Vector Boson Scattering at the ATLAS Detector

Seminar of IoP of CAS

IoP Slovanka, Prague
Czech Republic
13 Jan 2022
(online - zoom)

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on behalf of the ATLAS Collaboration

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  - Theory
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  - WW
  - WZ
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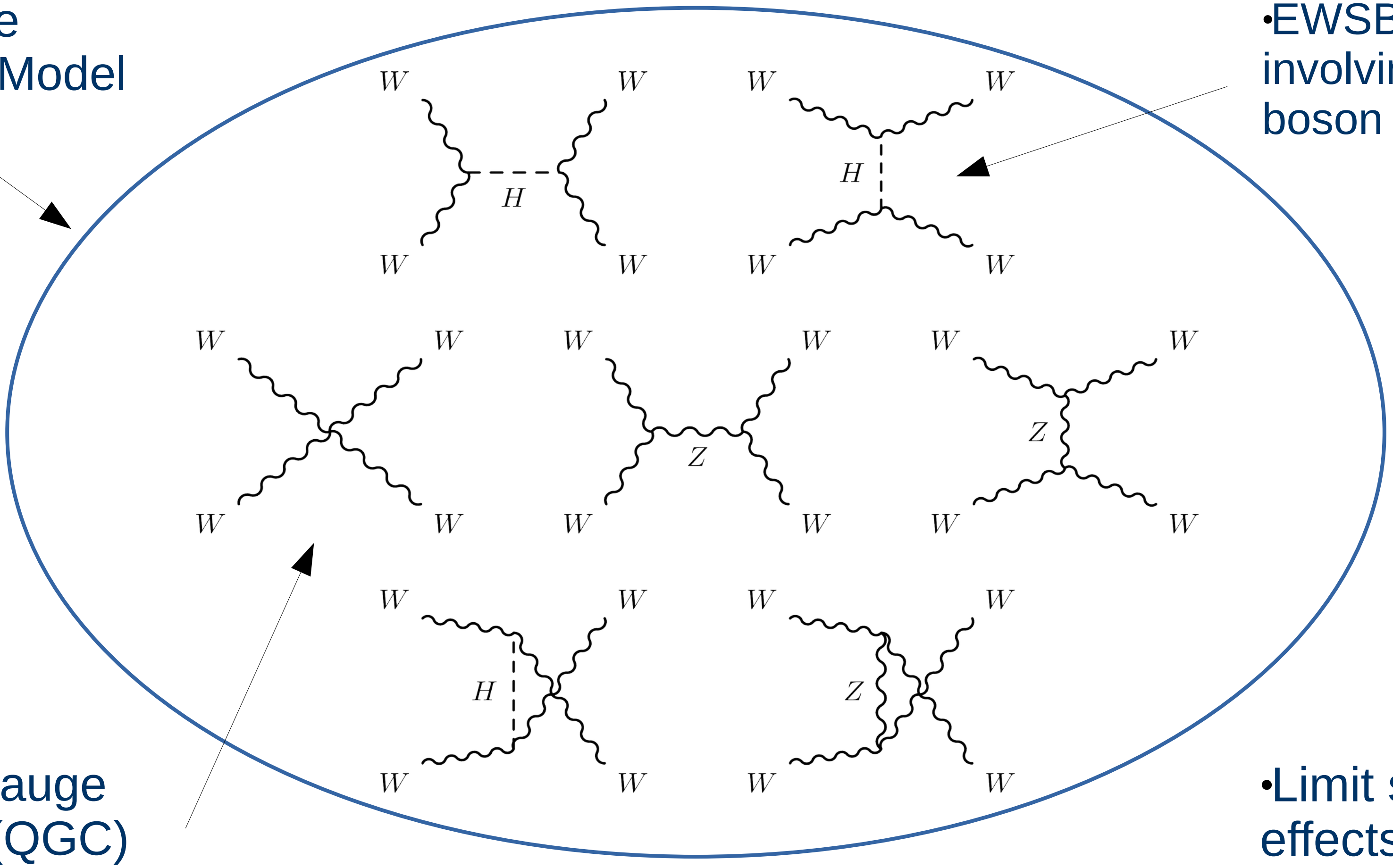
Introduction

Motivation

Vector Boson Scattering (VBS) is a scattering of massive intermediate vector bosons.

•Test of the Standard Model

•EWSB mechanism involving the Higgs boson



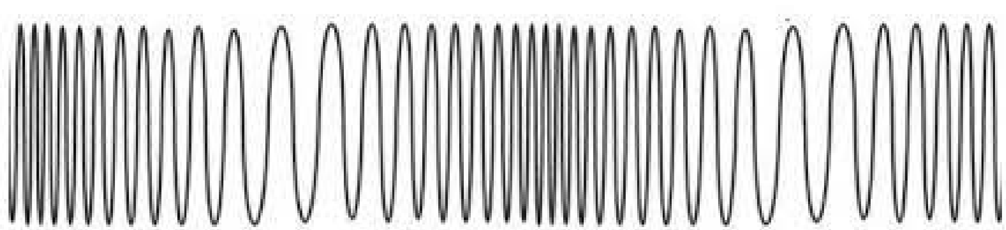
•Quartic Gauge Coupling (QGC) becomes accessible

•Limit settings on effects of BSM physics

Test of Standard Model

WW interaction, a special case of VBS in the evolution of the Standard Model.

- The Standard Model
  - Respects short distance of the beta-decay
  - Requires the W boson to be massive
  - Gives W boson a longitudinal polarization



Asymptotic behavior of the scattering in the context of theory evolution

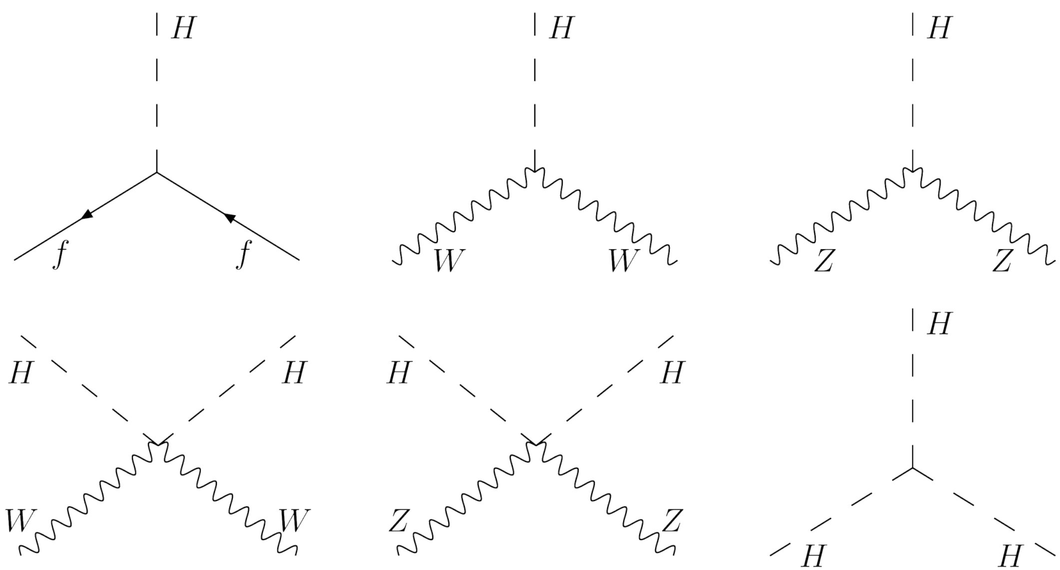
- Draws attention already since establishing of W
  - Intermediate Vector Boson (IVB) theory
  - Electromagnetic interaction of W boson
  - Residual ME = $O(E^2)$
- Persists as a difficulty also after the EW unification
  - Z boson and QGC interaction
  - Residual ME = $O(E)$
- Demands implementation of a scalar field for compensation of residual asymptotic divergences
  - Higgs interaction of W bosons
  - Outcome of EWSB
  - Residual ME = $O(1)$

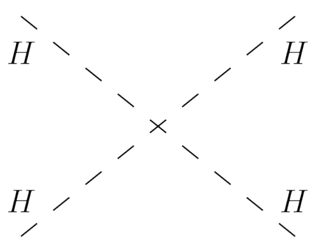
Electroweak symmetry breaking

The right parametrization and choice of gauge generates three vector and one scalar massive bosons in electroweakly unified SM.

$$\Phi\left(x\right) = \exp\left(\frac{i}{v}\pi^{a}(x)\tau^{a}\right)\left(\begin{array}{c} 0 \\ \frac{1}{\sqrt{2}}\left(v + H\left(x\right)\right) \end{array}\right)$$

- Parametrization
  - Parametrization utilizes Pauli matrices τ and introduces Goldstone bosons π (a = 1,2,3)
  - Weak isodublet introduces a massless scalar
- Result
  - Unitarity gauge
  - W± and Z bosons acquire mass spending three unphysical bosons
  - Scalar Higgs boson appears





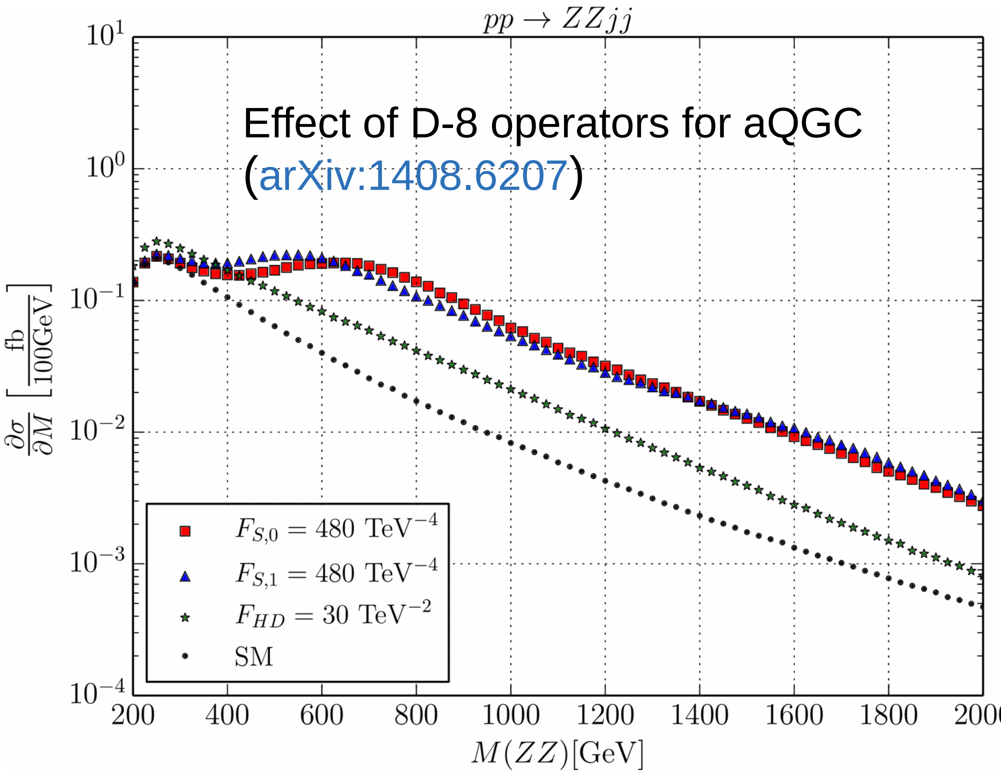
- In the end interaction with Higgs field gives particles their mass.

Beyond Standard Model

The process might be sensitive to the phenomena not covered by the Standard Model.

- Anomalous QGC
  - Neutral coupling, i.e. ZZZZ four-vertex
- Effective field theory
  - Addition of higher dimension operators to SM
  - Scales beyond the reach of the LHC
  - SM represents a “low” energy limit case of the new model

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \sum_{d\geq 4}\sum_{i} \frac{\alpha_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)}$$

