New Directions for Boosted Object Searches

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Based on work in progress, in collaboration with

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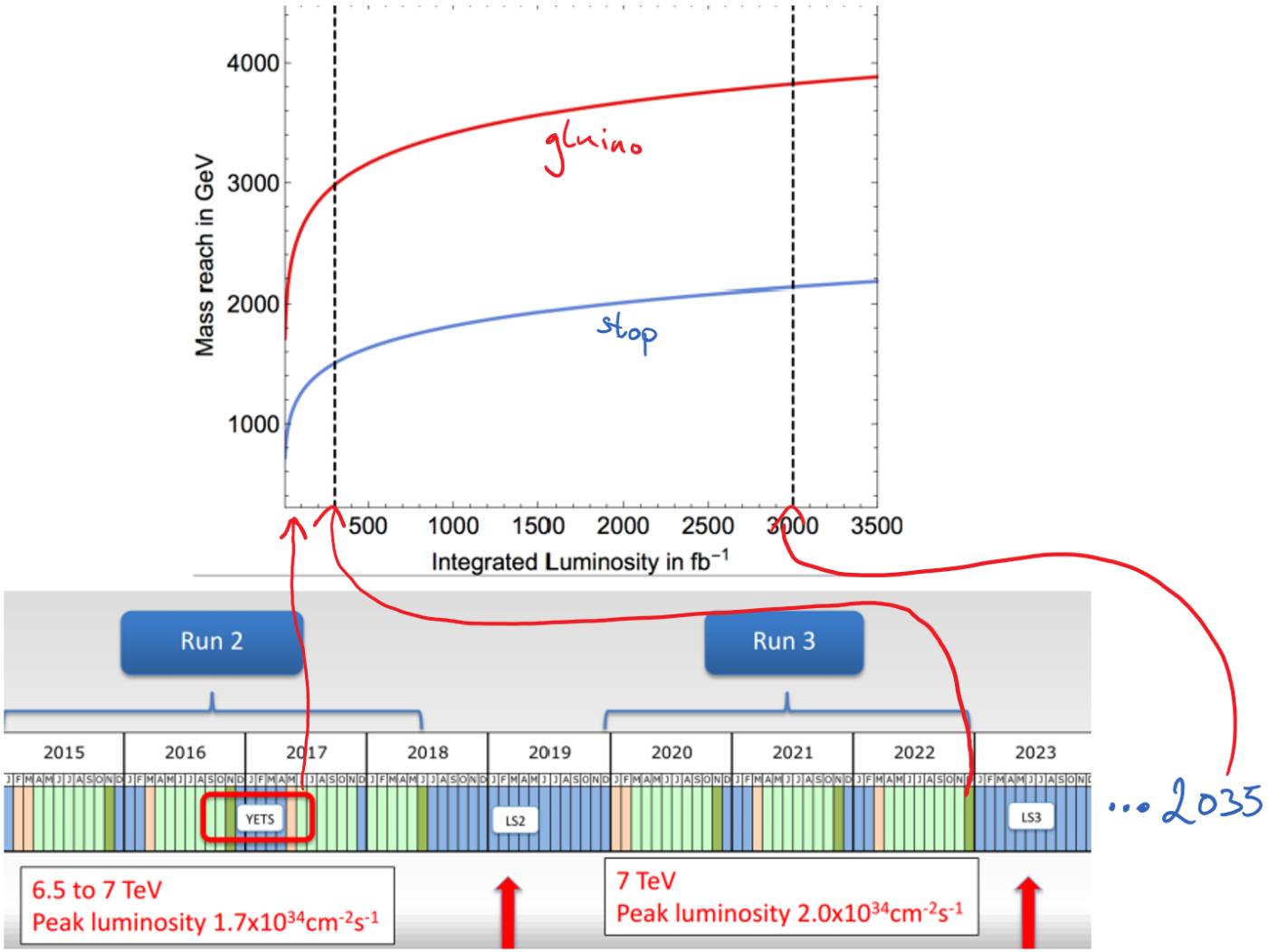
& with Yuhsin Tsai

UNIVERSITY OF MARYLAND

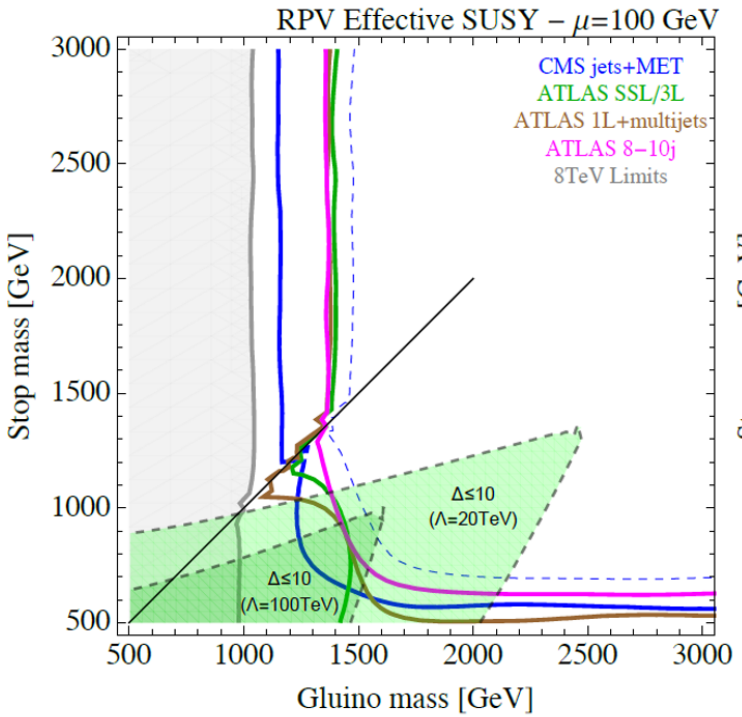
JOHNS HOPKINS UNIVERSITY

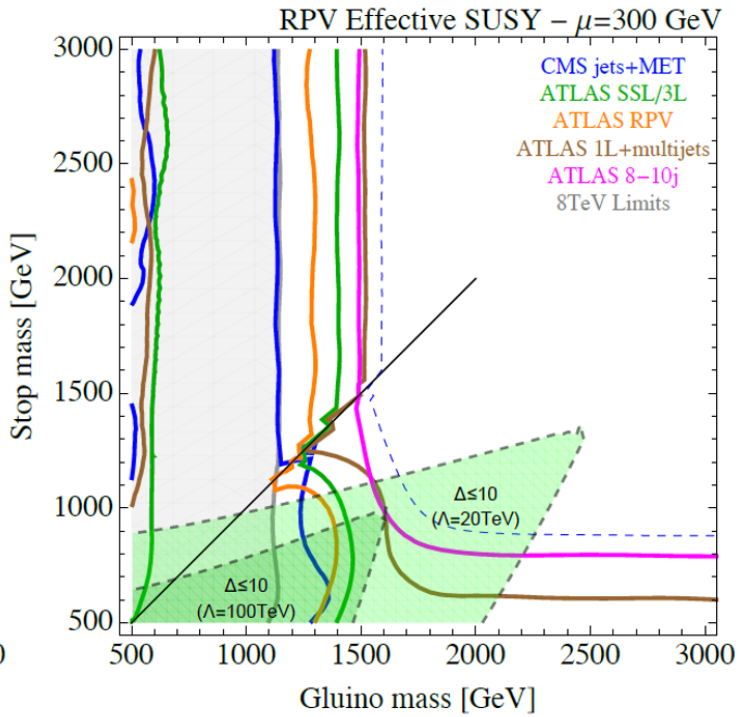
LHC: Where are we now?

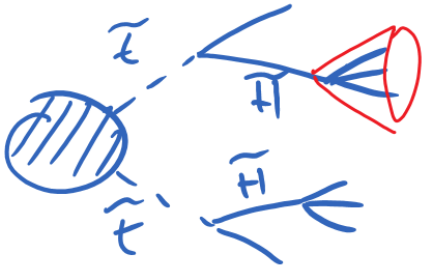


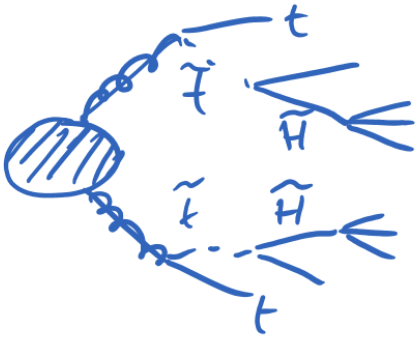
Plot thanks to Marco Farina, using
http://collider-reach.web.cern.ch/collider-reach/

Where might new physics hide: Boosted hadronic objects



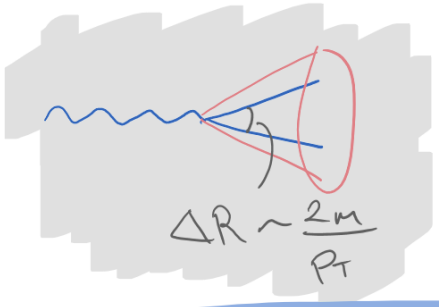


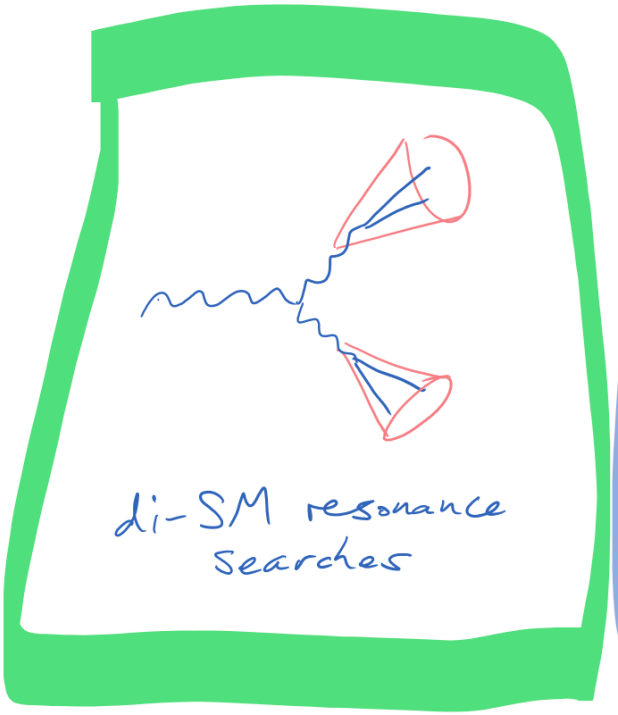


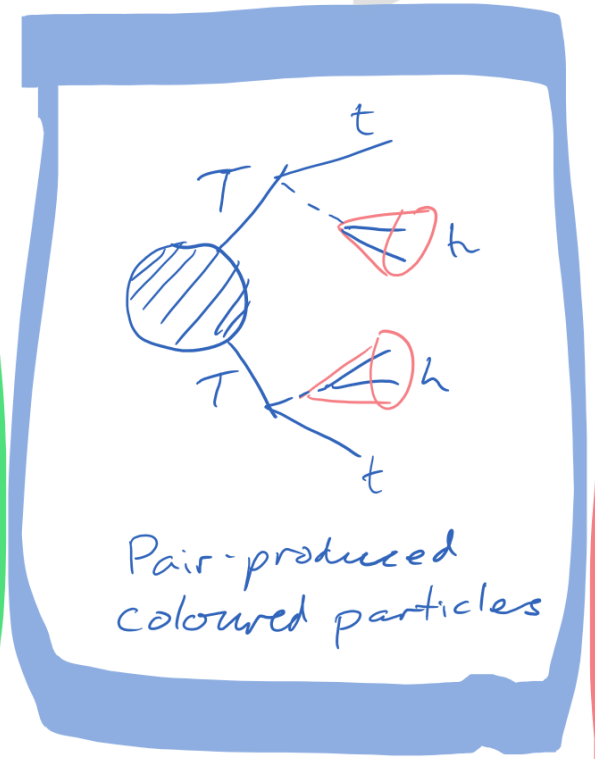


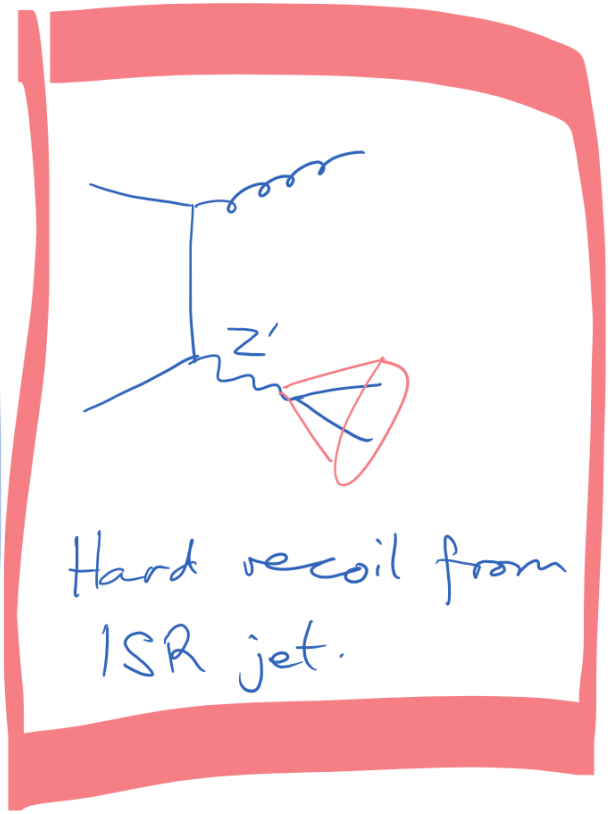
arXiv:1610.08059
Buckley, Feld, Macaluso, Monteux, Shih

Boosted Object Topologies

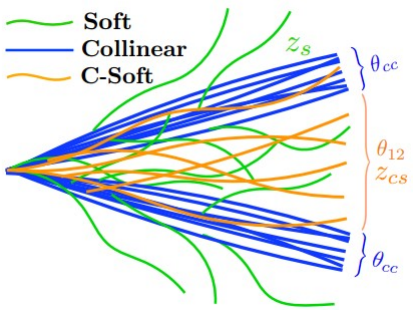


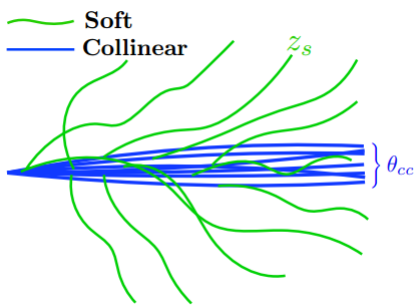






Identifying a BSM boosted object



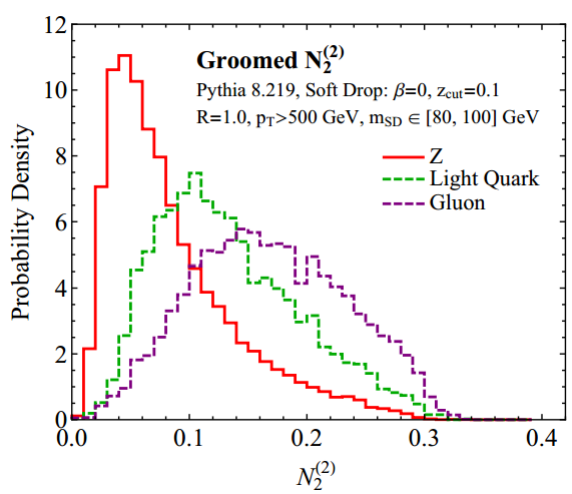


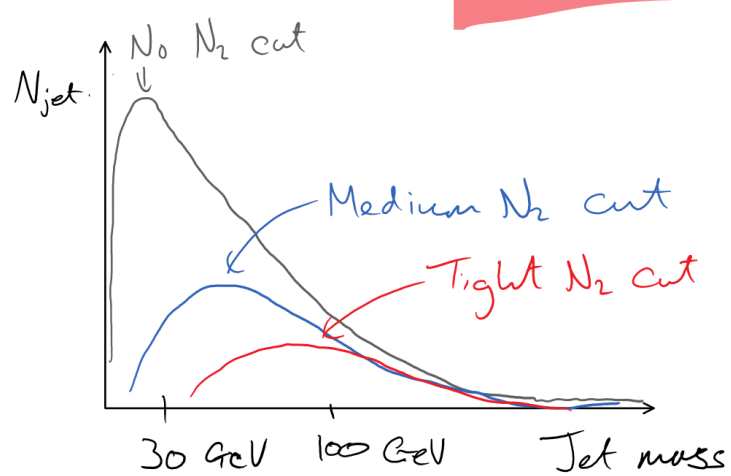
arXiv:1609.07483,
Ian Moult, Lina Necib, Jesse Thaler

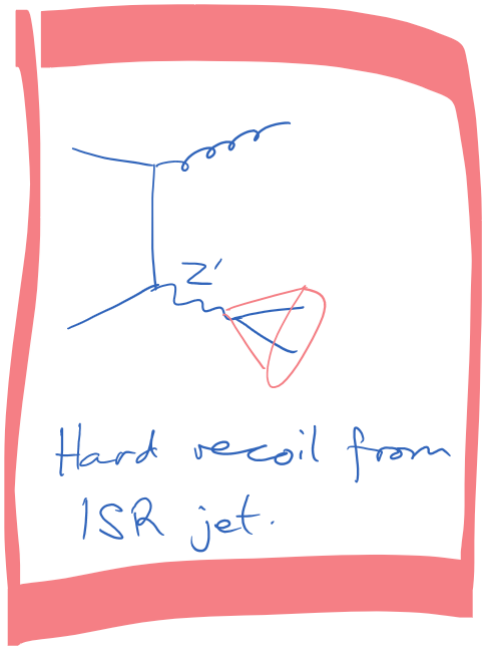
$$ {}_1e_2^{(\beta)} \equiv e_2^{(\beta)} = \sum_{1\le i<j\le n_J} z_i z_j \, \theta_{ij}^{\beta} $$

$$ {}_2e_3^{(\beta)} = \sum_{1\le i<j<k\le n_J} z_i z_j z_k \min\left\{\theta_{ij}^{\beta}\theta_{ik}^{\beta}, \theta_{ij}^{\beta}\theta_{jk}^{\beta}, \theta_{ik}^{\beta}\theta_{jk}^{\beta}\right\} $$

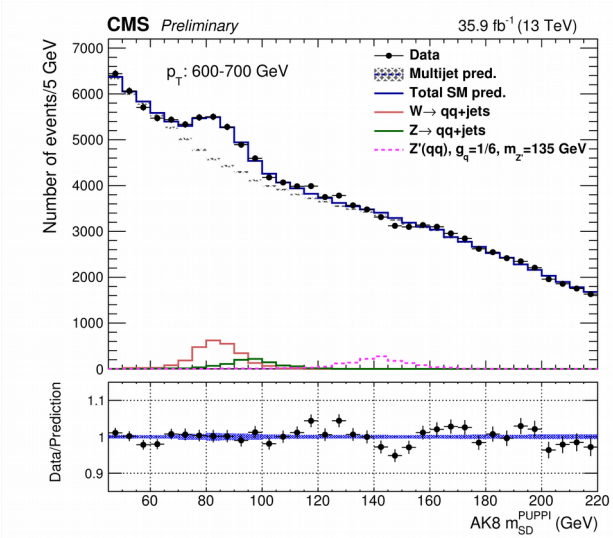
$$ N_2 = \frac{{}_2e_3^{(\beta)}}{({}_1e_2^{(\beta)})^2} $$

