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# Search for WH resonance in boosted region


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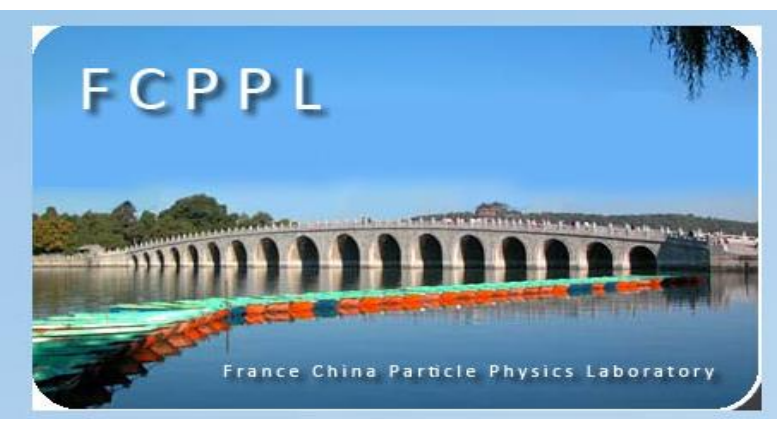


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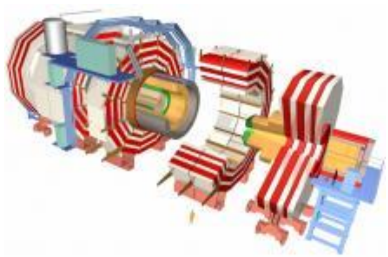

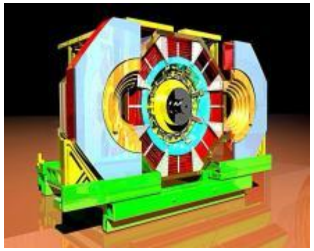


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**Dr. Siguang Wang, Dayong Wang, and Qiang Li**


2010/3/12

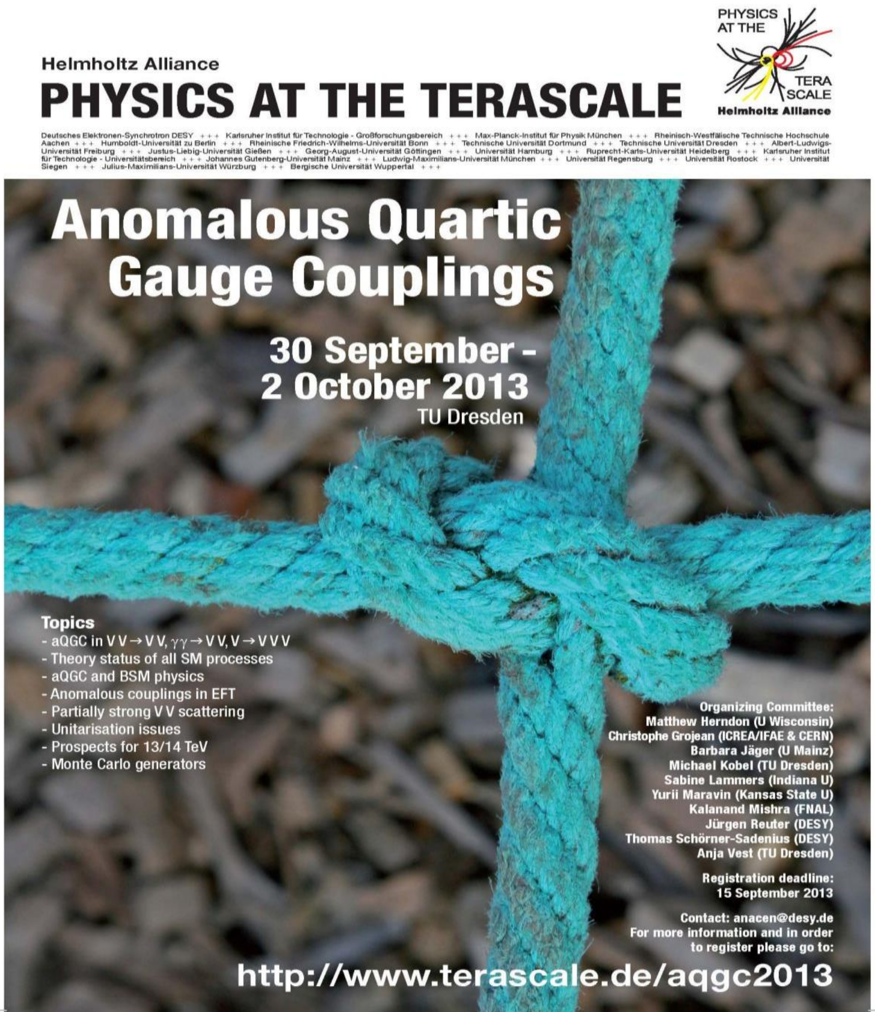
**We are open to wide cooperation with you, for which you are welcome to contact our leader, Prof. Yajun Mao <maoyj@pku.edu.cn>**

## Our CMS TeV Physics Analyses:
Focusing on

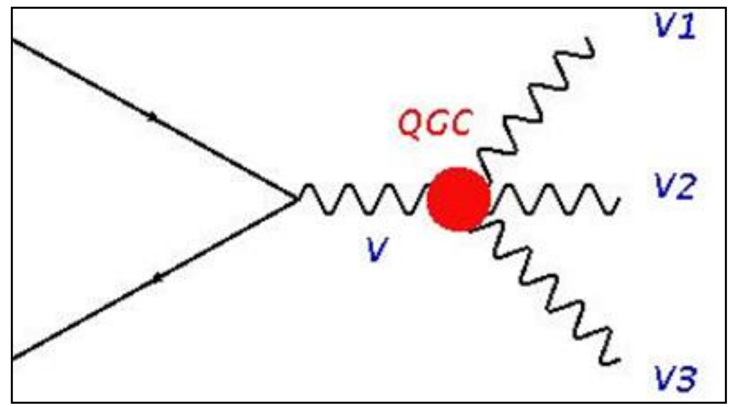
**(1) Multi-boson Measurement**

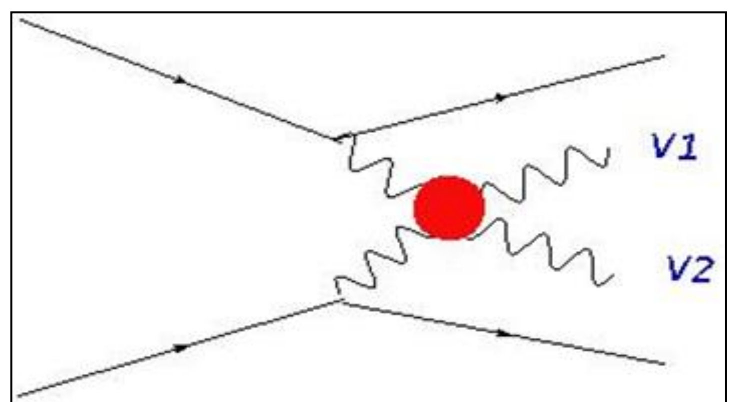
and

**(2) Exotica VV/VH  Searches**




**Many Thanks to Dr. Nicolas Chanon for his help and support while being the SMP-VV convener at CMS**



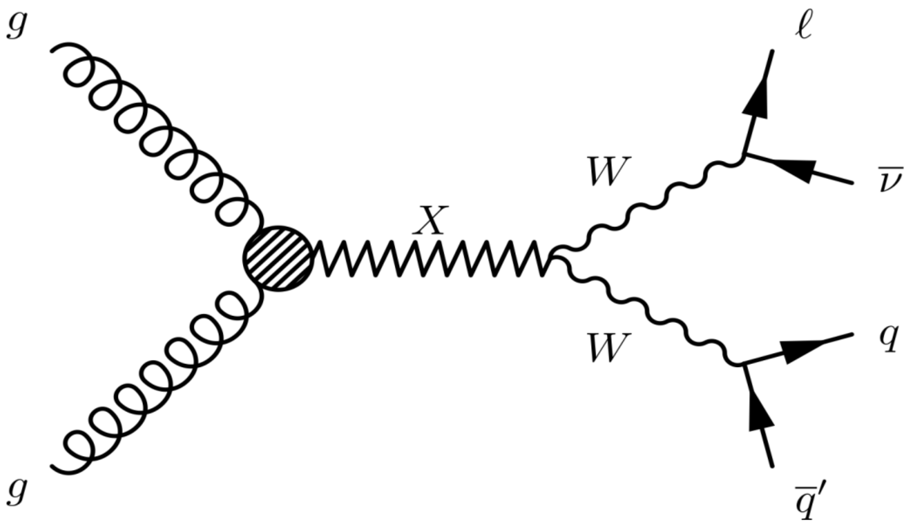
# Outline

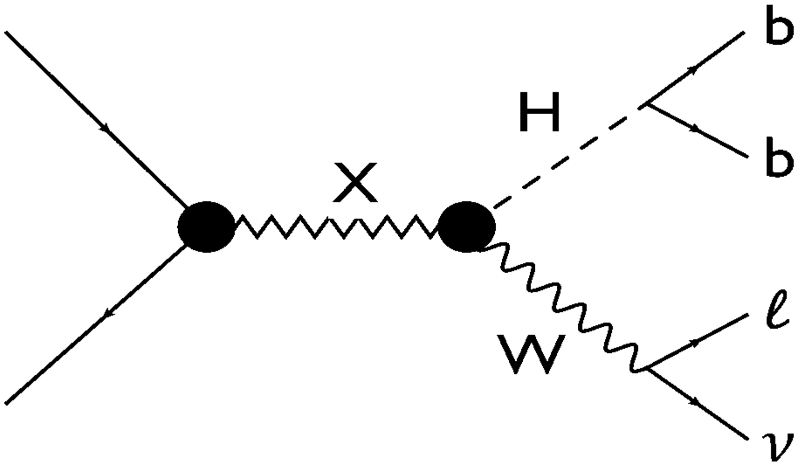
- **Introduction and Physics Motivation**
- **Boosted Technique at CMS**
- **Exotica WH resonance Search**
- **Summary**

EXO-WW: JHEP08(2014)174 ;

EXO-WH: CMS PAS-EXO-14-010 public in end March, 2015

# Introduction: Overview




- **VV, VH resonance motivated in many nice models**
  **Extra Dimension, Composite Higgs, Little Higgs**

- **Semi-leptonic channels: High rates, reconstructable spectrum**
  **Huge QCD Wjets bkg, data-driven estimation**

- **V/H highly boosted: Jet substructure and/or Subjet b-tagging**
  **TTbar control Region, Scale Factor**

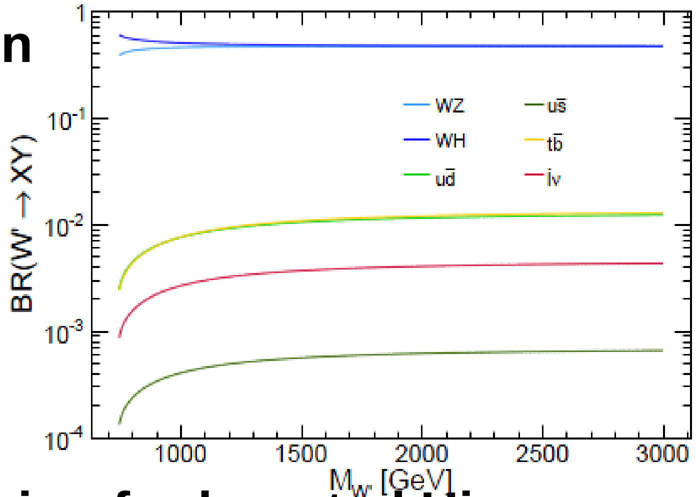
# Introduction: Physics

- **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**

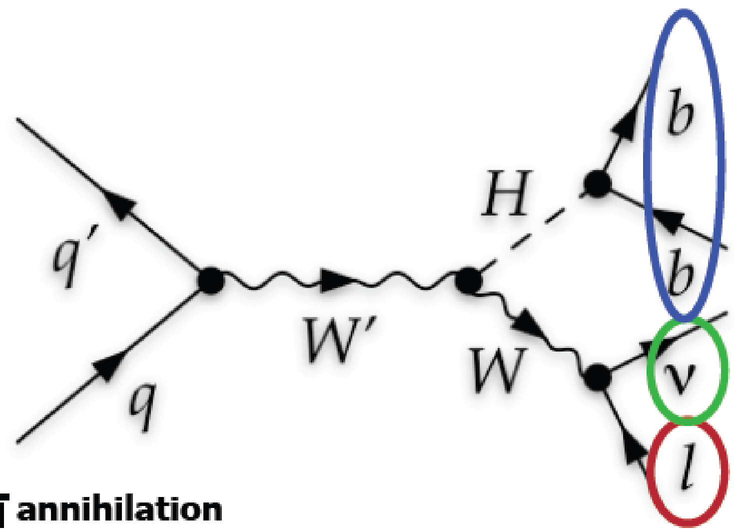
  **Model B case of (1), $g_V > 3$**
  **->**
  **Composite Higgs Model**




