Vector Boson Scattering at the ATLAS Detector

Seminar of IPNP

MFF CUNI, Prague
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on behalf of the ATLAS Collaboration

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  - Vectro boson scattering
- Common VBS selections
  - Object selection
  - Event selection
- Analyses
  - WW
  - WZ
  - Semileptonic
- ZZ analysis

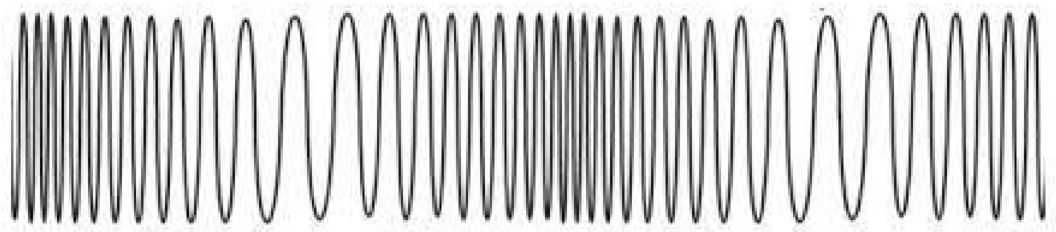
Introduction

Elastic WW scattering in SM

- Elastic WW scattering
  - Draws attention already since establishing of the Intermediate Vector Boson (IVB) theory
  - Persists as a difficulty also after the EW unification
  - Demands implementation of a scalar field for compensation of residual asymptotic divergences
- The scattering can be generalized as Vector Boson Scattering (VBS)
  - Interaction of W and Z bosons
  - Bosons possessing of longitudinal polarization

Asymptotic behavior of the scattering in the context of theory evolution

- Electromagnetic interaction of W boson
  - Difficulty of IVB model
  - M_res=O(E^2)
- EW interaction of W bosons
  - Outcome of EW unification
  - Z boson and QGC interaction
  - M_res=O(E)
- Higgs interaction of W bosons
  - Outcome of EWSB
  - M_res=O(1)

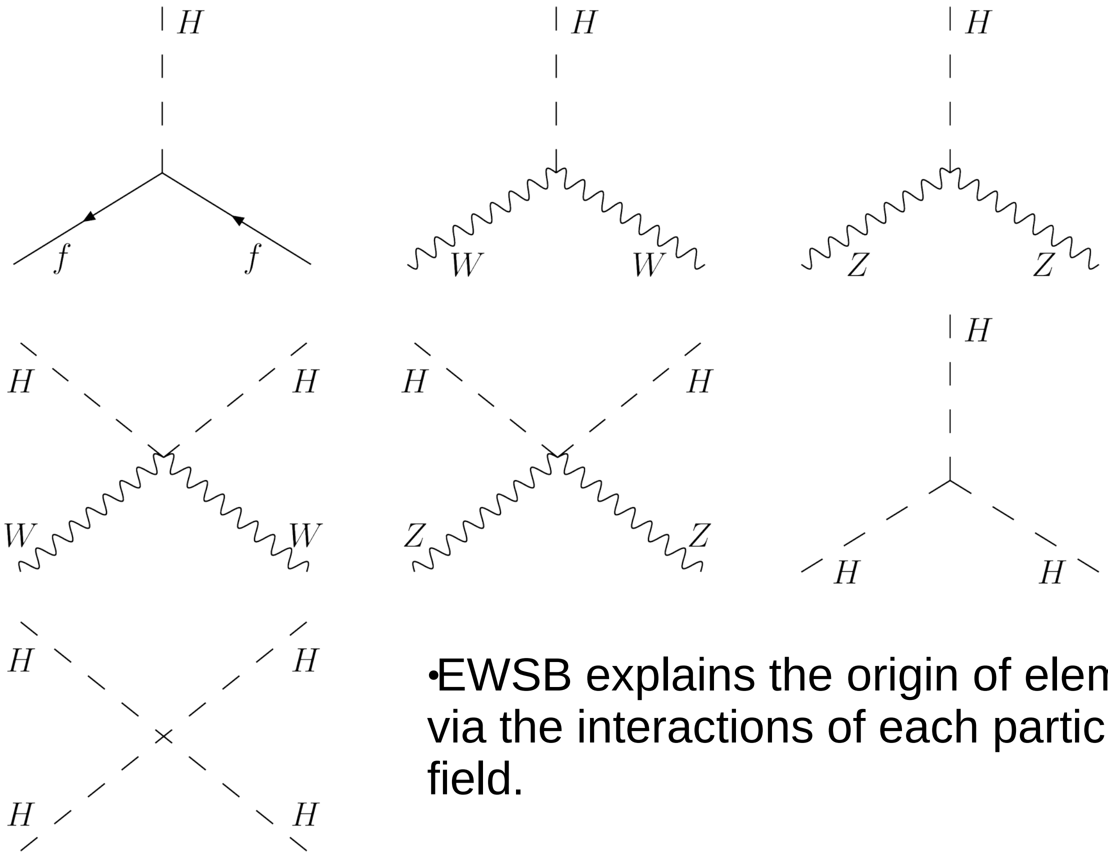


- VBS as Goldstone boson scattering (Goldstone Boson Equivalence Theorem)
  - W± and Z bosons acquire mass spending three Goldstone bosons (angular fields)
  - Parametrisation of weak isodoublet (a = 1,2,3)

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

Electro-weak symmetry breaking

- Theory model
  - Incorporates the Higgs boson to the SM
  - Generate boson masses
    - W and Z bosons
    - Higgs boson itself
- Consequences
  - Higgs field gives mass to all elementary particles
    - Through interaction with it (when the Yukawa interaction is employed)
  - Gives mass to Higgs boson itself
    - Higgs self interaction

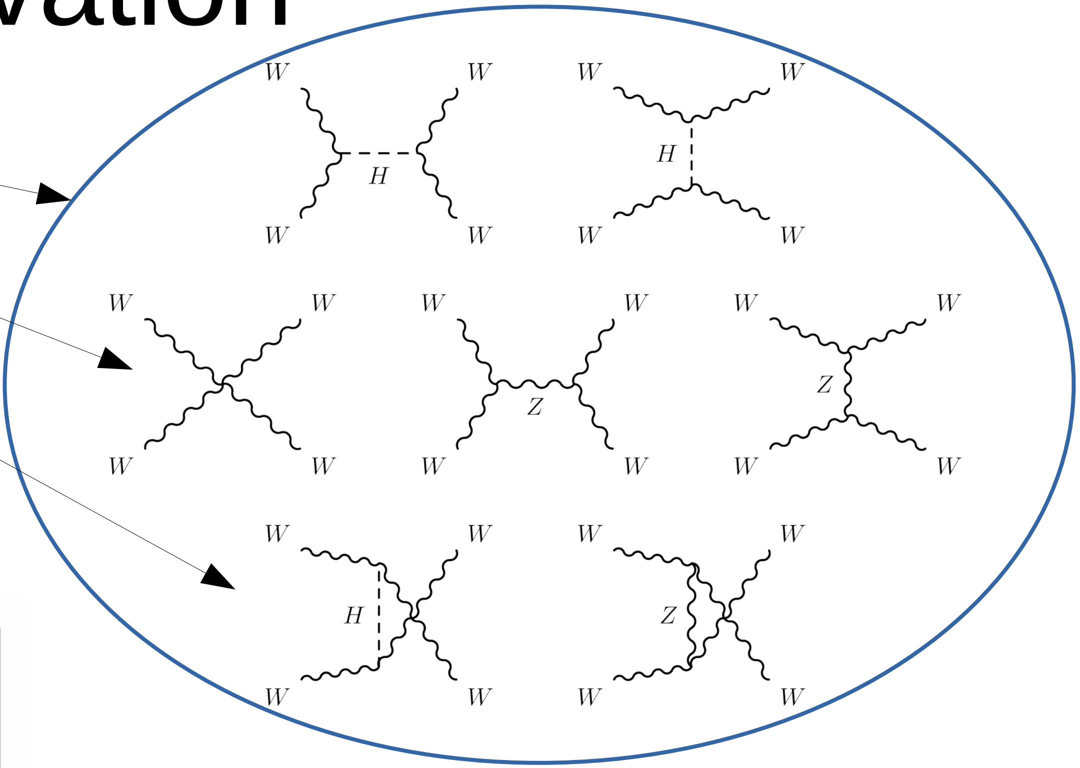


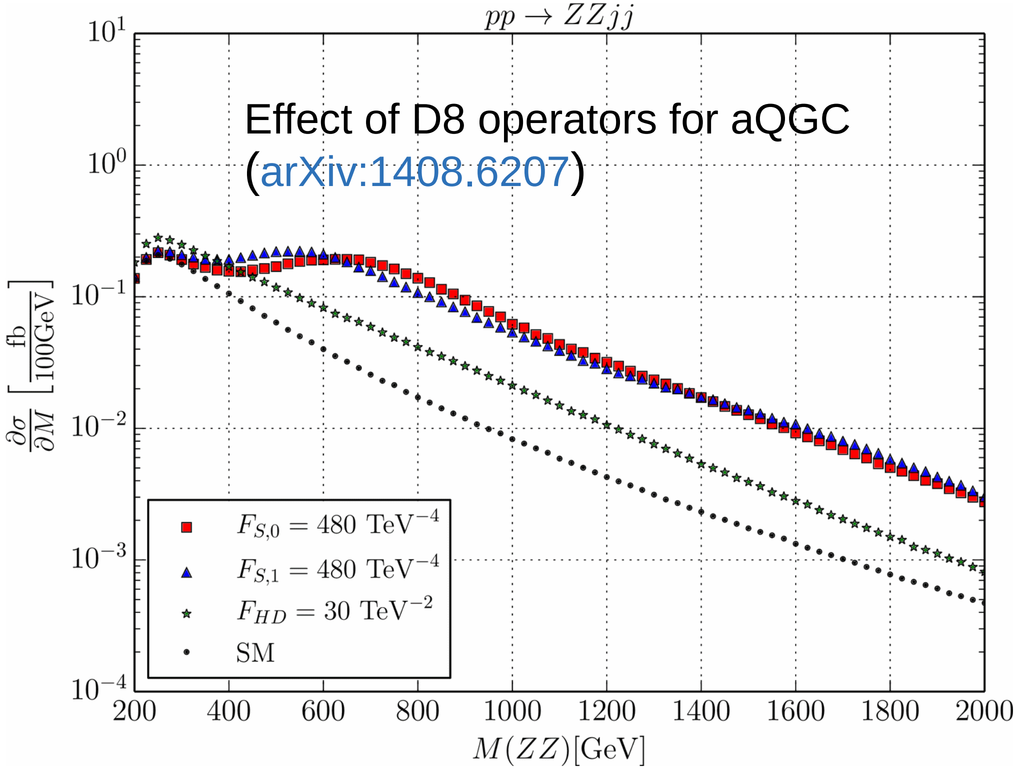
- EWSB explains the origin of elementary particle mass via the interactions of each particle with the Higgs field.

Motivation

Vector boson scattering

- Test of Standard Model gauge structure
- Quartic Gauge Coupling (QGC) becomes accessible
  - WWWW and WWZZ
- Better understanding of the nature of EWSB mechanism involving Higgs boson
- Limit settings on effects of the BSM physics



