

Physics at the LHC Beyond the Standard Model

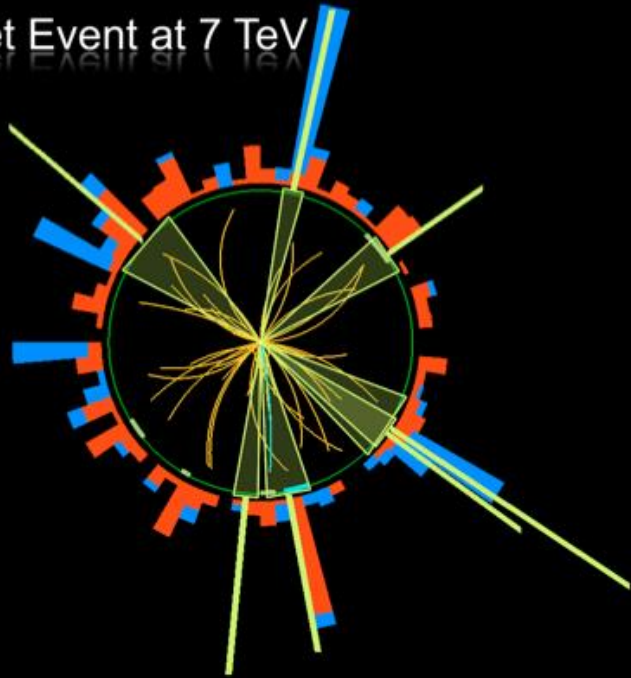
Albert De Roeck
CERN, Geneva, Switzerland
Antwerp University Belgium
UC-Davis California USA
IPPP, Durham, UK
British University of Egypt, Cairo

6th October 2014

International Workshop on LHC, Astrophysics, Medical and Environmental
Physics. Shkodra (Albania), 6-8 October 2014



Multi Jet Event at 7 TeV

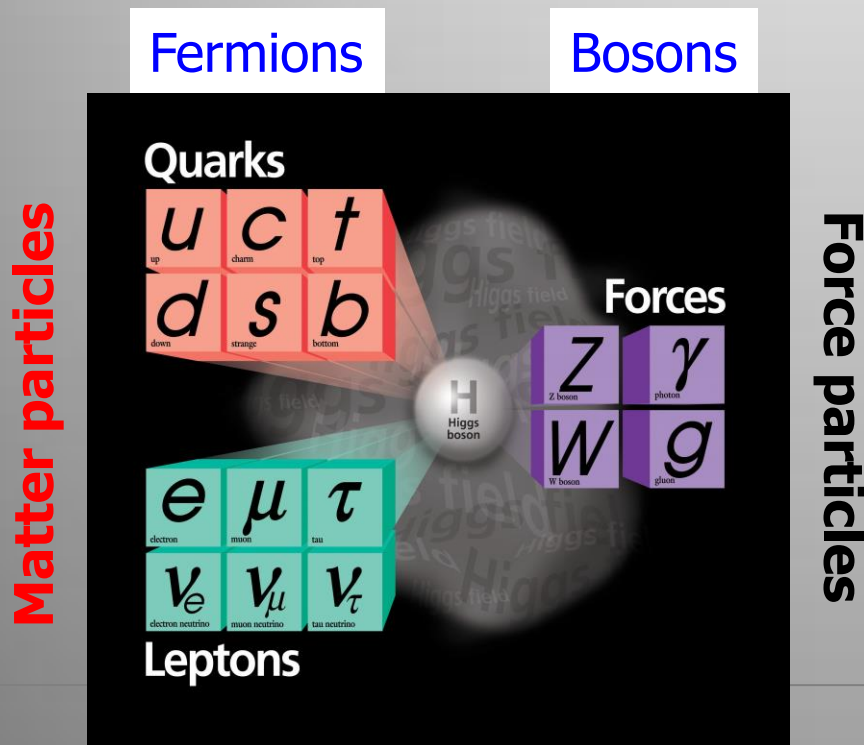


Outline

- 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:



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 $\frac{1}{2}$
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

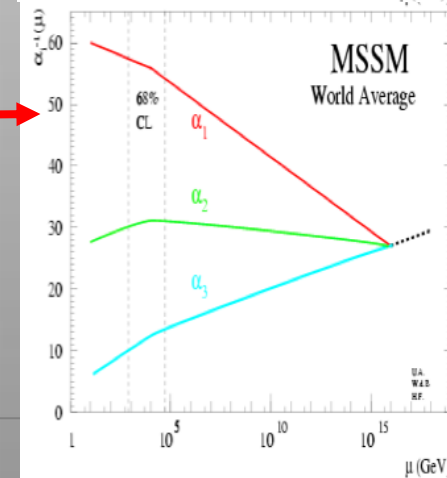
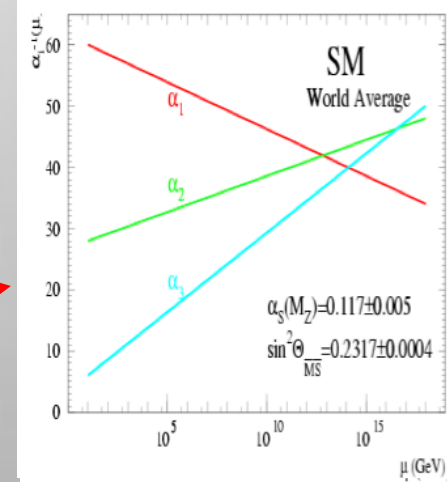
- tells us **how** but not **why**
 - 3 flavour families? Mass spectra? Hierarchy?
- needs fine tuning of parameters to level of 10^{-30} !
- has no connection with gravity
- no unification of the forces at high energy

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



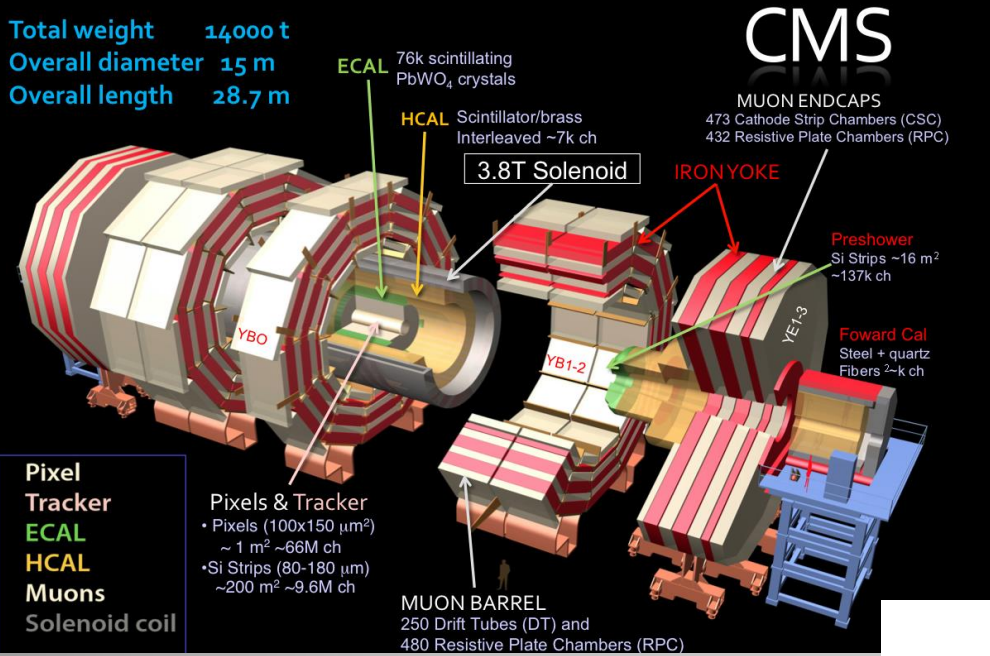
LHC BSM(*) Hunting Detectors

(*) Beyond the Standard Model

The CMS Experiment

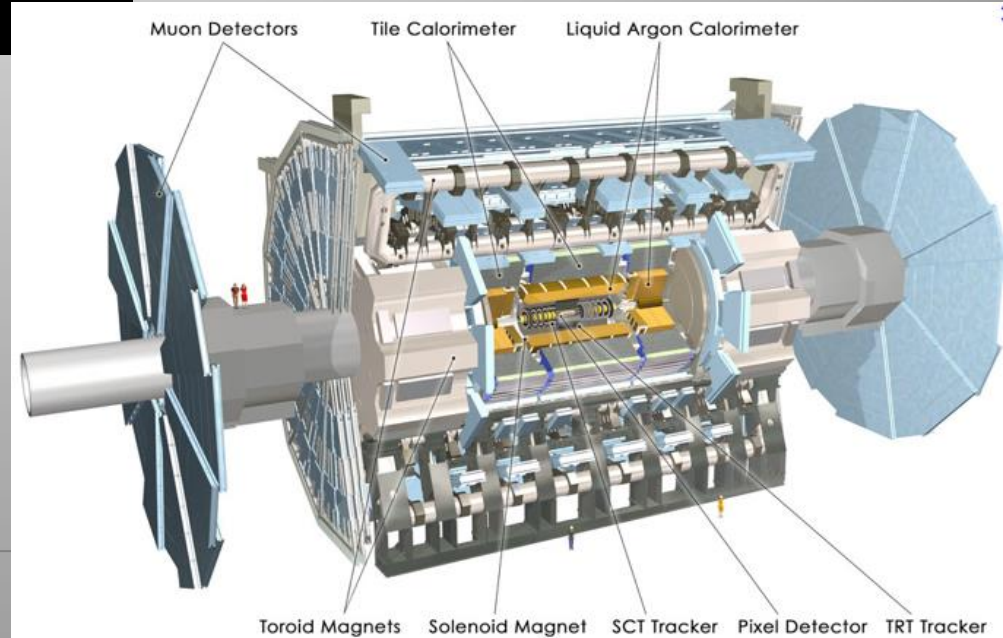
Luminosity: 5 fb^{-1} (7 TeV) and 20 fb^{-1} (8 TeV)

Total weight 14,000 t
Overall diameter 15 m
Overall length 28.7 m



The ATLAS Experiment

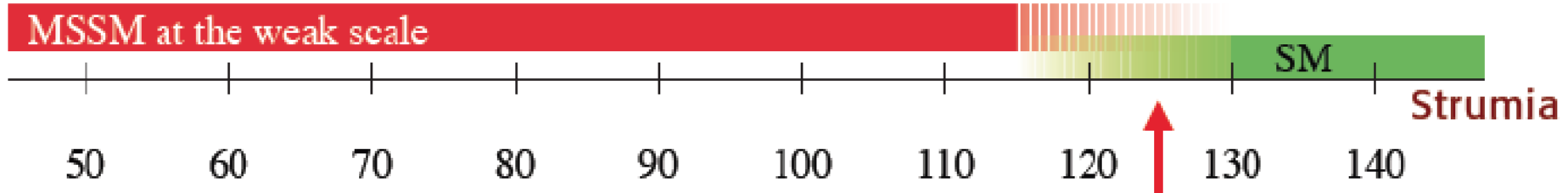
Also LHCb via eg $B_s \rightarrow \mu\mu$ and other precision flavor tests



A Higgs...

A malicious choice!

$$m_H = 125.6 \pm 0.4 \text{ GeV}$$



The Higgs:
so simple yet so unnatural

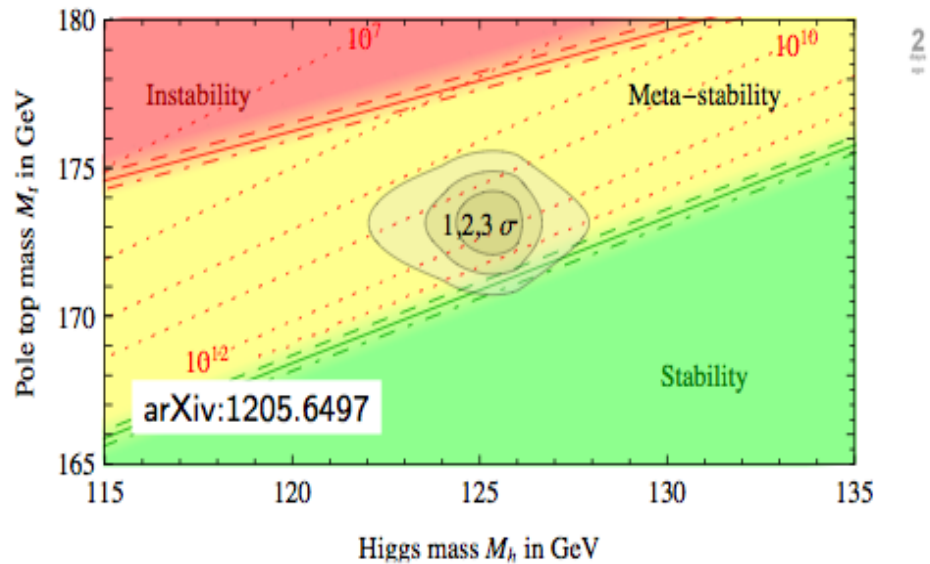
Guido Altarelli

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?

Important SM parameter → stability of EW vacuum



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)

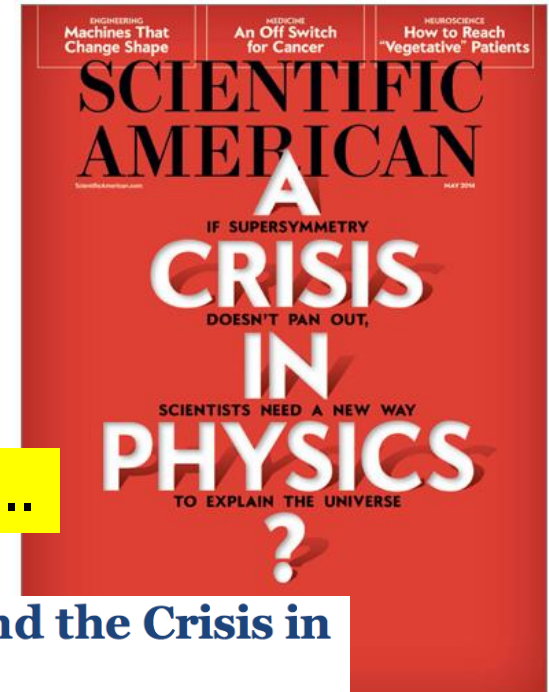
New Physics inevitable?
But at which scale/energy?

But Where Is Everybody?

N. Arkani-Hamed

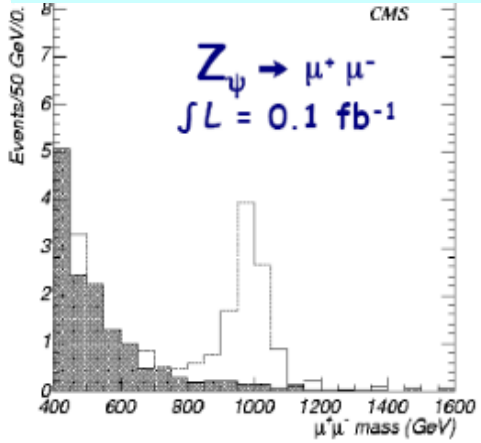
...The May Issue...

Supersymmetry and the Crisis in Physics

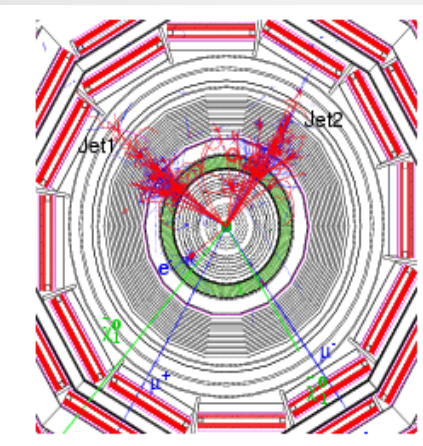


New Physics?

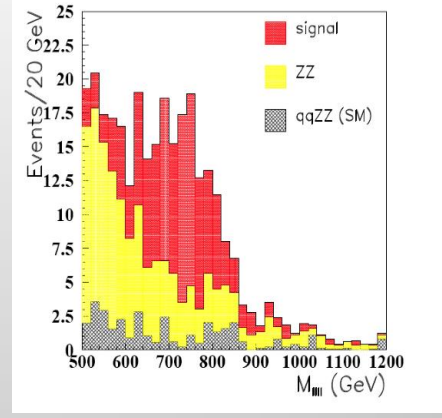
New Gauge Bosons?



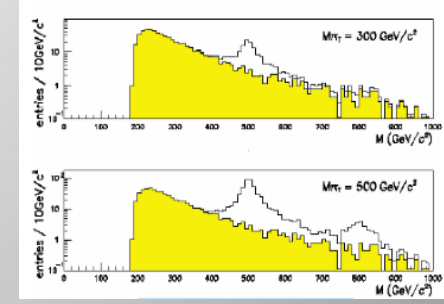
Supersymmetry



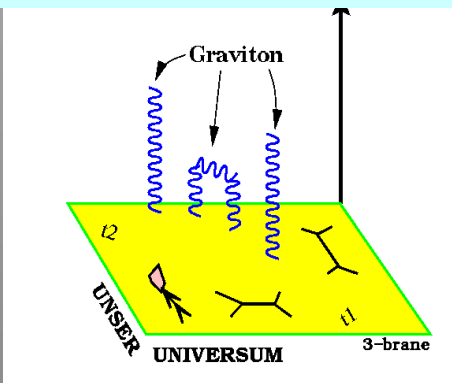
ZZ/WW resonances?



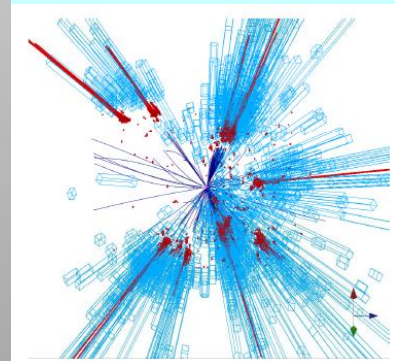
Technicolor?