- **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

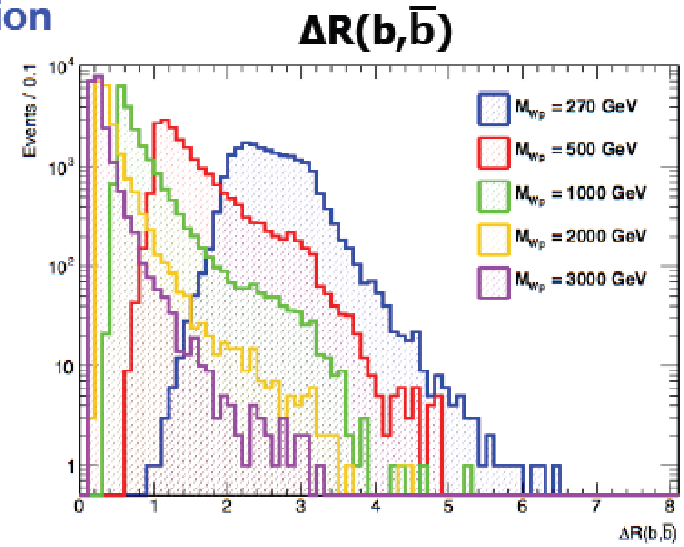



**$q\bar{q}$ annihilation**

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 $M_{W'}$ >0.8TeV**

**H(→bb) can look more and more like a single fat-jet ($\Delta R_{bb} \sim 2M_h/PT_h$).**

**Needs dedicated jet substructure and b-tagging techniques**

# 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

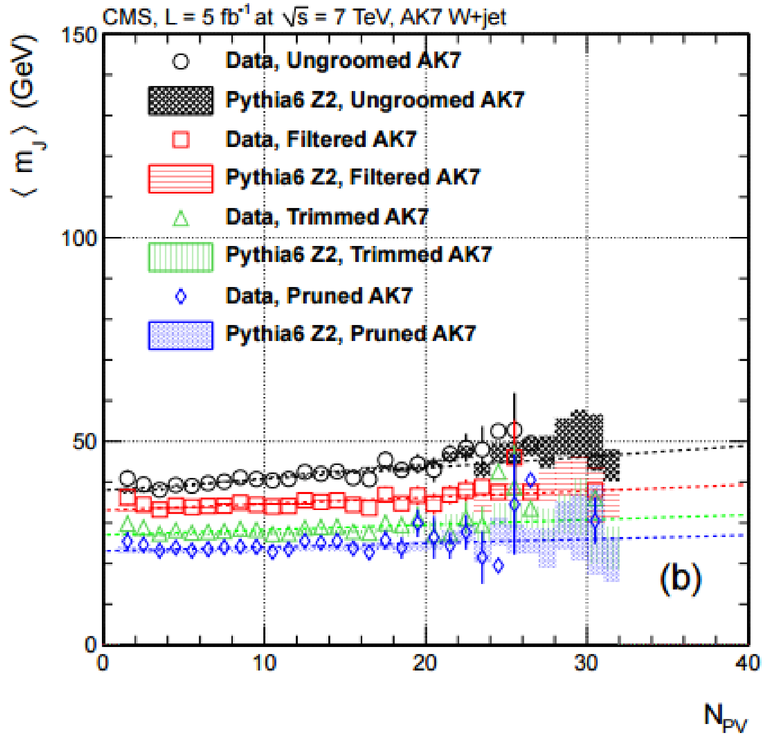
**7TeV  WZ/ZZ resonance:**
**Jet mass,  mass drop**
JHEP 1302 (2013) 036

**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**

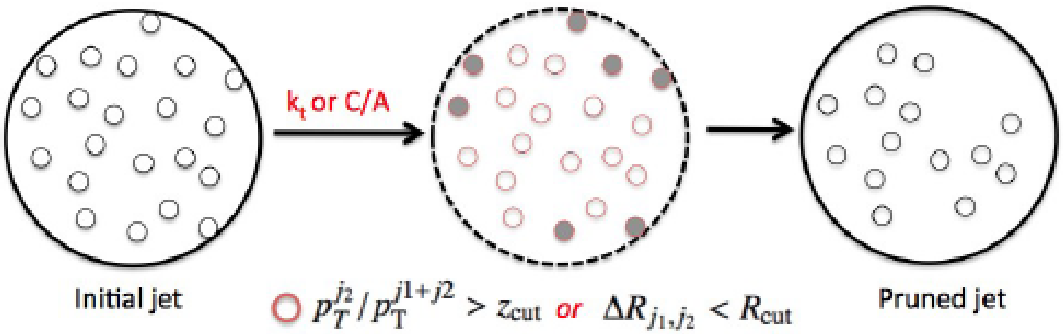
Top tagging …….




Groomed Jet more stable with PU

# 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 $z_{cut}$

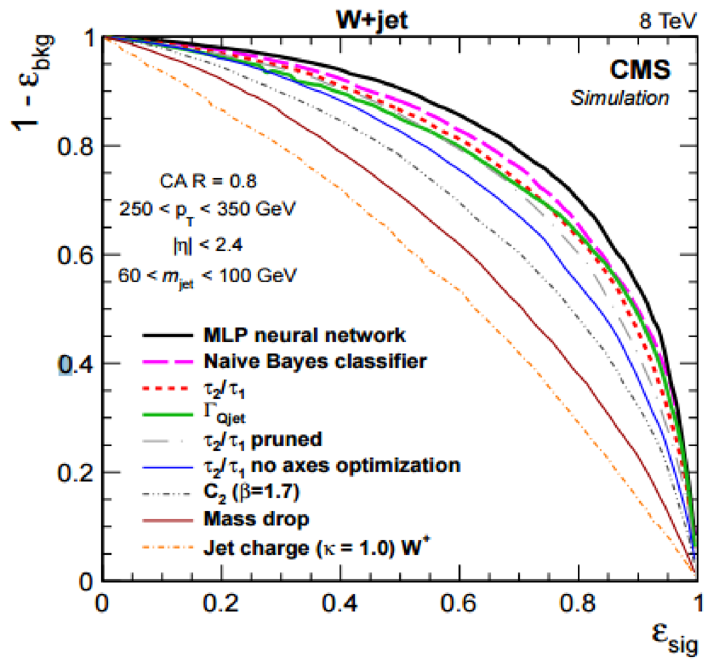
α and $z_{cut}$ are 0.5 and 0.1,

**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 bit beyond W-tagging

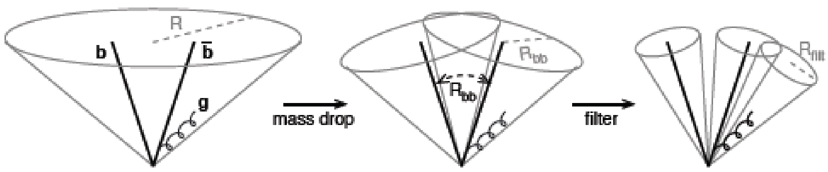
## 1. Mass of the H-jet as the main discriminating variable against QCD jets

**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**



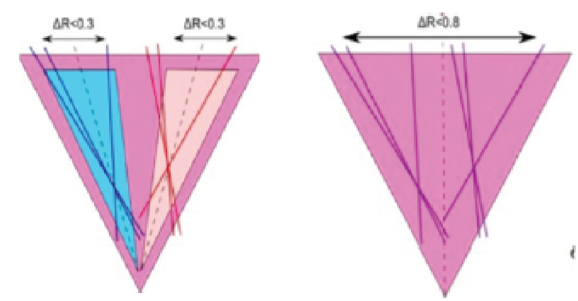

- removes the softest components of a jet
- improves discrimination by pushing the jet mass for QCD jets towards lower values while maintaining the jet mass for the H-jet at the H-mass
- studied in detail for W-tagging: JME-13-006

## 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 ΔR > 0.3
- **fat jet b-tagging:** when the subjets are too close (ΔR < 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

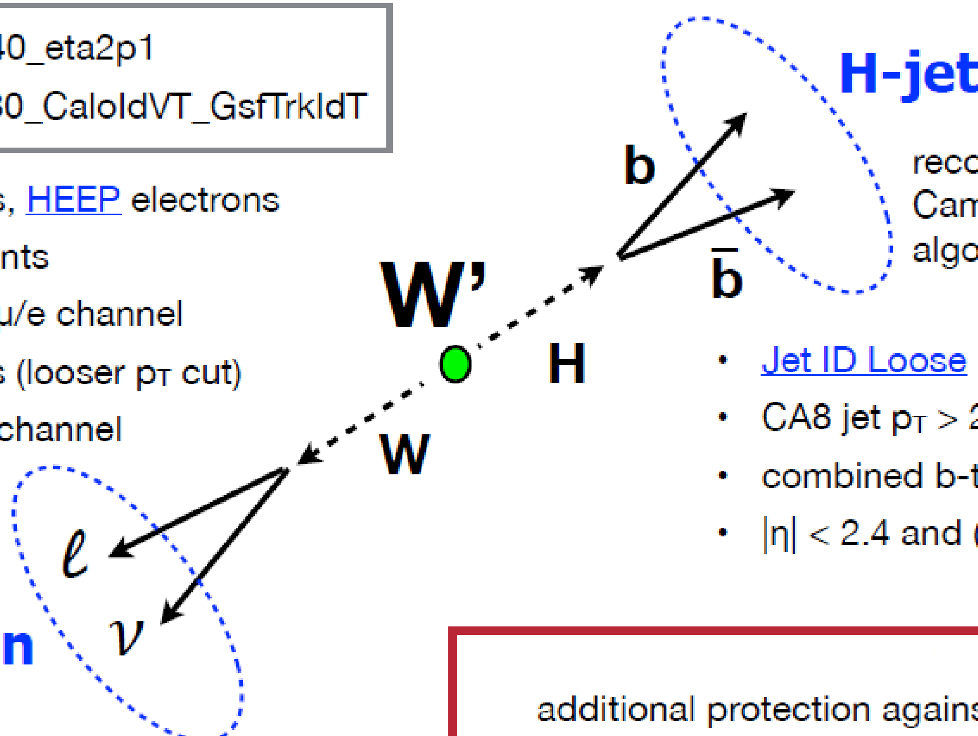



worse performance because JTA cones overlap

# Selection

| | |
|---|---|
| Online trigger: | • HLT_Mu40_eta2p1<br>• 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




W boson

H-jet reconstructed with Cambridge-Aachen algorithm with R=0.8

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

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**

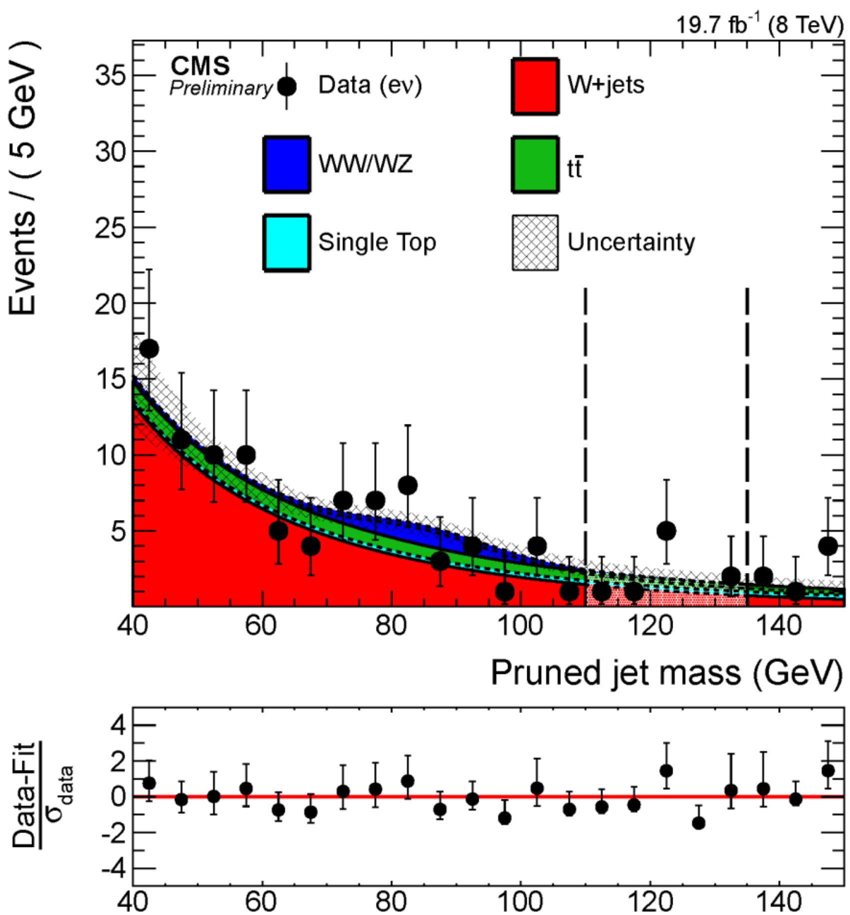
- $\Delta R(jet^{CA8}, lept) > \pi/2$
- $\Delta\Phi(E_T^{miss}, jet^{CA8}) > 2$
- $\Delta\Phi(jet^{CA8}, W) > 2$

