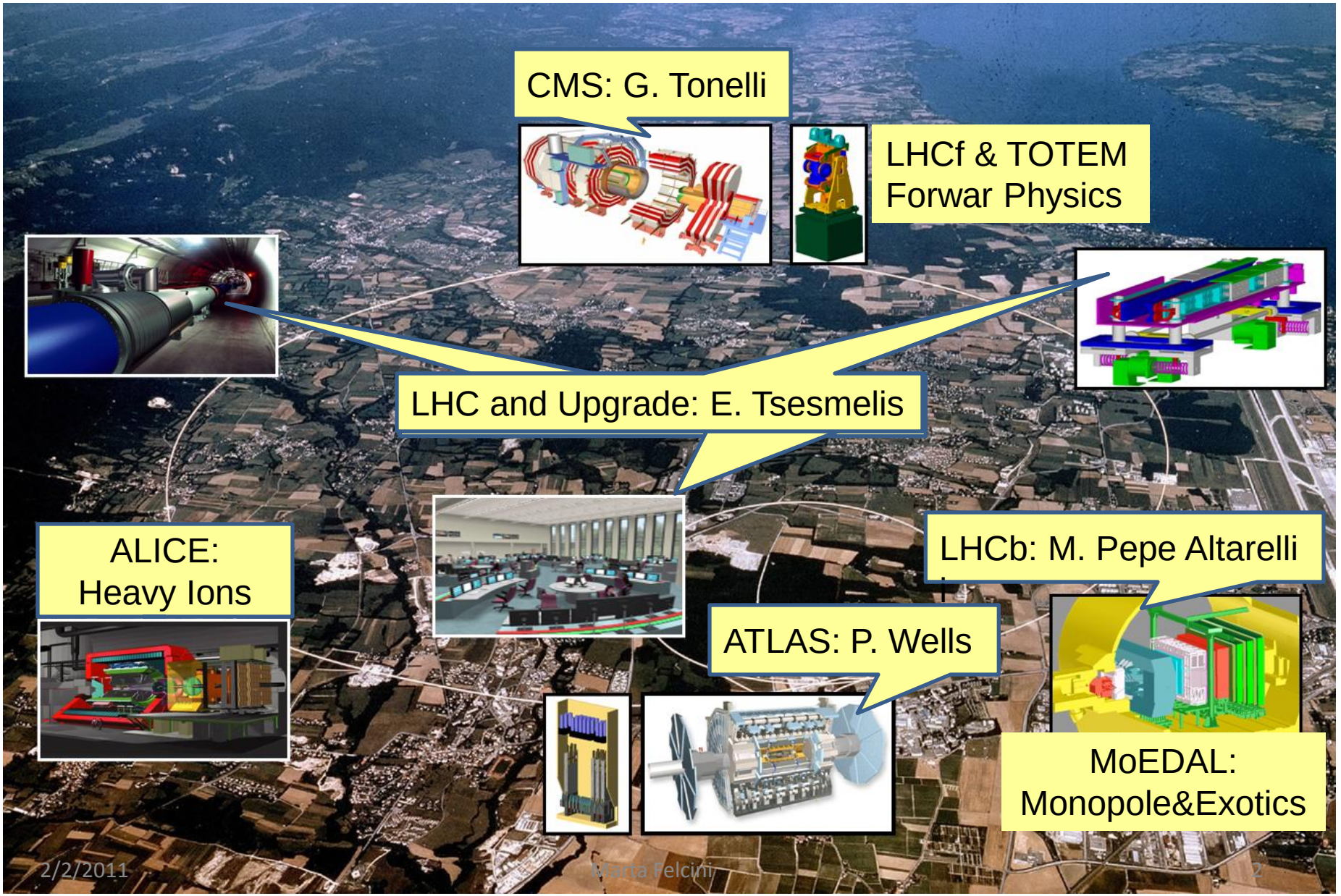
Corfu Summer Institute
12th Hellenic School and Workshops on Elementary Particle Physics and Gravity
Corfu, Greece 2012

Marta Felcini, IFCA & UCLA

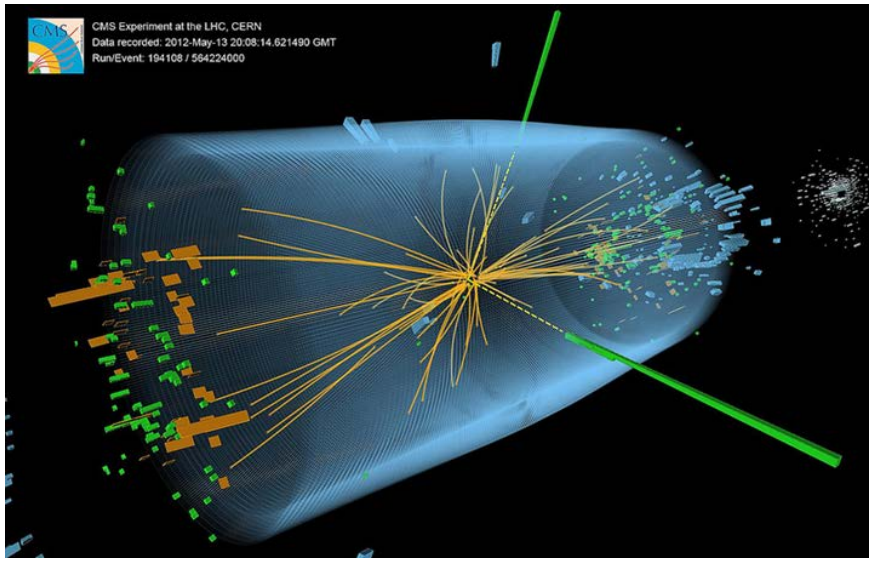
BSM SEARCHES AT THE LHC

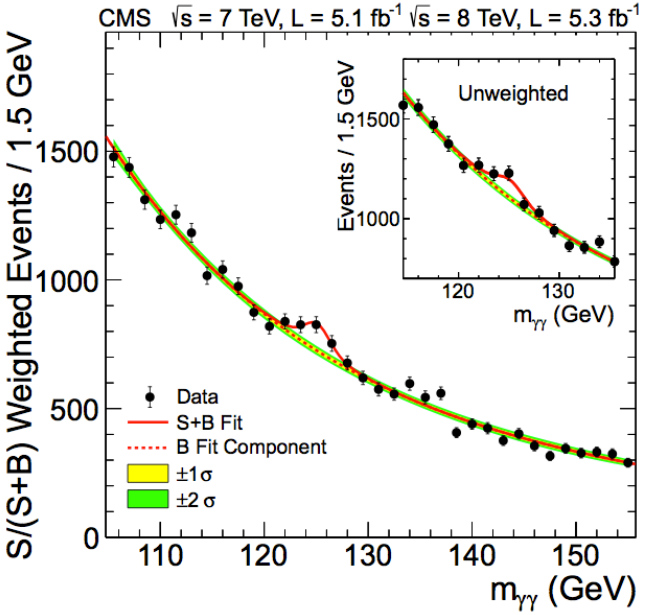
Summer School and Workshop on the SM and Beyond
Corfu Summer Institute, Corfu, Greece, Sept. 8-17, 2012

LHC Collider and Detectors

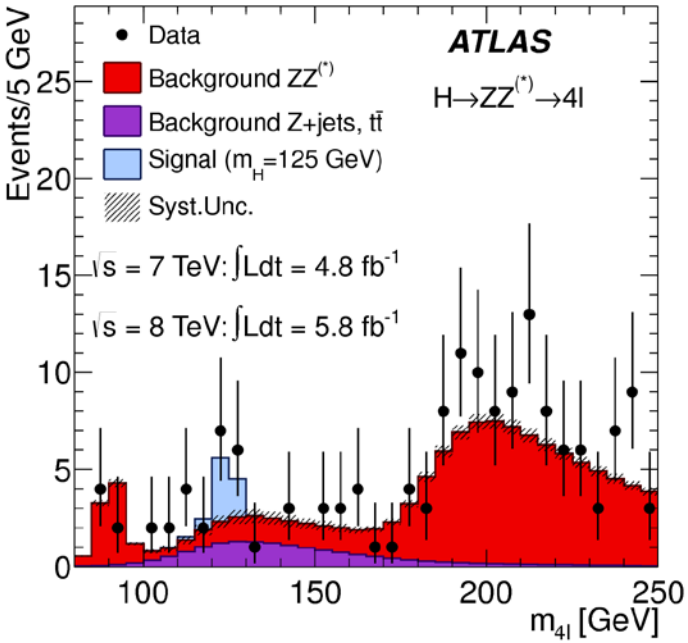


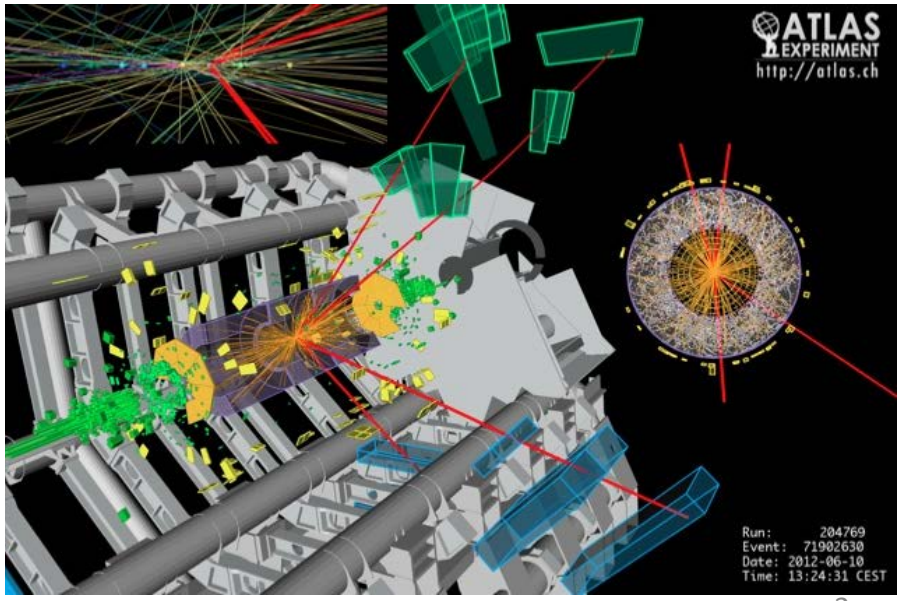
Higgs-like Boson Discovered





A. De Roeck
J. Varela
L. Fayard





Exhultation!

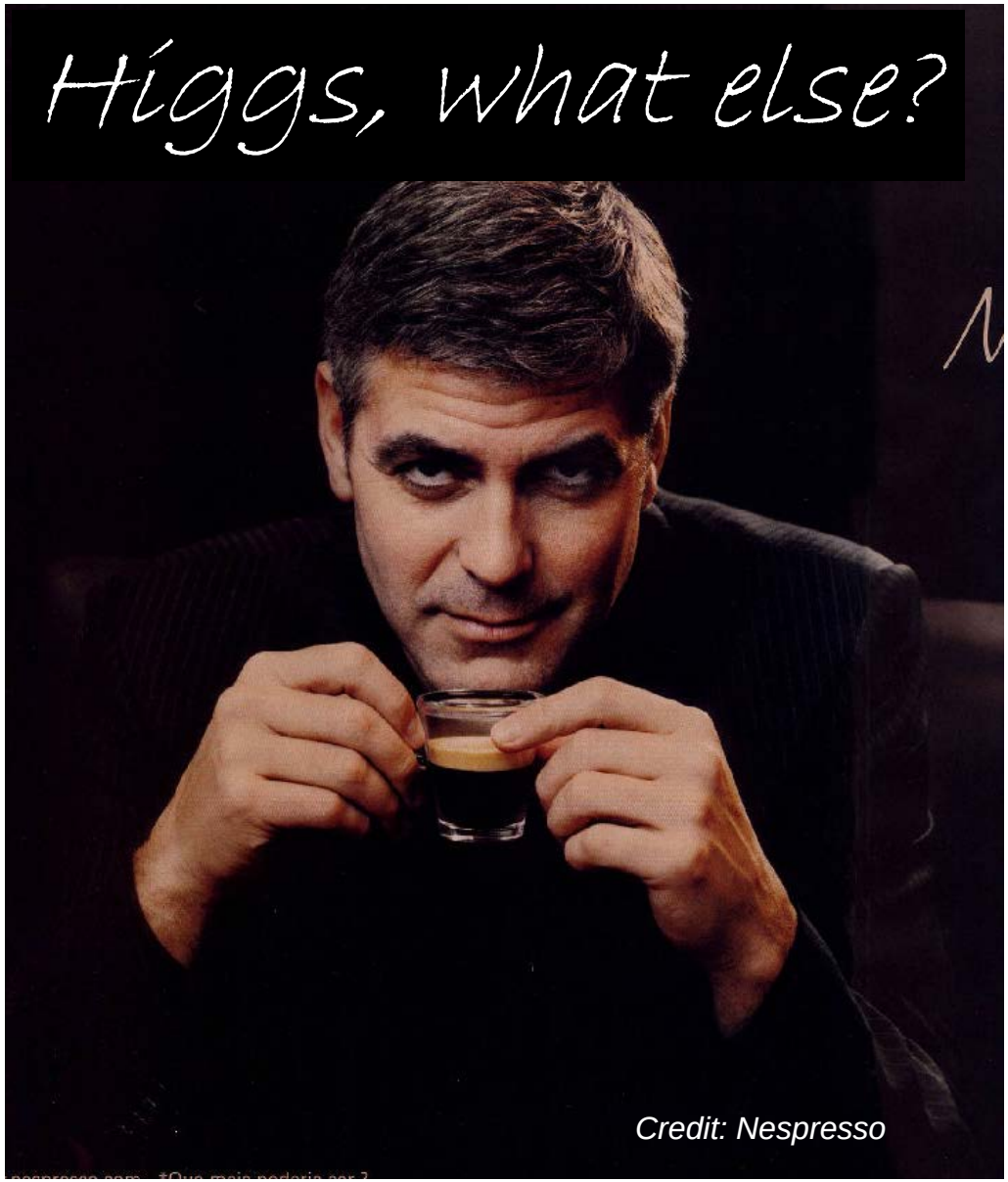
A question remains…

"Why not just **find the Higgs particle**, for completeness, and **declare that particle physics is closed?**

…

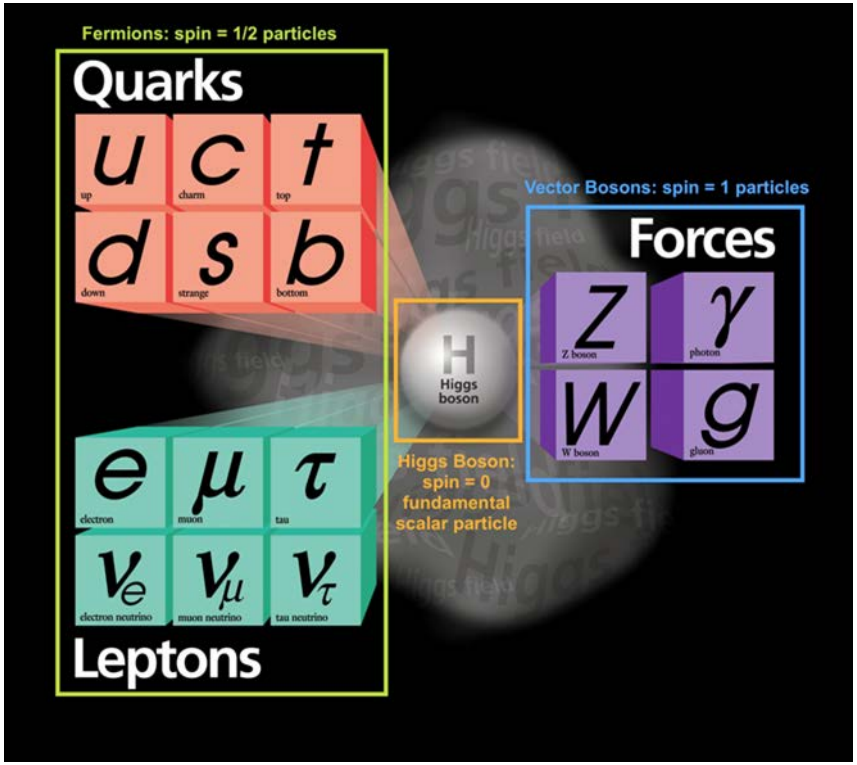
the reason is that **there are both conceptual problems and phenomenological indications for physics beyond the SM**."

G. Altarelli,
Moriond 2012 Summary,
arXiv:1206.1476



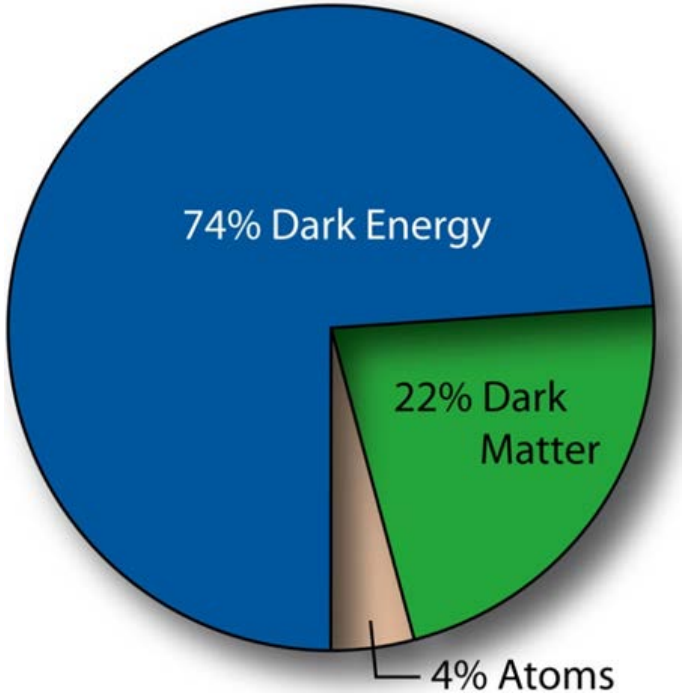
Present knowledge and problems

Standard Model



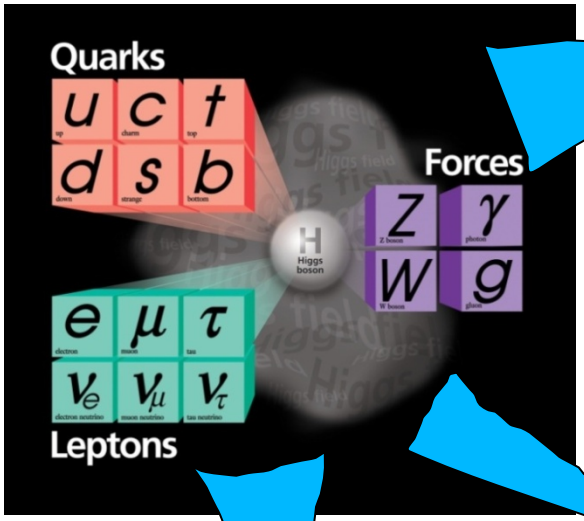
G. Degrassi, G. Altarelli, G. Perez, G. Branco, F. Maltoni, G. Zanderighi, R. Pittau, D. De Florian M. Rebelo

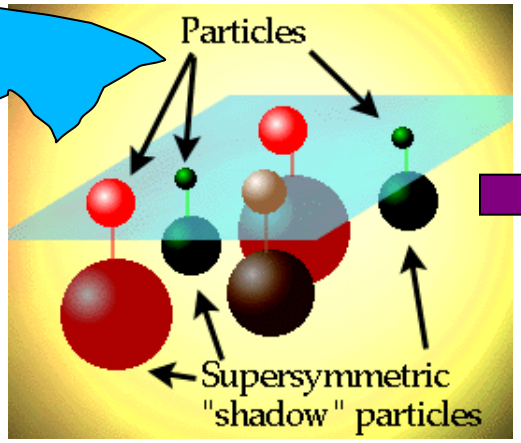
Beyond the Standard Model



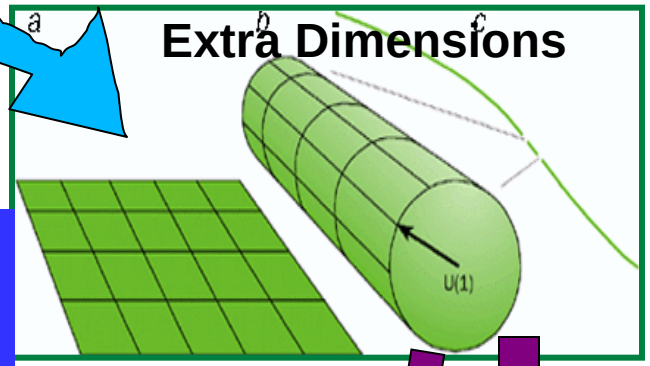
A. Santamaria, M. Nemevsek,G..Ross, E. Dudas, T Hahn, C. Hartmann, A: Hebecker, V. Mukhanov, P. Osland, G. Belanger, R. Harlander, D. Ghilencea P. Nilles, K. Papadodimas, E. Kiritsis, L. Covi, M. Krawkzyk, A. Iyer, F. Herrmann, M. Oleckowski, …

Beyond the Standard Model





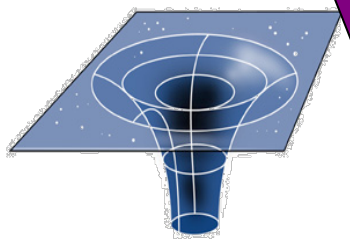
Dark matter candidates



New Gauge Symmetries, Higgs Compositeness, ...

