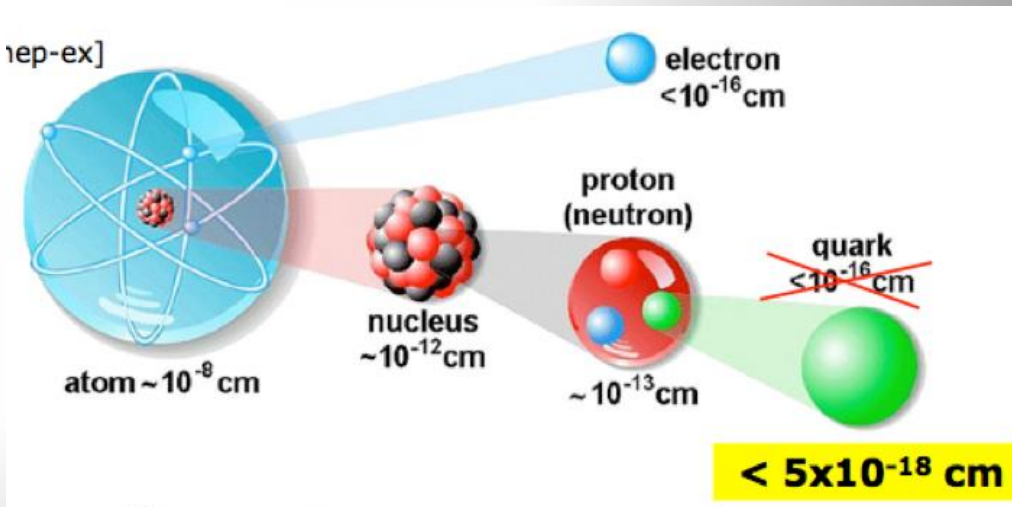






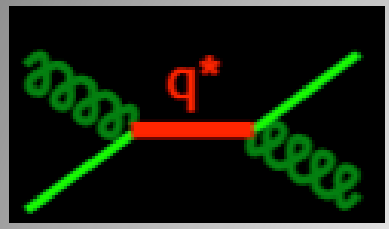


Measurement of the production angle of the jet with respect to the beam
-> High Energy Rutherford Experiment

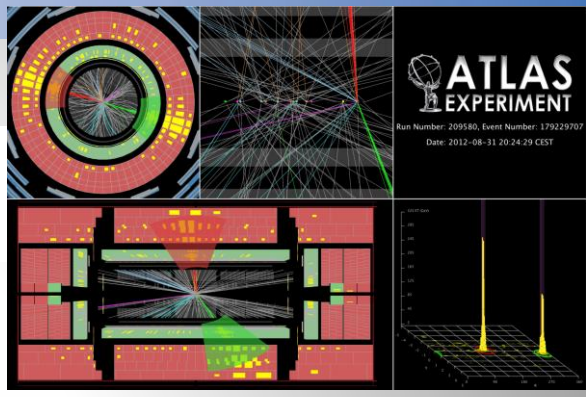


Quarks remain elementary particles after these first results

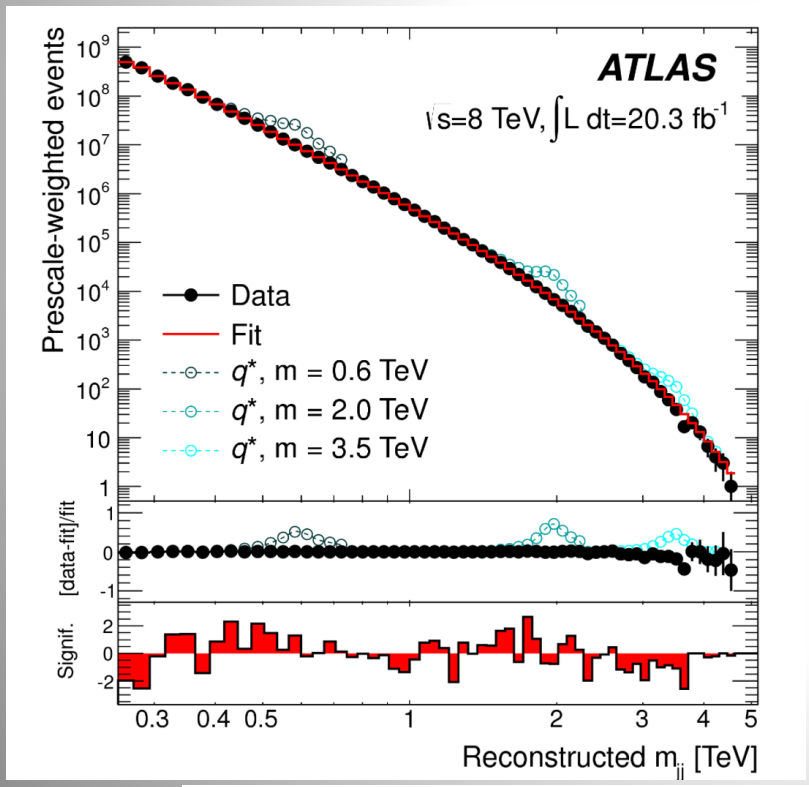
Excited Quark in Dijet Search

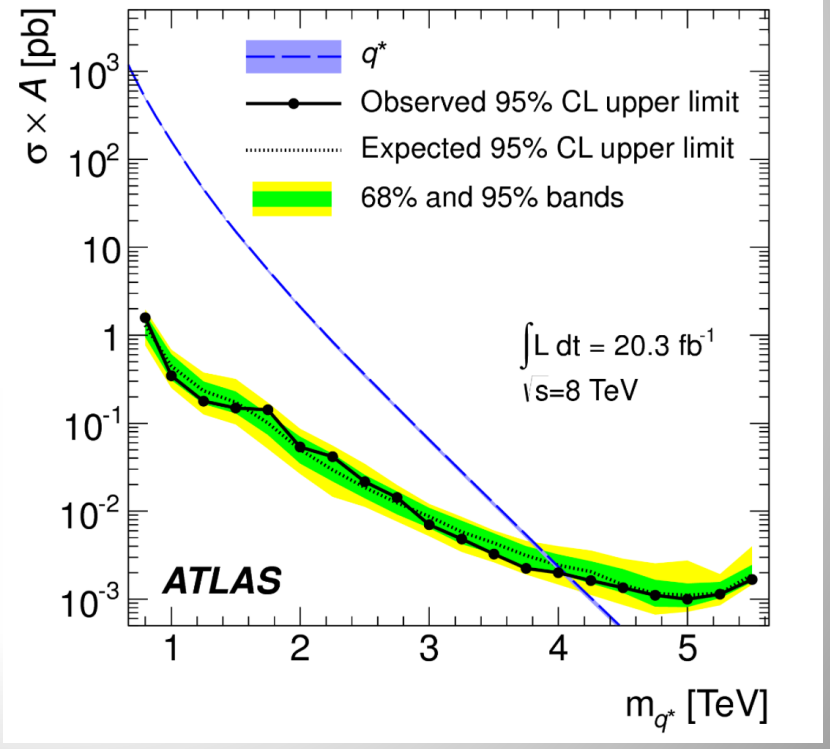


invariant mass of 4.69 TeV, and jets with a jet-p_T of 2.29 TeV and 2.19 TeV



arXiv:1407.1376





Limit on the mass of excited quarks > 4.09 TeV at 95% CL

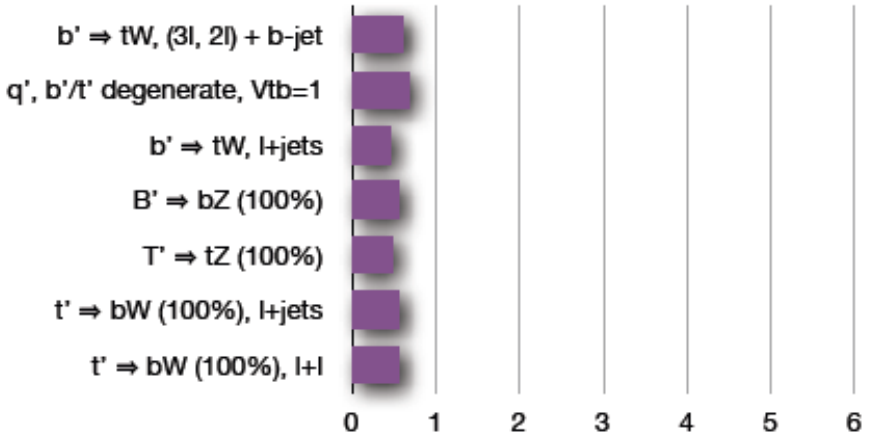
Search for a 4th Generation

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

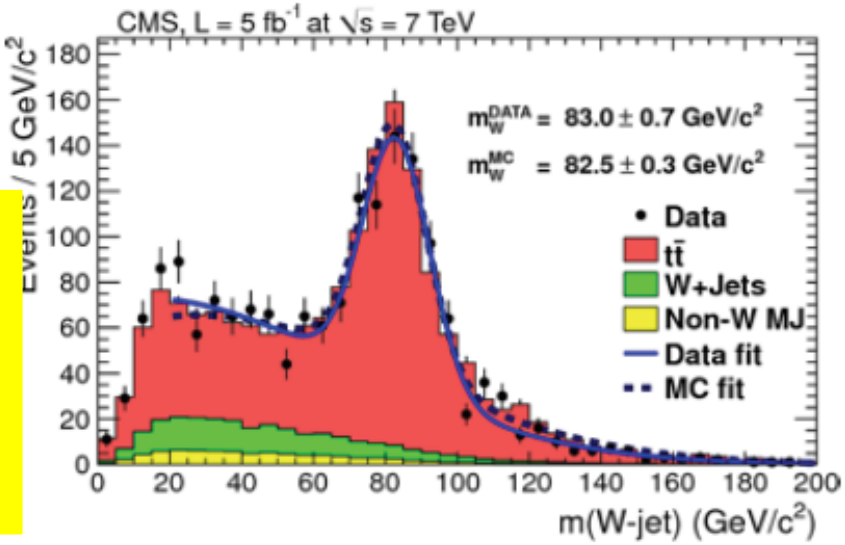
Look for b' and t' quarks

4th Generation Searches

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



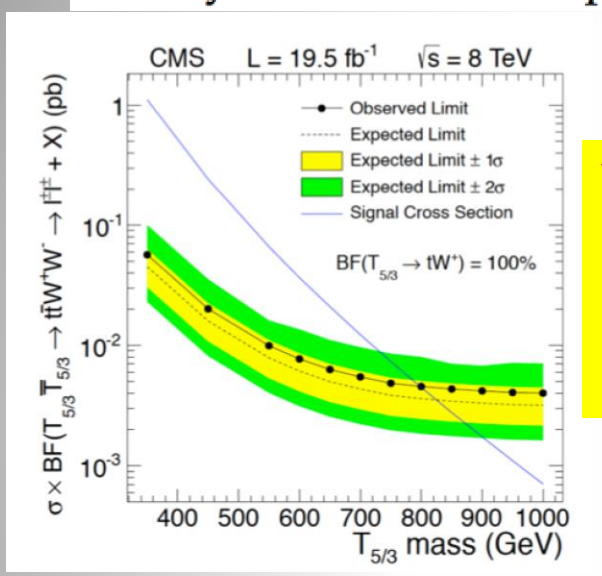
- ttbar resonances across the spectrum
  - boosted top technique at high mass
  - lepton + jets



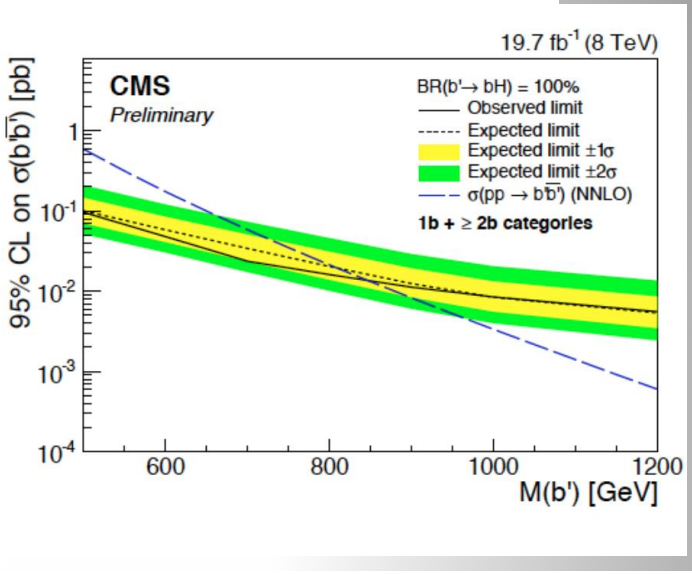
No evidence found for a new quark generation for quarks with mass < 550 GeV! A 4th generation would also affect the Higgs rate in a substantial way, so it is unlikely to exist!

