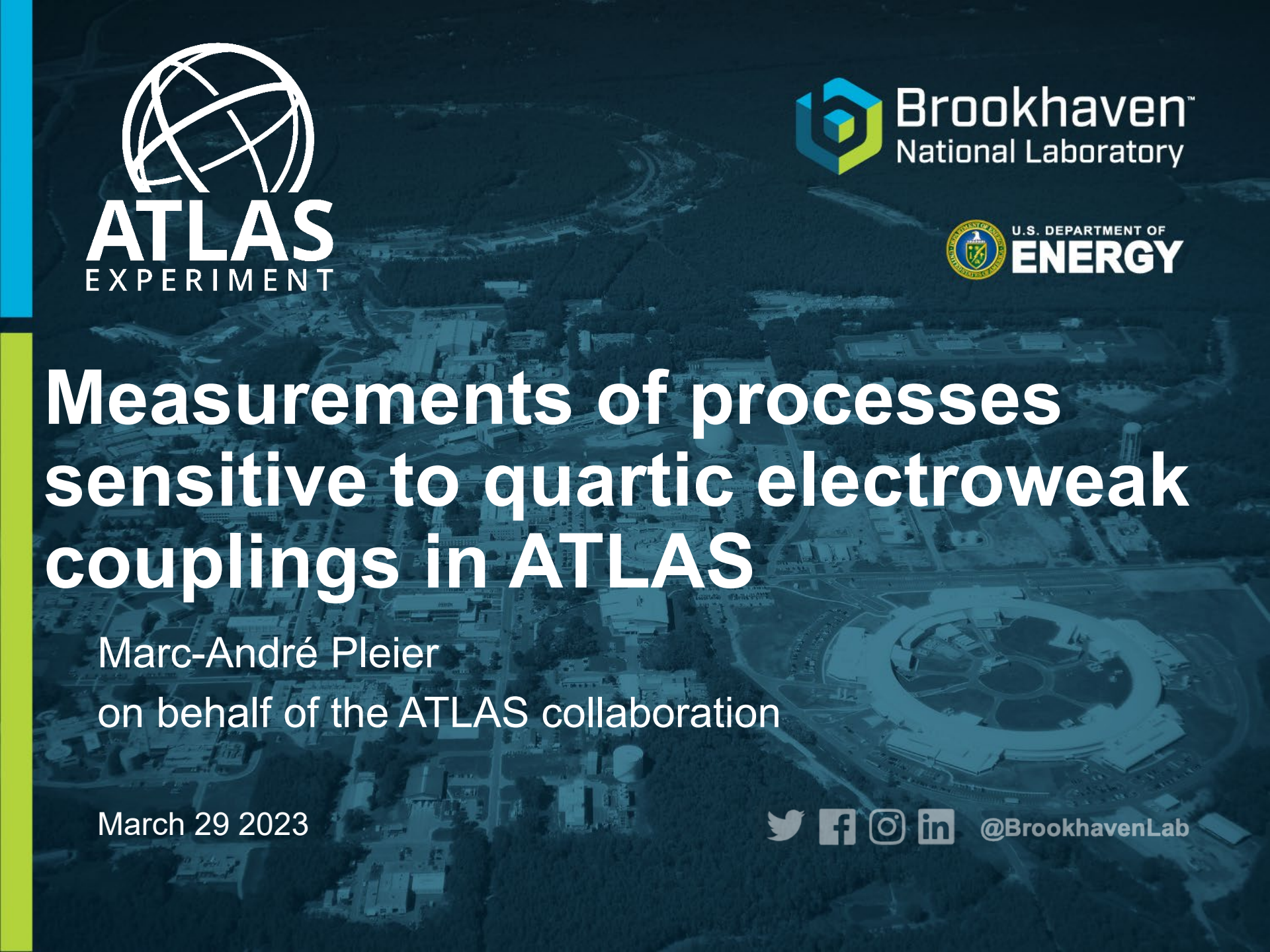


Measurements of processes sensitive to quartic electroweak couplings in ATLAS

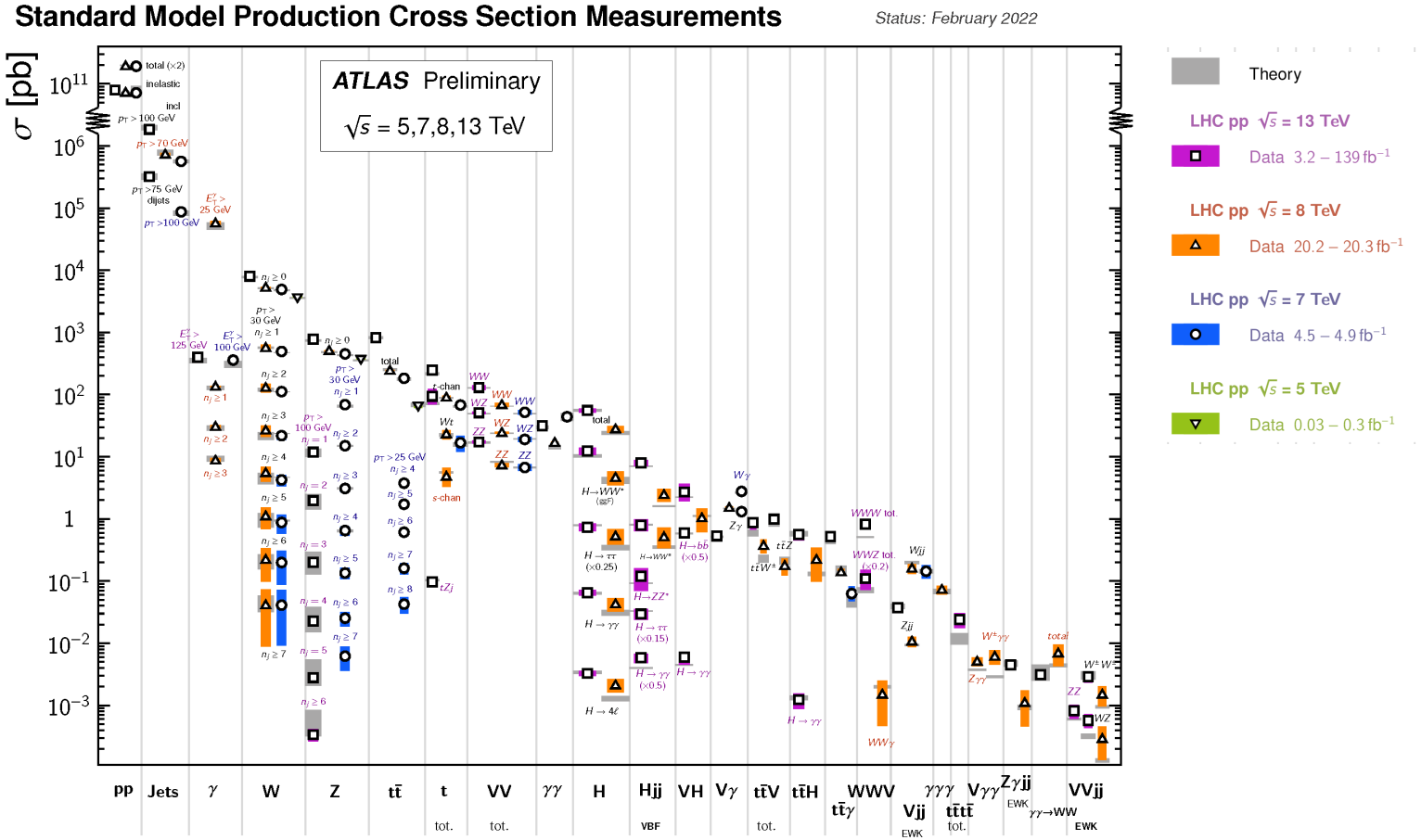
Marc-André Pleier
on behalf of the ATLAS collaboration

