Searches for heavy resonances in the W/Z-tagged di-jet spectrum with CMS

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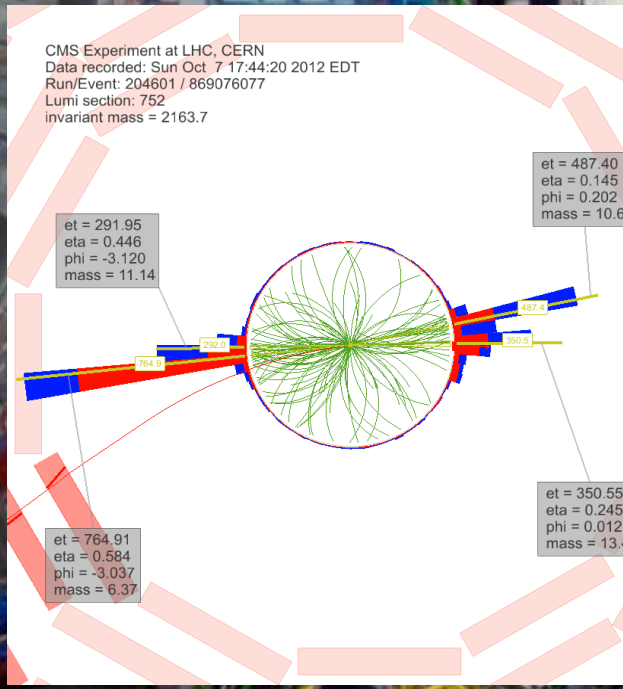
Johns Hopkins

Boston Jet Workshop 2014



Models considered

- We search for two types of heavy resonances:
  - Excited quarks: $q^* \to qW$ and $q^* \to qZ$
  - $X \to WW$, $X \to ZZ$, and $X \to WZ$
- Many options for $X \to VV$ $(V = W, Z)$:
  - Randall-Sundrum Gravitons $G_{\mathrm{RS}} \to WW, ZZ$
  - Bulk-graviton with enhanced coupling to WW or ZZ
  - $W' \to WZ$
    - with W' couplings from the extended gauge model
  - Low-Scale Technicolor, $\rho_{\mathrm{TC}} \to WZ$
  - SM Higgs-like boson, $H \to WW, ZZ$

    (in addition to 125 GeV Higgs, as a reference at high mass)

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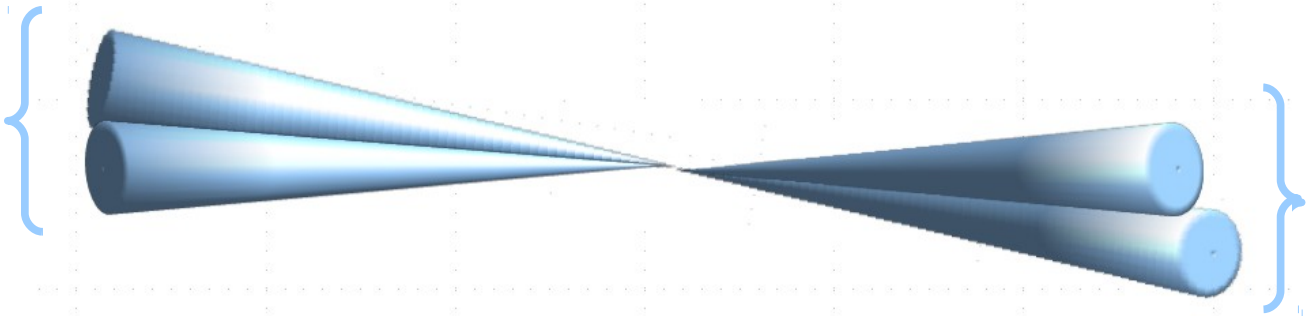
Covered in this talk

Analysis strategy

- Here consider hadronic decays $W \to jj$ and $Z \to jj$
- X is heavy → V's are boosted → merged in a single jet:

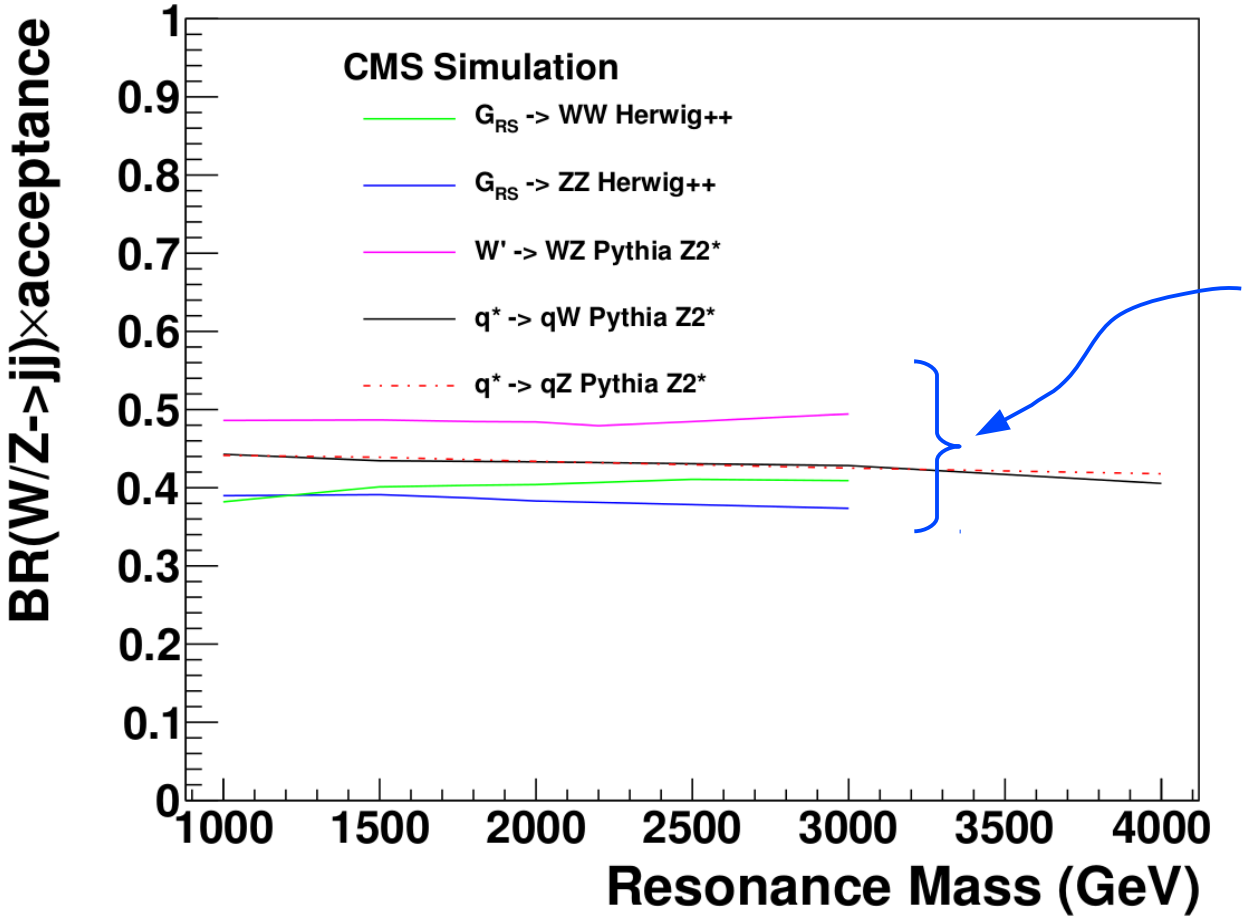


- Signal looks like:
  - a di-jet event
  - each V jet has two-prong substructure
- Apply “W/Z tagger” to one or both jets in dijet events
- Look for a peak on top of a smoothly falling background

Basic selection

EXO-12-024

- QCD is the only relevant background
- Reduce it with $|\eta_1 - \eta_2| < 1.3$ (similar to other di-jet searches)

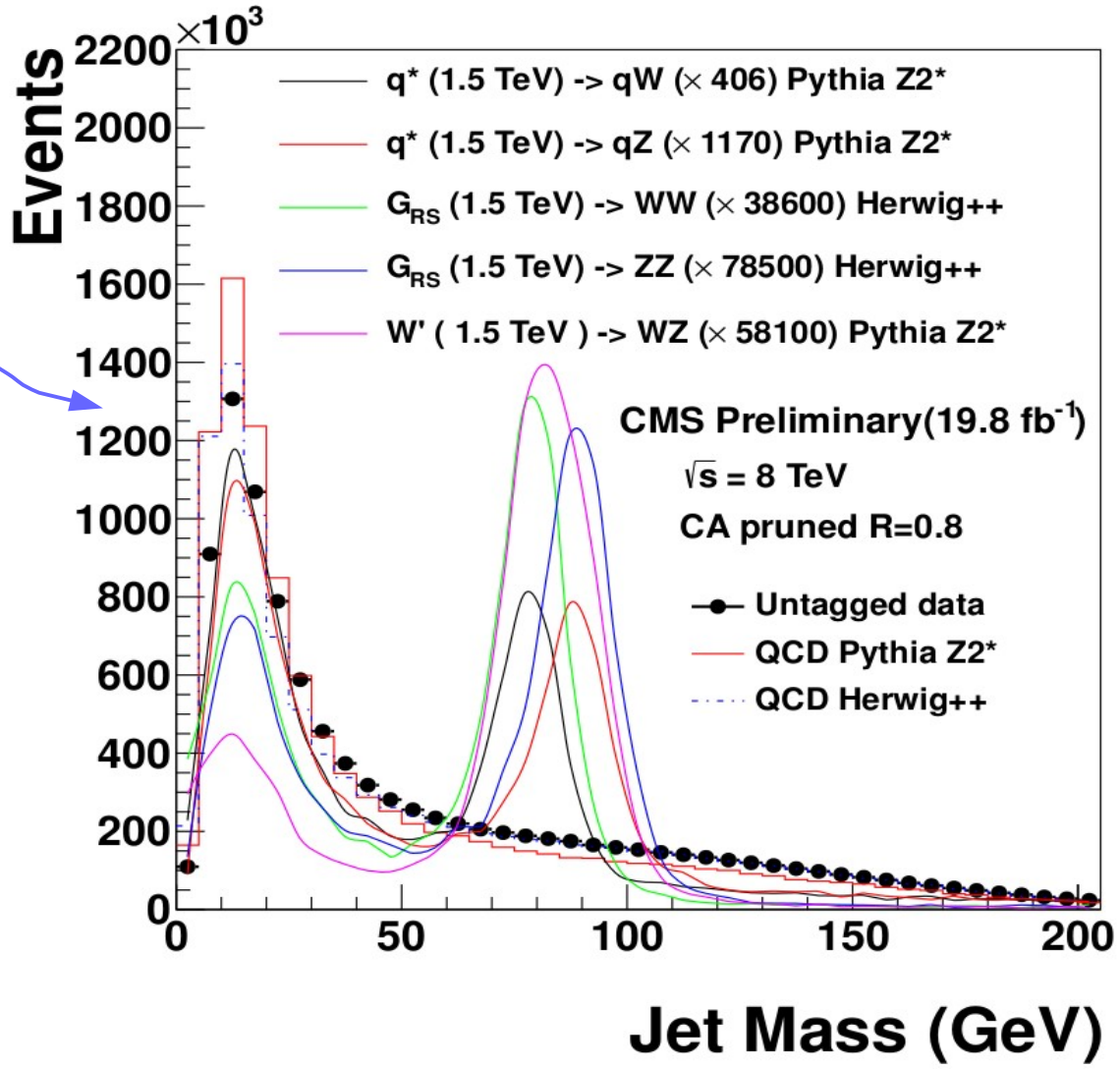


Before W/Z-tagging,
we still have
~ 40-50% of the signal

W/Z tagger (rehash)

