WV resonance searches at CMS (Run1)

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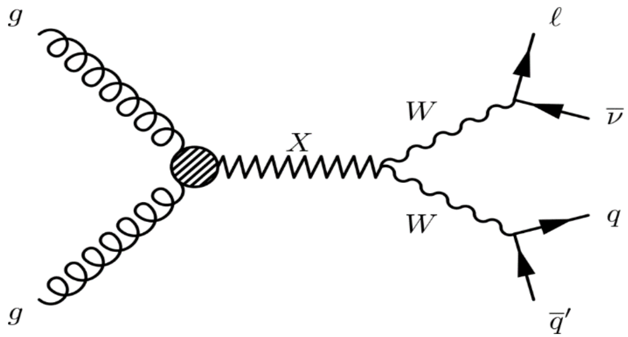
Outline

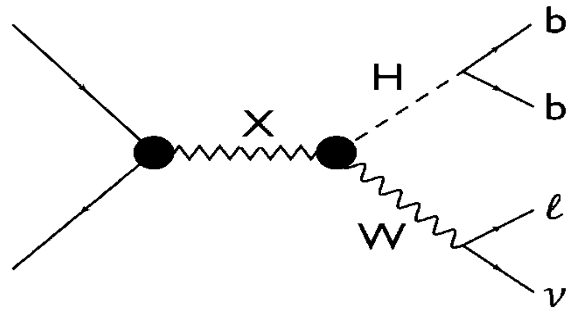
- **Introduction**
- **W/H Tagging Technique at CMS**
- **Run1 EXO-WW Search**
- **2015 and 2016 EXO-WW**
- **Summary**
- Backup: Run1 WH

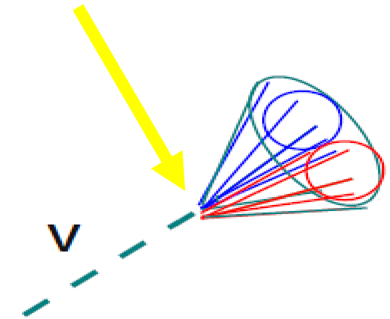
2016分析结果参见周三黄璜报告

北大 WW/WH 共振态寻找: 过去4年持续完成7个分析

Boosted V/H-Jet :
Merged Fat Jet







Run1 20fb-1

W-tagging: JHEP 12(2014)017 总次55
邹伟，徐子骏重要贡献

Heavy Higgs: JHEP 1510 (2015) 144 总引129
徐子骏Approval

EXO-WW: JHEP08(2014)174 ; 总次166
刘帅Preapproval

EXO-WH: EPJC76 (2016) 237
PAS-EXO-14-010 总引63
王蒙蒙Preapproval
李强负责人

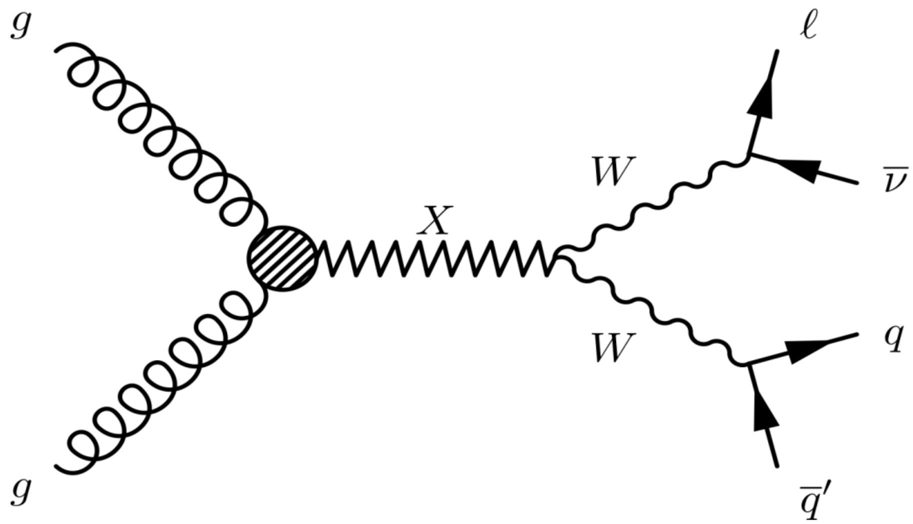
Run2 2015 2.2fb-1

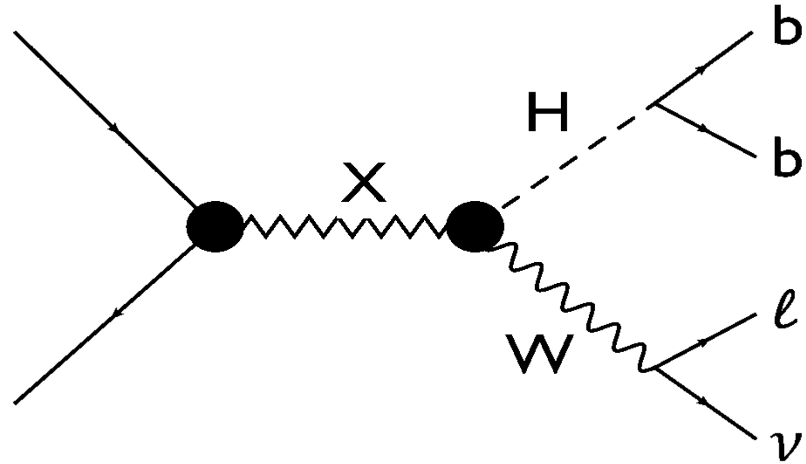
EXO-15-002 0.8-4TeV
王群 Approval
B2G-16-004 0.6-1TeV
徐子骏Preapproval
PAS总引37
Paper正在准备

Run2 2016 → ICHEP2016

B2G-16-020 0.6-4.5TeV
黄璜负责人, Preapproval
徐子骏Approval

EXO-VV Overview



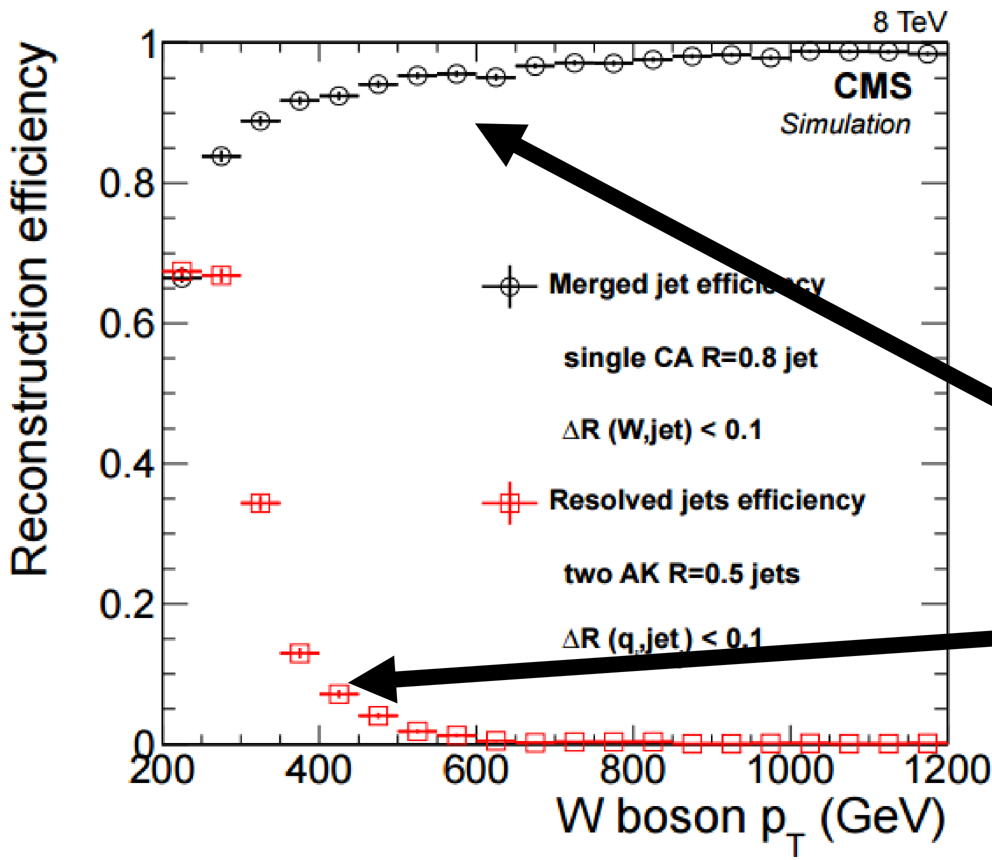


- **VV, VH resonance motivated in many nice models**
  Extra Dimension, Composite Higgs, Little Higgs
  Spin-0 Radion/Higgs; Spin-1 W'/Z'; Spin-2 Gravitons

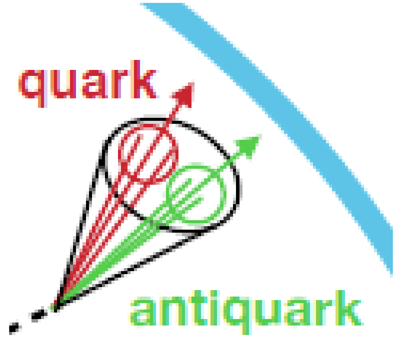
- **Semi-leptonic channels: High rates, reconstructable spectrum**
  Huge QCD Wjets bkg, data-driven estimation

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

Boosted V/H-Jet: Why?



$\Delta R_{jj} \sim 2M_w/PT_w$



For W pT>200 GeV,
One CA8 jet to identify W jets, becomes
more efficient than the reconstruction from
2 AK5 jets.

CA8: Cambridge-Aachen with Cone 0.8
AK5: Anti-Kt with Cone 0.5

W/H Tagging at CMS

JHEP 1412 (2014) 017
CMS PAS-BTV-13-001

W and Z bosons mass are rather close, we do not distinguish the two, and refer to such jets collectively as V jet

Fat Jet at CMS: an incomplete history

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

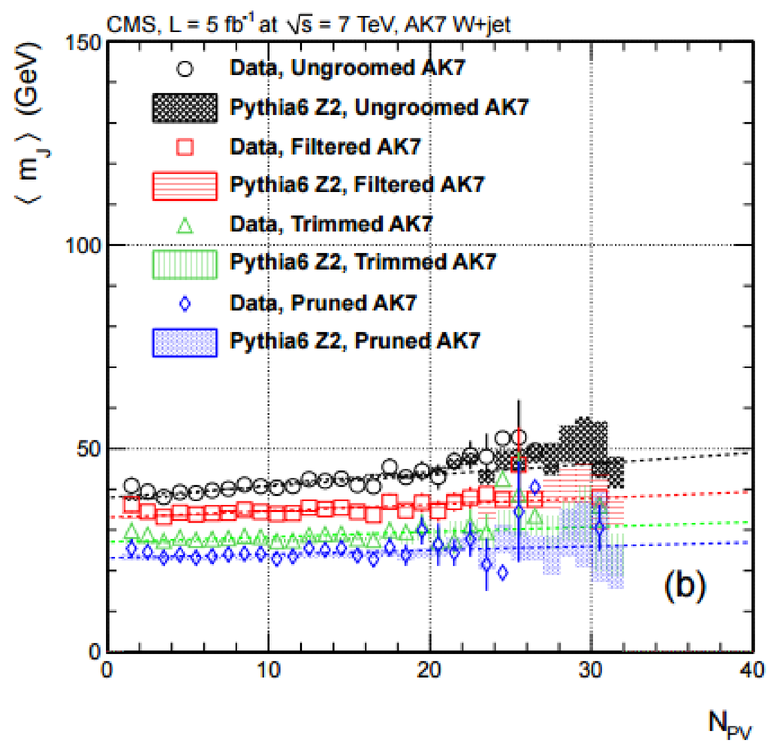
7TeV WZ/ZZ resonance:
Jet mass, mass drop
JHEP 1302 (2013) 036

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

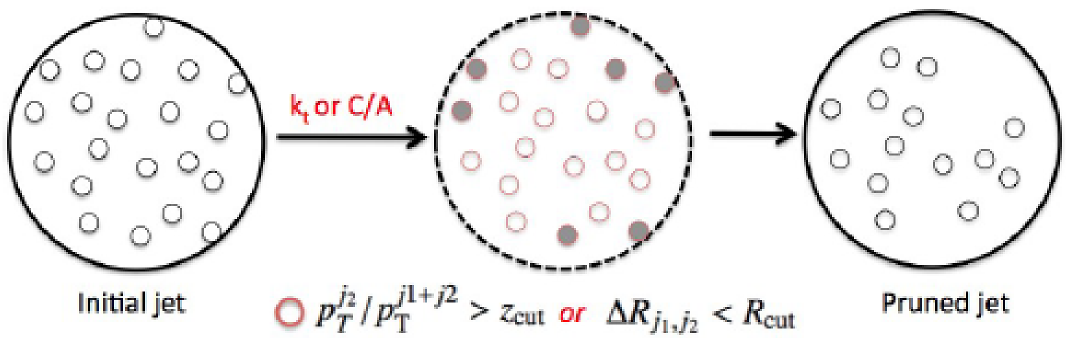
W-tagging Summary:
JHEP 1412 (2014) 017

MC works well
Groomed Jet mass more stable with PU



W-tagging: Pruning+Tau21

- **"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,

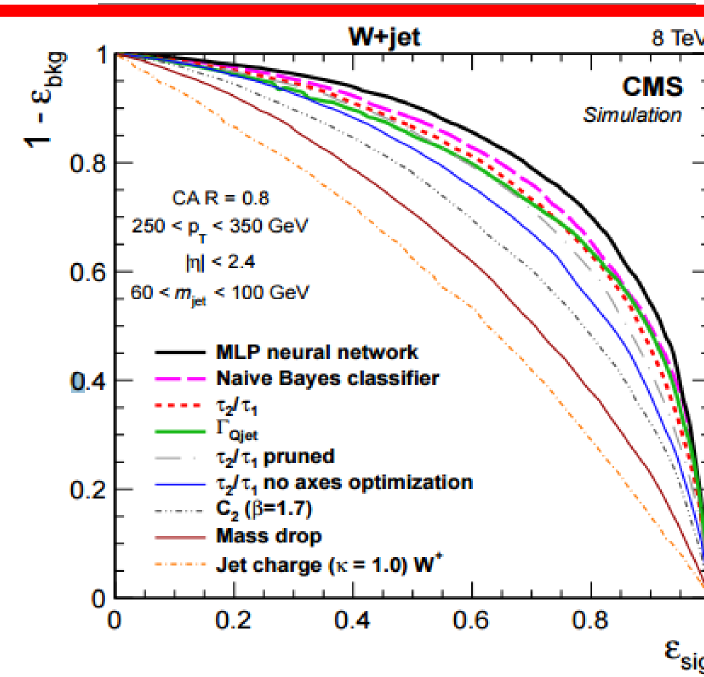
N-subjettiness (arXiv:1011.2268):

