Stealth bosons and where to find them

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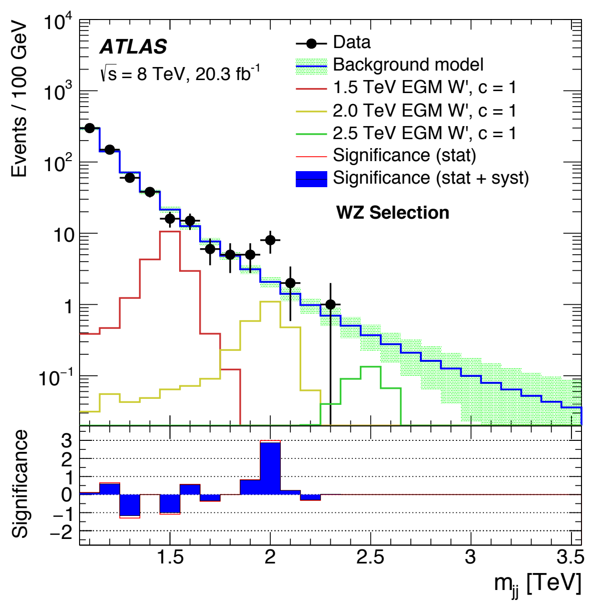
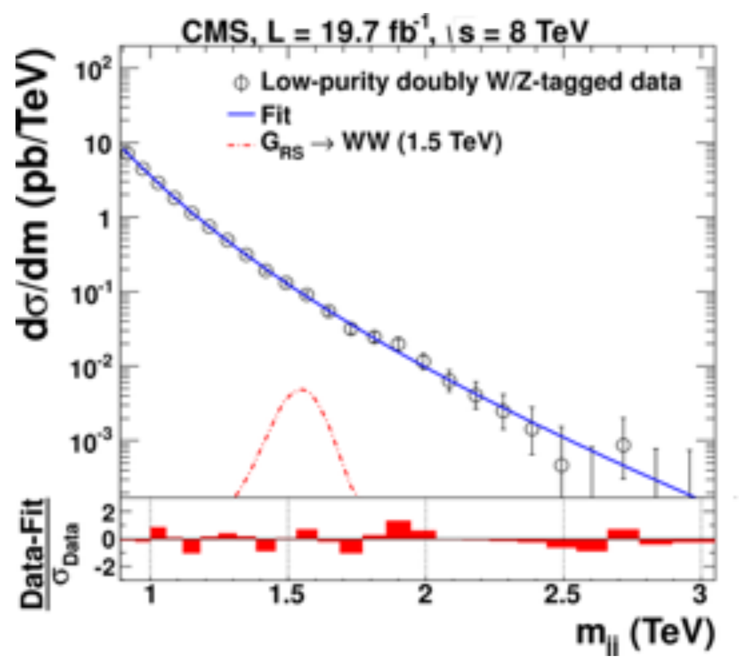
BOOST 2018, July 18th 2018

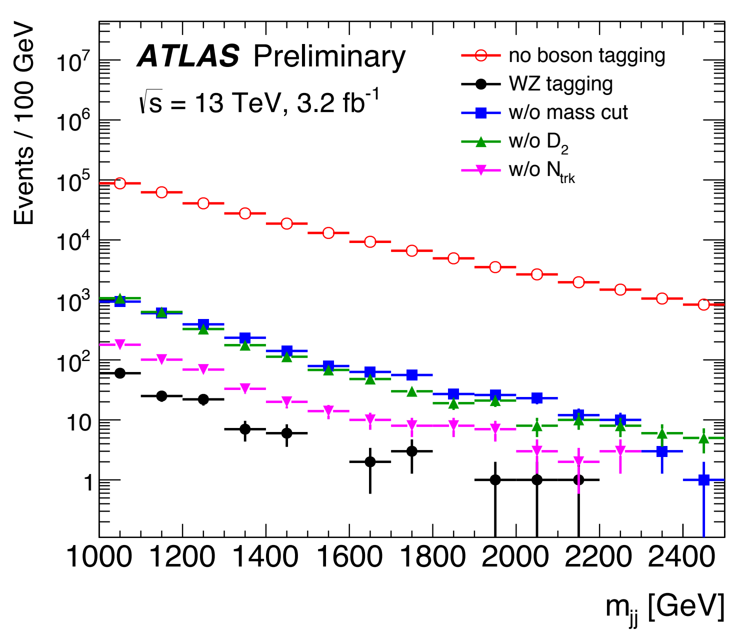
Motivation for all this stuff

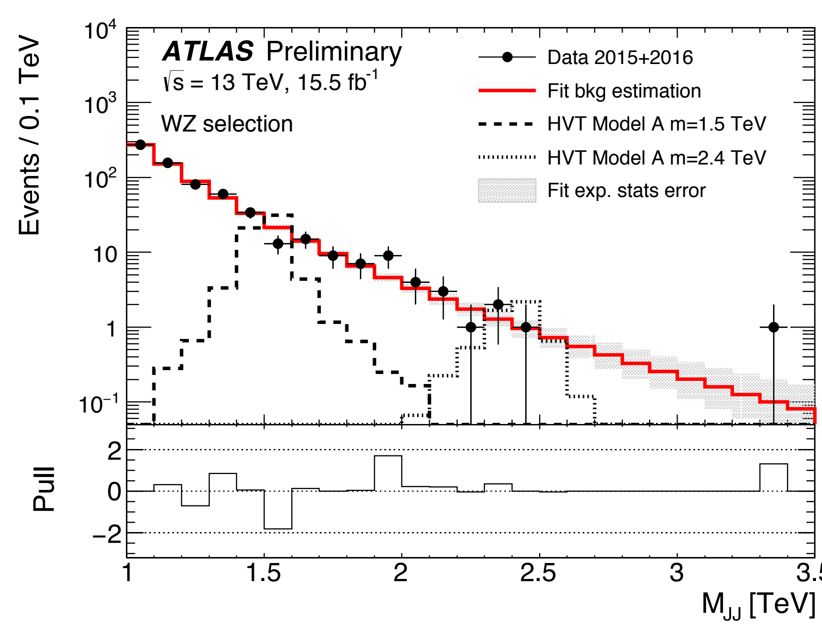
Several little bumps near 2 TeV in hadronic diboson resonance searches

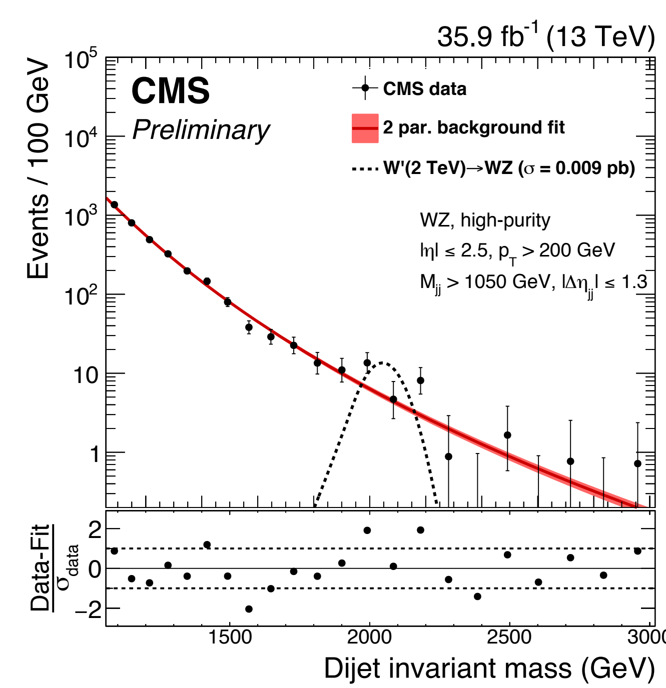
Obviously not diboson → think of something else, more elusive











Why dibosons? [≡ diboson resonances]

- New W' bosons can have decays $W' \rightarrow WZ$ with branching ratios at the percent level
- New neutral scalars H_l^0 can also decay to WW or ZZ, e.g. in composite Higgs models, … RS gravitons, … [lots of variants]

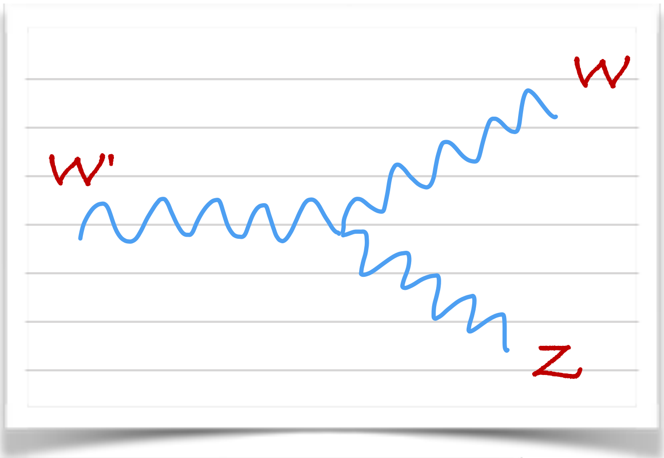
Nice and clean leptonic signals of these particles may well not exist.

→ extensive program for diboson searches at LHC mainly using a simplified model: Heavy Vector Triplet, a.k.a. HVT®

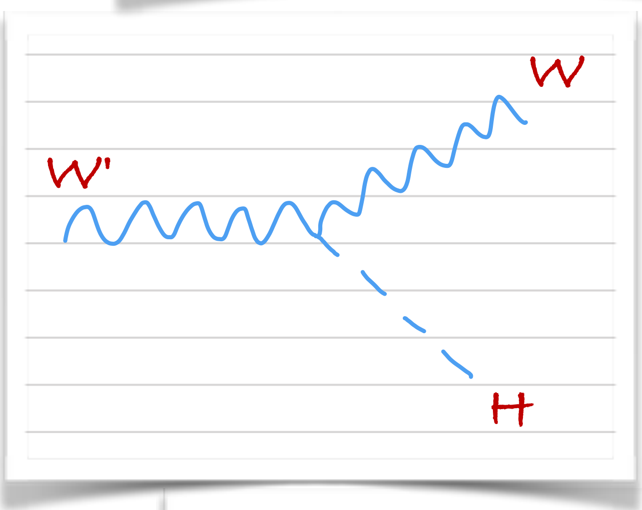
Simplied model confronts real model

take as example: left-right models

[manifest LR symmetry not required; alignment limit]



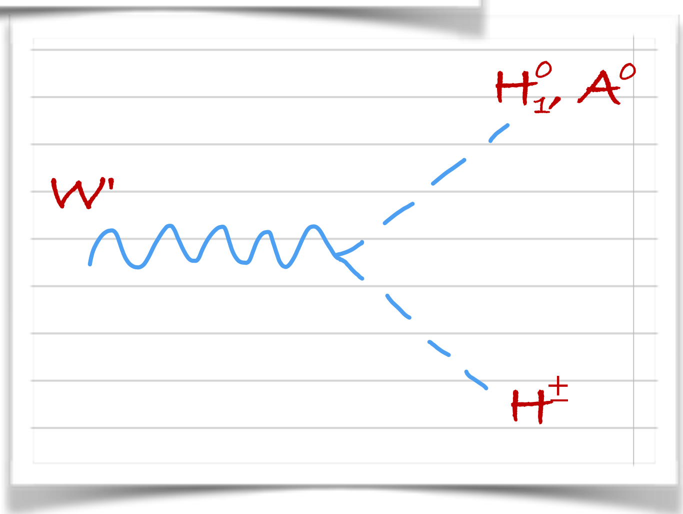
present in HVT® model

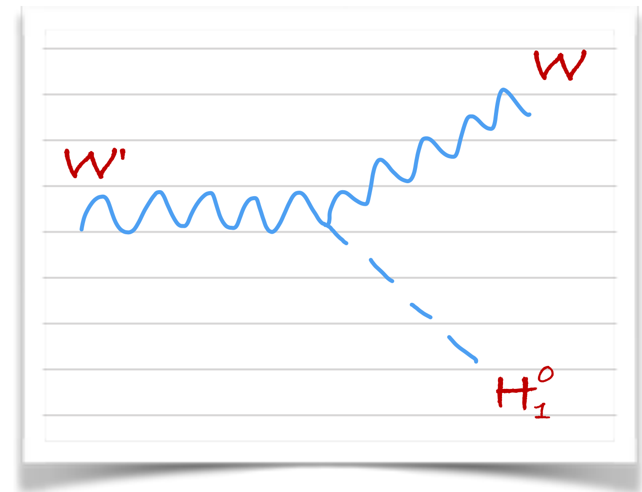


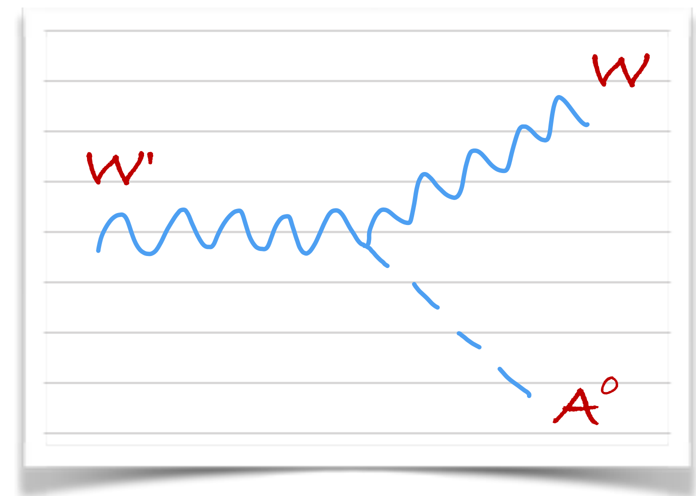
$$\Gamma \propto \sin^2 2\beta$$

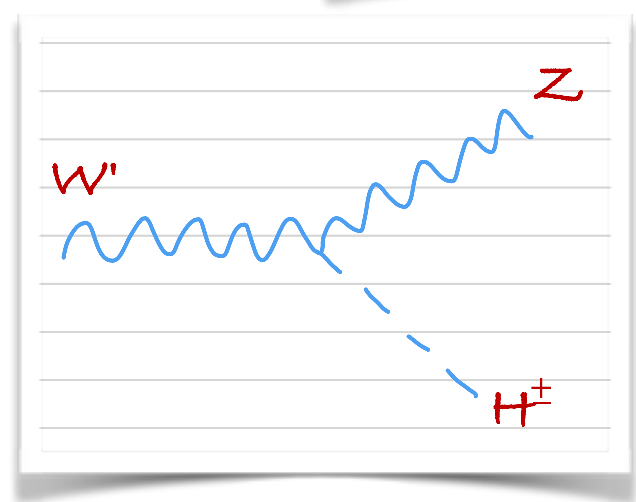
$$\Gamma \propto \cos^2 2\beta$$

$$\tan\beta = \frac{\langle \phi_2^0 \rangle}{\langle \phi_1^0 \rangle}$$









Reminder: we need an extended scalar sector anyway to give masses to the vector bosons! [several multiplets in LR model]

The heavy scalars will decay to lighter bosons, if kinematically allowed:

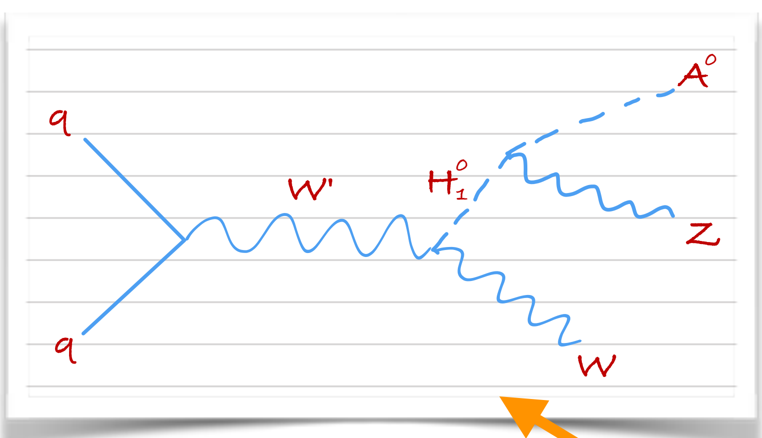
$$\Gamma(H_1^0 \to Z A^0) \propto M_{H_1^0}^3 / M_Z^2$$
$$\Gamma(H_1^0 \to f\bar{f}) \propto M_{H_1^0}$$

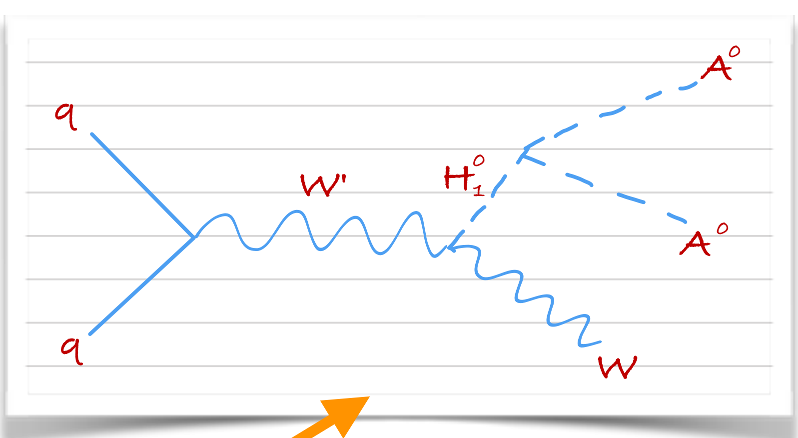
$$\Gamma(H^\pm \to W^\pm A^0) \propto M_{H^\pm}^3 / M_W^2$$
$$\Gamma(H^\pm \to f\bar{f}) \propto M_{H^\pm}$$

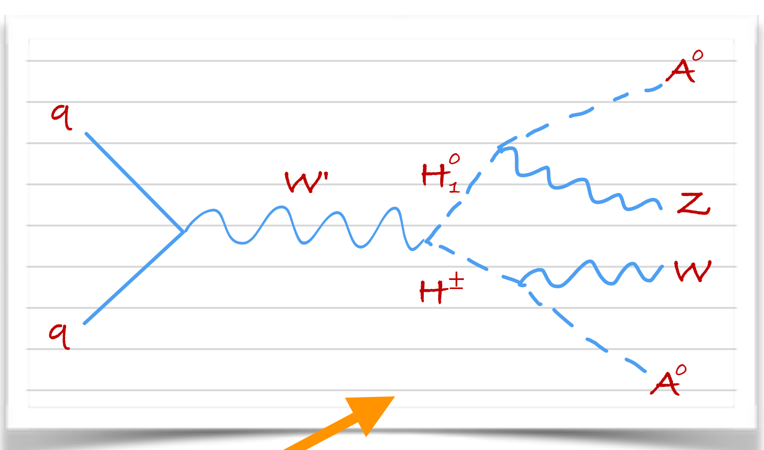
Therefore, as soon as we have a heavy resonance (W', Z') decaying into heavy scalars, we will naturally have multiboson signals from cascade decays.

Example: $M(H_1^0) \sim M(H^\pm)$ and A^0 lighter

JAAS, Joaquim 1512.00396
see also: Dobrescu, Fox 1511.02148







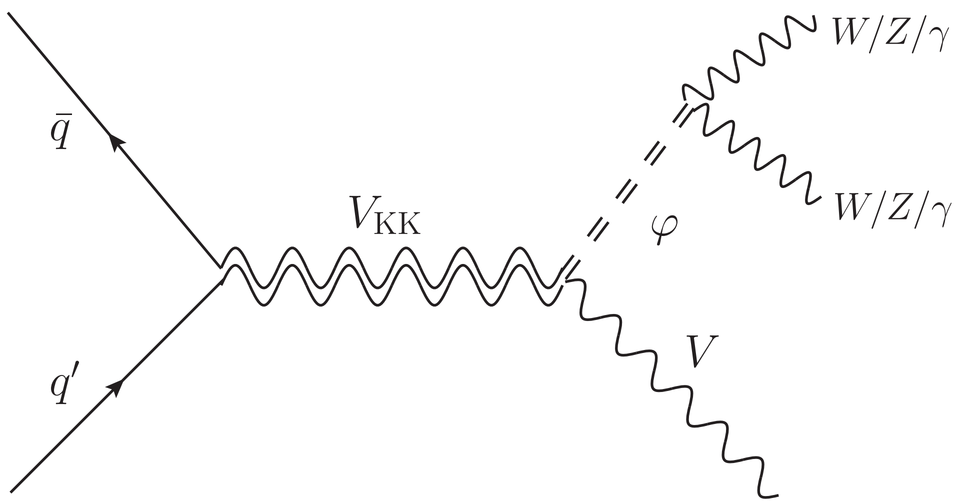
triboson

quadriboson

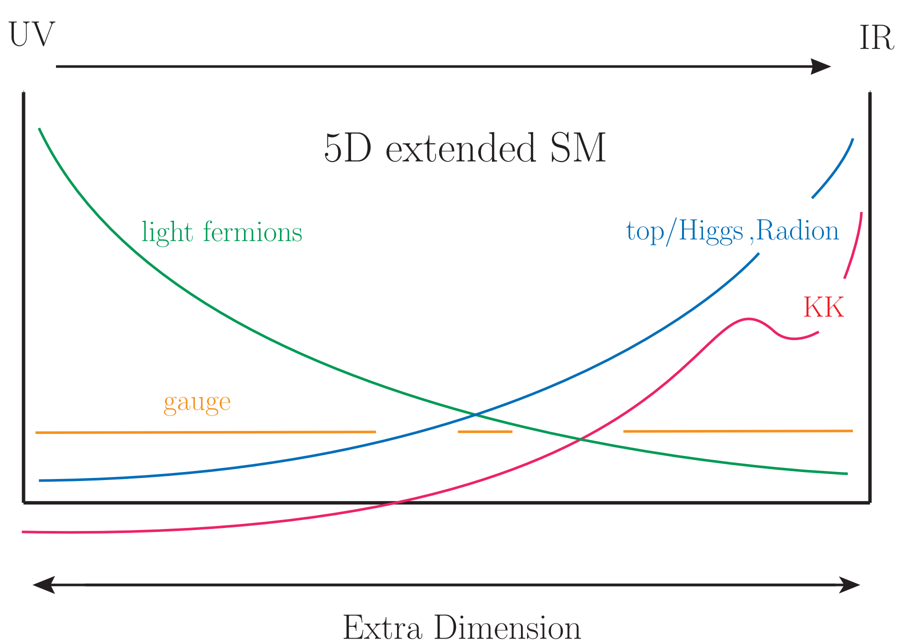
Further examples of multiboson signals:

- Next-to-minimal extra-dimensional models

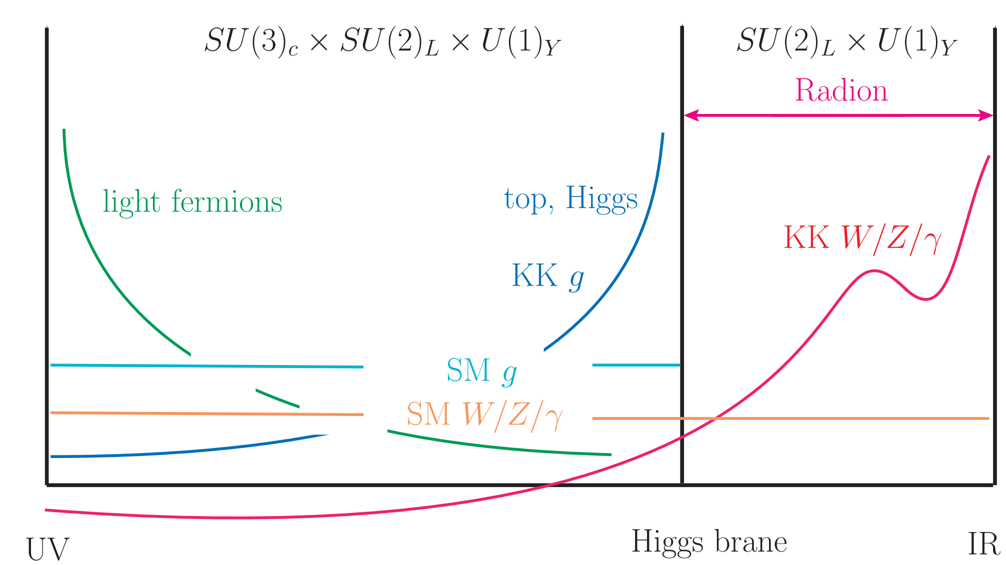
Agashe et al. 1711.09920
Agashe et al. 1612.00047



standard setup



next-to-minimal



Further examples of multiboson signals:

- Cascade decay of heavy scalars in SUSY

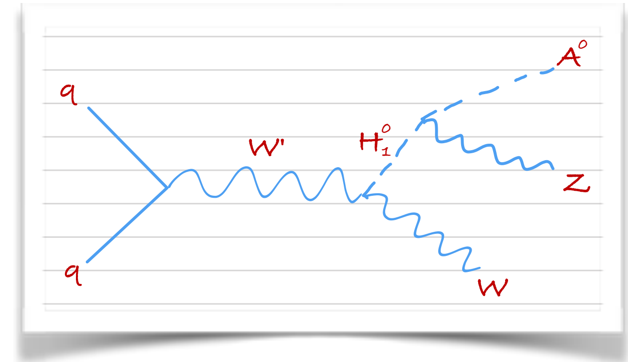
Fidalgo et al. 1107.4614
Ellwanger et al. 1707.08522

- Any model you imagine with extra gauge bosons and/or extra scalars
  - Z' + extra Higgs $SU(2)_L$ doublet
  - Z' + scalar $SU(2)_L$ singlet (?)
  - … and more models we don't yet imagine!