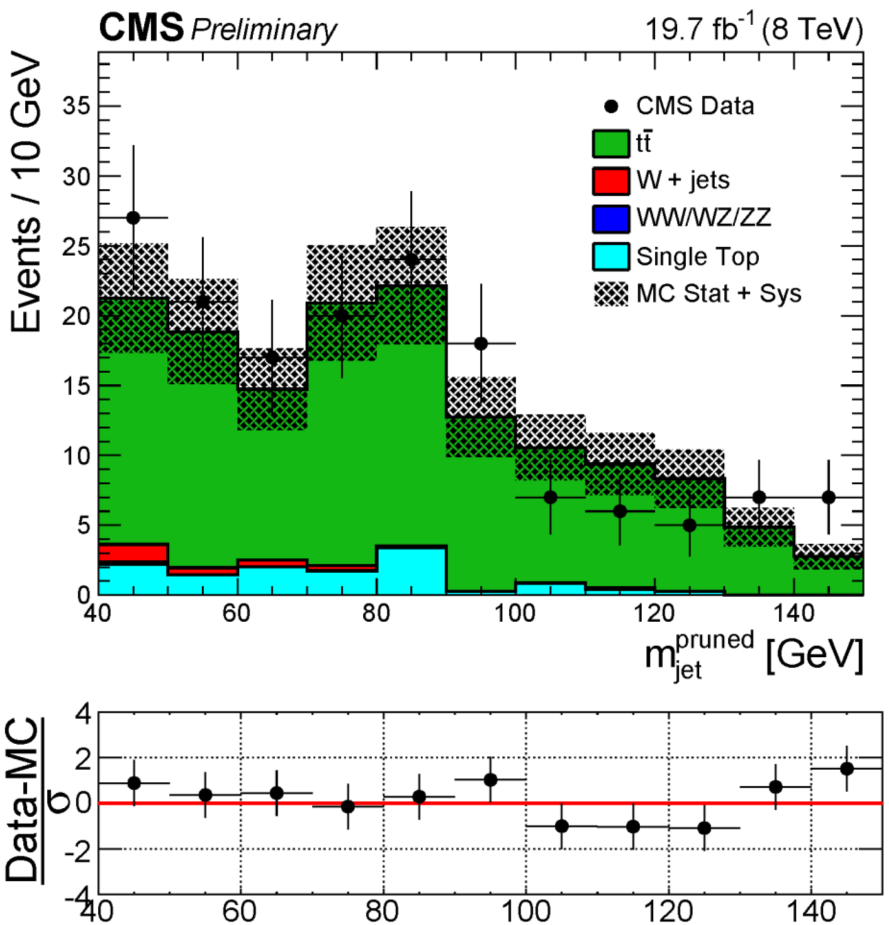
**TTbar rejection**

- 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:  ele channel




**Pruned Jet mass in  Search Region and TTbar Control Region**

# Bkg 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

# Bkg Modelling

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

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

---> data driven background extrapolation in SR

$$\underline{F_{\mathrm{data,SR}}(m_{l\nu j})} = \alpha_{\mathrm{MC}}(m_{l\nu j}) \times \underline{F_{\mathrm{data,SB}}(m_{l\nu j})}$$

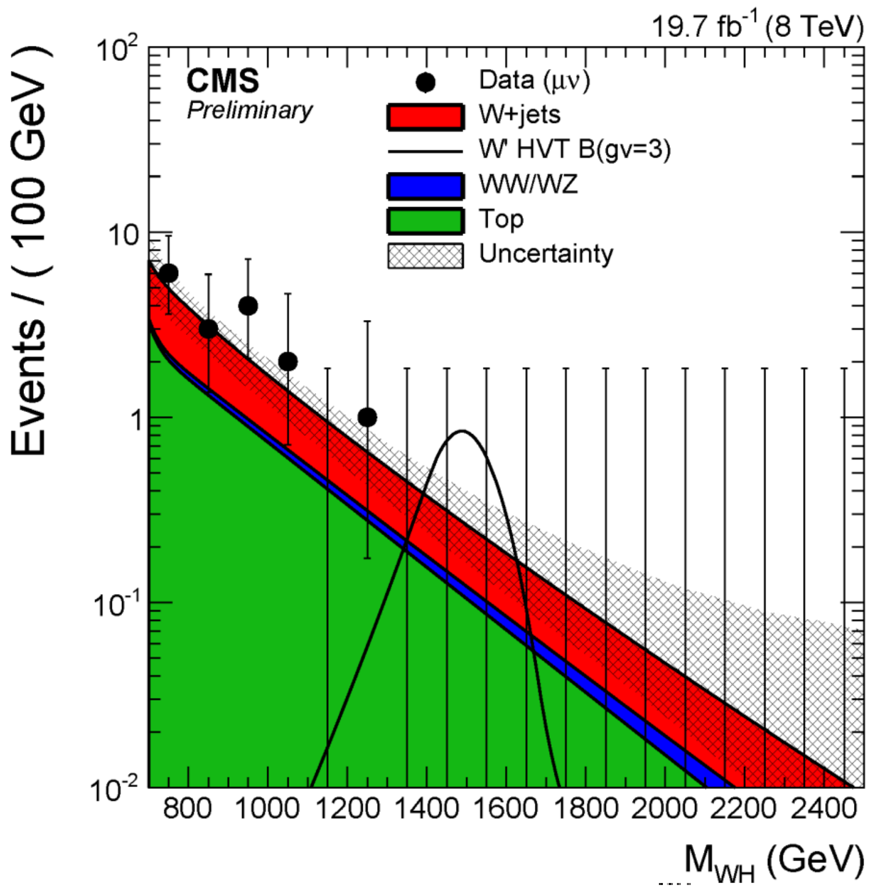
**Estimated wjets shape in SR**

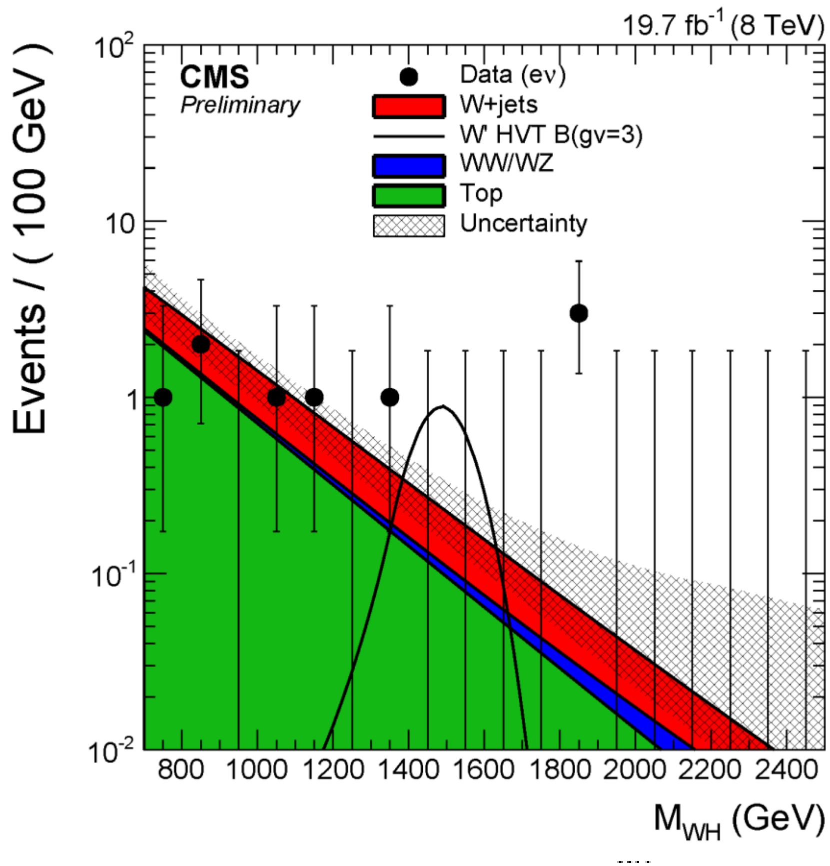
**Fit data SB with summed components to get wjets shape in low SB region**

$m_{jet}^{pruned}$ regions:

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

# Final $M_{WH}$ distribution




✓ Good data/MC agreement in the muon channel

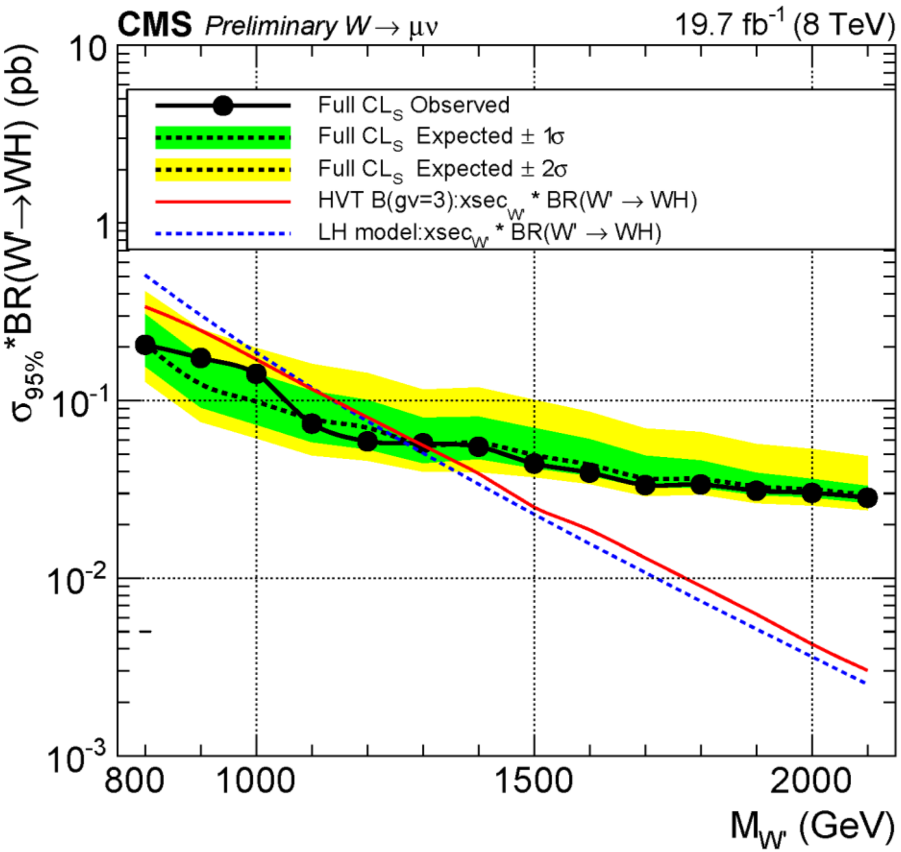
✓ Excess of 3 events in the electron channel with $M_{WH}$ > 1.8 TeV where less than 0.3 are expected

