Status of Searches for Composite Higgs Models

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for
ATLAS and CMS collaborations

SUSY2015

Composite Higgs models

- SM Higgs as a composite particle:
  - Solves Electroweak hierarchy problem (= a.k.a. “Higgs naturalness problem”)
    - Higgs = a pseudo-Nambu-Goldstone boson of approximate global symmetry of strong sector
  - In addition to SUSY, (at the moment) the only compelling solution (although I hope to be proven wrong)
  - Like SUSY, many models and variants
    - Realistic models, designed to agree with current data
- Basic prediction:
  - Heavy partners of SM particles = “excitations”
  - *TeV-scale* $Z'(\rho^0), W'(\rho^+), T', B', \ldots$

Constraints from data

- *Many* constraints from
  - Flavor physics, e.g. $B\bar{B}$ mixing, angular observables in $B \to K^* \mu\mu$, $\mathrm{BR}(B_s \to \phi\mu\mu)$, rare B decays, etc.
  - Z decays (e.g. its BRs)
  - Higgs production and decay
  - Contact interactions (e.g. dijet angular distribution)

  - Direct searches
    - Heavy resonances decaying to fermions
    - Heavy resonances decaying to W, Z, or H
    - Heavy quark partners

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  - Z decays (e.g. its BR)
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NOT COVERED TODAY

- Direct searches
  - Heavy resonances decaying to fermions
  - Heavy resonances decaying to W, Z, or H
  - Heavy quark partners

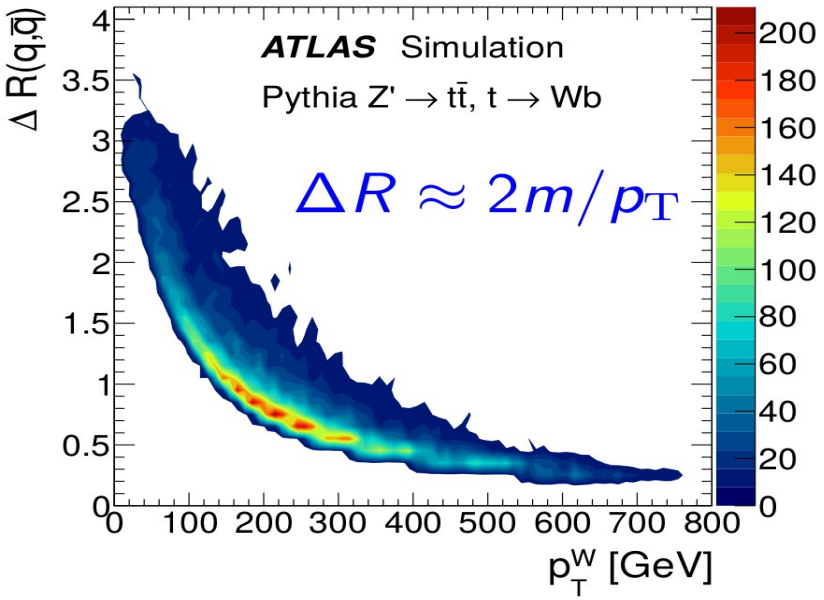
THE TOPIC OF THIS TALK
(as much as it could fit…)

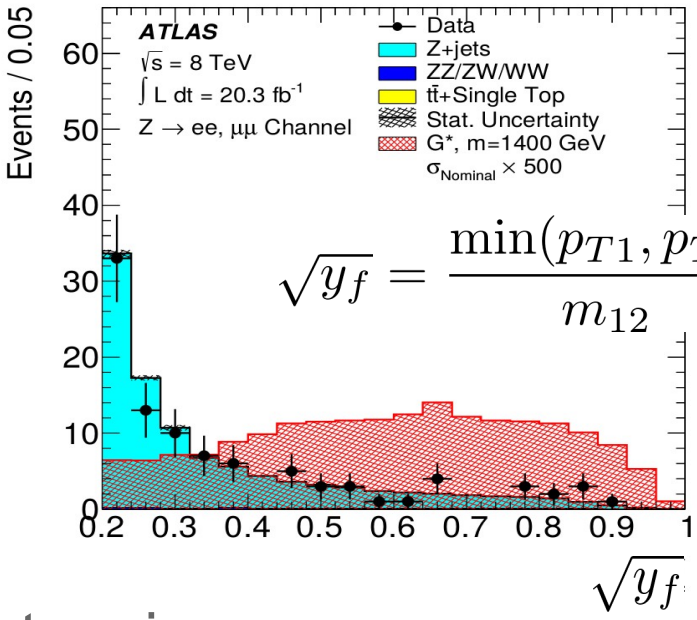
The layout of this talk

- Too many results to cover
- Focus on recent results, channels with large BR (e.g. hadronic), new techniques (e.g. substructure)
- $Z' \to t\bar{t}$
- $W' \to tb$
- Diboson resonances: $Z' \to WW, ZZ, \quad W' \to WZ$
- … also with Higgs: $Z' \to ZH, \quad W' \to WH$
- HH resonances
- Pair production of Vector-Like Quarks

Final states with boosted top / W / Z / H

- Above certain p_T, daughter quarks merge into a single large-R ("fat") jet



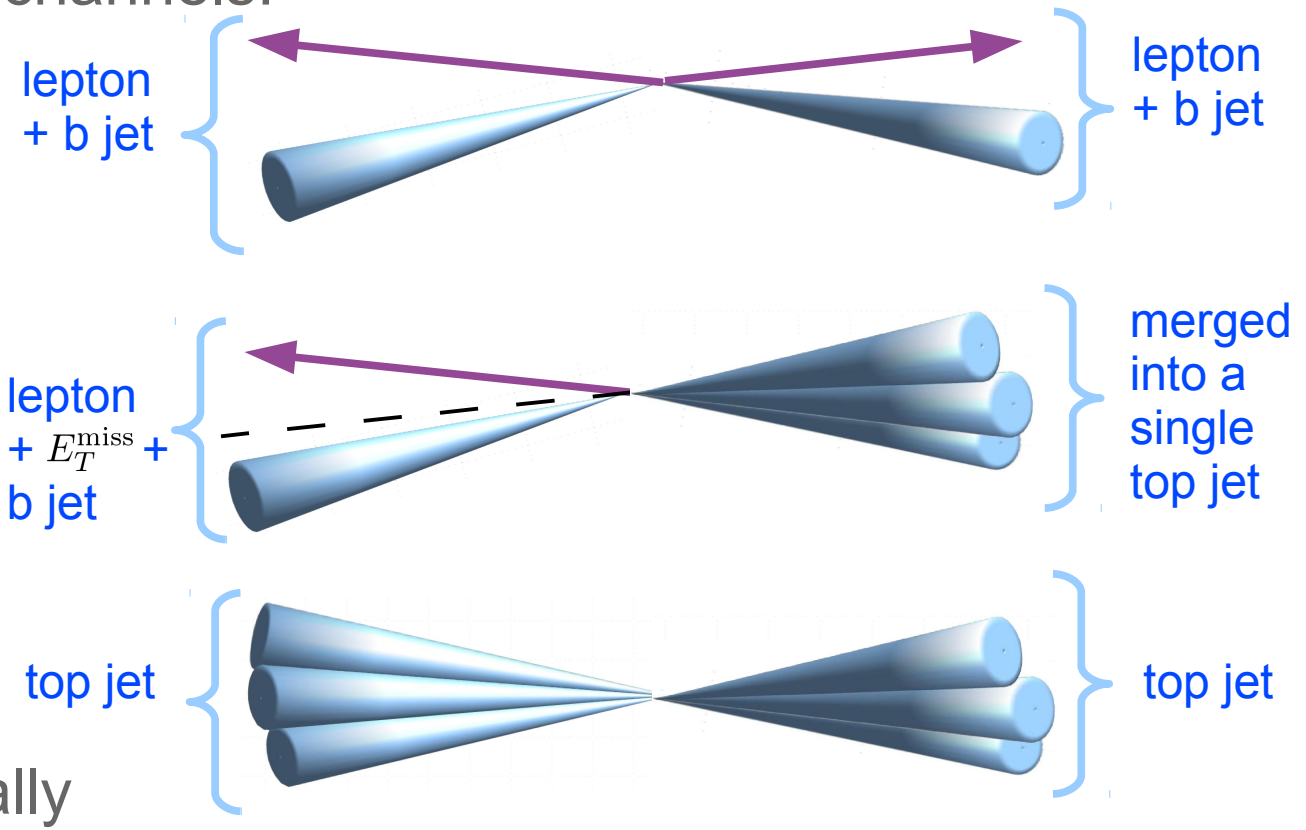


- Discriminants for top-, V-, H-tagging:
  - groomed jet mass (pruned, trimmed, or filtered)
    - removes soft gluon radiation + pile-up
  - substructure (n_{subjets}, N-subjettiness τ_N, $\sqrt{y_f}$, etc.)
  - subjet b-tagging

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

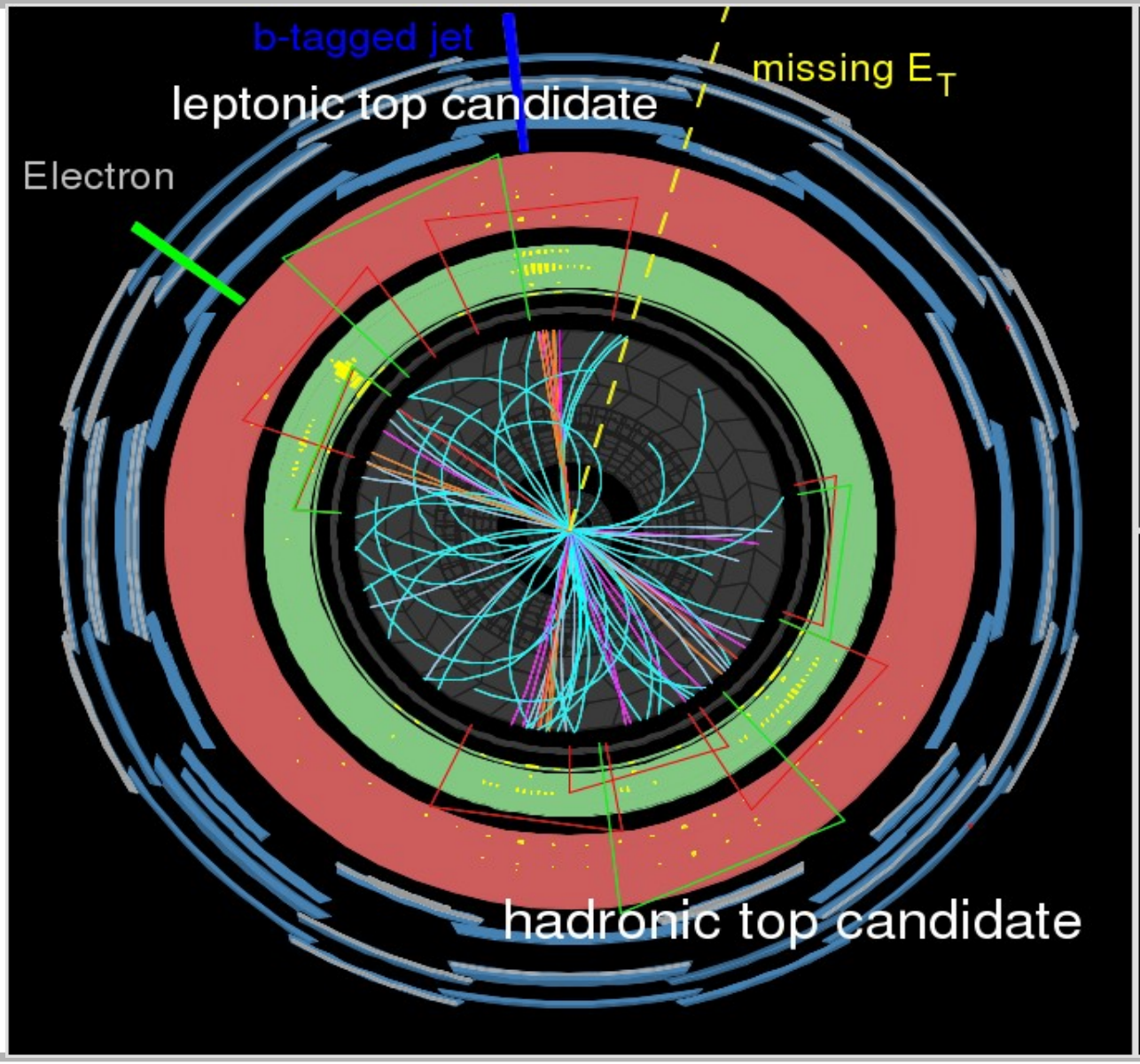
Z' → ttbar

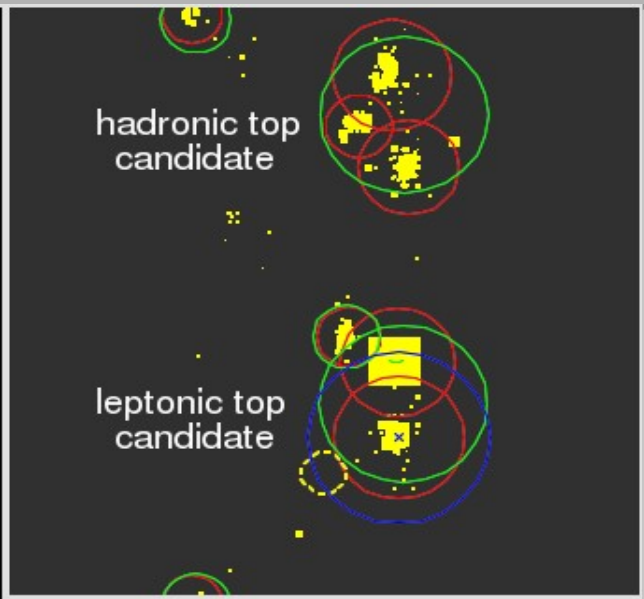
- Three boosted channels:
  - Dileptons
  - Semileptonic
  - All-hadronic



- Isolation specially handled
- Top tagging tools are by now quite mature

Example of a boosted ttbar event





ATLAS EXPERIMENT

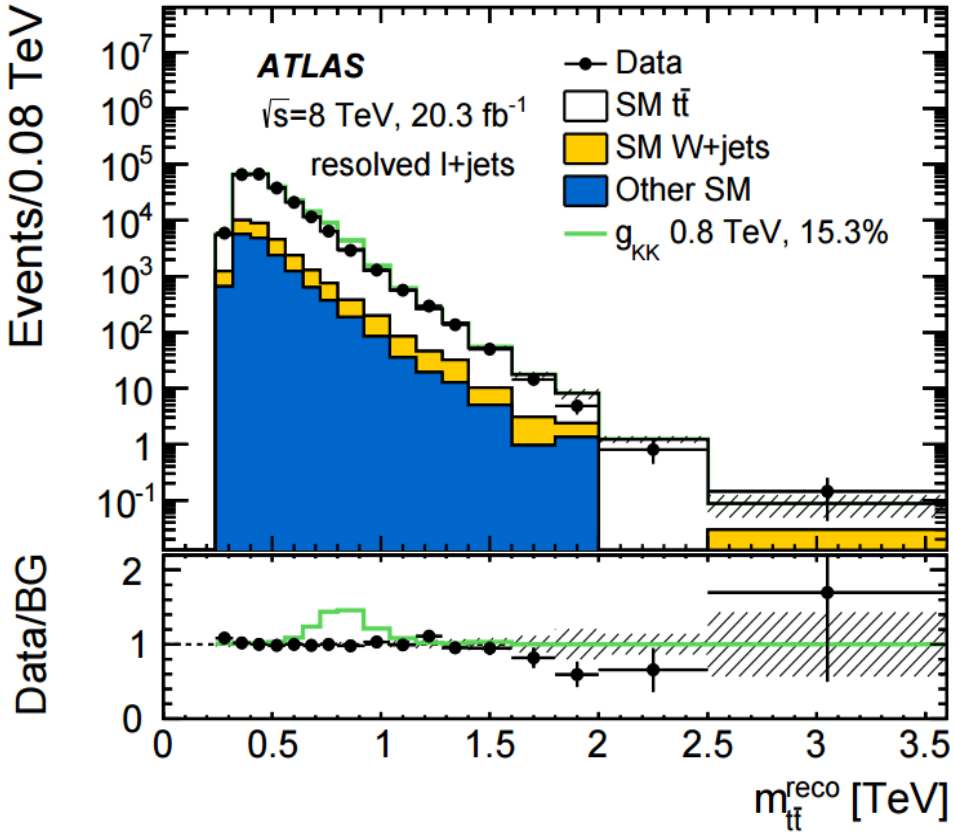
Run Number: 166658, Event Number: 34533931

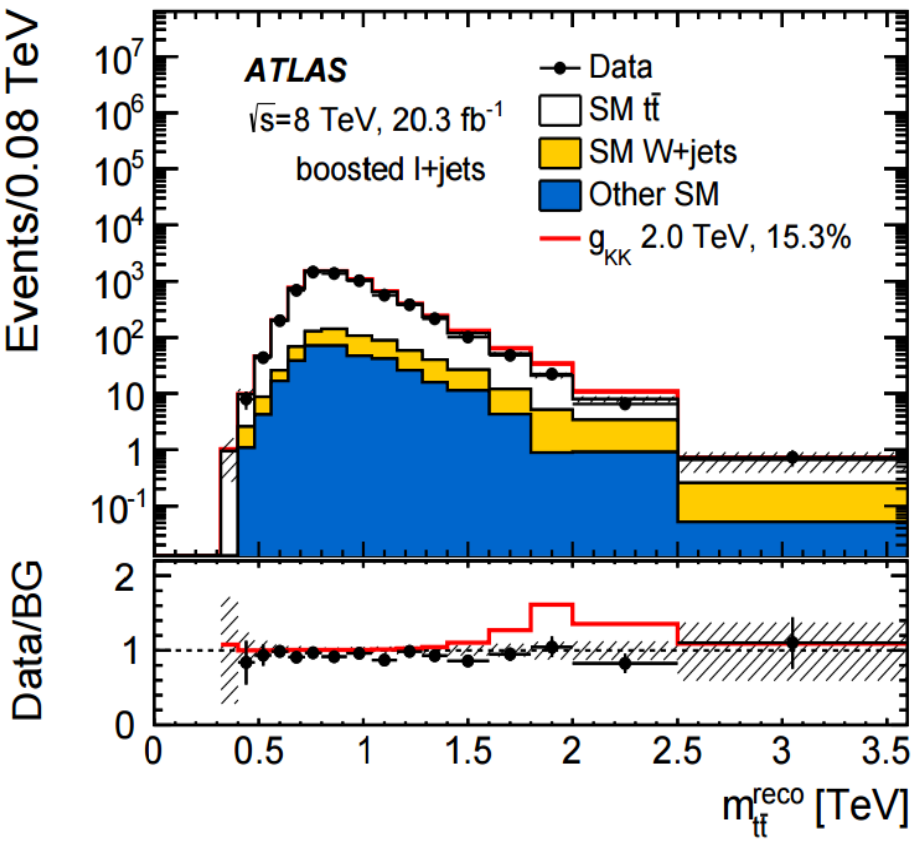
Date: 2010-10-11 23:57:42 CEST

Z' → ttbar

arXiv:1505.07018

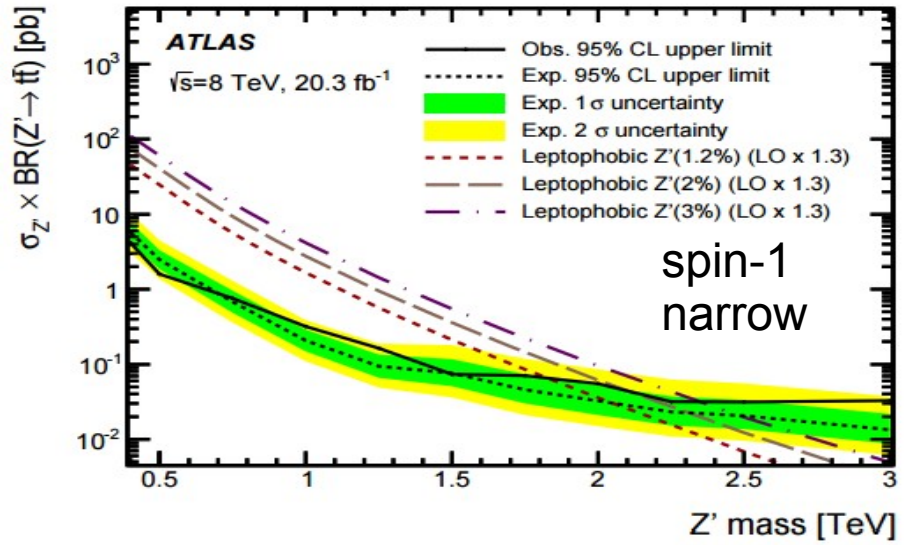
- Example: l+jets channel from ATLAS
  - combination of resolved and boosted
  - [CMS plots similar]

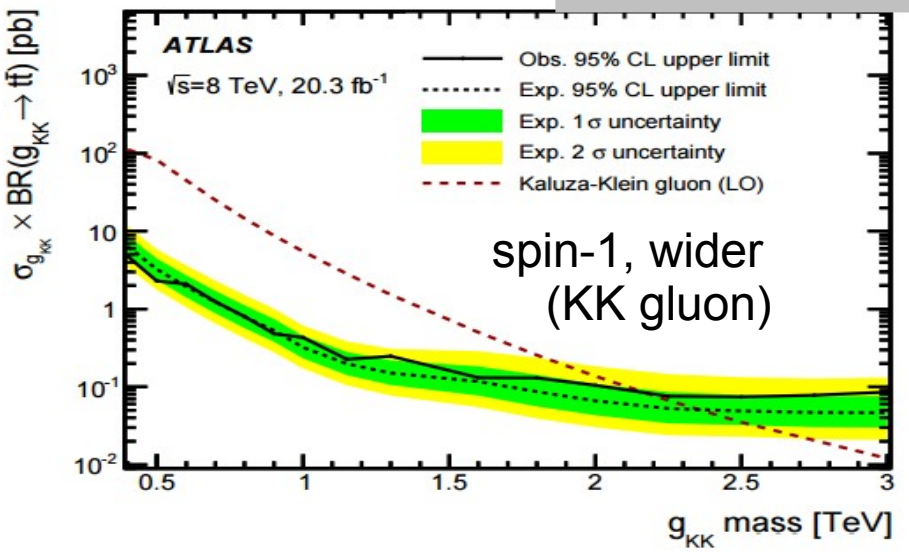




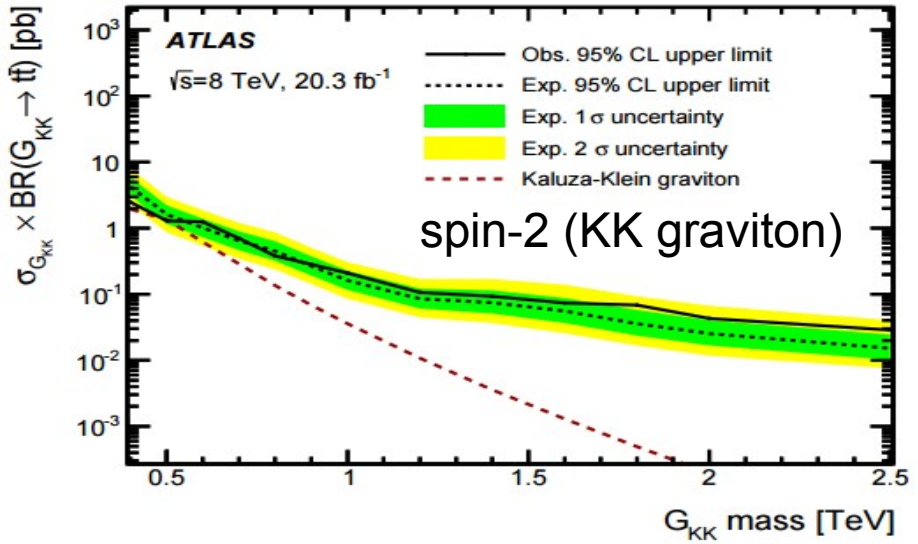
Z' → ttbar [l+jets, ATLAS]

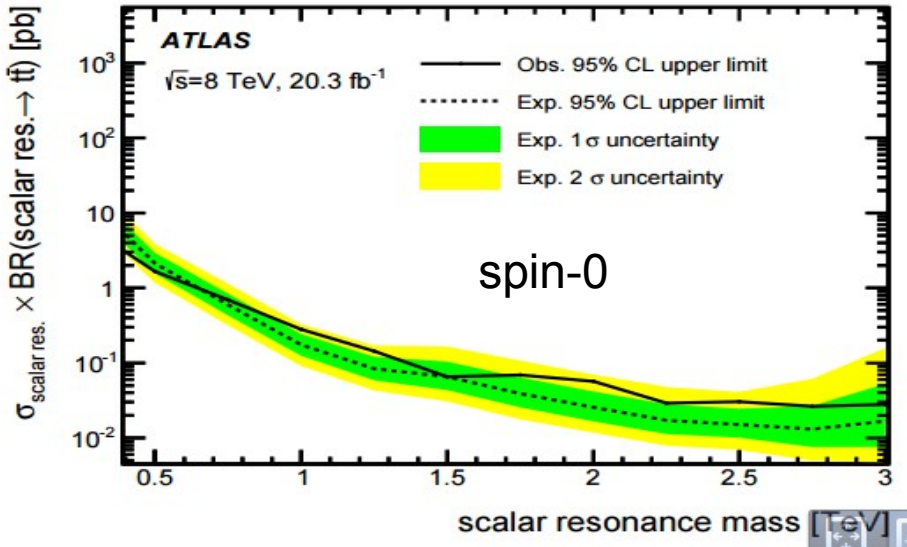
arXiv:1505.07018





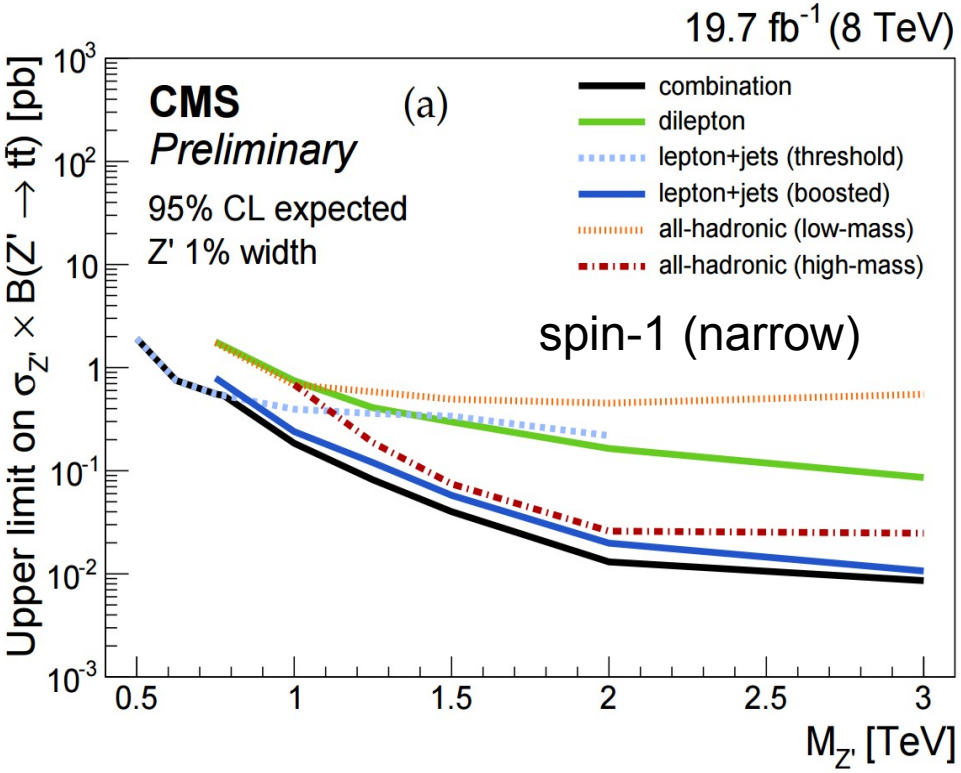
A whole series of models probed!





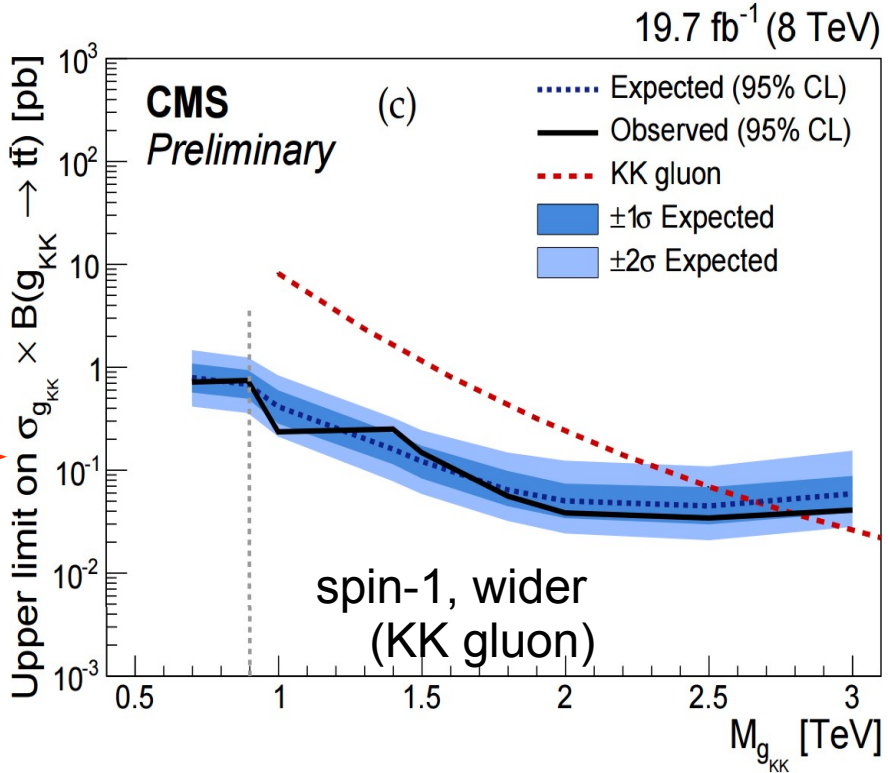
Z' → ttbar [CMS]

arXiv:1506.03062



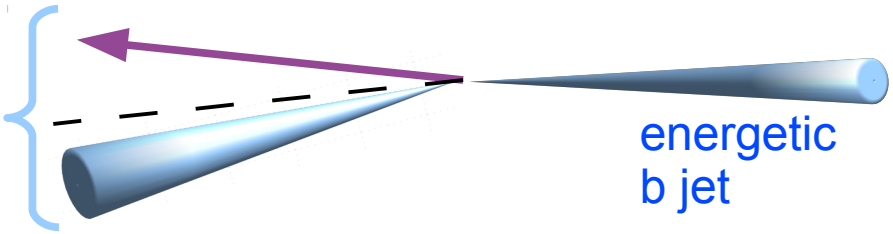
- Comparison of channels
  - l+jets the best, but
  - all-hadronic very close
  - both help combination
  - [true for ATLAS too]

- CMS: sample limit from combination of all channels



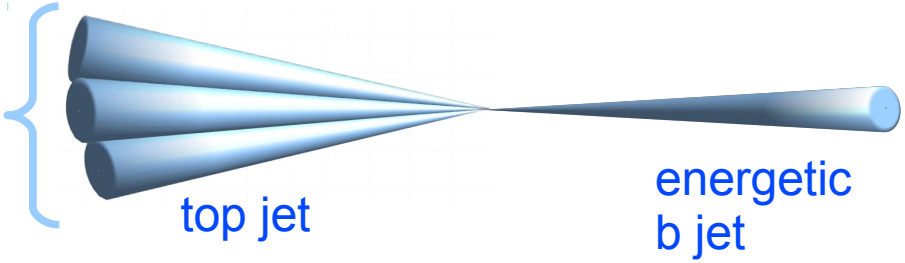
W' → tb

- Semileptonic channel



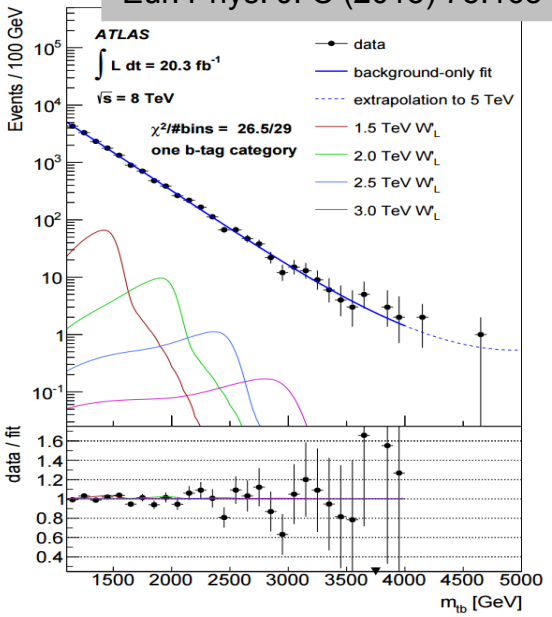
lepton + E_T^{miss} + b jet

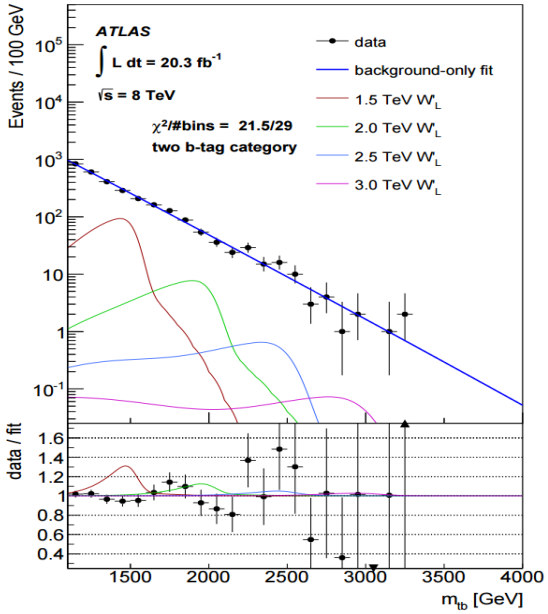
- All-hadronic channel



- Similar to $Z' \to t\bar{t}$, except only one boosted top
  - somewhat tricker (larger QCD background)

Eur. Phys. J. C (2015) 75:165





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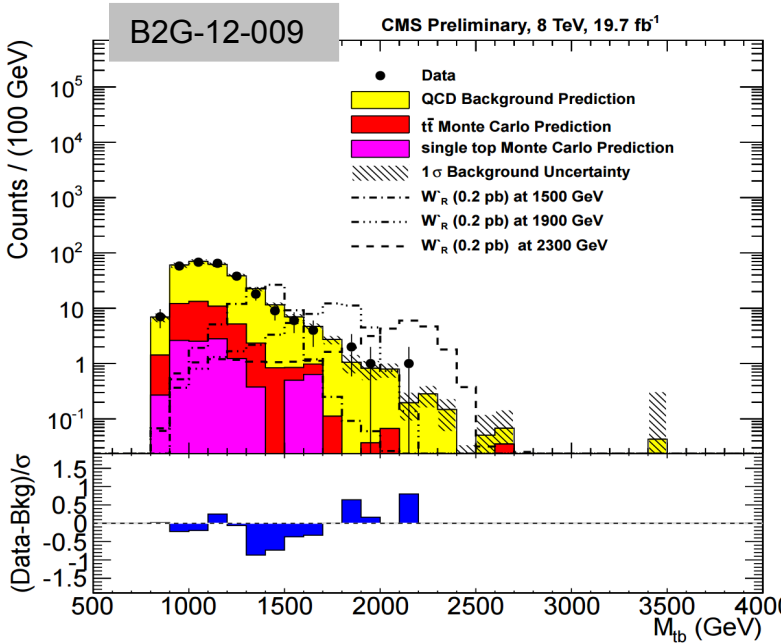
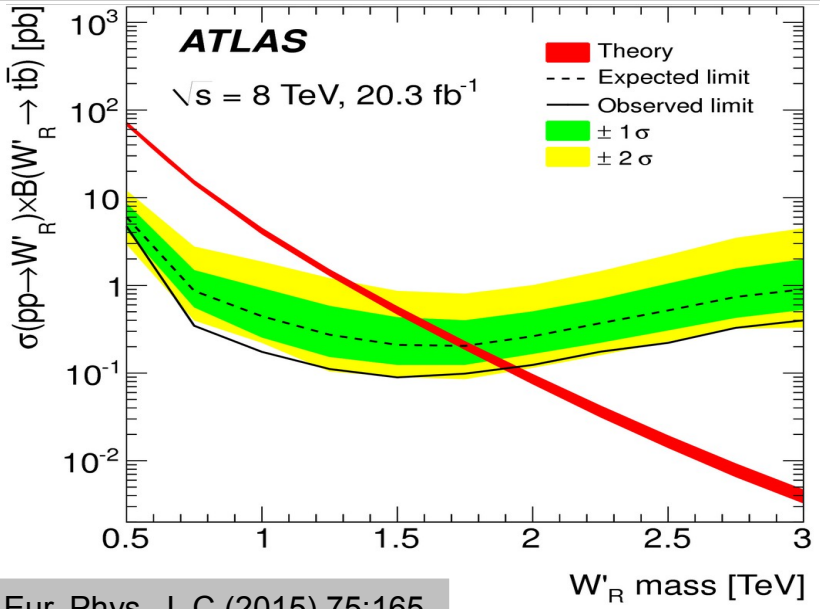
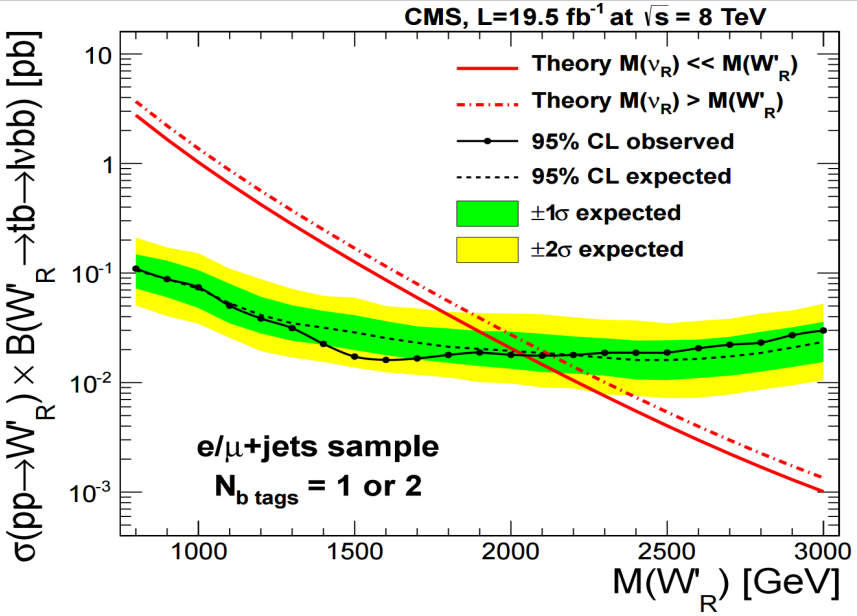


W' → tb

PLB 743, 235 (2015)



JHEP 05 (2014) 108



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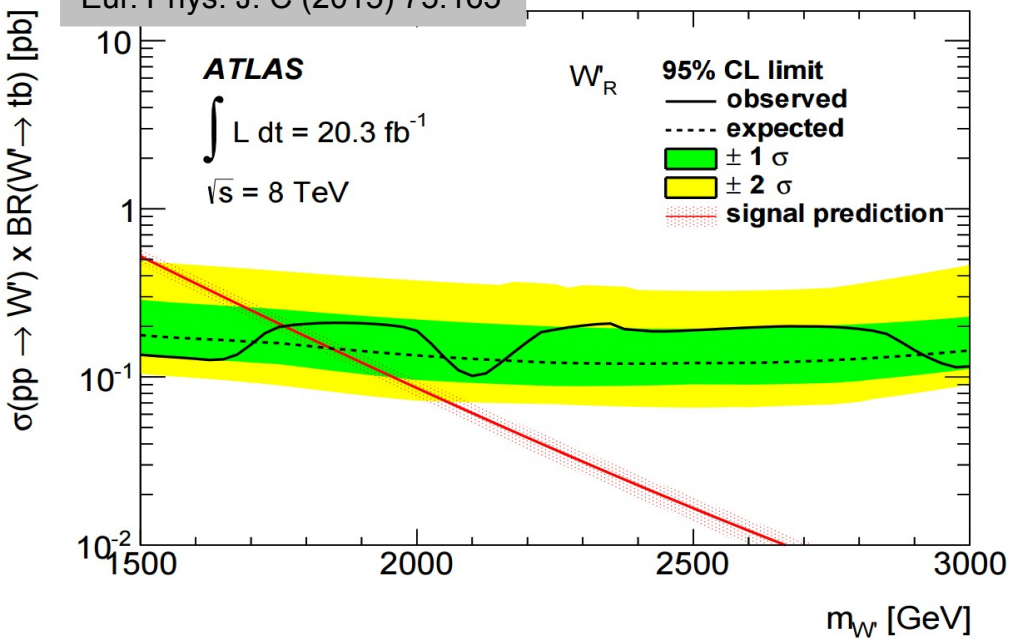
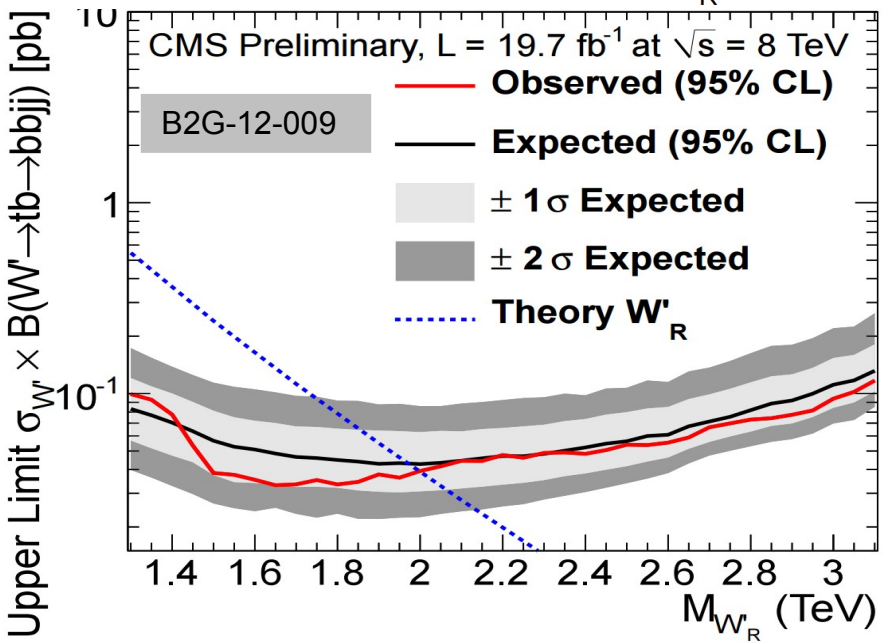
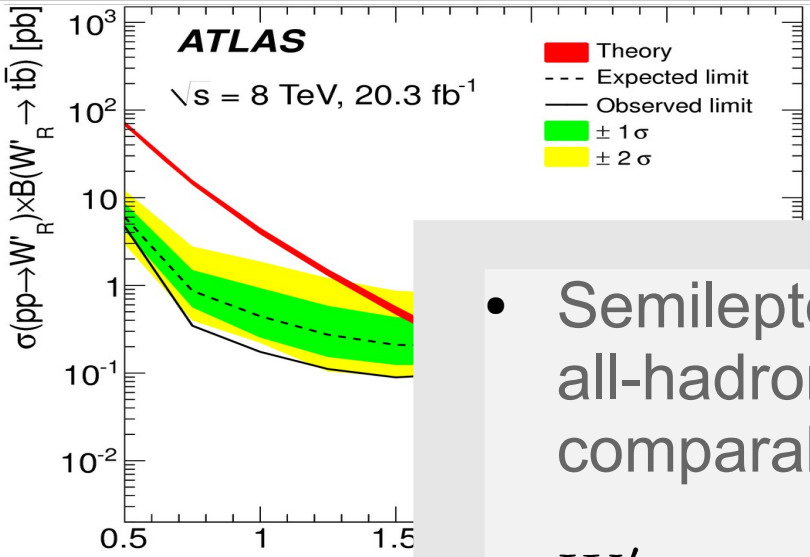


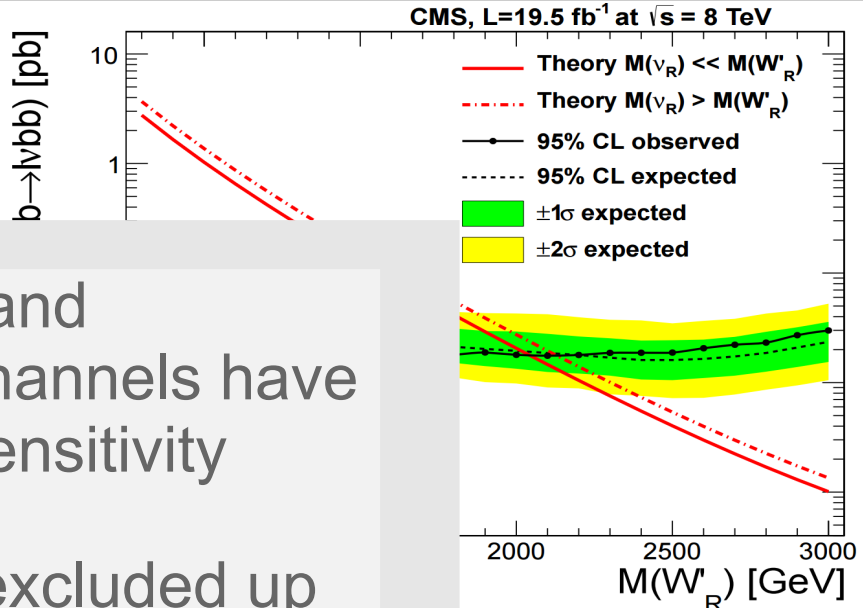


W' → tb

PLB 743, 235 (2015)

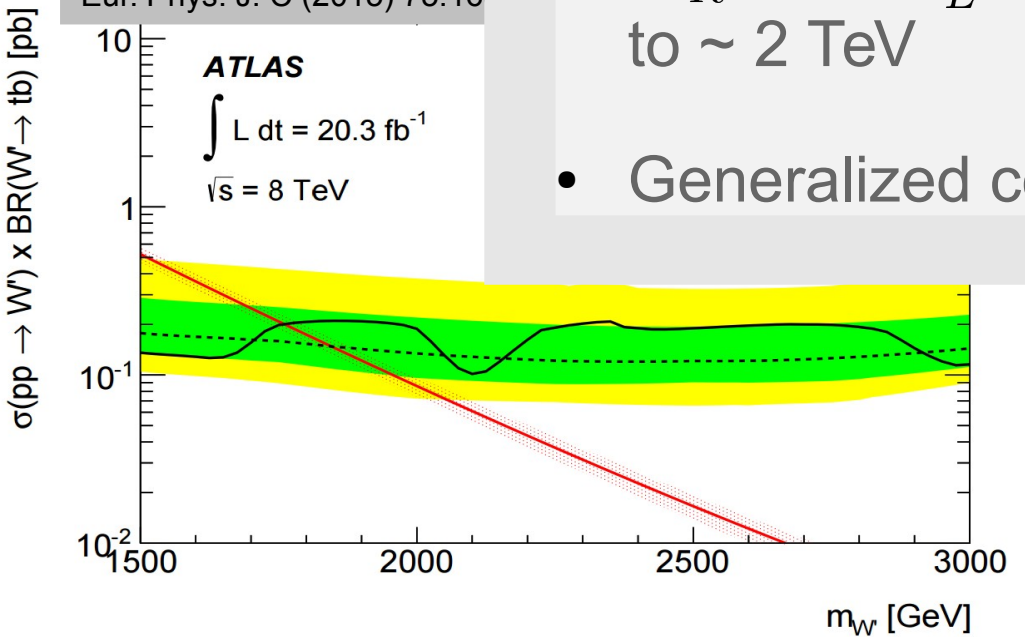
JHEP 05 (2014) 108

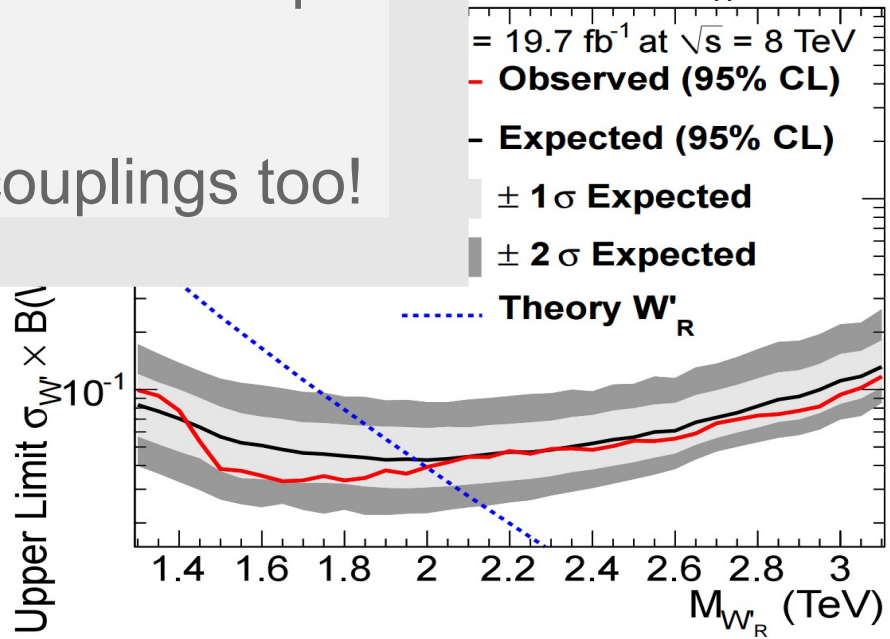




- Semileptonic and all-hadronic channels have comparable sensitivity
- W'_R and W'_L excluded up to ~ 2 TeV
- Generalized couplings too!

Eur. Phys. J. C (2015) 75:16



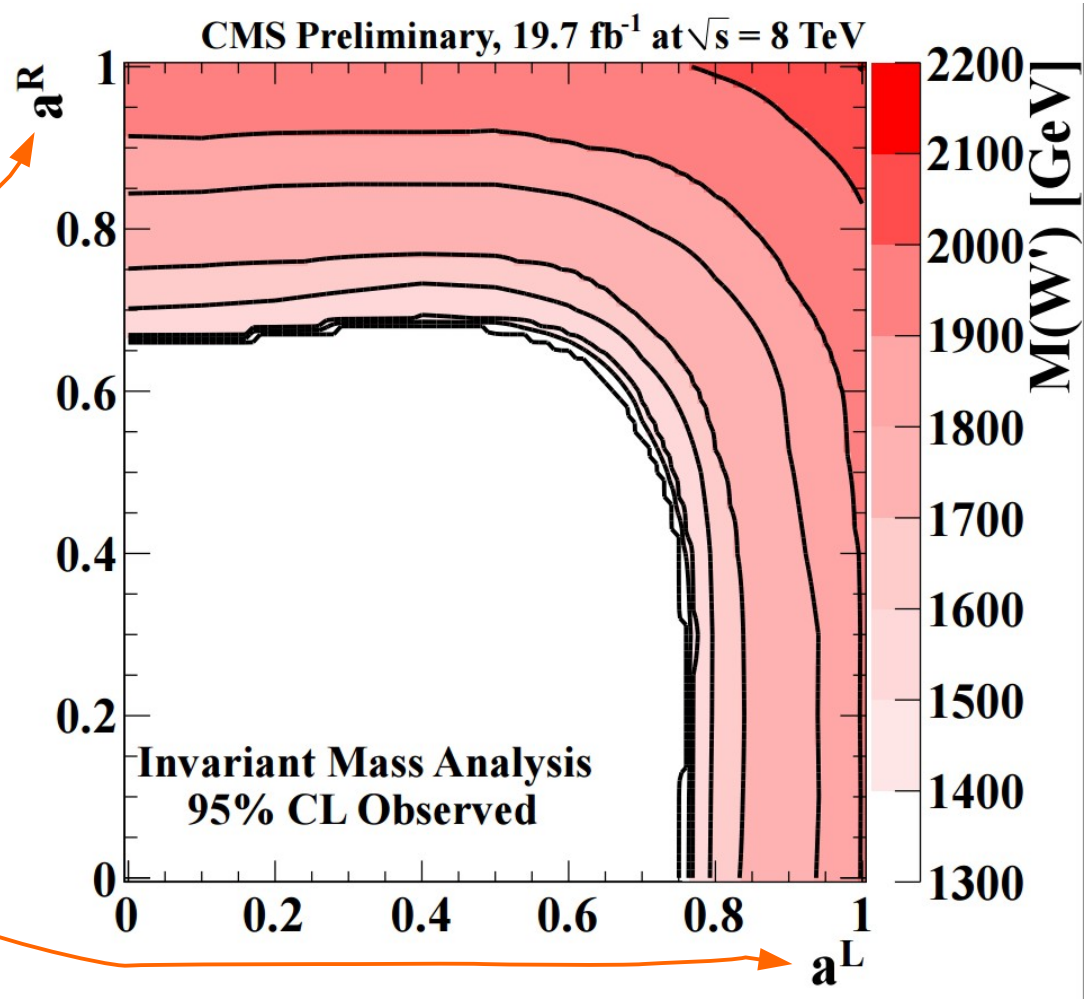


W' – generalized couplings

B2G-12-009

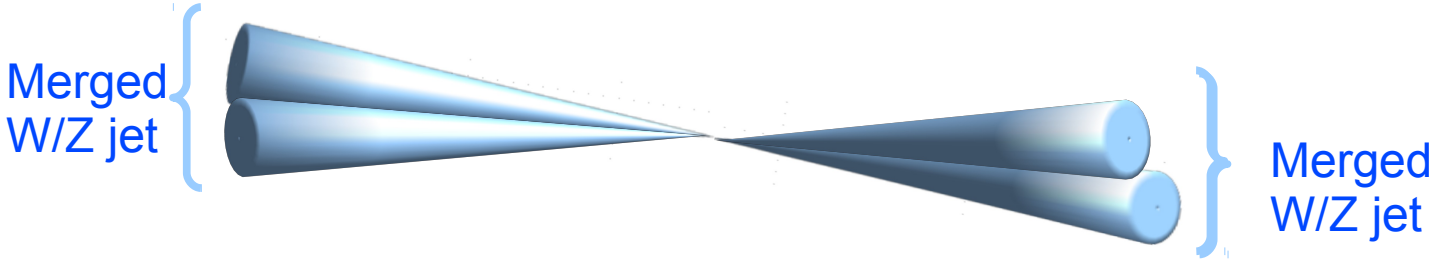
$$\mathcal{L} = \frac{V_{q_i q_j}}{2\sqrt{2}} g_w \bar{q}_i \gamma_\mu \left(a^R_{q_i q_j} (1+\gamma^5) + a^L_{q_i q_j} (1-\gamma^5) \right) \mathrm{W}' q_j + \mathrm{H.c.}$$

- Both W'_R and W'_L could contribute
- *Mass* limits can be interpreted as a function of both couplings: a^R_{tb}, a^L_{tb}



$X \to VV \to JJ \to (qq)(qq)$

- Fully hadronic decays $W \to jj$ and $Z \to jj$
  - boosted → merge in a single jet
  - QCD background suppressed by $|\eta_1 - \eta_2| < 1.3$



- Each jet is required to pass the "V-tagger"
  - ATLAS cuts on filtered jet mass + on $\sqrt{y_f}$ + on $n_{\mathrm{trk}} < 30$
  - CMS cuts on pruned jet mass + on τ_2/τ_1

- Background: smooth falling function (only for bump hunt!)
  - e.g. ATLAS uses $\dfrac{dN}{dx} = p_1(1-x)^{p_2-\xi p_3}x^{p_3}, \quad x = m_{jj}/\sqrt{s}$

X → VV → JJ → (qq)(qq) [ATLAS]

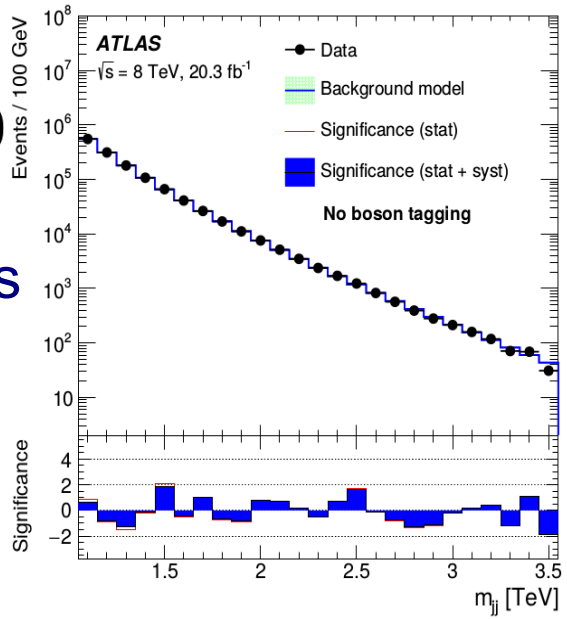
arXiv:1506.0962

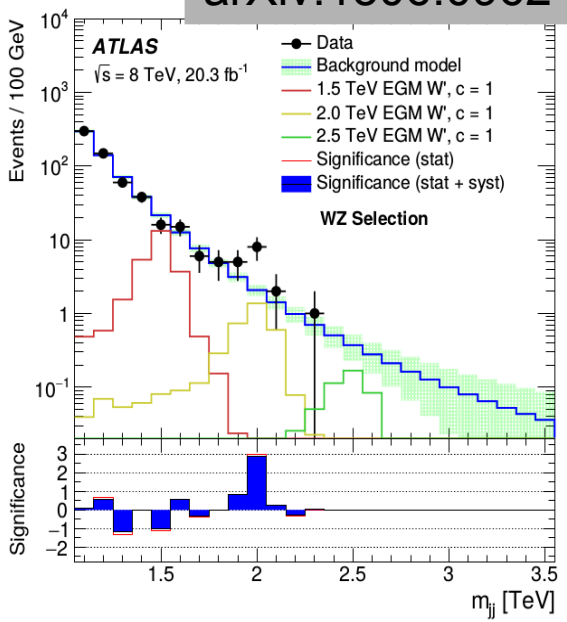
- # of charged tracks in ungroomed jet $n_{\mathrm{trk}} < 30$
- Cut on $\sqrt{y_f}$ prefers transversely polarized V's

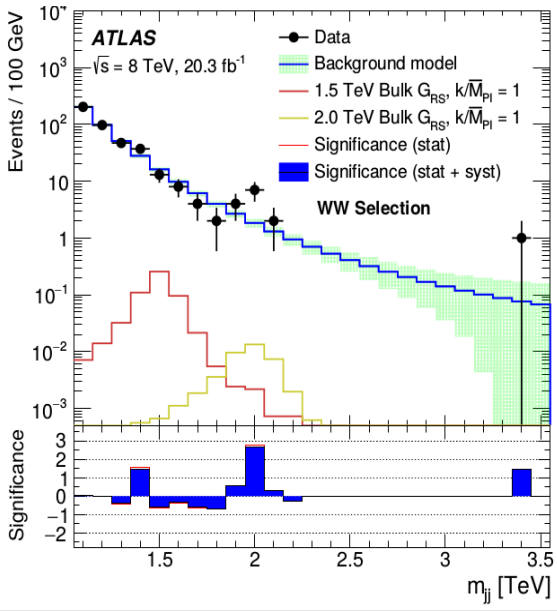
  (differences wrt CMS)

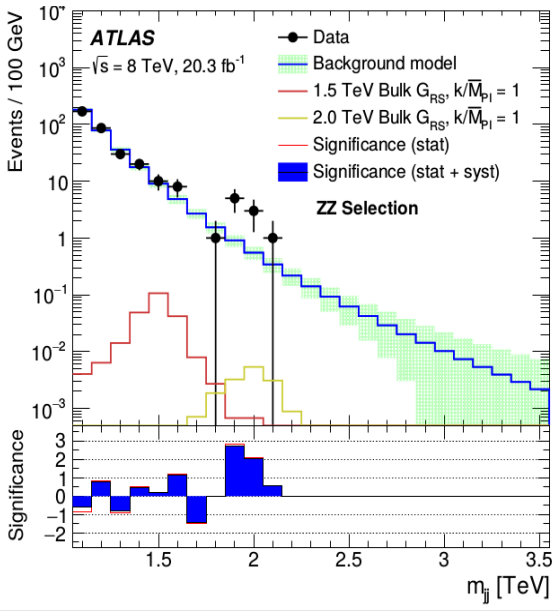
- Alternative selections for WW, WZ, ZZ

  (not independent!)
- Local significance:
  - WZ : 3.4σ,
  - WW : 2.6σ,
  - ZZ : 2.9σ
- Global significance:
  - WZ : 2.5σ



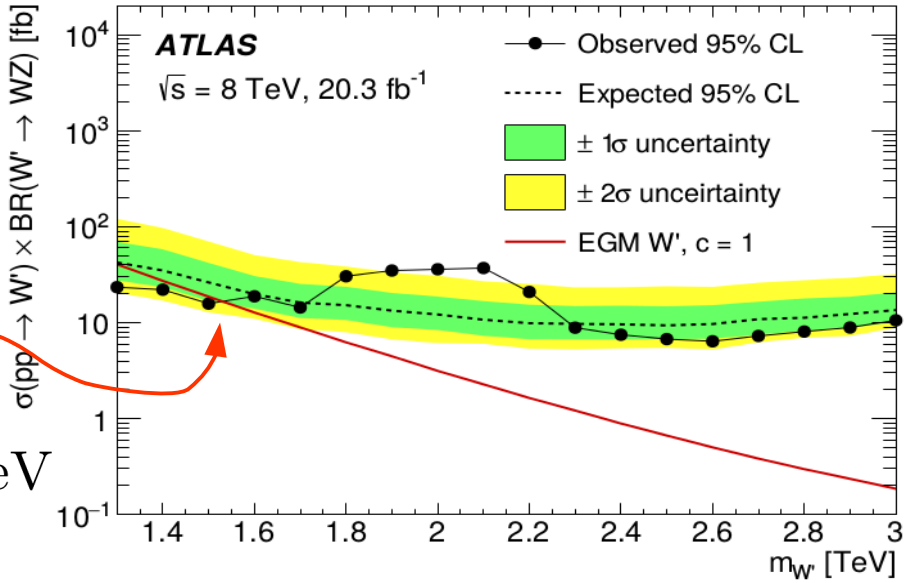






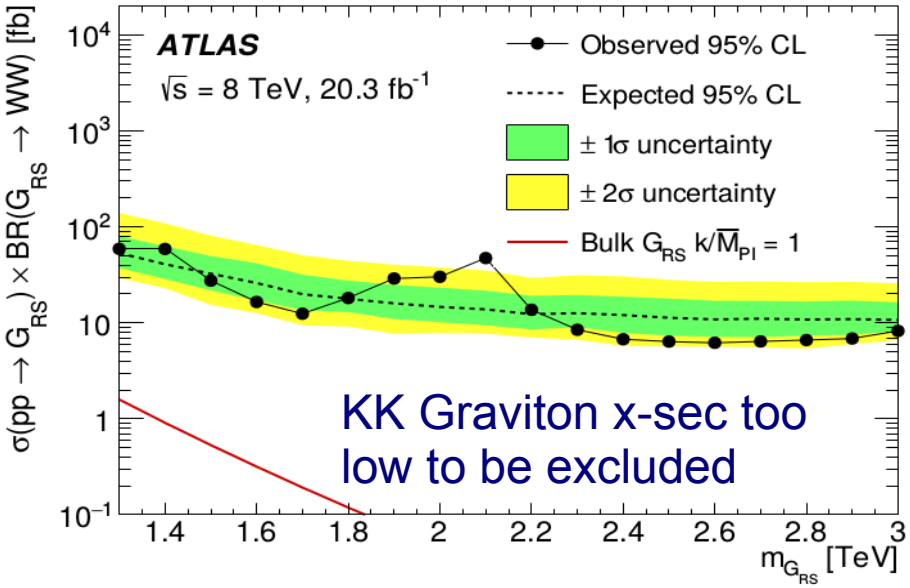
X → VV → JJ → (qq)(qq) [ATLAS]

arXiv:1506.0962

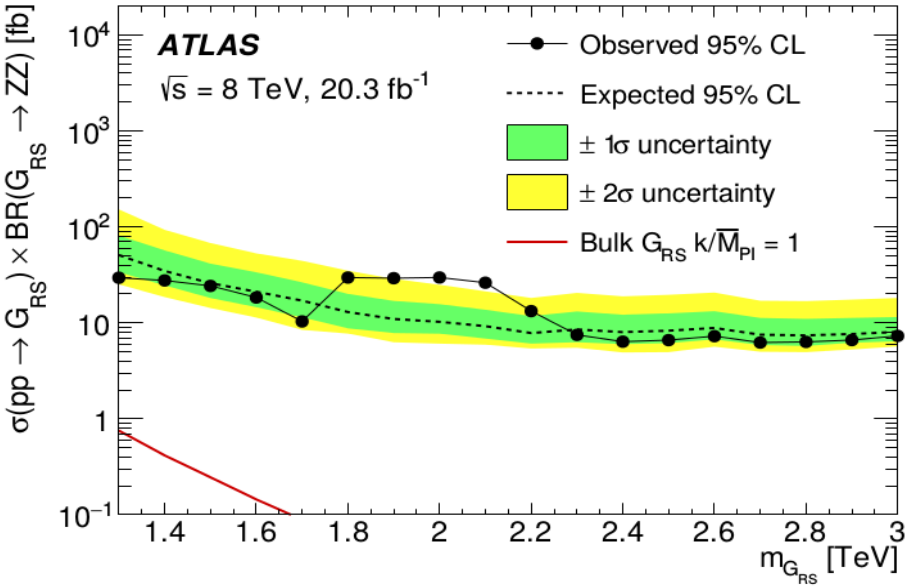


Excluded

$1.3 < m_{W'} < 1.5$ TeV



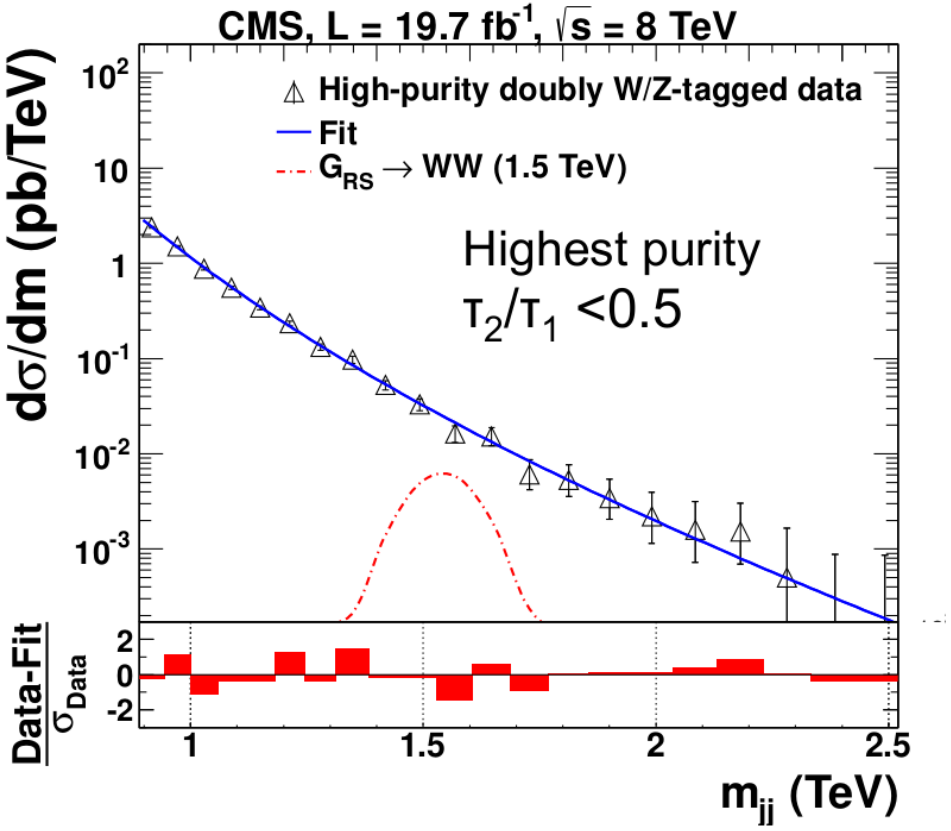
KK Graviton x-sec too low to be excluded

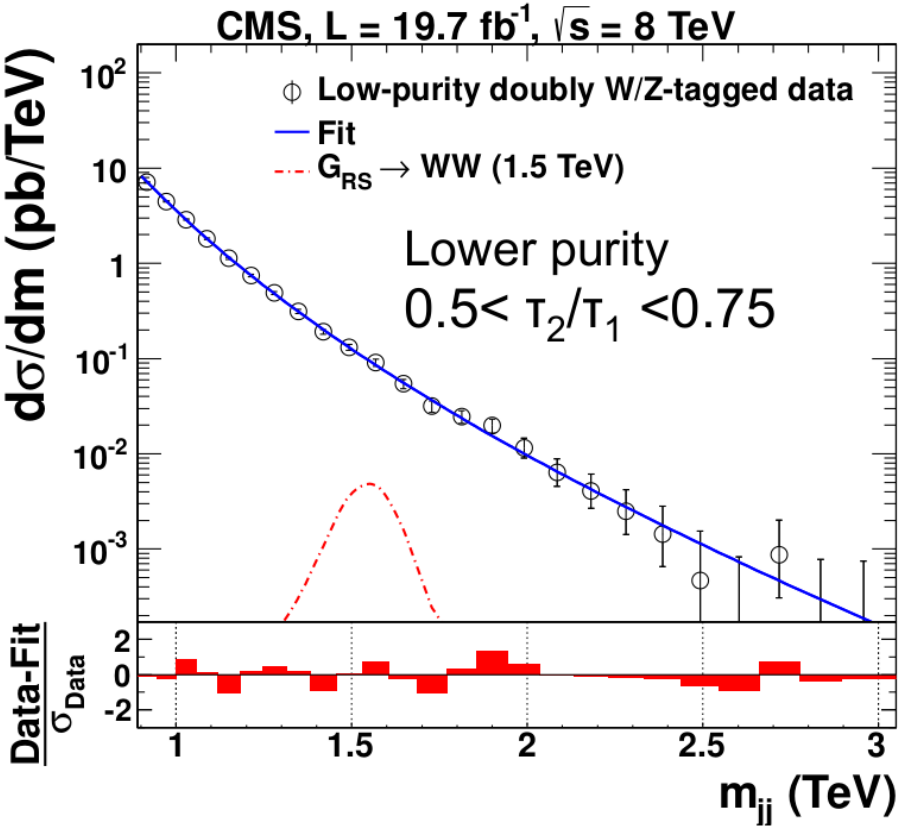


X → VV → JJ → (qq)(qq) [CMS]

arXiv:1405.1994

- Selection very similar to ATLAS, except n_{trk}
- Combined significance higher+lower purity at 1.8 TeV = 1.3σ





$X \to WV \to \nu l J \to (\nu l)(qq)$ [ATLAS]

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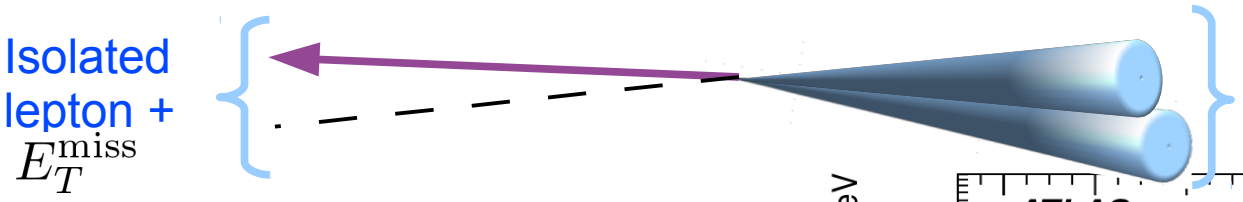
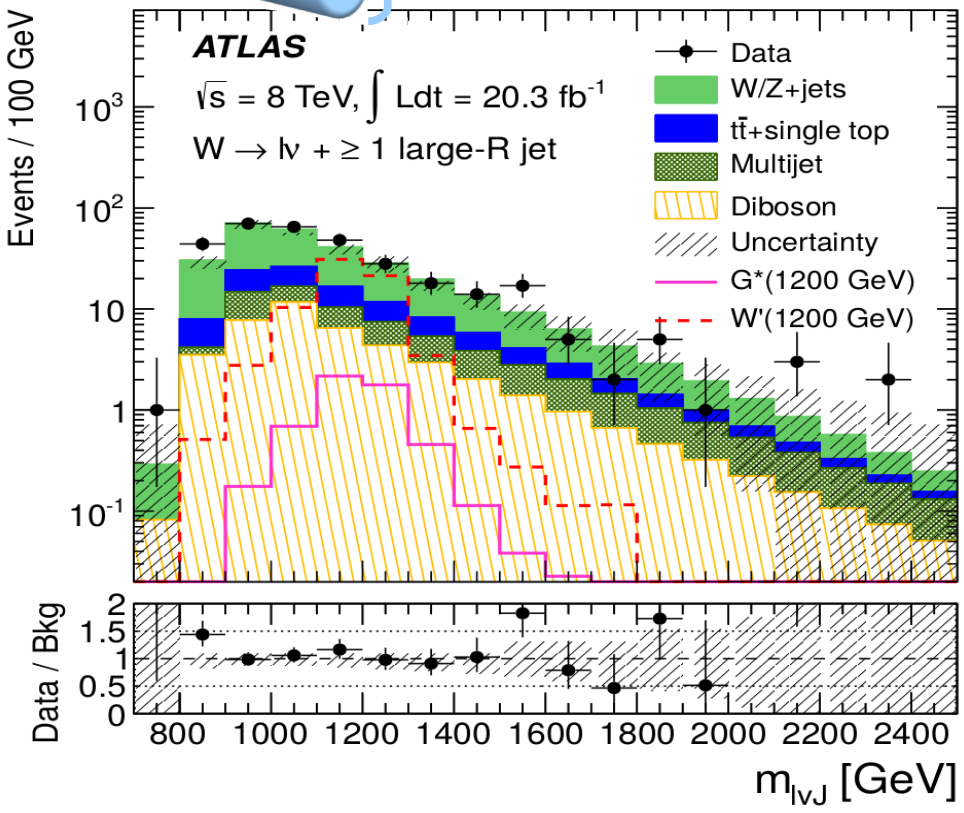
- One $W \to \nu\ell$, the other boosted $V \to jj$
  - one side: isolated lepton + missing energy
  - opposite side: V-tag



- ATLAS:
  - trigger on high-pt lepton
  - veto small-R b-tagged jets
  - W/Z+jets from V-jet mass sidebands + fit to E_T^{miss}



X → WV → νlJ → (νl)(qq) [ATLAS]

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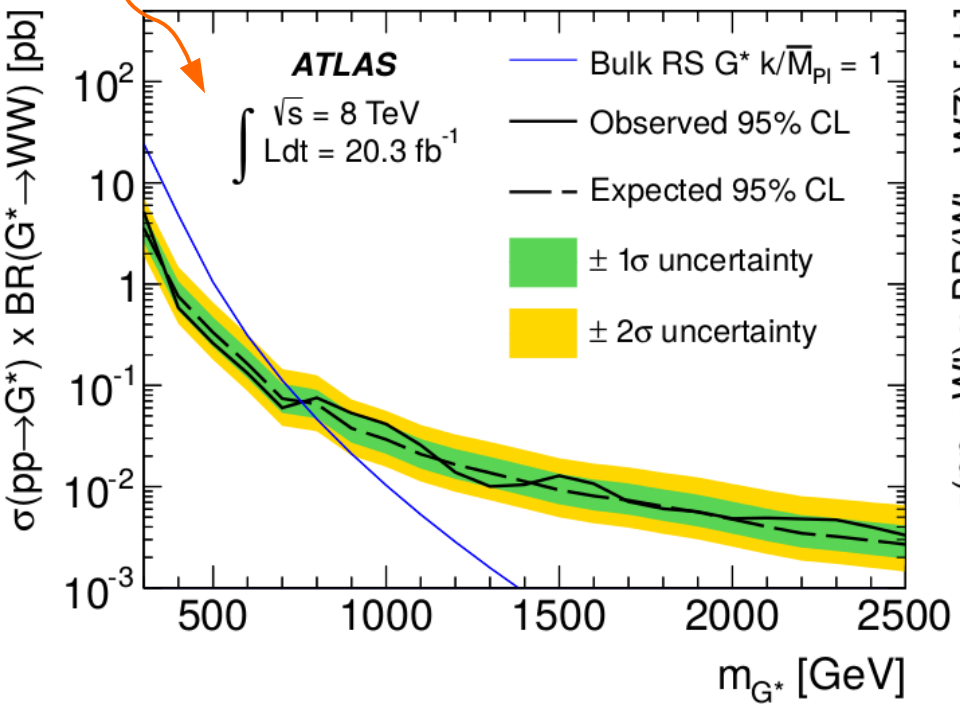
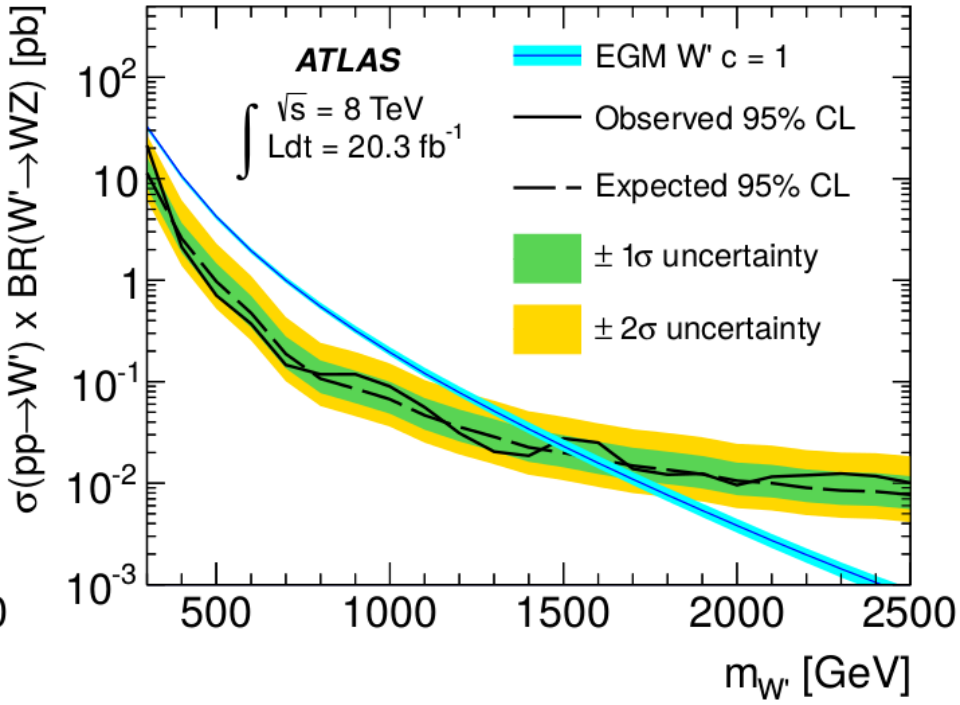
- (Also include low-pt and high-pt resolved channels)
- Exclude
  - M(W') up to ~ 1.5 TeV
  - bulk graviton with M(G*) up to ~ 800 GeV

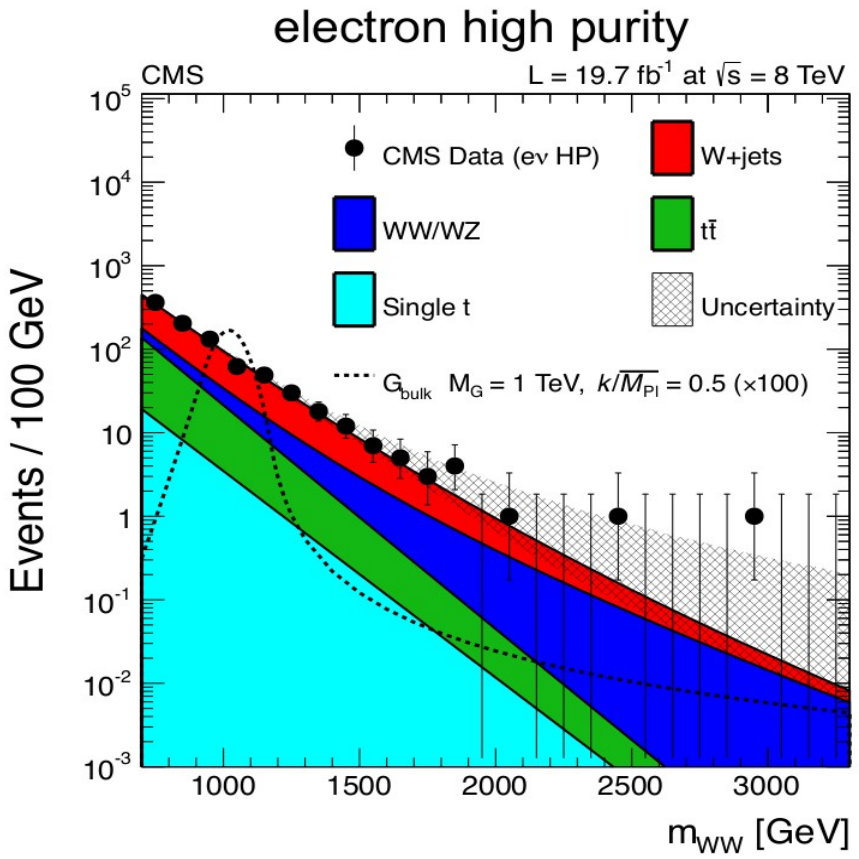


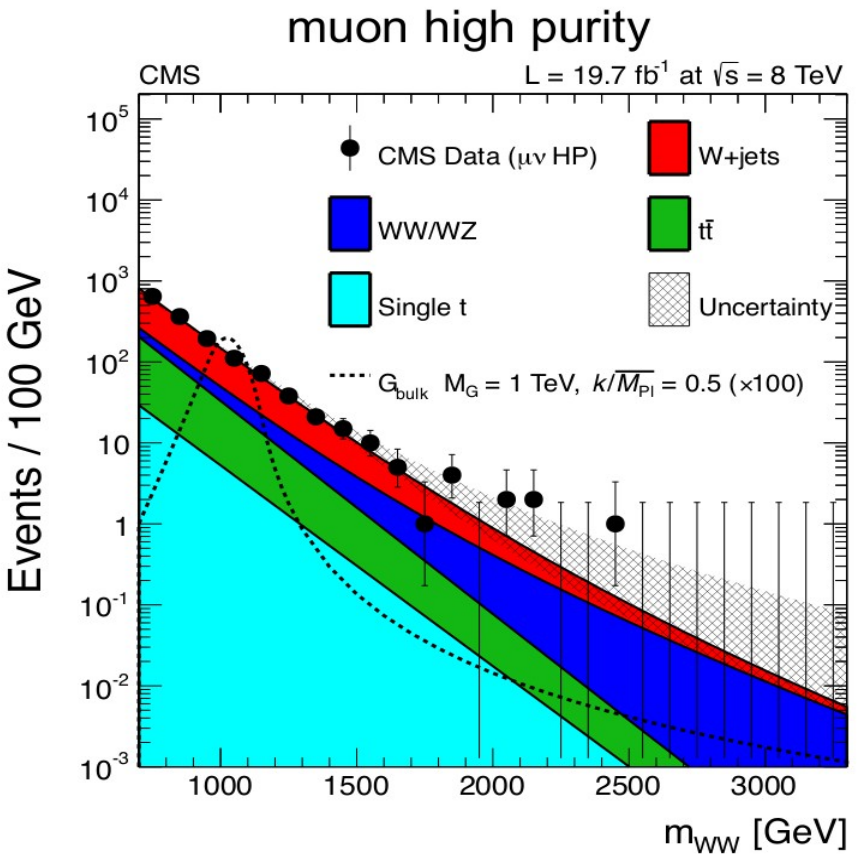


$X \rightarrow VV \rightarrow \nu lJ \rightarrow (\nu l)(qq)$ [CMS]

arXiv:1405.3447

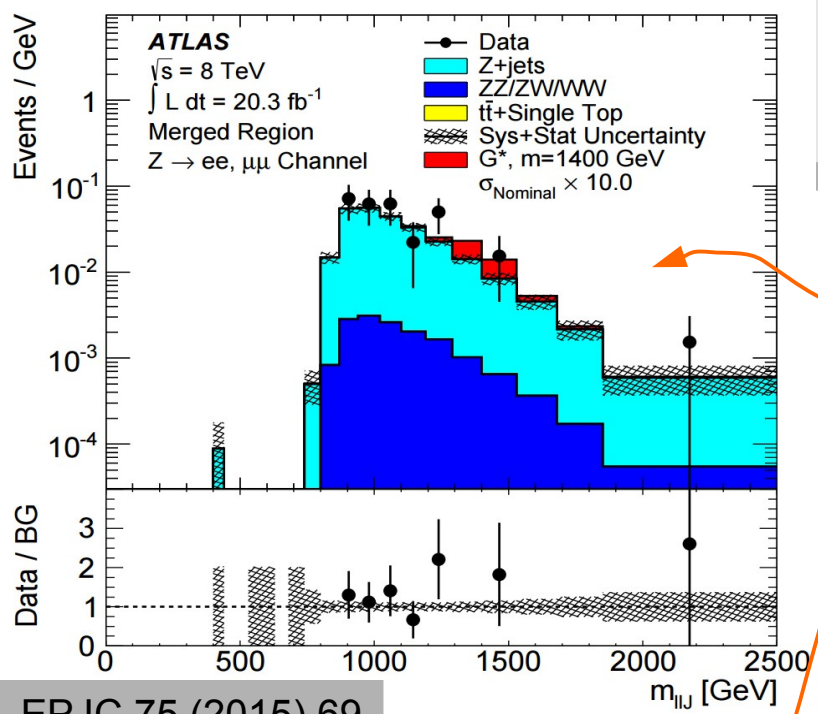
- V-tagged jet (use substructure for higher/lower purity)
- W+jets: from V jet mass sidebands





X → ZV → llJ → (ll)(qq)

- ATLAS: resolved (high and low pt) + boosted channels
- CMS: boosted only, ee, μμ, classify using substructure
- Z+jets: from V sidebands



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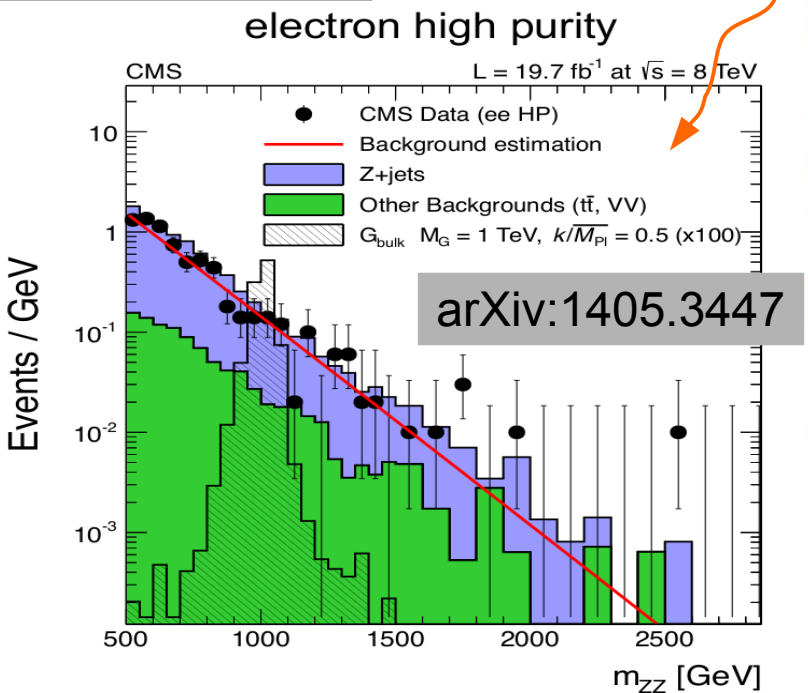
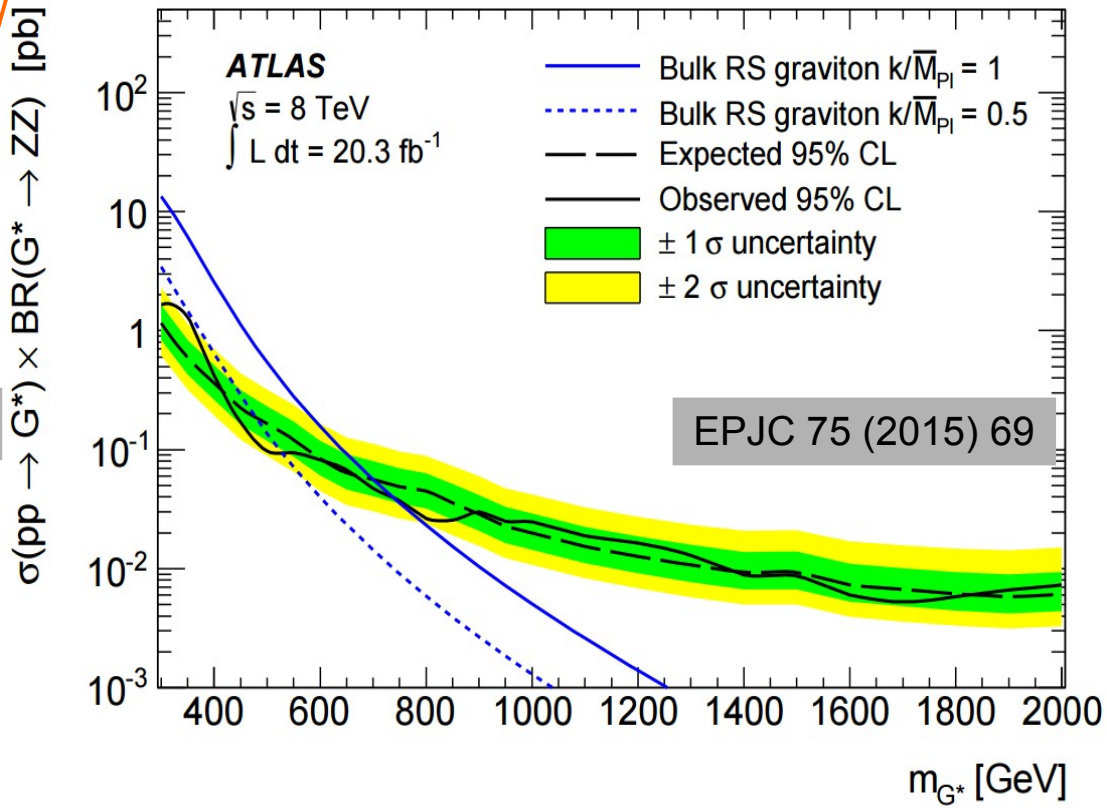


arXiv:1405.3447



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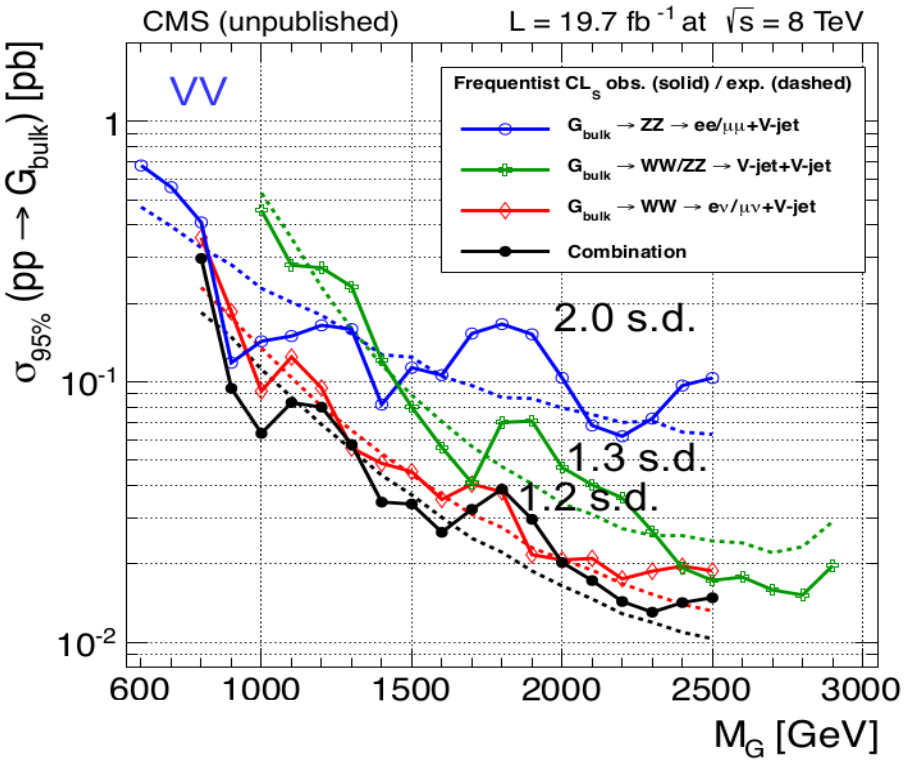
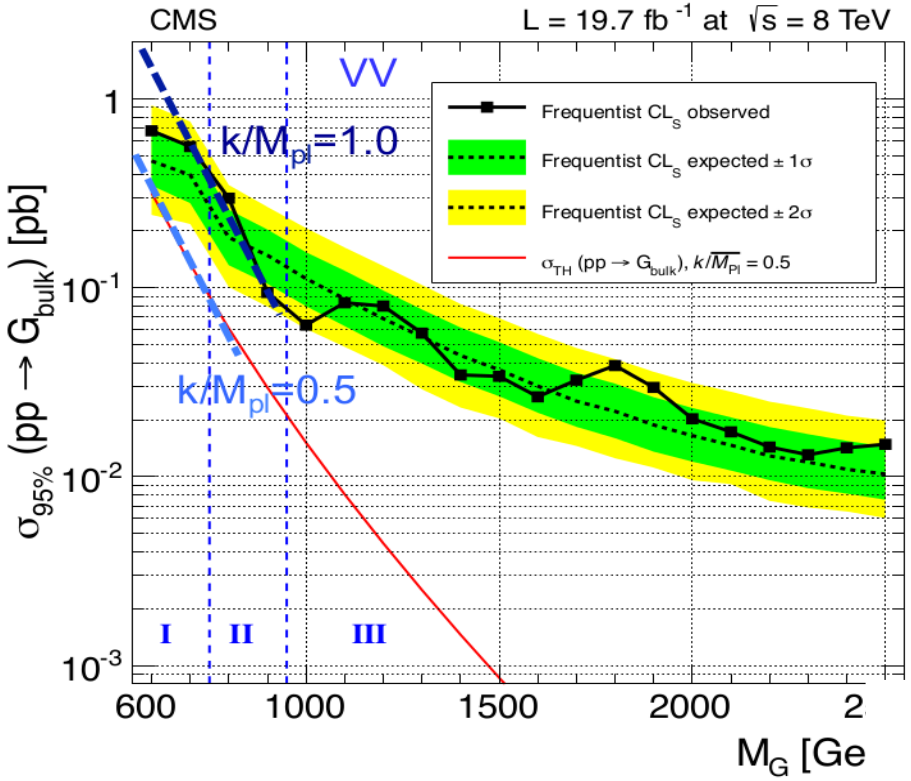
Limits on spin-2 WW / ZZ resonances

arXiv:1405.3447

- Run I searches start to be sensitive to gravitons in Bulk model
  - Cross section and width related to coupling parameter k/M pl
  - Narrow width for k/M pl ≤ 0.5
- Model-independent limits allow reinterpretation for wide width resonance and as spin-1 WZ resonance (see later)





X → VH → νν/ll/νl + 2b [ATLAS]

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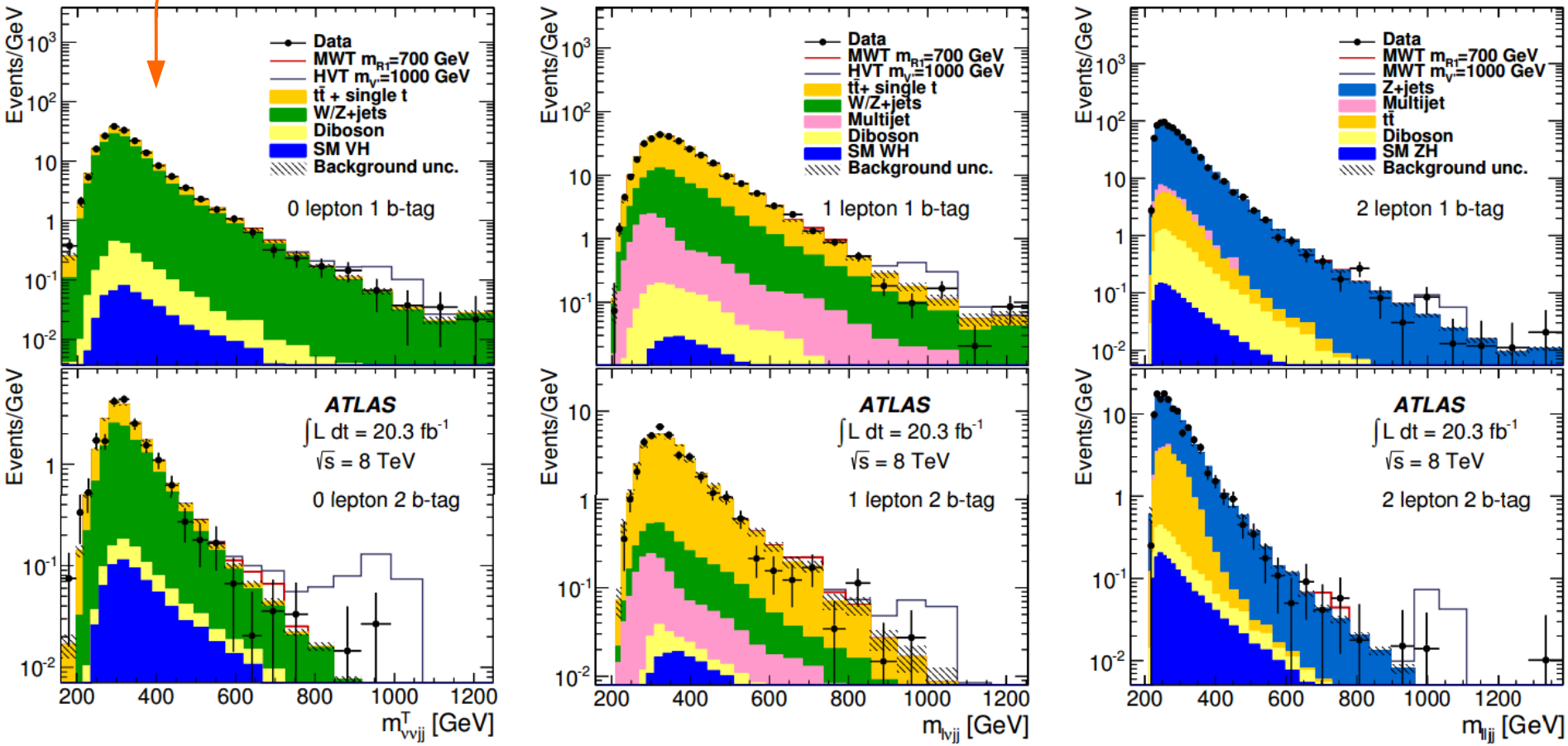
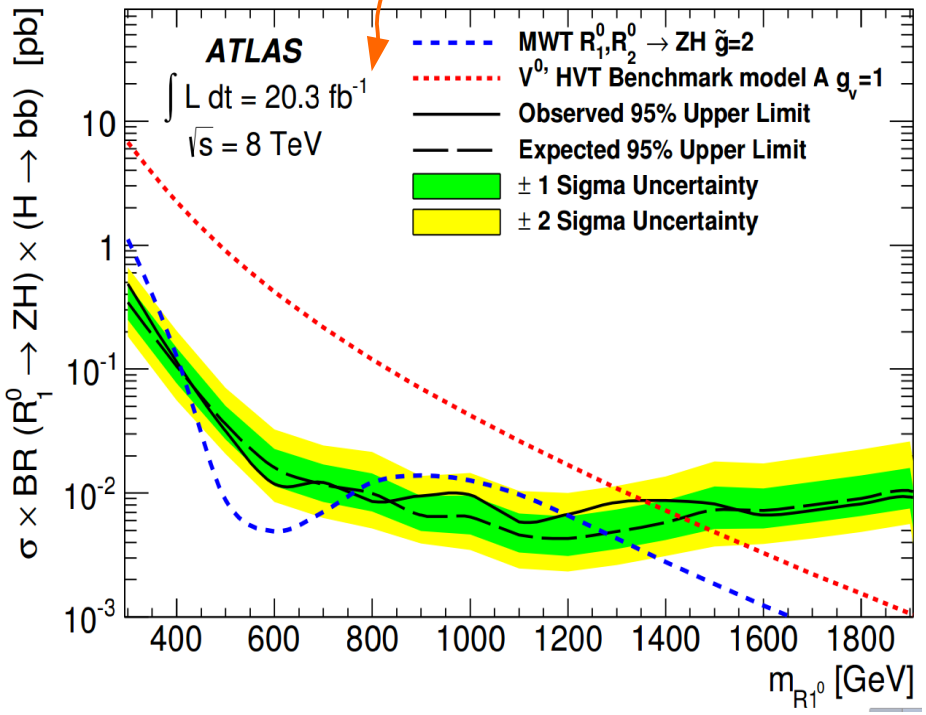
- Resolved analysis:
  - 0,1,2 leptons + MET + 1,2 b-tagged small-R jets
  - MET + 2b: use $m_{VH}^{\mathrm{T}} = \sqrt{(E_T^{b\bar{b}} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\boldsymbol{p}_{\mathrm{T}}^{b\bar{b}} + \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}})^2}$

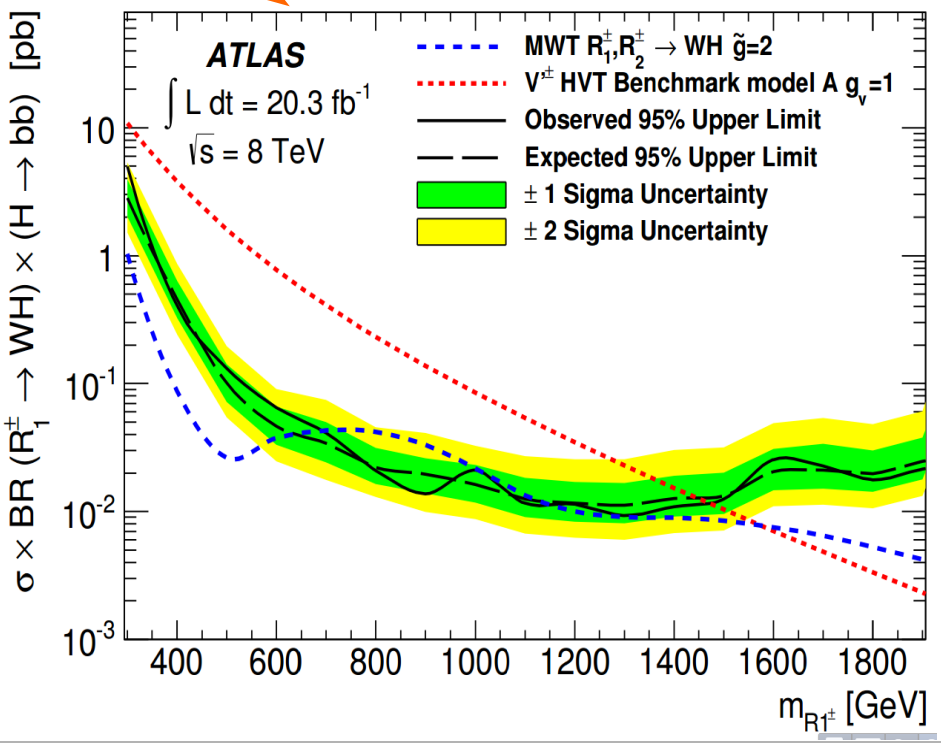


X → VH → νν/lll/νl + 2b [ATLAS]

EPJC 75 (2015) 263

- Consider Minimal Walking Technicolor (MWT) and Heavy Vector Triplet (HVT) model A
- Limits on neutral and charged resonances ~ 1.4-1.5 TeV

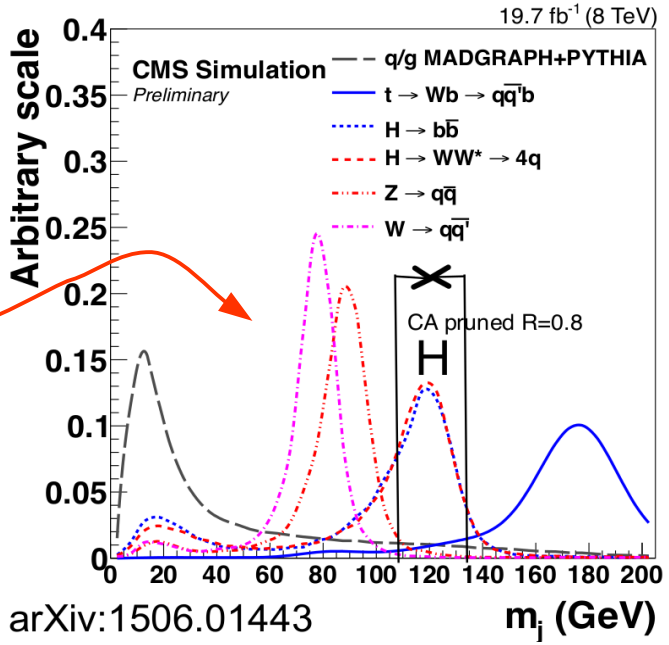




Boosted H → bb tagging

arXiv:1506.01443

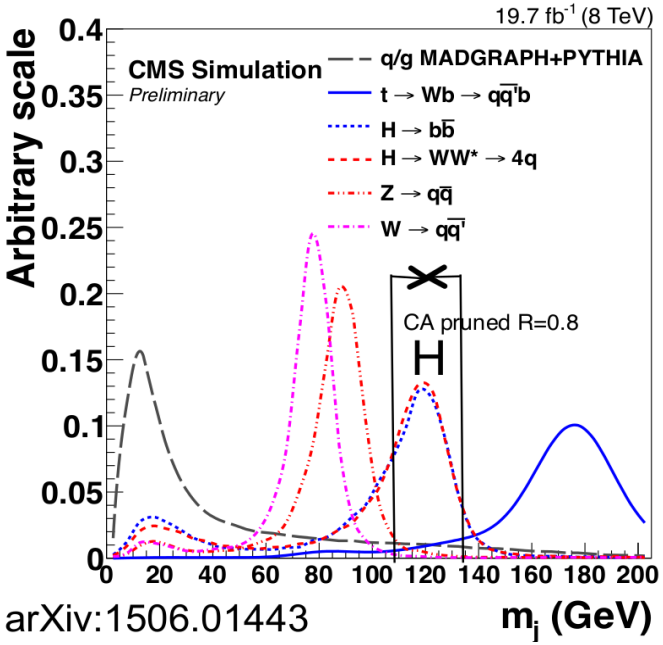
- Discriminants:
  - large R jet (ATLAS: anti-k_T R=1.0, CMS: CA R=0.8)
  - groomed jet mass (trimmed for ATLAS, pruned for CMS)

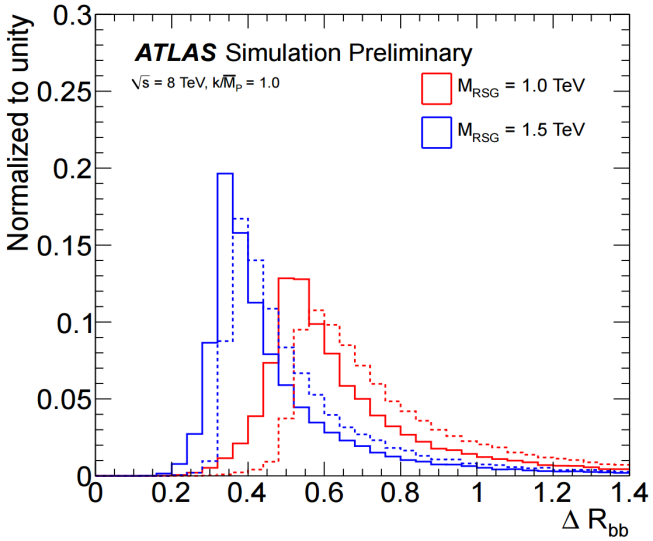


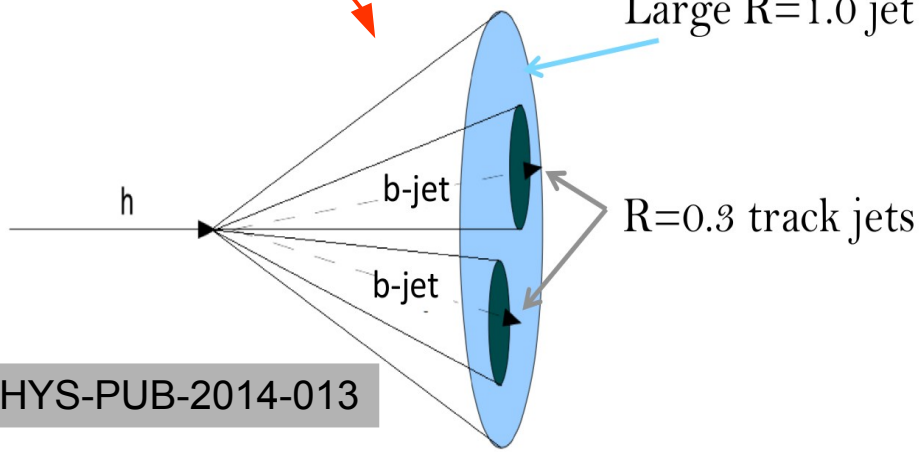
Boosted H → bb tagging

arXiv:1506.01443

- Discriminants:
  - large R jet (ATLAS: anti-k_T R=1.0, CMS: CA R=0.8)
  - groomed jet mass (trimmed for ATLAS, pruned for CMS)
  - "subjet b tagging"
    - track jets R=0.3 for ATLAS
    - pruned subjets for CMS





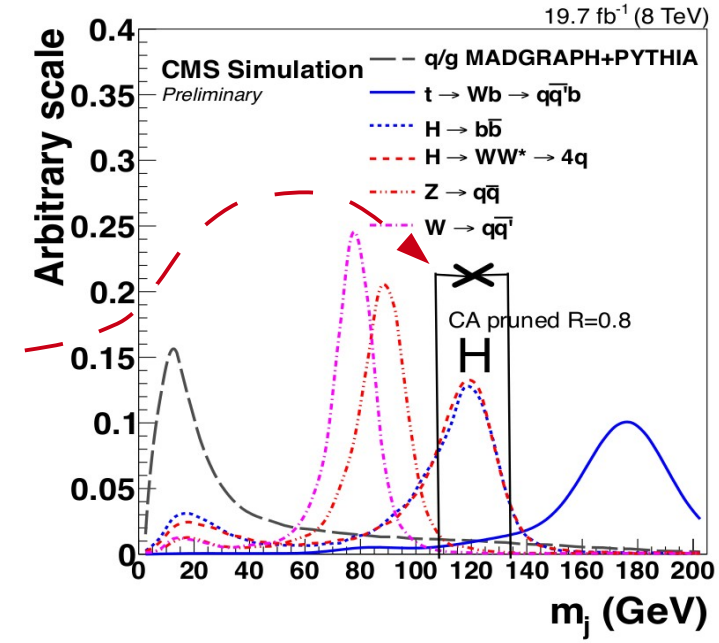


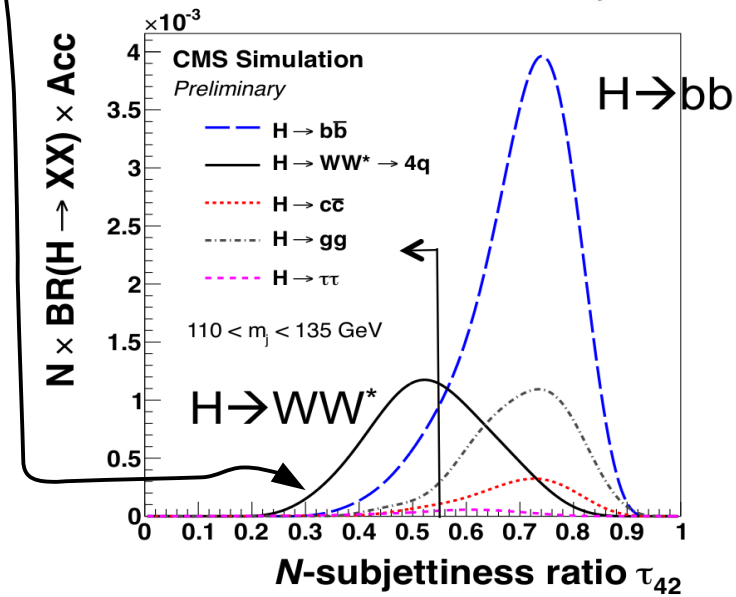
ATL-PHYS-PUB-2014-013

Boosted H → WW* → 4q tagging

arXiv:1506.01443

- BR(H → WW*) second highest after BR(H → bb)
- Discriminating variables:
  - Same mass window as H → bb
  - $\tau_{42} = \tau_4/\tau_2$
    - H → WW* decays are 4-prong
    - discriminate against g/q/W/Z/H(bb) (1- or 2-prong)

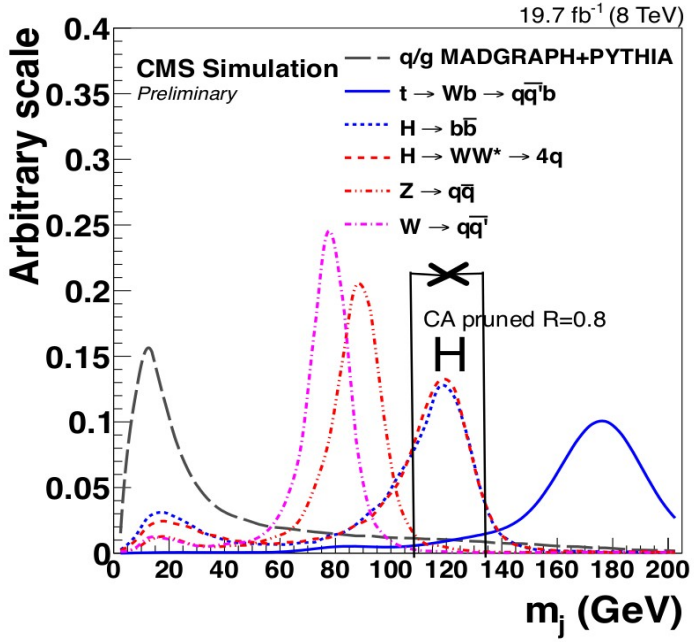


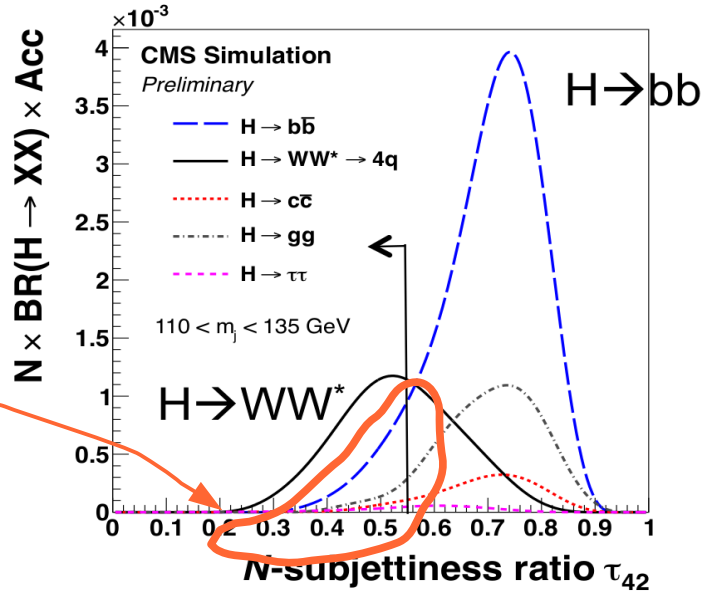


Boosted H → WW* → 4q tagging

arXiv:1506.01443

- BR(H → WW*) second highest after BR(H → bb)
- Discriminating variables:
  - Same mass window as H → bb
  - $\tau_{42} = \tau_4/\tau_2$
    - H → WW* decays are 4-prong
    - discriminate against g/q/W/Z/H(bb) (1- or 2-prong)
- Complication:
  - Fraction of H→bb events failing b-tagging, but passing τ_{42} selection non-negligible
  - Must consider all possible Higgs decays *simultaneously*

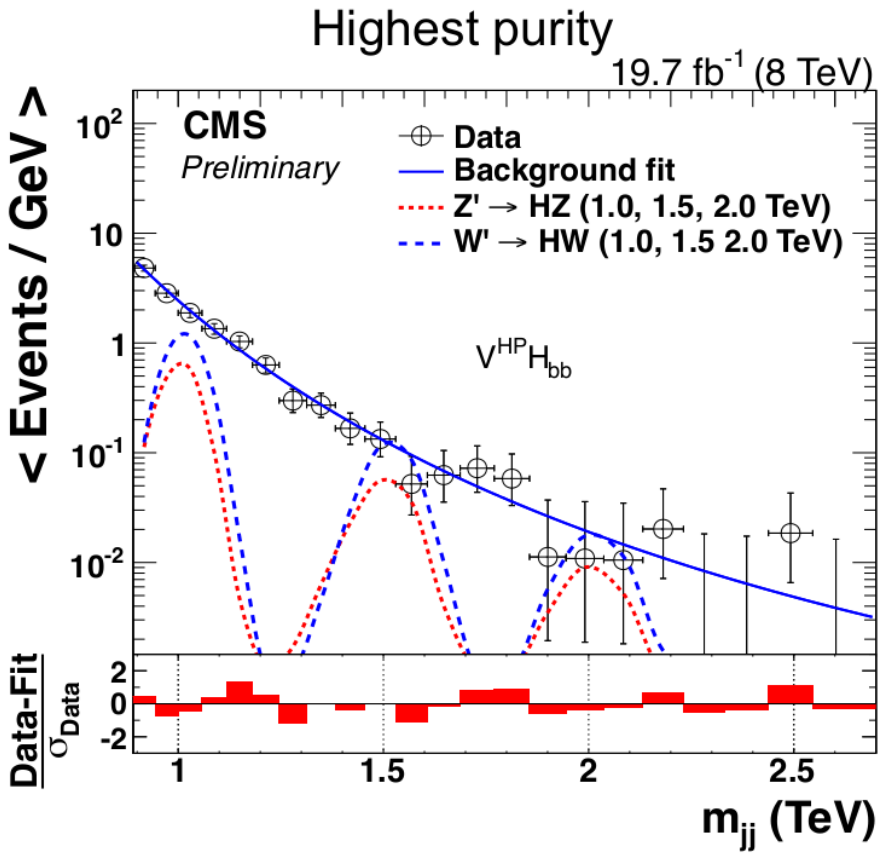


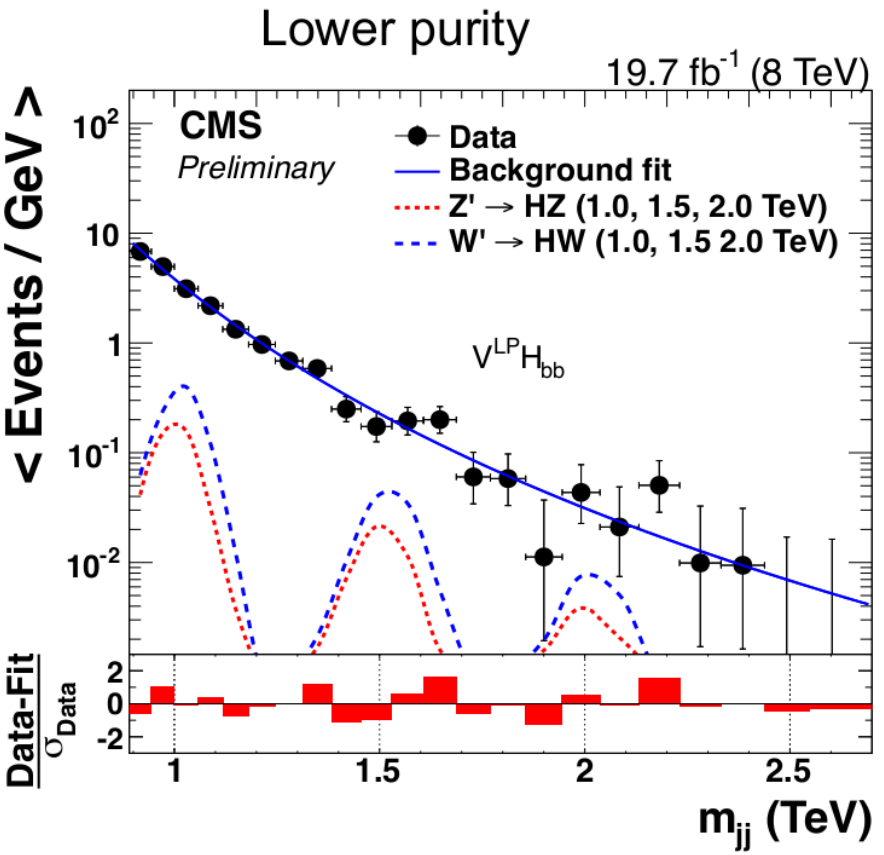


X → VH → JJ [CMS]

arXiv:1506.01443

- Same search technique as X → VV → JJ → (qq)(qq)
  - except use H → bb and H → WW* → 4q taggers
  - lower backgrounds due to better background rejection of H(bb)-tagger (compared to V-tagger)



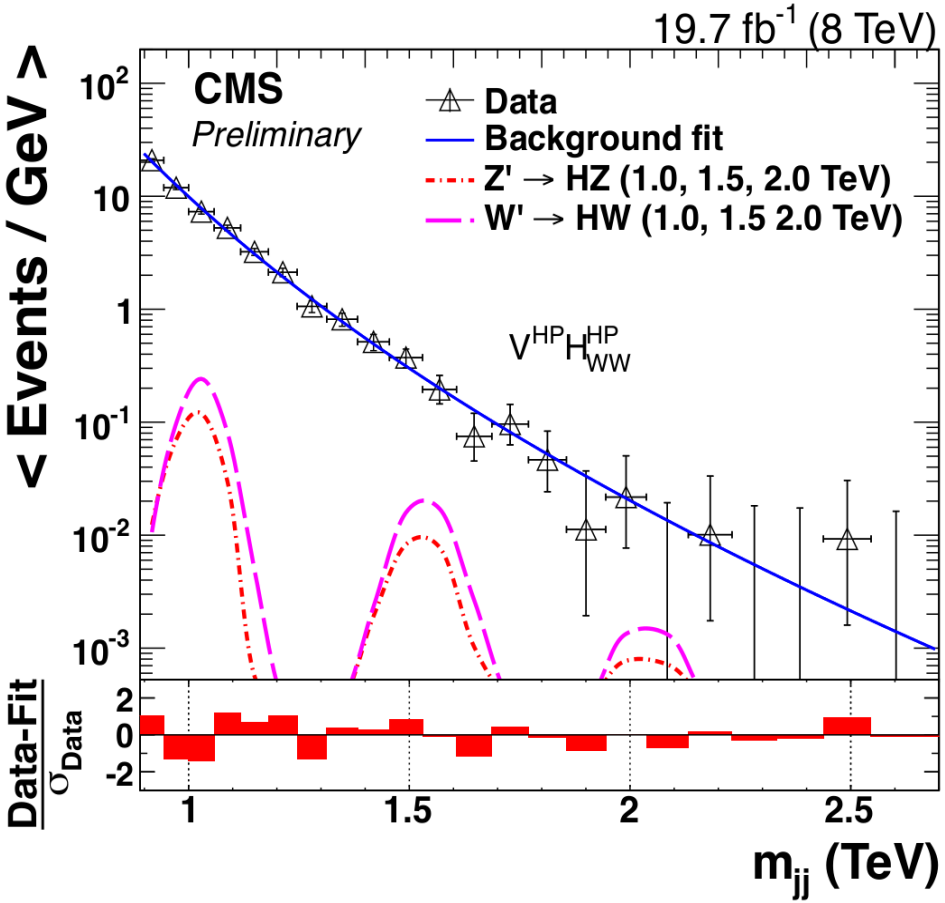


X → VH → JJ [CMS]

arXiv:1506.01443

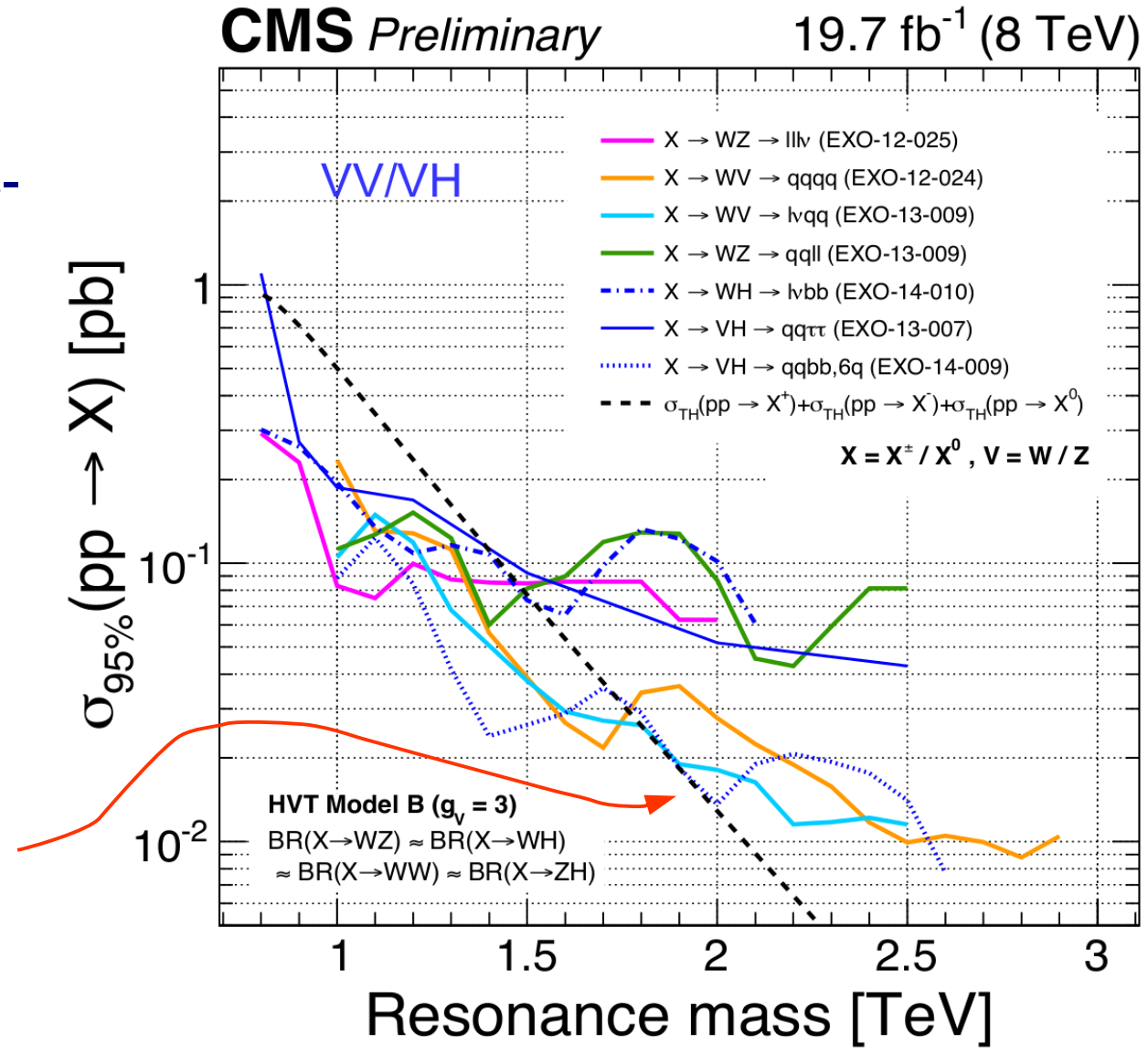
- VH with H → WW* → 4q is an *exclusive* channel:
  = use only events that fail H(bb) tagger

- Adds ~ 10% to combination with H(bb)



Limits on Spin-1 VV / VH resonances [CMS]

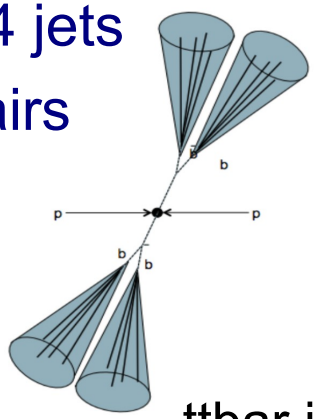
- Heavy Vector Triplet model B (composite Higgs-like model)
- m(W')=m(Z') excluded up to 1.8 TeV
- WV(lvqq), VV(qqqq) and VH(qqbb) have best sensitivity at high masses



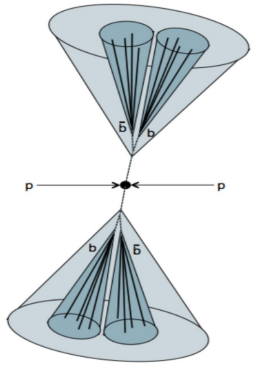
X → HH → (bb)(bb) [ATLAS]

arXiv:1506.00285

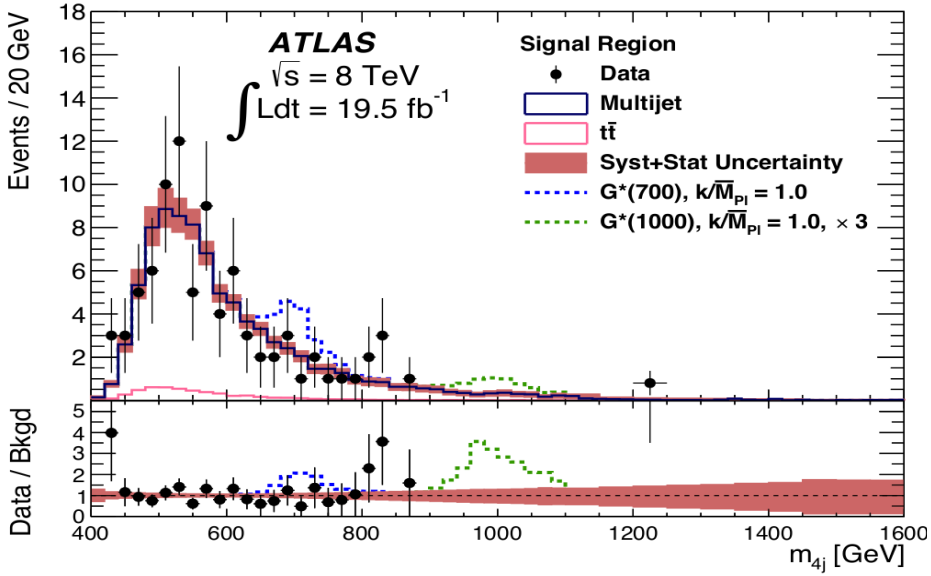
- Resolved analysis
  - 4 b-tagged R=0.4 jets
  - group in close pairs
  - ttbar veto

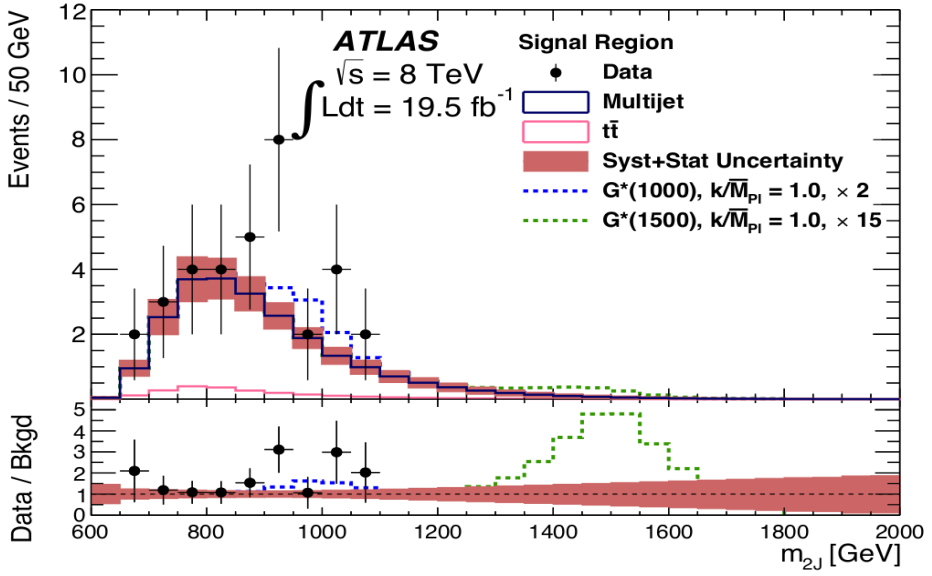


- Boosted analysis
  - 2 `fat' trimmed jets
  - each with 2 b-tagged R=0.3 tracking jets



Normalize QCD and ttbar in m_{lead} control region

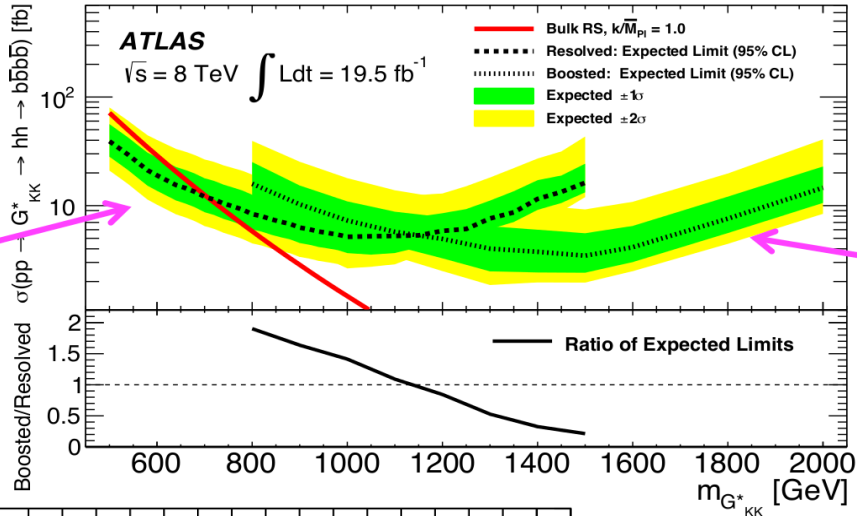




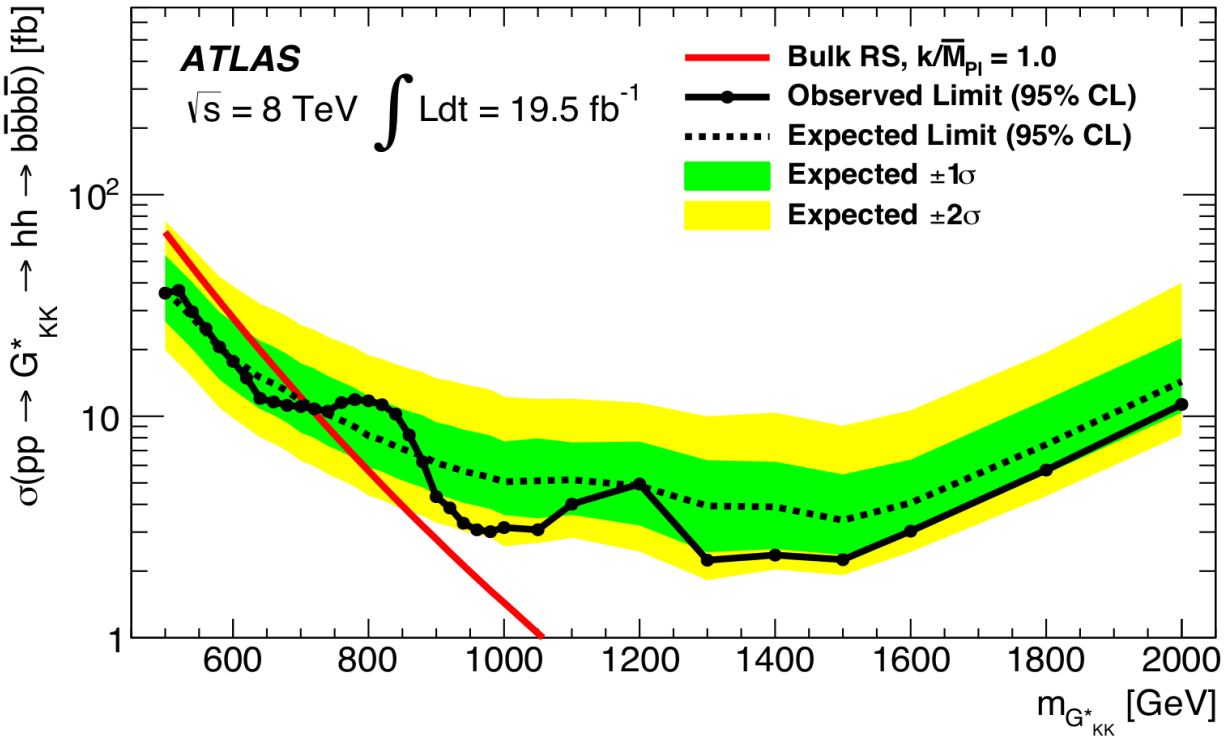
X → HH → (bb)(bb) [ATLAS]

arXiv:1506.00285

Resolved analysis



Boosted analysis

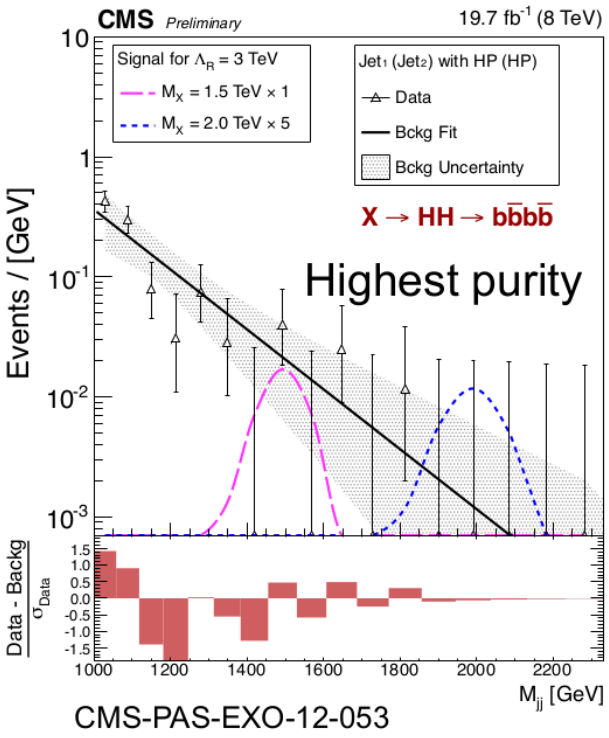


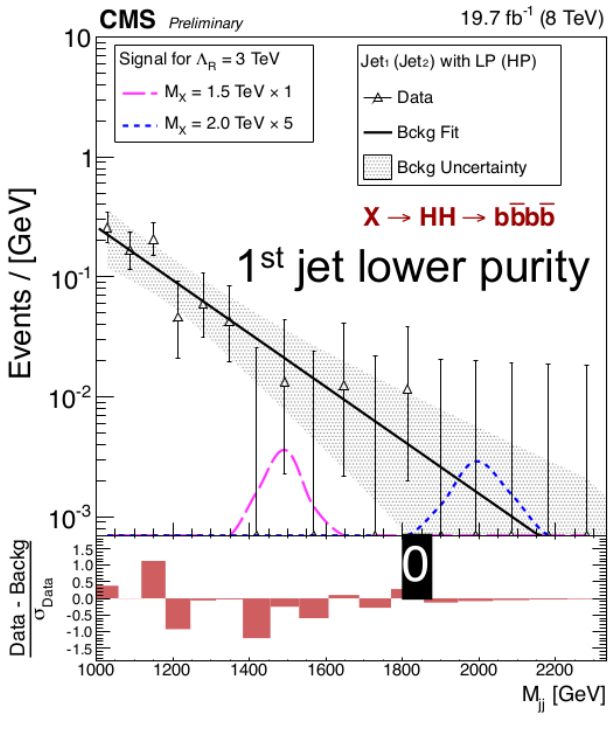
- Complementarity between regimes
- Combination reaching O(fb) sensitivity in 1 TeV range

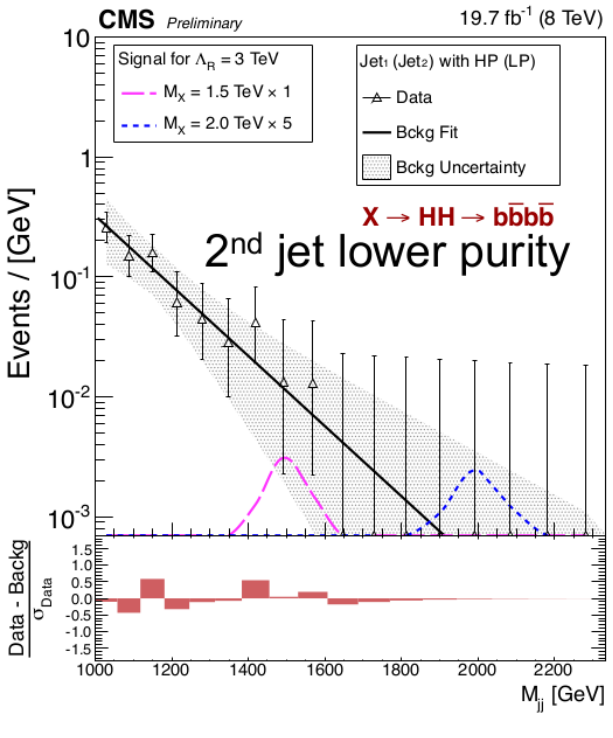
X → HH → (bb)(bb) [CMS]

CMS-PAS-EXO-12-053

- ≥3 b-tagged subjets; if ΔR(subjets)<0.3, b-tag fat jet instead
  - use substructure for higher/lower purity
- bkg from combination of
  - shape from sideband of (pruned) jet mass
  - normalization from fit to HH data without signal mass window

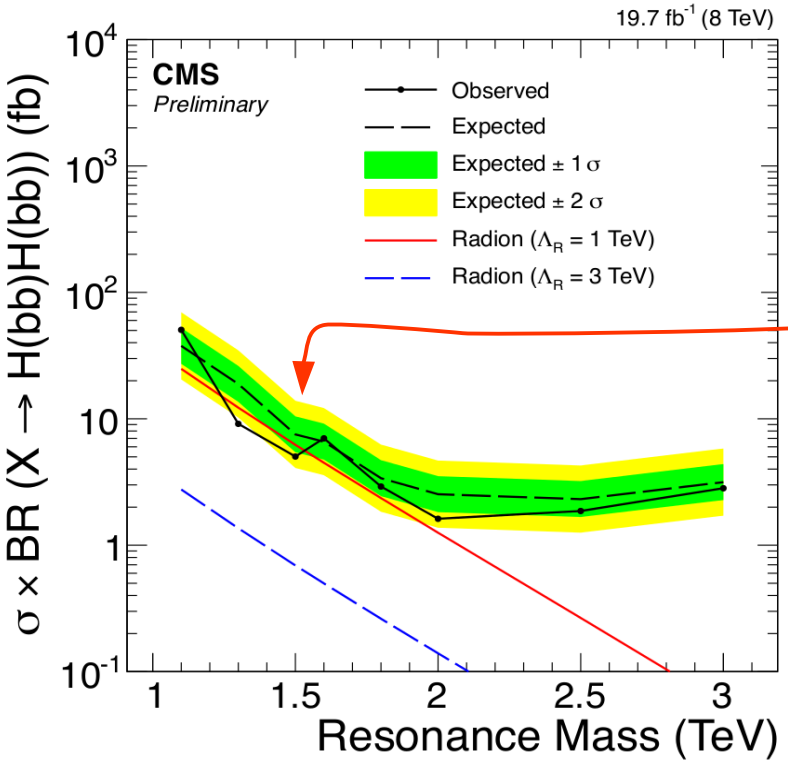






X → HH → (bb)(bb) [CMS]

