Search for new resonances with mass between 500 GeV and 1 TeV with final states other than two photons

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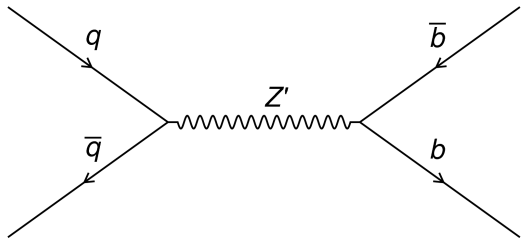
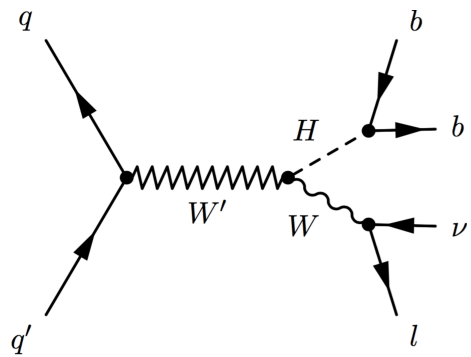
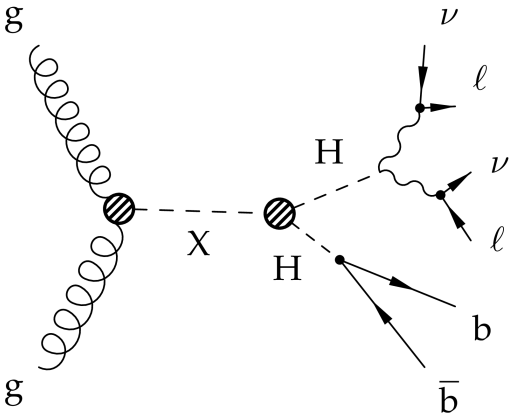
Introduction

- Higgs boson discovered by ATLAS and CMS in 2012
- Still open questions : hierarchy problem, gravity, dark matter, …
- Several BSM Models (with extension of the Higgs sector or by additional gauge field) predicts new resonances : Randall-Sundrum (RS) gravitation model , Composite Higgs models, …
- ATLAS and CMS showed a modest excess in the diphoton channel around 750 GeV with 2015 data. What are the observations in the other channels?

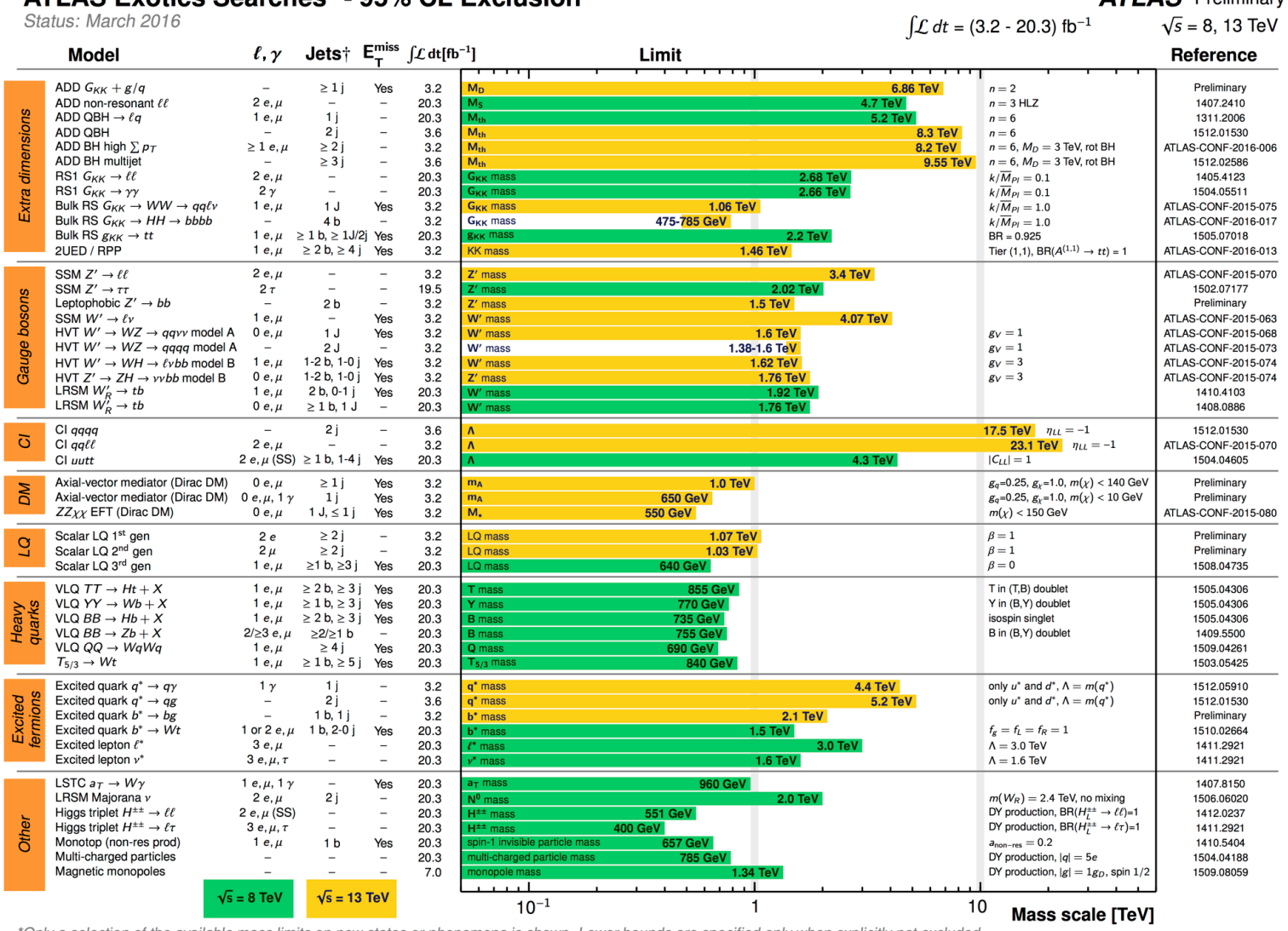






ATLAS Exotic Searches

Ref [2]

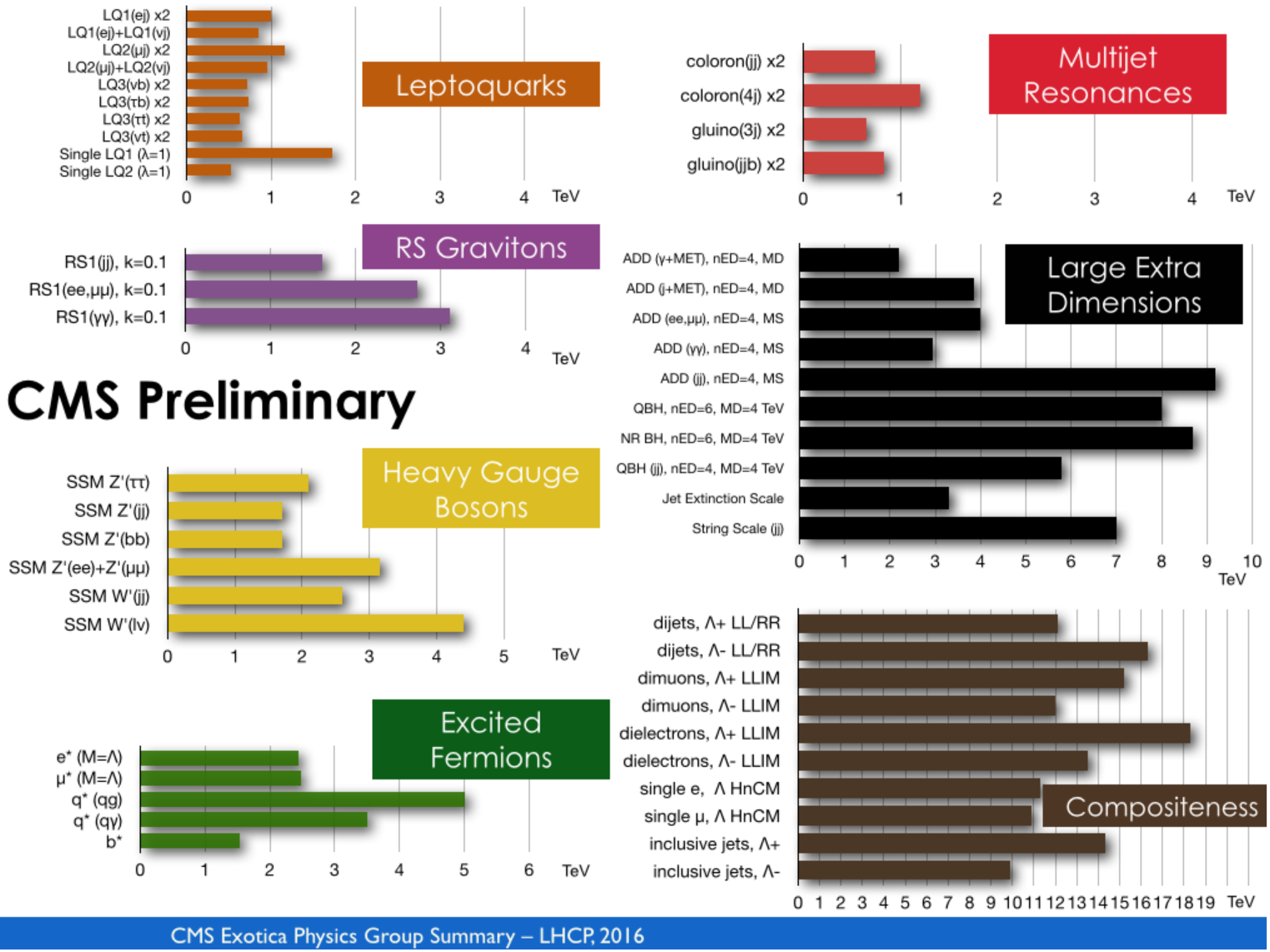


*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

†Small-radius (large-radius) jets are denoted by the letter j (J).

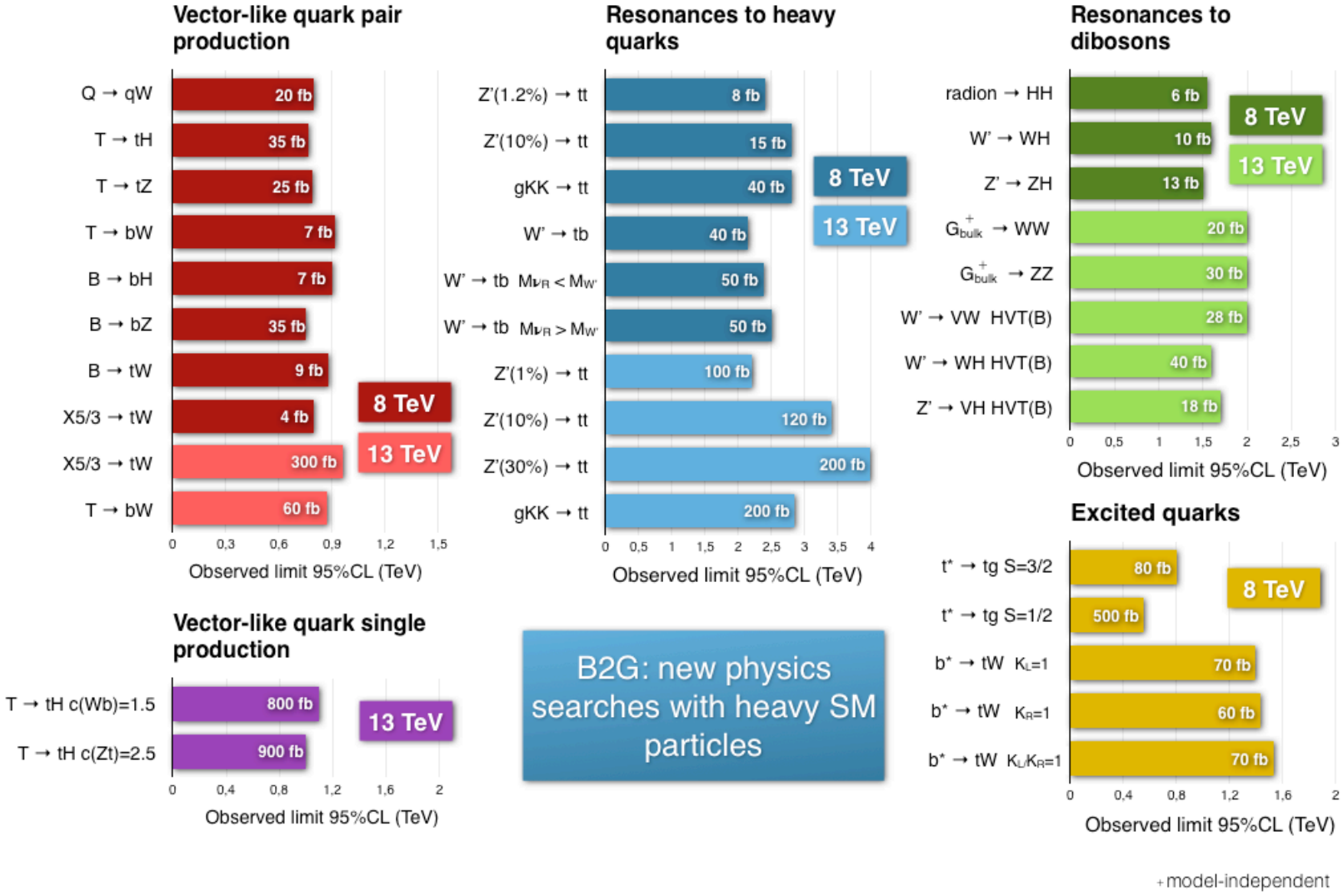
CMS Exotics Searches

Ref [4]



CMS B2G Searches

Ref [5]



Channels

- Zγ resonance
- Di-lepton
  - Z' resonance (Z' → ll)
  - W' resonance (W' → lν)
  - Z' resonance (Z' → ττ)
- Di-boson
  - VV resonance
  - VH resonance
- Di-quark
  - ttbar resonance
  - Di-jets resonance
  - Di-bjets resonance