# Systematics

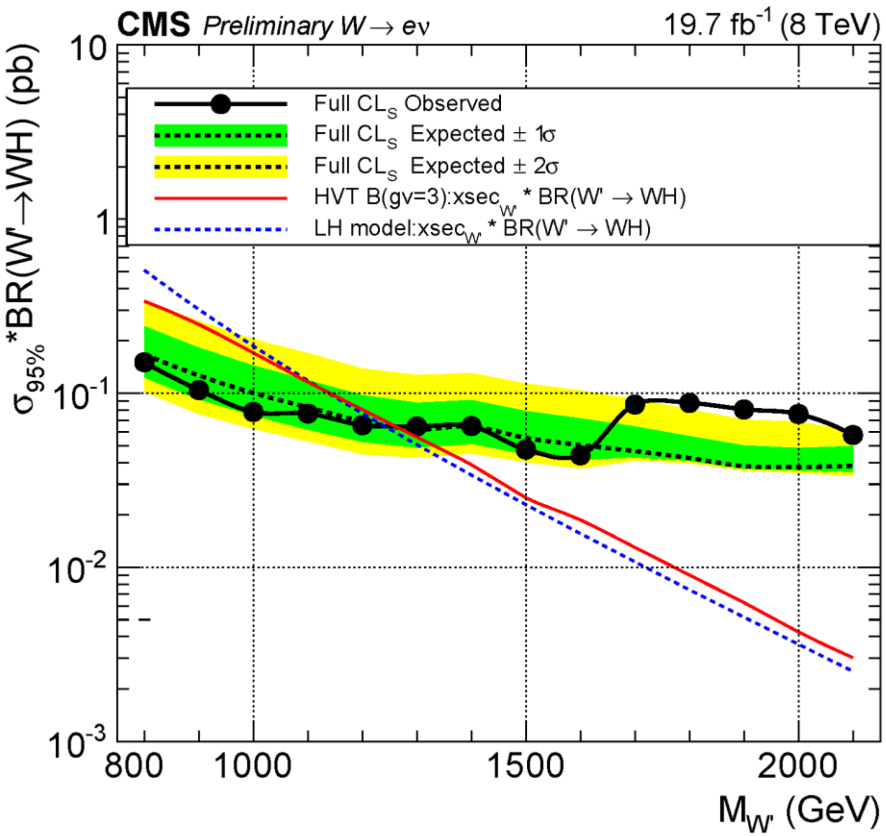
- W+jets background estimation:
  - normalization uncertainty dominated by statistics in sideband (~ 40%)
  - shape uncertainty from fit covariance matrix and parton showering uncertainties
- Other backgrounds normalization:
  - TTbar and Single Top: 18% (from TTbar control region)
  - VV: 20% (difference between CMS measurements and SM expectation)
- Signal shape and normalization:
  - normalization unc. dominated by H-tagging →
  - shape uncertainty in the signal width dominated by jet scale and resolution (~5%)
  - uncertainty on the peak < 1%

| Source | Uncertainty $e\nu$+H-jet | Uncertainty $\mu\nu$+H-jet |
|---|---|---|
| Muons (trigger and ID) | – | 2% |
| Muon scale | – | 1% |
| Muon resolution | – | <0.1% |
| Electrons (trigger and ID) | 3% | – |
| Electron scale | <0.5% | – |
| Electron resolution | <0.1% | – |
| Jet scale | 1–3% | |
| Jet resolution | <0.5% | |
| Higgs mass tagging | 2–10% | |
| Higgs b tagging | 2–8% | |
| Unclustered energy scale | <0.5% | |
| Pileup | 0.5% | |
| PDF | <0.5% | |
| Luminosity | 2.6% | |

# Results

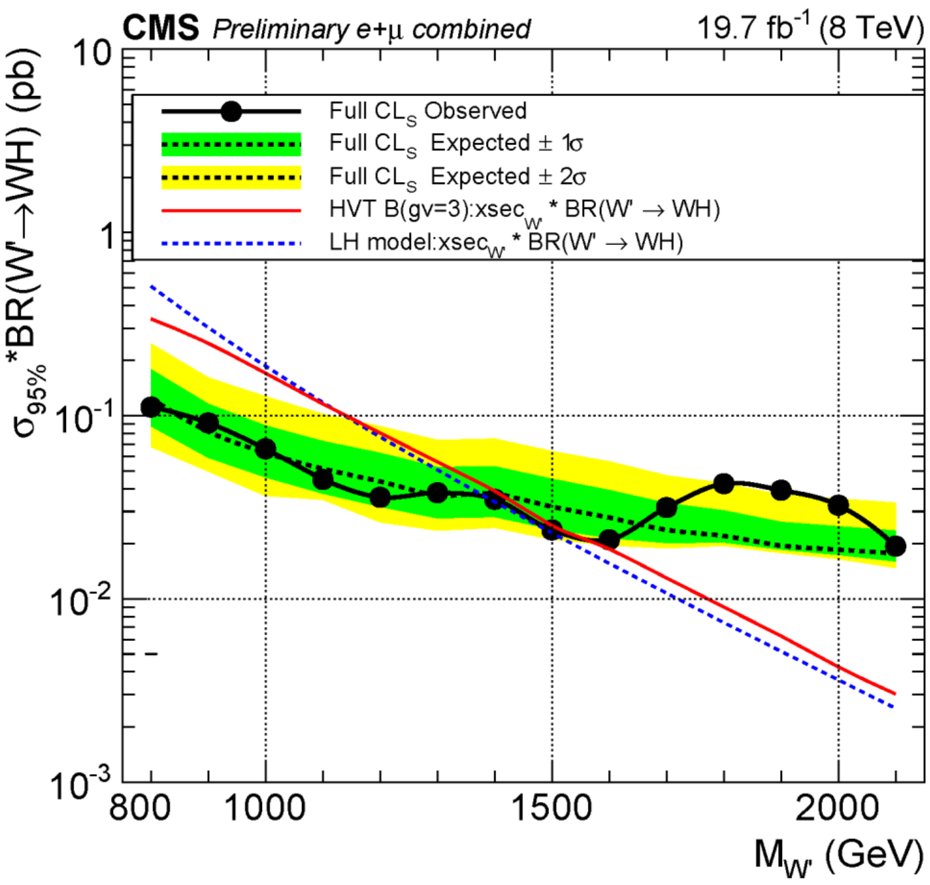


CMS Preliminary W → μν
19.7 fb-1 (8 TeV)
Full CLS Observed
Full CLS Expected ± 1σ
Full CLS Expected ± 2σ
HVT B(gv=3):xsecW' * BR(W' → WH)
LH model:xsecW' * BR(W' → WH)
σ95% *BR(W'→WH) (pb)
MW' (GeV)

CMS Preliminary W → eν
19.7 fb-1 (8 TeV)
Full CLS Observed
Full CLS Expected ± 1σ
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)