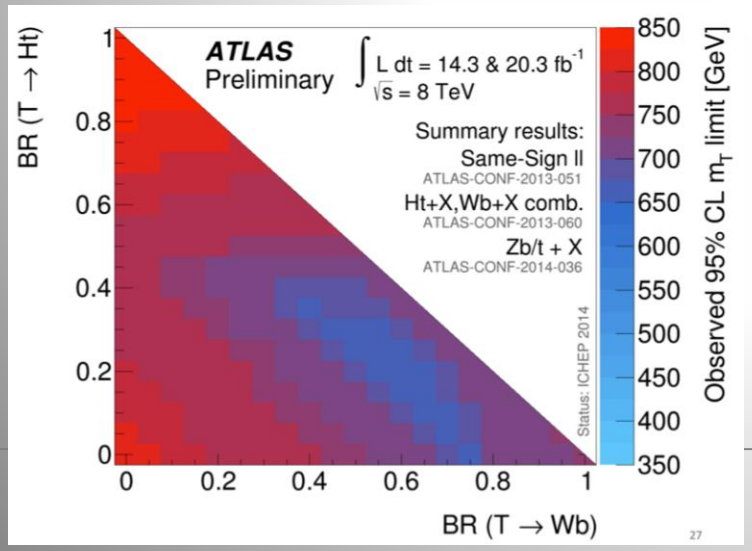
Searches for Top/Bottom Partners

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

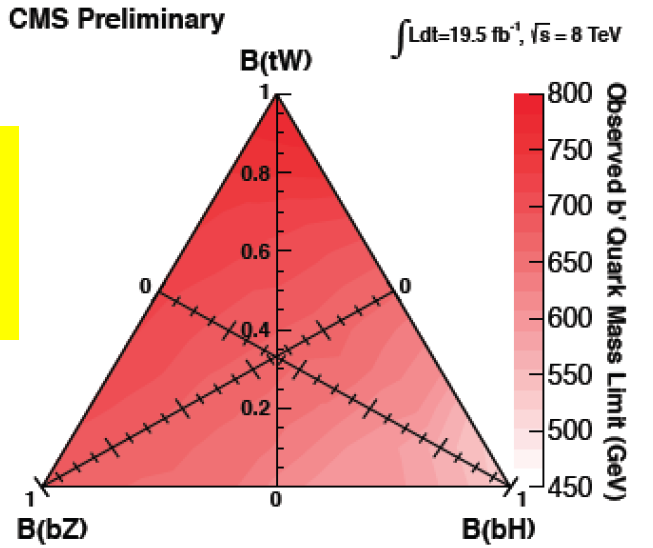


Vector-like quarks
Relevant eg in composite Higgs models



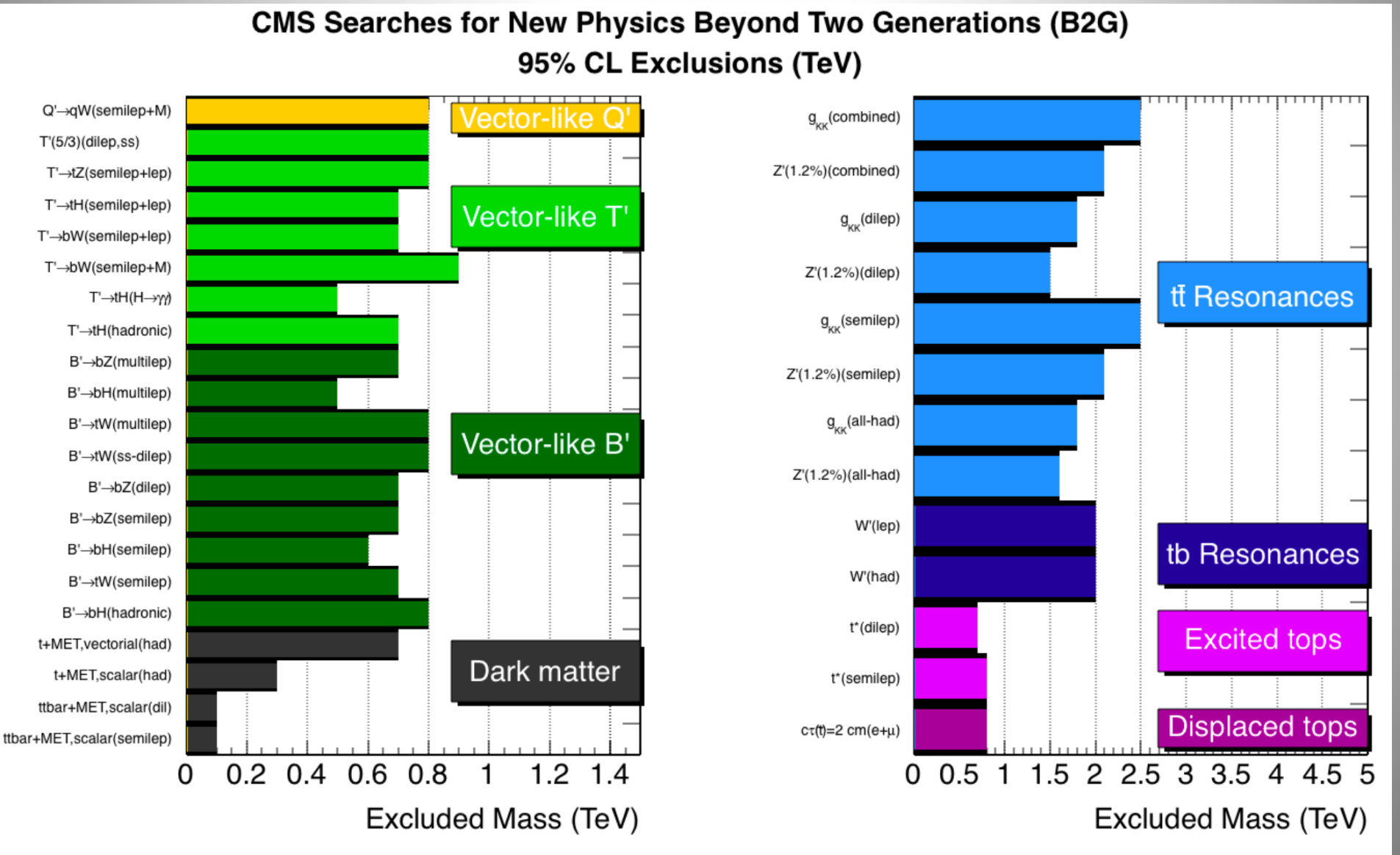


Exclusions up to masses of 800 GeV

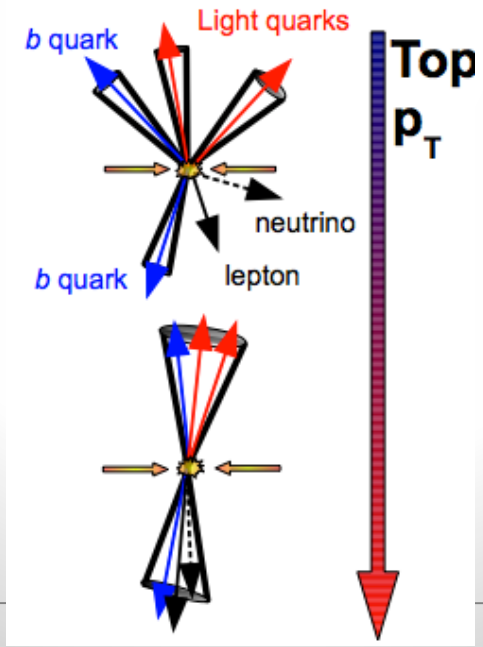


Searches for Top/Bottom Partners: CMS

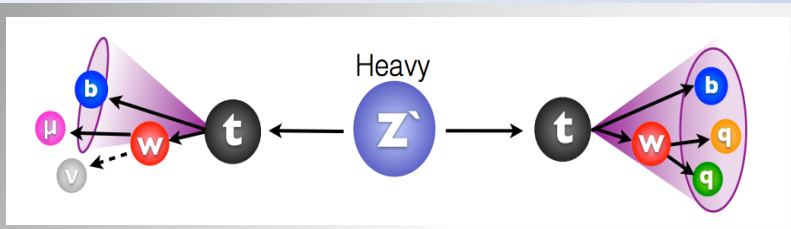
Summary



Searches with Boosted Objects



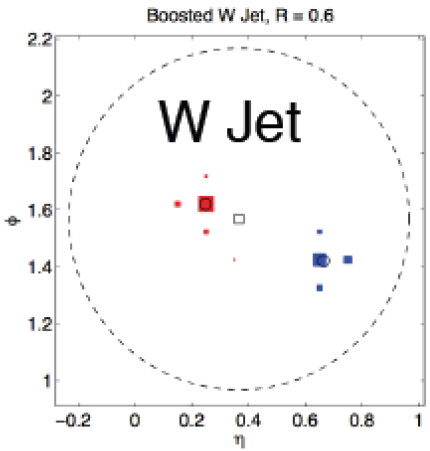
Searches with Boosted Objects

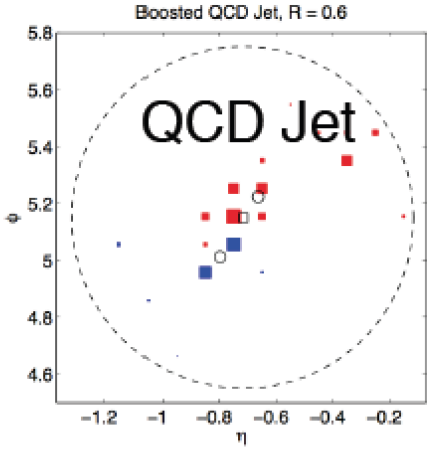


Discussed in topical "Boost Workshops"
Last one Chicago 10-14 August
http://boost2015.uchicago.edu/