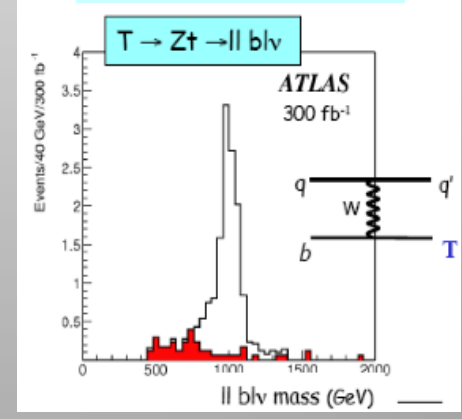
Extra Dimensions?



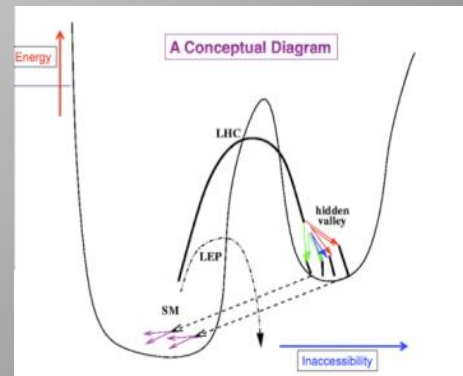
Black Holes???



Little Higgs?

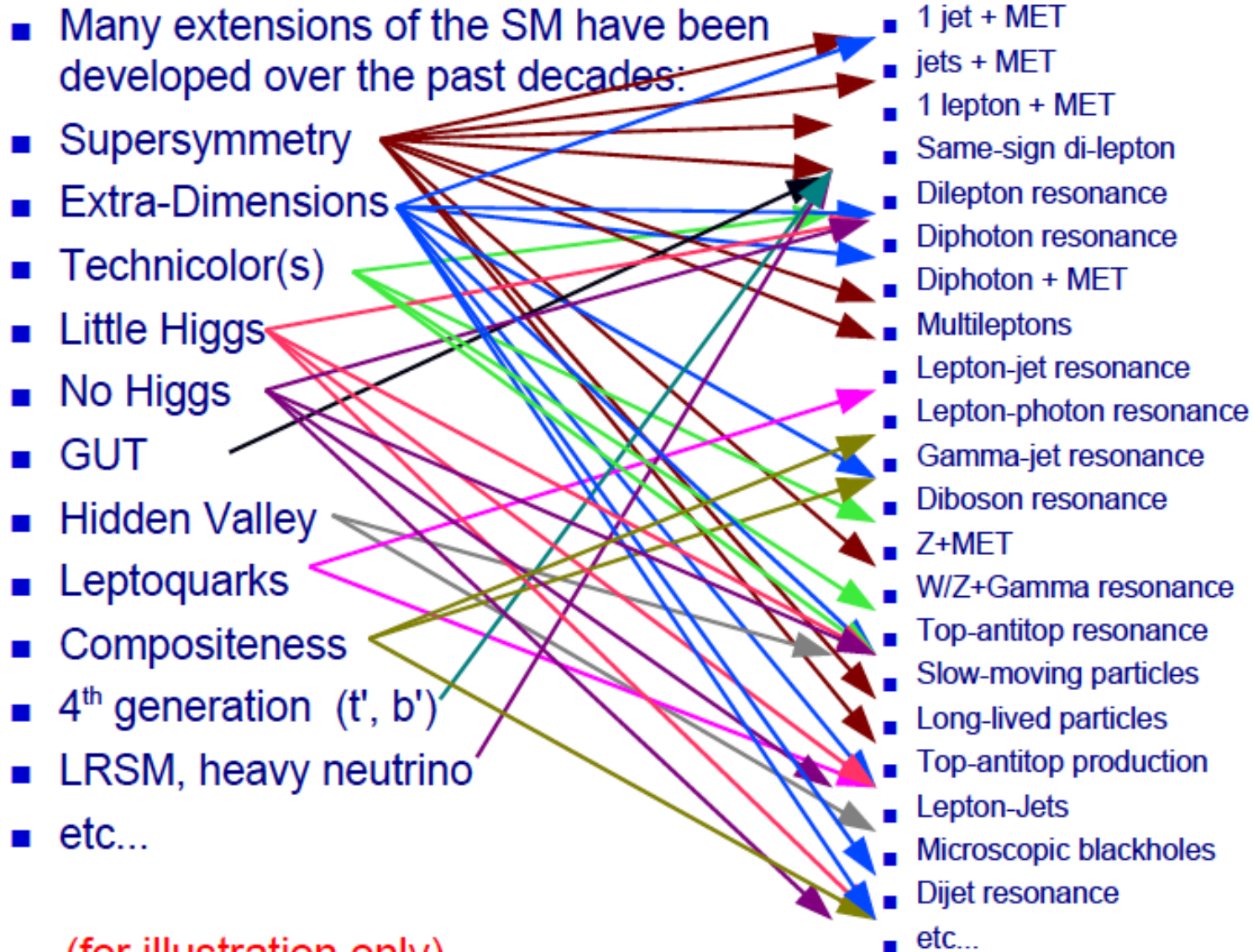


Hidden Valleys?



What stabilizes 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



(for illustration only)

LHC data and Theorists



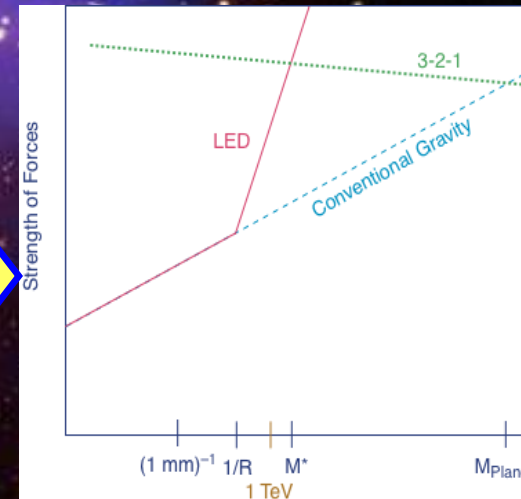
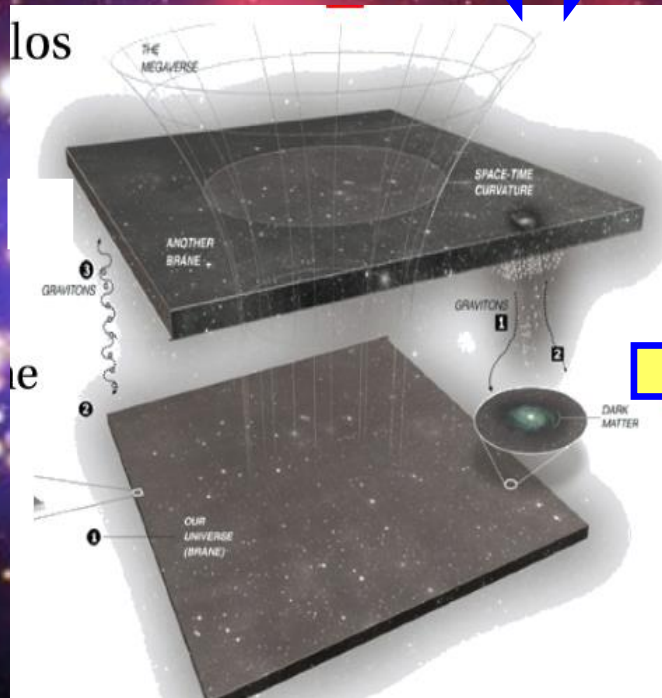
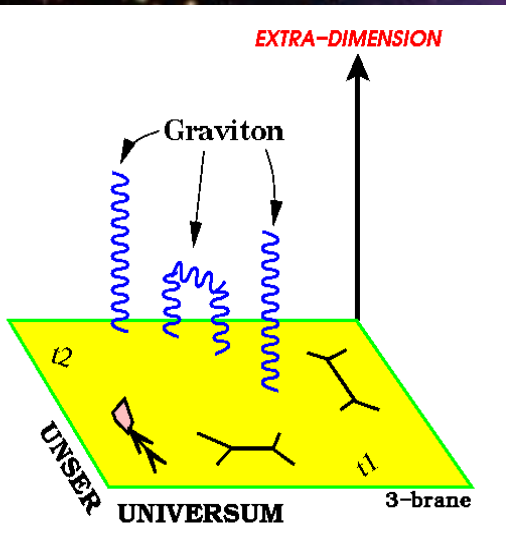
"Data are coming! Data are coming!"

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

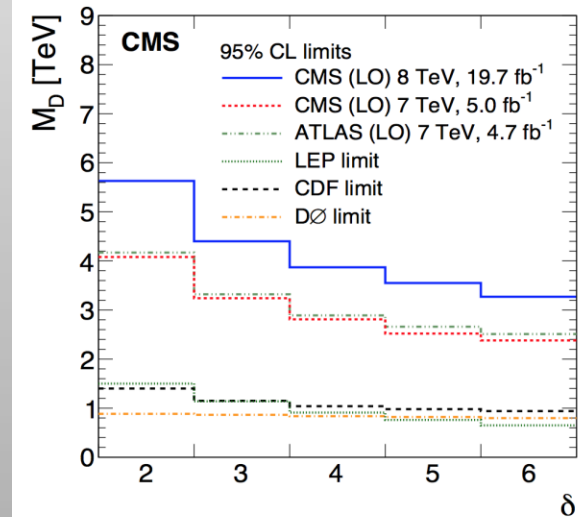
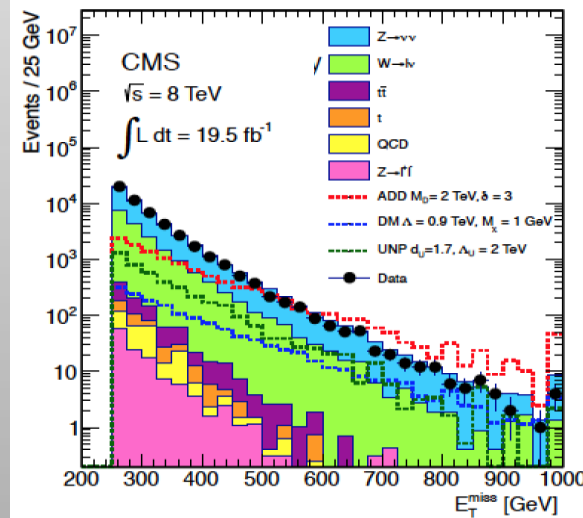
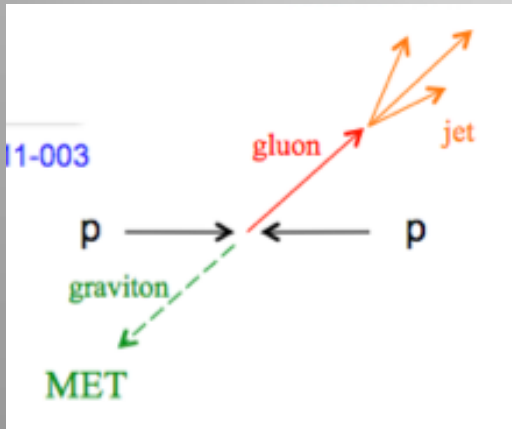
Mono-jet final state + Missing E_T (ADD)

$p_T \text{ jet} > 110 \text{ GeV}$
 $\text{MET} > 200 \text{ GeV}$

Limits on M_D
 between
 3 and 4 TeV

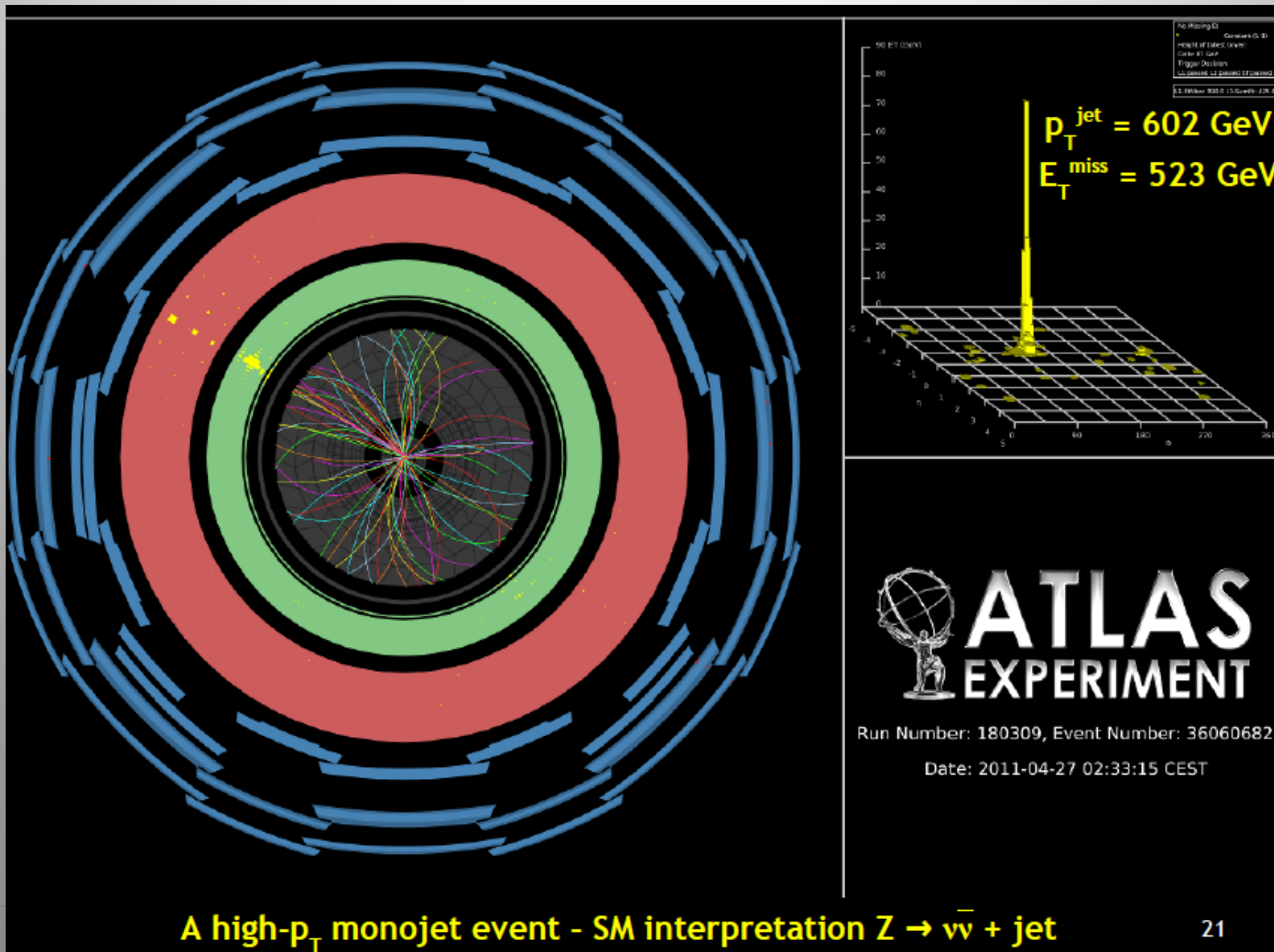
arXiv:1408.3583

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]	$\delta=3$ Exp.	$\delta=3$ Obs.	$\delta=6$ Exp.	$\delta=6$ Obs.
CMS Monojet	8	19.5	3.94	3.96	2.95	2.94

A High p_T Mono-jet event



Quantum Black Holes

- Schwarzschild radius

Landsberg, Dimopoulos, Giddings, Thomas, Rizzo

4-dim., $M_{\text{gravity}} = M_{\text{Planck}}$:

$$R_s \sim \frac{2}{M_{\text{Pl}}^2} \frac{M_{\text{BH}}}{c^2}$$

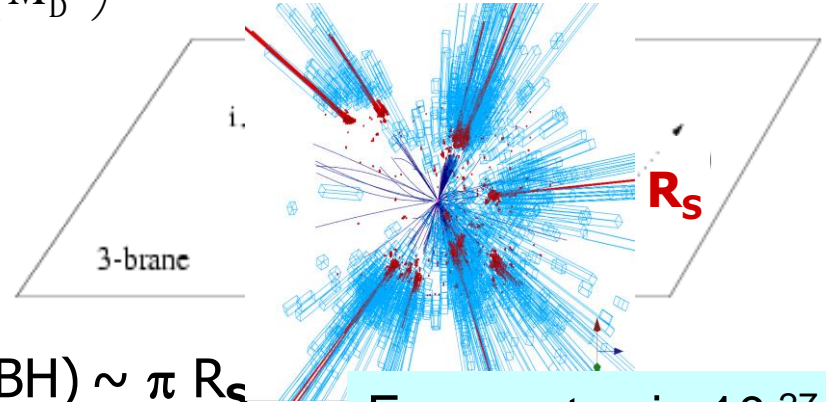
$$R_s \rightarrow \ll 10^{-35} \text{ m}$$

4 + n-dim., $M_{\text{gravity}} = M_{\text{D}} \sim \text{TeV}$:

$$R_s \sim \frac{1}{M_{\text{D}}} \left(\frac{M_{\text{BH}}}{M_{\text{D}}} \right)^{\frac{1}{n+1}}$$

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

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



Evaporates in 10^{-27} sec

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

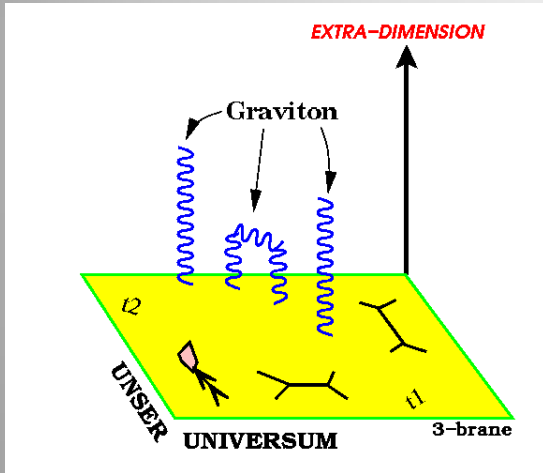
e.g. For $M_{\text{D}} \sim 1 \text{ TeV}$ and $n=3$, produce 1 event/second at the LHC

- Black holes decay immediately by Hawking radiation (democratic evaporation)

- large multiplicity
- small missing E
- jets/leptons ~ 5

expected signature (quite spectacular ...)

