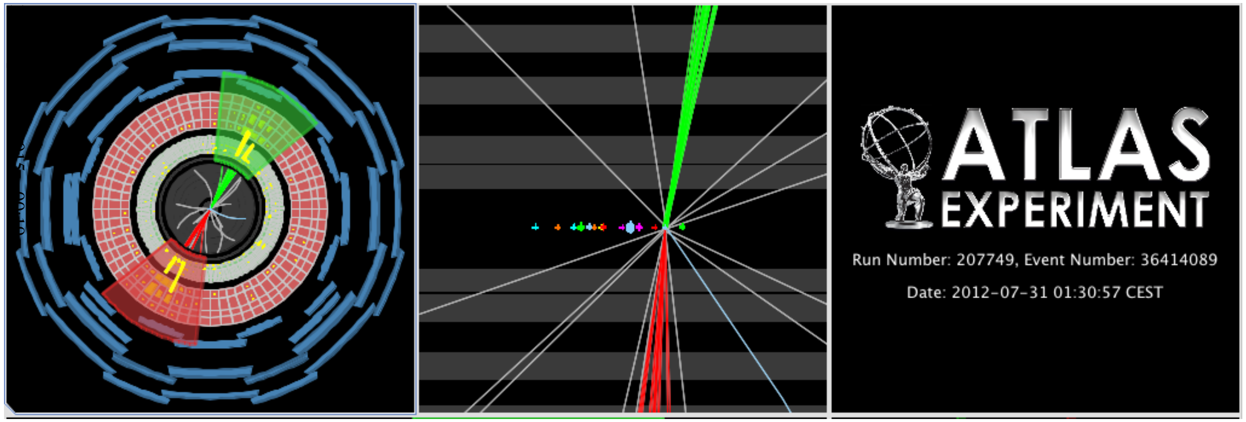
# Searching for Di-boson resonances at the edge of the LHC

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Theory Seminar ULB September 18th 2015

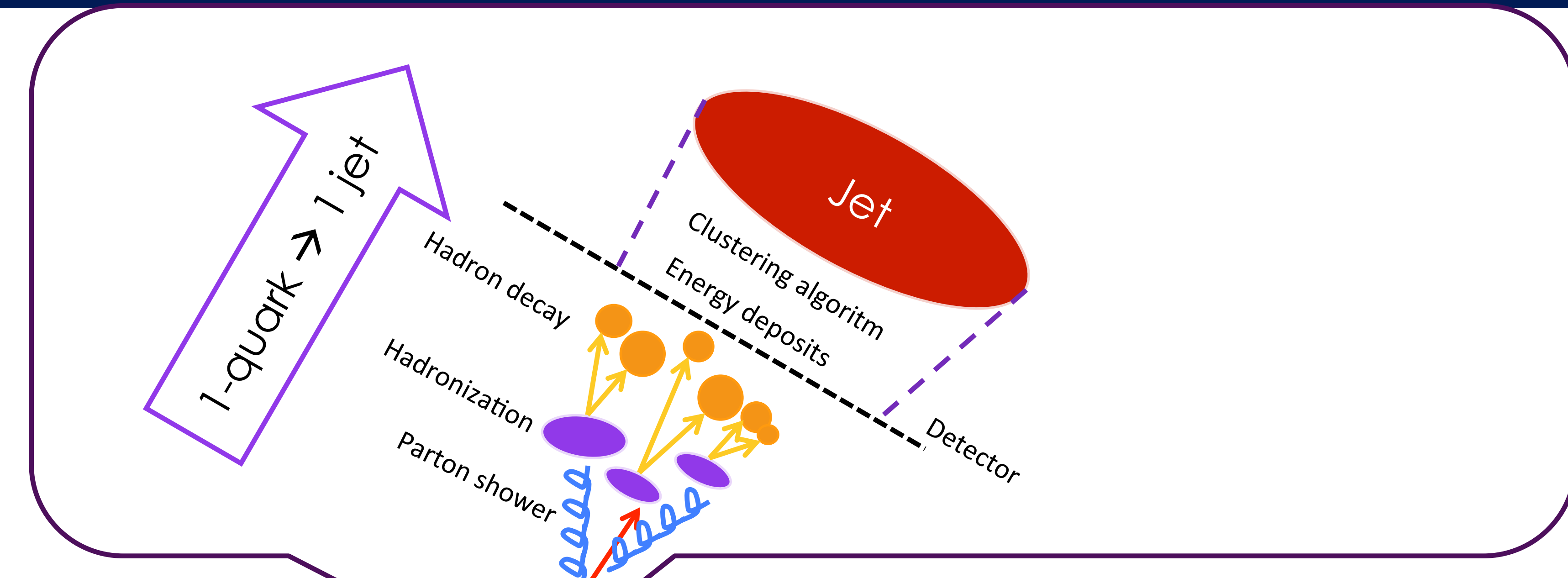
# Diboson resonances at the edge of the LHC

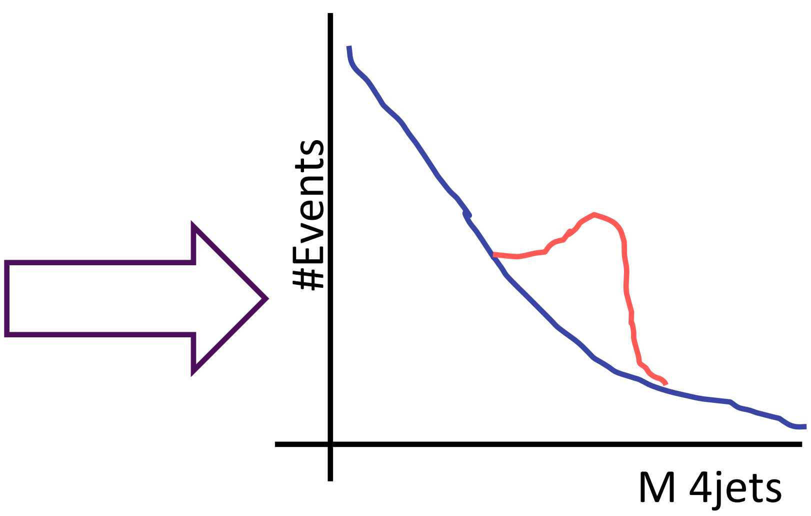
- Diboson resonances appear in many theories extending the SM
  - Simple benchmarks
    - Extended gauge sector models (W’→WZ)
    - Extra dimensions Models (G→WW,ZZ)
- We want to explore the high energy edge of the LHC
  - Leptonic decays suffer from low branching ratios
  - Hadronic decays suffer from large backgrounds and require special reconstruction techniques
  - Still… for resonances O(TeV) the cross section is so small that we want to take advantage of the large BR
- The challenge **- hadronic decays!**

| | W | Z |
|---|---|---|
| $l\nu$, $ll$ | 22% | 7% |
| $\tau\nu$, $\tau\tau$ | 11% | 3% |
| $\nu\nu$ | - | 20% |
| $qq$ | 67% | 70% |

Boson decay fractions

# Naïve approach to search for Diboson resonances with hadronic decays



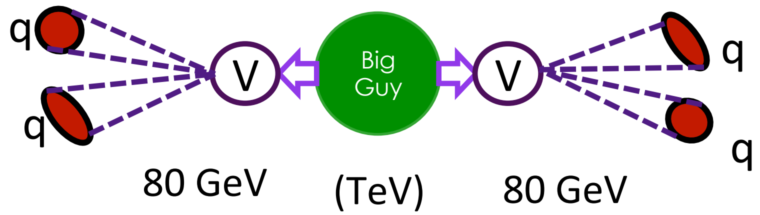



# At the edge bosons are boosted

The vector bosons have masses of O(100 GeV)

So most of the O(TeV) mass of the resonance transforms into large boost to the decaying products

In a decay like this we would have each boson with a momentum of the O(TeV)!

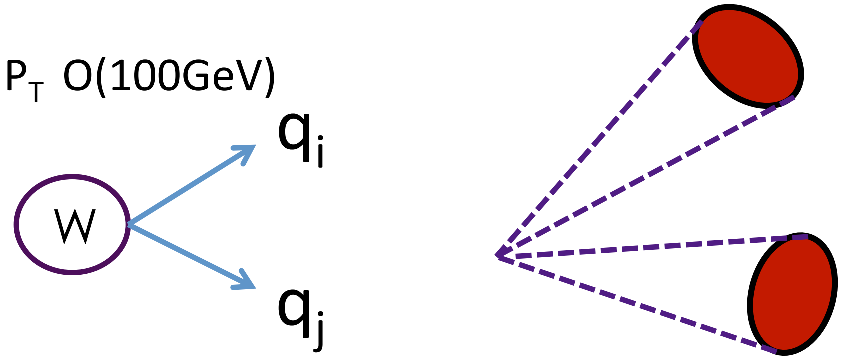


# Things are different at large boosts

“Natural” angular separation:

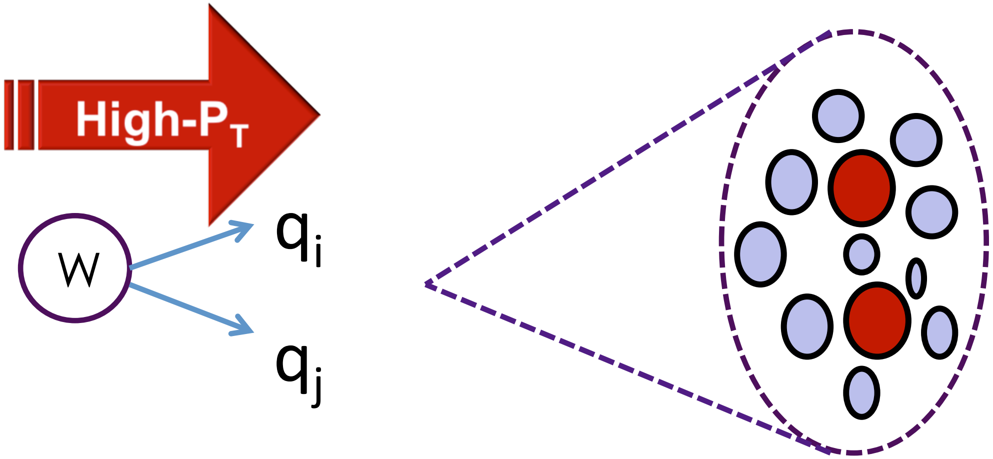
dR ~ 2m/(pT)

Normal jet clustering parameter R=0.4




- Resolved Regime: **Two jets**

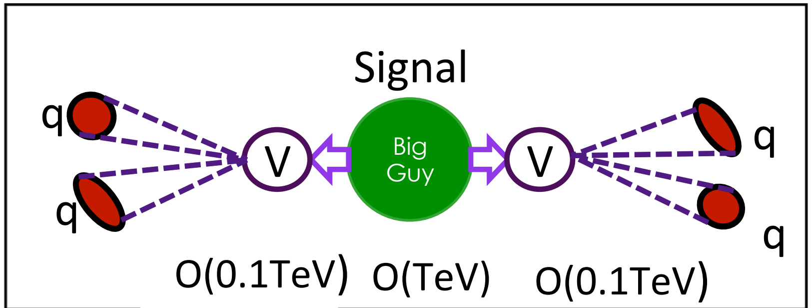
The boson has relatively low momentum in the lab frame so we are able to reconstruct one jet for each quark




- Boosted Regime: **Single *boson jet***

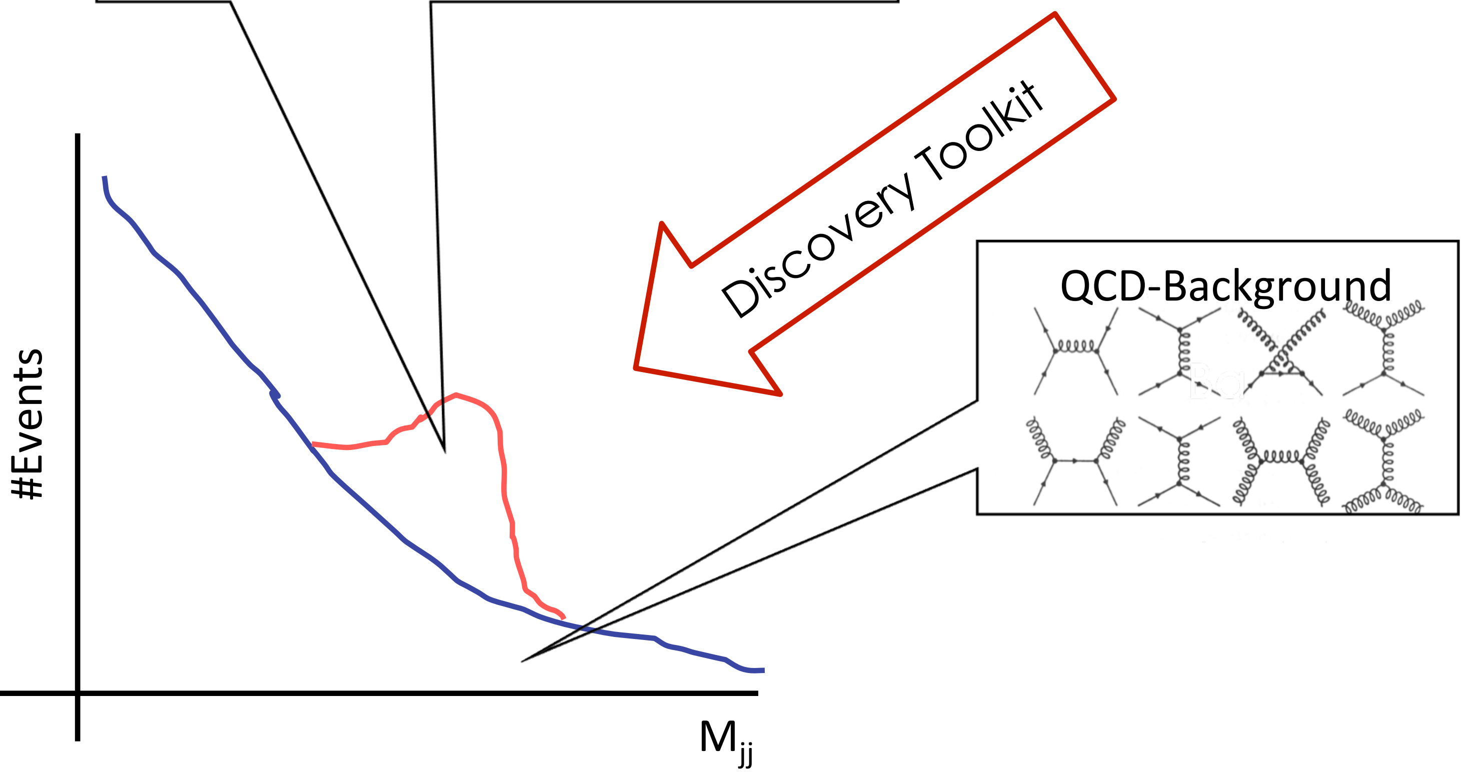
The boson has high momentum in the lab frame - the outgoing quarks are very close to each other so the jets begin to merge