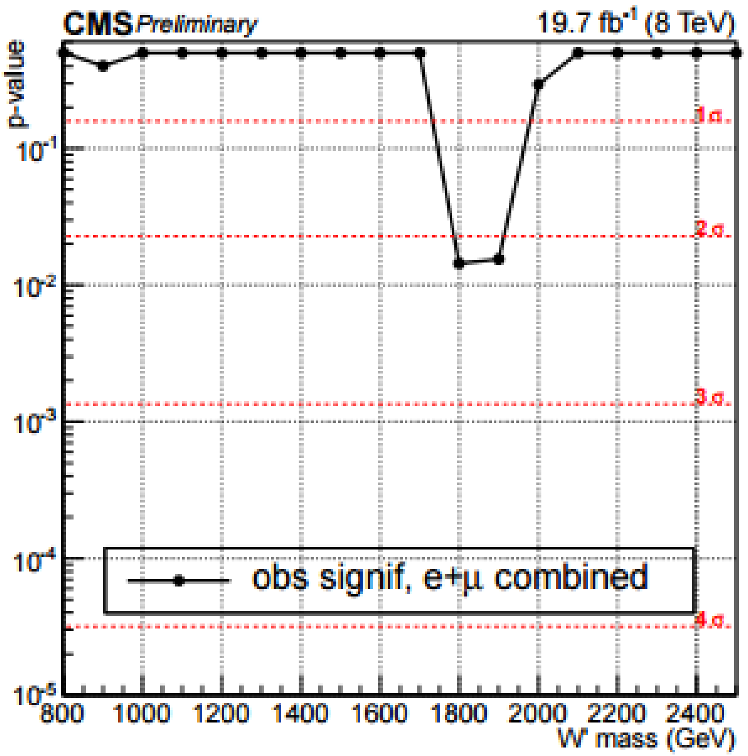
# Results




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

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

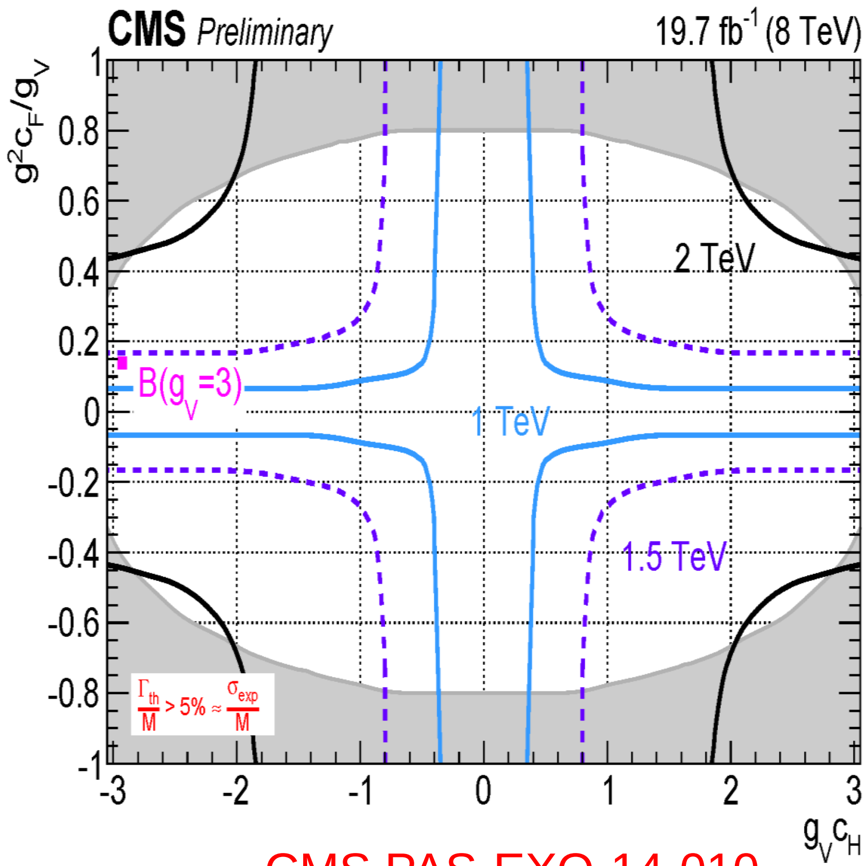
# Results



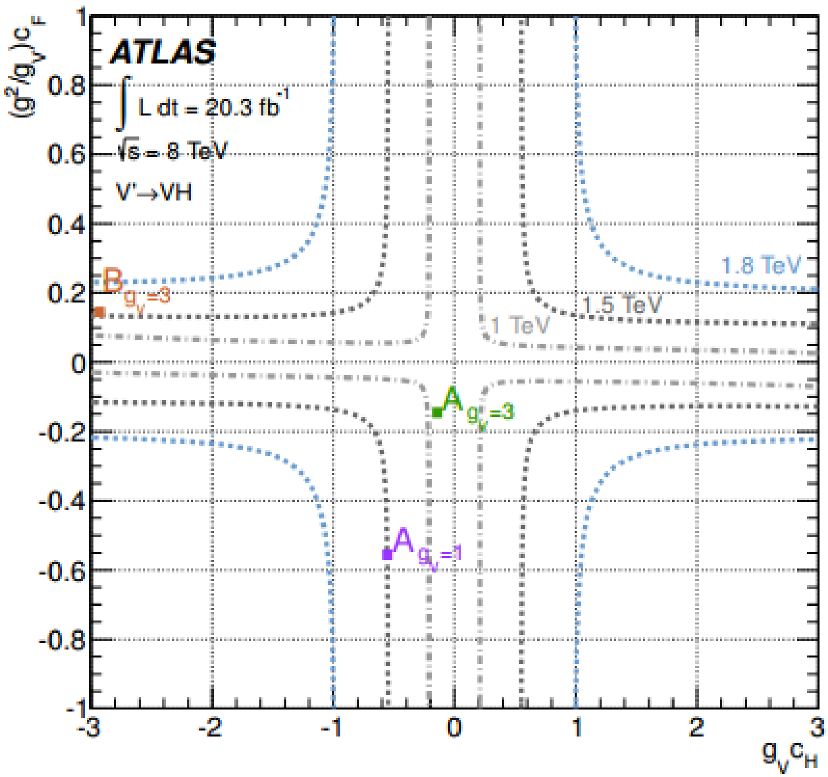

**Statistical Compatibility with the Standard Model within 2σ**

- 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

# Comparison between CMS and ATLAS




CMS PAS-EXO-14-010

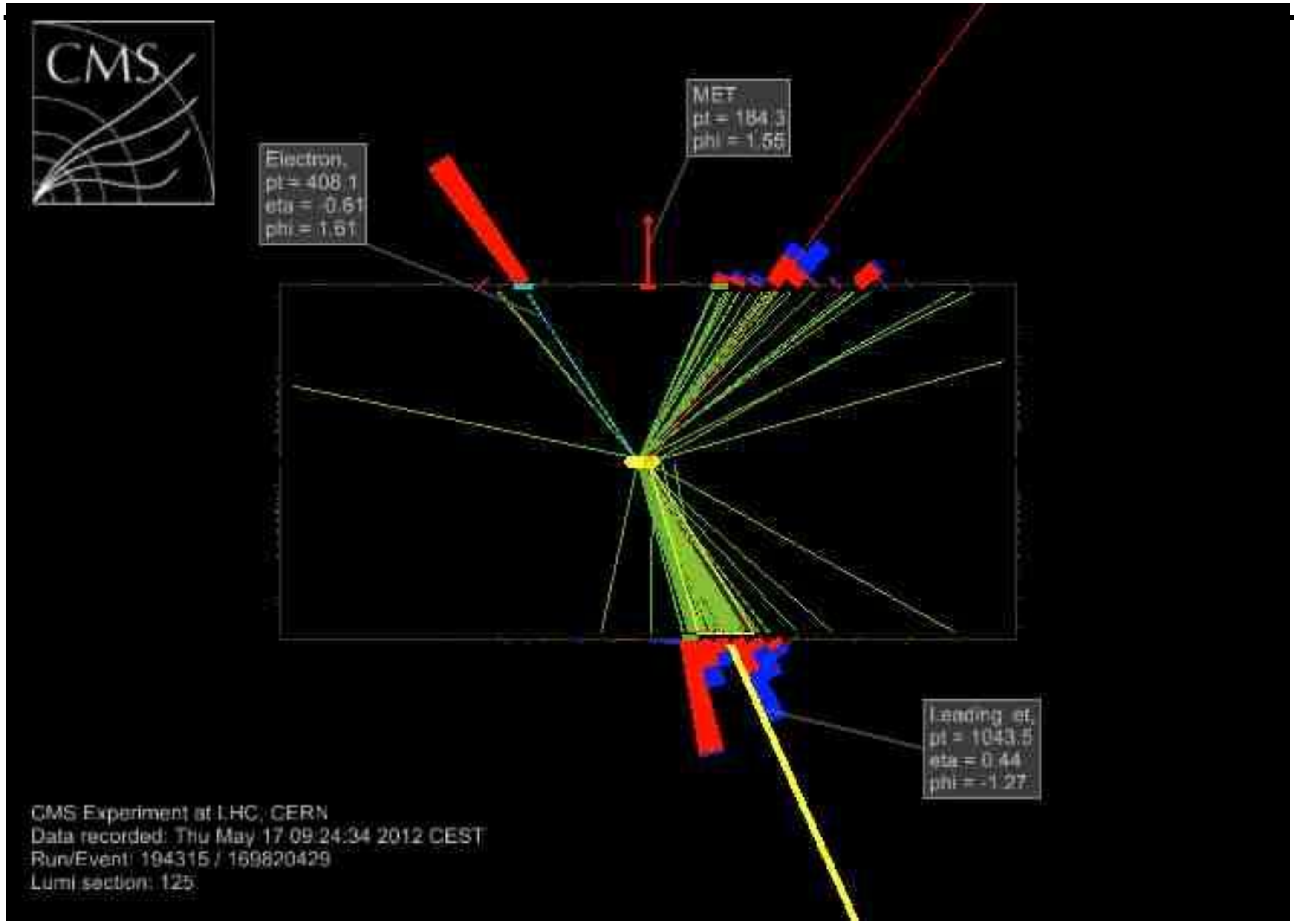



arXiv:1503.08089

Although a bit loose limit at low mass,

**We gain at high mass due to H-tagging: see point B**

# 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

# Summary

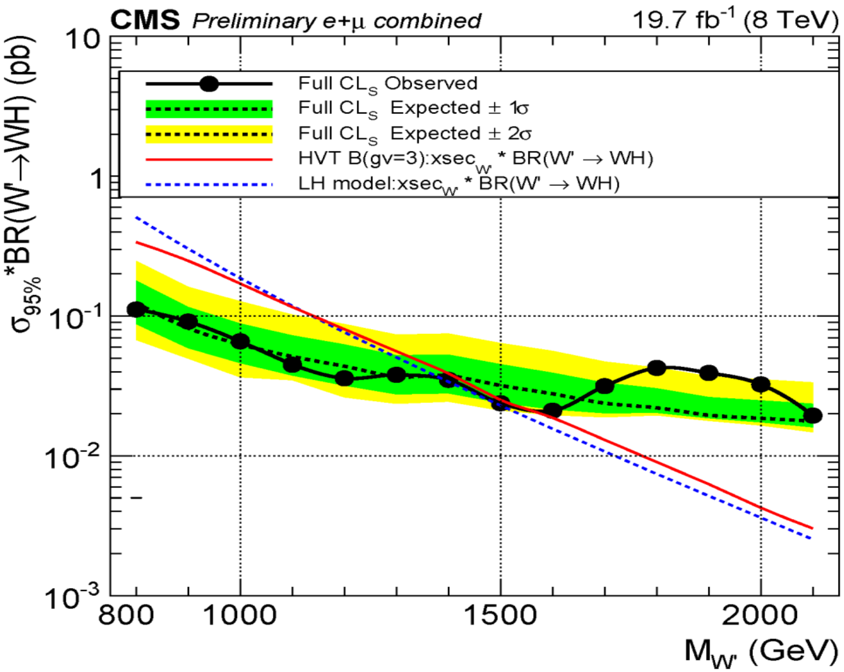
- **We presented the search for a new massive resonance decaying into WH in the lvbb final state.**

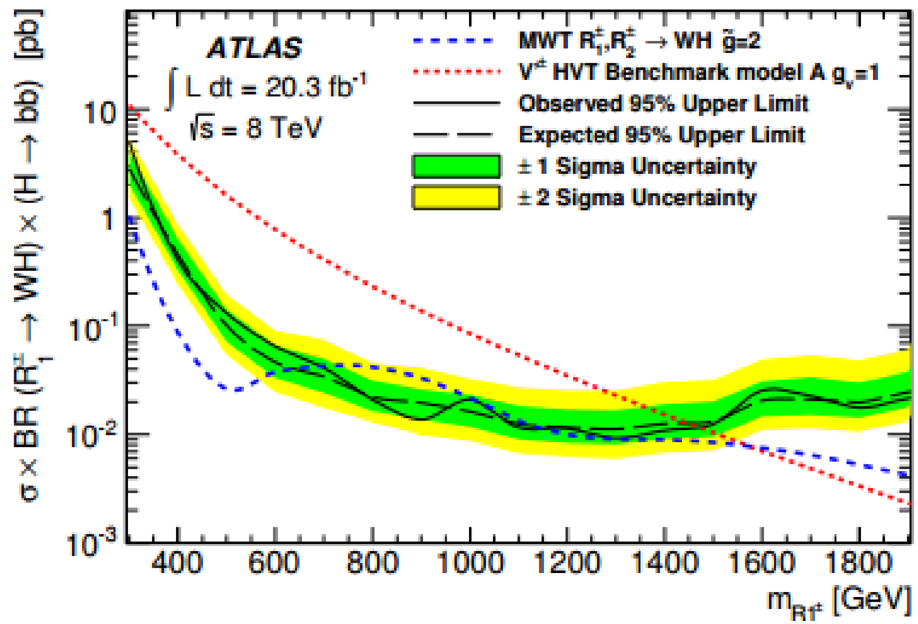
- **H-tagger exploited: Jet substructure and Sub-Jet b tagging**

- 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.

- **Run2 will definitely tell us more**

# Backup

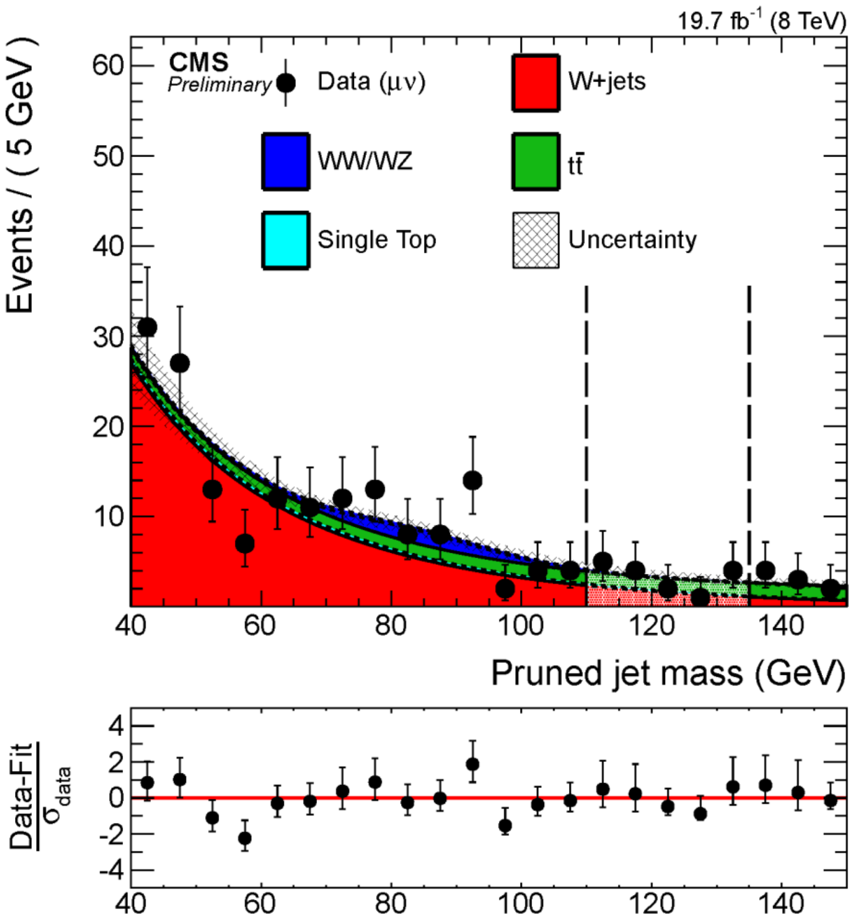


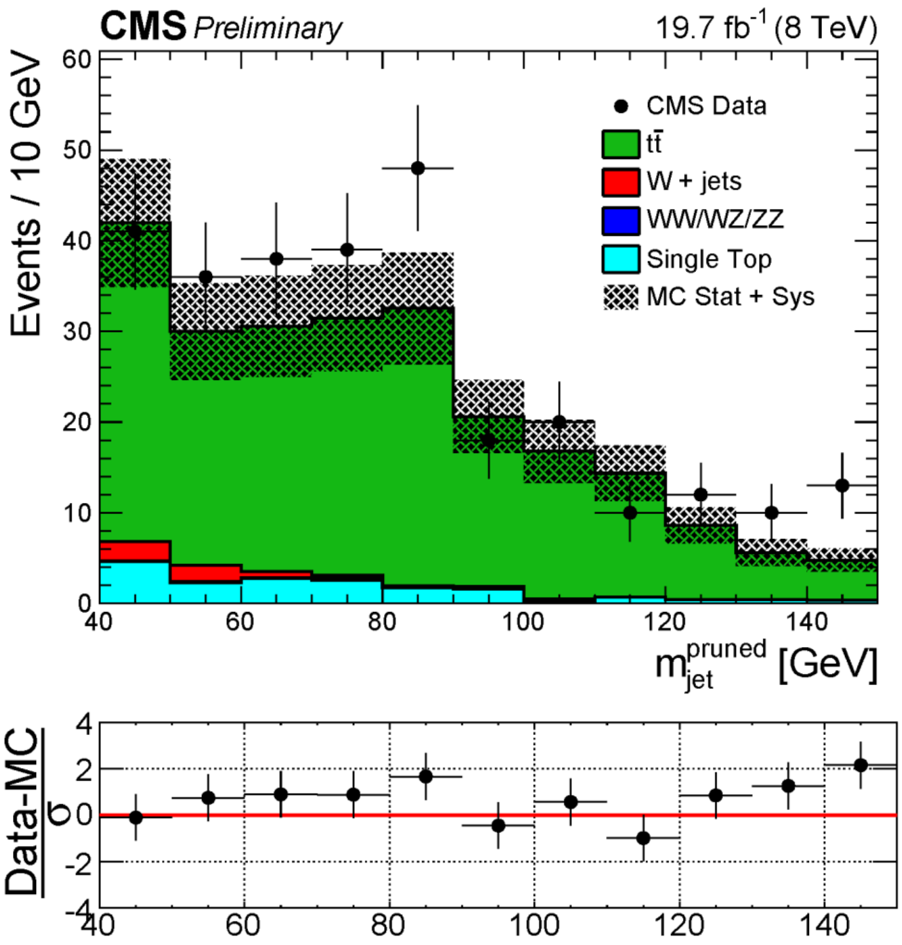




CMS PAS-EXO-14-010

arXiv:1503.08089

# Distribution Plots:  mu channel




**Pruned Jet mass in  Search Region and TTbar Control Region**

# W → lν reconstruction

- The identified electrons or muons are associated with the W → lν candidate → use the known W mass to calculate $p_{z,\nu}$
- Assume that $p_T$ neutrino = $E_T^{miss}$