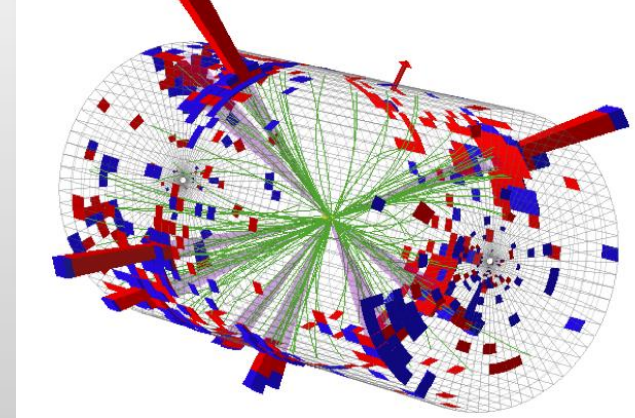
Search for Micro Black Holes



Nice events, eg a 10 jet event

Extra Dimensions!

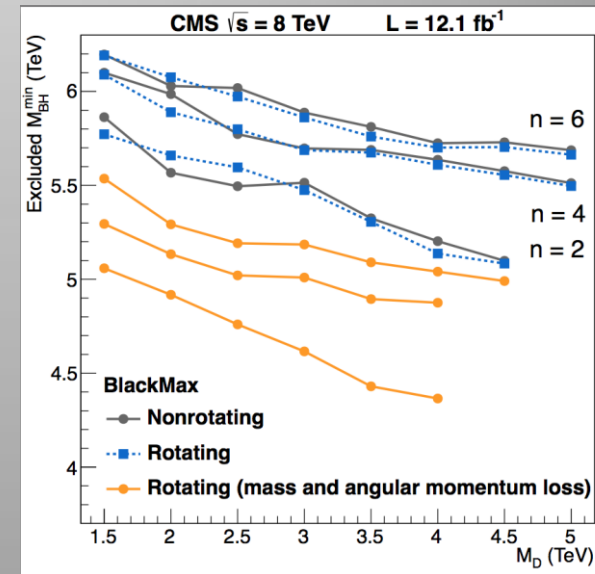
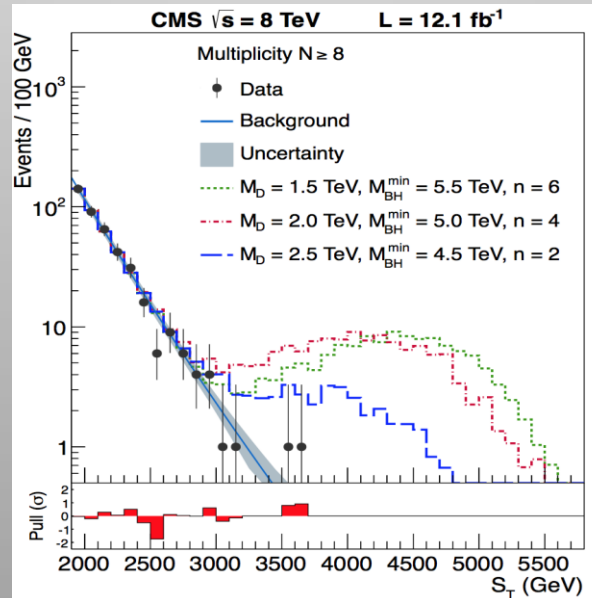
Planck scale
a few TeV?



arXiv:1202.6396

Look for the decay products
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 $\sim 5 \text{ TeV}$ depending on assumptions

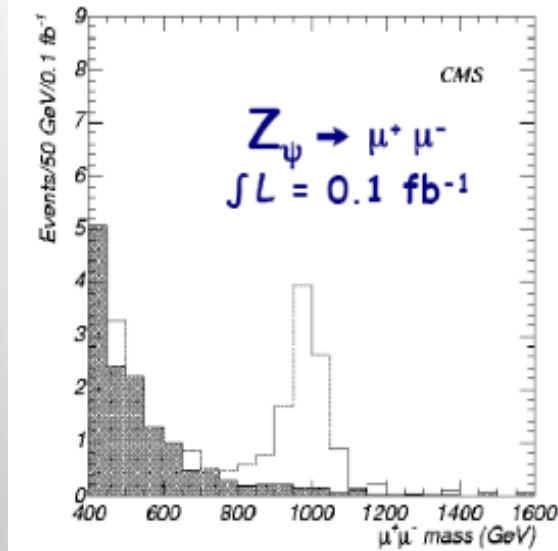
E.g. Di-lepton Resonance

Plot the di-lepton invariant mass

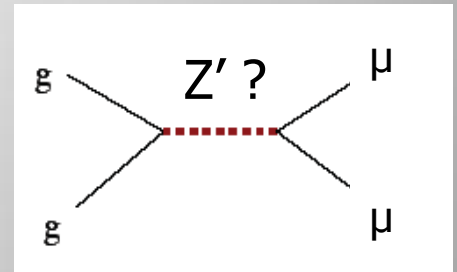
A peak!!

A new particle!!

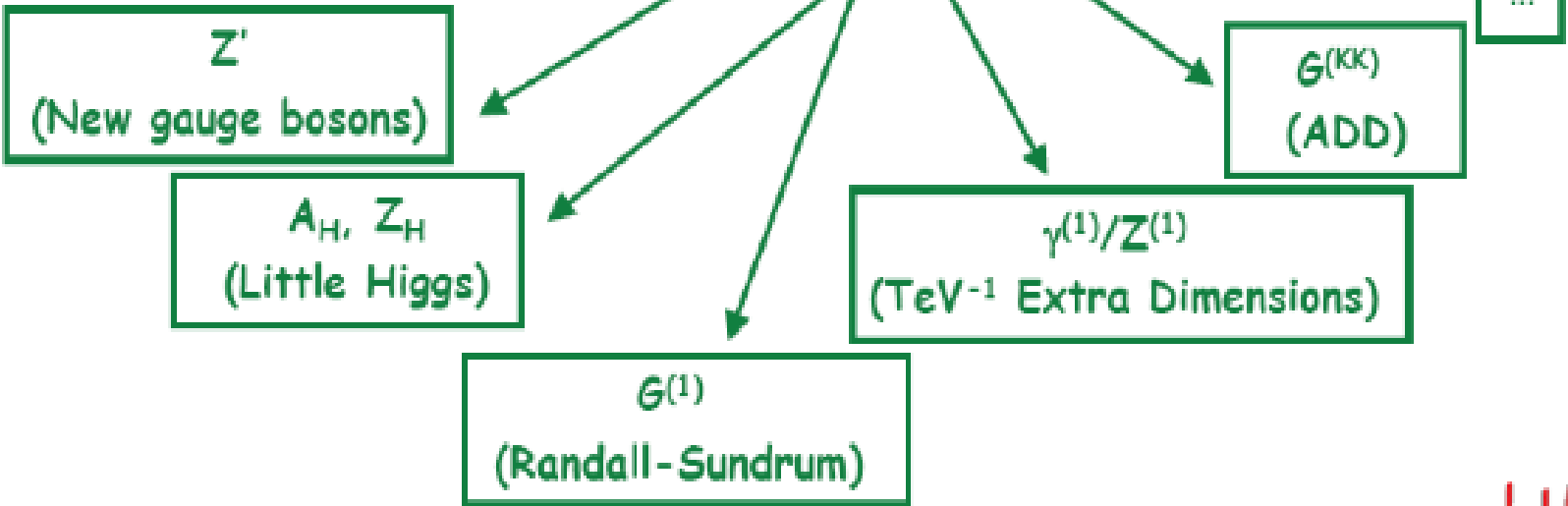
A discovery!!



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



Example : The Di-lepton channel



2011: Z' Boson to ee or μμ?

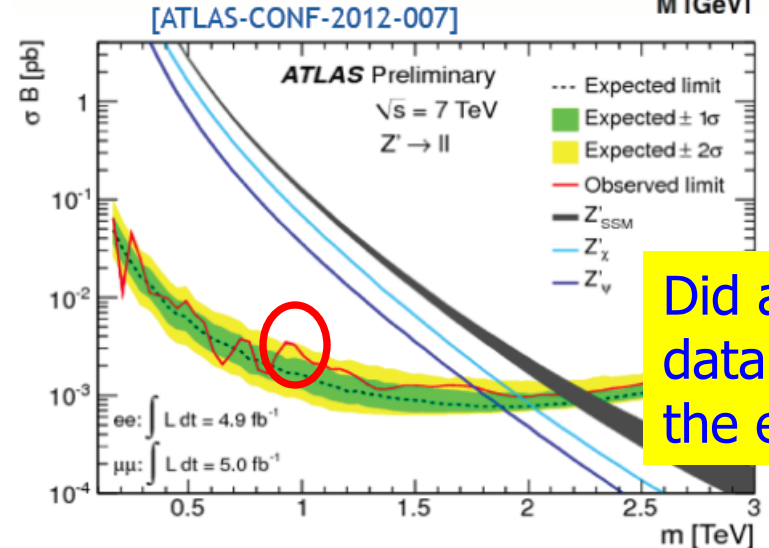
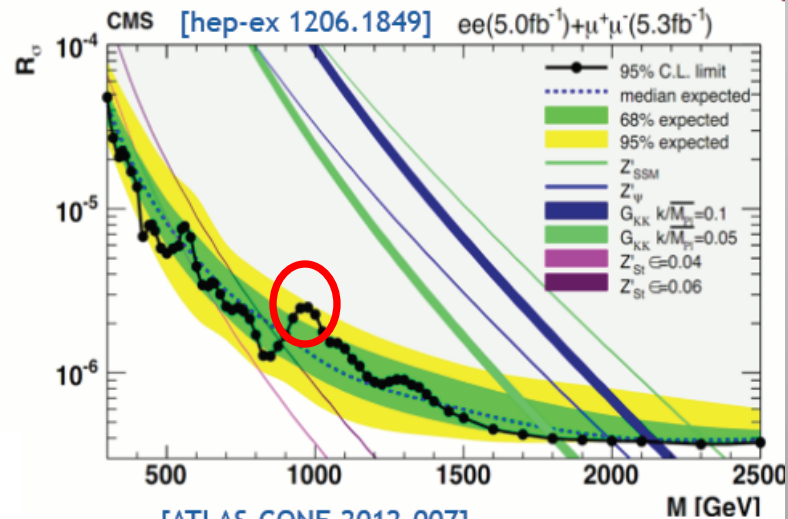
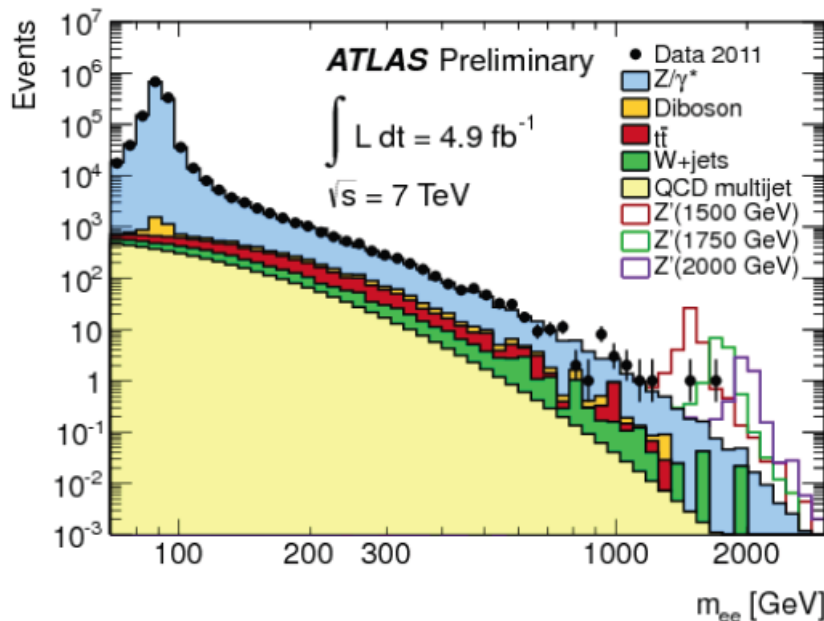
$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

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 $e+\mu$
 - similar in scale to 2011 Higgs excess

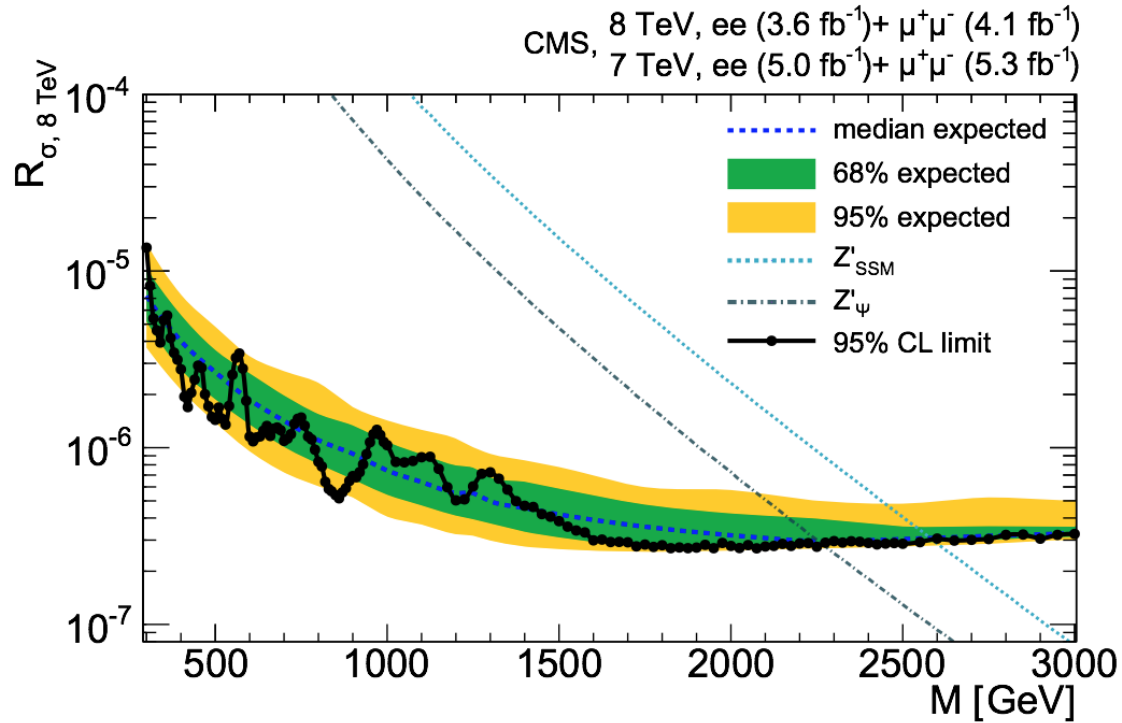
Worth watching in 2012's 8 TeV data...



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

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

- Limits on the combined 7 TeV and 8 TeV data from 2011+2012

- $M(Z'_{\text{SSM}}) : 2950 \text{ GeV}$ ' at 95% C.L.
- $M(Z'_\psi) > 2600 \text{ GeV}$ at 95% C.L.

