Diboson Resonance Searches at CMS

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on behalf of the CMS Collaboration

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Motivation for Diboson Search

Beyond the Standard Model

- Hierarchy problem
- Dark matter

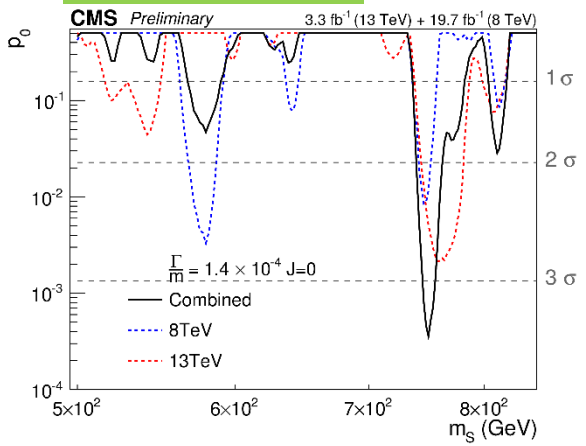
Search for heavy resonances decaying to diboson

- 750 Diphoton bump
  - γγ, Zγ, WW, ZZ
- Extra-dimension
  - Bulk Graviton: WW, ZZ
- Heavy Vector Triplet framework

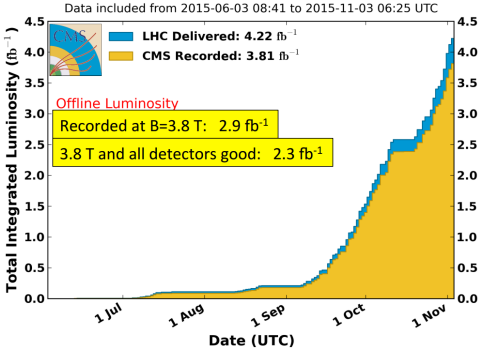
  In strongly coupled model:

  Br(X → VV) ≈ Br(X → VH) ≈ 50%

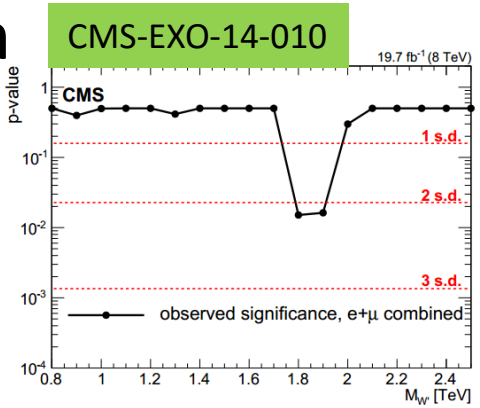
CMS-EXO-16-018

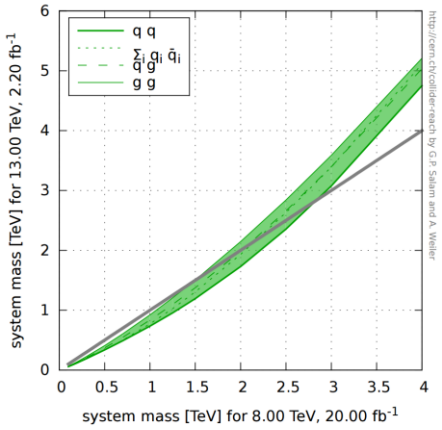


From Run1 to Run2

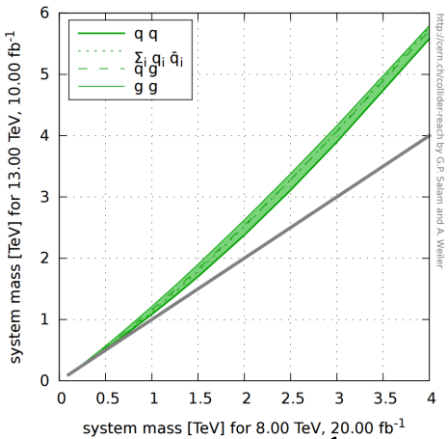


- In Run1, excess of events around 2 TeV in diboson analyses
  - ATLAS: largest excess in WZ all-hadronic
  - CMS: largest excess in WH semileptonic
- 8 TeV → 13 TeV
  - For 2 TeV Bulk Graviton, parton luminosity scaling by ~15





13 TeV, 2.2 fb^{-1}



13 TeV, 10 fb^{-1}

High-Mass Diboson Resonances

- CMS searches overview
  - 8 TeV, EXO-12-024: WW/ZZ/WZ→qqqq
  - 8 TeV, EXO-13-009: WW→lvqq, ZZ→llqq
  - 8 TeV, EXO-14-009: VH→qqbb, VH→qqWW→qqqqqq
  - 8 TeV, EXO-14-010: WH→lvbb
  - 13 TeV, EXO-15-002: WW/ZZ/WZ→qqqq, WW→lvqq
  - 13 TeV, B2G-16-003: WH→lvbb, ZH→llbb, ZH→vvbb
  - 13 TeV, B2G-16-004: WW→lvqq

More results for X→HH, or H→diboson

Luca Pernie: Searches for extended Higgs sectors with CMS

Luca Cadamuro: Searches for resonant di-Higgs production with CMS

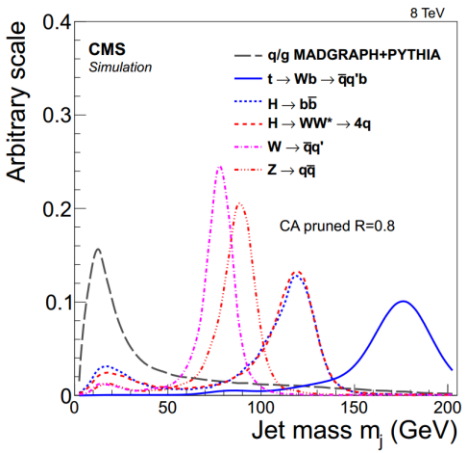
Resonance Search Strategy

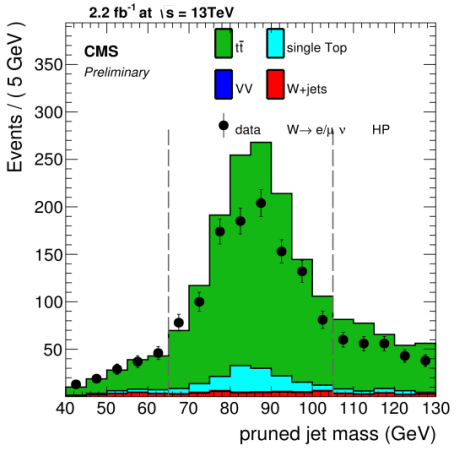
- Diboson decay channels:
  - All-hadronic, semi-leptonic
  - Fat jets for hadronic W/Z/H bosons
  - Leptonic W→lν, and Z→2l/2ν
- Backgrounds estimation
  - all hadronic:
    - Background is described by smooth fit function
  - semi-leptonic:
    - Each components are estimated from observed data or from simulation
- “Bump” search
  - 0 or 1 neutrino: search excess over the m_{VV} distributions
  - 2 neutrinos: transverse mass m_T

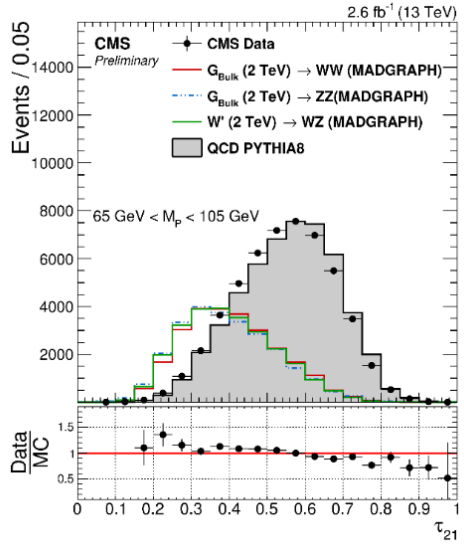
CMS-JME-13-006
CMS-EXO-14-009
CMS-EXO-15-002

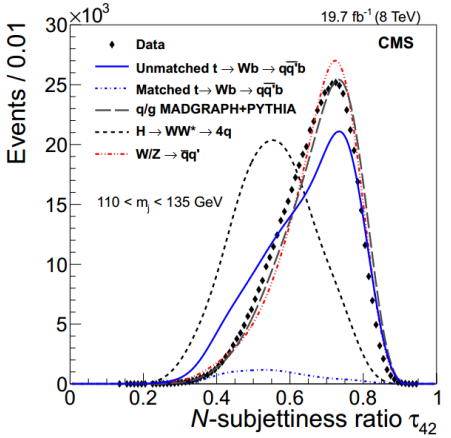
Hadronic W/Z/H Tagging

- W, Z, and H all have significant branching fractions to jets
  - When pT >~200 GeV, traditional dijet search begin to fail
- Jet Mass for W/Z/H
  - Pruning
- Jet substructure
  - N-subjettiness
  - τ2/τ1 for W/Z→qq
  - τ4/τ2 for H→WW→qqqq



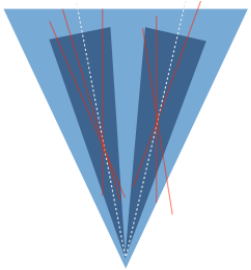






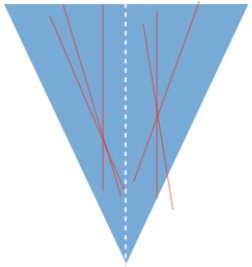
Hadronic H(bb) Tagging

- The boosted H(bb) signal can be identified by:
  - (old) 2 subjets of a fat jet
    - $\Delta R > 0.3$, subjets btag; $\Delta R < 0.3$, fatjet btag
  - (new) Double-b tag is a dedicated tagger to identify fat jets with 2 b-quarks



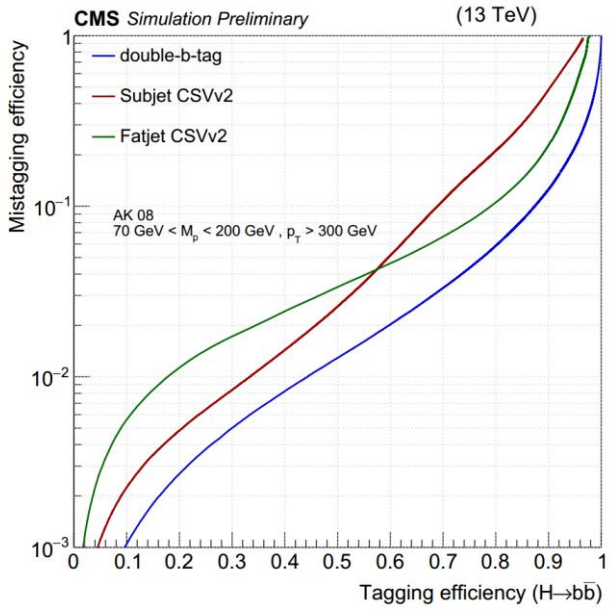
Sub-jets

Defines sub-jets
b-tagging observables for each sub-jet
explicit jet track association