New bosons
New fermions
Z',W',b',t',ν',l',...
LeptoQuarks, ...

Black Holes



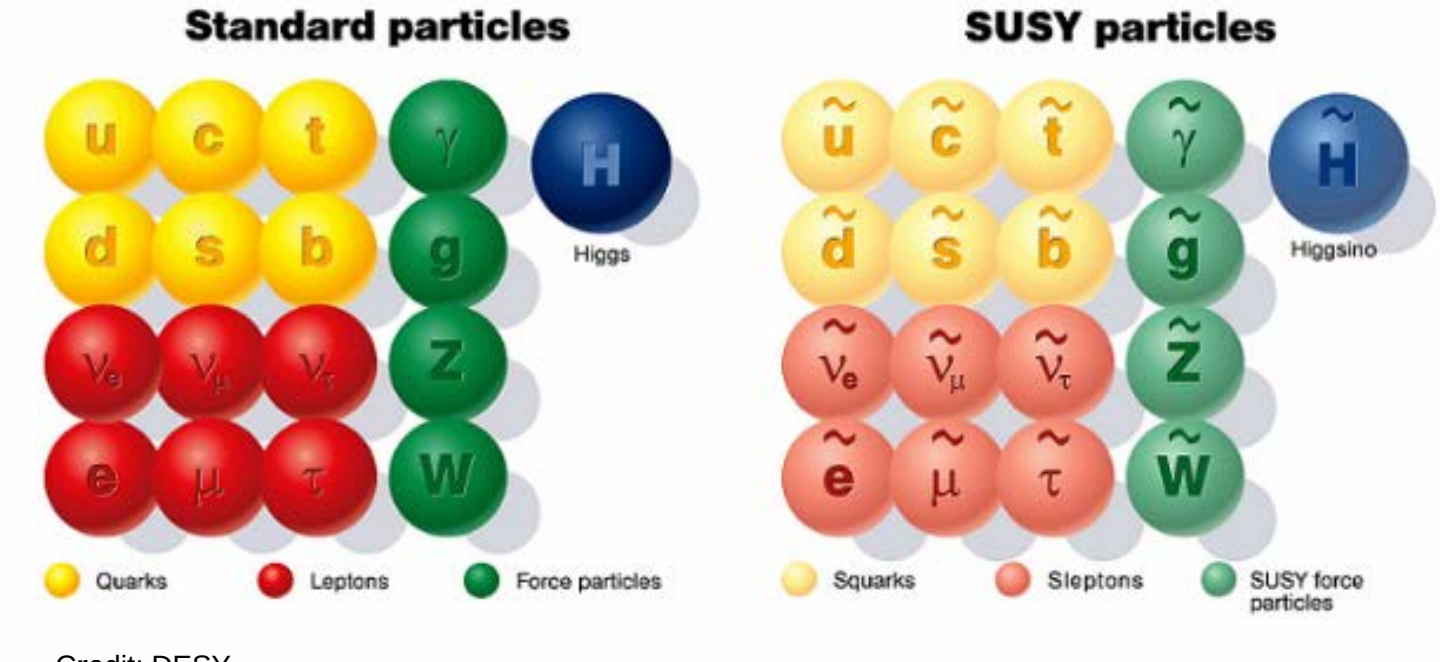
Graviton

Many possible BSM directions…

Need navigation aid =>specific BSM models: important benchmarks

to set-up the search strategies => particularly trigger (on-line) selections "an event missing the trigger is lost forever"

SUperSYmmetry

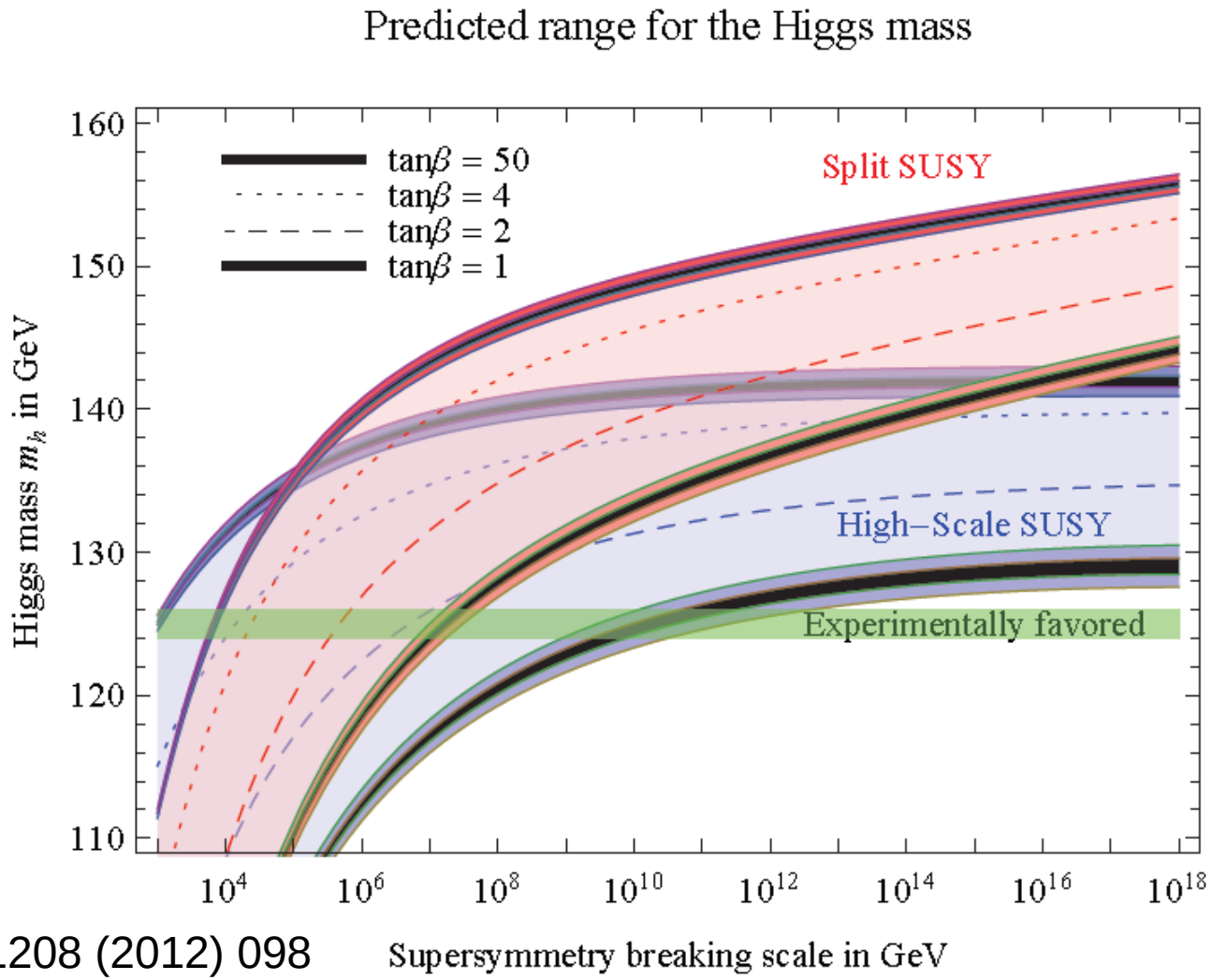


Credit: DESY

Higgs Mass and SUSY

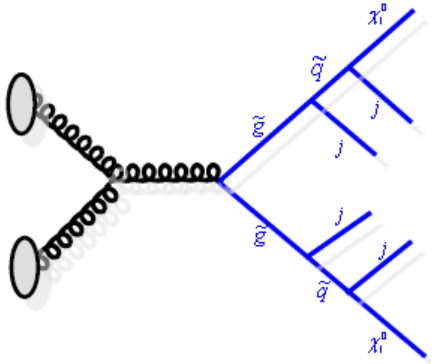
Example of SUSY constraints after Higgs-like boson mass measurement

usual scenario of weak-scale supersymmetry can account for the measured Higgs mass only for extreme values of the parameters, such as,
large tan β,
heavy stops,
maximal stop mixing.



G. Degrassi et al., JHEP 1208 (2012) 098

SUSY Inclusive Searches



pp -> squarks, gluinos

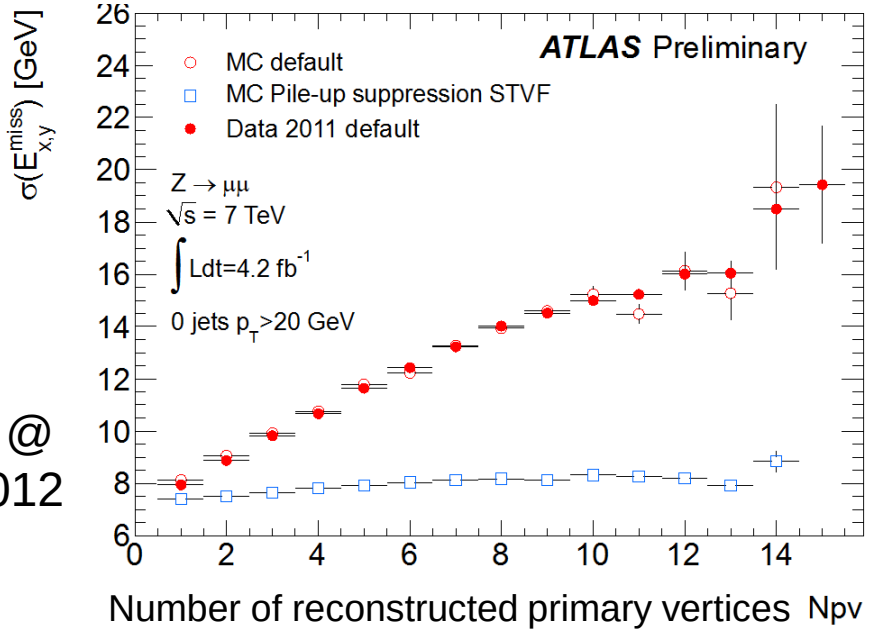
- hadronic
- Single lepton
- OS dileptons
- SS dileptons
- Multileptons

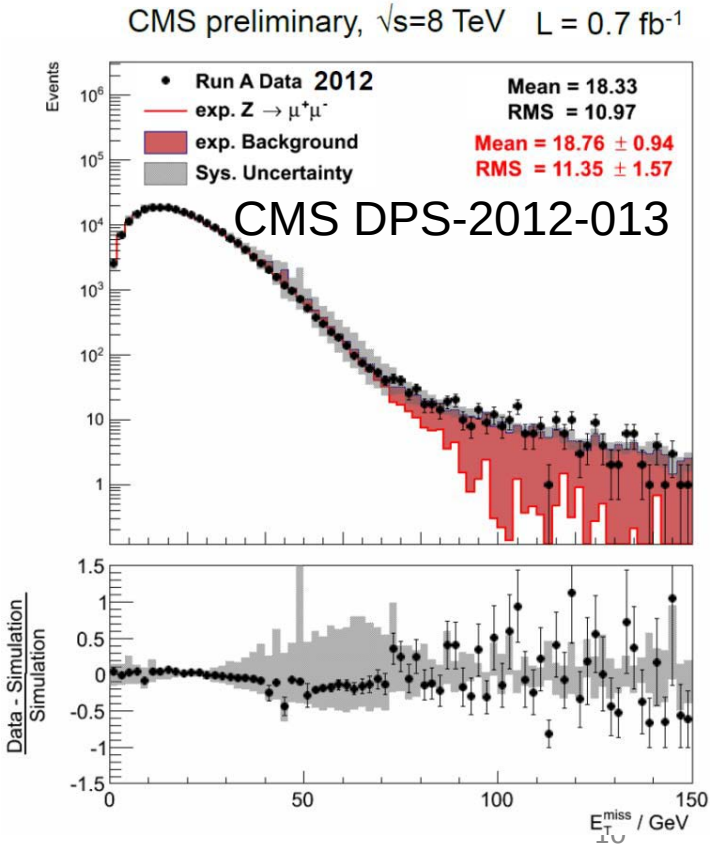
+ large Missing ET

MET sensitive to number of pp interactions/evt

- In 2011 in ave.~ 10 interations - doubled in 2012
- Good modelling and control of pileup effects

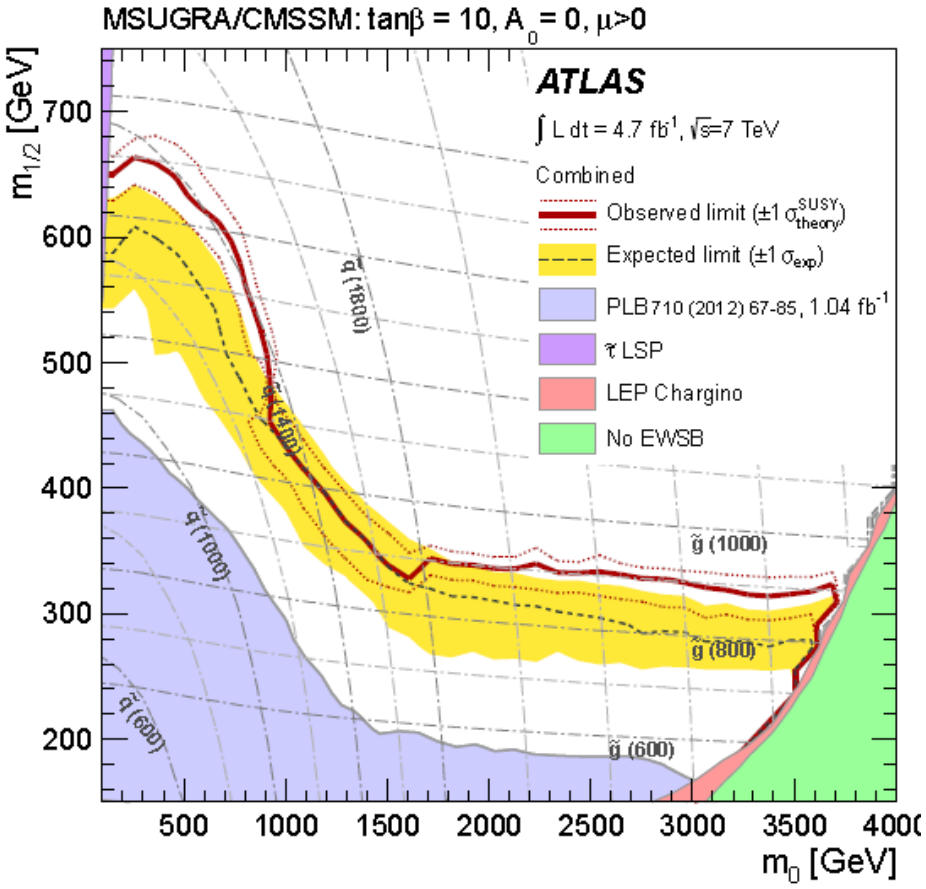
ATLAS @ Calor2012

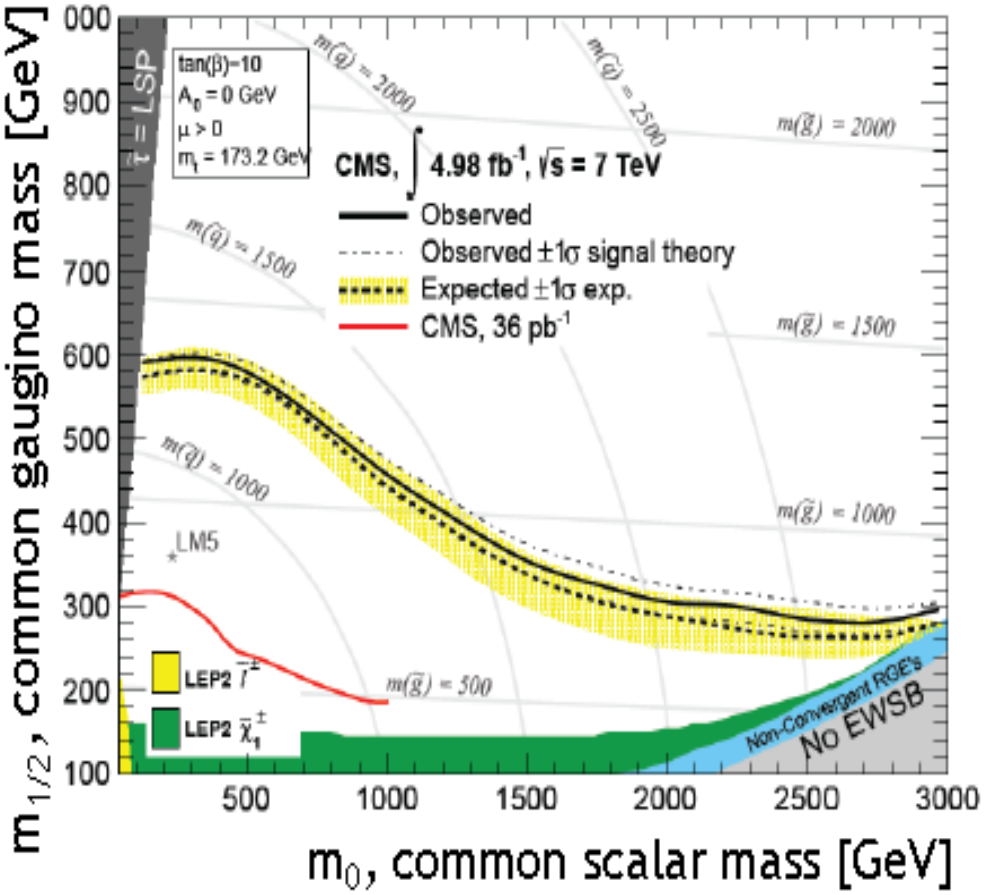




Interpretation in minimal SUSYscenarios

MSUGRA/CMSSM - five parameters:
common scalar, m_0, and gaugino, $m_{1/2}$, masses, A_0, tanβ, sign(μ)