March 29 2023

@BrookhavenLab

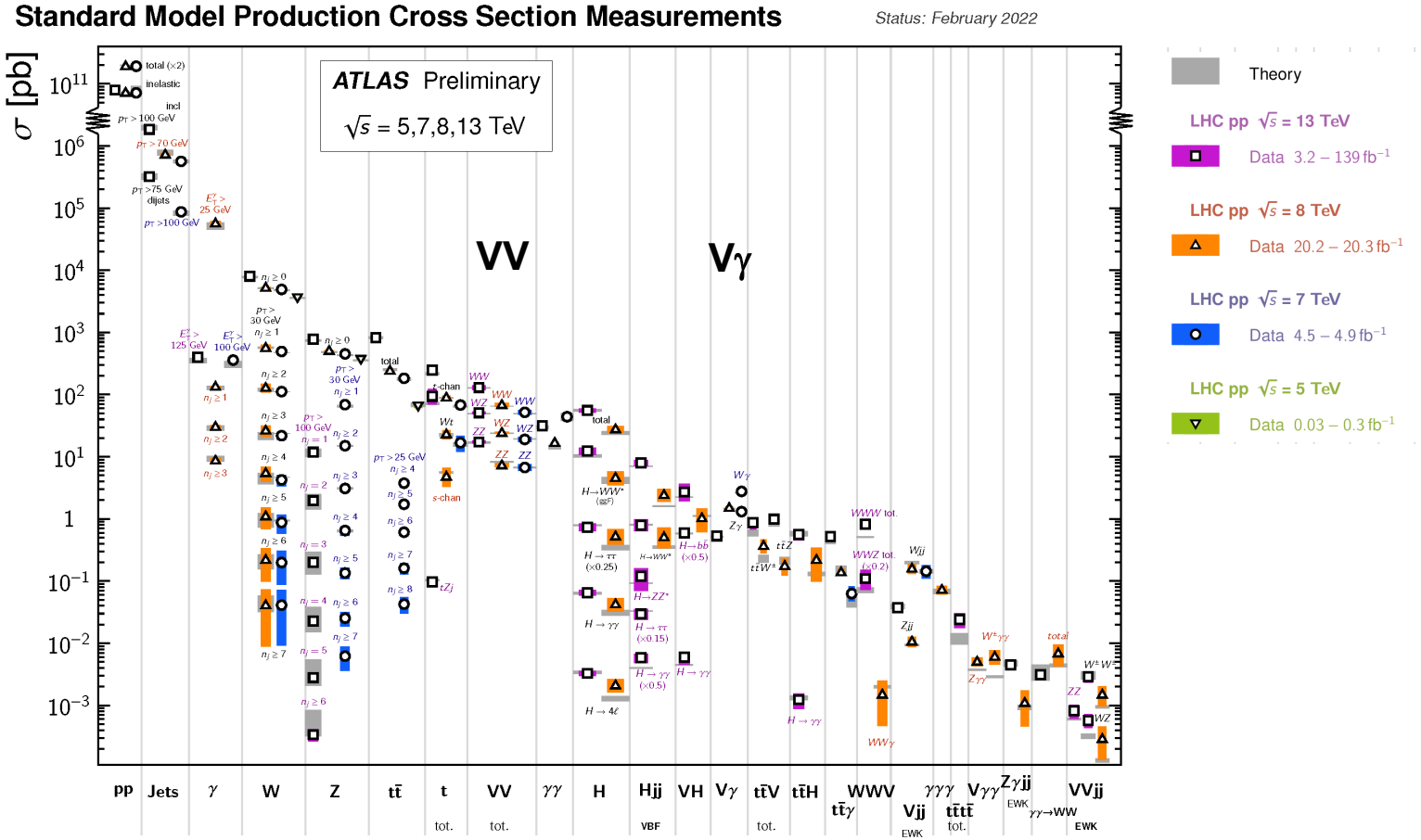
[ATL-PHYS-PUB-2022-009]

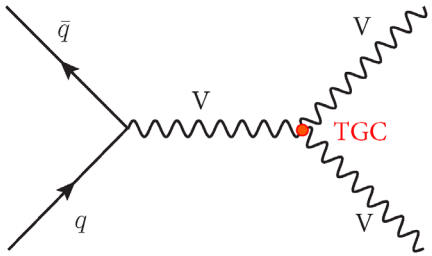
(Multi-) V Production



[ATL-PHYS-PUB-2022-009]