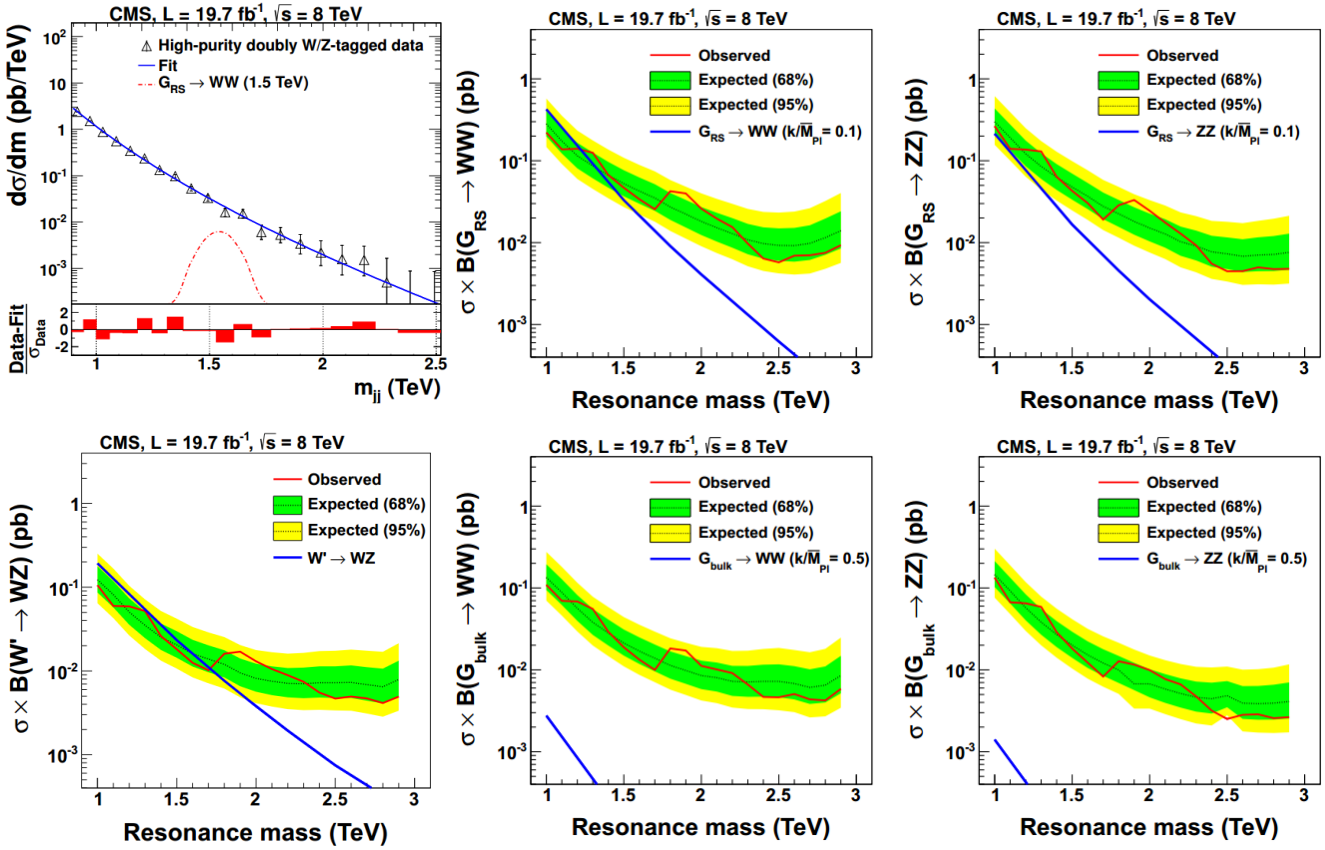
double-b

Secondary Vertex within the fat-jet cone
Observables built from secondary vertex
and tracks associated to fat-jet



All-hadronic VV search @8 TeV

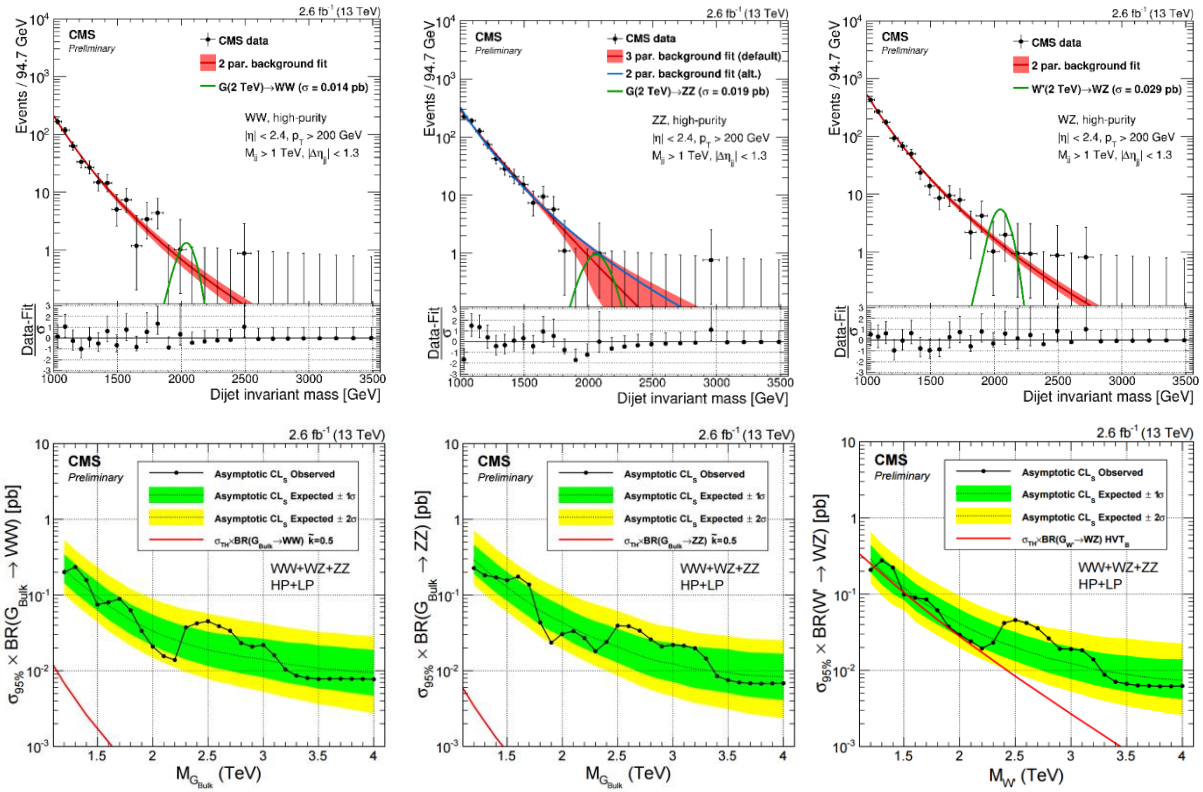
- Dijet, V-tagging: jet pruned mass + τ2/τ1



All-hadronic VV search @13 TeV

- Dijet, V-tagging: jet pruned mass + τ2/τ1
  - W-enriched:65-85 GeV; Z-enriched:85-105 GeV

WW ZZ WZ

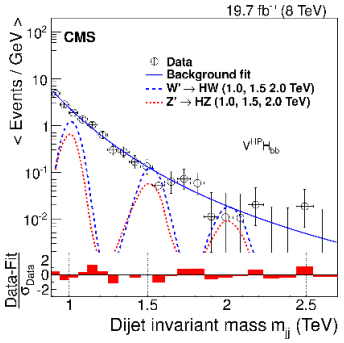


All-hadronic VH search @8TeV

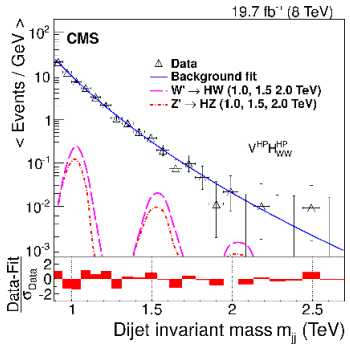
- Dijet
  - V-tagging
  - H→bb: fatjet and subjet b-tagging
  - H→WW→qqqq: τ4/τ2

Categories	V tag	H tag
$V^{HP}H_{bb}$	$\tau_{21} \leq 0.5$	b tag
$V^{LP}H_{bb}$	$0.5 < \tau_{21} < 0.75$	b tag
$V^{HP}H^{HP}_{WW}$	$\tau_{21} \leq 0.5$	$\tau_{42} \leq 0.55$
$V^{LP}H^{HP}_{WW}$	$0.5 < \tau_{21} < 0.75$	$\tau_{42} \leq 0.55$
$V^{HP}H^{LP}_{WW}$	$\tau_{21} \leq 0.5$	$0.55 < \tau_{42} < 0.65$

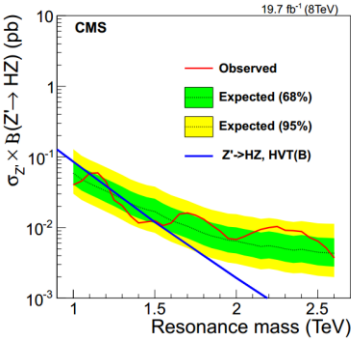
VHbb



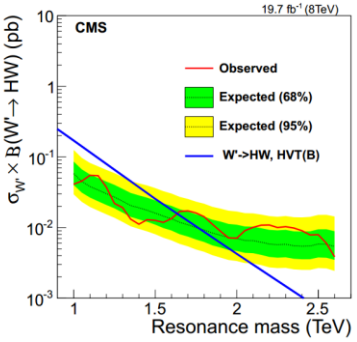
VHWW

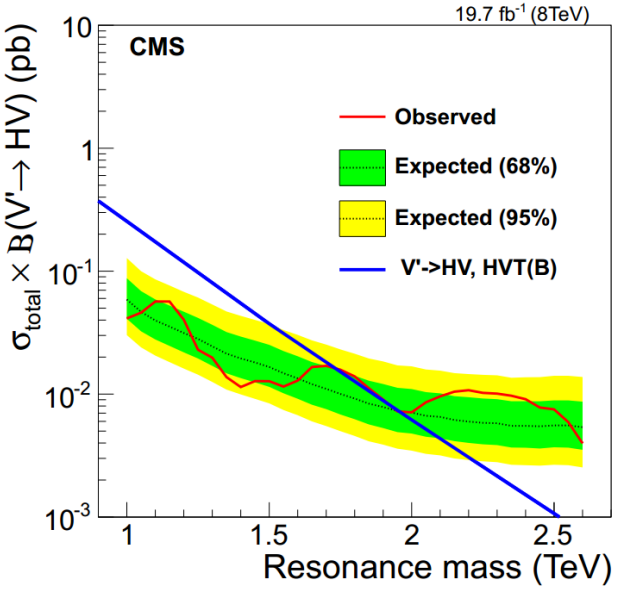


Z’



W’