EXO-12-024

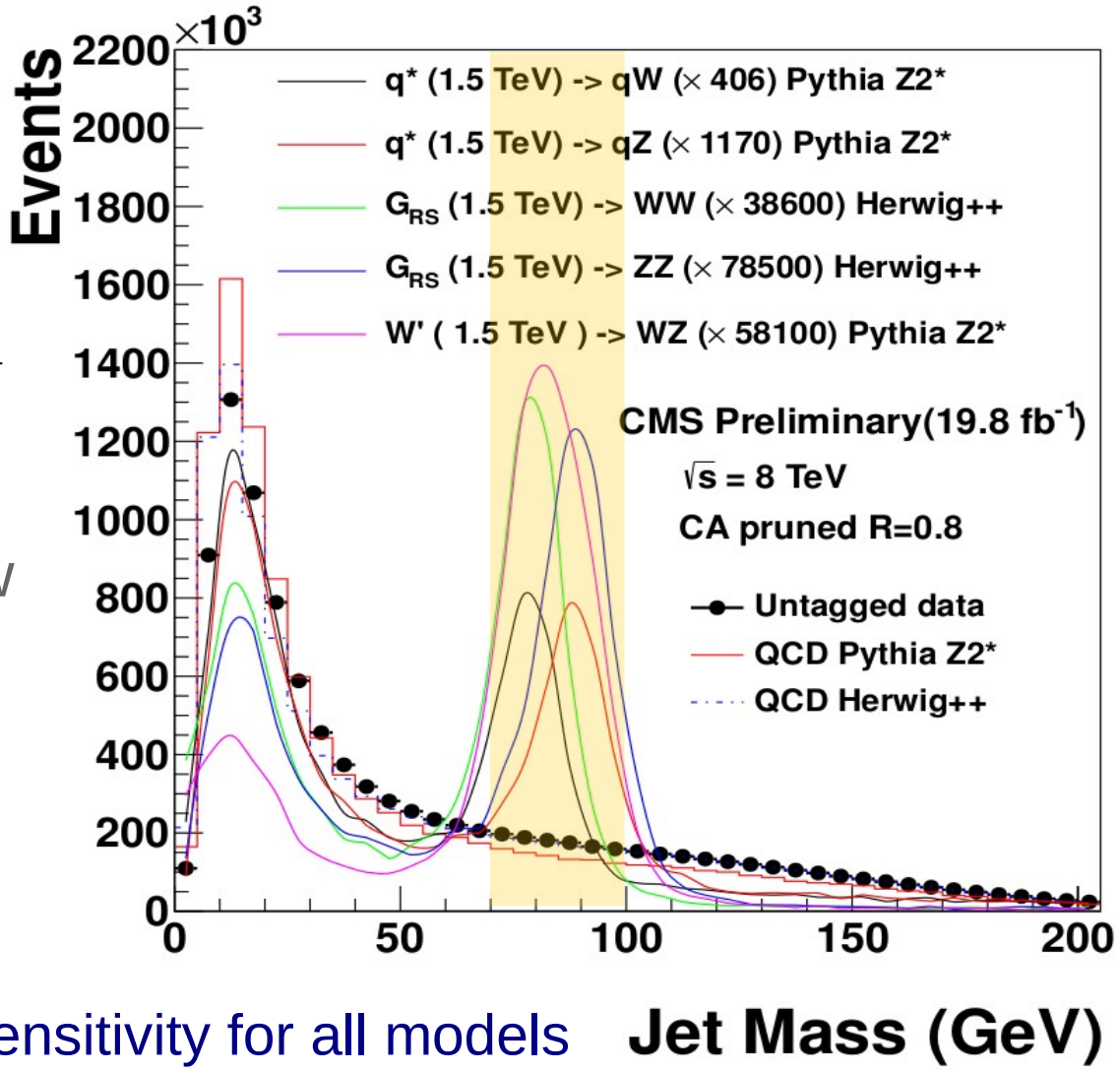
- Cambridge Aachen with jet pruning, using $R = 0.8$
- Pruned jet mass



W/Z tagger (rehash)

EXO-12-024

- Cambridge Aachen with jet pruning, using $R = 0.8$
- Pruned jet mass: $70 < M_{\text{jet}} < 100$ GeV
- NB: narrower window than in semileptonic searches
  - Here QCD is much higher
  - On average, best sensitivity for all models



W/Z tagger (rehash)

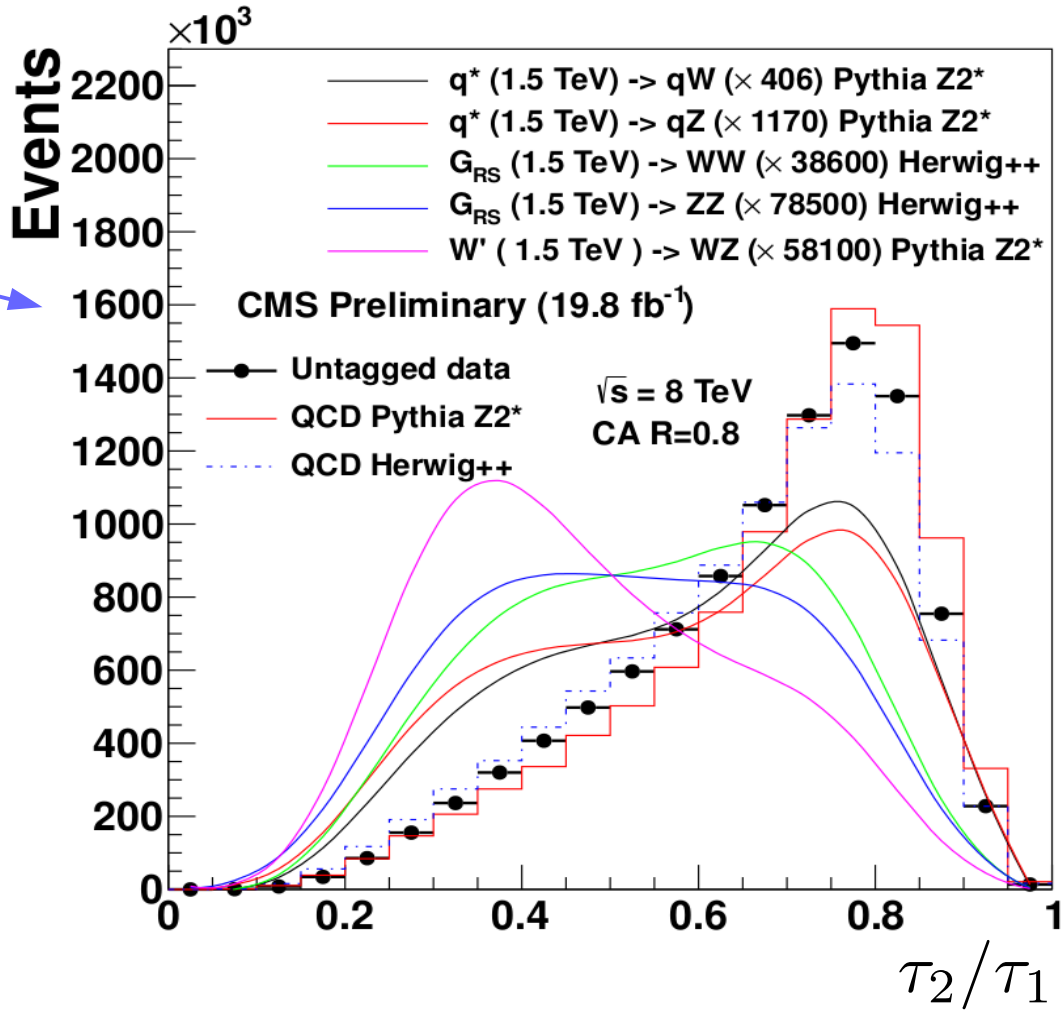
EXO-12-024

- Identify boosted V-jets using the "N-subjettiness"

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

(using unpruned jet)

- Consider τ_2/τ_1
  - close to 0 for jets with two subjets (signal)
  - closer to 1 for QCD



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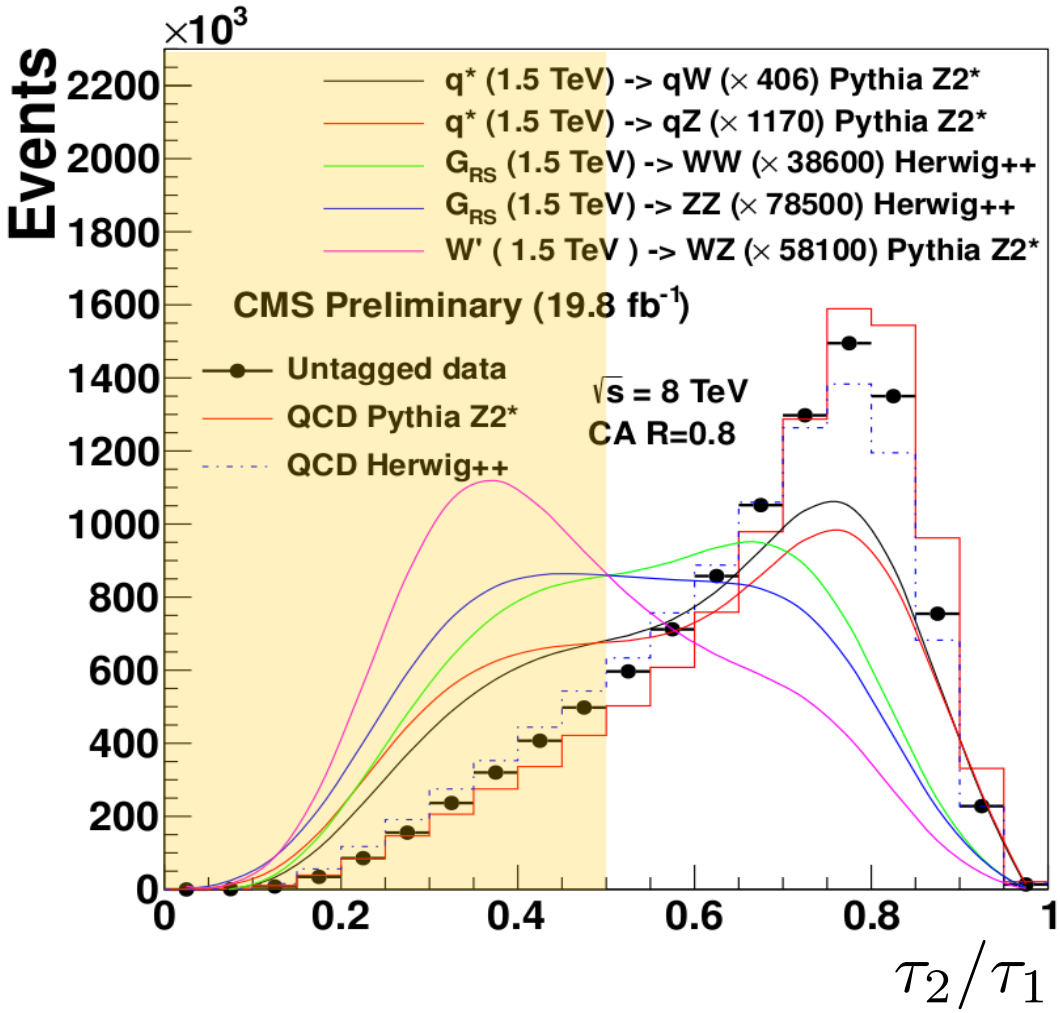
  - High purity: $\tau_2/\tau_1 < 0.5$