Channels

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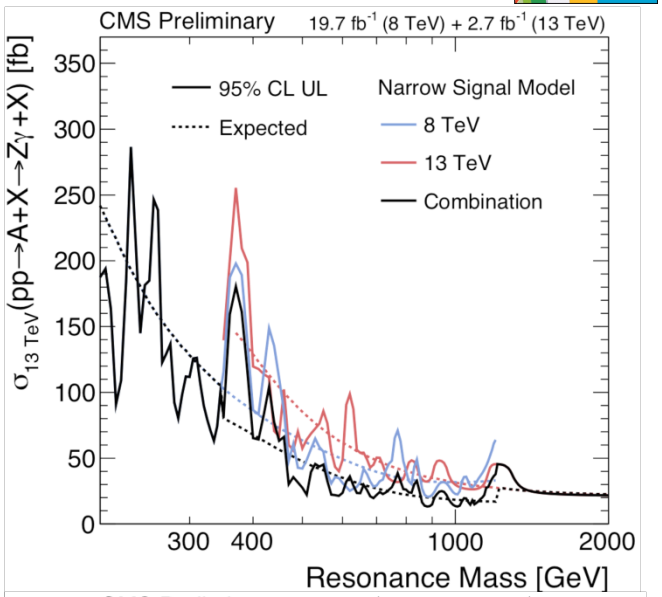
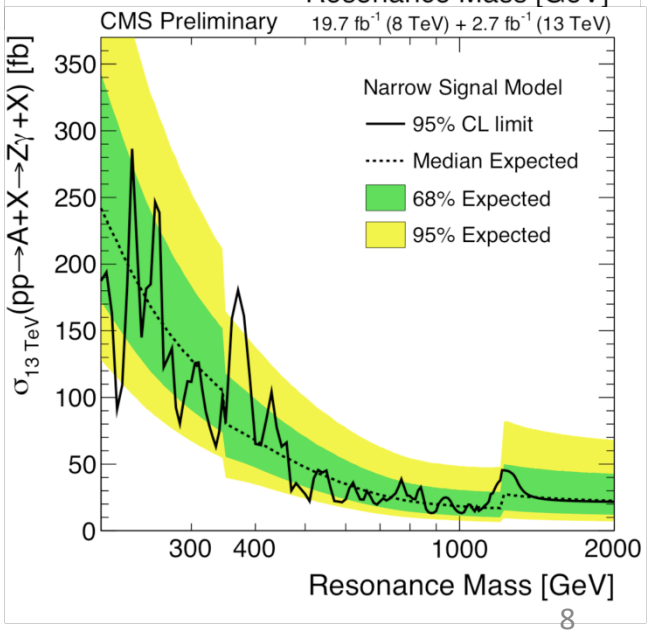
Zγ resonance

CMS-PAS-EXO-16-021

- Assumptions :
  - Higgs-like spin-0 particle
  - Gluon-gluon production
- Run 1 + Run 2
  - Run 1 : $200 < m_x < 1200$ GeV
  - Run 2 : $350 < m_x < 2000$ GeV
- Search channels : leptonic, Z→ll (ll = ee or μμ)
- Dominant backgrounds : SM continuum Zγ (main), Z+jet
- Systematics uncertainties on signal :

Source	8 TeV	13 TeV
Luminosity	2.6%	2.7%
PDF	1 %	1%
Lepton Efficiency	5%	5%
Trigger Efficiency	2–3%	2–3%
Photon Efficiency	1–2.6%	5%
Mass Scale/Resolution	1–10%	1–5%

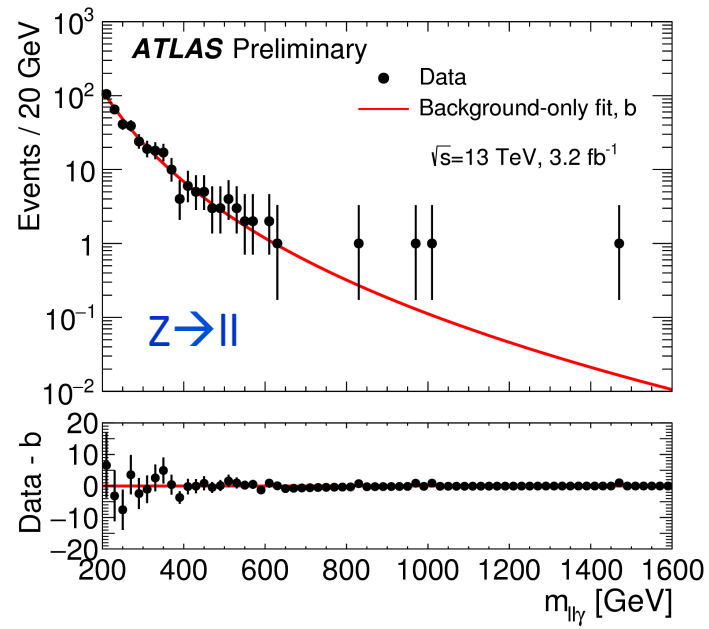


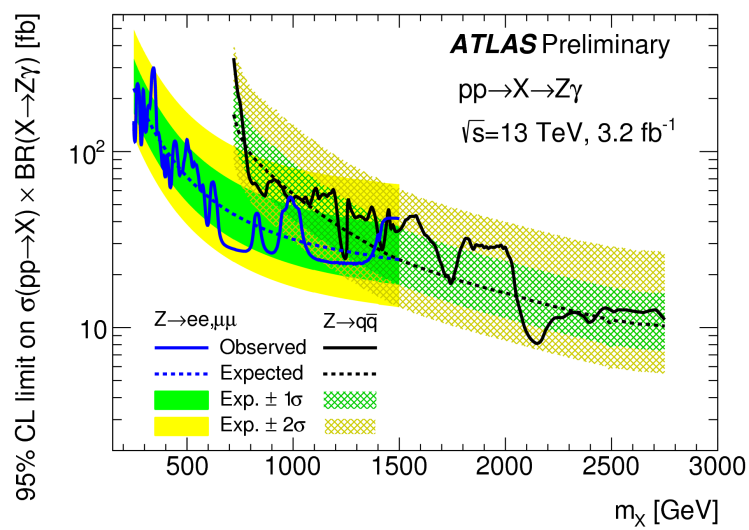


Zγ resonance

- Assumptions :
  - Higgs-like spin-0 particle
  - Gluon-gluon production
- Search channels :
  - Leptonic channel : Z → ll (ll = ee or μμ)
  - hadronic channel : Z → qq (qq in large-R jet)
- Dominant Backgrounds :
  - Z → ll channel : SM continuum Zγ
  - Z → qq channel : non-resonant γ+jet
- Dominant systematics :
  - Z → ll channel : γ and e resolution, spurious signal, and luminosity
  - Z → qq channel : jet mass resolution, jet and γ energy resolution

ATLAS-CONF-2016-010





Channels

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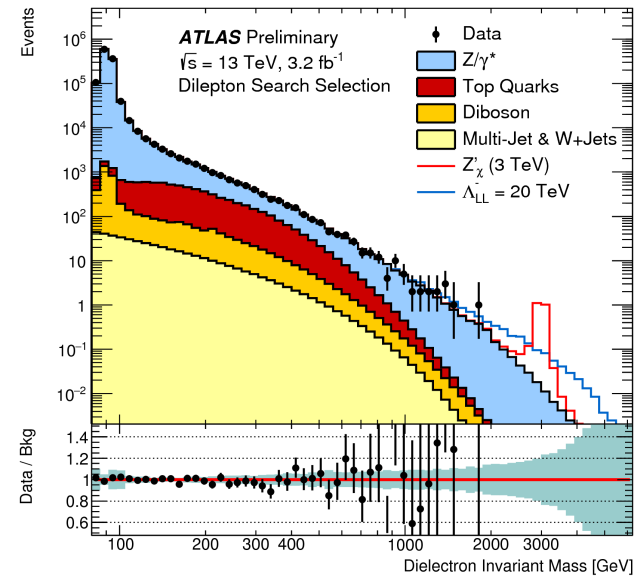
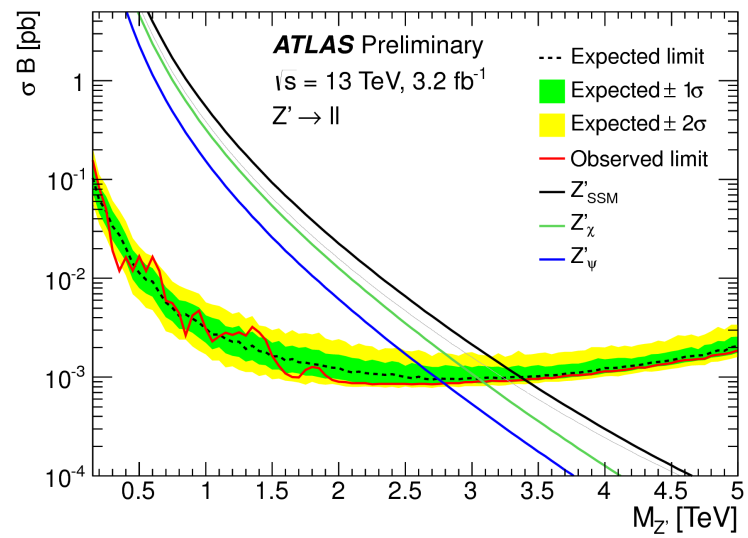
  - Z' resonance (Z' → ll)
  - W' resonance (W' → lν)
  - Z' resonance (Z' → ττ)
- Di-boson
  - VV resonance
  - VH resonance
- Di-quark
  - ttbar resonance
  - Di-jets resonance
  - Di-bjets resonance

Z' resonance (Z' → ll)

- Benchmark models:
  - E_6 (Z'_χ, Z'_ψ, …)
  - Sequential Standard Model (SSM)
- Search channels :
  - e-channel : Z' → ee
  - μ-channel : Z' → μμ
- Selection :
  - Electron : E_T > 30 GeV, |η| < 2.47
  - Muon : pT > 30 GeV, |η| < 2.5
- Dominant background : Z/γ*
- Dominant systematics :
  - PDF eigen-vector variation of Z/γ*
  - In Z' → μμ channel the muon energy resolution uncertainty becomes large at high mass

ATLAS-CONF-2015-070

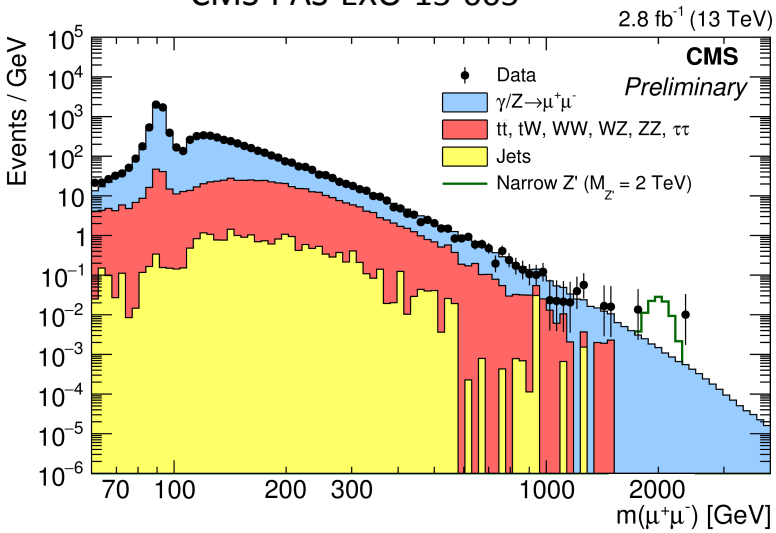


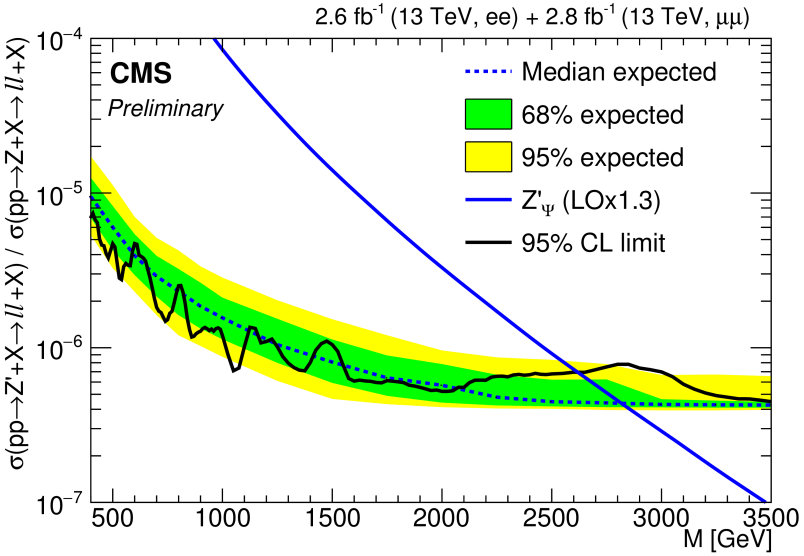


Z' resonance (Z' → ll)

- Benchmark models :
  - E_6 (Z'_ψ)
  - Sequential Standard Model (SSM)
- Search channels :
  - e-channel : Z' → ee
  - μ-channel : Z' → μμ
- Selection :
  - Electron : $E_T > 35$ GeV, $|\eta| < 2.5$
  - Muon : $p_T > 53$ GeV, $|\eta| < 2.4$
- Dominant background : Z/γ*
- Dominant systematics :
  - Signal : lepton efficiencies
  - Z/γ* : NNLO and PDF effects

