Beyond the Standard Model
Searches for Exotica

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The Abdus Salam International Centre for Theoretical Physics
50th Anniversary 1964–2014

ICTP-NCP School on LHC Physics
17 – 28 November 2014
(Islamabad, Pakistan)

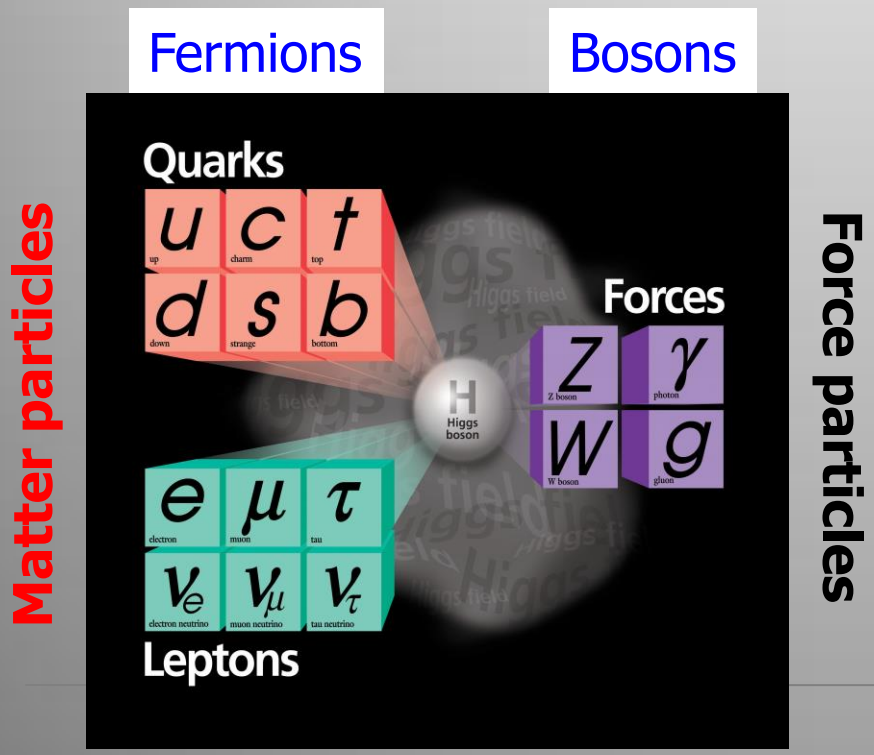
Lecture Plan

Overview of the 3 lectures in the next days

- Lecture 1: Searching for Physics Beyond the Standard Model: exotic signatures
- Lecture 2: The next ultimate challenge: identifying Dark Matter in the Universe, and its connection to Supersymmetry
- Lecture 3: The future program at the LHC and the studies/ideas for ‘beyond the LHC’

The "Standard Model"

Over the last 100 years: combination of
Quantum Mechanics and Special Theory of relativity
along with all new particles discovered has led to the
Standard Model of Particle Physics.
The new (final?) "Periodic Table" of fundamental elements:



The Standard model includes the strong and electroweak force

$$SU(3)\times SU(2)\times U(1)$$

The most basic mechanism of the SM, that of granting mass to particles remained a mystery for a long time

In 2012 a Higgs Boson was discovered at the LHC!!

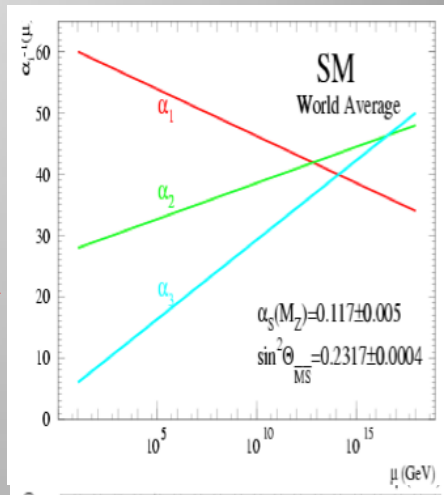
Fermions: particles with spin ½
Bosons: particles with integer spin

Physics case for new High Energy Machines

Understand the mechanism Electroweak Symmetry Breaking

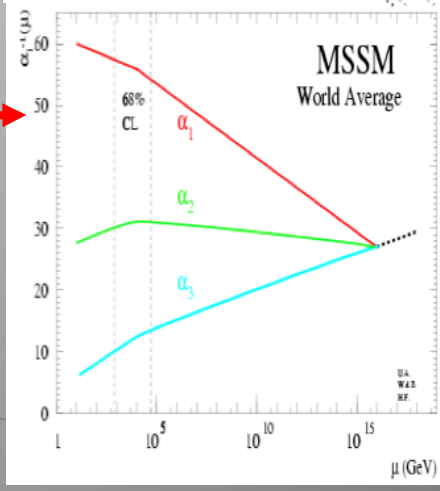
Discover physics beyond the Standard Model

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



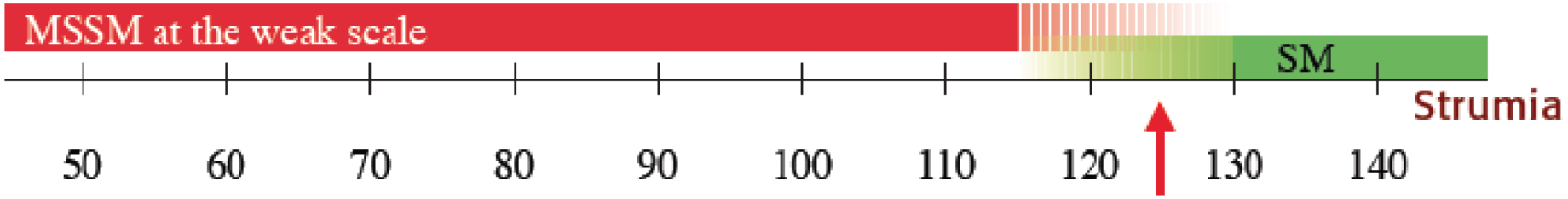
Many other ideas: More symmetry and gauge bosons,
L-R symmetry, quark & lepton substructure, Little Higgs models,
Technicolor, Hidden Valleys, 4th generation…

Higgsless models somewhat disfavoured these days

A Higgs…

A malicious choice!

$m_H = 125.6 \pm 0.4$ GeV



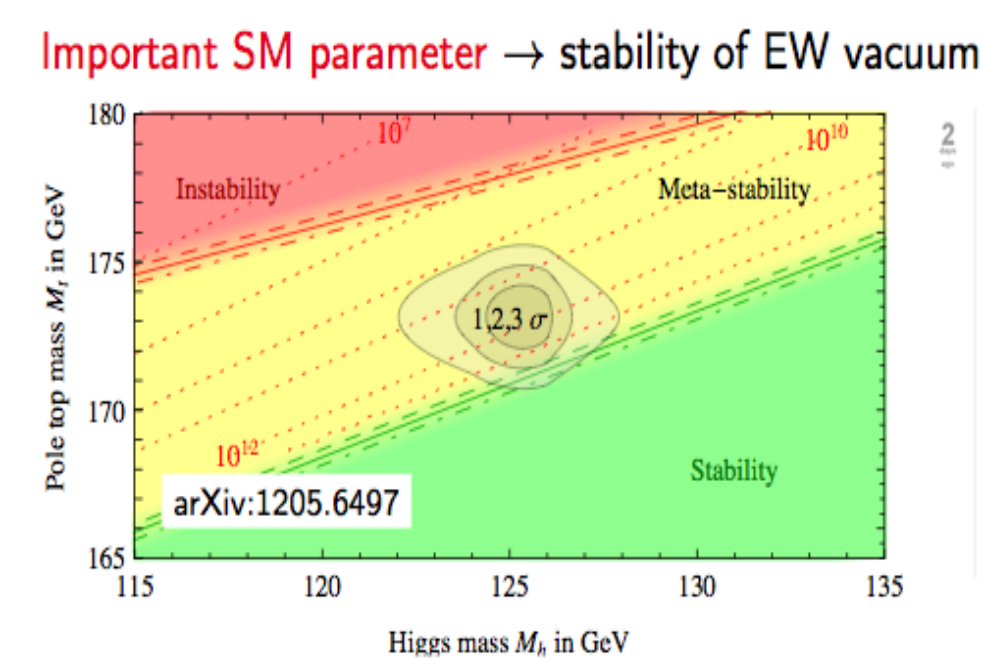
The Higgs:
so simple yet so unnatural

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

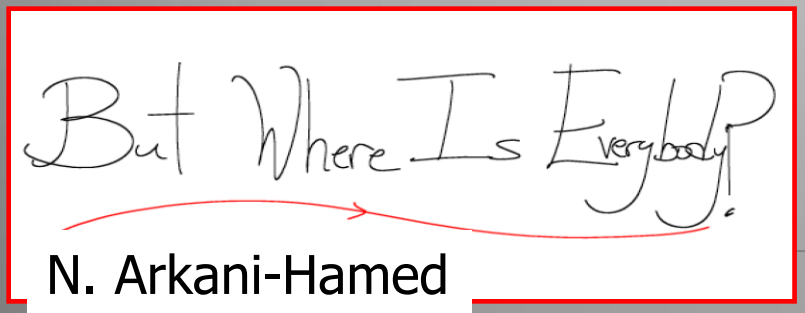
Consequences for our Universe?



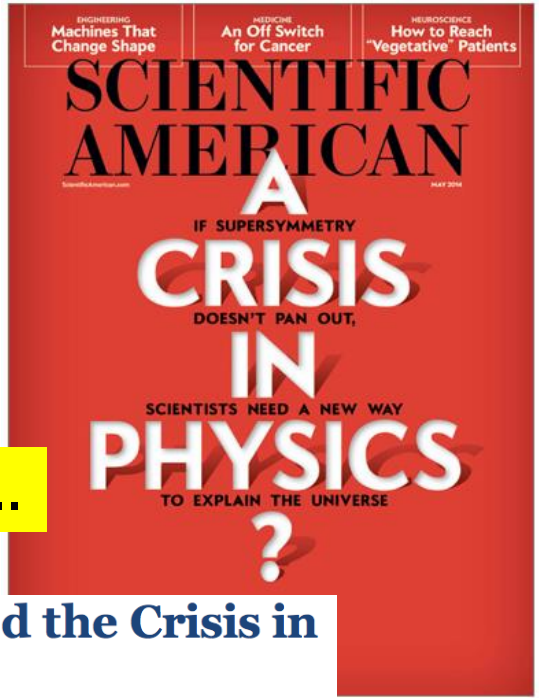
Precise measurements of the top quark and first measurements of the Higgs mass:

Our Universe meta-stable ?
Will the Universe disappear in a Big Slurp? (NBCNEWS.com)

New Physics inevitable?
But at which scale/energy?

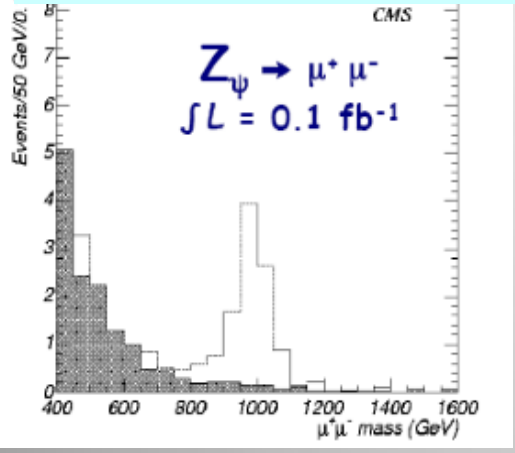


…The May Issue…

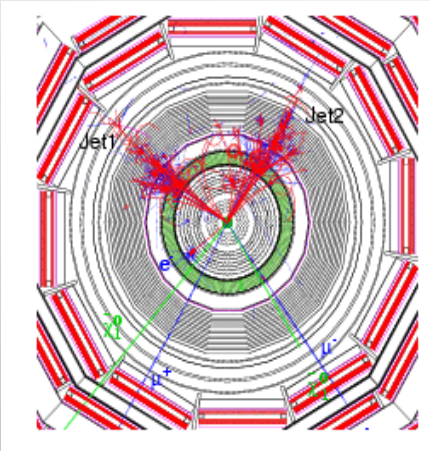


New Physics?

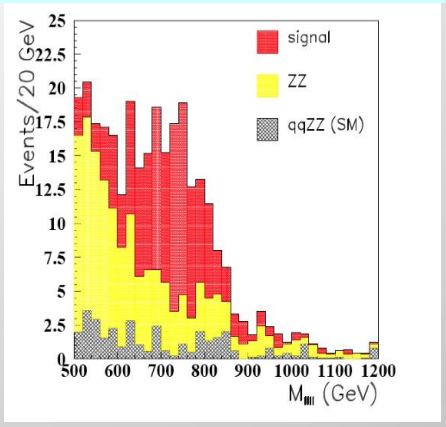
New Gauge Bosons?



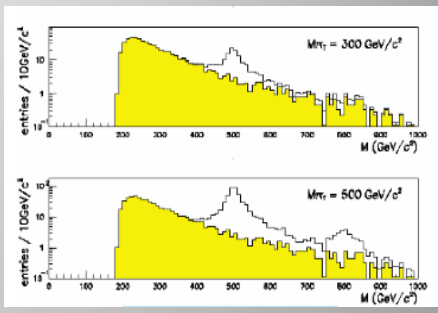
Supersymmetry



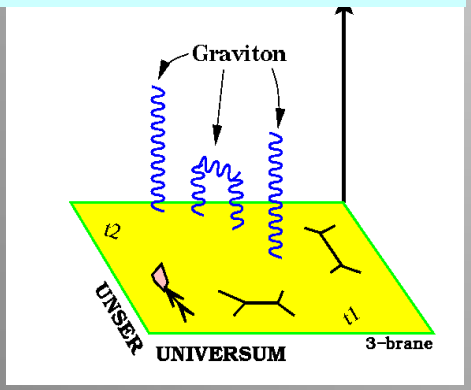
ZZ/WW resonances?



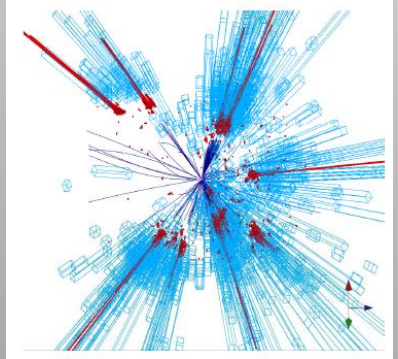
Technicolor?



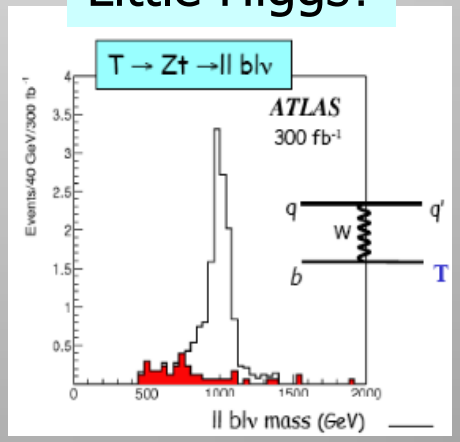
Extra Dimensions?



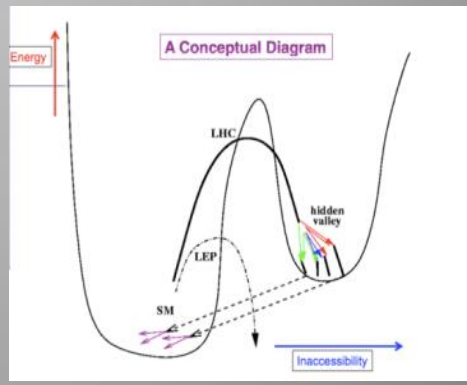
Black Holes???