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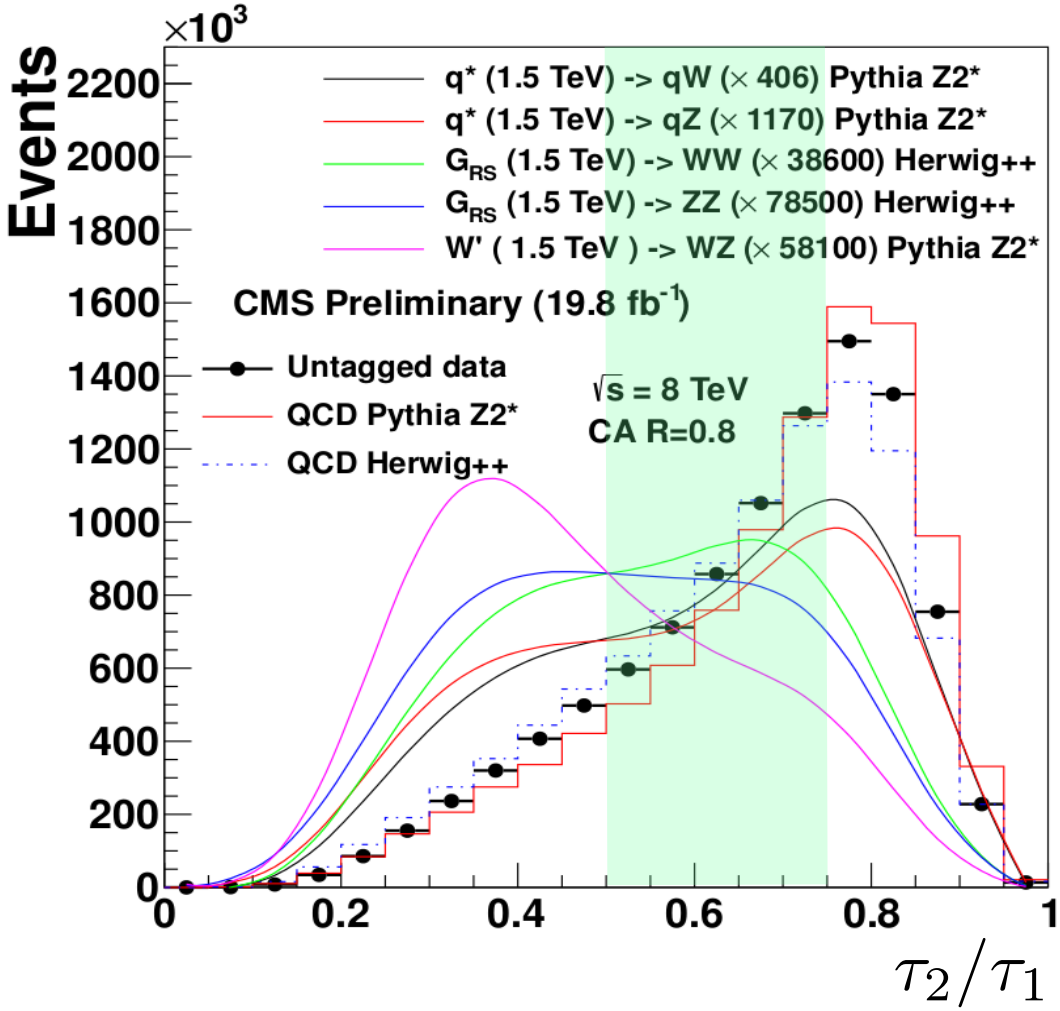
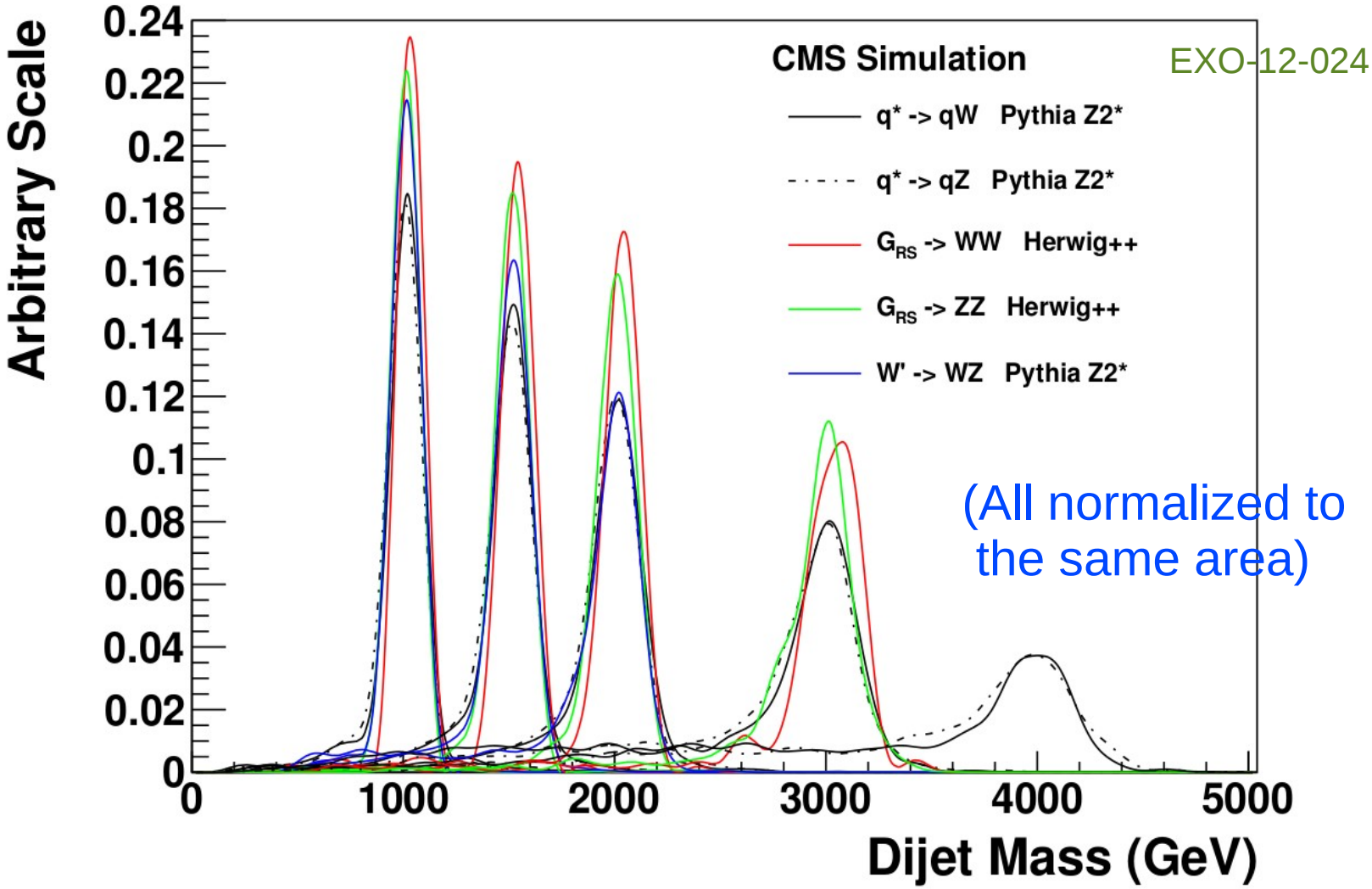
  - High purity:
    $\tau_2/\tau_1 < 0.5$
  - Low purity:
    $0.5 < \tau_2/\tau_1 < 0.75$



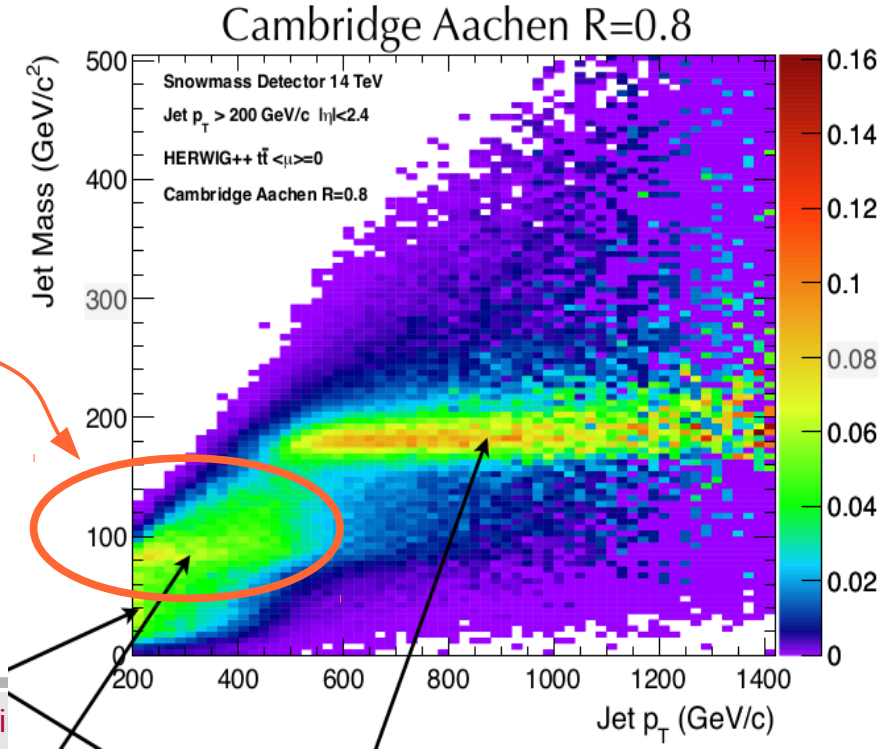
Signals after full selection

- Both $q^* \to qV$ and $X \to VV$ using high-purity W/Z-tag



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



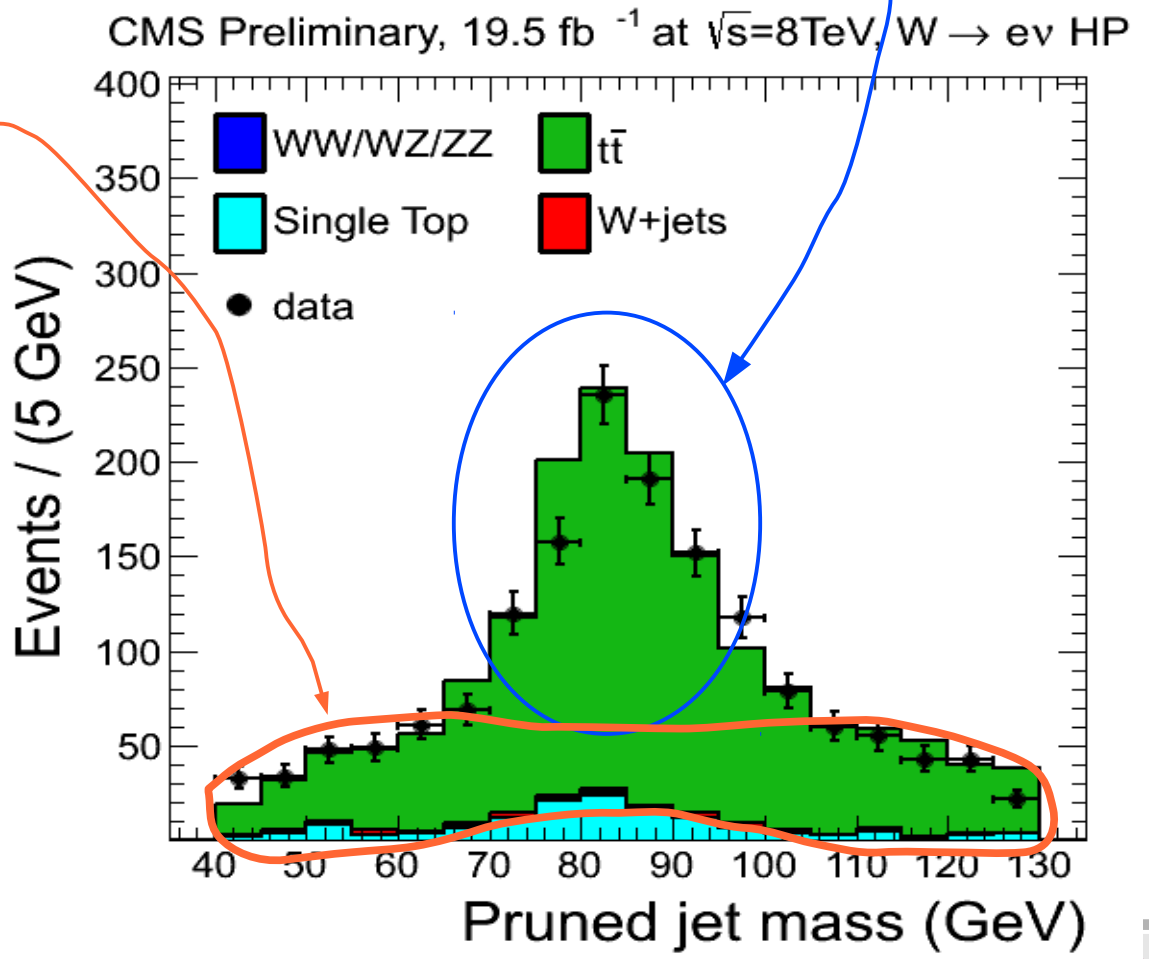
Substructure data/MC scale factor

- Anatomy of the W-peak:

Merged W → qq
This is what we want

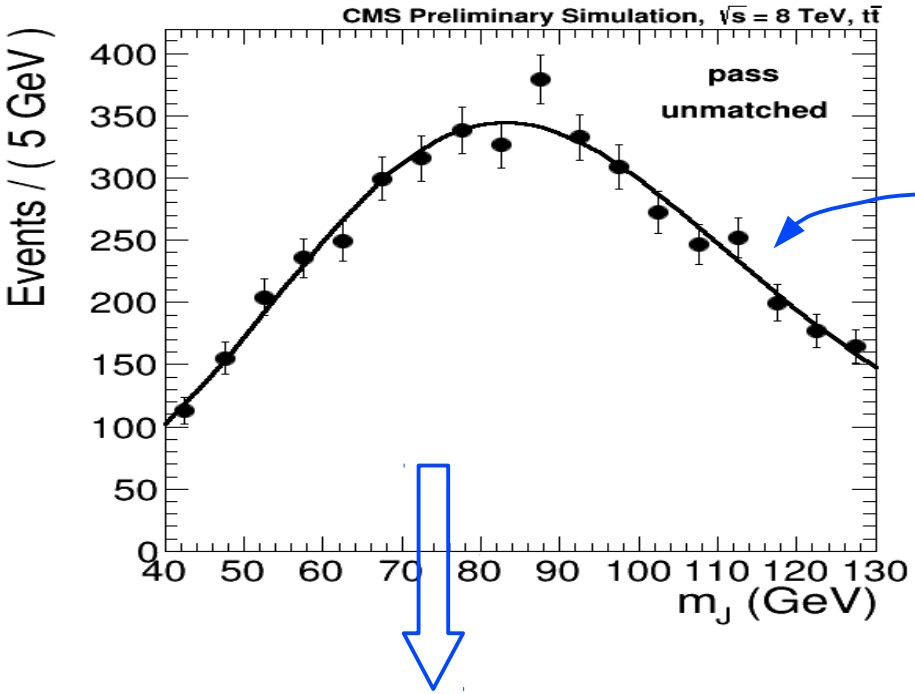
W → qq from $t\bar{t}$
which did not merge.