# Ultimate challenge - beat the QCD background




$d\sigma/pT$ x BR (rough numbers)*

| Leading Jet [GeV] | QCD [fb/GeV] | W'* [fb/GeV] |
|---|---|---|
| 0.5 TeV (1.2 TeV W') | $10^3$ | $10^{-1}$ |
| 1.0 TeV (2 TeV W') | 10 | $10^{-3}$ |



# Outline

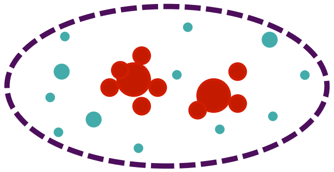
- Tagging Boson Jets
- Searches for Heavy Diboson resonances with ATLAS at $\sqrt{s}$ = 8 TeV
  - In depth look at the fully hadronic channel
  - Channels with leptons
  - Putting it all together
- What to expect

# Tagging Boson Jets

# Boson vs QCD jets

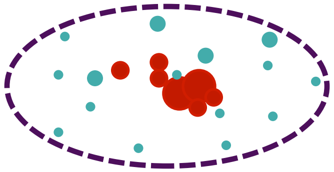
## Boson Jets

- Boson decay
  - Two narrow regions with high energy density corresponding to each quark
  - Each of the quarks carries comparable fraction of the boson momentum in the lab frame
  - Mass of the jet comes from the addition of the two regions corresponding to the quarks



## QCD Jets

- High-pT parton
  - Narrow region with high energy density
  - High energy density region has most of the momentum of the jet
  - Mass of the jet from the spread of the energy of the high pT parton



# Fat-jet – Grooming – Tagging

1

2

3

**Fat-jet**

- Large distance parameter to pick up all radiation from original decay

**Grooming**

- Signal – Take out jet constituents that don't belong to the signal decay
- Background – Preserve background characteristics in the jet

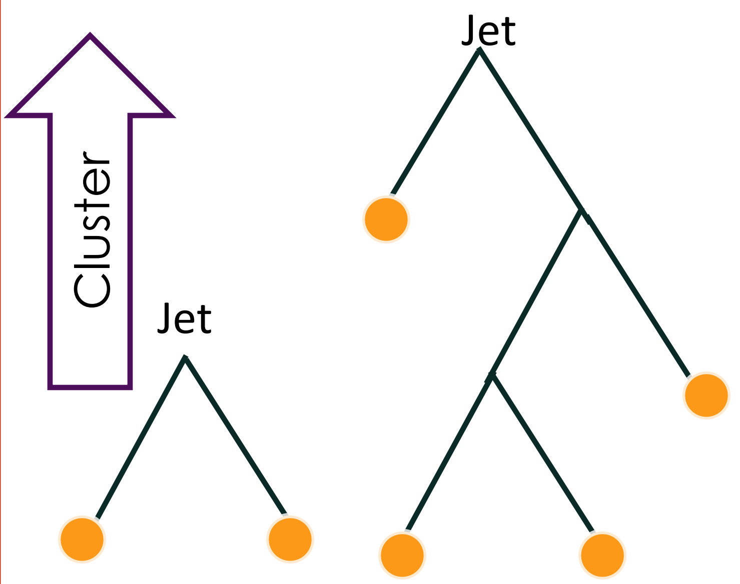

**Tagging**

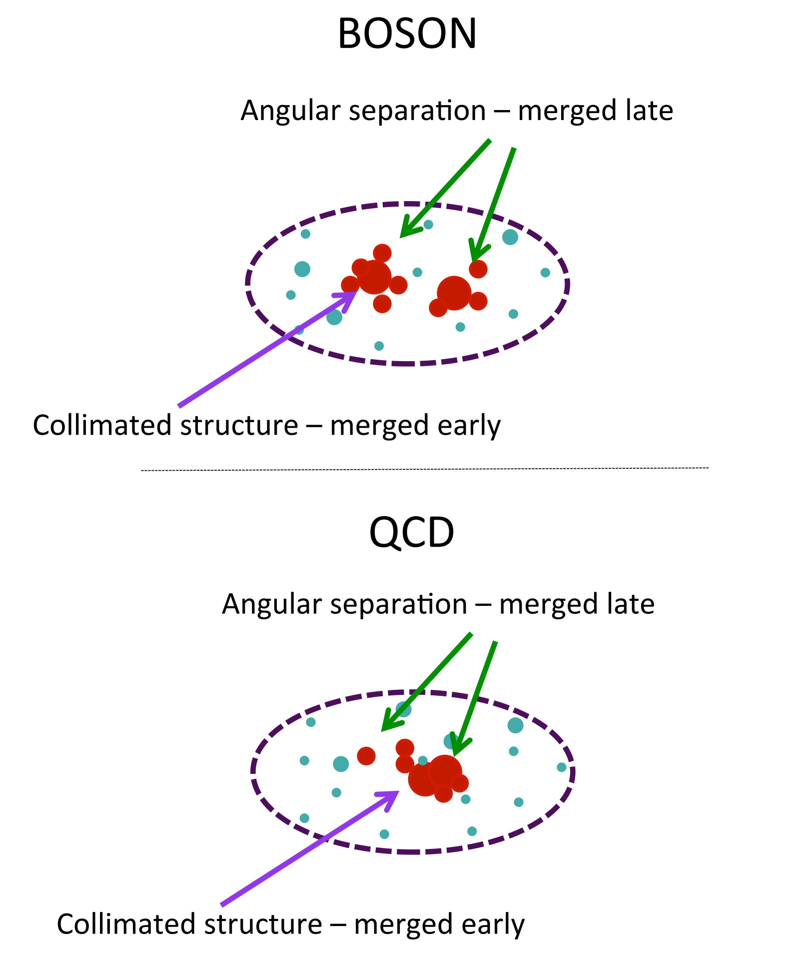
- Use differences in Signal and Background jet characteristics to reject background jets

# Fat jet

C/A Clustering

1) Smaller distance first
2) Merge if distance smaller than
   R = 1.2
3) Iterate until nothing to merge