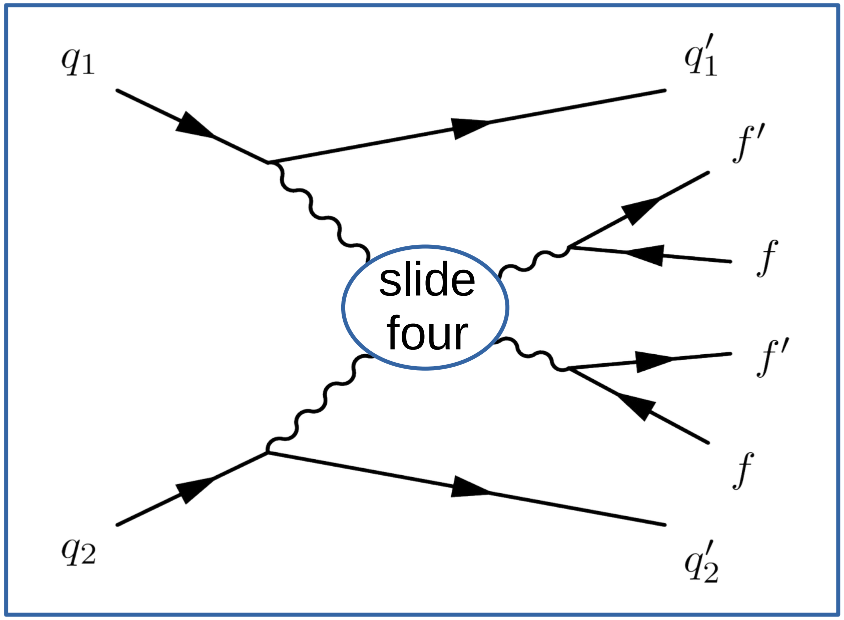


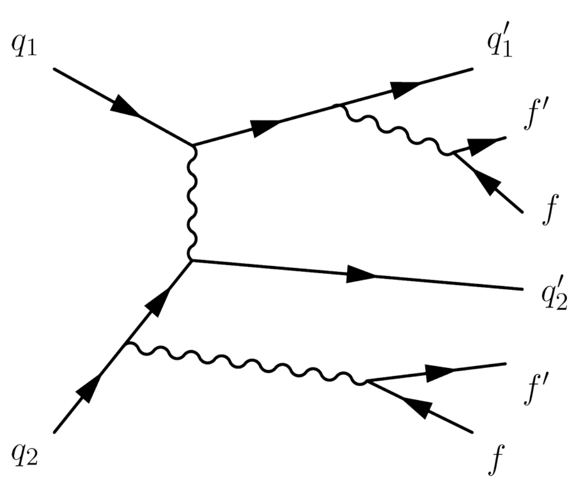
VBS at Large Hadron Collider

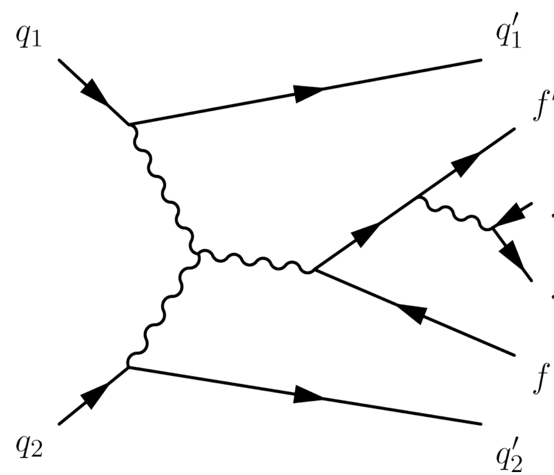
EWK VVjj production

Protons interact electro-weakly

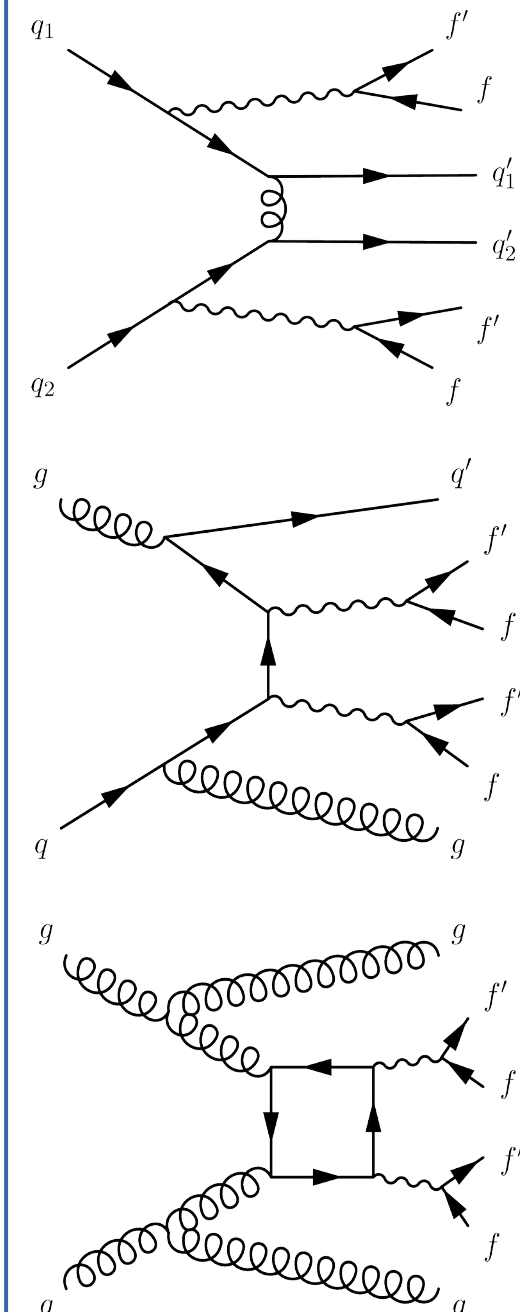
Vector Boson Scattering







QCD VVjj production

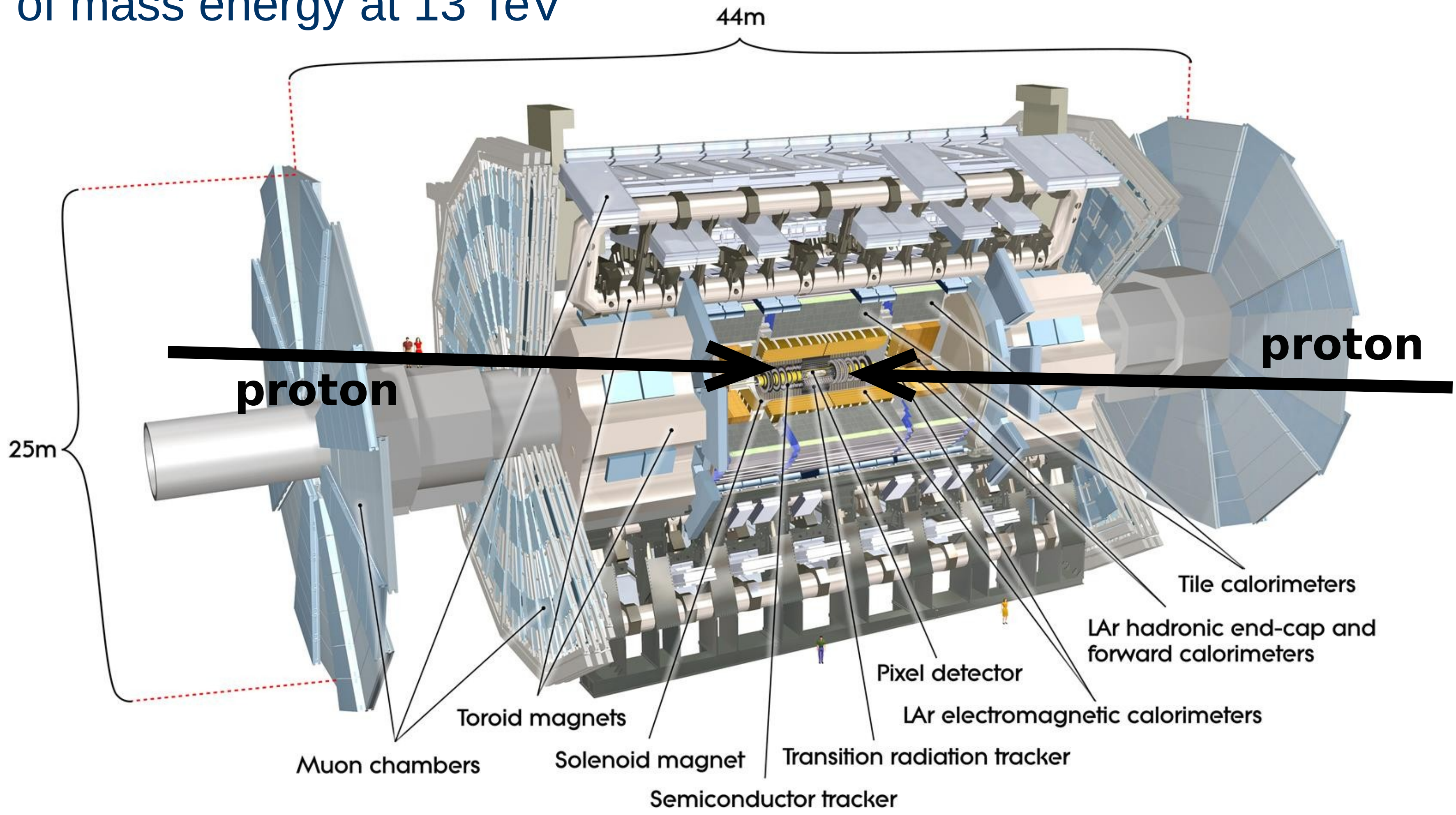


Common VBS selections

ATLAS Experiment

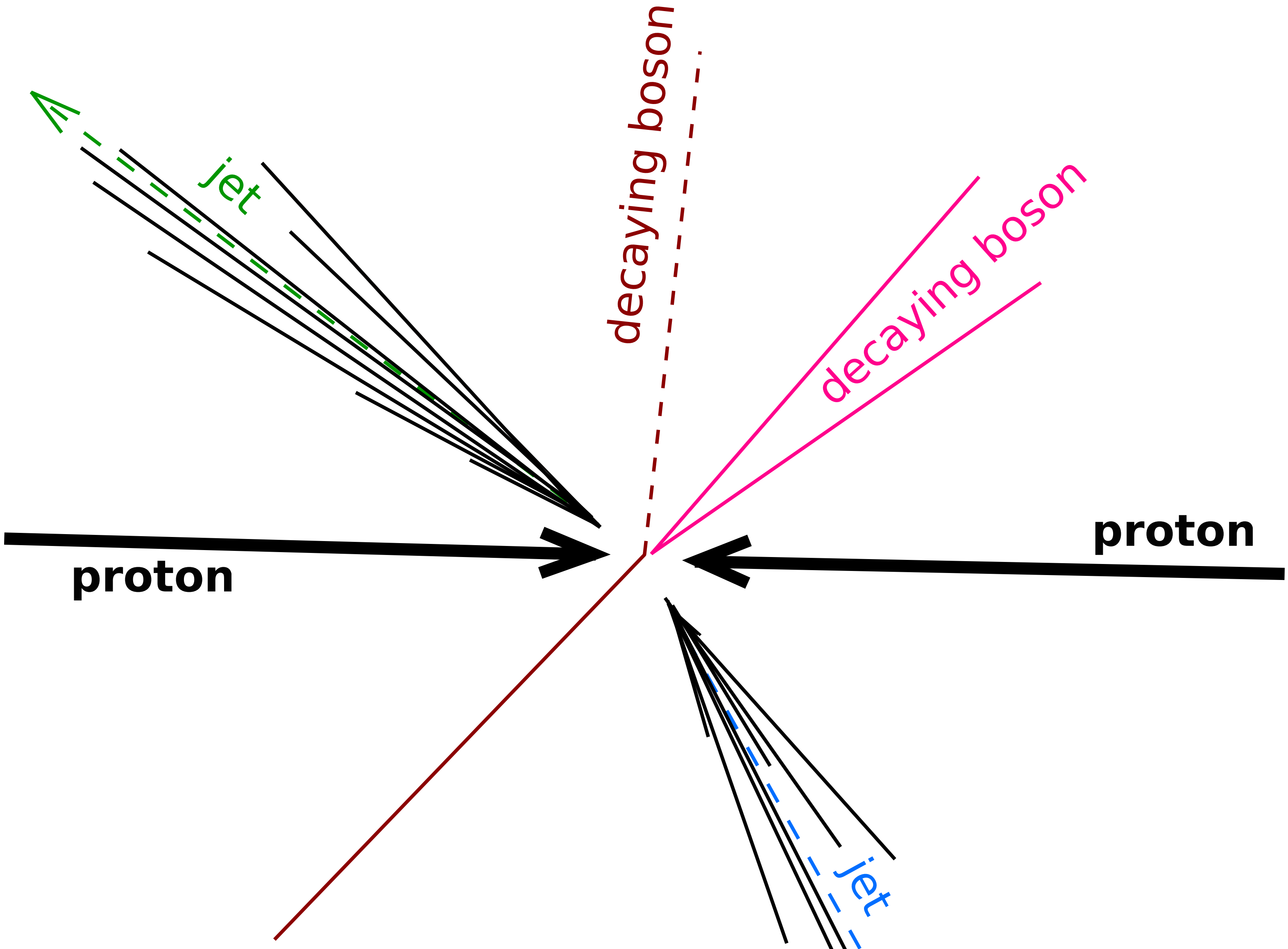
Proton-proton collisions

- Large Hadron Collider (LHC)
- Center of mass energy at 13 TeV



Object Selection

- Leptonic signatures
  - WWjj
    - νℓ + νℓ + jj
  - WZjj
    - νℓ + ℓℓ + jj
  - ZZjj
    - ℓℓ + ℓℓ + jj
    - νν + ℓℓ + jj
- Semi-leptonic signatures
  - VVjj
    - ℓℓ + jj + jj
    - νℓ + jj + jj
    - νν + jj + jj



Object Selection

- Leptonic signatures
  - WWjj
    - $\nu\ell + \nu\ell + jj$
  - WZjj
    - $\nu\ell + \ell\ell + jj$
  - ZZjj
    - $\ell\ell + \ell\ell + jj$
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- Semi-leptonic signatures
  - VVjj
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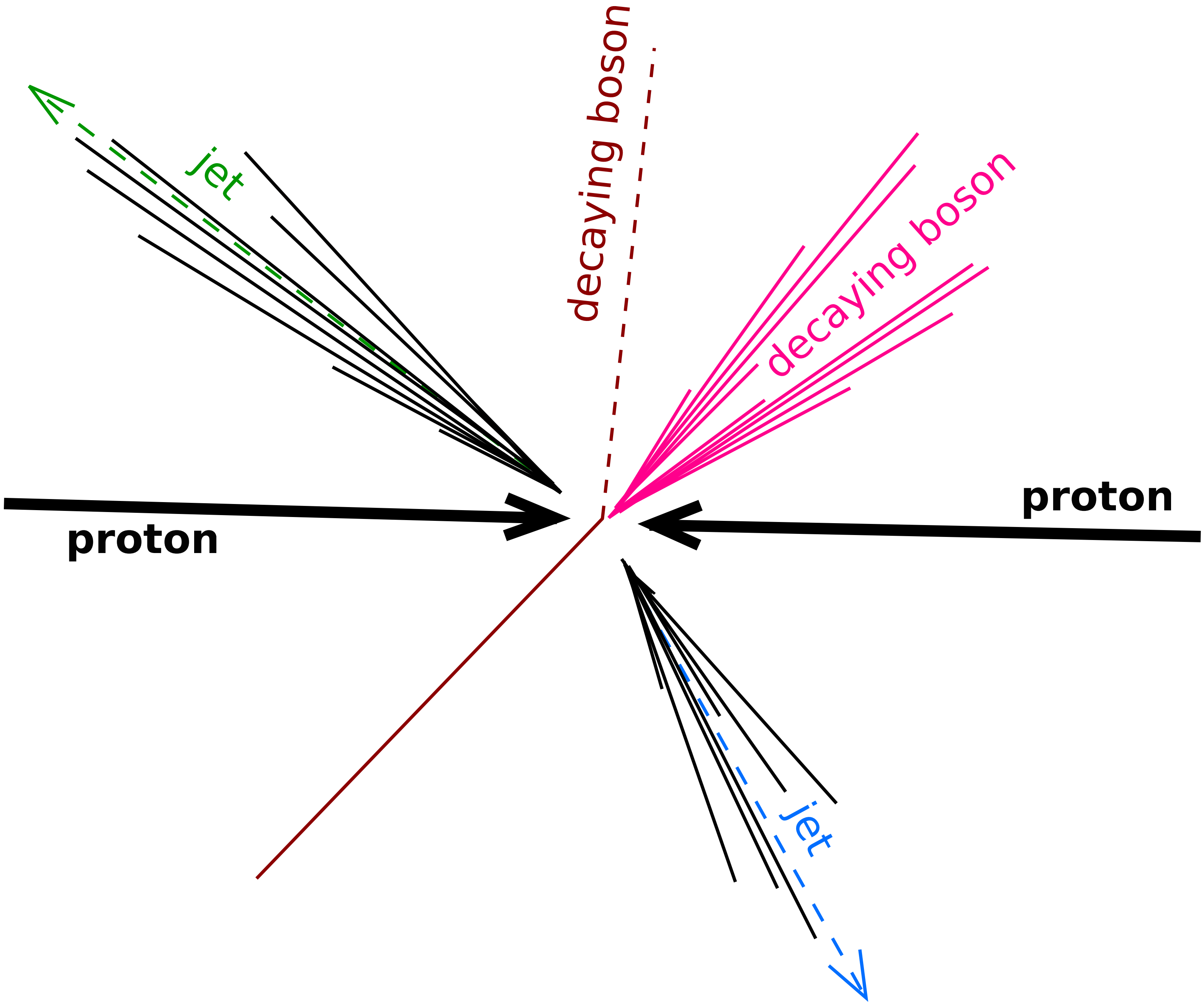
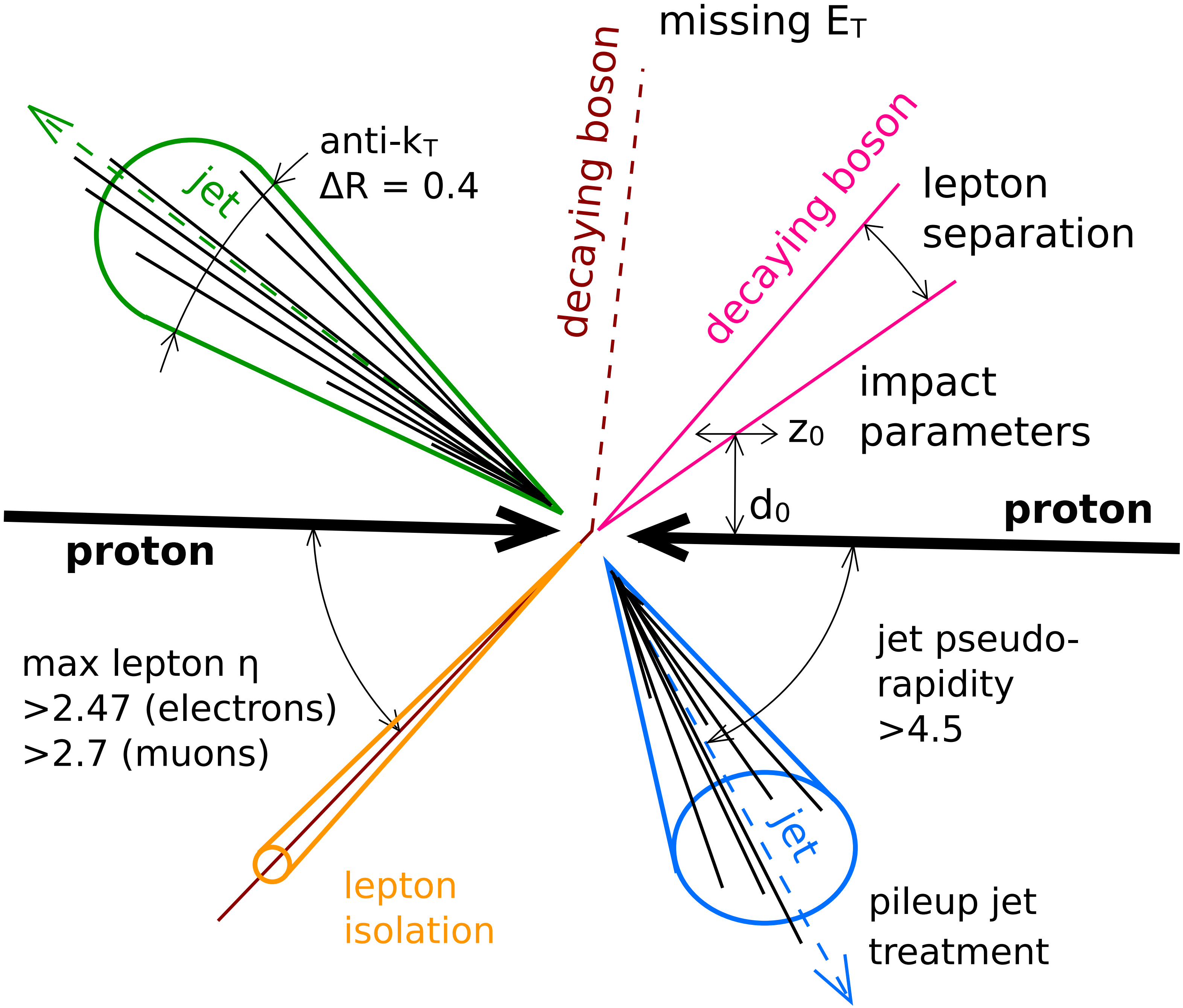