ICHEP2012

m(gluino) > 720 GeV, m(squark) > 1.2 TeV

Other SUSY scenarios investigated

Split generation

m ↑ ≈ $\tilde{q}(1,2\,\text{gen})$

$\tilde{g}$

$\tilde{t}$

Exclusive t and b squarks or gauginos searches…

- small cross sections of stop and gluino productions
- large # of final particles --> smaller p_T, $\not{E}_T$

$$\tilde{g} \to \tilde{t}t \to 2b + 4j + \tilde{\chi}_1^0$$

Compressed SUSY

m ↑ $\tilde{g}$, $\tilde{q}$

$\tilde{\chi}_1^0$

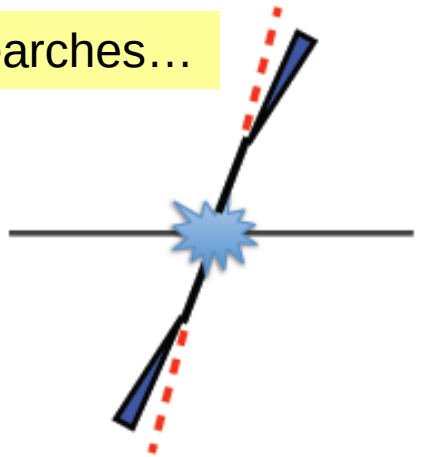
Topology based searches…

- small jet p_T

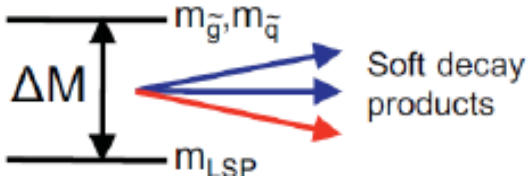
$$p_T \sim m_{\tilde{q}} - m_{\tilde{\chi}_1^0}$$

- small $\not{E}_T$

(LSPs are back-to-back and cancel each other in $\not{E}_T$)

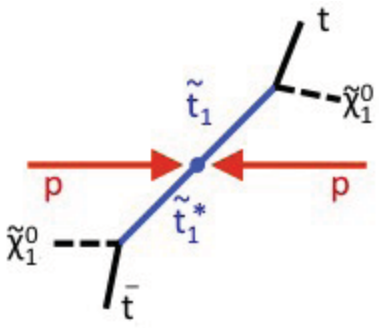


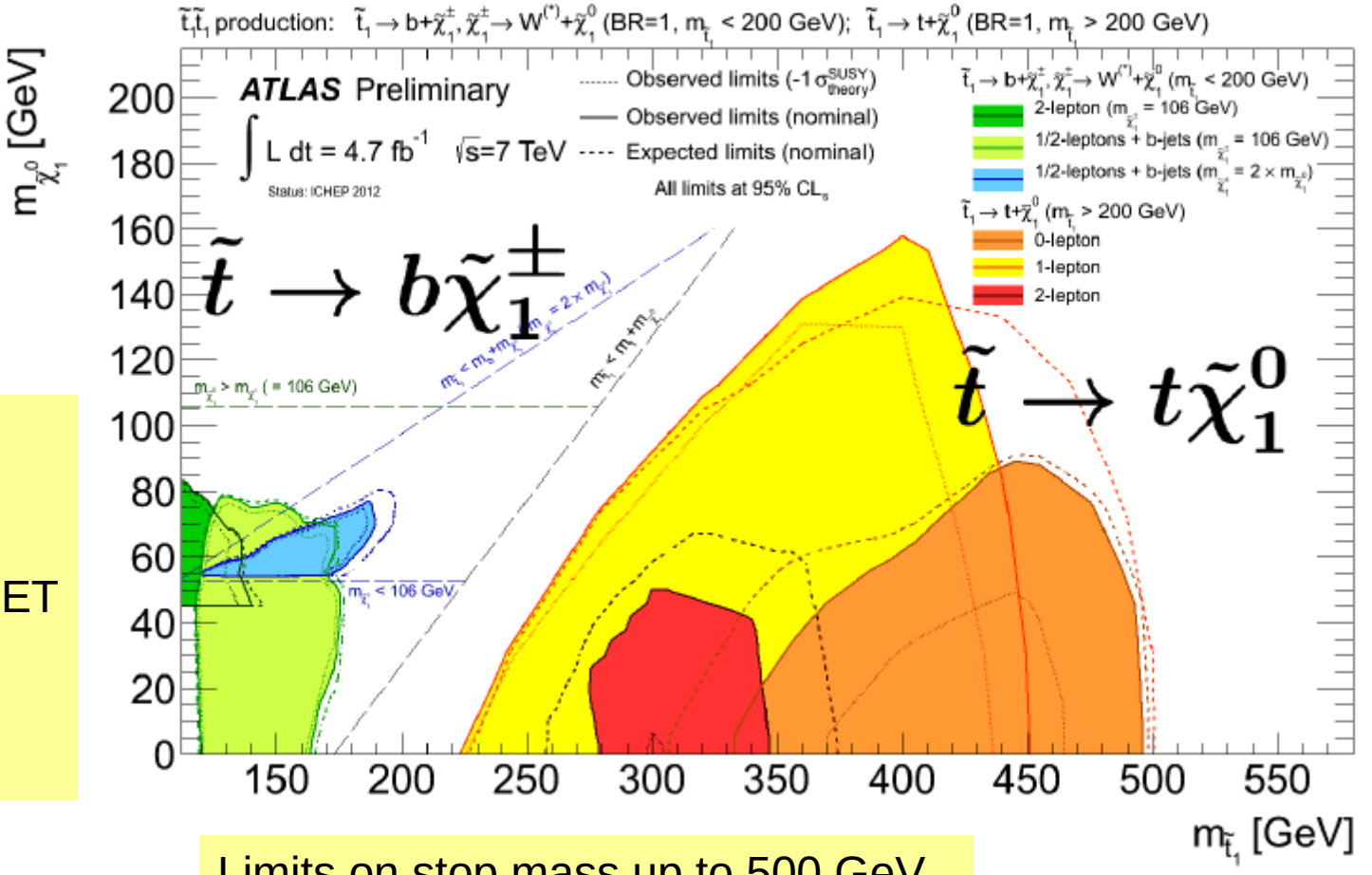
Experimental detection efficiency depends on splitting between the decaying particle and the LSP (MET)



Exclusive Stop Searches

ATLAS-CONF-2012-074





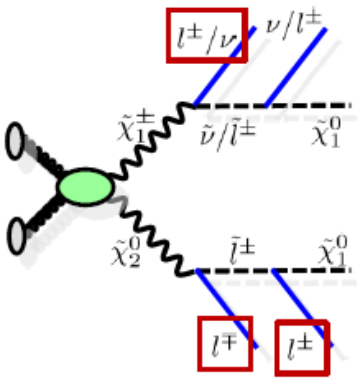
Search in two channels with
tt -> fully hadronic
tt->1 lept + jets + MET

Shown the Combined result

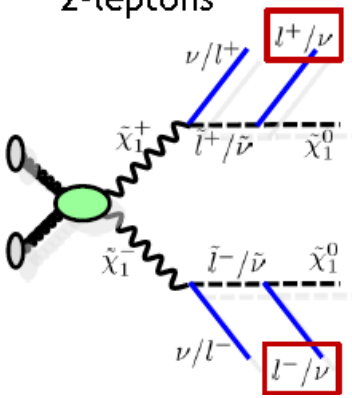
Limits on stop mass up to 500 GeV depending on LSP mass)

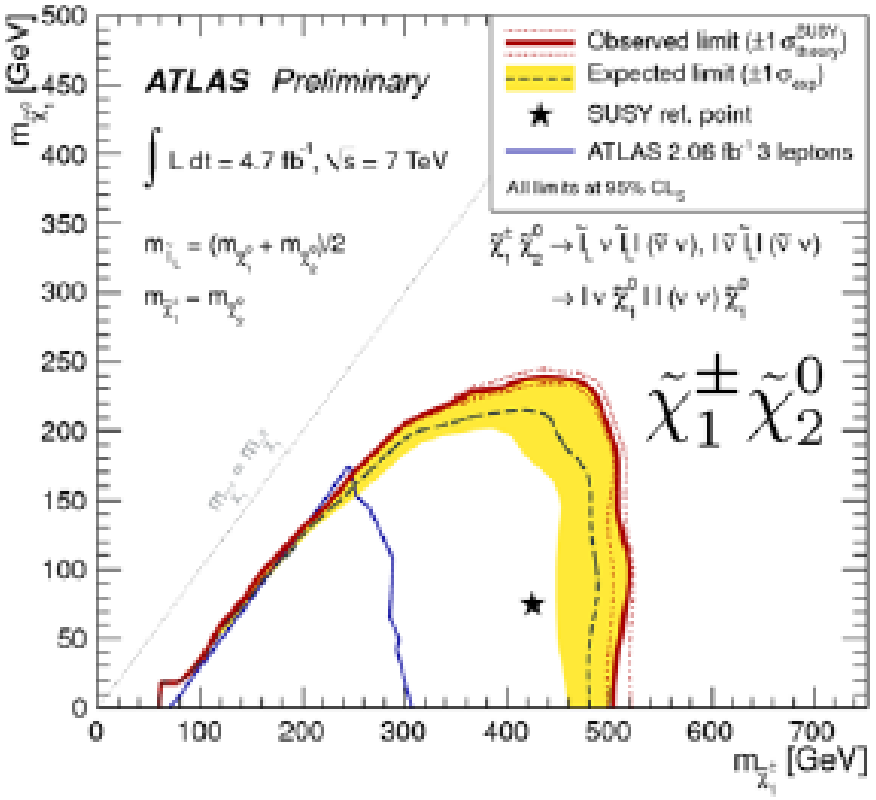
Exclusive Gaugino Searches

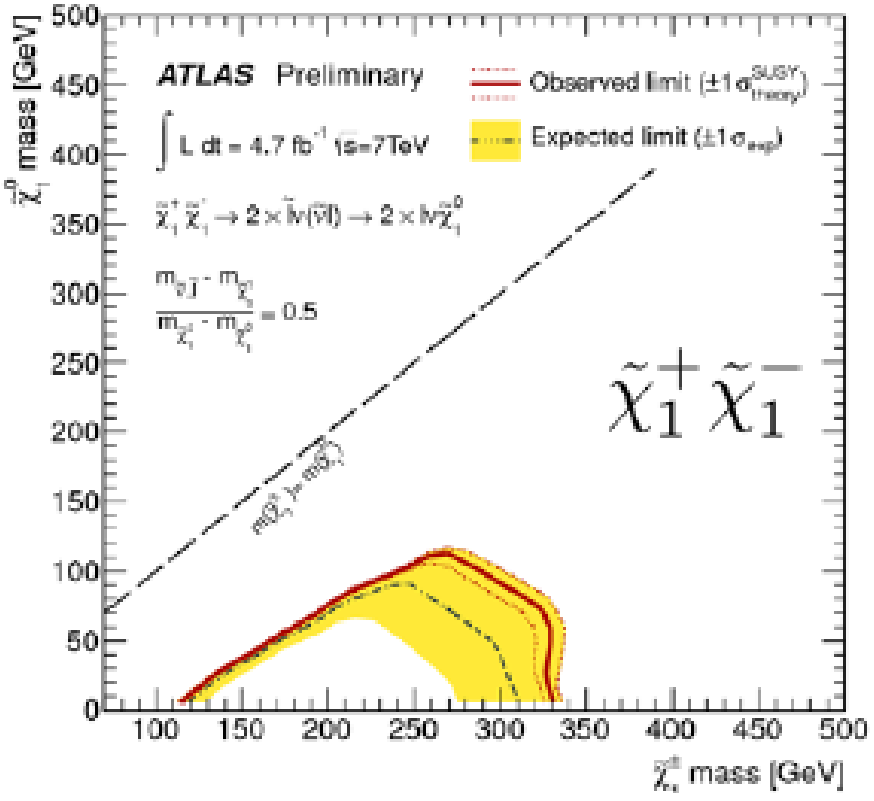
3-leptons



2-leptons

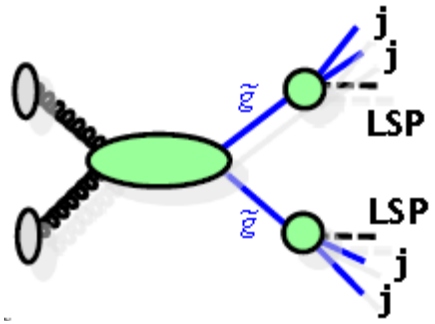


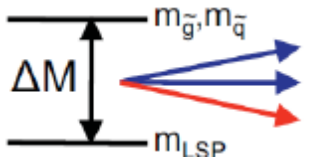




Simple Model (SM) Interpretation

example

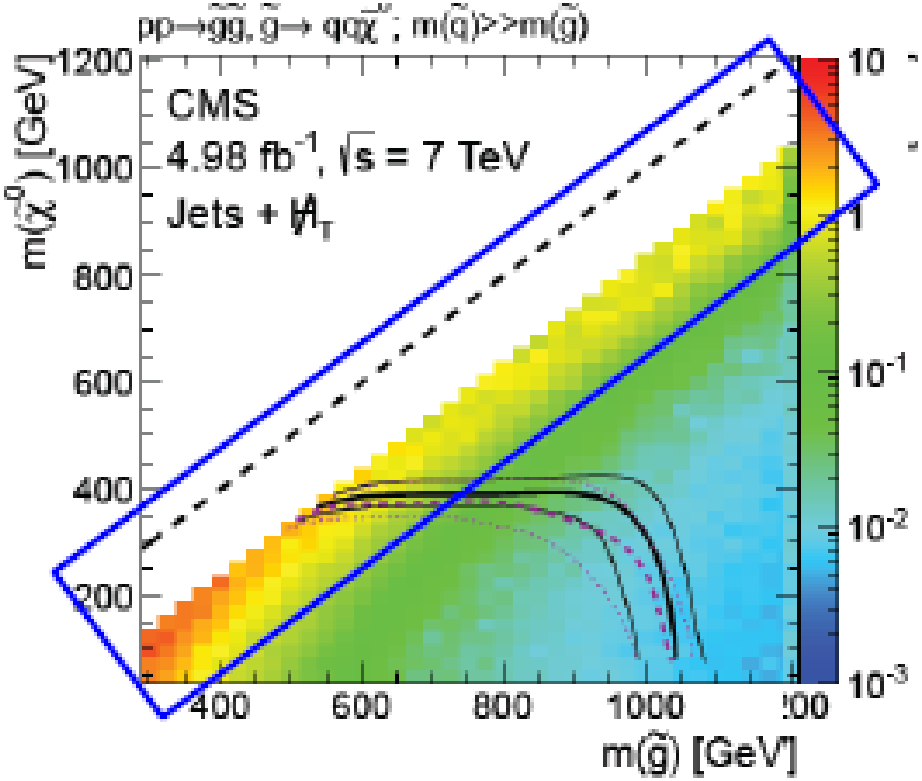




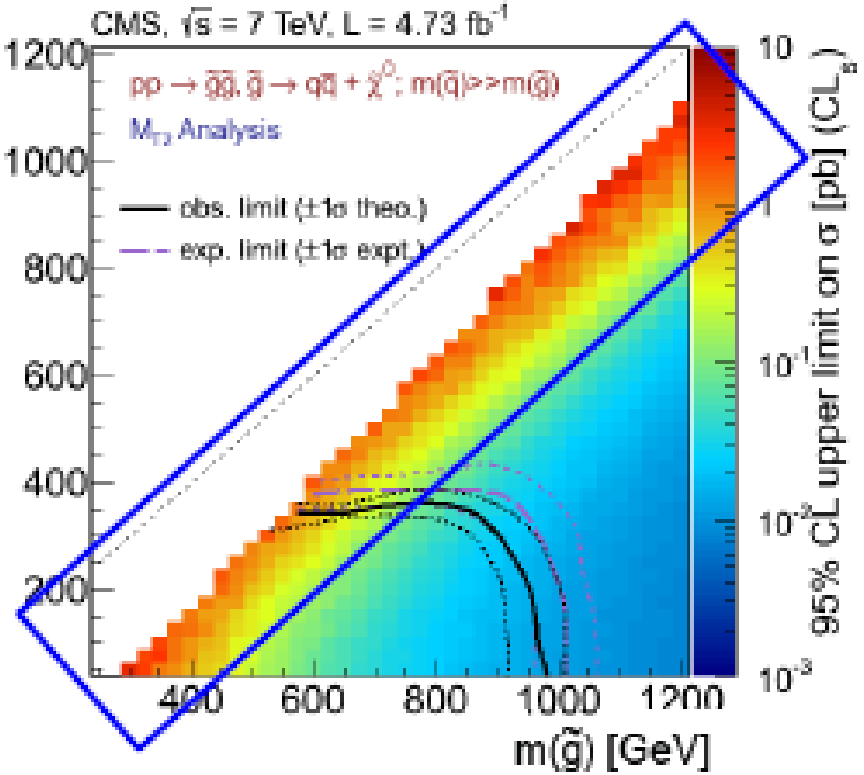
Detection efficiency depends on mass splitting

Results are presented in terms of cross-section upper limits in the relevant mass plane

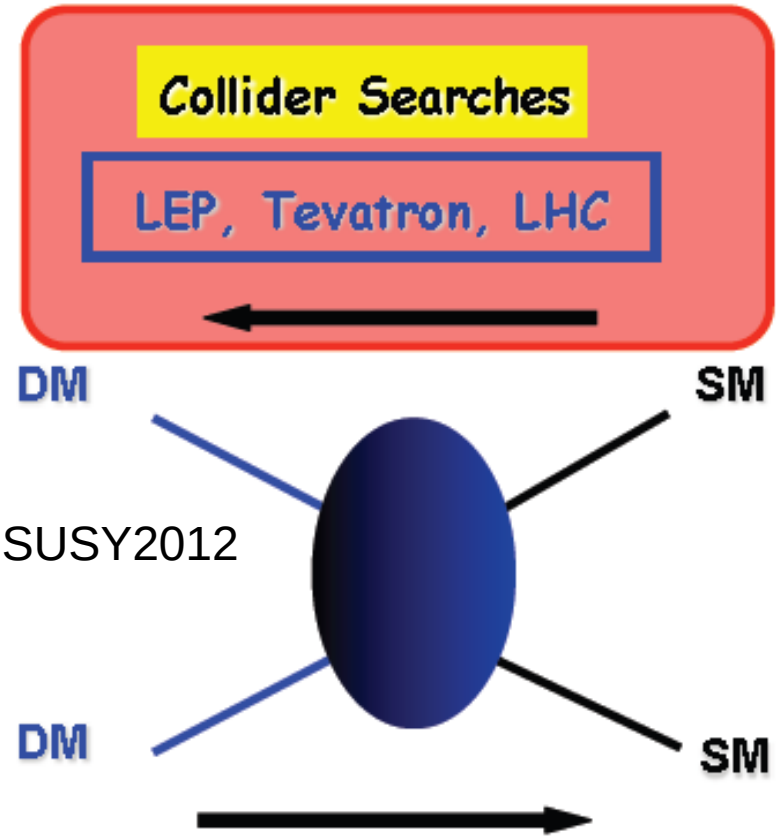
arXiv:1207.1898



arXiv:1207.1798



DM Candidate Search



S.Su, SUSY2012

Search for
direct DM particle production
In the collisions of SM particles

direct DM detection

CDMS, CoGeNT, COUPP,
CRESST, DAMA, XENON,...