↓

<u>Second order equation</u>

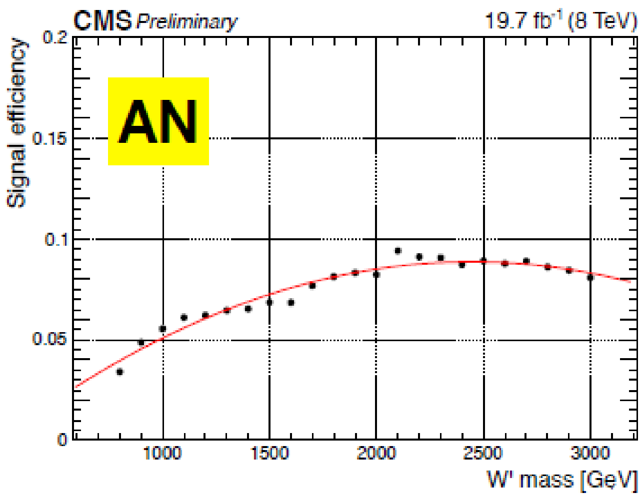
$$(E_\ell + \sqrt{{\mathbf{E}_T^{miss}}^2 + p_{z,\nu}^2})^2 - (\mathbf{p}_{T,l} + \mathbf{E}_T^{miss})^2 - (p_{z,l} + p_{z,\nu})^2 = M_W^2 = (80.4)^2 \qquad (1)$$

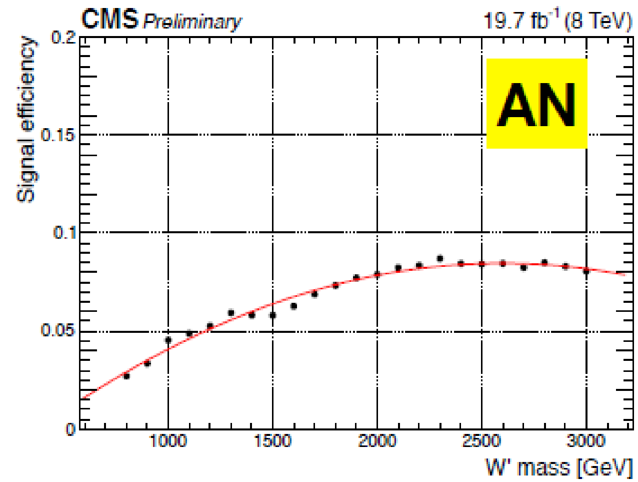
| Case 1: two real solutions | Case 2: two complex solutions |
| --- | --- |
| take the one with smallest $\lvert p_{z,\nu} \rvert$ | modify the components of the missing transverse energy to yield $M_T$=$M_W$ still respecting energy/momentum conservation |

# Signal efficiency and shape

ε = number of selected events/number of generated events (e+μ)

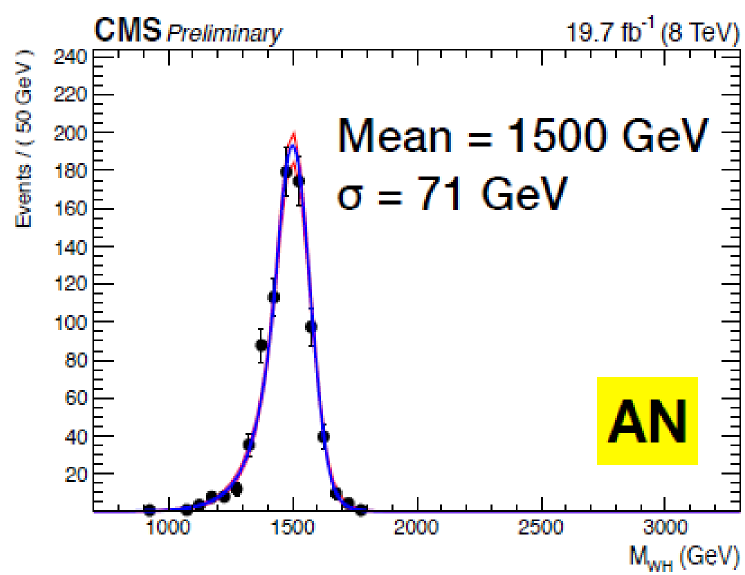
**Muon channel**




**Electron channel**

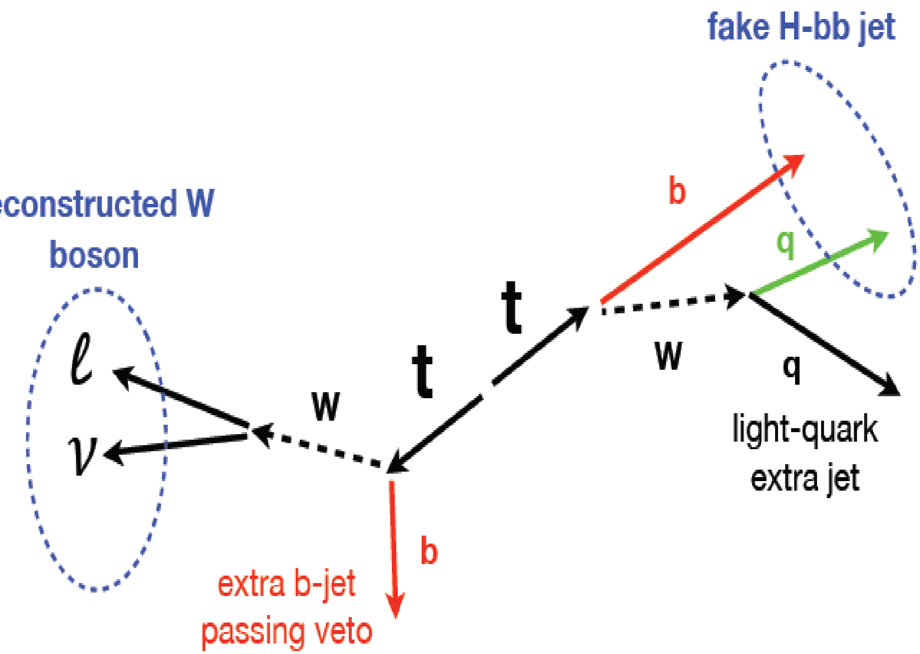
$M_{WH}$ shape parametrized with Crystal-Ball function: Gaussian core + power law tails




**Typical Gaussian core width 4-6%**

# TTbar rejection

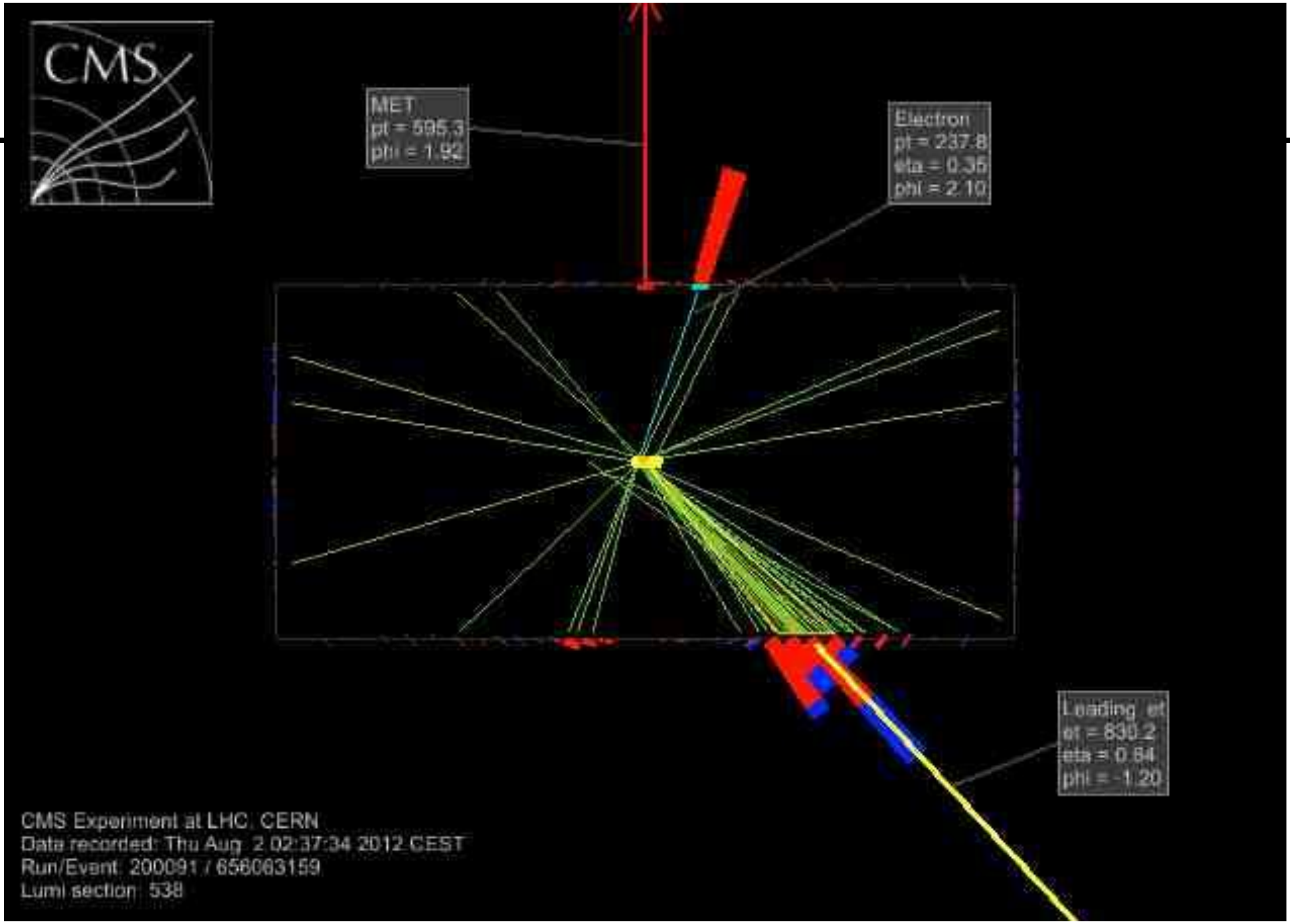
- TTbar background partially rejected with veto on extra b-tagged jets
- Still represents the main source of background in signal $m_{jet}^{pruned}$ window
- Exploit the possibility to reconstruct the invariant masses of the **hadronic (leptonic) top quarks** exploiting the presence of an extra jet in the event close to the CA8 jet (lepton)