Object Selection

- Transverse momentum
- Detector limit in pseudorapidity (η)
- Impact parameter
  - Cosmic rejection
  - Secondary vertex
- Overlap removal
  - Electrons, Muons, Jets
- Lepton quality and isolation
- Jet reconstruction
  - Anti-kT
  - Standard jet (ΔR = 0.4)
  - Large jet (ΔR = 1.0)
  - Track jet (ΔR = 0.2)
  - Pileup jet tagging
- Missing transverse momentum
  - Negative global vector sum of all identified objects and unclassified tracks and calorimeter clusters



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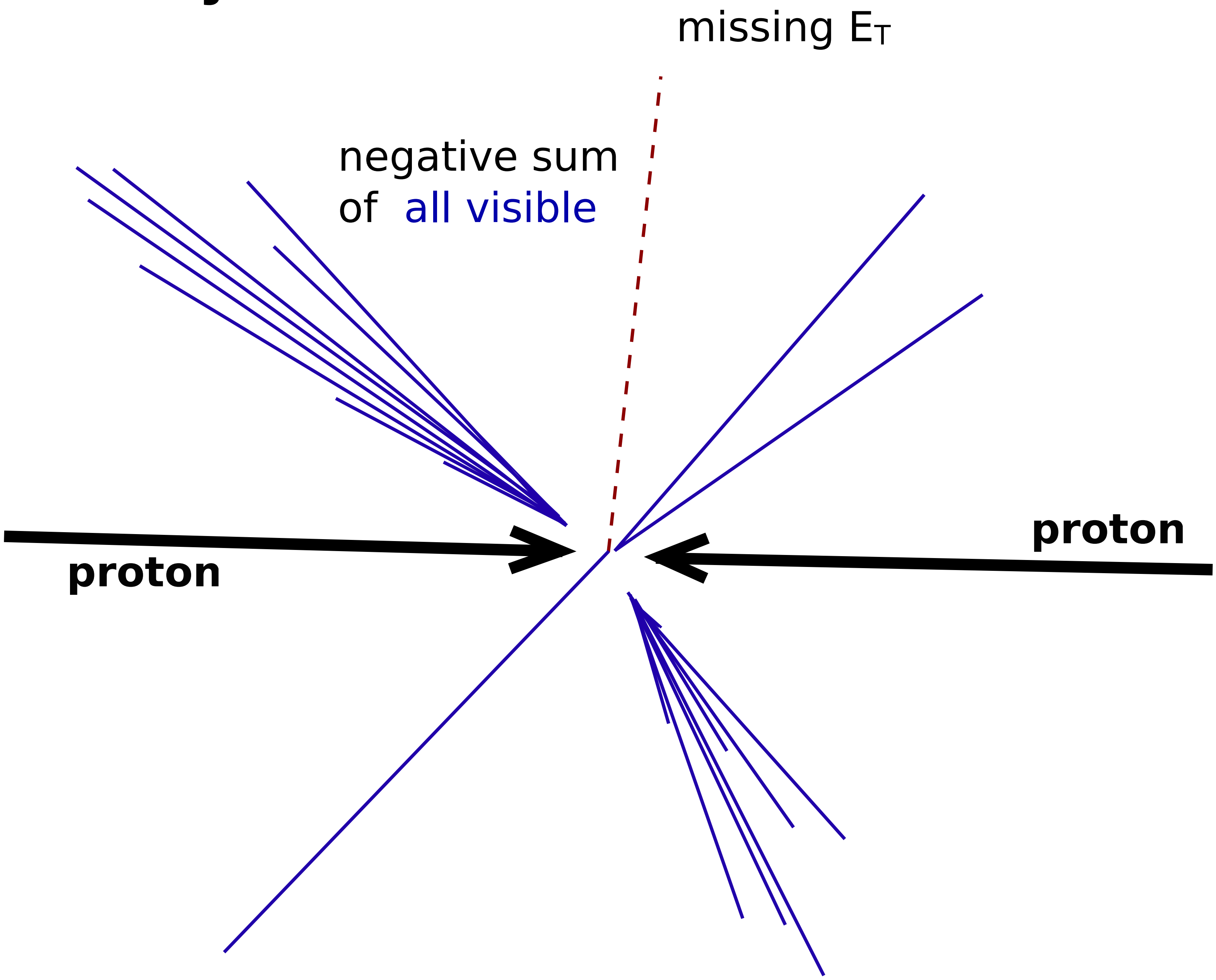
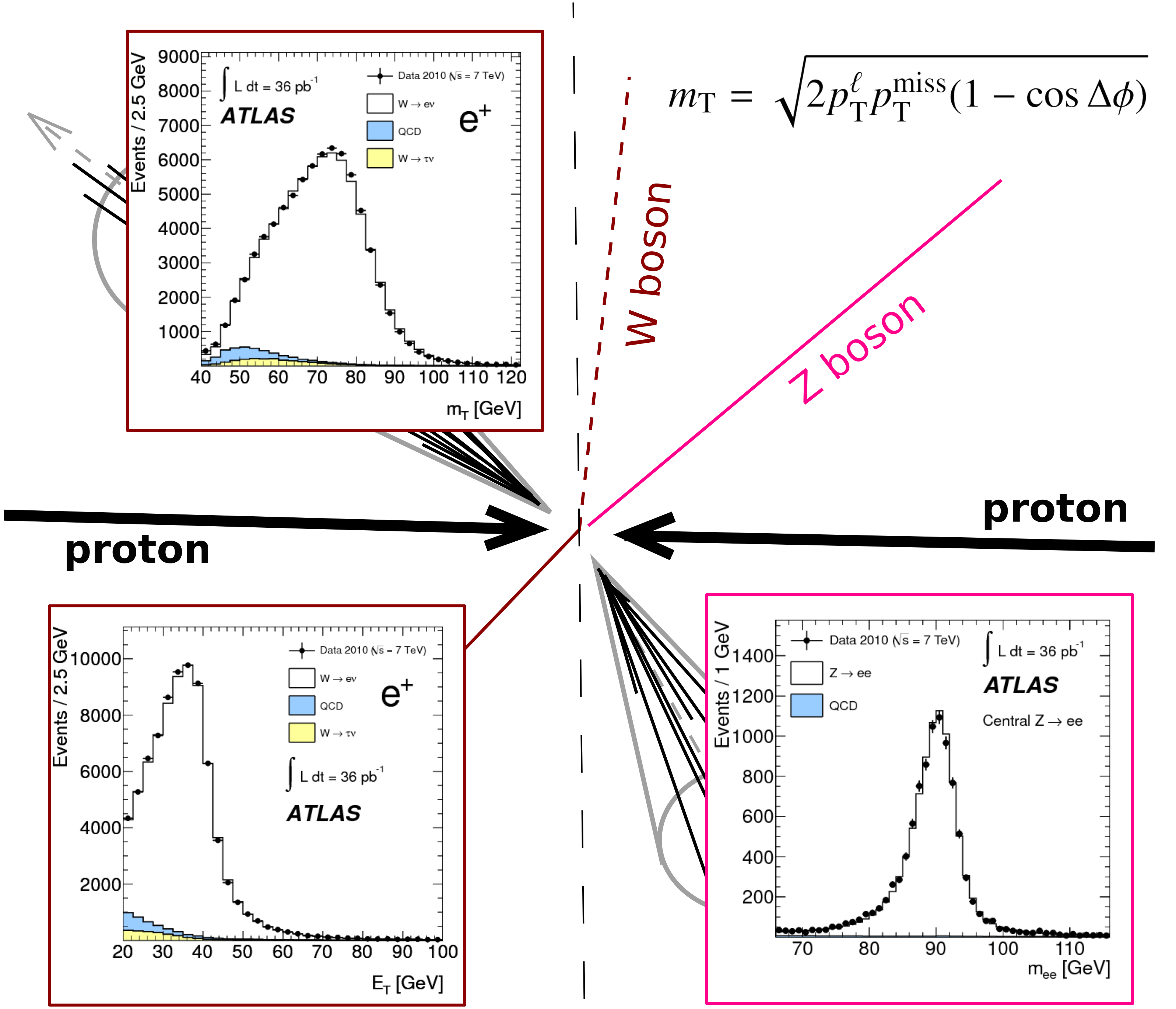


Event Selection

- Leptonic W boson
  - High quality lepton plus missing transverse momentum
  - bJet veto
- Leptonic Z boson
  - Same flavour opposite charge di-lepton (SFOC)
  - Di-lepton mass window
- Hadronic boson
  - Two standard jets
  - One large jet and jet substructure
  - Di-jet mass window
- Invisible boson
  - Large missing transverse energy
- Tagging di-jet selection
  - Hardest jet from opposite side of detector
  - Di-jet separation in rapidity
  - High di-jet mass requirement
- Jet-lepton centrality



$$m_T = \sqrt{2 p_T^{\ell} p_T^{miss} (1 - \cos \Delta\phi)}$$

arXiv:1109.5141

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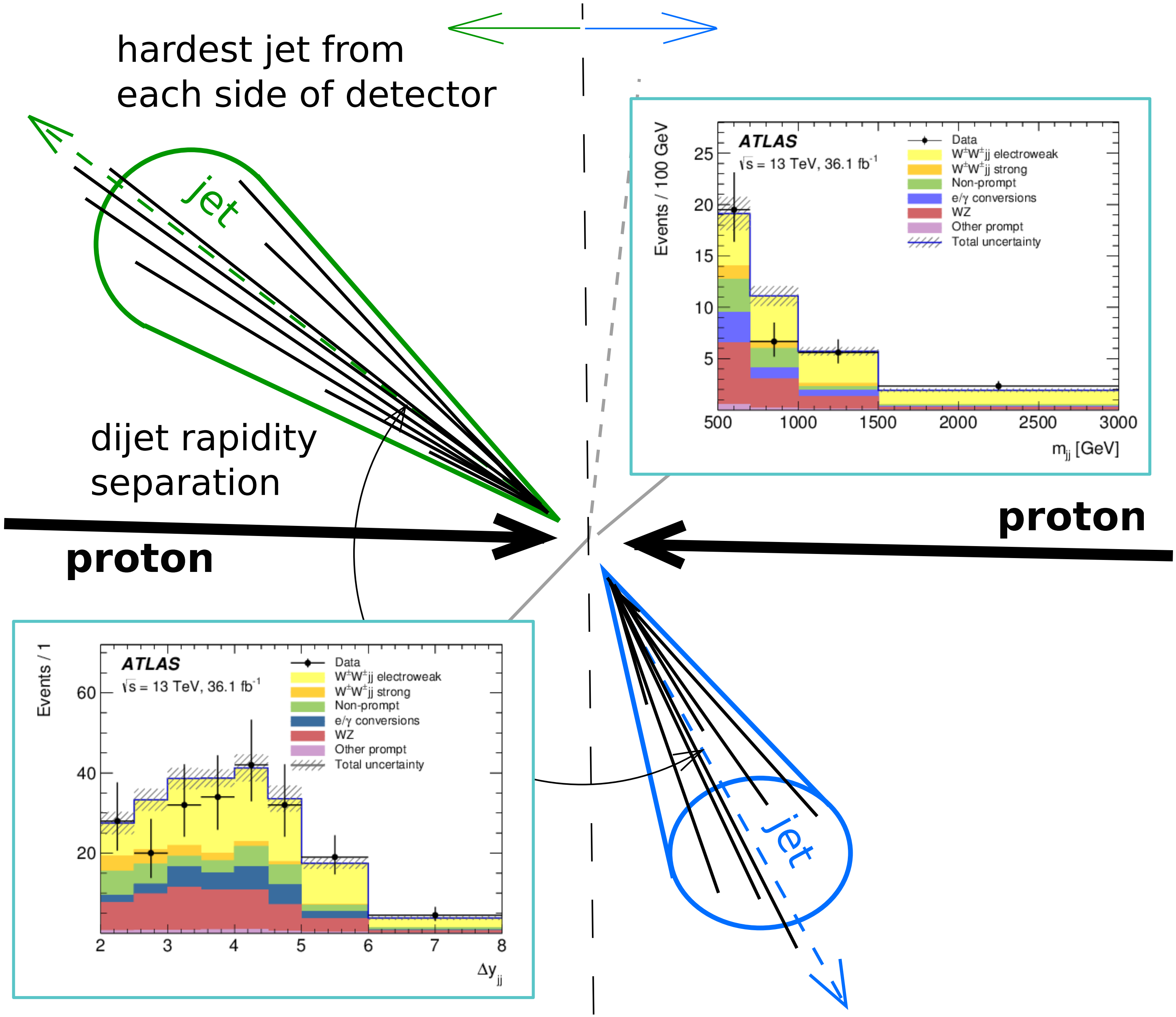
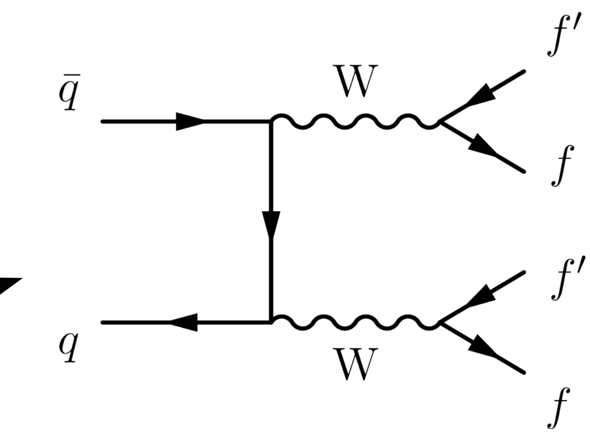