I am NOT claiming that any of these models is the answer. Rather, I insist that these signatures are well-motivated and uncovered, and must be searched for.

Multiboson signatures

JAAS 1506.06739



Case 1: Resolved triboson

Two SM bosons plus some extra particle

- The sensitivity of diboson searches to this type of signals depends on how tight the requirement of *only two objects* present is.

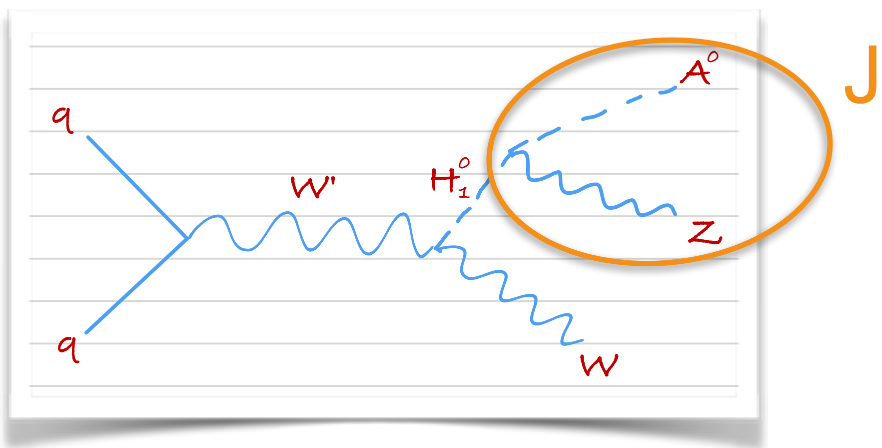
- It turns out that in semileptonic searches [leptonic object + jet J] this requirement is quite tight, e.g.
  - leptonic object and jet J back-to-back
  - leptonic object free from any nearby *contamination*
  - anti-*b*-tagging

- In fully hadronic searches there are other difficulties…

Multiboson signatures

Case II: Merged multibosons

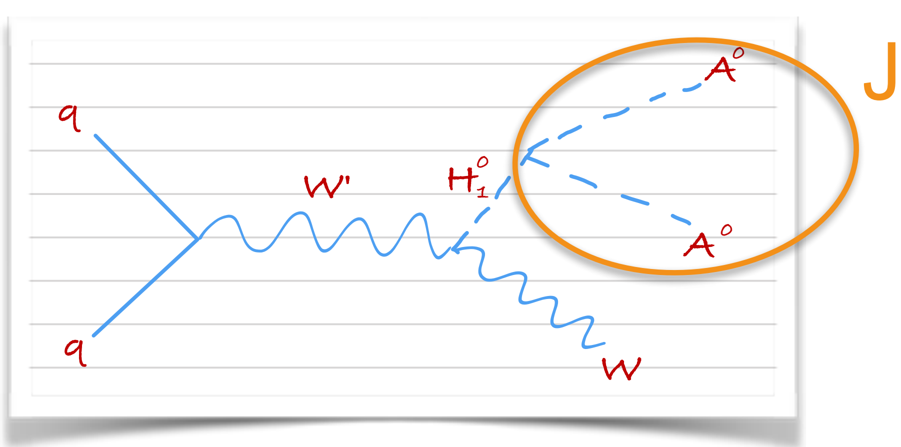
If intermediate particles are `light´, their decay products are merged



$$M_{W'} \gg M_{H_1^0} \gtrsim M_Z + M_{A^0}$$

$Z \to qq$ / …
$A^0 \to bb$

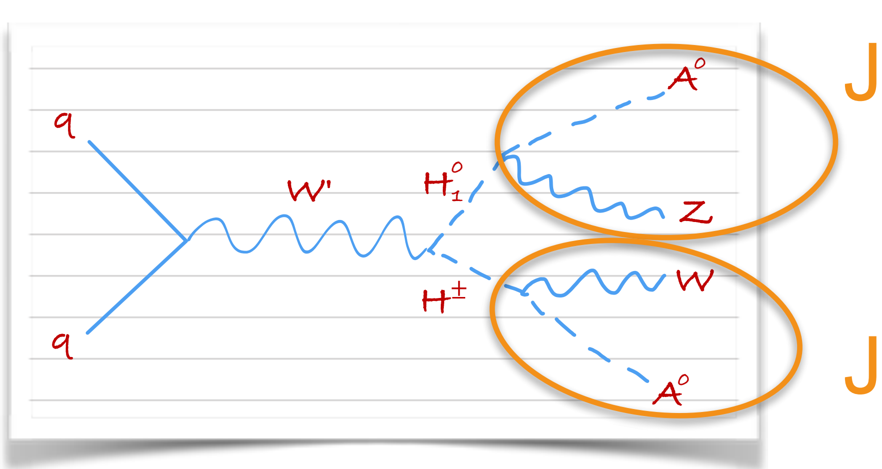
→ W + fat jet J



$$M_{W'} \gg M_{H_1^0} \gtrsim 2M_{A^0}$$

$A^0 \to bb$

→ W + fat jet J



$$M_{W'} \gg M_{H_1^0}, M_{H^\pm} \gtrsim M_Z + M_{A^0}$$

$W, Z \to qq$ / …
$A^0 \to bb$

→ two fat jets J

Stealth bosons

JAAS 1705.07885

When a very boosted particle *S* undergoes a cascade decay into several coloured particles, e.g.

$$S \to \cdots \to qqqq \quad J$$

it produces a multi-pronged fat jet J. All the heavy scalar decays in previous slide can be of such type

$$H_1^0 \to A^0 A^0 \qquad A^0 \to b\bar{b}$$

$$H_1^0 \to Z A^0 \qquad Z \to q\bar{q}\,,\, A^0 \to b\bar{b}$$

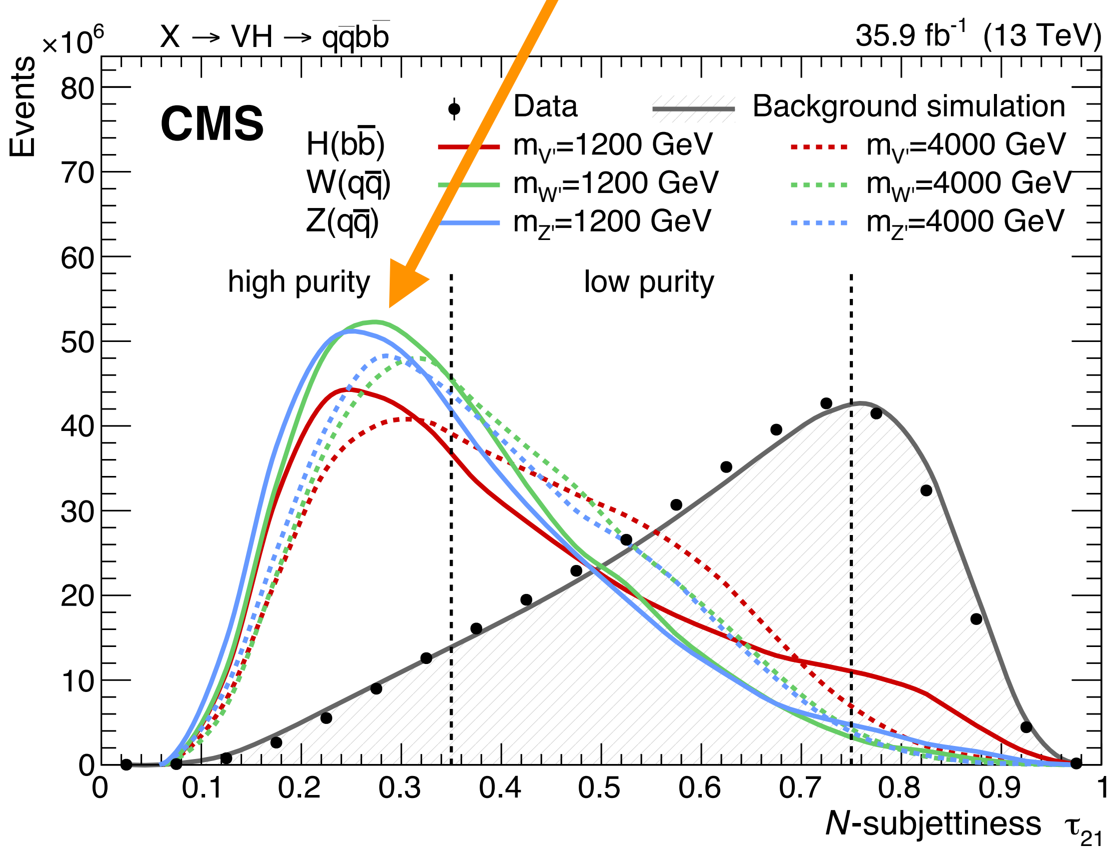
$$H^\pm \to W^\pm A^0 \qquad W \to q\bar{q}\,,\, A^0 \to b\bar{b}$$

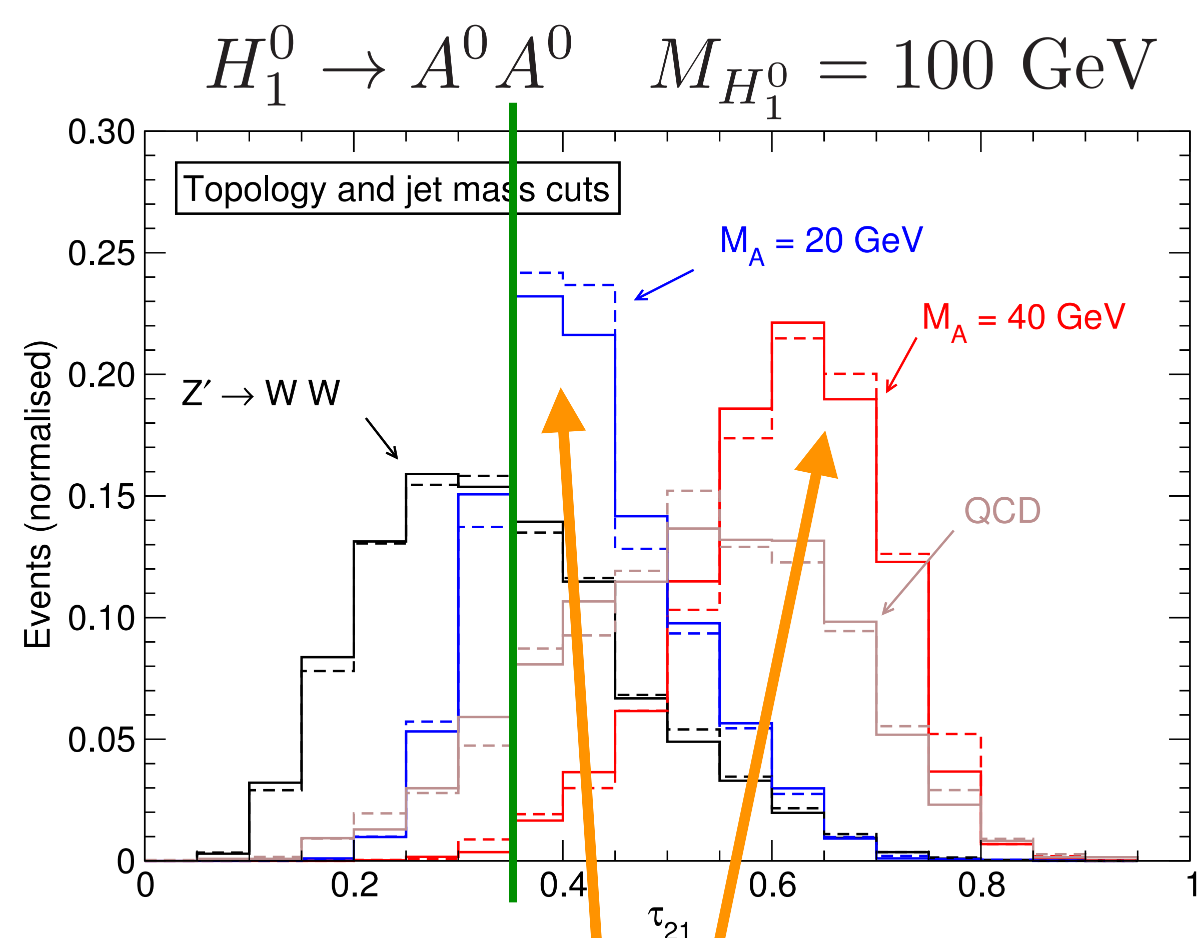
And these scalars will be very boosted if they are produced in the decay of a much heavier resonance *Z′* / *W′*/ …

Why I call them *stealth?*

Jet substructure

Standard diboson searches require that fat jets J look like they have two prongs by using some jet substructure variable, e.g. τ_{21} Thaler, Van Tilburg 1011.2268



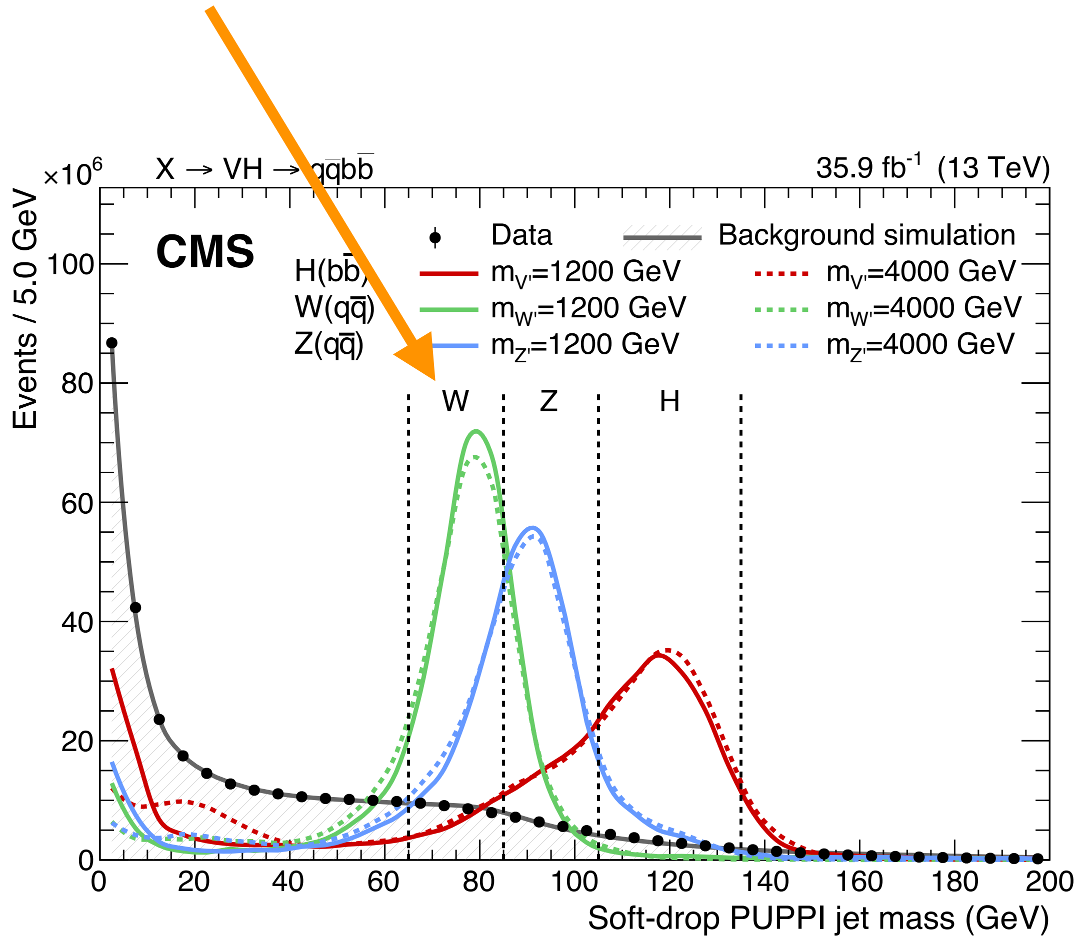


But stealth bosons with four-pronged decays don't look as signal but as background - ungroomed τ_{21} as often used by CMS

This feature may explain \`inconsistent´ size of excesses if signal is a bit background-like — see later!

Jet mass

Several grooming algorithms exist in the market, which work well to recover the mass of *W*, *Z*, *H* bosons from their hadronic decay …



Trimming, pruning, soft drop…

Butterworth et al 0802.2470
Krohn, Thaler, Wang 0912.1342
Ellis, Vermilion, Walsh 0912.0033
Larkoski et al. 1402.2657

… don't work so well for stealth bosons!

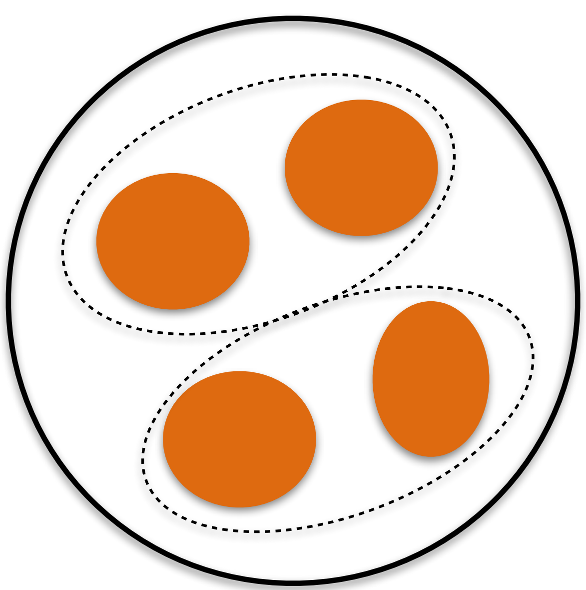
[recursive soft drop not checked]

Running bumps!

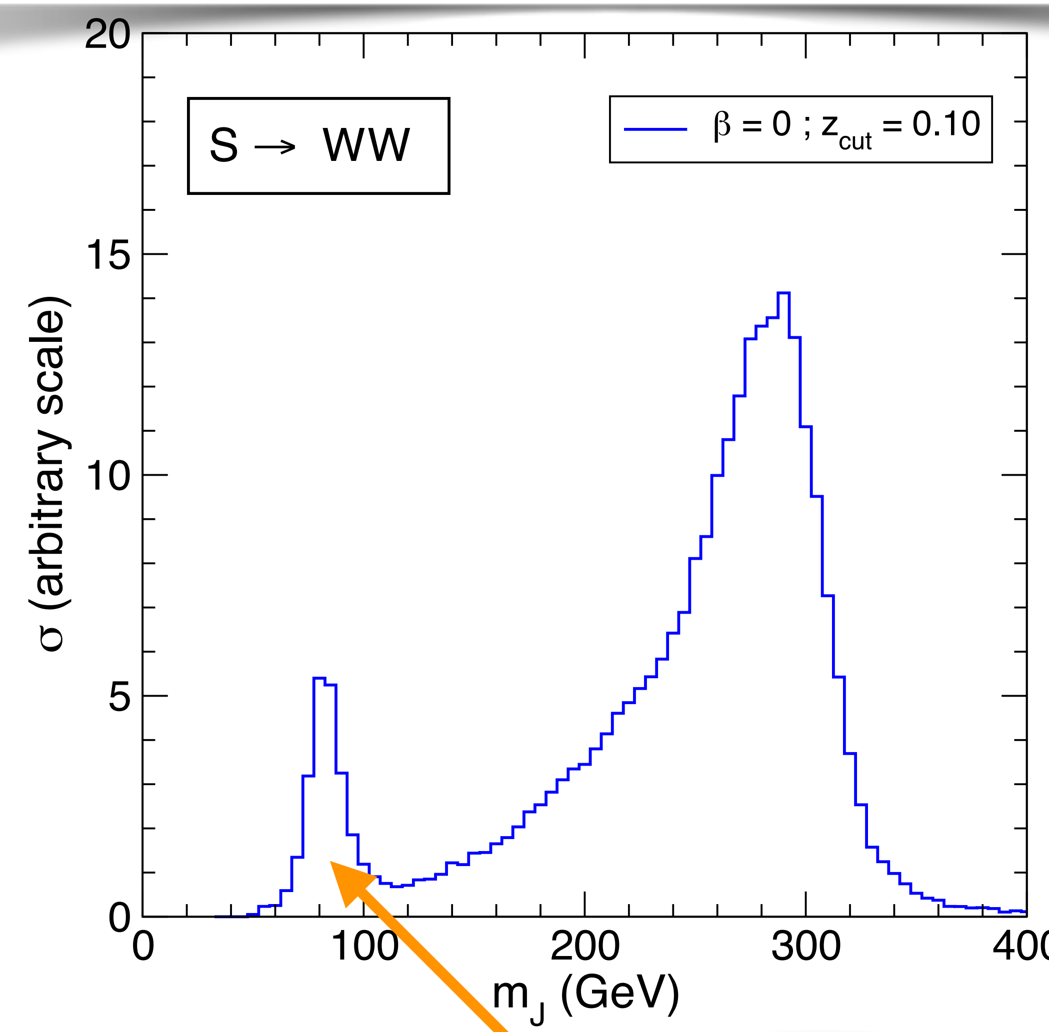
A four-pronged signal looks weird in standard analyses looking for two-pronged signals