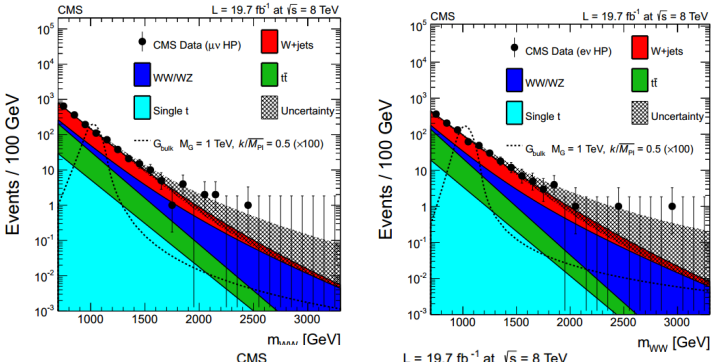


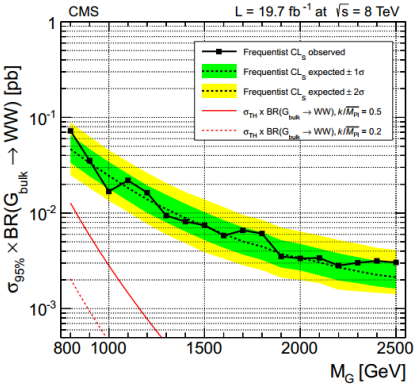


WV, ZV Semileptonic @8TeV

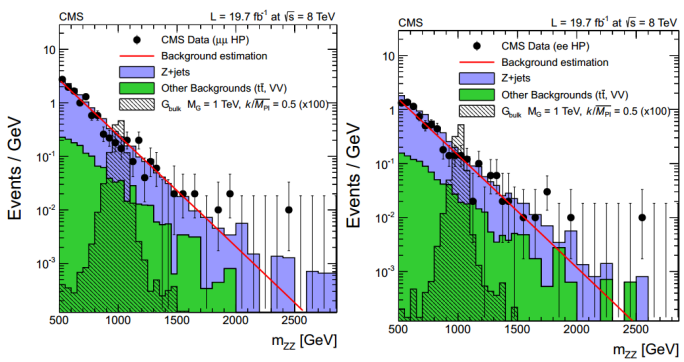
- W→lν, a fat jet
- Z→ll, a fat jet
  - No strong excess at 750 GeV

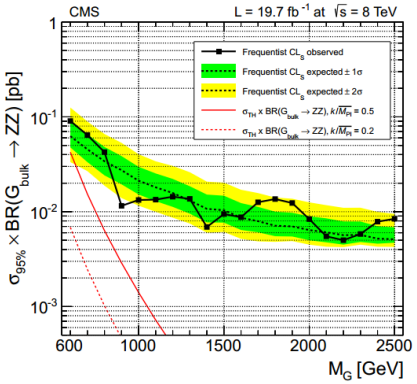
WW





ZZ



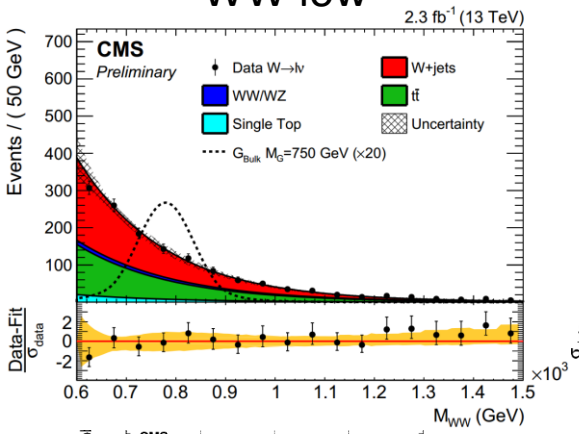


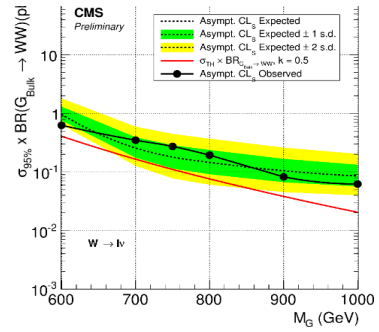
CMS-B2G-16-004
CMS-EXO-15-002

WV Semileptonic @13TeV

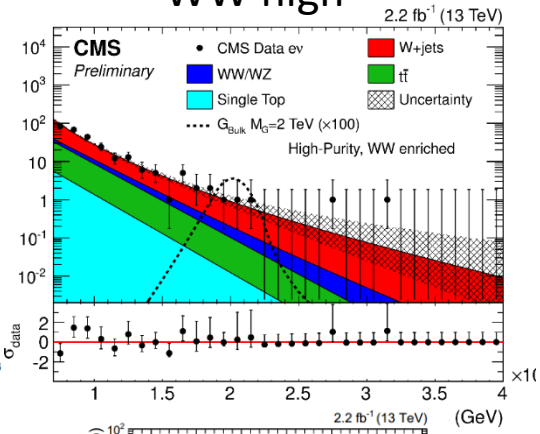
- WV: WW→lvqq and WZ→lvqq
- WW Run2 separate to low mass region and high mass region
  - Low mass analysis has loose triggers and event selections
  - No strong excess at 750 GeV

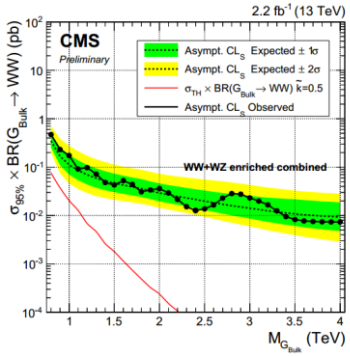
WW low



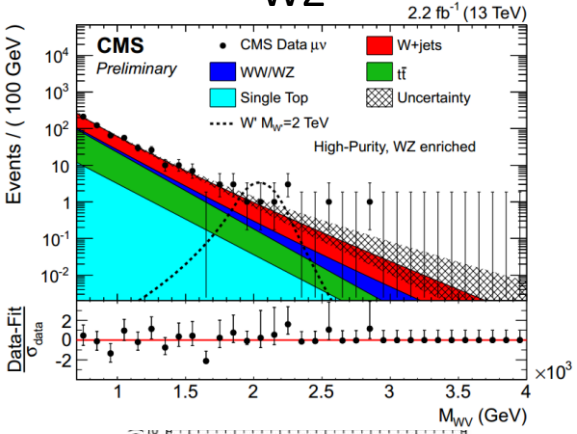


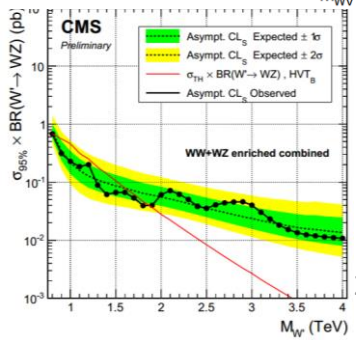
WW high





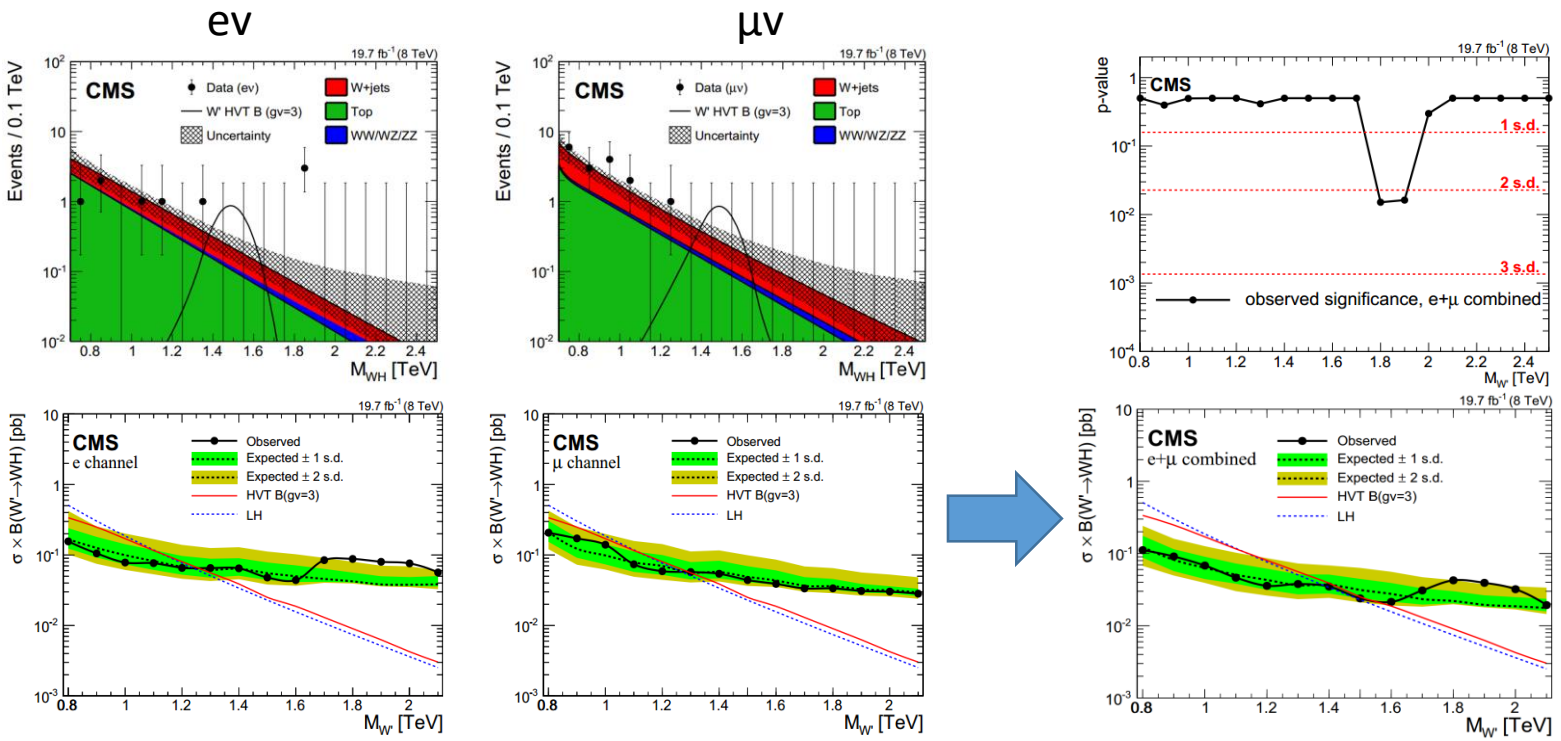
WZ





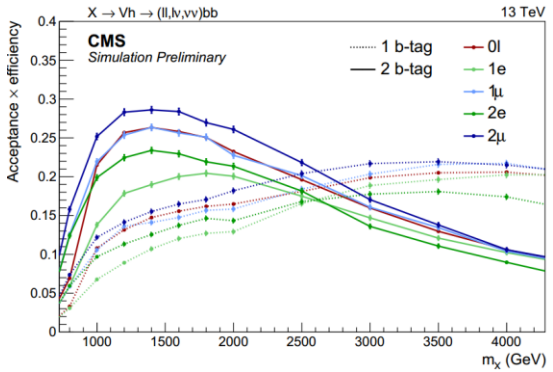
WH Semileptonic @8TeV

- W→lν, a fat jet with H(bb) tagging
- Excess at 2 TeV in el channel

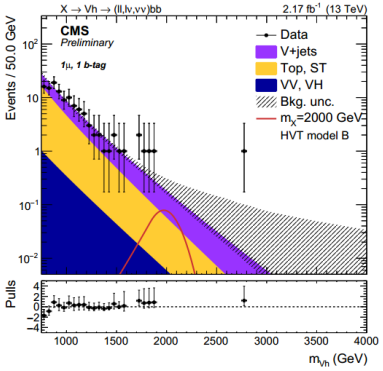


VH Semileptonic @13 TeV

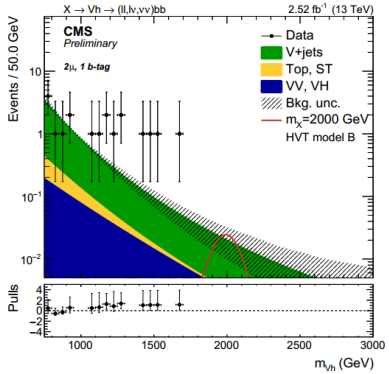
- W→lν, Z→νν/ll
- A fat jet with H(bb) tagging
- Excess at 2 TeV not be confirmed
  - Need more data