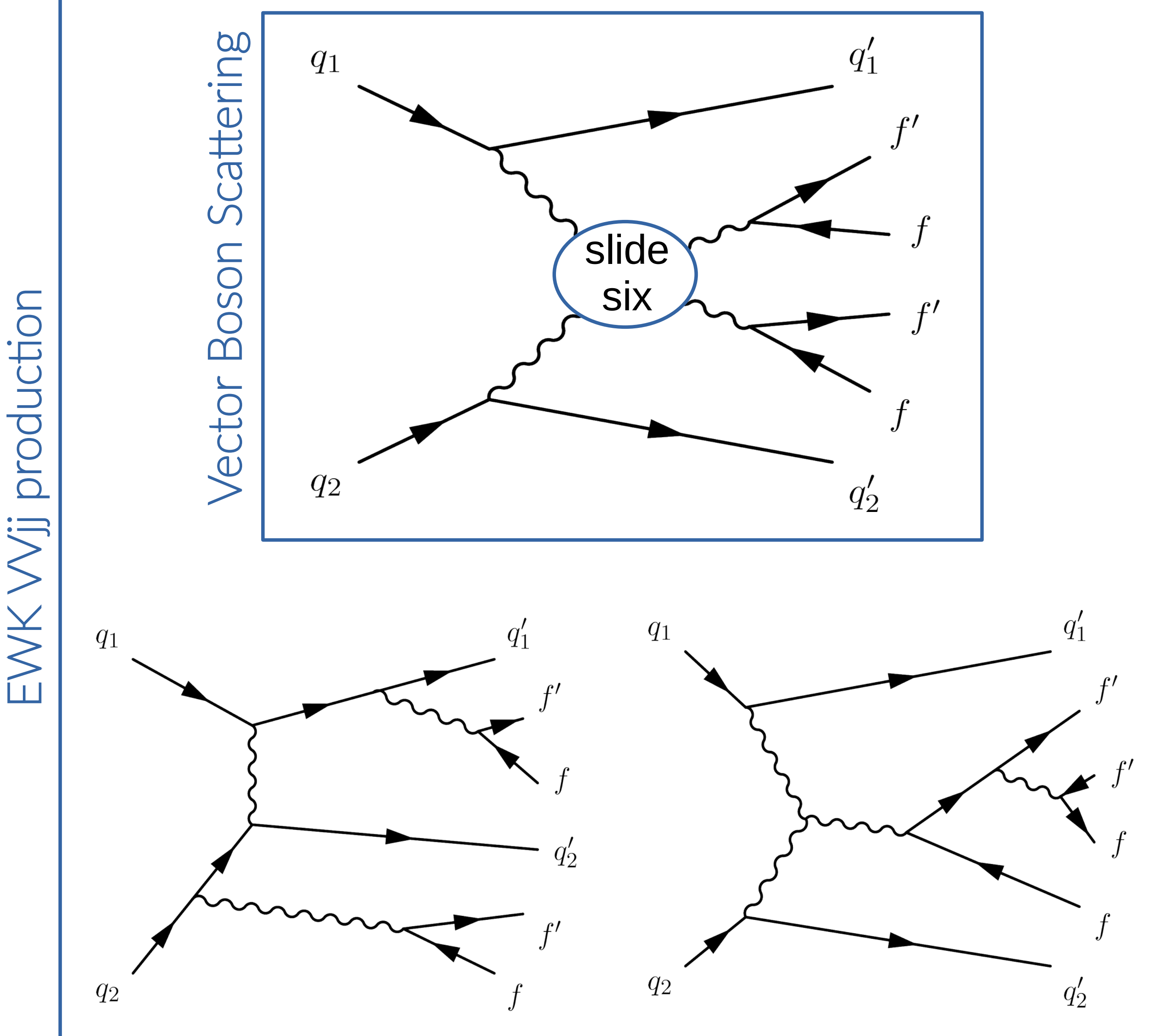


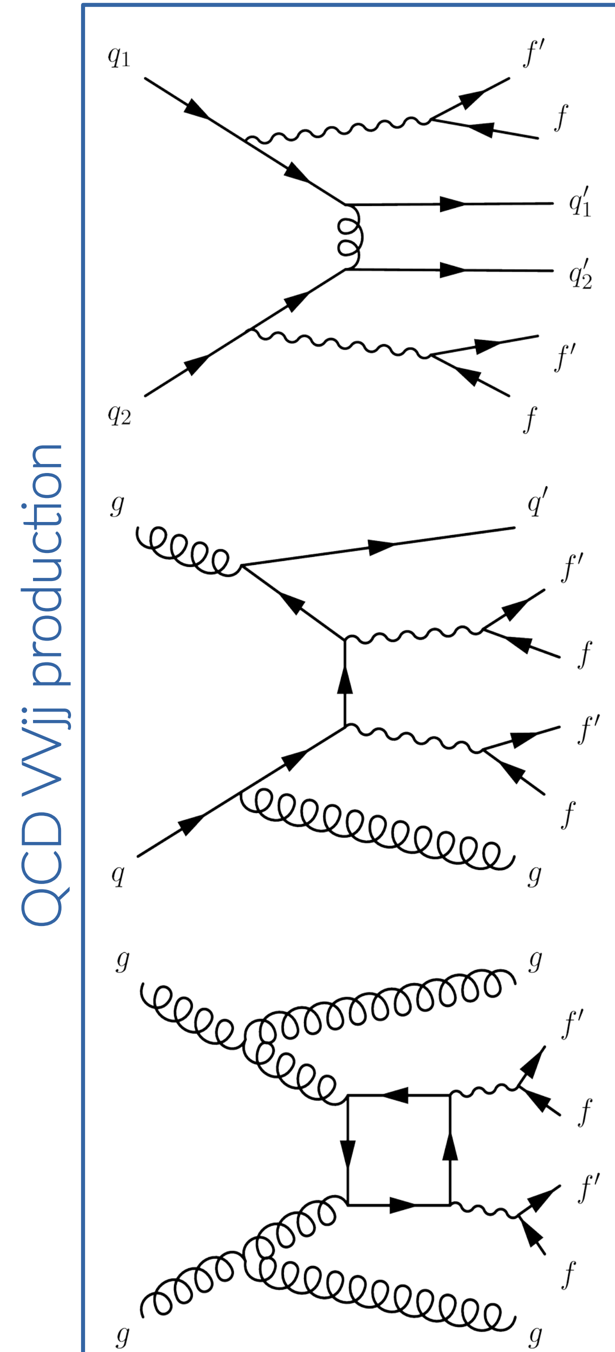
- Anomalous QGC
  - By hand addition of not allowed couplings by the SM
- Effective field theory
  - Addition of higher order operators to SM
  - SM represents a “low” energy limit case of the new model
  - Scales beyond the reach of the LHC