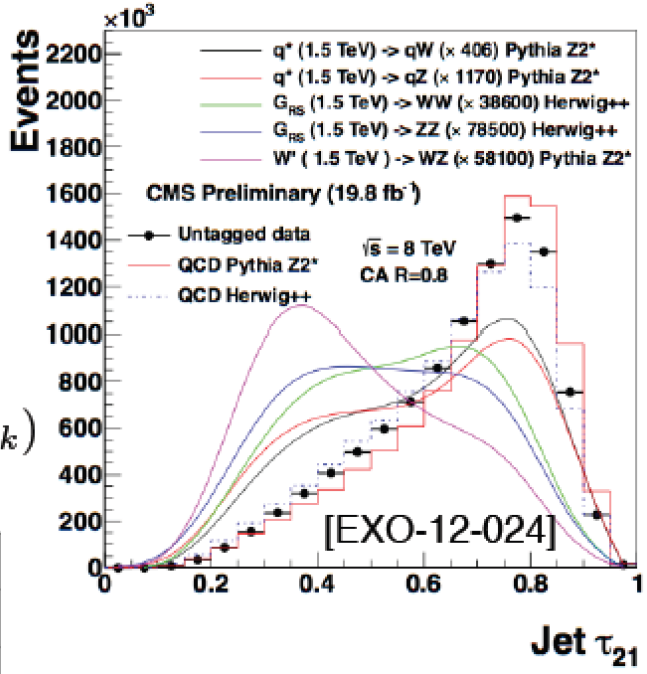
- Several different techniques to identify merged jets are on the market...
  - N-subjettiness, τ_N, uses $\tau_{21}=\tau_2/\tau_1$ as a discriminant to separate QCD jets from merged W/Z jets

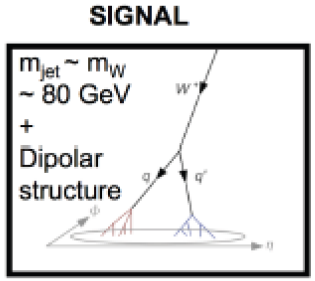
$$\tau_N = \frac{1}{d_0}\sum_k p_{T,k}\min\left(\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\right)$$

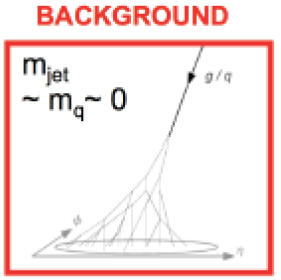




[Thaler, Tilburg, arXiv:1011.2268]



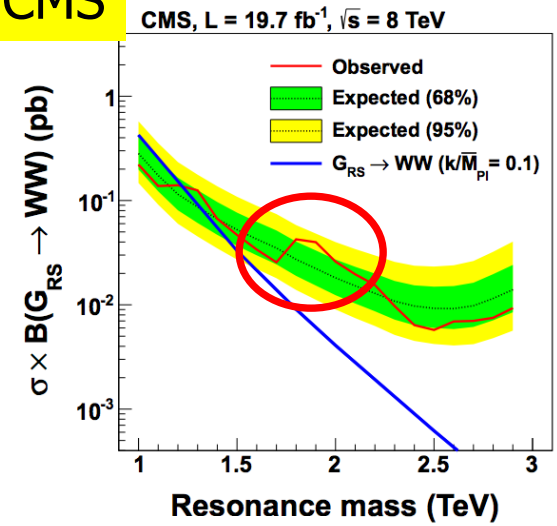


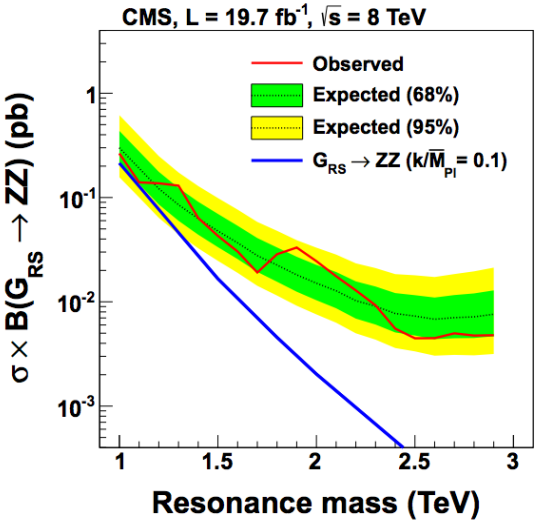


Resonances Decaying into qV or VV

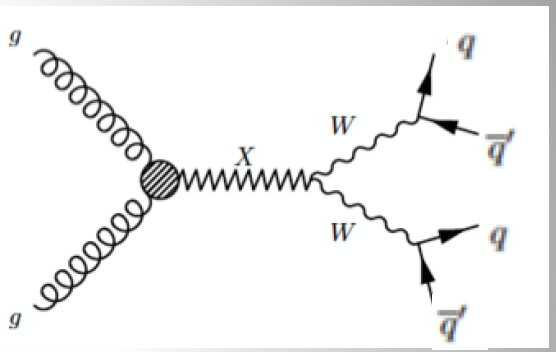
Heavy resonances decaying into qZ or qW, or VV jets only (CMS) or llqq (ATLAS) using boosted jets and jet substructure analysis

CMS



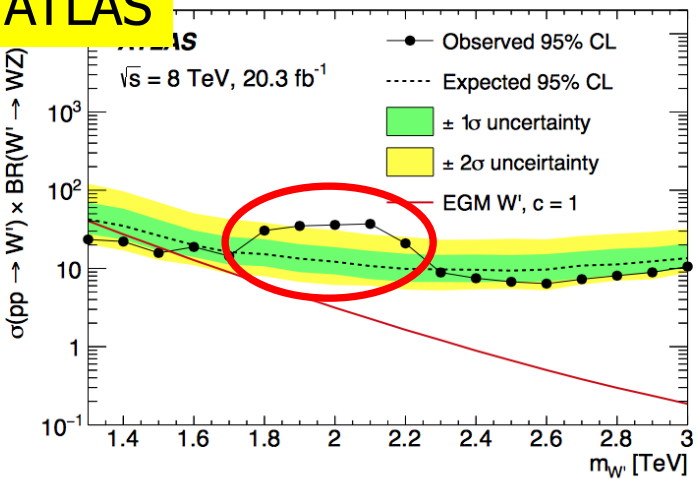


arXiv:1405.1994



Jets start to merge for X = 700-900 GeV

ATLAS



arXiv:1506.00962

Excess in WZ of 3.4σ (2.5 with LEE)

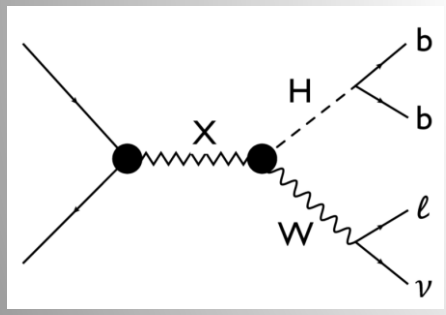
These type of analyses will get even more important at 13 TeV

Search for W+H Resonance

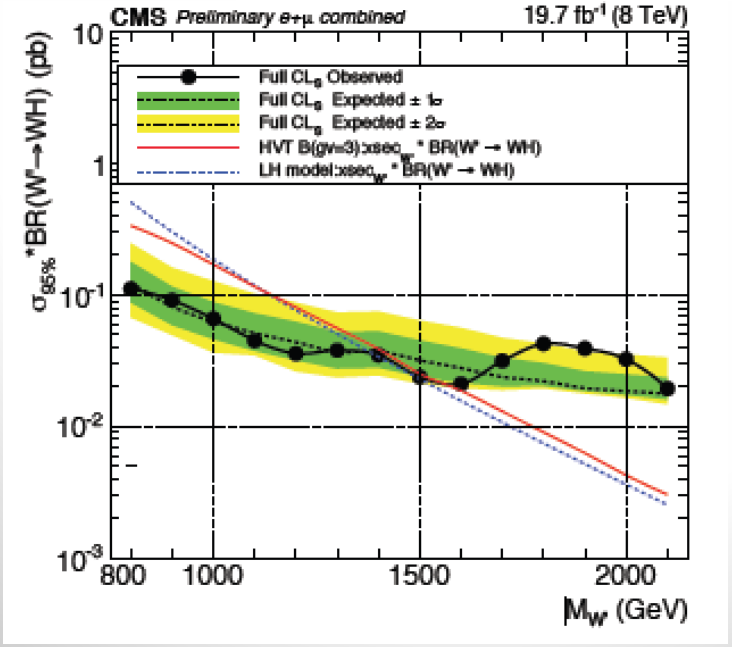
Enter the Higgs in the searches!!

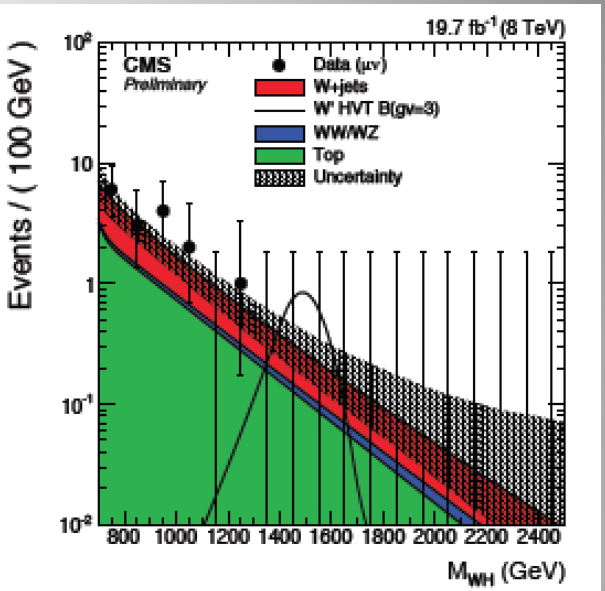
- Motivation: Compositness, GUTs…
- Lepton decay for the W boson
- H->bb for the Higgs generally boosted
  Make use of pruned jets and b-tagging in these jets