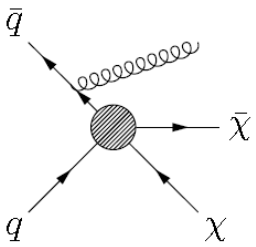
Search for DM particle scattering by SM particles

AMS2, PAMELA, Fermi-LAT,...

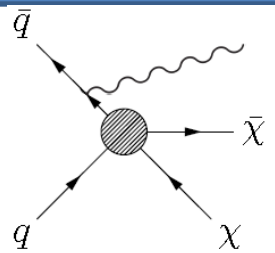
Search for DM particle annihilation into SM particles

Results of DM search at the LHC

Search Channels

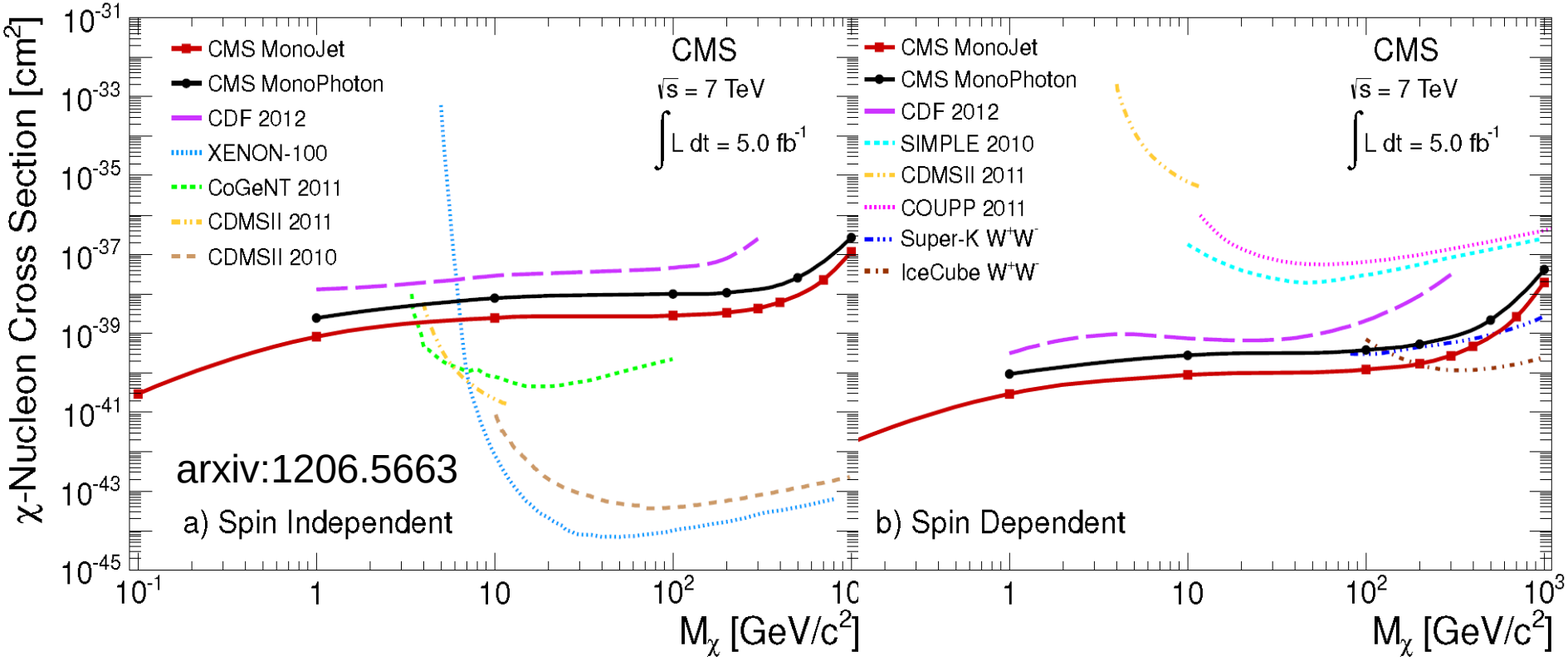


Single jet + MET



Single photon + MET

Upper limit on spin-independent or spin-dependent of Neutralino-Nucleon cross-section

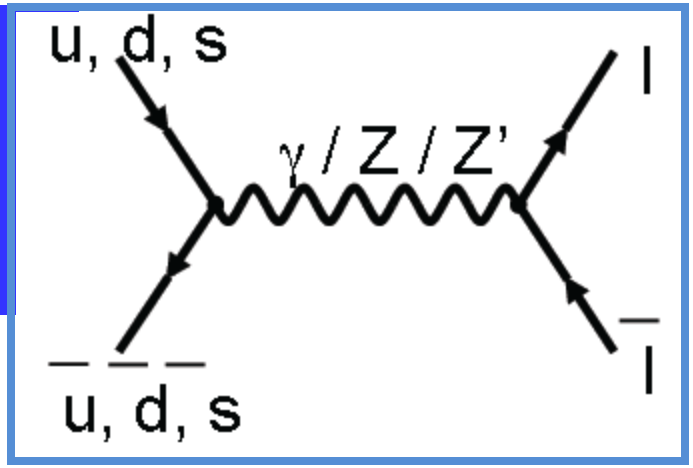


Similar results for single photon+MET channel: ATLAS-CONF-2012-085

New Bosons - Heavy Resonances

Extended Gauge Symmetries:
- **Z'_{SSM}/W'_{SSM} in Sequential Standard Model**
- **Z'/W from E6 and SO(10) GUT**
- **Narrow heavy particles from Technicolor**

…



Signatures

Z' → narrow resonance in dilepton/dijet mass

W'→ narrow resonance

Extra Dimensions Models

Randall Sundrum Kaluza Klein Graviton (1) exchange or (2) emission

…

Signatures

G → narrow resonance

Multi KK states →broad peak

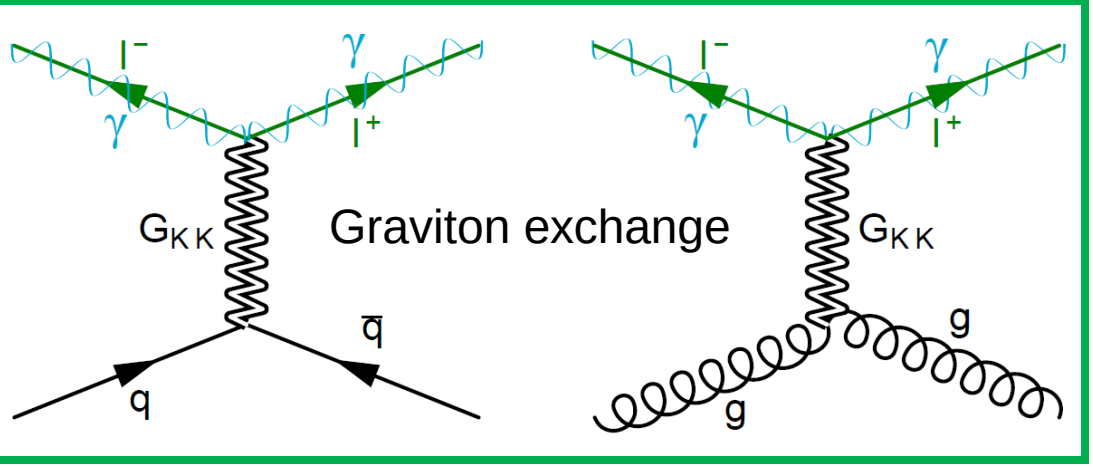
In e^+e^-, $\mu^+\mu^-$, dijet mass

Or

(2) Graviton emission

single jet/photon + missing E_T

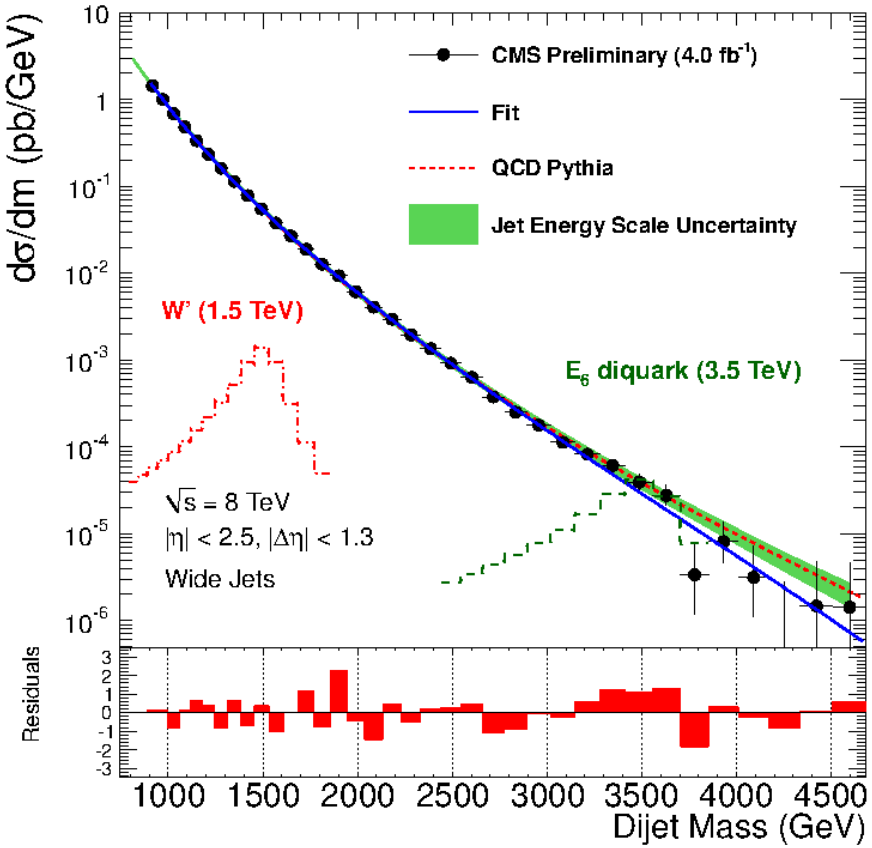
same as DM searches (above)

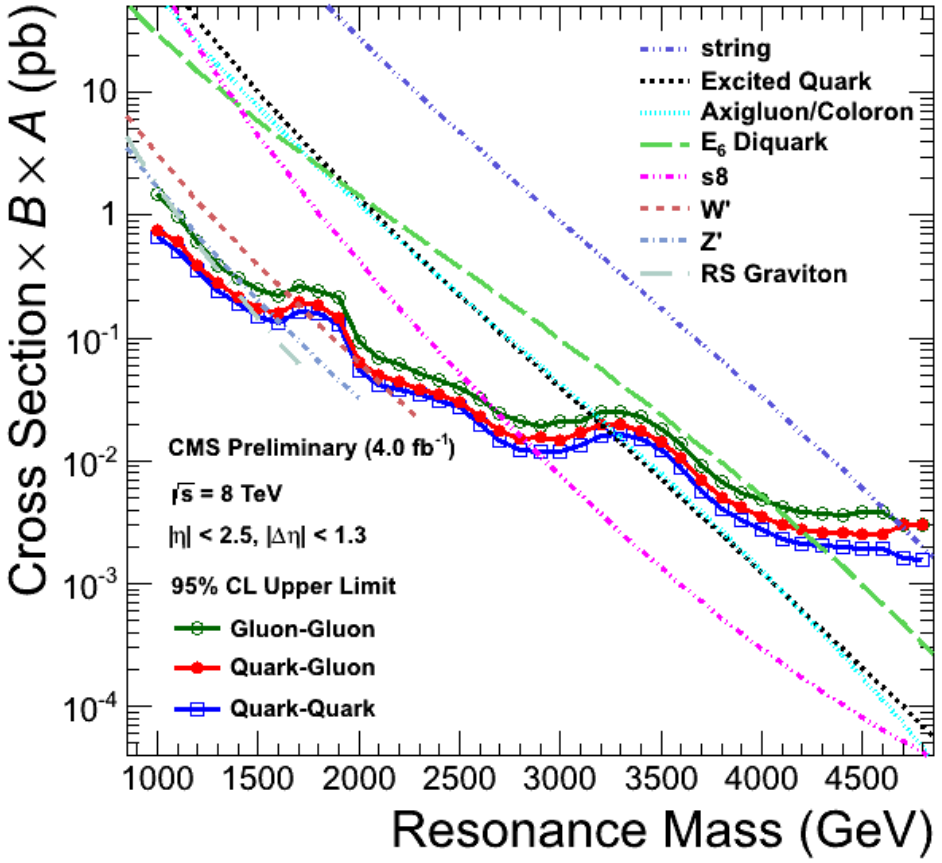


Dijets Resonances – several searches

Models with a narrow s-channel dijet resonance:
Randall-Sundrum Gravitons,
W′ , Z′ strings, diquarks, excited quarks, axigluons, colorons,..

CMS EXO-12-016
8 TeV data

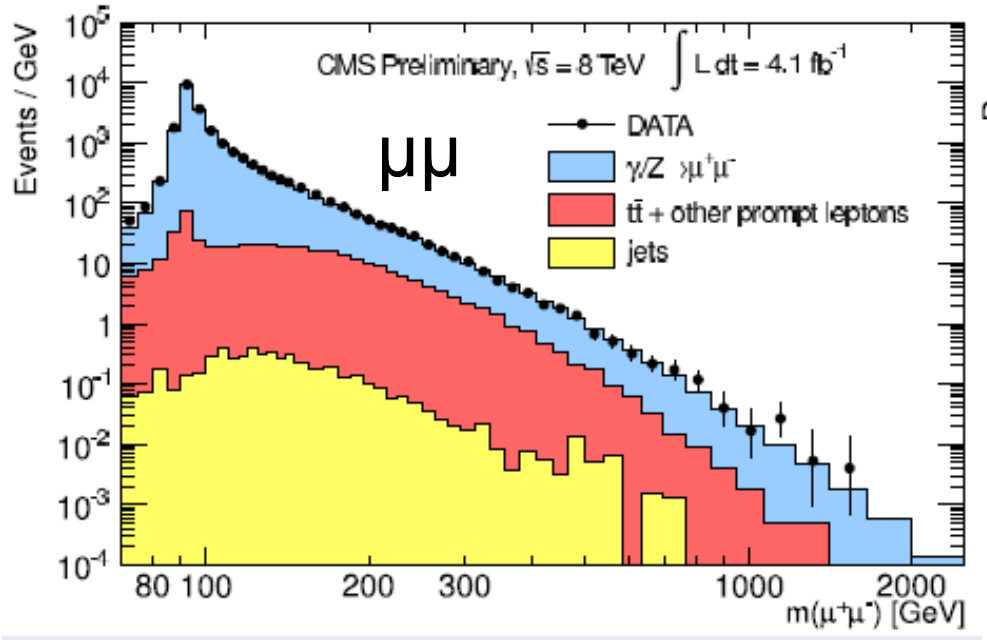


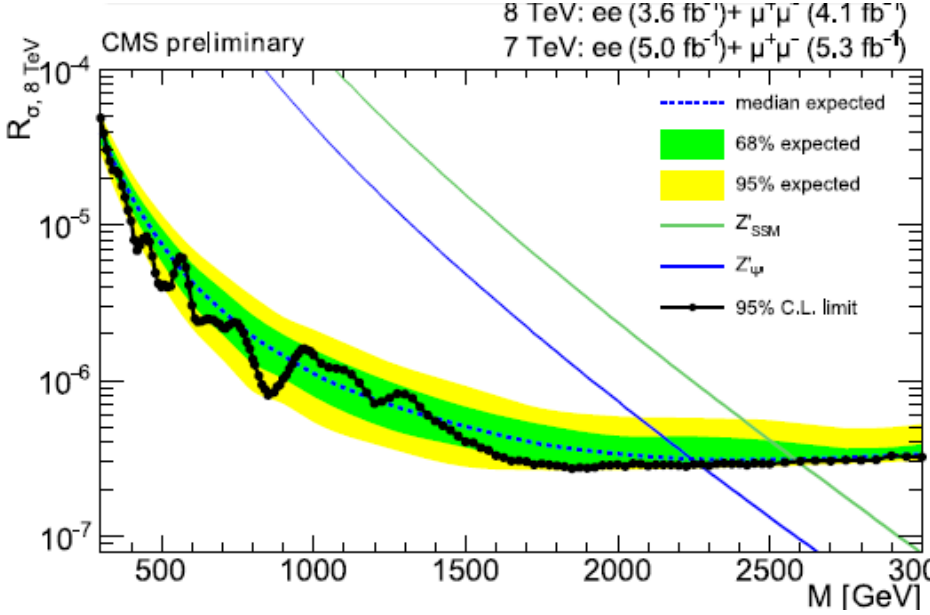


Dilepton Resonances – Z' searches

Search for narrow resonances decaying to muon (electron, tau) pairs

CMS EXO-12-015
8 TeV data





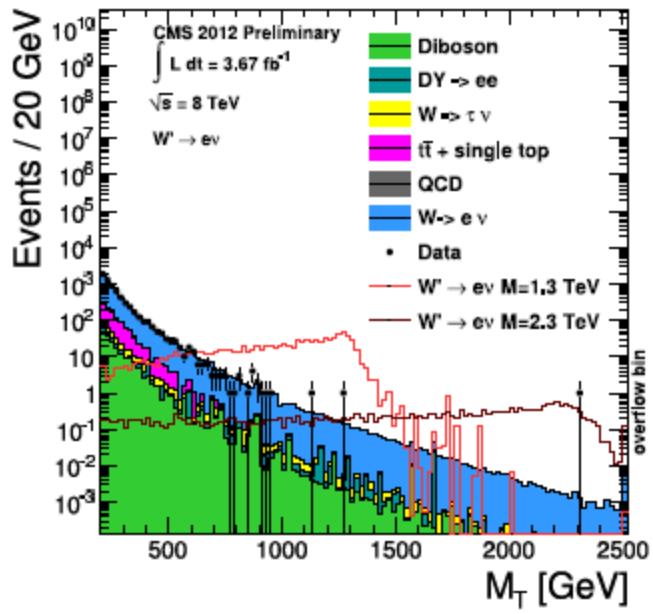
No excess observed:
Set limit on Zi mass for