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

Exotica

- Search for physics beyond the Standard Model.
- Looking for something weird and unexpected in the data.
- Wide range of possibilities with relative little guidance. Many models and possible phenomena.
- Unlike for Higgs or Supersymmetry (tomorrow's lecture)
  - No Exotica hunter's guide to show you the way
  - No SUSY map of parameter space to show you the incremental progress with each search
- Instead a wide variety of searches used. Will give examples of that to show the spectrum

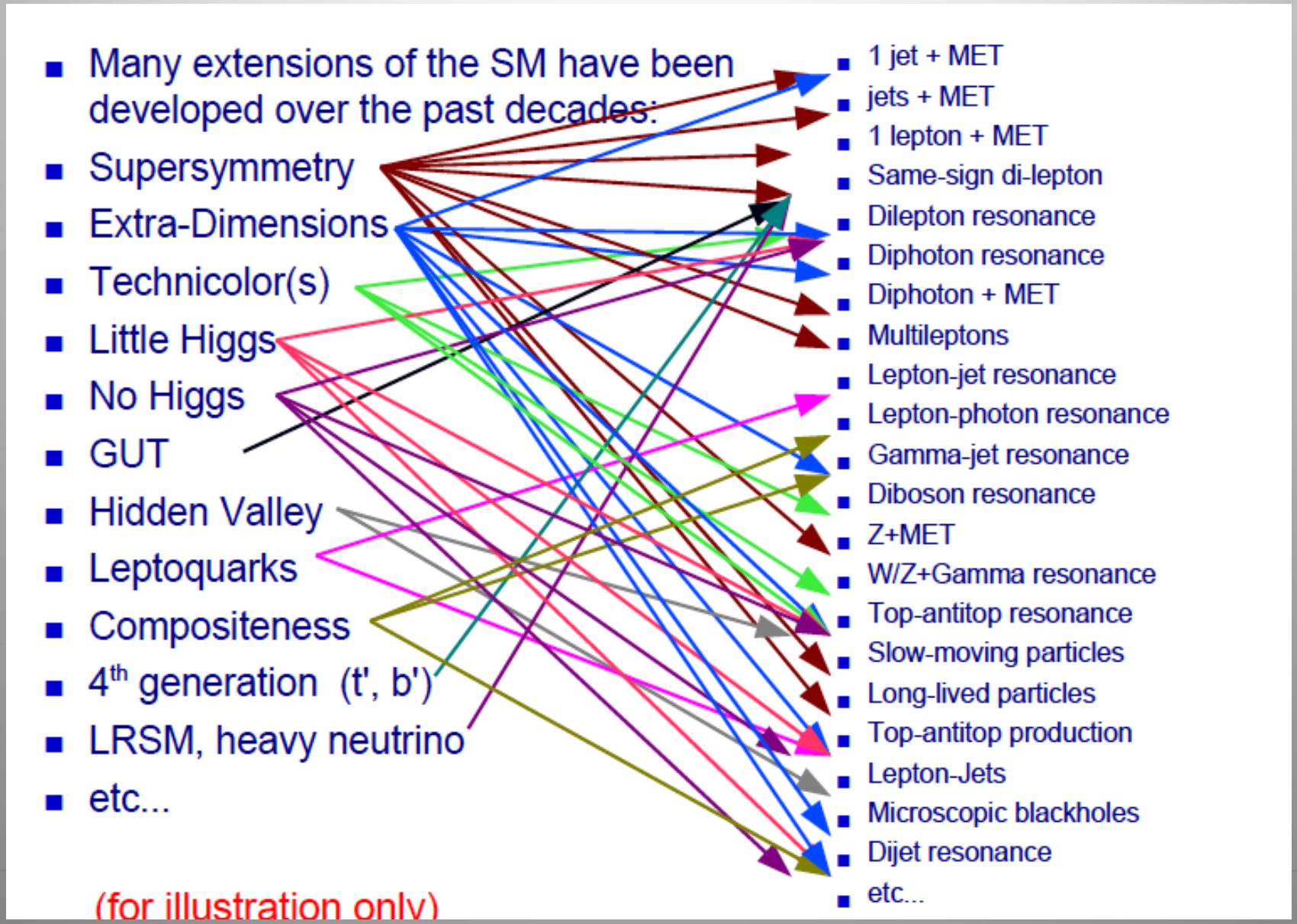
Exotica Topics this Lecture

Lecture Plan

- Extra dimensions
- Resonances (leptons, jets)
- Heavy Neutrinos
- The possible special role of top
- Special signatures (boosted, long lived…)
- General searches
- Summary

This is a small fraction of the possibilities

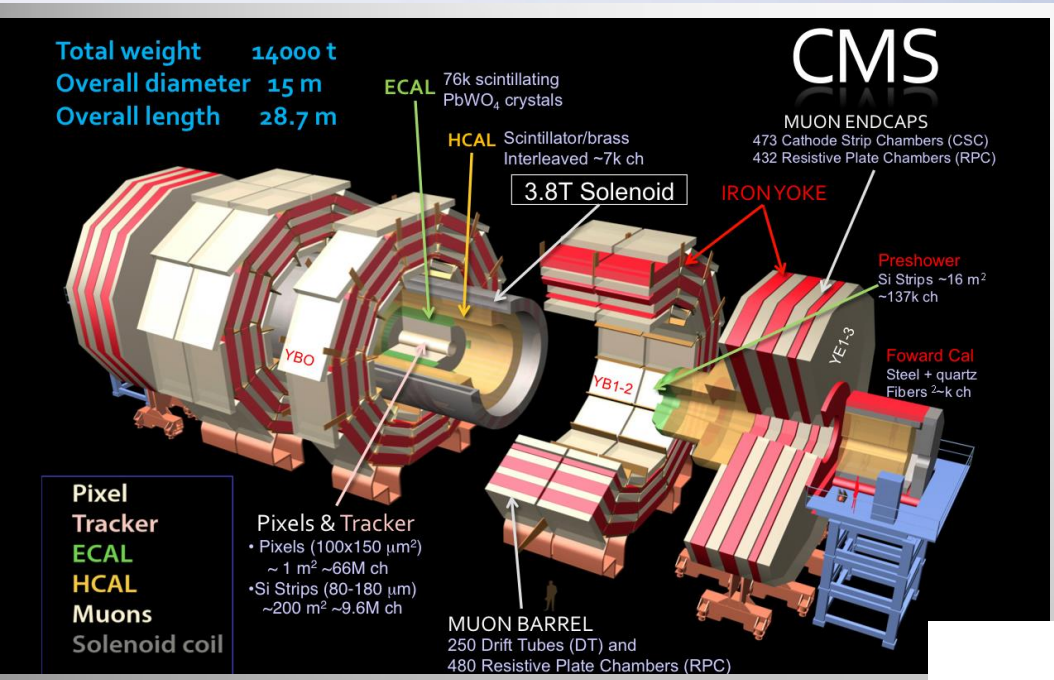
Beyond the SM Signatures



LHC data and Theorists

"Data are coming! Data are coming!"

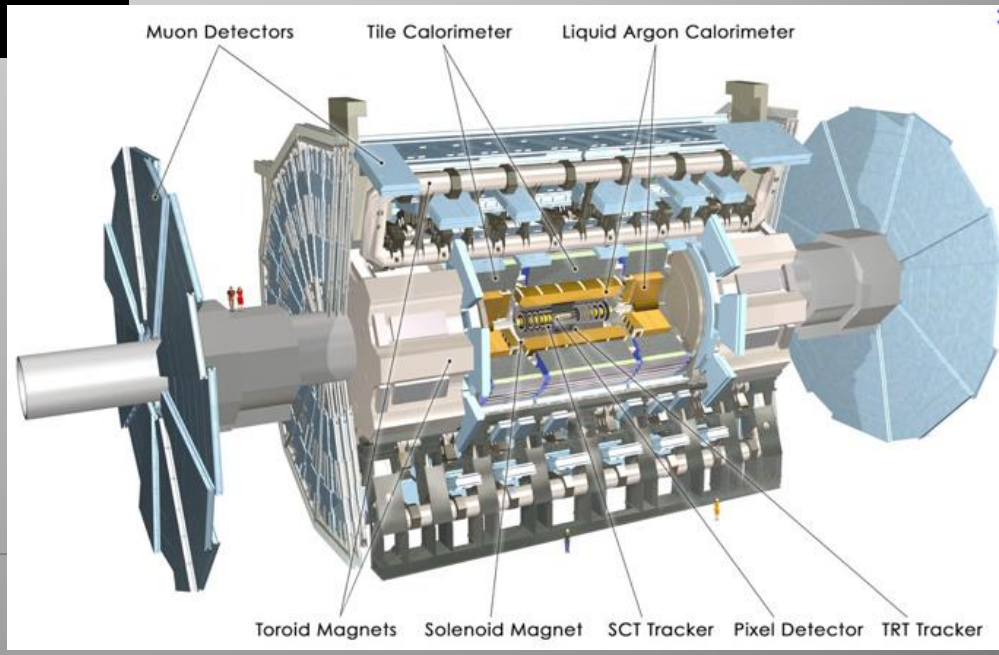
LHC BSM(*) Hunting Detectors



(*) Beyond the Standard Model

The CMS Experiment

Examples from these experiments

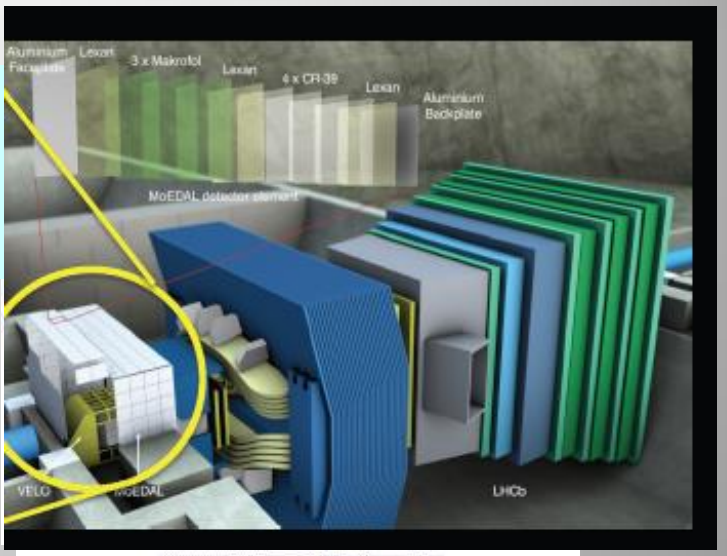


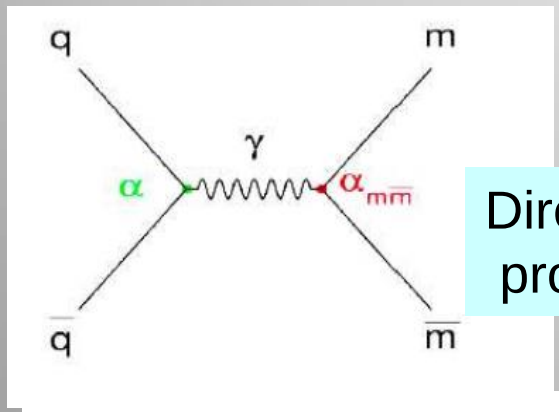
The ATLAS Experiment

Also LHCb via eg B_s-> μμ

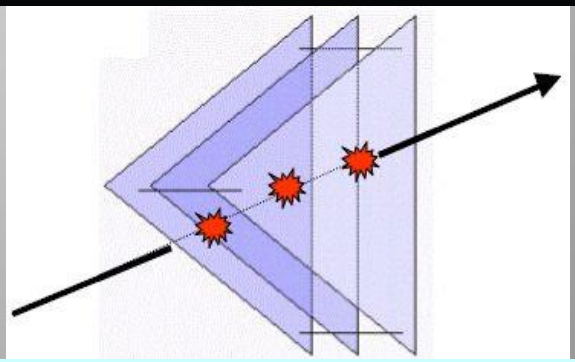
MoEDAL: Monopole and Exotics Detector at the LHC

Heavy particles which carry “magnetic charge”
Could eg explain why particles have “integer electric charge”

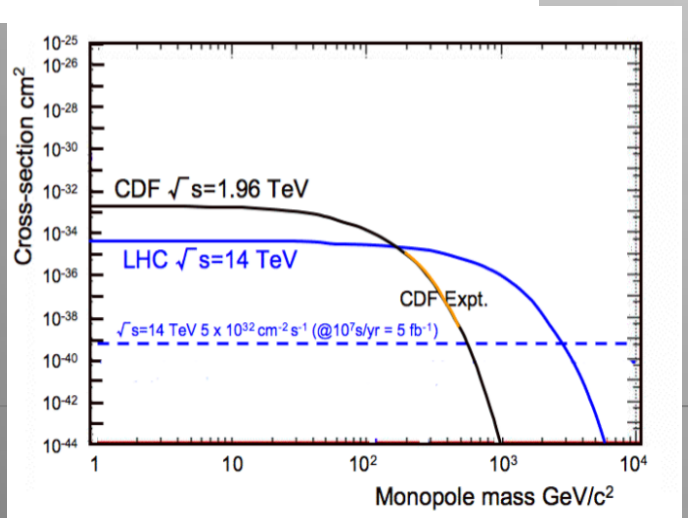




Direct Monopole production



Remove the sheets after some running time and inspect for ‘holes’



Monopoles also a topic in CMS/ATLAS

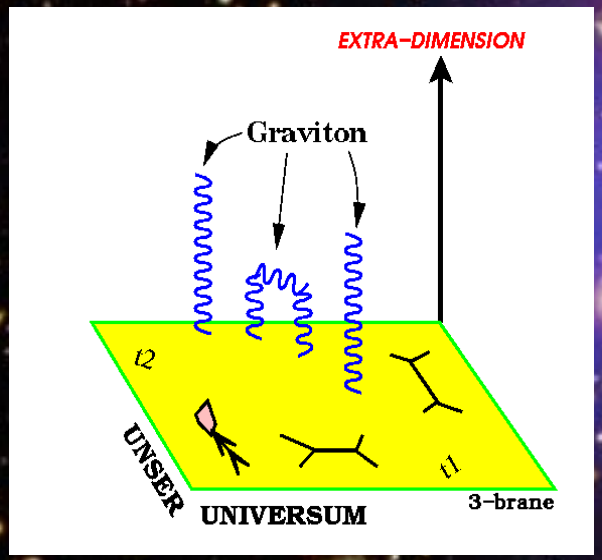
The Search for Extra Space Dimensions

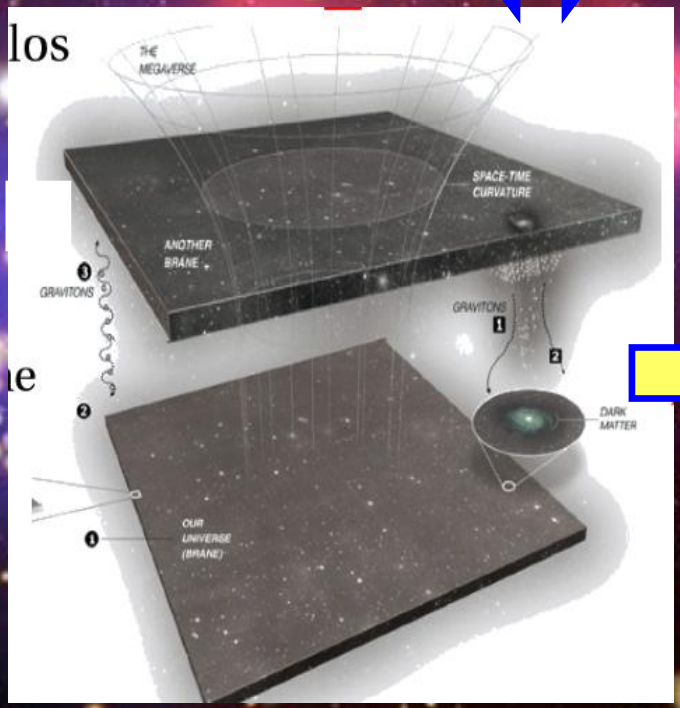
Extra Space Dimensions

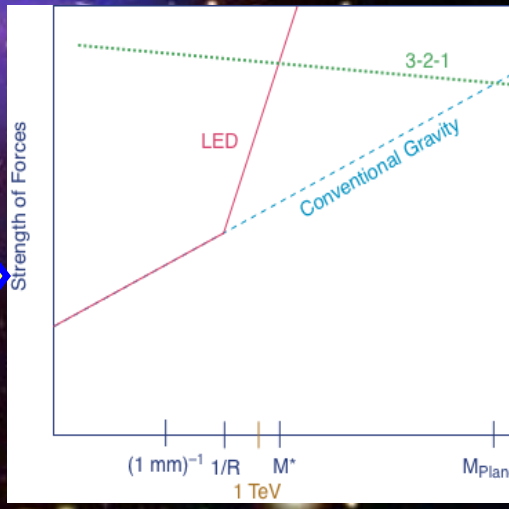
Problem:

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

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







The Gravity force becomes strong!