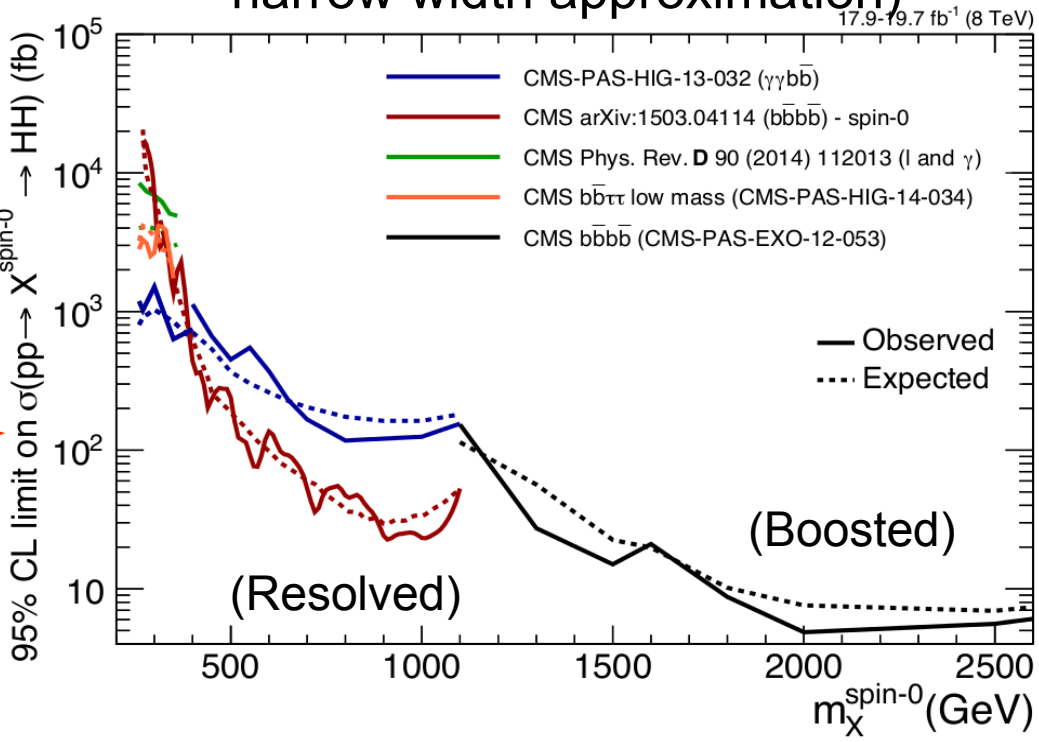
CMS-PAS-EXO-12-053



- Extra dimension spin-0 radion (Λ_R =1 TeV) excluded up to 1.5 TeV

(NB: model at edge of validity of narrow width approximation)

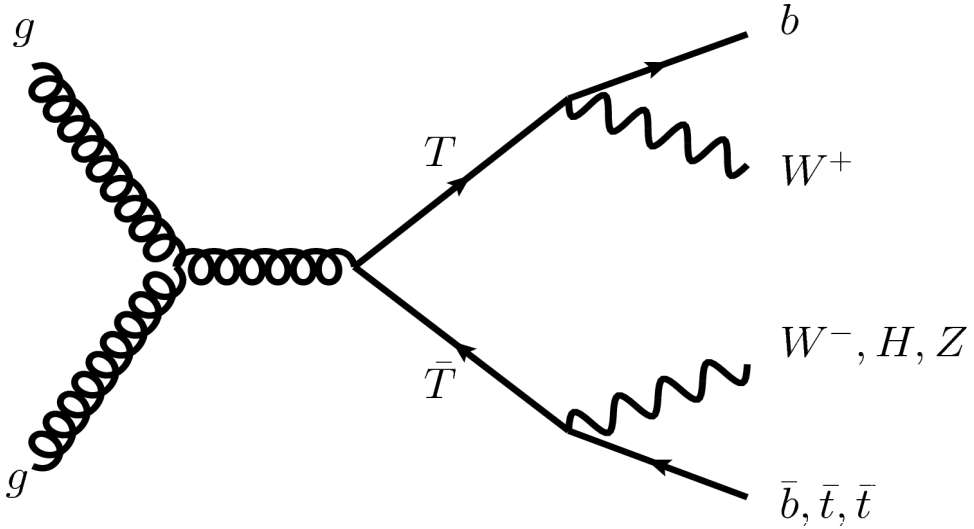
- CMS combination of HH searches



Vector-Like Quarks (VLQ)

arXiv:1505.04306

- Vector-like coupling to weak currents
  - singlet / doublet / triplet SU(2) representations possible
  - production: pair (QCD) or single (EW)
  - decay: heavy quark and W/Z/H boson

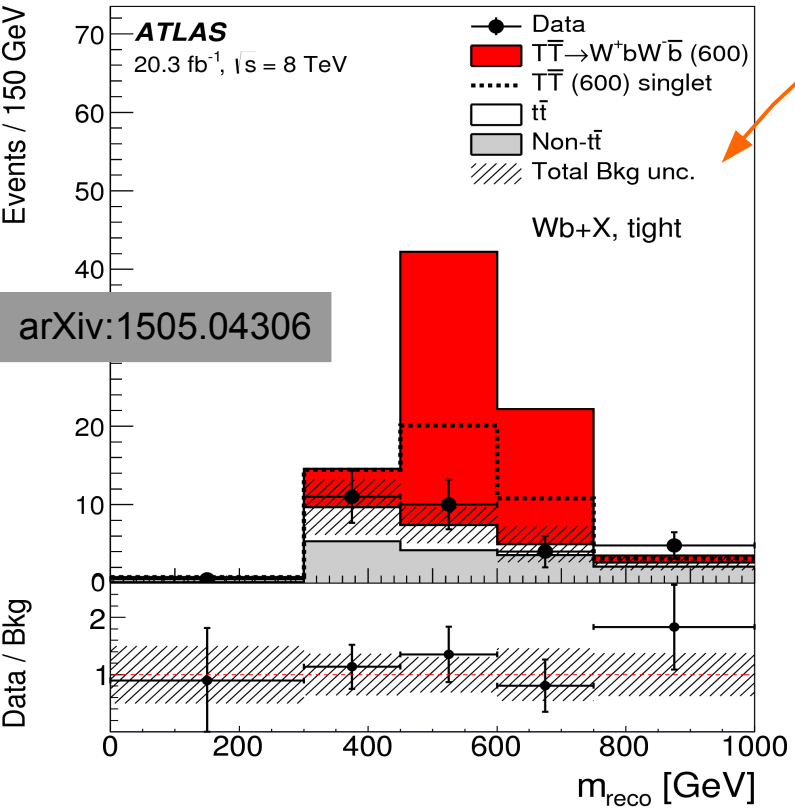


- Searches:
  - heavy VQL → boosted signature
  - top tagging, V tagging, H-tagging (with subjet b-tagging)

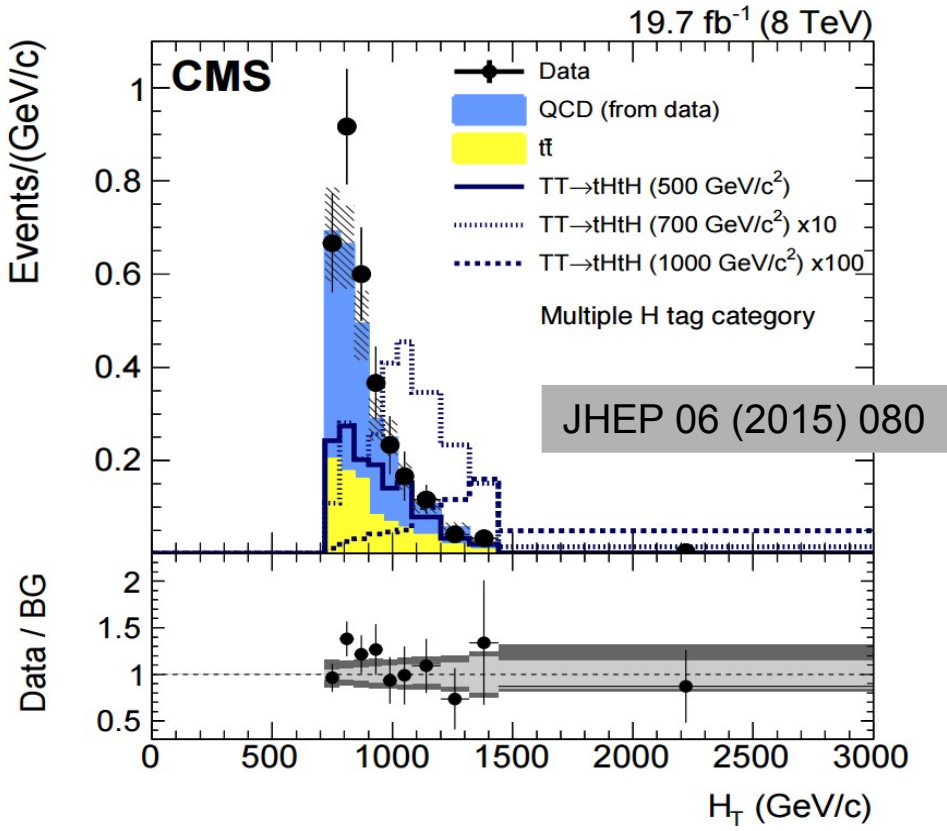
- All-had, l+jets, SS leptons, multilepton

VLQ reconstruction

- Example 1: ATLAS l+jets
  - reconstruct W + b + anything
  - resolved W → jj *and* boosted W → J
  - discriminant: $m(bW)$



arXiv:1505.04306



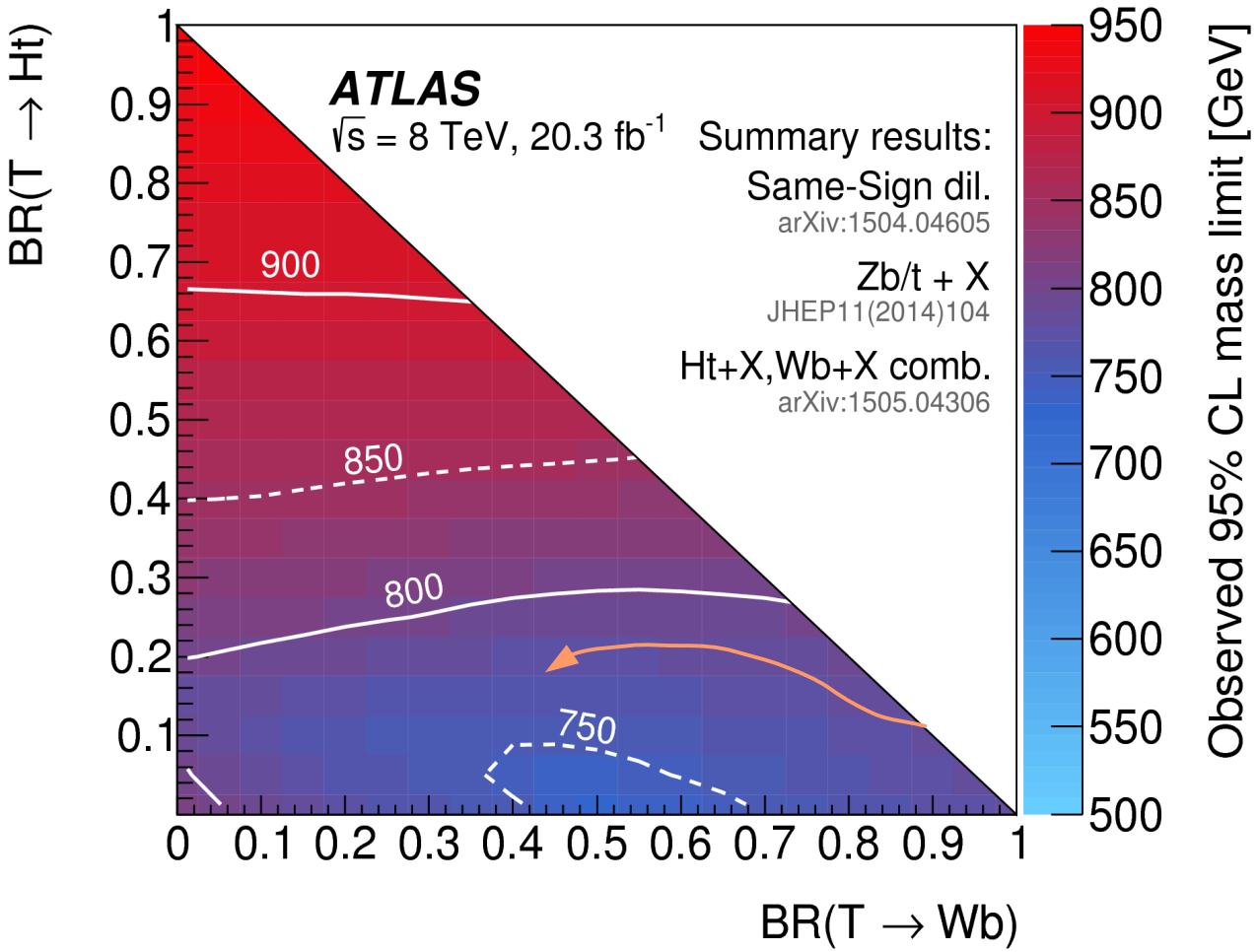
JHEP 06 (2015) 080

- Example 2: CMS all-hadronic
  - Top-tag + Higgs-tag
  - Discriminant H_T

VLQ: limits for different BRs

arXiv:1505.04306

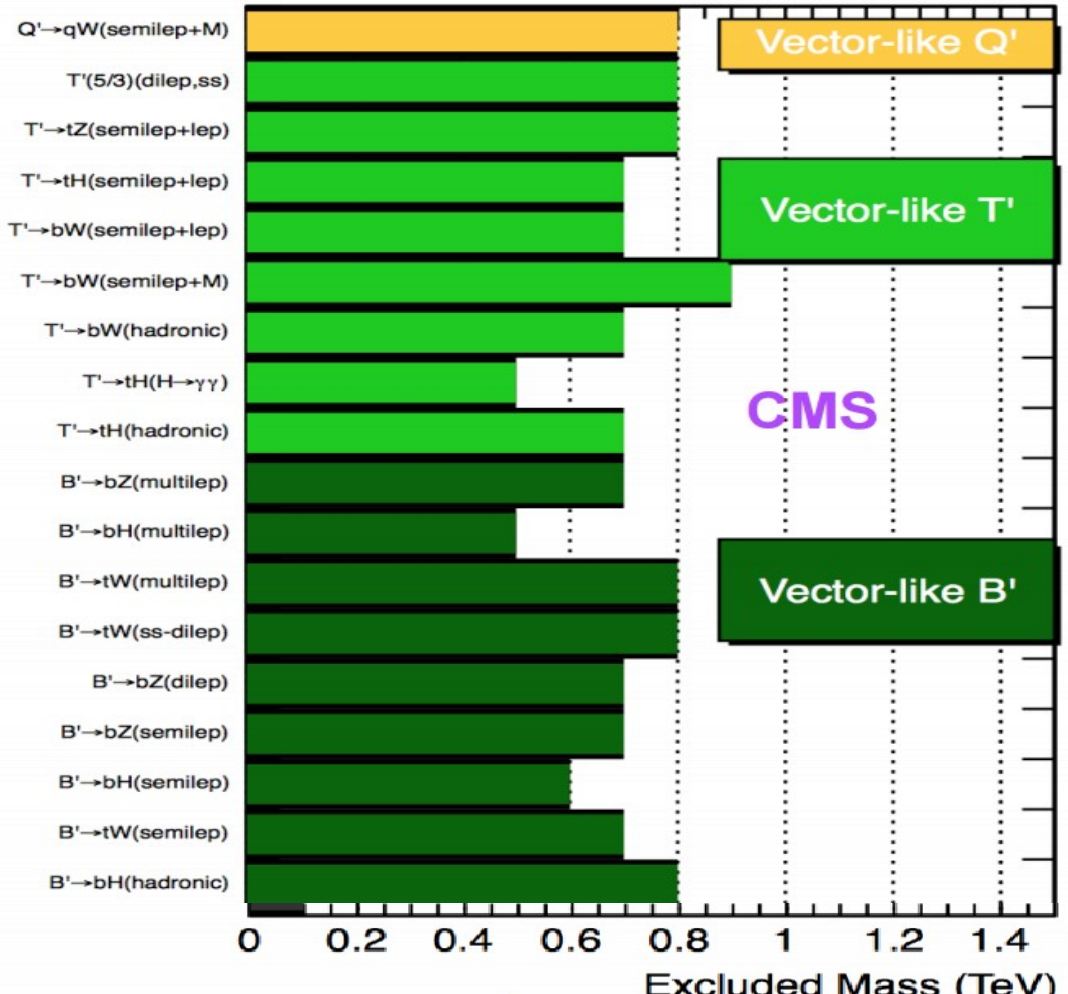
- Complementary searches used to cover the whole plane
  BR(T' → Wb) vs BR(T' → Ht) [similarly for CMS]



VLQ: status

VLQ $TT \to Ht + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3
VLQ $YY \to Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3
VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3
VLQ $BB \to Zb + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3
$T_{5/3} \to Wt$	1 e, μ	≥ 1 b, ≥ 5 j	Yes	20.3

- A large variety of searches have been performed
- Run 1 limits:
  - Exclude 600 – 900 GeV, depending on BR



Conclusions

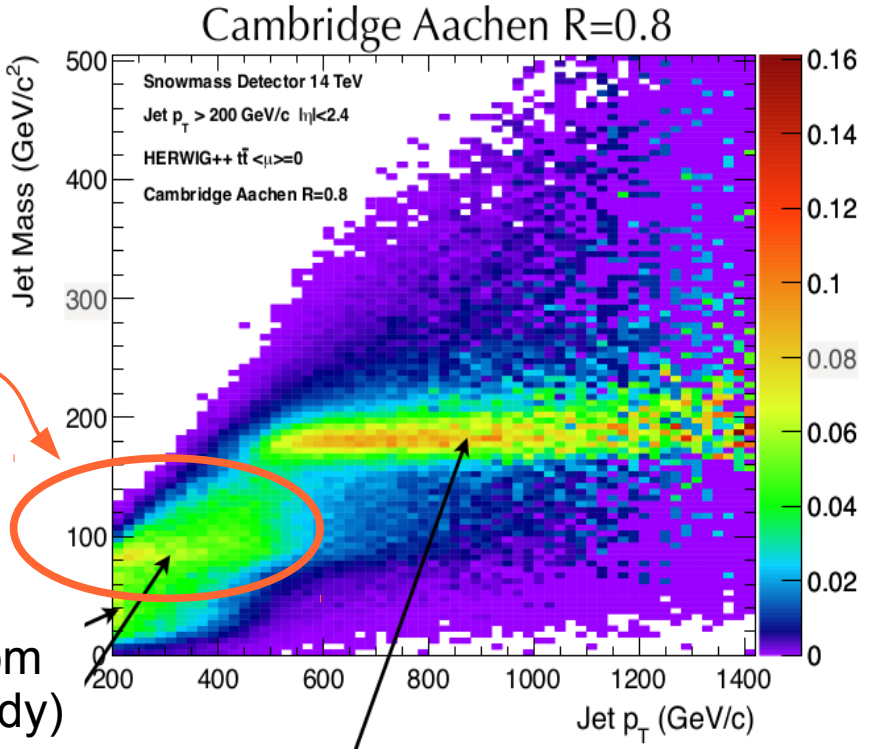
- LHC has a broad program of searches for VV, VH, HH, $t\bar{t}$, and tb resonances, as well as heavy top partners
- Covers most of the composite Higgs phenomenology
- We are getting quite good at dealing with boosted objects

  (both ATLAS and CMS deploying increasingly sophisticated techniques)
- Run 2 is starting
  - hopefully will shed some light on the interesting excesses in Run 1 data

BACKUP MATERIAL

Substructure data/MC scale factor

- Study performance of W-tagging in data
  - derive data/MC scale factor (SF)
  - error on this "substructure SF" → systematics on the signal!
- The only clean sample of merged hadronic W's is $t\bar{t}$ component of $\ell + \text{jets}$
  - where top enough boosted that $W \to qq$ merges into one jet
  - but not too boosted so that b-jet merges as well



(plot stolem from Snowmass study)

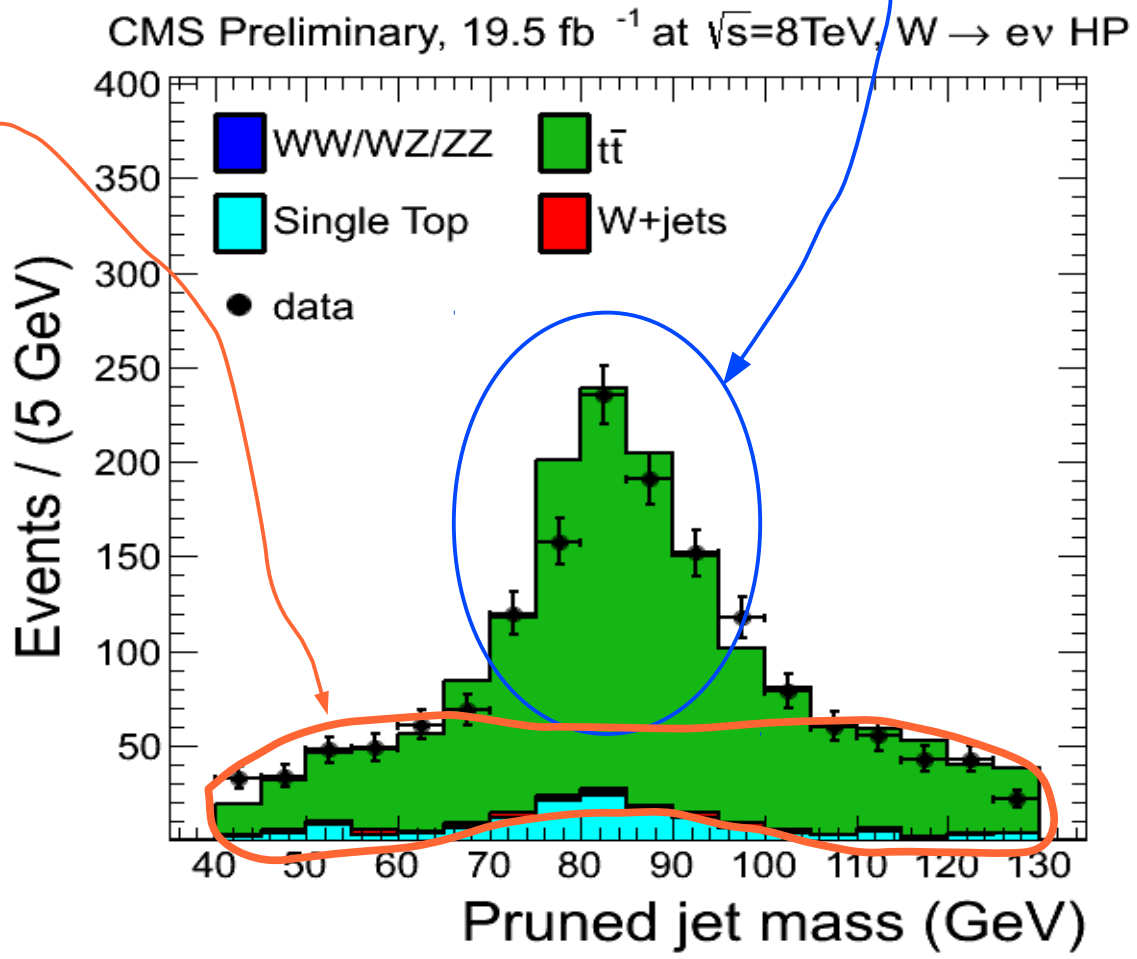
Substructure data/MC scale factor

- Anatomy of the W-peak:

Merged $W \rightarrow qq$
This is what we want

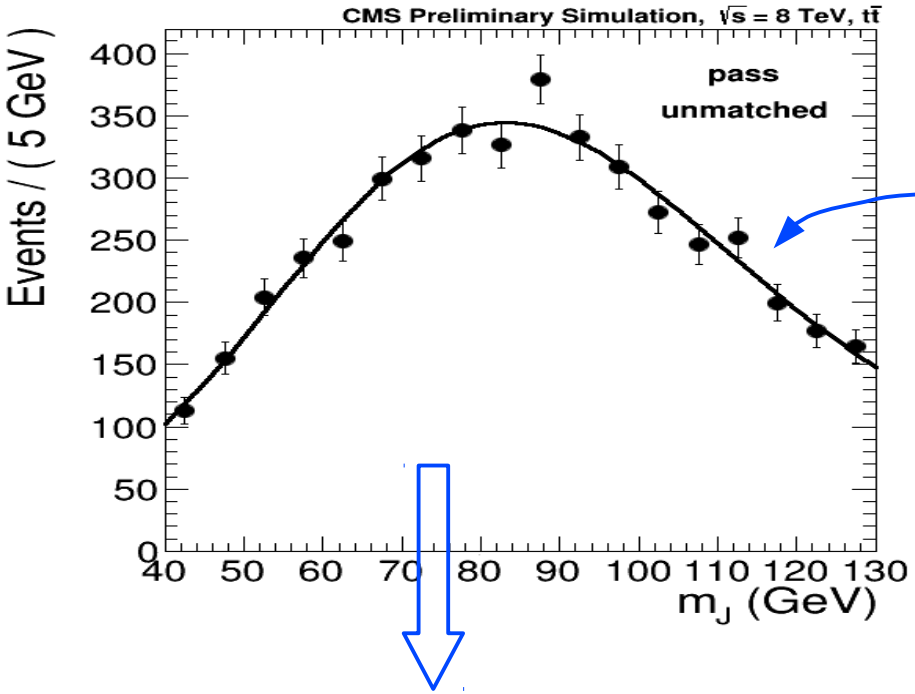
$W \rightarrow qq$ from $t\bar{t}$ which did not merge.