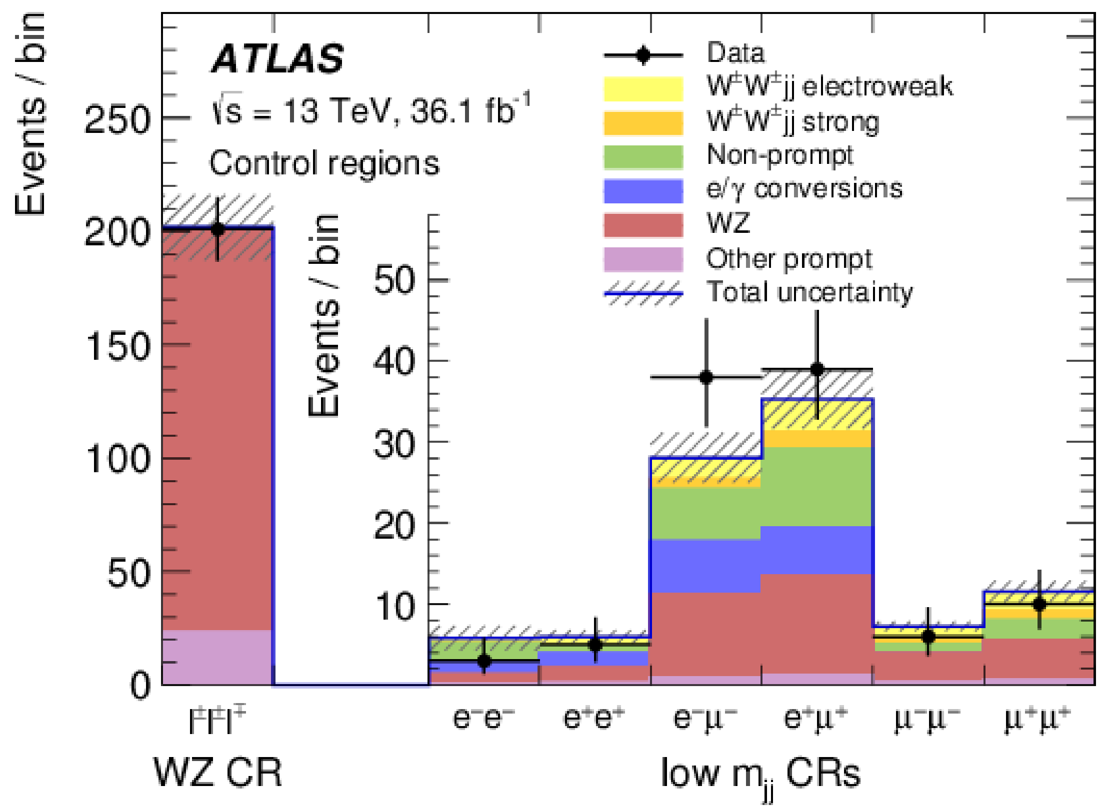
VBS Analyses

$W^{\pm}W^{\pm}$ - VBS "Discovery" Channel

- VBS final state: $\nu\ell^{\pm}\nu\ell^{\pm}$ + jj
- Dataset: 36.1 fb^{-1}, 13 TeV
- Expected significance:
  - 6.5 σ (Powheg-Box)
  - 4.4 σ (Sherpa)
- Main feature: same-sign requirement suppresses the $q\bar{q}$-initiated production



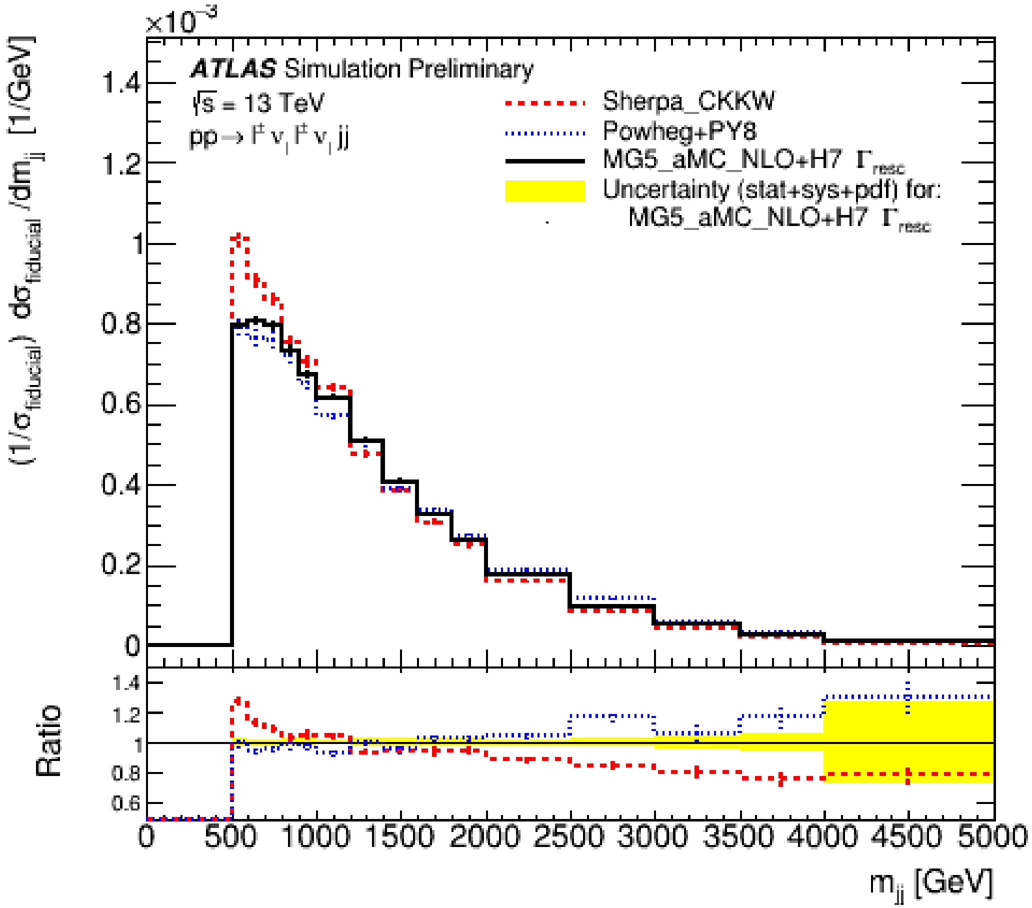
- Tagging jets:
  - m_{jj} > 400 GeV, $\Delta\eta_{jj}$ > 2, $p_{T,l1}$ > 65 GeV
- Prompt background (MC modeled)
  - WZ+jets (dominant), ssWW+jets (QCD) ZZ+jets, and Triboson
- Non-prompt background (data driven)
  - $t\bar{t}$, osWW+jets (QCD), Vγ+jets, W+jets, t+jets
  - Lepton misidentification (photon as electron)
  - Charge misidentification (same-sign leptons)



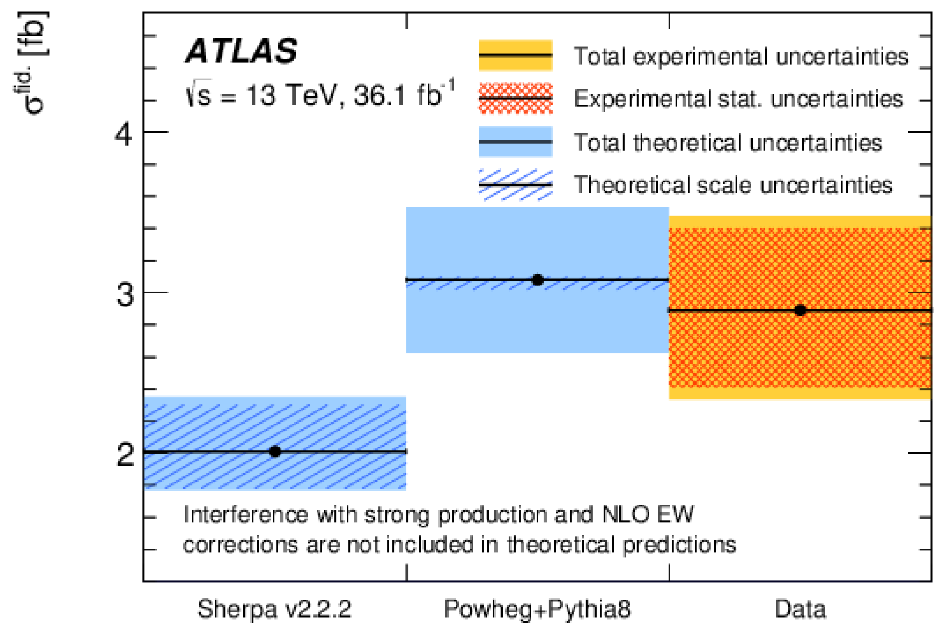
arXiv:1906.03203

MC simulations for W±W± VBS

- Extensive MC studies for the VBS first-evidence channel
- Comparison of predicted cross-sections and kinematic distributions



- Comparison settings
  - Generators: MadGraph5_aMC@NLO, Powheg-Box 2, Sherpa 2
  - Parton showering: Pythia 8, Herwig 7, Sherpa 2
  - Factorization and renormalization scales effects
    - W mass, di-boson invariant mass, $\sqrt{p_T^{j1}\,p_T^{j2}}$
- Non-optimal setting of the color flow for the Sherpa parton shower



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W±W± - Results

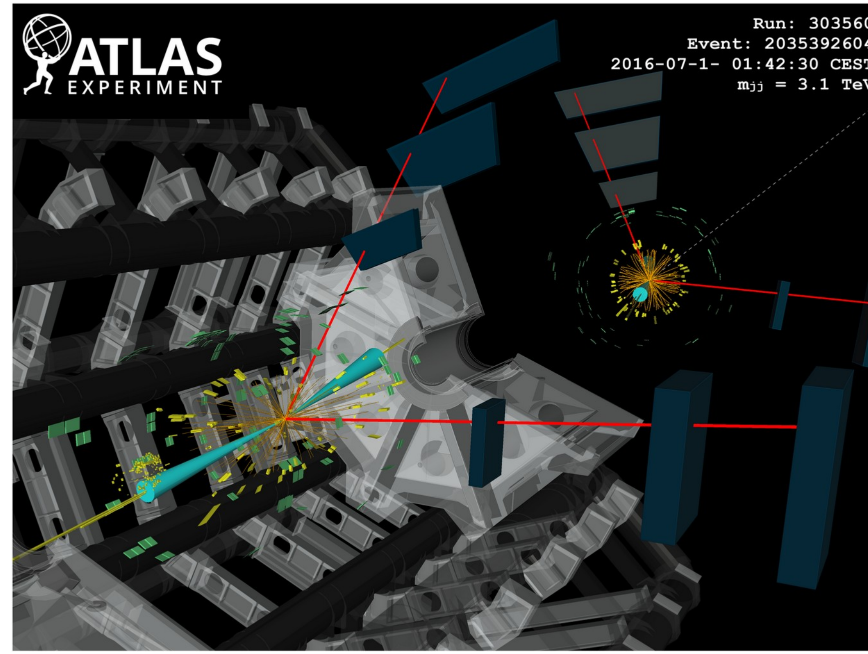
- Signal strength (compared to Sherpa)

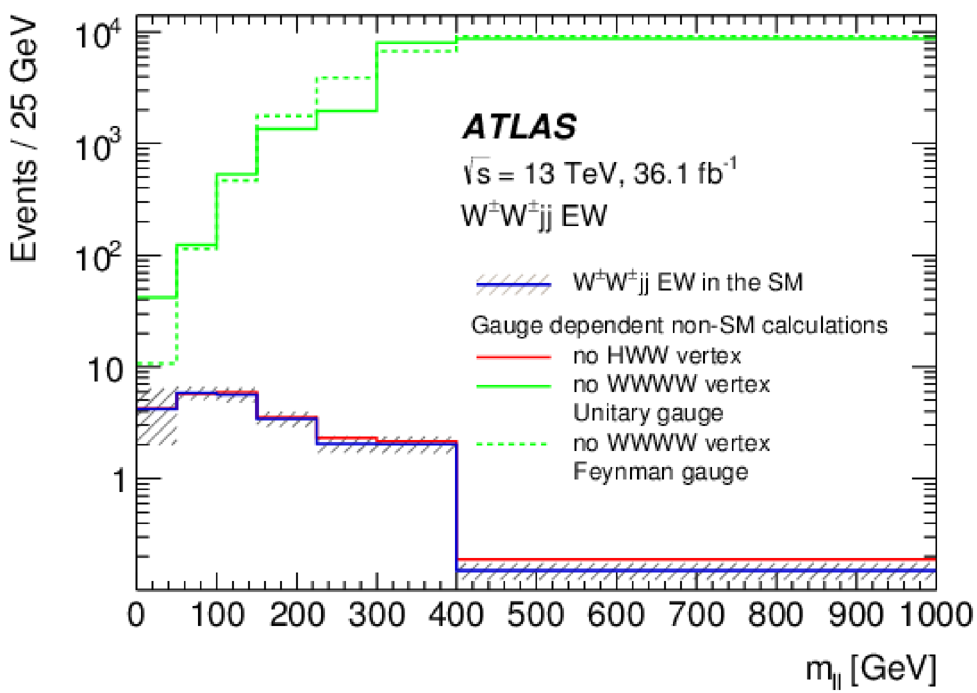
$$1.44^{+0.26}_{-0.24}(\mathrm{stat.})^{+0.28}_{-0.22}(\mathrm{syst.})$$

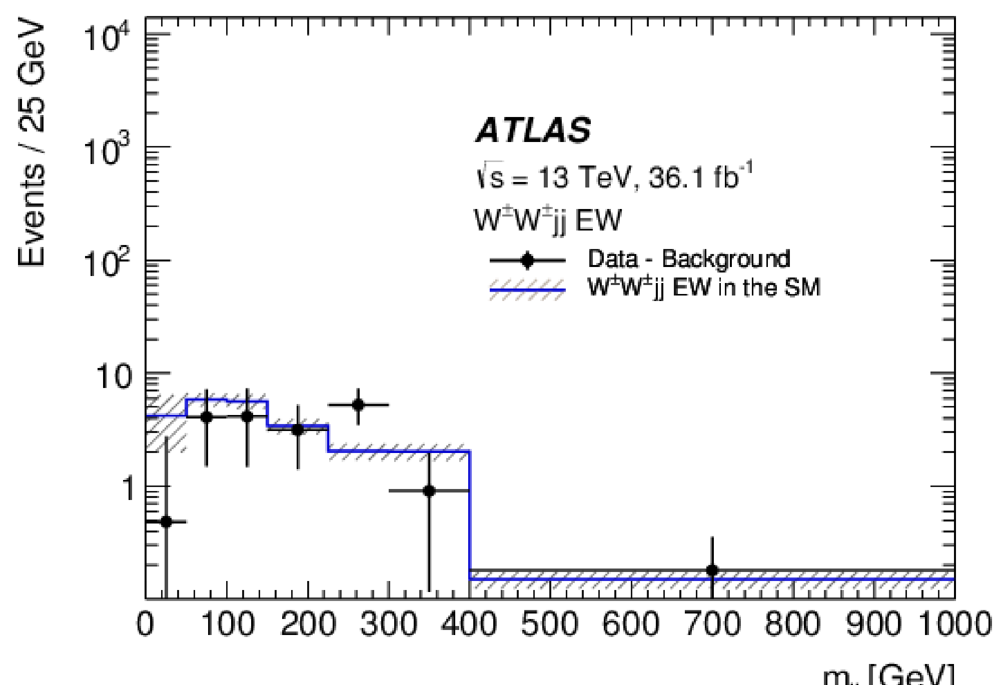
- Background only hypothesis rejected with significance 6.5 σ (expected 4.4/6.5 σ)
- EW Fiducial cross-section

$$2.89^{+0.51}_{-0.48}(\mathrm{stat.})^{+0.29}_{-0.28}(\mathrm{syst.})\ \mathrm{fb}$$