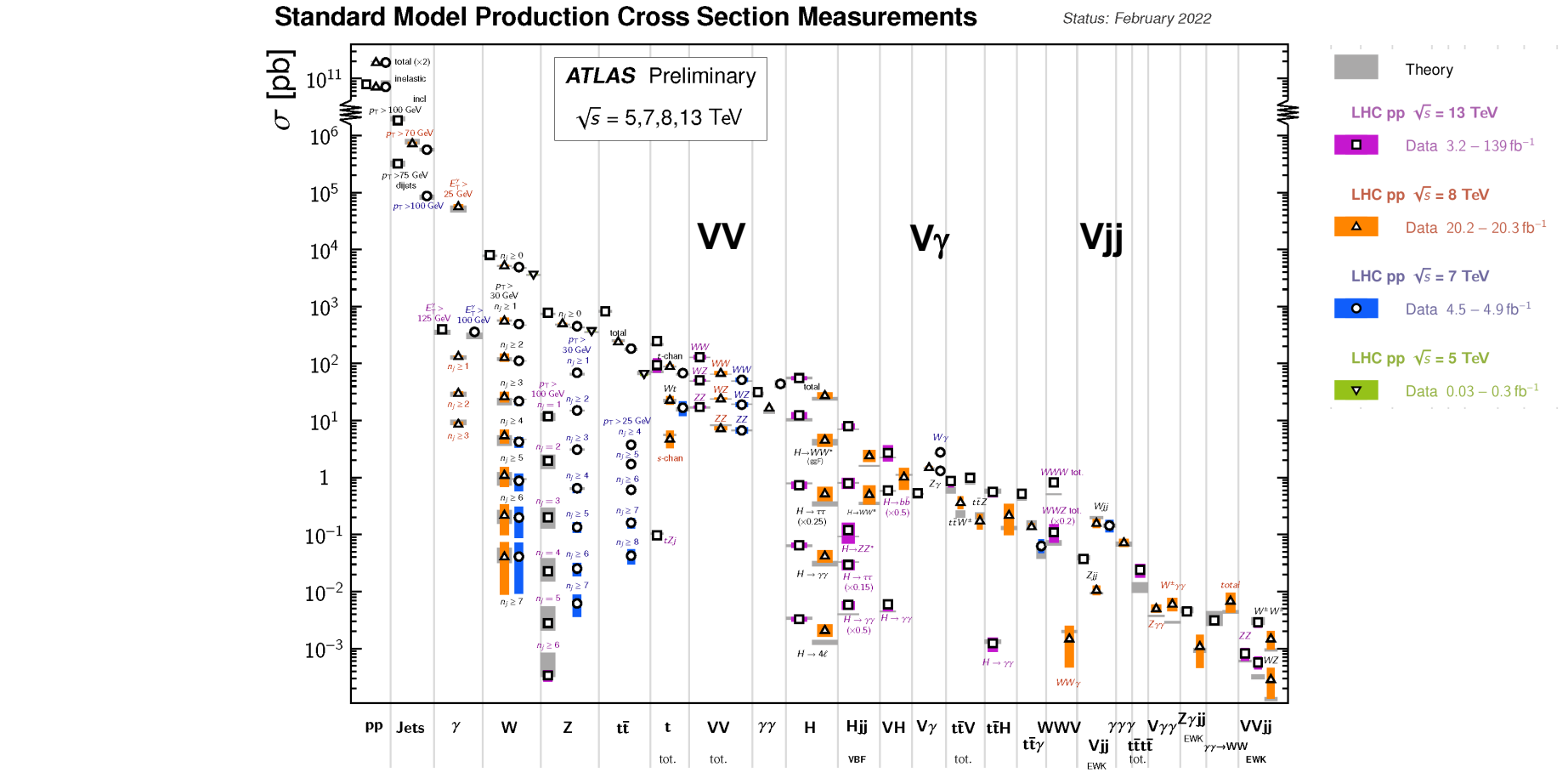
(Multi-) V Production

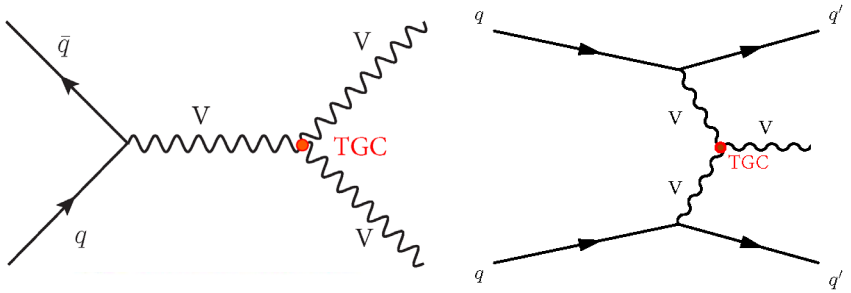




[ATL-PHYS-PUB-2022-009]

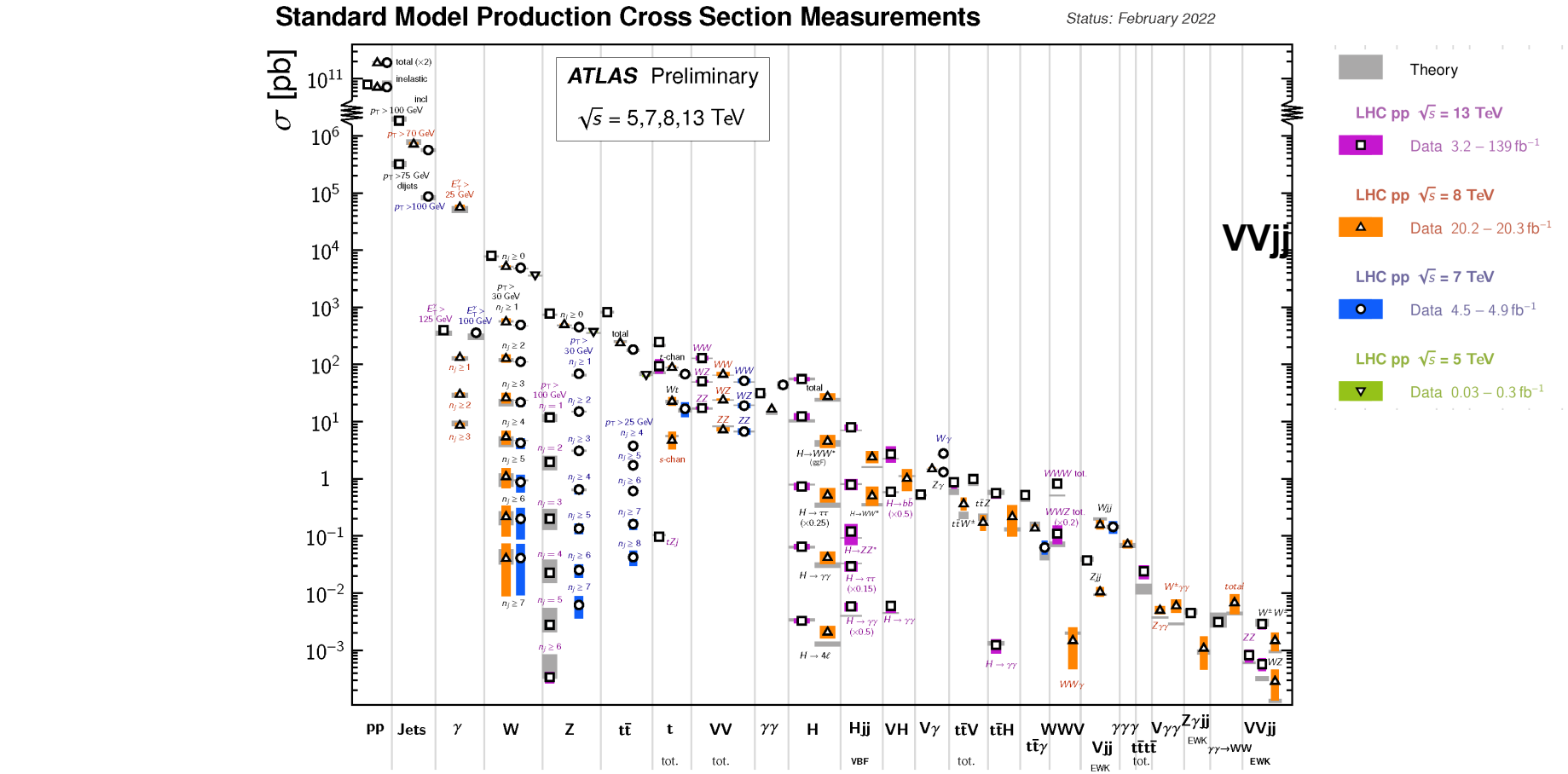
(Multi-) V Production

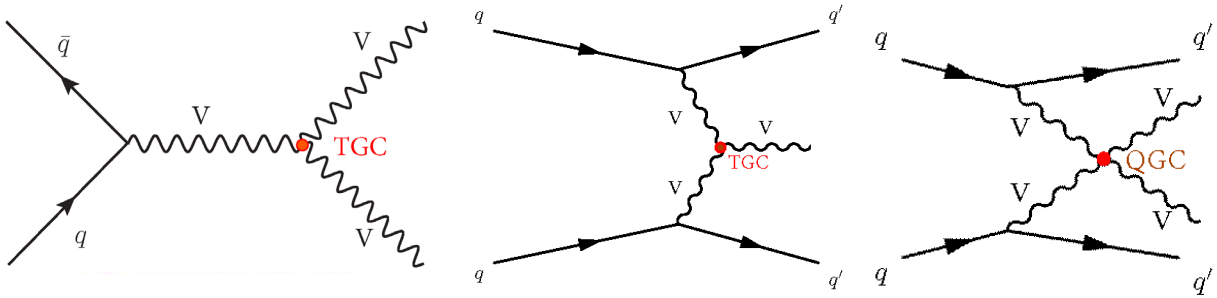




[ATL-PHYS-PUB-2022-009]