JAAS 1801.08129

`Stealth boson´

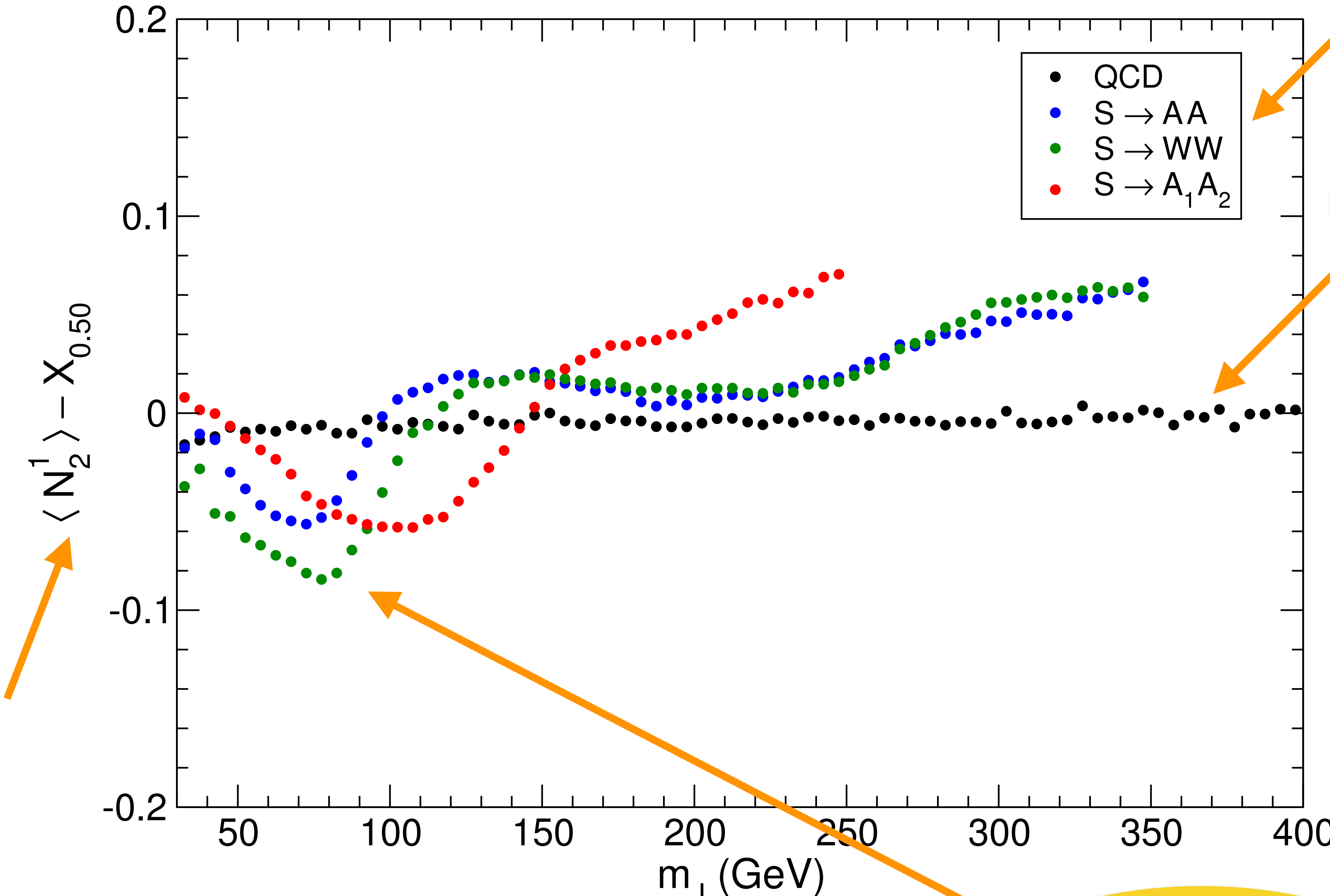


Recast of CMS light Z′ search, soft drop



grooming removes one W

Interplay between grooming and substructure



several possibilities

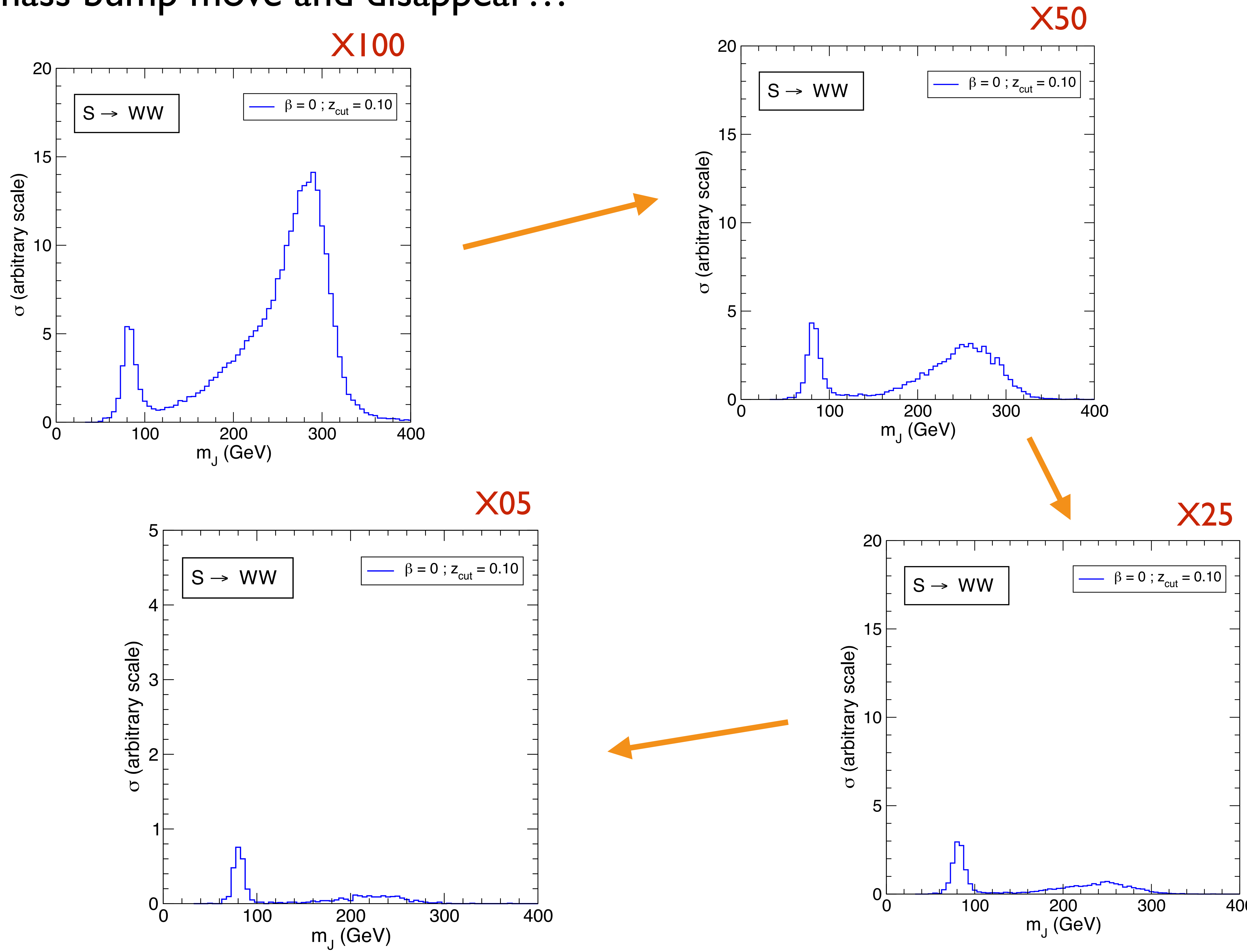
mass decorrelated tagger

dip when grooming removes one decay product of *S*

Decorrelated substructure variable, you may ask if you want

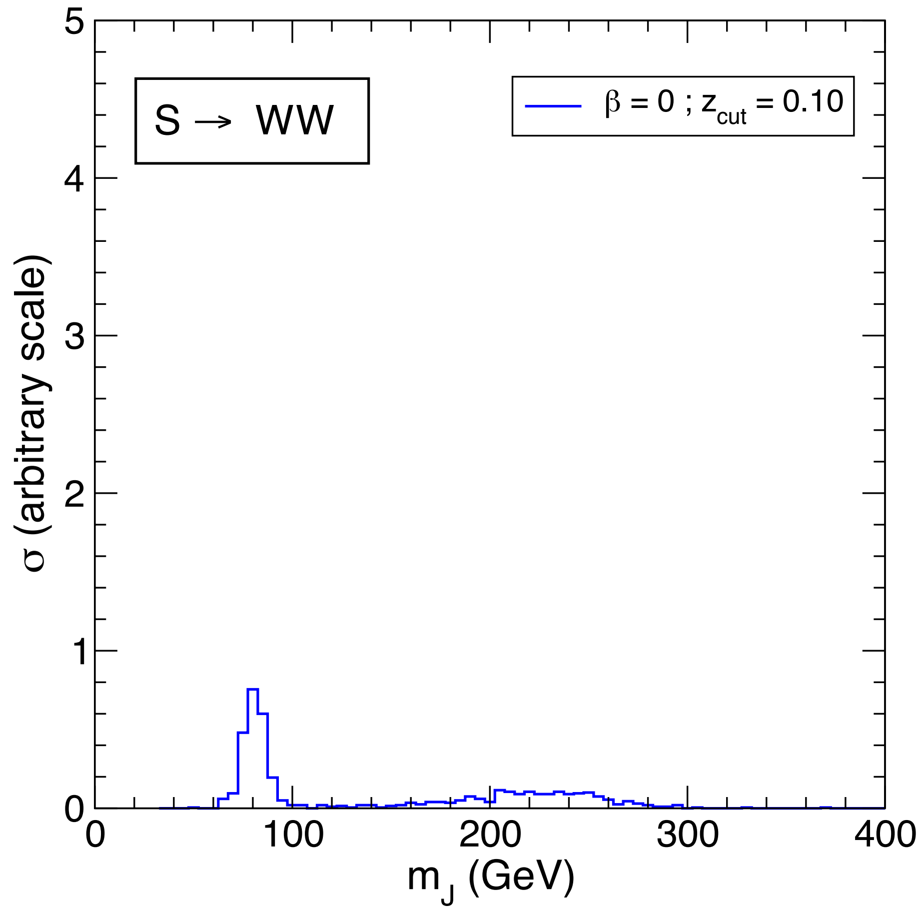
weak correlation when ungroomed substructure variables are used, e.g. in most CMS analyses

Therefore, an increasingly harsher cut on groomed N_2^1 makes the high-mass bump move and disappear…



Consequences I:

You may have a signal with a `W´ (or `Z´) that does not decay to leptons.



Note: this can also happen when substructure of ungroomed jet is used: the other bump is not seen if a mass window is selected.

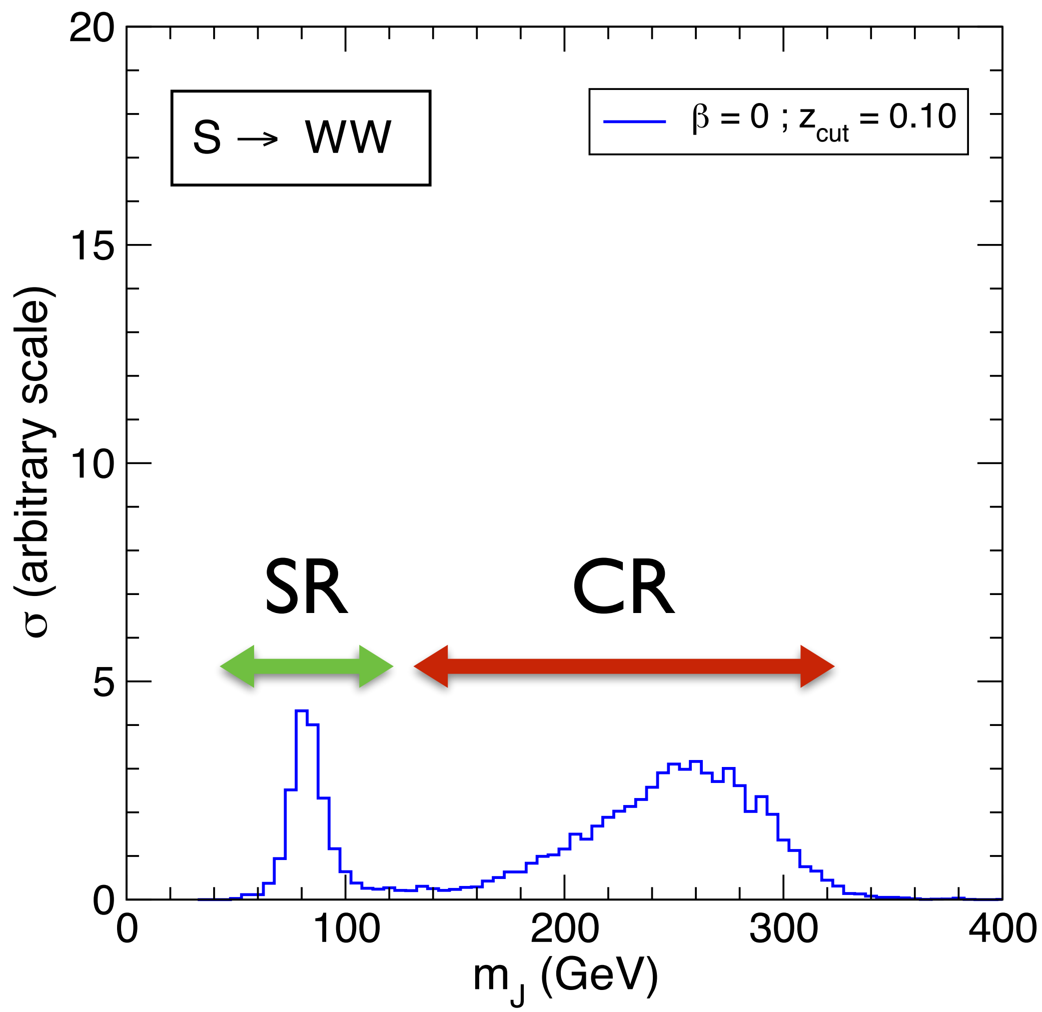
And this does not have anything to do with mass decorrelation.

That is, if you look for the sister signal with leptonic decay of *W/Z* you don't find it: $S \to WW$ with one or two leptonic *W* decays doesn't look like $W \to e\nu, \mu\nu$!

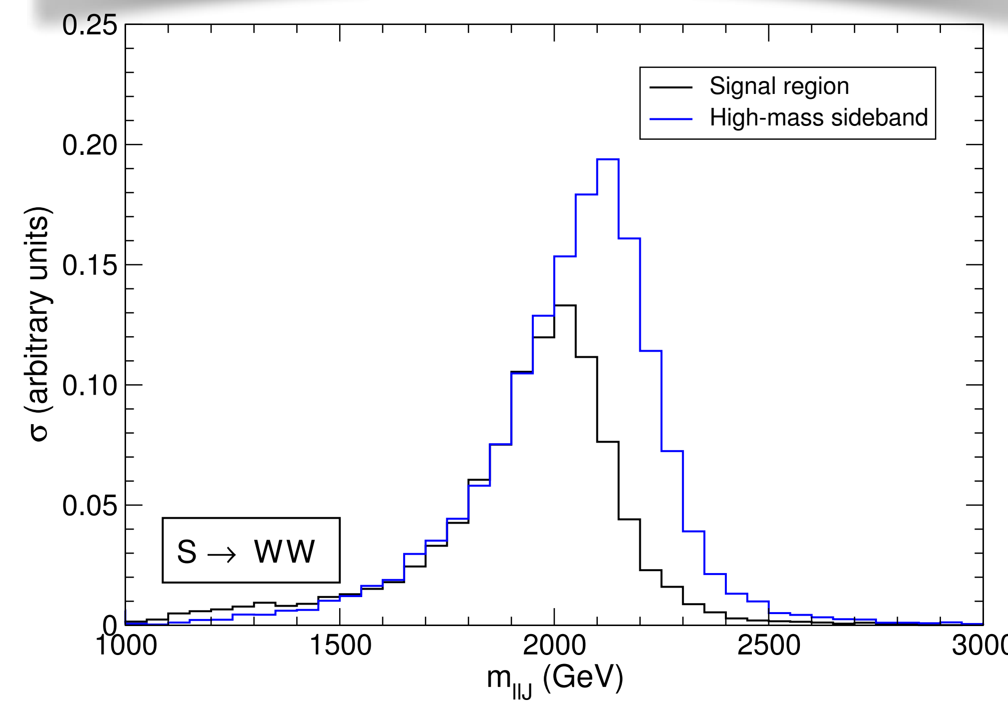
Consequences II

Also when substructure of ungroomed jet is used

For looser selections, a freaking signal like this also might seriously pollute the control regions where the background is normalised, yielding unaccountable results… maybe dips in the signal region!



Typical $Z'/W' \to \ell\ell J$ search

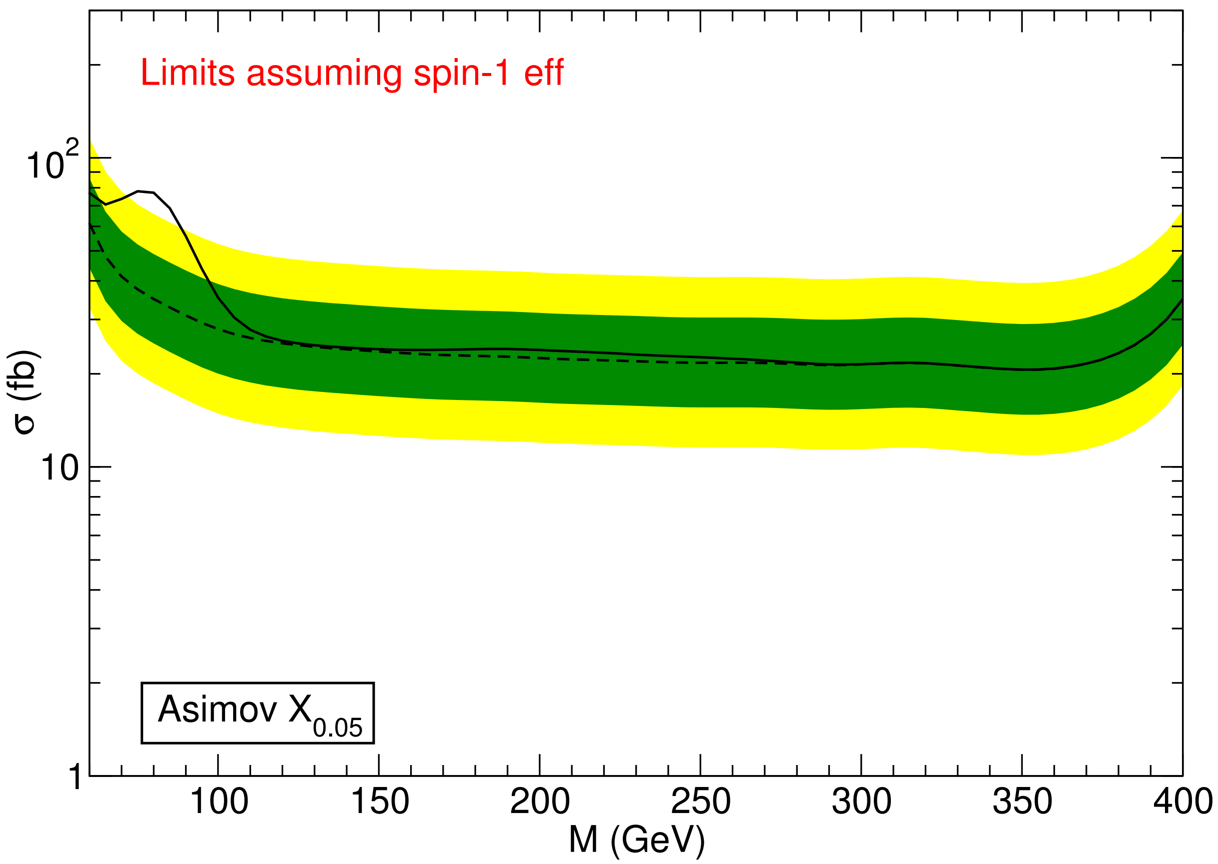


Remember the CDF *Wjj* excess in 2011!

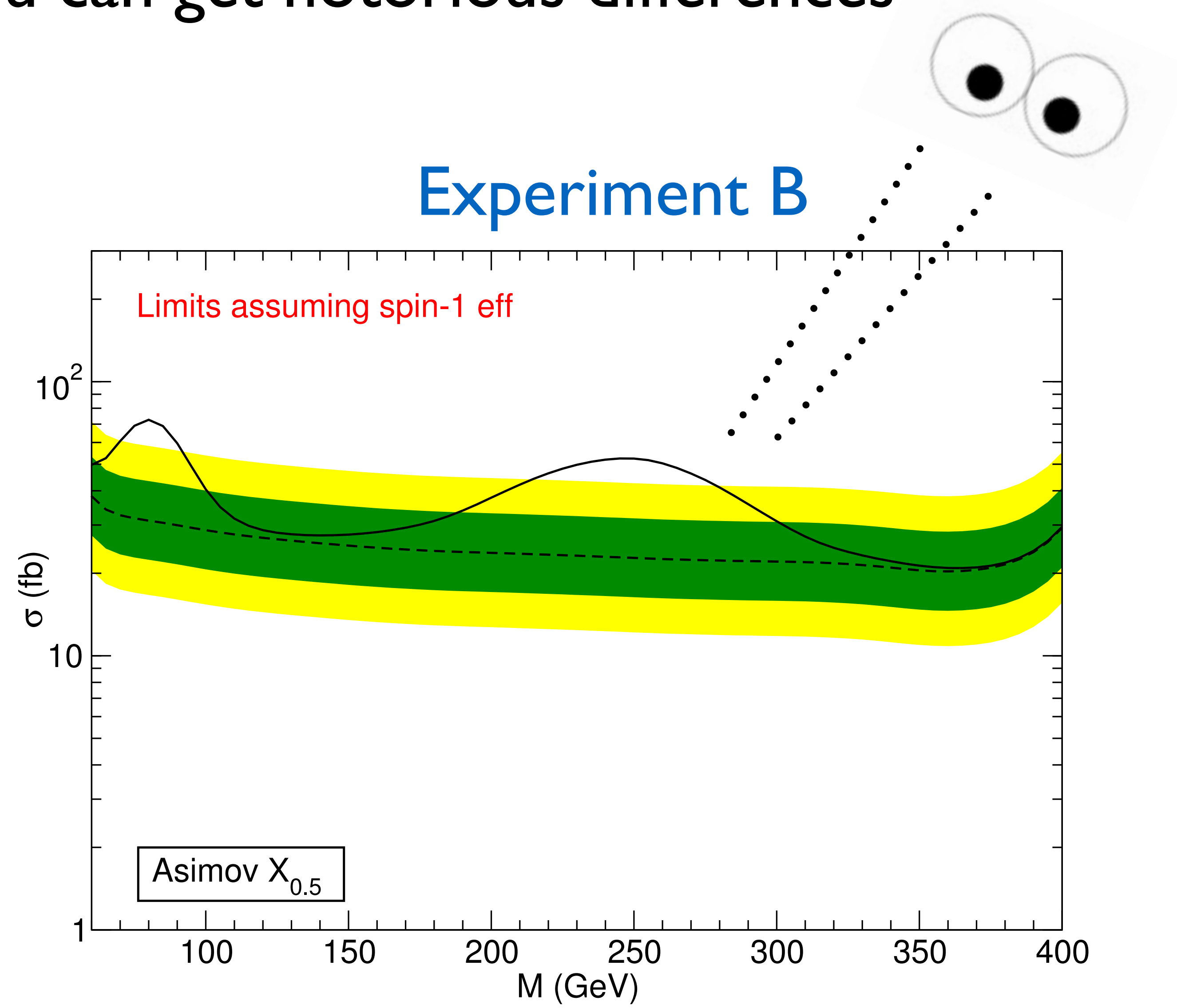
Consequences III

If you convert your observed limits on σ x eff to limits on σ by assuming the efficiency of some given signal, you can get notorious differences between different event selections.

Experiment A



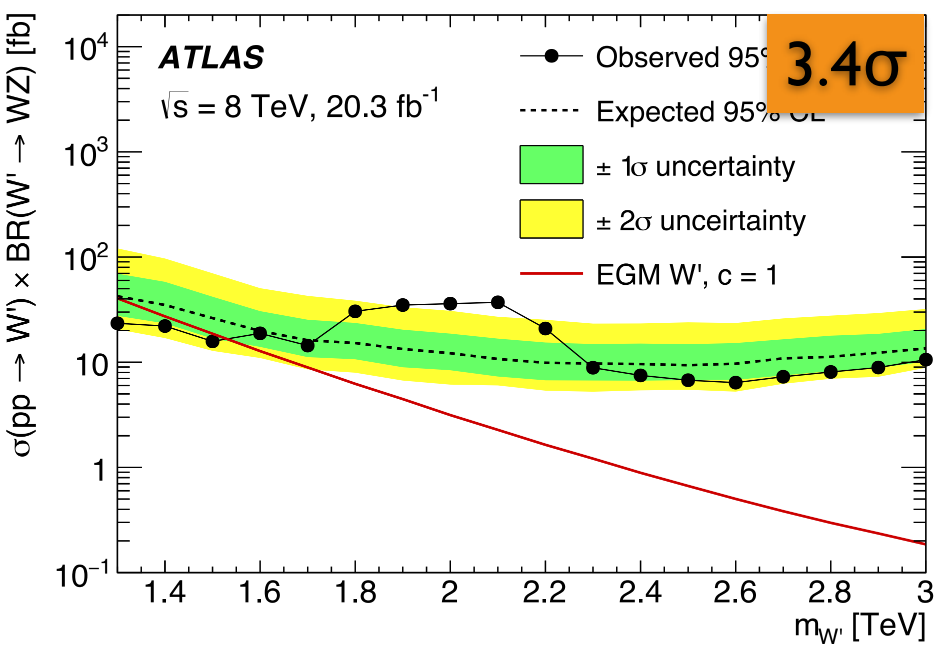
Experiment B

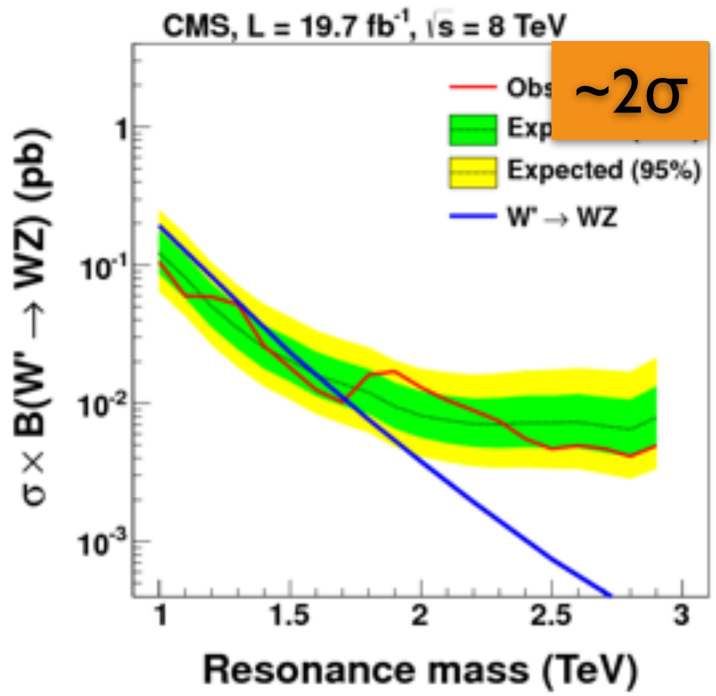


Never say you don't believe a bump may be something interesting because the other experiment doesn't see it.