Search for Large Extra Dimensions

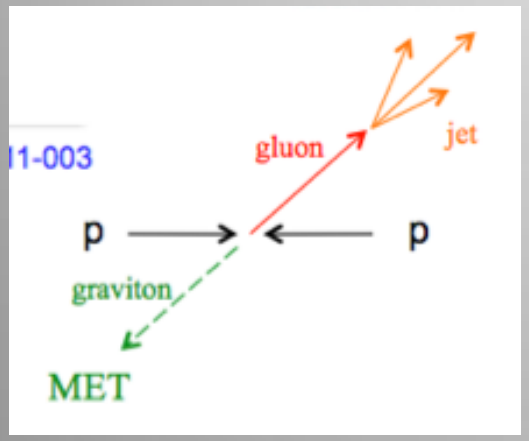
Mono-jet final state +Missing E_T (ADD)

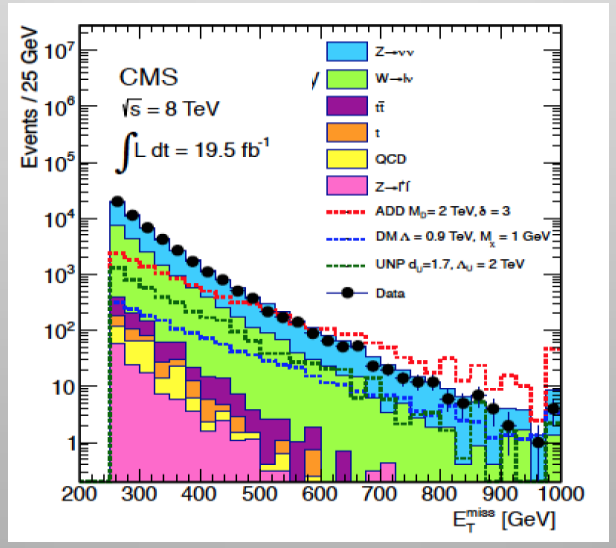
p_T jet > 110 GeV
MET > 200 GeV

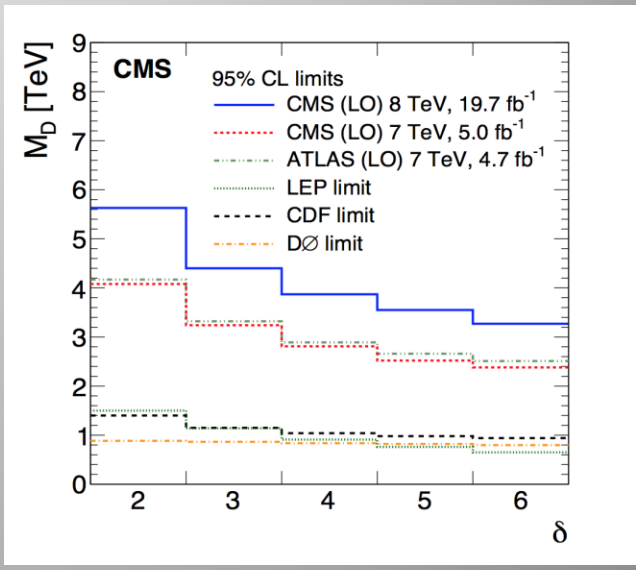
Limits on M_D between 3 and 4 TeV

arXiv:1408.3583

Lower limit on the Planck Scale versus number of extra dimensions

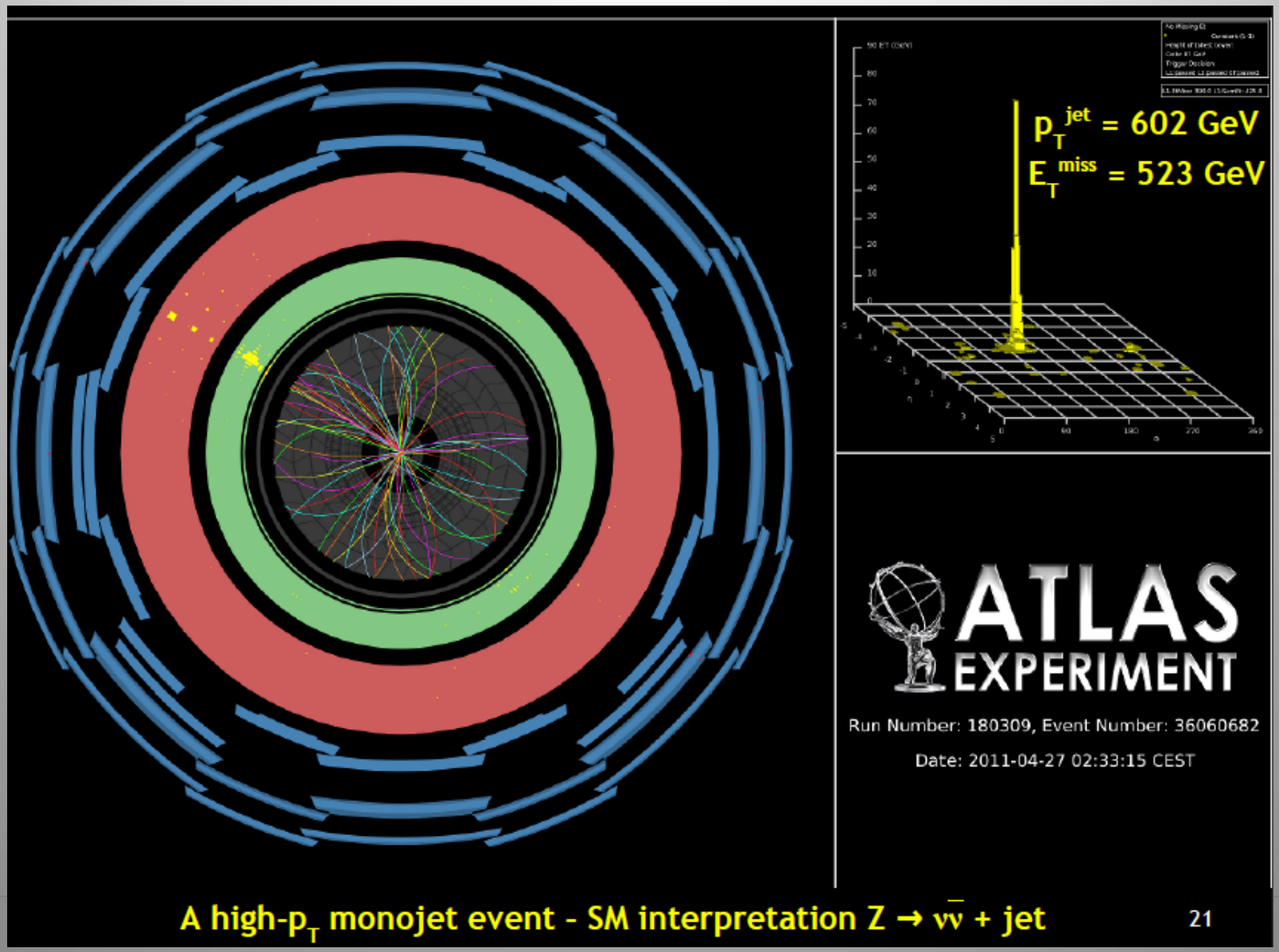






M_D (ADD) at LO 95% CL limits	√s [TeV]	Lumi [fb^{-1}]	δ=3 Exp.	δ=3 Obs.	δ=6 Exp.	δ=6 Obs.
CMS Monojet	8	19.5	3.94	3.96	2.95	2.94

A High p_T Mono-jet event

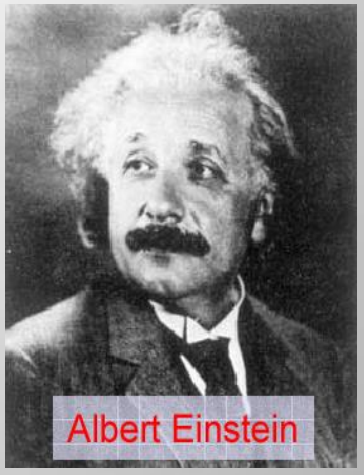


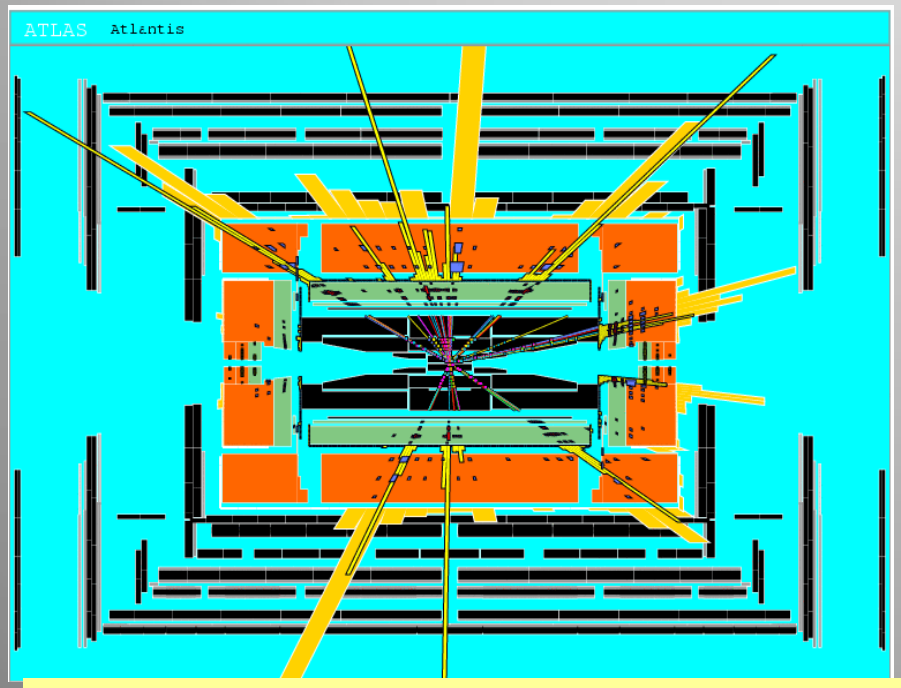
A high-p_T monojet event - SM interpretation $Z \rightarrow \nu\bar{\nu}$ + jet

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

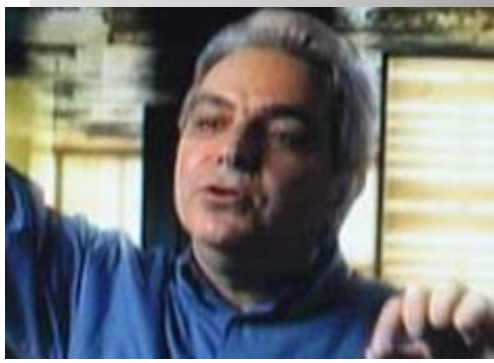
Savas Dimopoulos[a†] and Greg Landsberg[b*]

[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



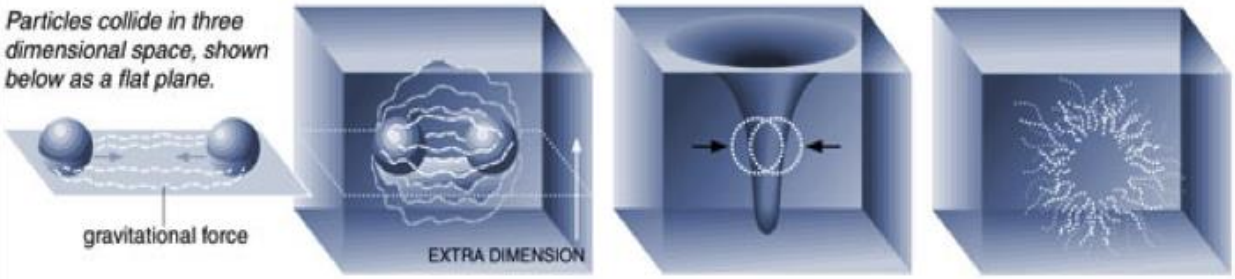
Savas Dimopoulos, theorist

Snowmass 2001

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.

Greg Landsberg
Previous CMS physics coordinator

Quantum Black Holes

- Schwarzschild radius

Landsberg, Dimopoulos, Giddings, Thomas, Rizzo

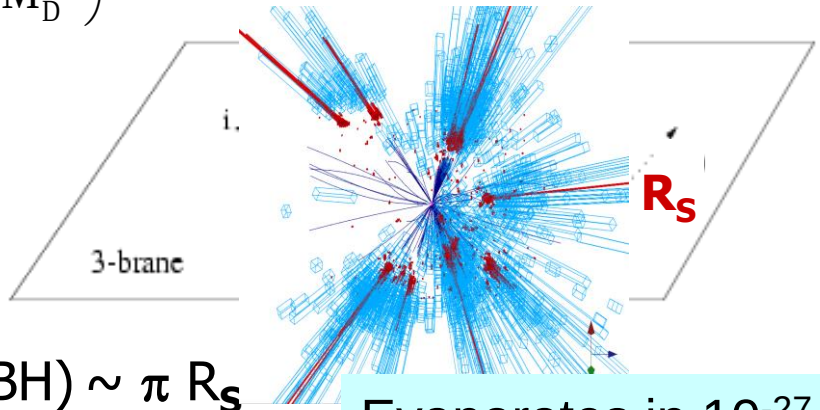
4-dim., $M_{gravity} = M_{Planck}$: $R_S \sim \frac{2}{M_{Pl}^2}\frac{M_{BH}}{c^2}$

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

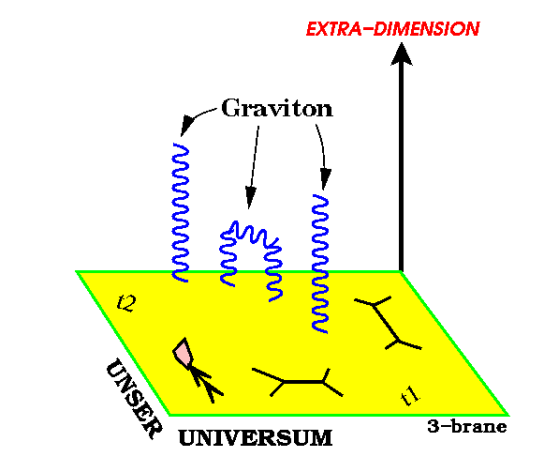
e.g. For $M_D \sim$1 TeV and n=3, produce 1 event/second at the LHC

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 …)

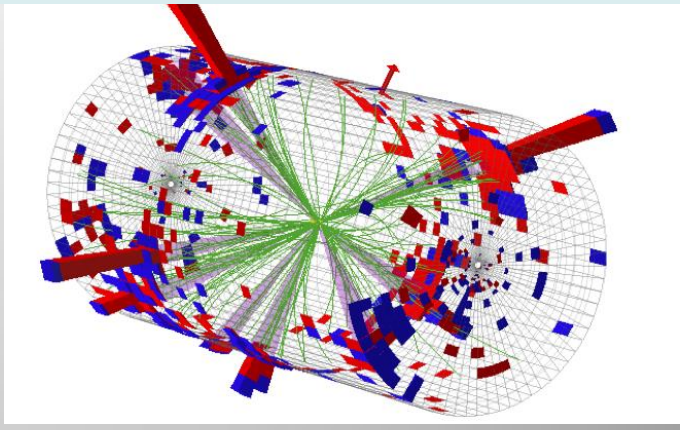
Search for Micro Black Holes



Extra Dimensions!

Planck scale
a few TeV?

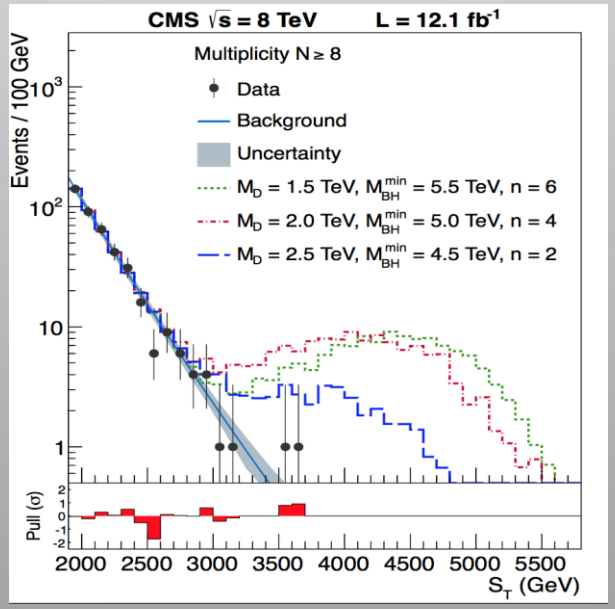
Nice events, eg a 10 jet event

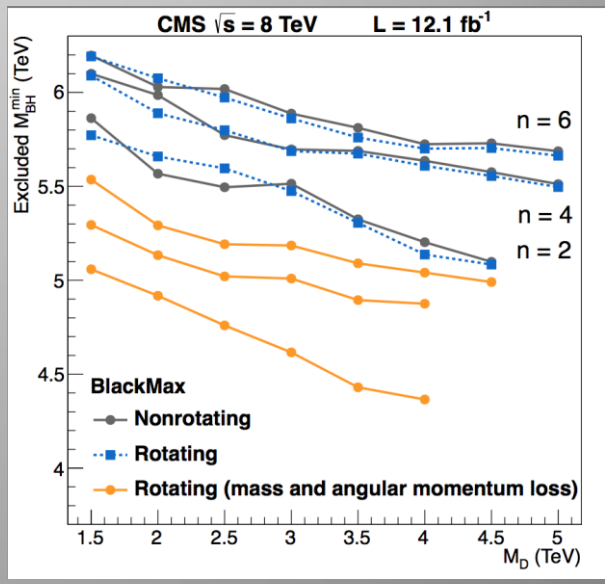


arXiv:1202.6396

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

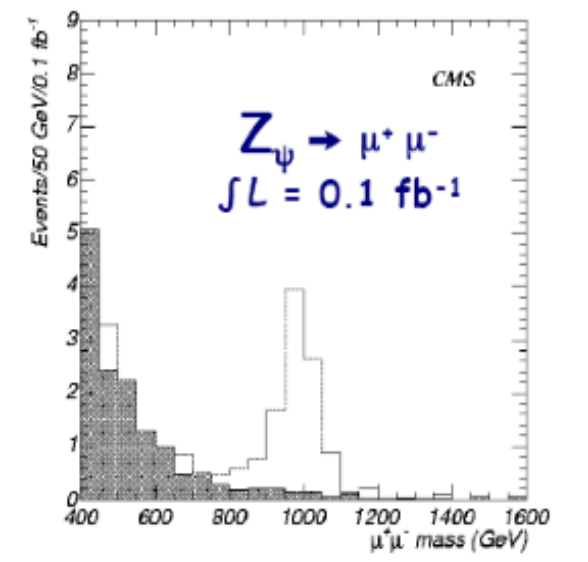
E.g. Di-lepton Resonance

Plot the di-lepton invariant mass

A peak!!

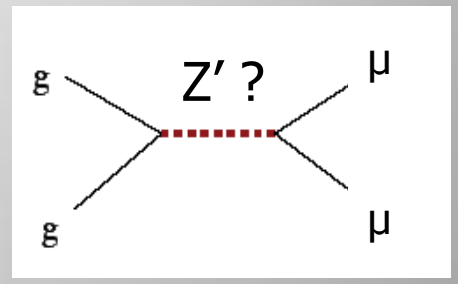
A new particle!!