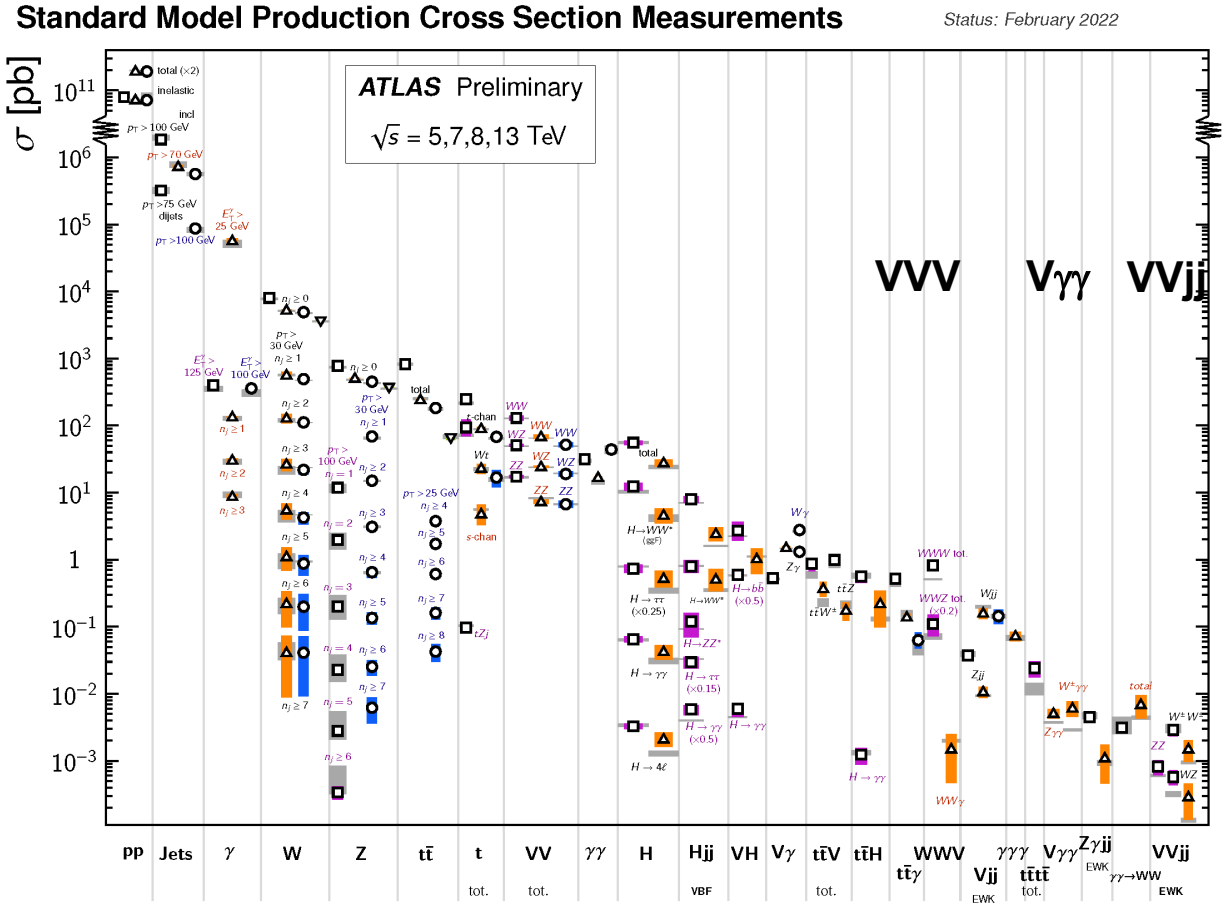
(Multi-) V Production

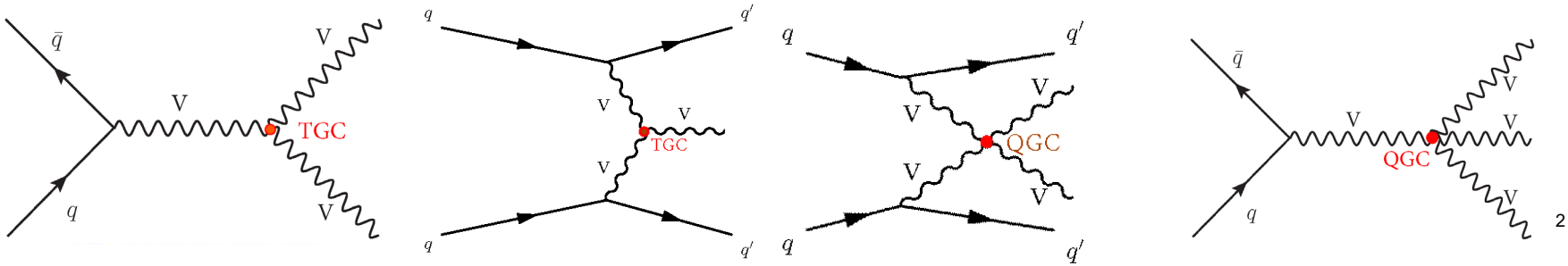




[ATL-PHYS-PUB-2022-009]