- No deviation from SM observed in W±W±jj EW







arXiv:1906.03203

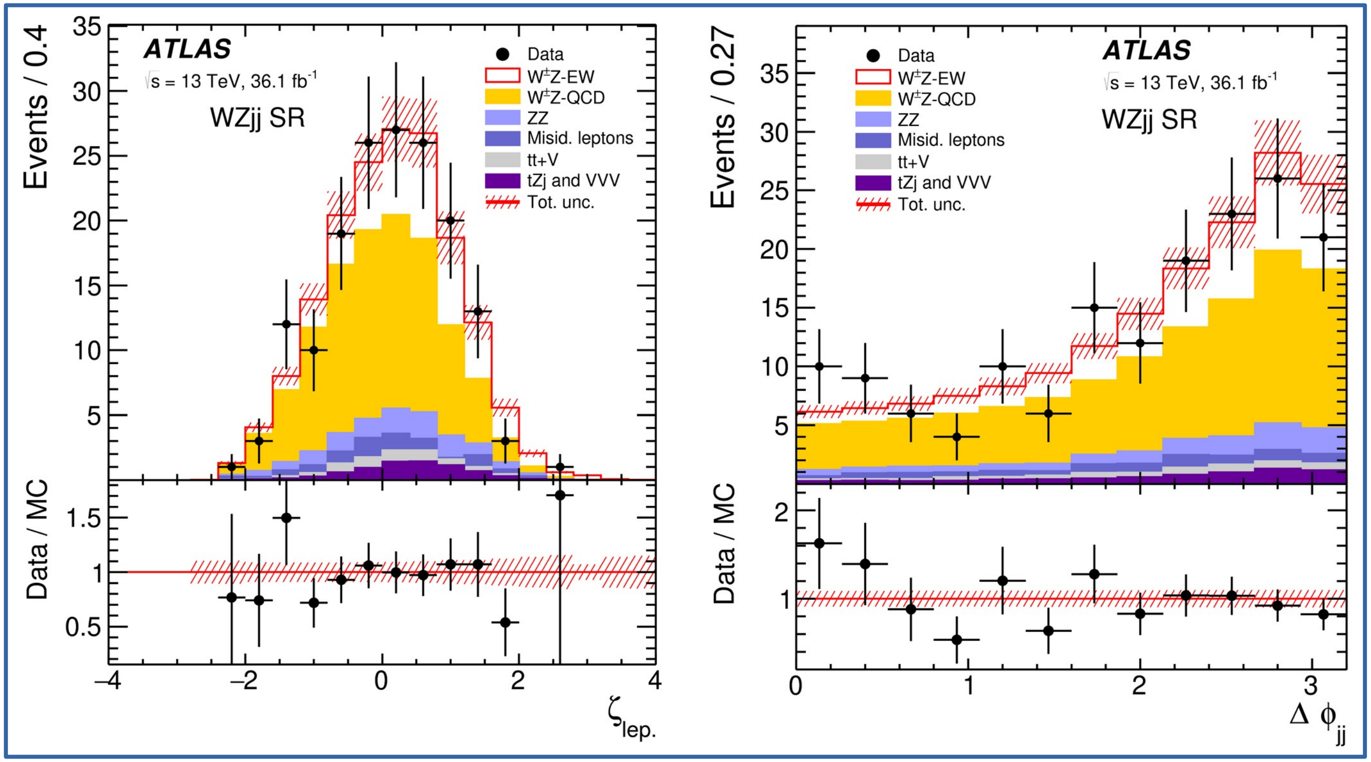
$W^{\pm}Z$ – VBS “Mix” Channel

- VBS final state: $\nu\ell\ell\ell$ + jj
- Dataset: 36.1 fb^{-1}, 13 TeV
- Expected significance: 3.2 σ
- Main feature: Fourth lepton veto, MVA - BDT
- Tagging jets:

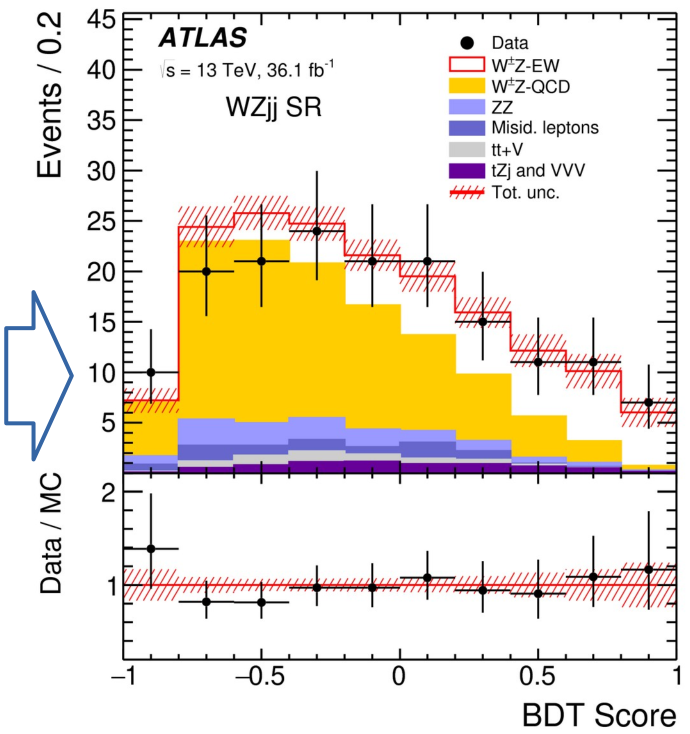
  m_{jj} > 500 GeV, opposite sides, p_T > 40 GeV

- Prompt background
  - WZ+jets (QCD), ZZ+jets, $t\bar{t}V$, VVV, tZ+jets
- Non-Prompt background
  - Z+jets, Zγ+jets, $t\bar{t}$, Wt+jets, WW+jets
  - Misidentified leptons (data driven)

Example of BDT Input



BDT Score



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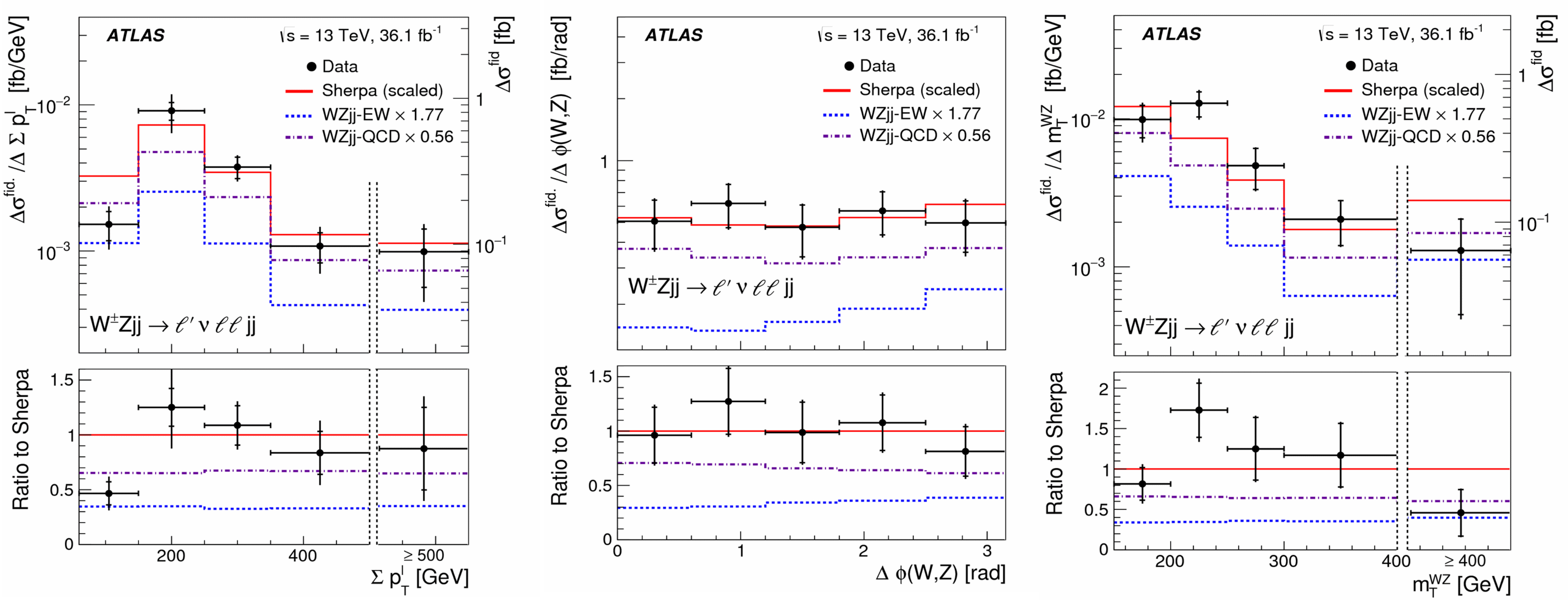
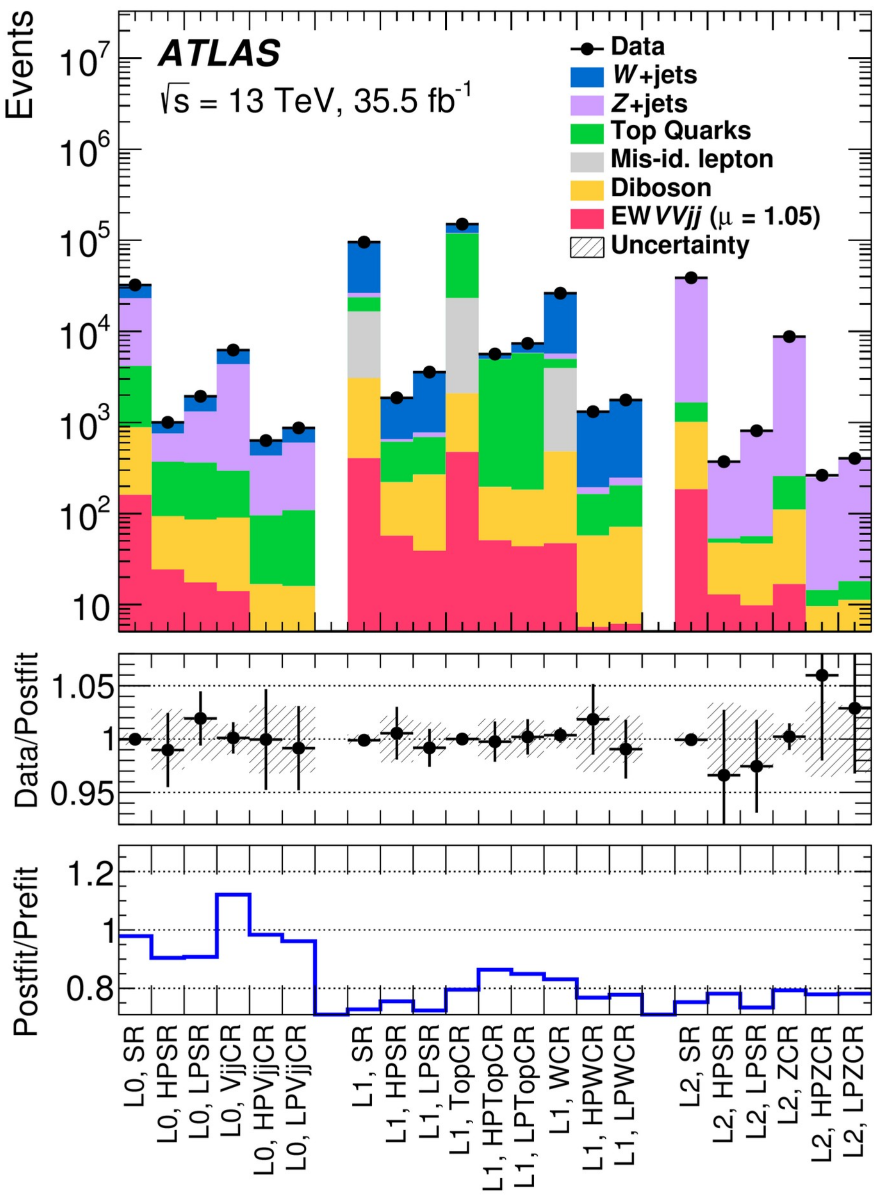
$W^{\pm}Z$ – Results

- EW Signal strength $1.77^{+0.44}_{-0.40}(\text{stat.})^{+0.26}_{-0.21}(\text{syst.})$
- Background only hypothesis rejected with significance 5.3 σ (expected 3.2 σ)
- EW fiducial cross-section $0.57^{+0.14}_{-0.13}(\text{stat.})^{+0.07}_{-0.06}(\text{syst.})\,\text{fb}$
- WZjj EW production **observed**
- Distributions sensitive to anomalous QGC unfolded
  - Inclusive fiducial phase space (EW + QCD)