- "combinatorial background"
- τ_2/τ_1 cut causes it to peak broadly
- needs to be sub-tracted away (done in the fit)



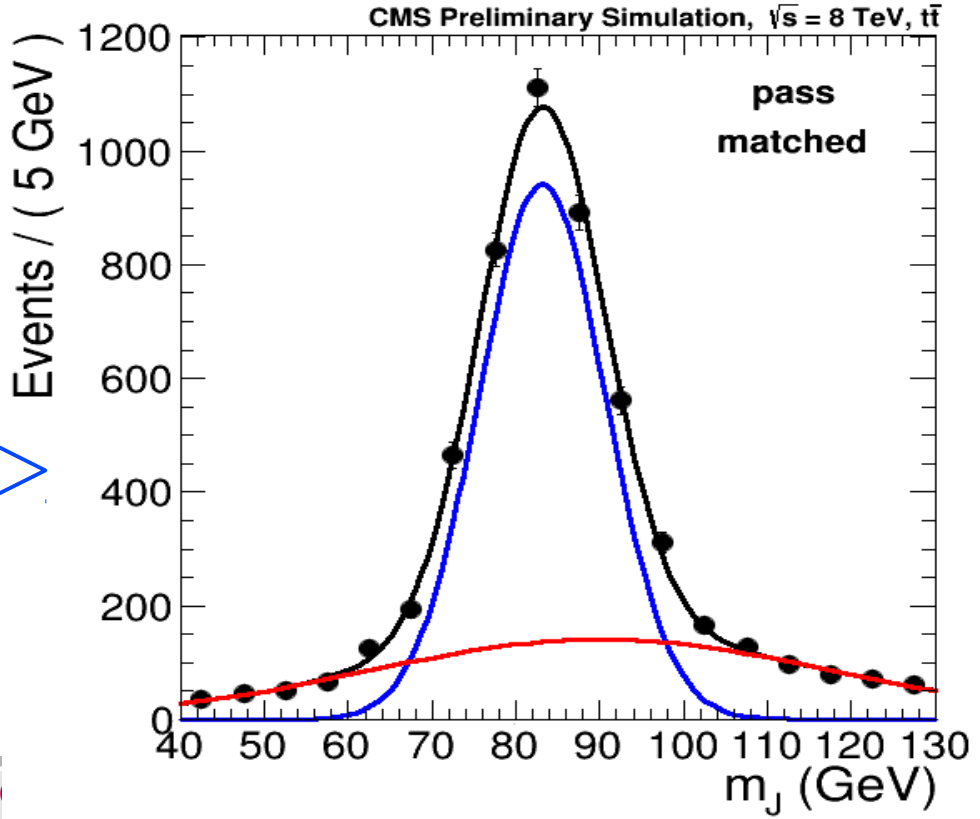
Substructure data/MC scale factor

JME-13-006



- Shape of non-merged hadronic W → qq decays from simulation
  - Match W-jet to generator-level W → qq

- Model jet mass in $t\bar{t}$ by narrow + wide components



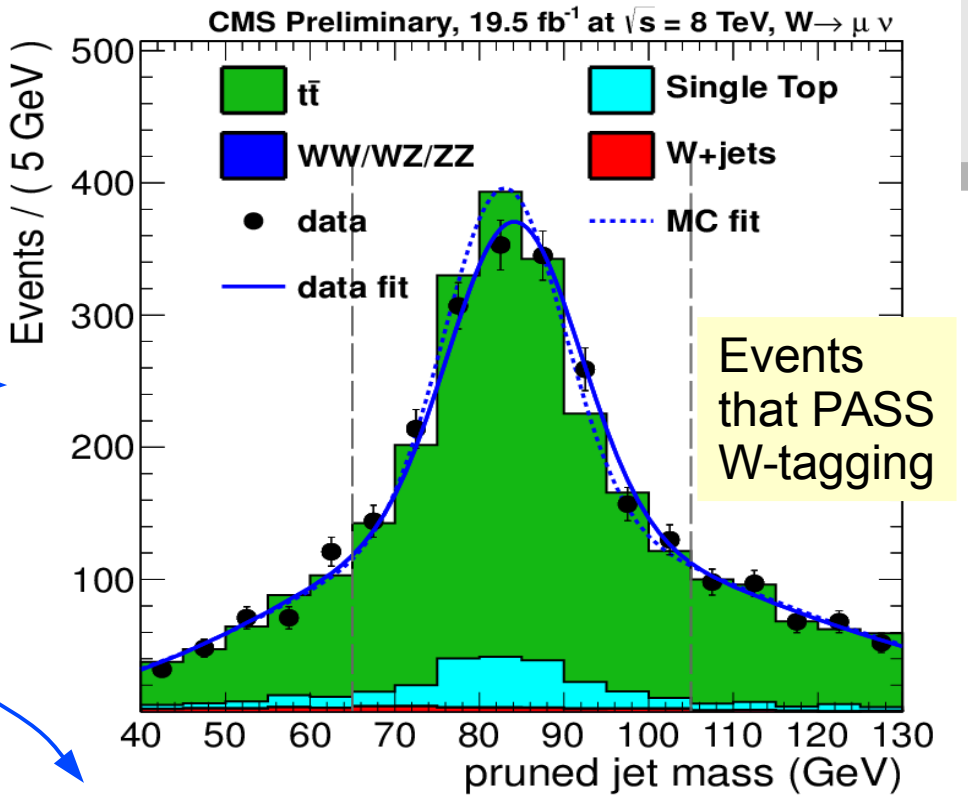
Substructure SF

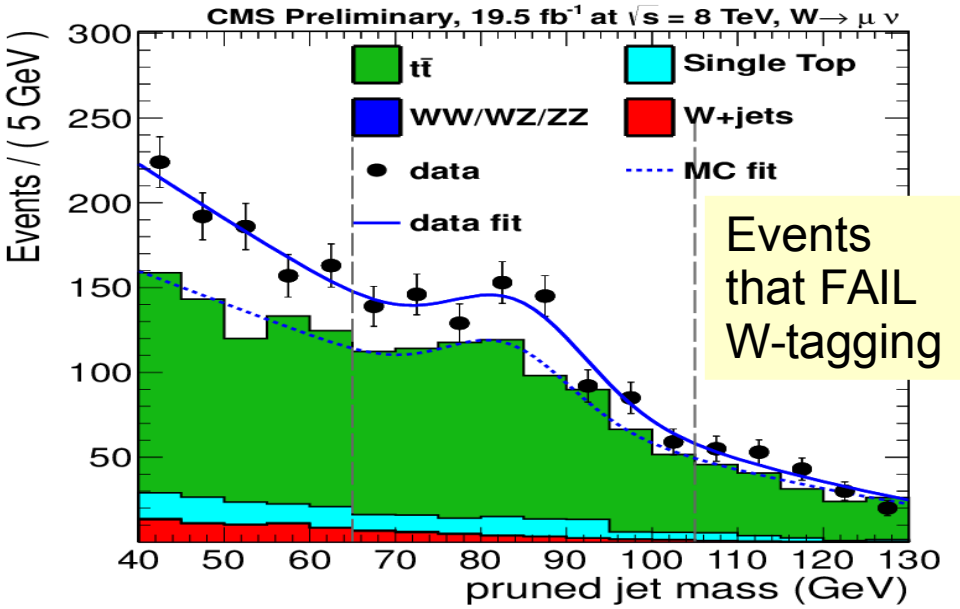
JME-13-006

- Simultaneous fit to events that pass and fail W-tagging, in $\mu + \text{jets}$ and $e + \text{jets}$
- High and low purity:

$$\text{SF}_{W\text{tag}} = 0.93 \pm 0.08$$
$$\text{SF}_{W\text{tag}} = 1.10 \pm 0.30$$

- Use MC to extrapolate to higher $p_T(\text{jet})$



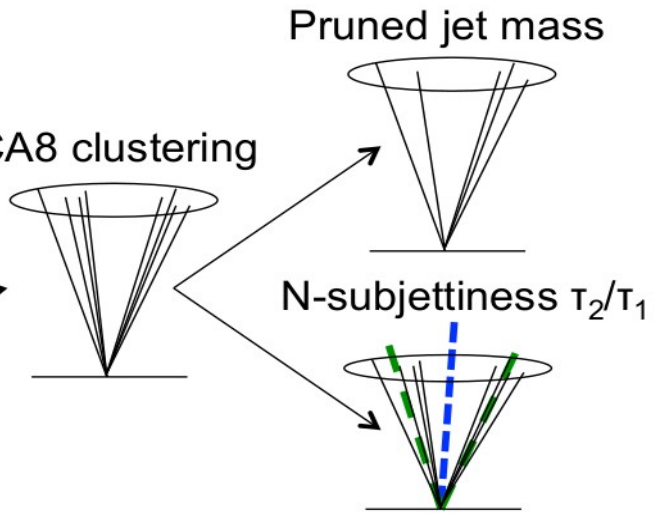


Analysis flow for X → VV / VH / HH

Trigger event

↓

Reconstruct two bosons
W(lν), Z(ll), H(ττ)
W(qq), Z(qq), H(bb), H(WW→qqqq)

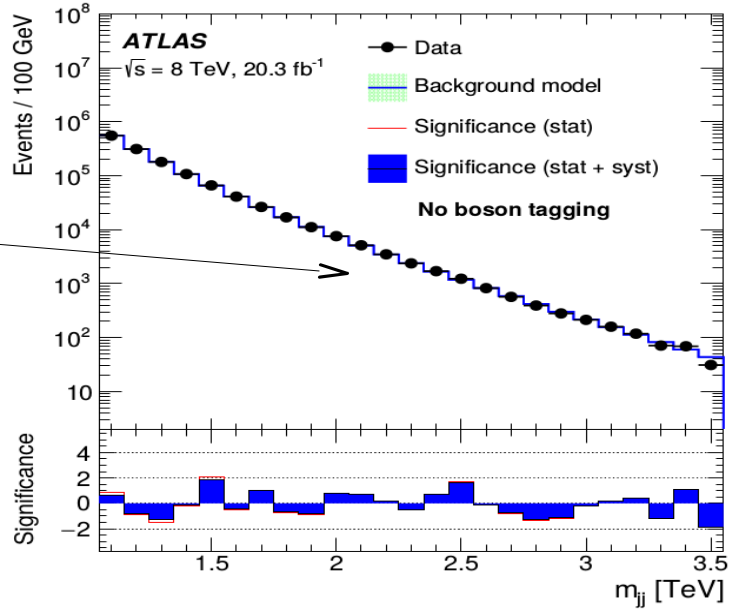


↓

Reconstruct VV/VH/HH invariant mass

↓

Estimate background



↓

Scan over resonance mass
searching for an excess

Bkg for X → VV → νlJ → (νl)(qq) [CMS]

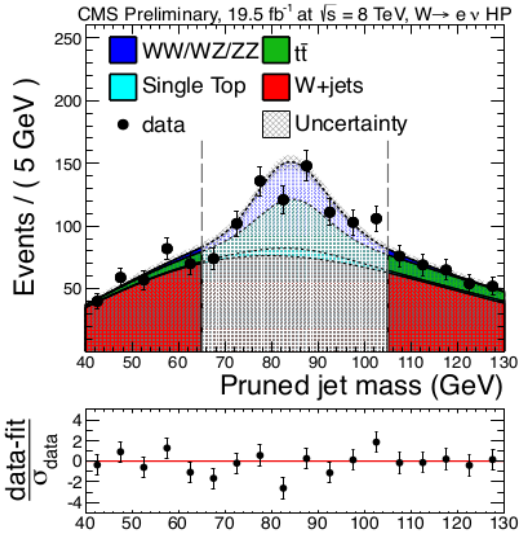
arXiv:1405.3447

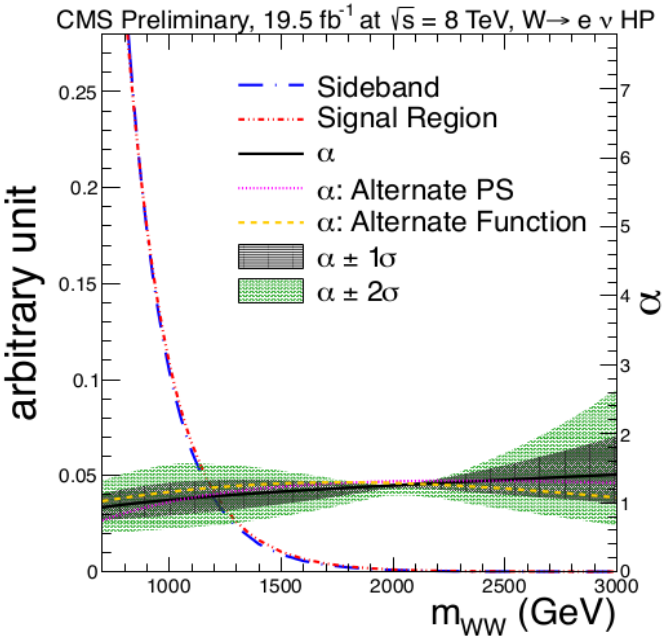
- Assumption: Observable in signal-depleted sideband closely related to signal region
- Background rate+shape estimated from data in sideband extrapolated to signal region using simulation

- Advantages:
  - Limited use of background simulation
  - Can search for enhancements in tails, not only bumps

- Disadvantages:
  - Uncertainties associated to extrapolation to signal region sometimes arbitrary

- Checks:
  - Closure test in simulation and/or other data sideband





Boosted H → bb tagging

- Discriminants:
  - large R jet (ATLAS: anti-k_T R=1.0, CMS: CA R=0.8)
  - groomed jet mass (trimmed for ATLAS, pruned for CMS)
  - "subjet b tagging"
    - track jets R=0.3 for ATLAS
    - pruned subjets for CMS

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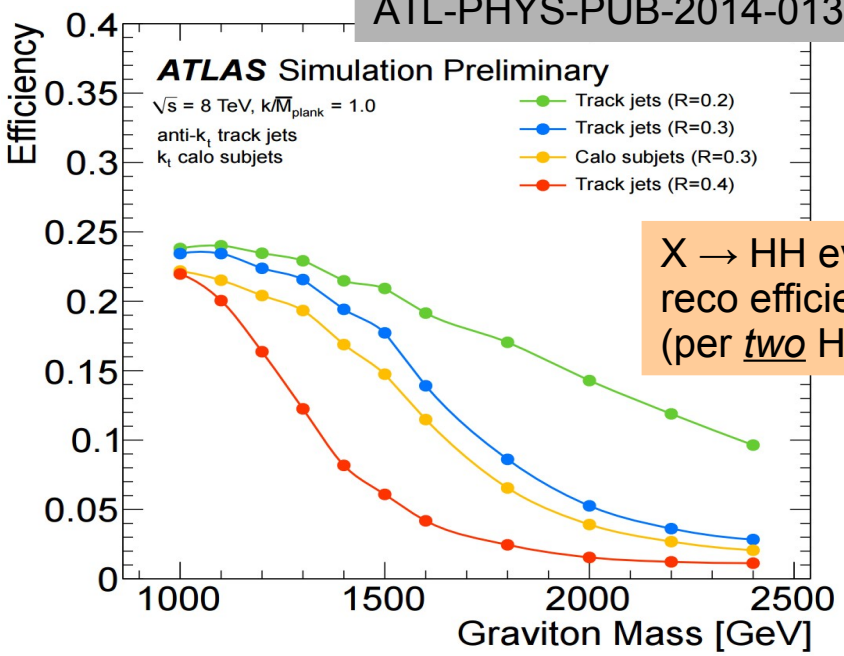

X → HH event reco efficiency (per *two* Higgs jets)

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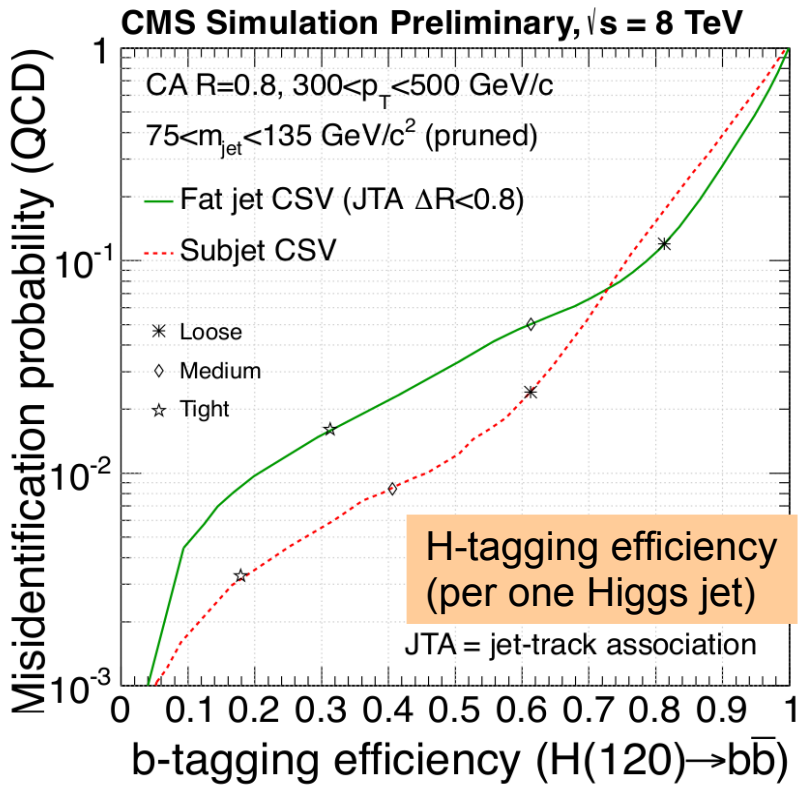
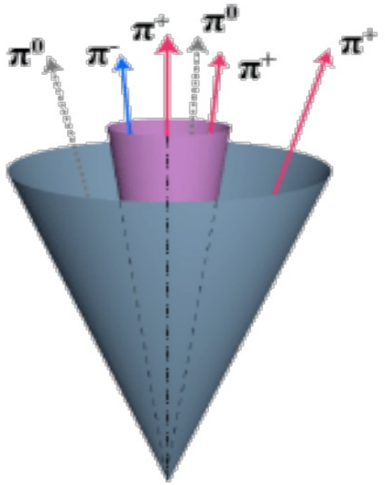


H-tagging efficiency (per one Higgs jet)

JTA = jet-track association

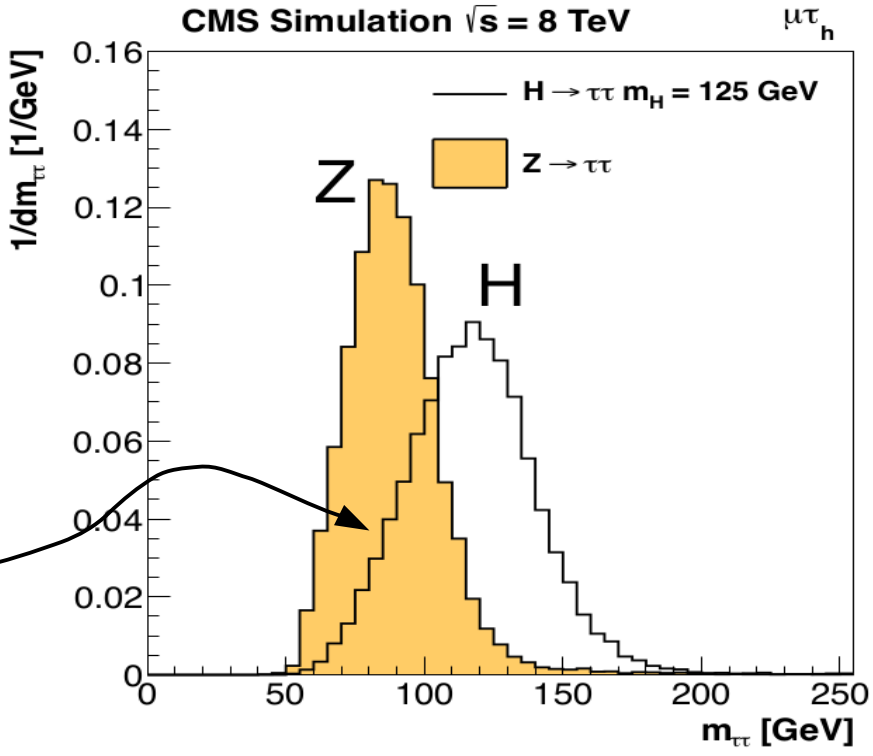
H → ττ tagging

- Main discriminant:
  - isolation around τ daughters
  - decay products of one τ excluded from isolation cone of other τ forming H → ττ



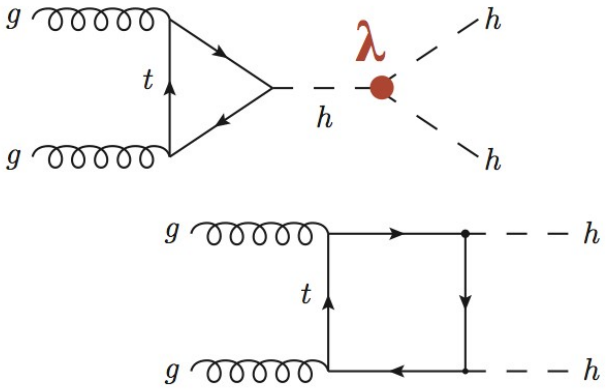
- H mass = from two τ's + MET

Decay Mode	Resonance	BR [%]
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$		17.8
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$		17.4
$\tau^- \to \pi^- \nu_\tau$	$\pi(140)$	11.6
$\tau^- \to \pi^- \pi^0 \nu_\tau$	$\rho(770)$	26.0
$\tau^- \to \pi^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	10.8
$\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$	$a_1(1260)$	9.8
$\tau^- \to \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$		4.8
Other hadronic modes		1.7
All hadronic modes		64.8



X → HH: motivation

- SM: pair HH production – direct test of Higgs potential
- BSM:
  - modified HHH coupling (non-res)
  - new heavy X → HH:
    - KK Gravitons, 2HDM, new scalar in Higgs portal, etc.



- Focus on H → bb channel
  - largest BR (33%)
  - heavy X – boosted H
  - combine substructre and b tagging