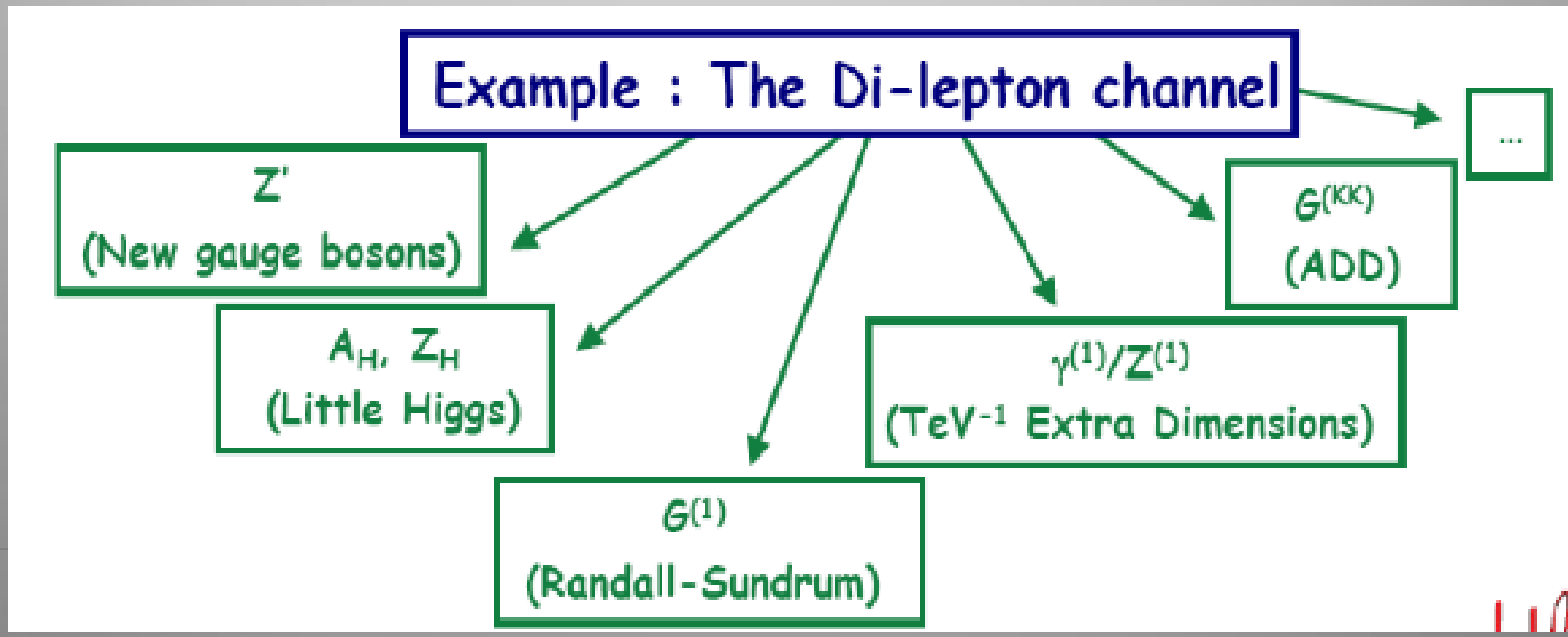
A discovery!!



Example

$pp \rightarrow \mu\mu + X$

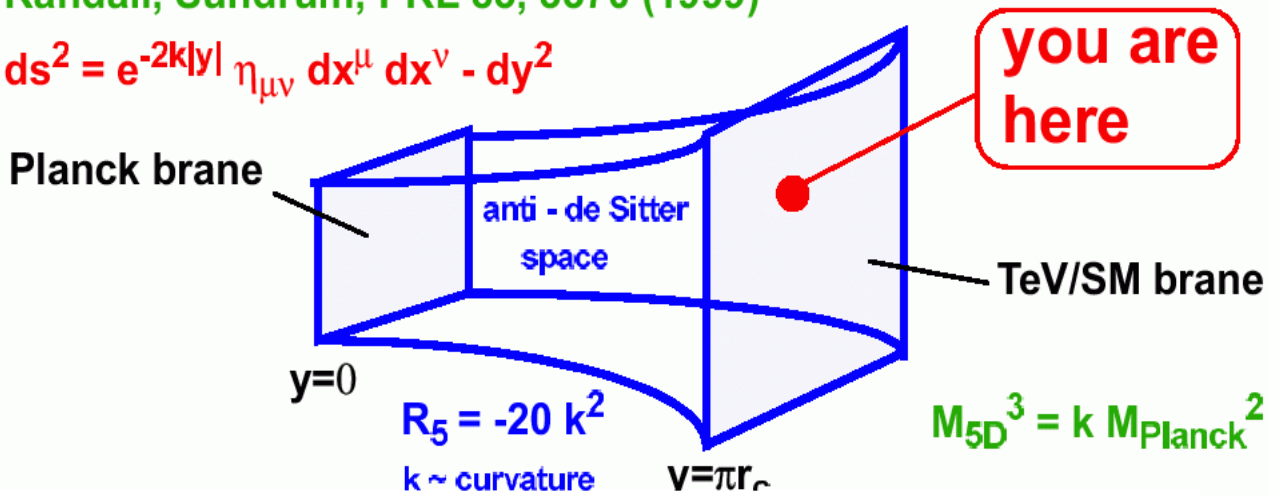




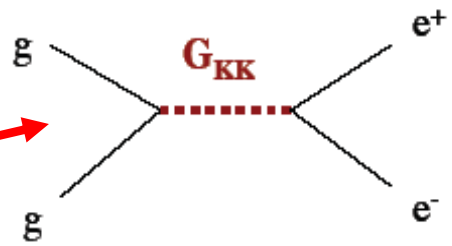
Curved Space: RS Extra Dimensions

Randall, Sundrum, PRL 83, 3370 (1999)

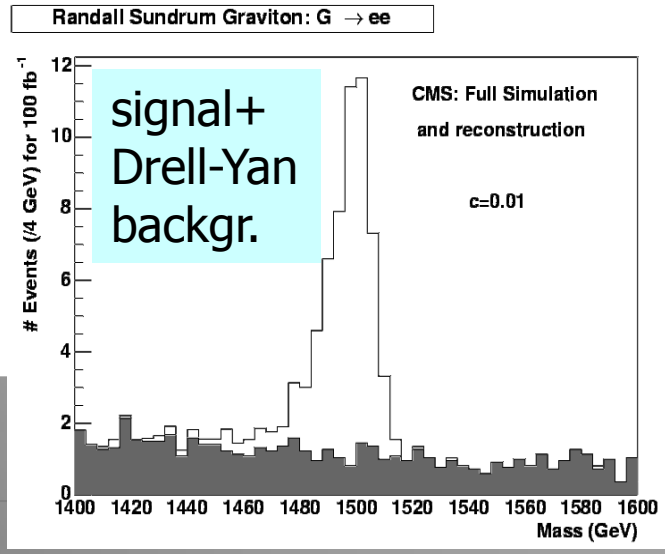
$ds^2 = e^{-2k|y|} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2$



phenomenology



Study the channel pp→Graviton→ e+e-



Signature: a resonance in the di-electron or di-muon final state a priori easy for the experiments

Caveat: new developments suggest that G_{KK} would couple dominantly to top anti-top…

2011: Z' Boson to ee or μμ?

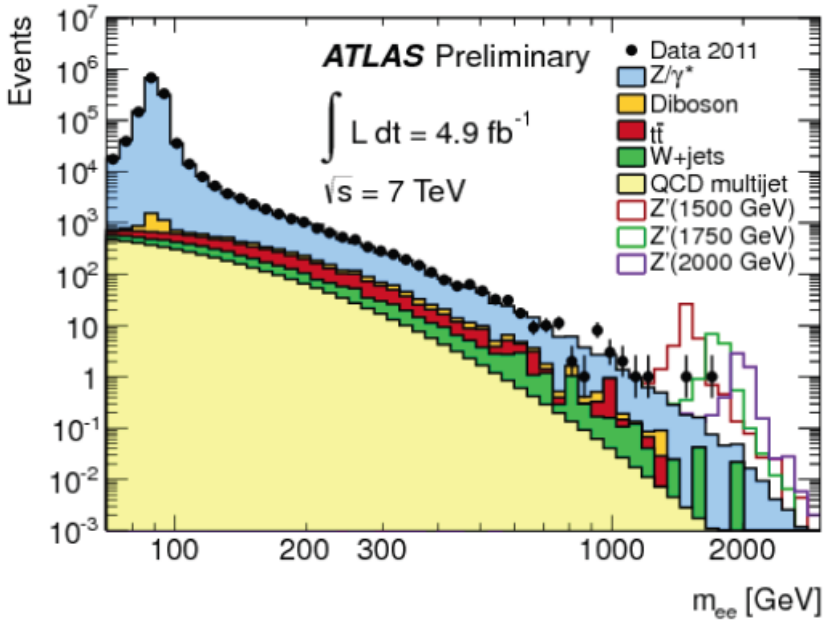
$SU(3)_C \times SU(2)_L \times U(1)_Y$

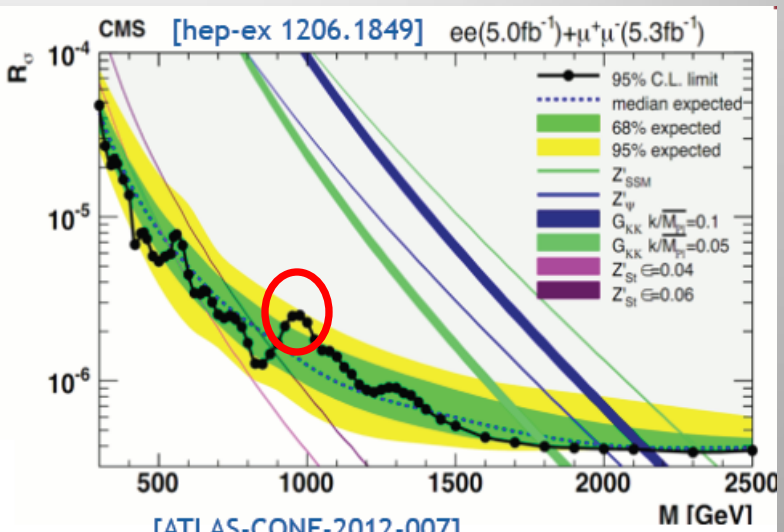
Extension of the symmetry?
New Gauge bosons?

Mid 2012

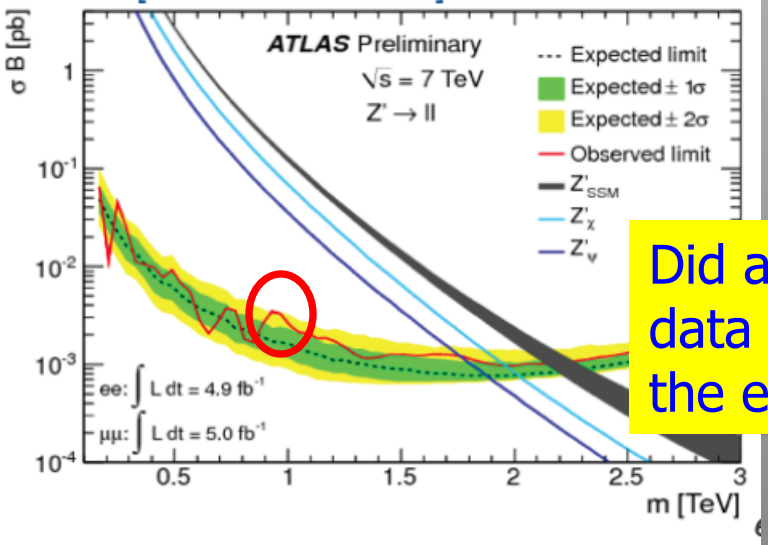
- Many new models have Z-like narrow resonances decaying to dileptons
- Interesting features in dilepton spectra
  - around 2σ each for CMS & ATLAS in e+μ
  - similar in scale to 2011 Higgs excess

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





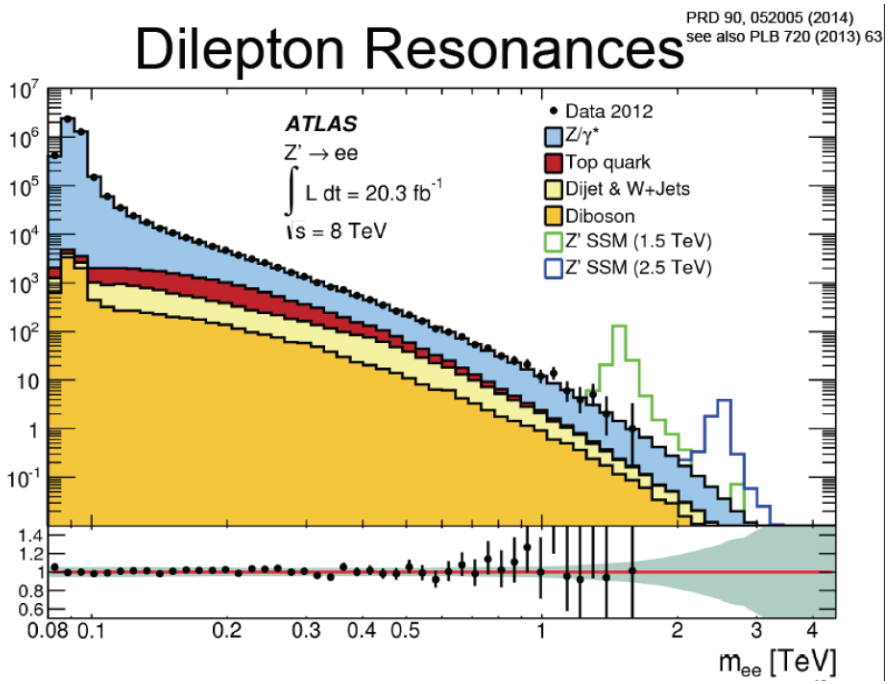
[ATLAS-CONF-2012-007]



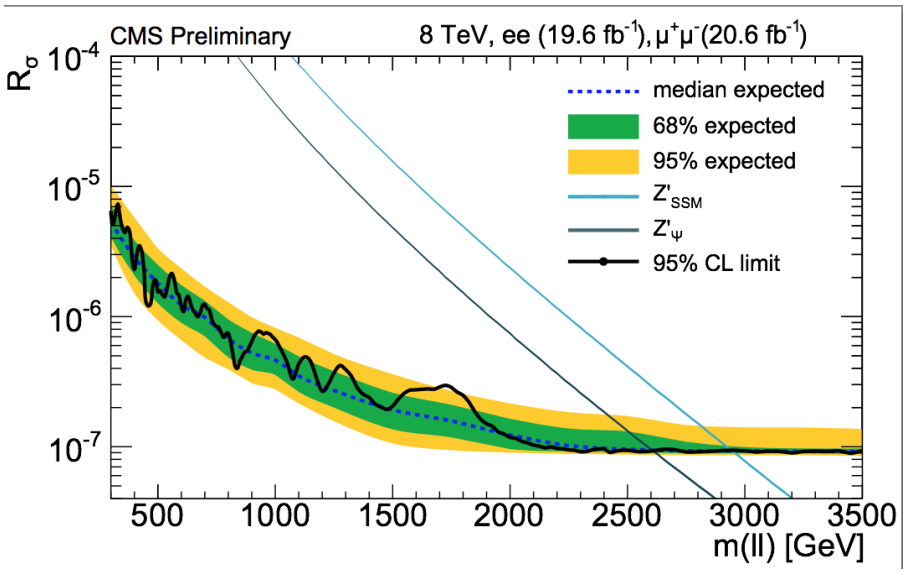
Did additional data confirm the excess??

Z' Combination of 7 & 8 TeV Data

[CMS EXO-12-015]



No... ☹



- Short time between data-taking and result

$$R_\sigma = \frac{\sigma(pp \to Z' + X \to \ell\ell + X)}{\sigma(pp \to Z + X \to \ell\ell + X)}$$

- Limits on the combined 7 TeV and 8 TeV data from 2011+2012
  - $M(Z'_{SSM}) >$ 2950 GeV at 95% C.L.
  - $M(Z'_{\psi}) >$ 2600 GeV at 95% C.L.

