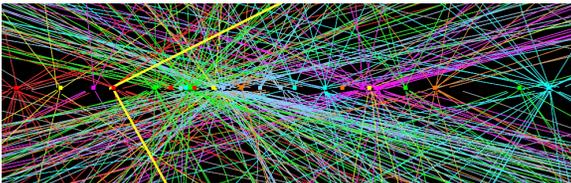


# Update on LHC Searches: experimental techniques and recent results

Ayana Arce  
ANL Lattice x BSM Workshop  
April 21<sup>st</sup> 2016

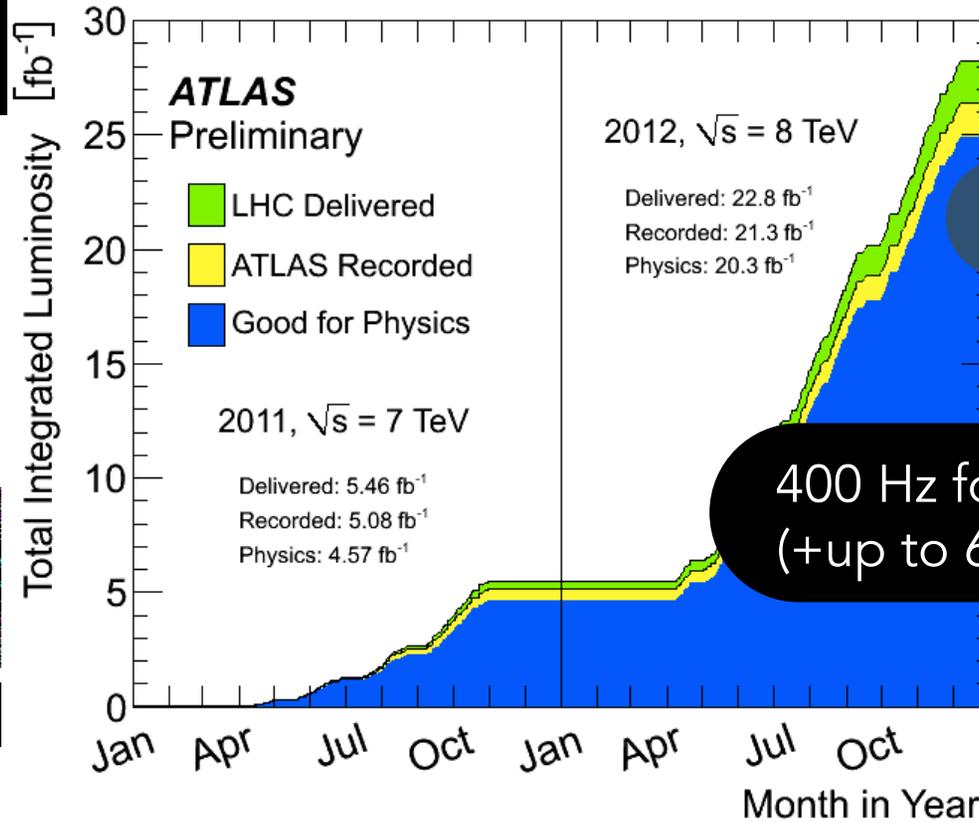
# Looking back...

1380 colliding bunches  
(50 ns spacing)



pileup: in ~5 cm!

900 H  $\rightarrow$   $\gamma\gamma$  events

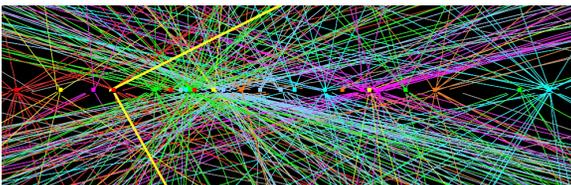


20M dijet events

400 Hz for prompt analysis  
(+up to 600 Hz "delayed")

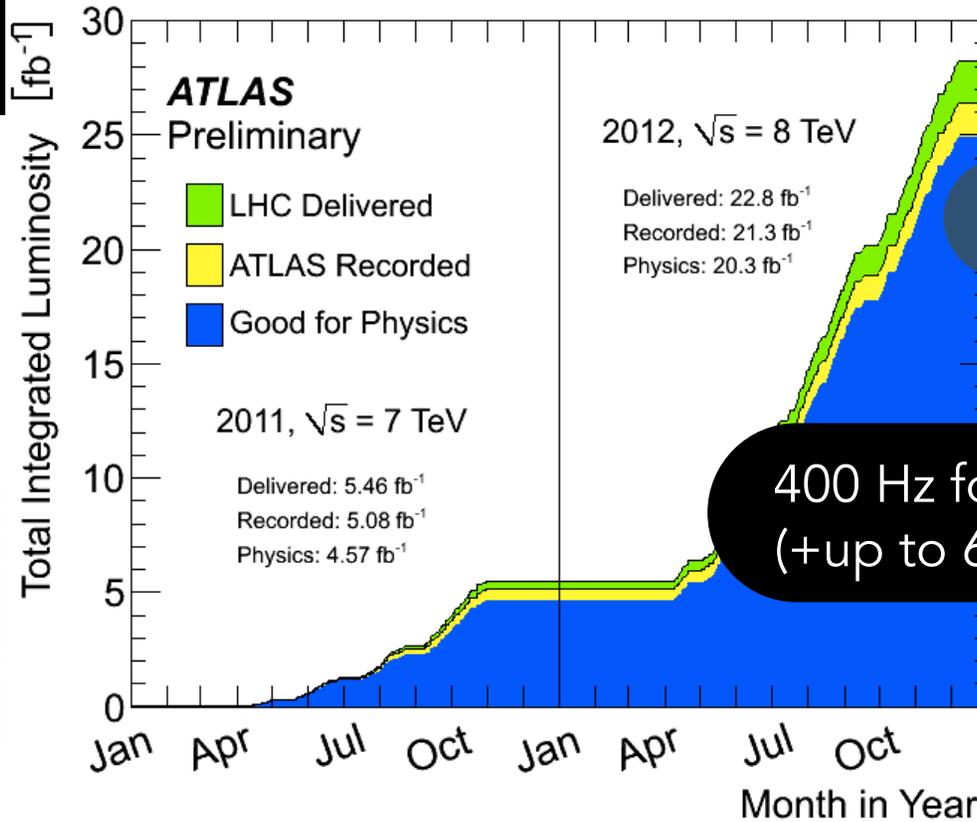
# Looking back...

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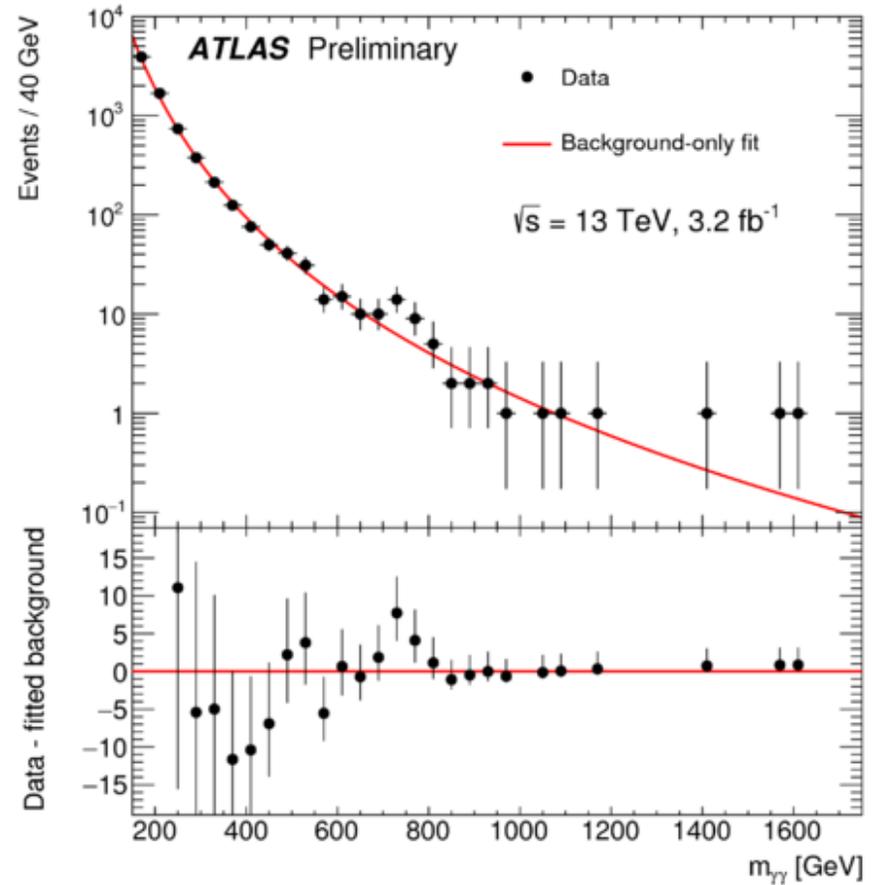
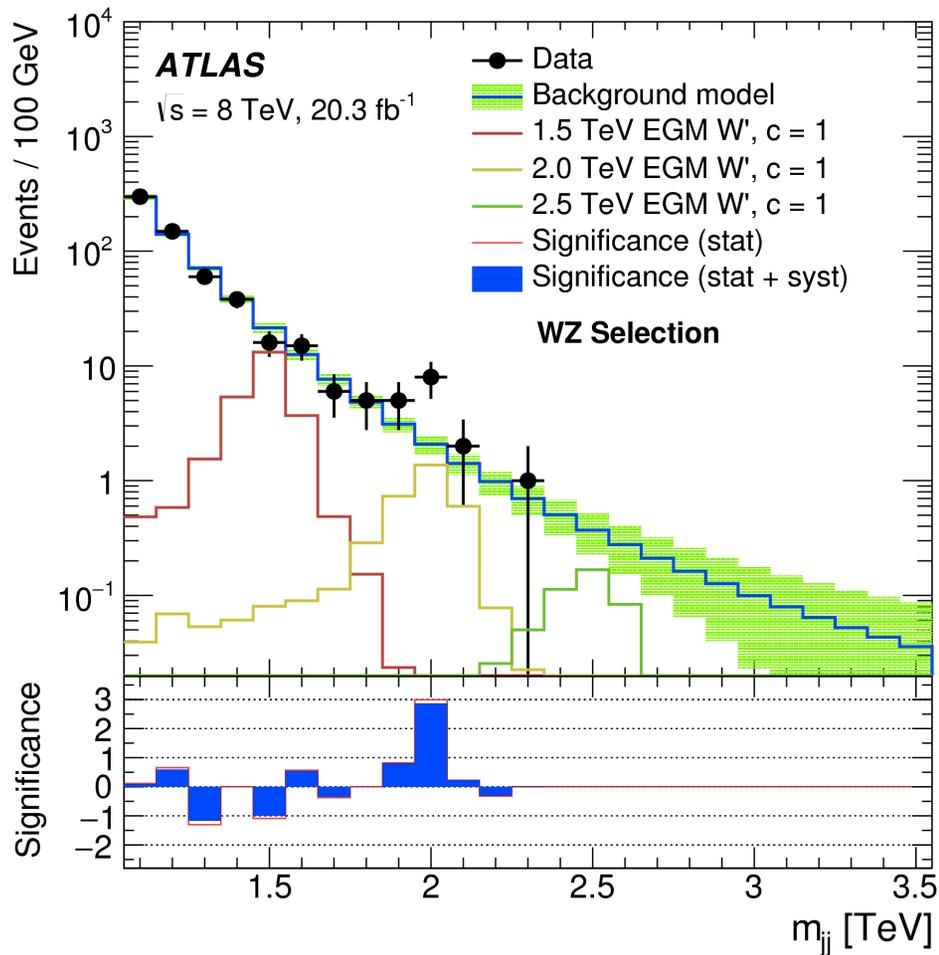


20M dijet events

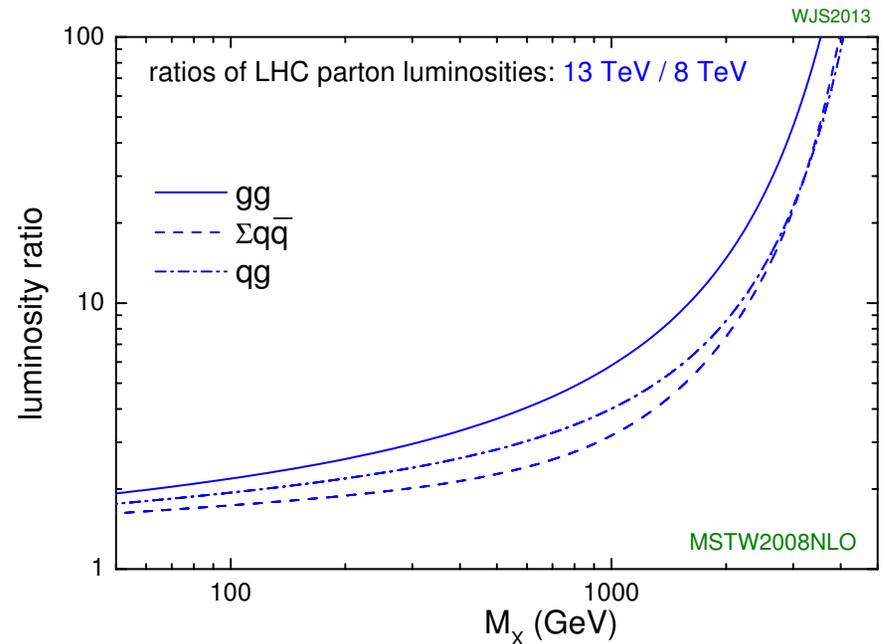
400 Hz for prompt analysis  
(+up to 600 Hz "delayed")

0 non-SM  
observations

# Recent developments



# Recent developments

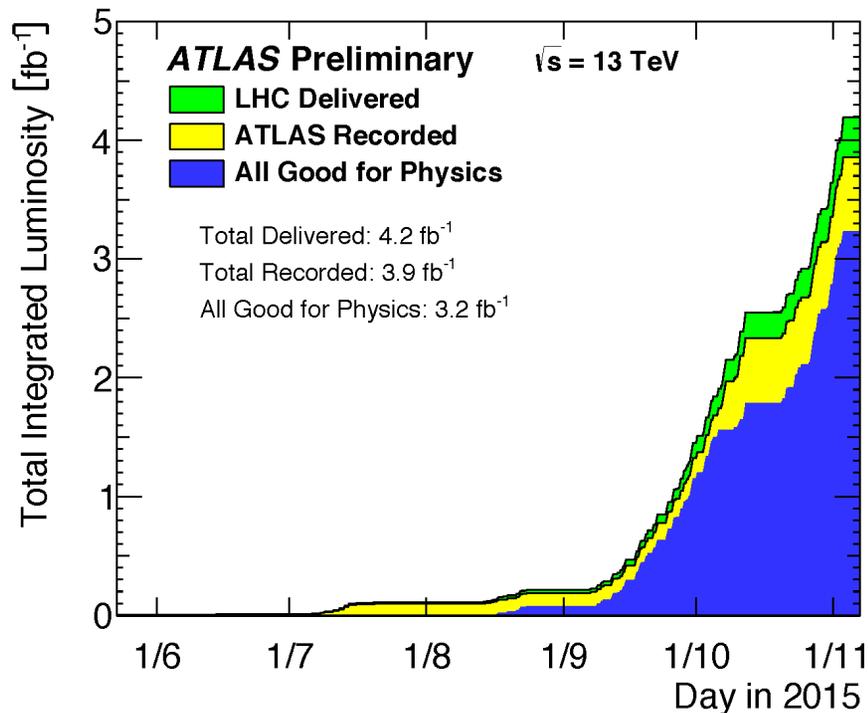


long shutdown (2013-2015):

- LHC splice repair to allow 13 TeV collisions
  - parton luminosity at 2 TeV increased more than 5x
  - 2x more colliding bunches
  - experiments collected  $1.9\text{-}3.2 \text{ fb}^{-1}$
- detector upgrades in ATLAS/CMS

# Recent developments

- ATLAS:
  - new innermost tracking layer: better vertex reconstruction
  - muon trigger improvements



new pixel layer in existing tracker

- CMS:
  - more muon coverage (trigger improvements)
  - new luminosity detectors
  - new calorimeter trigger (pileup robust)

# (atlas)

Muon drift tubes + cathode strips

$\mu$ -ID efficiency  $> 99\%$  in tracker acceptance

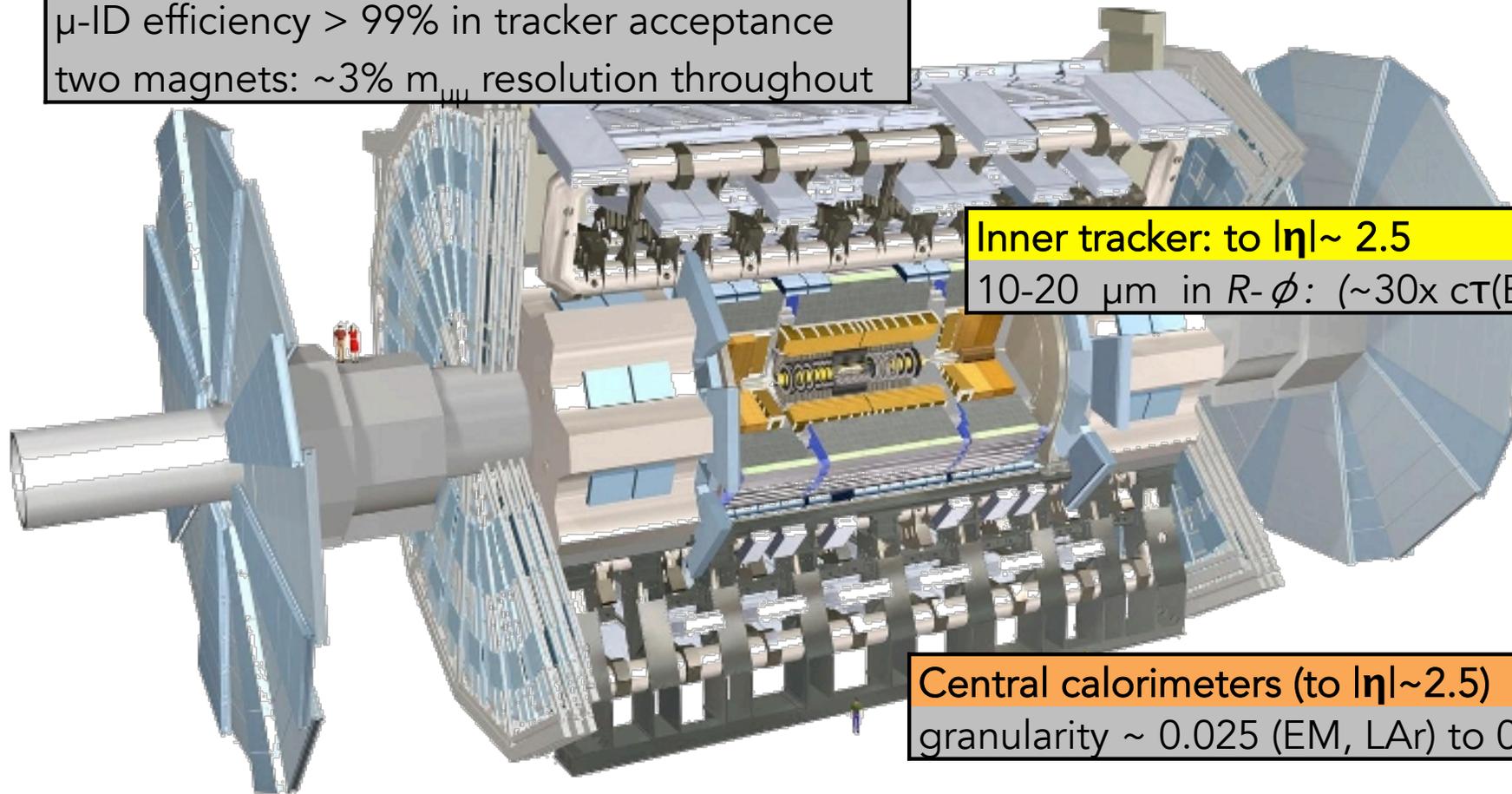
two magnets:  $\sim 3\%$   $m_{\mu\mu}$  resolution throughout

Inner tracker: to  $|\eta| \sim 2.5$

10-20  $\mu\text{m}$  in  $R-\phi$ : ( $\sim 30x$   $c\tau(B)$ )

Central calorimeters (to  $|\eta| \sim 2.5$ )

granularity  $\sim 0.025$  (EM, LAr) to 0.1 (HAD, Tile)



# (cms)

## muon systems

< 2%  $p_T$  resolution  
( $Z \rightarrow \mu\mu$ , barrel)

## tracking

10-20  $\mu\text{m}$  in  $R-\phi$ :  
( $\sim 30\times c\tau(B)$ )