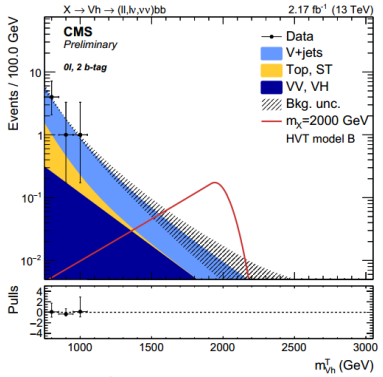
W(lν)H, 1 b-tag

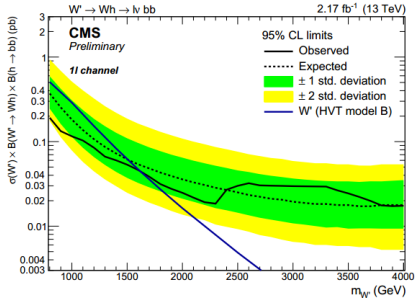


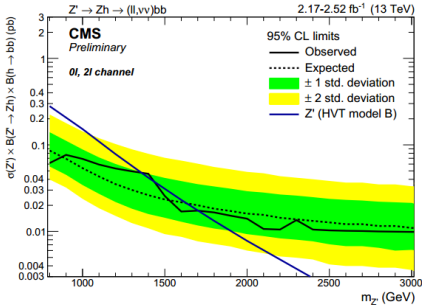
Z(ll)H , 1 b-tag



Z(νν)H , 2 b-tag





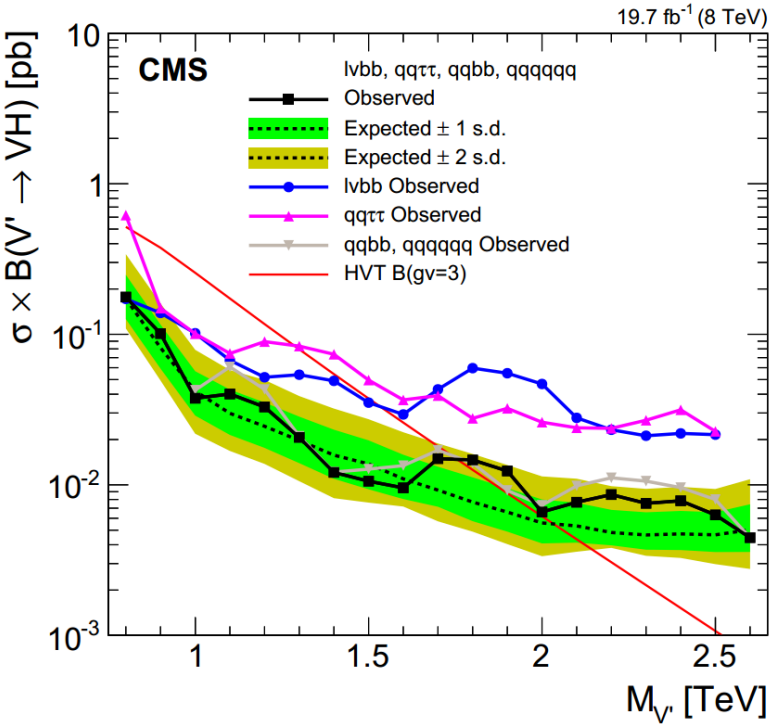


CMS-EXO-14-010
CMS-EXO-13-009

CMS Run1: HVT and Bulk Graviton

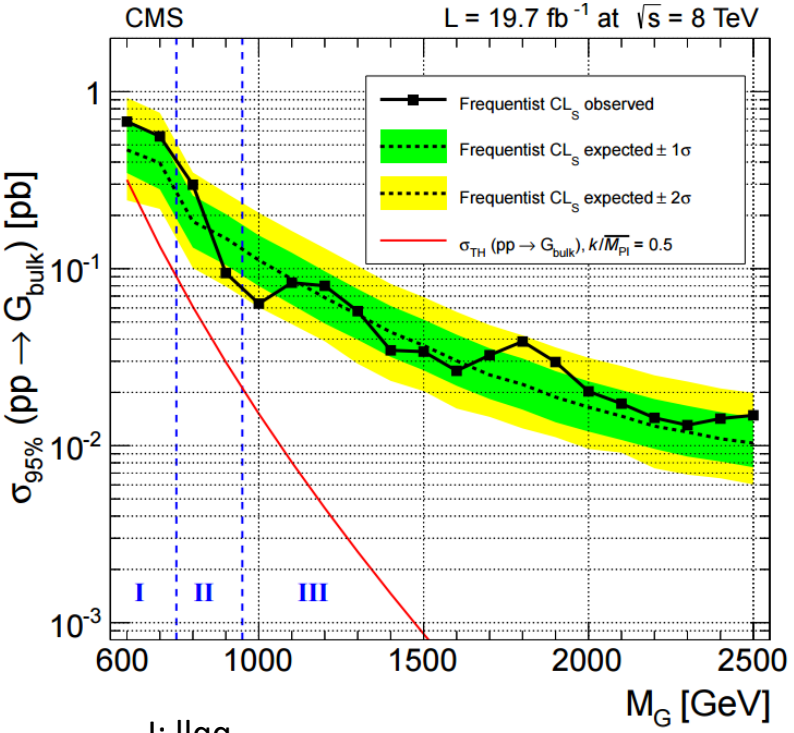
- No significant excess observed

lvbb,qqττ, qqbb, qqqqqq combine



V' limit is slightly improved to 1.8 TeV compared to the qqbb+qqqqqq

qqqq, lvqq, llqq combine

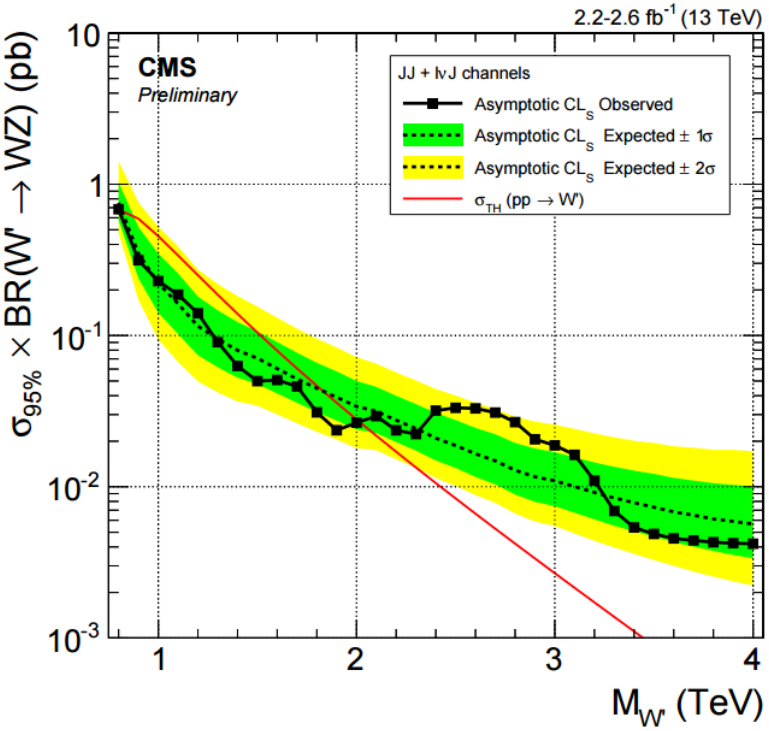


I: llqq
II: llqq+lvqq
III: llqq+lvqq+qqqq