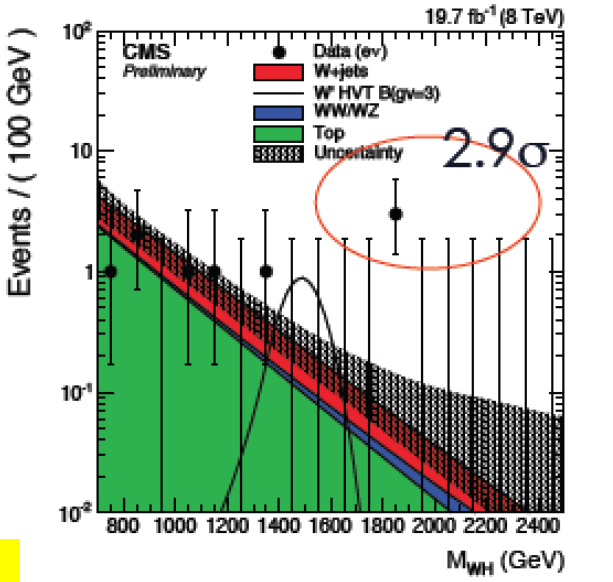
CMS-EXO-14-010



Shown last week in Moriond…

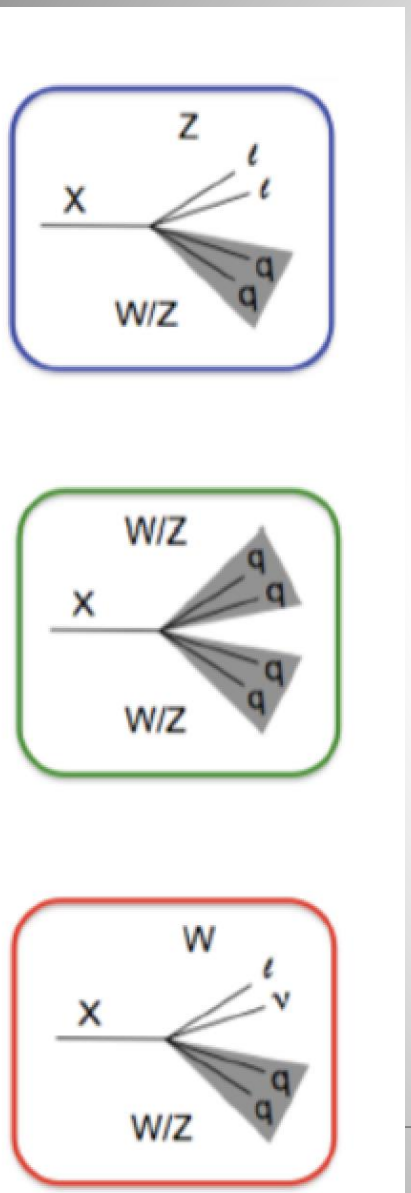






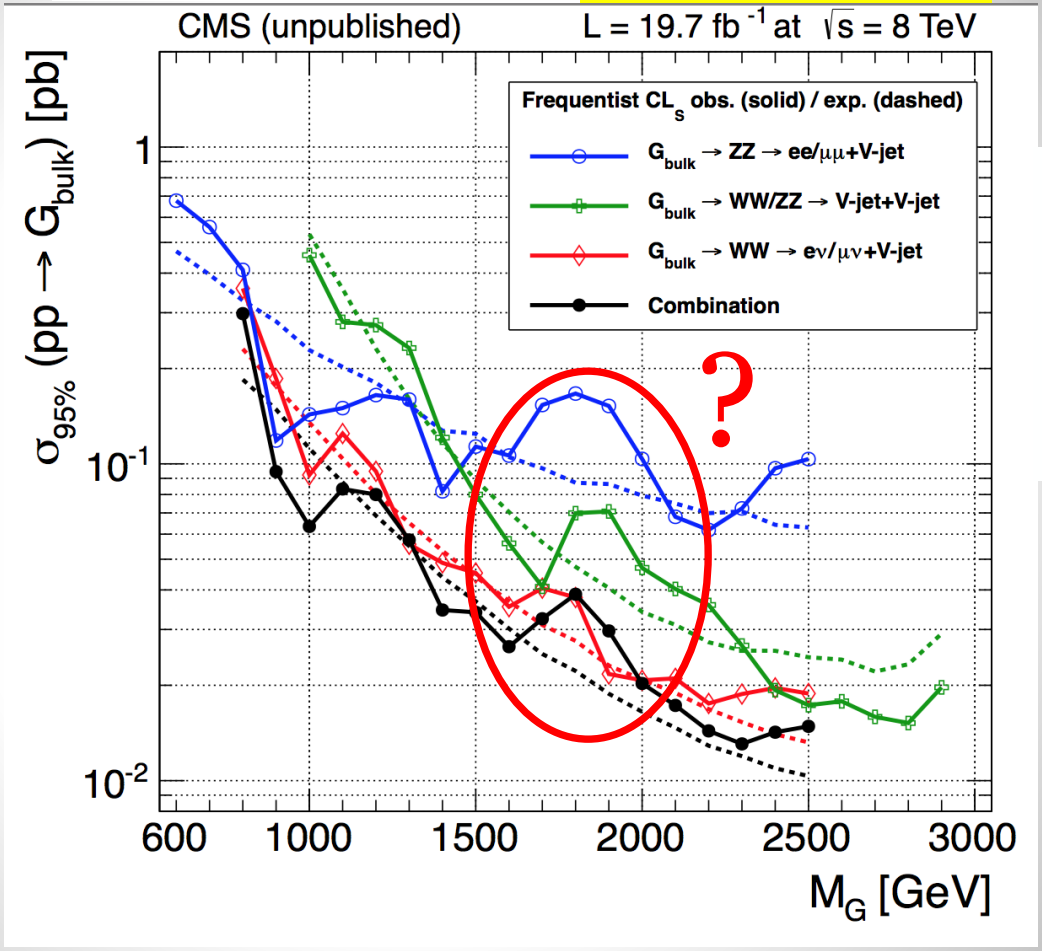
3 outlayer events in electron channel (2.9σ effect) !!

Is Something Going on Around 2 TeV?



CMS-EXO-13-009

Previous results



Combination assumes BRs and efficiencies of narrow bulk graviton model

2015-2016 data will clarify this!

Searches for Unusual Particles

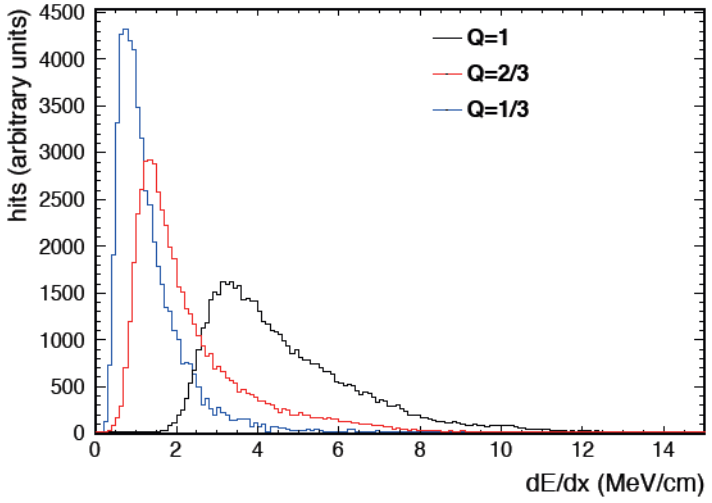
- Heavy stable charged particles with unit charge traversing the detector
- Heavy stable charged particles with multiple charge traversing the detectors
- Heavy stable charge particles with fractional charge traversing the detector
- Heavy new particles decaying in the detector
- Heavy new particles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

Fractional Charged Particles

FREE THE QUARKS

- The obvious example is to make careful searches for isolatable fractional charge particles at the Large Hadron Collider that will be in operation at CERN in a few years. In such searches it is important that the experimenters look for particles with all values of $f = q/e$ for which the apparatus is sensitive *not* just f values corresponding to quark charges such as $1/3$ and $2/3$. M. Perl et al., 2004

- Search possible @ LHC
- Both for q=1/3e and q=2/3e
- Tracks with a high number of low-ionizing hits in the tracker



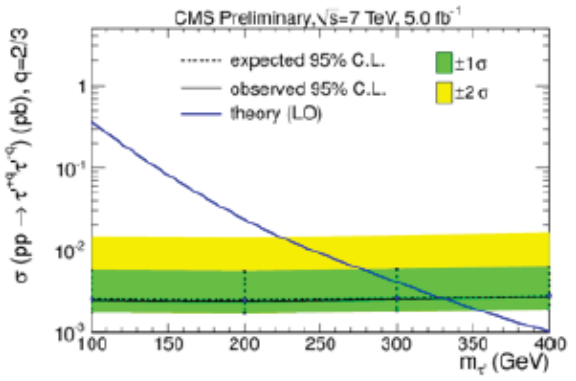
Particles with Fractional Charge

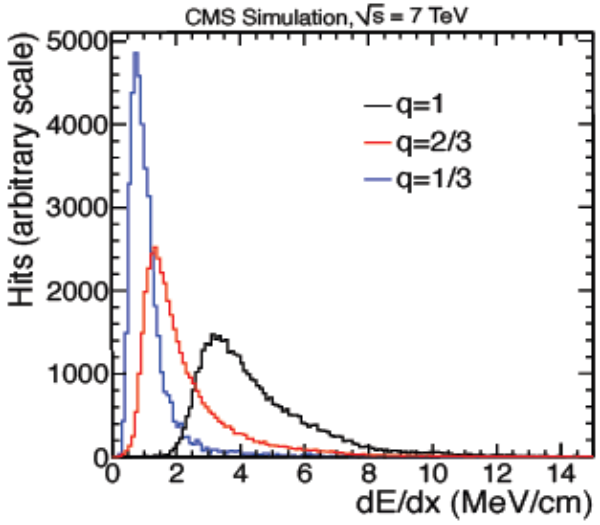
$$-\frac{dE}{dx} = K z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln f(\beta) - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

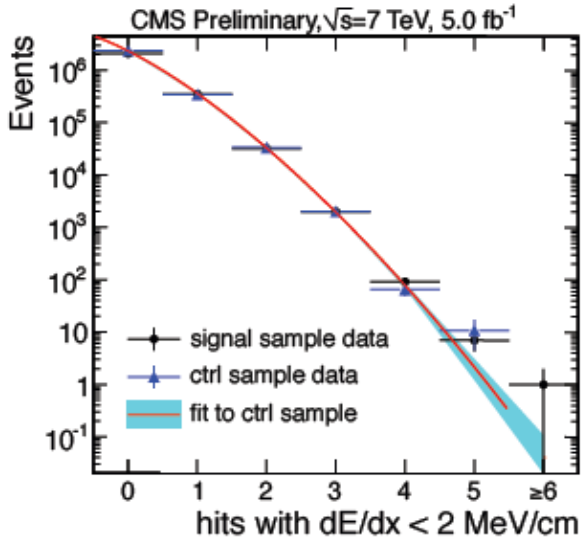
[CMS PAS EXO-11-074]

- Search for long-lived particles with fractional charge
- Backgrounds
  - Cosmics: estimate from d_{xy} sidebands
  - Collisions: using Z→μμ data, fit N_{hits} with low dE/dx
- Assume lepton-like spin=1/2 particle masses

Exclude: Q= e/3: m > 210
Q=2e/3: m > 330







Long Lived Particles

Split Supersymmetry

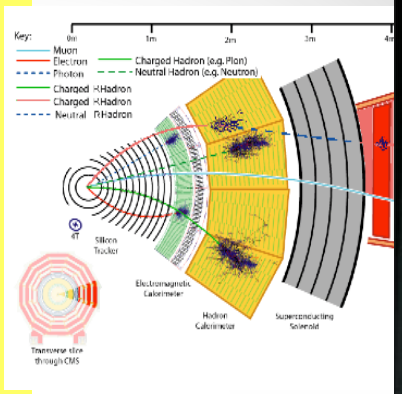
- The only light particles are the Higgs and the gauginos
  - Gluino can live long: sec, min, years!
  - R-hadron formation (eg: gluino+ gluon): slow, heavy particles