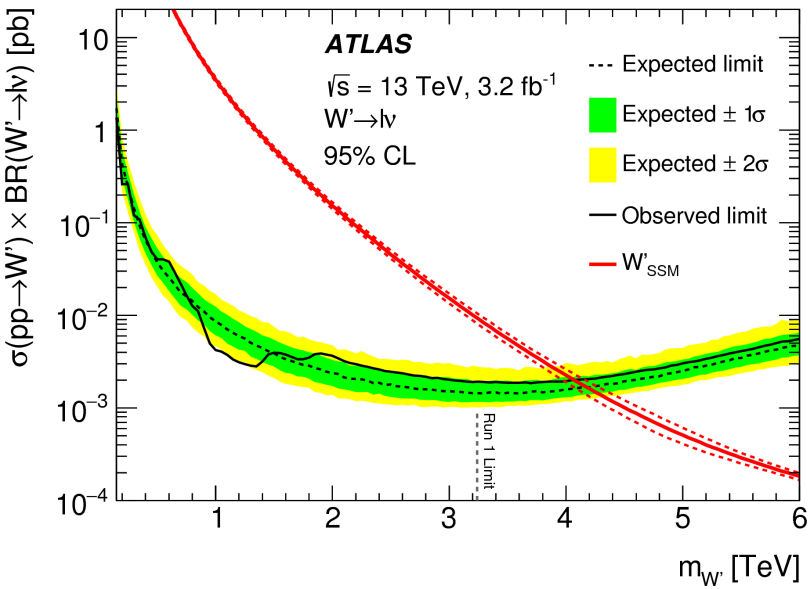
CMS-PAS-EXO-15-005



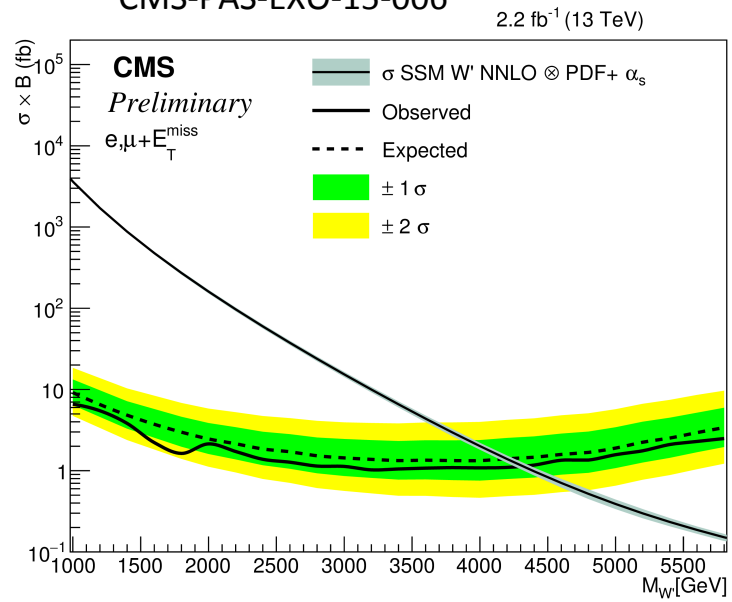


W' resonance (W' → lν)

arXiv:1606.03977

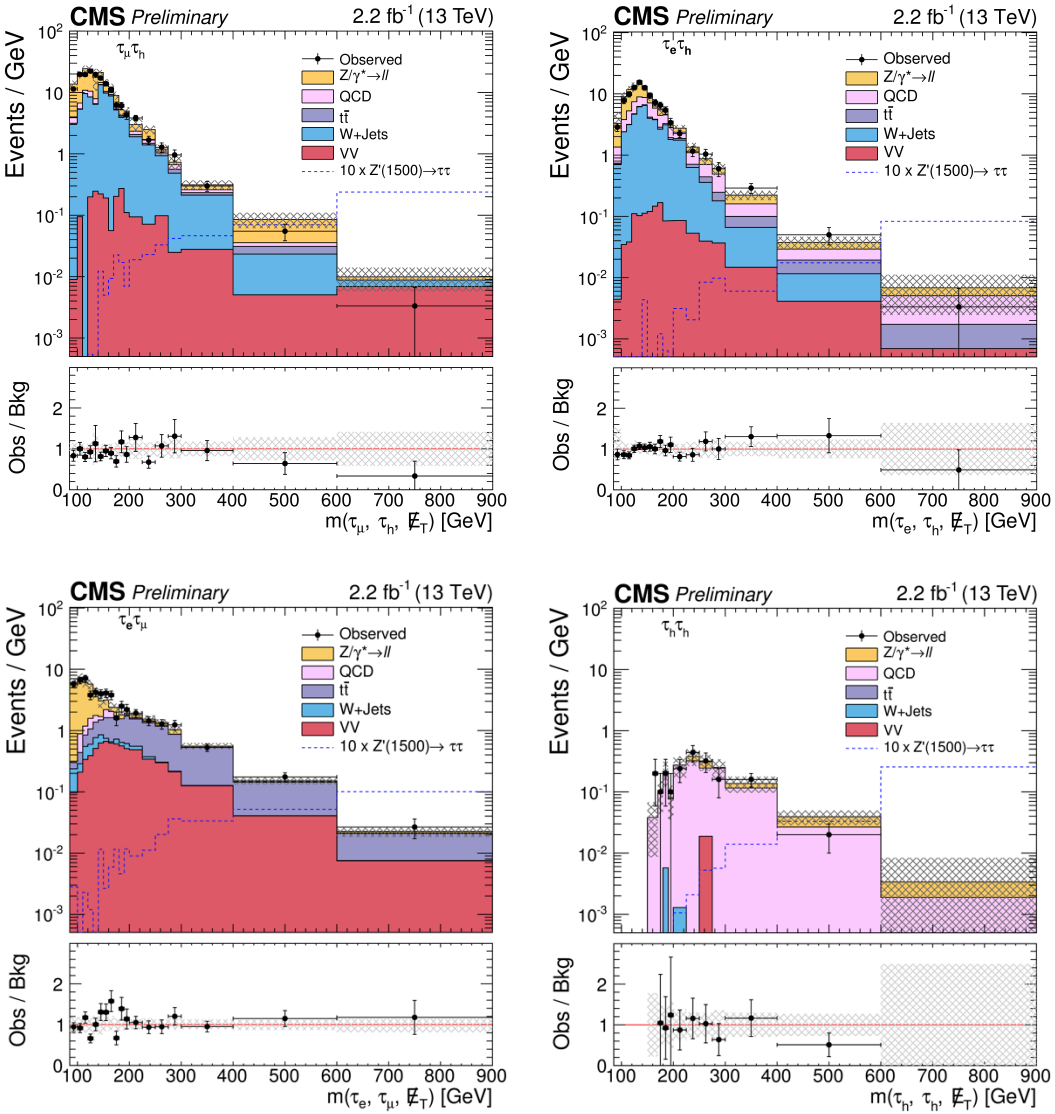


CMS-PAS-EXO-15-006



- Benchmark models : Sequential Standard Model (SSM)
- Assumptions :
  - Decay of SSM W' to SM bosons not allowed
  - Coupling(SSM W', SM fermions) = coupling(SM W, SM fermions)
  - Interference between SSM W' and SM W is negligible
- Search channels : W' → eν & W' → μν
- Background : W (main), top, Z/γ*, diboson, multijet

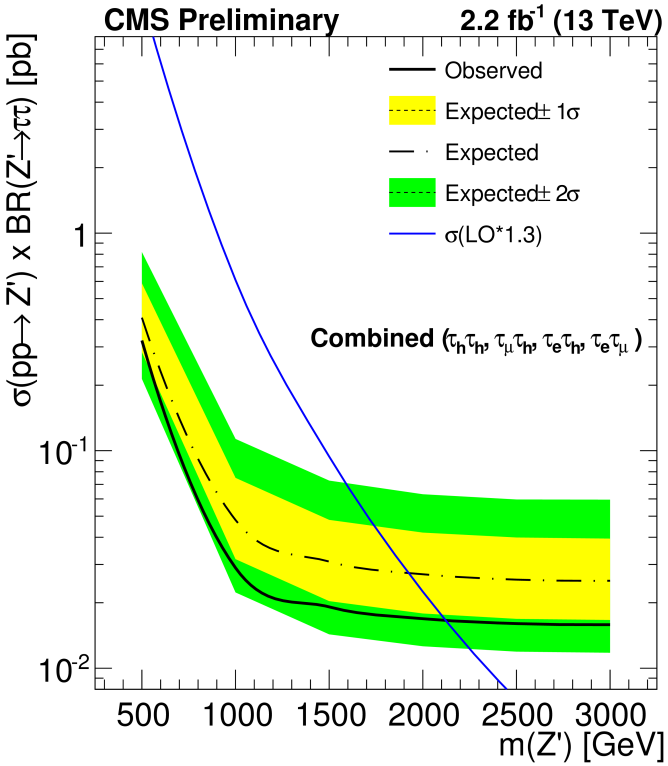
Z' resonance (Z' → ττ)



CMS-PAS-EXO-16-008

- Benchmark models : SSM
- Assumptions :

  Coupling (SSM Z', SM fermions) = coupling (SM Z, SM fermions)



Channels

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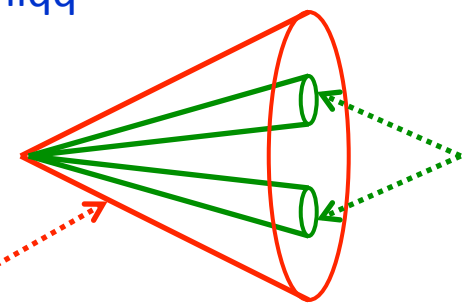
- Di-lepton
  - Z' resonance (Z' → ll)
  - W' resonance (W' → lν)
  - Z' resonance (Z' → ττ)
- Di-boson
  - VV resonance
  - VH resonance
- Di-quark
  - ttbar resonance
  - Di-jets resonance
  - Di-bjets resonance

VV resonance

arXiv:1606.04833

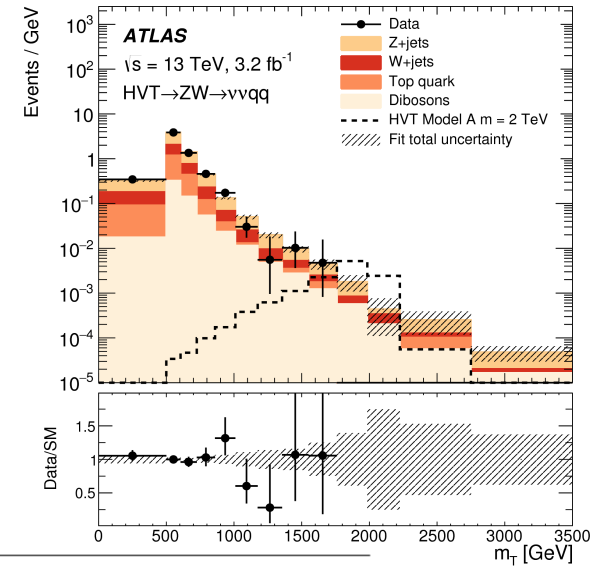
- Search for heavy resonances decaying to WW, WZ, ZZ
- Decay modes used in the search :
  qqqq, vvqq, lvqq, llqq
  (l = e or μ)

Hadronic decay of V



Sub-jets

Large-R jet



Selection level	Channel			
	$qqqq$	$\nu\nu qq$	$\ell\nu qq$	$\ell\ell qq$
Trigger	Large-R jet, $p_T > 360$ GeV	E_T^{miss}	E_T^{miss} ($\mu\nu qq$) or single electron ($e\nu qq$)	single electron or muon
Large-R jet	≥ 2, $N_{trk} < 30$, $p_{T,J_1} > 450$ GeV, $p_{T,J_2} > 200$ GeV	≥ 1, $p_{T,J} > 200$ GeV		
Baseline leptons	0	0	≥ 1	≥ 2
Good leptons	0	0	1 medium μ or tight† e	2 e or 2 μ, loose + medium
Topology	$E_T^{miss} < 250$ GeV, $\lvert y_{J_1} - y_{J_2}\rvert < 1.2$, $\frac{p_{T,J_1}-p_{T,J_2}}{p_{T,J_1}+p_{T,J_2}} < 0.15$	$E_T^{miss} > 250$ GeV, $p_T^{miss} > 30$ GeV, $\lvert\Delta\phi(\mathbf{E}_T^{miss}, p_T^{miss})\rvert < \frac{\pi}{2}$, $\lvert\Delta\phi(\mathbf{E}_T^{miss}, j)\rvert > 0.6$	no b-jet with $\Delta R(j, J) < 1.0$, $E_T^{miss} > 100$ GeV, $p_{T,\ell\nu} > 200$ GeV, $p_{T,J}/m_{\ell\nu J} > 0.4$, $p_{T,\ell\nu}/m_{\ell\nu J} > 0.4$	$p_{T,J}/m_{\ell\ell J} > 0.4$, $p_{T,\ell\ell}/m_{\ell\ell J} > 0.4$, $83 < m_{ee}/\text{GeV} < 99$, $66 < m_{\mu\mu}/\text{GeV} < 116$
Discriminant	m_{JJ}	m_T	$m_{\ell\nu J}$	$m_{\ell\ell J}$

† The electron, if over 300 GeV in p_T, need only be medium.

