Recent observations and measurements of vector-boson fusion and scattering with ATLAS

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on behalf of the ATLAS Collaboration

Carleton UNIVERSITY

WG3: Electroweak Physics and Beyond the Standard Model

May 3, 2022

Outline

- Scope and Goals
- **Vector Boson Fusion (VBF) versus Vector Boson Scattering (VBS)**
- Datasets and Event Topology
- **Measurement of Electroweak *Zjj***
- **Observation of Electroweak *ZZjj***
- $\gamma\gamma \rightarrow WW$ Production
- Prospect at HL-LHC
- Summary

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THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Eur. Phys. J. C 81 (2021) 163

Differential cross-section measurements for the electroweak production of dijets in association with a Z boson in proton–proton collisions at ATLAS

ATLAS Collaboration*

CERN, 1211 Geneva 23, Switzerland

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EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

Submitted to Nature Physics

Submitted to: Nature Physics

CERN

CERN-EP-2020-016
23rd April 2020

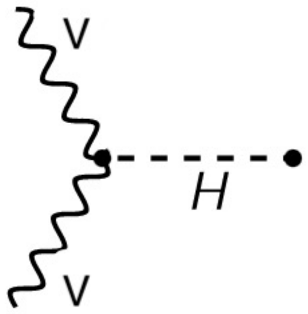
https://doi.org/10.48550/arXiv.2004.10612

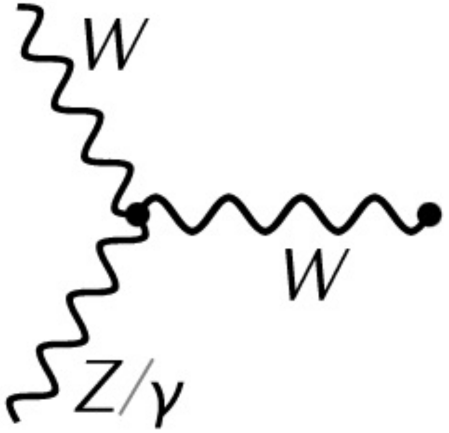
Observation of electroweak production of two jets and a Z-boson pair with the ATLAS detector at the LHC

The ATLAS Collaboration

Scope: Electroweak (EW) Gauge Couplings

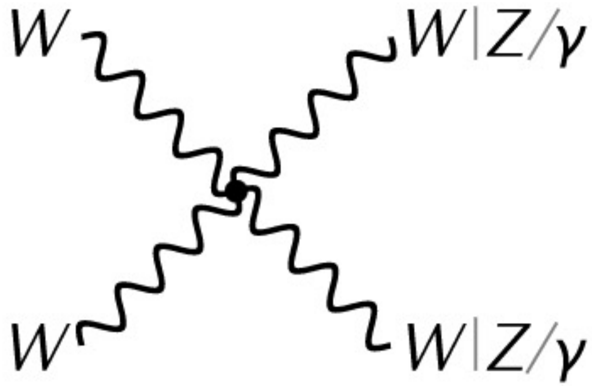
Exploration at the LHC of electroweak symmetry breaking in all aspects. In particular, the **self-couplings of the vector gauge bosons** are completely specified in the Standard Model (SM), as are the couplings of the Higgs boson to the vector bosons (V=W,Z) once the Higgs mass is known.





Vector Boson Fusion (VBF)

The only **triple gauge couplings (TGC)** allowed in the SM are **WWZ and WWγ**. There are no ZZZ, ZZγ, Zγγ, or γγγ couplings in the SM.



Vector Boson Scattering (VBS)

The only **quartic gauge couplings (QGC)** allowed in the SM are **WWWW, WWZZ, WWZγ and WWγγ**. There are no ZZZZ or γγγγ couplings in the SM.

Goals in general

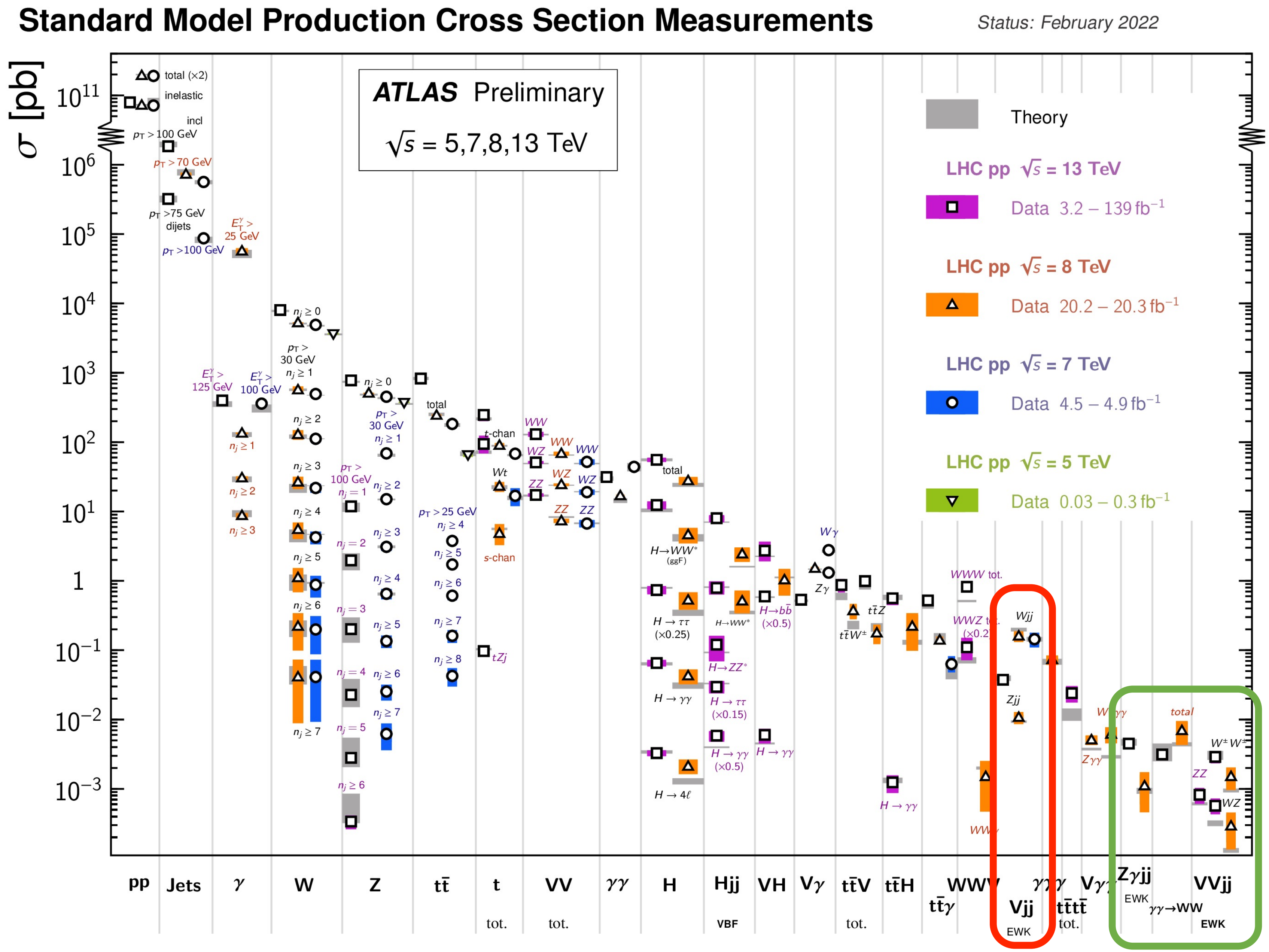
1. EW VBF production mechanism of Higgs created a vast interest in *H*+jets and *Z*+jets production as a function of N_{jets} in the final states.

2. Better understand strong **QCD** ***Vjj*** and ***VVjj*** as background for Higgs and electroweak physics, as well as for other precise Standard Model (SM) measurements and searches at the LHC. Thus, tuning of event generators at NLO.

3. Extract the rare electroweak (**EW**) production of ***Vjj*** and ***VVjj***.

4. Triple and Quartic Gauge **couplings** precise probe for testing the SM.

Goals in practice: VBF and VBS measurements



- Electroweak *Vjj* and *VVjj* and $\gamma\gamma \to WW$ production are all **very rare**
- Rate relative to inel. $pp \to X$

$$\sigma_{Zjj}/\sigma_{\text{inel}} \approx 10^{-12}$$

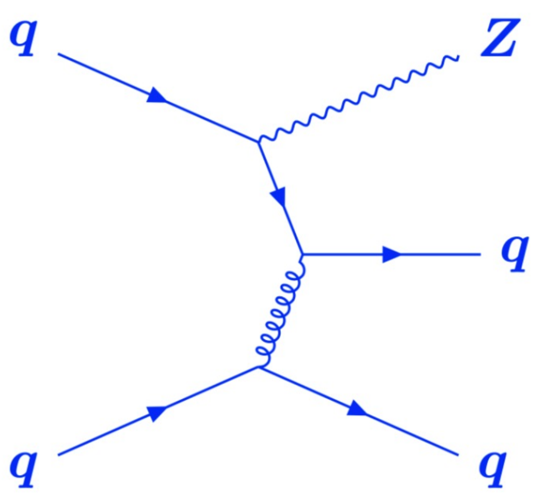
$$\sigma_{ZZjj}/\sigma_{\text{inel}} \approx 10^{-14}$$

- **Challenging analysis 13 TeV: small signal swamped by backgrounds; often poorly modelled**
- 5σ observation for $W^{\pm}W^{\pm}jj$ and $WZjj$, $ZZjj$ etc.

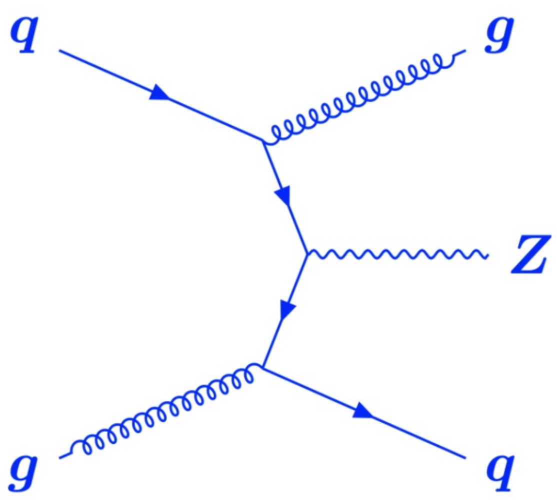
Phys. Rev. Lett. 123 (2019) 161801

Phys. Lett. B 793 (2019) 469

Strong vs Electroweak Zjj Production at 13 TeV



Z Bremsstrahlung



Quark-Quark fusion

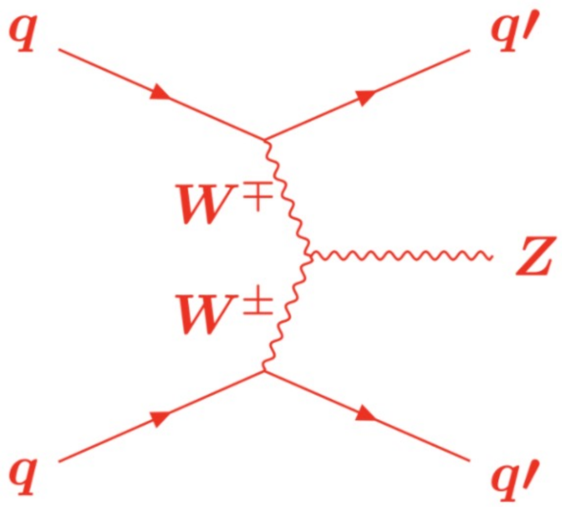
Strong $\mathbf{p + p \rightarrow Z + 2\ jets + X}$

$\boldsymbol{\sigma_{strong}(Z + \geq 2\ \text{jets}) \approx 27\ \text{pb}}$

ATLAS, Eur. Phys. J. C 75.2 (2015)

Electroweak (EW) is $\mathcal{O}(100)$ smaller

Goal: Differential cross-sections!!!



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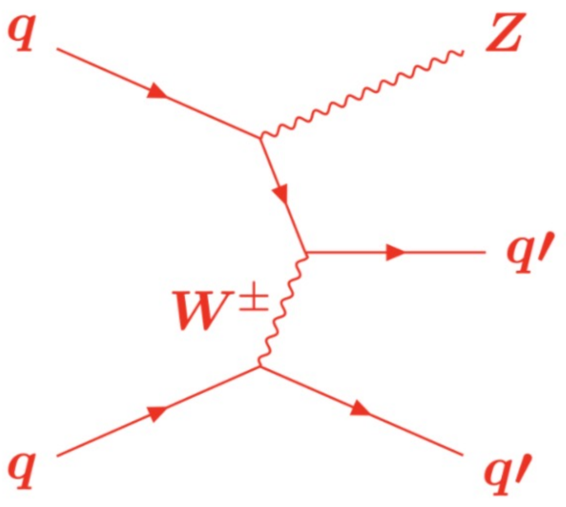

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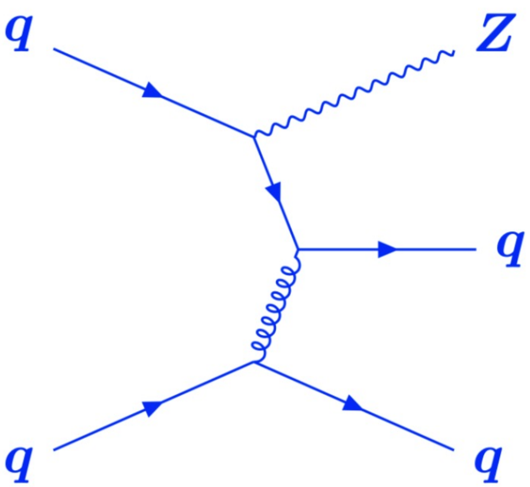

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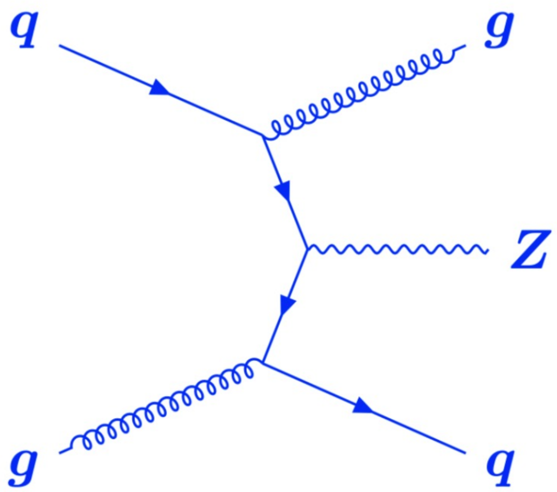

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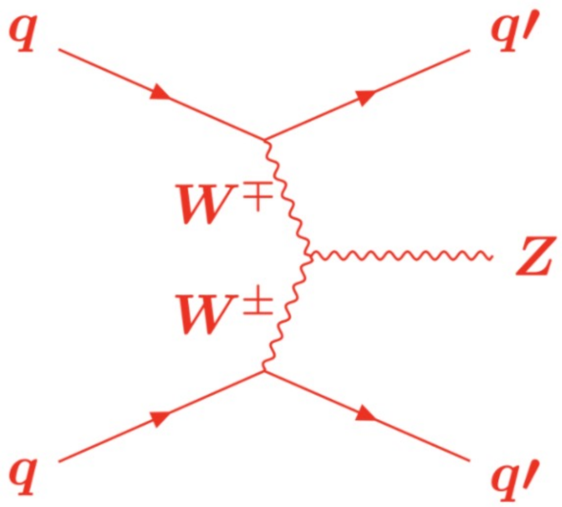

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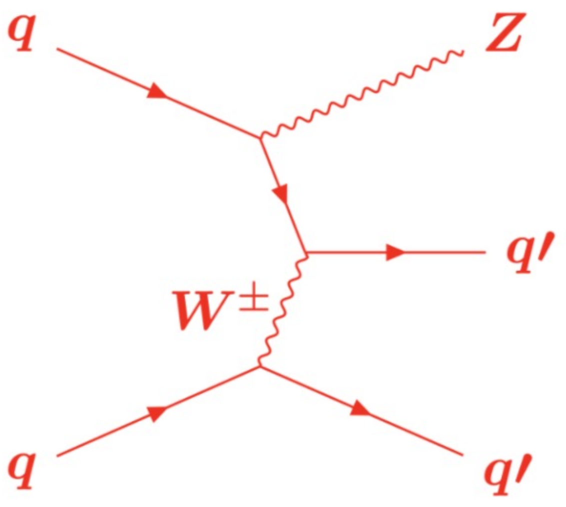

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Strong vs Electroweak $ZZjj$ Production at 13 TeV

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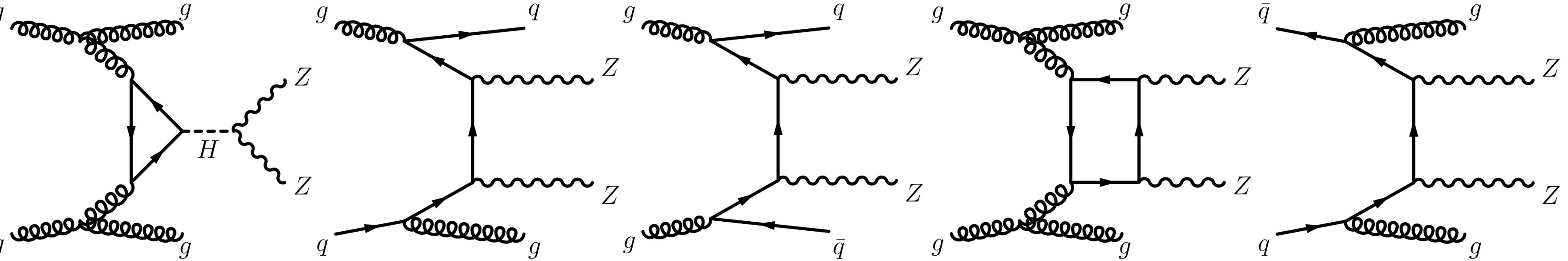
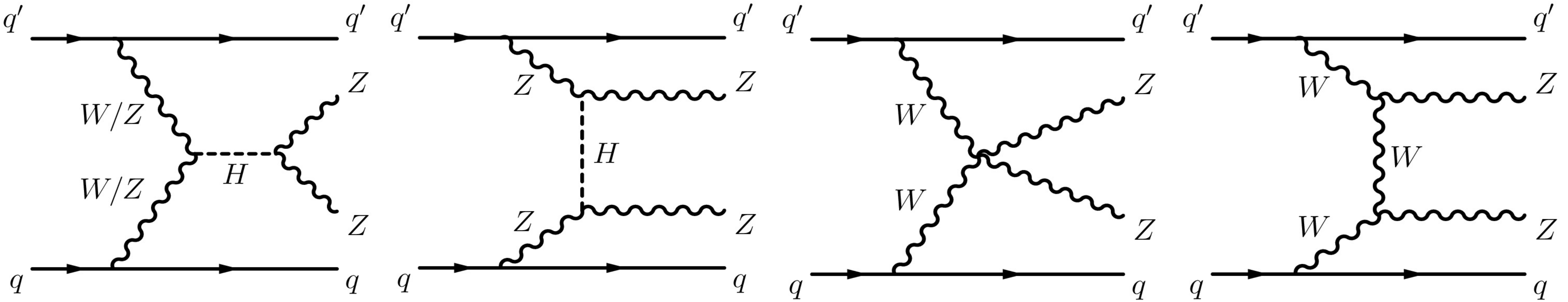


Rarest EW $VVjj$ with the goal to observe it!!!