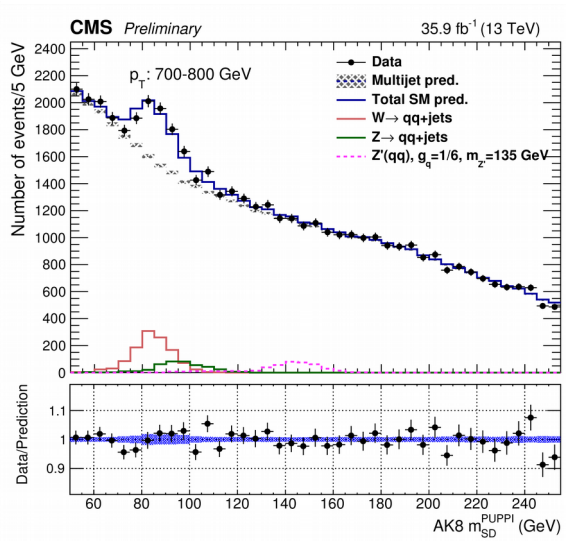


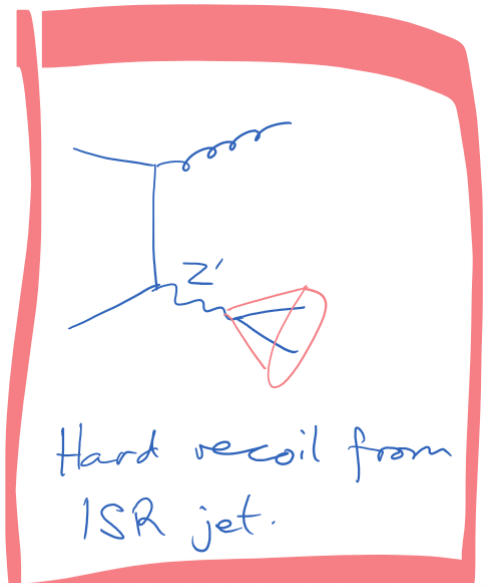


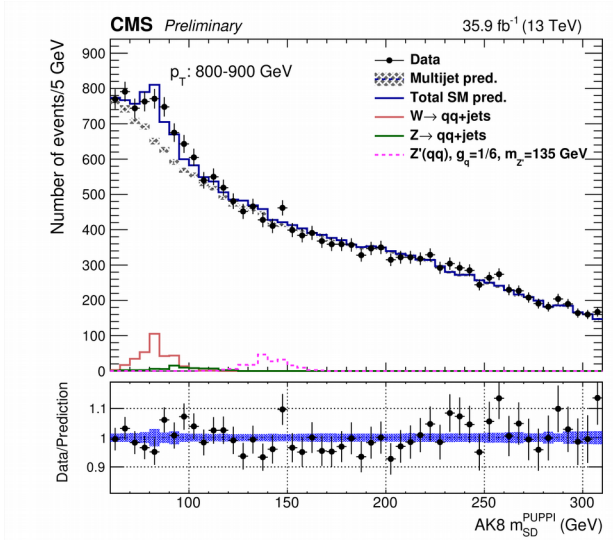


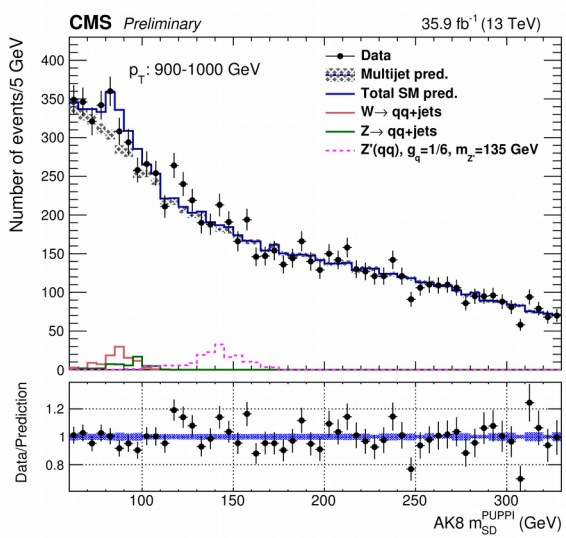
Identifying a BSM boosted object

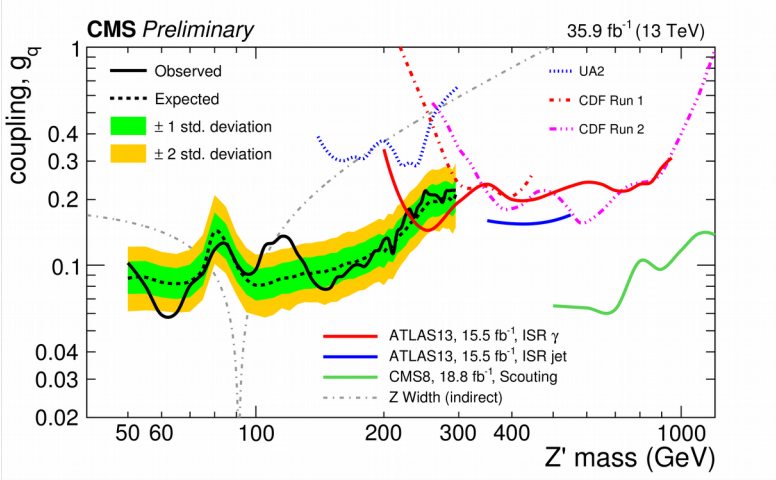






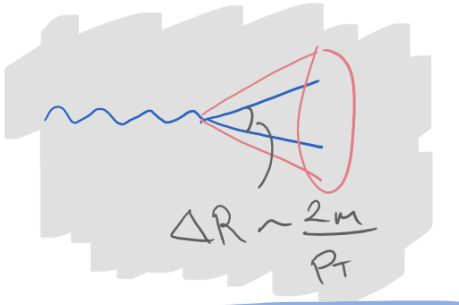


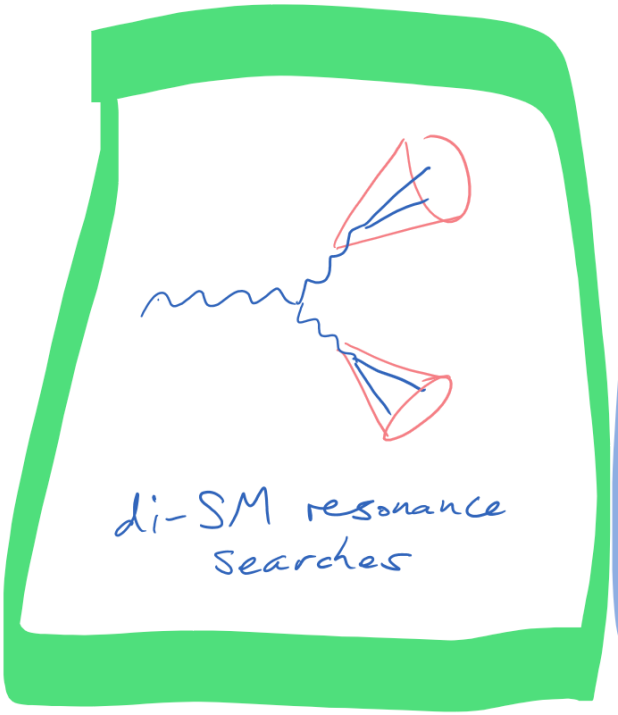


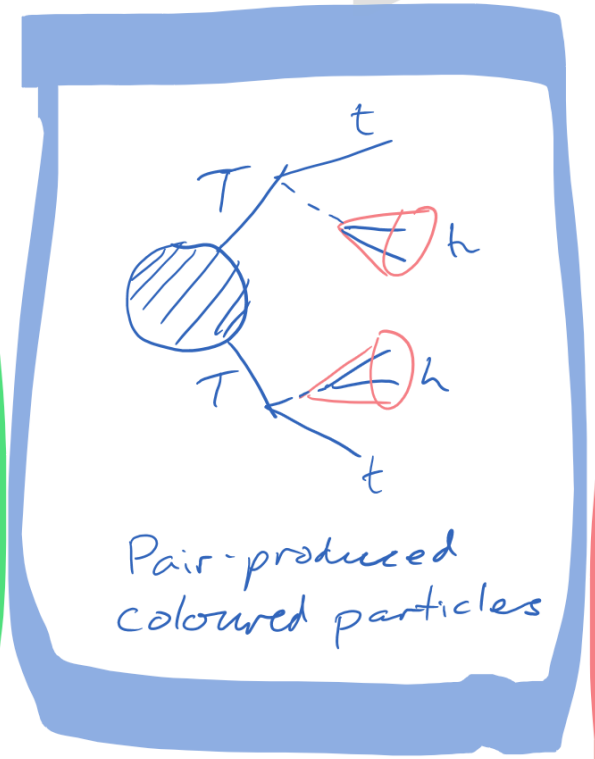


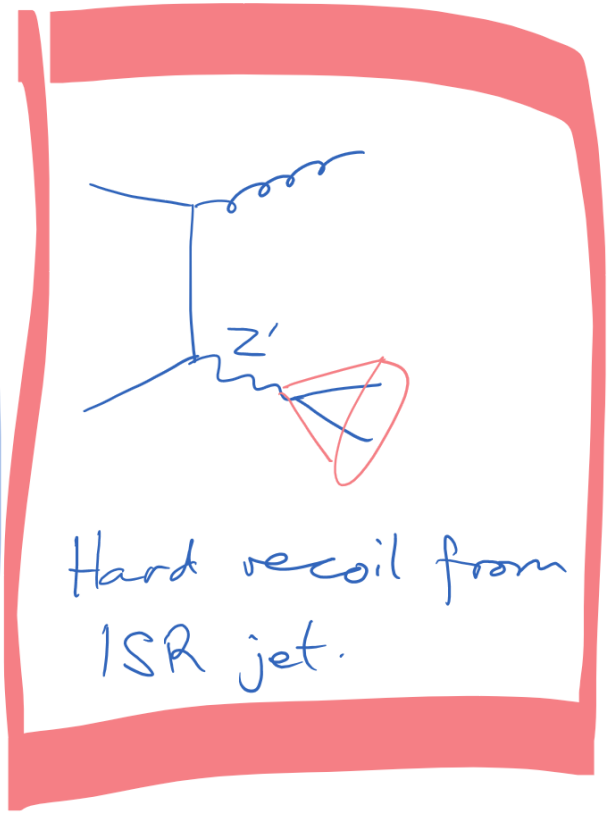
CMS-PAS-EXO-17-001

Boosted Object Topologies









Resonant Diboson Searches

ATLAS Exotics Public Results, 2016 Data

Search for Dark Matter production associated with bottom quarks in 13.3 fb−1 of pp collistions at √s=13 TeV with the ATLAS detector at the LHC	ATLAS-CONF-2016-086	13.3/fb	Aug 2016
A search for pair-produced resonances in four jets final states at √s=13 TeV with the ATLAS detector	ATLAS-CONF-2016-084	15.4/fb	Aug 2016
A Search for Resonances Decaying to a W or Z Boson and a Higgs Boson in the qqbarbbbar Final State	ATLAS-CONF-2016-083	13.3/fb	Aug 2016
Searches for heavy ZZ and ZW resonances in the llqq and vvqq final states in pp collisions at √s=13 TeV with the ATLAS detector	ATLAS-CONF-2016-082	13.2/fb	Aug 2016
Search for new light resonances decaying to jet pairs and produced in association with a photon or a jet in proton-proton collisions at √s=13 TeV with the ATLAS detector	ATLAS-CONF-2016-070	15.5/fb	Aug 2016
Search for new phenomena in dijet events collected in 2015 and 2016 pp collisions with the ATLAS detector at √s=13 TeV	ATLAS-CONF-2016-069	15.7/fb	Aug 2016
Search for diboson resonance production in the lnuqq final state using pp collisions at √s=13 TeV with the ATLAS detector at the LHC	ATLAS-CONF-2016-062	13.2/fb	Aug 2016
Search for new resonances decaying to a charged lepton and a neutrino in pp collisions at √s = 13 TeV with the ATLAS detector	ATLAS-CONF-2016-061	13.3/fb	Aug 2016
Search for resonances in the mass distribution of jet pairs with one or two jets identified as b-jets with the ATLAS detector with 2015 and 2016 data	ATLAS-CONF-2016-060	13.3/fb	Aug 2016
Search for scalar diphoton resonances with 15.4/fb of data collected at √s=13 TeV in 2015 and 2016 with the ATLAS detector	ATLAS-CONF-2016-059	15.4/fb	Aug 2016
Search for resonances with boson-tagged jets in 15.5/fb of pp collisions at √s=13 TeV collected with the ATLAS detector	ATLAS-CONF-2016-055	15.5/fb	Aug 2016
Search for doubly-charged Higgs bosons in same-charge electron pair final states using proton-proton collisions at √s=13 TeV with the ATLAS detector	ATLAS-CONF-2016-051	13.9/fb	Aug 2016
Search for pair production of Higgs bosons in the bbbar final state using proton--proton collisions at √s=13 TeV with the ATLAS detector	ATLAS-CONF-2016-049	13.3/fb	Aug 2016
Search for new high-mass resonances in the dilepton final state using proton--proton collisions at √s=13 TeV with the ATLAS detector	ATLAS-CONF-2016-045	13.3/fb	Aug 2016

Model 1/3:
Left-Right Symmetry

$UV: \; SU(2)_L \times SU(2)_R \times U(1)_{B-L}.$

$\cancel{SU(2)_R}$

few TeV $\uparrow$ $\langle \Delta \rangle_{(0,3)}$ or $\langle H_R \rangle_{(0,2)}$

$\Rightarrow M_{W'}, \; M_{Z'}$

Model 1/3:
Left-Right Symmetry

$$UV: \quad SU(2)_L \times SU(2)_R \times U(1)_{B-L}.$$

few TeV

$\cancel{SU(2)_R}$

$\langle \Delta \rangle_{(0,3)}$ or $\langle H_R \rangle_{(0,2)}$

$\Rightarrow M_{W'}, M_{Z'}$

~100 GeV

$\cancel{SU(2)_L}$ $\quad R \leftrightarrow$

$\langle \Phi \rangle_{(2,2)} \quad \begin{pmatrix} H_u & H_d \end{pmatrix} \updownarrow L$

Model 1/3:
Left-Right Symmetry

$$UV: \quad SU(2)_L \times SU(2)_R \times U(1)_{B-L}.$$

few TeV: $\langle \Delta \rangle_{(0,3)}$ (~~$SU(2)_R$~~) or $\langle H_R \rangle_{(0,2)}$

$\Rightarrow M_{W'}, M_{Z'}$

~100 GeV: $\langle \Phi \rangle_{(2,2)}$ (~~$SU(2)_L$~~, R) $\begin{pmatrix} H_u & H_d \end{pmatrix}$ L

$$D_\mu \Phi D^\mu \Phi \to W_L W_R \, \mathrm{Tr}\left[\begin{pmatrix} v_u & 0 \\ 0 & v_d \end{pmatrix}\begin{pmatrix} 0 & m \\ m & 0 \end{pmatrix}\begin{pmatrix} v_u & 0 \\ 0 & v_d \end{pmatrix}\begin{pmatrix} 0 & m \\ m & 0 \end{pmatrix}\right] g_L g_R$$

$$\to g_L g_R v_u v_d W_L W_R \propto \sin 2\beta$$

Model 1/3: Left-Right Symmetry

UV: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$.

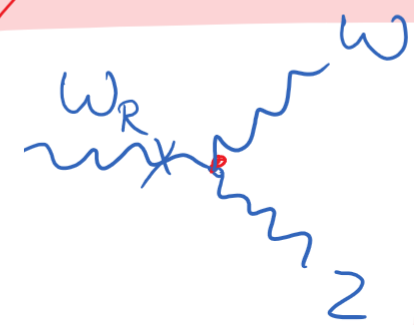
few TeV

$\langle \Delta \rangle_{(0,3)}$ or $\langle H_R \rangle_{(0,2)}$ ($\cancel{SU(2)_R}$)

$\Rightarrow m_{W'}, m_{Z'}$

~100 GeV

$\langle \Phi \rangle_{(2,2)}$ ($\cancel{SU(2)_L}$) $\begin{pmatrix} H_u & H_d \end{pmatrix}$ (R, L)



$\Gamma_{WZ} \sim g_R^2 \sin^2 2\beta$

$$D_\mu \Phi D^\mu \Phi \to W_L W_R \, \mathrm{Tr}\left[\begin{pmatrix} v_u & 0 \\ 0 & v_d \end{pmatrix}\begin{pmatrix} 0 & m \\ m & 0 \end{pmatrix}\begin{pmatrix} v_u & 0 \\ 0 & v_d \end{pmatrix}\begin{pmatrix} 0 & m \\ m & 0 \end{pmatrix}\right] g_L g_R$$

$$\to g_L g_R v_u v_d W_L W_R \propto \sin 2\beta$$

Model 1/3: Left-Right Symmetry

$UV: \; SU(2)_L \times SU(2)_R \times U(1)_{B-L}.$

$Q_R \subset \begin{pmatrix} u_R \\ d_R \end{pmatrix}$

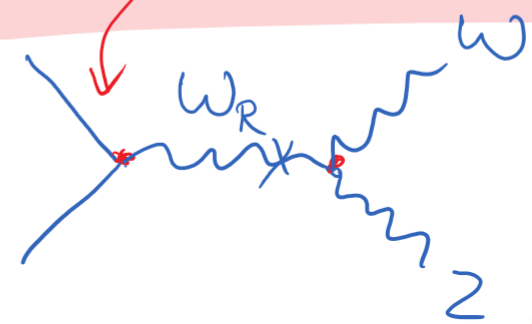
few TeV

$\langle \Delta \rangle_{(0,3)}$ ~~$SU(2)_R$~~ or $\langle H_R \rangle_{(0,2)}$

$\Rightarrow m_{W'}, \; m_{Z'}$

~100 GeV

$\langle \Phi \rangle_{(2,2)}$ ~~$SU(2)_L$~~ $\begin{pmatrix} H_u & H_d \end{pmatrix}$ $\overset{R}{\leftrightarrow}$ $\updownarrow L$

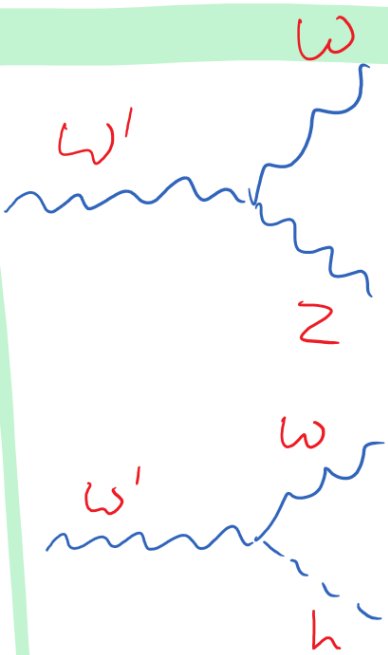


$\Gamma_{WZ} \sim g_R^2 \sin^2 2\beta$

$$D_\mu \Phi D^\mu \Phi \to W_L W_R \, \mathrm{Tr}\left[\begin{pmatrix} v_u & 0 \\ 0 & v_d \end{pmatrix} \begin{pmatrix} 0 & m \\ m & 0 \end{pmatrix} \begin{pmatrix} v_u & 0 \\ 0 & v_d \end{pmatrix} \begin{pmatrix} 0 & m \\ m & 0 \end{pmatrix} \right] g_L g_R$$

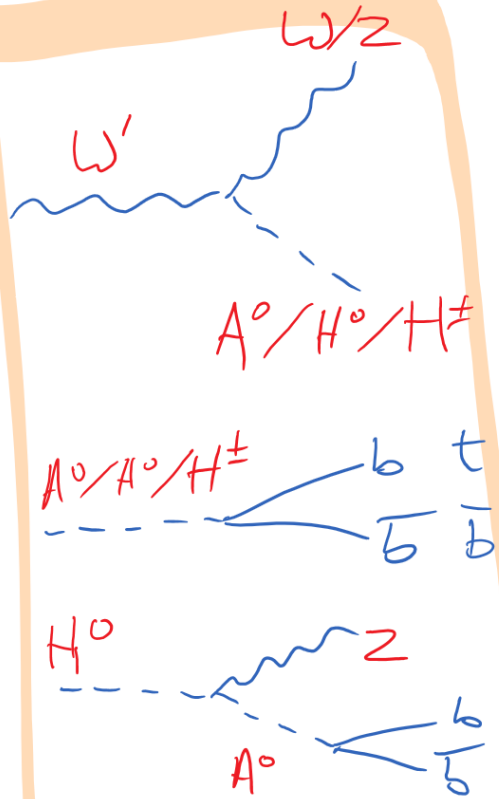
$$\to g_L g_R \, v_u v_d \, W_L W_R \propto \sin 2\beta$$

Model 1/3:
Left-Right Symmetry



$$D_\mu \Phi D^\mu \Phi$$
$$\Downarrow$$
$$W_R^\mu \Phi \partial_\mu \Phi$$

$BR \propto \sin^2 2\beta$



$BR \propto \cos^2 2\beta$

$$\Delta R \sim \frac{2m_h}{p_T} \sim \frac{4m_h}{m_{W'}}$$

$$\Delta R \sim 0.5$$

$$\Rightarrow \frac{m_{W'}}{m_h} \gtrsim 8$$

Model 1/3: Left-Right Symmetry

Why $\cos^2 2\beta \sim 1$ is prefered:

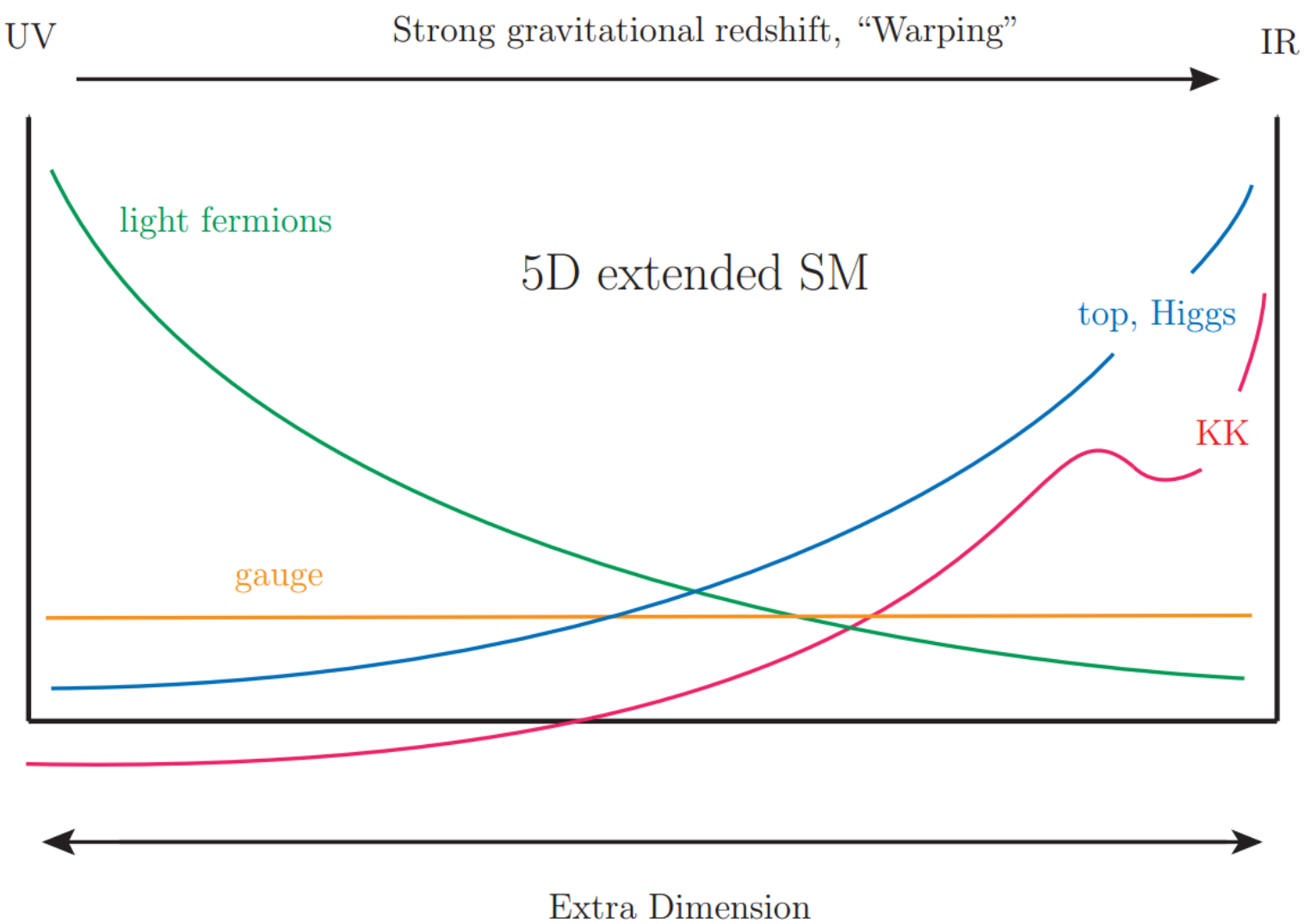
1) $\mathcal{L} \supset y_t Q_L \Phi Q_R^c \supset y_t v_u t_L t_R^c + y_t v_d b_L b_R^c$

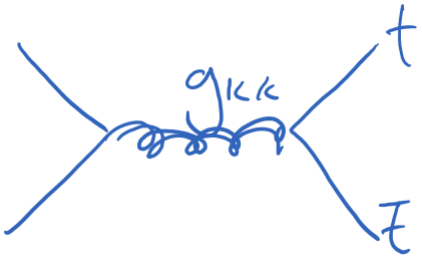
$$\Rightarrow \frac{v_u}{v_d} \sim \frac{m_t}{m_b} \sim 30 \Rightarrow \cos^2 2\beta \simeq 1.$$

2) SUSY Higgs mass:

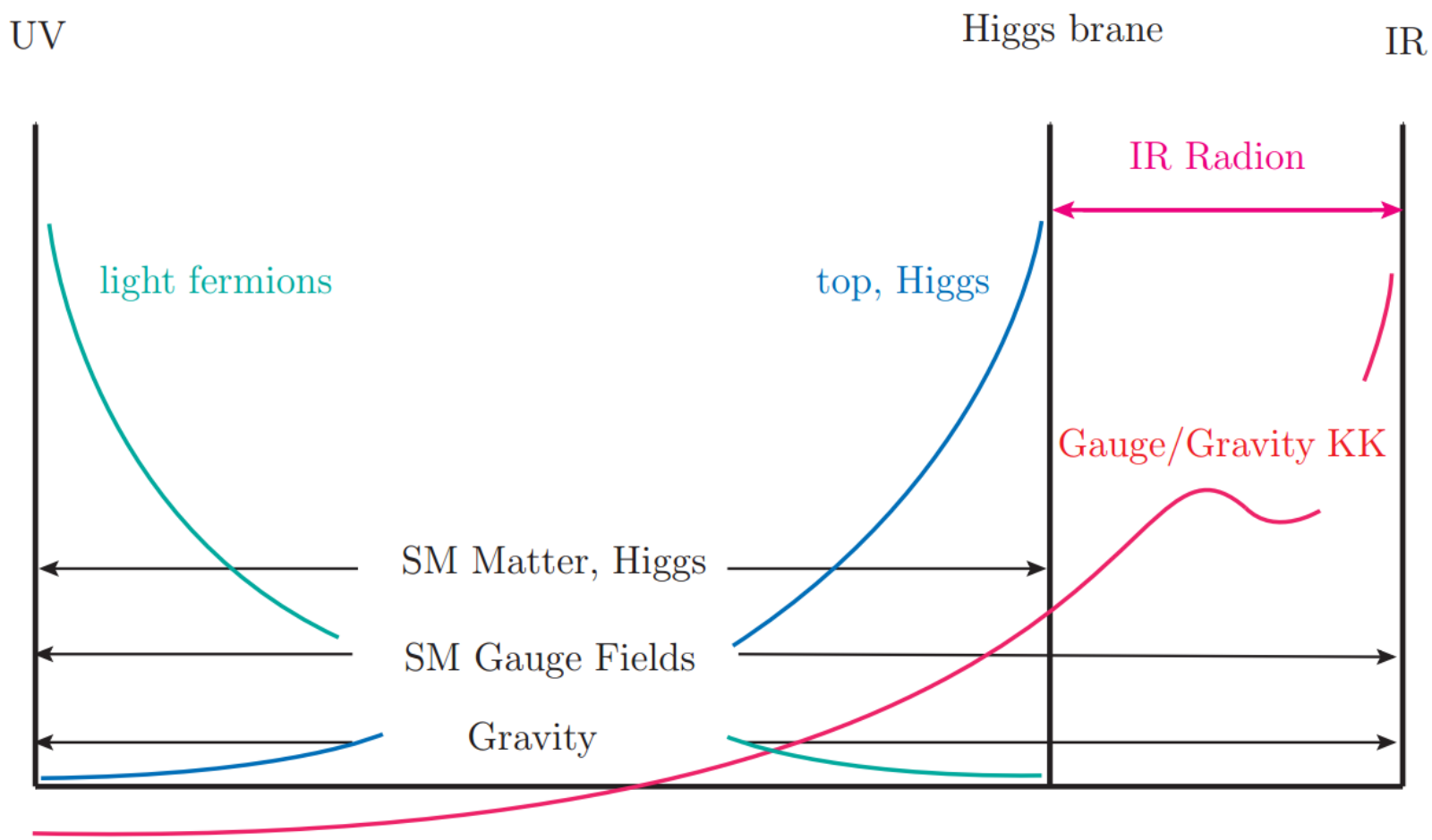
$$m^2_{h,tree} = \frac{1}{4} v^2 \left(g_L^2 + g_R^2\right) \cos^2 2\beta$$

Model 2/3:
Warped Extra Dimension



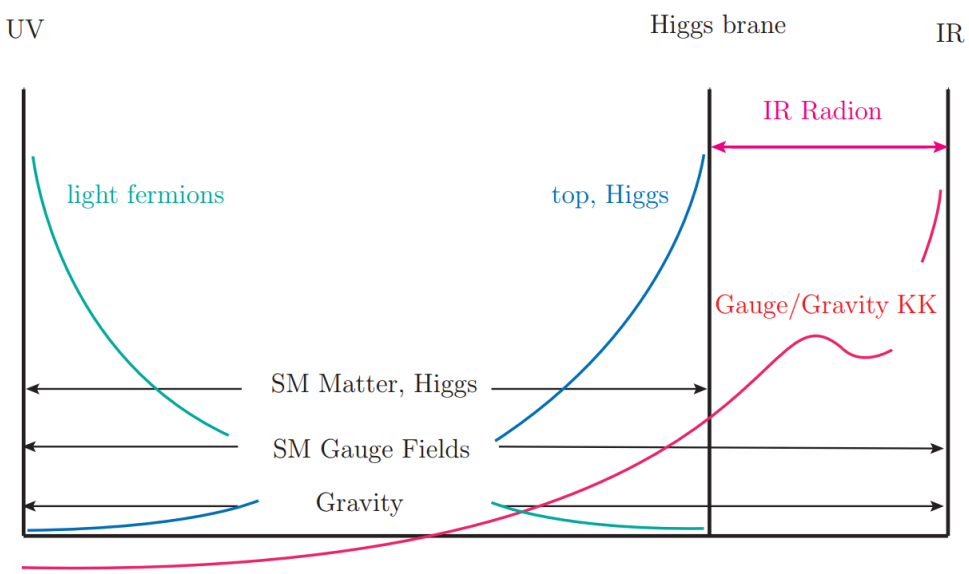


Model 2/3:
Warped Extra Dimension

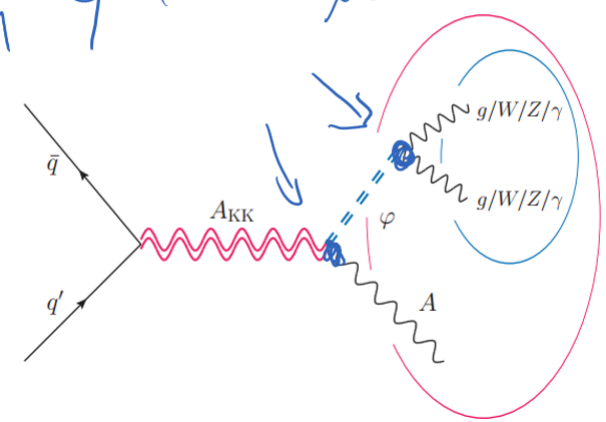


arXiv:1608.00526, Kaustubh Agashe, Peizhi Du, Sungwoo Hong, Raman Sundrum

Model 2/3:
Warped Extra Dimension – signatures



$\frac{1}{\Lambda} \phi F^{\mu\nu} F_{\mu\nu}$



Radion decay widths $\propto g_{SM}^2$

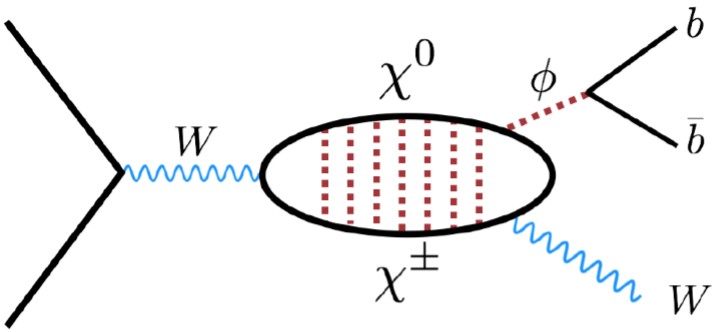
Model 1: Light KK gluon $\Rightarrow$ hadronic signatures (e.g. $j(jj)$, $j(WW)$, $j(\gamma\gamma)$)

