Beyond Two Generations Searches: Boosted Exotica at CMS

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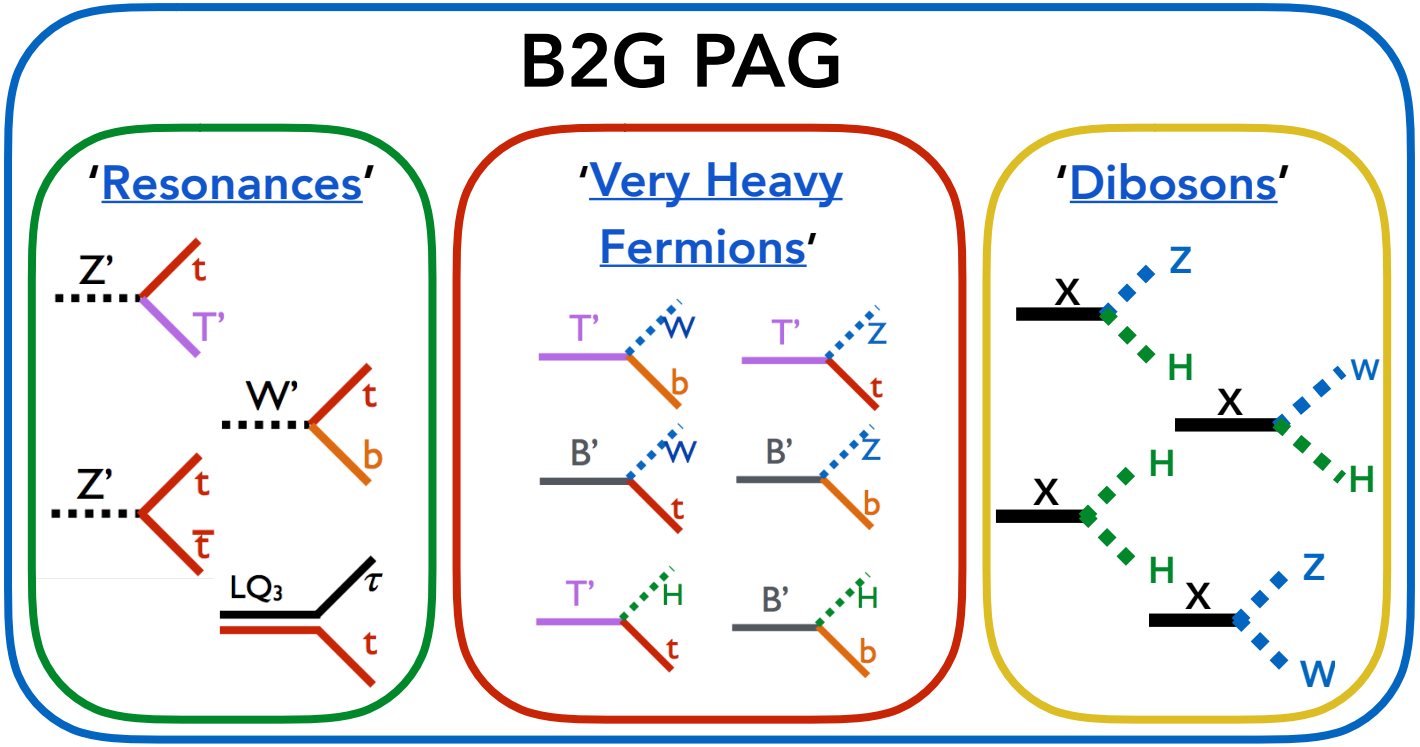
on behalf of the CMS B2G PAG

Boosted Objects for New Physics Workshop
November 13, 2018

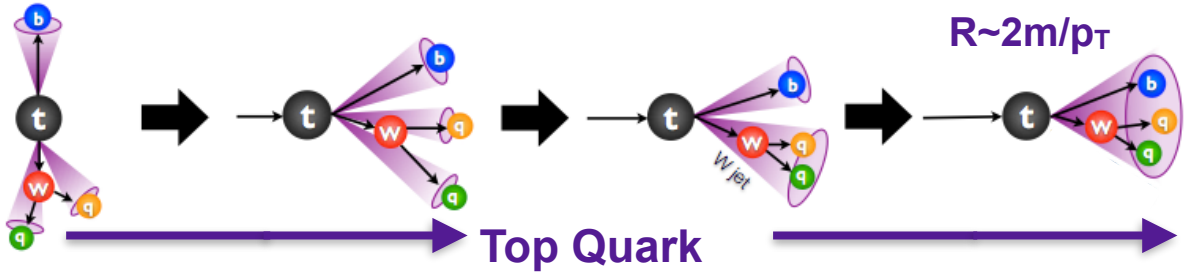
Beyond Two Generations (B2G)

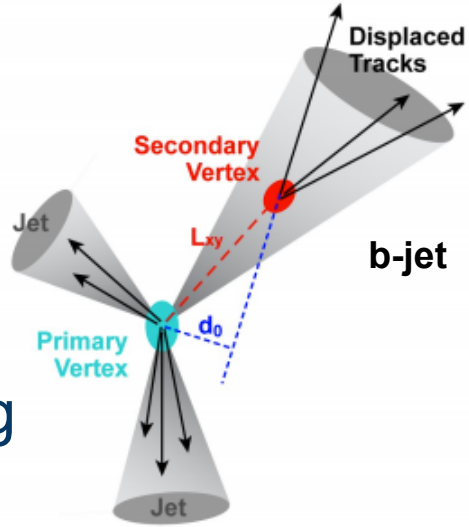
- Searches for new particles decaying to heavy SM particles
  - Resonances (RES)
    - Final state: heavy fermions
  - Very Heavy Fermions (VHF)
    - Vector-Like Quarks (VLQs)
  - Diboson Resonances (DIB)



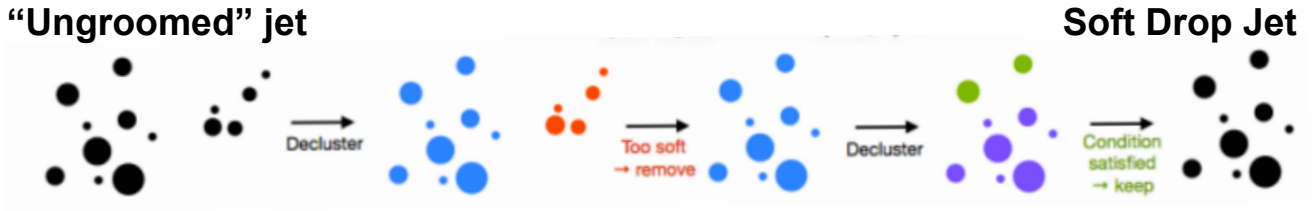
B2G Analysis Techniques

- Searches focus on the high energy regime
  - Signals up to 5 TeV - leads to boosted topologies





- Boosted object tagging: W,Z,H,t,b
  - Makes use of jet substructure tools
    - Softdrop mass, N-subjettiness, b-tagging



- Pileup mitigation: PUPPI (**P**ile**U**p **P**er **P**article **I**D)
- Look for peaks in falling background spectra
  - Data-driven background estimates

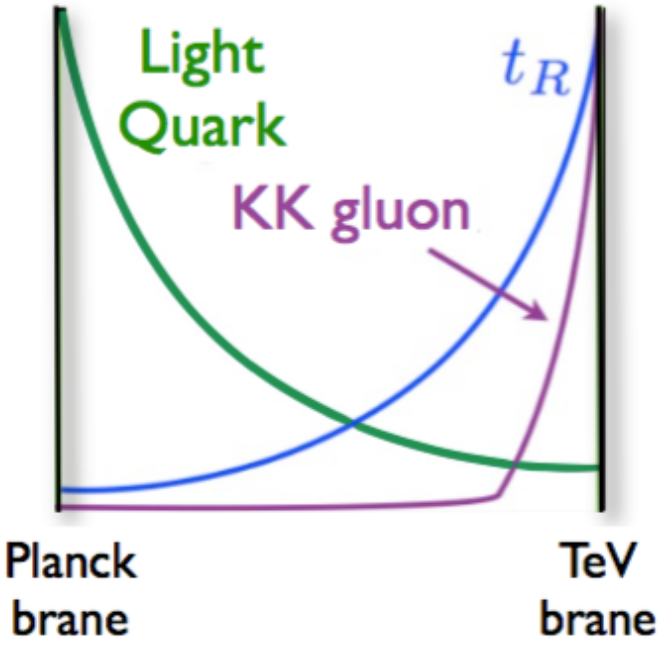
➤**Resonances**

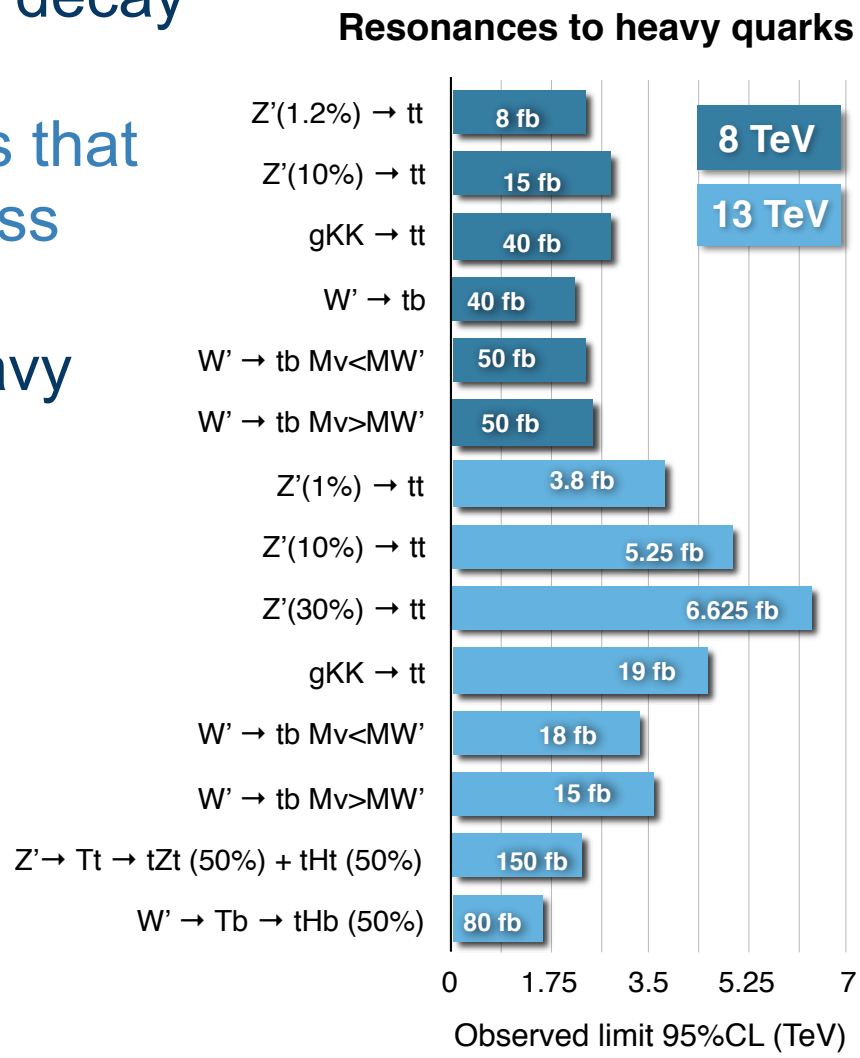
Vector-Like Quarks

Dibosons

Resonances

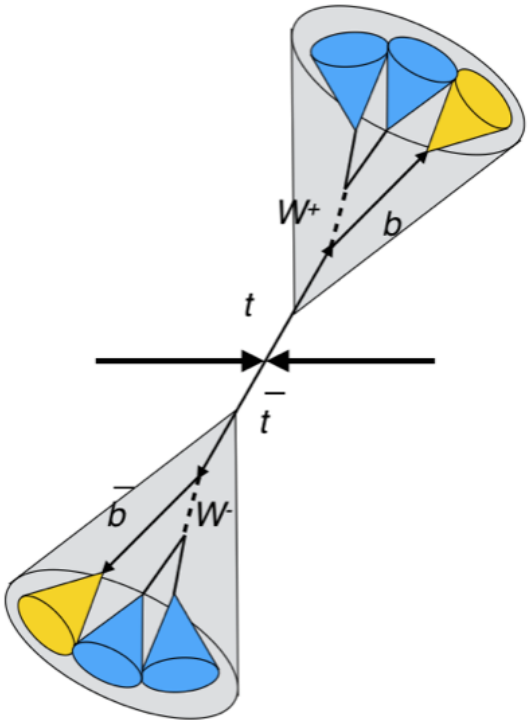
- High mass BSM particles that decay to third-generation fermions
  - Predicted by many theories that seek to preserve naturalness
    - e.g. RS2 model of extra dimensions predicts heavy gluon



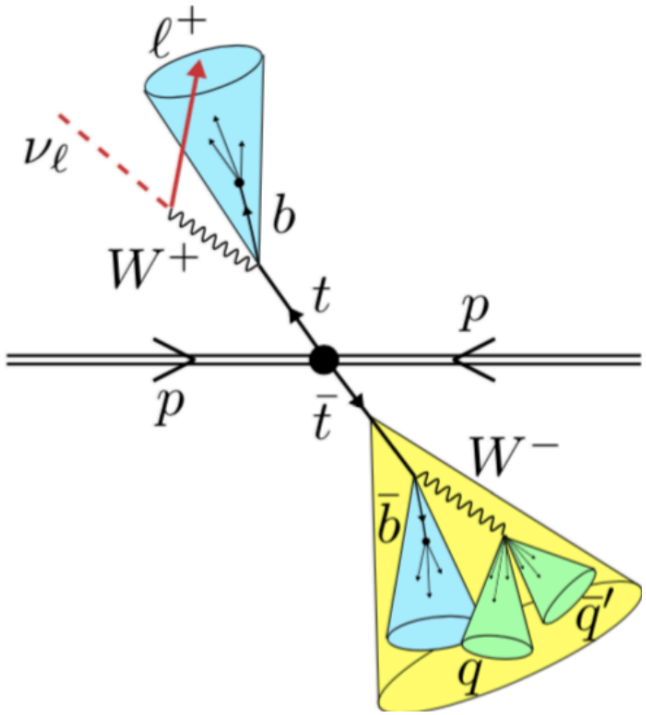


Heavy Resonances to $t\bar{t}$

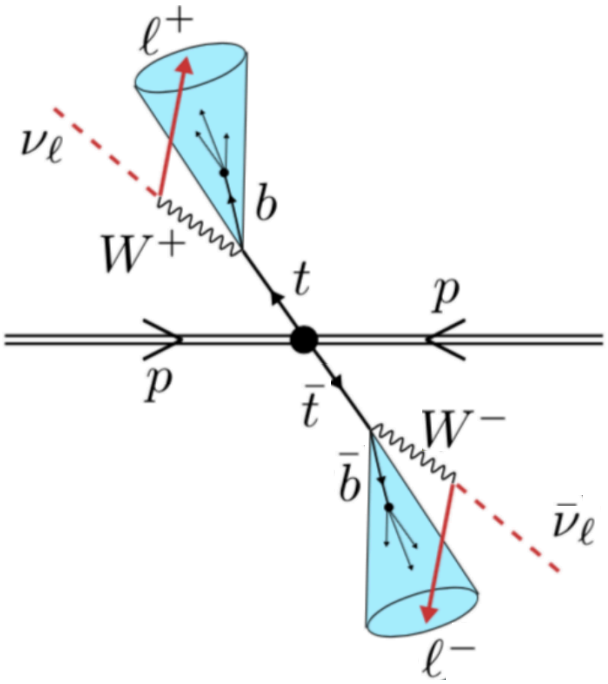
- Search for heavy spin-1 **RS KK gluon** & **Z'** decaying to $t\bar{t}$
  - **Channels:** all-hadronic, semileptonic, dileptonic