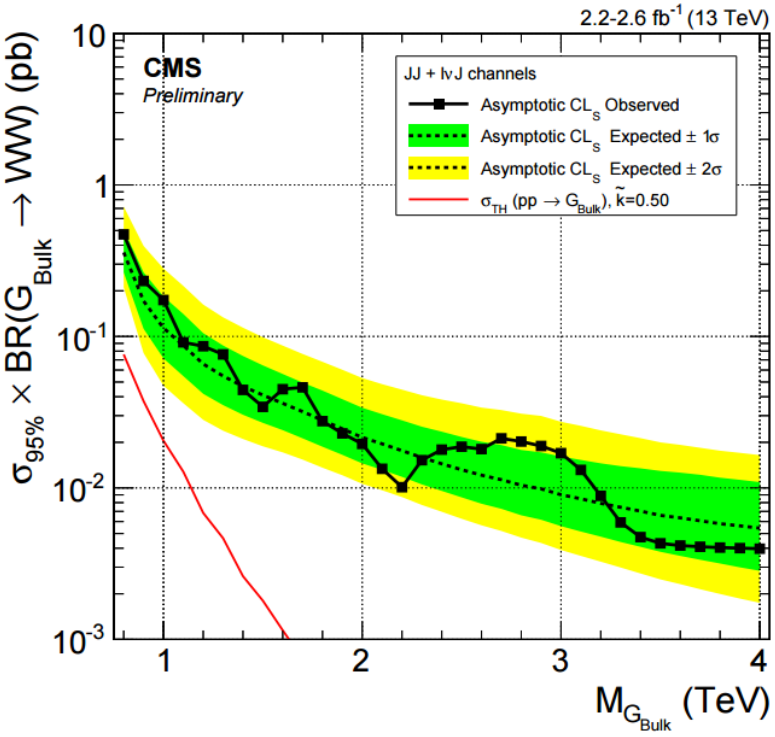
CMS Run2: HVT and Bulk Graviton

- No significant excess observed

qqqq, lvqq combine



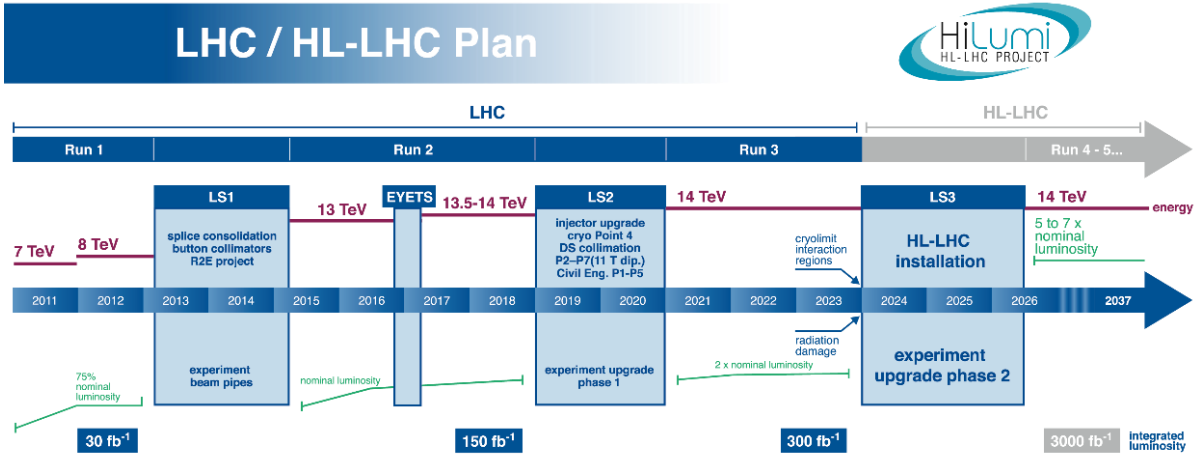
qqqq, lvqq combine



No significant excess is observed in 13 TeV data
W'(HVT) was excluded by ~1.8TeV

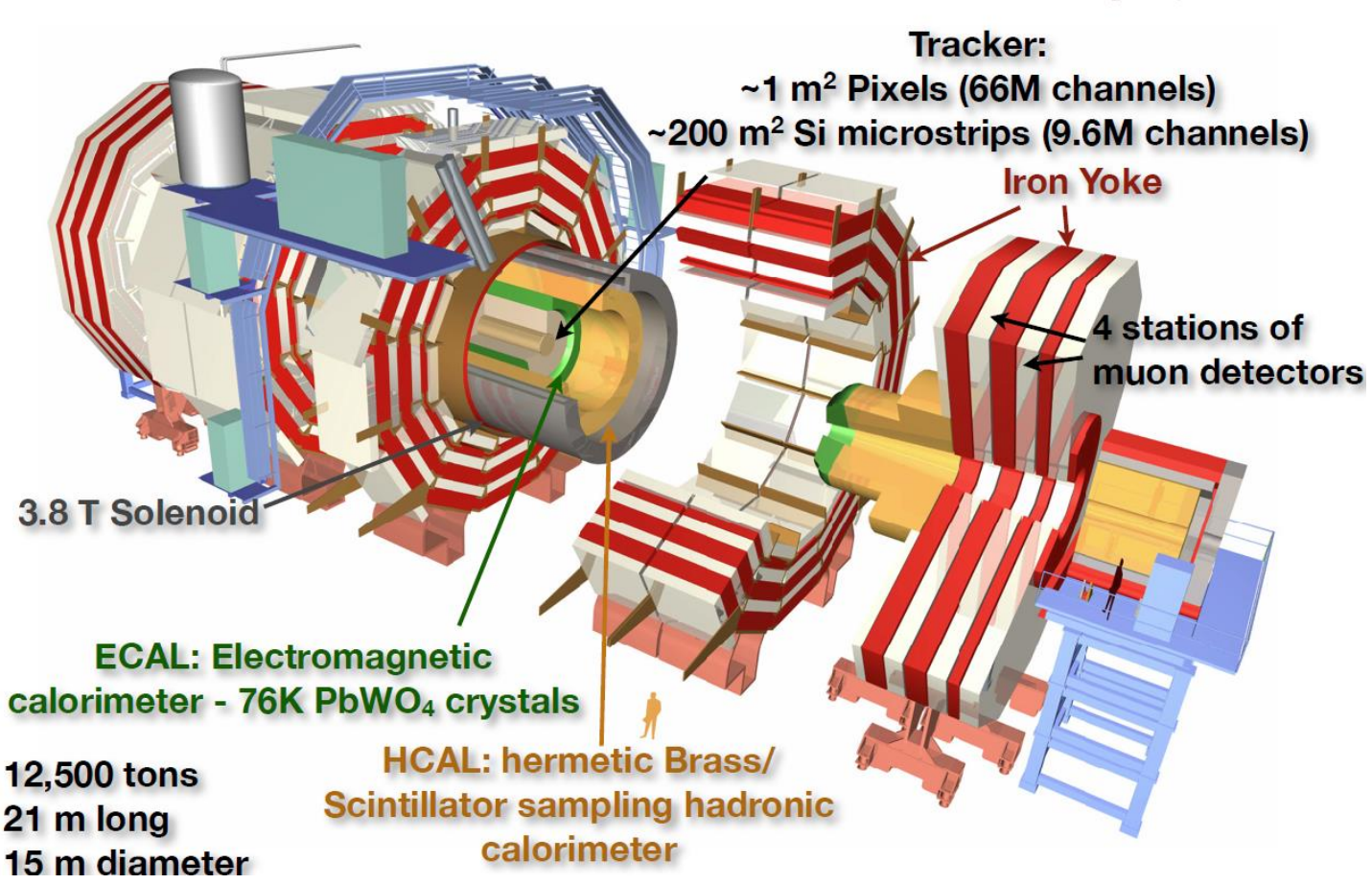
Summary

- Run 2 of the LHC is off to a good start
  - 13 TeV analysis already more sensitive at TeV scale
  - Many great results already now
- Looking forward to 2016 LHC run
  - Many new results expected for this summer
  - 750 GeV, 2-3 TeV, and ultra-high mass region

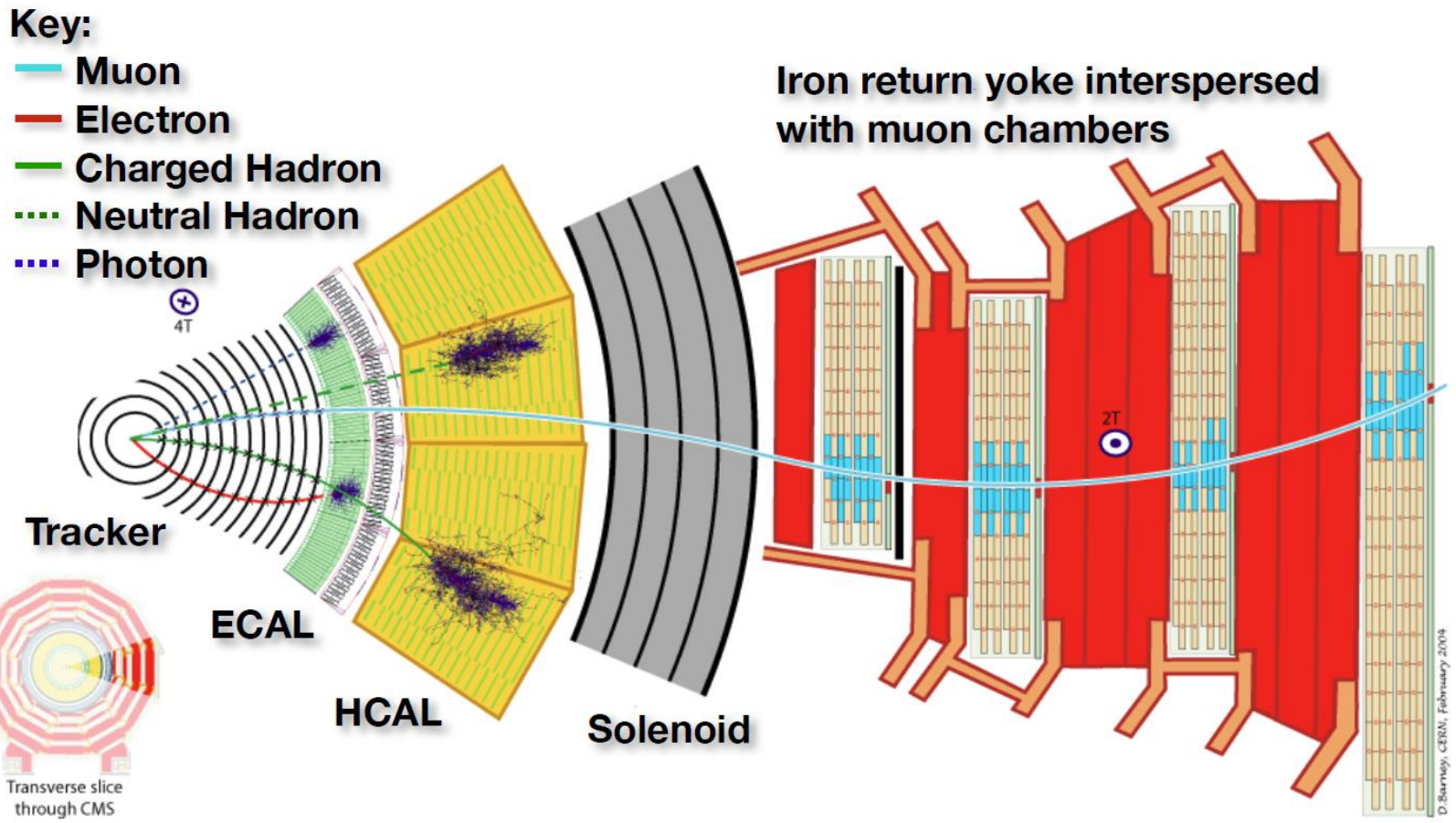


Backup

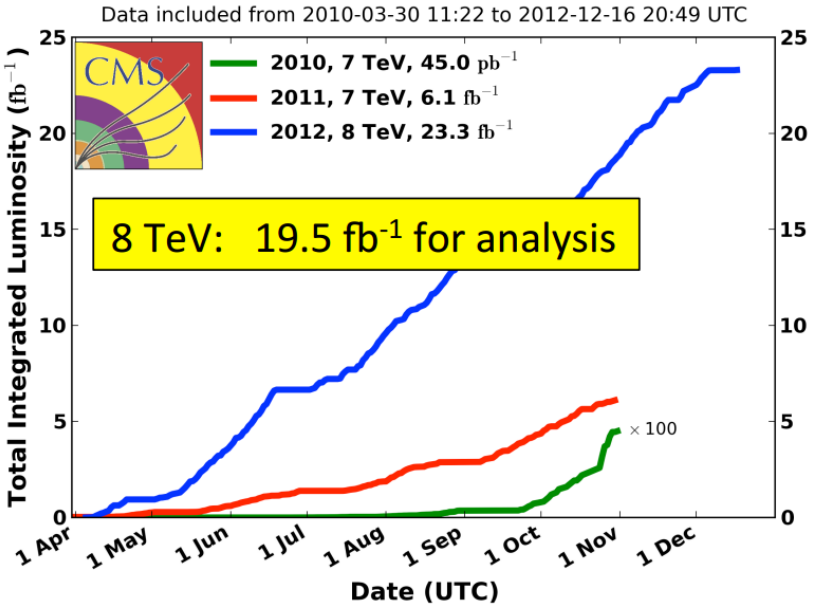
THE COMPACT MUON SOLENOID

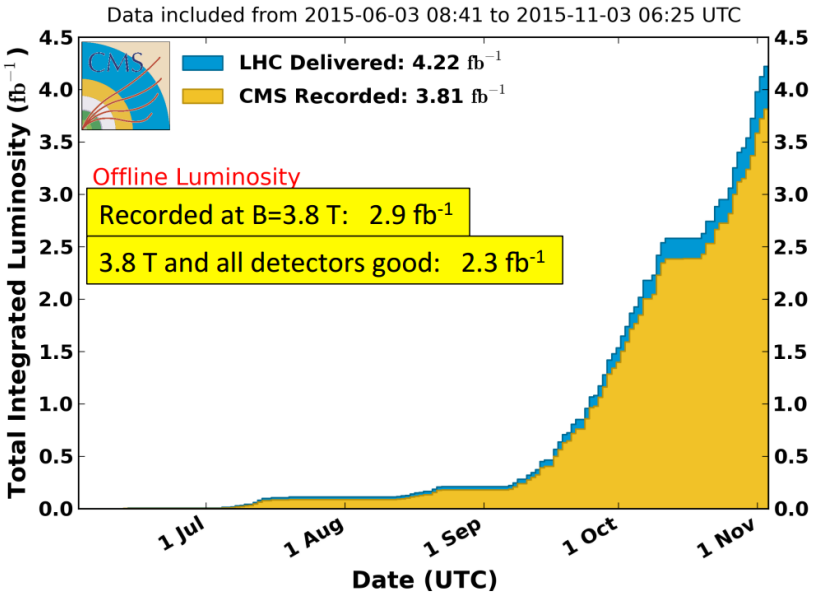


PARTICLE DETECTION AT CMS



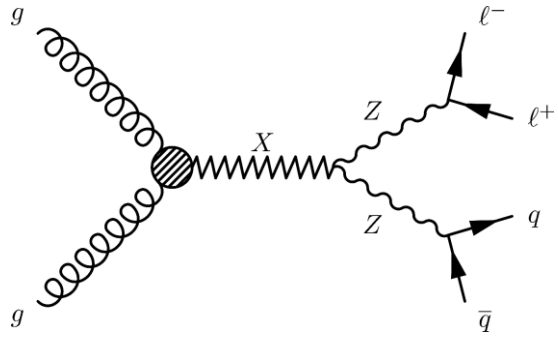
LHC Run1 and Run2

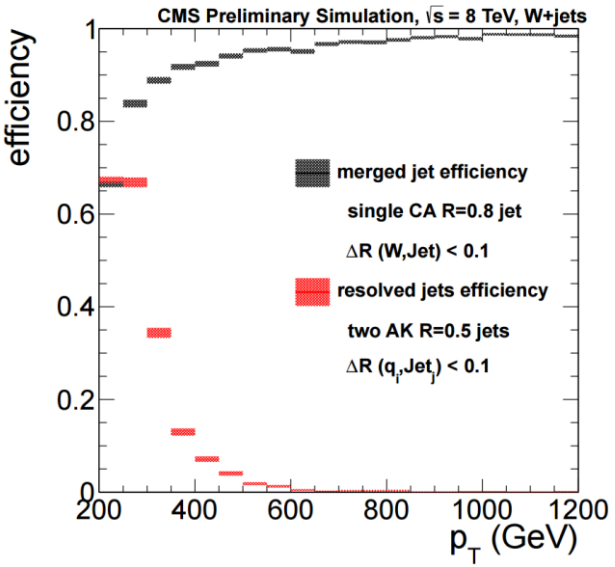




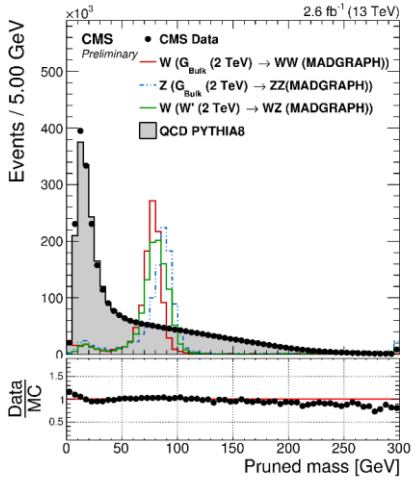
High-Mass Diboson Resonances

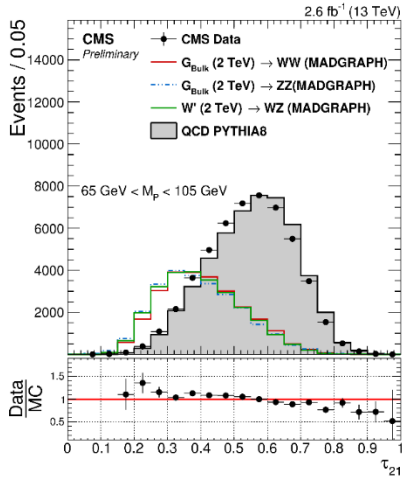
- Growing effort to explore high mass diboson resonances in a large variety of final states
  - WW, WZ, ZZ, WH, ZH, HH
- W, Z, and H all have significant branching fractions to jets
  - When X is massive (typically starting from ~600-900 GeV), traditional dijet search begin to fail
  - Need to use advanced techniques to identify (and even b-tag) merged jets

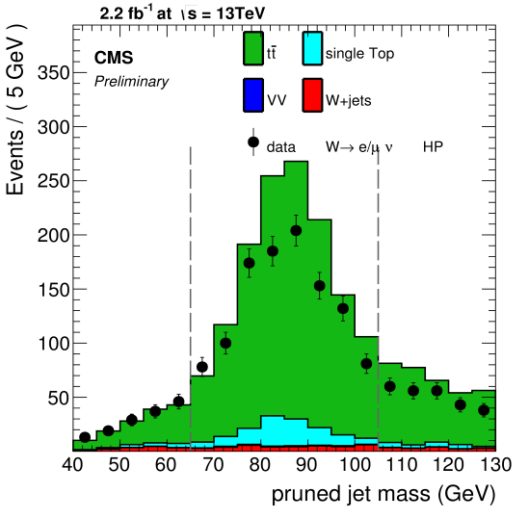




Hadronic W/Z Tagging

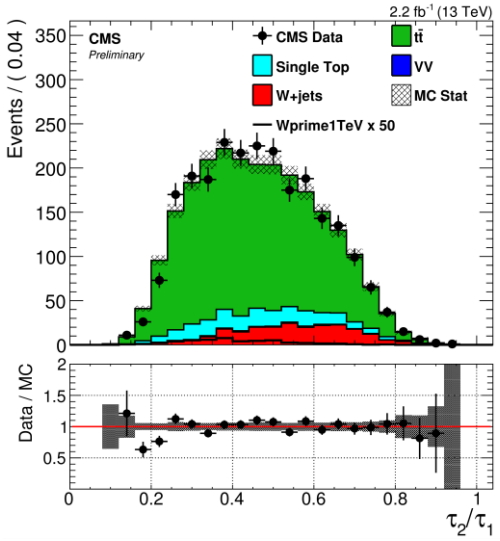




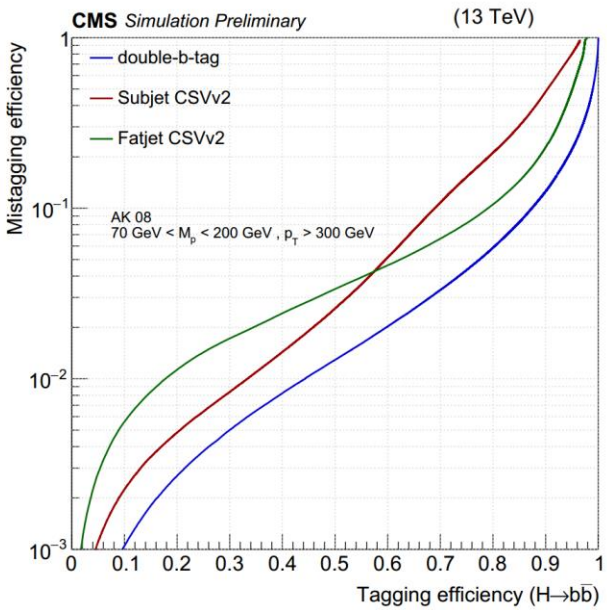


- Fat jet used in 2015
  - AK8, pT>200
  - Jet pruned mass
  - τ2/τ1
- Many interesting new techniques to be explored
  - PUPPI+Softdrop, DDT, …