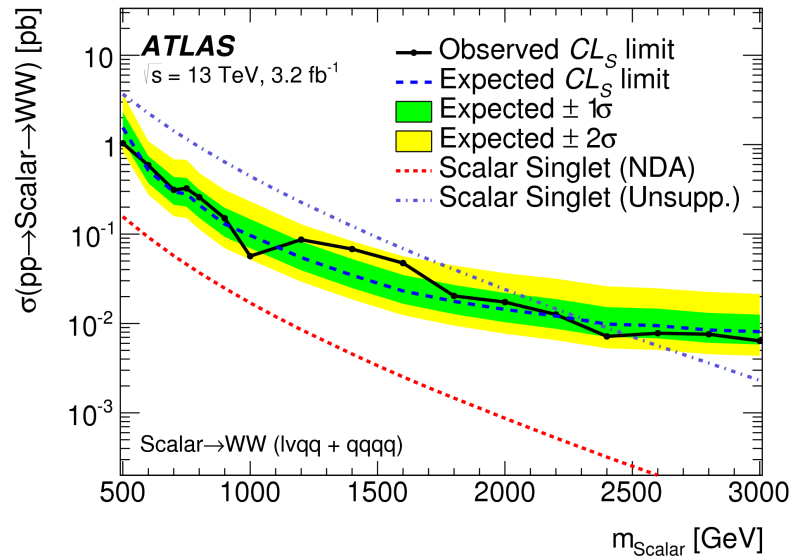
VV resonance

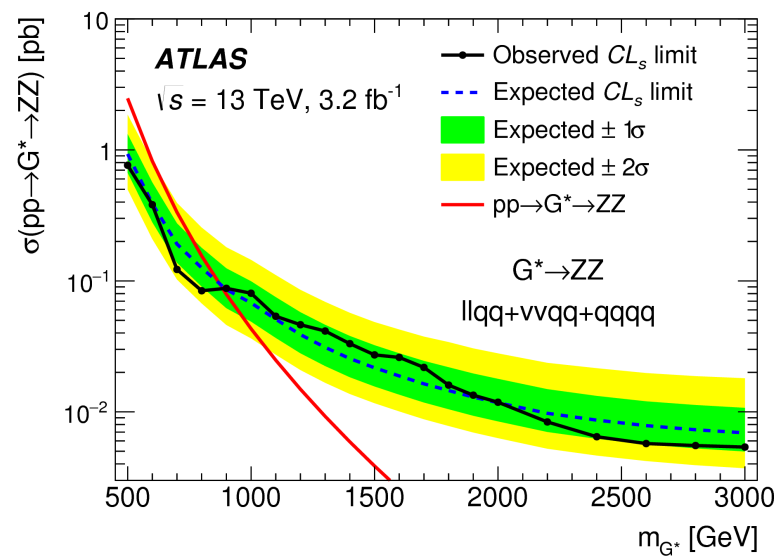
arXiv:1606.04833

- Background :
  - qqqq channel : dominant background is mulitjet

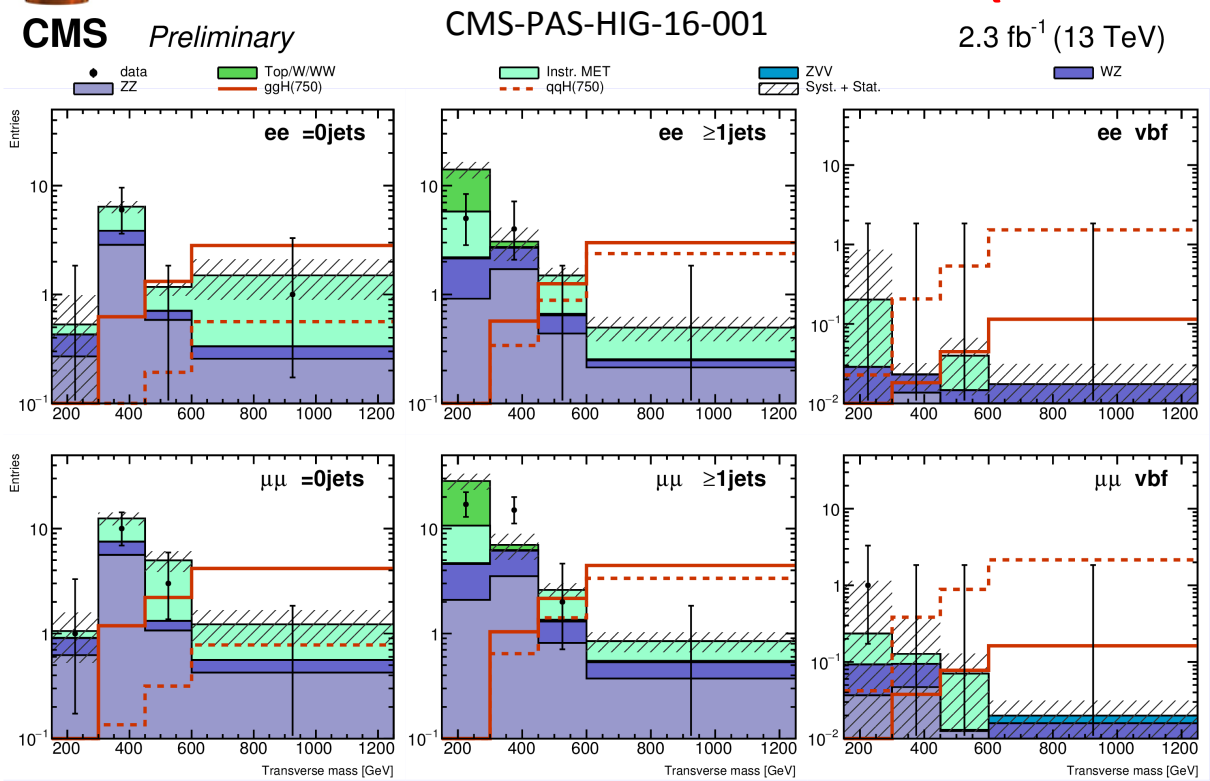
    Overall background is estimated as PDF

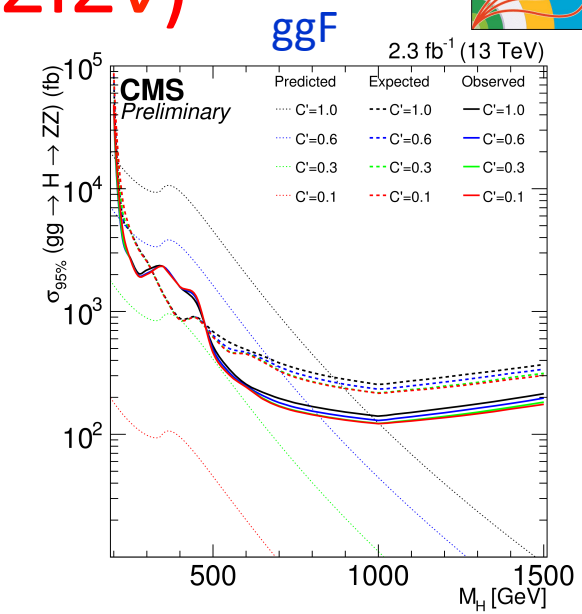
    $f(x) = N\,(1-x)^{p2 + \xi\, p3}\, x^{p3}$ with $x = m_{JJ} / \sqrt{s}$
  - Semi-leptonic channel : top, W+jets, and Z+jets
- Dominant systematics : energy scale and resolution of the large-R jet p_T, mass, and $D_2^{(\beta=1)}$
- Benchmark models :
  - Extension of SM with a new heavy scalar singlet
  - Heavy Vector Triplet
  - Bulk Randall–Sundrum (RS) model with a spin-2 G*

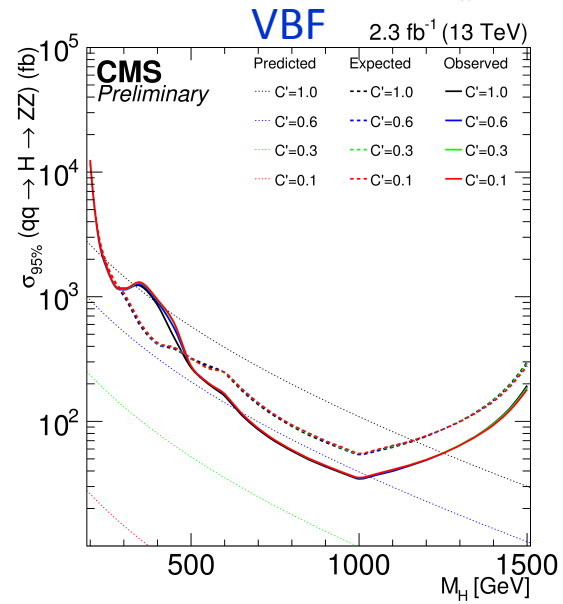




VV resonance (ZZ → 2l2ν)







- Search for generic heavy scalar in the electroweak singlet mixing with SM h(125)

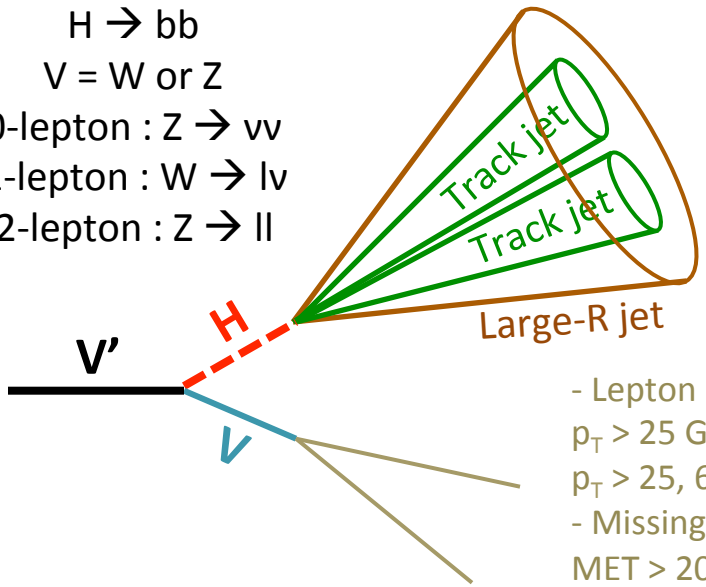
$$\mu' = C'^2 (1 - \mathcal{B}_{\text{new}}) \qquad \Gamma' = \Gamma_{\text{SM}} \frac{C'^2}{1 - \mathcal{B}_{\text{new}}}$$

- This search focus on $C' \leq (1 - B_{\text{new}})$

VH resonance

- Benchmark models : Heavy Vector Triplet
- Dominant backgrounds : top, W+jets, Z+jets

H → bb
V = W or Z
0-lepton : Z → νν
1-lepton : W → lν
2-lepton : Z → ll



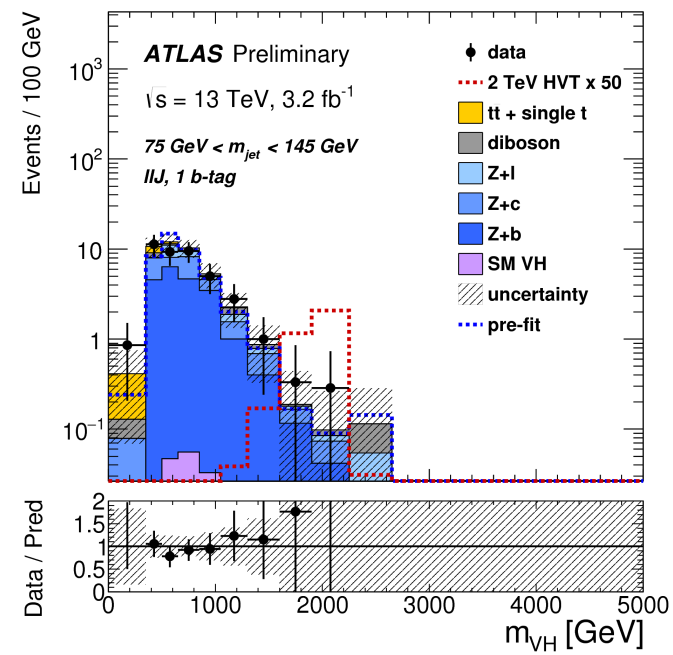
Large-R jet
p_T > 250 GeV
|η| < 2

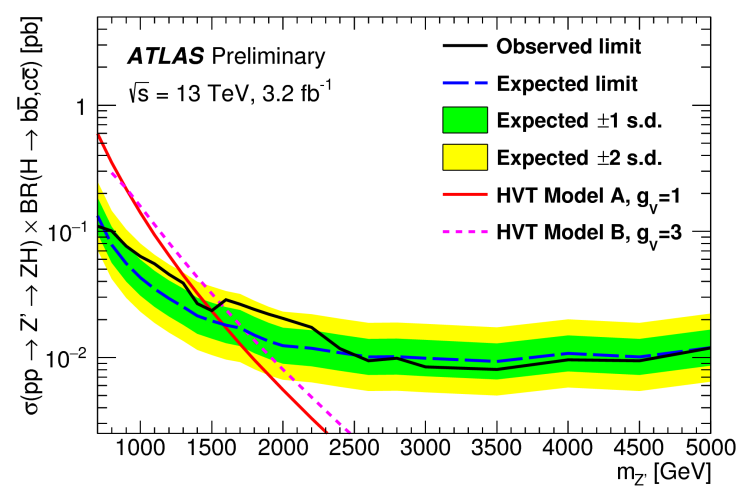
Track jet
p_T > 10 GeV, |η| < 2.5

- Lepton
p_T > 25 GeV (1-lepton)
p_T > 25, 60 GeV (2-lepton)
- Missing ET
MET > 200 GeV (0-lepton)
MET > 100 GeV (1-lepton)

- Dominant systematics :
  - calibration of the scale and resolution of the large-R jet energy and mass
  - track jet b-tagging efficiency and mistag rate

