Where is the New Physics? Results from LHC

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LCWS
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why should there be new physics?

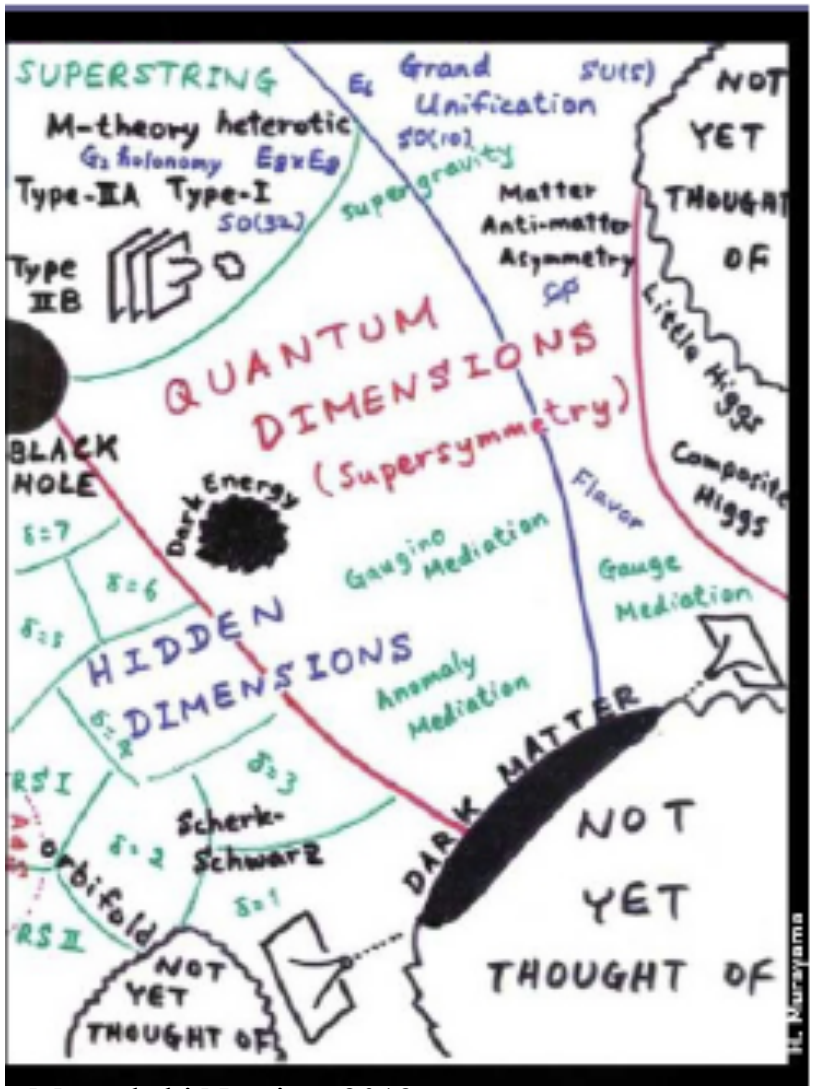
- hierarchy problem
  - stabilize the Higgs boson mass
  - biggest contribution from top quark loops
  - requires new particle with m < 1 TeV
  - could be vector-like quark or stop squark
- dark matter
  - the WIMP miracle
  - TeV mass, weakly interacting particle produces the correct relic density
  - could be lightest supersymmetric particle

what might it look like?

- possible phenomenologies
  - SUSY
    - solves hierarchy problem and provides dark matter candidate
    - jets, leptons, photons + large missing pT
  - extra dimensions
    - lower Planck scale
    - KK towers, black holes
  - little Higgs theories
    - push scale of new physics up
    - top quark and W boson partners
  - New/excited fermions
  - Leptoquarks
  - something completely different??

what might it look like?

A theorists view of the univers(es)



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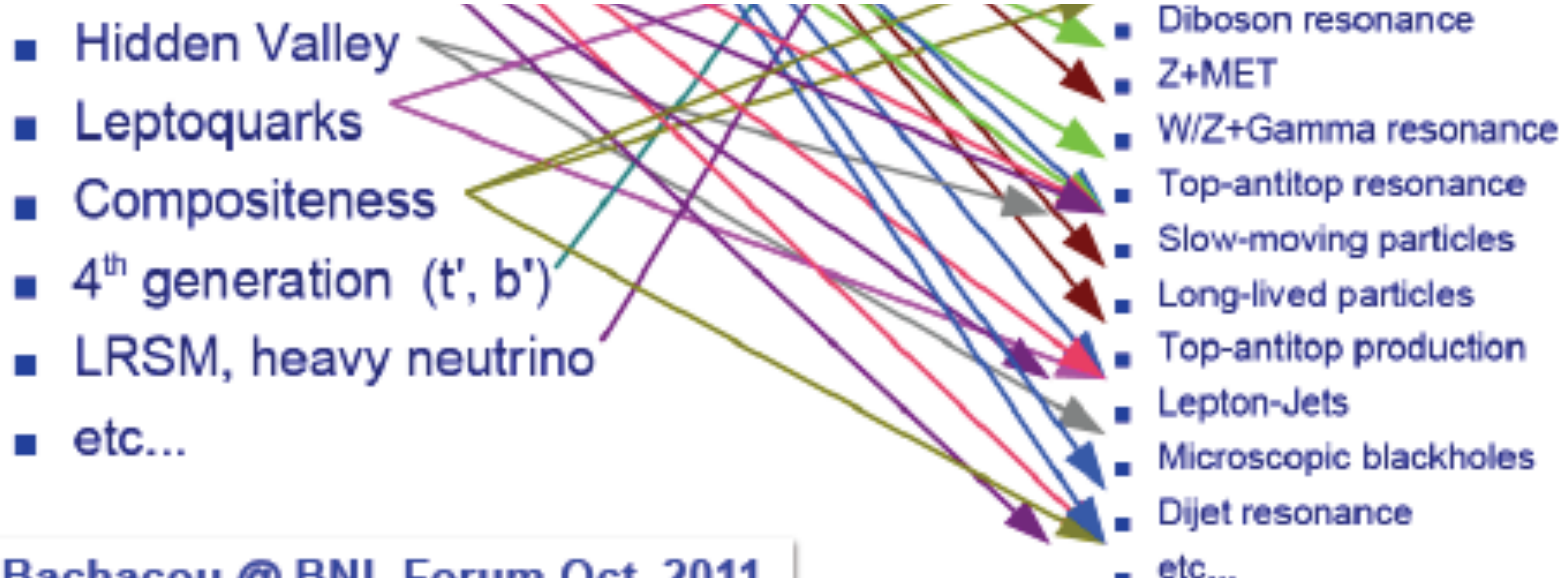
The Exotics Matrix

Given the diversity of signatures, a wide net needs to be cast



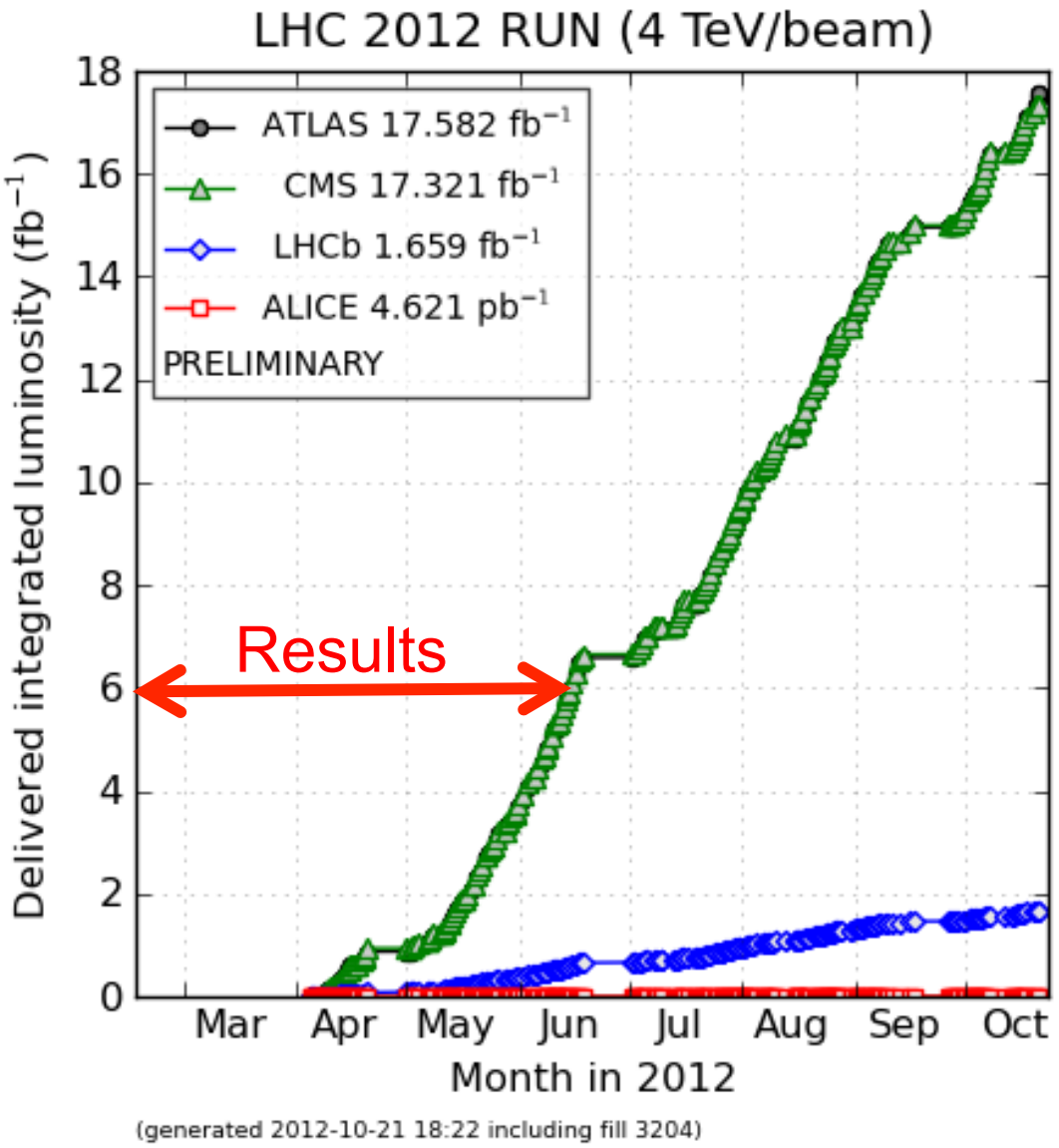
H. Bachacou @ BNL Forum Oct. 2011

LHC

Data collected in 2011: ≈ 5fb^{-1} of analyzable luminosity

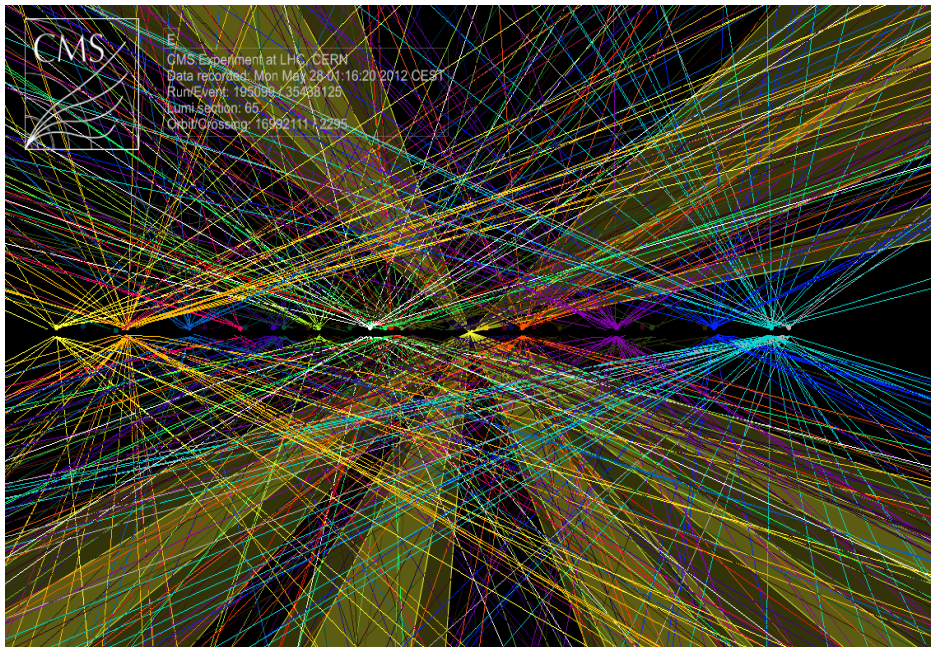
2012: ≈ 17.5fb^{-1} recorded and continuing…..

Impressive Machine Performance!



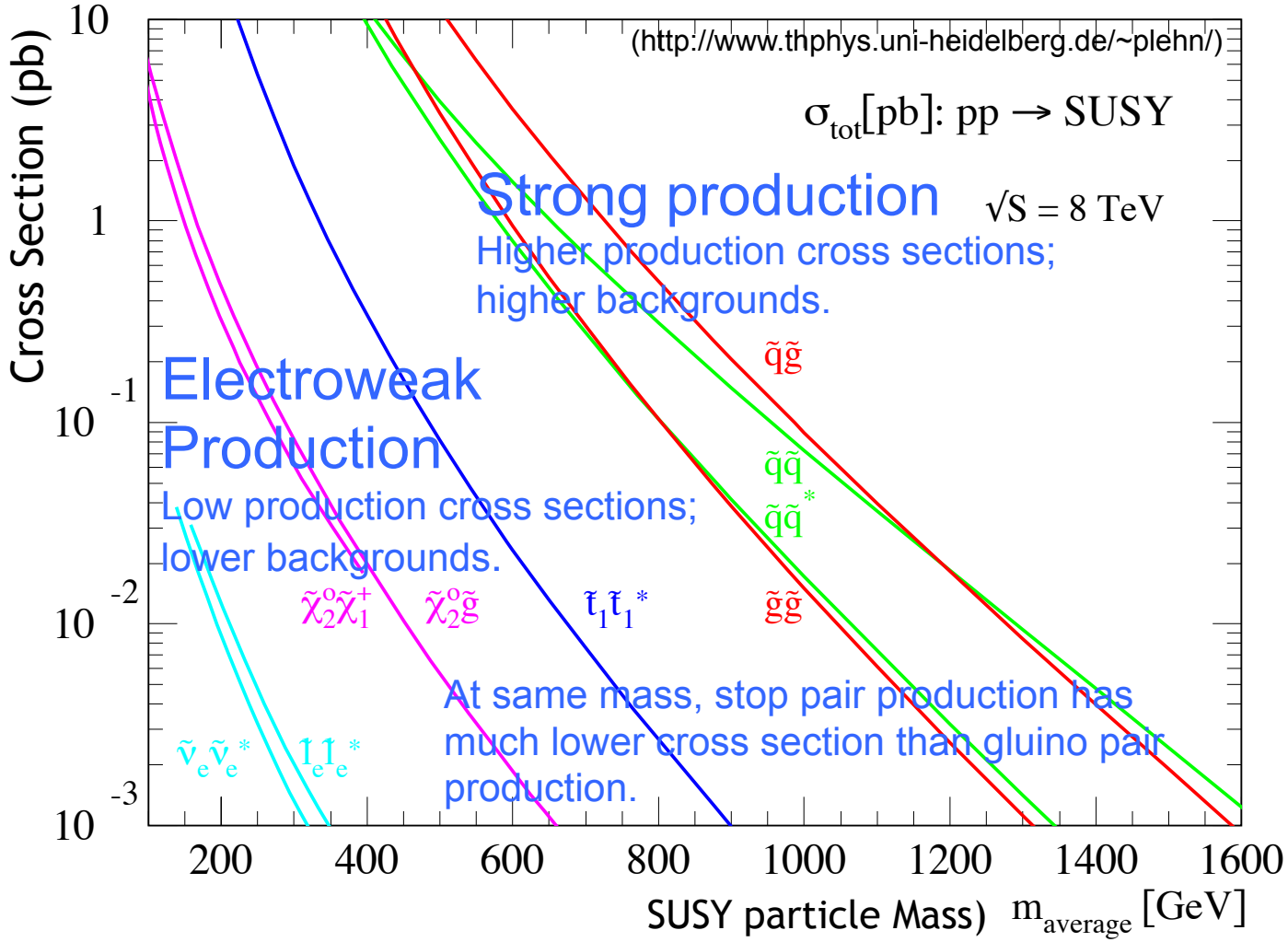
Event Pile-up issues:

- High luminosity comes at a cost: in 2012 already exceeding detector design capability for pile-up
- Presently: ~30 collisions on average /bunch-crossing



- Need to be mitigated at all stages:
  - Trigger, reconstruction of physics objects, isolation cuts, etc.
  - Data processing time

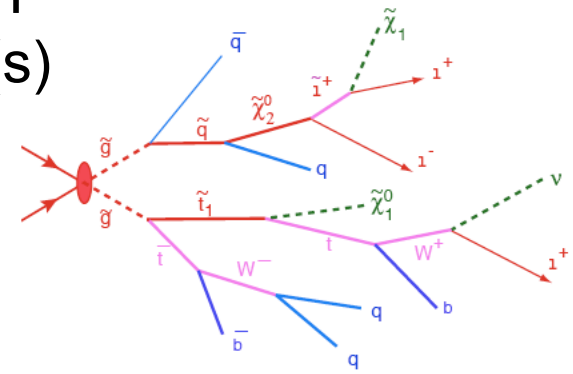
SUSY Searches



- Many powerful "inclusive" searches have been pursued
  - Searching in a broad spectrum of new physics scenarios – main sensitivities to gluino/squark production

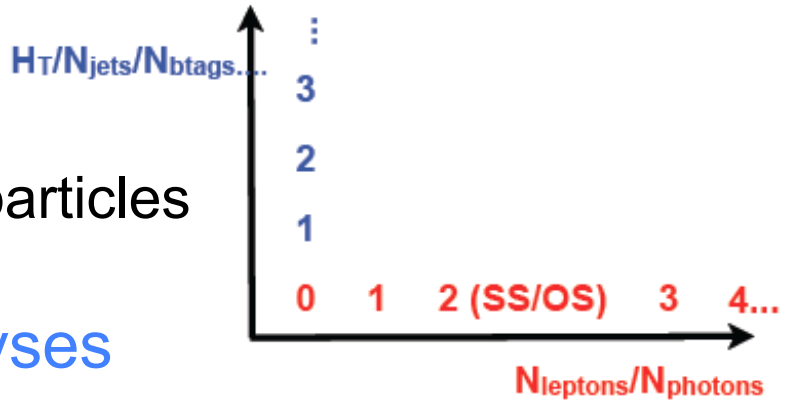
SUSY search strategies

- strongly produced spartners
  - cascade decays of squarks/gluinos to stable LSP
  - jets ➔ large transverse energy + missing pT
  - possibly additional lepton(s) and/or photon(s)



- 3rd generation squarks
  - top and bottom quarks + missing pT

- gaugino/slepton production
  - W or Z bosons/leptons + missing pT

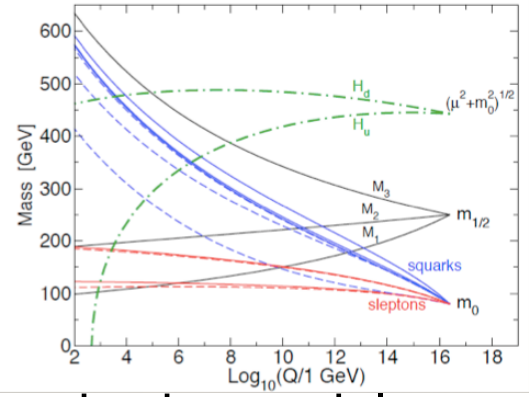


- RP violating SUSY
  - displaced vertex, heavy charged particles

- Final state signature based analyses

SUSY Search Interpretations

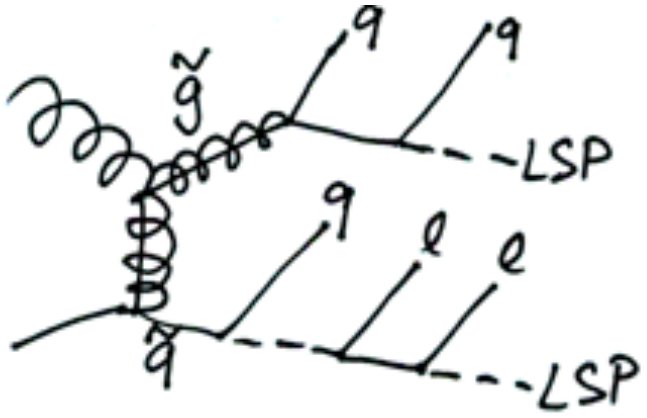
- In context of a specific model
  - Predictive but universality constraints result in significant restrictions on possible SUSY particle mass spectra
    - Constrained MSSM (mSUGRA)
    - Gauge-Mediated SUSY Breaking (GMSB)
    - Anomaly-Mediated SUSY Breaking (AMSB)



- Simplified Model Spectra:
  - Focus on topology rather than the underlying physics model
  - Limited set of particles; decays with less specific mass patterns and signatures
  - The exclusions depends strongly on the LSP mass.
  - Give acceptance x efficiency and cross-section limit
  - Building blocks that can be used to generalize to a more complete 'model'-space
  - Models proposed at: http://www.lhcnewphysics.org

jets+missing p_T search

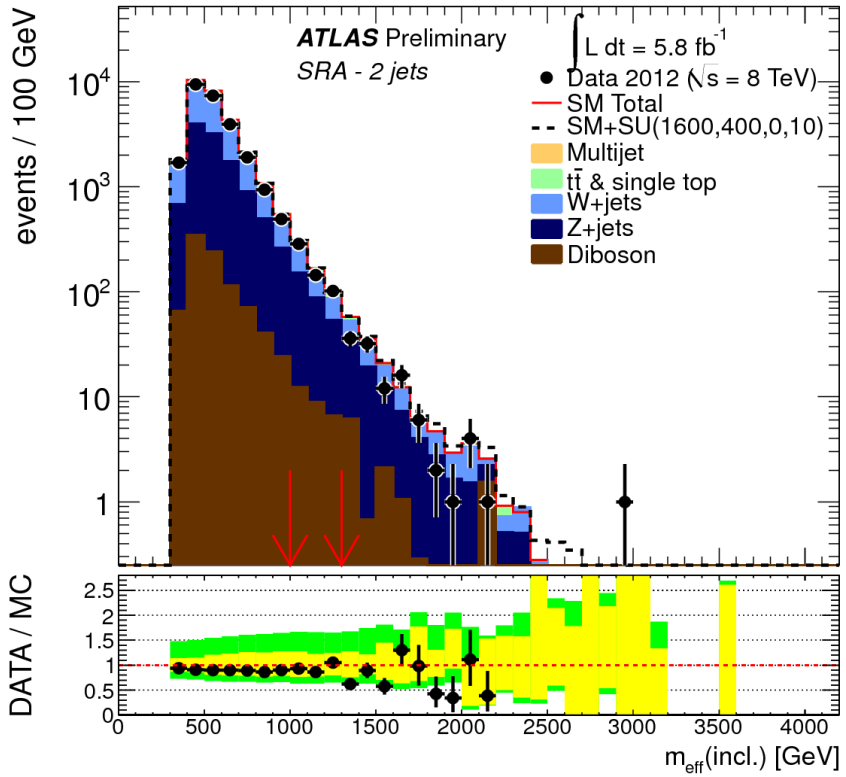
- very challenging due to large amount and wide range of backgrounds
- most sensitive search for strongly produced SUSY

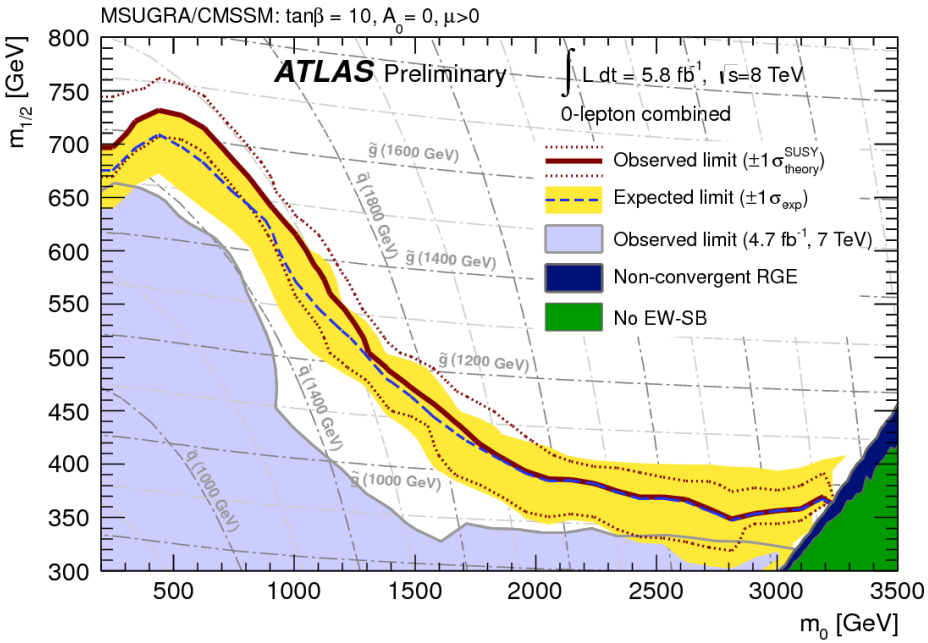


- selection
  - 2-6 jets with pT>60 GeV
  - missing pT > 160 GeV
  - no leptons
  - cuts on Δφ(jet, missing pT), missing pT/Meff
- dominant backgrounds
  - W+jets, Z+jets, top quark production, multijets
- constrain backgrounds with data in control regions

jets+missing p_T search

- count number of events in signal regions defined by
  - $m_{eff}=\Sigma|p_T(jet)| + |missing\ p_T|$, jet multiplicity
- no significant excess over background expectations





95% limits in MSUGRA/cMSSM with tanβ=10, A_0=0 and μ>0

ATLAS-CONF-2012-109

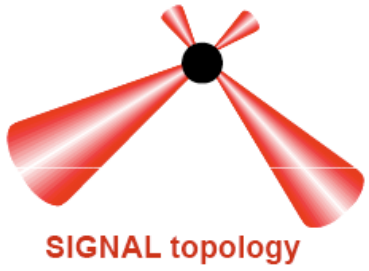
b-jets + missing p_T search

- Wide sensitivity to both inclusive and 3rd generation signatures
- event selection
  - no isolated leptons/photons
  - ≥2 jets with pT>100 GeV
  - analysis variable $\alpha_T = E_T^{j2}/M_T^{j1j2}$
  - $\alpha_T > 0.55$
- bin in H_T and b-jet multiplicity

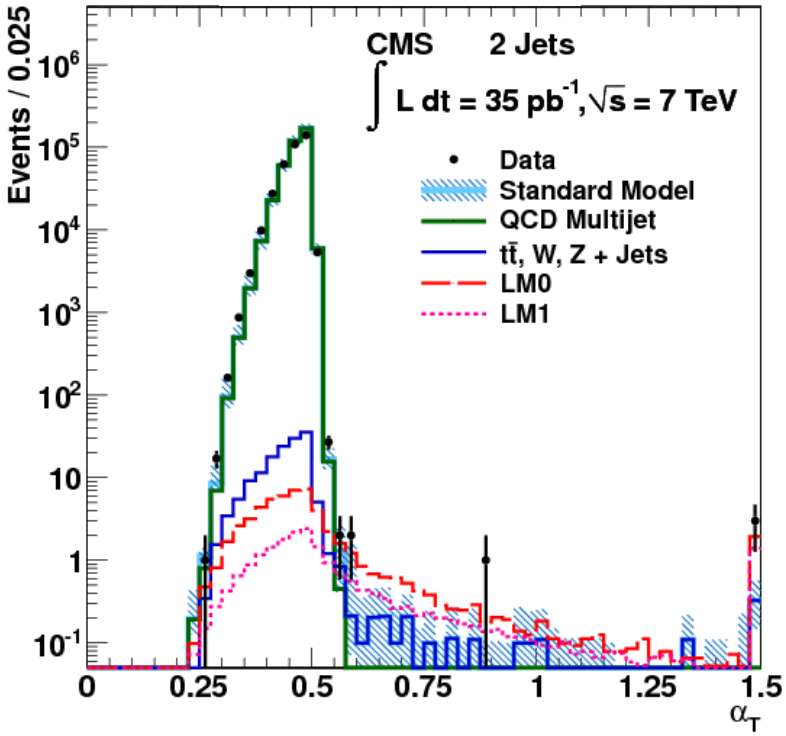
$$M_T = \sqrt{\left(\sum_{i=1}^{2} E_T^{j_i}\right)^2 - \left(\sum_{i=1}^{2} p_x^{j_i}\right)^2 - \left(\sum_{i=1}^{2} p_y^{j_i}\right)^2}.$$

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

$\alpha_T \leq 0.5$



$\alpha_T > 0.5$

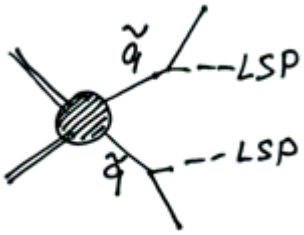


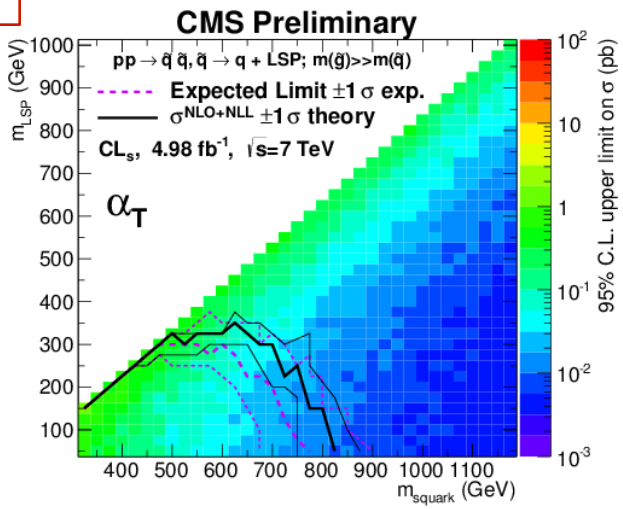
b-jets + missing p_T search

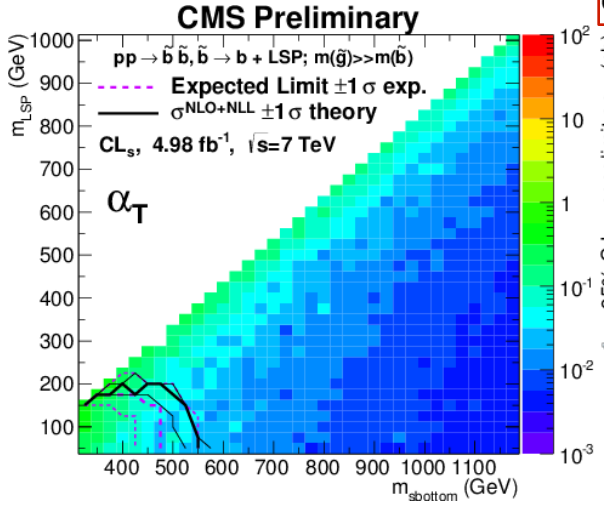
limits from 7 TeV data

CMS PAS SUS-11-022

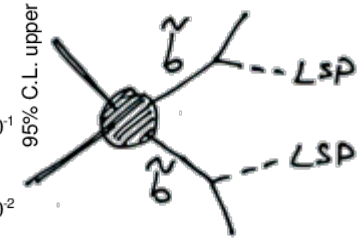
$\tilde{q}\tilde{q} \to qq\tilde{\chi}^0\tilde{\chi}^0$



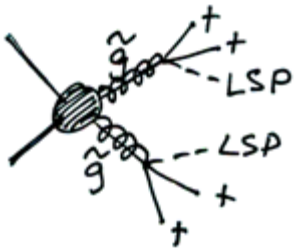


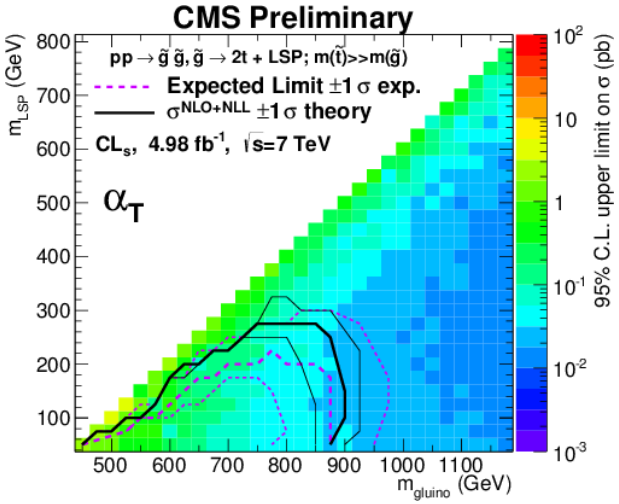


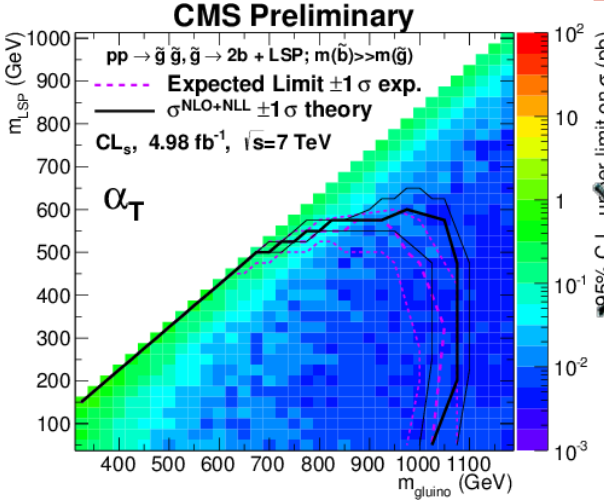
$\tilde{b}\tilde{b} \to bb\tilde{\chi}^0\tilde{\chi}^0$



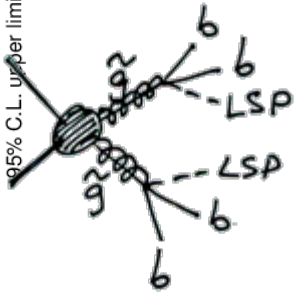
$\tilde{g}\tilde{g} \to tttt\tilde{\chi}^0\tilde{\chi}^0$