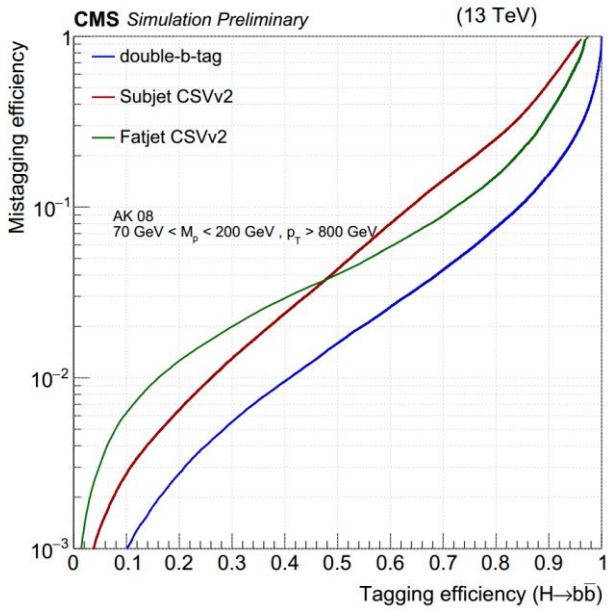
arXiv:1407.6013 arXiv:1603.00027



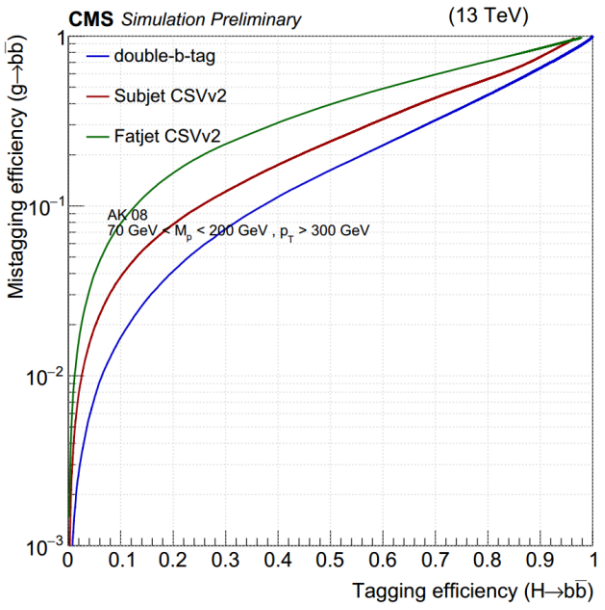
Hadronic H(bb) Tagging



inclusive
pT>300 GeV



inclusive
pT>800 GeV

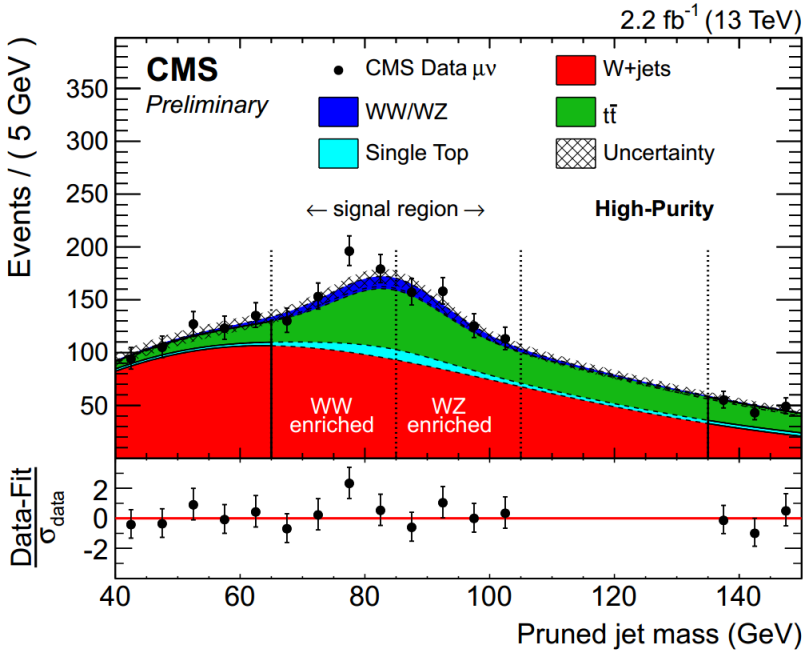


gluon splitting
pT>300 GeV

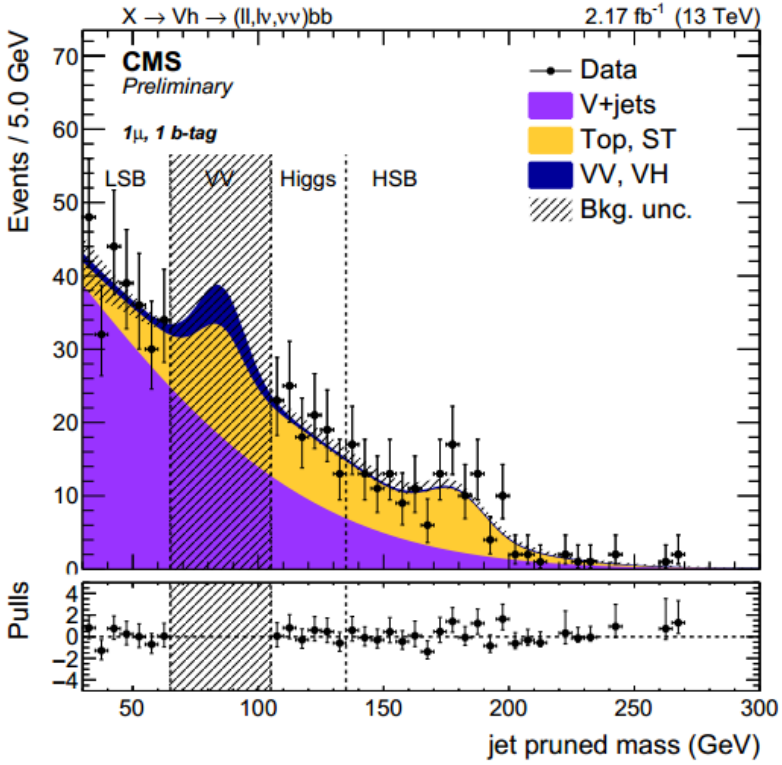
CMS-EXO-15-002
CMS-B2G-16-003

Data-Driven for Backgrounds

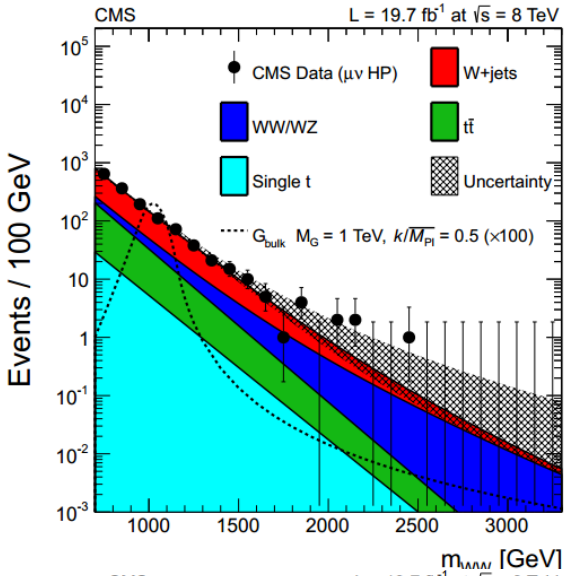
WV run2

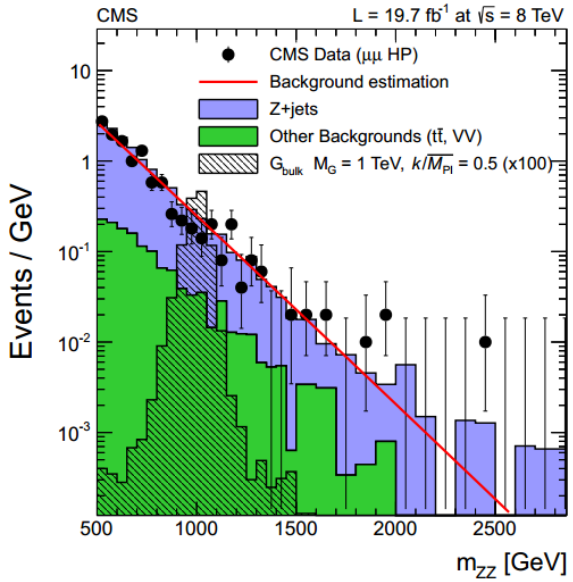


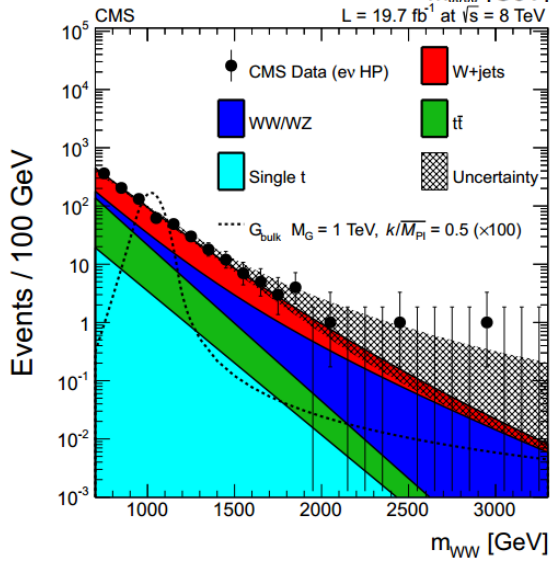
WH run2

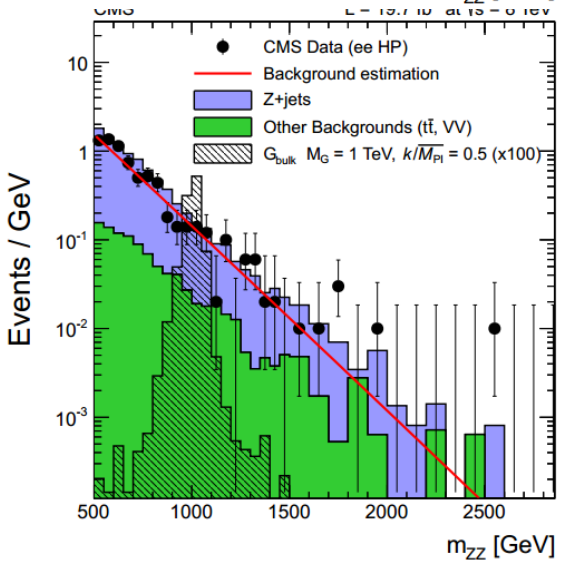


WV, ZV Semileptonic @8TeV

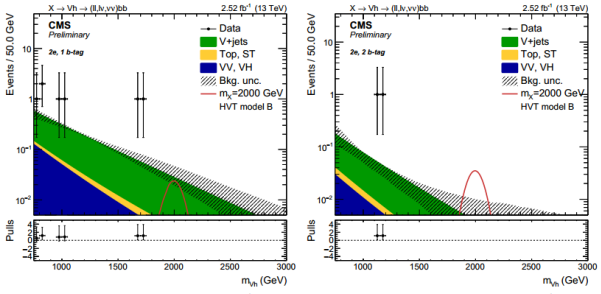


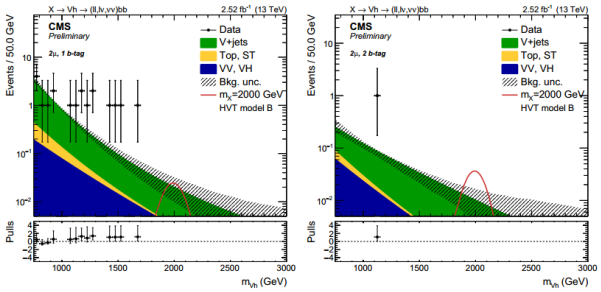


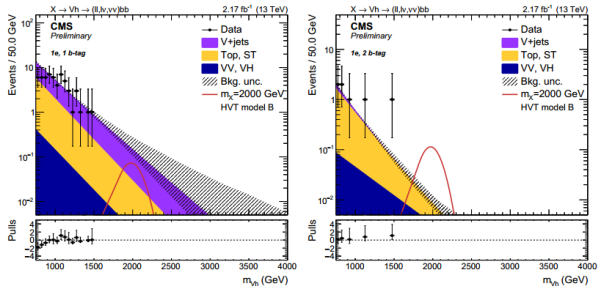


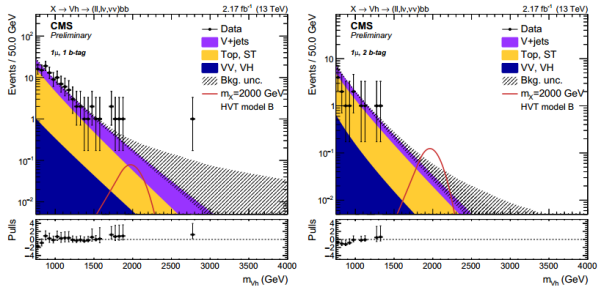


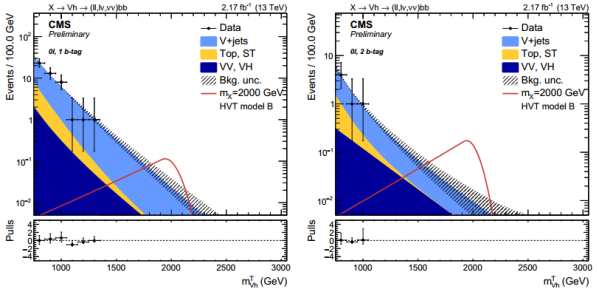
VH Semileptonic @13 TeV

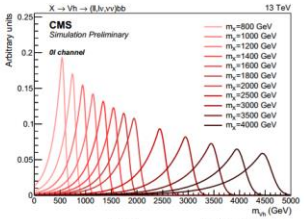


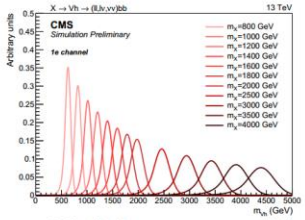


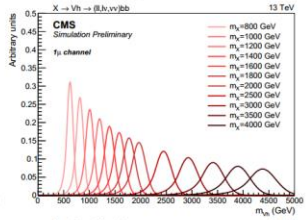


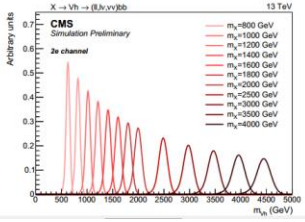


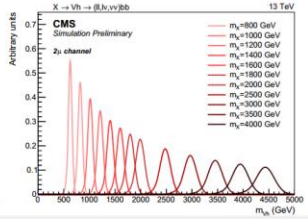




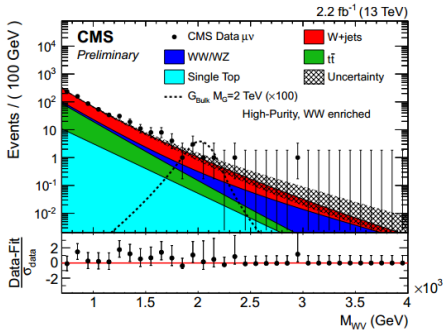


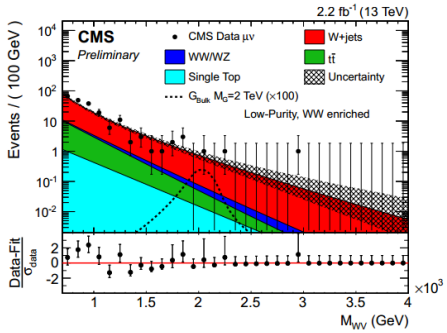


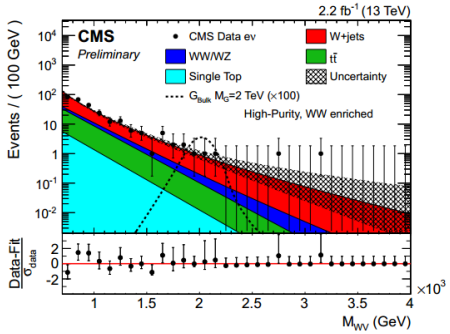


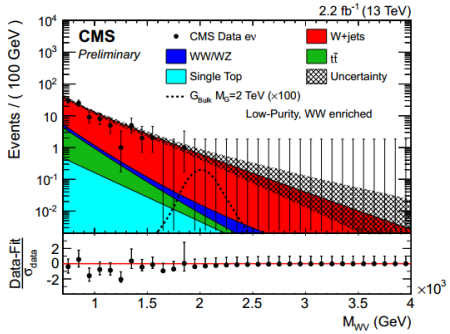


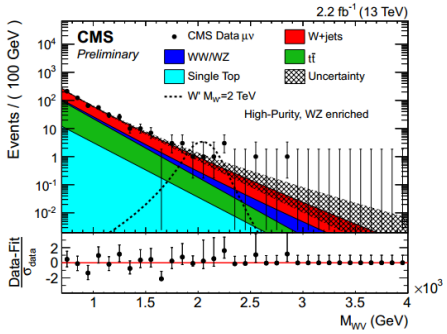
WV Semileptonic @13TeV

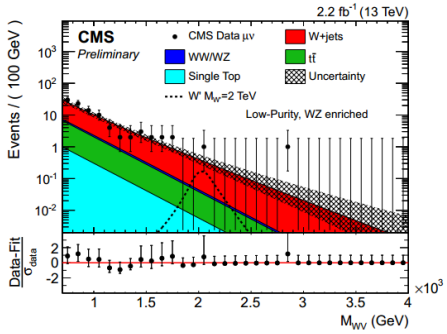


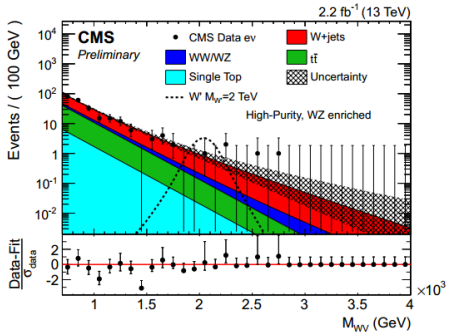


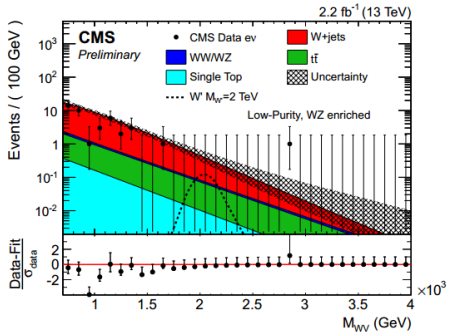