EW $ZZjj$



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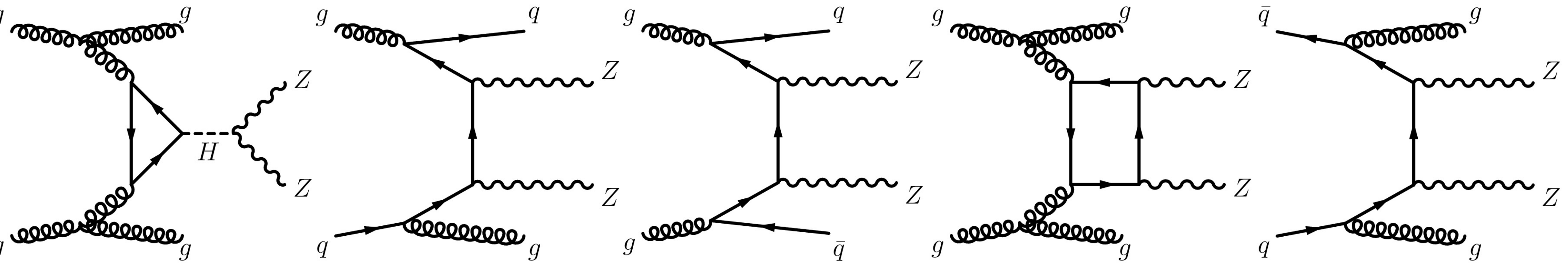

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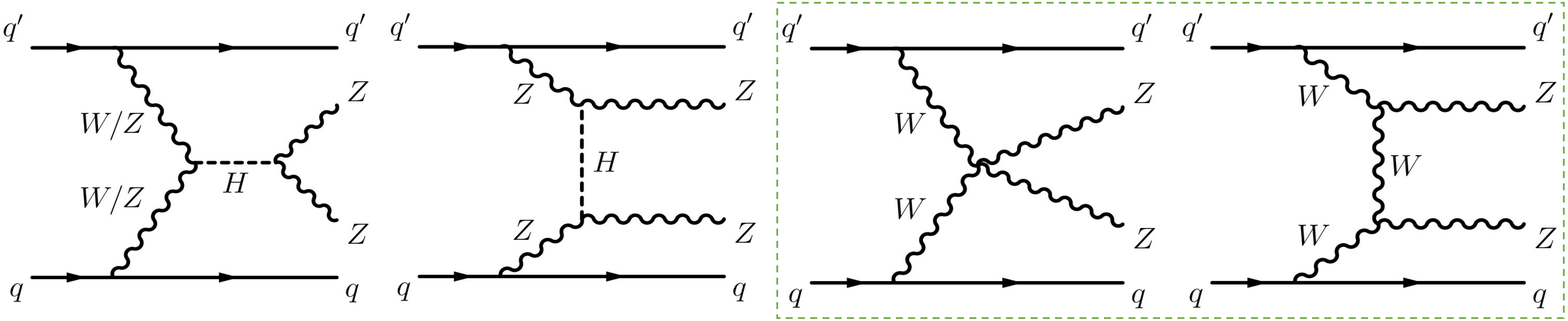
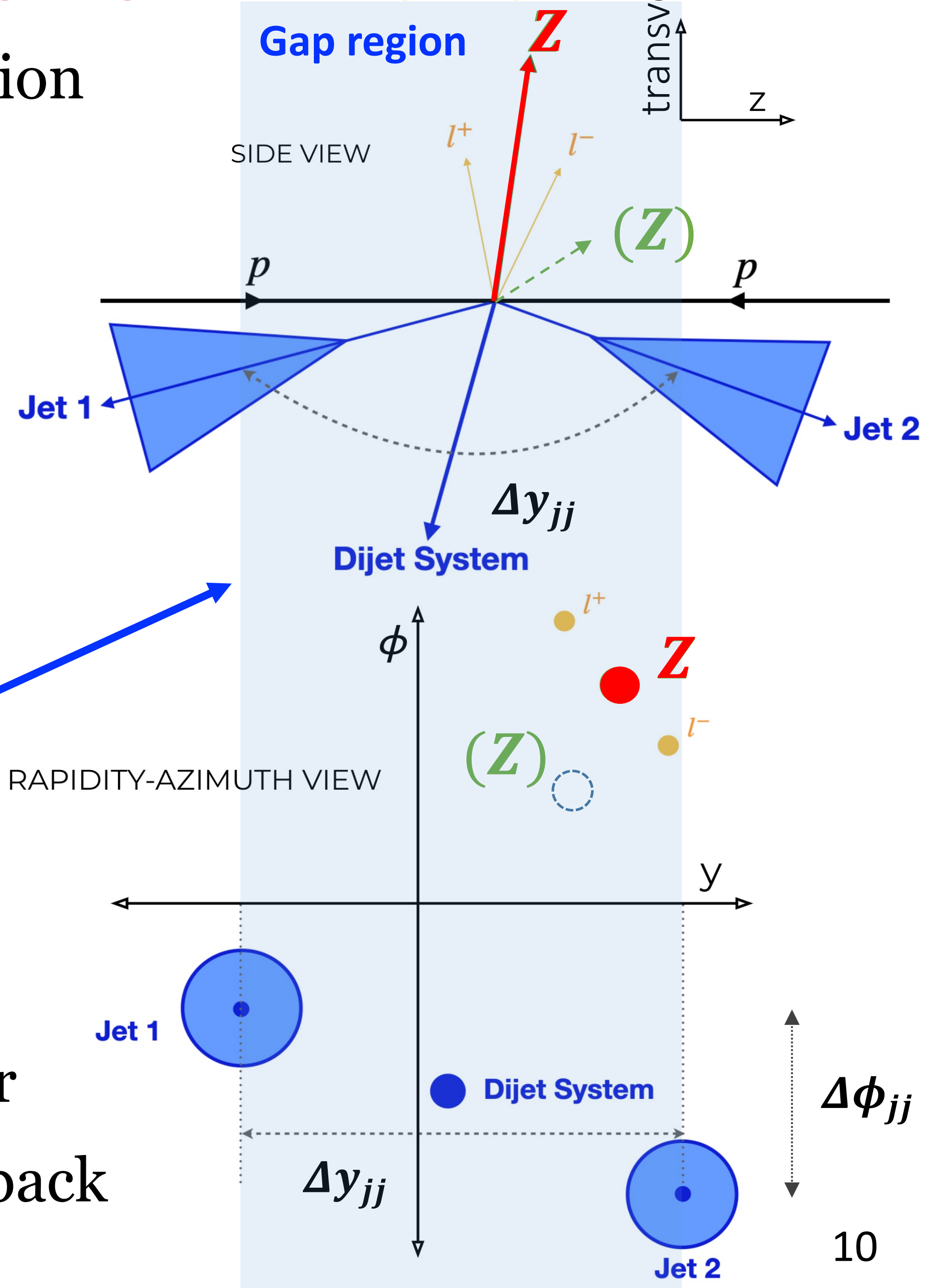


Topology EW $(Z)Zjj$ with at least one $Z \to \ell^+\ell^-$

The strategy is to study **EW Vjj** and **EW $VVjj$** production via which the **VBF** and **VBS** diagram contribution.

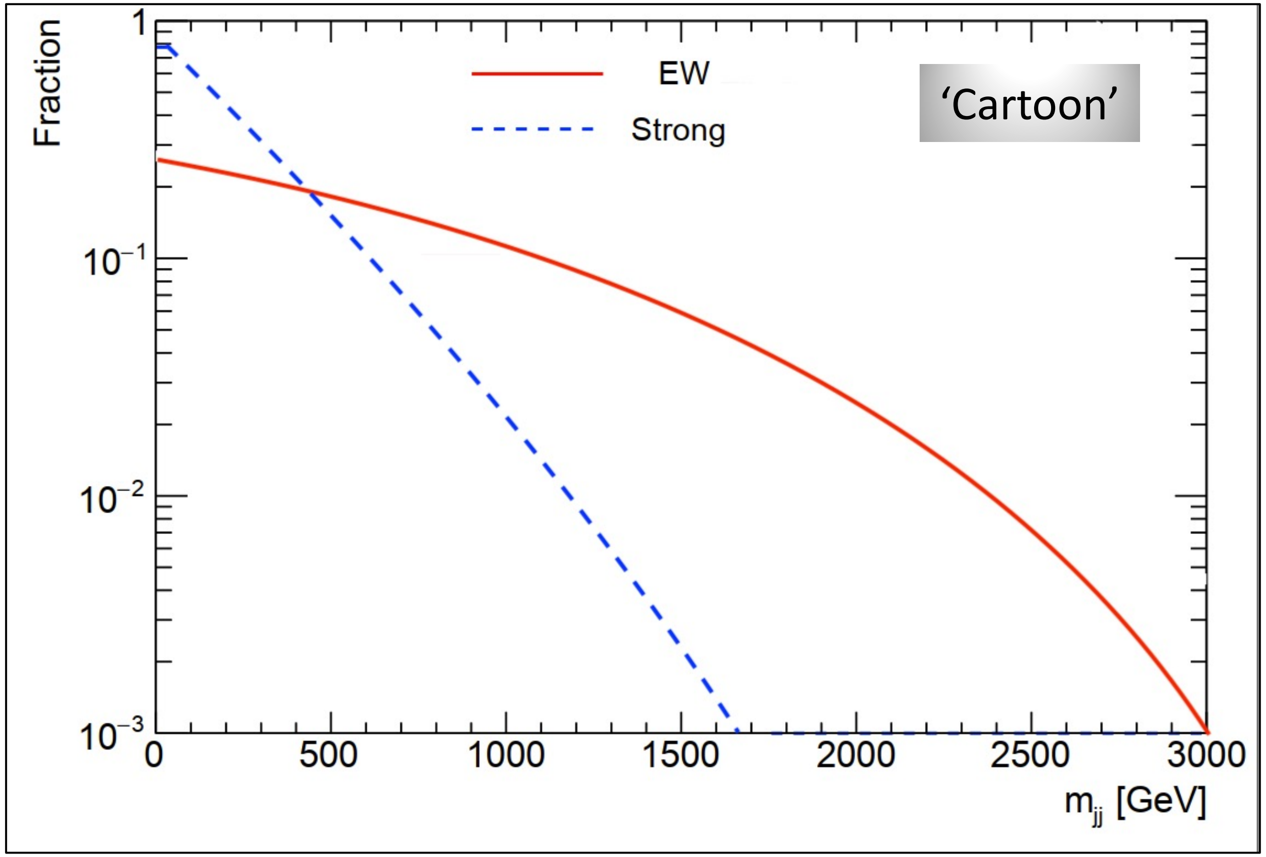
Signature of EW $(Z)Zjj$:

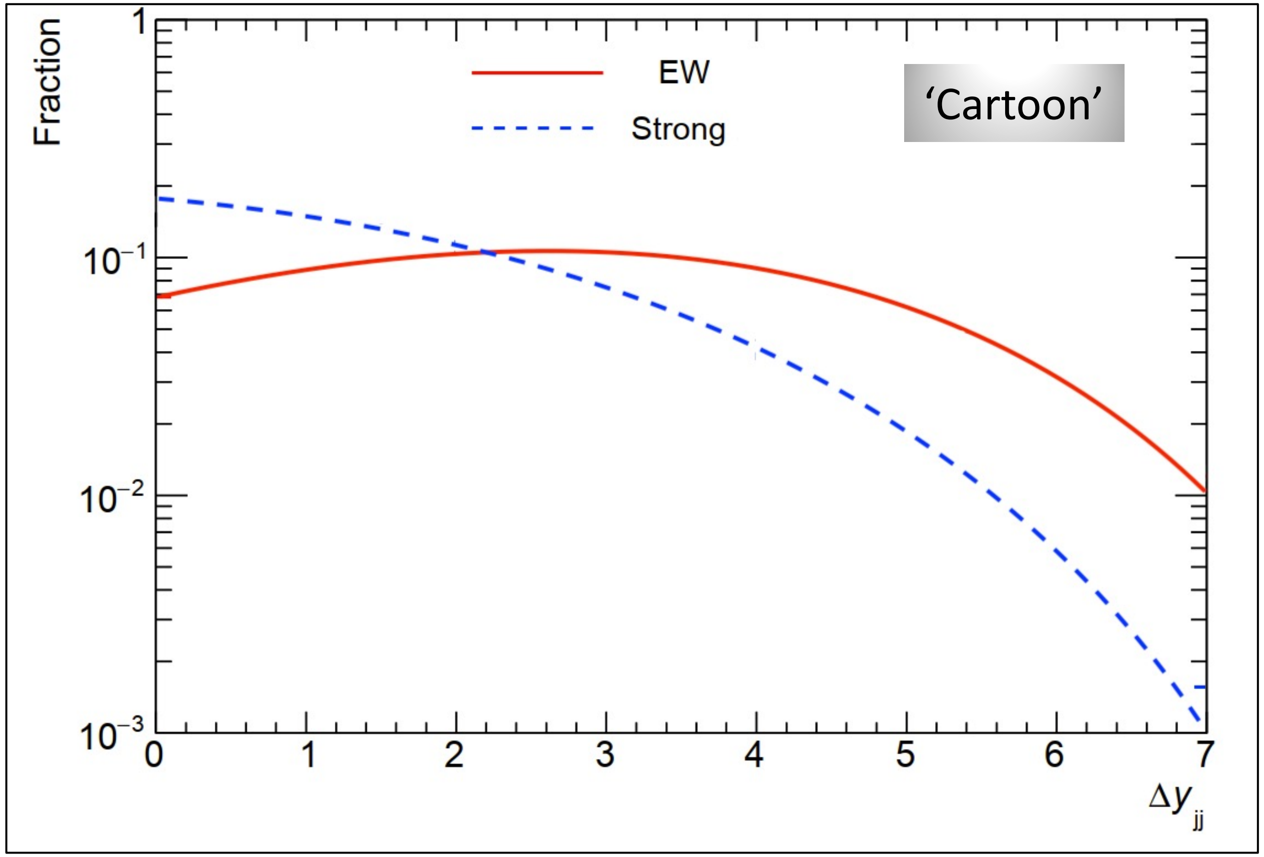
- Rapidity of observables $y = \frac{1}{2} \ln \left[\frac{E+p_z}{E-p_z}\right]$
- Centrality $\xi \approx (y_{V(V)} - y_{jj})/\Delta y_{jj}$
- **Large rapidity gap between jets Δy_{jj}**
- **Large dijet invariant mass m_{jj}**
- **Little hadronic activity** (few extra jets), within **rapidity gap** between two leading jets
- Low p_T (or lack) of third jet / low p_T of $(V)Vjj$ system
- Boost (rapidity) of (di)boson and dijet system similar
- p_T of (di)boson and dijet system similar, so back-to-back in ϕ



Typical Signal Region for VBF and VBS Topology

Signature of EW signal and Strong background





- **EW Zjj and $ZZjj$**: Lack of colour connection means little hadronic activity between outgoing internal quarks. Thus larger $\boldsymbol{\Delta y_{jj}}$, larger $\boldsymbol{m_{jj}}$ and lager $\boldsymbol{p_T^Z}$ for **EW signal**, with more $\mathbf{N_{jet}= 0}$ in gap region and centrality $\boldsymbol{\xi < 0.5}$.