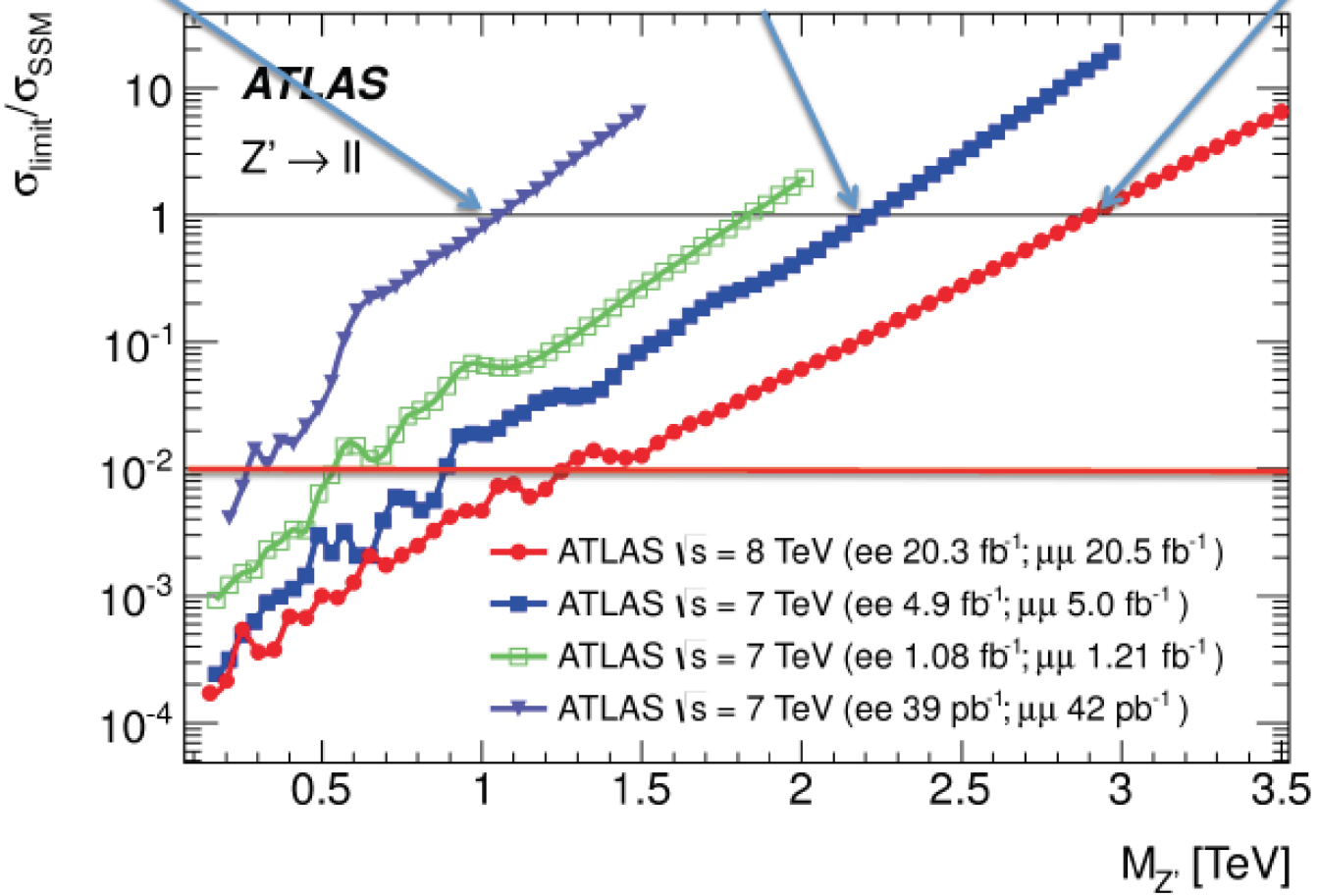
Excess just below 1 TeV all but gone in CMS data

Development over the Years

Tevatron limits (approx. 1 TeV) reached with 2010 data

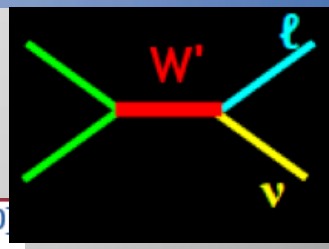
2011 data → 2.2 TeV limit

2012 data → 2.9 TeV limit



Fast increase in limits (1 TeV → 3 TeV) in short period of time

W' → eν and μν Production



Search for the charged partner of the gauge bosons

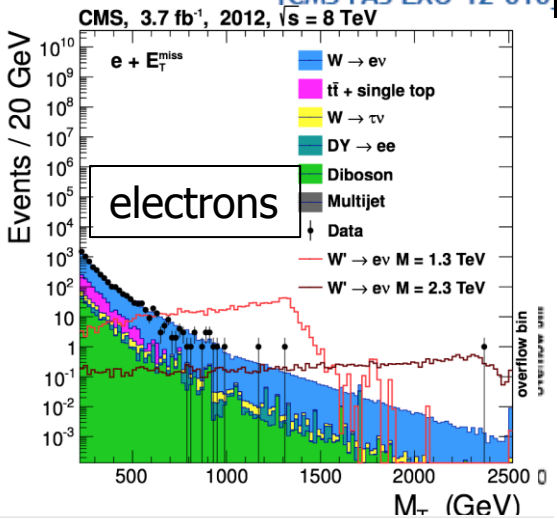
- Search for a new heavy gauge boson W' decaying to a charged lepton (μ or e) and ν

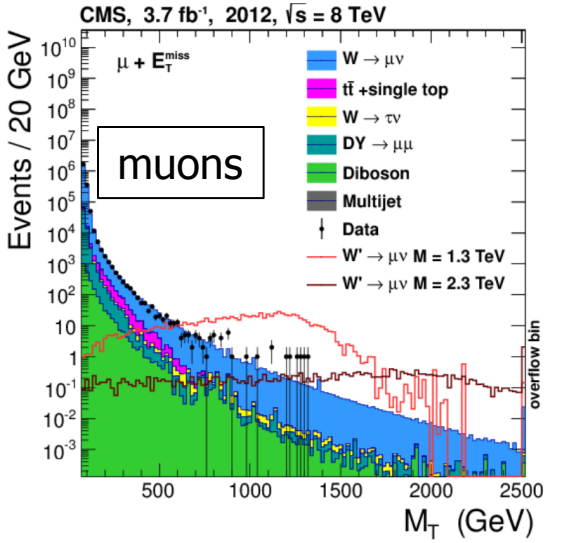
$$M_{\mathrm{T}} = \sqrt{2 \cdot p_{\mathrm{T}}^{\ell} \cdot E_{\mathrm{T}}^{\mathrm{miss}} \cdot (1 - \cos \Delta\phi_{\ell,\nu})}$$

- Many models possible
  - right-handed W' bosons with standard-model couplings
  - left-handed W' bosons including interference
  - Kaluza-Klein W'_{KK}-states in split-UED
  - Excited chiral boson (W*)
- Event Selection and Backgrounds
  - back-to-back isolated lepton and E_T^{miss}
  - Plot transverse mass of lν system
  - backgrounds from W, QCD, tt+single t, DY, VV from data

No significant excess observed

[CMS PAS EXO-12-010]

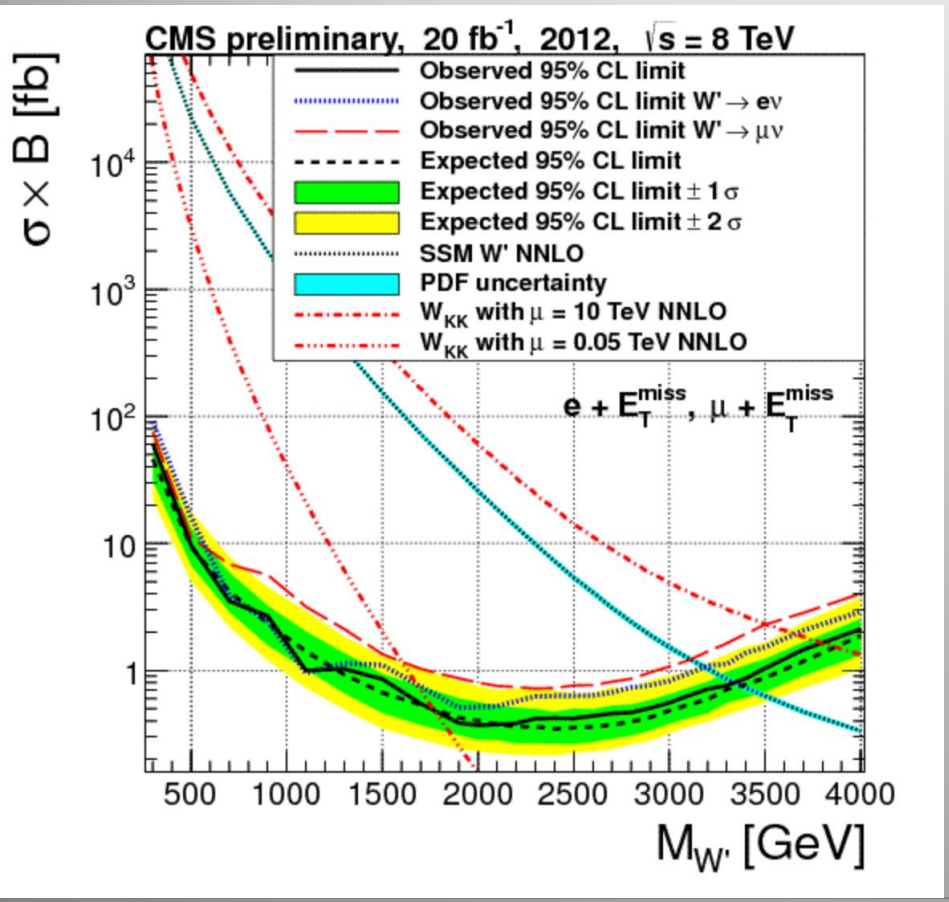




W' → eν and μν Production

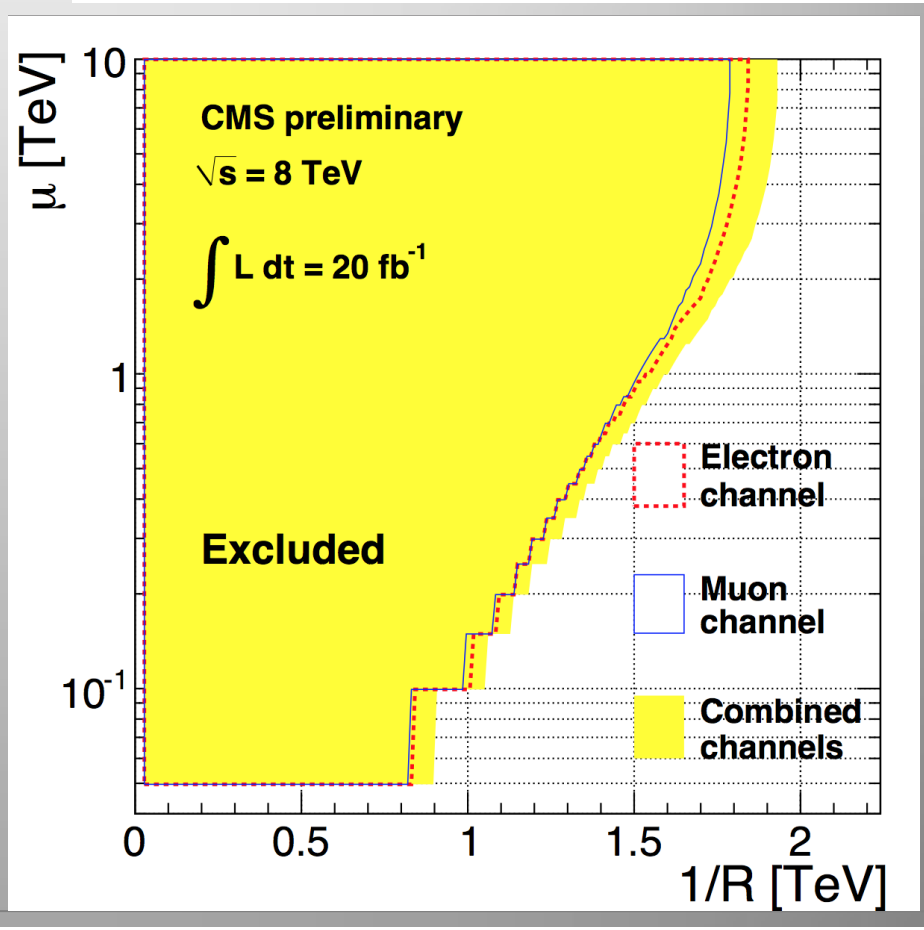
Update with the full statistics at 8 TeV

W' searches



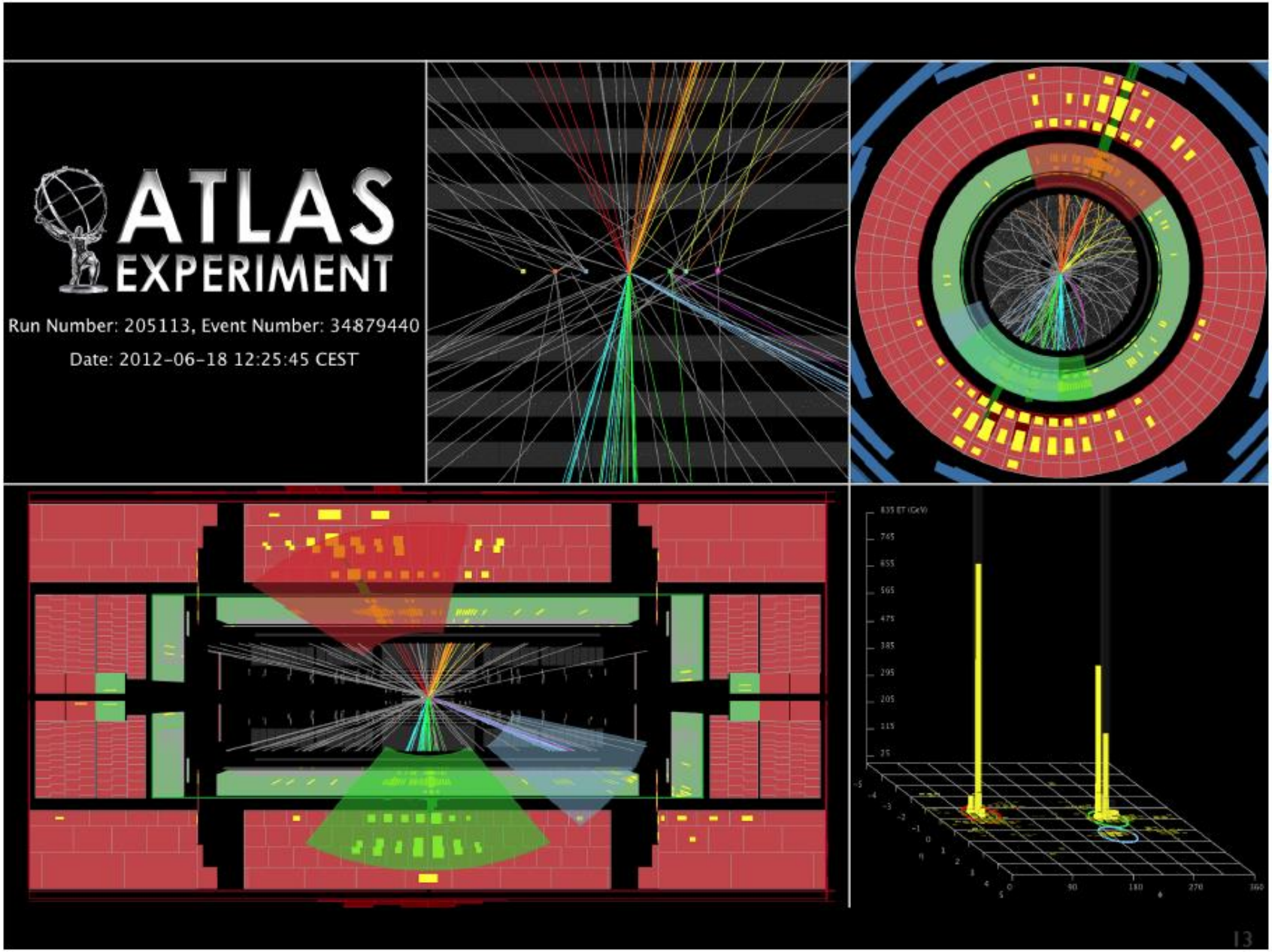
$M_{W'}$> 3 TeV (95% CL)

Universal Extra Dimension searches

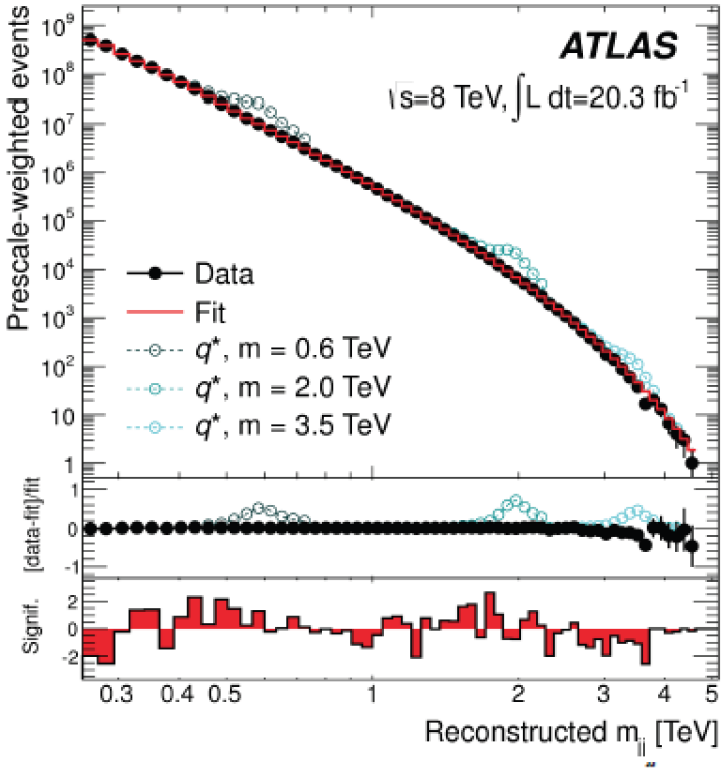


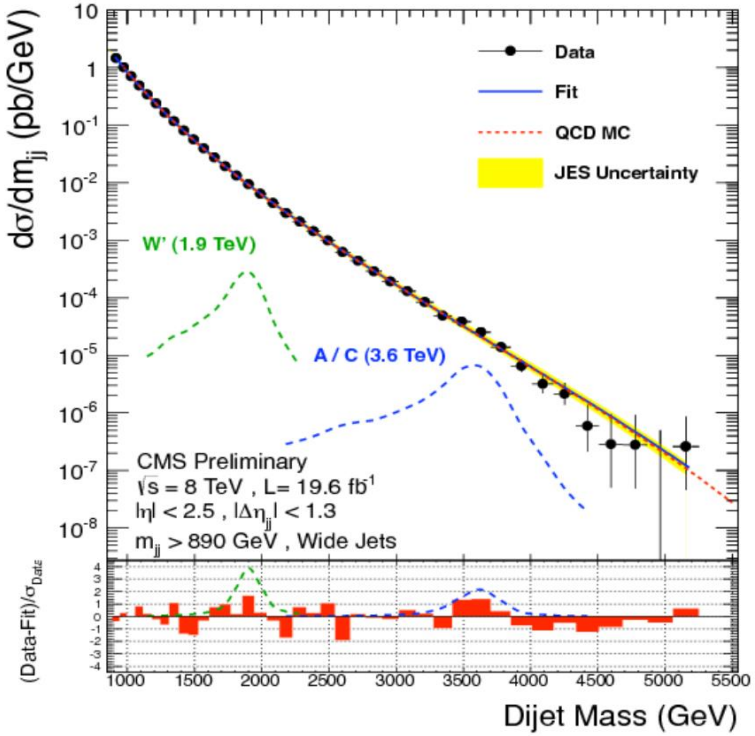
Bulk mass parameter and size of the UEDs