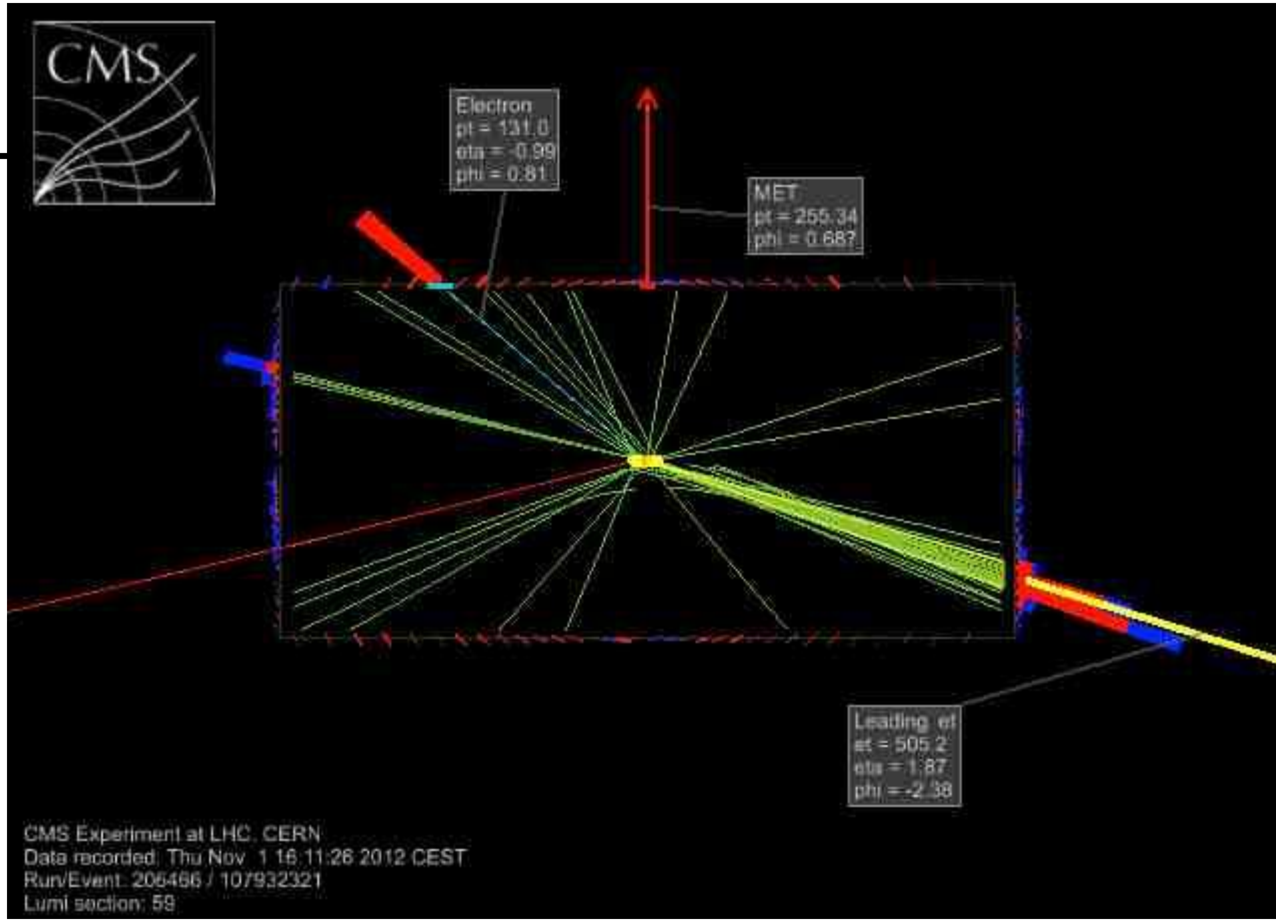

<u>Comparison between different ttbar rejection strategies</u>

| Veto | BDT input variables | P |
|---|---|---|
| b-tag veto | - | $0.030 \pm 0.003$ |
| b-tag veto + (150< $M_{lt}$ <220 GeV \|\| 150< $M_{ht}$ <300 GeV) | - | $0.038 \pm 0.004$ |
| 0 extra jets | - | $0.036 \pm 0.003$ |

| Veto | 1 TeV | 1.5 TeV | 2 TeV |
|---|---|---|---|
| b-tag veto | $0.039 \pm 0.002$ | $0.099 \pm 0.008$ | $0.1532 \pm 0.019$ |
| b-tag veto + (150< $M_{lt}$ <220 GeV \|\| 150< $M_{ht}$ <300 GeV) | $0.047 \pm 0.003$ | $0.102 \pm 0.009$ | $0.158 \pm 0.020$ |



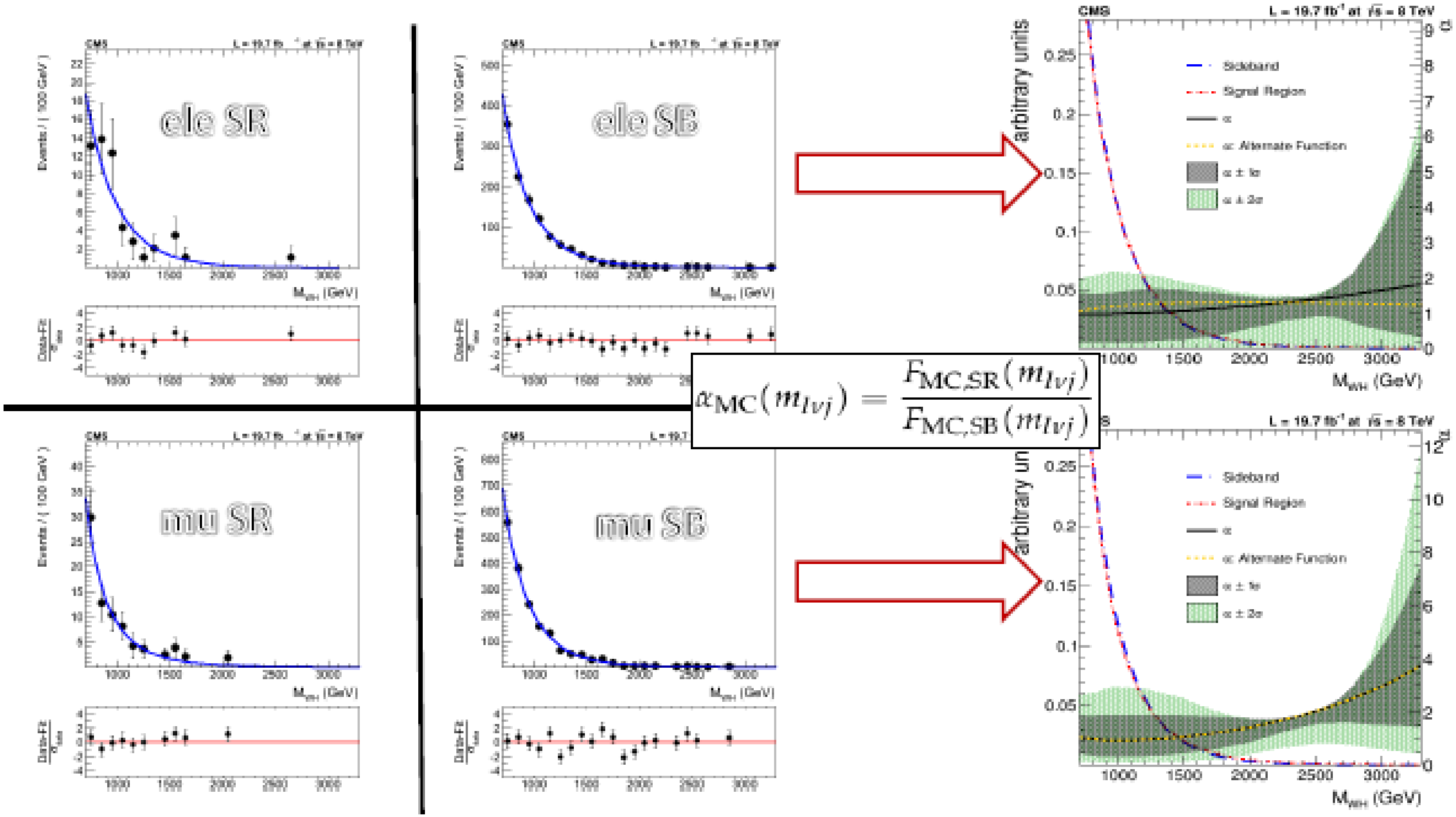

Event display of a nicely balanced leptonic W plus H-tagged jet event with a WH invariant mass of 1.88 TeV. The leptonic W is reconstructed from the electron and the missing transverse energy in the event and it has a transverse momentum of 0.91TeV. The transverse momentum of the H-tagged jet is 0.87 TeV while the mass of the associated pruned jet is 112.1 GeV.



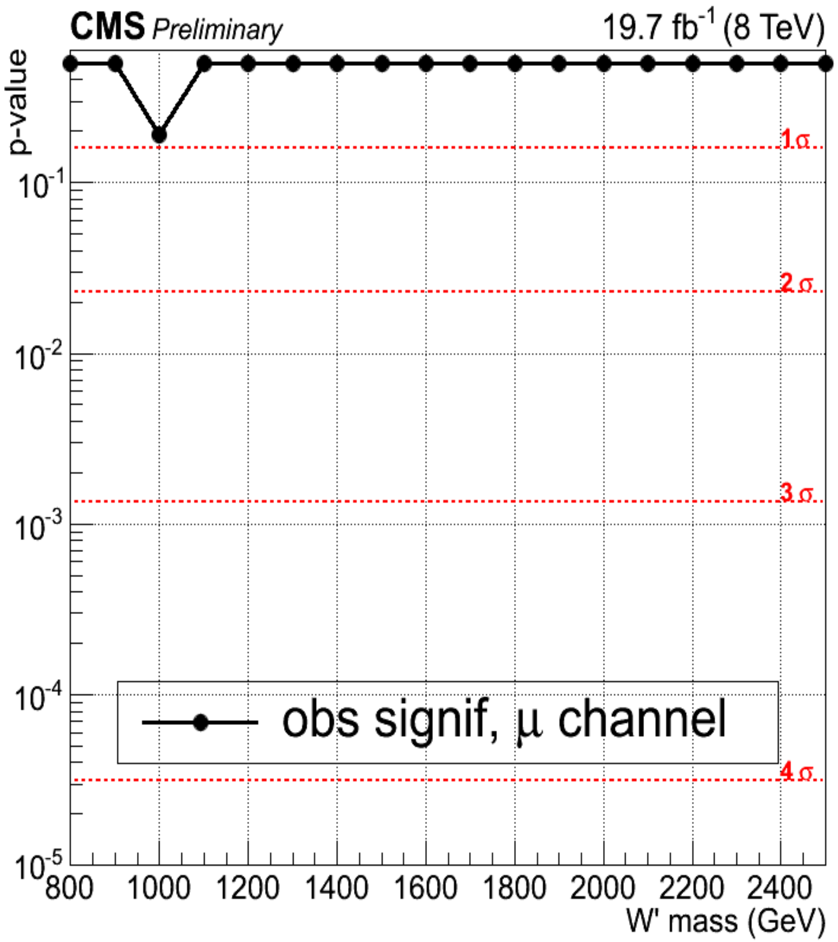

Event display of a nicely balanced leptonic W plus H-tagged jet event with a WH invariant mass of 1.80 TeV. The leptonic W is reconstructed from the electron and the missing transverse energy in the event and it has a transverse momentum of 0.39 TeV. The transverse momentum of the H-tagged jet is 0.52 TeV while the mass of the associated pruned jet is 122.0 GeV.