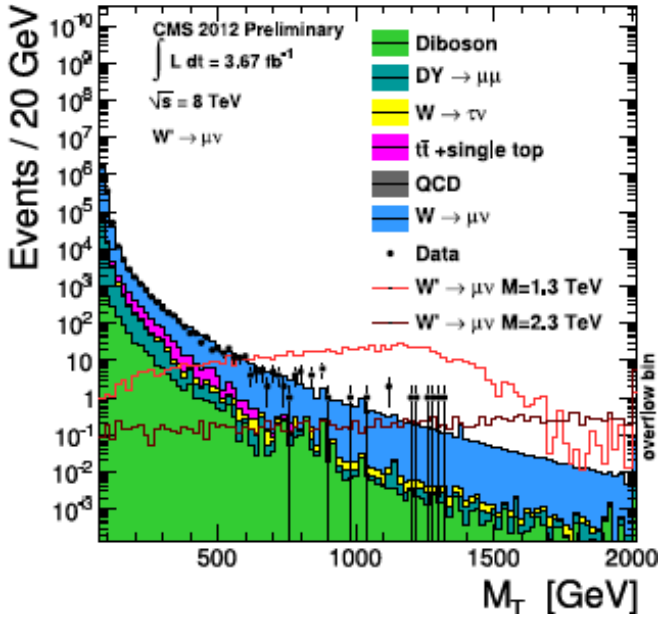
- Sequential Standard Model: Z'_{SSM}
- Super-strings inspired Model: Z'_{ψ}

Signal	Mass Limit (TeV)
Z'_{SSM}	2.59
Z'_{ψ}	2.26

Lepton + MET – W' search

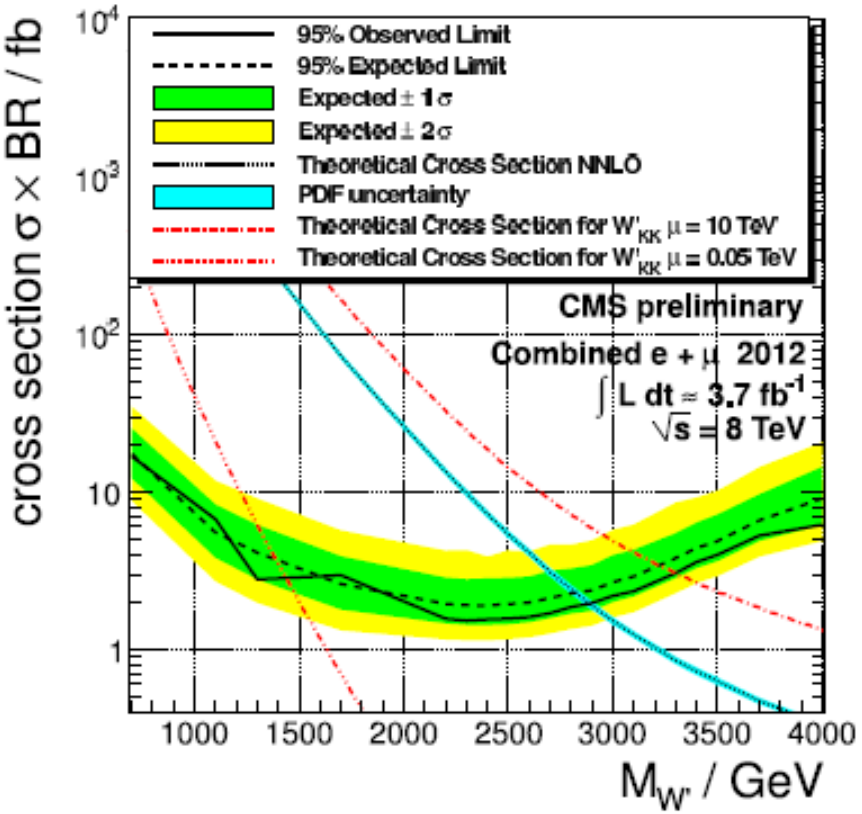
Search for Jacobian peak in transverse l + MET mass





- Data agree with SM expectation
- Use data to set limit on W' production

CMS EXO-12-010 - 8 TeV data

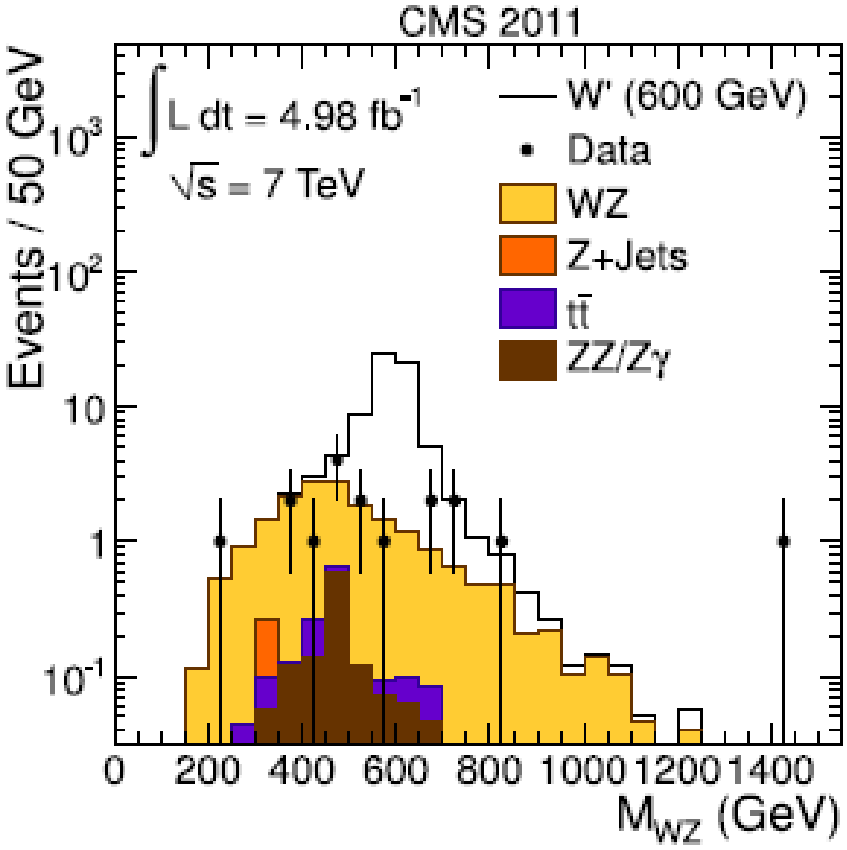


Sequential W' $M(W'_{SSM}) > 2.85$ TeV

KK resonance $M(W'_{SSM}) > 1.4$- 3.3 TeV depending on μ value

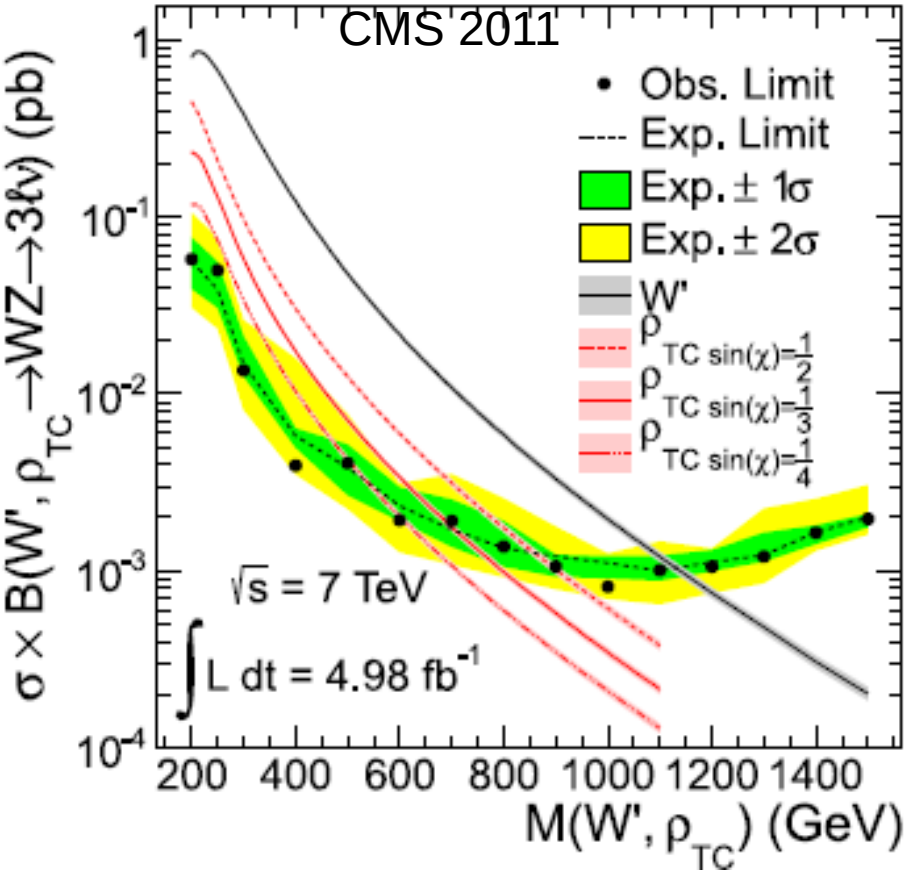
WZ Resonances – W',Techni-ρ search

Select 3 isolated leptons + some MET
Compute transverse mass of WZ candidate



No excess observed
-> exclusion of Techni-rho or W' signals

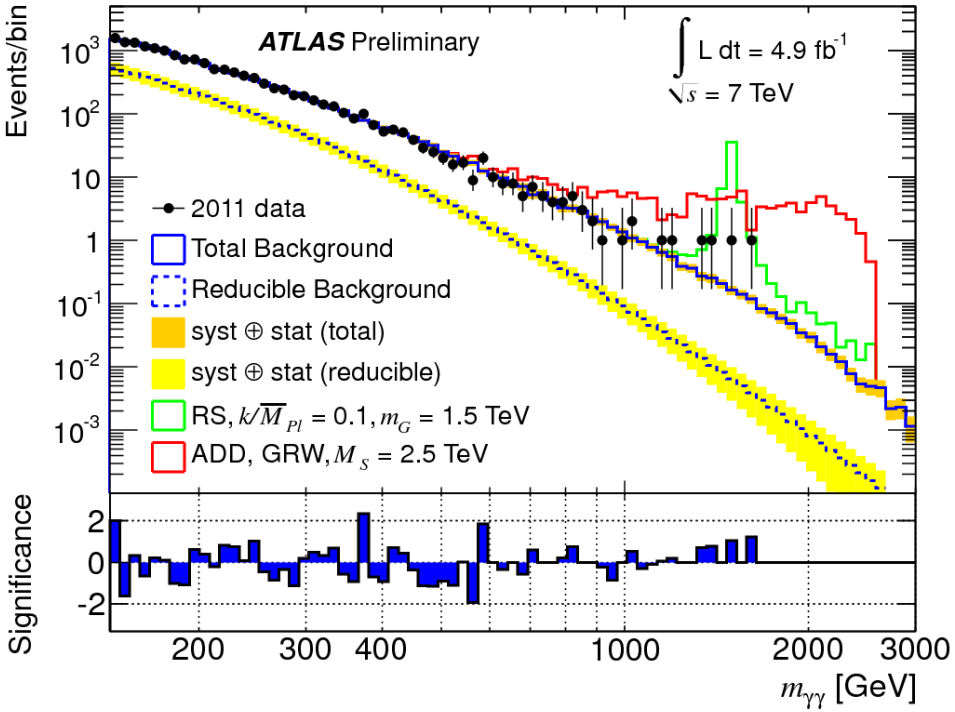
CMS EXO-11-041



$M(W'_{SSM}) > 1.14$ TeV
M(techni-rho) > 540 – 850 GeV
in the parameter range investigated

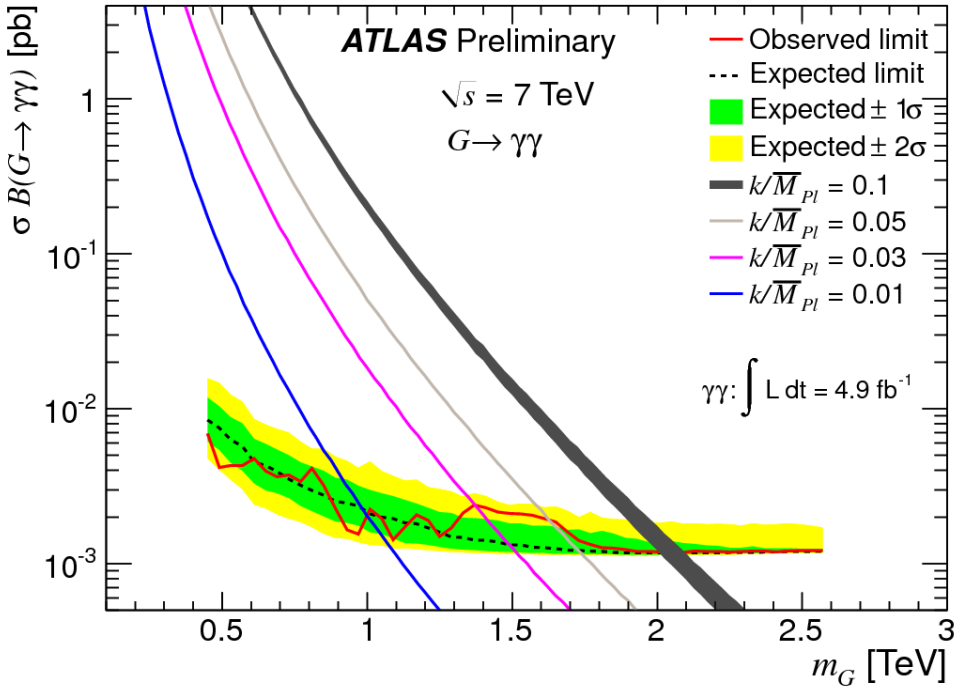
Diphoton Resonances – Graviton search

Same final state as for low mass Higgs:
– irreducible background from MC
– reducible backgr. (fake photon) from data



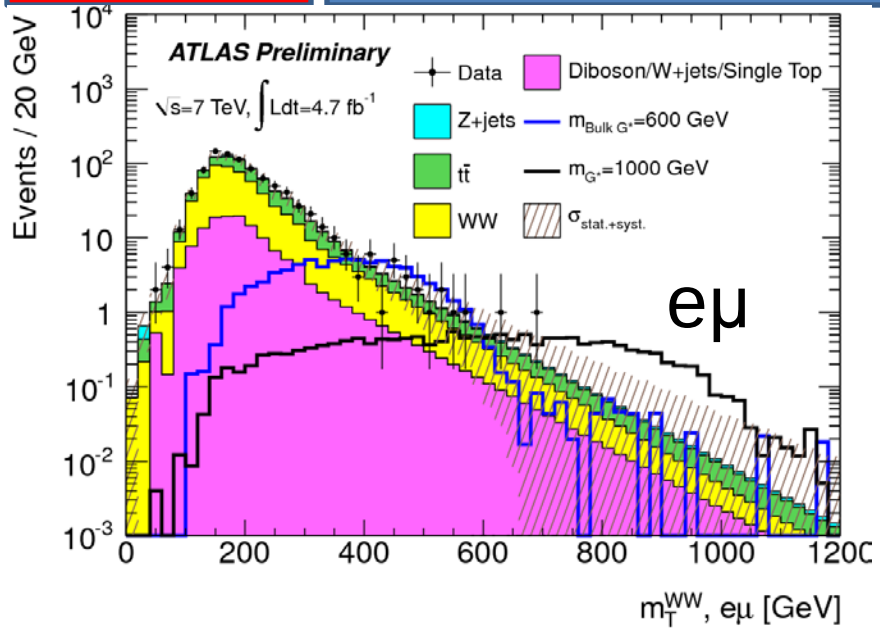
Data consistent with expected background
• Limit on RS graviton mass

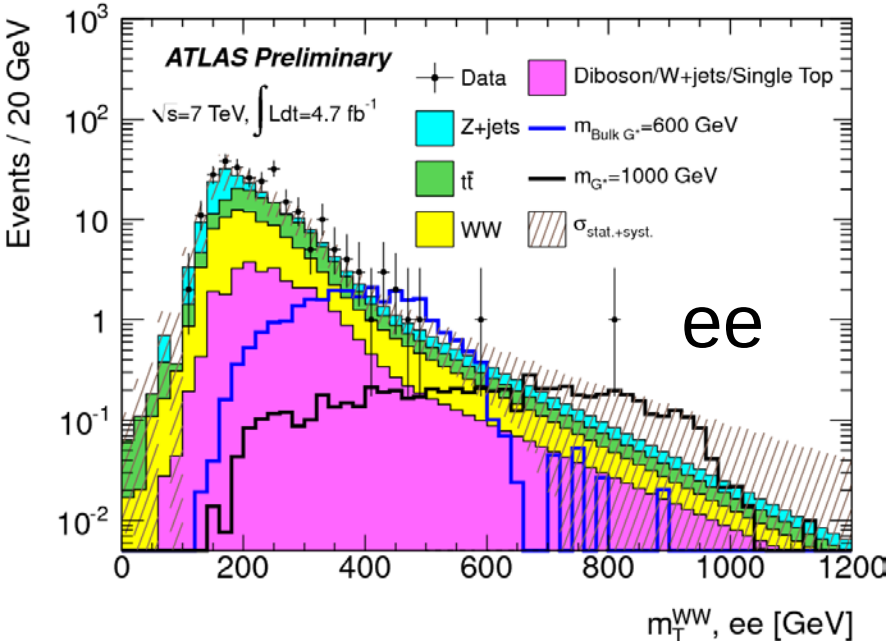
ATLAS-CONF-2012-088



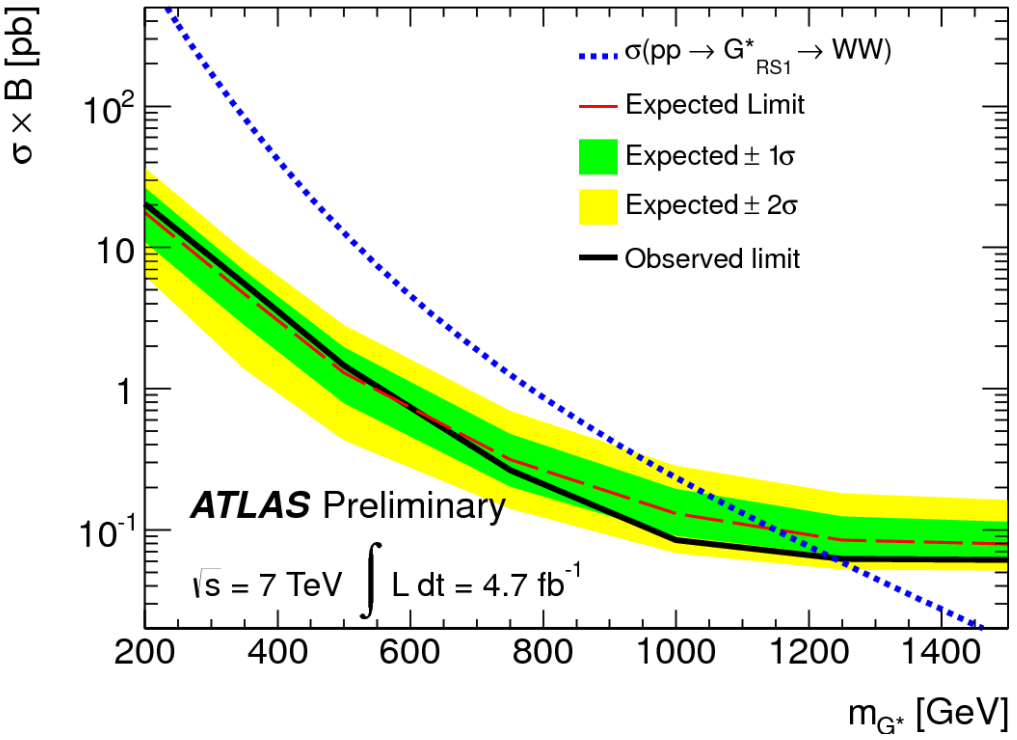
K-factor value	95 % CL Observed (Expected) Limit [TeV]			
	$k/\overline{M}_{Pl}$ value			
	0.01	0.03	0.05	0.1
1	0.87 (0.88)	1.31 (1.36)	1.49 (1.60)	1.91 (1.92)
1.75	1.00 (0.98)	1.37 (1.49)	1.63 (1.73)	2.06 (2.05)

WW Resonances – Graviton search





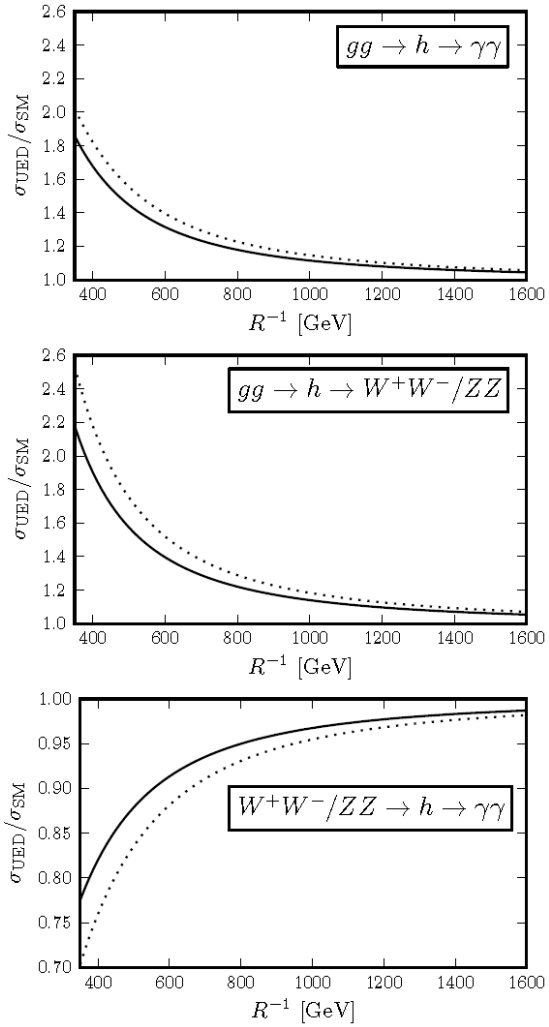
ATLAS-CONF-2012-068



No excess observed -> signal exclusion:
RS graviton mass > 1.23 TeV

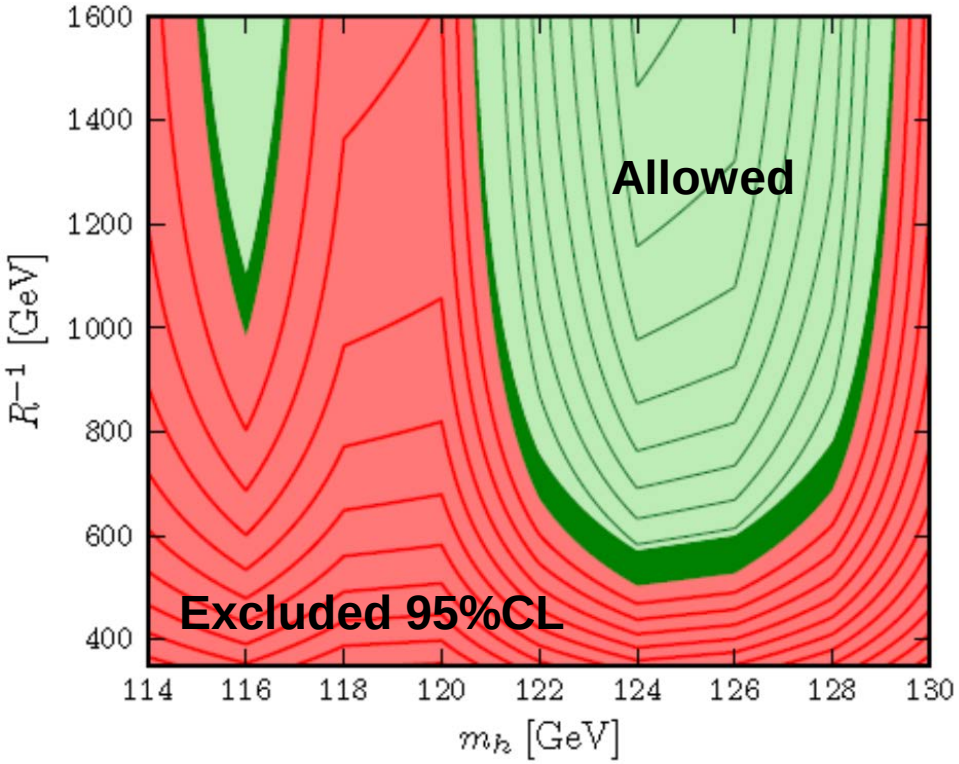
Higgs Constraints on Extra Dimensions

effect of KK-particles on Higgs production and decay



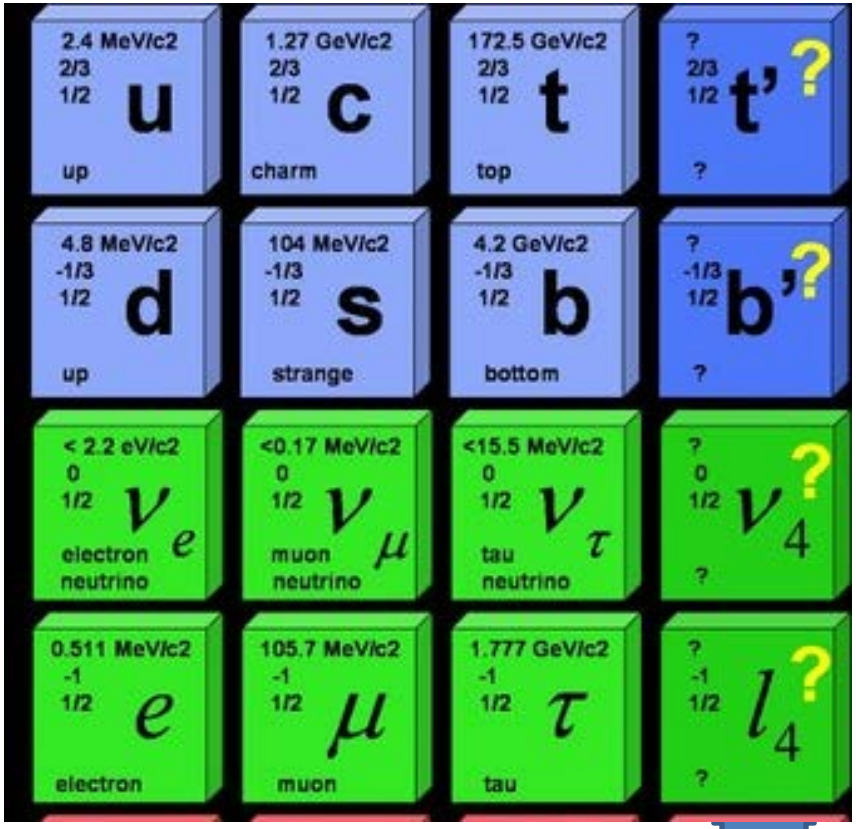
Example of constraints on a ED model after Higgs-like boson cross-section xBR measurement

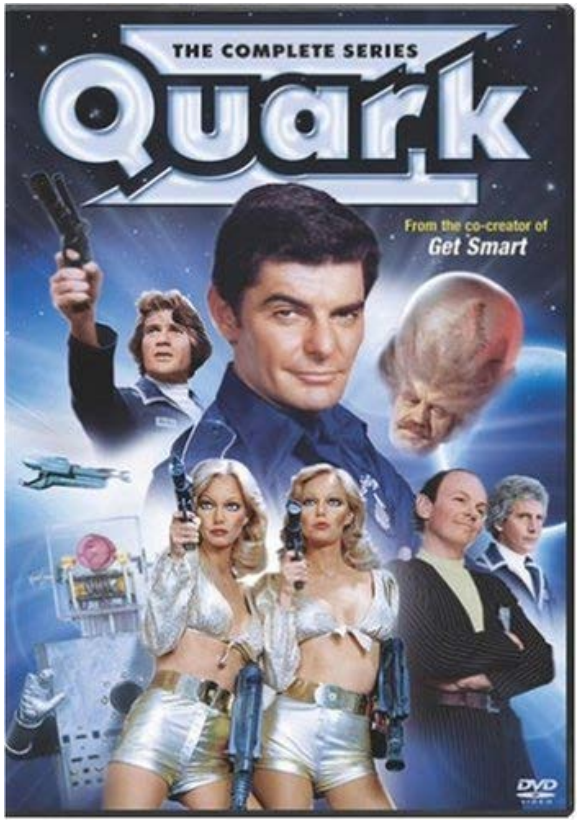
Minimal Universal Extra Dimensions (**mUED**) Model
G. Belanger et al, http://arxiv.org/abs/arXiv:1207.0798



Lower limit on mass scale:
$R^{-1} > 500$ GeV at 95% CL,

New Heavy Fermions

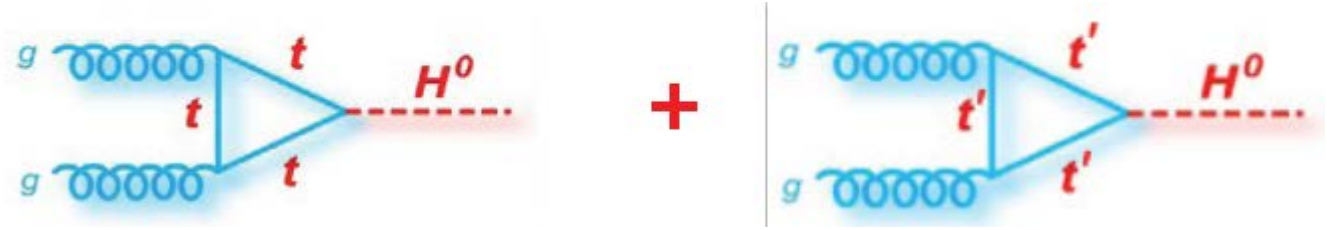




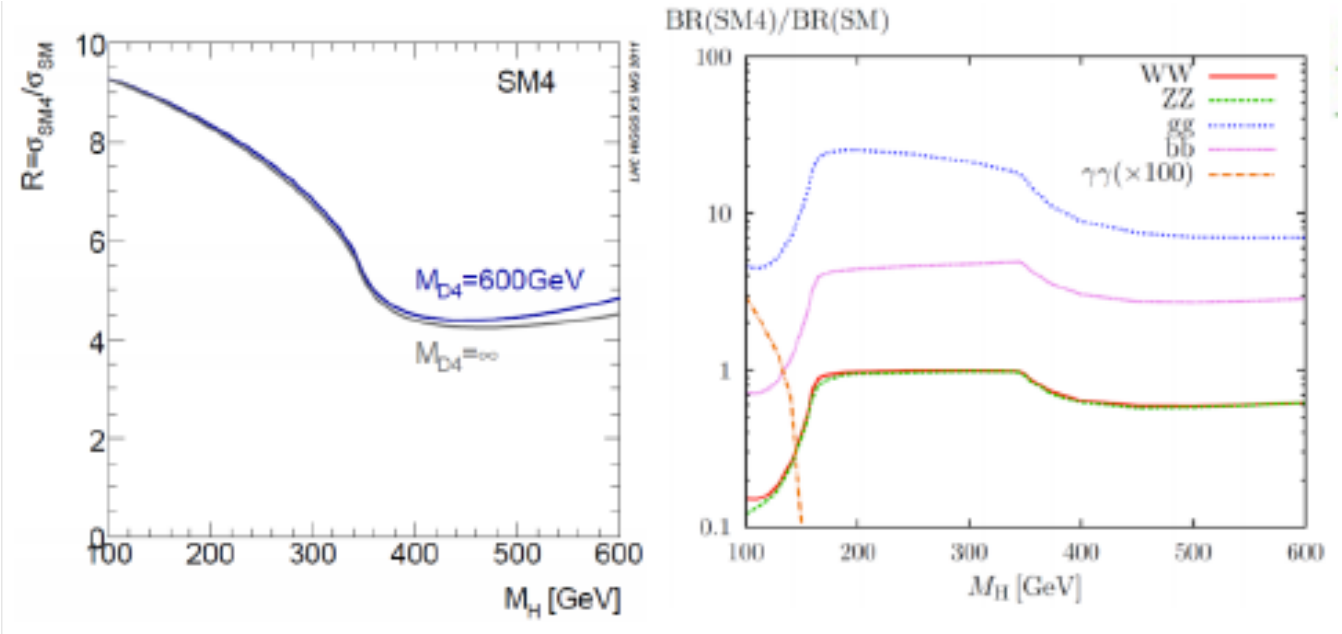
Also called
Q = T, B (Quark – already a TV series)
L = N, E (Lepton – coming soon…)

Higgs and Sequential 4th Generation

Higgs production cross-section greatly enhanced by 4th Generation



LHC Higgs XS working group



Observation of the SM-like Higgs boson would rule out simple sequential 4G
Additional new physics (eg heavy neutrinos or extended Higgs sector) is needed to reconcile the Higgs-like boson observation with sequential 4G.

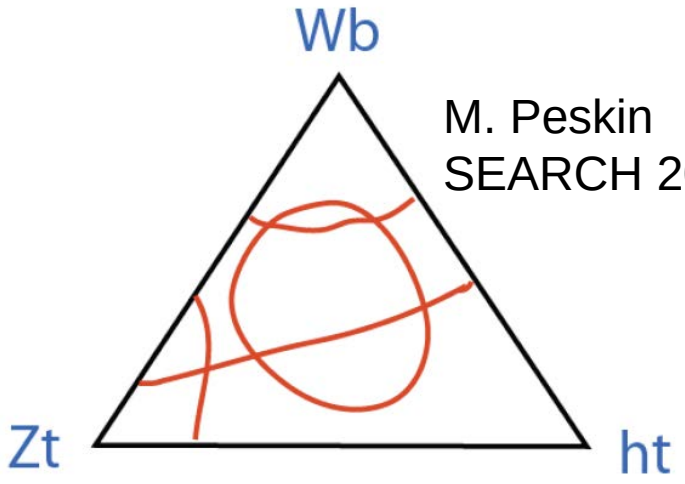
Beyond S4G: Vector-like quarks

Vector-like quarks predicted by many models: extra-dimensions, Composite Higgs, GUTs,…

Richer phenomenology than for minimal S4G:

J.A. Aguilar-Saavedra, JHEP 11, 030 (2009)

	Label	Charge	Decay mode
T singlet	T_S	+2/3	$T \to W^+ b$, Zt, ht
B singlet	B_S	-1/3	$B \to W^- t$, Zb, hb
(T,B) doublet	TB_d	(+2/3, -1/3)	$T \to W^+ b$, Zt, ht $B \to W^- t$, Zb, hb
(X,T) doublet	XT_d	(+5/3, +2/3)	$X \to W^+ t$ $T \to Zt$, ht
(B,Y) doublet	BY_d	(-1/3, -4/3)	$B \to Zb$, hb $Y \to W^- b$



M. Peskin
SEARCH 2012

Search for all possible FS
Note: h is a Higgs-like particle

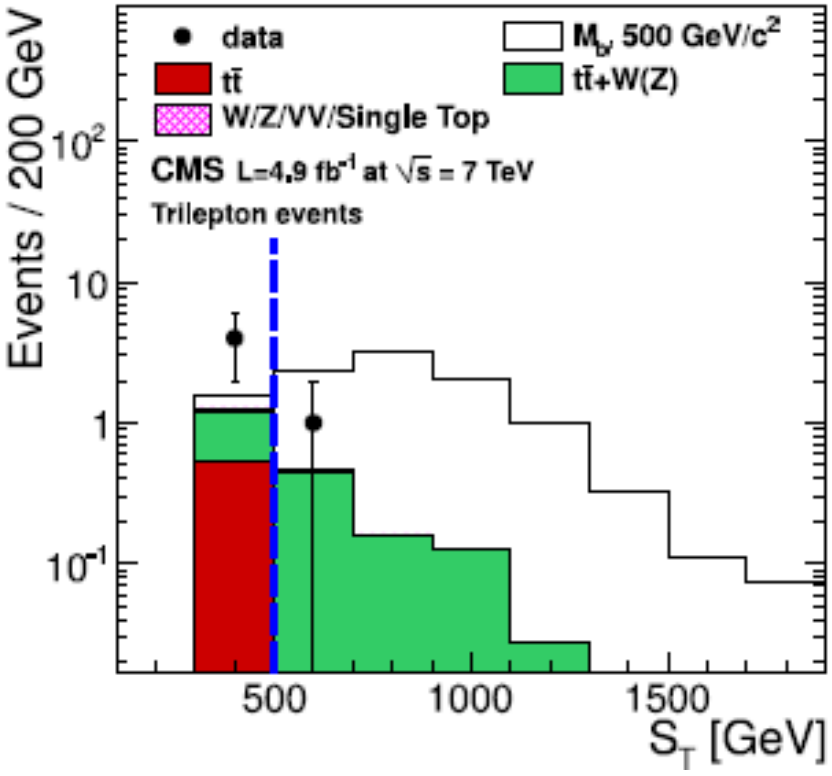
Pair produced, as in S4G, but the two quarks may each have a different decay
Singly produced, in association with an ordinary quark, eg pp-> Qq