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



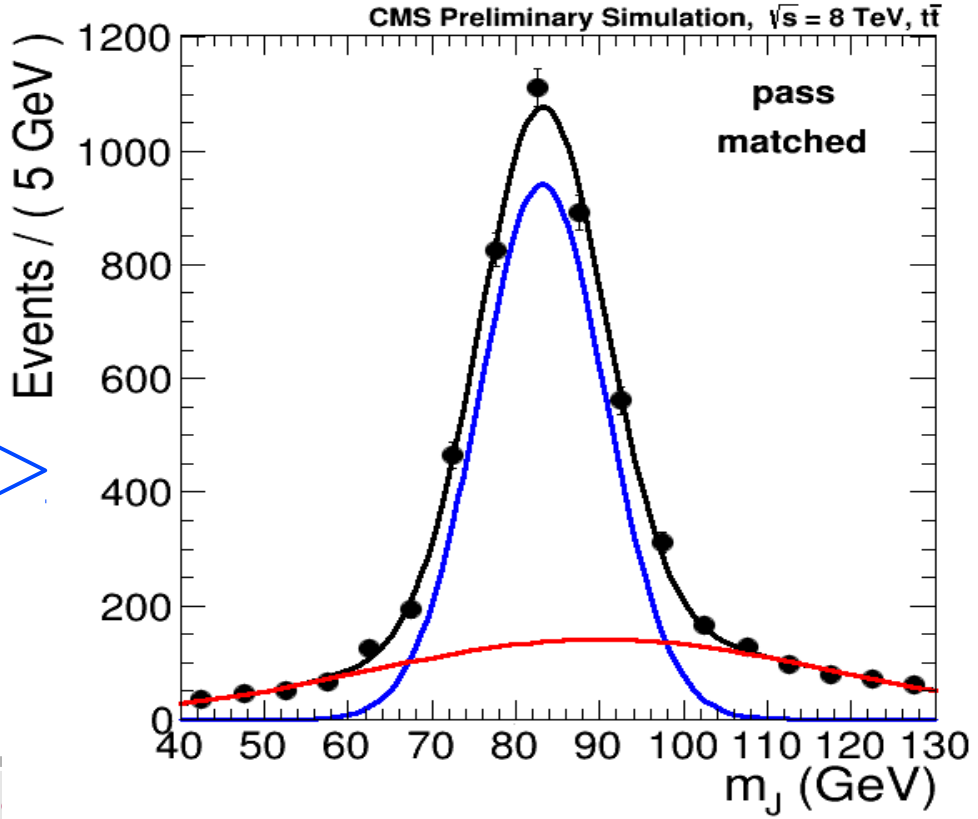
Substructure data/MC scale factor

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



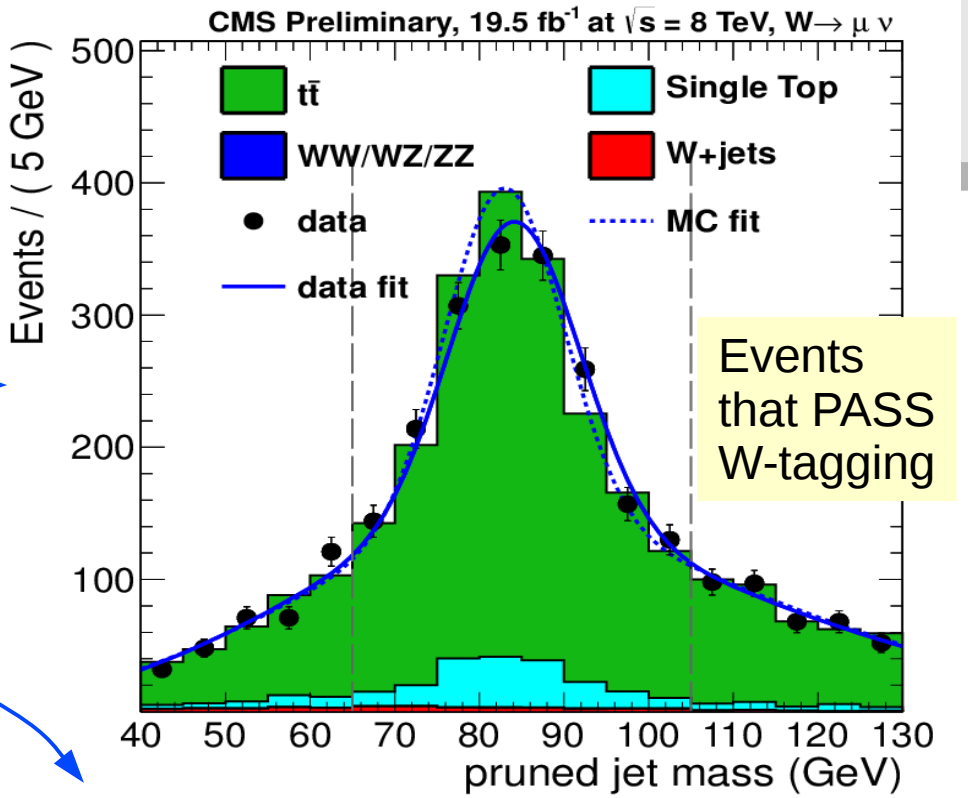
Substructure SF

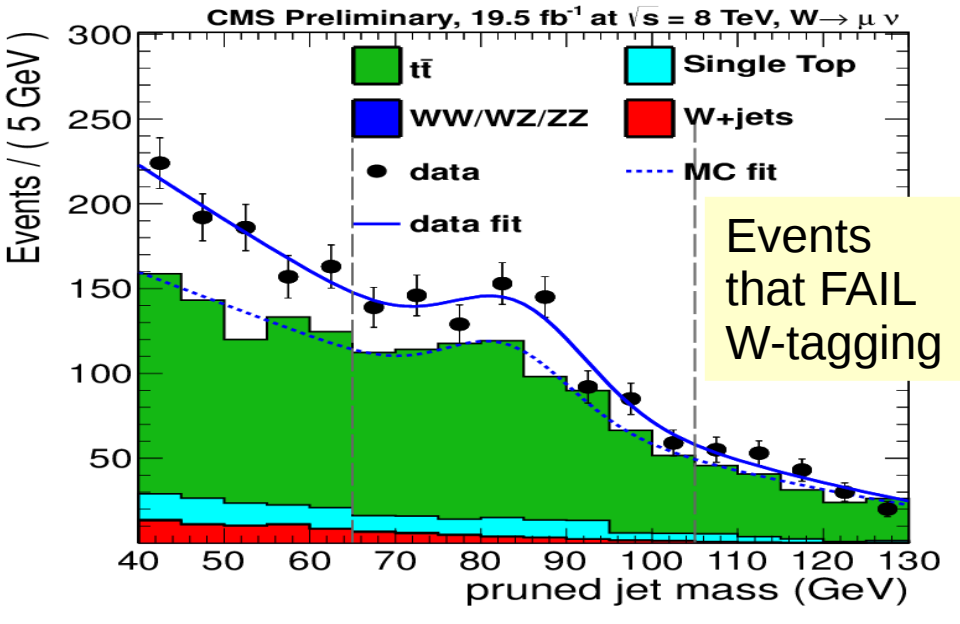
JME-13-006

- Simultaneous fit to events that pass and fail W-tagging, in $\mu + \text{jets}$ and $e + \text{jets}$
- Scale factor

$$SF_{\text{Wtag}} = 0.89 \pm 0.12$$

- Use MC to extrapolate to higher $p_T(\text{jet})$
- Systematics (12%) from comparison of HERWIG++ and Pythia6

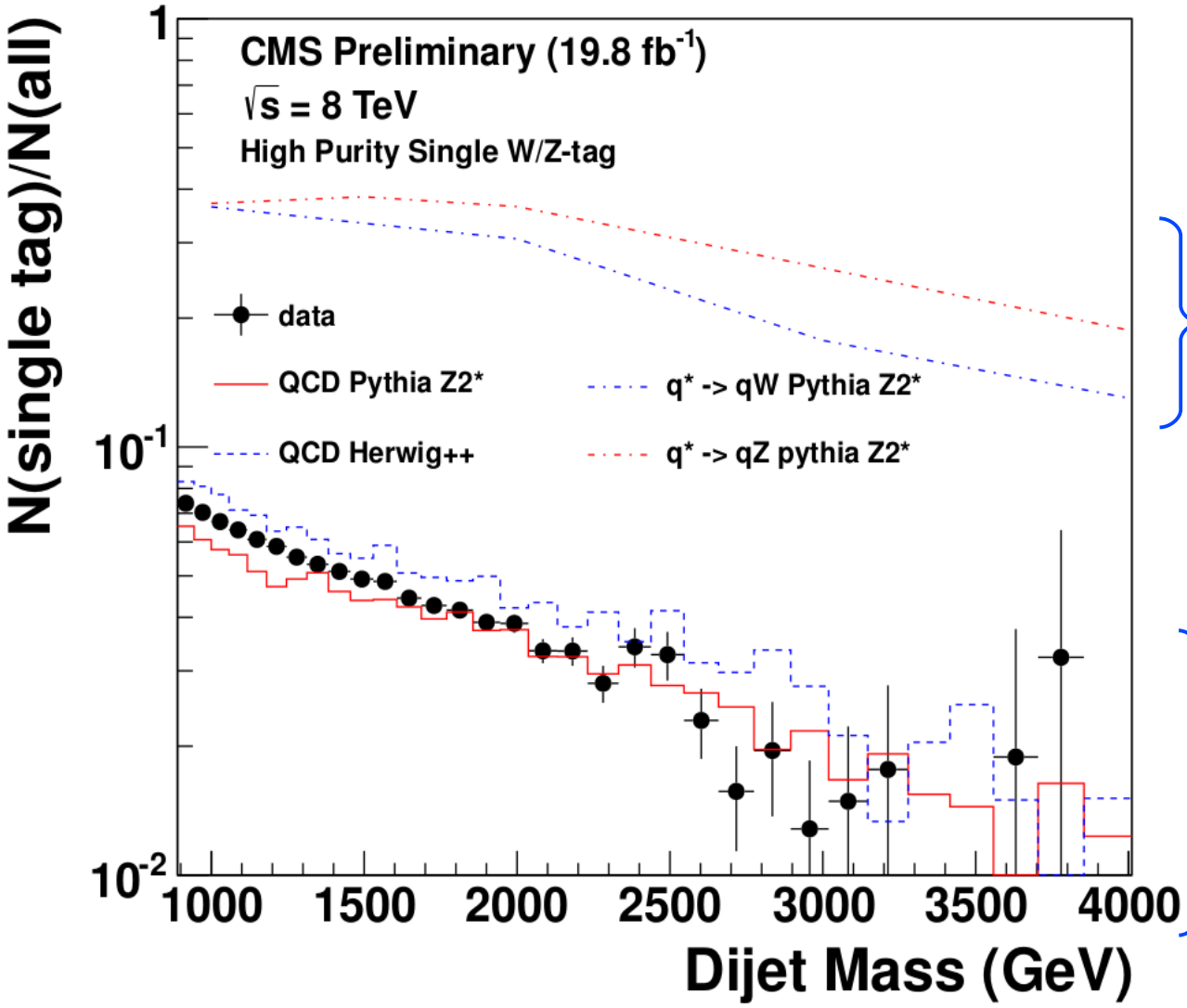




Effect of one W/Z-tag

EXO-12-024

- Fraction of events passing one-“W/Z-tag” requirement



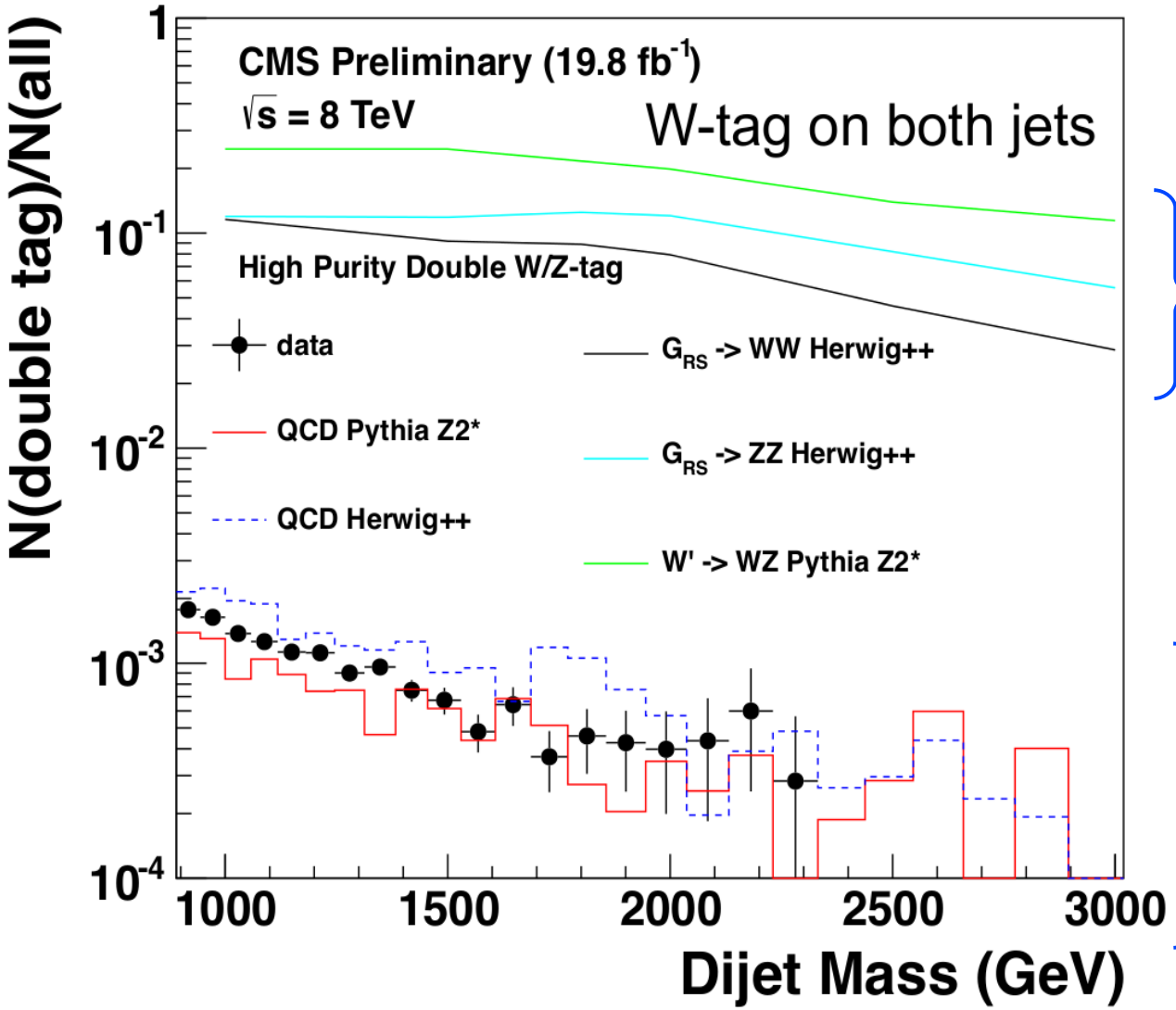
Excited quark signal models

QCD: suppressed ~ 10 times

Effect of two W/Z-tags

EXO-12-024

- Fraction of events passing two-“W/Z-tag” requirement



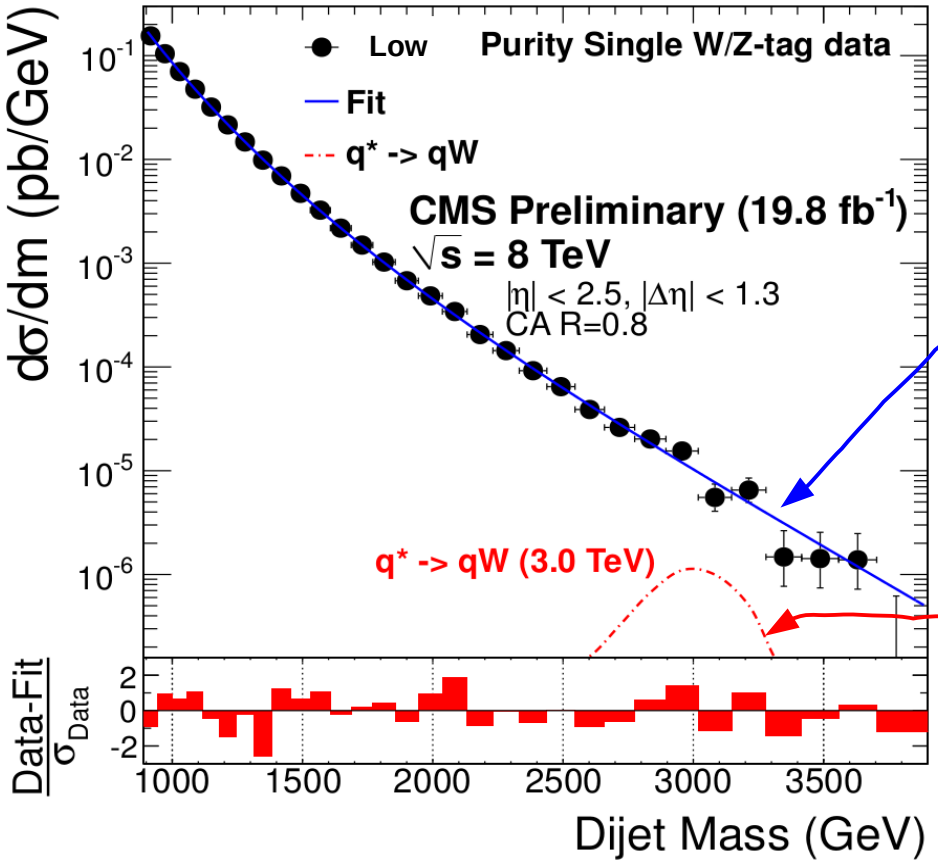
Various $X \to VV$ signal models

QCD: suppressed ~ 10^2 times

“Bump hunt” in di-jet data

EXO-12-024

- Background: smooth fit to data (no need for background MC)
- Parameterization same as other CMS di-jet searches

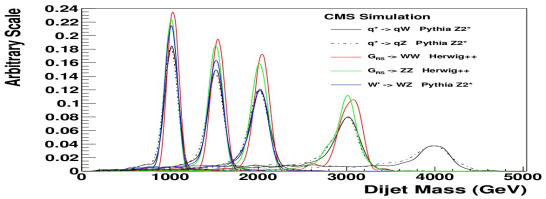


$$P_D(m_{jj}) = \frac{\mathrm{d}\sigma}{\mathrm{d}m_{jj}} = \frac{P_0(1-m_{jj}/\sqrt{s})^{P_1}}{(m_{jj}/\sqrt{s})^{P_2}}$$

(Fisher F-test: no additional parameters are necessary)

Joint likelihood for S+B

- marginalized over nuisance parameters:
- flat priors for signal, P_0, P_1, P_2



Single W/Z-tag data

EXO-12-024

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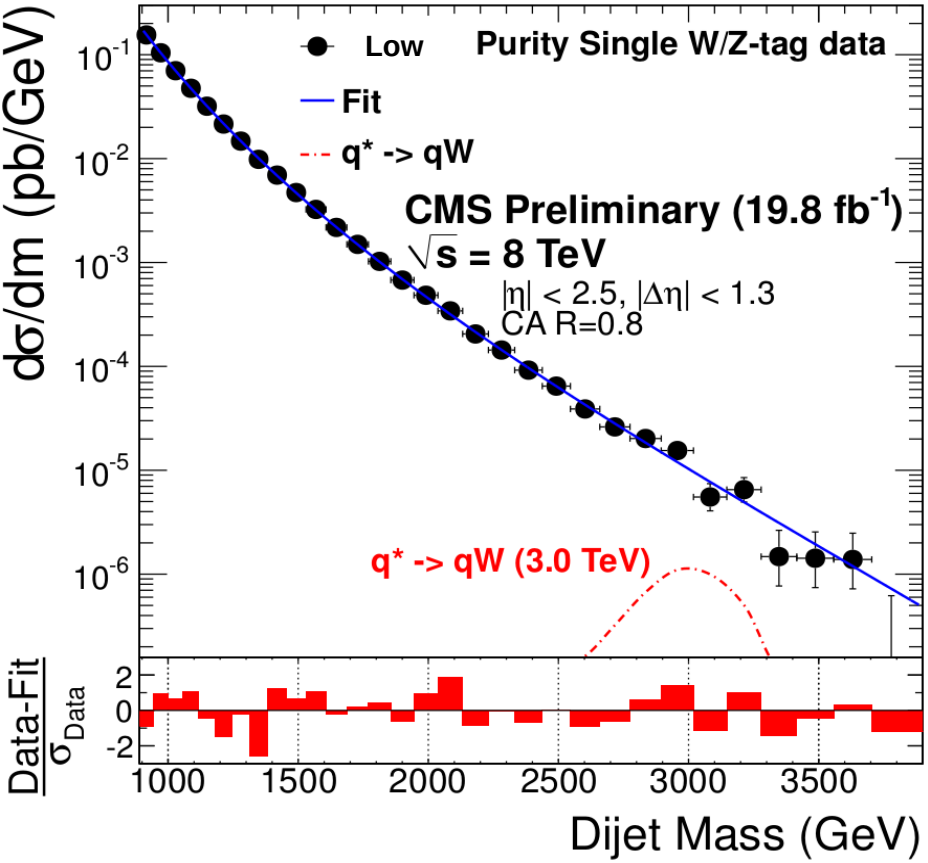

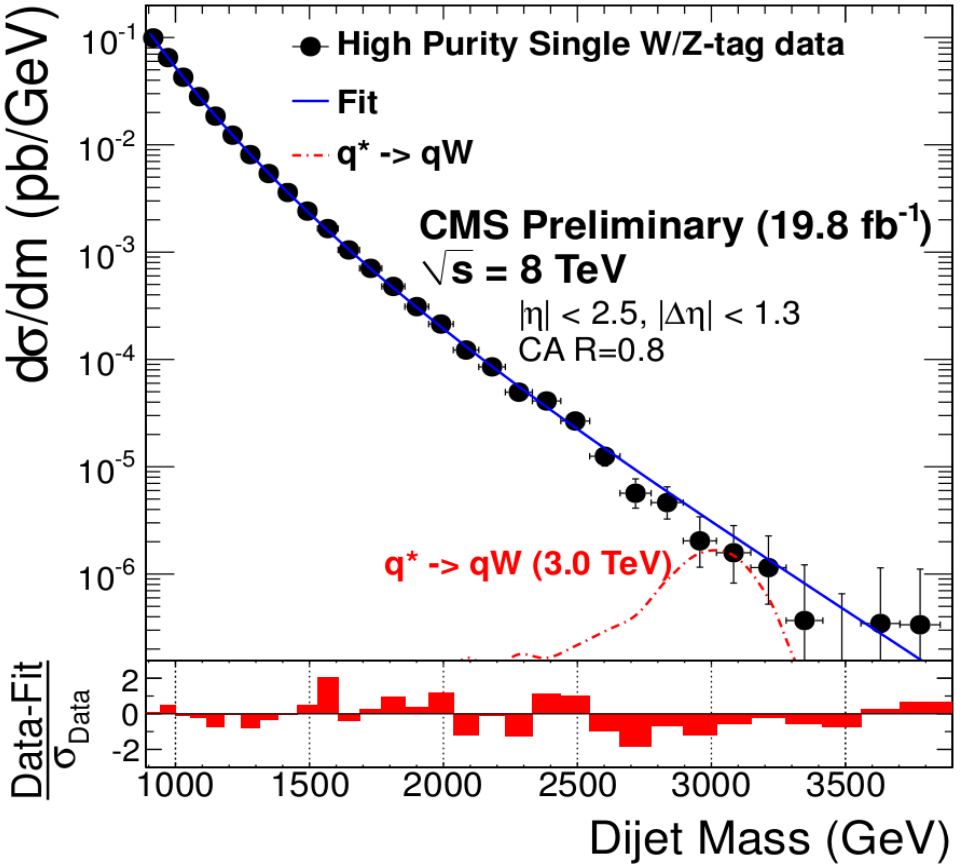

Double W/Z-tag data

EXO-12-024

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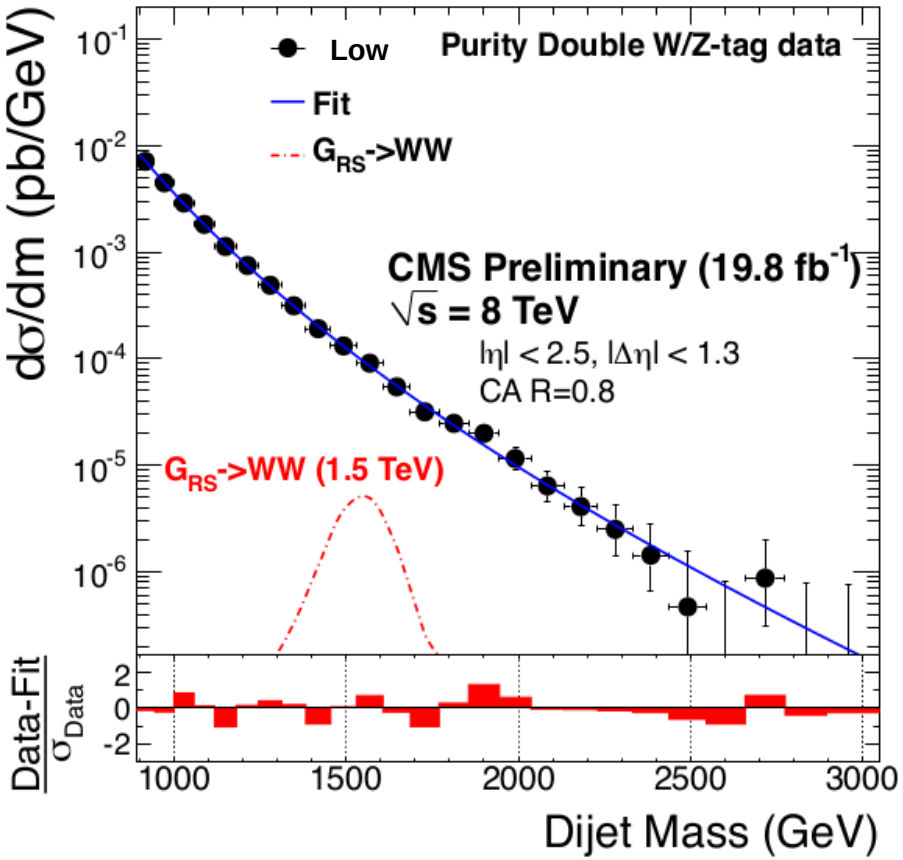
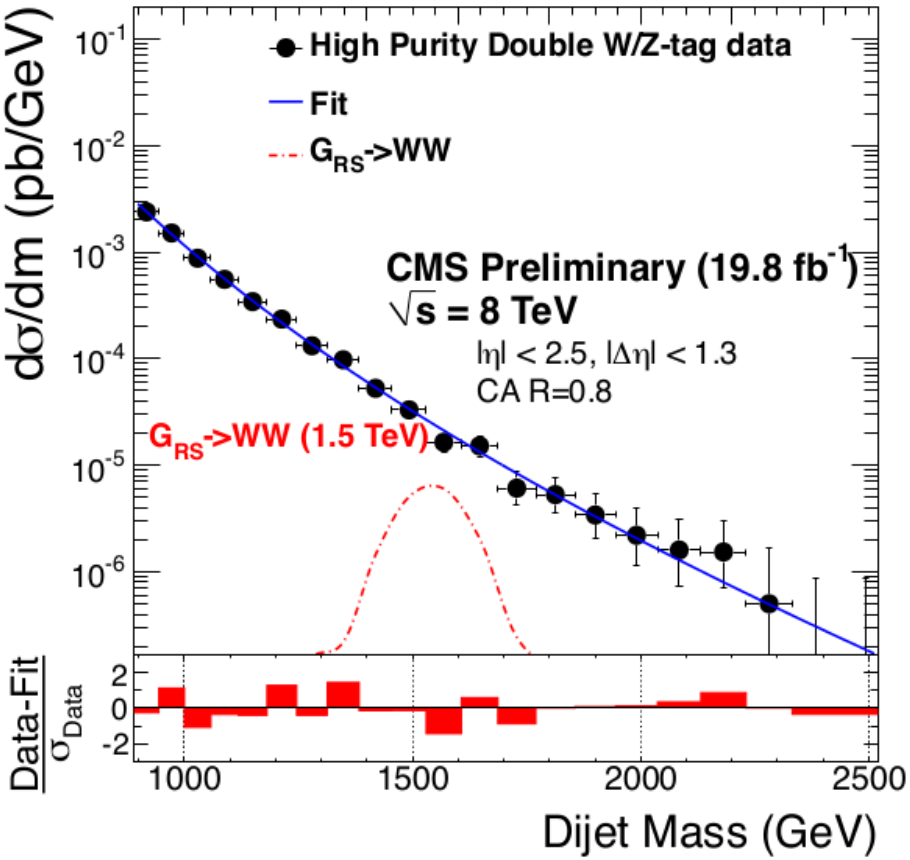
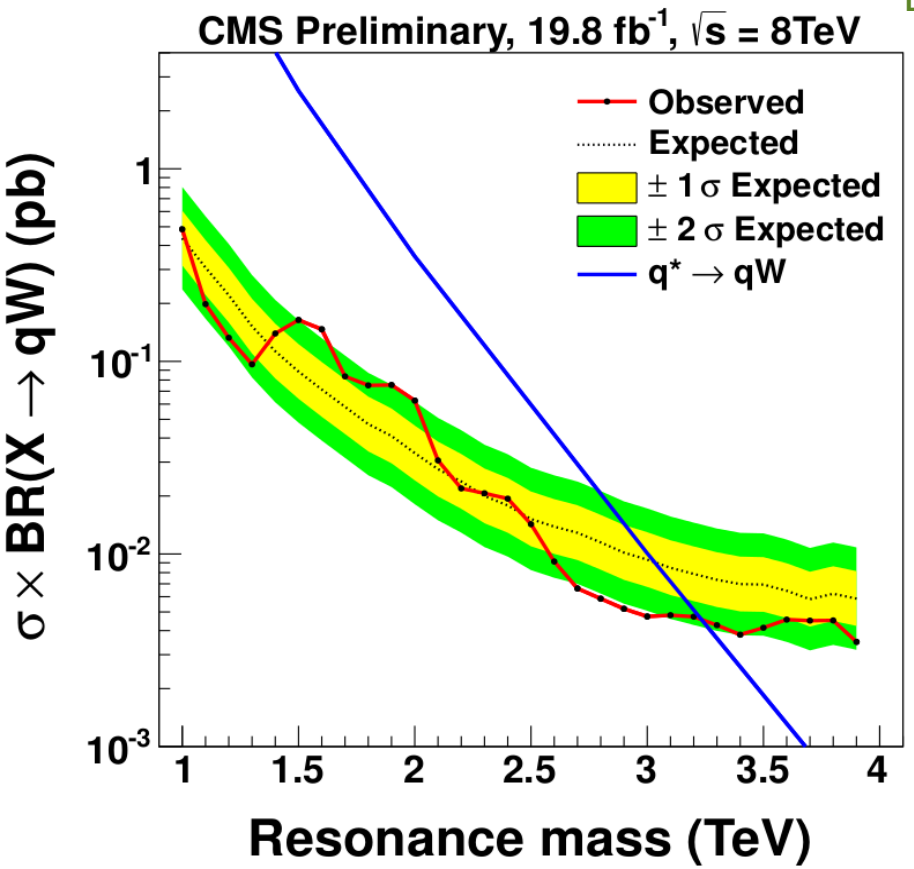
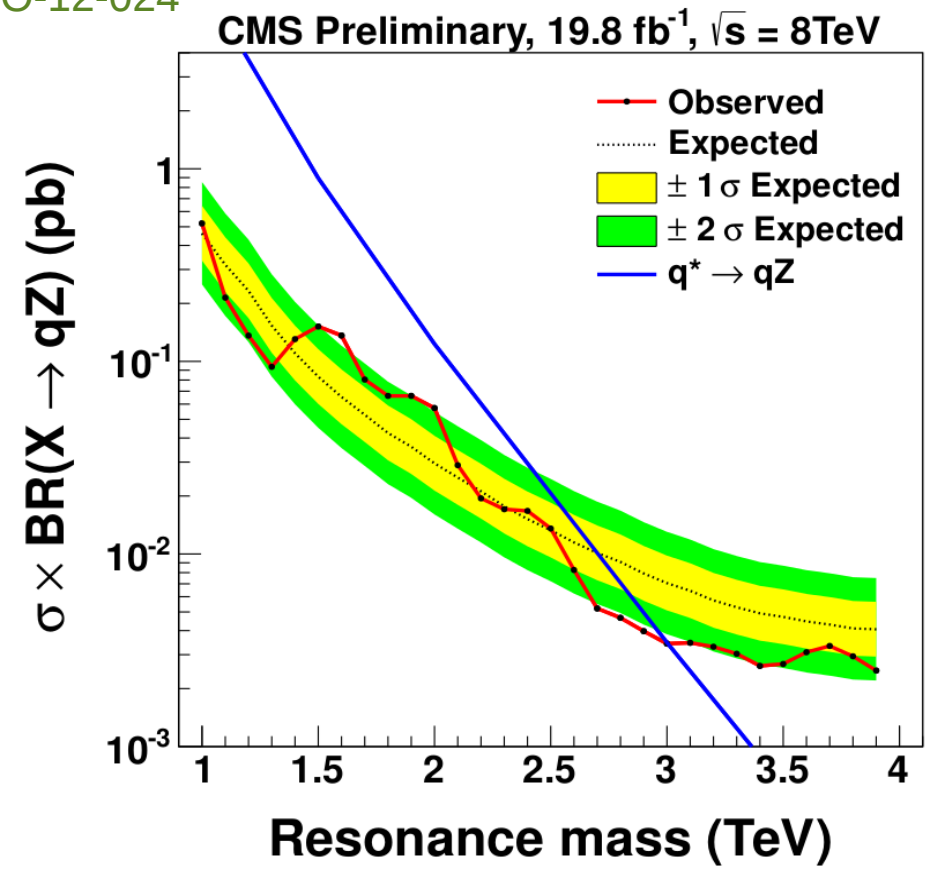