VV Semi-leptonic – VBS "Jet" Channel

- VBS final states: ννjj + jj, ℓνjj + jj, ℓℓjj + jj (0-, 1-, and 2-lepton channel)
- Dataset: 35.5 fb^{-1}, 13 TeV
- Expected significance: 2.5 σ
- Tagging jets:
  - m_{jj} > 400 GeV, opposite sides, p_T > 30 GeV
- MVA: BDT, 4 – 16 variables
- 9 signal regions, 12 control regions
  - Working points: resolved, high/low purity merged jets
- Dominant background
  - 0-lepton channel
    - W+jets, Z+jets
  - 1-lepton channel
    - W+jets, $t\bar{t}$
  - 2-lepton channel
    - Z+jets
- Minor background (all channels)
    - VVjj (QCD)



arXiv:1905.07714

VV Semi-leptonic – Results

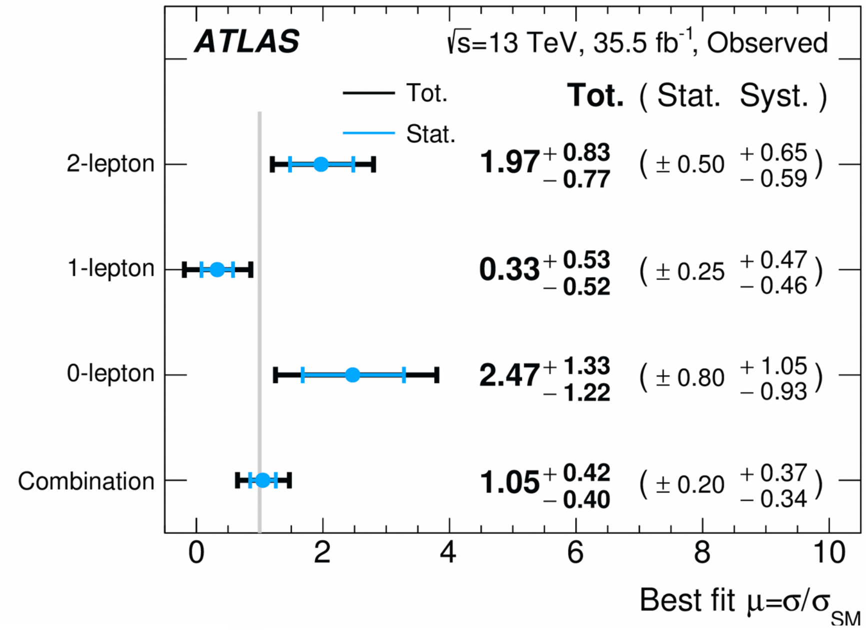
- EW signal strength

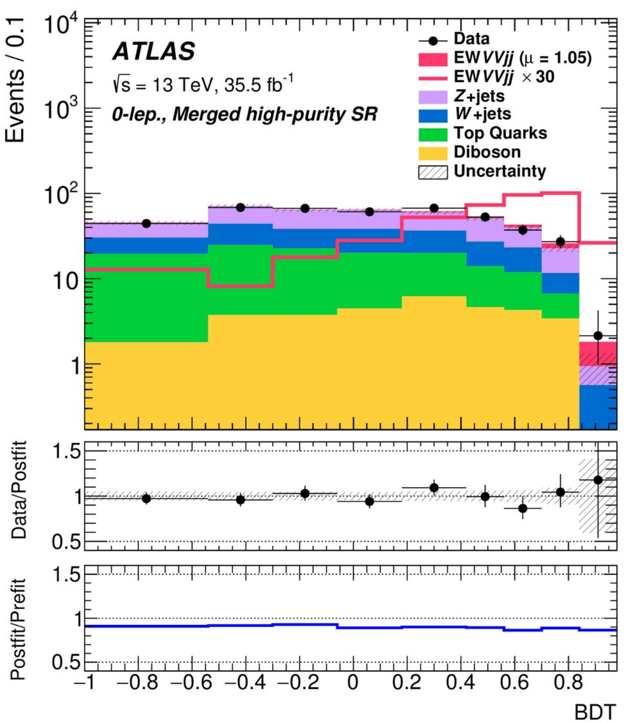
$$1.05^{+0.20}_{-0.20}(\text{stat.})^{+0.37}_{-0.34}(\text{syst.})$$

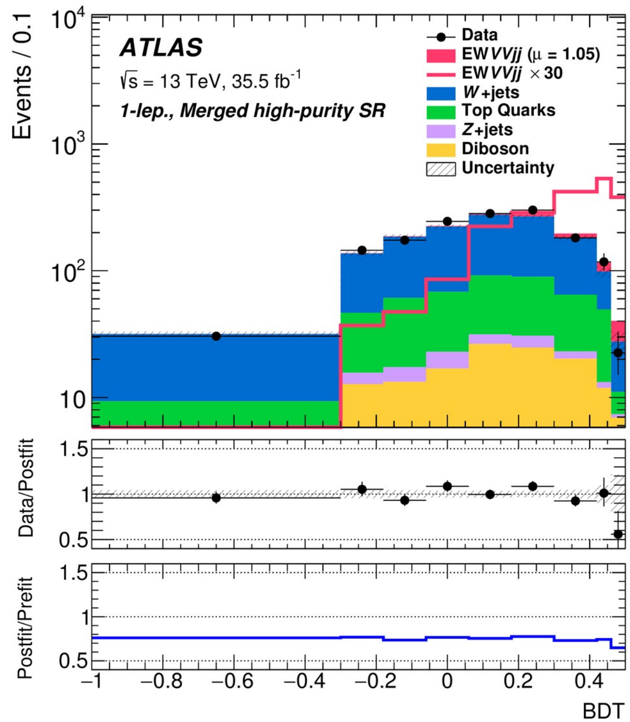
- Background only hypothesis rejected with significance 2.7 σ (expected 2.5 σ)
- EW fiducial cross-section

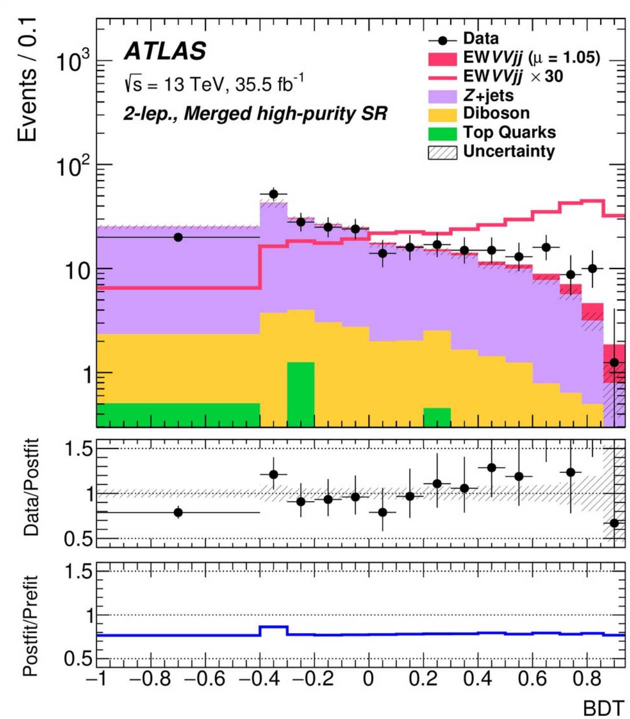
$$45.1^{+8.6}_{-8.6}(\text{stat.})^{+15.9}_{-14.6}(\text{syst.})\,\text{fb}$$

- Extensive combined fit (21 signal/control regions)
- Still **waiting for evidence**









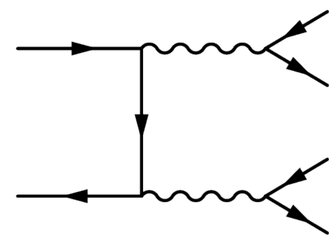
arXiv:1905.07714

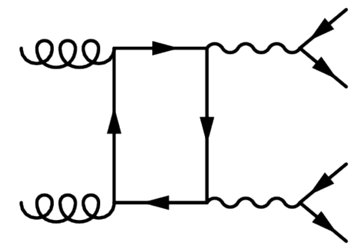
ZZ VBS analysis

ZZ Overview

Input

Overview
- Channels: $\ell\ell\ell\ell$ + jj, $\nu\nu\ell\ell$ + jj
- Dataset: 139 fb^{-1}, 13 TeV
- Overwhelmed by QCD background


qq-ZZ


gg-ZZ

Selection

VBS pre-selection
- ZZ quadruplet
- Dijet system

Background estimation

MVA
- Signal/Background
- BDT
- Input observables

Statistical fit

Results

Inclusive (QCD + EW) ZZ+2j cross-section measurement in VBS enhanced region

EW ZZ+2j production detection significance extraction and ZZ VBS evidence

ZZ Selection (ℓℓℓℓ)

Object Selection

Electrons

- Identification
  - LH Loose
- $|\eta| < 2.47$
- $p_T > 7$ GeV
- $|z_0 \sin\theta| < 0.5$ mm
- d_0 significance < 5.0
- Isolation
  - FixedCutLoose

Muons

- Quality
  - Loose
- $|\eta| < 2.7$
- $p_T > 7$ GeV (15 GeV for Calo)
- $|z_0 \sin\theta| < 0.5$ mm
- d_0 significance < 3.0
- Isolation
  - FixedCutLoose

Jets

- AntiKt4EMTopo, R = 0.4
- $|\eta| < 4.5$
- Central jets ($|\eta| < 2.4$)
  - $p_T > 30$ GeV, JVT > 0.59
- Forward jets ($2.4 < |\eta| < 4.5$)
  - $p_T > 40$ GeV
- Loose cleaning
- Lepton favouring overlap removal

Event Selection

ZZ

- Quadruplet building SFOC pairs
- Hierarchical p_T cut (20, 20, 10, 7 GeV)
- Quarkonia veto $m_{ll} > 10$ GeV
- <2 CaloTagged or StandAlone muons
- 66 GeV < m_{ll} < 116 GeV

Dijet

- $y_{j1} \times y_{j2} < 0$ (different detector sides)
- Highest jet p_T from each side
- $|\Delta y_{jj}| > 2$, $m_{jj} > 300$ GeV

ZZ Background (ℓℓℓℓ)

- Prompt background
  - $t\bar{t}Z$, triboson, ZZ to tau, $t\bar{t}WW$
  - MC modeled
- Misidentified leptons background
  - Z+jets, $t\bar{t}$, WZ+jets
  - Data-driven method

- Fake factor method
  - Extrapolation of lepton misidentification effect
    - From a fake enriched kinematic region in data
    - To signal region
    - Loosening lepton criteria
      - Inversion of isolation, identification, and transverse impact parameter
  - Fake factor (2D: η, p_T)
    - Ratio of probability
      - Fake leptons passing the signal criteria over
      - Fake leptons passing the loosened criteria

MC sample	Event yield	
	SR	QCD-CR
EW $ZZjj$	$17.52^{+2.74}_{-2.69}$	3.22 ± 0.68
QCD $ZZjj$ (Quark-induced)	$60.58^{+20.37}_{-14.13}$	$114.81^{+34.31}_{-24.69}$
QCD $ZZjj$ (Gluon-induced)	$11.13^{+5.44}_{-4.22}$	$14.75^{+7.14}_{-5.50}$
$t\bar{t}Z$	$3.86^{+0.35}_{-0.26}$	$8.21^{+0.33}_{-0.38}$
Fakes background	$2.27^{+1.33}_{-1.33}$	$4.75^{+2.55}_{-2.55}$
Tri-boson	$0.61^{+0.20}_{-0.17}$	$0.97^{+0.31}_{-0.26}$
MC Total	$95.97^{+21.31}_{-15.05}$	$146.71^{+35.15}_{-25.44}$
Real data	–	129.00

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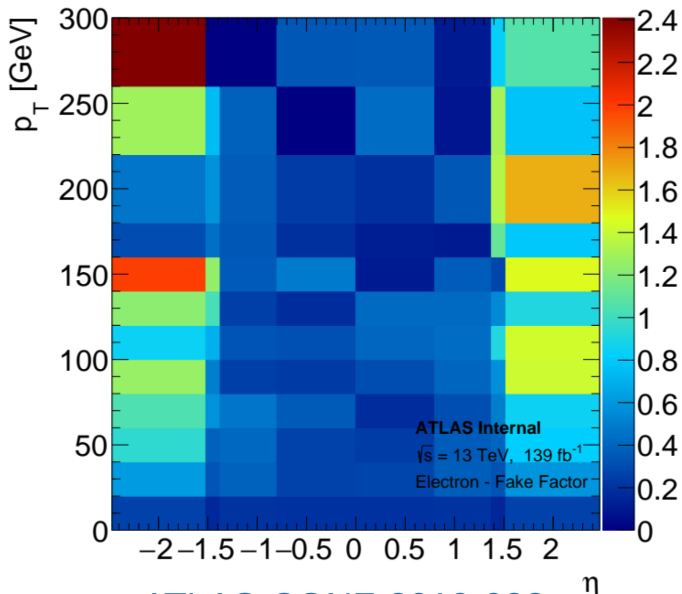
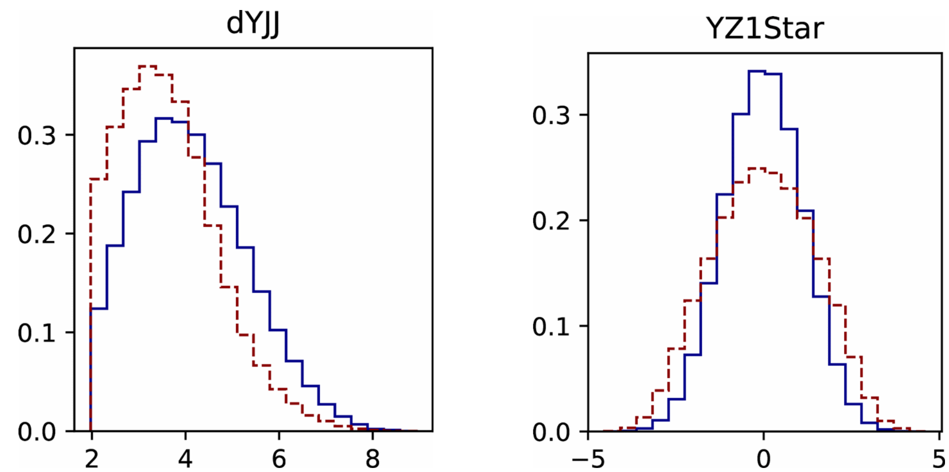


ATLAS-CONF-2019-033

ZZ Multivariate Analysis (ℓℓℓℓ)

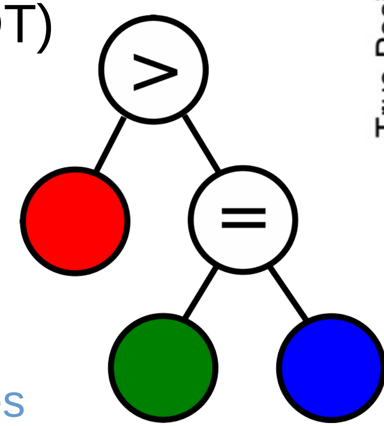
- Multivariate analysis
  - ROOT - TMVA
  - Scikit-learn
- Input variables (12)
  - Di-jet: mass, separation, opposite detector sides
  - Bosons: mass, momentum (p_T)
  - Single objects: p_T
  - Whole system: p_T to H_T ratio, boson centrality