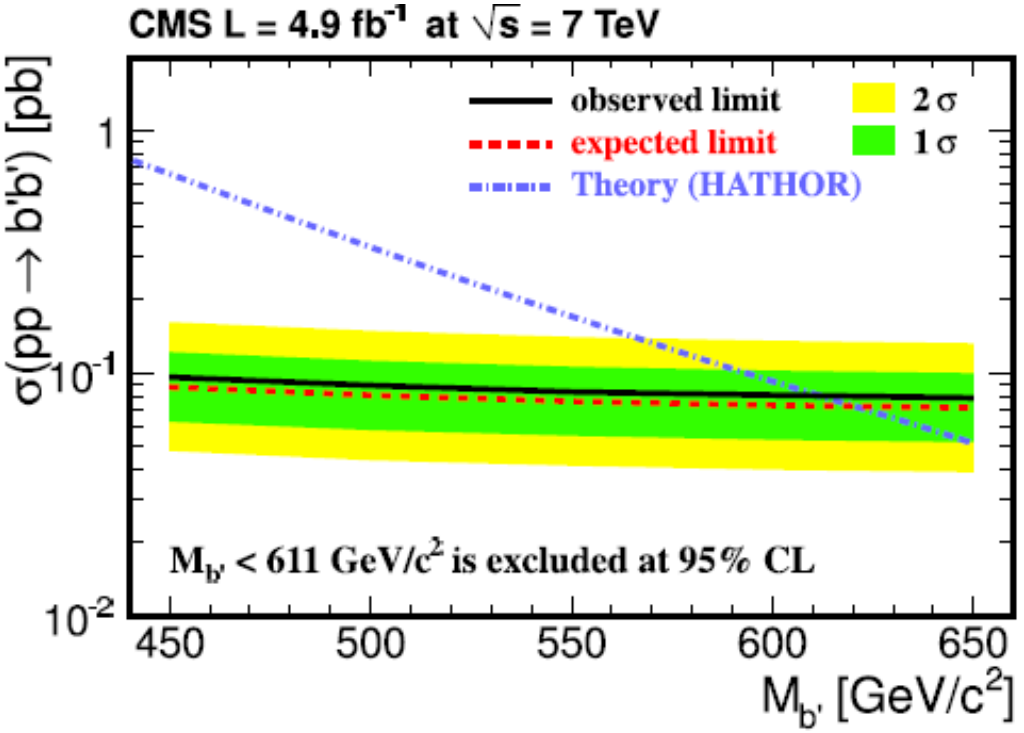
Heavy Bottom-like Quark b'→ t + W

- b'b' pair production
- BR(b'→tW) = 100%
- Decay : b'b'→tWtW→**bbW+W-W+W-**
- **Same sign dileptons or trileptons**

CMS: 7 TeV, 4.9 fb-1, EXO-11-036

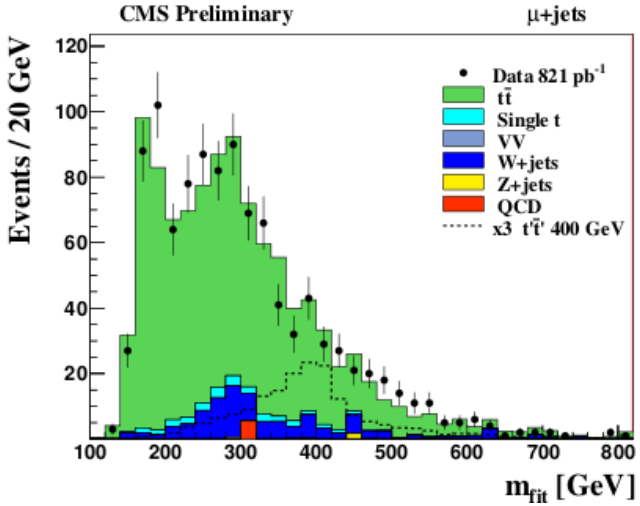
Cross-section upper limit to
b' mass lower limit $M_{b'} > 611$ GeV
for BR(b'→ tW)=100%





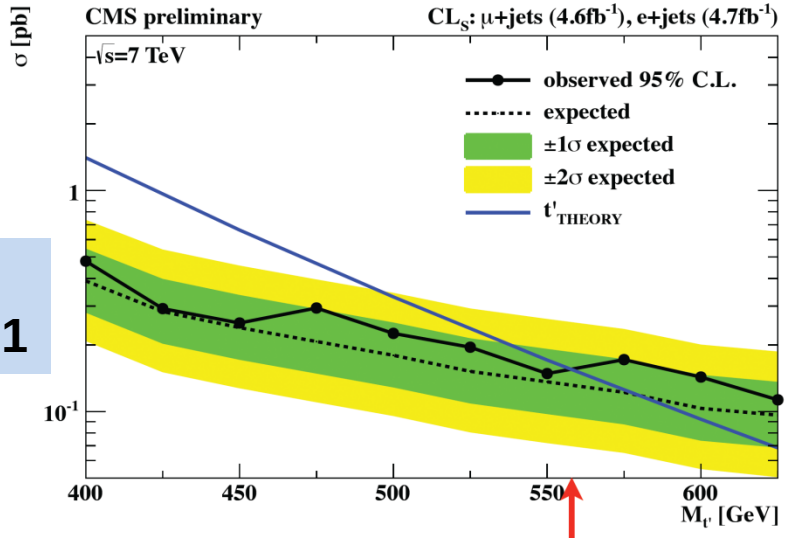
Heavy Top-Like Quark t'→b+W

t't'→bWbW→lepton+jets

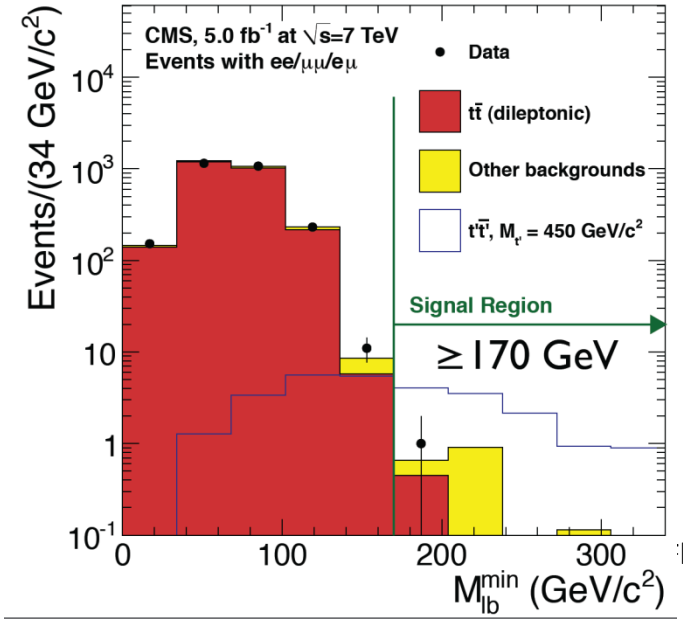


CMS:
7 TeV, 4.7 fb^{-1},
EXO-11-099

m(t') > 560 GeV
for BR(t'→ bW)=1

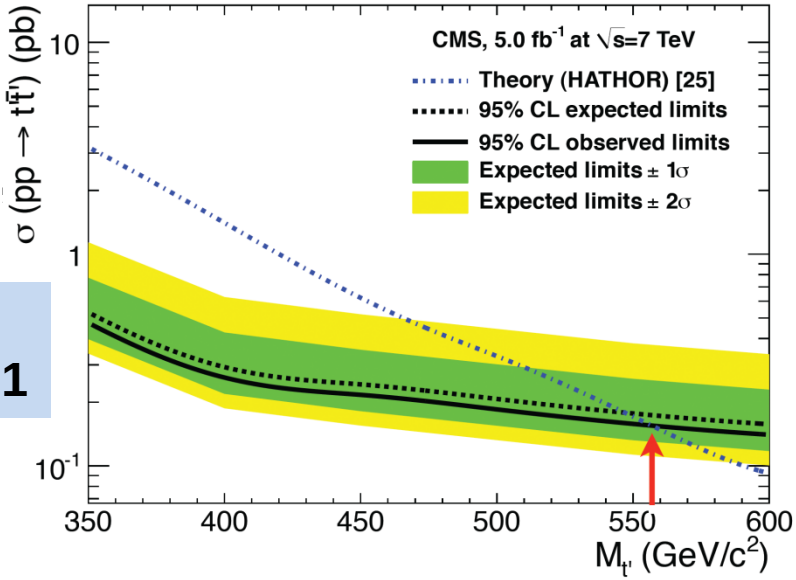


t't'→bWbW →dilepton+jets



CMS:
7 TeV, 4.7 fb^{-1}, ,
EXO-11-050,
arXiv:1203.5410

m(t') > 557 GeV
for BR(t'→ bW)=1



lorence,

Simultaneous t', b' search, with $m_{t'} = m_{b'}$

Search for multiple b and W FS

➔t'b→bWb

➔b't→tWbW→bWWbW

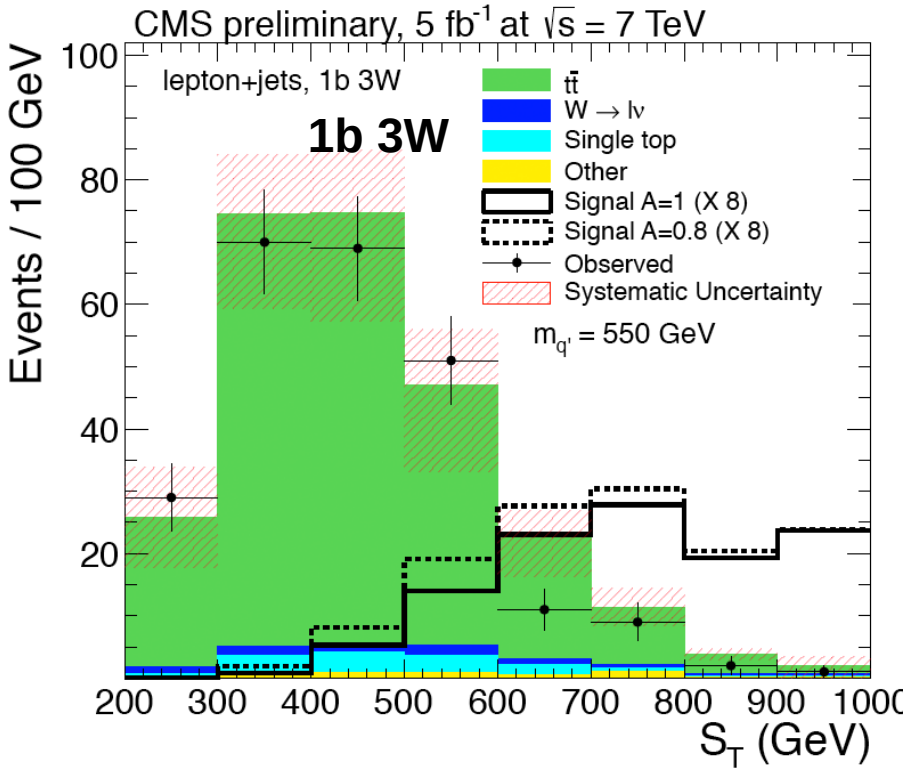
➔t't'→bWbW

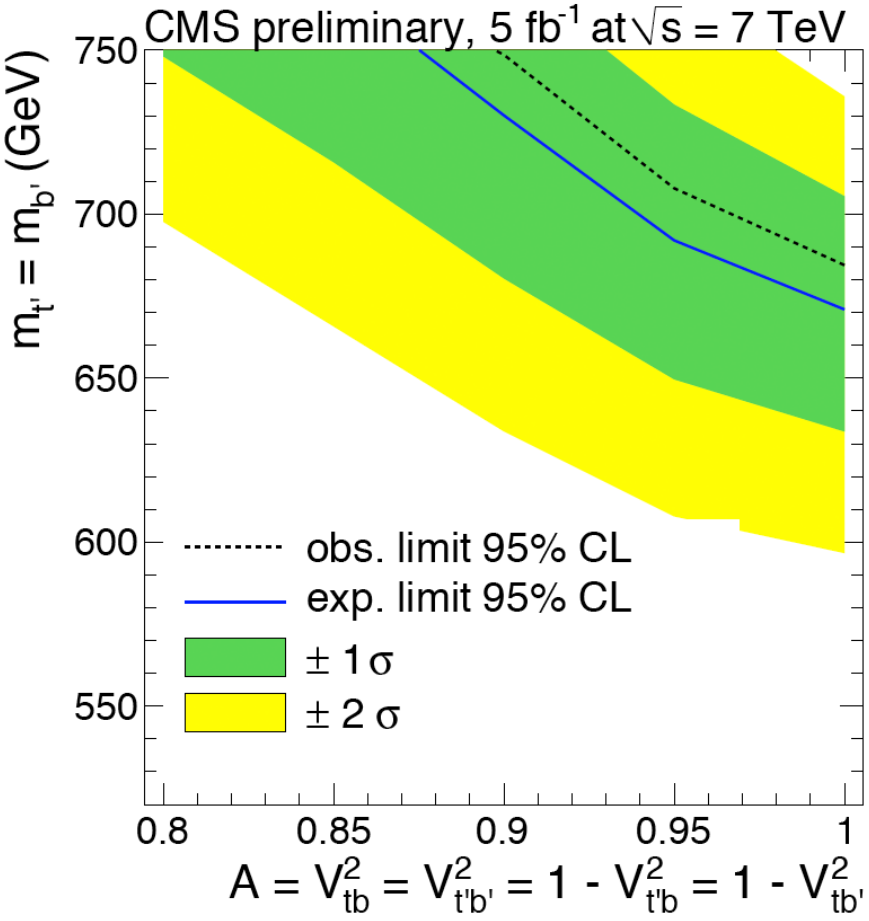
➔b'b'→tWtW→bWWbWW

CMS: 7 TeV, 5 fb–1, EXO-11-098

Interpretation in terms of $m_{t'} = m_{b'}$ and $A = |Vtb|^2 = |Vt'b'|^2$

m(t') = m(b') > 685 GeV for A=1



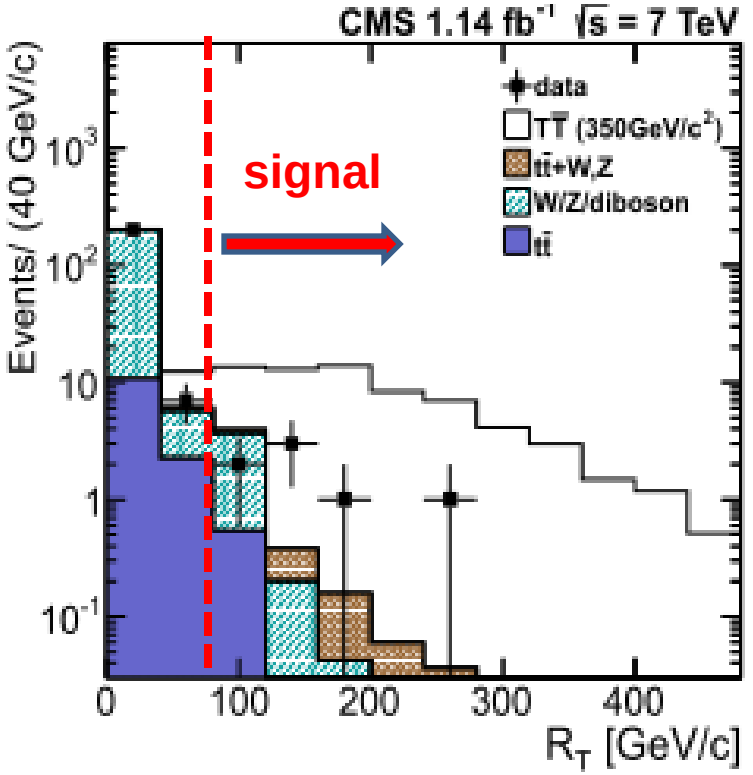


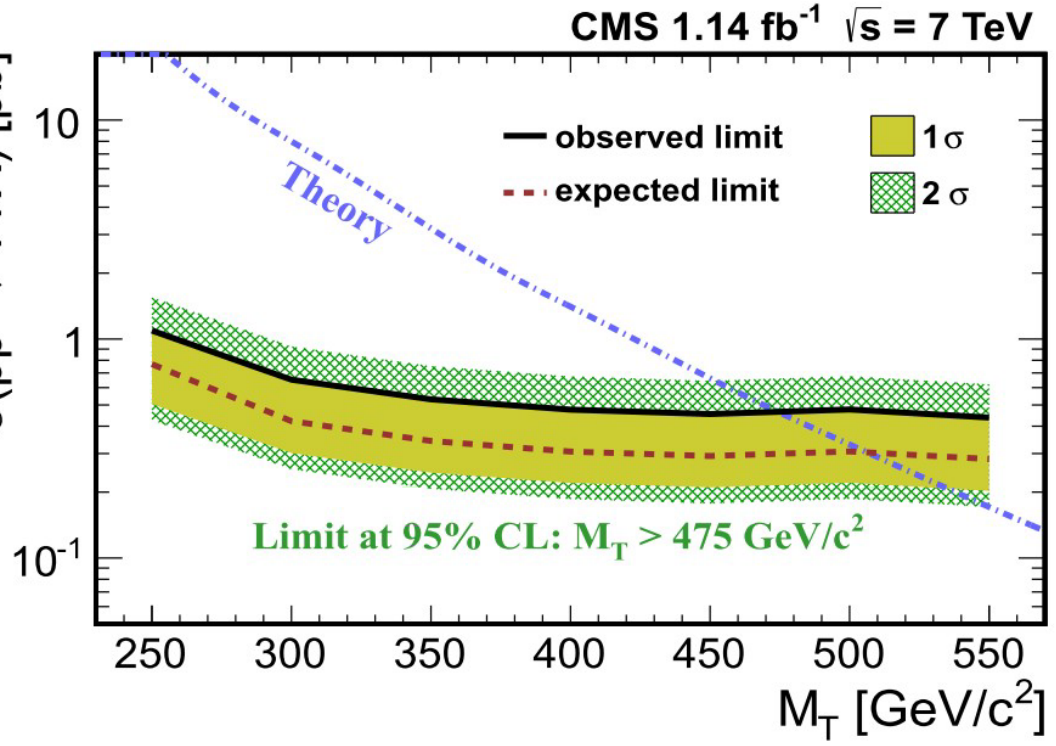
Vector-like Heavy T quark, T→ tZ

- **Vector-like charge 2/3 heavy top (T)**
- **FCNC tZ decay**
- Decay Chain: TT→**tZtZ→bbWWZZ**
- **Signature : 3 leptons+jets**

CMS: 7 TeV, 1.14 fb-1 arXiv:1109.4985v1

Cross-section upper limit translating into
T mass lower limit M_T>475 GeV
for BR(T→ tZ)=100%