All-hadronic



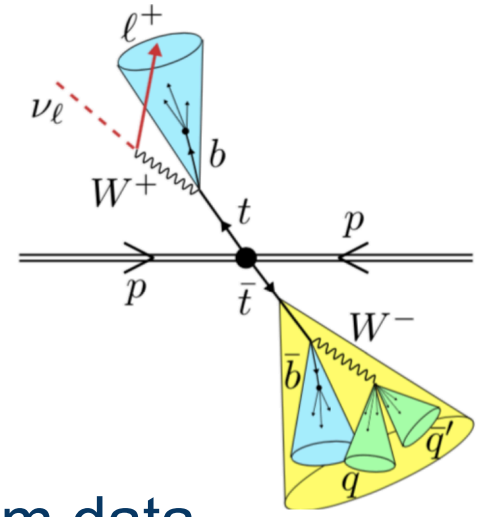
Semileptonic

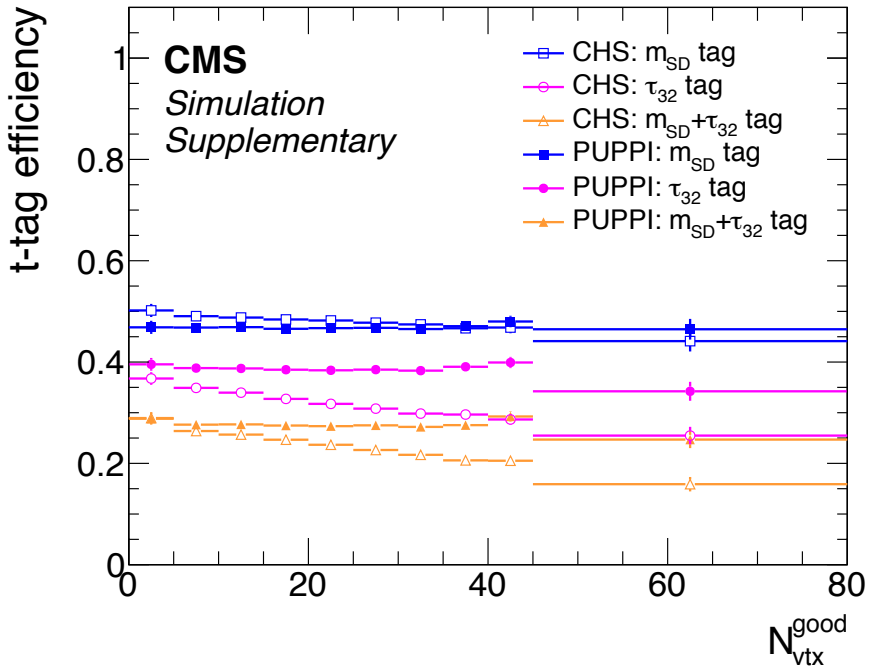


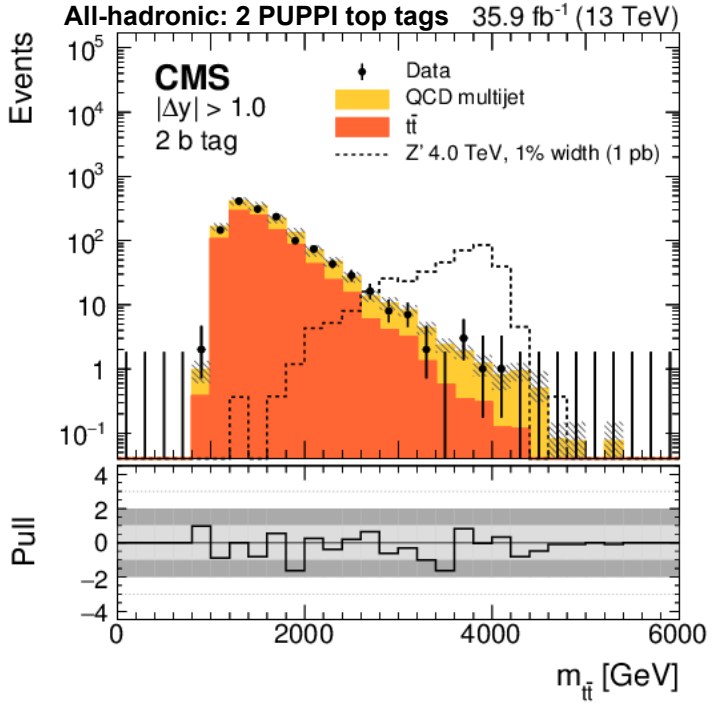
Dileptonic

Heavy Resonances to $t\bar{t}$

- **Channels: all-hadronic, semileptonic, dileptonic**
- Reconstruct back-to-back $t\bar{t}$ events
  - **Tools:** PUPPI top-tagging, b-tagging, lepton 2D isolation
- All-hadronic QCD background derived from data
- New: W+jets background suppressed by BDT

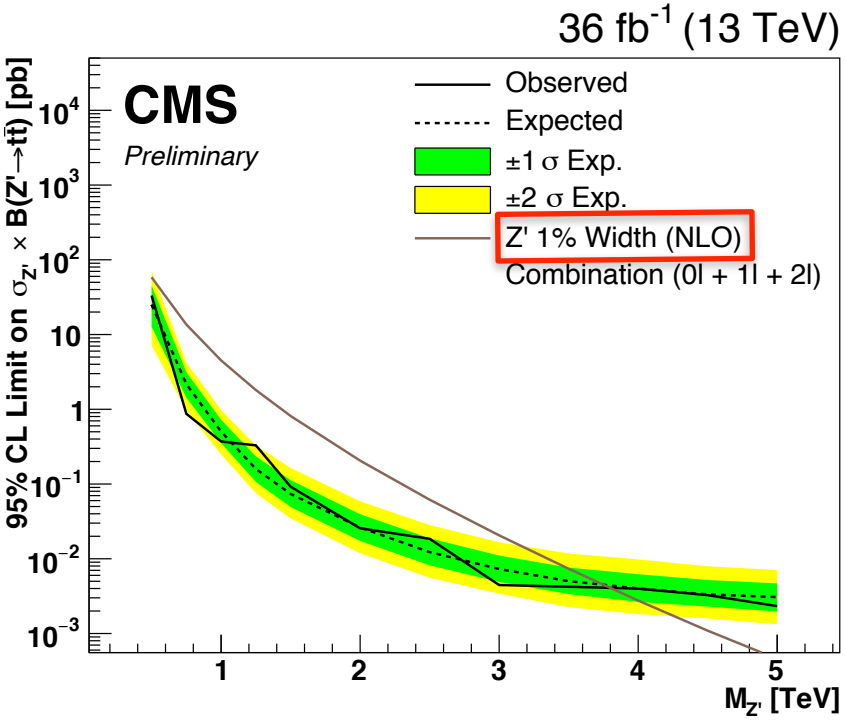


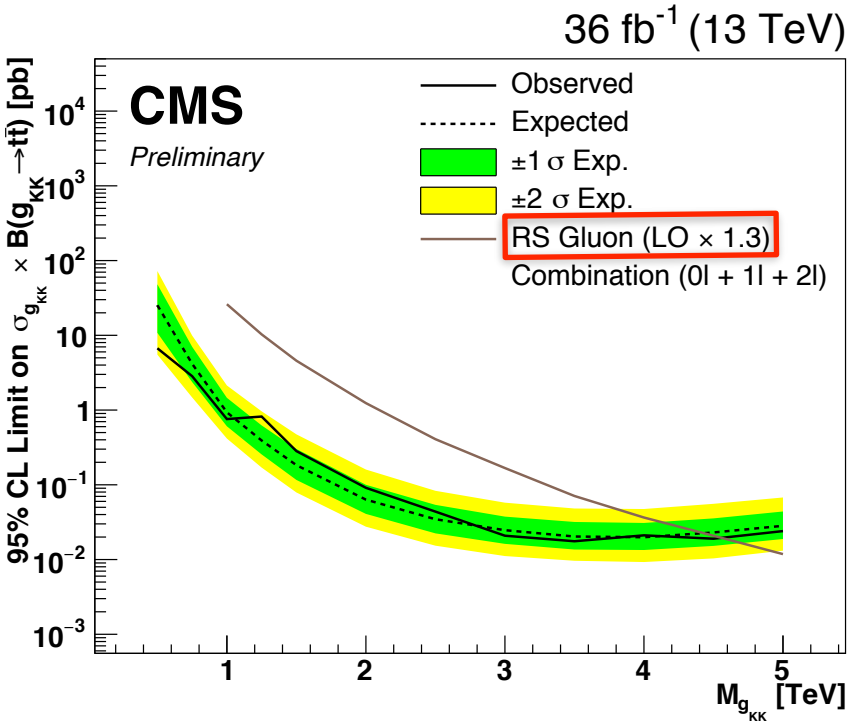




Heavy Resonances to $t\bar{t}$: Results

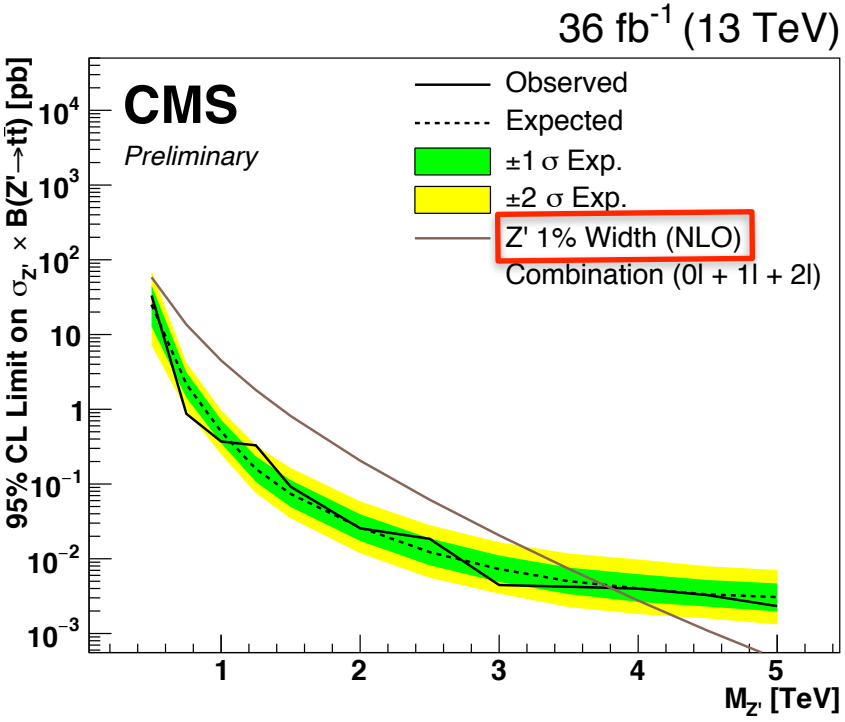
- Consider RS Gluon and Z' (Γ/M = 1%, 10%, 30%) models
- Discriminating variables:
  - $M_{t\bar{t}}$ (all-hadronic, semileptonic), S_T (dileptonic)

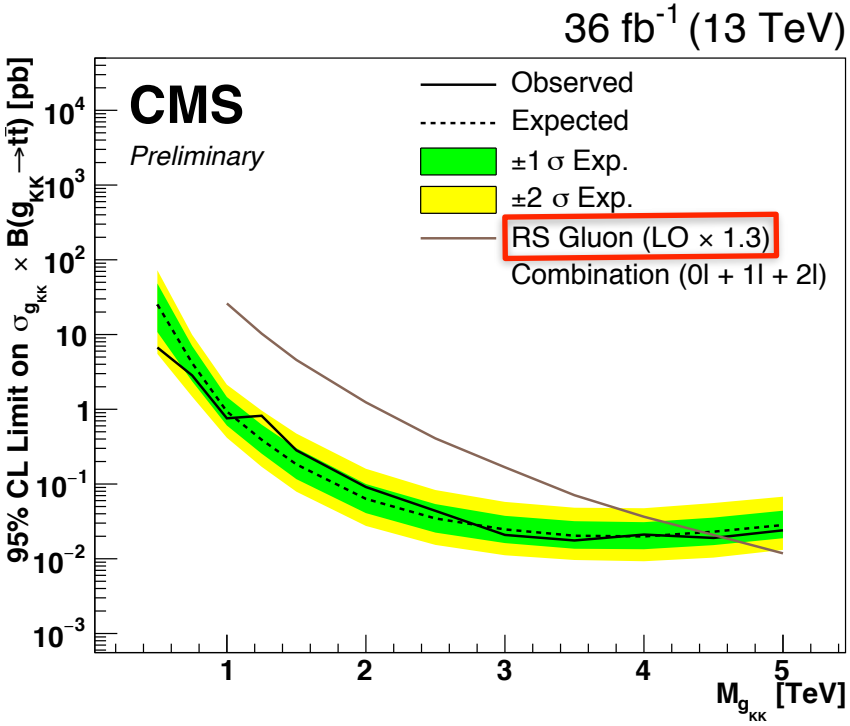




Heavy Resonances to $t\bar{t}$: Results

- Consider RS Gluon and Z' (Γ/M = 1%, 10%, 30%) models
- Discriminating variables:
  - $M_{t\bar{t}}$ (all-hadronic, semileptonic), S_T (dileptonic)
- **Most recent CMS search: large gains in sensitivity!**





CMS Improvement (Combination)

1804.10823 ATLAS CMS Semileptonic Sensitivity ATLAS CMS

CMS Dileptonic, All-Hadronic Sensitivity

Resonances

➤**Vector-Like Quarks**

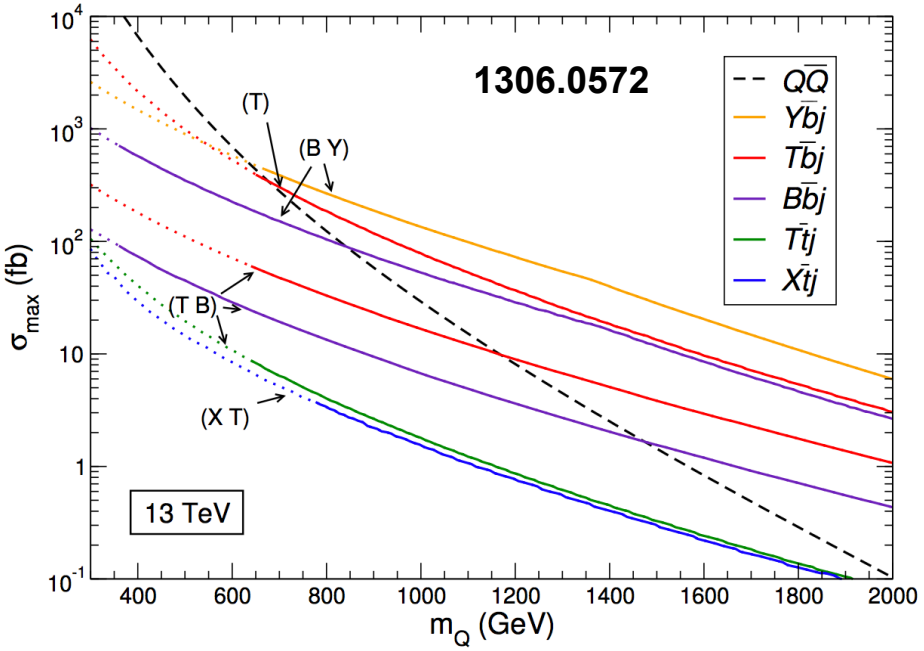
Dibosons

Vector-Like Quarks

- VLQs: non-traditional quarks
  - **The standard:** spin-1/2, colored, charged particles
  - **The unusual:** both left- and right-handed coupling to CCs
    - Mass not acquired through Higgs coupling - **don't affect Higgs cross section or width!**
- Predicted by composite Higgs and little Higgs models
- Both single- and pair-production
  - Single production dominates at high masses (above ~ 2 TeV)