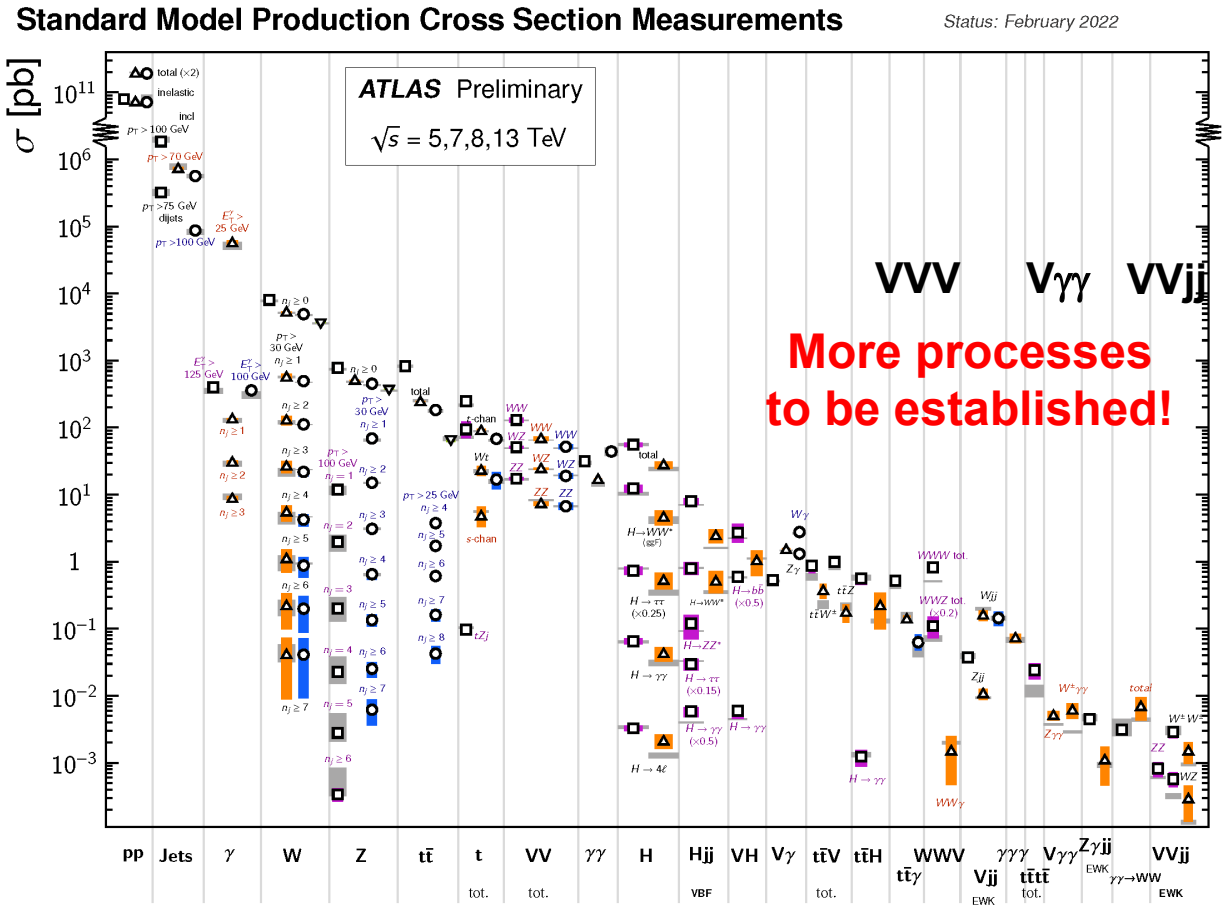
(Multi-) V Production

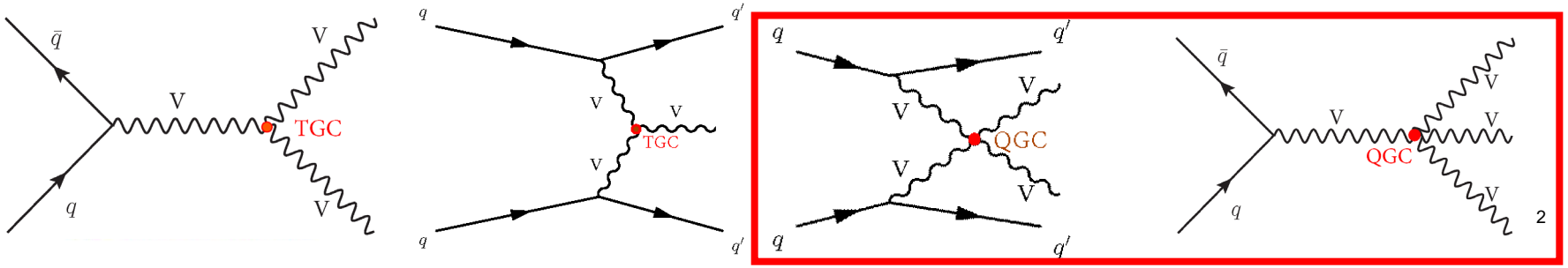




[ATL-PHYS-PUB-2022-009]

(Multi-) V Production

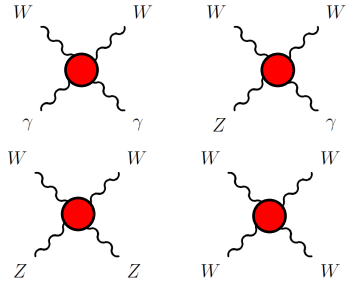




VBS/VVV Production and aQGCs

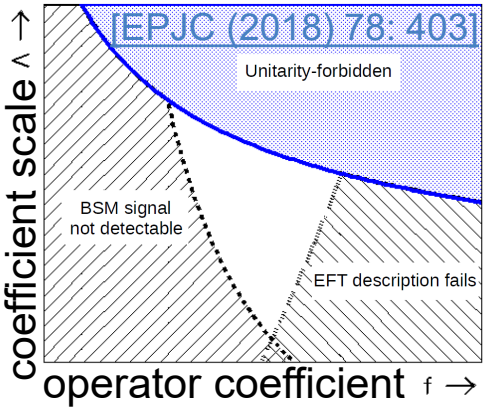
Quartic self-interactions of W/Z/γ never observed before LHC era – untested territory!

- Quartic self interactions just involving γ/Z forbidden…



Overview of studied aQGCs: $\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \cdots$

	$WWWW$	$WWZZ$	$WW\gamma Z$	$WW\gamma\gamma$	$ZZZZ$	$ZZZ\gamma$	$ZZ\gamma\gamma$	$Z\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	✓	✓			✓				
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$,$\mathcal{O}_{M,6}$,$\mathcal{O}_{M,7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2}$,$\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$,$\mathcal{O}_{M,5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T,0}$,$\mathcal{O}_{T,1}$,$\mathcal{O}_{T,2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5}$,$\mathcal{O}_{T,6}$,$\mathcal{O}_{T,7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8}$,$\mathcal{O}_{T,9}$					✓	✓	✓	✓	✓

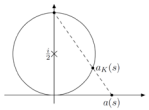


Experimental access: aQGCs modify total production rate as well as event kinematics

- Use cross-section measurement or kinematics to constrain aQGCs

Unitarisation methods: Form factor, K-matrix, clipping

$$\lambda(\hat{s}) = \frac{\lambda_0}{(1+\hat{s}/\Lambda_{FF}^2)^n}$$



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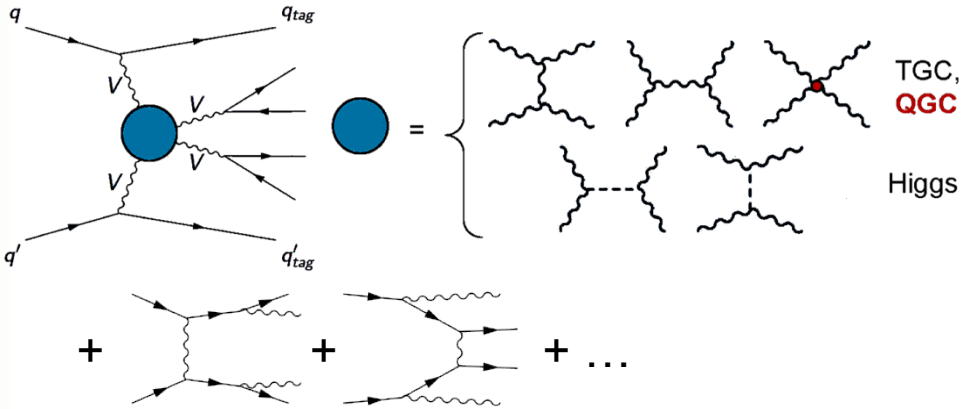
Vector Boson Scattering

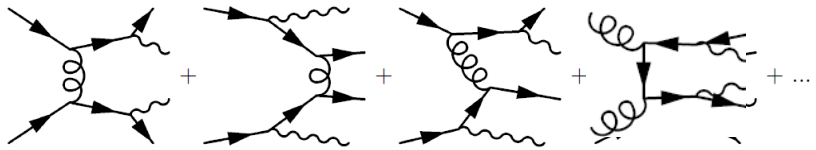
Vector Boson Scattering

- VV → VV provides insight into EWSB mechanism, quartic couplings access:

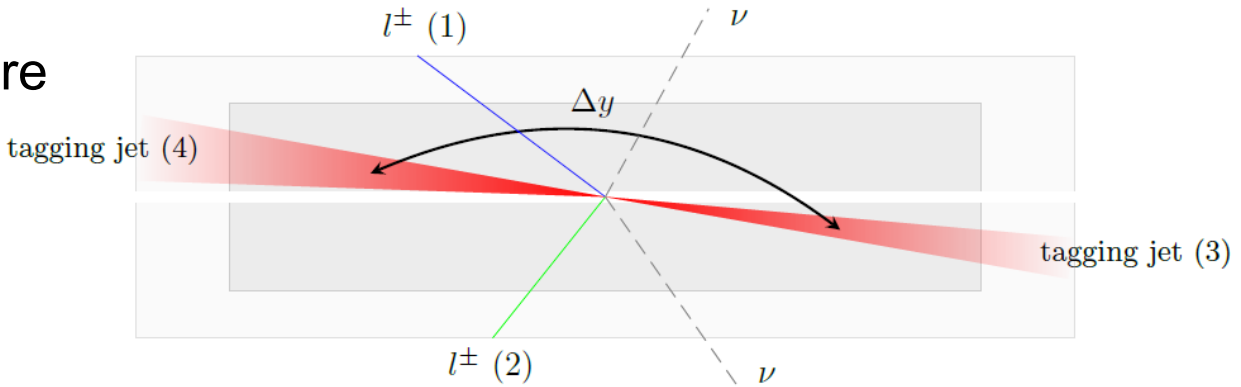
electroweak VVjj production includes:



strong VVjj production includes:



- Experimental signature ($W^{\pm}W^{\pm}$ example):



- 1,2 = Central, high-p_T charged leptons from V decays
- 3,4 = Forward/backward tagging jets (large m_{jj} and well separated in y)

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[arXiv:2208.12741]
accepted by JHEP

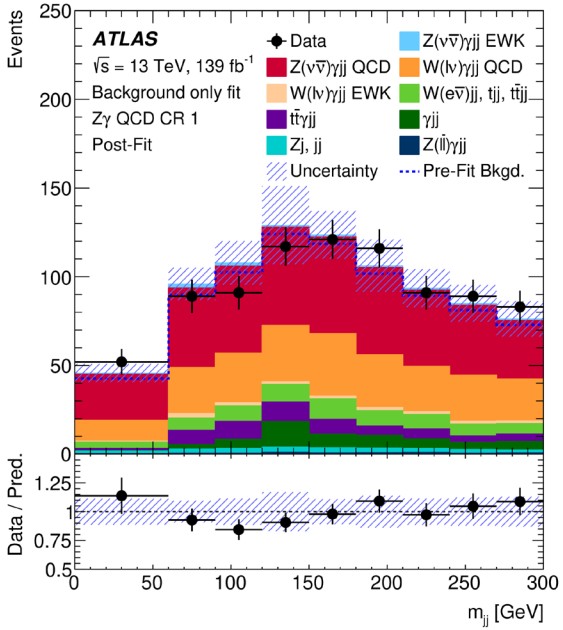
Electroweak Z(νν)γ jj production

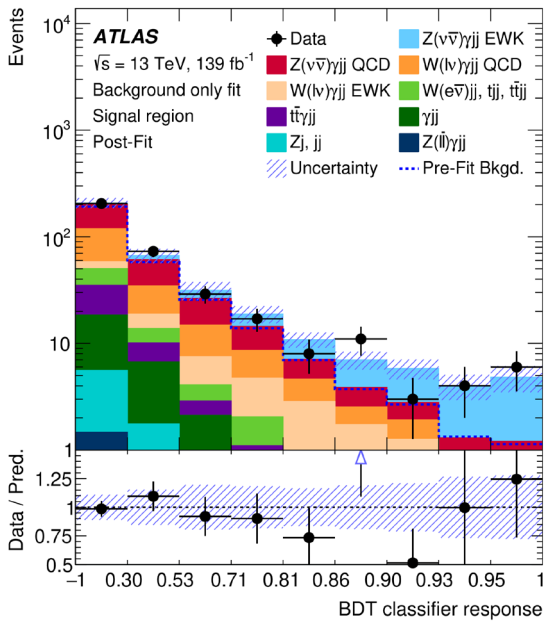
Isolated high E_T γ (>150 GeV), MET > 120 GeV, m_{jj} > 300 GeV

- High Energy, high ν-BR => increased aQGC sensitivity
- Dominant BG: QCD Z(νν)γ jj, Wγ jj: use simultaneous fit to data CRs
- MET, $e \rightarrow \gamma$ and $j \rightarrow \gamma$ mis-ID evaluated using data-driven methods

Extract electroweak signal with fit to BDT classifier

- observed (expected) significance of the result is 3.2σ (3.7σ)
- combination with lower E_T γ ATLAS observation yields 6.3σ (6.6σ)





$$\mu_{Z\gamma\mathrm{EWK}} = 0.78^{+0.25}_{-0.23}\ (\mathrm{stat.})\ ^{+0.21}_{-0.17}\ (\mathrm{syst.})$$

$$\sigma^{\mathrm{pred}}_{Z\gamma\mathrm{EWK}} = 0.98 \pm 0.02\ (\mathrm{stat.}) \pm 0.09\ (\mathrm{scale}) \pm 0.02\ (\mathrm{PDF})\ \mathrm{fb}$$

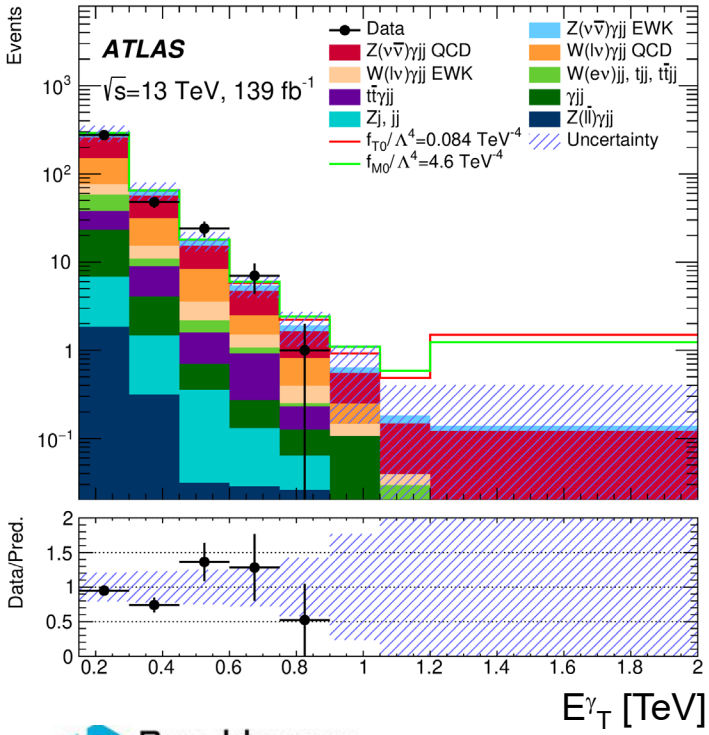
$$\sigma_{Z\gamma\mathrm{EWK}} = 0.77^{+0.34}_{-0.30}\ \mathrm{fb}$$

[arXiv:2208.12741]
accepted by JHEP

Electroweak Z(νν)γ jj production - aQGC

Use high E_T γ tail to constrain aQGCs

- (Un-)unitarized limits are obtained for coefficients of EFT dimension-8 operators T0, T5, T8, T9, M0, M1 and M2
- "Clipping" is used to illustrate unitarization impact: remove anomalous signal contribution for $m_{Z\gamma}$>E_c(using particle-level information)



Coefficient	Observed limit [TeV^{-4}]	Expected limit [TeV^{-4}]
f_{T0}/Λ^4	$[-9.4, 8.4] \times 10^{-2}$	$[-1.3, 1.2] \times 10^{-1}$
f_{T5}/Λ^4	$[-8.8, 9.9] \times 10^{-2}$	$[-1.2, 1.3] \times 10^{-1}$
f_{T8}/Λ^4	$[-5.9, 5.9] \times 10^{-2}$	$[-8.1, 8.0] \times 10^{-2}$
f_{T9}/Λ^4	$[-1.3, 1.3] \times 10^{-1}$	$[-1.7, 1.7] \times 10^{-1}$
f_{M0}/Λ^4	$[-4.6, 4.6]$	$[-6.2, 6.2]$
f_{M1}/Λ^4	$[-7.7, 7.7]$	$[-1.0, 1.0] \times 10^{1}$
f_{M2}/Λ^4	$[-1.9, 1.9]$	$[-2.6, 2.6]$

Coefficient	E_c [TeV]	Observed limit [TeV^{-4}]	Expected limit [TeV^{-4}]
f_{T0}/Λ^4	1.7	$[-8.7, 7.1] \times 10^{-1}$	$[-8.9, 7.3] \times 10^{-1}$
f_{T5}/Λ^4	2.4	$[-3.4, 4.2] \times 10^{-1}$	$[-3.5, 4.3] \times 10^{-1}$
f_{T8}/Λ^4	1.7	$[-5.2, 5.2] \times 10^{-1}$	$[-5.3, 5.3] \times 10^{-1}$
f_{T9}/Λ^4	1.9	$[-7.9, 7.9] \times 10^{-1}$	$[-8.1, 8.1] \times 10^{-1}$
f_{M0}/Λ^4	0.7	$[-1.6, 1.6] \times 10^{2}$	$[-1.5, 1.5] \times 10^{2}$
f_{M1}/Λ^4	1.0	$[-1.6, 1.5] \times 10^{2}$	$[-1.4, 1.4] \times 10^{2}$
f_{M2}/Λ^4	1.0	$[-3.3, 3.2] \times 10^{1}$	$[-3.0, 3.0] \times 10^{1}$

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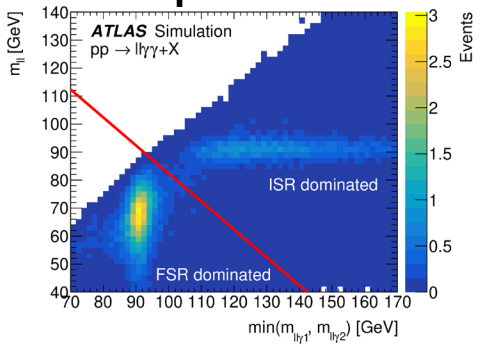
Triboson Production

[arXiv:2211.14171]

Measurement of Zγγ production

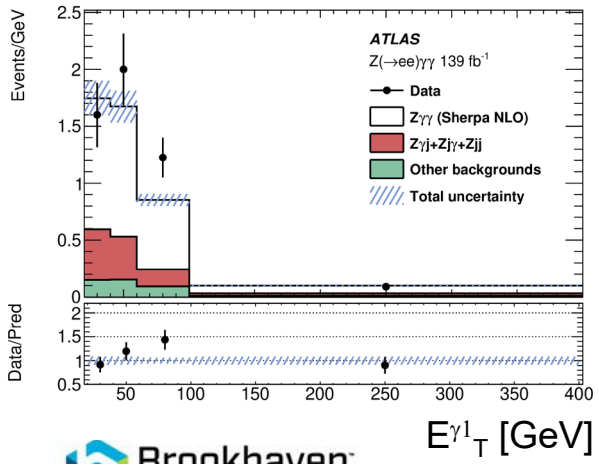
Charged lepton pair (e^+e^-, $\mu^+\mu^-$) + 2 isolated photons

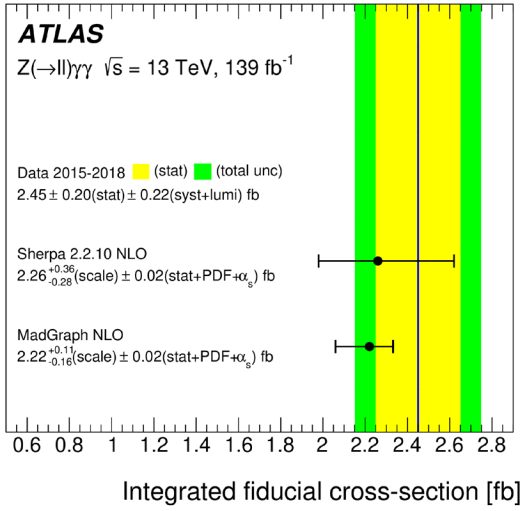
- Enhance signal (ISR) region:
  $m_{\ell\ell} + \min(m_{\ell\ell\gamma 1}, m_{\ell\ell\gamma 2}) > 2m_Z$
- Dominant BG: $j \rightarrow \gamma$ mis-ID,
  evaluated using data-driven method

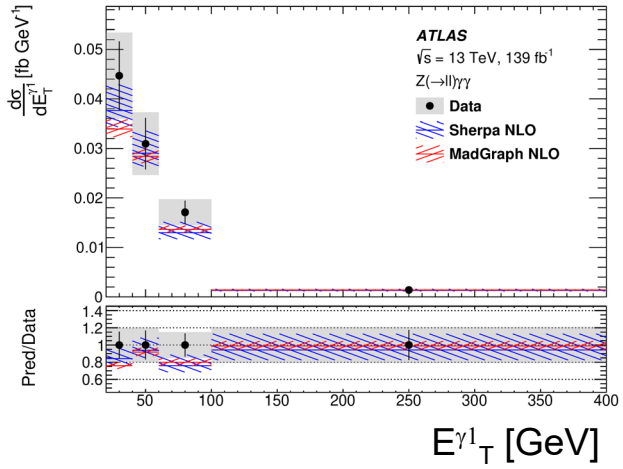


Integrated cross-section measurement precision: 12%

- Unfolded differential cross-sections provided for first time
- Test SM predictions at up to NLO accuracy with Sherpa & MG5







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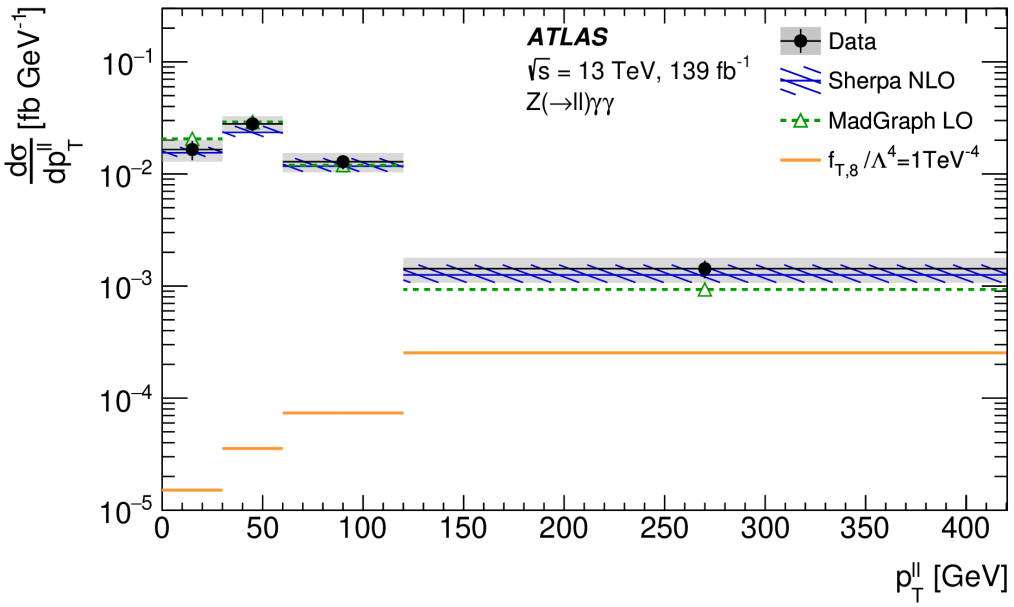
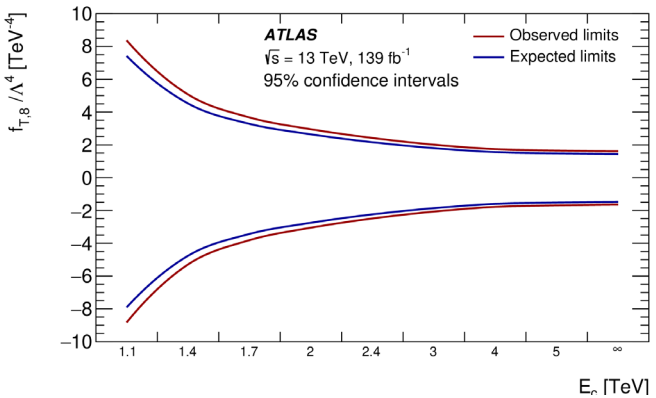
[arXiv:2211.14171]

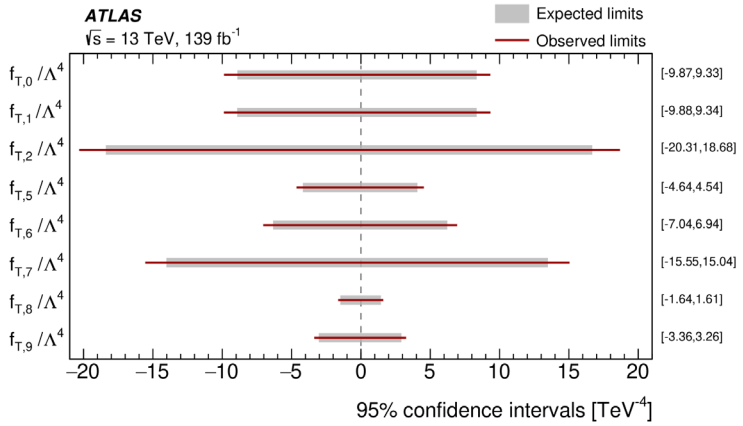
Measurement of Zγγ production - aQGC

Use unfolded $p_T^{\ell\ell}$ to constrain aQGCs

- Ununitarized limits are obtained for coefficients of EFT dimension-8 operators T0, T1, T2, T5, T6, T7, T8 and T9
- "Clipping" is used to illustrate unitarization impact as a function of E_c, the $\ell\ell\gamma\gamma$ invariant mass







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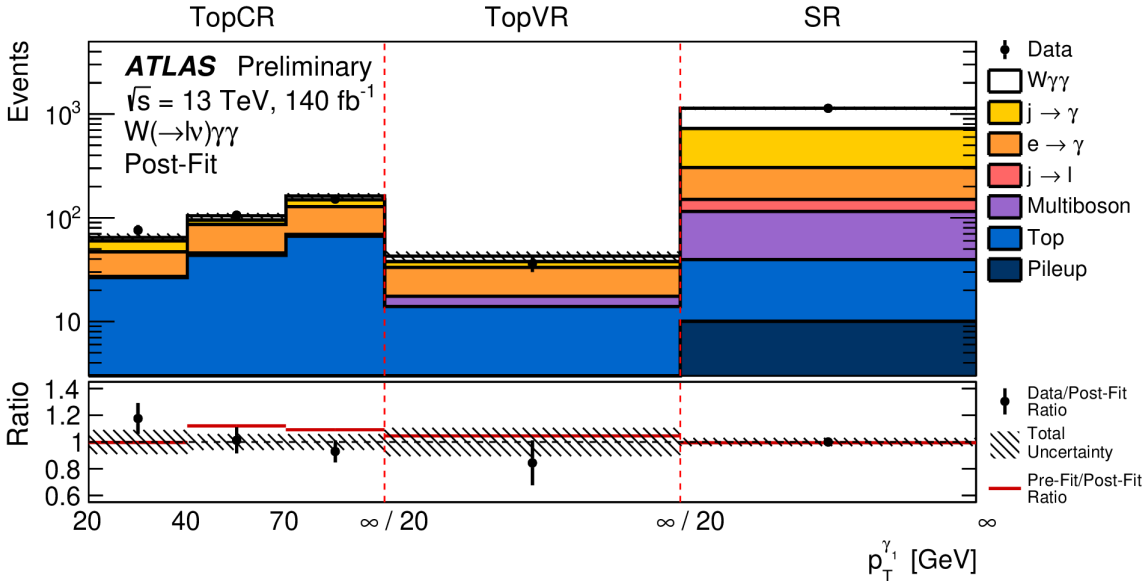
[ATLAS-CONF-2023-005]

First observation of Wγγ production

Charged lepton (e, μ) + MET + 2 isolated photons

- Dominant BG: $j \rightarrow \gamma$ mis-ID and $e \rightarrow \gamma$ mis-ID in electron channel, evaluated using data-driven methods
- ttγ background normalization uses simultaneous fit to data CR



$$\sigma_{\text{pred}} = 12.02 \pm 0.31 \text{ fb}$$

$$\sigma_{\text{fid}} = 12.2^{+2.1}_{-2.0} \text{ fb}$$

Observed (exp.) significance: 5.6σ (5.6σ): **First observation!**

- Good agreement between prediction and measurement
- Dominant sources of uncertainty: data-driven bg & statistical uncertainty

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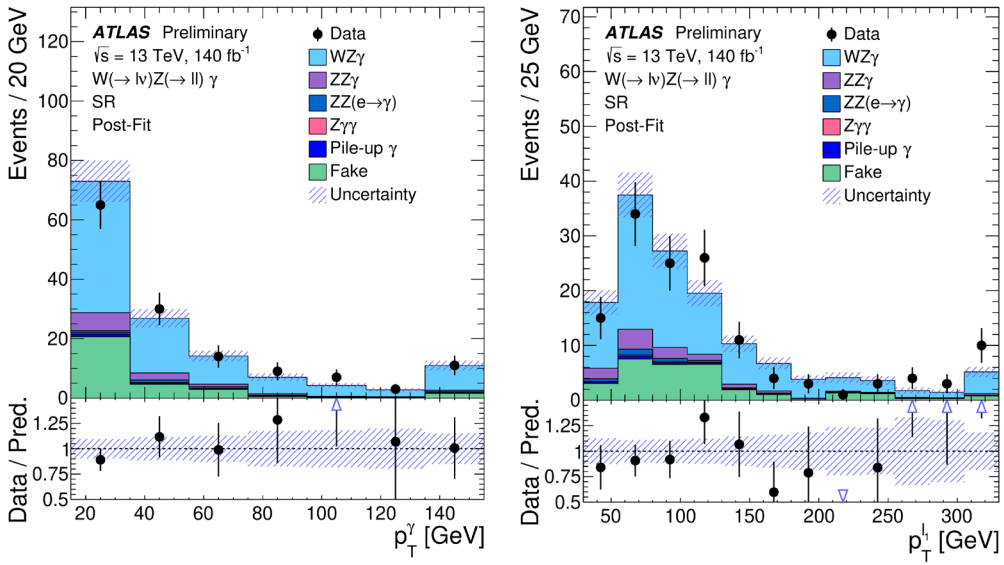
[ATLAS-CONF-2023-014]

First observation of WZγ production

3 charged leptons (e, μ) + MET + 1 isolated photon

- Dominant BG: $j \rightarrow \gamma$ and $j \rightarrow \ell$ mis-ID, using data-driven evaluation
- ZZγ and ZZ (e→ γ) bg normalization uses simultaneous fit to data CR



$\sigma^{pred}(pp \rightarrow WZ\gamma) = 1.50 \pm 0.06$ fb
(NLO QCD, LO EW)

$\sigma^{meas}(pp \rightarrow WZ\gamma) = 2.01 \pm 0.30$ (stat)
± 0.16 (syst) fb

Observed (exp.) significance: 6.3σ (5.0σ): **First observation!**

- $\mu_{WZ\gamma} = 1.34 \pm 0.21\,(\text{stat.}) \pm 0.10\,(\text{syst.}) \pm 0.07\,(\text{theory})$
- Consistent with SM prediction within 1.5 standard deviations

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Conclusions

Harvest of Run 2 multi-boson analyses still going strong:

- Precision measurements of first VBS/triboson processes,
- Establishing new triboson processes,
- Improving sensitivity to new couplings.

VBS/VVV processes are unique windows into testing the SM

No aQGCs seen so far

Conclusions

Harvest of Run 2 multi-boson analyses still going strong:

- Precision measurements of first VBS/triboson processes,
- Establishing new triboson processes,
- Improving sensitivity to new couplings.

VBS/VVV processes are unique windows into testing the SM

No aQGCs seen so far

The SM is a tough nut to crack,
but there is a lot more
data to come!

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