Di-boson Resonance Searches at CMS

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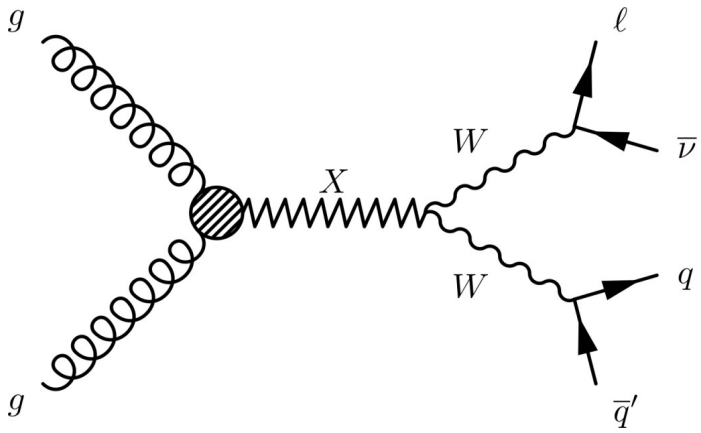
Outline

- Introduction and physics motivation
- Exotica WW resonance search
- Exotica WH resonance search
- Other search
- Summary

(1) EXO-VV: JHEP08(2014)174 ;
(2) W-tagging at CMS: JHEP1412 （2014） 017 , CMS PAS-JME-13-006
刘帅，徐子骏，邹伟 Pre-approval talk
(3) EXO-WH: CMS PAS-EXO-14-010 public weeks ago
王蒙蒙 Pre-approval ，李强 Analysis Contact

Introduction

Many Extensions of the SM predict heavy resonances decaying to vector boson pair

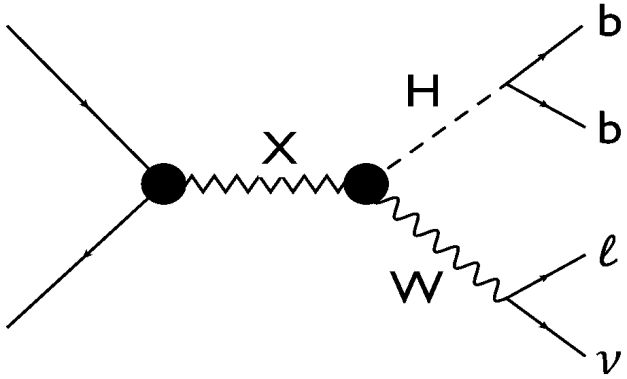


- **VV, VH resonance motivated in many nice models**

  Extra Dimension, Composite Higgs, Little Higgs, Bulk graviton model

- **V/H highly boosted: Jet substructure and/or subjet b-tagging**

  TTbar control Region, Scale Factor



  - WZ decaying into leptons
    - $W'/\rho_{\mathrm{TC}} \to WZ \to 3\ell + E_T^{\mathrm{miss}}$ (EXO-12-025)
  - WW, one W decaying leptonically, other hadronically
    - $G_{\mathrm{bulk}} \to WW \to \ell + E_T^{\mathrm{miss}} + \mathrm{jet}$ (EXO-12-021)
  - WW, WZ, ZZ, each V decaying hadronically
    - $G_{\mathrm{RS}} \to WW/ZZ$ and $W' \to WZ$ (EXO-12-024)
  - WH, W decaying leptonically, H hadronically

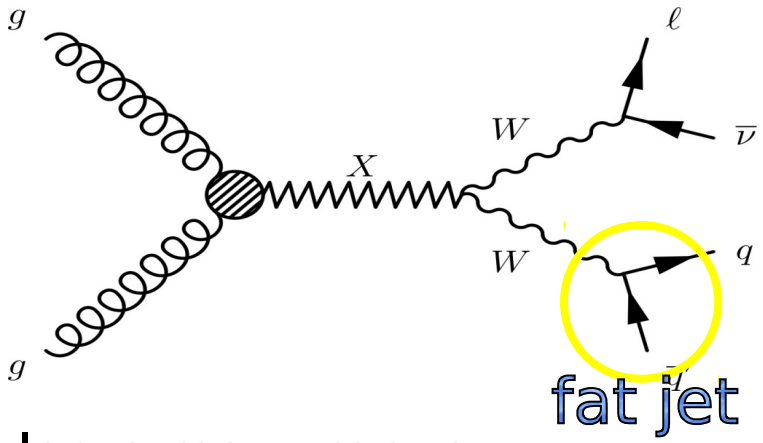
    W' → WH → lep + MET + jet

Exo-WW Resonance

Introduction

- **Search for new resonsances decaying to**

  WW semi-leptonic final state



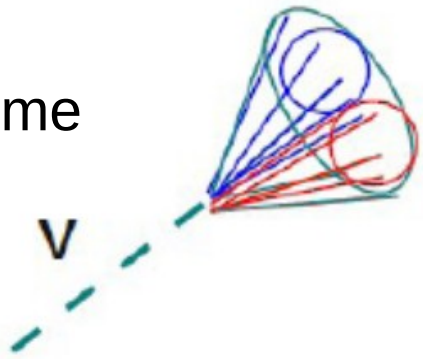
- Look for “bumps” in the mWW spectrum in a large mass range

  M_WW in [800, 2500] GeV

- Bulk Graviton Model : G-> $W_L W_L$ is used as a benchmark
- The WW final state represents a benchmark for future di-boson scattering measurements at high mass

  is meaningful: TGC, unitarization ....

  jet sub-structure will be fundamental in high boosted regime



Fat Jet at CMS: an incomplete history

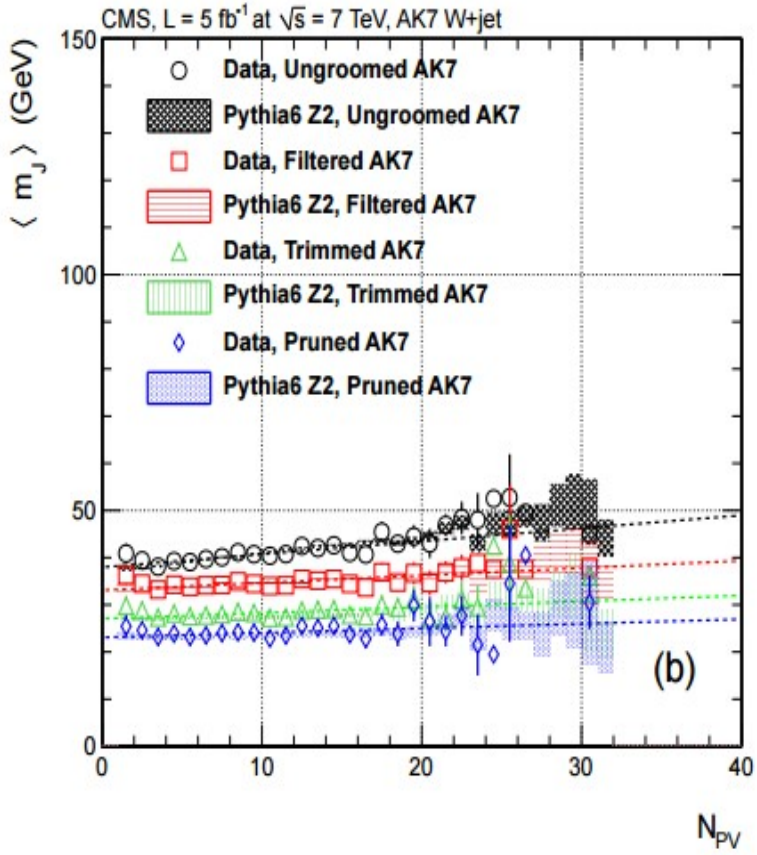
7TeV Z'->ttbar: **Proposed Jet Pruning, C-A 0.8 Jet, TTbar control**
JHEP 1209 (2012) 029, Erratum-ibid. 1403 (2014) 132

7TeV WZ/ZZ resonance:
Jet mass, mass drop: JHEP 1302 (2013) 036

Dijets and V+jets,
jet mass and substructure at 7 TeV:
Comprehensive overview of various jet grooming techniques: JHEP 1305 (2013) 090

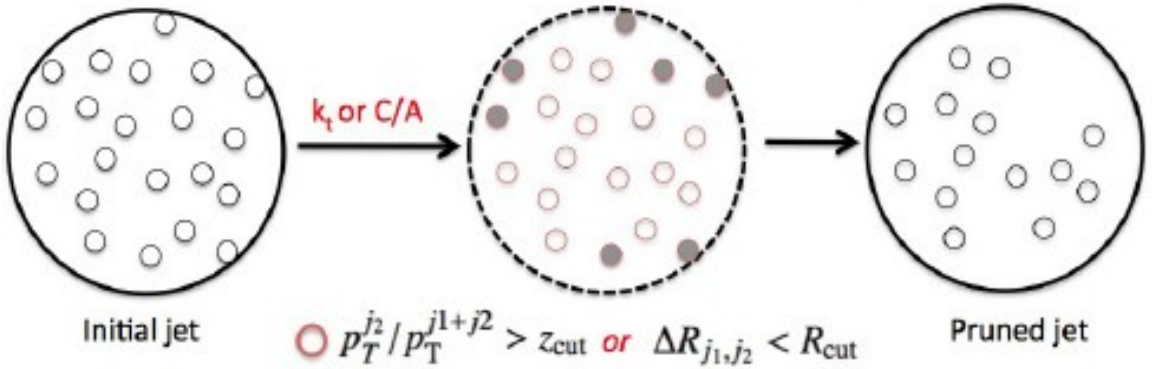
8TeV WW/WZ/ZZ resonance:
W-tagging, Pruning, CA8, Nsubjettiness
JHEP 1408 (2014) 173 ; JHEP 1408 (2014) 174

W-tagging Summary: **JHEP 1412 (2014) 017**
Top tagging …….



W-tagging

- **"Pruning"** http://arxiv.org/abs/0912.0033 (S. Ellis, C. Vermilion, J. Walsh)
  - Recombine jet constituents with C/A or kt while vetoing wide angle (R_{cut}) and softer (z_{cut}) constituents. Does not recreate subjets but prunes at each point in jet reconstruction



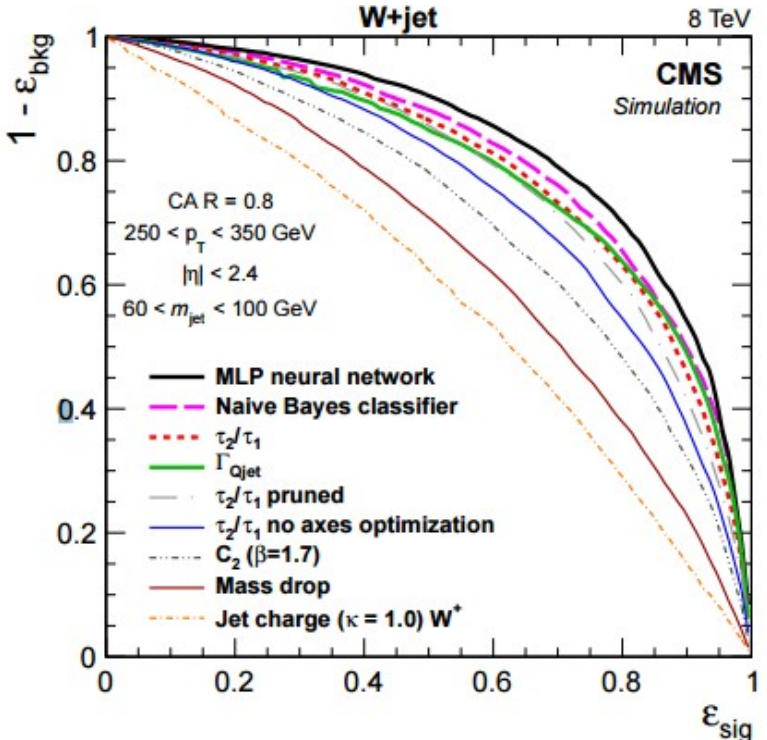
Tuned parameters: R_{cut} and z_{cut}

N-subjettiness (arXiv:1011.2268):

how likely is a jet to have "N" subjets

Wjet tagger: *tau2/tau1*

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\}$$



Higgs Tagging: a little beyond W-tagging

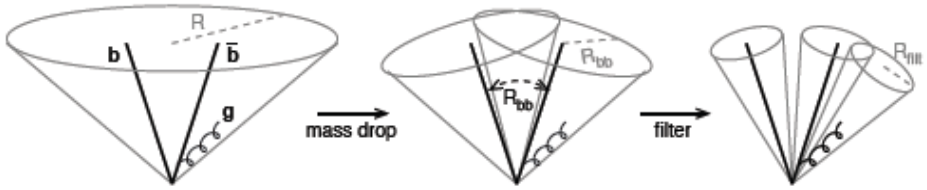
1. Mass of the H-jet as the main discriminating variable against QCD jets

Boosted H-boson:

- b-quarks merged into a single jet
- recontructed with CA algorithm with R=0.8
- traditional dijet searches cannot be performed
- use jet substructure techniques