Dataset Run-2

EW Zjj

Eur. Phys. J. C81 (2021) 163

EW $ZZjj$

arXiv.2004.10612

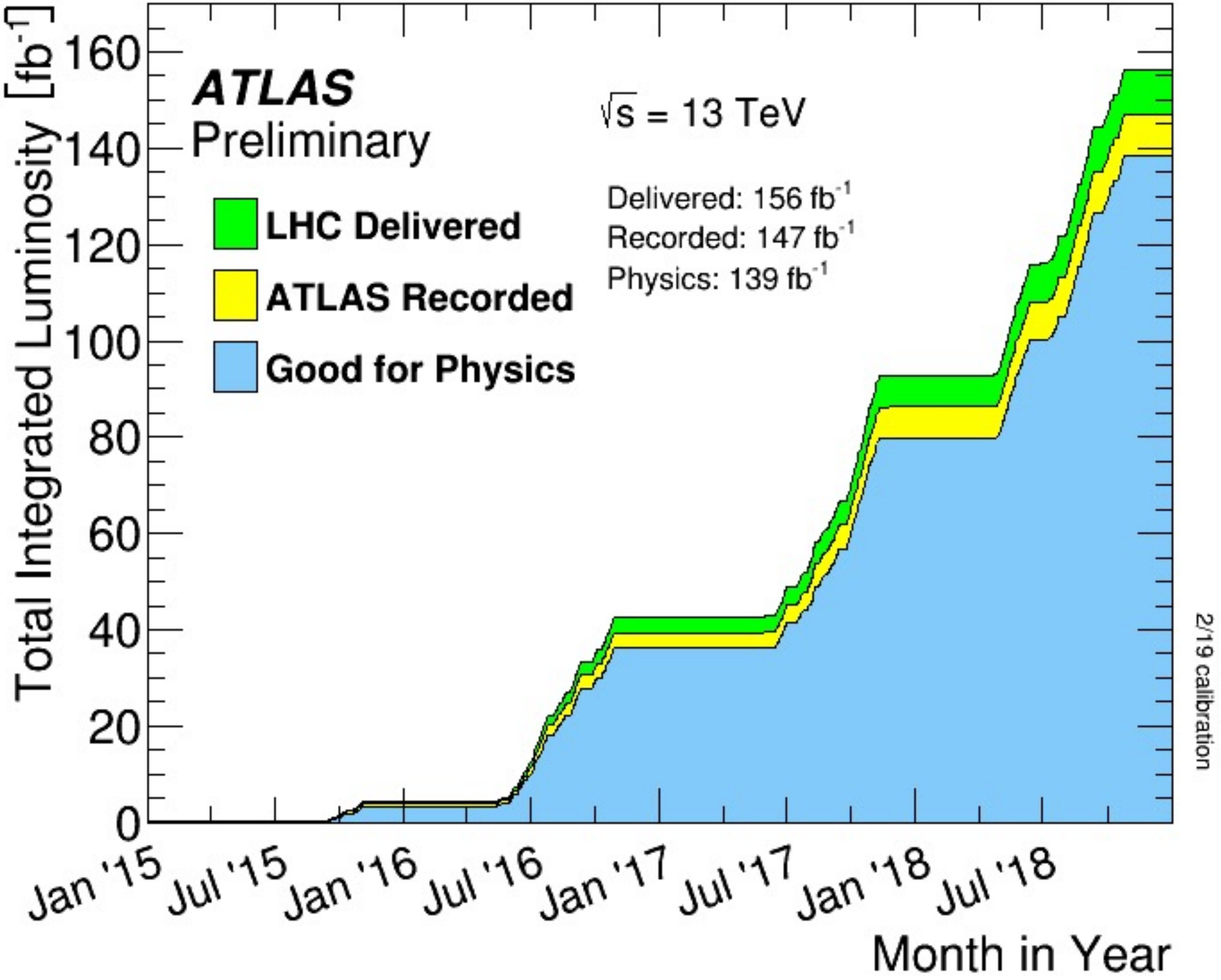
$\gamma\gamma \rightarrow WW$

Phys. Lett. B816 (2021) 136190

$\sqrt{s}$ = 13 TeV

Run2 period: 2015 - 2018

Total Physics: 139 fb^{-1}



Zjj

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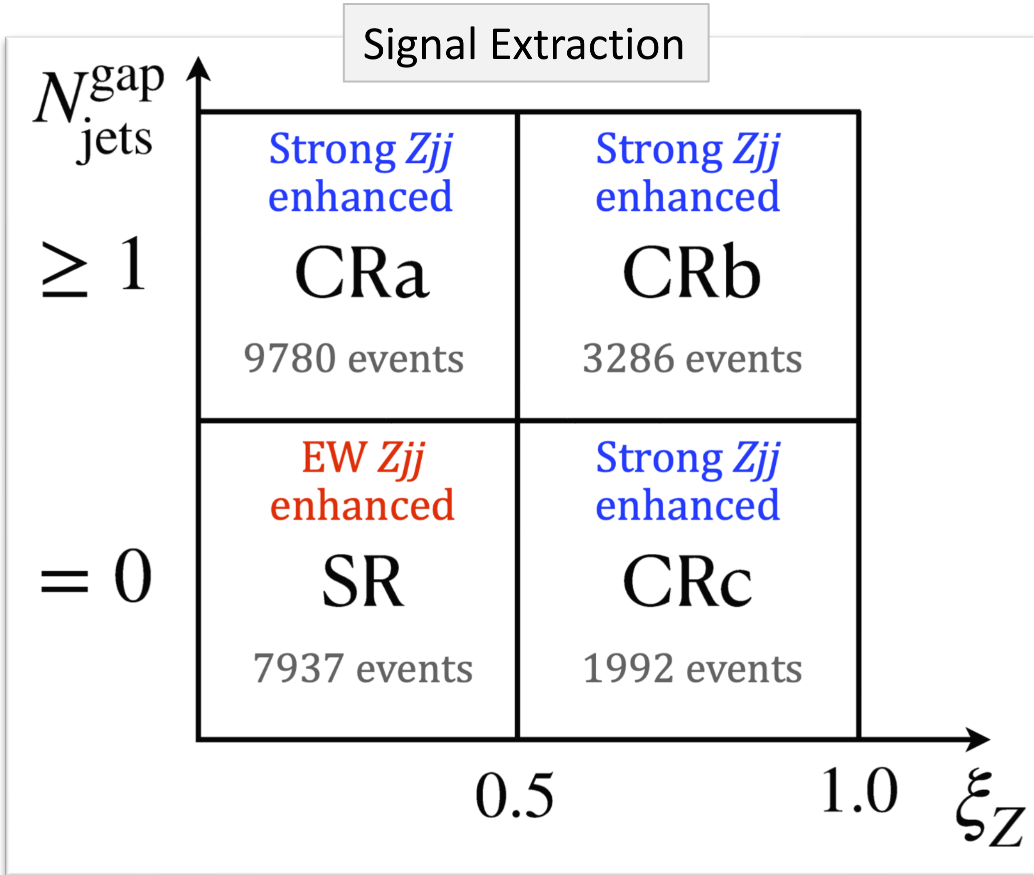
Measurement of EW Zjj with $Z \to \ell\ell$ (1/4)

EPJC 81 (2021) 163

- EW Zjj was first observed by ATLAS using Run-1 data JHEP 04 (2014) 031
- **Full Run-2 dataset, measured differential cross sections of four characteristic observables: Dijet mass m_{jj} / rapidity separation Δy_{jj} / azimuthal dijet separation $\Delta\phi_{jj}$ / leptons $p_T^{\ell\ell}$**
- $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$, with $p_T^{\ell} > 25$ GeV, $m_{\ell\ell} \in (81 - 101)$ GeV and $p_T^{\ell\ell} > 20$ GeV
- $p_T^{j} > 25$ GeV, $p_T^{j1(j2)} > 85\ (80)$ GeV, $\Delta y_{jj} > 2$ and $m_{jj} > 1000$ GeV
- Main challenge: separate strong Zjj and EW Zjj
- EW Zjj enhanced signal region using VBF topology cuts
- Strong Zjj poorly modelled in VBF topology region
- Control regions used to constrain strong Zjj prediction
- **Likelihood fit measures EW Zjj bin-by-bin**

$$\ln \mathcal{L} = -\sum \nu_{ri}(\boldsymbol{\theta}) + \sum N_{ri}^{\mathrm{data}} \ln \nu_{ri}(\boldsymbol{\theta}) - \sum \frac{\theta_s^2}{2}$$

with $\nu_{ri} = \mu_i\, \nu_{ri}^{\mathrm{EW,MC}} + \nu_{ri}^{\mathrm{strong}} + \nu_{ri}^{\mathrm{other,MC}}$



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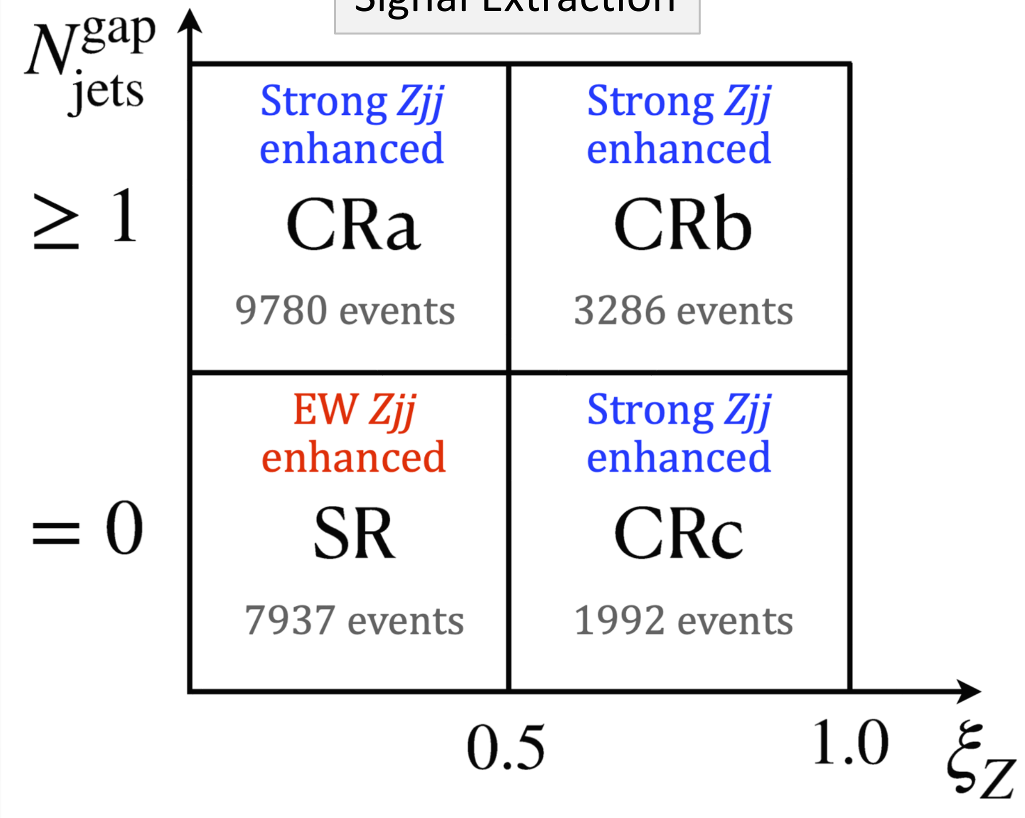
Signal Extraction



Measurement of EW Zjj with $Z \to \ell\ell$ (2/4)

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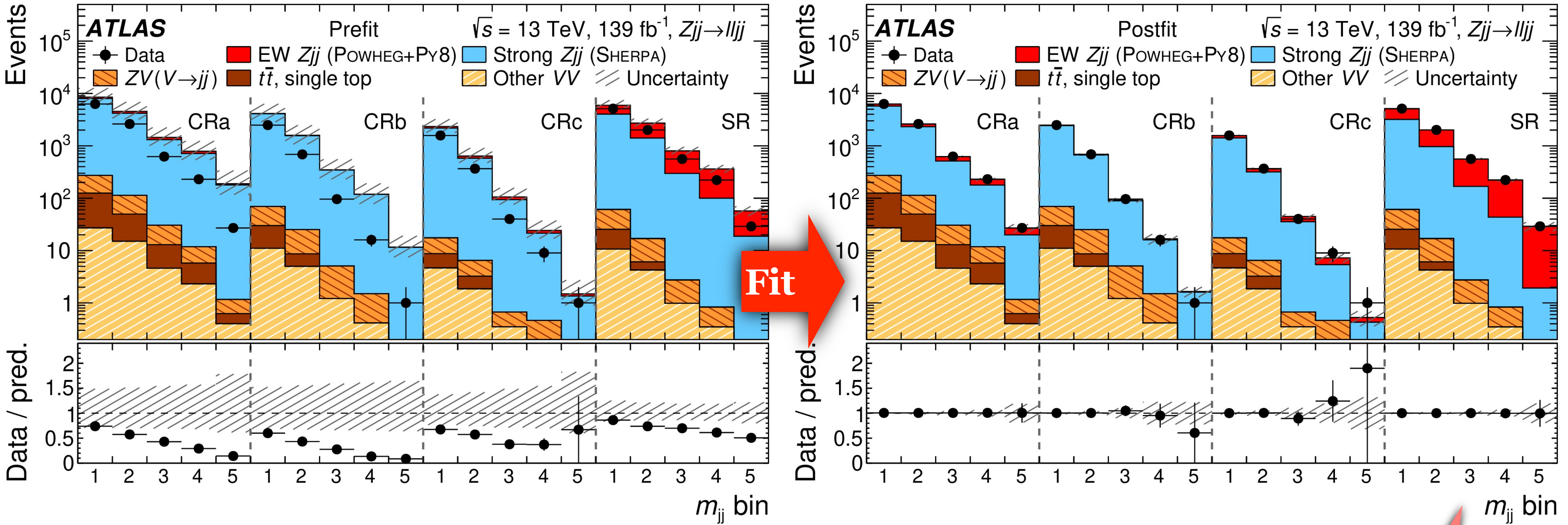

Fit: 36 **EW μ_i** and 74 parameters to constrain **strong Zjj**

- 144 measurement bins / 110 free parameters

EW Zjj measured in 5 m_{jj} bins
Analogously in 9 Δy_{jj}, 10 $p_T^{\ell\ell}$ and 12 $\Delta\phi_{jj}$ bins

Main uncertainties:

- Data statistics
- Strong generator choice (switching between 3)
- Jet systematics (JES, JER)

EW Zjj

$$\sigma_{\mathrm{EW}} = 37.4 \pm 3.5\ (\mathrm{stat}) \pm 5.5\ (\mathrm{syst})\ \mathrm{fb}.$$

Measurement of EW Zjj with $Z \to \ell\ell$ (3/4)

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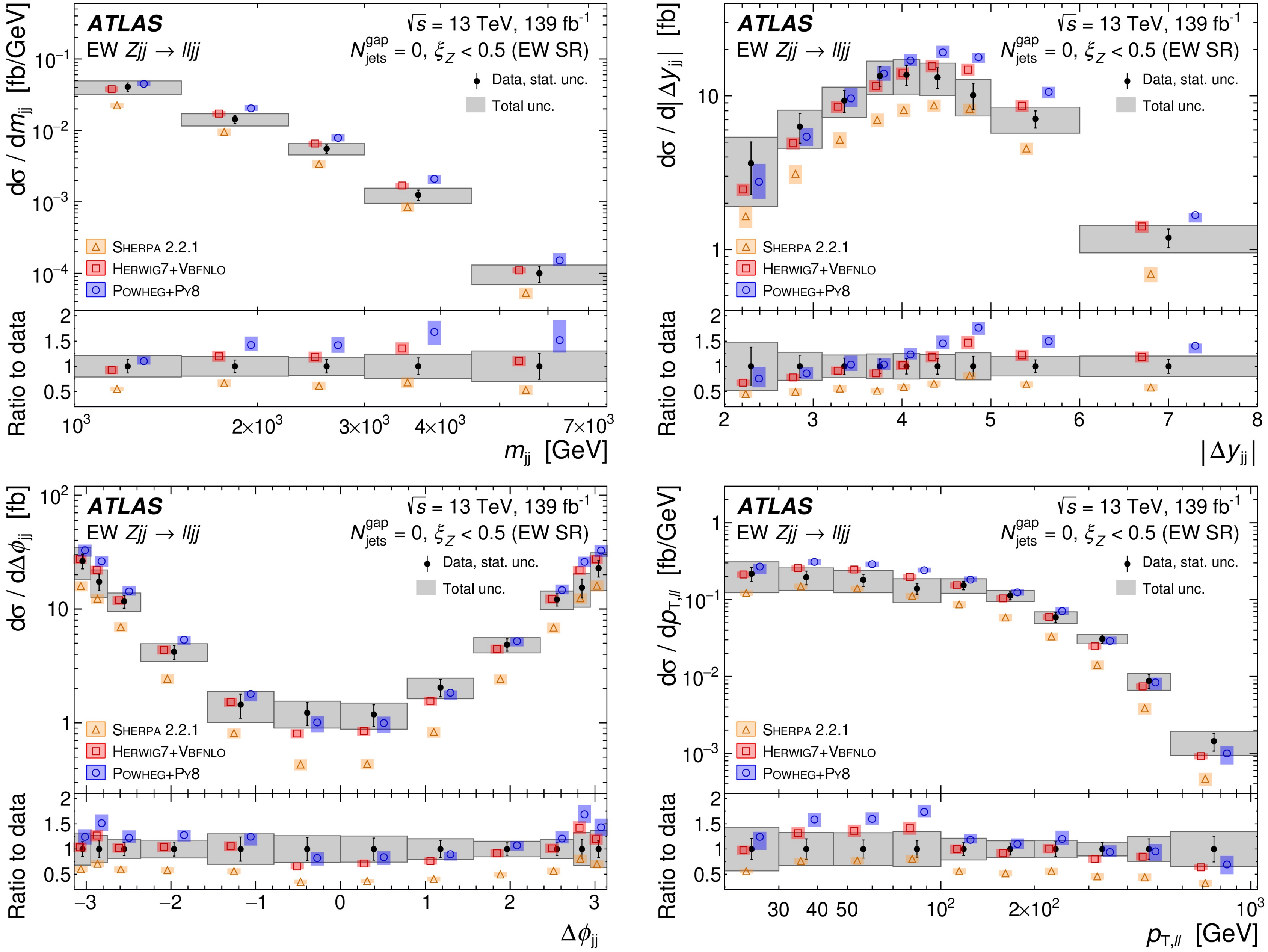
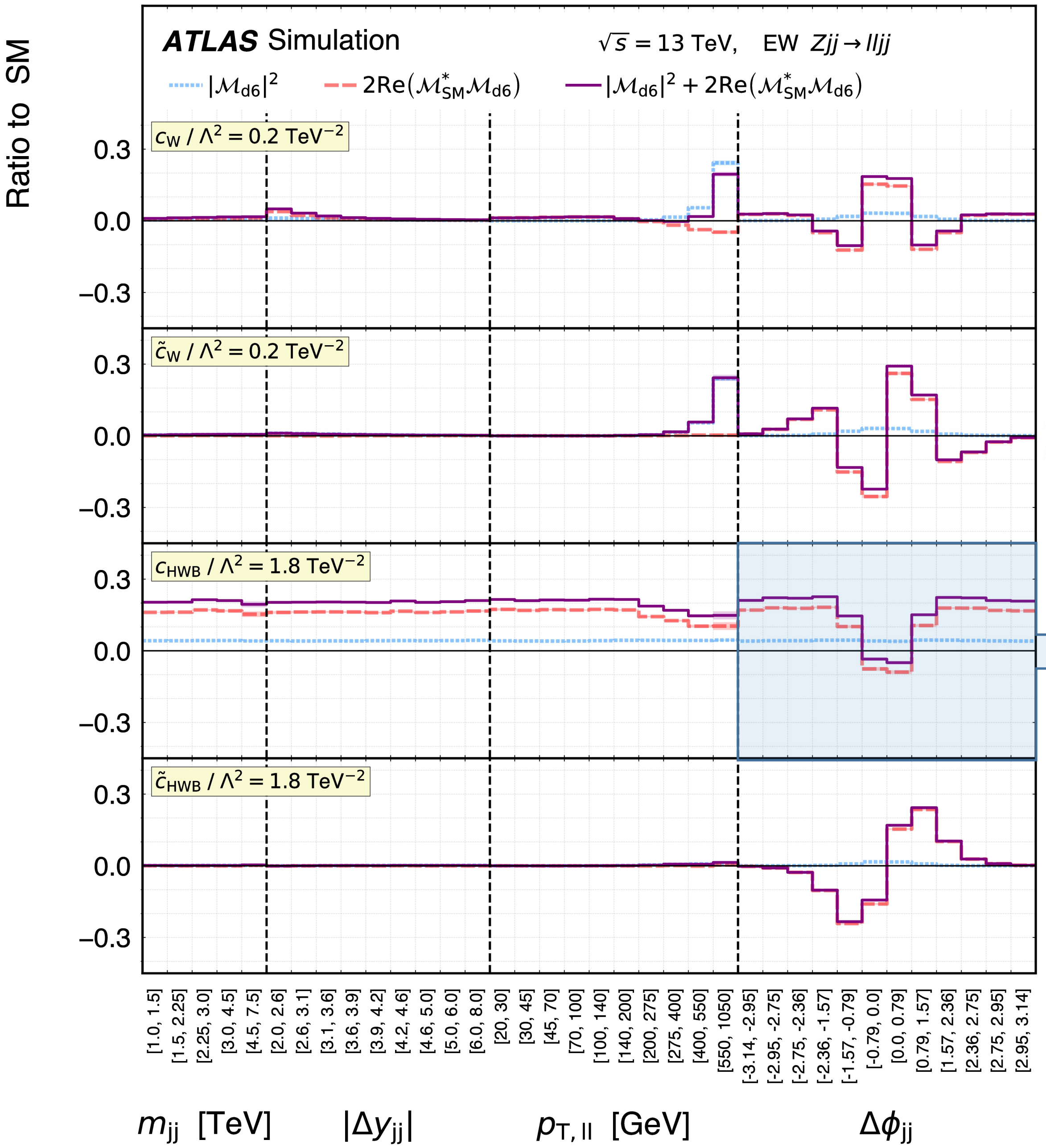
- **EW SR Differential Cross Sections:**
  1. **dijet mass m_{jj}**
  2. **rapidity separation Δy_{jj}**
  3. **azimuthal dijet separation $\Delta\phi_{jj}$**
  4. **leptons $p_T^{\ell\ell}$**
- Measured event yields are corrected to **particle level** (iterative Bayesian unfolding)
- **Measurements compared to various MC prediction**
  - **Guidance on generator choice; refinement of parameter settings**
  - **Herwig7+V_{BFNLO} in reasonable agreement with the data for all measured distributions.**
- EW+strong differential cross sections measured separately
- EW differential cross sections are used to set limits on BSM models using an EFT framework
  - $\Delta\phi_{jj}$ is CP-odd and very sensitive to certain Wilson coefficients (c_W)