$q^* \to qZ, qW$ in di-jets

EXO-12-024

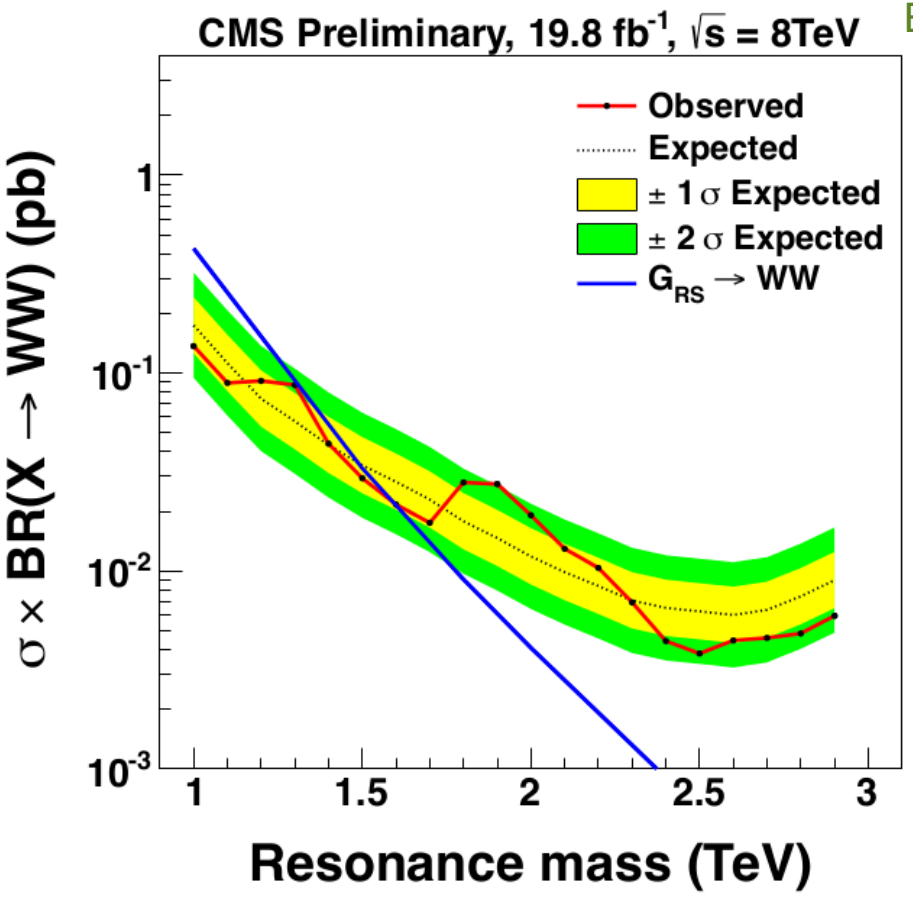


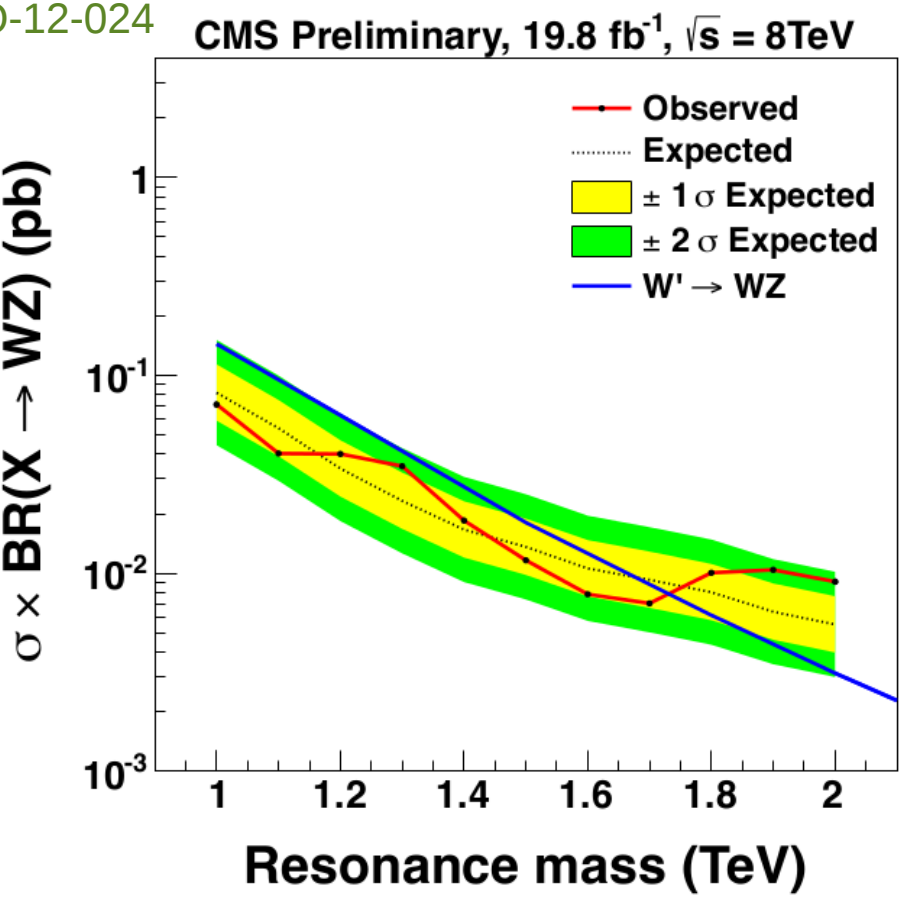


- q* → qW(qZ) excluded in mass range 1.0 to 3.23(3.00) TeV

$G_{RS} \to WW/ZZ$ and $W' \to WZ$ in di-jets

EXO-12-024





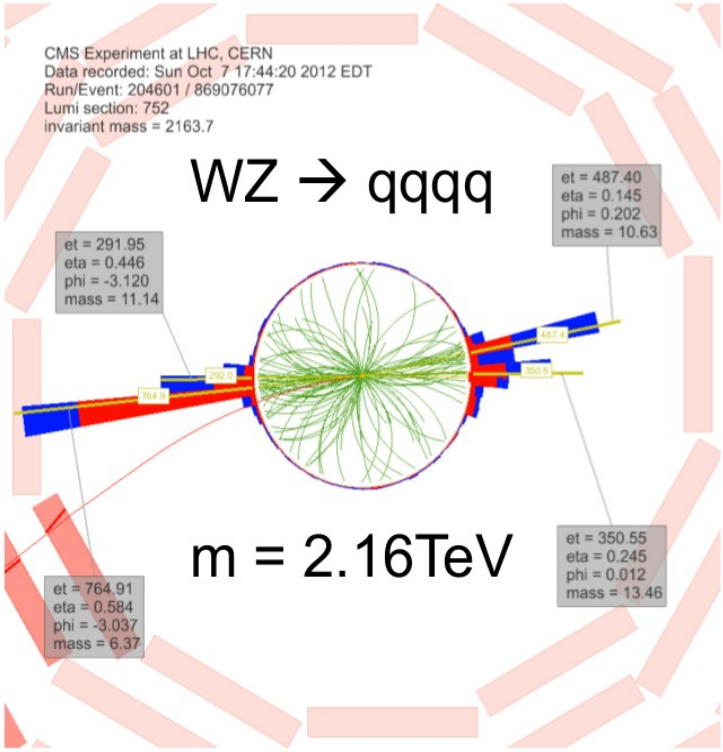
- G_{RS} (k/M_{PL}=0.1) → WW(ZZ) excluded in mass range 1.0 to 1.59(1.17) TeV
- W' → WZ excluded in mass range 1.0 to 1.73 TeV

Where we are now

- CMS has a broad program of searches to qV and VV heavy resonances
- We are getting a handle on how to deal with boosted objects
  - special isolation of leptons from Z's and tops [cf. other talks]
  - deconstruct merged jets from W and Z (and tops)
- Deploying these tools in analyses – several results are the best of its kind
  - most stringent limits on
    - $q* \to qW$ and $q* \to qZ$
    - $W' \to WZ$

Where we are going

- Aim at covering all possible final states for best sensitivity over the full mass range
  - Including semileptonic channels, nost stringent limits to date in all final states (qW, qZ, WW, ZZ, WZ)
  - Combine 8 TeV searches (synchronize models across analyses)
- Upgrade everything for 13 TeV
- No excess so far, but stay tuned!



BACKUP MATERIAL

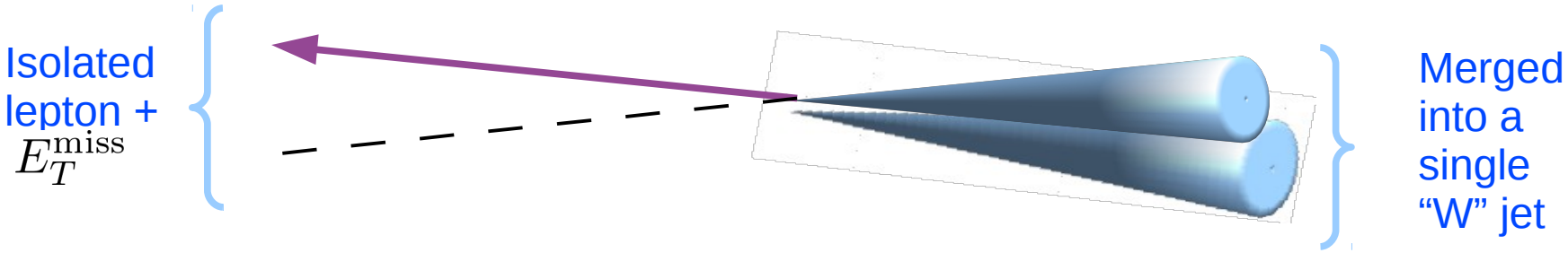
Final states in play

- Covered today (recent 8 TeV results)
  - 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)

- Not covered (7 TeV results, updates in progress)
  - ZZ, WZ, Z decaying to dileptons, V decaying hadronically
    - $G_{\mathrm{RS}} \to ZZ$ and $W' \to WZ$
  - ZZ,one Z decaying to neutrinos, other Z hadronically
    - $G_{\mathrm{RS}} \to ZZ$

$G_{\text{bulk}} \to WW \to \ell + E_T^{\text{miss}} + \text{jet}$

- One $W \to \nu\ell$, the other $W \to jj$
  - one side: isolated lepton + missing energy
  - opposite side: highly boosted $W \to jj$, merged into one jet



- Same as for heavy Higgs, but boost is larger
  (see talk by Zijun)

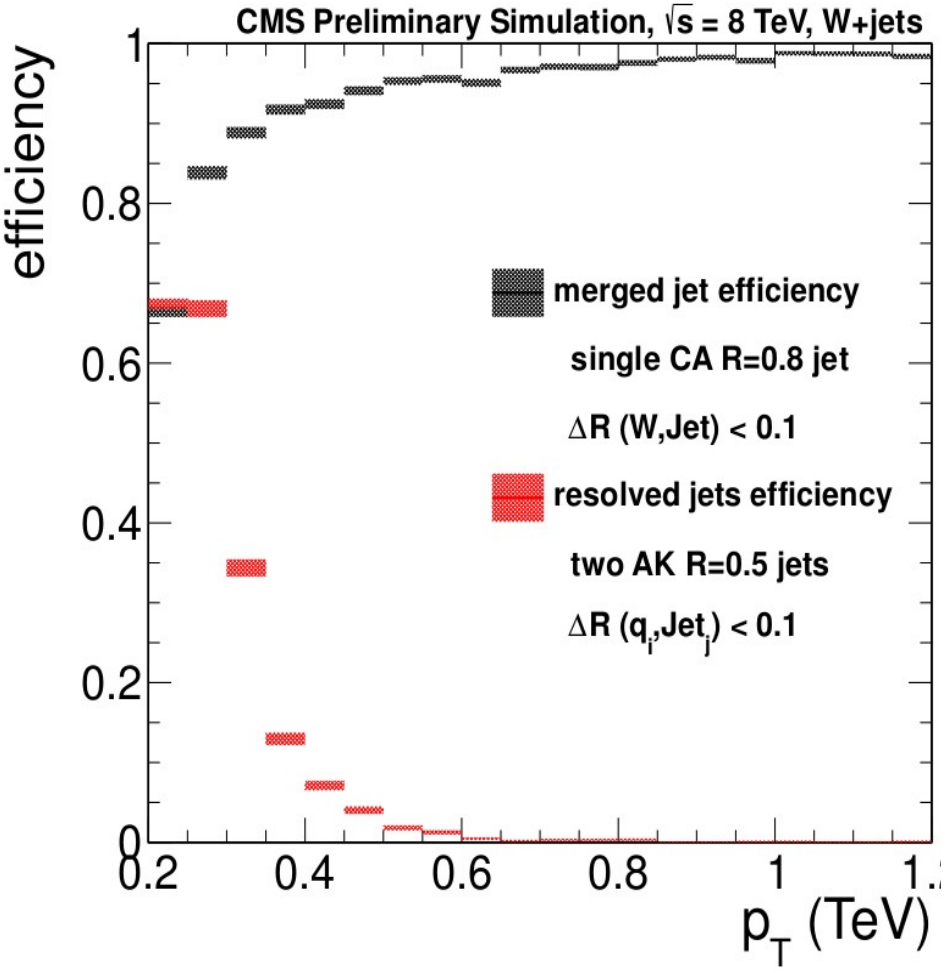
- Identify boosted W-jets with "N-subjettiness" variable τ_2/τ_1

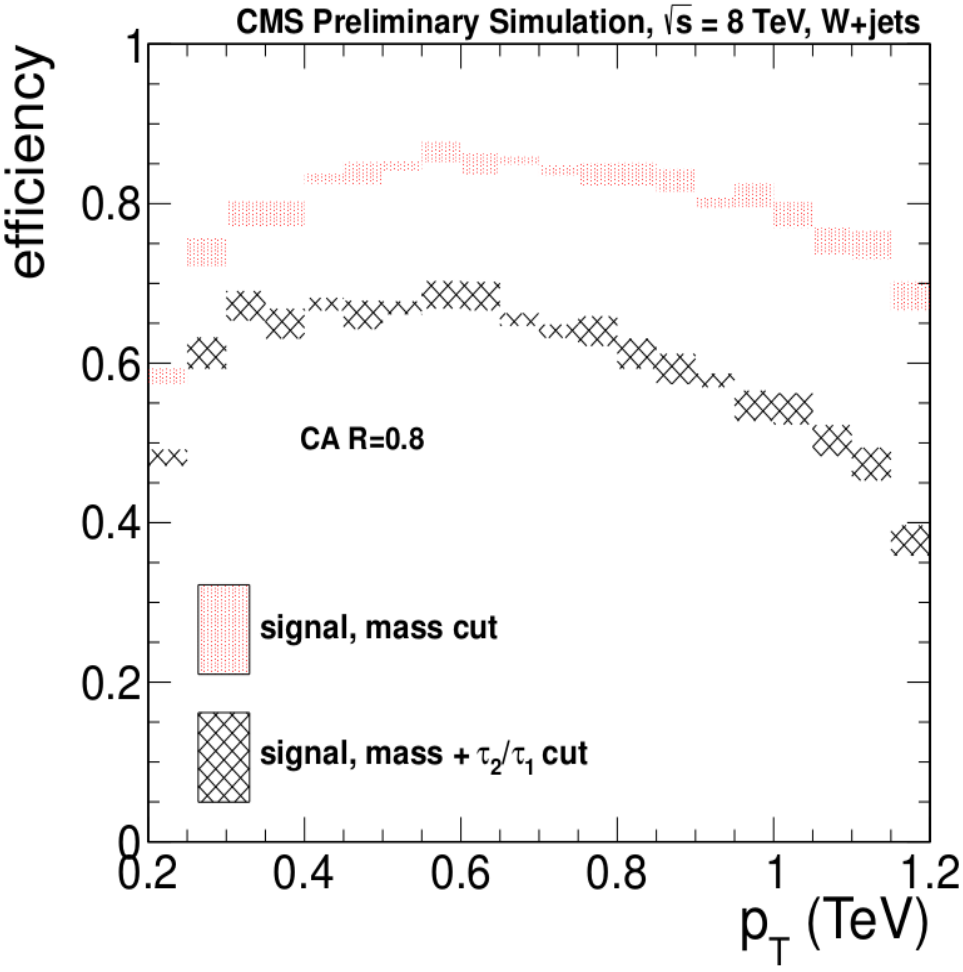
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \Delta R_{1.k}, \Delta R_{2.k}, ..., \Delta R_{N.k}$$

  - τ_2/τ_1 peaks near zero for two subjets

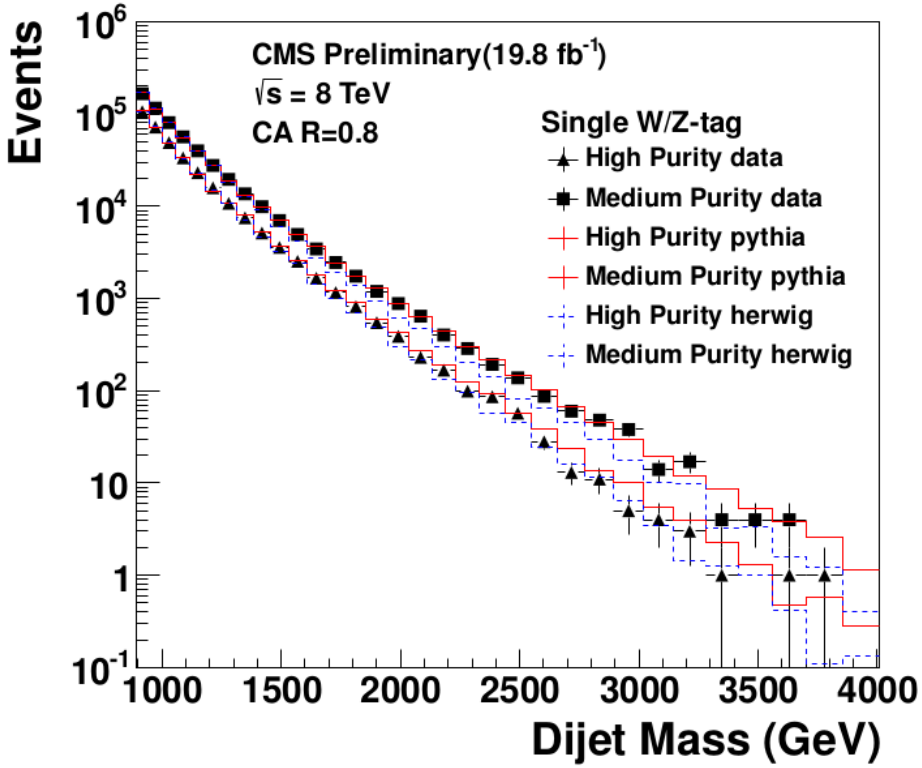
W-tagging efficiency

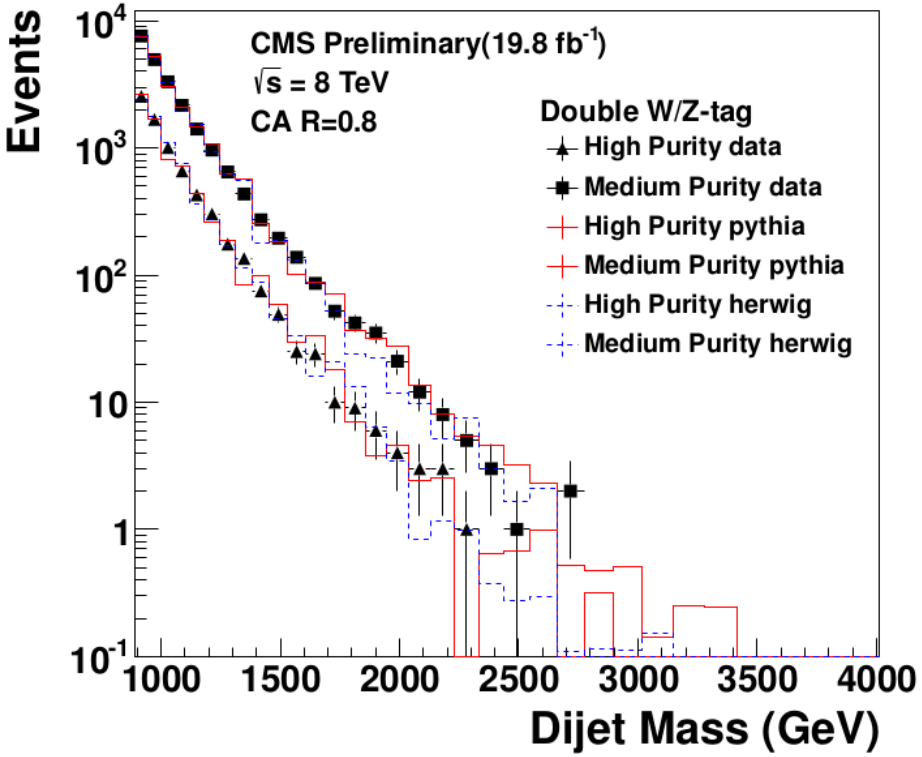
- Efficiency to reconstruct a W as a single CA8 jet.
- Once we have a W in a CA8, efficiency to pass W-tagging





Di-jet mass distribution: MC vs data



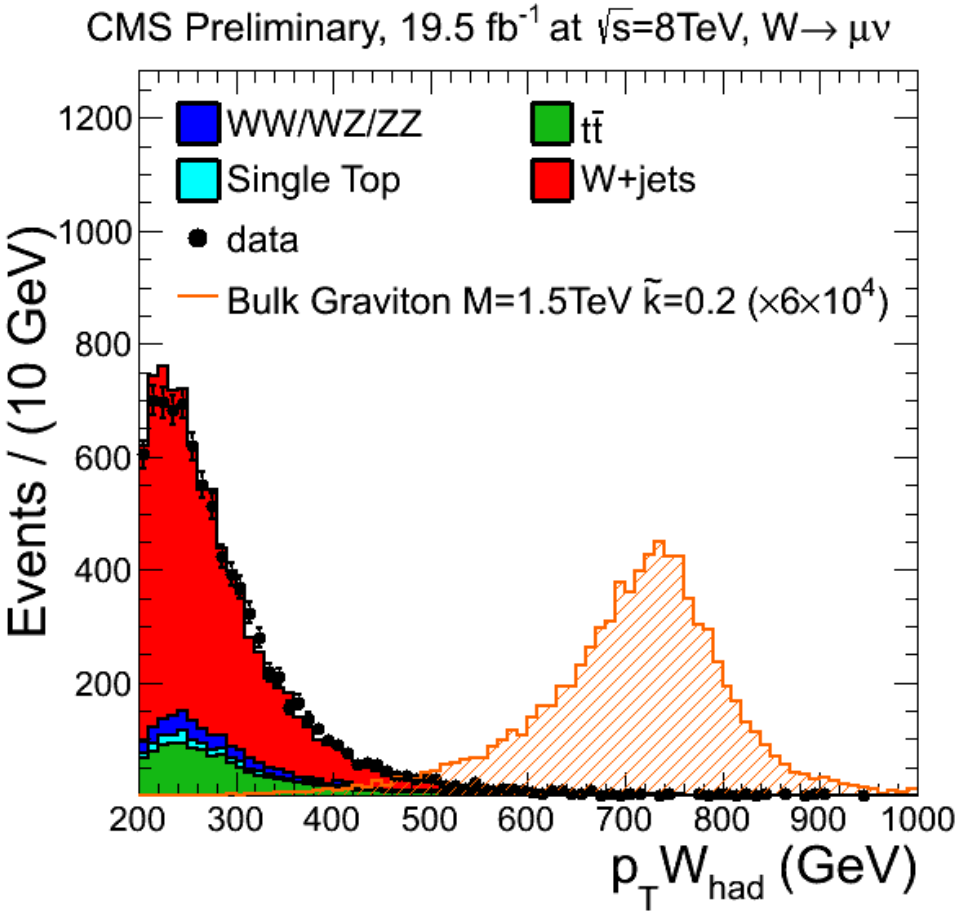


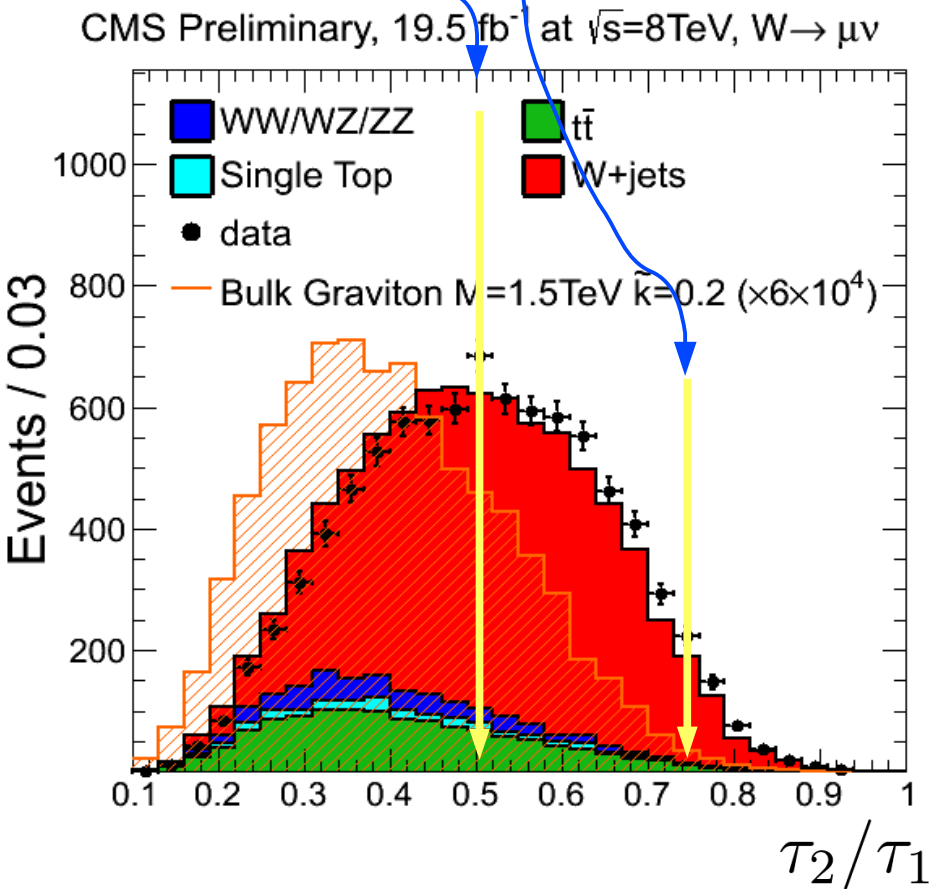
- A fairly impressive agreement between Herwig++ and PYTHIA6 QCD samples and data

$G_{\mathrm{bulk}} \to WW \to \ell + E_T^{\mathrm{miss}} + \mathrm{jet}$

EXO-12-021

- Require pruned jet mass $65 < m_{\mathrm{jet}} < 105$ GeV
- N-subjettiness: $\tau_2/\tau_1 < 0.5$ (high purity) < 0.75 (low purity)





Complementarity

- Most stringent limits to date in all final states WW, ZZ, WZ (,qW, qZ)
- Compare analyses sensitivity in 2-D plane of coupling k/M_{PL} and mass of RS1 Graviton
- Different channels are complementary
- Plan to combine all 8 TeV results