Model 2: Light KK $W \Rightarrow$ EW signatures (e.g. $W(WW)$, $W(\gamma\gamma)$)

arXiv:1612.00047
K. Agashe, JHC, P. Du, S. Hong, D. Kim, R.K. Mishra

arXiv:1707.?????
K. Agashe, JHC, P. Du, S. Hong, D. Kim, R.K. Mishra

Model 3/3:
Hidden Forces and Dark Matter Self-Annihilation



Toy Model: λ_{SUSY}

$W \supset \lambda S H_u H_d$

$\chi^0 \leftrightarrow \tilde{H}^0, \ \chi^\pm \leftrightarrow \tilde{H}^\pm, \ S \leftrightarrow \phi$

Bound state formation:

$$m_s \lesssim \frac{1}{r_{Bohr}} \lesssim \frac{(2m_{\tilde{H}})\lambda^2}{16\pi} \lesssim \frac{(2m_H)}{10}$$

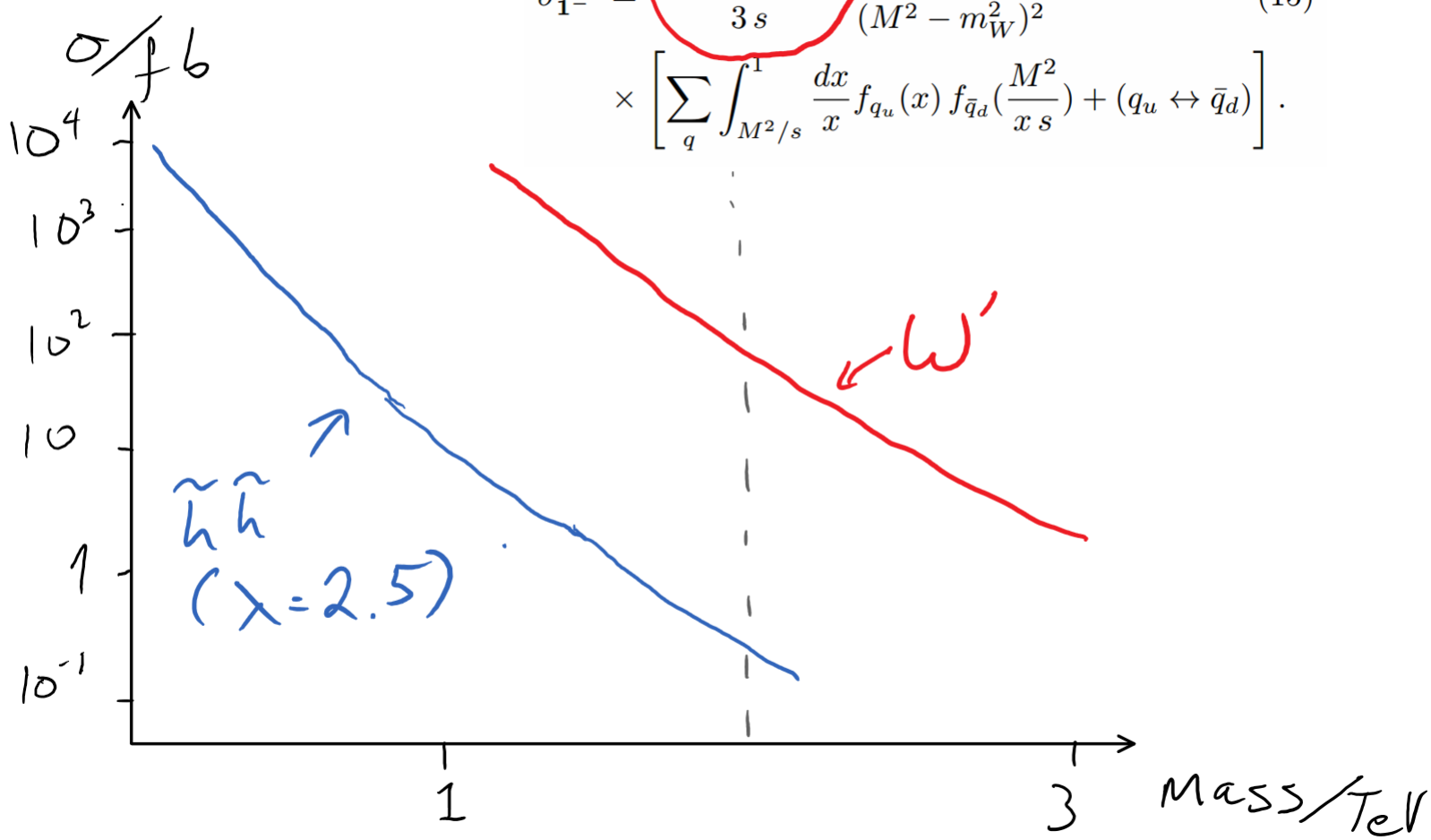
Boosted $\phi \Rightarrow m_s \lesssim \frac{(2m_H)}{8}$

arXiv:1511.07433, Yuhsin Tsai, Lian-Tao Wang, and Yue Zhao

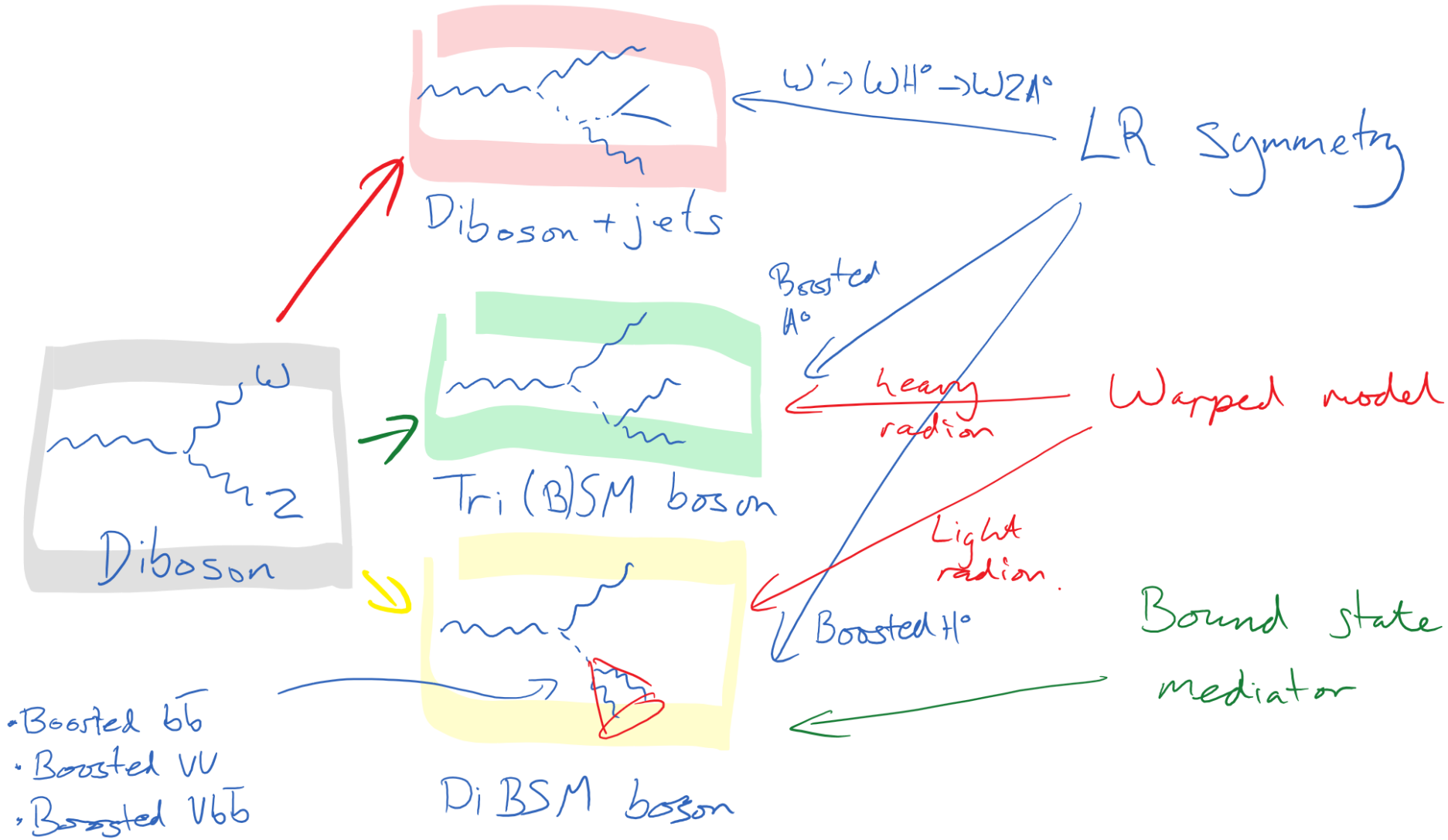
Model 3/3:
Hidden Forces and Dark Matter Self-Annihilation

$$\sigma^{NC}_{\mathbf{1}^-} = \frac{\pi^2\,\zeta(3)\,\alpha_\lambda^3\,\alpha_W^2}{3\,s}\,\frac{M^4}{(M^2-m_W^2)^2} \times \left[\sum_q \int_{M^2/s}^1 \frac{dx}{x} f_{q_u}(x)\, f_{\bar{q}_d}\!\left(\frac{M^2}{x\,s}\right) + (q_u \leftrightarrow \bar{q}_d)\right]. \tag{15}$$

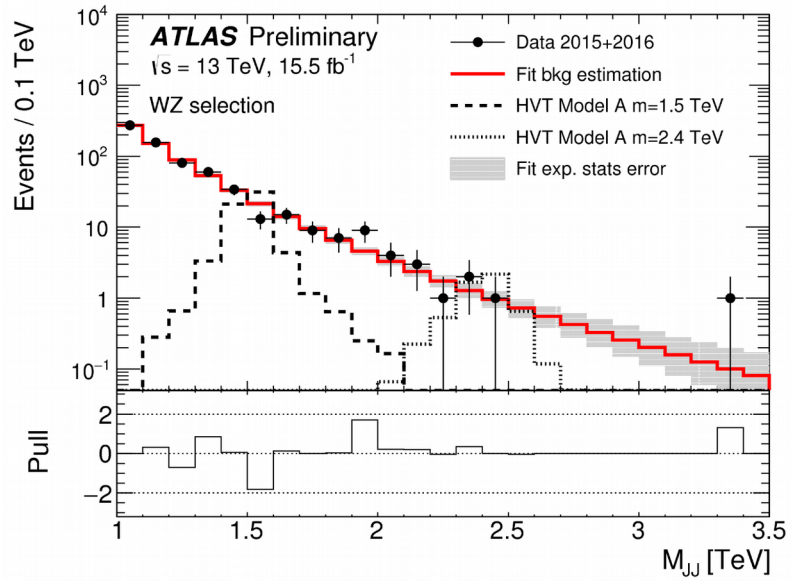
~ 10^3 suppression



Summary of Diboson-ish Signatures

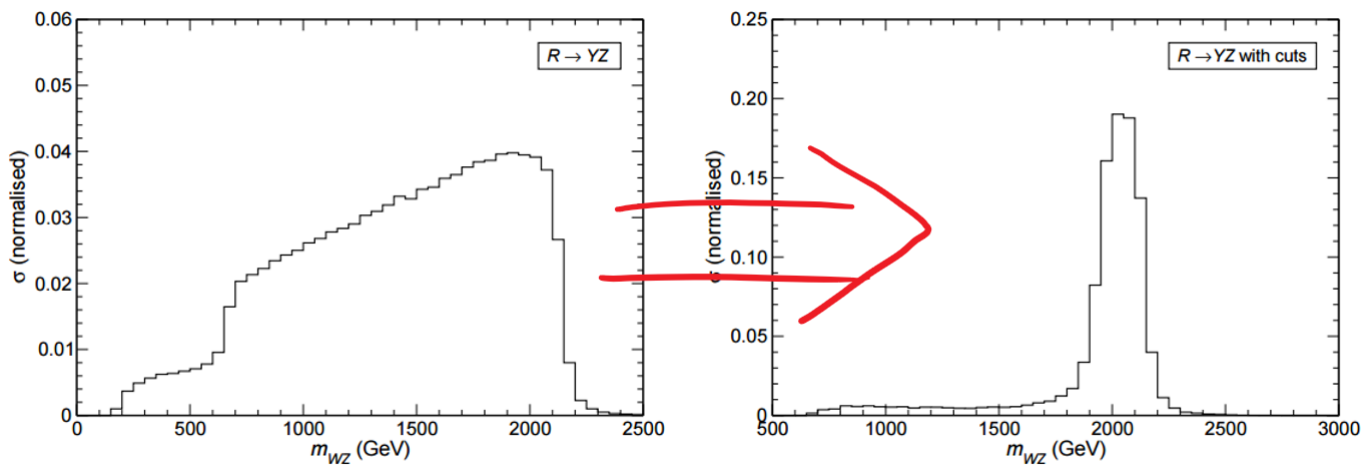


Triboson WWW Signature in Diboson Searches: 1) ATLAS VV fully hadronic recast



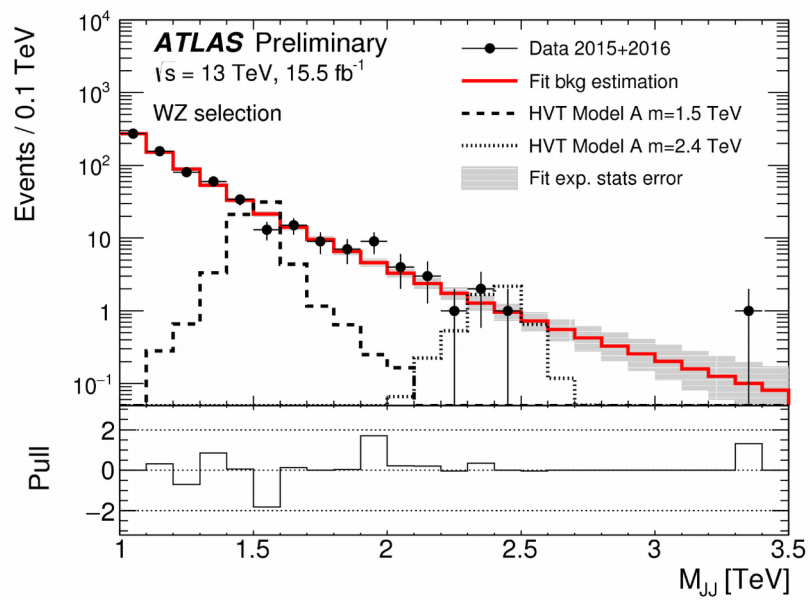
P_T asymmetry cut

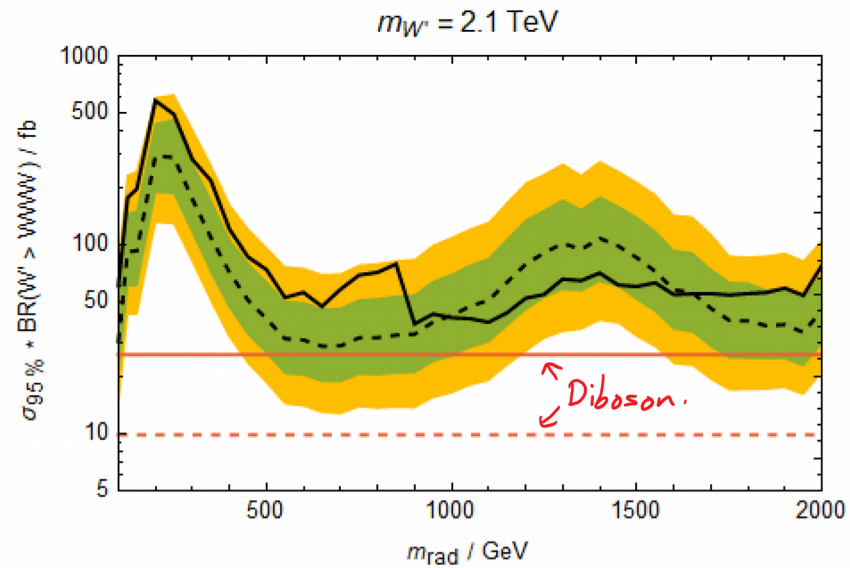
$$\frac{P_{T1} - P_{T2}}{P_{T1} + P_{T2}} \leq 0.15$$

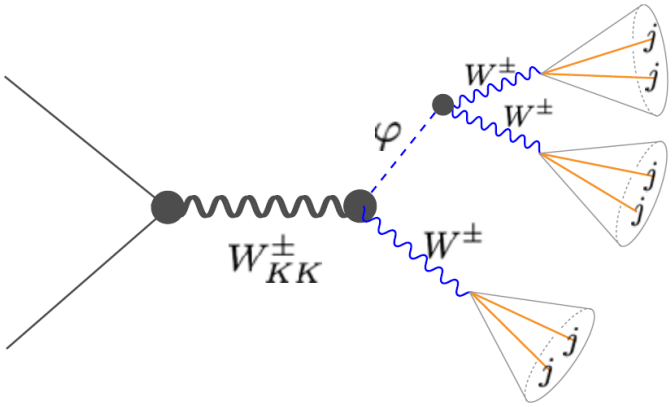


arXiv:1506.06739, J. A. Aguilar–Saavedra

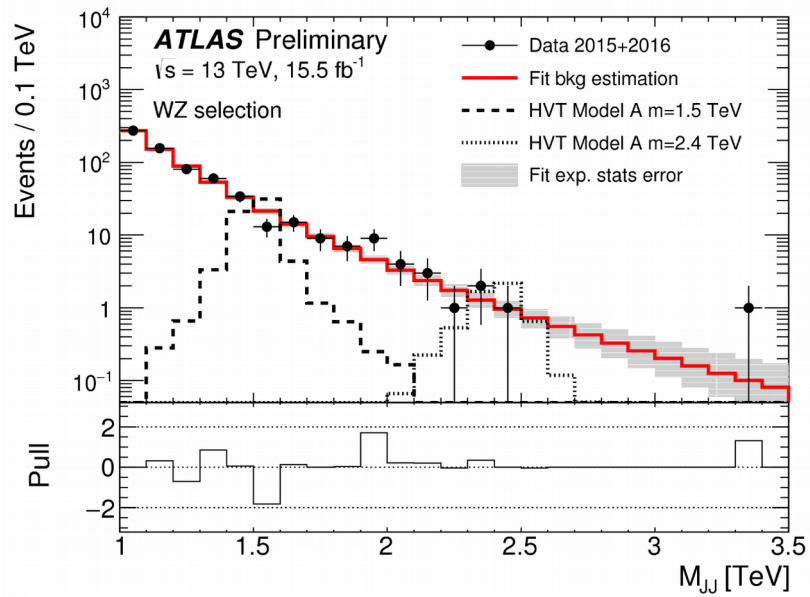
Triboson WWW Signature in Diboson Searches: 1) ATLAS VV fully hadronic recast