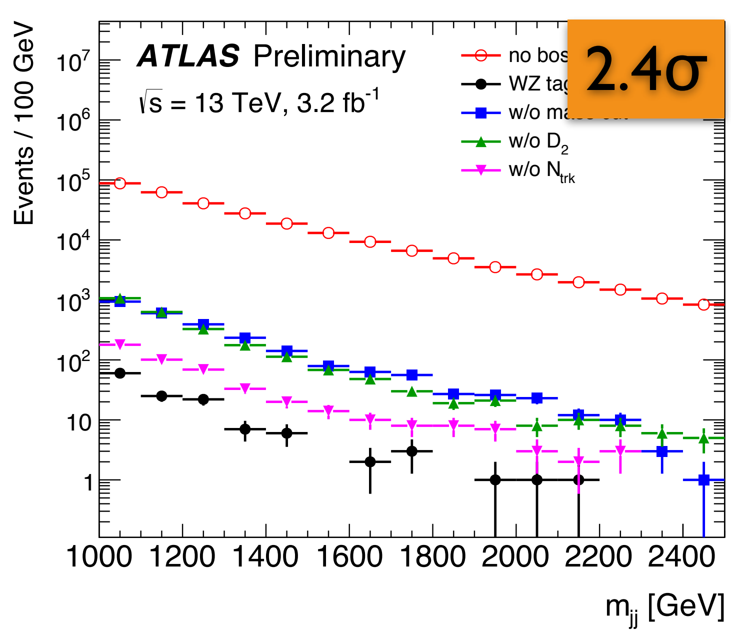
Experimental results: 2 TeV

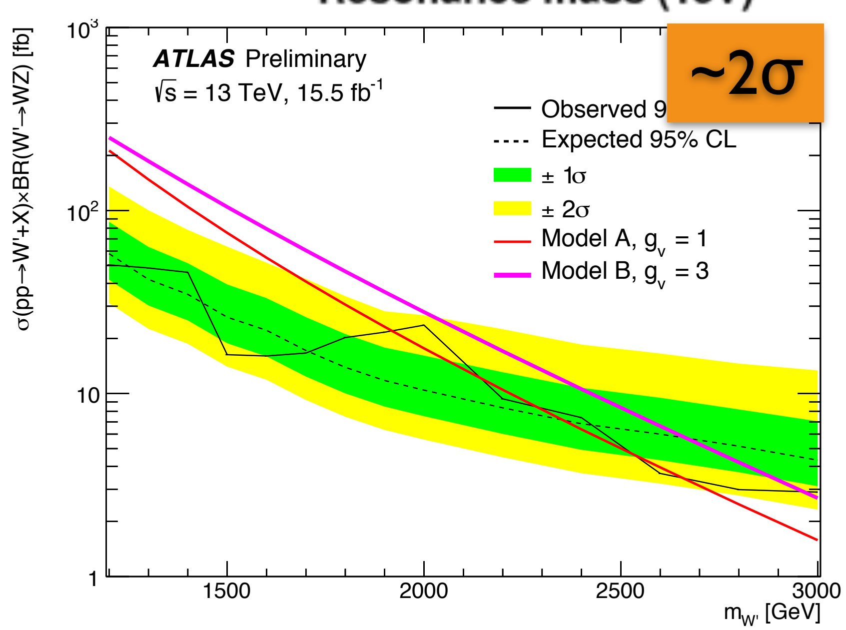
As stressed before, five little bumps appeared around M = 2 TeV in diboson resonance searches in the fully hadronic channel

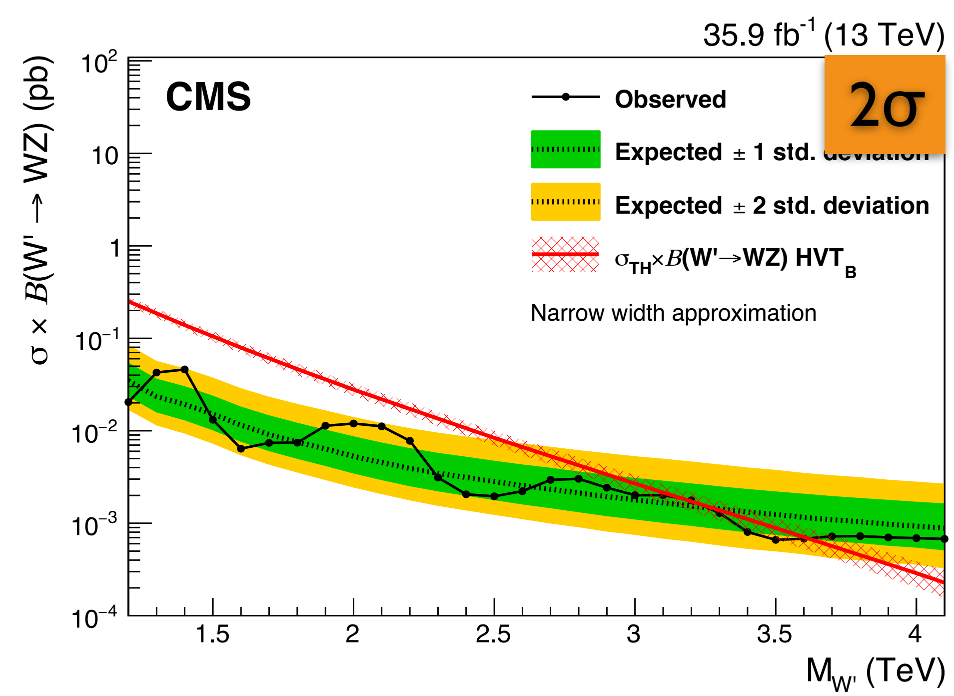




Run 1	ATLAS 1506.00962
Run 1	CMS 1405.1994
Run 2 3.2 fb^{-1}	ATLAS-CONF-2015-073
Run 2 15.5 fb^{-1}	ATLAS-CONF-2016-055
Run 2 35.9 fb^{-1}	CMS 1708.05379

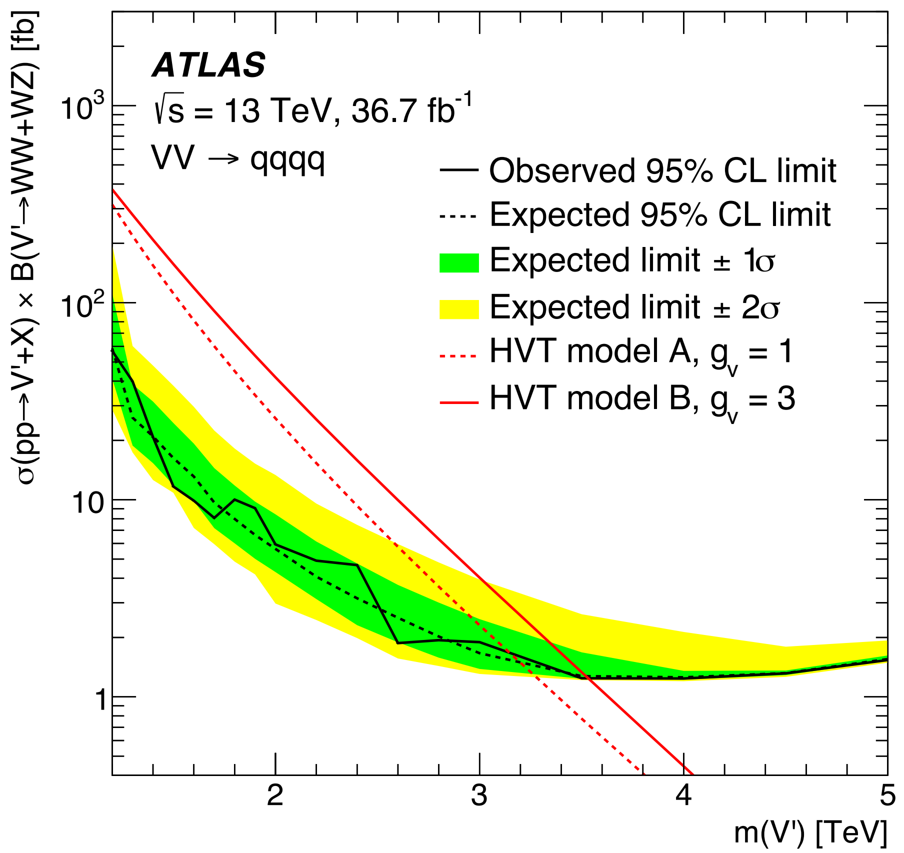


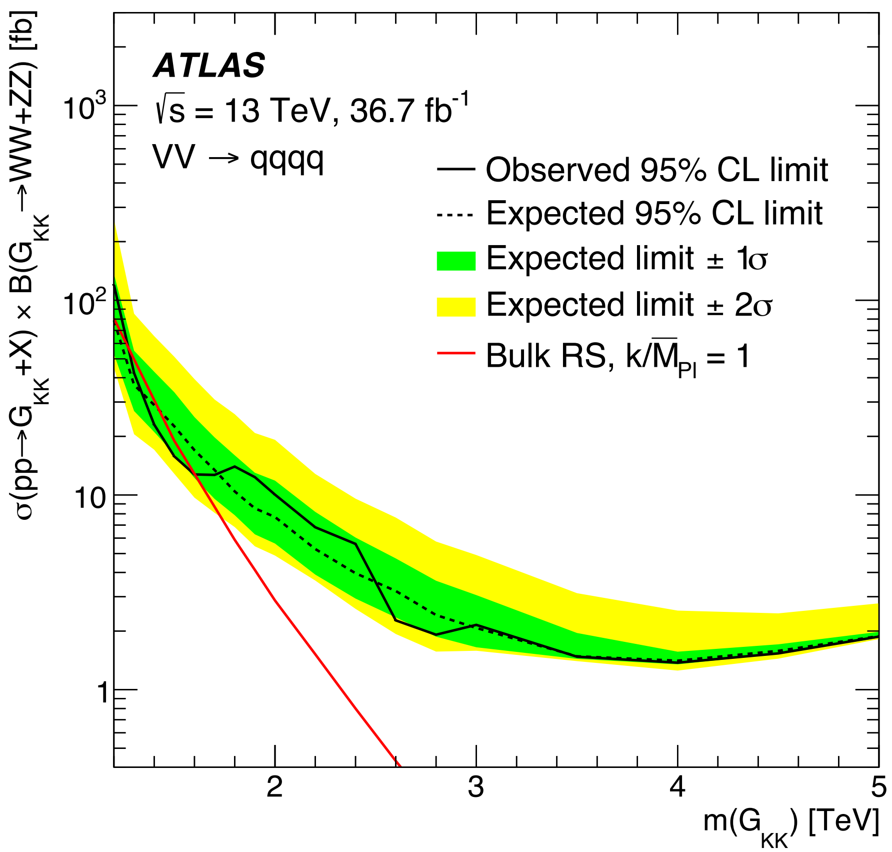




2017 ATLAS result with 36.7 fb^{-1} shows no excess around 2 TeV. New jet mass calibration, new D_2 / jet mass cut optimisation.

ATLAS 1708.04445



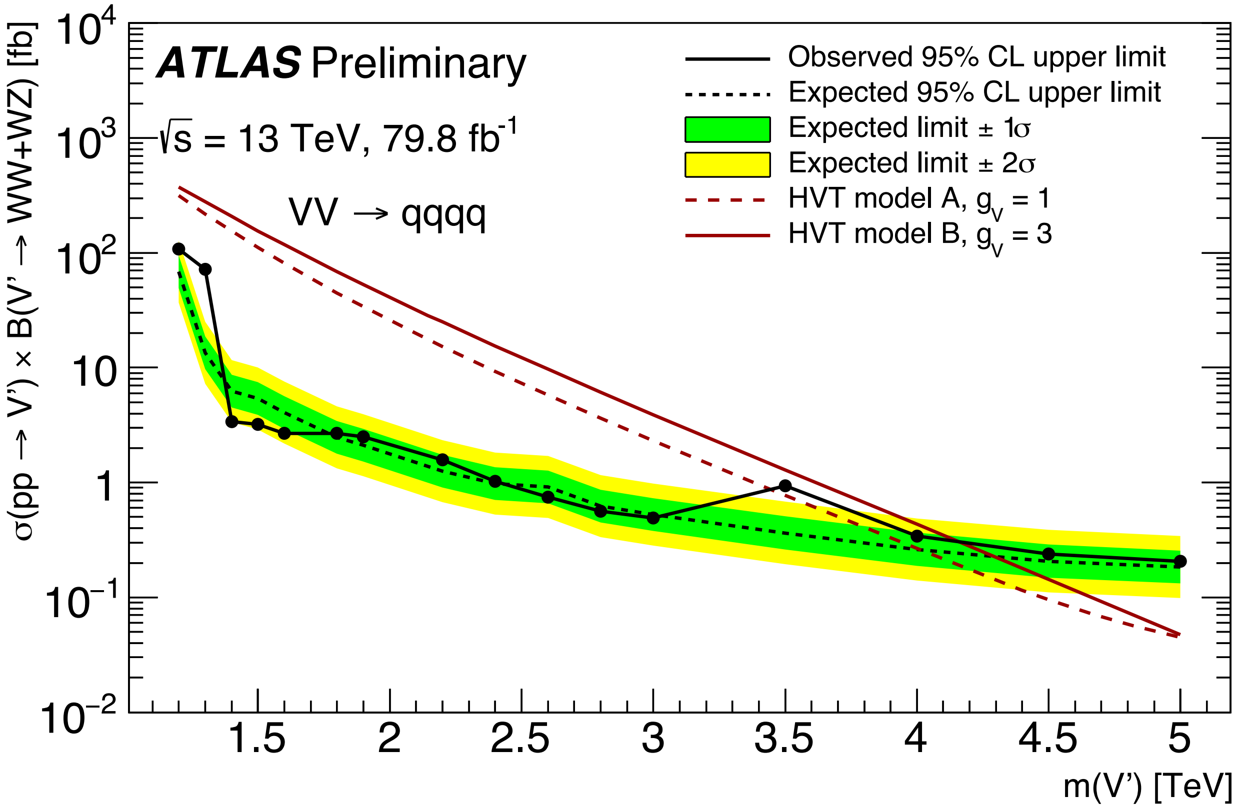


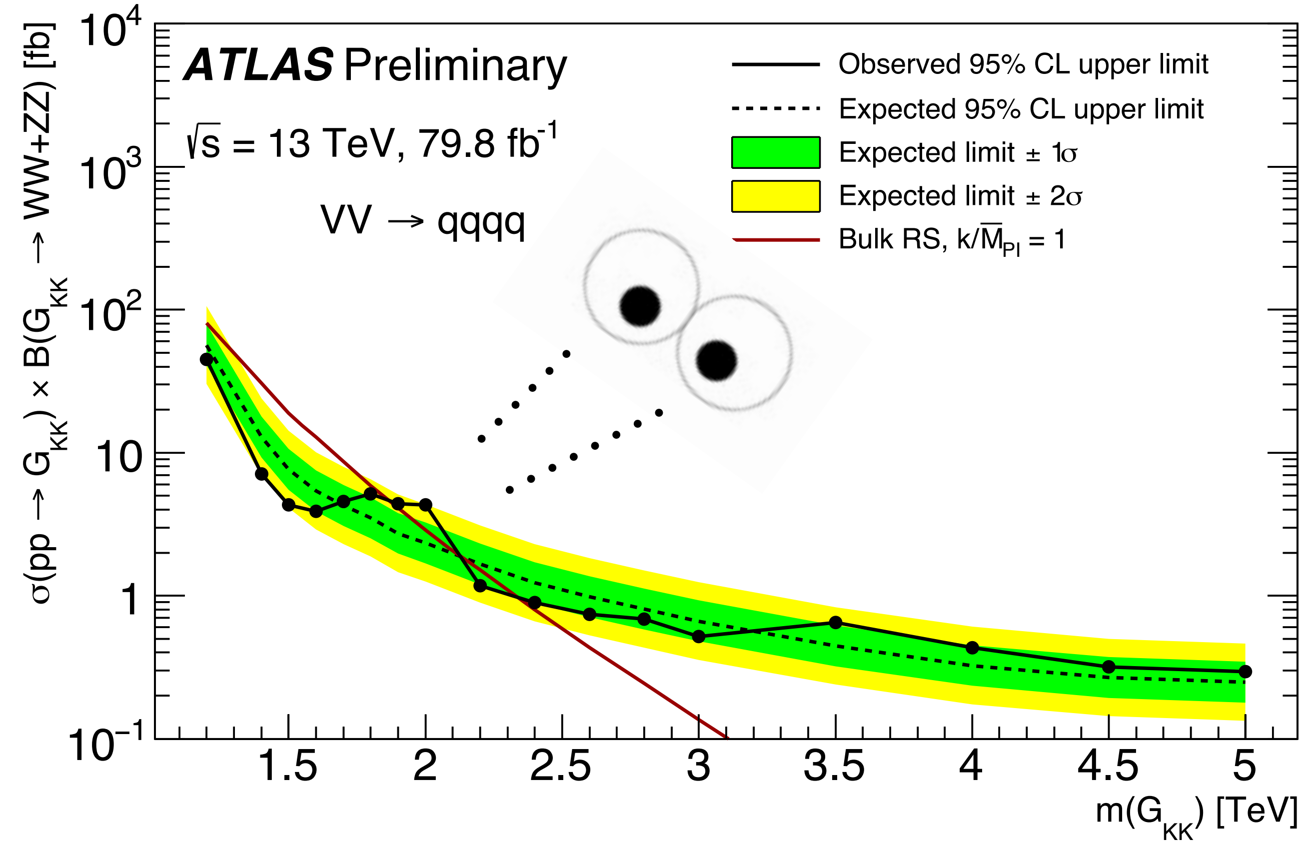
Disappointing? Certainly.

Conclusive? Not really.

2018 ATLAS result with 79.8 fb^{-1} … new event selection again …

ATLAS-CONF-2018-016



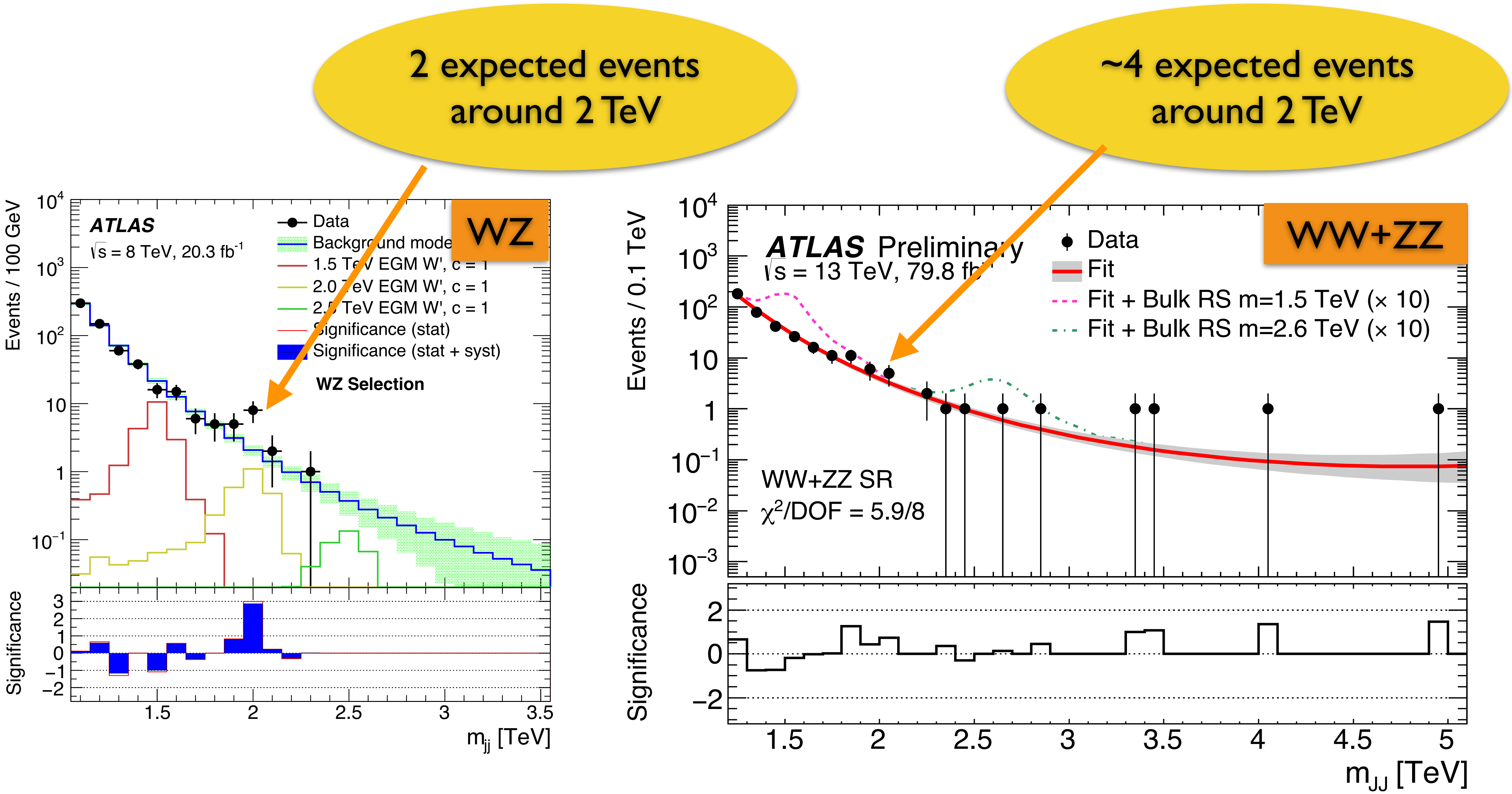


Encouraging? Certainly.

Conclusive? Of course not!

Shouldn't a signal be growing? No, the dataset is not growing either!

From 8x PDF & 4x lumi, 32x event increase expected.



Compatible with `stealth boson´ hypothesis

Tools

Existing tools cannot properly handle BSM multi-pronged hadronic jets that can result, for example, from cascade decays of boosted particles.

- Tagging tools mostly classify them as background-like
- Grooming tools do not recover the originating particle mass

If we want to perform [quite] model-independent searches, we need new tools.

See also Jack's talk about unsupervised tagger

Generic anti-QCD tagger

Machine learning techniques allow to build generic anti-QCD taggers that efficiently discriminate multipronged jets [considered as signals] against jets from quarks and gluons [considered as background].

These taggers use as input a generalised set of variables measuring the jet *N*-subjettiness [i.e. how it looks *N*-pronged] Datta, Larkoski, 1704.08249

$$\tau_N^{(\beta)} = \frac{1}{p_{T\,J}} \sum_i p_{Ti} \min\left\{\Delta R_{1i}^{\beta}, \Delta R_{2i}^{\beta}, \ldots, \Delta R_{Ni}^{\beta}\right\}$$

of which the previously seen τ_{21} corresponds to τ_2^1/τ_1^1.

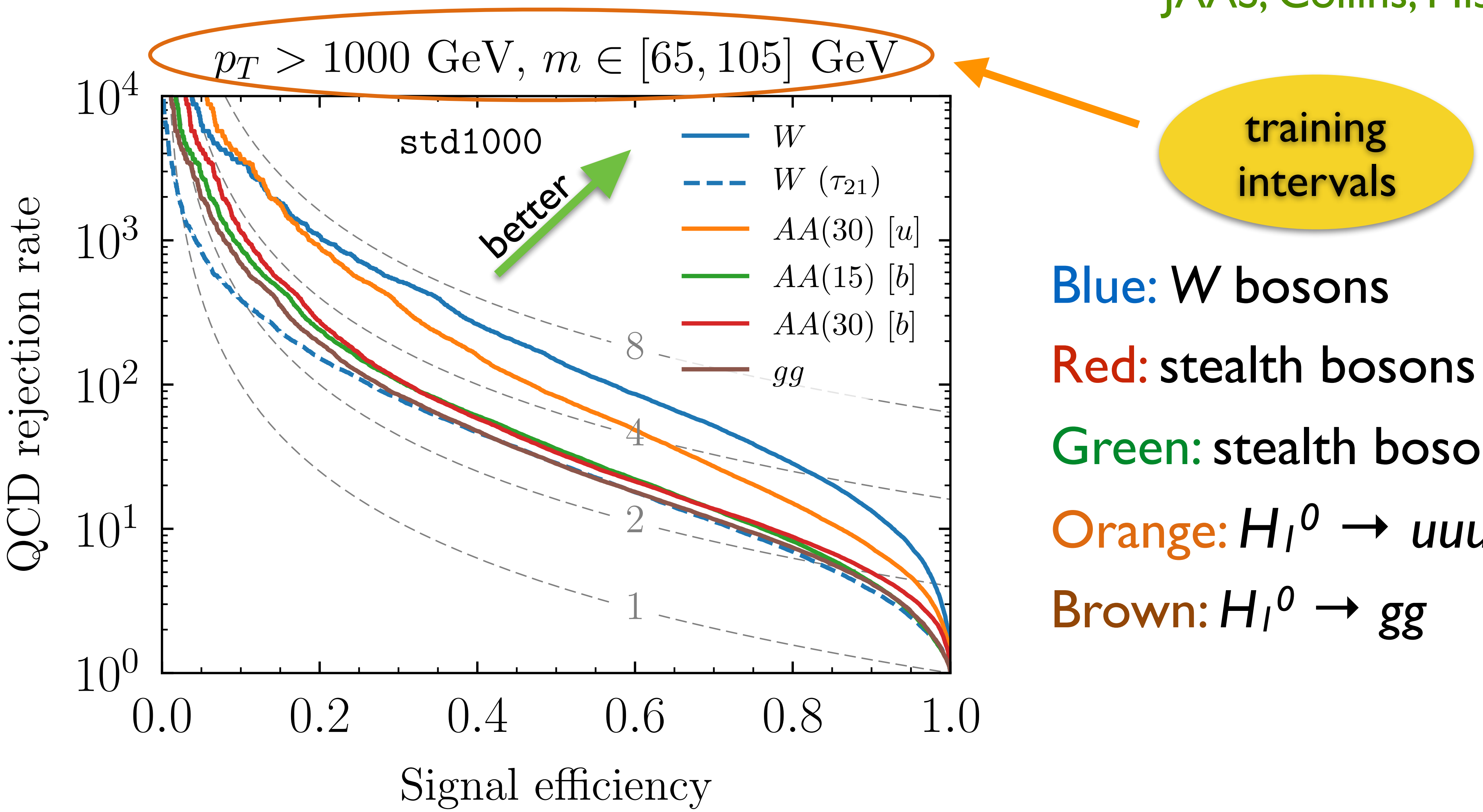
These variables are the input to a neural network that is trained using

- signals: jets with 2, 3 and 4-pronged decays, model-agnostic.
- background: jets from quarks and gluons.

And the tagger even learns to identify signals for which it is not trained.

Example: tagger performance for particles with *M* = 80 GeV

JAAS, Collins, Mishra, 1709.01087



Blue: *W* bosons

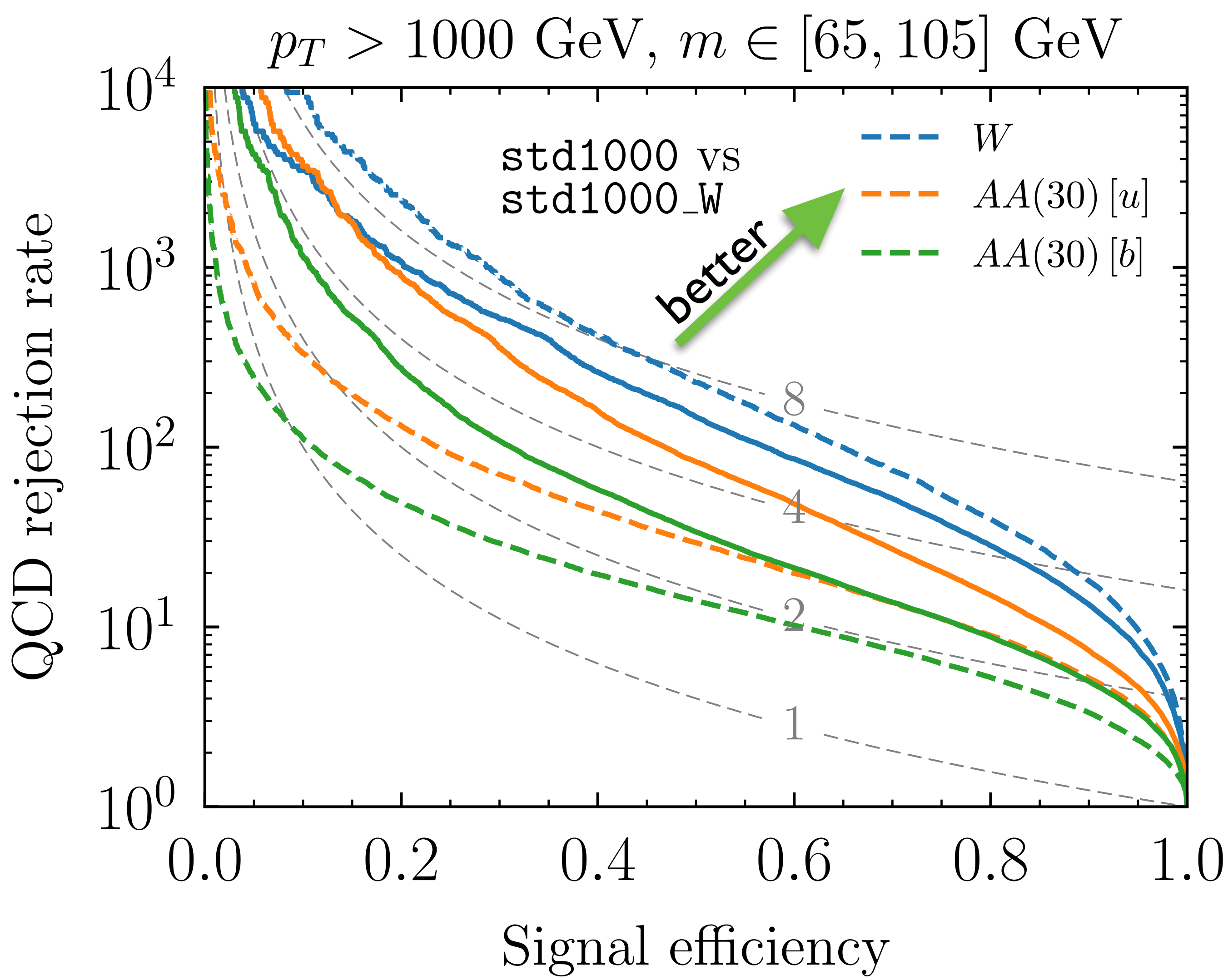
Red: stealth bosons M_A = 30 GeV

Green: stealth bosons M_A = 15 GeV

Orange: $H_1^0 \rightarrow uuuu$ M_A = 30 GeV

Brown: $H_1^0 \rightarrow gg$

Comparison with dedicated *W* tagger [trained on *W* bosons] for particles with M = 80 GeV



Blue: *W* bosons

Green: stealth bosons M_A = 30 GeV

Orange: $H_I^0 \rightarrow uuuu$ M_A = 30 GeV

Solid: generic tagger

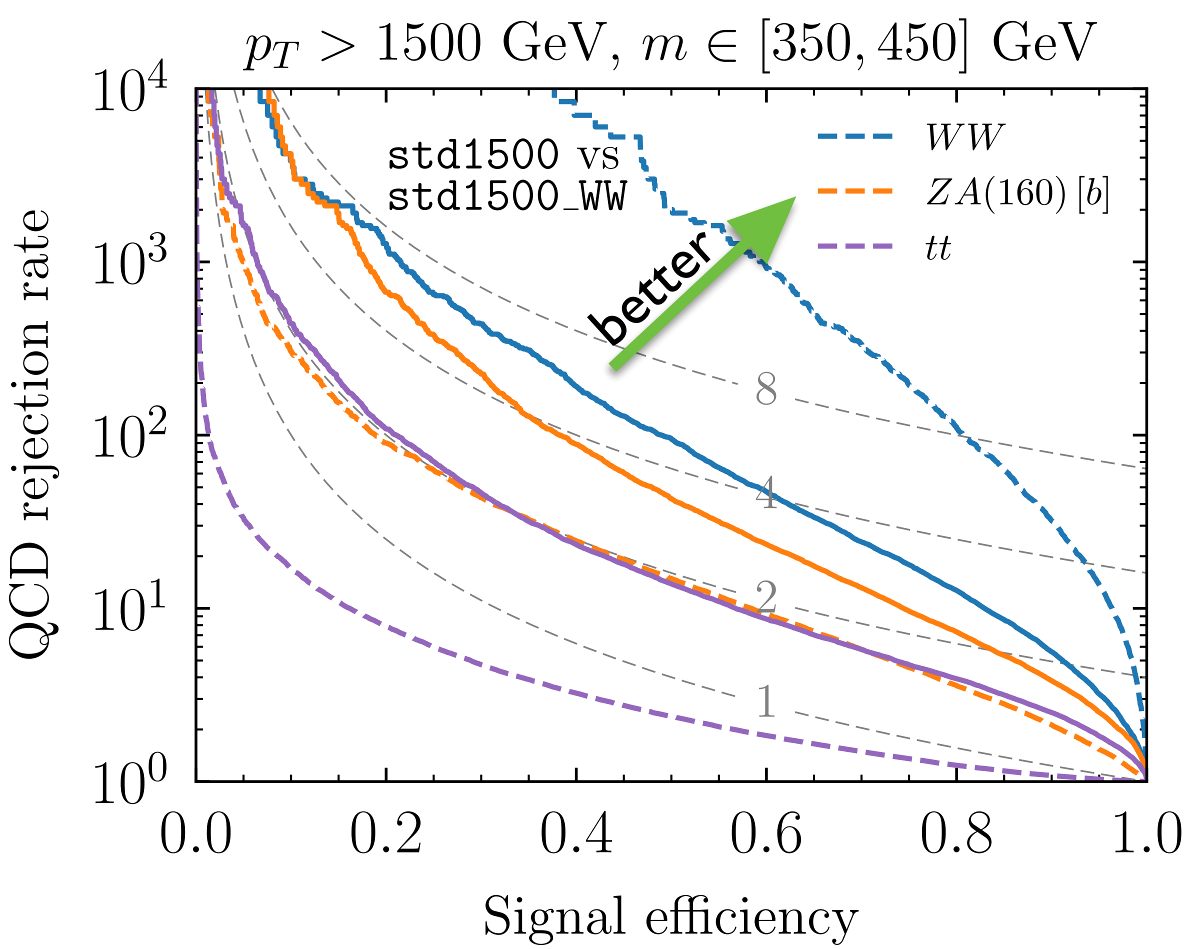
Dotted: dedicated tagger

The dedicated *W* tagger is slightly better for *W*´s

The generic tagger is way better for stealth bosons

Key feature: model independent (MI) data

NNs are trained on signal jets corresponding to decays with flat matrix element and phase space [generated using Protos] to achieve wider sensitivity



Comparison with dedicated *WW* tagger for particles with *M* = 400 GeV

Blue: $H_l^0 \to WW$

Orange: $H_l^0 \to ZA$ M_A = 160 GeV

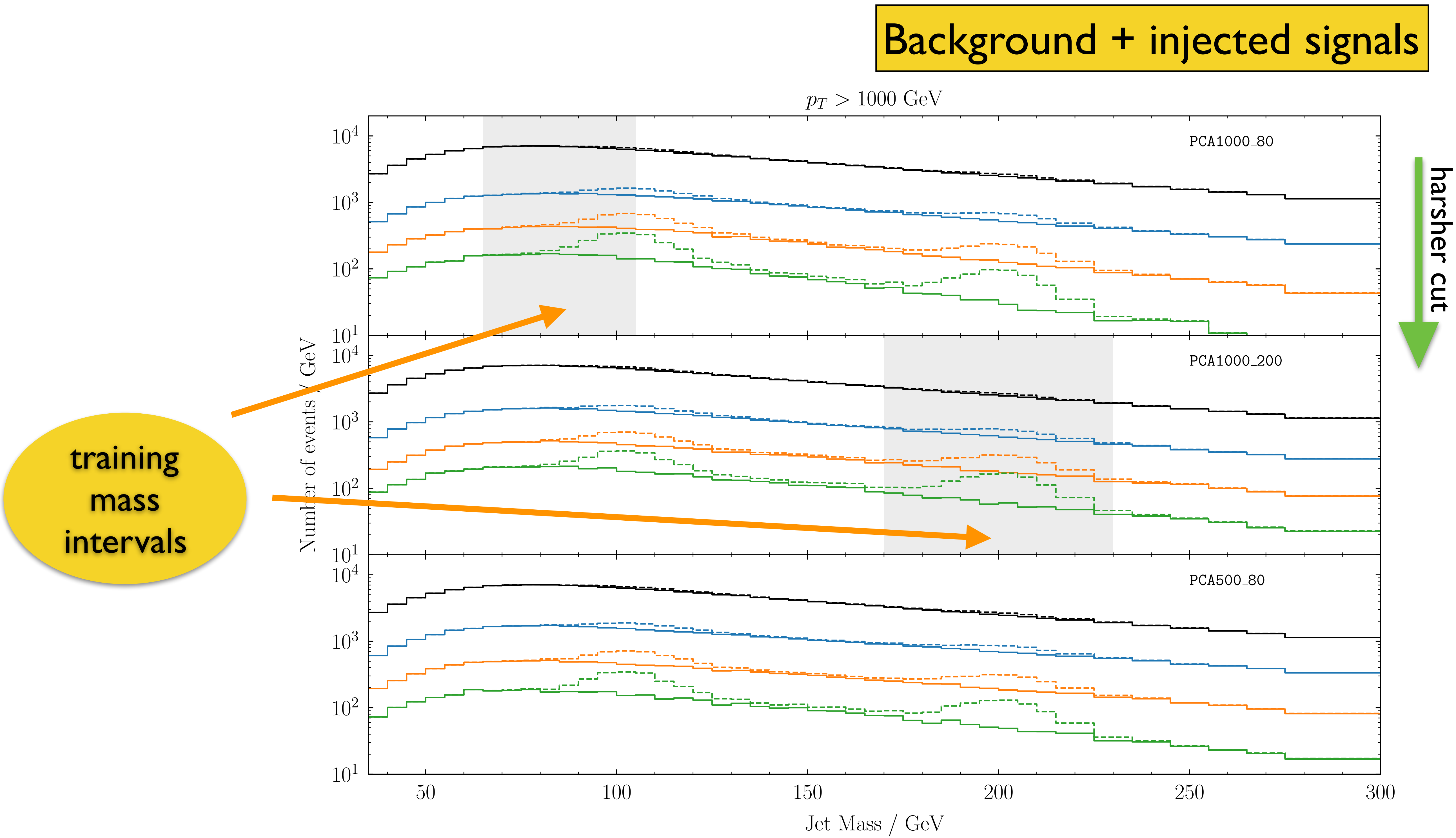
Purple: $H_l^0 \to tt$ six-pronged jet!

Solid: generic tagger

Dashed: dedicated tagger

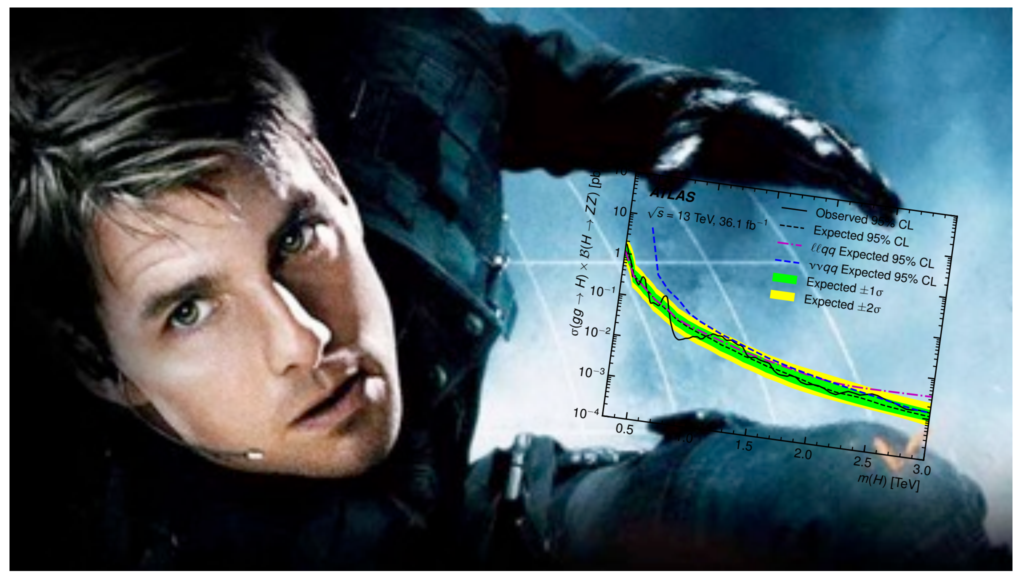
The dedicated *WW* tagger is way better for *WW*, worse for *ZA*, and completely fails for *tt*

Mass-decorrelated taggers that do not shape background can spot signals with masses different from those used for training



Last Words

- Recasting experimental results for non-minimal models, to see what may be in data, is becoming Mission: Impossible.



- And it does not give any information if sensitivity is lost.

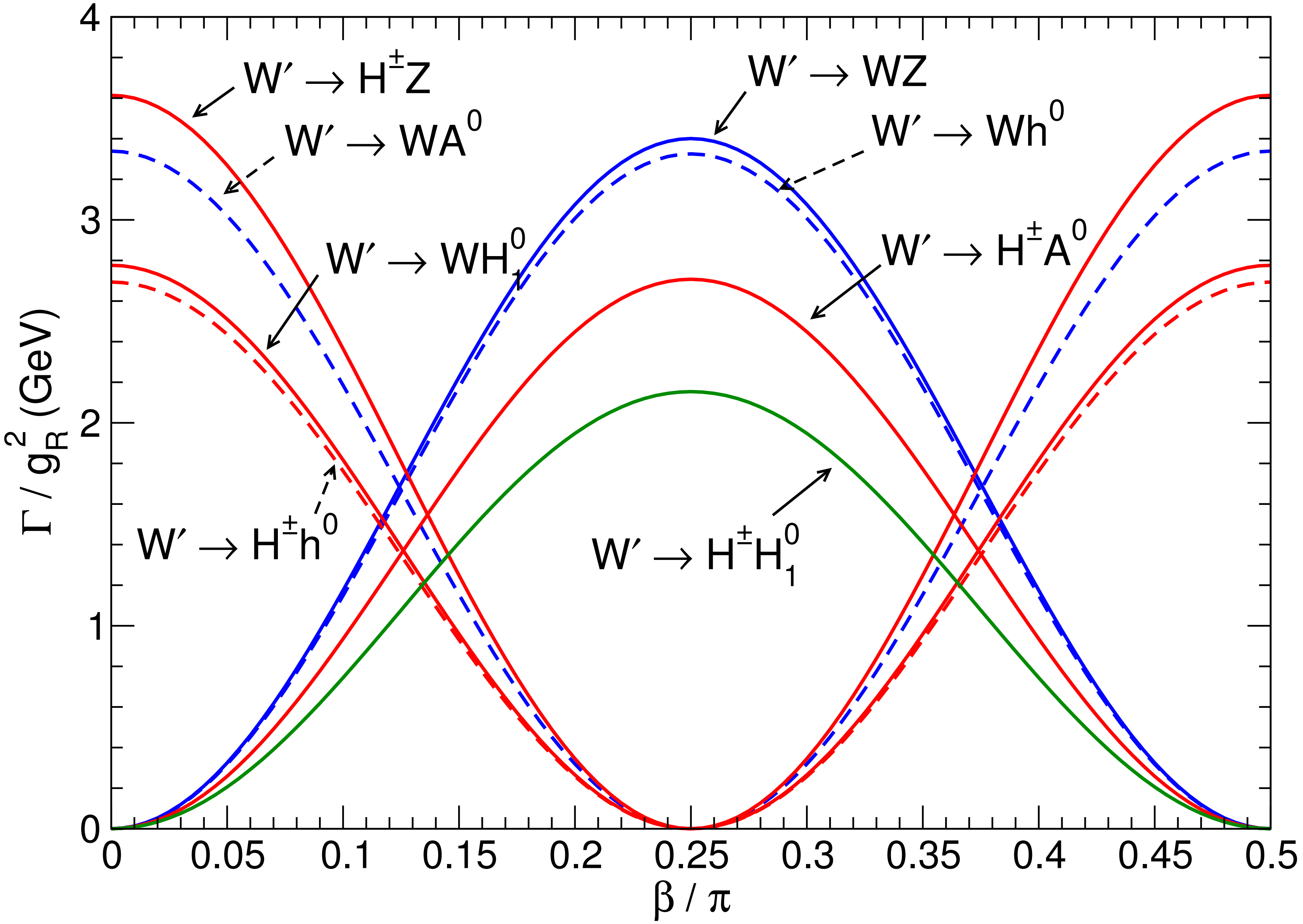
- With new tools, model-independent new physics searches giving boosted fat jets are possible.

- This would be a breakthrough, as we would be sensitive to many non-minimal new physics scenarios we are not really sensitive to.

Extra!

Dibosons vs tribosons & quadribosons

Assuming $M(H_1^0) \sim M(H^{\pm})$ and A^0 lighter



Blue: dibosons

Red: tribosons

Green: quadribosons

Features / caveats of the LR model

- $\beta = \pi/4$ ($\langle\phi_1^0\rangle = \langle\phi_2^0\rangle$) implies $m_t = m_b$ [in minimal model with bidoublet]

  Some fine tuning of Yukawa couplings required unless $\beta \sim 0$ or $\beta \sim \pi/2$, therefore multibosons are natural.

- Extra scalars $H_l^0, A^0, H^\pm$ give unacceptable FCNC unless $M \geq 10$ TeV

  This does not seem natural: why should one scalar have $M(H)$ = 125 GeV and the rest of scalars in the multiplet M = 10 TeV???

  - add matter?
  - add scalars?

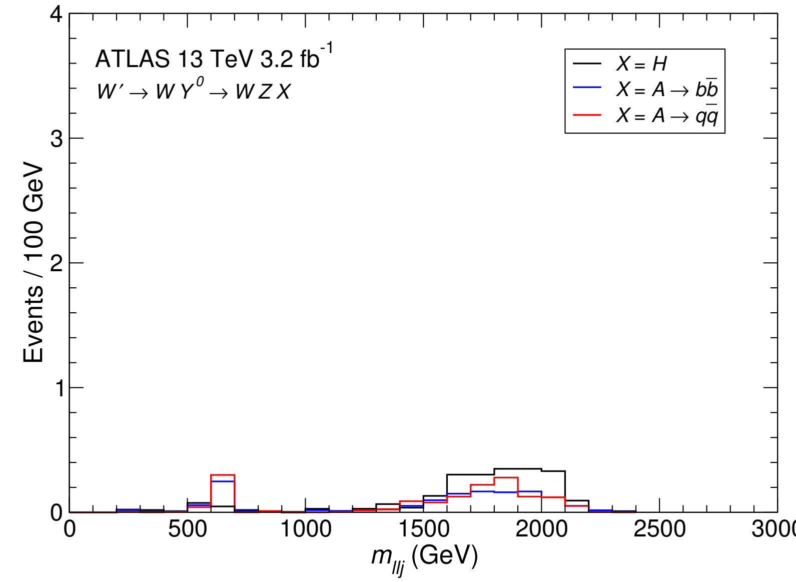
- Z' is not leptophobic! Stringent limits

$W' \to W H_1^0\,,\ H_1^0 \to Z X$

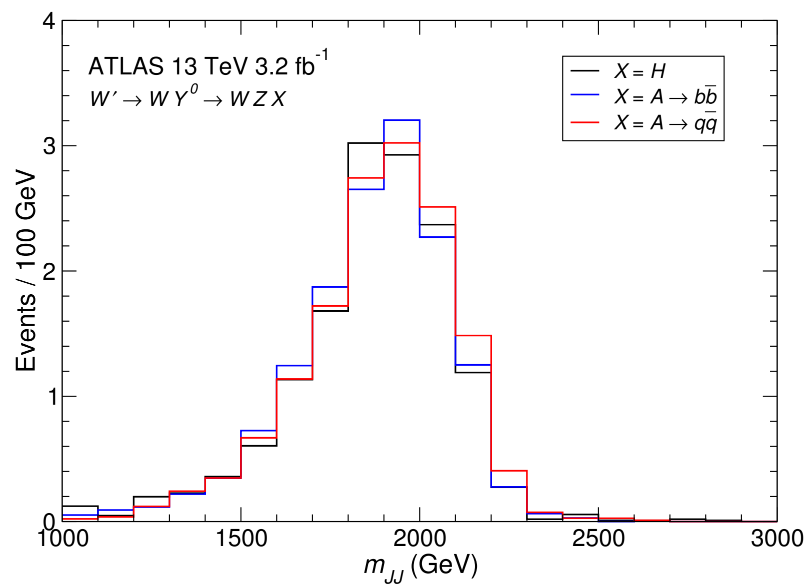
JAAS, Collins, Lombardo 1607.08911

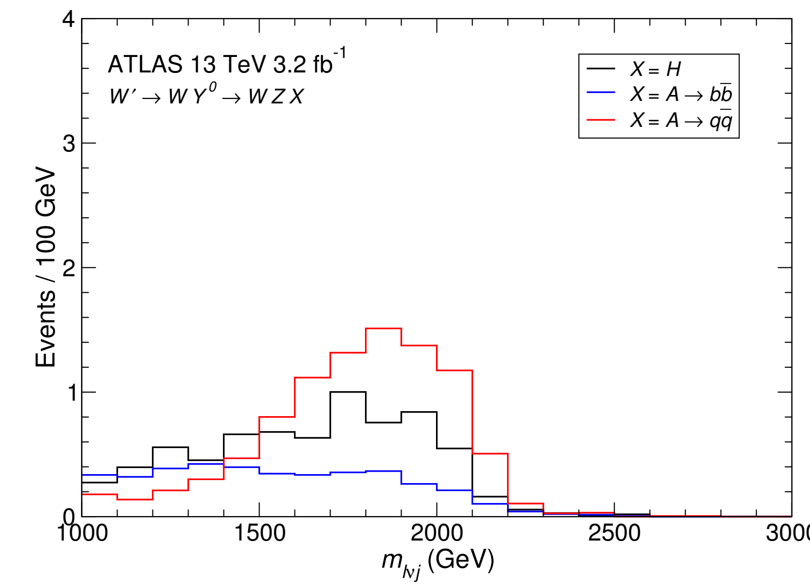
Signals at a glance:
- same scale
- same luminosity

eeJ / μμJ

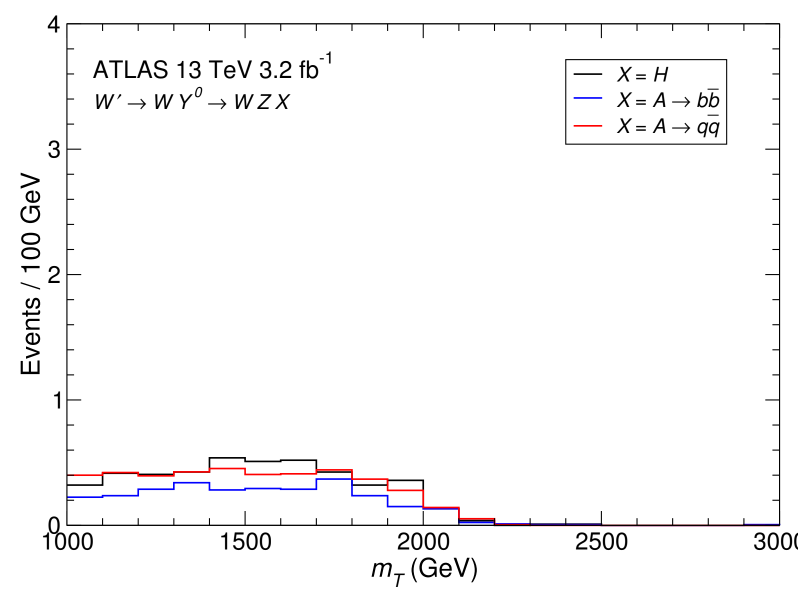


evJ / μvJ





JJ

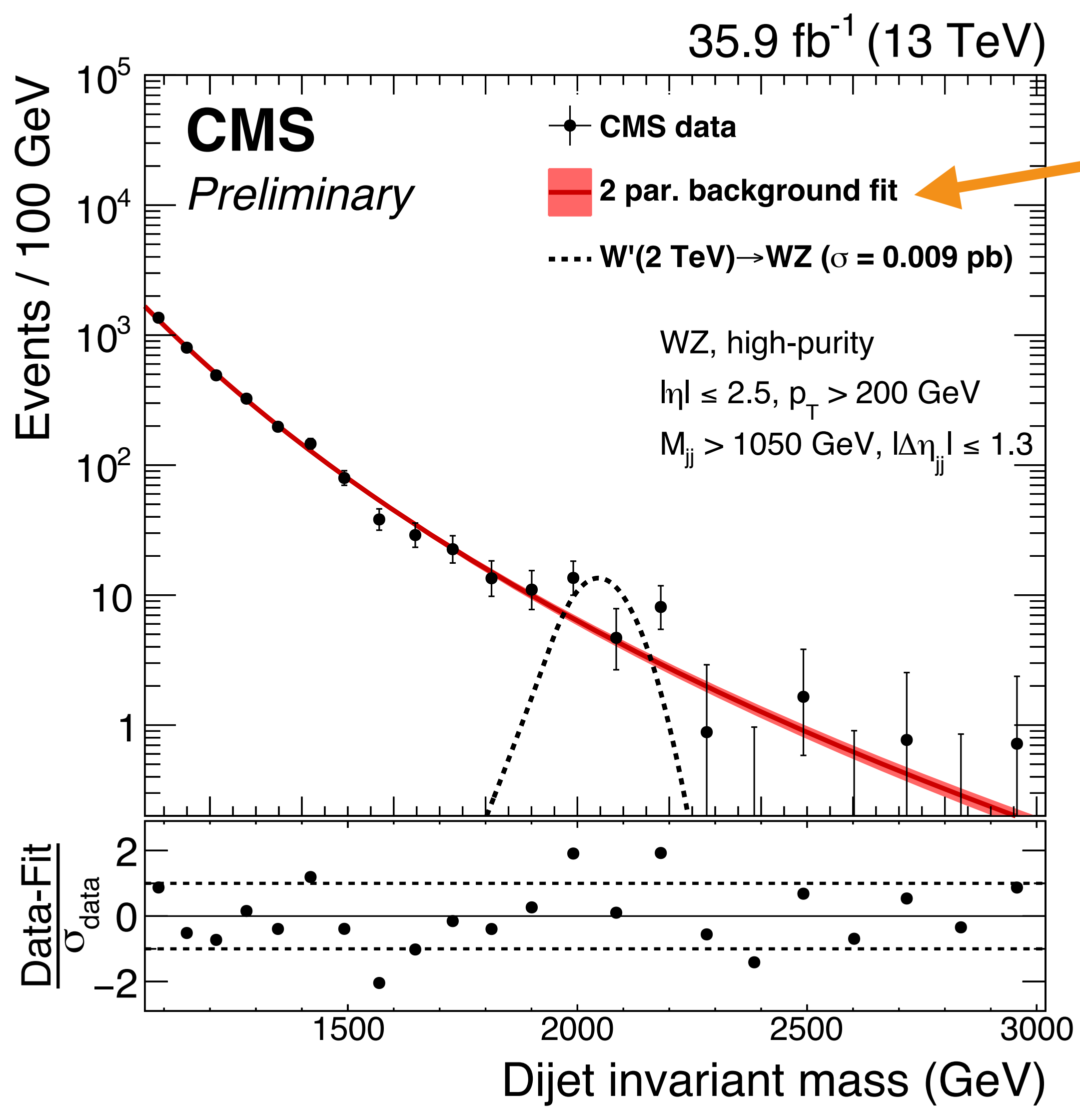


vvJ

Achiles’ heel of hadronic diboson searches

The main background is QCD dijet production, which cannot be accurately predicted by Monte Carlo calculations.

Therefore, the background is determined by a fit to data in the signal region using some smooth functional form.



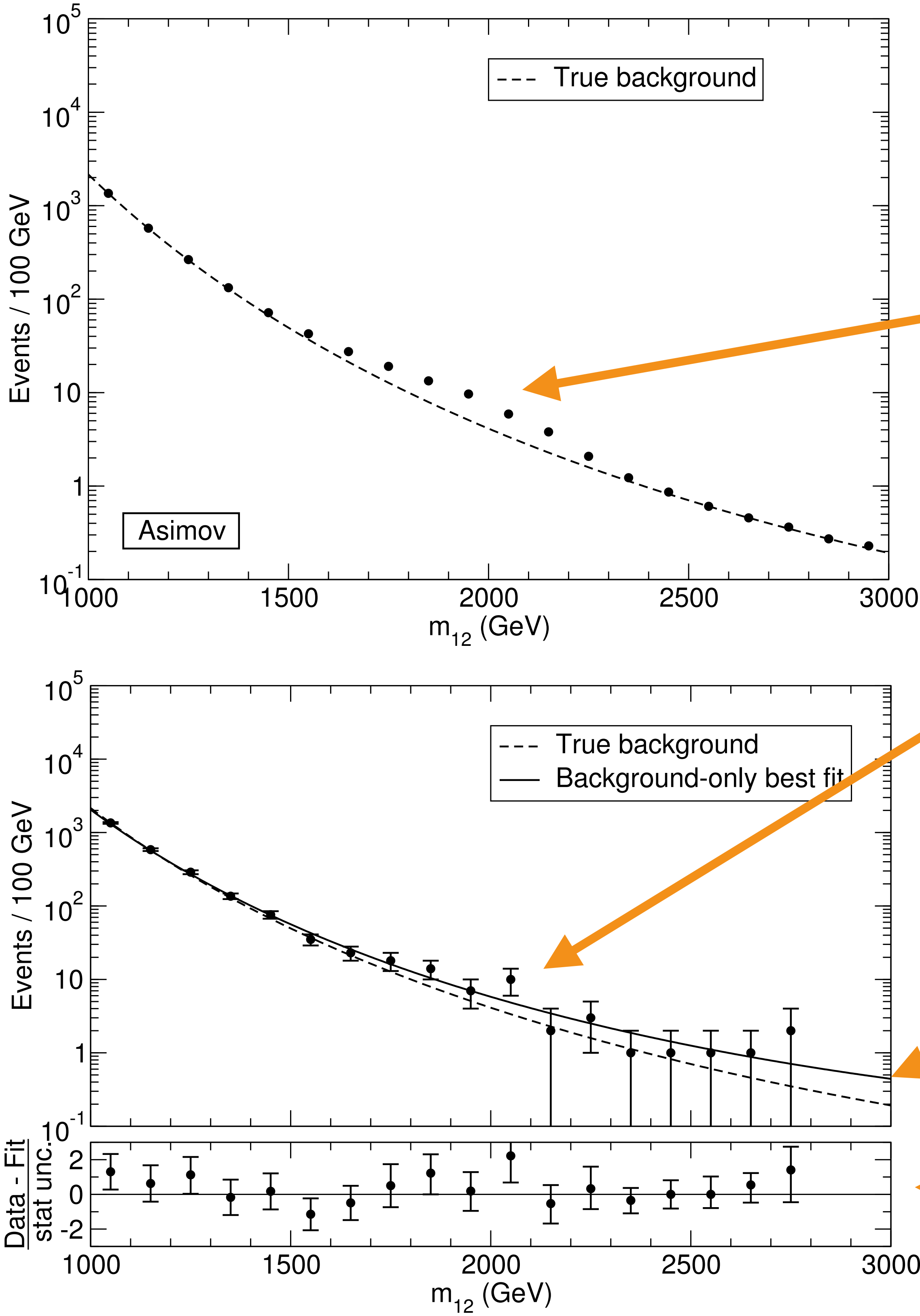
$$\frac{dN}{dm_{JJ}} = \frac{P_0(1 - m_{JJ}/\sqrt{s})^{P_1}}{(m_{JJ}/\sqrt{s})^{P_2}}$$

P_1, P_2 free parameters

P_0 normalisation

This may be fine for narrow resonances, but new physics signals giving wide bumps are mostly absorbed by the background fit if statistics are small.

JAAS 1703.06153



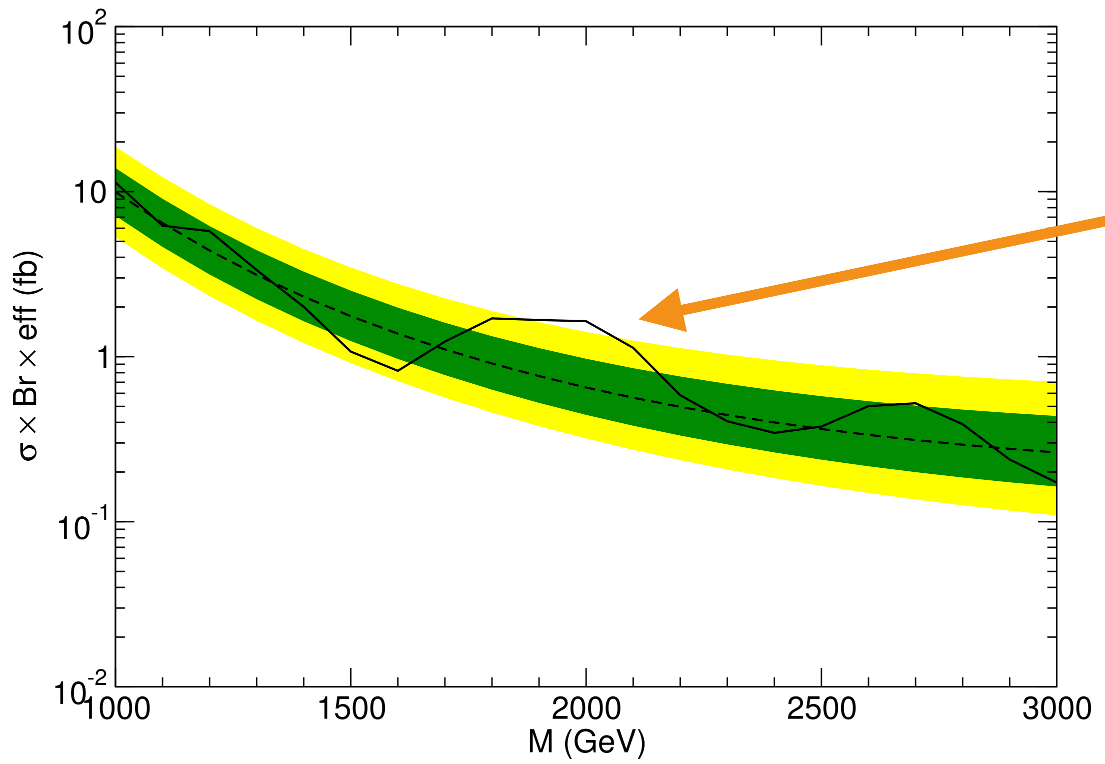
triboson signal is a large wide bump on top of smooth background

in pseudo-experiment, many extra `signal´ events and also some fluctuations

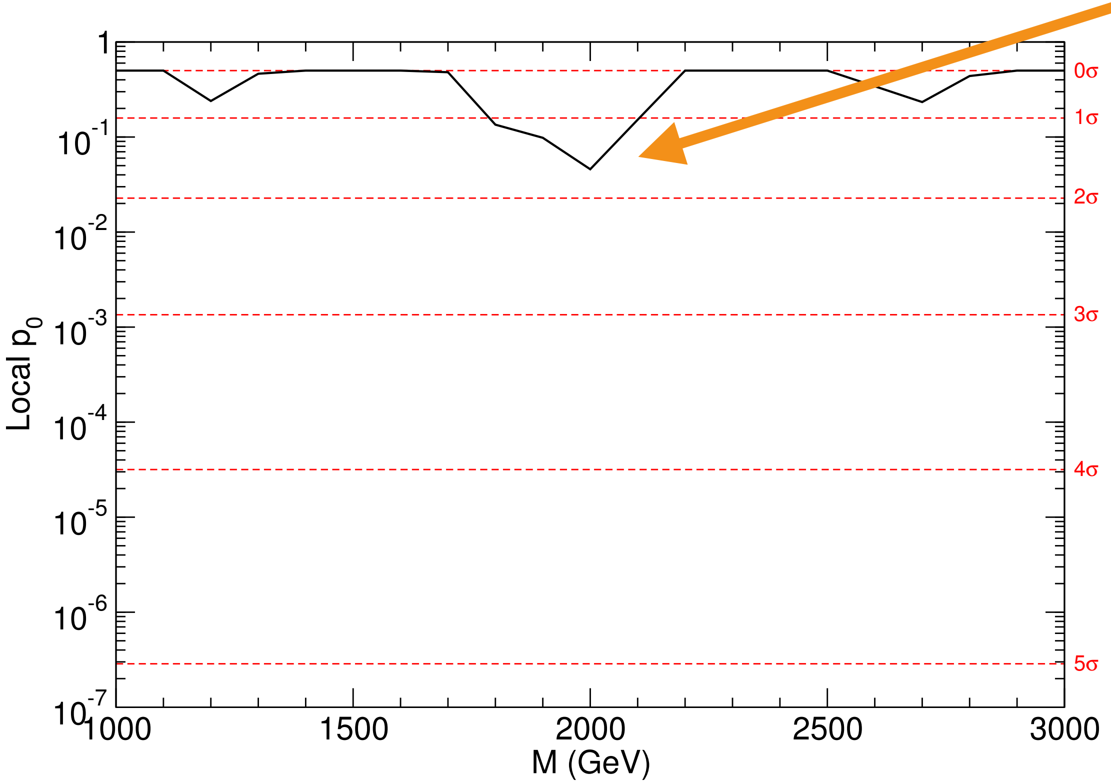
the `best background-only fit´ absorbs part of the bump

data exhibits smallish deviations w.r.t. best fit

Therefore…



upper limit does not show anything remarkable

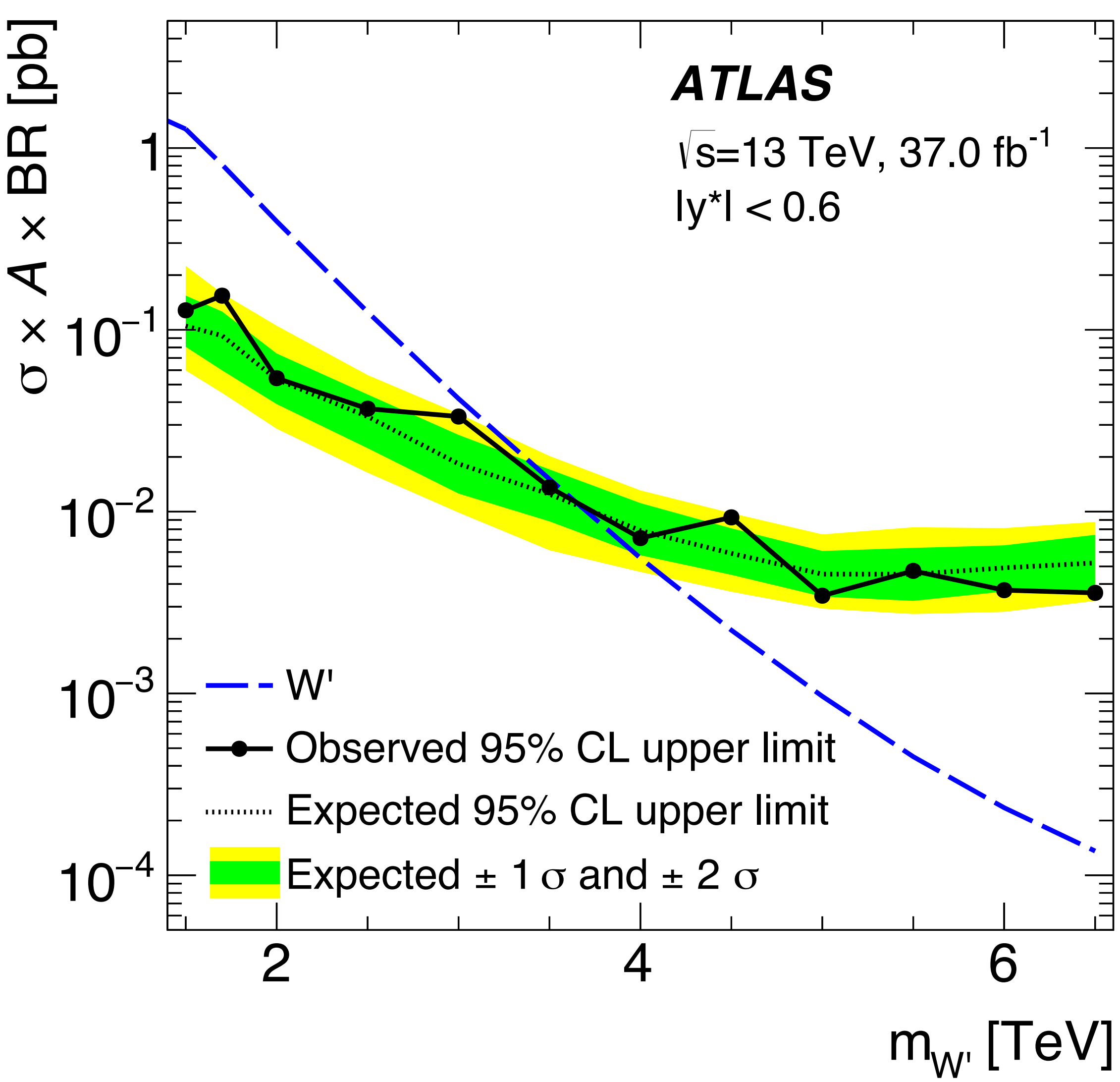


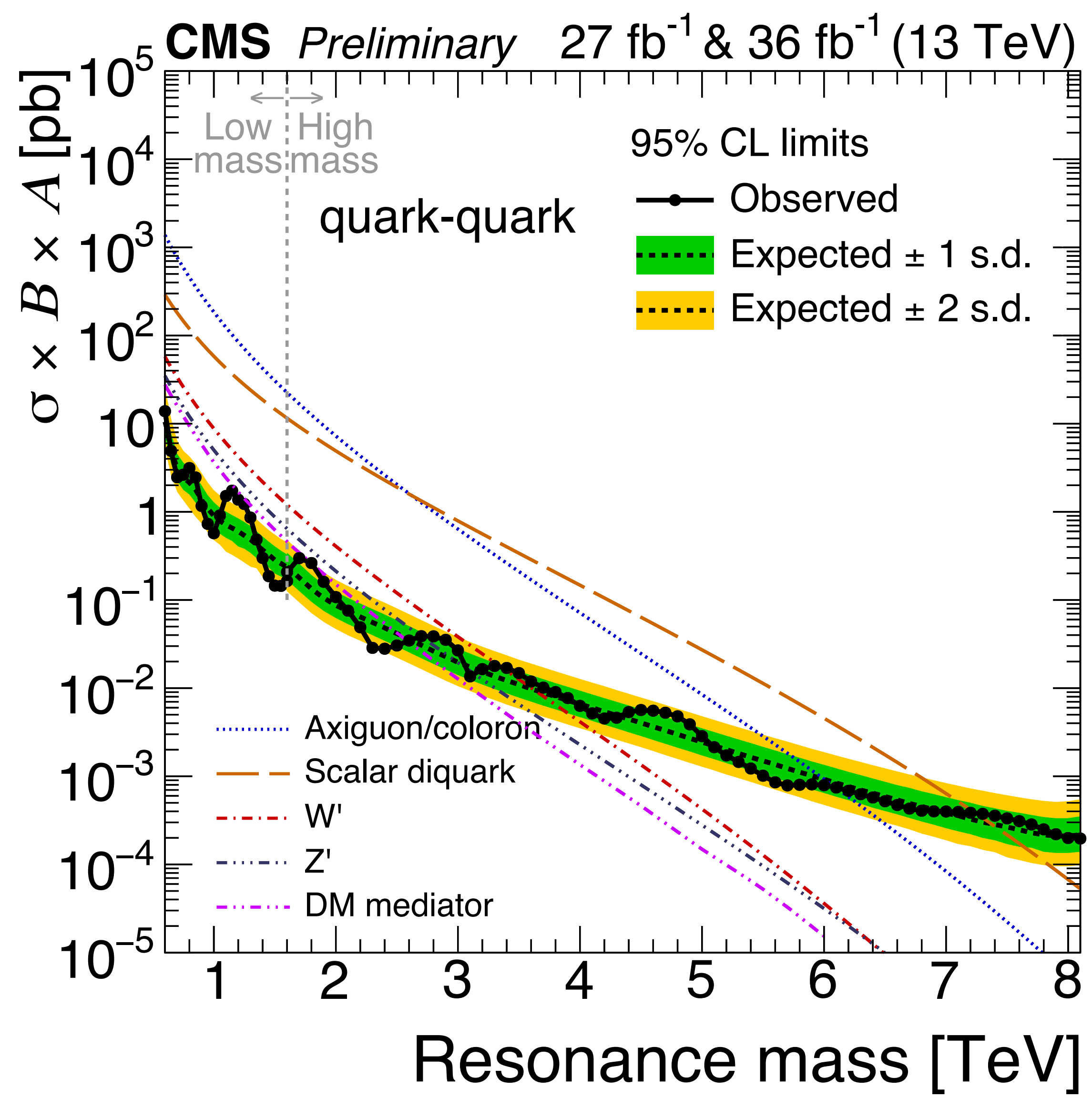
P-value calculated assuming narrow resonance does not either

\`No significant excess is observed´

Dijet searches with untagged jets also have some features, but there are too many features to conclude something.

ATLAS 1703.09127
CMS-PAS-EXO-16-056

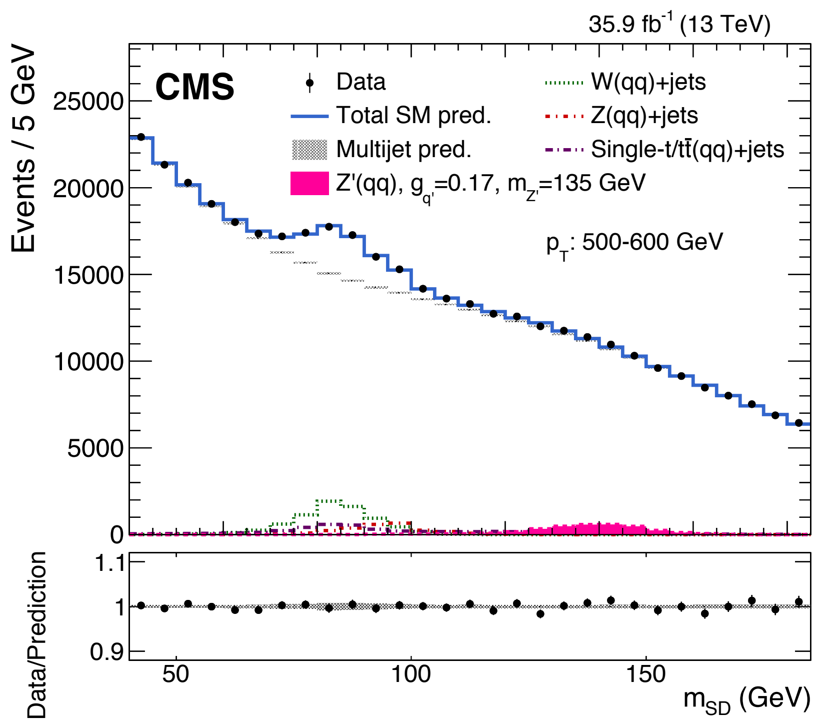


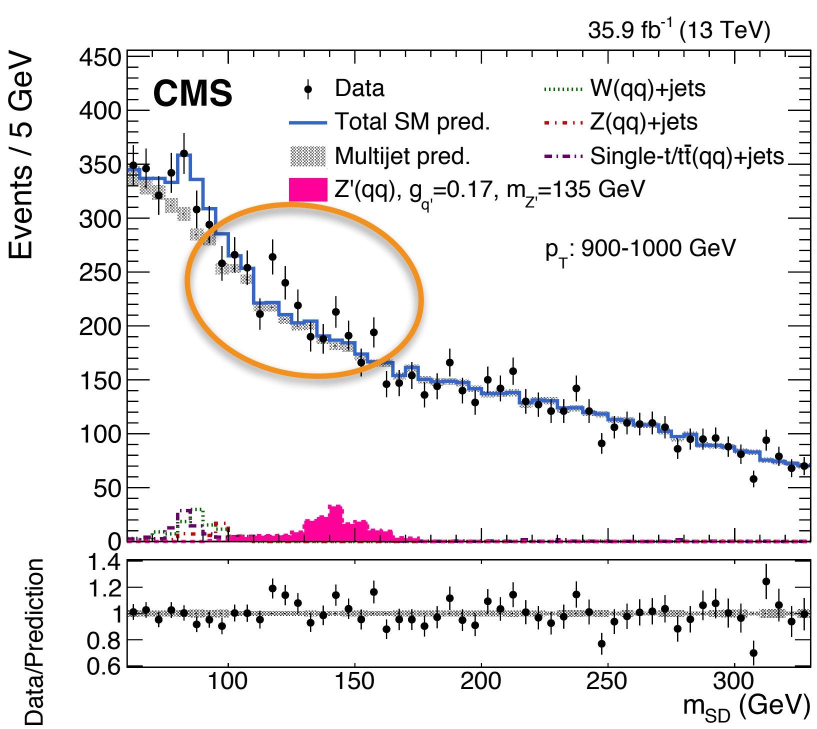


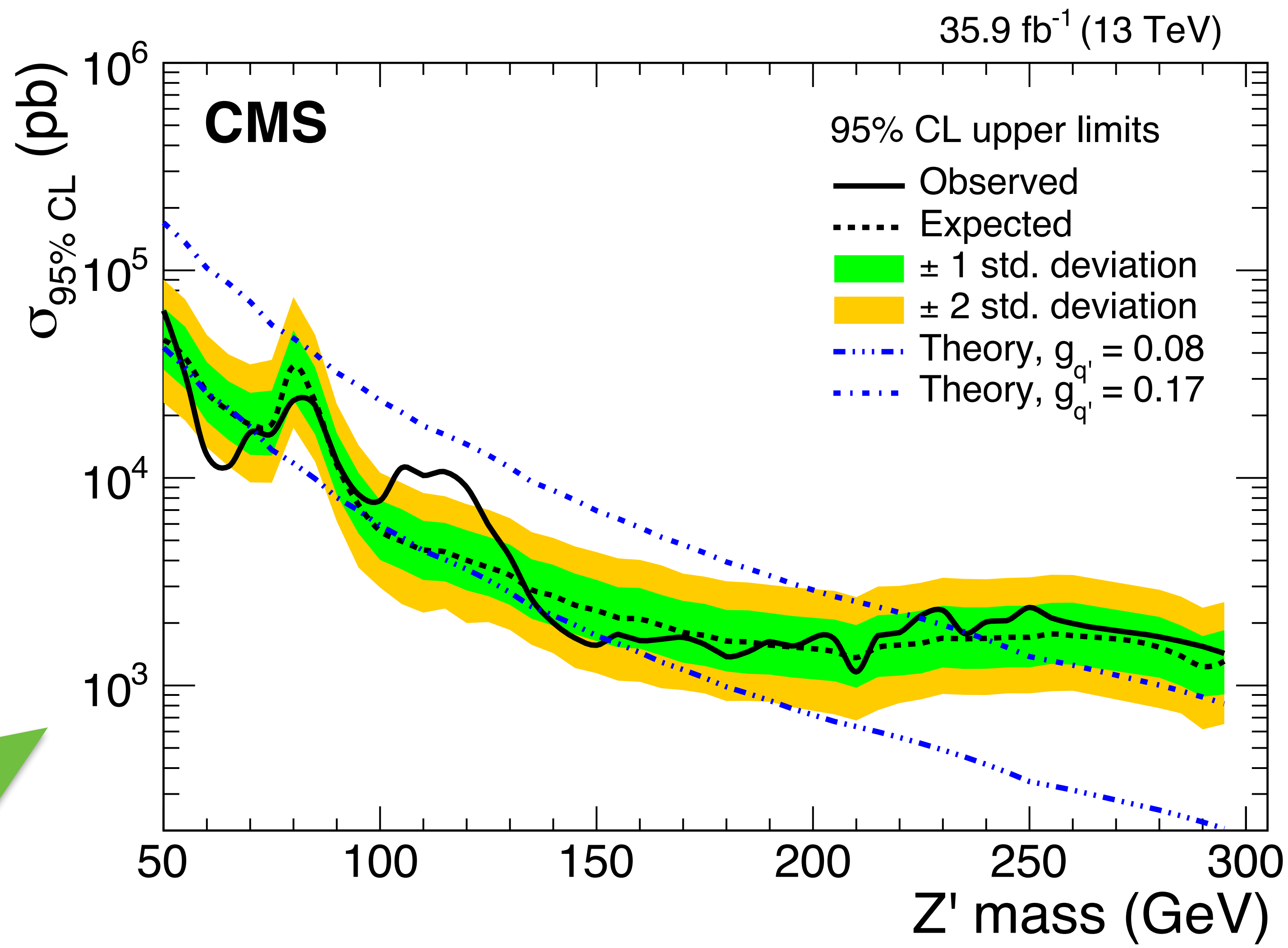
Experimental results: ~ 100 GeV

CMS search for light Z' decaying hadronically, and produced in association with a jet, observe a 2.9σ excess at M = 110 GeV

CMS 1710.00159





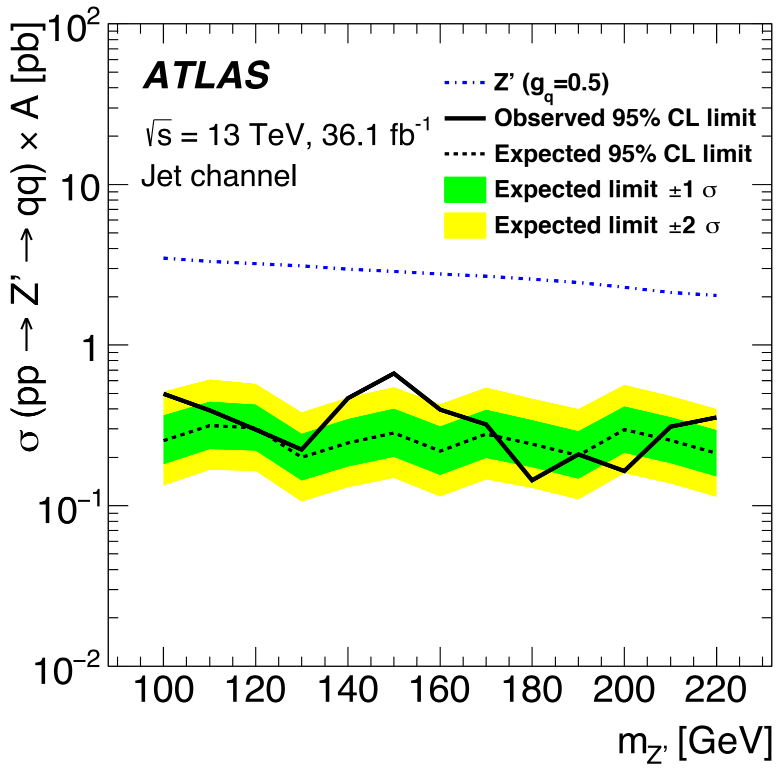


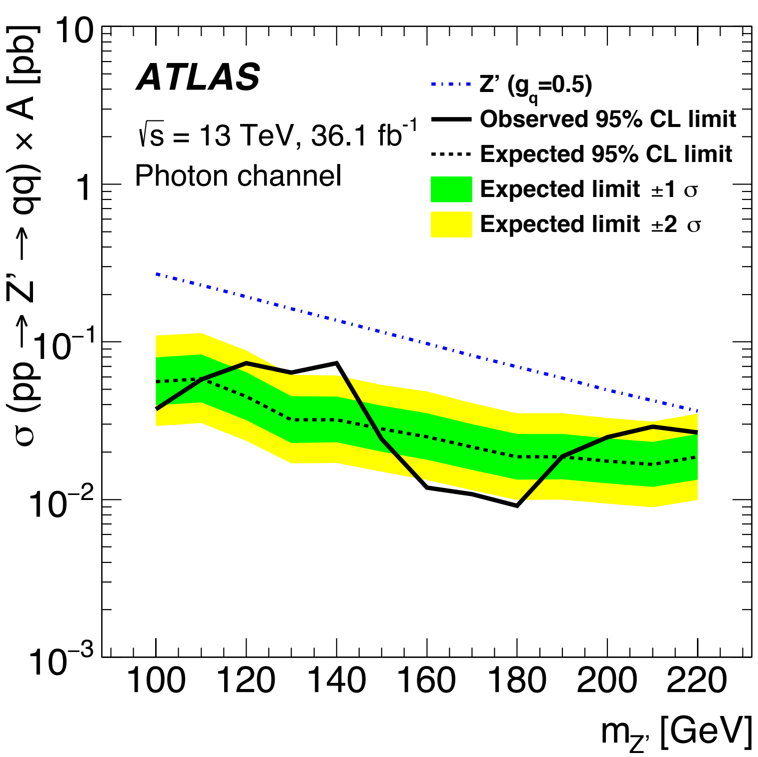
Excess most prominent in high-p_T samples, $p_T \in [900, 1000]$ GeV

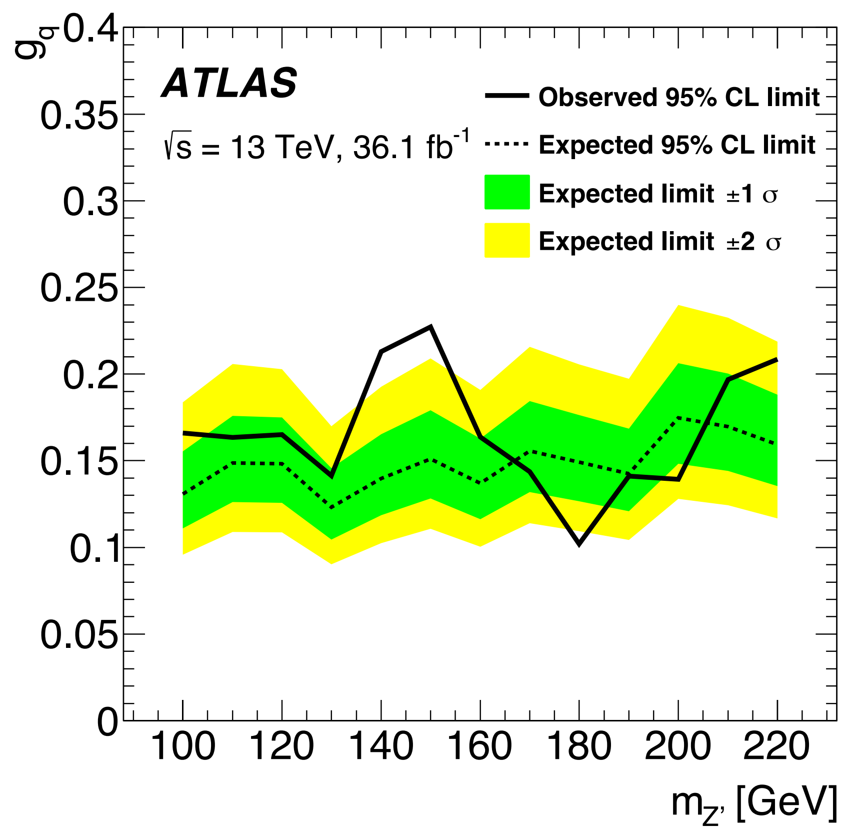
Experimental results: ~ 100 GeV

ATLAS has excess at slightly larger masses, in Z'+j and $Z'+\gamma$

ATLAS 1801.08769



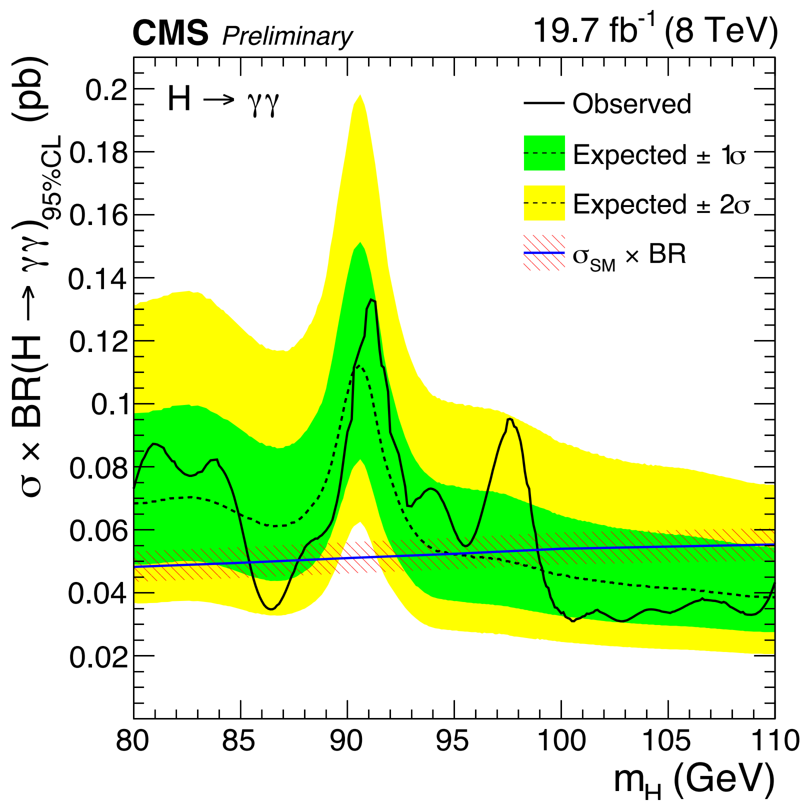


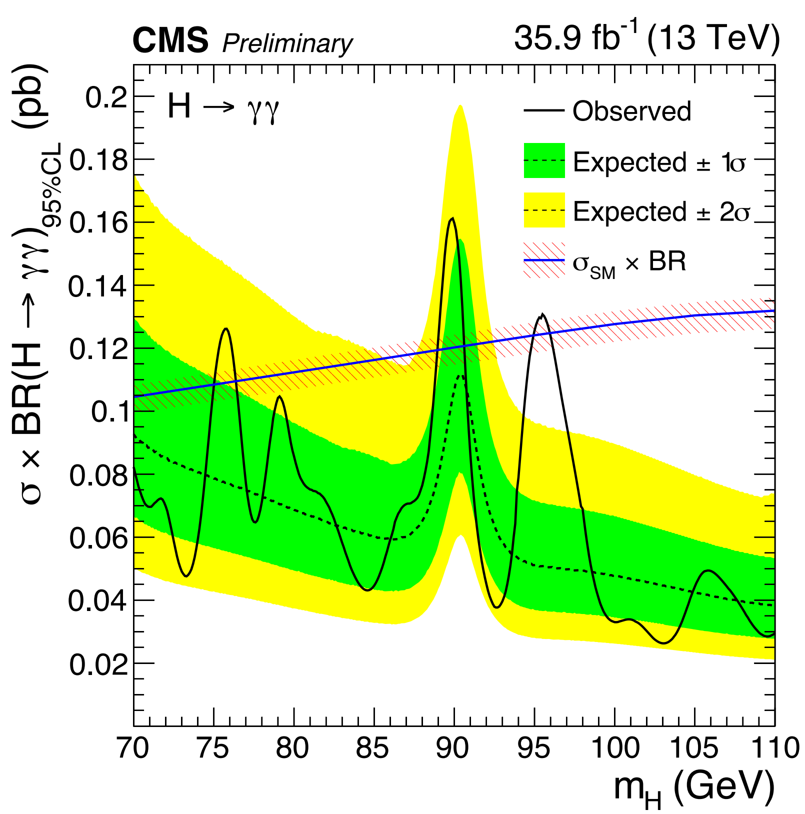


Bump running? Checked, not likely …

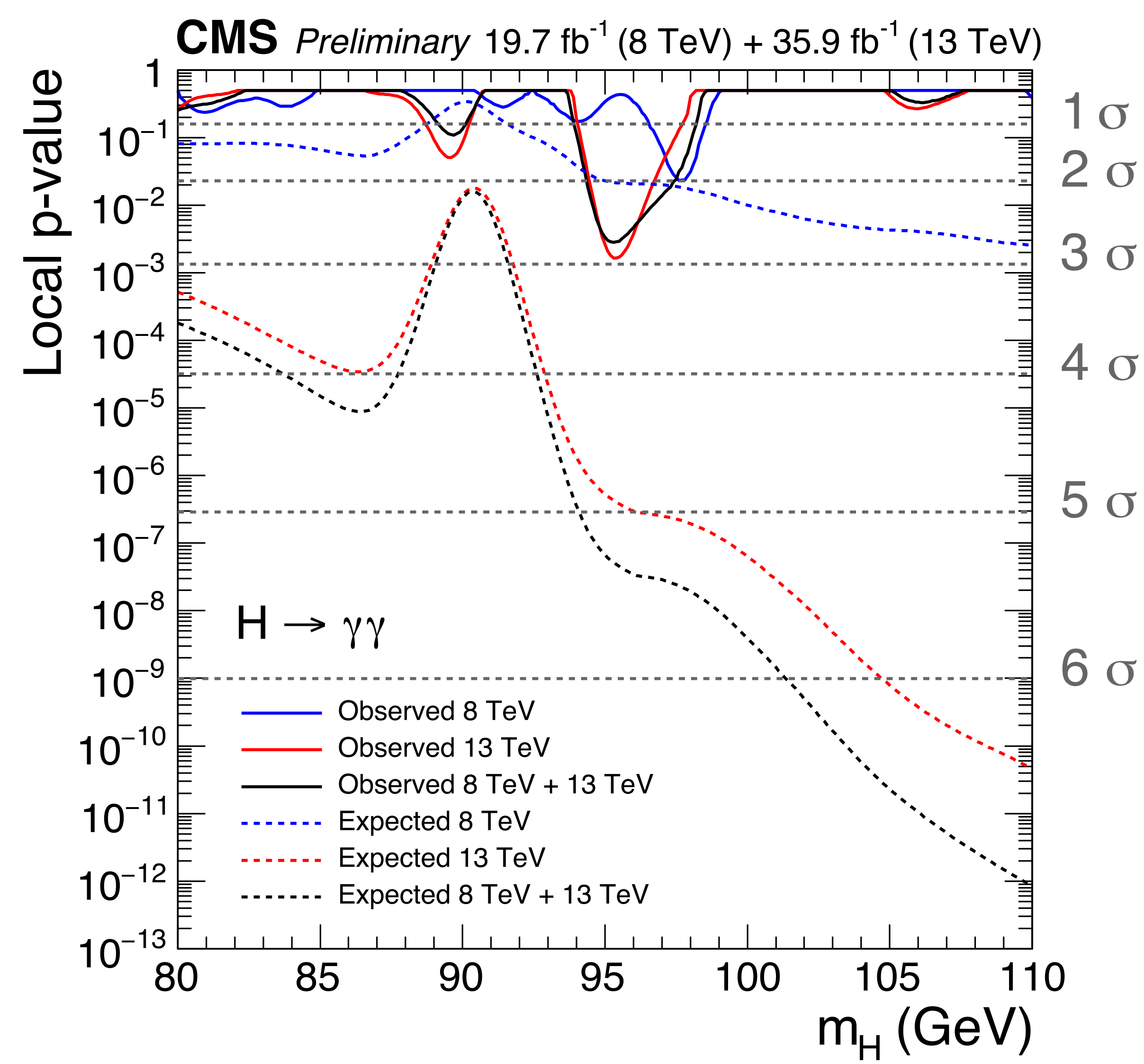
Experimental results: ~ 100 GeV

We have a CMS 95 GeV diphoton! [ATLAS does not look at such low masses]





CMS-PAS-HIG-17-013

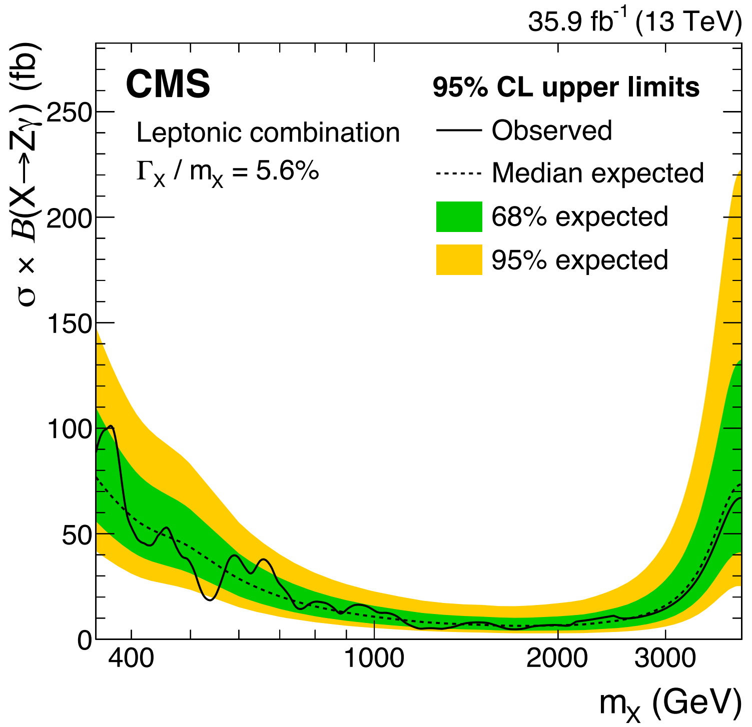


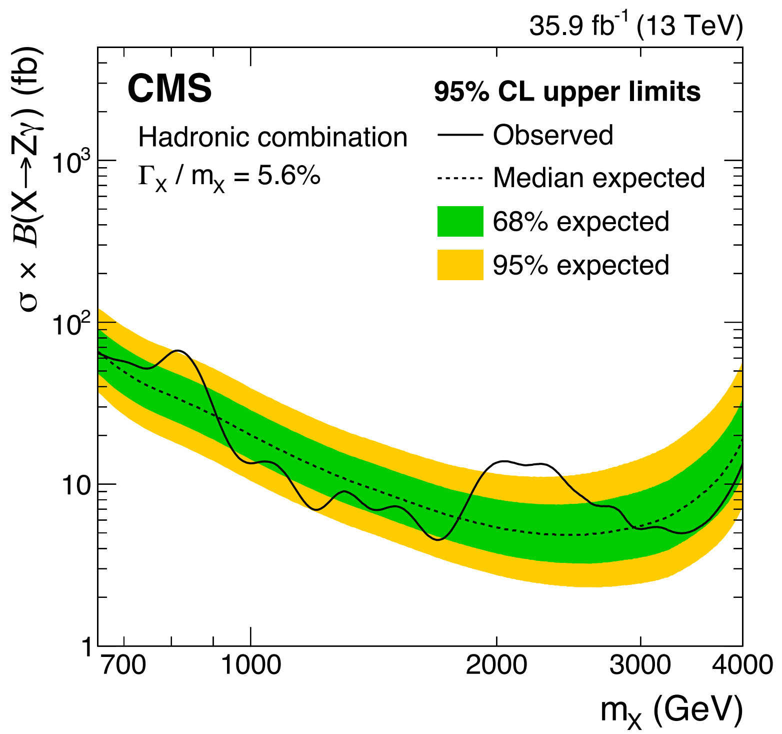
8 TeV and 13 TeV excesses not at the same place, they do not add

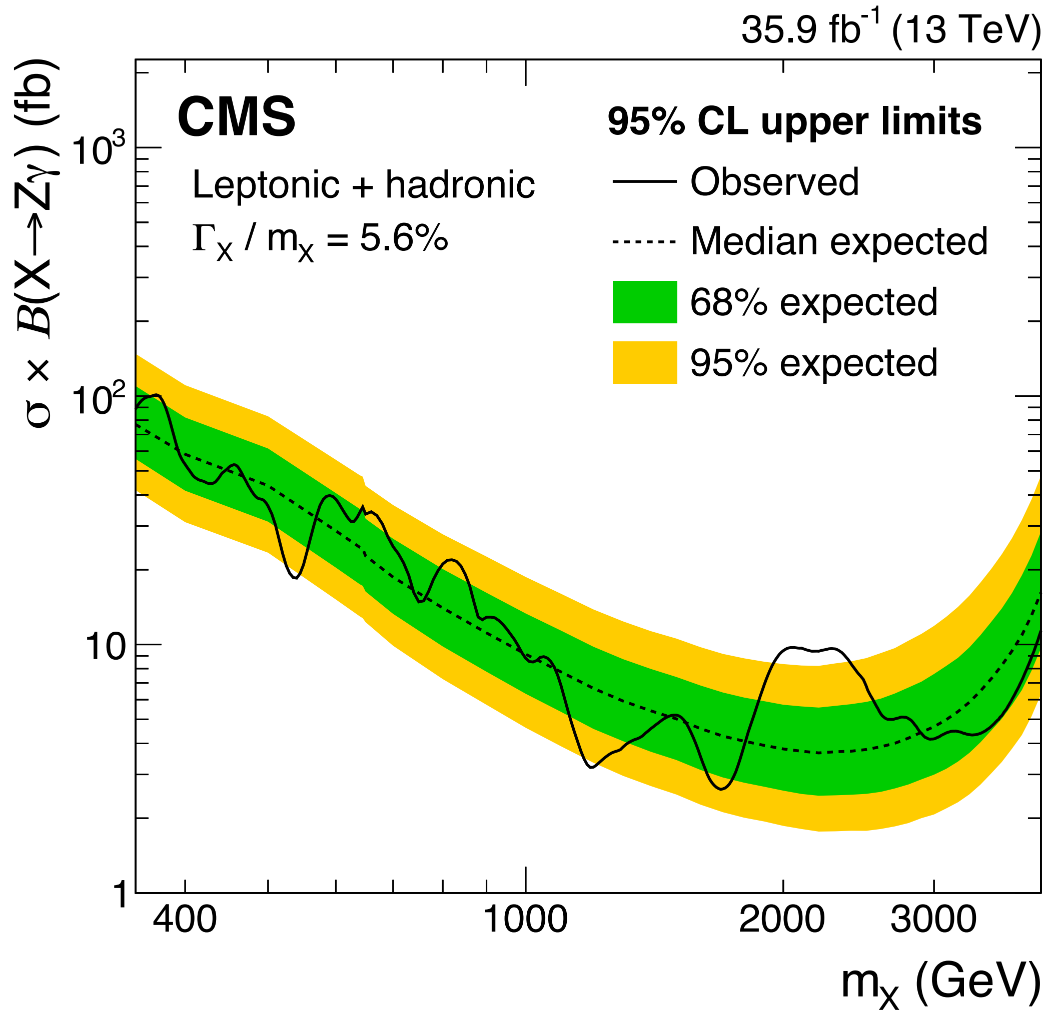
Experimental results: 2 TeV

CMS search for $Z\gamma$ resonances finds 3.2σ excess at M = 2 TeV in hadronic channel $J\gamma$, no excess in leptonic channel [similar sensitivity].

CMS 1712.03143



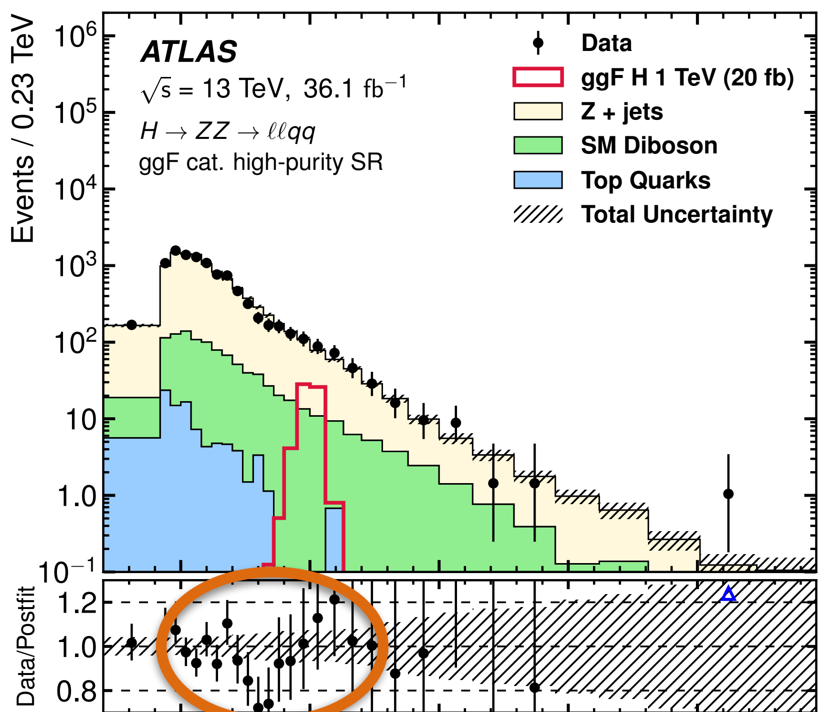


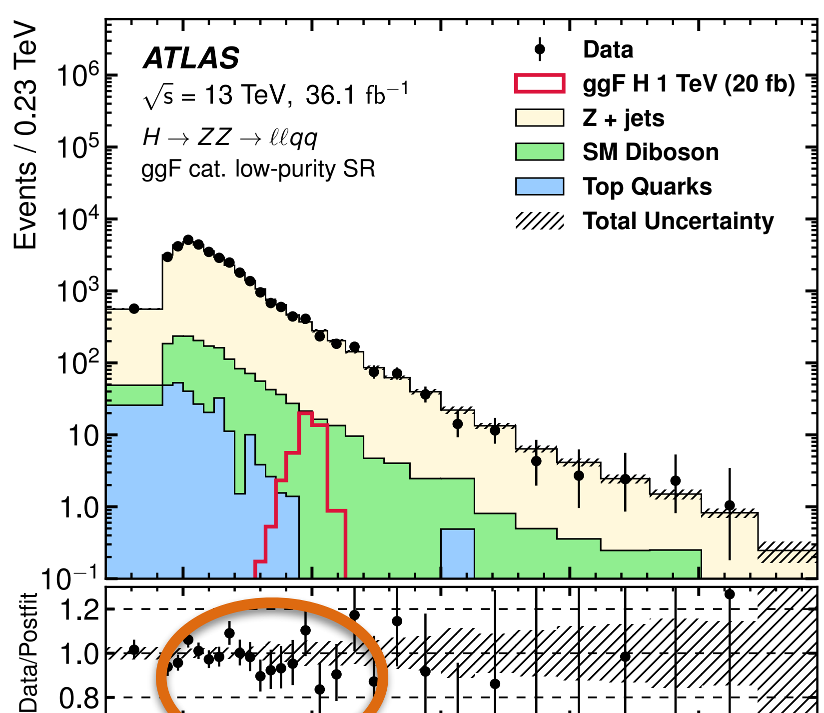


Experimental results: ~ 800 GeV

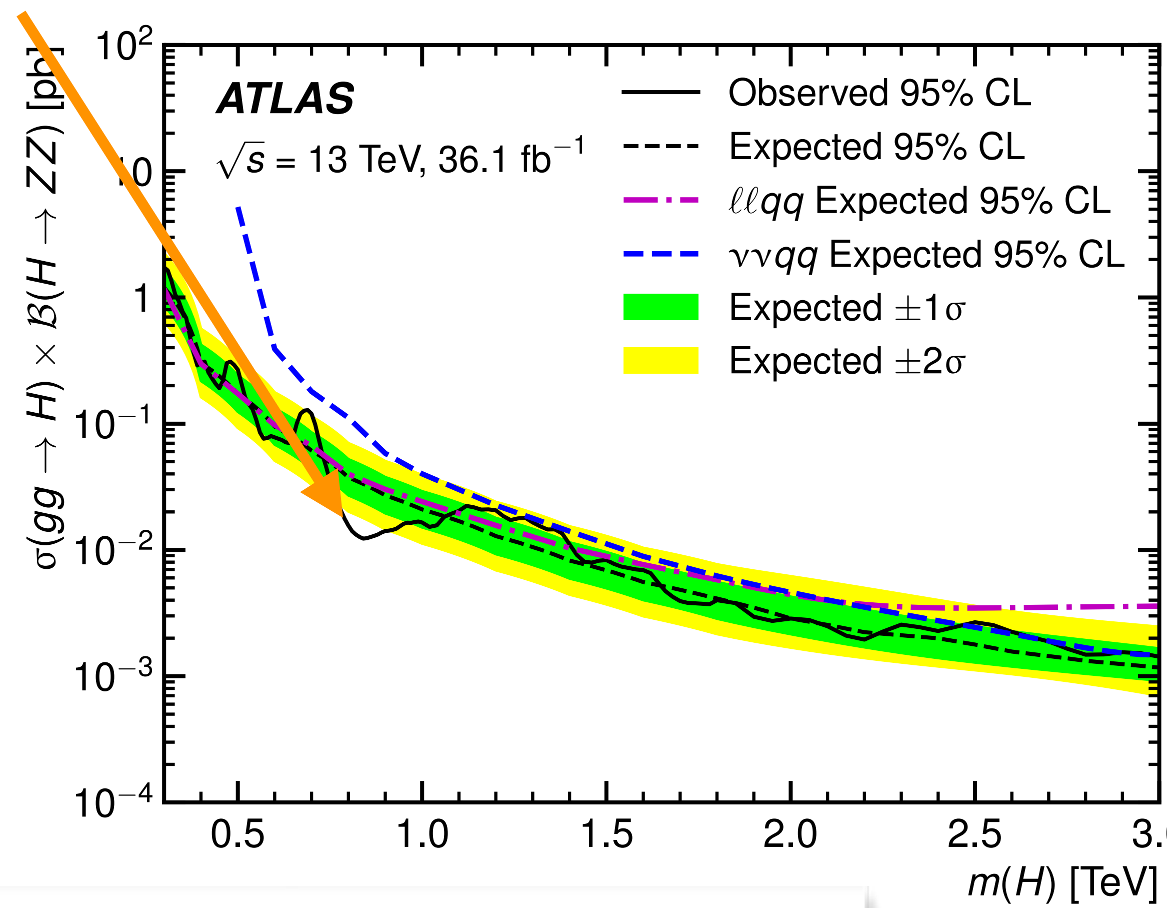
ATLAS search for ZZ resonances in ee / μμ + J channel has… big ~3σ dip at 800 GeV!

ATLAS 1708.09638

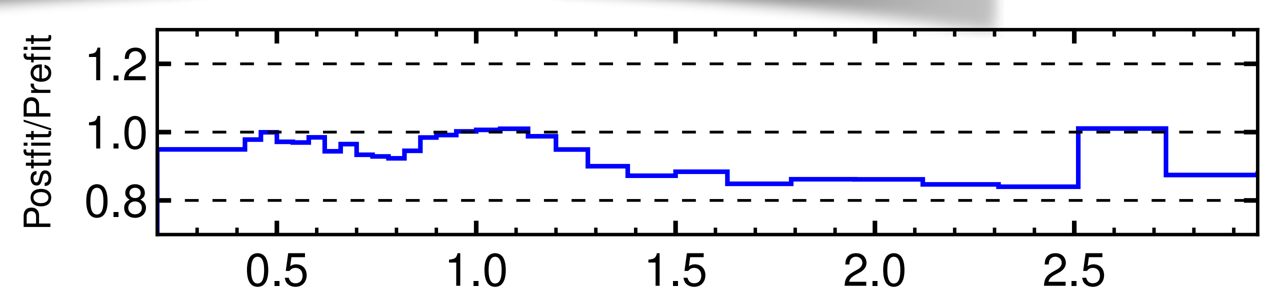




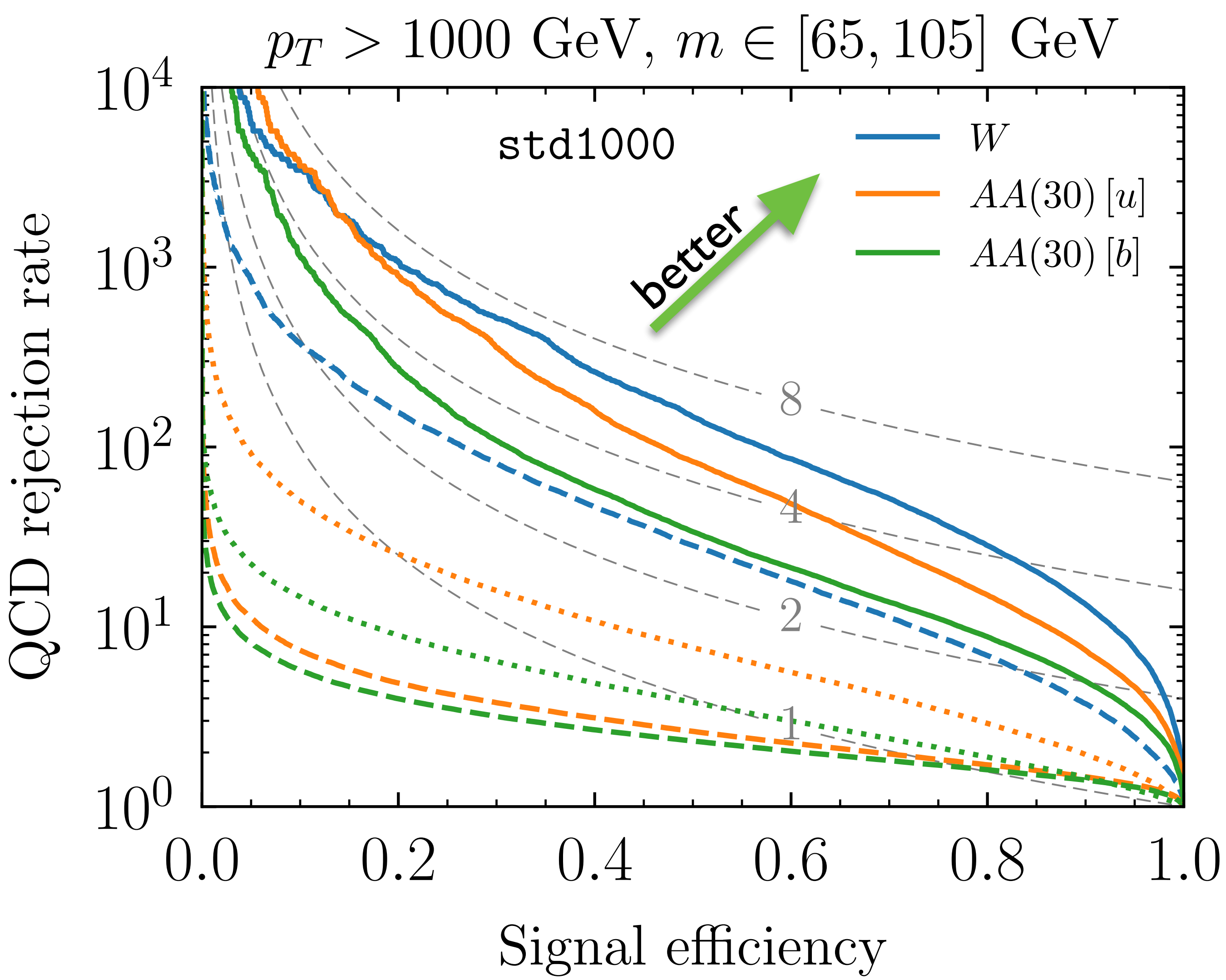
Combined with νν + J



If not merely statistical, dips indicate mismodeling



Comparison with τ ratios for particles with M = 80 GeV



Blue: W bosons

Green: stealth bosons M_A = 30 GeV

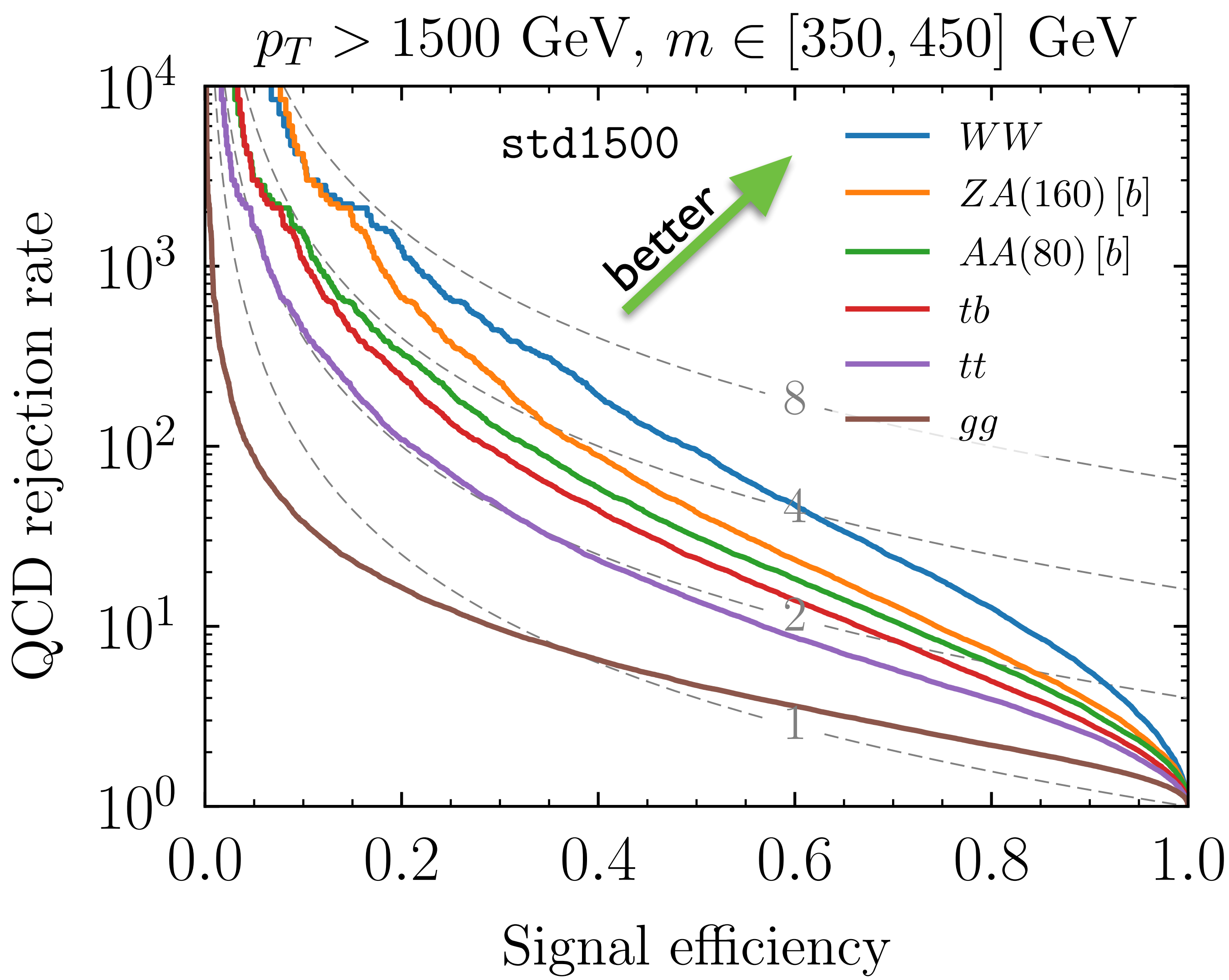
Orange: $H_1^0 \rightarrow uuuu$ M_A = 30 GeV

Dashed: τ_{21}

Dotted: τ_{42}

τ_{21} actually reduces the signal significance for stealth bosons, as could be guessed from slide 3

Example: tagger performance for particles with M = 400 GeV



Blue: $H_l^0 \to WW$

Red: $H^\pm \to tb$ M_A = 30 GeV

Green: $H_l^0 \to bbbb$ M_A = 80 GeV

Orange: $H_l^0 \to ZA$ M_A = 160 GeV

Purple: $H_l^0 \to tt$ six-pronged jet!

Brown: $H_l^0 \to gg$

The tagger works well for various topologies, even for a six-pronged jet