Preliminary

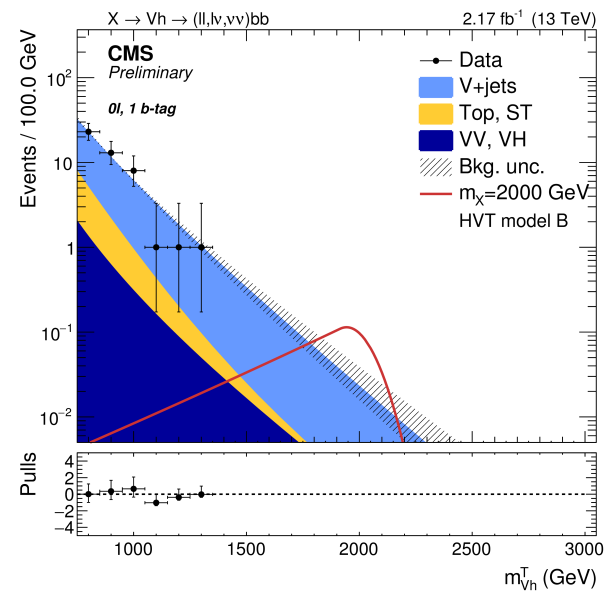


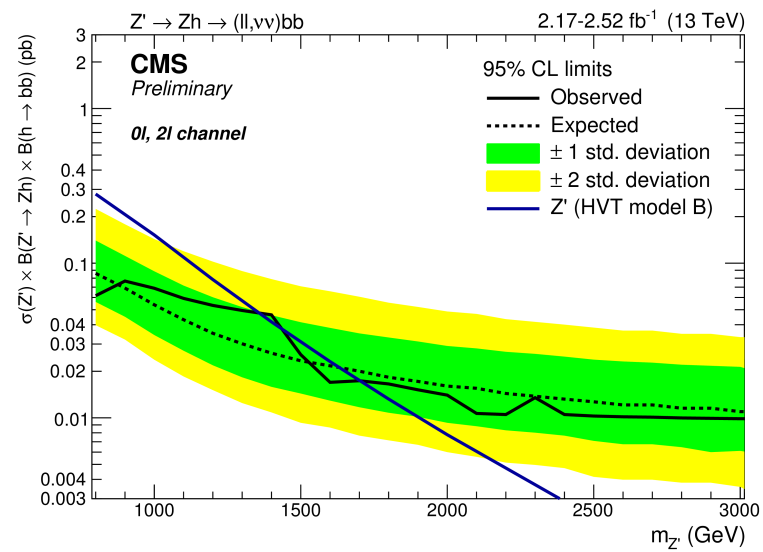


VH resonance

CMS-PAS-B2G-16-003

- Benchmark models :
  - Heavy Vector Triplet
- Decay modes used in the search :
  - llbb : $70 < m_{ll} < 110$ GeV,
    $p_T^Z > 200$ GeV
  - lvbb : 1 e ($p_T > 135$ GeV) or 1 μ ($p_T > 55$ GeV)
    $E_T^{miss} > 80$ GeV, $p_T^W > 200$ GeV
  - ννbb : lepton (pT > 10 GeV), had τ, and γ veto,
    $E_T^{miss} > 200$ GeV
- H-tagging :
  - Highest pT large-R jet in the event
  - $p_T > 200$ GeV
  - $105 < m_J < 135$
- Dominant backgrounds : W+jets and Z+jets
- Statistical uncertainty dominates the systematic uncertainty





Channels

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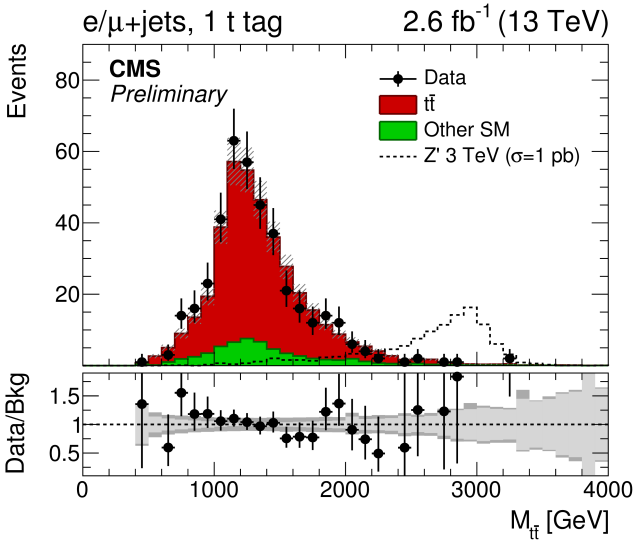
  - Z' resonance (Z' → ll)
  - W' resonance (W' → lν)
  - Z' resonance (Z' → ττ)
- Di-boson
  - VV resonance
  - VH resonance
- Di-quark
  - ttbar resonance
  - Di-jets resonance
  - Di-bjets resonance

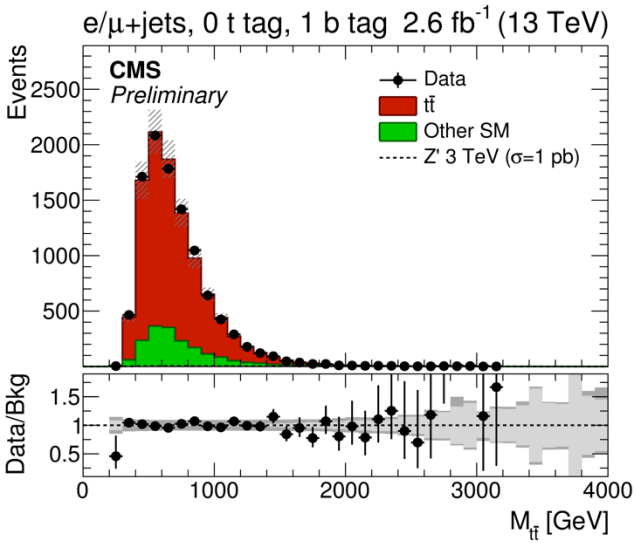
ttbar resonance

- Search channel :
  - bW(→lν) + bW(→qq)
- Use of top tagging
- Dominant background : ttbar
- Selection :
  - 1 e or μ : $p_T > 50$ GeV, $|\eta_{(e)}| < 2.5$, $|\eta_{(\mu)}| < 2.1$
  - ≥ 2 jets :
    - e-channel : leading jet $p_T > 250$ GeV
      sub-leading jet $p_T > 50$ GeV
    - μ-channel : leading jet $p_T > 150$ GeV
      sub-leading jet $p_T > 70$ GeV
    - Additional jet $p_T > 30$ GeV
  - No lepton isolation but 2D cut $\Delta R(l,j) > 0.4$ or $p_T^{rel}(l,j) > 20$ GeV

    j = small-R jet with pT > 15 GeV and $|\eta| < 3$
  - In μ-channel : $E_T^{miss} + p_T^{lep} > 150$ GeV
  - In e-channel : $E_T^{miss} > 120$ GeV

CMS-PAS-B2G-15-002

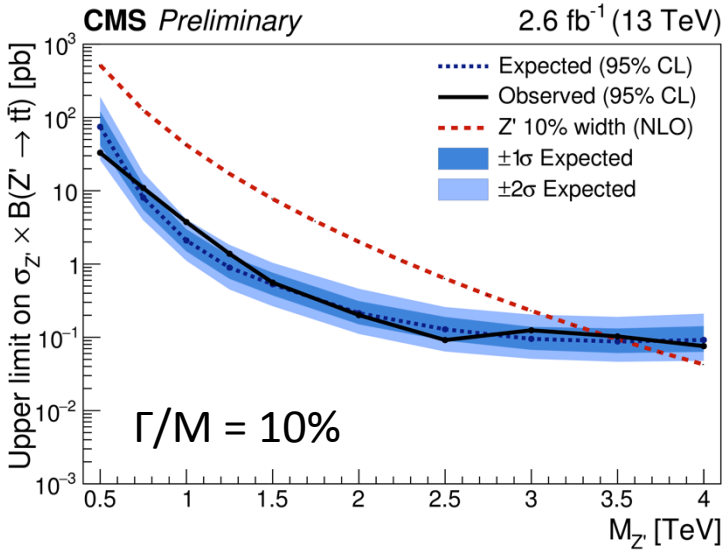




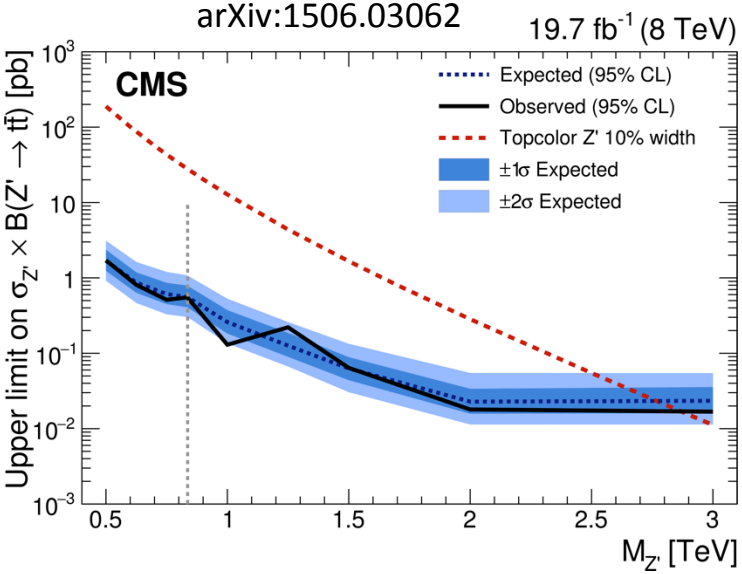
ttbar resonance

- Events with and without t-tagged jet :
  - Event without t-tagged jet → use only small-R jet
  - Event with t-tagged jet :
    - Number of t-tagged jet = 1
    - Assigned to hadronic top
    - ΔR(t-tagged jet, jet used in lep top) > 1.2
- Dominant systematics :
  - t- and b-tagging
  - Scale uncertainty
  - PDF
- Model independent search
- Search channels in Run 1 :
  - bW(→lν) + bW(→lν)
  - bW(→lν) + bW(→qq)
  - bW(→qq) + bW(→qq)

CMS-PAS-B2G-15-002



arXiv:1506.03062



ttbar resonance

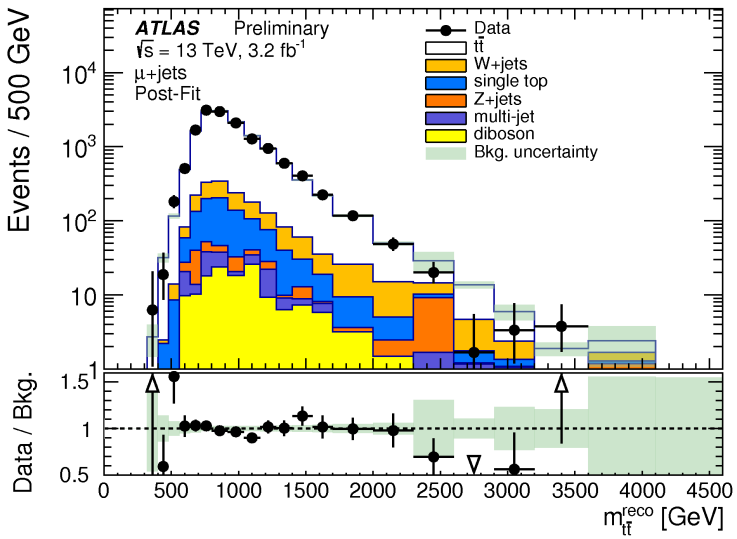
- Decay mode used in the search, lepton-plus-jets:
  - One top decays leptonically : b + W(→lν)
  - One top decays hadronically : b + W(→qq)
- Selection :
  - 1 e or μ : $p_T^{(e)} > 30$ GeV, $p_T^{(\mu)} > 25$ GeV
  - 1 small-R jet : $p_T > 25$ GeV, $|\eta| < 2.5$
  - 1 track jet : $p_T > 10$ GeV, $|\eta| < 2.5$
  - 1 Large-R jet : $p_T > 300$ GeV, $|\eta| < 2.$

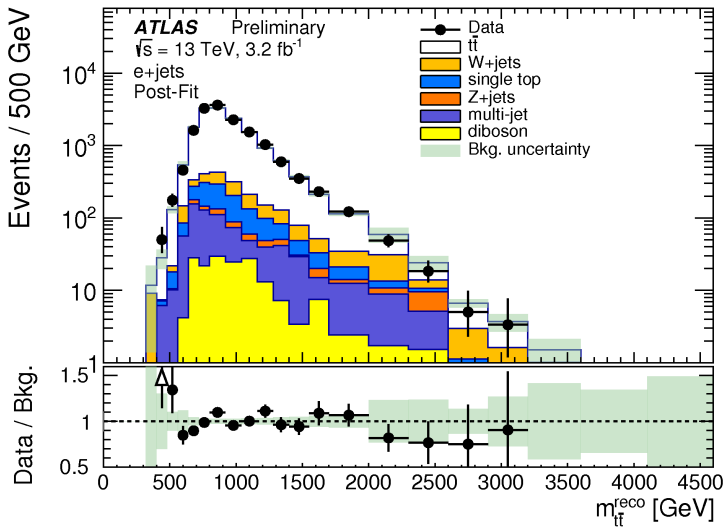
    Substructure ~ hadronic top decay →

    Top tagging based on the invariant mass and the n-subjettiness ratio τ_{32}
  - ΔR(highest p_T small-R jet, lepton) < 1.5
  - ΔR(large-R jet, lepton) > 2.3
  - ΔR(highest p_T small-R jet, large-R jet) > 1.5
- Dominant background : SM ttbar.