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

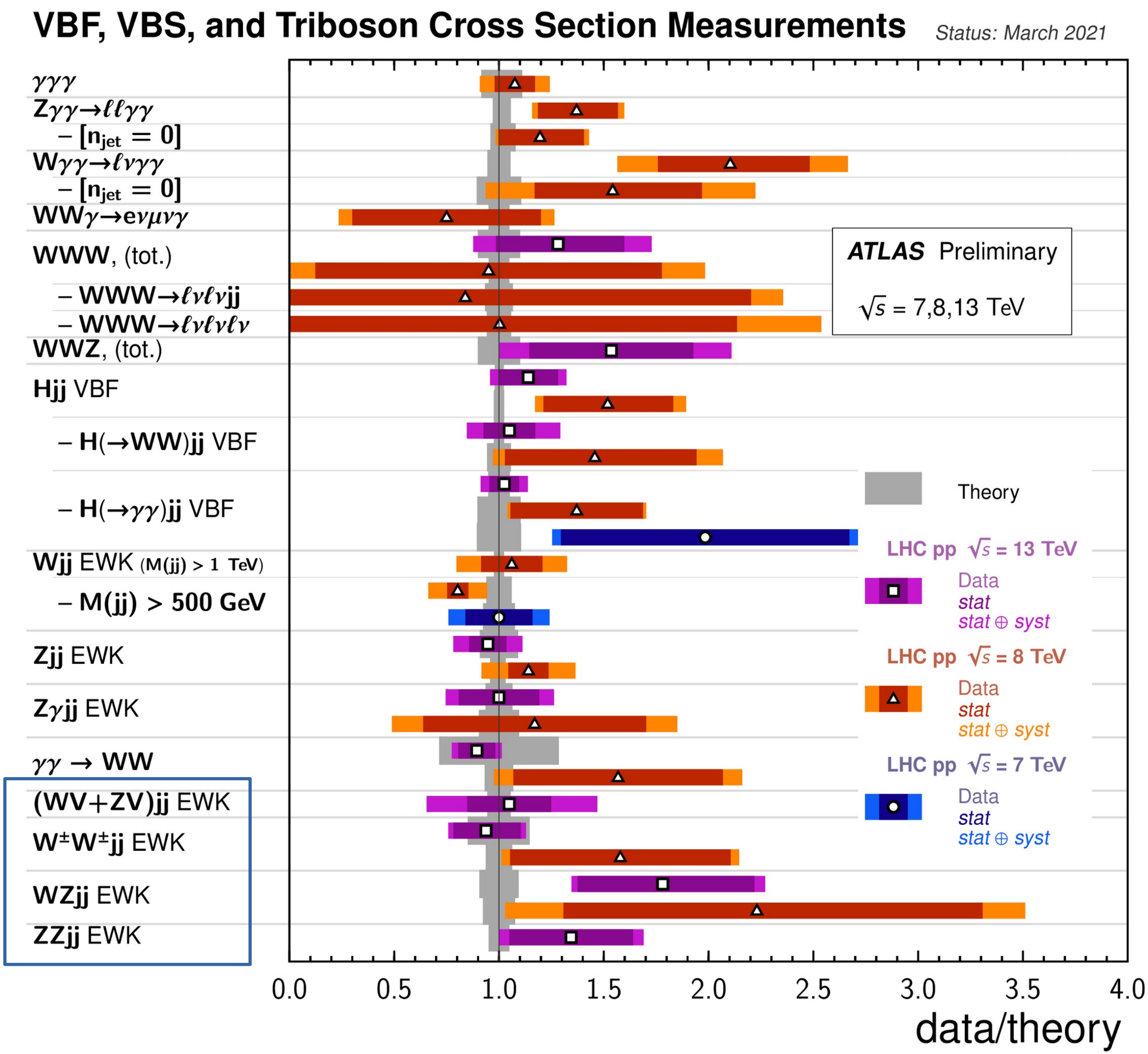
VBS at LHC

Protons interact electro-weakly



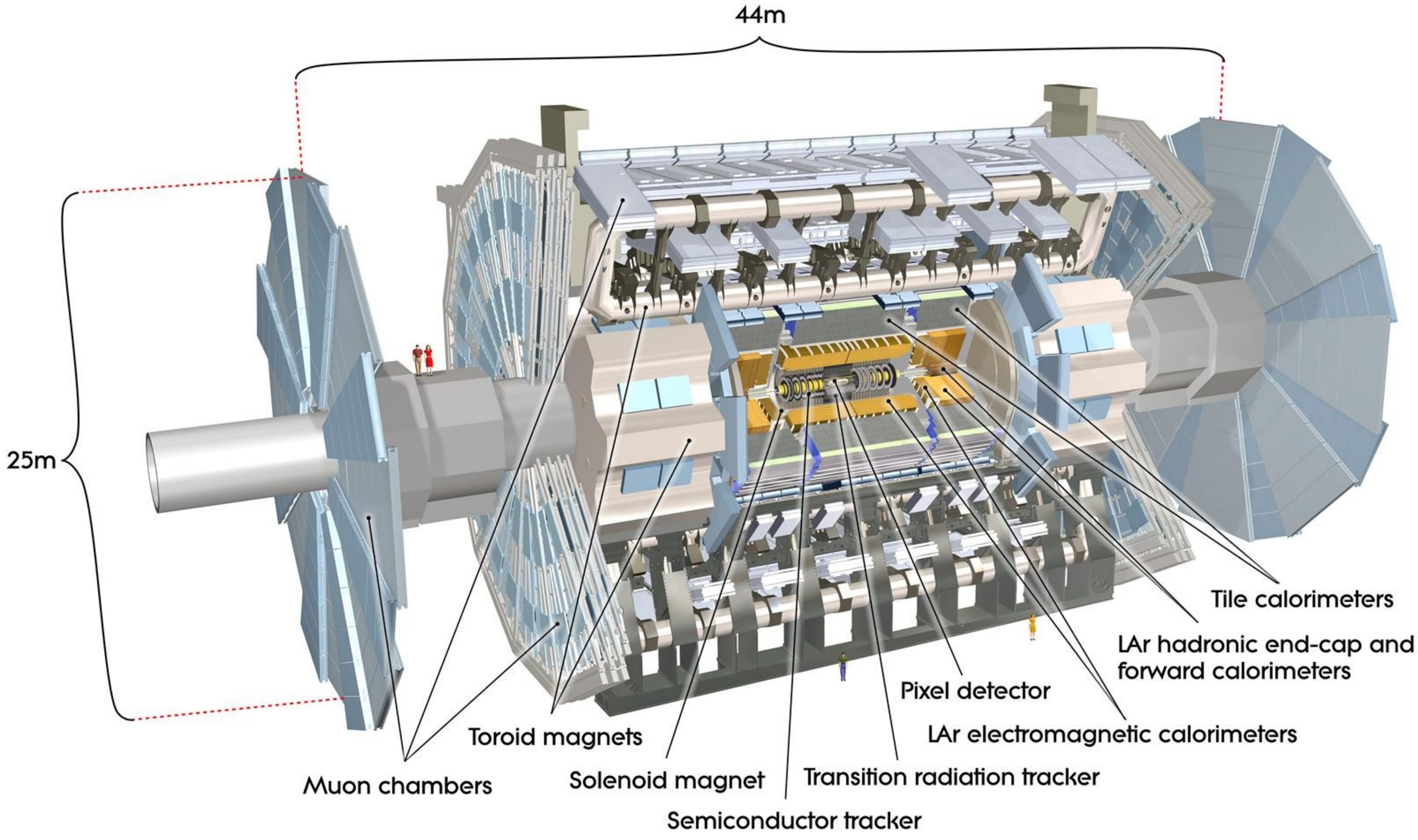


ATLAS VBS Measurements



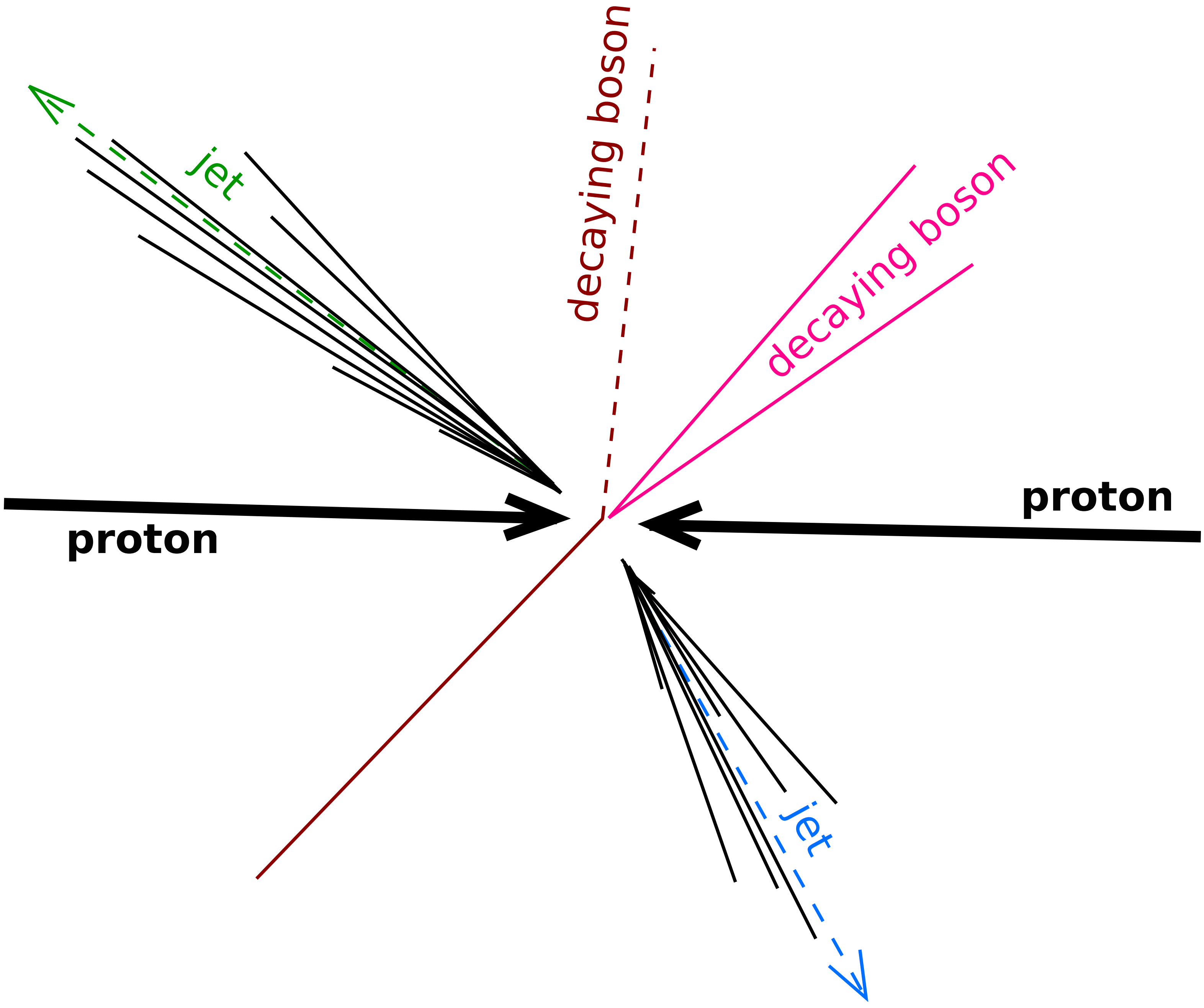
Common VBS selections

ATLAS detector



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



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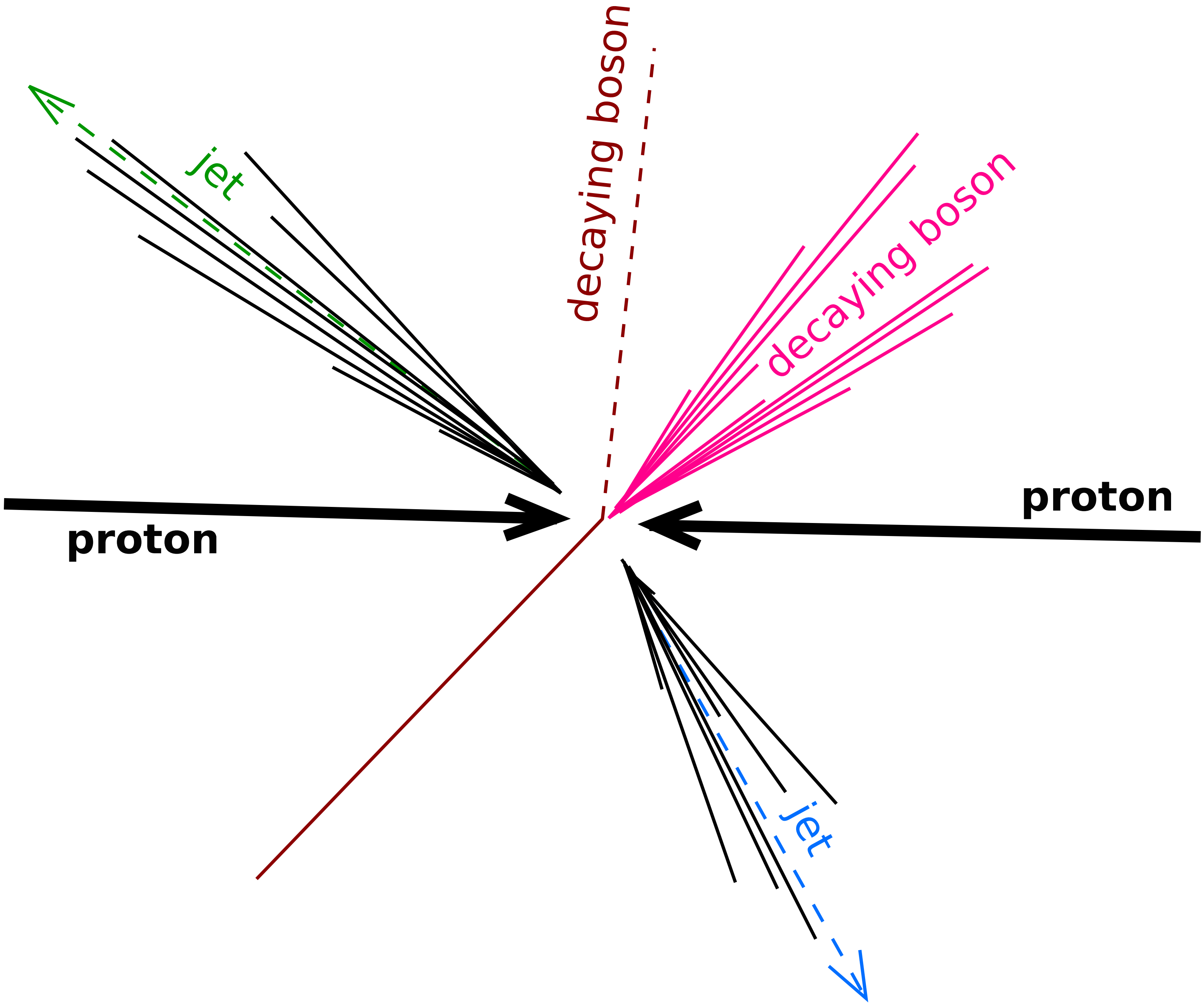
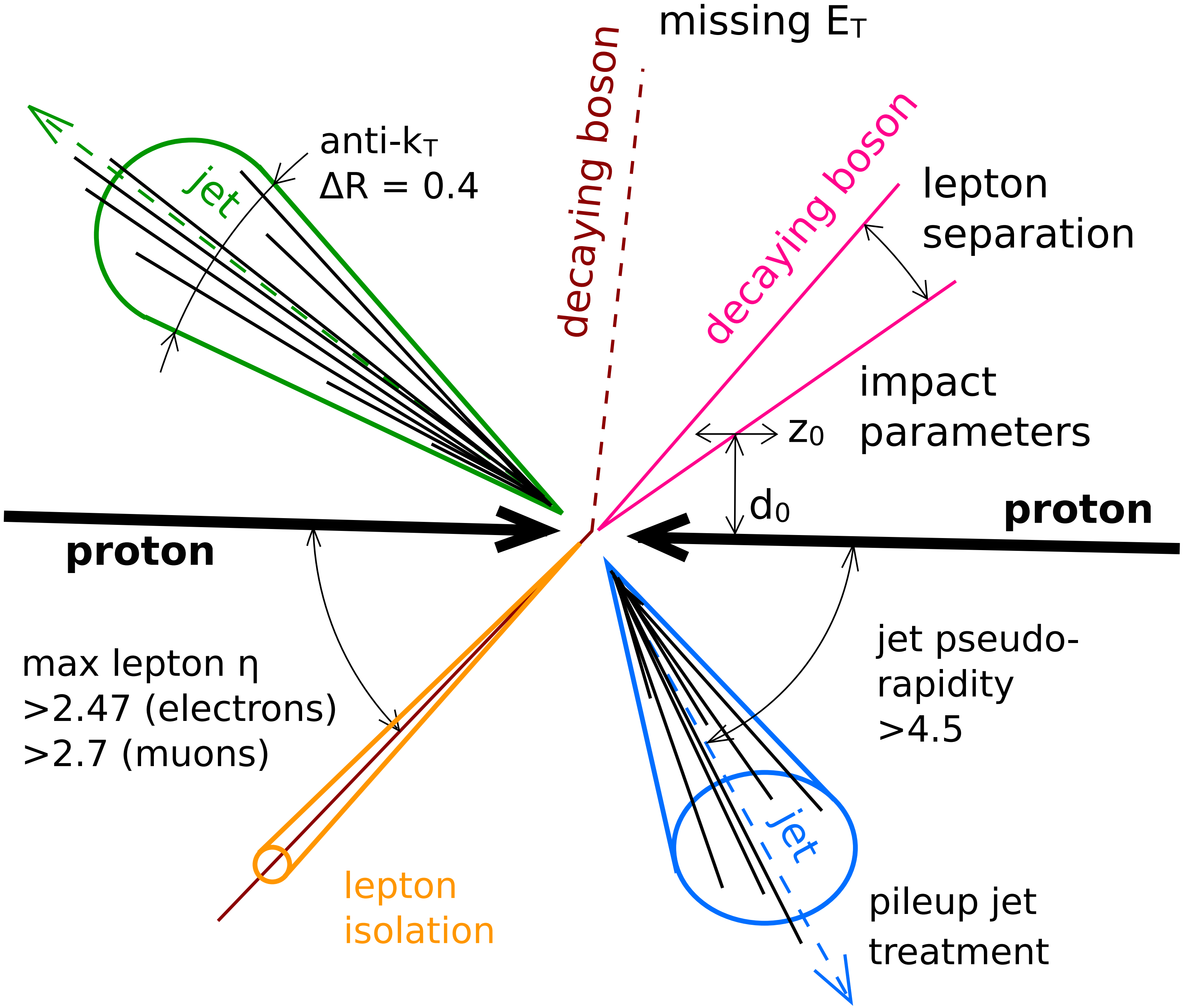


Object Selection

- 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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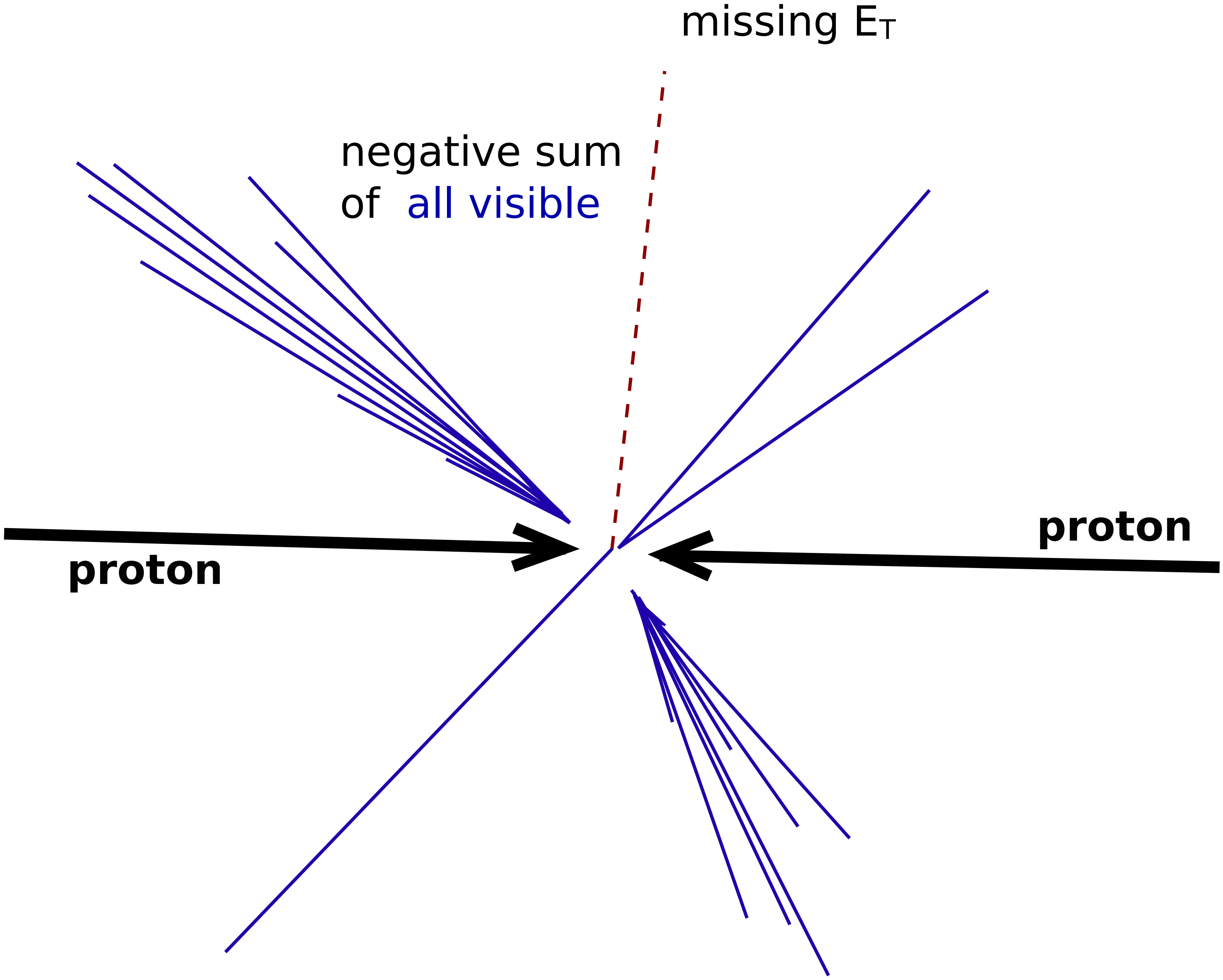
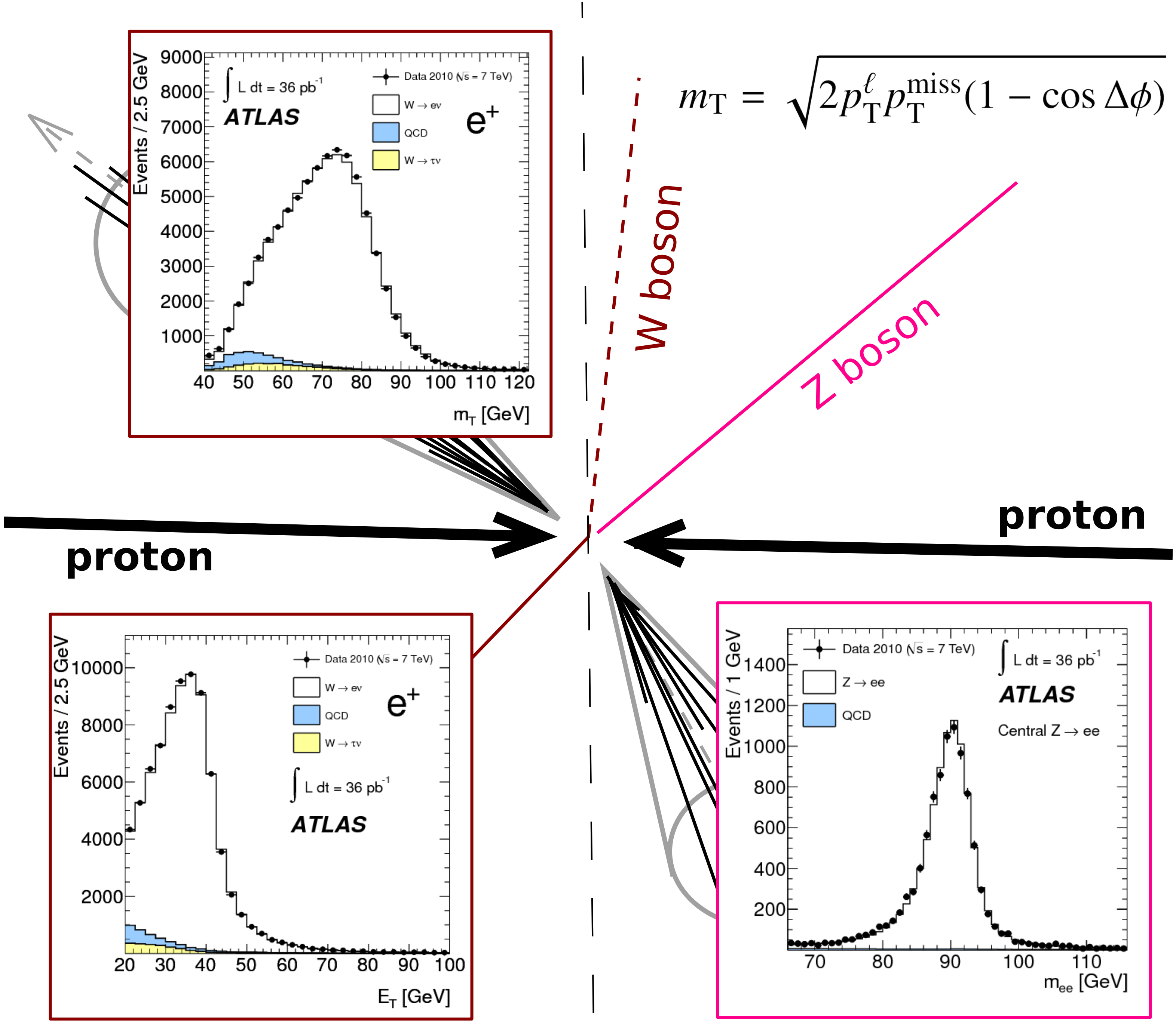


Event Selection

- 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

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi)}$$



arXiv:1109.5141

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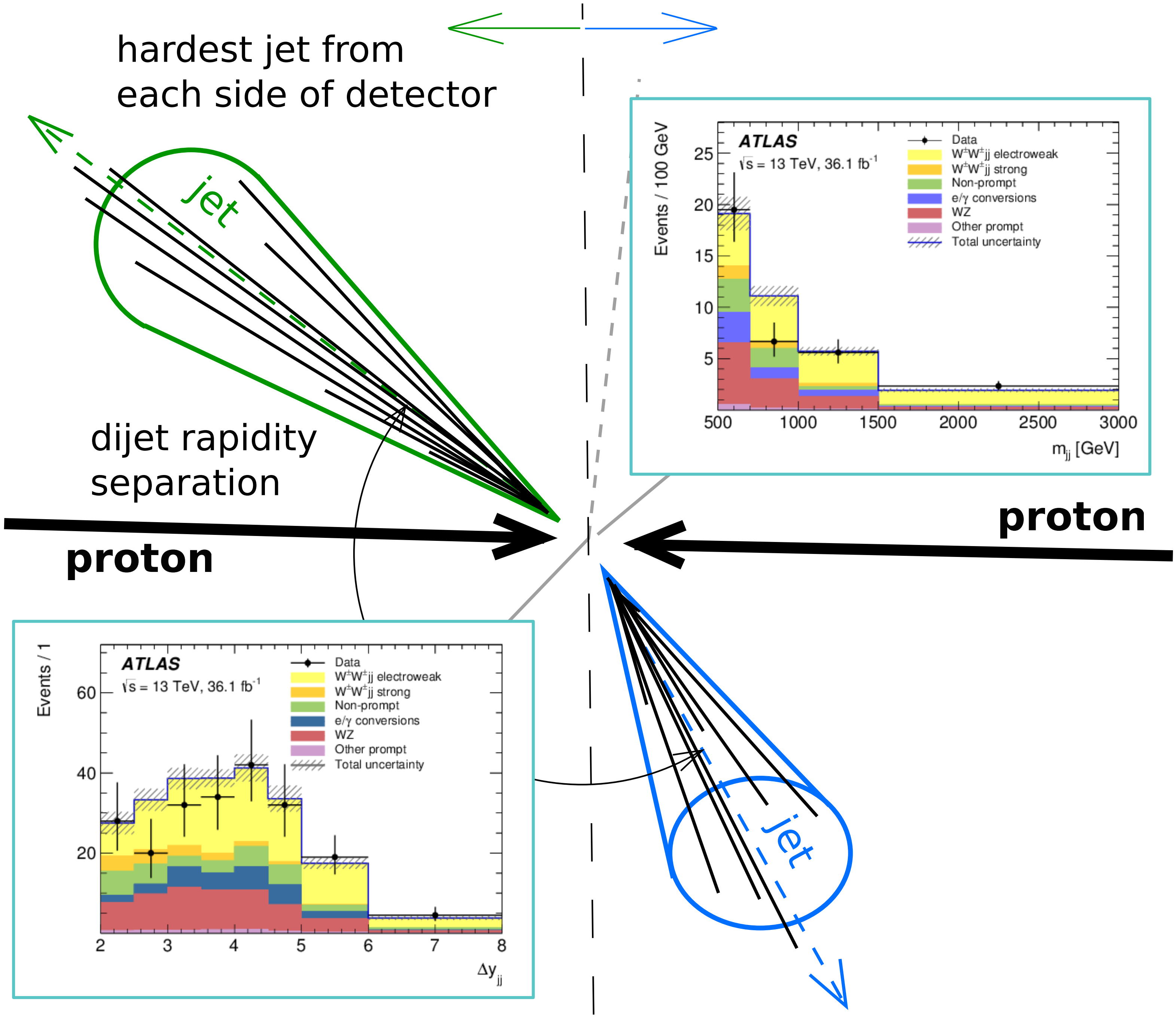
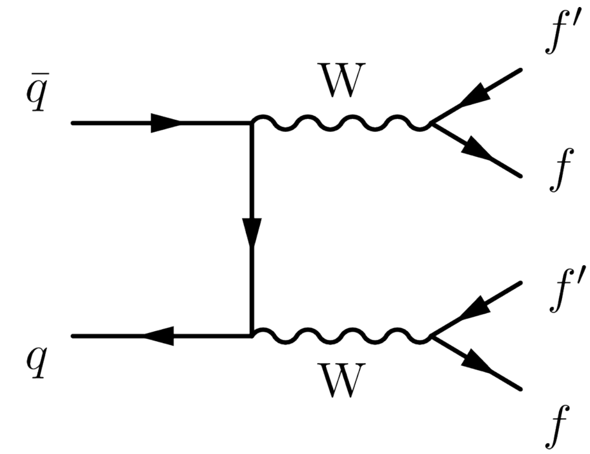


Analyses

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

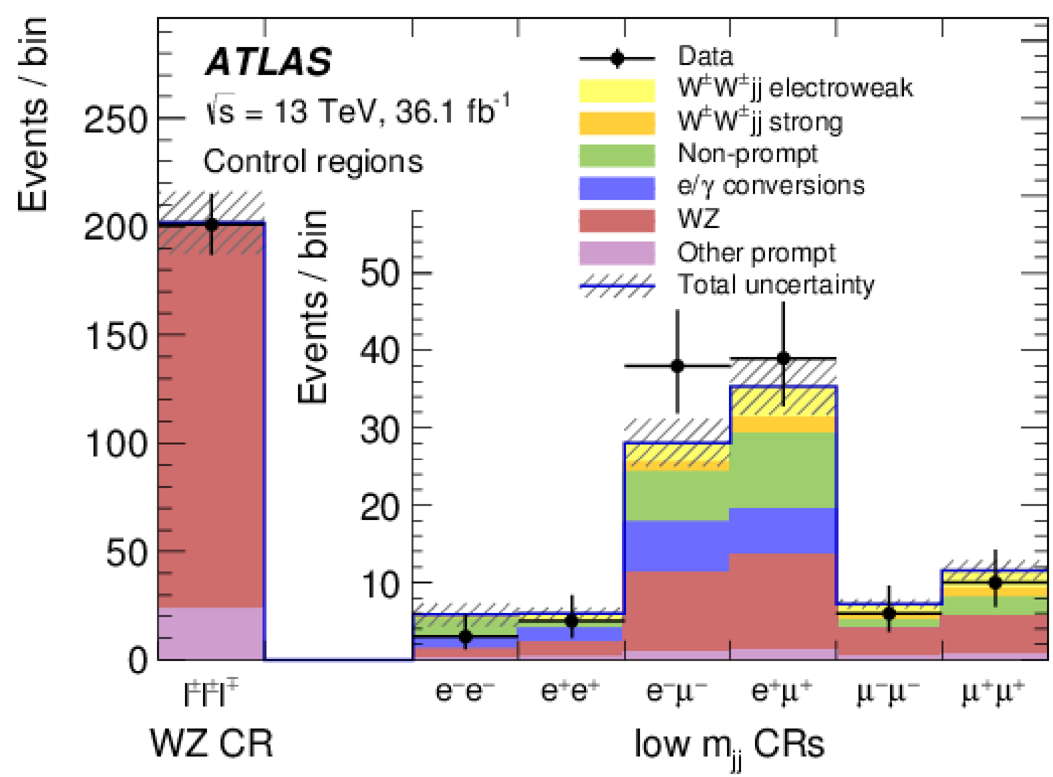
- VBS final state: $\nu\ell^{\pm}\nu\ell^{\pm}$ + jj
- Dataset: 36.1 fb^{-1}, 13 TeV
- Expected significance: 6.5 σ (Powheg-Box) and 4.4 σ (Sherpa)
- Same sign requirement suppress $q\bar{q}$ production



- Prompt background (MC modeled)
  - WZ+jets (dominant), WW+jets (QCD), ZZ+jets, and VVV

Non-prompt background (data driven)

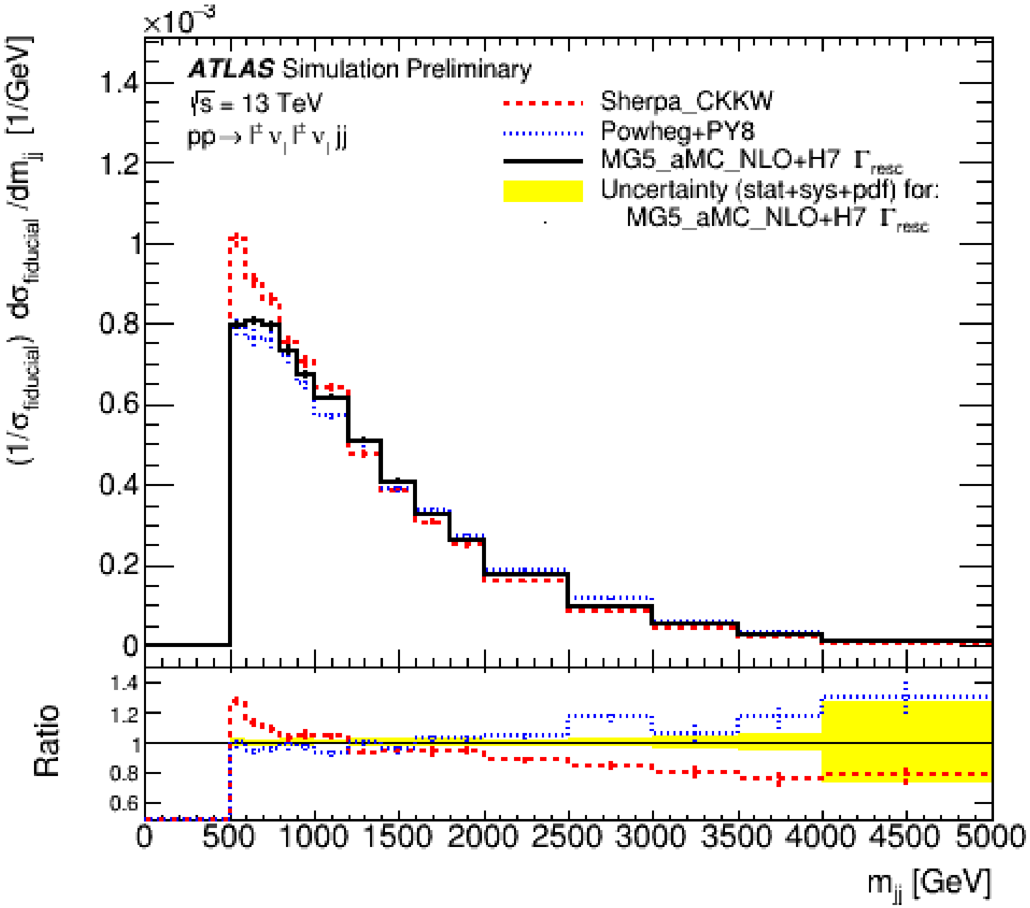
  - $t\bar{t}$, WW+jets (QCD), Vγ+jets, W+jets, t+jets
  - Lepton misidentification (photon as electron)
  - Charge misidentification (same sign leptons)



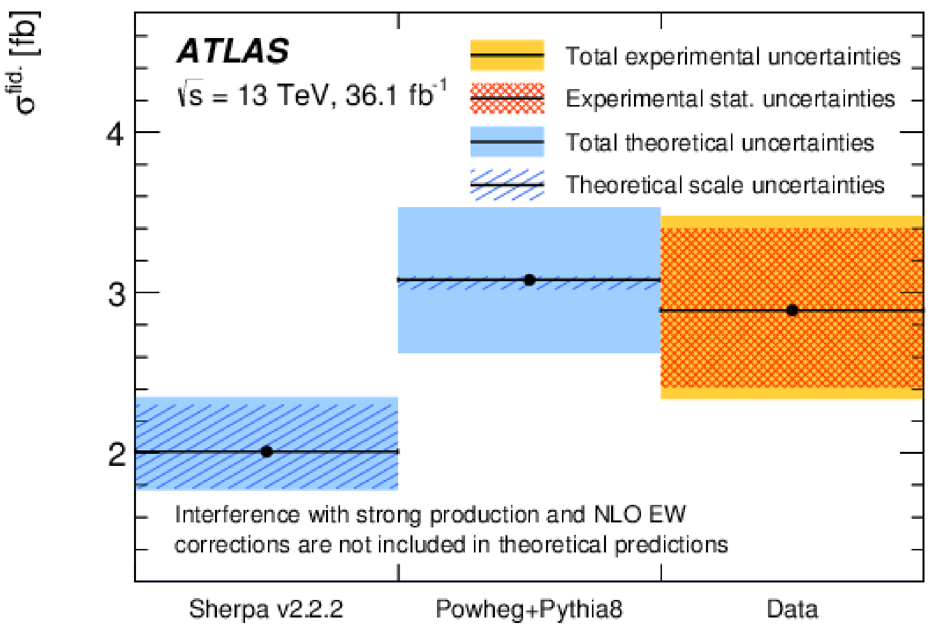
arXiv:1906.03203

MC simulations for $W^\pm W^\pm$ VBS

- Extensive MC studies for VBS first evidence channel
- Predicted cross-section and kinematic distribution comparison studies
- Low di-jet mass disagreement



- 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



ATL-PHYS-PUB-2019-004

W±W± - Results

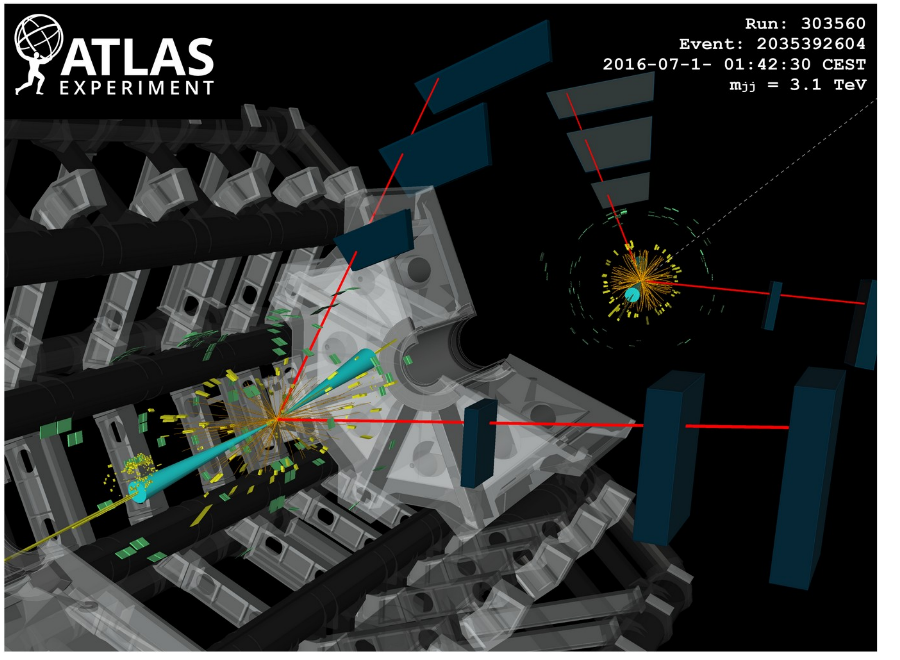
- Signal strength (compared to Sherpa)

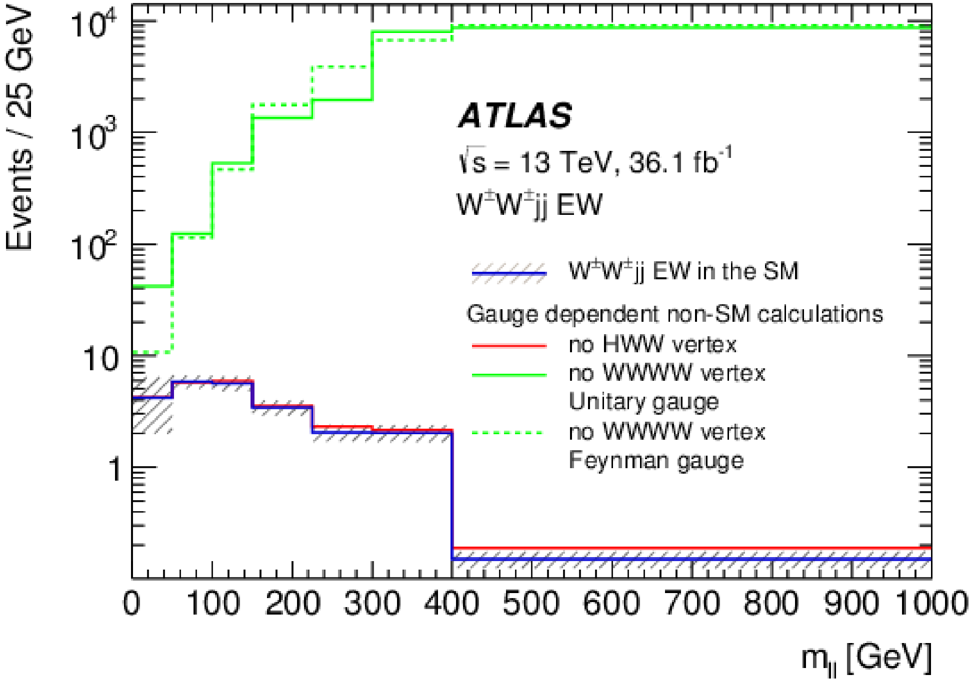
$$1.44^{+0.26}_{-0.24}(\text{stat.})^{+0.28}_{-0.22}(\text{syst.})$$

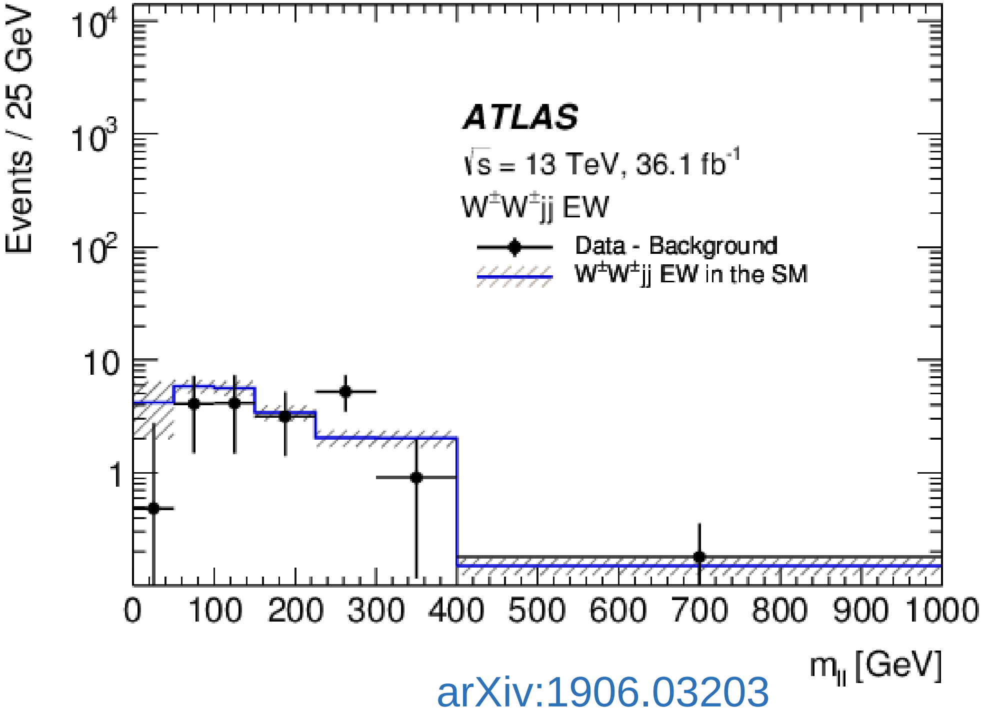
- Background only hypothesis rejected with significance 6.5 σ (expected 4.4/6.5 σ)
- EW Fiducial cross-section

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

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



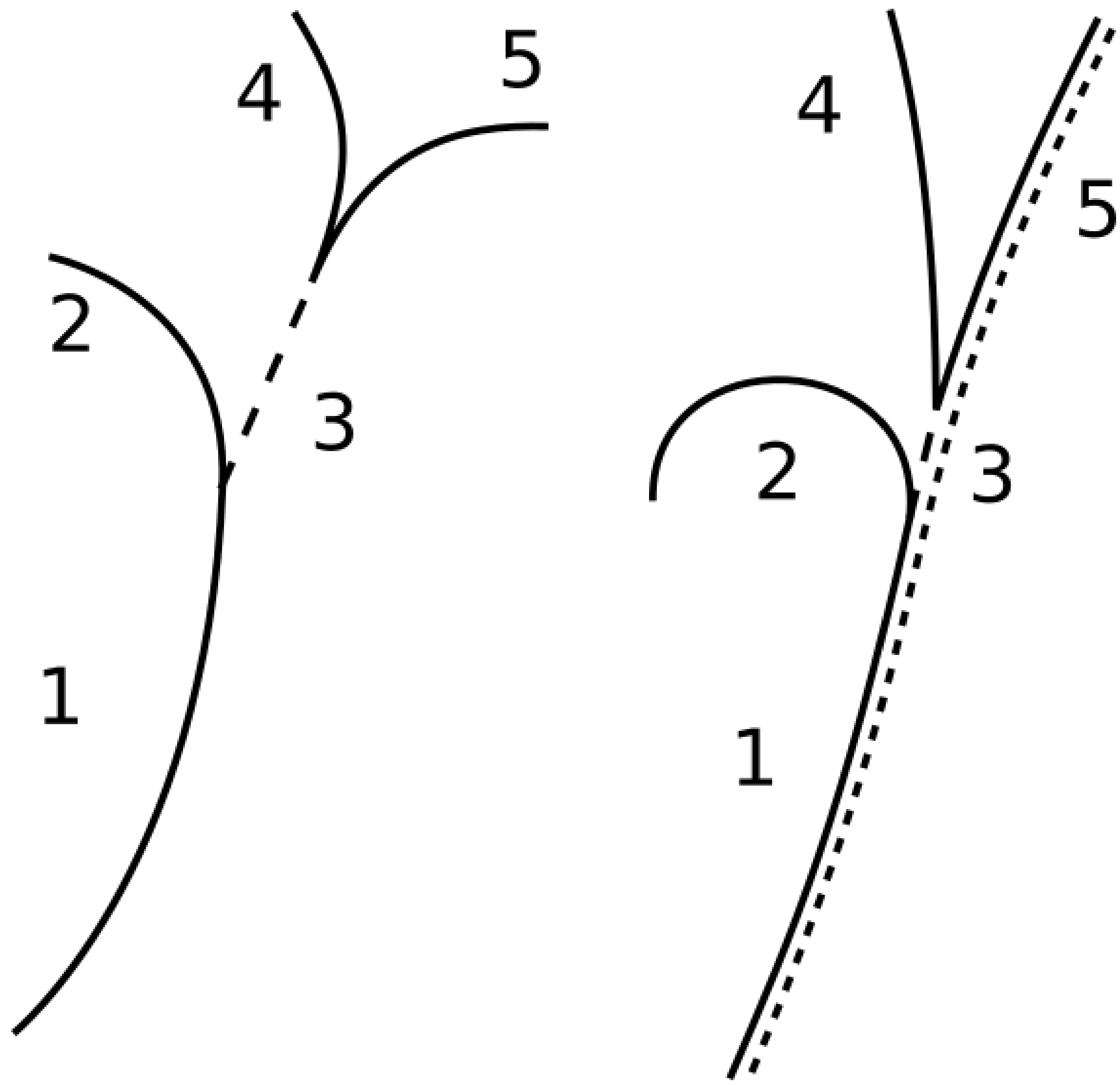




arXiv:1906.03203

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

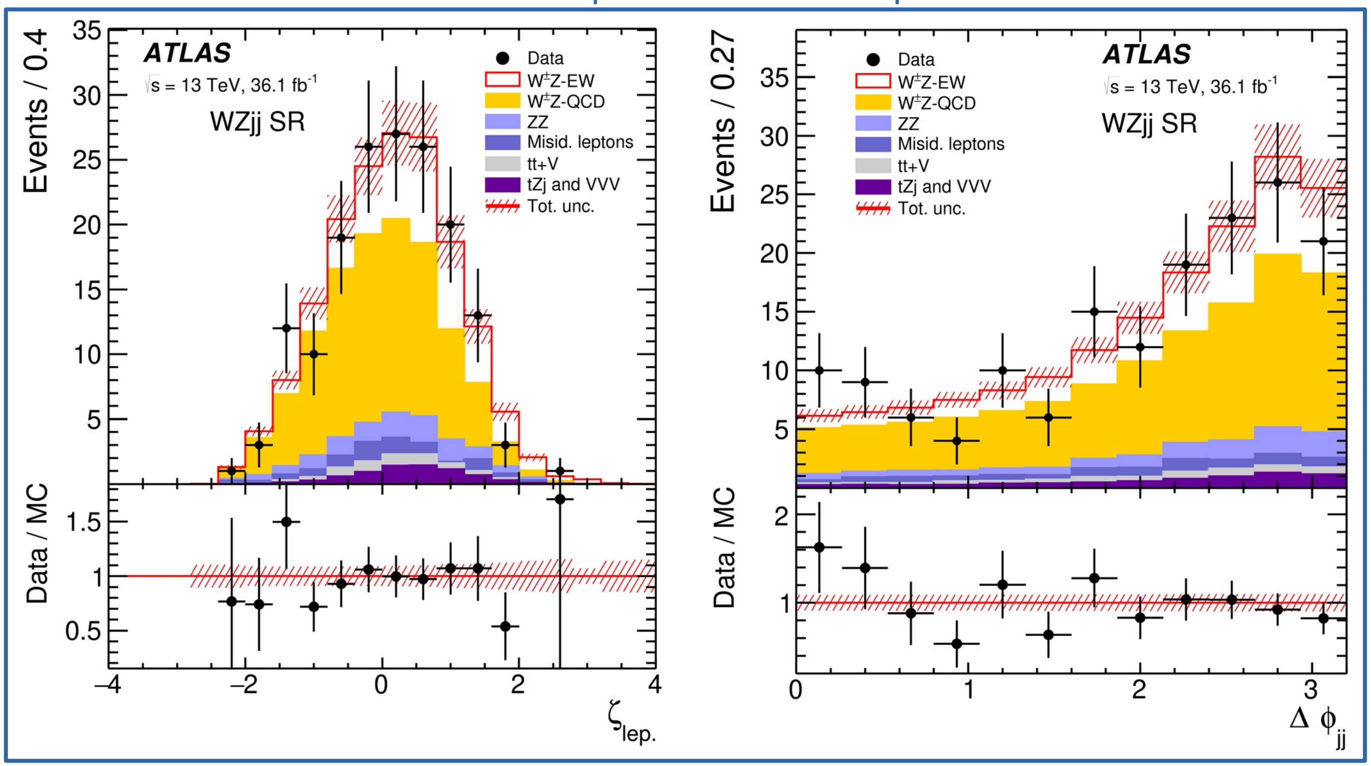


W±Z – VBS "Mix" Channel

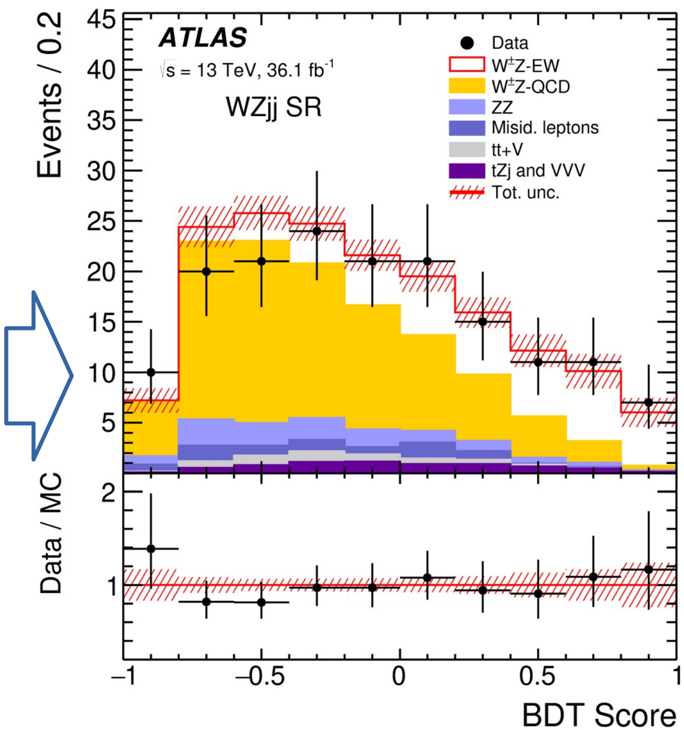
- VBS final state: νℓℓℓ + jj
- Dataset: 36.1 fb^{-1}, 13 TeV
- Expected significance: 3.2 σ
- MVA: TMVA BDT, 15 variables
- W and Z reconstruction using Resonant Shape algorithm

- Fourth lepton veto
- 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±Z – Results

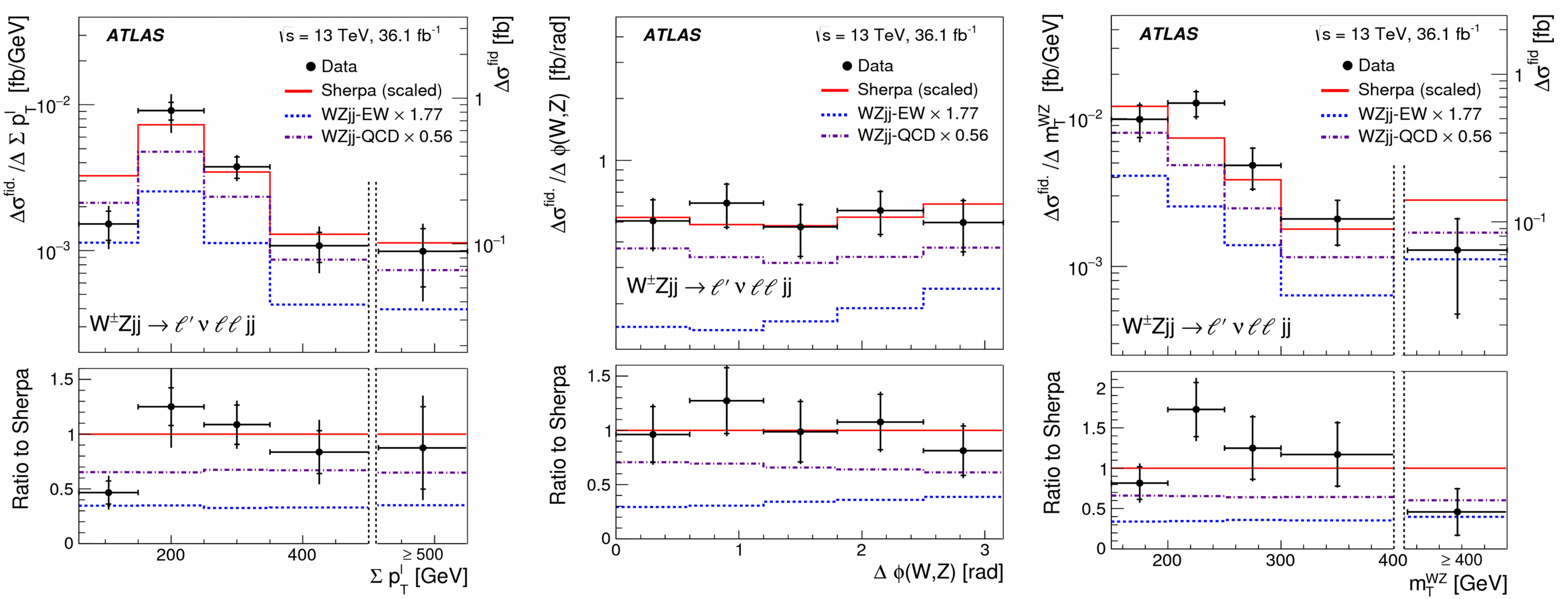
- EW Signal strength

$$1.77^{+0.44}_{-0.40}(\text{stat.})^{+0.26}_{-0.21}(\text{syst.})$$

- 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
  - Inclusive fiducial phase space (EW + QCD)



Resonant Shape Algorithm

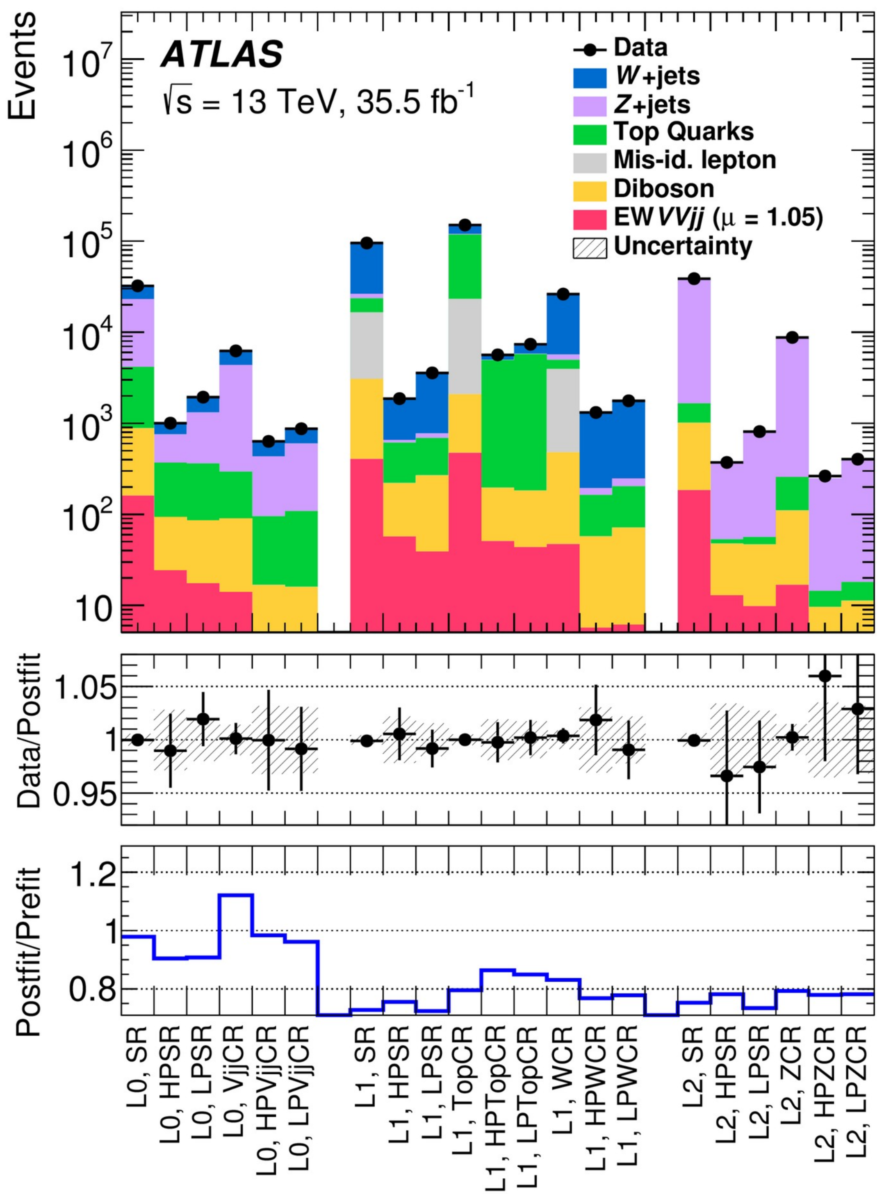
- Event MC generators do not always provide full information
  - Huge amount of events
  - Storage consumption
- Used for WZ VBS channel arXiv:1603.02151
- Based on value of the following estimator

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

- 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

VV Semi-leptonic – VBS "Jet" Channel

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



arXiv:1905.07714

VV Semi-leptonic – Results

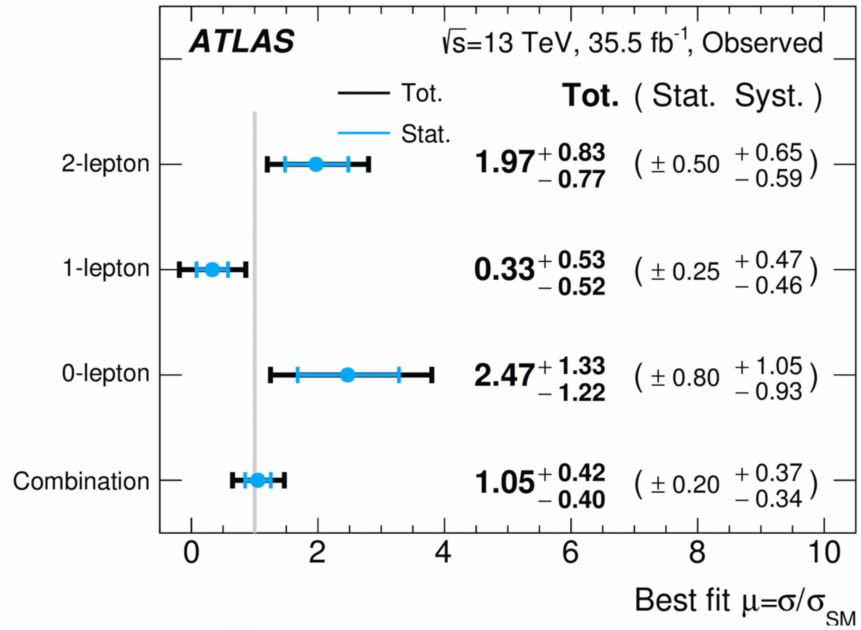
- EW signal strength

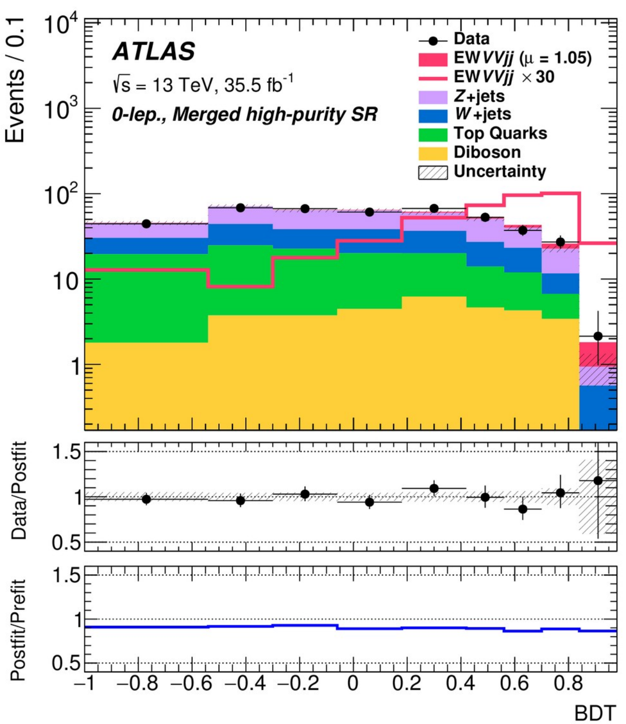
$$1.05^{+0.20}_{-0.20}(\text{stat.})^{+0.37}_{-0.34}(\text{syst.})$$

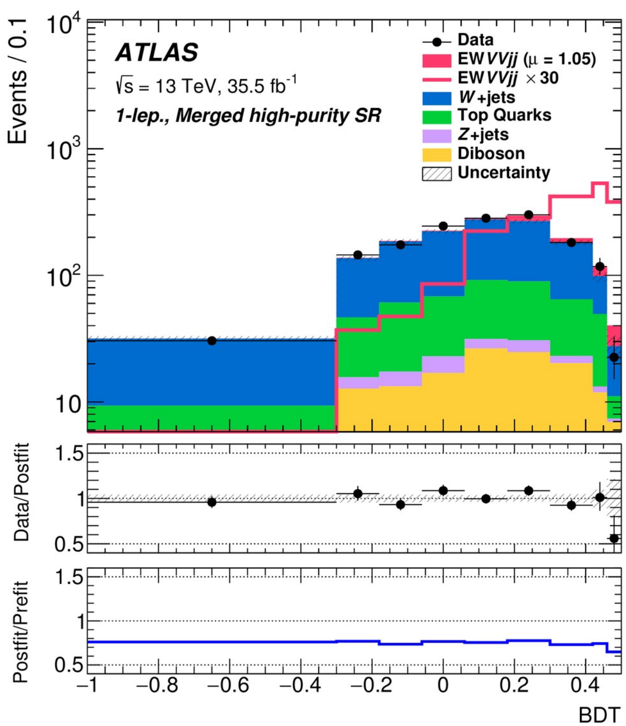
- Background only hypothesis rejected with significance 2.7 σ (expected 2.5 σ)
- EW fiducial cross-section

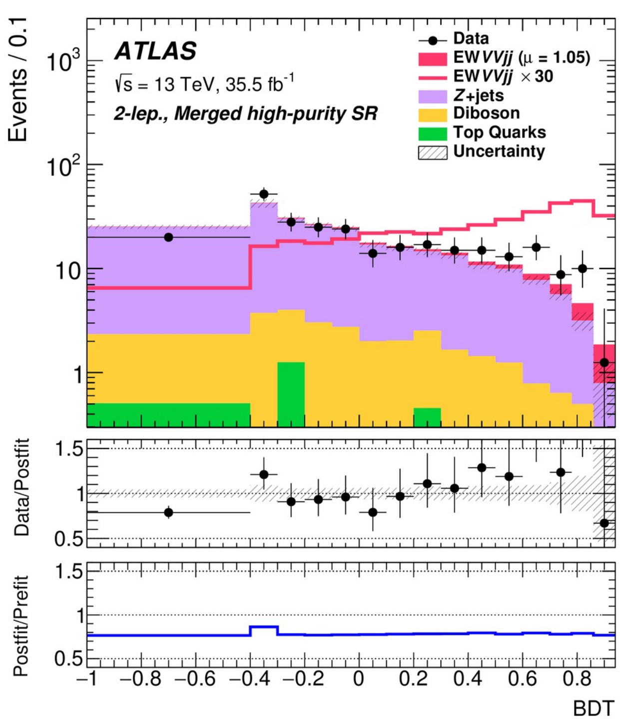
$$45.1^{+8.6}_{-8.6}(\text{stat.})^{+15.9}_{-14.6}(\text{syst.})\,\text{fb}$$

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







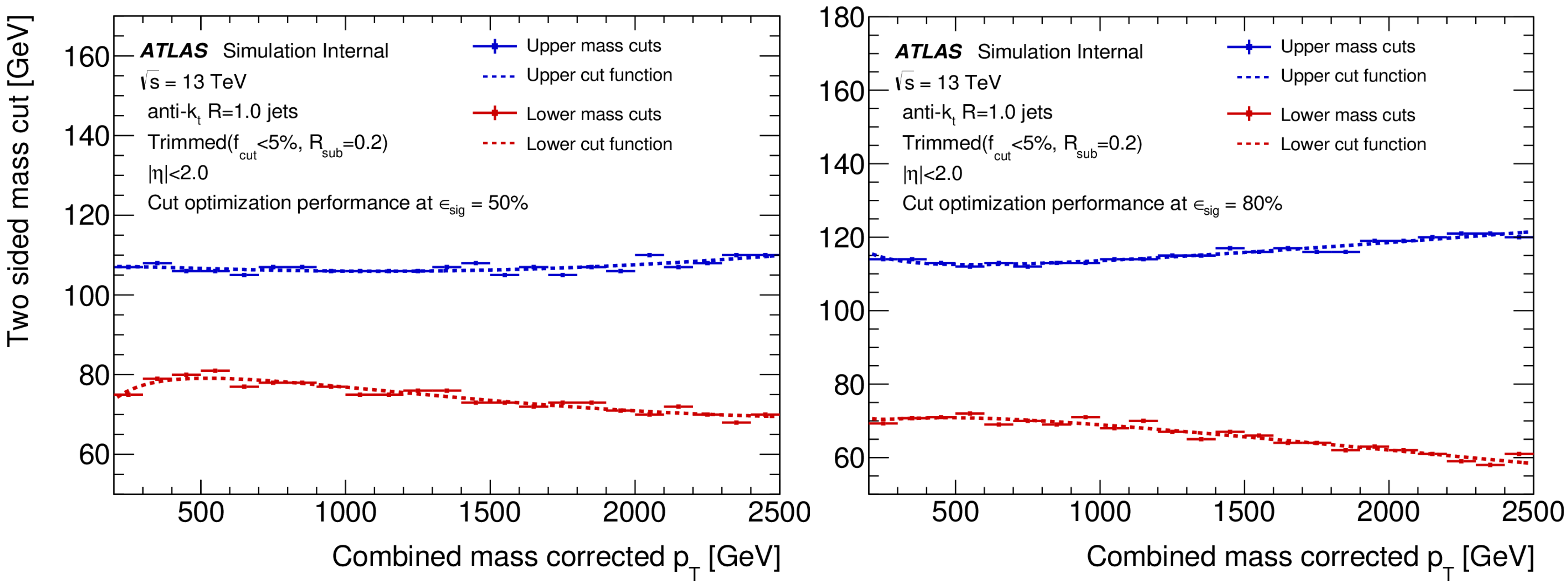


arXiv:1905.07714

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

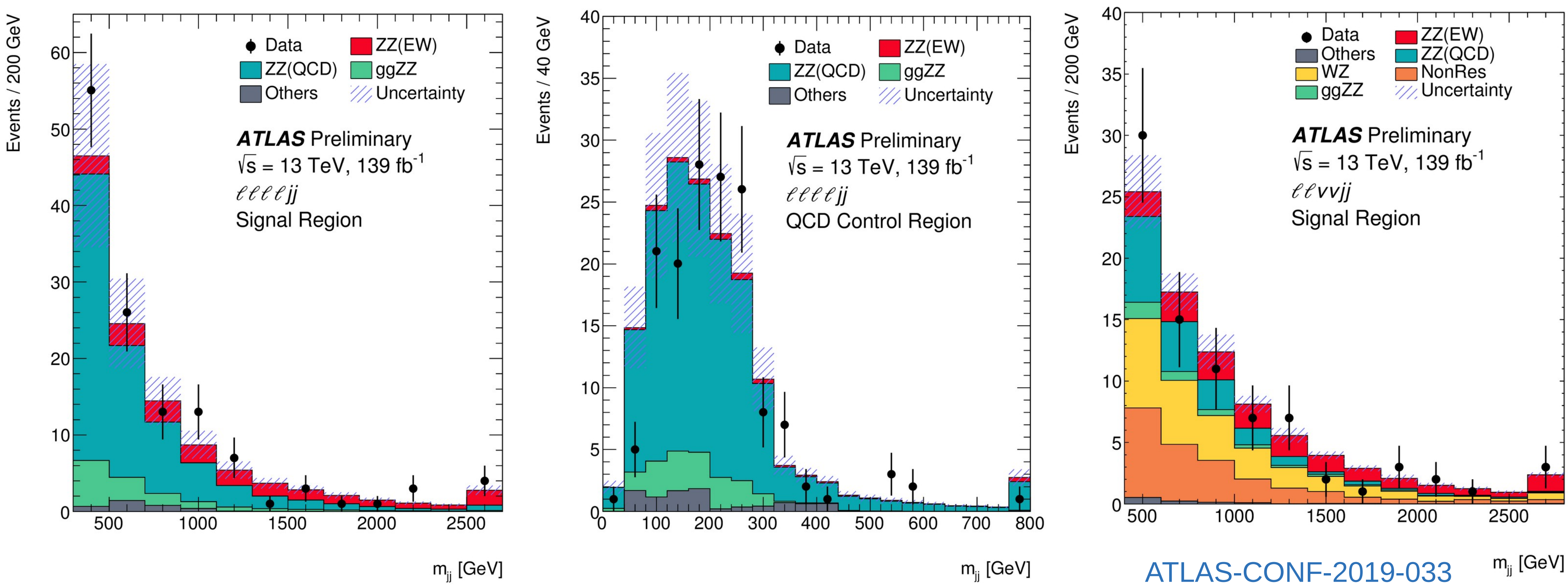
ZZ VBS analysis

ZZ – VBS “Golden” Channel

NEWEST RESULT!

- VBS final states: ℓℓℓℓ + jj, ννℓℓ + jj
- Dataset: 139 fb^{-1}, 13 TeV
  - First VBS analysis of full Run 2 of LHC
- Expected significance: 4.3 σ
- MVA: TMVA Gradient BDT, 14 variables
- 2 signal regions, 1 control region (only ℓℓℓℓ)

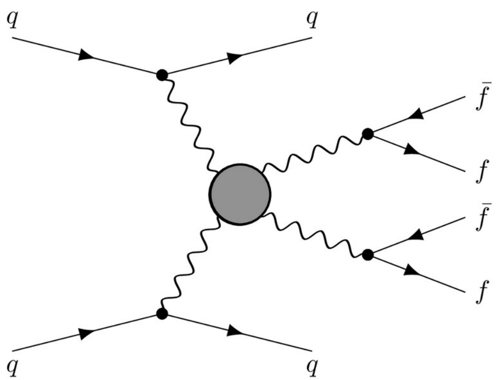
- Background
  - ℓℓℓℓ
    - Dominant: ZZ+jets (QCD)
    - Otherwise very clean channel (3%): misidentified leptons, Z+jets, $t\bar{t}$, WZ+jets
  - ννℓℓ
    - Dominant: ZZ+jets (QCD), WZ+jets, WW+jets
    - $t\bar{t}$, Z+jets



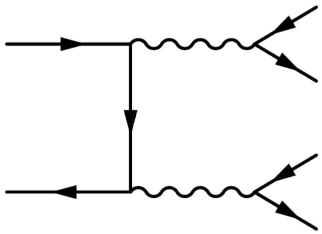
ATLAS-CONF-2019-033

Analysis Overview

Physics



ZZ - VBS



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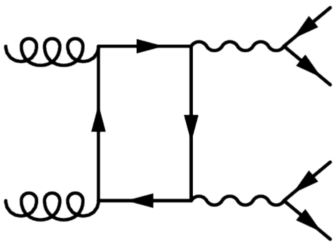


ggZZ

Selection

VBS pre-selection
- ZZ
- Dijet (A/C detector side)
  - Mass, jet delta rapidity

Background estimation

MVA
- Signal/Background
- EW/QCD
- BDTG
- 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

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

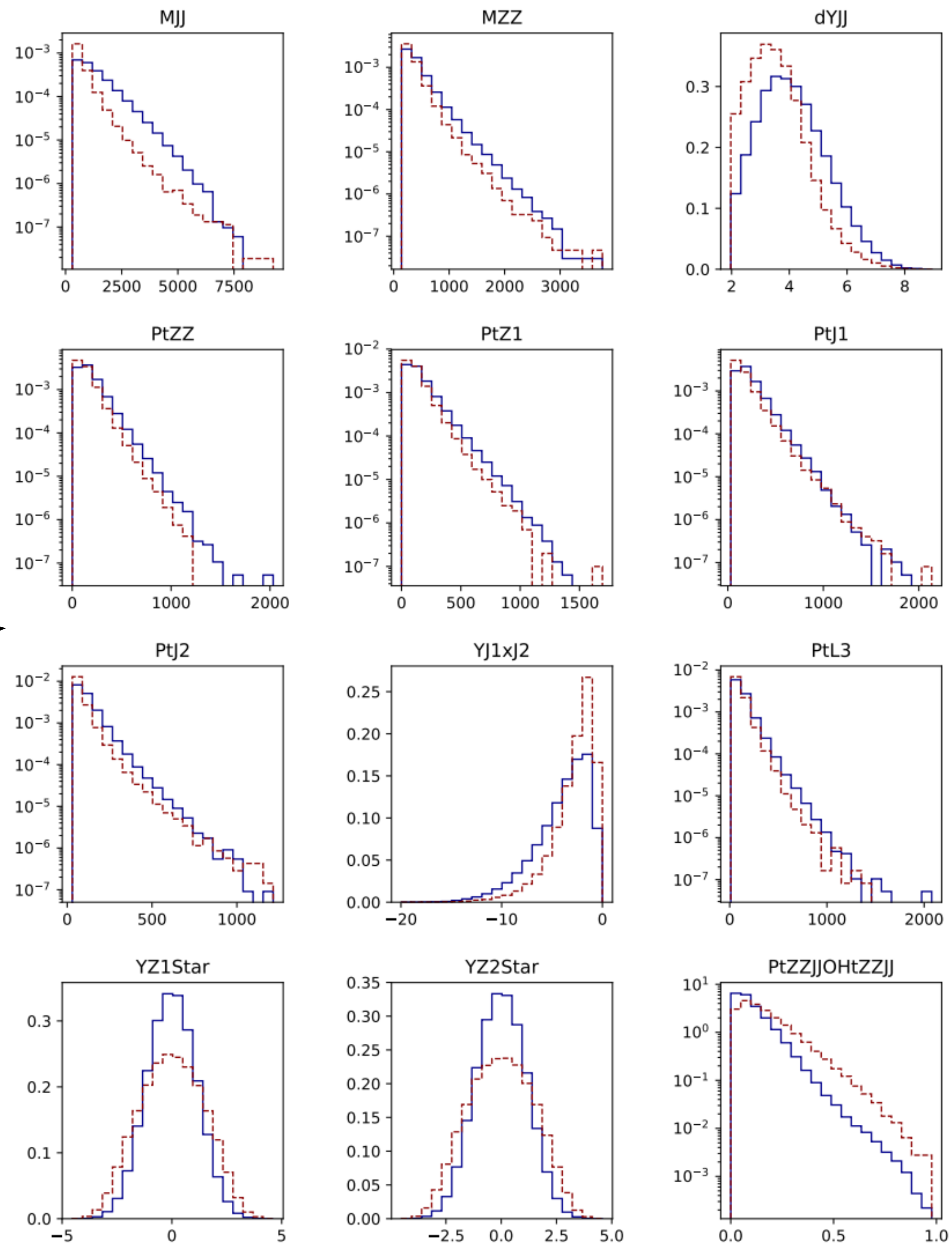
- Quadruplet building SFOC pairs
- Hierarchical p_T cut (20, 20, 10, 7 GeV)
- Quarkonia veto $m_{ll} > 10$ GeV
- <2 CaloTagged or StandAlone muons
- 66 GeV < m_{ll} < 116 GeV

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

•Multivariate analysis (ℓℓℓℓ)

- Multivariate analysis
  - ROOT
- Variables
  - 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
- Comparison
  - Signal vs background



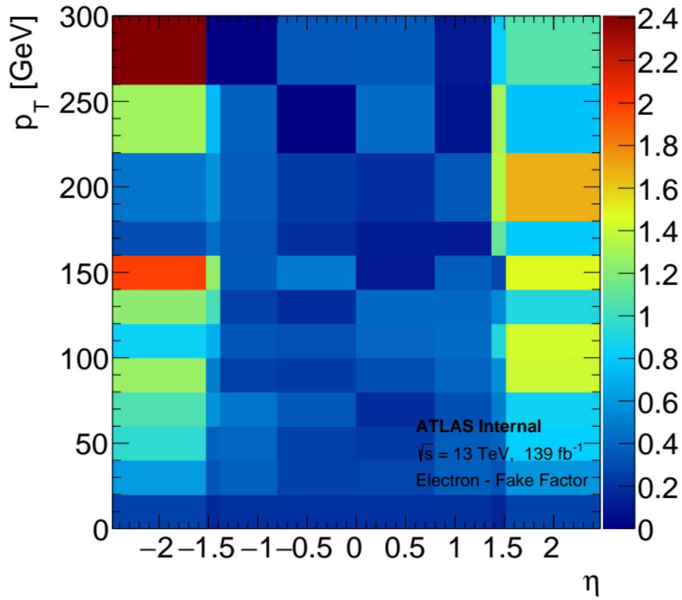
- Boosted decision trees
  - Decision trees
  - Ensemble of trees
  - Gradient Boosting
    - Weak learner
    - Optimal classifier
    - Learning suppression
    - Sum of decisions of all trees

Yields and Background (ℓℓℓℓ)

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

- QCD Background
  - qqZZ and ggZZ
    Dedicated control region
    - $|\Delta y_{jj}| < 2$
    - $m_{jj} < 300$ GeV
- Prompt
  - $t\bar{t}Z$, 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
    - Using loosening of particular 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



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)

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

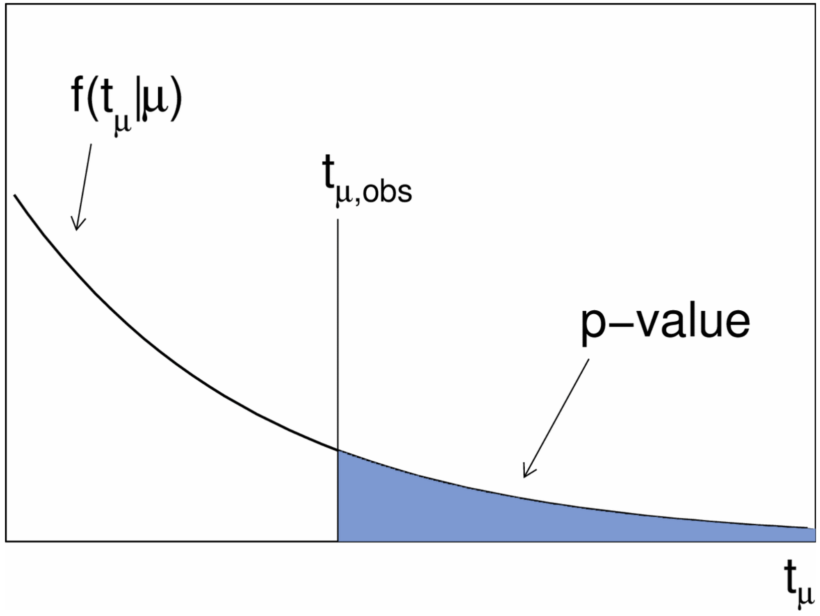
  - Data-hypothesis discrepancy

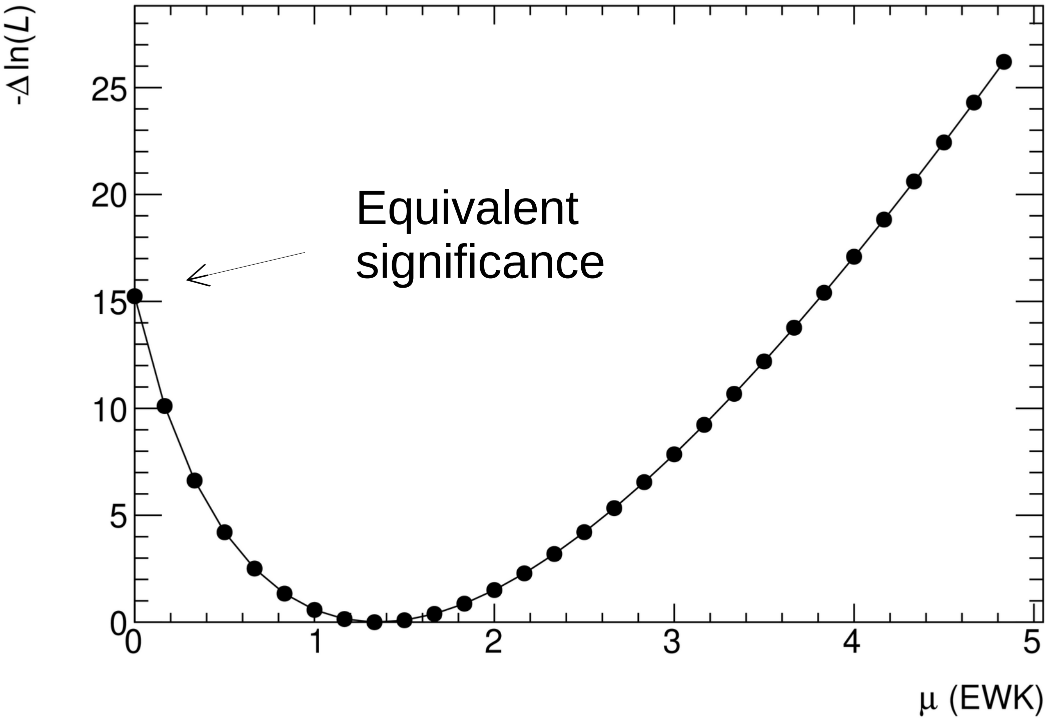
Profile likelihood ratio

- 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

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

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





ZZ Channels

- Comparison of contributions from ℓℓℓℓ and ννℓℓ channels

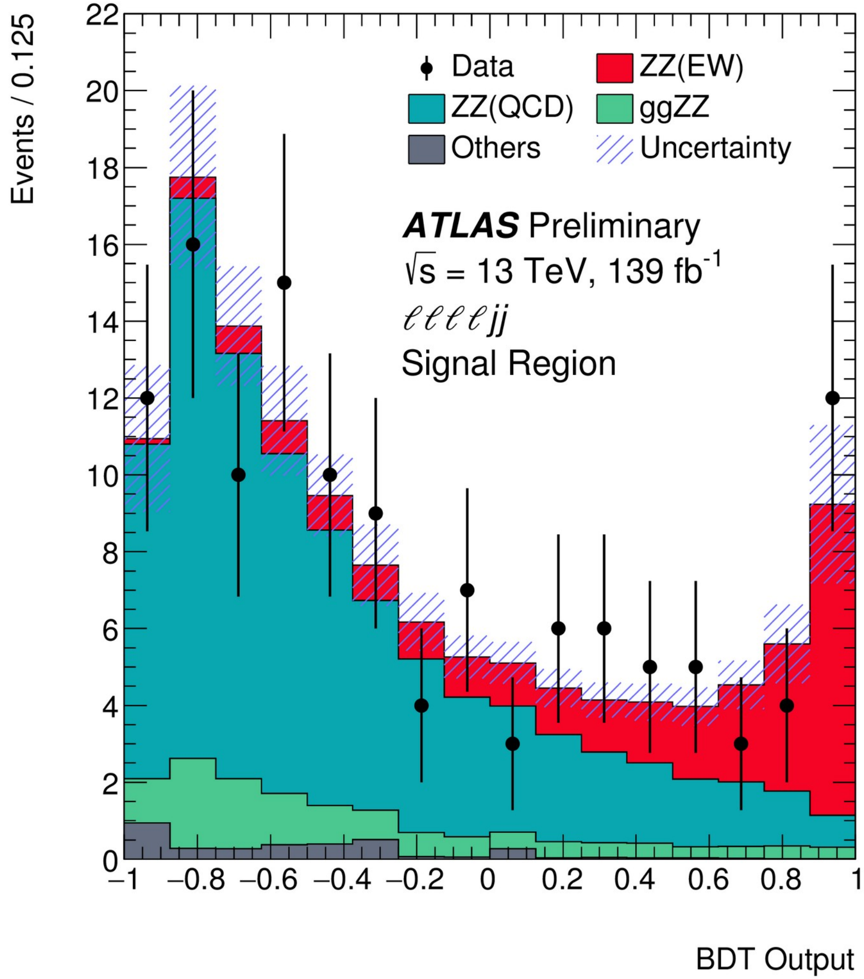
	μ_{EW}	$\mu_{\text{QCD}}^{\ell\ell\ell\ell jj}$	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	1.5 ± 0.4	0.95 ± 0.22	5.48 (3.89) σ
$\ell\ell\nu\nu jj$	0.7 ± 0.7	fixed	1.15 (1.80) σ
Combined	1.35 ± 0.34	0.96 ± 0.22	5.52 (4.29) σ

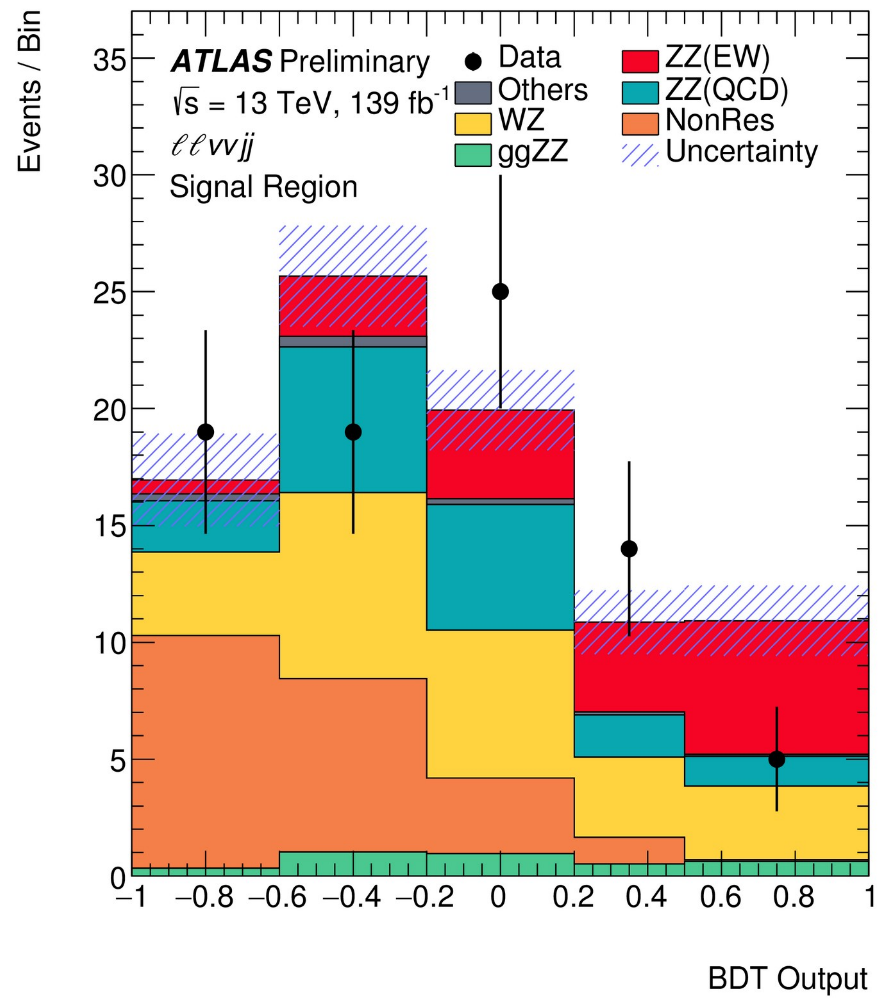
- Two-lepton channel not as lucky as four-lepton
  - Two-lepton contributes to the expectation though
  - Makes analysis more "safe"
  - We were blinded at the beginning

	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

ZZ – Results

- EW signal strength 1.35 ± 0.34
- Background only hypothesis rejected with significance 5.5 σ (expected 4.3 σ)
- EW fiducial cross-section $0.82 \pm 0.21\,\text{fb}$
- ZZjj EW production **observed**

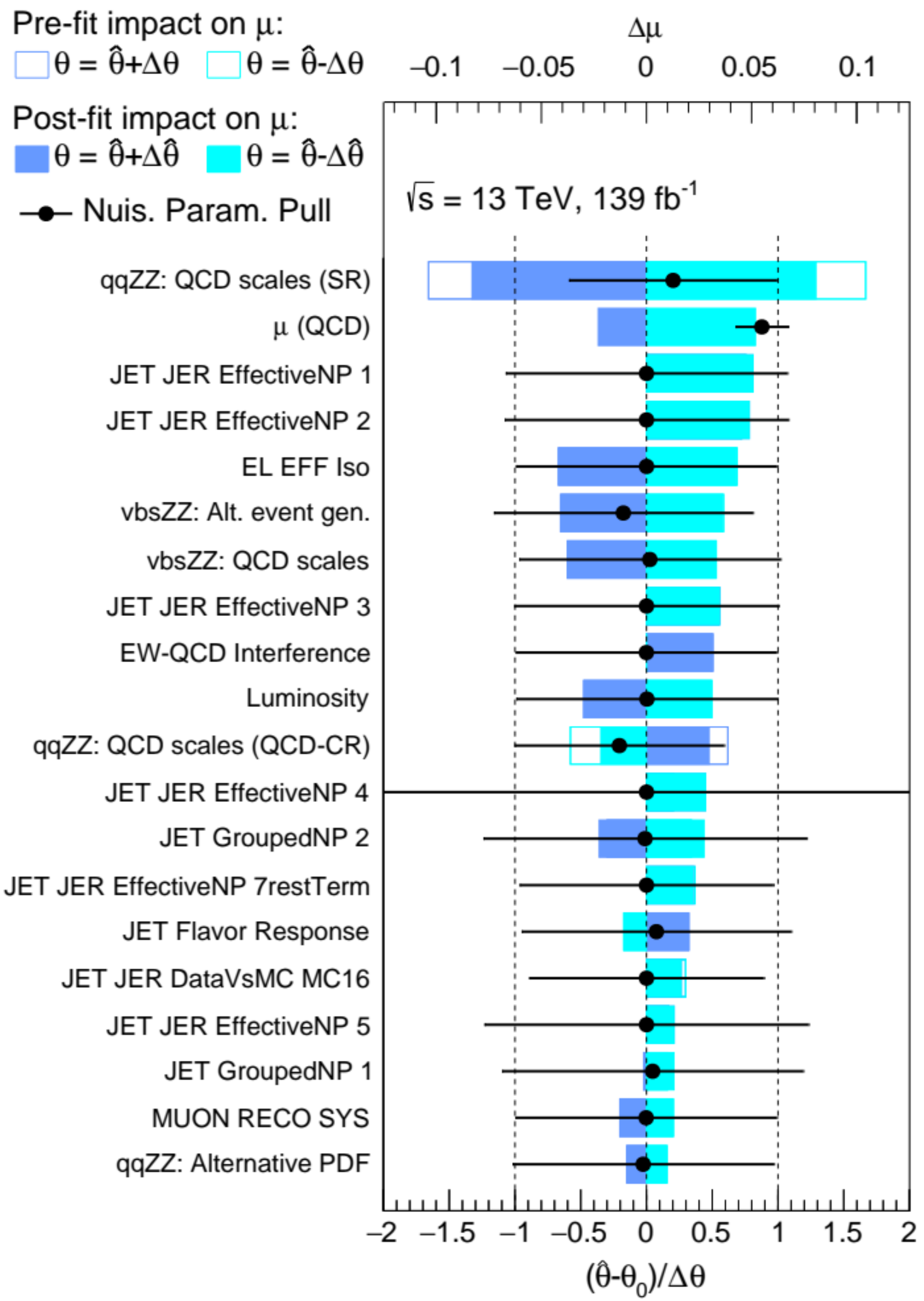




ATLAS-CONF-2019-033

Uncertainties

- The measurement is overall dominated by statistical uncertainty
  - Accounts for 88% of the total uncertainty
- Systematic uncertainty is dominated by the theory component
- 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%



ZZ Paper

- Conveners said
  - Nice result
  - Choose a journal
- We randomly picked one :-)

- Politically interesting choice
  - General afraid: what if we would be rejected
  - Is the channel better than the others, studied by the collaboration

- Still in review
  - Stuck at modeling of the QCD background prediction in Powheg
  - Alternative to Sherpa

Not reviewed, for internal circulation only

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

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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