Measurement of EW Zjj with $Z \to \ell\ell$ (4/4)

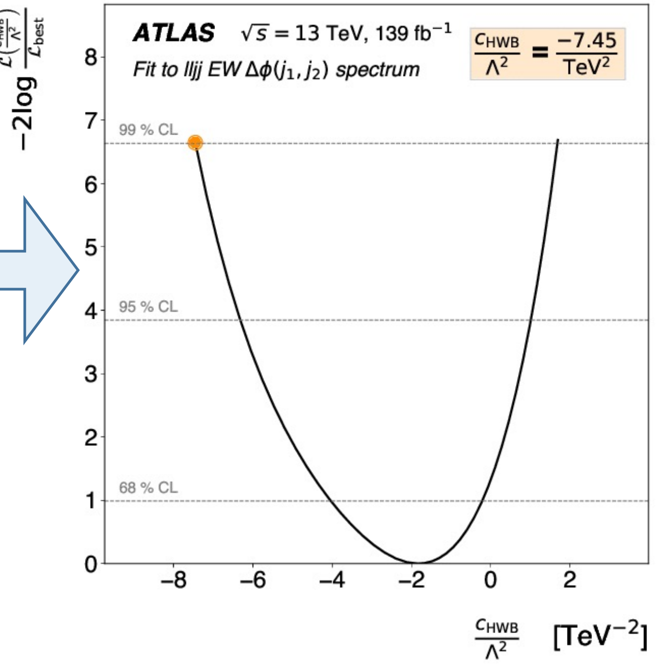
EPJC 81 (2021) 163

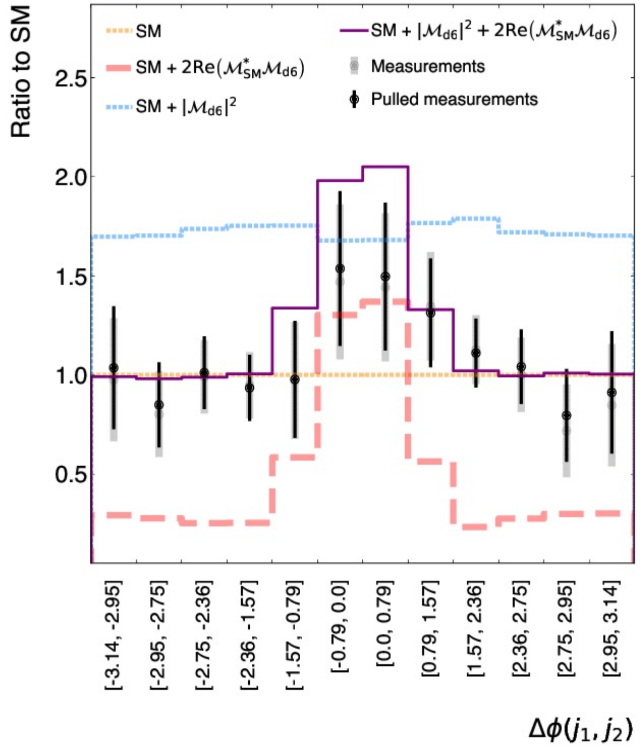


Effective Field Theory (EFT) to **test anomalous coupling** and deviations from the SM attributed to dimension-six corrections in the **WWZ** vertex by exploiting the sensitivity of the signed $\Delta\phi_{jj}$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + 2\,\text{Re}(\mathcal{M}^*_{\text{SM}} \mathcal{M}_{\text{d6}}) + |\mathcal{M}_{\text{d6}}|^2$$





Overall, the results are consistent with the SM.

$ZZjj$

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EW $ZZjj$ candidate

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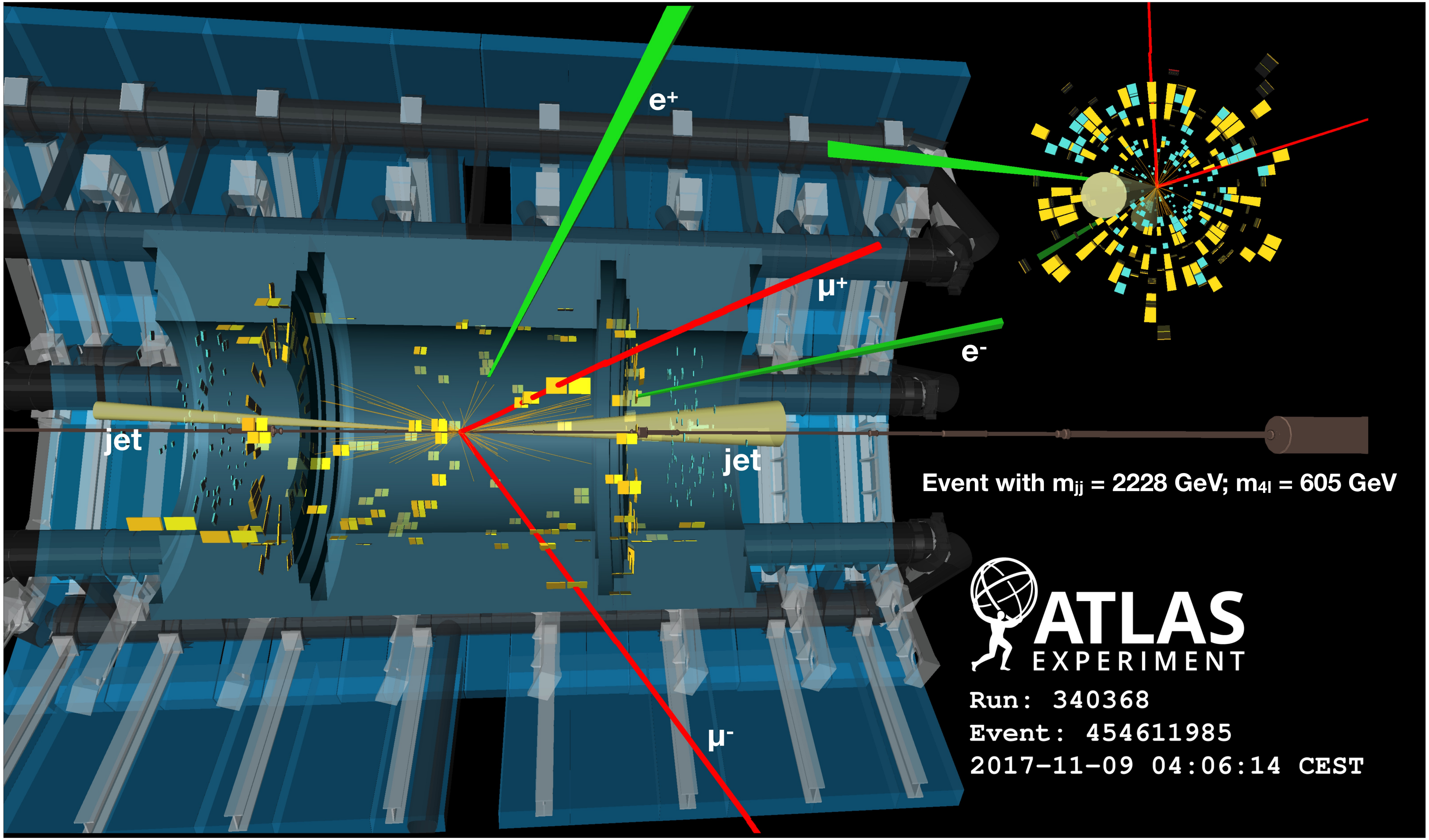

Observation of EW $ZZjj$ (1/3)

arXiv.2004.10612

- **EW $ZZjj$**: very rare; unique sensitivity to non-SM **quartic $ZZZZ$ coupling**
- Main challenge: separate **EW $ZZjj$** from **strong $ZZjj$ production** / Use b-jet veto to reduce $t\bar{t}$
- Decay channels: $ZZjj \to 4\ell jj$ and $ZZjj \to \ell\ell\nu\nu jj$ [OSSF = opposite-sign, same-flavour leptons]
- Modelling of **strong $ZZjj$** validated in **EW-suppressed CR** defined by $\xi > 0.5$ for at least one Z
- **Multivariate Discriminants (MDs)** based on Gradient Boosted Decision Tree algorithm are trained with simulated events using TMVA framework to separate **EW $ZZjj$** from backgrounds

	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
Electrons	$p_T > 7$ GeV, $\|\eta\| < 2.47$ $\|d_0/\sigma_{d_0}\| < 5$ and $\|z_0 \times \sin\theta\| < 0.5$ mm	(same for both)
Muons	$p_T > 7$ GeV, $\|\eta\| < 2.7$ $\|d_0/\sigma_{d_0}\| < 3$ and $\|z_0 \times \sin\theta\| < 0.5$ mm (both)	$p_T > 7$ GeV, $\|\eta\| < 2.5$
Jets	$p_T > 30$ (40) GeV for $\|\eta\| < 2.4$ ($2.4 < \|\eta\| < 4.5$)	$p_T > 60$ (40) GeV for the leading (sub-leading) jet
ZZ selection	$p_T > 20, 20, 10$ GeV for the leading, sub-leading and third leptons Two OSSF lepton pairs with smallest $\|m_{\ell^+\ell^-} - m_Z\| + \|m_{\ell'^+\ell'^-} - m_Z\|$ $m_{\ell^+\ell^-} > 10$ GeV for lepton pairs $\Delta R(\ell, \ell') > 0.2$ $66 < m_{\ell^+\ell^-} < 116$ GeV	$p_T > 30$ (20) GeV for the leading (sub-leading) lepton One OSSF lepton pair and no third leptons $80 < m_{\ell^+\ell^-} < 100$ GeV No b-tagged jets E_T^{miss}-significance > 12
Dijet selection	Two most energetic jets with $y_{j_1} \times y_{j_2} < 0$ (both) $m_{jj} > 300$ GeV and $\Delta y(jj) > 2$	$m_{jj} > 400$ GeV and $\Delta y(jj) > 2$

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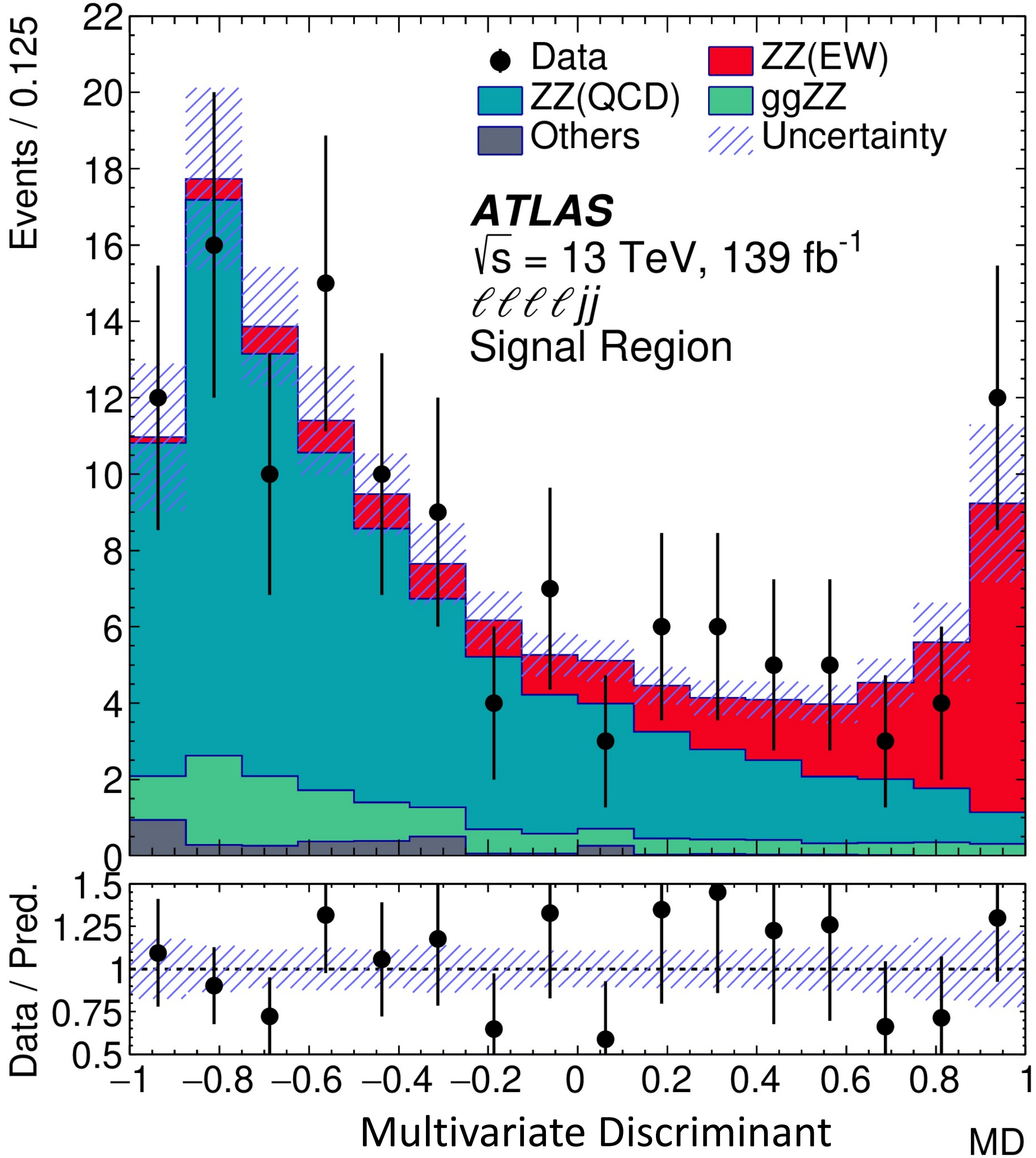
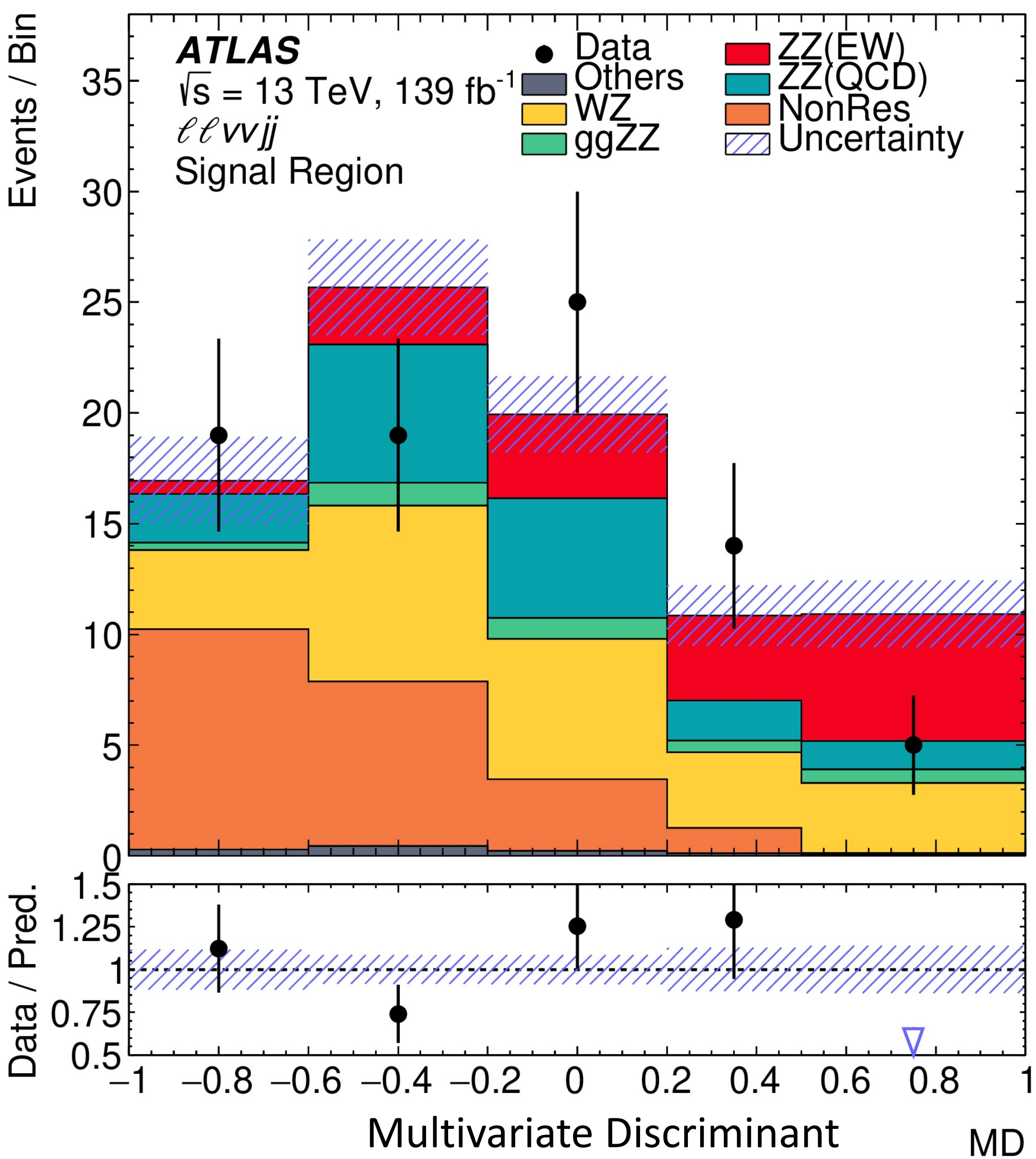


Multivariate Discriminant with twelve input variables



Multivariate Discriminant with thirteen input variables

Observation of EW $ZZjj$ (3/3)

arXiv.2004.10612

- EW and strong $ZZjj$ measurements: $\mu_{EW} = 1.35 \pm 0.34$ and $\mu_{strong} = 0.96 \pm 0.22$
  - EW $ZZjj$ significance: 5.5σ (4.3σ expected)

Statistical Fit

Process	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
EW $ZZjj$	20.6 ± 2.5	12.3 ± 0.7
QCD $ZZjj$	77 ± 25	17.2 ± 3.5
QCD $ggZZjj$	13.1 ± 4.4	3.5 ± 1.1
Non-resonant-$\ell\ell$	–	21.4 ± 4.8
WZ	–	22.8 ± 1.1
Others	3.2 ± 2.1	1.2 ± 0.9
Total	114 ± 26	78.4 ± 6.2
Data	127	82

- Inclusive EW + Strong fiducial cross sections measured for $4\ell jj$ and $\ell\ell\nu\nu jj$ separately

	Measured fiducial σ [fb]	Predicted fiducial σ [fb]
$\ell\ell\ell\ell jj$	$1.27 \pm 0.12(\text{stat}) \pm 0.02(\text{theo}) \pm 0.07(\text{exp}) \pm 0.01(\text{bkg}) \pm 0.03(\text{lumi})$	$1.14 \pm 0.04(\text{stat}) \pm 0.20(\text{theo})$
$\ell\ell\nu\nu jj$	$1.22 \pm 0.30(\text{stat}) \pm 0.04(\text{theo}) \pm 0.06(\text{exp}) \pm 0.16(\text{bkg}) \pm 0.03(\text{lumi})$	$1.07 \pm 0.01(\text{stat}) \pm 0.12(\text{theo})$

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$\gamma\gamma \rightarrow WW$

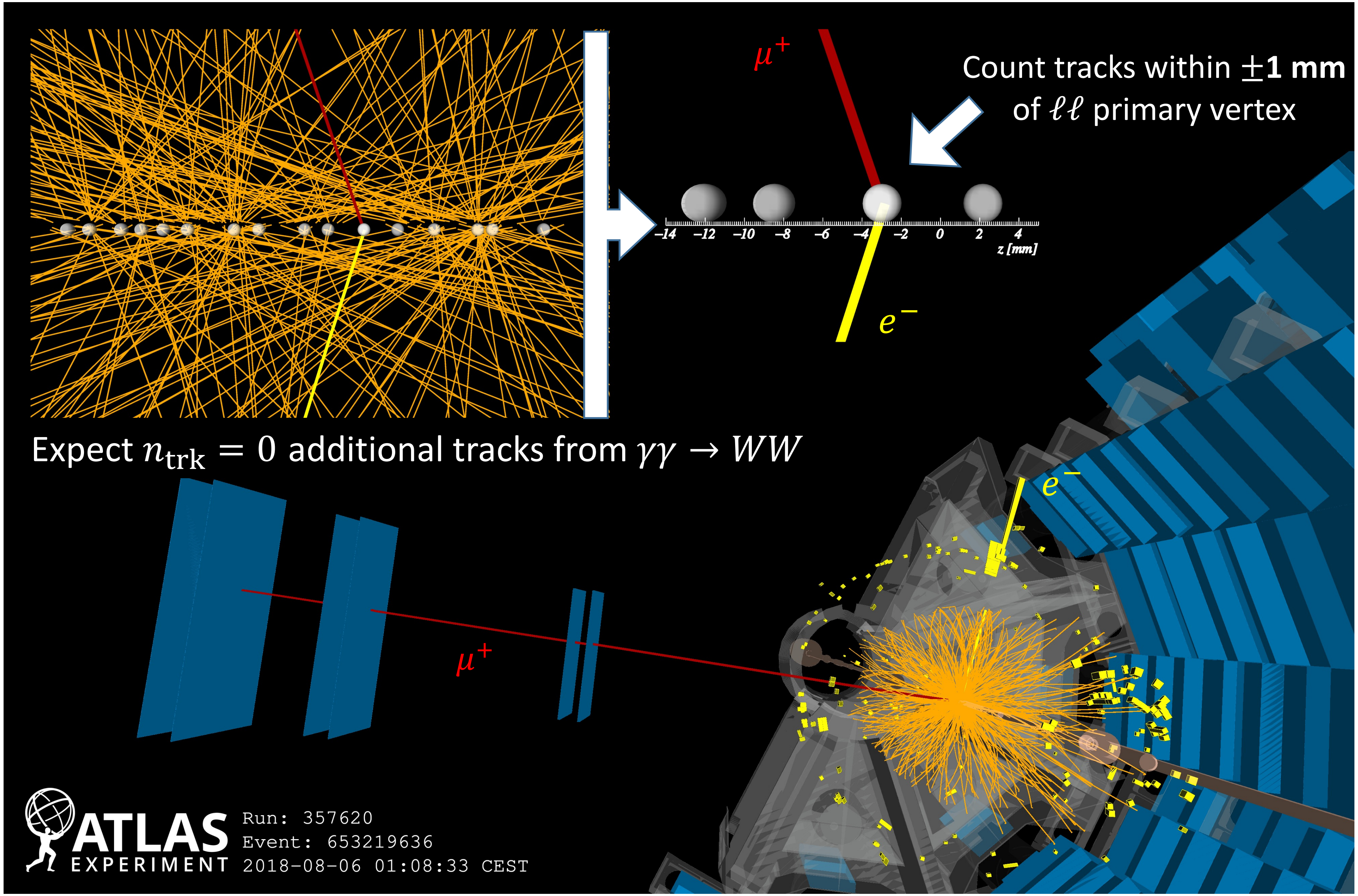
Physics Letters B
Volume 816, 10 May 2021, 136190

Observation of photon-induced W^+W^- production in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector

The ATLAS Collaboration★

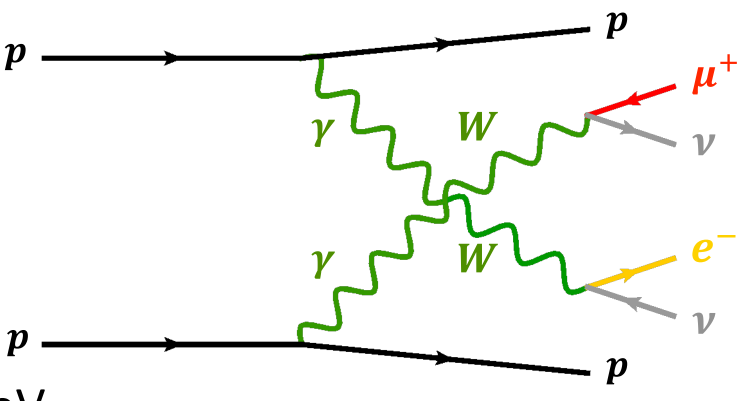
Observation of $\gamma\gamma \rightarrow WW$

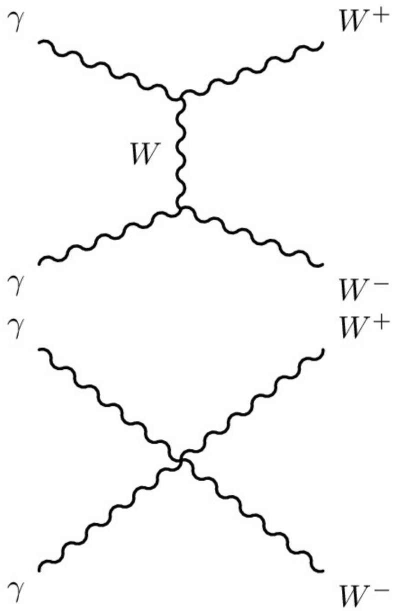
Phys. Lett. B 816 (2021) 136190



Observation of $\gamma\gamma \rightarrow WW$

Phys. Lett. B 816 (2021) 136190

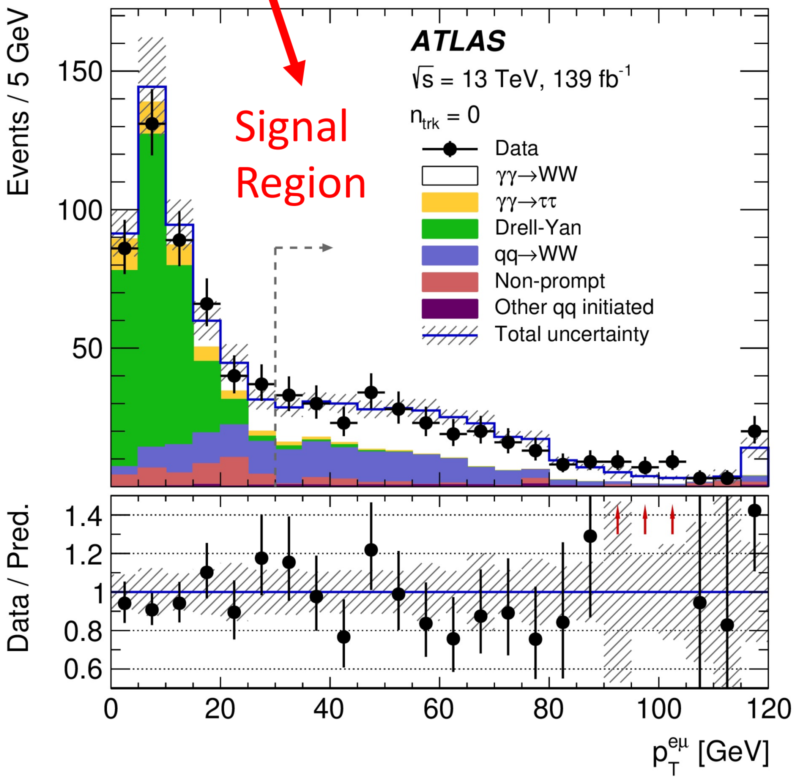


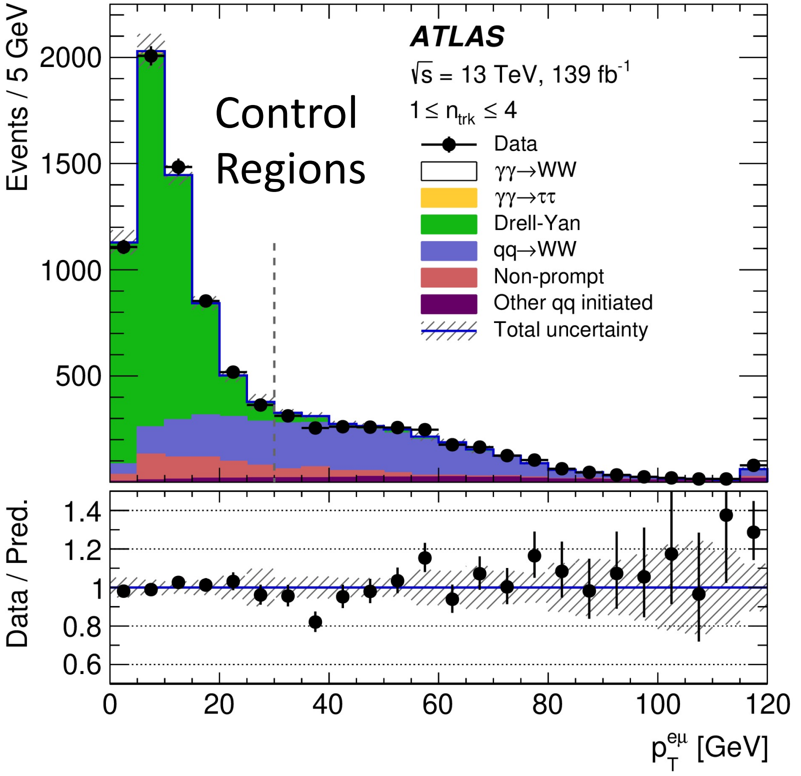


- Photon-photon scattering: incoming protons intact or fragment outside acceptance
- $WW \rightarrow e\nu\mu\nu$ **very clean**; opposite charged ℓ, no other tracks
- **Analysis** selects $\ell^{\pm}\ell^{\mp}$ events, fulfilling:
  $p_{\mathrm{T}}^{\ell 1} > 27$ GeV, $p_{\mathrm{T}}^{\ell 2} > 20$ GeV, $m_{\ell\ell} > 30$ GeV, SR: $p_{\mathrm{T}}^{e\mu} > 30$ GeV
- Expect $n_{trk} = 0$ additional tracks from $\gamma\gamma \rightarrow WW$
- Backgrounds constrained using CRs: $p_{\mathrm{T}}^{e\mu} < 30$ GeV and $n_{\mathrm{trk}} \geq 1$
- Background-only hypothesis rejected with 8.4σ significance

$\sigma_{\mathrm{fid}} = 3.13 \pm 0.31(\mathrm{stat}) \pm 0.28(\mathrm{syst})$ fb

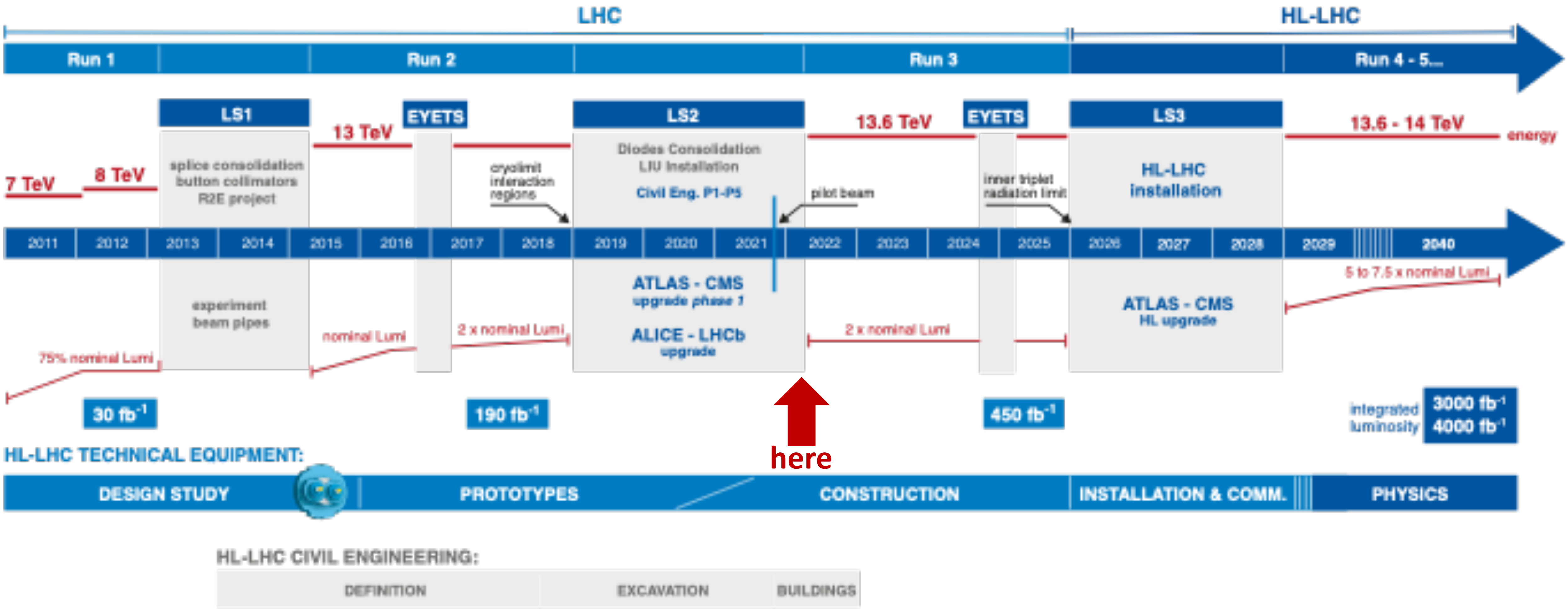
	Signal region	
n_{trk}	$n_{\mathrm{trk}} = 0$	
$p_{\mathrm{T}}^{e\mu}$	> 30 GeV	< 30 GeV
$\gamma\gamma \rightarrow WW$	174 ± 20	45 ± 6
$\gamma\gamma \rightarrow \ell\ell$	5.5 ± 0.3	39.6 ± 1.9
Drell–Yan	4.5 ± 0.9	280 ± 40
$qq \rightarrow WW$ (incl. gg and VBS)	101 ± 17	55 ± 10
Non-prompt	14 ± 14	36 ± 35
Other backgrounds	7.1 ± 1.7	1.9 ± 0.4
Total	305 ± 18	459 ± 19
Data	307	449





LHC / HL-LHC Plan

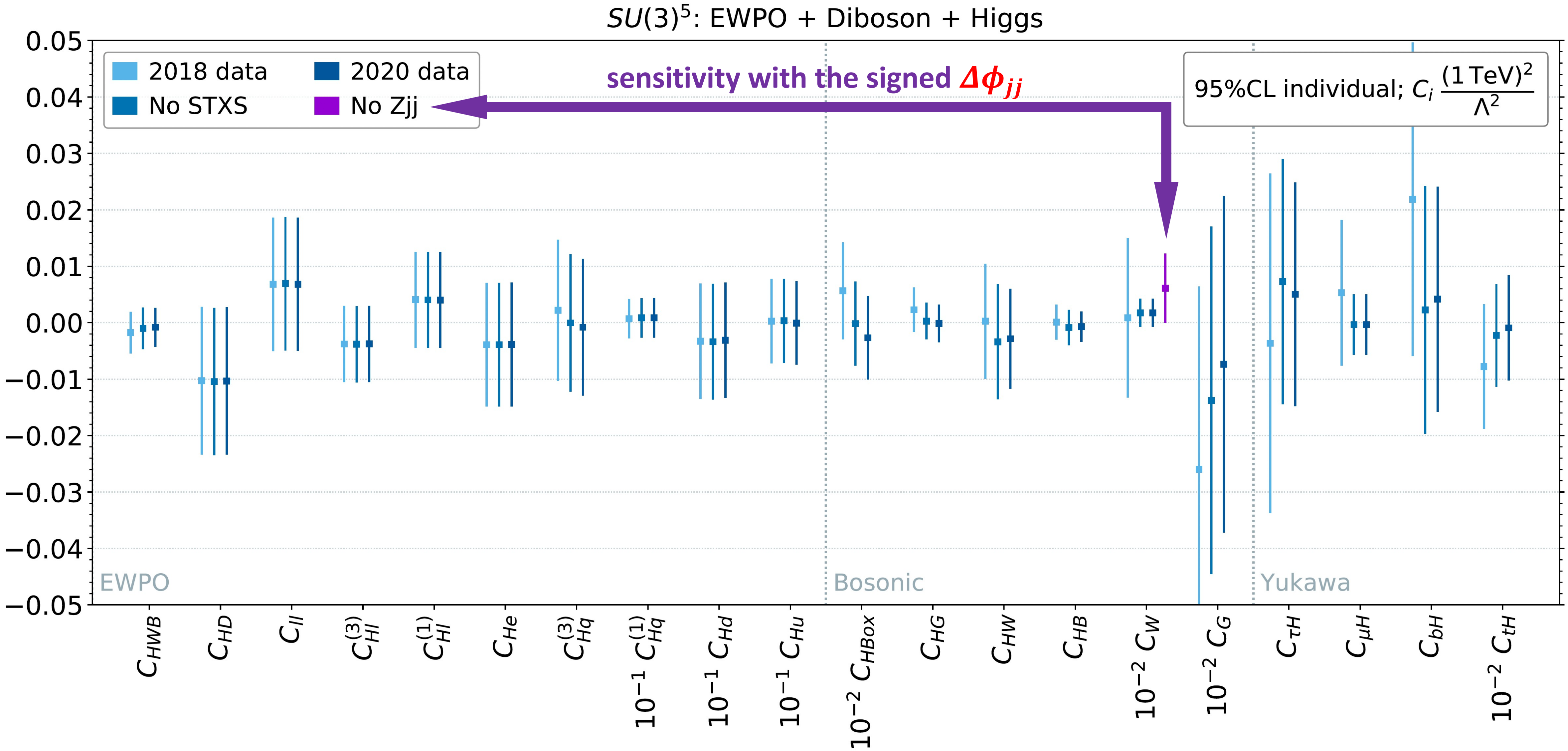
Update 07 March, 2022



https://hilumilhc.web.cern.ch/article/ls3-schedule-change

EW Vjj & $VVjj$ measurements in global BSM fits

John Ellis, Maeve Madigan, Ken Mimasu, Veronica Sanz & Tevong You JHEP 04 (2021) 278

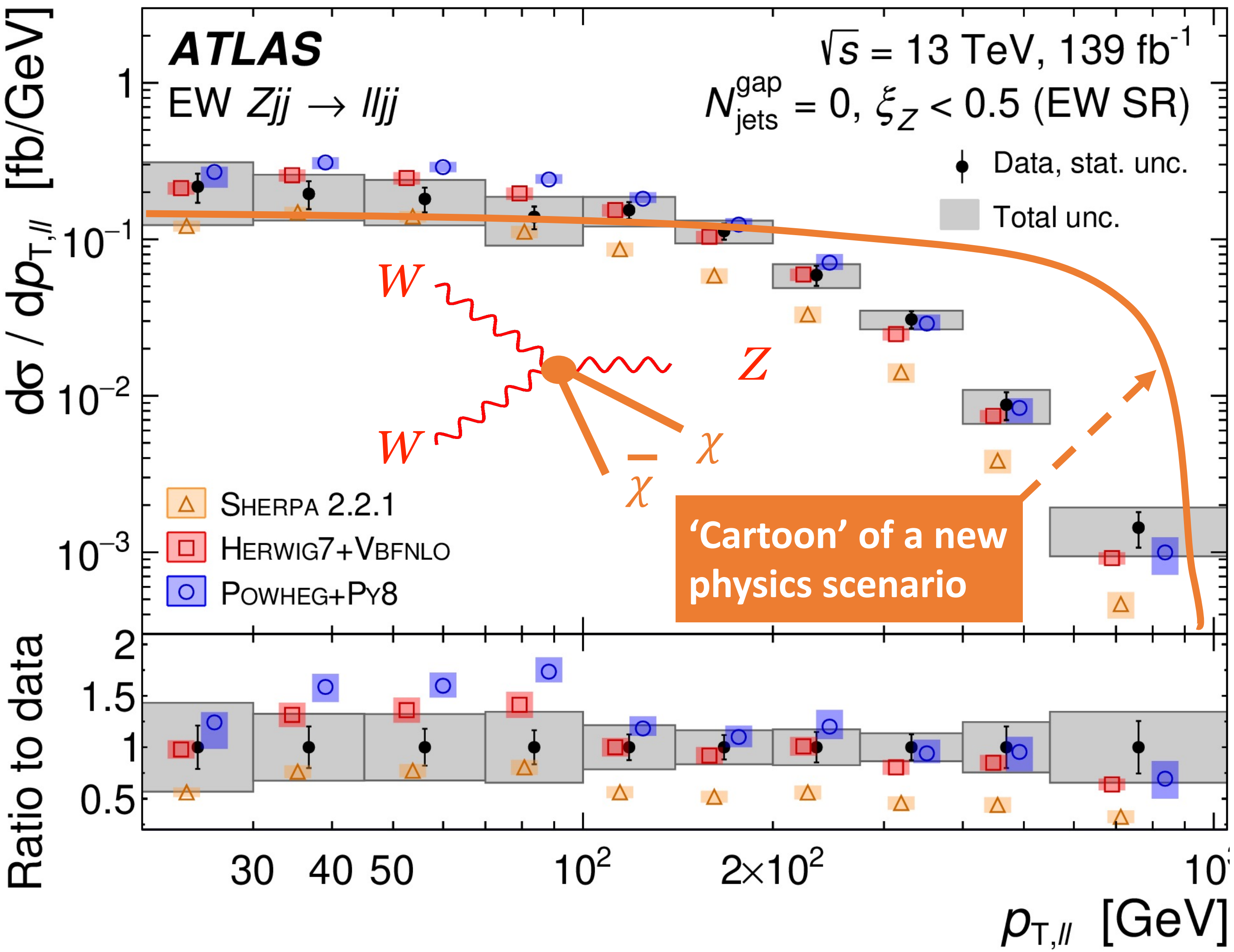


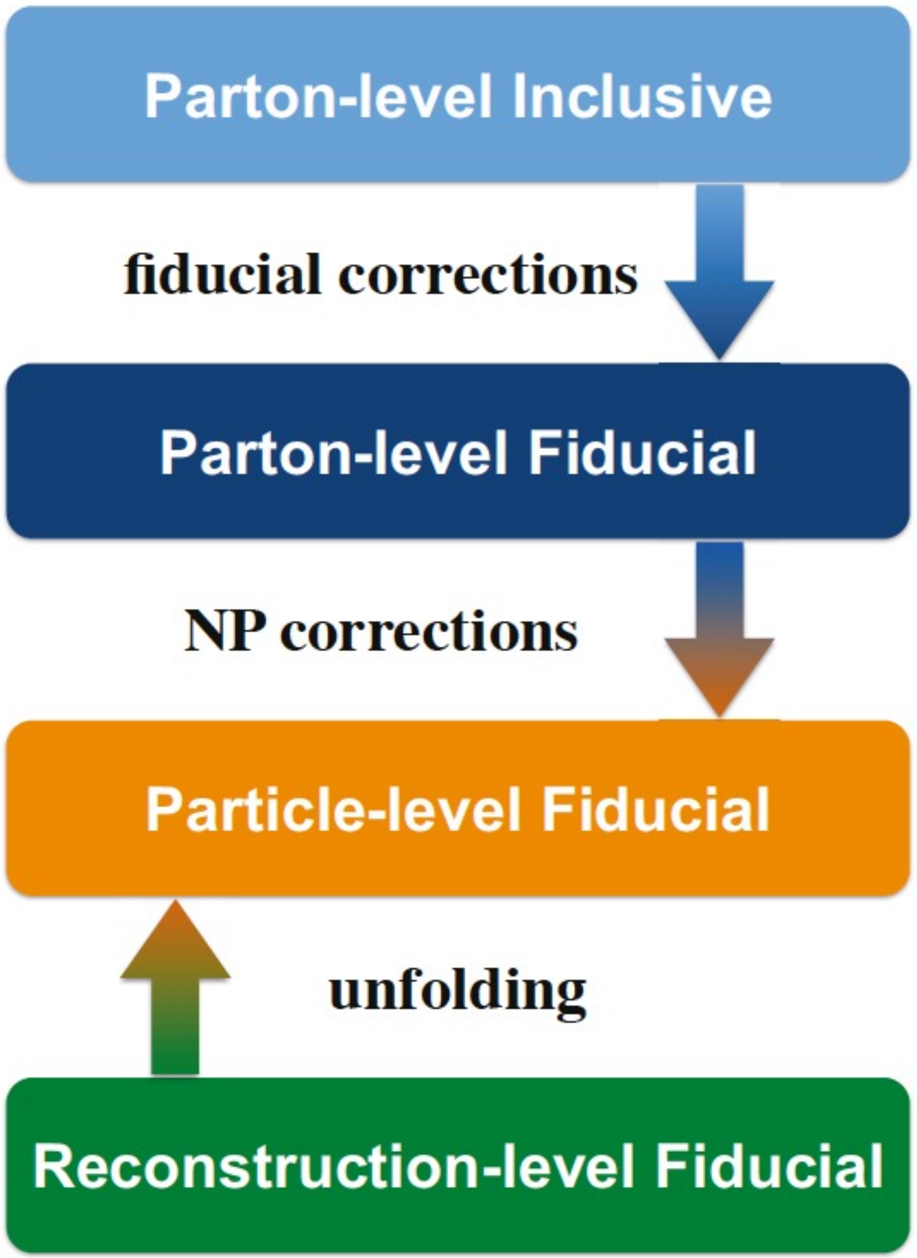
The ATLAS EW Zjj measurements helps constrain di-boson C_W in particular with

Unfolding to particle-level

EW Zjj

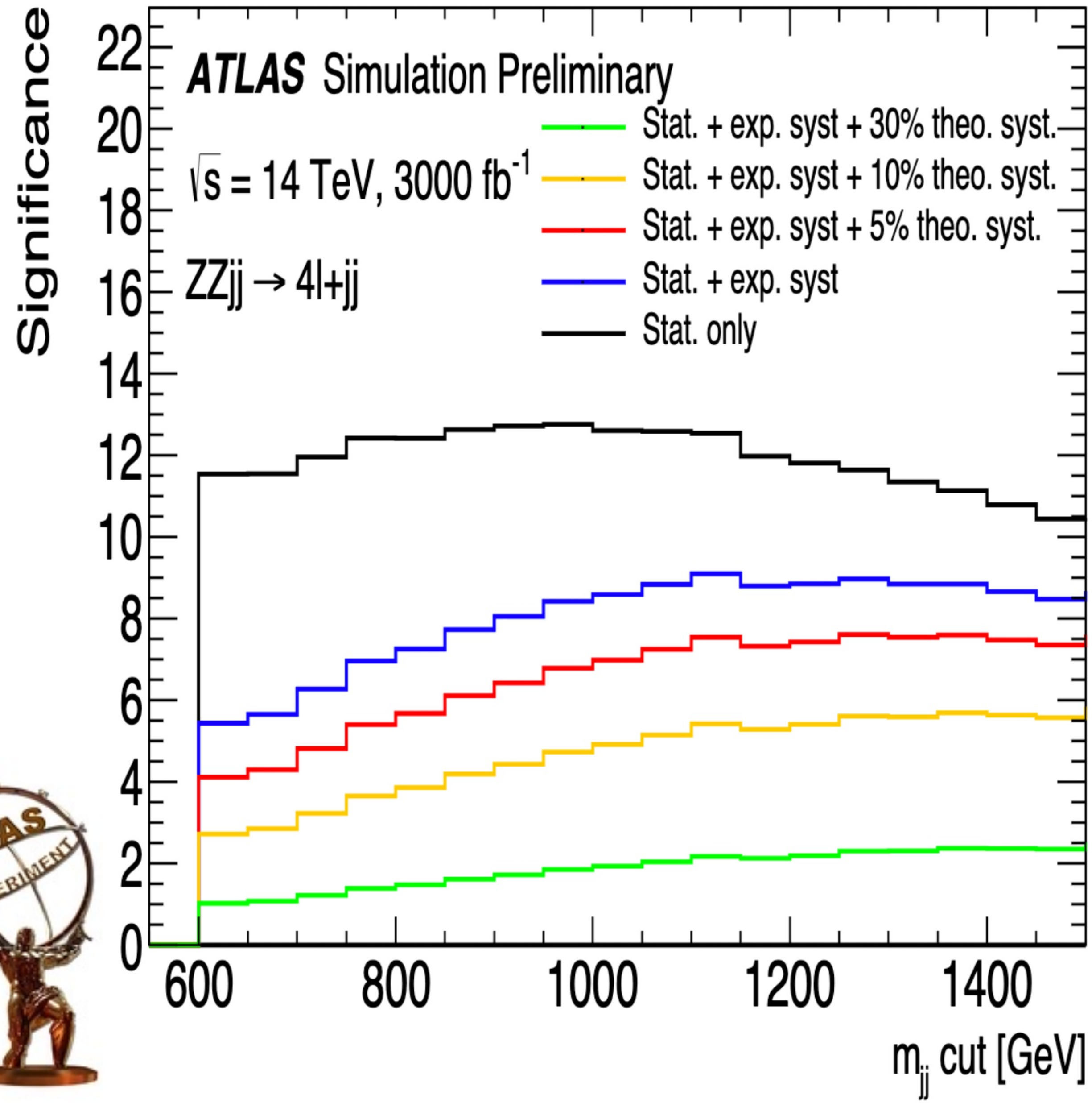
EPJC 81 (2021) 163





Prospect at HL-LHC: EW $ZZjj$

Yellow Report CERN-2019-007
https://doi.org/10.23731/CYRM-2019-007



- **VBS** offers a sensitive means to search for new phenomena related to **anomalies** in the weak-boson self-interactions
- Supersymmetry, Little Higgs, or Composite Higgs models, offer alternative EWSB mechanisms that would manifest as **deviations** from the SM VBS production cross-sections at high energies.
- **Precision measurements** of high-mass VBS *ZZ* production also allow an almost model-independent measurement of the **Higgs boson width**

Summary

Today: a suite of full Run-2 ATLAS results on vector-boson fusion and scattering

Conclusion: pp → Vjj and $VVjj$ via VBF and VBS topologies provide:

- Acute exploration of electroweak symmetry breaking in all aspects
- **Self-couplings of the vector gauge bosons** are completely specified in the SM, as are the couplings of the Higgs boson to the vector bosons once the Higgs mass is known.
- Sensitivity to searches for new phenomena (physics beyond the Standard Model)
- Crucial input to Effective Field Theory (EFT) fits

- Typically, the associated **EW** production cross sections are very small → small signal swamped by large & challenging backgrounds
  - Precision analyses only recently possible due to large dataset acquired at Run-2
  - Most measurements are statistics limited
- **5σ observation established for major VBF and VBS sensitive processes & channels**
  - Focus shifting to **precision** differential cross section measurements
  - Fiducial and differential cross sections are the most model independent characterization of the events (from detector to particle-level fiducial phase space)
- Exciting **prospect** at the LHC with the larger datasets of Run-3 and beyond at HL-LHC

Acknowledgement and Thank You

Figures, slides and comments: Dag Gillberg & Stephen Weber

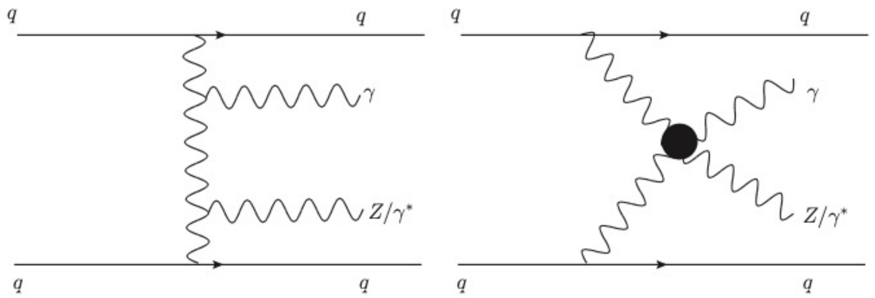
Comments and suggestions: Bing Li, Philippe Calfayan, Patrick Rieck and Danika MacDonell

Funding agencies in Canada

Covered in other DIS2022 talk by Ruchi Gupta

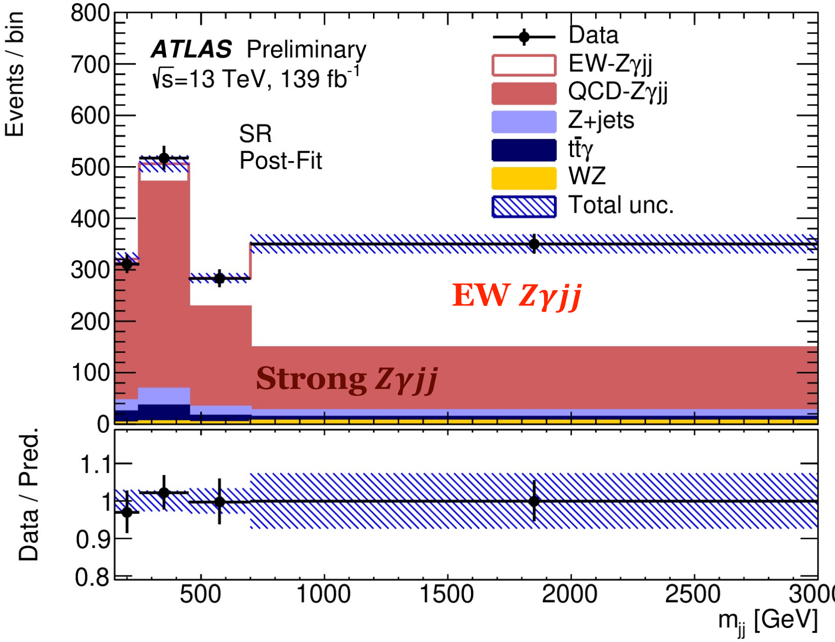
Observation of EW $Z(\ell\ell)\gamma jj$

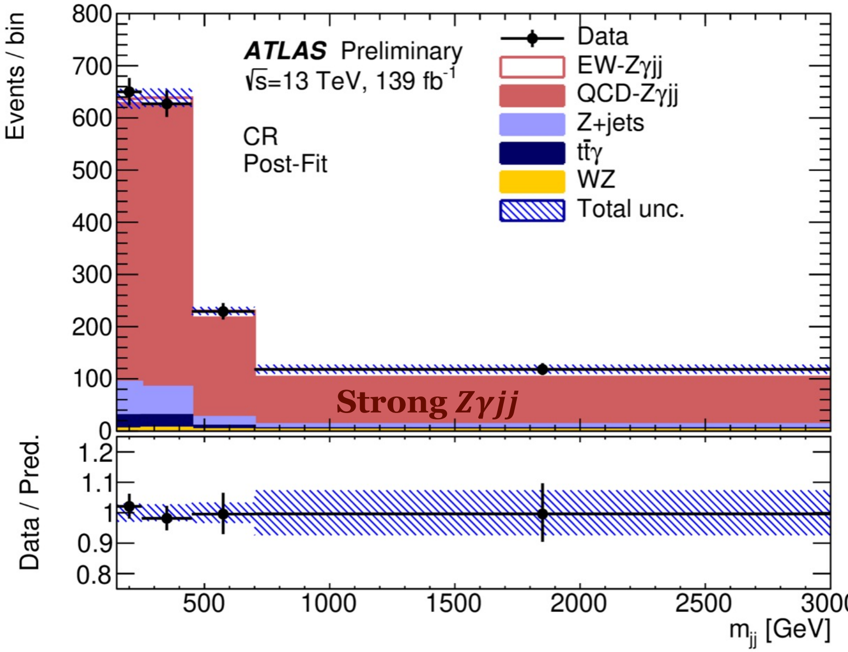
ATLAS-CONF-2021-038



- EW $Z\gamma jj$ measured in the $ee\gamma jj$ and $\mu\mu\gamma jj$ channels
- Analysis targets **VBF topology** + $Z \to \ell\ell + \gamma$:
  $p_T^{j1} > 50$ GeV, $p_T^{j2} > 50$ GeV, $p_T^{\gamma} > 25$ GeV, $m_{jj} > 150$ GeV, $\Delta y_{jj} > 1$
  $m_{\ell\ell} > 40$ GeV, and $m_{\gamma\ell\ell} + m_{\ell\ell} > 2m_Z$ (veto $Z \to \gamma\ell\ell$)
- Main backgrounds: Strong $Z\gamma jj$, Z+jets with fake γ, $t\bar{t}\gamma$
- Key observable: $Z\gamma$ centrality $\xi_{\ell\ell\gamma}$ and **SR:** $\xi_{\ell\ell\gamma} < 0.4$
- Fit performed to m_{jj} spectrum
- Observation of **EW $Z(\ell\ell)\gamma jj$** with significance well above 5σ ($\sim 10\sigma$)
- **Fiducial cross section is measured:**
  $\sigma_{EWZ\gamma}^{fid} = 4.49 \pm 0.58\, fb$
  $\sigma_{EWZ\gamma}^{pred} = 4.73 \pm 0.27\, fb$
- The EW $Z\gamma jj$ + strong cross section is measured to be:
  $20.6^{+1.4}_{-1.2}$fb (predicted: $20.4^{+2.6}_{-2.0}$fb)

$$\xi_{\ell\ell\gamma} = \left|\frac{y_{\ell\ell\gamma} - (y_{j1} + y_{j2}/2)}{y_{j1} - y_{j2}}\right| \approx (y_{\ell\ell\gamma} - y_{jj})/\Delta y_{jj}$$





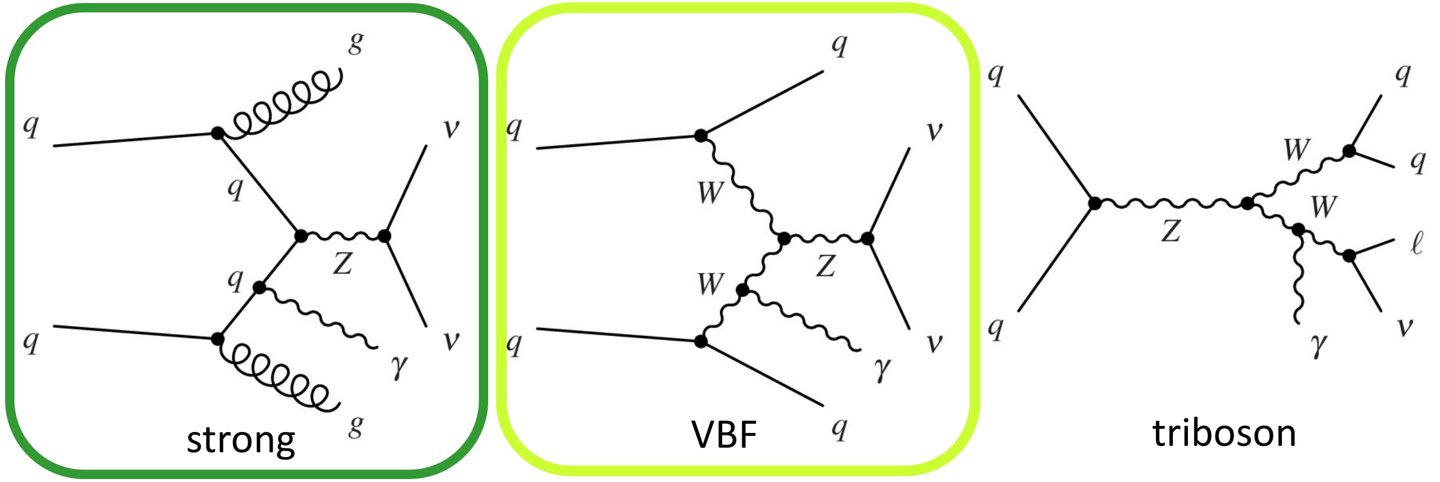
First Observation of EW $Z(\nu\nu)\gamma jj$

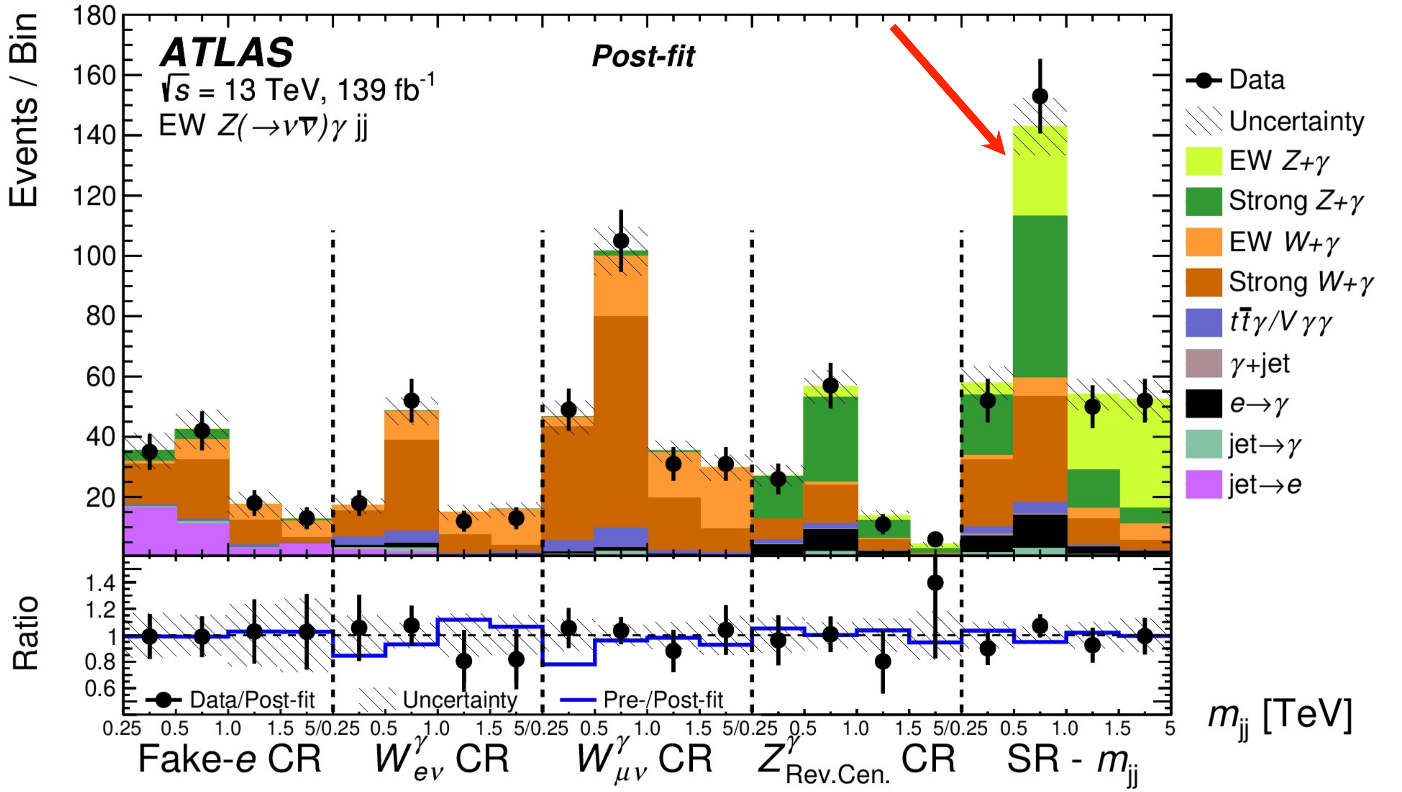
Eur. Phys. J. C 82 (2022) 105

- Strategy: target VBF topology+$E_{\mathrm{T}}^{\mathrm{miss}}$:

$p_{\mathrm{T}}^{j1} > 60$ GeV, $p_{\mathrm{T}}^{j2} > 50$ GeV, $\Delta\phi_{jj} < 2.5$
$N_\gamma = 1$, $N_\ell = 0$, $m_{jj} > 250$ GeV,
γ between jets (*i.e.* central)

- Multiple control regions to constrain backgrounds
- **EW $Z(\nu\nu)\gamma jj$** signal established with 5.2σ (5.1σ) observed (expected)
- **Measurements:**
  EW $\mu_{Z\gamma} = 1.03 \pm 0.25$
  $\sigma_{\mathrm{fid}} = 1.31 \pm 0.29$ fb
- In addition to EW $Z\gamma jj$ measurements, also sets limits on invisible / partially inv. decays of Higgs boson (VBF $H\rightarrow$invisible)

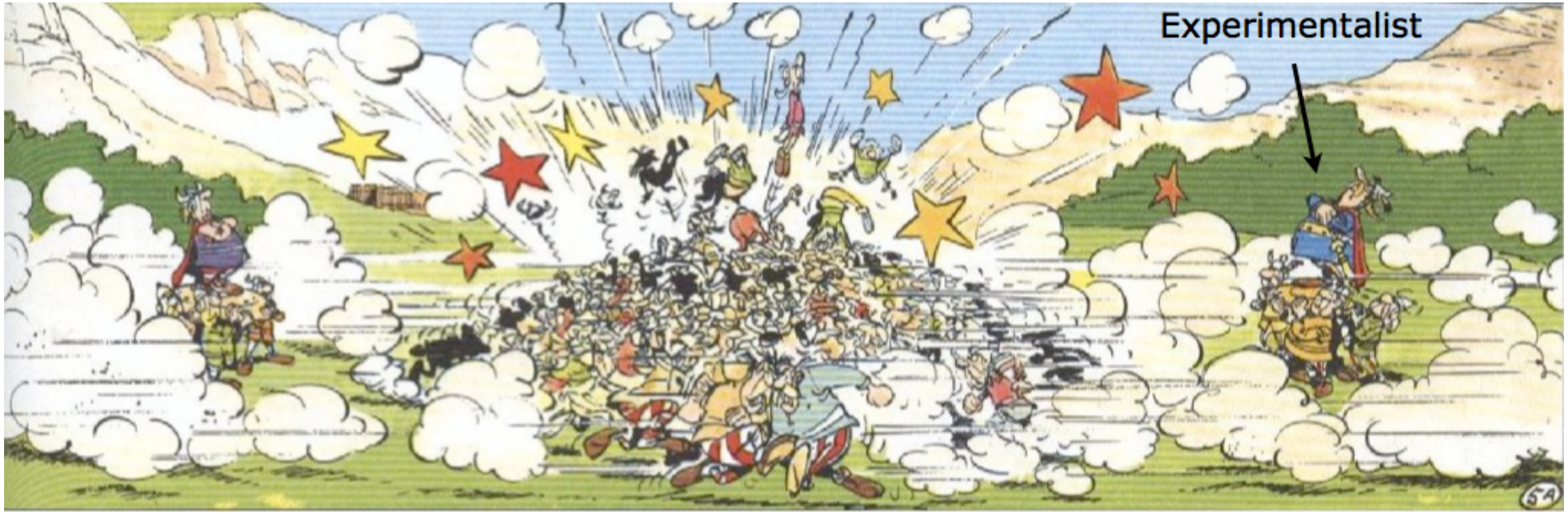


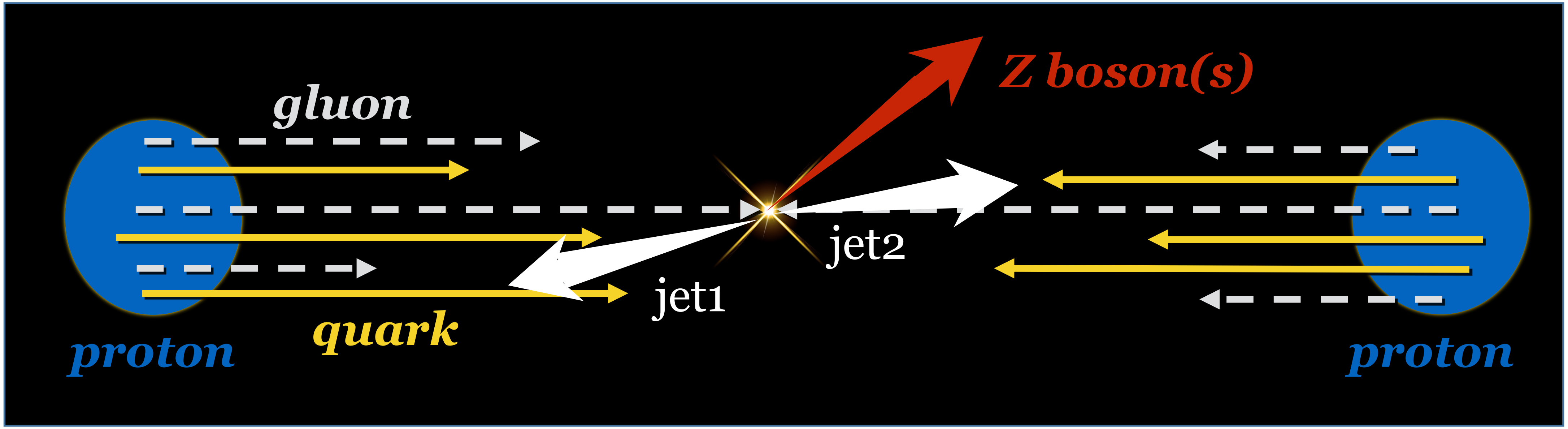


Extra backup slides

Strategy at the LHC

“Produce as many collisions as possible as fast as possible”



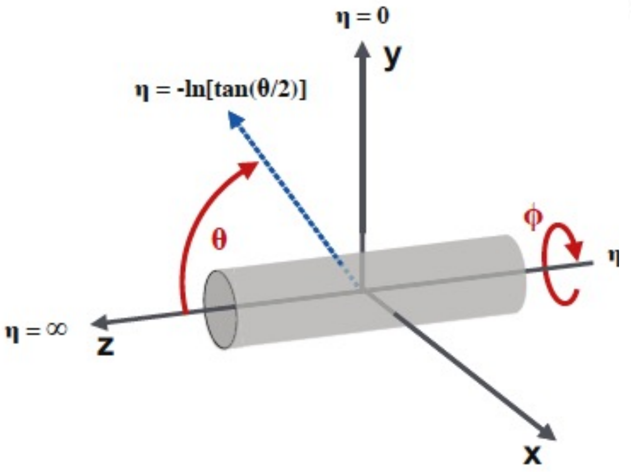


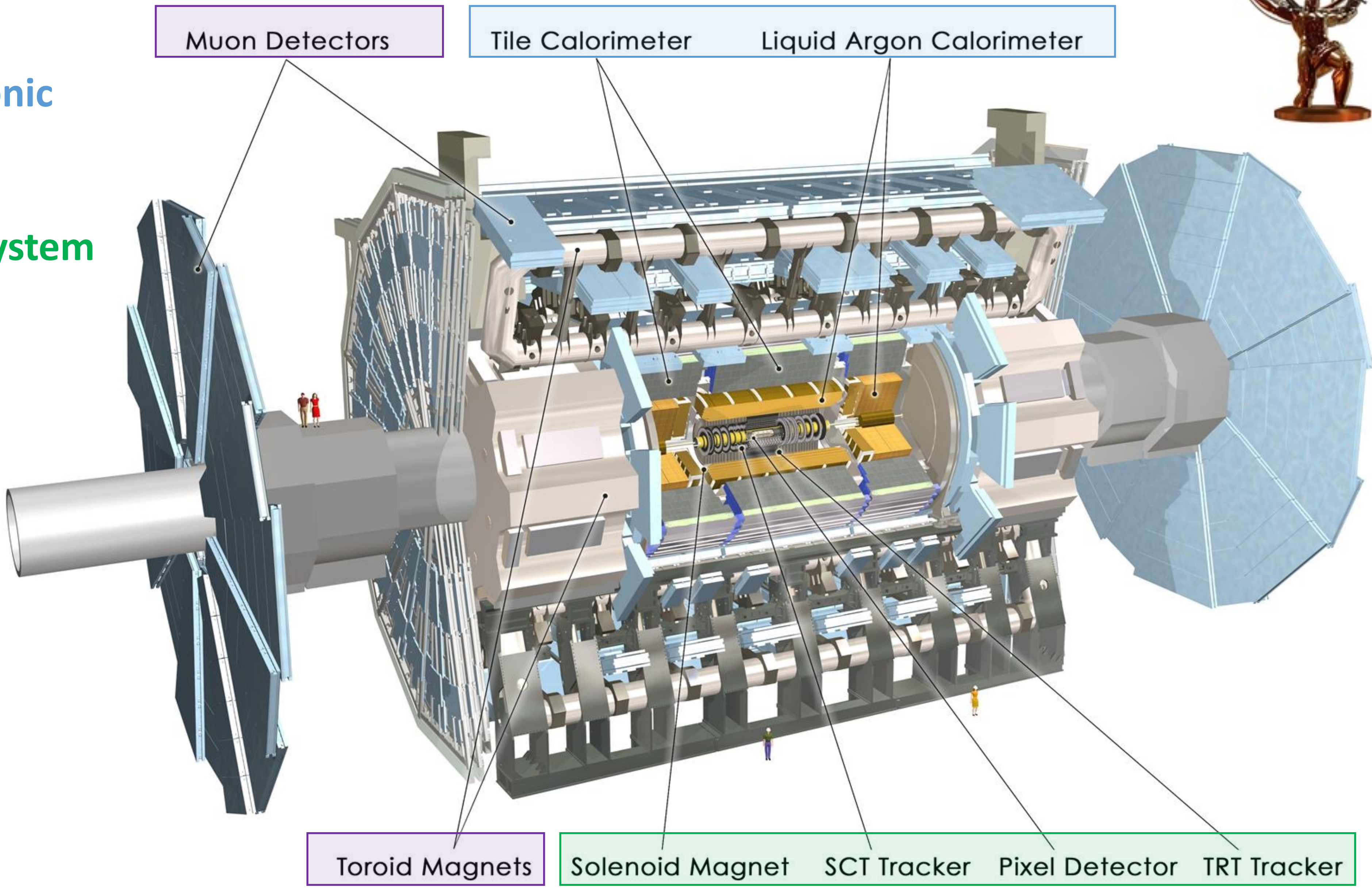
The ATLAS Detector

Electromagnetic and Hadronic Calorimeters

Charged particle tracking system

Muon spectrometer





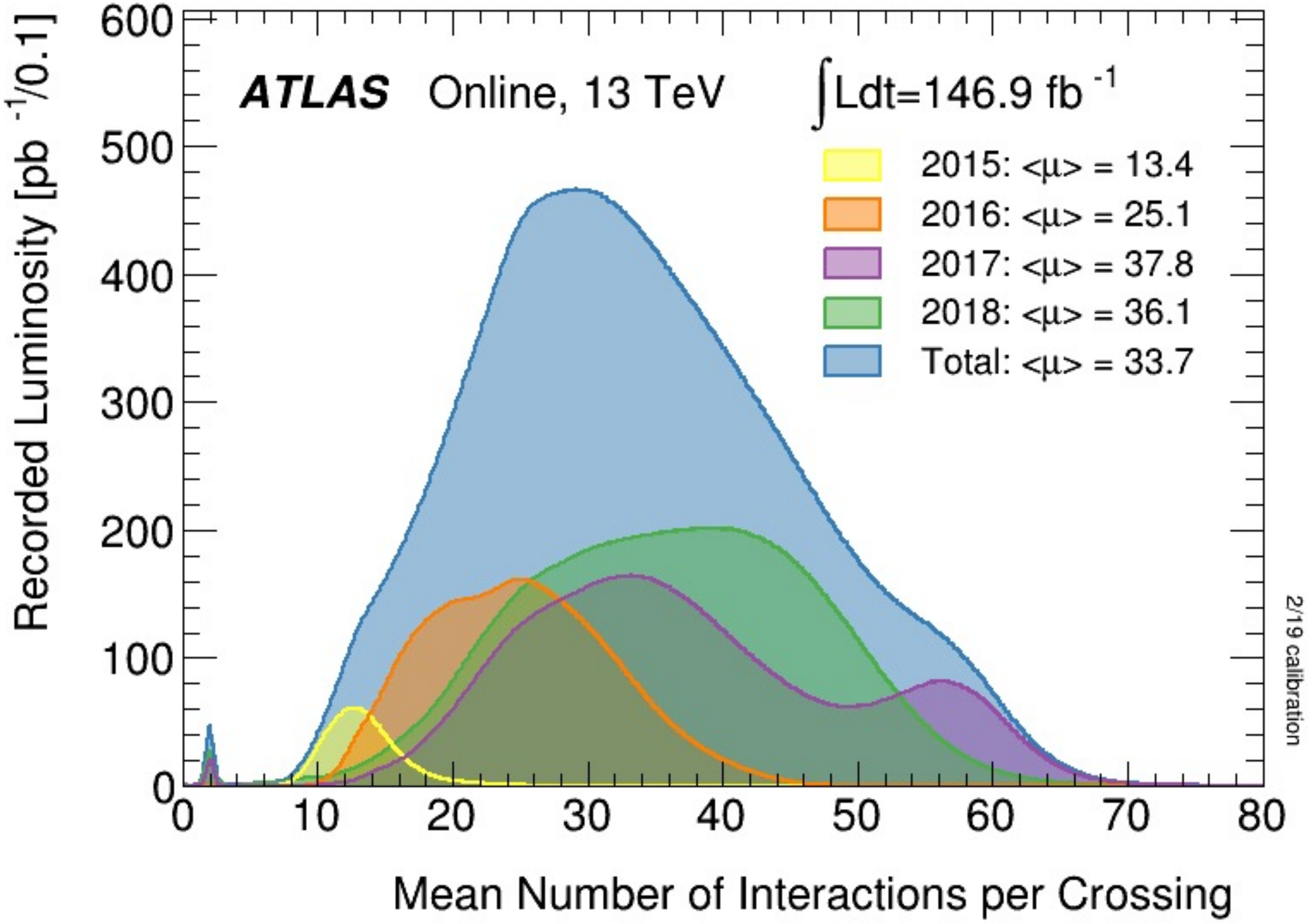
Dataset

EW Zjj
Eur. Phys. J. C 81 (2021) 163

EW $ZZjj$
arXiv.2004.10612

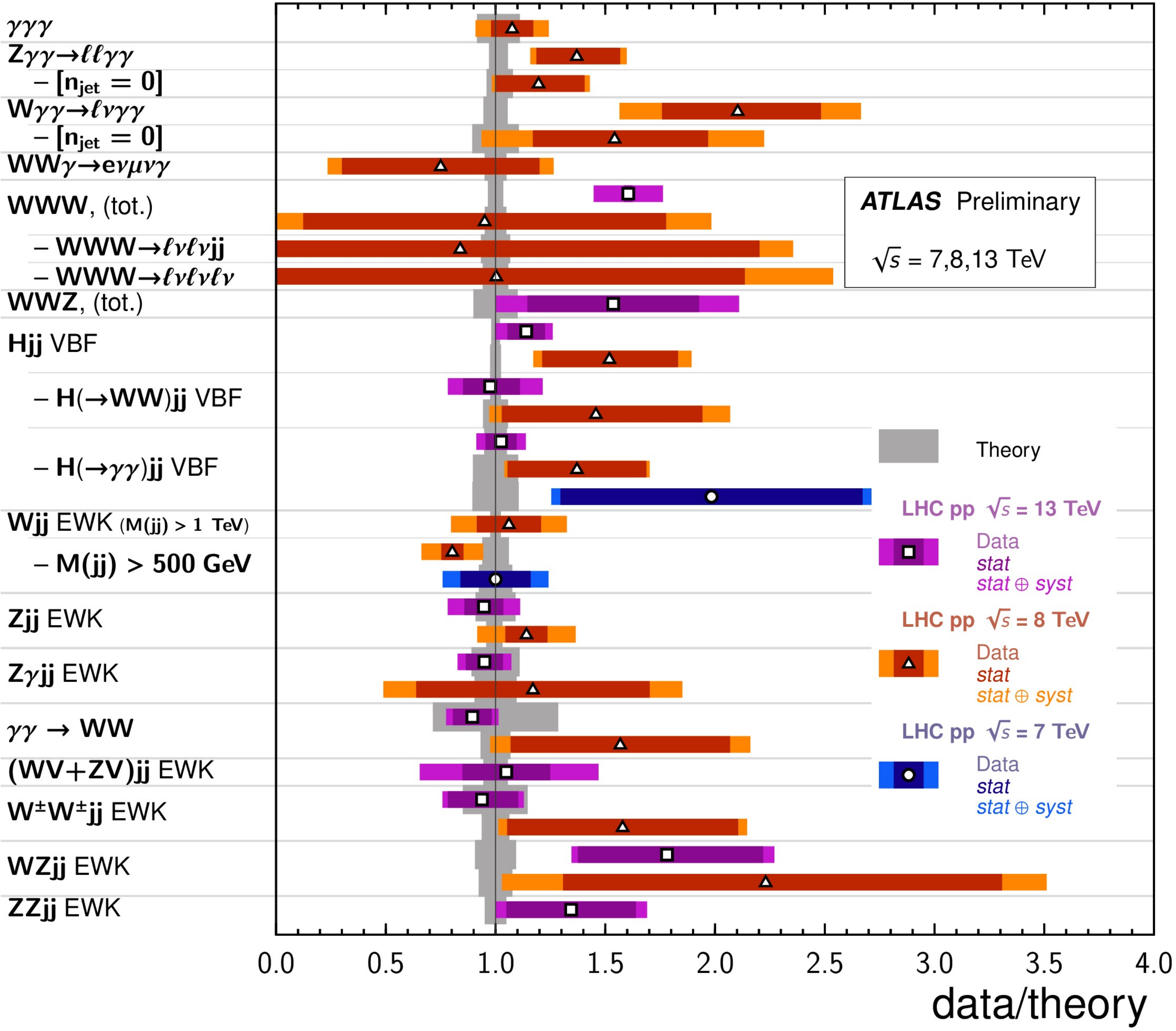
$\sqrt{s}$ = 13 TeV
Run2 period: 2015 - 2018

Total recorded: 147 fb^{-1}



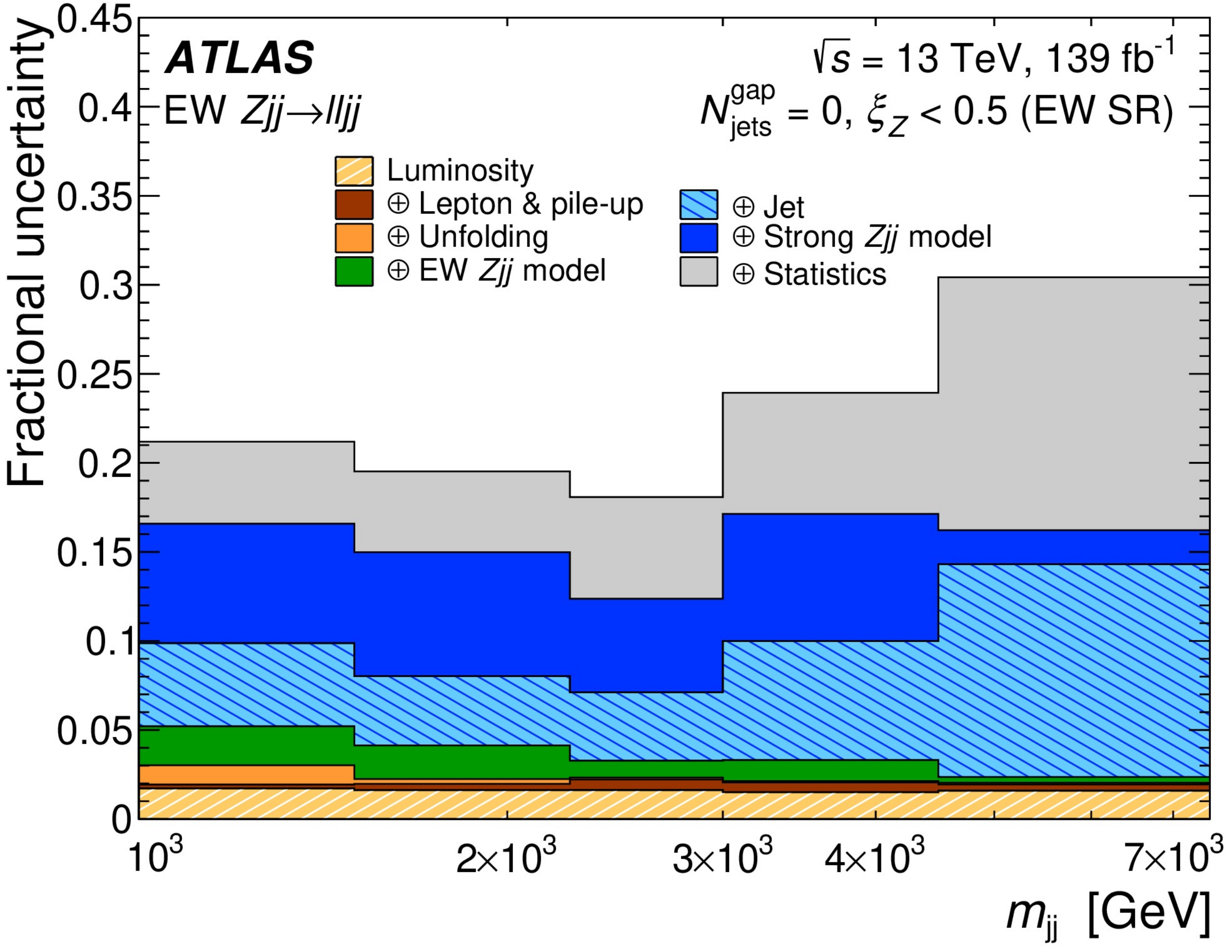
VBF, VBS, and Triboson Cross Section Measurements

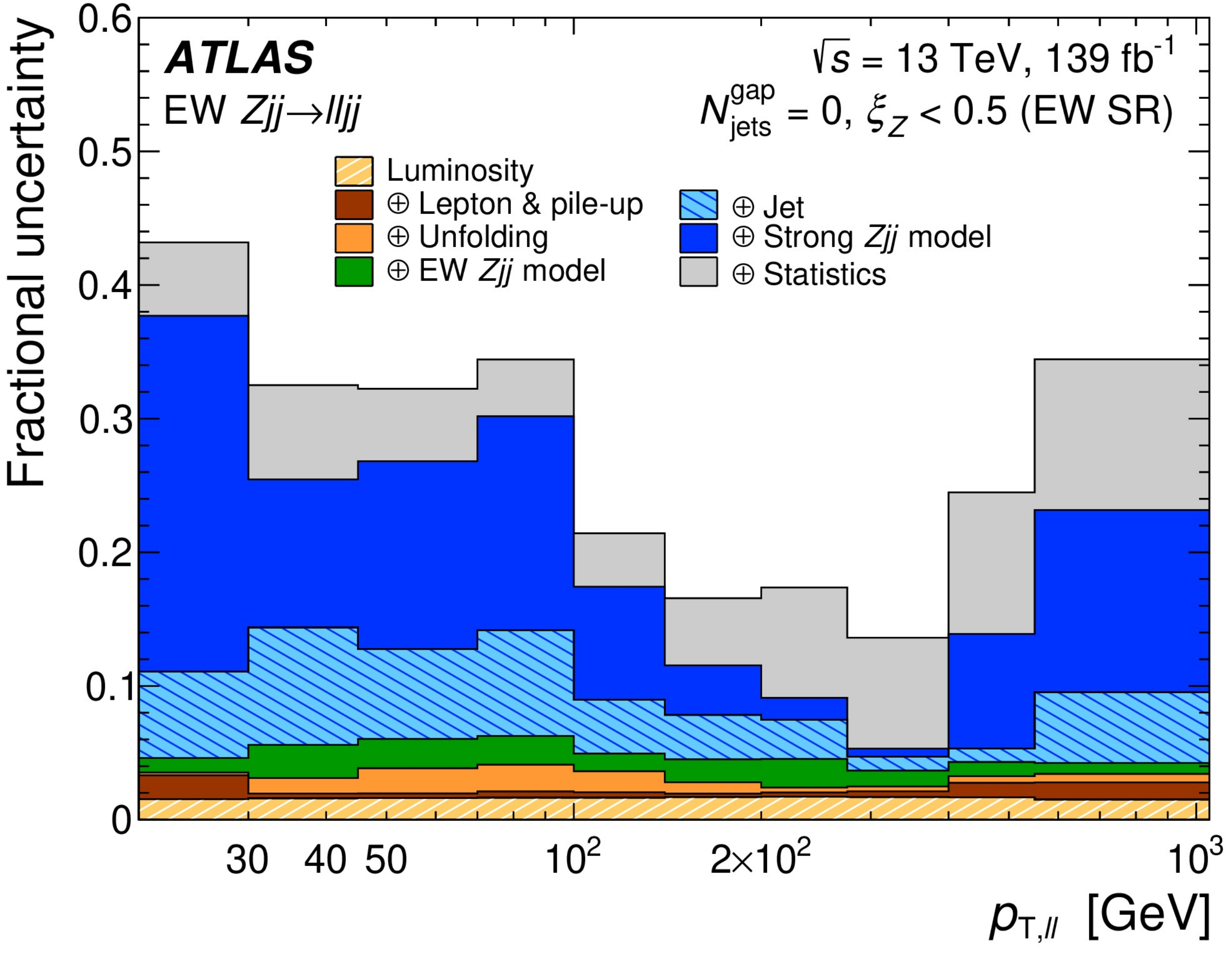
Status: February 2022



Systematic Uncertainties of EW Zjj

EPJC 81 (2021) 163





Multivariate Discriminants (MDs) EW $ZZjj$

arXiv.2004.10612

MD input variables $\ell\ell\ell\ell jj$

m_{jj}
Δy_{jj}
p_T^{j1} and p_T^{j2}
$y_{j1} \times y_{j2}$
p_T^{Zi} with m_{Zi} closet to M_Z $(i = 1,2)$
y_{Z1} and y_{Z2}
$p_T^{\ell\ell\ell\ell}$
$m_{\ell\ell\ell\ell}$
$p_T^{\ell 3}$
$\frac{|\sum \vec{p}_T|}{\sum p_T}$ with sum over the two Z's and two jets

MD input variables $\ell\ell\nu\nu jj$

m_{jj}
Δy_{jj}
p_T^{j2}
$y_{j1} \times y_{j2}$
E_T^{miss}
E_T^{miss}- significance
$\frac{|\sum \vec{p}_T|}{\sum p_T}$ with sum over the two Z's and two jets
$\Delta \eta_{\ell\ell}$
$\Delta \phi_{\ell\ell}$
$\Delta R_{\ell\ell}$
$m_{\ell\ell}$
$p_T^{\ell 1}$ and $p_T^{\ell 2}$

Multivariate Discriminants (MDs) based on Gradient Boosted Decision Tree algorithm are trained with simulated events using TMVA framework to separate **EW $ZZjj$** from backgrounds

Control Regions for $ZZjj$ analysis

arXiv.2004.10612