NOBEL SYMPOSIA

Beyond the Standard Model

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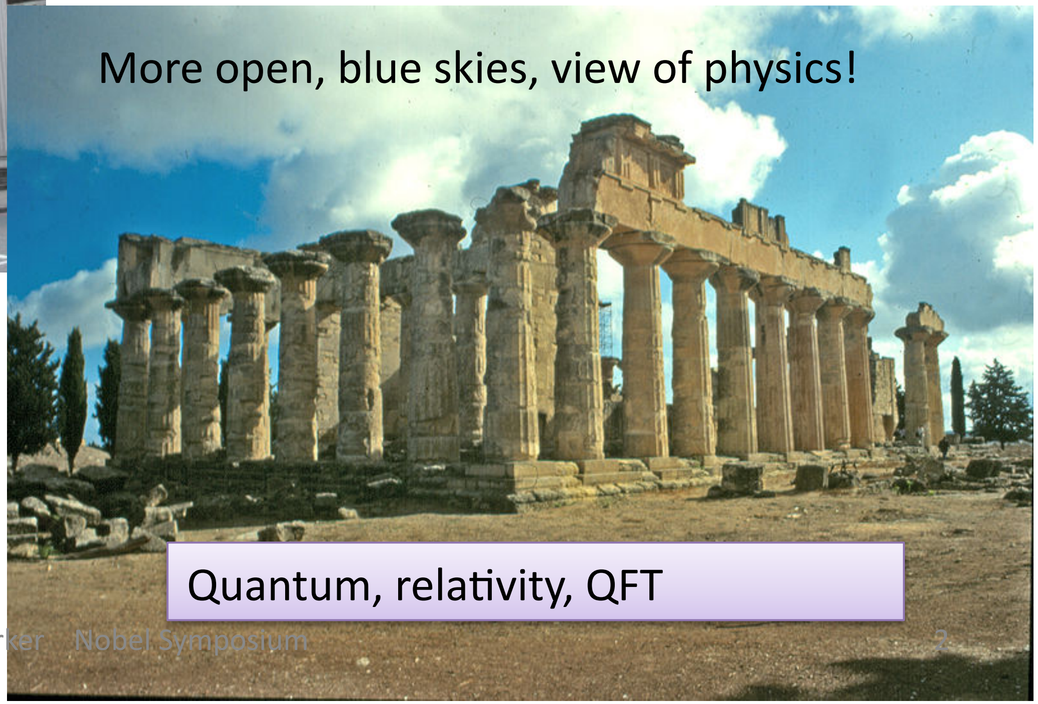
Most interesting time in physics for 100 years

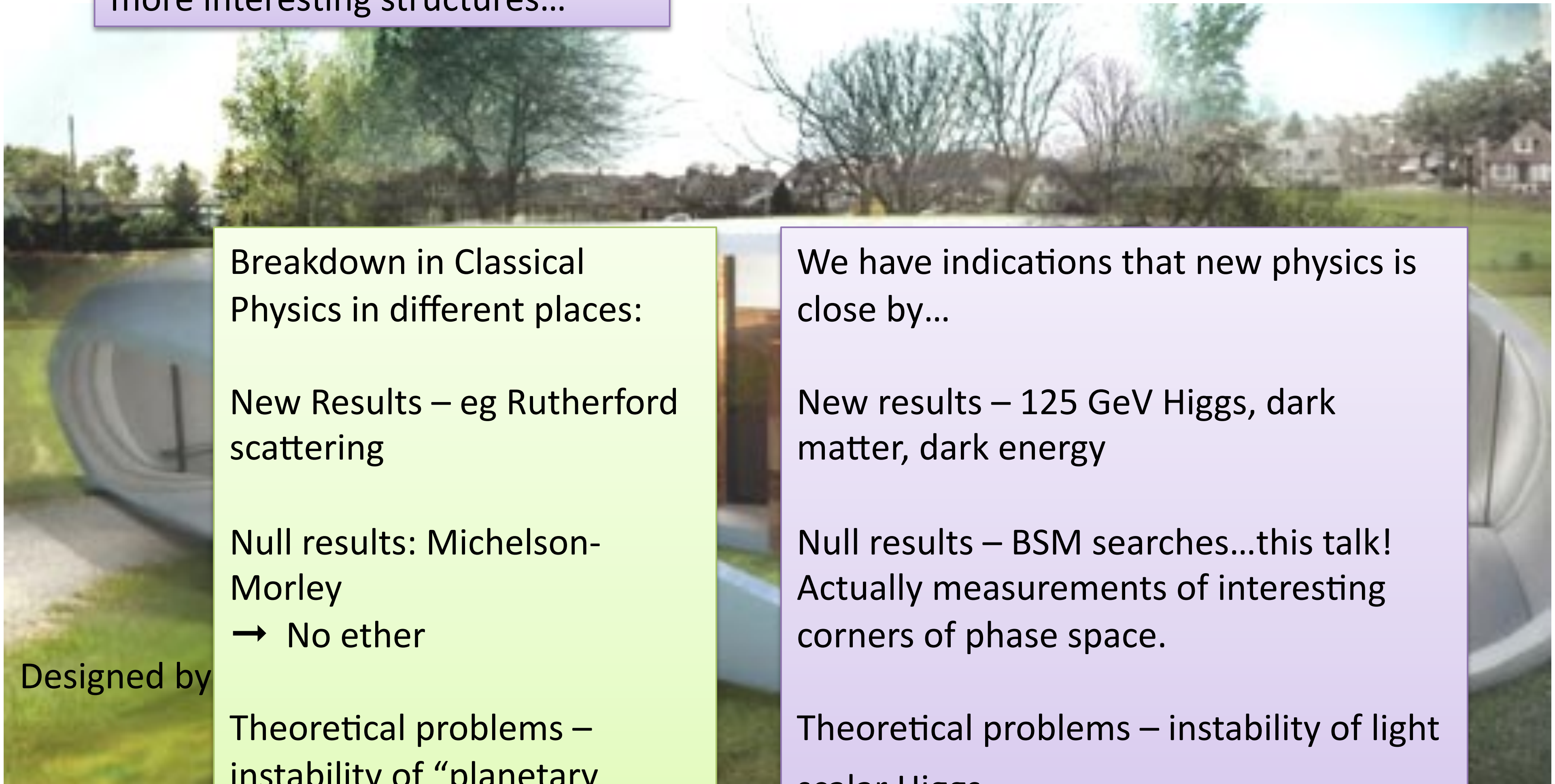
Classical internet

Unexplained results:
Photoelectric effect
Radioactivity
→ Nuclear structure…

The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote. **A.A. Michelson *Light Waves and Their Uses (1903), 23-4.***



Modern physics allows much more interesting structures…



Designed by

Breakdown in Classical Physics in different places:

New Results – eg Rutherford scattering

Null results: Michelson-Morley
→ No ether

Theoretical problems – instability of “planetary atom”, UV catastrophe

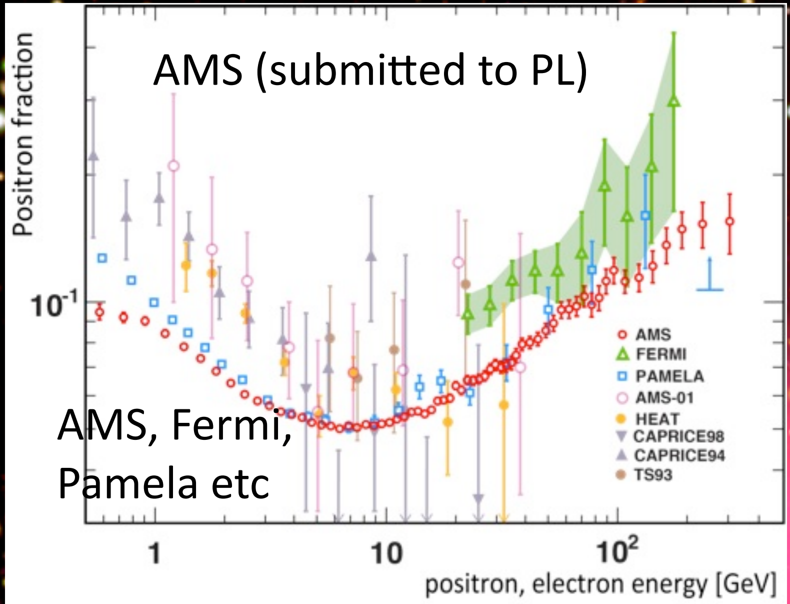
We have indications that new physics is close by…

New results – 125 GeV Higgs, dark matter, dark energy

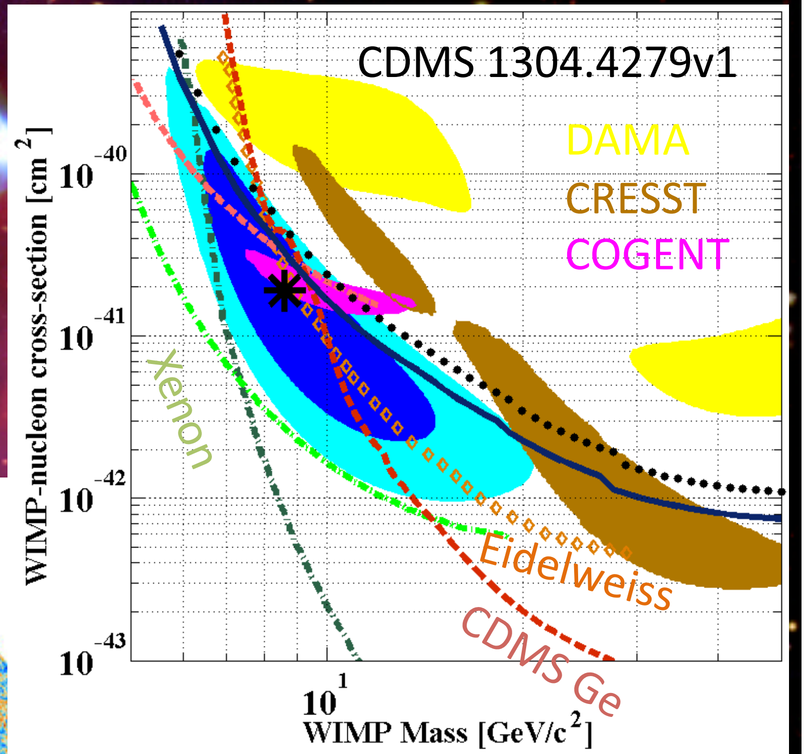
Null results – BSM searches…this talk! Actually measurements of interesting corners of phase space.

Theoretical problems – instability of light scalar Higgs

Q1: Where/what is Dark Matter(and Dark Energy)?



ΛCDM ≠ SM



Planck

Neutralinos? The conventional wisdom

Gravitinos? alternative SUSY route (eg 0911.3376 Bomark, Lola, Osland, Raklev)

Axions? Solution to strong CP problem with PQ symmetry (eg 0910.5914v1 ADMX)

MOND/TeVeS? Milgrom/Bekenstein

Markevitch et al. (2004)
Clowe et al. (2004)

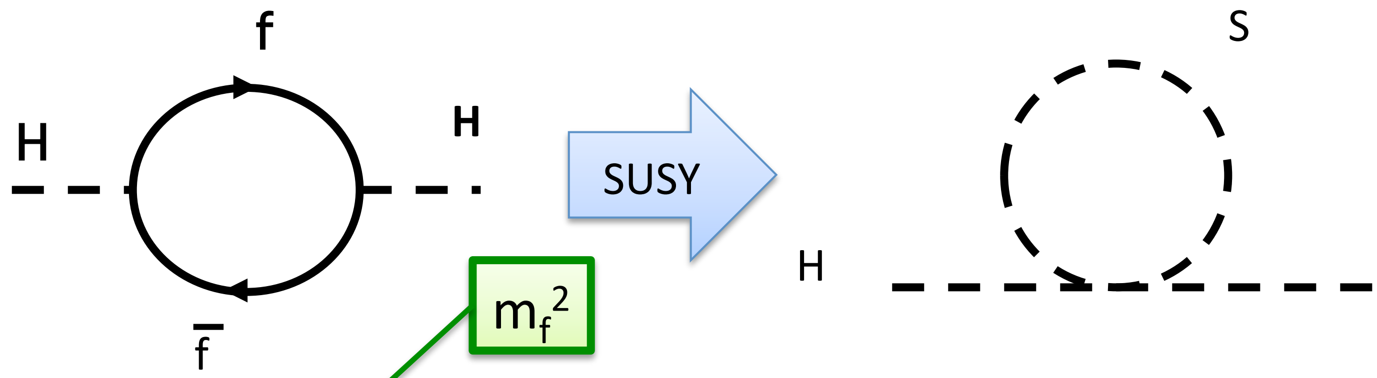
We also have some interesting null results…

Impressive edifice…

…now looks less robust!

Why SUSY?