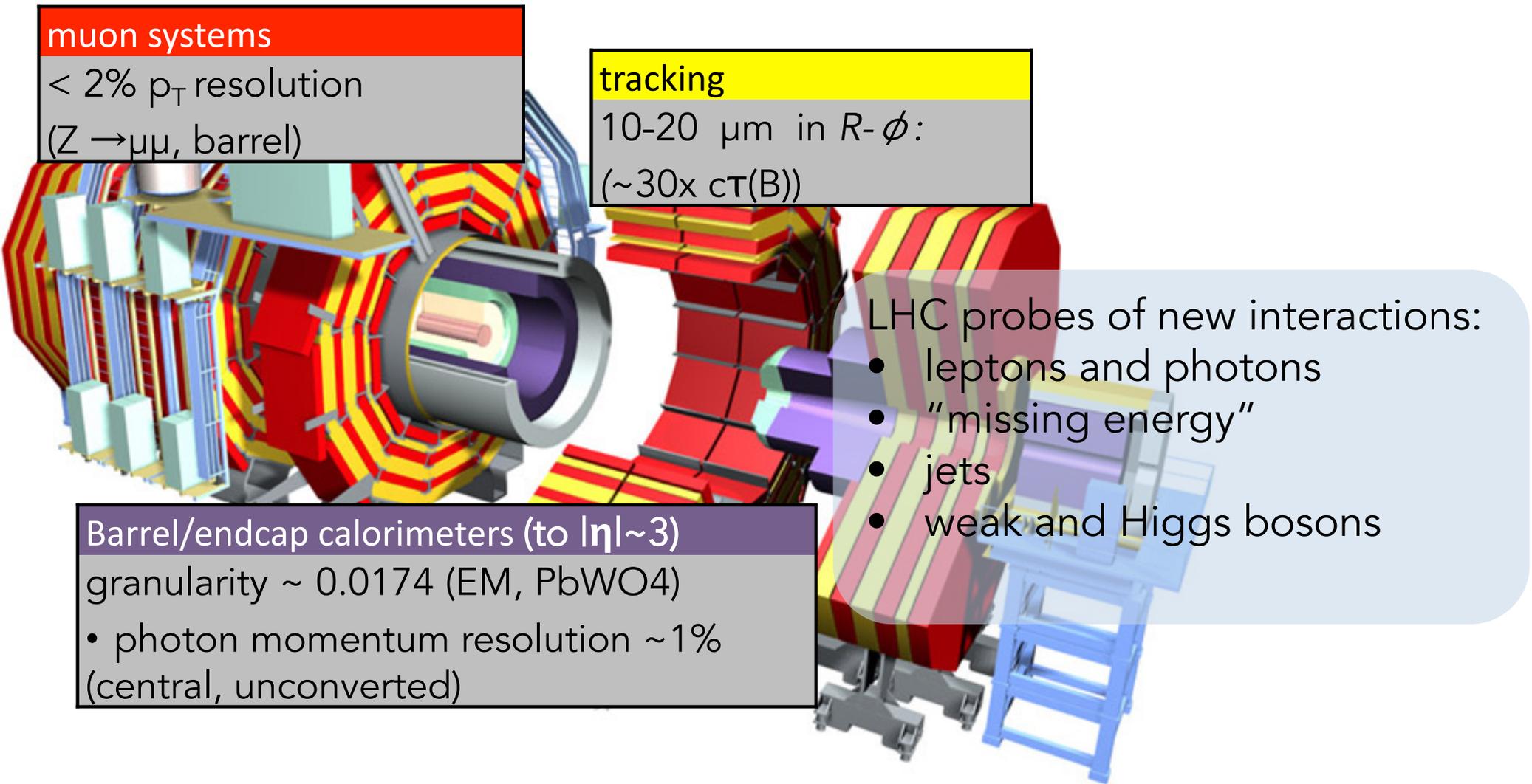
LHC probes of new interactions:

- leptons and photons
- "missing energy"
- jets
- weak and Higgs bosons

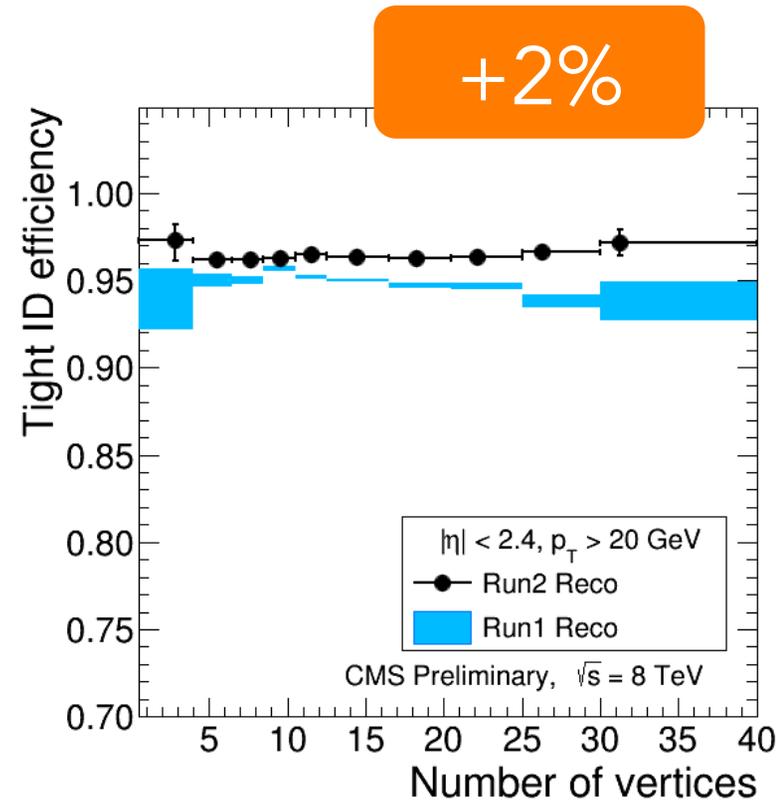
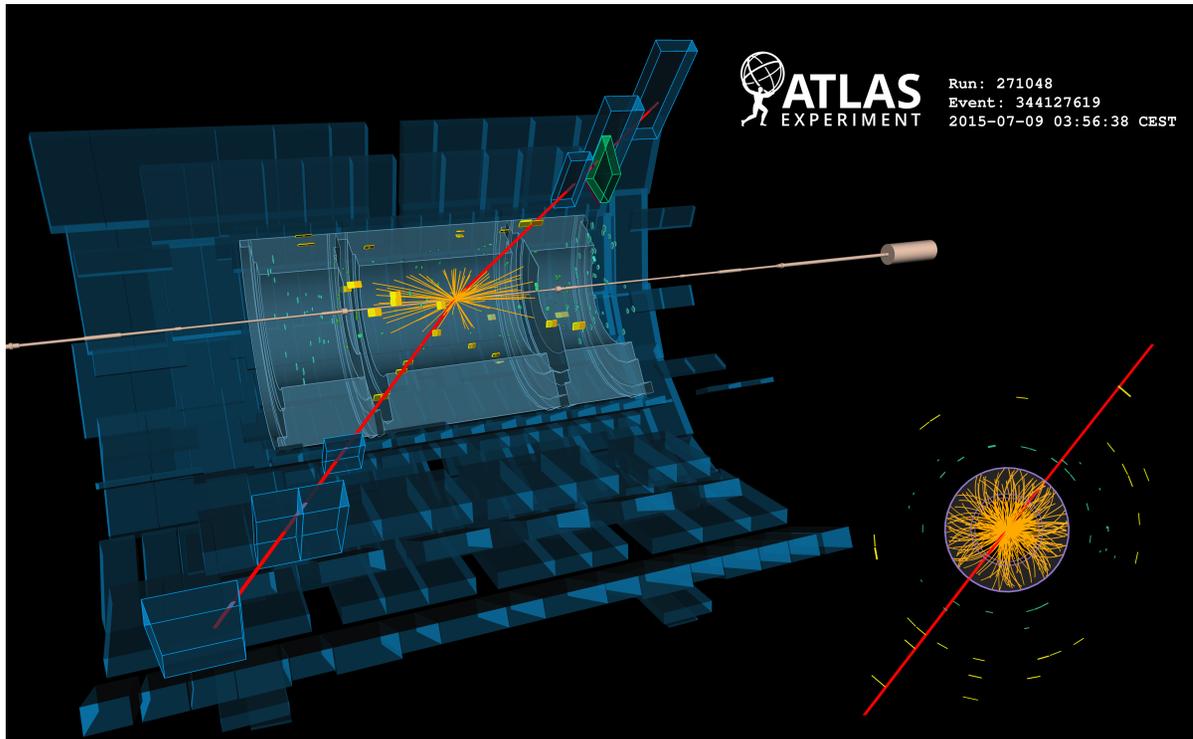
## Barrel/endcap calorimeters (to $|\eta| \sim 3$ )

granularity  $\sim 0.0174$  (EM, PbWO<sub>4</sub>)

- photon momentum resolution  $\sim 1\%$   
(central, unconverted)

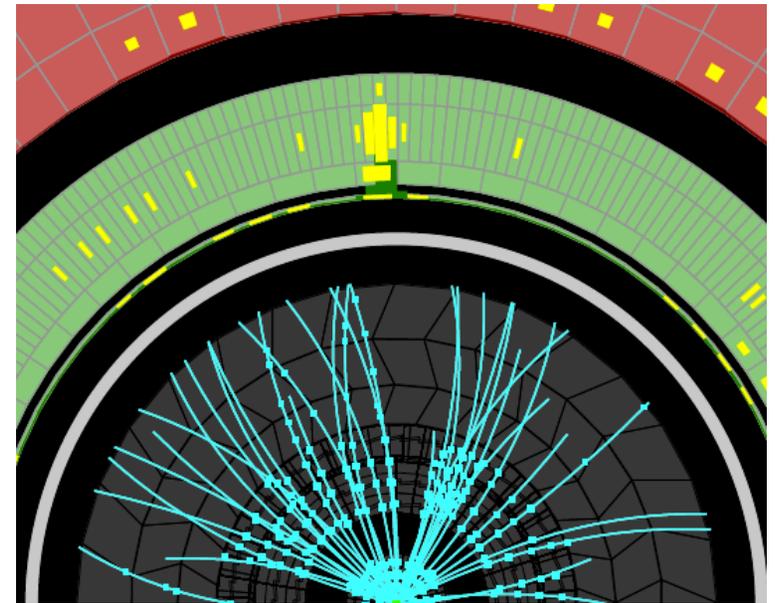
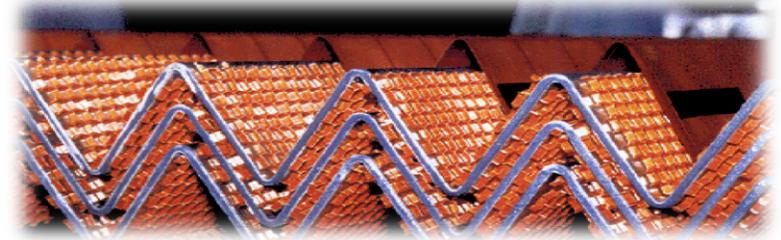
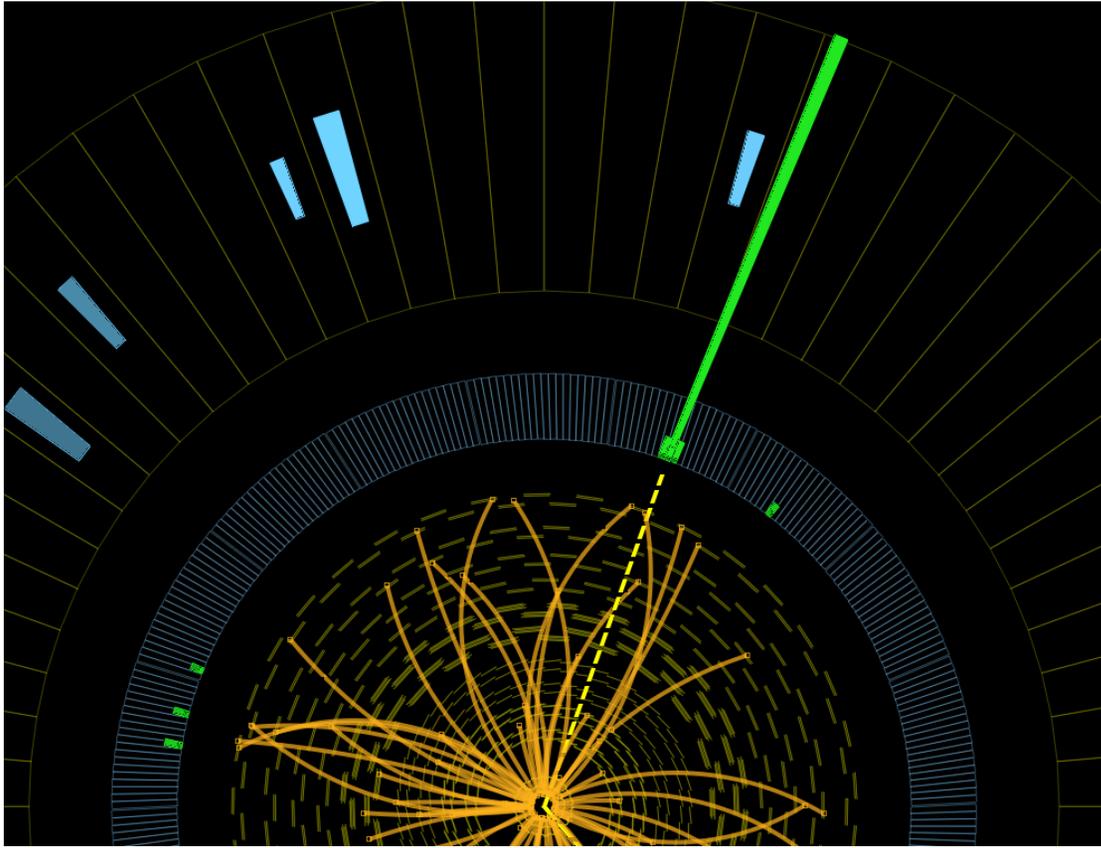


# leptons



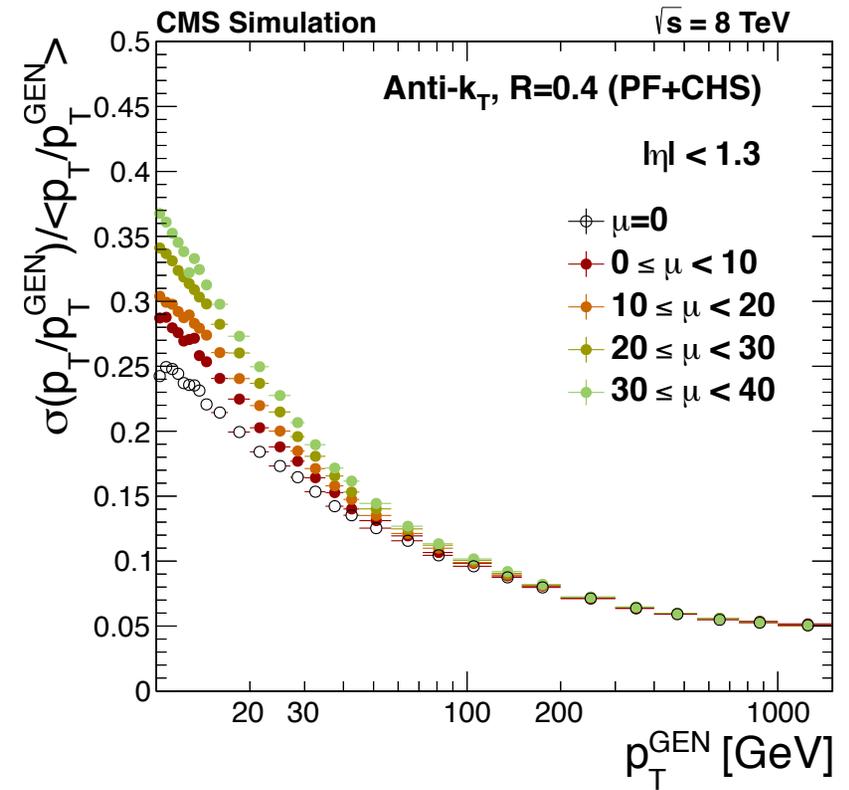
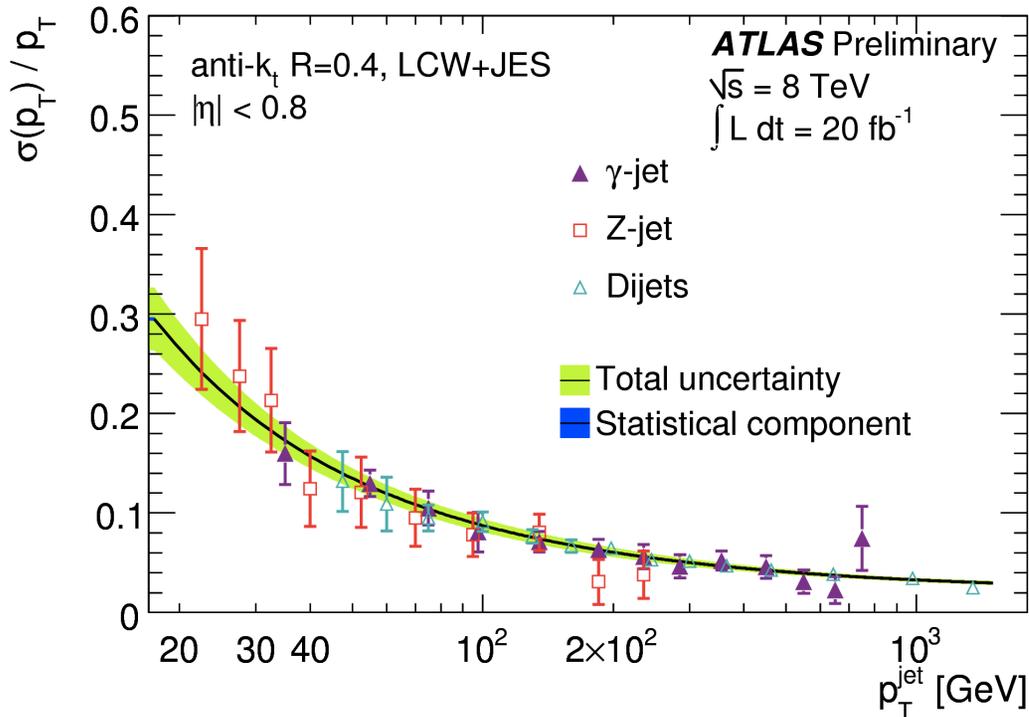
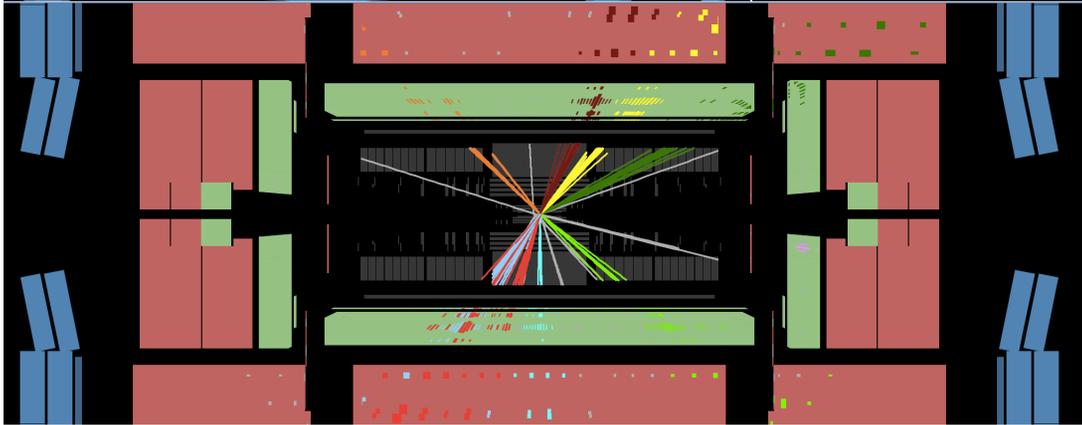
Dedicated reconstruction: clean signatures

# photons



	CMS	ATLAS
inner detector material	up to $2X_0$	up to $2.5 X_0$
energy resolution	1.5-3% (unconverted)	$10\%/\sqrt{E}$ (+) 1%
energy scale	0.1-0.3%	0.2-0.5%

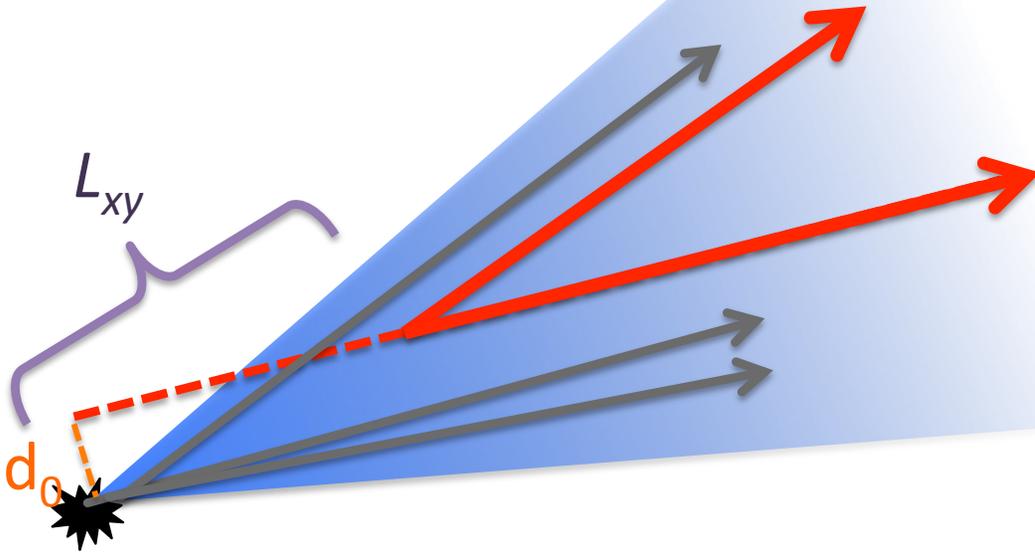
# jets



better than 10% resolution  
above 0.1 TeV

# b-jets

+6%



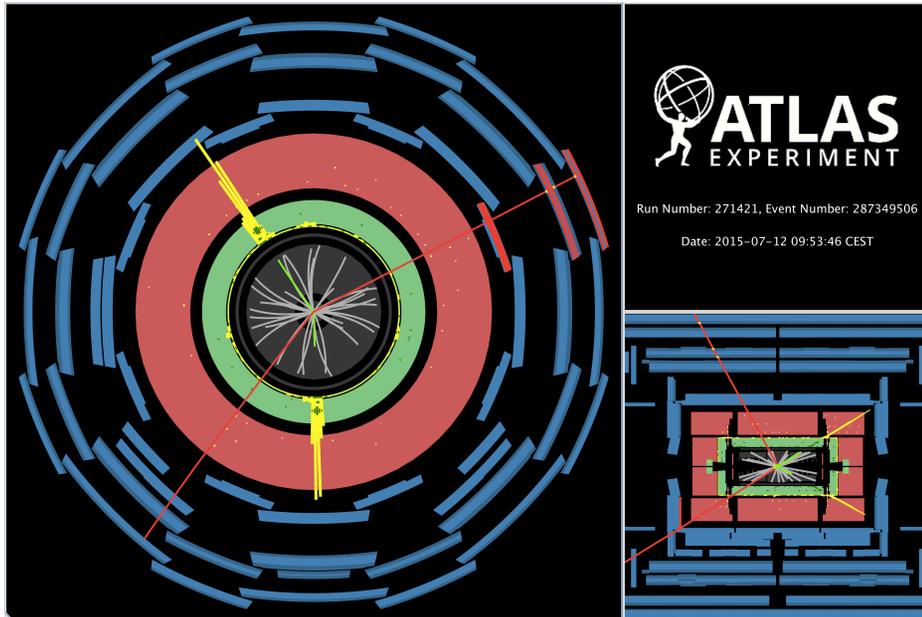
combine discriminating variables:

- ▶  $N_{\text{tracks}}, m_{\text{vertex}}$
- ▶ vertex  $L_{xy}$  significance
- ▶ track impact parameter  $d_0$
- ▶ vertex  $p_T$  ratio

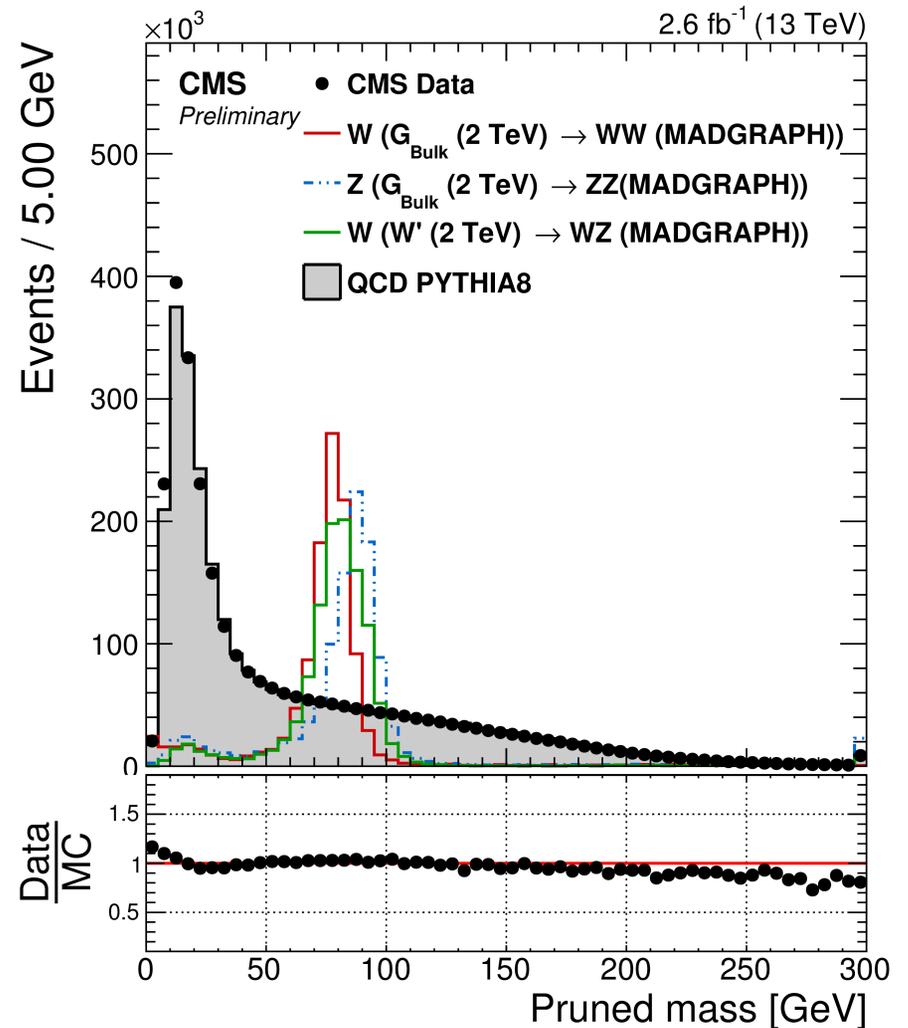
ATLAS tracker upgrade  
~doubles rejection power  
at 60% efficiency

- b-jets identified by tracker properties: useful independence from calorimeter
  - muons, neutrinos in b-jets degrade jet energy response and resolution

# W/Z bosons



Efficient: pairs of **quarks**



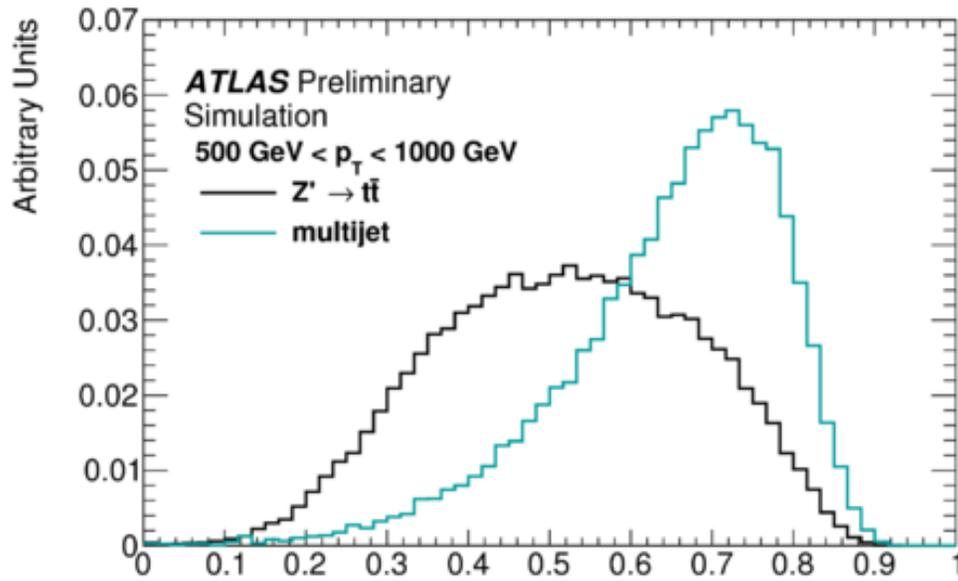
Pure: isolated **electrons**  
and **muons** and/or  
missing transverse  
energy

# t/W/Z jets

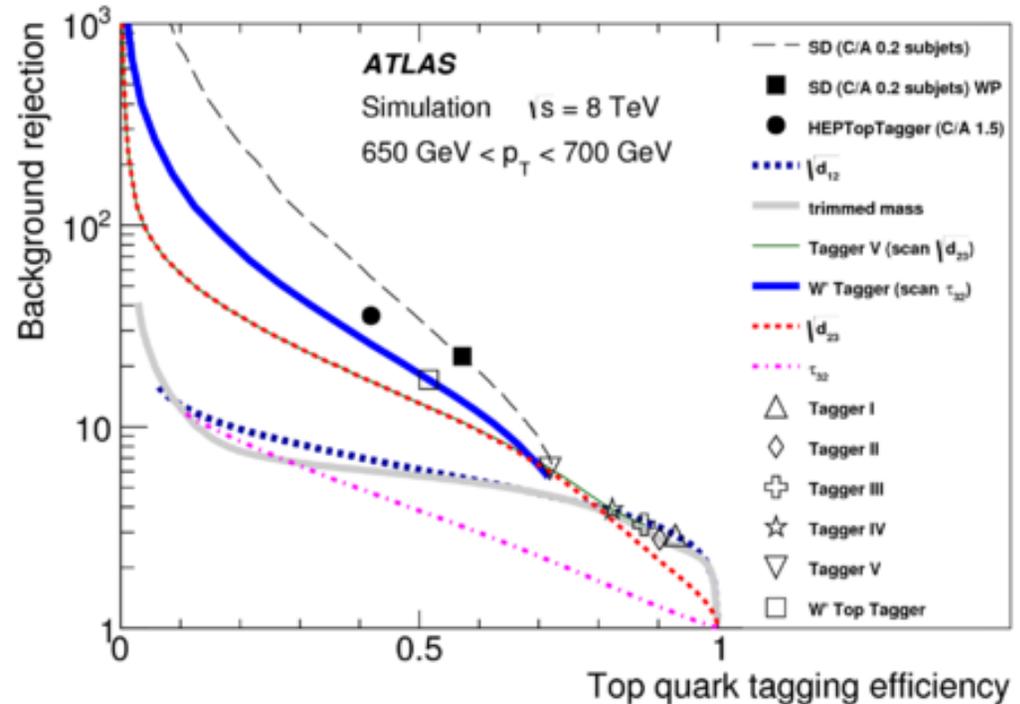
## ATLAS & CMS: groomed mass + substructure tags

- typical top tag: 50% efficiency, light jet rejection factor  $\sim 10$
- typical boson tag: 50% efficiency, rejection factor of 30-40

$Z \rightarrow$	$q\bar{q}$ (70%)	$\nu\nu$ (20%)	$ll$ (10%)
$W \rightarrow l\nu$ (33%)	23%	7%	3%
$W \rightarrow q\bar{q}$ (67%)	47%	13%	7%



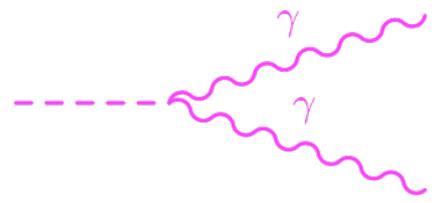
$$\tau_N = \frac{\sum_i p_{T_i} \min(\Delta R_{(1,i)}, \dots, \Delta R_{(N,i)})}{R_{\text{jet}} \sum_i p_{T_i}}$$



# higgs bosons

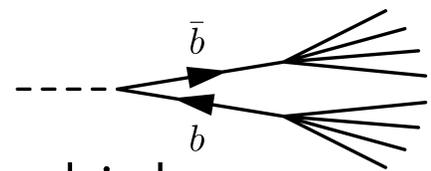
look in  $\gamma, \tau, W, b$  pairs

pure

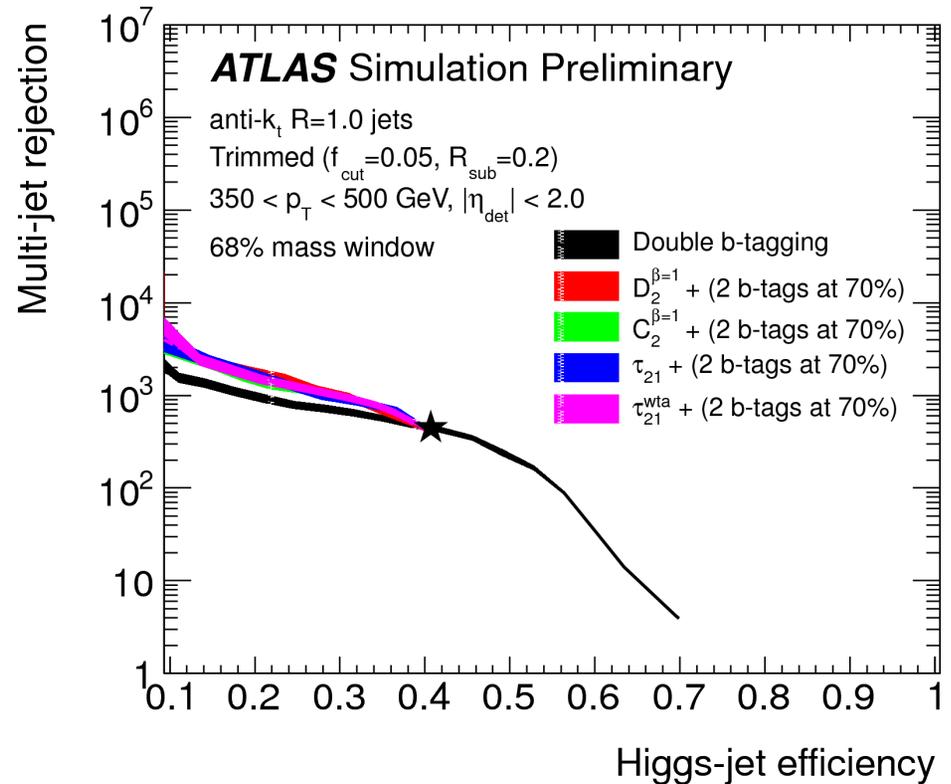


- optimal for low- $p_T$  BSM Higgs production

efficient



- better for higher  $p_T$  or second tag
  - $b$  decays degrade mass resolution



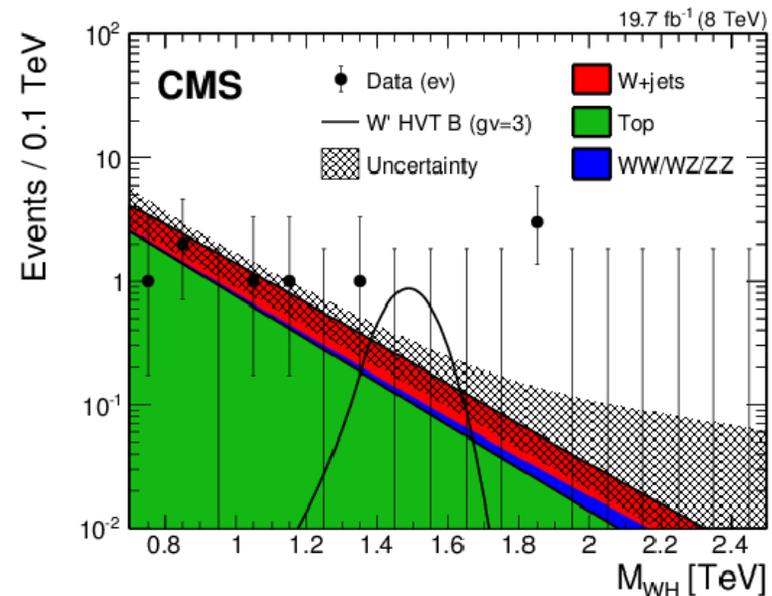
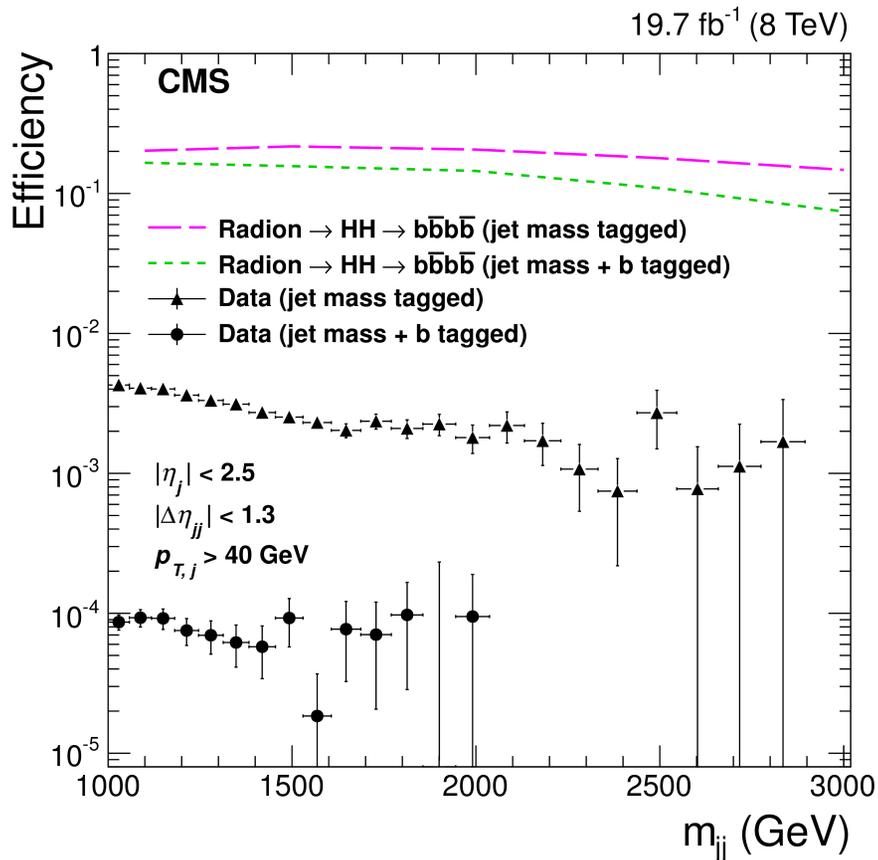
# Impact of LS1 activities

8 TeV $\rightarrow$ 13 TeV	Excited quarks? TeV gravity?
new pixel layers (ATLAS)	natural explanations for EWSB?
new displaced vertex reconstruction (CMS)	
optimized boosted hadronic decay tagging	compositeness/warped ED signatures
improved muon reconstruction (CMS)	BSM higgs decays
new beam structure/ detector hardware	larger systematic uncertainties (for now)

# SEARCHES

# Resonance searches with Higgs

- Strategy: exploit efficiency
  - b-tags are powerful (but efficiency falls off at high  $m_X$  due to b-tag merging)
  - top backgrounds can remain



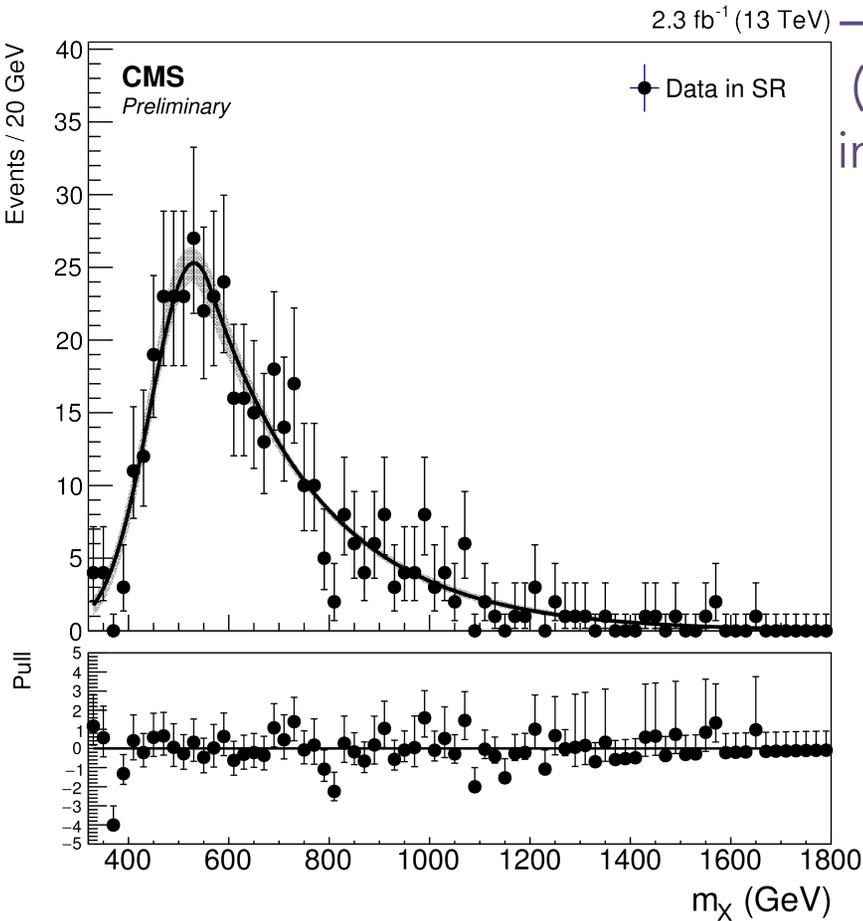
# Resonance searches in $X \rightarrow HH$

CMS fully-hadronic search for 13 TeV

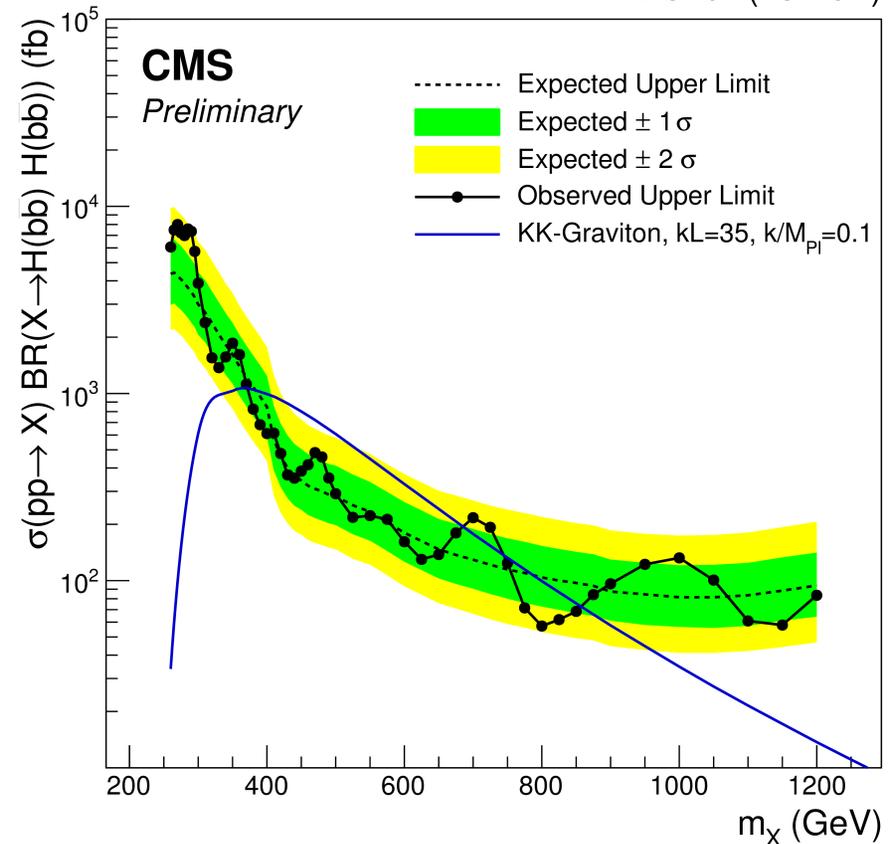
→ improved Run 2 b-tagging  
(72% efficient, rejection  $\sim 100$ )

interpreted as  $G^*$  and scalar search

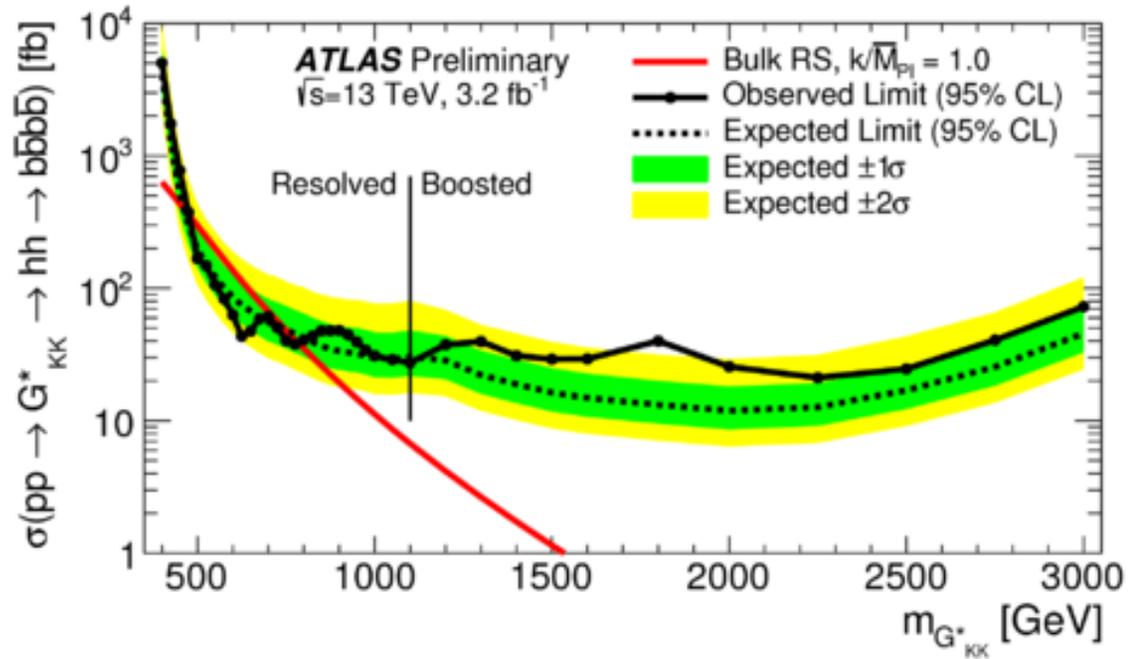
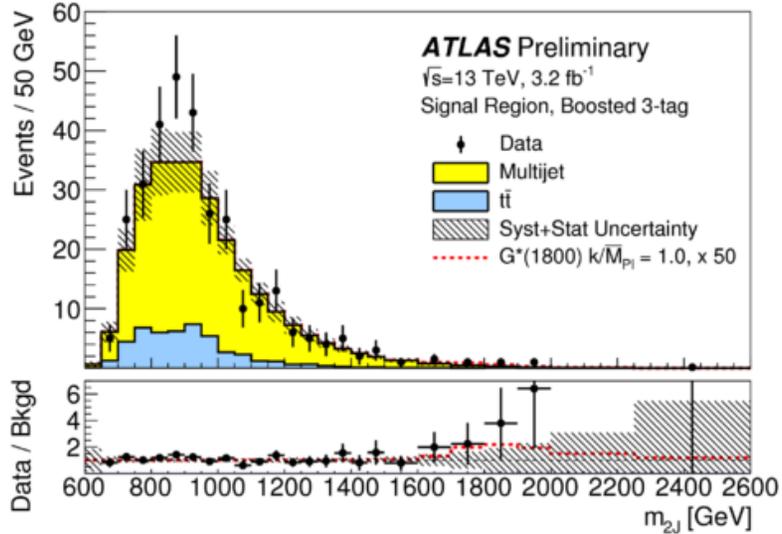
2.3 fb<sup>-1</sup> (13 TeV)



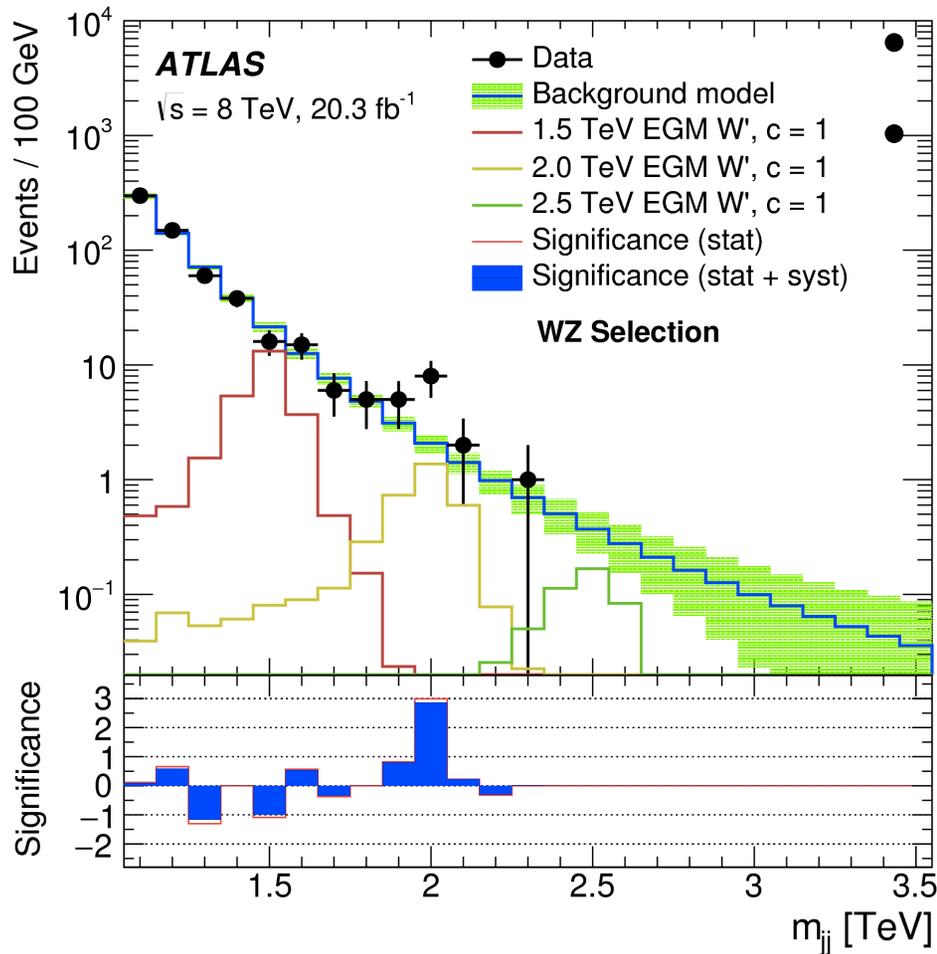
limit extended to 850 GeV



# Resonance searches in $X \rightarrow HH$



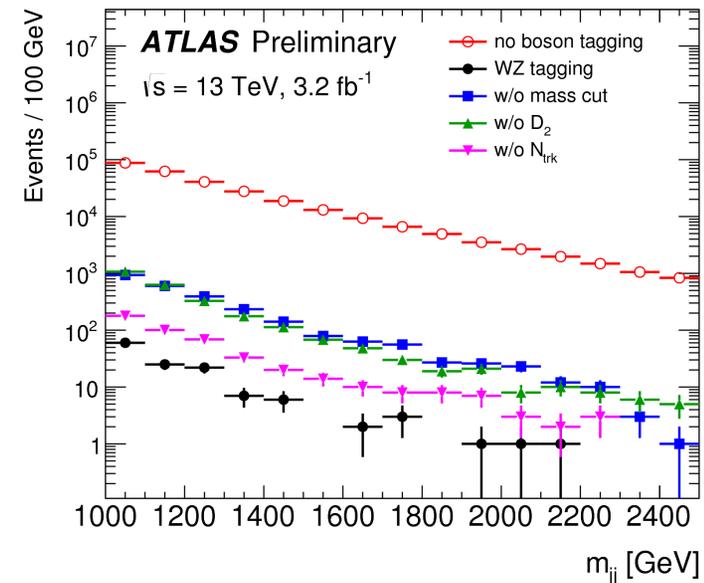
# Resonance searches with W/Z



Look out for 2 TeV...

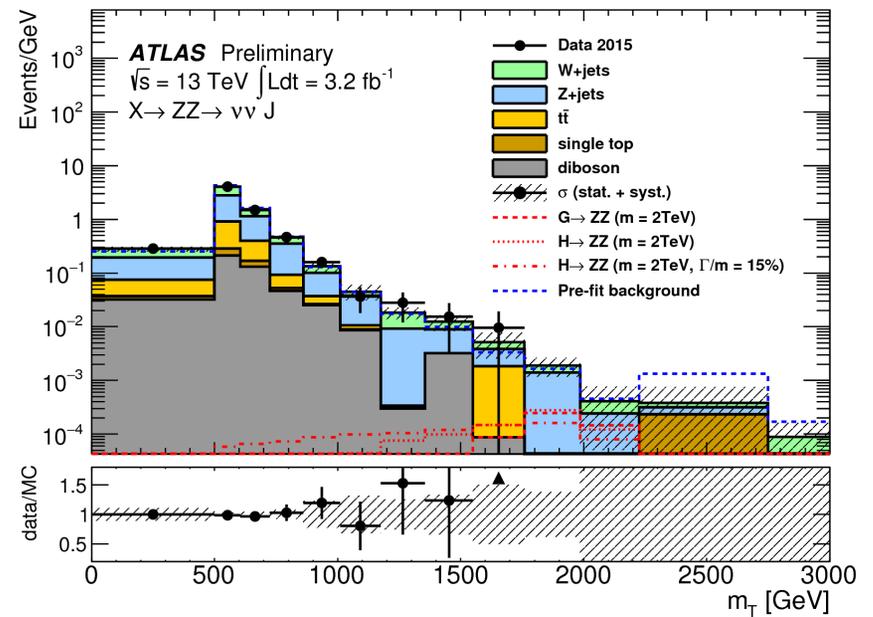
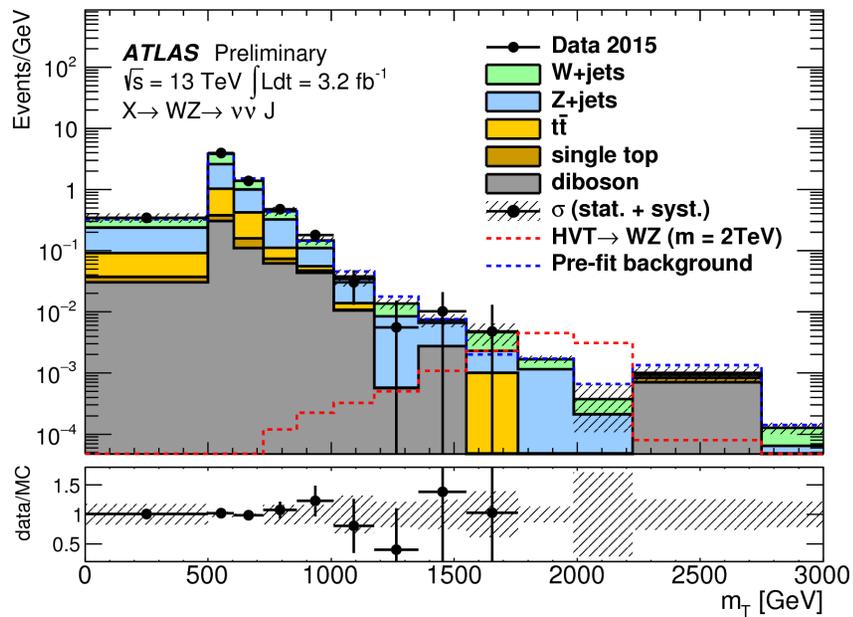
Strategy:

- constrain BG to data
- maintain/improve performance
- increase overall acceptance



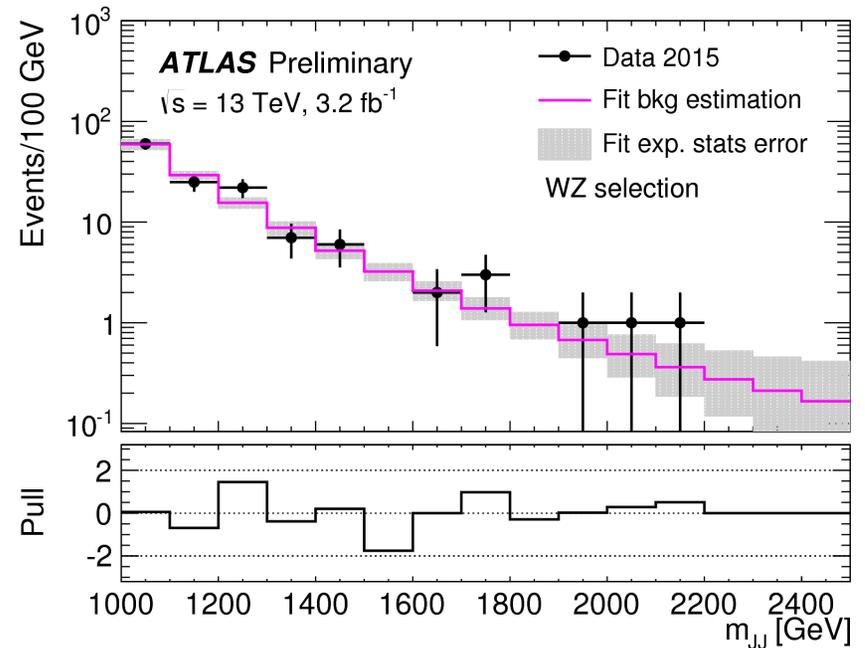
# Increasing acceptance: $Z \rightarrow \nu\nu$

fit Z+jet, W+jet, top backgrounds in enriched sidebands  
 \* one or two leptons; b-tag



# All-hadronic (ATLAS)

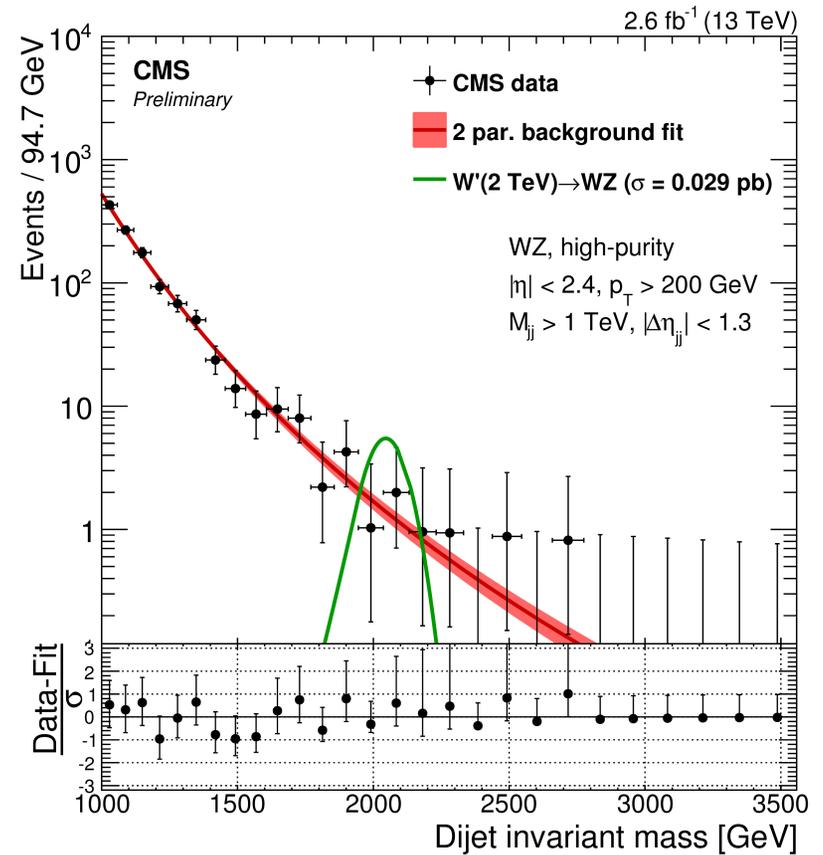
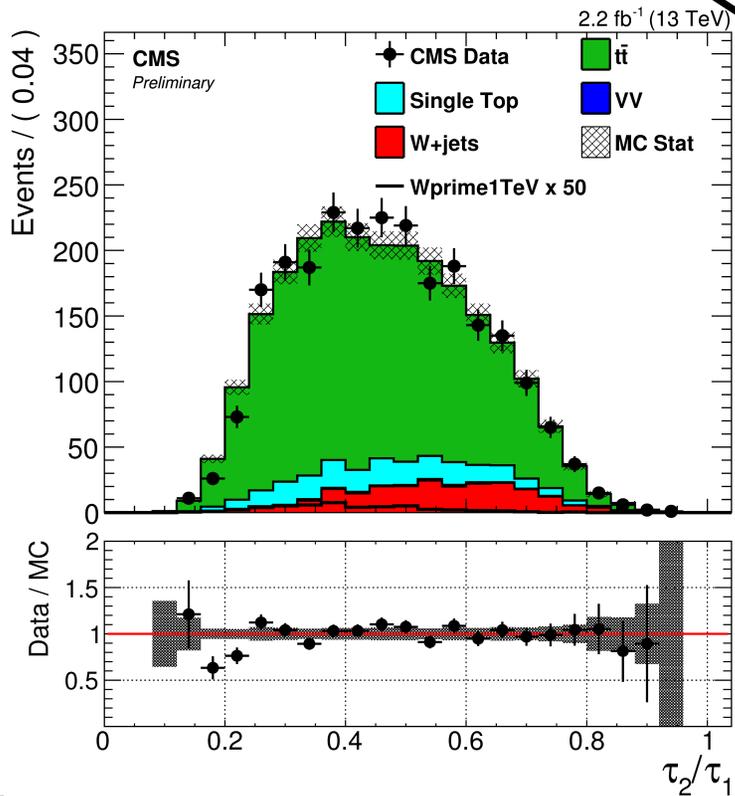
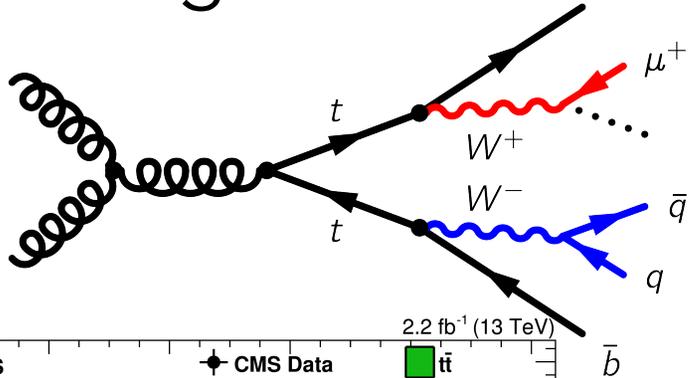
- Same kinematic cuts as Run 1
- different boson tagging
  - ATLAS maintains cut on  $n(\text{trk})$  to improve sensitivity



Selection	Data	HVT $W'$ simulation
$m_{JJ} > 1000 \text{ GeV}$	972069	$21.5 \pm 0.1$
Topological selections	285474	$15.4 \pm 0.1$
Boson tagging	128	$3.09 \pm 0.05$

# All-hadronic (CMS)

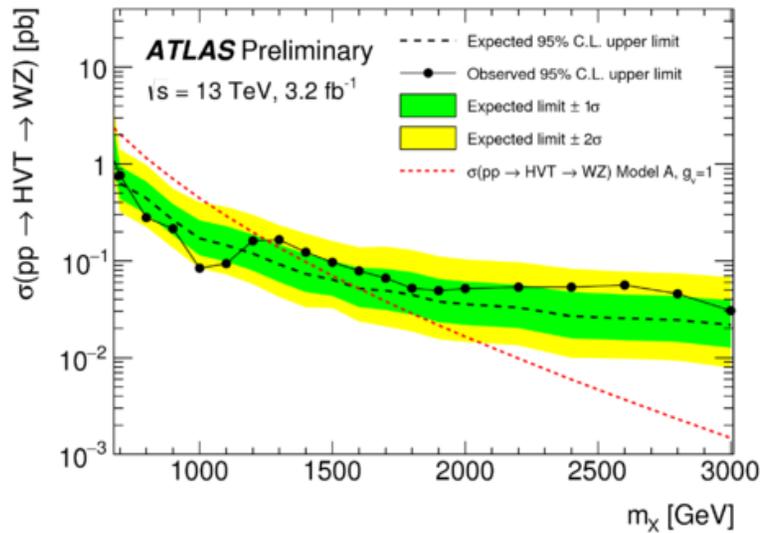
check signal efficiencies



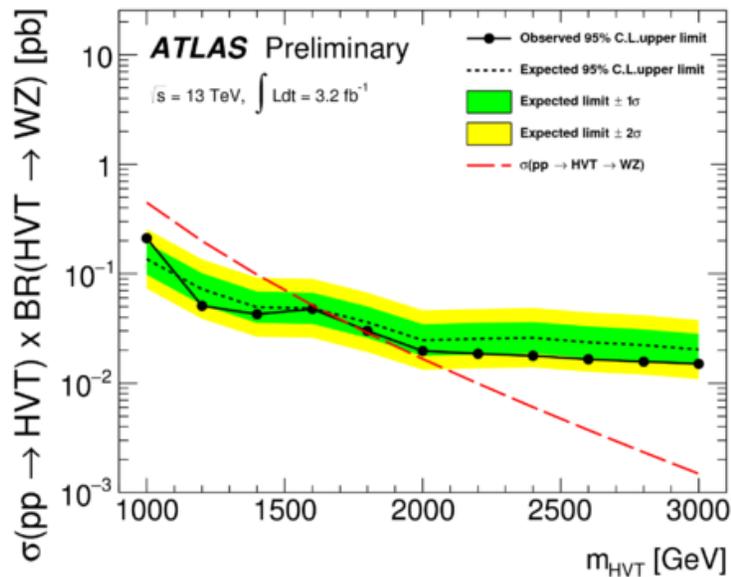
tight selection

# WZ summary (ATLAS)

one lepton

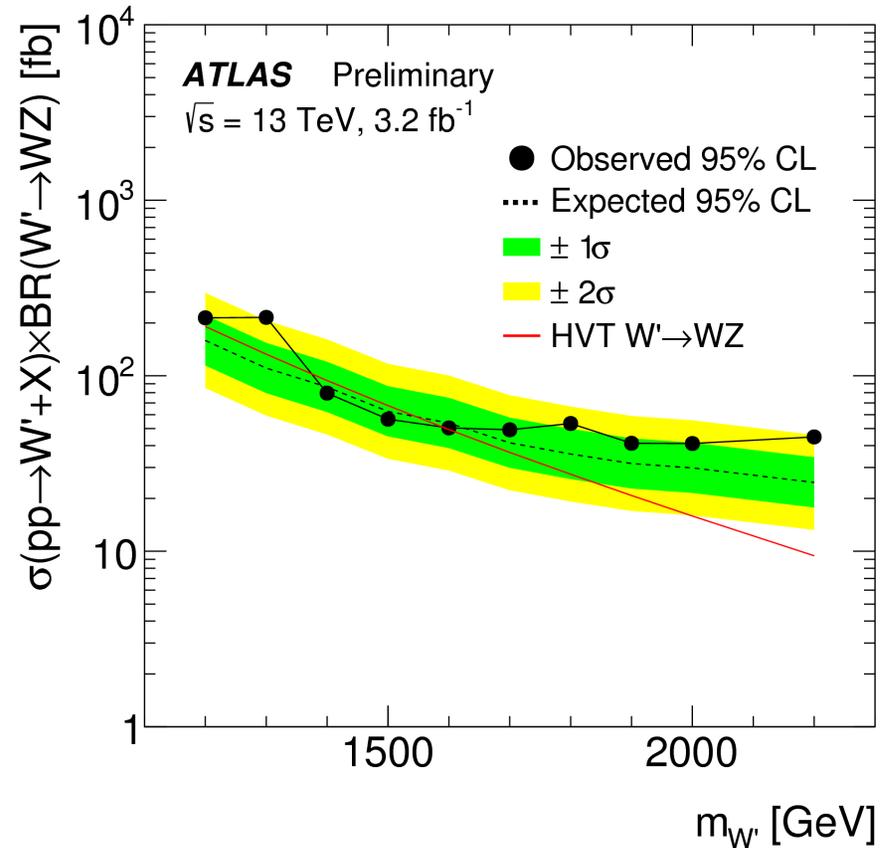


monojet

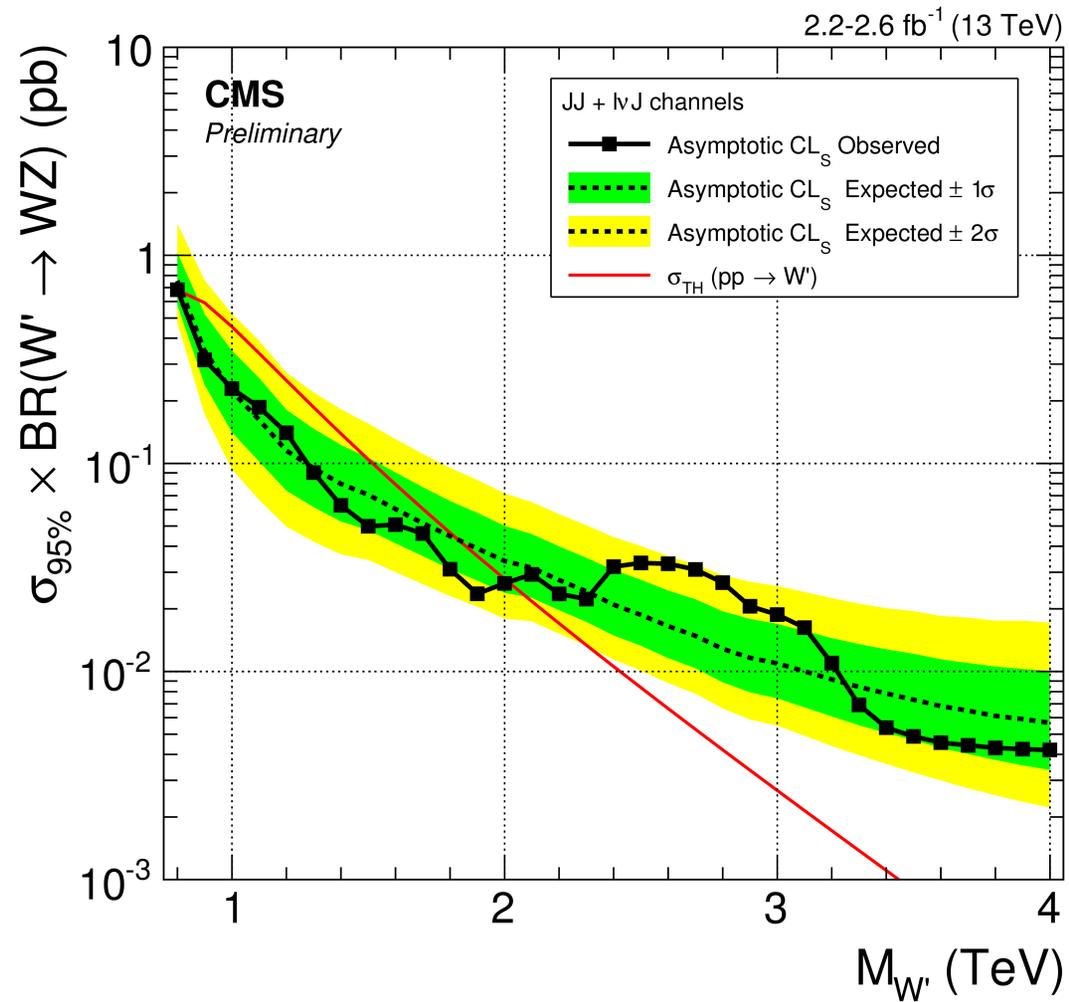


monojet channel adds a strong constraint  
 no unusual features

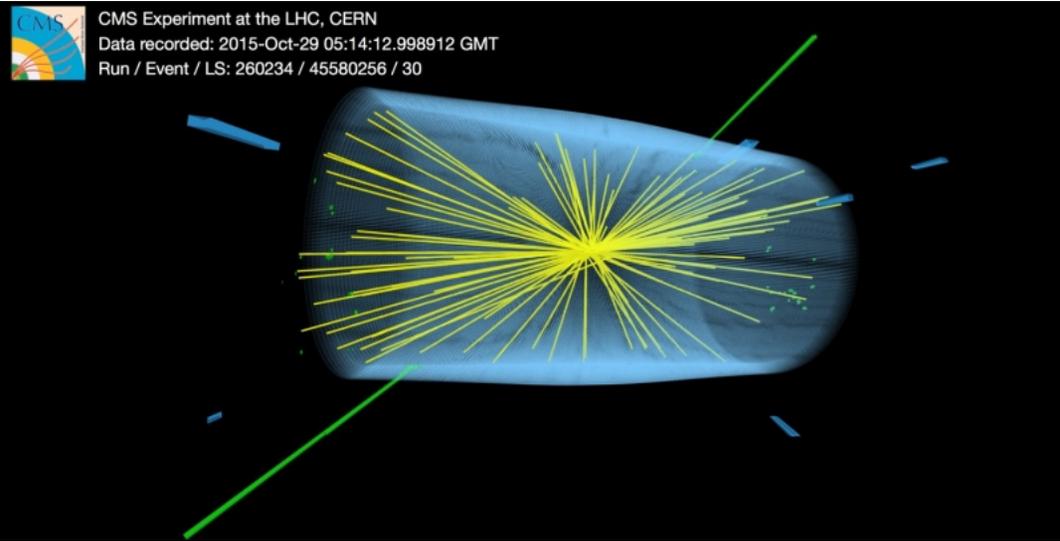
all-hadronic



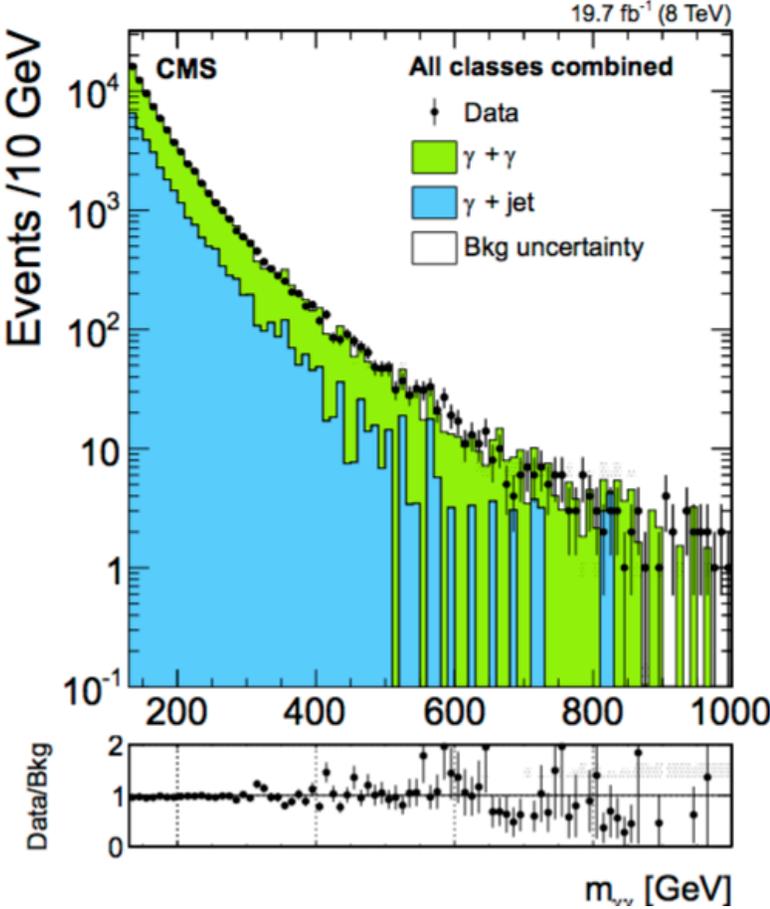
# WZ combination (CMS)



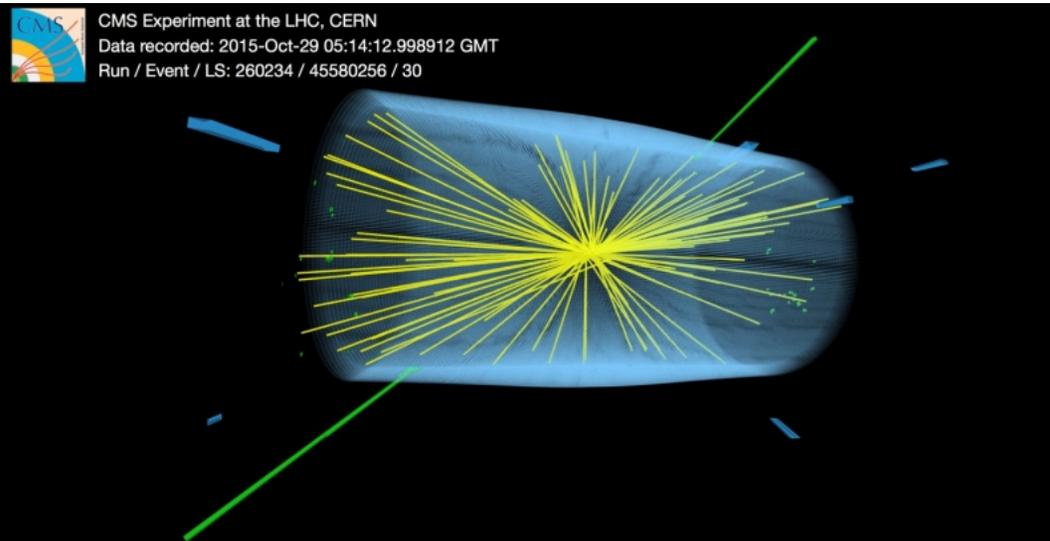
# diphoton resonance search



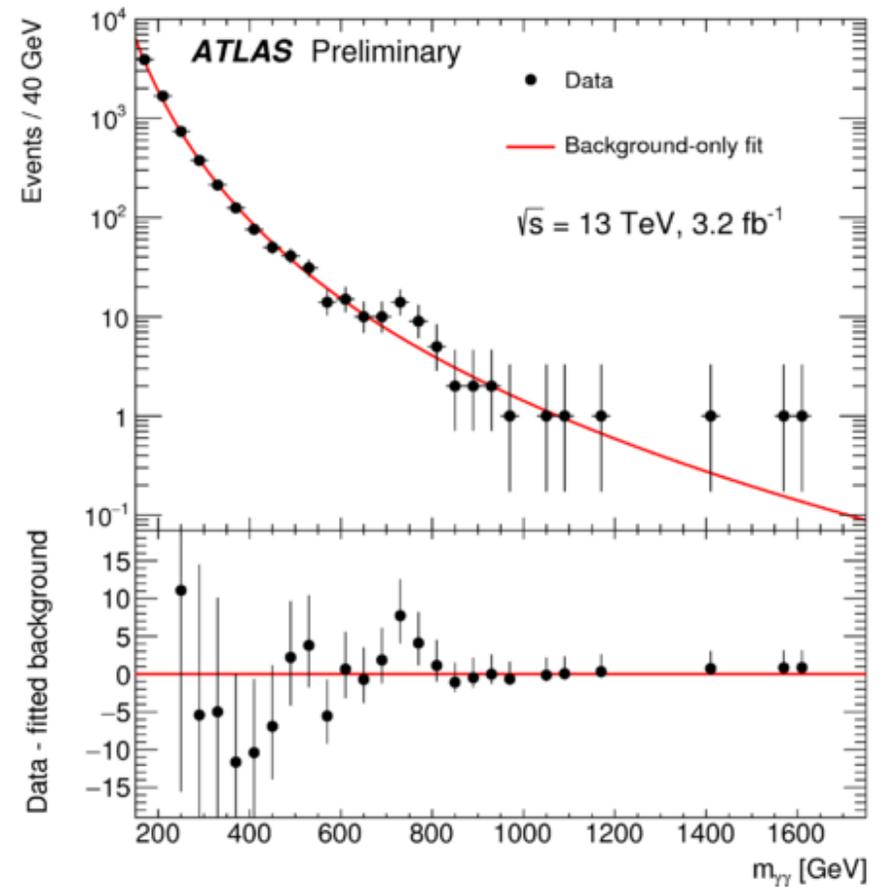
irreducible, smooth background



# diphoton resonance search



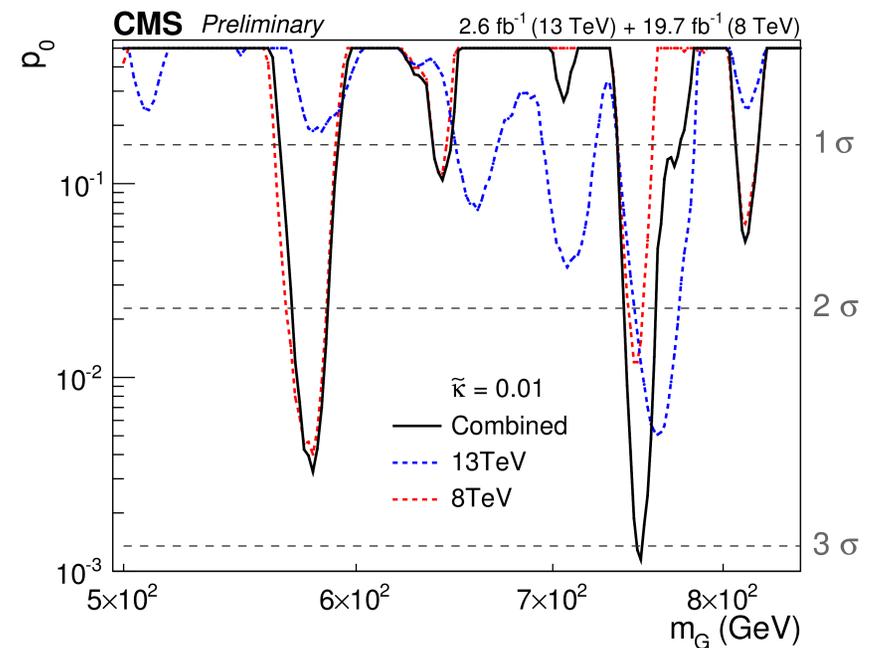
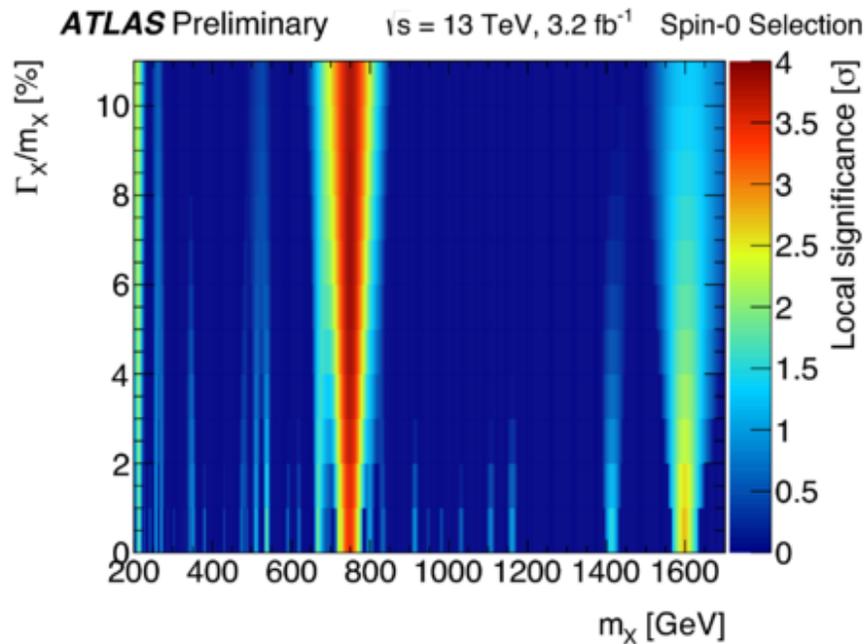
irreducible, smooth background?



# local significance @ 750 GeV

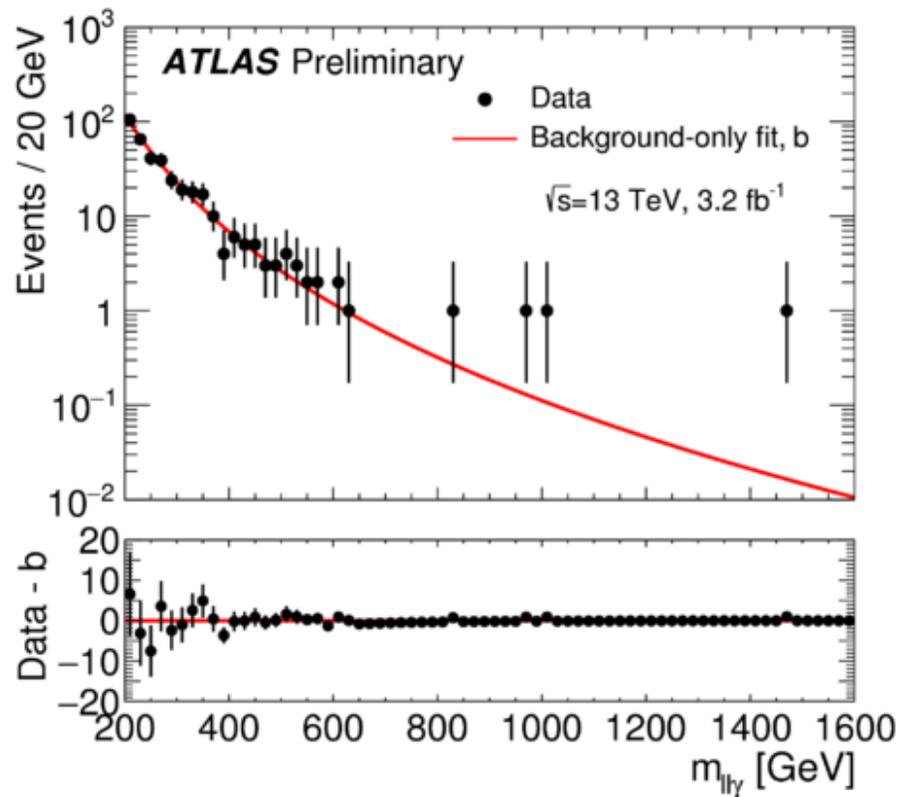
ATLAS

CMS

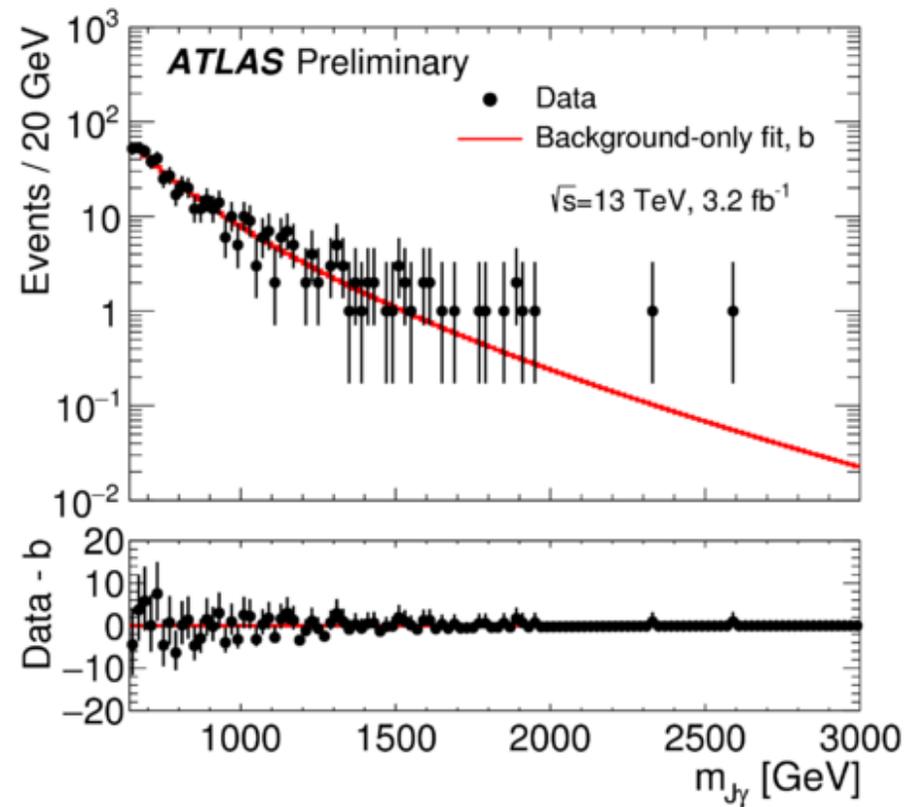


# Testing the $\gamma\gamma$ excess

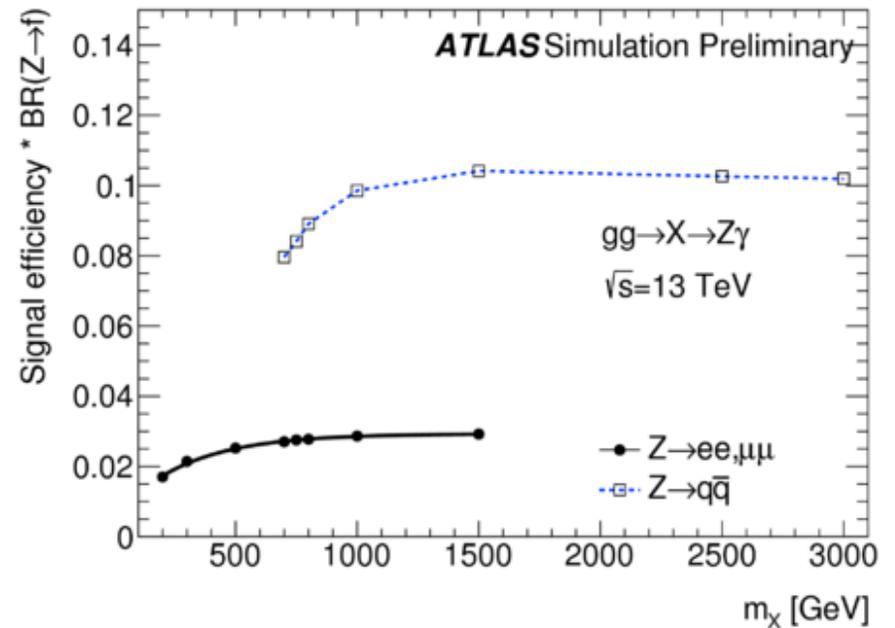
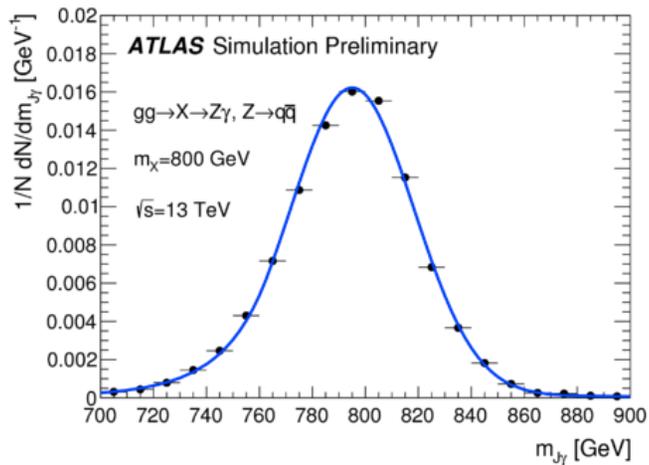
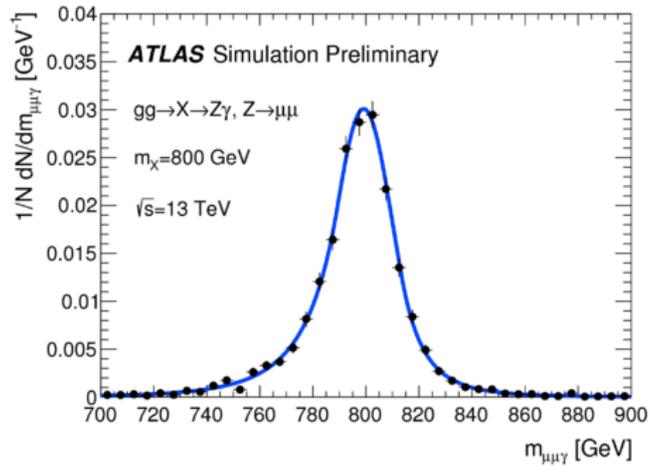
$Z\gamma$  with leptons



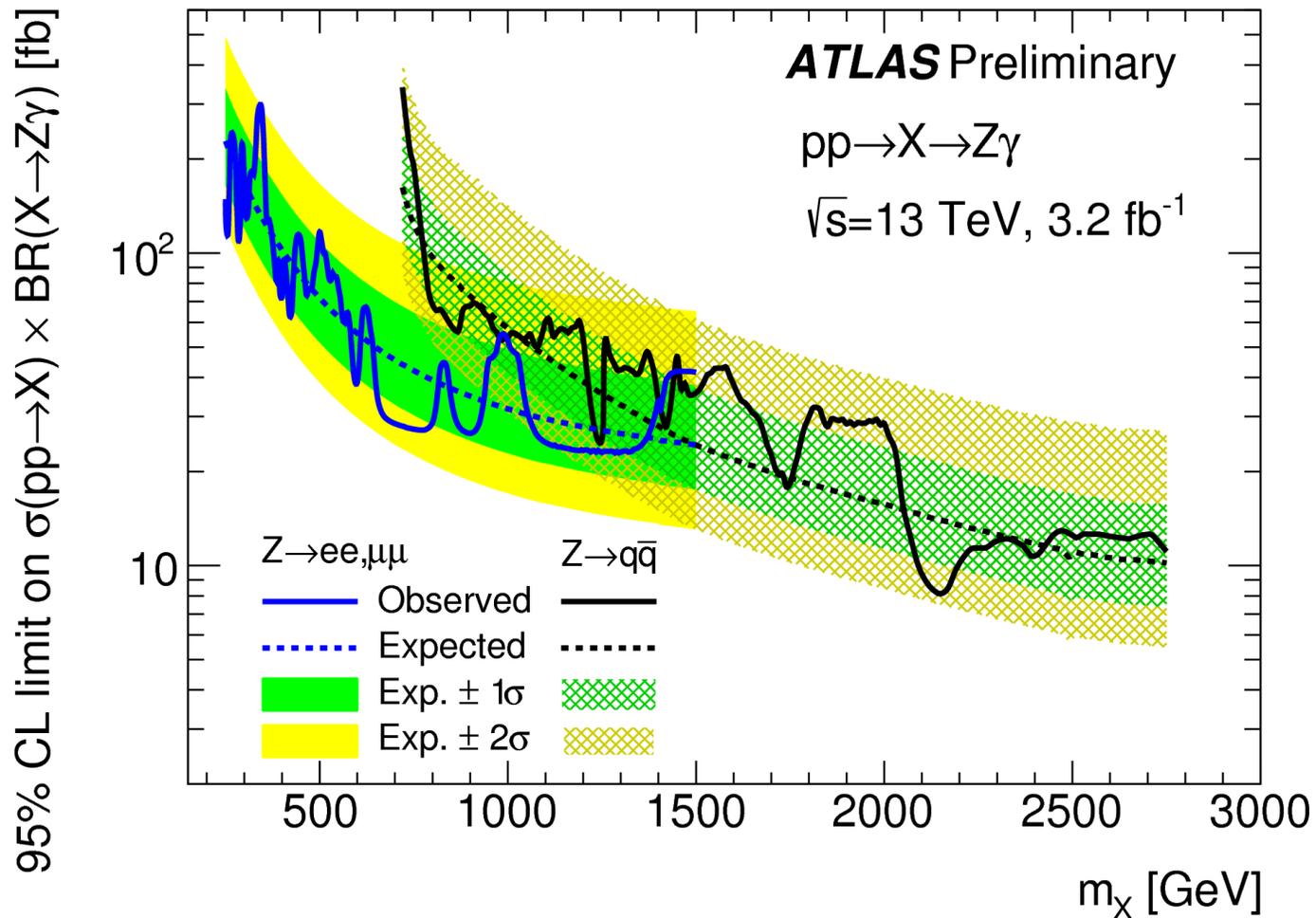
$Z\gamma$  with jets



# Testing the $\gamma\gamma$ excess

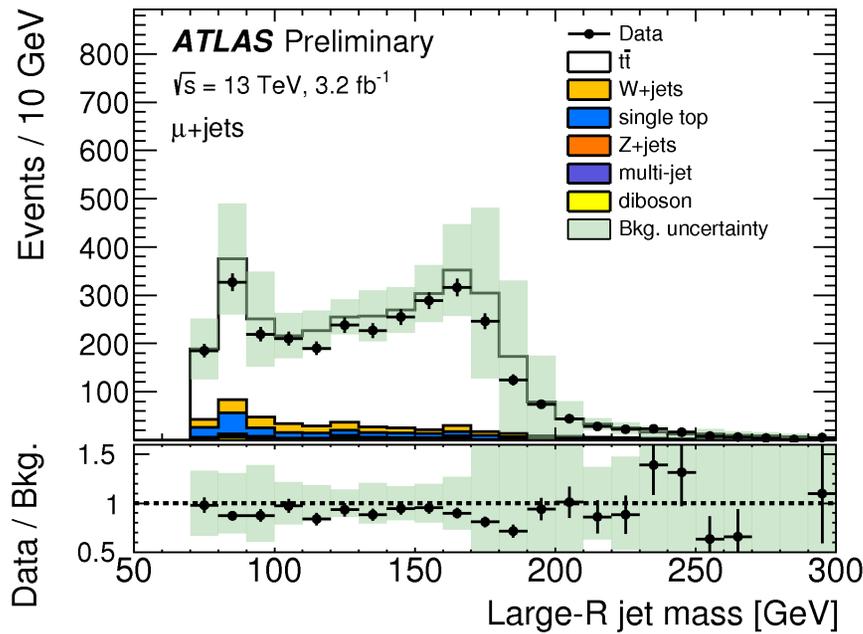


# Testing the $\gamma\gamma$ excess

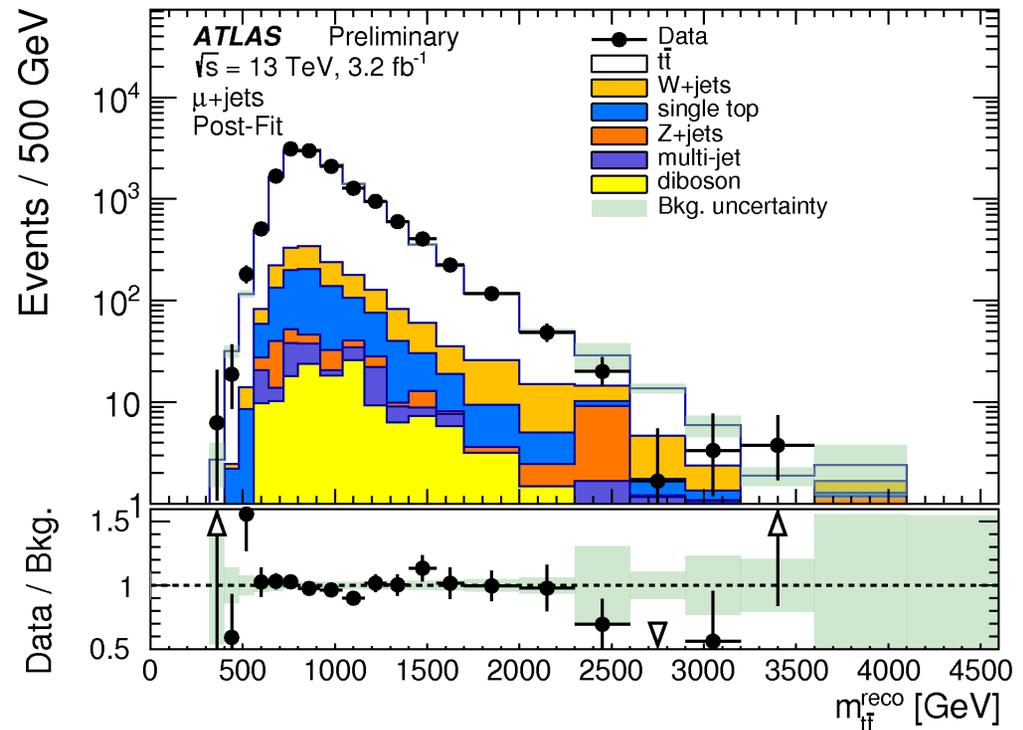
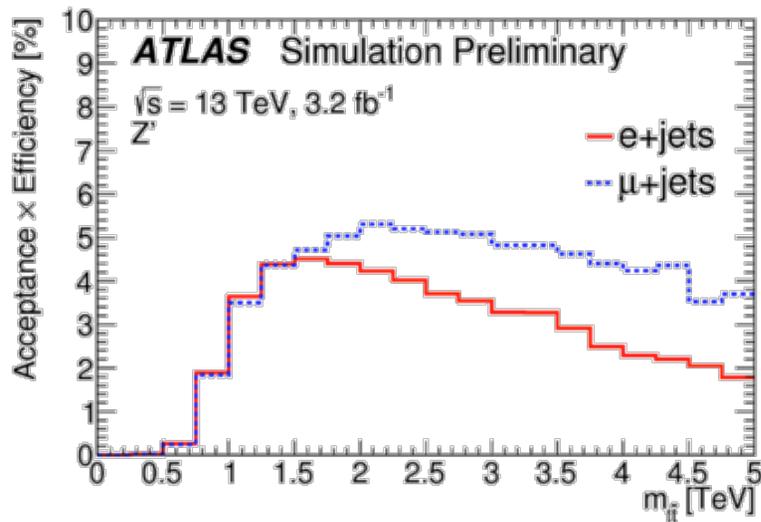


CMS: similar sensitivity at 750 GeV (leptons only)

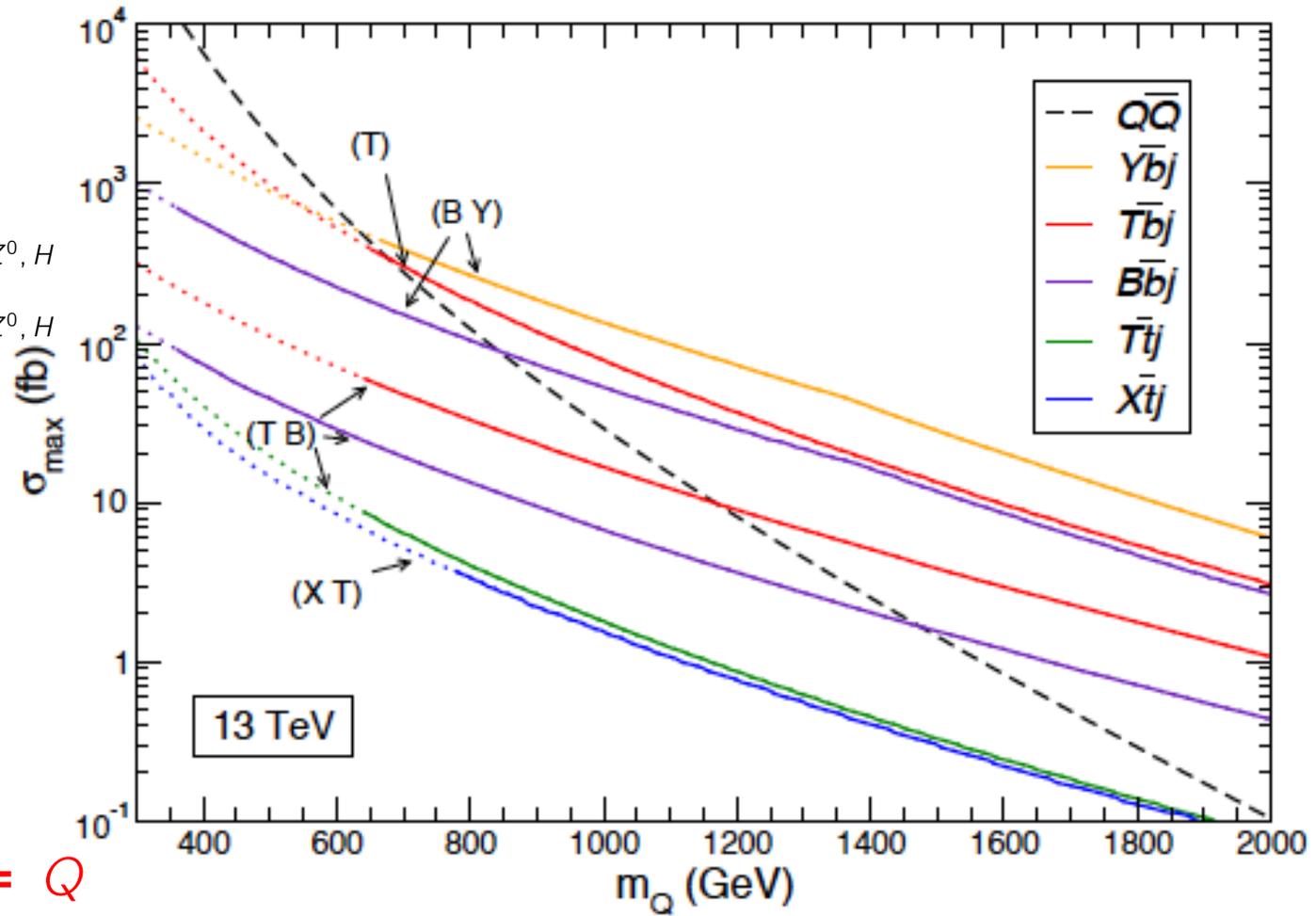
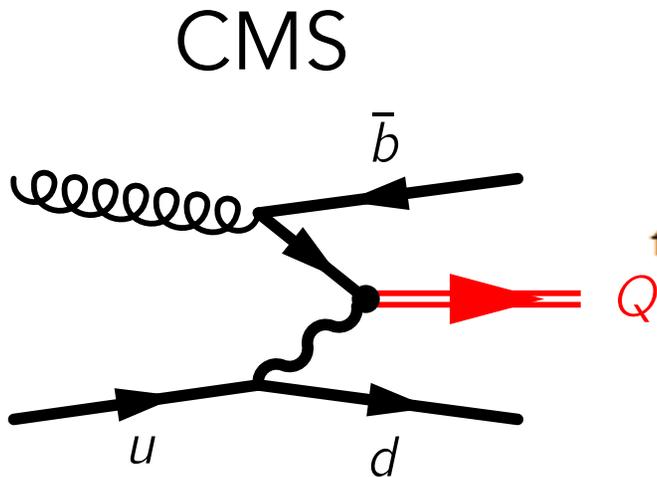
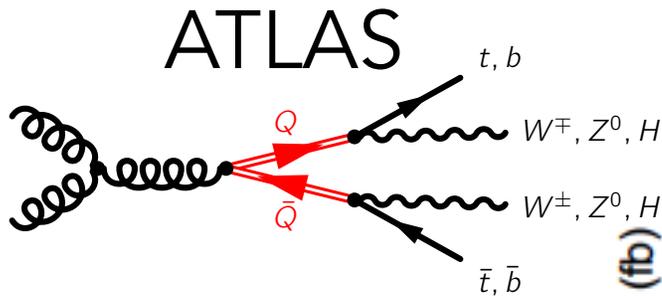
# di-top



- ATLAS search in clean semileptonic channel
- top tag efficiency and rejection  
 $\sim$  flat with  $p_T$



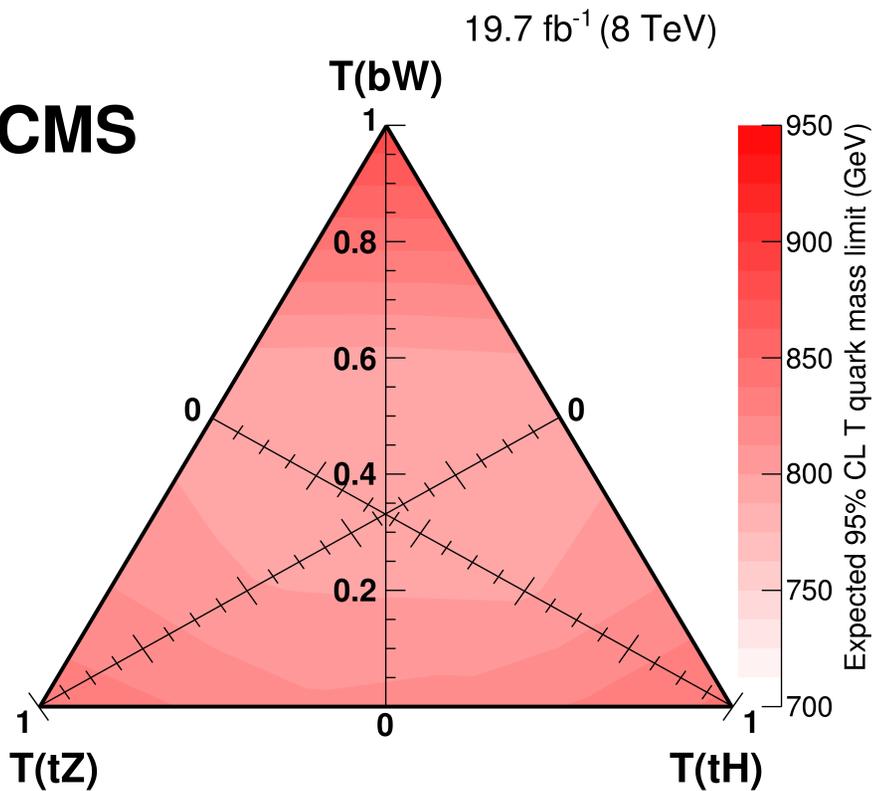
# searches for vector-like quarks



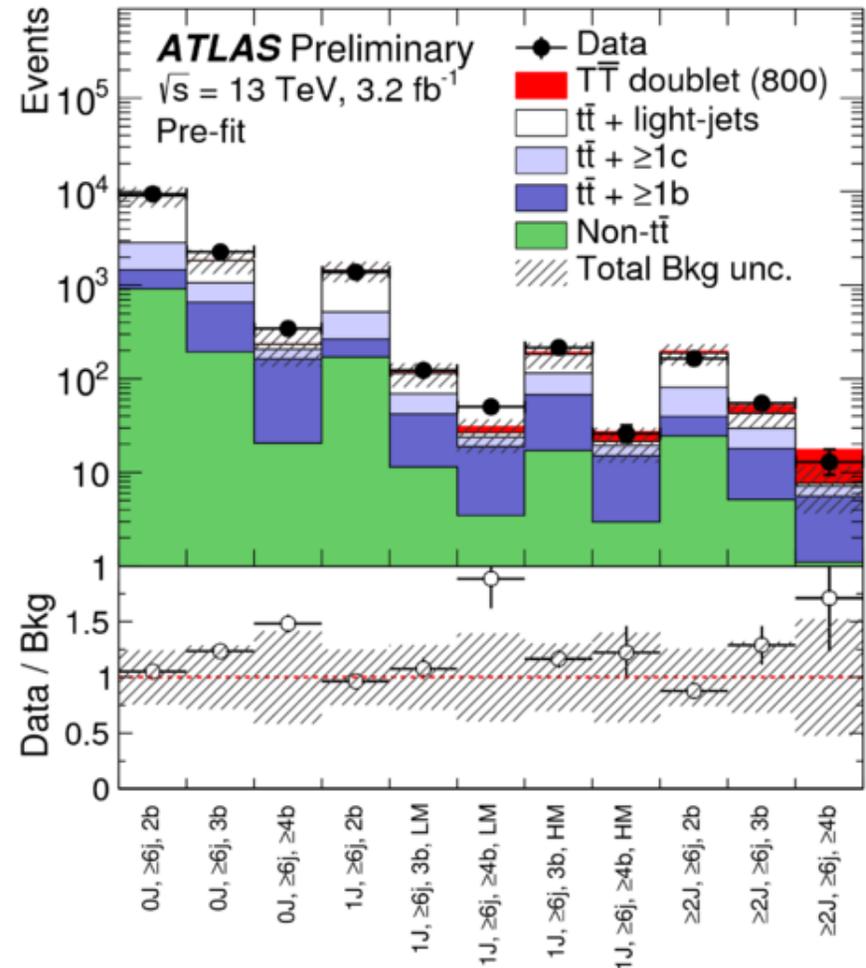
# VLQ search overview

complex: final states

CMS



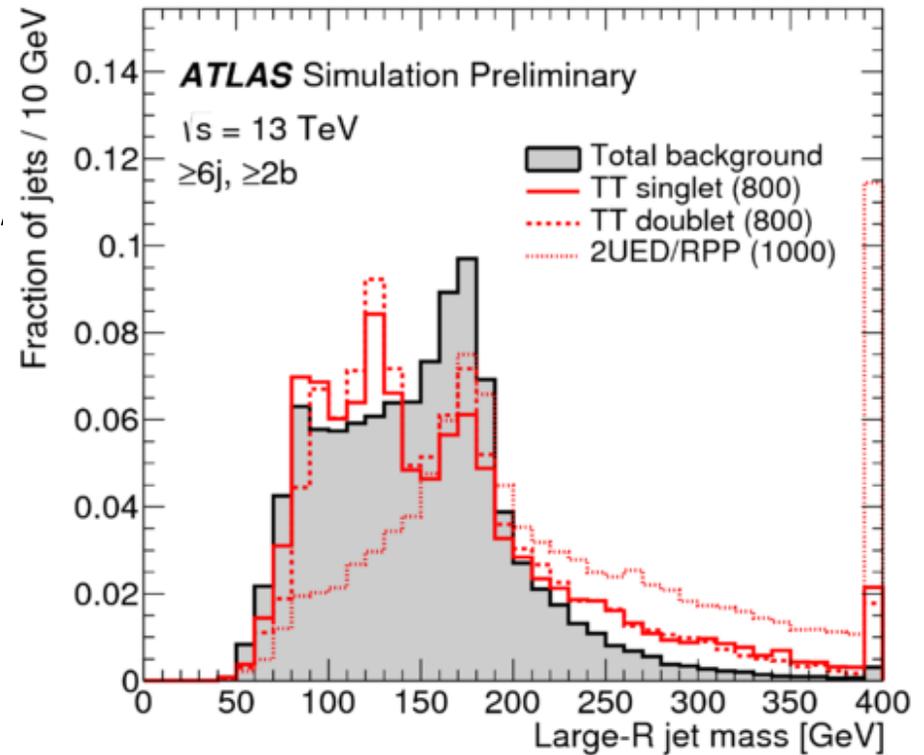
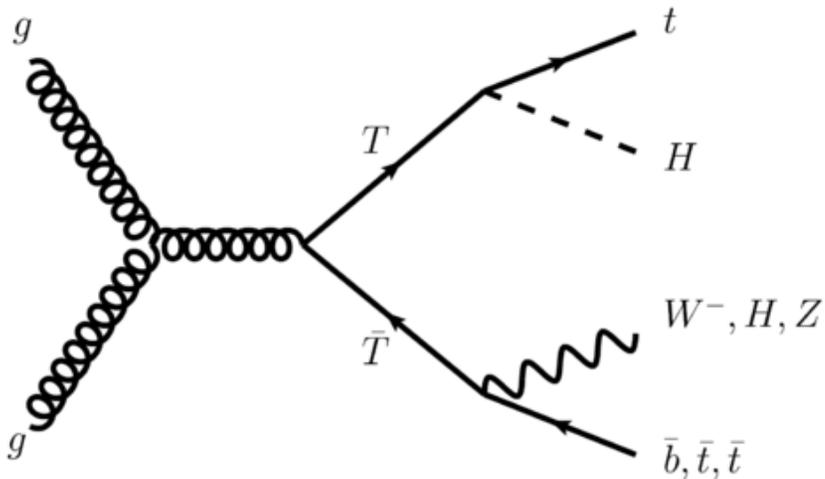
simple: VLQ decay



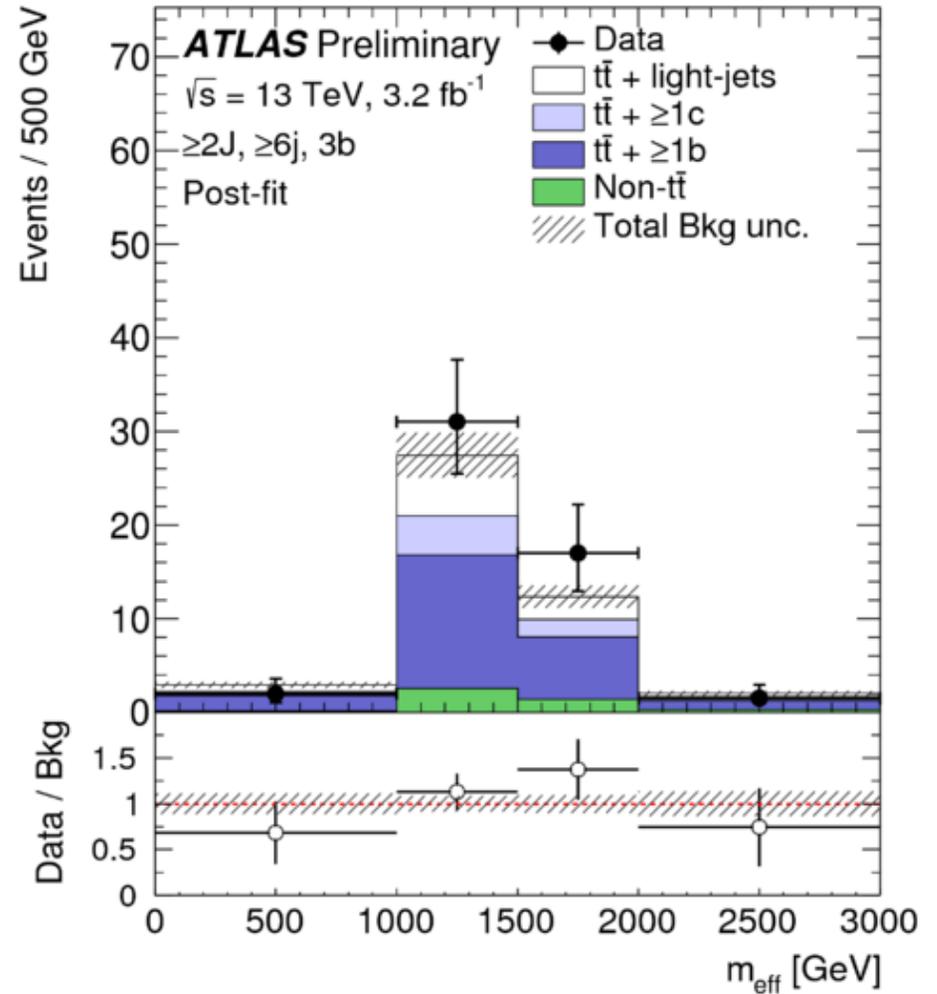
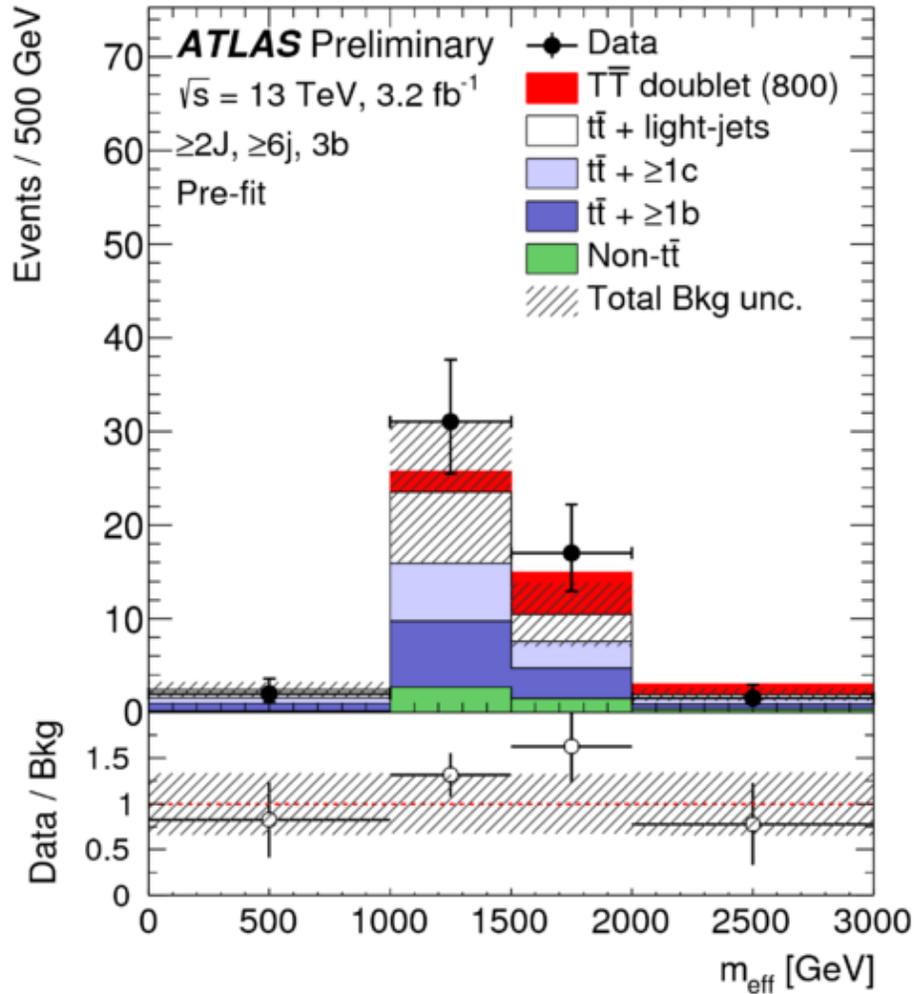
# search for heavy $T\bar{T}$ production

ATLAS: single-lepton channel

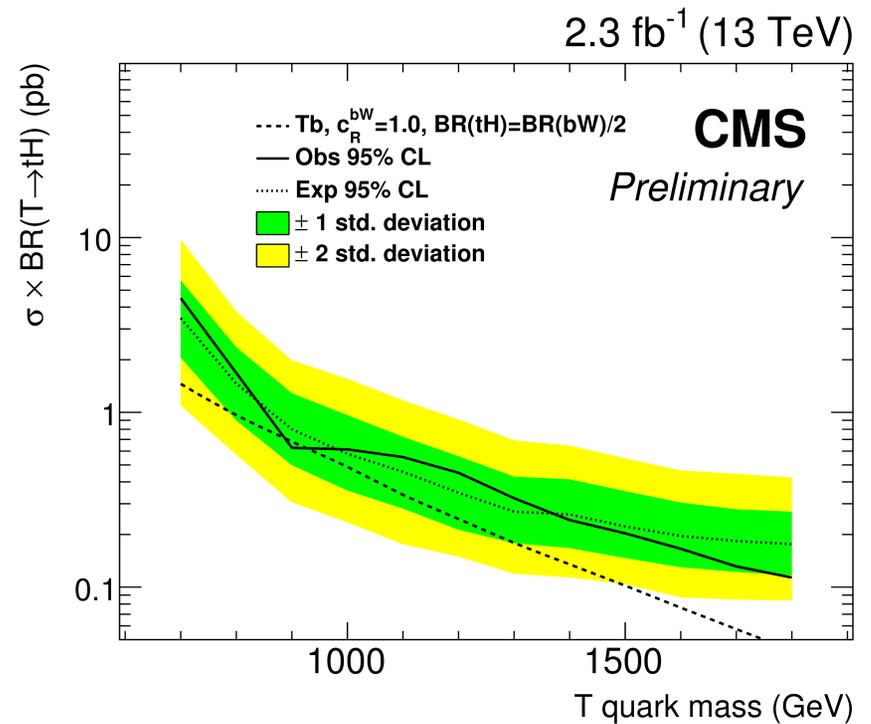
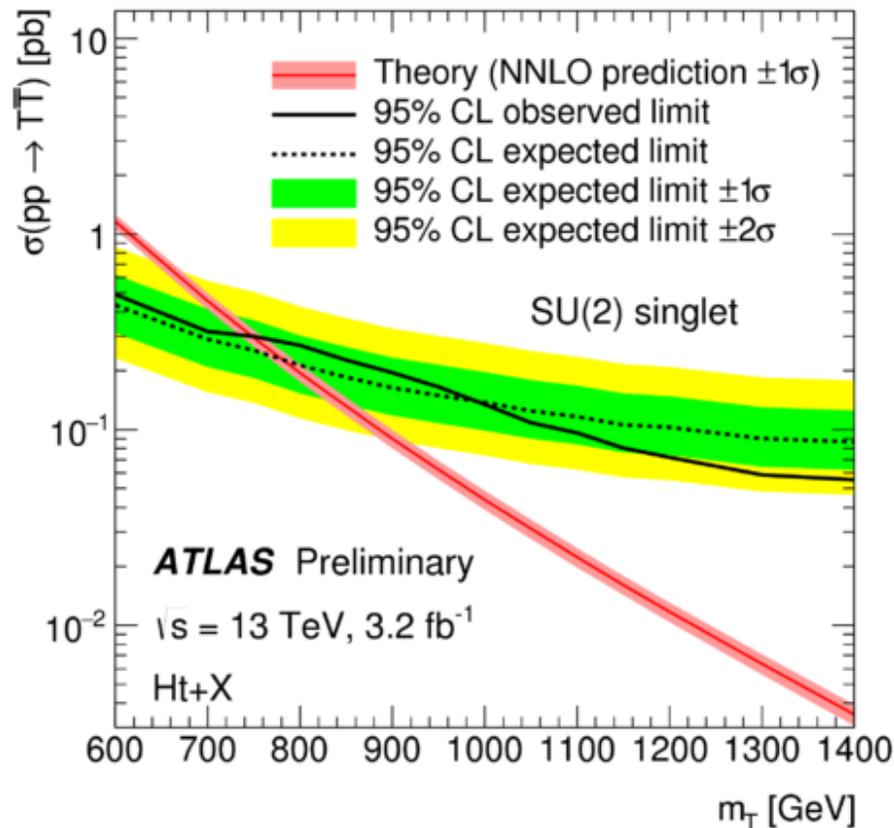
busy final state: use small radius jets and "reclustered" boson/top jets



# search for heavy $T\bar{T}$ production



# TT and single-T limits



# Outlook

- Collisions (now-2018)!
  - intensity ramp through spring
  - July:  $\sim 6 \text{ fb}^{-1}$
- pileup increases:
  - modest in 2017, but tremendous for high-luminosity upgrade
- boost increases:
  - b-tagging? Higgs and boson tagging?

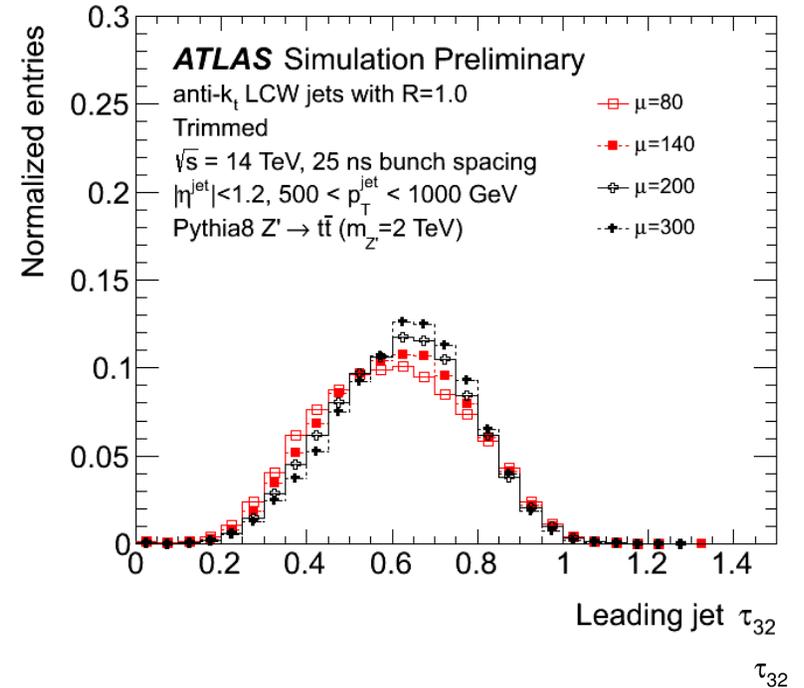
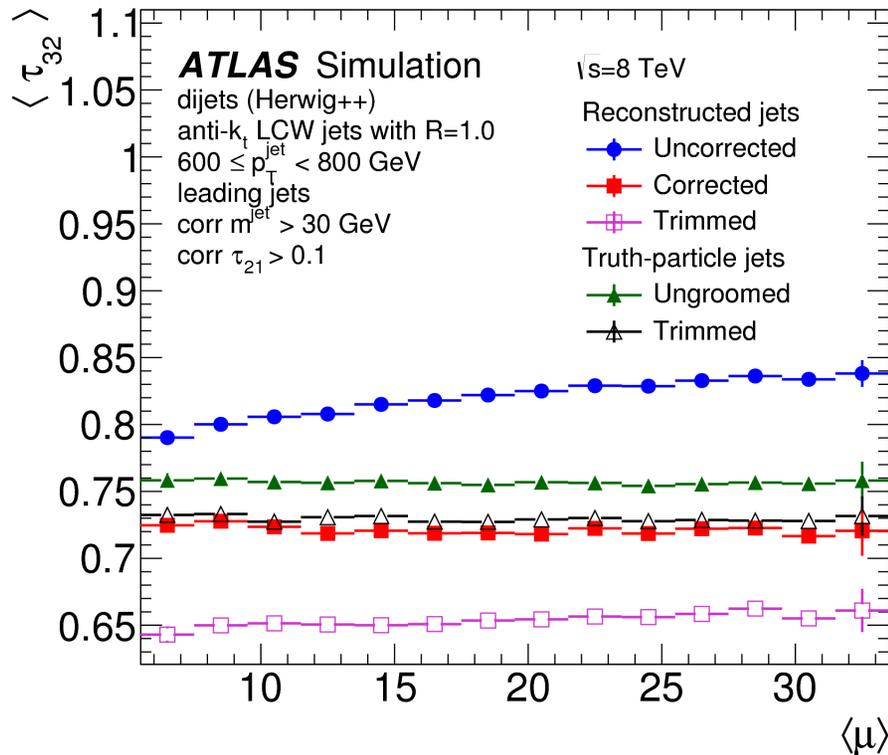
# Conclusions

- New search results poured in from early Run 2 dataset...
  - new physics explanations for ATLAS  $WW$  excess are disfavored
  - a new diboson excess to make bets on for summer
- A sure bet: LHC/detector improvements and new analysis tools play a starring role

# handling high pileup

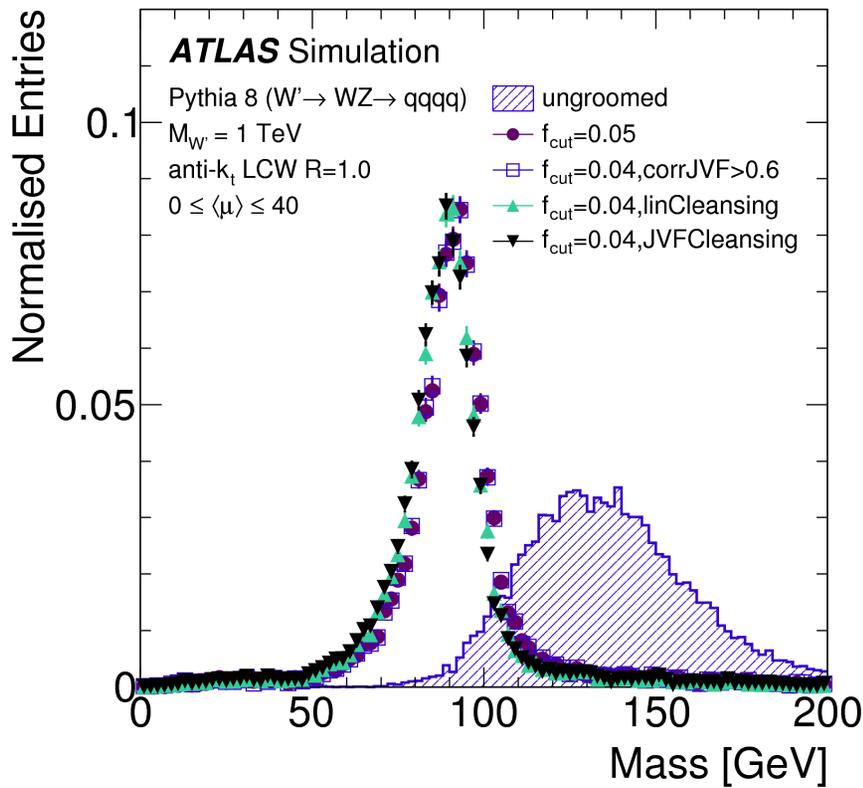
standard grooming

event-by-event corrections

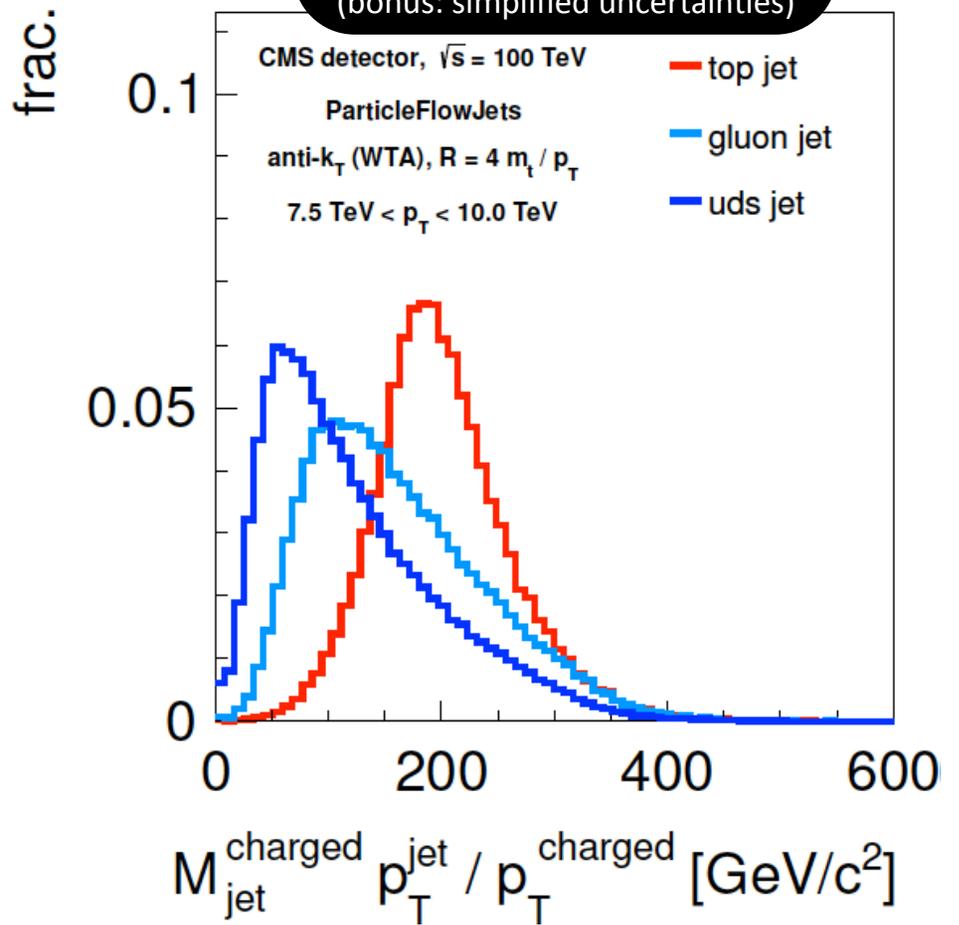


$$\mathcal{V}_{\text{corr}} = \sum_{k=0}^{\infty} (-\rho \cdot A_g)^k \left. \frac{\partial^k \mathcal{V}(\rho, g_t)}{\partial g_t^k} \right|_{g_t=0}$$

# tracks vs. pileup and boost



track-based pileup removal



# kilometers apart...

## CMS

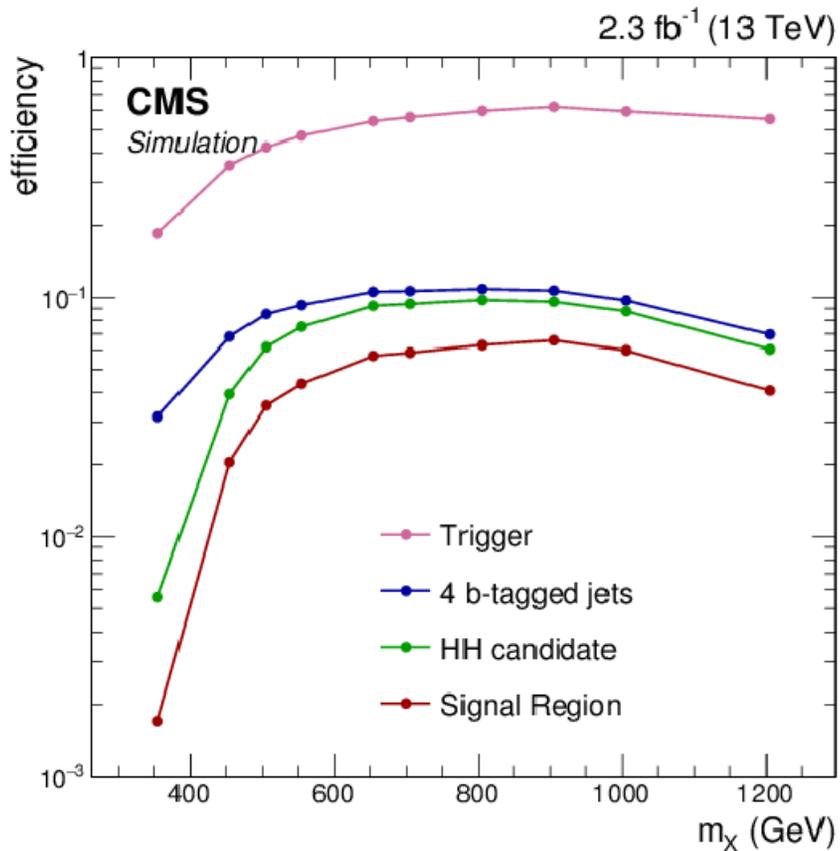
- HVT Model B
  - CHM-like: suppressed fermion couplings
- RS model with  $k/M \sim 0.1$

## ATLAS

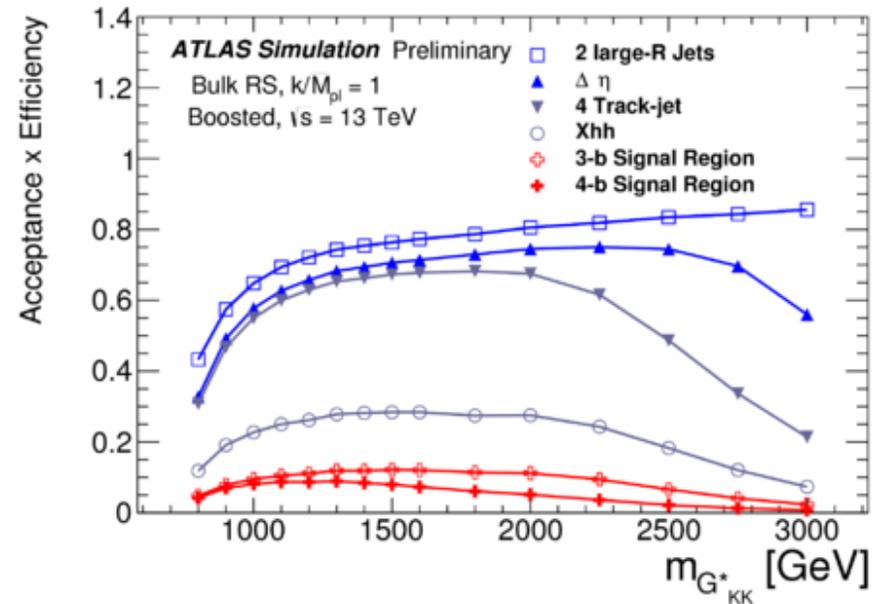
- HVT Model A
  - EGM-like: comparable fermion & vector couplings
- RS model with  $k/M \sim 1$ 
  - higher cross-section, broader resonance

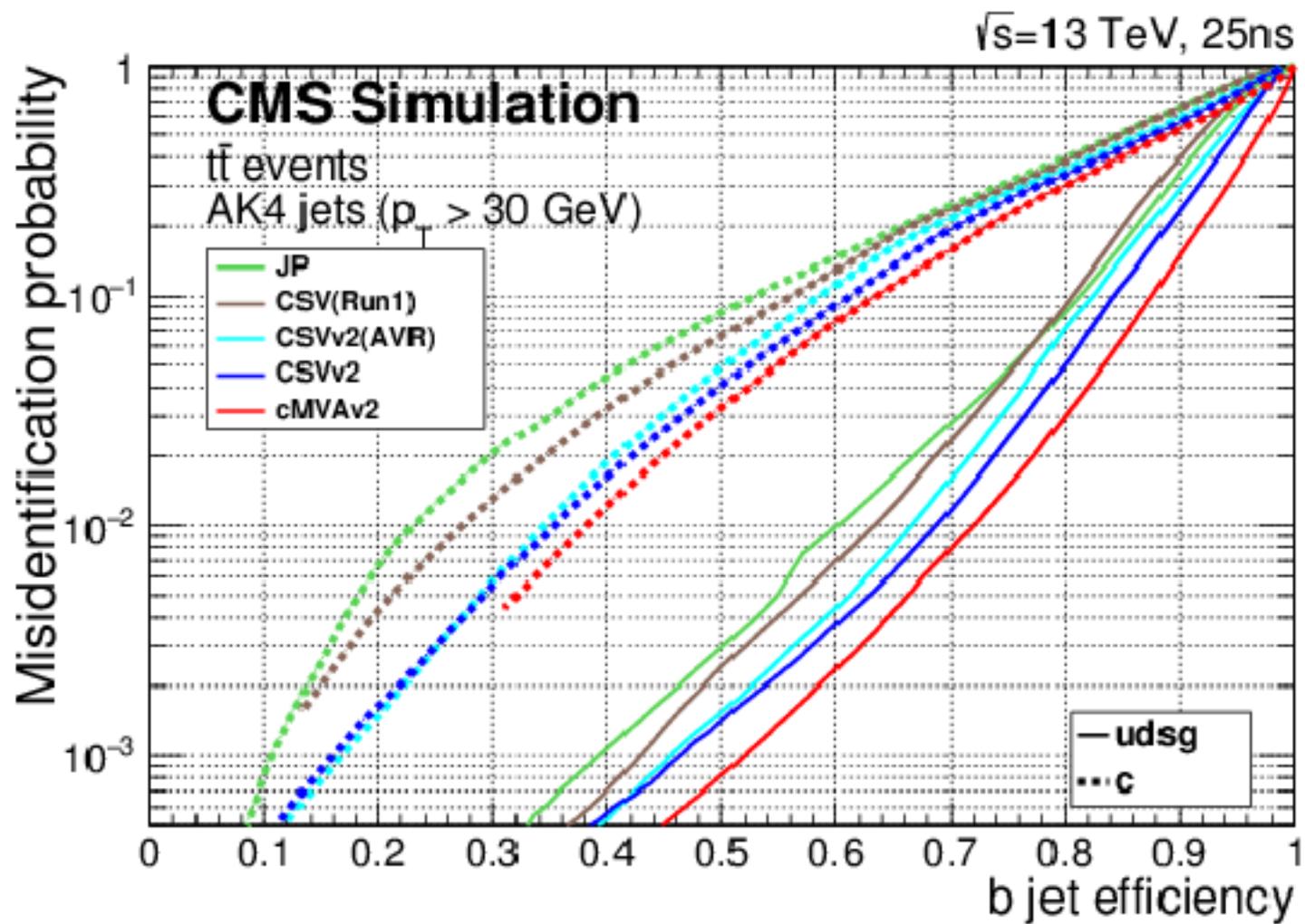
# Higgs strategies

## Resolved analysis



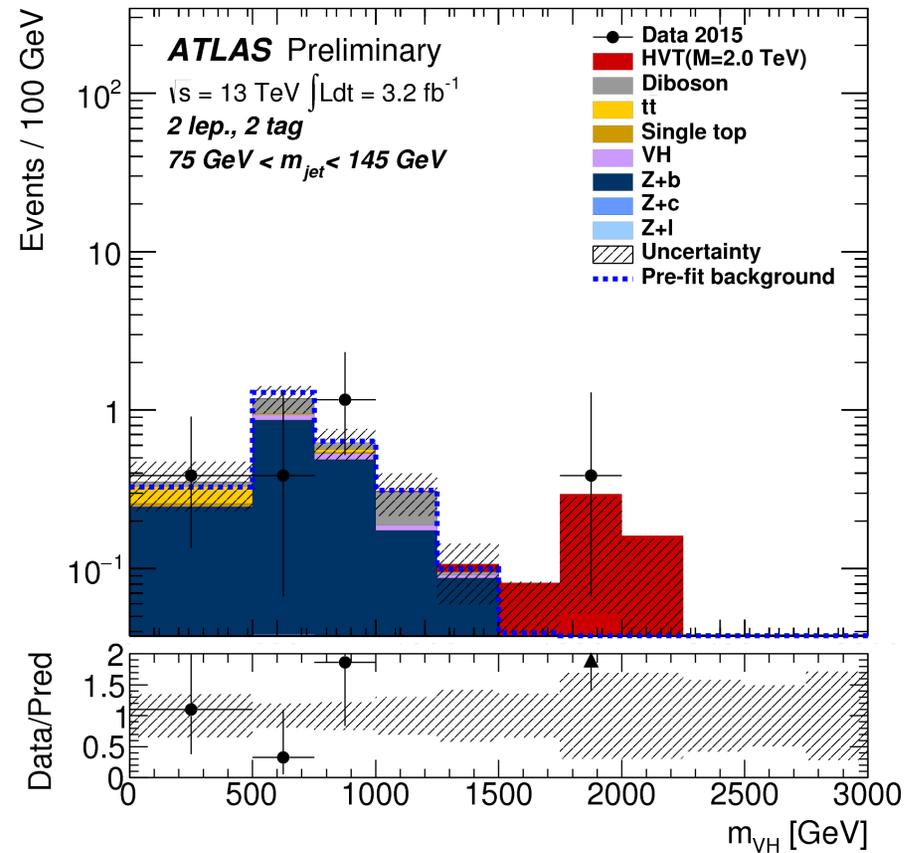
## Di-higgs signal efficiency



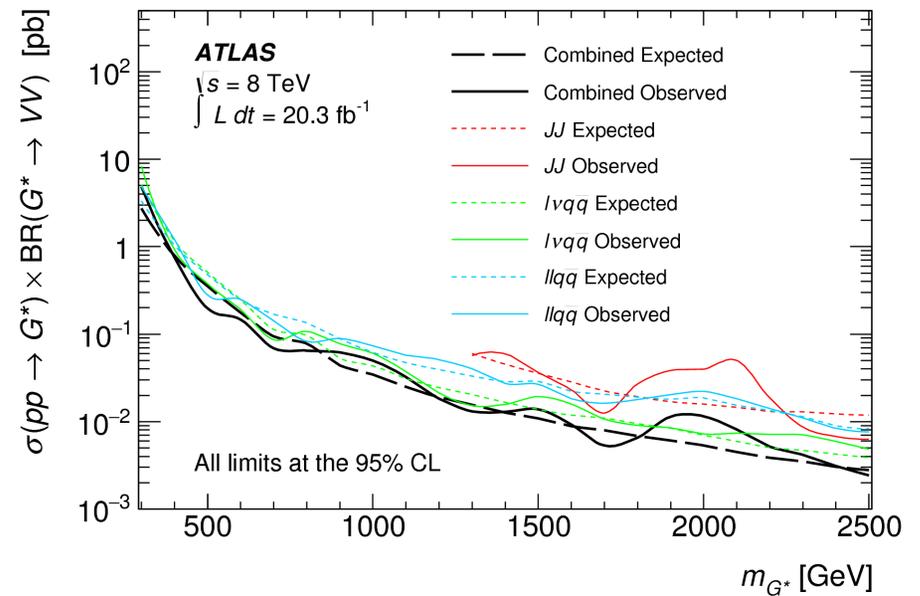
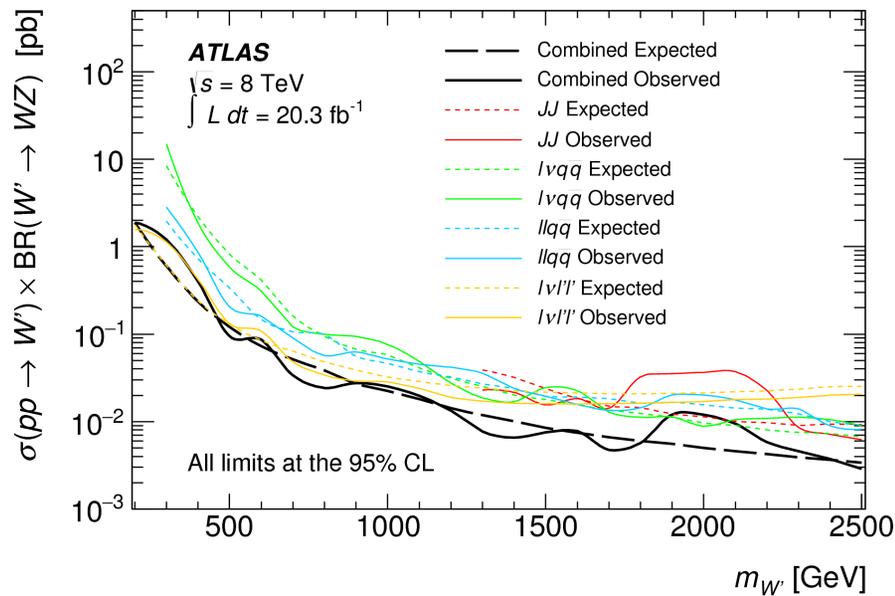


# Resonance searches with Higgs

ATLAS searches for  
WH,ZH with  $H \rightarrow bb$ :



# combination of diboson searches



after combination, local excess significance is strongly reduced: (to 2.6 sigma)

# CMS summary

