Physics at the LHC
Beyond the Standard Model

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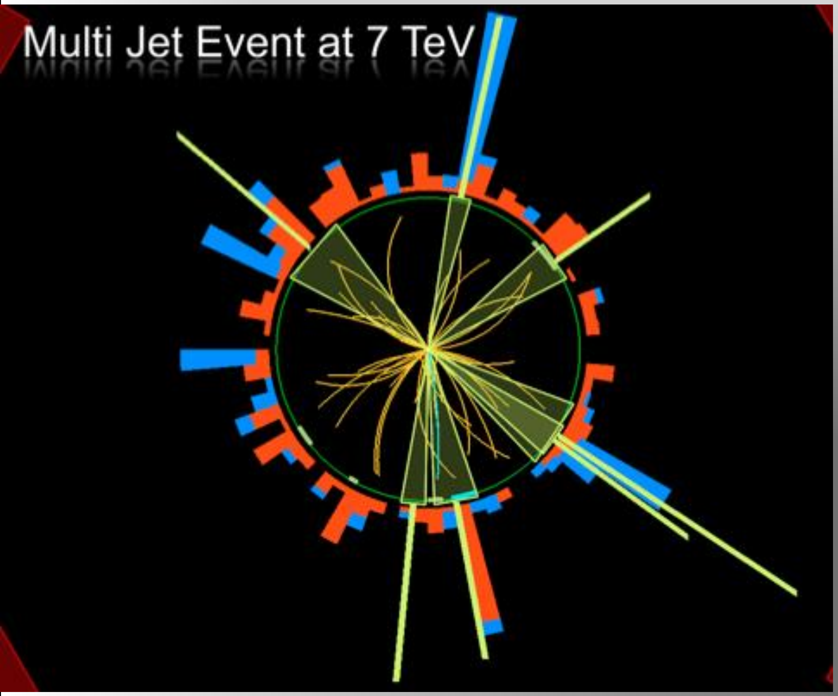
CERN



Outline

- Search for Physics Beyond the Standard Model
- Search for Exotica
- Search for Supersymmetry
- The dark matter connection
- Outlook with the LHC and beyond…
- Summary

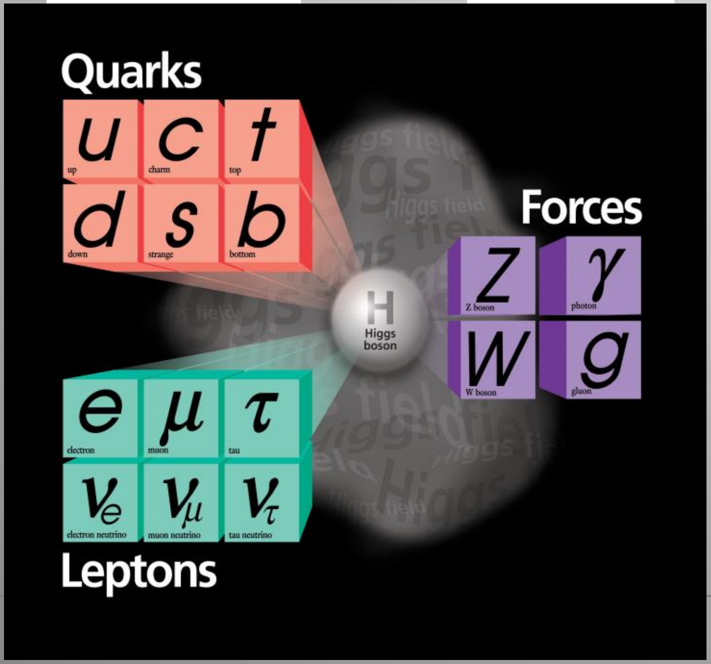
The "Standard Model"

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:

Fermions

Bosons

Matter particles



Force particles

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!!

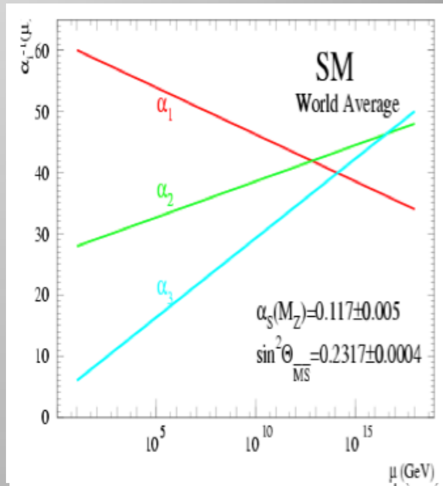
Fermions: particles with spin ½
Bosons: particles with integer spin

Physics case for new High Energy Machines

➡ **Understand the mechanism Electroweak Symmetry Breaking**

➡ **Discover physics beyond the Standard Model**

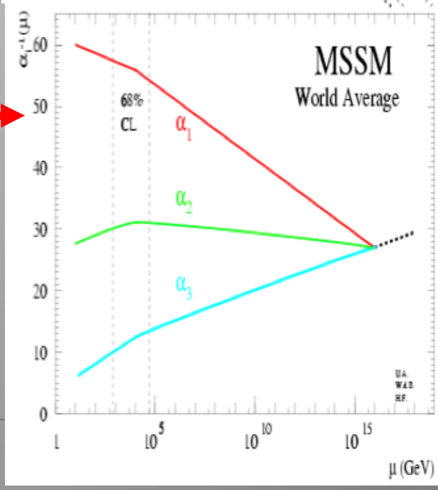
Reminder: The Standard Model
- tells us how but not why
  3 flavour families? Mass spectra? Hierarchy?
- needs fine tuning of parameters to level of 10^{-30} !
- has no connection with gravity
- no unification of the forces at high energy



Most popular extensions since 2000

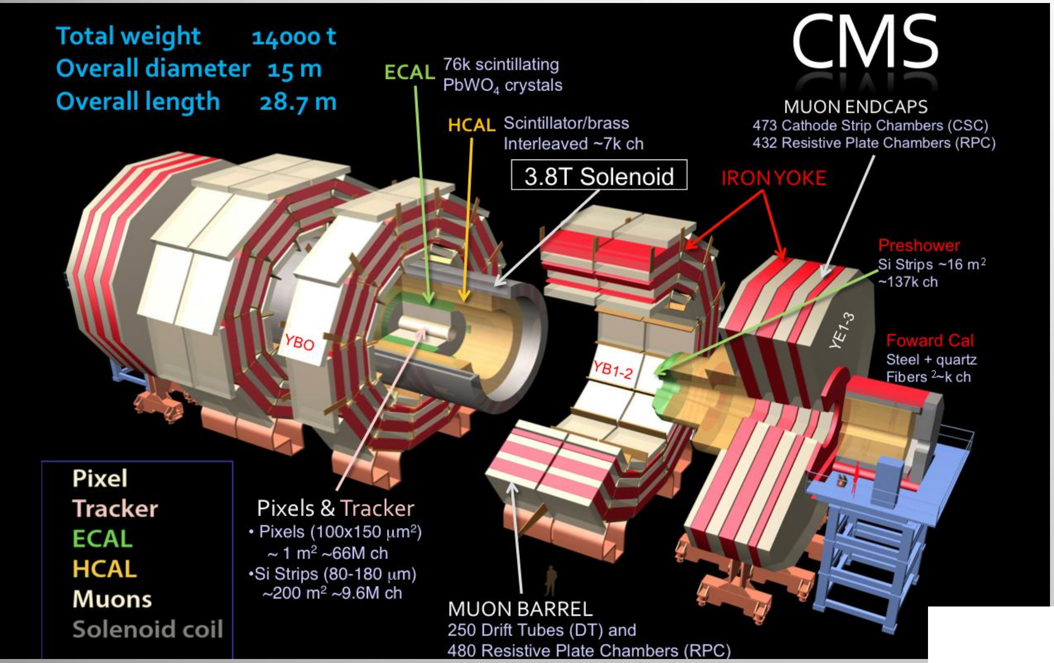
- Supersymmetry
- Extra space dimensions

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

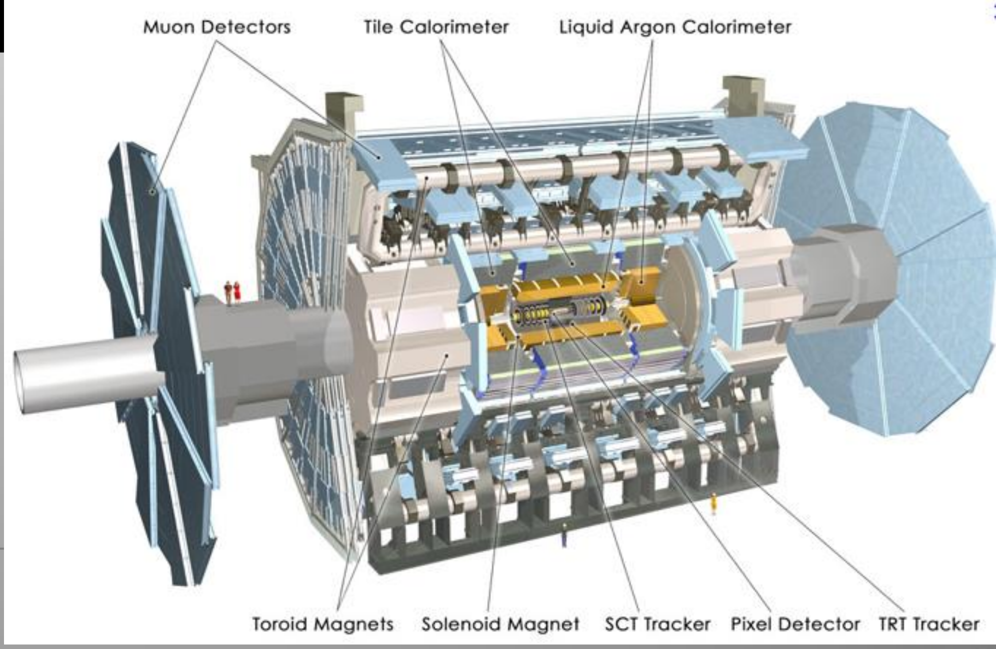
LHC BSM(*) Hunting Detectors



(*) Beyond the Standard Model

The CMS Experiment

Luminosity: 5 fb^{-1} (7 TeV) and 20 fb^{-1} (8 TeV)



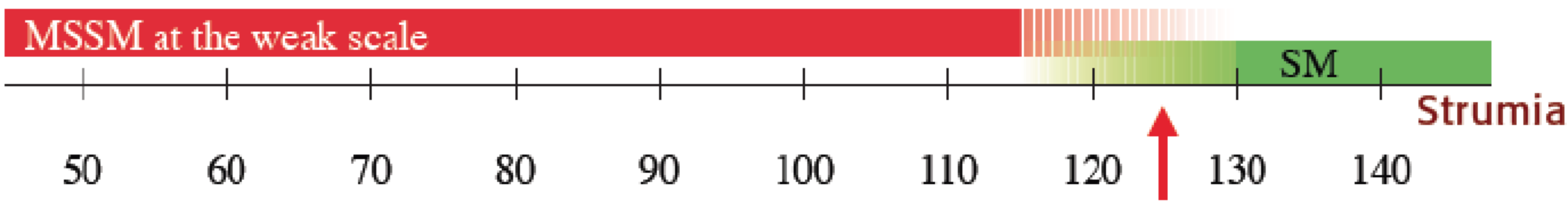
The ATLAS Experiment

Also LHCb via eg $B_s \to \mu\mu$
and other precision flavor tests

A Higgs…

A malicious choice!

$m_H = 125.6 \pm 0.4$ GeV



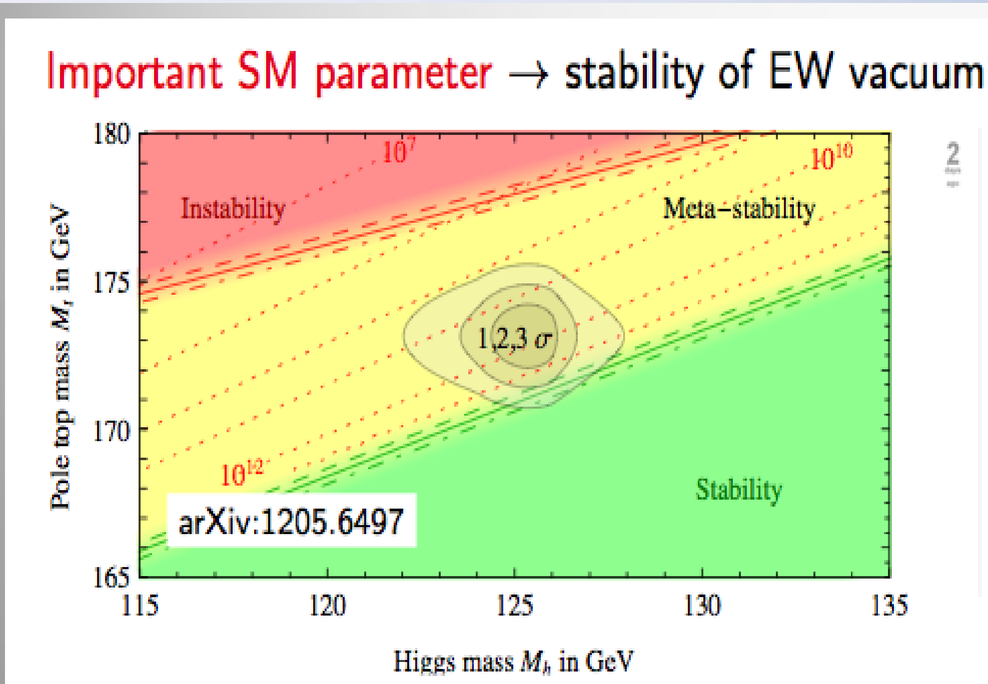
The Higgs: so simple yet so unnatural

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?



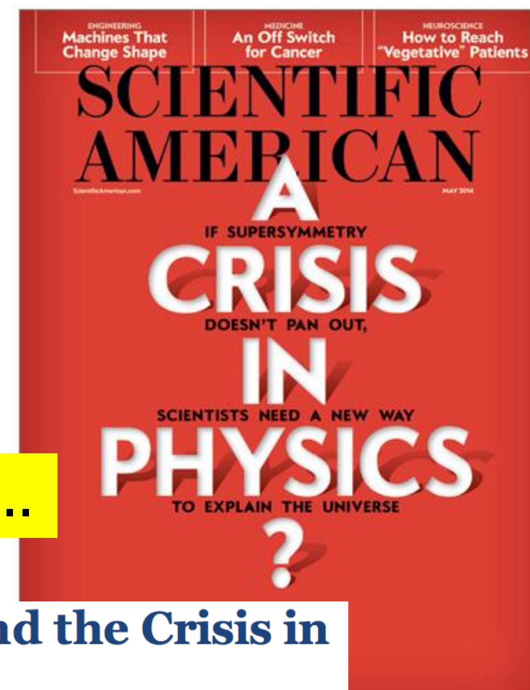
Precise measurements of the top quark and first measurements of the Higgs mass:

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

New Physics inevitable?
But at which scale/energy?

N. Arkani-Hamed

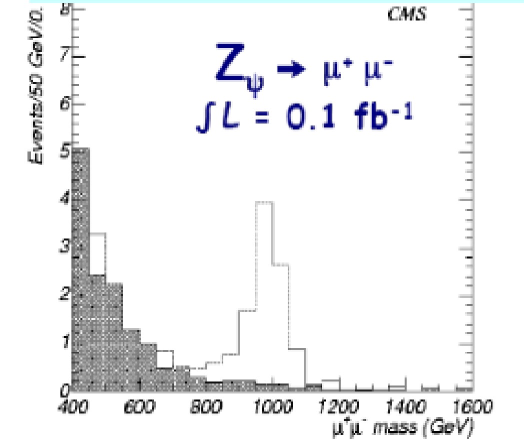
...The May Issue...



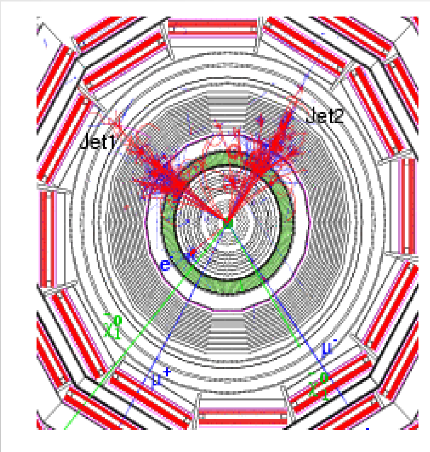
Supersymmetry and the Crisis in Physics

New Physics?

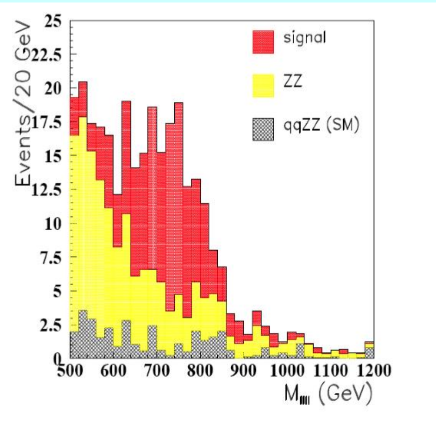
New Gauge Bosons?



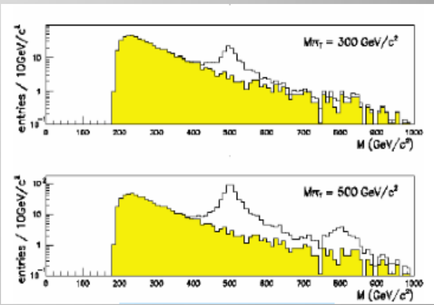
Supersymmetry



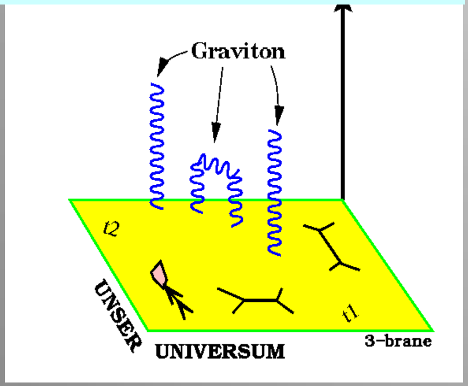
ZZ/WW resonances?



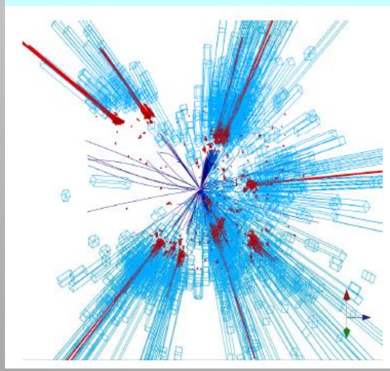
Technicolor?



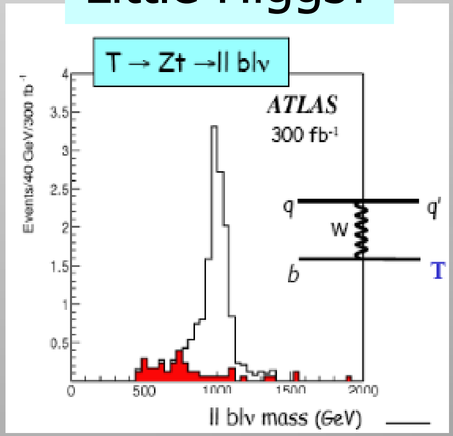
Extra Dimensions?



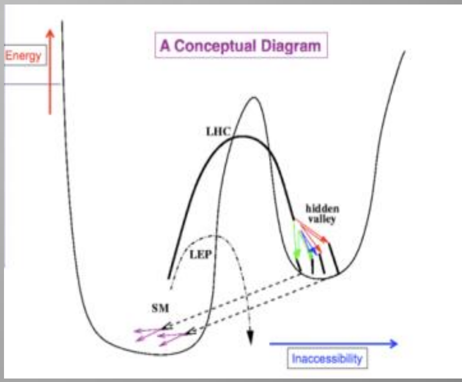
Black Holes???



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

- Many extensions of the SM have been developed over the past decades:
- Supersymmetry
- Extra-Dimensions
- Technicolor(s)
- Little Higgs
- No Higgs
- GUT
- Hidden Valley
- Leptoquarks
- Compositeness
- 4th generation (t', b')
- LRSM, heavy neutrino
- etc...

(for illustration only)

- 1 jet + MET
- jets + MET
- 1 lepton + MET
- Same-sign di-lepton
- Dilepton resonance
- Diphoton resonance
- Diphoton + MET
- Multileptons
- Lepton-jet resonance
- Lepton-photon resonance
- Gamma-jet resonance
- Diboson resonance
- Z+MET
- W/Z+Gamma resonance
- Top-antitop resonance
- Slow-moving particles
- Long-lived particles
- Top-antitop production
- Lepton-Jets
- Microscopic blackholes
- Dijet resonance
- etc...

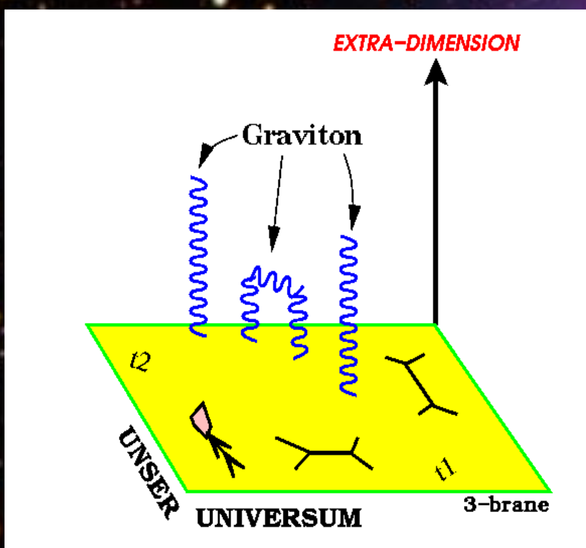
LHC data and Theorists

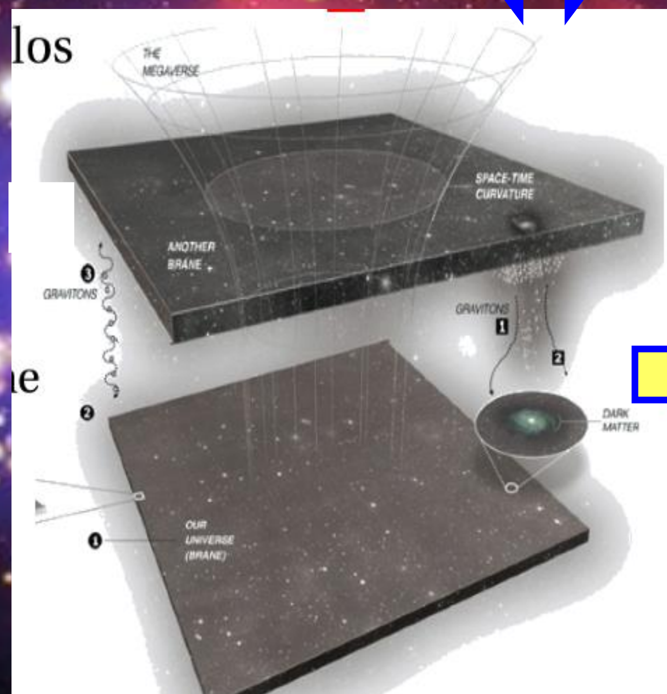
NOW!

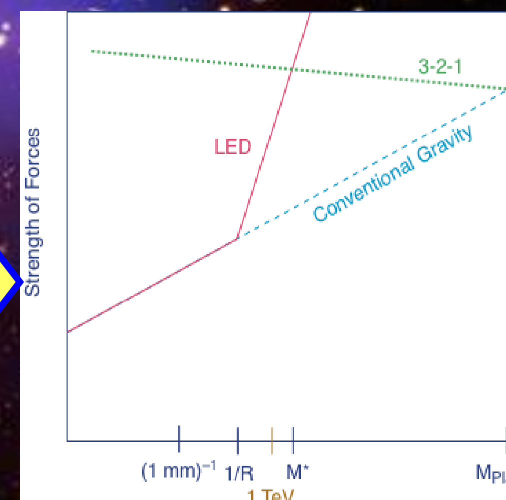
"Data are coming! Data are coming!"

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

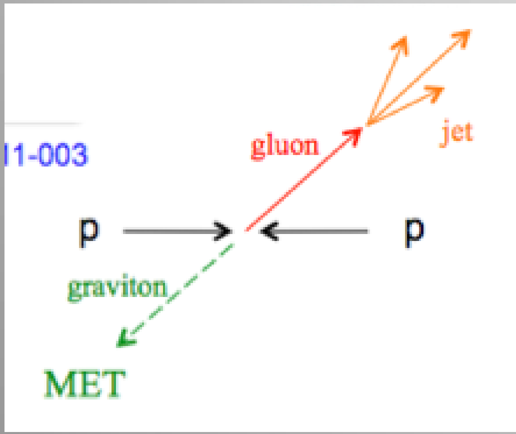
Mono-jet final state +Missing E_T (ADD)

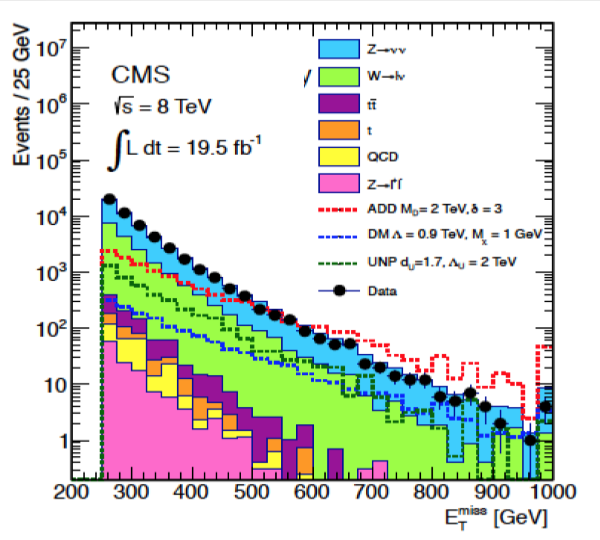
p_T jet > 110 GeV
MET > 200 GeV

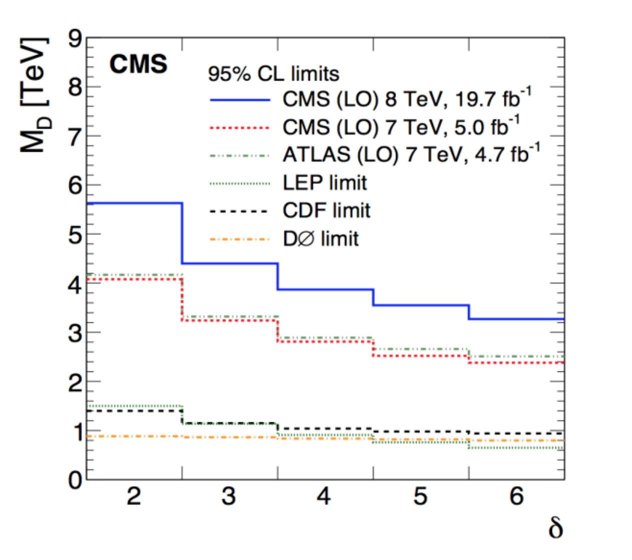
Limits on M_D between 3 and 4 TeV

arXiv:1408.3583

Lower limit on the Planck Scale versus number of extra dimensions

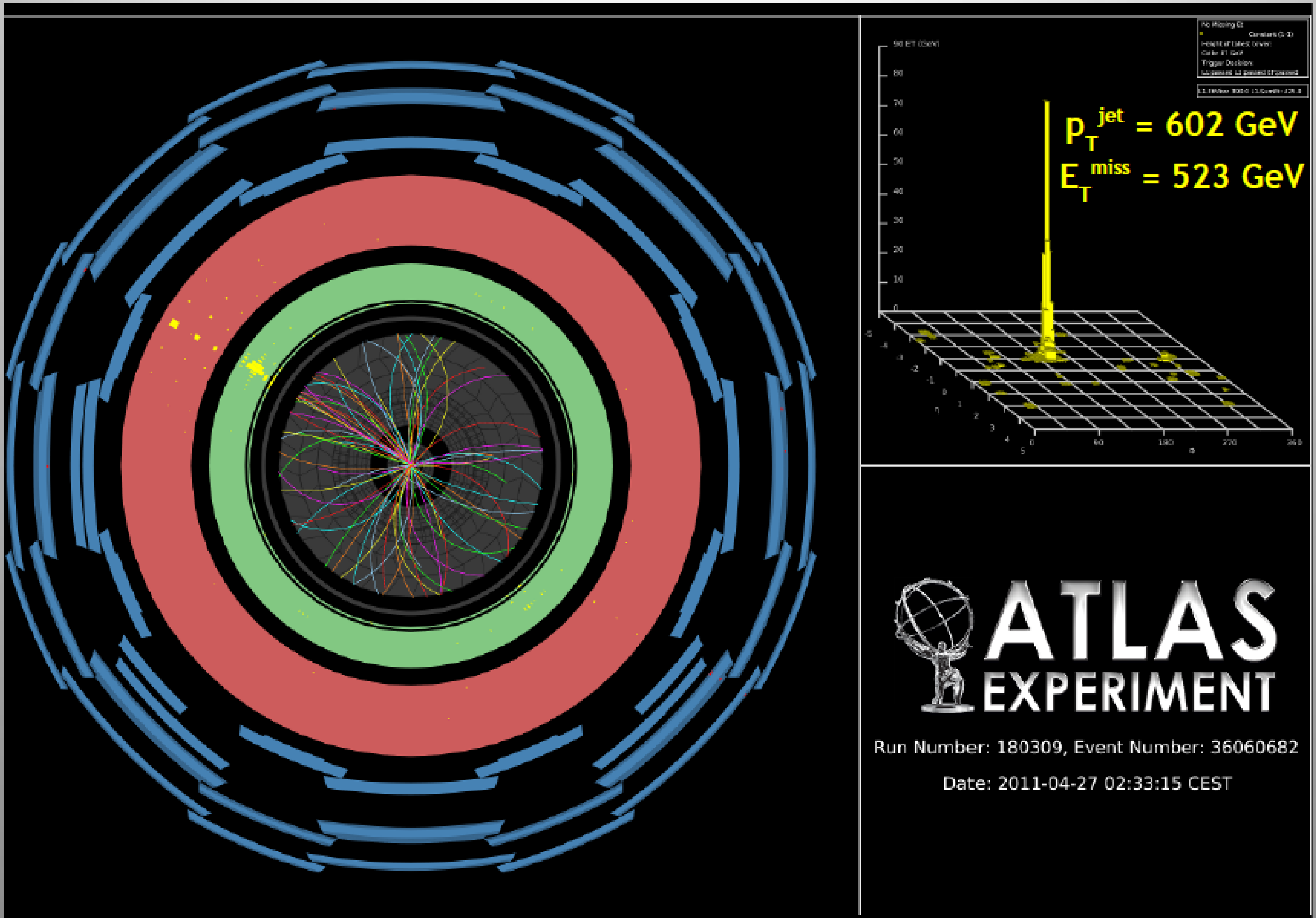






M_D (ADD) at LO 95% CL limits	√s [TeV]	Lumi [fb^{-1}]	δ=3 Exp.	δ=3 Obs.	δ=6 Exp.	δ=6 Obs.
CMS Monojet	8	19.5	3.94	3.96	2.95	2.94

A High p_T Mono-jet event



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

Quantum Black Holes

- Schwarzschild radius

Landsberg, Dimopoulos, Giddings, Thomas, Rizzo

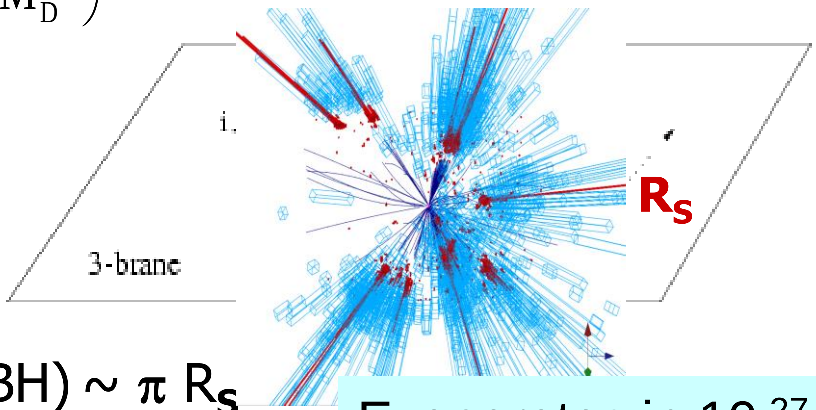
4-dim., $M_{gravity} = M_{Planck}$: $R_S \sim \frac{2}{M_{Pl}^2} \frac{M_{BH}}{c^2}$

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

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

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

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



Evaporates in 10^{-27} sec

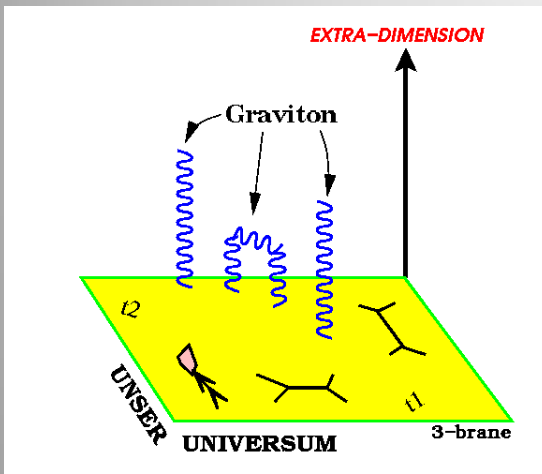
- Large partonic cross-section : $\sigma(ij \rightarrow BH) \sim \pi R_S^2$
- $\sigma(pp \rightarrow BH)$ is in the range of 1 nb – 1 fb

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

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

} expected signature (quite spectacular ...)

Search for Micro Black Holes

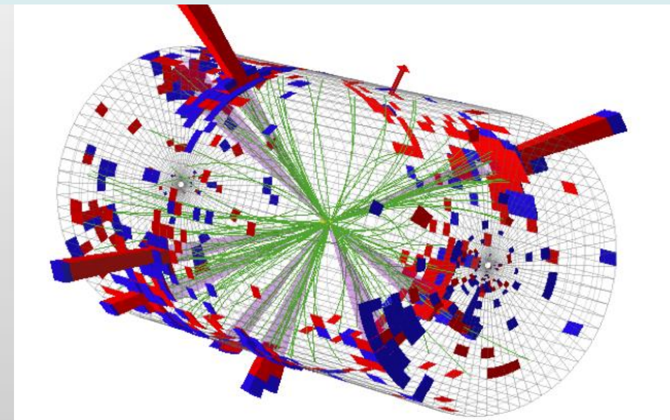


arXiv:1202.6396

Extra Dimensions!

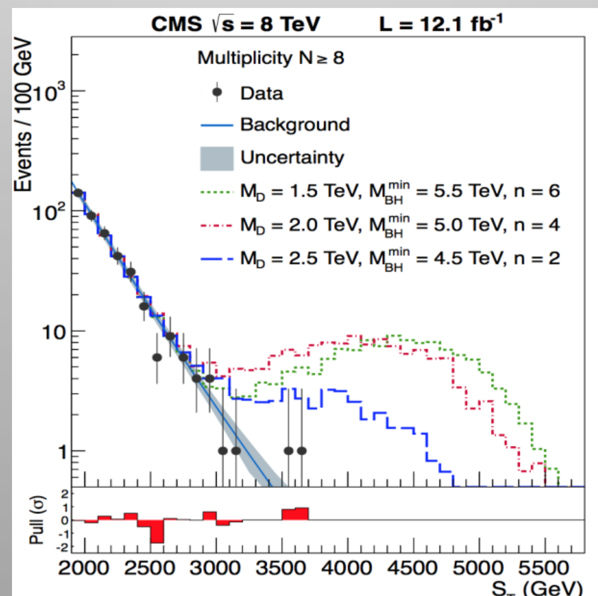
Planck scale
a few TeV?

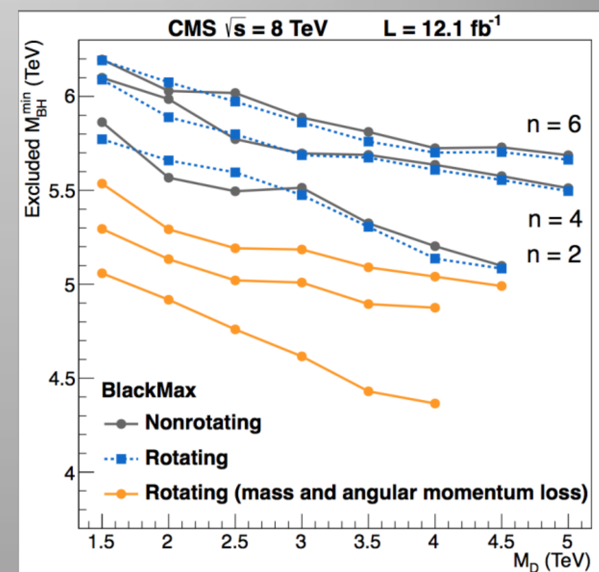
Nice events, eg a 10 jet event



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

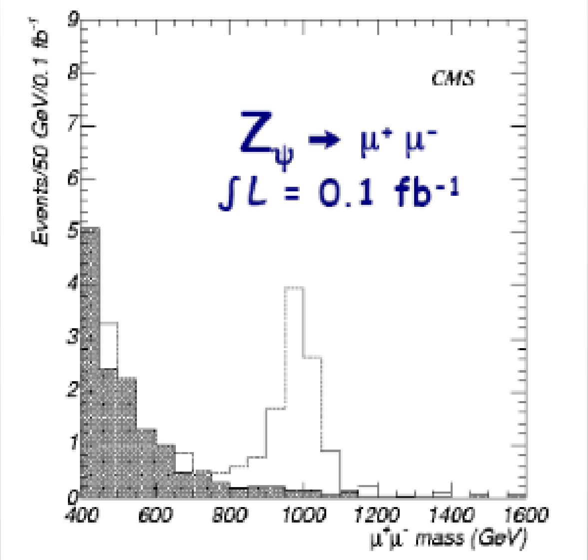
E.g. Di-lepton Resonance

Plot the di-lepton invariant mass

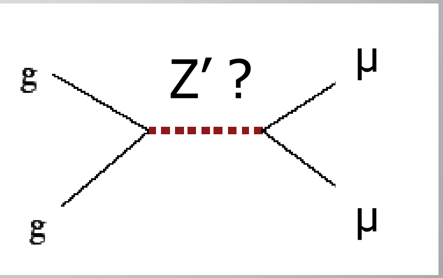
A peak!!

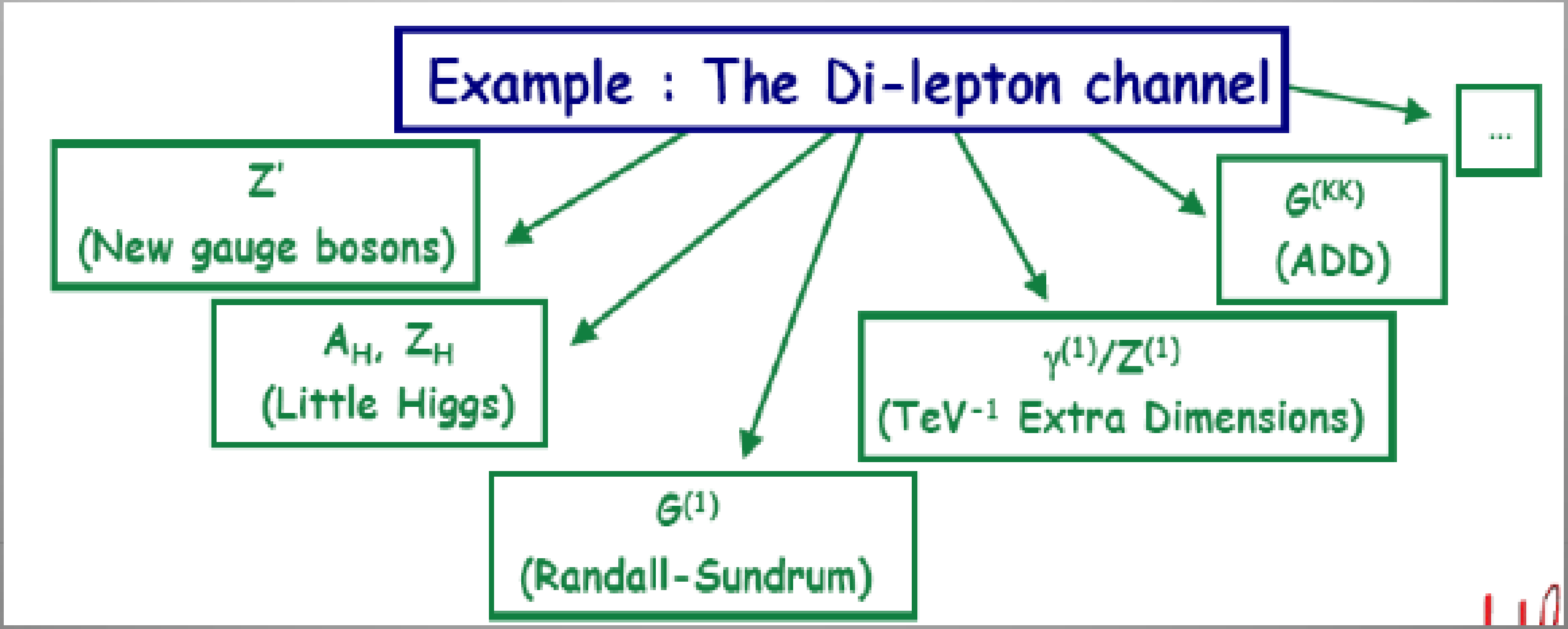
A new particle!!

A discovery!!



Example
pp$\to\mu\mu$ +X





2011: Z' Boson to ee or μμ?

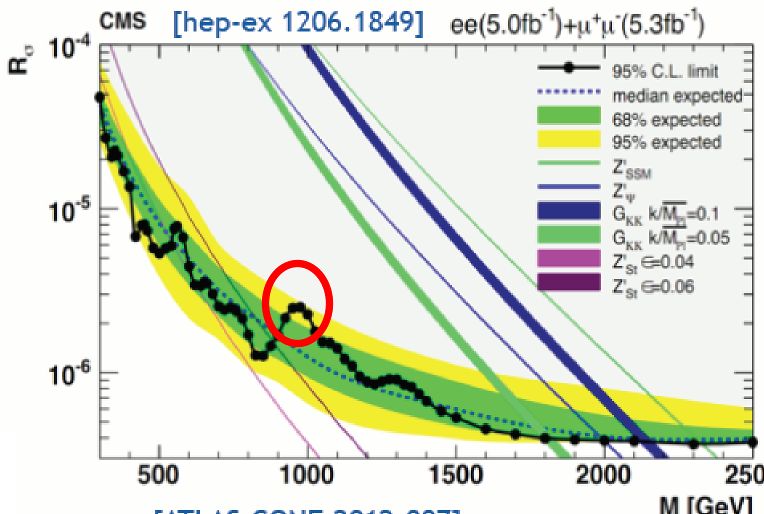
$SU(3)_C \times SU(2)_L \times U(1)_Y$

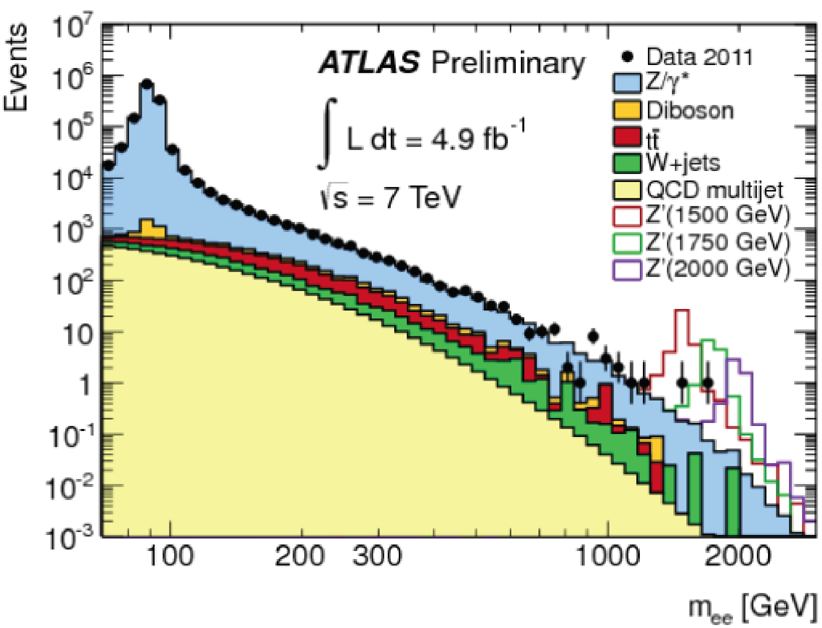
Extension of the symmetry?
New Gauge bosons?

Mid 2012

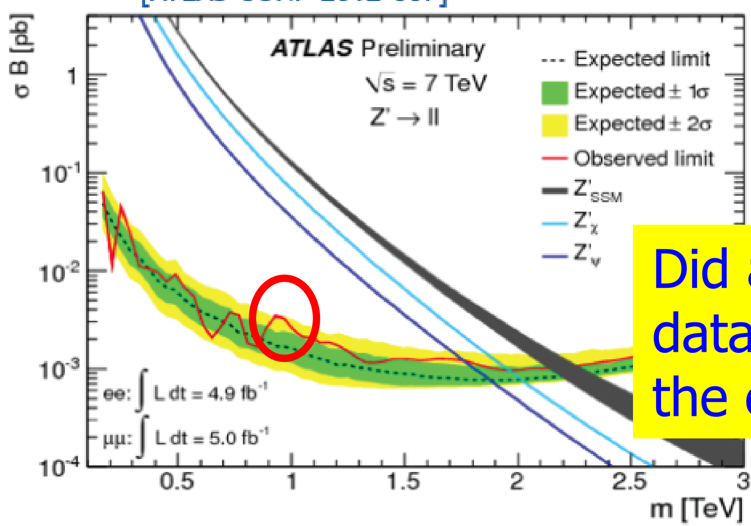
- Many new models have Z-like narrow resonances decaying to dileptons
- Interesting features in dilepton spectra
  - around 2σ each for CMS & ATLAS in e+μ
  - similar in scale to 2011 Higgs excess

Worth watching in 2012's 8 TeV data…





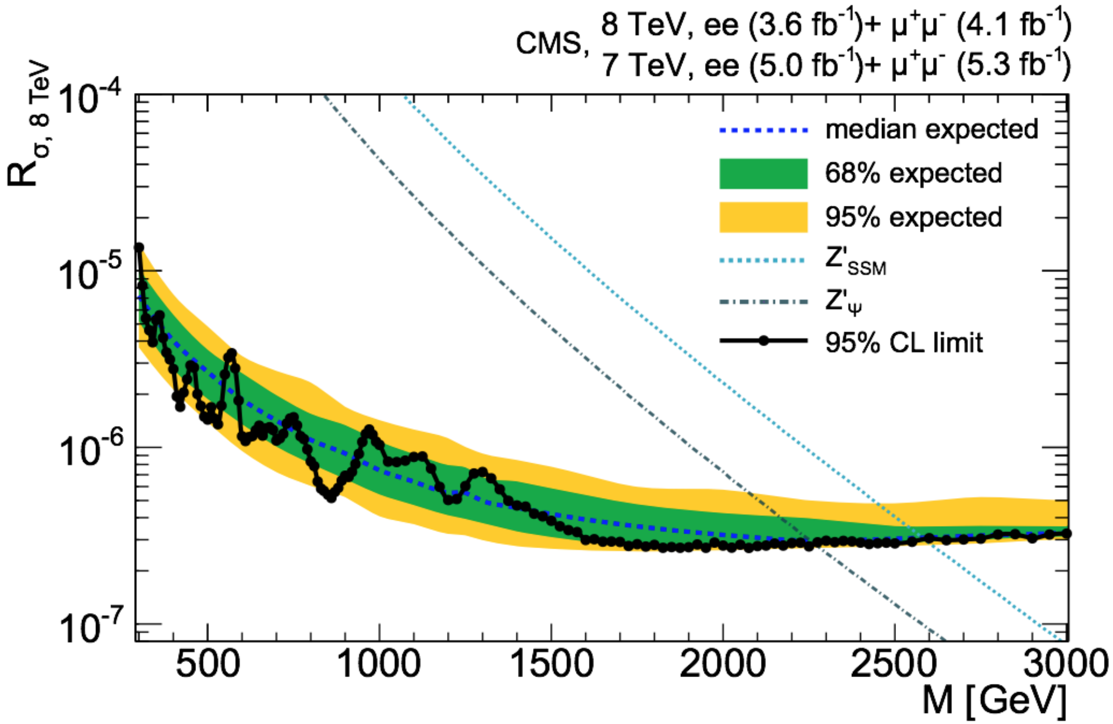
[ATLAS-CONF-2012-007]



Did additional data confirm the excess??

Z’ Combination of 7 & 8 TeV Data

[CMS EXO-12-015]



No... ☹

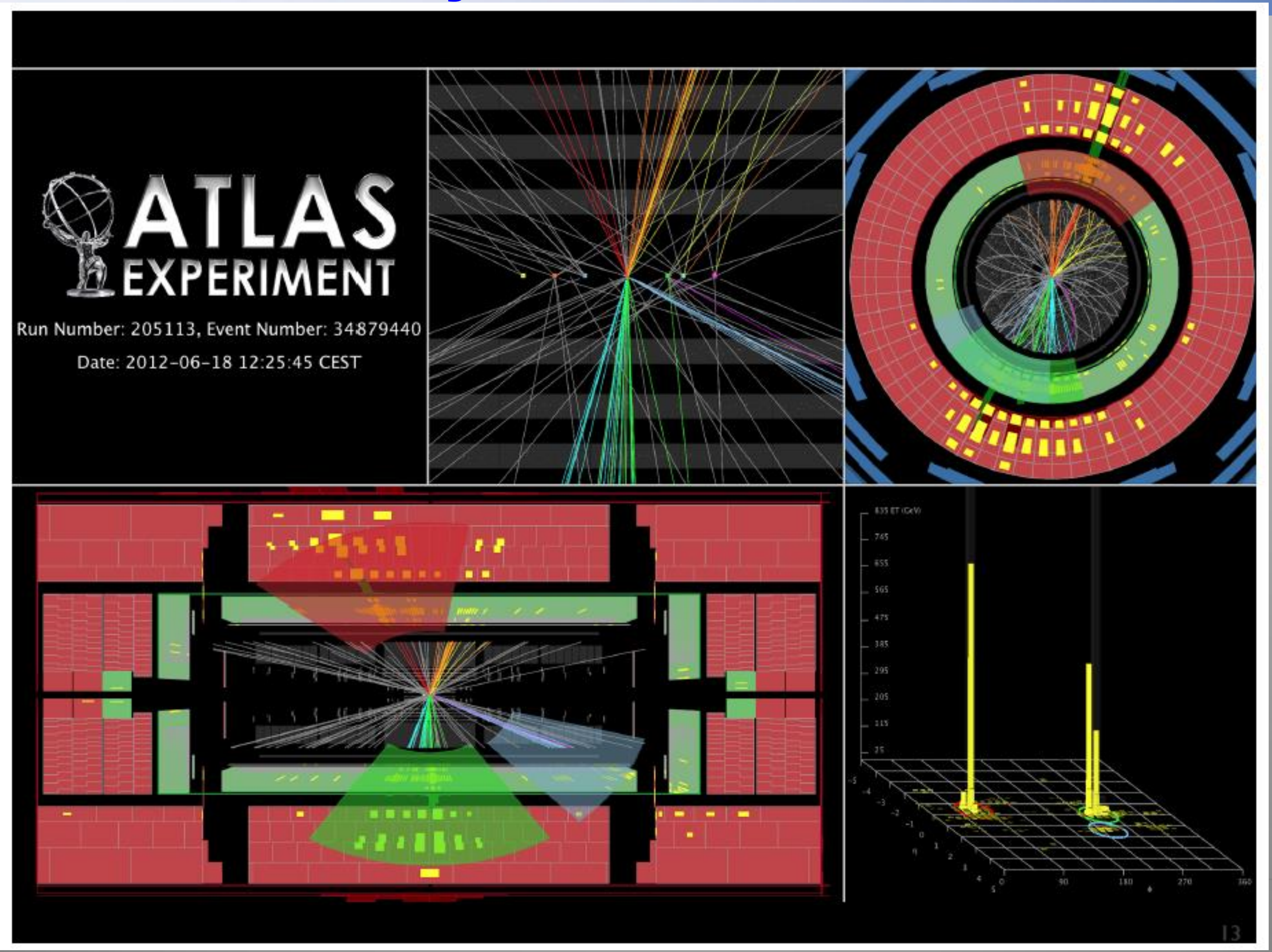
- Short time between data-taking and result

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

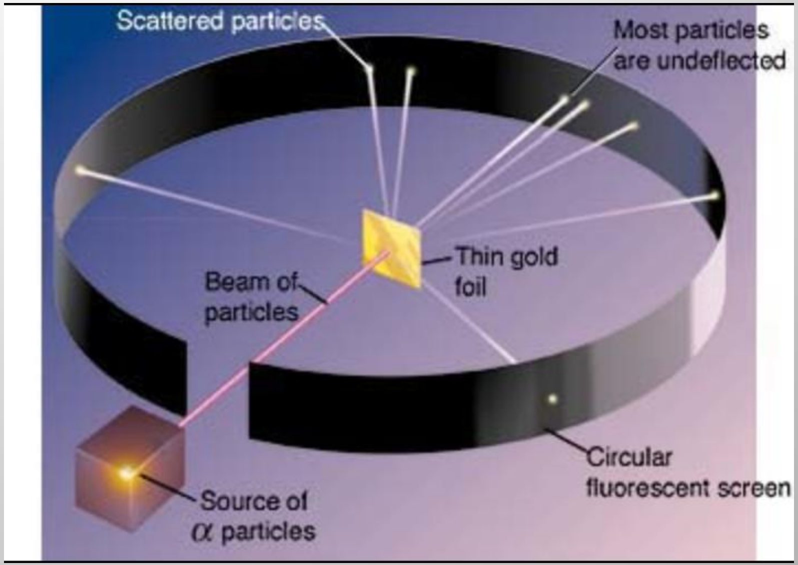
- Limits on the combined 7 TeV and 8 TeV data from 2011+2012
  - M(Z’$_{SSM}$) > 2950 GeV at 95% C.L.
  - M(Z’$_{\psi}$) > 2600 GeV at 95% C.L.

Excess just below 1 TeV all but gone in CMS data

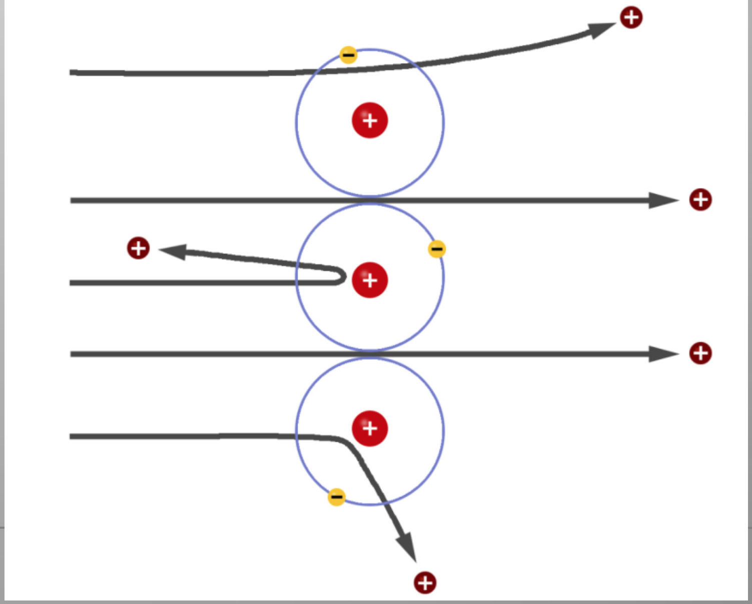
Di-jet Resonances



Are Quarks Elementary Particles?



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



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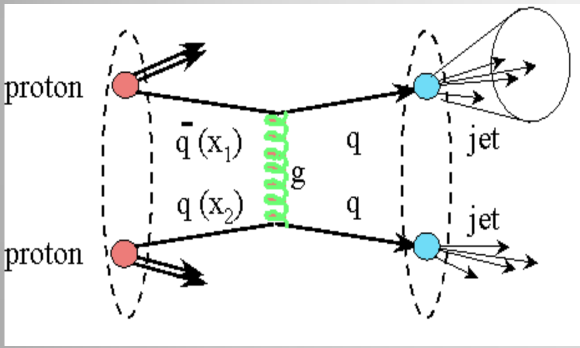
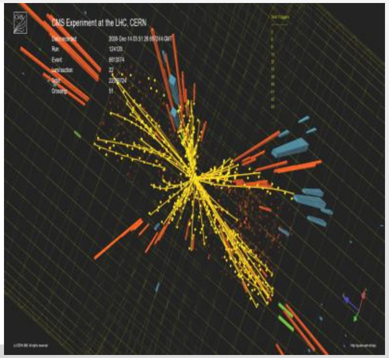
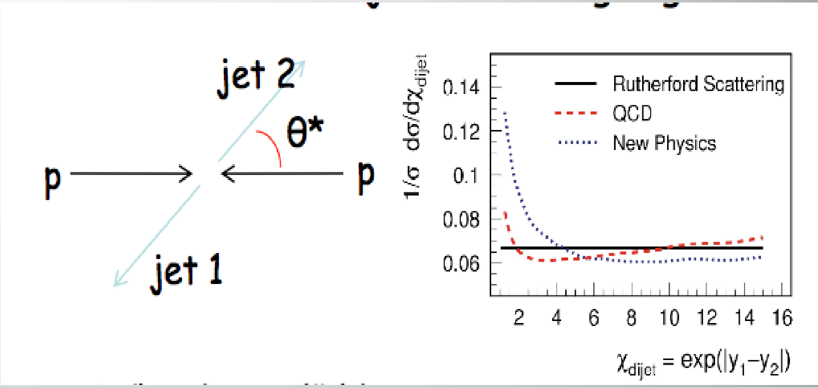
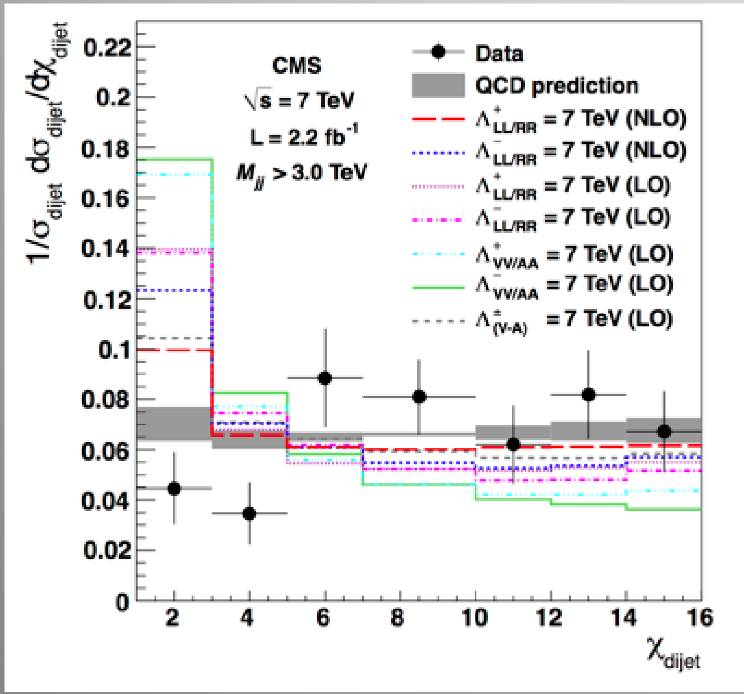
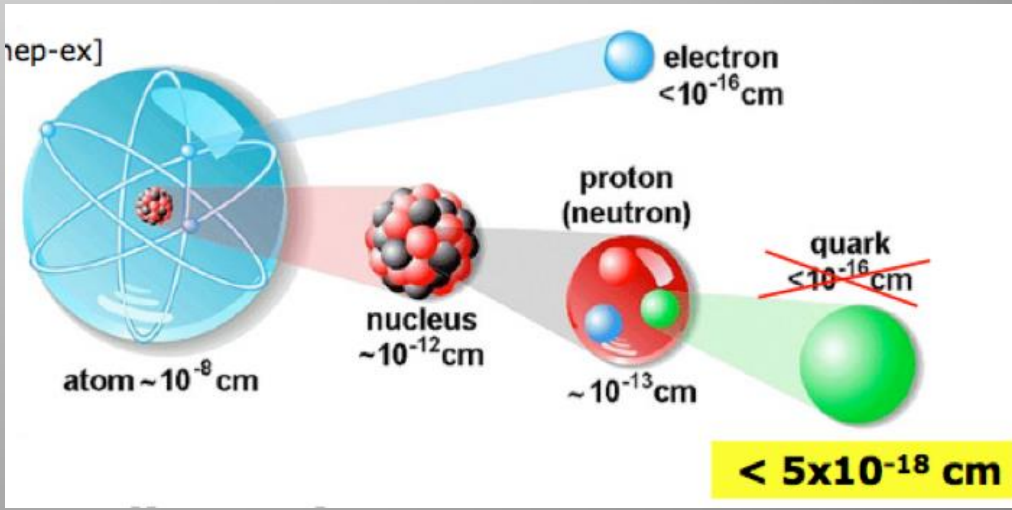






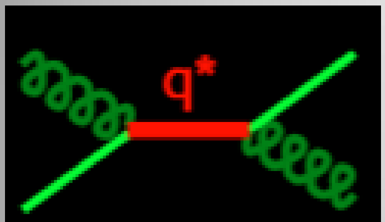
Measurement of the production angle of the jet with respect to the beam
-> High Energy Rutherford Experiment



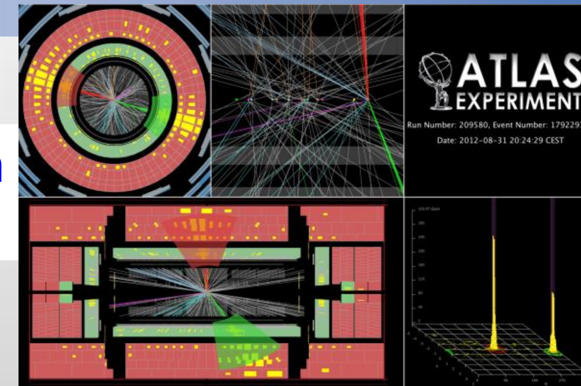


Quarks remain elementary particles after these first results

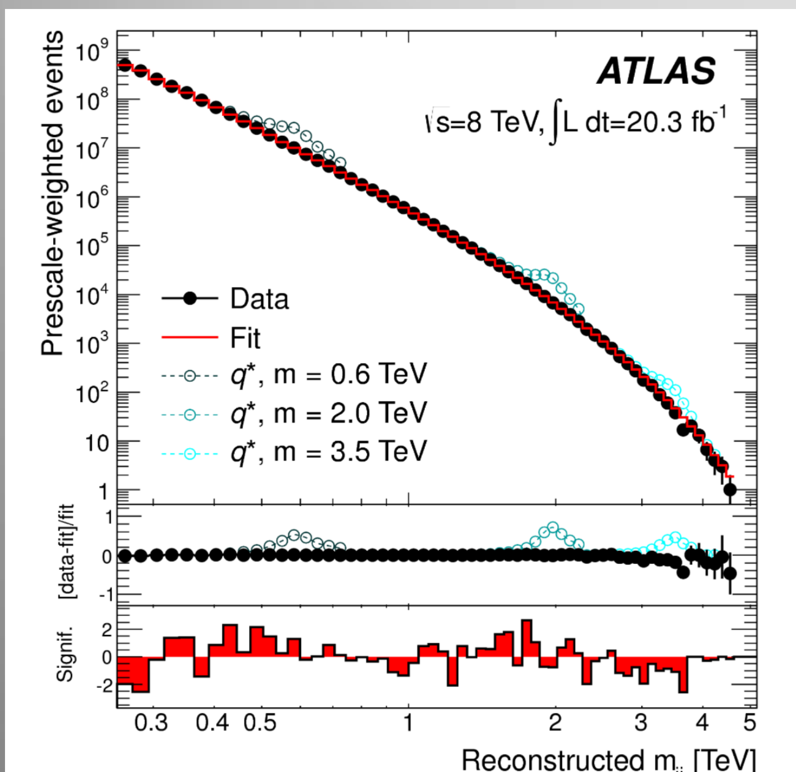
Excited Quark in Dijet Search

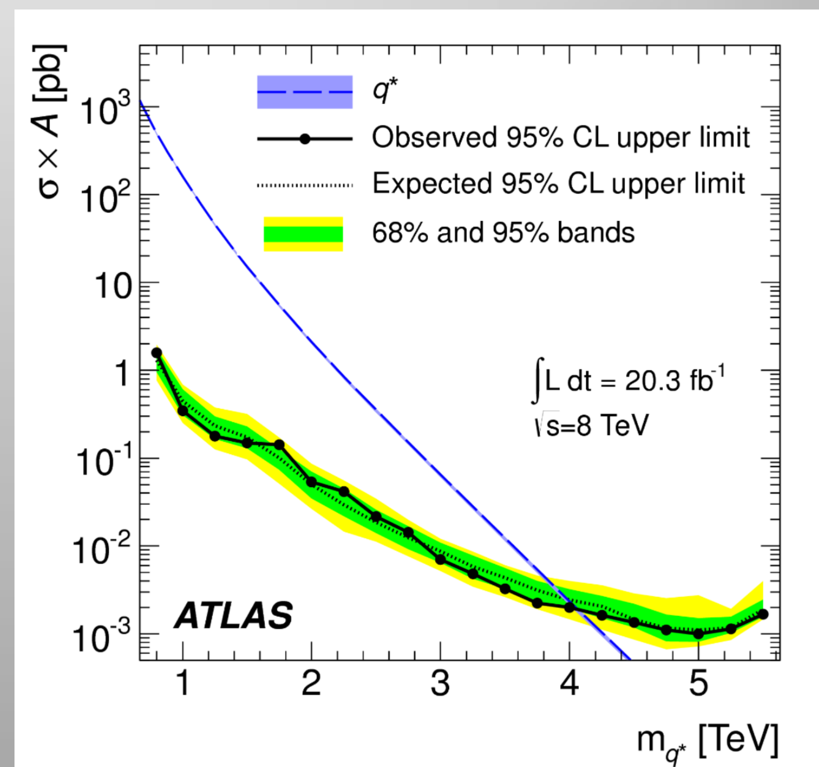


invariant mass of 4.69 TeV, and jets with a jet-p_T of 2.29 TeV and 2.19 TeV



arXiv:1407.1376

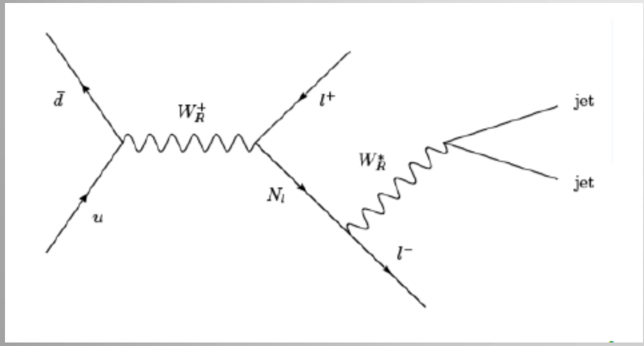




Limit on the mass of excited quarks > 4.09 TeV at 95% CL

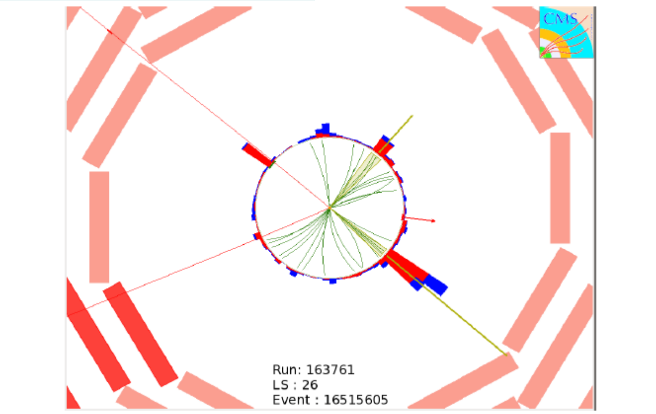
Search for Heavy Neutrinos and W_R

Left-right symmetric extension of the Standard Model

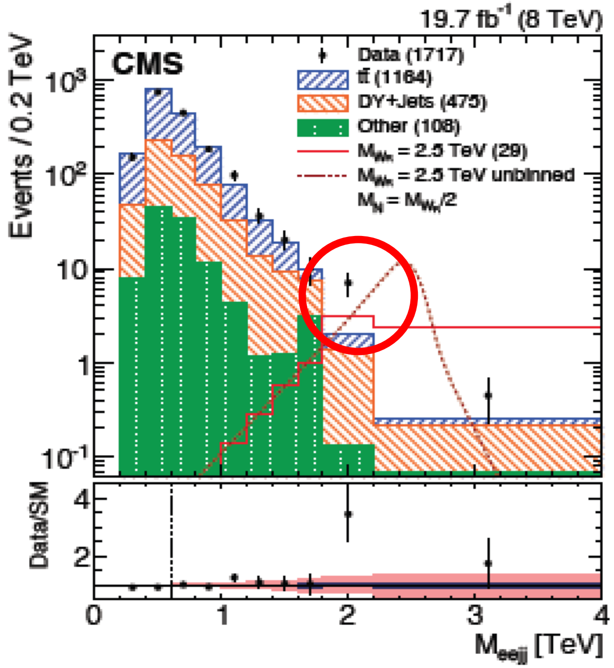


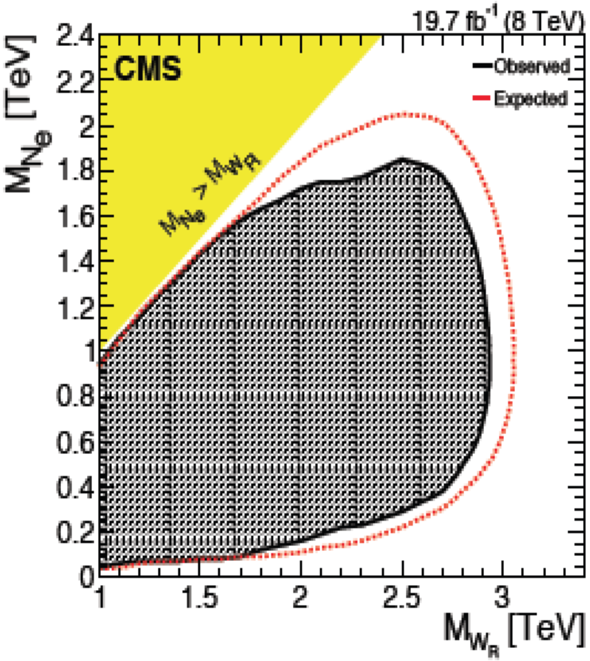
arXiv:1407.3683

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 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

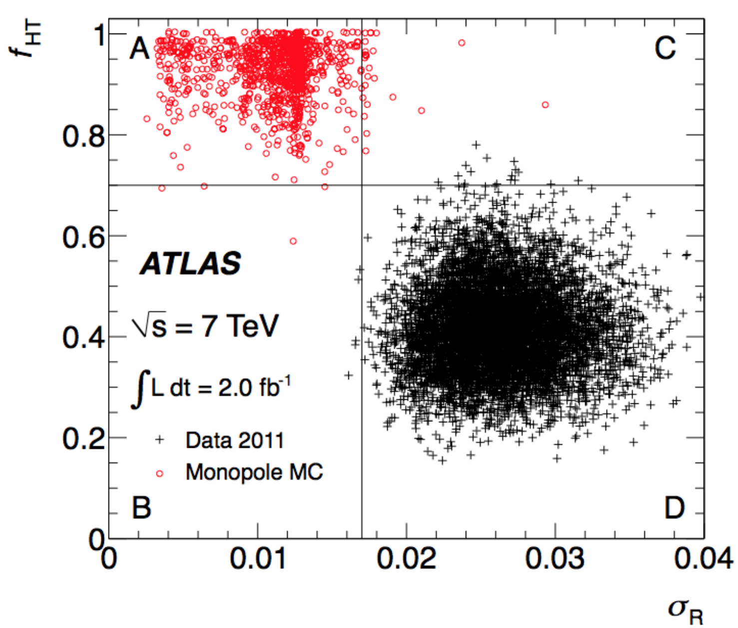
- Magnetic charge g yields strong coupling α_m and very high ionisation

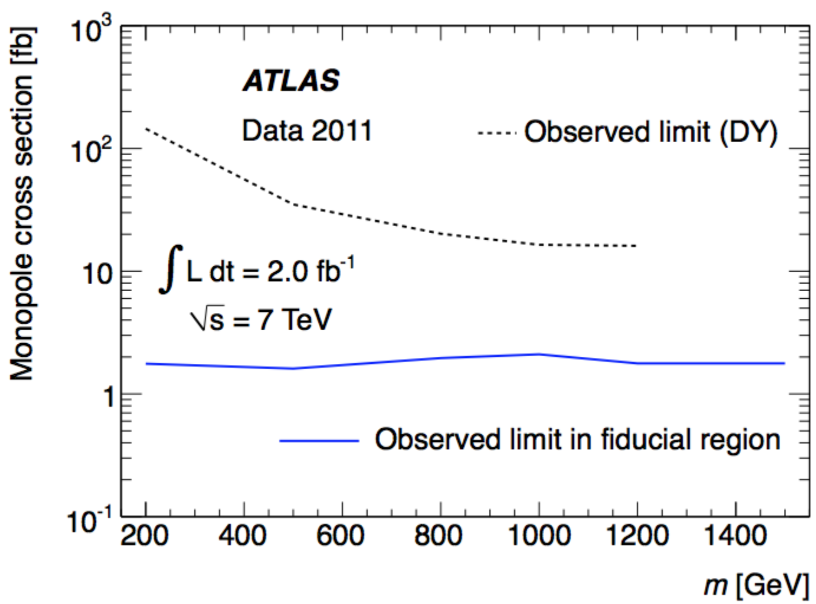
$$\frac{ge}{\hbar c} = \frac{1}{2} \Rightarrow \frac{g}{e} = \frac{1}{2\alpha_e} \approx 68.5 \qquad \alpha_m = \frac{(g\beta)^2}{\hbar c} = \frac{1}{4\alpha_e}\beta^2$$

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

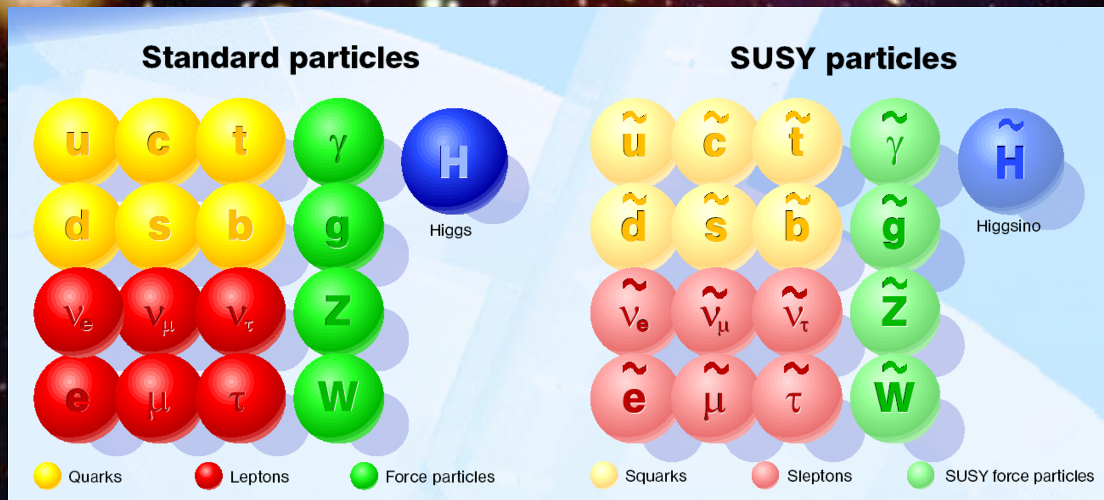
- Pair-produced (Drell-Yan) production

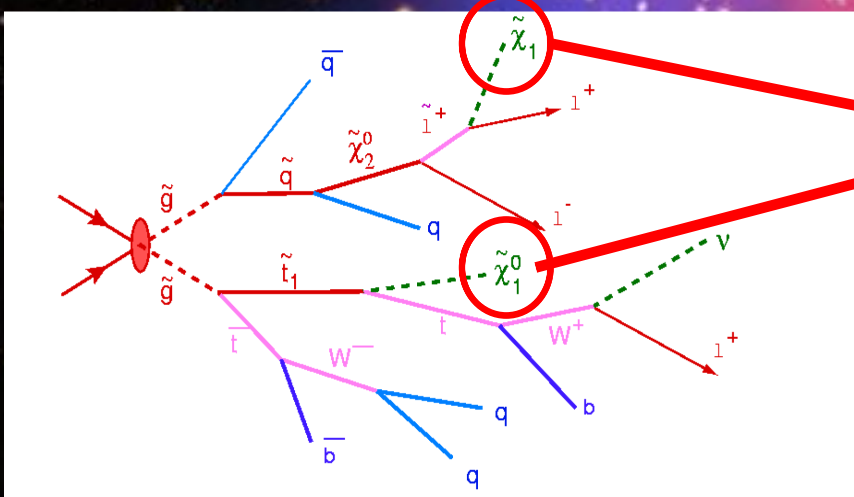
Cross Section limits set for m(M) = 0.2–1.2 TeV





Supersymmetry: a new symmetry in Nature?



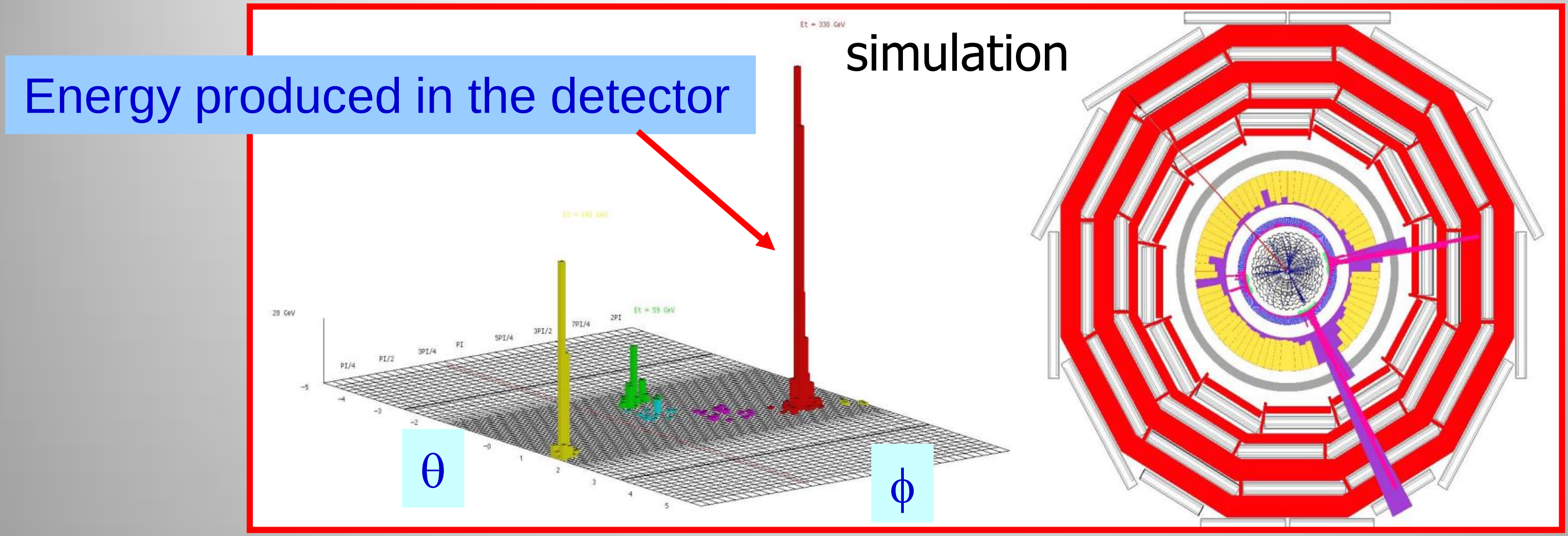


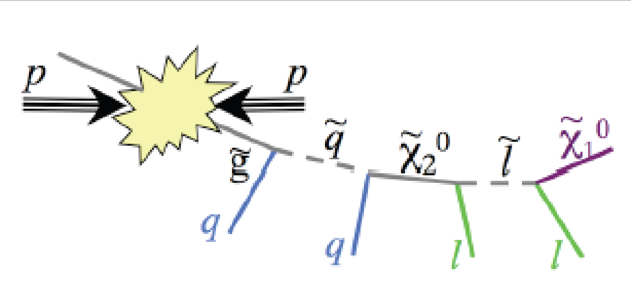
Candidate particles for Dark Matter
⇒ Produce Dark Matter in the lab

SUSY particle production at the LHC

Picture from Marusa Bradac

Detecting Supersymmetric Particles



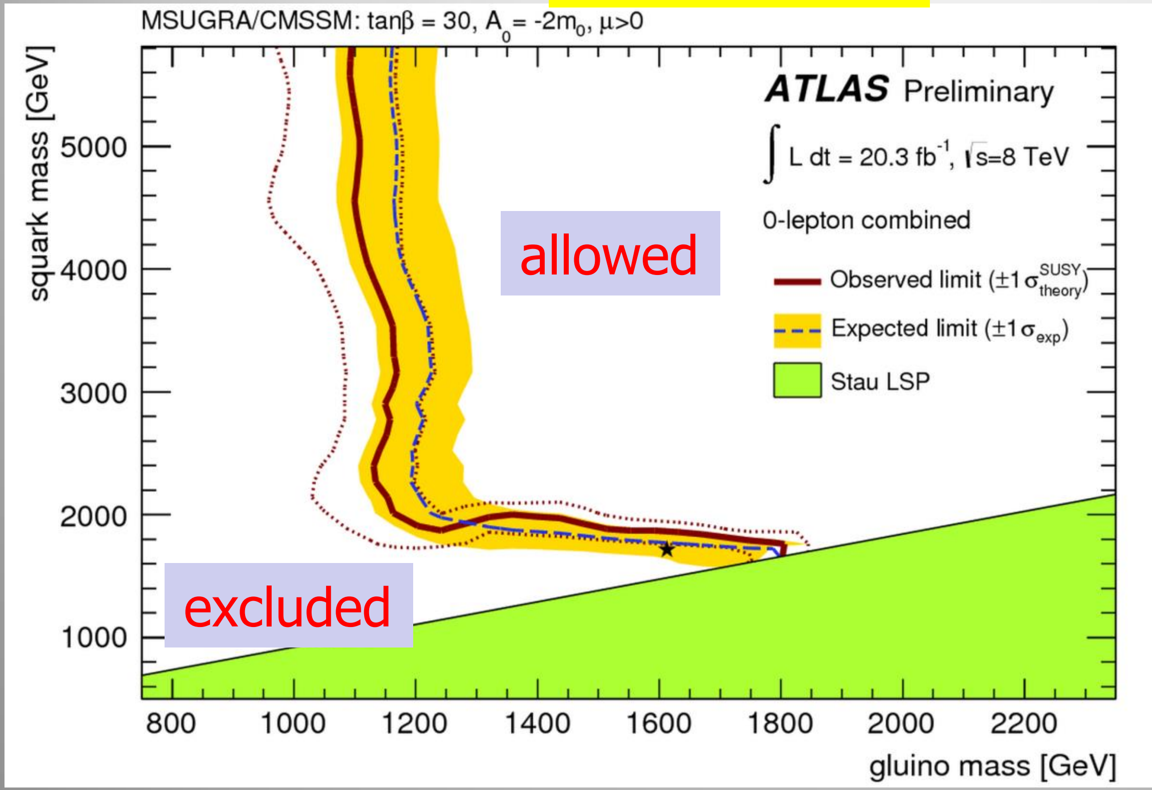


Supersymmetric particles decay and produce a cascade of jets, leptons and missing transverse energy (MET) due to escaping ‘dark matter’ particle candidates

➡ Very prominent signatures in CMS and ATLAS

SUSY Searches: No signal yet to date…

Status in 2013



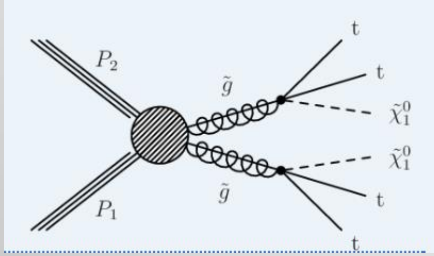
- So far NO clear signal of supersymmetric particles has been found
- We can exclude regions where the new particles could exist.
- Searches will continue for the higher energy in 2015

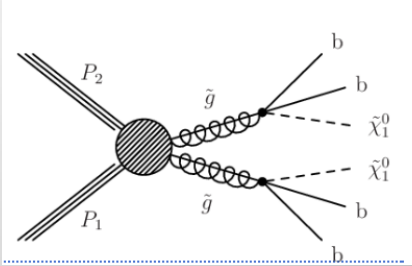
Plenty of searches ongoing: with jets, leptons, photons, W/Z, top, Higgs, with and without large missing transverse energy

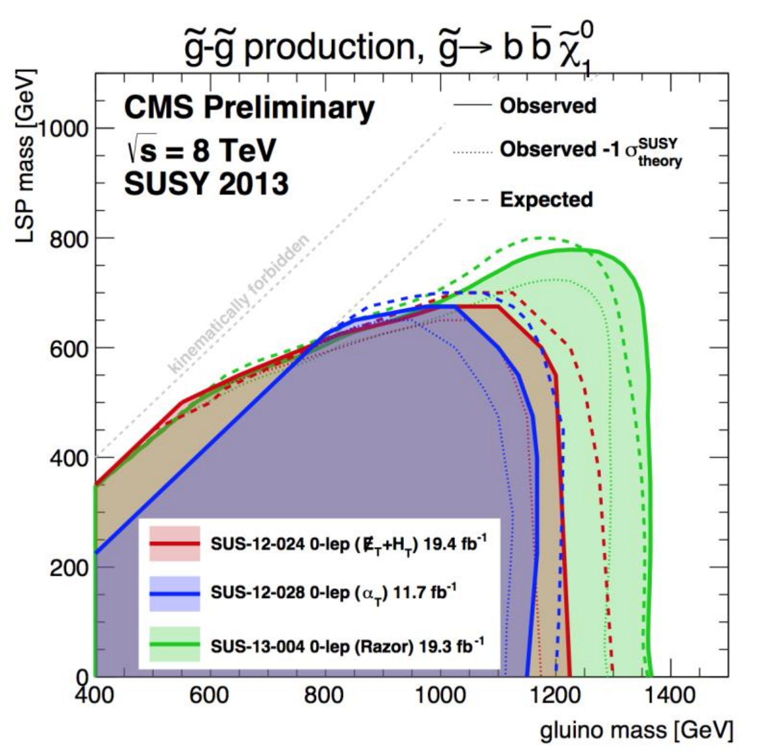
Also special searches for contrived model regions

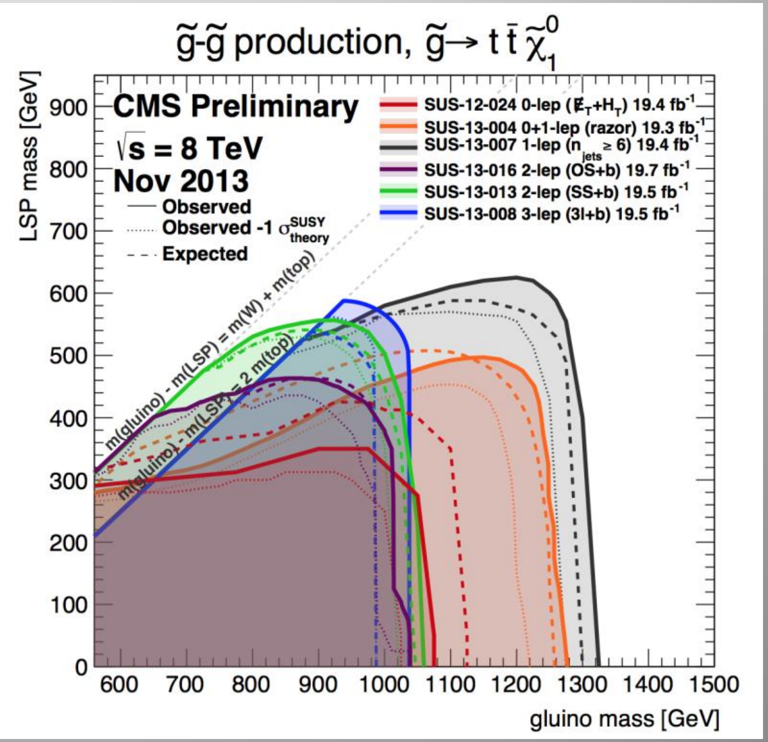
Limits on Squarks and Gluinos

Examples using b and t quarks









Combined limits typically > 1-1.5 TeV on sparticle masses

What is really needed from SUSY?

End 2011: Revision!

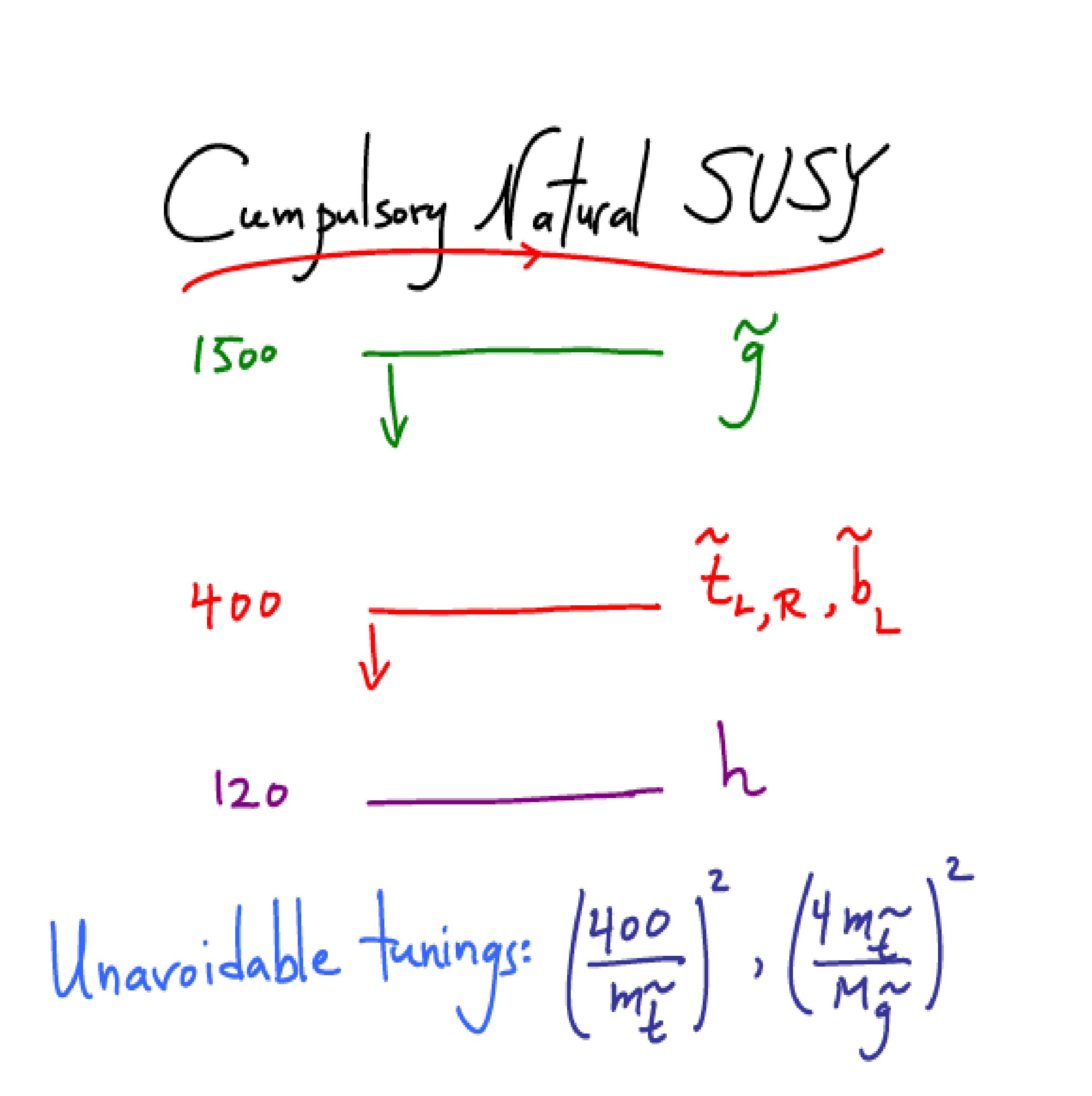
N. Arkani-Ahmed
CERN Nov 2011

Papucci, Ruderman, Weiler arXiv:1110.6926

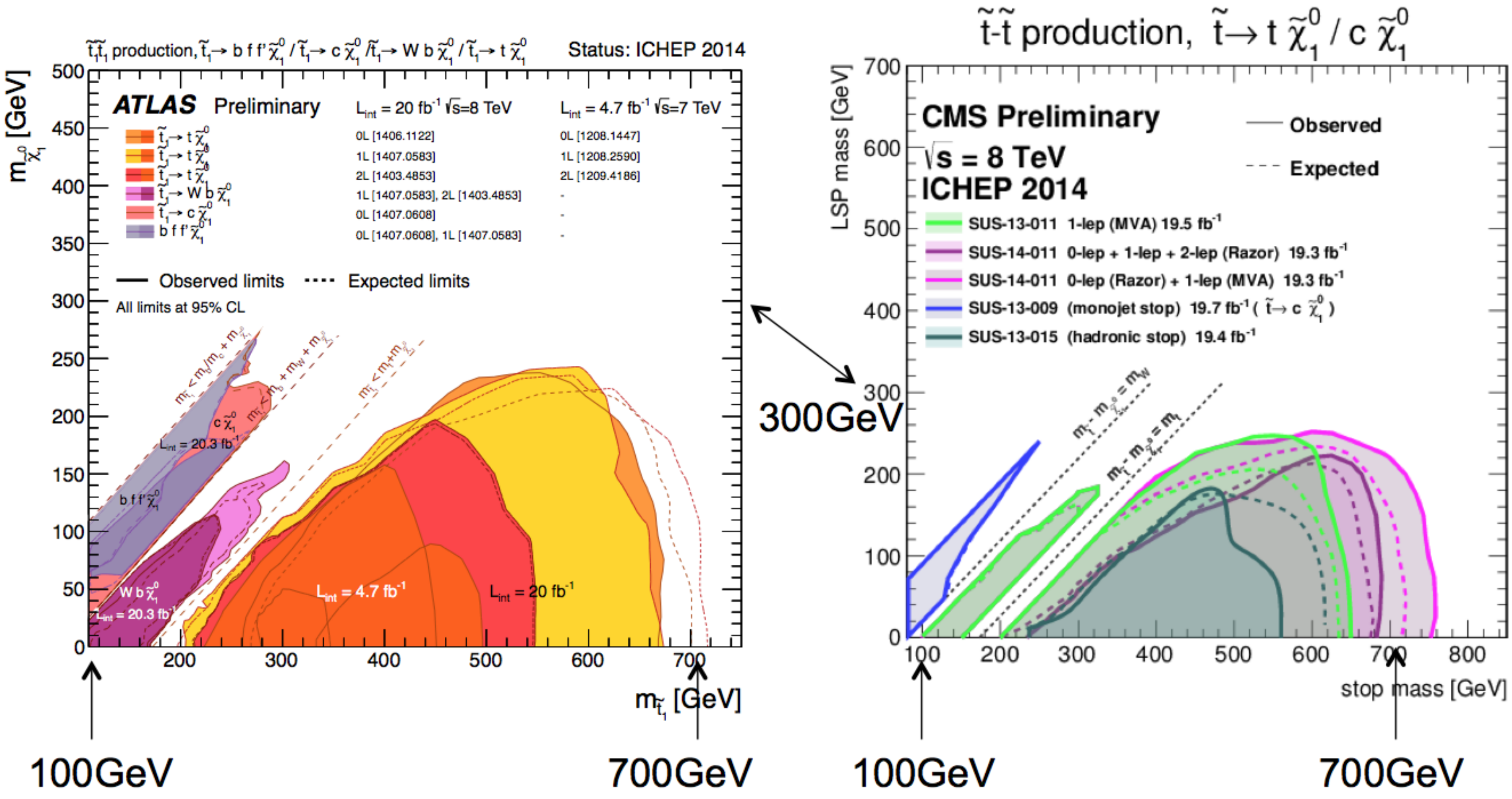
LHC data end 2011
Stops > 200-300 GeV
Gluino > 600-800 GeV

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!



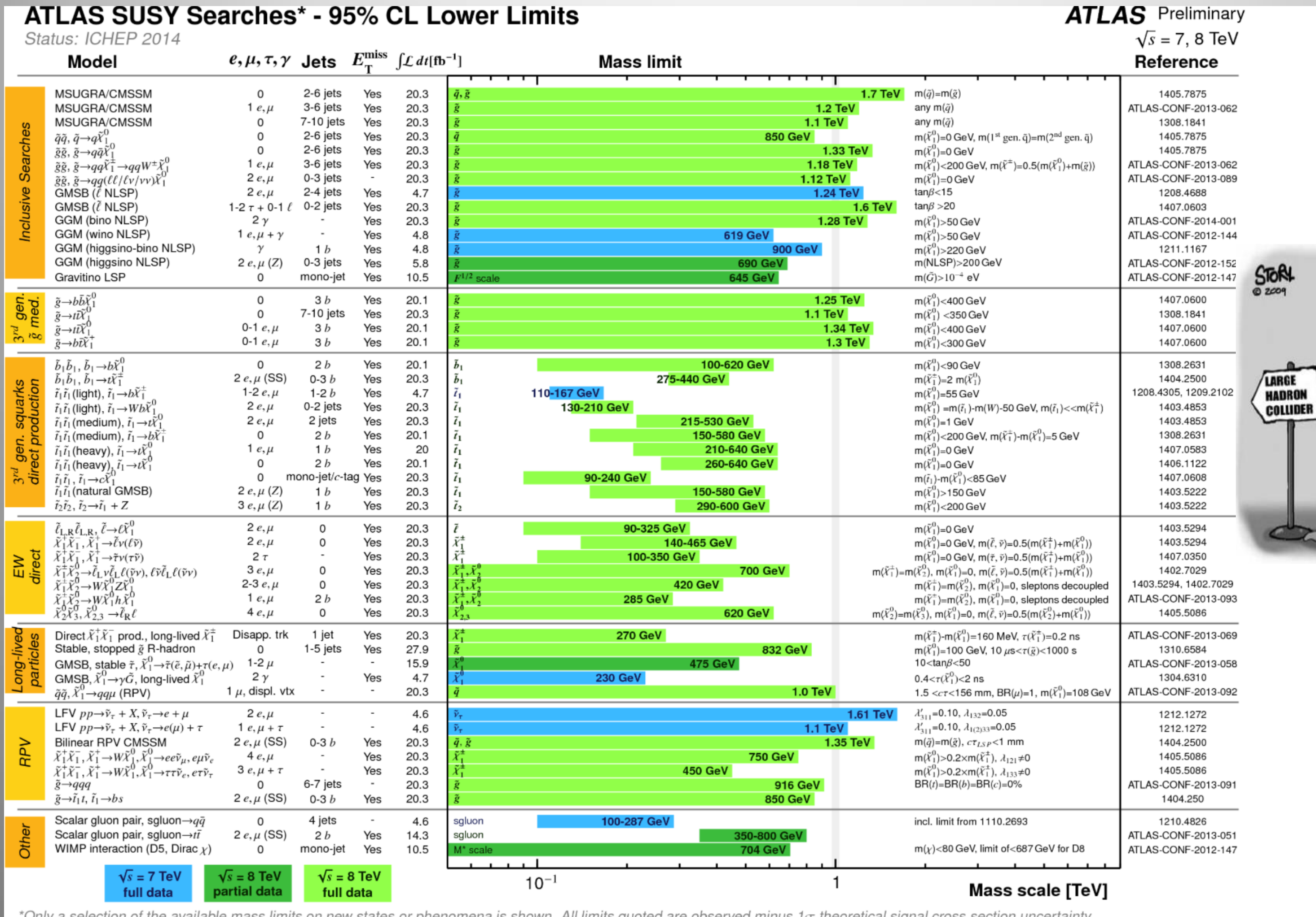
Natural SUSY?

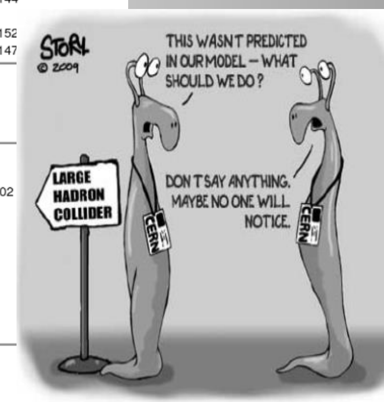


Searches for stop quarks are pushing limits now to 700 GeV

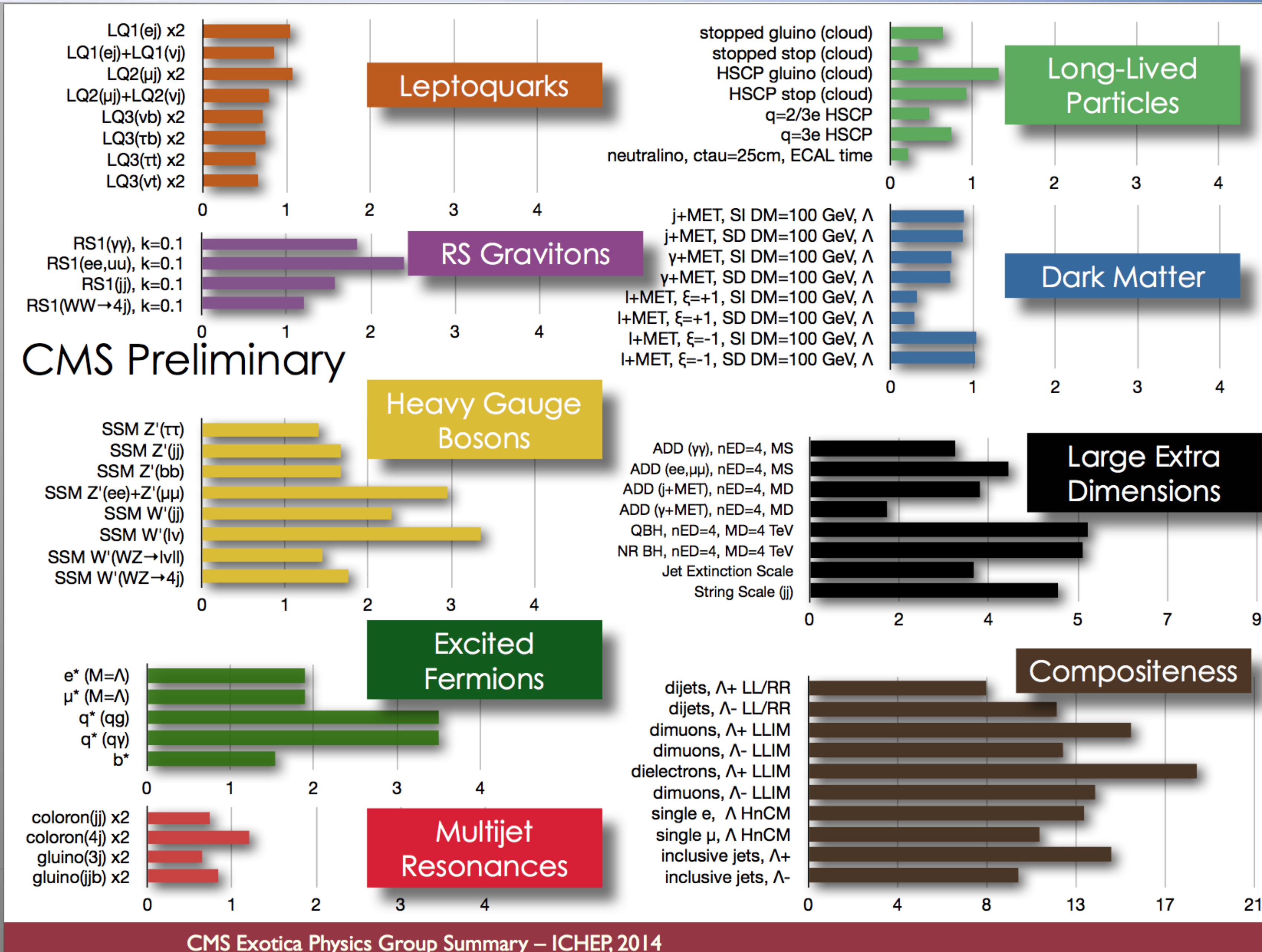
Summary of SUSY Searches

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



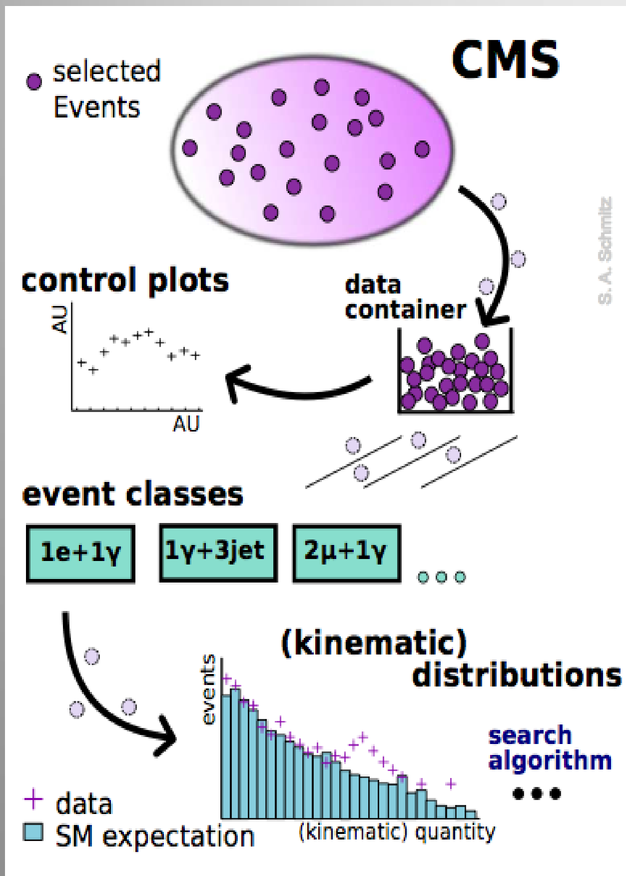


Summary of Exotica Searches



A Global View!

CMS-EXO-10-021



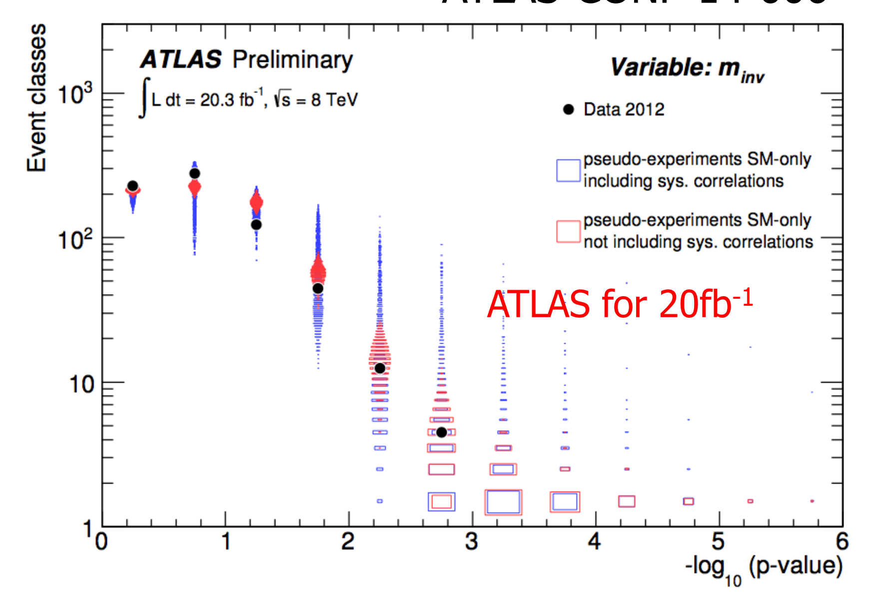
Model independent search

- 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

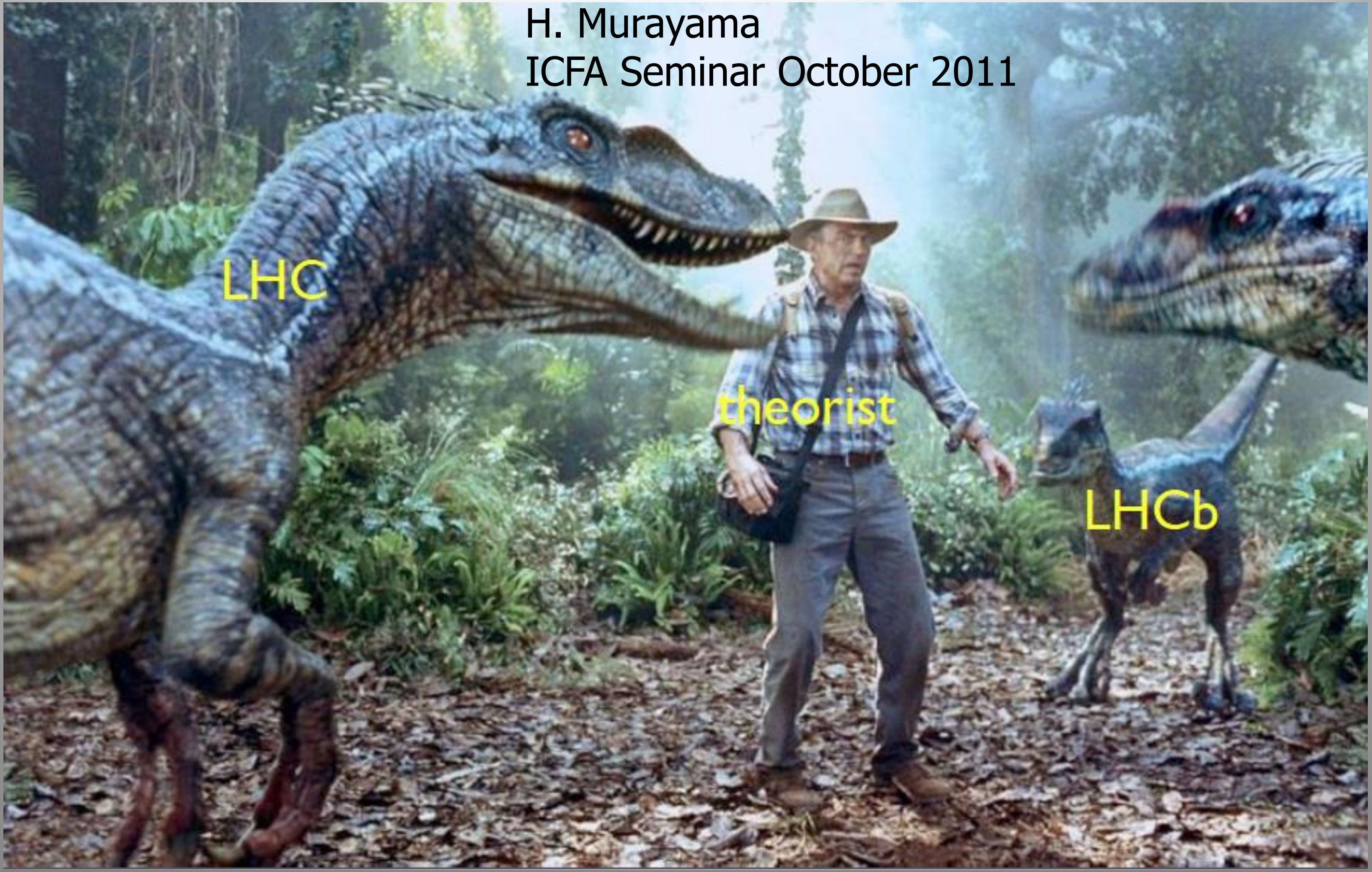
ATLAS-CONF-14-006



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

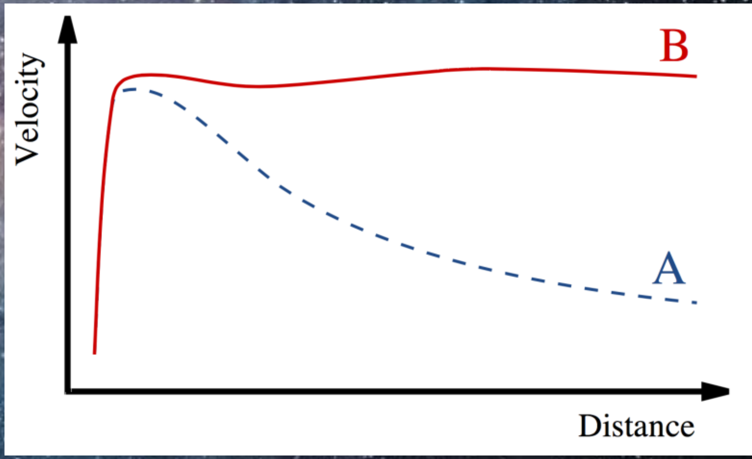
→muons, electrons, photons, (b)jets, MET

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



Dark Matter: The Next Challenge !?!

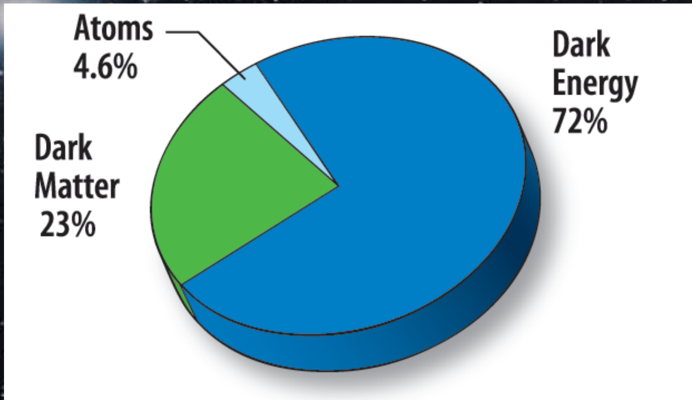
Astronomers found that most of the matter in the Universe must be invisible Dark Matter



'Supersymmetric' particles ?

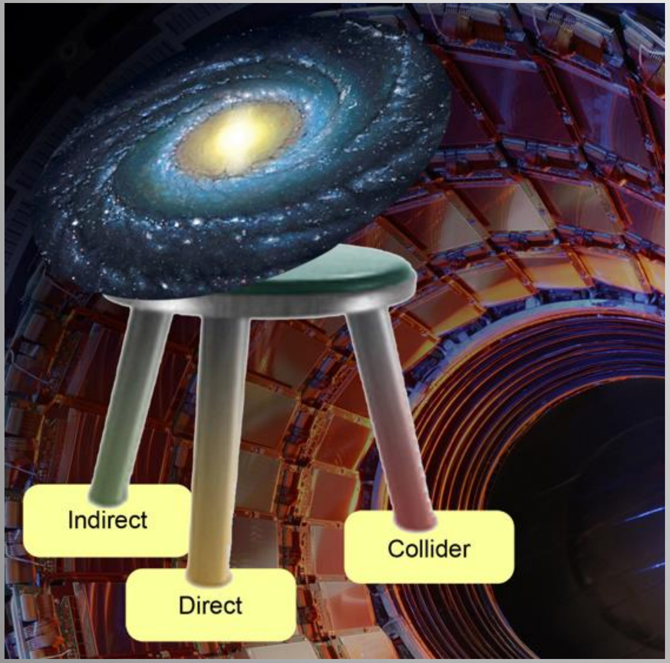
F. Zwicky 1898-1974

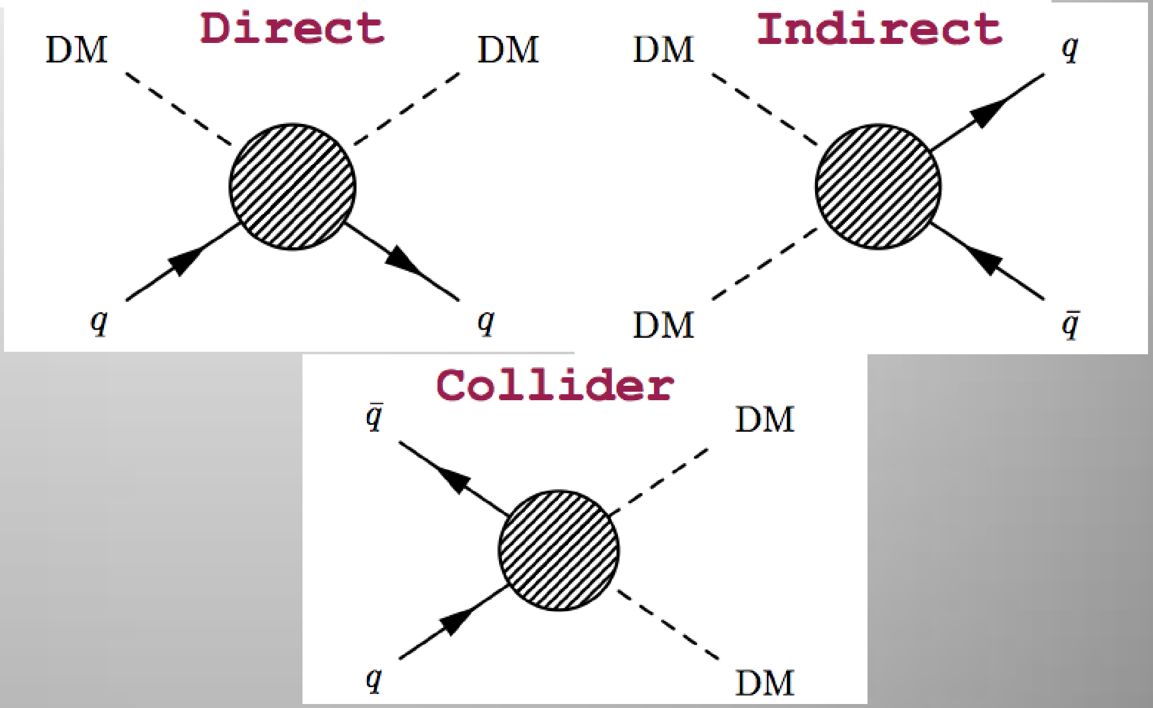
Vera Rubin ~ 1970



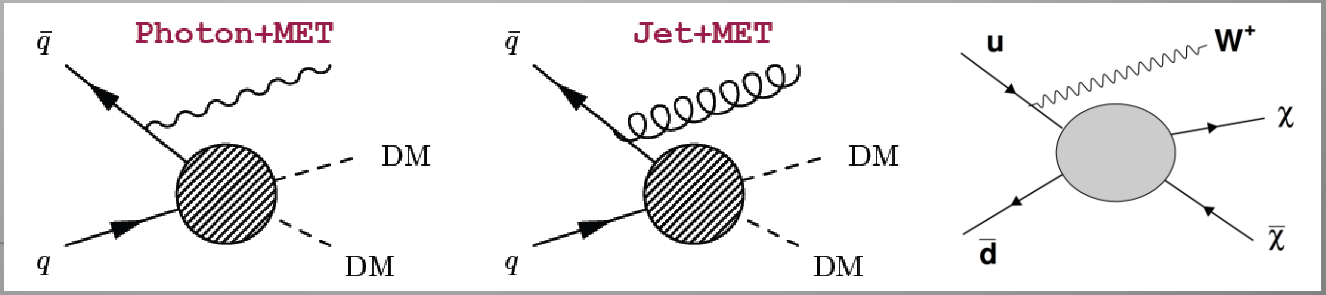
The Generic Dark Matter Connection

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

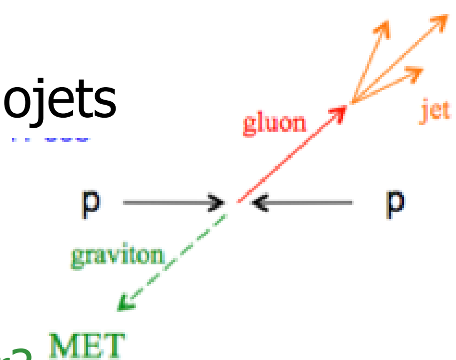


Mono-object Searches in CMS

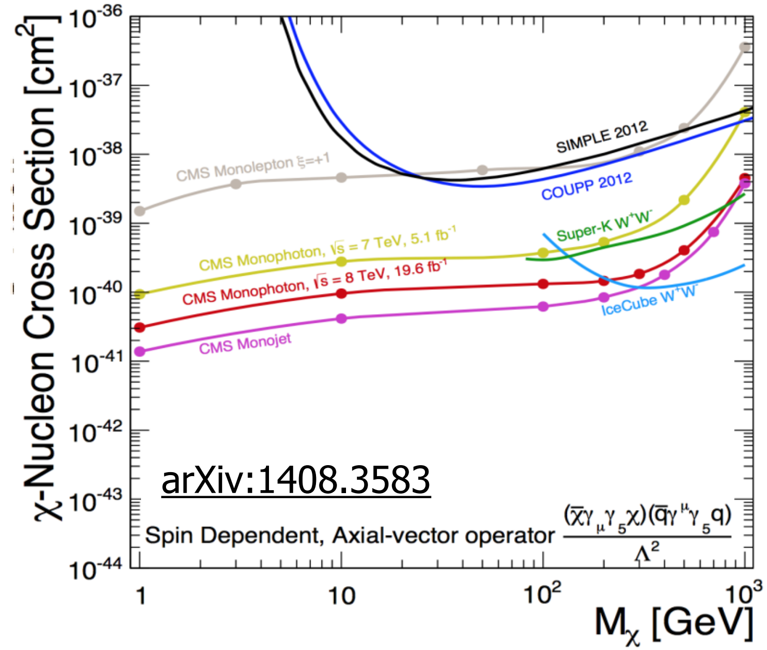
- Mono-jets: Generally the most powerful
- Mono-photons: First used for dark matter Searches
- Mono-Ws: Distinguish dark matter couplings to u- and d-type of quarks
- Mono-Zs: Clean signature
- Mono-Tops: Couplings to tops
- Mono-Higgs: Higgs-portals
- Higgs Decays?

Effective Field Theories for DM interpretation are under attack! Alternatives like SMS proposed…

Example Monojets



Dark Matter?



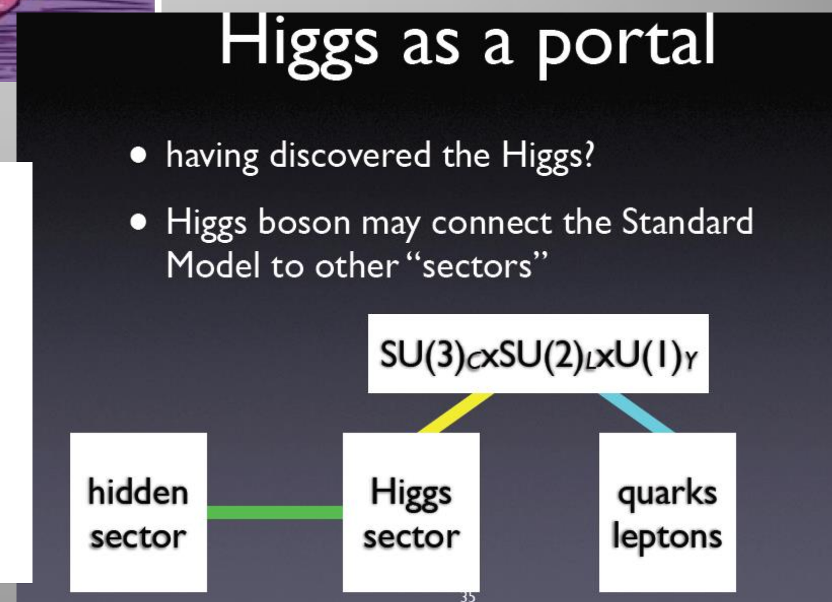
The Future…

The Future: Studying the Higgs…

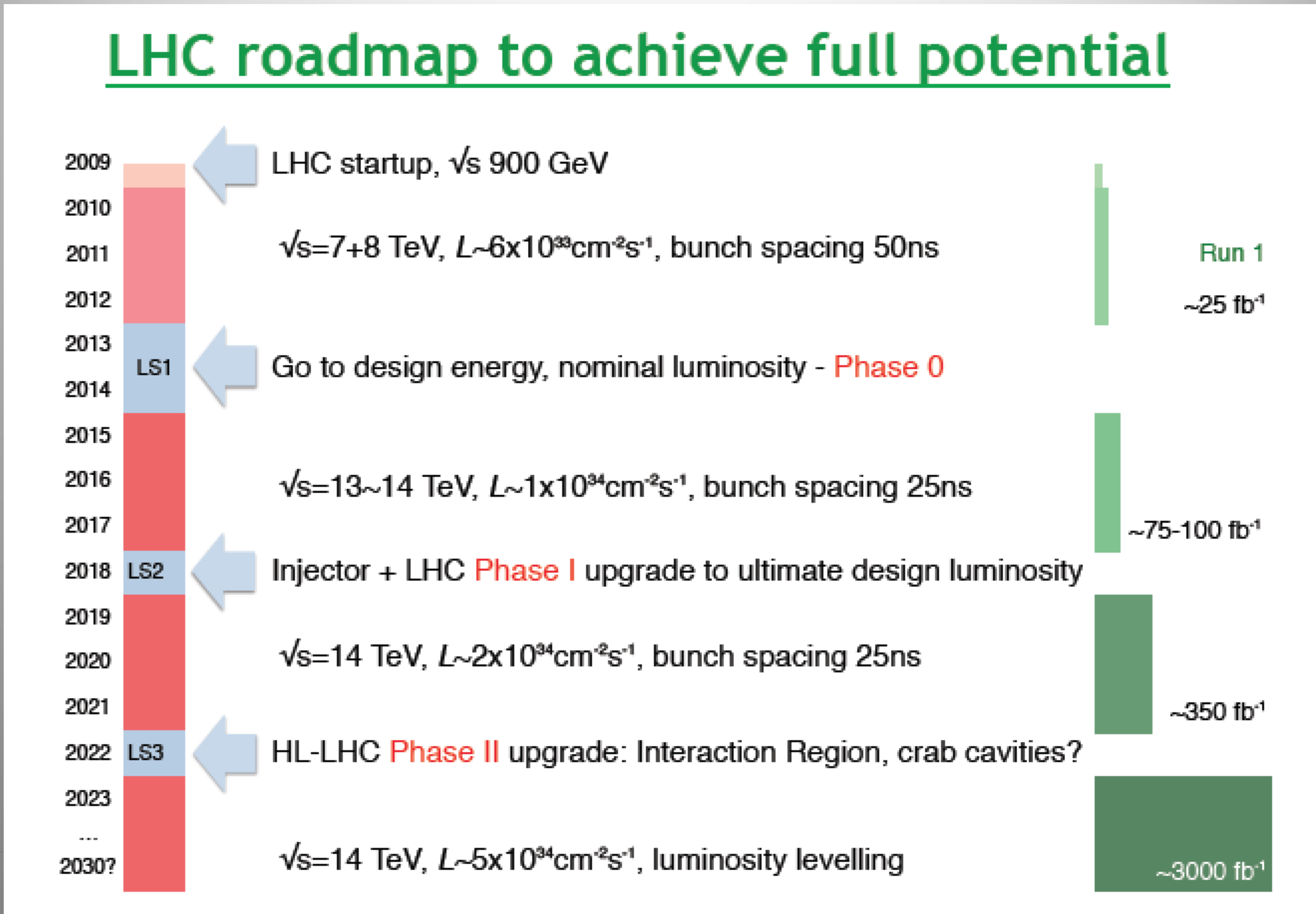
The Higgs is the new particle that may give us crucial insight into the new physics world
We will have to study it!!

Many questions are still unanswered:

- What explain a Higgs mass ~ 126 GeV?
- What explains the particle mass pattern?
- Connection with Dark Matter?
- Where is the antimatter in the Universe?
- ⑤



The LHC Schedule



LHC 2015

- Start with 50 ns – scrub – 25 ns operation
- Conservative beta* to start
- Conservative bunch population
- Reasonable emittance into collisions
- Assuming same machine availability as 2012…

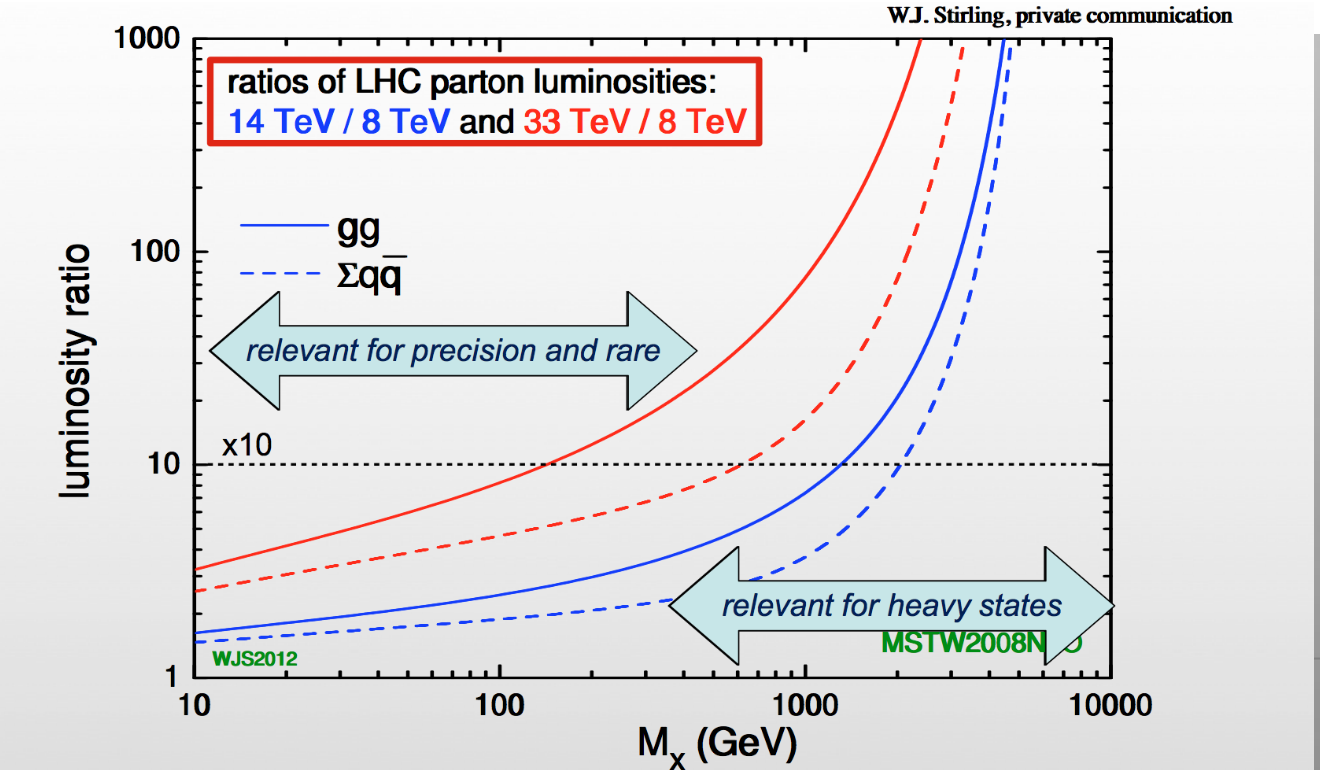
M. Lamont

	Nc	beta* [cm]	ppb	EmitN [um]	Lumi [cm-2s-1]	Days (approx)	Int lumi	Pileup
50 ns	1300	80	1.2e11	2.5	4.6e33	21	**~1 fb^{-1}**	**27**
25 ns (1)	2496	80	1.1e11	2.5	7.4e33	75	**6.8 fb^{-1}**	**22**
25 ns (2)	2496	40	1.1e11	2.5	1.3e34	46	**9.2 fb^{-1}**	**39**

F. Zimmerman, 12/9/14

Physics Program: Key Topics

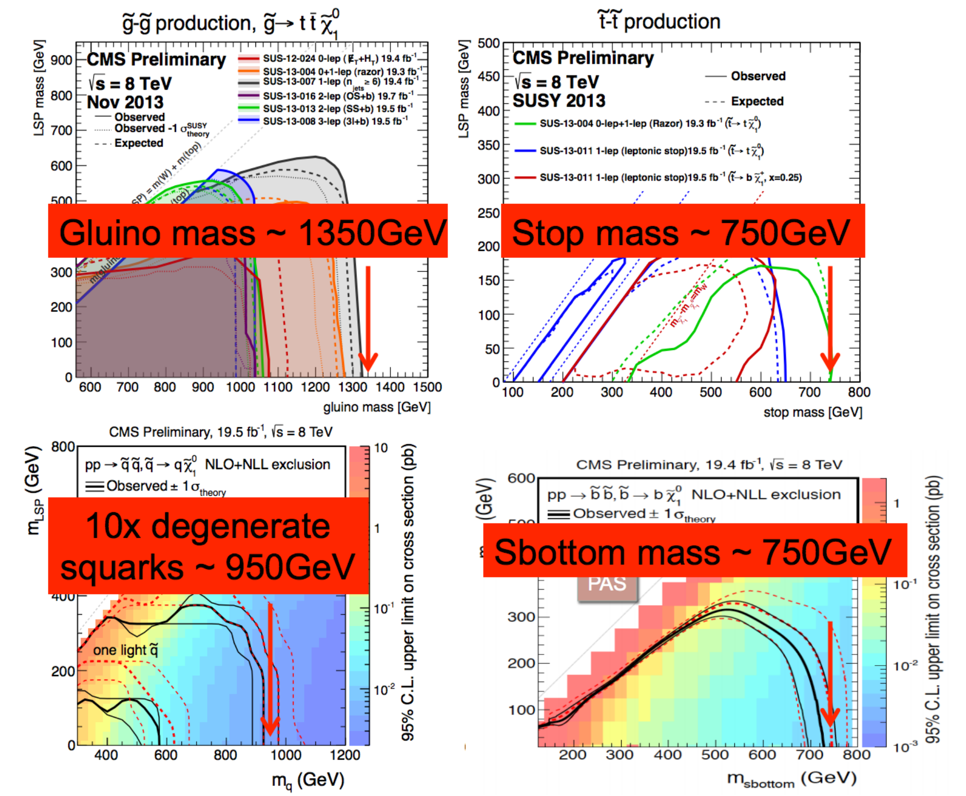
- Properties of the new Higgs boson, precise determination of its characteristics
- High mass reach for new particles and interactions
- Precision measurements
- Rare process



SUSY Prospects @ 2015/2016

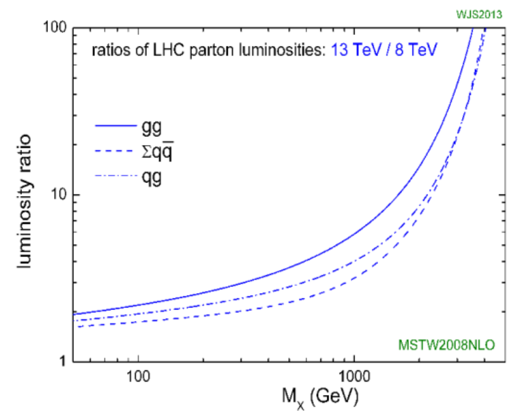
Expect ~ 10-20 fb^{-1} in 2015 & 40 fb^{-1} in 2016 (present guestimates)

Now 2014



2015-2016

Cross Section Scaling 8 -> 13 TeV



Xsection Ratios 13/8 TeV

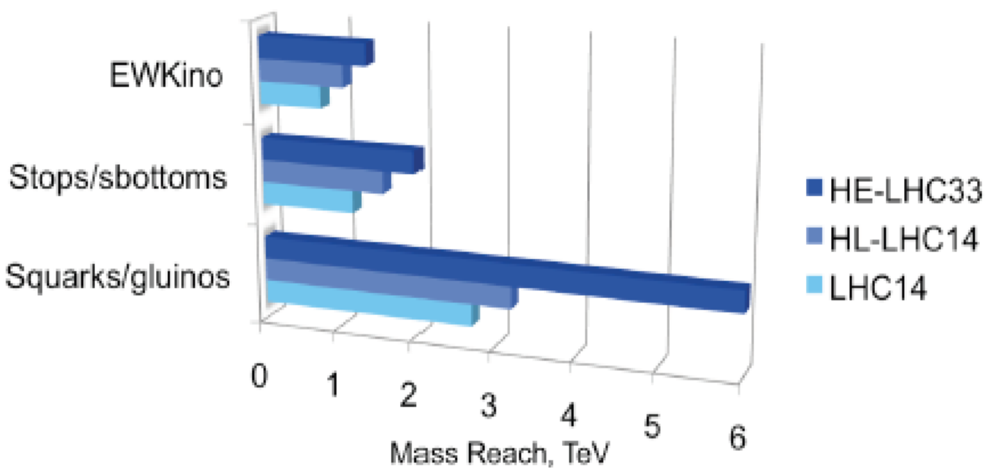
1350GeV gluino: x30
950GeV squark: x20
750GeV squark: x9
350GeV $X^{+-}X^0$: x3
top pairs: x4

~1/fb of 13TeV data surpasses our best gluino limits.
~3/fb of 13TeV data surpasses our sbottom and stop limits.
There will be no relevant SM measurements at 13TeV by the time we have already stepped well into new territory!!!

0.5-1 fb^{-1} would be enough for first analyses entering new territory
We expect that have such a sample by Summer 2015!!

Searches for New Particles in pp

Searches for pair produced SUSY particles



FCC-hh

- Reach sparticle masses search up to about 20 TeV for squarks of light quarks and 6 TeV for stops
- Excited quarks probe the structure of quarks down to 4×10^{-21} m
- Discovery of resonances up to masses of 40 TeV

E.g. 2HDM in SUSY

$m_h, m_H, m_A, m_{H^\pm}$ $\tan\beta \equiv \langle\Phi_2\rangle / \langle\Phi_1\rangle$

Fine tuning and naturalness: (N.Craig, BSM@100 Wshop)

$\Delta \approx \sin^2(2\beta)\frac{m_H^2}{m_h^2}$ $\Delta(\tan\beta = 50) \leq 1 \rightarrow m_H \lesssim 3.1 \text{ TeV}$

Extra H can be heavy, well above LHC reach, but cannot be arbitrarily heavy

Upper limit for higher Higgs mass in 2HDM models?

- **Why 100 TeV ?**
  - Need for O(100 TeV) in the cards since the SSC days: fully explore EWSB, probing in particular unitarization of WW scattering at m(WW)> TeV, and explore dynamics well above EWSB

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, like SUSY
- 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: