Observation and Measurements of Vector-Boson Scattering at the ATLAS Detector

Workshop EJČF 2020

Bílý Potok (u Frýdlantu)
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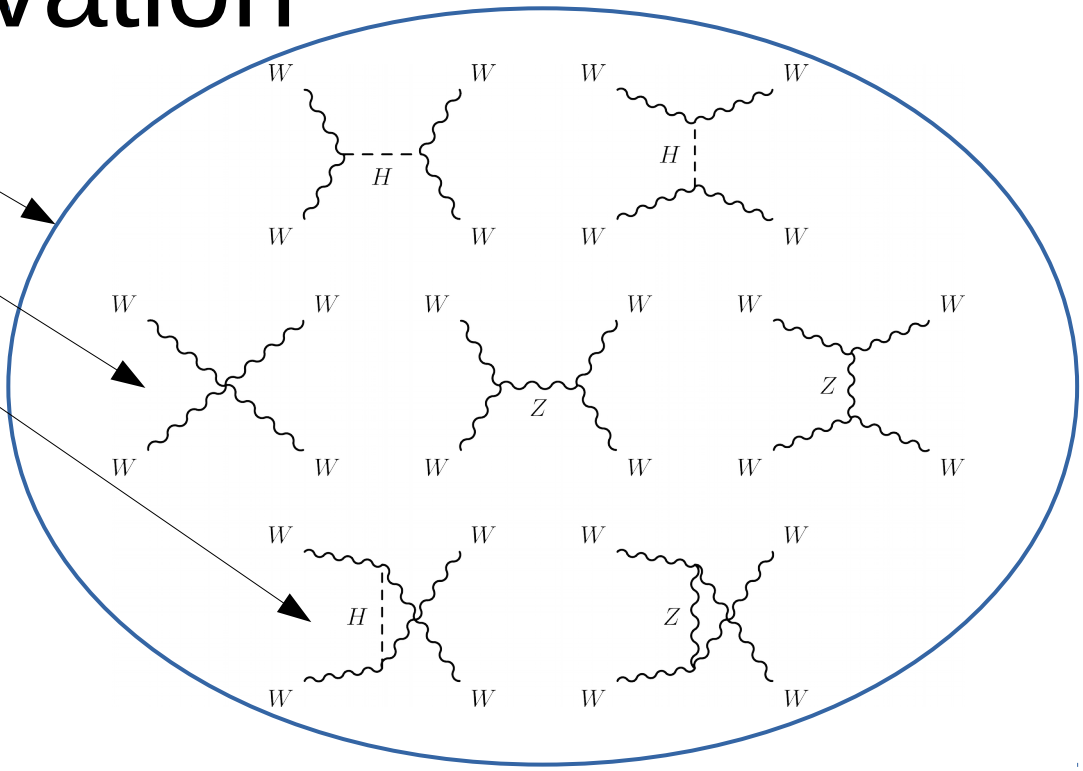
Ondřej Penc
ondrej.penc@cern.ch

on behalf of ATLAS Collaboration

Motivation

Vector boson scattering (massive bosons)

- Test of Standard Model (SM) gauge structure
- QGC becomes accessible (i.e. WWWW)
- Better understanding of the nature of EWSB mechanism since involves Higgs boson
- BSM anomalous QGC limits

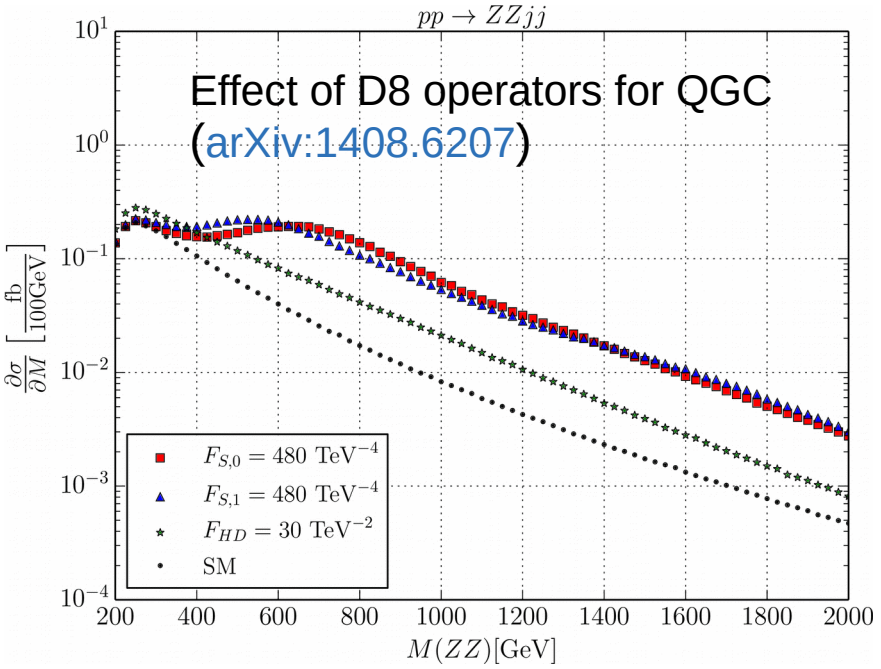


- VBS as Goldstone boson scattering (Goldstone Boson Equivalence Theorem)
  - W± and Z bosons acquire mass spending three Goldstone bosons (angular fields)
  - Parametrisation of weak isodoublet (a = 1,2,3)

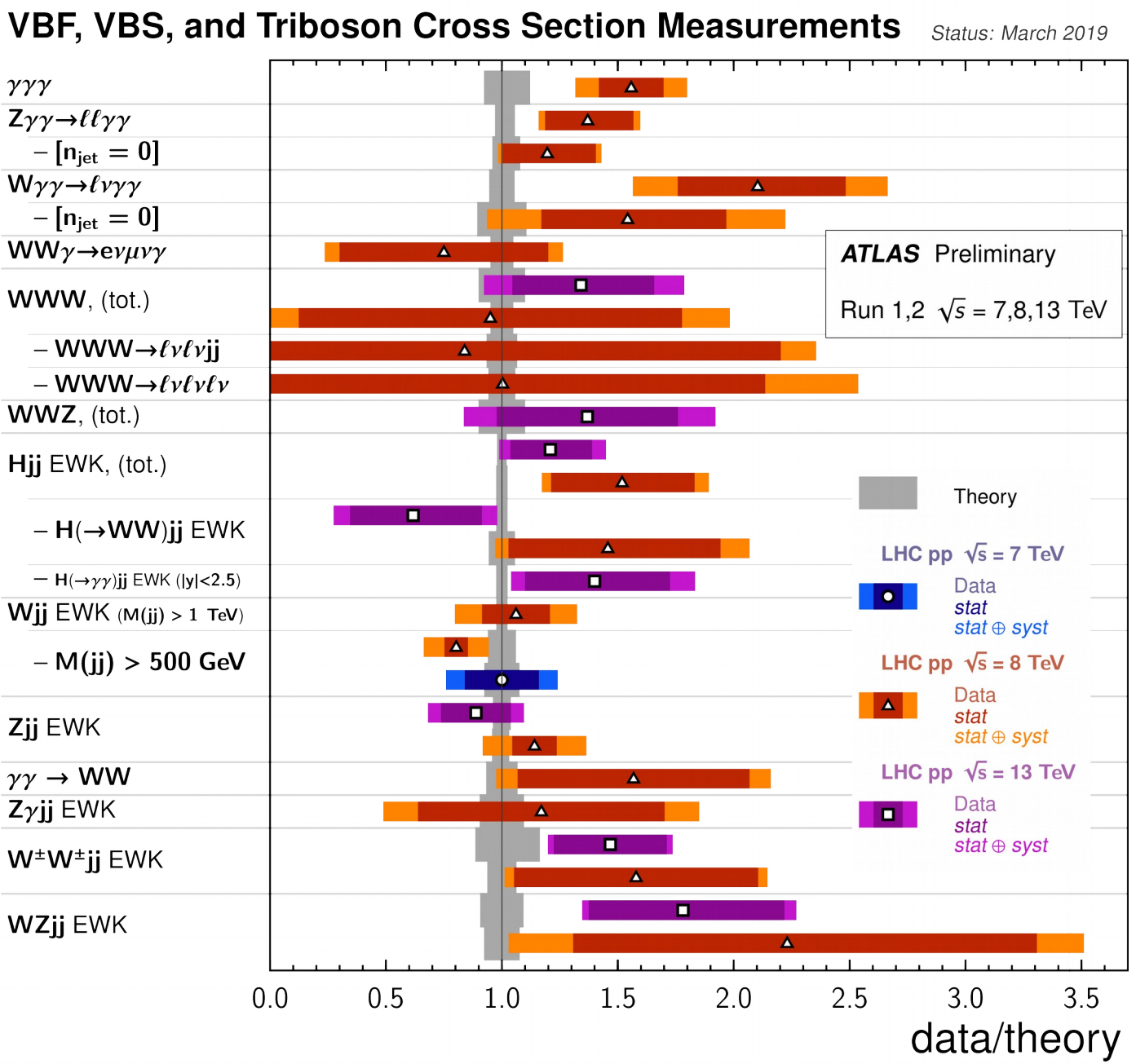
$$\Phi(x) = \exp\left(\frac{i}{v}\pi^a(x)\tau^a\right)\begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v + H(x)) \end{pmatrix}$$

- Effective field theory
  - Addition of higher order operators to SM
  - SM as the limit case of the new model
  - Scales beyond the reach of the LHC

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

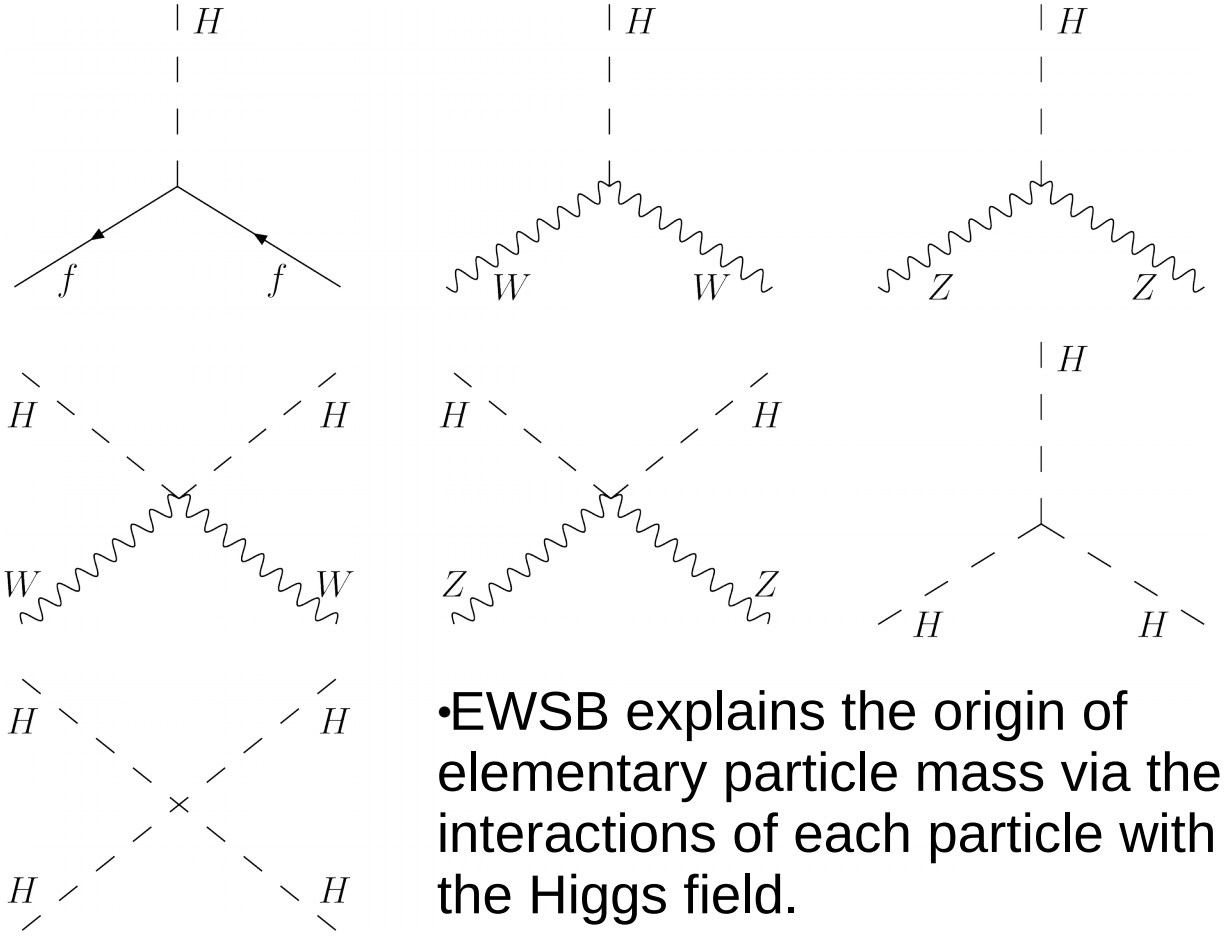


Motivation - Context



Electro-weak symmetry breaking

- Math
  - Generate Higgs
  - Gives mass to electroweak bosons
  - Gives mass to Higgs
  - When the Yukawa interaction employed
    - Gives mass to leptons
- Physics
  - Higgs field gives mass to all elementary particles
  - Through interaction with it
  - Gives mass to Higgs itself
    - Triple and four vertex



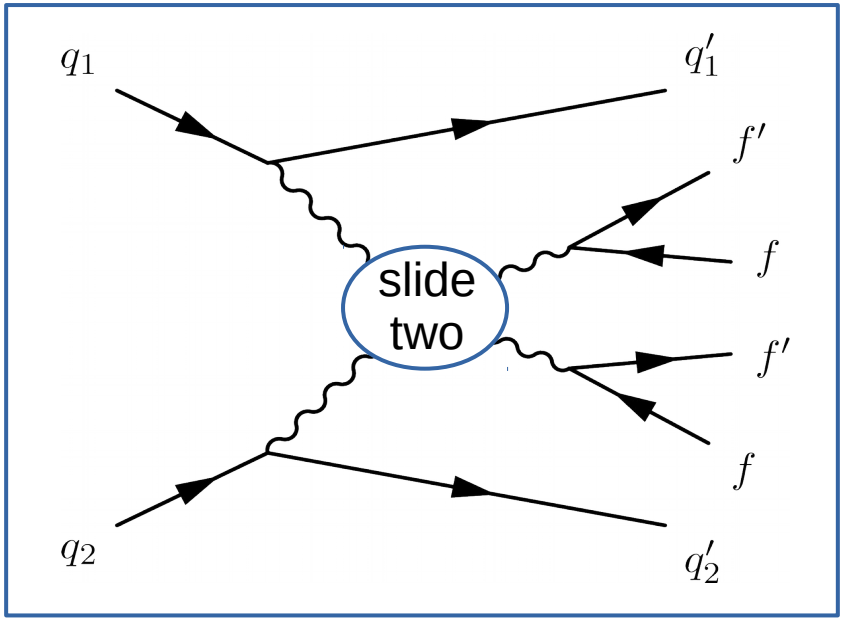
- EWSB explains the origin of elementary particle mass via the interactions of each particle with the Higgs field.

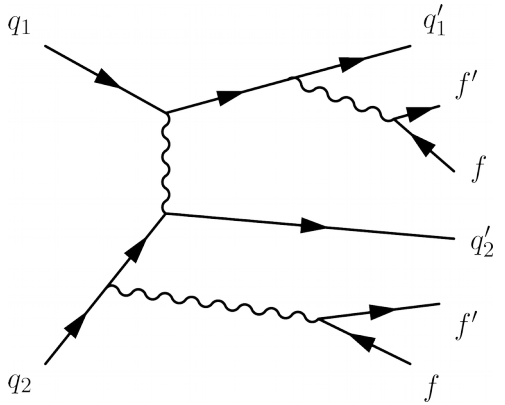
Vector Boson Scattering Diagrams

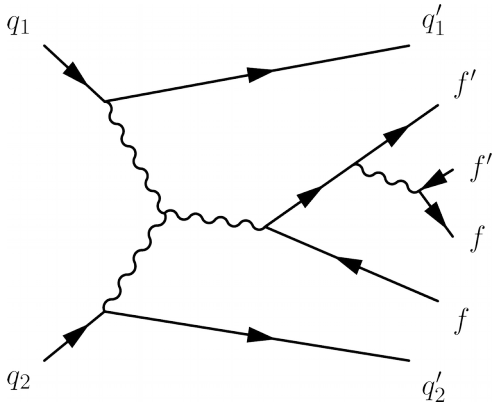
EWK VVjj production

Protons interact electro-weakly

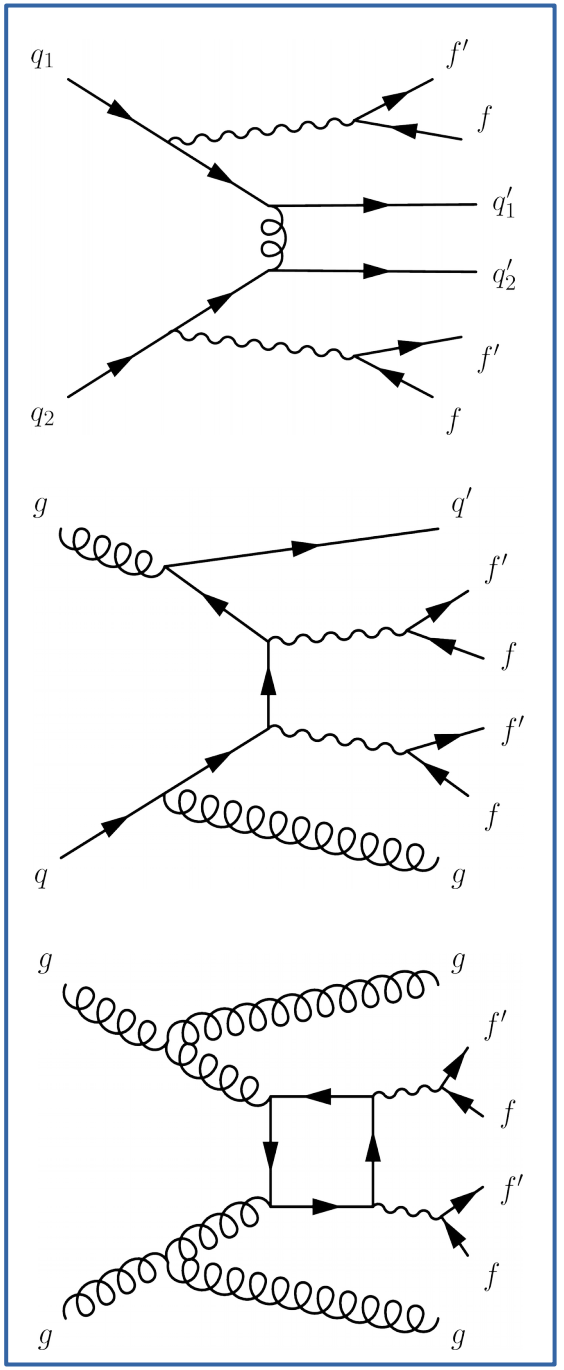
Vector Boson Scattering





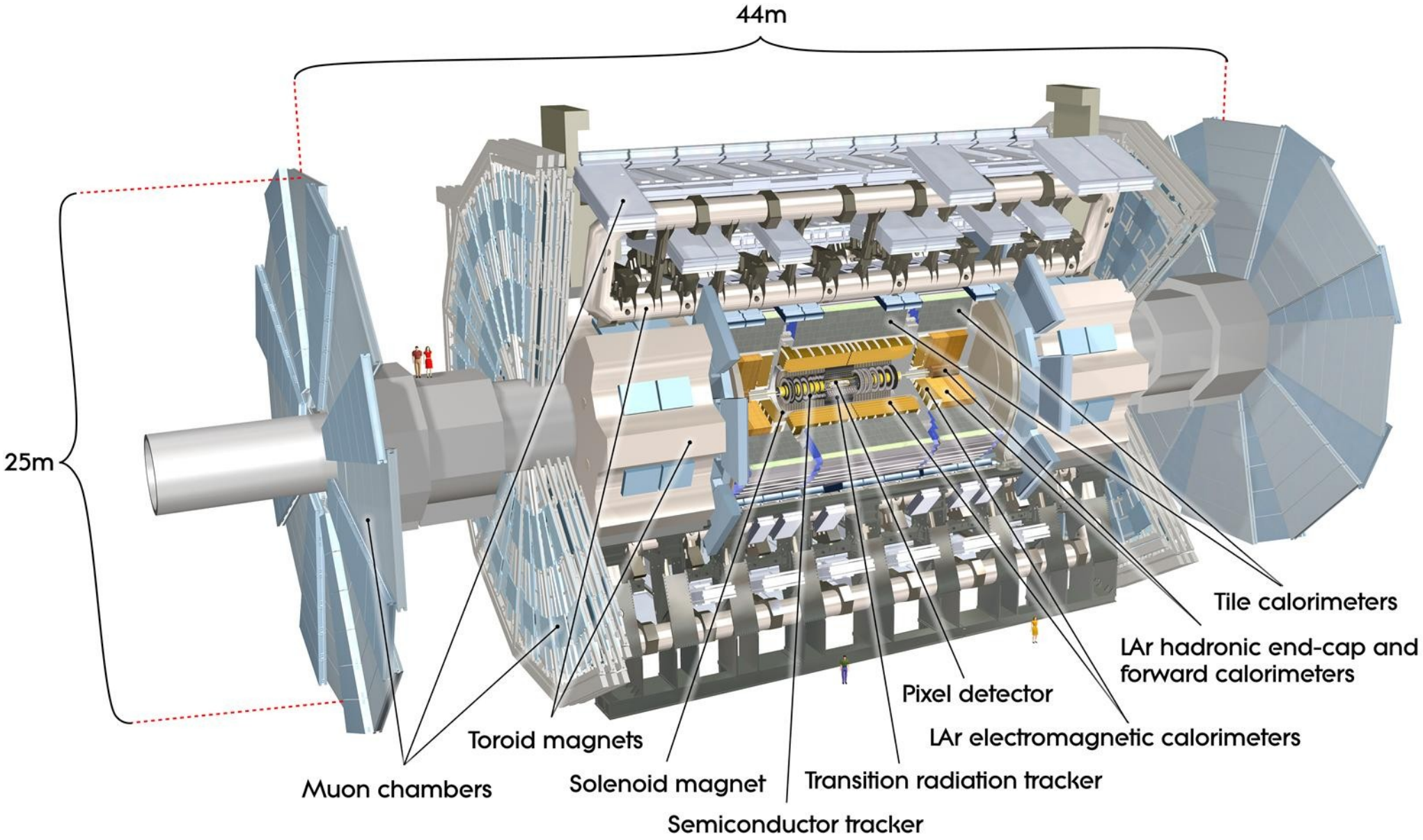


QCD VVjj production



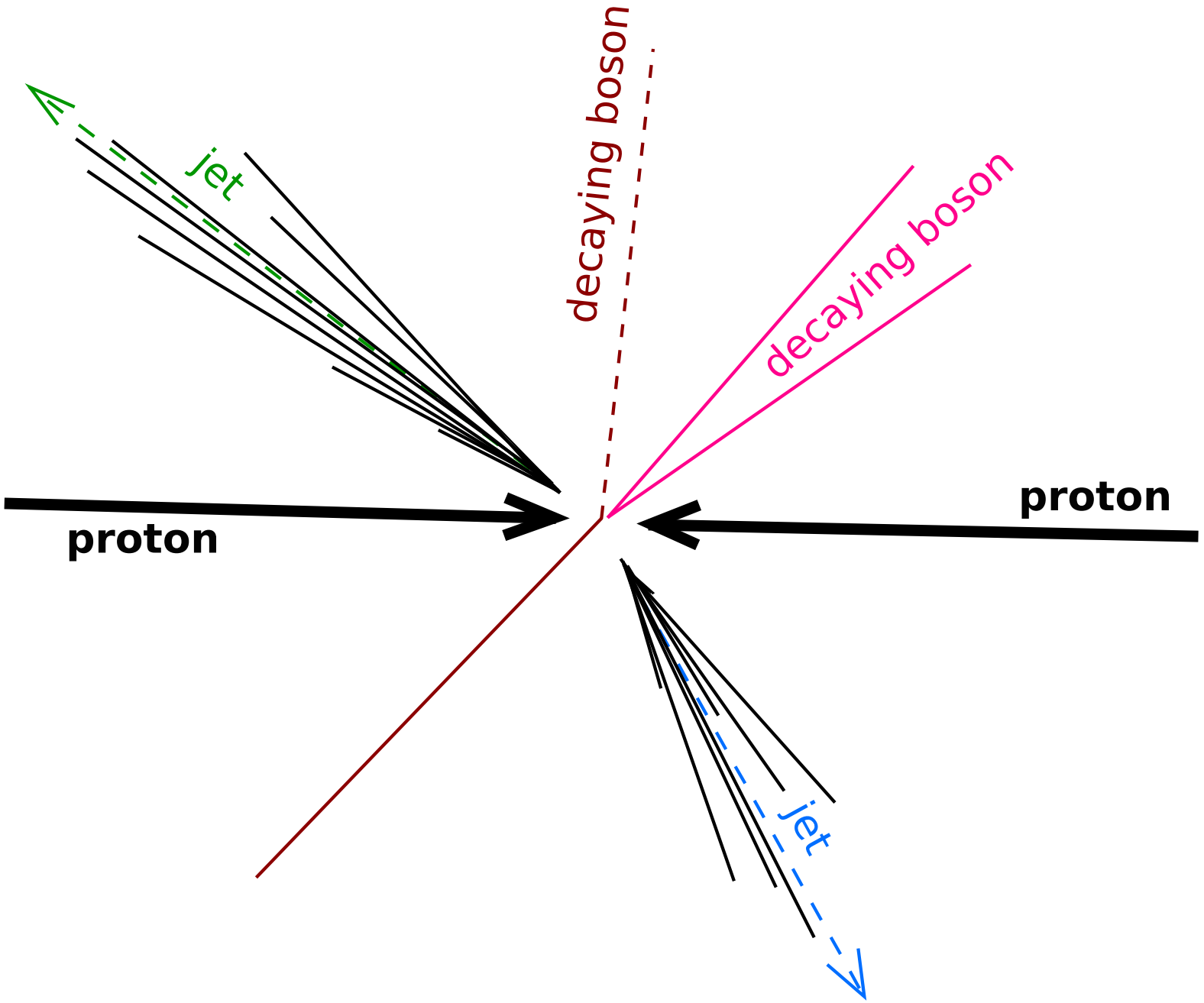
Common VBS selections

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



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
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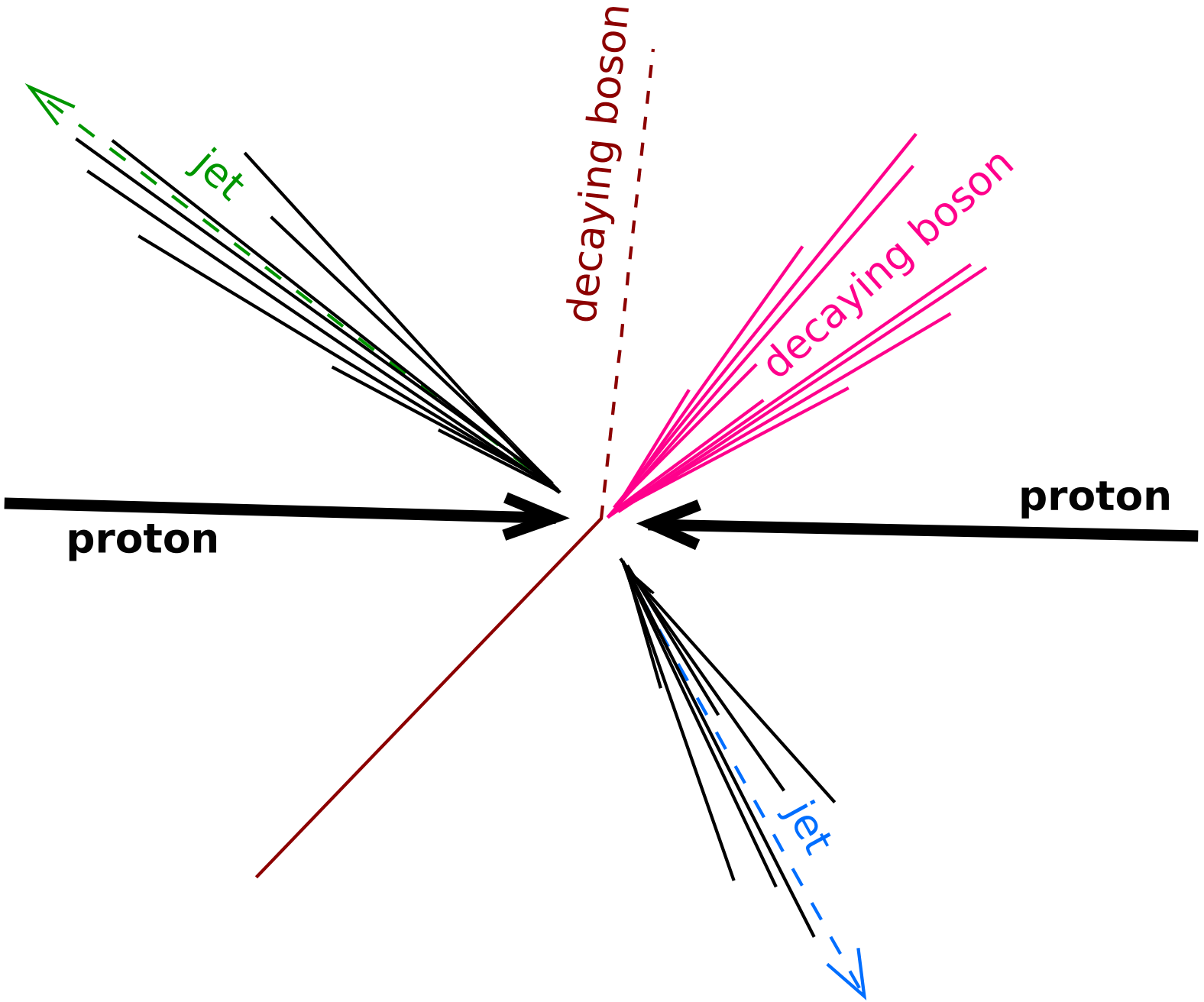
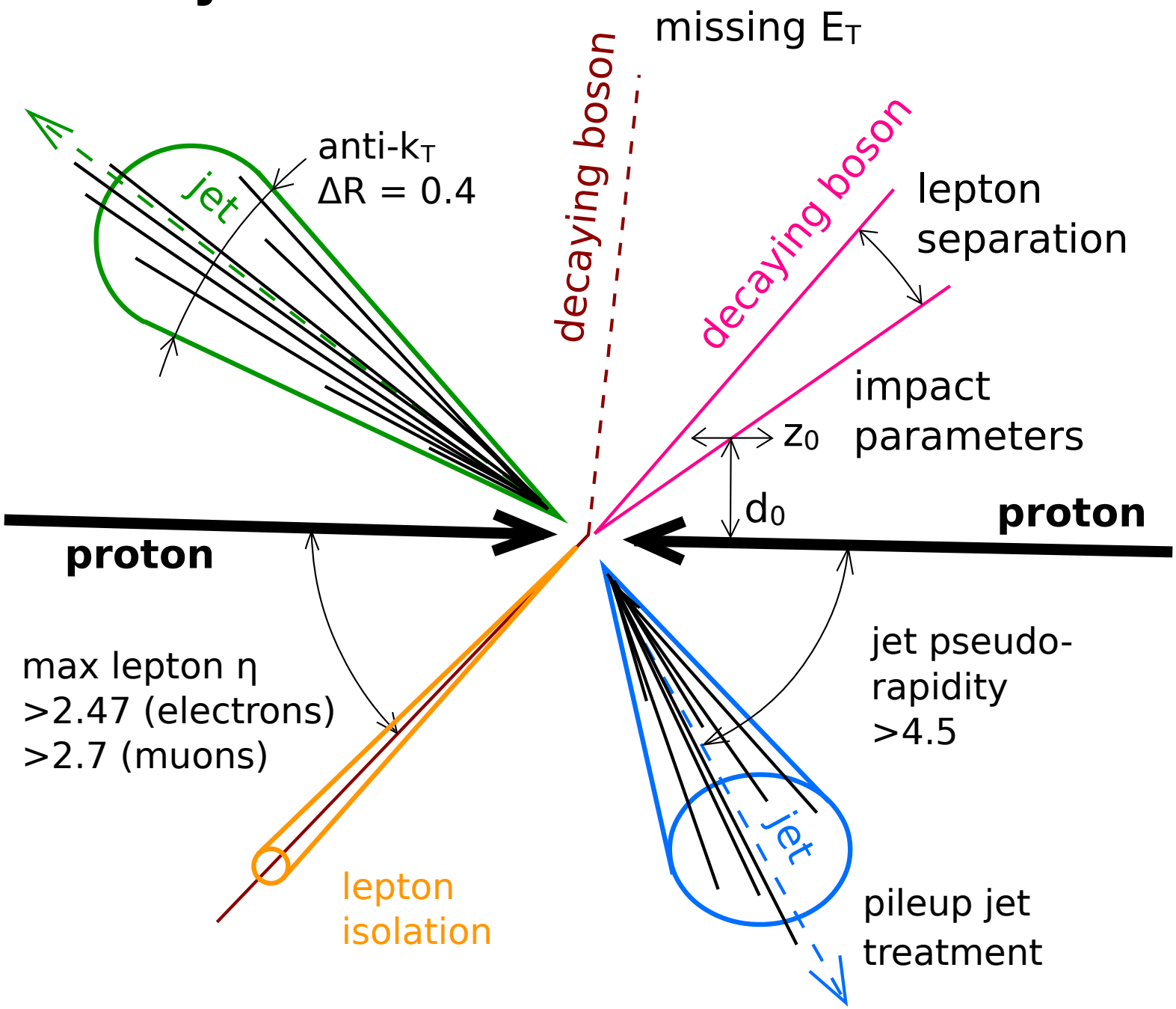


Object Selection

- 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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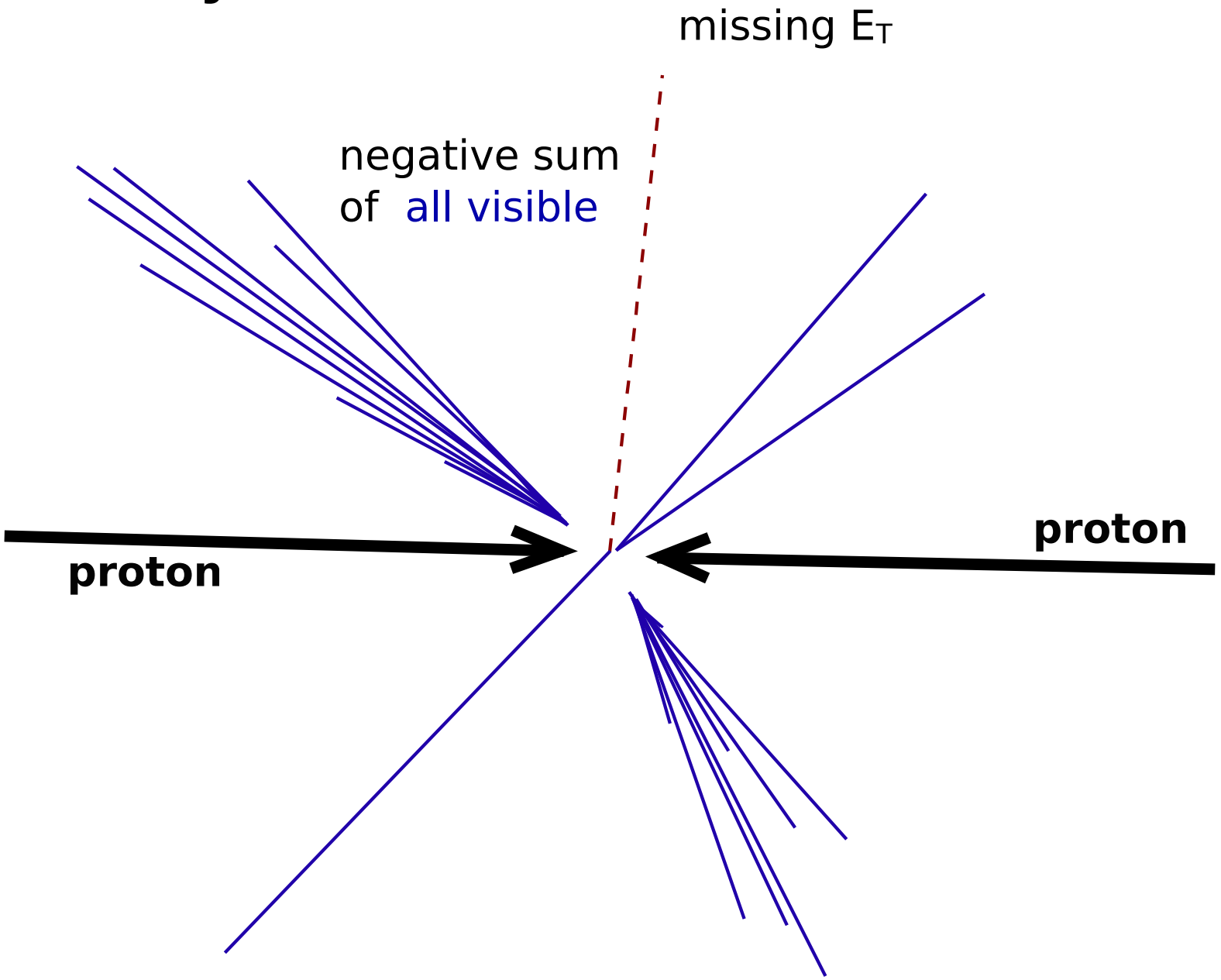
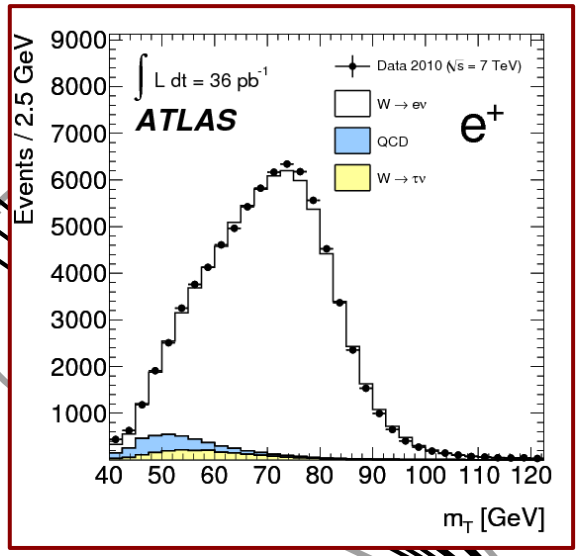


Event Selection

- 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



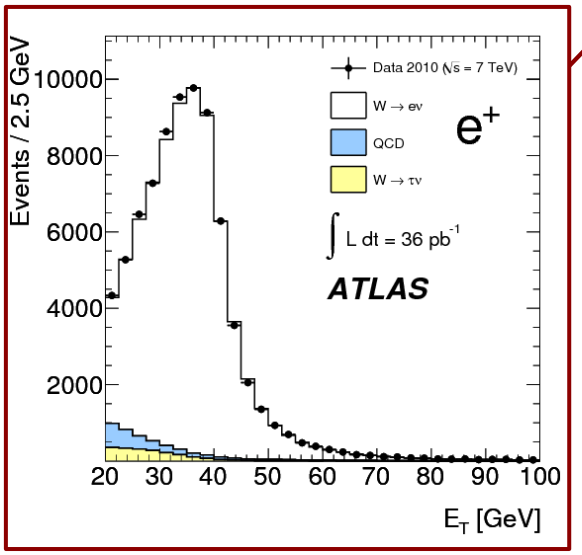
$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi)}$$

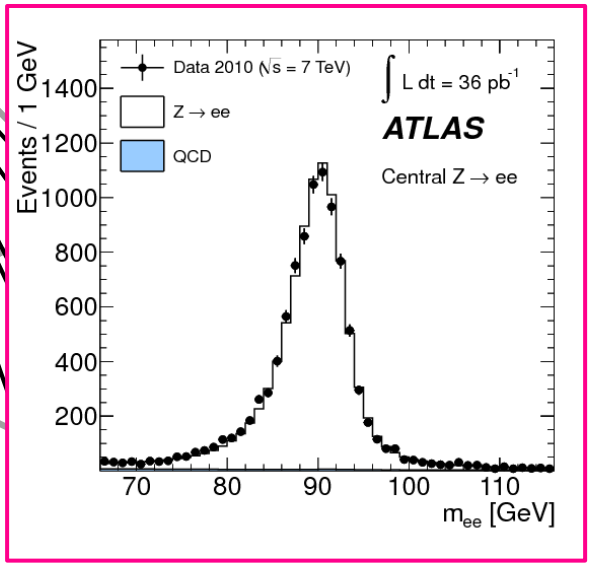
W boson

Z boson

proton

proton





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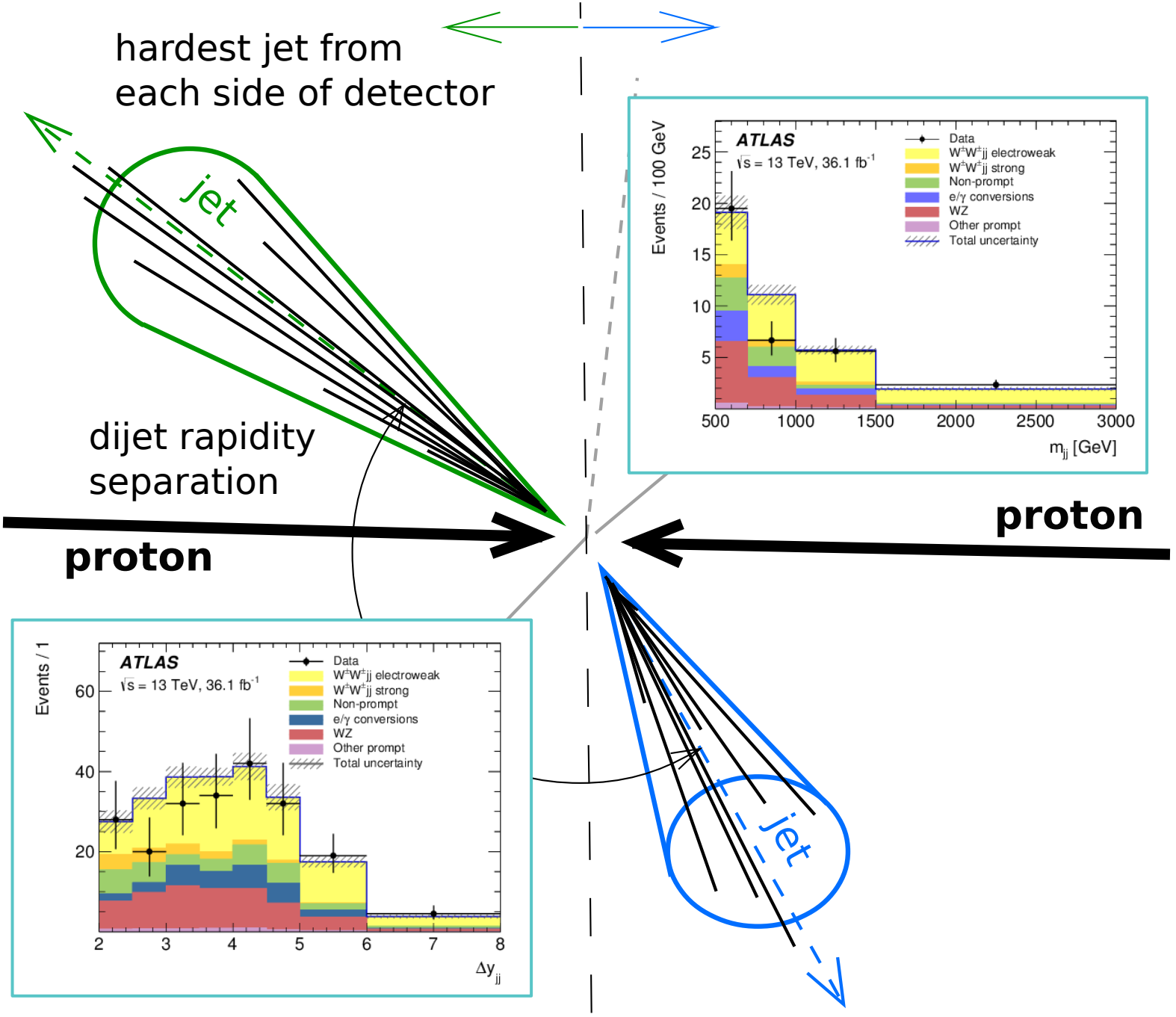
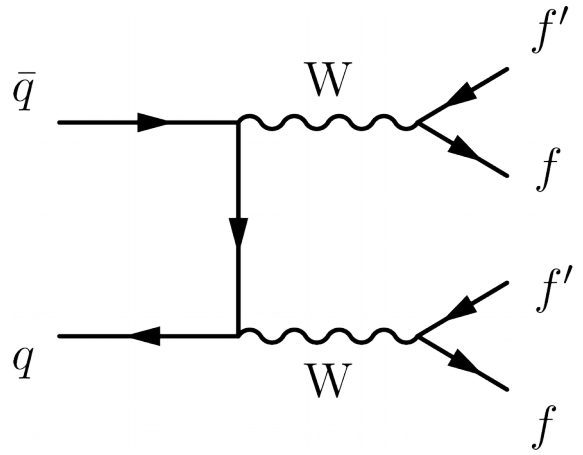


Analyses

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

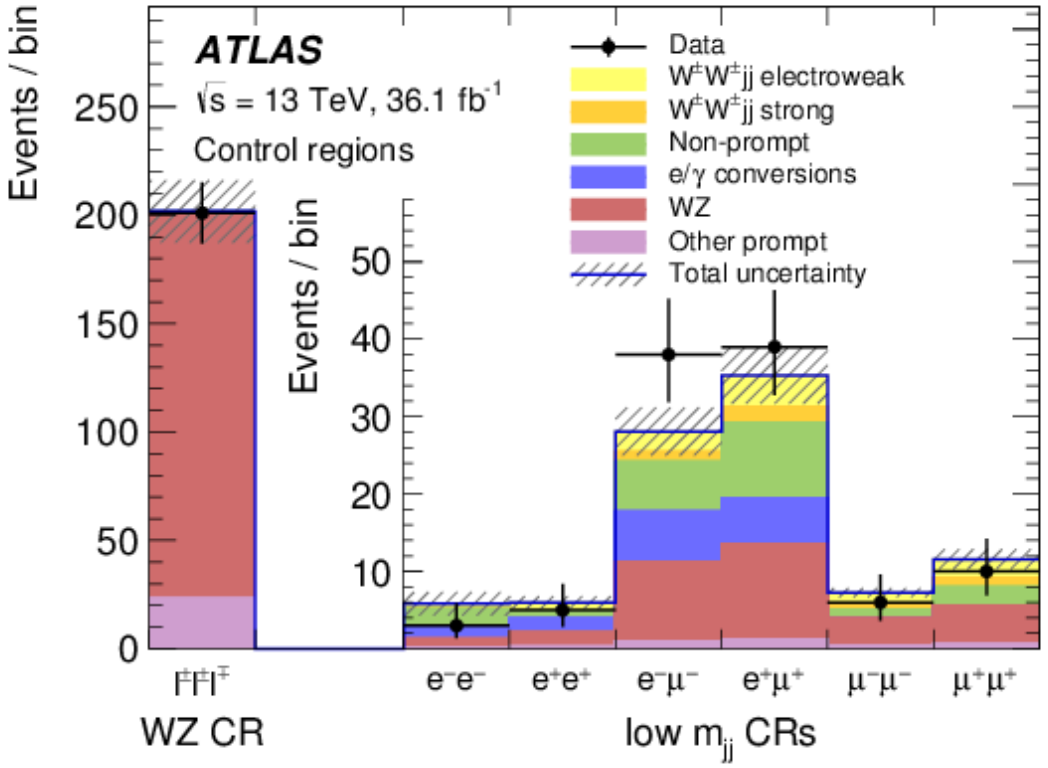
- VBS final state: $\nu\ell^{\pm}\nu\ell^{\pm}$ + jj
- Dataset: 36.1 fb^{-1}, 13 TeV
- Expected significance: 6.5 σ (Powheg-Box) and 4.4 σ (Sherpa)
- Same sign requirement suppress $q\bar{q}$ production



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

Non-prompt background (data driven)

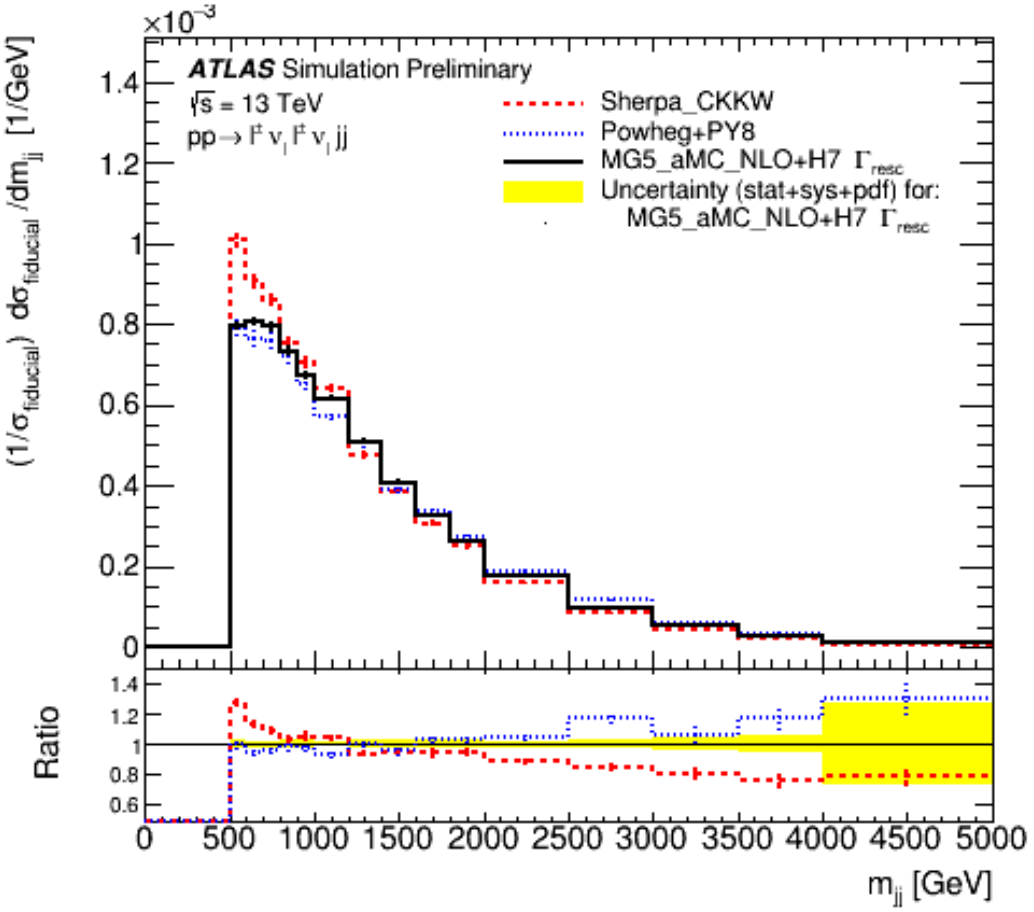
- $t\bar{t}$, WW+jets (QCD), Vγ+jets, W+jets, t+jets
- Lepton misidentification (photon as electron)
- Charge misidentification (same sign leptons)



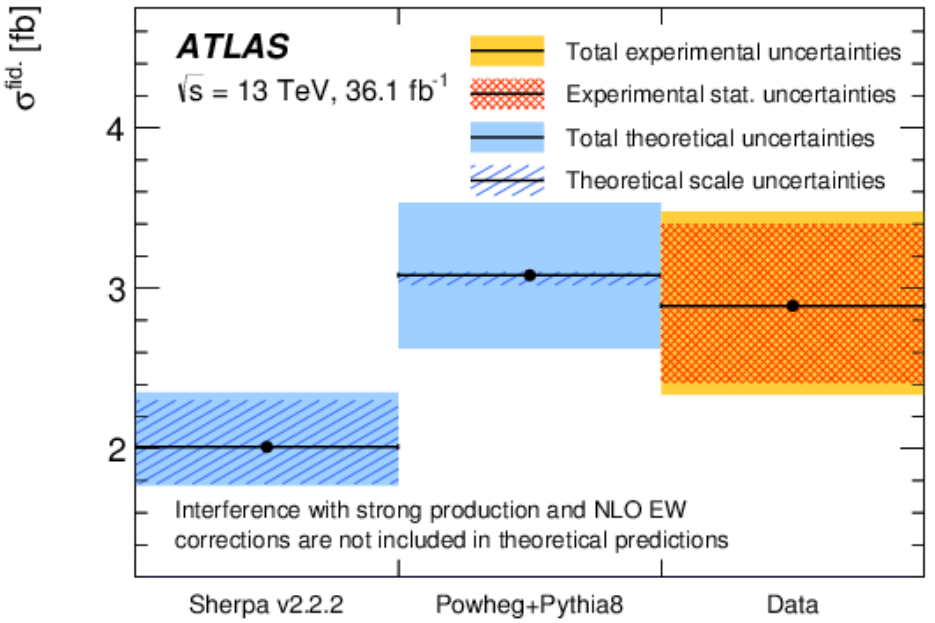
arXiv:1906.03203

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, $\sqrt{p_{\mathrm{T}}^{j1}\, p_{\mathrm{T}}^{j2}}$
- Non-optimal setting of the color flow for the Sherpa parton shower



ATL-PHYS-PUB-2019-004

$W^{\pm}W^{\pm}$ - Results

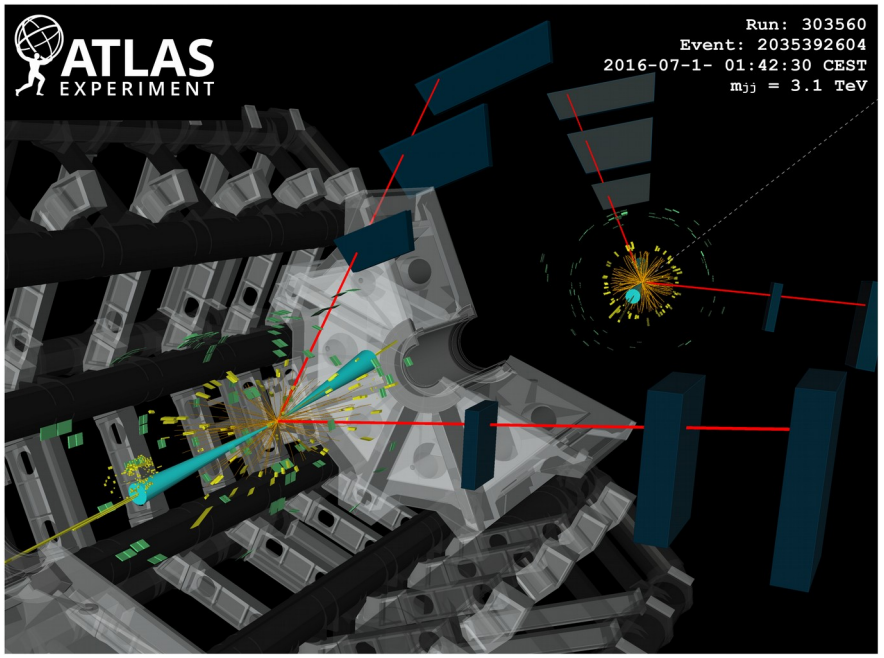
- Signal strength (compared to Sherpa)

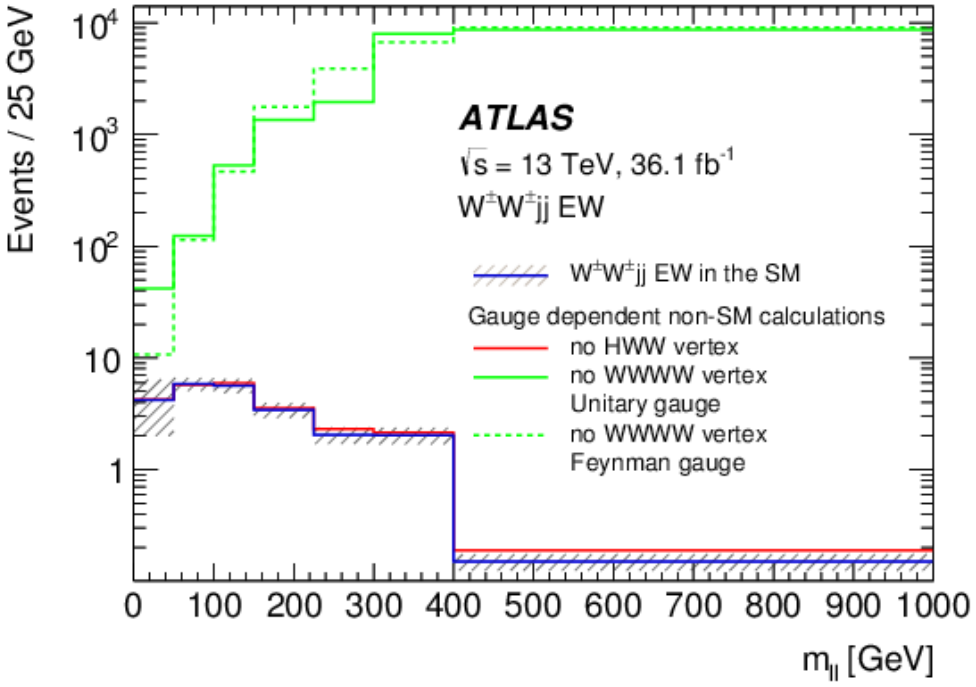
$$1.44^{+0.26}_{-0.24}\,(\mathrm{stat.})^{+0.28}_{-0.22}\,(\mathrm{syst.})$$

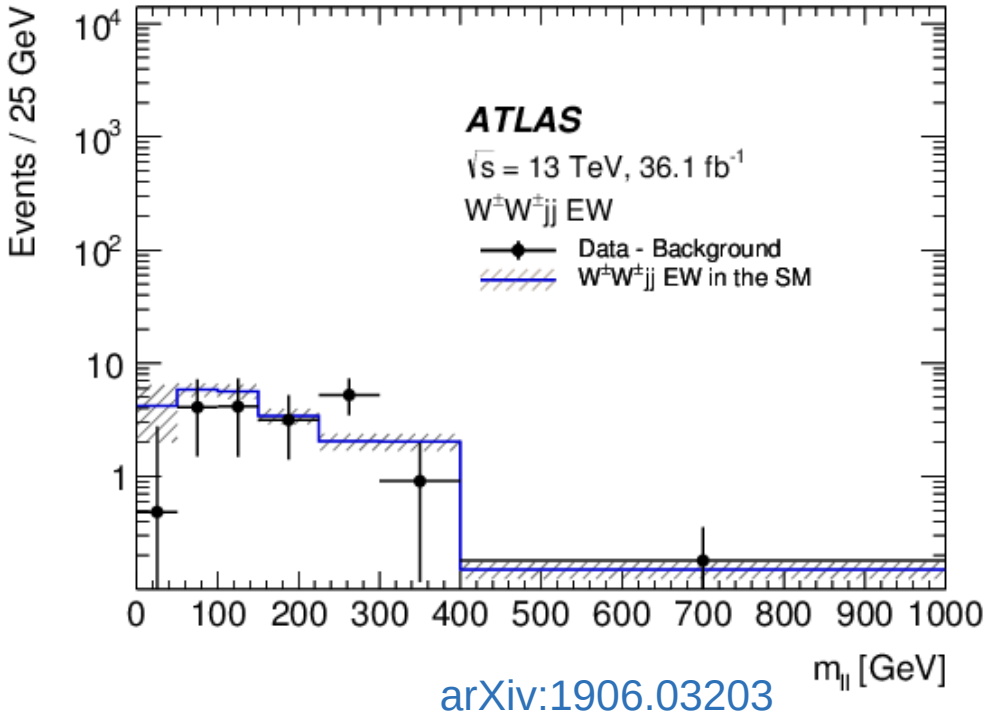
- Background only hypothesis rejected with significance 6.5 σ (expected 4.4/6.5 σ)
- EWK Fiducial cross-section

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

- No deviation from SM observed in $W^{\pm}W^{\pm}jj$ EWK



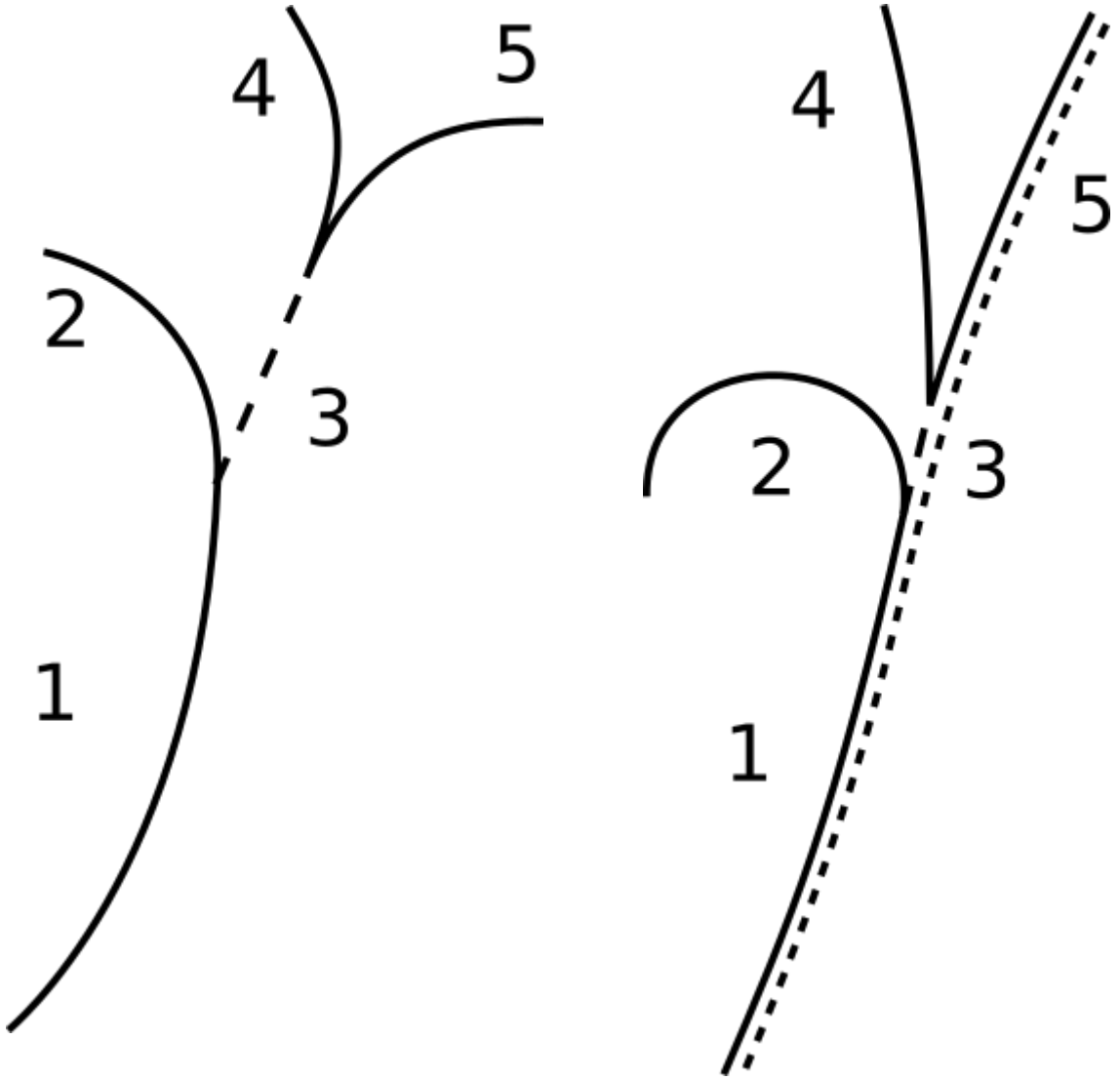




arXiv:1906.03203

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

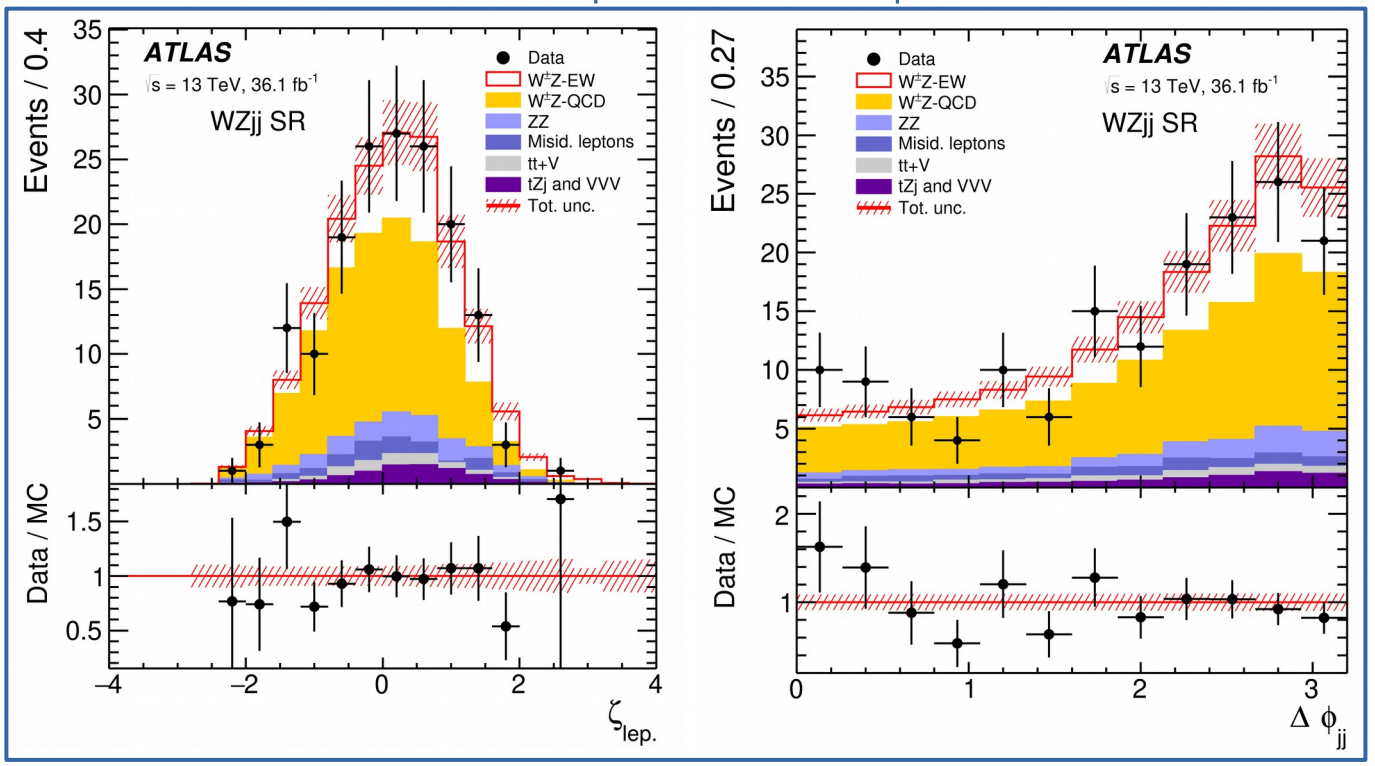


$W^{\pm}Z$ – VBS "Mix" Channel

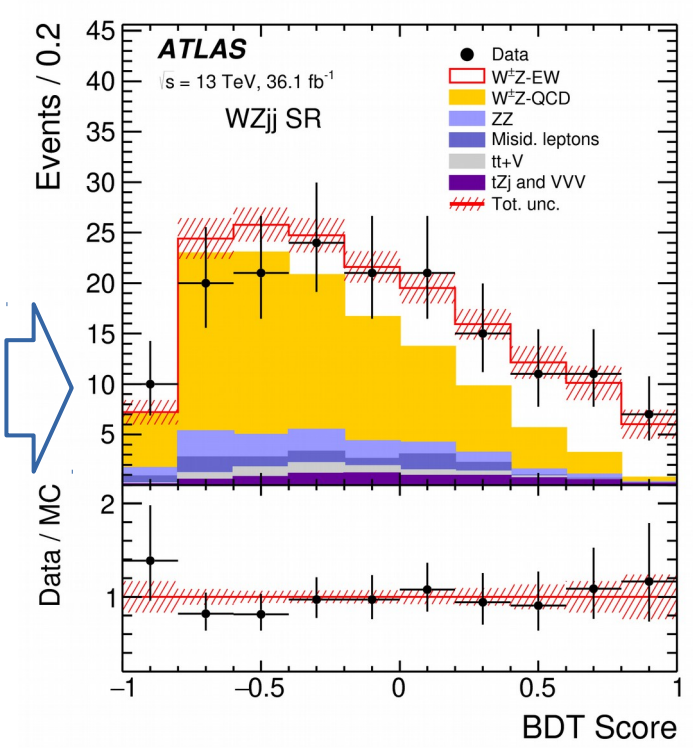
- VBS final state: $\nu\ell\ell\ell$ + jj
- Dataset: 36.1 fb^{-1}, 13 TeV
- Expected significance: 3.2 σ
- MVA: TMVA BDT, 15 variables
- W and Z reconstruction using Resonant Shape algorithm

- 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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$W^{\pm}Z$ – Results

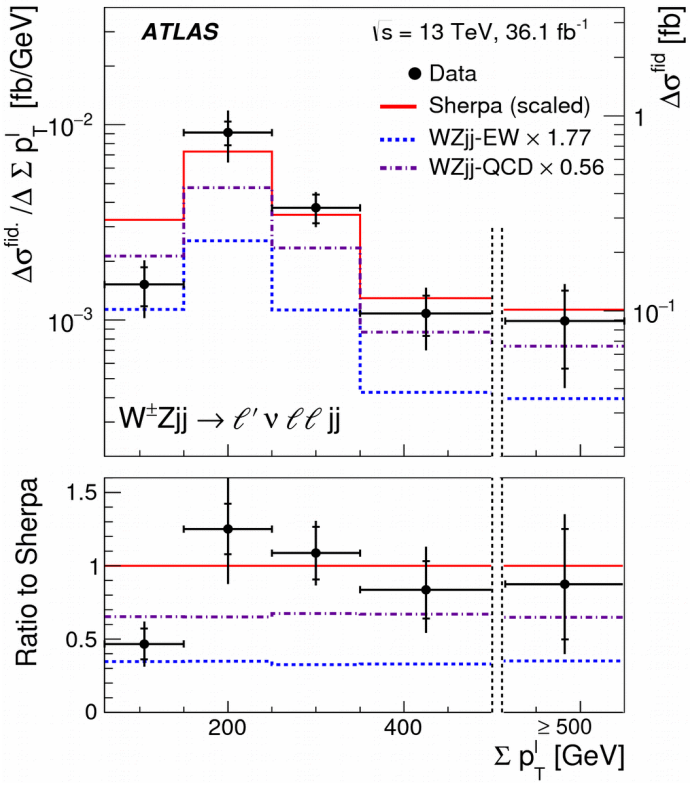
- EWK Signal strength

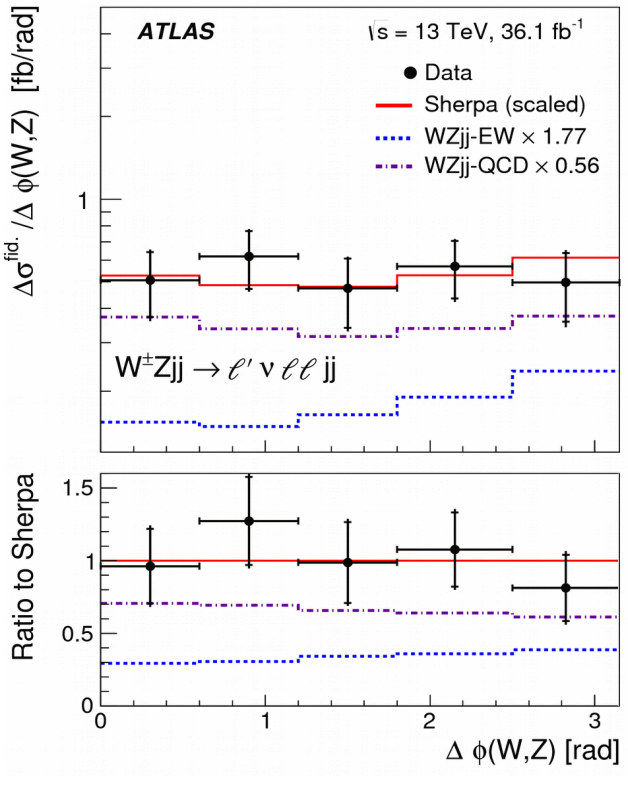
$$1.77^{+0.44}_{-0.40}\,(\text{stat.})^{+0.26}_{-0.21}\,(\text{syst.})$$

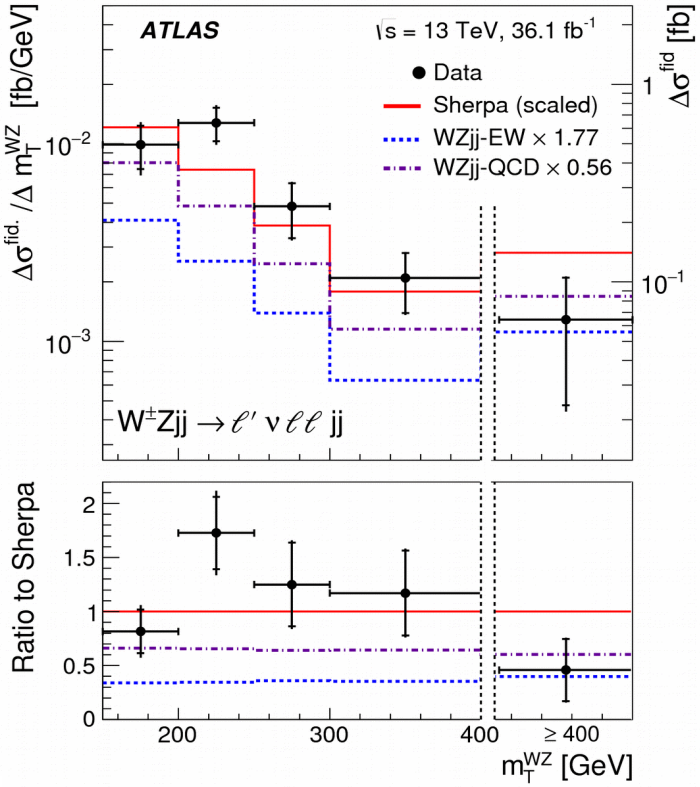
- Background only hypothesis rejected with significance 5.3 σ (expected 3.2 σ)
- EWK fiducial cross-section

$$0.57^{+0.14}_{-0.13}\,(\text{stat.})^{+0.07}_{-0.06}\,(\text{syst.})\,\text{fb}$$

- WZjj EWK production **observed**
- Distributions sensitive to anomalous QGC
  - Inclusive fiducial phase space (EWK + QCD)







Resonant Shape Algorithm

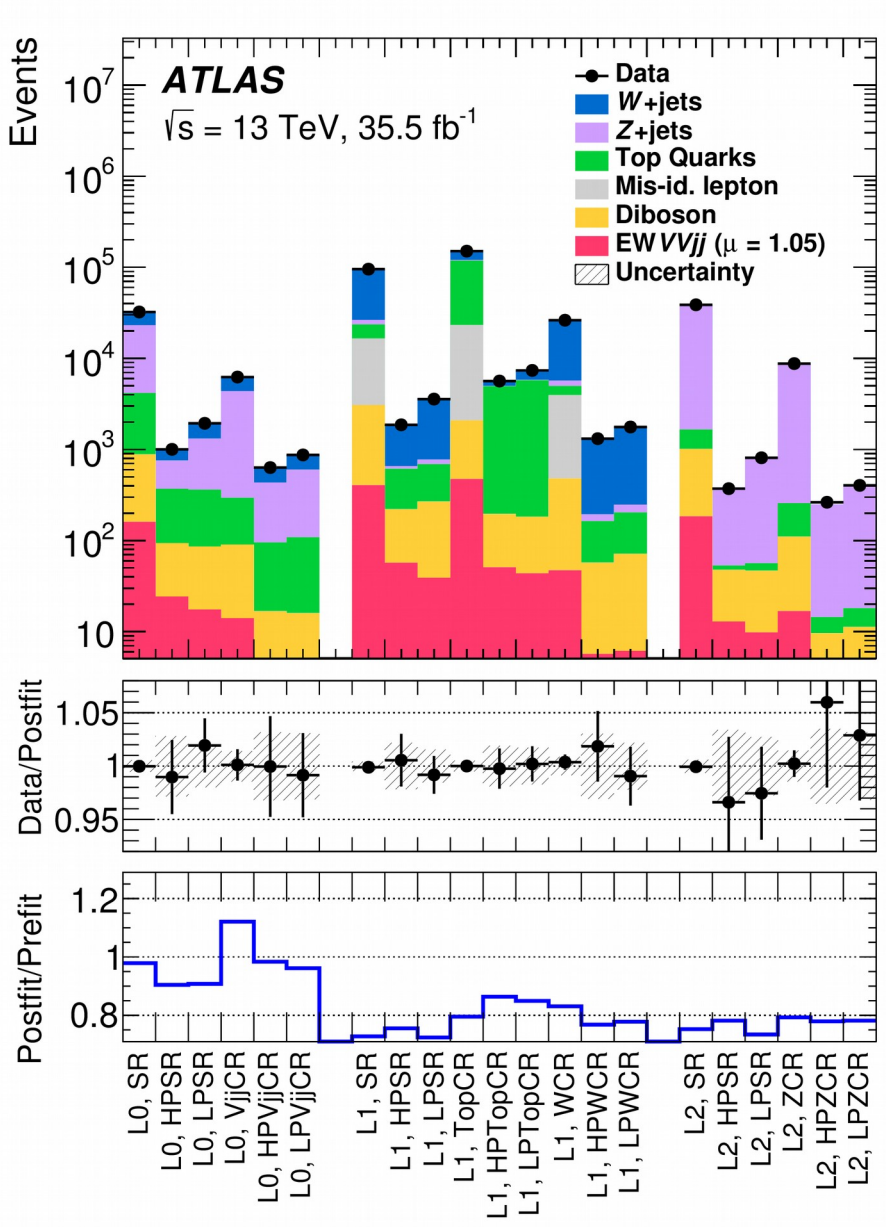
- Event MC generators do not always provide full information
  - Huge amount of events
  - Storage consumption
- Used for WZ VBS channel arXiv:1603.02151
- Based on value of the following estimator

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

- 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, $t\bar{t}$
  - 0-lepton channel
    - V+jets, $t\bar{t}$
- Minor background (all channels)
    - VVjj (QCD), t+jets, multijet



VV Semi-leptonic – Results

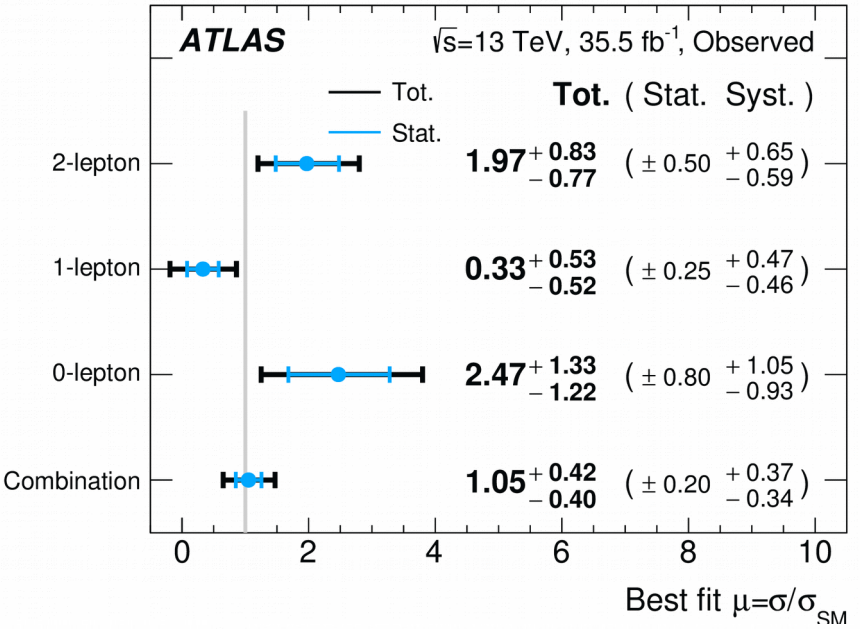
- EWK signal strength

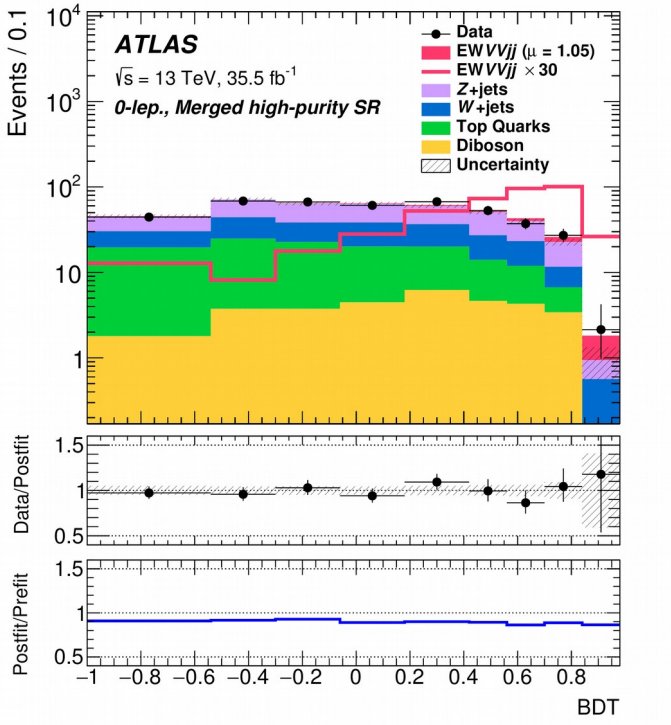
$$1.05^{+0.20}_{-0.20}\,(\text{stat.})^{+0.37}_{-0.34}\,(\text{syst.})$$

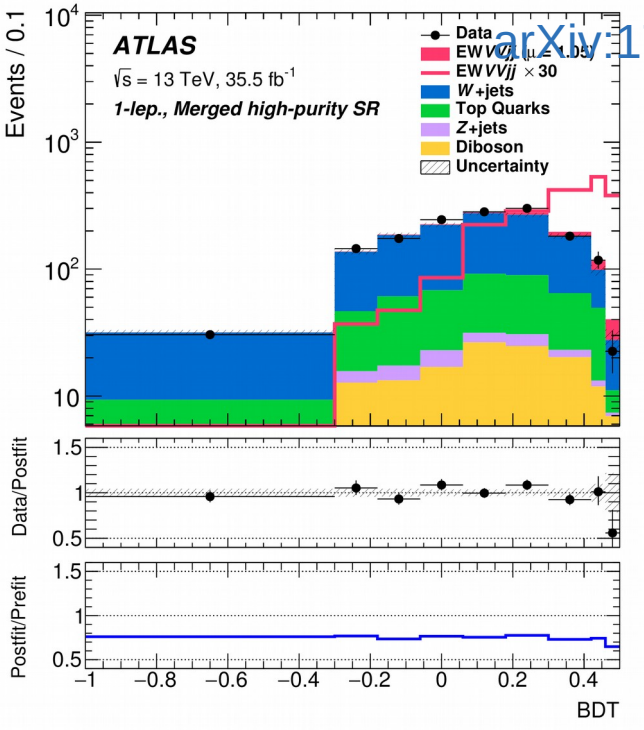
- Background only hypothesis rejected with significance 2.7 σ (expected 2.5 σ)
- EWK fiducial cross-section

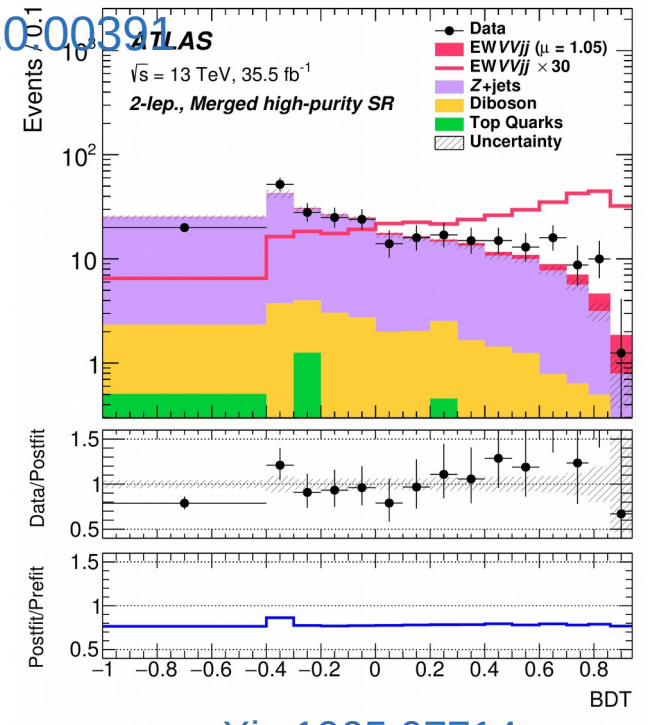
$$45.1^{+8.6}_{-8.6}\,(\text{stat.})^{+15.9}_{-14\,6}\,(\text{syst.})\,\text{fb}$$

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









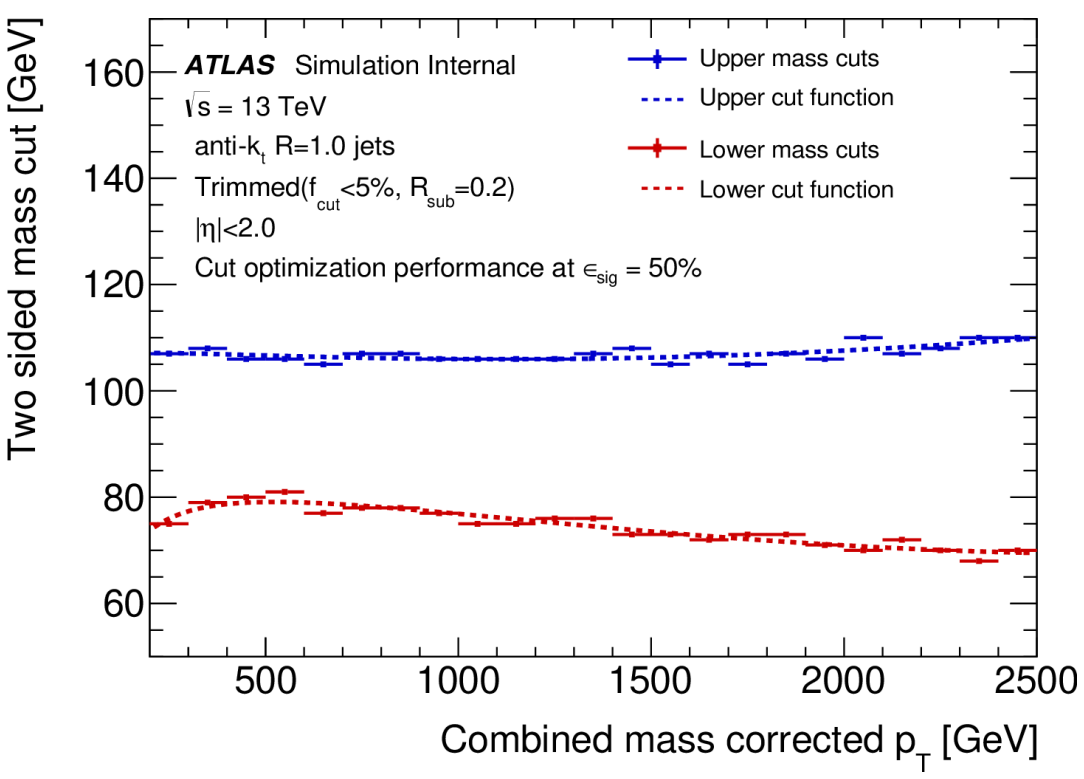
arXiv:1710.00391

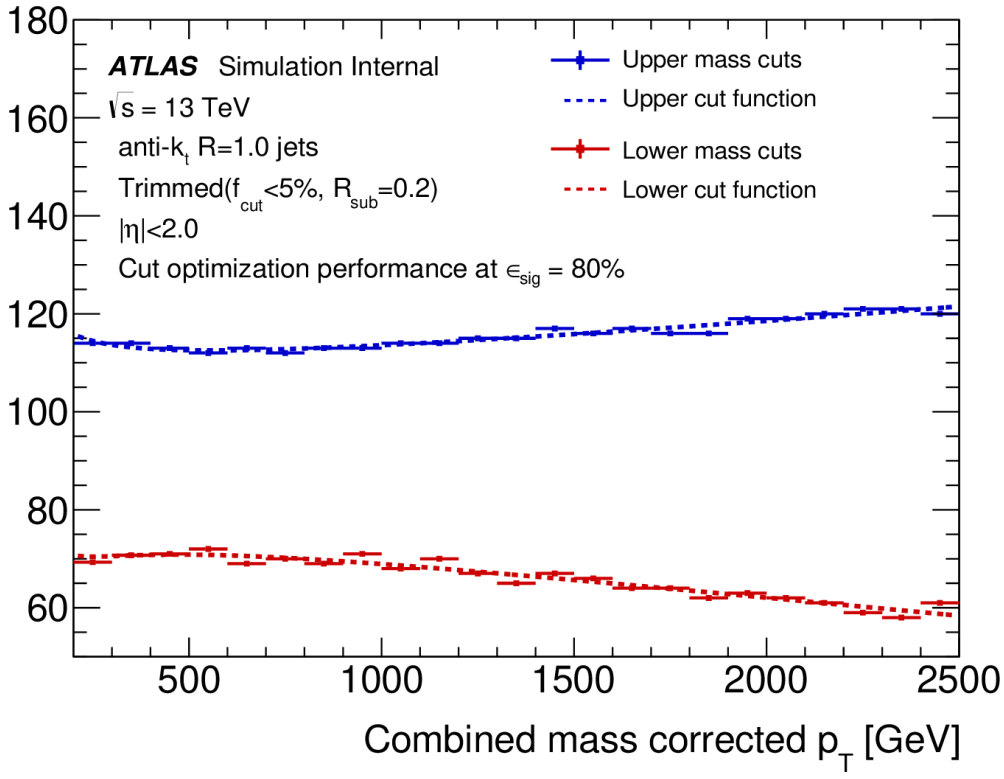
arXiv:1905.07714

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





Binned Profile Likelihood Ratio

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

- Construct Asimov dataset
  - Set all the observed values as the expected ones
  - Technically speaking it is the moment you go from histogram to a graph
- Building of the likelihood
  - Poisson distribution

- Observation
  - Ratio range (0,1)
  - Data choose value of NP (profiling)

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

  - Data-hypothesis discrepancy

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

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

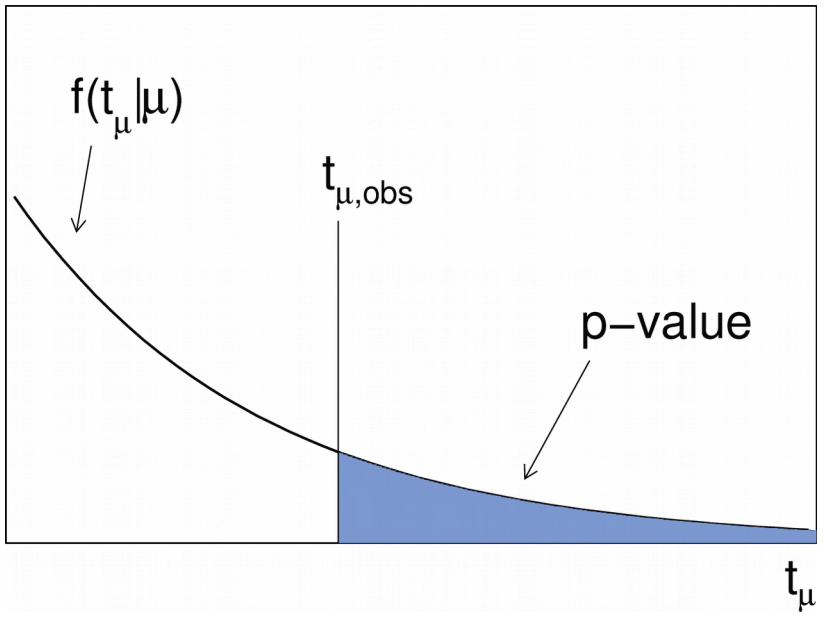
- Calculate the maximized unconditional likelihood function
  - Overall maximum
  - Varying POI (μ) and NP (θ)
  - Denominator

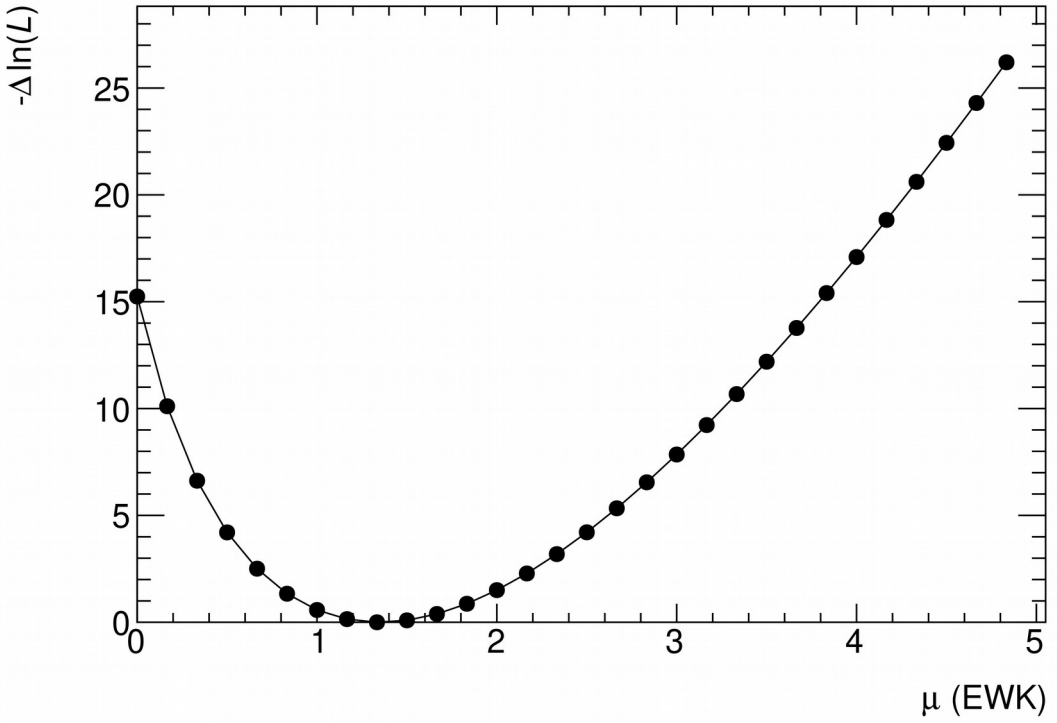
Profile likelihood ratio

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

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

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



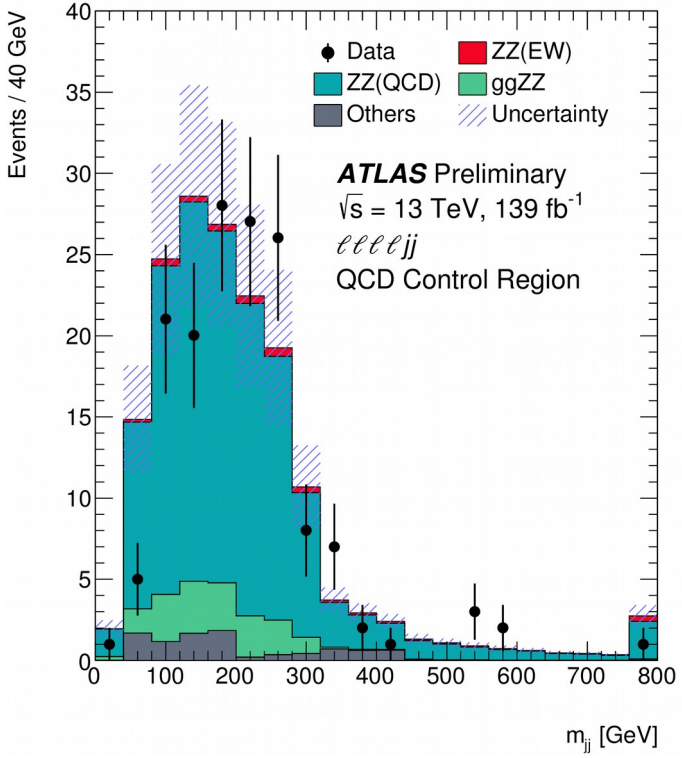


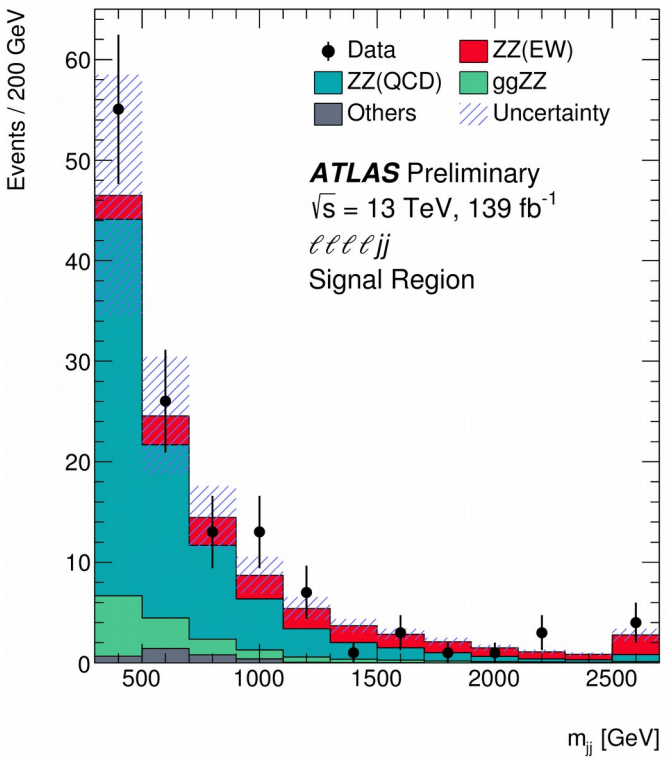
ZZ – VBS “Golden” Channel

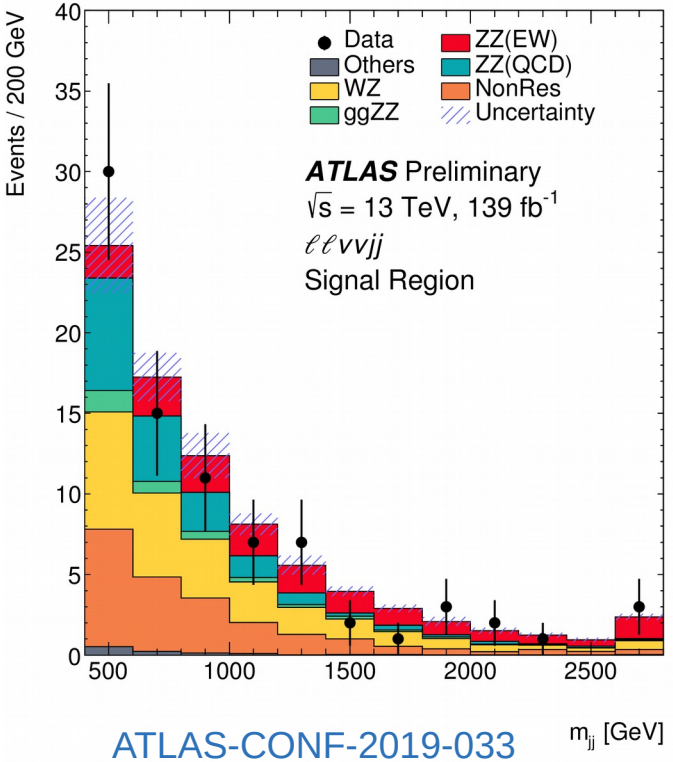
NEWEST!

- VBS final states: $\ell\ell\ell\ell$ + jj, $\nu\nu\ell\ell$ + 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 $\ell\ell\ell\ell$)

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







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ZZ Channels

- Comparison of contributions from $\ell\ell\ell\ell$ and $\nu\nu\ell\ell$ channels

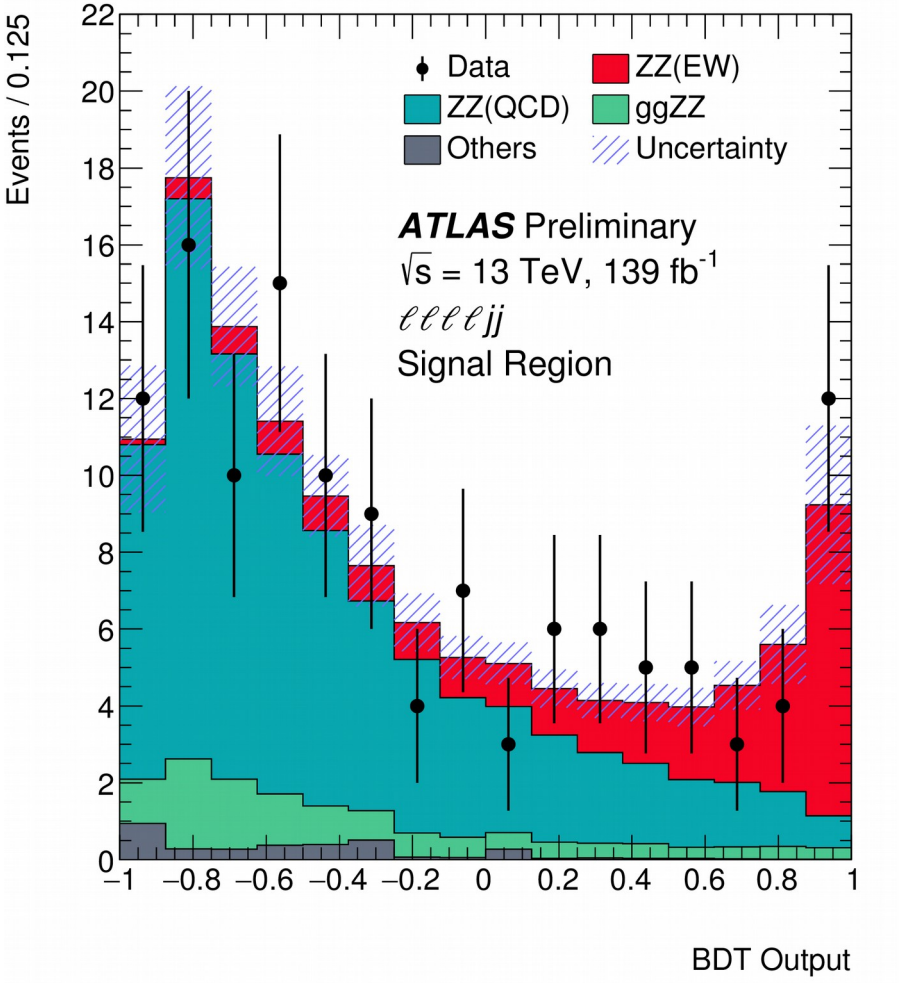
	μ_{EW}	$\mu_{\mathrm{QCD}}^{\ell\ell\ell\ell jj}$	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	1.5 ± 0.4	0.95 ± 0.22	5.48 (3.89) σ
$\ell\ell\nu\nu jj$	0.7 ± 0.7	fixed	1.15 (1.80) σ
Combined	1.35 ± 0.34	0.96 ± 0.22	5.52 (4.29) σ

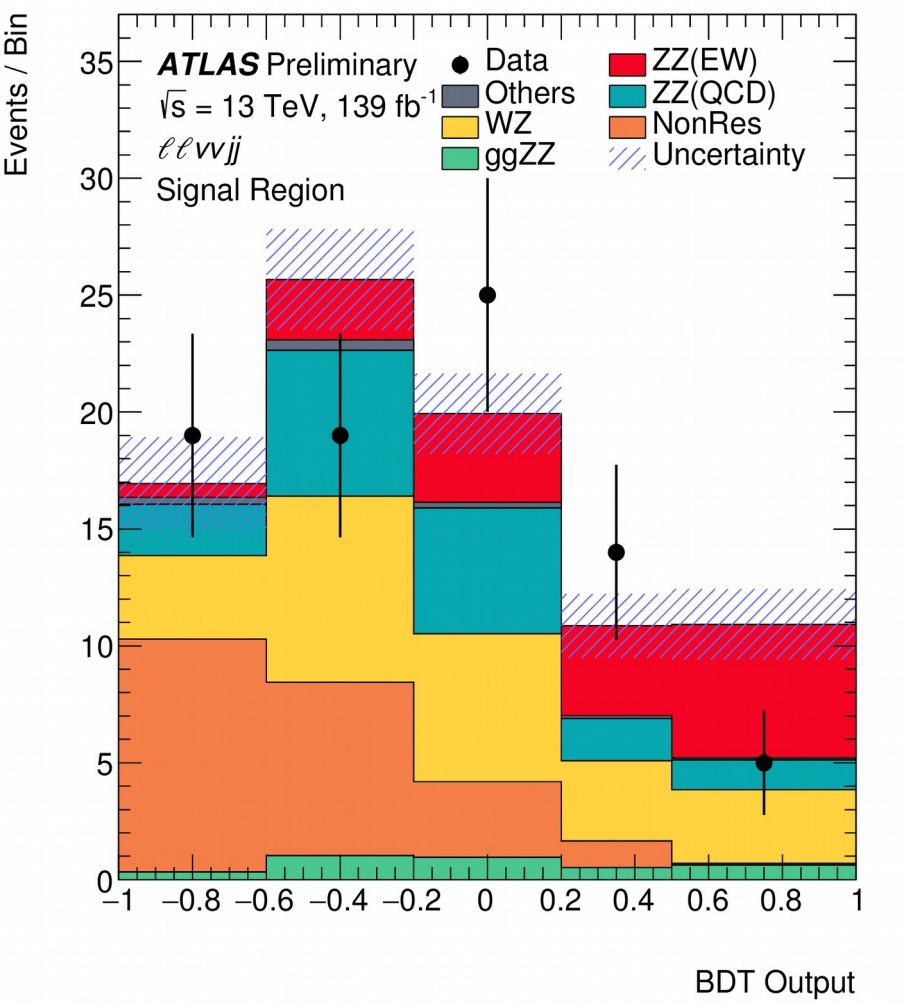
- Two-lepton channel not as lucky as four-lepton
  - Two-lepton contributes to the expectation though
  - Makes analysis more “safe”
  - We were blinded at the beginning

	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

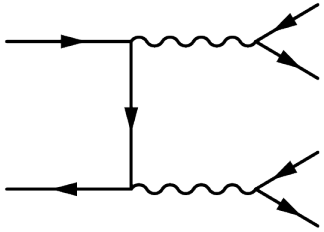
- EWK signal strength 1.35 ± 0.21
- Background only hypothesis rejected with significance 5.5 σ (expected 4.3 σ)
- EWK fiducial cross-section $0.82 \pm 0.34\,\text{fb}$
- ZZjj EWK production **observed**





Analysis Overview

Physics



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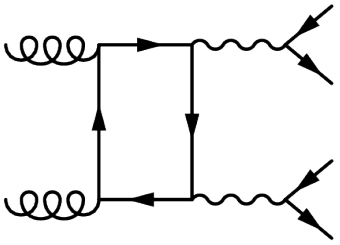

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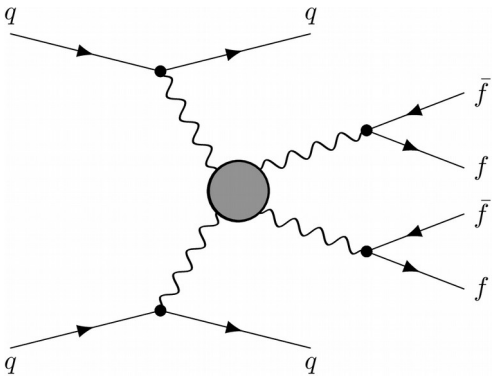
ZZ - VBS



Selection

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

Background estimation

MVA
- Signal/Background
- EWK/QCD
- BDTG
- Input observables

Statistical fit

Results

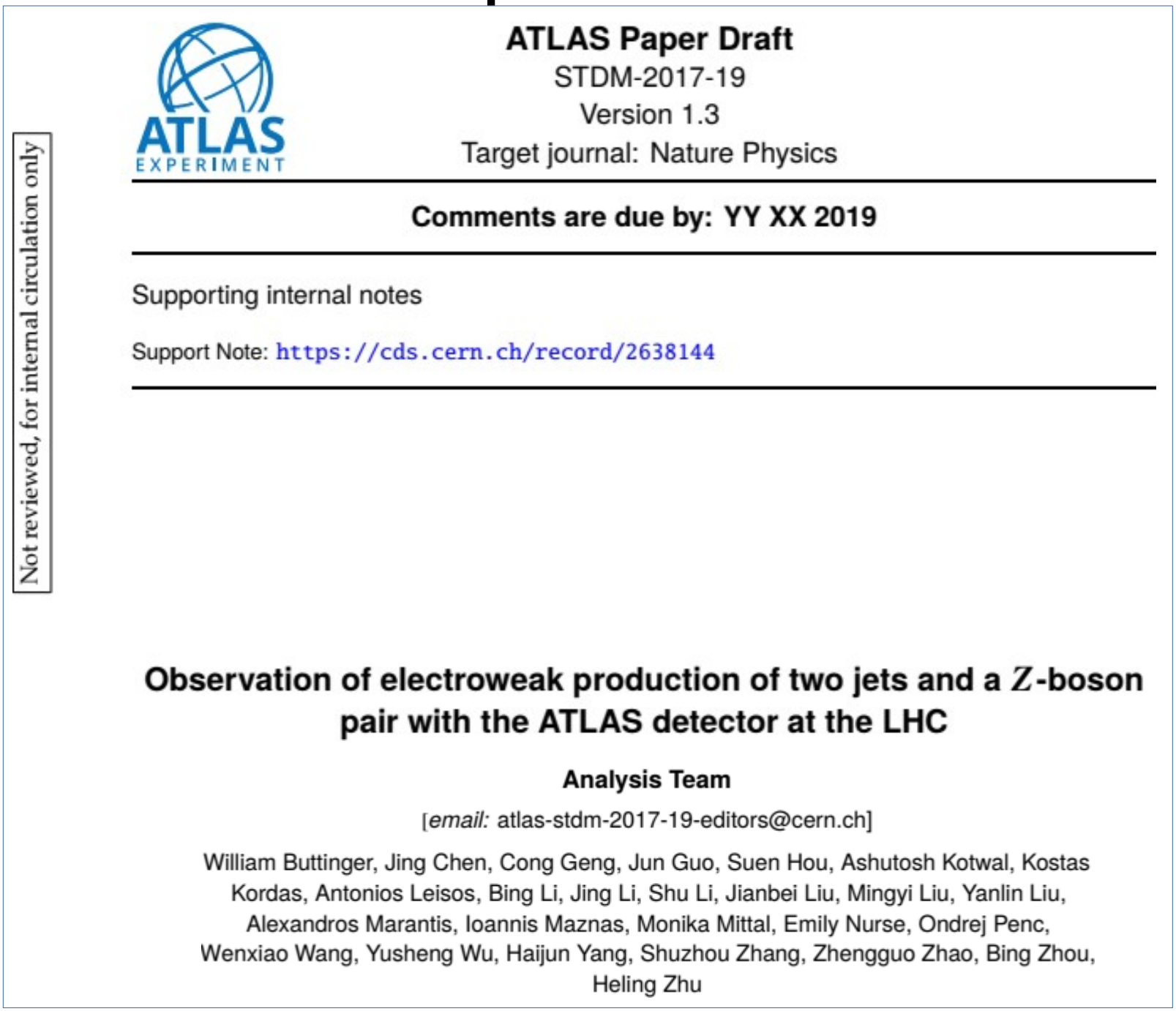
Inclusive (QCD + EWK) ZZ+2j cross-section measurement in VBS enhanced region

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

ZZ Paper

- They said
  - Nice result
  - Choose any journal
- We randomly picked one :-)

- Politically problematic choice
  - You-know-which one
  - General afraid: what if we would be rejected
  - Are they better than the rest of collaboration?



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

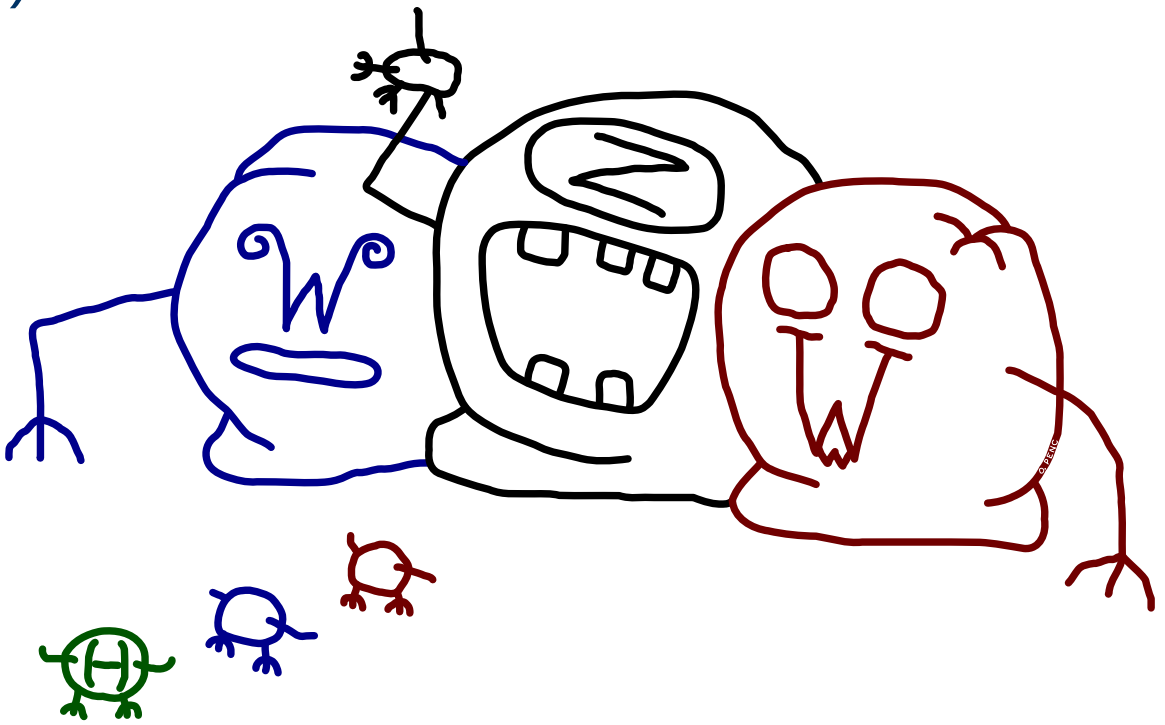
Analysis Team

[*email:* atlas-stdm-2017-19-editors@cern.ch]

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

Summary

- ATLAS Vector Boson Scattering
  - 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 phenomena
    - Semi-leptonic channel
    - Channels including gamma
    - Polarization studies



BACKUP