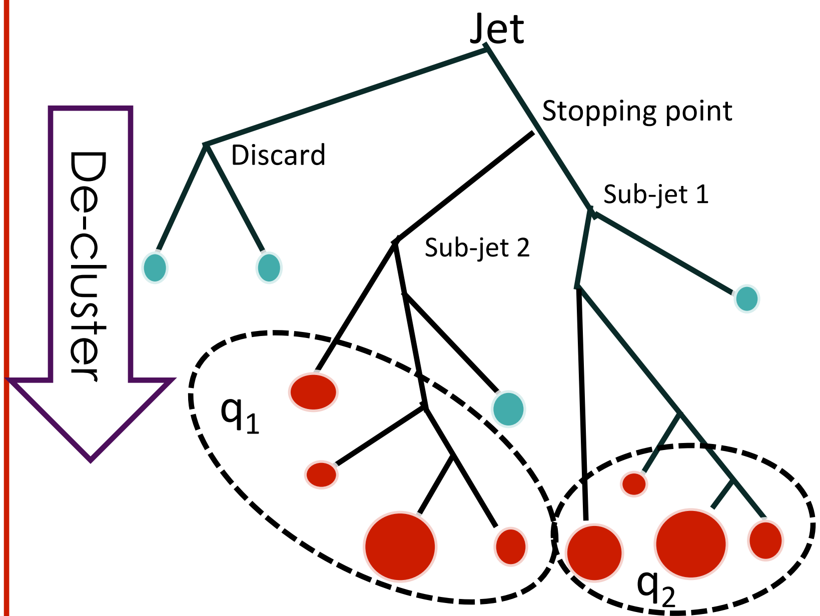


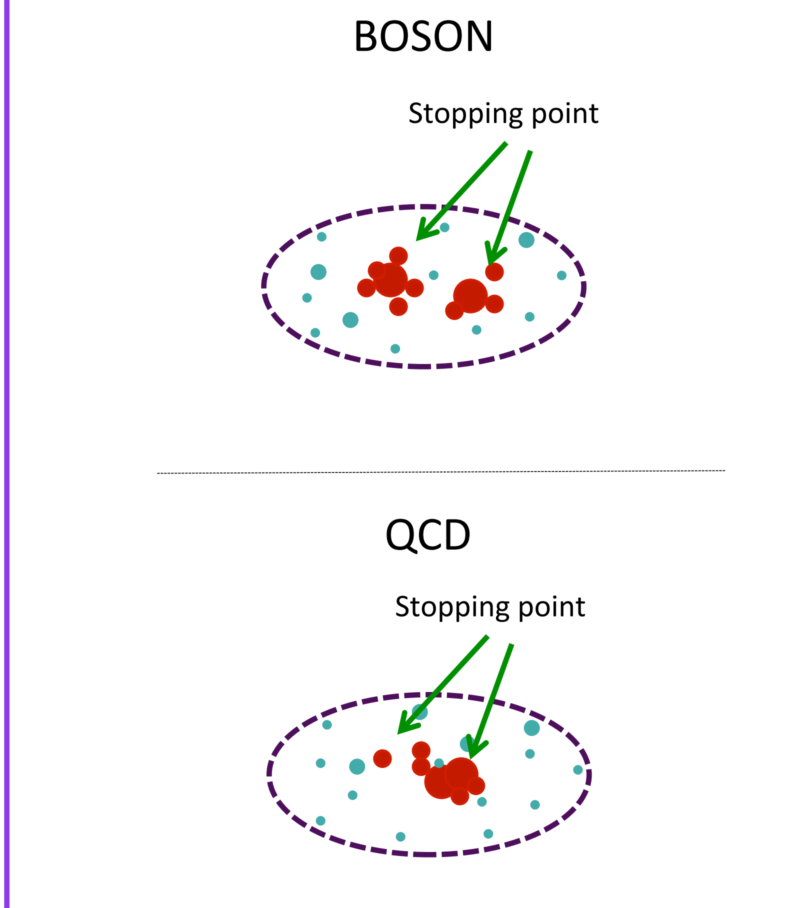



# Mass Drop Grooming

*Mass Drop Filter**

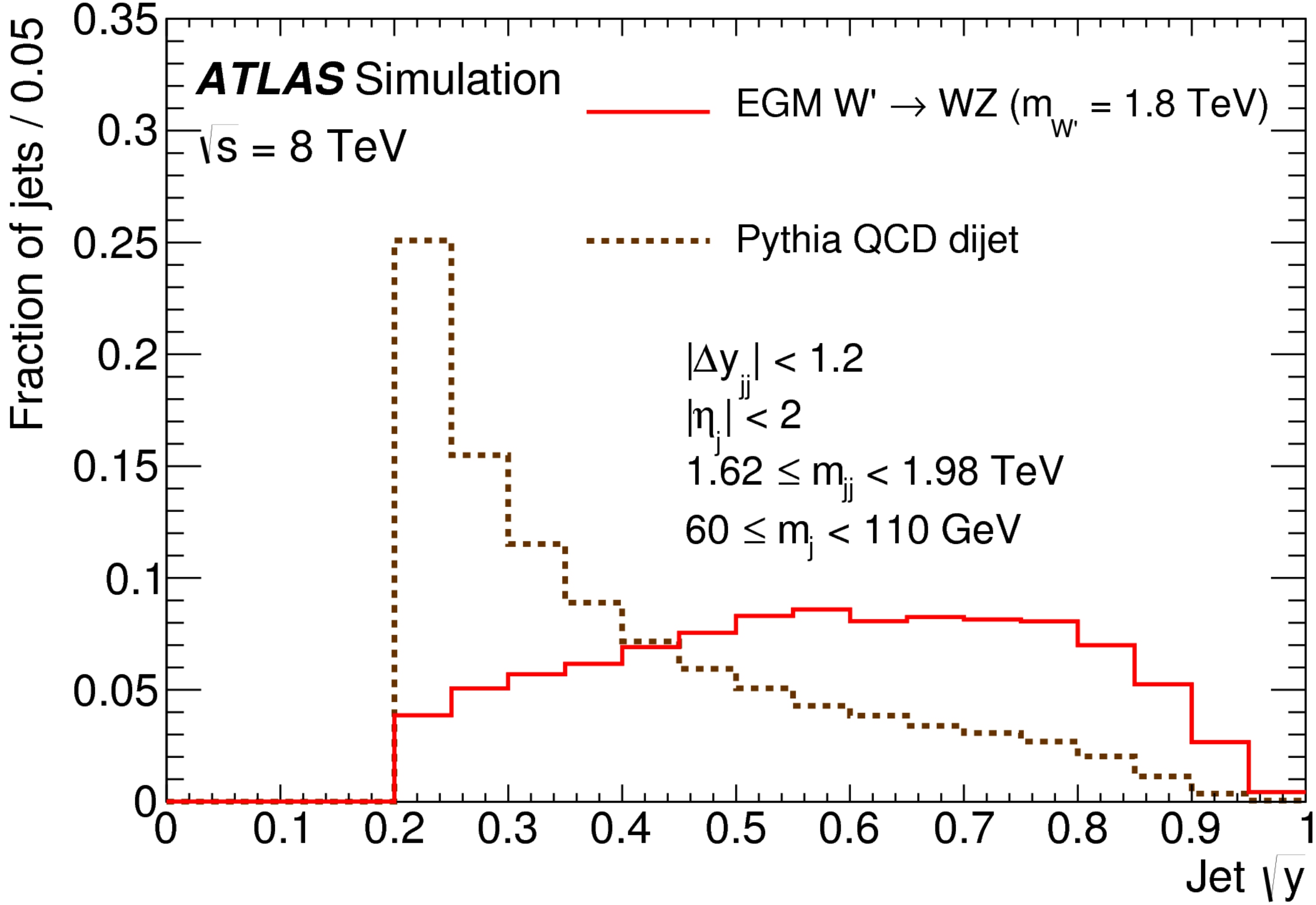
1) Go back in clustering
2) Find point where momentum is balanced amongst proto jets and mass of proto jets is small compared to merged jet



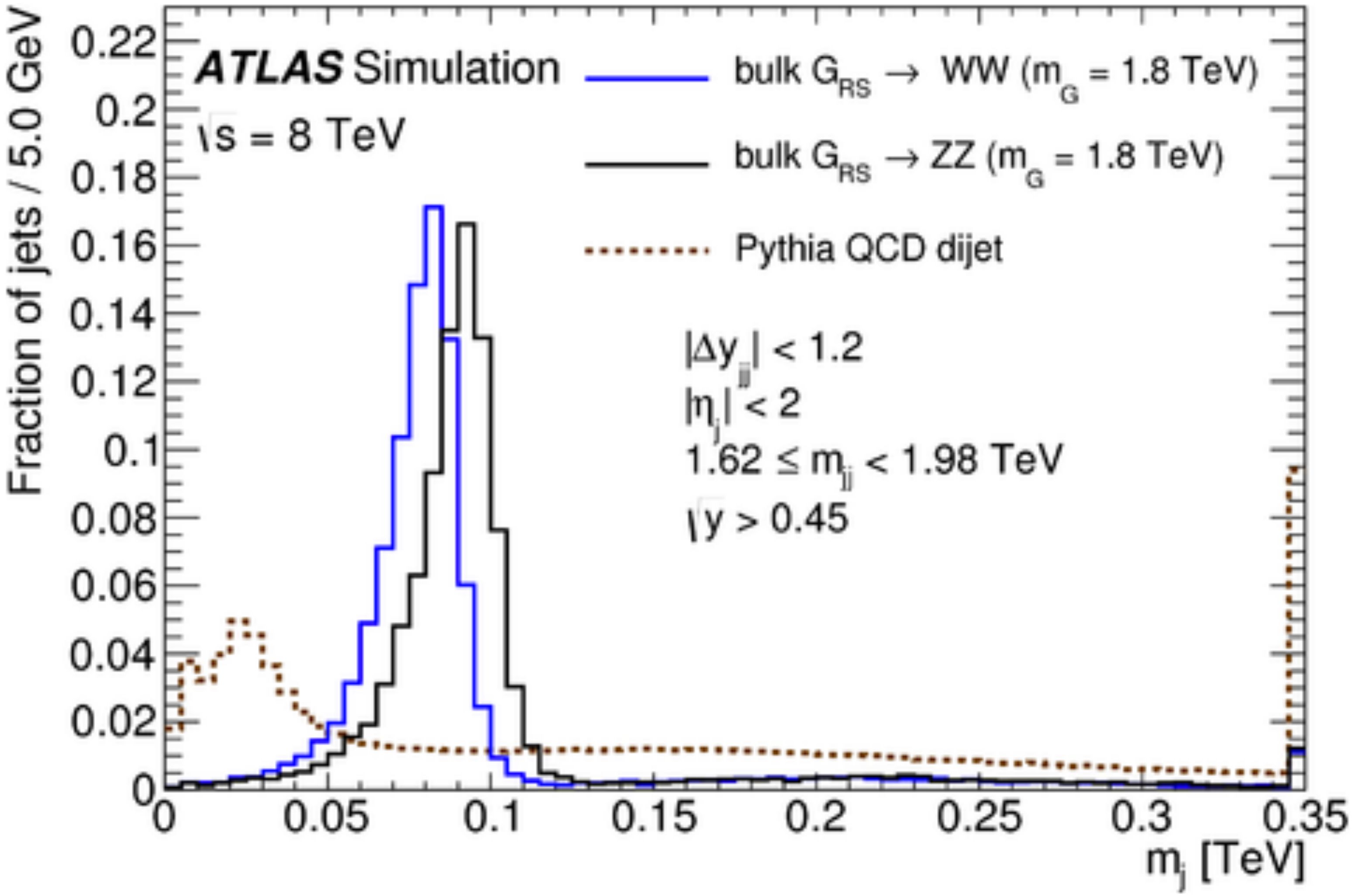




* Only most important details for large boosts

# Sub-jet momentum balance after grooming

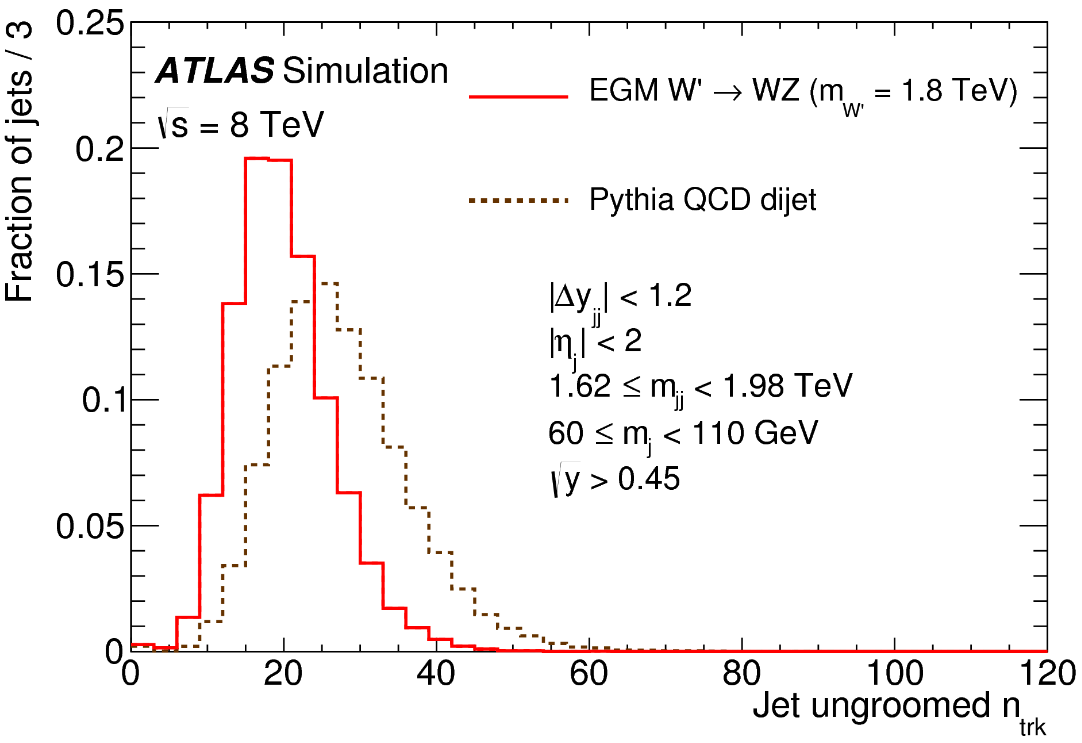


# Jet mass after grooming



# Other handles for discrimination – Hadronic activity

- We've applied selection criteria based on the jet mass and momentum balance
- Remaining background is enriched with gluon splitting jets
  - Increased hadronic activity
- Use number of tracks associated to the jet as a proxy



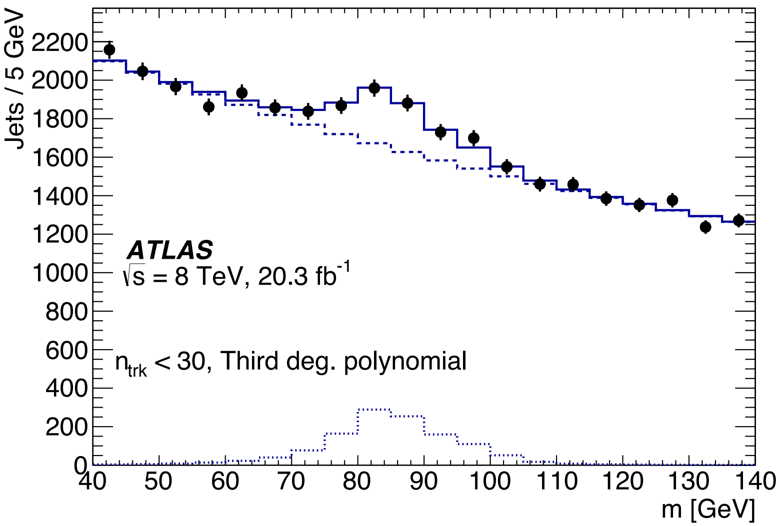
# Data driven estimate of the $n_{trk}$ selection efficiency

- Monte Carlo simulations of $\mathbf{n_{trk}}$ predict a good discriminating power to distinguish between boson jets and the background for this variable

- However, the simulation is not precise enough to determine the efficiency and background rejection to the necessary accuracy

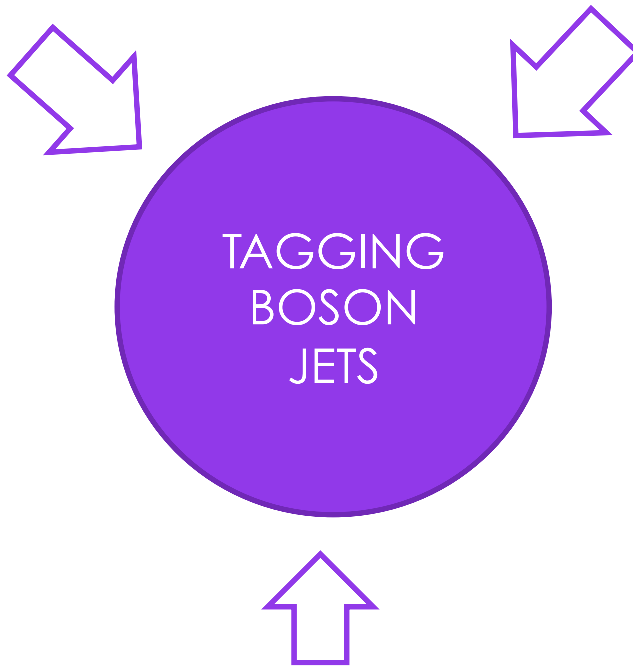
- Use a ***control region*** in data to determine the properties of a selection requirement on this variable
  - Select a W/Z+jets enriched sample by selecting those events with a jet passing the boson selection criteria on the sub-jet momentum balance
  - Use the jet mass distribution to determine the relative signal efficiency of a cut on $n_{trk}$
  - Dominant uncertainty is the mass distribution of the background

***Control Region***
**W/Z+jets enriched sample**



# Tagging "Boson Jets"

## Jet Mass:
- Boson jet mass peaks at nominal boson mass
- QCD mostly falling mass distribution

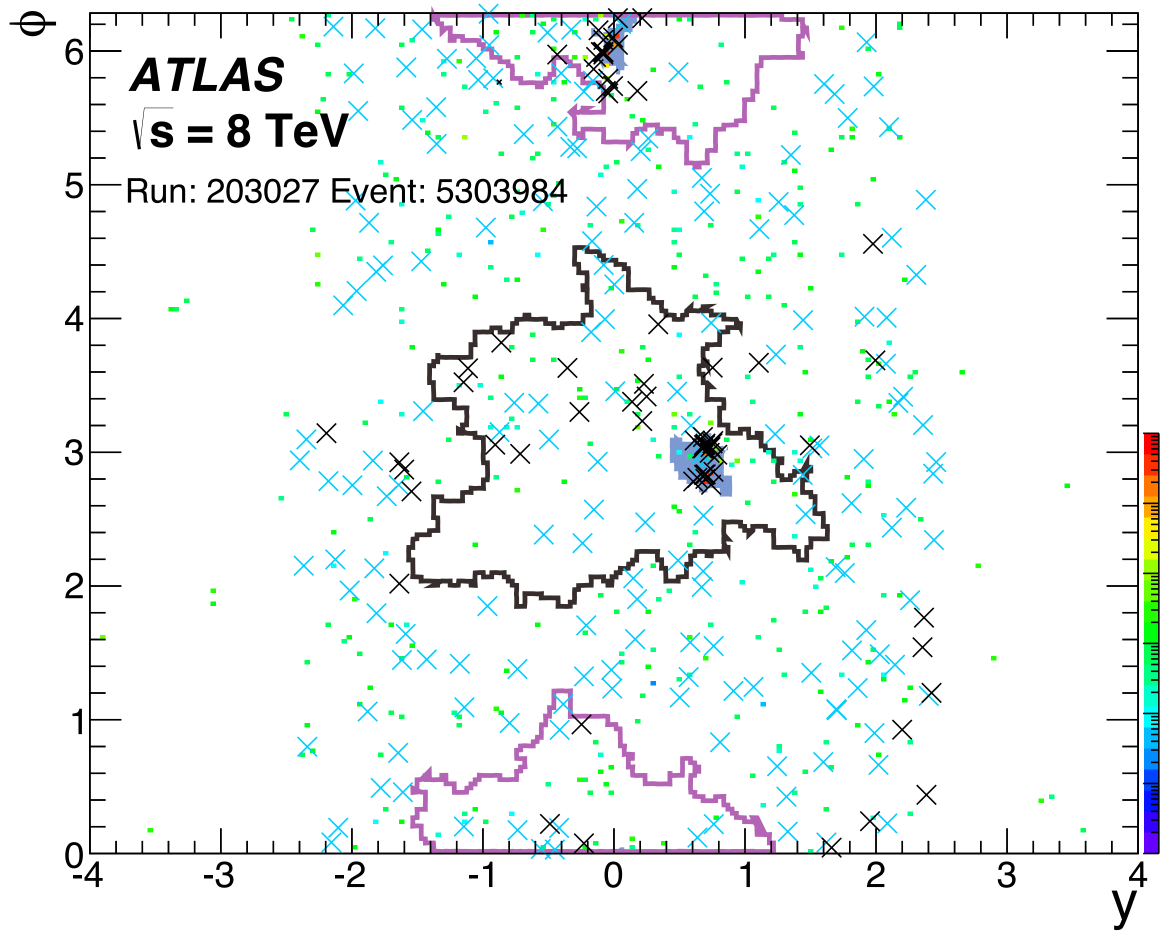



## Momentum balance:
- For boson jets the subjets have comparable momenta at the stopping point
- For QCD jets one of the subjets will have most of the momentum

## Hadronic activity:
- Increased hadronic activity in gluon-like jets

For each search channel the optimal tagging point will depend on the backgrounds

# Boson tagged jets in data



# Searching for diboson resonances: In depth look at the fully hadronic channel

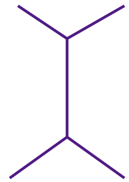
arxiv:1506.00962

# Fully hadronic channel

- Huge backgrounds! - Apply a **tight** tagging selection
  - Different narrow jet mass windows for selecting W or Z
    - Simple strategy optimized for model rejection
    - Considerable overlap between the windows
- Backgrounds are so large that additional handles are needed
  - Event topology
- Additional selection criteria dictated / driven by detector considerations

# Event topology

QCD

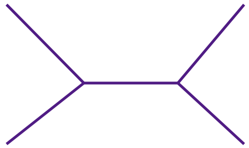


t-channel

Jets tend to go more "forward"

Rapidity difference between jets has higher probability to be large

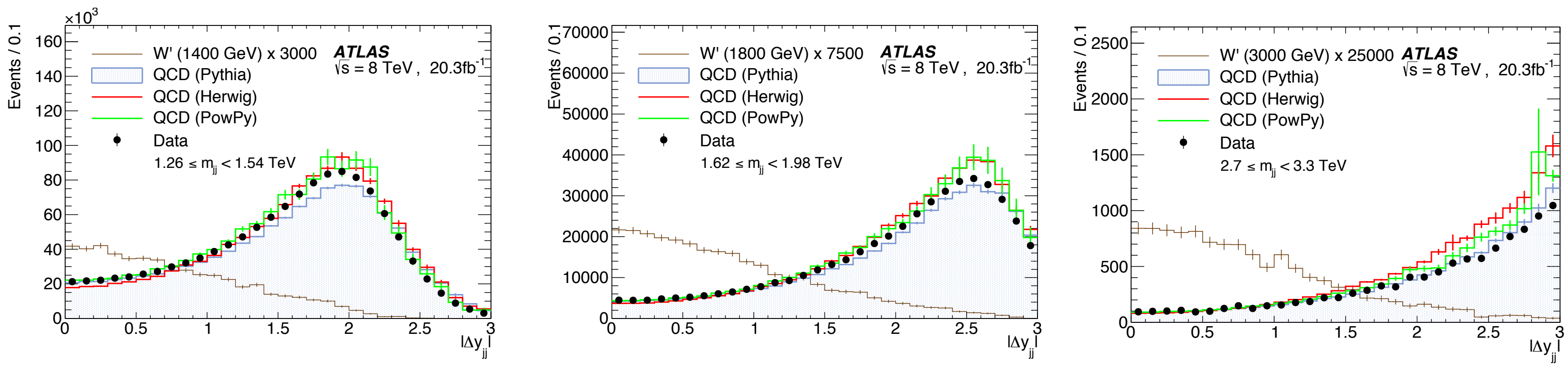
New Particle



s-channel

Jets tend to go more "central"

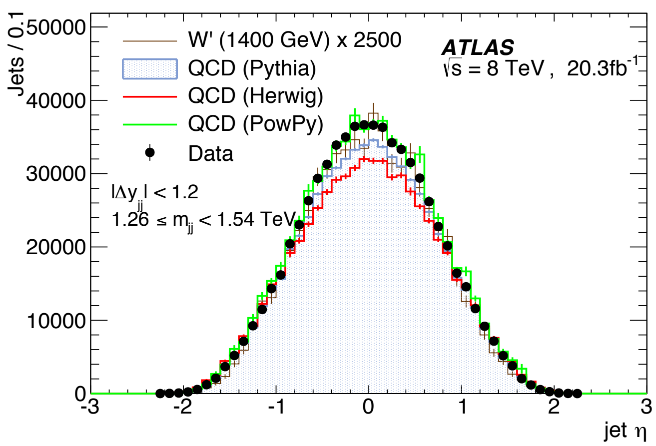
Rapidity difference between jets has higher probability to be small

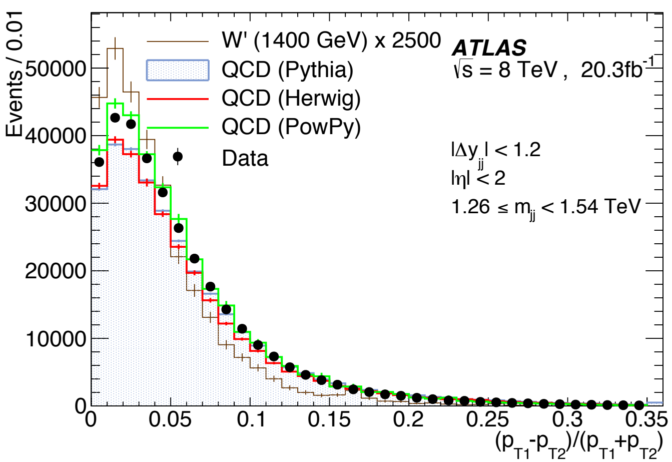


# Additional requirements

Pseudo rapidity requirement

$P_T$ asymmetry requirement



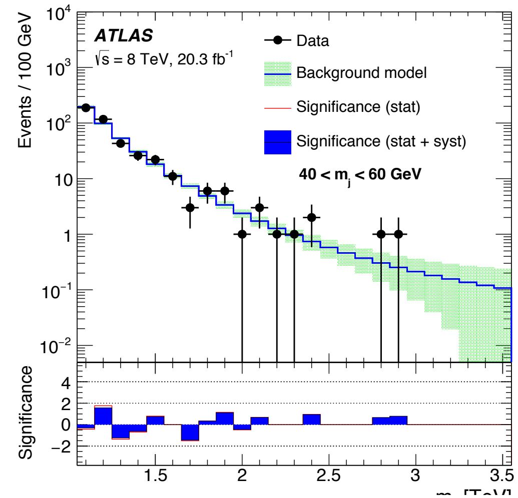
# Estimating the background

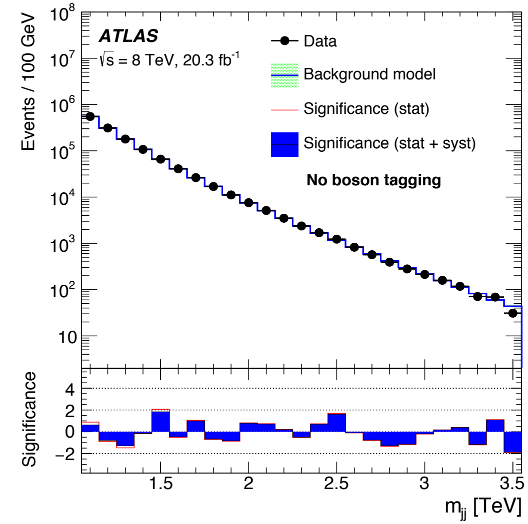
- Dominant background are dijet events from QCD processes
  - Simulation is not accurate enough to provide a robust prediction for estimating the background
- Data driven estimate
  - Smoothly and steeply falling distribution for backgrounds
  - Signal is narrow (only a small region is affected by the presence of a signal)
  - Fit a parametric shape to the data
- For the parameterization we need to ensure
  - Has adequate complexity
  - Will not produce fake signals

$$\frac{\mathrm{d}n}{\mathrm{d}x} = p_1(1-x)^{p_2+\xi p_3}x^{p_3}$$

# Tests on background parameterization

- Two types of tests
  - *Spurious* signal: Fit S+B in background only distributions and best fit signal is small compared to background uncertainty
  - Parameterization complexity: Adding additional parameters does not result in a significant better fit
- Test parameterization in control regions
  - Sidebands in data
  - Untagged data
  - Mixture of sideband spectra
- Test parameterization in background simulations
  - Different dijet simulation
  - Consider large variations in the background composition



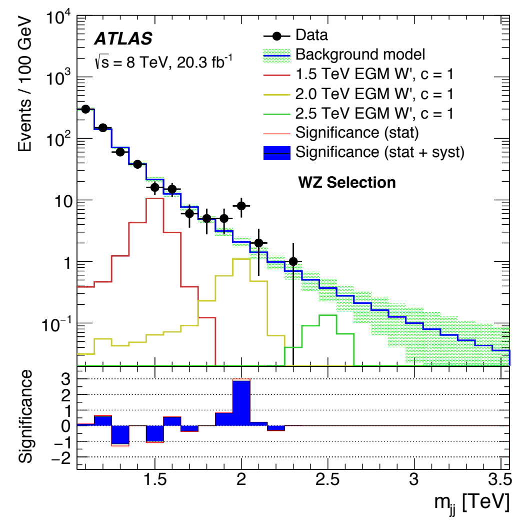



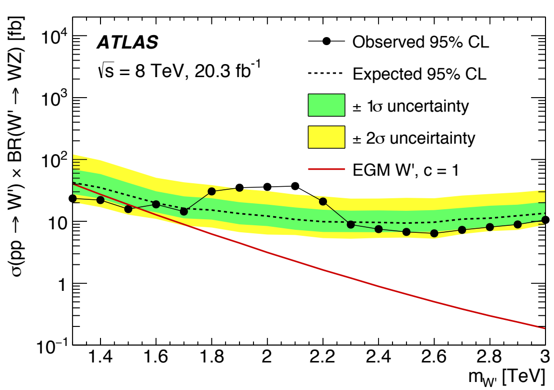
# Results in the fully hadronic channel

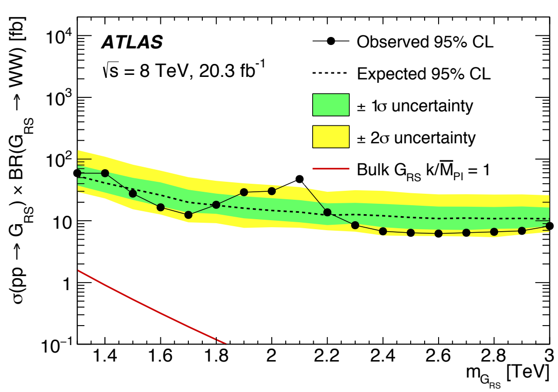
In most of the range there is good agreement between the background estimate and the observed data

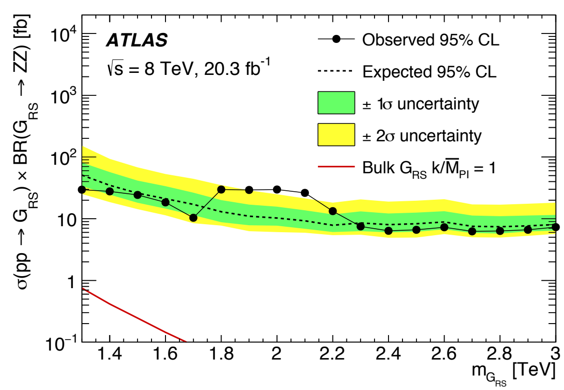
At ~2 TeV the three channels (WW/WZ/ZZ) observe statistically mild deviations from the background. Approximately 20% of the events are shared in the three signal regions. Overlap between WW/WZ or WZ/ZZ is larger

Largest deviation is in the WZ channel 2.5 sigma global (3.4 local)

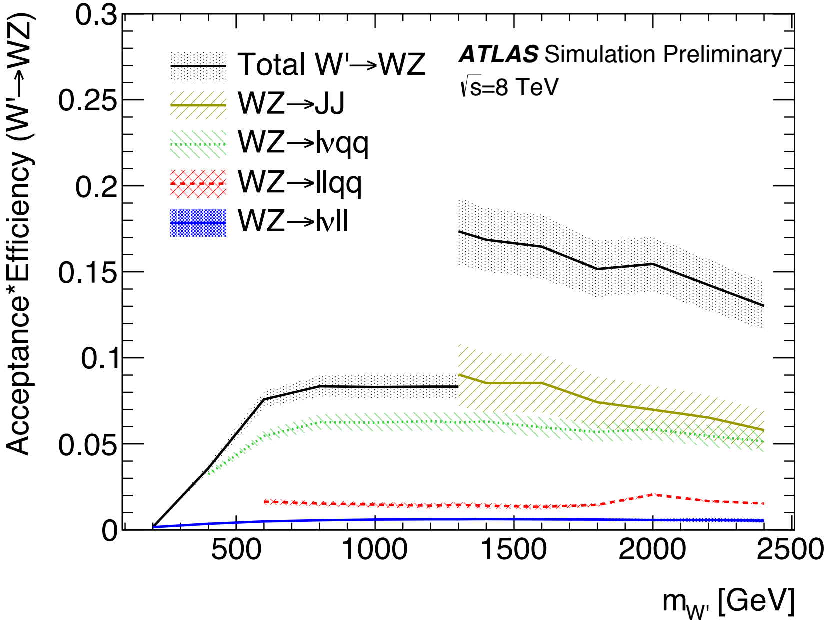


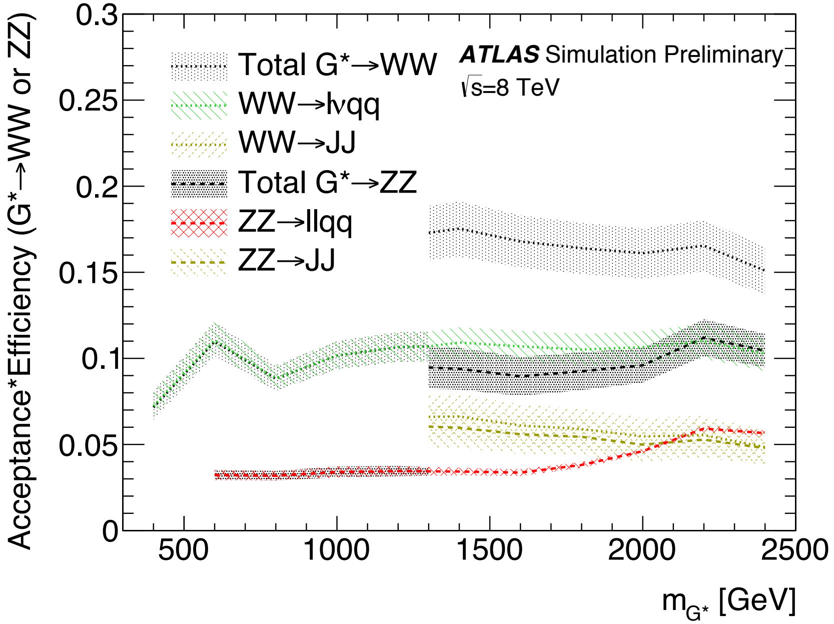



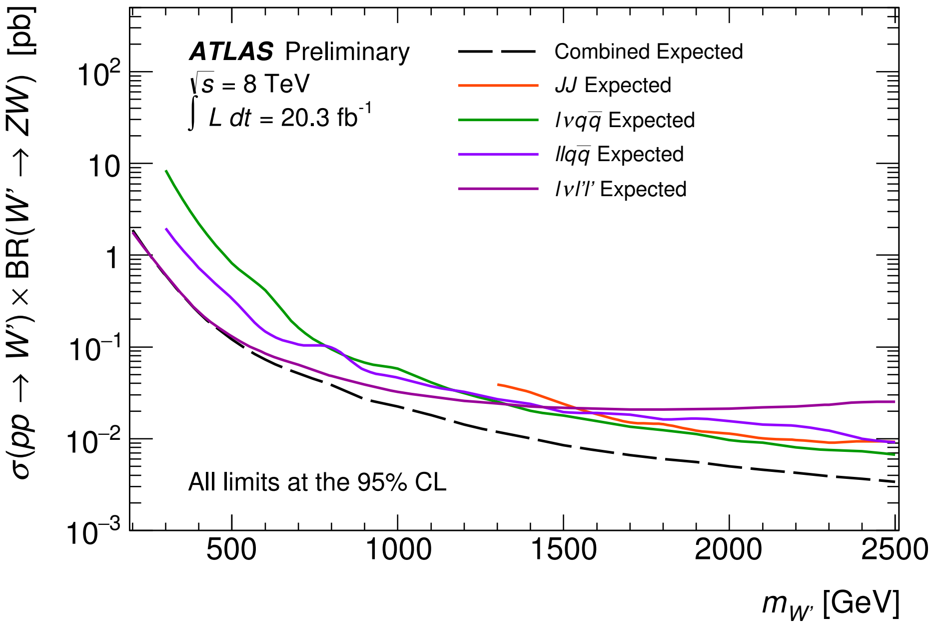
# Channels with leptons in ATLAS

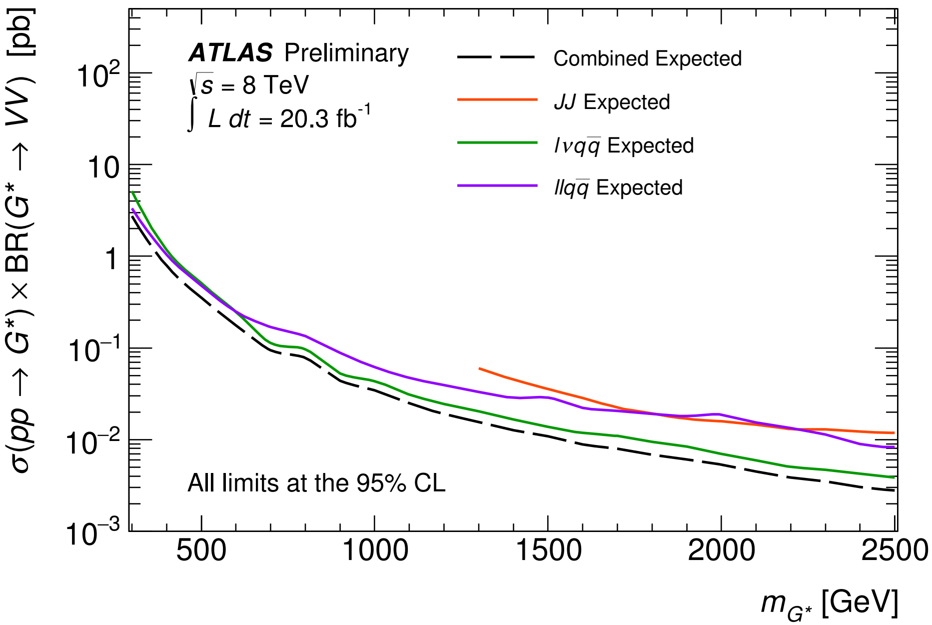



ATLAS-CONF-2015-045 (Combination)
arXiv:1406.4456 (lvll)
arXiv:1409.6190 (llqq)
arXiv:1503.04677 (lvqq)

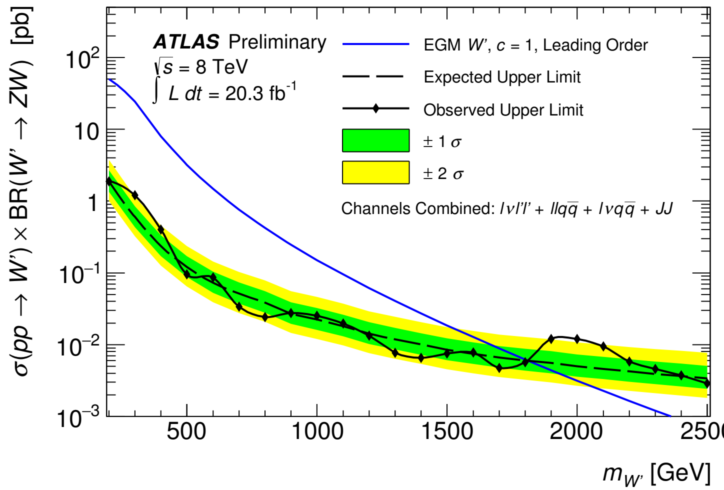
# Sensitivity to diboson resonances

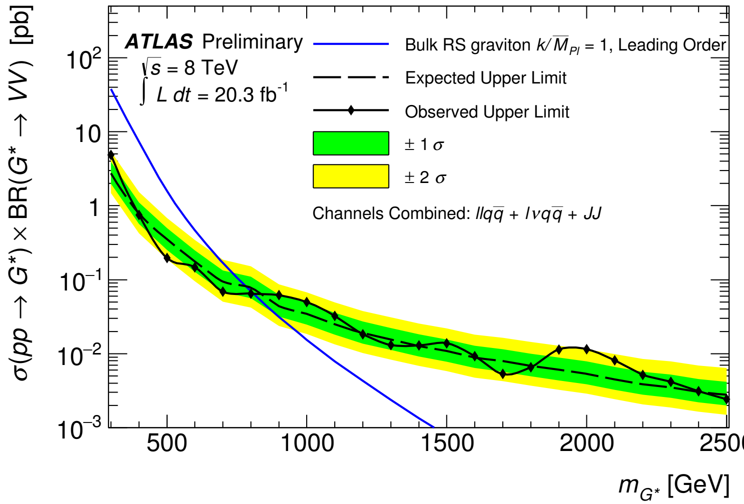


# Combined picture in ATLAS

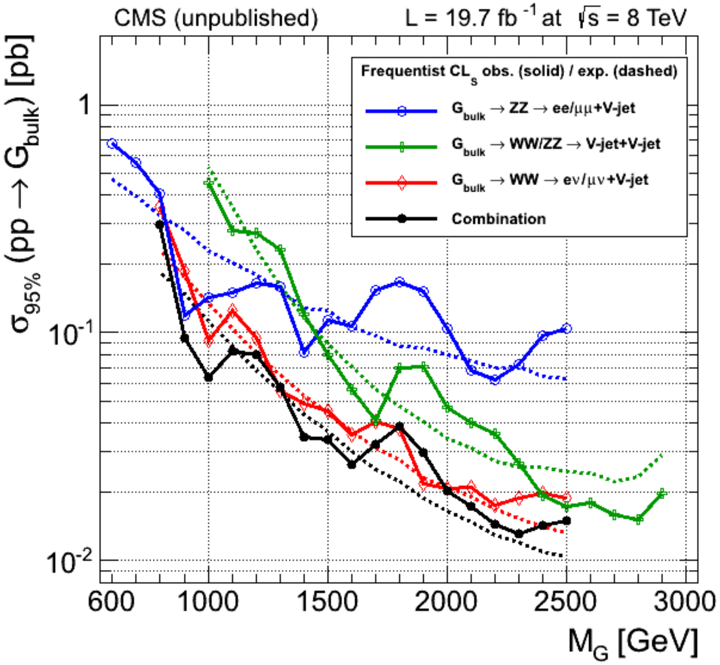
- The single lepton channel has a comparable sensitivity in most of the range where the fully hadronic search takes place
  - Excellent agreement with the background only hypothesis. No excess is observed
- The two and three lepton channels have less sensitivity at high masses but no excesses are observed either
  - Local significance in WZ is reduced to 2.5 sigma (at the global level this is a very mild excess)

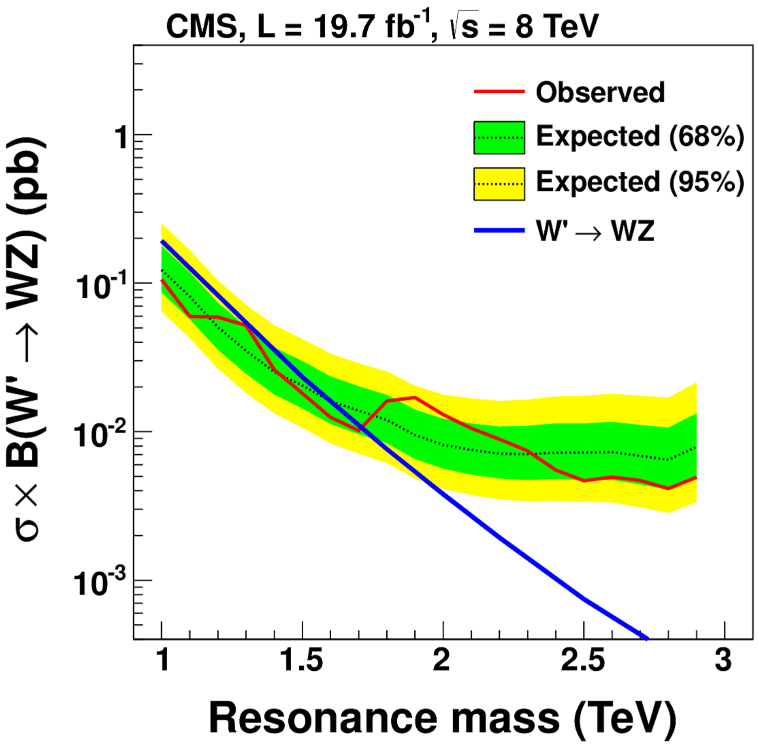


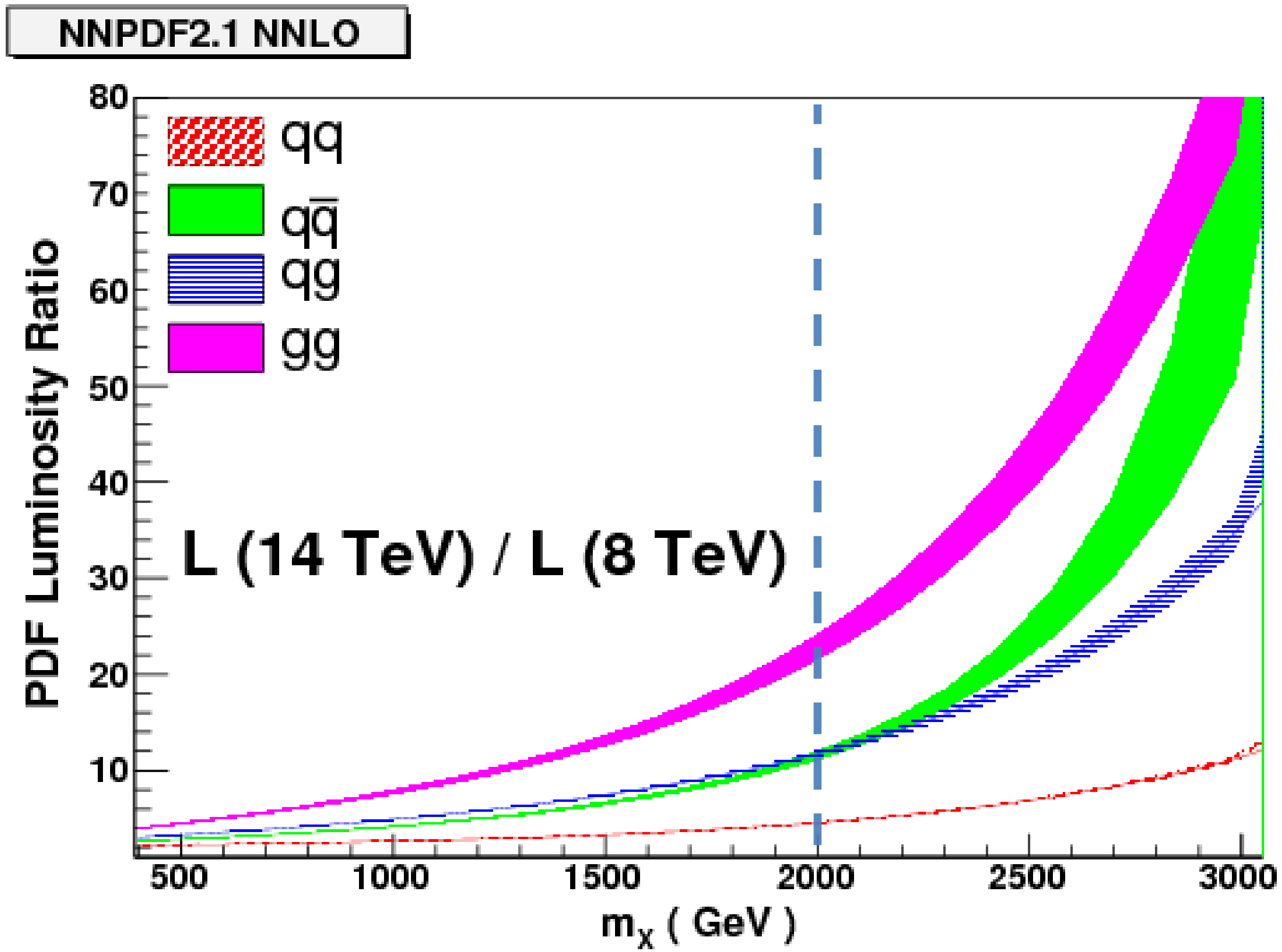
# CMS results

- CMS has performed searches for diboson resonances in similar channels
  - arXiv:1405.1994 (fully hadronic)
  - arXiv:1405.3447 (semileptonic)



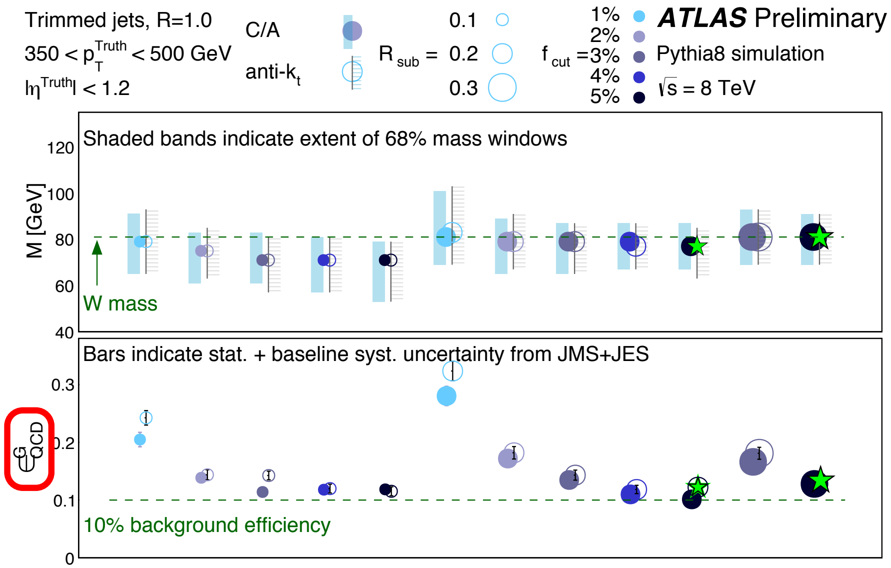
# The future…



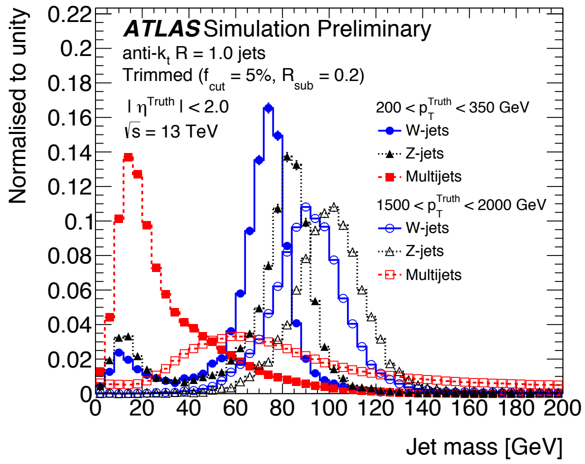
NNPDF2.1 NNLO
qq
$q\bar{q}$
qg
gg
L (14 TeV) / L (8 TeV)
PDF Luminosity Ratio
80
70
60
50
40
30
20
10
500
1000
1500
2000
2500
3000
$m_X$ ( GeV )

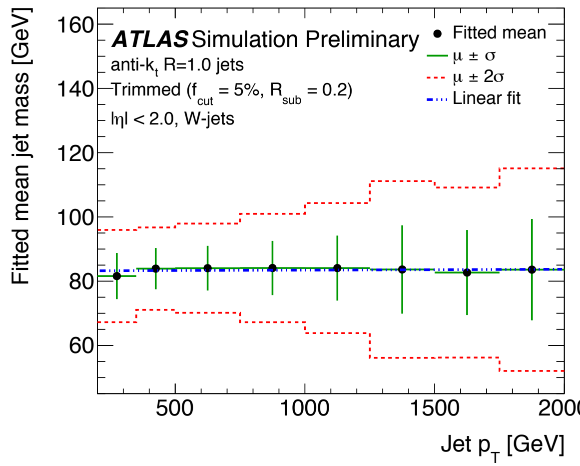
# Exhaustive boson tagging studies from Run-1 (ATL-PERF-2015-03)

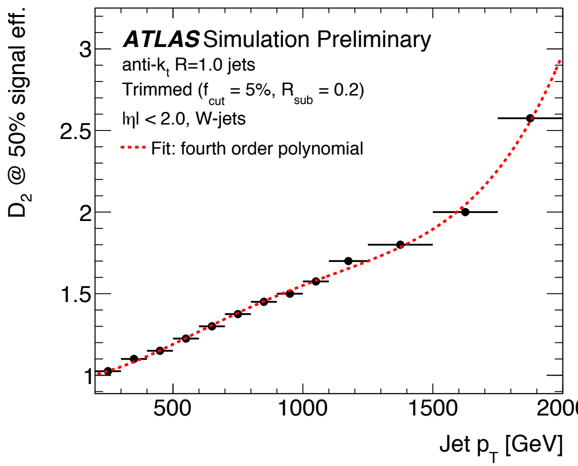
- Consider large space of grooming / tagging configurations
  - O(500) configurations tested
- Step-1
  - Determination of grooming algorithm based on jet mass (bkg rejection for 68% signal eff)
  - Additional considerations
    - Pileup dependence
- Step-2
  - Single variable tagging
    - Analyzed O(20) variables
    - Best variables appear to be “proneness” related variables



# Improved tagging at Run-2 based on Run-1 experience




ATLAS-PHYS-PUB-2015-033

# Summary

- The large dataset collected in Run-1 of the LHC provided the exciting opportunity to explore new particles at the TeV scale decaying to W/Z's
- The excellent spatial resolution of the calorimeters in the experiment(s) allowed to develop dedicated techniques to reconstruct boosted bosons decaying to hadrons
  - This is just the beginning!
- There is tension with other searches
  - In ATLAS the fully hadronic channel shows a not-significant-enough excess around 2 TeV. But… other channels of comparable sensitivity are in good agreement with background only predictions
  - CMS has seen some mild excesses in the same general region in searches with comparable sensitivity in this region. But… at lower mass scale. The uncertainty in the Jet Energy Scale estimated by both experiments is smaller than the difference in the mass of the excesses.
- Run-2 is here! Data is beginning to flow quickly
  - Massive cross section increase if the excess depending on production mechanism
  - If all goes well O(5fb-1)… in Spring experiments could confirm / exclude the excess.

# Thanks!

# Backup

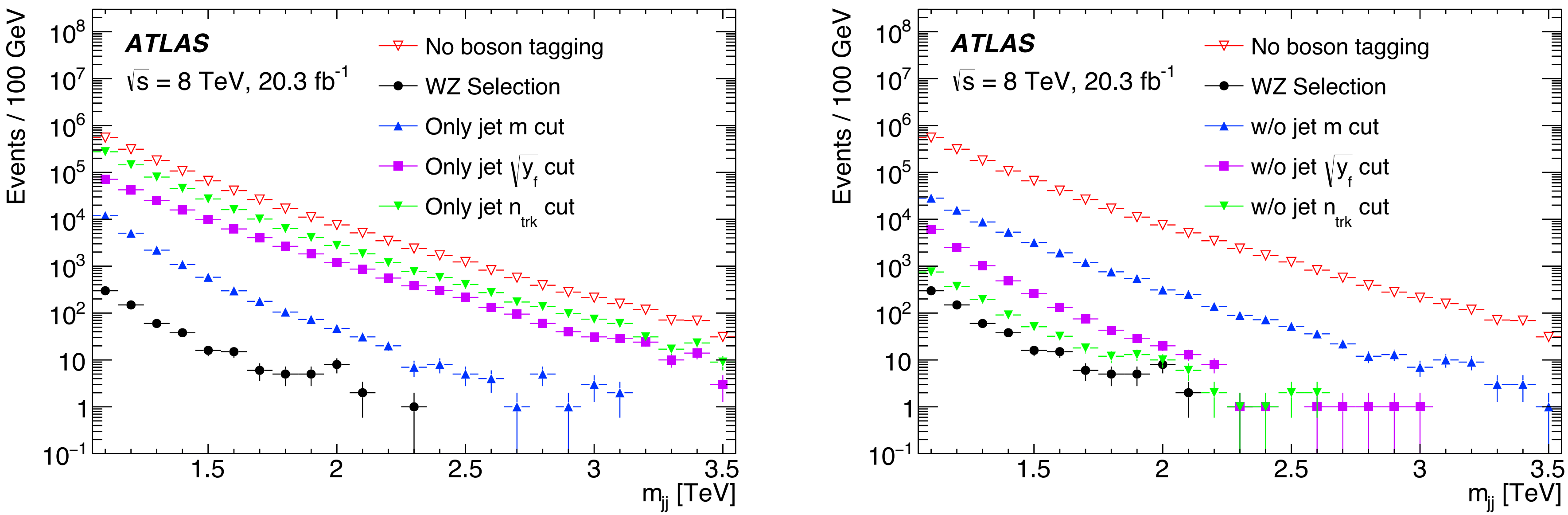
# Systematic uncertainties

- In ATLAS systematic uncertainties follow the following approach
  - Two independent measurements for jet related quantities
    - Track based
    - Calo based
  - Compare ratio of Calo / Track in data to MC and use maximal deviation from unity to derive uncertainty
  - Check with different simulations

| Source | Uncertainty | Constraining pdf |
|---|---|---|
| Jet $p_T$ scale | 2% | $G(\alpha_{PT}\|1, 0.02)$ |
| Jet $p_T$ resolution | 20% | $G(\sigma_{r_E}\|0, 0.05 \times \sqrt{1.2^2 - 1^2})$ |
| Jet mass scale | 3% | $G(\alpha_m\|1, 0.03)$ |

| Source | Normalisation uncertainty |
|---|---|
| Efficiency of the track-multiplicity cut | 20.0% |
| Jet mass scale | 5.0% |
| Jet mass resolution | 5.5% |
| Subjet momentum-balance scale | 3.5% |
| Subjet momentum-balance resolution | 2.0% |
| Parton shower model | 5.0% |
| Parton distribution functions | 3.5% |
| Luminosity | 2.8% |

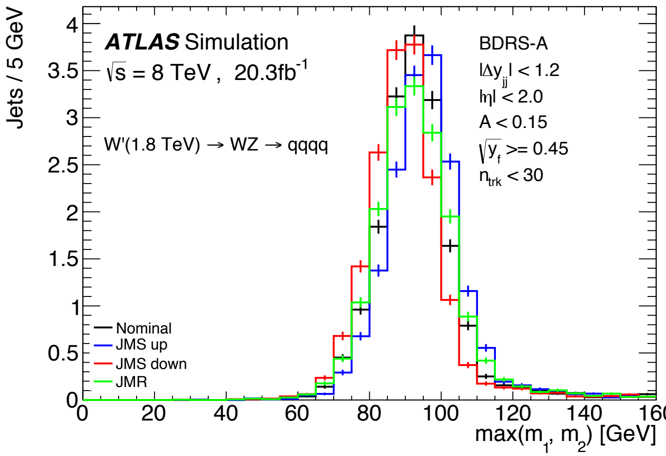
# Kinematic effects?

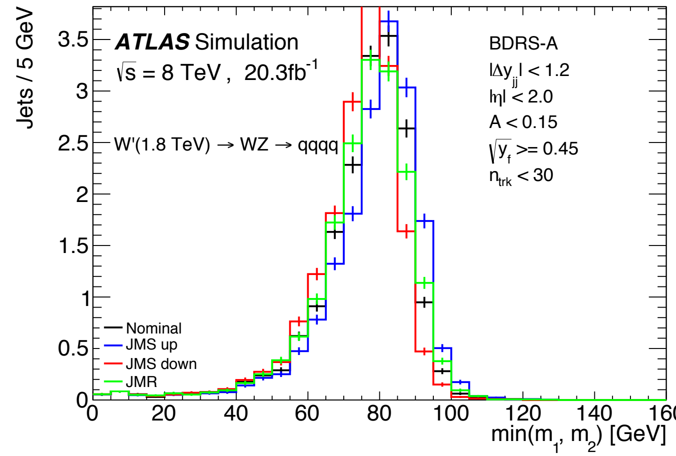


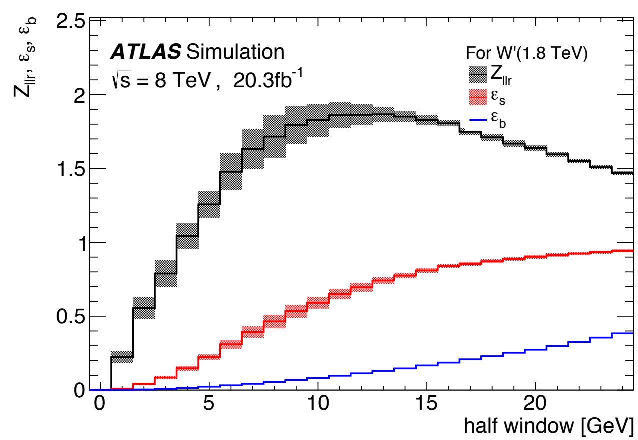

(a) Single boson tagging requirement applied

(b) All tagging requirements except one applied

# Mass window optimization



# Summary of the boson tagging selection

| Channel | Selection |
|---|---|
| ***llqq*** | $70 < m_J < 110$ GeV<br>$\sqrt{y} > 0.45$ |
| ***lvqq*** | $65 < m_J < 105$ GeV<br>$\sqrt{y} > 0.45$ |
| ***JJ*** | $\lvert m_J - m_V \rvert < 13$ GeV<br>$\sqrt{y} > 0.45$<br>$n_{trk} < 30$ |

Due to the large backgrounds in the fully hadronic (JJ) channel a **tight** selection is necessary

In the JJ channel different mass windows are used for W and Z. However, there is a considerable overlap between them (more on this later in the talk)

# Analyses summary - selection

| Channel | Leptons | Jets | $E_T^{miss}$ | Boson Identification |
|---|---|---|---|---|
| $\ell\nu\ell'\ell'$ | 3 leptons<br>$p_T > 25$ GeV | – | $E_T^{miss} > 25$ GeV | $\|m_{ll} - m_Z\| < 20$ GeV |
| $\ell\ell q\bar{q}$ | 2 leptons<br>$p_T > 25$ GeV | 2 small-$R$ jets or 1 large-$R$ jet | – | $\|m_{ll} - m_Z\| < 25$ GeV<br>70 GeV $< m_{jj} <$ 110 GeV<br>70 GeV $< m_J <$ 110 GeV , $\sqrt{y} > 0.45$ |
| $\ell\nu q\bar{q}$ | 1 lepton<br>$p_T > 25$ GeV | 2 small-$R$ jets or 1 large-$R$ jet<br>No $b$-jet with $\Delta R(b, W/Z) > 0.8$ | $E_T^{miss} > 30$ GeV | 65 GeV $< m_{jj} <$ 105 GeV<br>65 GeV $< m_J <$ 105 GeV, $\sqrt{y} > 0.45$ |
| $JJ$ | 0 lepton | 2 large-$R$ jets, $\|\eta\| < 2.0$ | $E_T^{miss} < 350$ GeV | $\|m_{W/Z} - m_J\| < 13$ GeV<br>$\sqrt{y} > 0.45$, $n_{trk} < 30$ |

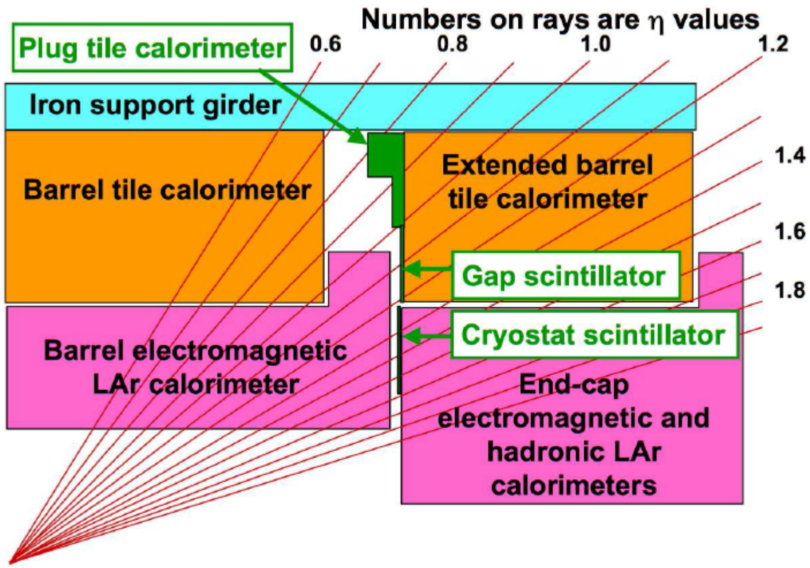
# Analyses summary - regions

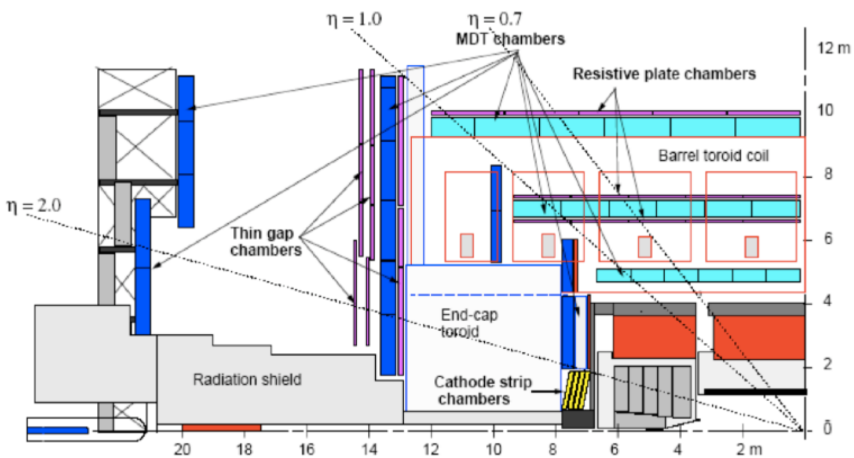
| Channel | High-$p_{\mathrm{T}}$ merged | High-$p_{\mathrm{T}}$ resolved (high mass) | Low-$p_{\mathrm{T}}$ resolved (low mass) |
|---|---|---|---|
| $\ell\nu\ell'\ell'$ | – | $\Delta y(W,Z) < 1.5$ | |
| | | $\Delta\phi(\ell^{3rd}, E_{\mathrm{T}}^{\mathrm{miss}}) < 1.5$ | $\Delta\phi(\ell^{3rd}, E_{\mathrm{T}}^{\mathrm{miss}}) > 1.5$ |
| $\ell\ell q\bar{q}$ | $p_{\mathrm{T}}(\ell\ell) > 400$ GeV<br>$p_{\mathrm{T}}(J) > 400$ GeV | $p_{\mathrm{T}}(\ell\ell) > 250$ GeV<br>$p_{\mathrm{T}}(jj) > 250$ GeV | $p_{\mathrm{T}}(\ell\ell) > 100$ GeV<br>$p_{\mathrm{T}}(jj) > 100$ GeV |
| $\ell\nu q\bar{q}$ | 1 large-$R$ jet, $p_{\mathrm{T}} > 400$ GeV | 2 small-$R$ jets, $p_{\mathrm{T}} > 80$ GeV | 2 small-$R$ jets, $p_{\mathrm{T}} > 30$ GeV |
| | $p_{\mathrm{T}}(\ell\nu) > 400$ GeV | $p_{\mathrm{T}}(jj) > 300$ GeV<br>$p_{\mathrm{T}}(\ell\nu) > 300$ GeV | $p_{\mathrm{T}}(jj) > 100$ GeV<br>$p_{\mathrm{T}}(\ell\nu) > 100$ GeV |
| | $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, j) > 1$ (electron channel) | | |
| $JJ$ | $\lvert\Delta y_{12}\rvert < 1.2$<br>$m(JJ) > 1.05$ TeV | – | |

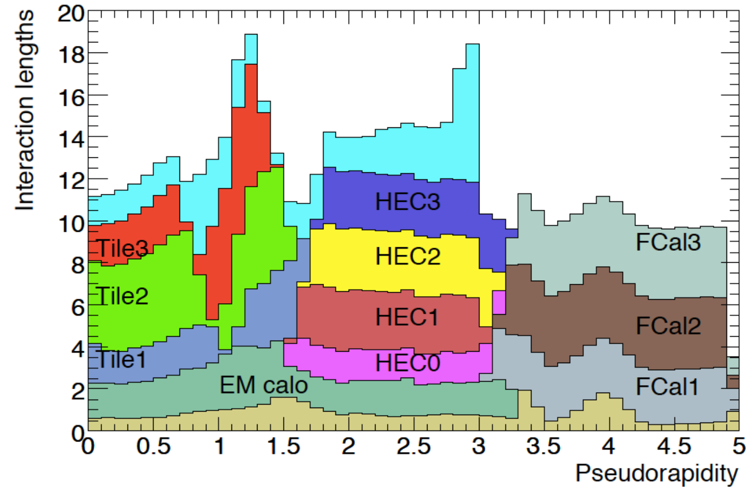
# Analyses summary - contributions

| Channel | Signal Region | $W'$ mass range [TeV] | $G^*$ mass range [TeV] |
|---|---|---|---|
| $\ell\nu\ell'\ell'$ | low-mass | 0.2-1.9 | – |
| | high-mass | 0.2-2.5 | – |
| $\ell\ell q\bar{q}$ | low-$p_{\mathrm{T}}$ resolved | 0.3-0.9 | 0.2-0.9 |
| | high-$p_{\mathrm{T}}$ resolved | 0.6-2.5 | 0.6-0.9 |
| | merged | 0.9-2.5 | 0.9-2.5 |
| $\ell\nu q\bar{q}$ | low-$p_{\mathrm{T}}$ resolved | 0.3-0.8 | 0.2-0.7 |
| | high-$p_{\mathrm{T}}$ resolved | 0.6-1.1 | 0.6-0.9 |
| | merged | 0.8-2.5 | 0.8-2.5 |
| $JJ$ | $WZ$ selection | 1.3-2.5 | – |
| | $WW$+$ZZ$ selection | – | 1.3-2.5 |

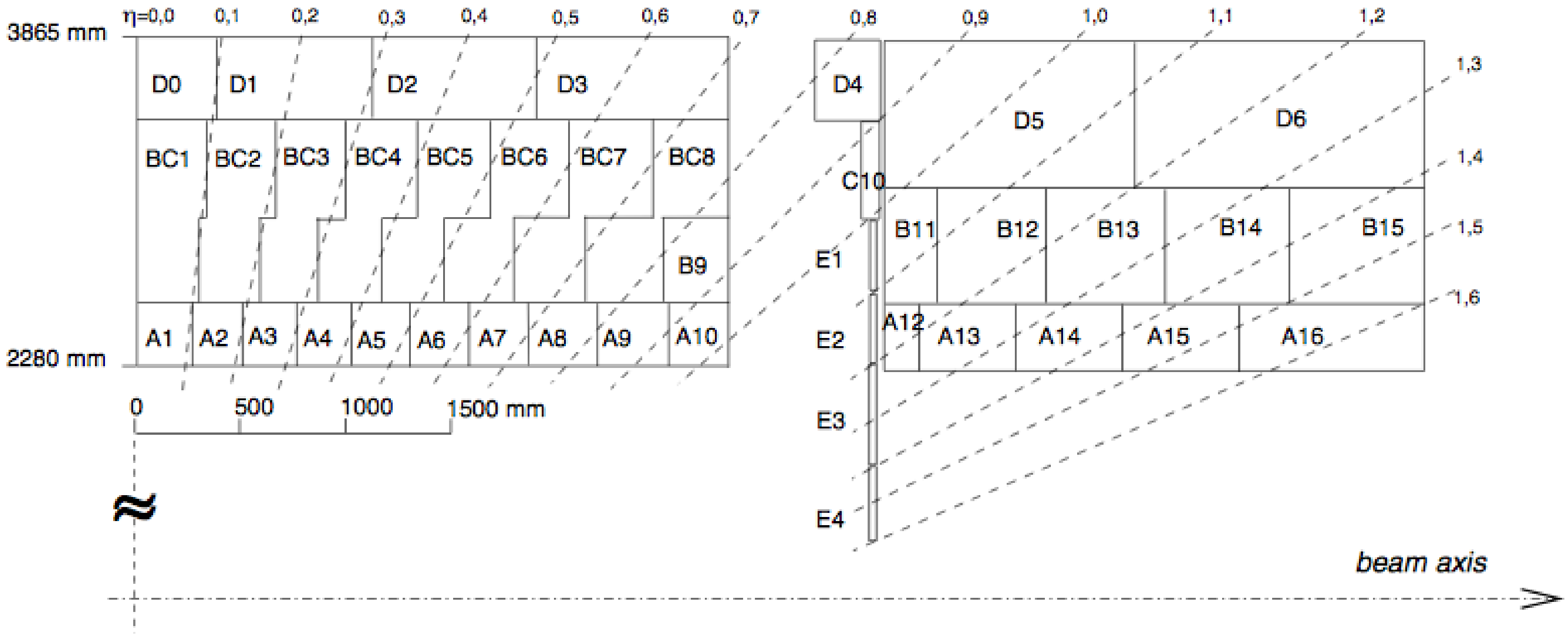
# ATLAS detector

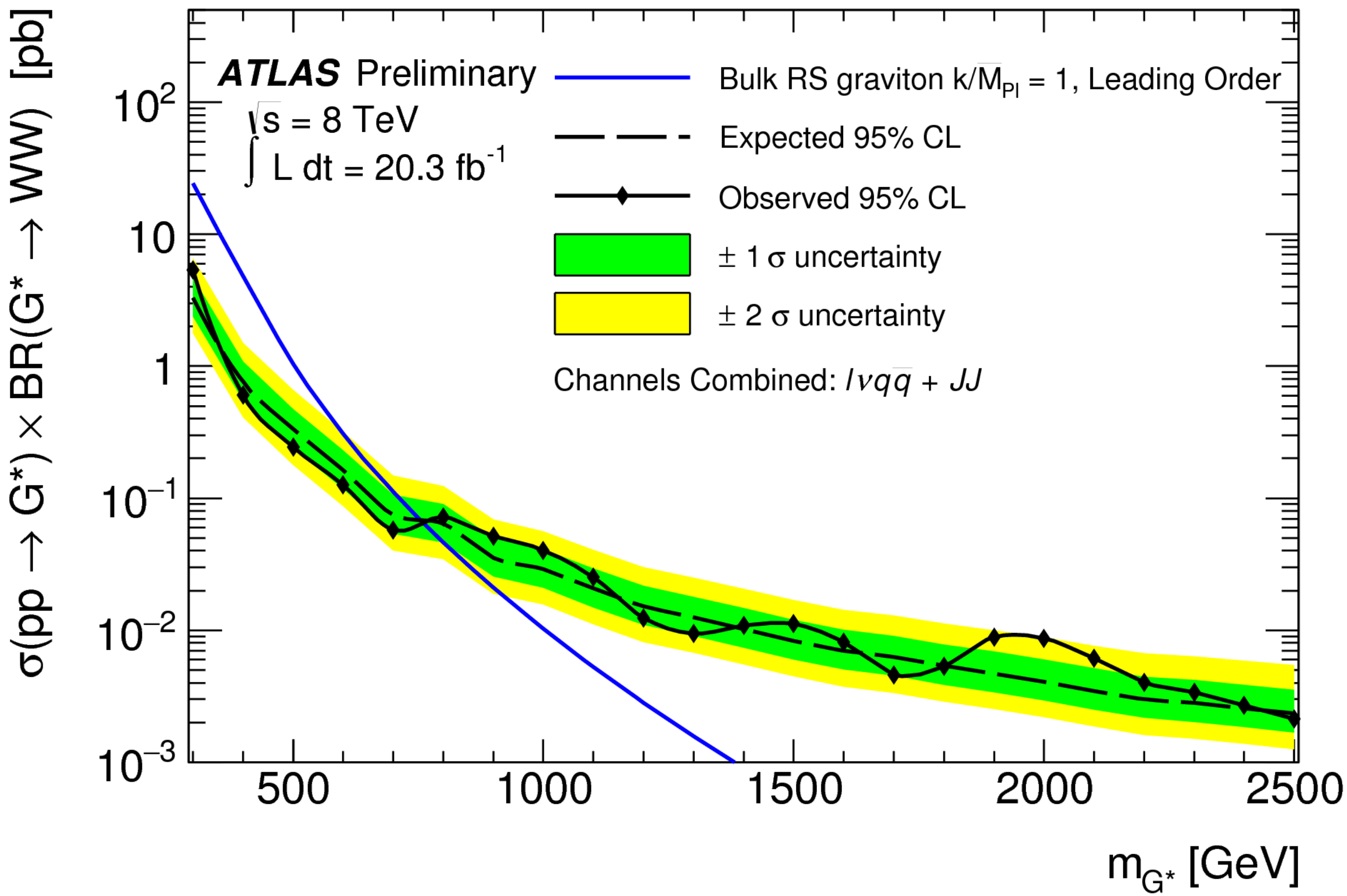


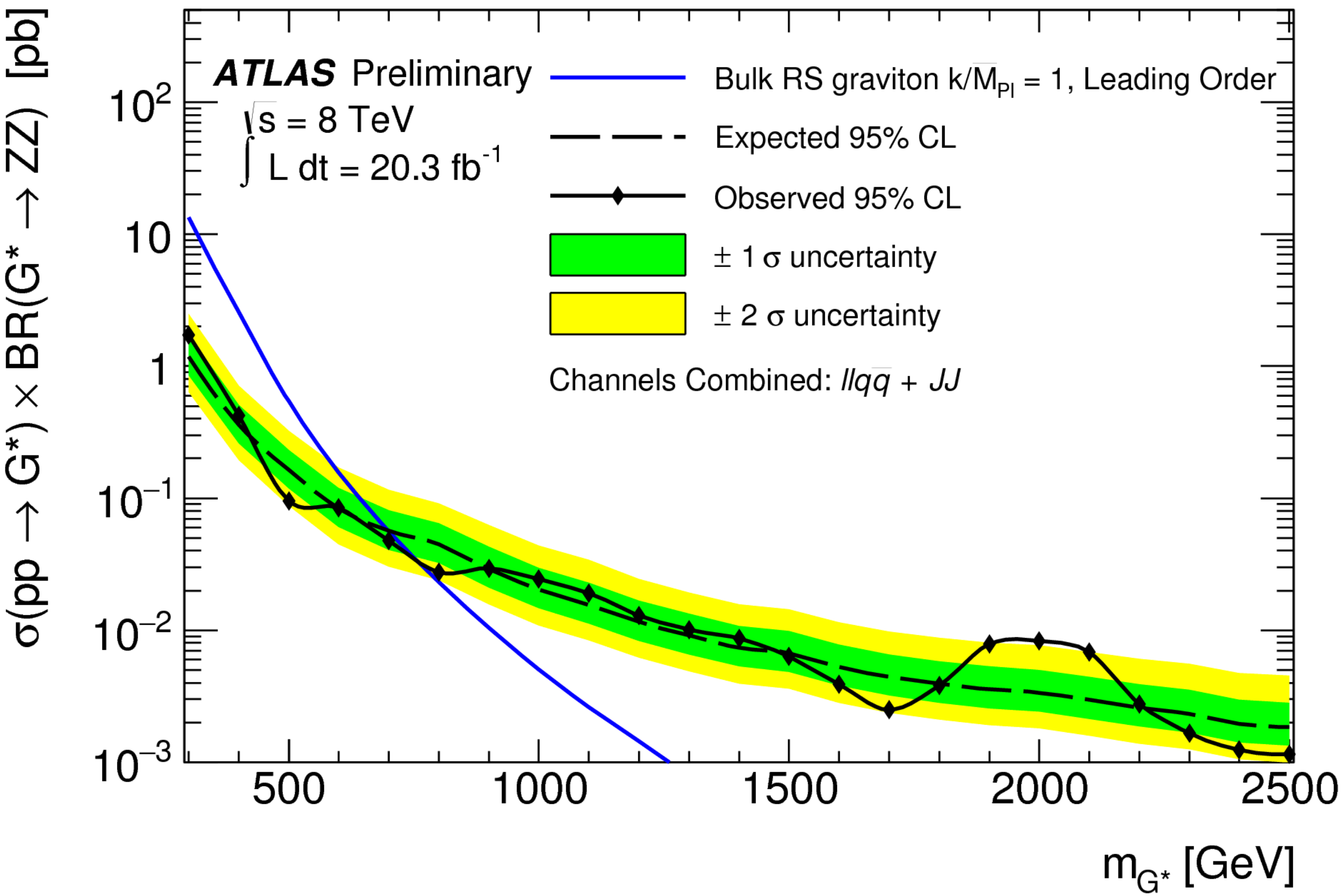



# ATLAS tile calo sectioning




ATLAS Preliminary
√s = 8 TeV
∫ L dt = 20.3 fb⁻¹
Bulk RS graviton k/M̄Pl = 1, Leading Order
Expected 95% CL
Observed 95% CL
± 1 σ uncertainty
± 2 σ uncertainty
Channels Combined: lνqq̄ + JJ
σ(pp → G*) × BR(G* → WW) [pb]
m_G* [GeV]
10²
10
1
10⁻¹
10⁻²
10⁻³
500
1000
1500
2000
2500


ATLAS Preliminary
$\sqrt{s}$ = 8 TeV
$\int L\,dt$ = 20.3 fb$^{-1}$
Bulk RS graviton $k/\overline{M}_{Pl}$ = 1, Leading Order
Expected 95% CL
Observed 95% CL
± 1 σ uncertainty
± 2 σ uncertainty
Channels Combined: $ll q\bar{q}$ + $JJ$
$\sigma(pp \rightarrow G^*) \times BR(G^* \rightarrow ZZ)$ [pb]
$m_{G^*}$ [GeV]
$10^2$
10
1
$10^{-1}$
$10^{-2}$
$10^{-3}$
500
1000
1500
2000
2500