Excess just below 1 TeV all but gone in CMS data

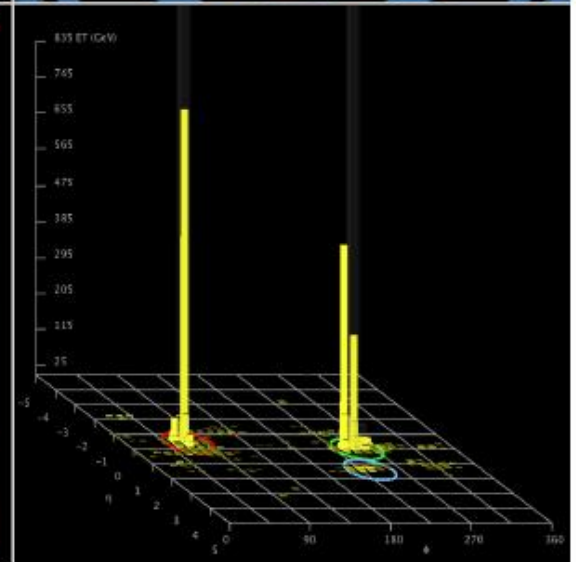
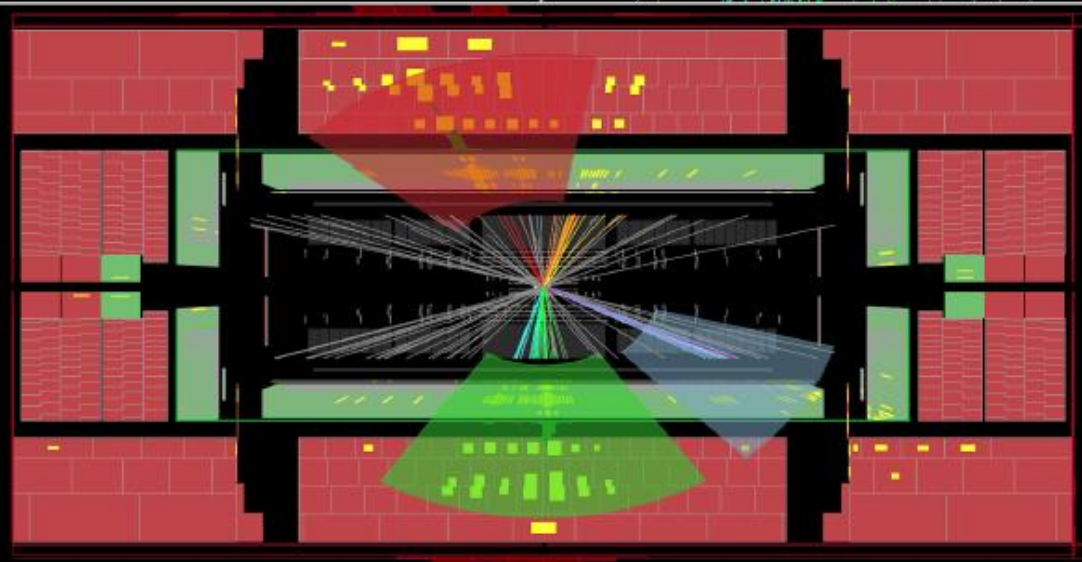
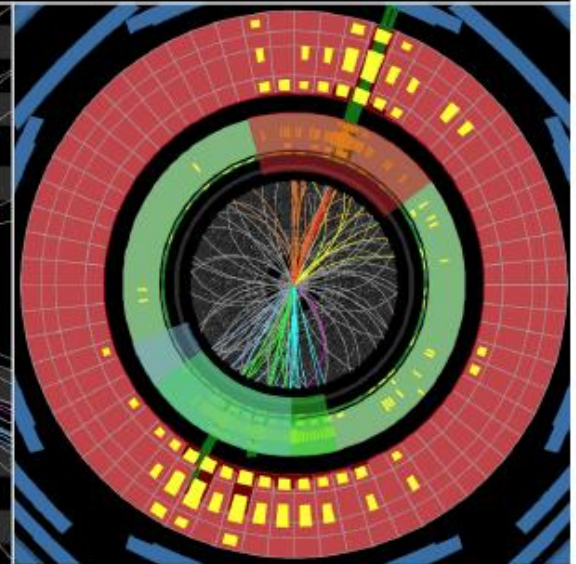
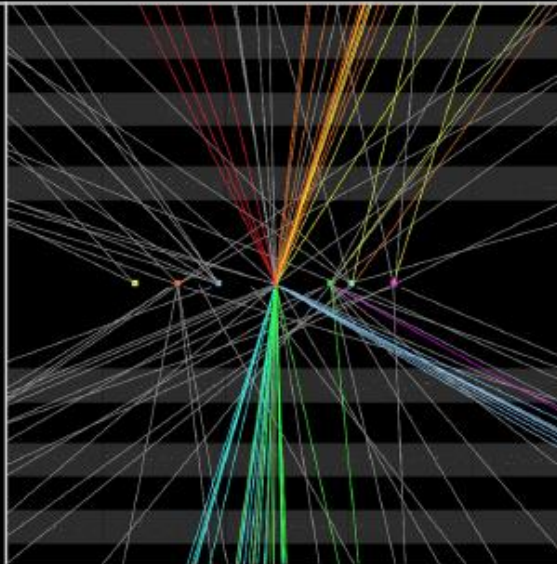
Di-jet Resonances



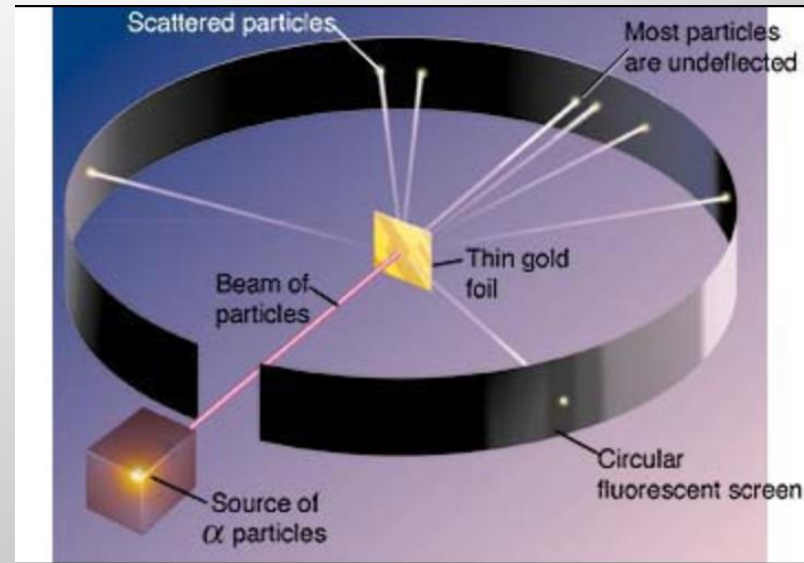
ATLAS
EXPERIMENT

Run Number: 205113, Event Number: 34879440

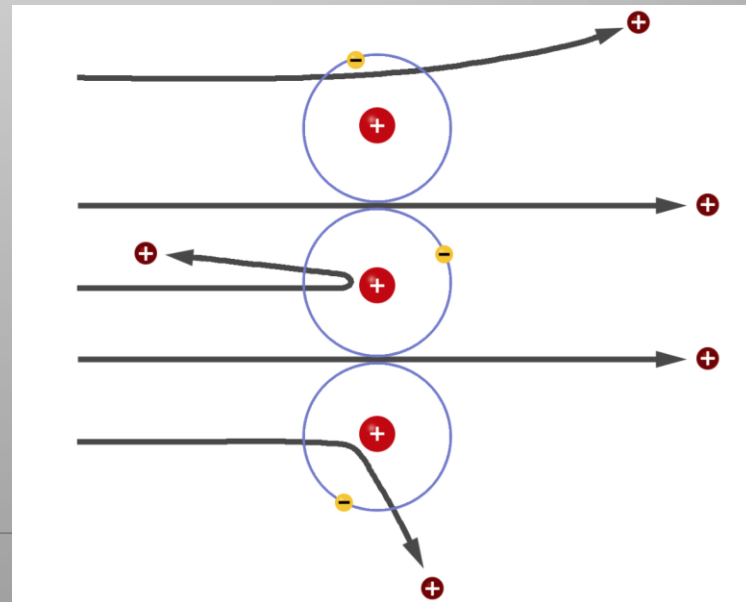
Date: 2012-06-18 12:25:45 CEST



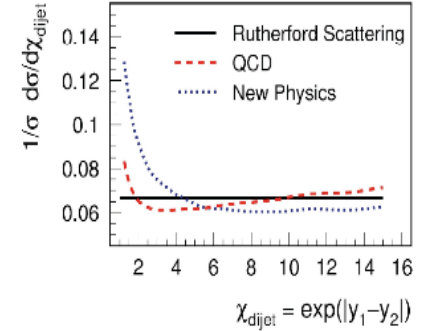
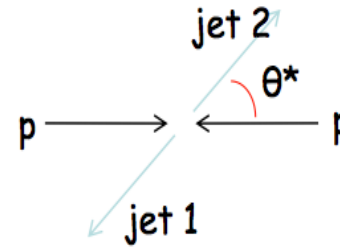
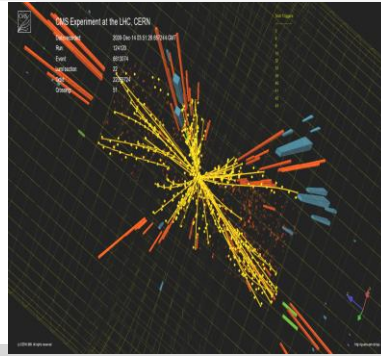
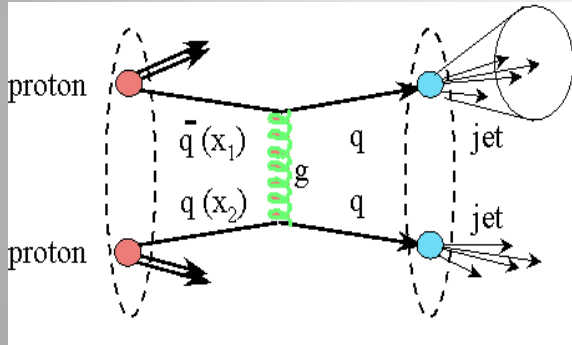
Are Quarks Elementary Particles?



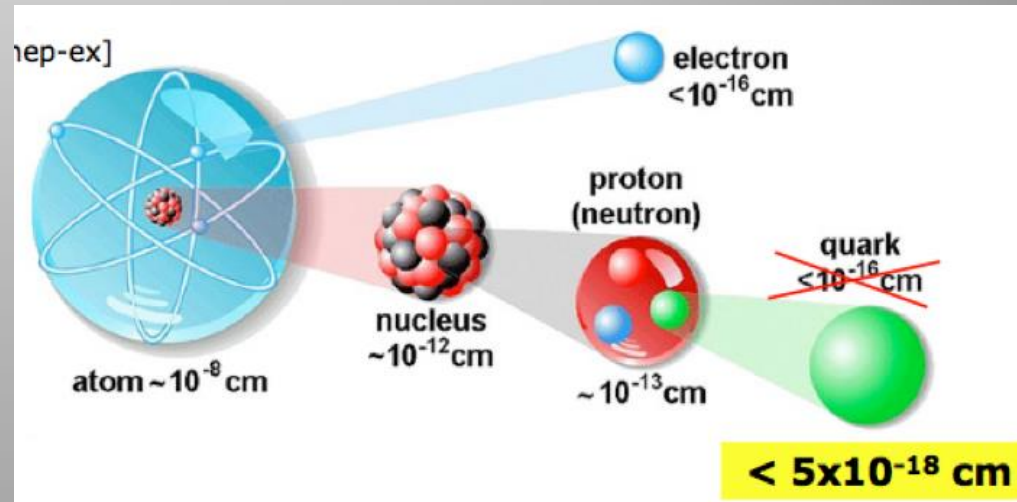
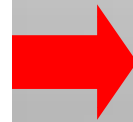
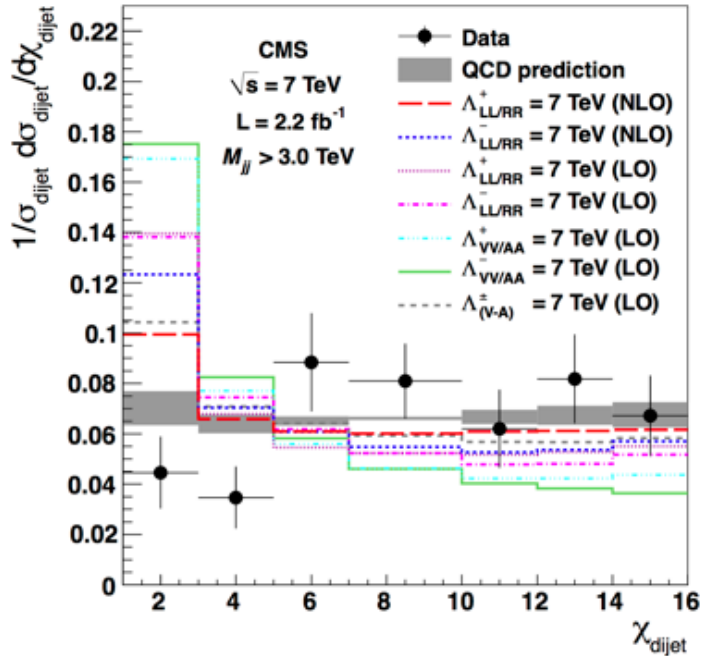
Rutherford experiment:
Unexpected backscattering
of α -particles:
Evidence for the structure
of atoms !! (1911)



Are Quarks Elementary Particles?

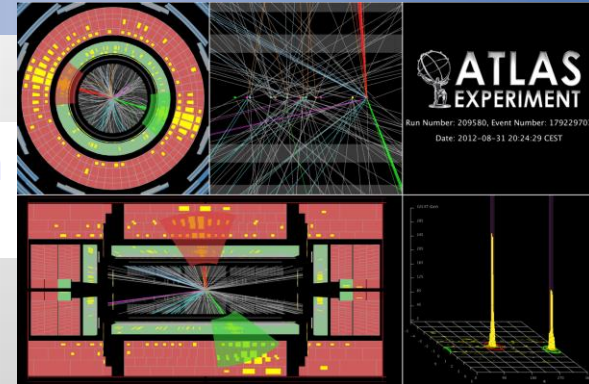


Measurement of the production angle of the jet with respect to the beam
 -> High Energy Rutherford Experiment



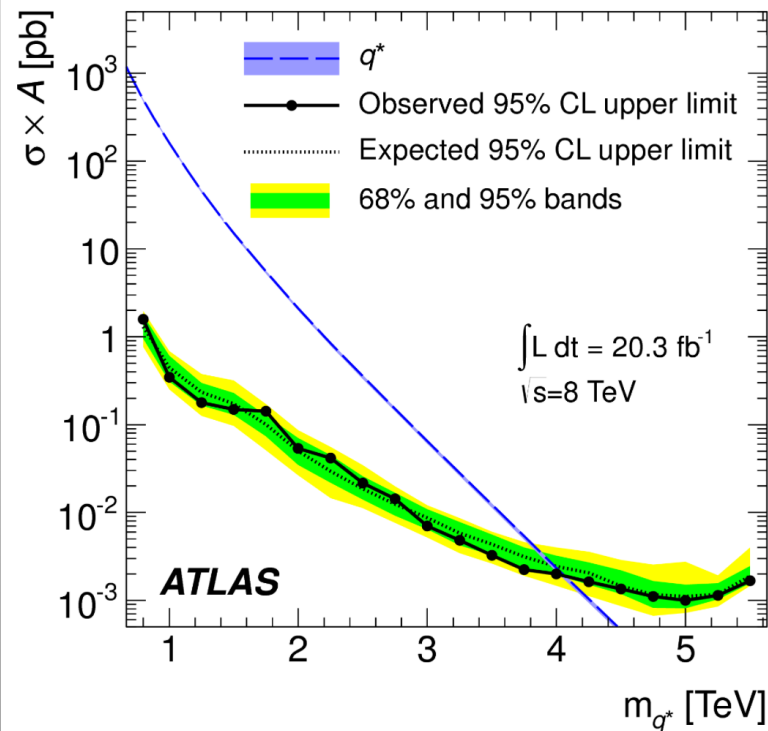
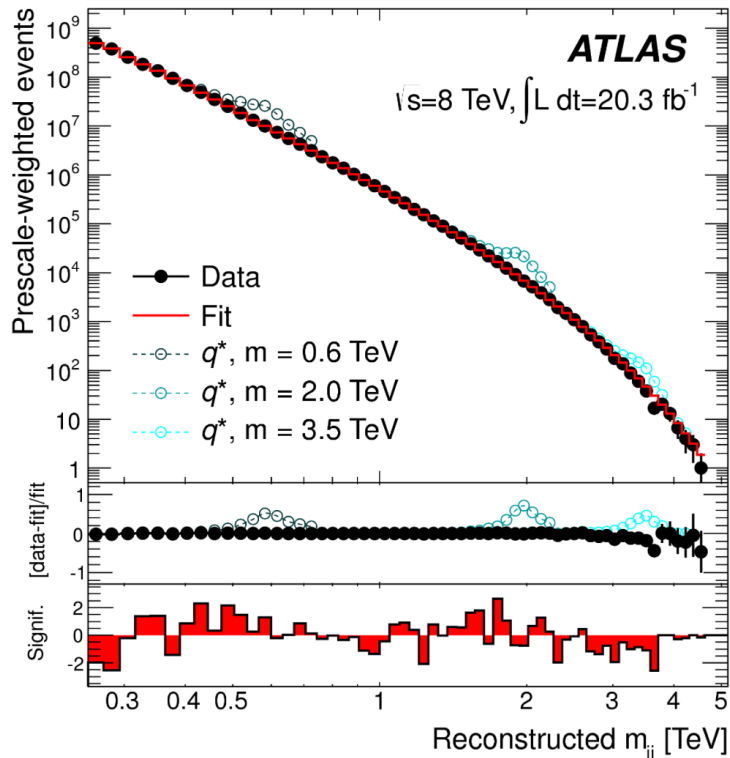
Quarks remain elementary particles after these first results