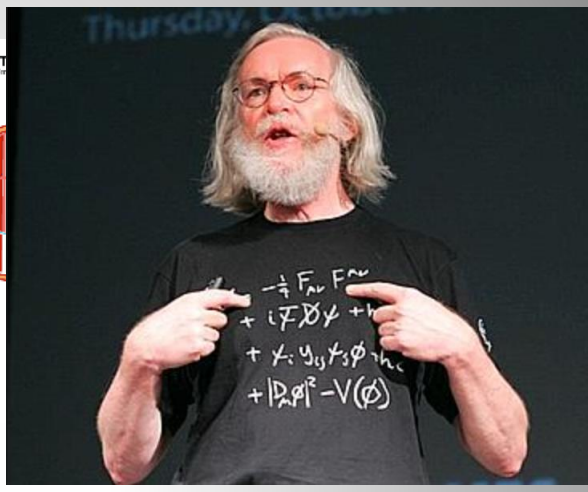
Gravitino Dark Matter and GMSB

- In some models/phase space the gravitino is the LSP
- ⇒ NLSP (neutralino, stau lepton) can live 'long'
- ⇒ non-pointing photons

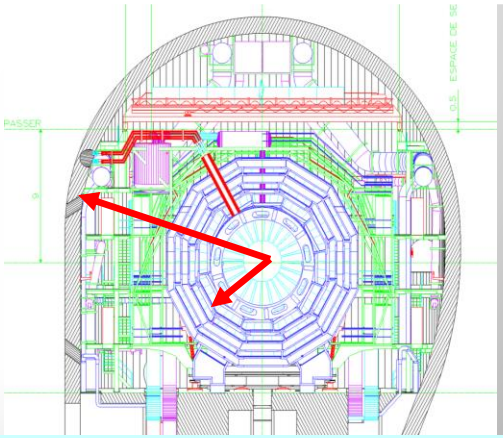
Hidden Valley modes!…

Plethora of possibilities for long lived neutrals





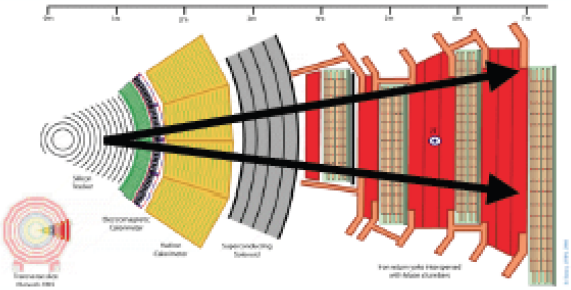
EG: K. Hamaguchi,M Nojiri,ADR hep-ph/0612060
ADR, J. Ellis et al. hep-ph/0508198

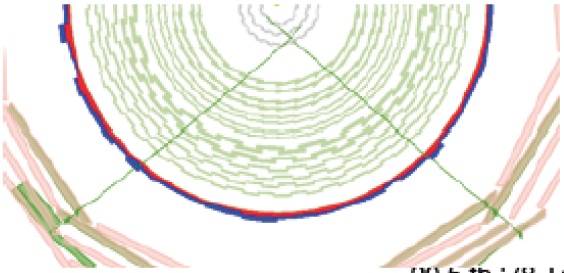


Sparticles stopped in the detector,walls of the cavern, or dense 'stopper' detector. They decay after hours---months…

⇒Challenges to the experiments!

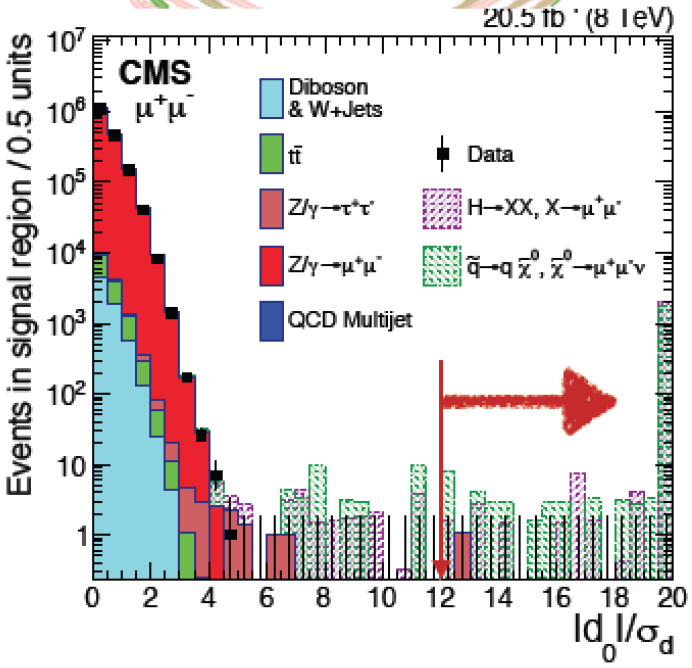
Displaced leptons ($e^+e^-/\mu^+\mu^-$) from common vertex

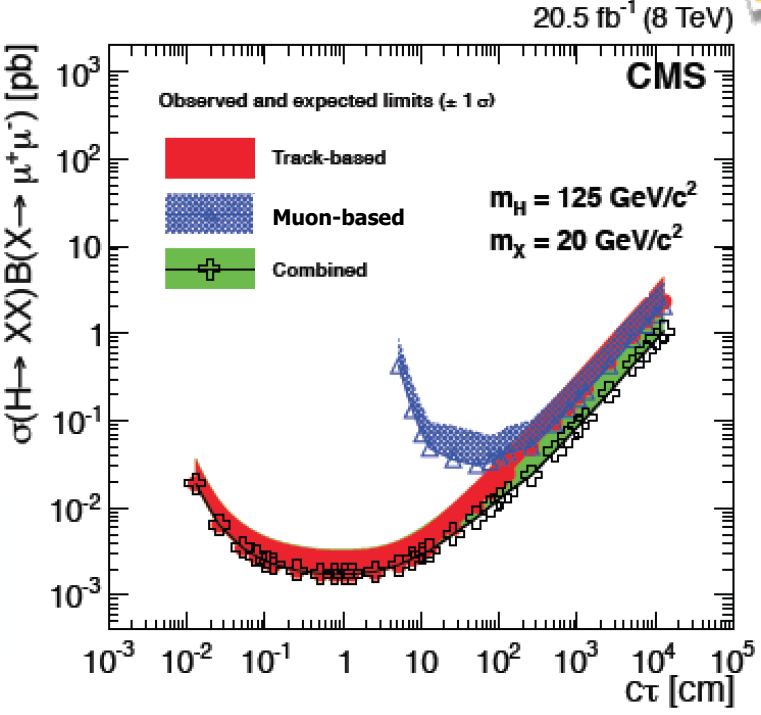




	Control region	Signal region
Observation	0	0

Set limits on Hidden Valley & RPV SUSY ($\chi^0 \rightarrow l^+l^-\upsilon$).
Combine with search using muon chamber tracks only (CMS-PAS-EXO-14-012). NEW!

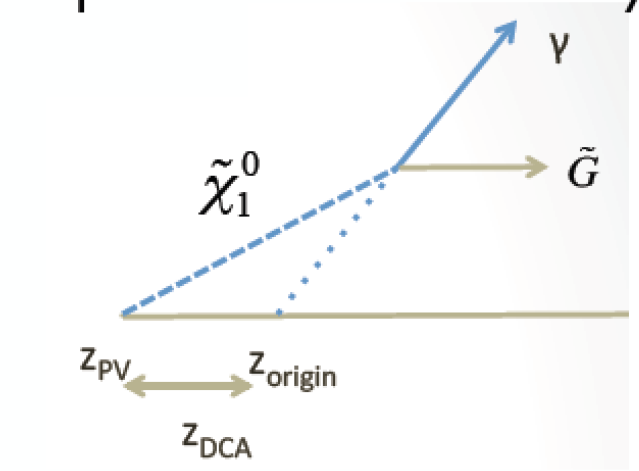


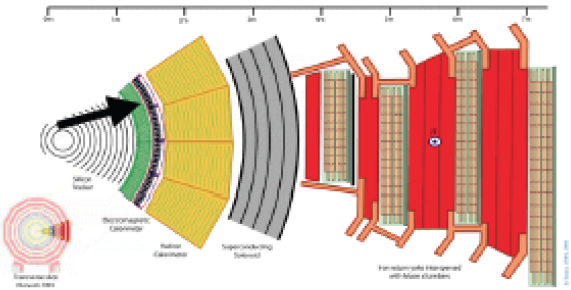


Suppress $Z/\gamma \rightarrow l^+l^-$ bkgd with $|d_0|/\sigma_d > 12$.
Estimate bkgd from control region: dilepton momentum opposite the direction from primary to secondary vertex.

arXiv:1411.6977

Displaced / delayed photons

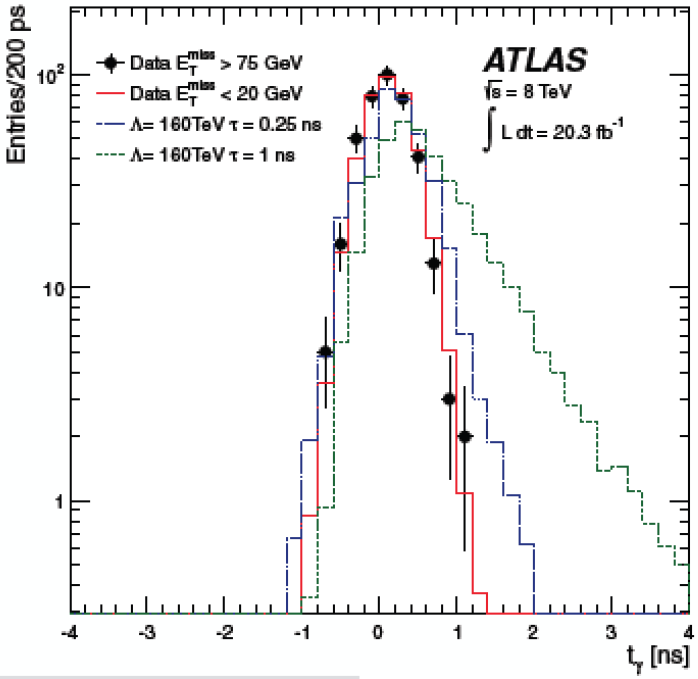




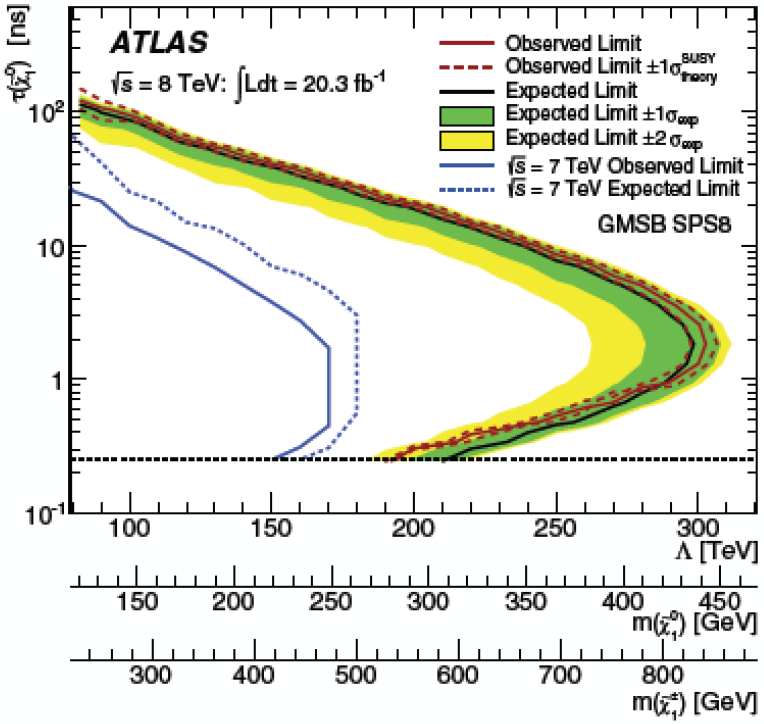
- Signal region: 2 photons (E_T>50 GeV) & MET>75 GeV.
- 2D search in z_{DCA} and t_γ.
- Low-MET control region used to model bkgd.

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).



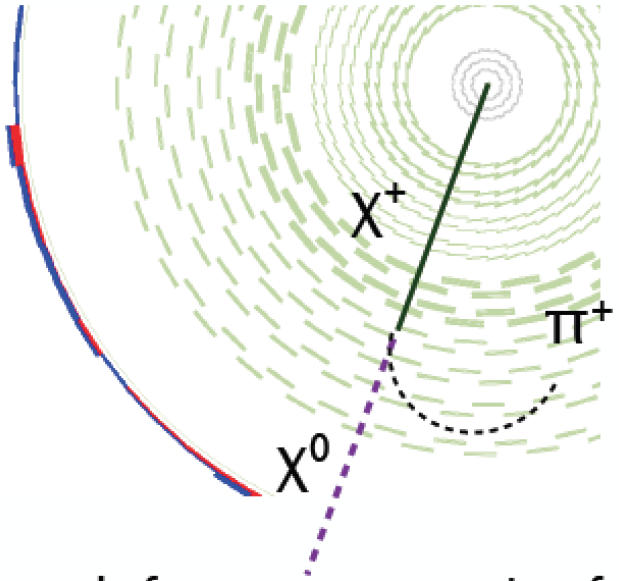
Set limits on GMSB SPS8 model.

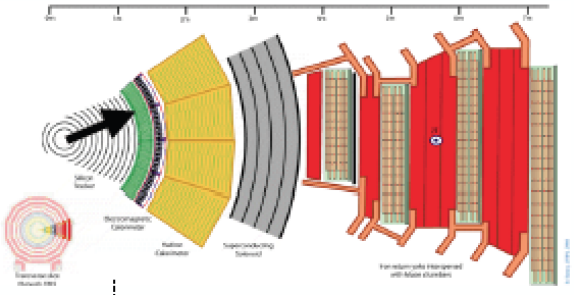


Phys. Rev. D 90, 112005 (2014)

Disappearing tracks

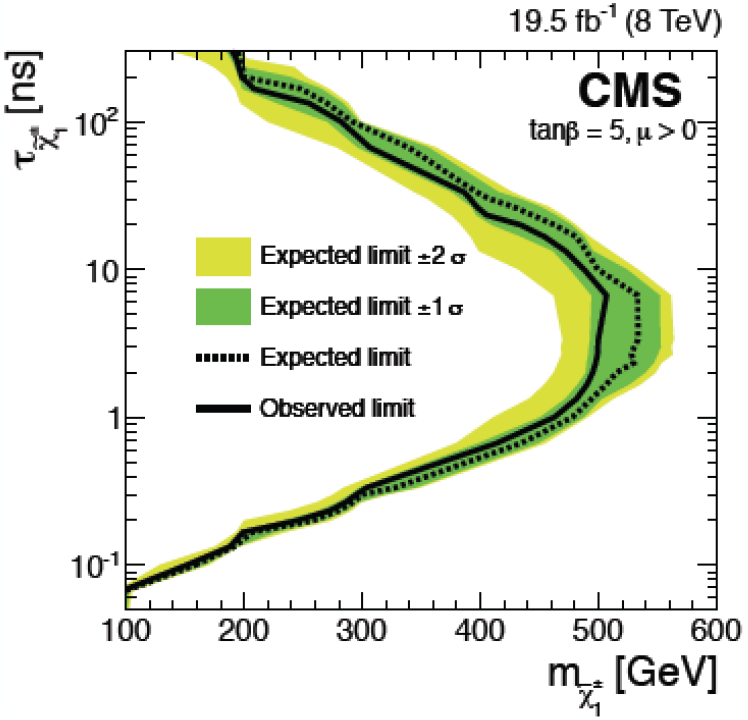
Require high-p_T isolated track with little energy deposited in calorimeters (E_{calo} < 10 GeV) and ≥3 missing hits in outer layers of tracker.





	Signal region
Expected bkgd	1.4 ± 1.2
Observation	2

Set limits on AMSB chargino production



Backgrounds from reconstruction failure modes:

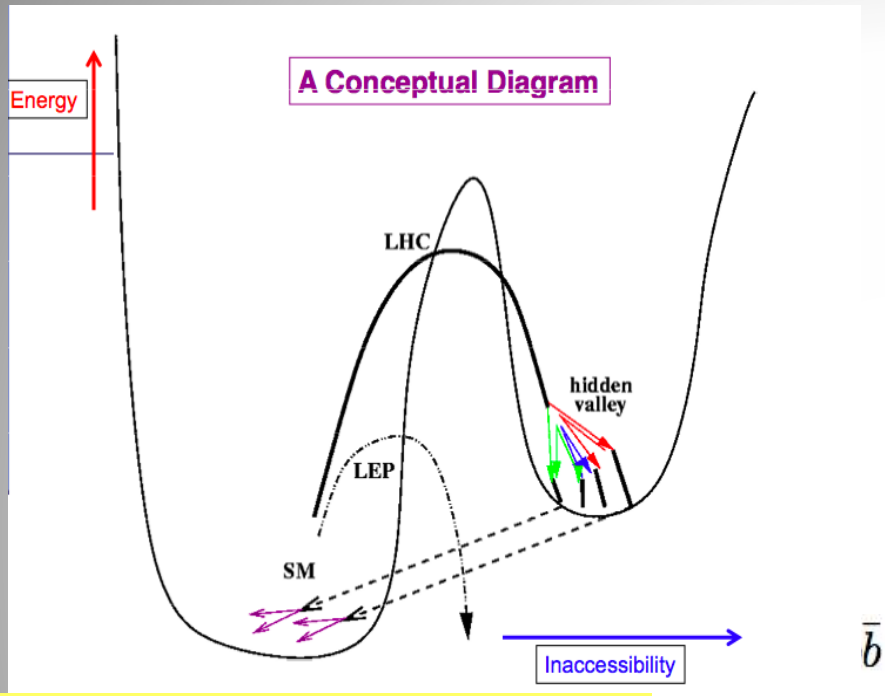
- unidentified electrons
- unidentified muons
- hadrons with mismeasured p_T
- fake tracks

Estimate backgrounds with tag-and-probe methods.

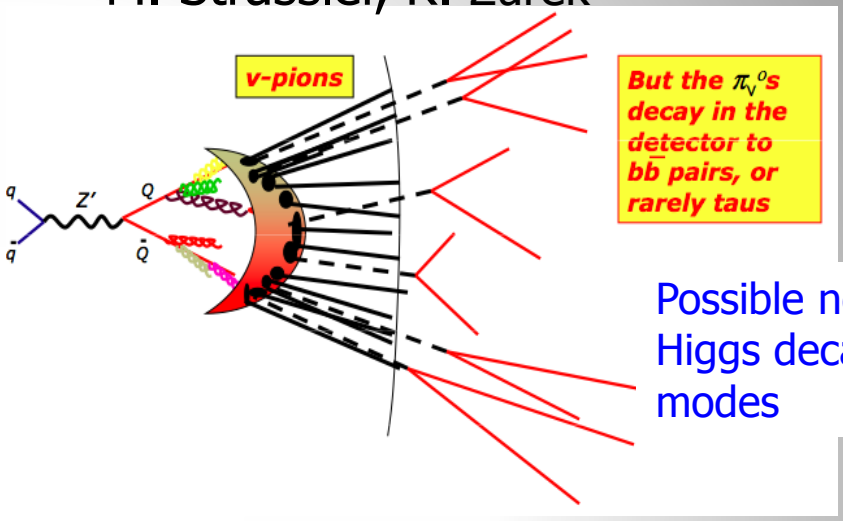
JHEP 01 (2015) 096

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

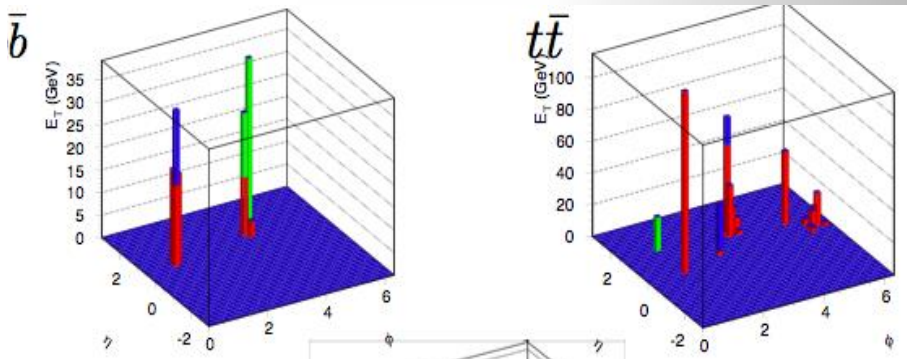
Hidden Valley Physics: New Signatures

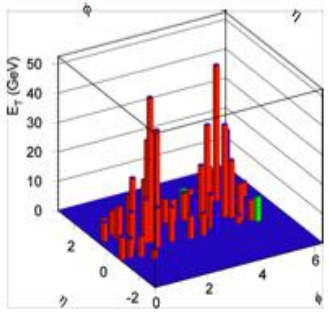


M. Strassler, K. Zurek



Will produce "Weird Jets" and a lot of secondary vertices from b-quark jets



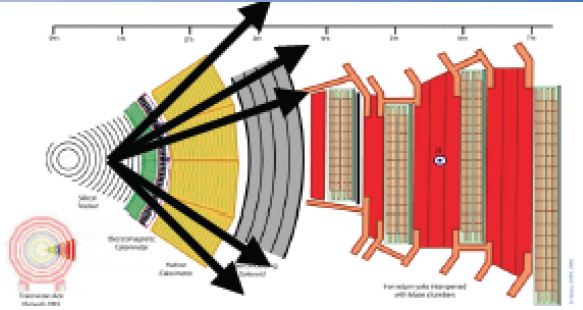


Hidden valley

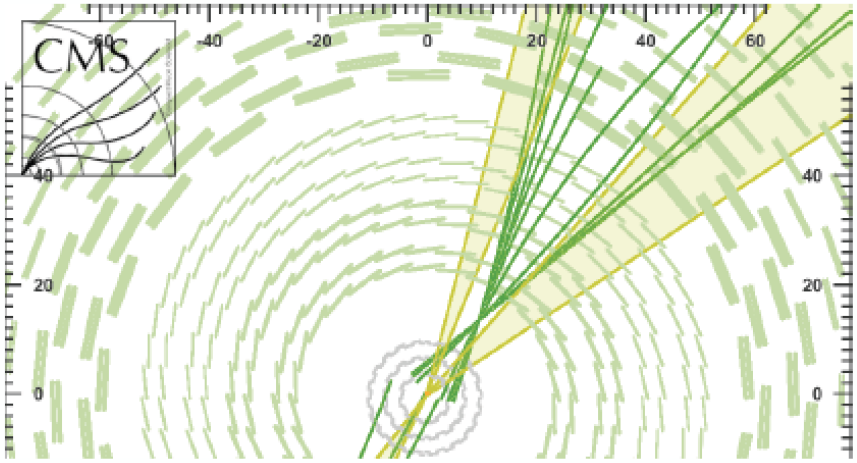
⇒ Difference with QCD jets??

⇒ Study SM jet structure!!

Displaced dijets

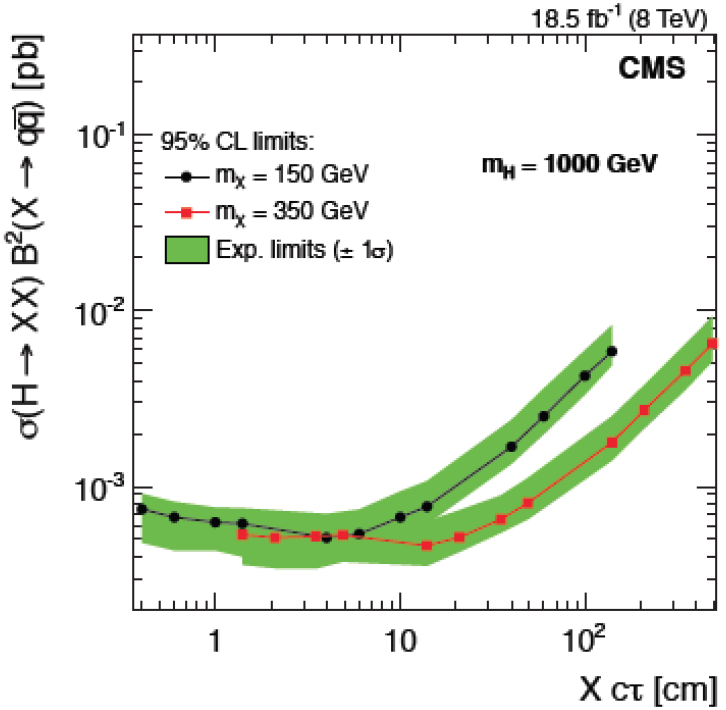


Require 2 jets (≥1 track each) from common displaced vertex



	Loose selection	Tight selection
Expected bkgd	1.56 ± 0.25 ± 0.47	1.13 ± 0.15 ± 0.50
Observation	2	1

Set limits on Hidden Valley and RPV SUSY ($\chi^0 \rightarrow qq\mu$)



Reduce dominant background from QCD with requirements on:

- # prompt tracks
- prompt track energy fraction
- vertex / cluster discriminant

Estimate remaining background by extrapolating from uncorrelated data sideband control regions ("ABCD" method).

Phys. Rev. D 91, 012007 (2015)

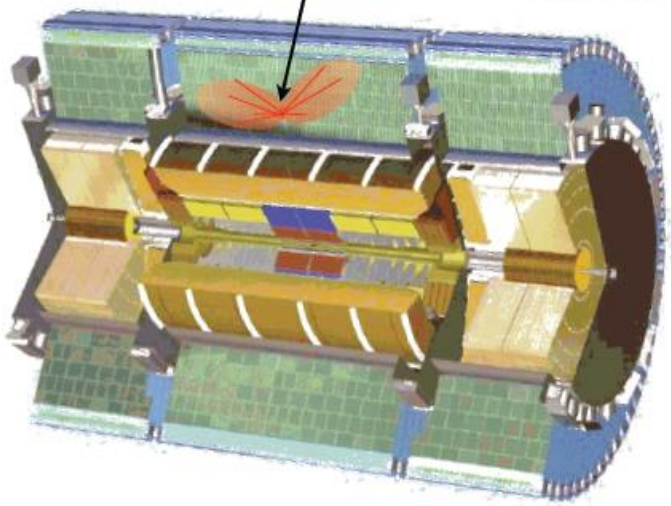
Stopped R-hadrons or Gluinos!

Long Lived Gluinos

$\tau_{\tilde{g}} > 100$ ns

looking for stopped gluinos that later decay

100s GeV Unbalanced $= \not{E}_T$



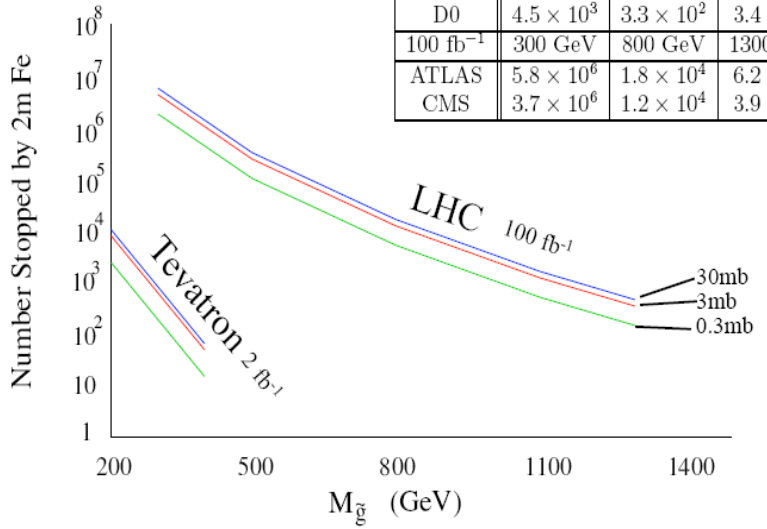
Uncorrelated with any beam crossing
No tracks going to or from activity

The R-hadrons may loose so much energy that they simply stop in the detector …and decay some time later

Total Number of Stopped Gluinos

Arvanitaki, Dimopoulos, Pierce, Rajendran, JW hep-ph/0506242

2 fb^{-1}	200 GeV	300 GeV	400 GeV
CDF	4.1×10^3	3.1×10^2	3.3×10^1
D0	4.5×10^3	3.3×10^2	3.4×10^1
100 fb^{-1}	300 GeV	800 GeV	1300 GeV
ATLAS	5.8×10^6	1.8×10^4	6.2×10^2
CMS	3.7×10^6	1.2×10^4	3.9×10^2



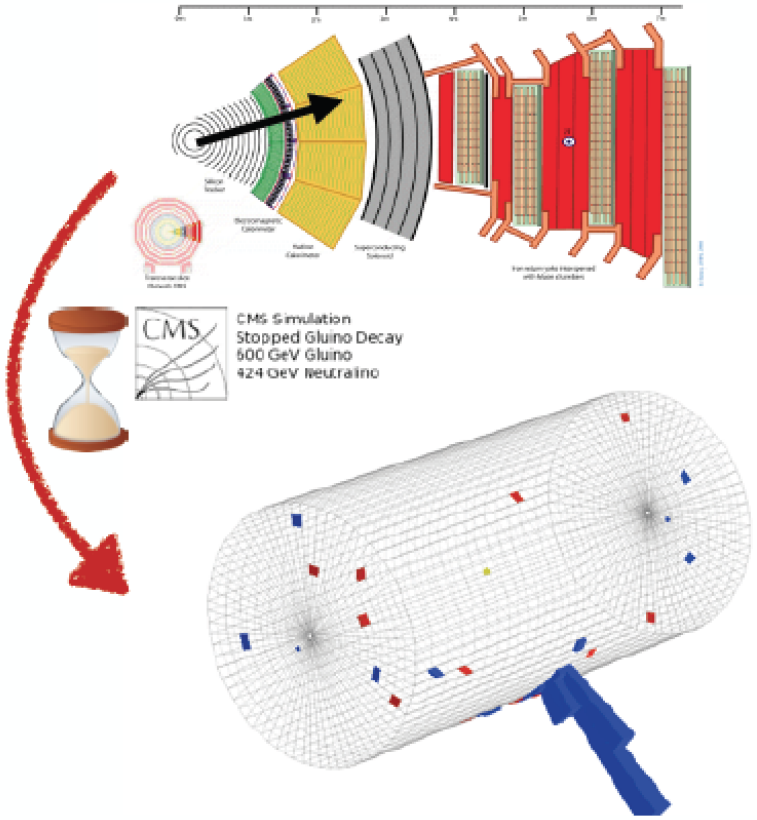
⇒ Special triggers needed, asynchronous with the bunch crossing

Stopped particles

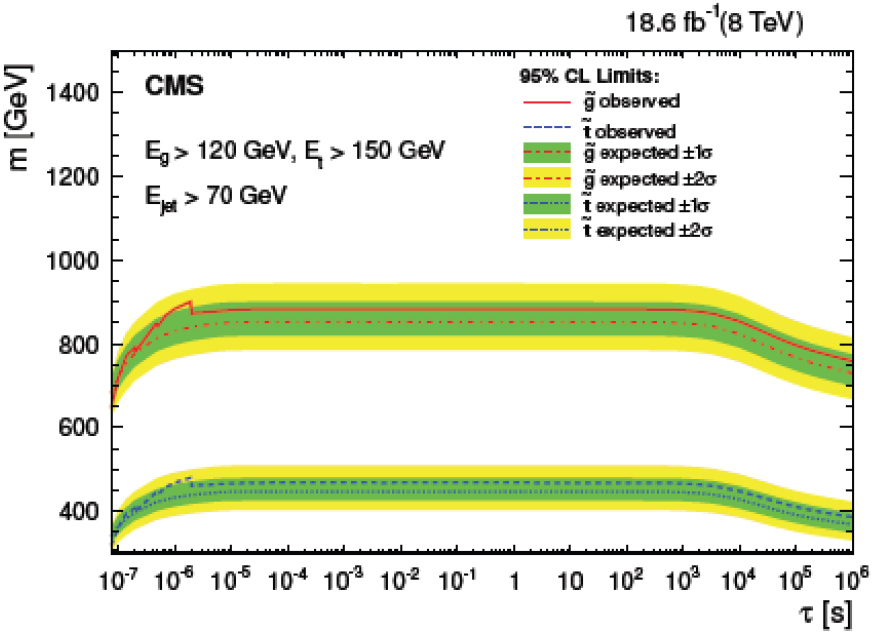
Backgrounds: beam halo muons, cosmic rays, HCAL noise.

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

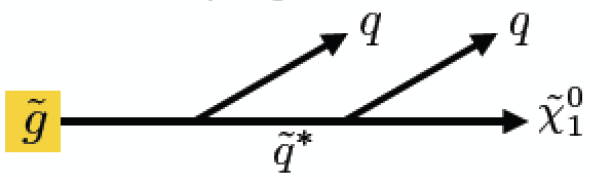
Limits on gluino, stop mass for **over 13 orders of magnitude!**



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

Monopoles

Magnetic Monopoles to explain the quantization of electric charge (Dirac '31)

$$\nabla.\mathbf{E} = 4\pi\rho_e$$

$$\nabla.\mathbf{B} = 4\pi\rho_m$$

$$-\nabla\times\mathbf{E} = \frac{1}{c}\frac{\partial\mathbf{B}}{\partial t} + \frac{4\pi}{c}\mathbf{j_m}$$

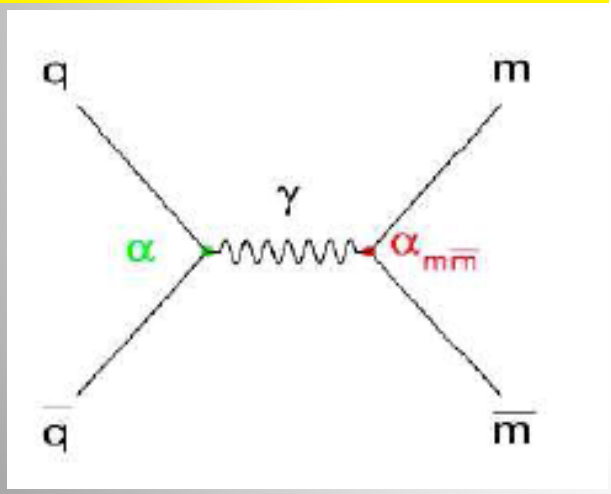
$$\nabla\times\mathbf{B} = \frac{1}{c}\frac{\partial\mathbf{E}}{\partial t} + \frac{4\pi}{c}\mathbf{j_e}$$

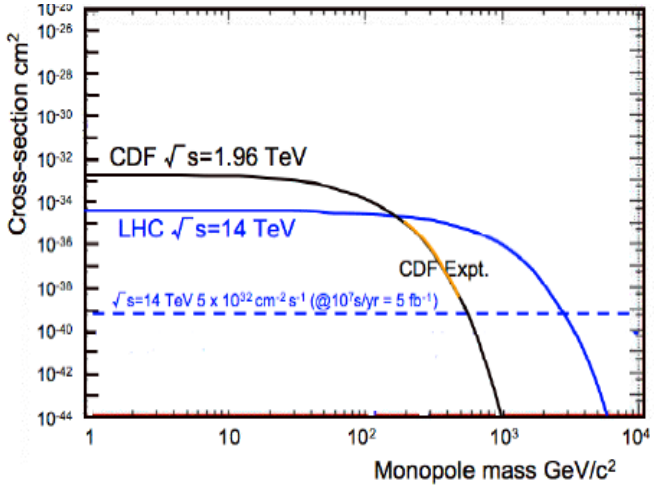
$$\mathbf{F} = q_e\left(\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}\right) + q_m\left(\mathbf{B} - \frac{\mathbf{v}}{c}\times\mathbf{E}\right)$$

$$eg = n\hbar c/2 = ng_D$$ = n 68.5e

$$\sigma_{D(m)} = \left(\frac{g_D}{e}\right)^2 \times \sigma_{\mu\mu}(>2m) \times (1 - 4\frac{m^2}{s})$$

Symmetrizes maxwell equations
Searched for at all colliders
Tevatron limits ~ 400-800 GeV





Sensitivity of LHC experiments to exotic highly ionising particles

A. De Roeck[1,2,3], A. Katre[4], P. Mermod[a,4,5], D. Milstead[6], T. Sloan[7]

arXiv: 1112.2999

Search for Monopoles

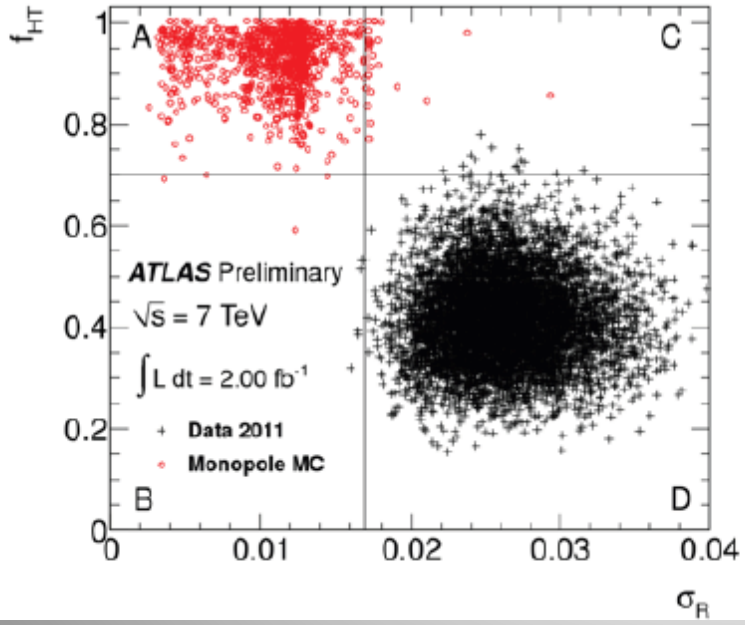
[ATLAS-CONF-2012-062]

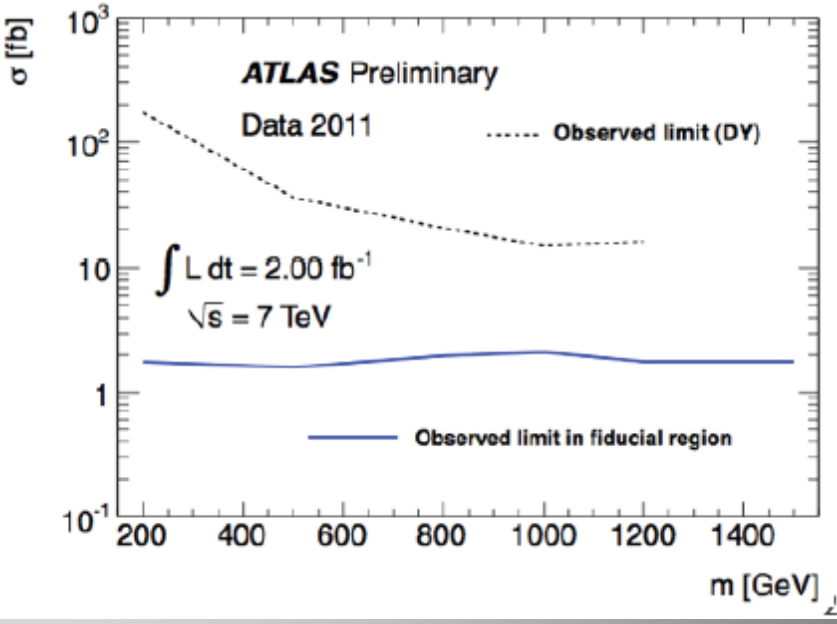
- Magnetic charge g yields strong coupling α_m and very high ionisation

$$\frac{ge}{\hbar c} = \frac{1}{2} \Rightarrow \frac{g}{e} = \frac{1}{2\alpha_e} \approx 68.5 \qquad \alpha_m = \frac{(g\beta)^2}{\hbar c} = \frac{1}{4\alpha_e}\beta^2$$

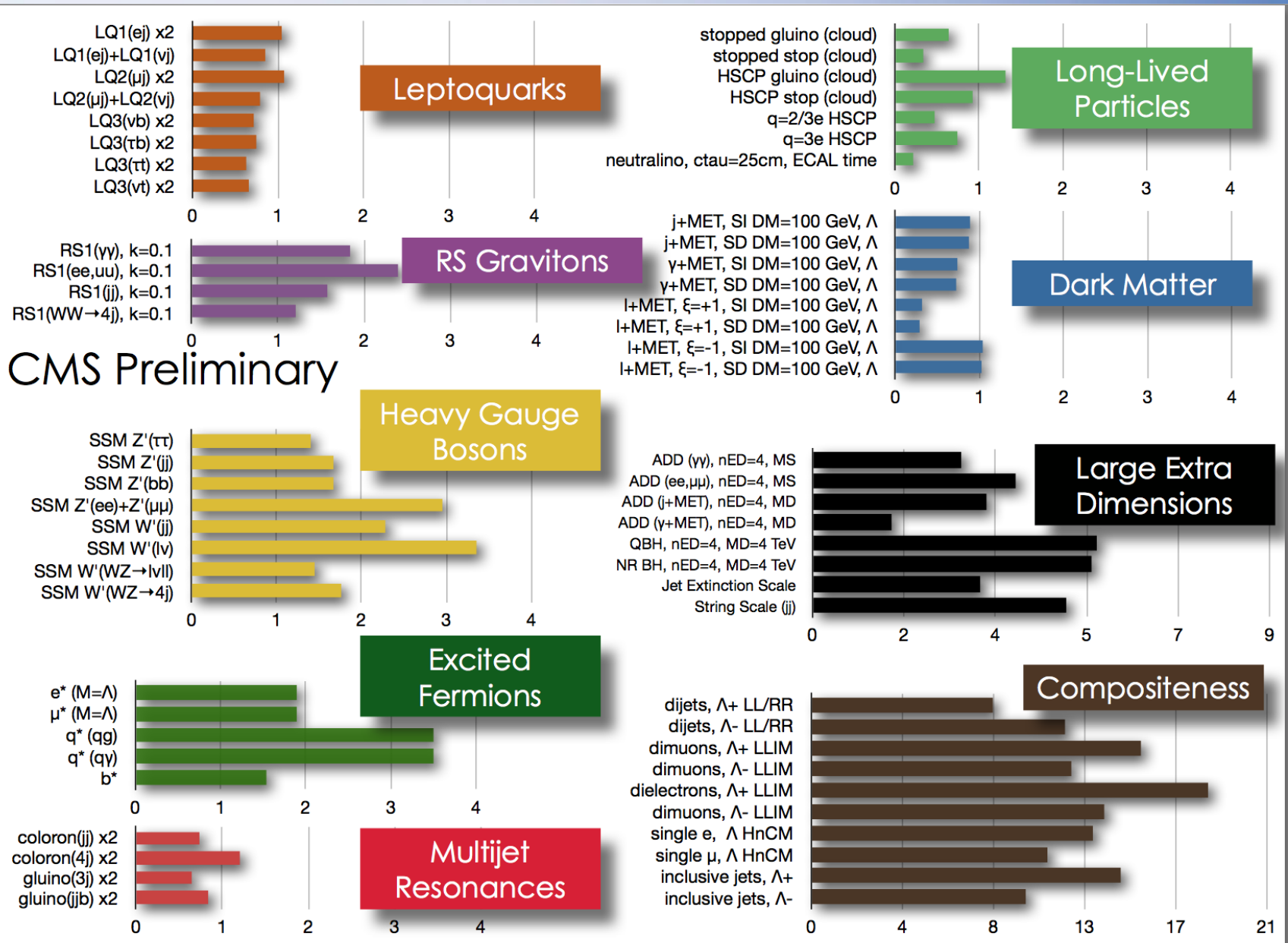
- Look for high ionisation in Transition Radiation Tracker and high hit fraction (f_{HT}) and also deposition in the Liquid Argon Electromagnetic Calorimeter
- Pair-produced (Drell-Yan) production

Cross Section limits set for m(M) = 0.2–1.2 TeV





Summary of Exotica Searches



End of Lecture I