Di-jet Resonances



Di-jet Searches





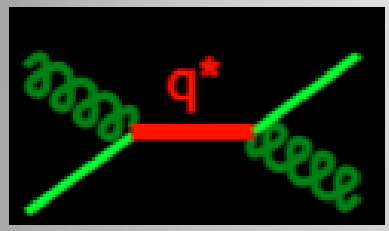
- Search for dijet resonance in smoothly falling mass spectrum
  - leading jet mass m_{jj} > 0.9-1 TeV from trigger and other constraints
  - Background estimated from smooth functional fit

CMS-EXO-12-059
arXiv:1407.1376

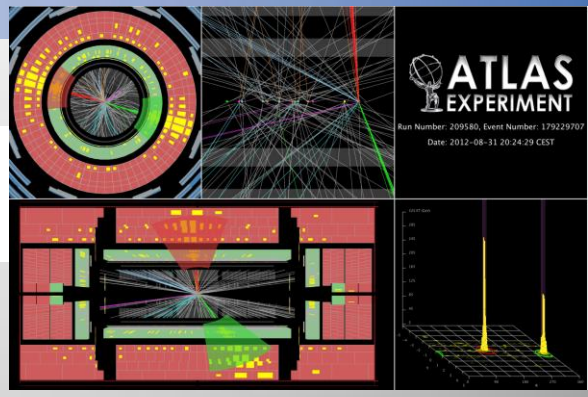
$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}}$$

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

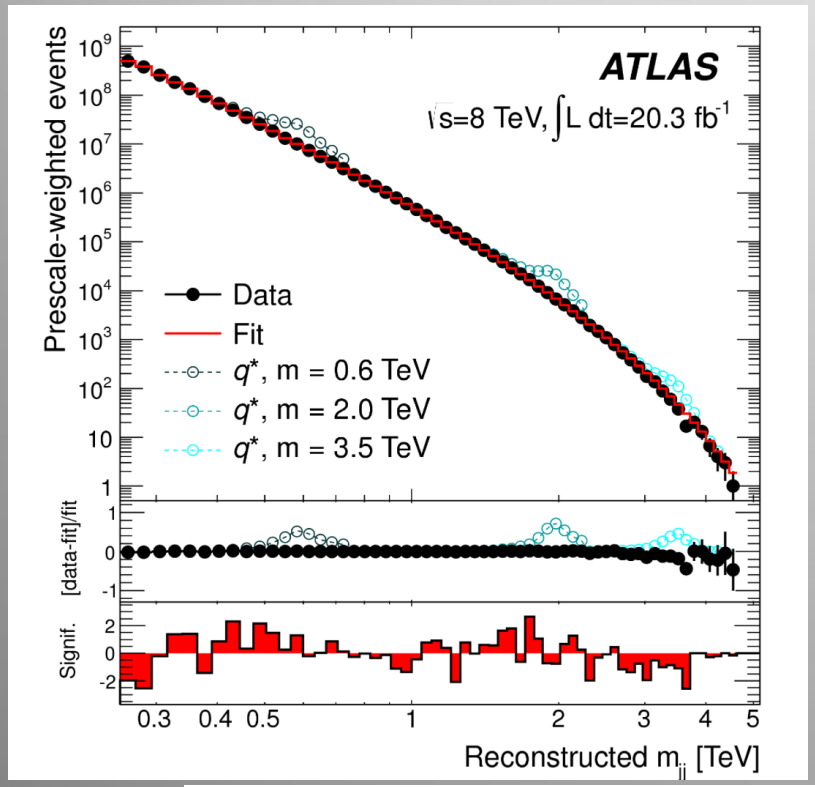
Excited Quark in Dijet Search

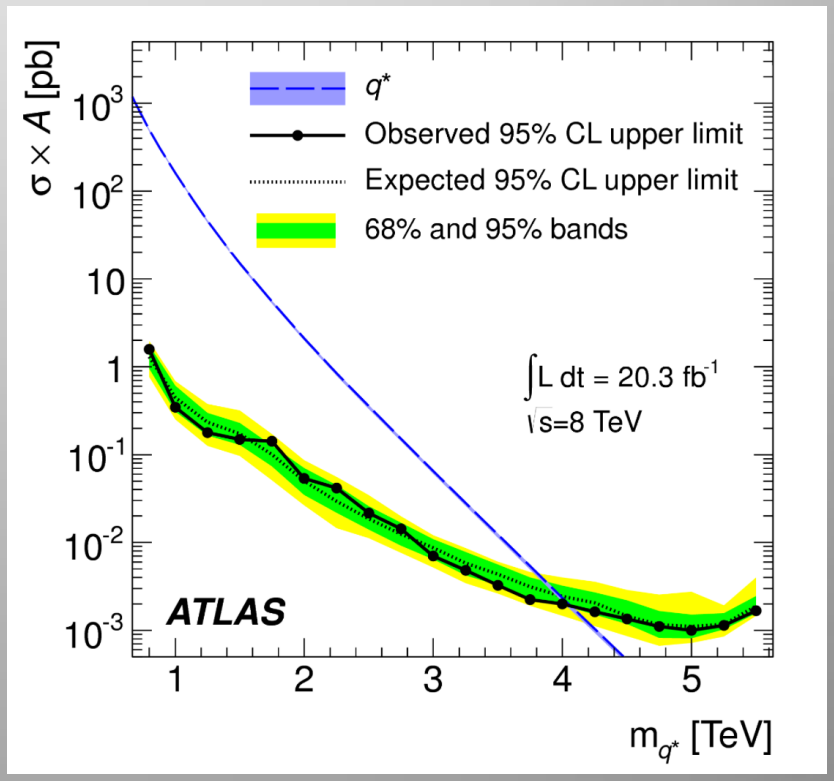


invariant mass of 4.69 TeV, and jets with a jet-p_T of 2.29 TeV and 2.19 TeV



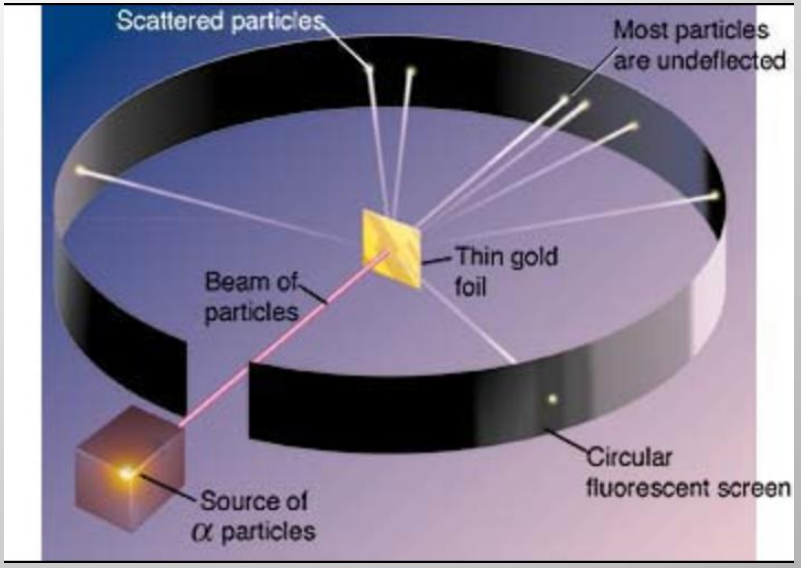
arXiv:1407.1376



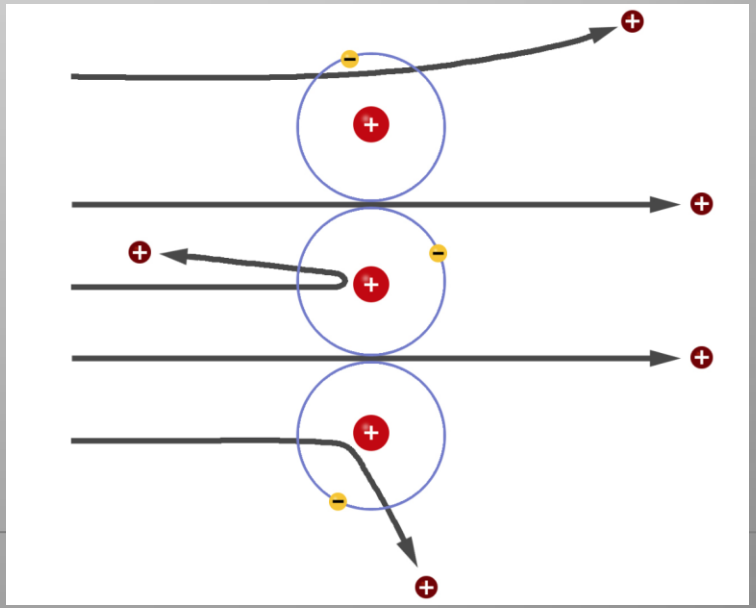


Limit on the mass of excited quarks > 4.09 TeV at 95% CL

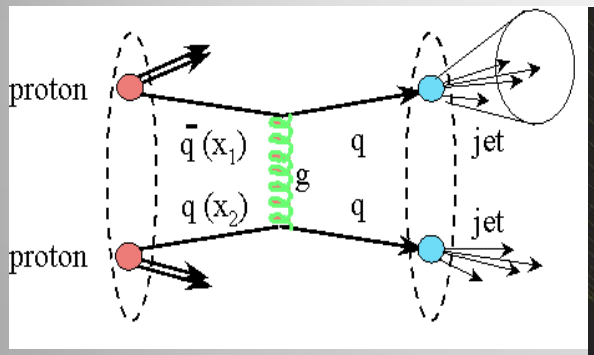
Are Quarks Elementary Particles?

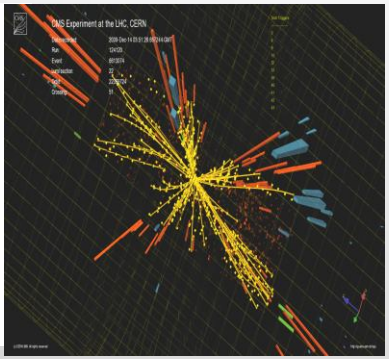


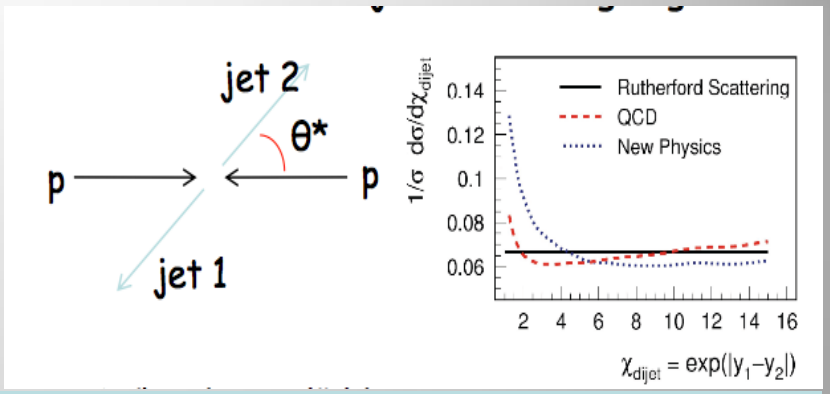
Rutherford experiment:
Unexpected backscattering of α-particles:
Evidence for the structure of atoms !! (1911)



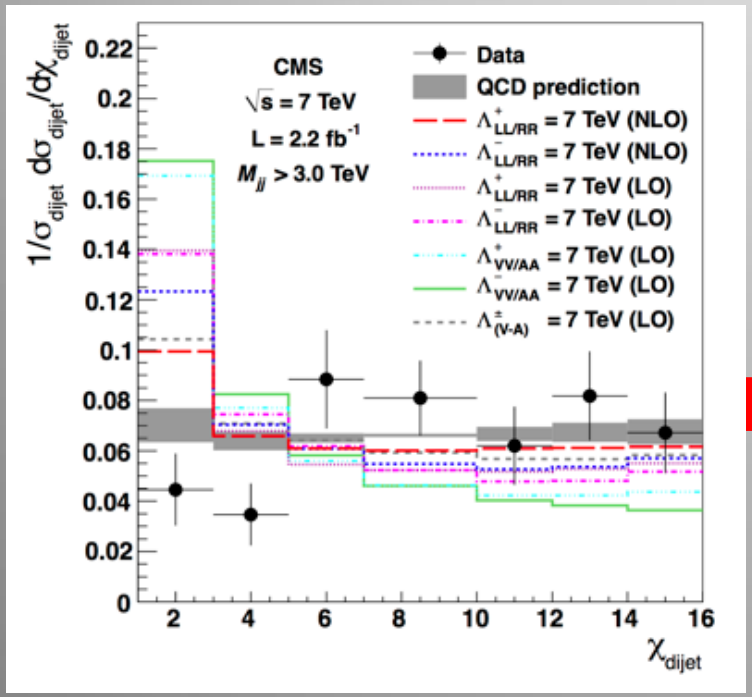
Are Quarks Elementary Particles?

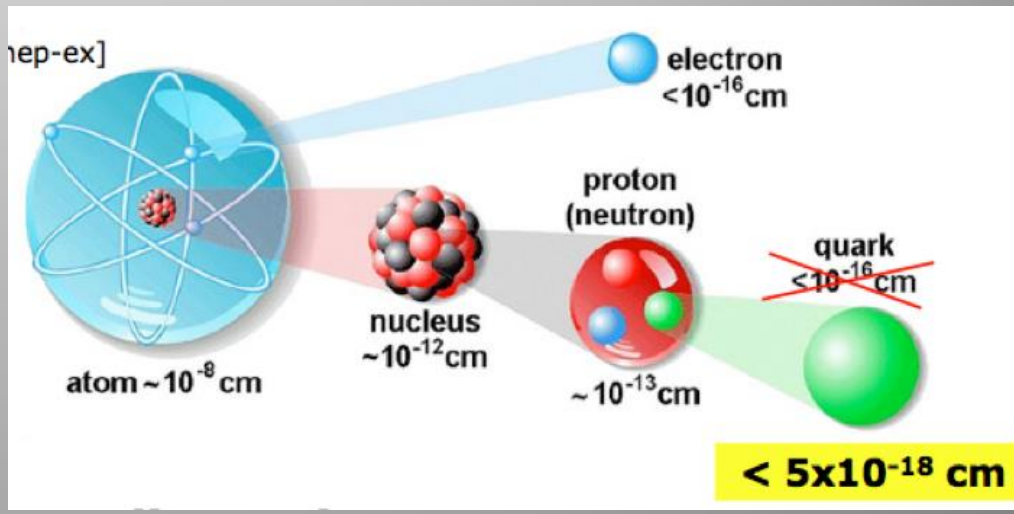






Measurement of the production angle of the jet with respect to the beam
-> High Energy Rutherford Experiment