H-tagged jet ➠ $110 < m_{jet}^{pruned} < 135$ GeV

Jet substructure: jet pruning



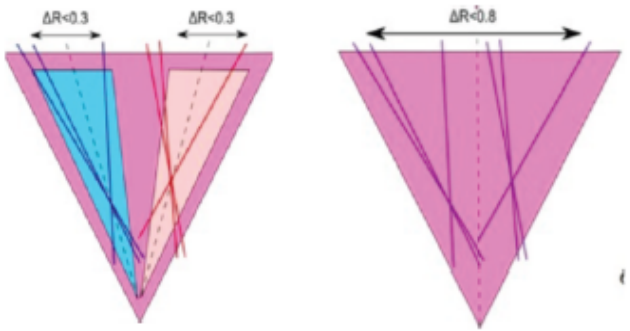
- removes the softest components of a jet
- improves discrimination by pushing the jet mass for QCD jets towards lower values while maintaining the jet mass for the H-jet at the H-mass
- studied in detail for W-tagging: JME-13-006

2. Discriminate b-quark initiated jets from light quark or gluon jets

- use CSV b-tagging algorithm
- the jet is split into 2 subjets by undoing the last iteration of the pruned jet clustering
- **subjet b-tagging:** apply b-tagging to the subjets if $\Delta R > 0.3$
- **fat jet b-tagging:** when the subjets are too close ($\Delta R < 0.3$) apply b-tagging to the CA8 jet
- studied in detail in BTV-13-001

Combined b-tagging:

Subjet b-tagging Fat jet b-tagging



worse performance because JTA cones overlap

Object

Data: Full 2012 8TeV data by CMS, 19.7fb-1

Signal: Bulk graviton from JHUGEN

Main Background: Wjets, TTbar, single Top, Di-boson

- **Signature:** **WW → l (μ, e) + MET + Merged Jet**

Muon ID + Selection:

High pT Muon ID (Old) [1]

pT > 50 GeV, |eta|<2.1

Electron ID + Selection:

Electron HEEP ID [2]

pT > 90 GeV, |eta|<2.4

Veto on extra loose leptons:
Pass id/iso, pt>20(35) for mu(ele)

MC lepton efficiencies corrected by Tag&Probe on Z

PF Met + Type I + Shift Correction

Jets from single quark not resolved in boosted regime

Merged Jet from CA8 CHS

→ Loose Jet ID

→ TOBTEC Filter [3]

AK7 JEC applied on CA8

AK5 for standard btag cuts
Loose jet ID + pt>30GeV

Pre-Selection

- **Event Selections :**

1) PT_wlep >200 GeV
2) PT_AK8 >200GeV
3) PFMET > 40 (80) GeV for muon (electron) channel
4) Lepton PT > 50 (90) GeV for muon (electron) channel
5) b-tagging veto: no btagged AK4 jets (CSVM)
6) back to back topology: dR(lep, jet)>π/2, dφ(jet, W)>2.0, dφ(jet, MET)>2.0

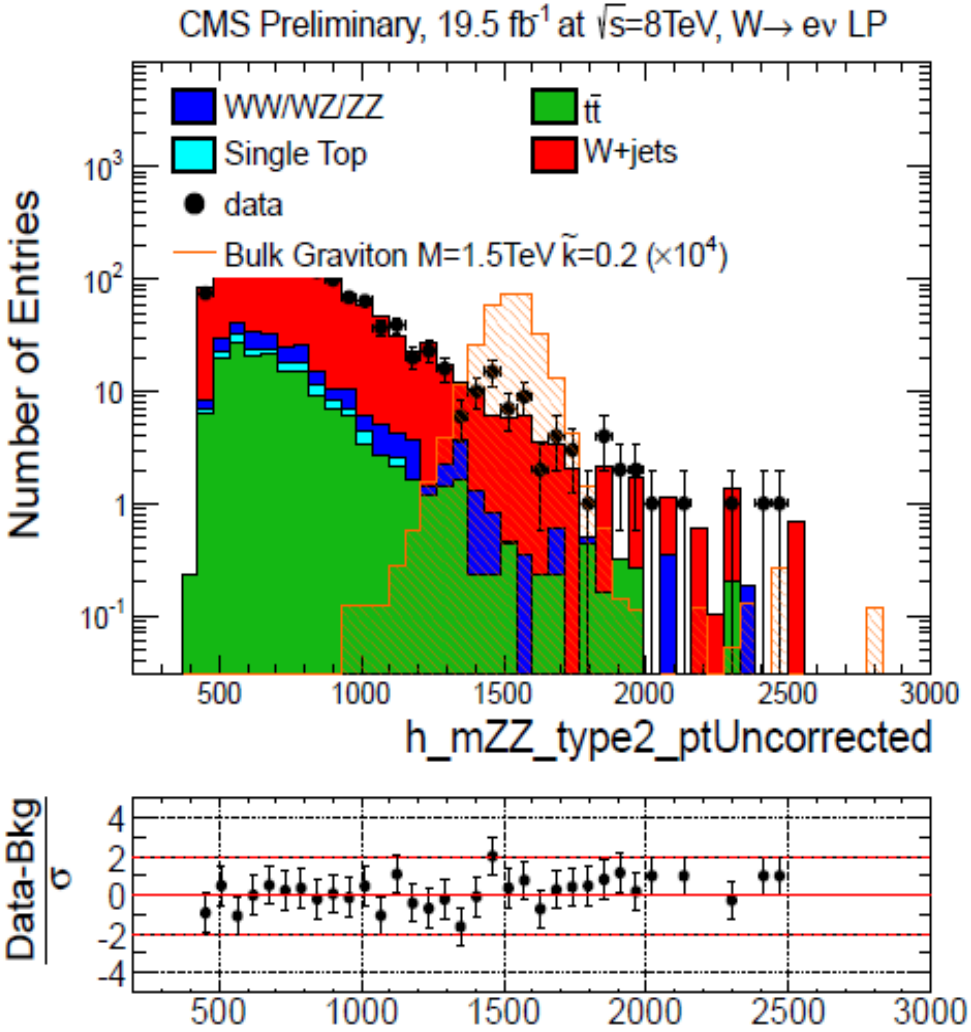
- **Control Plots at Pre-Selection Level:**

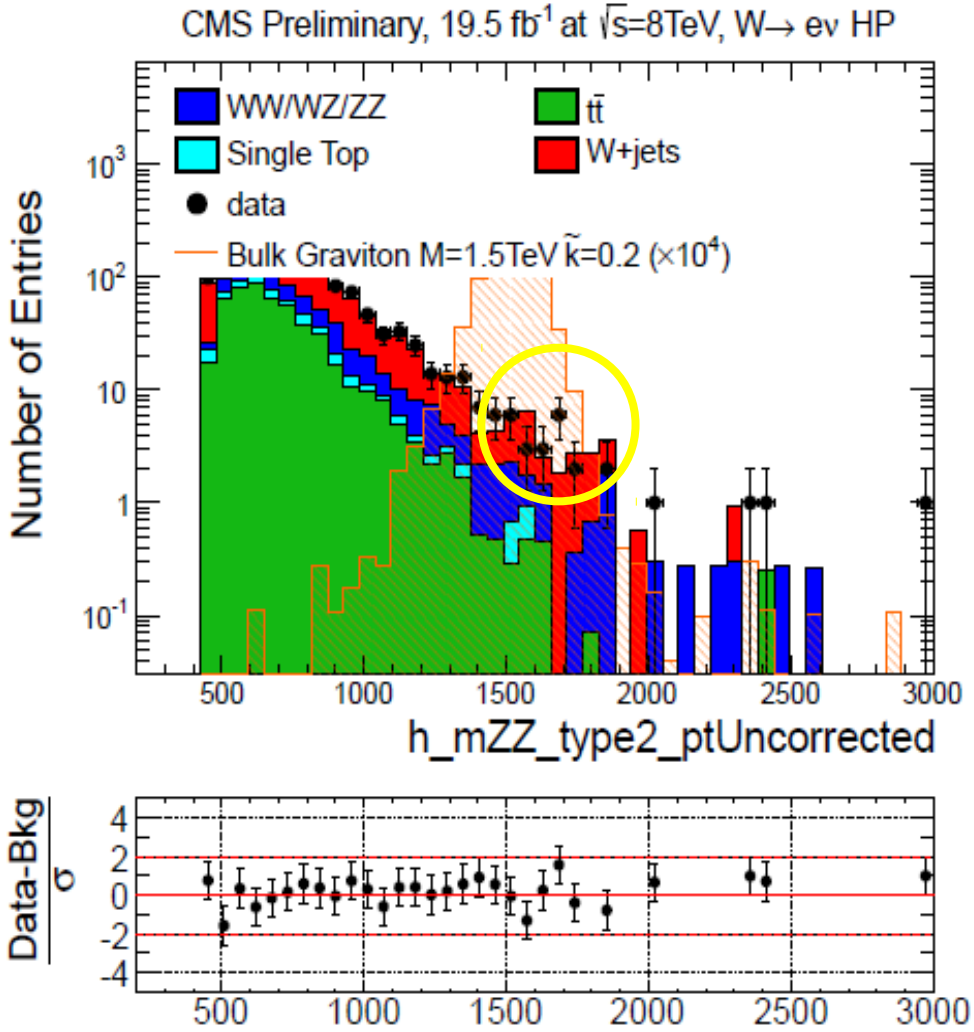
all the above selection are applied

Cut on the jet mass(Pruned) : [40,130] GeV SB+SR

[65, 105]

Distribution Plots: ele channel





W-jet tagging

- **In this analysis we have 4 main sources of Bkg. : W+jets TTbar WW/WZ SingleTop**

TTbar + SingleTop : Shape from MC + TTBar Scale Factor on normalization

WW/WZ : Shape from MC + W-Tag Scale Factor on normalization

W+Jets : W+jets normalization and shape from fit to data

1) Fit in SB to extract W+jets normalization in SR

2) Alpha Function from MC:

$$\alpha_{\mathrm{MC}}(m_{lvj}) = \frac{F_{\mathrm{MC,SR}}(m_{lvj})}{F_{\mathrm{MC,SB}}(m_{lvj})}$$

Fit signal region wjets MC

Fit **low** sideband region wjets MC

3) Data Driven Background Extrapolation in the SR

$$F_{\mathrm{data,SR}}(m_{lvj}) = \alpha_{\mathrm{MC}}(m_{lvj}) \times F_{\mathrm{data,SB}}(m_{lvj})$$

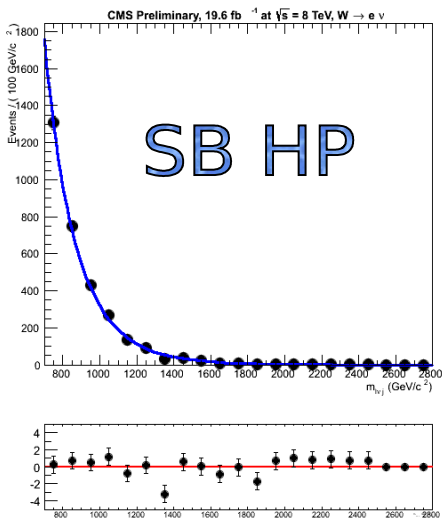
Estimated wjets shape in signal region

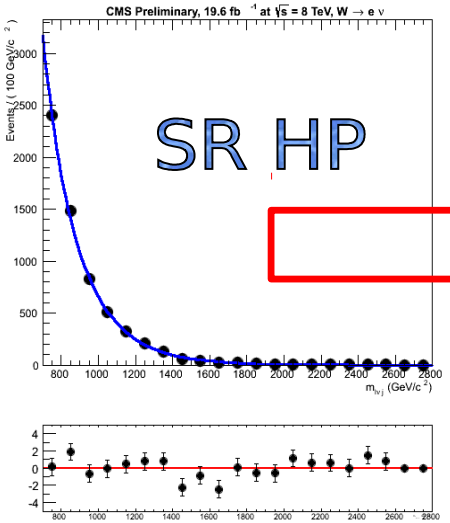
Fit Data sideband with summed components to get wjets shape in **low** sideband region

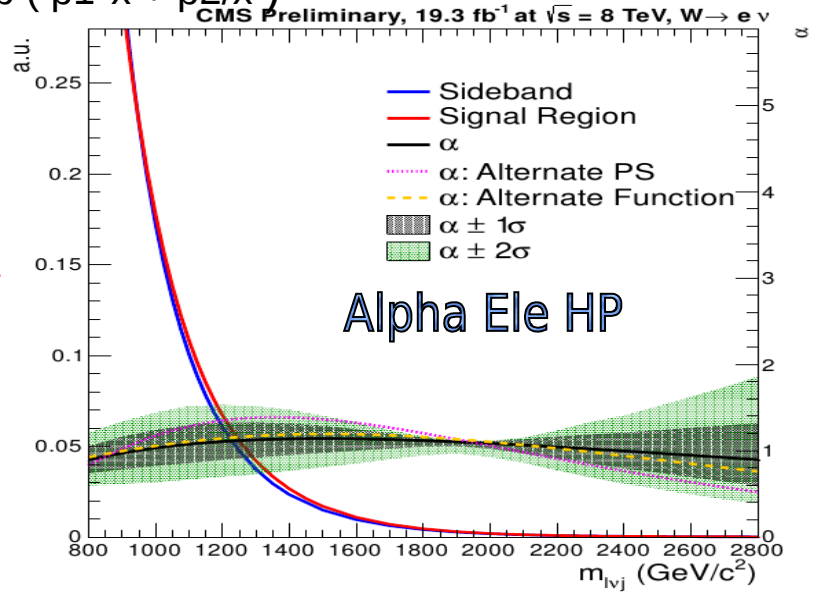
Extrapolation Function Alpha

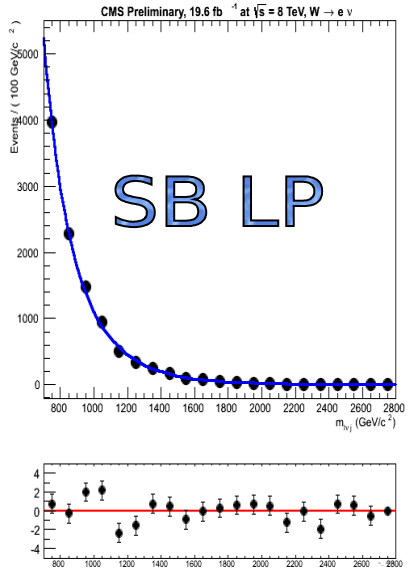
Fit Wjets MC in signal region and sideband region