- Two big reasons:
- Dark matter – strong evidence from astrophysics – WIMP miracle fits with SUSY
- Light Higgs – need new physics to stabilise mass



$$\Delta m_H^2 = \frac{|\lambda_f|^2}{16\pi^2}\left[-2\Lambda_{UV}^2 + 6m_f^2 \ln(\Lambda_{UV}/m_f) + \ldots\right]$$

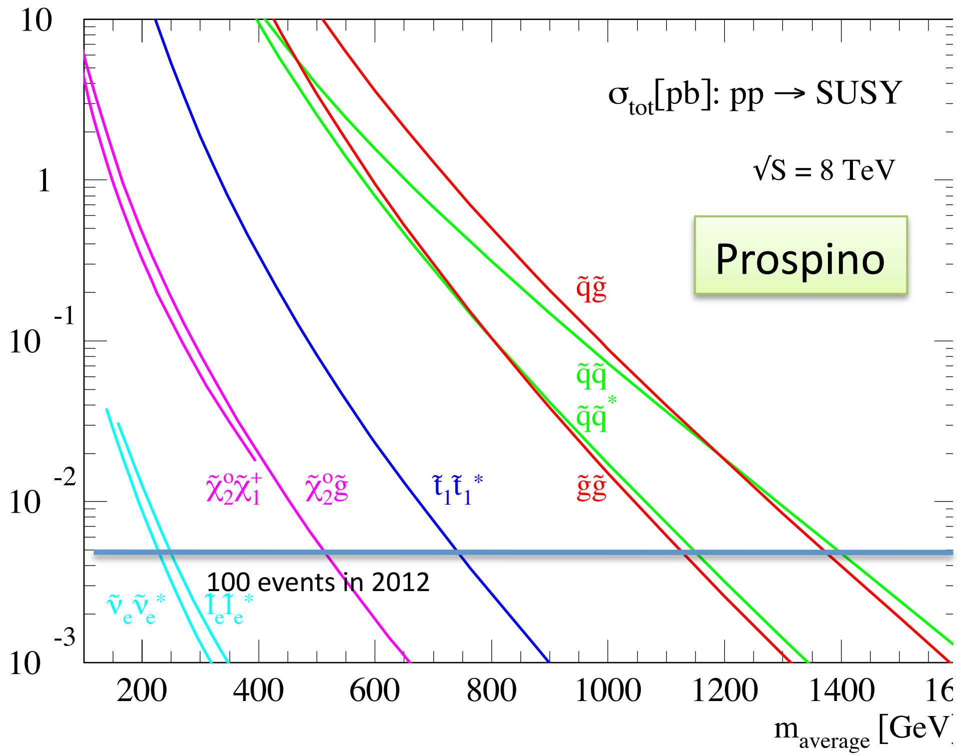
Need UV cut-off to get finite mass

$$\Delta m_H^2 = \frac{\lambda_s}{16\pi^2}\left[\Lambda_{UV}^2 - 2m_s^2 \ln(\Lambda_{UV}/m_s) + \ldots\right]$$

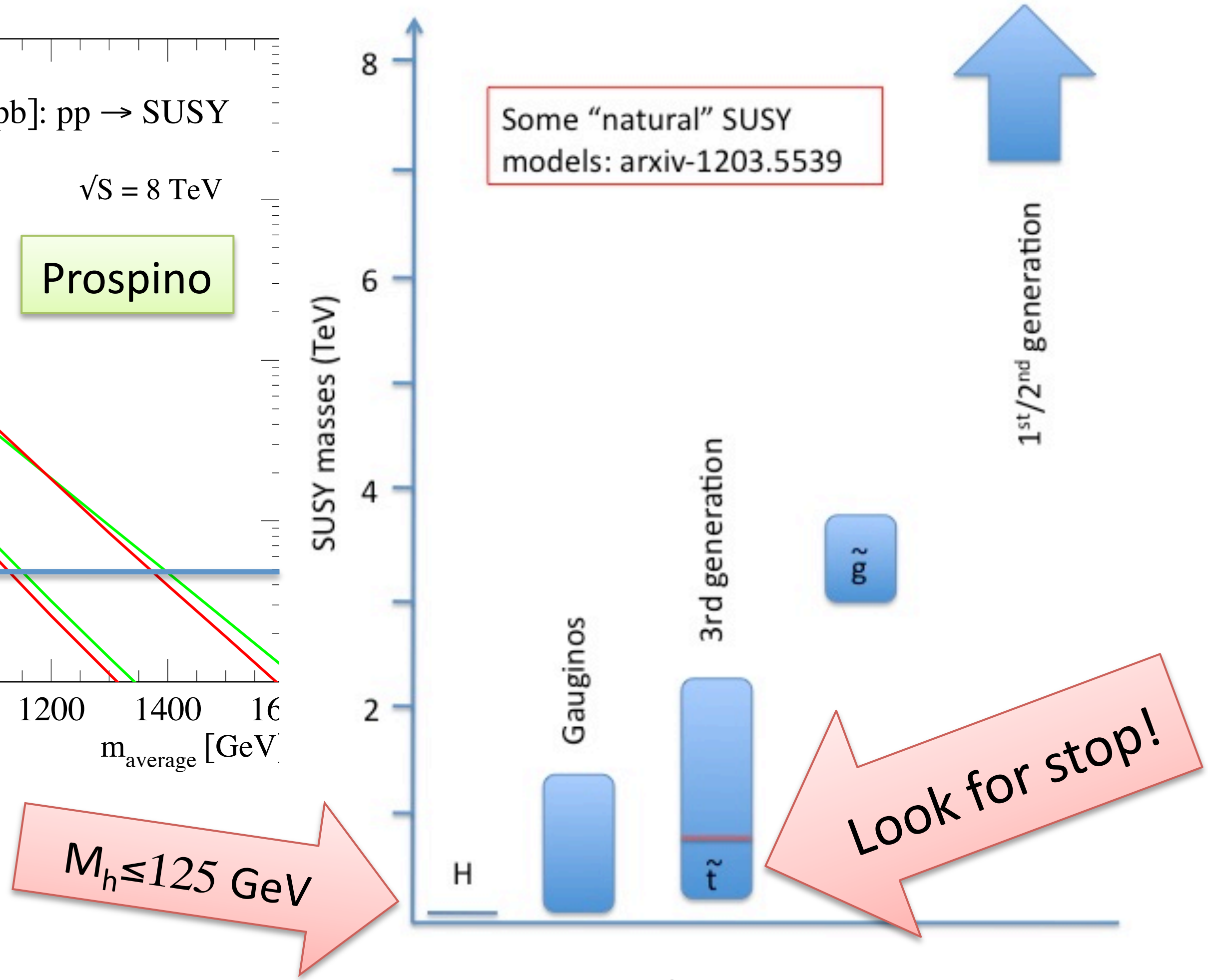
SUSY provides correct coupling and number of states for cancellations

SUSY Mass spectrum and cross section

Sensitivity depends on which process is accessible.



Spectrum is model dependent



Limits are model dependent – assumptions affect production and decay. Use simplified scenarios for interpretation.

Classical SUSY Searches

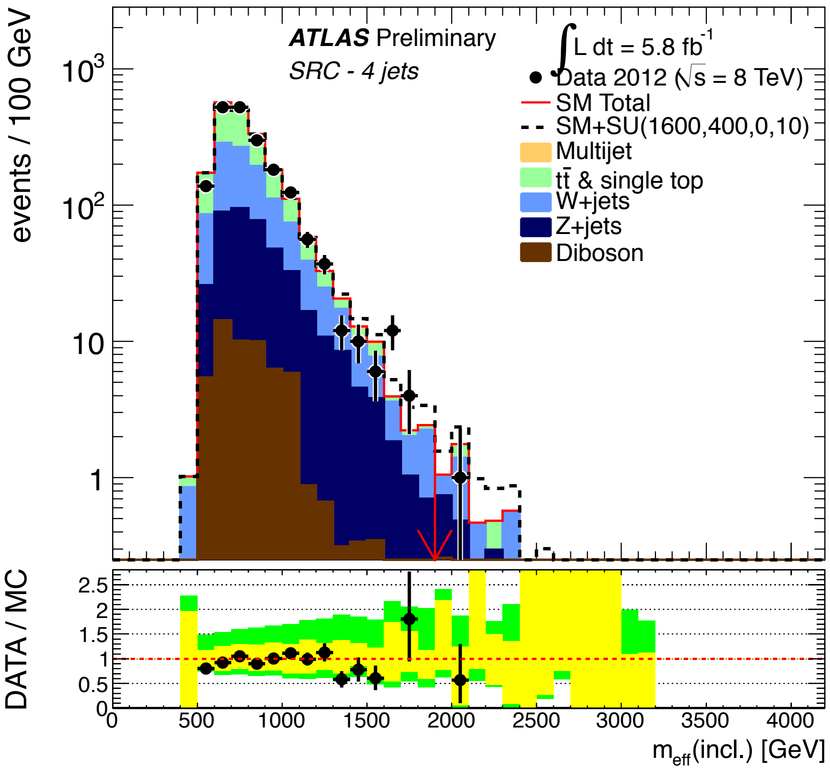
- R-parity conservation: neutral light LSP, (DM candidate), SUSY objects produced in pairs.

- Search for production and decay of gluinos and squarks – should have high rates.
- Search for sleptons and gauginos produced directly and also in cascade decays from strong production: lower rate, but cleaner signature.
- E_T^{miss} is key part of signatures.
- Emphasis now on 3rd generation
- Interpret in simplified models – less emphasis on MSSM etc

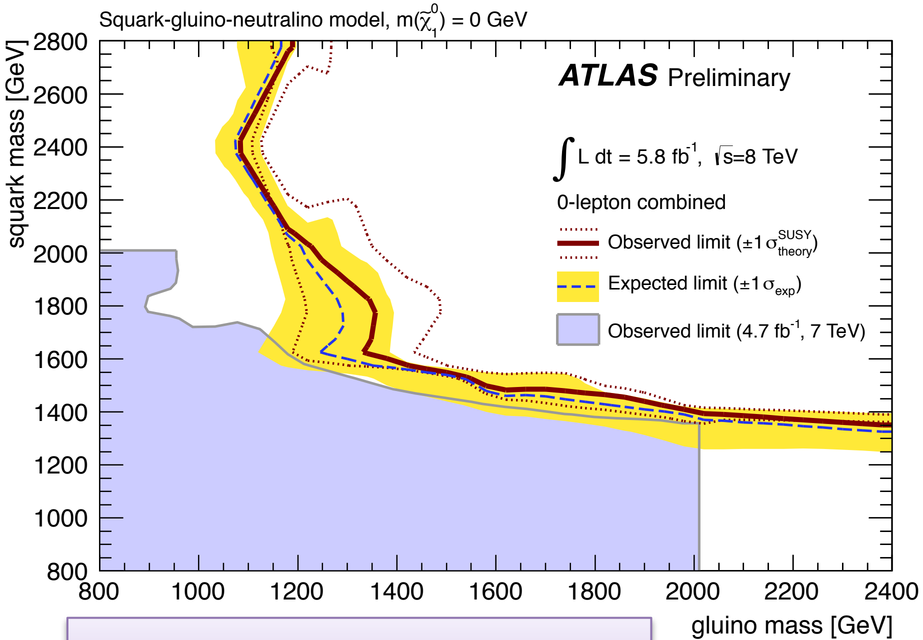
ATLAS 0-lepton search

2-6 jets + E_T^{miss}

M_{eff} defines signal regions



Look for squarks and gluinos with direct decays to SM+LSP



ATLAS-CONF-2012-109

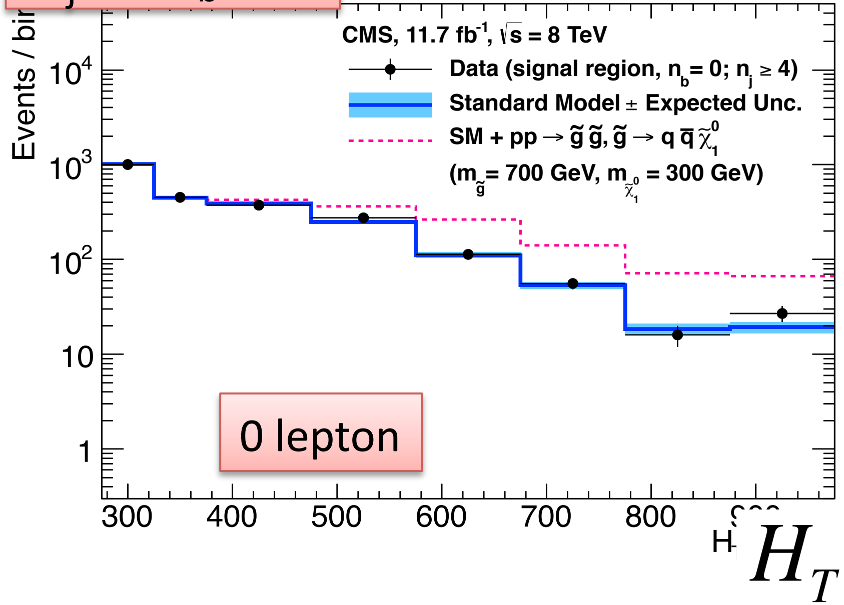
Search for strong production of squarks and gluinos.
Very strong limits from counting experiment.
Dominant background from Z–> νν.
Limits do not apply to stop/sbottom production.

$$m_{\tilde{g}} > 1400 \text{ GeV}$$

$$m_{\tilde{q}} > 1100 \text{ GeV}$$

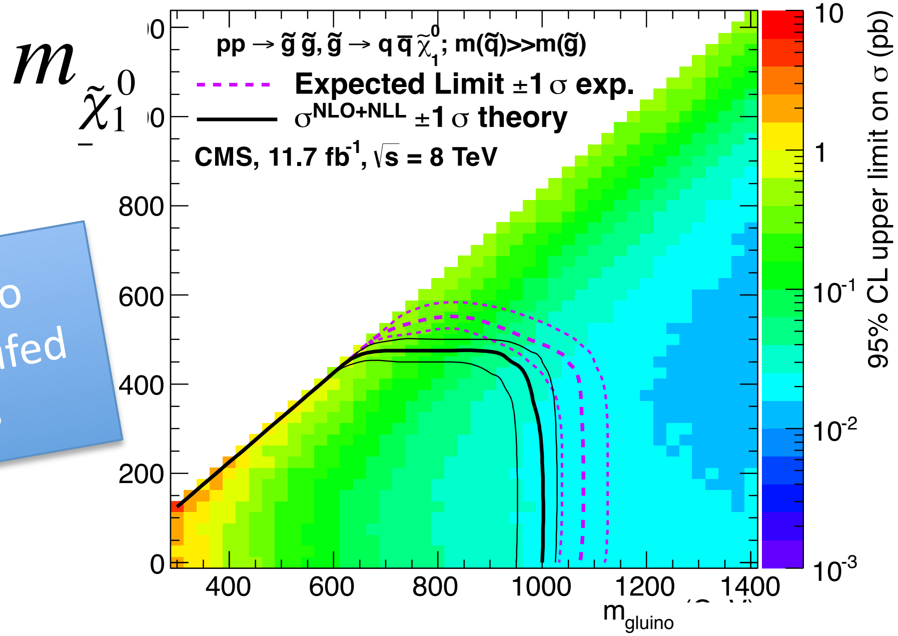
CMS α_T analysis: 8 TeV, 11.7 fb^{-1}

$N_j \geq 4$ $N_b = 0$



Very interesting generic analysis: covers all hadronic events with 0-4 b-tagged jets. Use α_T to remove QCD

One interpretation in simplified model: $\tilde{g} \to q\bar{q}\,\tilde{\chi}^0_1$



$$\tilde{q}\tilde{q}^* \to q\tilde{\chi}^0_1\,\bar{q}\tilde{\chi}^0_1$$
$$\tilde{b}\tilde{b}^* \to b\tilde{\chi}^0_1\,\bar{b}\tilde{\chi}^0_1$$
$$\tilde{t}\tilde{t}^* \to t\tilde{\chi}^0_1\,\bar{t}\tilde{\chi}^0_1$$
$$\tilde{g}\tilde{g} \to q\bar{q}\tilde{\chi}^0_1\,q\bar{q}\tilde{\chi}^0_1$$
$$\tilde{g}\tilde{g} \to b\bar{b}\tilde{\chi}^0_1\,b\bar{b}\tilde{\chi}^0_1$$
$$\tilde{g}\tilde{g} \to t\bar{t}\tilde{\chi}^0_1\,t\bar{t}\tilde{\chi}^0_1$$

Sensitive to many simplifed models

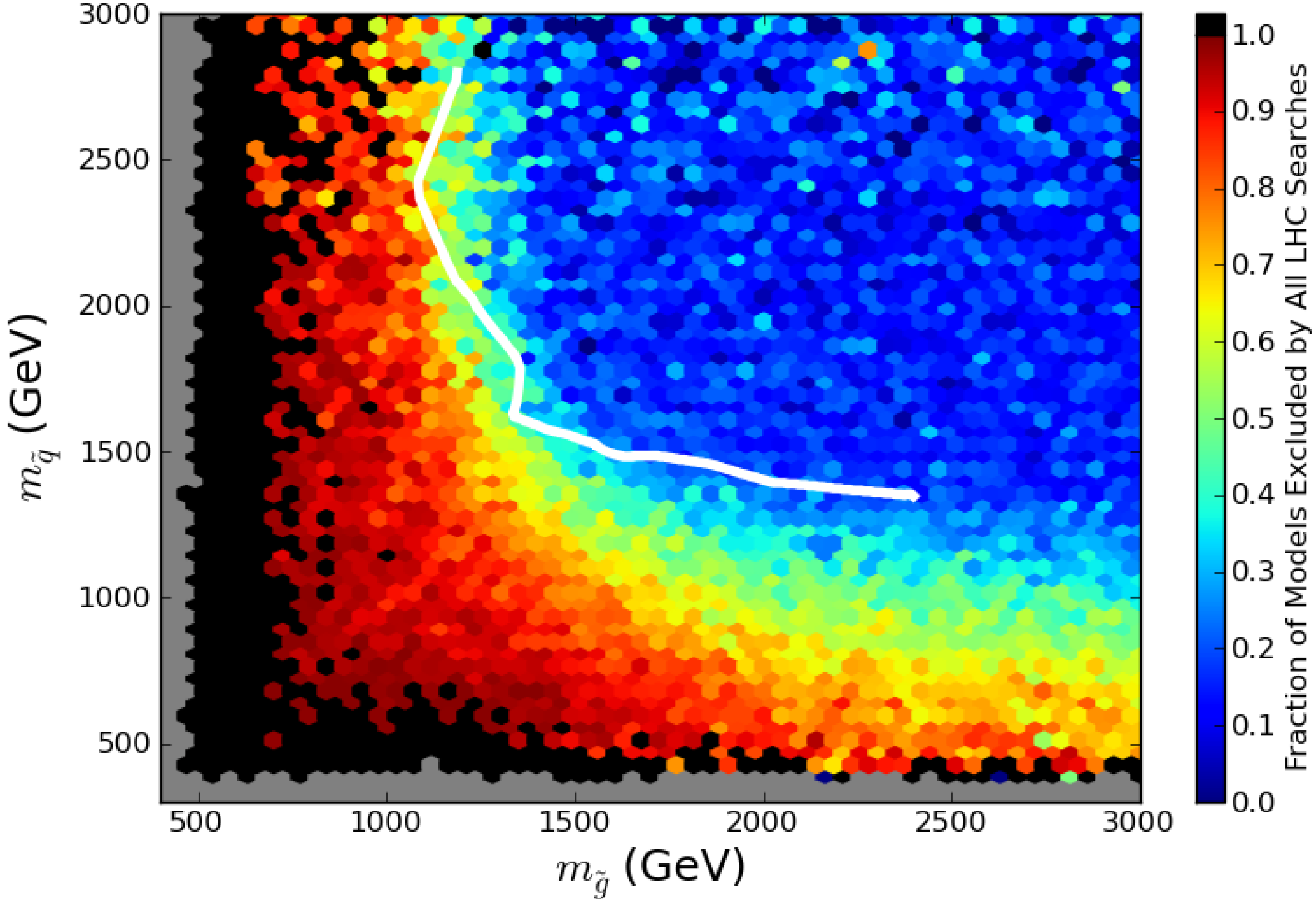
$m_{\tilde{g}}$

CMS PAS SUS-12-028

pMSSM comparison

Rizzo et al
1211.1981

Compare simplified model exclusion to pMSSM with 20 parameters



Some pMSSM model points survive below the “excluded” line –

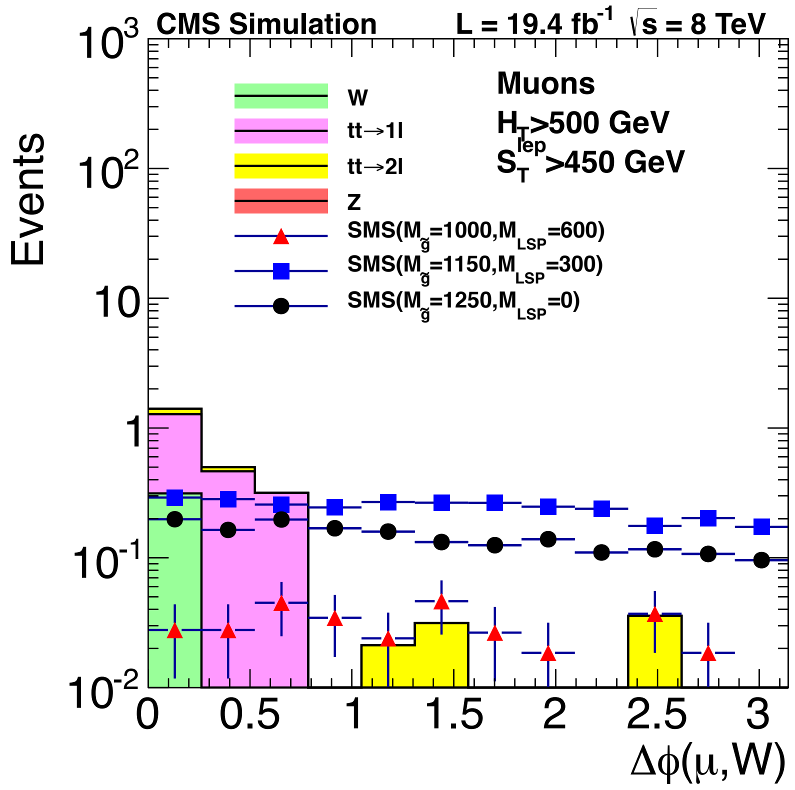
Plane shown is only one slice through parameter space

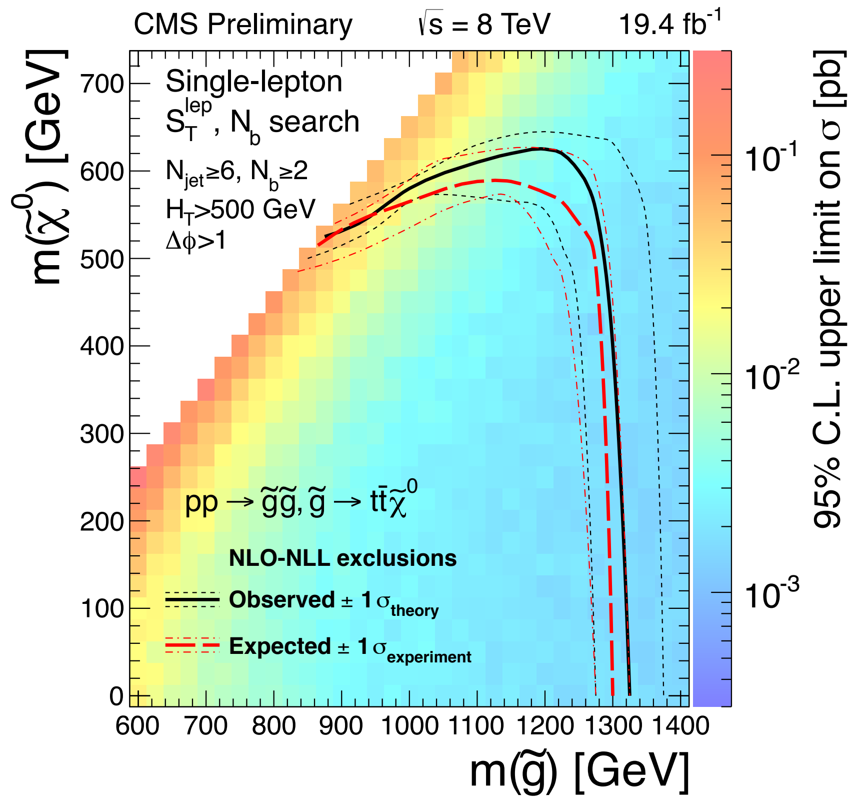
Exclusion ≈ LD50

CMS single lepton search 8 TeV

Target natural SUSY with light gluino decaying to t or b giving lepton, jets, b's

$$pp \rightarrow \tilde{g}\tilde{g} \qquad \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$$





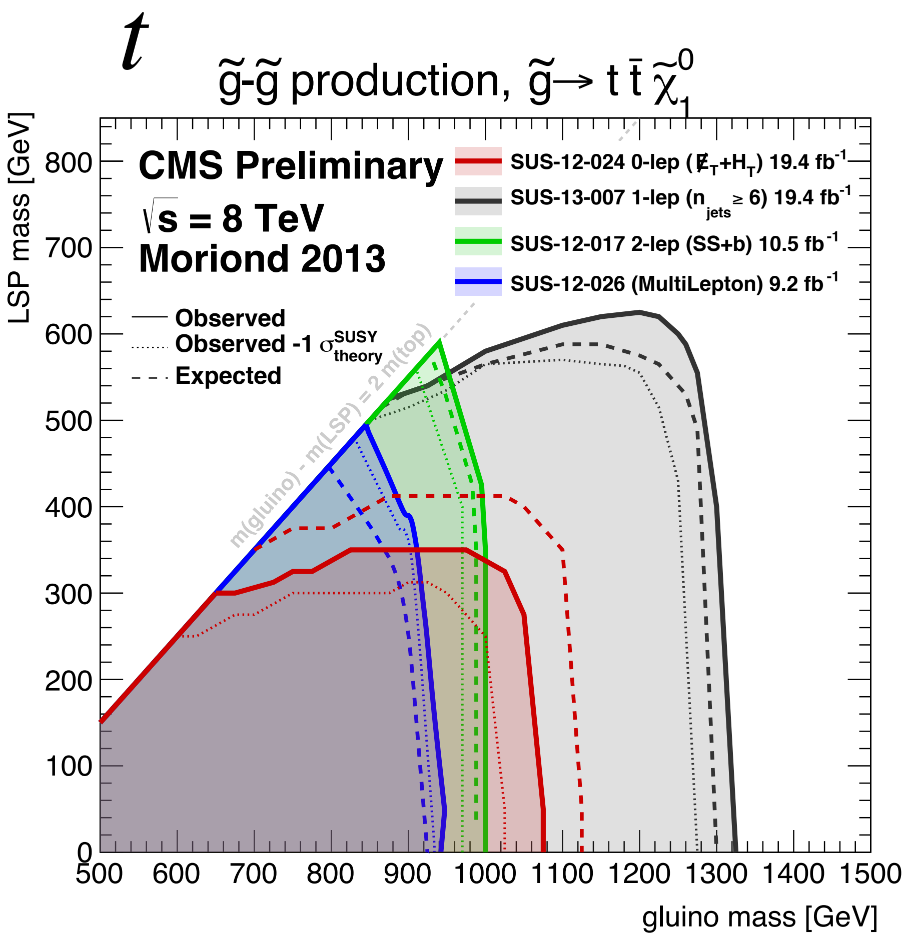
Background from high p_T W has small angle between lepton and W formed from $l+E_T^{miss}$

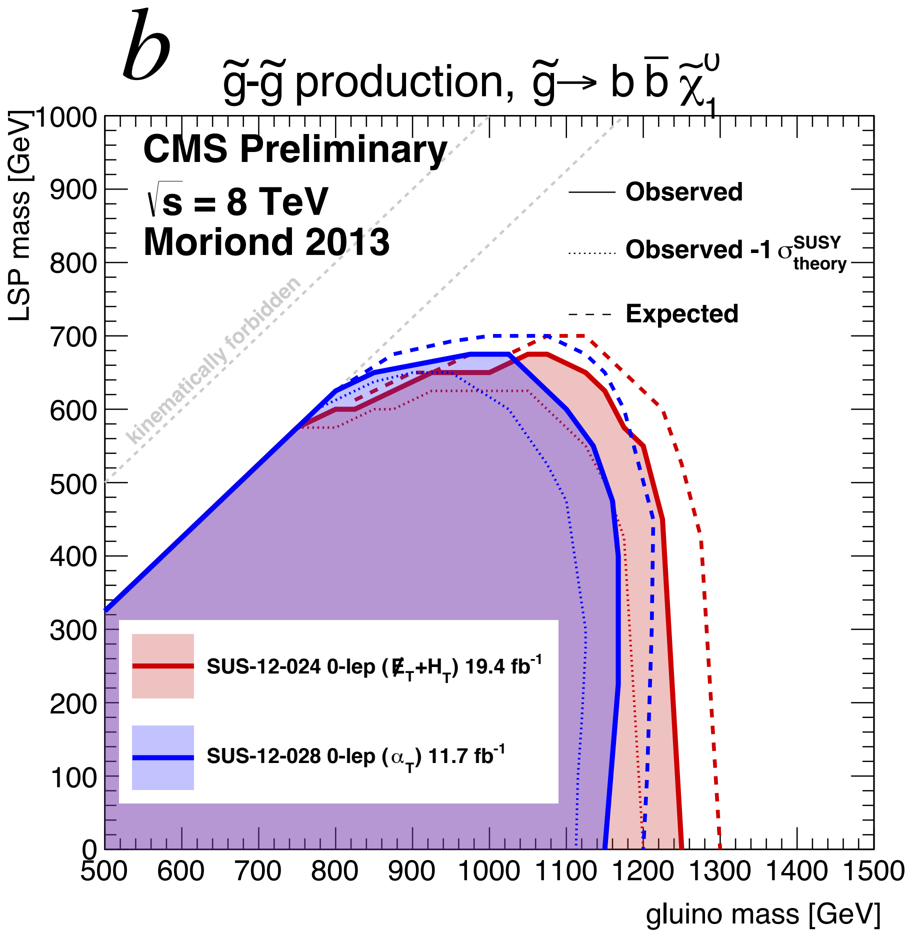
$$m_{\tilde{g}} > 1.3 \text{ TeV for } m_{\tilde{\chi}} < 500 \text{ GeV}$$

CMS PAS SUS-13-007

CMS gluino searches

Look for decays to third family quarks





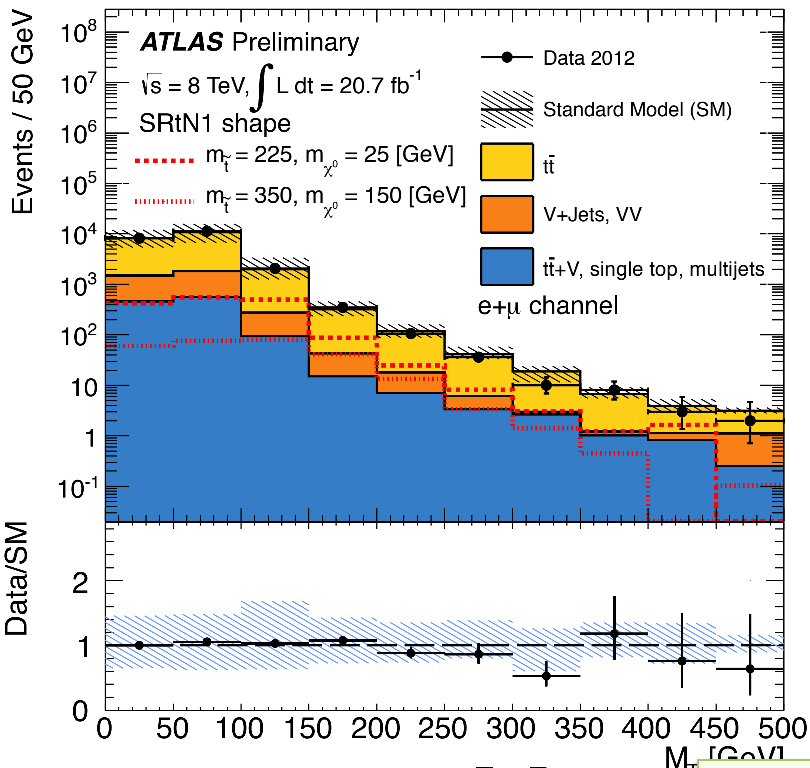
Gluino mass limits now above 1.3 TeV in these models

ATLAS Direct Stop searches

ATLAS-CONF-2013-037

Heavy stop > m_t : look for hadronic or leptonic top decays with extra E_T^{miss}

$$\tilde{t}_1 \rightarrow t\,\tilde{\chi}_1^0 \rightarrow Wb\,\tilde{\chi}_1^0$$



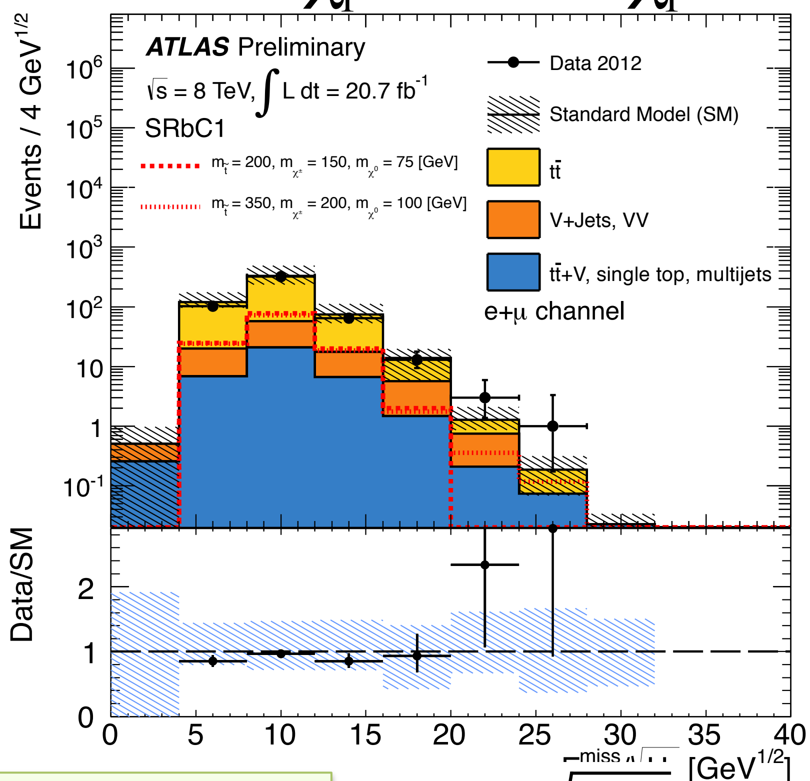
$$M_T$$

Light stop <m_t : top-like decay via chargino. Events contain lower p_T leptons, and subsystem mass below $2m_t$

$$m_t > m_{\tilde{t}} > m_{\tilde{\chi}_1^\pm}$$

What mass?

$$\tilde{t} \rightarrow b\,\tilde{\chi}_1^\pm \rightarrow bW^{(*)}\tilde{\chi}_1^0$$

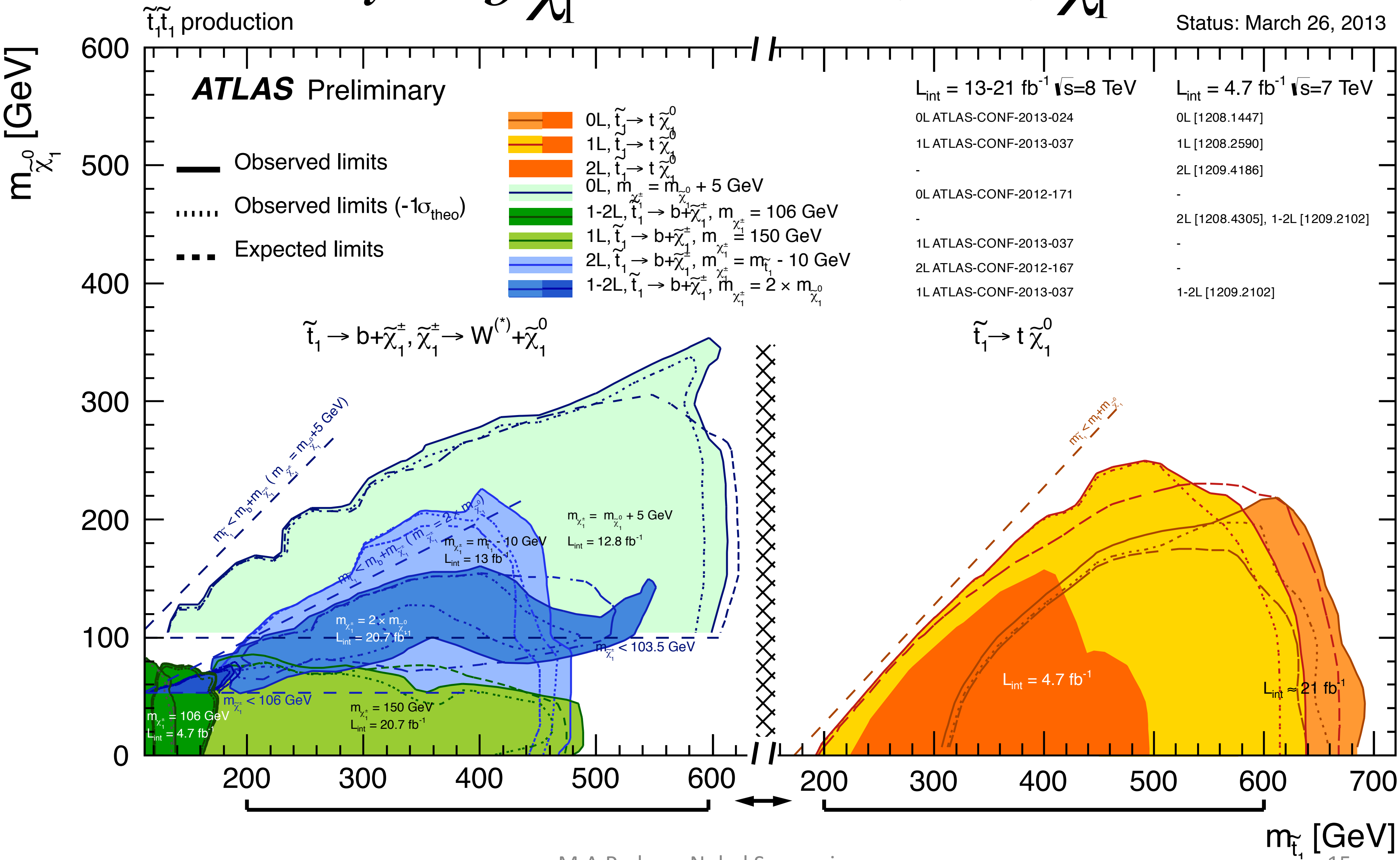


Single lepton example

$$E_T^{Miss} / \sqrt{H_T}$$

ATLAS Combined Stop Exclusion

$\tilde{t} \rightarrow b\,\tilde{\chi}_1^{\pm}$ $\qquad$ $\tilde{t} \rightarrow t\,\tilde{\chi}_1^{0}$



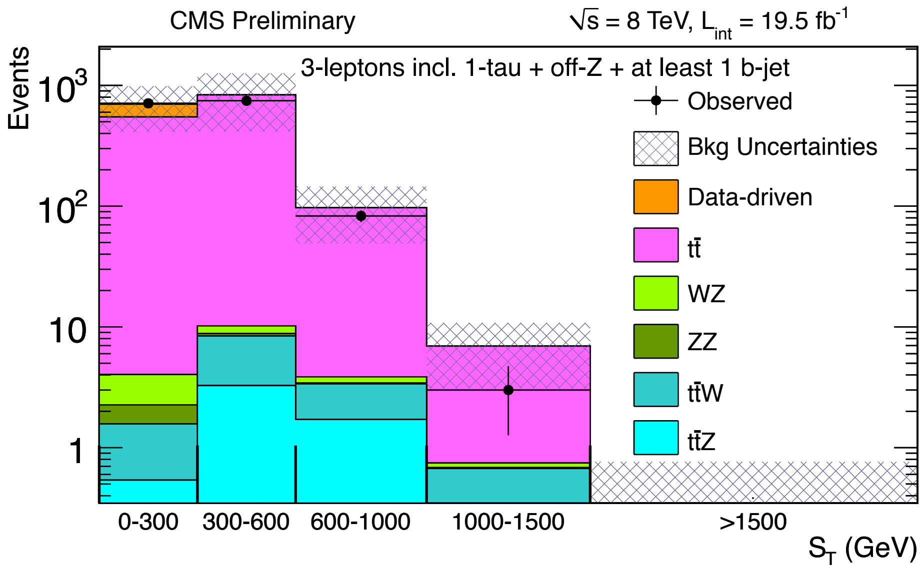
Did we miss something?

- Some escape routes:
- RPV – reduced missing energy, long-lived LSP
- Compressed/degenerate spectra – reduced pT final state objects, long-lived LSP
- Other SUSY breaking mechanisms (GMSB, AMSB) with altered phenomenology
- Stealth SUSY – low p_T final states
- More parameters eg pMSSM

Not just retreating to high mass scale

CMS multi-lepton with b search

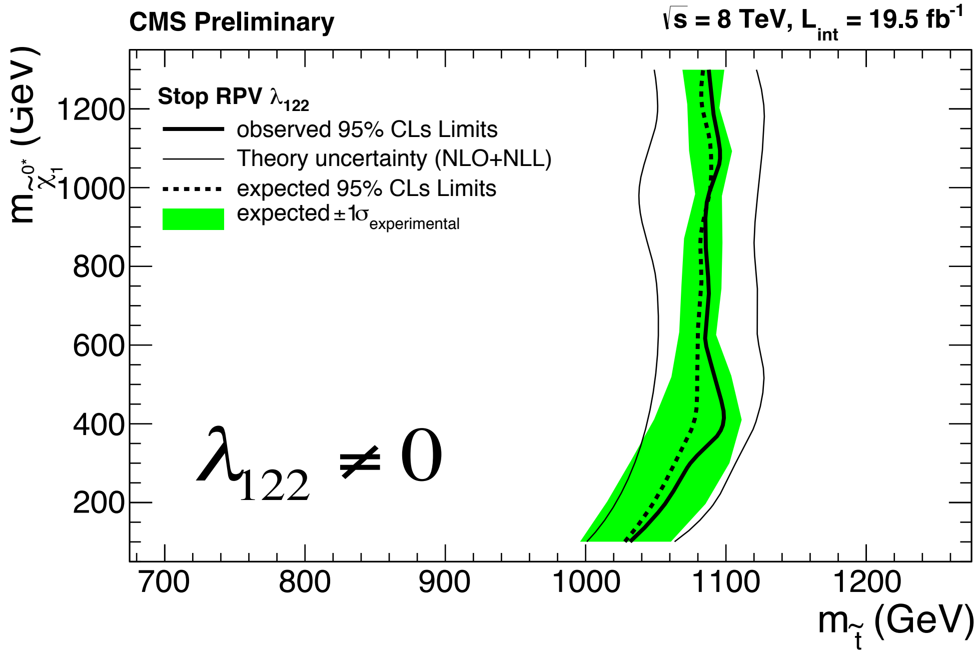
3 leptons (1 tau) ≥1 b



$$S_T = H_T + E_T^{Miss} + \sum_{Leptons} p_T$$

RPV events have less missing energy: LSP can decay to SM particles. Use S_T instead of E_T^{miss}

Sensitive to RPV stop decays



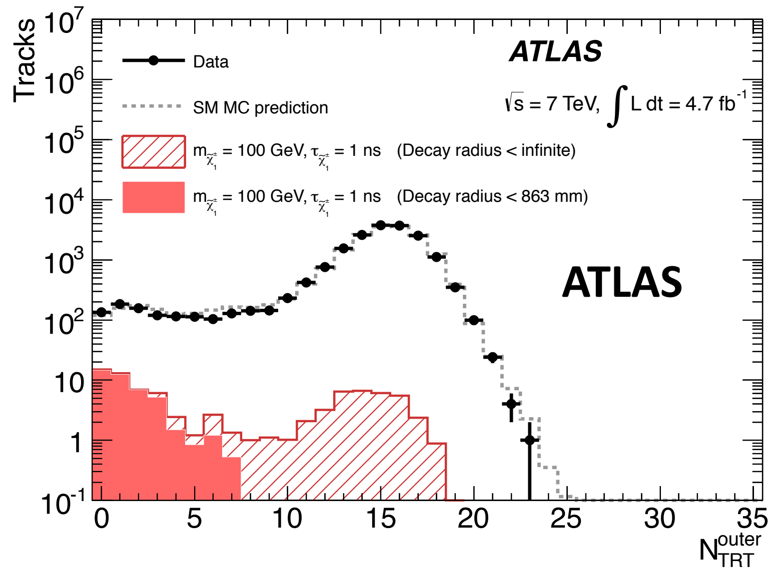
Limit above on leptonic RPV scenario Analysis also sensitive to many other scenarios.

$$W_{R_p} = \frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

SUS-13-003-pas

Long-lived particles

Small Δm: SUSY particle decays in flight: look for disappearing tracks



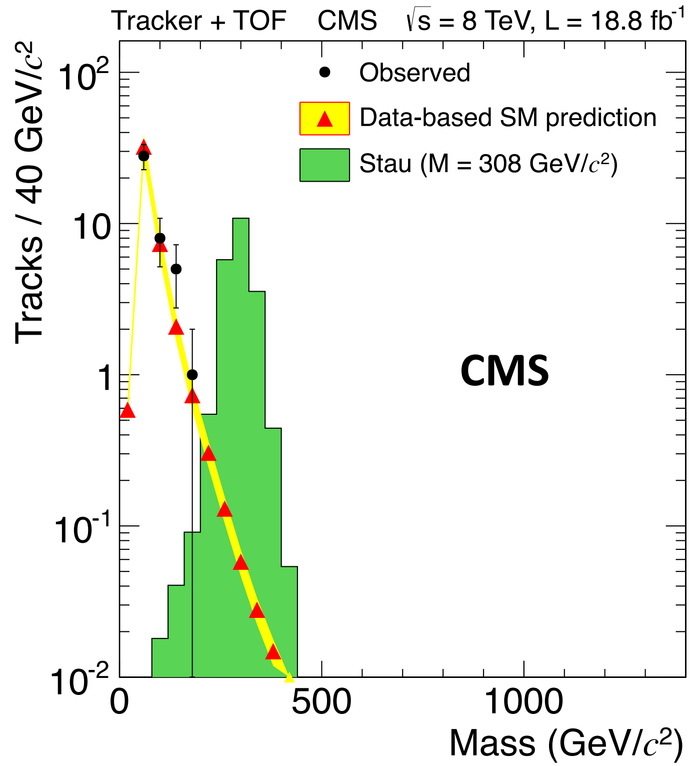
AMSB models: $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 \pi^{\pm}$

Signal: high pT isolated tracks ≤ 5 hits in TRT

Exclude: m(chargino) < 103 GeV
for m(chargino)-m(LSP) < 160 MeV

JHEP 01 (2013) 131

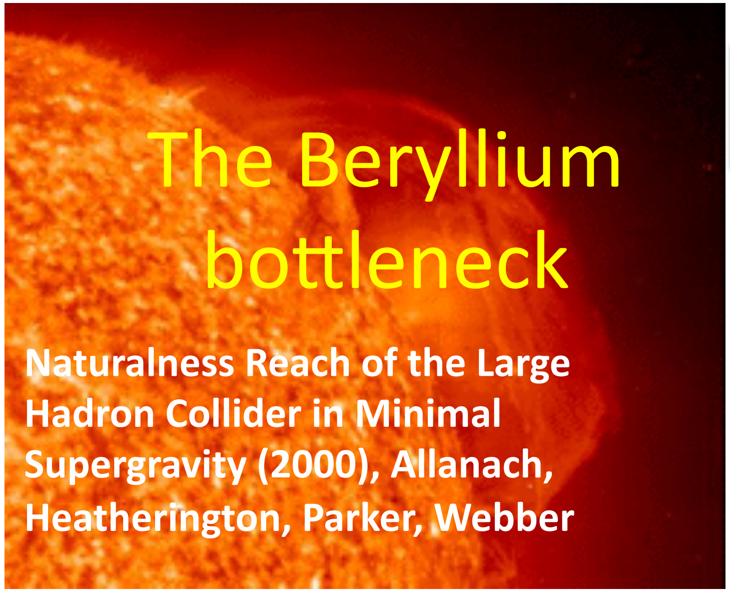
Very long lifetime: SUSY particle leaves detector - look for slow tracks



Signal: high mass from time-of-flight

Exclude: fractional/multiple Q
- staus <435 GeV
- Gluino R hadron < 1.3 TeV

1305.0491



Q2: Is naturalness a good guide?

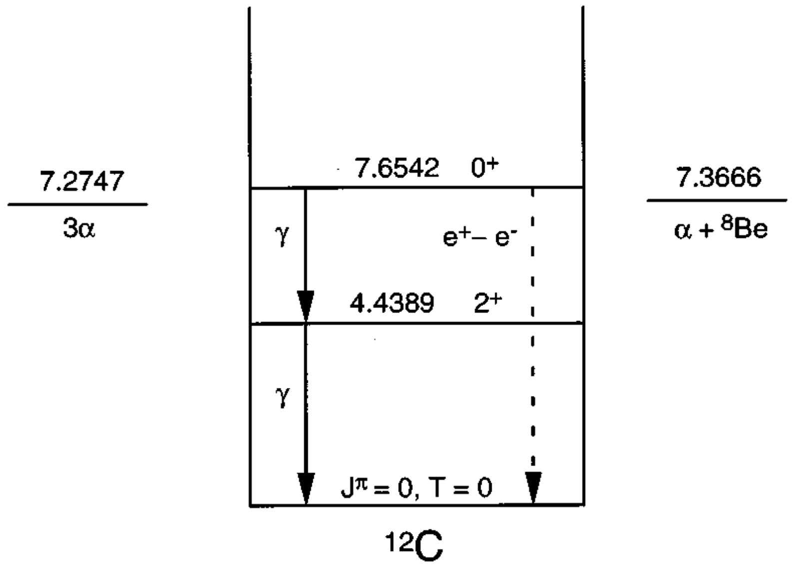
- Big bang makes Hydrogen, Helium, ^{2}D, ^{3}He, ^{7}Li
- He+p -> ^{5}Li – highly unstable
- He+He-> ^{8}Be – decays back to 2α with lifetime of 10^{-16} s
- Path to heavier nuclei appears to be blocked!

In stars, density is high enough for

$$^8\text{Be} + {}^4\text{He} \rightarrow {}^{12}\text{C}^{**}$$

…but rate should be very low.

Hoyle et al, 1953, predicted existence of resonance at 7.65 MeV to enhance rate. Found experimentally with required 0^+ quantum numbers.



Wallerstein 1997

Crucial to Universe we know, is it natural?

Extra dimensions and other exotica

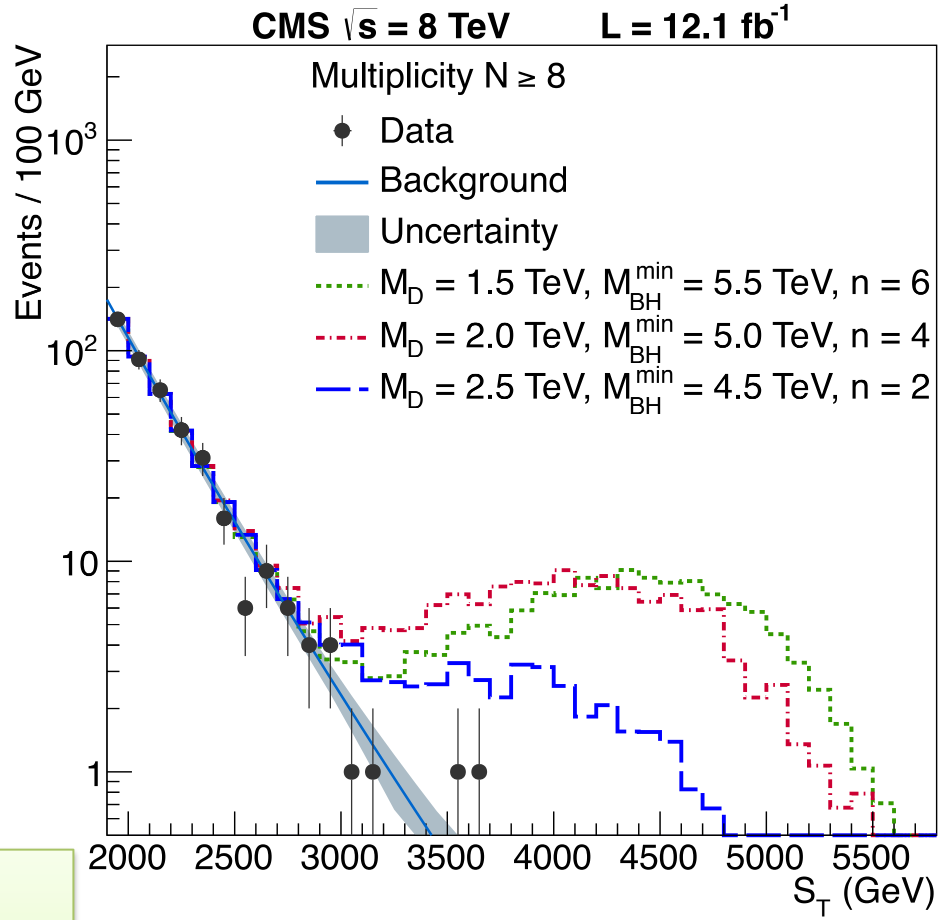
Too much for today!

- Extra dimensions are a popular alternative to SUSY
  - Black holes
  - Two body scattering
  - Monojets
  - Excess high-pT leptons
- Other exotic models
  - W' and Z'
  - Compositeness/techicolour
  - Leptoquarks
  - Dijet/dilepton resonances
  - 4^{th} generation
  - …..

Lodewijk Toeput 1587

CMS Black Hole search

- Look for high mass states as function of multiplicity
- Calibrate background using invariance of S_T distribution with final state multiplicity
- Set limits on effective Planck scale and number of ED

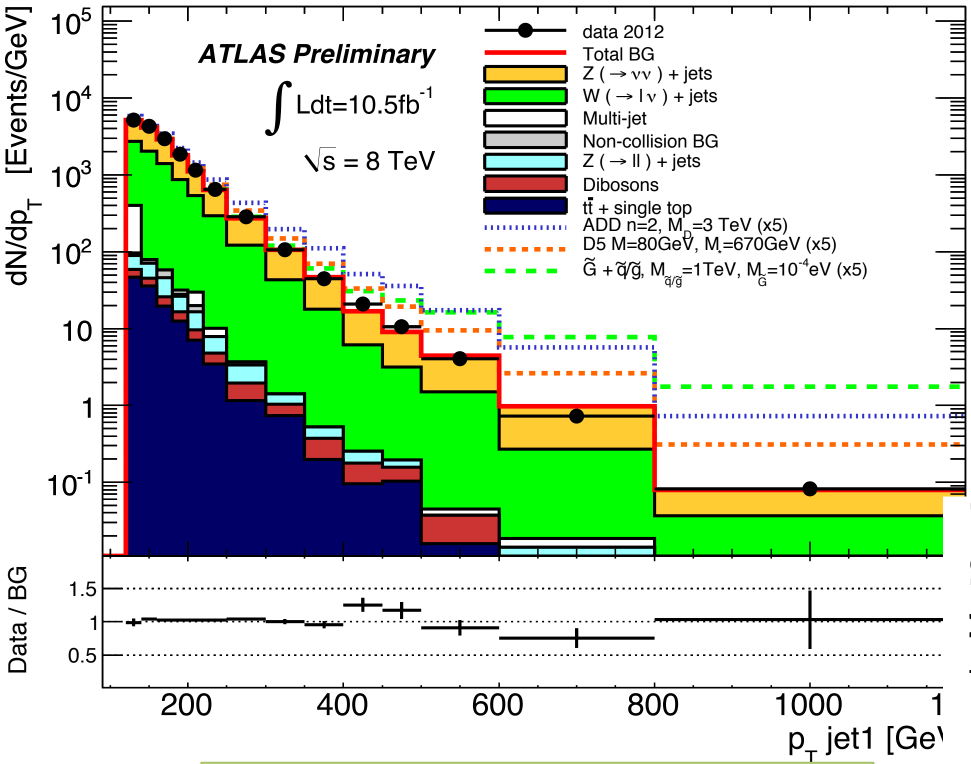


Limits on black hole production with masses in range 4.3-6.2 TeV

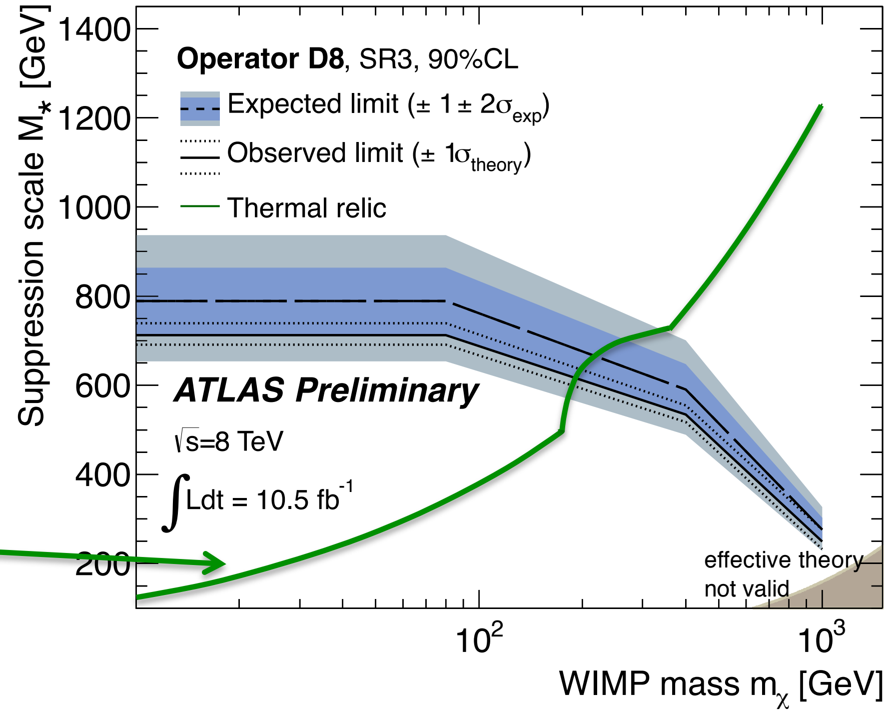
CMS-EXO-12-009

ATLAS-CONF-2012-147

ATLAS Monojets



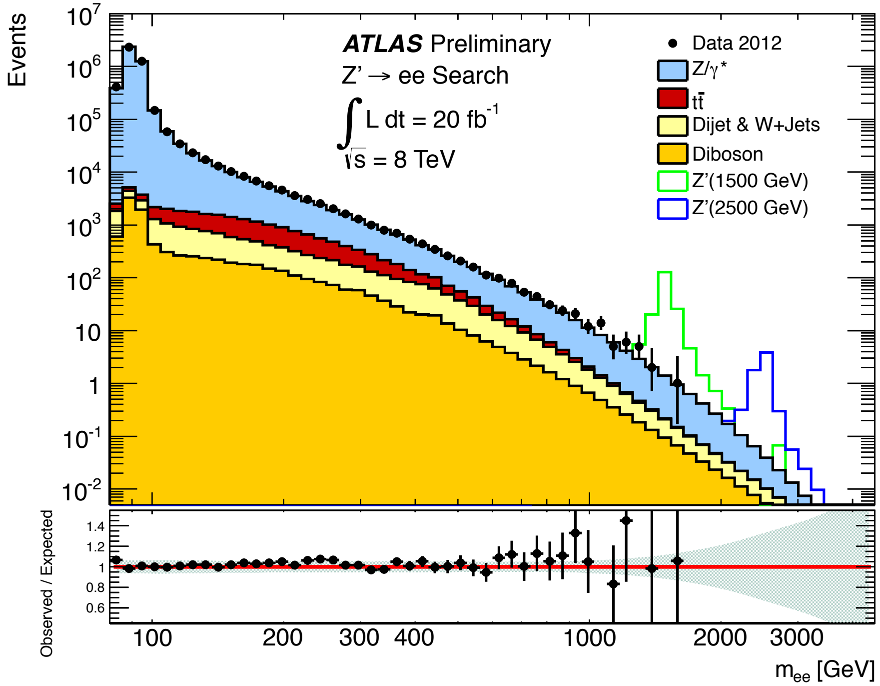
- Monojets sensitive to ED models, WIMP production, gravitinos (GMSB) …



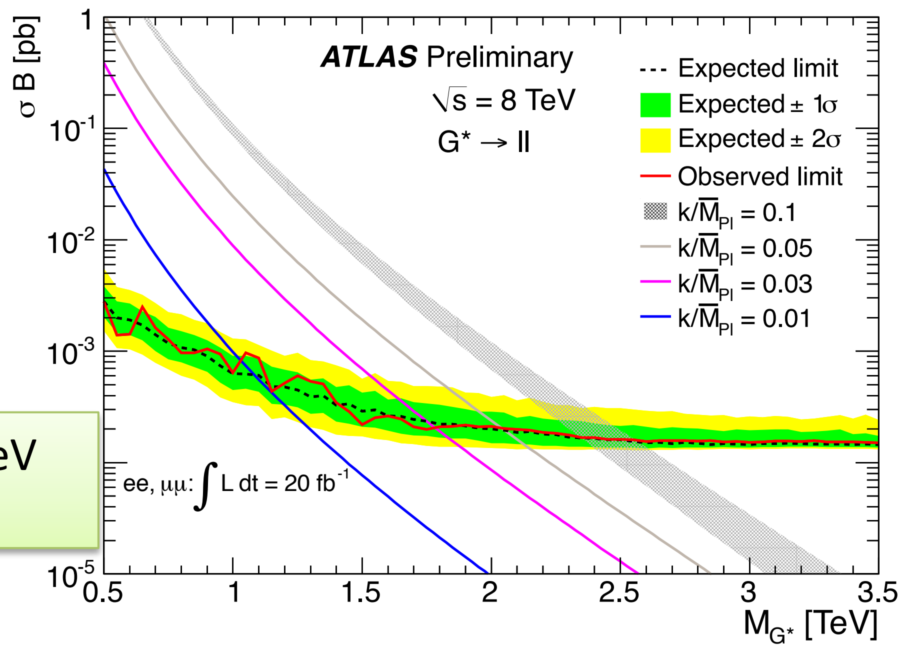
WIMP interactions in effective theory with mediator mass M* and various possible operators.

Green line shows value needed to match WMAP relic density

ATLAS high mass dilepton resonances



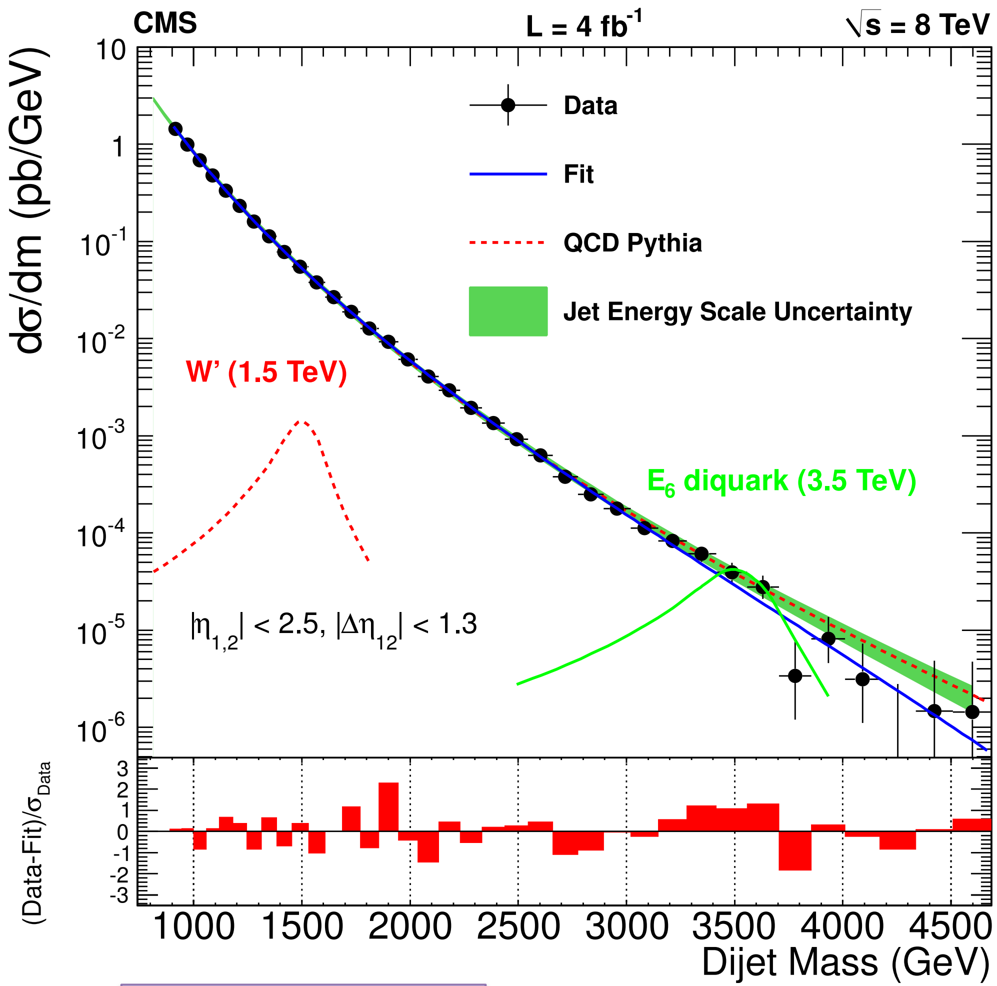
Sensitive to many forms of new physics – Z', RS gravitons, E(6) GUT, composite technicolour Higgs



M(Z')>2.4-2.9 TeV in various models

RS Graviton>2.47 TeV for k/M_{Pl}=0.1

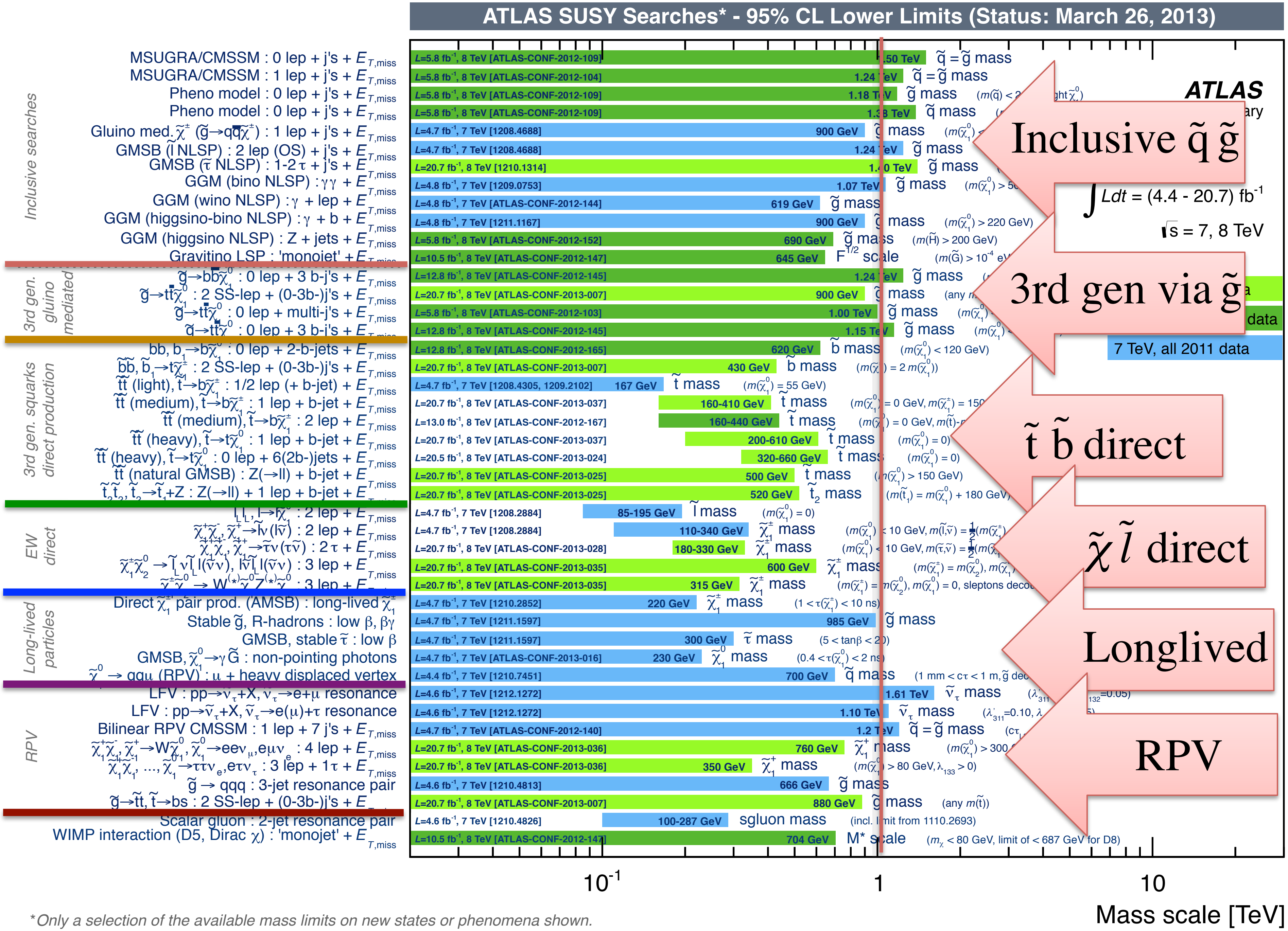
CMS narrow dijet resonances



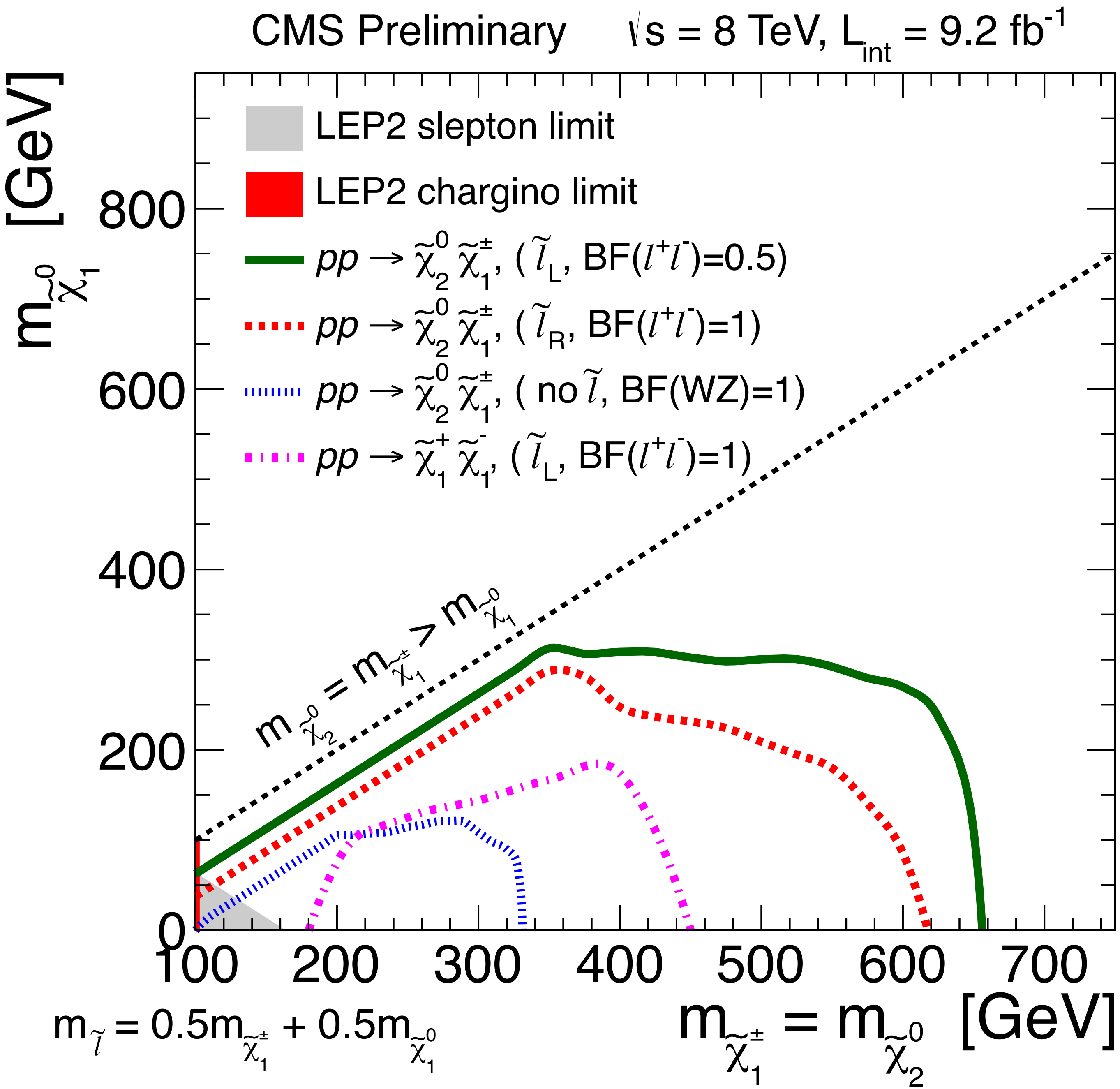
arXiv:1302.4794

- Sensitive to many BSM models. First limits on RS Graviton to jets.

Model	Final state	Observed excluded mass range [TeV]
String Resonance	qg	[1.0, 4.78]
Excited Quark	qg	[1.0, 3.19]
E_6 Diquark	qq	[1.0, 4.28]
Axigluon/Coloron	$q\bar{q}$	[1.0, 3.27]
S8 Resonance	gg	[1.0, 2.79]
W′ Boson	$q\bar{q}$	[1.0, 1.73]
Z′ Boson	$q\bar{q}$	[1.0, 1.62]
RS Graviton	$q\bar{q} + gg$	[1.0, 1.45]

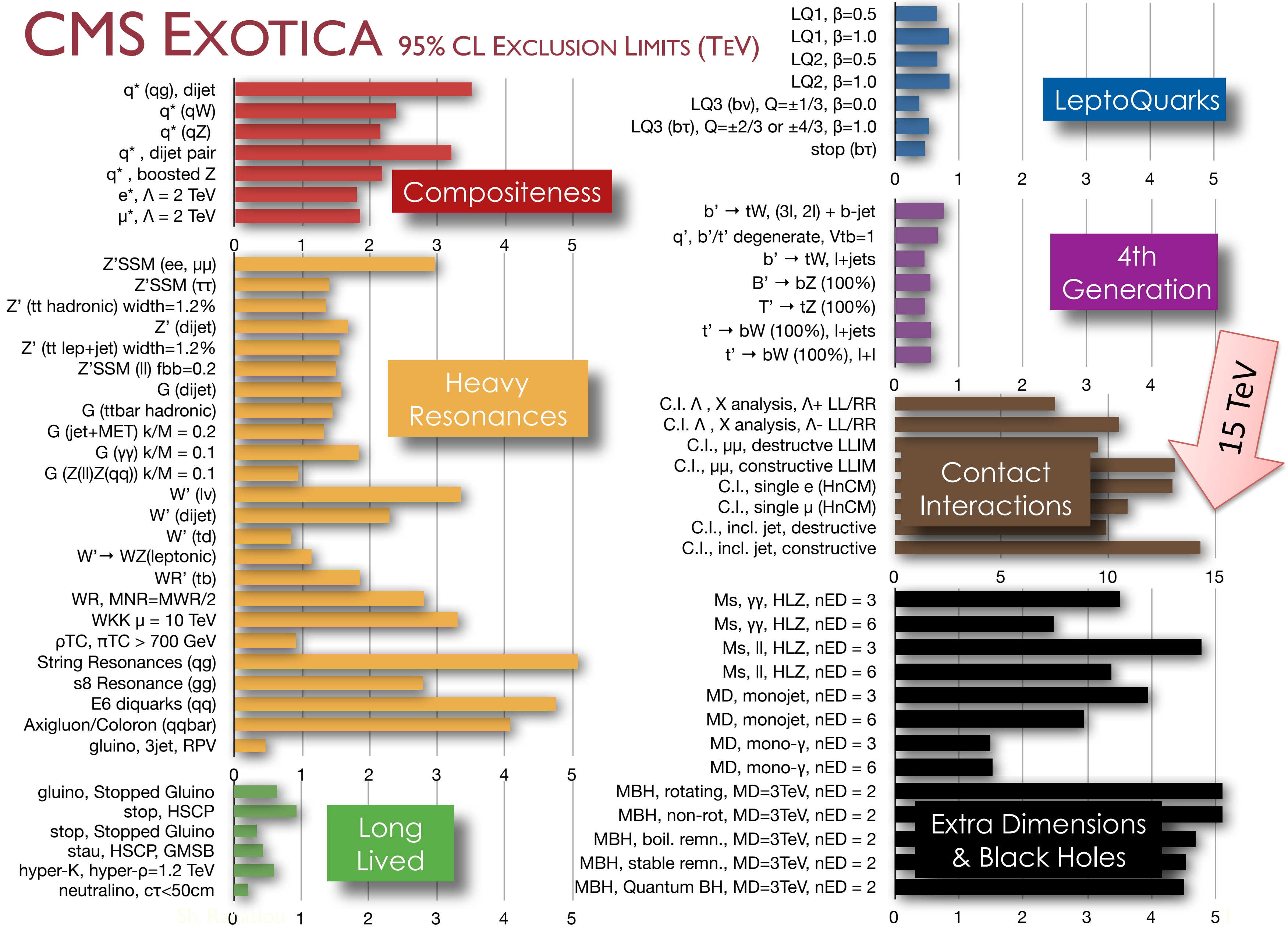


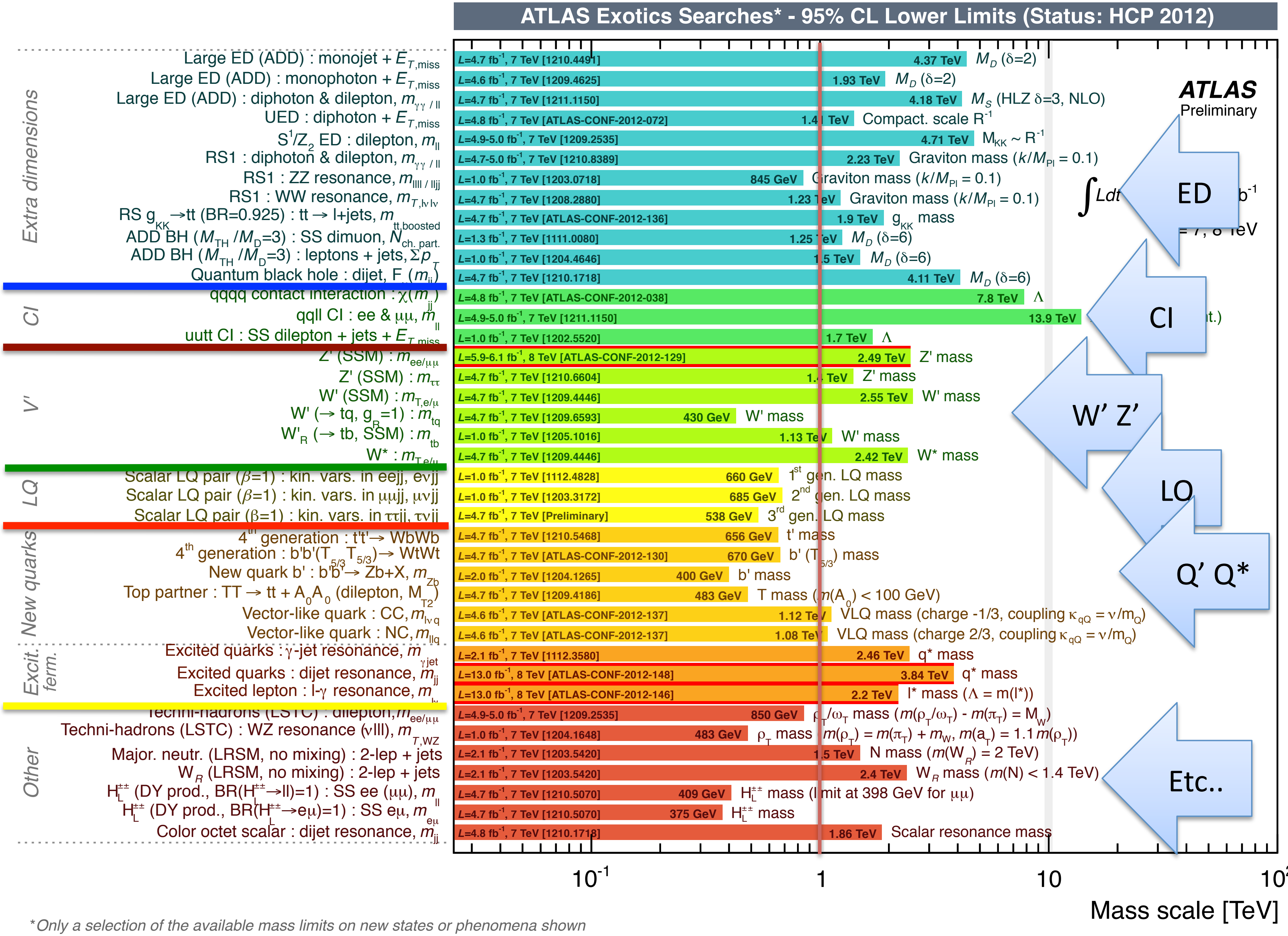
*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.



CMS Preliminary $\sqrt{s}$ = 8 TeV, L_{int} = 9.2 fb^{-1}
LEP2 slepton limit
LEP2 chargino limit
$pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^{\pm}$, ($\tilde{l}_L$, BF($l^+l^-$)=0.5)
$pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^{\pm}$, ($\tilde{l}_R$, BF($l^+l^-$)=1)
$pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^{\pm}$, (no $\tilde{l}$, BF(WZ)=1)
$pp \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$, ($\tilde{l}_L$, BF($l^+l^-$)=1)
$m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^{\pm}} > m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_1^{\pm}} = m_{\tilde{\chi}_2^0}$ [GeV]
$m_{\tilde{l}} = 0.5 m_{\tilde{\chi}_1^{\pm}} + 0.5 m_{\tilde{\chi}_1^0}$
0
200
400
600
800
100
200
300
400
500
600
700

CMS EXOTICA 95% CL EXCLUSION LIMITS (TEV)





ATLAS Exotics Searches* - 95% CL Lower Limits (Status: HCP 2012)
Extra dimensions
CI
V'
LQ
New quarks
Excit. ferm.
Other
Large ED (ADD) : monojet + E_T,miss — 4.37 TeV M_D (δ=2)
Large ED (ADD) : monophoton + E_T,miss — 1.93 TeV M_D (δ=2)
Large ED (ADD) : diphoton & dilepton — 4.18 TeV M_S (HLZ δ=3, NLO)
UED : diphoton + E_T,miss — 1.41 TeV Compact. scale R^-1
S1/Z2 ED : dilepton — 4.71 TeV M_KK ~ R^-1
RS1 : diphoton & dilepton — 2.23 TeV Graviton mass (k/M_Pl = 0.1)
RS1 : ZZ resonance — 845 GeV Graviton mass (k/M_Pl = 0.1)
RS1 : WW resonance — 1.23 TeV Graviton mass (k/M_Pl = 0.1)
RS g_KK → tt (BR=0.925) : tt → l+jets — 1.9 TeV g_KK mass
ADD BH (M_TH/M_D=3) : SS dimuon — 1.25 TeV M_D (δ=6)
ADD BH (M_TH/M_D=3) : leptons + jets — 1.5 TeV M_D (δ=6)
Quantum black hole : dijet, F(m_jj) — 4.11 TeV M_D (δ=6)
qqqq contact interaction : χ(m_jj) — 7.8 TeV Λ
qqll CI : ee & μμ, m_ll — 13.9 TeV
uutt CI : SS dilepton + jets + E_T,miss — 1.7 TeV Λ
Z' (SSM) : m_ee/μμ — 2.49 TeV Z' mass
Z' (SSM) : m_ττ — 1.4 TeV Z' mass
W' (SSM) : m_T,e/μ — 2.55 TeV W' mass
W' (→ tq, g_R=1) : m_tq — 430 GeV W' mass
W'_R (→ tb, SSM) : m_tb — 1.13 TeV W' mass
W* : m_T,e/μ — 2.42 TeV W* mass
Scalar LQ pair (β=1) : kin. vars. in eejj, eνjj — 660 GeV 1st gen. LQ mass
Scalar LQ pair (β=1) : kin. vars. in μμjj, μνjj — 685 GeV 2nd gen. LQ mass
Scalar LQ pair (β=1) : kin. vars. in ττjj, τνjj — 538 GeV 3rd gen. LQ mass
4th generation : t't' → WbWb — 656 GeV t' mass
4th generation : b'b'(T5/3T5/3) → WtWt — 670 GeV b' (T5/3) mass
New quark b' : b'b' → Zb+X — 400 GeV b' mass
Top partner : TT → tt + A0A0 (dilepton, M_T2) — 483 GeV T mass (m(A0) < 100 GeV)
Vector-like quark : CC — 1.12 TeV VLQ mass (charge -1/3, coupling κ_qQ = ν/m_Q)
Vector-like quark : NC — 1.08 TeV VLQ mass (charge 2/3, coupling κ_qQ = ν/m_Q)
Excited quarks : γ-jet resonance — 2.46 TeV q* mass
Excited quarks : dijet resonance — 3.84 TeV q* mass
Excited lepton : l-γ resonance — 2.2 TeV l* mass (Λ = m(l*))
Techni-hadrons (LSTC) : dilepton — 850 GeV ρ_T/ω_T mass
Techni-hadrons (LSTC) : WZ resonance (νlll) — 483 GeV ρ_T mass
Major. neutr. (LRSM, no mixing) : 2-lep + jets — 1.5 TeV N mass (m(W_R) = 2 TeV)
W_R (LRSM, no mixing) : 2-lep + jets — 2.4 TeV W_R mass (m(N) < 1.4 TeV)
H_L^±± (DY prod., BR(H_L^±±→ll)=1) : SS ee (μμ) — 409 GeV H_L^±± mass (limit at 398 GeV for μμ)
H_L^±± (DY prod., BR(H_L^±±→eμ)=1) : SS eμ — 375 GeV H_L^±± mass
Color octet scalar : dijet resonance — 1.86 TeV Scalar resonance mass
ATLAS Preliminary
ED
CI
W' Z'
LQ
Q' Q*
Etc..
10^-1
1
10
10^2
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena shown

Q3: Do we have solid foundations?

500-year-old Srikalahasti temple in Andhra Pradesh collapsed in 2010 –
Foundations were only 45cm thick.

Should we consider some basic assumptions?

-CPT theorem?
-Lorentz invariance/ discreteness of space-time?
-Time varying coupling constants?
-Much more complex dark sector?

We cannot solve our problems with the same thinking we used when we created them.
Albert Einstein

Conclusions

To explain the current and future LHC data, we need a strong structure, with solid foundations, with both symmetry and variety, capable of facing what ever Nature may produce….

Gripsholms slott, Mariefred

Backups

What is α_T?

$$\alpha_T = \frac{E_T^{j_2}}{M_T}$$

For well balanced dijet systems, $\alpha_T = 0.5$

For an multi-jet system, jets are merged to make an equivalent dijet system such that difference in E_T of two systems (ΔH_T) is minimum.

$$\alpha_T = \frac{1}{2} \cdot \frac{H_T - \Delta H_T}{\sqrt{H_T^2 - \not{H}_T^2}}$$