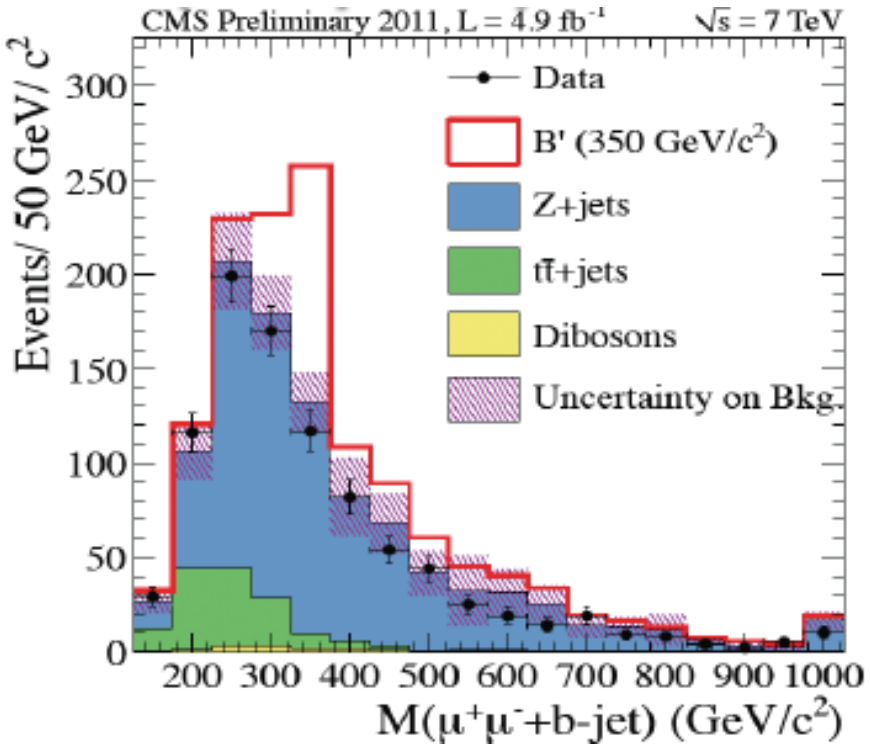


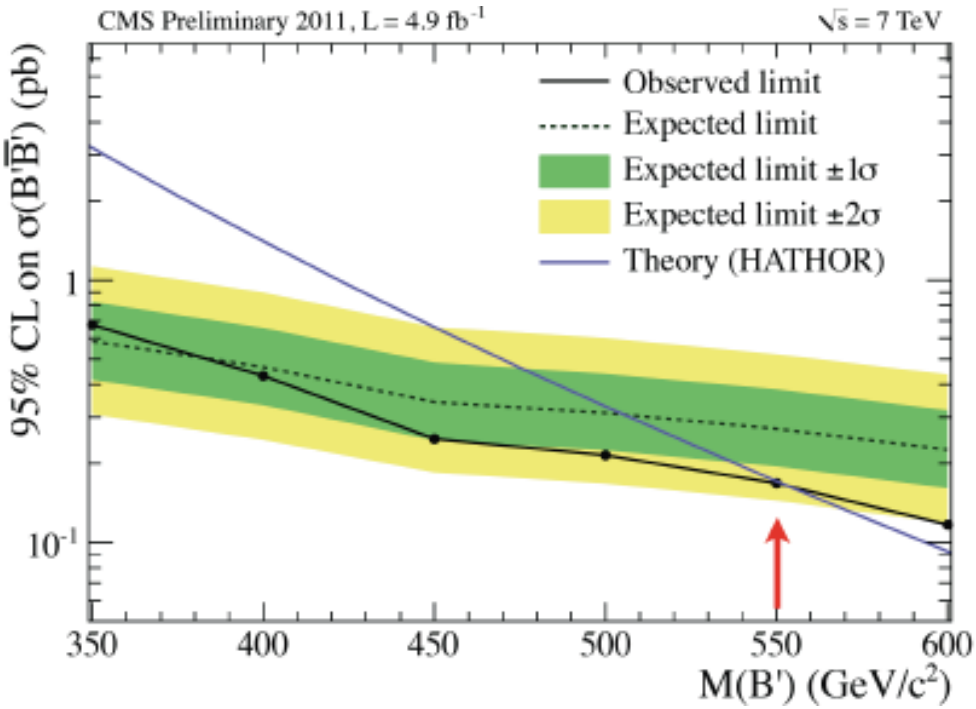
Vector-like Heavy B quark, B→ bZ

- **Vector-like charge 1/3 heavy b-quark (b)**
- **FCNC bZ decay**
- Decay Chain: BB→**bZbZ→bbZZ**
- **Signature : 2 leptons (Z) +1 jet + b-jet**

CMS: 7 TeV, 4.9 fb–1
EXO-11-066

Cross-section upper limit to
B mass lower limit M_T>550 GeV
for BR(T→ tZ)=100%

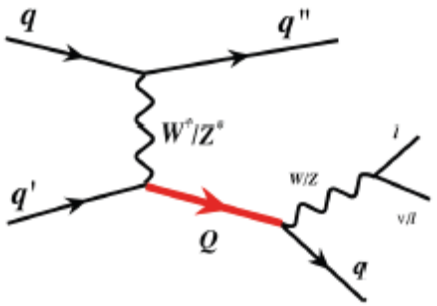




Vector-Like Quark in single production

Some models, e.g. Atre, et al., arXiv:0806.396 predict two VLQ doublets.

$\begin{pmatrix} U \\ D \end{pmatrix}, \begin{pmatrix} X \\ Y \end{pmatrix}$ $Q_U = \frac{2}{3}, Q_D = -\frac{1}{3}, Q_X = -\frac{5}{3}$ and $Q_Y = \frac{4}{3}$



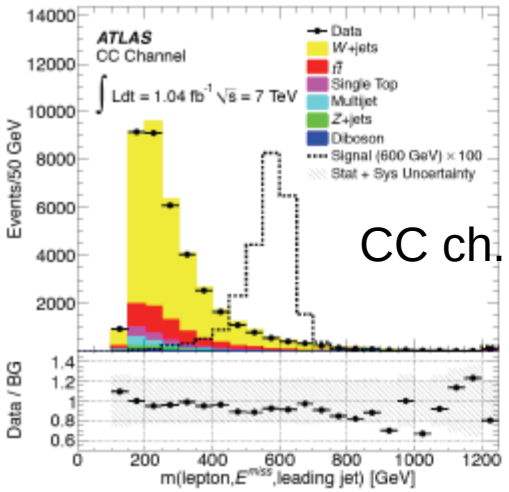
No excess in either channel

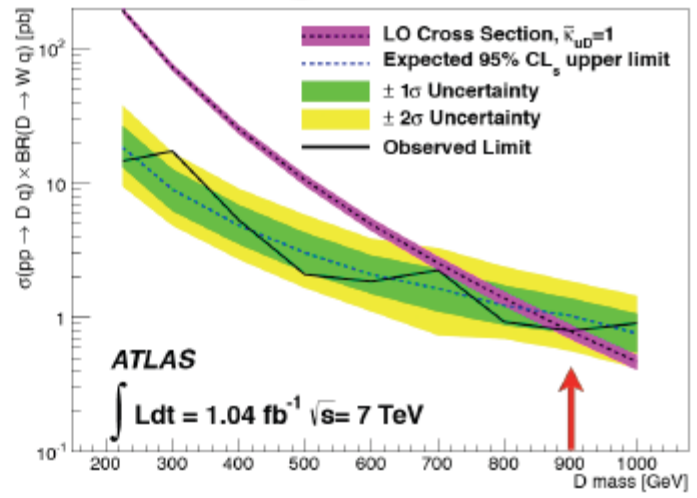
compute limits with assumption that uU and uD couplings = 1

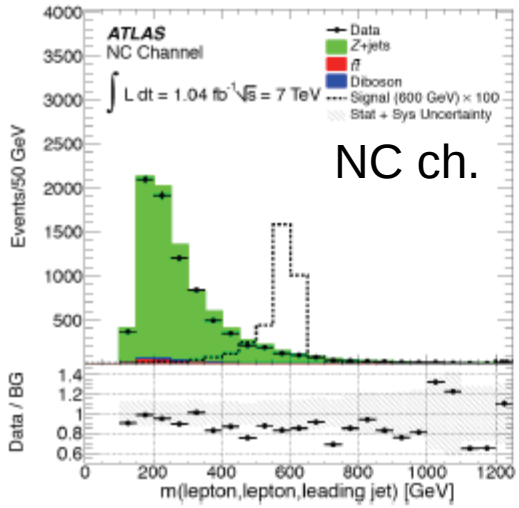
CC channel: m_D > 900 GeV

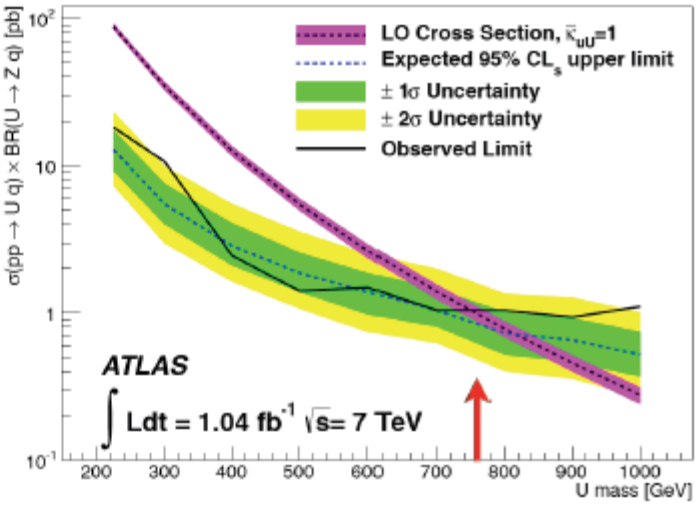
NC channel: m_U >760 GeV

ATLAS: 7TeV, 1.04 fb–1, arXiv:1112.5755



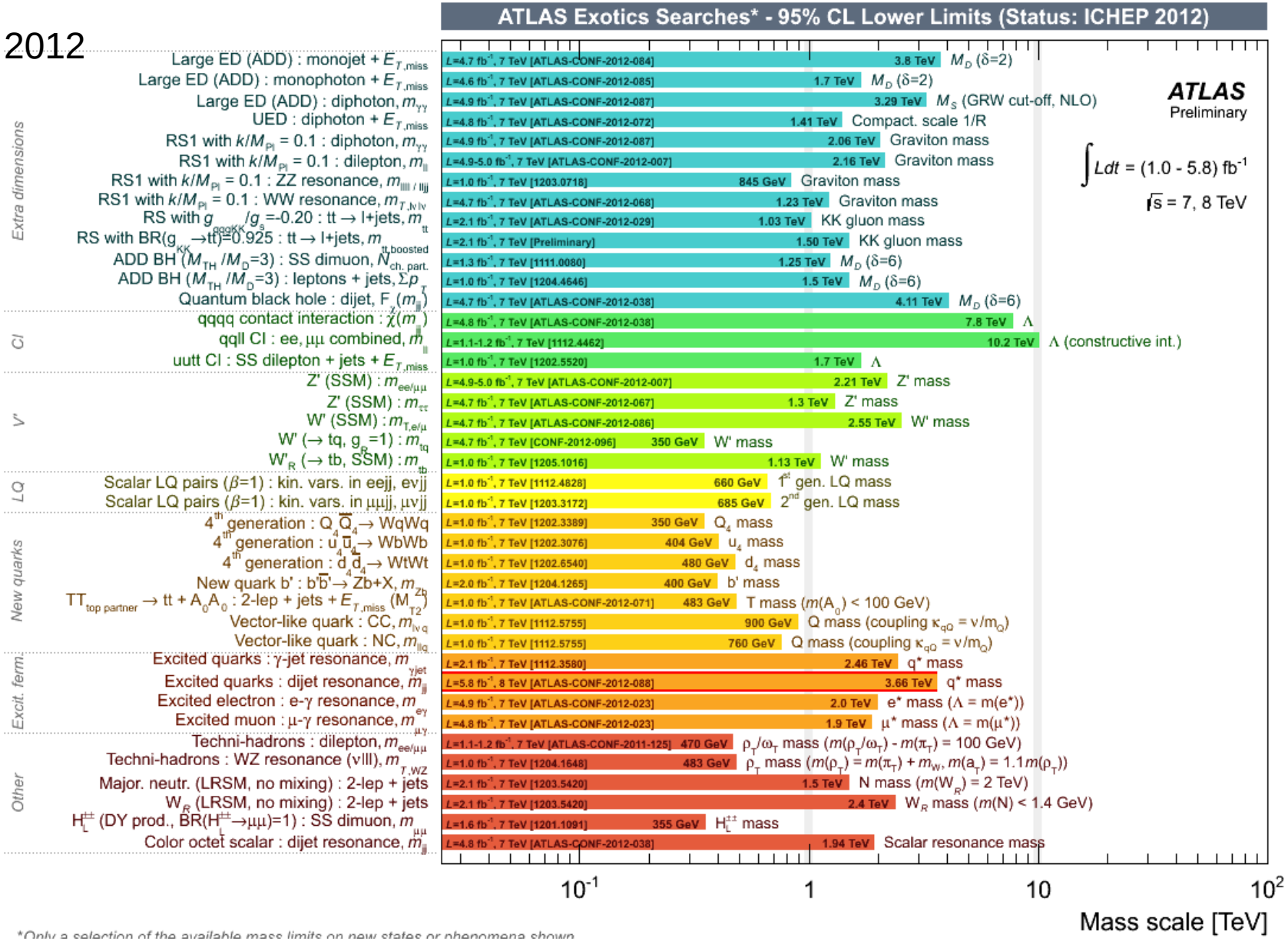






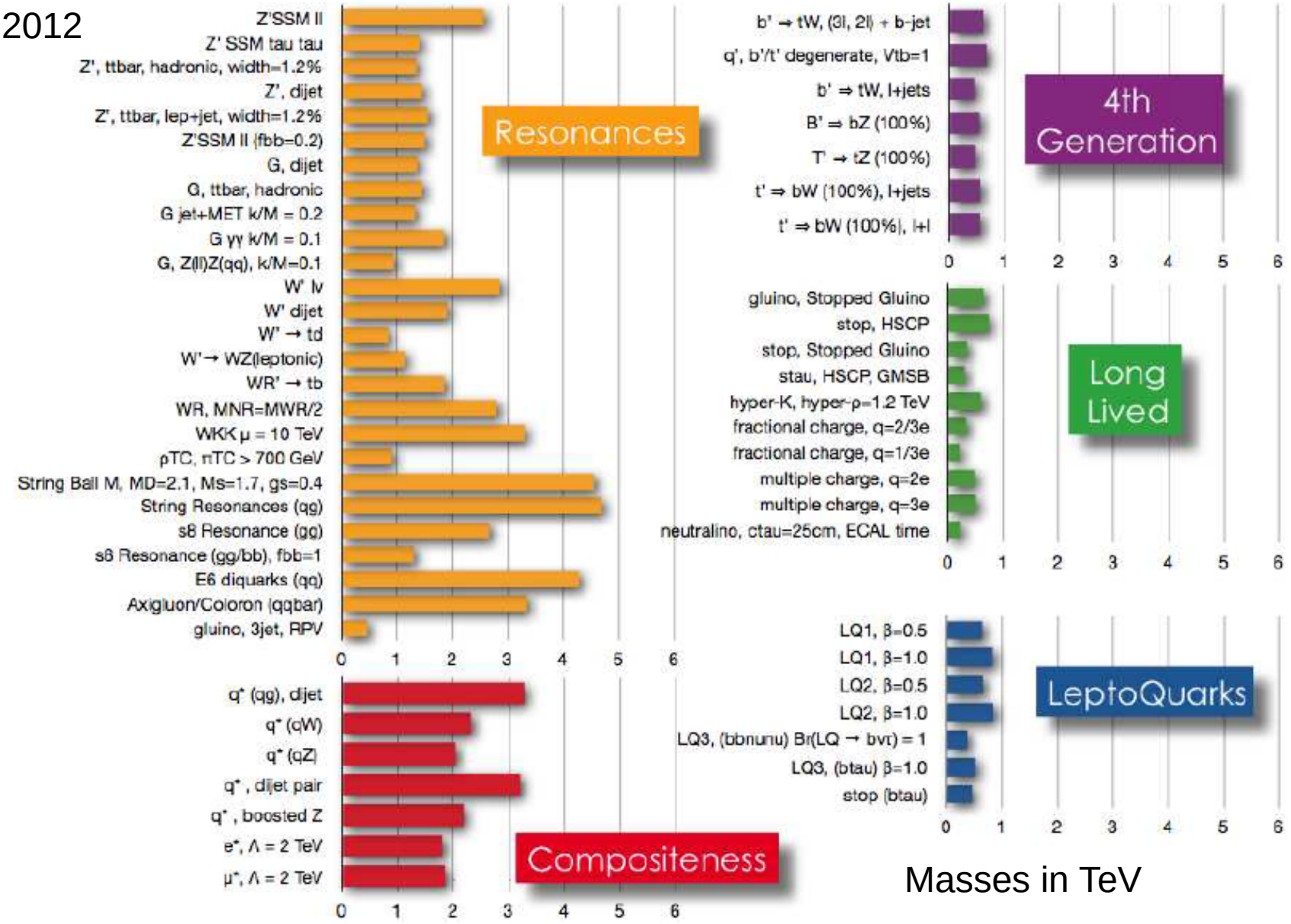
ATLAS mass limits from BSM searches

ICHEP 2012



CMS mass limits from BSM searches

ICHEP 2012



Masses in TeV

Summary

A **Higgs-like boson exists** -> set **important constraints on many BSM scenarios**

- Precise measurements of the new boson's properties may reveal BSM physics
- Search for **additional Higgs-like bosons** may also reveal BSM physics
  (not discussed here but see M. Krakwikz and P. Osland talks)

From the searches for other particles predicted by most popular BSM scenarios

- **Minimal SUSY models (cMSSM, mSUGRA)** constrained **~>1TeV scale**
  (Signals from heavier SUSY could still appear especially at the 14 TeV LHC)
  New SUSY models being considered: **split SUSY, compressed SUSY**, ...
  Many SUSY signals expected to be within discovery reach
  light 3rd generation squarks, light gauginos -> DM candidates, …
- New resonances (Graviton, W', Z', …) no signals yet -> constrained ~>1 – 4 TeV
- Minimal **sequential 4th generation disfavoured** if Higgs proven to be SM-like
- **New heavy vector like quarks** from eg ED; GUT; composite Higgs models -> new signals expected, to be searched for…
- Many others BSM signals (…) expected

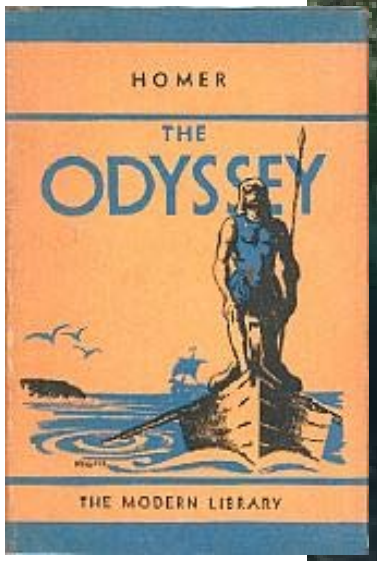
Many searches ongoing (much more than I could cover here), see public results

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/
https://twiki.cern.ch/twiki/bin/view/CMSPublic/

The journey continues…

Epilogue… for now…

Suggested reading:

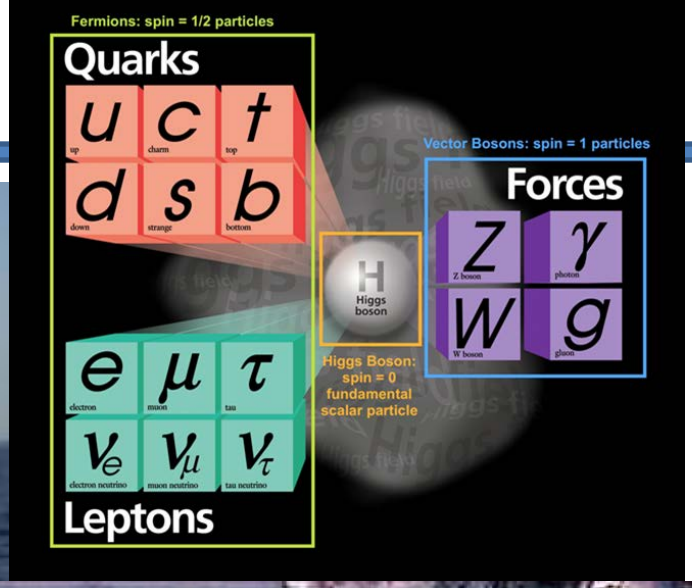


a Higgs-like boson appeared. «We got it!» they said.

They were now sailing to unknown lands…

...to be continued...

Terra incognita



New particles...