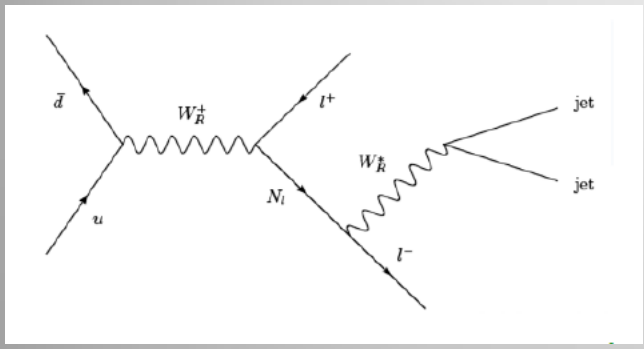


Quarks remain elementary particles after these first results

Search for Heavy Neutrinos

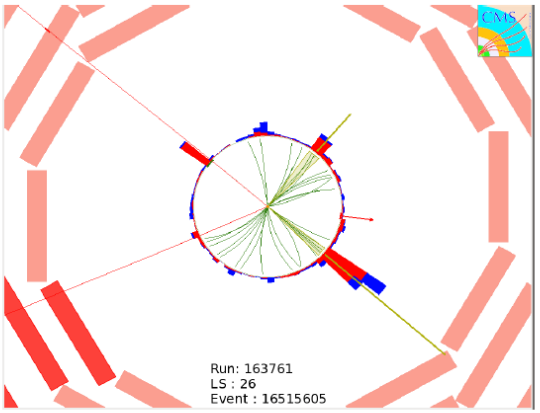
Search for Heavy Neutrinos and W_R

Left-right symmetric extension of the Standard Model

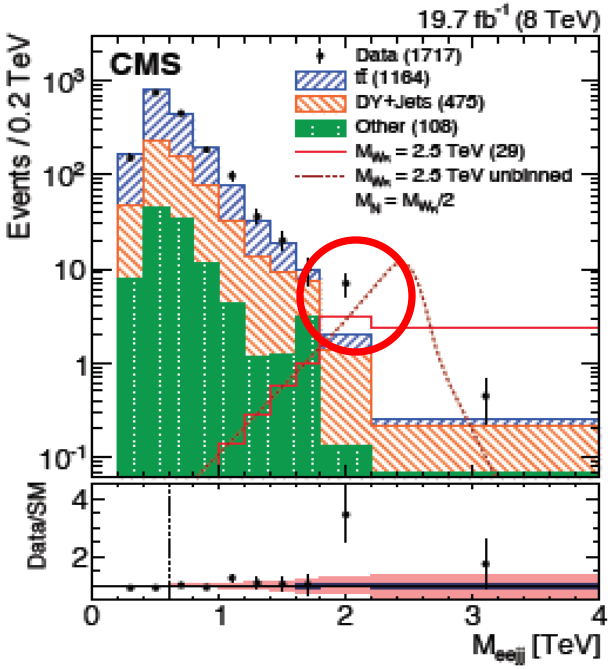


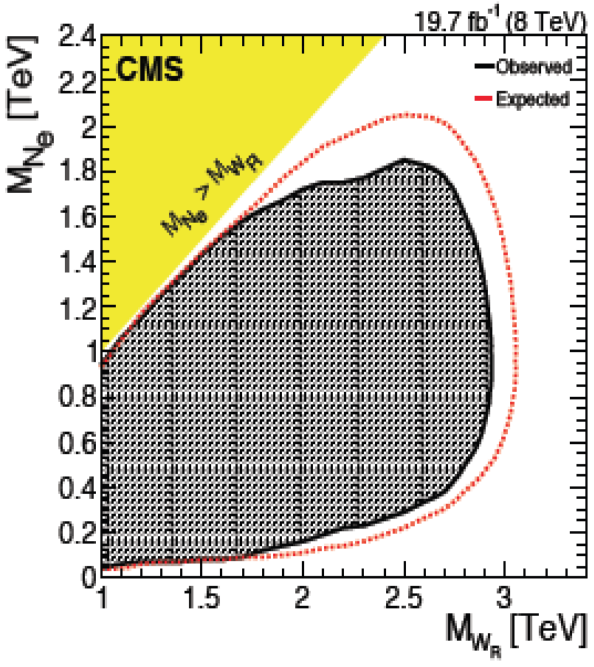
arXiv:1407.3683

Select events with
2 leptons and 2 jets



Muon channel: Event with $M_{\mu\mu}$ = 331 GeV, $M_{\mu\mu jj}$ = 881 GeV





Large exclusion range in mass of the W_R and heavy neutrino

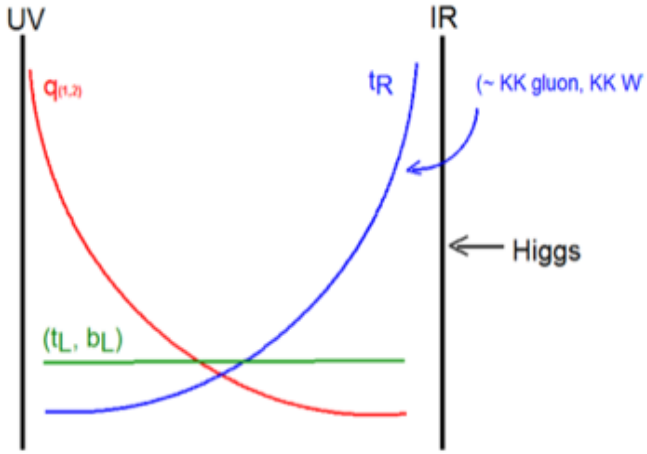
Observe a 2.8 sigma excess in the electron channel around 2 TeV W_R mass

Searches with Top Quark

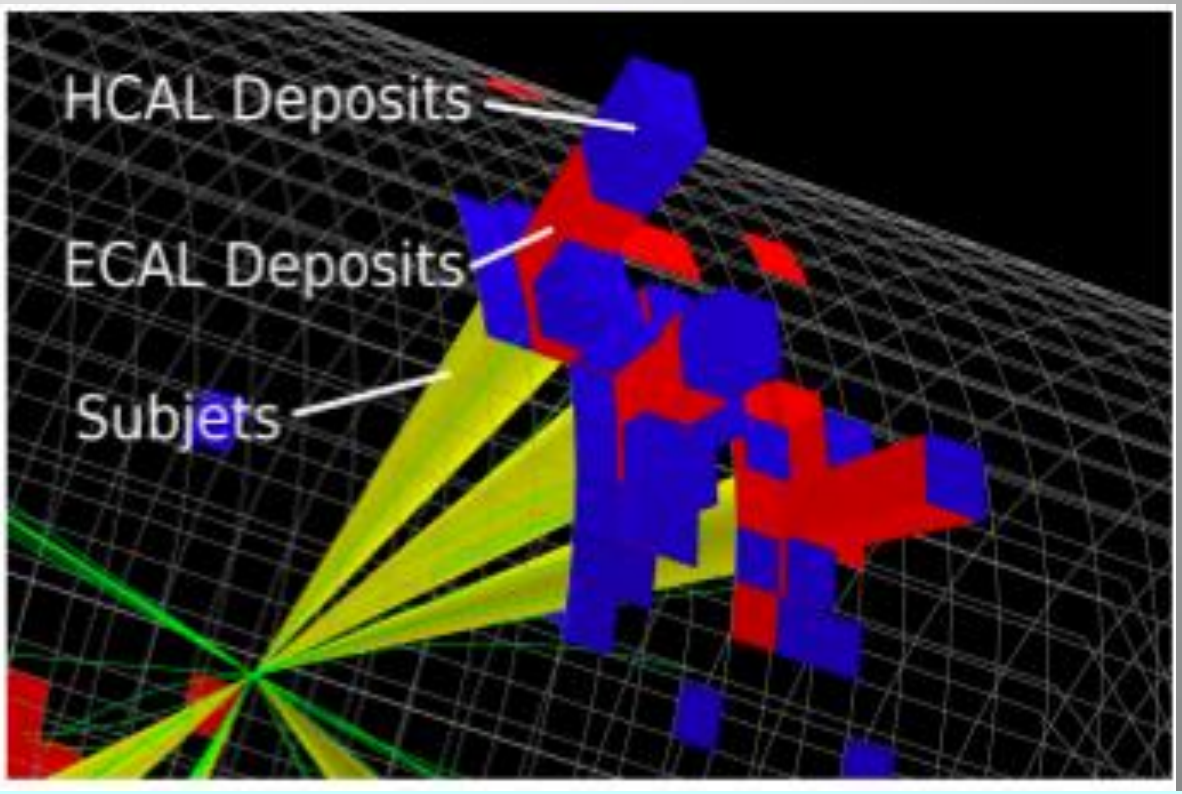
TeV Resonances into Top Quark Pairs

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

- Eg RS → t tbar

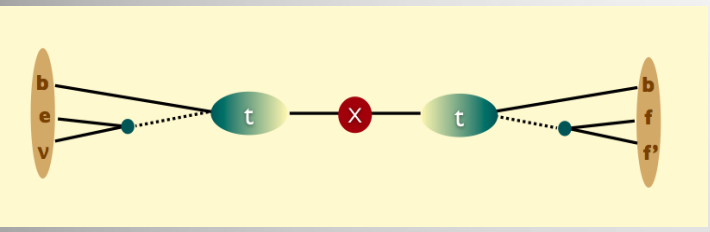


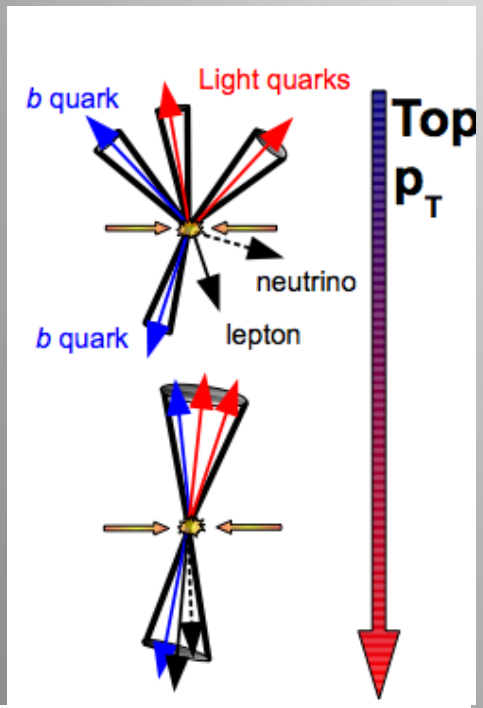
⇒High P_T tops



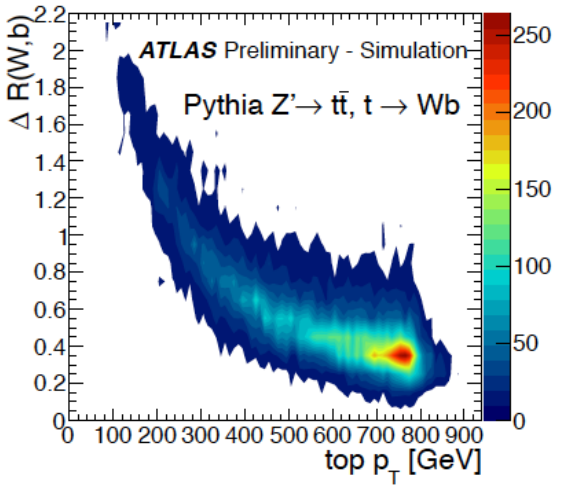
Methods are prepared to tackle the early data

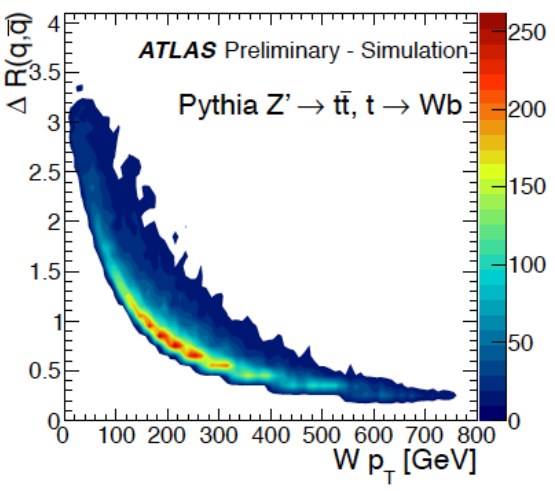
New Physics with Boosted Objects





ATLAS-CONF-2012-065



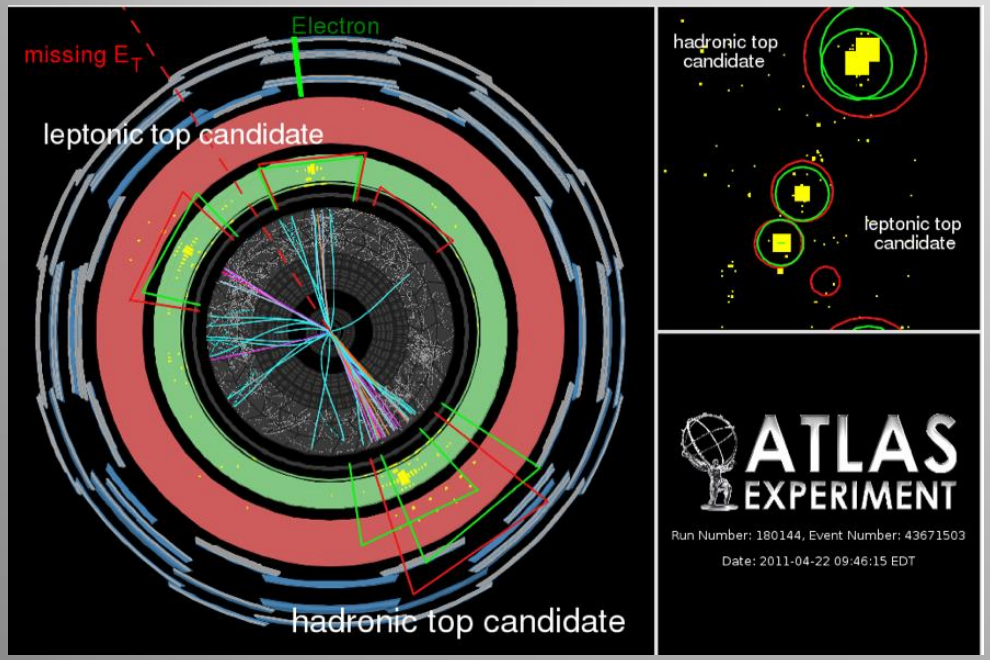


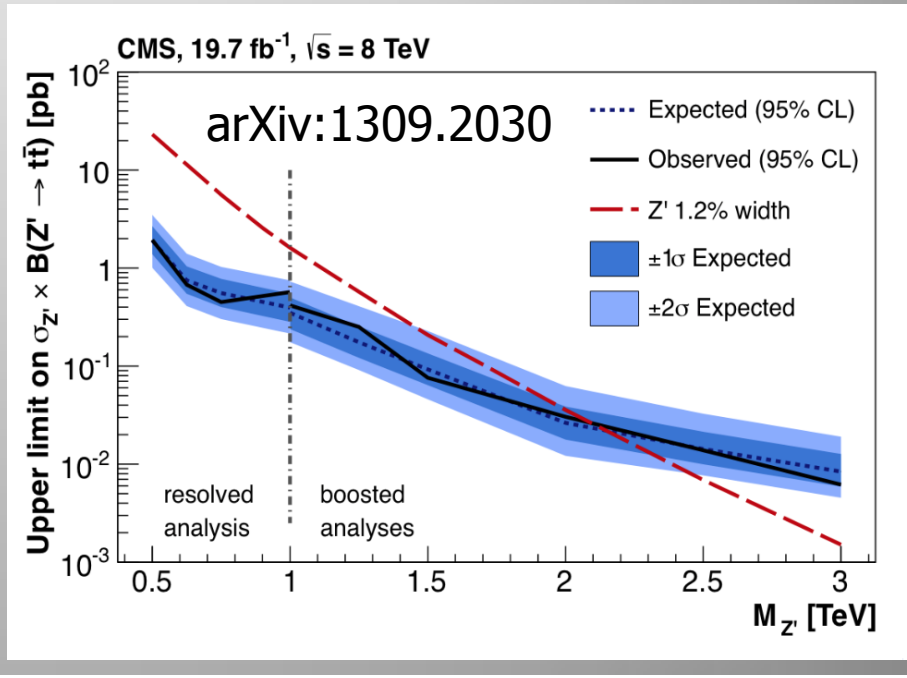
W,Z and top decays from heavy, typically multi-TeV objects are of special interest at the LHC

- $\Delta R \sim 2m/p_T$: decay product merge at large p_T
- New techniques developed – and discussed in this series of topical Workshops- for leptonic and hadronic decays of W,Z, top…
  Eg.: Jet substructure, grooming: mass drop filtering, trimming, pruning…

Top resonance study

- Both ‘all hadronic’ and ‘semi-leptonic’ channels analysed
- Boosted objects are reconstructed as one fat jet R=0.8, p_T> 400 GeV. Analyse the jet substructure
- Modified isolation for the leptonic decay side





$$pp \to t\bar{t} \to b\bar{b}q\bar{q}'\ell\nu_\ell$$

Model	Observed Limit	Expected Limit
$Z', \Gamma_{Z'}/M_{Z'} = 1.2\%$	2.1 TeV	2.1 TeV
$Z', \Gamma_{Z'}/M_{Z'} = 10\%$	2.7 TeV	2.6 TeV
RS KK gluon	2.5 TeV	2.4 TeV

Real Exotic Objects!