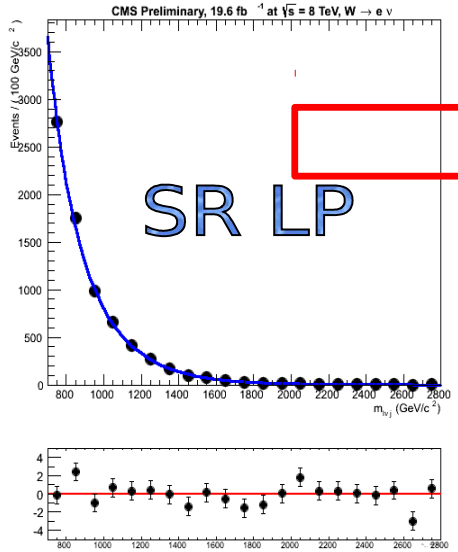
$f(x) = \exp (p1*x + p2/x)$

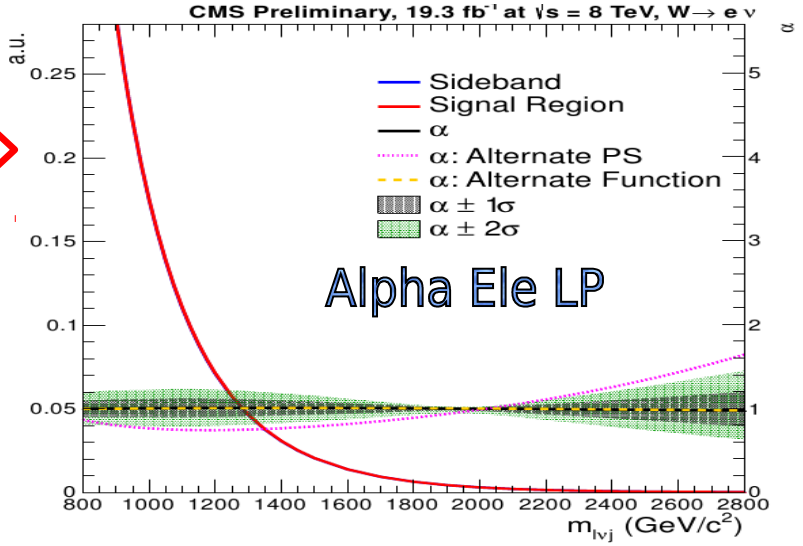












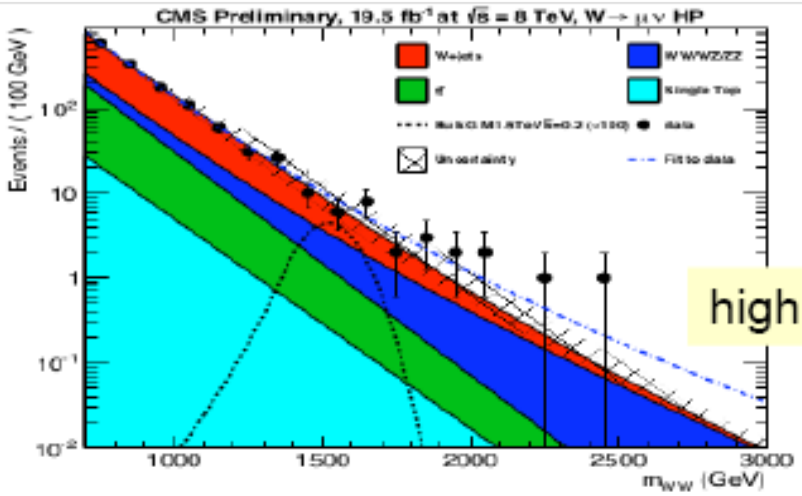
W-jet tagging

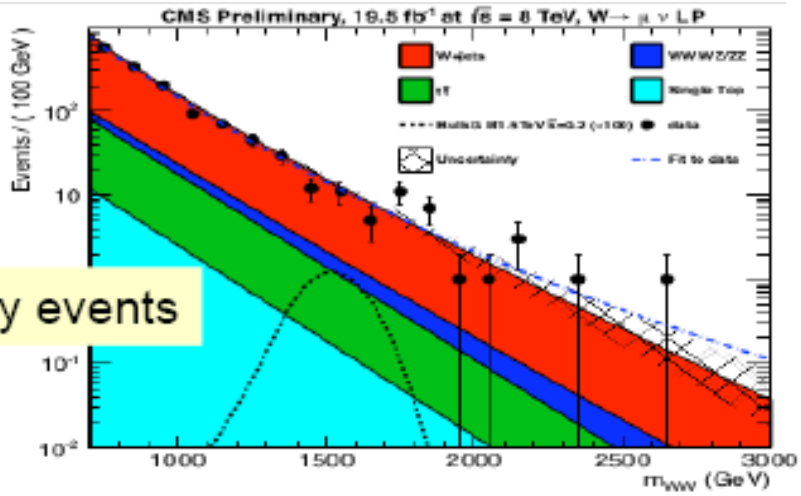
high purity events

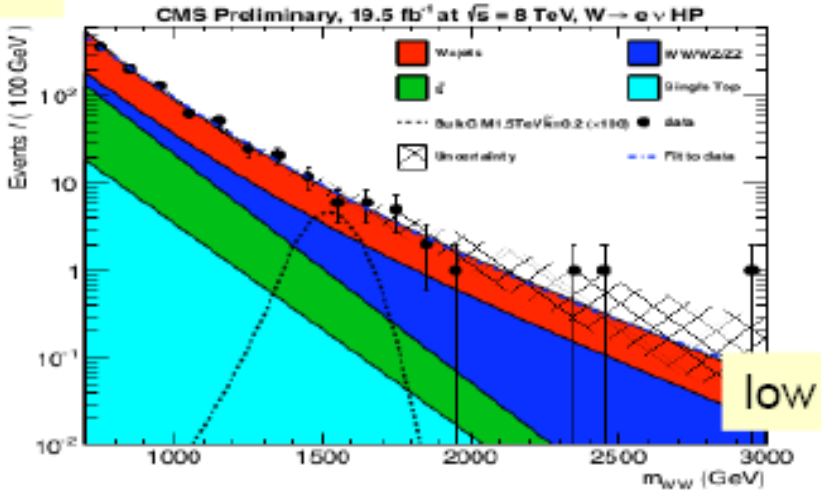
low purity events

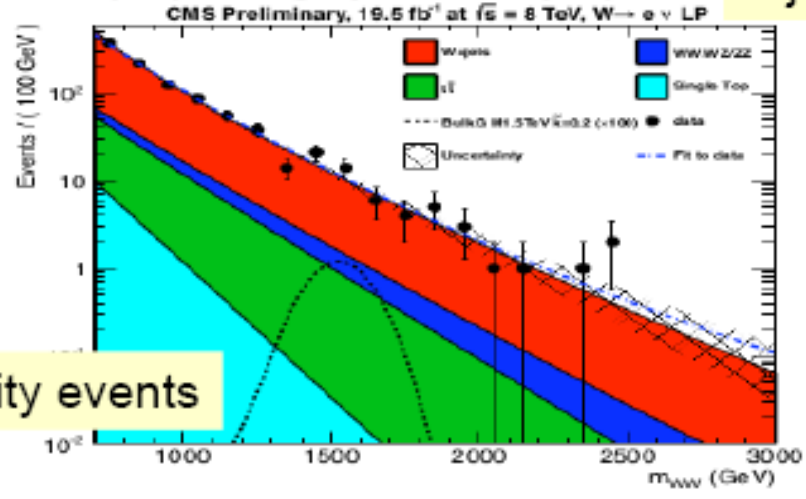
muon + jets

electron + jets

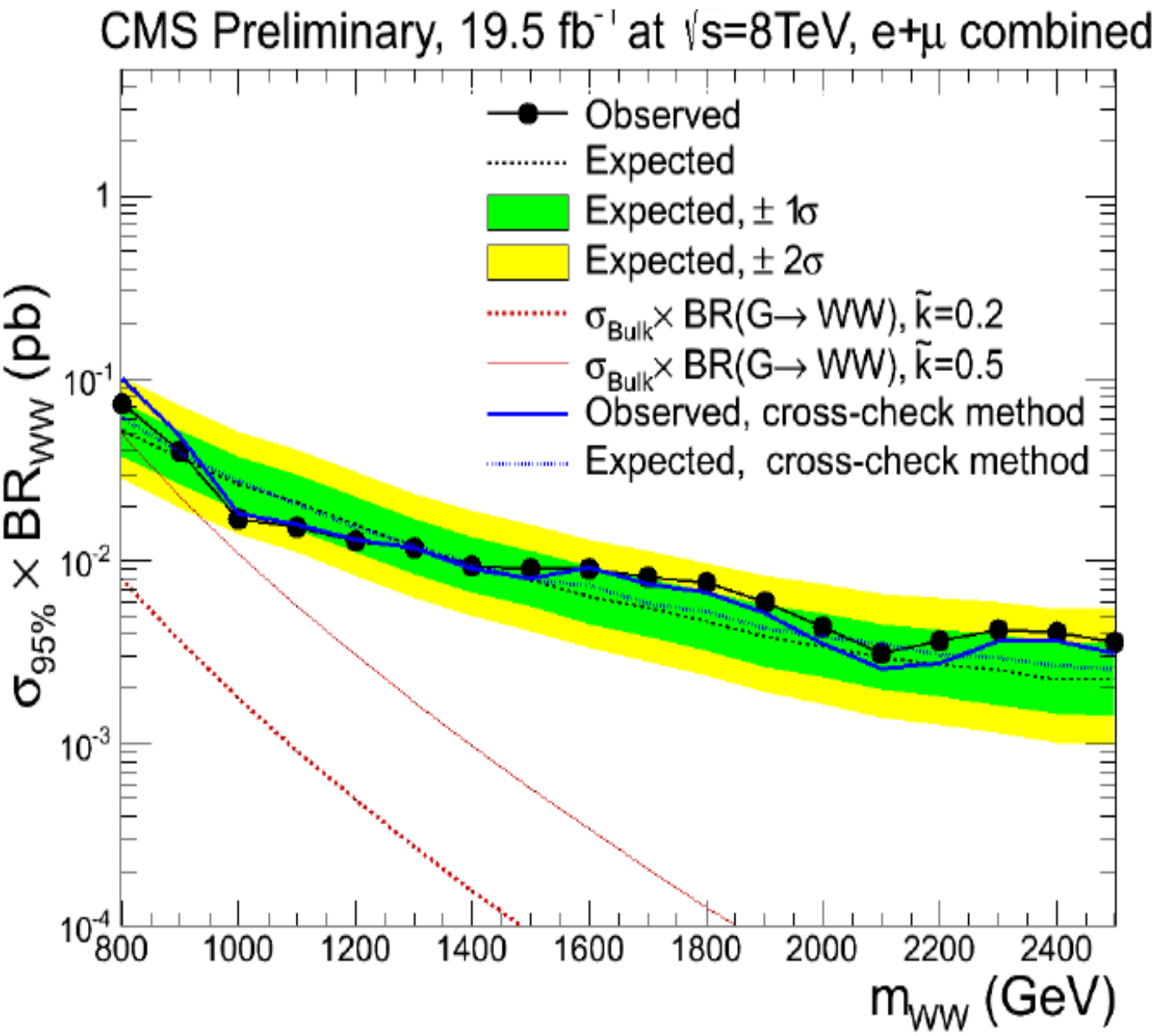








Result


CMS Preliminary, 19.5 fb^{-1} at √s=8TeV, e+μ combined
Observed
Expected
Expected, ± 1σ
Expected, ± 2σ
σ_{Bulk}× BR(G→ WW), $\tilde{k}$=0.2
σ_{Bulk}× BR(G→ WW), $\tilde{k}$=0.5
Observed, cross-check method
Expected, cross-check method
$\sigma_{95\%}$ × BR_{WW} (pb)
m_{WW} (GeV)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
800
1000
1200
1400
1600
1800
2000
2200
2400

Exo-WH Resonance

Introduction: Physics V'->VH

- **Many well motivated New Physics Model predict extra gauge boson**

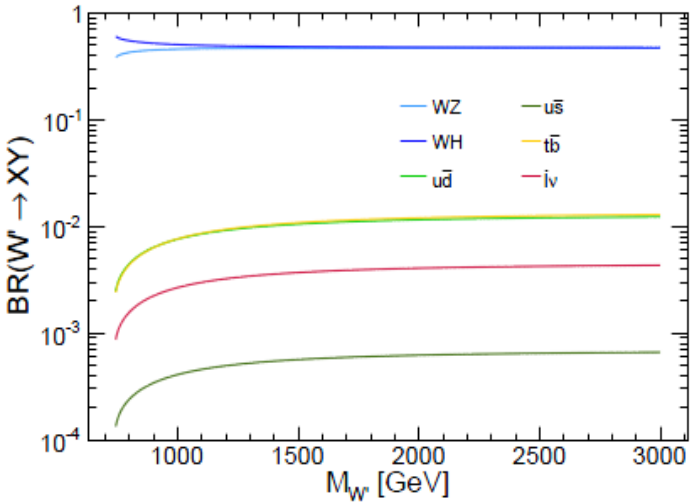
  (1) Heavy Vector Triplet D.Pappadopulo et.al., JHEP 1409 (2014) 060

  (2) Little Higgs see e.g. JHEP 0601 (2006) 099

- **V' can have enhanced coupling to boson**

  Model B case of (1), gv >3

  -> Composite Higgs Model



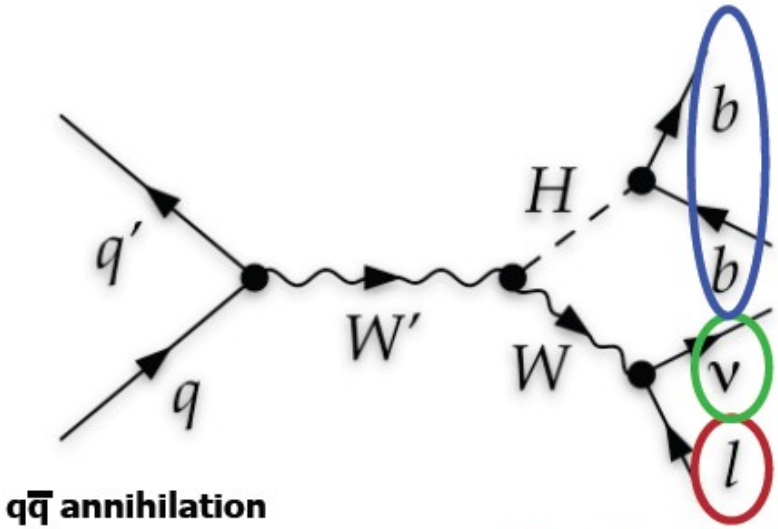
- **One of the first resonance searches looking for boosted Higgs**

  CMS PAS EXO-14-009 V'->VH->fully hadronic

  CMS arXiv:1502.04994 Z'->ZH->jjττ

  ATLAS arXiv:1503.08089 V'->VH->ll/lv/vv+bbar

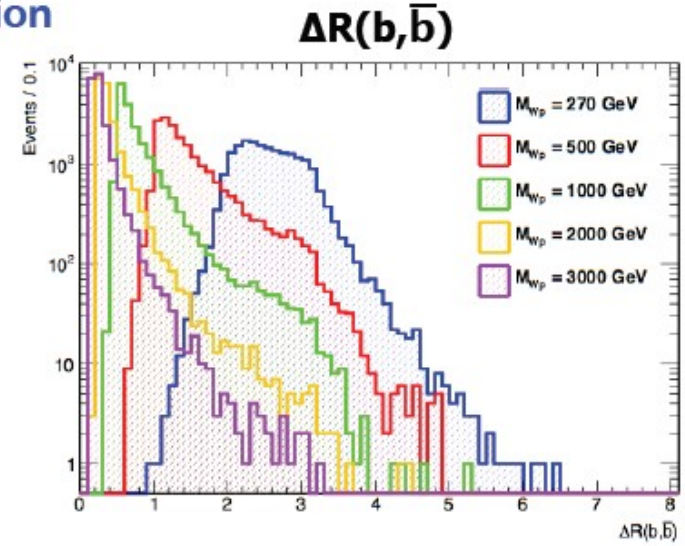
Our Signal: Fat Jet, H-tagging



one high p_T jet from the hadronization of two collimated b-quarks

large missing transverse energy

One high p_T isolated lepton



Search for MW' >0.8TeV

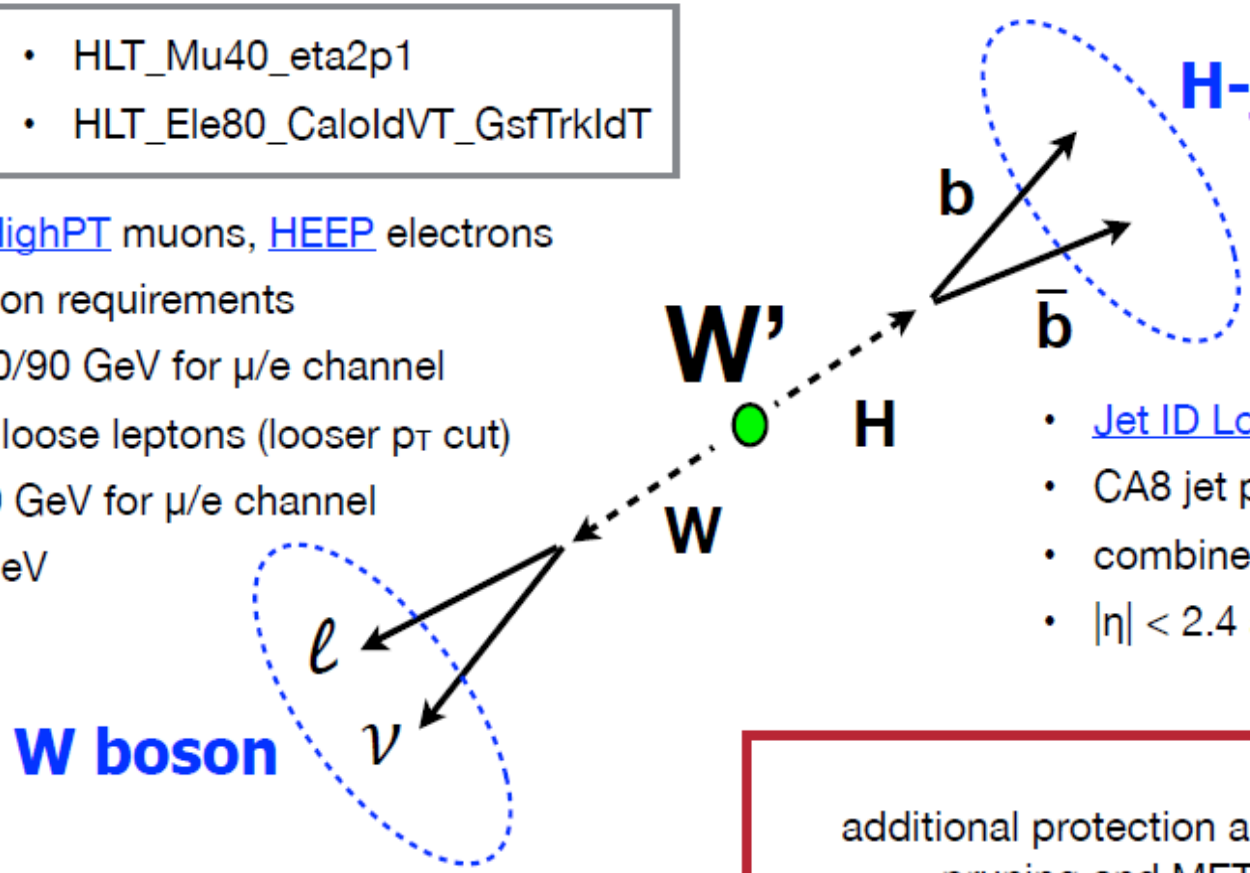
H(→bb) can look more and more like a single fat-jet (ΔRbb ~ 2Mh/PTh).

Needs dedicated jet substructure and b-tagging techniques

Selection

Online trigger:
- HLT_Mu40_eta2p1
- HLT_Ele80_CaloIdVT_GsfTrkIdT

- Lepton IDs: HighPT muons, HEEP electrons
- Lepton isolation requirements
- lepton p_T > 50/90 GeV for μ/e channel
- no additional loose leptons (looser p_T cut)
- E_T^{miss} > 50/80 GeV for μ/e channel
- W p_T > 200 GeV



reconstructed with Cambridge-Aachen algorithm with R=0.8

- Jet ID Loose
- CA8 jet p_T > 200 GeV
- combined b-tagging with CSVL
- |η| < 2.4 and (|η| < 1 or |η| > 1.8)

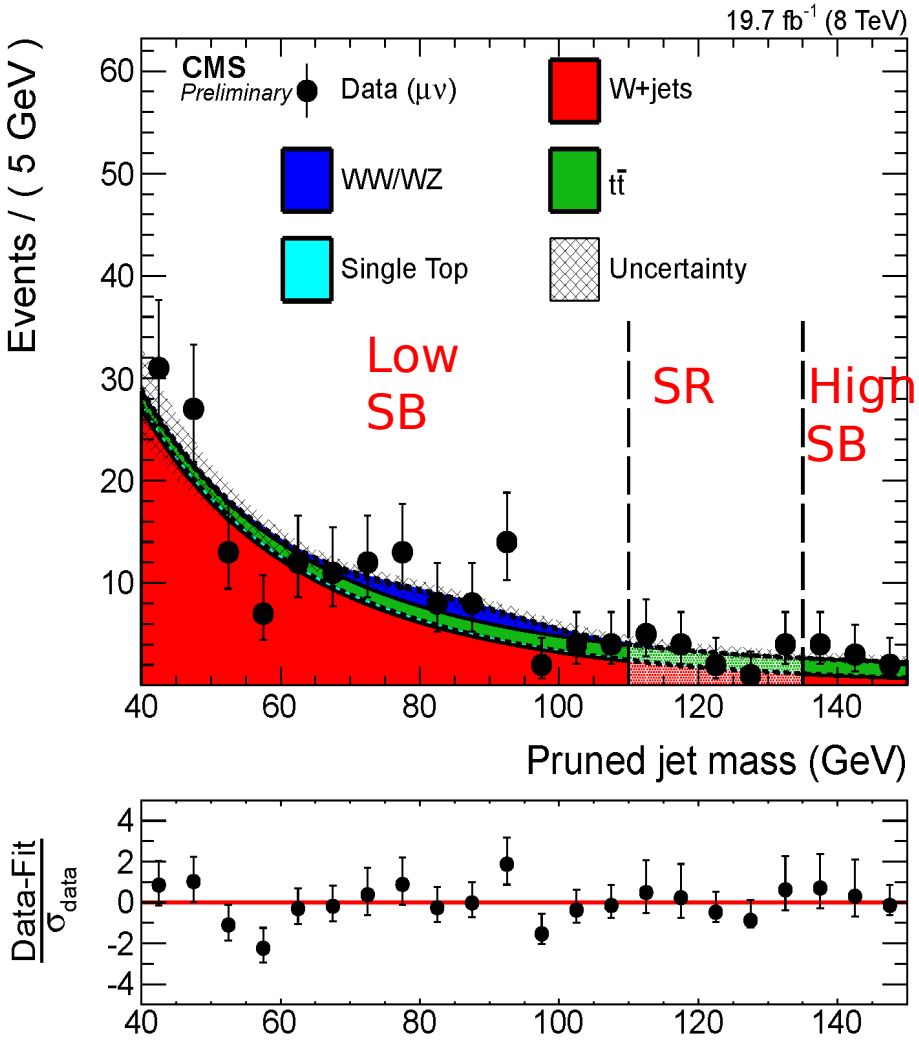
additional protection against bias in b-tagging, pruning and MET introduced by TOBTEC anomalous events with many displaced fake tracks in the jet (tobtec filter rejection inefficiency)

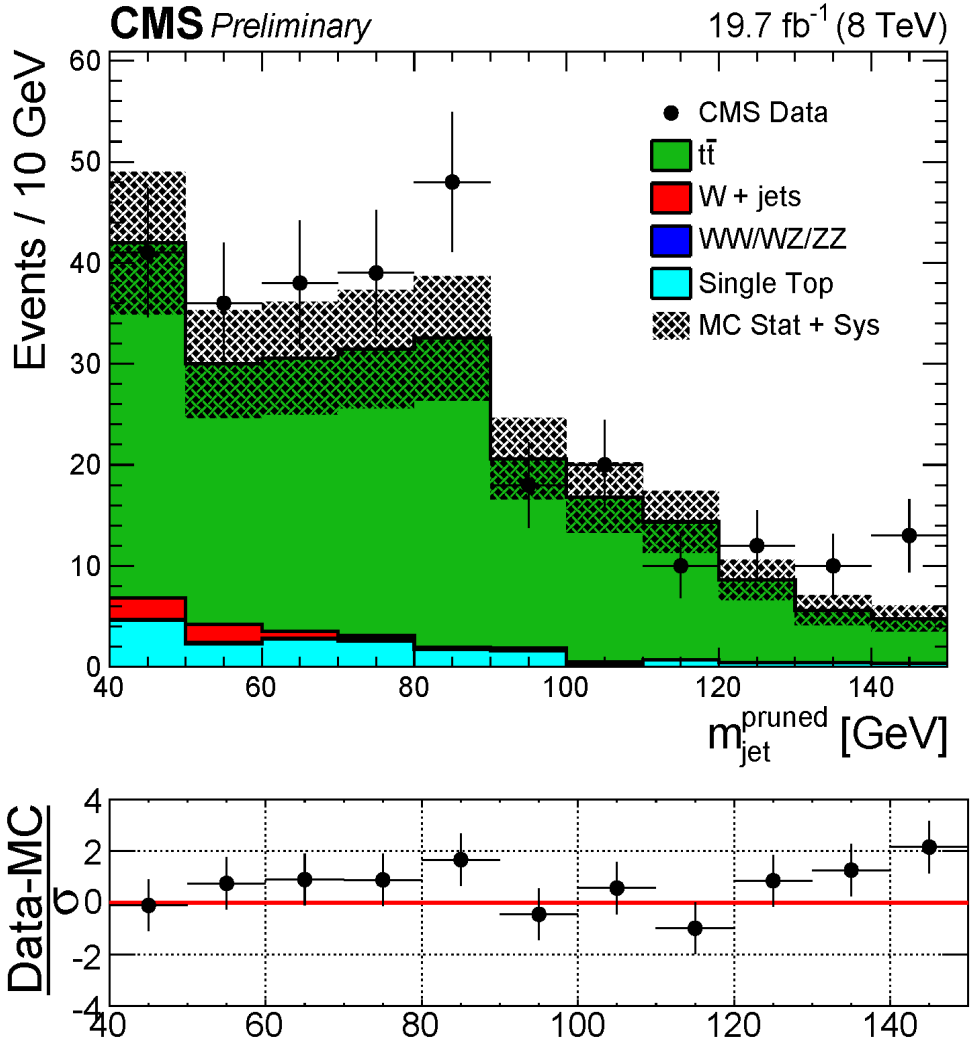
Back-to-back topology
- $\Delta R(jet^{CA8}, lept) > \pi/2$
- $\Delta\Phi(E_T^{miss}, jet^{CA8}) > 2$
- $\Delta\Phi(jet^{CA8}, W) > 2$

TTbar rejection
- no b-tagged AK5 jets outside the H-jet cone of 0.8 with CSVM
- $120 < m_{top}^{lept} < 240$ GeV or $160 < m_{top}^{hadr} < 280$ GeV

For TTbar Control: we reverse b-veto and don't require back to back

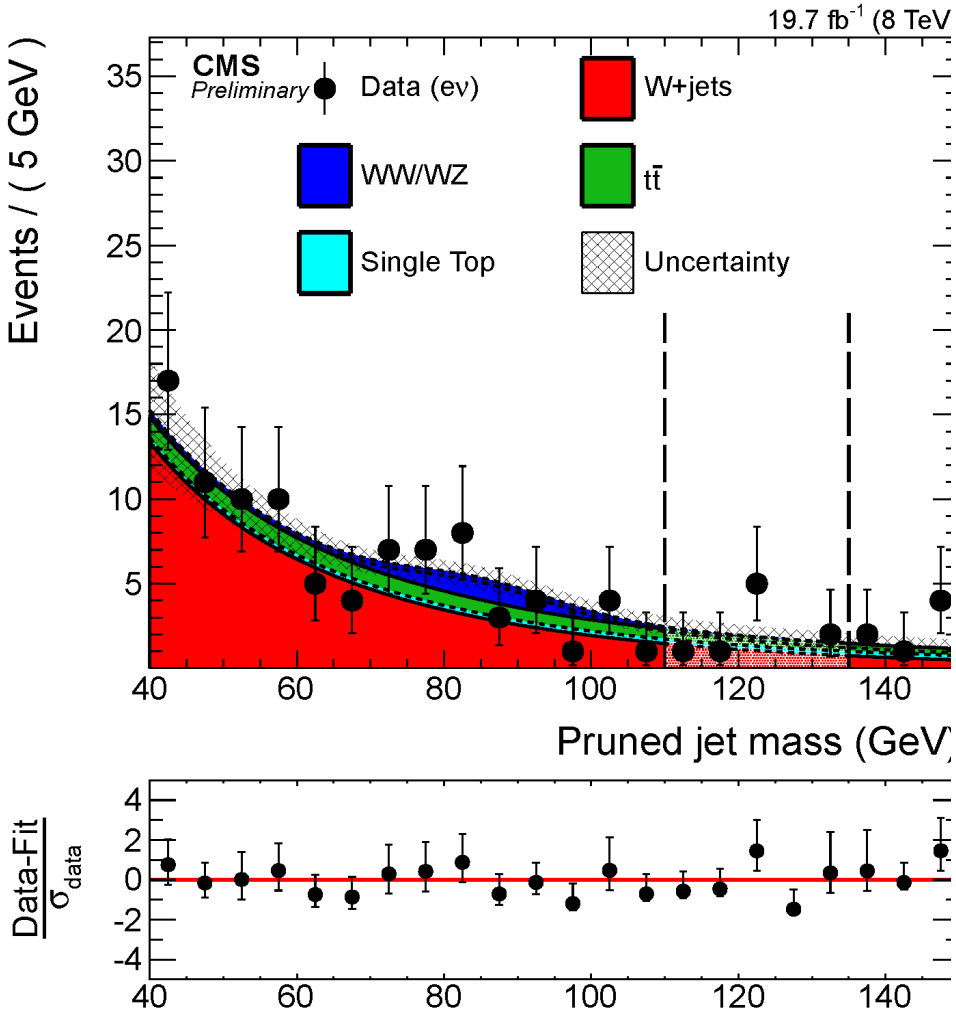
Distribution Plots: mu channel

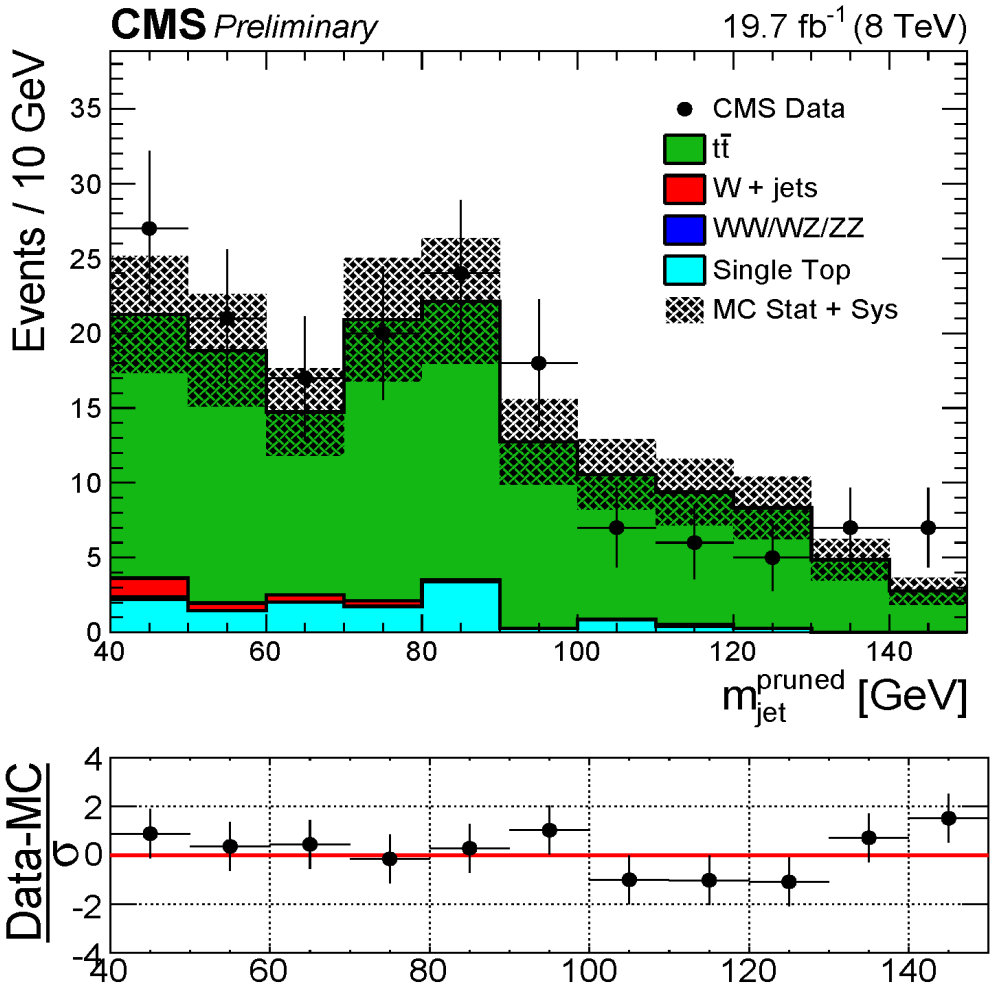




Pruned Jet mass in Search Region and TTbar Control Region

Distribution Plots: el channel





Pruned Jet mass in Search Region and TTbar Control Region

Background Modelling

- W+jets estimated from data in sidebands → 2 steps:

1. W+jets normalization from m_{jet}^{pruned} sidebands
2. W+jets M_{WH} shape with alpha-method

- TTbar, Single Top, VV shape and normalization taken from MC
  - obtained fitting the individual MC predictions with suitable functions
  - fit parameters fixed by the MC prediction
- TTbar MC as input to W+jets estimation
  - main background in signal region
  - check data/MC agreement in control region

Alpha-method:

---> fit SR and low SB m_{WH} of Wjets MC to extract Wjets shape

$$\alpha_{\mathrm{MC}}(m_{lvj}) = \frac{F_{\mathrm{MC,SR}}(m_{lvj})}{F_{\mathrm{MC,SB}}(m_{lvj})}$$

---> data driven background extrapolation in SR

$$F_{\mathrm{data,SR}}(m_{lvj}) = \alpha_{\mathrm{MC}}(m_{lvj}) \times F_{\mathrm{data,SB}}(m_{lvj})$$

Estimated wjets shape in SR

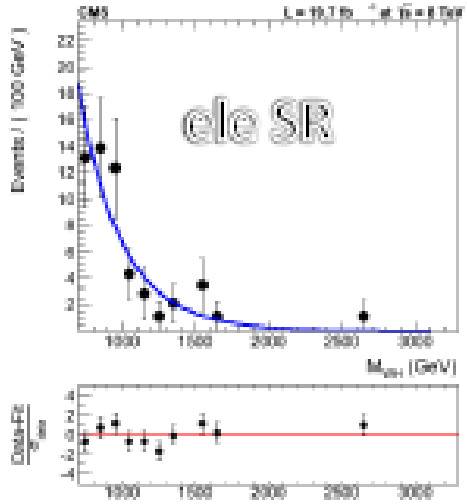
Fit data SB with summed components to get wjets shape in low SB region

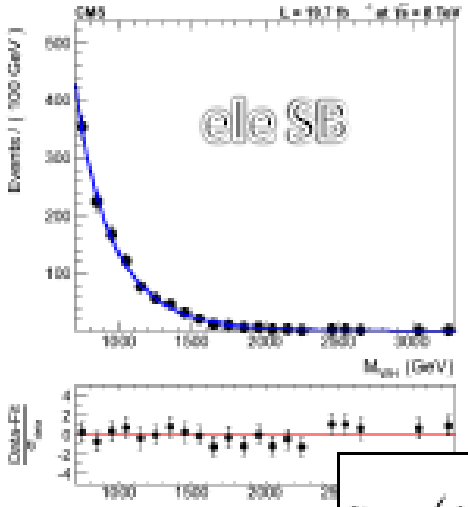
m_{jet}^{pruned} regions:

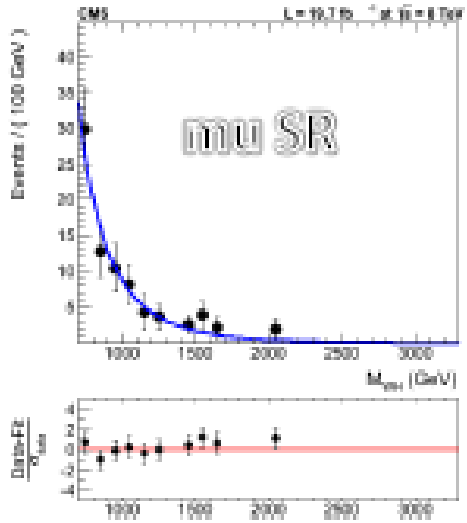
- low sideband: 40-110 GeV
- signal region: 110-135 GeV
- high sideband: 135-150 GeV

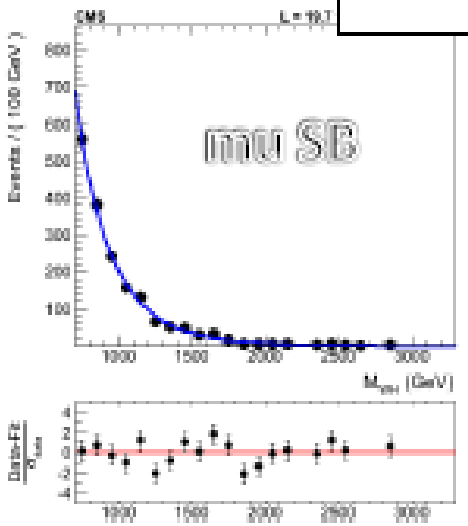
Extrapolation function alpha(MC)

- Fit the mWH distribution of Wjets MC in both sideband region and signal region
- Levelled exponential function is used for [0.7, 3.3] TeV: **f(x) = exp (p1*x + p2/x)**

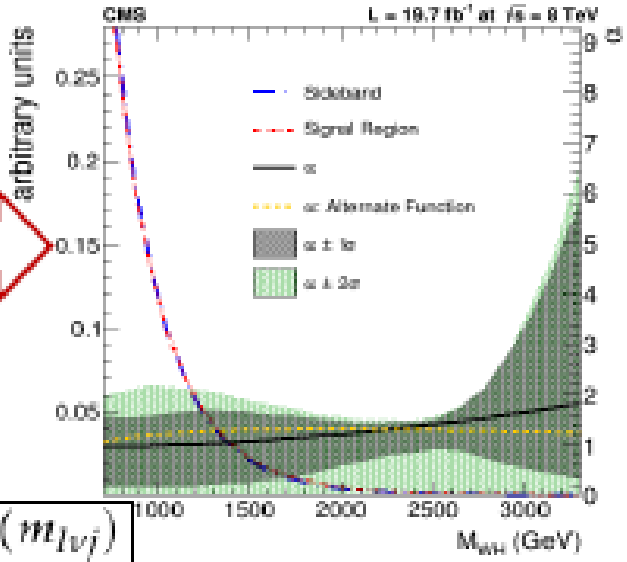


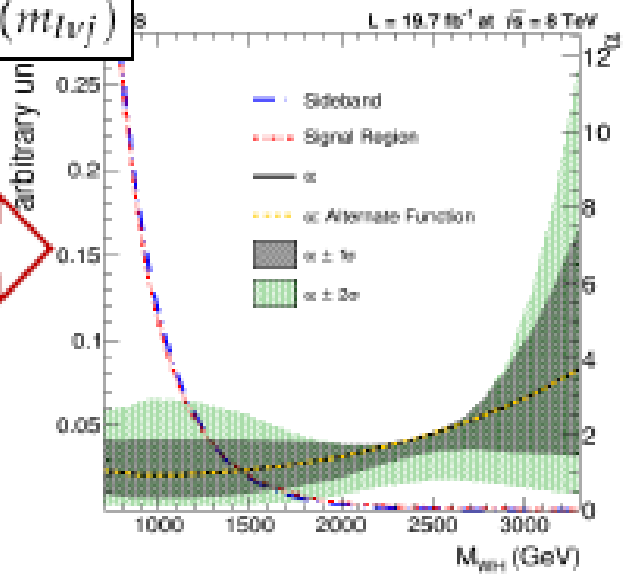




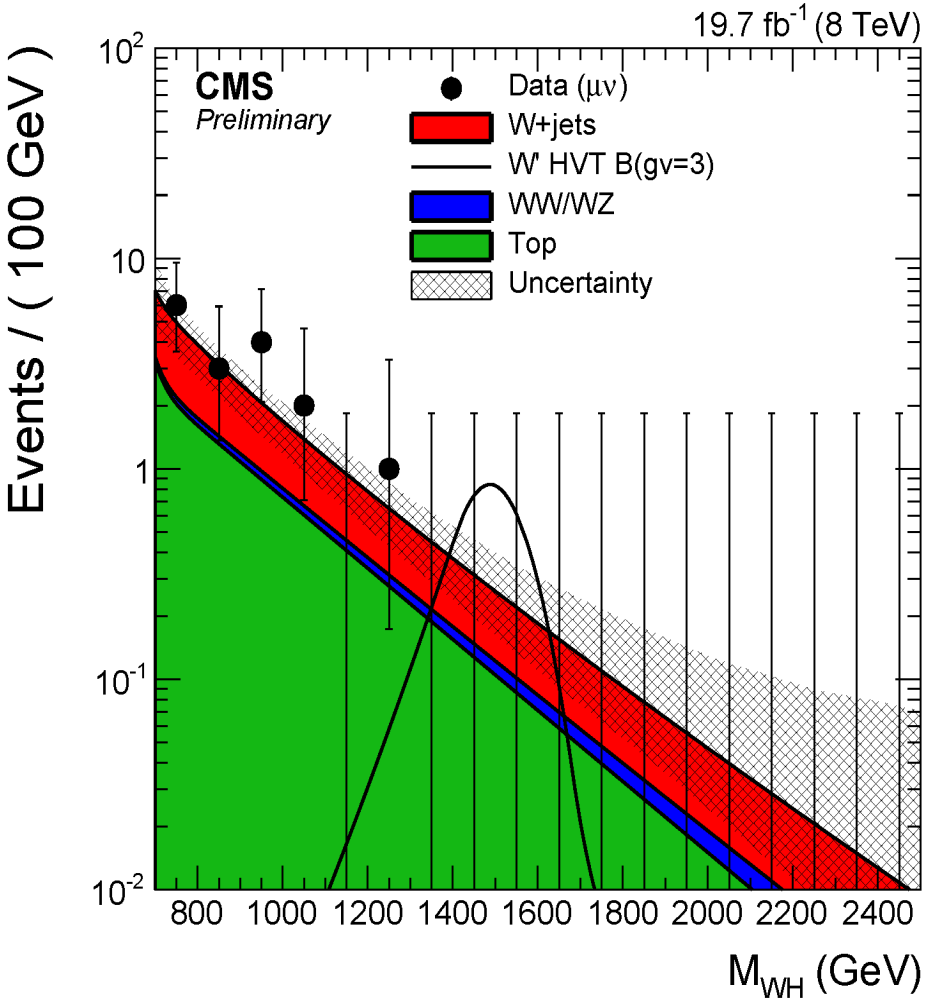


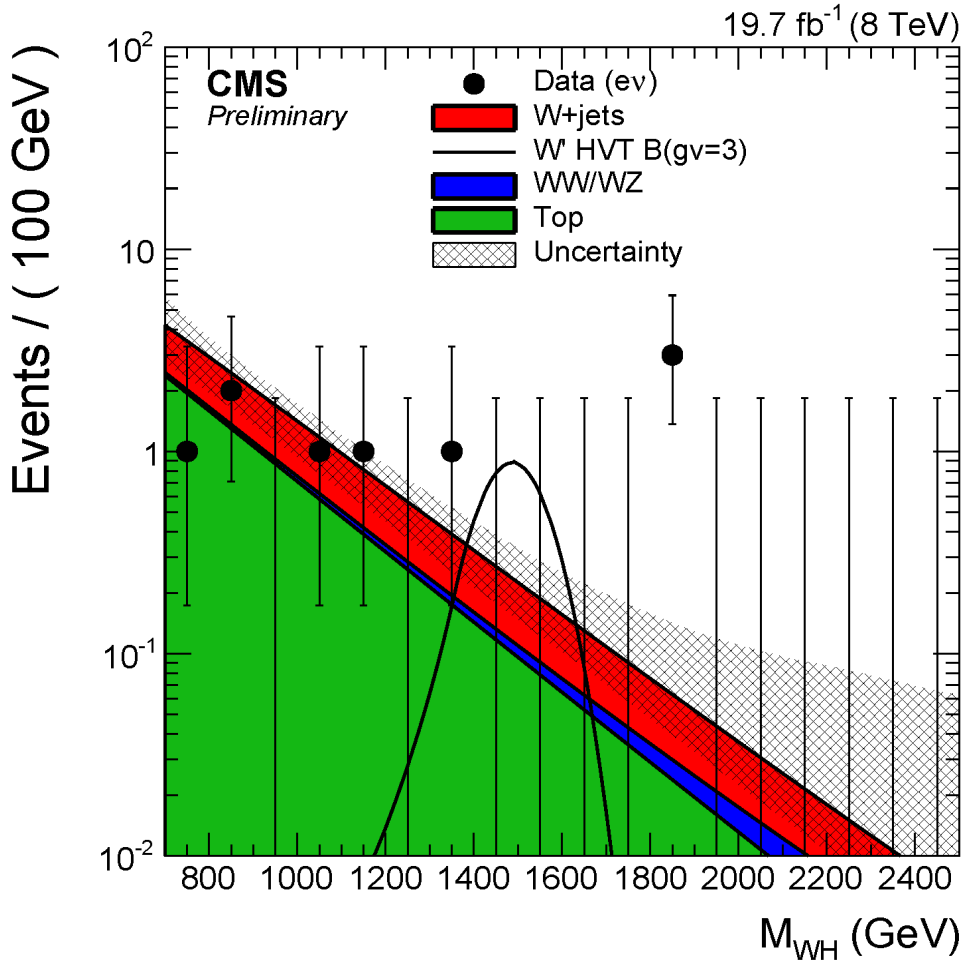
$$\alpha_{MC}(m_{lvj}) = \frac{F_{MC,SR}(m_{lvj})}{F_{MC,SB}(m_{lvj})}$$





Final M_WH Distribution

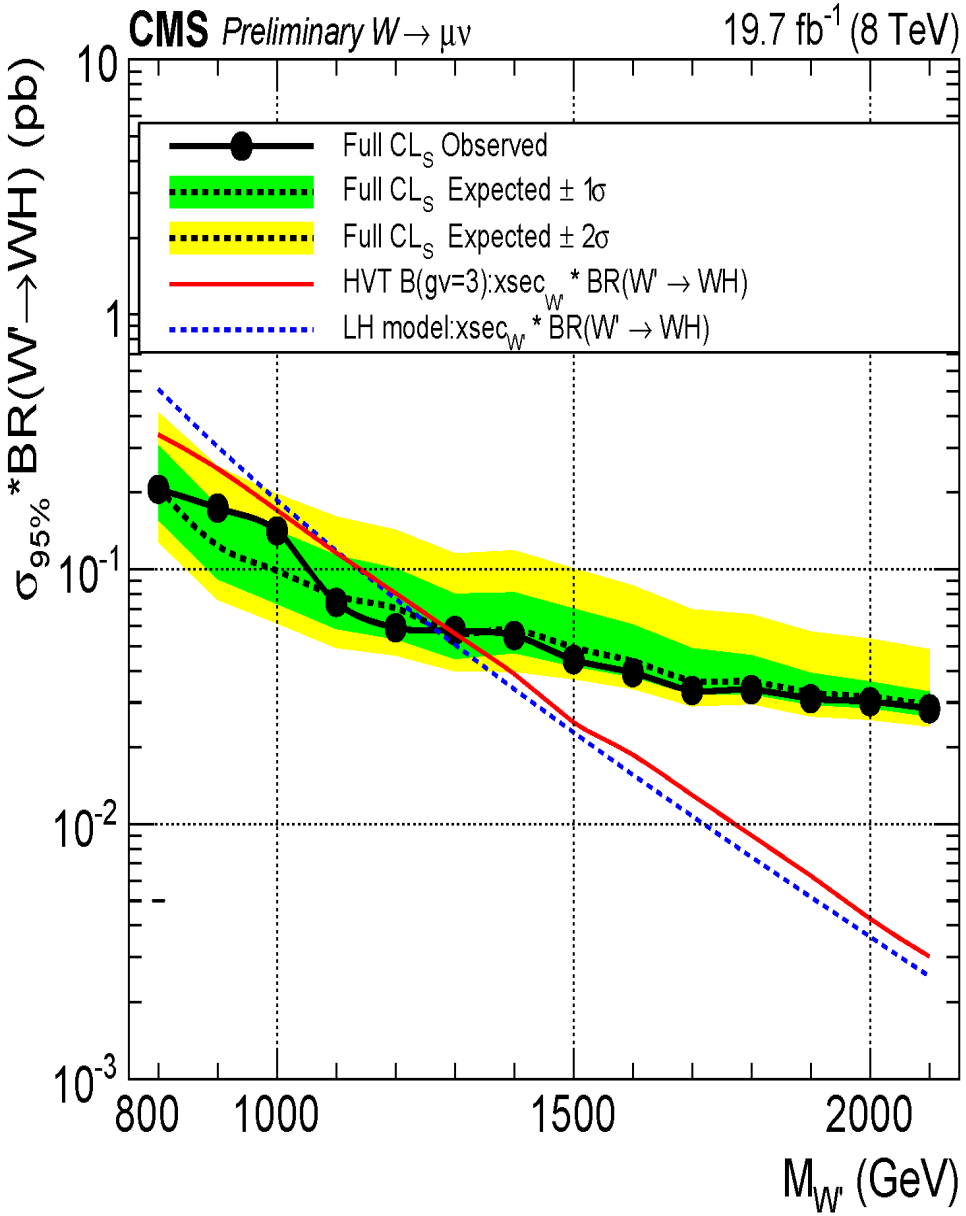


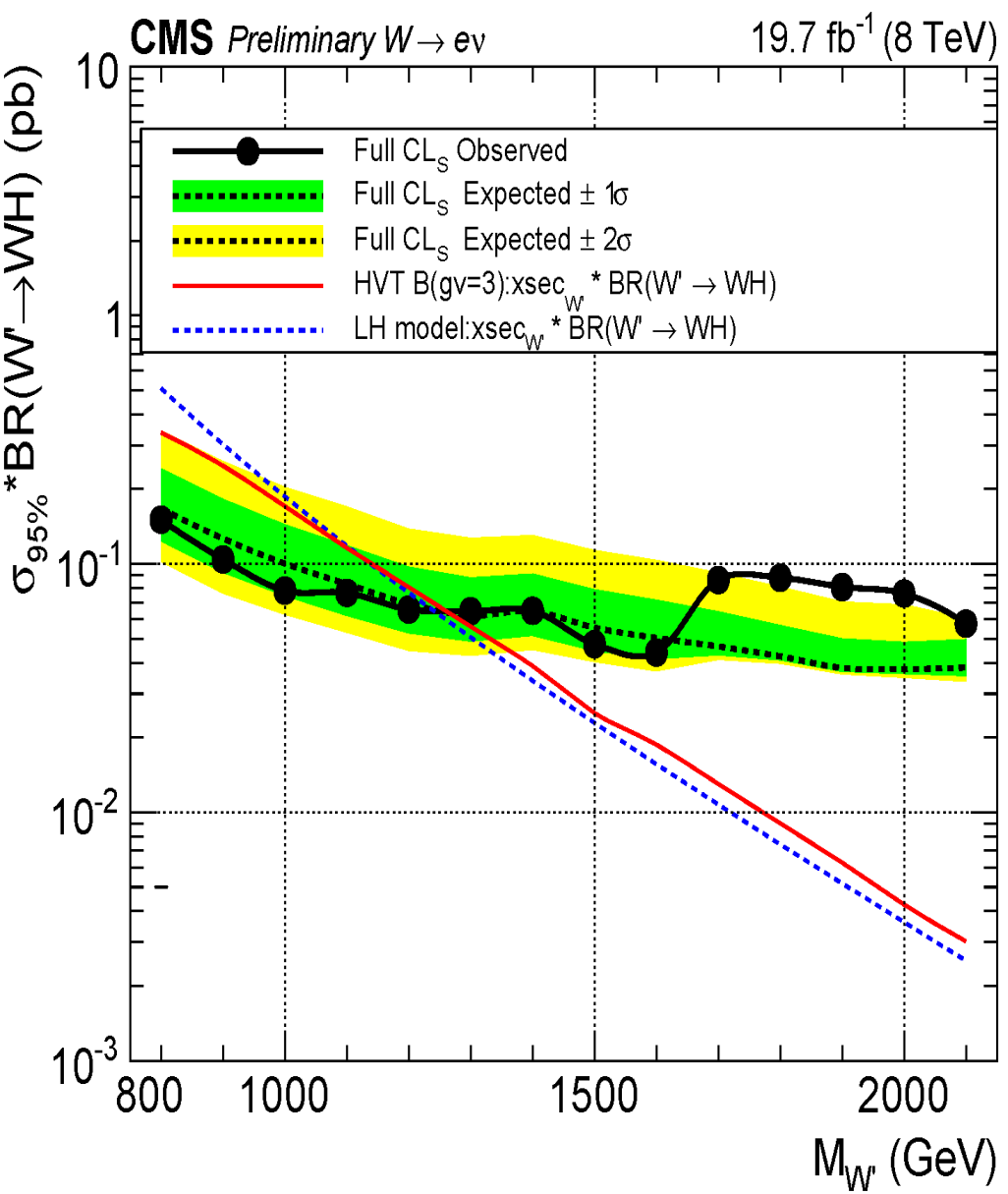


✓ Good data/MC agreement in the muon channel

✓ Excess of 3 events in the electron channel with $M_{WH} > 1.8$ TeV where less than 0.3 are expected

Result


CMS Preliminary W→ μν
19.7 fb-1 (8 TeV)
Full CLS Observed
Full CLS Expected ± 1σ
Full CLS Expected ± 2σ
HVT B(gv=3):xsecW' * BR(W' → WH)
LH model:xsecW' * BR(W' → WH)
σ95% *BR(W'→WH) (pb)
MW' (GeV)


CMS Preliminary W→ eν
19.7 fb-1 (8 TeV)
Full CLS Observed
Full CLS Expected ± 1σ
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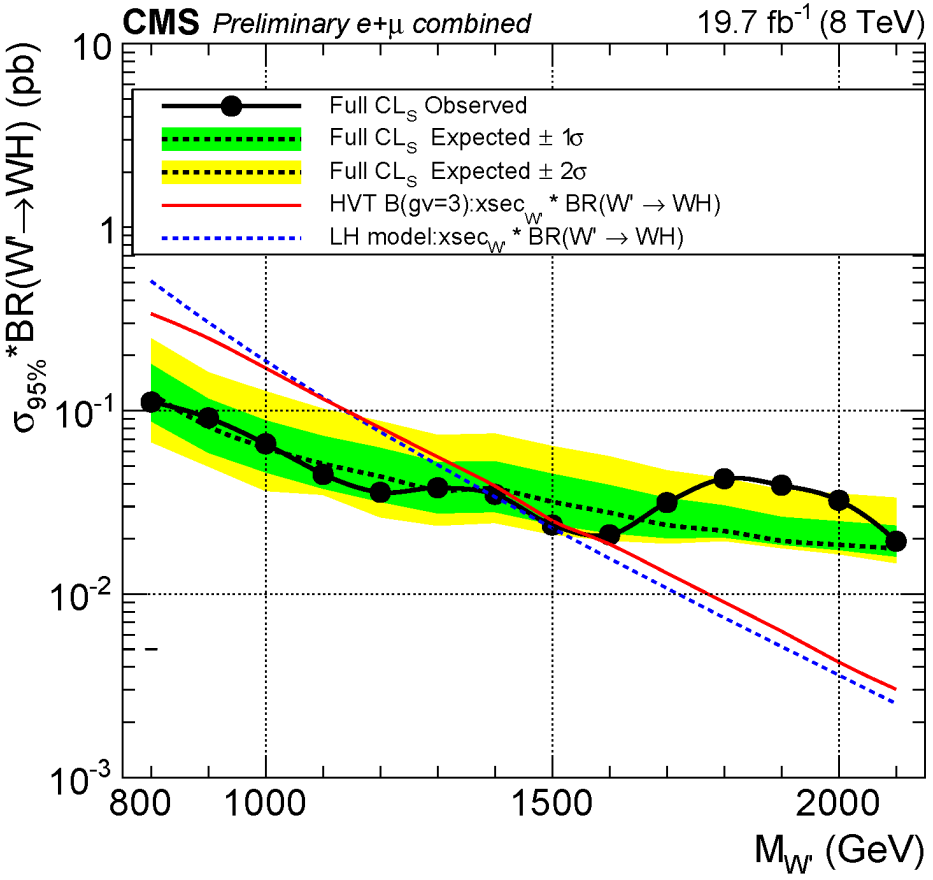
σ95% *BR(W'→WH) (pb)
MW' (GeV)

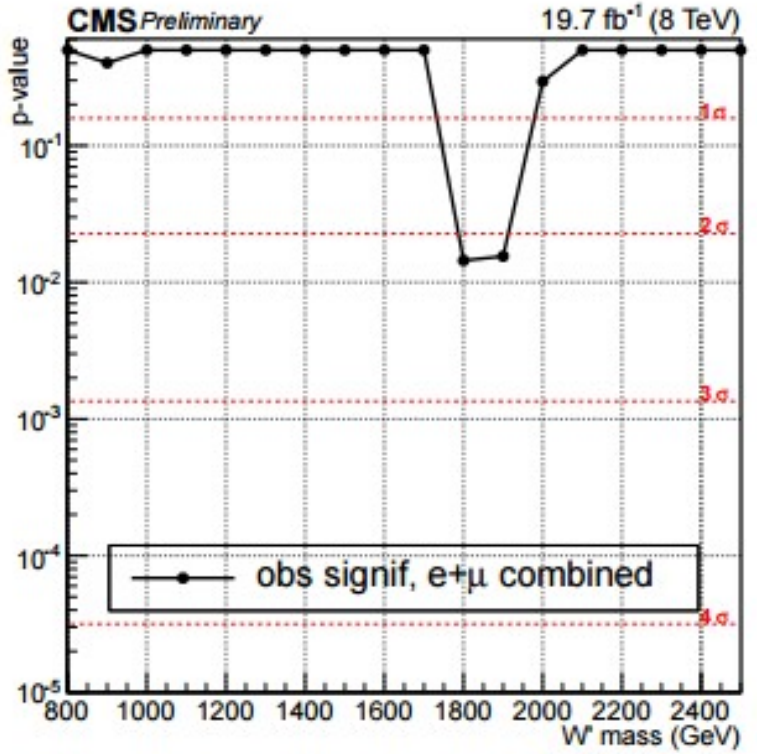
Result



Little Higgs: lower limit on the W' mass of 1.4 TeV

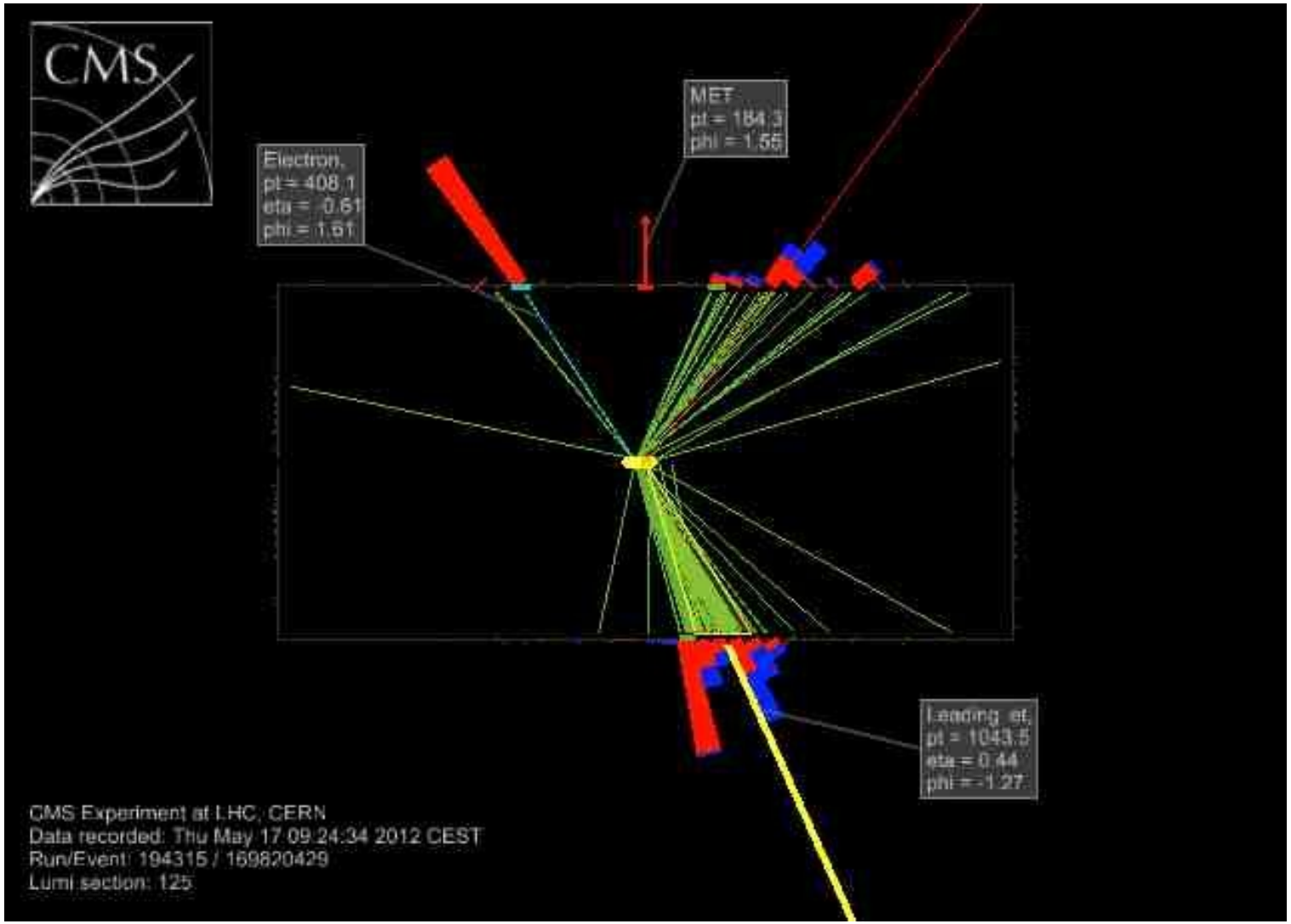
HVT$_B$: lower limit on the W' mass of 1.5 TeV

Statistical Compatibility with the Standard Model within 2σ



- Highest local significance of 2.2σ for M(W') = 1.8 TeV
- Taking into account the look-else-where effect we estimate a global significance of 1.9σ for a local significance of 2.9σ in a specific channel at a specific mass

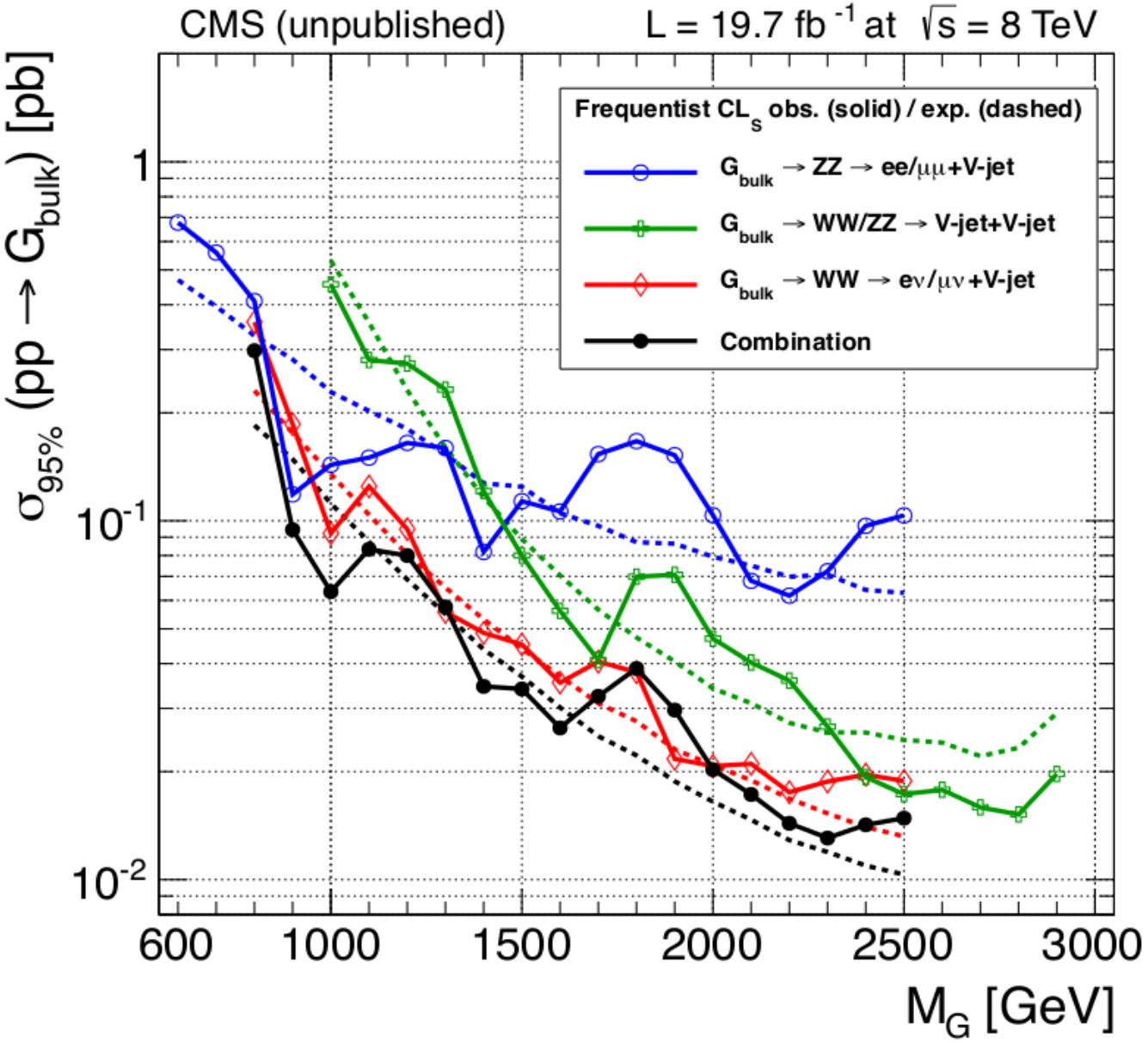
Event Display



The leptonic W has a transverse momentum of 0.61TeV. The transverse momentum of the H-tagged jet is 1.08TeV while the mass of the associated pruned jet is 123.8GeV.

WH invariant mass of 1.81TeV

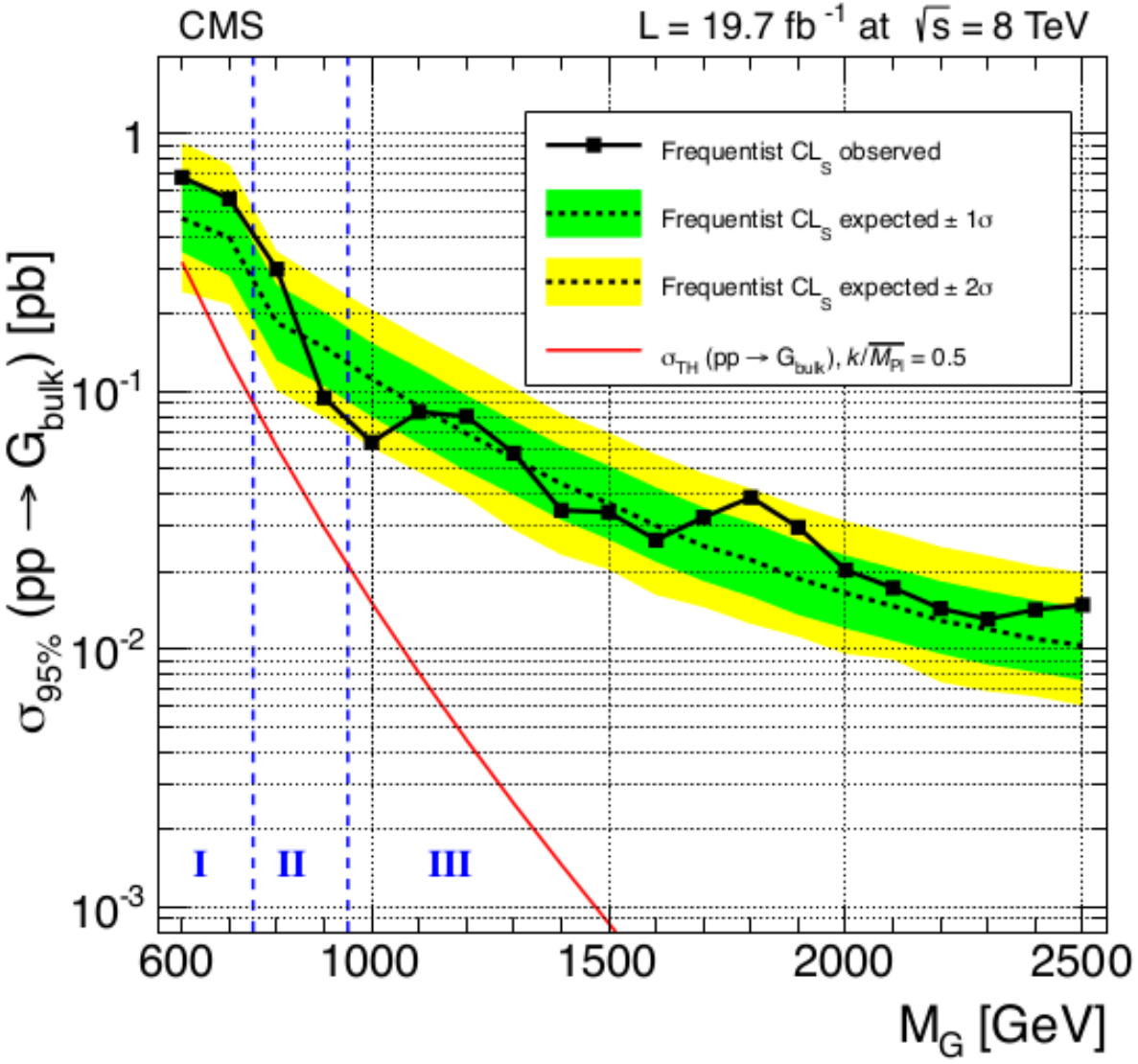
Combination of VV Searches



Combination in bulk graviton model

- Highest sensitivity from lν+jet channel
- Sensitivity of Jet+Jet channel comparable at high mass
- ll+jet channel reaches lower mass
- Combination improves sensitivity by 15-20%

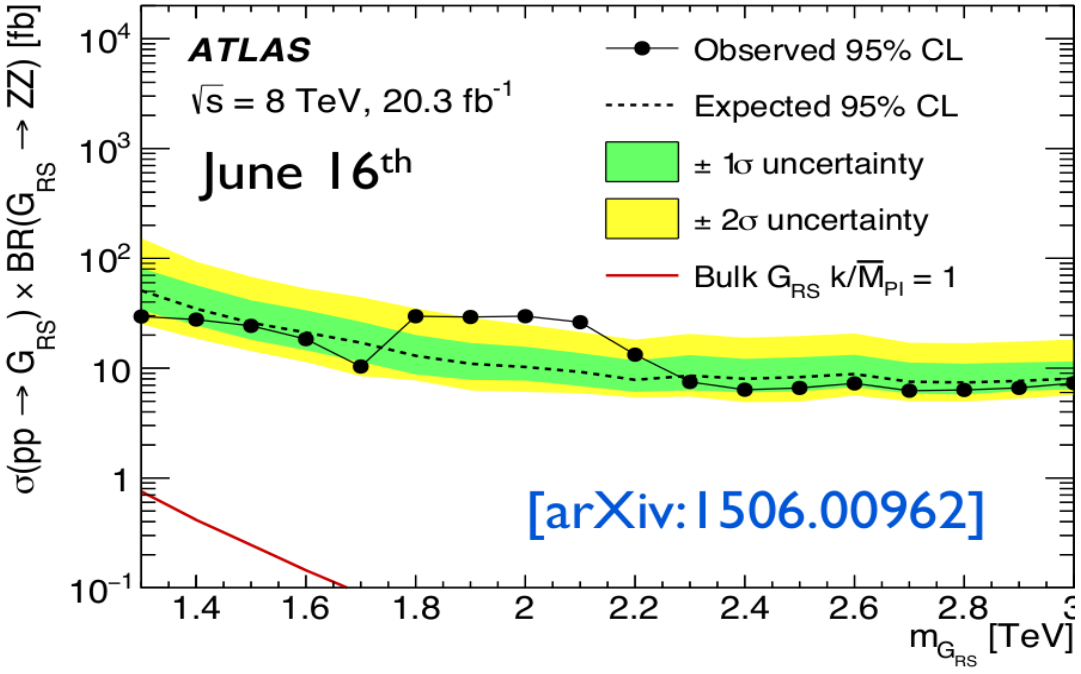
Combination of VV Searches

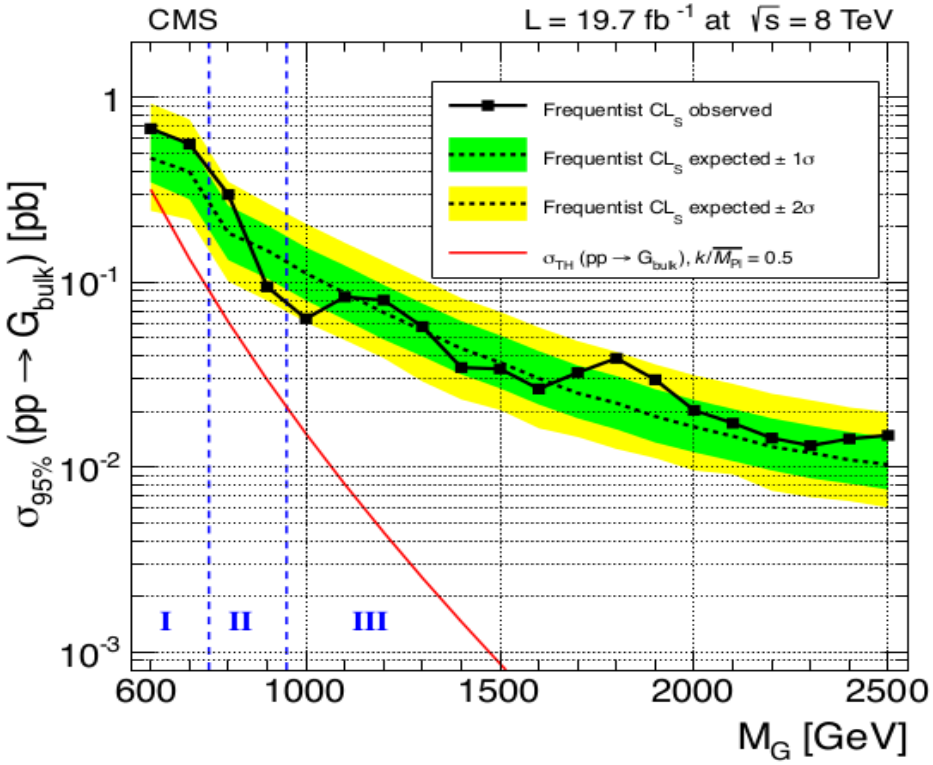


Combination in bulk graviton model

- No significant deviations from expected
- Sensitivity not high enough to exclude graviton in this model (with k/MPl = 0.5)

Comparison to ATLAS





Comparable sensitivity on $\sigma_{95\%}(pp \to G) \times BR(G \to ZZ)$

Deviations from expected limit at 1.8 - 2.0 TeV (if larger than 1σ):

local p-values

	CMS	ATLAS
$V_{jet}\,V_{jet}$	1.3σ	3.4σ (2.5σ global)
$\ell\ell\,V_{jet}$	2σ	-
$\ell\nu\,V_{jet}$	1.2σ	-

Summary

- We presented the search for a new massive resonance decaying into WH in the lvbb final state.
- H-tagger exploited: Jet substructure and Sub-Jet b tagging
- In the context of the Little Higgs model, we set a lower limit on the W' mass of 1.4TeV. In a model of a Heavy Vector Triplet that mimics the properties of the Composite Higgs model, we set a lower limit on the W' mass of 1.5TeV.
- The search for new resonances decaying into the WW semi-leptonic final state at 8TeV, no significant excess is observe.
- Deviations from excepted limit at 1.8-2.0 TeV for both CMS and ATLAS
- Run2 will definitely tell us more