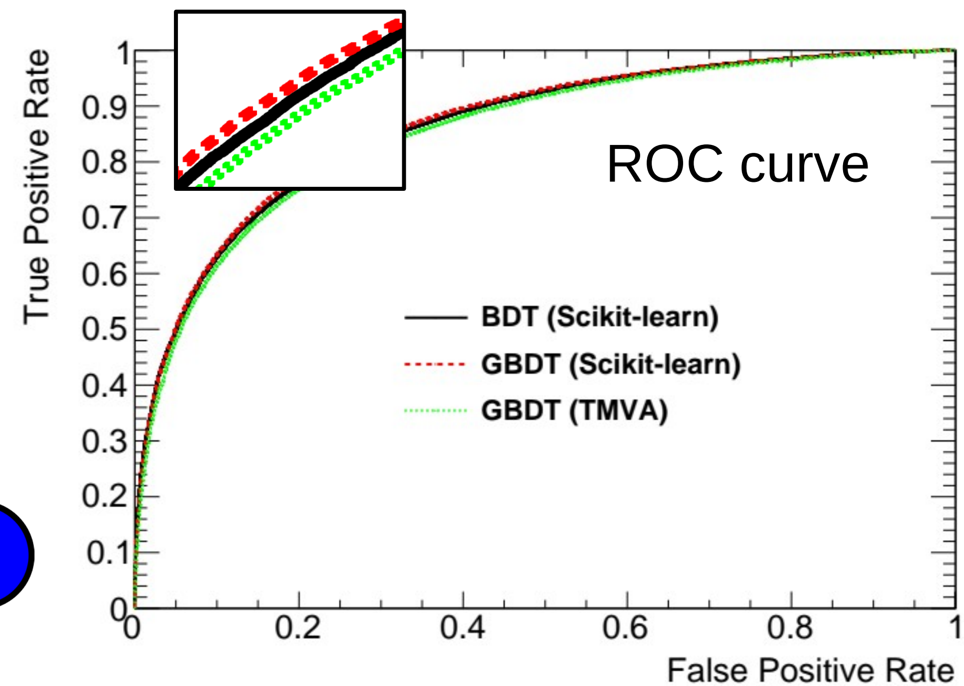
BDT input: signal vs background



CERN-THESIS-2021-179

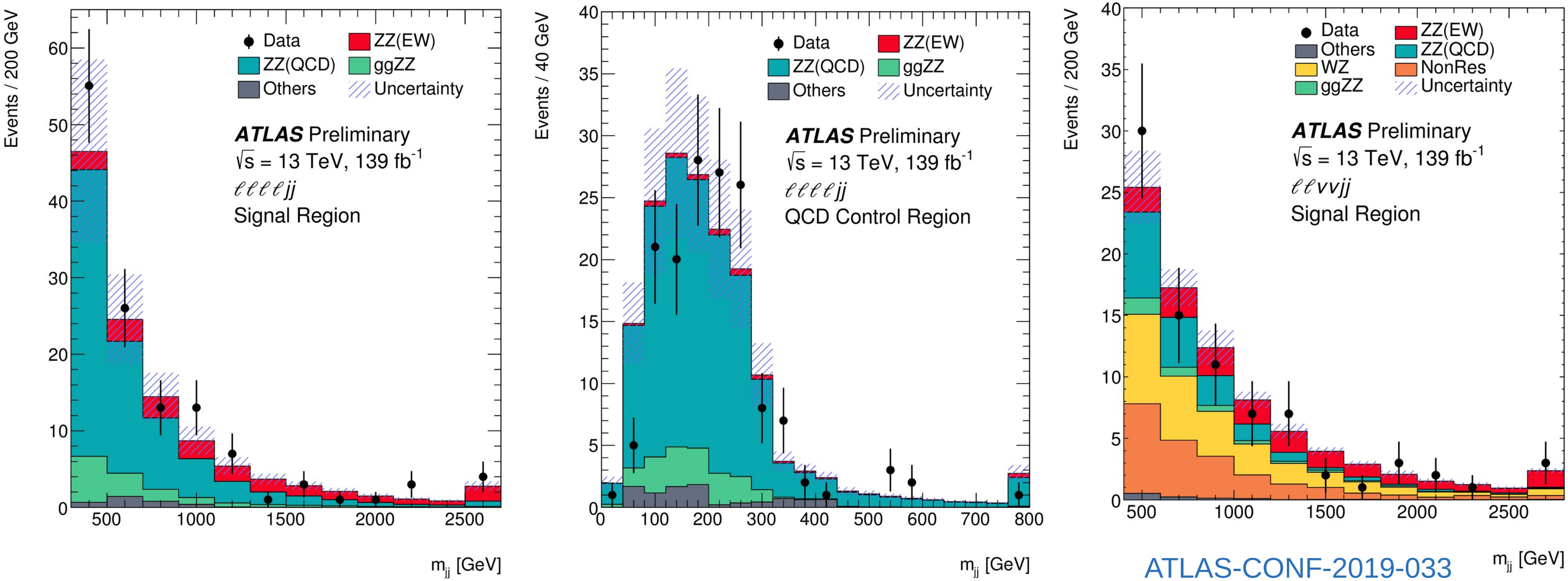
- Boosted decision trees (BDT)
  - Trees ensemble
  - Gradient Boosting
    - Weak learner
    - Optimal classifier
    - Learning suppression
    - Sum of decisions of all trees





ZZ Data – MC Comparison

Examples of input observables for the multivariate analysis compared to the data.

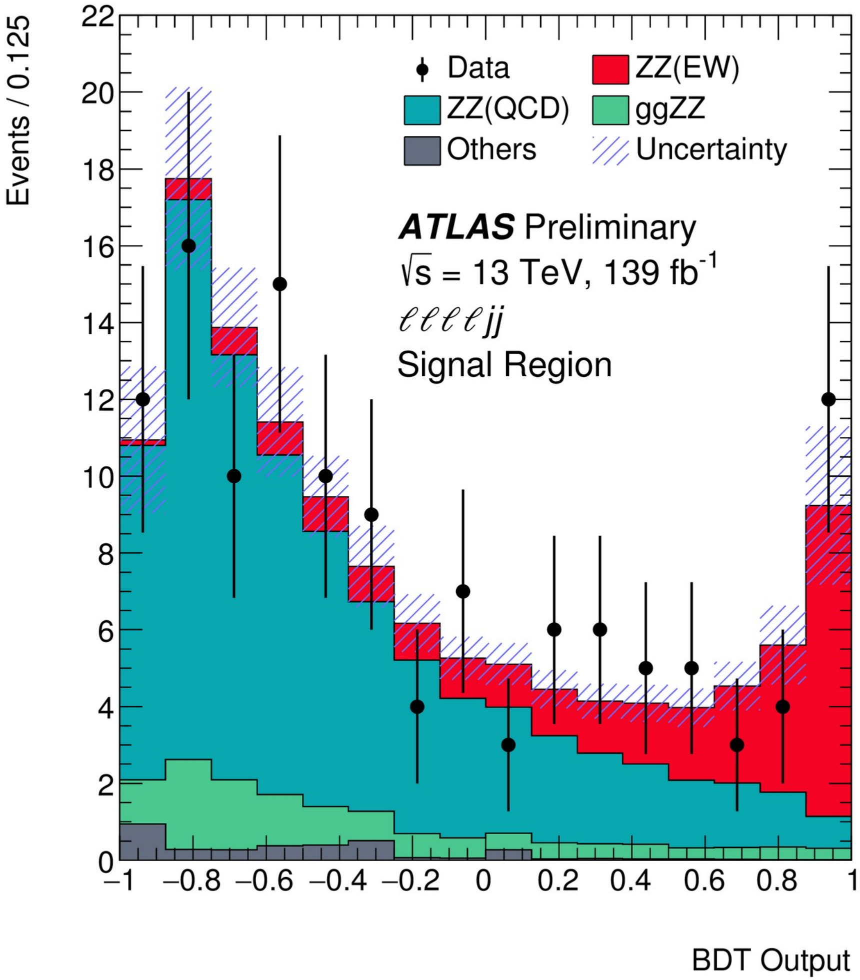


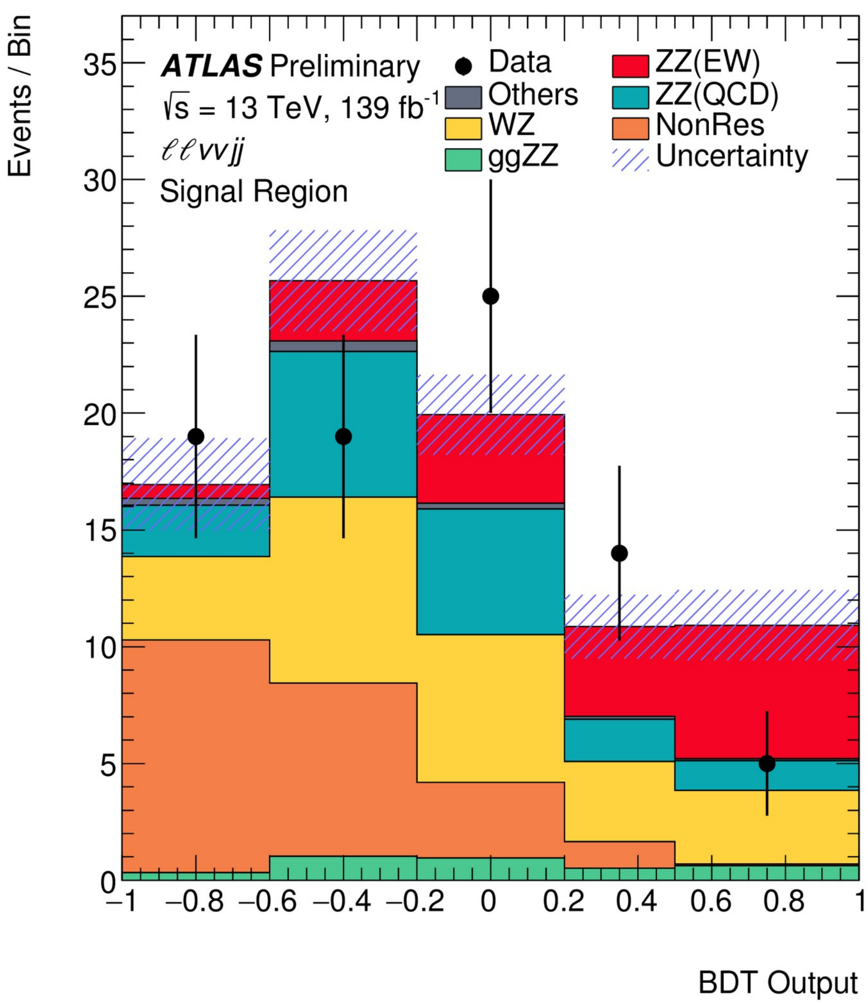
ATLAS-CONF-2019-033

ZZ – Fitting

- Standard fitting procedure
  - Binned Profile Likelihood Ratio
  - Poisson likelihood
  - Gaussian nuisance parameter profile

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\boldsymbol{\theta}}})}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}$$





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ZZ – Results

- Signal strength $1.35^{+0.30}_{-0.30}(\text{stat.})^{+0.16}_{-0.16}(\text{syst.})$
- EW fiducial cross-section $0.82^{+0.18}_{-0.18}(\text{stat.})^{+0.10}_{-0.10}(\text{syst.})\,\text{fb}$
- ZZjj EW production **observed (5.5 σ)** in agreement with the SM
- The $\nu\nu\ell\ell$ channel not as lucky as the $\ell\ell\ell\ell$

	Expected	Observed
4l	3.86 σ	5.48 σ
$\ell\ell\nu\nu$	1.80 σ	1.15 σ
combined	4.28 σ	5.52 σ

- The measurement is overall dominated by statistical uncertainty
  - Accounts for 88% of the total uncertainty
- Theoretical uncertainty
  - EW signal
    - PDF: 6%, QCD scales: 6%
  - QCD background
    - QCD scales: 30 – 35%
- Experimental uncertainty
  - EW signal
    - Electron identification: 2%
  - QCD background
    - Jet energy scale: 9 – 10%

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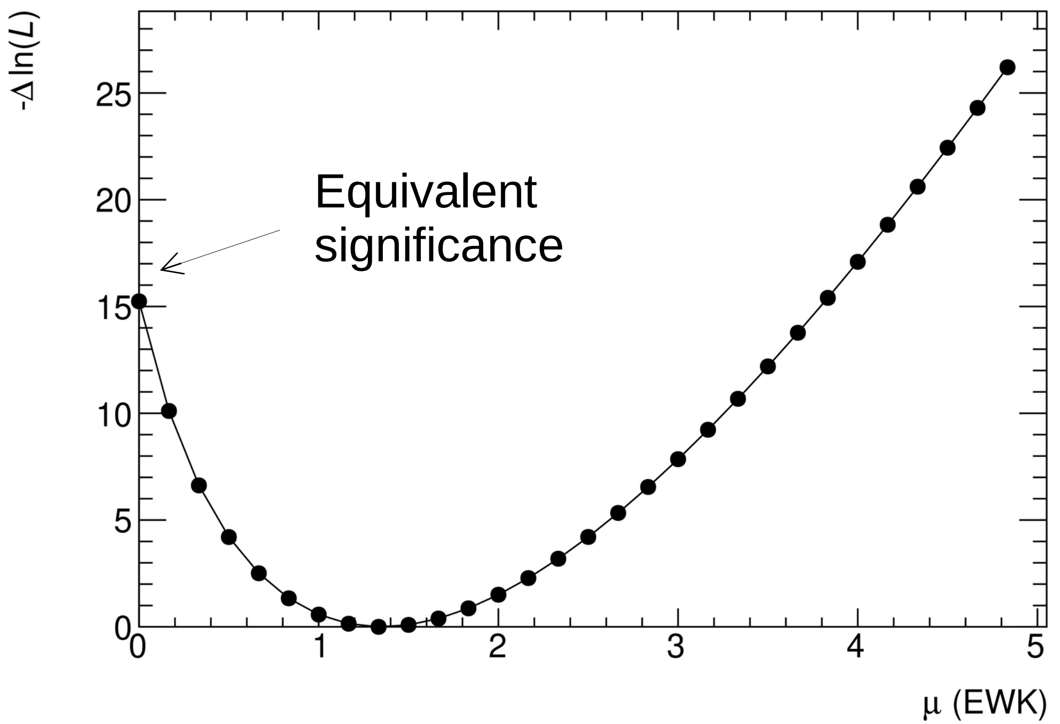

ZZ Paper

- Still in review
  - Request for modeling of the EW signal prediction in higher precison NLO-QCD
- Hope
  - Prediction modeled in PowHeg
  - Agreement with the LO-QCD MadGraph prediction
- Recap
  - Analysis kick off in 2017
  - Publication expected in 2022

Not reviewed, for internal circulation only

ATLAS EXPERIMENT

ATLAS Paper Draft

STDM-2017-19

Version 1.3

Target journal: Nature Physics

Comments are due by: YY XX 2019

Supporting internal notes

Support Note: https://cds.cern.ch/record/2638144

Observation of electroweak production of two jets and a Z-boson pair with the ATLAS detector at the LHC

Analysis Team

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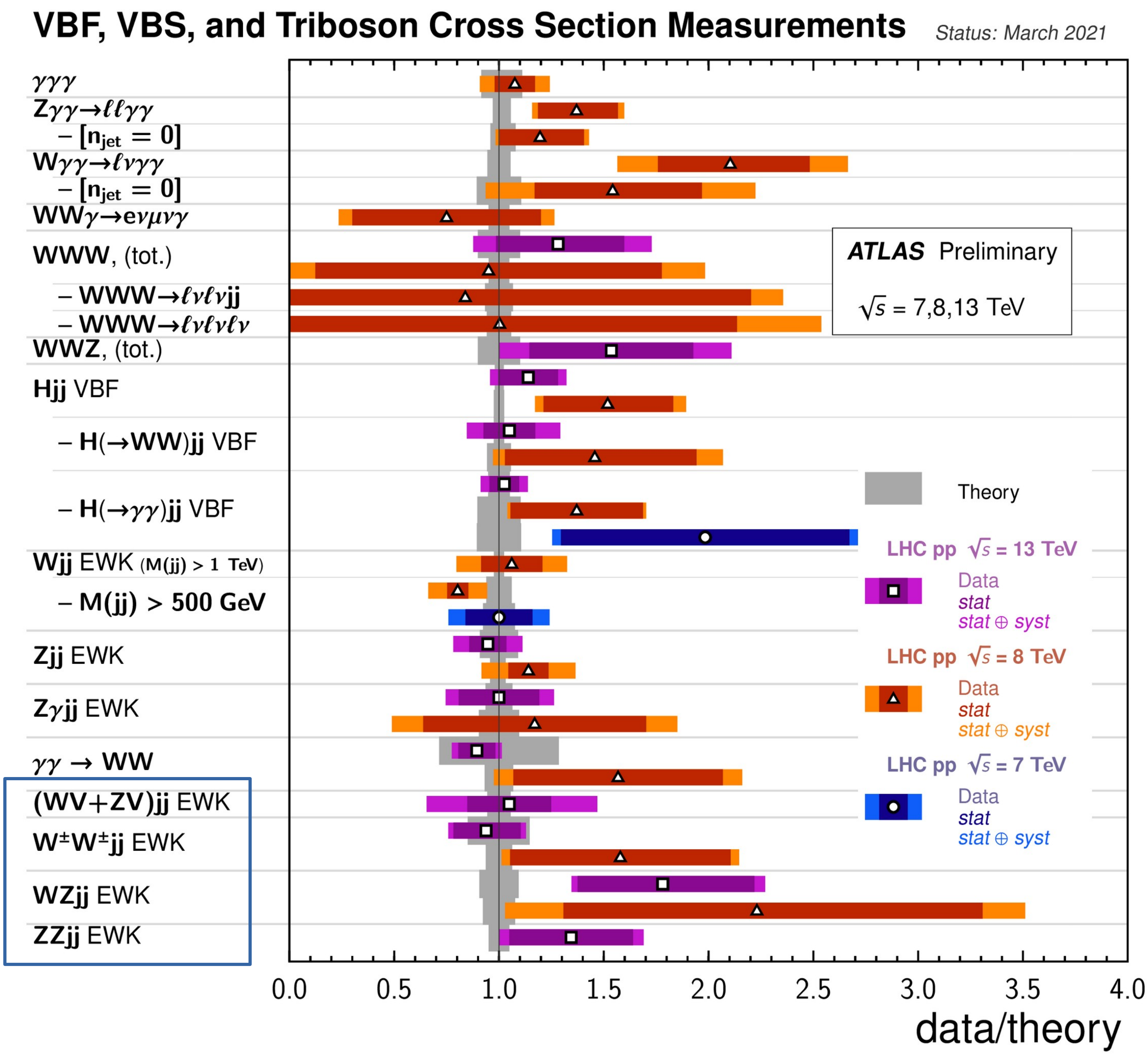
William Buttinger, Jing Chen, Cong Geng, Jun Guo, Suen Hou, Ashutosh Kotwal, Kostas Kordas, Antonios Leisos, Bing Li, Jing Li, Shu Li, Jianbei Liu, Mingyi Liu, Yanlin Liu, Alexandros Marantis, Ioannis Maznas, Monika Mittal, Emily Nurse, Ondrej Penc, Wenxiao Wang, Yusheng Wu, Haijun Yang, Shuzhou Zhang, Zhengguo Zhao, Bing Zhou, Heling Zhu