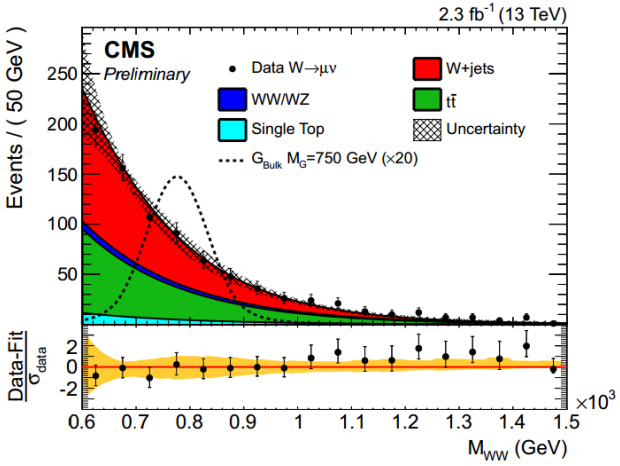


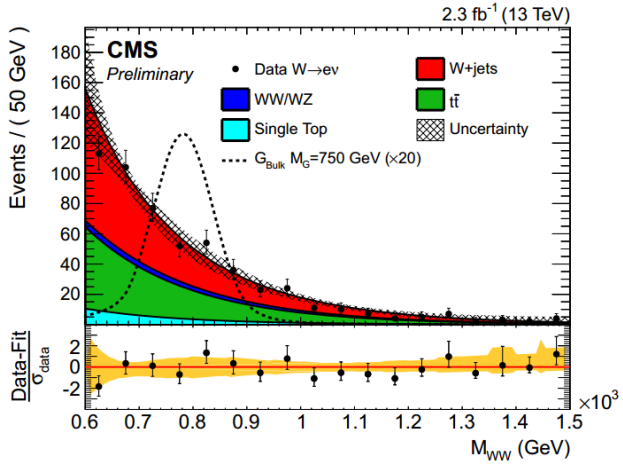


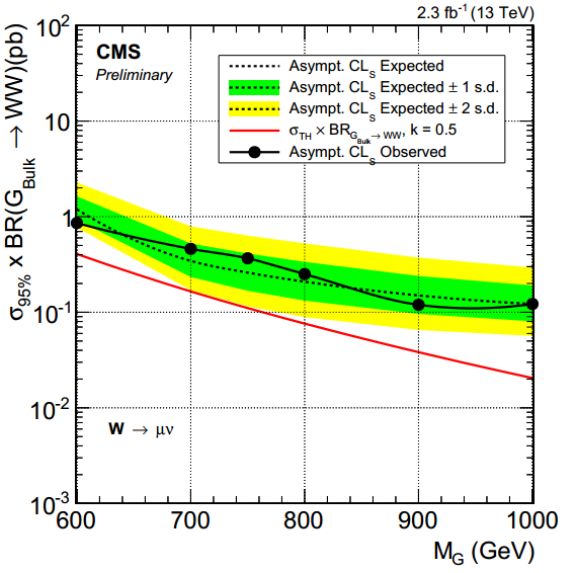


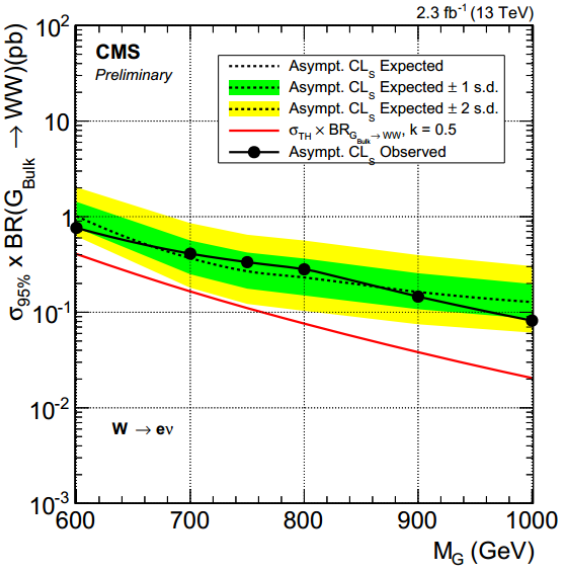


WV Semileptonic @13TeV









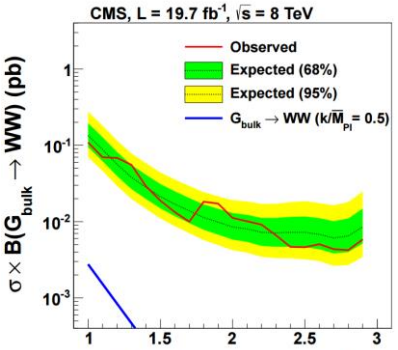
Systematics Uncertainty

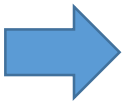
- WV search
  - Signal: PDF, scale, W-tagging scale factor,…
  - Background normalization
    - W+jets normalization driven by amount of data in sideband
    - TTbar and Single Top normalization by the scale factor derived in top-enriched control sample
    - VV normalization by the W-tagging scale factor derived in top-enriched control sample
  - W+jets M_{VV} shape
    - M_{VV} shape in sideband driven by data
    - alpha shape driven by W+jets MC statistics
- ZV search is very similar to the WV search
  - Same hadronic V-tagger for example
  - Special lepton ID for boosted topologies

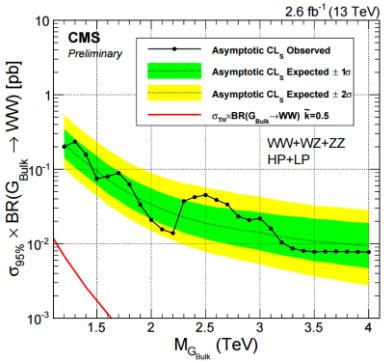
CMS Run1 → Run2

- Sensitivity higher for 13 TeV analysis due to parton luminosity and cut optimizations
- New for 13 TeV: Sensitivity improved when splitting into W/Z mass categories

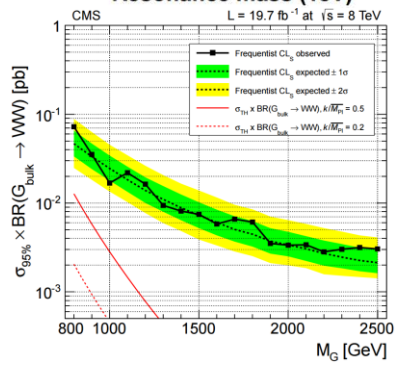
VV

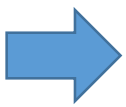


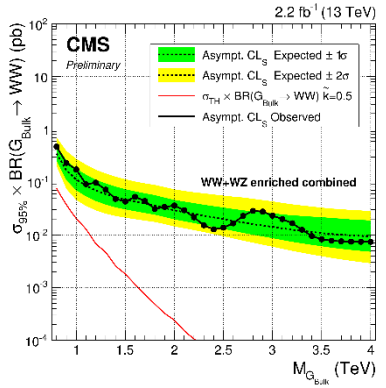




WV







CMS Run1: VV+WV+ZV

- No significant excesses observed combining all-hadronic and semileptonic channels