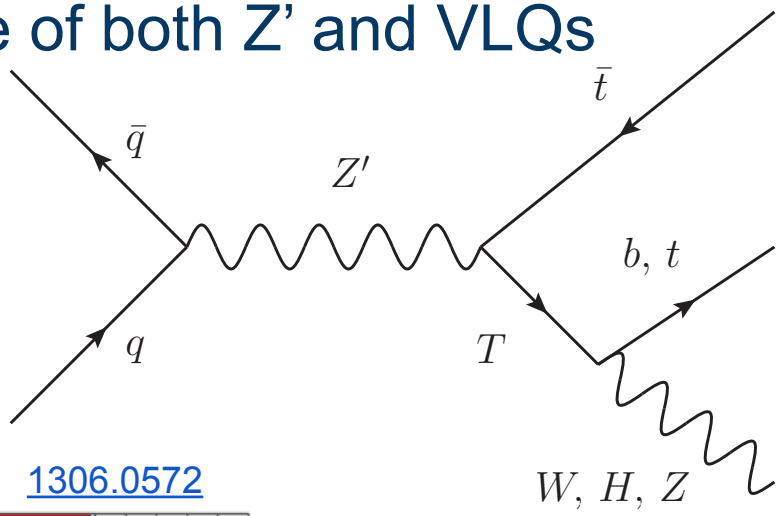
Weak multiplets (isospin$_{\text{hypercharge}}$)

Singlets	Doublets	Triplets
$\mathbf{1}_{2/3} = T$	$\mathbf{2}_{1/6} = \begin{pmatrix} T \\ B \end{pmatrix}$	$\mathbf{3}_{2/3} = \begin{pmatrix} X \\ T \\ B \end{pmatrix}$
	$\mathbf{2}_{7/6} = \begin{pmatrix} X \\ T \end{pmatrix}$	
$\mathbf{1}_{-1/3} = B$	$\mathbf{2}_{-5/6} = \begin{pmatrix} B \\ Y \end{pmatrix}$	$\mathbf{3}_{-1/3} = \begin{pmatrix} T \\ B \\ Y \end{pmatrix}$



Z' → tT (Lepton + jets)

- BSM models motivate existence of both Z' and VLQs
- This search considers all three T decay modes (semileptonic)
  - Optimized for Ht/Zt
  - Looks for boosted H/Z/W/t!



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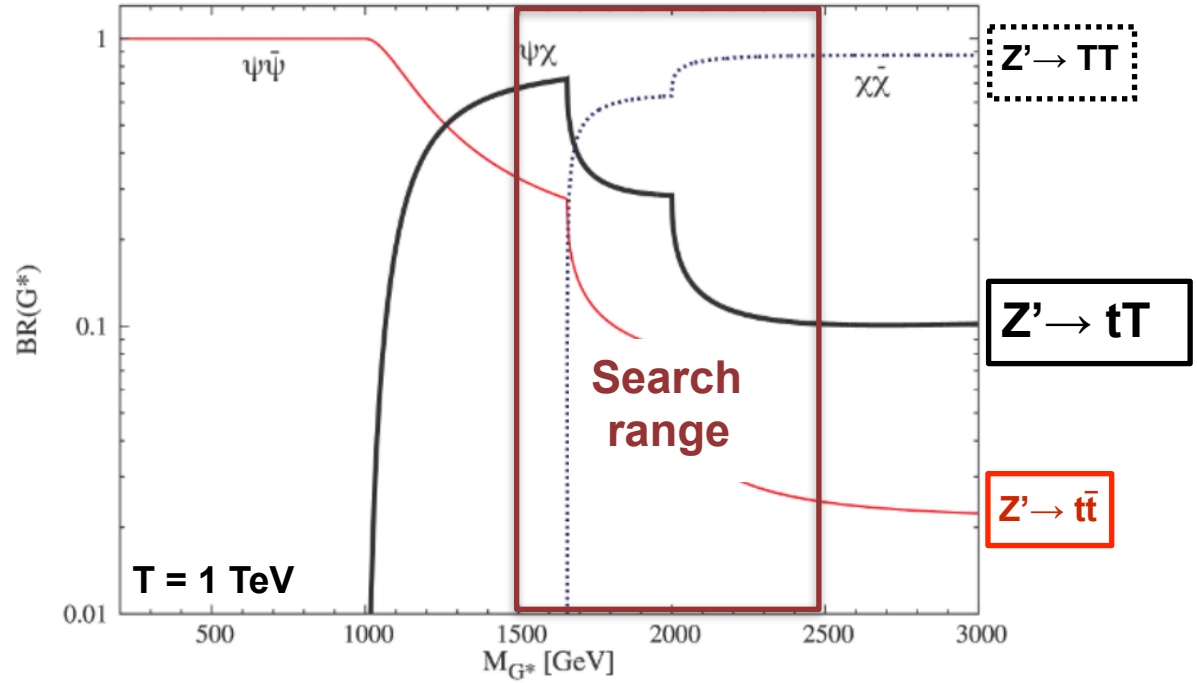
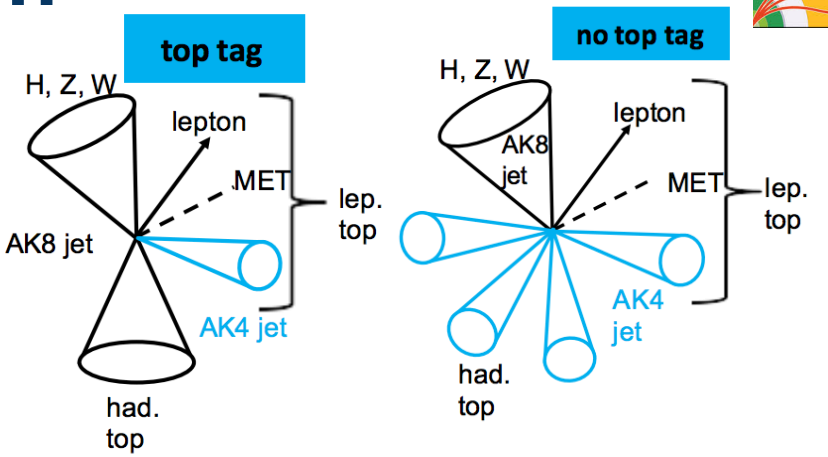
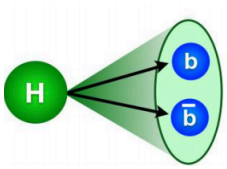


Z' → tT: Event Selection

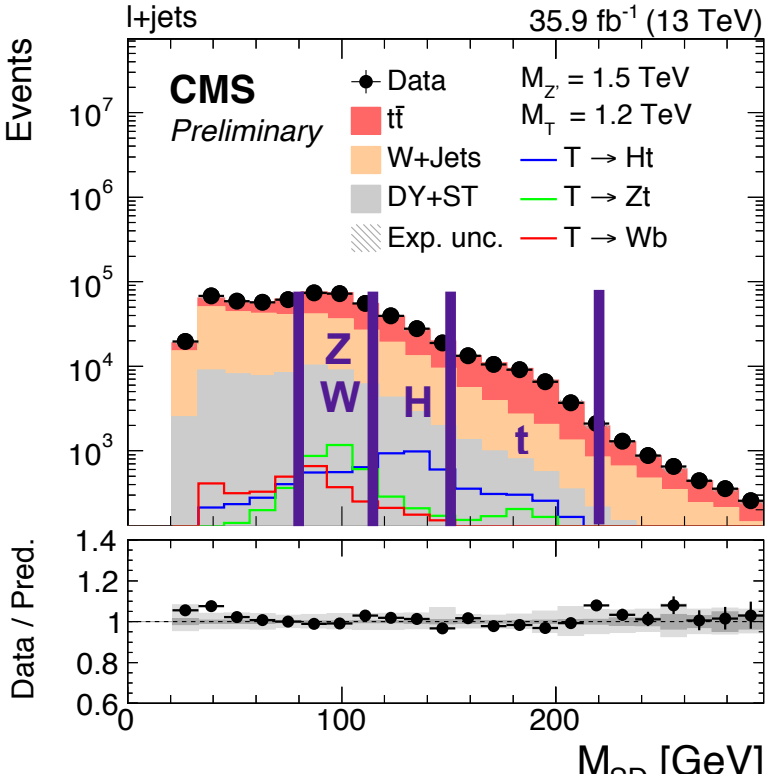
- Preselection:
  - exactly one e or μ
  - ≥ 1 AK4, ≥ 1 AK8 jet
  - MET
  - Non-isolated lepton



- Signal region:
  - Categorize based on number of boosted jet (Z/W/H/t) tags
    - Softdrop mass
    - τ_{32} (t), τ_{21} (Z/W)
    - subjet b-tags (H)

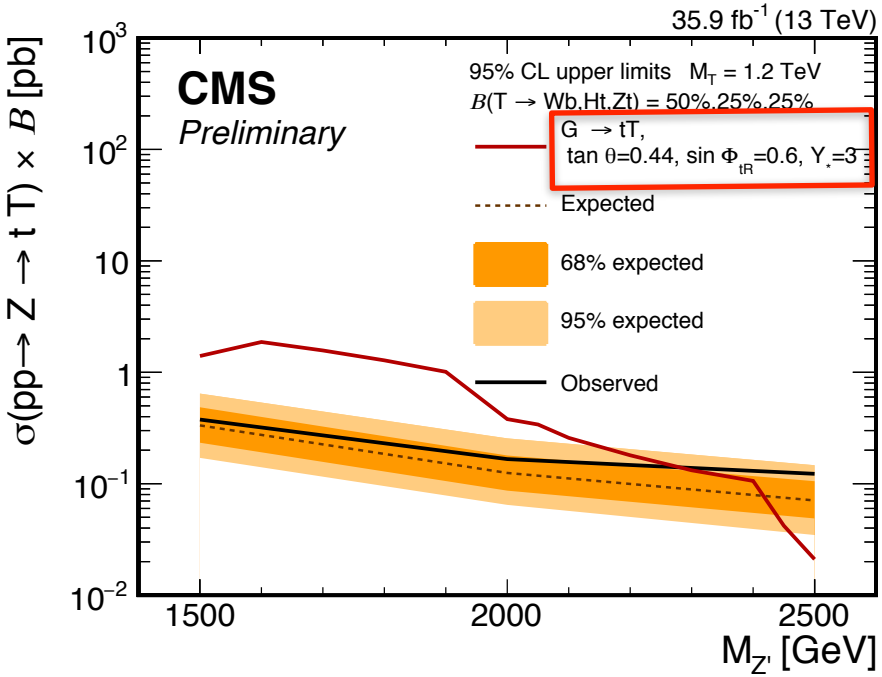


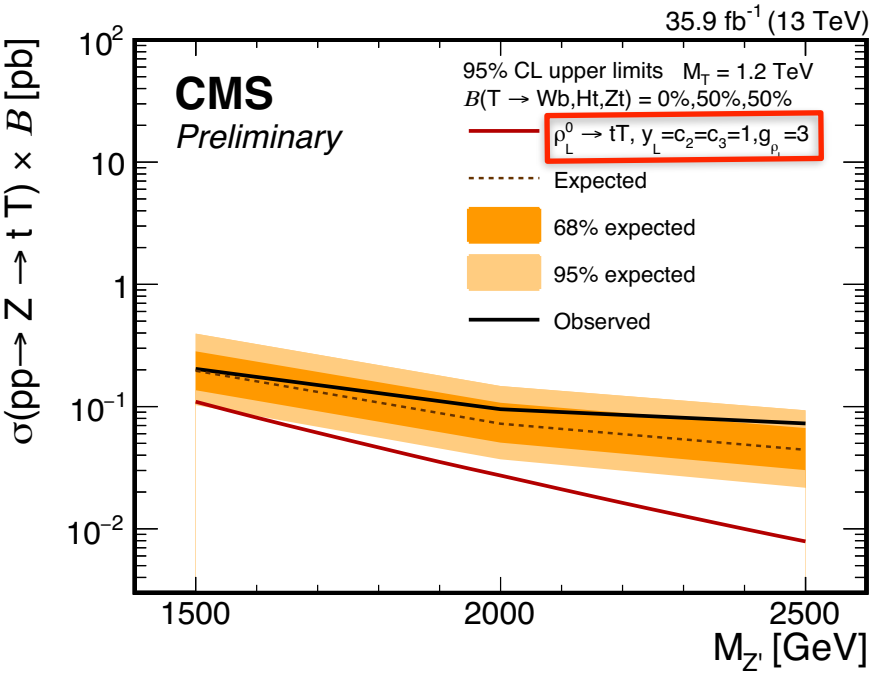
- Perform X^2 reconstruction of the system



Z' → tT: Results

- Consider T masses between 700 -1500 GeV
  - Below: m_T = 1.2 TeV
- Limits set as a function of Z' mass
  - **First results for Ht channel!**
  - Exceeds sensitivity of previous searches





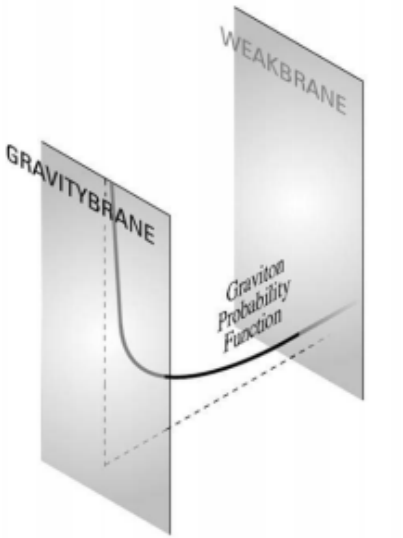
Resonances

Vector-Like Quarks

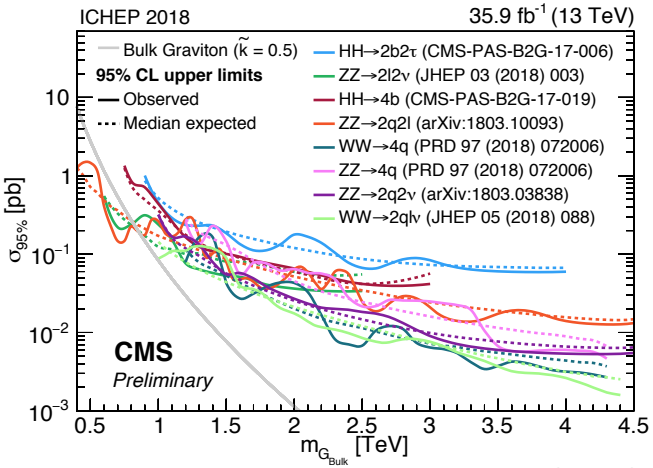
➤**Dibosons**

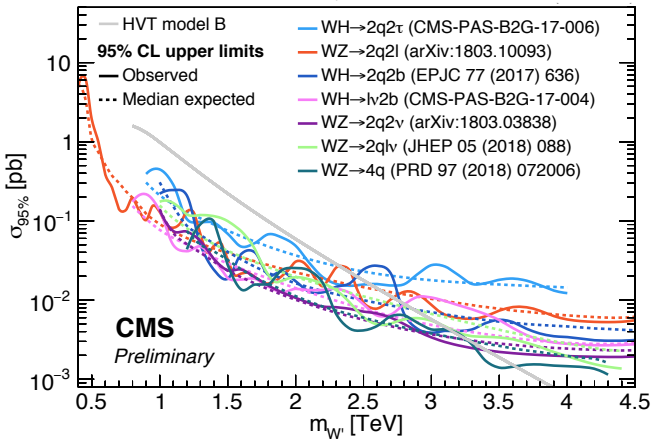
Diboson Resonances

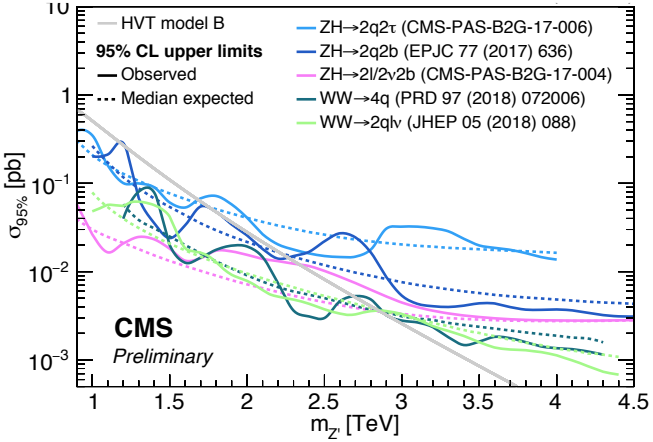
- Warped extra dimensional (WED) models aim to incorporate gravity into the SM
  - Predict spin-2 bulk graviton