ATLAS VBS Measurements



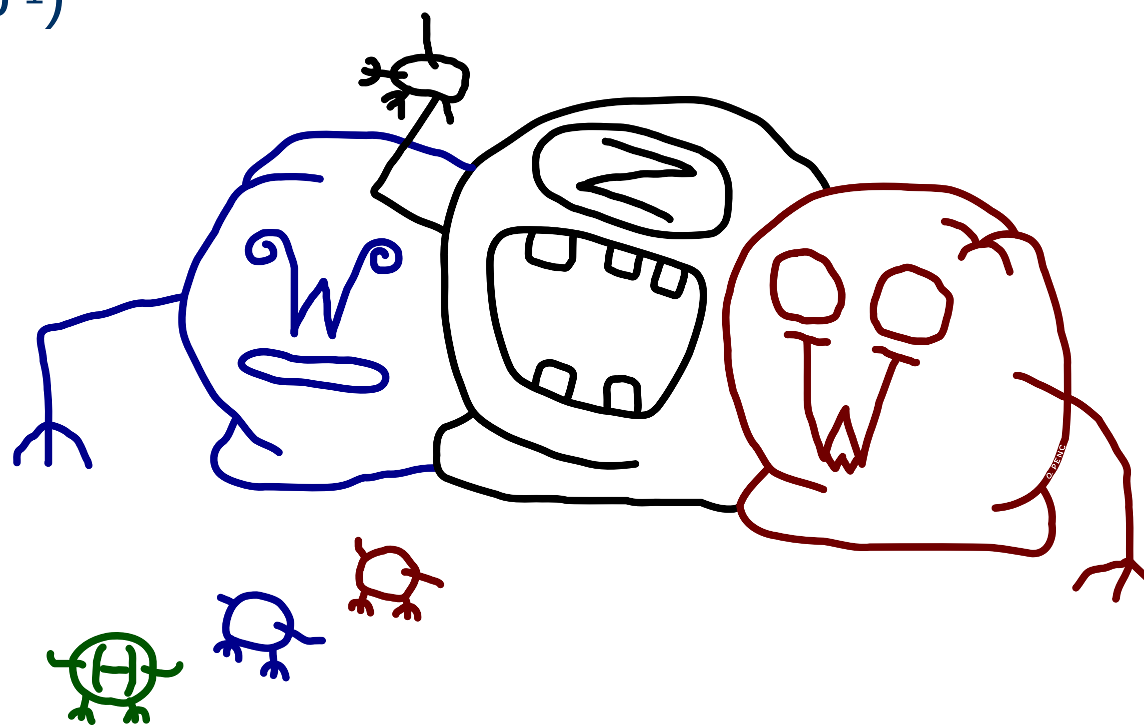
ATL-PHYS-PUB-2021-032

Summary

- ATLAS VBS status
  - Observation in **all leptonic channels** WW, WZ, ZZ
  - Waiting for evidence in VV semi-leptonic channel
  - Latest observation in the ZZ channel in full Run 2 (139 fb^{-1})

- Beyond the Standard Model
  - No obvious disagreement with standard model observed
  - Limit settings of the anomalous Quartic Gauge Couplings are ongoing

- Outlook
  - Full Run 2 still offers the further studies and measurements of the VBS phenomenon
    - Semi-leptonic channel
    - Polarization studies
    - Limit settings on aQGC
    - Channels including gamma



CERN-THESIS-2021-179

BACKUP

Resonant Shape Algorithm

- Event MC generators do not always provide full information
  - Huge amount of events
  - Storage consumption
- Used for WZ VBS channel arXiv:1603.02151
- Based on value of the following estimator

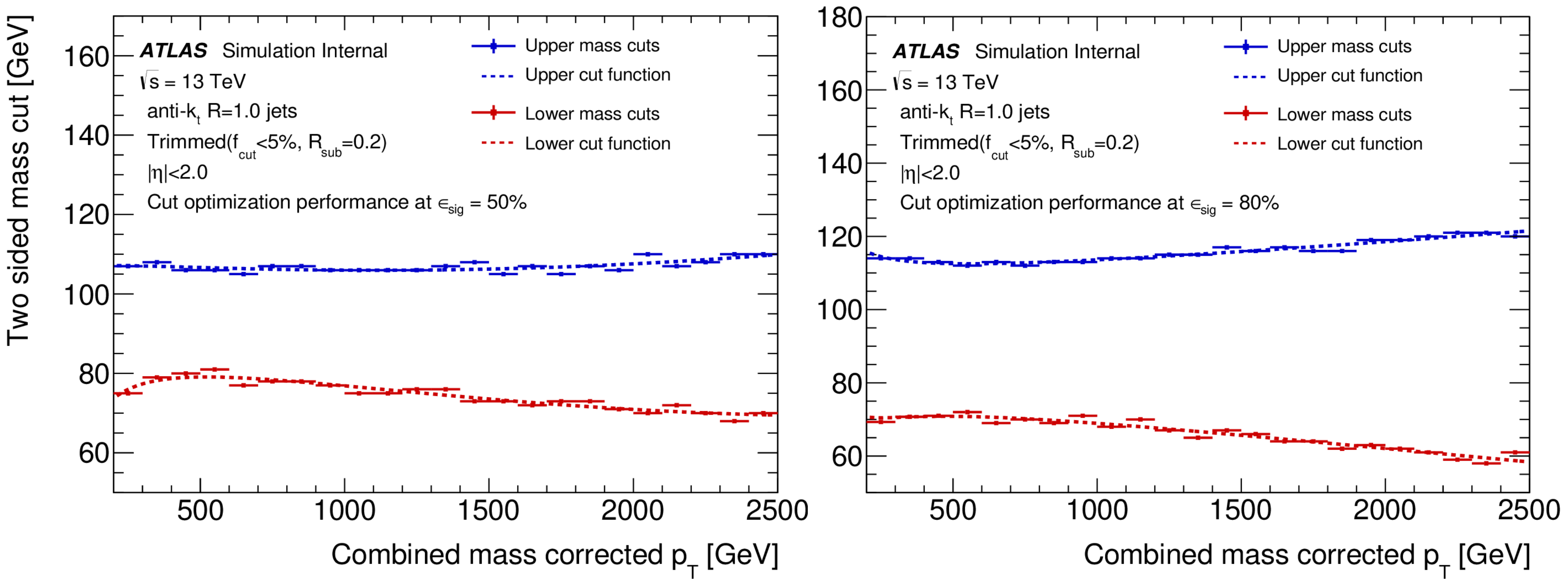
$$P = \left| \frac{1}{m^2_{(\ell^+,\ell^-)} - \left(m_Z^{\mathrm{PDG}}\right)^2 + i\,\Gamma_Z^{\mathrm{PDG}}\; m_Z^{\mathrm{PDG}}} \right|^2 \times \left| \frac{1}{m^2_{(\ell',\nu_{\ell'})} - \left(m_W^{\mathrm{PDG}}\right)^2 + i\,\Gamma_W^{\mathrm{PDG}}\; m_W^{\mathrm{PDG}}} \right|^2$$

- Input
  - Mass of all possible di-lepton and neutrino-lepton pairs
  - PDG mass and width of W and Z bosons
- The best evaluated triplet is the WZ candidate
  - Highest *P* value
- Monte Carlo independent method
  - Used for all generators

W/Z hadronic tagger

- Vector bosons reconstruction
  - Hadronically decaying and boosted
- Jet substructure
  - Large jet (ΔR = 1.0) are re-clustered with anti-kT algorithm again with smaller radius
  - $D_2(\beta = 1)$ jet substructure variable
    - Two-point to three-point energy correlation function ratio
    - Based on pairwise angular separation of particles and energy clusters within the jet

- Merged working points
  - High purity
    - Pass 50% working point
  - Low purity
    - Fail 50% but pass 80% working point



arXiv:1905.07714

Binned Profile Likelihood Ratio

$$L(\mu, \boldsymbol{\theta}) = \prod_{j=1}^{N} \frac{(\mu s_j + b_j)^{n_j}}{n_j!} e^{-(\mu s_j + b_j)} \prod_{k=1}^{M} \frac{u_k^{m_k}}{m_k!} e^{-u_k}$$

Building of the likelihood

- Finding distribution parameters fitting the observed histograms
- Poisson distribution, Gaussian etc.
- Data choose value of NP (profiling)

- Construct Asimov dataset
  - Internal cross-check if the likelihood is consistent with theory prediction
  - Set all the observed values as the expected ones

- Calculate the conditional maximized likelihood function
  - Calculate maximum for each value of POI (μ)
  - Varying the NP (θ)

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\boldsymbol{\theta}}})}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}$$

- Calculate the maximized unconditional likelihood function
  - Overall maximum
  - Varying POI (μ) and NP (θ)

- Observation
  - Test statistic of incompatibility of μ and data
    - Range (0,1)

$$t_\mu = -2 \ln \lambda(\mu)$$

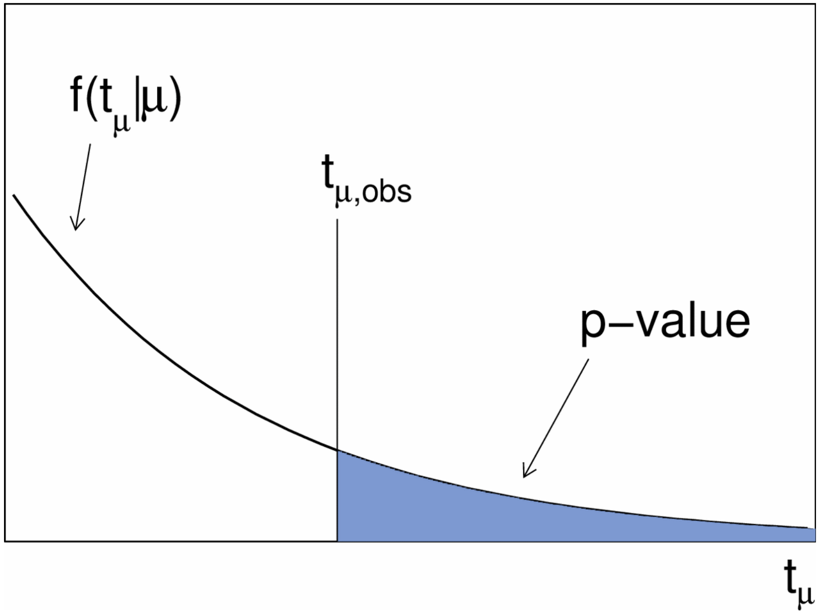
  - Data-hypothesis discrepancy

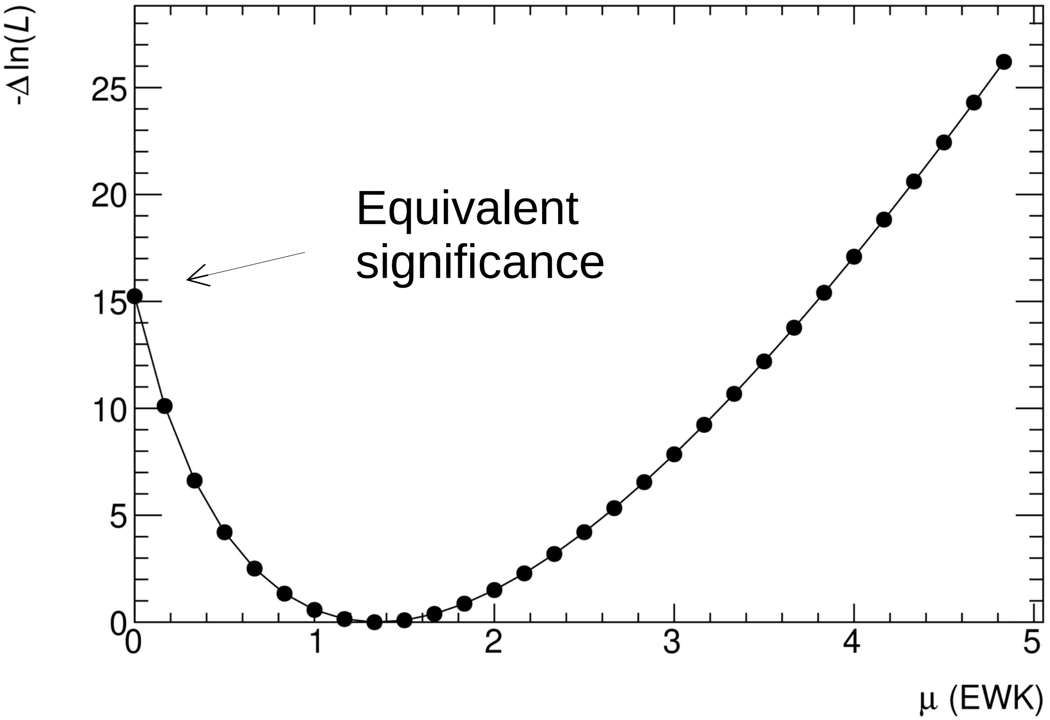
Profile likelihood ratio

- Wilks theorem (1939)
  - The profile likelihood ratio -2ln(λ) asymptotically behaves as the chi-square distribution, under assumption the null hypothesis is true
- Wald theorem (1943)
  - Generalization of the previous to the non-null hypothesis

$$p_\mu = \int_{t_{\mu,\mathrm{obs}}}^{\infty} f(t_\mu|\mu)\, dt_\mu$$

$$-2\ln\lambda(\mu) = \frac{(\mu-\hat{\mu})^2}{\sigma^2} + \mathcal{O}(1/\sqrt{N})$$





Troubles with electrons

- 13 TeV centre-of-mass energy
  - High energy electrons
  - Interaction with the detector
- Detector material interaction
  - Bremsstrahlung
  - Detector material interaction
  - Electron-gamma conversion
  - Charge misidentification
  - Electron dressing