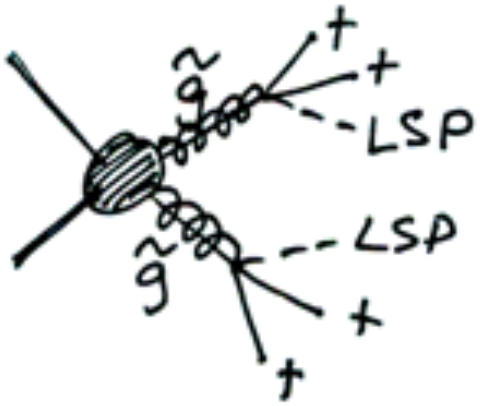


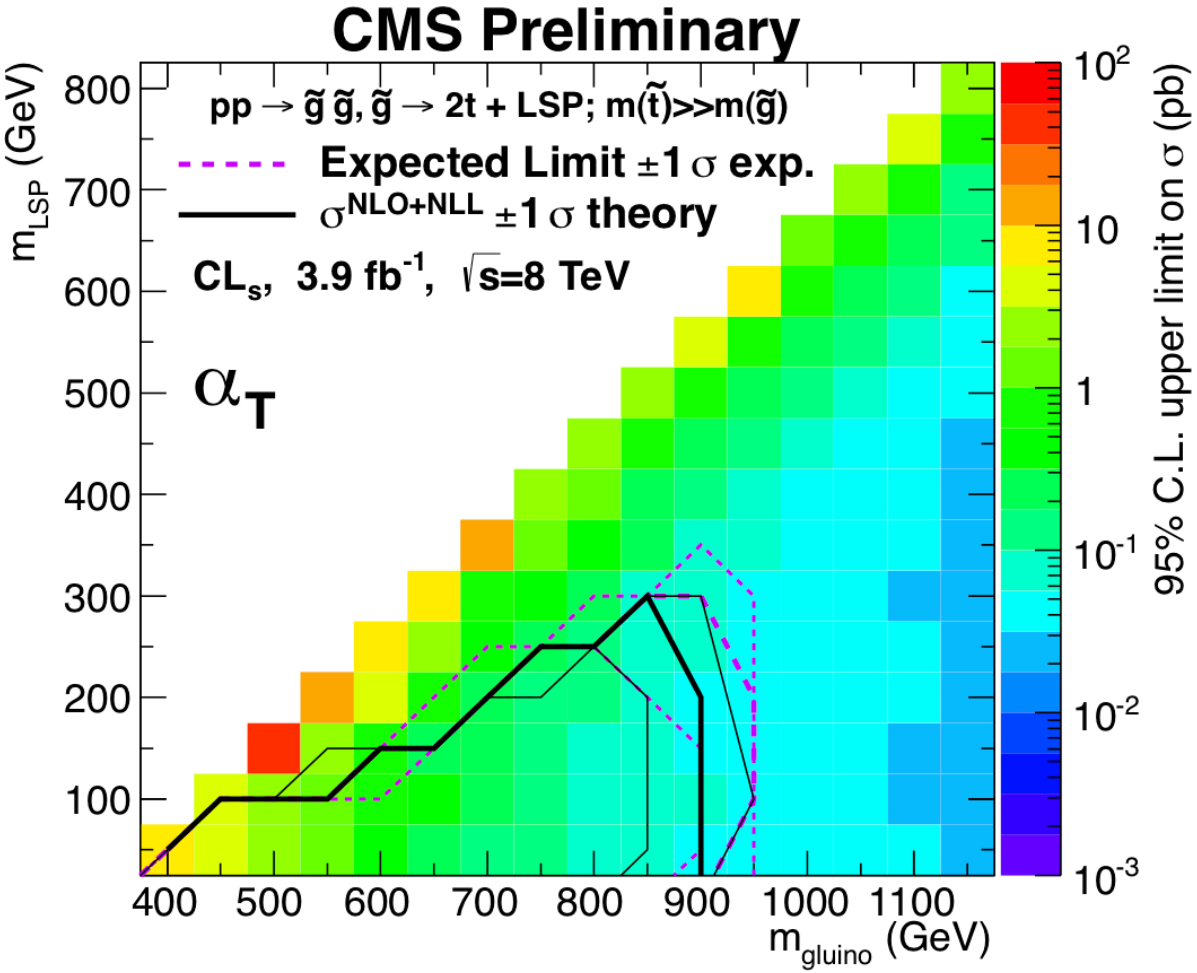
$\tilde{g}\tilde{g} \to bbbb\tilde{\chi}^0\tilde{\chi}^0$



b-jets + missing p_T search

CMS PAS SUS-12-016

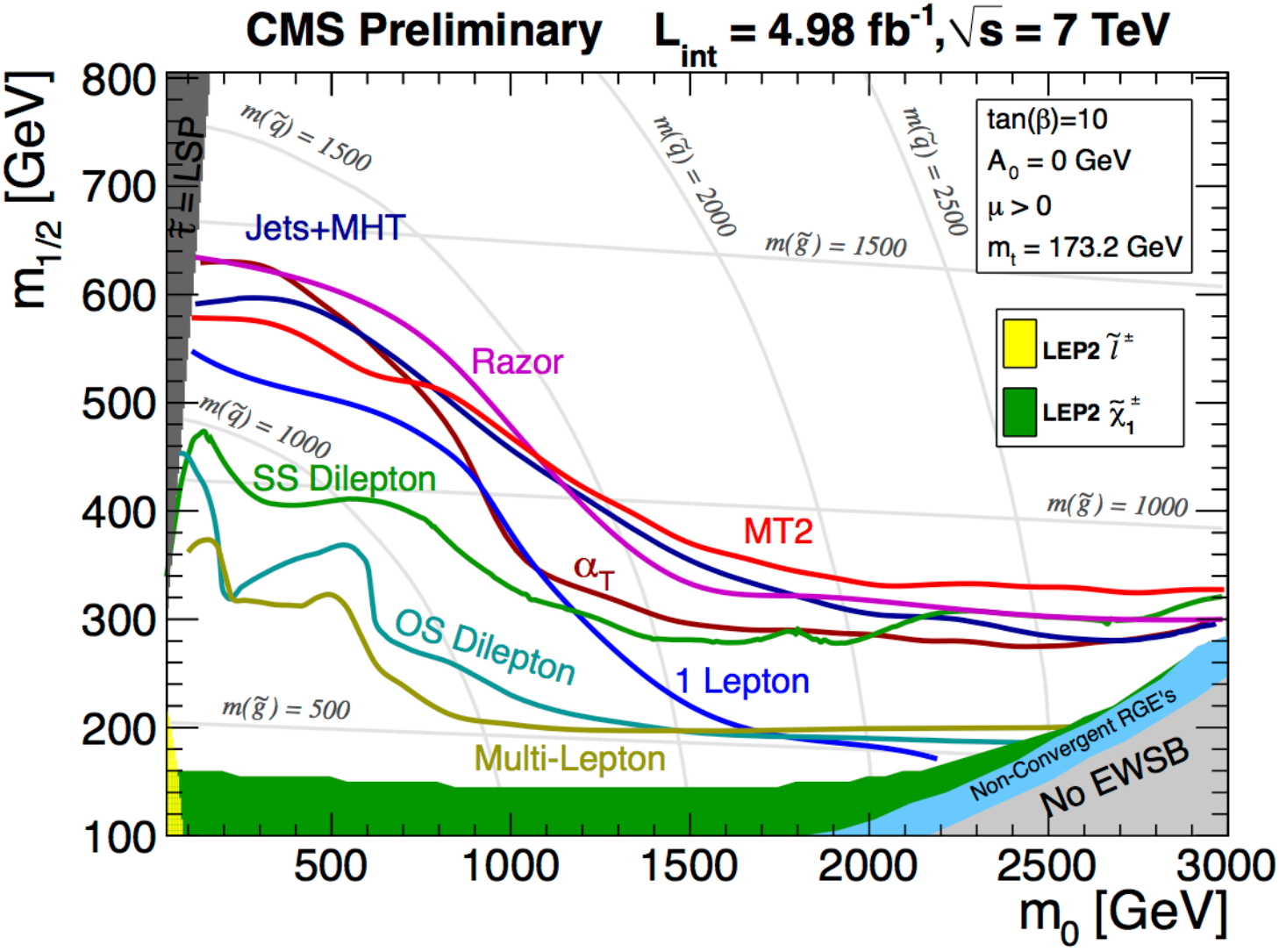




- m(gluino) > 850 GeV for m(neutralino) = 50 GeV

constrained MSSM summary

5 parameters:
tanβ
A_0
Sign(μ)
m_0
$m_{1/2}$

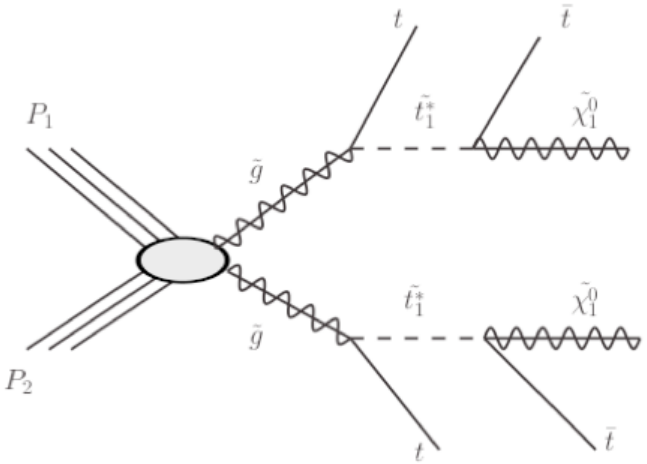


Probing 1 TeV mass scale and beyond for squarks or gluinos

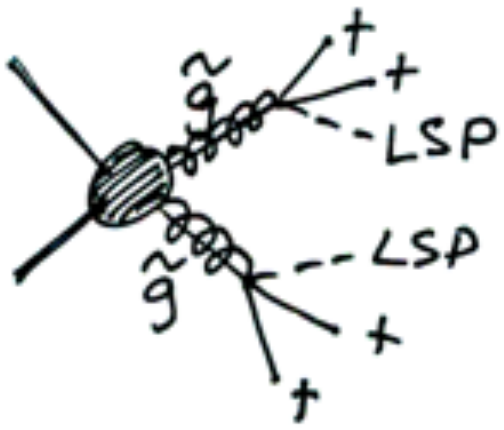
3rd generation squarks

- Natural SUSY
  - Light squarks and gluinos M $\lesssim$ 1 TeV excluded
  - Light stops needed
  - Dedicated searches for best sensitivity
  - multiple b-tags and ETmiss

Gluino-mediated

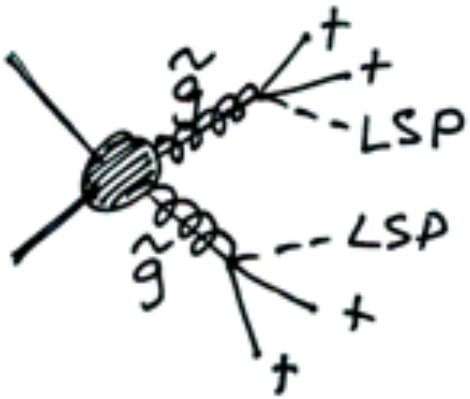


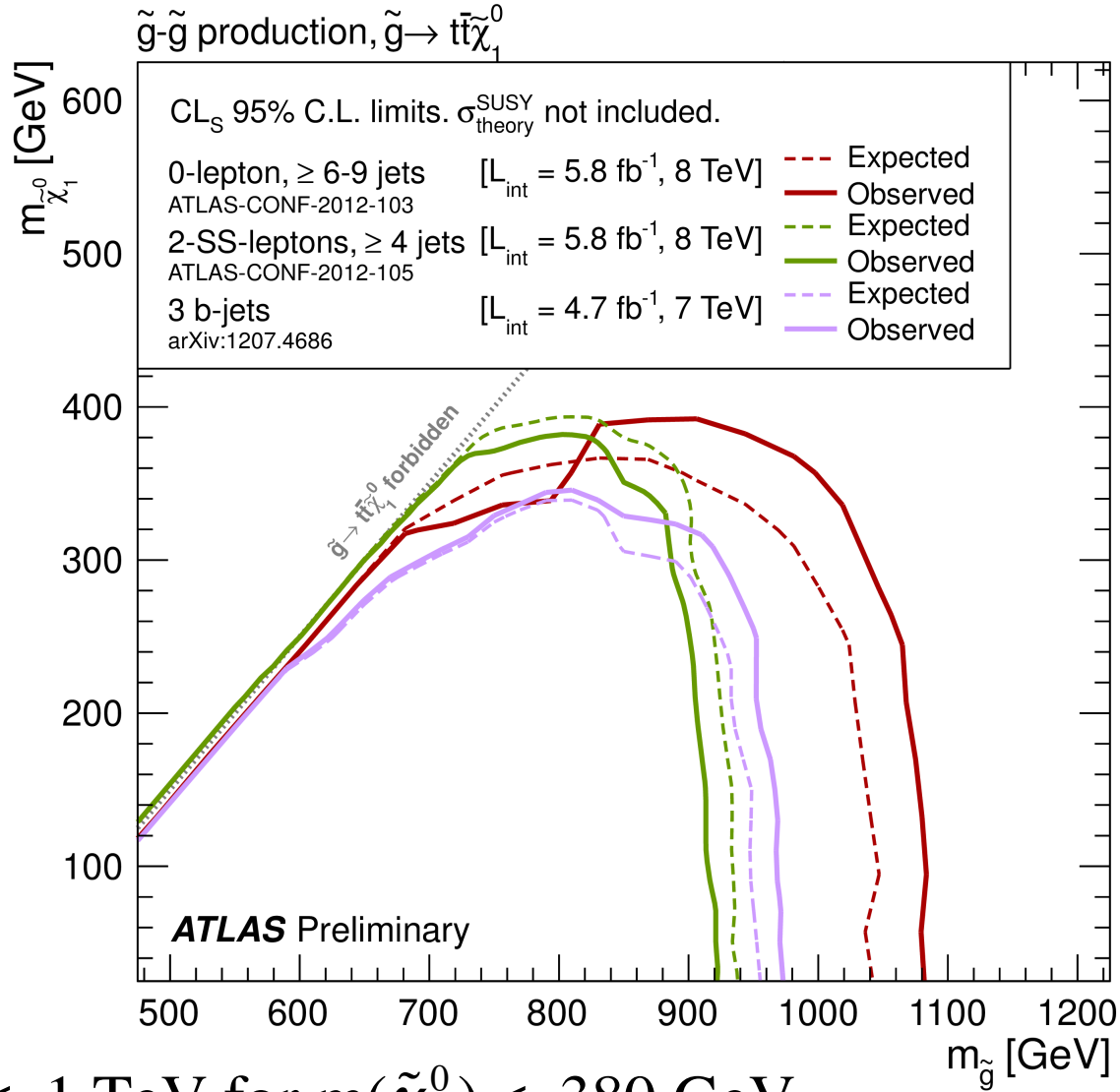
Direct Stop



gluino induced stop production

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





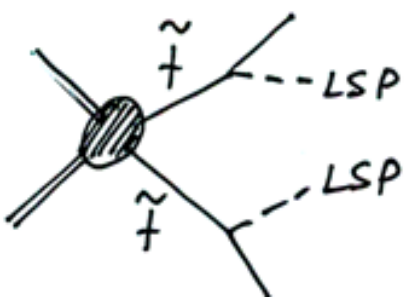
Exclude $m(\tilde{g}) < 1$ TeV for $m(\tilde{\chi}_1^0) < 380$ GeV

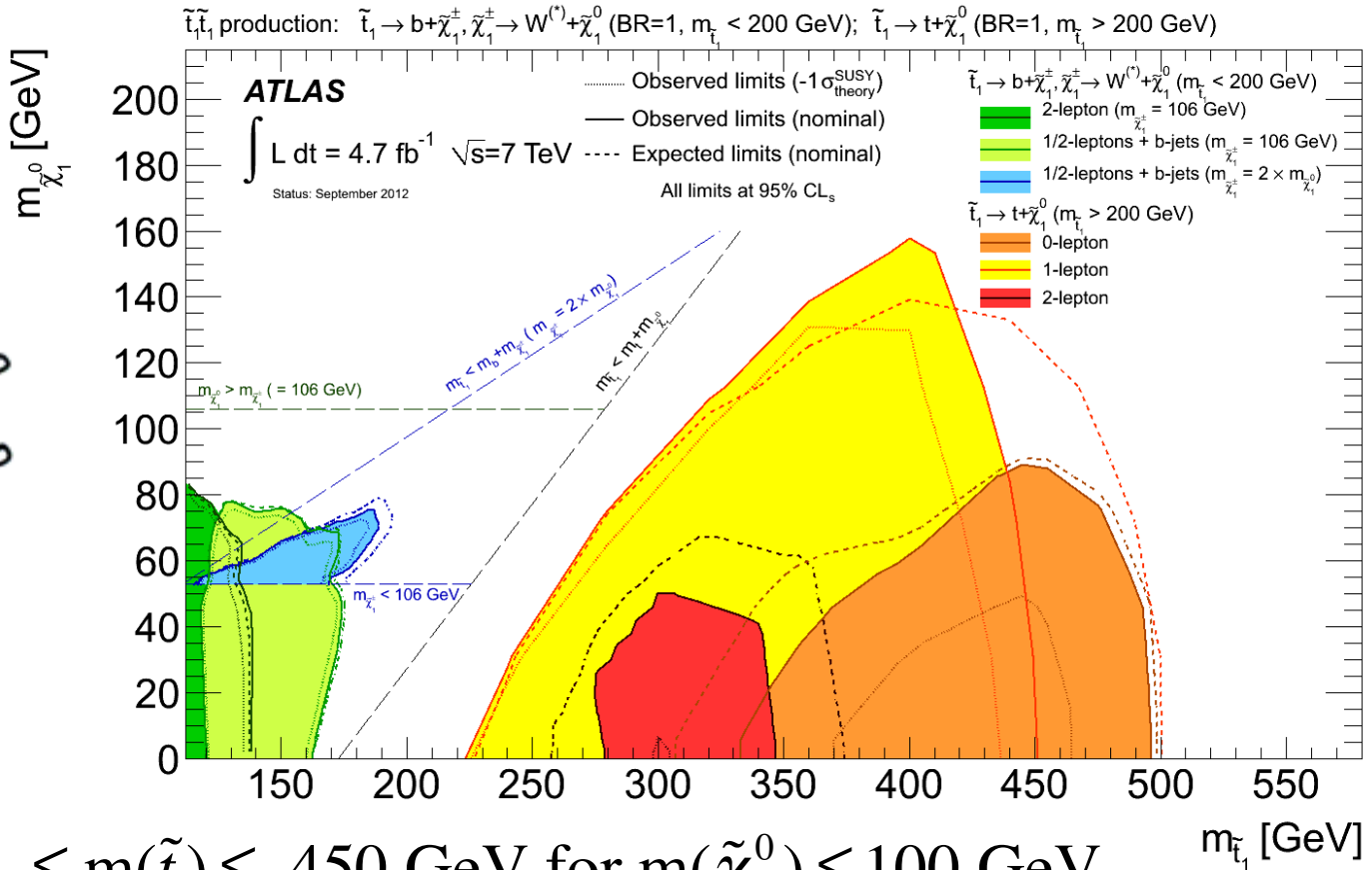
direct stop production

arXiv:1208.4305
arXiv:1209.2102
arXiv:1208.1447
arXiv:1208.2590
arXiv:1209.4186

$$\text{for } m_{\tilde{t}} < m_t : \tilde{t} \to b\tilde{\chi}_1^{\pm} \quad \tilde{\chi}_1^{\pm} \to W\tilde{\chi}_1^0$$

$$\text{for } m_{\tilde{t}} > m_t : \tilde{t} \to t\tilde{\chi}_1^0$$



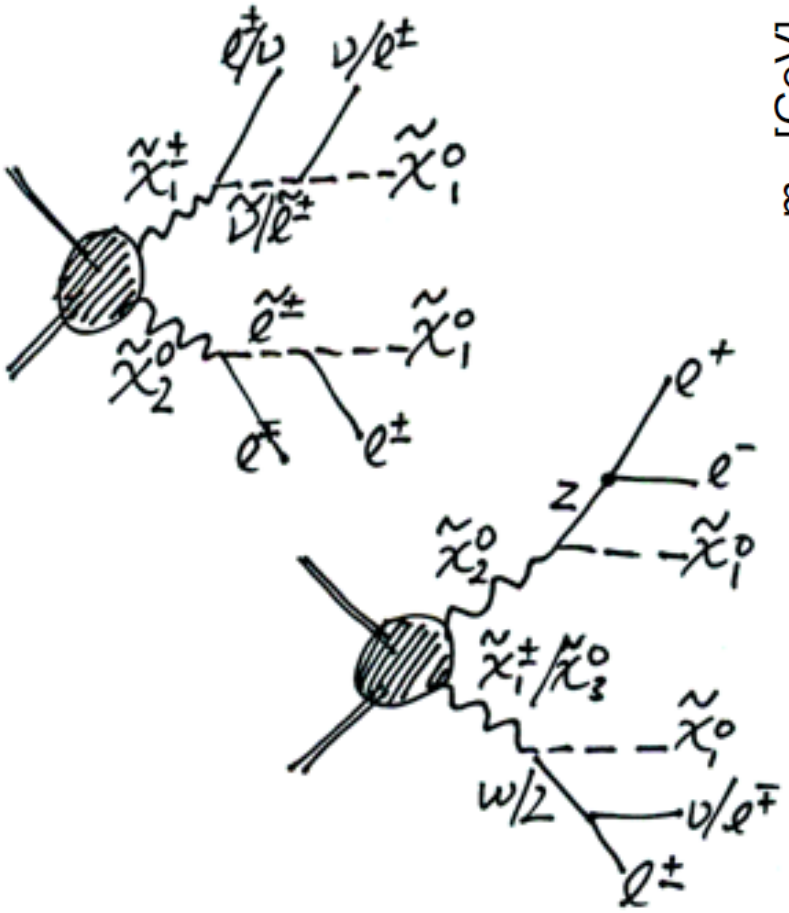


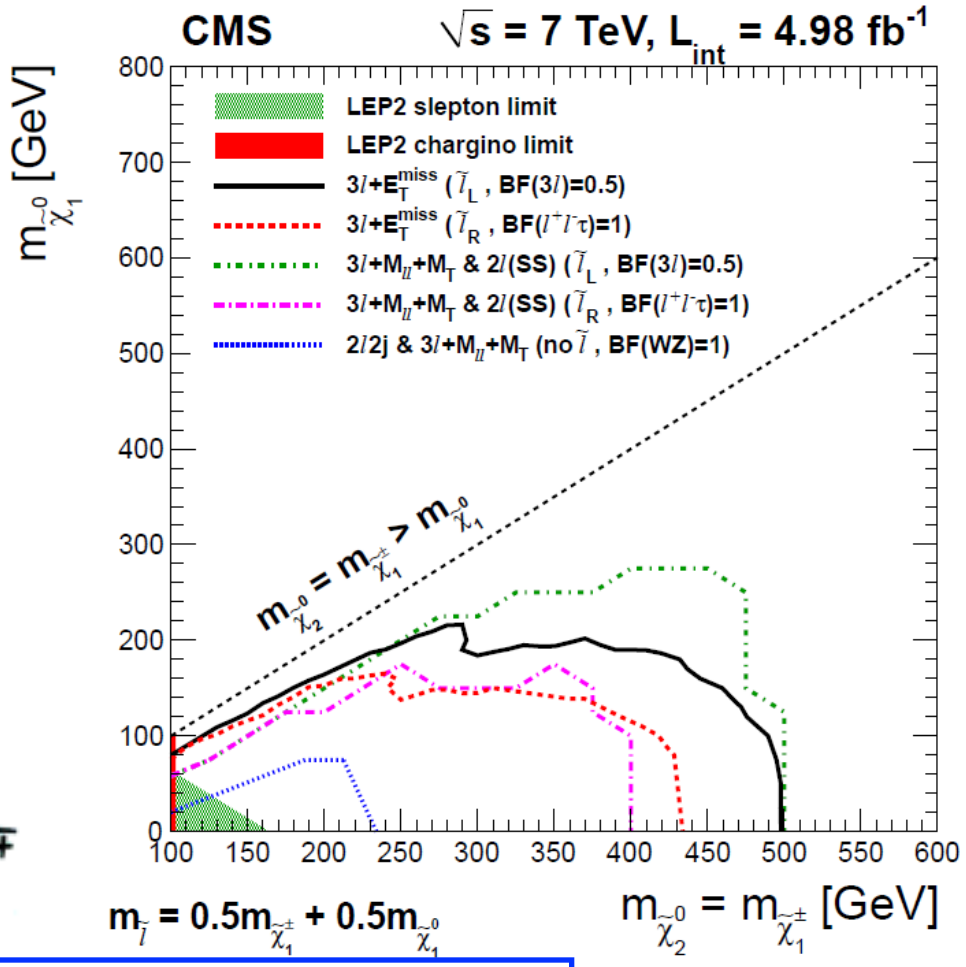
Exclude $300 \leq m(\tilde{t}) \leq 450$ GeV for $m(\tilde{\chi}_1^0) \leq 100$ GeV

direct gaugino production

- if squarks and gluinos are too massive, direct gaugino production may dominate

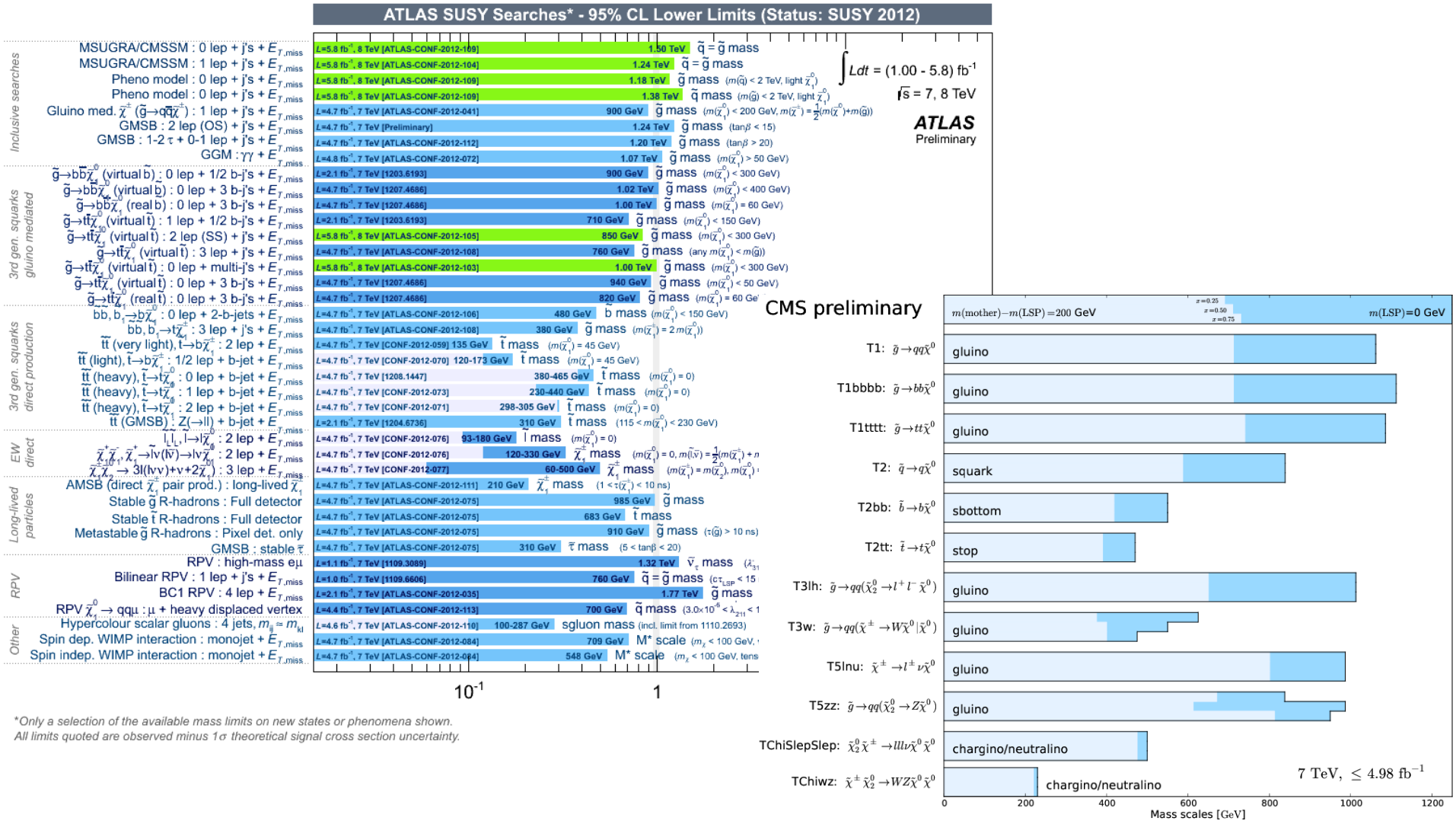
CMS PAS SUS-12-006





1st set of results/limits on direct EWKino production

the big picture



coloured SUSY particles excluded up to ~1.5TeV

third generation and electroweak SUSY particles probed up to ~300 GeV

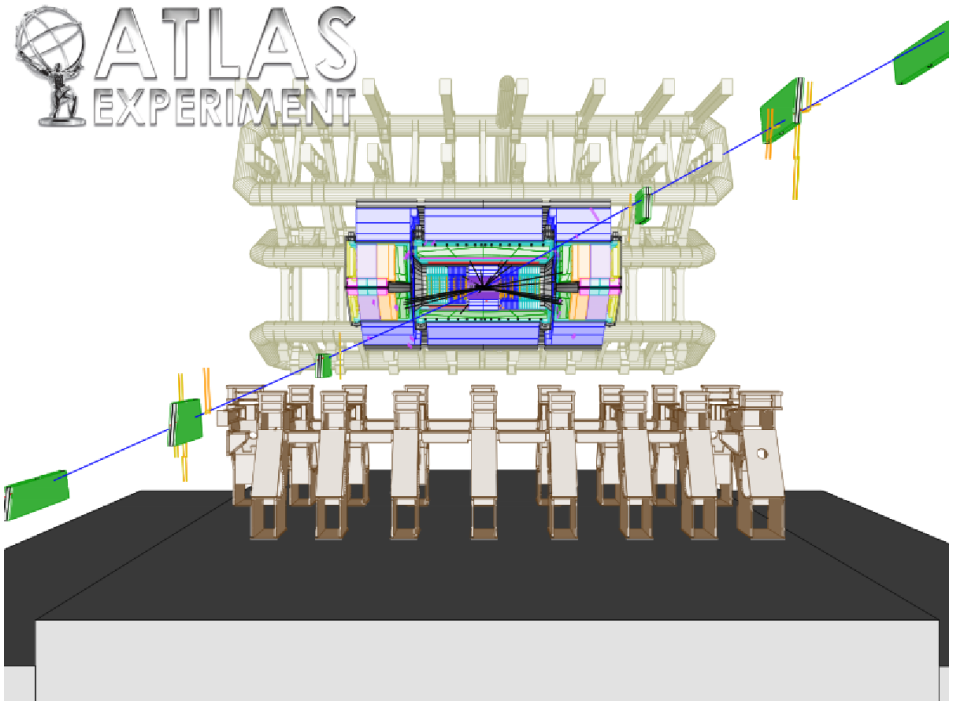
Non SUSY exotic searches

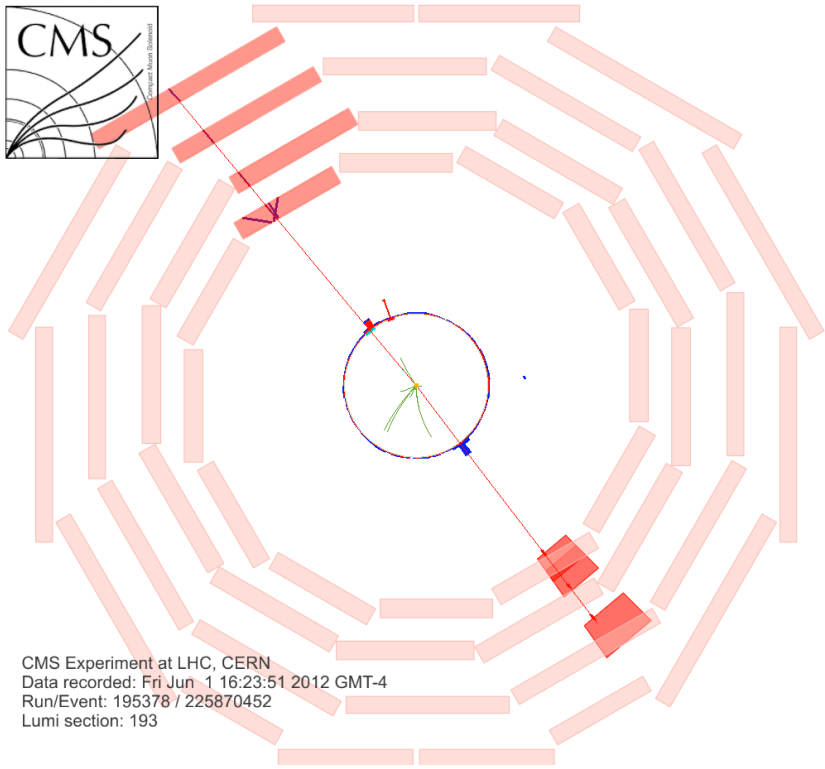
- new bosons
  - gauge bosons (W', Z'), KK states
- new fermions
  - 4^{th} generation, vector-like
- leptoquarks
- new dimensions
  - gravitons participate in particle interactions
- dark Matter
- something completely different

new bosons

- may appear as resonances: “Bump Hunting”
  - dileptons
  - dijets
  - diphotons
  - ttbar

dilepton resonances



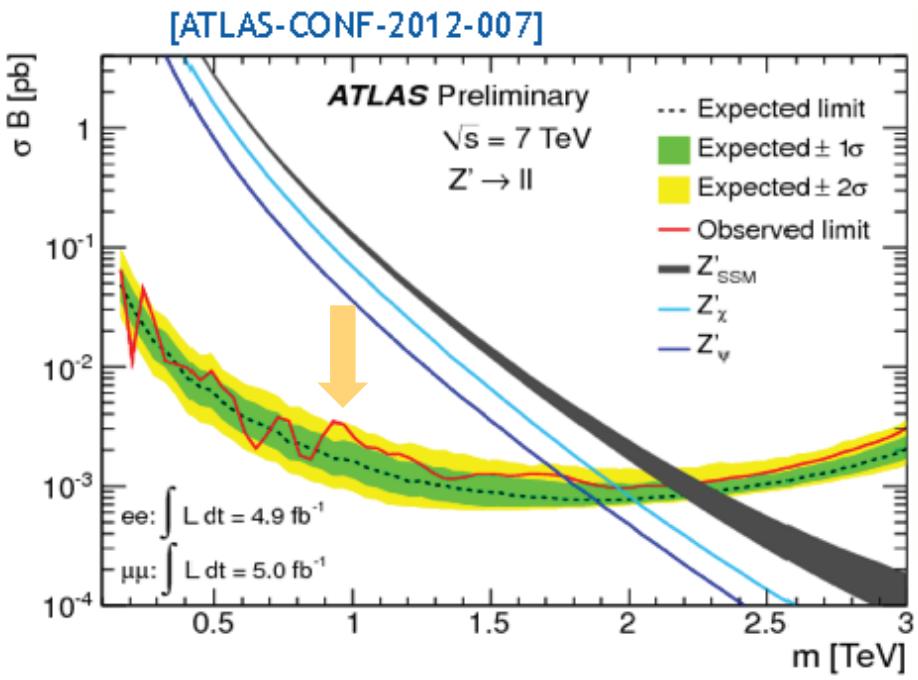


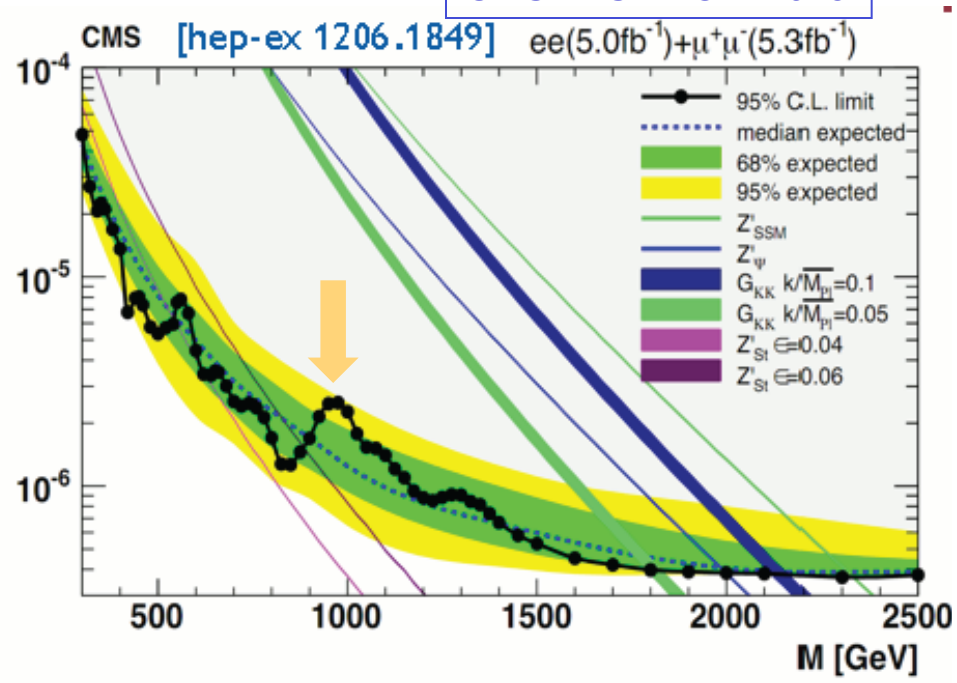
dilepton resonances: Z'/G_{KK}

7 TeV
5/fb

- many BSM models predict narrow ll resonances
  - Z' with sm like couplings (Γ=30 GeV @ M=1 TeV)
  - Z' of grand unified theories (Γ=6 GeV @ M=1 TeV)
- some excitement in 2011 data

CMS PAS EXO-12-015

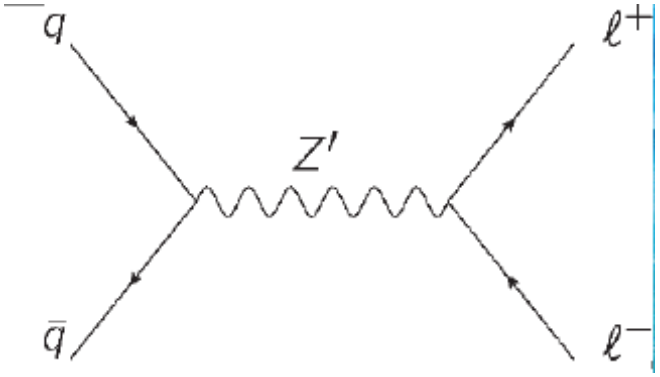




dilepton resonances: Z'/G

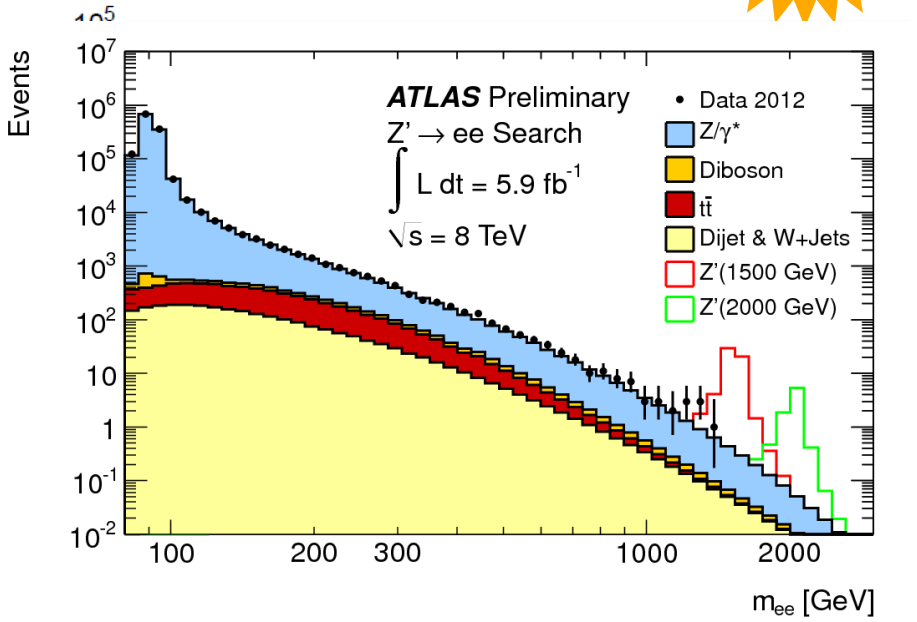
8 TeV
6/fb

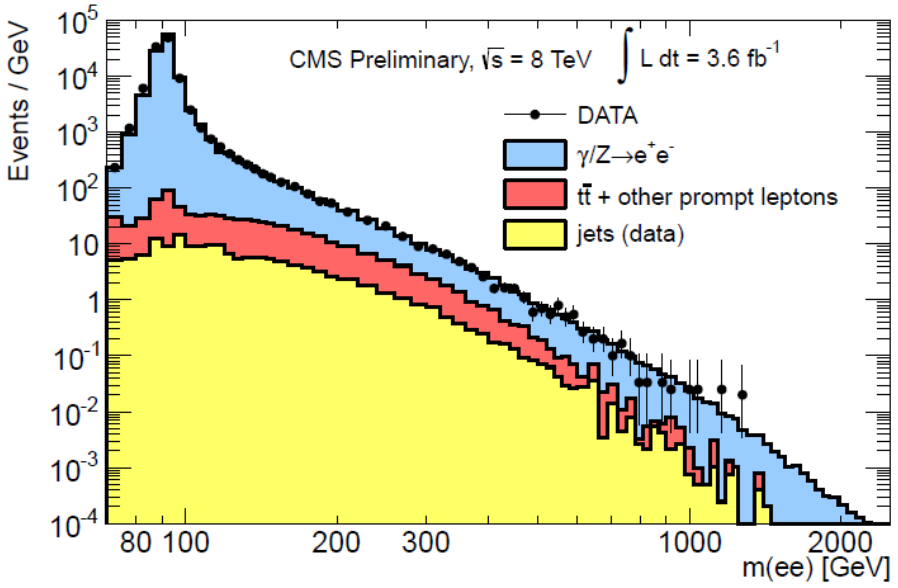
- event selection
  - isolated e: pT > 35 GeV
  - Isolated μ: pT > 45 GeV



- Background
  - prompt leptons
    - based on MC
    - verify data-MC agreement in eμ
  - Jets
    - based on data

- No sign of excess at high mass especially at 1 TeV in the 2012 data





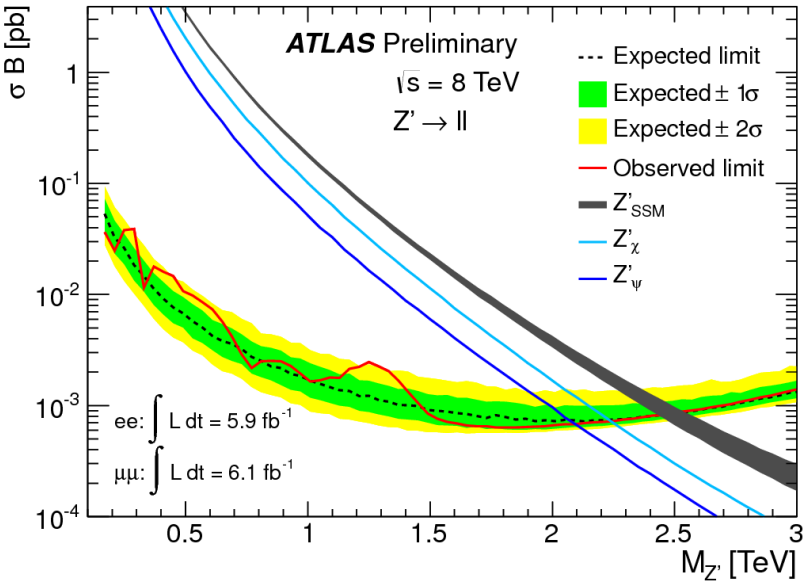
dilepton resonances: Z'

8 TeV
6/fb

Search for narrow [4-14% σ(M)/M] resonance predicted in many models.

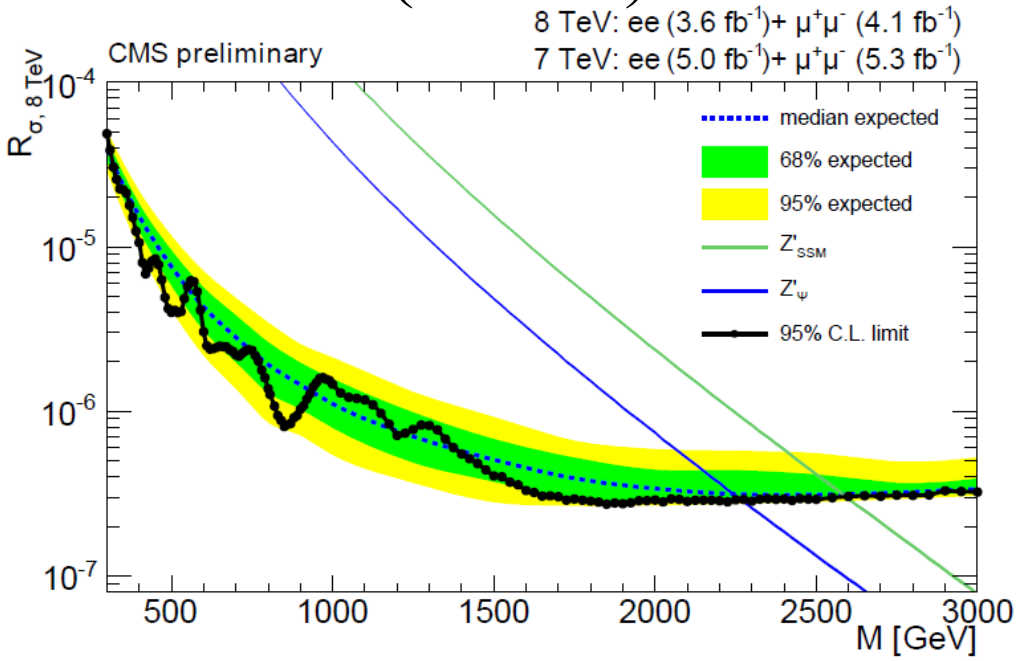
CMS limits on

$$R_\sigma = \frac{\sigma(Z' \to ll)}{\sigma(Z \to ll)}$$



SSM $M_{Z'}$ > 2.49 TeV
GUTs: $M_{Z'}$ > 2.09 TeV

ATLAS-CONF 2012-129



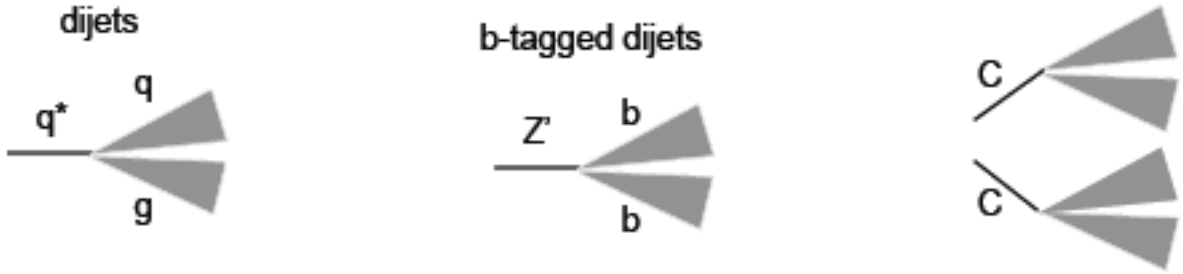
SSM: $M_{Z'}$ > 2.59 TeV

GUTs: $M_{Z'}$ > 2.26 TeV

CMS PAS EXO-12-015

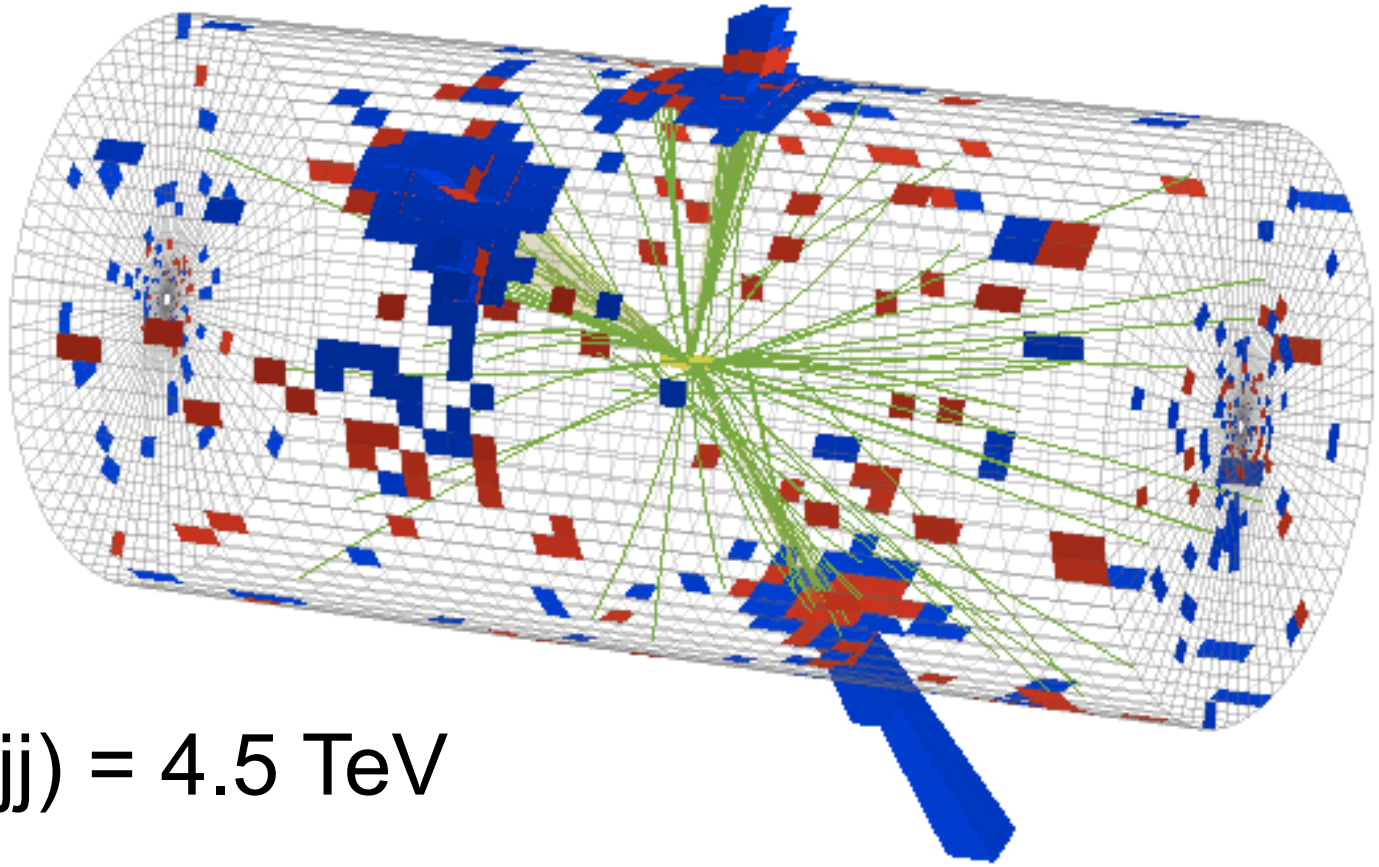
dijet resonances

- Resonances predicted in many BSM models
  - String resonances
    - (Regge excitations of quarks and gluons) S → q g
  - Scalar diquarks (E6 GUT) D → qq or $\overline{q}\overline{q}$
  - Excited quarks (compositeness) q* → q g
  - Axigluons (chiral symmetry group) A → $q\overline{q}$
  - Color-octet (large symmetry group)
    - colorons and scalars C → $q\overline{q}$
  - Heavy gauge bosons (new gauge symmetries)
    - W' → $q\overline{q}$ and Z' → $q\overline{q}$
  - Randall-Sundrum gravitons (extra dimensions)
    - G → $q\overline{q}$ and g g



CMS Experiment at LHC, CERN
Data recorded: Sat May 26 13:25:29 2012 CEST
Run/Event: 195016 / 425646417
Lumi section: 384

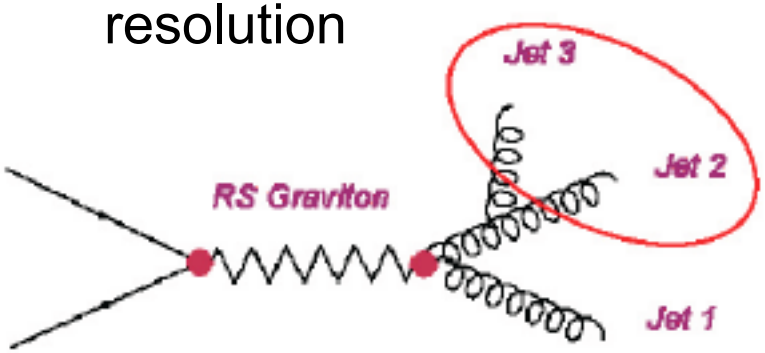
dijet resonances



m(jj) = 4.5 TeV

dijet resonances

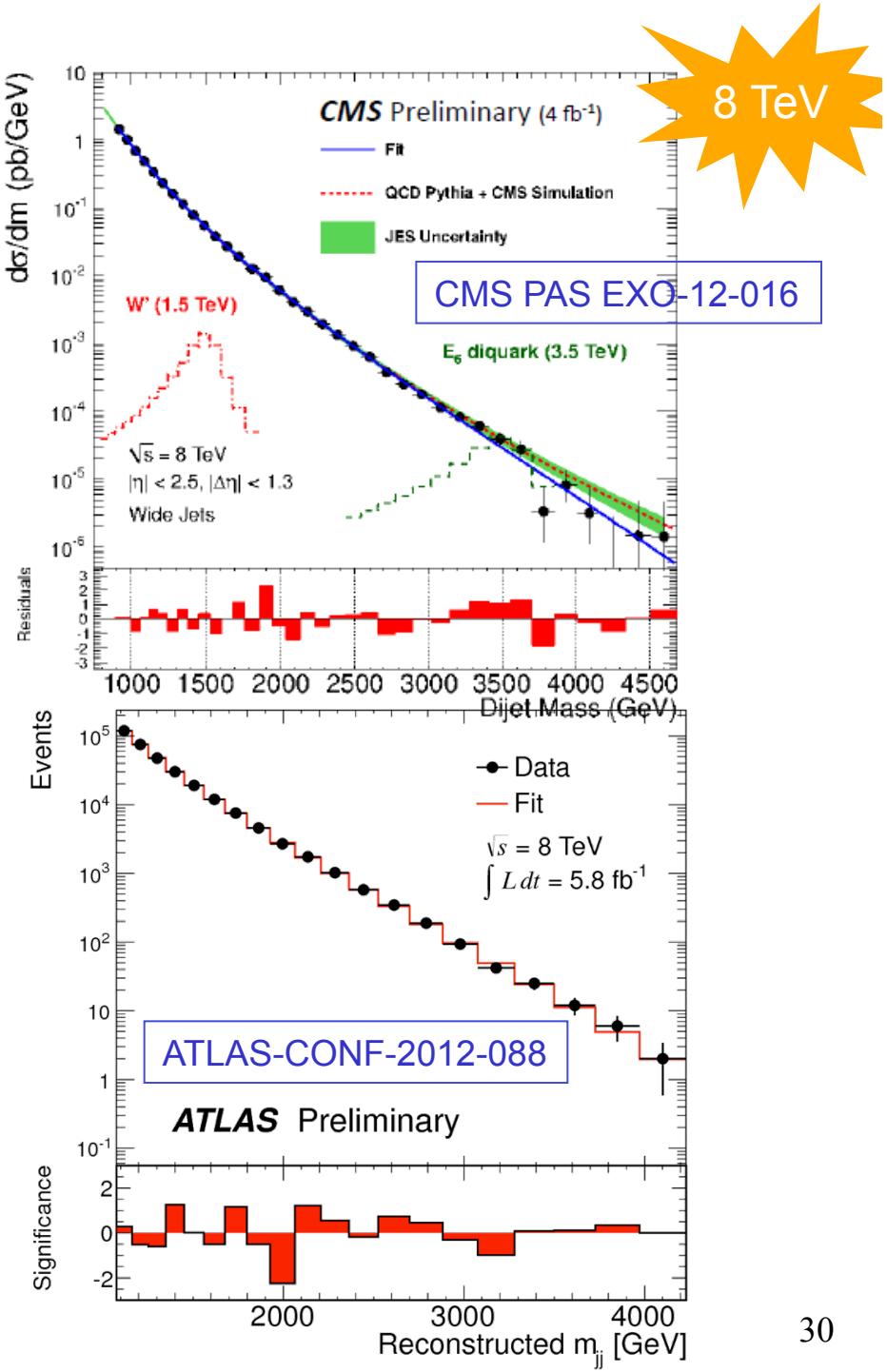
- "wide jets"
  - absorb jets within ΔR < 1.1 into leading two jets
    - cluster final state radiation for better gg resonance resolution



- fit background to

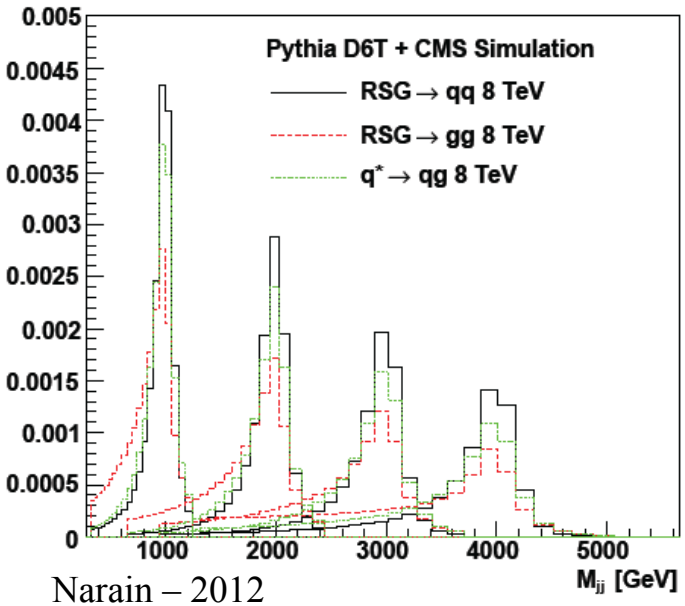
$$\frac{p_0(1-x)^{p_1}}{x^{p_2+p_3\ln(x)}}$$

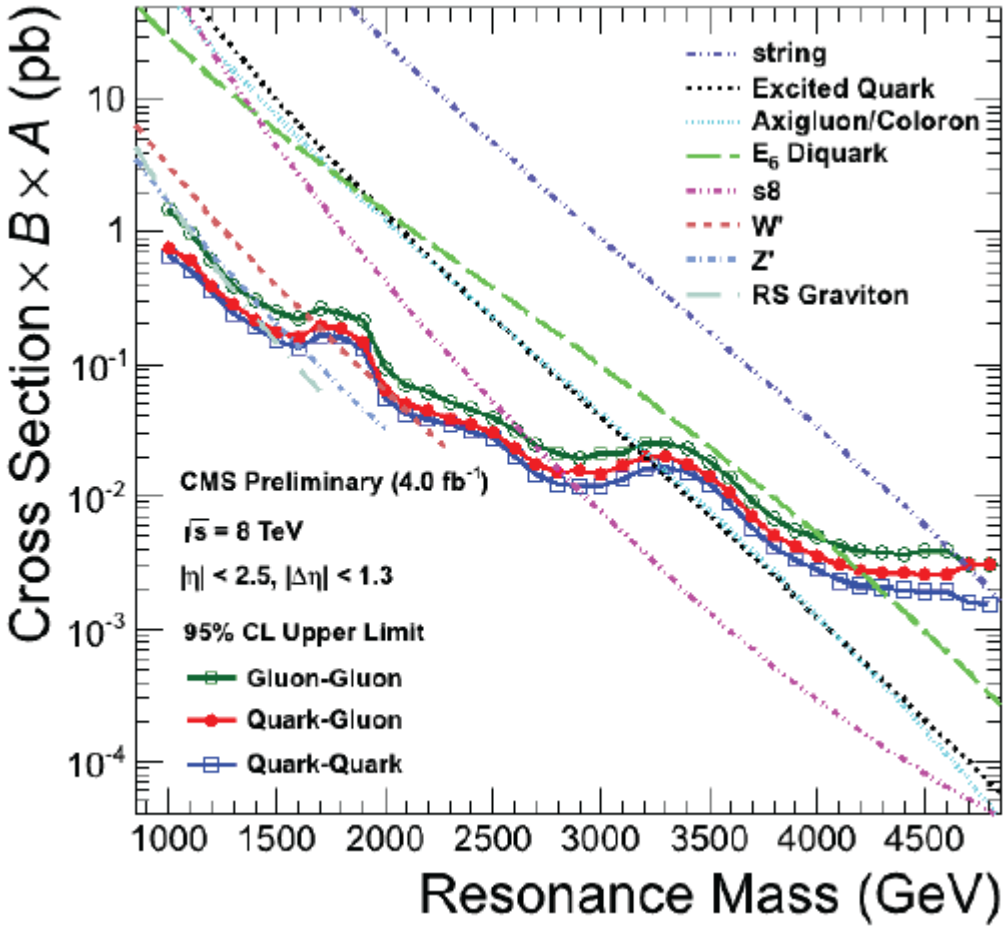
where $x = mjj/\sqrt{s}$



dijet resonances @8 TeV

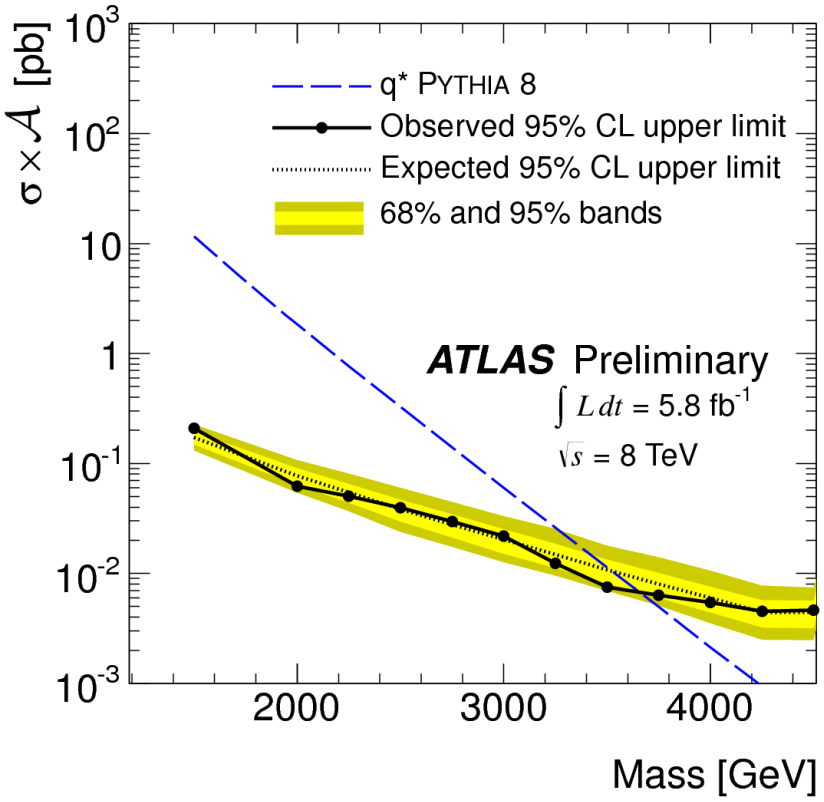
- upper limits on σ x B x A
  - Bayesian statistics
  - signal shapes for
    - qq resonances
    - qg resonances
    - gg resonances





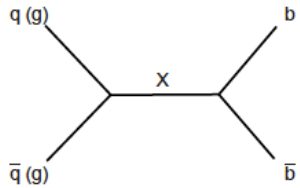
dijet resonances

ATLAS

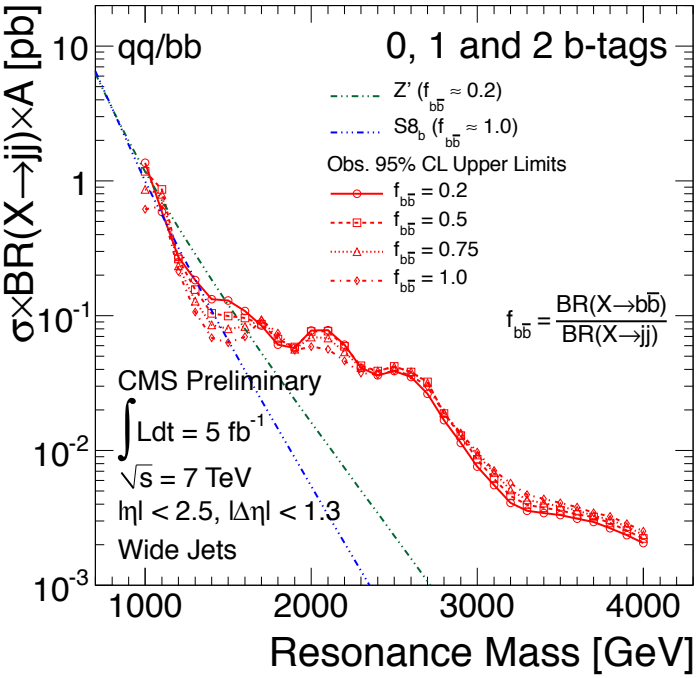


$m(q^*)$>3.66 TeV @ 95% CL

CMS



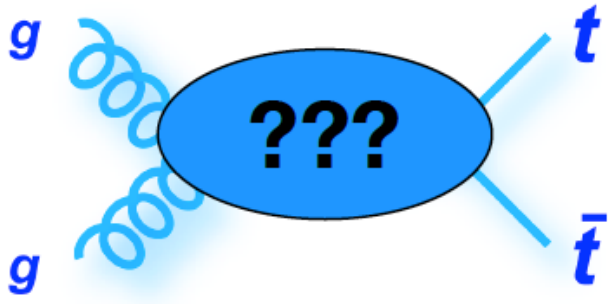
- Classiy in 0, 1, 2 btag categories.
- Upper limits on the production of narrow resonances are set as a function of the bb jet fraction f_{bb}

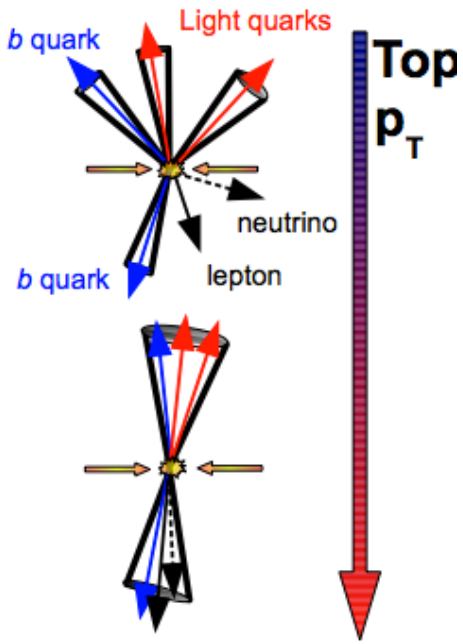


massive ttbar resonances

- Many models of new physics have large couplings to the top quark and prefer the 3rd generation
- benchmark models
  - leptophobic topcolor Z'
    - (Harris et al., hep-ph/9911288)
  - KK gluon
    - (Lillie et al., PRD 76 (2007) 115016)

- As we probe higher and higher mass scales, the phenomenology of the top quarks produced in collision events changes
  - Boosted regime

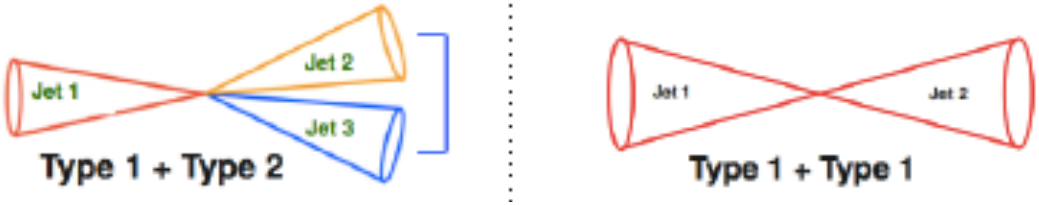




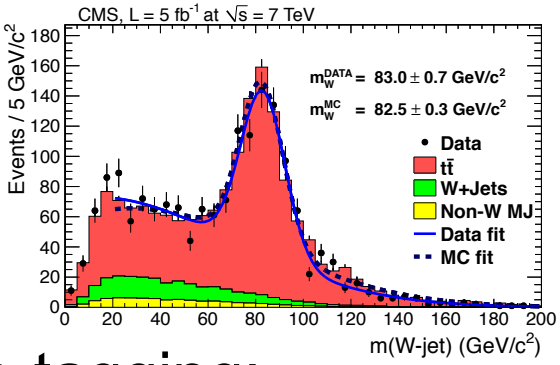
ATLAS-CONF-2012-065

massive ttbar resonances

- Search in the all hadronic decay channel for the tops
- Both top quarks produced by the Z' decay hadronically
- Two top candidate types:

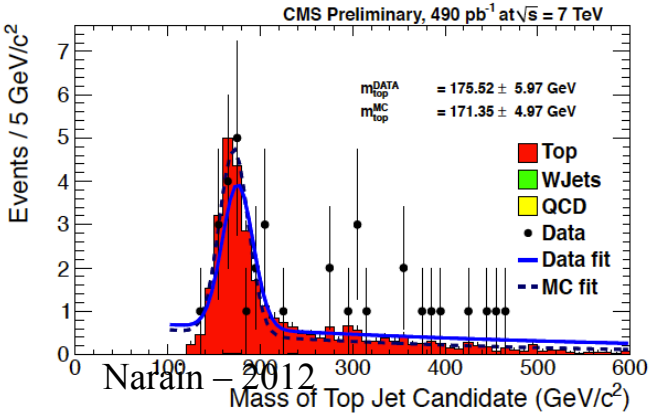


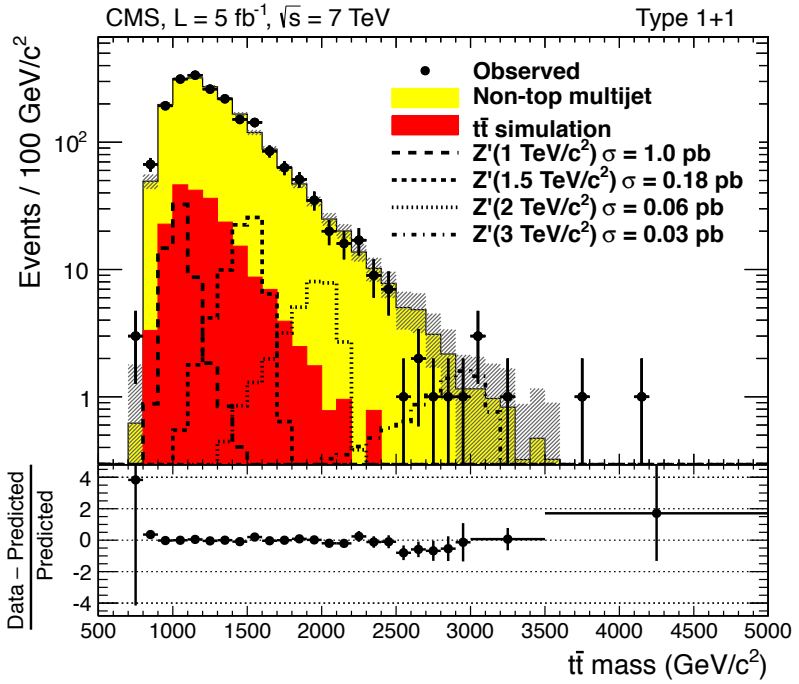
hadronic W-subjet



top-tagging:

"type 2" top candidate, formed by adding the closest jet to the "type 2" W candidate.

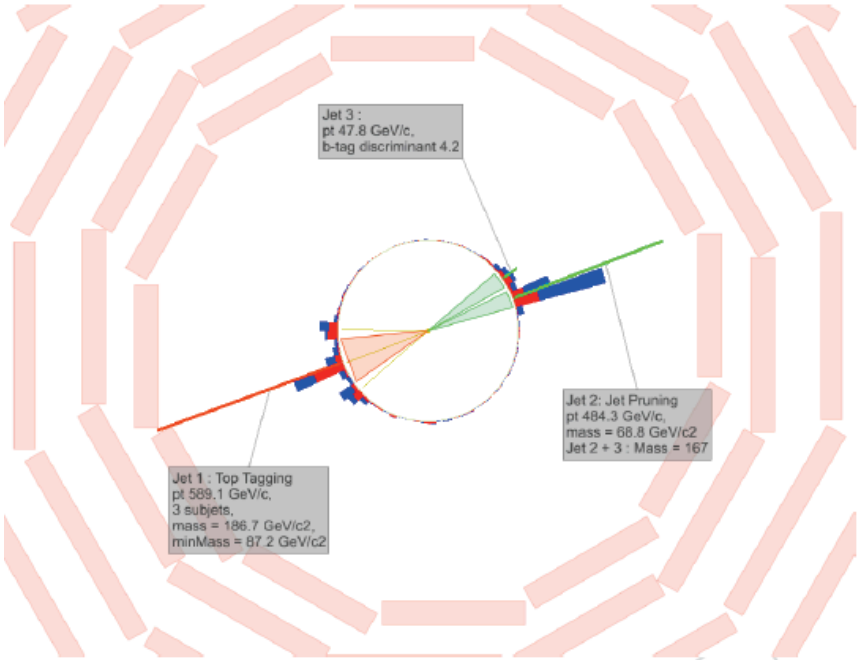


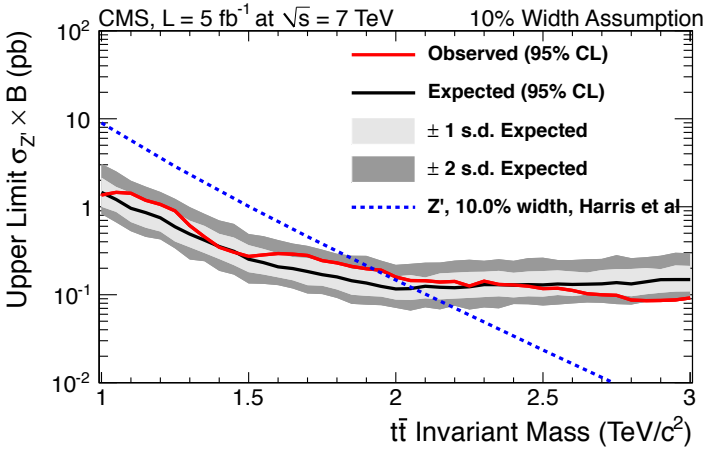


massive ttbar resonances

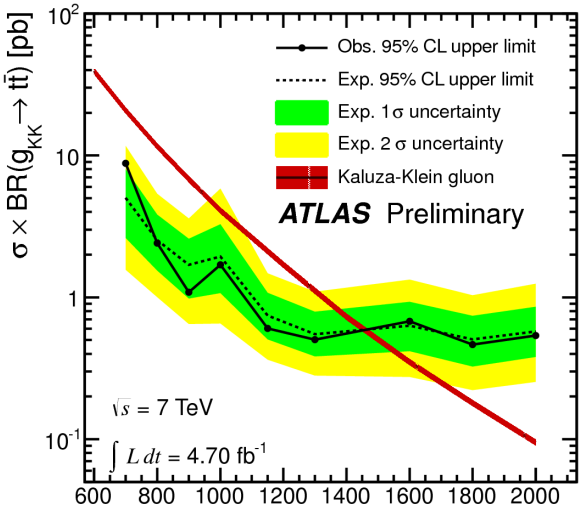
- data compatible with background, no excess

arXiv:1204.2488
CMS EXO-11-006





Exclude Z'
1<M< 2 TeV



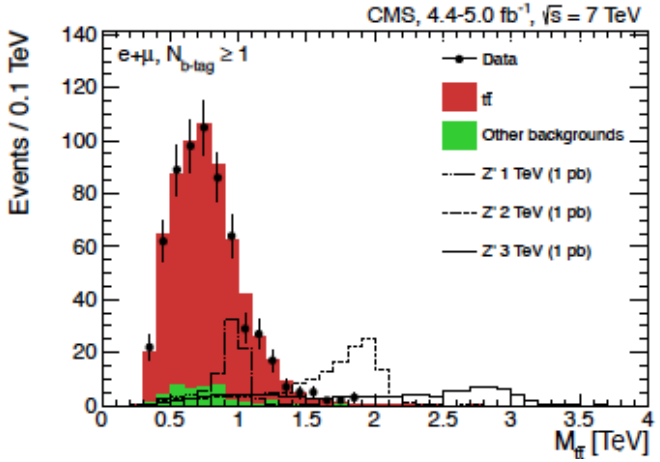
Exclude
KK-Gluons
0.7<M<1.5 TeV

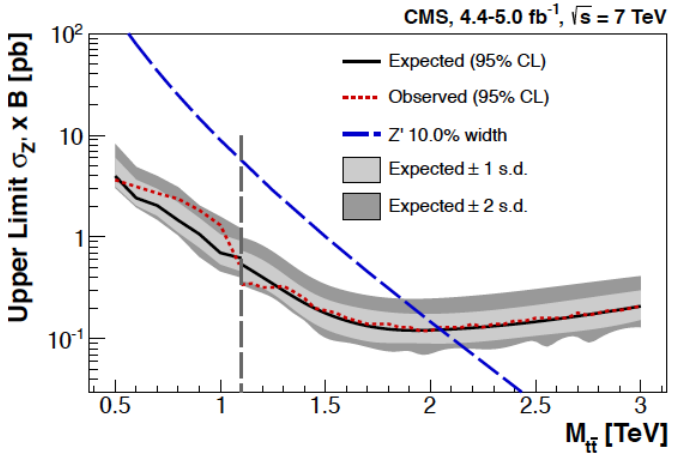
ATLAS-CONF-2012-102

massive ttbar resonances

7 TeV

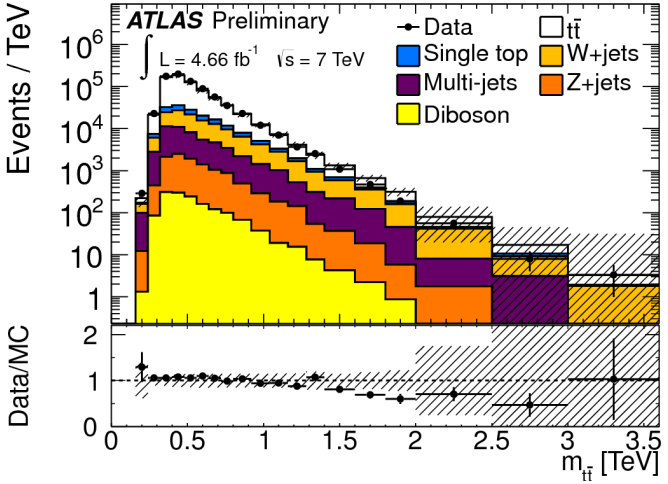
- Using lepton+jets events. For m(tt)>1 TeV the decay products of hadronic t quark decay are not resolved

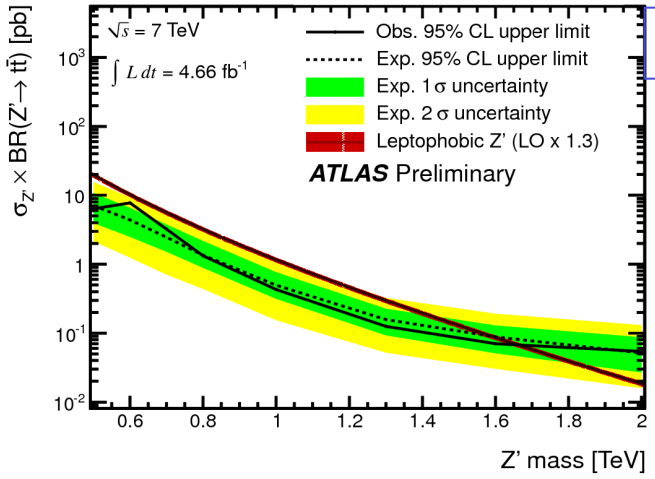




CMS TOP-11-021

CMS:
$M_{Z'} > 2.04$ TeV



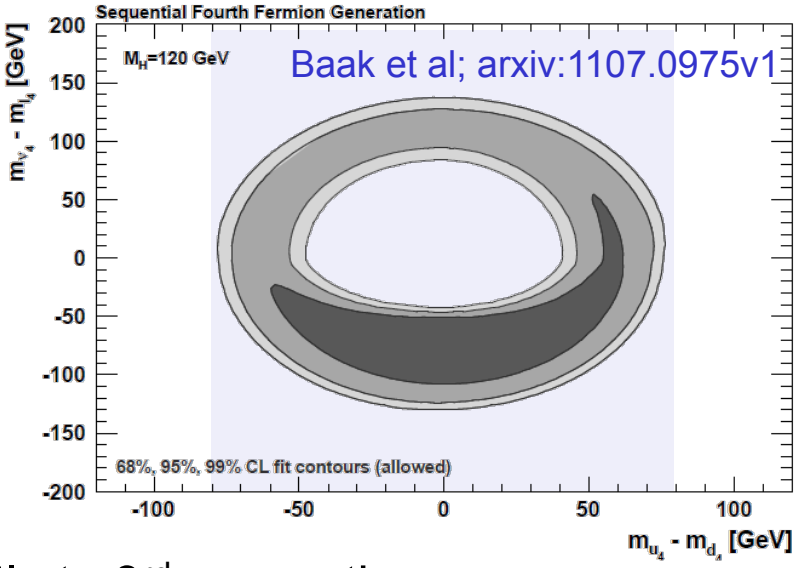


ATLAS-CONF-2012-136

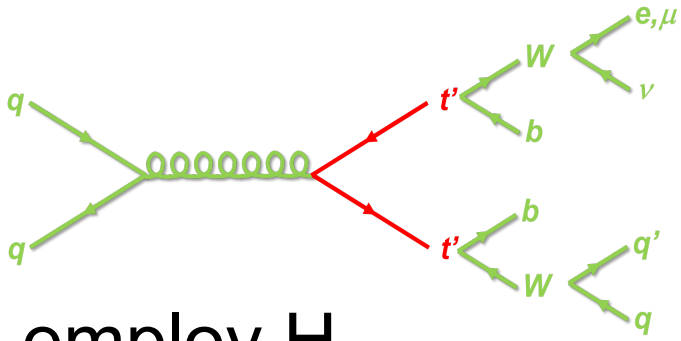
ATLAS:
$M_{Z'} > 1.7$ TeV

new fermions

- 4th generation is straightforward extension of sm
  - constraints from experiment
    - $m_{V'} > \frac{1}{2} M_Z$
    - $m_{t'} > 358$ GeV
    - $m_{b'} > 385$ GeV
    - $|m_{t'} - m_{b'}| < M_W$
  - decay modes
    - $t' \rightarrow bW$
    - $b' \rightarrow tW \rightarrow bWW$
    - 4th generation decays predominantly to 3rd generation
  - 4th generation would
    - enhance production cross section of a Higgs boson
    - make ewk measurements consistent with larger m_H
- vector-like fermions
  - avoid sm constraints

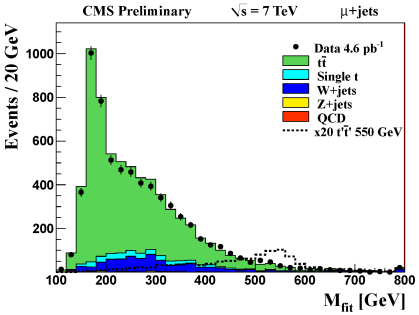


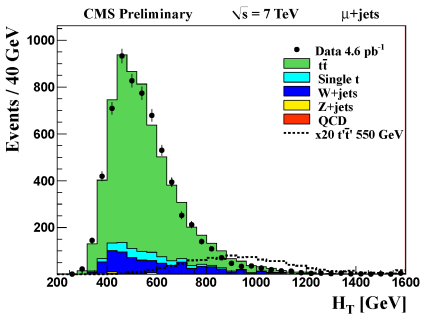
t'→bW



7 TeV

- lepton+jets
- reconstruct t' mass and employ H_T



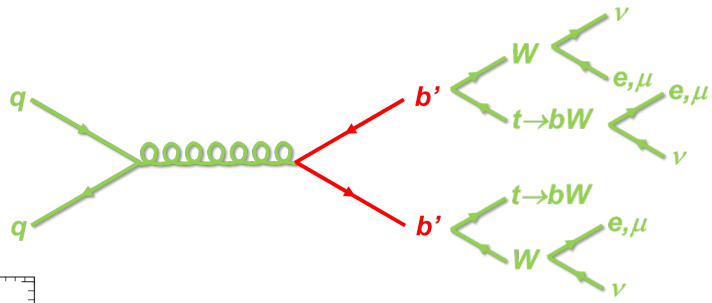


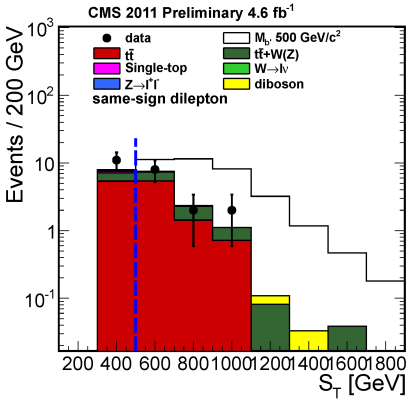
M(t')>404 GeV ATLAS
>560 GeV CMS

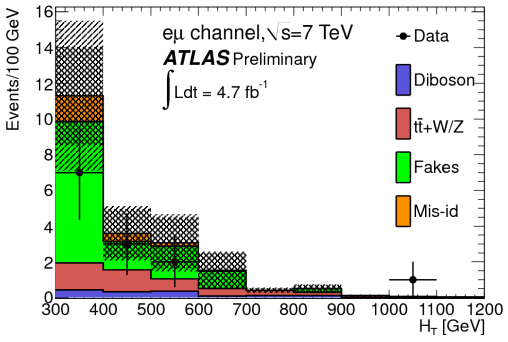
ATLAS PRL 108 (2012) 261802
CMS PAS EXO-11-099

b'→tW

- same sign leptons







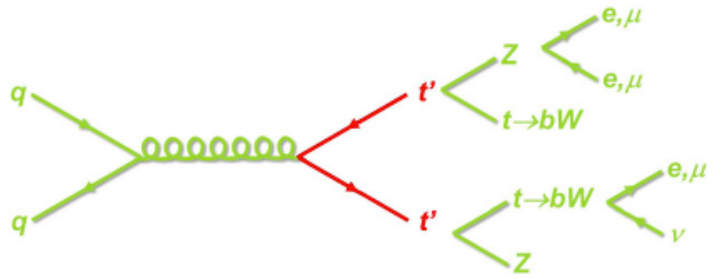
m(b')>670 GeV ATLAS
>611 GeV CMS

ATLAS-CONF-2012-130
CMS arXiv:1204.1088

vector-like quarks

7 TeV

- not subject to sm constraints, eg on FCNC do not have to couple to Higgs boson predicted e.g. by little Higgs models can decay to bW, tZ, tH

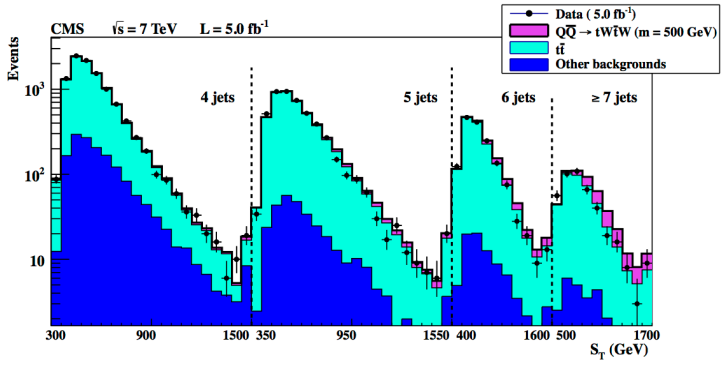


- assume 100% Q->tZ
  - Lepton+jets and at least one bjet

  ➔m(Q)>625 GeV
- Assume 100% Q->tW

  ➔m(Q)>675 GeV

CMS PAS B2G-12-004

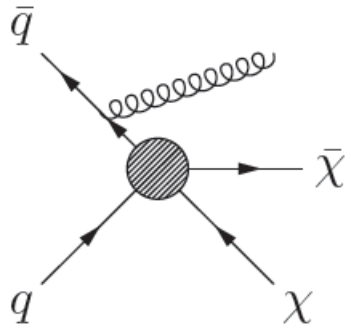


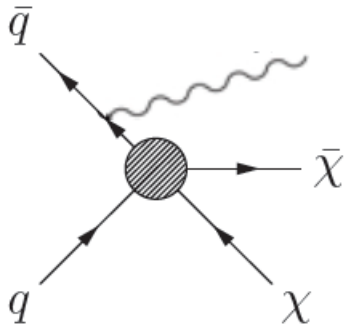
- assume 100% b'->bZ
  - 2 isolated leptons 60<mll<120 GeV
  - reconstruct bZ mass spectrum

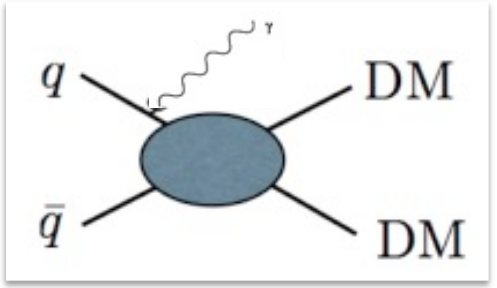
  ➔m(b')>550 GeV

CMS PAS EXO-11-066

monojets/monophotons (ISR)

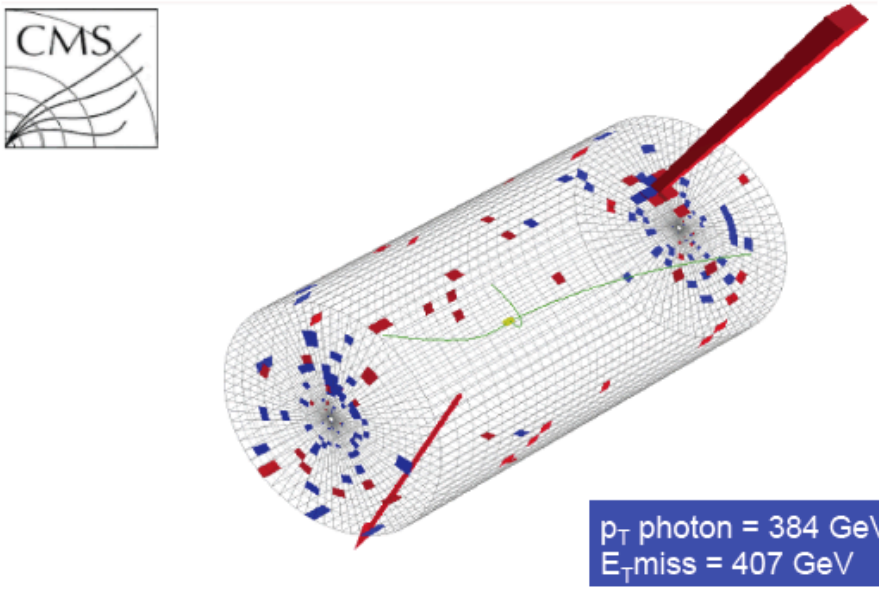


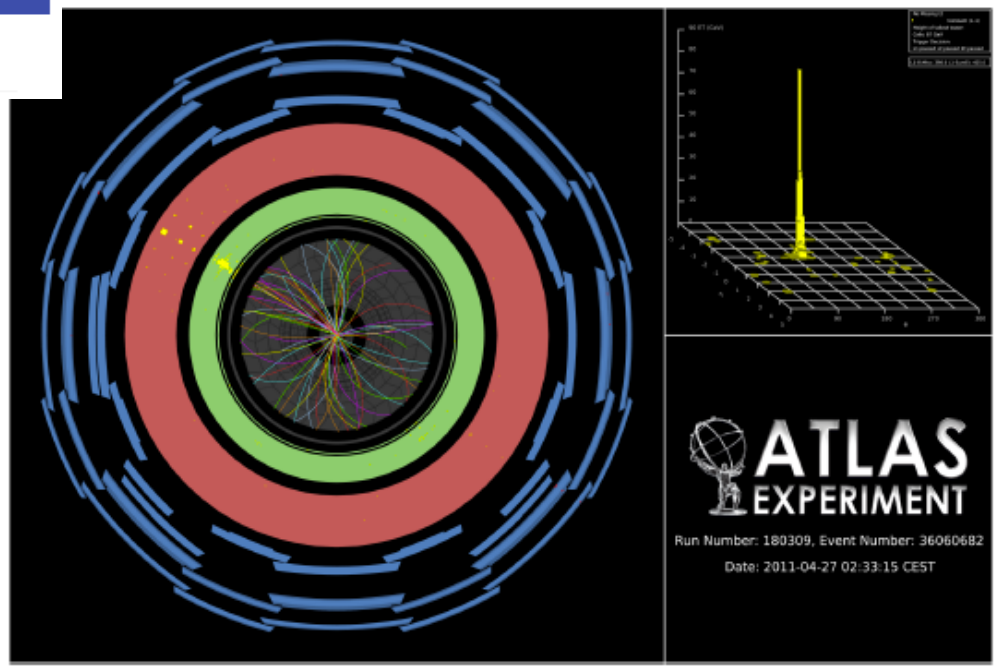




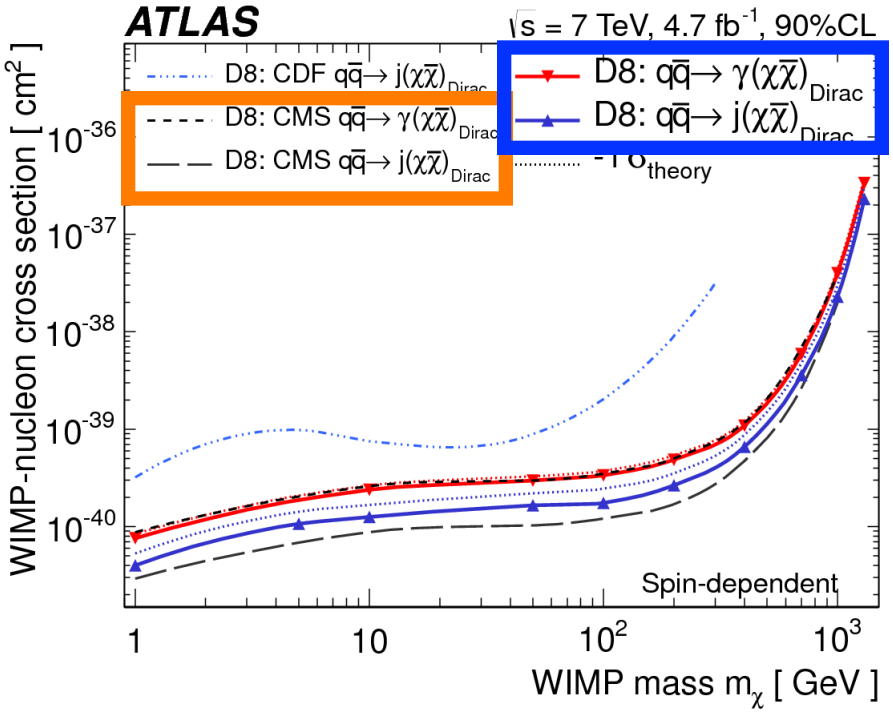
- gravitons in extra dimension models
- dark matter particles WIMPs (χ)
  - kinematically accessible
  - produced via exchange of particle with mass M
  - contact interaction with scale $\Lambda = M/\sqrt{g_\chi g_q}$
  - assume Dirac fermions
  - relate production at LHC to χ nucleon interactions
  - Probing the same effective operators as in direct detection
  - High sensitivity to spin-dependent couplings
  - Extends direct detection below 5 GeV
- Background
  - Z(νν) or W(*l*ν) + jets
  - Non-collision backgrounds - noise, cosmics, beam-related)

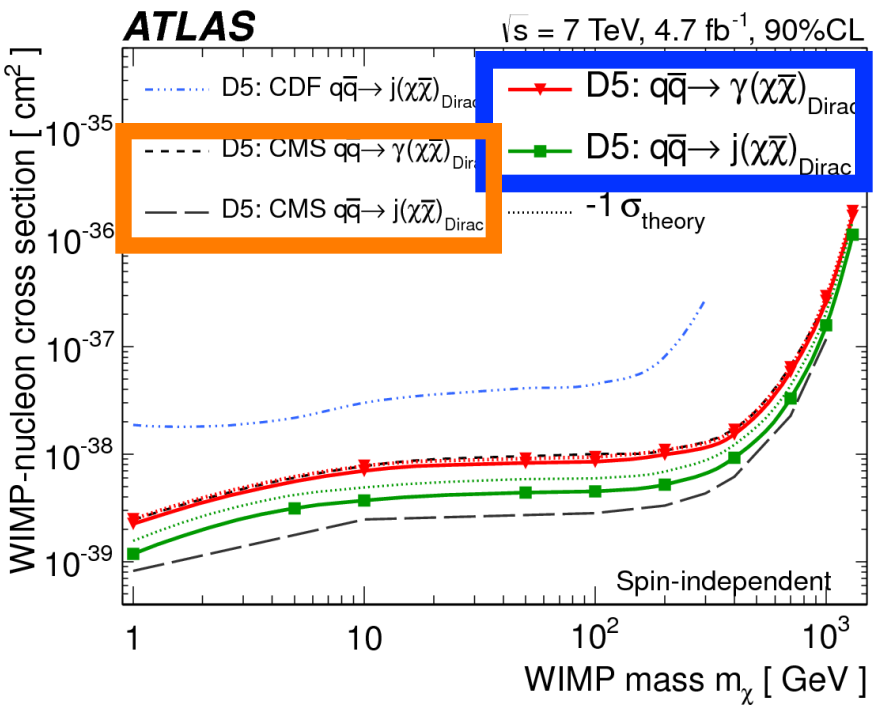
monojets/monophotons





limits on Dark Matter



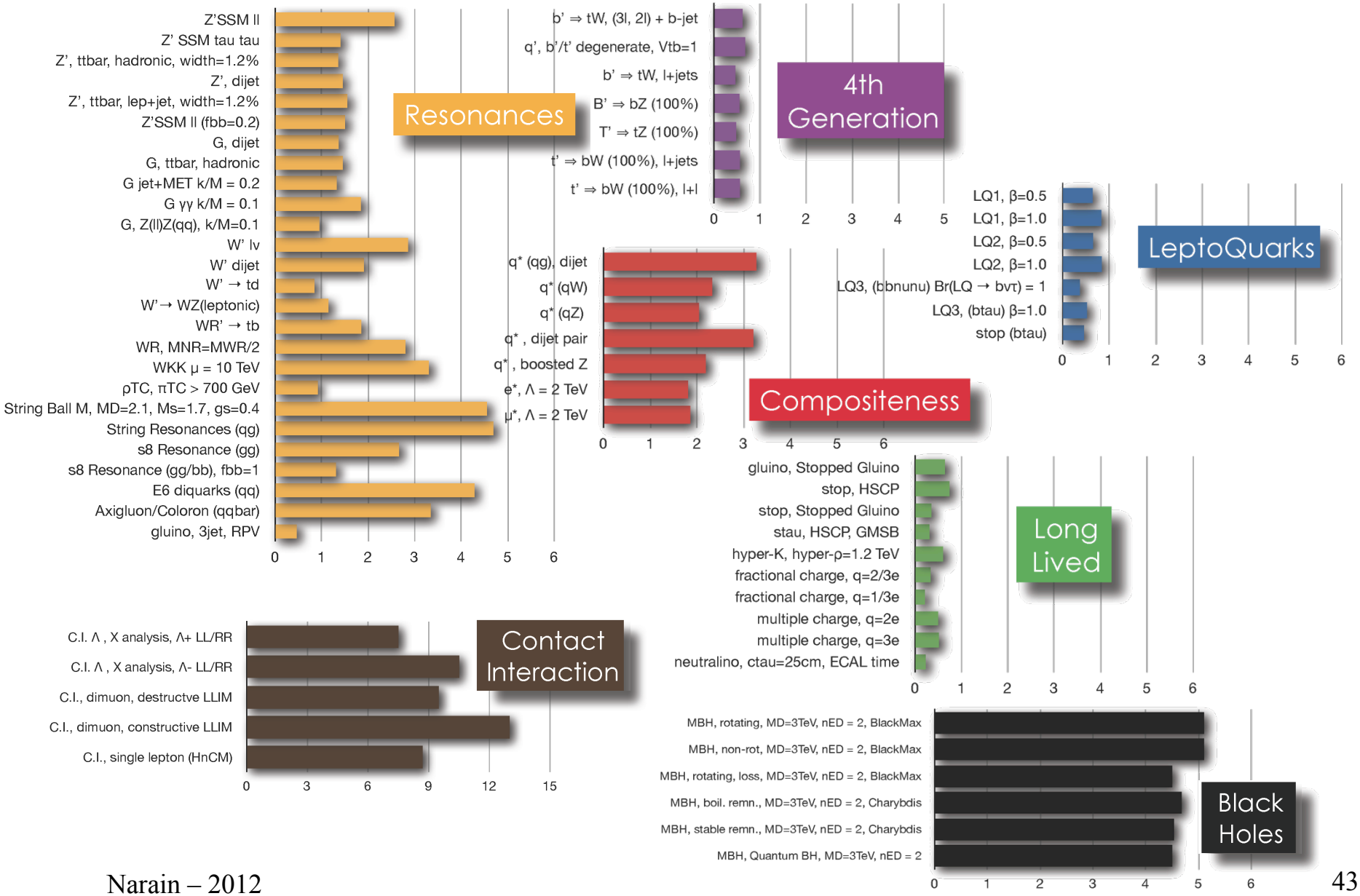


LHC results *complement* direct detection experiments

exceed sensitivity of cryogenic searches for DM spin dependent DM couplings

Add to reach for low DM masses, M<10 GeV, for spin independent couplings

summary of limits from CMS

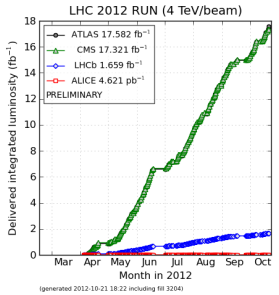


summary of limits from ATLAS

*Only a selection of the available mass limits on new states or phenomena shown

summary

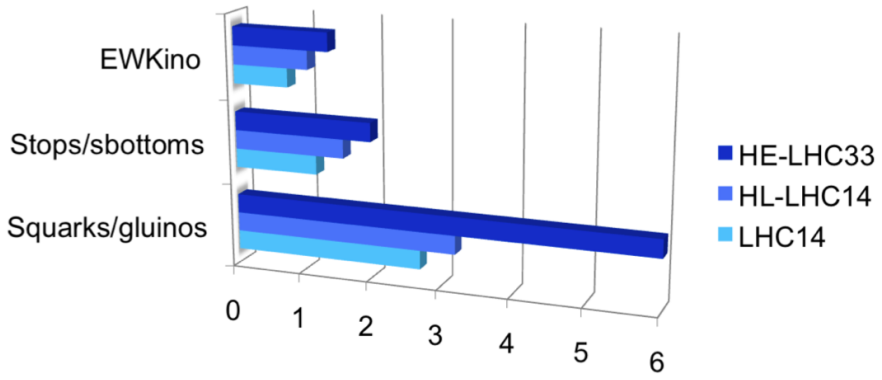
- **where is the new physics?**
  - no colored SUSY particles (first generations) below O(1 TeV), for a light LSP
  - no "natural" SUSY at a few hundred GeV of 3rd generation spartners
  - no exotic heavy objects below 2-3 TeV
    - Data is challenging many BSM models
- this is an extraordinary time in science:
  - LHC results are already changing our understanding of nature at a fundamental level.
  - We hope that the results from the 2012 dataset (> 25 fb-1) will bring more discoveries
  - and a clearer picture will emerge

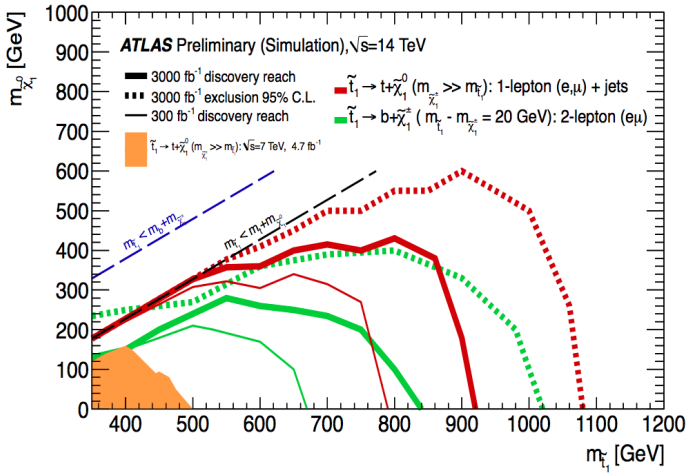


summary

- **however**
  - there is still a lot of room to be searched,
- **we are merely at the beginning of the exploration of the TeV scale at the LHC**

- 14 TeV collisions
  - much larger reach!





New Physics Unleashed?

PARTICLE PANIC

The Game:

Torus Lab is the world's largest particle collider, unleashing new exotic particles unknown to science.

Now the lab is out of control! The scientists must input the self-destruct codes or the unstable particles will endanger the world.

thank you

and many thanks to my colleagues in the
ATLAS and CMS collaboration
for the material used in this presentation