  ~30 of ttbar decalys W(→lν)b+W(→qq)b

ATLAS-CONF-2016-014



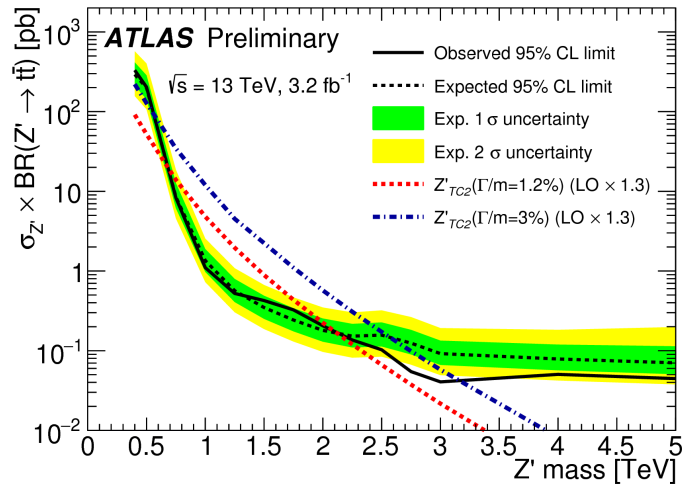


ttbar resonance

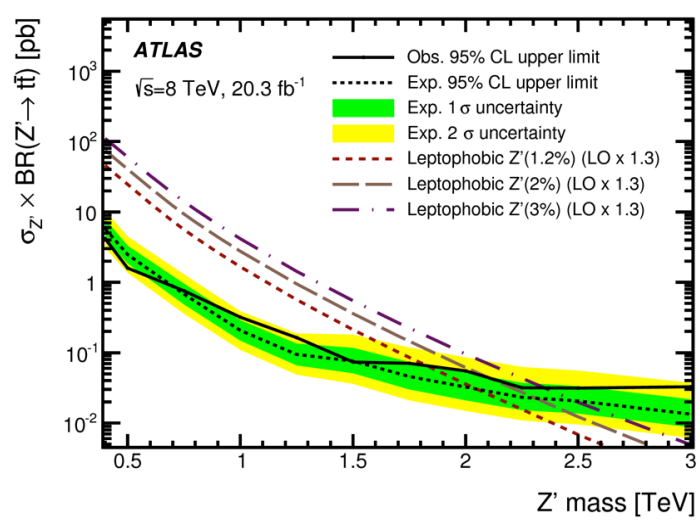
- Other backgrounds :
  - W+jets : contribution grows at high m_{tt}

    Normalization from data by charge asymmetry (W^++W^-)
  - Multijet : data driven using a matrix method
- Benchmark models :
  - Spin-1 colour singlet : Topcolour-assited technicolour, Z'_{TC2} (Γ/m = 1.2%)
- Dominant systematics :
  - large-R jet uncertainties
- In Run 1, better sensitivity at low mass with resolved (hadronic top reconstructed by small-R jets) & merged (hadronic top reconstructed by large-R jet) analyses

ATLAS-CONF-2016-014



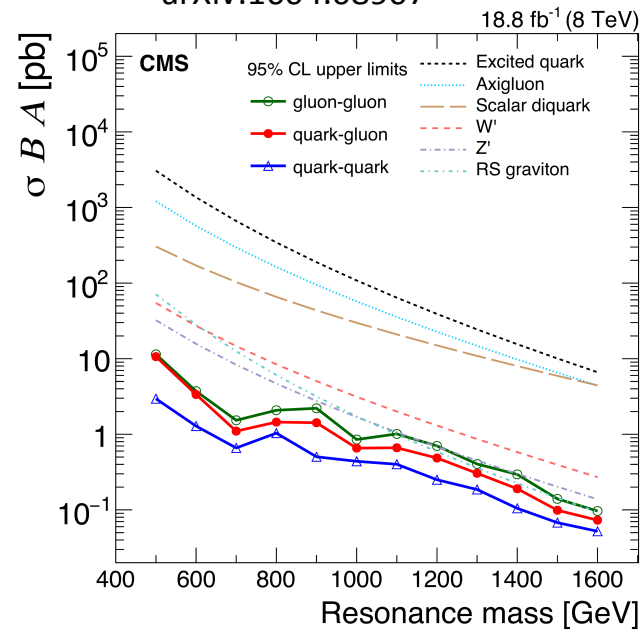
arXiv:1505.07018

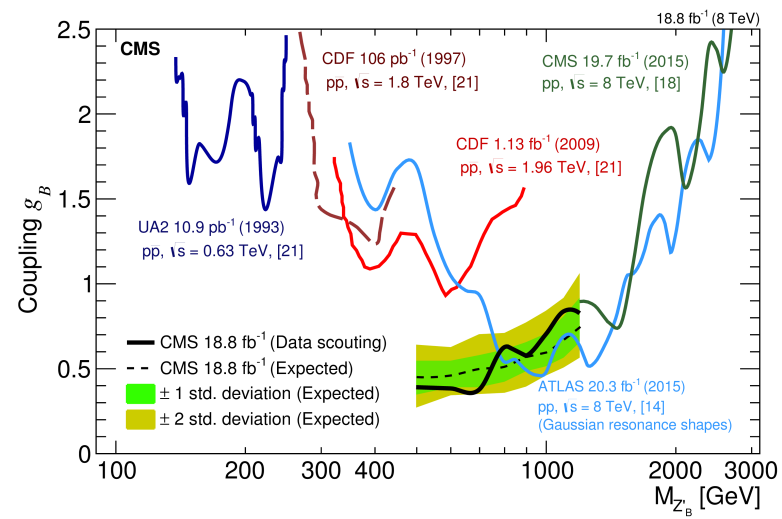


di-jets resonance

- Data scouting technique
  - Online analysis
  - Collecting events with ~ 1kHz
  - Extend the search to low mass (m_{jj} = 500 GeV)
- HLT requires $\Sigma_{jet} p_T$ > 250 GeV using jets with p_T > 40 GeV and $|\eta|$ < 3
- Selection :
  - p_T > 30 GeV and $|\eta|$ < 2.5
  - $\Delta\phi > \pi/3$
- Use the 2 highest pT jet for m_{jj}, merge other secondary jets with the main jets if ΔR(main jet, secondary jet) < 1.1
- Dominant systematics :
  - jet energy scale and resolution
  - luminosity
  - estimation of the background

arXiv:1604.08907

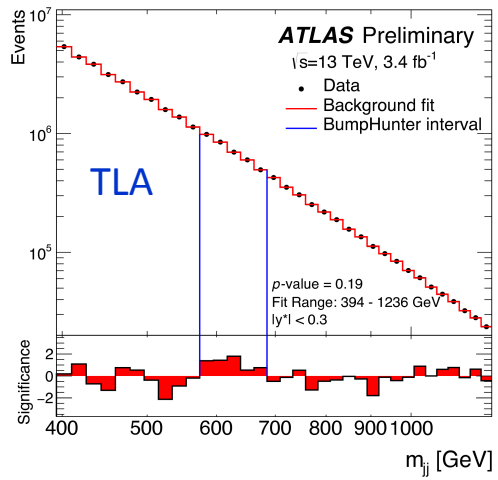




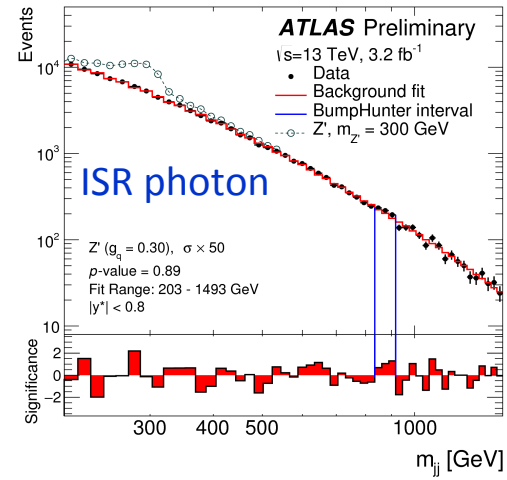
di-jets resonance

- Trigger-object Level Analysis (TLA)
  - Trigged events :
    - L1 jet ROI : ET > 75 GeV (EM-scale)
    - Trigger jet: pT > 4 GeV
  - Selection :
    - ≥ 2 trigger jet p_T > 85 GeV
    - Highest pT trigger jet : p_T > 185 GeV

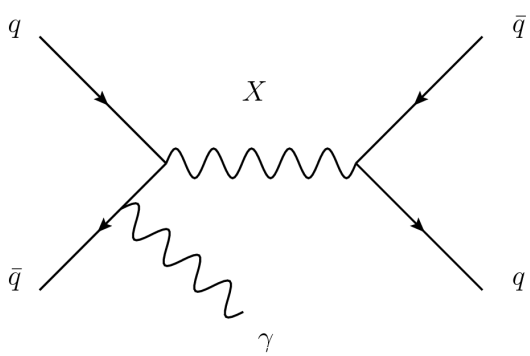
ATLAS-CONF-2016-030



ATLAS-CONF-2016-029



- Di-jets with ISR photon
  - Trigged events : Photon p_T > 120 GeV
  - Selection : Jet p_T > 25 GeV



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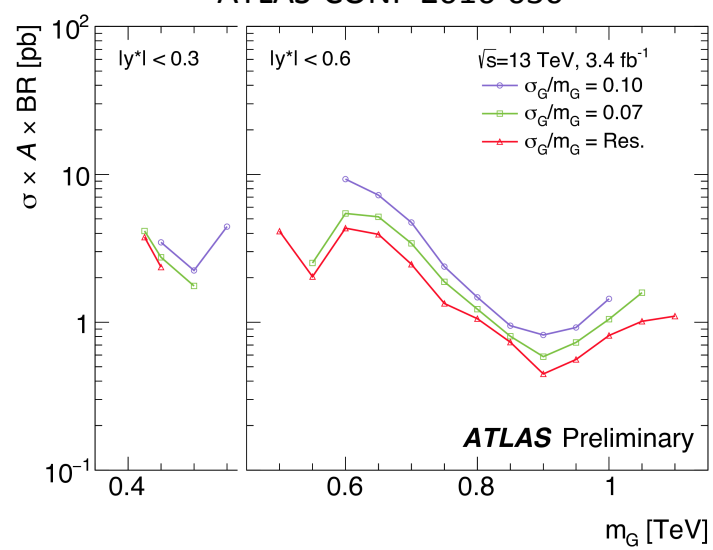
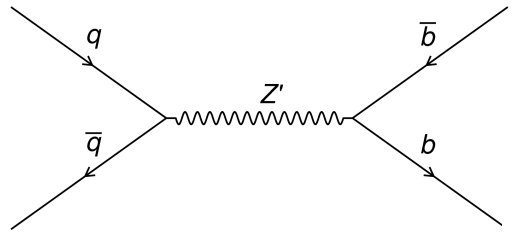


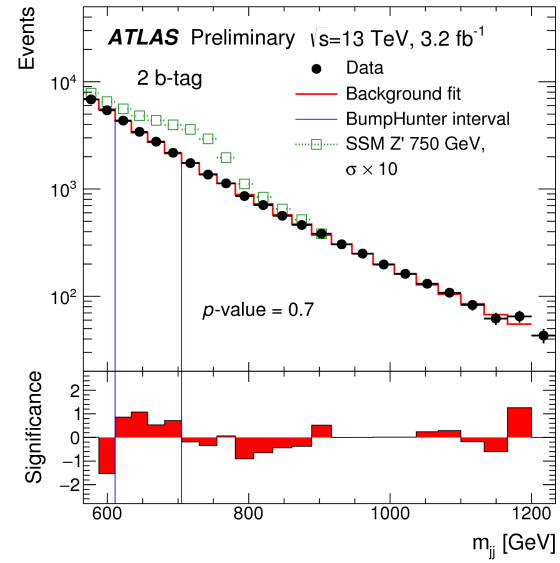
di-bjets resonance

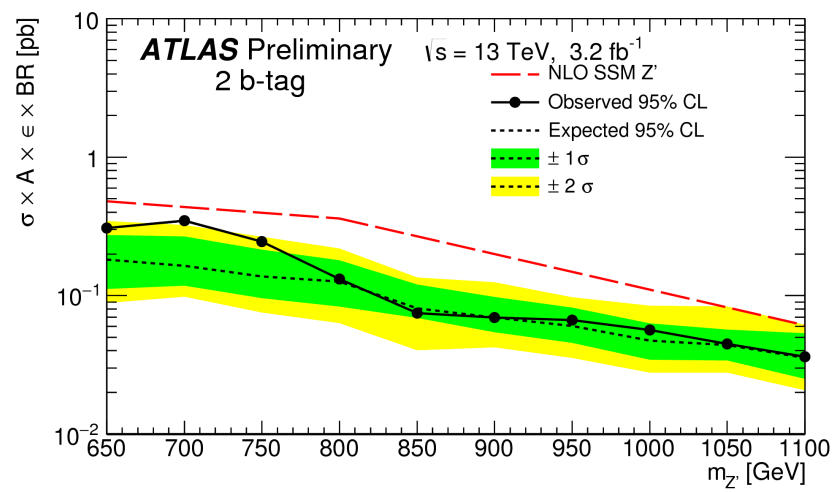


- Assumptions:
  - Z' model with SM-like fermion couplings in the SSM
  - Gaussian-shape signal
- Trigger : ≥ 2 b-jets requirement ($p_{T(1)}$ > 175 GeV & $p_{T(2)}$ > 60 GeV)
- Selection :
  - Highest pT b-jet : p_T > 230 GeV
  - Second highest pT b-jet : p_T > 90 GeV
  - $|y^*| < 0.6$ where $y^* = 0.5(y_{(b1)} - y_{(b2)})$
- Dominant background : Multi-jet
- Invariant mass spectrum :

$$f(x) = p_1(1-x)^{p_2}\, x^{p_3+p_4(\ln x)+p_5(\ln x)^2},\ x = m_{jj}/\sqrt{s}$$

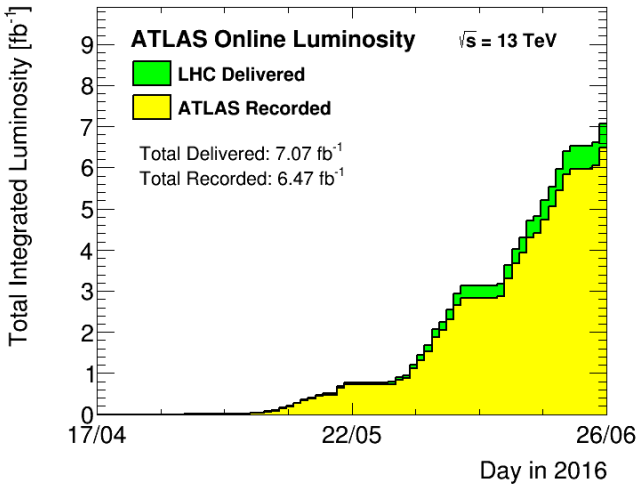
ATLAS-CONF-2016-031





Summary

- Several BSM Models predicts new resonances
- ATLAS and CMS collaborations provides several exotics searches for resonance in dilepton, diboson, and diquark
- In the searches of new resonances with mass between 500 GeV and 1 TeV with final states other than two photons, no significant excess is observed
- Looking forward to more data in 2016 (expecting about 30 fb^{-1})



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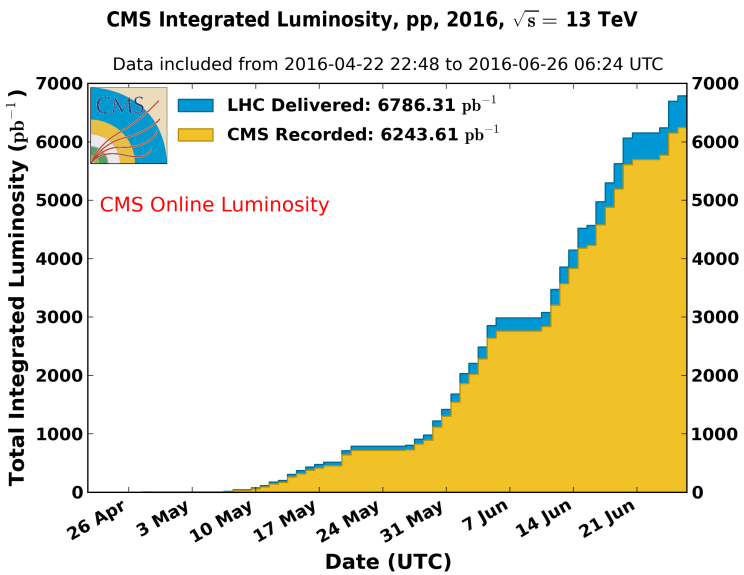


Ref [7]

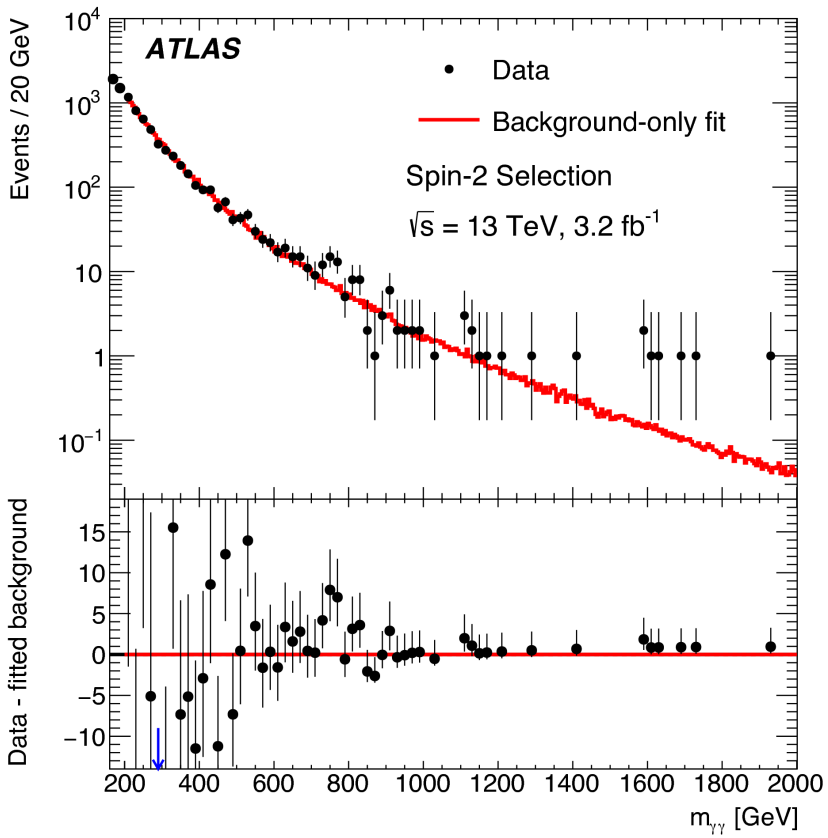
References

- ATLAS Higgs public page :
  [1] https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
- ATLAS Exotics public page :
  [2] https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
- CMS Higgs public page :
  [3] https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG
- CMS Exotics public page :
  [4] https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
- CMS Beyond-Two-Generations public page :
  [5] https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G
- ATLAS Luminosity public page :
  [6] https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2
- CMS Luminosity public page :
  [7] https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults#2016_Proton_Proton_13_TeV_Collis

Backup

Di-photon

arXiv:1606.03833



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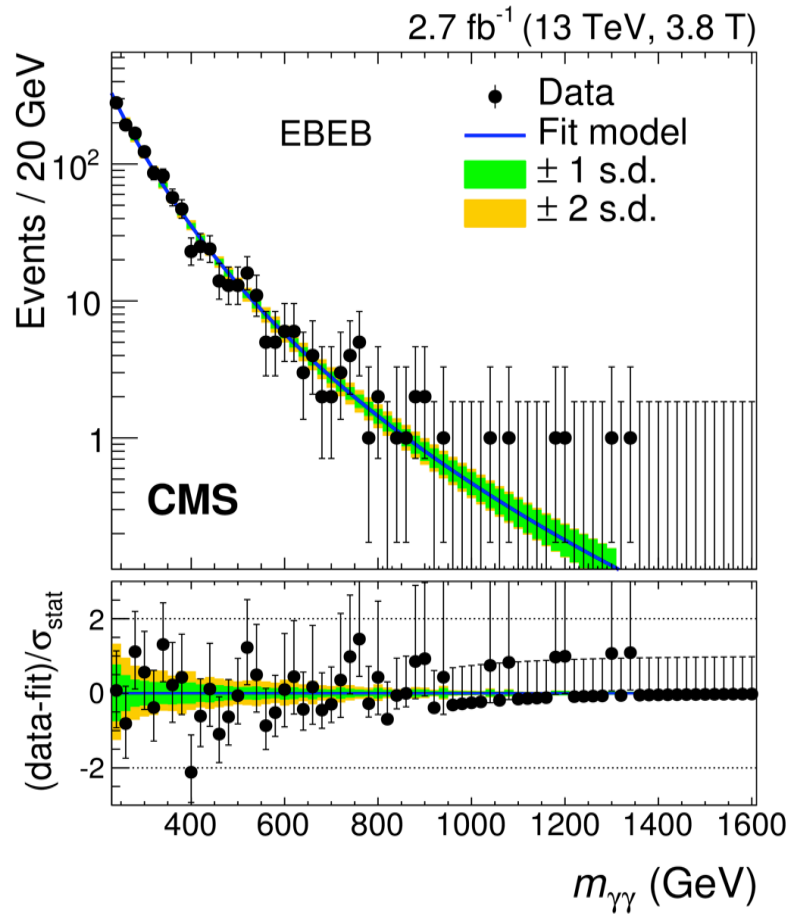
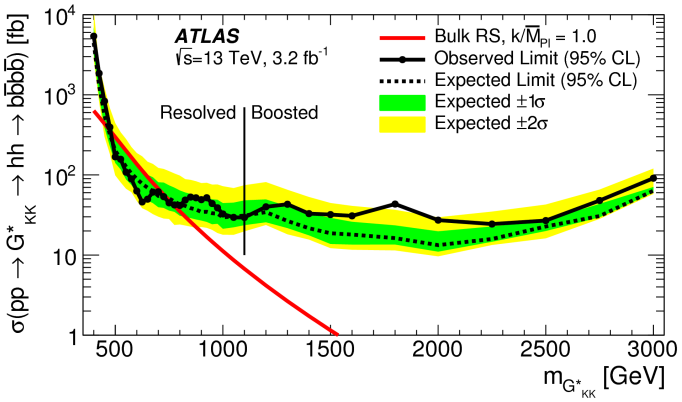


X → HH

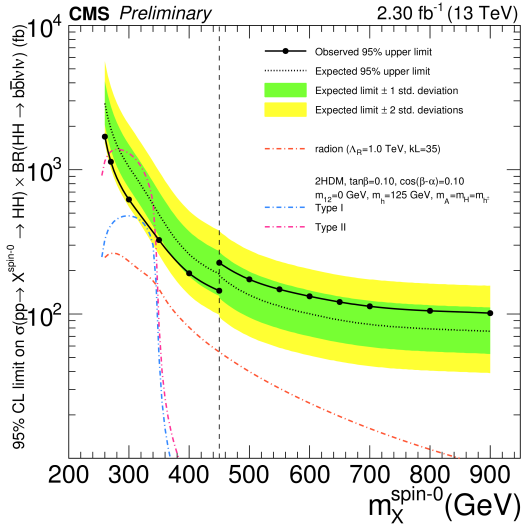
arXiv:1606.04782

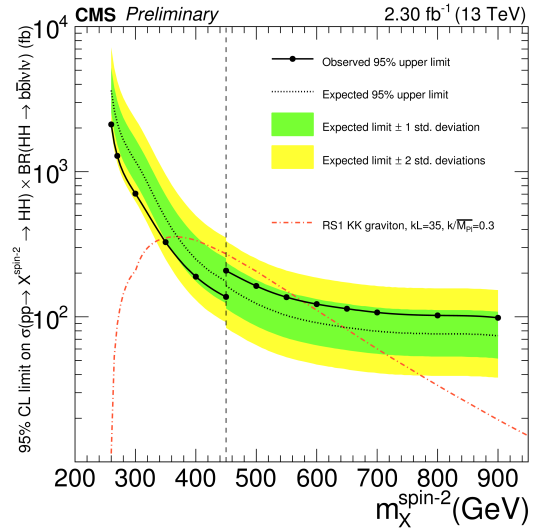
X → HH → bbbb



CMS-PAS-HIG-16-011

X → HH → bbWW → bblvlv





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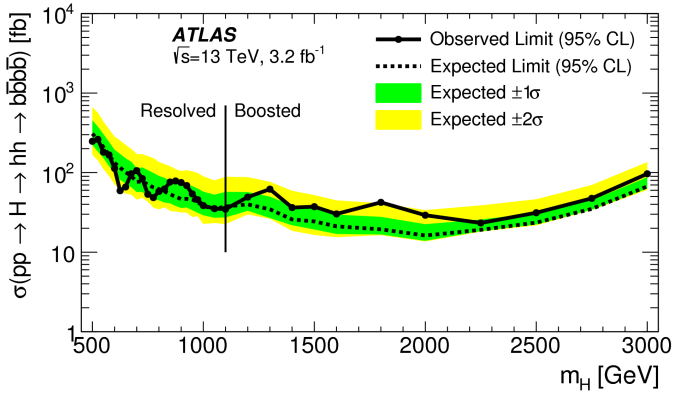

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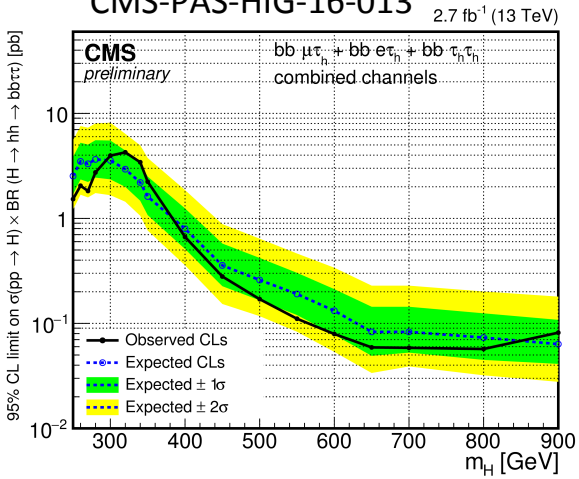
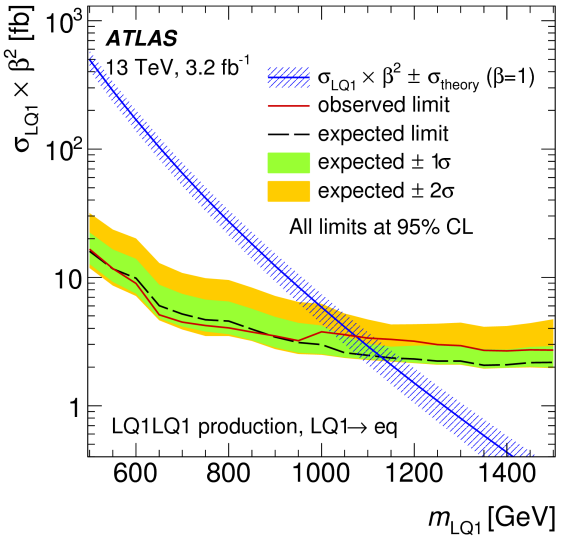
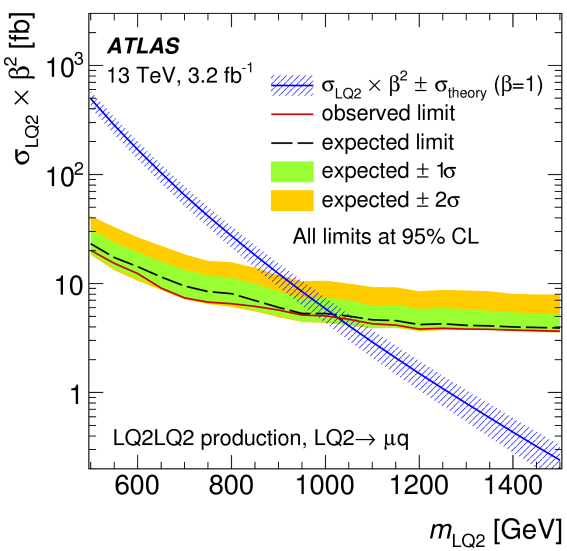


Leptoquarks

arXiv:1605.06035





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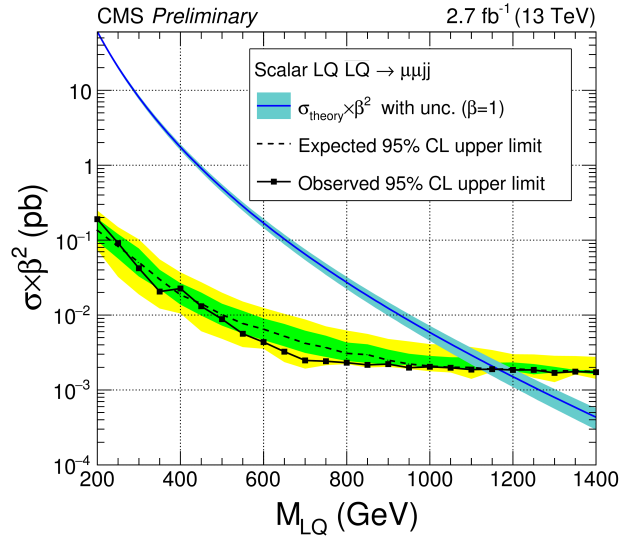