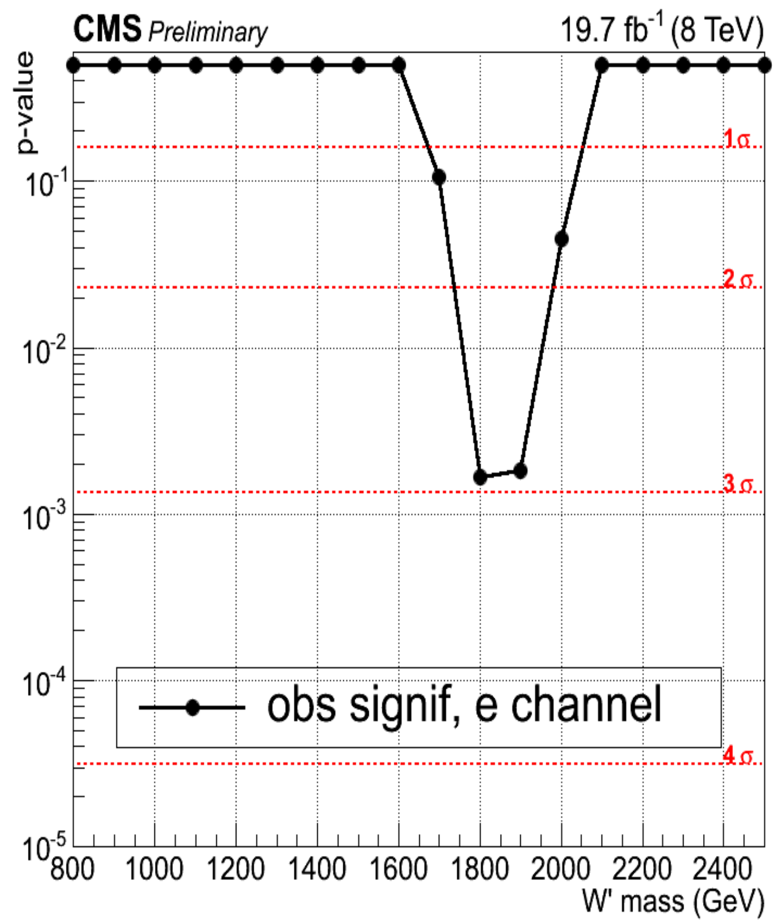
# Extrapolation function alpha(MC)

- 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)**




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


CMS Preliminary
19.7 fb$^{-1}$ (8 TeV)
p-value
1σ
2σ
3σ
4σ
obs signif, μ channel
W' mass (GeV)


CMS Preliminary
19.7 fb$^{-1}$ (8 TeV)
p-value
1σ
2σ
3σ
4σ
obs signif, e channel
W' mass (GeV)

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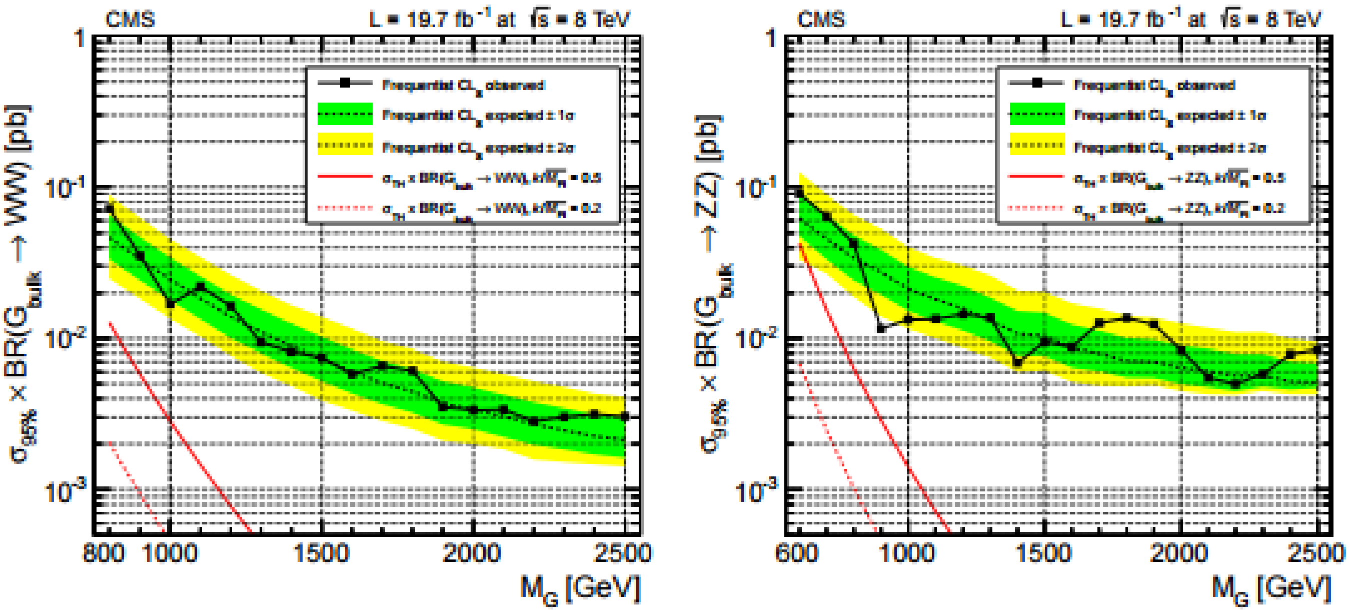


Figure 9: Observed (solid) and expected (dashed) 95% CL upper limits on the product of the graviton production cross section and the branching fraction of $G_{bulk} \to WW$ (left) and $G_{bulk} \to ZZ$ (right). The cross section for the production of a bulk graviton multiplied by its branching fraction for the relevant process is shown as a red solid (dashed) curve for $k/\overline{M}_{Pl} = 0.5$ (0.2), respectively.

# W-tagging

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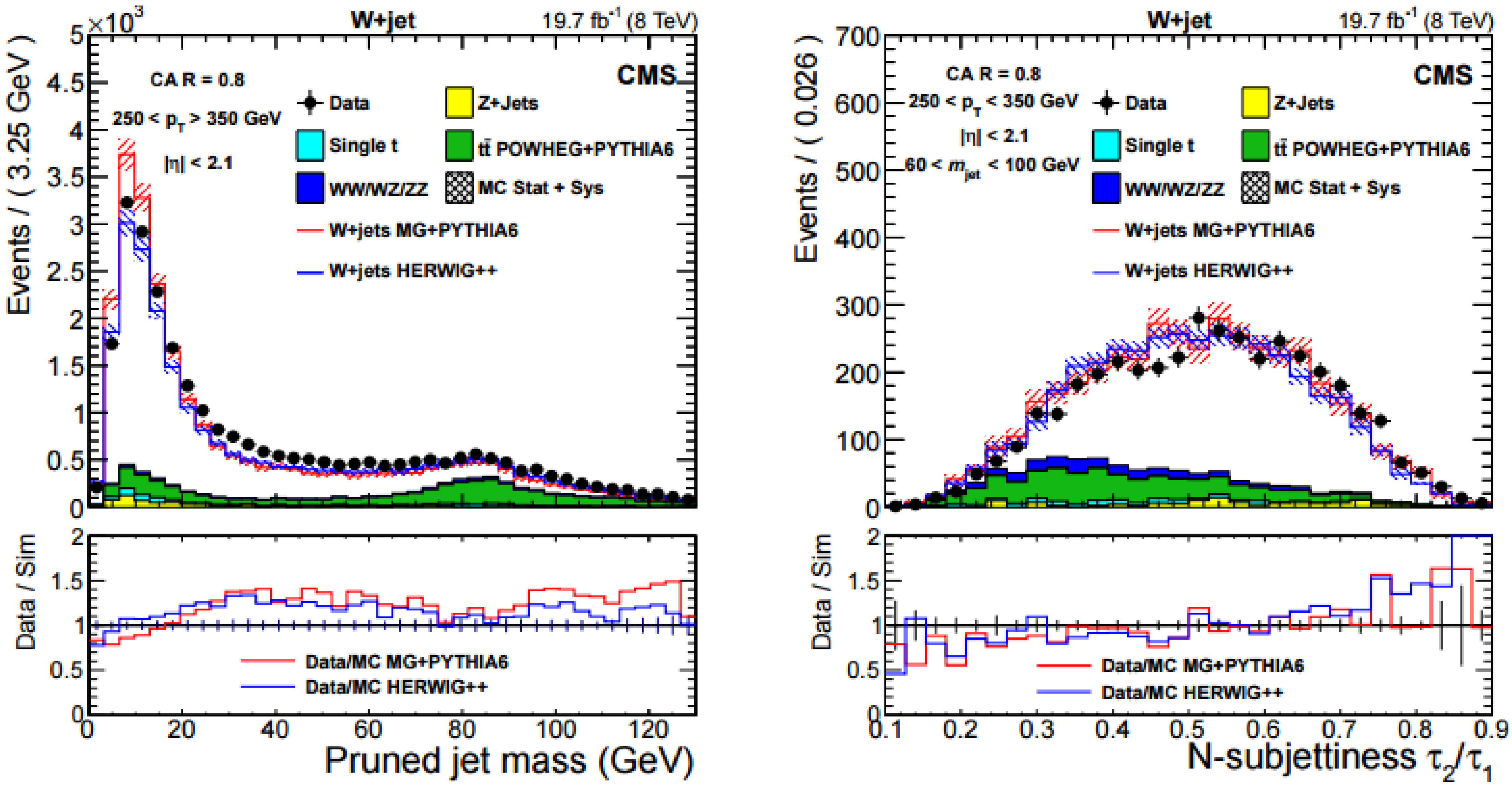


**W+jets: Data vs MC**

**Discrepancy Seen -> Corrected in TTbar Control Region**

# W-tagging: TTbar Control Region

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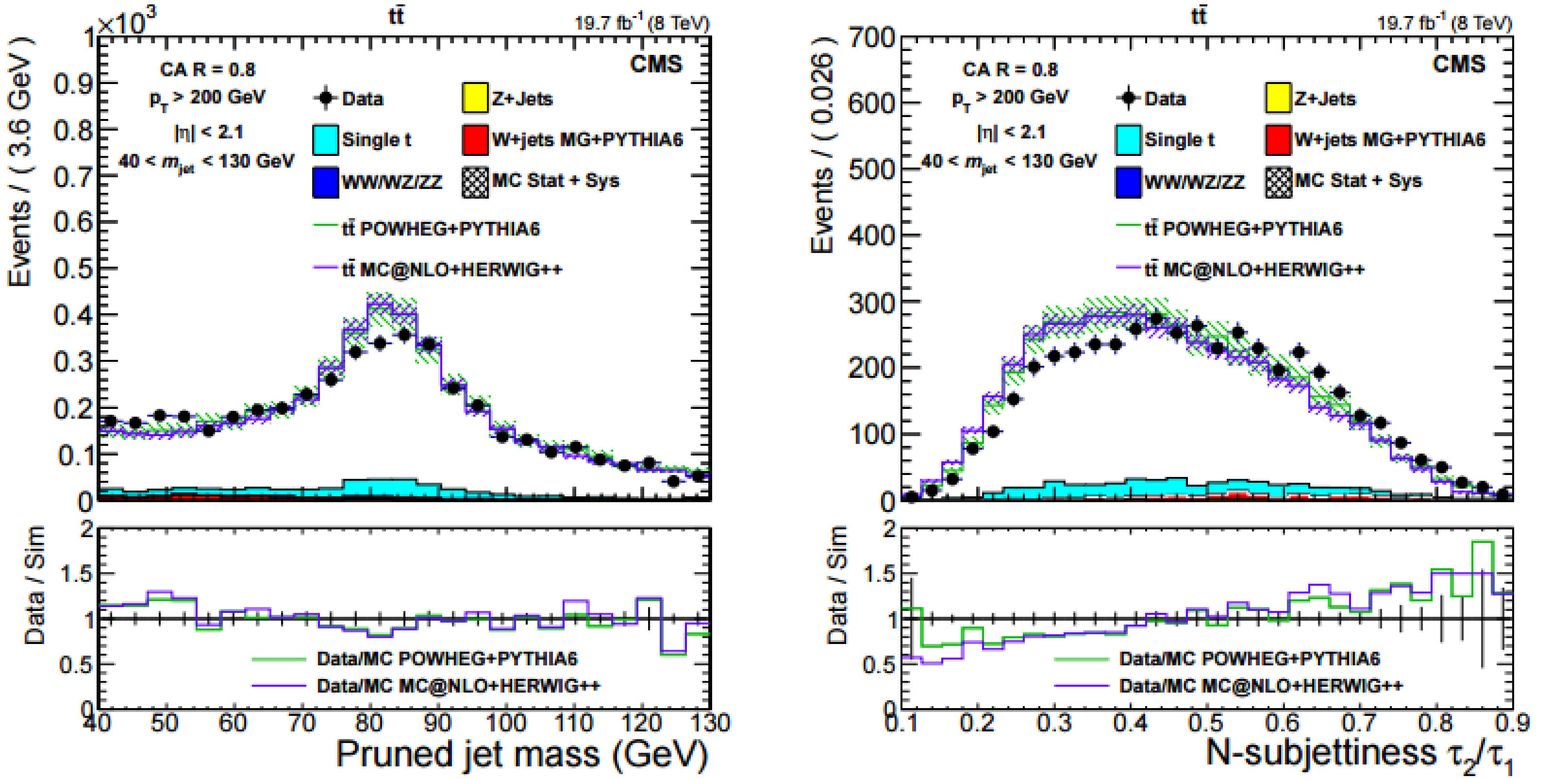


**Scale Factors extracted in TTbar Control Region**