- Heavy Vector Triplet (HVT) models
  - Include weakly coupled Z'^{0}, W'^{0}; strongly coupled composite Higgs; and little Higgs models
  - Predict heavy spin-1 resonances

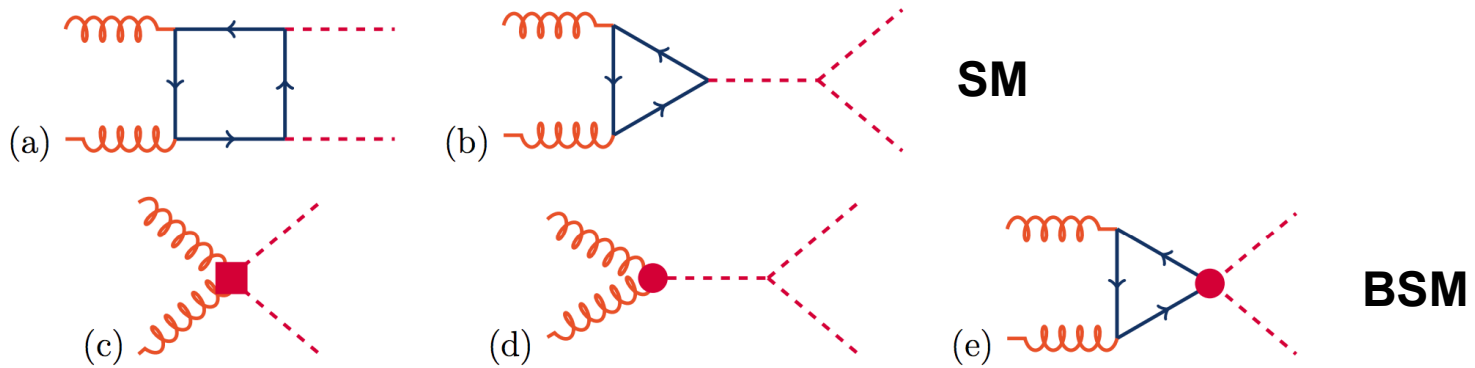




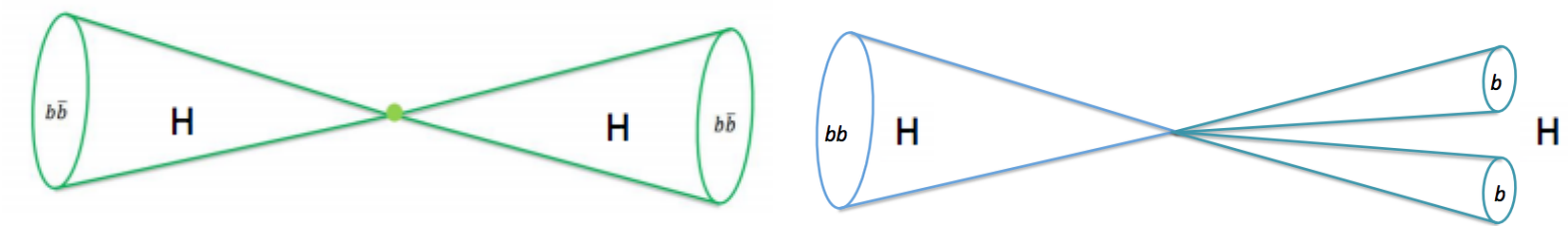


Resonant and Non-Resonant HH → bbbb

- Resonant: WED models predict spin-2 graviton, spin-0 radion
  - Largest branching ratio to HH
- Non-resonant: Deviations from SM (a,b), BSM contact interactions between Higgs and gluons (c,d) or tops (e)
  - Consider 12 benchmark BSM models

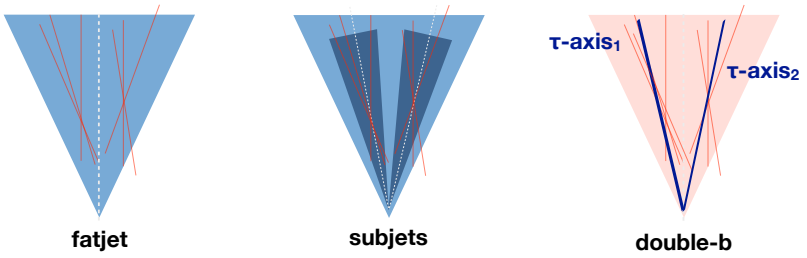


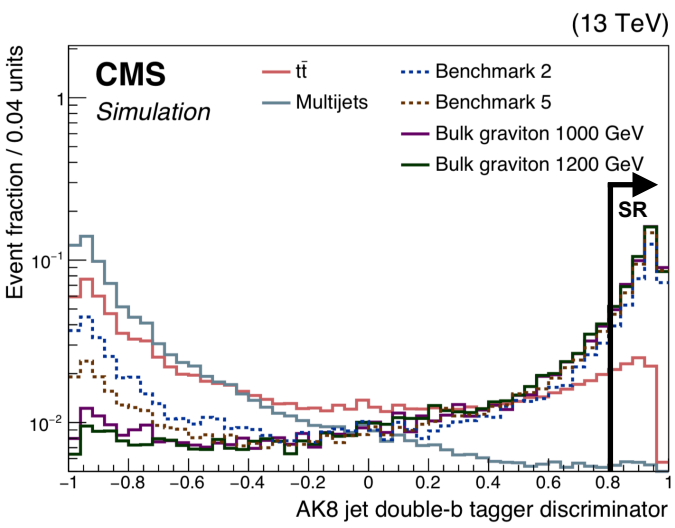
- Look for H → bb
- Consider both **fully** merged and semi-merged cases

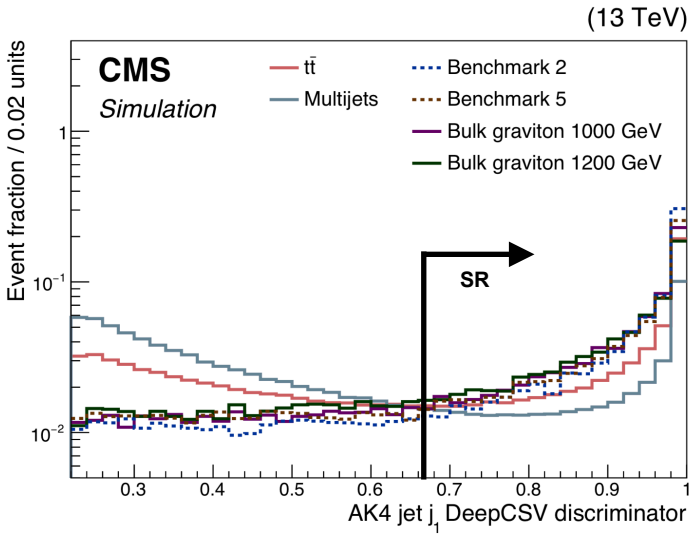


HH → bbbb: Event Selections

- Use jet substructure tools to distinguish signal from main background: top, QCD
  - Fully merged H: AK8 jet
    - Softdrop mass cut
    - PUPPI τ_{21} cut
    - Double b-tagger
  - Partially merged H: two AK4 jets
    - Deep CSV
      - **New!** Deep NN for jet flavor tagging
    - Combined mass near H mass

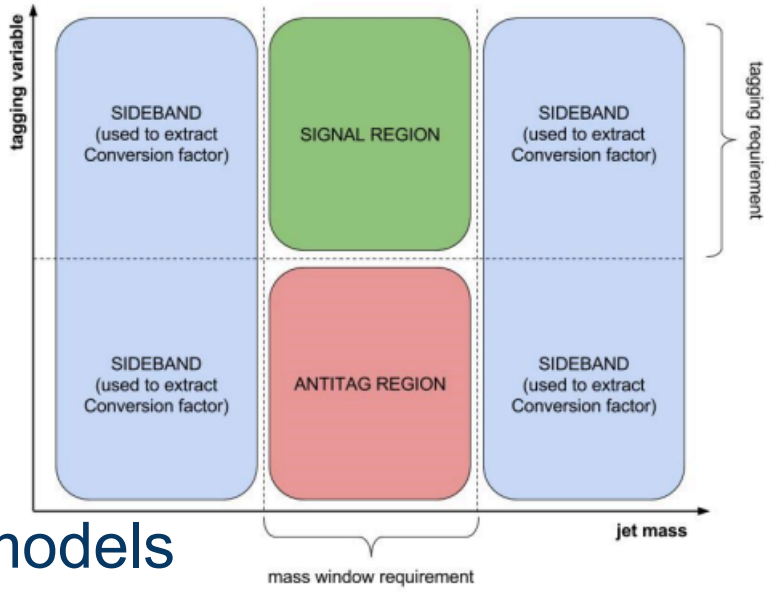




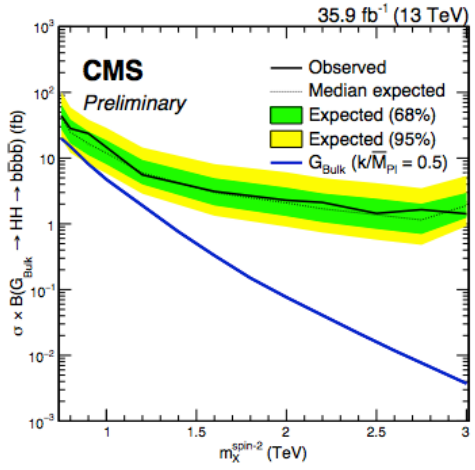


HH → bbbb: Background Estimation and Results

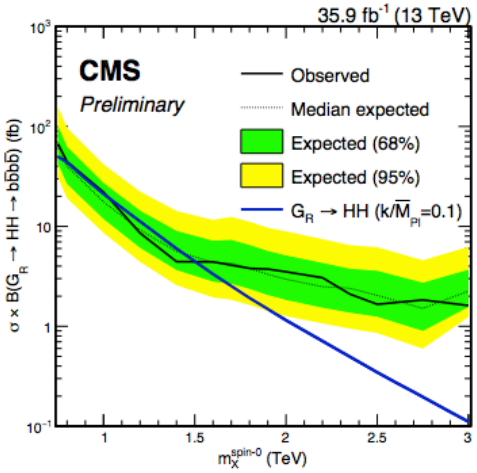
- Use alphabet method to estimate QCD background
  - Popular method in B2G
  - Sidebands used to estimate background in SR
    - Done in bins to predict entire background shape



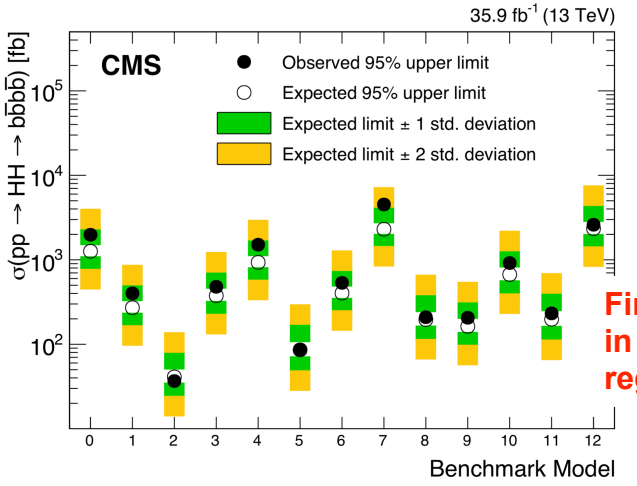
- **Improved limits** set for graviton, radion, non-resonant benchmark models



bulk graviton > 2.0 TeV fully merged limits only



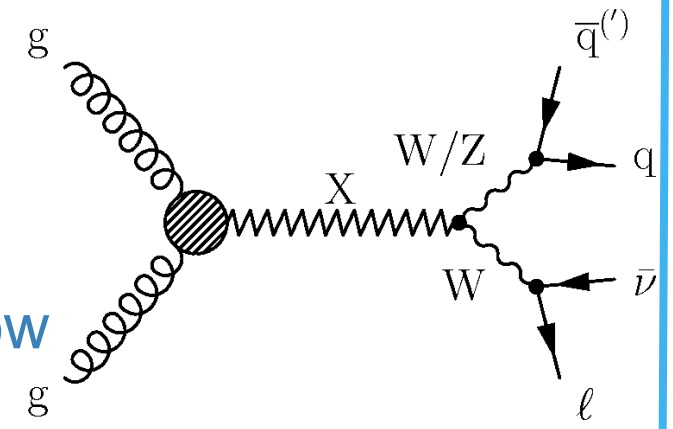
radion > 1.6 TeV fully merged limits only

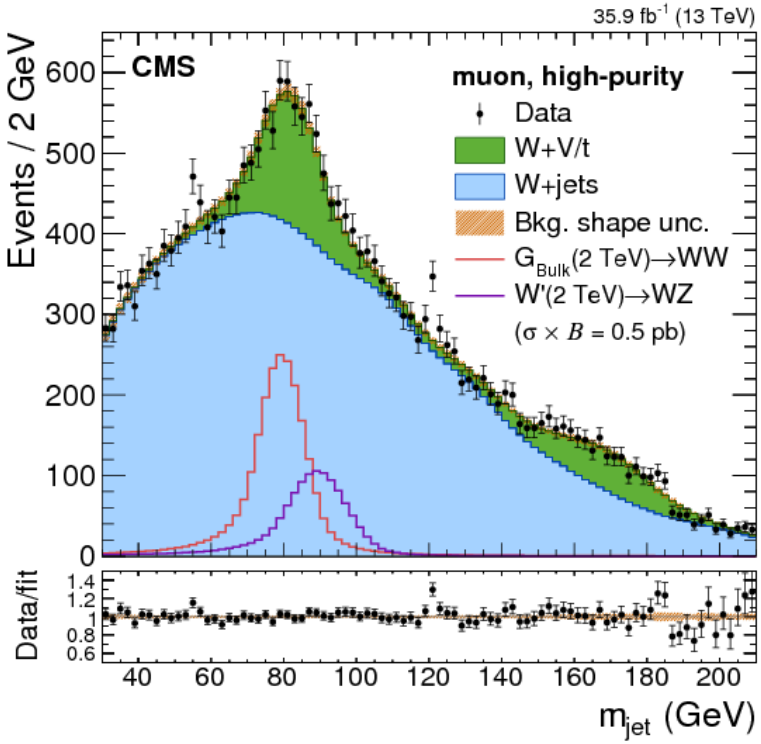


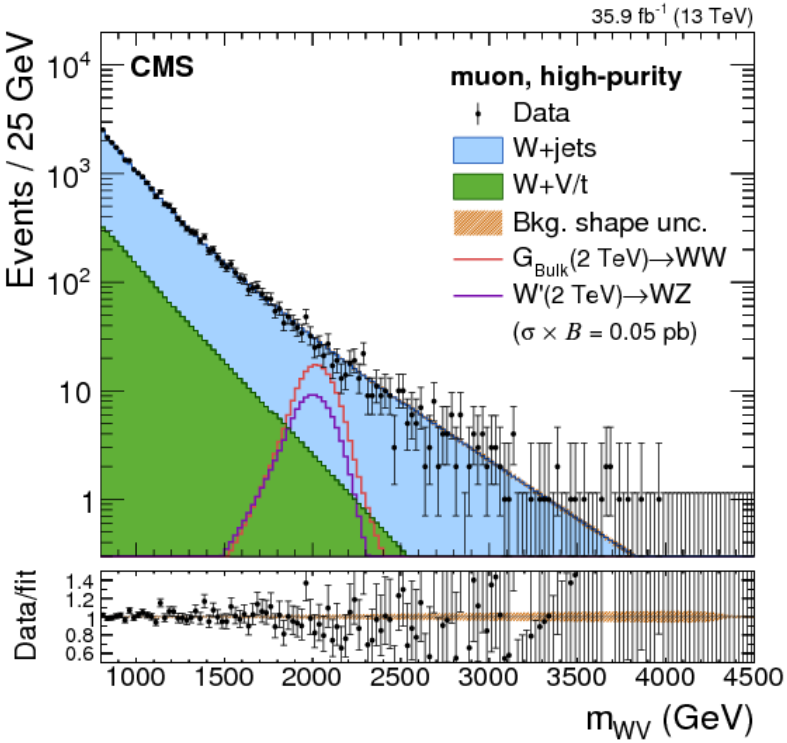
First limits in boosted regime!

Two-Dimensional Search: WV Resonance

- Search: X → WV, semileptonic
- Two dimensional search!
  - Simultaneously fit m_{jet}, m_{WV} spectra
  - N-subjettiness cut, wide mass window
  - Increase sideband statistics

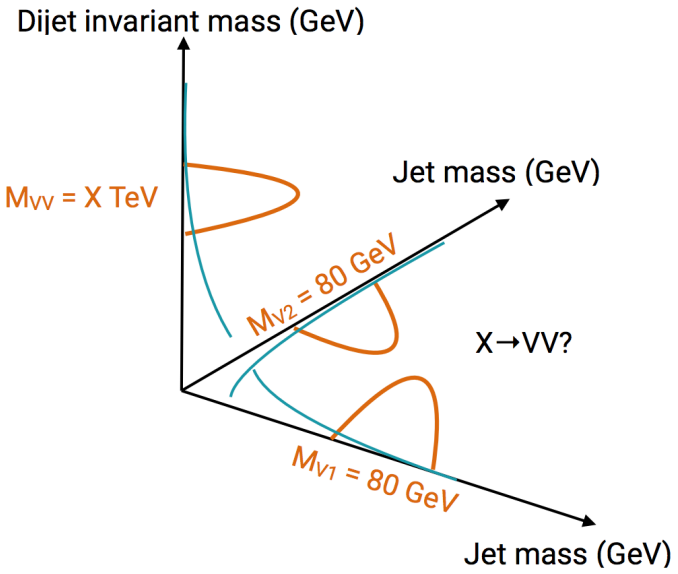


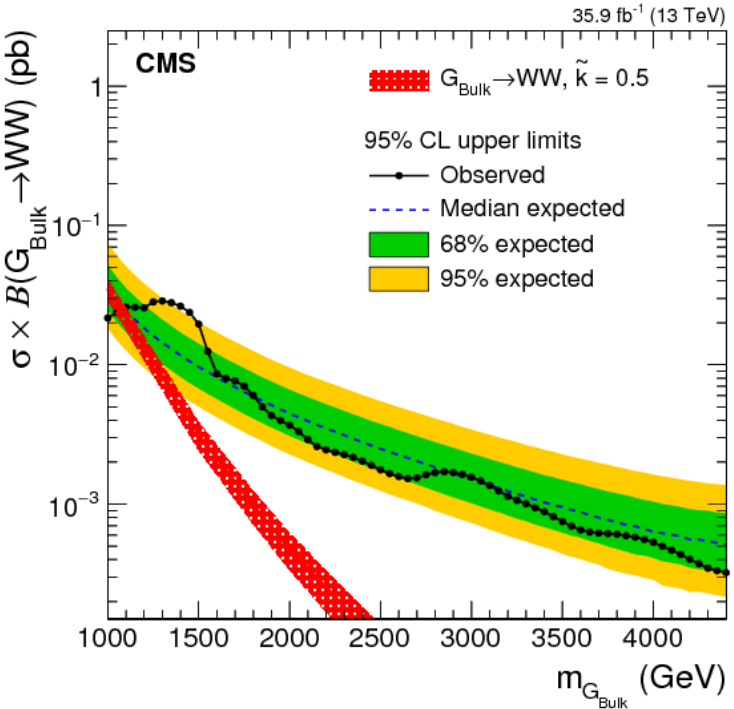


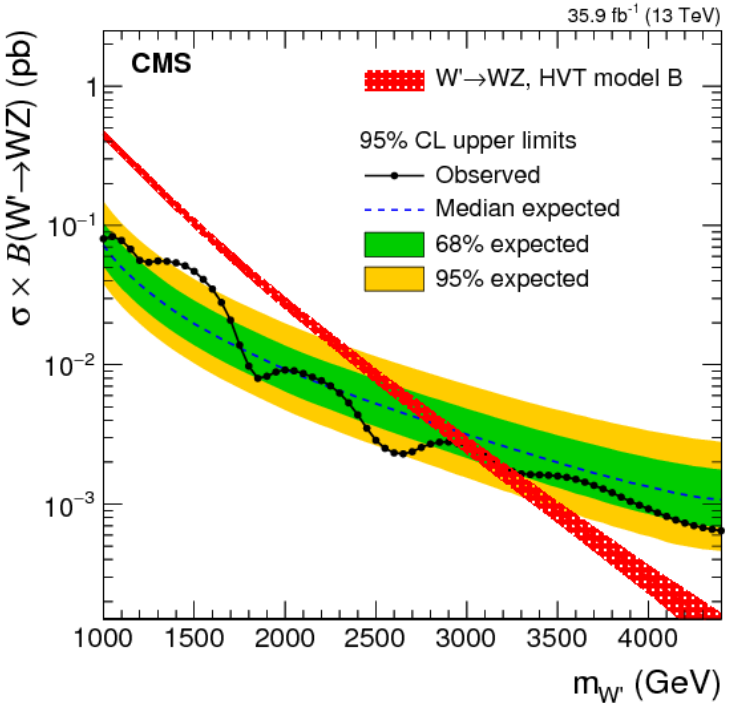


WV: Results and Future

- No new physics found yet!
- Outlook: extend this method into 3D with the all-hadronic channel



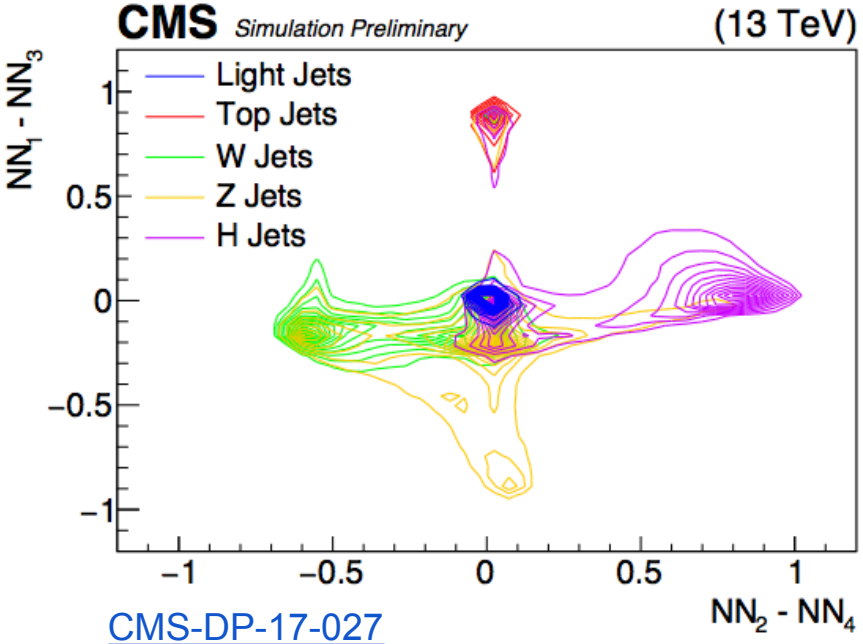




Conclusions

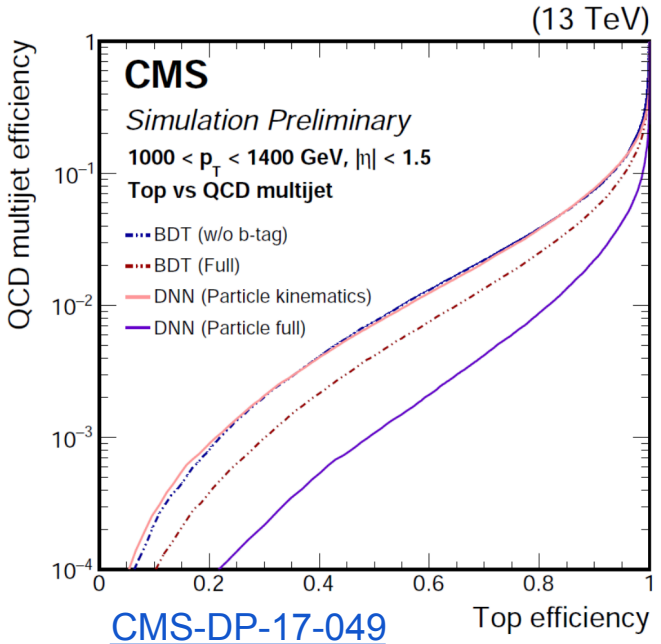
- B2G: search for new particles decaying to heavy SM particles
  - No signs of new physics yet!
- Boosted objects are the bread and butter of B2G!
  - Jet substructure tools widely used
- New tools being implemented
  - 2D alphabet, multidimensional fits
  - ML tools: stay tuned for ML4Jets workshop

Boosted Event Shape Tagger



CMS-DP-17-027

DeepAK8



CMS-DP-17-049

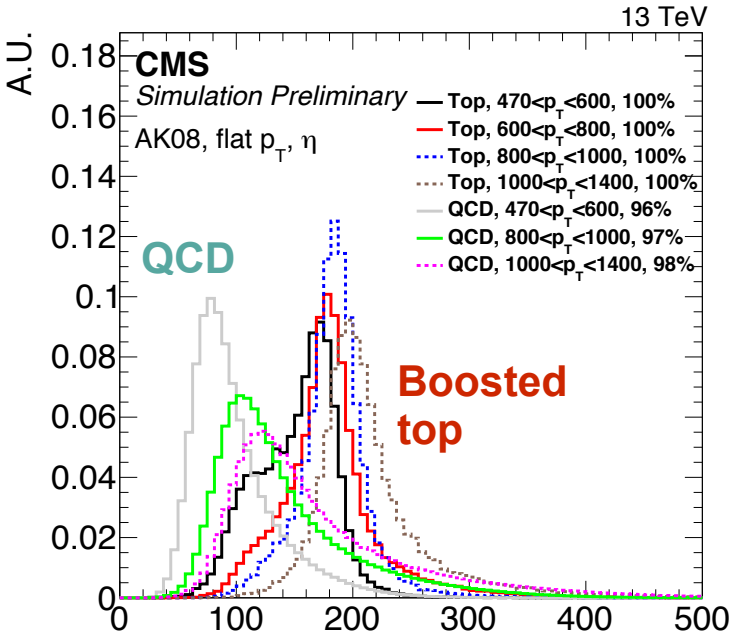
Additional Material

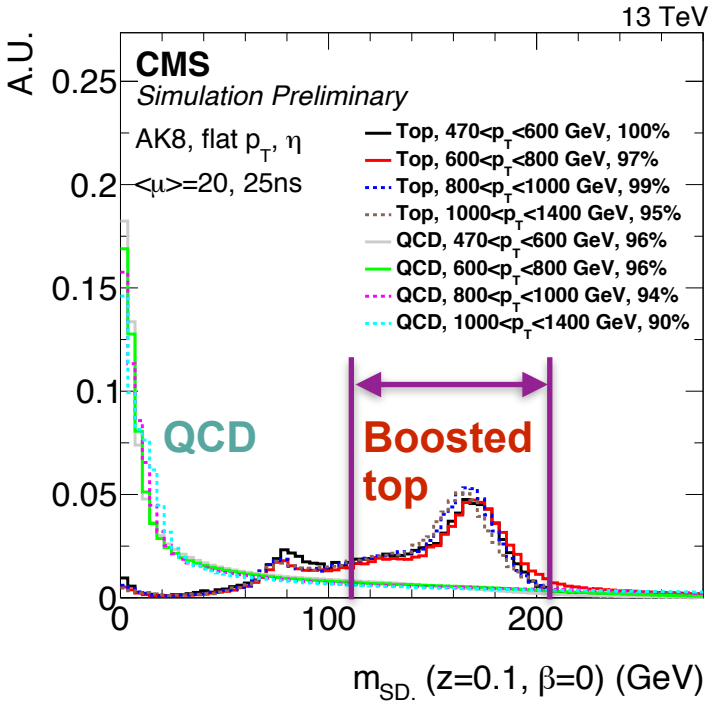
Boosted Top Quark ID: Jet Mass

- Signal jet mass should be ~ top quark mass

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}$$ tunable variables

- Measure groomed jet mass
  - **Soft drop** algorithm removes soft, wide-angle radiation from a jet





CMS-PAS-JME-15-002

Boosted Top Quark ID: N-subjettiness

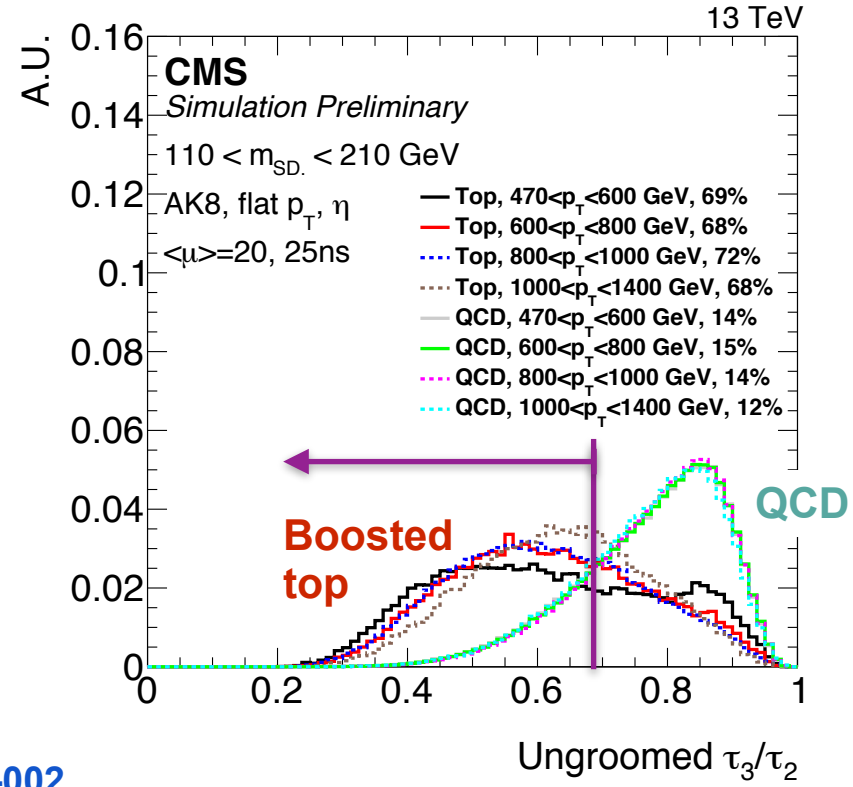
- N-subjettiness: Jet shape variable to measure consistency of jet to have N or fewer subjets

$$\tau_N = \frac{1}{d_0}\sum_k p_{Tk} \times \Delta R_k^{\min} \quad \text{with} \quad d_0 \equiv \sum_k p_{Tk} \times R$$

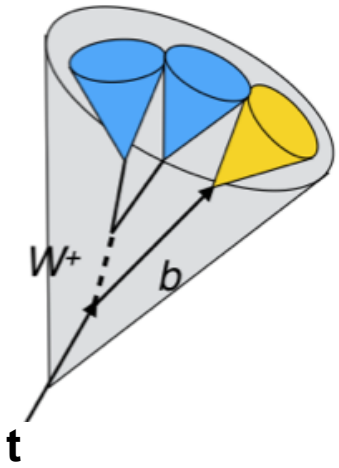
p_{Tk}: p_T of constituent k

$\Delta R_k^{\min}$: distance between constituent k & axis of closest subjet

R: large-R jet distance parameter



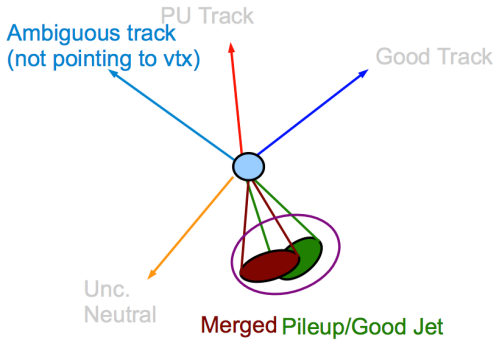
Boosted top: 3 subjets



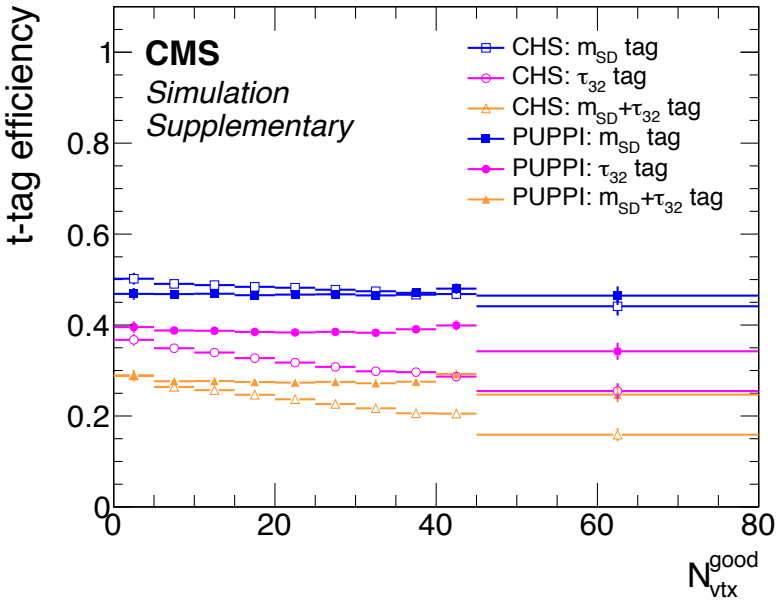
CMS-PAS-JME-15-002

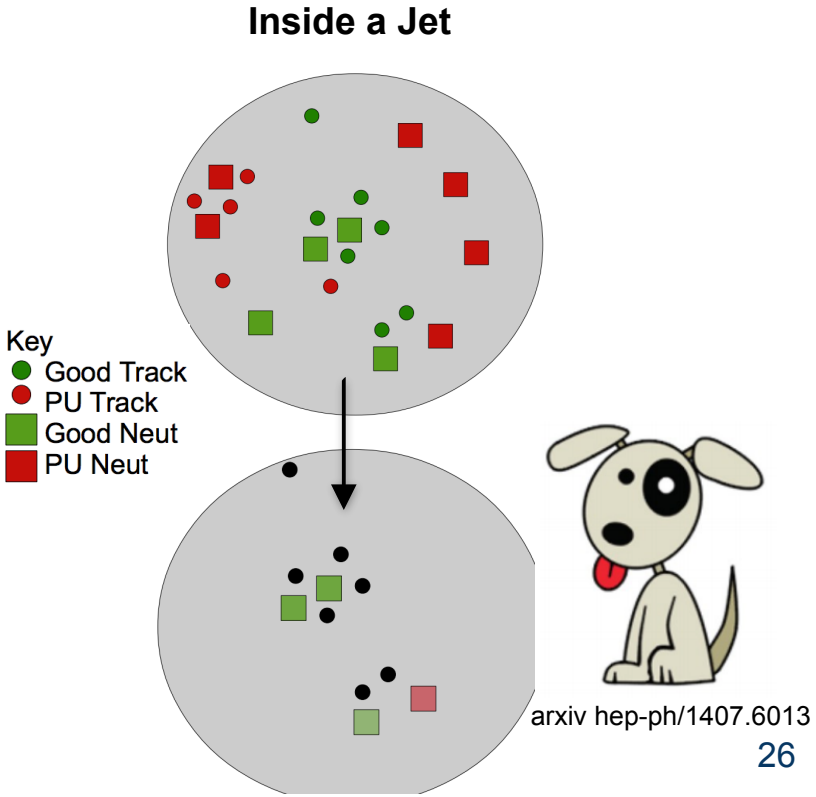
PUPPI

- **PUPPI - PileUp Per Particle Id**
  - weights particles based on their probability to have originated from a pileup vertex



- PUPPI variables improve performance w.r.t. number of primary vertices

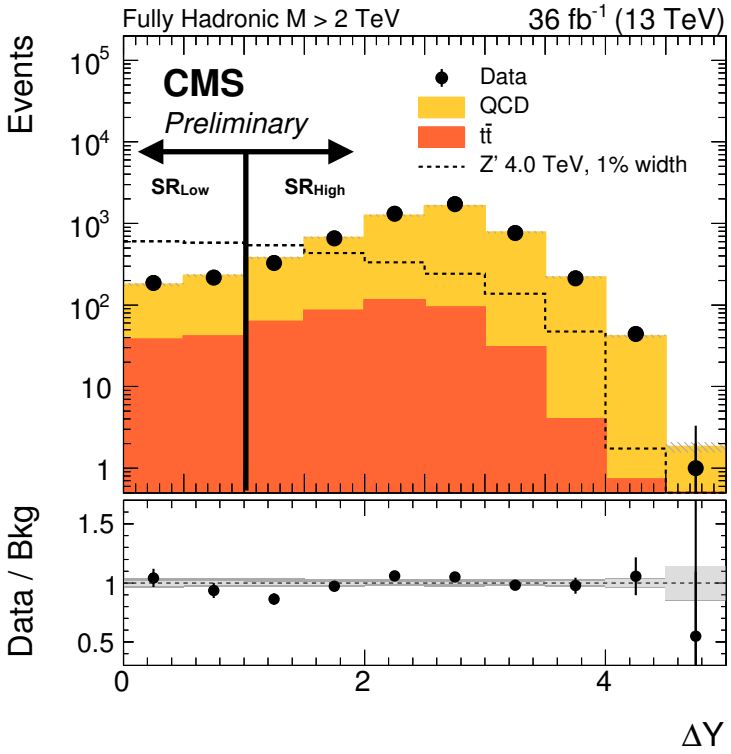


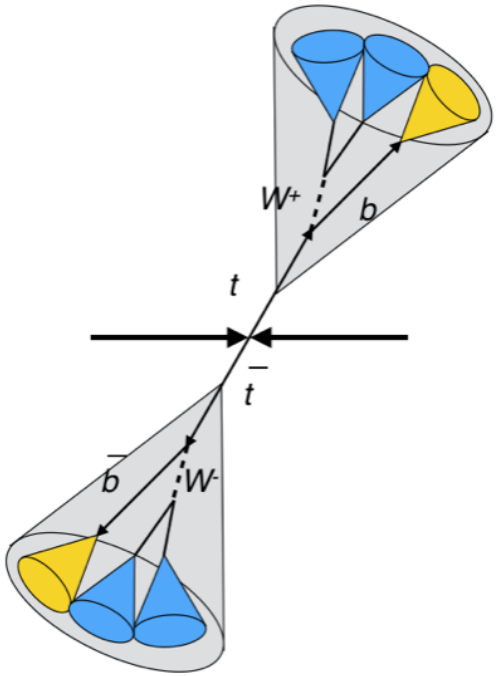


arxiv hep-ph/1407.6013

Heavy Resonances to $t\bar{t}$

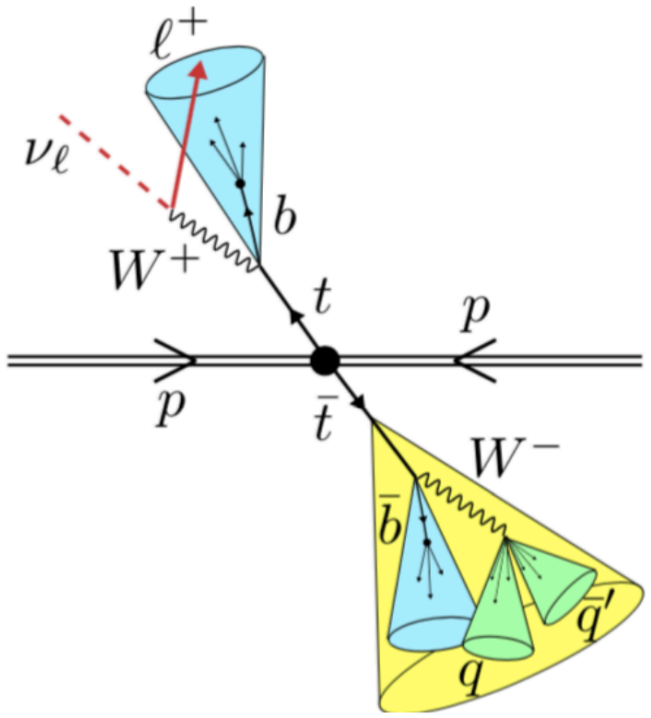
- Search for heavy spin-1 **RS KK gluon** & **Z'**(1%, 10%, 30% widths) decaying to $t\bar{t}$
  - **All-hadronic channel** - two back-to-back top-tagged **PUPPI** jets
    - Categorized by number of subjet b-tags (0,1,2) & $|\Delta y|_{tt}$
    - QCD background estimated from data, $t\bar{t}$ from MC





Heavy Resonances to $t\bar{t}$

- Search for heavy spin-1 **RS KK gluon** & **Z'**(1%, 10%, 30% widths) decaying to $t\bar{t}$
  - All-hadronic channel
  - **Semileptonic channel:**
    - e+jets, μ+jets channels
    - Lepton 2D isolation cut
      - Suppresses QCD
    - X^2-based reconstruction of top system
    - Categorized by number of top tags (0,1)
    - Background estimated from Monte Carlo
      - **W + jets suppressed by BDT**



Heavy Resonances to tt: Semileptonic

- W+jets BDT:

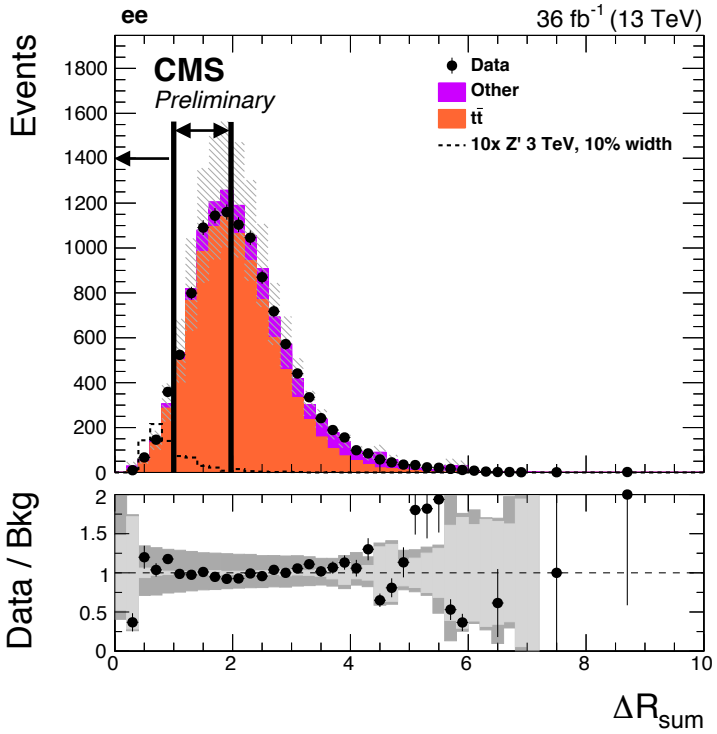
  - $\Delta R_{min}(\ell, j)$,the separation between the lepton and its closest jet
  - The CSV score of the subleading and the leading AK4 jets
  - The number of jets
  - $p_{T,rel}(\ell, j)$
  - The reconstructed mass of the leading AK4 jet
  - $\Delta R_{min}(\ell, j) \times p_T(j)$
  - The reconstructed mass of the subleading AK4 jet
  - The shape variable S_{33} of the sphericity tensor $S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |p_i|^2}$ where α, β correspond to the x, y and z components of the momentum vectors of the jets
  - $S_T \equiv H_T + H_T^{lep}$, where H_T is the scalar sum of the p_T of the jets

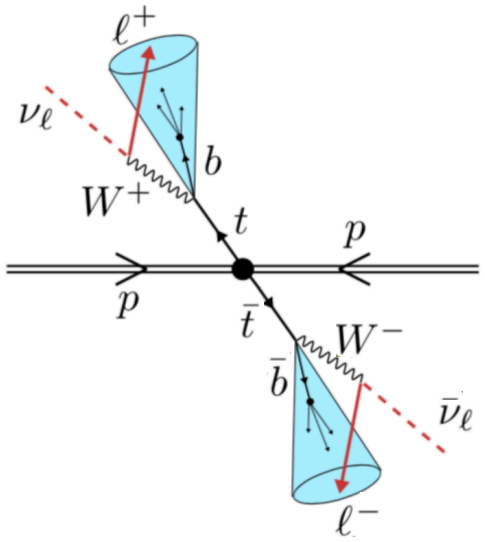
$$\chi^2 < 30$$

$$\chi^2 = \chi^2_{lep} + \chi^2_{had} = \left[\frac{M_{lep} - \bar{M}_{lep}}{\sigma_{M_{lep}}}\right]^2 + \left[\frac{M_{had} - \bar{M}_{had}}{\sigma_{M_{had}}}\right]^2$$

Heavy Resonances to $t\bar{t}$

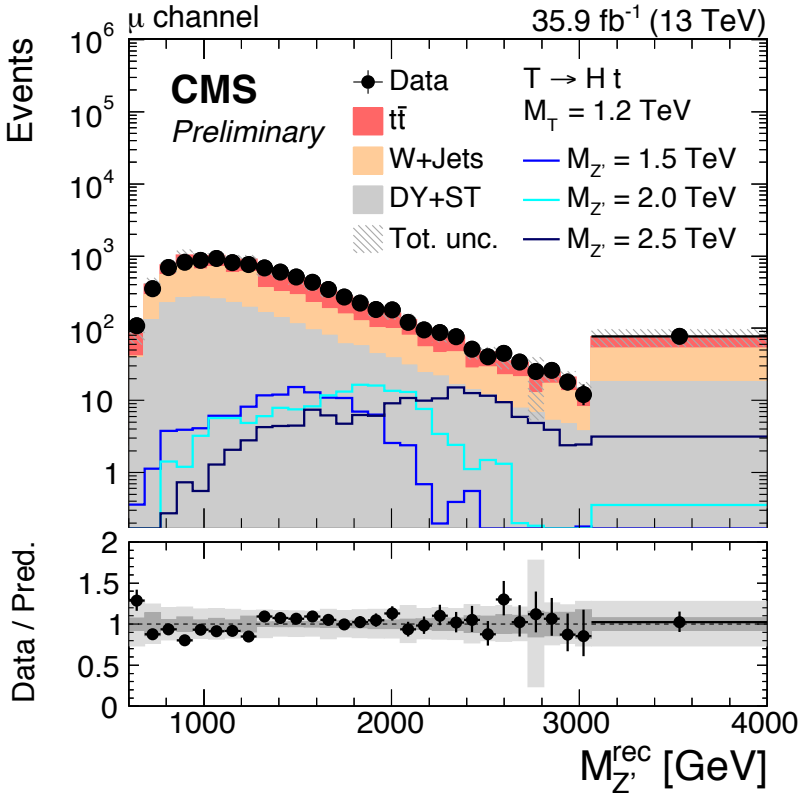
- Search for heavy spin-1 **RS KK gluon** & **Z'**(1%, 10%, 30% widths) decaying to $t\bar{t}$
  - All-hadronic channel
  - Semileptonic channel
  - **Dileptonic channel**
    - ee, μμ channels
    - Lepton 2D isolation cut
    - At least one b-tagged jet
    - Characterize signal region by lepton/jet separation
    - Background: $t\bar{t}$ (MC)

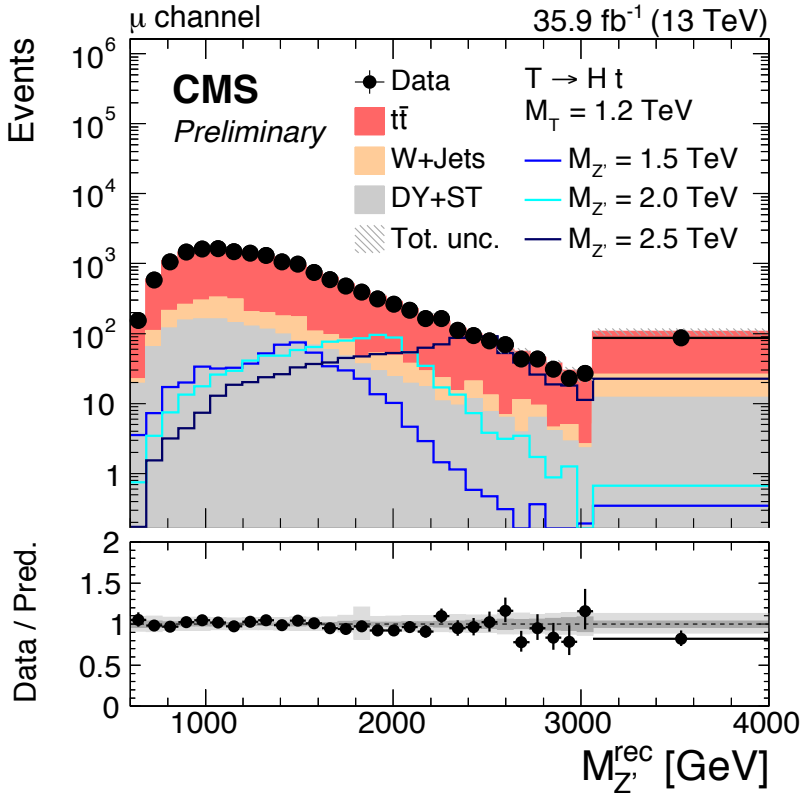




Z' → tT: Backgrounds

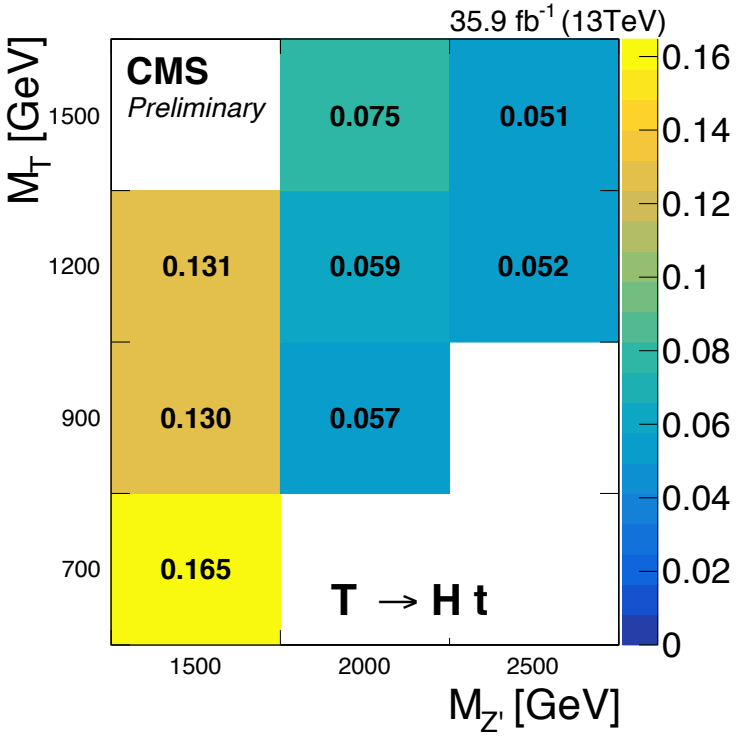
- Take background from simulation
- Fit control regions to simultaneously constrain backgrounds
  - Mass sideband: M_{SD} < 60 GeV & 150 GeV > M_{SD}
  - X^2 < 50
  - 0 b-tags: W+jets; 1 b-tag: $t\bar{t}$

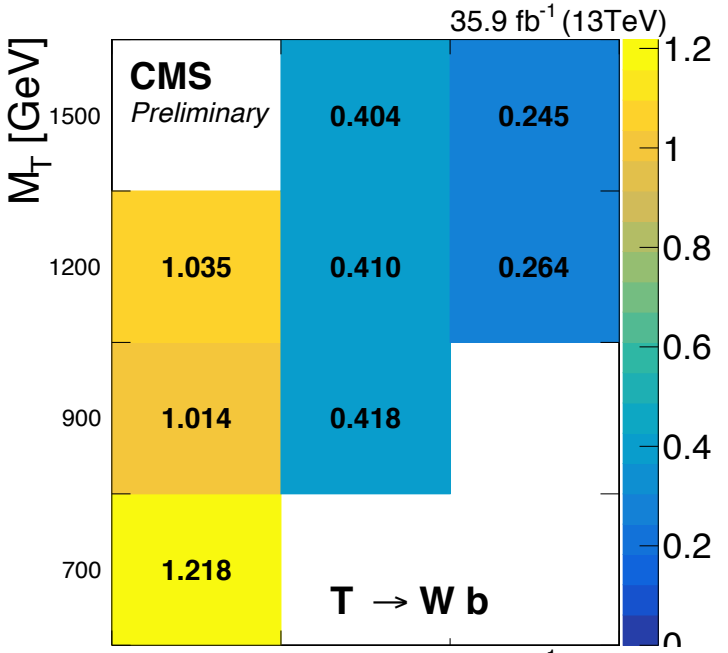


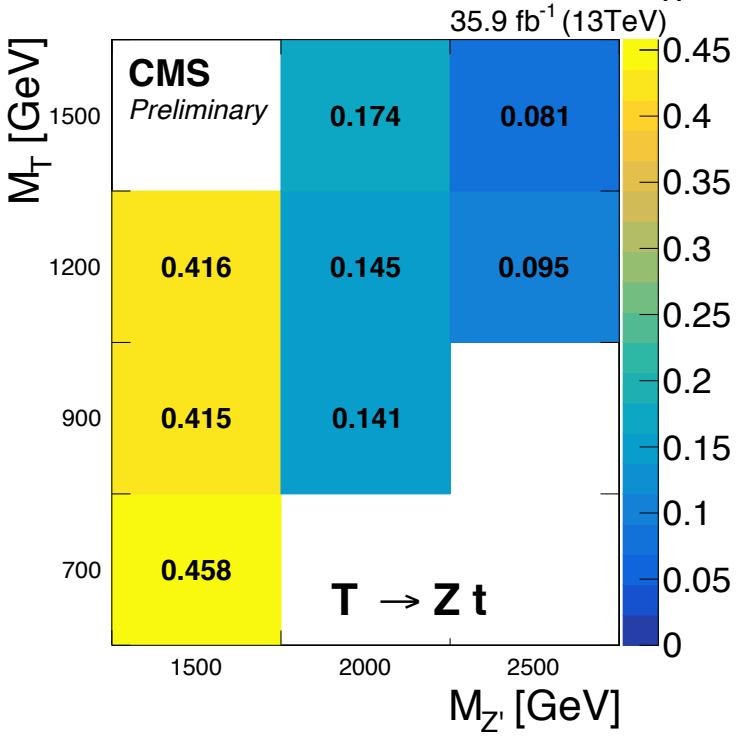


Z' → tT: Results

- Limits set as a function of Z' mass and T mass
  - **First results for Ht channel!**
  - Assume 100% BR for given T decay mode

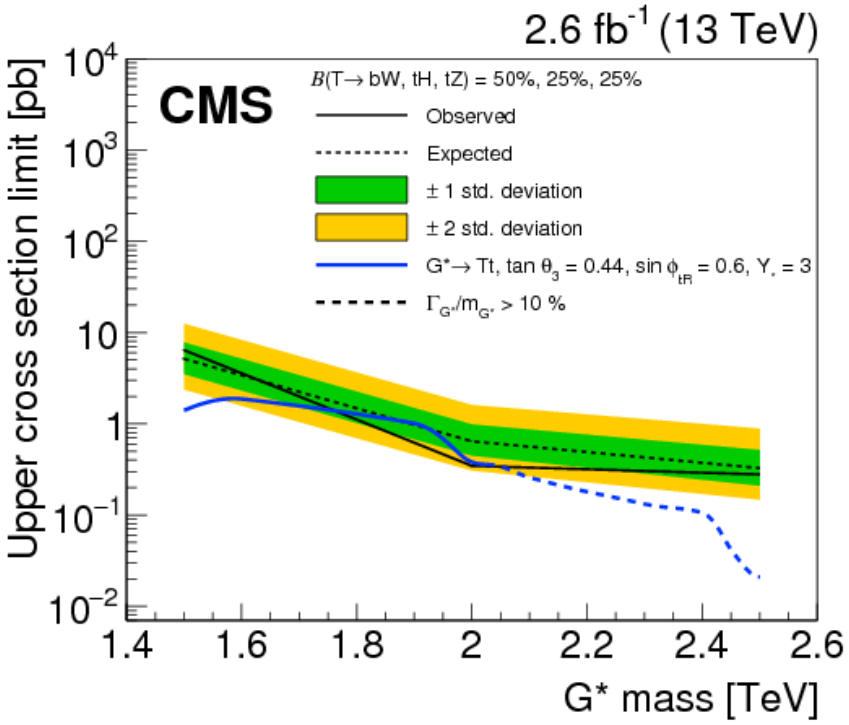


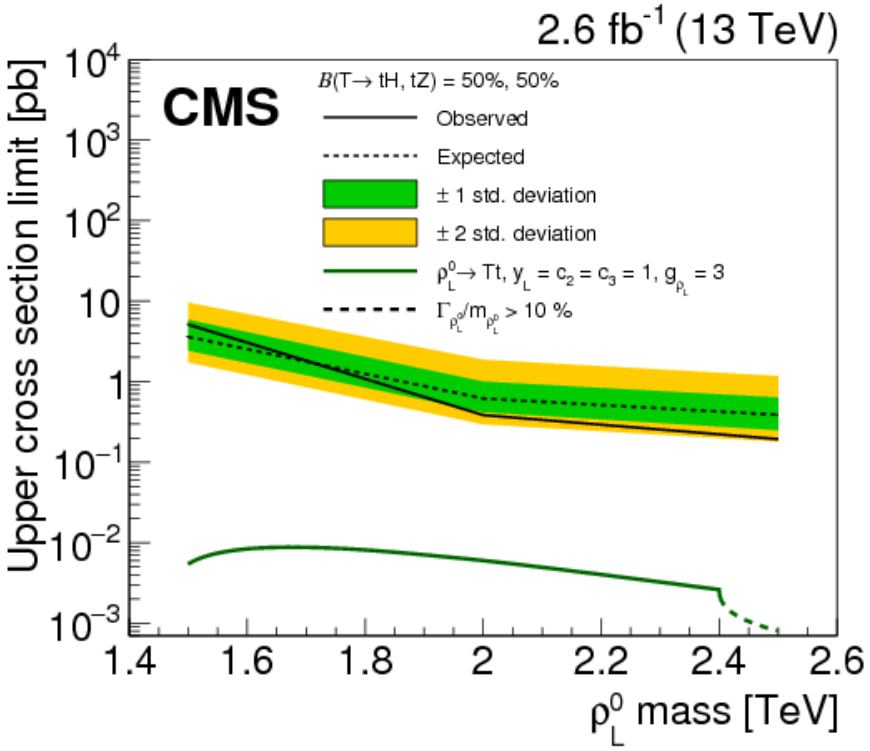




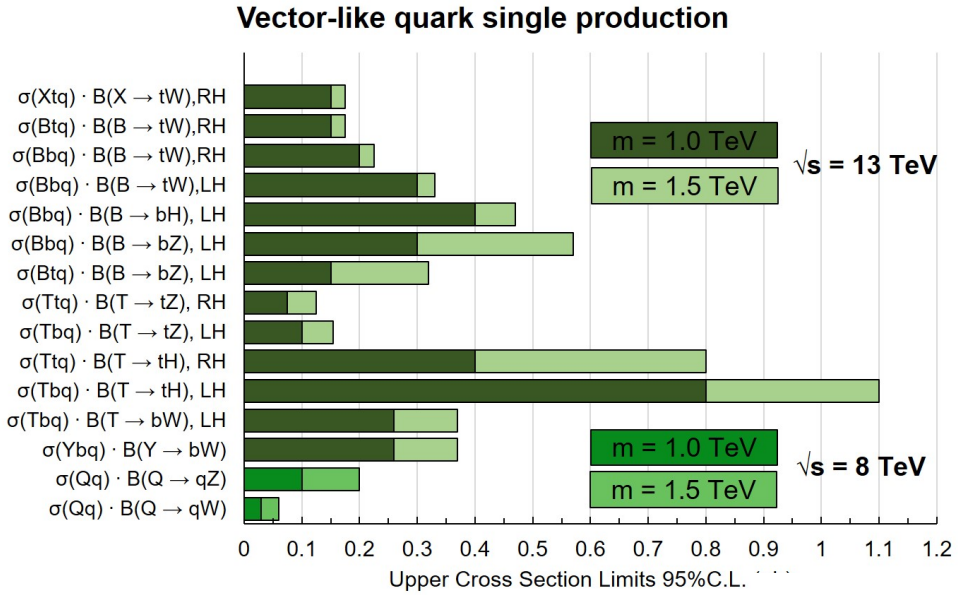
Z' → tT: Previous Results

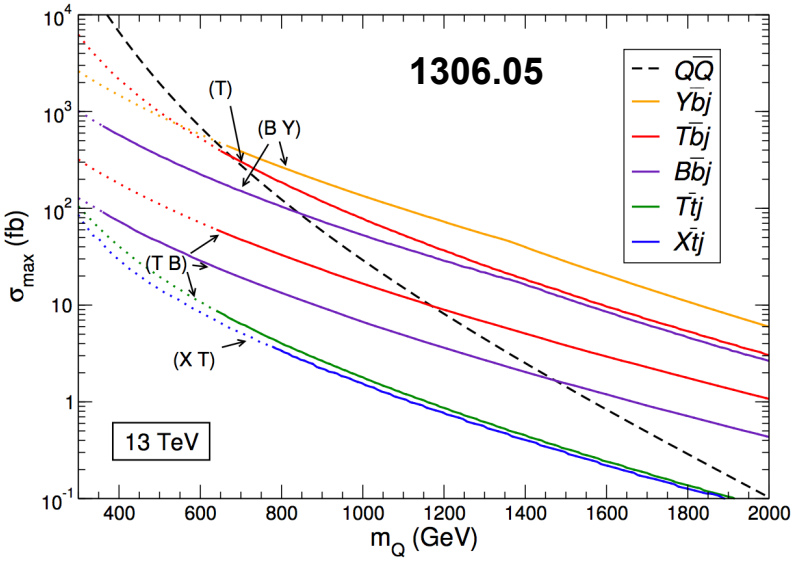
- Limits set as a function of Z' mass
  - **Optimized for bW channel**





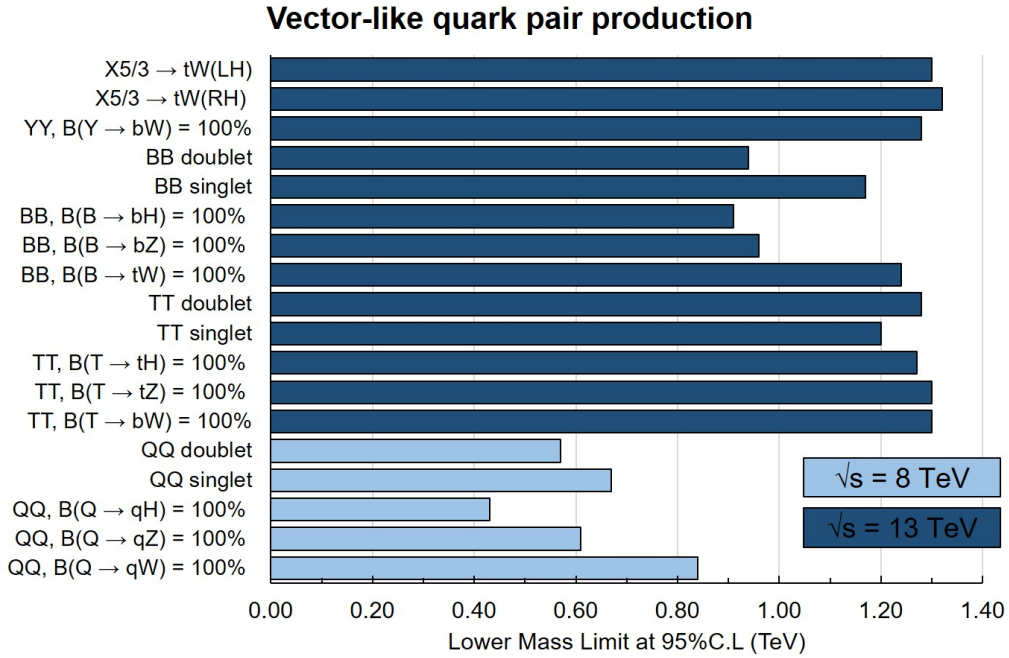
VLQ Results





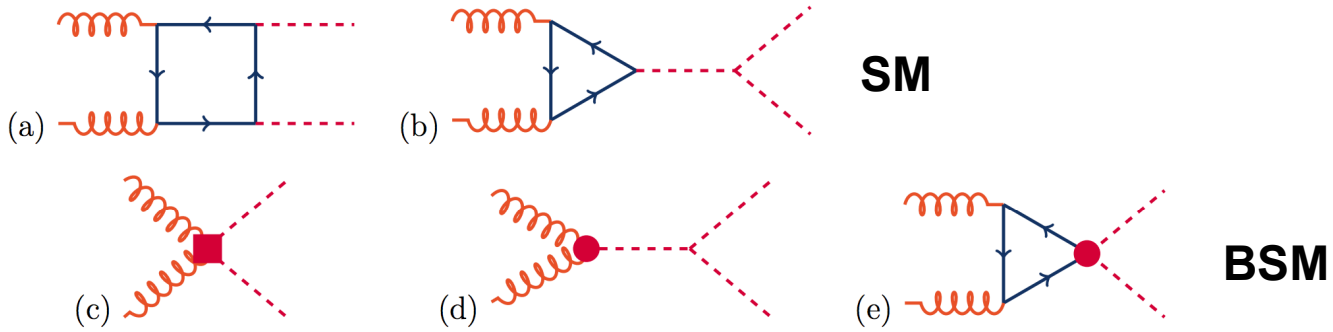
Weak multiplets (isospin$_{\text{hypercharge}}$)

Singlets	Doublets	Triplets
$\mathbf{1}_{2/3} = T$	$\mathbf{2}_{1/6} = \begin{pmatrix} T \\ B \end{pmatrix}$	$\mathbf{3}_{2/3} = \begin{pmatrix} X \\ T \\ B \end{pmatrix}$
	$\mathbf{2}_{7/6} = \begin{pmatrix} X \\ T \end{pmatrix}$	
$\mathbf{1}_{-1/3} = B$	$\mathbf{2}_{-5/6} = \begin{pmatrix} B \\ Y \end{pmatrix}$	$\mathbf{3}_{-1/3} = \begin{pmatrix} T \\ B \\ Y \end{pmatrix}$



Non-Resonant HH → bbbb

- Non-resonant: Deviations from SM (a,b), BSM contact interactions between Higgs and gluons (c,d) or tops (e)



- Consider 12 benchmark BSM models

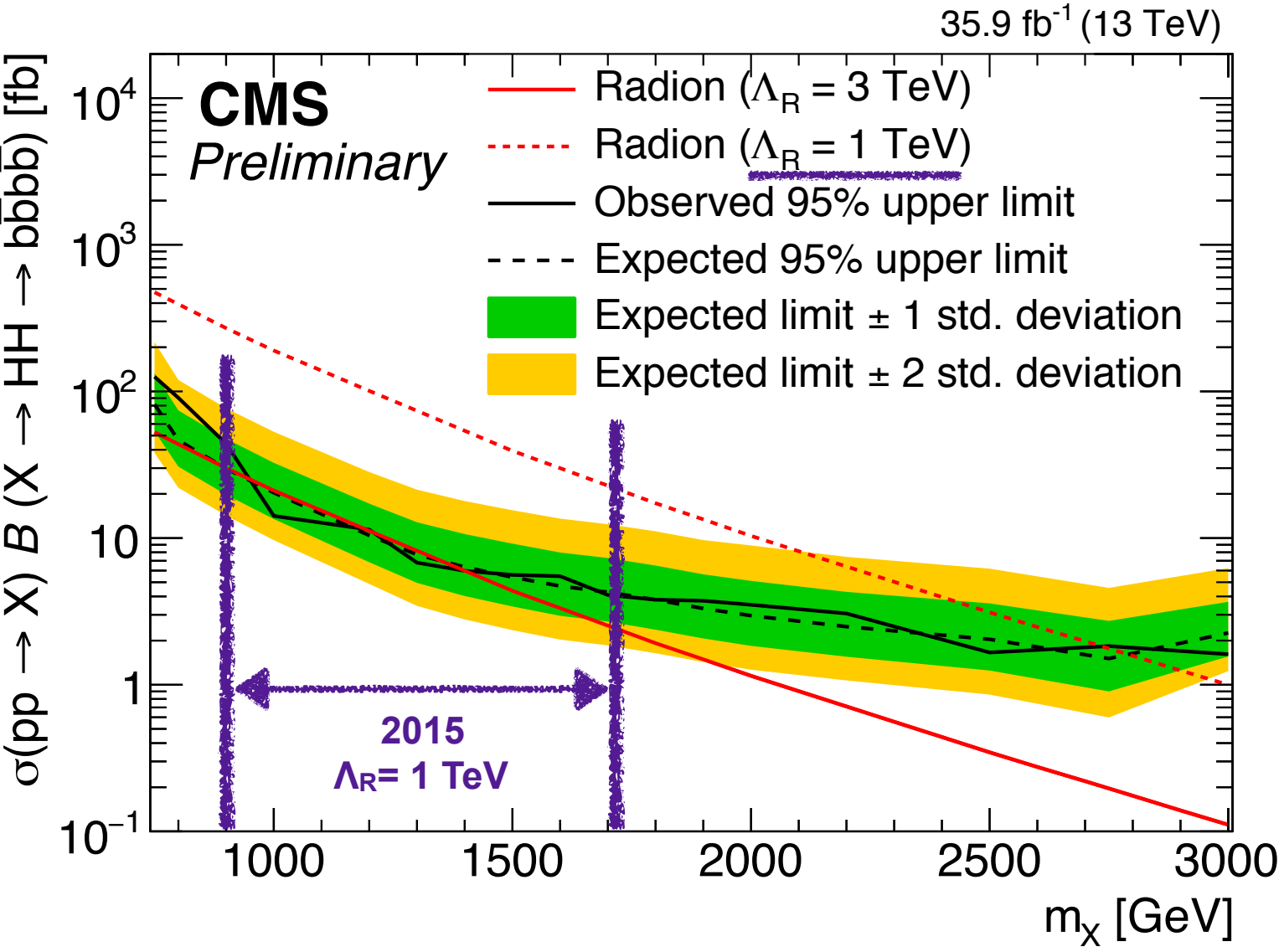
Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1.0
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1.0	1.0
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1.0	-1.0
12	15.0	1.0	1.0	0.0	0.0
SM	1.0	1.0	0.0	0.0	0.0

Semi-Resolved HH → bbbb

Table 2: Summary of the selection criteria for semi-resolved HH → $b\bar{b}b\bar{b}$ events.

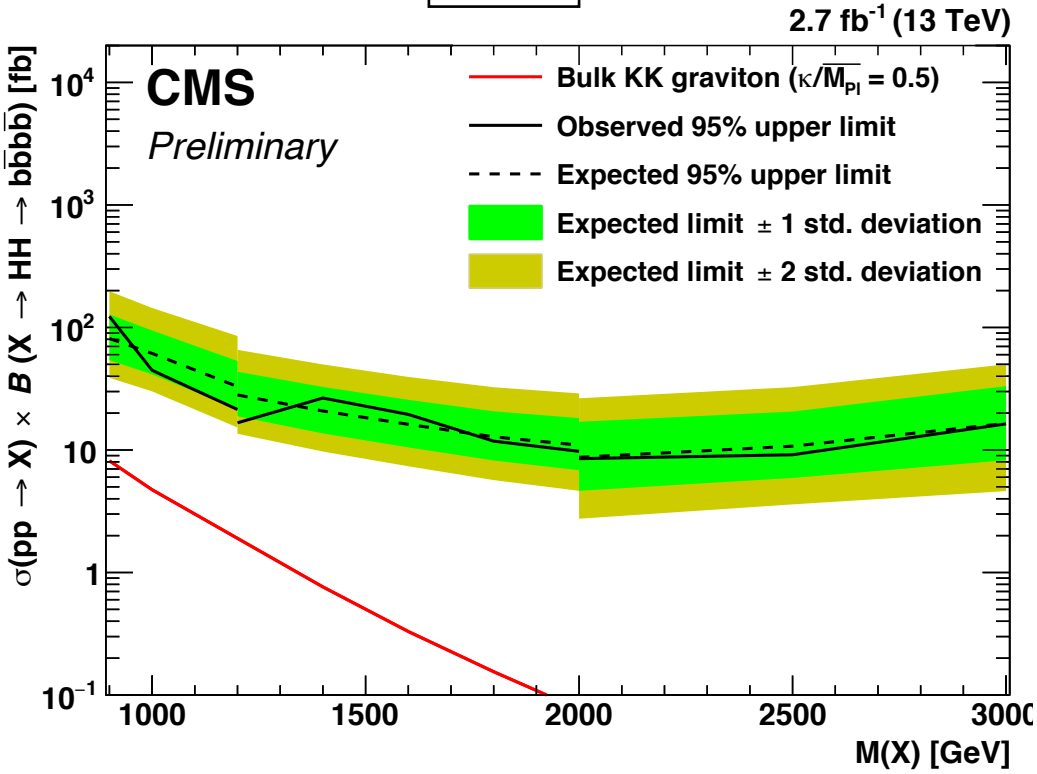
Variable	Selection
Trigger Selection	
1 AK8 jet J	$p_T > 300$ GeV, $\lvert\eta\rvert < 2.4$
2 AK4 jets j_1 and j_2	$p_T > 30$ GeV, $\lvert\eta\rvert < 2.4$
$\Delta R(J, j_i)$	> 0.8
$\Delta R(j_1, j_2)$	< 1.5
$\lvert\Delta\eta(J, j_1 + j_2)\rvert$	< 2.0
$m_{Jjj,\mathrm{red}}$	> 750 GeV
J soft-drop mass	105–135 GeV
J τ_{21}	< 0.55
J double-b tagger discriminator	> 0.8
j_1+j_2 mass	90–140 GeV
j_1+j_2+(nearest AK4 jet) mass	> 200 GeV
j_1 and j_2 DeepCSV	> 0.6632
Lepton veto	

HH → bbbb: Fully-Merged Radion Limits

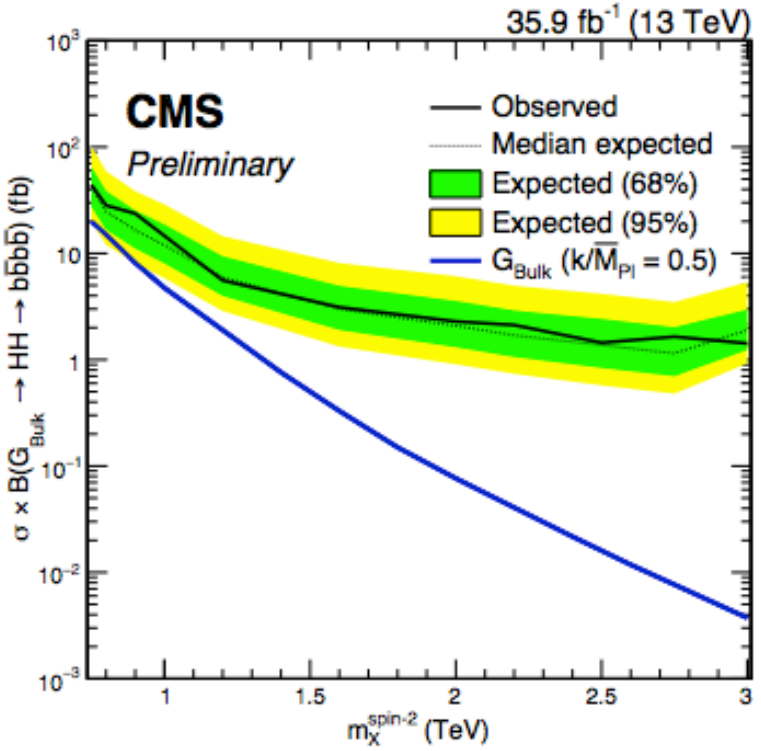


HH → bbbb: Bulk Graviton Comparisons

2015



2016



bulk graviton > 2.0 TeV fully merged limits only

Two-Dimensional Search: WV Resonance

- Search: X → WV, semileptonic
  - V-tagged jet, well-separated from lepton & MET
- Two dimensional search!
  - Simultaneously fit m_{jet}, m_{WV} spectra