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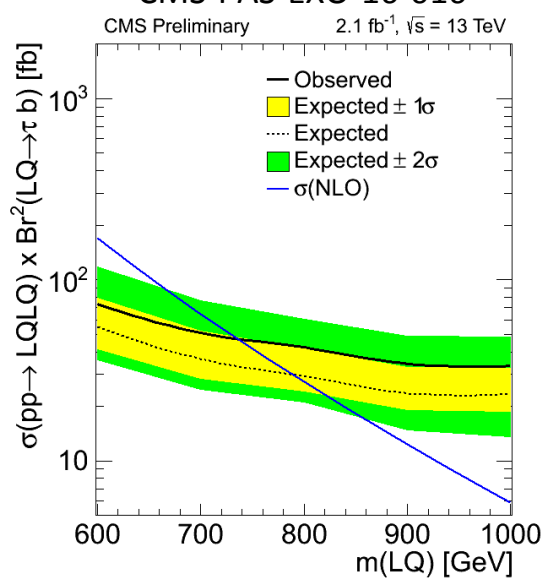

QBH

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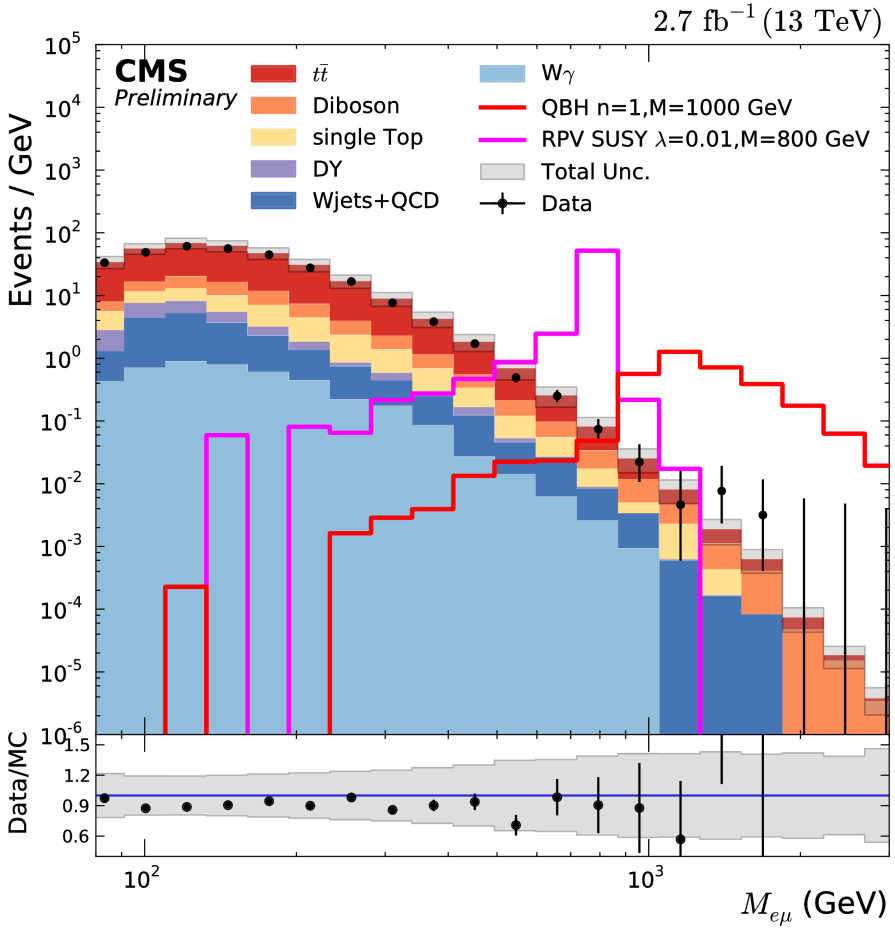
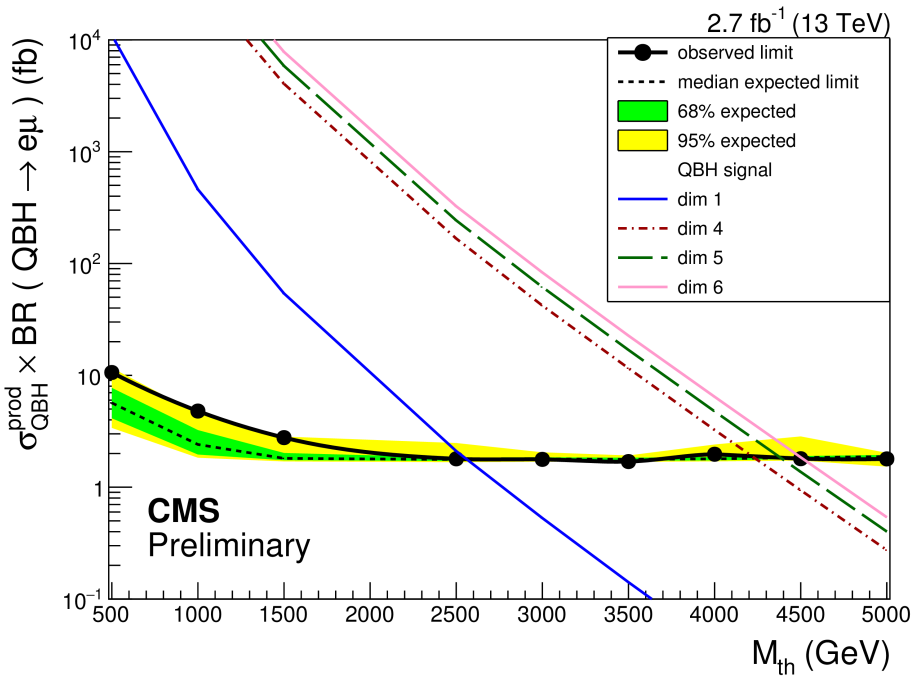
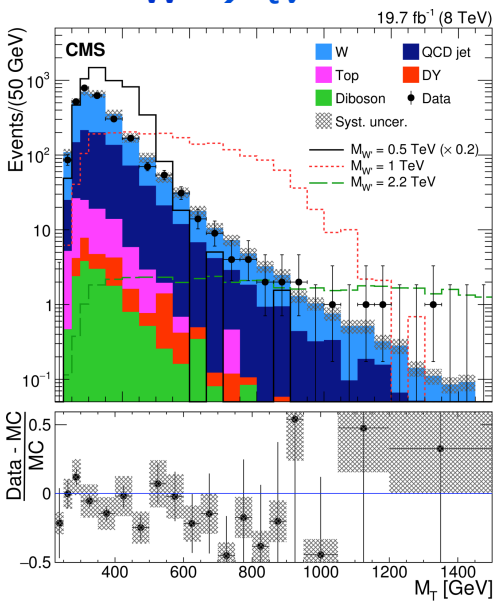


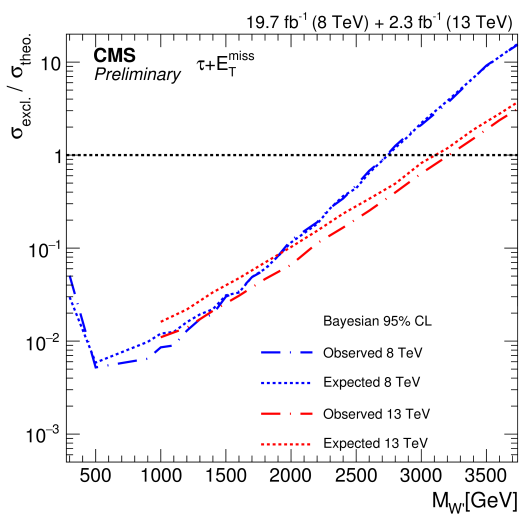


W’ → τν & W’→tb

W’ → τν



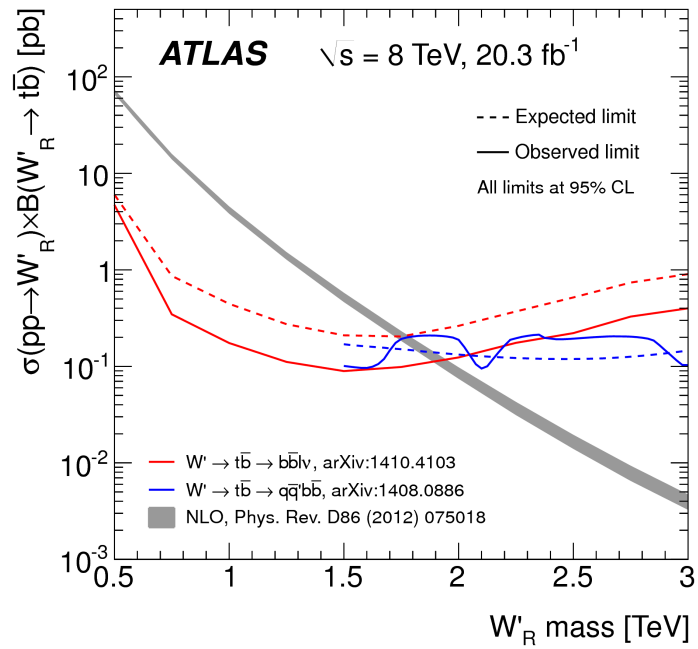
arXiv:1508.04308

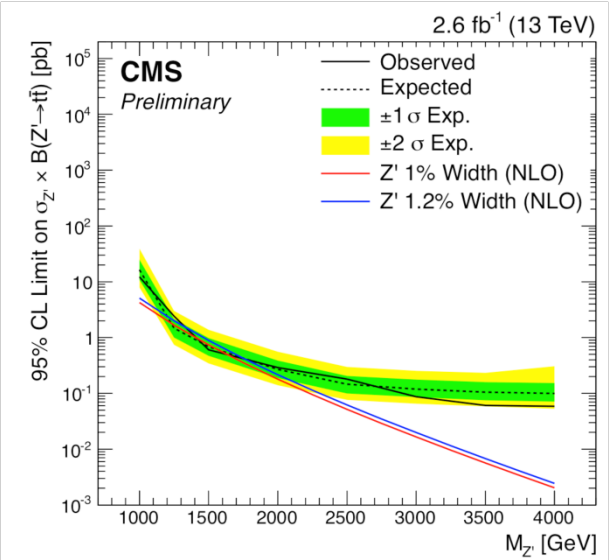
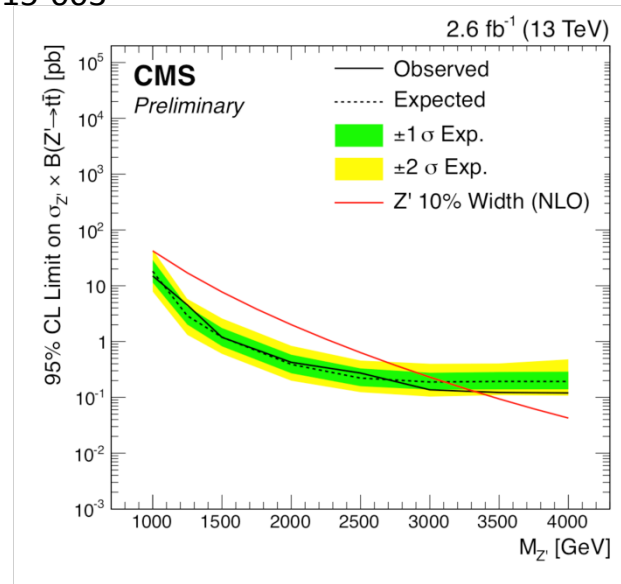
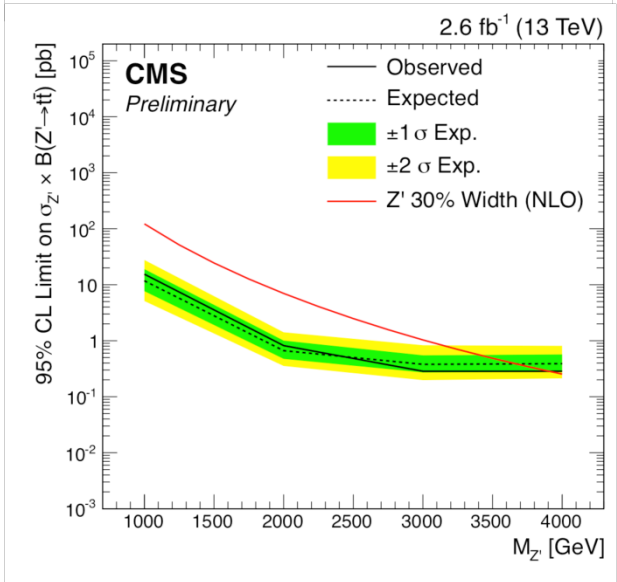
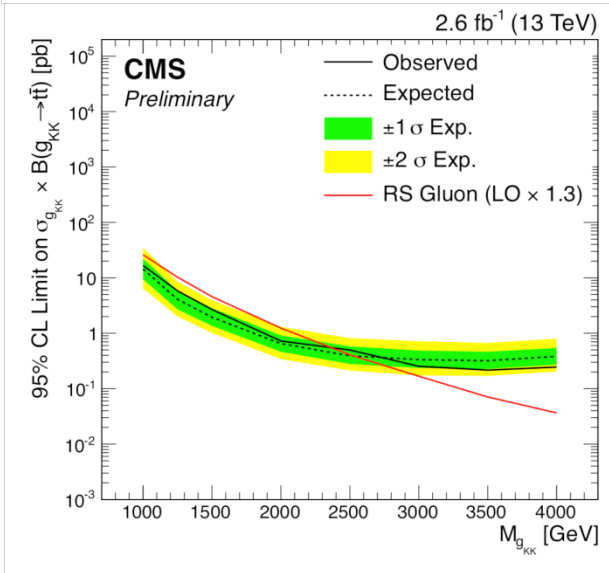


CMS-PAS-EXO-16-006

W’→tb

arXiv:1410.4103



ttbar resonance (all hadronic)

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