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

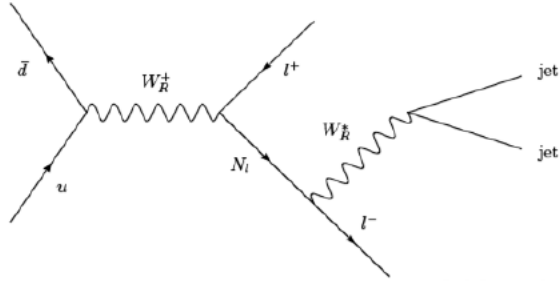
arXiv:1407.1376



Limit on the mass of excited quarks $> 4.09\text{ TeV}$ at 95% CL

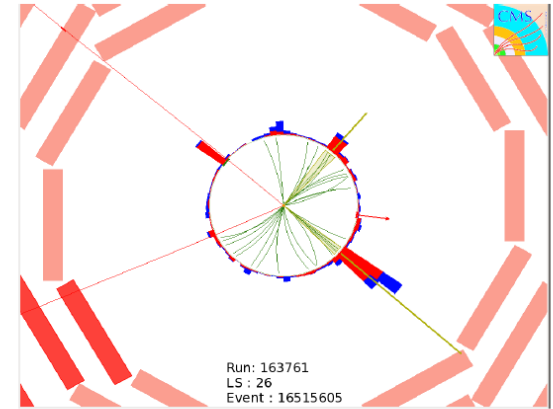
Search for Heavy Neutrinos and W_R

Left-right symmetric extension of the Standard Model

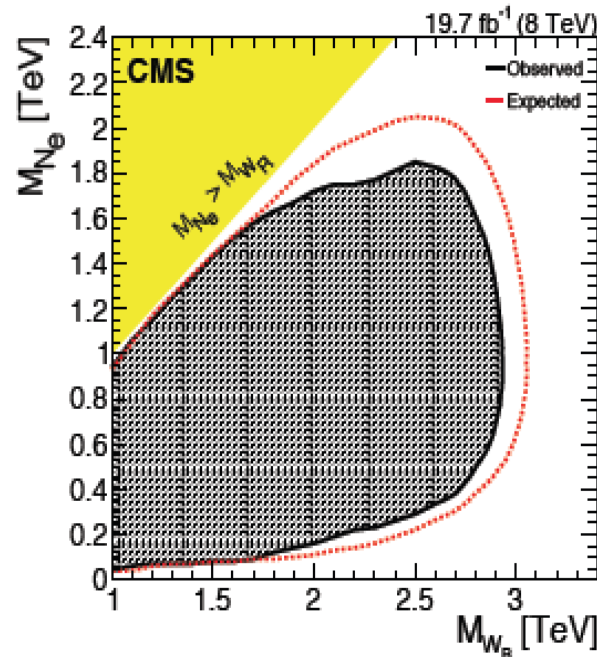
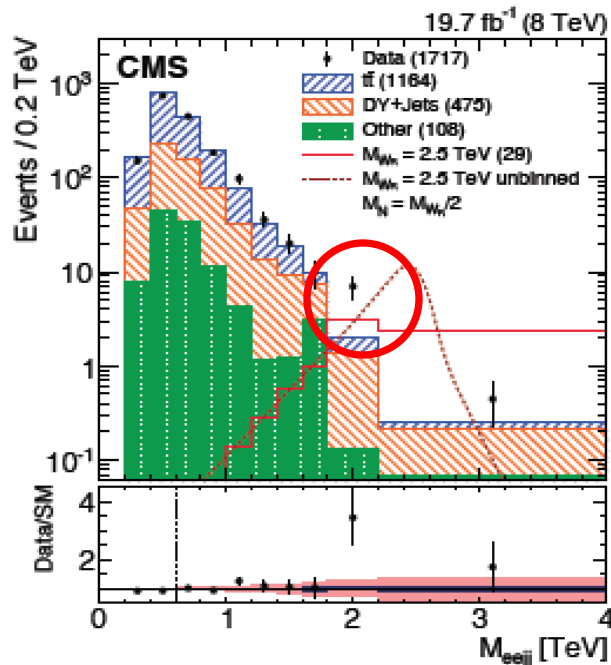


arXiv:1407.3683

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

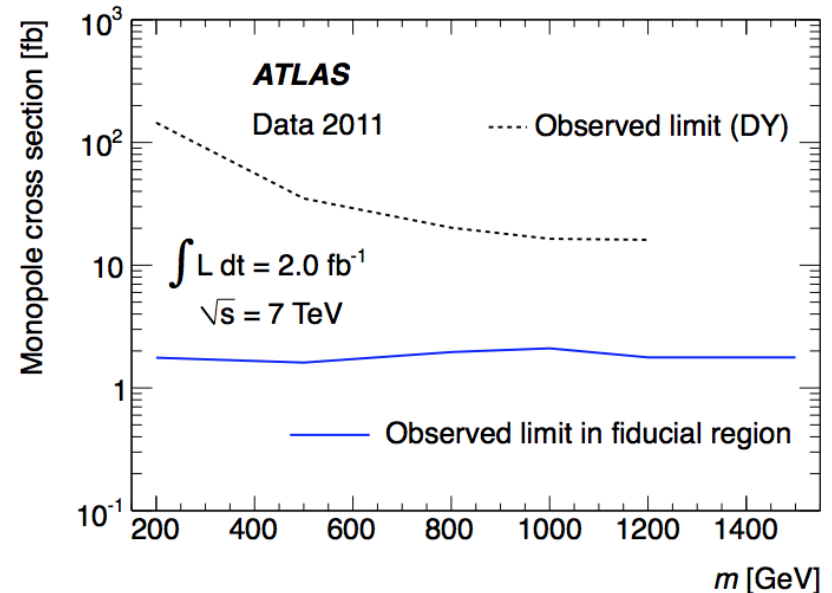
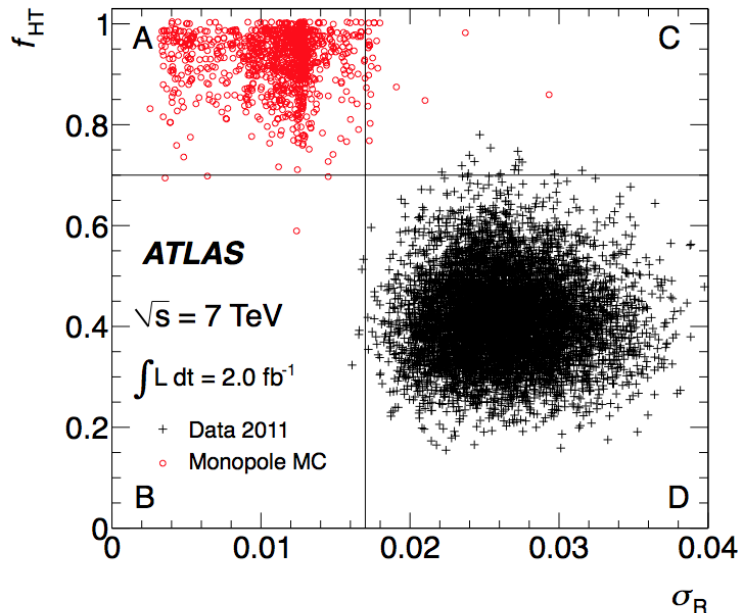
- Magnetic charge g yields strong coupling α_m and very high ionisation

$$\frac{ge}{\hbar c} = \frac{1}{2} \Rightarrow \frac{g}{e} = \frac{1}{2\alpha_e} \approx 68.5$$

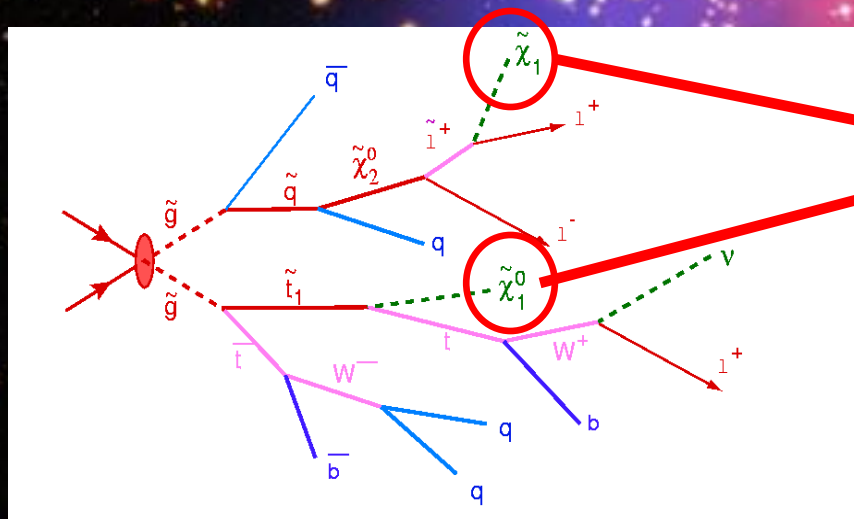
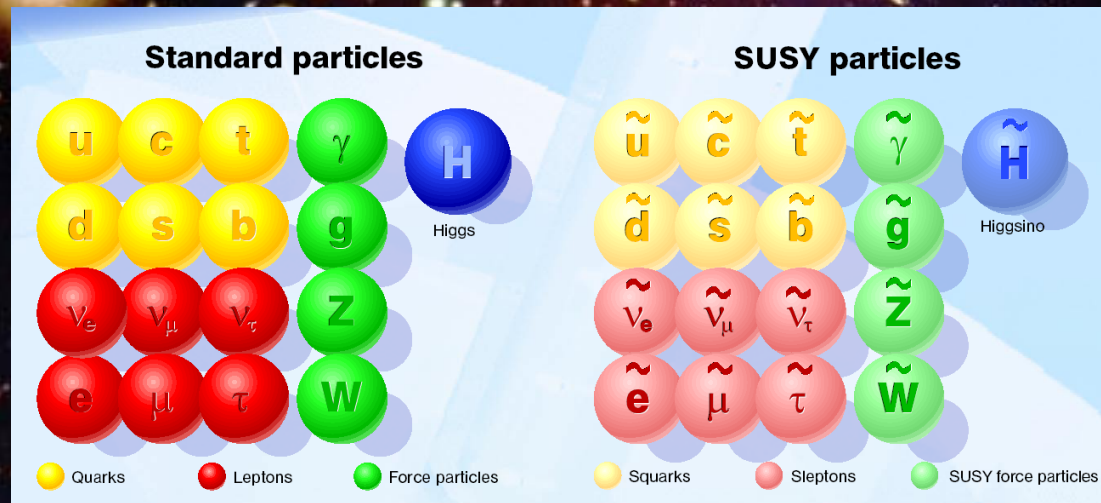
$$\alpha_m = \frac{(g\beta)^2}{\hbar c} = \frac{1}{4\alpha_e}\beta^2$$

- 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?



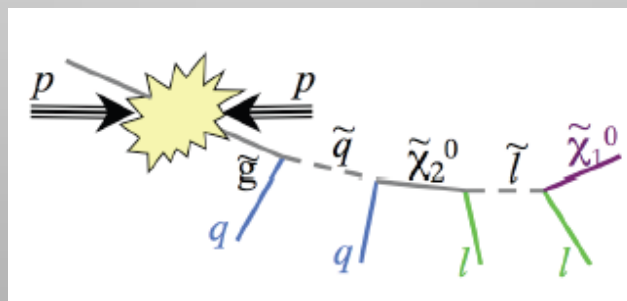
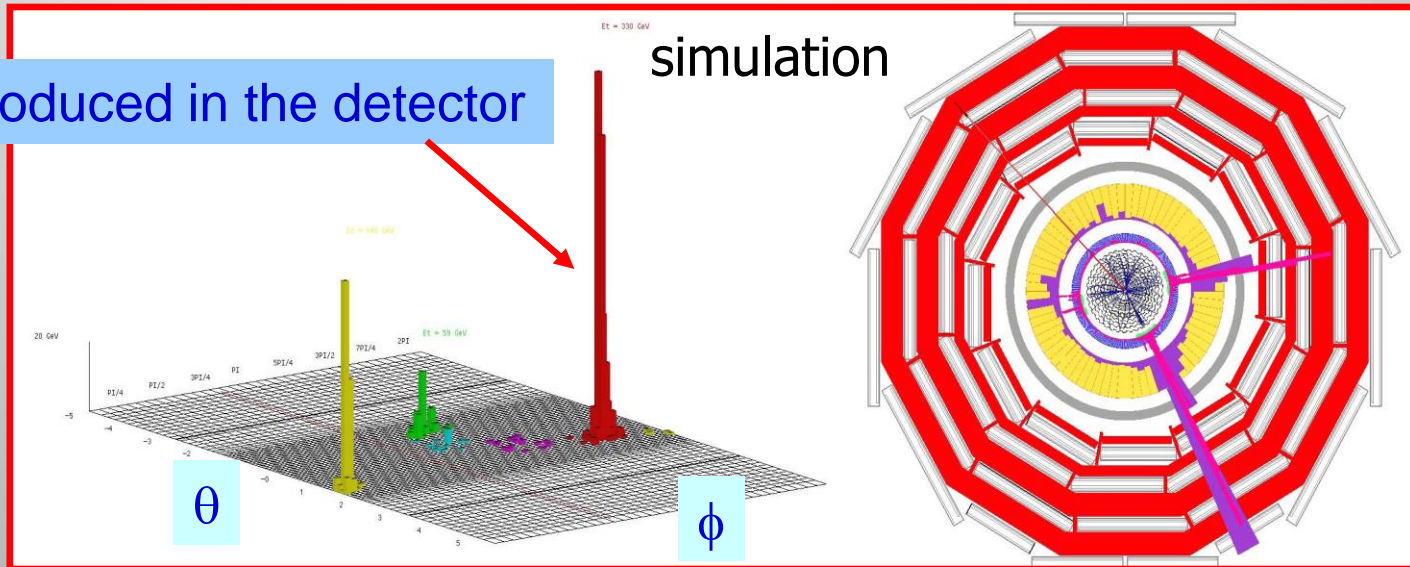
Candidate particles for Dark Matter
 \Rightarrow Produce Dark Matter in the lab

SUSY particle production at the LHC

Picture from Marusa Bradac

Detecting Supersymmetric Particles

Energy produced in the detector

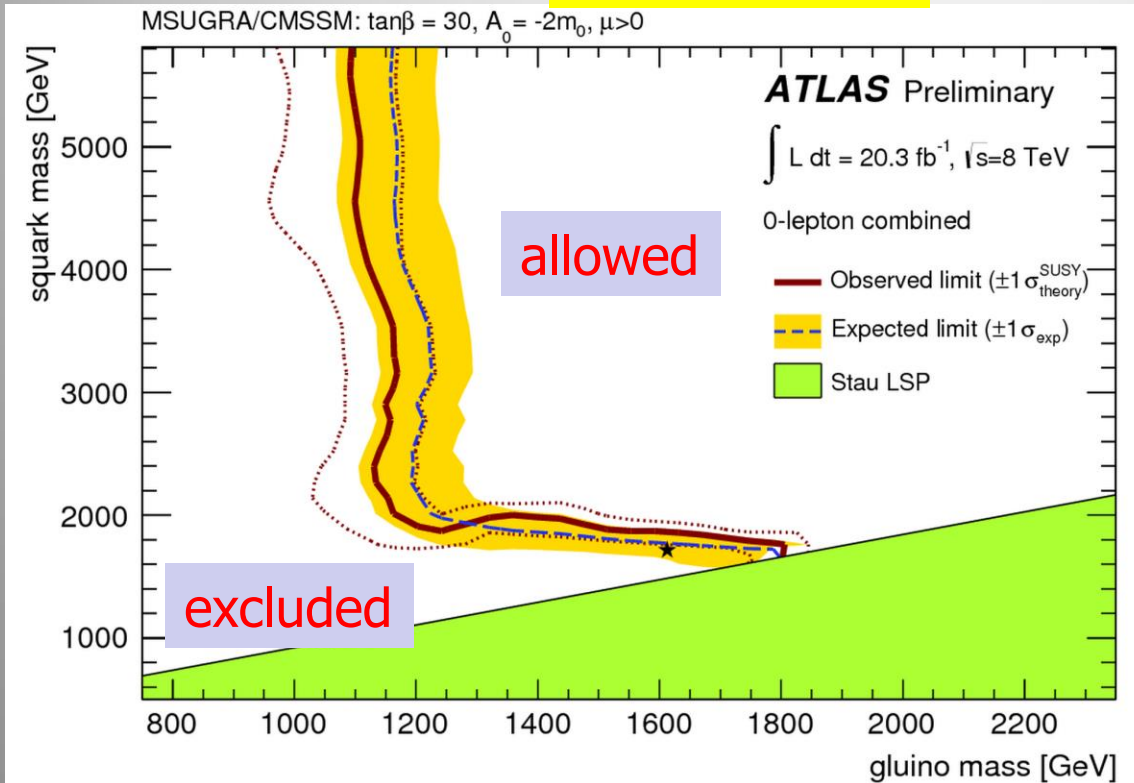


Supersymmetric particles decay and produce a cascade of jets, leptons and missing transverse energy (MET) due to escaping 'dark matter' particle candidates

Very prominent signatures in CMS and ATLAS

SUSY Searches: No signal yet to date...