how likely is a jet to have "N" subjets

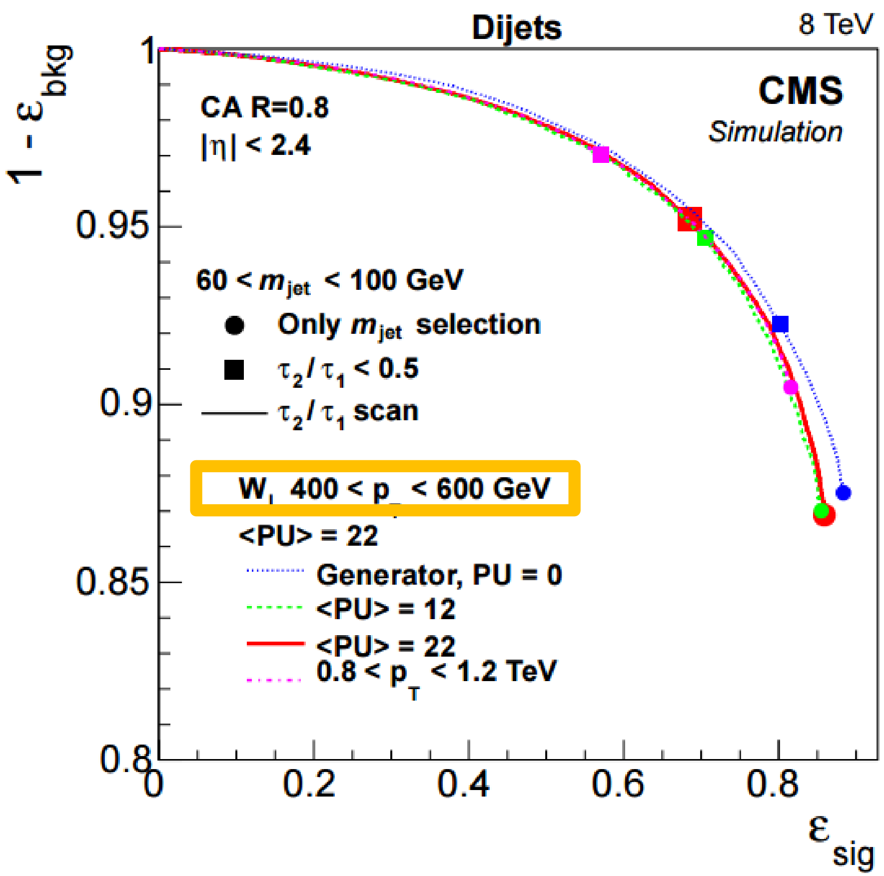
Wjet tagger: τ_{21}

H→WW→4q: τ_{42}

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



W-tagging Efficiency (Run1)



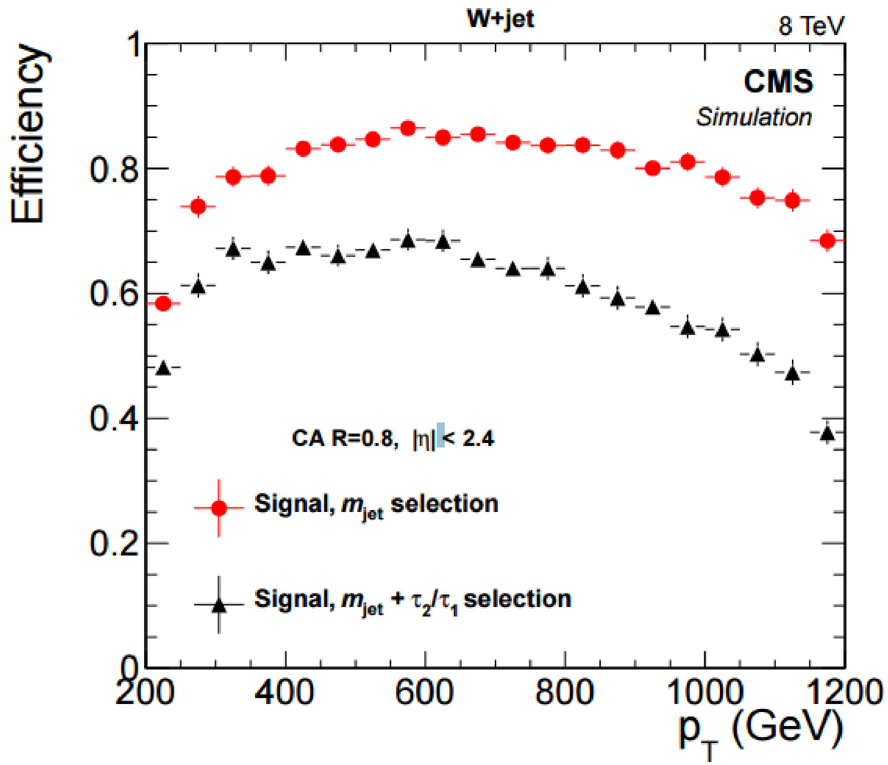
Signal: Bulk Graviton->2 W_L
Bkg: QCD WJets

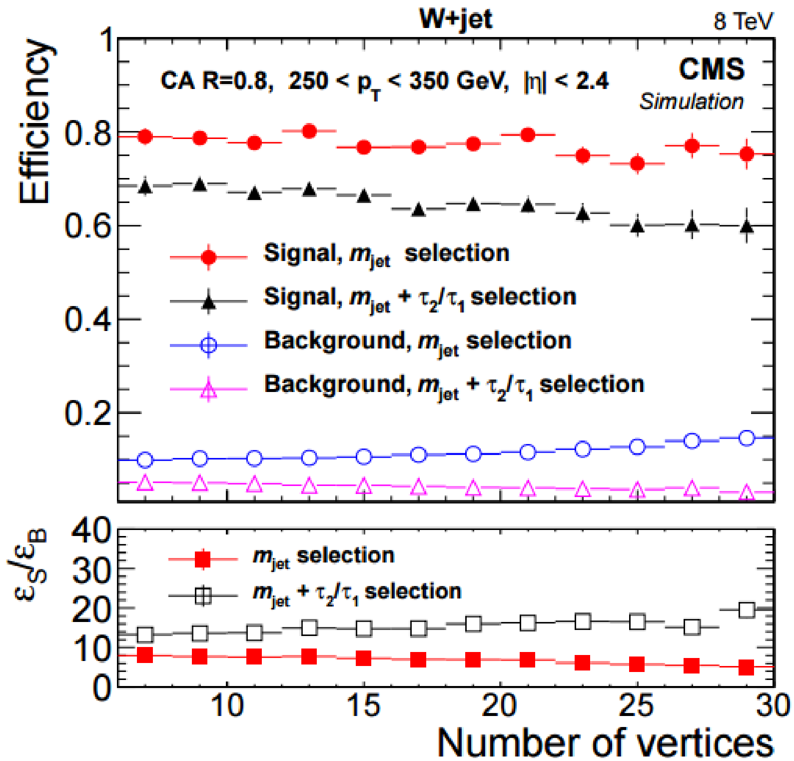
Some differences w/o PU
Stable for PU=12 or 22

For τ_{21}<0.5 and mjet [60,100]
eff(bkg)~ 5% - 3%,
eff(sig) ~ 70%-55%,
for PT~0.5TeV and 1TeV

Run1	τ_{21}<0.5 as High-Purity working points; 0.5<τ_{21}<0.75 as LP
Run2	changes to 0.45 and 0.6 (见黄璜报告)

W-tagging Signal Efficiency (Run1)

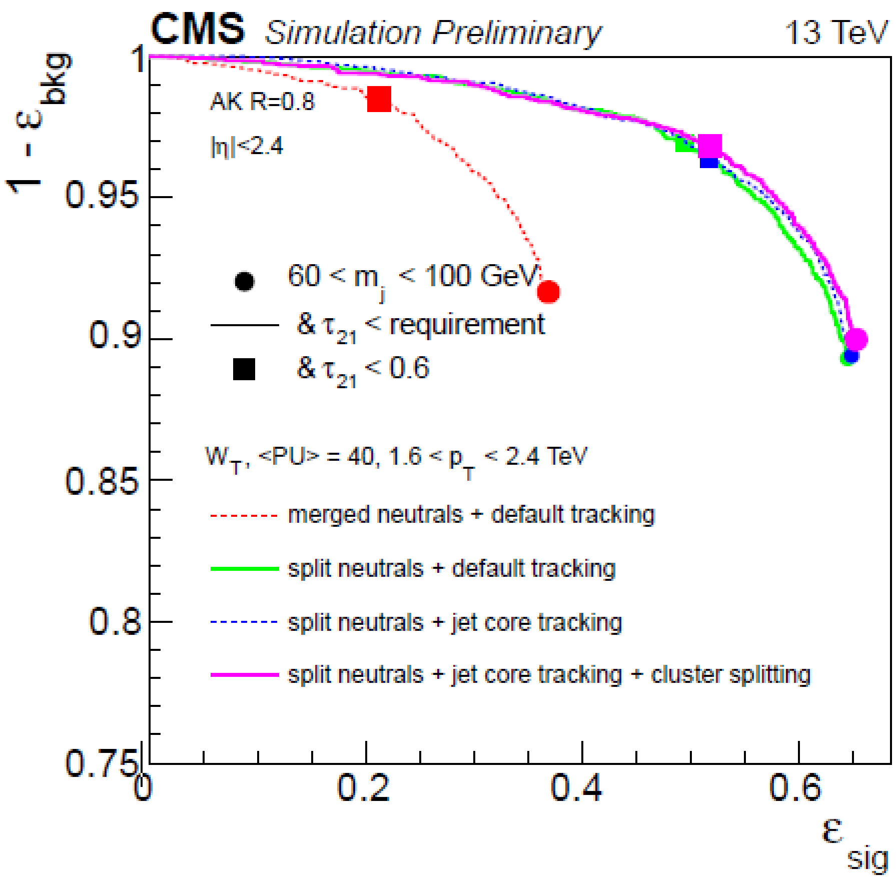




At large pT, eff drops due to PF reconstruction degrades in resolving the jet substructure and pruning therefore removes too large fraction of jet mass.

Run2 Improvement JME-14-002

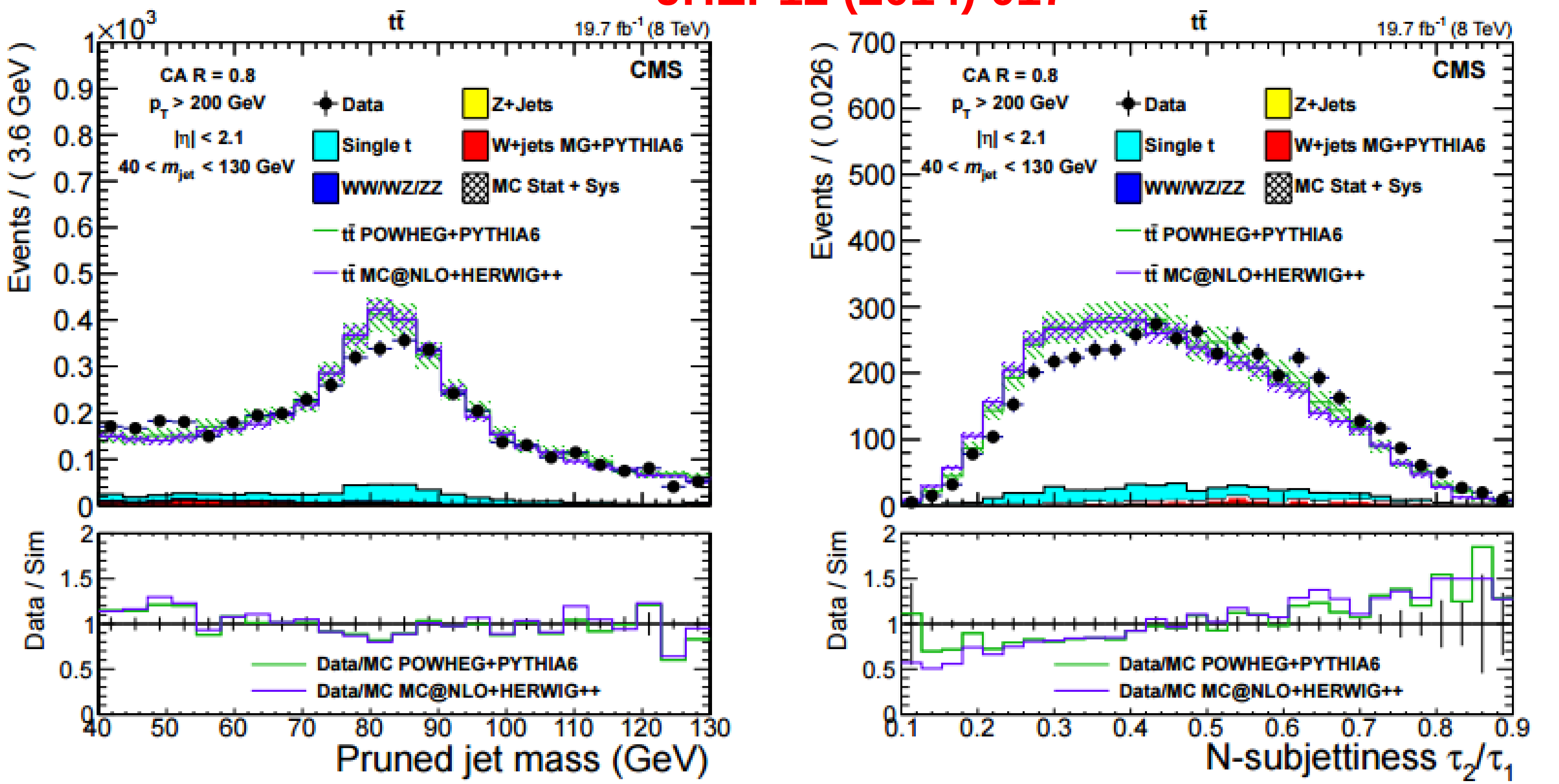
For Run II, PF reconstruction has been optimized by making better usage of the segmentation of the ECAL(0.0175*0.0175), to maintain constant efficiency up to at least pT = 3.5 TeV



split PF neutrals:
a neutral hadron is created in the direction of each ECAL cluster and the total energy measured in ECAL and HCAL calibrated for hadrons is distributed to the neutral hadrons according to the fraction of the ECAL cluster energy with respect to the sum of all ECAL clusters considered.

W-tagging Calibration: TTbar Control Region

JHEP12 (2014) 017



POWHEG + PY6 works better

Scale Factors extracted in TTbar Control Region

Table 1: Summary of the fitted W-mass peak fit parameters.

Parameter	Data	Simulation	Data/Simulation
$\langle m \rangle$	84.1 ± 0.4 GeV	82.7 ± 0.3 GeV	1.017 ± 0.006
σ	8.4 ± 0.6 GeV	7.6 ± 0.4 GeV	1.11 ± 0.09

EXO-WW Resonance Searches

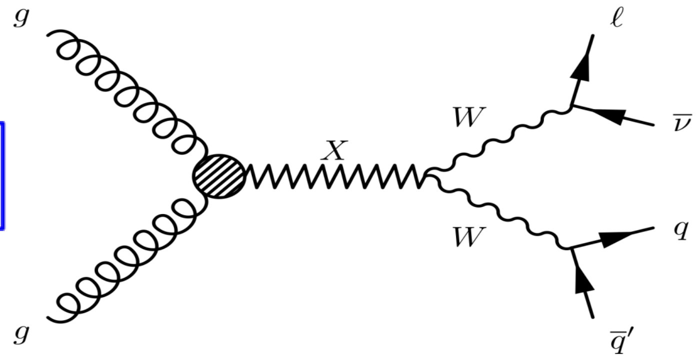
JHEP 08 (2014) 174

EXO-WW Searches

Look for "bumps" in the mWW spectrum in a large mass range in [800, 2500] GeV

Bulk Graviton Model : G-> $W_L W_L$ is used as a benchmark

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



Jet mass Signal Region: [65-105]GeV (Run2改进 见黄璜报告)

Low Sideband: [40-65]GeV

High Sideband: [105-130]GeV

τ_{21}<0.5 High Purity;

0.5<τ_{21}<0.75 Low Purity

Bkg Modelling

- **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:

Fit signal region wjets MC

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

Fit low sideband region wjets MC

3) Data Driven Background Extrapolation in the SR

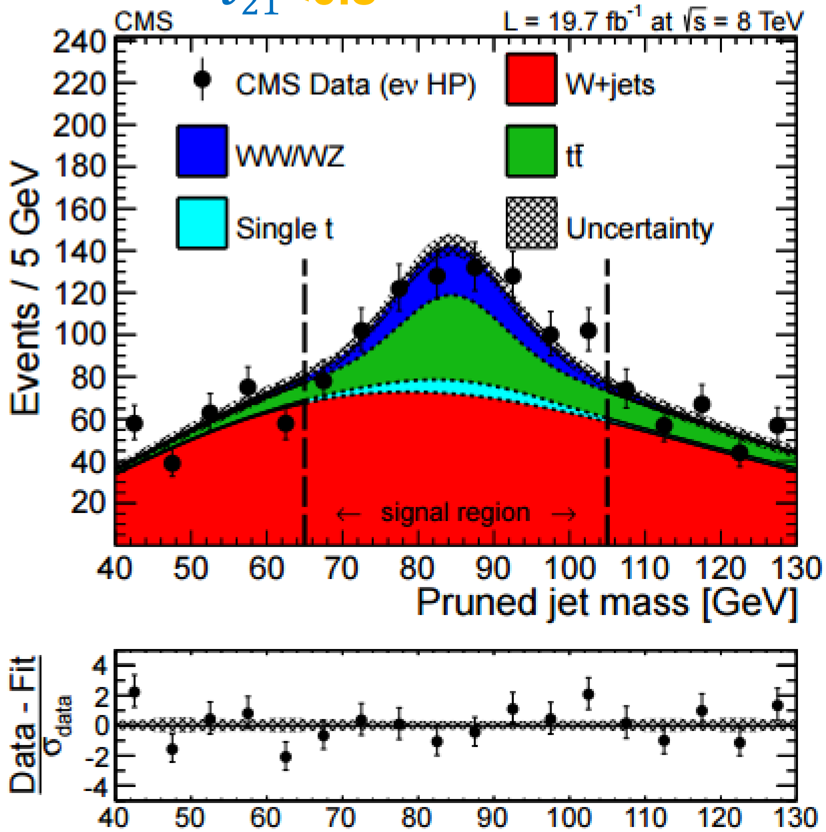
$$F_{\mathrm{data,SR}}(m_{lvj}) = \alpha_{\mathrm{MC}}(m_{lvj}) \times F_{\mathrm{data,SB}}(m_{lvj})$$

Estimated wjets shape
in signal region

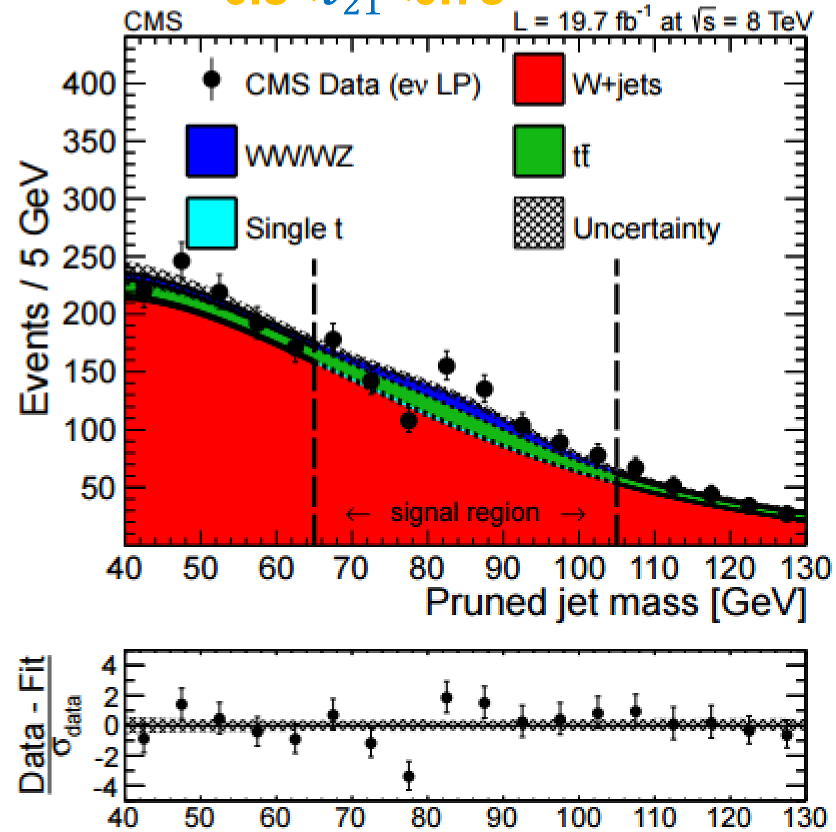
Fit Data sideband with summed components
to get wjets shape in low sideband region

Pruned Jet mass

τ_{21}<0.5



0.5<τ_{21}<0.75

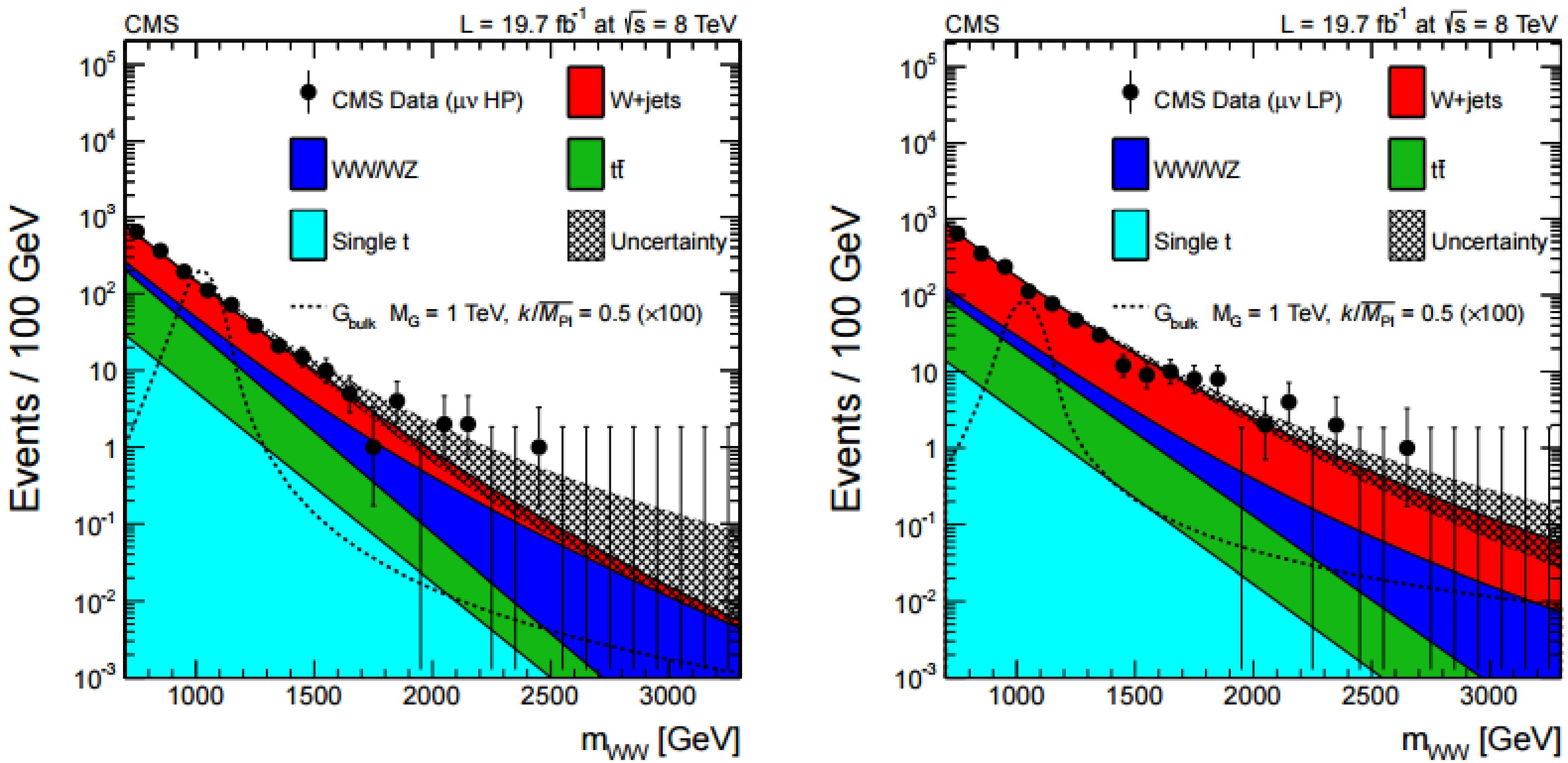


Jet mass Signal Region: [65-105]GeV

Low Sideband: [40-65]GeV **High Sideband: [105-130]GeV**

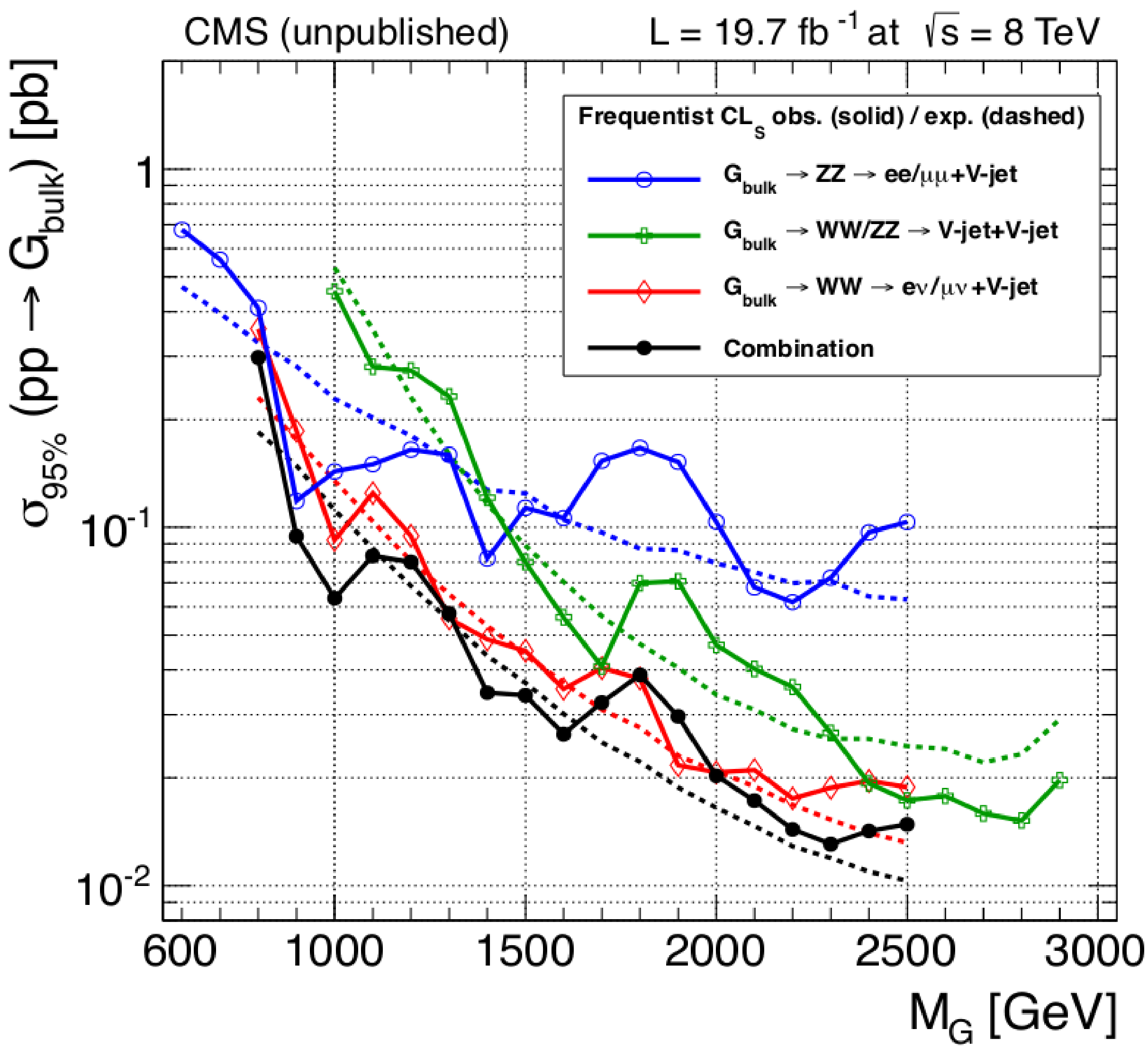
Final M(lvj) Distributions

Mu channel



Signal Shape described by a double-sided Crystal-Ball (CB) function (i.e., a Gaussian core with power law tails on both sides)

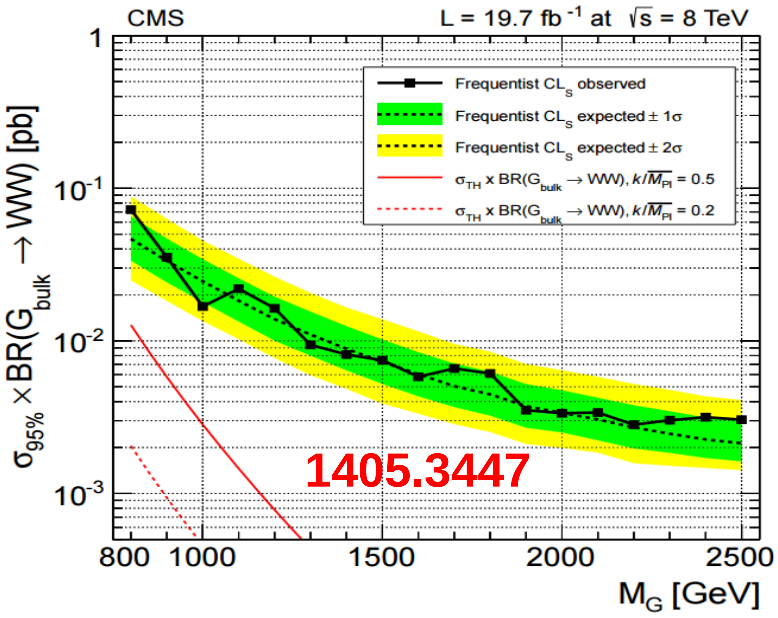
Combination of VV Searches

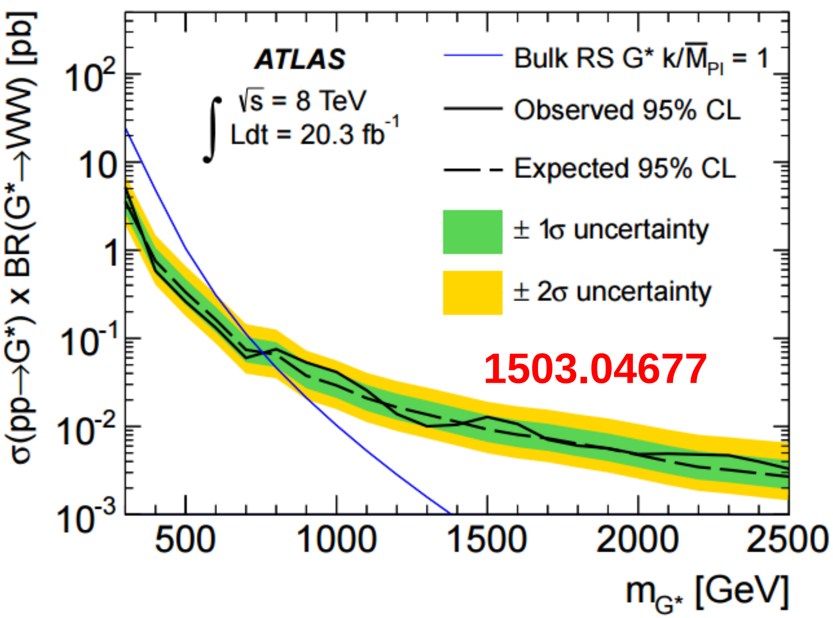


Combination in bulk graviton model

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

LVJ: CMS vs. ATLAS





ATLAS limit about factor 2 loose

ATLAS: AK4 for resolved jet -> lower mass
CA1.2 for fat jet;
Filtering/Splitting for subjets;

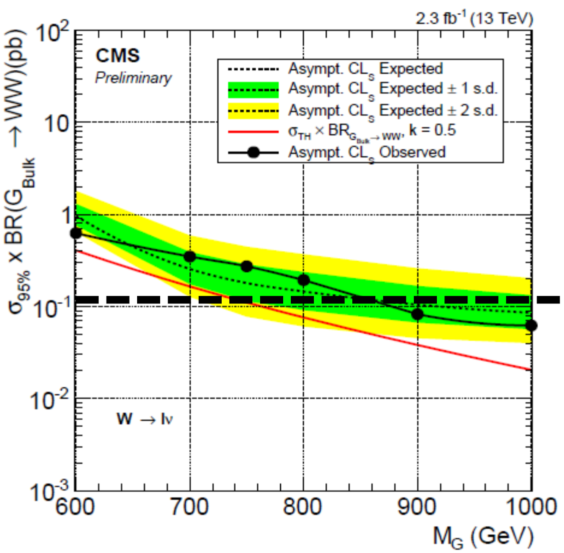
CMS: CA8 for fat jet; Jet pruning, tau21

2015 WV共振态寻找

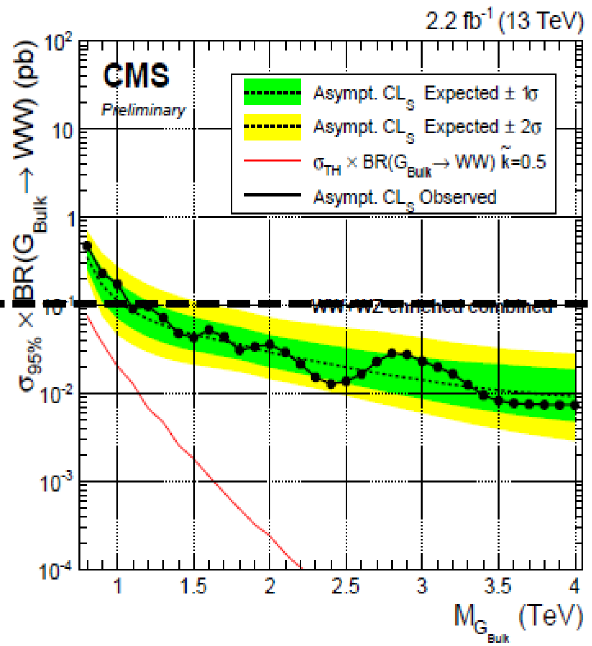
CMS-PAS-EXO-15-002
CMS-PAS-B2G-16-004

Run2-2015 CMS (low, high mass) and ATLAS

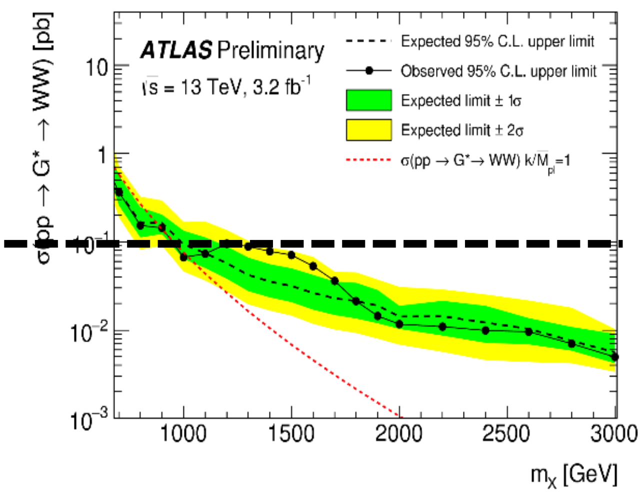
Low mass extension
B2G-16-004



Main analysis
EXO-15-002



ATLAS VW
CONF-2015-075



徐子骏 Preapproval

王群Approval

Shown at ICHEP2016, in presentation by Salvatore Rappoccio

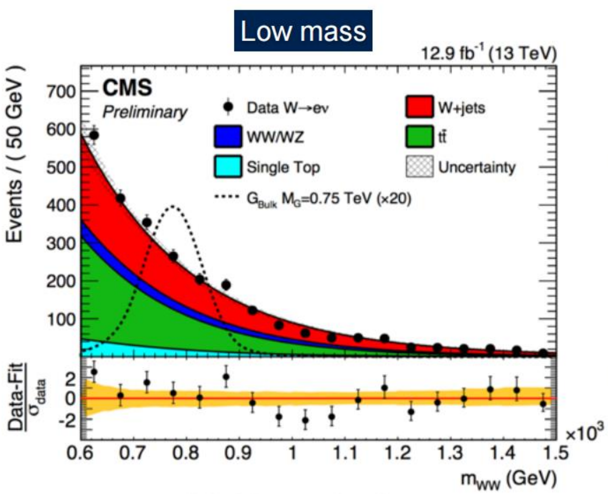
2016 WV共振态寻找

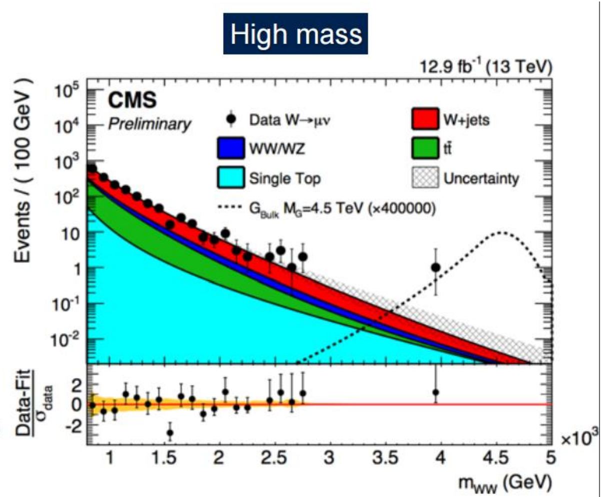
CMS-PAS-B2G-16-020

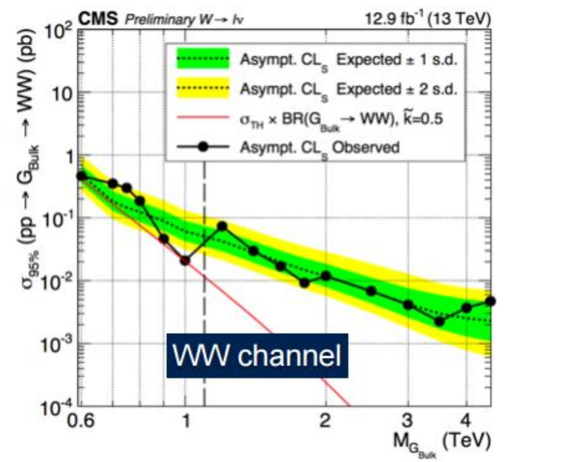
Isolated lepton + MET

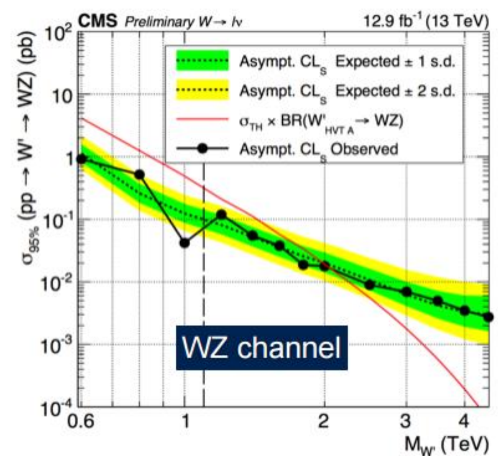
Merged W/Z jet

low and high mass τ_{21}<0.45, 0.6
W and Z regions 65-95 / 75-105









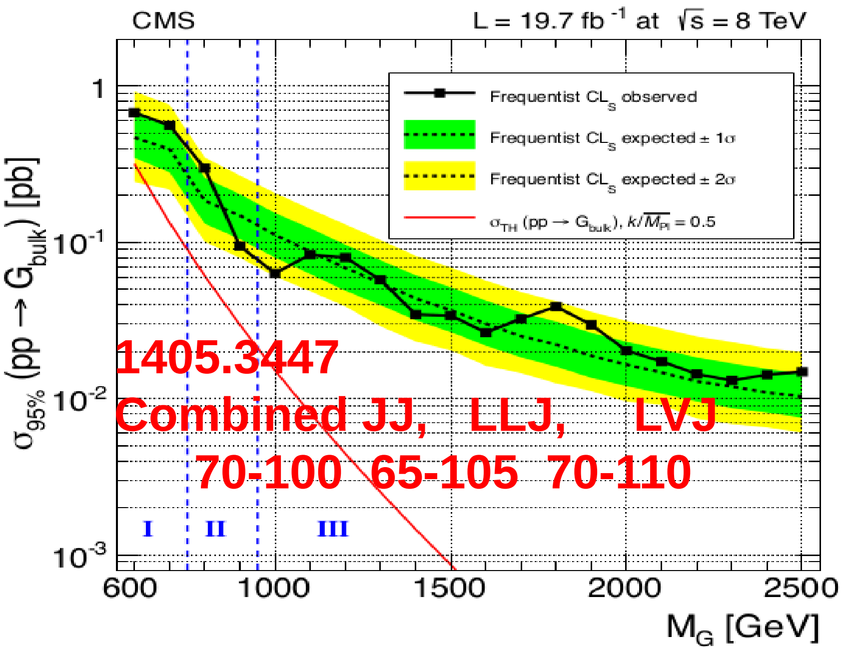
北大黄璜为分析负责人
黄璜Preapproval
徐子骏 Approval
Shown at ICHEP2016, in presentation by Salvatore Rappoccio

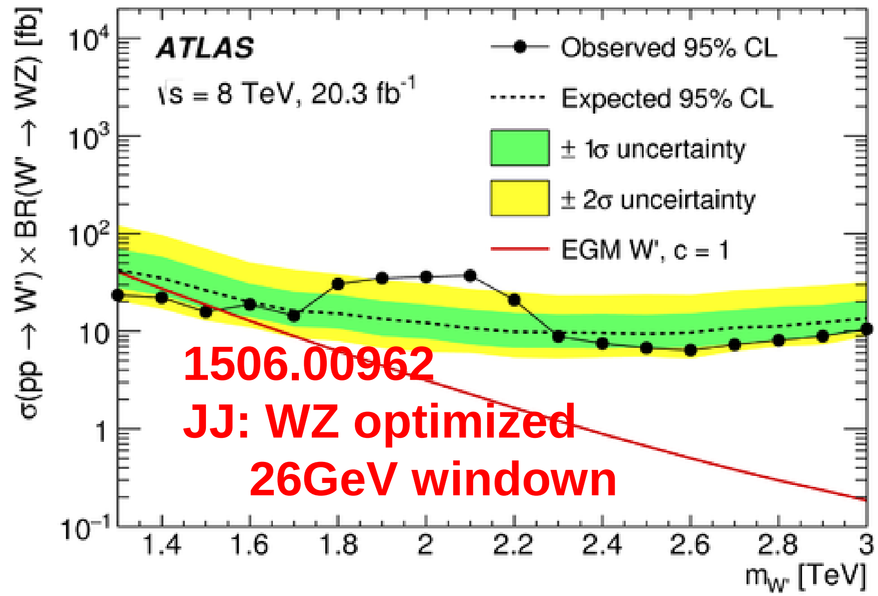
Summary

- Rich results from di-boson resonance searches
- V and H-tagger exploited: Jet substructure and Sub-Jet b tagging
- This area is now becoming more and more active in CMS and ATLAS
- Run2 will definitely tell us more
- We hope LHC will be a discovery machine!

Backup

ATLAS/CMS VV Excess?





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	-

1-2σ

ATLAS: **Mass Drop-F*iltering***

Cambridge-Aachen 1.2 Jets

Reverse jet clustering until 2 subjet balance

$$\sqrt{y} \equiv \min(p_{\mathrm{T}\,j_1}, p_{\mathrm{T}\,j_2}) \frac{\Delta R_{(j_1,j_2)}}{m_0} \geq \sqrt{y_{\mathrm{f}}},$$

***Filtering 2 subjets with CA0.3:* all but 3 highest pt jets remained**

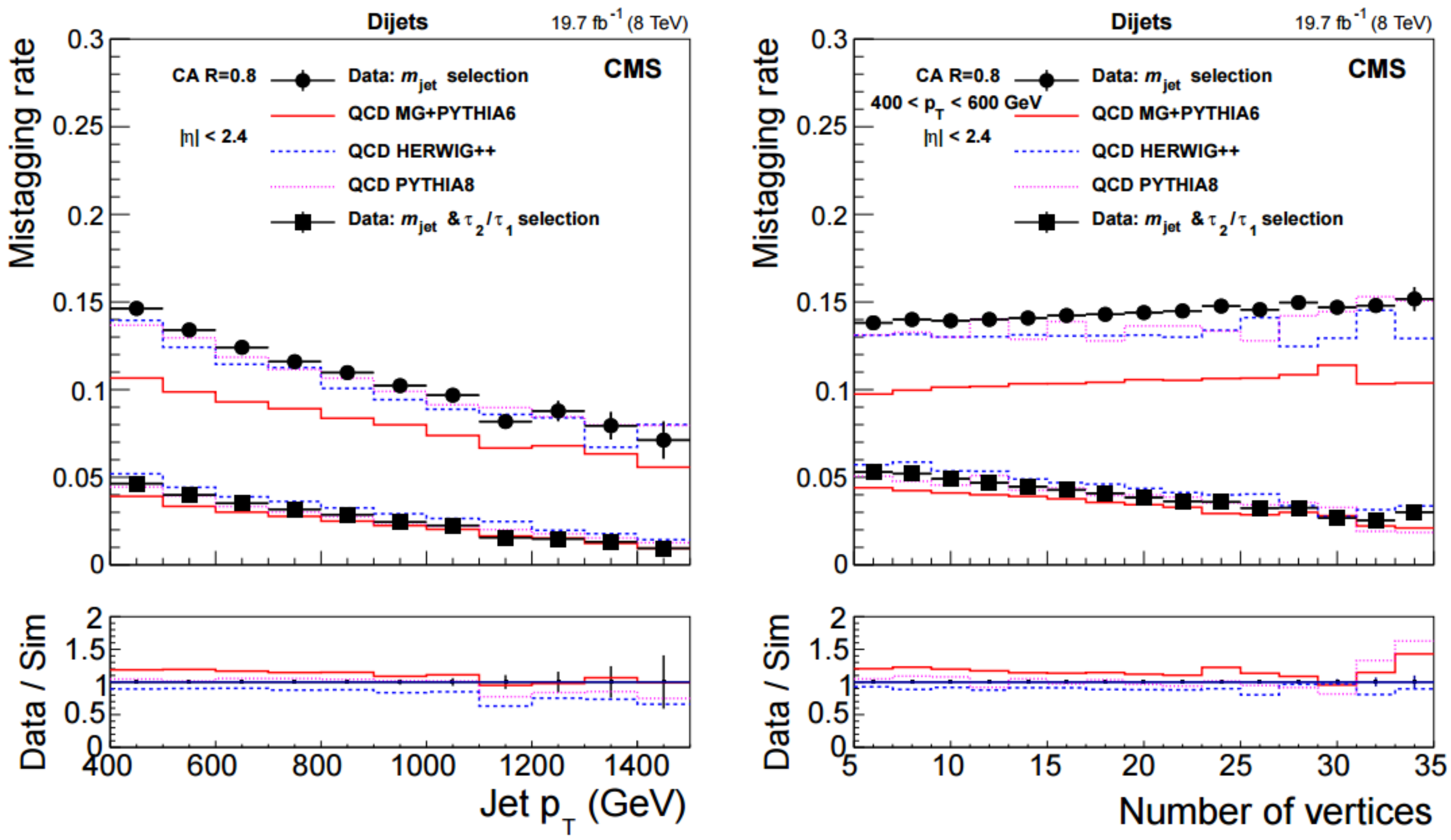
In addition, for VV->JJ, require N_track<30

Filtering parameter	Value
$\sqrt{y_{\mathrm{f}}}$	0.2
μ_{f}	1
R_{r}	0.3
n_{r}	3

->0.45

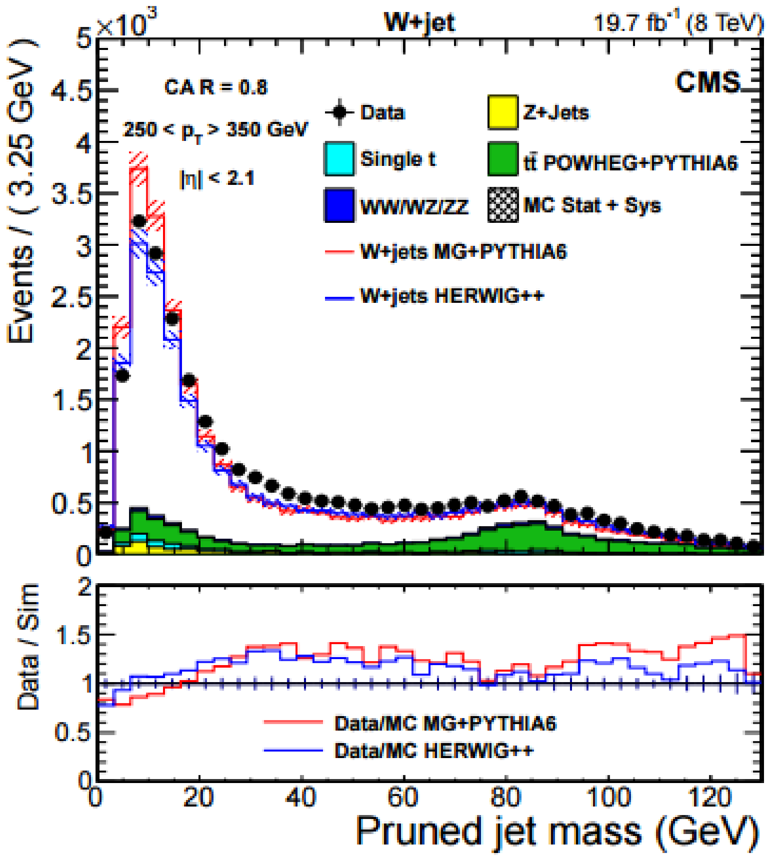
$|m_J - m_{w/z}| < 13GeV$

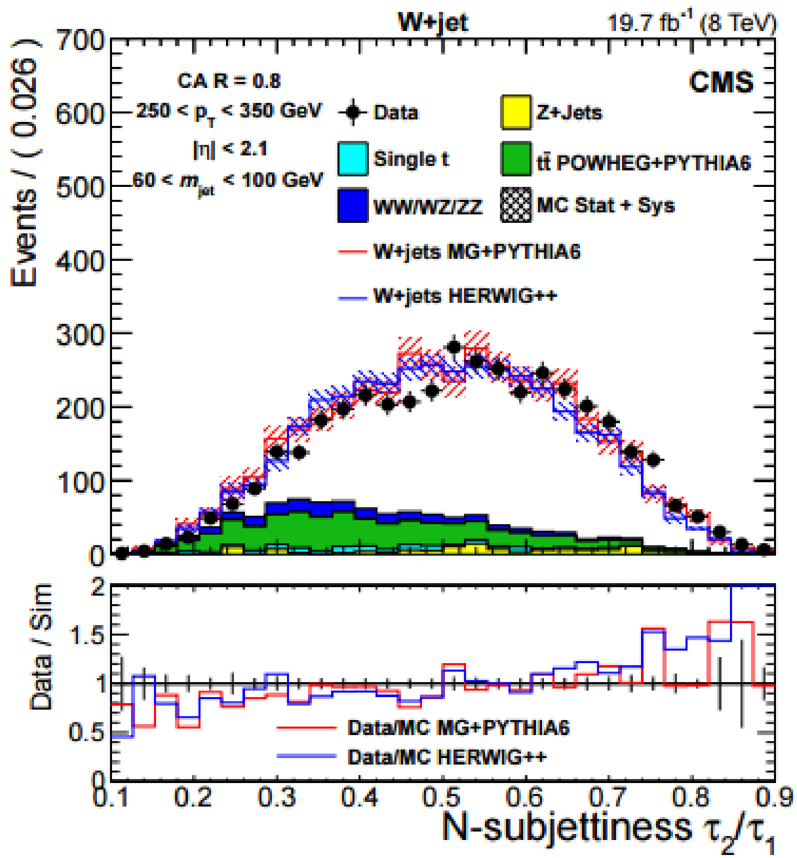
W-tagging Mistag rate



W-tagging

JHEP12 (2014) 017





W+jets: Data vs MC

Discrepancy Seen -> Corrected in TTbar Control Region

$W \to l\nu$ reconstruction

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

↓

<u>Second order equation</u>

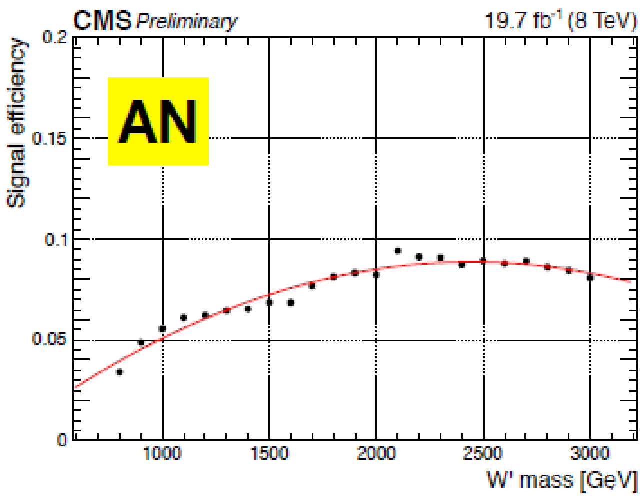
$$(E_\ell + \sqrt{\mathbf{E}_T^{miss\,2} + p_{z,\nu}^2})^2 - (\mathbf{p}_{T,l} + \mathbf{E}_T^{miss})^2 - (p_{z,l} + p_{z,\nu})^2 = M_W^2 = (80.4)^2 \qquad (1)$$

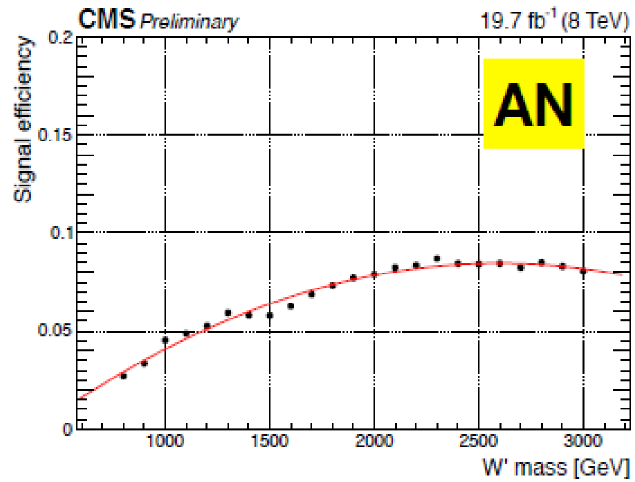
Case 1: two real solutions	Case 2: two complex solutions
take the one with smallest $\|p_{z,\nu}\|$	modify the components of the missing transverse energy to yield $M_T = M_W$ still respecting energy/momentum conservation

Signal efficiency and shape

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

Muon channel

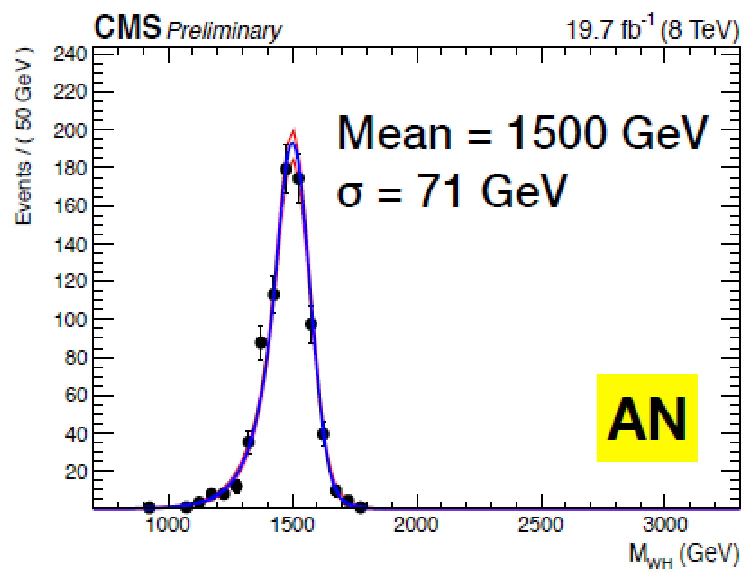




Electron channel

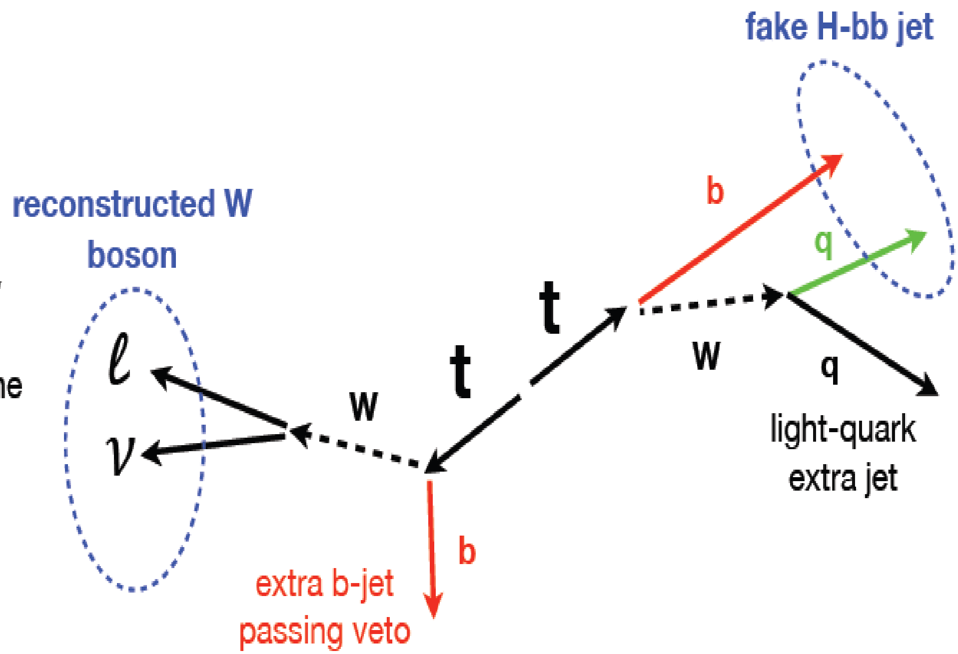
M_{WH} shape parametrized with Crystal-Ball function: Gaussian core + power law tails

Typical Gaussian core width 4-6%



TTbar rejection

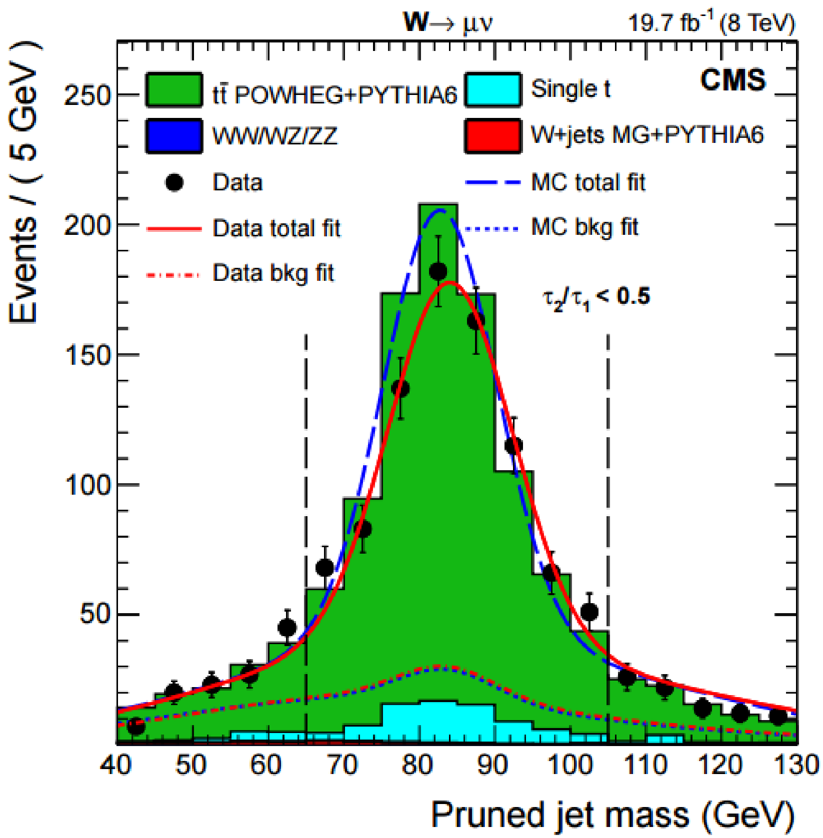
- TTbar background partially rejected with veto on extra b-tagged jets
- Still represents the main source of background in signal m_{jet}^{pruned} window
- Exploit the possibility to reconstruct the invariant masses of the **hadronic (leptonic) top quarks** exploiting the presence of an extra jet in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



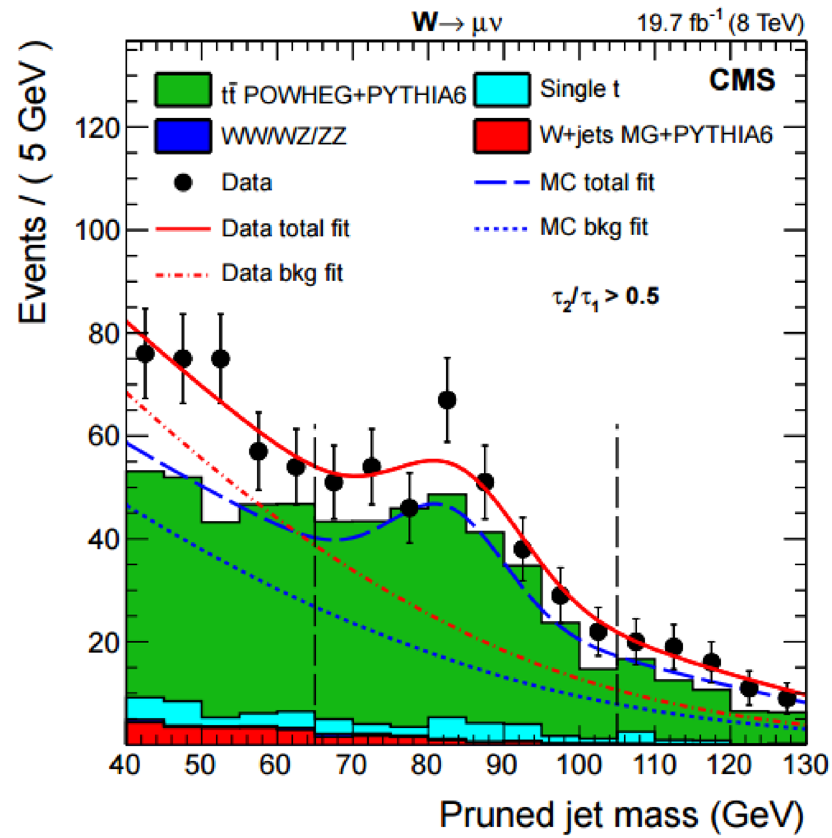
<u>Comparison between different ttbar rejection strategies</u>

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

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

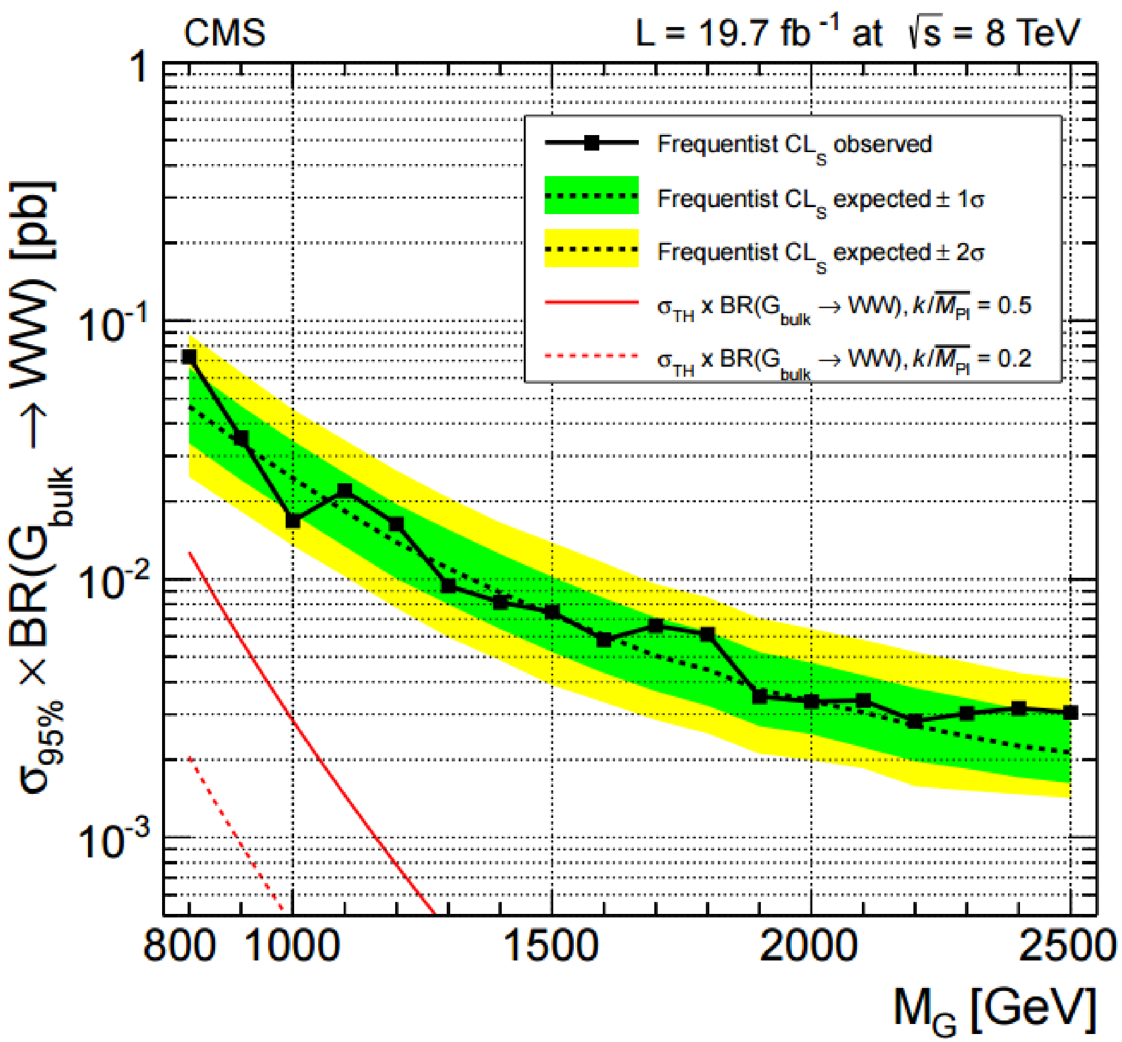


W→ μν
19.7 fb-1 (8 TeV)
CMS
tt̄ POWHEG+PYTHIA6
Single t
WW/WZ/ZZ
W+jets MG+PYTHIA6
Data
MC total fit
Data total fit
MC bkg fit
Data bkg fit
τ2/τ1 < 0.5
Events / (5 GeV)
Pruned jet mass (GeV)



W→ μν
19.7 fb-1 (8 TeV)
CMS
tt̄ POWHEG+PYTHIA6
Single t
WW/WZ/ZZ
W+jets MG+PYTHIA6
Data
MC total fit
Data total fit
MC bkg fit
Data bkg fit
τ2/τ1 > 0.5
Events / (5 GeV)
Pruned jet mass (GeV)

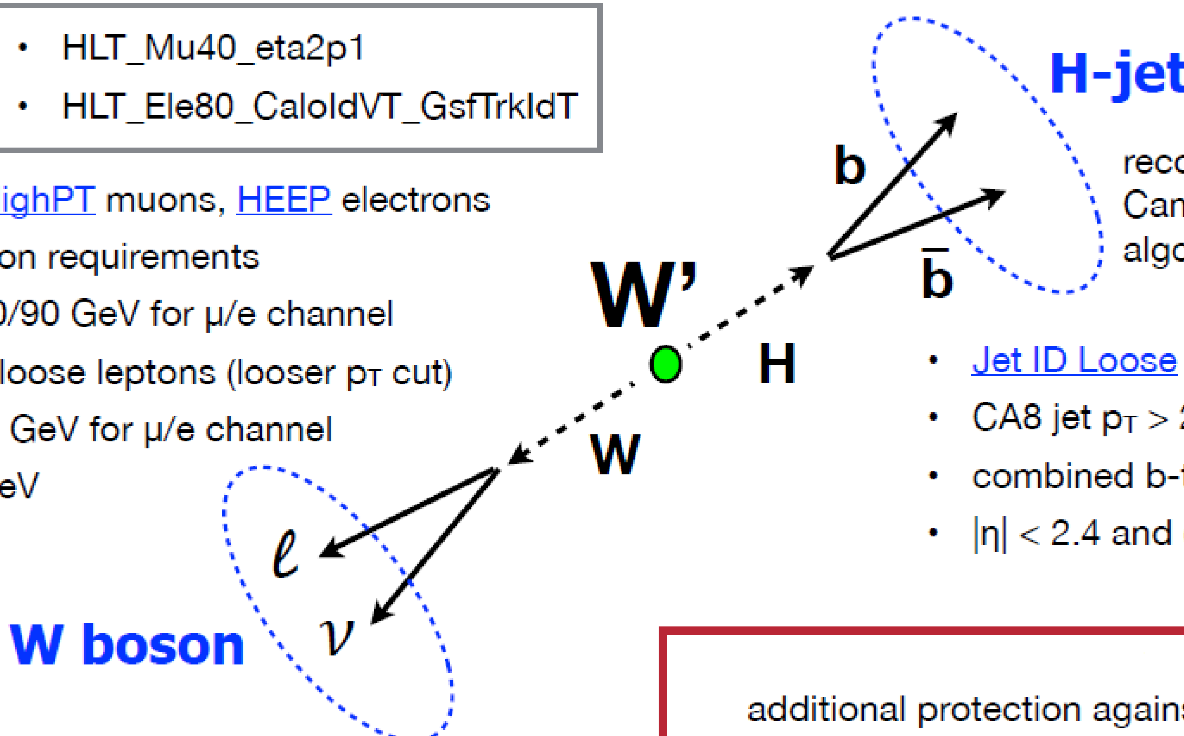
Limit Result



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
- $|\eta| < 2.4$ and ($|\eta| < 1$ or $|\eta| > 1.8$)

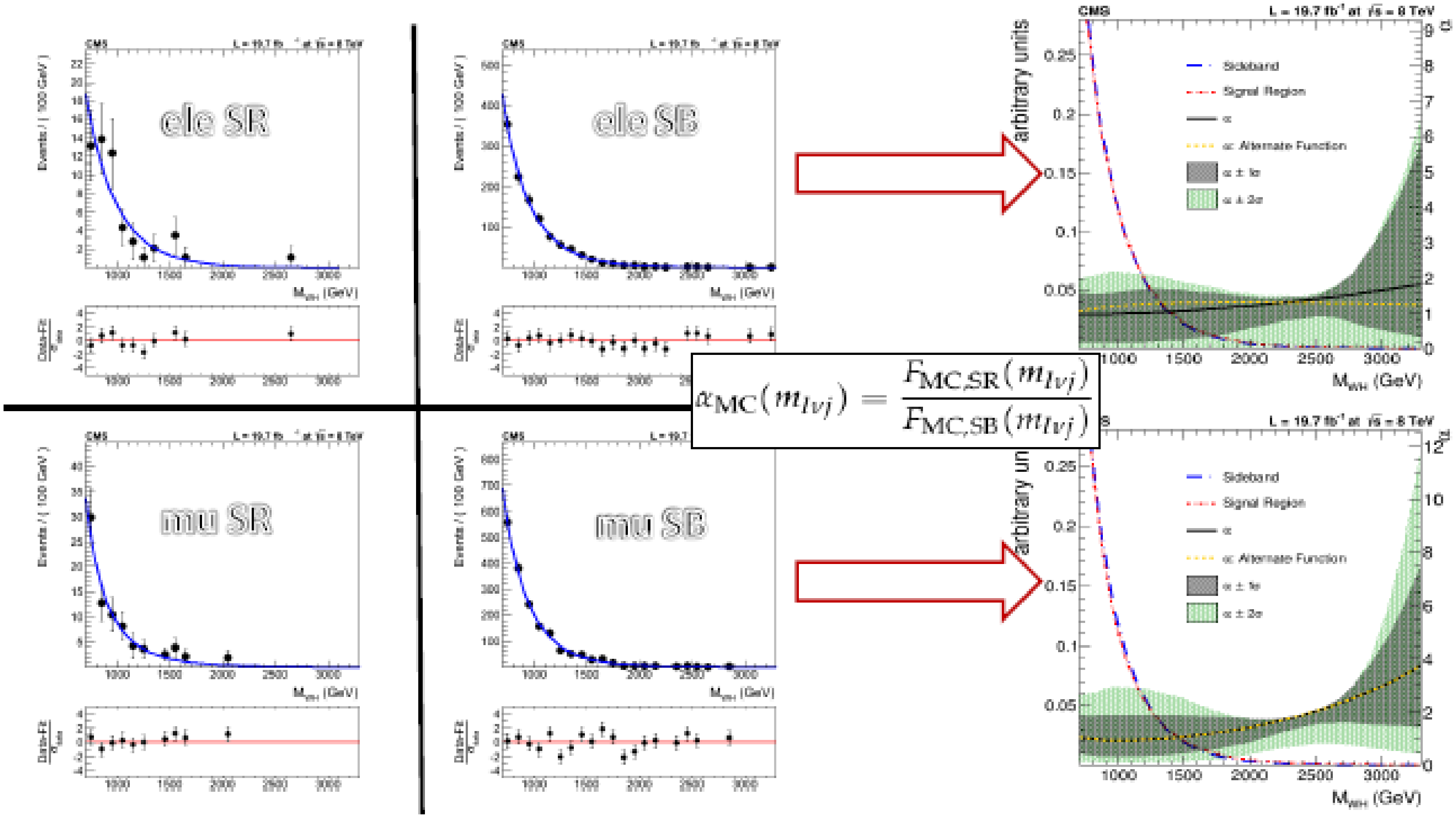
additional protection against bias in b-tagging, pruning and MET introduced by TOBTEC anomalous events with many displaced fake tracks in the jet (tobtec filter rejection inefficiency)

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

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

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)**



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

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

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

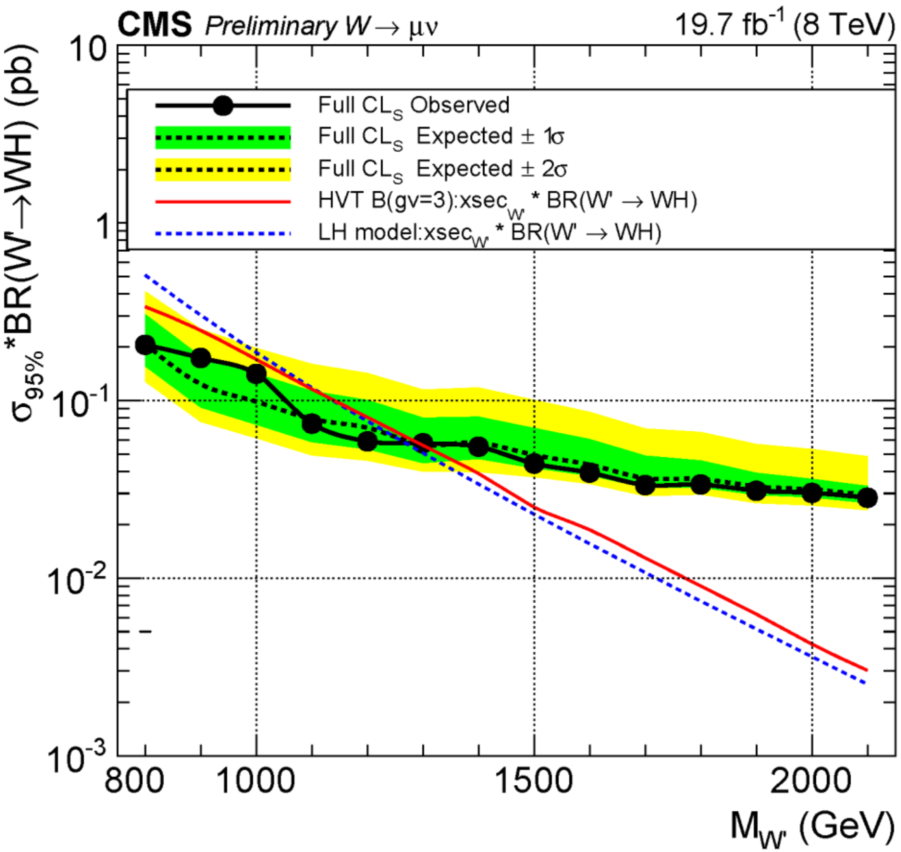
Estimated wjets shape in SR

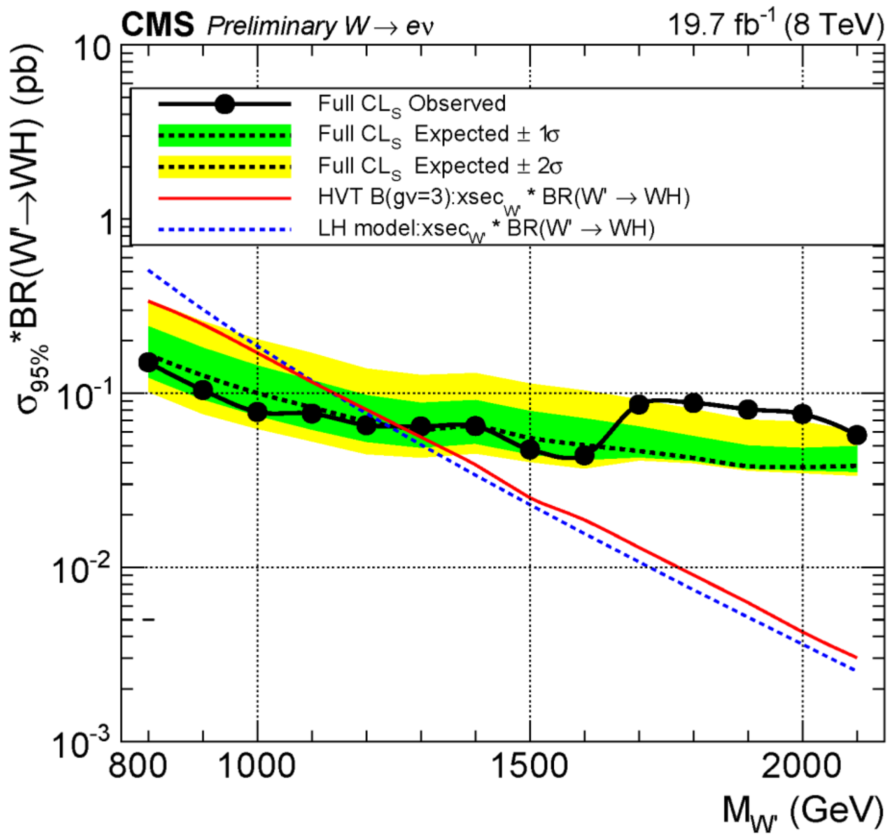
Fit data SB with summed components to get wjets shape in low SB region

m_{jet}^{pruned} regions:

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

mu/ele Results





EXO-WH Resonance Searches

CMS PAS-EXO-14-010

Higgs Tagging: a bit beyond W-tagging

CMS PAS-BTV-13-001

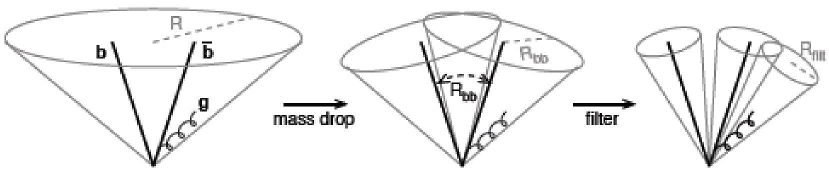
1. Mass of the H-jet as the main discriminating variable against QCD jets

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



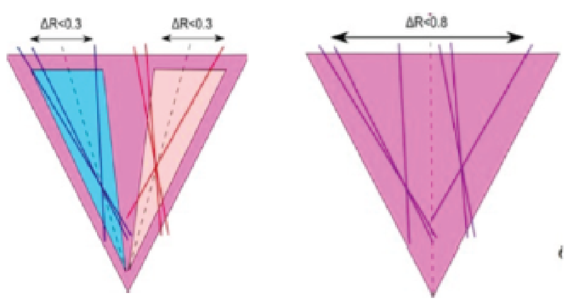
- removes the softest components of a jet
- improves discrimination by pushing the jet mass for QCD jets towards lower values while maintaining the jet mass for the H-jet at the H-mass
- studied in detail for W-tagging: JME-13-006

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

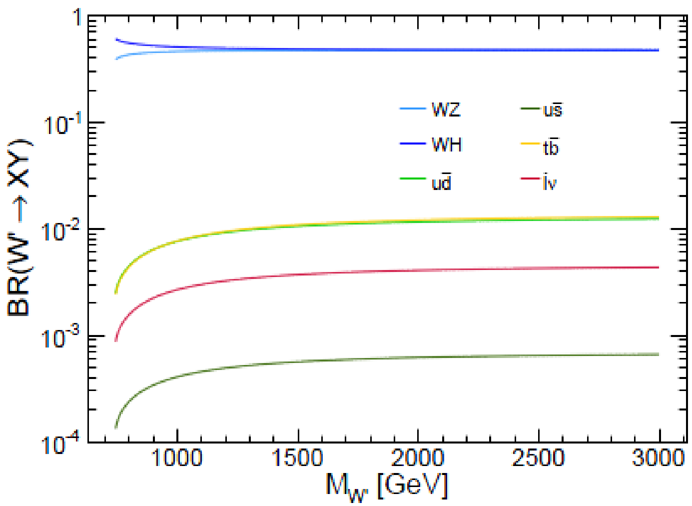
EXO-WH Searches

- **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**

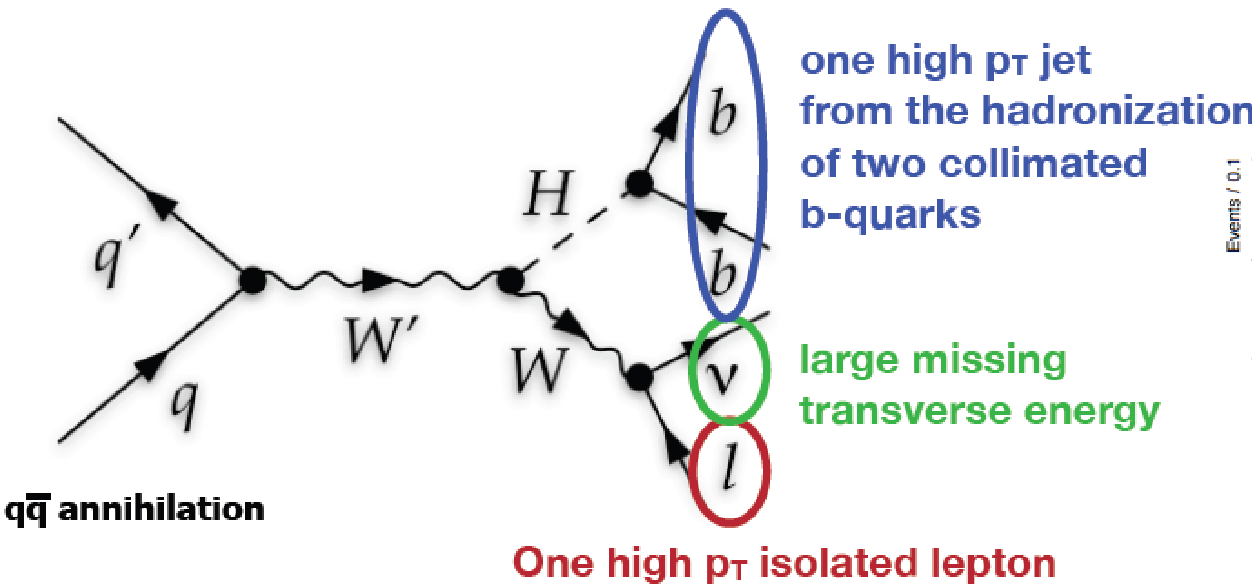
Model B case of (1), g_V >3 ->
Composite Higgs Model Like

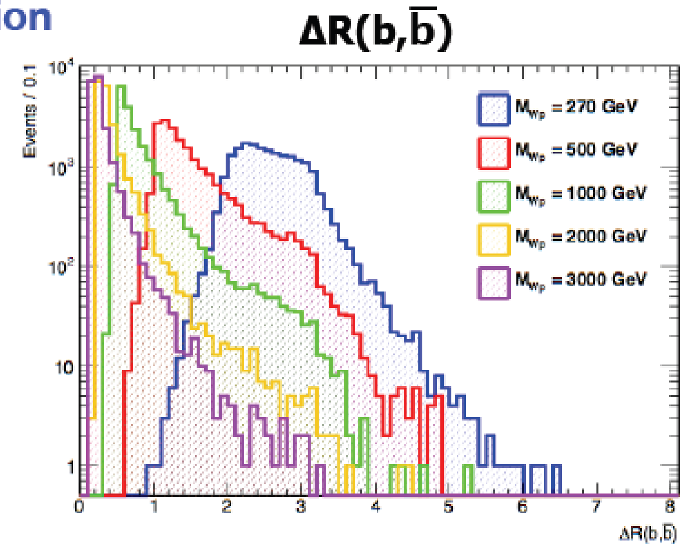


- **One of the first resonance searches looking for boosted Higgs**

CMS arXiv:1506.01443 V'->VH->fully hadronic
CMS arXiv:1502.04994 Z'->ZH->jjττ
ATLAS arXiv:1503.08089 V'->VH->ll/lv/vv+bbar

Signal: Fat Jet, H-tagging



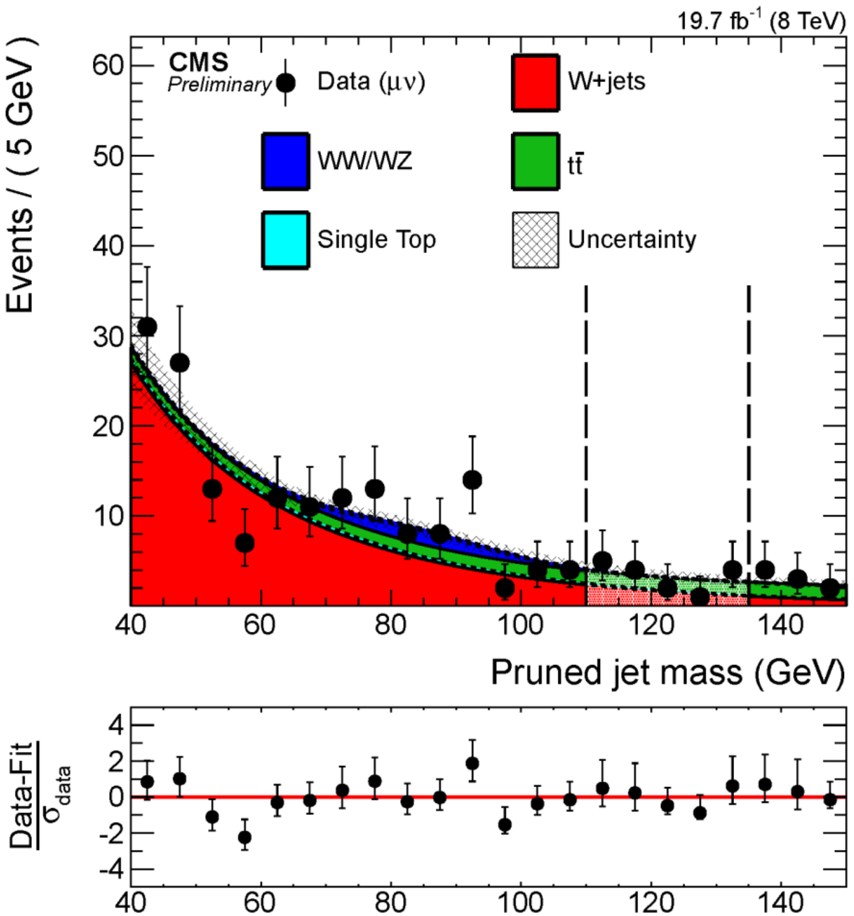


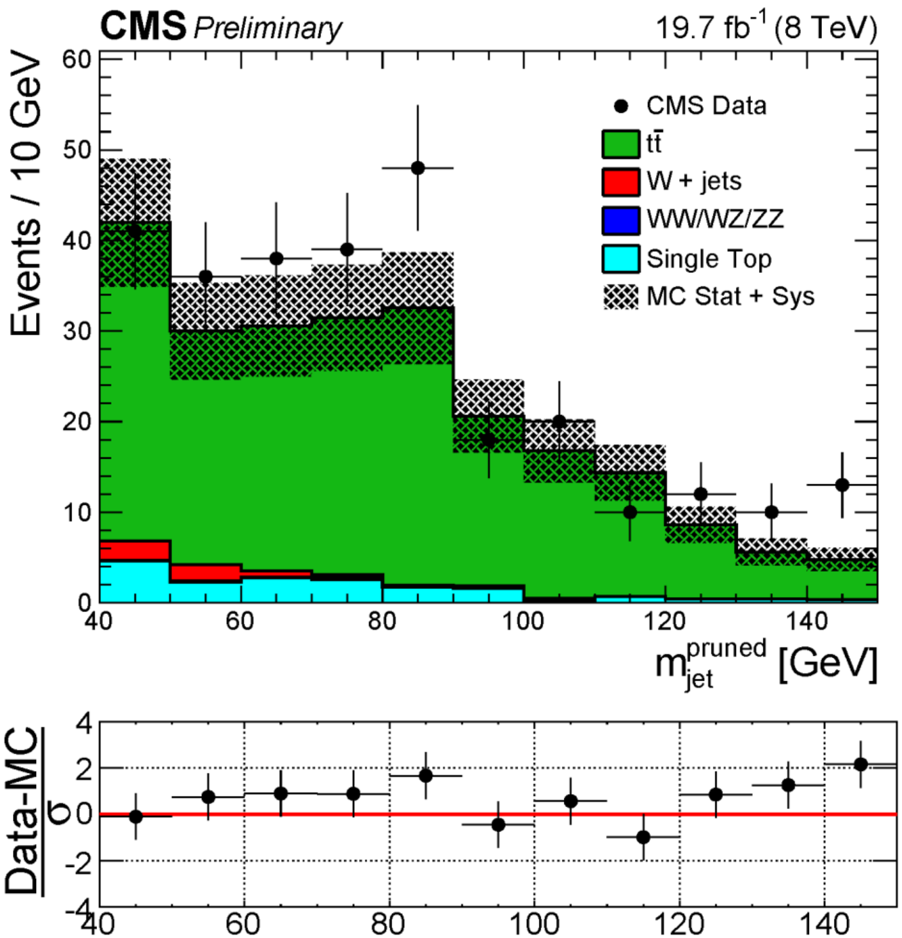
Search for $M_{W'}$ >0.8TeV

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

Distribution Plots: mu channel





Pruned Jet mass in Search Region and TTbar Control Region

Bkg Modelling

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

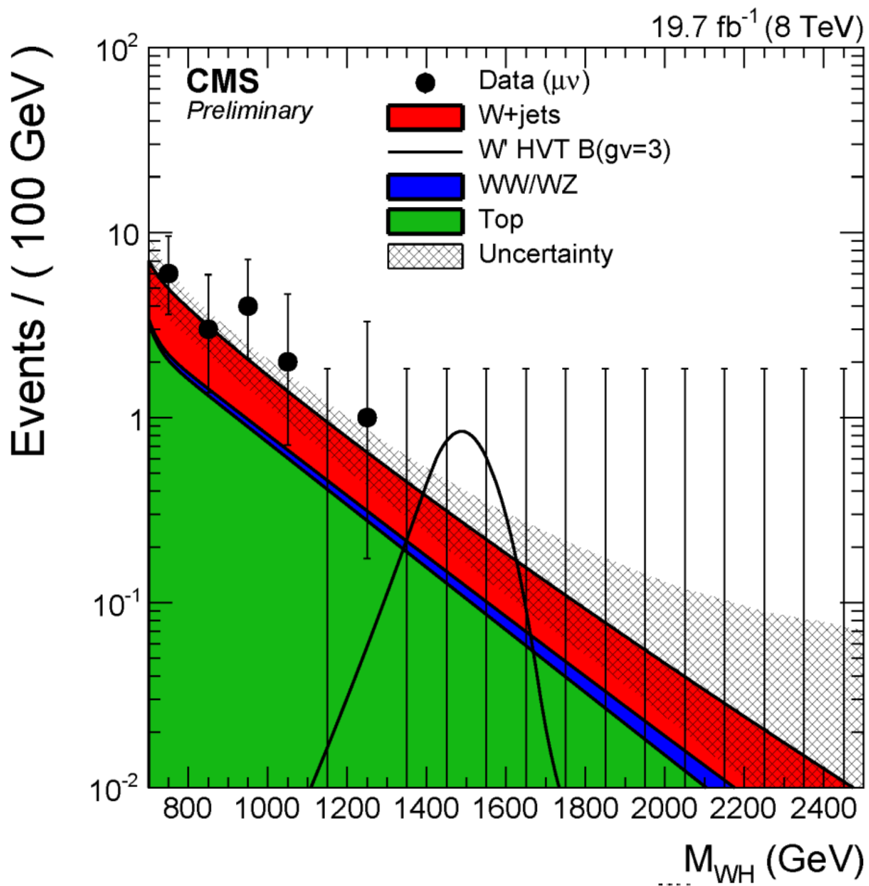
1. W+jets normalization from m_{jet}^{pruned} sidebands
2. W+jets M_{WH} shape with alpha-method

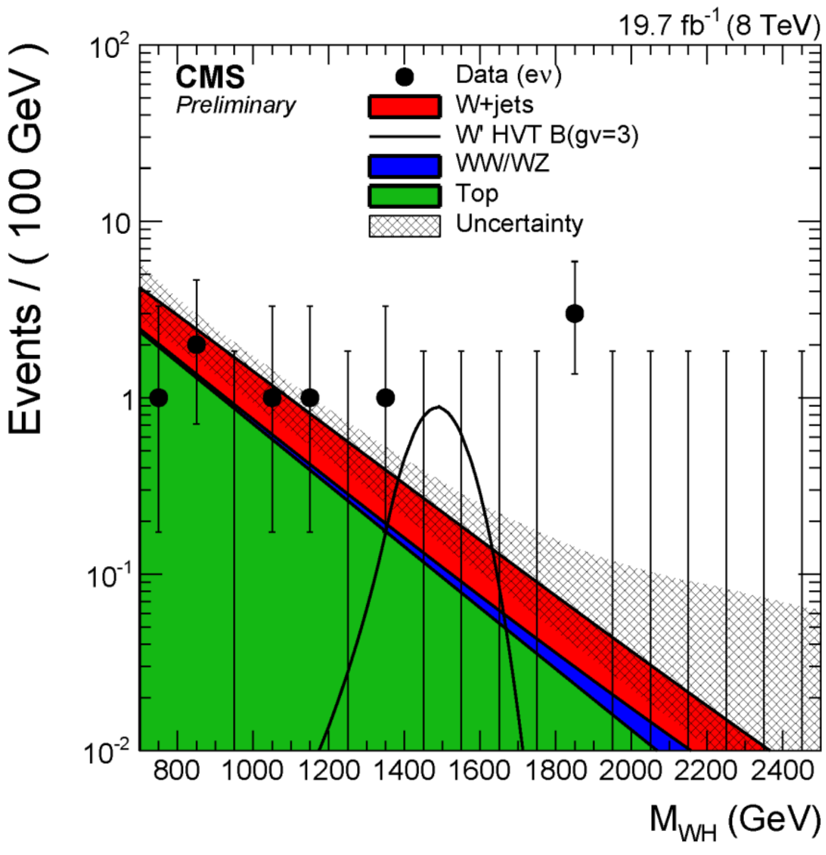
- TTbar, Single Top, VV shape and normalization taken from MC
  - obtained fitting the individual MC predictions with suitable functions
  - fit parameters fixed by the MC prediction
- TTbar MC as input to W+jets estimation
  - main background in signal region
  - check data/MC agreement in control region

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

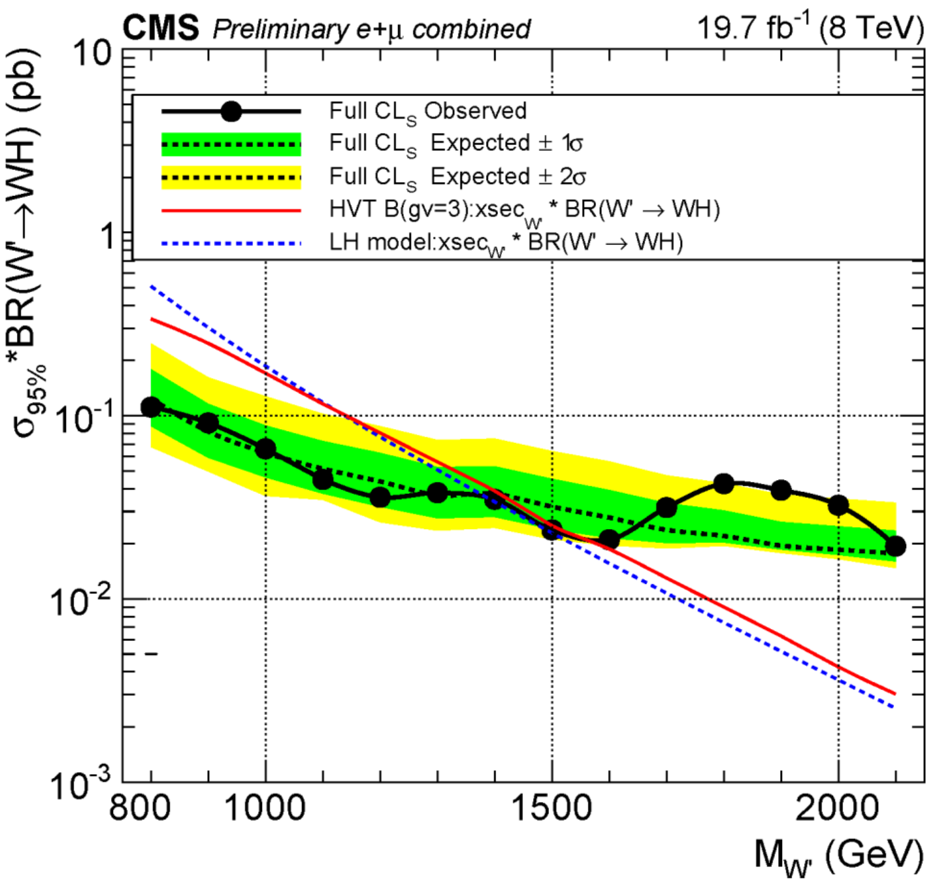
✓ Excess of 3 events in the electron channel with M_{WH} > 1.8 TeV where less than 0.3 are expected

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%	1–3%
Jet resolution	<0.5%	<0.5%
Higgs mass tagging	2–10%	2–10%
Higgs b tagging	2–8%	2–8%
Unclustered energy scale	<0.5%	<0.5%
Pileup	0.5%	0.5%
PDF	<0.5%	<0.5%
Luminosity	2.6%	2.6%

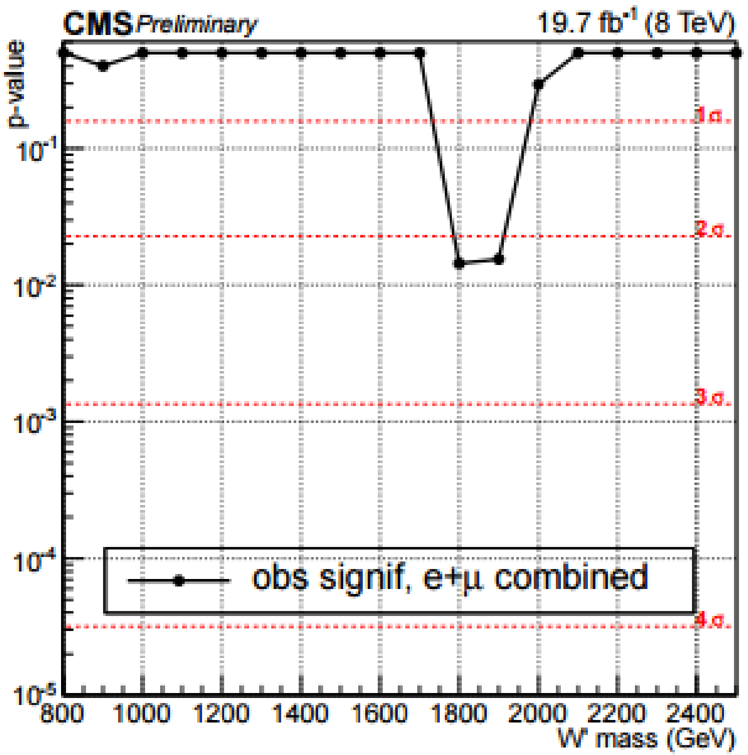
Combined Results



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

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

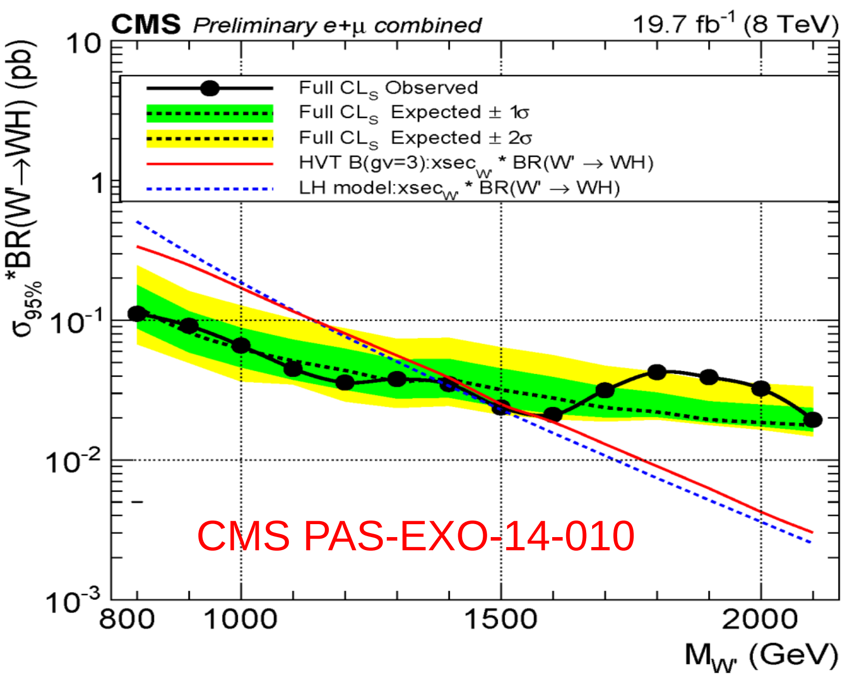
Significance Results

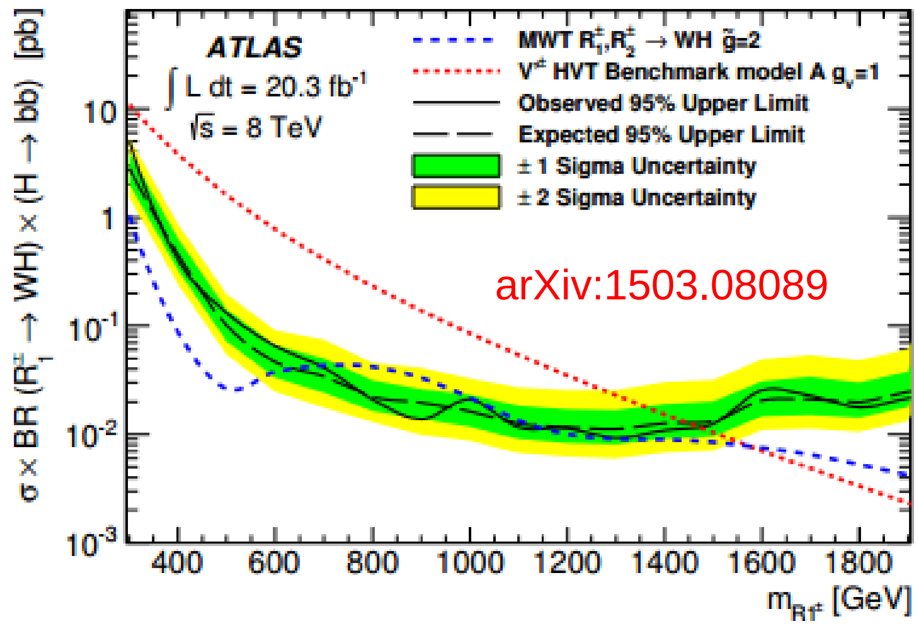


Statistical Compatibility with the Standard Model within 2σ

- 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





Although a bit loose limit at low mass,

We gain at high mass due to H-tagging

ATLAS: 2 resolved AK0.4 jets, 1 or 2 btag catagories

CMS: CA8 for fat jet; Jet pruning, subjet b tagging