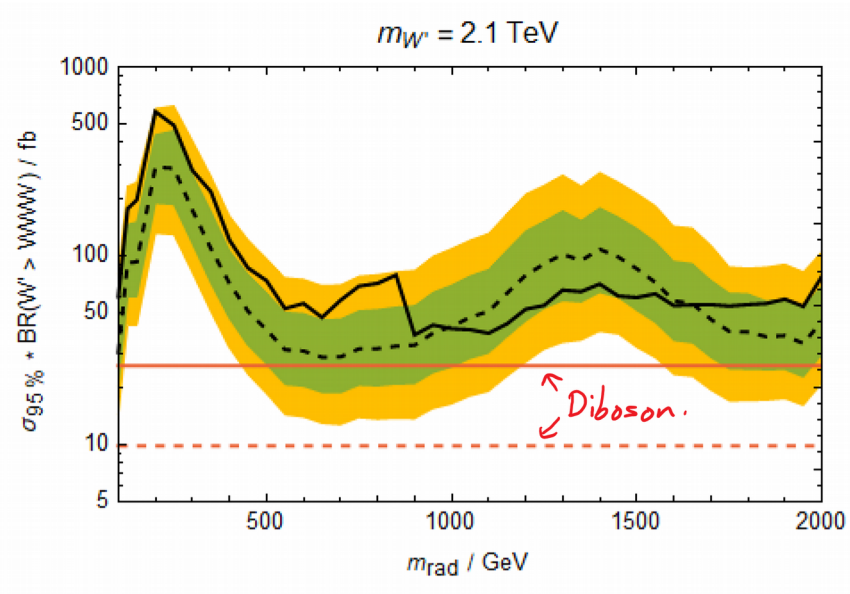


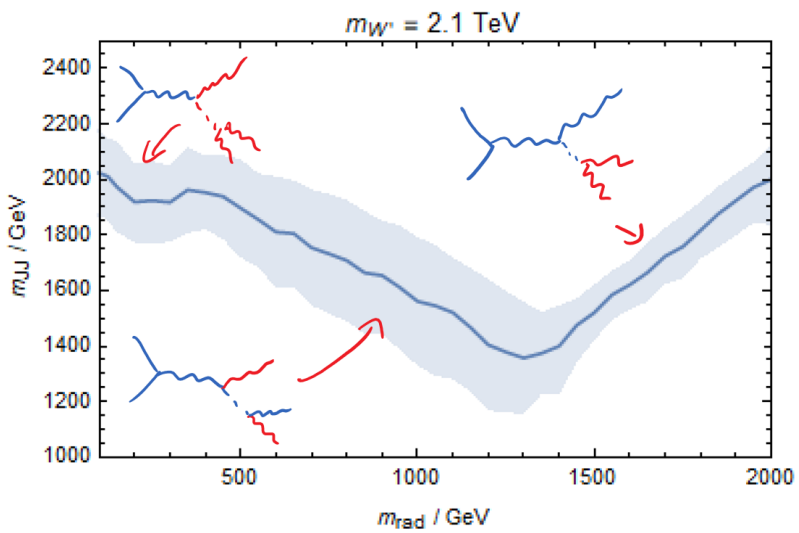


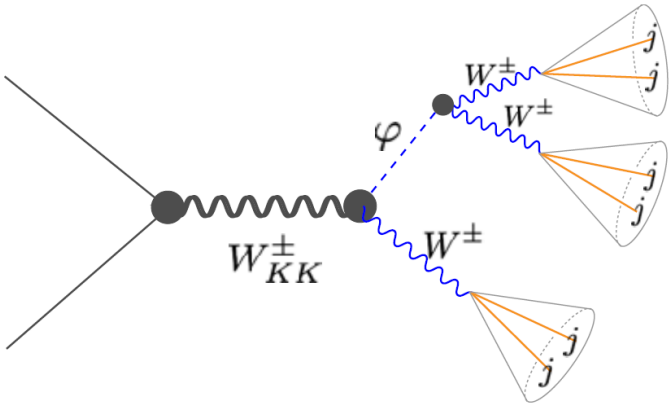


Triboson WWW Signature in Diboson Searches: 1) ATLAS VV fully hadronic recast

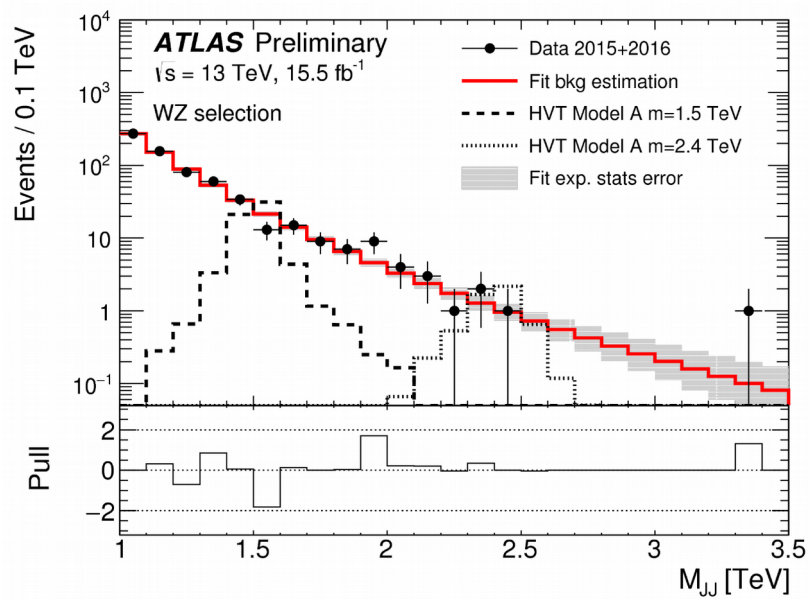


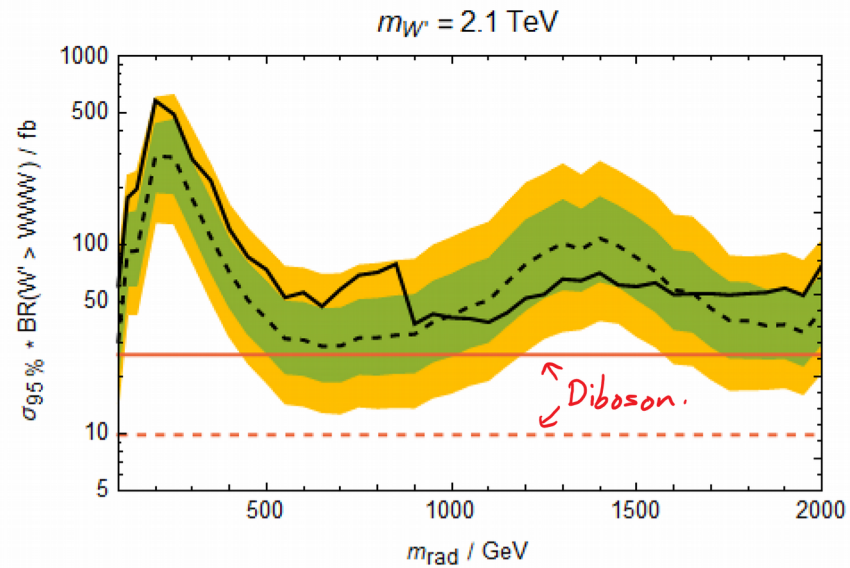


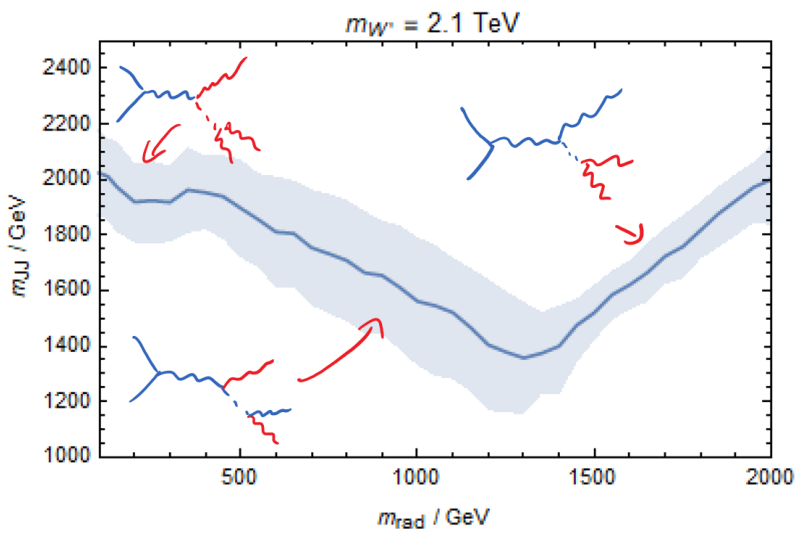


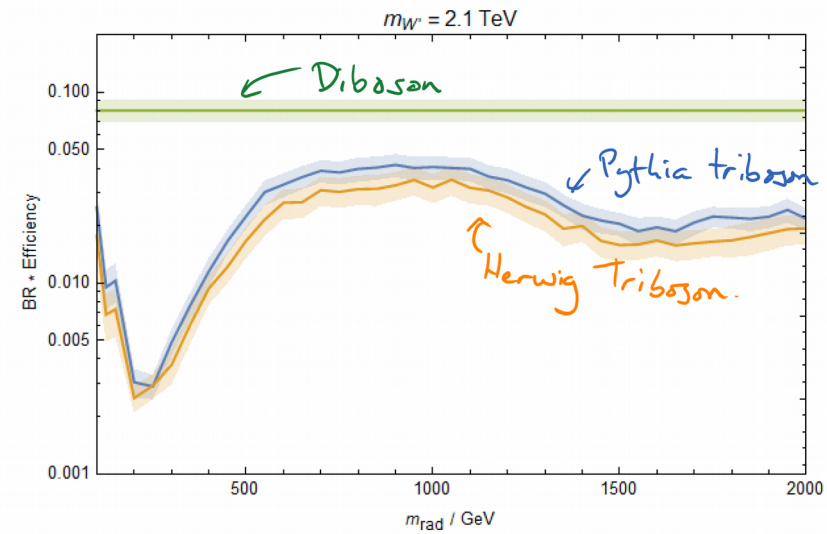


Triboson WWW Signature in Diboson Searches: 1) ATLAS VV fully hadronic recast

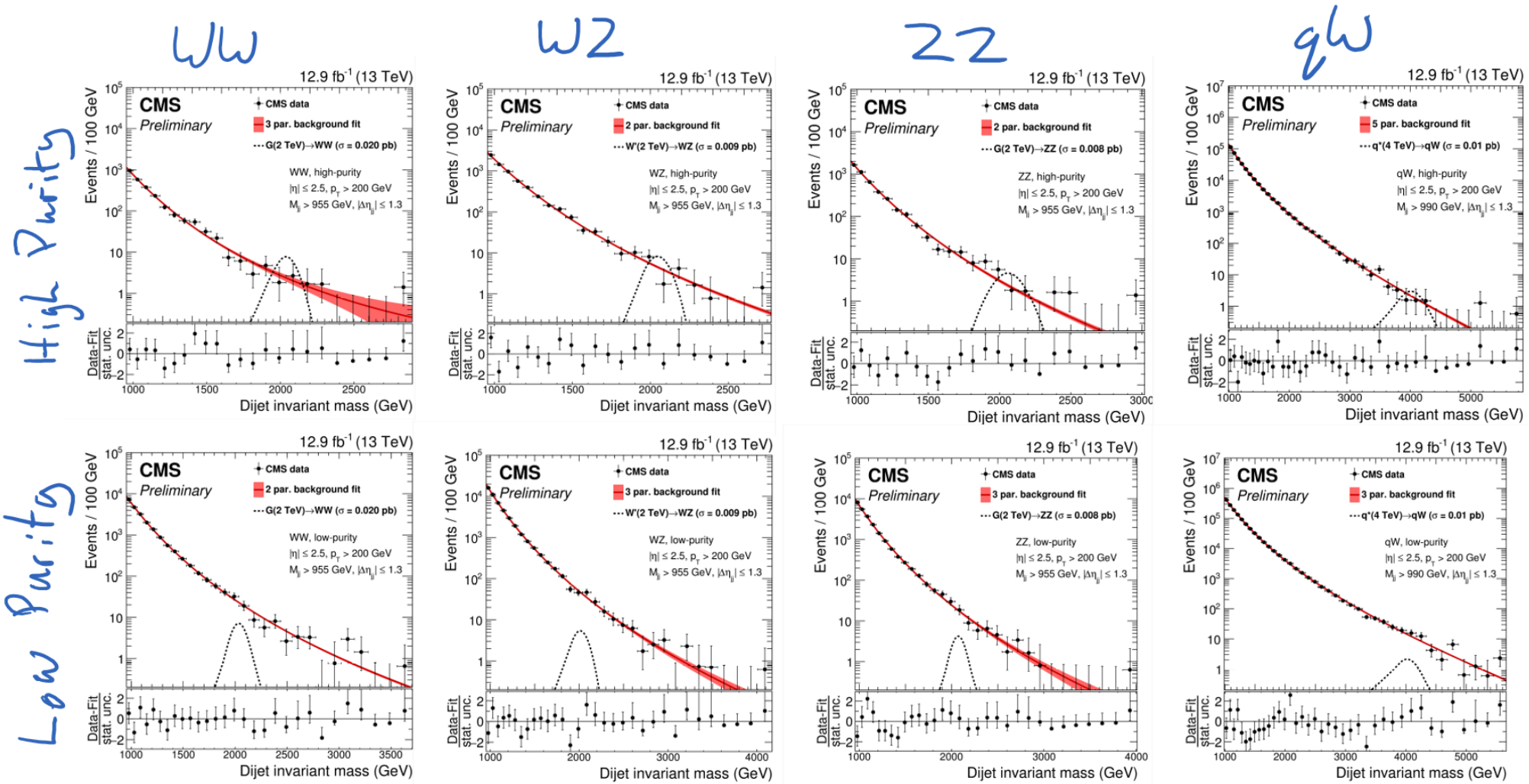






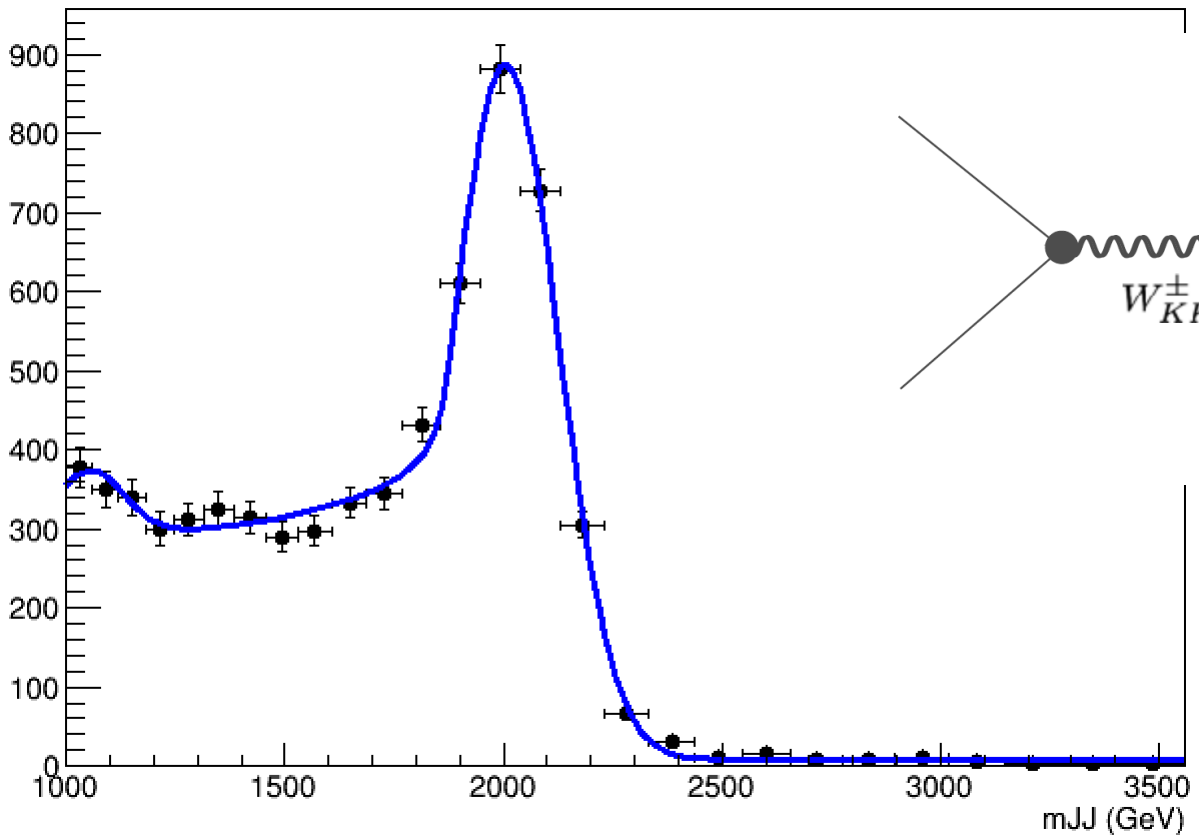


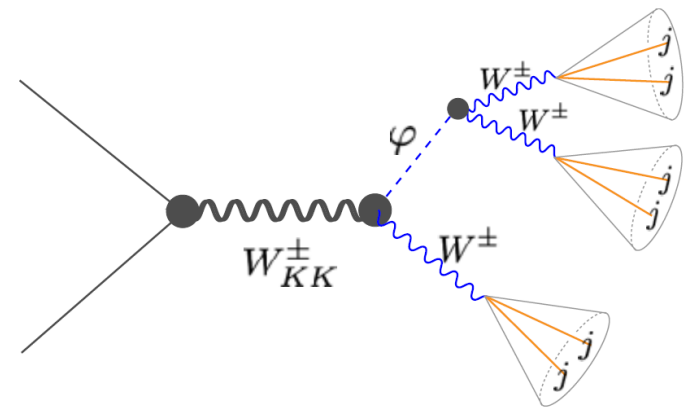
Triboson WWW Signature in Diboson Searches: 3) CMS VV fully hadronic recast



Triboson WWW Signature in Diboson Searches: 3) CMS VV fully hadronic recast

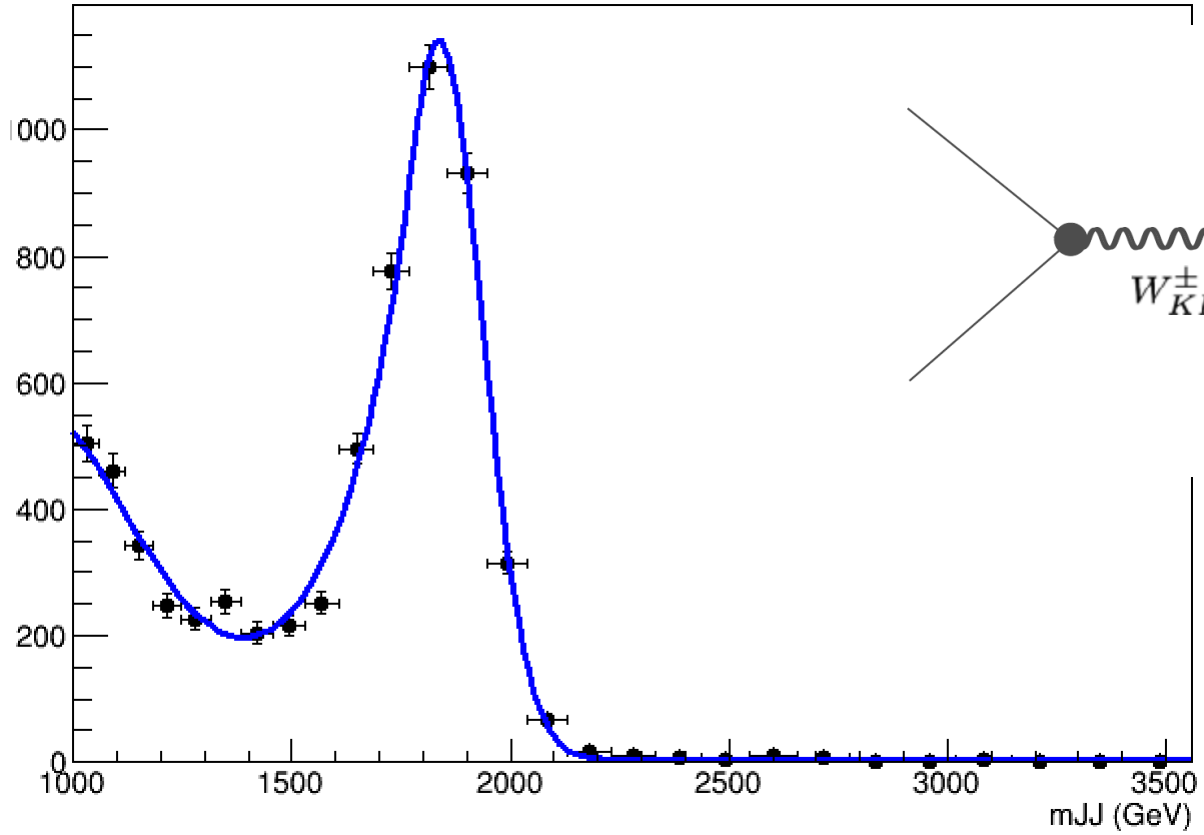
Radion mass = 2 TeV (W' mass = 2.1 TeV)

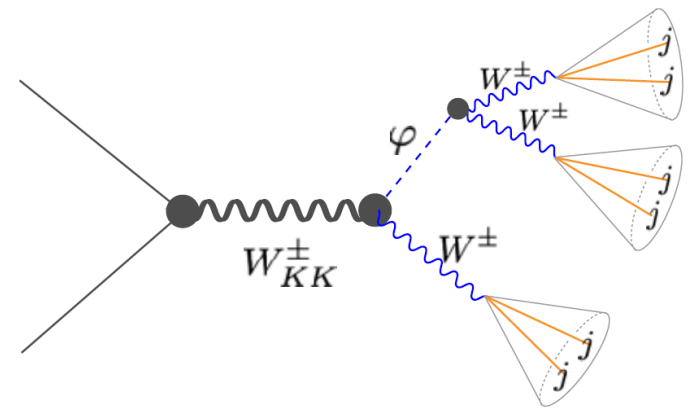




Triboson WWW Signature in Diboson Searches: 3) CMS VV fully hadronic recast

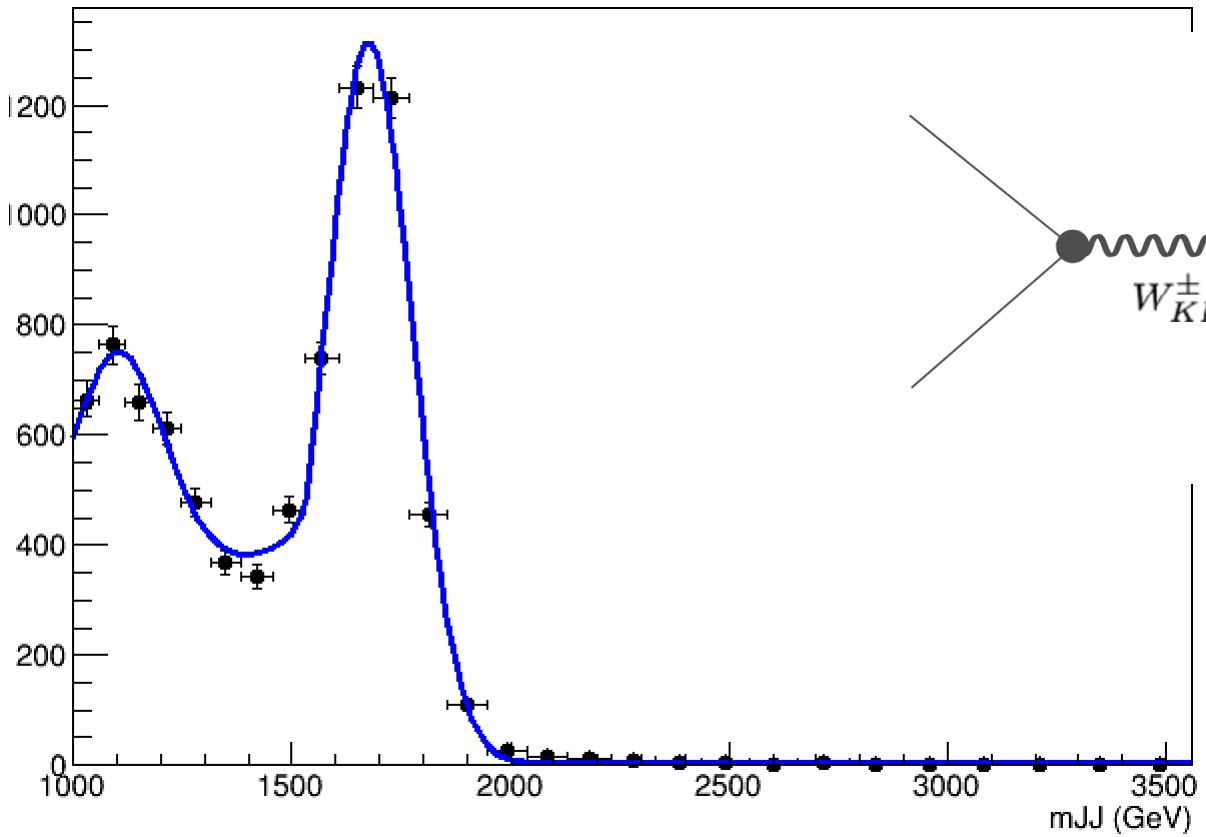
Radion mass = 1.8 TeV (W' mass = 2.1 TeV)

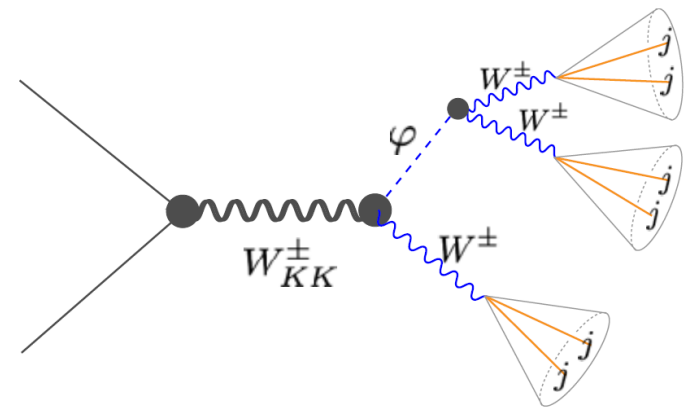




Triboson WWW Signature in Diboson Searches: 3) CMS VV fully hadronic recast

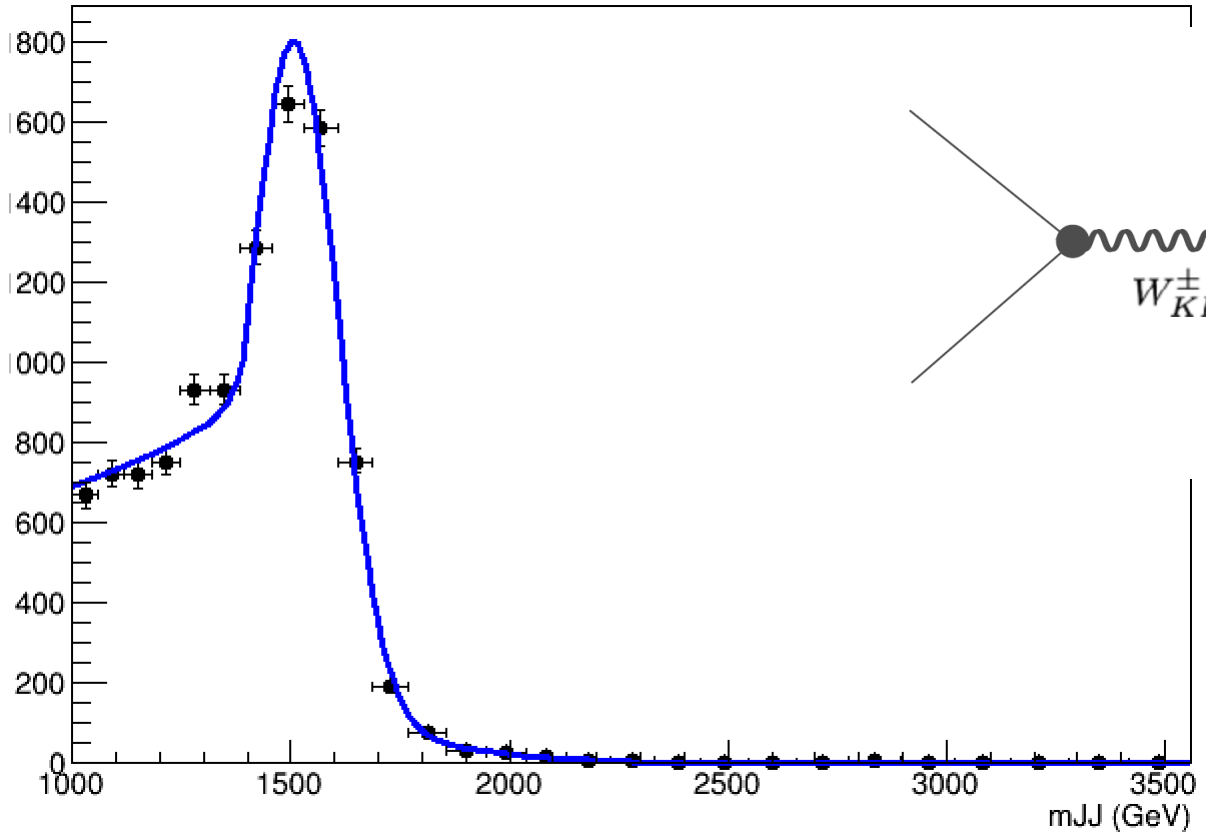
Radion mass = 1.65 TeV (W' mass = 2.1 TeV)

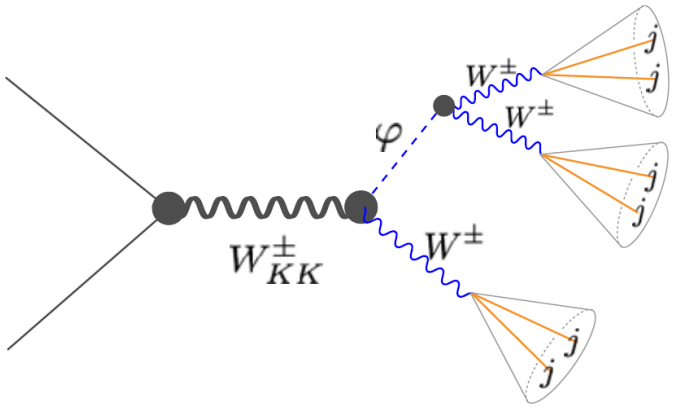




Triboson WWW Signature in Diboson Searches: 3) CMS VV fully hadronic recast

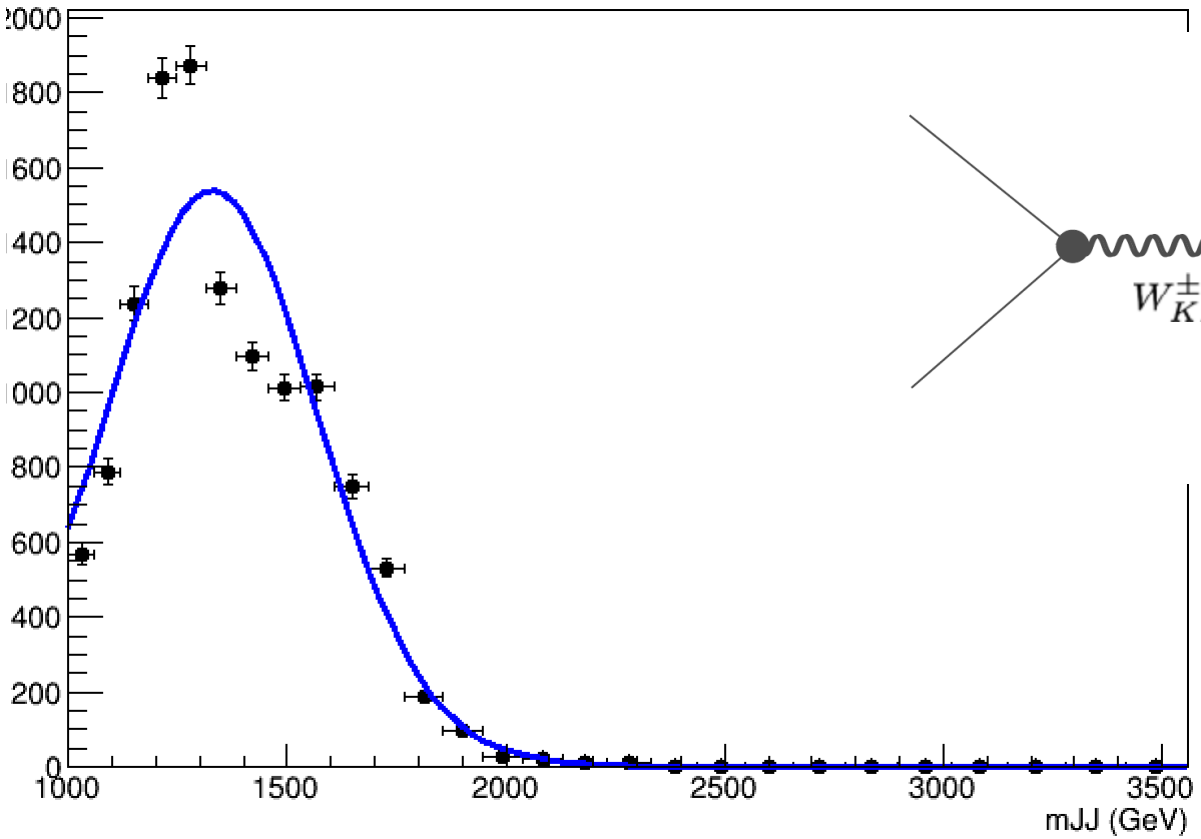
Radion mass = 1.5 TeV (W' mass = 2.1 TeV)

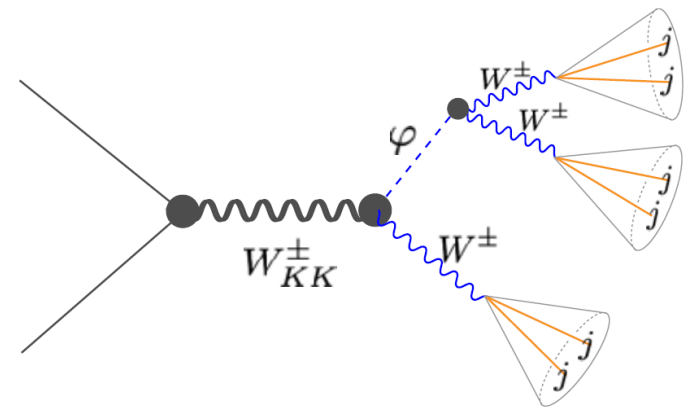




Triboson WWW Signature in Diboson Searches: 3) CMS VV fully hadronic recast

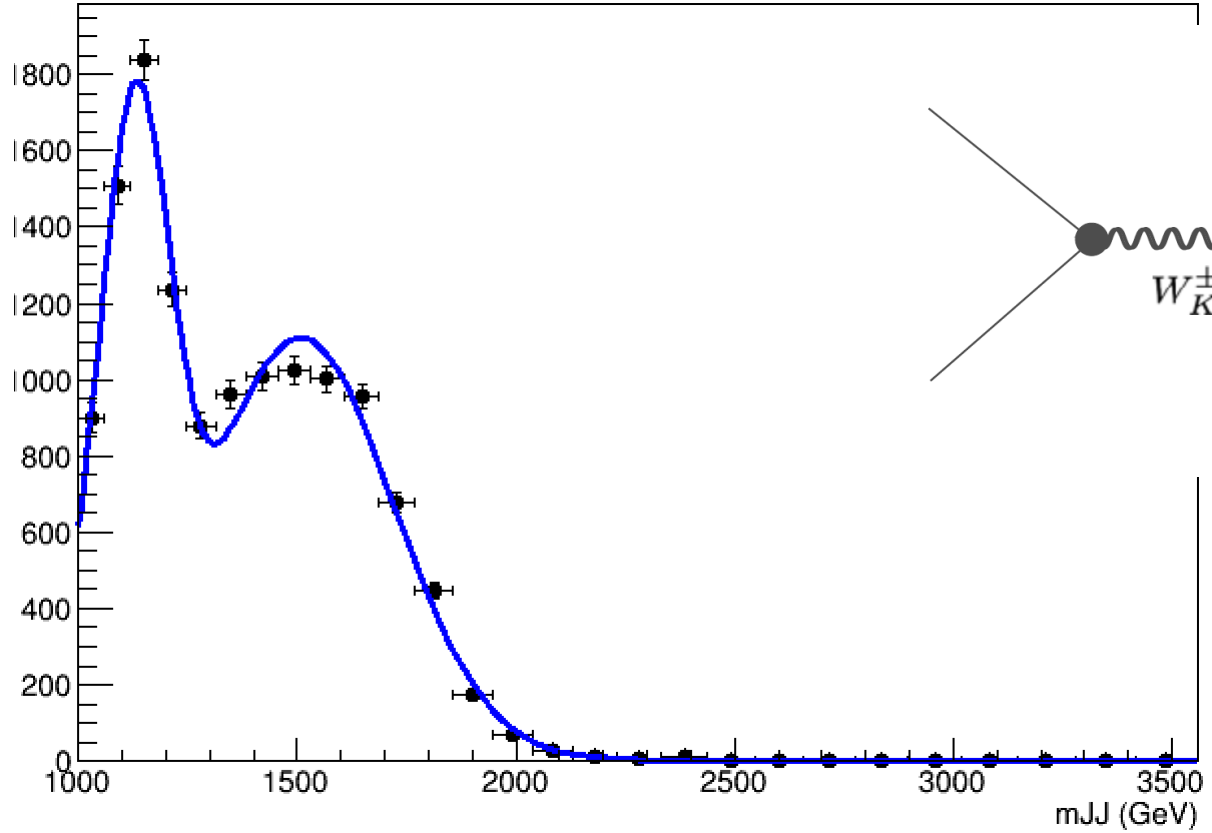
Radion mass = 1.2 TeV (W' mass = 2.1 TeV)

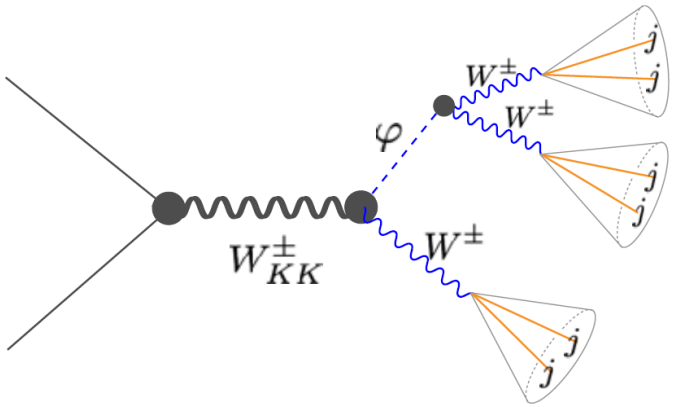




Triboson WWW Signature in Diboson Searches: 3) CMS VV fully hadronic recast

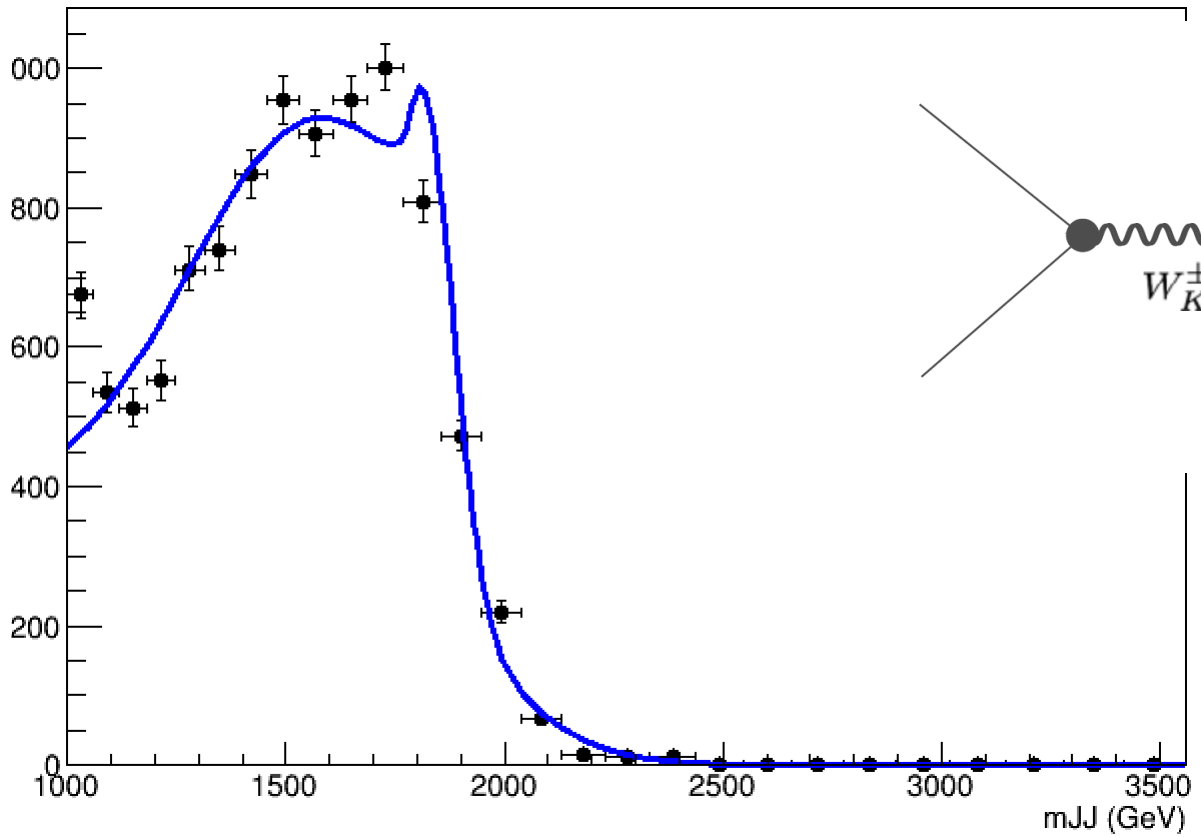
Radion mass = 1.1 TeV (W' mass = 2.1 TeV)

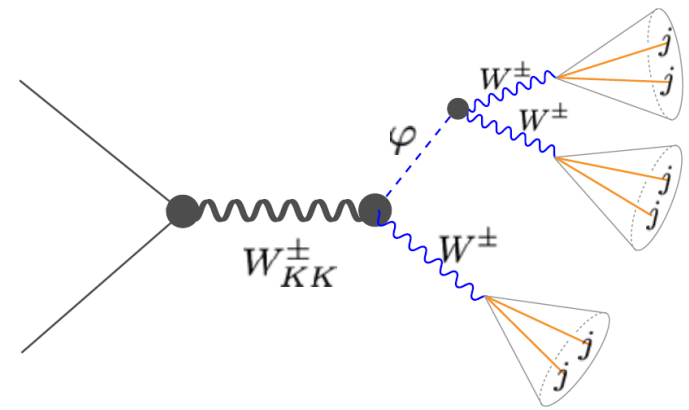




Triboson WWW Signature in Diboson Searches: 3) CMS VV fully hadronic recast

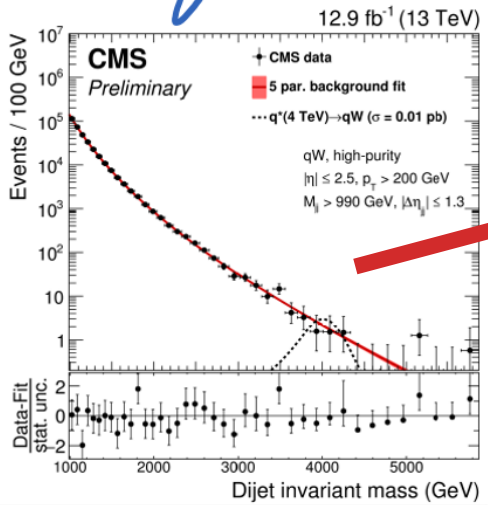
Radion mass = 1 TeV (W' mass = 2.1 TeV)

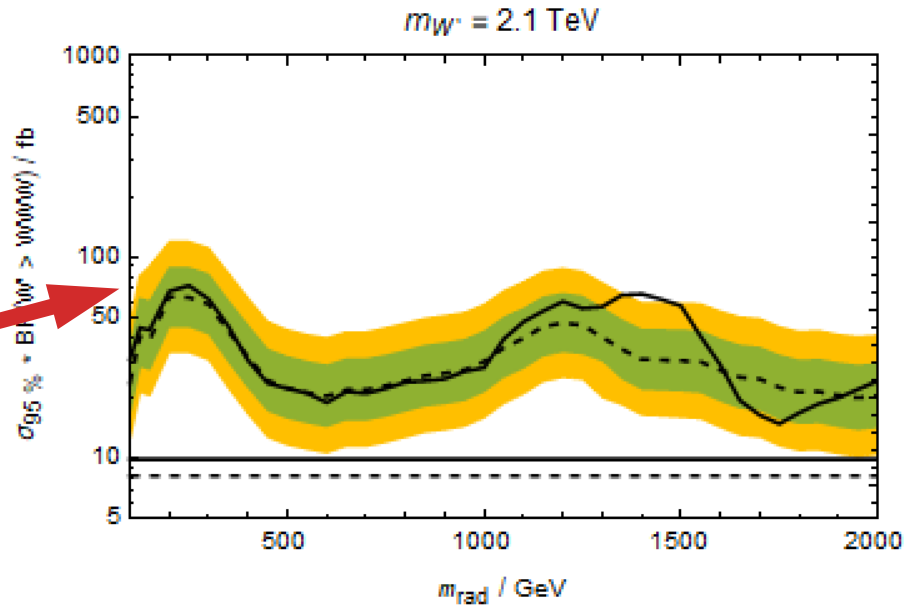


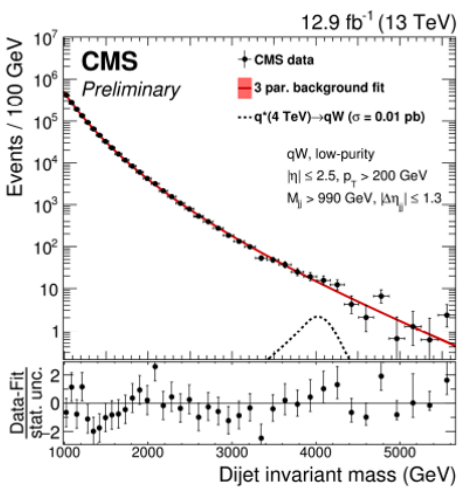


Triboson WWW Signature in Diboson Searches: 3) CMS VV fully hadronic recast

qW



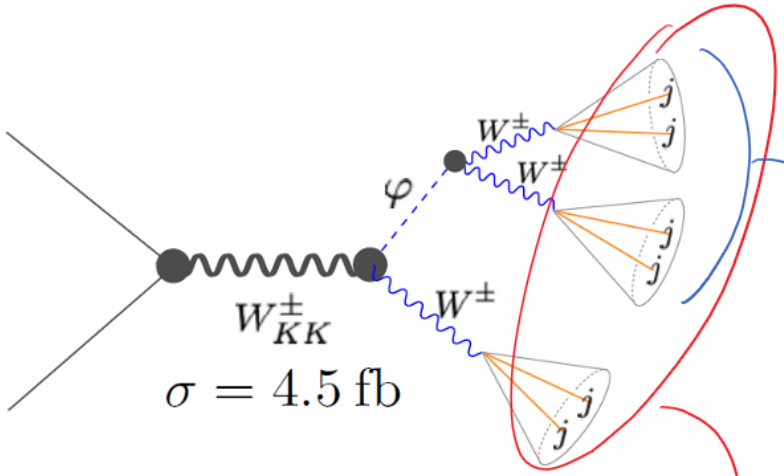


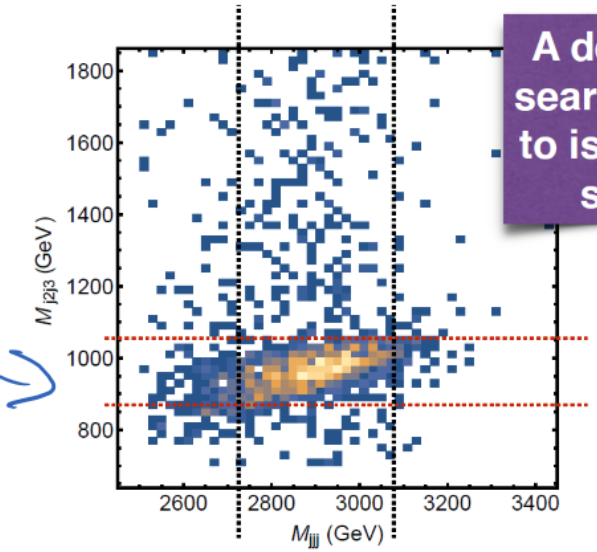


Differences from ATLAS:

1) No $p_{T\,Asym}$ cut ⇒ interesting shapes
2) Select 2 hardest tagged jets
   (vs tag 2 hardest jets)
   ⇒ sensitive to subleading jets

Searching for WWW (heavy radion)





A dedicated search useful to isolate the signal.

300 fb

$M_{rad} = 1$ TeV

fully hadronic: $S=9$, $B=3$, $S/\sqrt{B}=5$

semi-leptonic $S=19$, $B=9$, $S/\sqrt{B}=6$

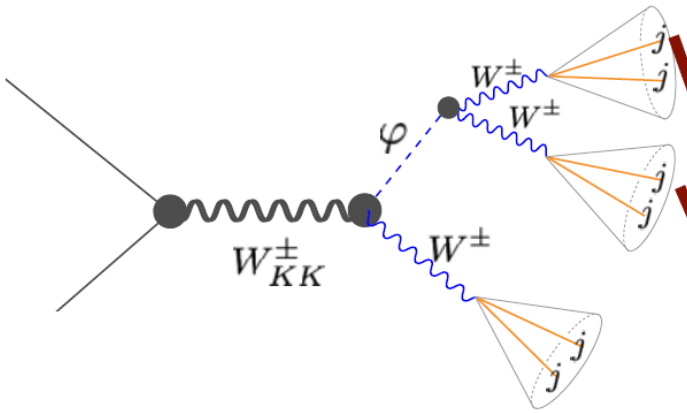
$M_{rad} = 1.5$ TeV

fully hadronic: $S=8$, $B=5$, $S/\sqrt{B}=4$

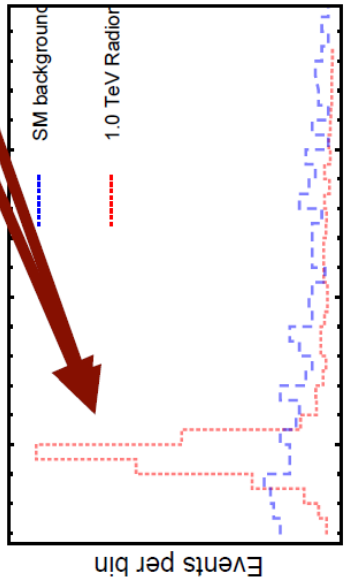
semi-leptonic: $S=15$, $B=4$, $S/\sqrt{B}=8$

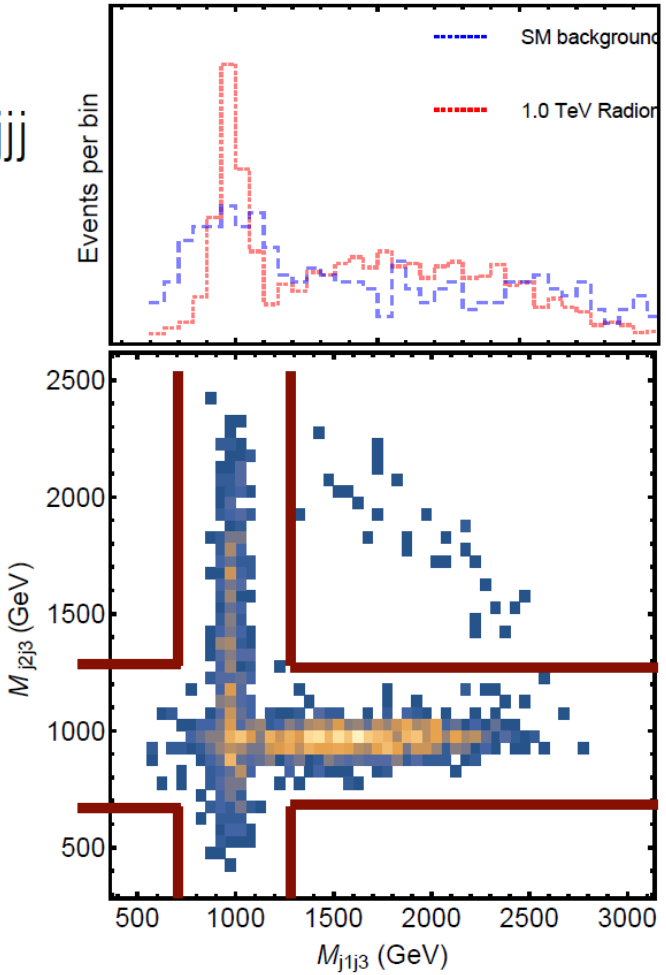
Slide taken from Rashimish Mishra's Pheno talk

Searching for WWW (heavy radion)



"+" cut after Mjjj window cut

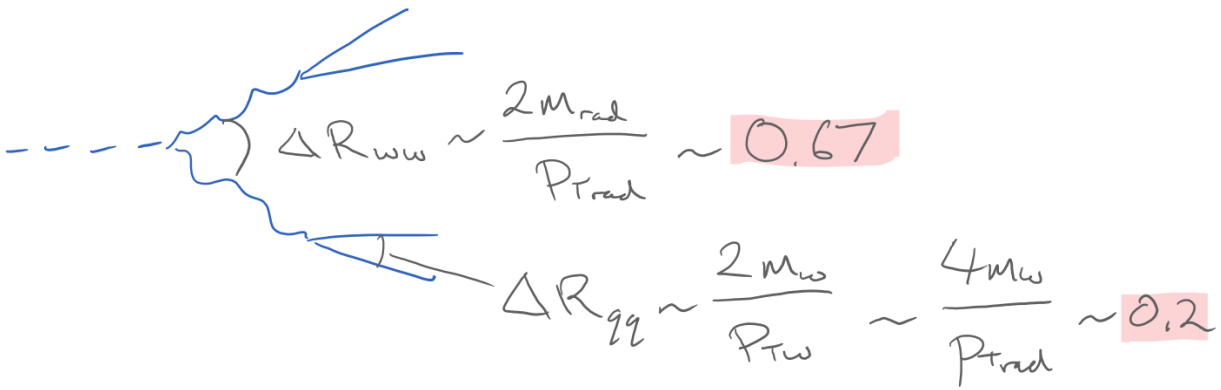




Slide taken from Rashimish Mishra's Pheno talk

Searching for W(WW) (light radion): Boosted WW

$M_{rad} = 500$ GeV

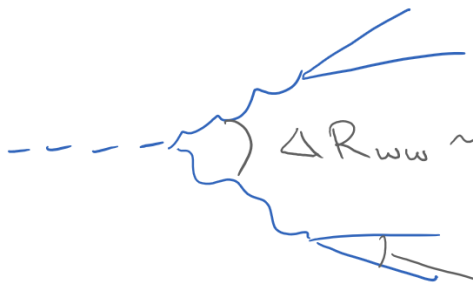


Stop when soft-drop condition reached

Soft Drop Condition: $\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\rm cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$

Searching for W(WW) (light radion): Boosted WW

$M_{rad} = 500$ GeV



$$\Delta R_{WW} \sim \frac{2M_{rad}}{p_{T\,rad}} \sim 0.67$$

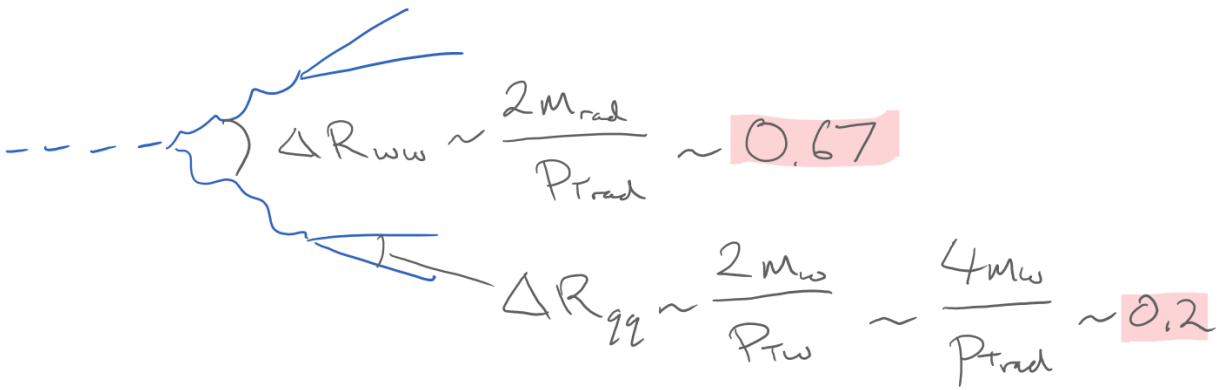
$$\Delta R_{qq} \sim \frac{2M_W}{p_{TW}} \sim \frac{4M_W}{p_{T\,rad}} \sim 0.2$$

Stop when soft-drop condition reached

Soft Drop Condition: $$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\rm cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

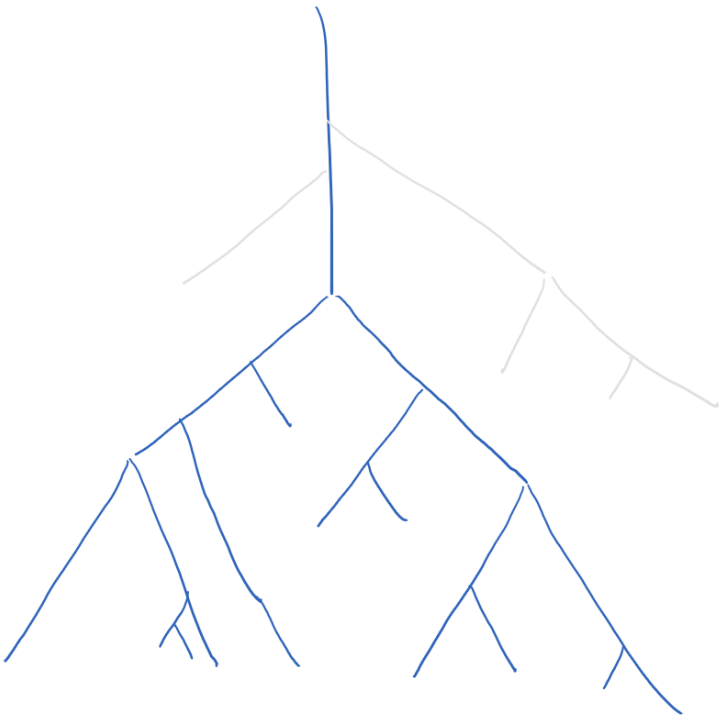
Searching for W(WW) (light radion): Boosted WW

$M_{rad} = 500$ GeV



Stop when soft-drop condition reached

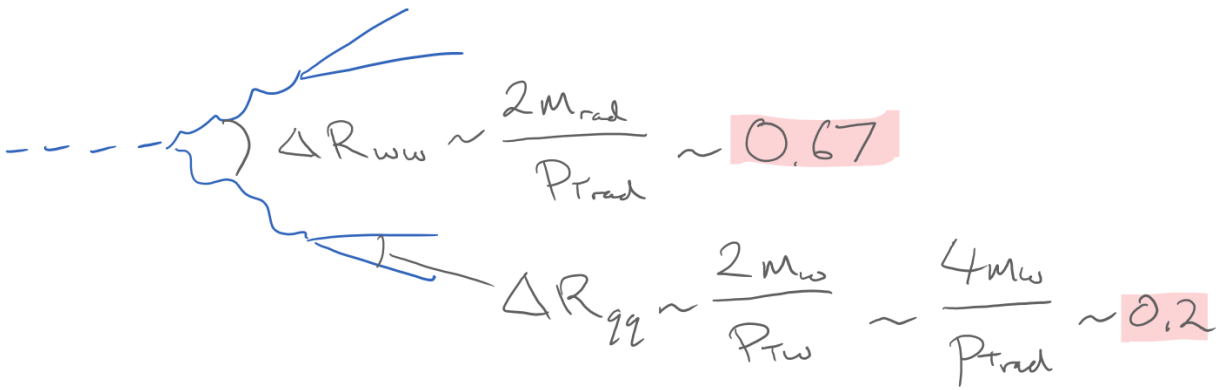
Soft Drop Condition: $\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\rm cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$



Now run on the two subjets!

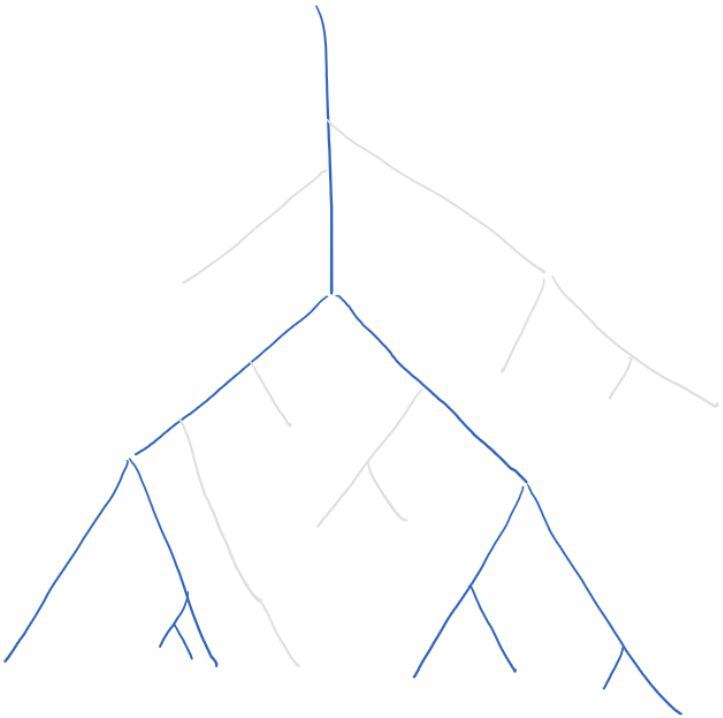
Searching for W(WW) (light radion): Boosted WW

$M_{rad} = 500$ GeV



Stop when soft-drop condition reached

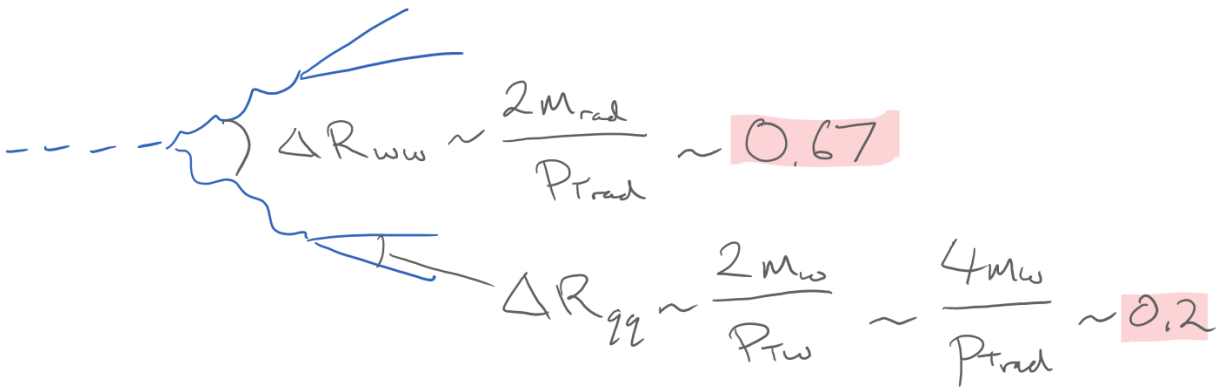
Soft Drop Condition: $\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\rm cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$



Now run on the two subjets!

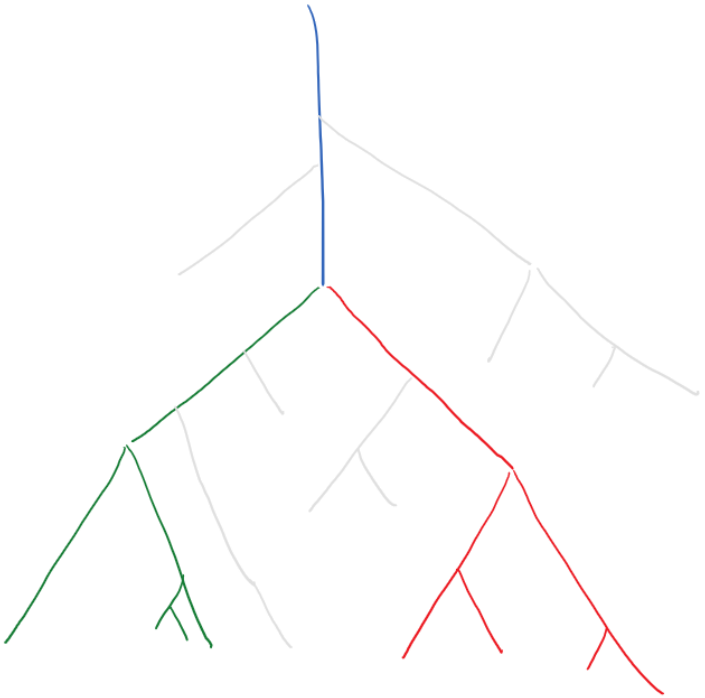
Searching for W(WW) (light radion): Boosted WW

$M_{rad} = 500$ GeV



Stop when soft-drop condition reached

Soft Drop Condition: $\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\rm cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$

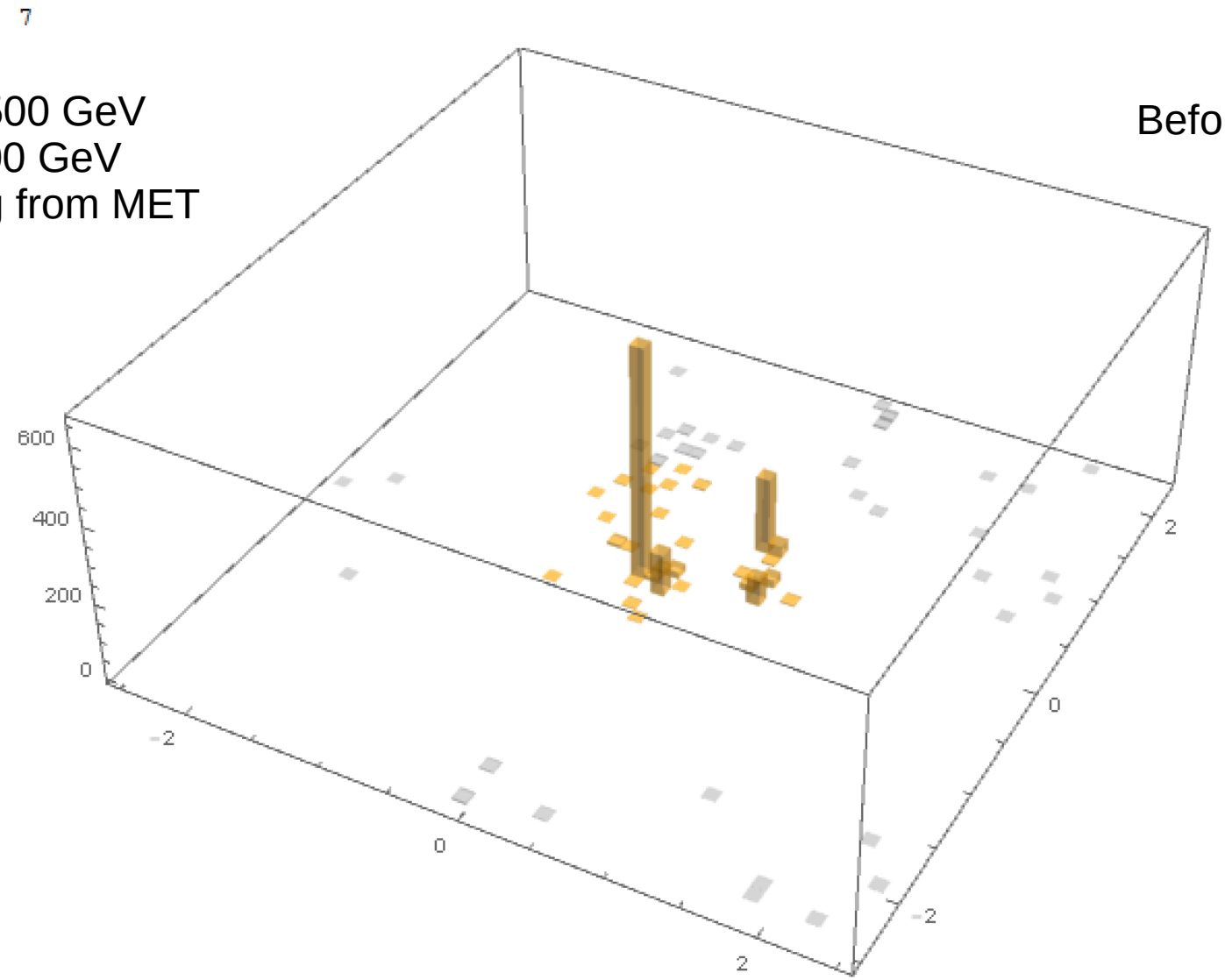


Now run on the two subjets!

Searching for W(WW) (light radion): Boosted WW

Mass = 500 GeV
PT ~ 1500 GeV
Recoiling from MET

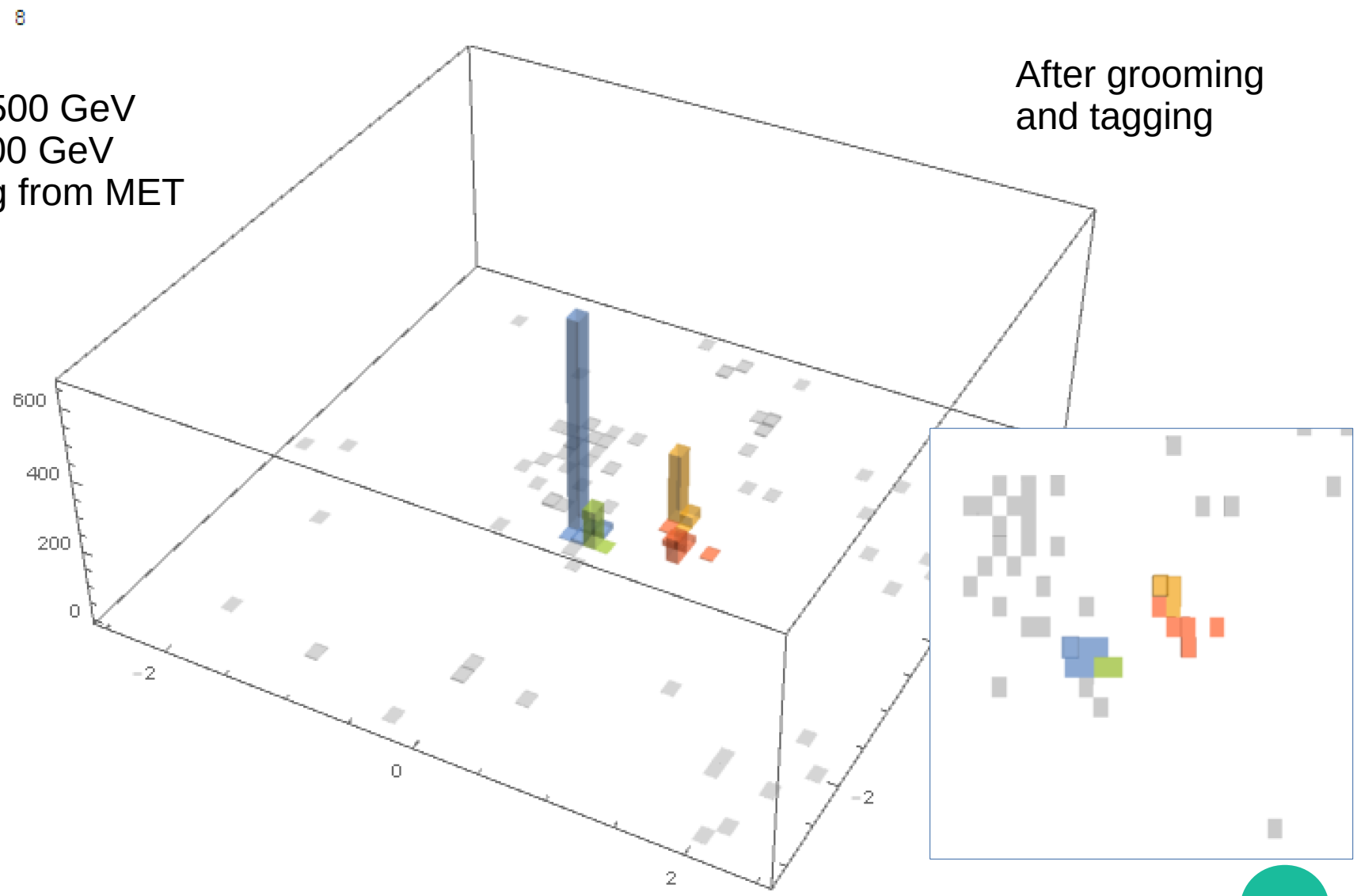
Before grooming



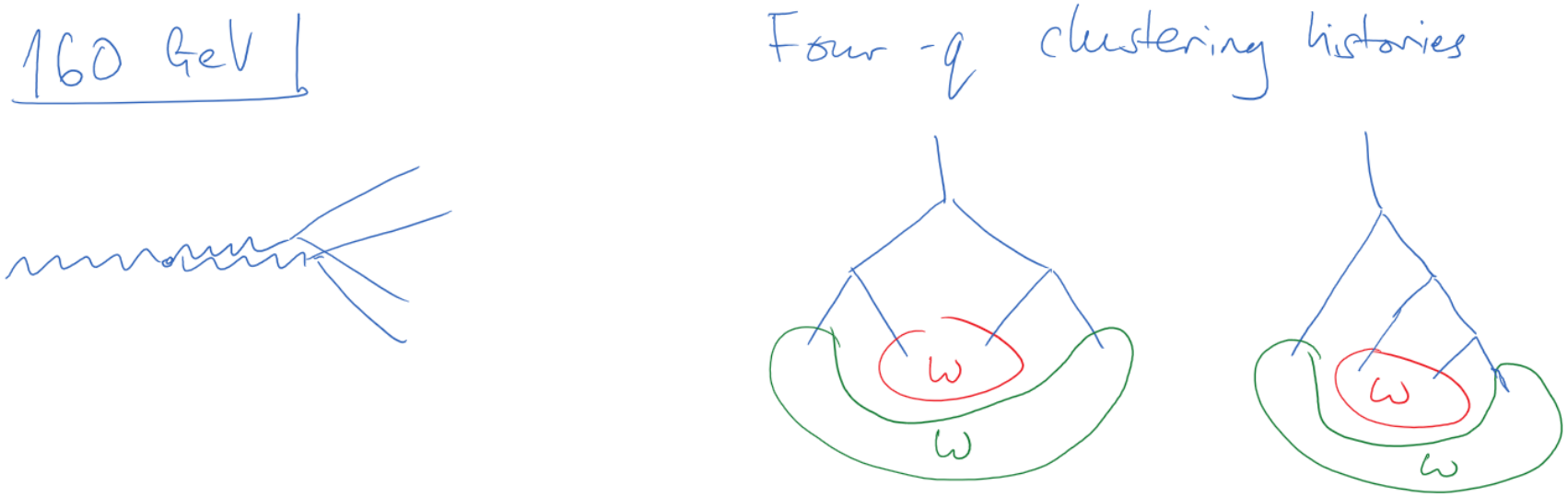
Searching for W(WW) (light radion): Boosted WW

Mass = 500 GeV
PT ~ 1500 GeV
Recoiling from MET

After grooming and tagging



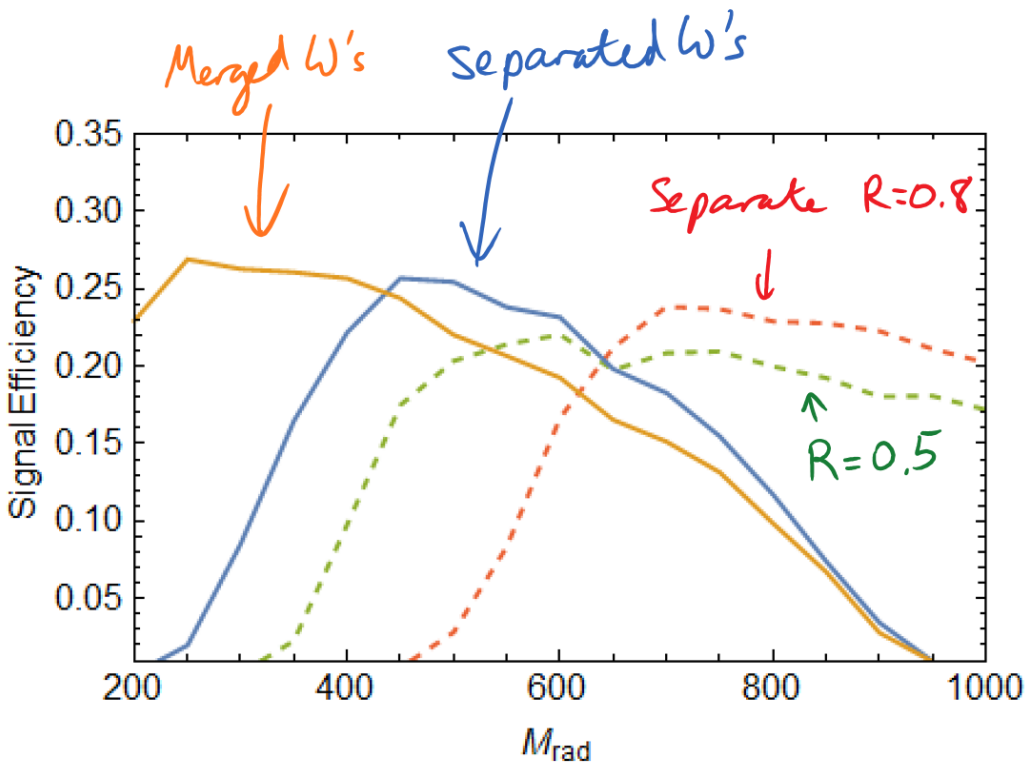
Searching for W(WW) (light radion): Boosted WW



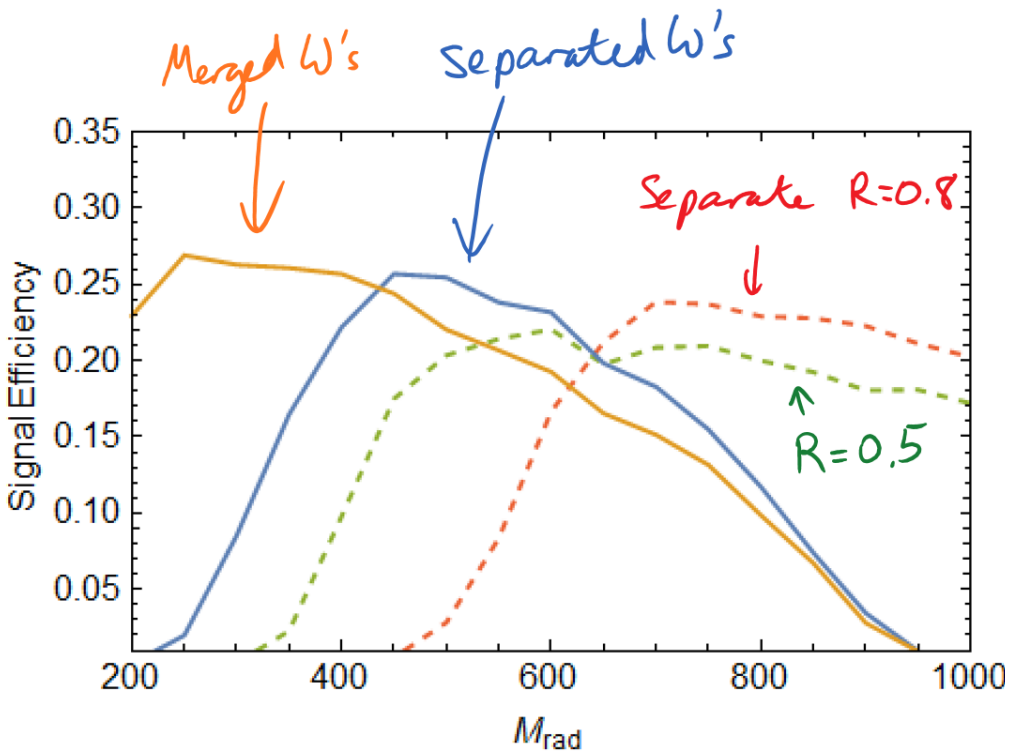
Algorithm (very closely based on arXiv:1204.0525, M. Son, C. Spethmann, B. Tweedie)

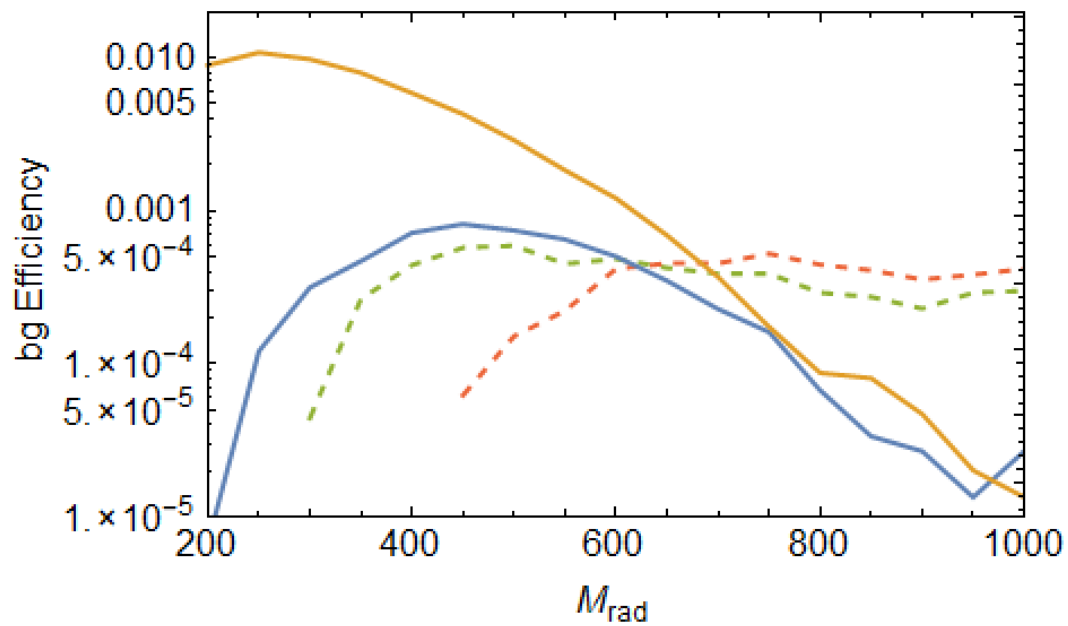
1) Find **ALL** hard splittings in clustering history
2) Take the three splittings with the largest mass, leaving six daughters.
3) Among these, two are parents of selected splittings. Choose remaining four daughters.
4) Make pairwise combinations of quark-candidates to find the pair of W-candidates with smallest mass difference.

Searching for W(WW) (light radion): Boosted WW

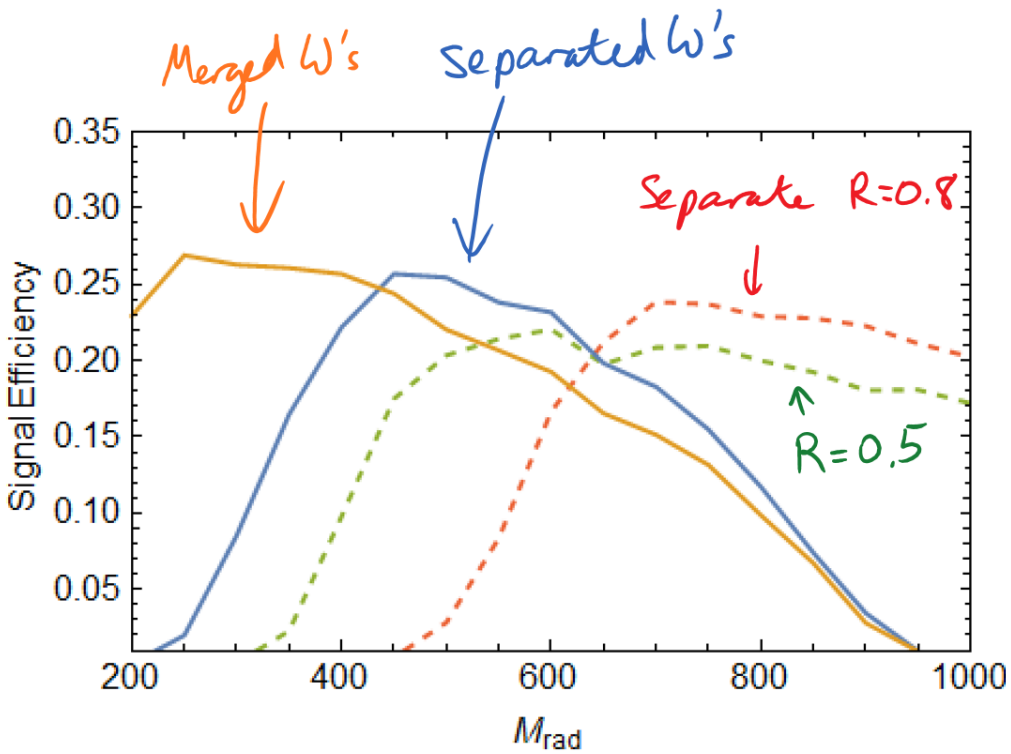


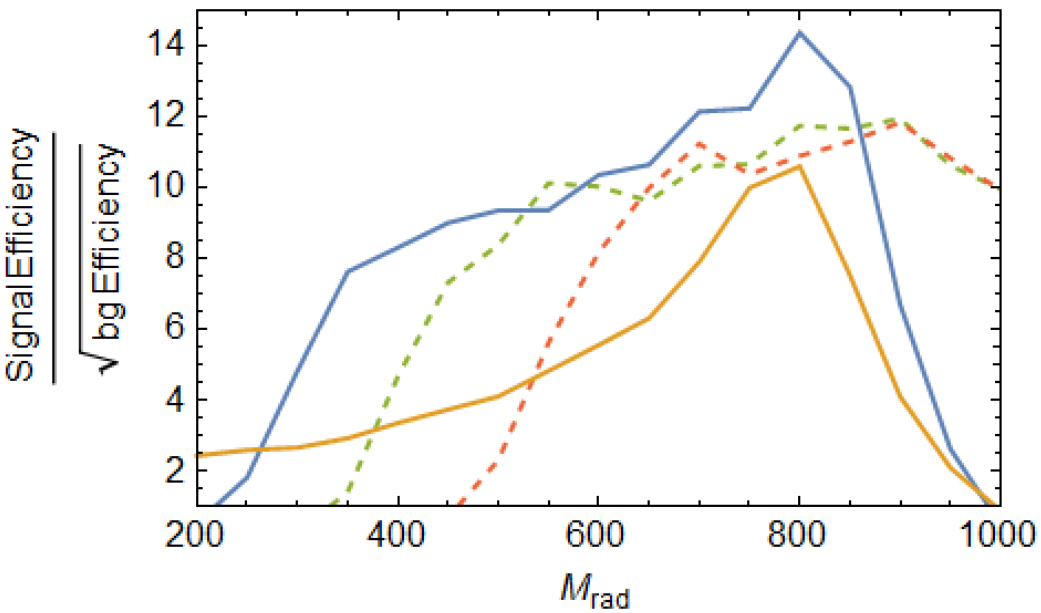
Searching for W(WW) (light radion): Boosted WW





Searching for W(WW) (light radion): Boosted WW





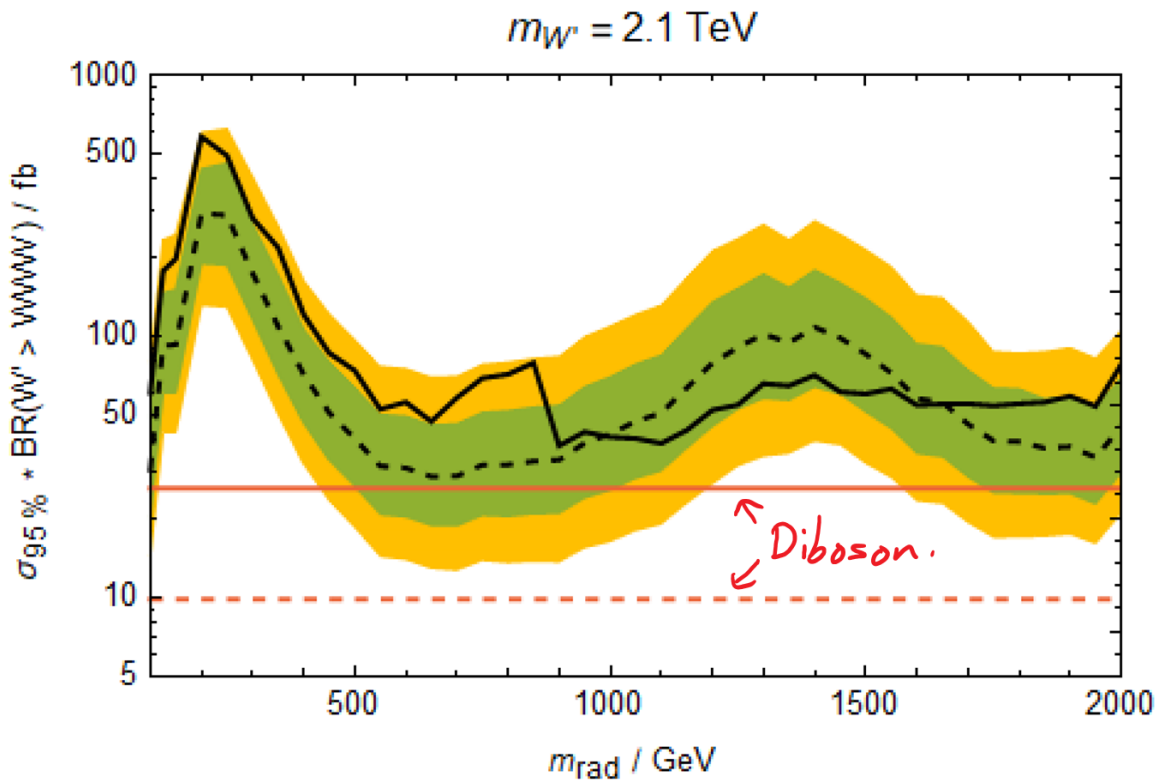
For W/Z discrimination

$$S/\sqrt{B} \sim \left(\frac{0.5}{0.02^{1/2}}\right) \sim 3$$

So $9 \sim (3)^2$

(WW) $(W)^2$

Searching for W(WW) (light radion): Boosted WW



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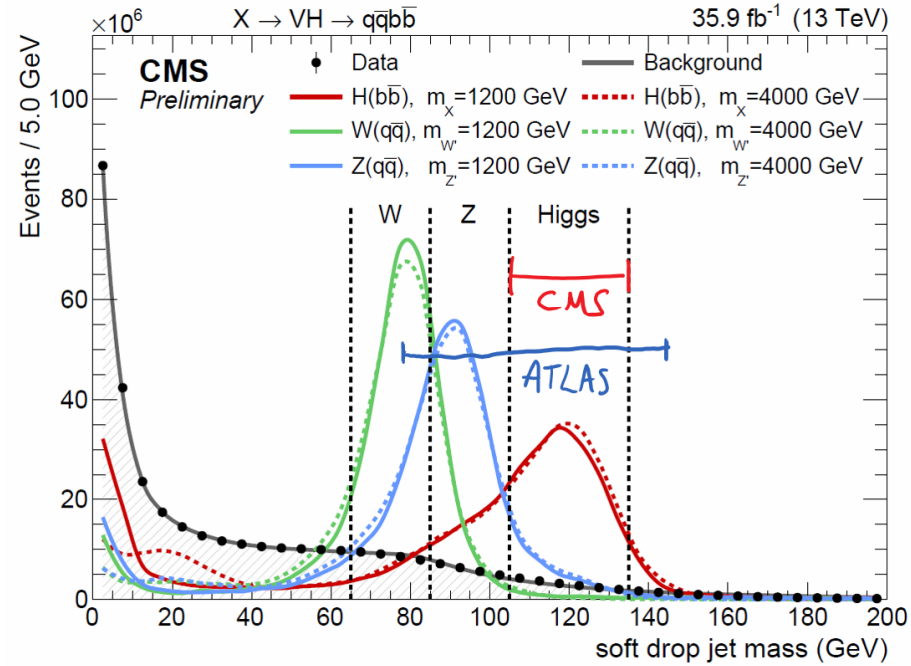
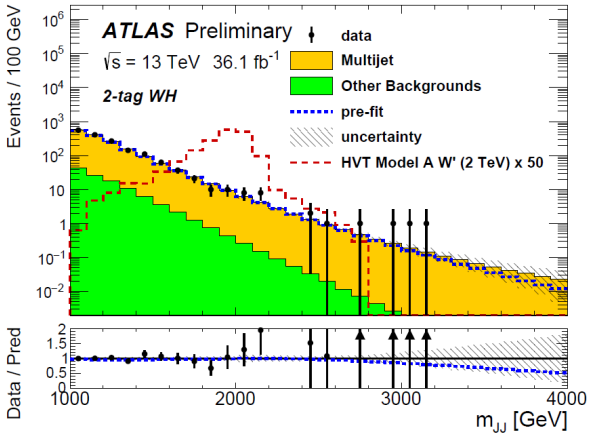
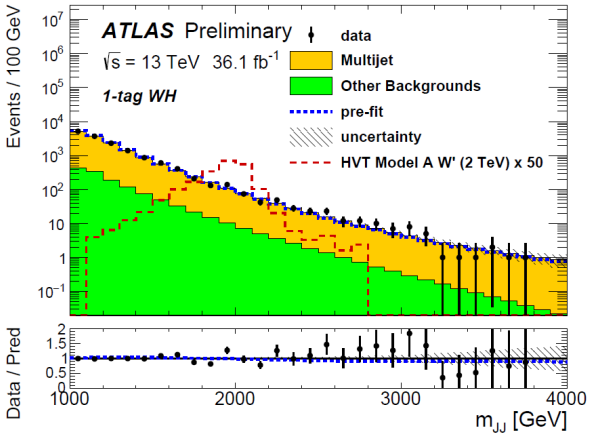
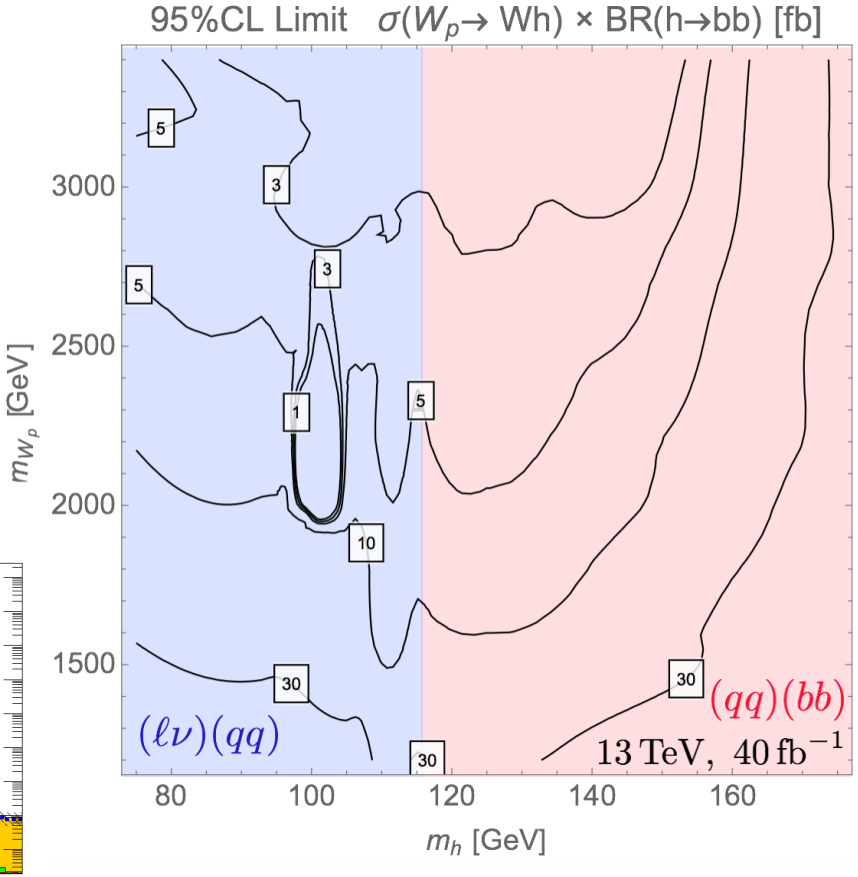
Final Topic:
VS resonances (with S → bb)



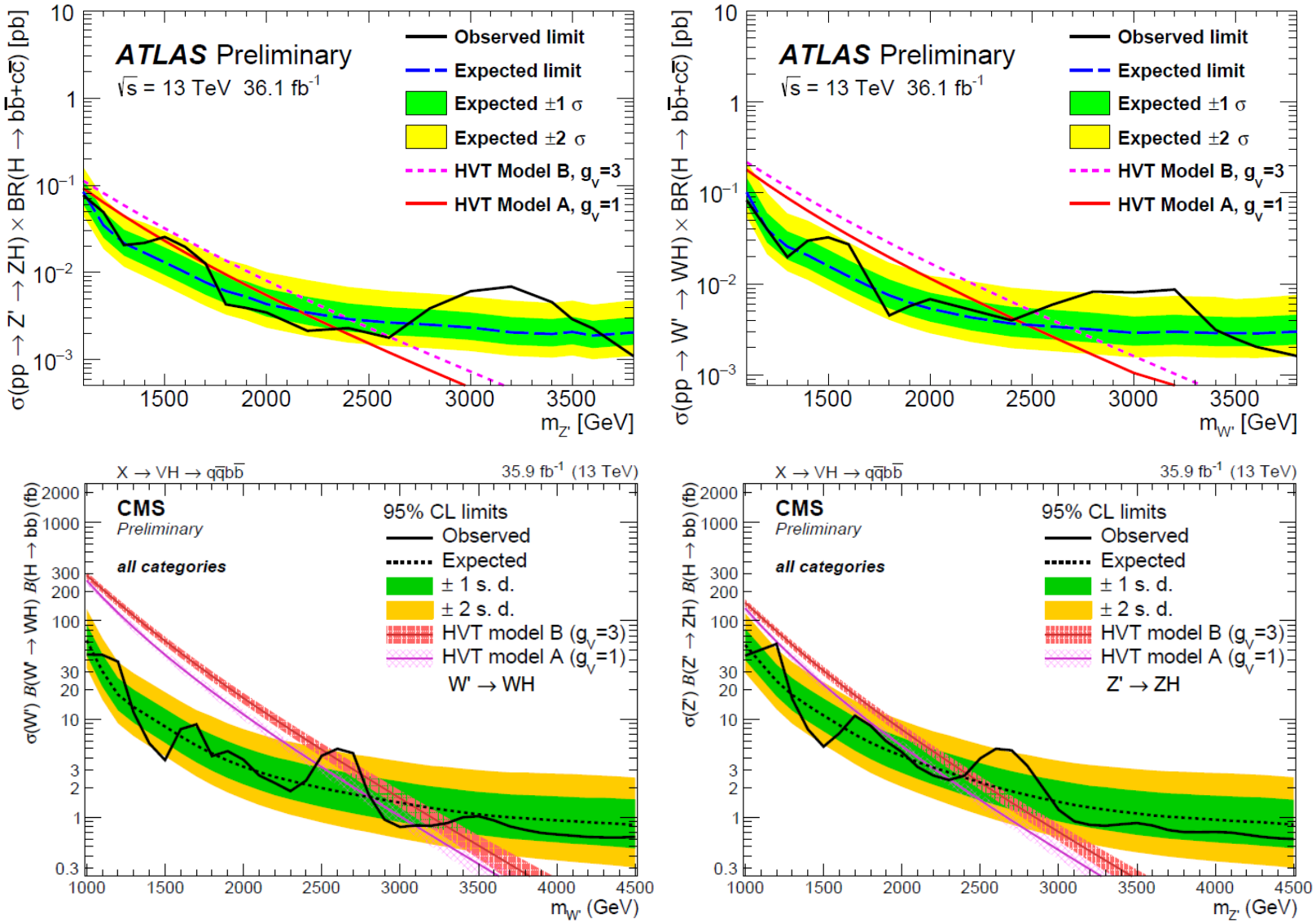




Expected limit (sensitivity)

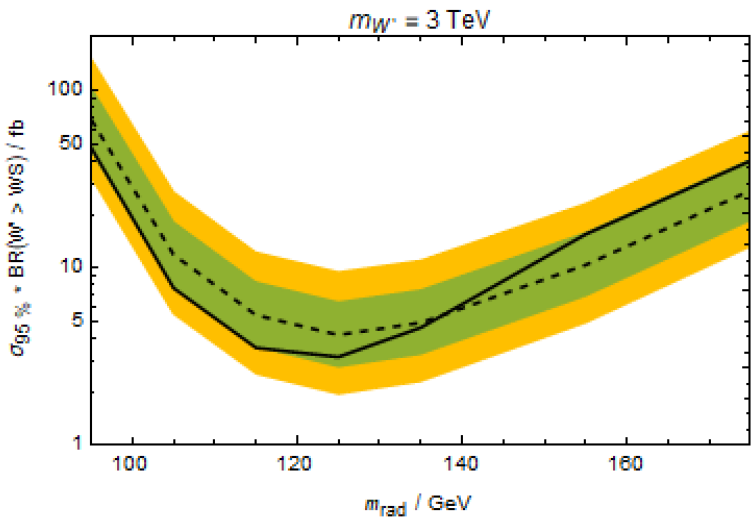


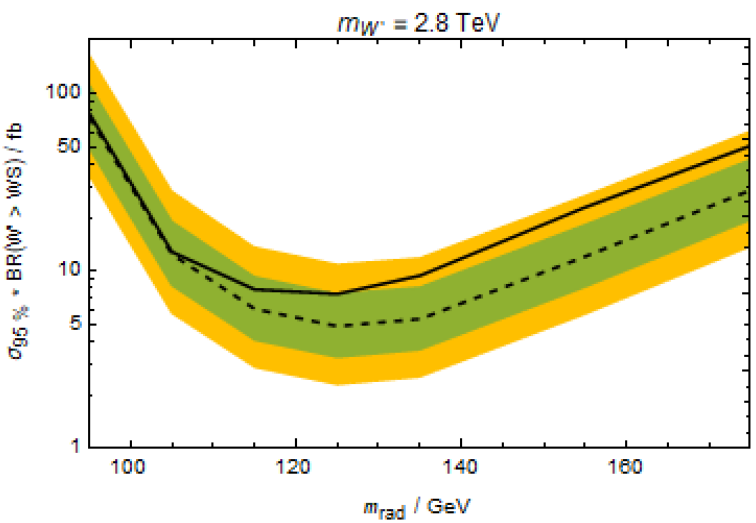
Final Topic:
VS resonances (with S → bb)



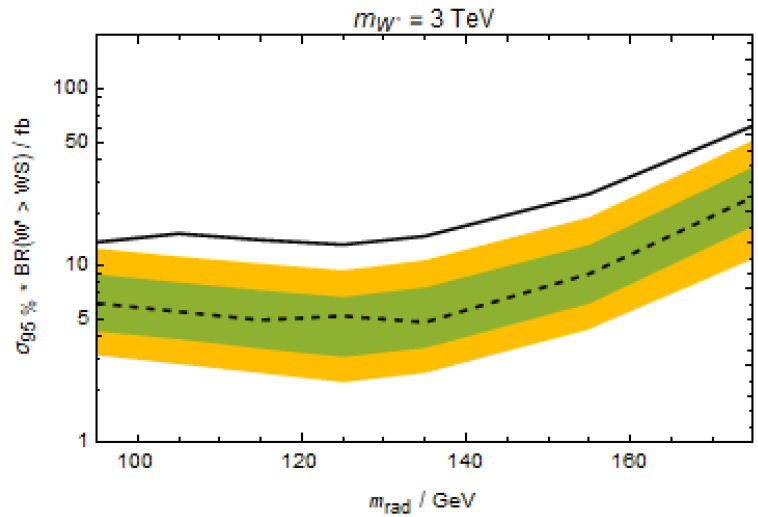
Final Topic:
VS resonances (with S → bb)

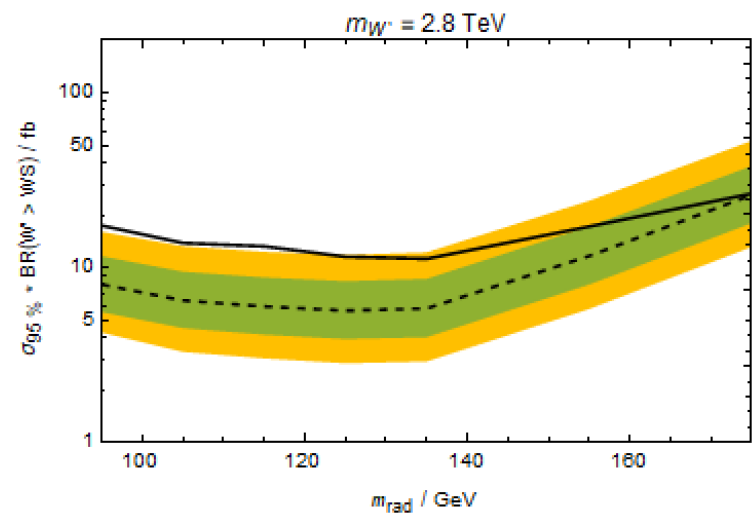
CMS recast





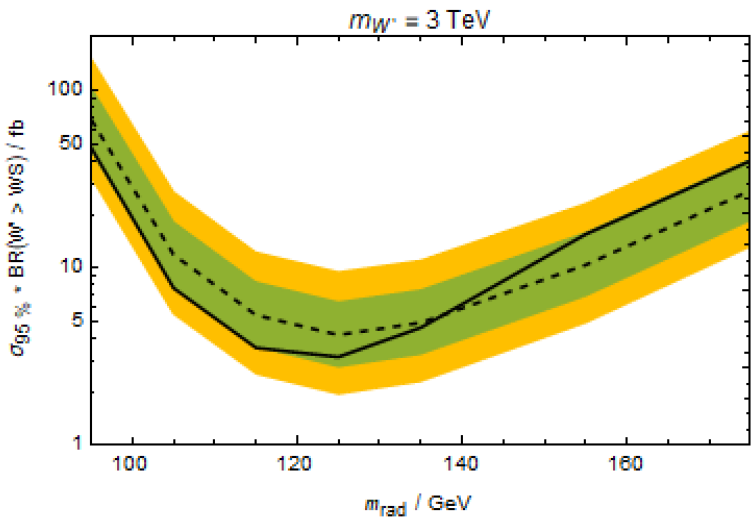
ATLAS recast

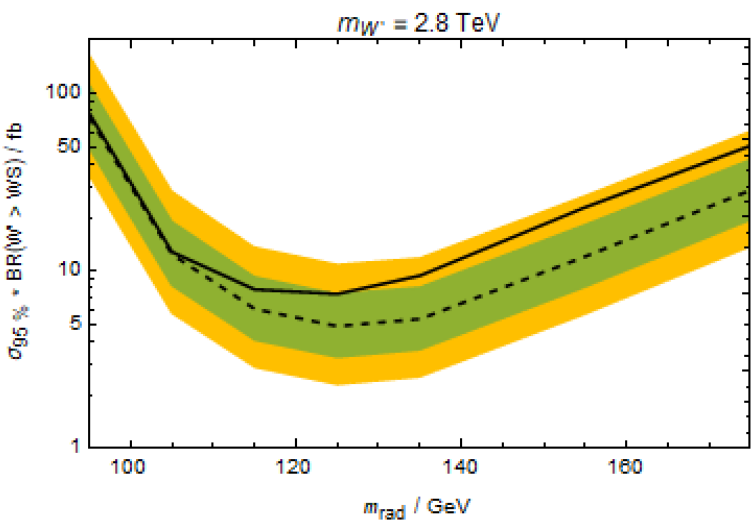


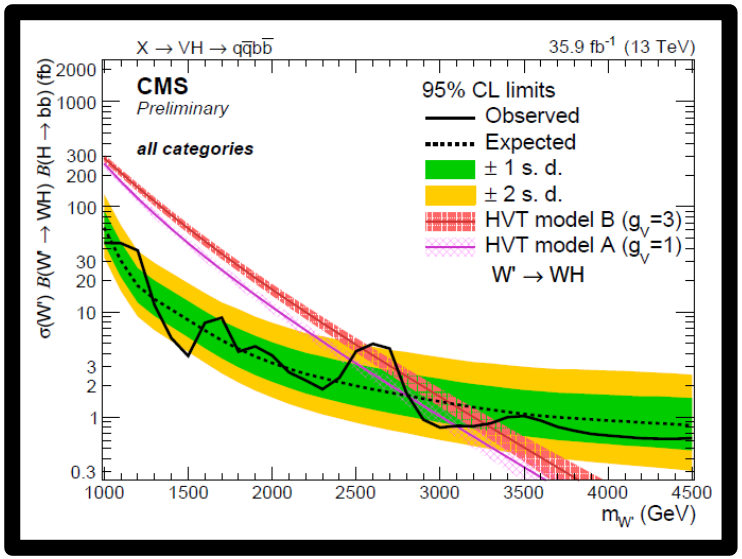


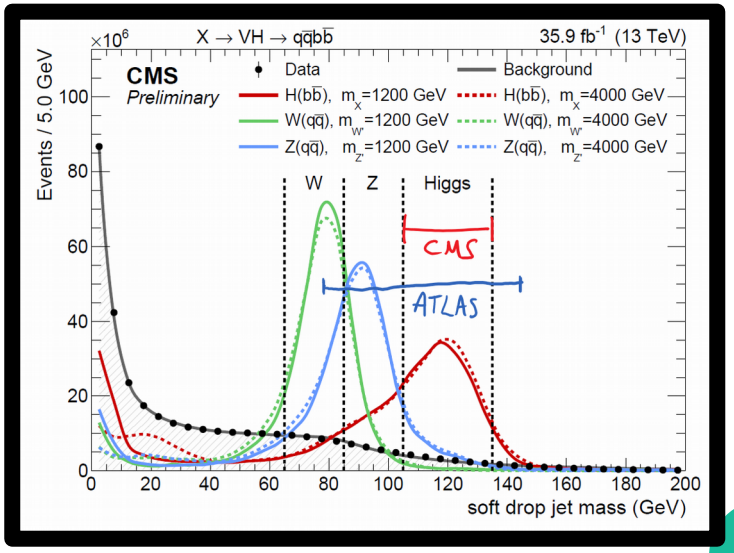
Final Topic:
VS resonances (with S → bb)

CMS recast

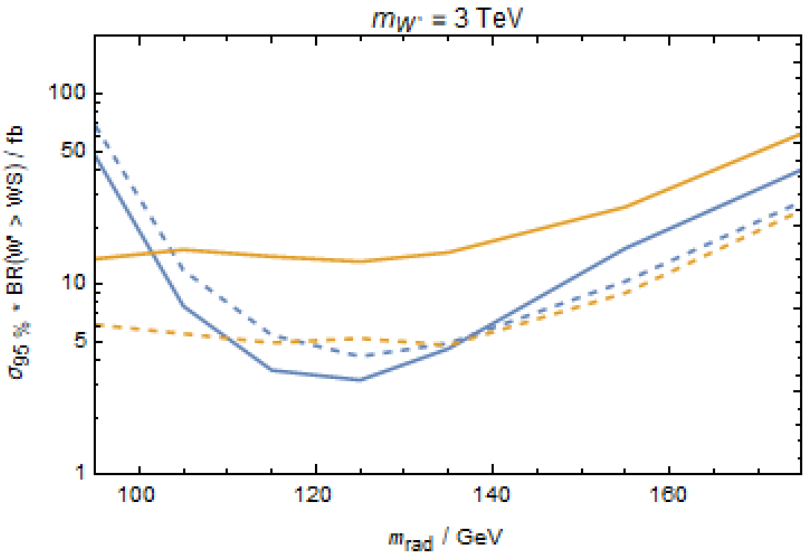


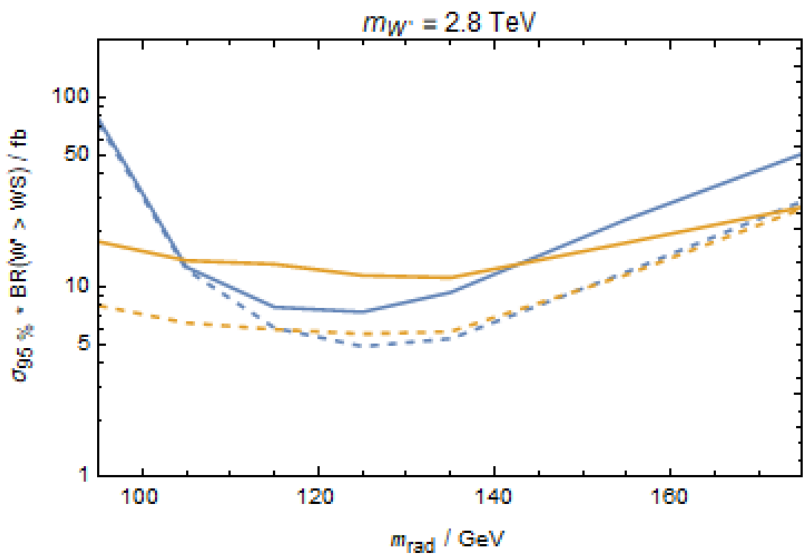


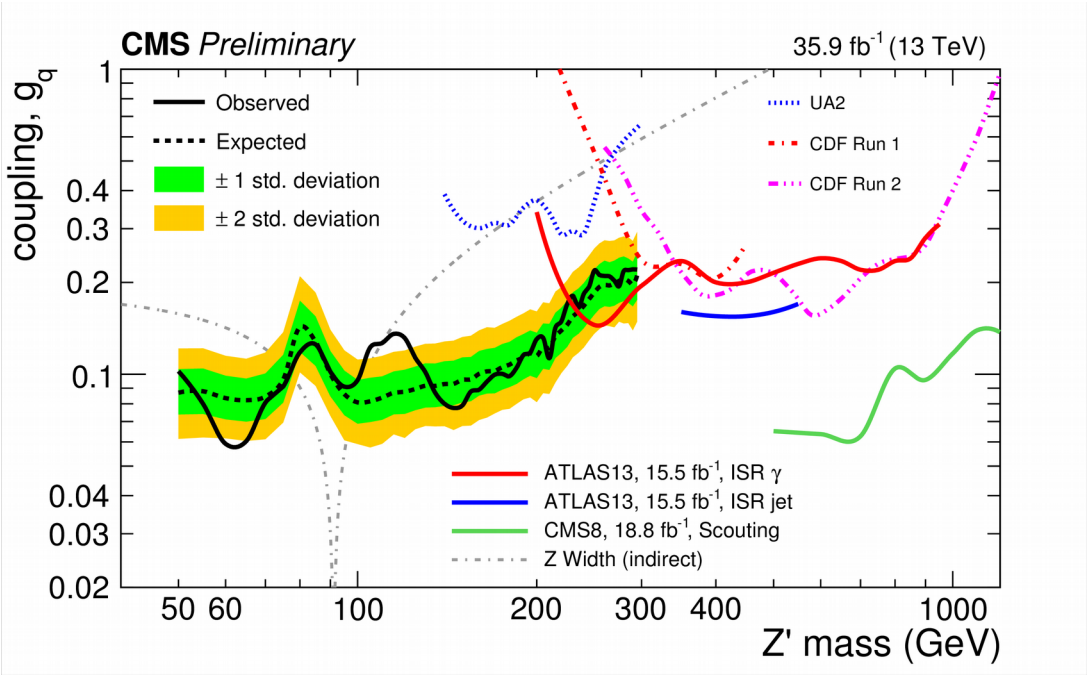




Final Topic:
VS resonances (with S → bb)







Conclusion

- Main point: Boosted objects are a curse, a place that new physics can hide if we do not look hard enough

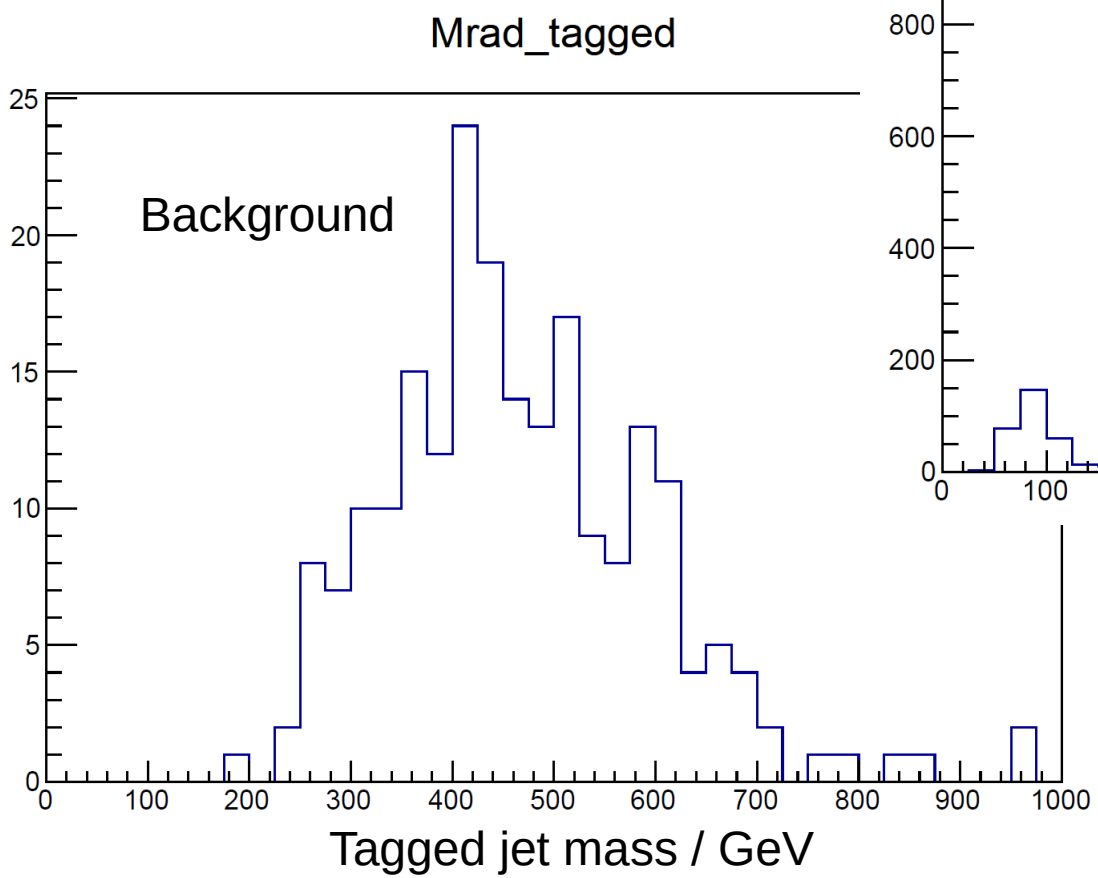
  ...but they are also a blessing, a possible window into new physics.

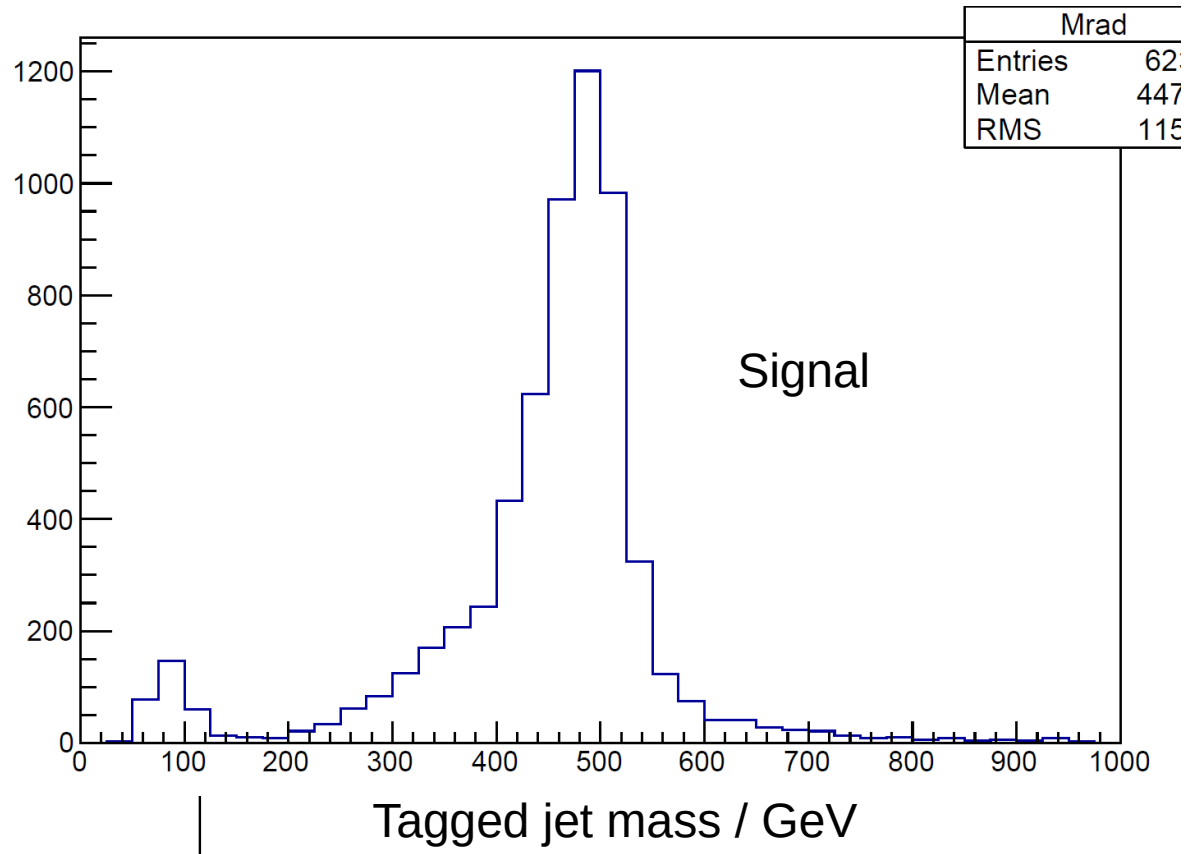
- Secondary point: Diboson searches are non-trivial in the context of generic new physics. It is possible for signatures to show up differently in different searches, in seemingly contradictory ways.

- Future direction: Can we make a reasonably generic 'anti-QCD' tagger for general BSM boosted topologies?

  bb, WW, HH, ZZ, tb, bb, bbV, btV, general multiprong hidden sector decay chains?

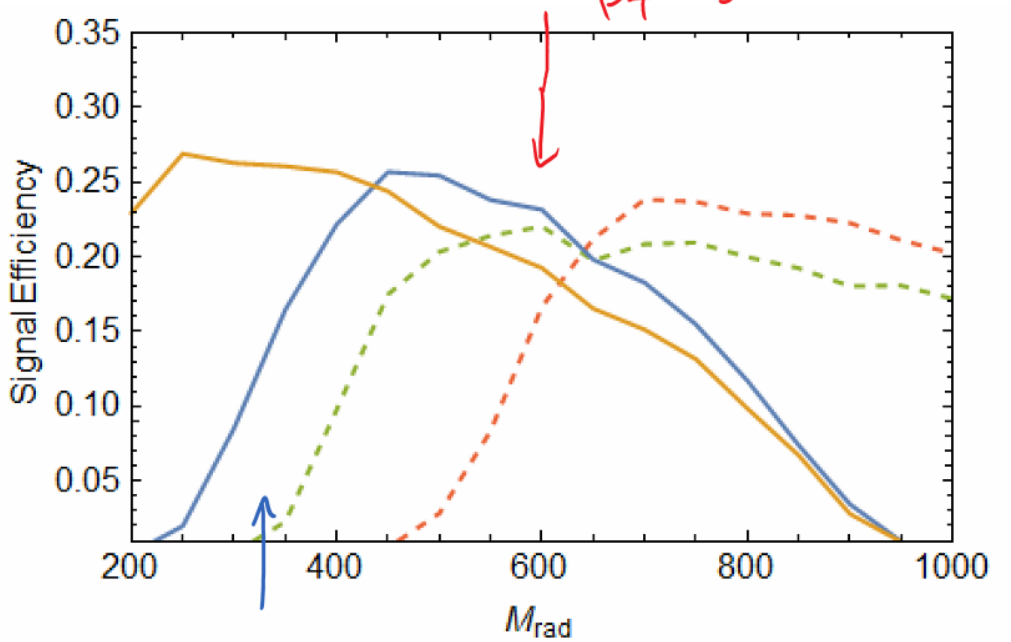
Searching for W(WW) (light radion): Boosted WW





Searching for W(WW) (light radion): Boosted WW

$\Delta R = \frac{2m}{p_T}$; $\Delta R = 0.8 \Rightarrow m = 600$ GeV



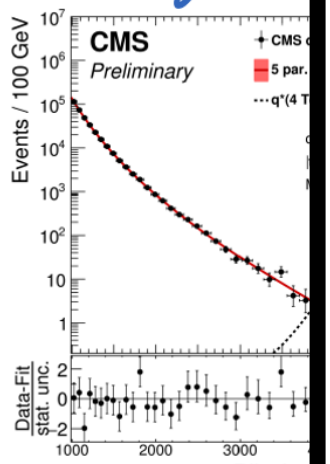
$$m_{rad}^2 = (p_{w_1} + p_{w_2})^2$$

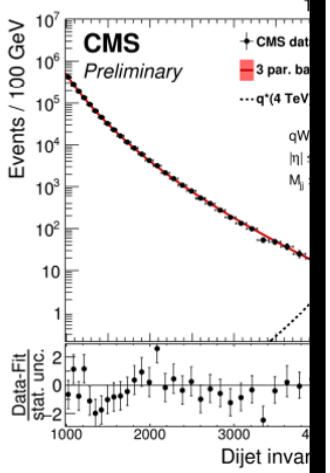
$$\Rightarrow \Delta R^2 = \frac{4m^2 - 16m_w^2}{p_T^2}$$

$\Delta R_{WW} = 2\Delta R_{qq} \Rightarrow M_{rad} = 340$ GeV.

Triboson WWW Signature in Diboson Searches: 3) CMS VV fully hadronic recast

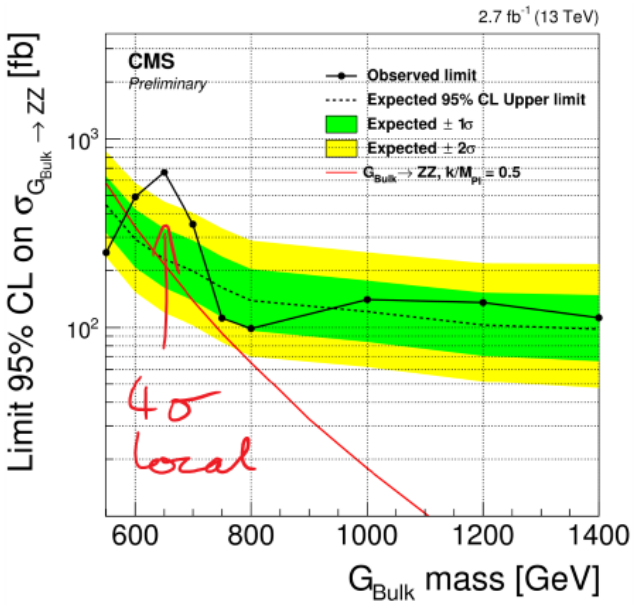
qW

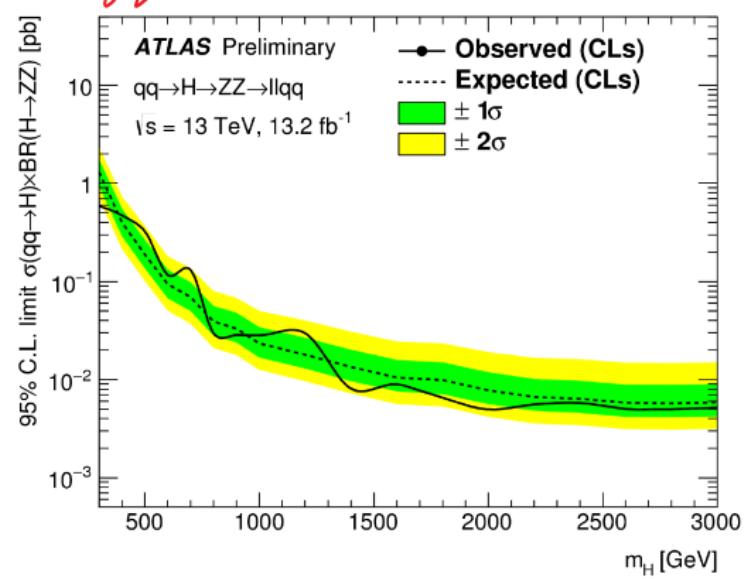


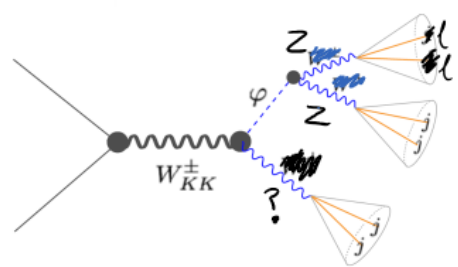


Fun anomaly-chasing application:

$R \to VZ \to qq\ell\ell$





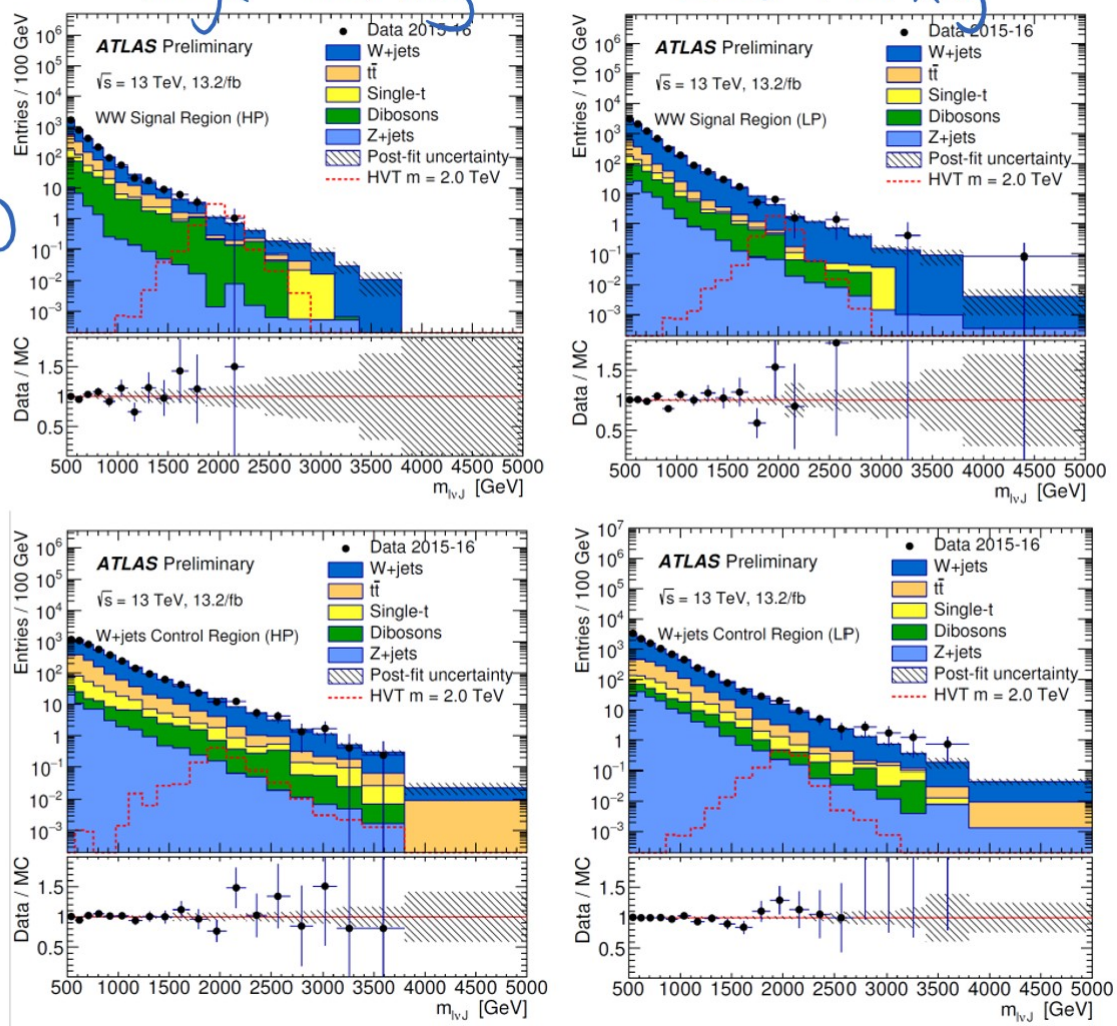


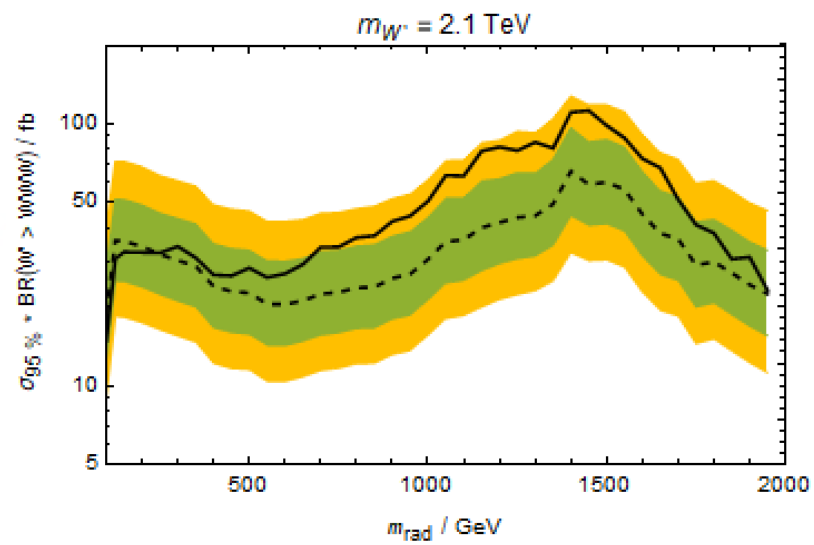
Triboson WWW Signature in Diboson Searches: 2) ATLAS VV lnuqq recast

High Purity | Low Purity

WW

Wj

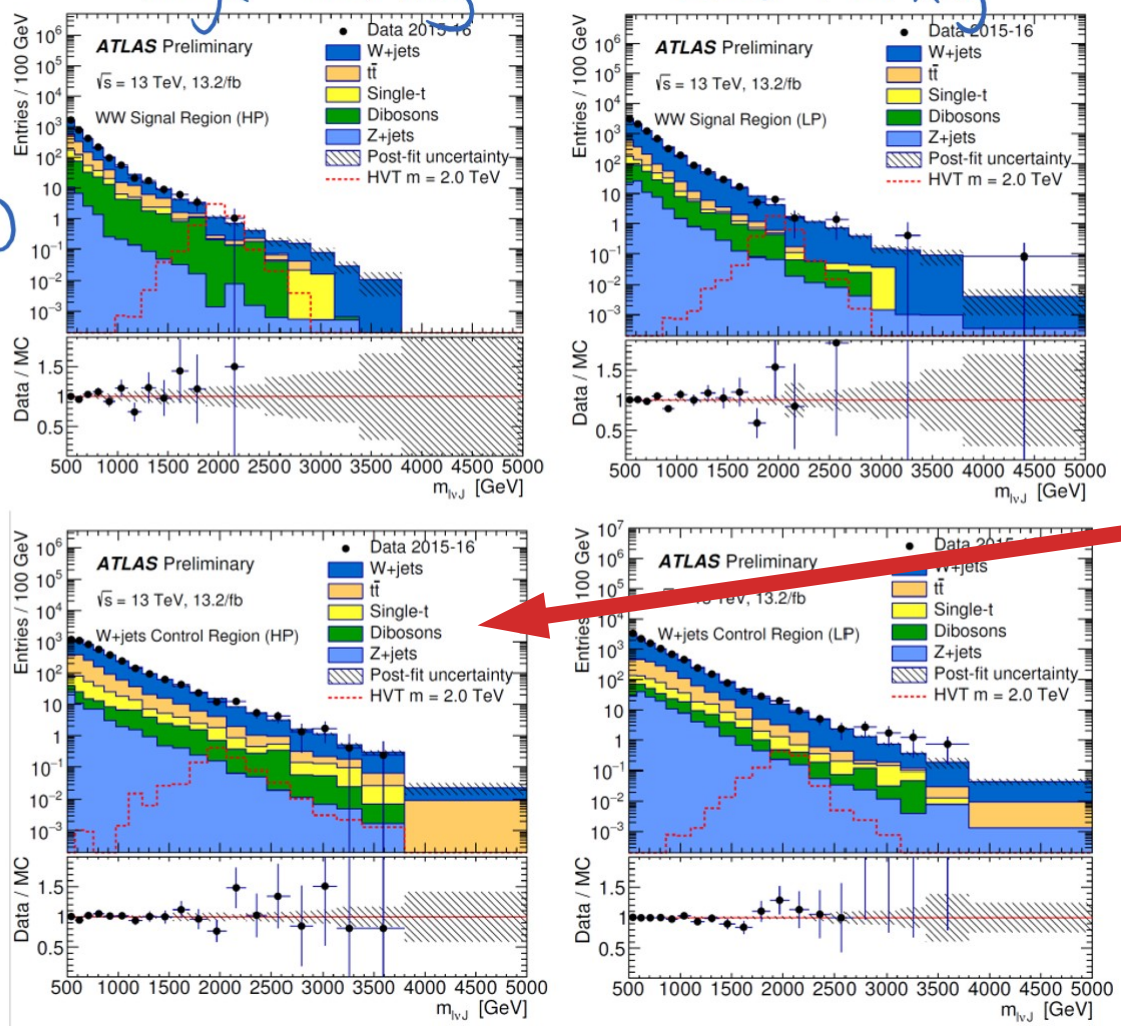
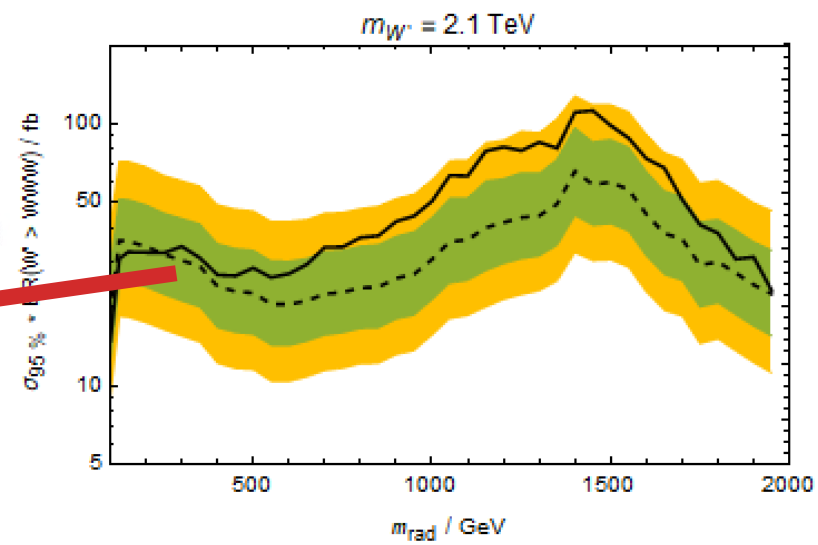




Triboson WWW Signature in Diboson Searches: 2) ATLAS VV lnuqq recast

High Purity

Low Purity

WW

Wj