Status in 2013



- So far **NO** clear signal of **supersymmetric particles** has been found

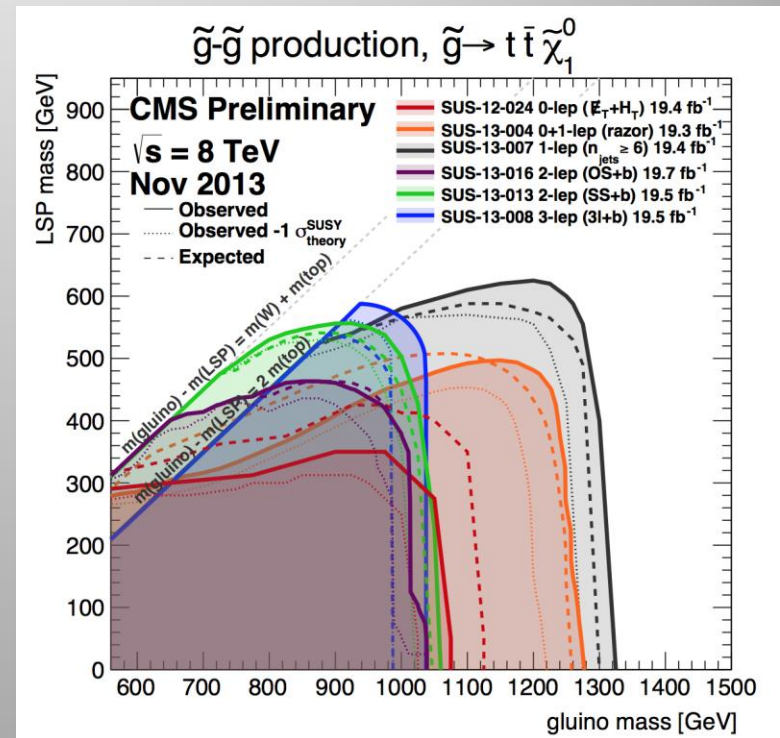
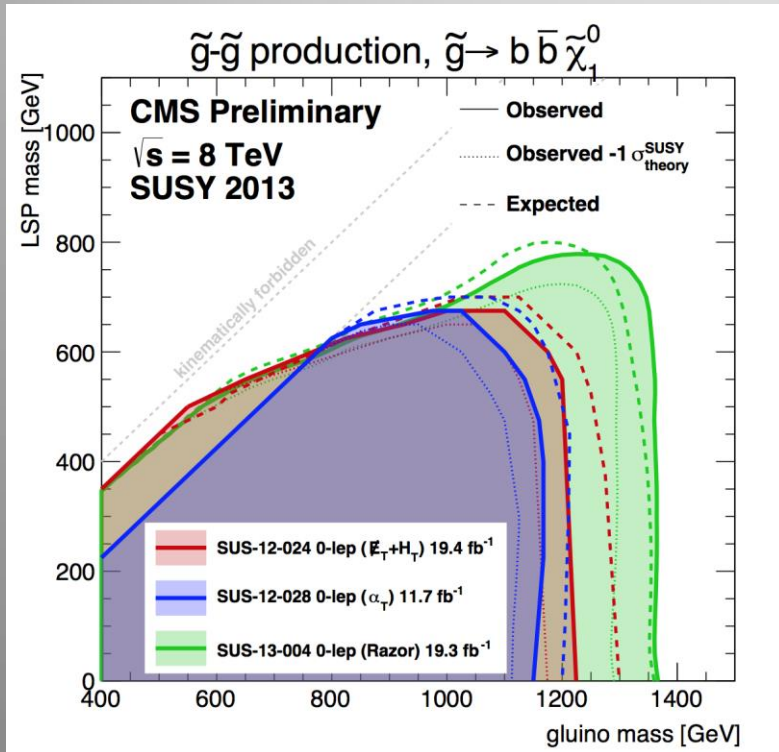
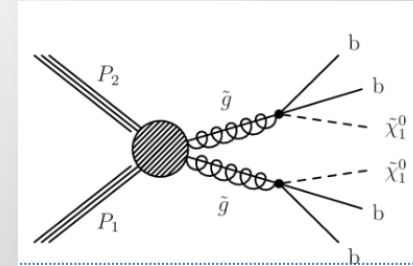
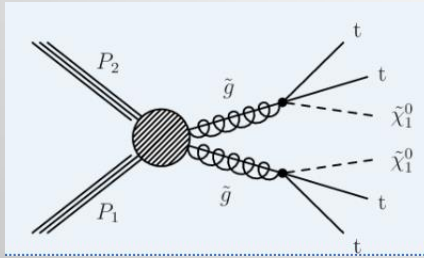
- We can exclude regions where the new particles could exist.

- Searches will continue for the **higher energy in 2015**

Plenty of searches ongoing: with jets, leptons, photons, W/Z, top, Higgs, with and without large missing transverse energy
Also special searches for contrived model regions

Limits on Squarks and Gluinos

Examples using b and t quarks



Combined limits typically $> 1\text{-}1.5 \text{ TeV}$ on sparticle masses

What is really needed from SUSY?

End 2011: Revision!

N. Arkani-Ahmed
CERN Nov 2011

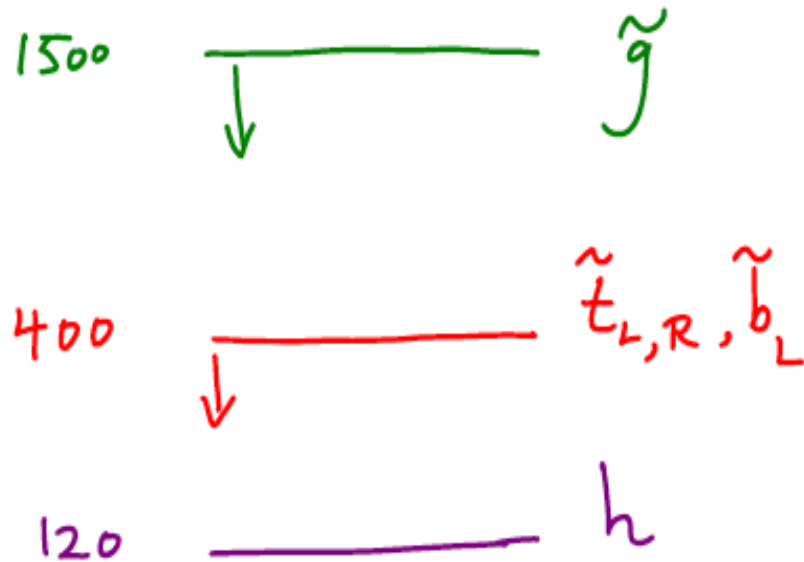
Papucci, Ruderman,
Weiler arXiv:1110.6926

LHC data end 2011
Stops > 200-300 GeV
Glino > 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!

Compulsory Natural SUSY



Unavoidable tunings: $\left(\frac{400}{m_{\tilde{t}}}\right)^2, \left(\frac{4m_{\tilde{t}}}{M_{\tilde{g}}}\right)^2$

Summary of SUSY Searches

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

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

ATLAS Preliminary

$\sqrt{s} = 7, 8 \text{ TeV}$

Reference

Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit		Reference	
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	\tilde{g}, \tilde{q}	1.7 TeV	$m(\tilde{g})=m(\tilde{q})$ 1405.7875
	MSUGRA/CMSSM	$1 e, \mu$	3-6 jets	Yes	20.3	\tilde{g}	1.2 TeV	any $m(\tilde{g})$ ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	\tilde{g}	1.1 TeV	any $m(\tilde{g})$ 1308.1841
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow \tilde{q}\tilde{q}^0$	0	2-6 jets	Yes	20.3	\tilde{q}	850 GeV	$m(\tilde{q}^0)=0 \text{ GeV}, m(1^{\text{st}} \text{ gen. } \tilde{q})=m(2^{\text{nd}} \text{ gen. } \tilde{q})$ 1405.7875
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{g}\tilde{g}^0$	0	2-6 jets	Yes	20.3	\tilde{g}	1.33 TeV	$m(\tilde{q}^0)=0 \text{ GeV}$ 1405.7875
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{g}\tilde{g}\tilde{g}^0$	$1 e, \mu$	3-6 jets	Yes	20.3	\tilde{g}	1.18 TeV	$m(\tilde{q}^0)<200 \text{ GeV}, m(\tilde{\tau}^{\pm})=0.5(m(\tilde{q}^0)+m(\tilde{g}))$ ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{g}\tilde{g}(\ell\ell/\nu\nu)\tilde{q}^0$	$2 e, \mu$	0-3 jets	-	20.3	\tilde{g}	1.12 TeV	$m(\tilde{q}^0)=0 \text{ GeV}$ ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	$2 e, \mu$	2-4 jets	Yes	4.7	\tilde{g}	1.24 TeV	$\tan\beta < 15$ 1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	$1-2 \tau + 0-1 \ell$	0-2 jets	Yes	20.3	\tilde{g}	1.6 TeV	$\tan\beta > 20$ 1407.0603
	GGM (bino NLSP)	2γ	-	Yes	20.3	\tilde{g}	1.28 TeV	$m(\tilde{q}^0)>50 \text{ GeV}$ ATLAS-CONF-2014-001
GGM (wino NLSP)	$1 e, \mu + \gamma$	-	Yes	4.8	\tilde{g}	619 GeV	$m(\tilde{q}^0)>50 \text{ GeV}$ ATLAS-CONF-2012-144	
GGM (higgsino-bino NLSP)	γ	$1 b$	Yes	4.8	\tilde{g}	900 GeV	$m(\tilde{q}^0)>220 \text{ GeV}$ 1211.1167	
GGM (higgsino NLSP)	$2 e, \mu (Z)$	0-3 jets	Yes	5.8	\tilde{g}	690 GeV	$m(\text{NLSP})>200 \text{ GeV}$ ATLAS-CONF-2012-152	
Gravitino LSP	0	mono-jet	Yes	10.5	M^{scale}	645 GeV	$m(\tilde{G})>10^4 eV$ ATLAS-CONF-2012-147	
3^{rd} gen. \tilde{g} med.	$\tilde{g} \rightarrow b\tilde{b}\tilde{q}^0$	0	3 b	Yes	20.1	\tilde{g}	1.25 TeV	$m(\tilde{q}^0)<400 \text{ GeV}$ 1407.0600
	$\tilde{g} \rightarrow t\tilde{b}\tilde{q}^0$	0	7-10 jets	Yes	20.3	\tilde{g}	1.1 TeV	$m(\tilde{q}^0) < 350 \text{ GeV}$ 1308.1841
	$\tilde{g} \rightarrow t\tilde{b}\tilde{q}^0$	$0-1 e, \mu$	3 b	Yes	20.1	\tilde{g}	1.34 TeV	$m(\tilde{q}^0)<400 \text{ GeV}$ 1407.0600
	$\tilde{g} \rightarrow b\tilde{t}\tilde{q}^0$	$0-1 e, \mu$	3 b	Yes	20.1	\tilde{g}	1.3 TeV	$m(\tilde{q}^0)<300 \text{ GeV}$ 1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{q}^0$	0	2 b	Yes	20.1	\tilde{b}_1	100-620 GeV	$m(\tilde{q}^0)<90 \text{ GeV}$ 1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{q}^0$	$2 e, \mu$ (SS)	0-3 b	Yes	20.3	\tilde{b}_1	275-440 GeV	$100 < 2 m(\tilde{q}^0)$ 1404.2500
	$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1 \rightarrow b\tilde{q}^0$	$1-2 e, \mu$	1-2 b	Yes	4.7	\tilde{t}_1	110-167 GeV	$m(\tilde{q}^0)=55 \text{ GeV}$ 1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1 \rightarrow Wb\tilde{q}^0$	$2 e, \mu$	0-2 jets	Yes	20.3	\tilde{t}_1	130-210 GeV	$m(\tilde{q}^0) = m(\tilde{t}_1) - m(W) - 50 \text{ GeV}, m(\tilde{t}_1) < m(\tilde{q}^0)$ 1403.4853
	$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1 \rightarrow t\tilde{q}^0$	$2 e, \mu$	2 jets	Yes	20.3	\tilde{t}_1	215-530 GeV	$m(\tilde{q}^0) = 1 \text{ GeV}$ 1403.4853
	$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1 \rightarrow b\tilde{q}^0$	0	2 b	Yes	20.1	\tilde{t}_1	150-580 GeV	$m(\tilde{q}^0)<200 \text{ GeV}, m(\tilde{q}^0) - m(\tilde{q}^0) = 5 \text{ GeV}$ 1308.2631
	$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1 \rightarrow t\tilde{q}^0$	$1 e, \mu$	1 b	Yes	20	\tilde{t}_1	210-640 GeV	$m(\tilde{q}^0)=0 \text{ GeV}$ 1407.0583
	$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1 \rightarrow t\tilde{q}^0$	0	2 b	Yes	20.1	\tilde{t}_1	260-640 GeV	$m(\tilde{q}^0)=0 \text{ GeV}$ 1406.1122
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{q}^0$	0	mono-jet/c-tag	Yes	20.3	\tilde{t}_1	90-240 GeV	$m(\tilde{t}_1) - m(\tilde{q}^0) < 85 \text{ GeV}$ 1407.0608
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	$2 e, \mu (Z)$	1 b	Yes	20.3	\tilde{t}_1	150-580 GeV	$m(\tilde{q}^0)>150 \text{ GeV}$ 1403.5222
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	$3 e, \mu (Z)$	1 b	Yes	20.3	\tilde{t}_2	290-600 GeV	$m(\tilde{q}^0)<200 \text{ GeV}$ 1403.5222	
EW direct	$\tilde{\chi}_{1,R}^0\tilde{\chi}_{1,R}^0, \tilde{\chi} \rightarrow \tilde{\chi}^0\tilde{q}^0$	$2 e, \mu$	0	Yes	20.3	$\tilde{\chi}$	90-325 GeV	$m(\tilde{q}^0)=0 \text{ GeV}$ 1403.5294
	$\tilde{\chi}_{1,1}^{\pm}\tilde{\chi}_{1,1}^{\mp}, \tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^0(\tilde{\nu})$	$2 e, \mu$	0	Yes	20.3	$\tilde{\chi}_{1,1}^{\pm}$	140-465 GeV	$m(\tilde{q}^0)=0 \text{ GeV}, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{q}^0))$ 1403.5294
	$\tilde{\chi}_{1,1}^{\pm}\tilde{\chi}_{1,1}^{\mp}, \tilde{\chi}_1^{\pm} \rightarrow \tilde{\tau}(\tilde{\nu}, \tilde{\tau})$	2τ	-	Yes	20.3	$\tilde{\chi}_{1,1}^{\pm}$	100-350 GeV	$m(\tilde{q}^0)=0 \text{ GeV}, m(\tilde{\tau}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{q}^0))$ 1407.0350
	$\tilde{\chi}_{1,1}^{\pm}\tilde{\chi}_{1,1}^{\mp} \rightarrow \tilde{L}_1\tilde{L}_1(\tilde{\nu}\nu), \tilde{\chi}_1^{\pm} \rightarrow \tilde{\tau}(\tilde{\nu}, \tilde{\tau})$	$3 e, \mu$	0	Yes	20.3	$\tilde{\chi}_{1,1}^{\pm}$	700 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_1^0), m(\tilde{\chi}_1^0)=0, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{q}^0))$ 1402.7029
	$\tilde{\chi}_{1,1}^{\pm}\tilde{\chi}_{1,1}^{\mp} \rightarrow W\tilde{L}_1\tilde{Z}\tilde{q}^0$	$2-3 e, \mu$	0	Yes	20.3	$\tilde{\chi}_{1,1}^{\pm}$	420 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{q}^0), m(\tilde{\chi}_1^0)=0, \text{ sleptons decoupled}$ 1403.5294, 1402.7029
	$\tilde{\chi}_{1,1}^{\pm}\tilde{\chi}_{1,1}^{\mp} \rightarrow W\tilde{L}_1\tilde{h}\tilde{q}^0$	$1 e, \mu$	2 b	Yes	20.3	$\tilde{\chi}_{1,1}^{\pm}$	285 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{q}^0), m(\tilde{\chi}_1^0)=0, \text{ sleptons decoupled}$ ATLAS-CONF-2013-093
$\tilde{\chi}_{2,3}^0\tilde{\chi}_{2,3}^0, \tilde{\chi}_2^0 \rightarrow \tilde{t}_R\tilde{\ell}$	$4 e, \mu$	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$	620 GeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0), m(\tilde{\chi}_1^0)=0, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{q}^0))$ 1405.5086	
Long-lived particles	Direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$	270 GeV	$m(\tilde{\chi}_1^{\pm}) - m(\tilde{q}^0) = 160 \text{ MeV}, \tau(\tilde{\chi}_1^{\pm}) = 0.2 \text{ ns}$ ATLAS-CONF-2013-069
	Stable, stopped \tilde{g} R-hadron	0	1-5 jets	Yes	27.9	\tilde{g}	832 GeV	$m(\tilde{q}^0)=100 \text{ GeV}, 10 \mu\text{s} < \tau(\tilde{g}) < 1000 \text{ s}$ 1310.6584
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{\nu}, \tilde{\tau}) + \tau(e, \mu)$	$1-2 \mu$	-	Yes	15.9	$\tilde{\tau}$	475 GeV	$10 < \tan\beta < 50$ ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0 \rightarrow \tilde{G}$, long-lived $\tilde{\chi}_1^0$	2γ	-	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV	$0.4 < \tau(\tilde{\chi}_1^0) < 2 \text{ ns}$ 1304.6310
$\tilde{q}\tilde{q}, \tilde{\chi}_1^0 \rightarrow \tilde{q}\tilde{q}\mu$ (RPV)	1μ , displ. vtx	-	-	20.3	\tilde{q}	1.0 TeV	$1.5 < c\tau < 156 \text{ mm}, \text{BR}(\mu)=1, m(\tilde{\chi}_1^0)=108 \text{ GeV}$ ATLAS-CONF-2013-092	
RPV	LFV $pp \rightarrow \tilde{\nu}_e + X, \tilde{\nu}_e \rightarrow e + \mu$	$2 e, \mu$	-	-	4.6	$\tilde{\nu}_e$	1.61 TeV	$\lambda_{111}^e = 0.10, \lambda_{132} = 0.05$ 1212.1272
	LFV $pp \rightarrow \tilde{\nu}_e + X, \tilde{\nu}_e \rightarrow e(\mu) + \tau$	$1 e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_e$	1.1 TeV	$\lambda_{111}^e = 0.10, \lambda_{12333} = 0.05$ 1212.1272
	Bilinear RPV CMSSM	$2 e, \mu$ (SS)	0-3 b	Yes	20.3	\tilde{g}, \tilde{q}	1.35 TeV	$m(\tilde{q})=m(\tilde{g}), c\tau_{LSP} < 1 \text{ mm}$ 1404.2500
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_1^{\pm} \rightarrow W\tilde{L}_1\tilde{q}^0, \tilde{\chi}_1^0 \rightarrow e\tilde{\nu}_e, e\mu\tilde{\nu}_e$	$4 e, \mu$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	750 GeV	$m(\tilde{q}^0) > 0.2 \times m(\tilde{\chi}_1^{\pm}), \lambda_{121} \neq 0$ 1405.5086
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_1^{\pm} \rightarrow W\tilde{L}_1\tilde{q}^0, \tilde{\chi}_1^0 \rightarrow \tau\tilde{\nu}_e, e\tau\tilde{\nu}_e$	$3 e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	450 GeV	$m(\tilde{q}^0) > 0.2 \times m(\tilde{\chi}_1^{\pm}), \lambda_{133} \neq 0$ 1405.5086
	$\tilde{g} \rightarrow q\tilde{q}\tilde{q}$	0	6-7 jets	Yes	20.3	\tilde{g}	916 GeV	$\text{BR}(\gamma) = \text{BR}(\beta) = \text{BR}(c) = 0\%$ ATLAS-CONF-2013-091
$\tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow b s$	$2 e, \mu$ (SS)	0-3 b	Yes	20.3	\tilde{g}	850 GeV	1404.250	
Other	Scalar gluon pair, sgluon $\rightarrow q\tilde{q}$	0	4 jets	Yes	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693 1210.4826
	Scalar gluon pair, sgluon $\rightarrow \tilde{t}\tilde{t}$	$2 e, \mu$ (SS)	2 b	Yes	14.3	sgluon	350-800 GeV	ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M^{scale}	704 GeV	$m(\chi) < 80 \text{ GeV}, \text{limit of } c87 \text{ GeV for D8}$ ATLAS-CONF-2012-147

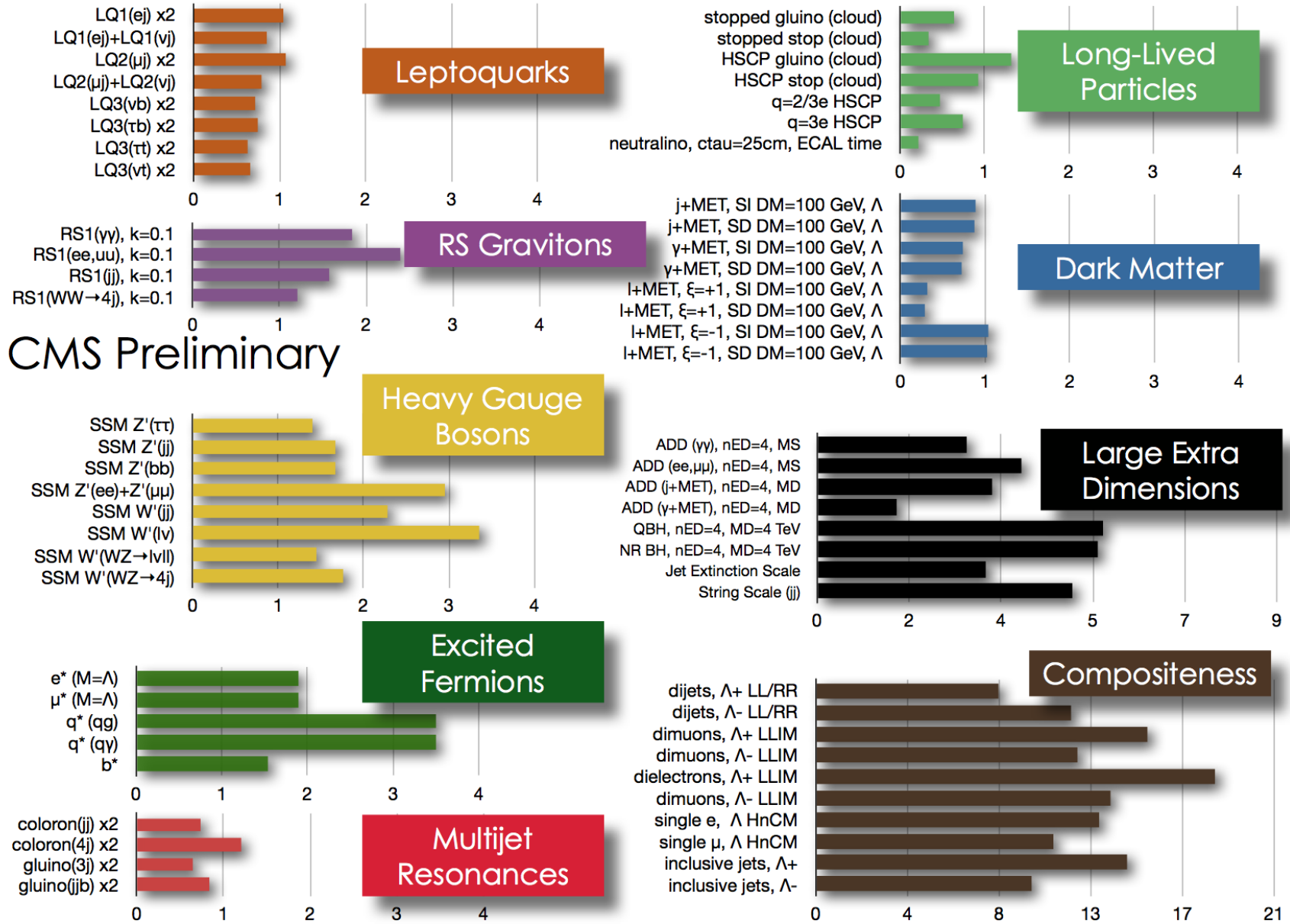


$\sqrt{s} = 7 \text{ TeV}$ full data
 $\sqrt{s} = 8 \text{ TeV}$ partial data
 $\sqrt{s} = 8 \text{ TeV}$ full data

Mass scale [TeV]

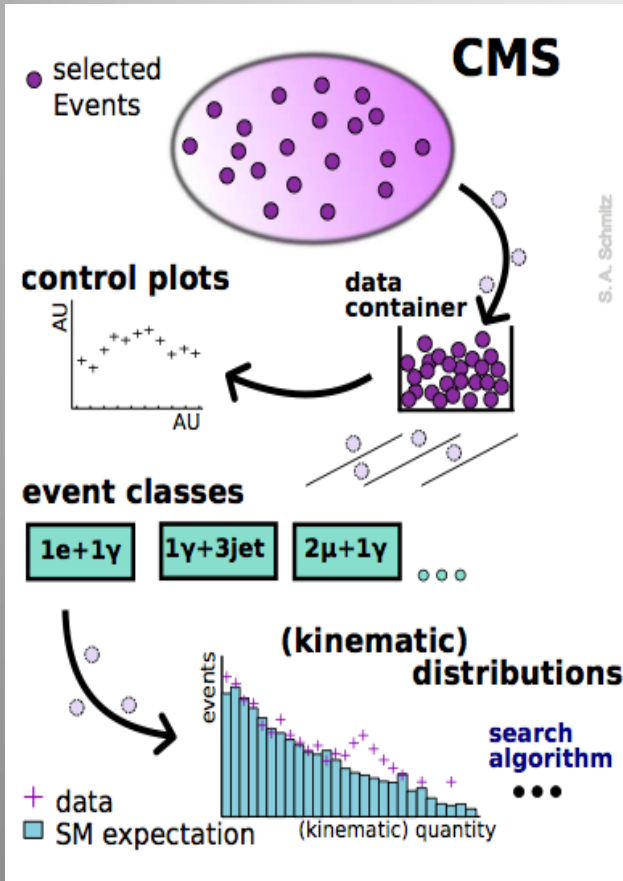
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Summary of Exotica Searches



A Global View!

CMS-EXO-10-021



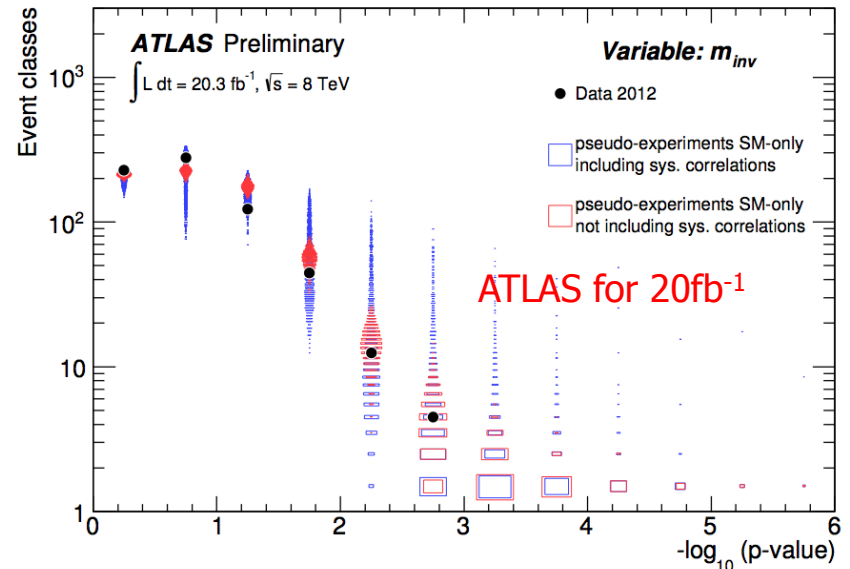
Model independent search

- 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



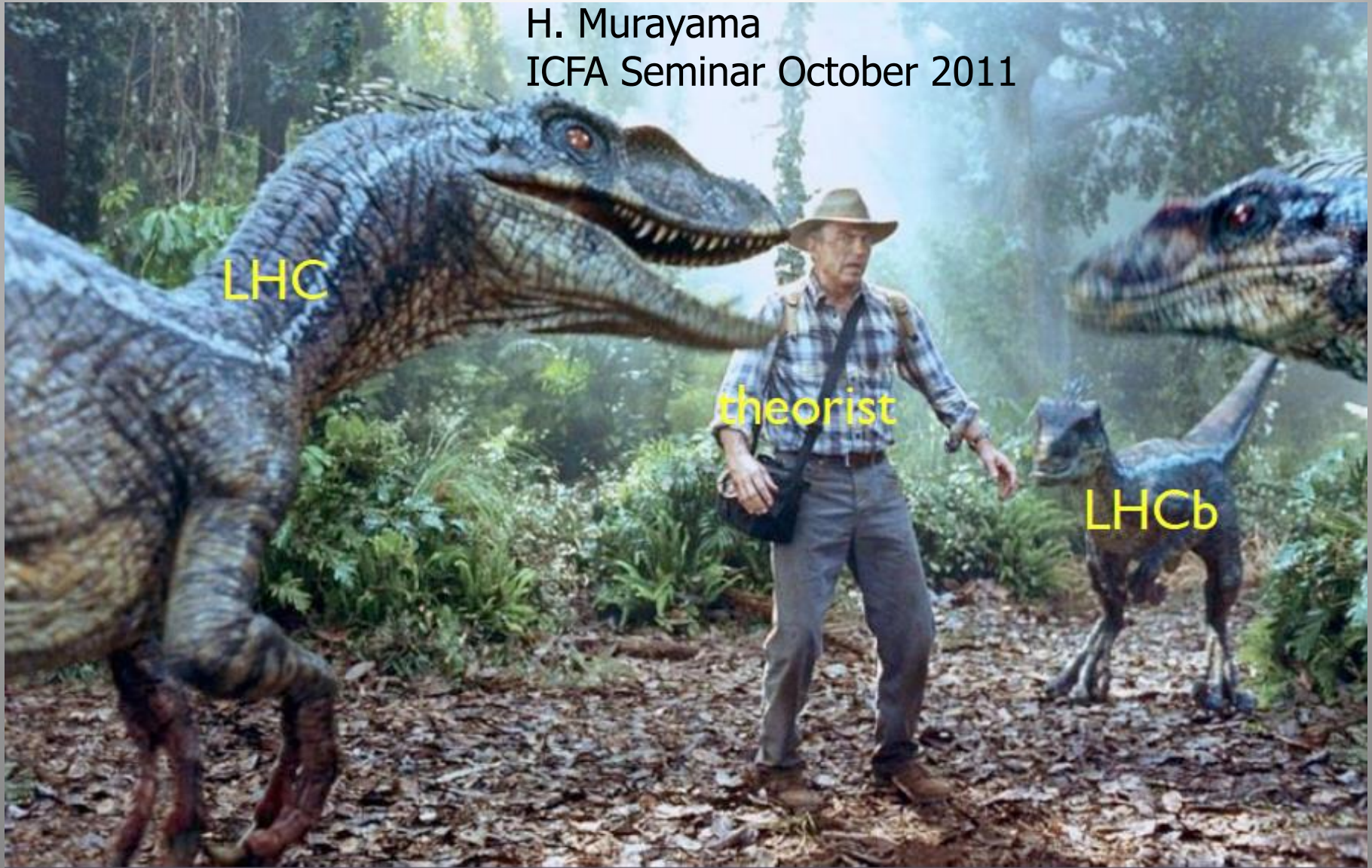
Probability distribution as expected for 35 pb⁻¹ for CMS

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

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

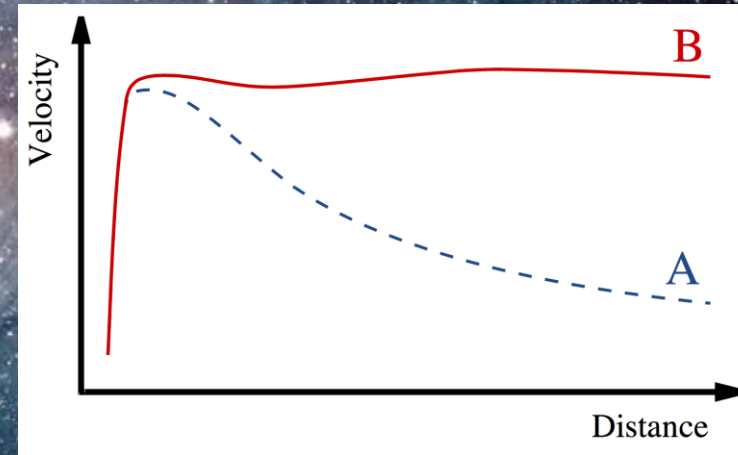
H. Murayama

ICFA Seminar October 2011

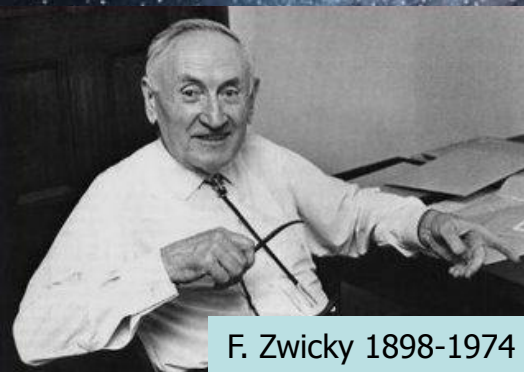


Dark Matter: The Next Challenge !?!

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



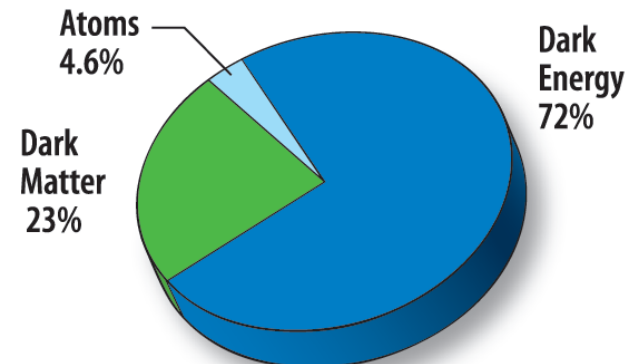
'Supersymmetric' particles ?



F. Zwicky 1898-1974

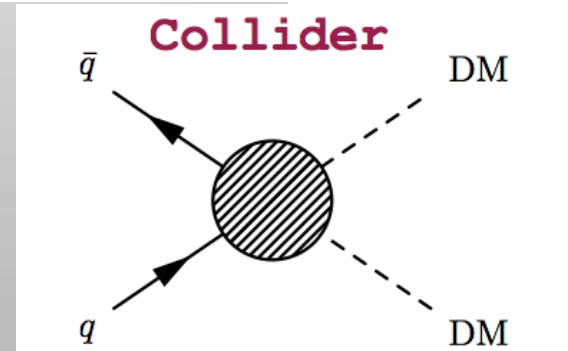
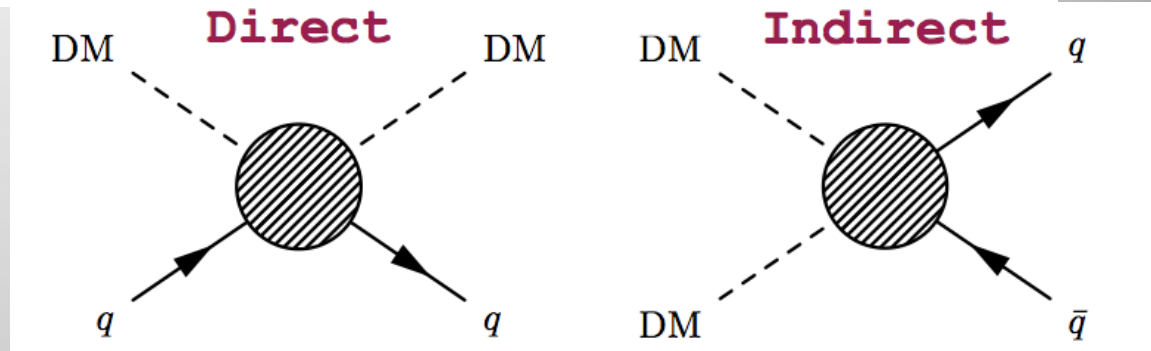
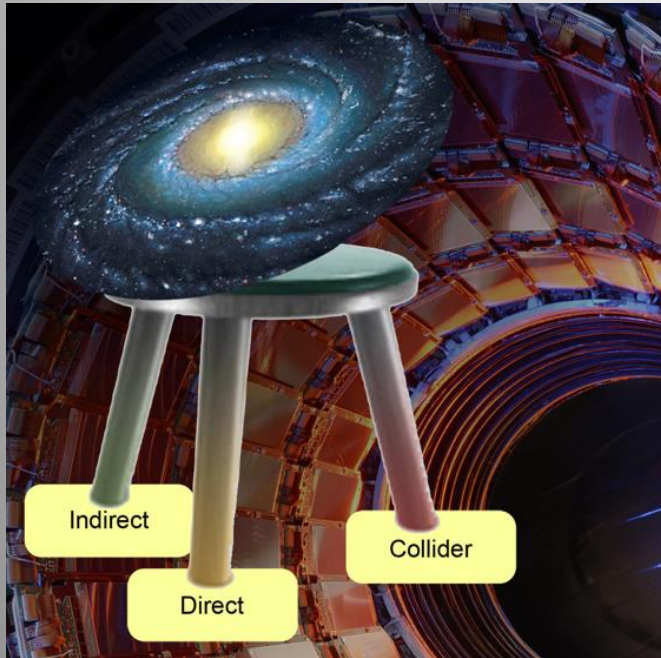


Vera Rubin ~ 1970

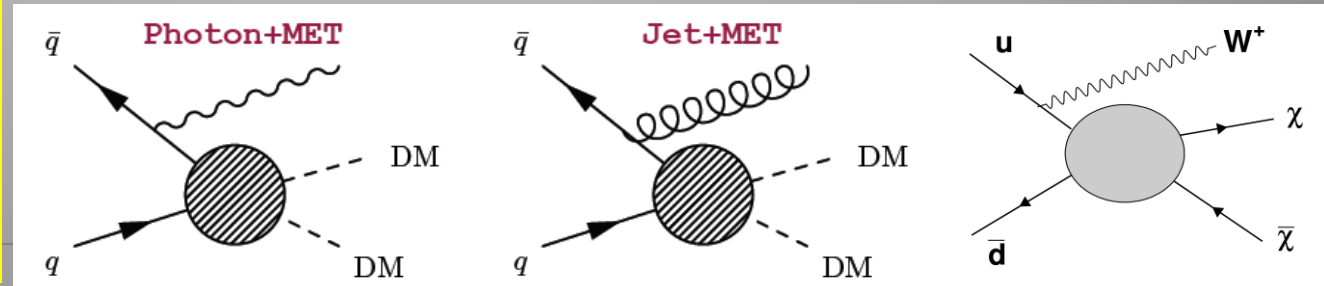


The Generic Dark Matter Connection

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

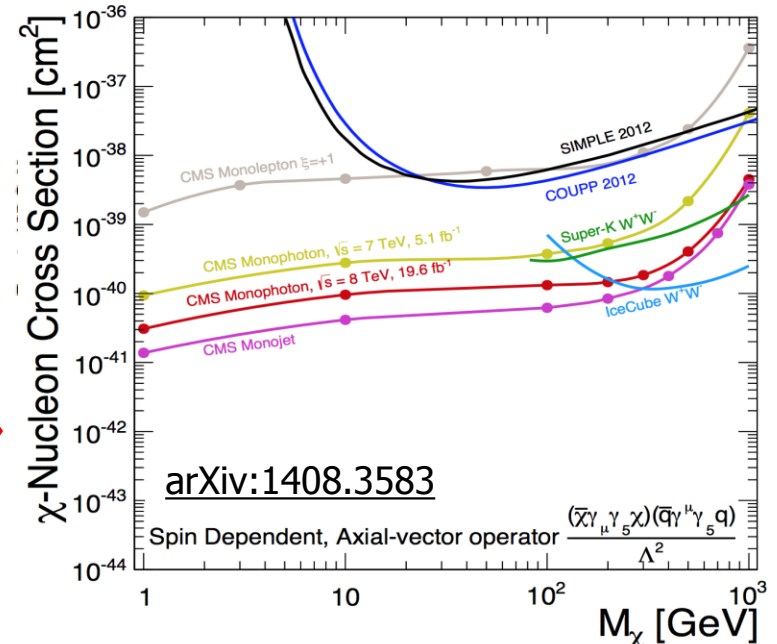
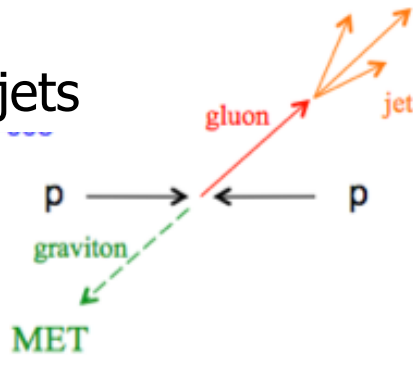


Mono-object Searches in CMS

- **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



The Future...

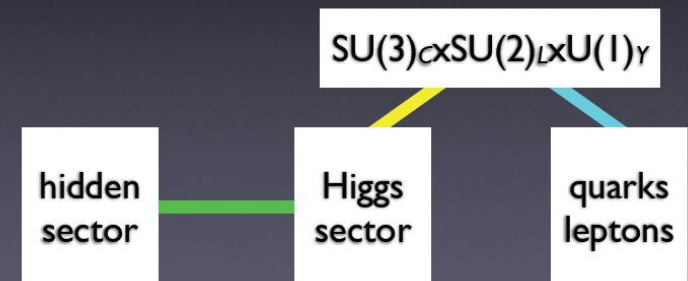
The Future: Studying the Higgs...



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

Higgs as a portal

- having discovered the Higgs?
- Higgs boson may connect the Standard Model to other “sectors”

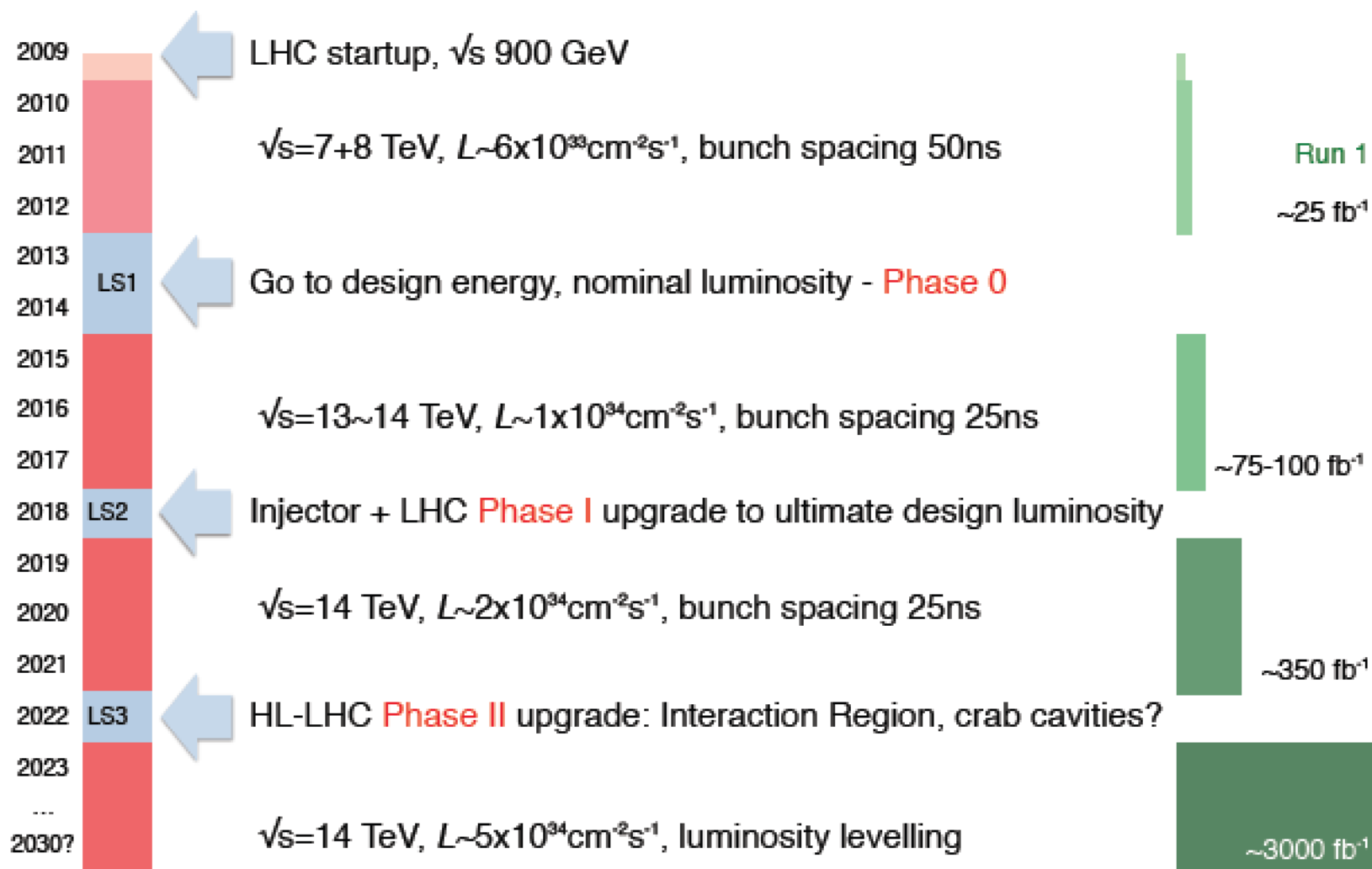


Many questions are still unanswered:

- 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 roadmap to achieve full potential



LHC 2015

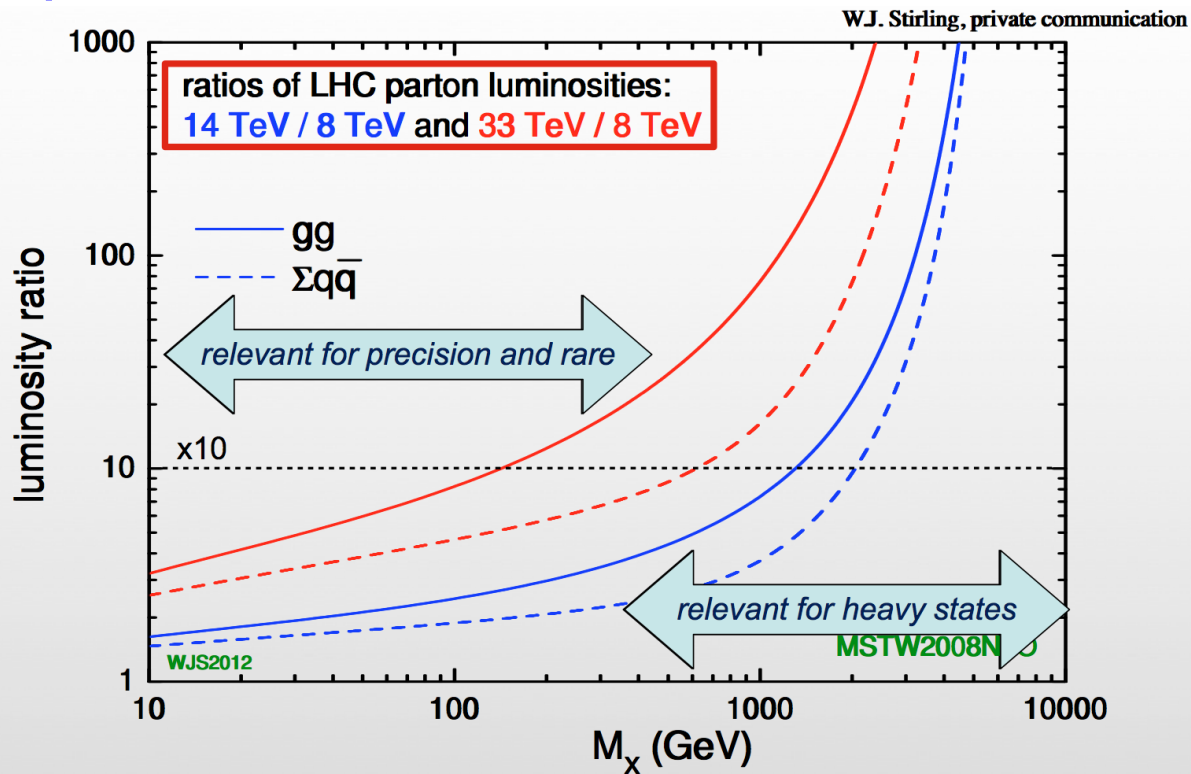
- Start with 50 ns – scrub – 25 ns operation
- Conservative beta* to start
- Conservative bunch population
- Reasonable emittance into collisions
- Assuming same machine availability as 2012...

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

Physics Program: Key Topics

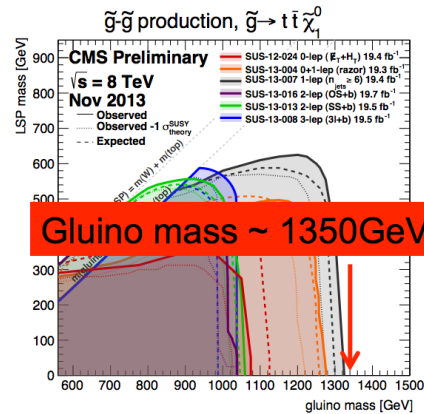
- Properties of the new Higgs boson, precise determination of its characteristics
- High mass reach for new particles and interactions
- Precision measurements
- Rare process



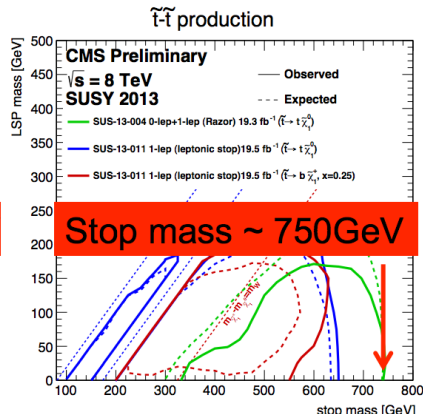
SUSY Prospects @ 2015/2016

Expect $\sim 10\text{-}20 \text{ fb}^{-1}$ in 2015 & 40 fb^{-1} in 2016 (present guestimates)

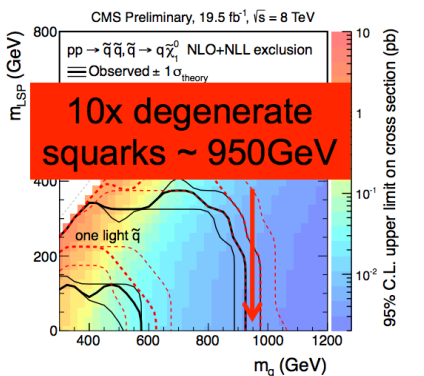
Now 2014



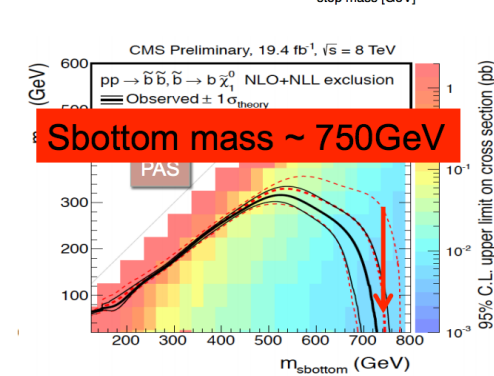
Gluino mass $\sim 1350 \text{ GeV}$



Stop mass $\sim 750 \text{ GeV}$



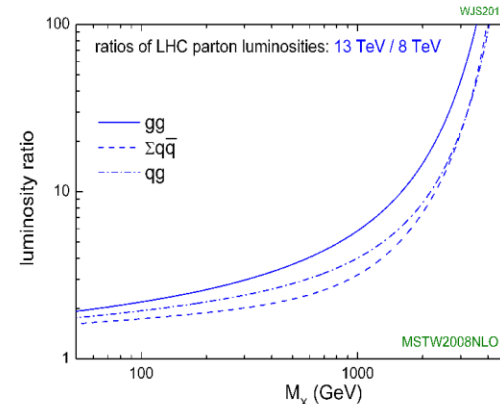
10x degenerate squarks $\sim 950 \text{ GeV}$



Sbottom mass $\sim 750 \text{ GeV}$

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

$\sim 1 \text{ fb}^{-1}$ of 13TeV data surpasses our best gluino limits.
 $\sim 3 \text{ fb}^{-1}$ 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!!

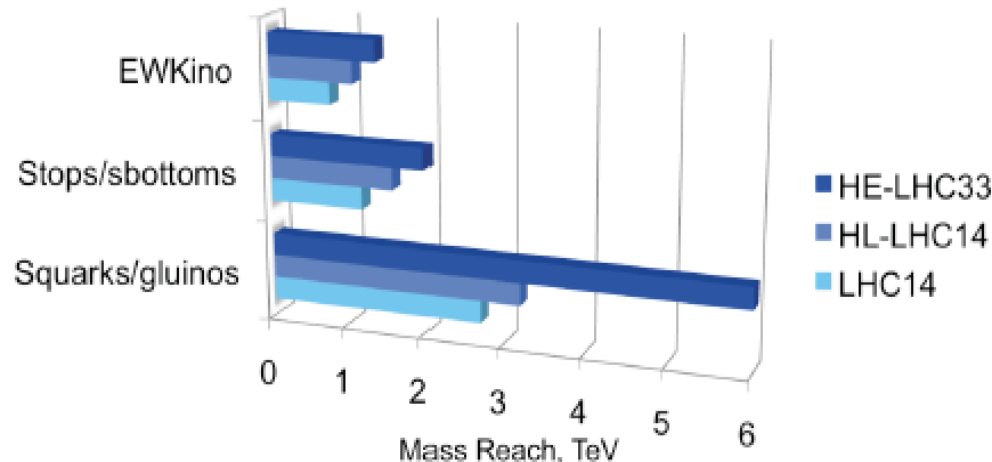
Searches for New Particles in pp

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 $4 \times 10^{-21} m$
- Discovery of resonances up to masses of 40 TeV

Upper limit for higher Higgs mass in 2HDM models?



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

● Why 100 TeV ?

- Need for O(100 TeV) in the cards since the SSC days: fully explore EWWSB, probing in particular unitarization of WW scattering at $m(WW) > \text{TeV}$, and explore dynamics well above EWWSB

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 2012. 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:

