

Observation of electroweak $WZjj$ production and studies on pileup mitigation with the ATLAS Detector

Ph.D. thesis defence - Thursday October 1, 2020

Louis Portales

Ph.D. candidate (LAPP, USMB)

Supervised by

Iro Koletsou & Emmanuel Sauvan



Content

> Standard Model and VBS

- Theory motivations
- Experimental challenges

> Experimental setup

- The LHC
- The ATLAS detector
- Particles reconstruction

> WZjj-EW observation

- Analysis design and challenges
- Signal extraction and WZjj-EW first observation

> Forward pileup jet tagging

- Base tools & current limitations
- Multivariate tagger development
- Tagging efficiency correction

Content

> Standard Model and VBS

- Theory motivations
- Experimental challenges

> Experimental setup

- The LHC
- The ATLAS detector
- Particles reconstruction

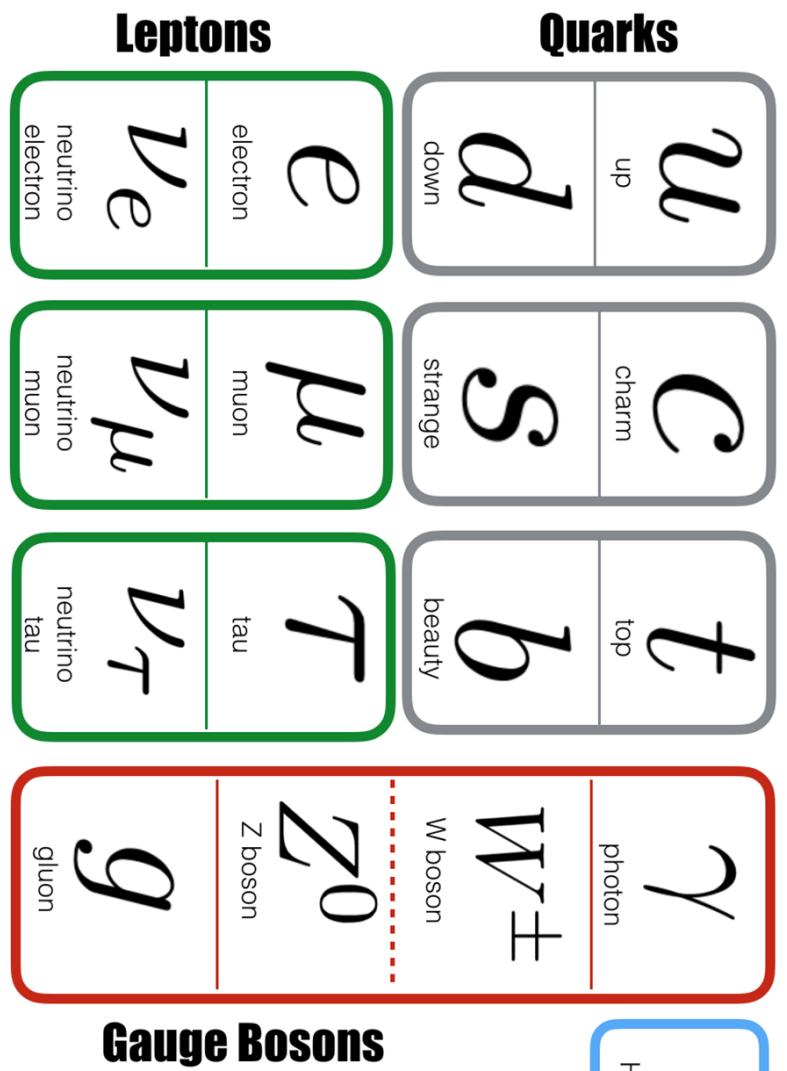
> WZjj-EW observation

- Analysis design and challenges
- Signal extraction and WZjj-EW first observation

> Forward pileup jet tagging

- Base tools & current limitations
- Multivariate tagger development
- Tagging efficiency correction

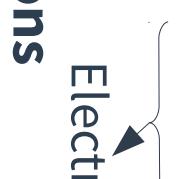
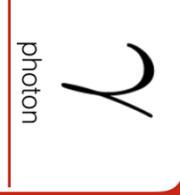
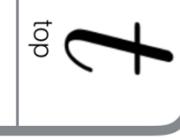
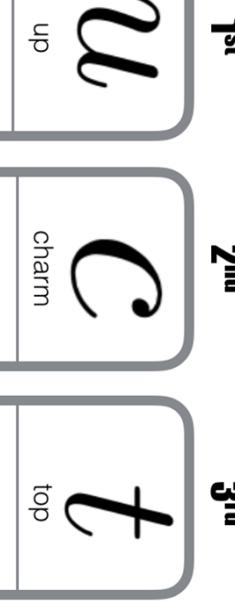
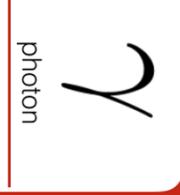
The Standard Model



> Quantum field theory

- $SU(3) \times SU(2) \times U(1)$ invariant

\downarrow
Strong Electroweak
 \curvearrowright
Fermions



- Quarks & Leptons
- Matter particles

> Gauge bosons

- Carriers of the interactions

> Higgs boson

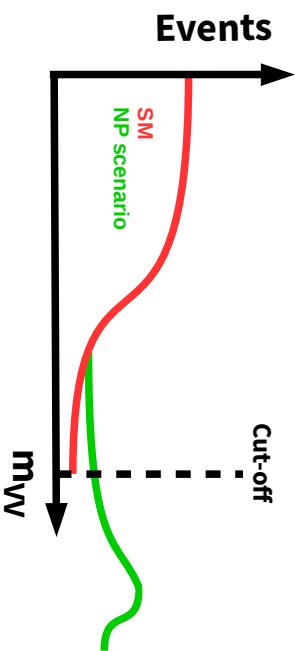
- Scalar boson
- Linked to EWSB mechanism
- Observed in 2012

The Standard Model – Experimental status

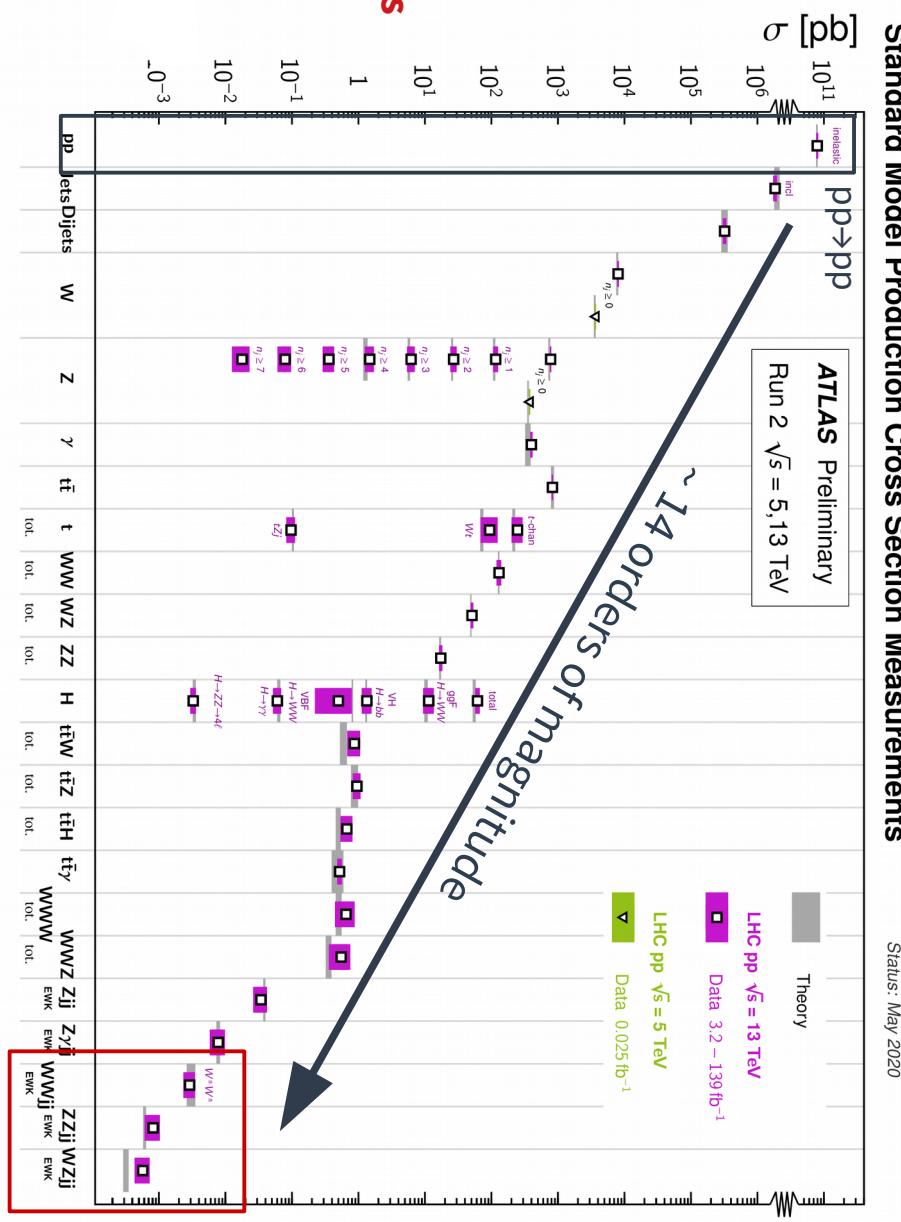
> **SM extensively tested**

- Current main physics goals

- Higgs boson properties
- Search for new physics
- **Accessible through rare SM processes**



~14 orders of magnitude



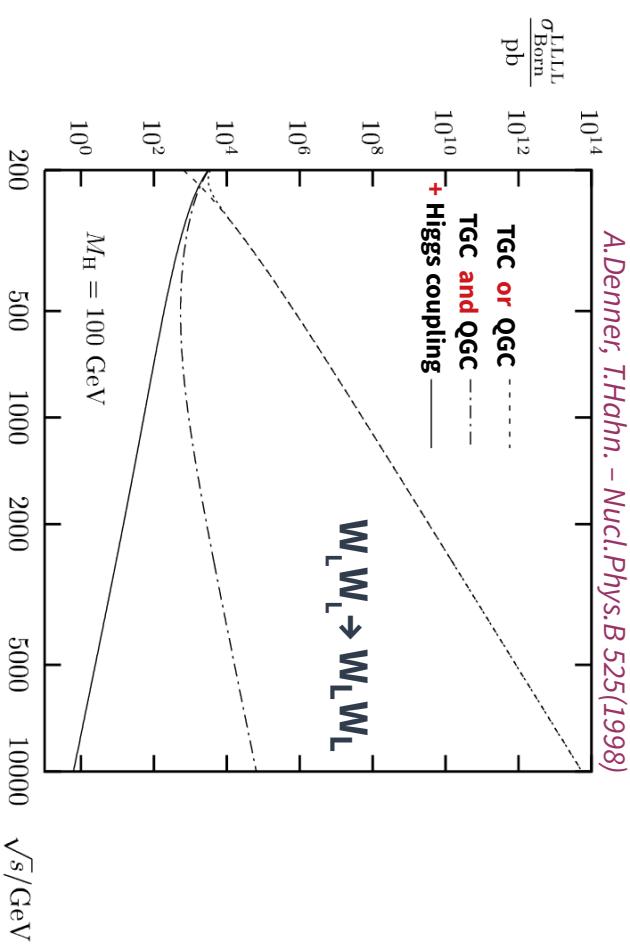
Vector Boson Scattering

> **VVjj-EW production**

- $\mathcal{O}(\alpha^6)$ processes for $V = W, Z$
- Includes **Vector Boson Scattering (VBS)**

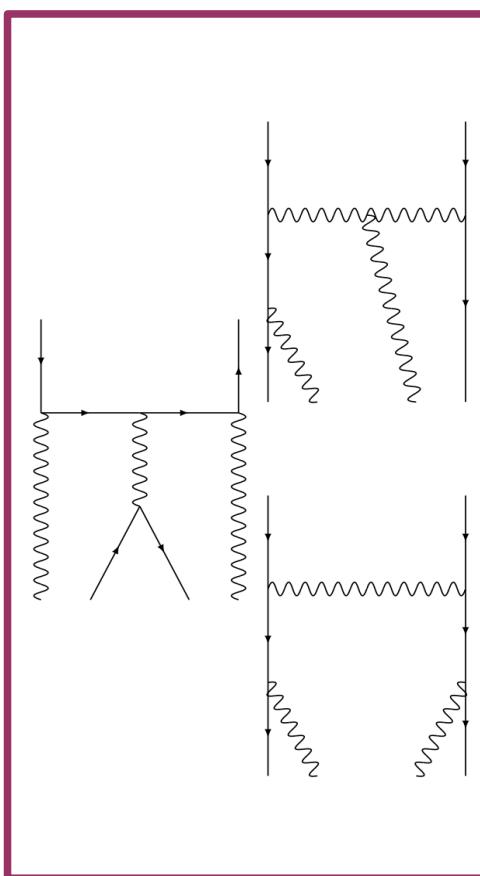
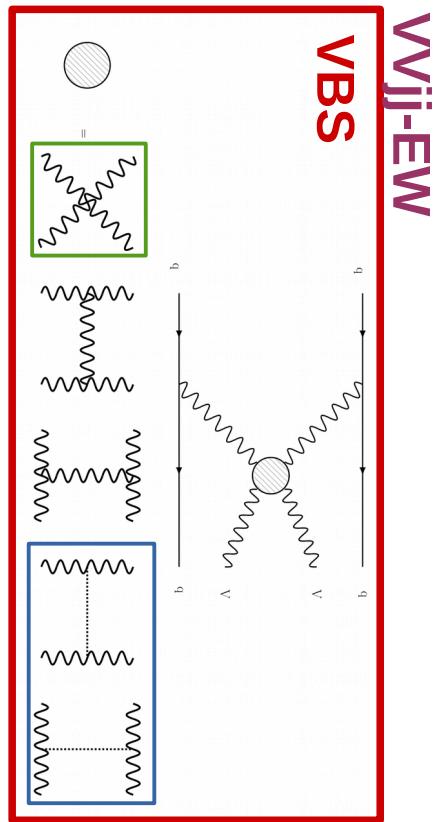
> Important process to constrain (B)SM

- **(anomalous) quartic gauge coupling**
- **Higgs sector:** $V V \rightarrow V_L V_L$ unitarity



VVjj-EW

VBS



Experimental considerations

> Many VBS channels

- ~90% of decays include qq pair(s)

- **Fully leptonic** decays preferred for observation

→ Small Branching Ratios ~ 1-9%

→ **Small cross-sections** – $\mathcal{O}(1 \text{ fb})$

Process	$W^\pm W^\pm jj \rightarrow \ell^\pm \ell^\pm \nu_\ell \nu_{\ell'}$	$WZjj \rightarrow \ell^+ \ell^- \ell'^\pm \nu_{\ell'}$	$ZZjj \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$
$\sigma(pp \rightarrow X) [\text{fb}] (\text{EW})$	3.97	2.34	0.098
$\sigma(pp \rightarrow X) [\text{fb}] (\text{QCD})$	0.35	4.38	0.1
EW/QCD	~ 10	~ 0.5	~ 1

> First **Wjj-EW observation: ssWWjj-EW**

CMS Collaboration – PLB 120 (2018) 8, 081801

- Largest cross-section, large fake background

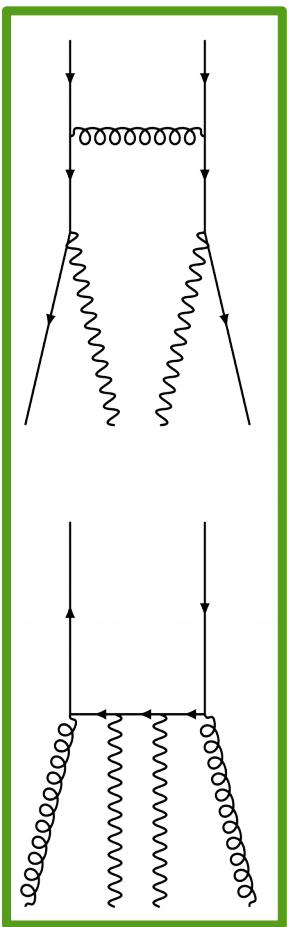
- Only limits on other channels

> Focus on **WZjj-EW production**

- Second-to-best cross-section

- Clearer final state ($l l l \nu + jj$) → lower fake rate

- Larger $\mathcal{O}(\alpha^4 \alpha_S^2)$ **WZjj-QCD background** → Similar topology as signal



VBS signature

> WZjj-EW has specific signature

> **Vector bosons centrally emitted**

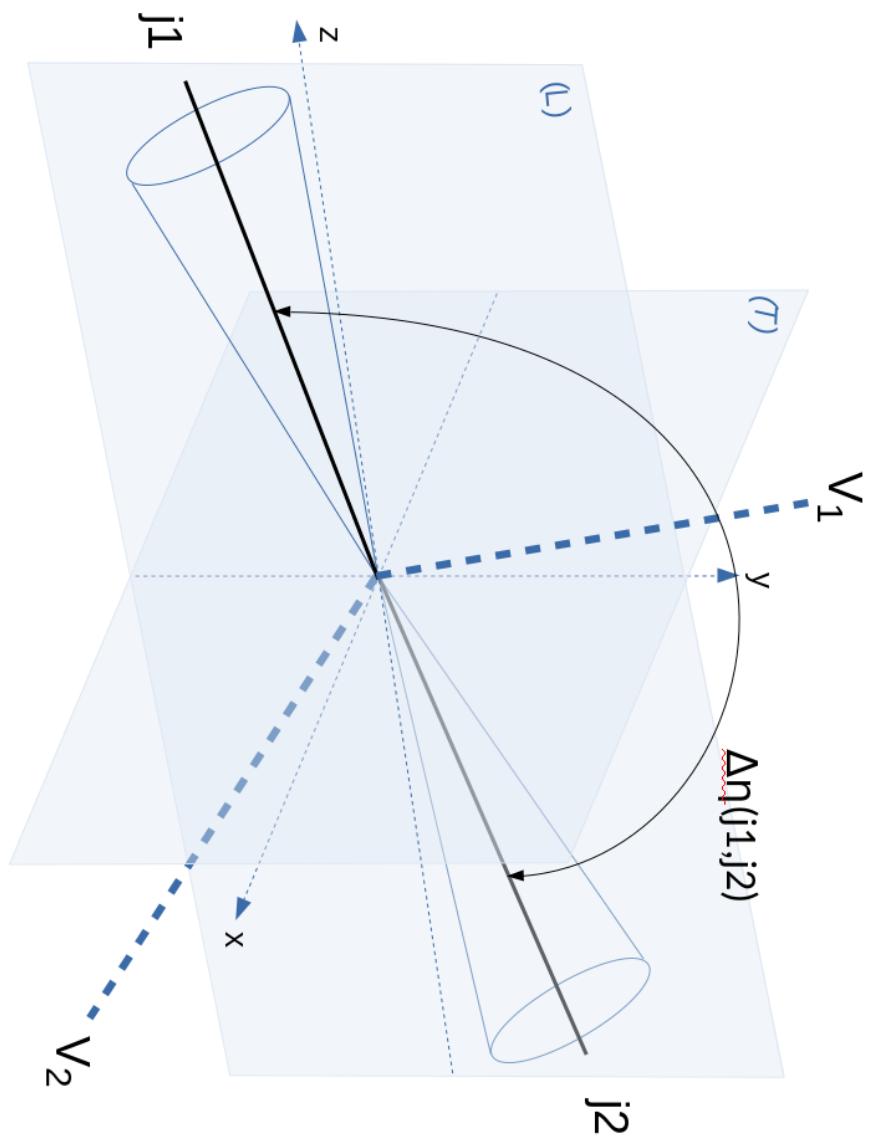
> **Forward quark-jets**

→ Large angular separation

→ High invariant mass

→ **Main tool** to characterise/reduce

WZjj-QCD contamination

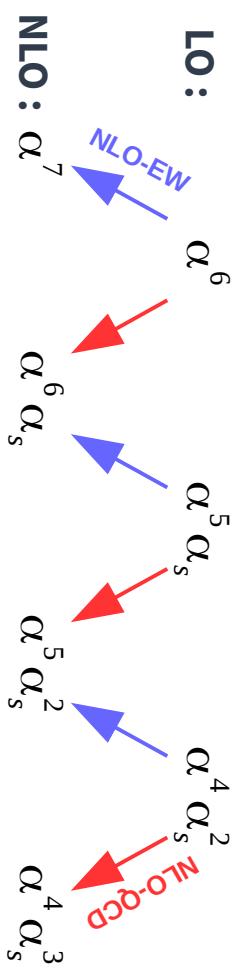


Theoretical considerations – Modelling

> WZjj-EW/WZjj-QCD separation studied in Monte Carlo simulations

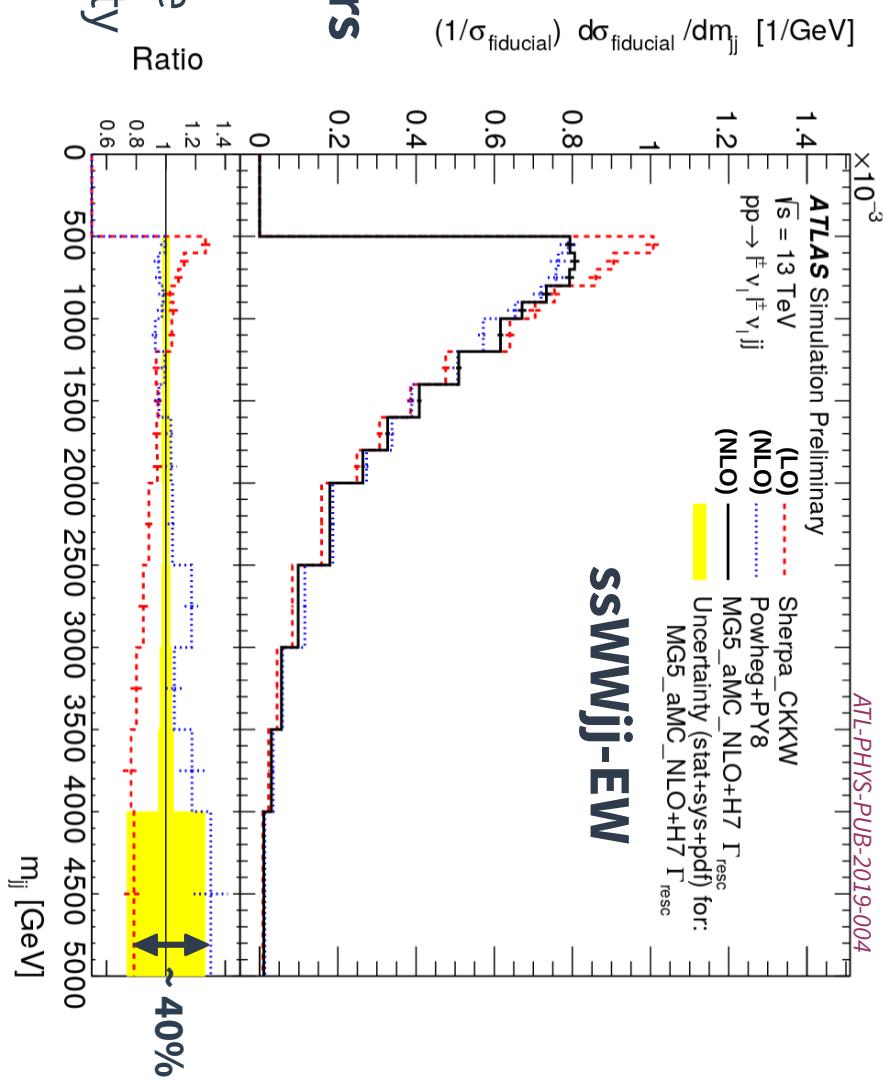
> LO generators still mostly used

WZjj-EW **Interference** **WZjj-QCD**



> Large difference between generators

- Mostly QCD-related
- NLO-QCD & approximations disagree
- Concerns jet kinematics & multiplicity



Theoretical considerations – Higher order corrections

> Important NLO-EW corrections

WZjj-EW

Interference

WZjj-QCD

L0: α^6

NLO: α^7

NLO-EW: $\alpha^6 \alpha_s$

Interference: $\alpha^5 \alpha_s$

NLO-QCD: $\alpha^4 \alpha_s^2$

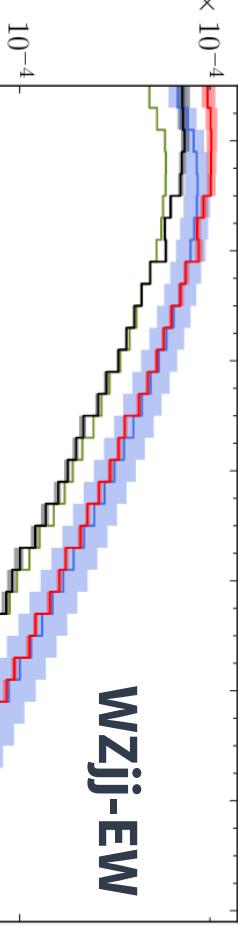
NLO-QCD: $\alpha^5 \alpha_s^2$

NLO-QCD: $\alpha^4 \alpha_s^3$

$d\sigma/dM_{jjj_2} [\text{fb GeV}^{-1}]$

A.Denner et al. – JHEP, 67(2019)

WZjj-EW

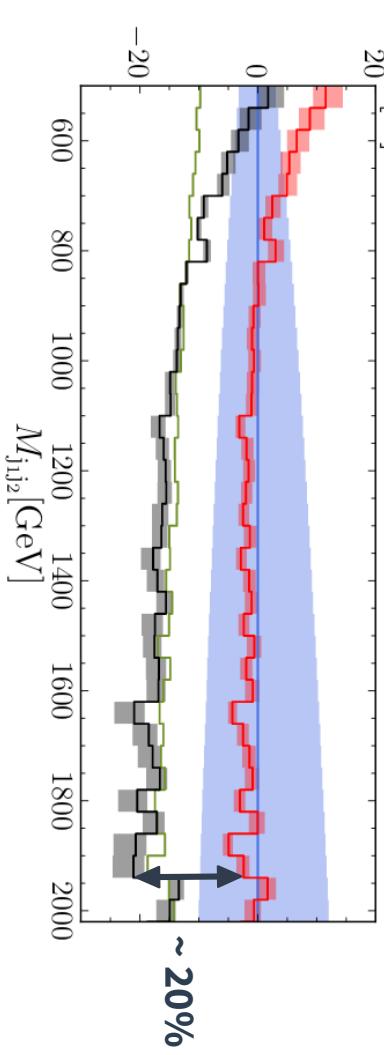


– Only recently computed

→ WW (2017): B.Biedermann et al. – JHEP, 124(2017)

→ WZ (2019): A.Denner et al. – JHEP, 67(2019)

→ ZZ (2020): A.Denner et al. – (Preprint) arXiv:2009.00



Content

> Standard Model and VBS

- Theory motivations
- Experimental challenges

> Experimental setup

- The LHC
- The ATLAS detector
- Particles reconstruction

> WZjj-EW observation

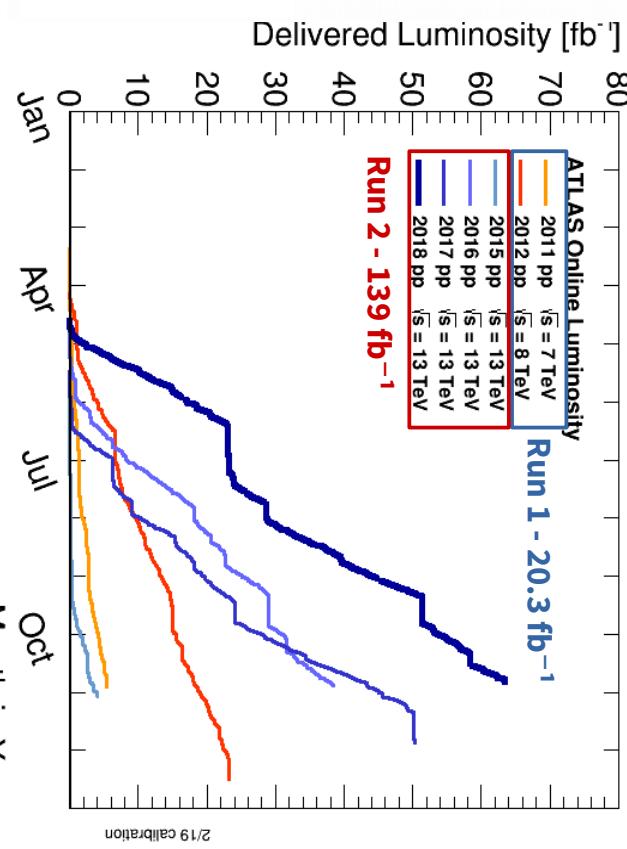
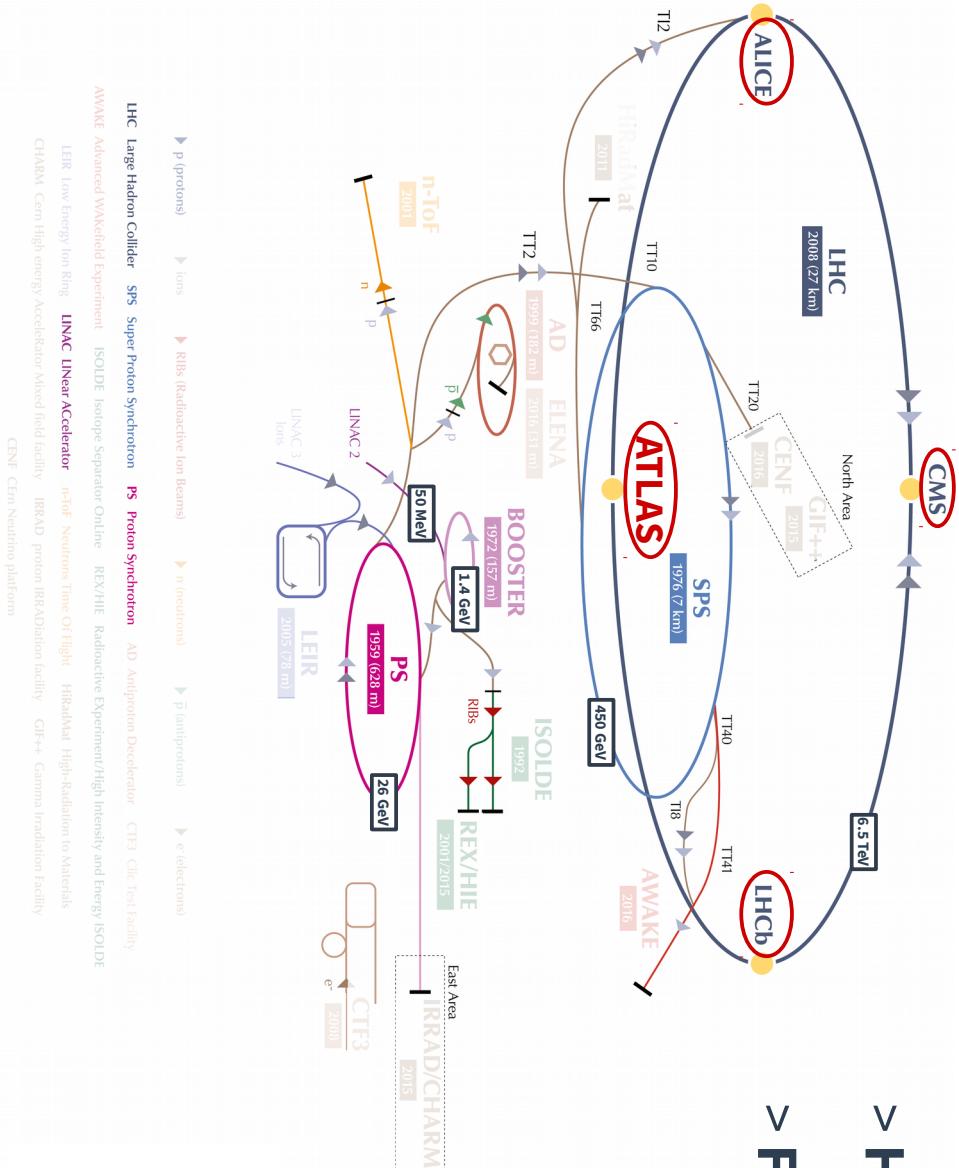
- Analysis design and challenges
- Signal extraction and WZjj-EW first observation

> Forward pileup jet tagging

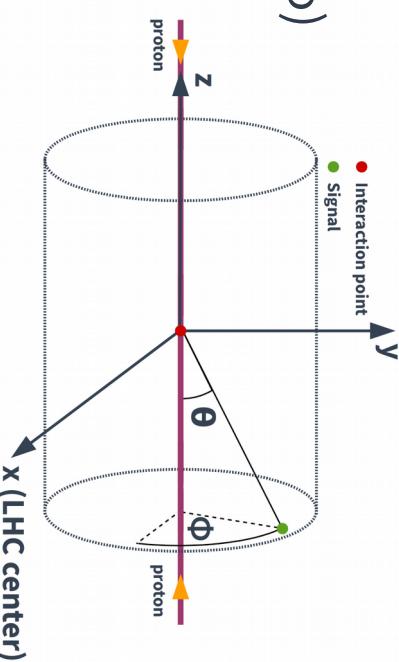
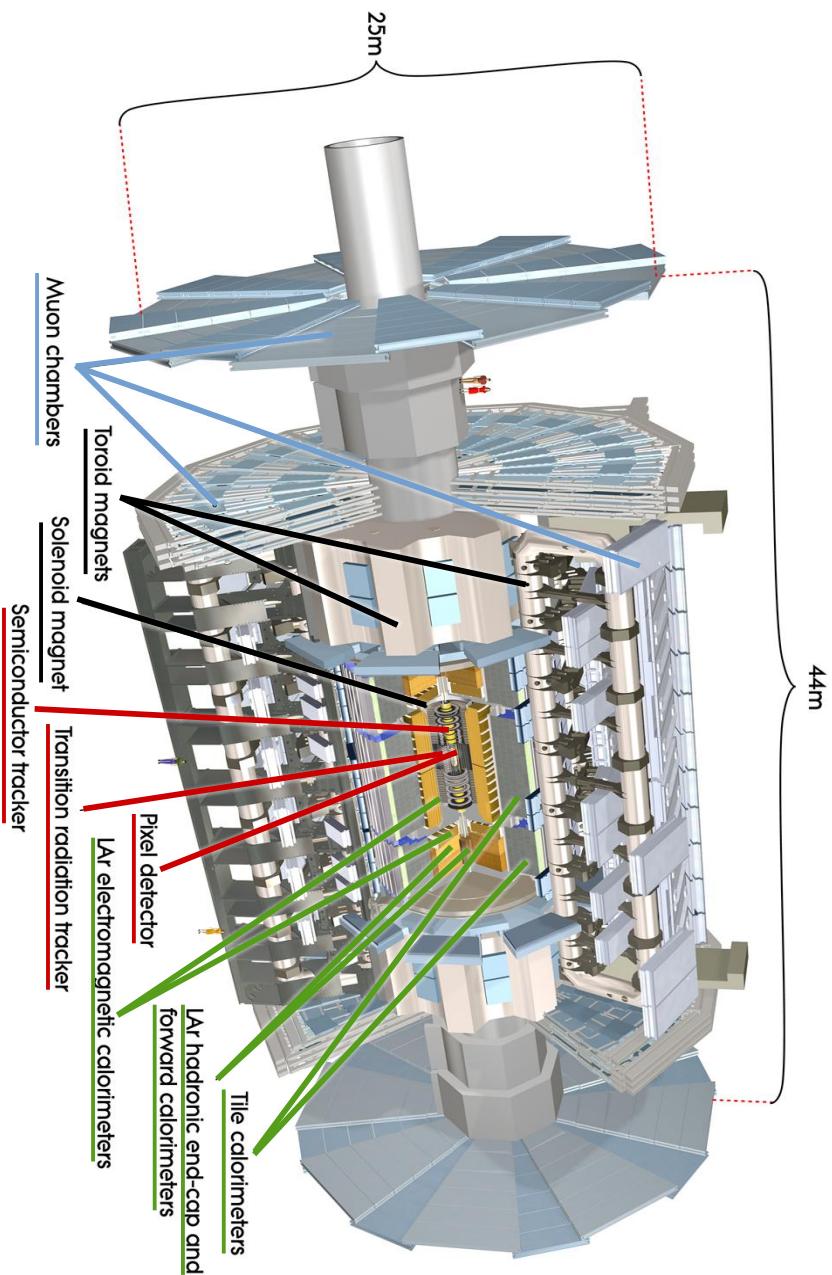
- Base tools & current limitations
- Multivariate tagger development
- Tagging efficiency correction

CERN accelerator complex and the Large Hadron Collider

> Proton collisions, up-to $\sqrt{s}=13$ TeV
 > High collision frequency ~ 40 MHz
 > Four large-scale experiments



The ATLAS detector



→ Coordinates expressed as (η, ϕ)

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

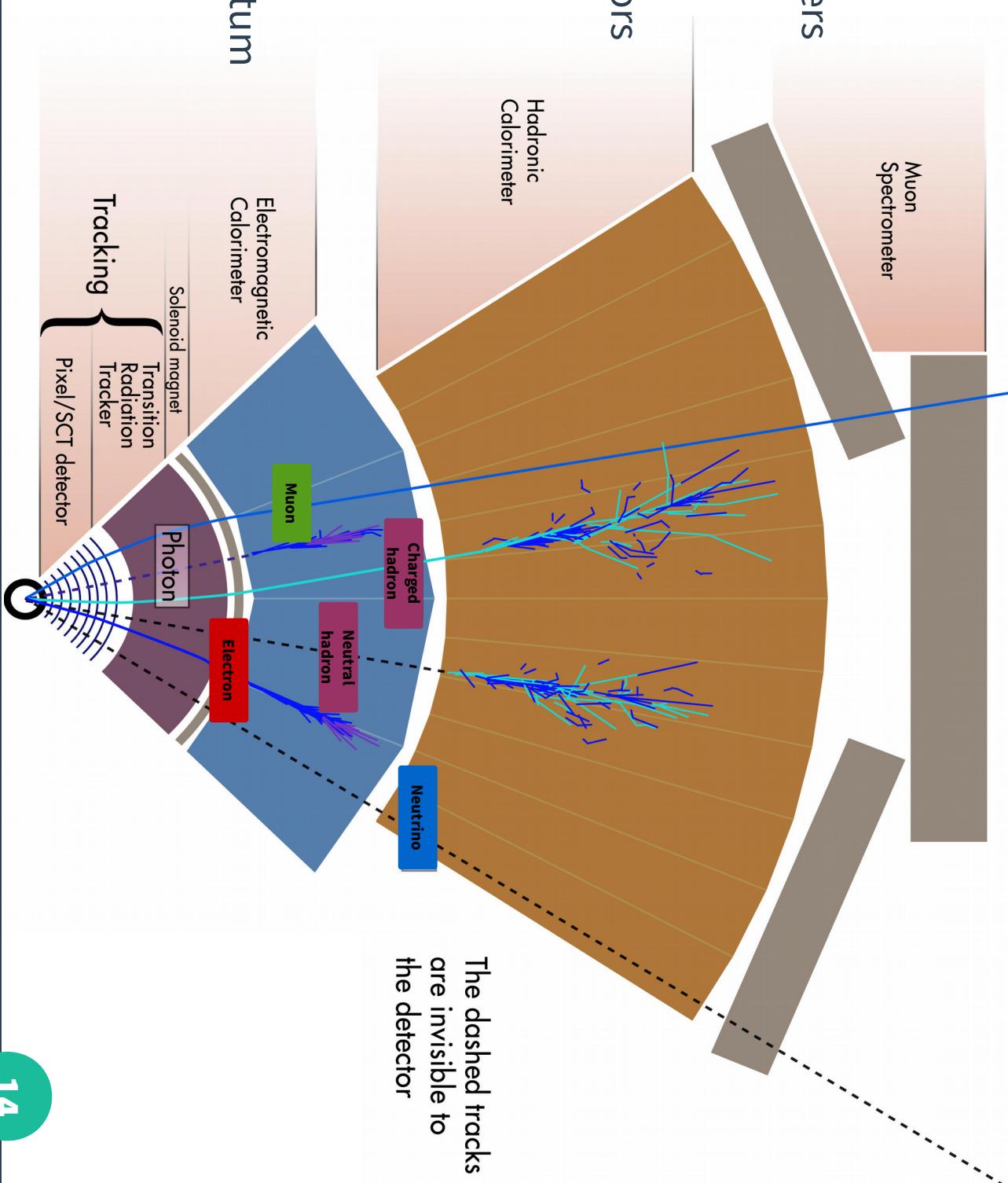
- > **Muon Spectrometer**
 - Muon tracks

$$\frac{\sigma_{p_T}}{p_T} \simeq 1\% - 3\%$$

- > **Calorimeters**
 - Charged particles tracks
 - EMC Cal: e/ γ energy
 - $$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E [GeV]}} \oplus 0.7\%$$
 - HCal: hadrons energy
 - $$\frac{\sigma_E}{E} = \frac{53\%}{\sqrt{E [GeV]}} \oplus 3\%$$
- > **Inner Detector**
 - Solenoid: $B = 2\text{ T}$
 - Toroids: $B = 4\text{ T}$

Particle detection and reconstruction

- > **Electrons**
 - ID track + EMCal clusters
- > **Muons**
 - Track in all subdetectors
- > **Hadrons (Jets)**
 - EMCal/HCal clusters (+ ID tracks)
- > **Neutrinos**
 - From missing momentum

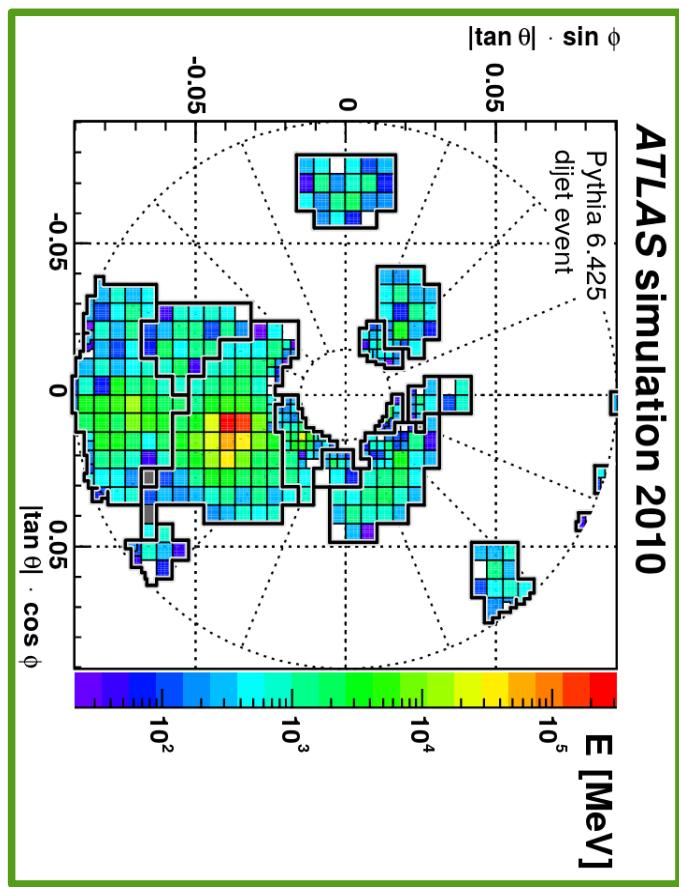
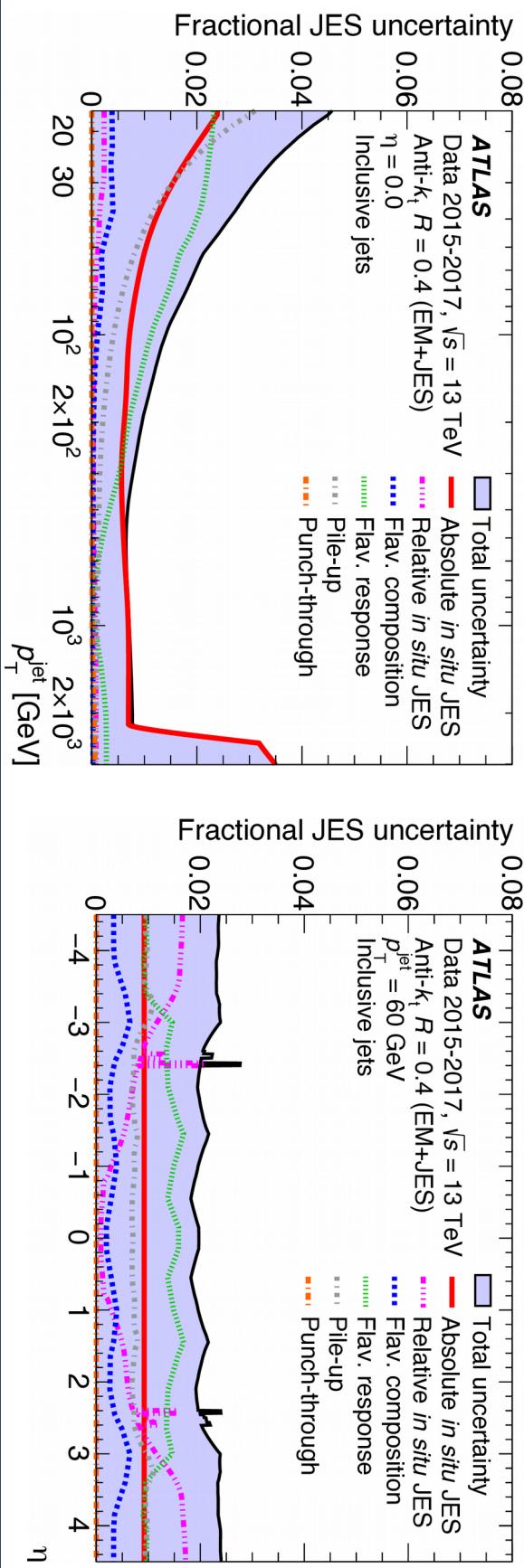


Jet reconstruction & performance

EMTopo jets: “historical” approach

- 1 Build **Topoclusters** from neighbouring calorimeter cells ($|E_{\text{cell}}| > 2\sigma_{\text{noise}}$)
- 2 Identify most energetic cluster, combine neighbouring clusters using **Anti- k_T** ($R=0.4$):

$$\min(k_{T,i}^{-2}, k_{T,j}^{-2}) \frac{\Delta R_{ij}}{R^2} < k_{T,i}^{-2}$$



Content

> Standard Model and VBS

- Theory motivations
 - Experimental challenges

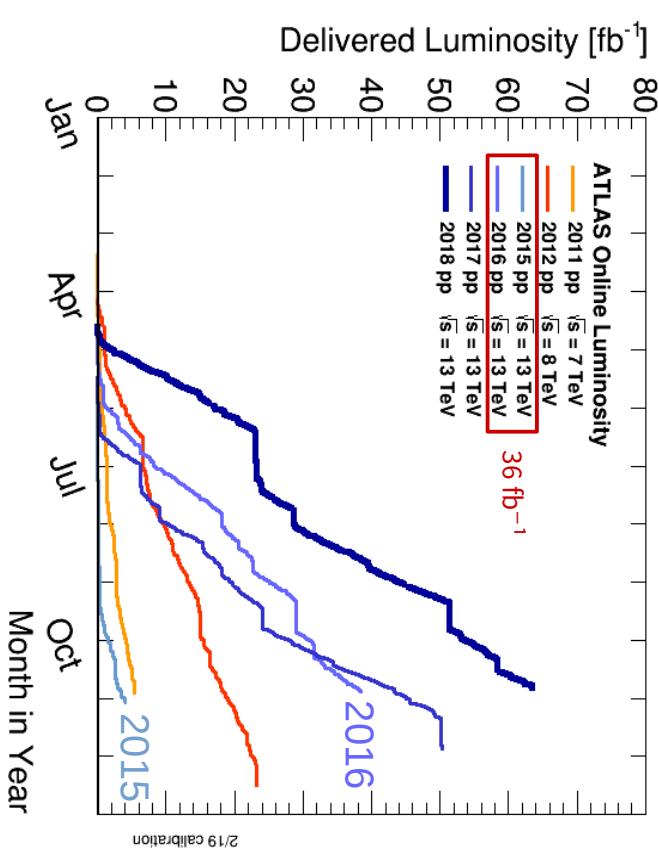
> Experimental setup

- The LHC
 - The ATLAS detector
 - Particles reconstruction

> WZjj-EW observation

- Analysis design and challenges
 - Signal extraction and WZjj-EW first observation

> Forward pileup jet tagging



VBS selection

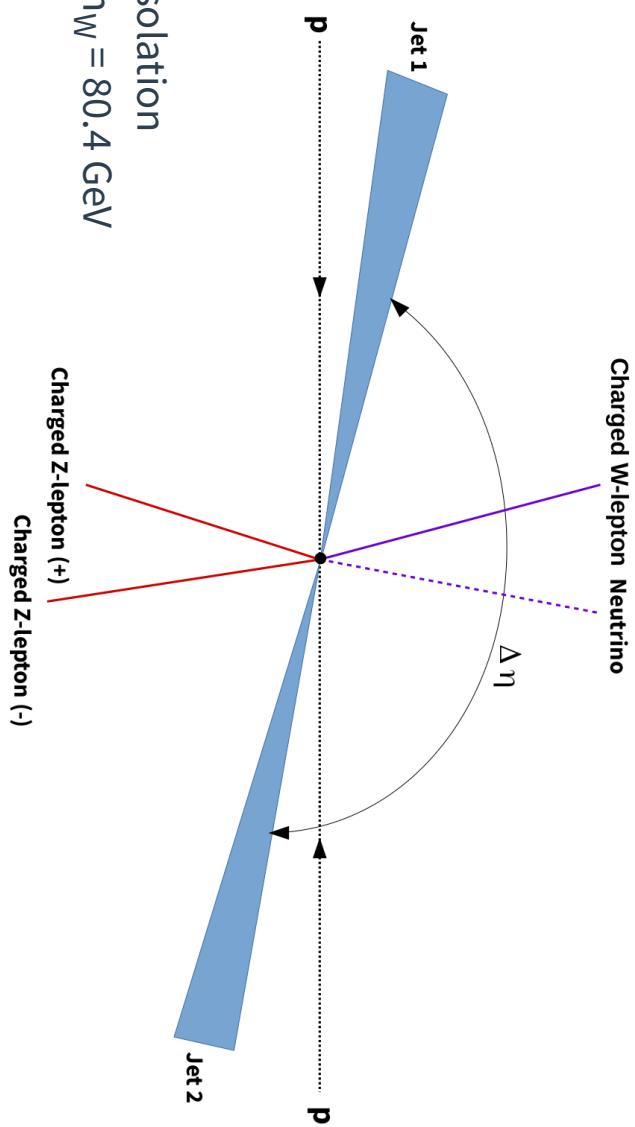
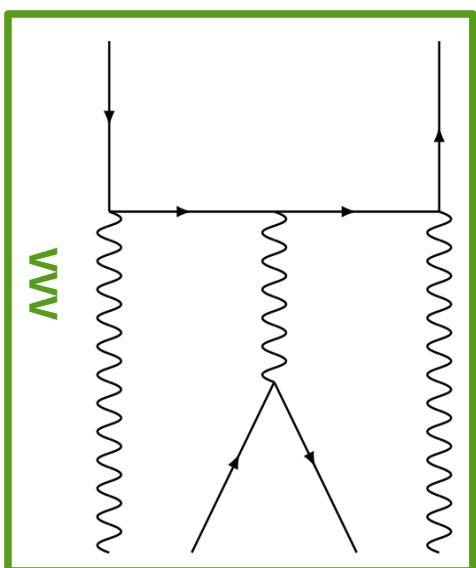
> Single-lepton triggers (e/μ)

> Leptons & Bosons

- Exactly 3 isolated leptons
- Z boson: 2 SFOS “ Z leptons”, $|m_{ll} - m_Z| < 10$ GeV
- W boson: $\rightarrow 3^{\text{rd}}$ lepton: $p_T > 20$ GeV + tightened isolation
 \rightarrow matched to E_T^{miss} (neutrino), fixing $m_W = 80.4$ GeV

> Jets

- At least two (EMTopo) jets
- $p_T > 40$ GeV \rightarrow **JES impact reduction**
- In opposite hemispheres ($\eta_{j1}\eta_{j2} < 0$)
 \rightarrow **Tagging jets**
- $m_{jj} > 150$ GeV \rightarrow **VBS selection**



VBS selection

> **WZjj-EW signal**

- Subdominant

> **WZjj-QCD background**

- Largely dominant

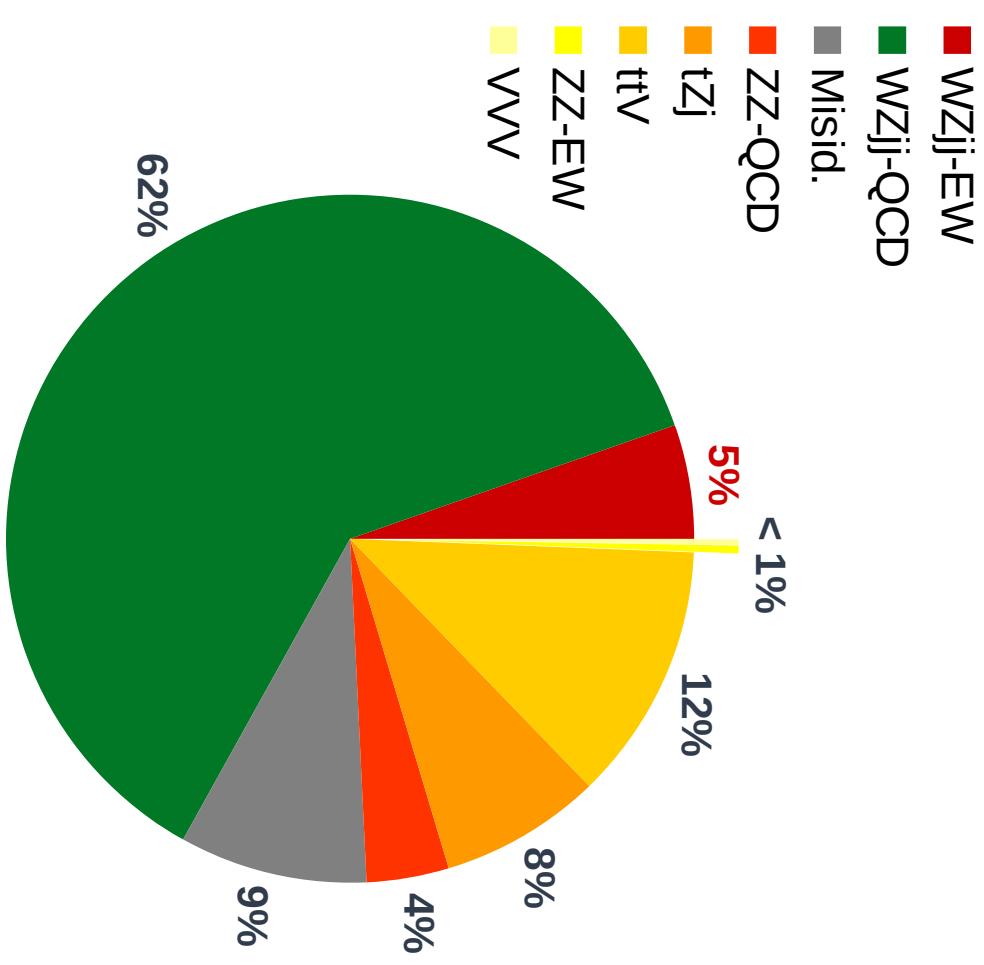
> **“Irreducible” background**

- Same final-state particle content as signal
- **Or** Additional particles not reconstructed

→ **tZj, ttV, ZZ**

> **“Reducible” background**

- Misidentified leptons
- **tt, Z+jets, Zy**
- Data-driven estimate used (Matrix Method)



VBS selection

Strategy overview

- > Signal extraction strategy designed to deal with low signal purity
- > **Necessity to control backgrounds**
- > **WZjj-EW and WZjj-QCD separation**
- > **Low statistics in signal-pure regimes**

Strategy overview

- > **Signal extraction strategy designed to deal with low signal purity**
- > **Necessity to control backgrounds**
 - High- m_{jj} Signal Region (SR) + additional regions for background control
- > **WZjj-EW and WZjj-QCD separation**
 - Multivariate discriminant in SR
- > **Low statistics in signal-pure regimes**
 - Combined likelihood fit (SR + CR)
- > **Analysis optimised with Blinded SR**

VBS selection splitting

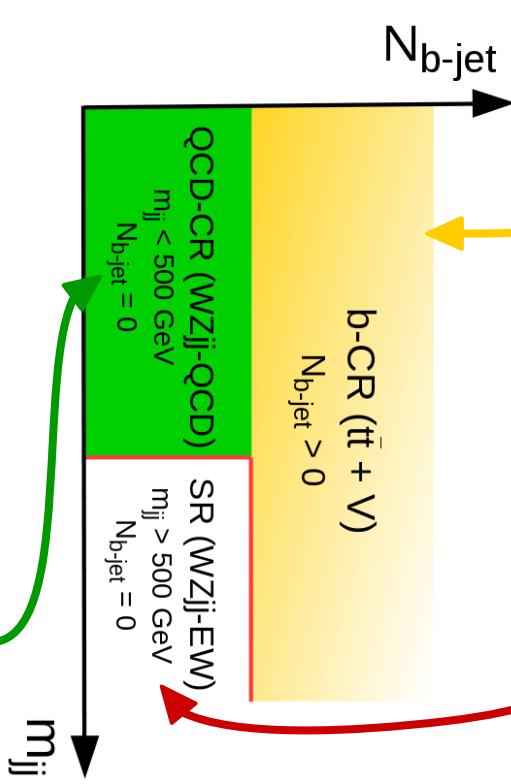
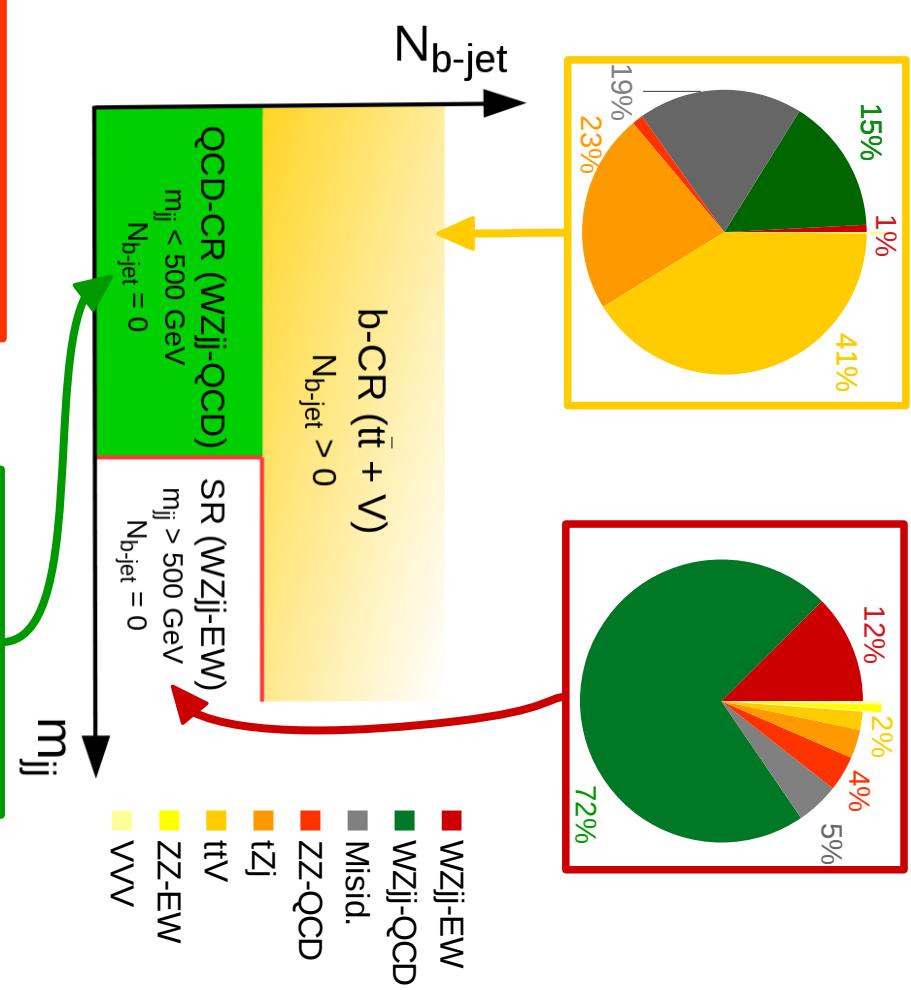
> VBS selection split in three regions

- **Signal Region** → $N_{b\text{-jet}} = 0, m_{jj} > 500 \text{ GeV}$
- **QCD-CR** → $N_{b\text{-jet}} = 0, m_{jj} < 500 \text{ GeV}$
- **b-CR** → $N_{b\text{-jet}} > 0$

> Additional region for ZZ background

- ZZ-CR

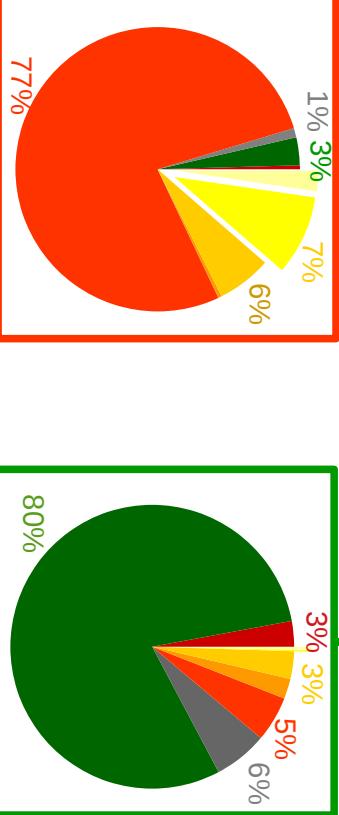
→ Same as VBS selection, but exactly 4 leptons



- WZjj-EW
- ZZ-QCD
- tZj
- ttV
- ZZ-EW
- VVV

> WZjj-EW purity in SR still low

- MV discriminant justified further

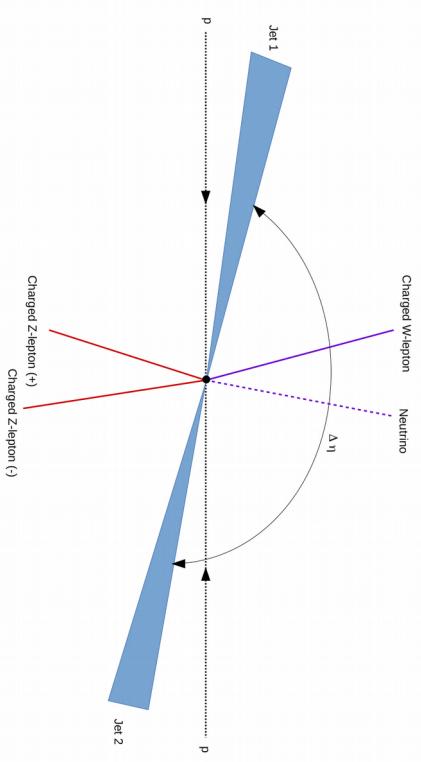
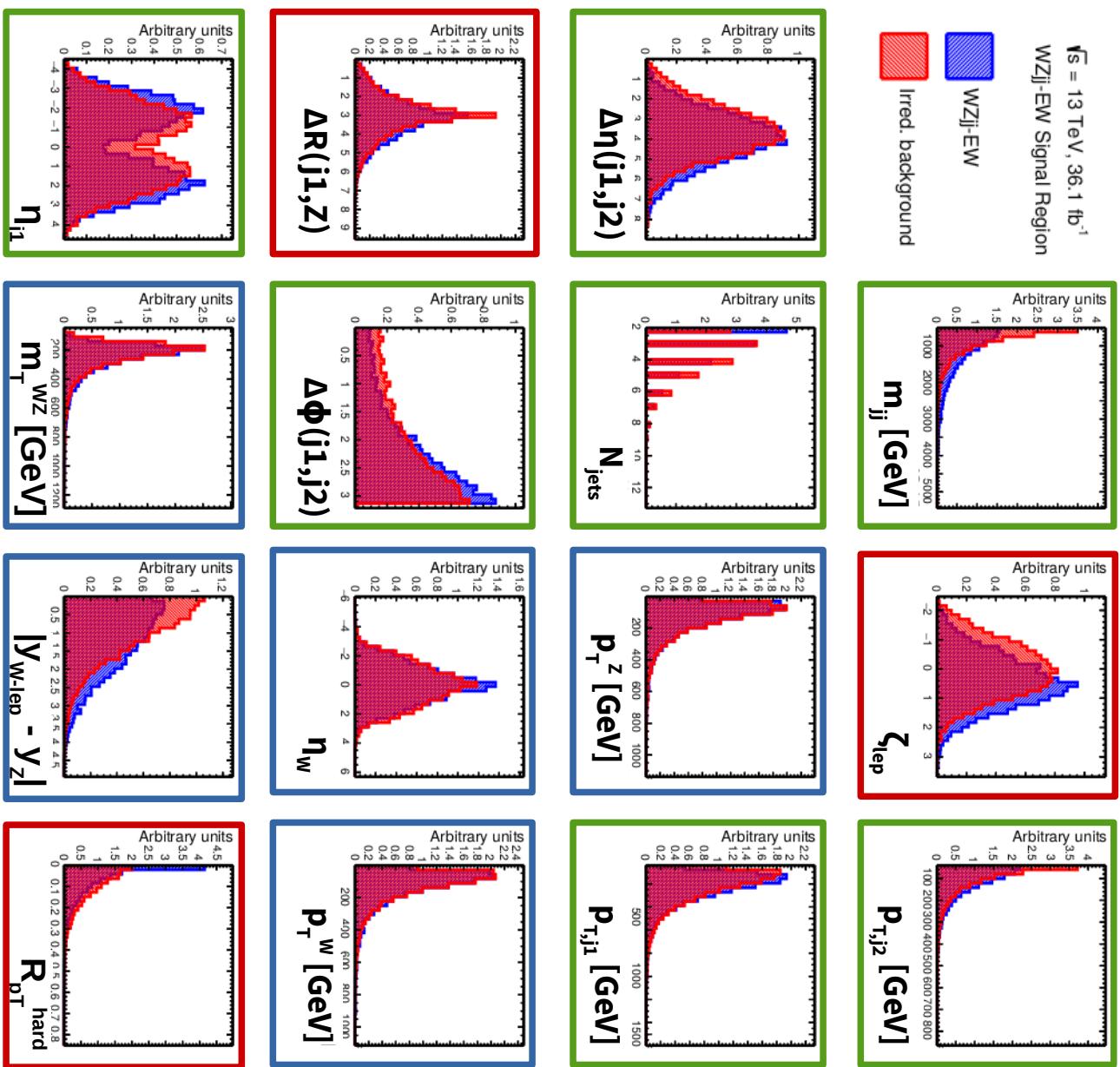


Discriminative variables

$\sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1}$

WZjj-EW Signal Region

Irred. background



> **Jet-related variables**

m_{jj} , $p_T^{j1,j2}$, N_{jets} , $\Delta\eta(j1,j2)$, $\Delta\phi(j1,j2)$, η_{j1}

> **Bosons kinematics**

p_T^z , p_T^w , η_z , η_w , m_T^{WZ} , $|y_{W-lep} - y_Z|$

> **Global variables**

ζ_{lep} , $\Delta R(j1,Z)$, R_{pT}^{hard}

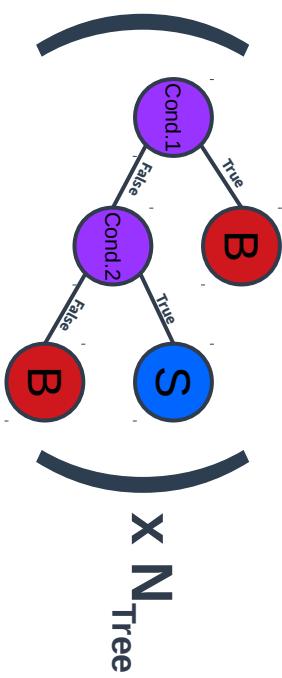
> **Low discrimination power with single variables**

Multivariate discriminant – Definition & Performance

> Multivariate discriminant

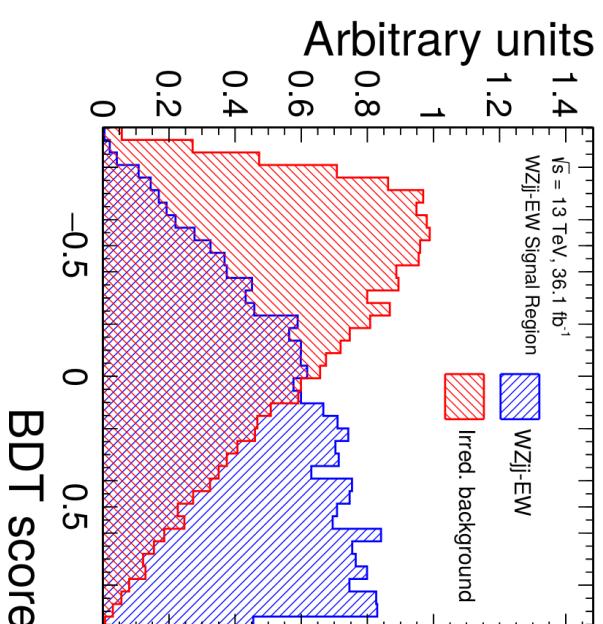
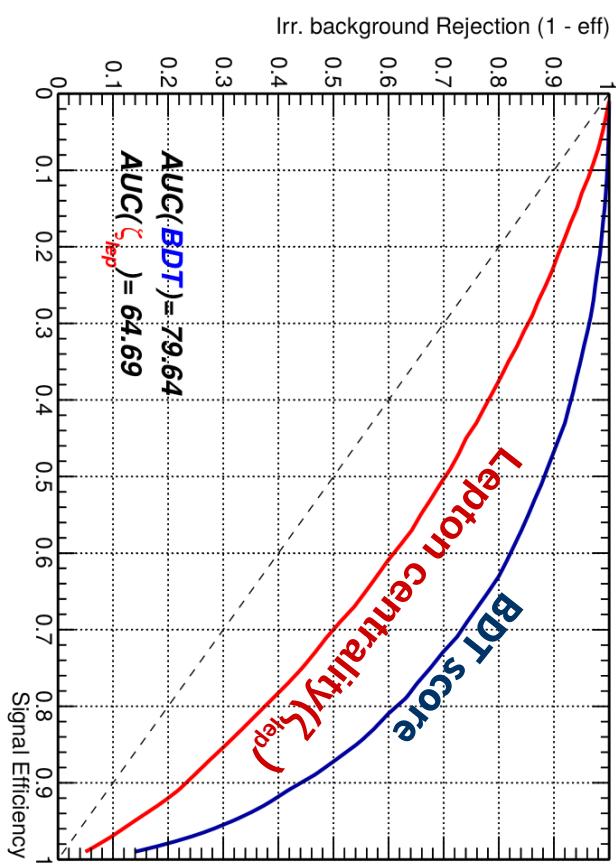
- Optimised combination of variables
- Accounts for both **single-variable discrimination** and **correlations**

> Using Boosted Decision Trees



> 23% improvement seen in MC

- Compared to lepton centrality



Multivariate discriminant – Inputs

> Mismodelling of BDT inputs can bias sensitivity estimates

> Variables modelling assessed

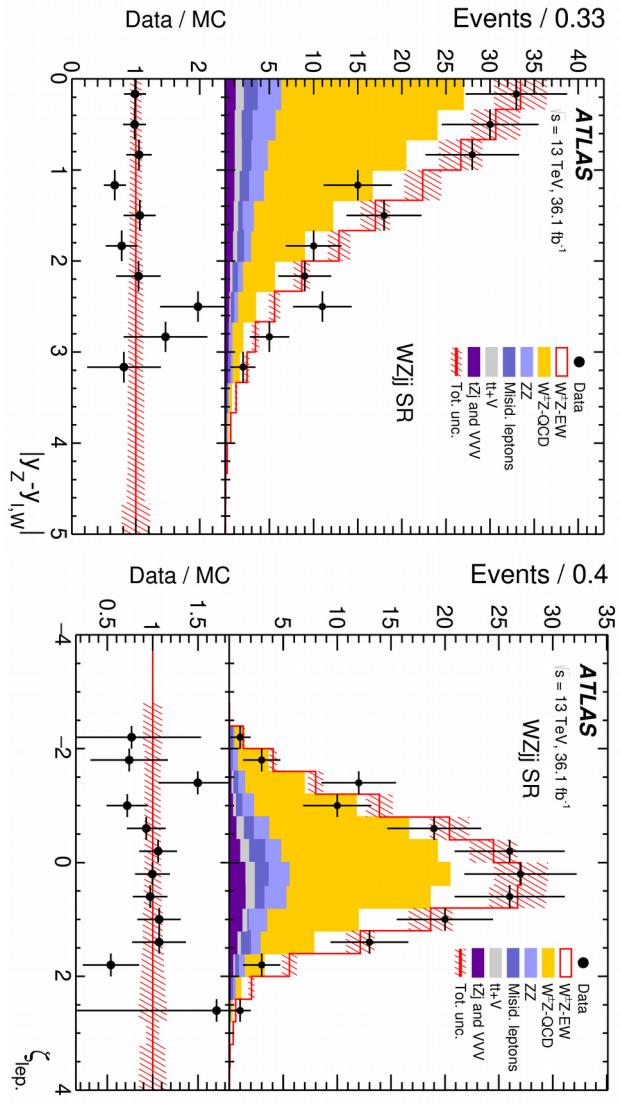
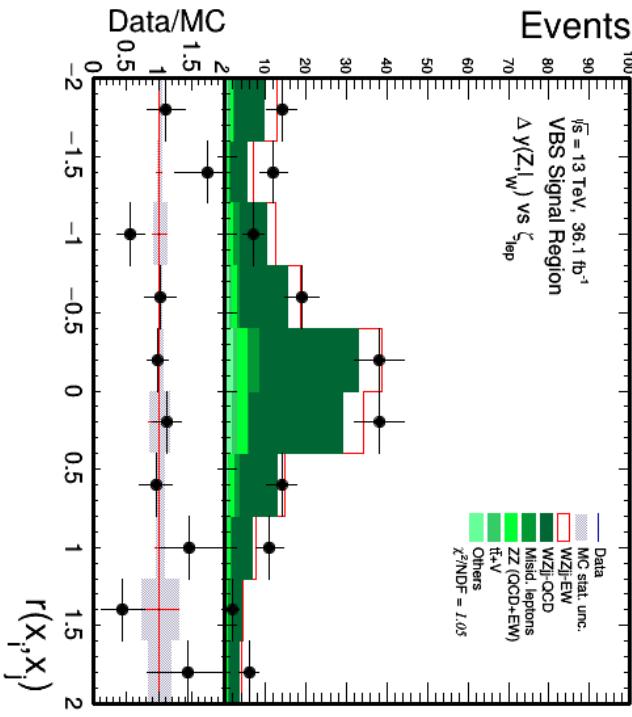
- In CR before unblinding
- Cross-checked in SR post-unblinding

> MV methods use variables correlations

- **correlation modelling** also checked

→ Decomposed correlation coefficients for simple data/MC comparison

$$r(x_i, x_j) = \frac{(x_i - \langle x_i \rangle)(x_j - \langle x_j \rangle)}{\sigma_i \sigma_j}$$



Likelihood fit

> Combined likelihood fit

> Using the four regions

- m_{jj} in ZZ-CR and QCD-CR

- $N_{b\text{-jets}}$ in b-CR

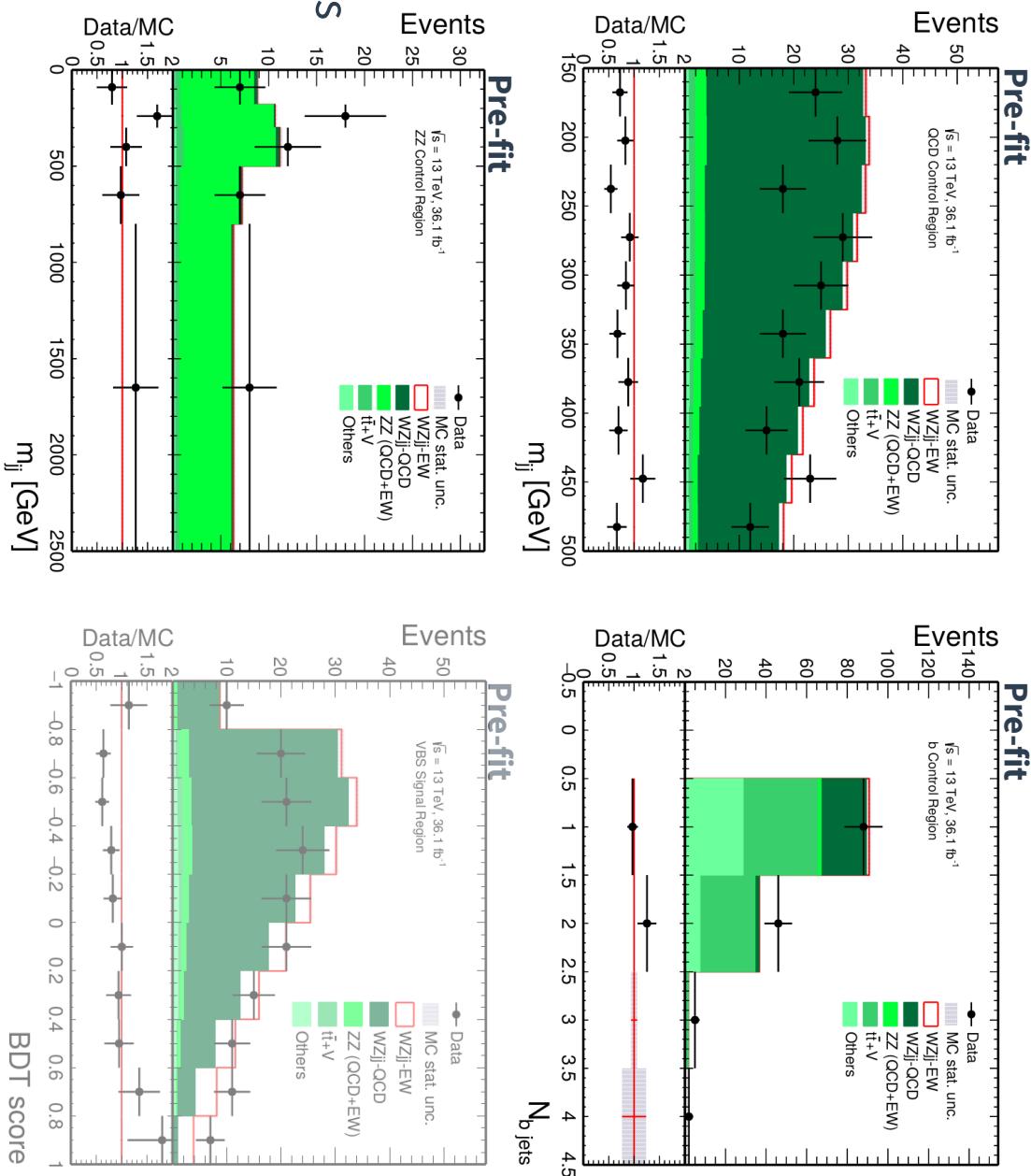
- BDT score in SR

> Pre-unblinding strategy

Only impacts expected results

1 CR-only fit → correct backgrounds

Correction factor	Value
$\mu_{WZjj\text{-QCD}}$	0.68 ± 0.21
$\mu_{t\bar{t}+V}$	1.22 ± 0.23
$\mu_{ZZ\text{-QCD}}$	1.20 ± 0.31



Likelihood fit

> Combined likelihood fit

> Using the four regions

- m_{jj} in ZZ-CR and QCD-CR

- $N_{b\text{-jets}}$ in b-CR

- BDT score in SR

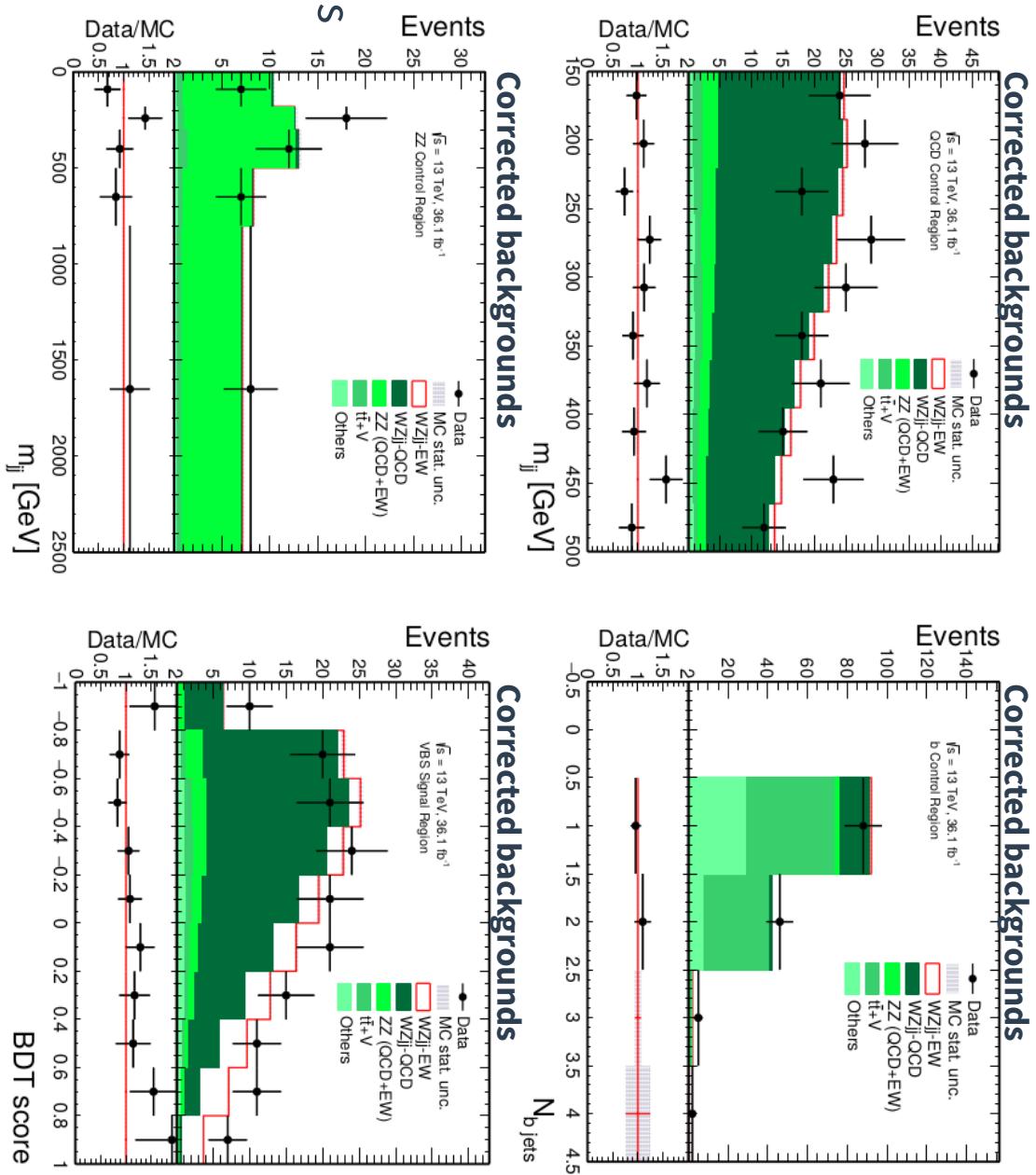
> Pre-unblinding strategy

Only impacts expected results

1 CR-only fit → correct backgrounds

Correction factor	Value
$\mu_{WZjj\text{-QCD}}$	0.68 ± 0.21
$\mu_{t\bar{t}+V}$	1.22 ± 0.23
$\mu_{ZZ\text{-QCD}}$	1.20 ± 0.31

2 Signal-extraction fit



Sensitivity gains

- > Gain in sensitivity assessed for all analysis steps
- > Compared to baseline analysis methodology:
 - No multivariate discriminant
 - Cut & count measurement
- > 69% sensitivity gain from strategy optimisation
- > 3.2 σ expected after background correction
 - Justified unblinding and result publication

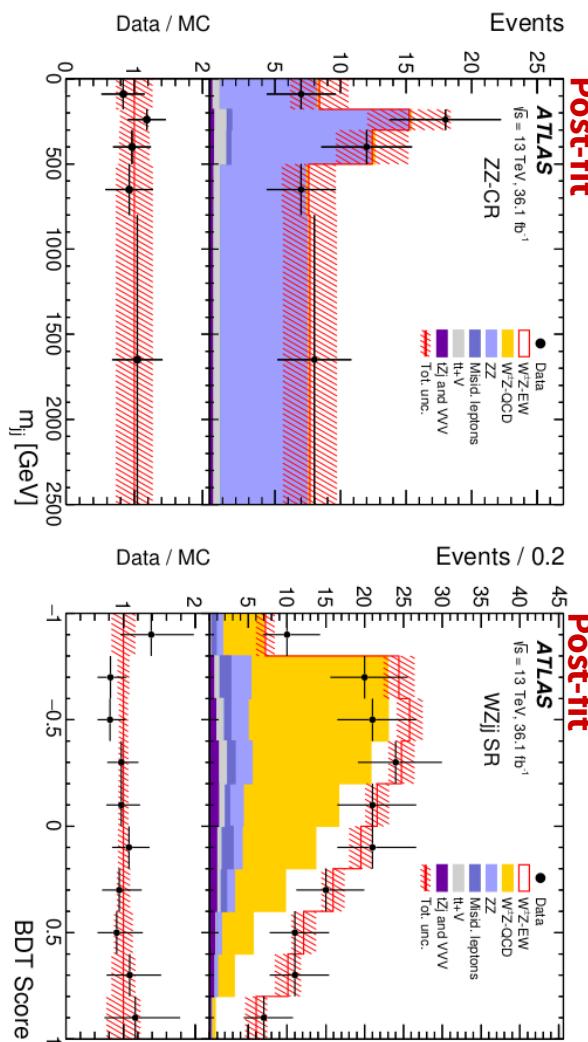
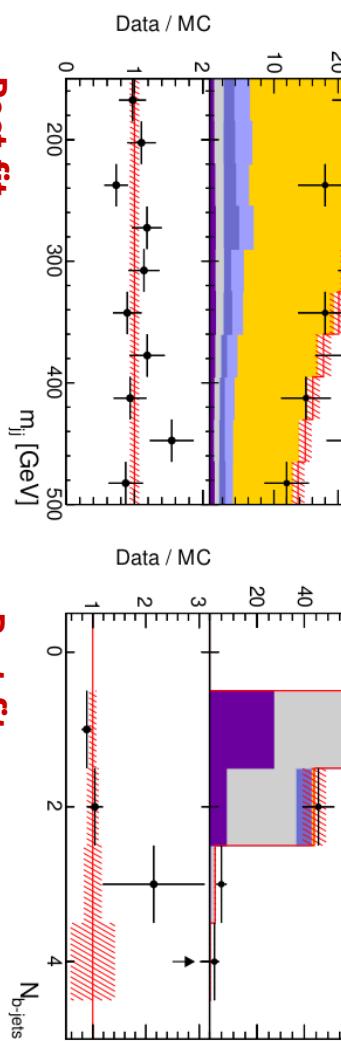
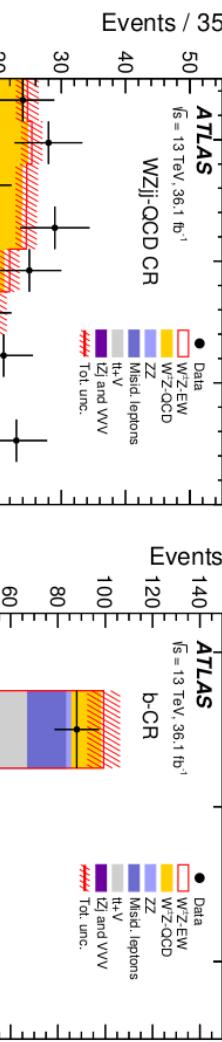
Method	Baseline	centrality fit	BDT fit	BDT fit + CR corrections
Expected significance [σ]	1.6	1.85	2.7	3.2
Gain over baseline	+ 0 %	+ 15.6 %	+ 69 %	+ 100 %

Fit results – Parameters constraints

Post-fit

Post-fit

> Overall background correction factors



> Statistically-dominated measurement

→ Non-negligible systematics impact:

- Theory and Modelling

- Jet reconstruction and calibration

Source	Uncertainty [%]
WZjj-EW theory modelling	4.8
WZjj-QCD theory modelling	5.2
WZjj-EW and WZjj-QCD interference	1.9
Jets	6.6
Pile-up	2.2
Electrons	1.4
Muons	0.4
b-tagging	0.1
MC statistics	1.9
Misid. lepton background	0.9
Other backgrounds	0.8
Luminosity	2.1
Total Systematics	10.7

Fit results – Cross section measurement

> Background-only hypothesis rejected at **5.3 σ**

→ **First observation of WZjj-EW production**

Physics Letters B 793 (2019), 469-492

> WZjj-EW cross-section derived from fit result

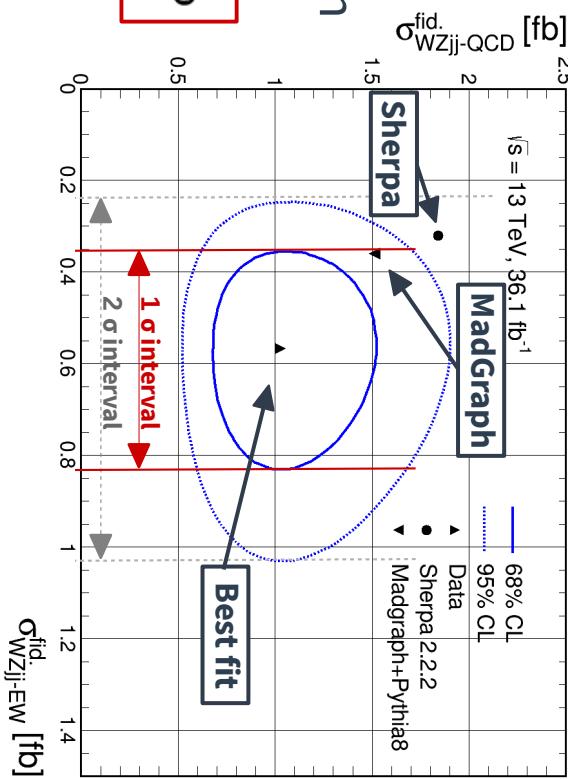
→ Extracted in fiducial phase-space close to SR definition

$$\sigma_{WZjj-EW}^{fid.} = 0.57^{+0.14}_{-0.13} (\text{stat.})^{+0.07}_{-0.06} (\text{syst.}) \text{ fb} = 0.57^{+0.16}_{-0.14} \text{ fb}$$

$$\sigma_{\text{Sherpa}}^{\text{fid.}, \text{EW th.}} = 0.321 \pm 0.002 (\text{stat.})^{+0.005}_{-0.005} (\text{PDF})^{+0.027}_{-0.023} (\text{scale}) \text{ fb}$$

$$\sigma_{\text{MadGraph}}^{\text{fid.}, \text{EW th.}} = 0.366 \pm 0.004 (\text{stat.}) \text{ fb}$$

→ Measurement within 2σ of MC predictions



VBS prospects

- > WZjj-EW observed with partial Run 2 dataset
 - Used 36 fb^{-1} of data
 - **140 fb^{-1} now available**
- > New problematics are considered
 - **Pileup impact on forward jet selection**
 - ~8% of simulated WZjj-QCD events contain has a pileup jet as tagging jets
 - Can contribute to jet multiplicity mismodelling

Content

> Standard Model and VBS

- Theory motivations
- Experimental challenges

> Experimental setup

- The LHC
- The ATLAS detector
- Particles reconstruction

> WZjj-EW observation

- Analysis design and challenges
- Signal extraction and WZjj-EW first observation

> Forward pileup jet tagging

- Base tools & current limitations
- Multivariate tagger development
- Tagging efficiency correction

Luminosity and Pileup

> Physics over ~14 orders of magnitude

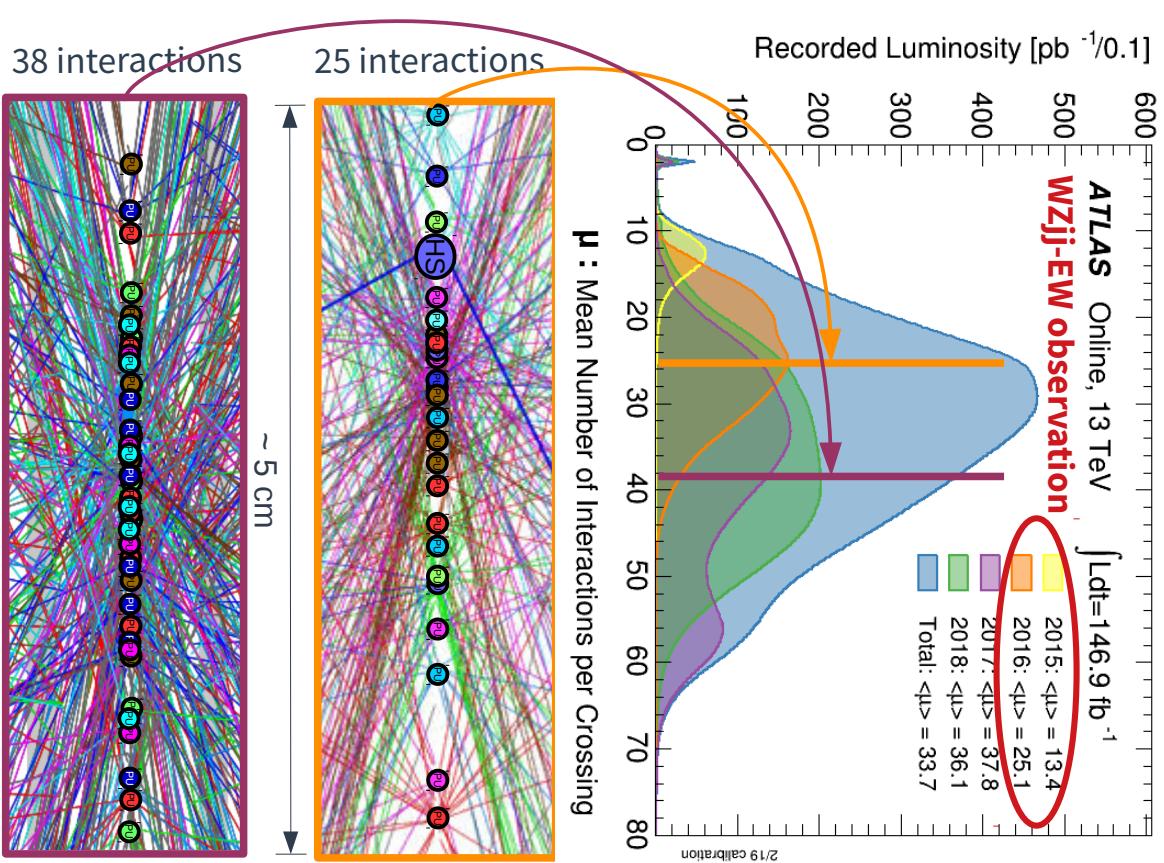
- Possible thanks to high luminosity:

$$L = \frac{N_b^2 n_b f_{rev} \gamma}{4 \pi \epsilon_n \beta^*} F \simeq 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$$

$N_b \simeq 10^{11}$ → Number of protons in a “bunch”

> Downside: **Pileup**

- Up-to ~80 simultaneous collision in an event
- Can impact reconstruction performance
- Yields additional **jets from pileup**



Pileup jets

> HS jet (signal jets)

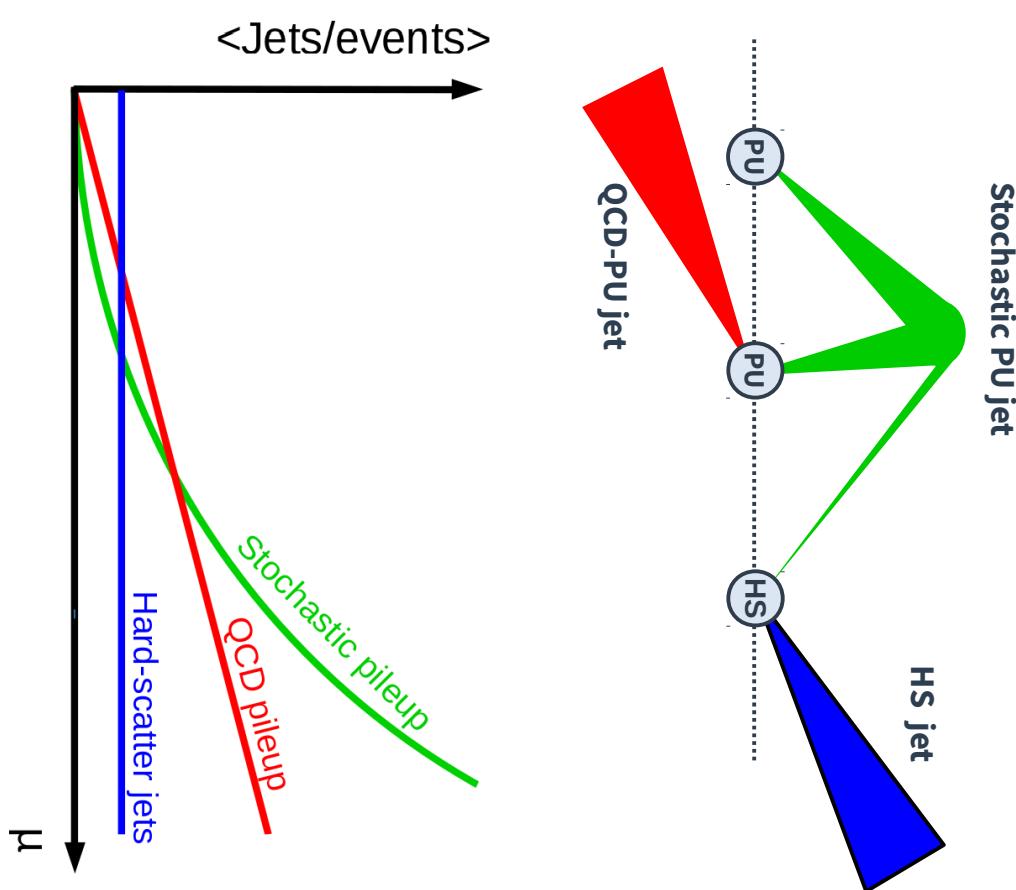
- Originates from the main interaction vertex
→ HS vertex
- Nature depends on the targeted interaction
→ **Independent of μ**

> QCD-PU

- Well defined hadronic jet
 - Originates from a PU vertex
- **Linear increase with μ**

> Stochastic PU

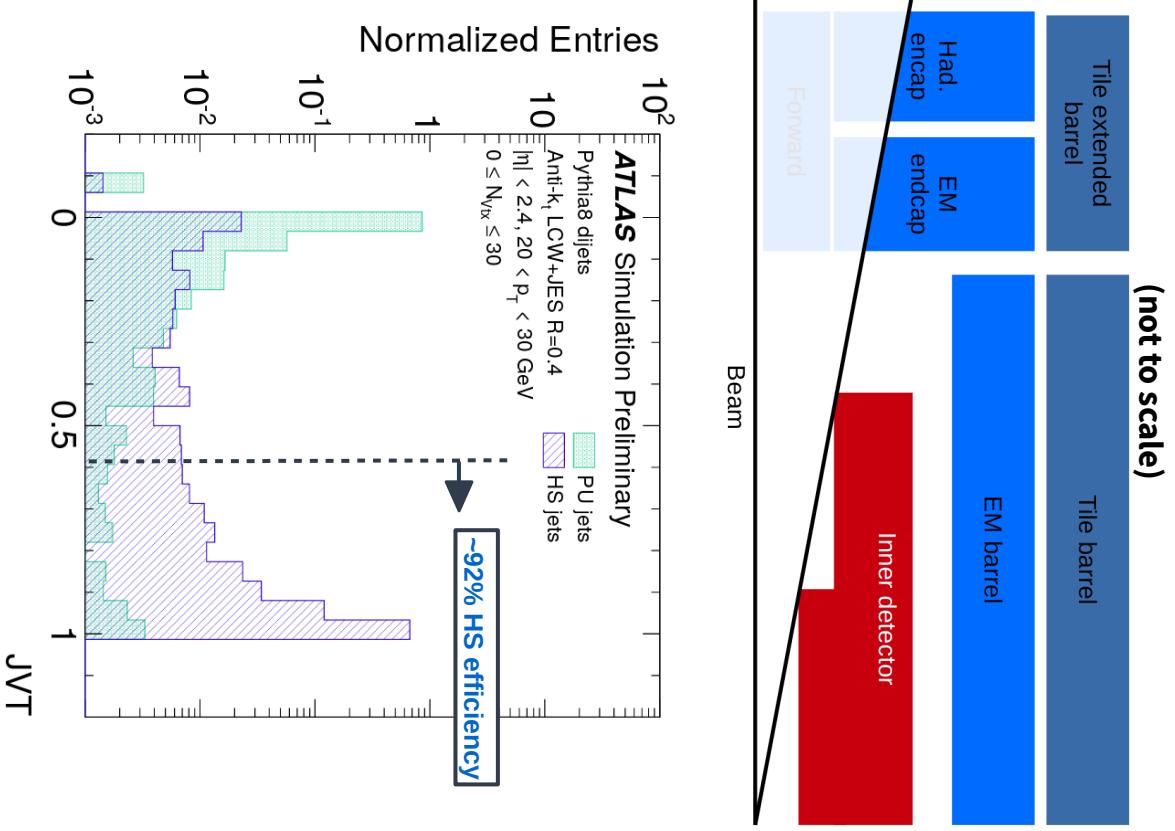
- Jet composed of uncorrelated components
 - Typically not associative to a single vertex
- **Faster than linear**



The Jet-Vertex-Taggers - JVT

> Pileup-jet suppression strategy

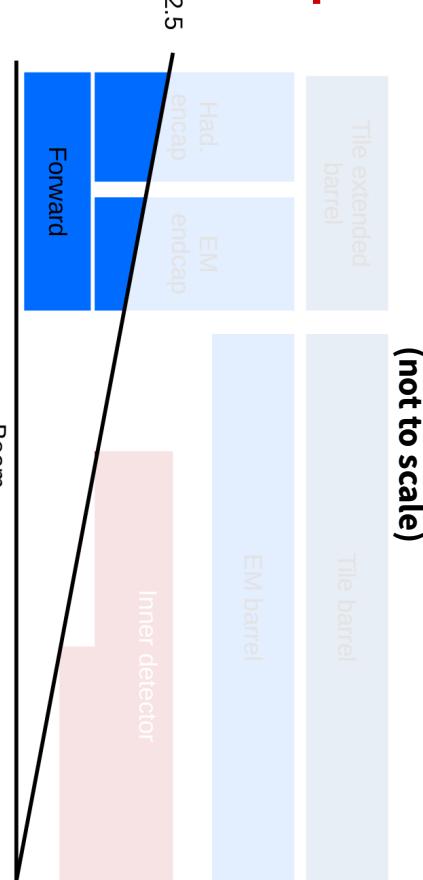
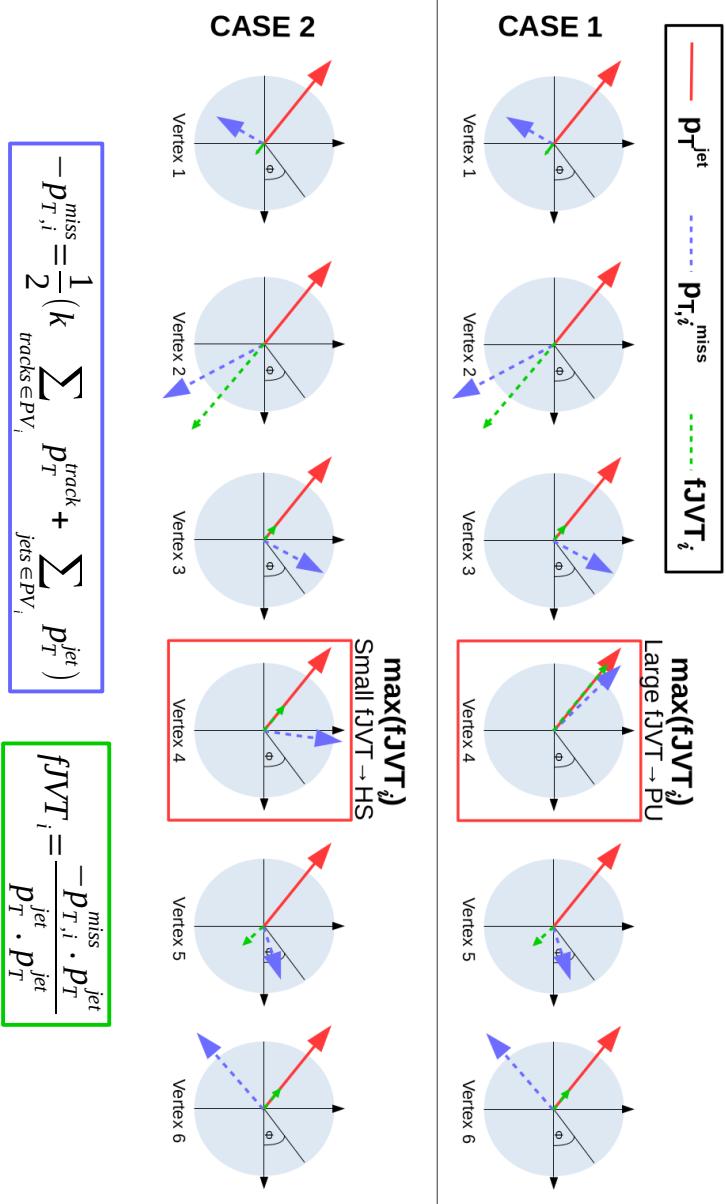
- Match jets to the interaction vertices
- Remove jets originating from PU vertices
- > **Within tracker acceptance ($|\eta| < 2.5$) \rightarrow JVT**
- Highly efficient track-based discriminant



The Jet-Vertex-Taggers - fJVT

> Outside tracker acceptance ($|\eta| > 2.5$) \rightarrow **fJVT**

- Match forward jets to vertices with topological information

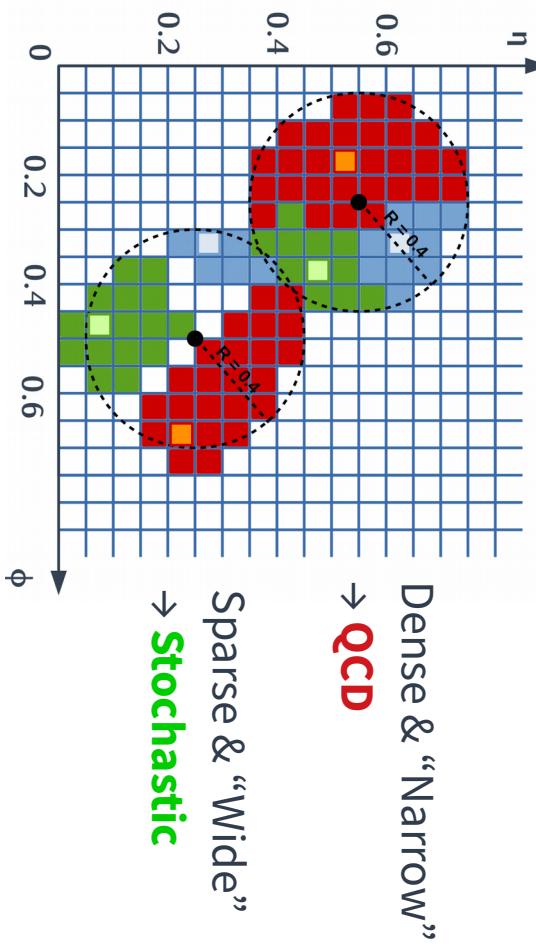


Improving the fJVT

> fJVT not adapted for stochastic PU

- Other jet properties can help

> Jet shape and structure



> Jet timing

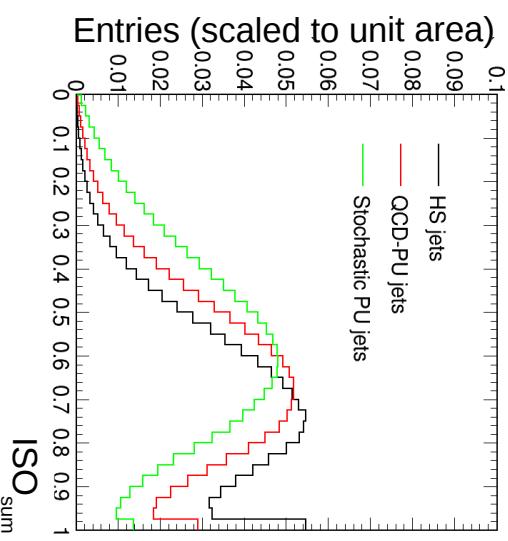
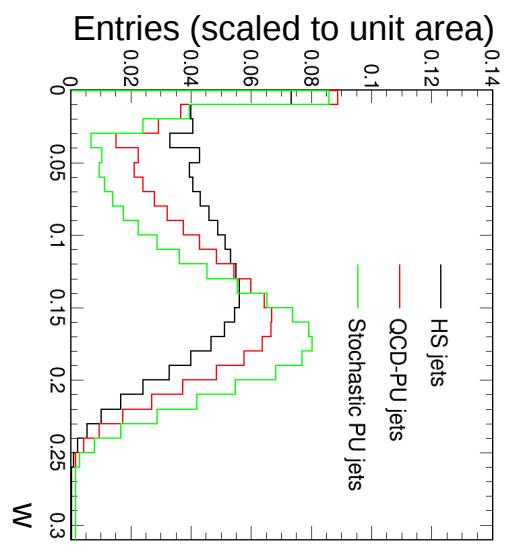
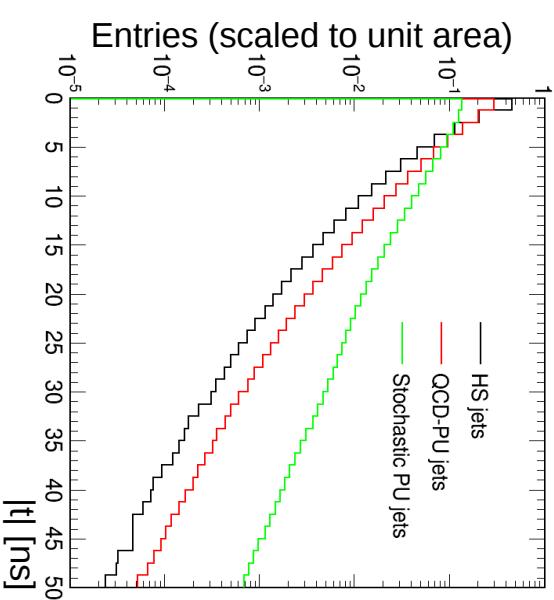
- Already used with fJVT, $|t| < 10$ ns cut

$$t_{\text{cluster}} = \frac{\sum t_{\text{cell}} E_{\text{cell}}^2}{\sum E_{\text{cell}}^2}$$

$$t = \frac{\sum t_{\text{cluster}} E_{\text{cluster}}^2}{\sum E_{\text{cluster}}^2}$$

$$w = \frac{\sum \Delta R(\text{jet}, \text{cluster}) p_T^{\text{cluster}}}{\sum p_T^{\text{cluster}}}$$

$$\text{ISO}_{\text{sum}} = \frac{\sum \left(\frac{N_{\text{cells}}^{\text{clustered}}}{N_{\text{cells}}^{\text{outer}}} \right) E_{\text{cluster}}^2}{\sum E_{\text{cluster}}^2}$$



Multivariate fJVT

> Multivariate combination of **8 variables**

- Using **Boosted Decision Trees** (BDT)
- Selected for optimal PU discrimination

> Aim at **global PU-jet suppression**

- No QCD/stochastic PU distinction in training

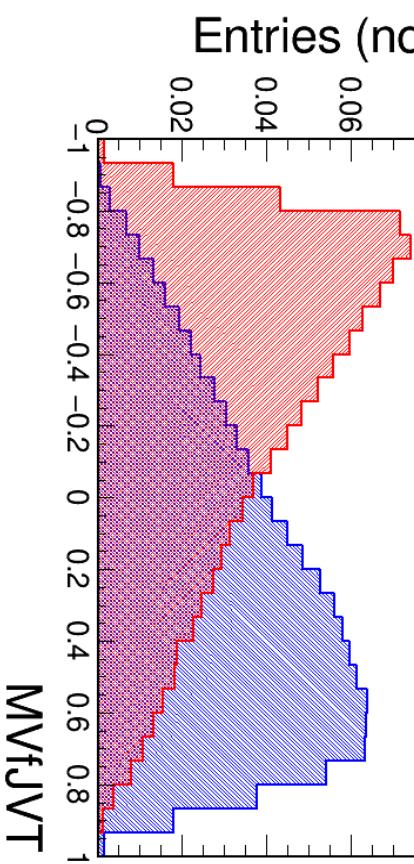
fJVT, |t|, w, ISO_{sum}

→ Provides most of the separation

Entries (normalised)

$\sqrt{s} = 13 \text{ TeV}, \text{mc16a+d+e}$
 $Z(\rightarrow \mu\mu/\text{ee}) + \text{jets, Powheg+Pythia8}$
 $\text{Anti-}k_{\text{T}}, R=0.4, \text{EMTopo+JES}$
 $30 < p_{\text{T}} < 40 \text{ GeV}, 2.5 < |\eta| < 3.2$

$P(\text{EM})_{\text{sum}}, E_{\text{sum}}$ (Sum over all clusters, $\Delta R < 0.6$)
 $\langle \lambda^2 \rangle_{\text{lead}}, \sigma_{\eta}^{\text{lead}}$ (Leading cluster properties)
→ Performance fine-tuning

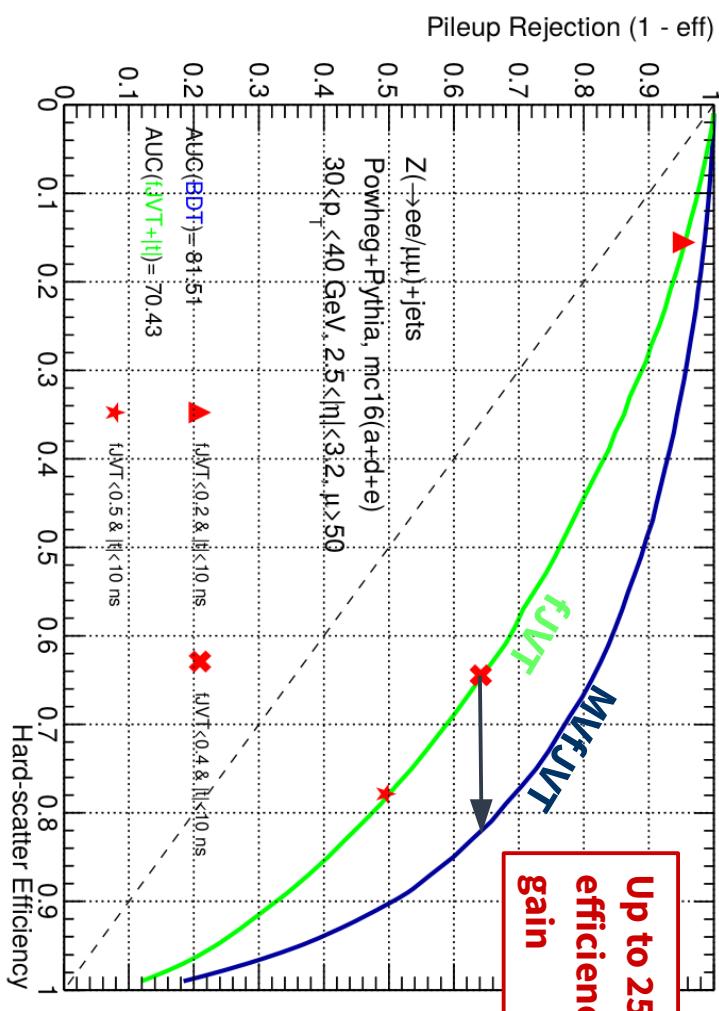
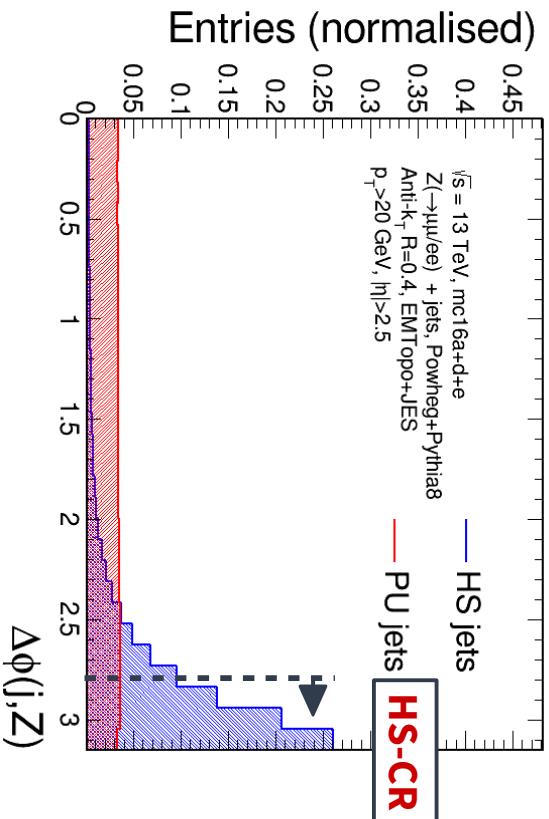


The MVfJVT – Performance

> Performance validated in Z+jets MC

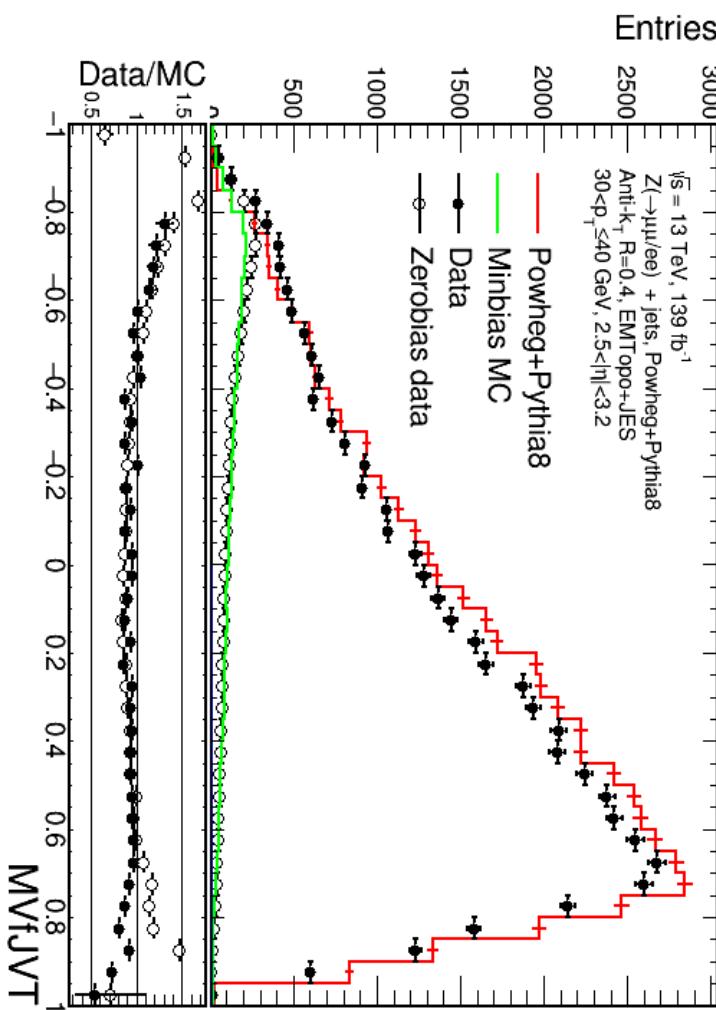
> Z+jets selection

- Single-lepton trigger
- Two isolated Same-flavor, opposite-sign leptons (e/μ)
- $|m_l - m_Z| < 10 \text{ GeV}$, $p_T^Z > 30 \text{ GeV}$
- $N_{\text{jets}} > 0$
- **HS-CR: $\Delta\phi(j, Z) > 2.8$**



The MVfJVT – Pileup Modelling

- > **Jet shape and structure often poorly modelled**
 - Can lead to different performance in data
- > **Modelling check**
 - **Zerobias data** for PU estimate
 - Randomly triggered events
 - Scaled to match HS-CR event yield
 - Compared to **Minbias MC**
 - Pythia8, dijet events with $p_T^{\text{jet}} < 20 \text{ GeV}$
 - Non-negligible data/MC discrepancies
 - Especially in PU-rich tail



Forward taggers efficiency correction

> Data/MC discrepancy translates to the **tagging efficiency**

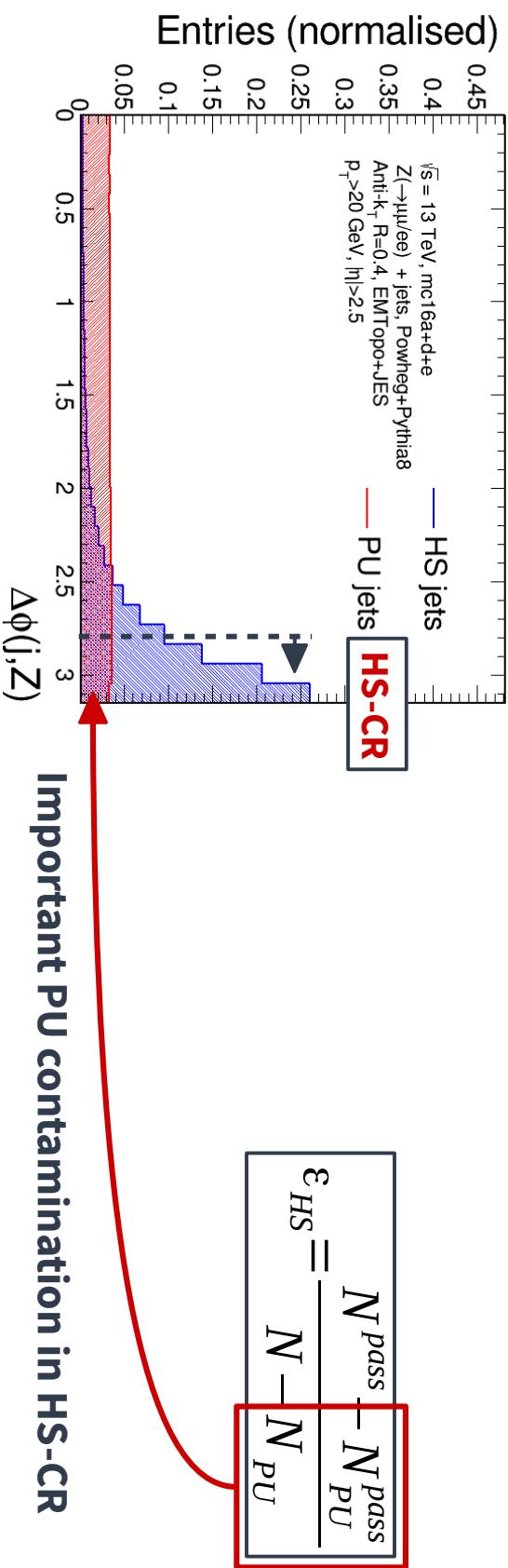
> This efficiency must be measured in data and corrected in MC

- Efficiency measured in **HS-CR**

→ **Enhanced HS purity**

- Define MVfJVT operating points to get **same PU rejection as fJVT**

- Derive **scale-factors** to correct the MC



Efficiency scale factors

> Data/MC discrepancy translates to the **tagging efficiency**

> **Comparable uncertainties**

- Improved efficiency also in data
- Improved data/MC agreement

> **Comparable uncertainties**

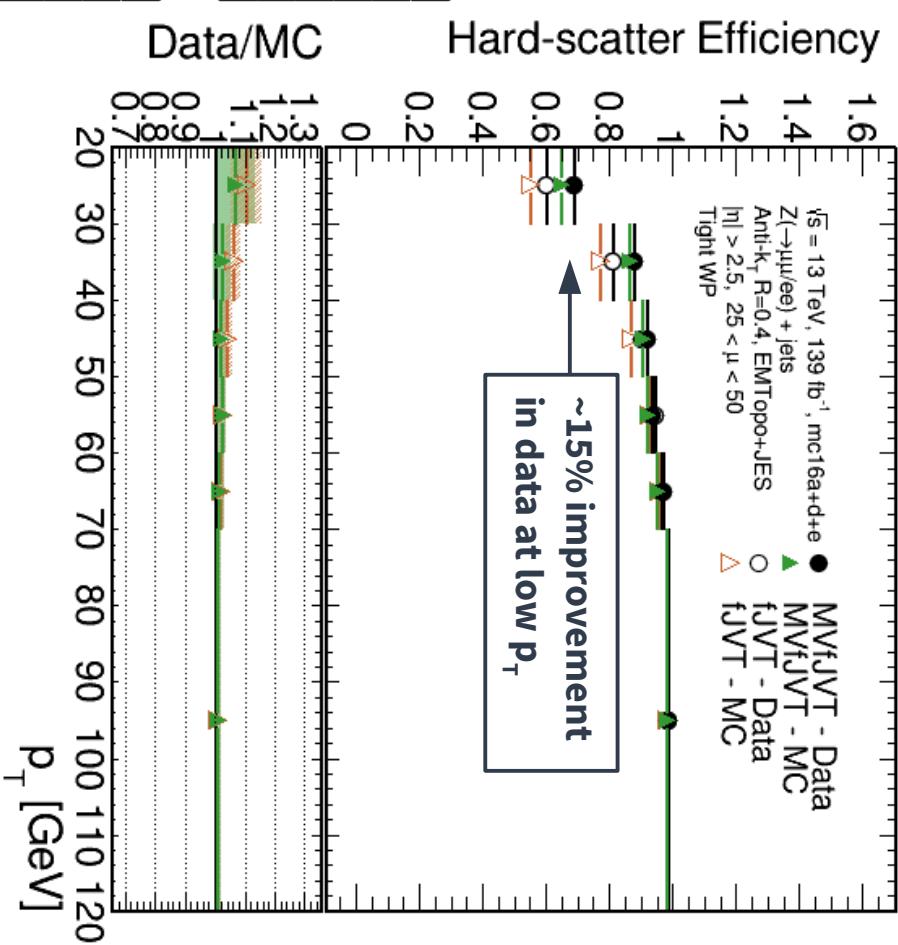
- **Model-dependence included for MVfJVT**

fJVT, Tight operating point, $25 < \mu < 50$

p_T bin [GeV]	[20,30]	[30,40]	[40,50]	[50,60]	[60,70]	[70,120]
Relative unc. [%]	4.5	2.3	1.5	0.9	1.0	0.8
Statistical [%]	0.5	0.5	0.5	0.7	0.9	0.7
PU estimate [%]	0.2	0.0	0.0	0.0	0.0	0.0
$ \eta $ -dependence [%]	1.9	0.8	0.1	0.2	0.0	0.1
Year dependence [%]	4.1	2.2	1.3	0.5	0.5	0.3

MVfJVT, Tight operating point, $25 < \mu < 50$

p_T bin [GeV]	[20,30]	[30,40]	[40,50]	[50,60]	[60,70]	[70,120]
Relative unc. [%]	6.4	2.7	1.4	1.1	1.2	0.9
Statistical [%]	0.5	0.5	0.6	0.7	0.9	0.7
PU estimate [%]	0.2	0.0	0.0	0.0	0.0	0.0
$ \eta $ -dependence [%]	2.5	1.0	0.3	0.6	0.3	0.2
Year dependence [%]	5.4	2.3	1.2	0.6	0.7	0.3
Modelling [%]	2.4	1.0	0.2	0.1	0.2	0.5



Conclusion

> Studies on pileup mitigation have been presented

- A new multivariate PU tagger for forward jets was developed
- The tagger yields up-to 25% higher performance than the fJVT
- Scale factors derived using the full Run 2 dataset
- MVfJVT and scale factors available for the ATLAS collaboration

> First observation of WZjj-EW production

Physics Letters B 793 (2019), 469-492

- Using the 36 fb^{-1} partial dataset gathered in 2015-2016
- Based on MV discriminant used as template in an optimised combined likelihood fit
- Similar analysis design now found in several VBS-related analyses:
 - WZjj-EW observation by CMS (137 fb^{-1} of data)
 - ZZjj-EW observation by ATLAS (139 fb^{-1} of data)

> Parallel work and responsibilities

- PU-jet tagging effort co-contact:
 - Analysis support and student supervision
- Teaching at the IUT d'Annecy
 - 110 h lab work and tutoring (IUT Annecy)

Ongoing work and prospects

> The WZjj-EW study keeps going with full Run 2 data

→ **Impact of forward PU jet tagging**

8% of selected WZjj-QCD events have at least one forward PU jet
3% purity gain from forward PU tagging in simulation

→ **Investigation of q/g tagging**

Truth studies show huge potential (55% of WZjj-QCD events have a gluon jet)
No improvement from available (low- η) tools
→ Potentially improved by MVfJVT-like development

→ **Sensitivity studies for differential measurements**

m_{jj} [GeV]	[500,1300]	[1300,2000]	[2000, ∞]
$(\delta\sigma)/\sigma$ (WZjj-EW)	0.32	0.33	0.30
WZjj-EW significance (exp.)	3.5 σ	3.7 σ	4.6 σ
$(\delta\sigma)/\sigma$ (WZjj-QCD)	0.075	0.18	0.30
WZjj-QCD significance (exp.)	> 5 σ	> 5 σ	4.9 σ

> Run 3 & HL-LHC will highly improve the sensitivity

→ Up-to 3000 fb^{-1} of data: Potential access to $V_L V_L$ scattering

→ $\langle \mu \rangle \sim 200$: Hardware (ITk, HGTD) and software development required



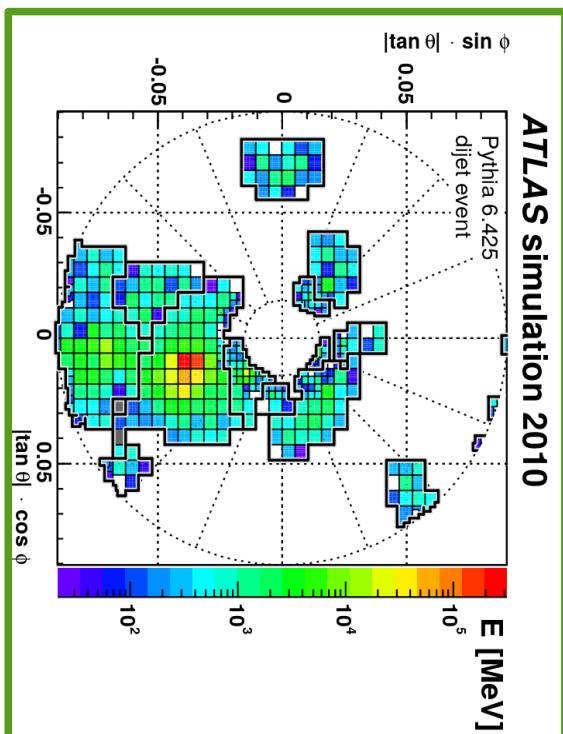
Backup Slides



Experiment & Pileup

Jet reconstruction

EMTopo: “historical” approach



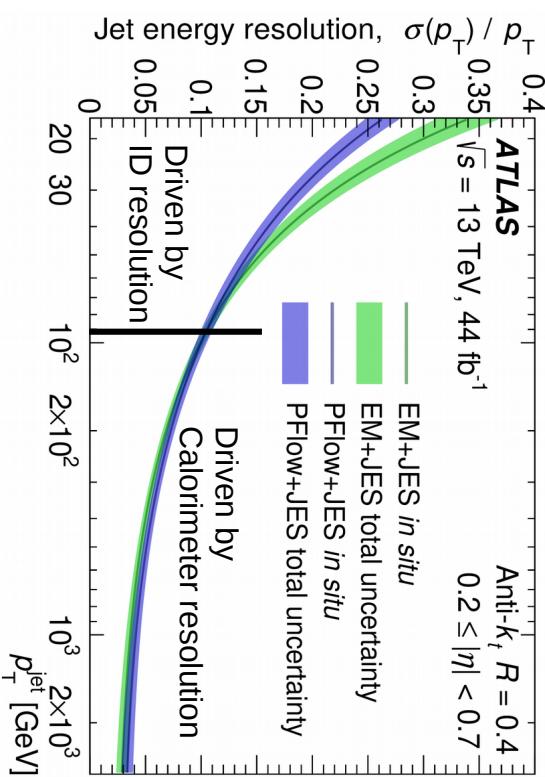
- 1 Build **Topoclusters** from neighbouring calorimeter cells ($|E_{\text{cell}}| > 2\sigma_{\text{noise}}$)
- 2 Identify most energetic cluster, combine neighbouring clusters using **Anti- k_T** ($R=0.4$):

$$\min(k_{T,i}^{-2}, k_{T,j}^{-2}) \frac{\Delta R_{ij}}{R^2} < k_{T,i}^{-2}$$

PFlow: (Particle Flow) full Run 2 baseline

- 1 Build **Topoclusters** from neighbouring calorimeter cells ($|E_{\text{cell}}| > 2\sigma_{\text{noise}}$)
- 2 Build **Pflow Objects** (PFO) from topoclusters and ID tracks:

Charged PFO Cluster matched to track \rightarrow keep track as PFO	Neutral PFO No track \rightarrow keep cluster as PFO
---	---
- 3 Build jet from PFO using **Anti- k_T** ($R=0.4$)



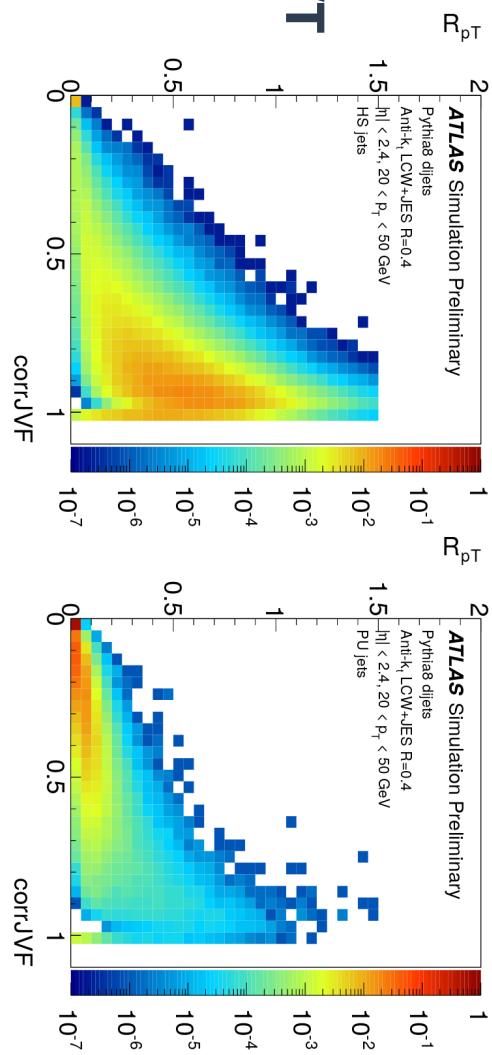
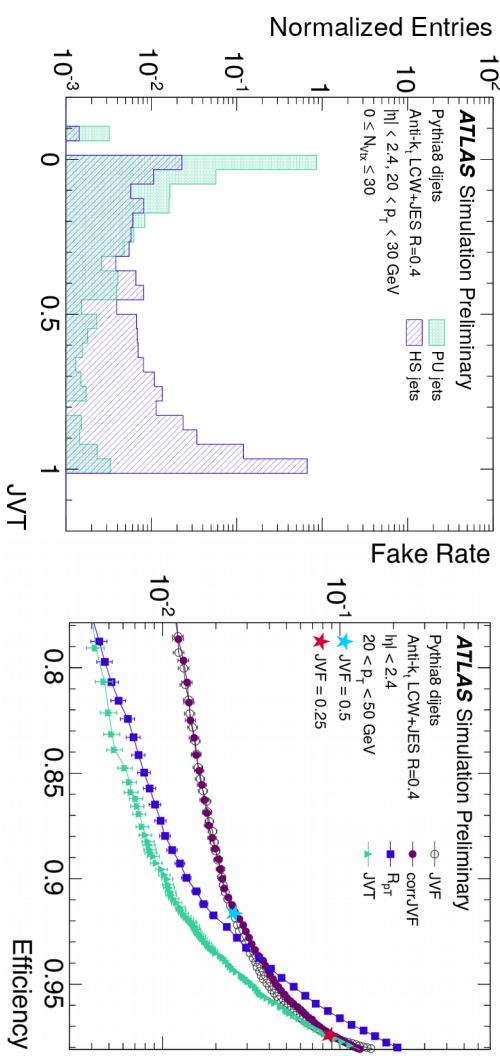
The Jet-Vertex-Tagger

> Within tracker acceptance ($|\eta| < 2.5$) $\rightarrow \text{JVT}$

- Combine two track-based variables:

$$R_{pT} = \frac{\sum_k p_T^{\text{track}_k}(PV_0)}{p_T^{\text{jet}}}$$

$$\text{corrJVF} = \frac{\sum_k p_T^{\text{track}_k}(PV_0)}{\sum_i p_T^{\text{track}_i}(PV_0) + \frac{p_T^{\text{PU}}}{k \cdot n_{\text{tracks}}}}$$



The forward Jet-Vertex-Tagger

> Outside tracker acceptance ($|\eta| > 2.5$) $\rightarrow \text{fJVT}$

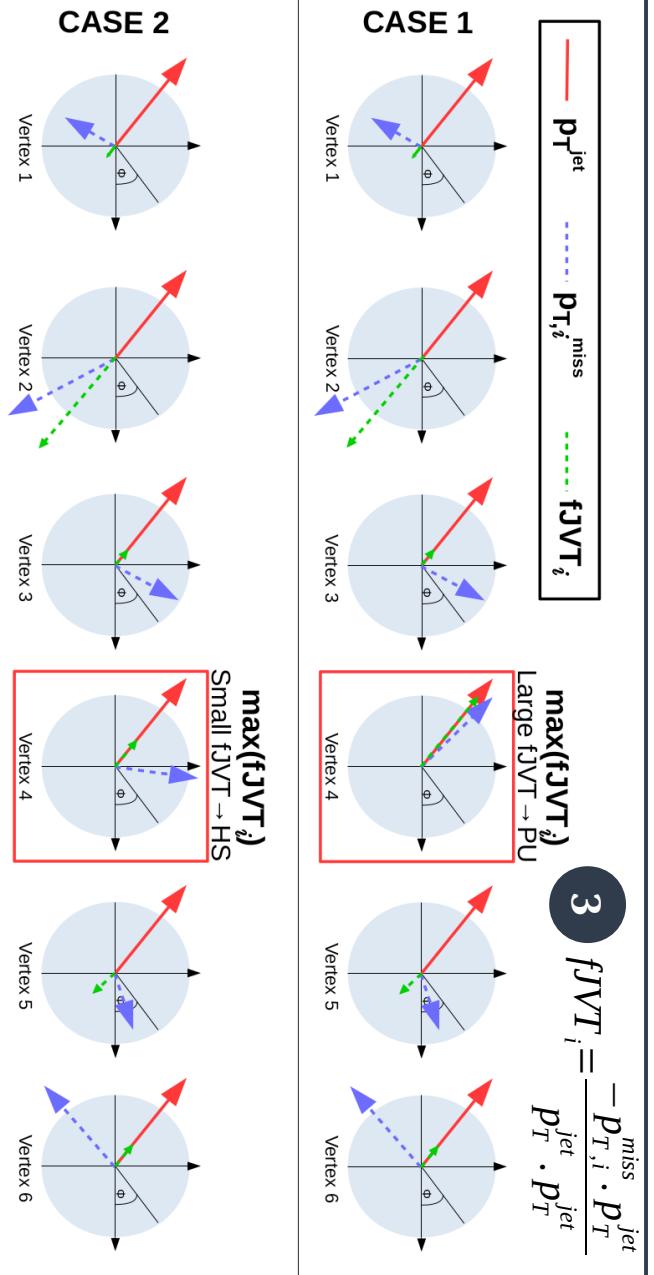
1 Match central jets to PU vertices

$$\rightarrow |\eta| < 2.5$$

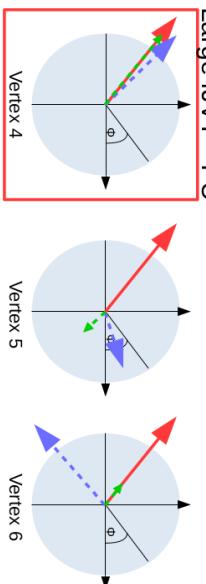
$$\rightarrow p_T > 35 \text{ GeV}$$

$$\rightarrow JVT < 0.11$$

$$\rightarrow |(R_{pT}^i)_{\text{lead}} - (R_{pT}^i)_{\text{sublead}}| > 0.2$$



$$3 \quad f\text{JVT}_i = \frac{-p_{T,i}^{\text{miss}} \cdot p_T^{\text{jet}}}{p_T^{\text{jet}} \cdot p_T^{\text{jet}}}$$



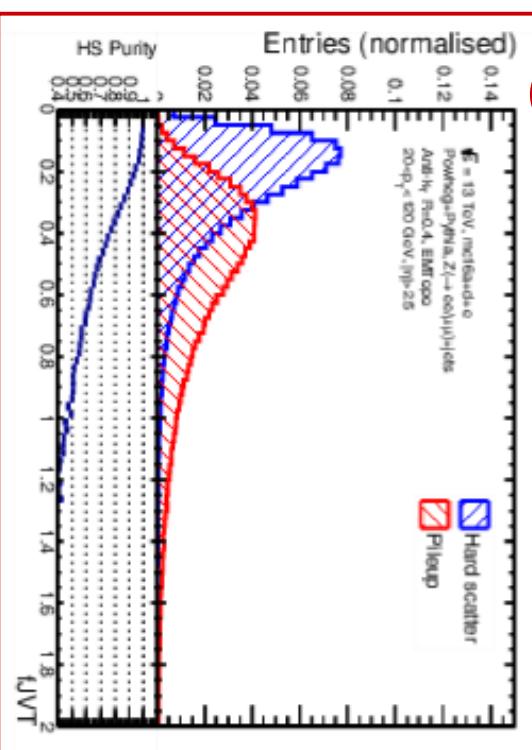
2 Compute missing momentum for each PU vertex

$$R_{pT}^i = \frac{\sum p_T^{\text{track}_k}(PV_i)}{p_T^{\text{jet}}}$$

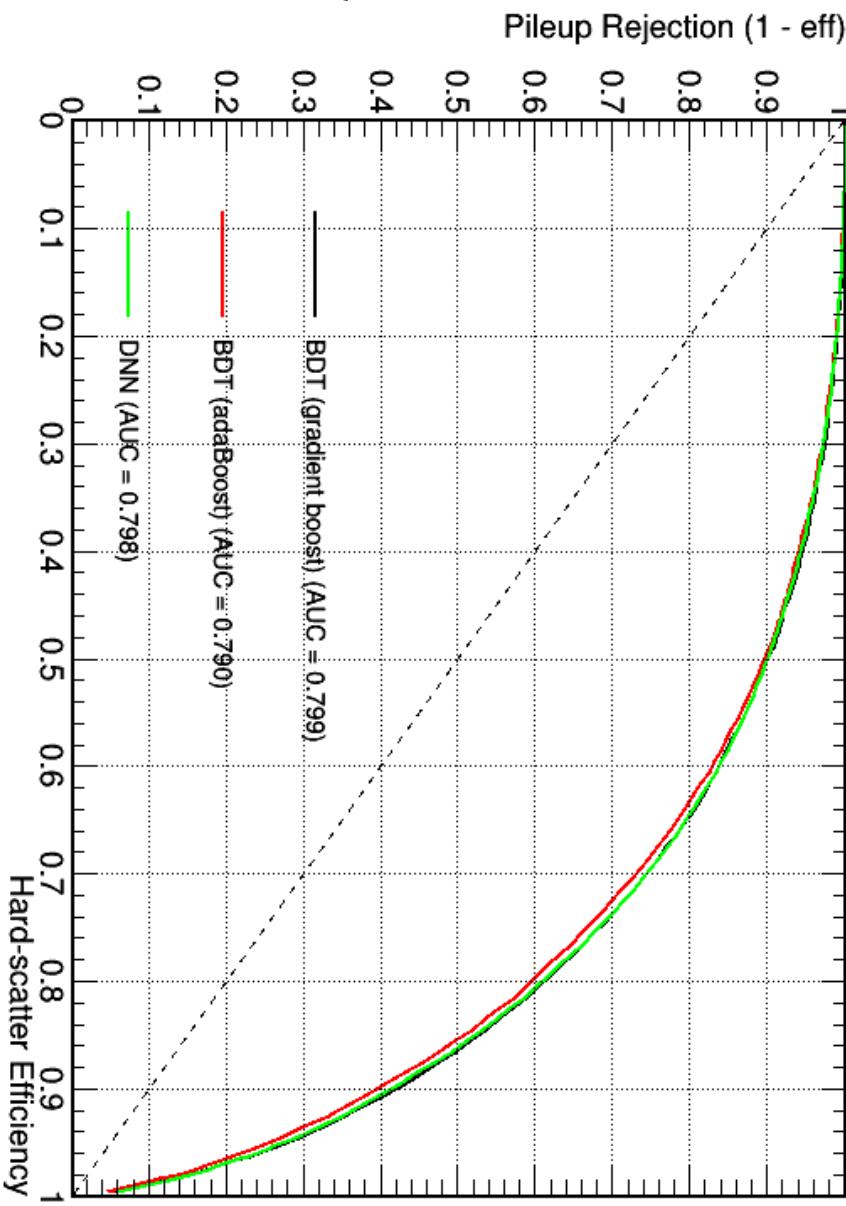
$$-p_{T,i}^{\text{miss}} = \frac{1}{2} \left(k \sum_{\text{tracks} \in PV_i} p_T^{\text{track}} + \sum_{\text{jets} \in PV_i} p_T^{\text{jet}} \right)$$

$k=2.5$ Compensates for neutral hadrons

$$4 \quad f\text{JVT} = \max(f\text{JVT}_i)$$

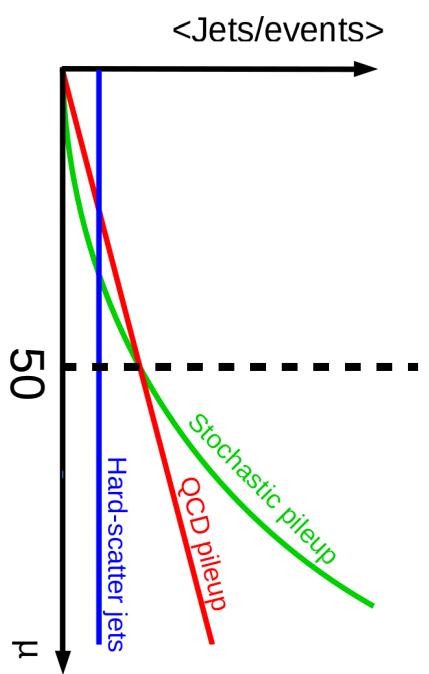
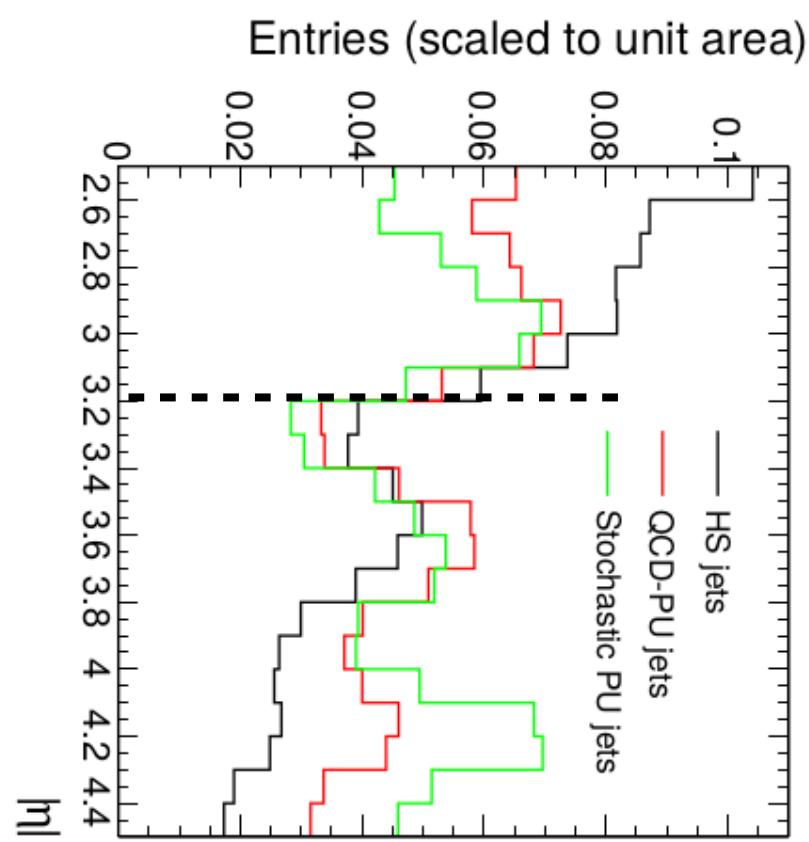
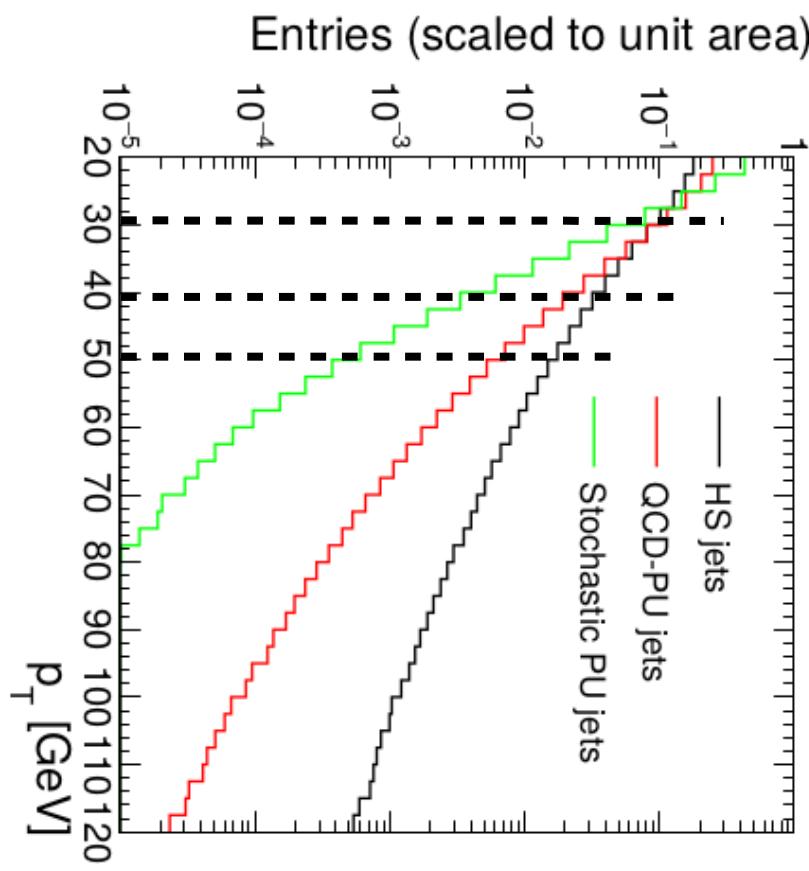


MV method choice

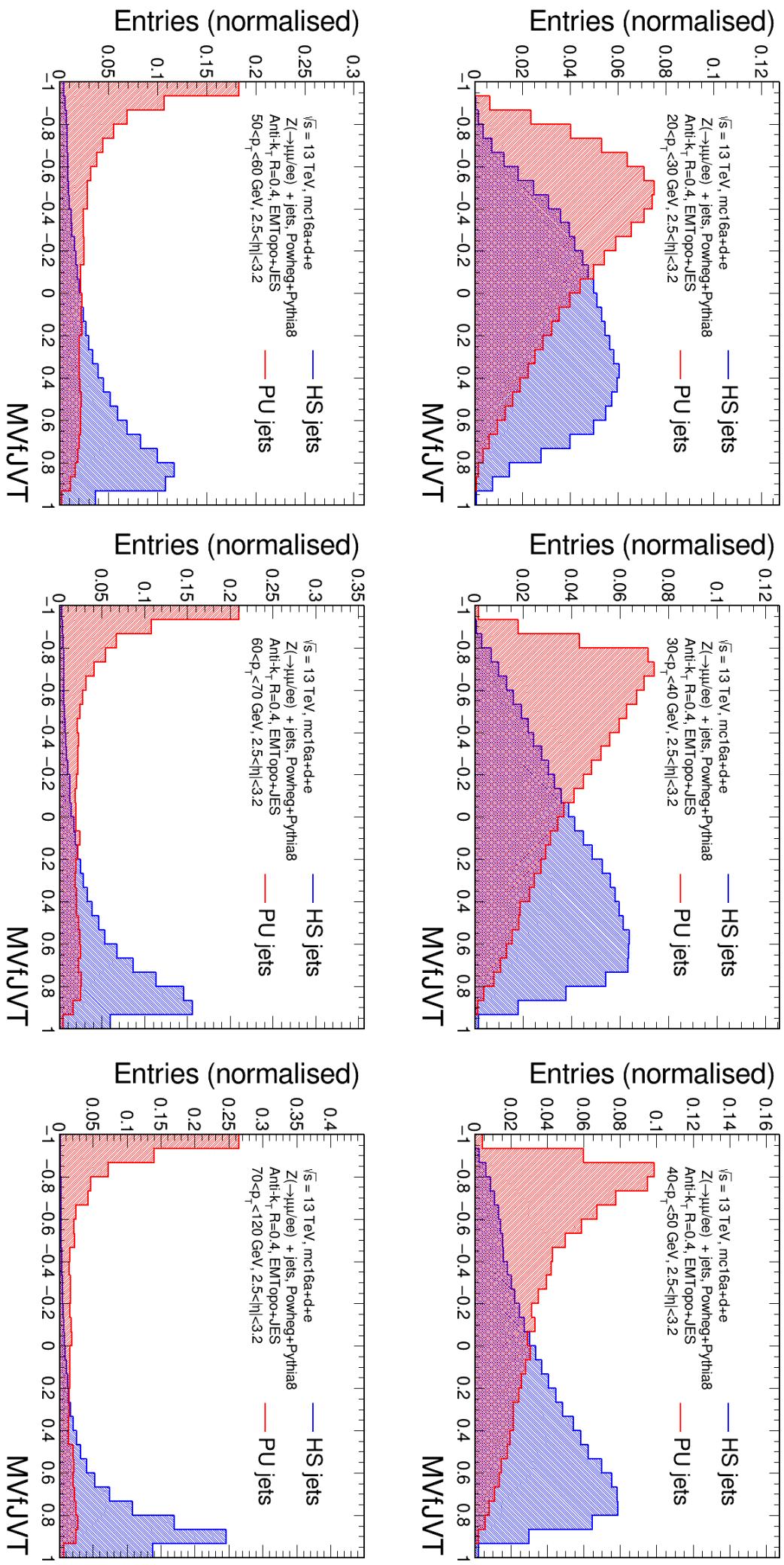
- > MV discriminants built with same Set of inputs
 - DNN vs BDT (with different boosting methods)
 - Similar level of hyperparameter Tuning
 - Similar performance
- 
- The figure is a Receiver Operating Characteristic (ROC) plot. The vertical axis is labeled "Pileup Rejection (1 - eff)" and ranges from 0.0 to 1.0. The horizontal axis is labeled "Hard-scatter Efficiency" and ranges from 0.0 to 1.0. A dashed black line represents a random classifier. Two solid lines represent the performance of the DNN (green) and BDT (red). Both curves start at (0,0) and end at (1,1). The DNN curve is slightly above the BDT curve for most of the plot, indicating better performance. A legend in the bottom left corner identifies the lines: "BDT (gradient boost) (AUC = 0.799)" and "DNN (AUC = 0.798)".
- | Efficiency | DNN (1 - eff) | BDT (1 - eff) |
|------------|---------------|---------------|
| 0.0 | 0.00 | 0.00 |
| 0.1 | 0.05 | 0.04 |
| 0.2 | 0.10 | 0.08 |
| 0.3 | 0.15 | 0.12 |
| 0.4 | 0.20 | 0.16 |
| 0.5 | 0.25 | 0.20 |
| 0.6 | 0.30 | 0.24 |
| 0.7 | 0.35 | 0.28 |
| 0.8 | 0.40 | 0.32 |
| 0.9 | 0.45 | 0.36 |
| 1.0 | 0.50 | 0.40 |

MVfJVT binned training

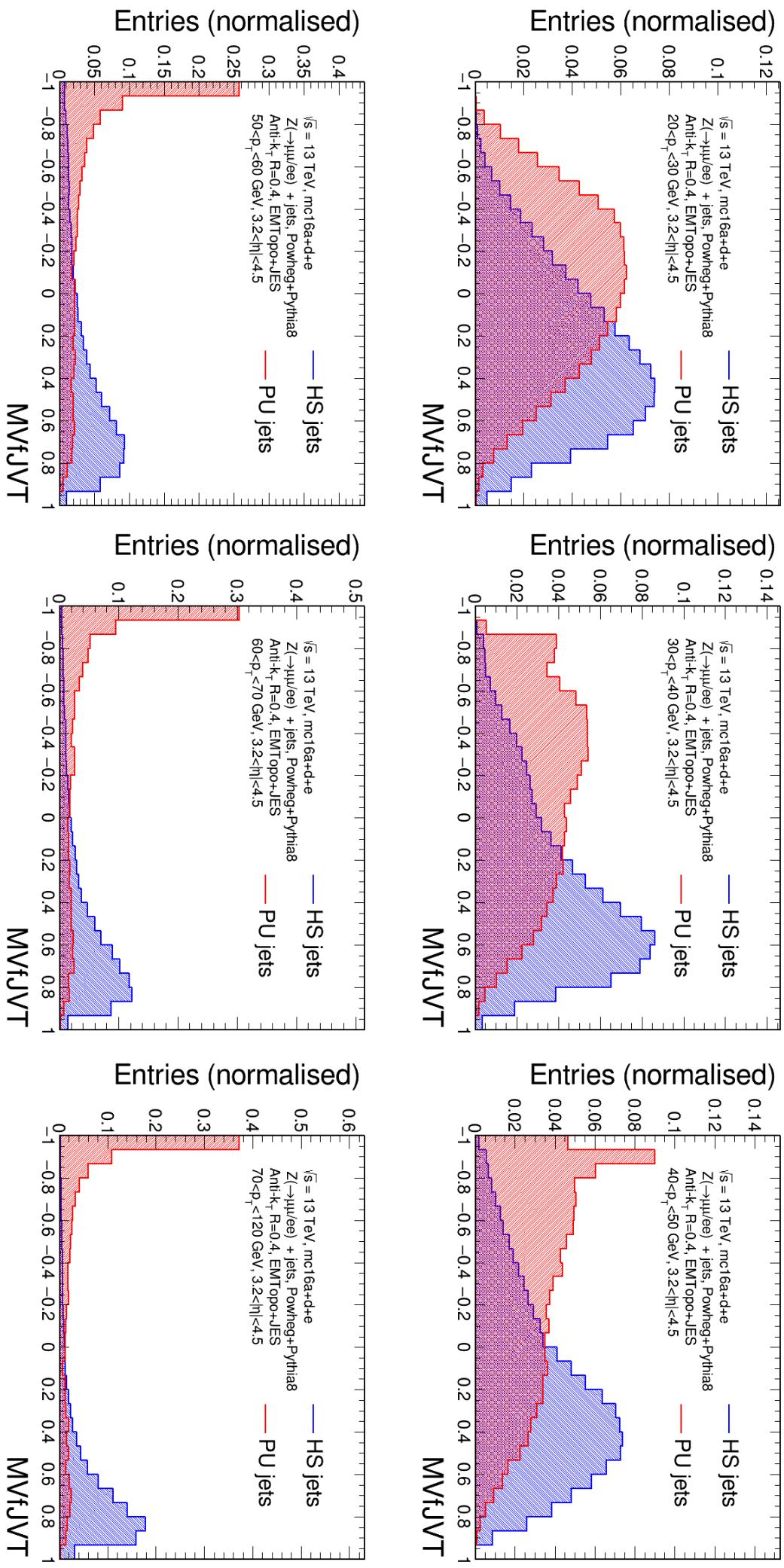
- > PU jet properties depends on p_T , $|\eta|$ and μ
- More PU at low p_T , high μ
- Lower detector resolution at high $|\eta|$
- Mitigated improvement from structure variables



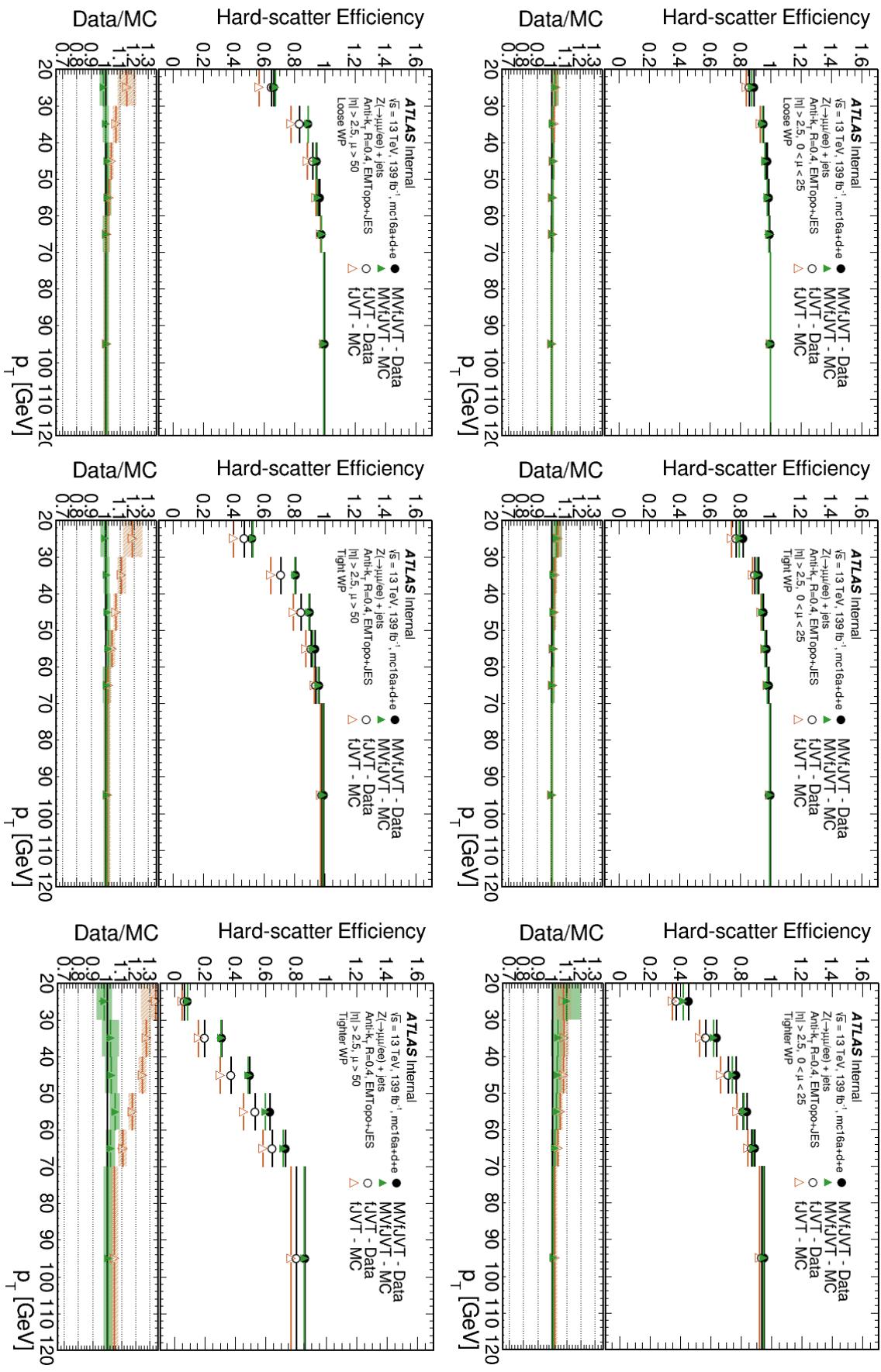
Multivariate fJVT - $2.5 < |\eta| < 3.2$



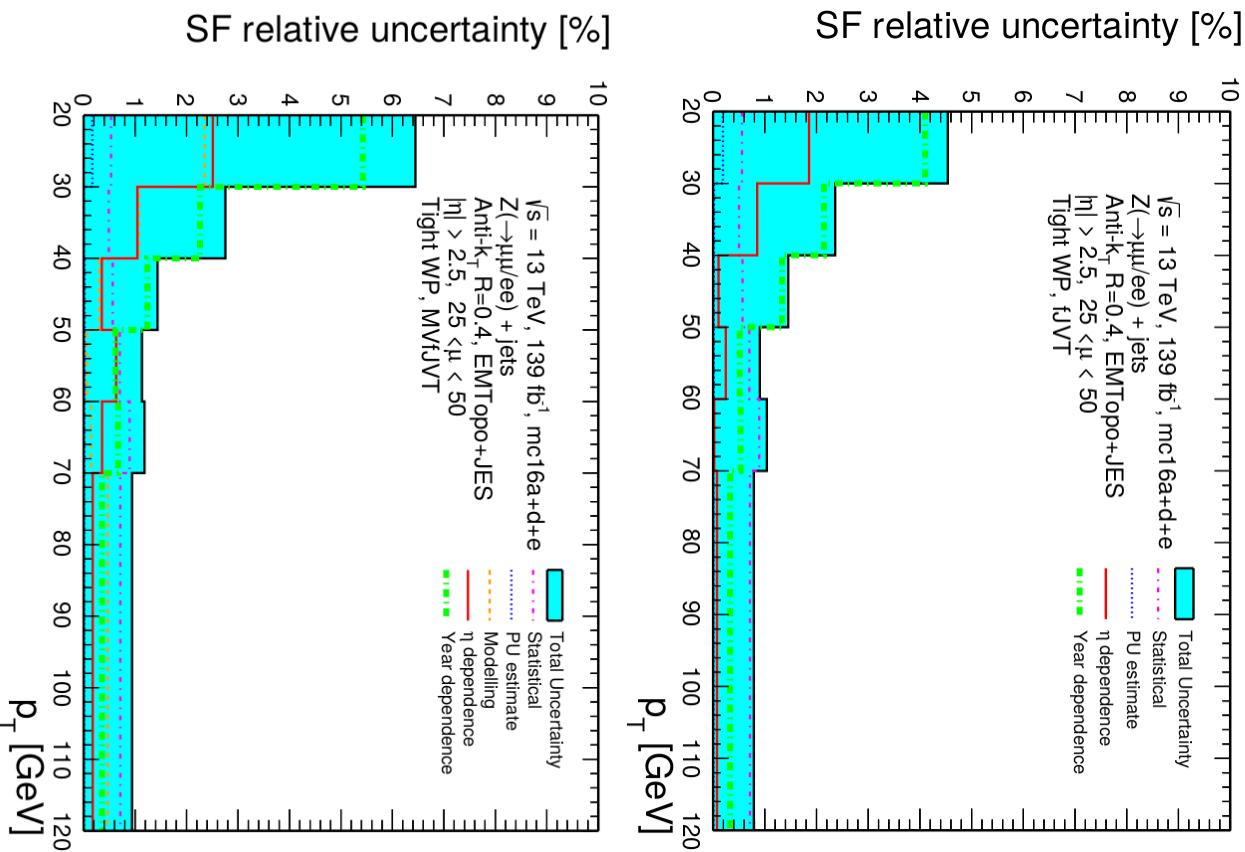
Multivariate fJVT - $3.2 < |\eta| < 4.0$



(MV)fJVT calibration



Forward taggers uncertainties



- > Overall similar between the two taggers
- > Uncertainties propagated to the SF
- Statistical uncertainty
 - Data and MC
- Pileup estimate
 - 10% variation of PU yield
 - Covers fJVT bias + PU modelling
- η -dependence
 - Envelop of SF variations w.r.t. η
 - Year dependence
 - Envelop of SF variations between years
(~ “internal” μ -dependence)
 - Monte Carlo modelling (MVfJVT)
 - Sherpa vs Powheg+Pythia Z+jet modelling

Forward taggers efficiency correction

> Data/MC discrepancy impacts the tagging efficiency

- Define MVfJVT operating points to get **same PU rejection as fJVT**
- Derive **scale-factors in (\mathbf{pT}, μ) bins**

$$\epsilon_{HS} = \frac{N^{pass} - N_{PU}^{pass}}{N - N_{PU}}, \quad SF = \frac{\epsilon_{HS}^{data}}{\epsilon_{HS}^{MC}}$$

> Two PU subtraction methods compared

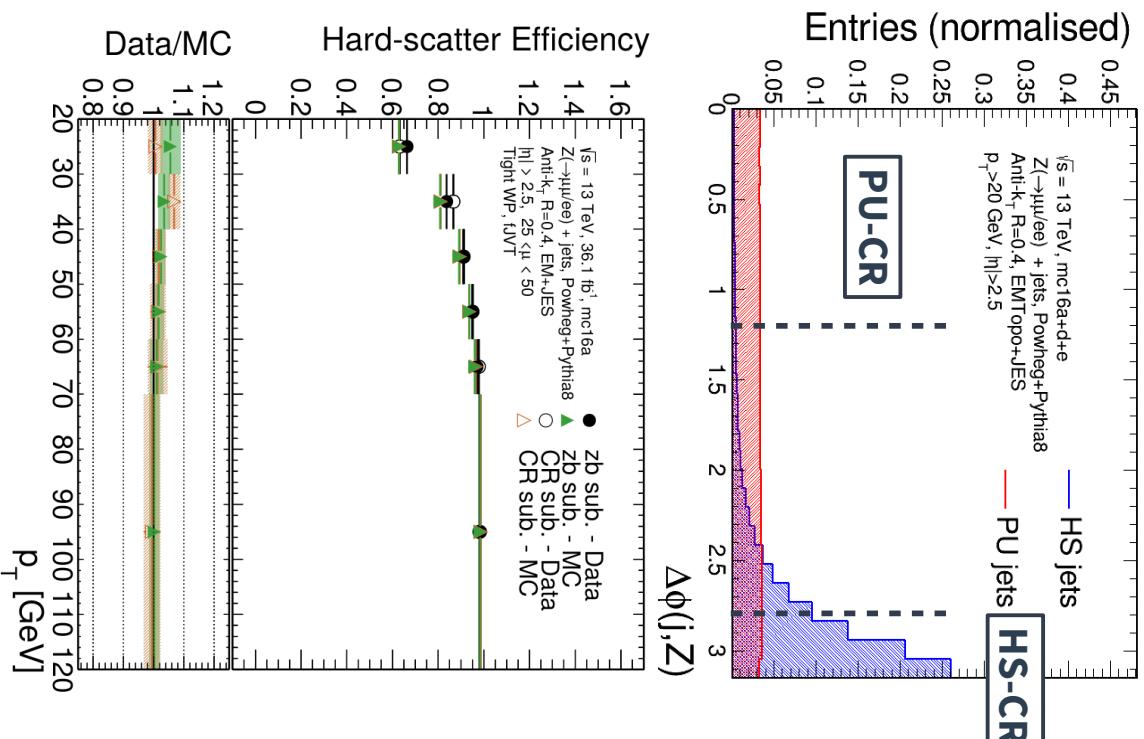
- **Extrapolation from PU-CR** (CR sub.)
 - Exact same event selection as HS
 - Impacted by event statistics and HS modelling

$$N_{PU}^{(\Delta\phi>2.8)} = \frac{\pi - 2.8}{1.2} (N^{(\Delta\phi<1.2)} - N_{HS}^{(\Delta\phi<1.2)})$$

- **Zerobias subtraction** (zb sub.)

- Model independent and large PU statistics
- Slight bias as no HS vertex removed

- Good overall agreement



Forward taggers for Pflow jets

> PFlow jets are now the baseline

- fJVT needed to be adapted

- Track-to-cluster matching suppresses central PU jets

- Need to be reconstructed and calibrated prior to fJVT computation

- PU vertices p_T^{miss} optimised

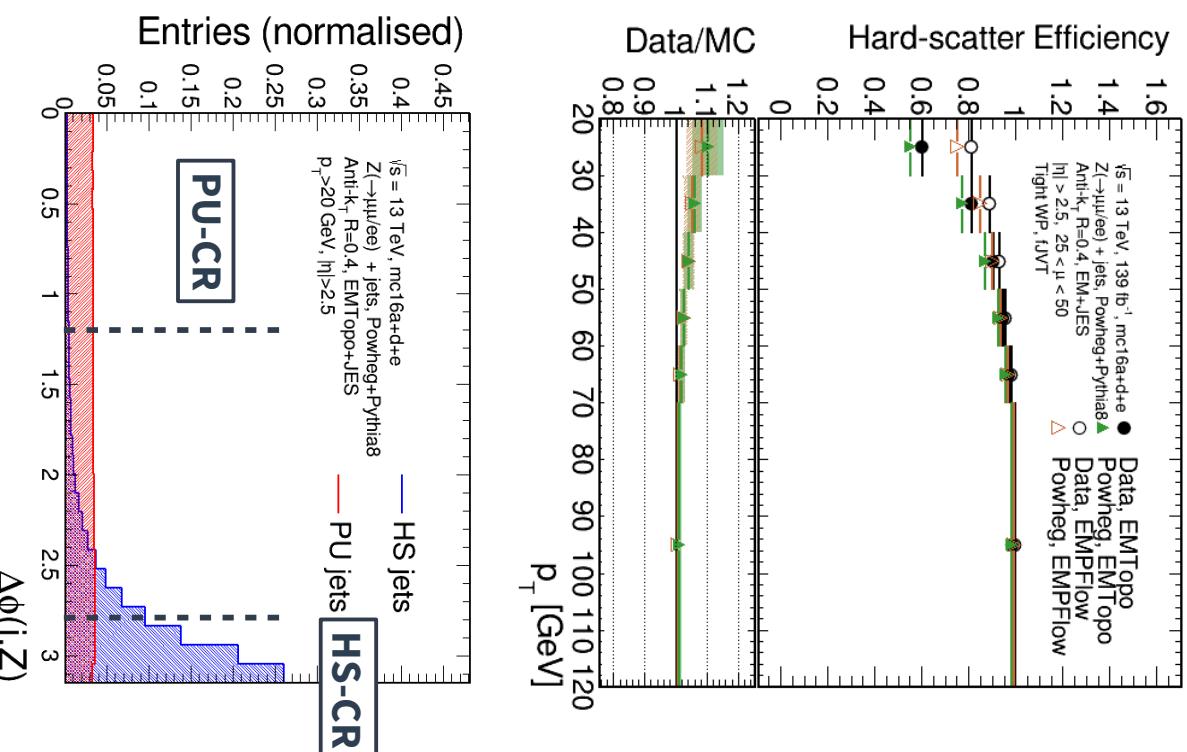
$$- p_{T,i}^{\text{miss}} = \left(\sum_{\substack{\text{jets}, p_T^{\text{jet}} > 20 \text{ GeV}}} p_T^{\text{jet}} + \sum_{\substack{\text{tracks}, p_T^{\text{jet}} < 20 \text{ GeV}}} p_T^{\text{track}} + \sum_{\substack{\text{tracks}, R_{pT}^{\text{jet}} < 0.1}} p_T^{\text{track}} \right)$$

> Performed calibration for the first time

- Using PU-CR method:

$$N_{PU}^{(\Delta\phi>2.8)} = \frac{\pi - 2.8}{1.2} (N_{HS}^{(\Delta\phi<1.2)} - N_{HS}^{(\Delta\phi>1.2)})$$

- Higher efficiency than EMTopo
- SF and uncertainties comparable to EMTopo jets



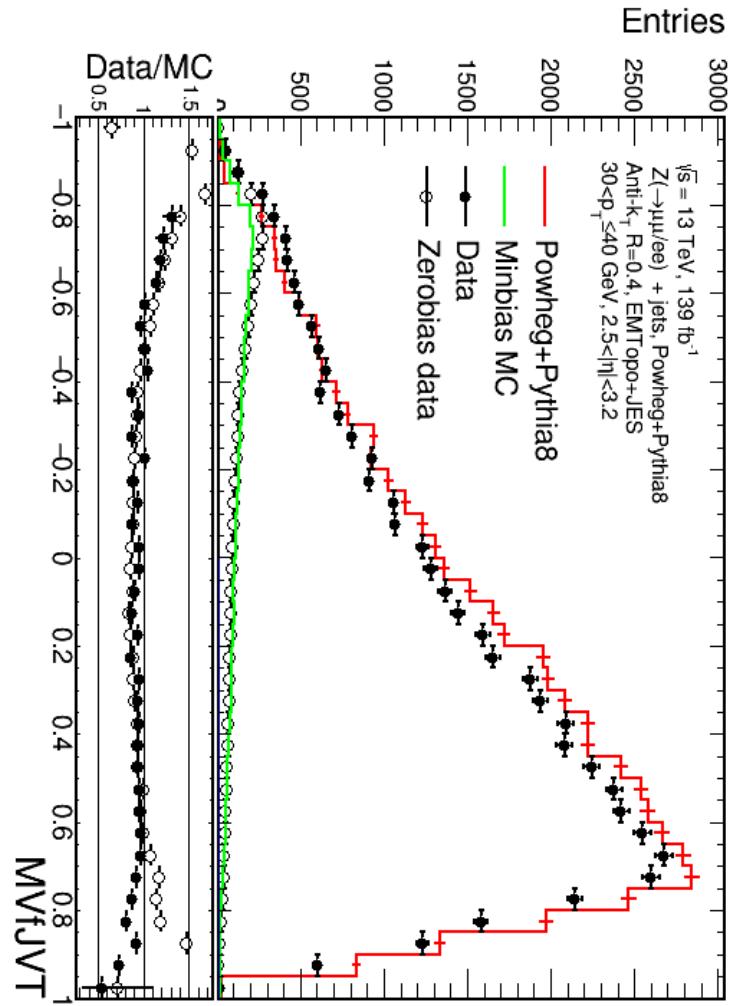
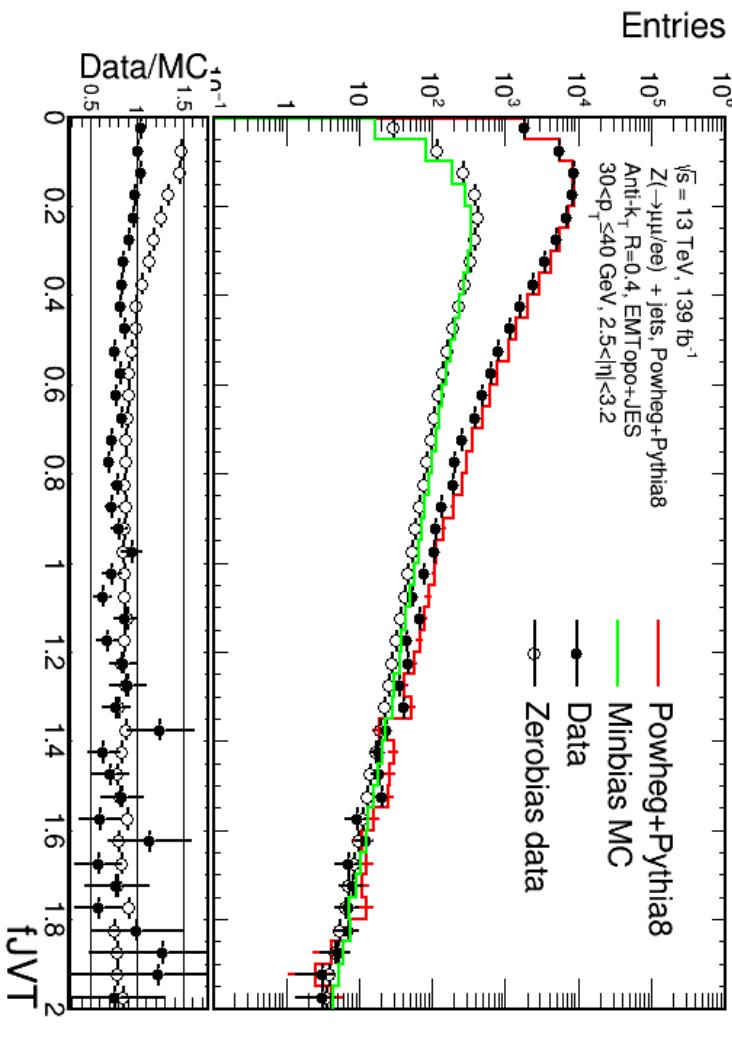
Pileup Modelling

- > PU modelling
- > Similar behaviour between fJVT and MVfJVT

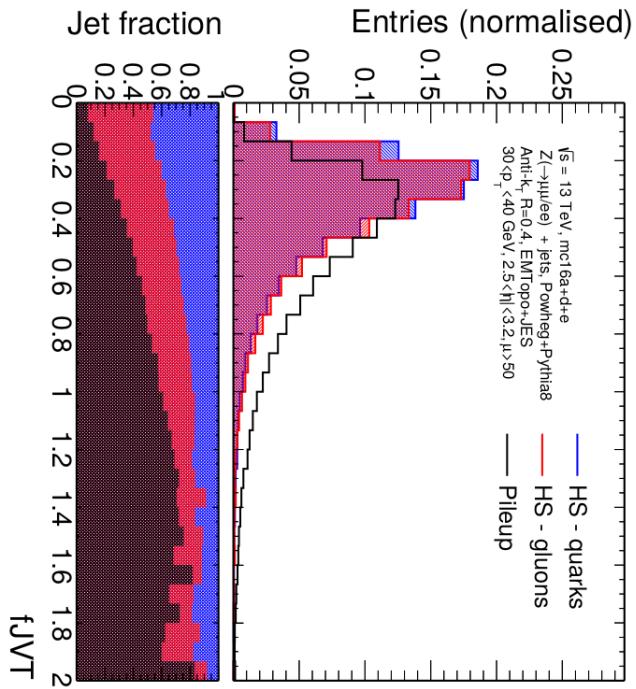
> HS modelling

→ fJVT decently modelled

→ MVfJVT shows more discrepancy

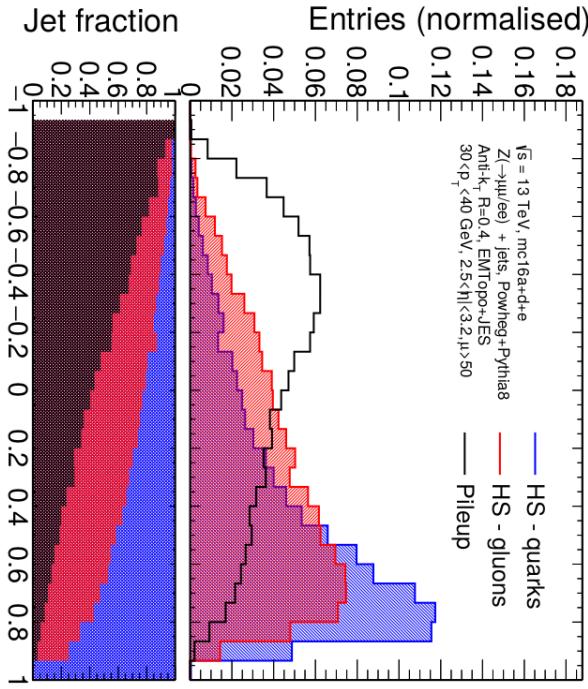


MVfJVT - Quark/Gluon dependence



- > Using jet shape leads to q/g dependence
 - gluon jets broader than quark jets
 - Better separation for quarks than gluons

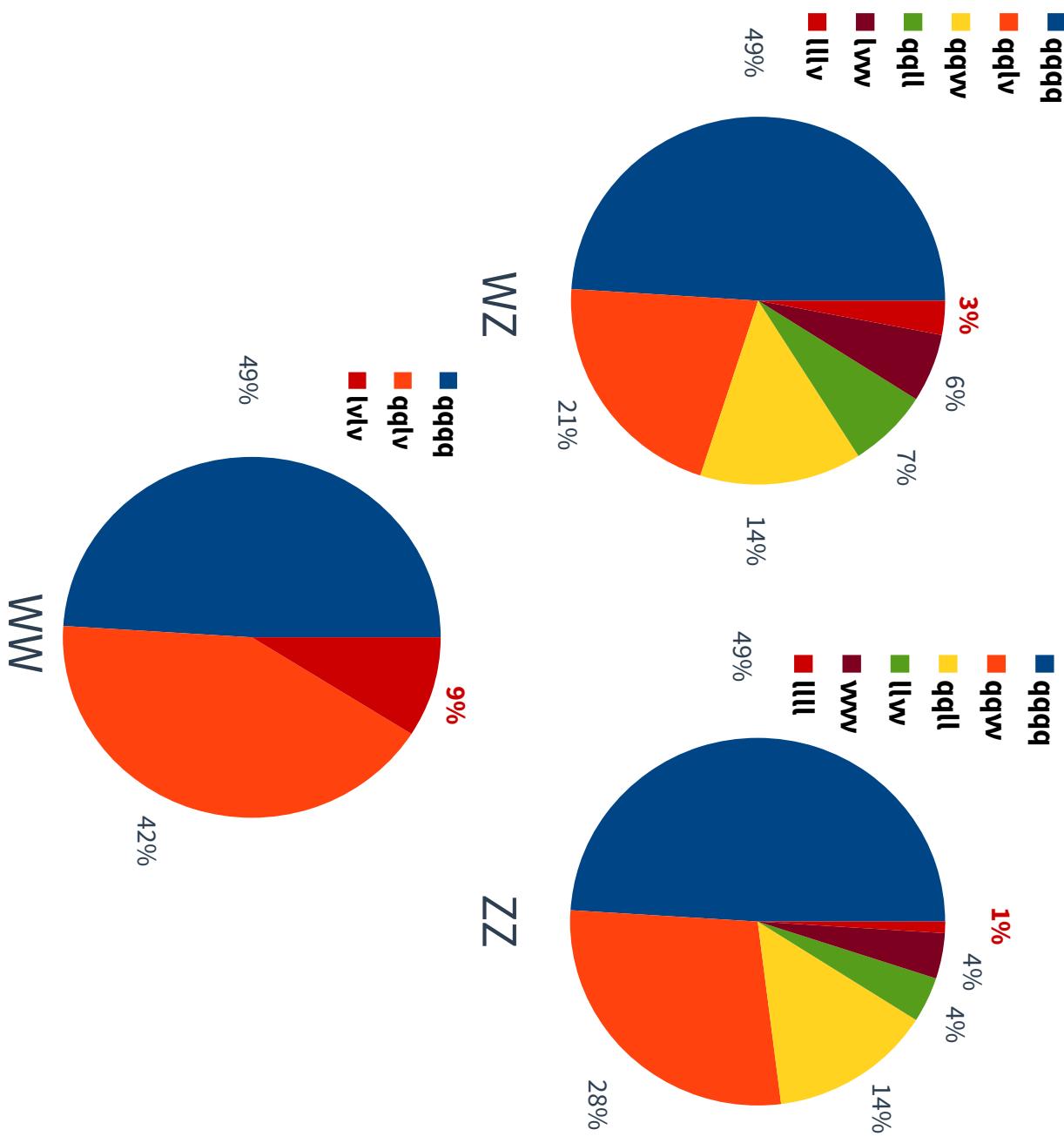
- > Impact in data need to be probed
 - Could be done through performance comparison in samples with well measured q/g fractions





WZjj-EW analysis

VV Branching ratios



Event selection - Leptons

Electron object selection			
Selection	Baseline selection	Z selection	W selection
$p_T > 5 \text{ GeV}$	✓	✓	✓
Electron object quality	✓	✓	✓
$ \eta_{\text{cluster}} < 2.47$, $ \eta < 2.5$	✓	✓	✓
Loose identification	✓	✓	✓
$ d_0/\sigma(d_0) < 5$	✓	✓	✓
$ \Delta z_0 \sin \theta < 0.5 \text{ mm}$	✓	✓	✓
Loose isolation	✓	✓	✓
e-to- μ and e-to-e overlap removal	✓	✓	✓
e-to-jets overlap removal	✓	✓	✓
$p_T > 15 \text{ GeV}$	✓	✓	✓
Exclude $1.37 < \eta^{\text{cluster}} < 1.52$	✓	✓	✓
Medium identification	✓	✓	✓
Gradient isolation	✓	✓	✓
$p_T > 20 \text{ GeV}$		✓	
Tight identification		✓	
Unambiguous author		✓	

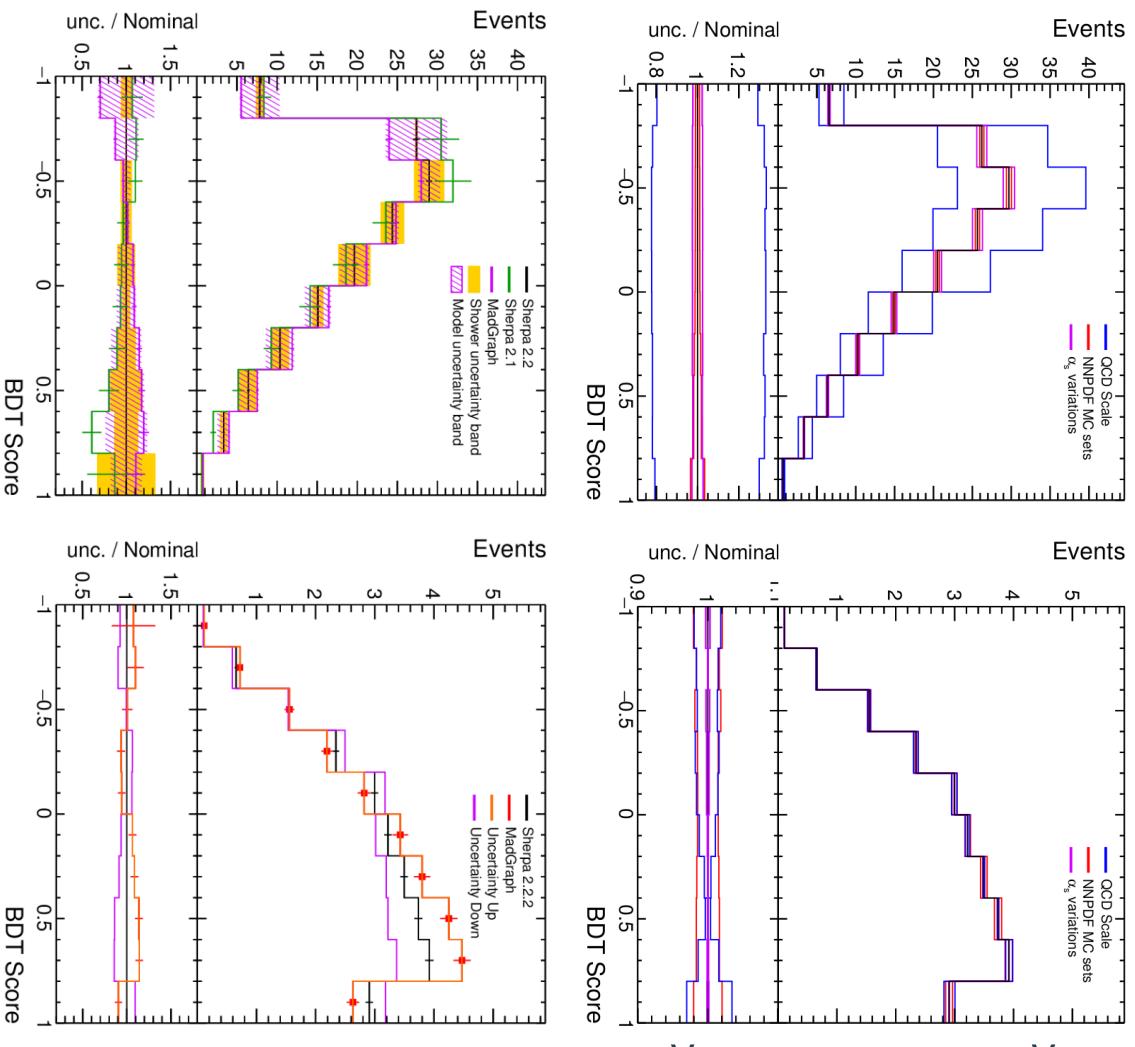
Muon object selection			
Selection	Baseline selection	Z selection	W selection
$p_T > 5 \text{ GeV}$	✓	✓	✓
$ \eta < 2.7$	✓	✓	✓
Loose quality	✓	✓	✓
$ d_0/\sigma(d_0) < 3$ (<i>for $\eta < 2.5$ only</i>)	✓	✓	✓
$ \Delta z_0 \sin \theta < 0.5 \text{ mm}$ (<i>for $\eta < 2.5$ only</i>)	✓	✓	✓
Loose isolation	✓	✓	✓
μ -jet Overlap Removal	✓	✓	✓
$p_T > 15 \text{ GeV}$	✓	✓	✓
$ \eta < 2.5$	✓	✓	✓
Medium quality	✓	✓	✓
$p_T > 20 \text{ GeV}$		✓	
Tight quality		✓	
Tight isolation		✓	

MC generators

Process	Generator (PDF)	Order (α_s)	Nominal
			Mod. Unc.
$WZjj\text{-EW}$	SHERPA2.2.2 (NNPDF3.0nnlo)	LO	
	MADGRAPH5+PYTHIA8 (NNPDF3.0nlo)		
$WZjj\text{-QCD}$	SHERPA2.2.1 (NNPDF3.0nnlo) SHERPA2.2.2 (NNPDF3.0nnlo)	(0,1)jNLO + (2,3)jLO (0,1)jNLO + (2,3)jLO	+ Powheg+Pythia8 (01)jNLO+(2,3)jLO
	SHERPA2.1 (NNPDF3.0nnlo)	(0,1)jNLO + (2,3)jLO	
	MADGRAPH5+PYTHIA8 (NNPDF3.0nlo)	(0,1,2)jLO	
tZj	MADGRAPH5+PYTHIA8 (NNPDF3.0nlo)	LO	
$ZZjj\text{-QCD}$	SHERPA2.2.2 (NNPDF3.0nnlo)	(0,1)jNLO + (2,3)jLO	
$ZZjj\text{-EW}$	SHERPA2.2.2 (NNPDF3.0nnlo)	LO	
$t\bar{t} + V$	MADGRAPH5+PYTHIA8 (NNPDF3.0nlo)	NLO	
$VV\bar{V}$	SHERPA2.2.1 (CT10)	LO	
$Z+\text{jets}$	POWHEG+PYTHIA8 (NNPDF3.0nnlo) POWHEG+PYTHIA8 (NNPDF3.0nlo)	NLO NLO	
$t\bar{t}$	SHERPA2.2.2 (NNPDF3.0nnlo)	NLO	
$Z\gamma$			

Theory uncertainties uncertainties

- > Theory uncertainties
 - QCD scale: variation envelope of μ_R , μ_F
 - **NNPDF3.0**: MC replicas standard deviation
 - $\alpha_S = 0.118 \pm 0.001$



- **WZjj-EW:**
 - Sherpa 2.2.2 vs Madgraph
 - Matched generator-level cross-section
- **WZjj-QCD:**
 - Sherpa 2.2.2 vs Madgraph
 - Compared to PS-only uncertainty
 - Pythia8 vs Herwig7, ME from Powheg

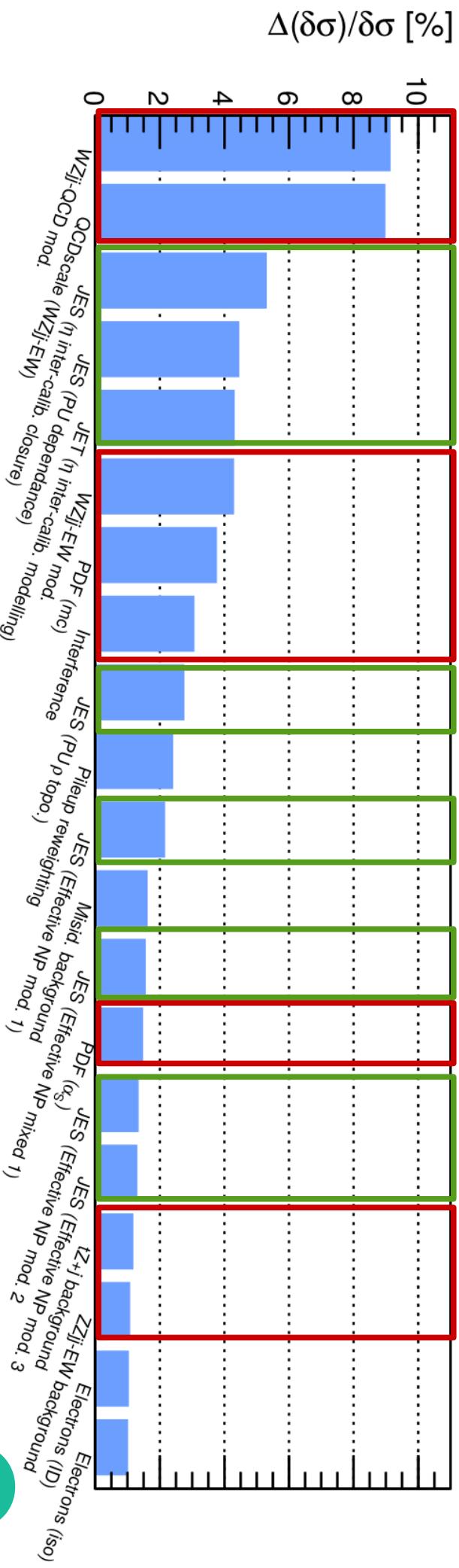
WZjj-EW observation: Systematic uncertainties

> Additional uncertainties from particle reconstruction and calibration

- Main impact from JES uncertainties

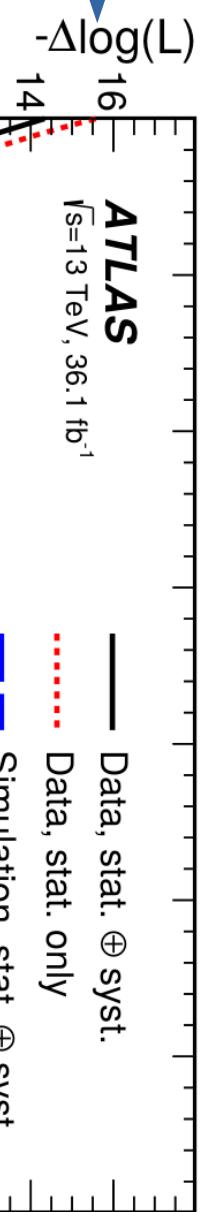
> Pruning and smoothing procedure applied

- Take variation envelope if +1 and -1 variations go in the same direction
- Remove all uncertainties with negligible impact on the final result



Fit results – Negative Log. Likelihood

$$\text{NLL}(\lambda(\mu, \hat{\mu}, \hat{\theta}, \hat{\hat{\theta}})) = -\ln \frac{\mathcal{L}(\mu, \hat{\theta})}{\mathcal{L}(\hat{\mu}, \hat{\theta})}$$



$$\mathcal{L}(\mu, \theta) = \prod_{i \in \text{bins}} \frac{(\mu S_i(\theta) + B_i(\theta))^{n_i}}{n_i!} e^{\mu S_i(\theta) + B_i(\theta)}$$

Λ → Globally maximising value(s)

Λ → Maximising value(s) with fixed
Values of other parameters

Significance:

$$Z = \sqrt{2 \text{ NLL}(\lambda(\mu=0))}$$

$$\mu_{WZjj-\text{EW}} = \frac{N_{\text{signal}}}{N_{\text{MC}}} = \frac{\sigma_{WZjj-\text{EW}}^{\text{fid.,meas.}}}{\sigma_{WZjj-\text{EW}}^{\text{fid.,MC}}}$$

WZjj-EW observation: Phase space

> Lepton matching to W and Z bosons

→ Resonant shape algorithm:

$$P = \left| \frac{1}{m_{\ell^+\ell^-}^2 - (m_Z^{\text{PDG}})^2 + i\Gamma_Z^{\text{PDG}} m_Z^{\text{PDG}}} \right|^2 \times \left| \frac{1}{m_{\ell^\pm\nu}^2 - (m_W^{\text{PDG}})^2 + i\Gamma_W^{\text{PDG}} m_W^{\text{PDG}}} \right|^2$$

Variable	Phase-space requirement
Lepton $ \eta $	< 2.5
$p_T^{\ell_Z^-}$ [GeV]	> 15
$p_T^{\ell_W^-}$ [GeV]	> 20
m_T^W [GeV]	< 10
$ m_Z - m_Z^{\text{PDG}} $ [GeV]	> 30
$\Delta R(\ell_Z^-, \ell_Z^+)$	> 0.2
$\Delta R(\ell_Z, \ell_W^-)$	> 0.3
two leading jets [GeV]	> 40
$ \eta_j $ two leading jets	< 4.5
Jet multiplicity	≥ 2
$\eta_{j1} \cdot \eta_{j1}$	< 0
m_{jj} [GeV]	> 500
$\Delta R(j, \ell)$	> 0.3
$N_{b\text{-quark}}$	$= 0$

WZjj-EW observation: Signal cross-section

> WZjj-EW cross-section derived from fit result

$$\mu_{WZjj-EW} = \frac{N_{\text{data}}^{\text{signal}}}{N_{\text{MC}}^{\text{signal}}} = \frac{\sigma_{WZjj-EW}^{\text{fid.,meas.}}}{\sigma_{WZjj-EW}^{\text{fid.,MC}}}$$

m_T^W [GeV]
 $|m_Z - m_Z^{\text{PDG}}|$ [GeV]
 $\Delta R(\ell_Z^-, \ell_Z^+)$
 $\Delta R(\ell_Z, \ell_W)$

two leading jets [GeV]
 $|\eta_j|$ two leading jets

Jet multiplicity
 $\eta_{j1} \cdot \eta_{j1}$

m_{jj} [GeV]
 $\Delta R(j, \ell)$

$N_{b-\text{quark}}$

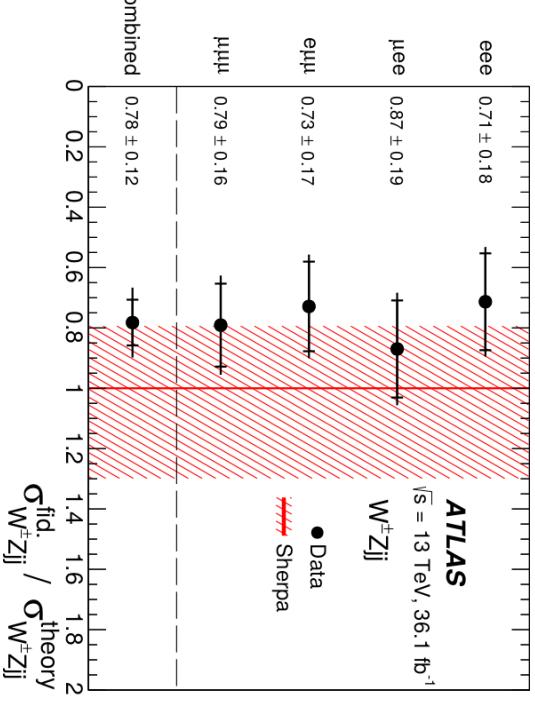
→ Extracted in fiducial phase-space close to SR definition
 → Using predicted cross-section from Sherpa 2.2.2

$$\sigma_{\text{Sherpa}}^{\text{fid., EW th.}} = 0.321 \pm 0.002 \text{ (stat.)}^{+0.005}_{-0.005} \text{ (PDF)}^{+0.027}_{-0.023} \text{ (scale) fb}$$

$$\sigma_{WZjj-EW}^{\text{fid.}} = 0.57^{+0.14}_{-0.13} \text{ (stat.)}^{+0.07}_{-0.06} \text{ (syst.) fb} = 0.57^{+0.16}_{-0.14} \text{ fb}$$

> WZjj-(EW+QCD) cross-section also derived as well

$$\rightarrow \text{Different approach: } \sigma_{WZjj}^{\text{fid.}} = \frac{N_{\text{data}} - N_{\text{bkg}}}{\mathcal{L} \cdot C_{WZjj}} \times \left(1 - \frac{N_\tau}{N_{\text{all}}}\right)$$



ATLAS
 $\sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1}$
 $W^\pm Zjj$

● Data
 Sherpa

Yields

Pre-fit

	SR	QCD-CR	b -CR	ZZ -CR
Data	161	213	141	52
Total MC	200 \pm 41	290 \pm 61	159.4 \pm 13.5	45.2 \pm 7.5
$WZjj$ -EW (signal)	24.9 \pm 1.4	8.45 \pm 0.37	1.36 \pm 0.10	0.21 \pm 0.12
$WZjj$ -QCD	144 \pm 41	231 \pm 60	24.4 \pm 1.7	1.43 \pm 0.22
Misid. leptons	9.8 \pm 3.9	17.7 \pm 7.1	29.8 \pm 11.9	0.47 \pm 0.21
ZZ -QCD	8.10 \pm 0.84	14.98 \pm 0.92	1.96 \pm 0.08	35.0 \pm 5.0
tZ	6.5 \pm 1.2	6.6 \pm 1.1	36.2 \pm 5.7	0.18 \pm 0.04
$t\bar{t} + V$	4.21 \pm 0.42	9.11 \pm 0.29	65.4 \pm 2.7	2.8 \pm 0.44
ZZ -EW	1.80 \pm 0.45	0.53 \pm 0.14	0.12 \pm 0.09	4.1 \pm 1.4
VVV	0.59 \pm 0.15	0.93 \pm 0.23	0.13 \pm 0.03	1.05 \pm 0.30

Post-fit

	SR	QCD-CR	b -CR	ZZ -CR
Data	161	213	141	52
Total predicted	167 \pm 11	204 \pm 12	146 \pm 11	51.3 \pm 7.0
$WZjj$ -EW (signal)	44 \pm 11	8.52 \pm 0.41	1.38 \pm 0.10	0.211 \pm 0.004
$WZjj$ -QCD	91 \pm 10	144 \pm 14	13.9 \pm 3.8	0.94 \pm 0.14
Misid. leptons	7.8 \pm 3.2	14.0 \pm 5.7	23.5 \pm 9.6	0.41 \pm 0.18
ZZ -QCD	11.1 \pm 2.8	18.3 \pm 1.1	2.35 \pm 0.06	40.8 \pm 7.2
$tZ + j$	6.2 \pm 1.1	6.3 \pm 1.1	34.0 \pm 5.3	0.17 \pm 0.04
$t\bar{t} + V$	4.7 \pm 1.0	11.14 \pm 0.37	71 \pm 15	3.47 \pm 0.54
ZZ -EW	1.80 \pm 0.45	0.44 \pm 0.10	0.10 \pm 0.03	4.2 \pm 1.2
VVV	0.59 \pm 0.15	0.93 \pm 0.23	0.13 \pm 0.03	1.06 \pm 0.30

WZjj-EW observation: fit cross-checks

	Cross-check 1	Cross-check 2	Cross-check 3	Main result
$WZjj$ -QCD correction	1	0.68	1	0.68 ± 0.23
μ_{WZjj} -QCD	0.59 ± 0.16	N/A	N/A	
QCD scale pull [σ]	0.34 ± 0.95	-0.27 ± 0.42	-1.6 ± 0.38	0.00 ± 0.99
QCD modelling pull [σ]	0.22 ± 0.81	0.13 ± 0.71	0.0 ± 0.73	0.21 ± 0.79
μ_{WZjj} -EW				
Significance (exp.) [σ]	1.74 ± 0.43	1.75 ± 0.48	1.69 ± 0.40	1.77 ± 0.46
Significance (meas.) [σ]	2.7	3.2	2.7	3.2
	5.3	5.3	5.2	5.3

No “background-only” fit

No background norm. correction

No “background-only” fit
No background norm. correction

No “background-only” fit

No background norm. correction

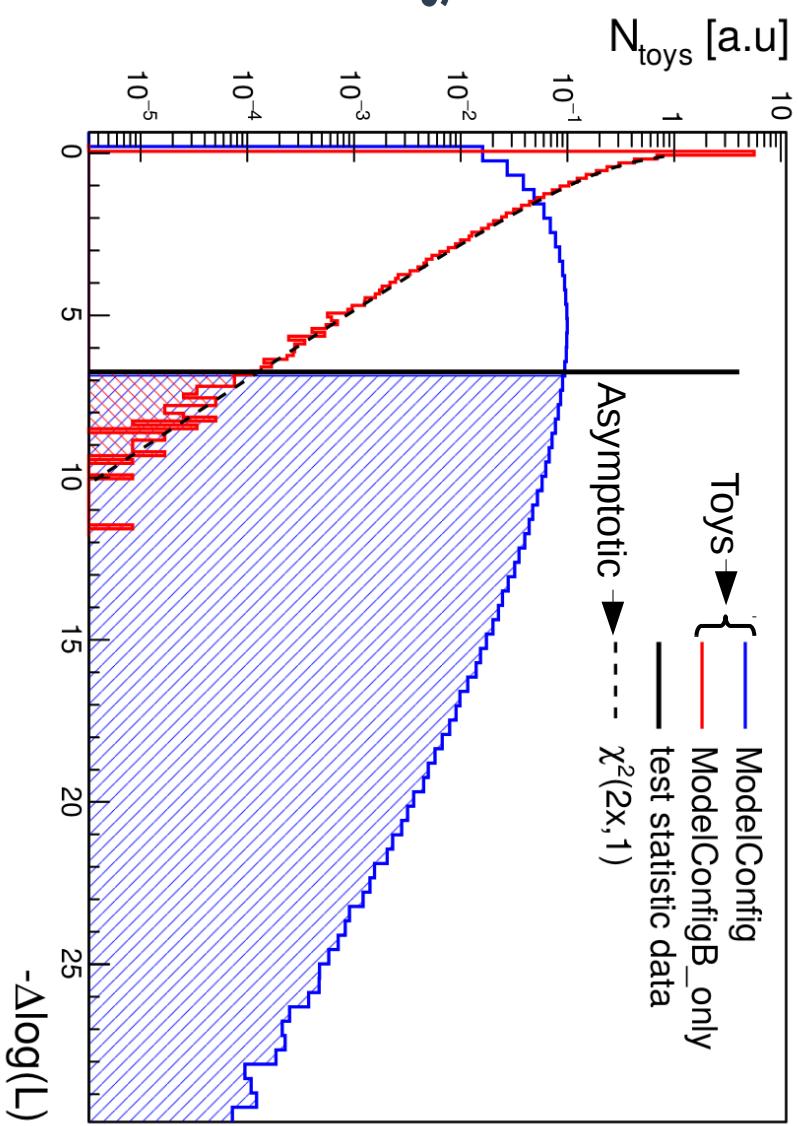
No “background-only” fit
No background norm. correction

WZjj-EW observation: fit cross-checks

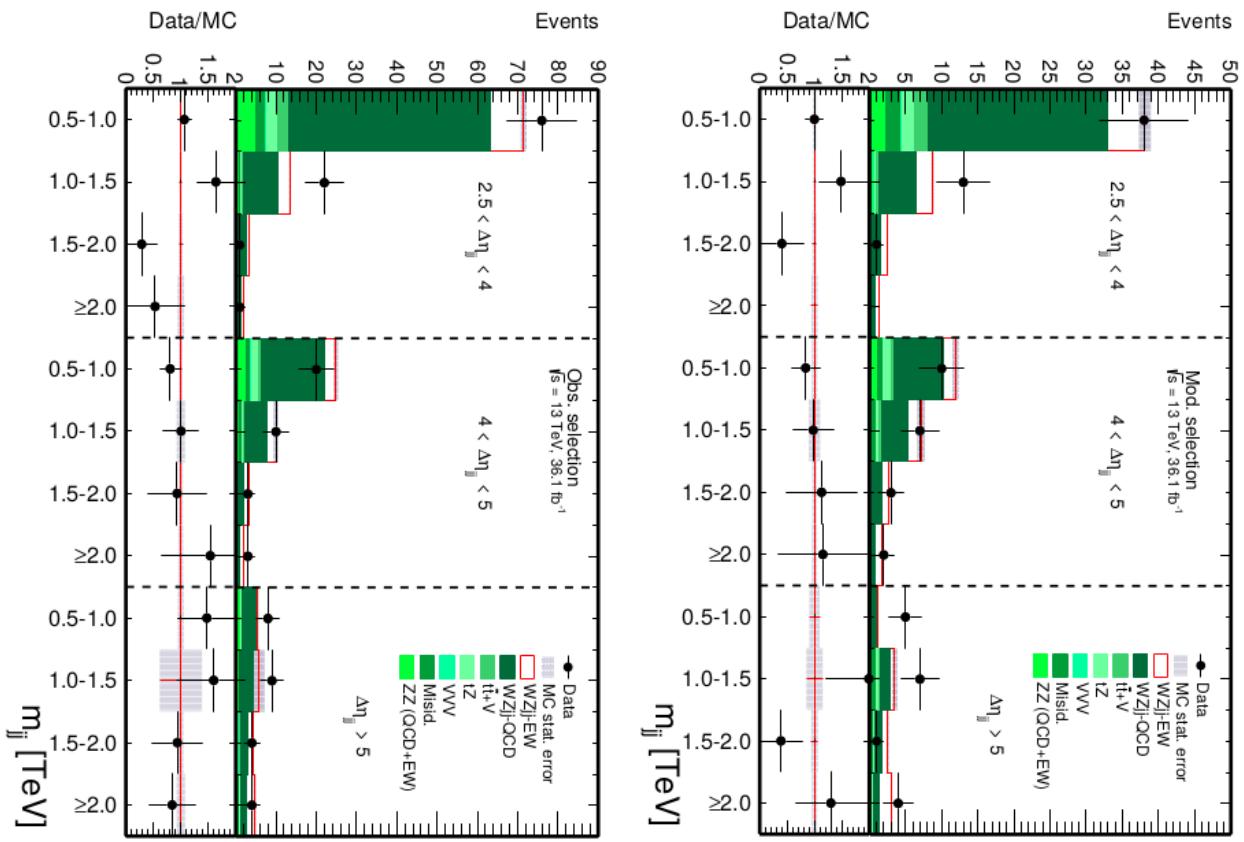
> **Fit strategy assumes asymptotic regime**

> **Cross-checked using toy experiments**

- 1 M toys for Null hypothesis
- 500k toys for tested hypothesis
- Allow to validate $> 3 \sigma$ sensitivity
($\leftrightarrow p\text{-value} \sim 10^{-4}$)



WZjj-EW observation: Strategy comparison with CMS



- > Reproduced event selection & fit strategy
- > Higher sensitivity mainly due to BDT use

	$m_{jj} \times \Delta\eta(j1, j2)$	BDT score	
Mod.	Obs.	Mod.	Obs.
$\mu_{WZjj-EW}$ (SHERPA)	1.21 ± 0.53	1.12 ± 0.53	1.72 ± 0.46
$\mu_{WZjj-EW}$ (MADGRAPH)	1.06 ± 0.46	0.98 ± 0.46	1.51 ± 0.40
Significance (exp.) [σ]	2.23	2.12	3.16
Significance (meas.) [σ]	2.60	2.30	5.24
			5.58

Effective Field Theory interpretations

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{f_i^{(6)}}{\Lambda^2} \mathcal{L}_i^{(6)} + \sum_i \frac{f_i^{(8)}}{\Lambda^4} \mathcal{L}_i^{(8)}$$

Dimension 6 operators:
 > Mostly concerns aTGCs, could also impact VBS
 > Better constrained by other processes (e.g. inclusive WW)

Dimension 8 operators:
 > "Pure" aQGCs terms found there
 > Would highly benefit from VBS constraints

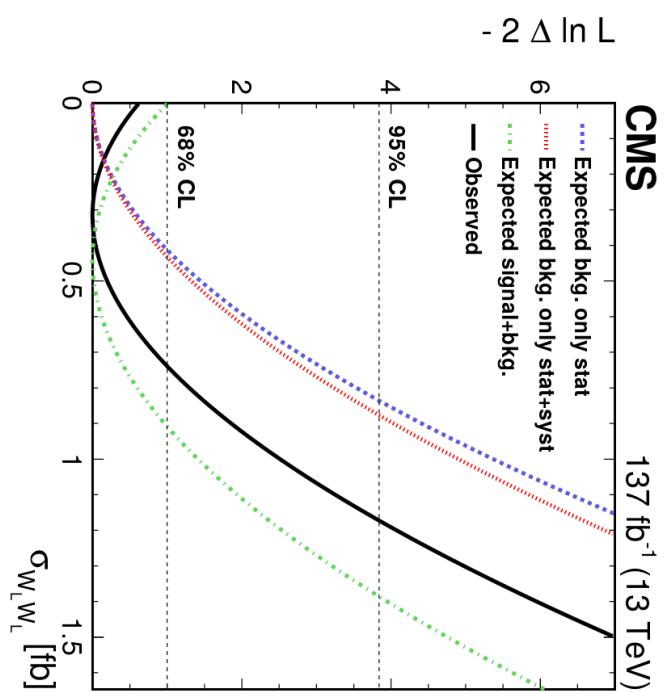
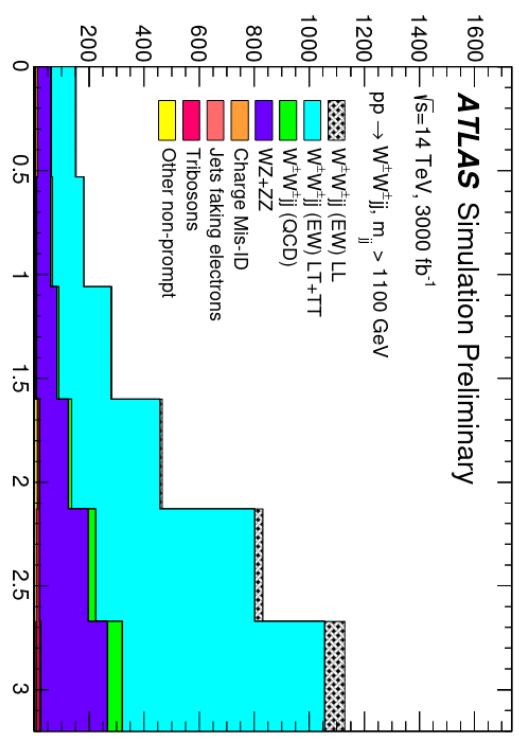
$\mathcal{L}_{M,0}$	$\text{Tr} [\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}] \times [(D_\beta \Phi)^\dagger D^\beta \Phi]$	$\mathcal{L}_{T,0}$	$\text{Tr} [\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}] \times \text{Tr} [\hat{W}_{\alpha\beta} \hat{W}^{\alpha\beta}]$
$\mathcal{L}_{M,1}$	$\text{Tr} [\hat{W}_{\mu\nu} \hat{W}^{\nu\beta}] \times [(D_\beta \Phi)^\dagger D^\mu \Phi]$	$\mathcal{L}_{T,1}$	$\text{Tr} [\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta}] \times \text{Tr} [\hat{W}_{\mu\beta} \hat{W}^{\alpha\nu}]$
$\mathcal{L}_{M,2}$	$[B_{\mu\nu} B^{\mu\nu}] \times [(D_\beta \Phi)^\dagger D^\beta \Phi]$	$\mathcal{L}_{T,2}$	$\text{Tr} [\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta}] \times \text{Tr} [\hat{W}_{\beta\nu} \hat{W}^{\nu\alpha}]$
$\mathcal{L}_{M,3}$	$[B_{\mu\nu} B^{\nu\beta}] \times [(D_\beta \Phi)^\dagger D^\mu \Phi]$	$\mathcal{L}_{T,5}$	$\text{Tr} [\hat{W}_{\mu\nu} \hat{W}^{\mu\beta}] \times B_{\alpha\beta} B^{\alpha\beta}$
$\mathcal{L}_{M,4}$	$[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} D^\mu \Phi] \times B^{\beta\nu}$	$\mathcal{L}_{T,6}$	$\text{Tr} [\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta}] \times B_{\mu\beta} B^{\alpha\nu}$
$\mathcal{L}_{M,5}$	$[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} D^\nu \Phi] \times B^{\beta\mu}$	$\mathcal{L}_{T,7}$	$\text{Tr} [\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta}] \times B_{\beta\nu} B^{\nu\alpha}$
$\mathcal{L}_{M,6}$	$[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\nu} D^\mu \Phi]$	$\mathcal{L}_{T,8}$	$B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta}$
$\mathcal{L}_{M,7}$	$[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\mu} D^\nu \Phi]$	$\mathcal{L}_{T,9}$	$B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha}$

observed (WW $^\pm$ WW $^\pm$) (TeV $^{-4}$)	Expected (WW $^\pm$ WW $^\pm$) (TeV $^{-4}$)	observed (WZ) (TeV $^{-4}$)	Expected (WZ) (TeV $^{-4}$)	observed (TeV $^{-4}$)	Expected (TeV $^{-4}$)
f_{T0}/Λ^4 [-0.81, 12]	[1.5, 2.3]	f_{T1}/Λ^4 [-0.98, 14]	[2.1, 2.7]	f_{T2}/Λ^4 [-2.1, 4.4]	[1.6, 1.9]
f_{M0}/Λ^4 [-13, 16]		f_{M1}/Λ^4 [-20, 19]		f_{M6}/Λ^4 [-27, 32]	
f_{M7}/Λ^4 [-35, 36]		f_{S1}/Λ^4 [-100, 120]		f_{S0}/Λ^4 [-100, 120]	

CMS EW
 WWjj+WZjj
 combination

Polarised VBS

- > Recent result from CMS on $W_L W_L$ scattering
- Evidence-level sensitivity to single-boson longitudinal polarisation
- LL scattering ~ 1 standard deviation
- > HL-LHC predictions indicates potential for double-longitudinal polarisation evidence
- CMS + ATLAS combination required
- Some time left to optimise the analyses



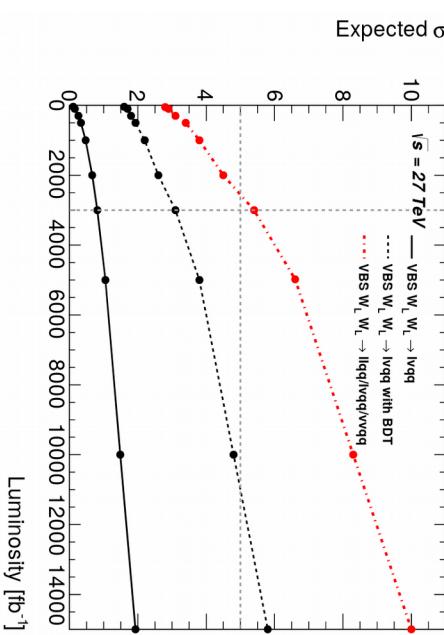
- Some studies regarding HE-LHC

- Potential future of HL-LHC, with a CoM energy increased to 27 TeV
- These studies assume 15 ab^{-1} of data, and a pileup of 800
- Prospect studies shows that this would highly benefit to VBS-related studies:

aQGC limits (ssWW,WZ)

	14 TeV		27 TeV	
	$WZjj$	$W^\pm W^\pm jj$	$WZjj$	$W^\pm W^\pm jj$
f_{S_0}/Λ^4	[-8,8]	[-6,6]	[-1.5,1.5]	[-1.5,1.5]
f_{S_1}/Λ^4	[-18,18]	[-16,16]	[-3,3]	[-2.5,2.5]
f_{T_0}/Λ^4	[-0.76,0.76]	[-0.6,0.6]	[-0.04,0.04]	[-0.027,0.027]
f_{T_1}/Λ^4	[-0.50,0.50]	[-0.4,0.4]	[-0.03,0.03]	[-0.016,0.016]
f_{M_0}/Λ^4	[-3.8,3.8]	[-4.0,4.0]	[-0.5,0.5]	[-0.28,0.28]
f_{M_1}/Λ^4	[-5.0,5.0]	[-12,12]	[-0.8,0.8]	[-0.90,0.90]

Polarisation (WW(\rightarrow qq))



Polarisation (ZZ)

	significance		precision (%)	
	w/ syst. uncert.	w/o syst. uncert.	w/ syst. uncert.	w/o syst. uncert.)
HL-LHC	1.4σ	1.4σ	75%	75%
HE-LHC	5.2σ	5.7σ	20%	19%