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

Search for Monopoles

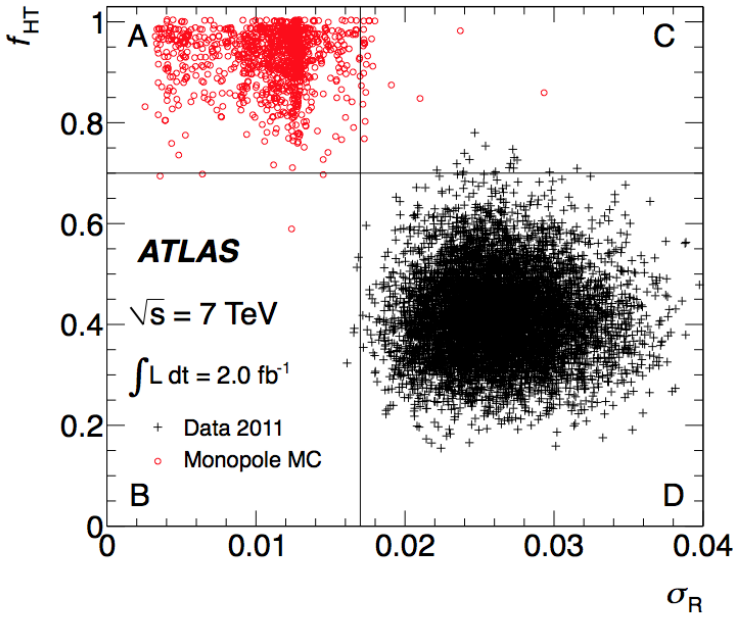
arXiv:1207.6411

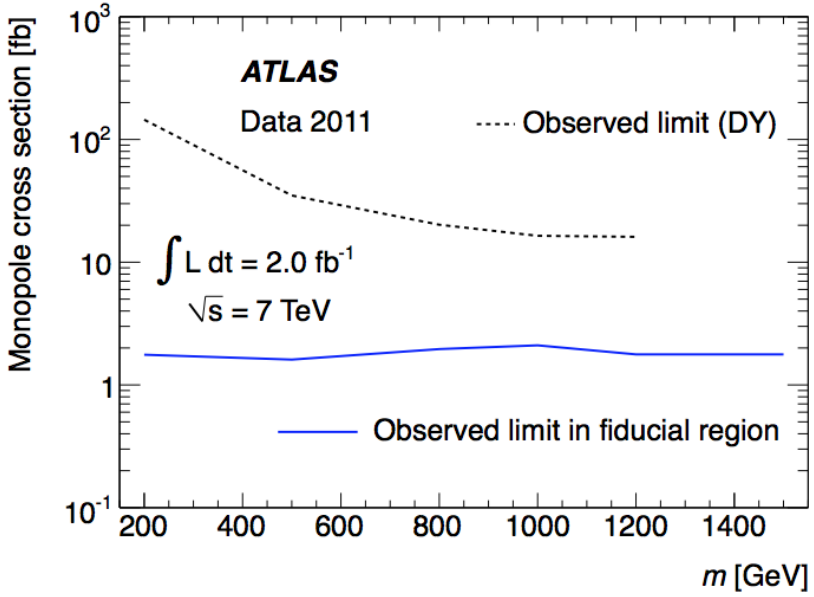
- Magnetic charge g yields strong coupling α_m and very high ionisation

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

- 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

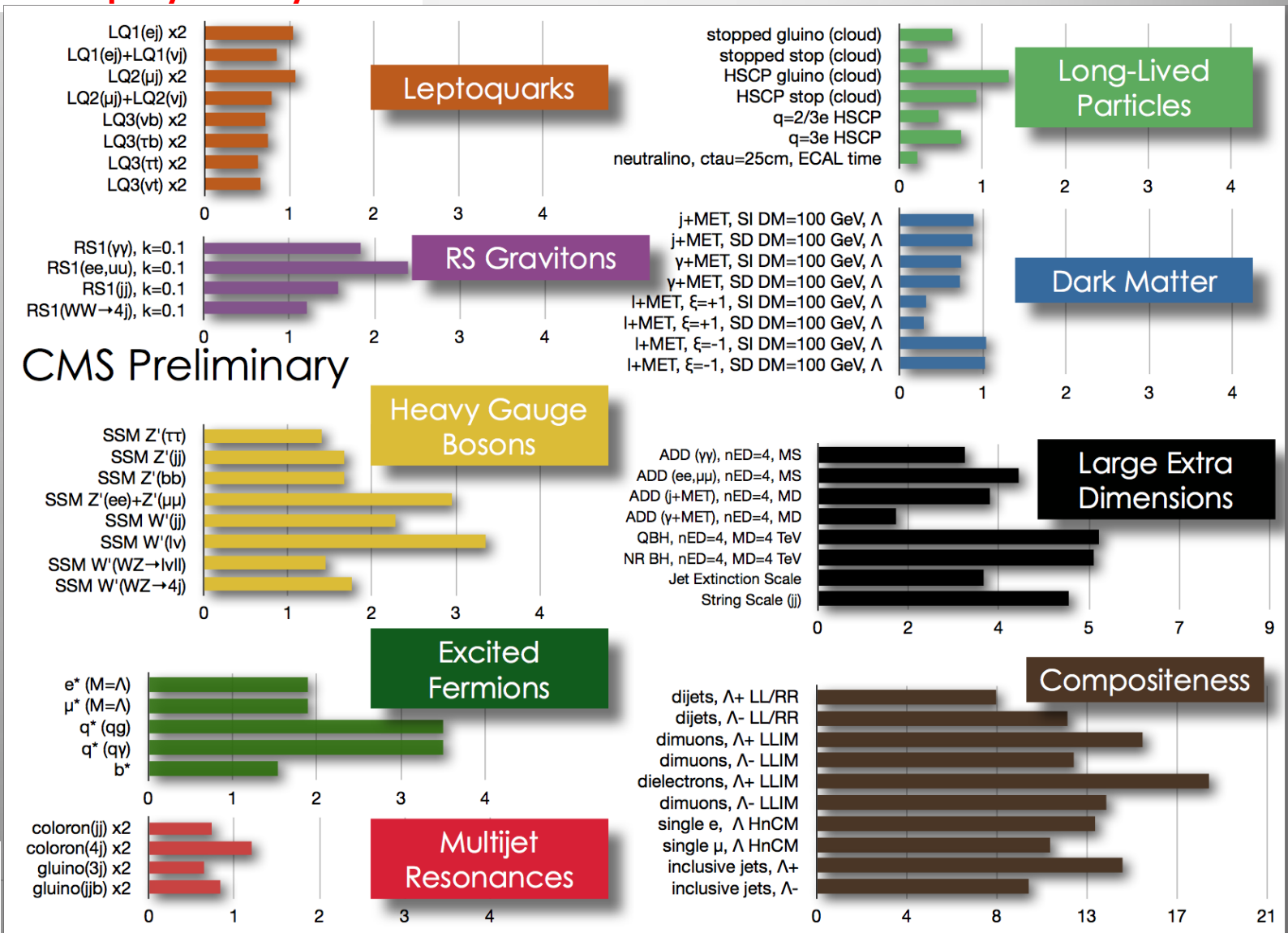
Cross Section limits set for m(M) = 0.2–1.2 TeV





Searches for New Physics: CMS

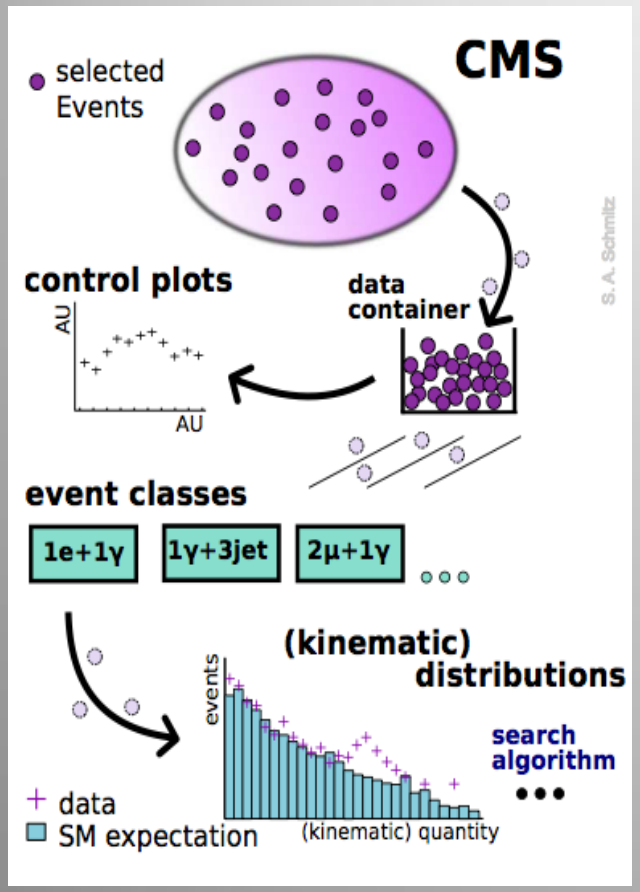
No sign of new physics yet...



Similar table for ATLAS

A Global View!

CMS-EXO-10-021



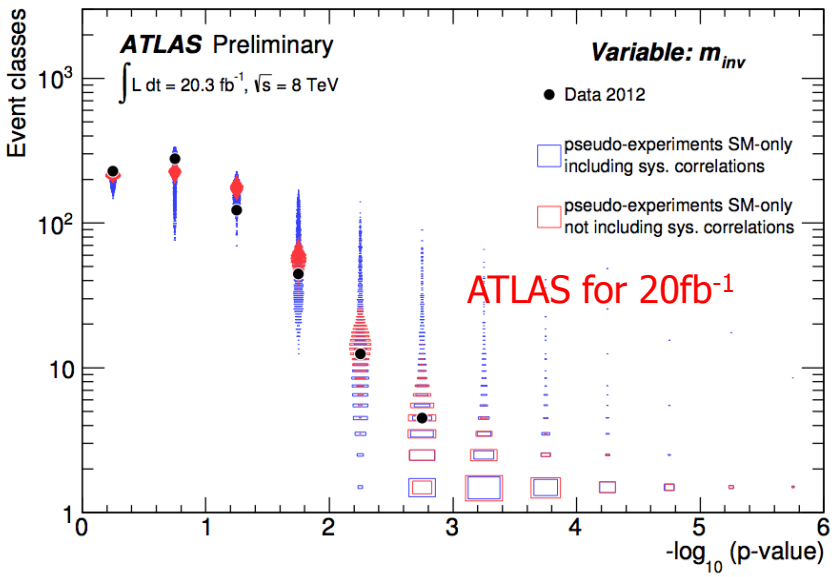
Model independent search

- Divide events into exclusive classes
- Study deviations from SM predictions in a statistical way

Distributions in each class

- $\sum p_T$ - Most general
- $M_{inv}^{(T)}$ - Good for resonances
- MET - Escaping particles

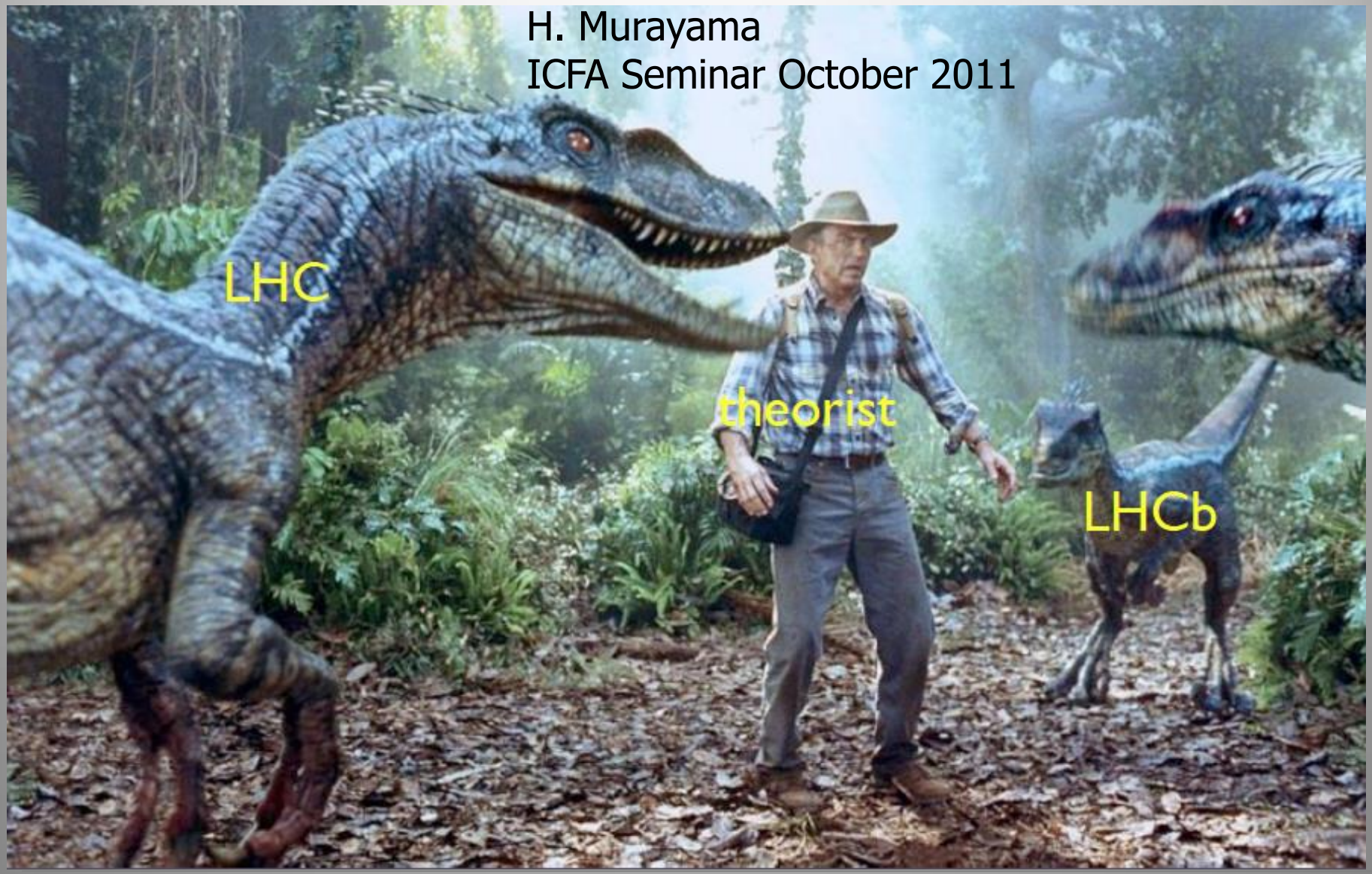
ATLAS-CONF-14-006



Probability distribution as expected for 35 pb^{-1} for CMS

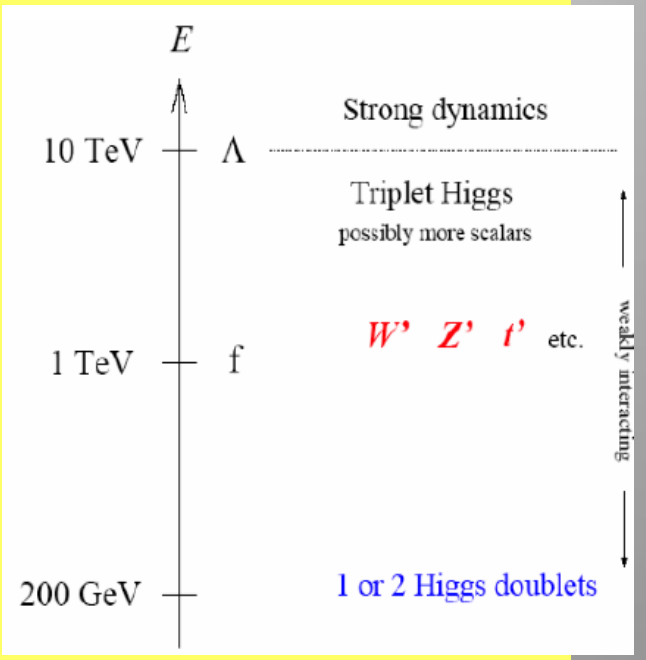
→muons, electrons, photons, (b)jets, MET

How does it feel to be a (BSM) Theorist?



Other New Physics Ideas…

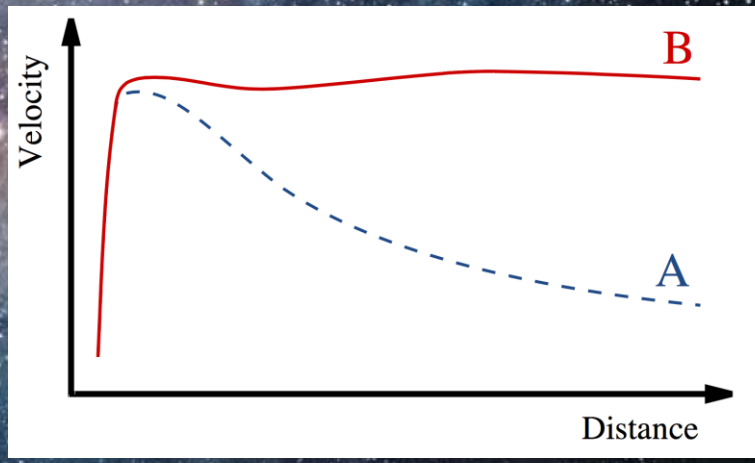
- Plenty!
  - Compositeness/excited quarks & leptons
  - Little Higgs Models
  - leptoquarks
  - String balls/T balls
  - Bi-leptons
  - RP-Violating SUSY
  - SUSY+ Extra dimensions
  - Unparticles, Quirks
  - Classicalons
  - Dark/Hidden sectors
  - Colored resonances
  - And more….



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

Dark Matter: The Next Challenge !?!

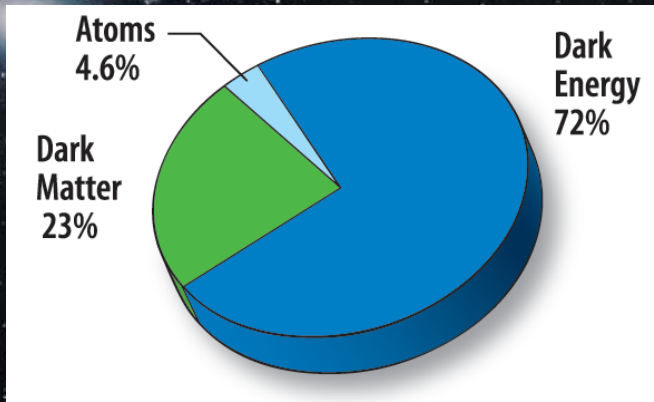
Astronomers found that most of the matter in the Universe must be invisible Dark Matter



'Supersymmetric' particles ? This is the next lecture!


F. Zwicky 1898-1974


Vera Rubin ~ 1970



Summary: The Searches are on!

- 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 SUSY, but many other New Physics model searches are covered.
- No sign of new physics yet in the first 20 fb^{-1} at 8 TeV with the analyses reported in this lecture.. This starts to cut into the 'preferred regions' for a large number of models
- More exotic channels are now being covered: monopoles, fractional or multiple charged 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
- In 2015 the energy will be 13/14 TeV, excellent
- And maybe one day soon: