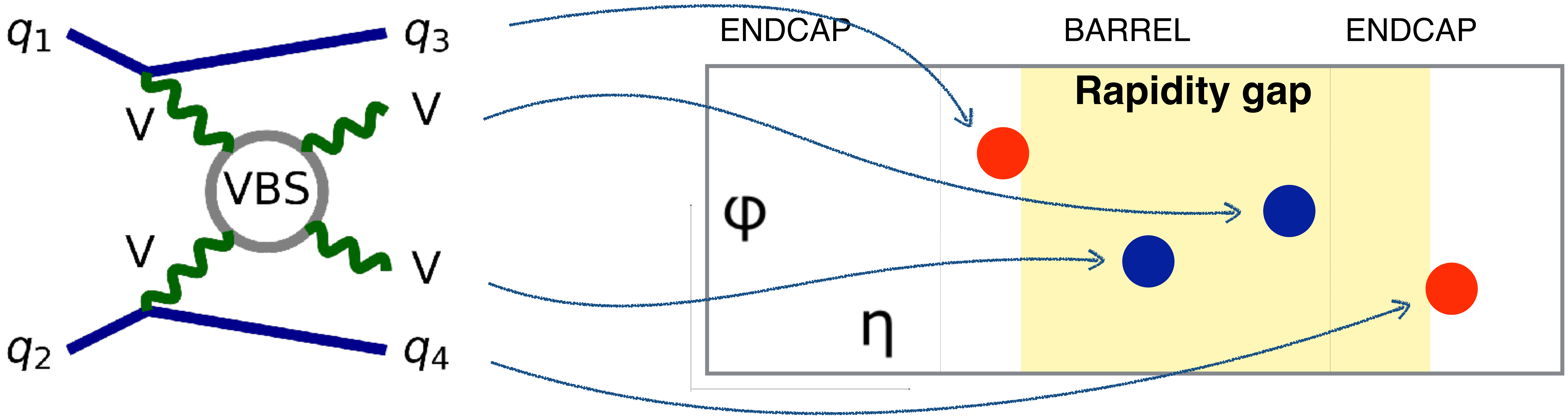
LHCP Boston 2024

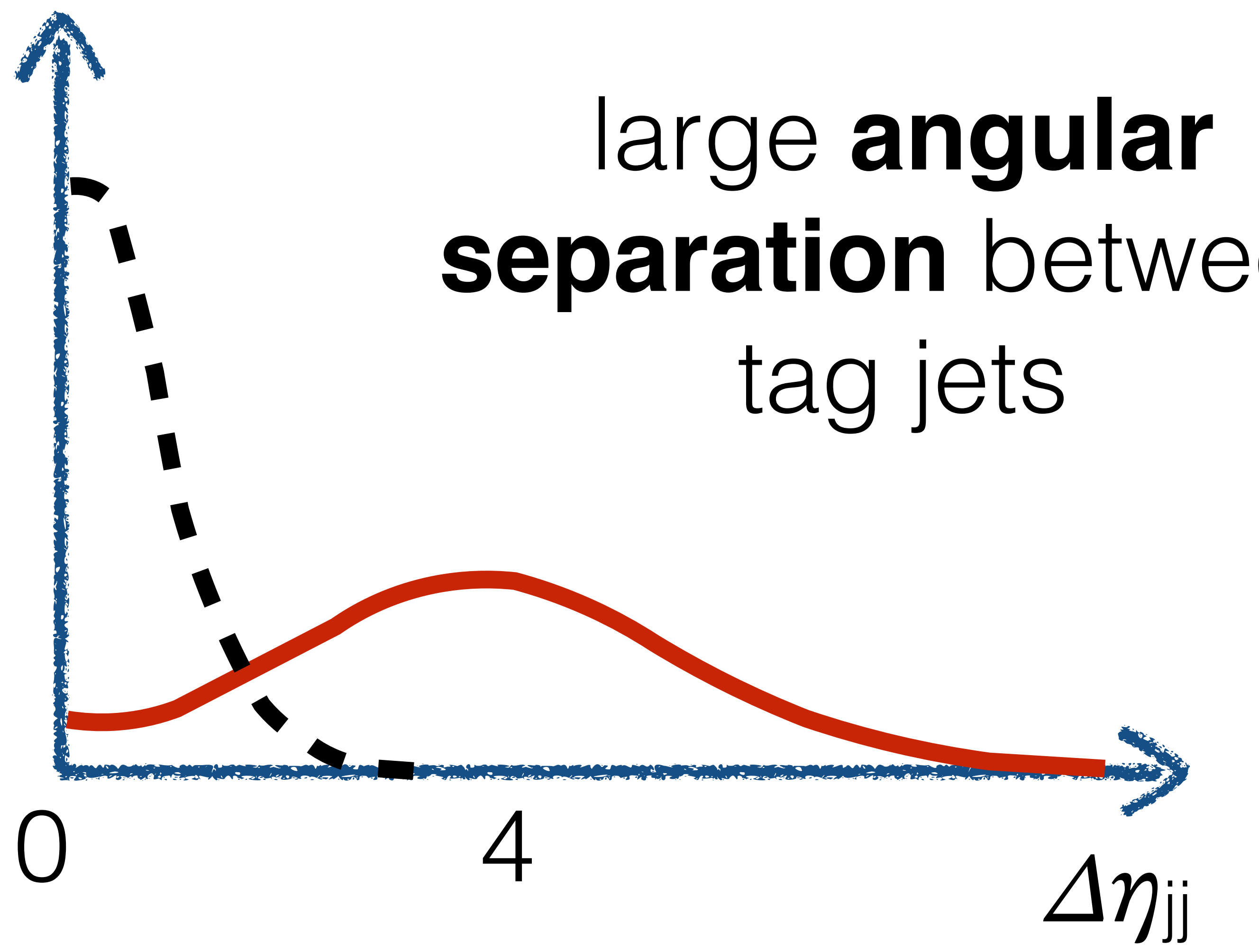
Experimental overview of VBS/VBF measurements at the LHC

(with Run 2 data)

Pietro Govoni,
INFN and University of Milano - Bicocca
on behalf of the ATLAS and CMS Collaborations

vector boson scattering

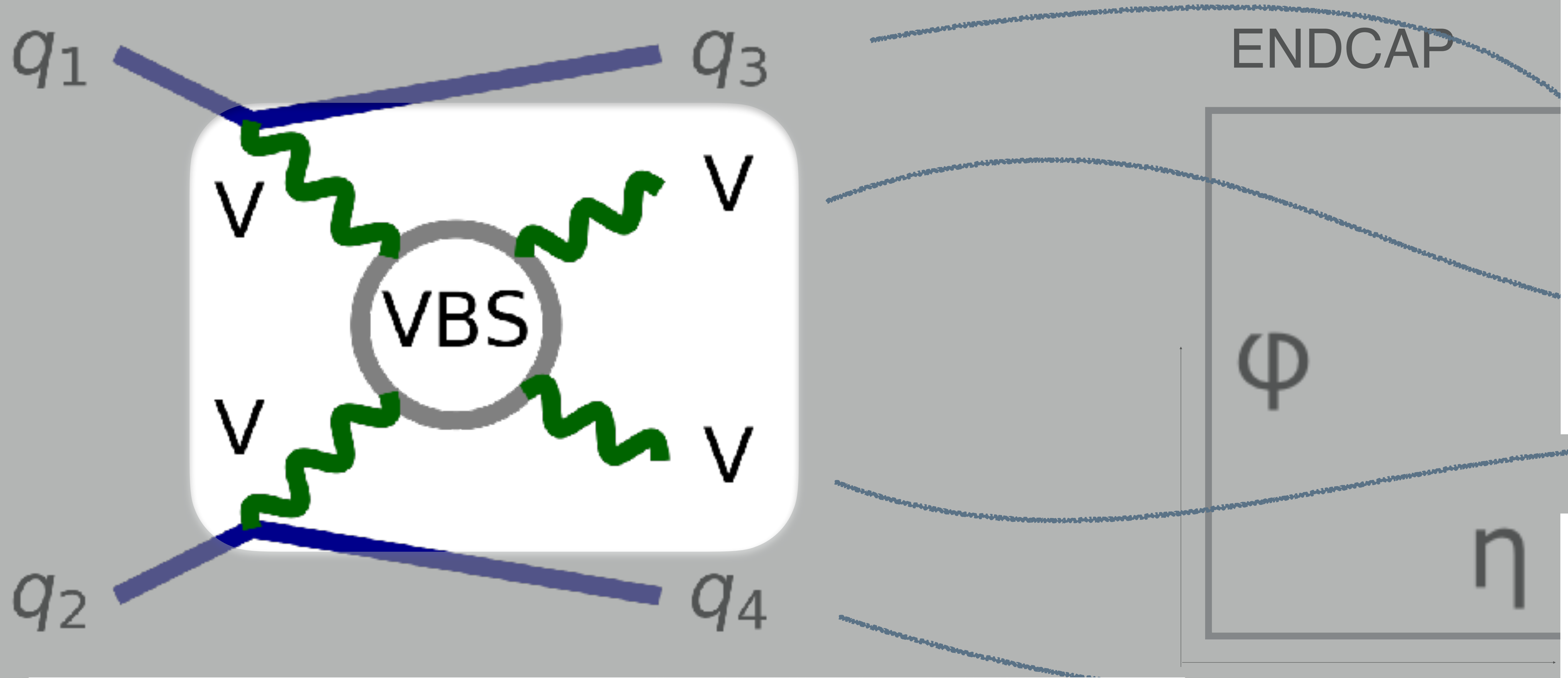


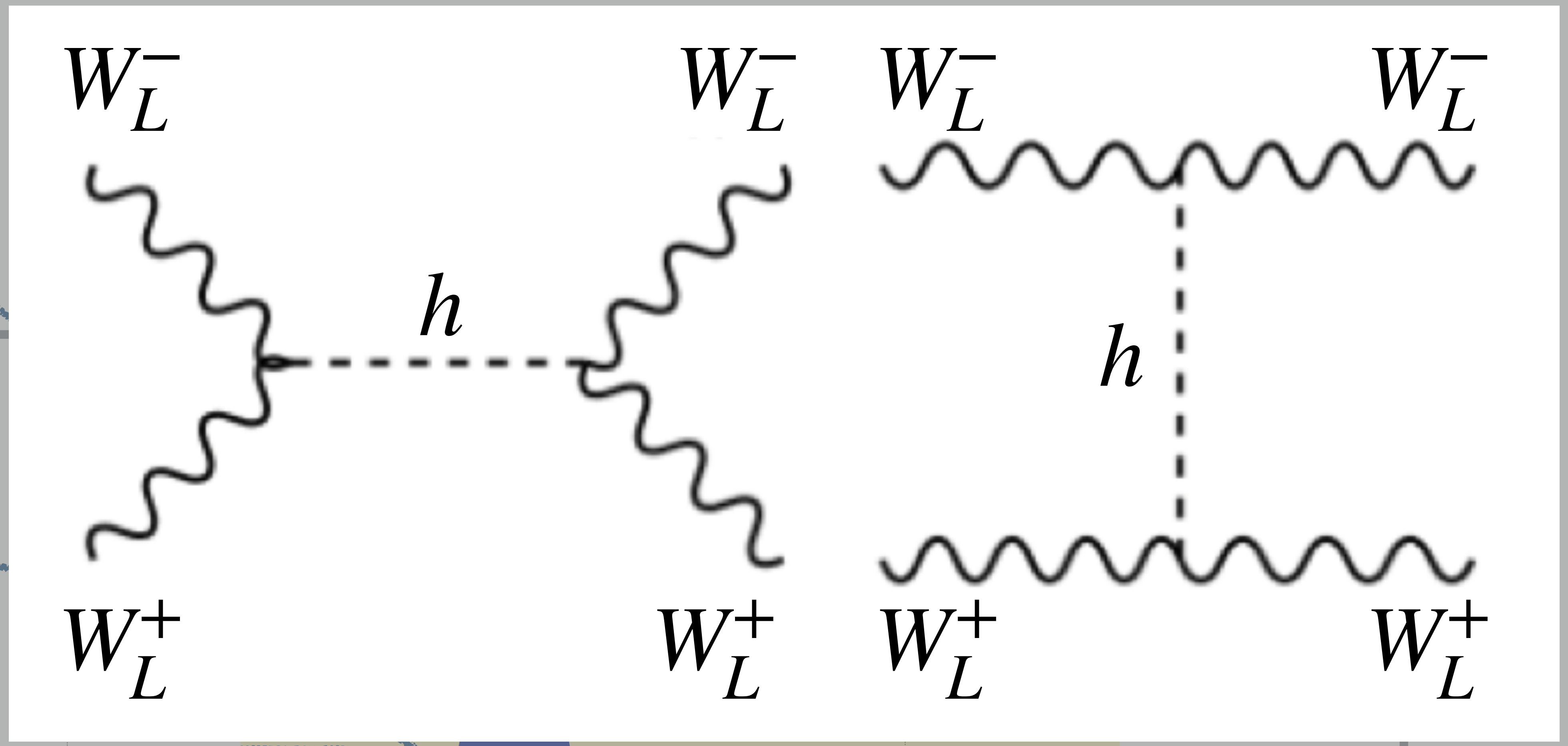


large **angular separation** between tag jets

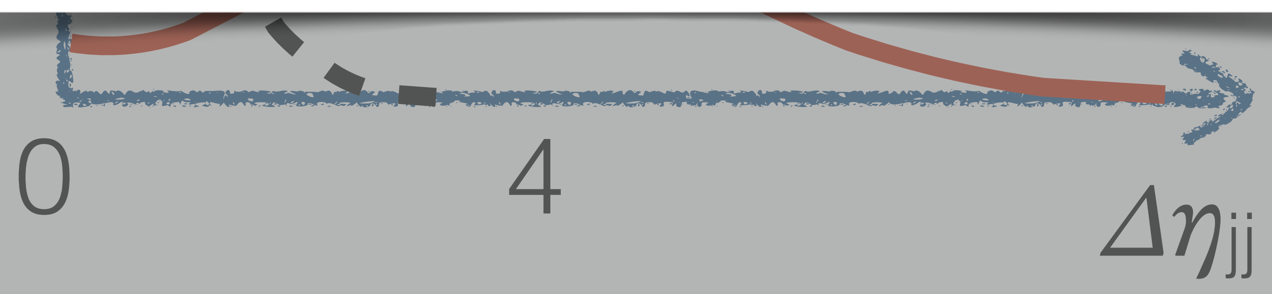
low QCD activity between tag jets, since there's no color flow between the two protons

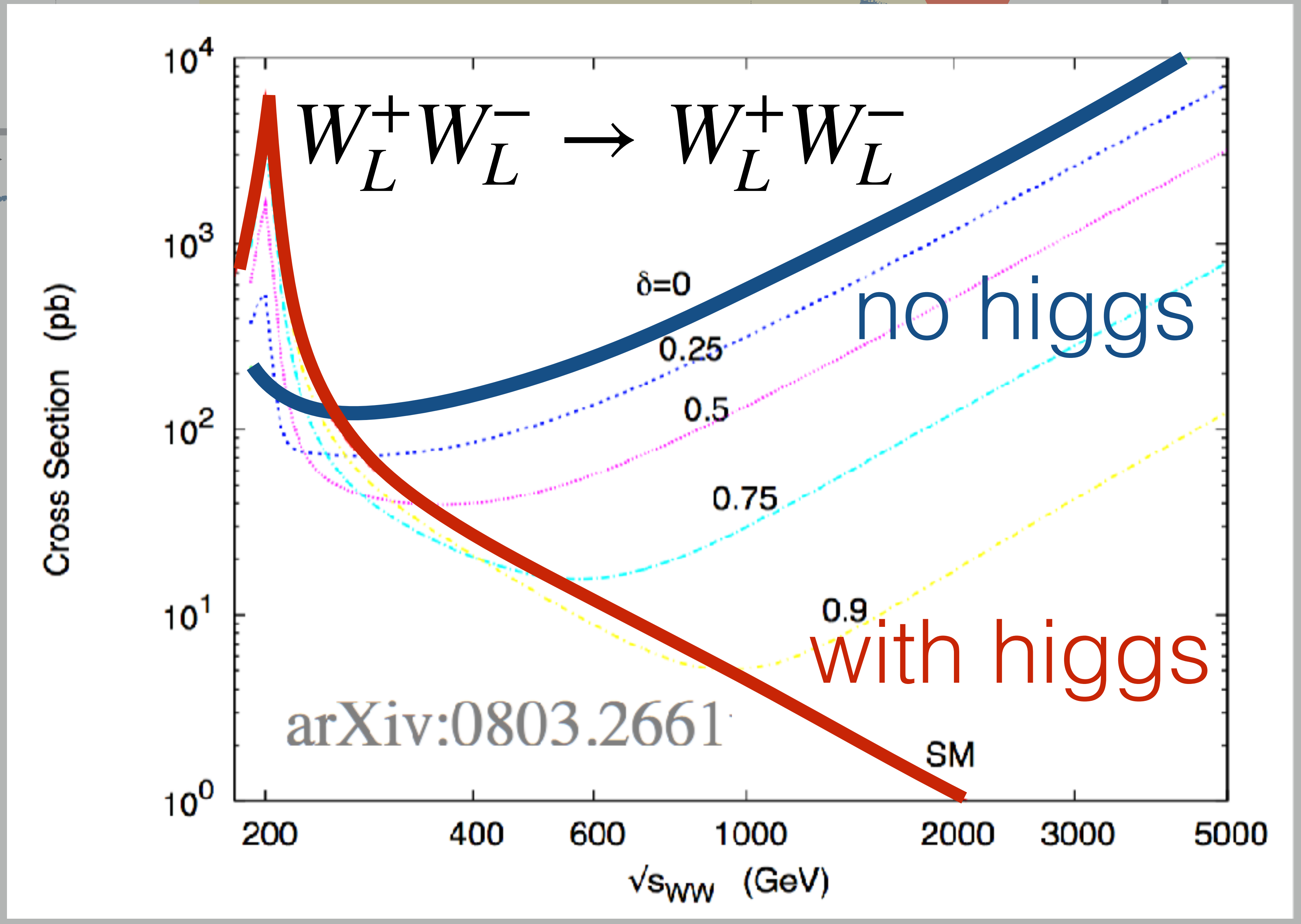
vector boson scattering





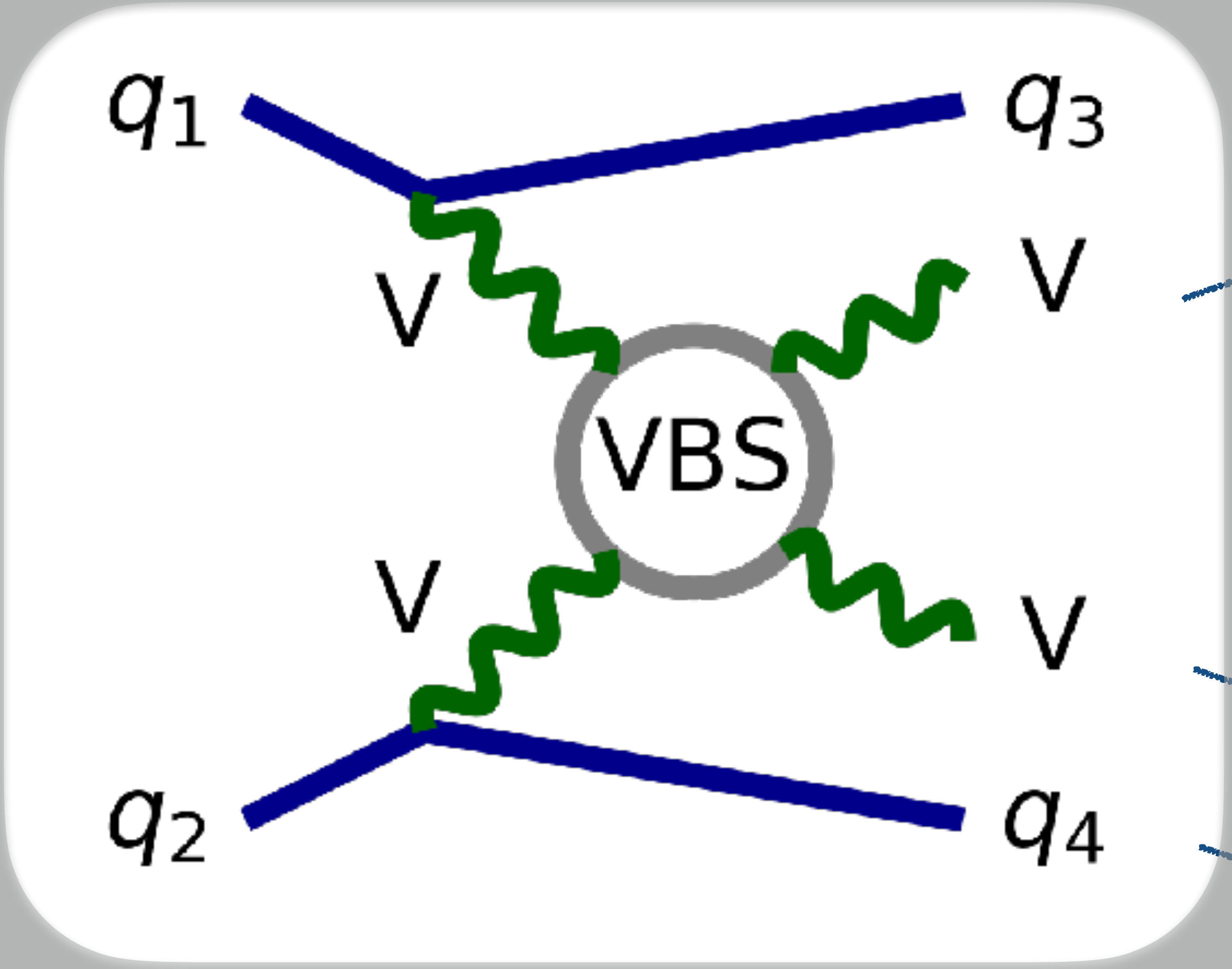
Access **electroweak processes** at hadron colliders, allowing for a direct check of the **EWSB-induced unitarisation**





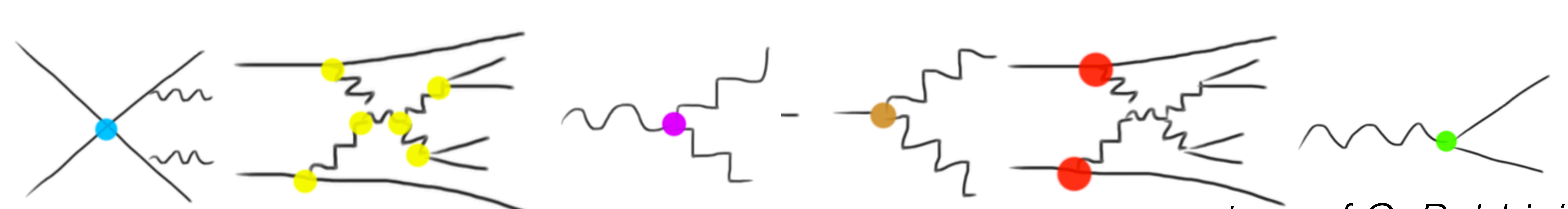
vector boson scattering

see A. Apyan's talk



Produces a large number of diagrams for each process
that offer many ways to constrain EFT operators

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{f_i^{(6)}}{\Lambda^2} O_i + \sum_j \frac{f_j^{(8)}}{\Lambda^4} O_j + \ldots$$



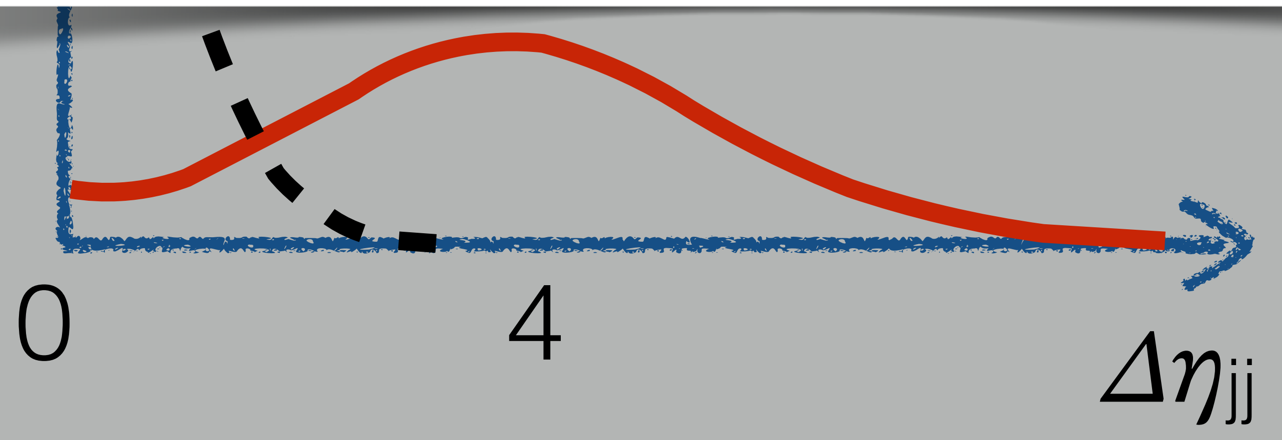
courtesy of G. Boldrini

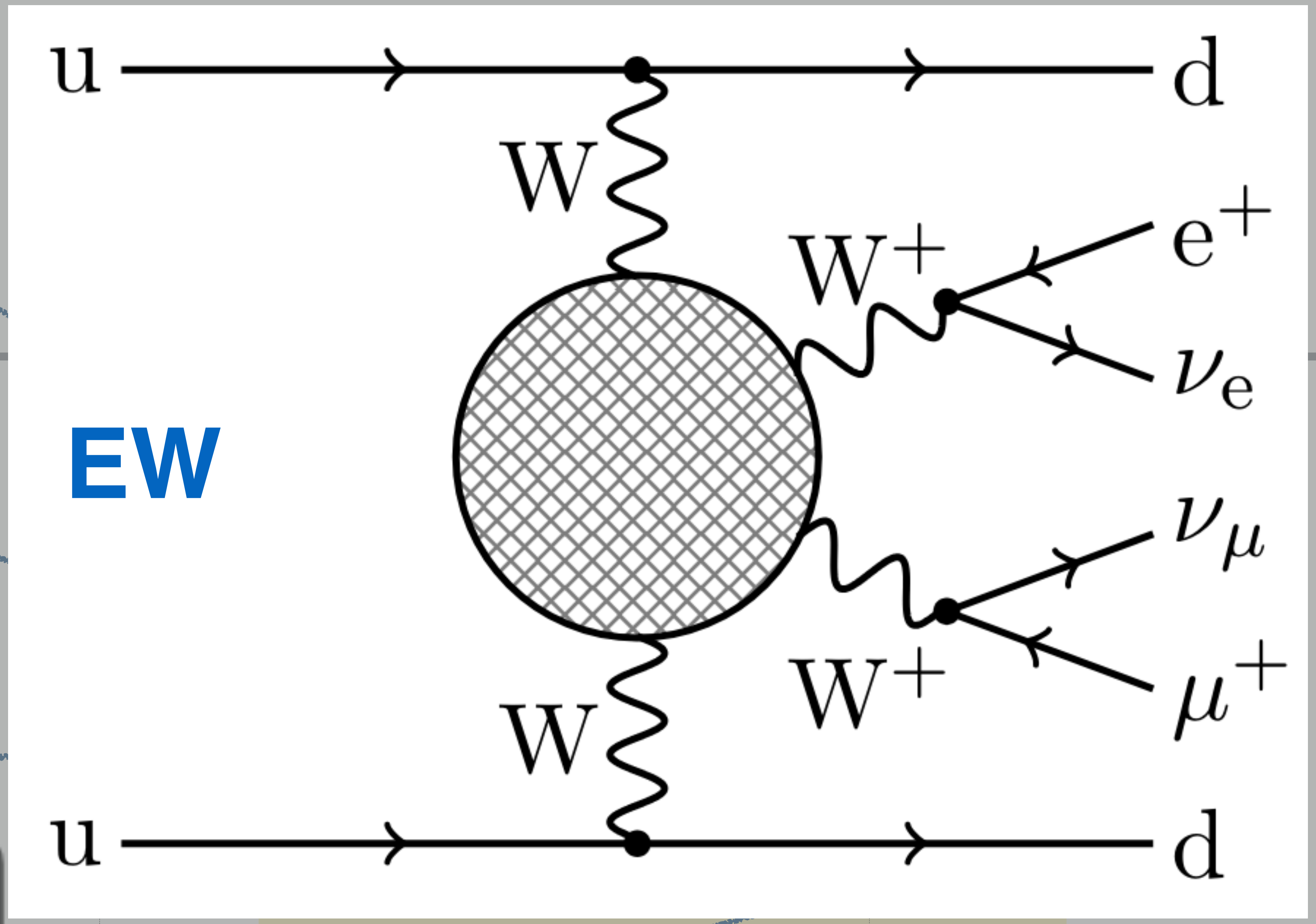
vector boson scattering

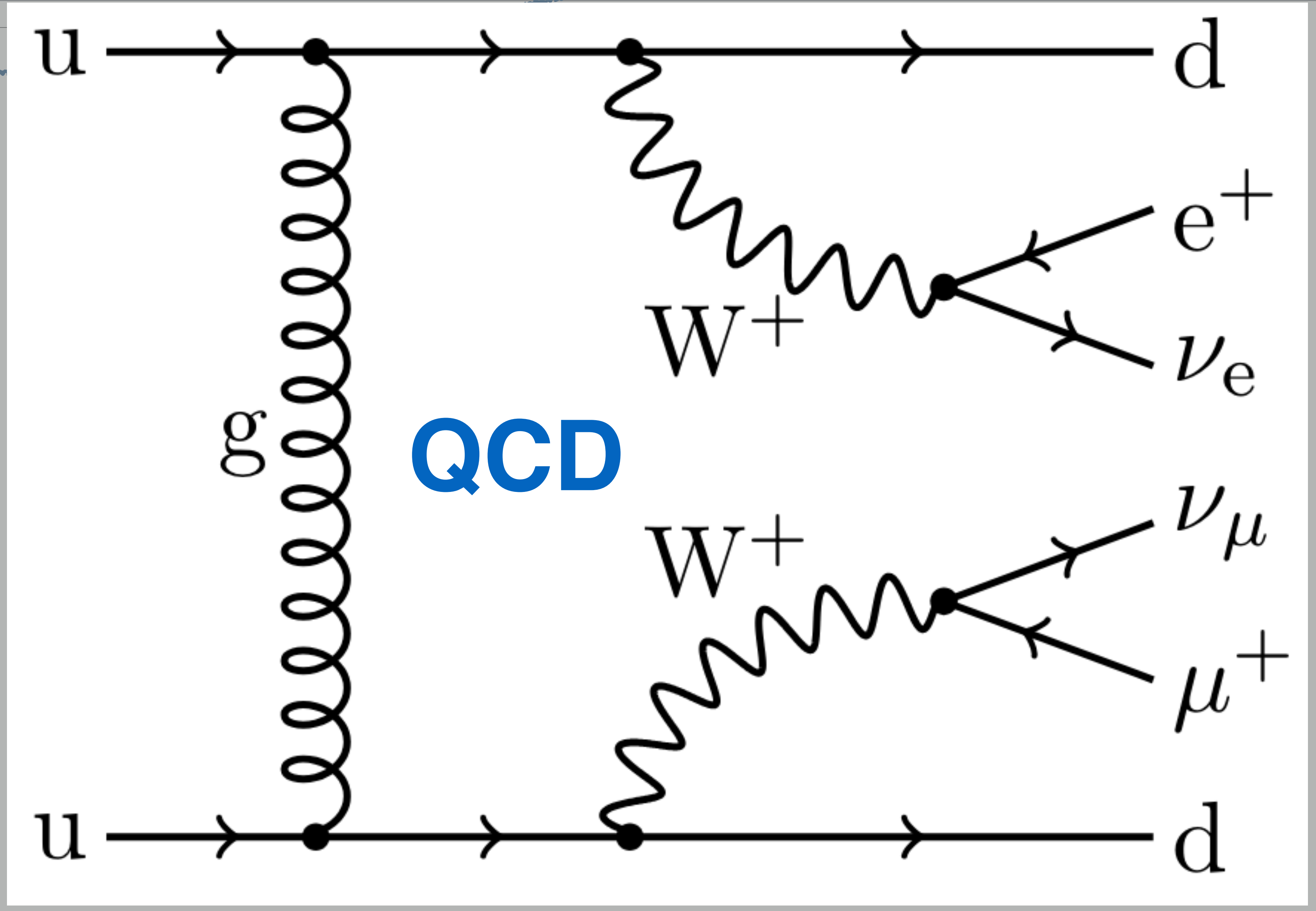
see M. Zaro's talk

EW and QCD production **coexistent in the signal region**

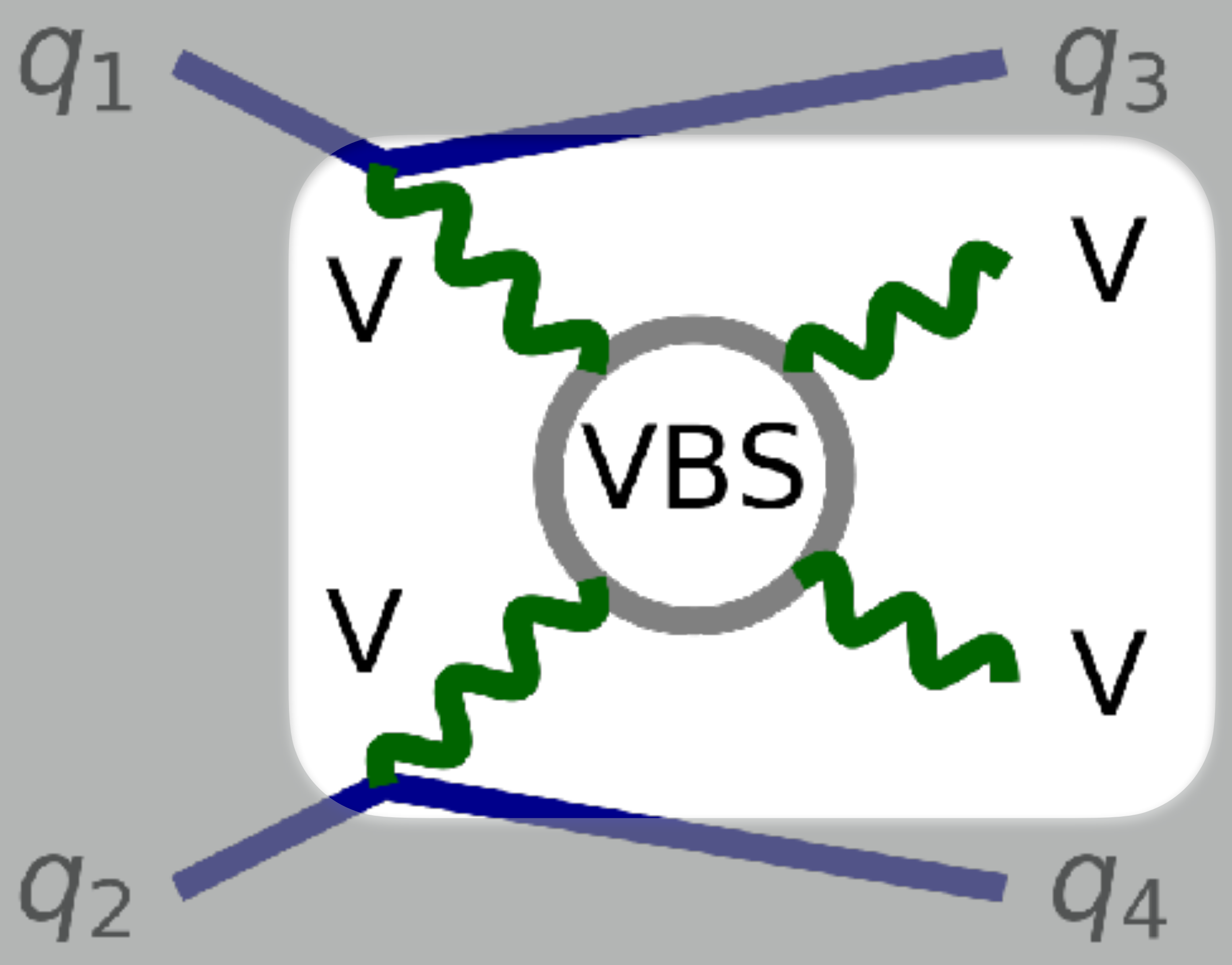
- **interfering**
- the gauge-invariant cross-section is **the sum of the two contributions**
- perform inclusive measurements

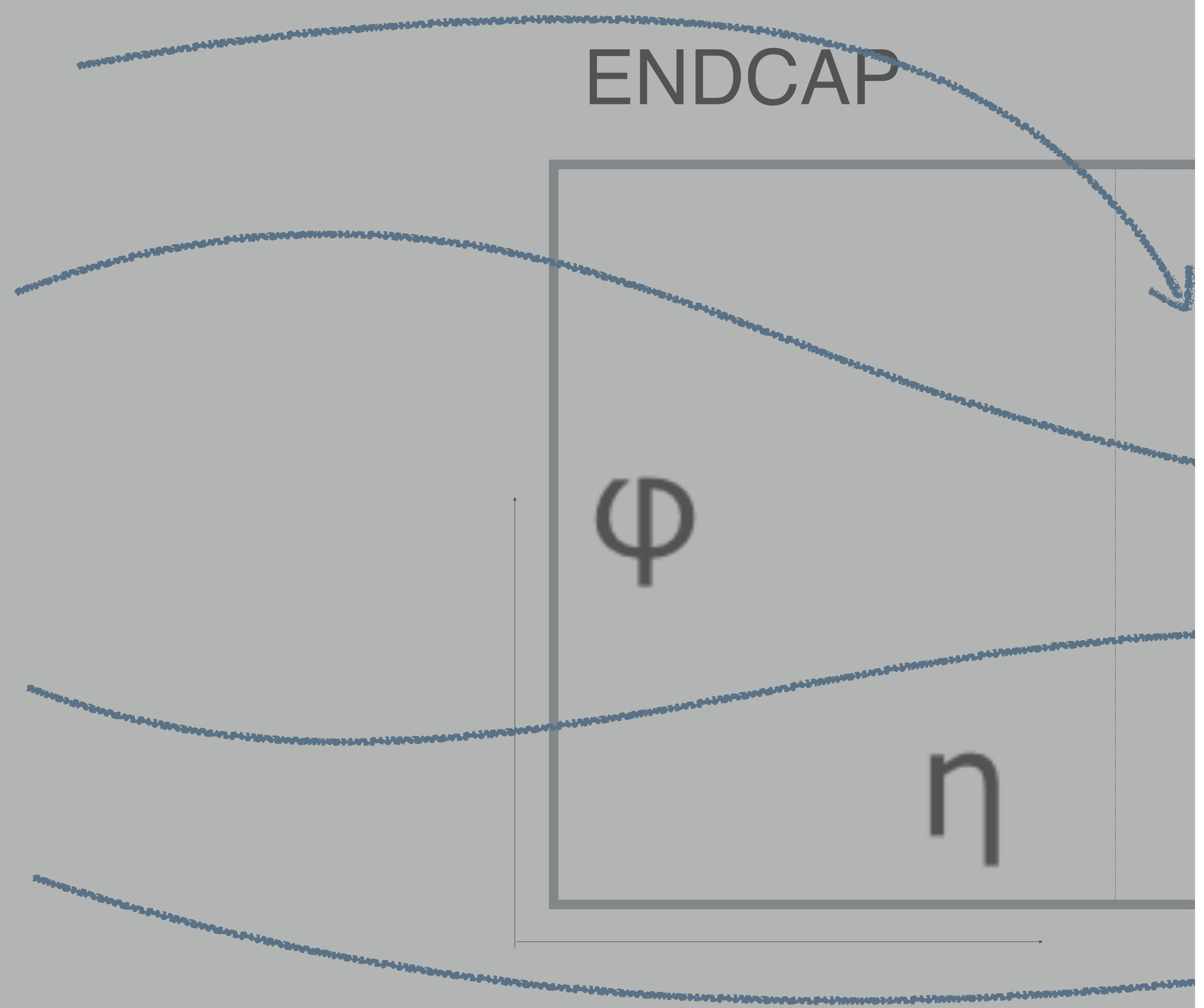




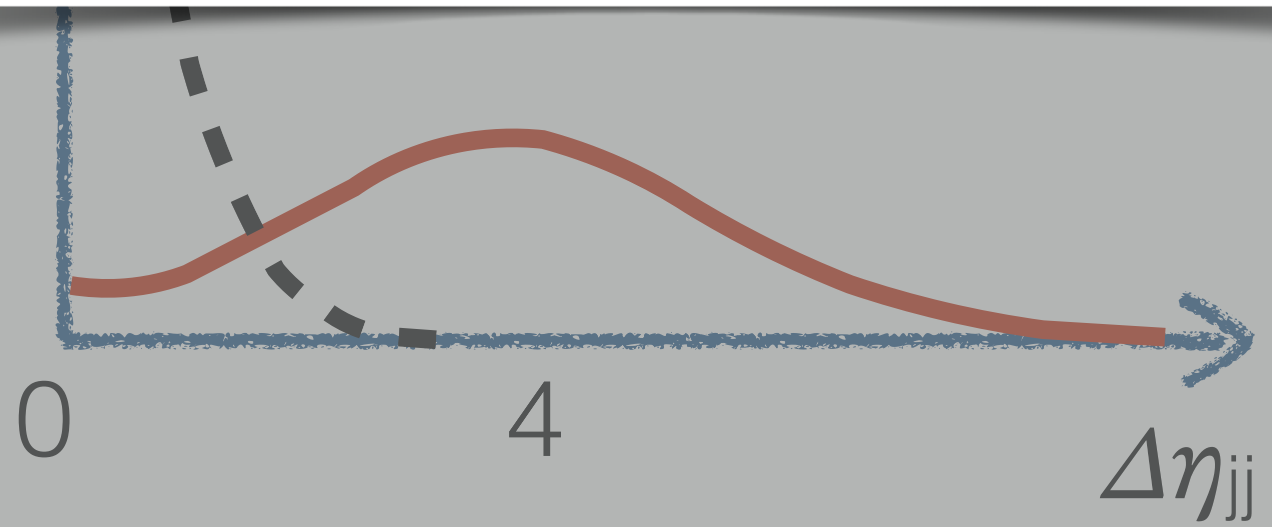


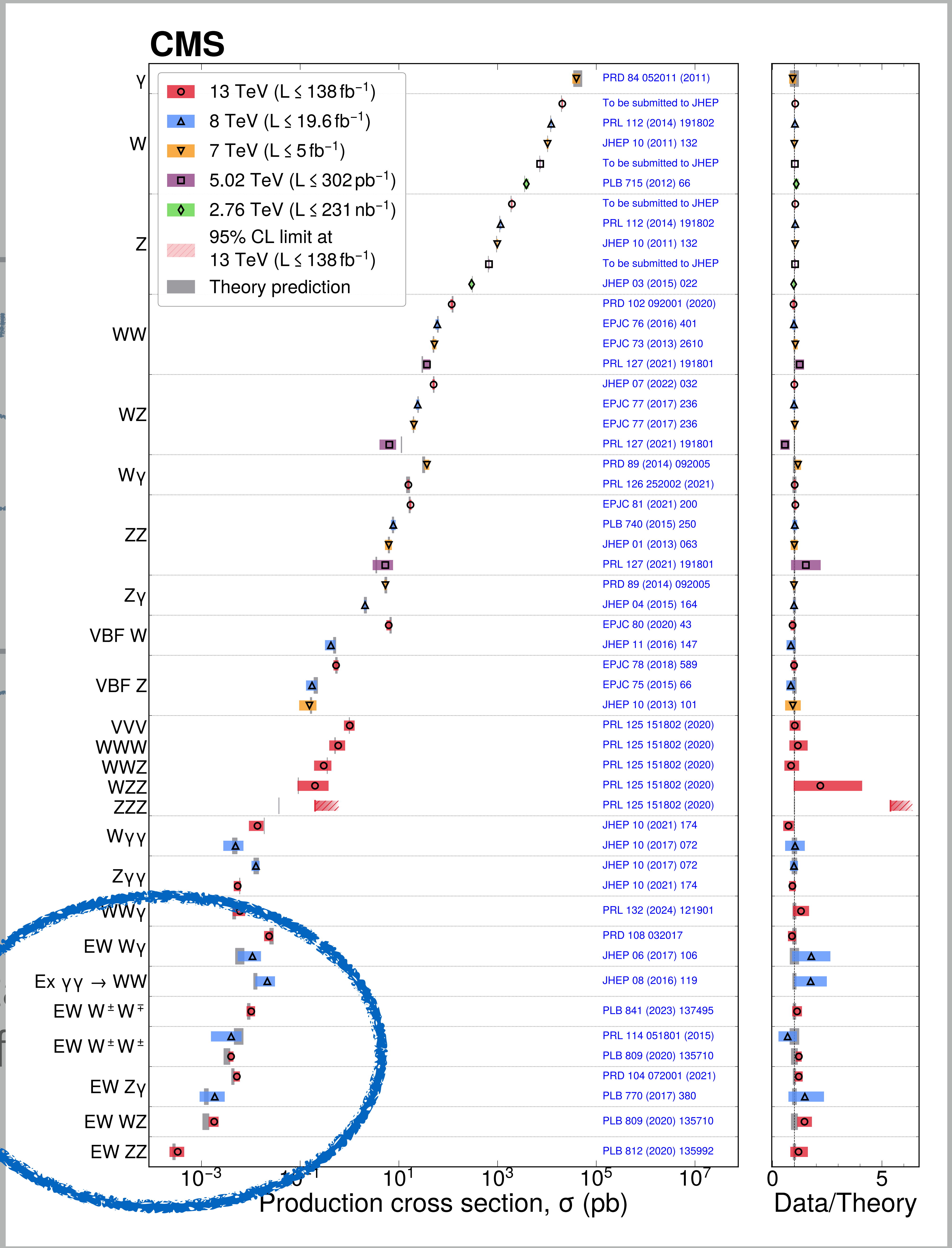
vector boson scattering





six-fermion final states have **very low production cross sections**



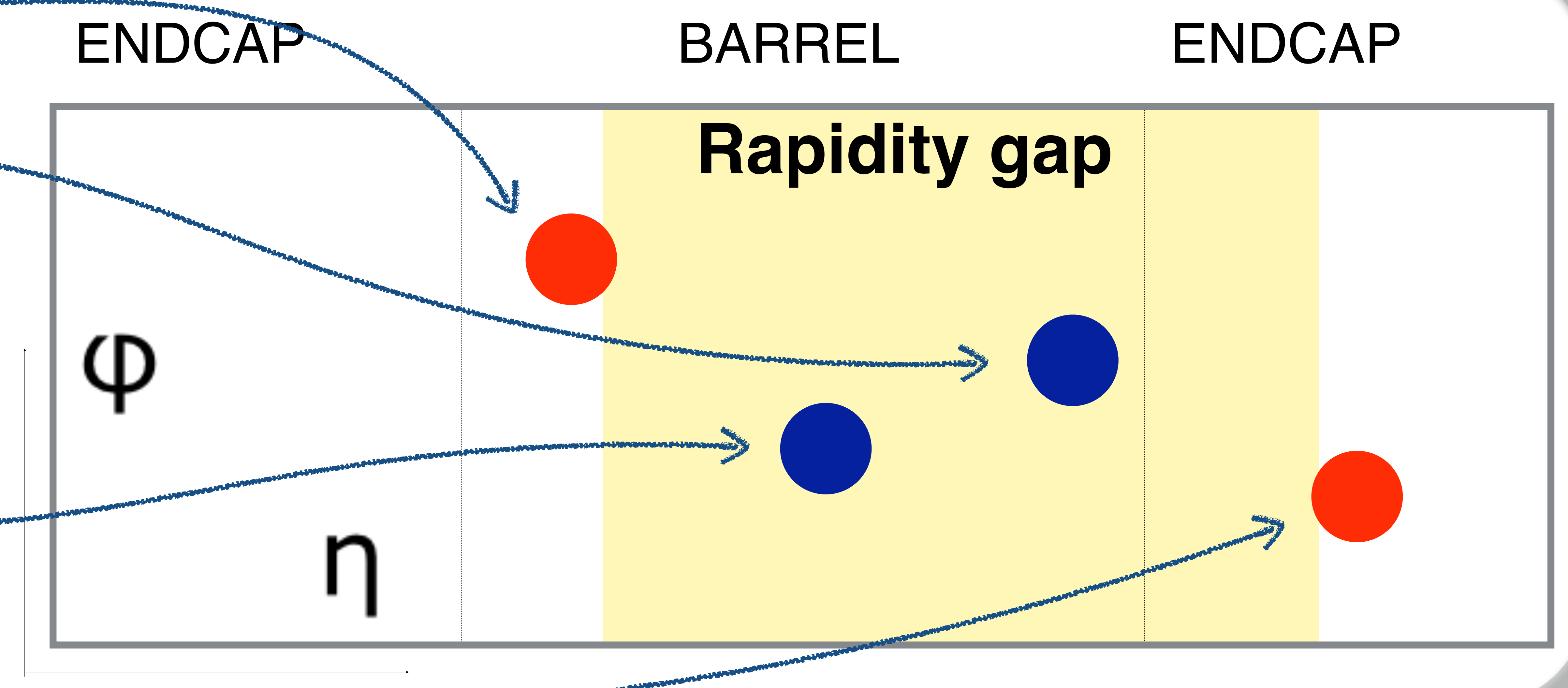


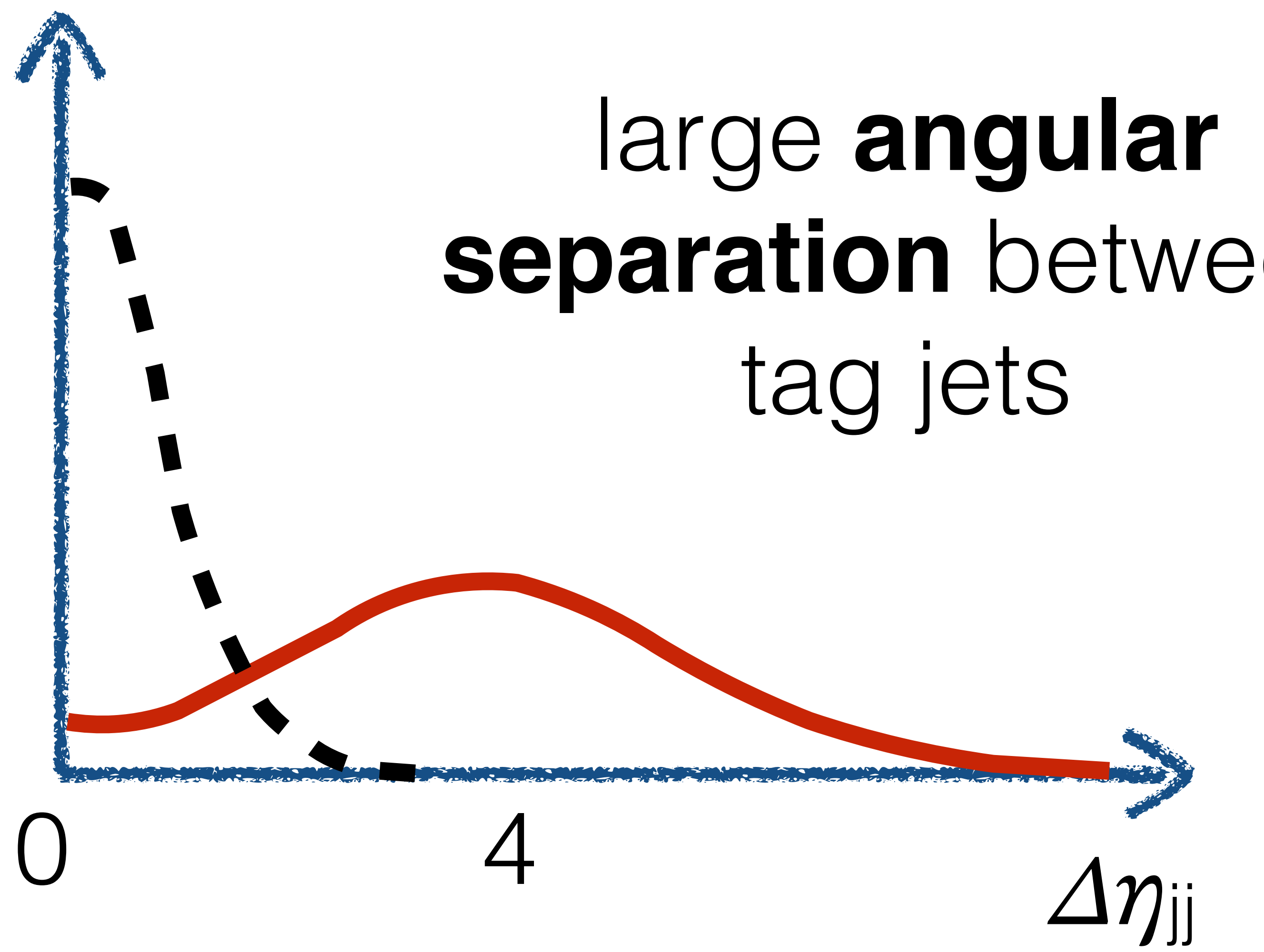
vector boson scattering

Significantly reduce backgrounds with typical selections:

$$m_{jj} > 500 \text{ GeV}$$

$$\Delta\eta_{jj} > 2.5$$





large **angular separation** between tag jets

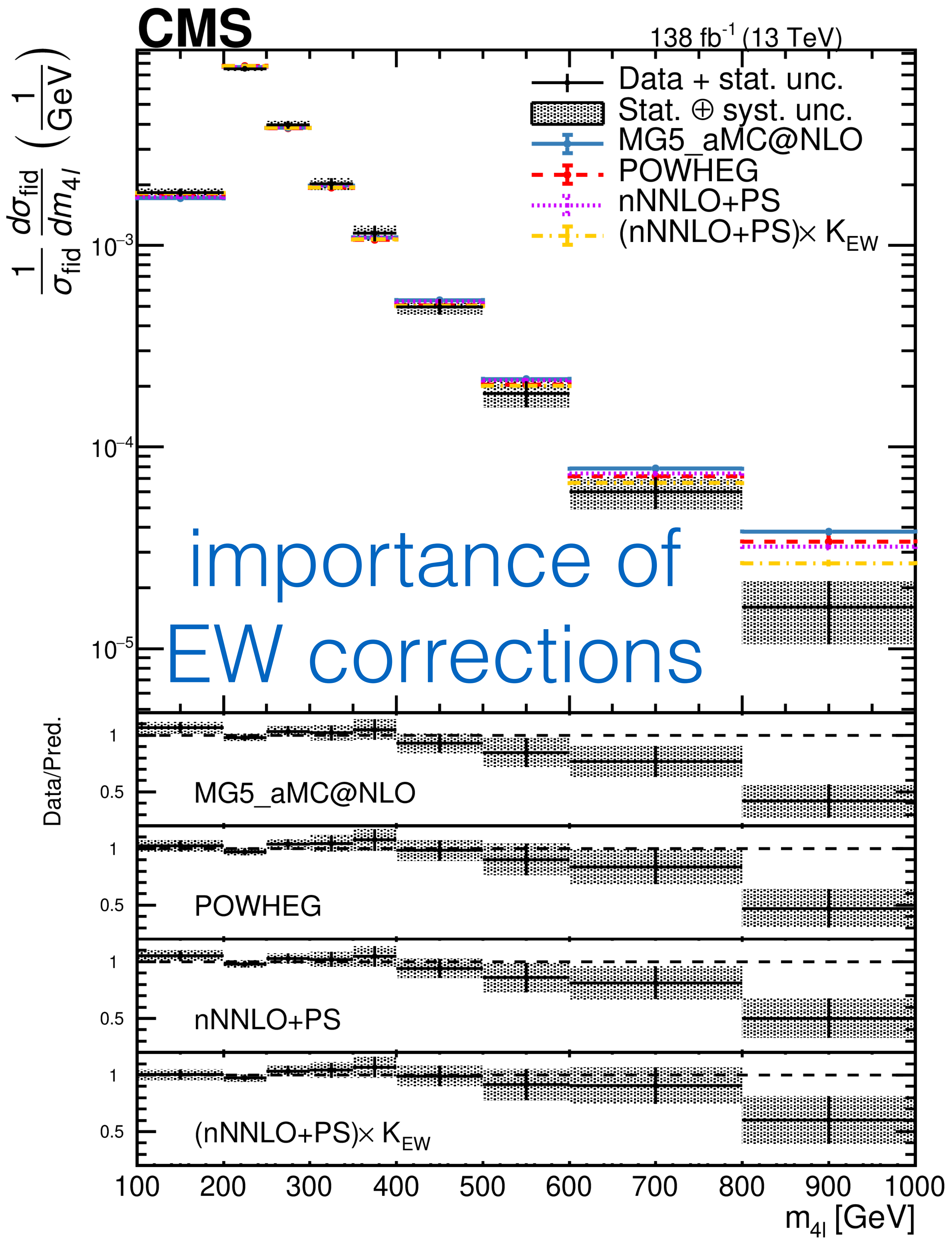
low QCD activity between tag jets, since there's no color flow between the two protons

background understanding

see G. Sorrentino's and J Roloff's talks

arxiv:2404.02711
ATLAS: arxiv:2308.12324
arxiv:2403.02793

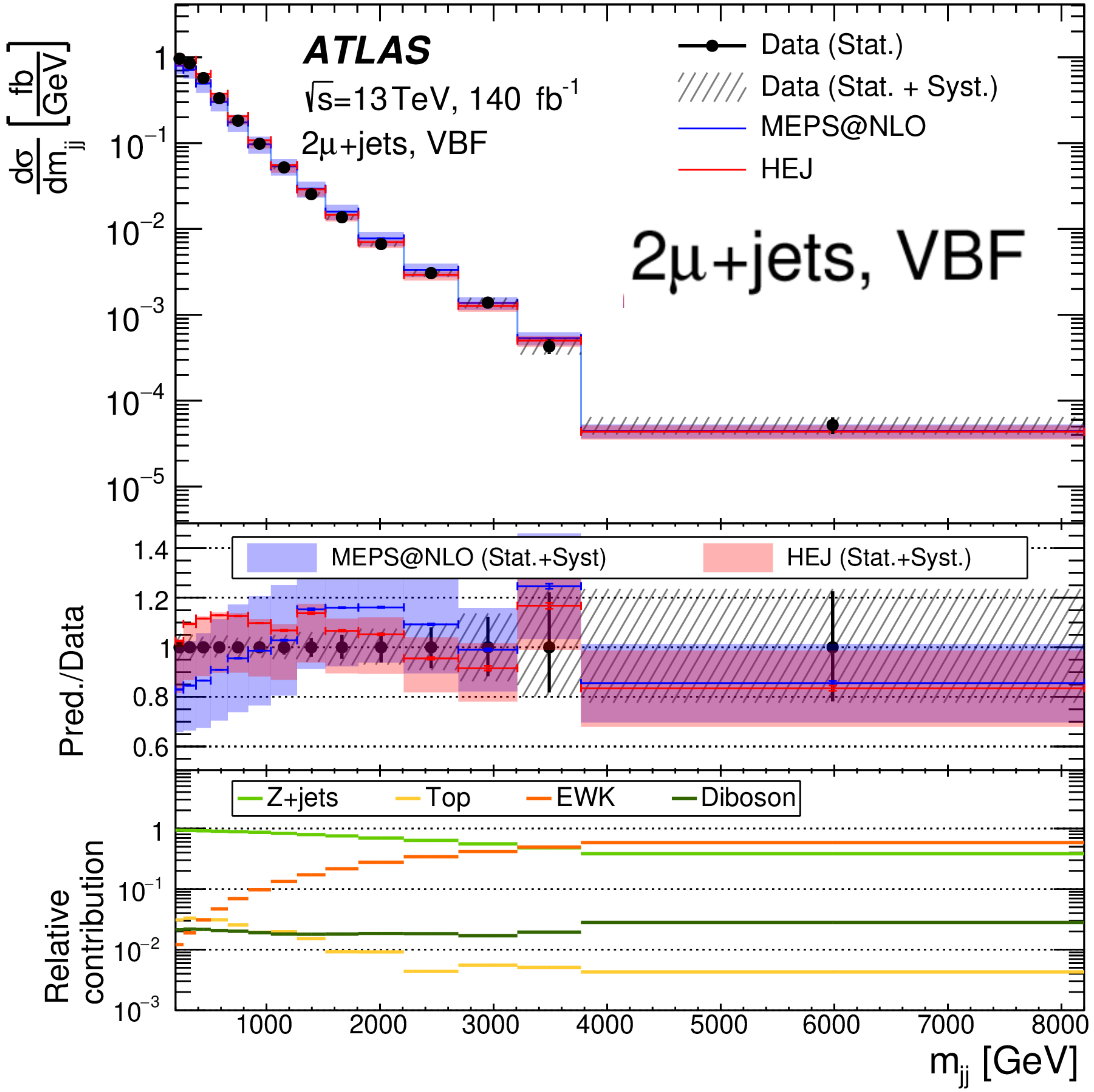
inclusive ZZ → 4ℓ + jets



importance of EW corrections

$m_{4\ell}$

MET + jets



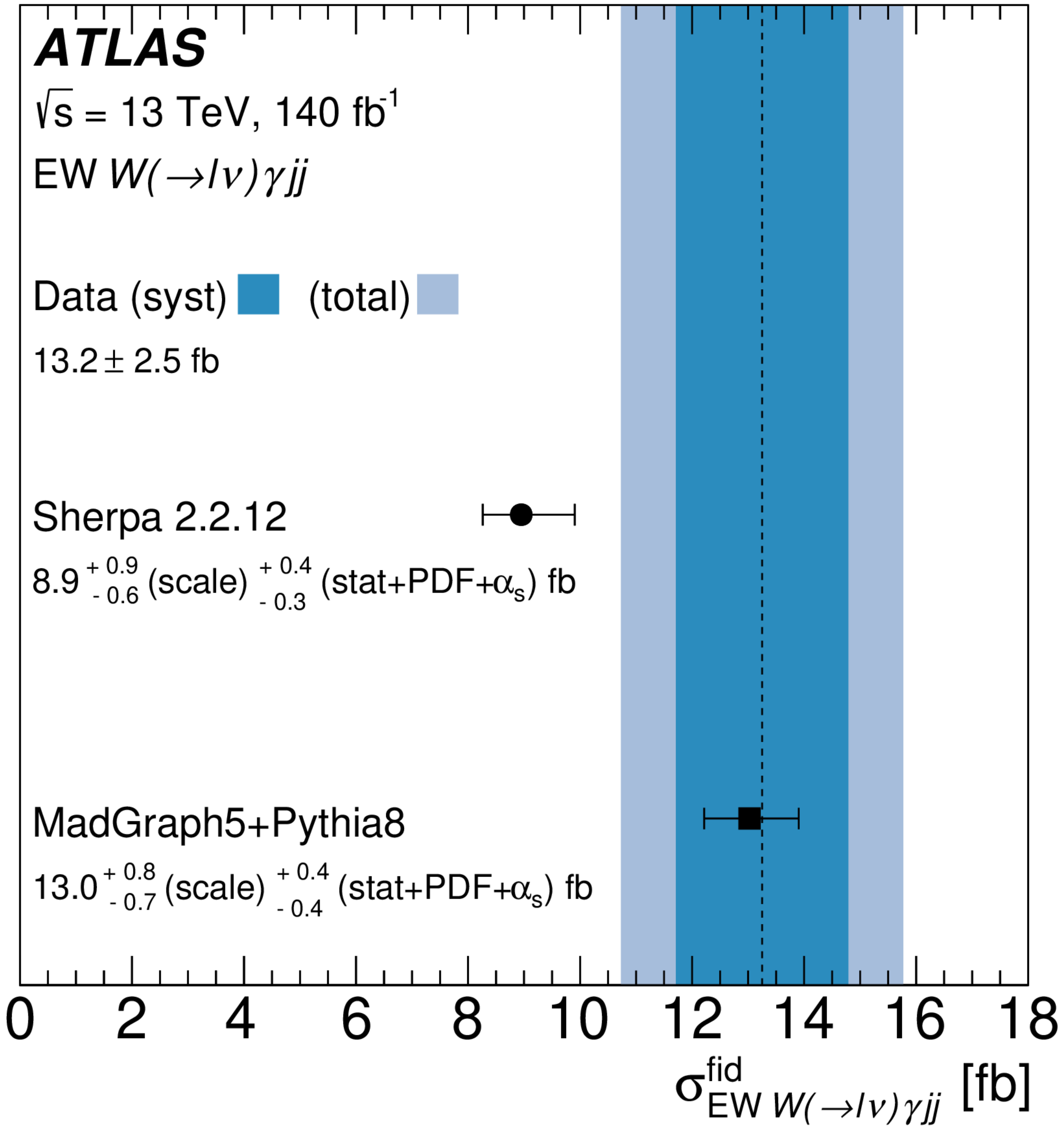
m_{jj}

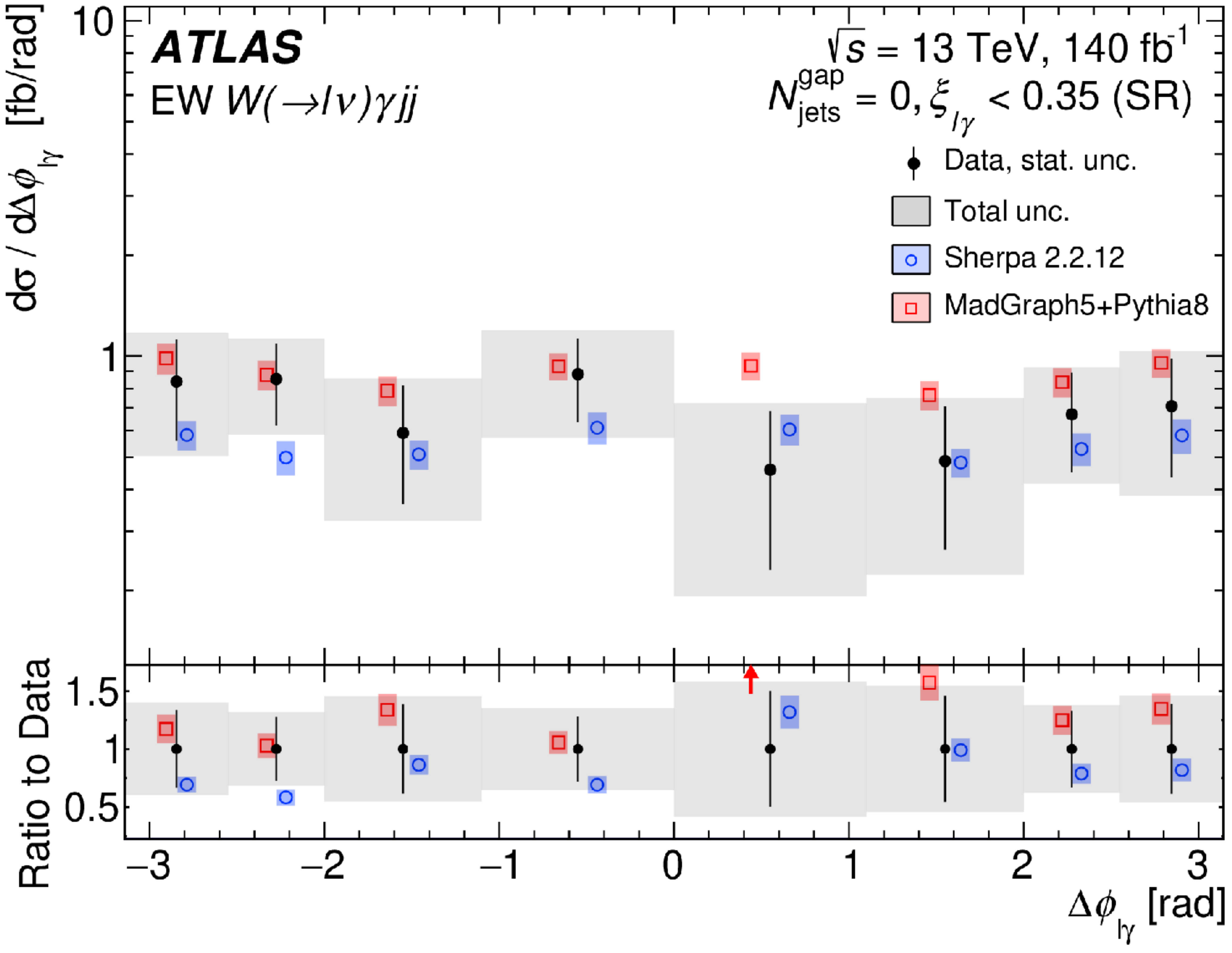
electroweak $W\gamma \to \ell\nu\gamma jj$ in ATLAS

arxiv:2403.02809

- observation sensitivity fitting the **distribution of two averaged DNNs**
- background control regions defined **based on the jet counting in the rapidity gap**
- **dimension-8 EFT limits** (f_{T3} and f_{T4} studied for the first time)

statistically dominated, following dominant uncertainties are related to **physics objects and theory modelling**





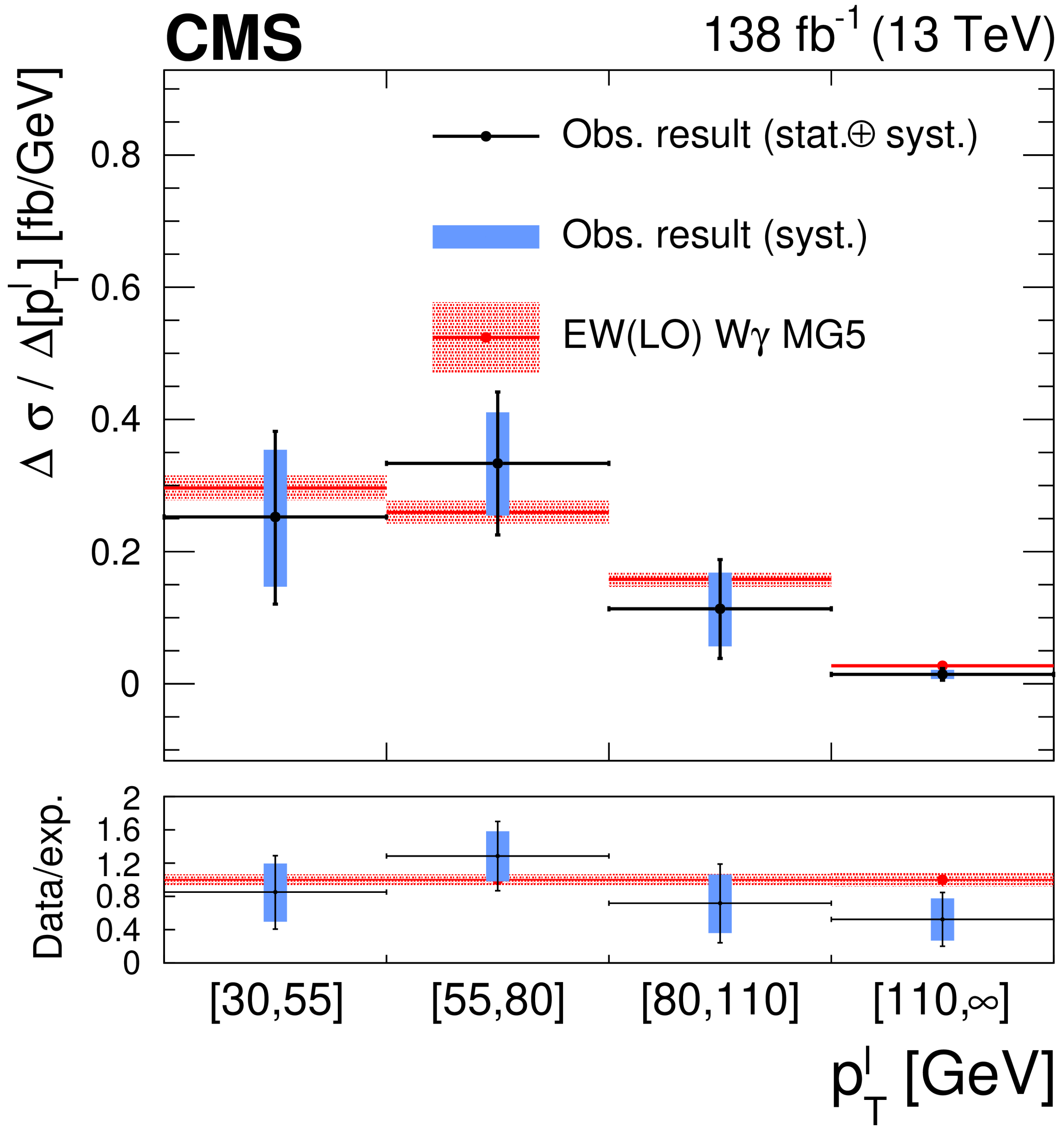
EW W$\gamma \to \ell\nu\gamma$jj in CMS

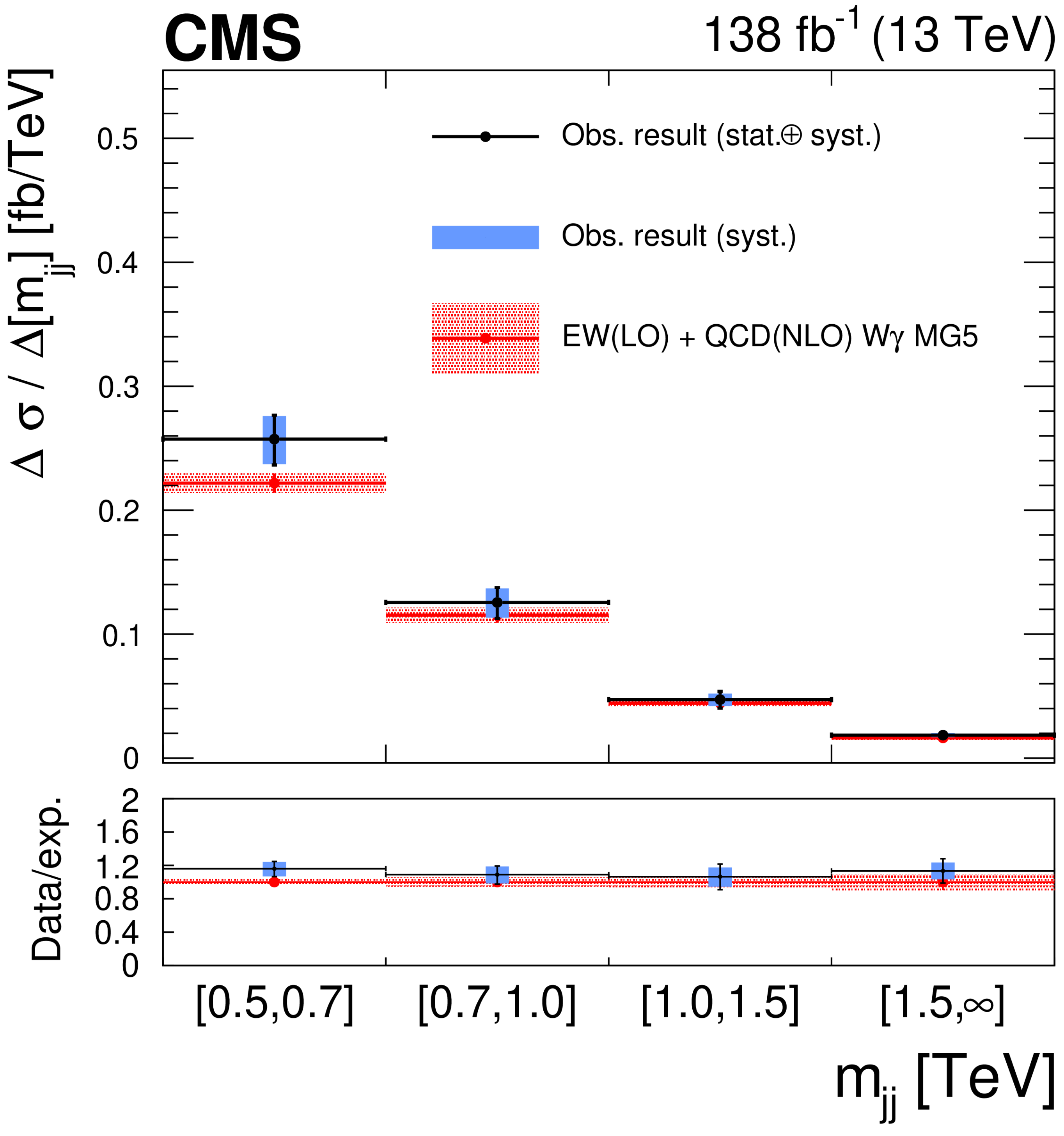
arxiv:2212.12592

observed significance of 6.0 s.d.

$$\sigma^{\text{fid}}_{\text{EW}} = 23.5 \pm 2.8\,(\text{stat})^{+1.9}_{-1.7}\,(\text{theo})^{+3.5}_{-3.4}\,(\text{syst})\,\text{fb} = 23.5^{+4.9}_{-4.7}\,\text{fb}$$

$$\sigma^{\text{fid}}_{\text{EW+QCD}} = 113 \pm 2.0\,(\text{stat})^{+2.5}_{-2.3}\,(\text{theo})^{+13}_{-13}\,(\text{syst})\,\text{fb} = 113 \pm 13\,\text{fb}$$



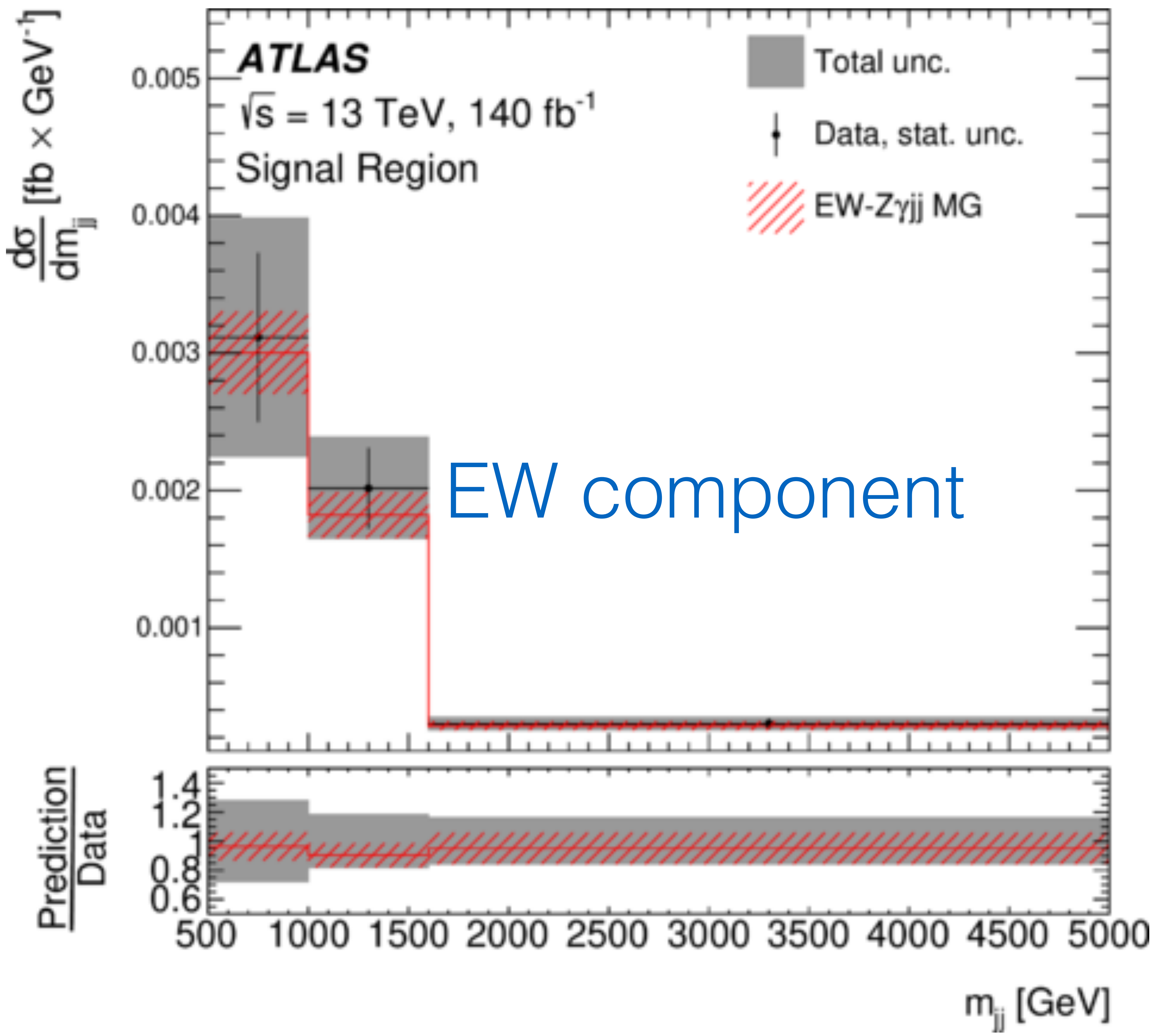


Expected limit	Observed limit	U_{bound}
$-5.1 < f_{M,0}/\Lambda^4 < 5.1$	$-5.6 < f_{M,0}/\Lambda^4 < 5.5$	1.7
$-7.1 < f_{M,1}/\Lambda^4 < 7.4$	$-7.8 < f_{M,1}/\Lambda^4 < 8.1$	2.1
$-1.8 < f_{M,2}/\Lambda^4 < 1.8$	$-1.9 < f_{M,2}/\Lambda^4 < 1.9$	2.0
$-2.5 < f_{M,3}/\Lambda^4 < 2.5$	$-2.7 < f_{M,3}/\Lambda^4 < 2.7$	2.7
$-3.3 < f_{M,4}/\Lambda^4 < 3.3$	$-3.7 < f_{M,4}/\Lambda^4 < 3.6$	2.3
$-3.4 < f_{M,5}/\Lambda^4 < 3.6$	$-3.9 < f_{M,5}/\Lambda^4 < 3.9$	2.7
$-13 < f_{M,7}/\Lambda^4 < 13$	$-14 < f_{M7}/\Lambda^4 < 14$	2.2
$-0.43 < f_{T,0}/\Lambda^4 < 0.51$	$-0.47 < f_{T,0}/\Lambda^4 < 0.51$	1.9
$-0.27 < f_{T,1}/\Lambda^4 < 0.31$	$-0.31 < f_{T,1}/\Lambda^4 < 0.34$	2.5
$-0.72 < f_{T,2}/\Lambda^4 < 0.92$	$-0.85 < f_{T,2}/\Lambda^4 < 1.0$	2.3
$-0.29 < f_{T,5}/\Lambda^4 < 0.31$	$-0.31 < f_{T,5}/\Lambda^4 < 0.33$	2.6
$-0.23 < f_{T,6}/\Lambda^4 < 0.25$	$-0.25 < f_{T,6}/\Lambda^4 < 0.27$	2.9
$-0.60 < f_{T,7}/\Lambda^4 < 0.68$	$-0.67 < f_{T,7}/\Lambda^4 < 0.73$	3.1

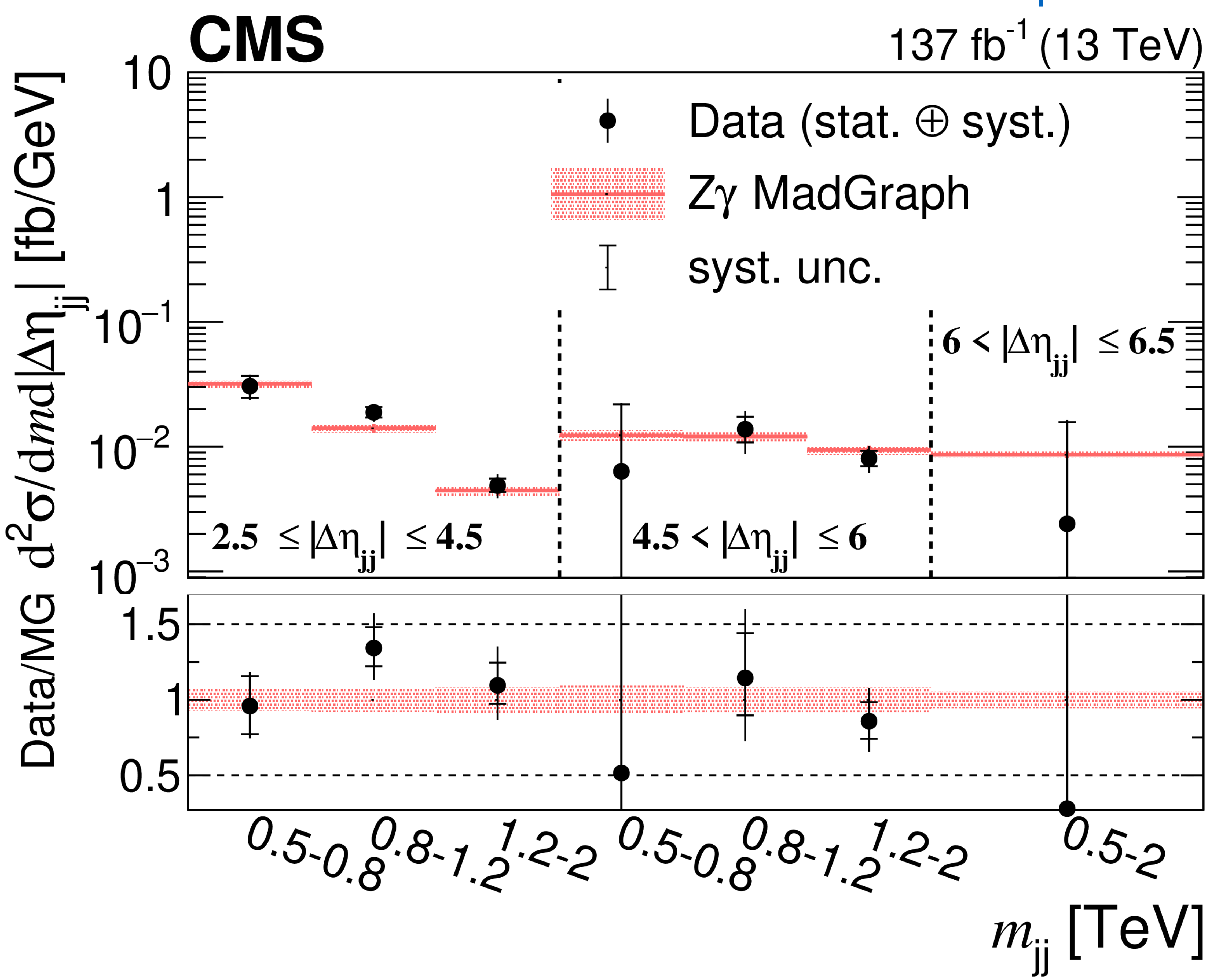
EW Zγ → ℓℓγjj production

arxiv:2305.19142
arxiv:2106.11082
ATLAS Zγ→ννγ arxiv:2208.12741

- **cross-section** measurements, unfolded distributions
- limits on BSM **quartic neutral gauge couplings**



EW + QCD component

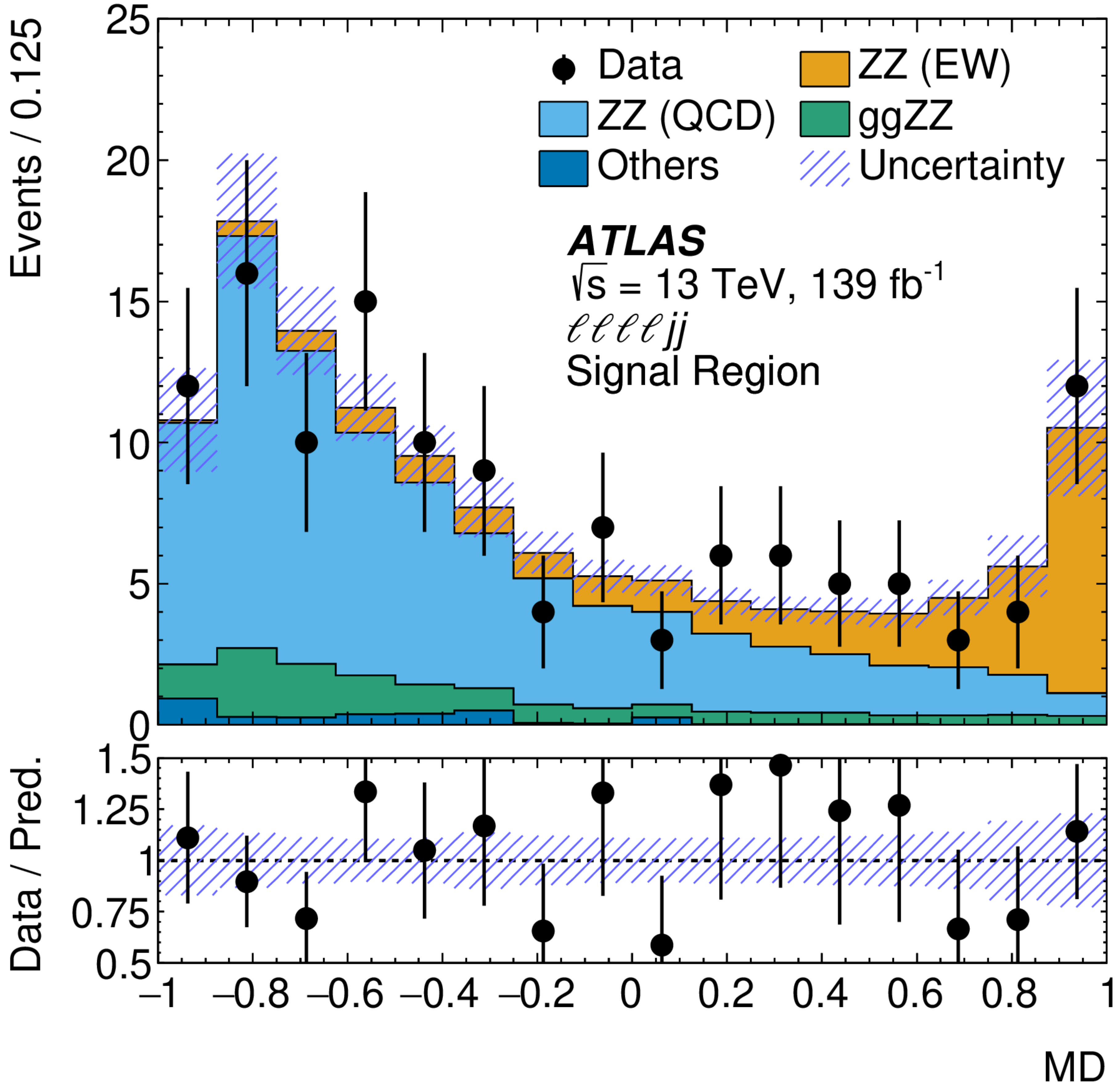


EW ZZ → 4ℓ production

arxiv:2004.10612
CMS: arxiv:2008.07013

- **NLO pQCD signal** model
- fit on multivariate discriminants (MD)
- sensitivity larger than 5 s.d.
- **statistically dominated**

	μ_{EW}	$\mu_{QCD}^{\ell\ell\ell\ell jj}$	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	0.97 ± 0.27	0.99 ± 0.22	5.5 (5.6) σ
$\ell\ell\nu\nu jj$	0.7 ± 0.5	–	1.3 (2.1) σ
Combined	0.92 ± 0.24	0.99 ± 0.22	5.7 (5.9) σ



- inclusive fiducial **cross-sections** measurement:

	Measured fiducial σ [fb]	Predicted fiducial σ [fb]
$\ell\ell\ell\ell jj$	$1.27 \pm 0.12(\text{stat}) \pm 0.02(\text{theo}) \pm 0.07(\text{exp}) \pm 0.01(\text{bkg}) \pm 0.02(\text{lumi})$	$1.26 \pm 0.04(\text{stat}) \pm 0.22(\text{theo})$
$\ell\ell\nu\nu jj$	$1.13 \pm 0.28(\text{stat}) \pm 0.04(\text{theo}) \pm 0.06(\text{exp}) \pm 0.15(\text{bkg}) \pm 0.02(\text{lumi})$	$1.11 \pm 0.01(\text{stat}) \pm 0.12(\text{theo})$

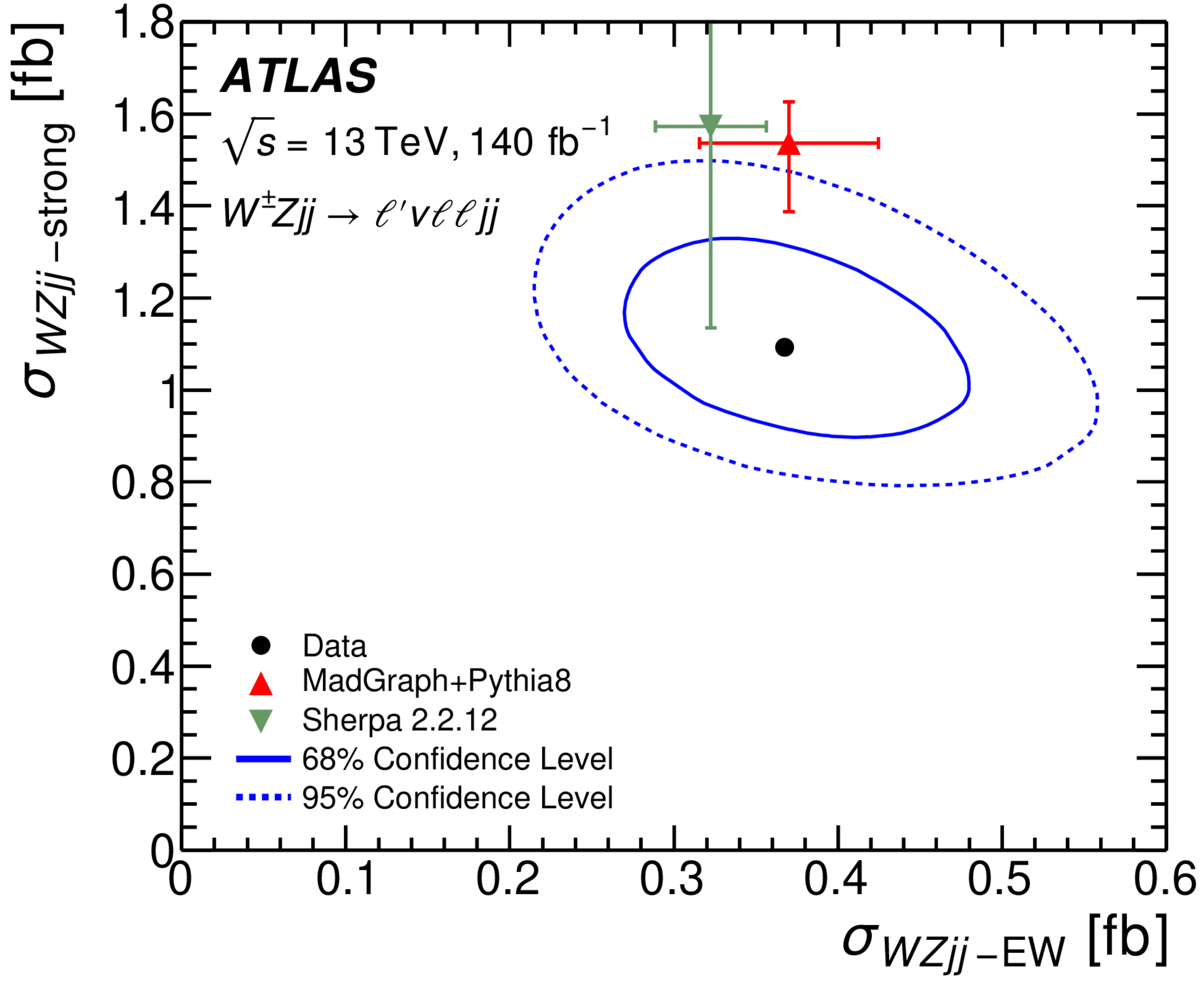
EW WZ → $3\ell\nu$ production

arxiv:2403.15296

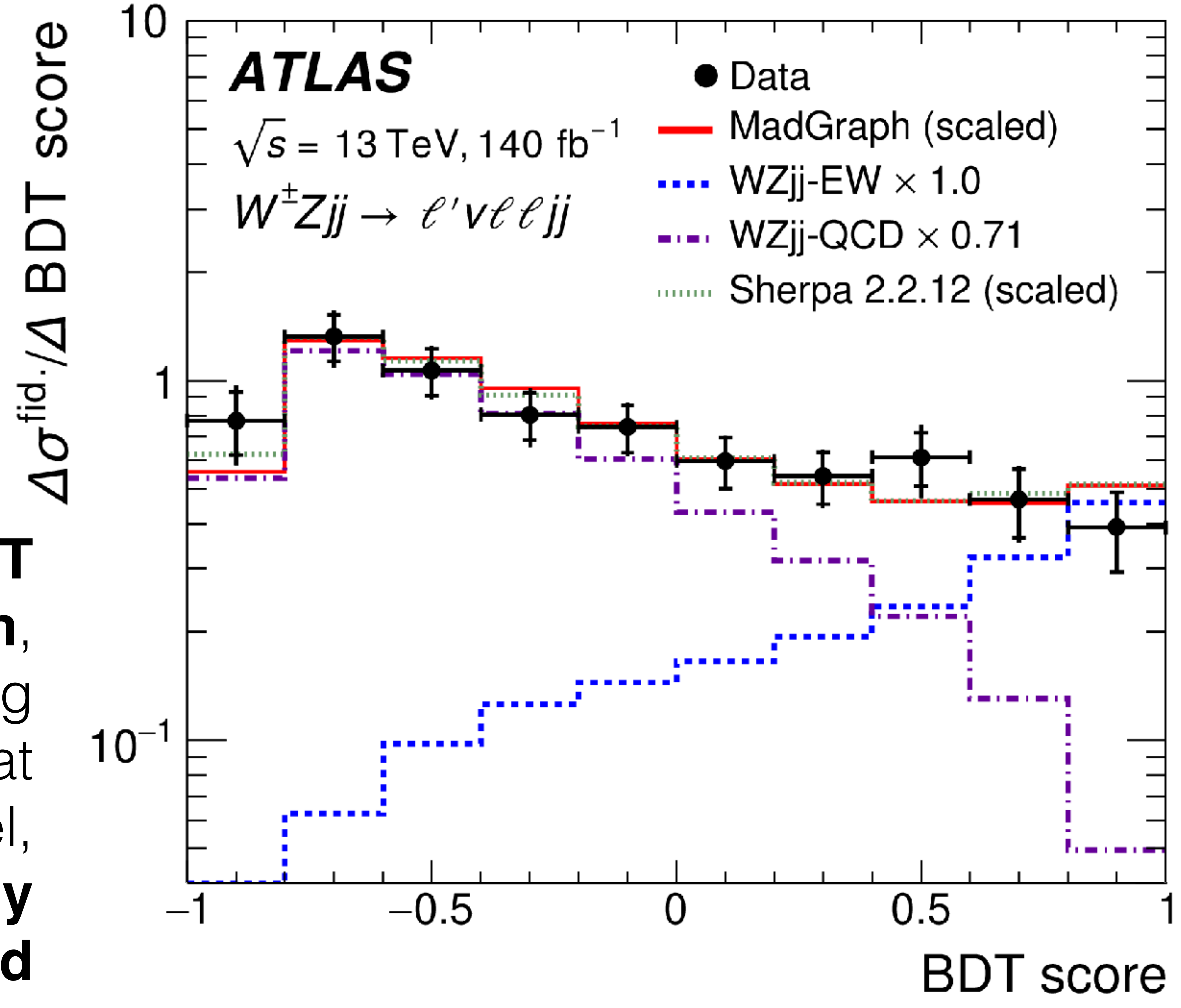
- extensive use of **MVA techniques**
- **main uncertainties** from theory modelling and jet reco
- **dim-8 EFT limits** comparable with CMS ones

$$\sigma_{EW} = 0.37 \pm 0.07 \text{ fb}$$

$$\sigma_{QCD} = 1.09 \pm 0.14 \text{ fb}$$



unfolded BDT distribution, obtained training the same BDT at particle level, **statistically dominated**

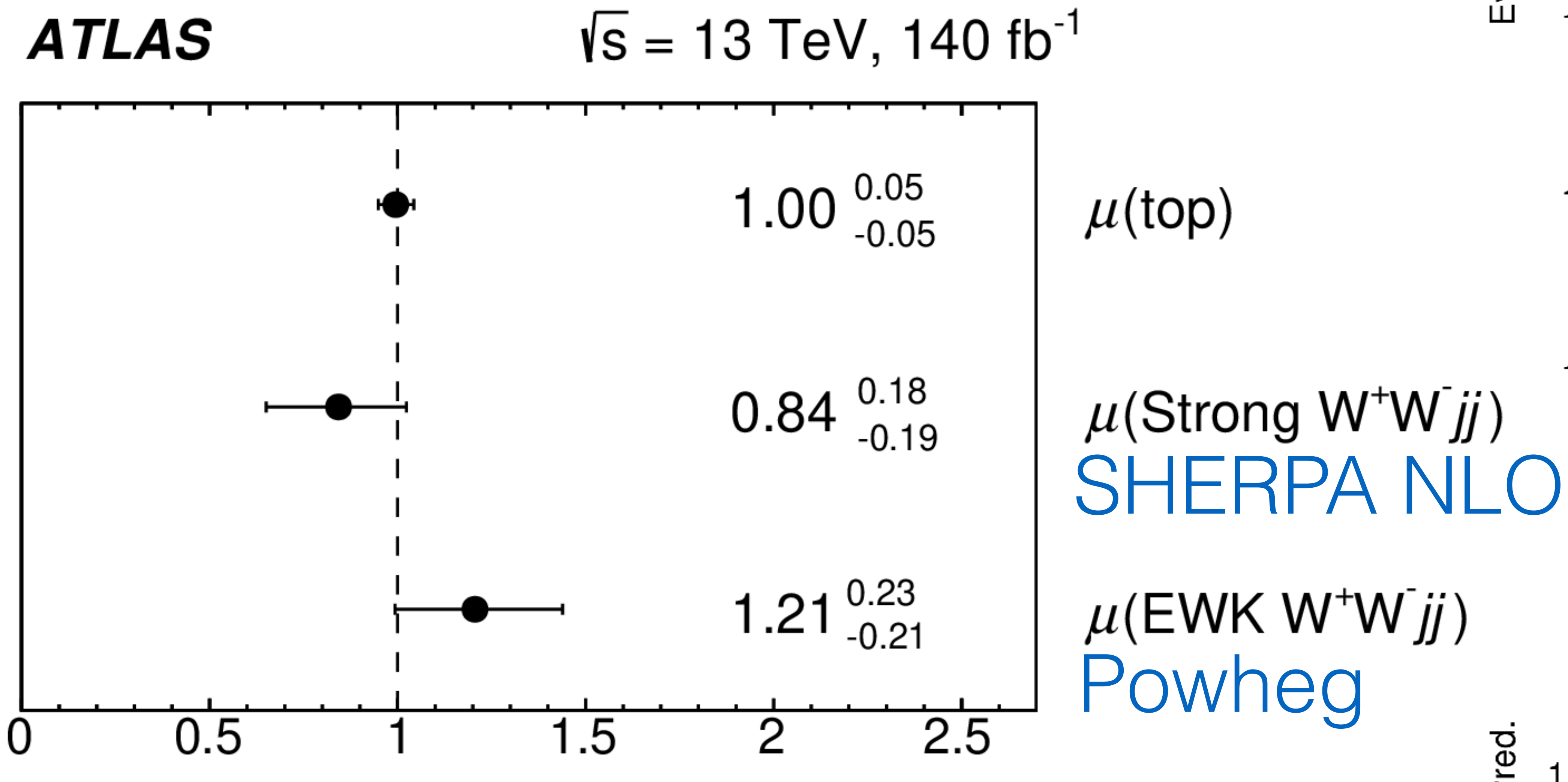


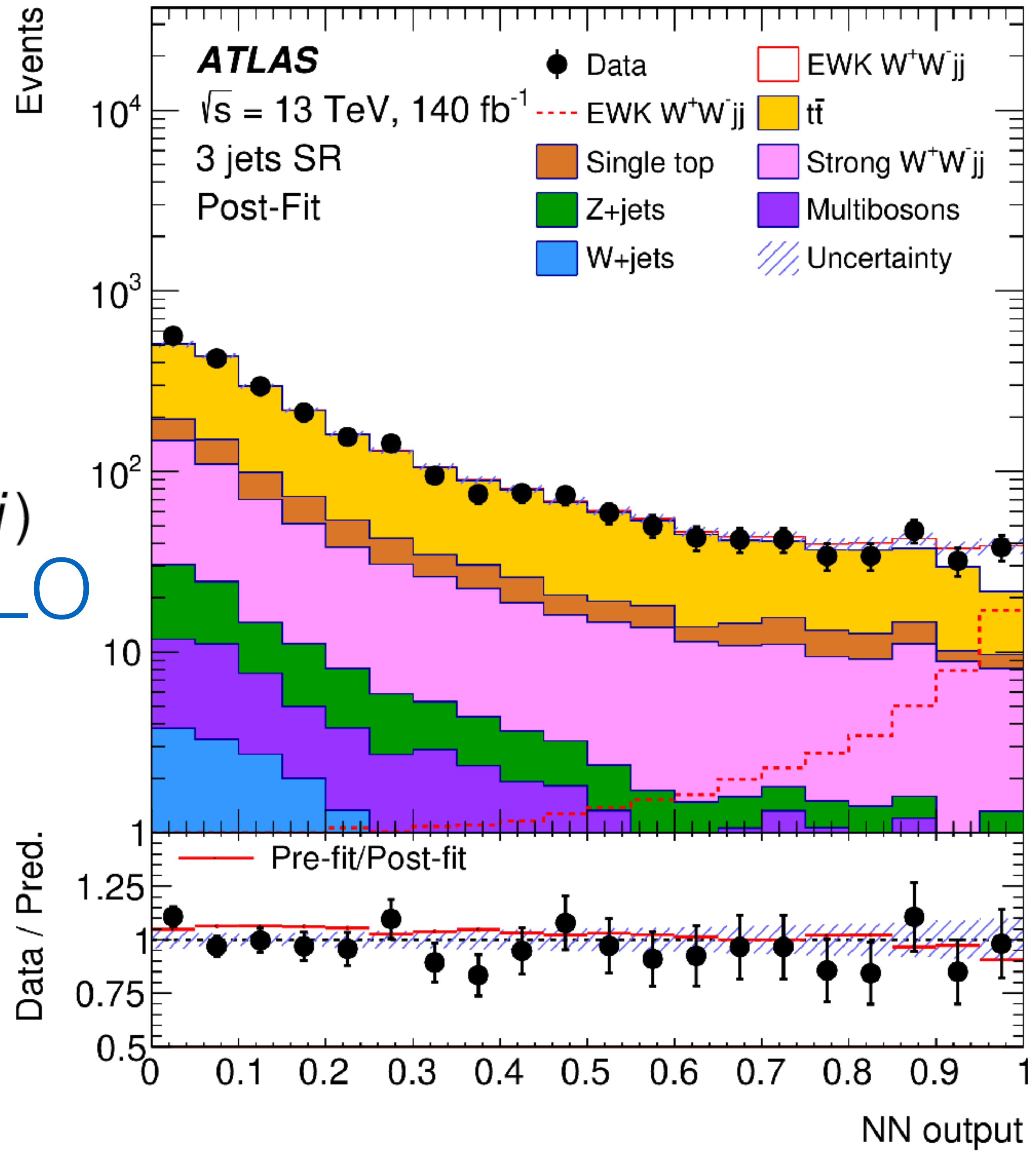
EW $W^+W^- \to \ell^+\nu\ell^-\nu$ cross-section

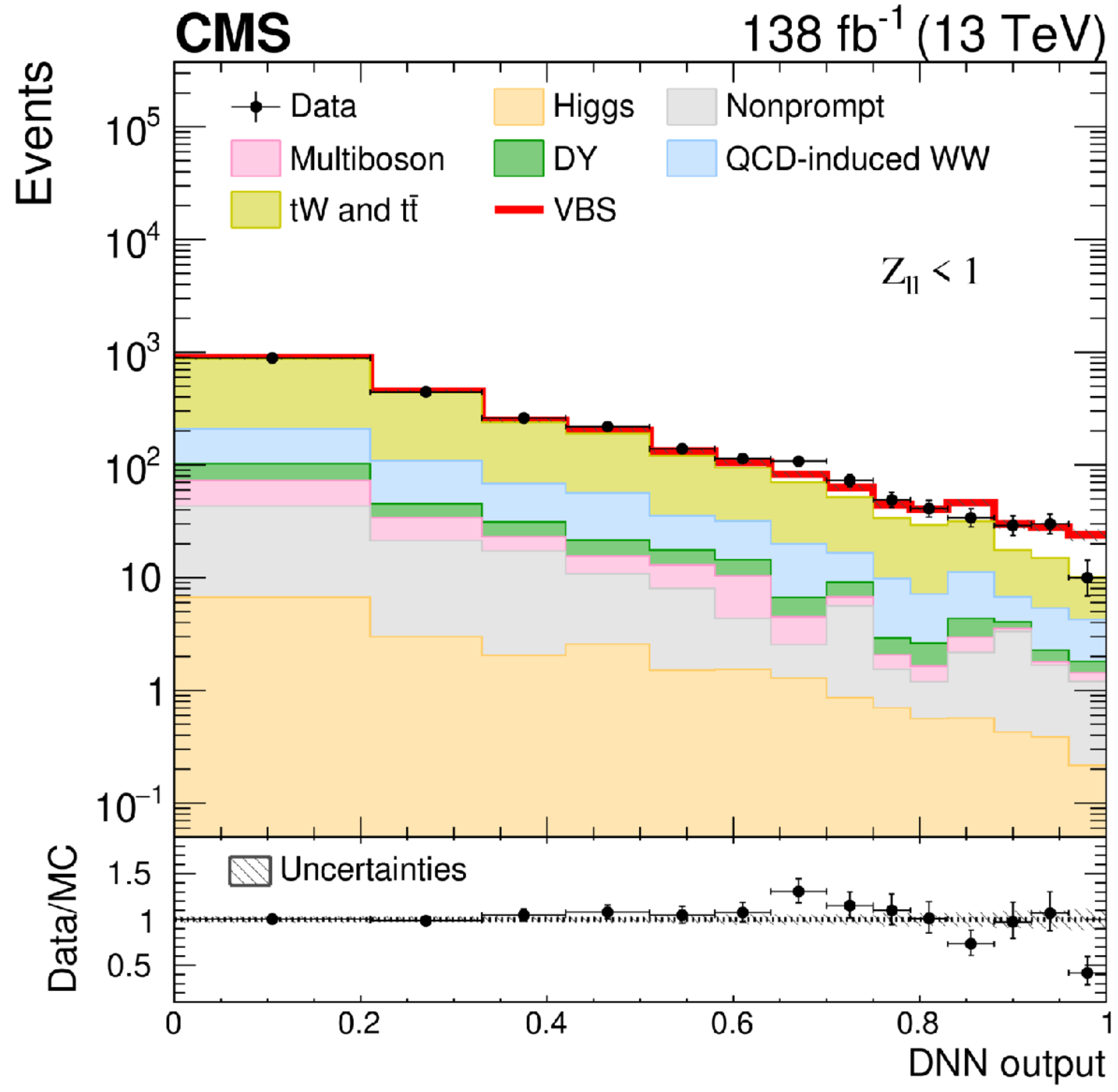
arxiv:2205.05711

arxiv:2403.04869

- **DNN's used** in both collaborations to enhance signal sensitivity
- ATLAS focussing on the **eμ final state** only, **also ee and $\mu\mu$** considered in CMS
- ATLAS simulates the EW signal at **NLO pQCD** precision with Powheg



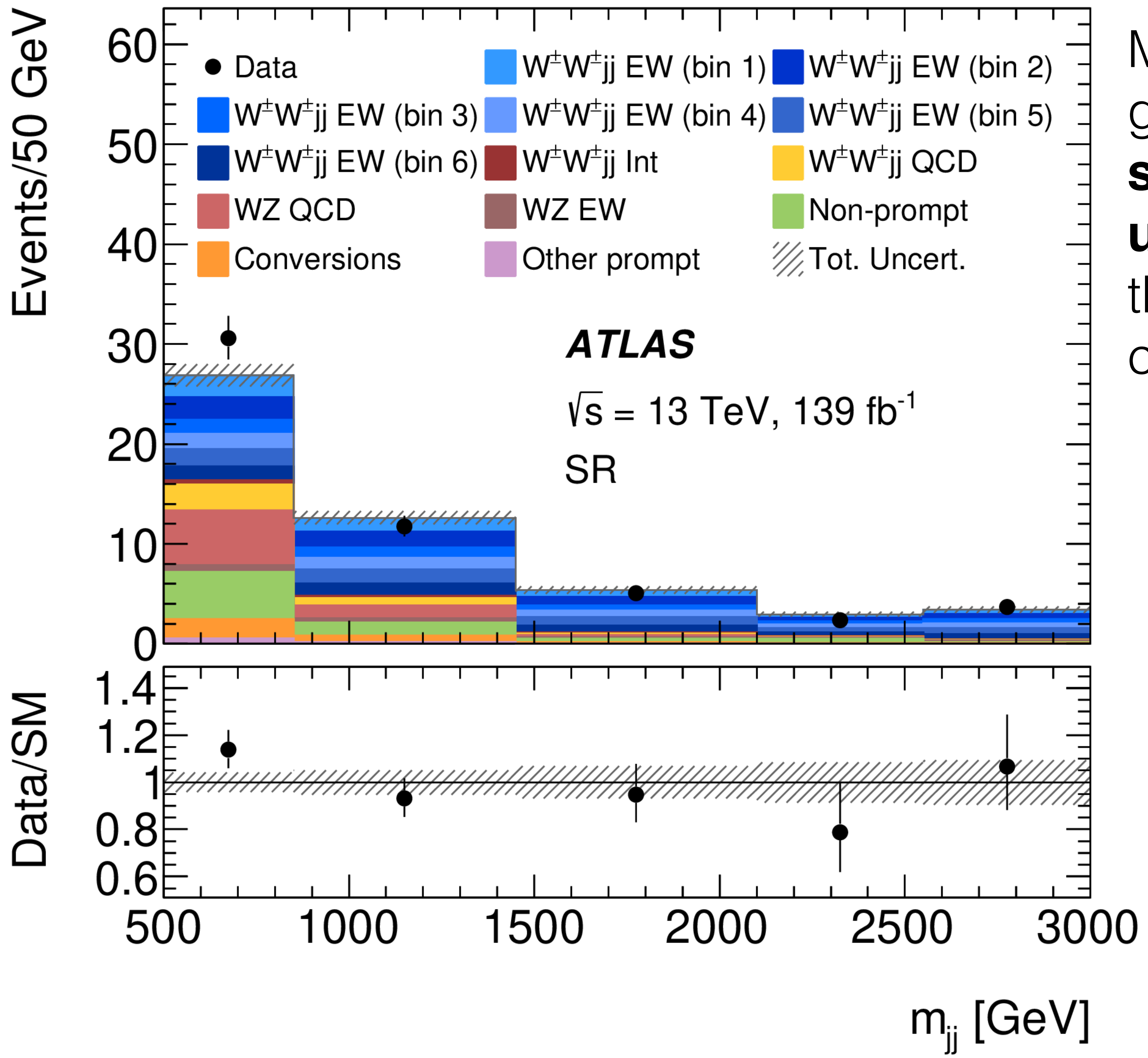




EW $W^\pm W^\pm \to \ell^\pm\nu\ell^\pm\nu$ from ATLAS

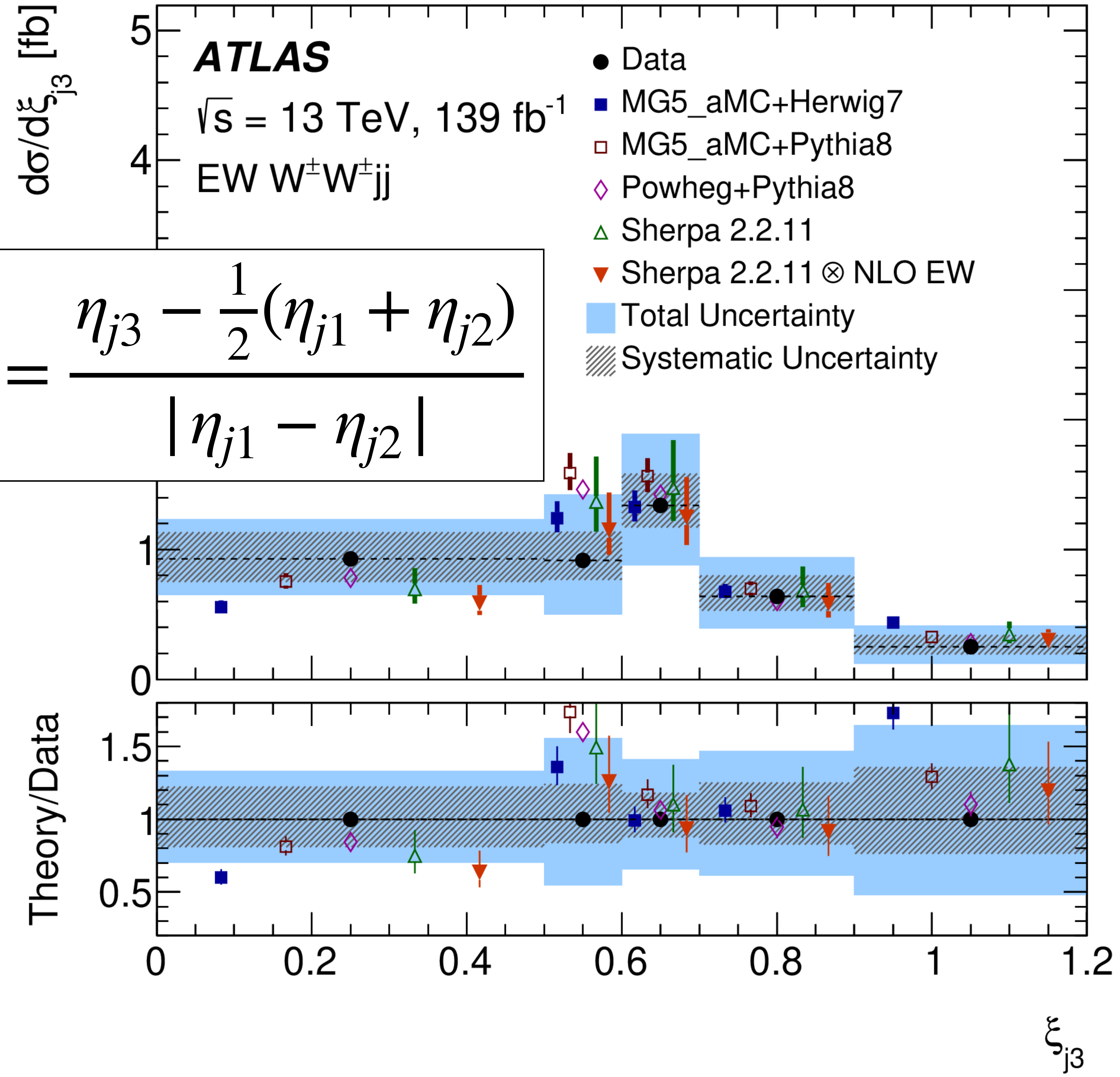
arxiv:2312.00420

- cross-sections of the **EW-only and EW+QCD components**
- **data driven estimates** of main backgrounds due to WZ and non-prompt leptons



Monte Carlo generators **slightly underestimate** the measured cross-section

$$\xi_{j3} = \frac{\eta_{j3} - \frac{1}{2}(\eta_{j1} + \eta_{j2})}{|\eta_{j1} - \eta_{j2}|}$$

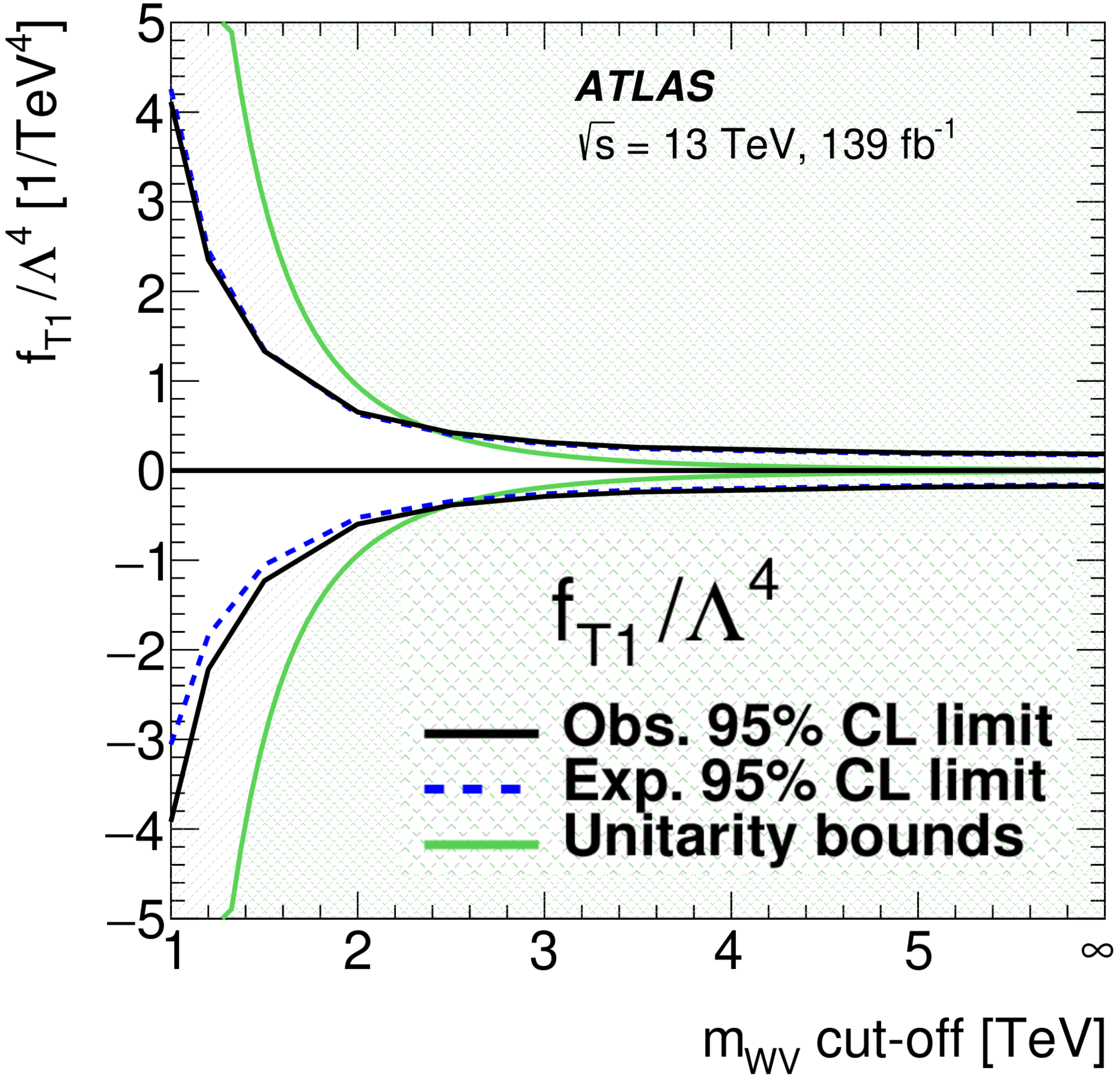


differential cross sections still **statistically dominated**

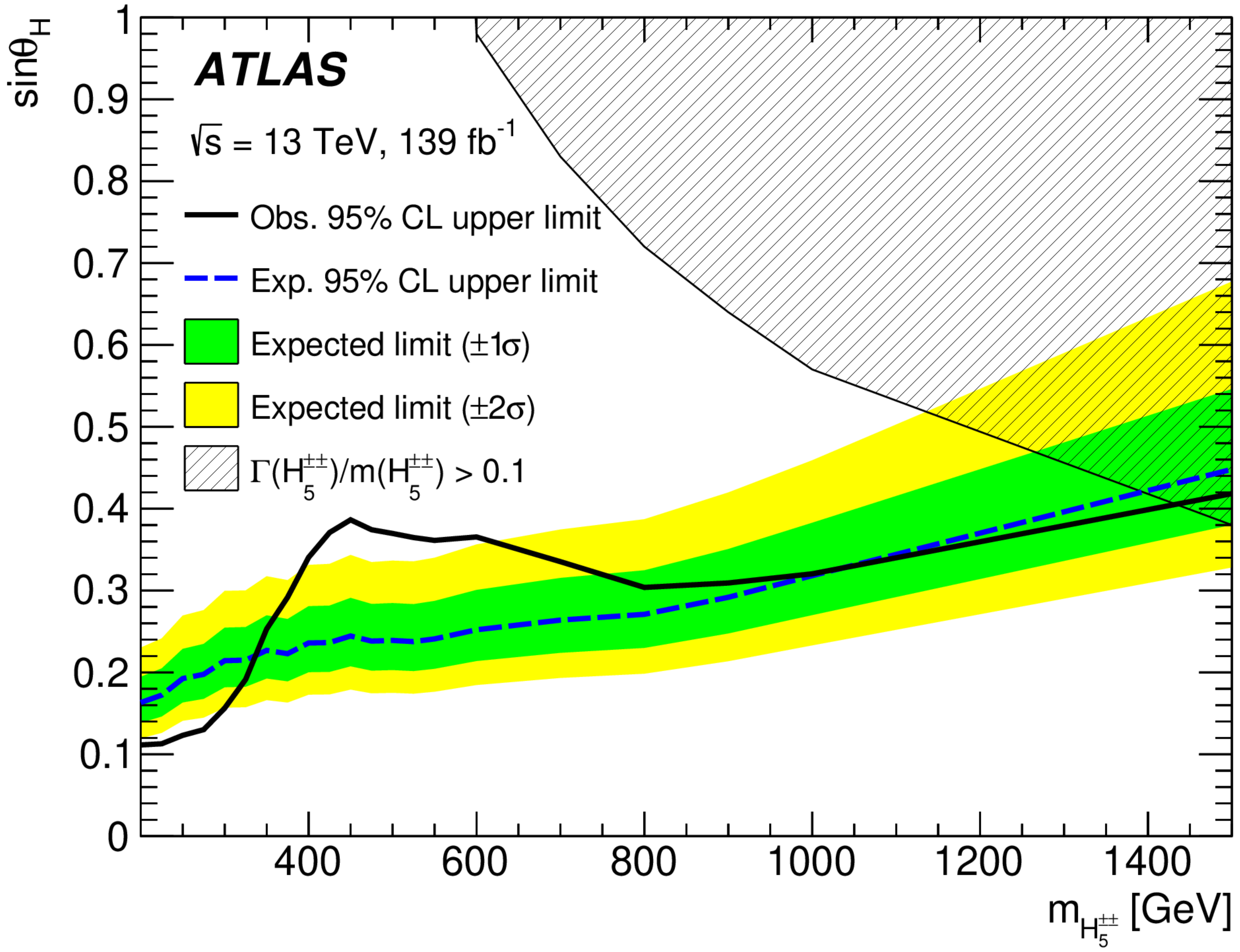
study of BSM physics

(CMS arxiv:2104.04762)

limits on **dimension-8 EFT operators** with cut-off regularisation



limits on **Georgi - Machacek model** parameters

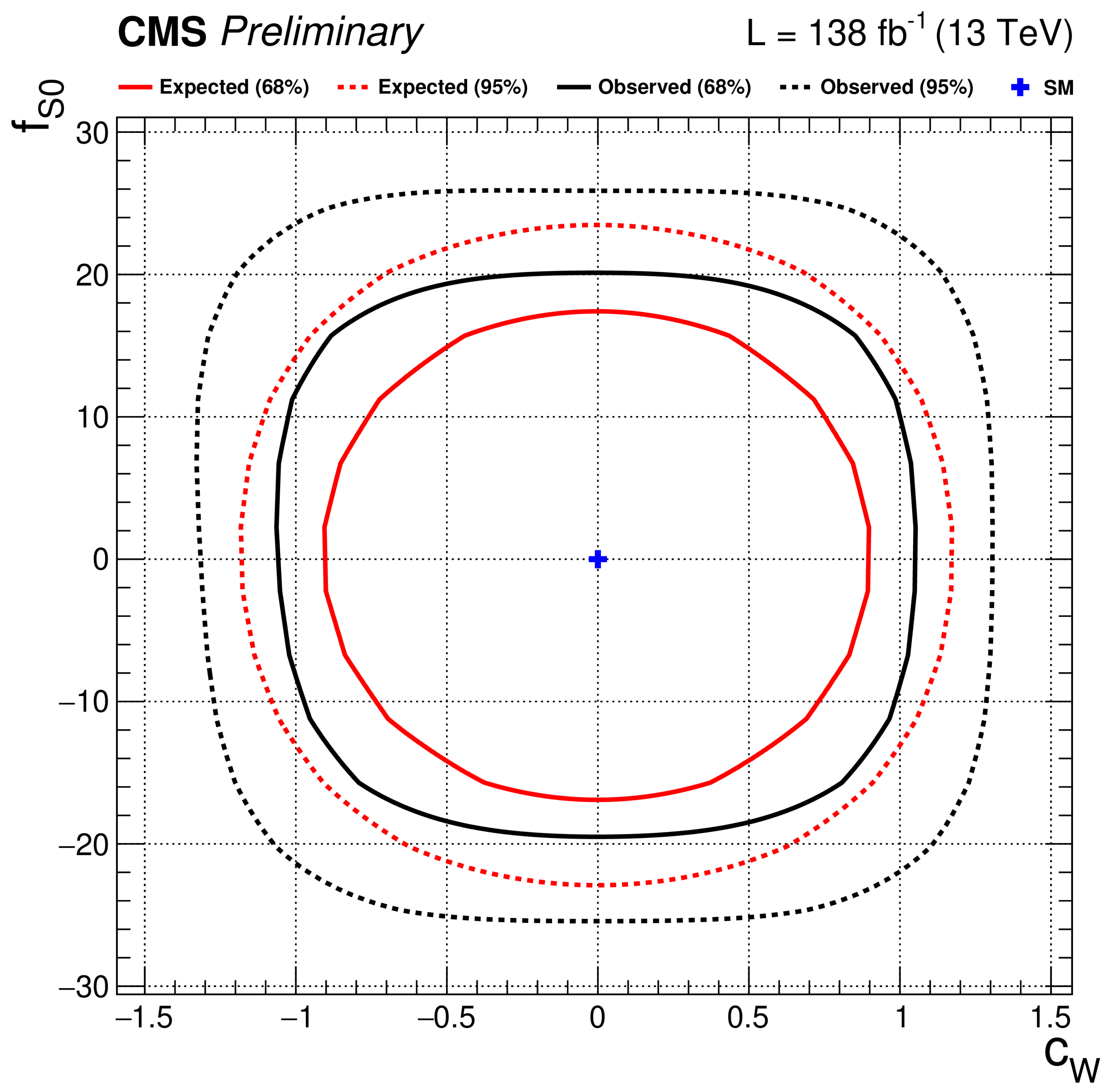


EW $W^\pm W^\pm \to \ell^\pm \nu \tau^\pm \nu$ in CMS

CMS-PAS-SMP-22-008

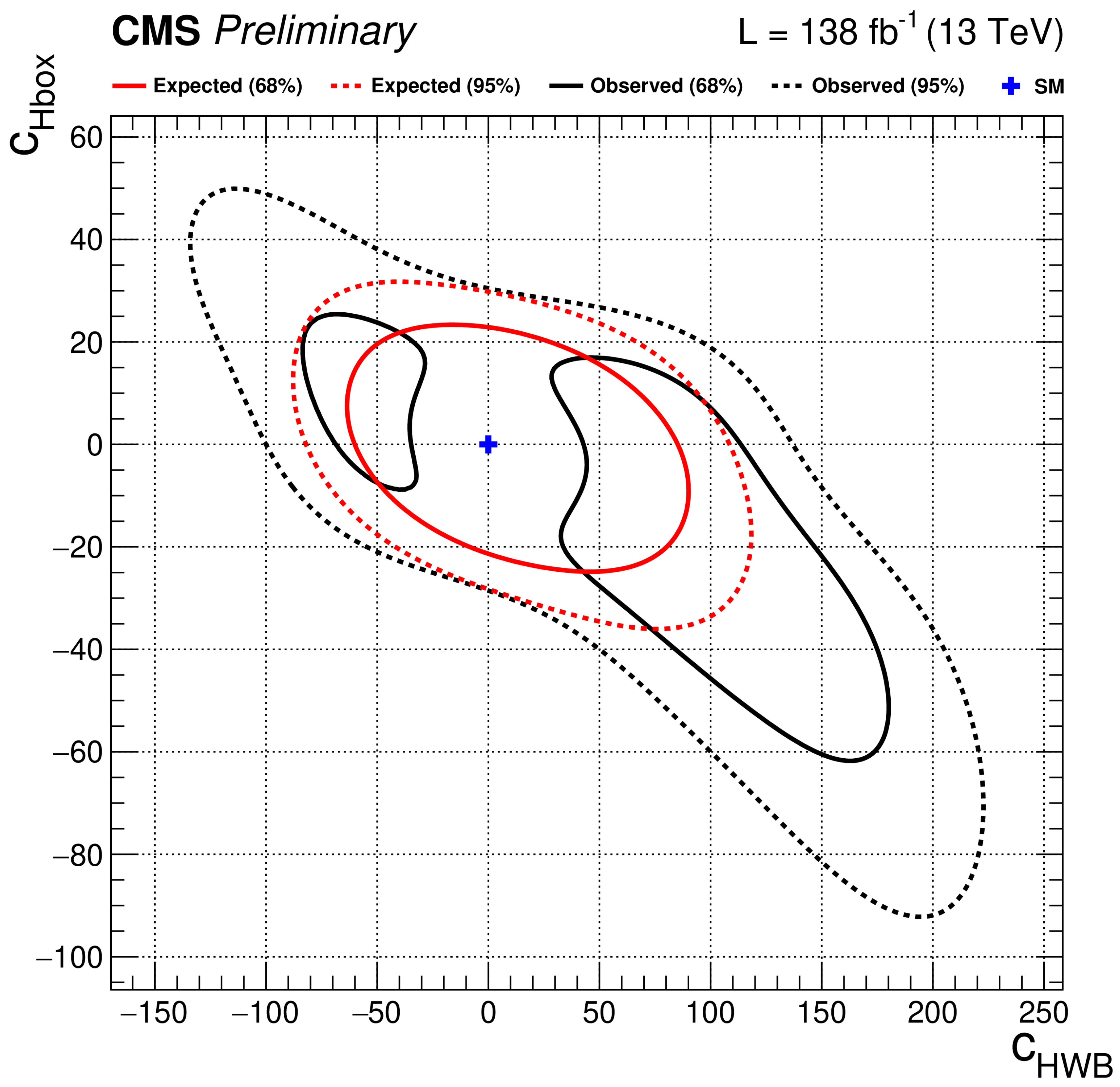
see K. Potamianos' talk

- one of the two same-signed W-bosons decays to a **hadronic τ lepton**
- Significance of SM process at **2.7 s.d.**, **signal strength 1.44** $^{+0.63}_{-0.56}$
- first **simultaneous extraction of dim-6 and dim-8 constraints** on EFT BSM terms



dim-6 including linear, BSM and mixed contributions, **dim-8** including linear and BSM contributions

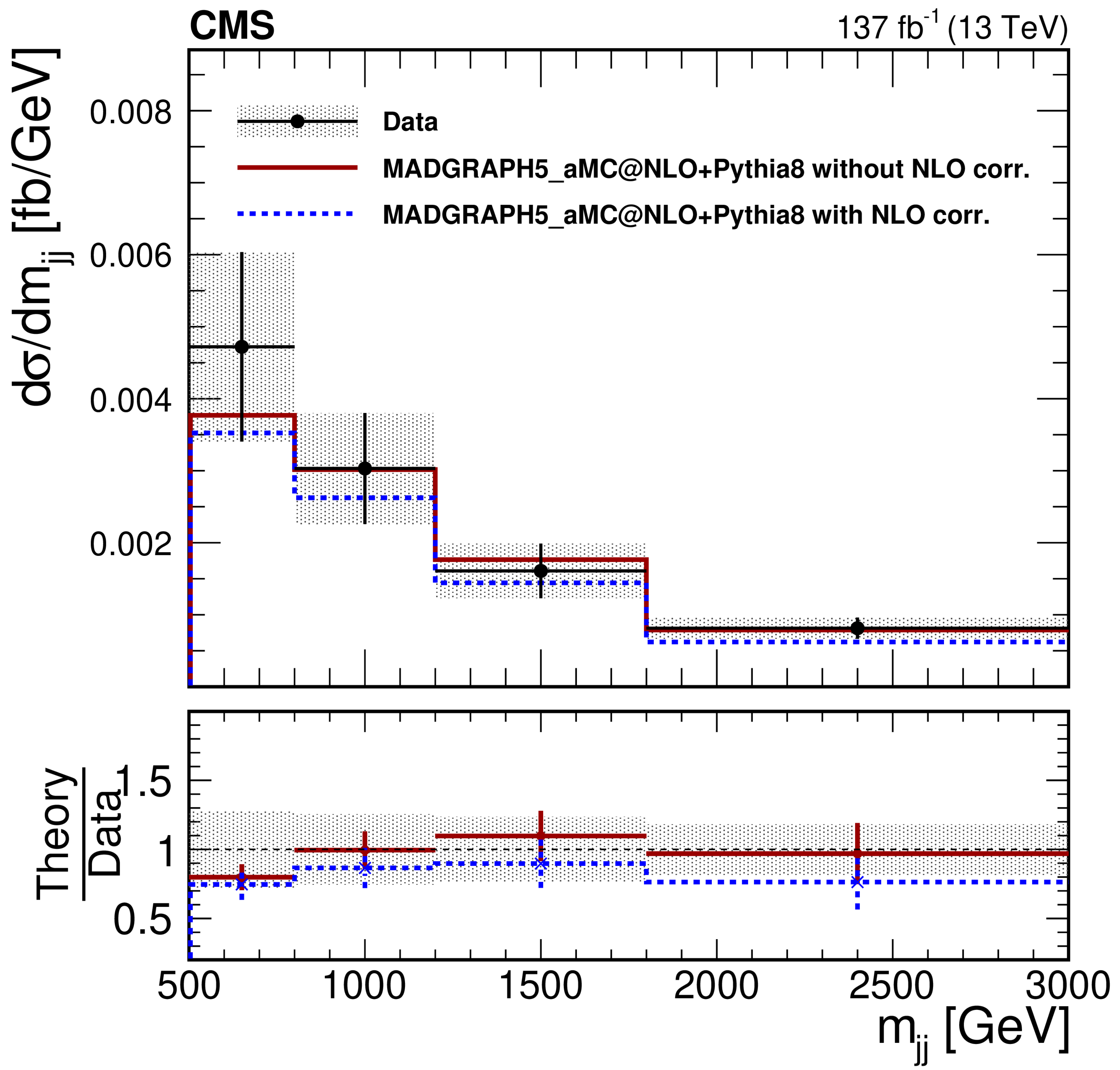
most 2D plots show **little correlation between operators**



$W^\pm W^\pm \to \ell^\pm \nu \ell^\pm \nu$ and $WZ \to 3\ell\nu$ in CMS

arxiv:2008.07013

- **NLO EW and QCD corrections** applied to the LO signal samples
- **data-driven backgrounds** whenever the MC predictions are not reliable enough
- BDT to separate the **EW WZ and QCD WZ processes**



Process	$\sigma \mathcal{B}$ (fb)	Theoretical prediction without NLO corrections (fb)	Theoretical prediction with NLO corrections (fb)
EW $W^\pm W^\pm$	3.98 ± 0.45 $0.37\,(\text{stat}) \pm 0.25\,(\text{syst})$	3.93 ± 0.57	3.31 ± 0.47
EW+QCD $W^\pm W^\pm$	4.42 ± 0.47 $0.39\,(\text{stat}) \pm 0.25\,(\text{syst})$	4.34 ± 0.69	3.72 ± 0.59
EW WZ	1.81 ± 0.41 $0.39\,(\text{stat}) \pm 0.14\,(\text{syst})$	1.41 ± 0.21	1.24 ± 0.18
EW+QCD WZ	4.97 ± 0.46 $0.40\,(\text{stat}) \pm 0.23\,(\text{syst})$	4.54 ± 0.90	4.36 ± 0.88
QCD WZ	3.15 ± 0.49 $0.45\,(\text{stat}) \pm 0.18\,(\text{syst})$	3.12 ± 0.70	3.12 ± 0.70

- limits on **dimension-8 EFT operators**

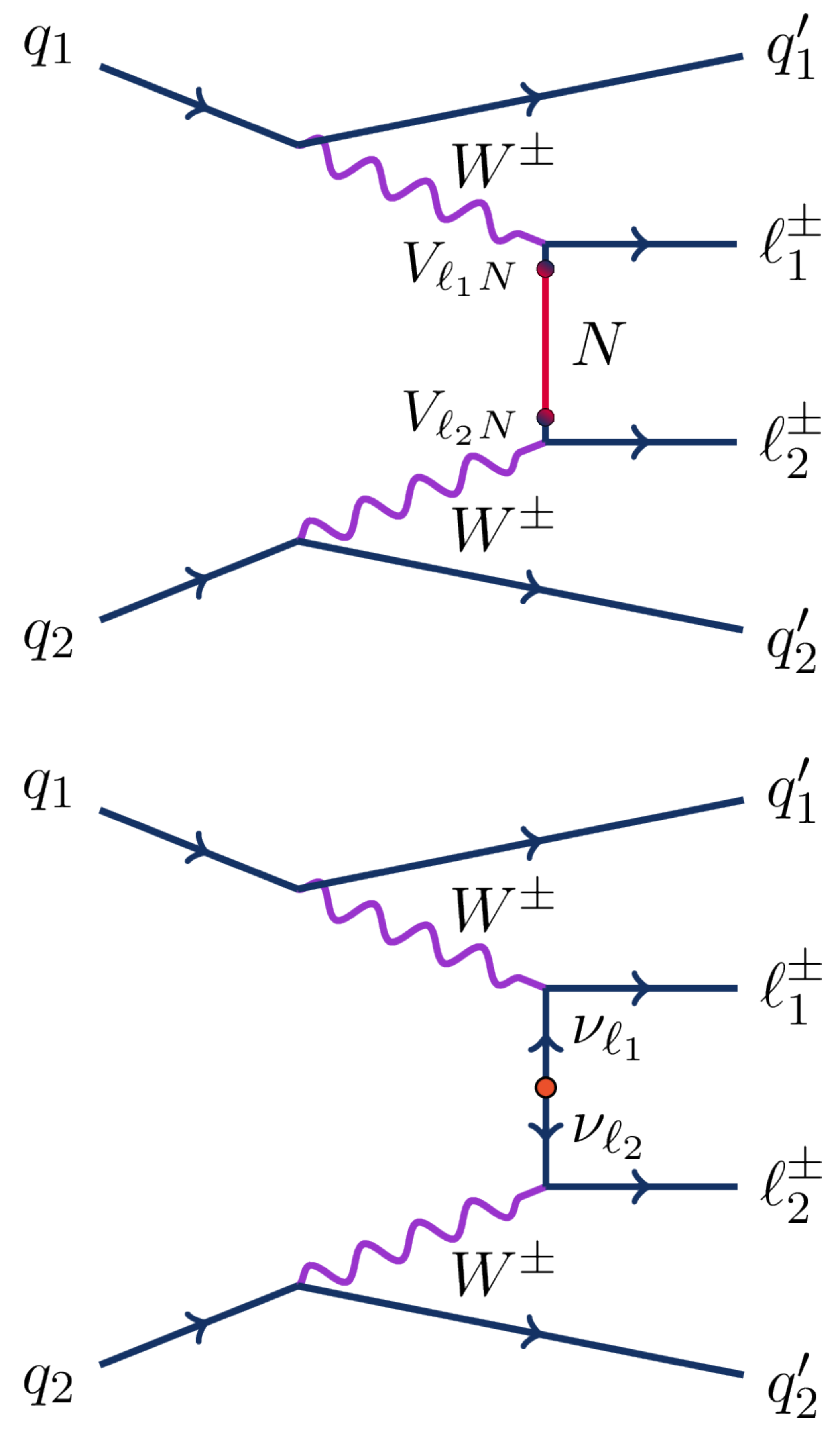
likelihood-based unfolding

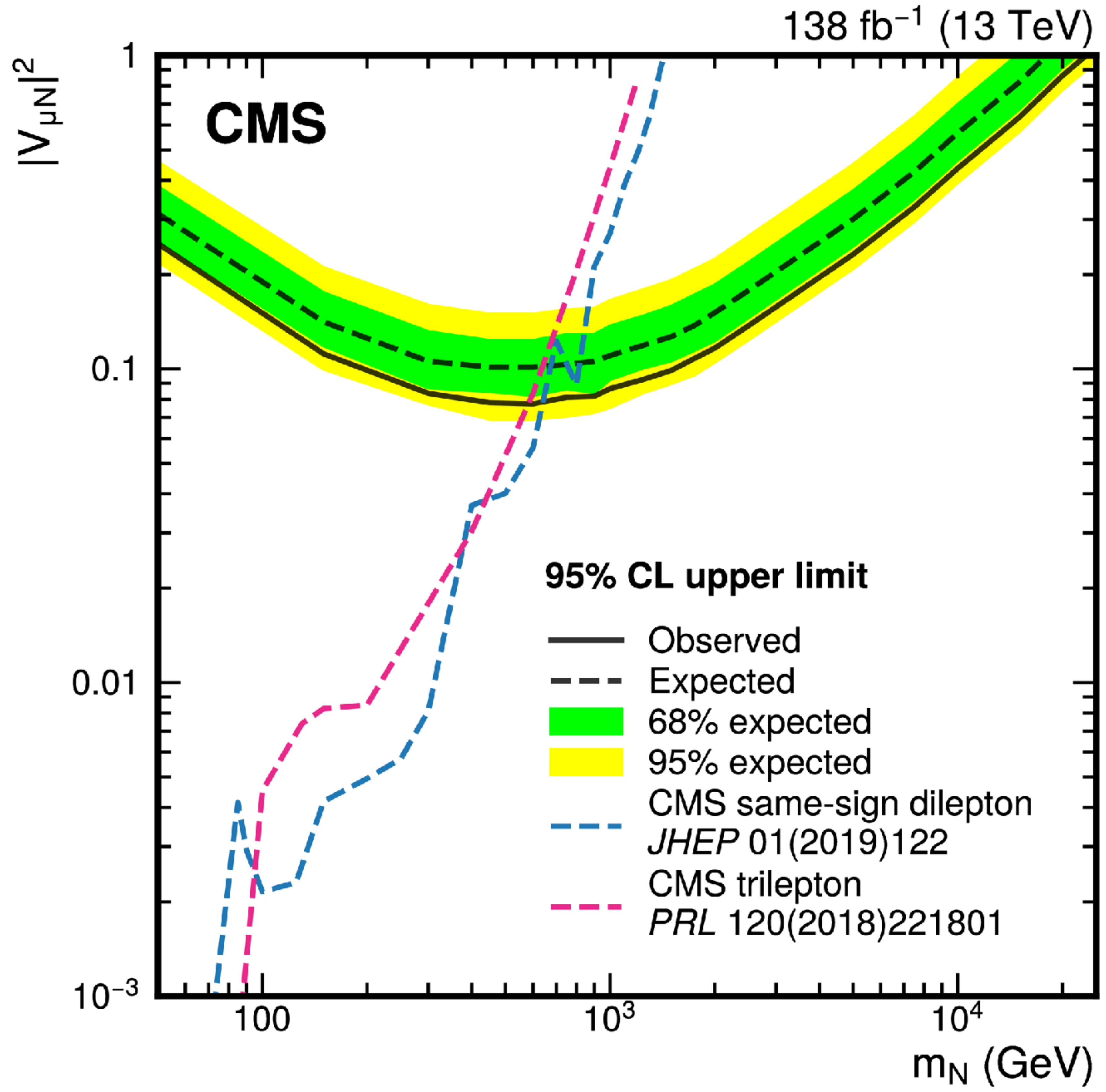
W±W± and majorana neutrinos

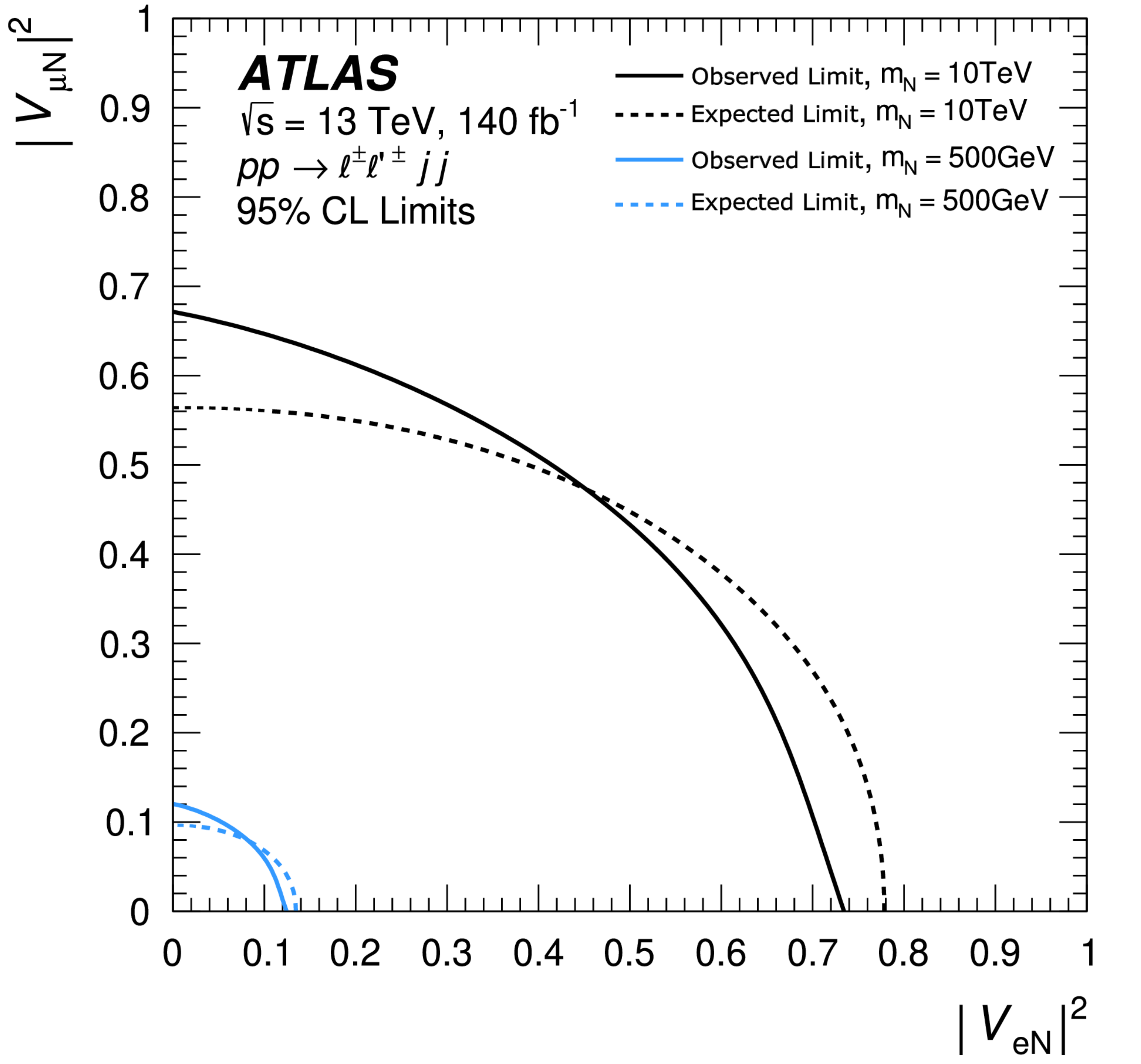
arxiv:2206.08956

arxiv:2403.15016

- probe **heavy Majorana neutrinos** and the Weinberg operator at the LHC



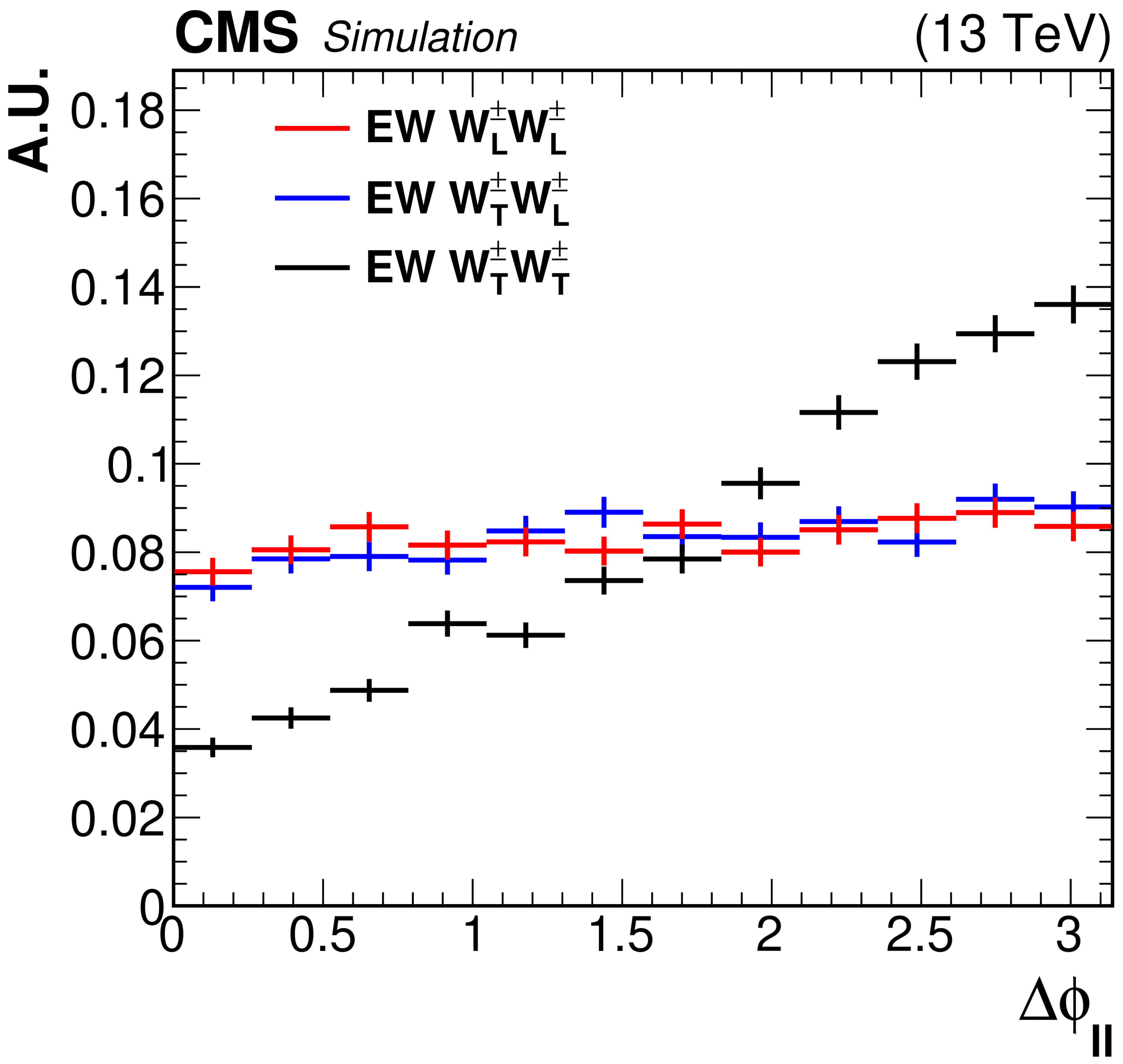


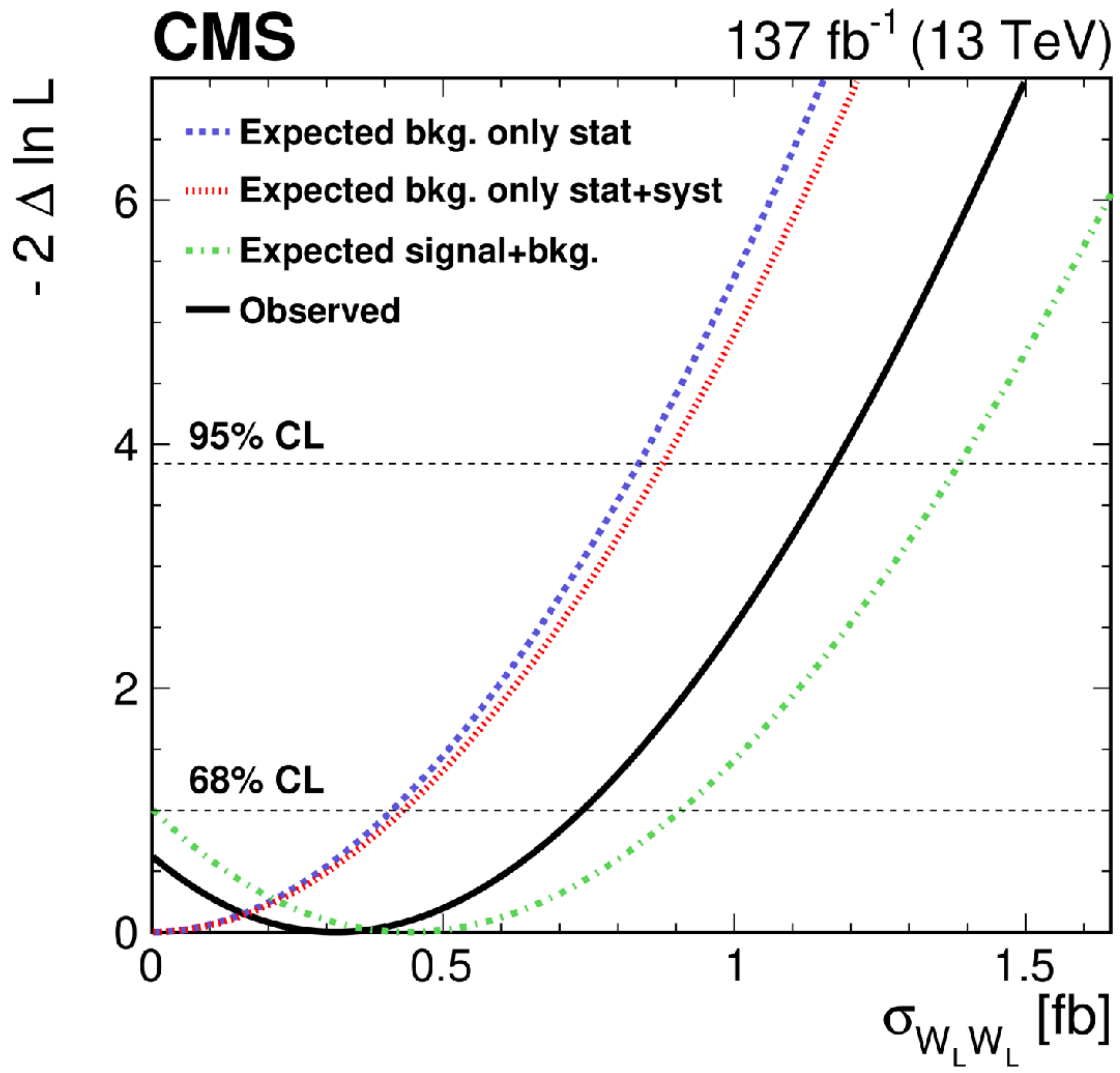


polarisation studies in CMS

arxiv:2009.09429

- EW production of same-sign WW boson pairs with **at least one of the W bosons longitudinally polarized** is measured with an observed significance of 2.3 s.d.





semi-leptonic VBS WV in CMS

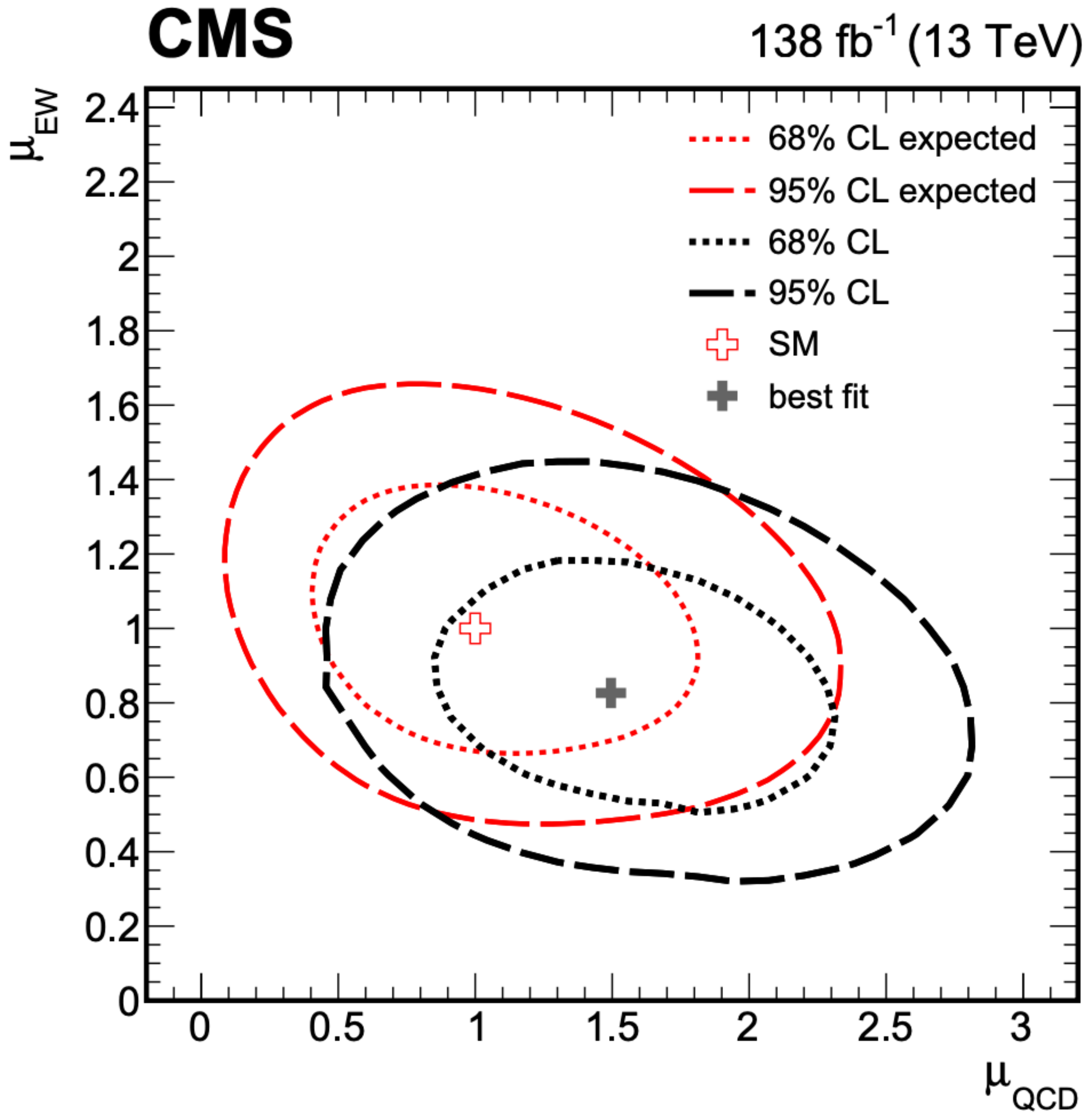
arxiv:2112.05259

- **resolved and merged** hadronic V decay categories
- **W+jets and ttbar suppression** with a DNN
- data-driven estimate of residual backgrounds
- significance **close to the 5 s.d.** level

$$\sigma_{observed} = 1.90^{+0.53}_{-0.46} \text{ pb}$$

$$\sigma_{theory} = 2.23^{+0.08}_{-0.11} \text{ (scale)} \pm 0.05 \text{ (PDF) pb}$$

$$\mu_{EW} = \frac{\sigma_{observed}}{\sigma_{theory}} = 0.85 \pm 0.12 \text{ (stat)} {}^{+0.19}_{-0.17} \text{ (syst)}$$



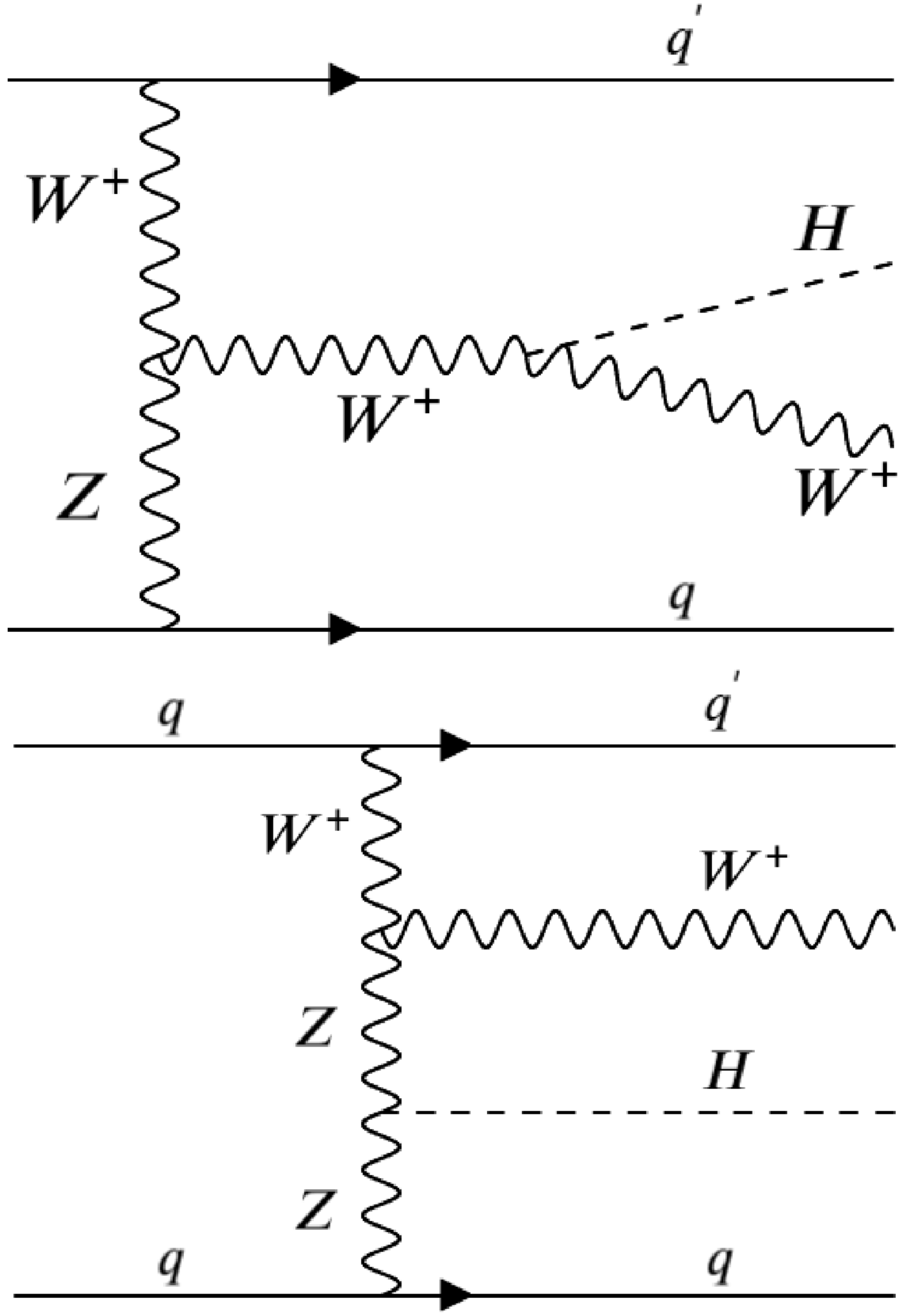
the sign of the HVV couplings

see A. de Wit's talk

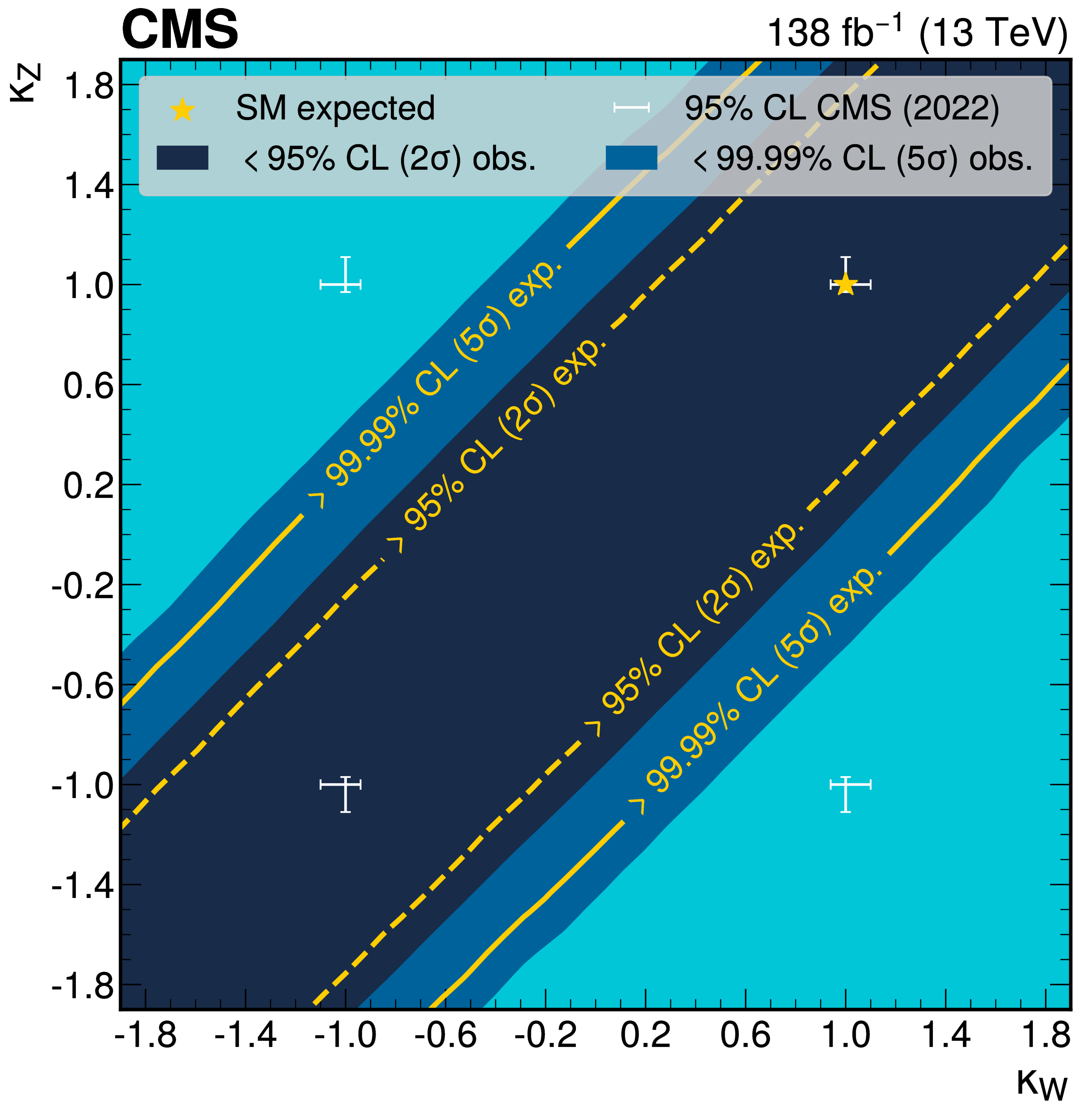
arxiv:2402.00426

arxiv:2405.16566

- (BSM) **discordant sign in HZZ and HWW couplings** would lead to cross-section enhancements in VBS WH production



interfering diagrams



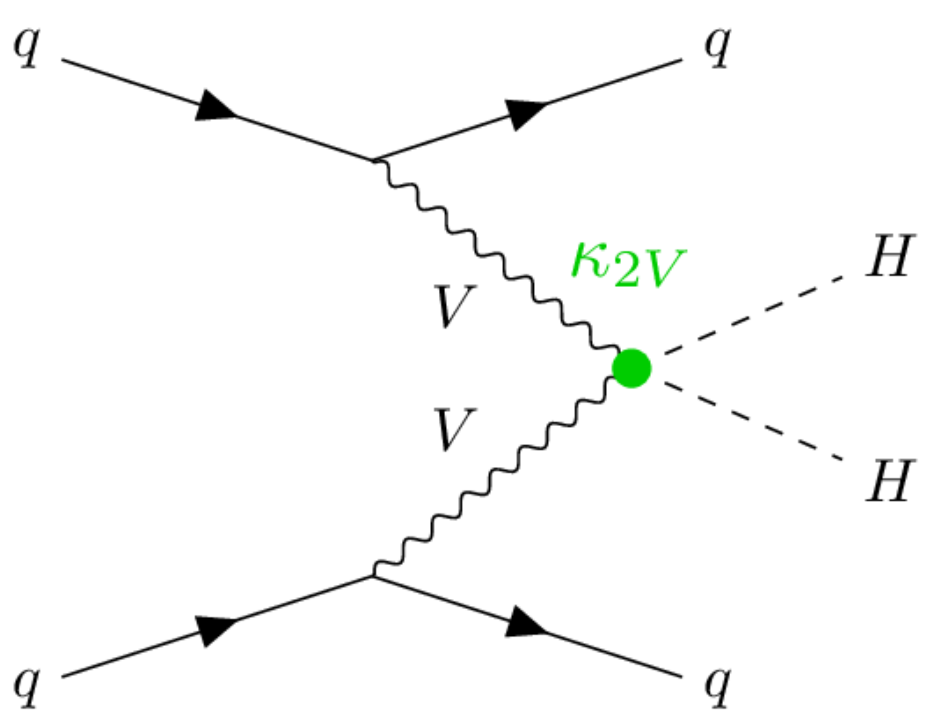
the SM case of κ_W and κ_Z having the same sign **is largely favoured**

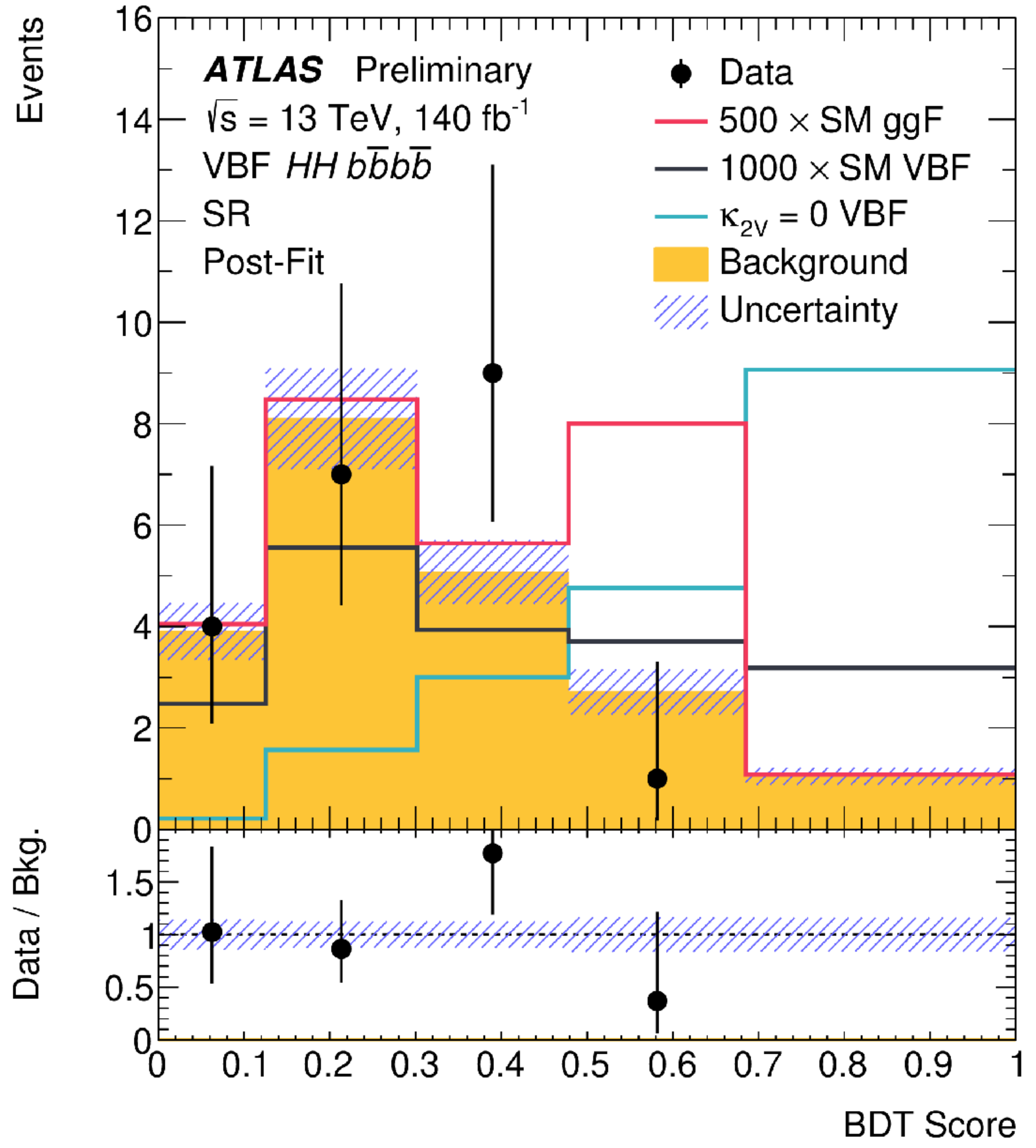
VBF HH → 4b in ATLAS

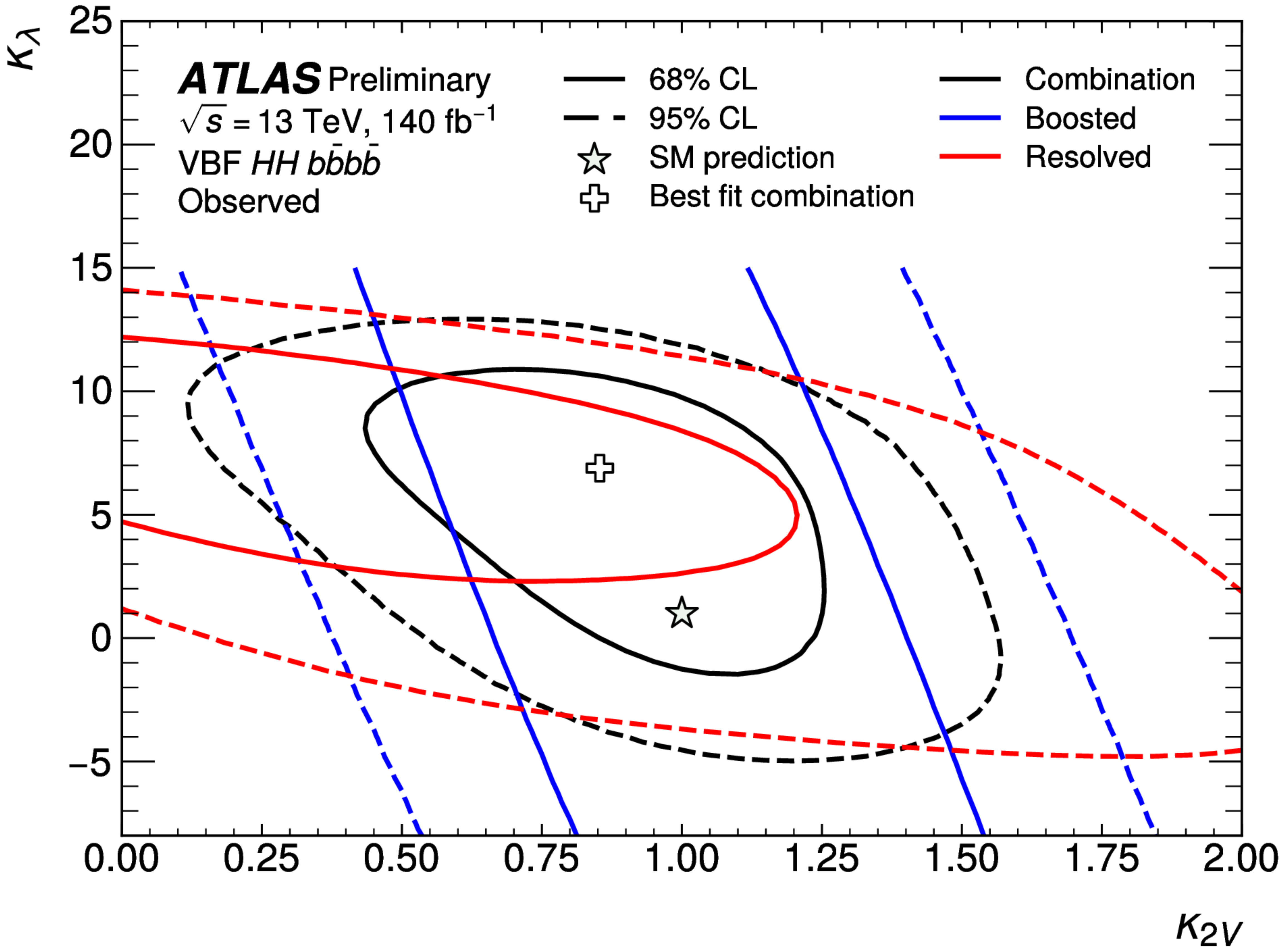
see J. Alison's talk

arxiv:2404.17193

- **VBF signature** + boosted Higgs boson tagging
- particular sensitivity to **anomalous κ_{2V} values**







in **combination** with the gluon fusion and VBF resolved results

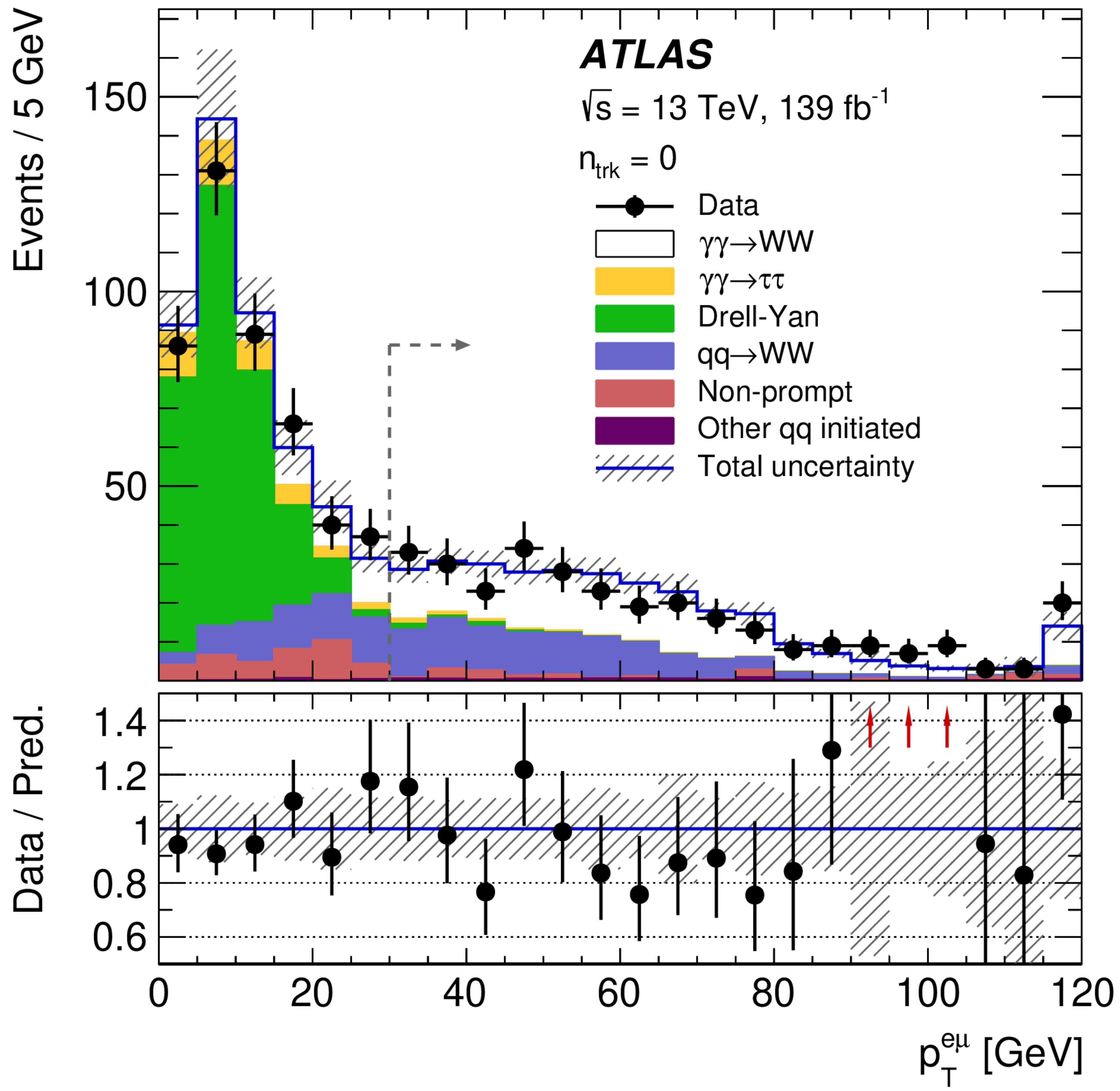
LHC as a photon collider

see A. Gilbert's talk

arxiv:2010.04019

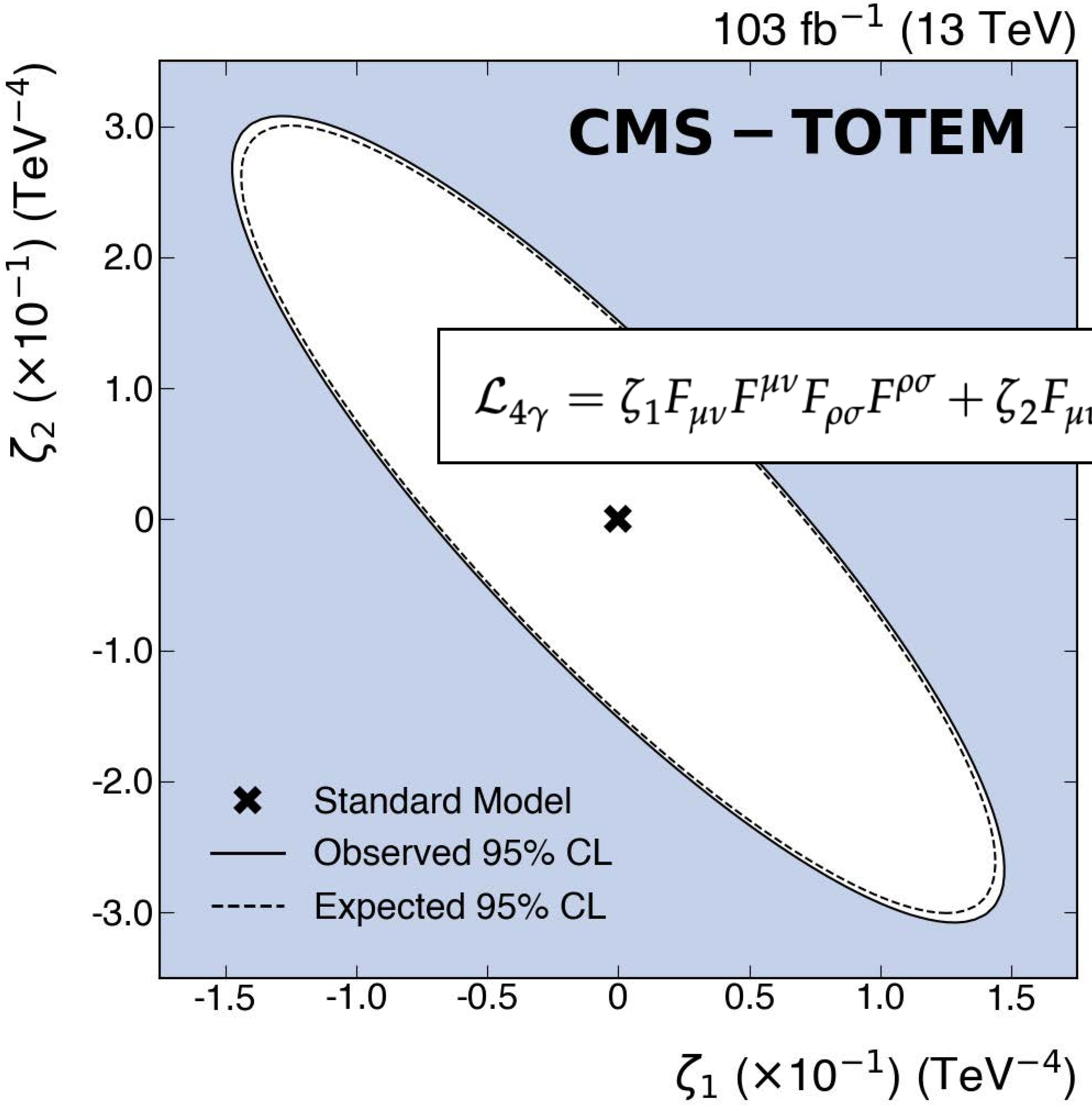
arxiv:2311.02725

$$pp(\gamma\gamma) \rightarrow p^{(*)}\, WW\, p^{(*)}$$



$$\sigma_{meas} = 3.13 \pm 0.31\,(\text{stat.}) \pm 0.28\,(\text{syst.})\ \text{fb}$$

$$pp(\gamma\gamma) \rightarrow p\,\gamma\gamma\,p$$

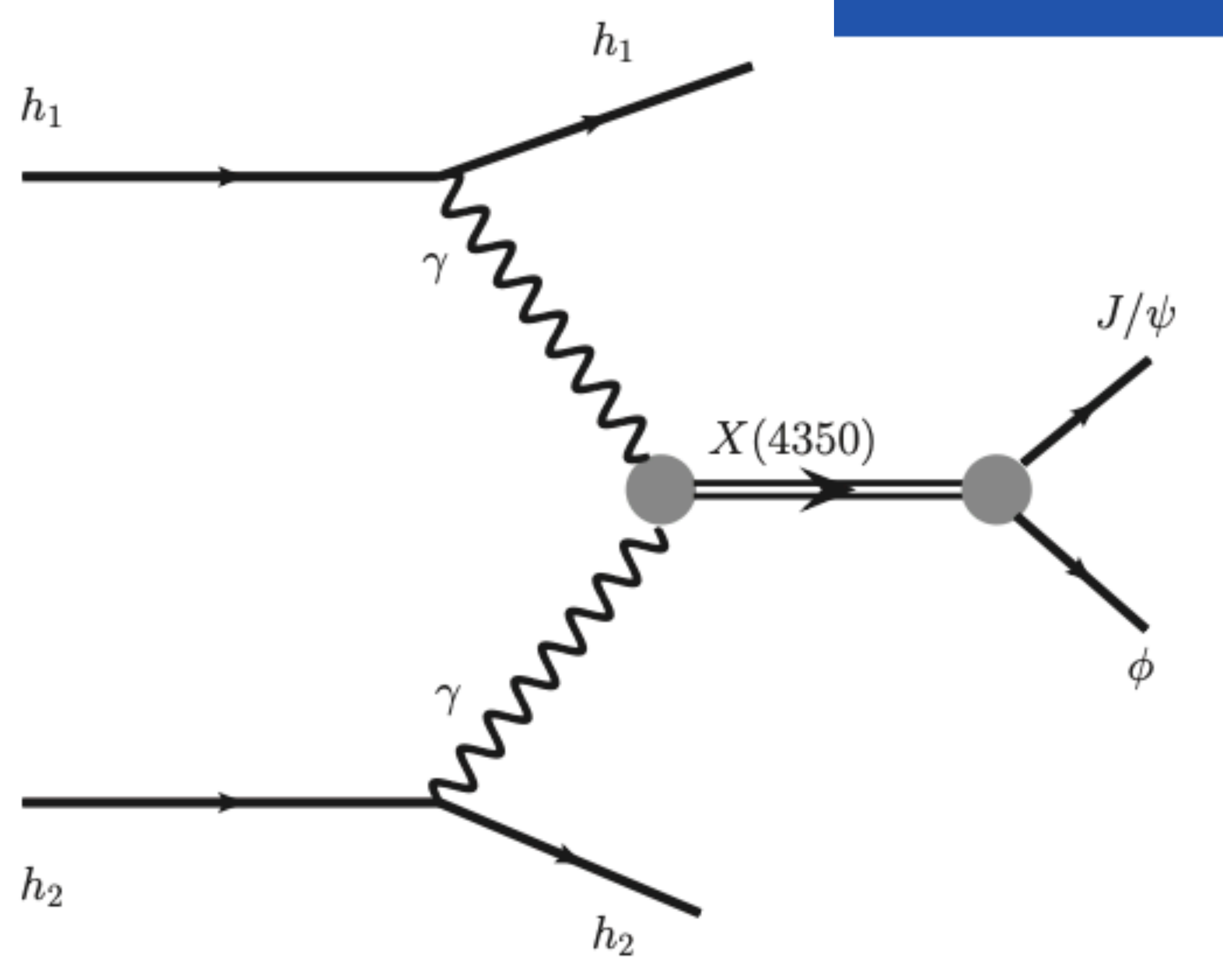


$$\mathcal{L}_{4\gamma} = \zeta_1 F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2 F_{\mu\nu}F^{\nu\rho}F_{\rho\lambda}F^{\lambda\mu}$$

exclusive J/ψ ϕ production in LHCb

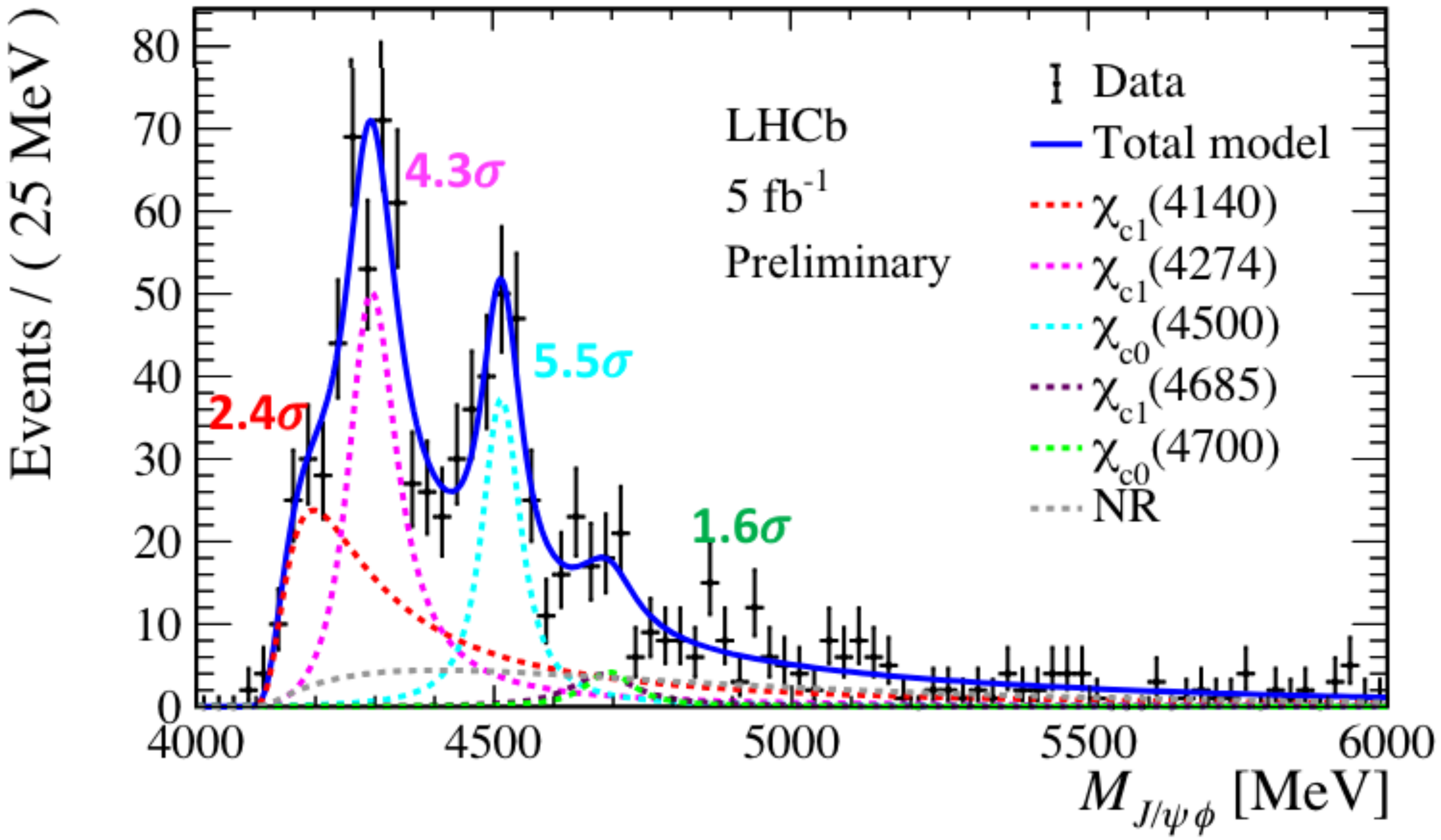
LHCb-PAPER-2023-043
in preparation

- first observation of the **direct production of χ exotic states** with no additional visible activity
- **non-resonant contribution** shape parameters measured in a sideband region



measured cross-sections

$$\sigma_{\chi_{c1}(4140)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4140)} = (0.85 \pm 0.16 \pm 0.30)\,\text{pb},$$
$$\sigma_{\chi_{c1}(4274)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4274)} = (0.77^{+0.14}_{-0.13} \pm 0.18)\,\text{pb},$$
$$\sigma_{\chi_{c0}(4500)} \times \mathcal{B}_{\text{eff}}^{\chi_{c0}(4500)} = (0.44^{+0.09}_{-0.08} \pm 0.07)\,\text{pb},$$
$$\sigma_{\chi_{c1}(4685)+\chi_{c0}(4700)} \times \mathcal{B}_{\text{eff}}^{\chi_{c1}(4685)+\chi_{c0}(4700)} = (0.14^{+0.07}_{-0.06} \pm 0.06)\,\text{pb},$$
$$\sigma_{NR} \times \mathcal{B}_{\text{eff}}^{NR} = (0.46^{+0.25}_{-0.19}\,{}^{+0.21}_{-0.22})\,\text{pb},$$

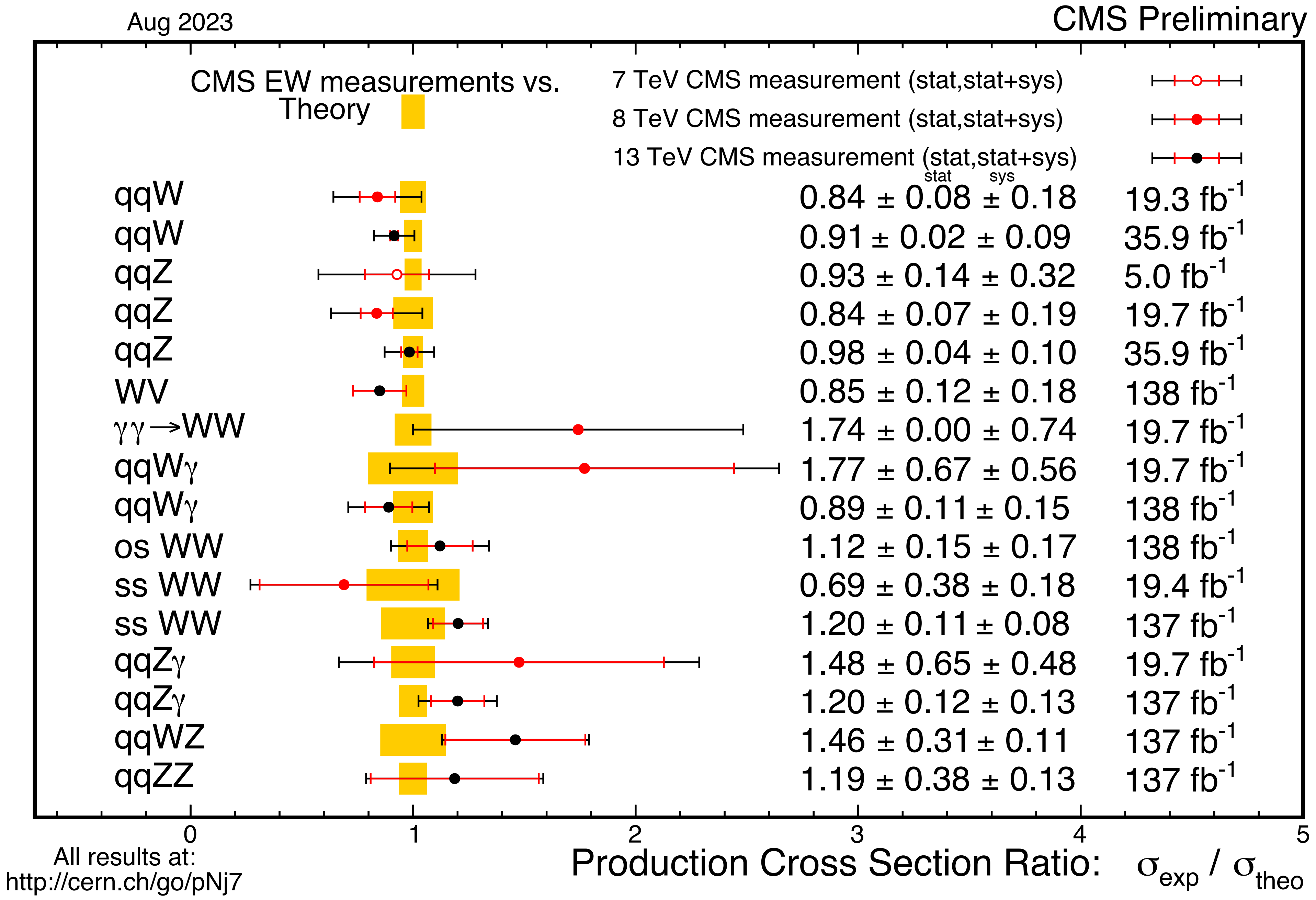


summary 1/4

- a **wide landscape** of VBF + VBS final states studied at the LHC
- **room for improvement**: final states still to be used, e.g. semi-leptonic ones, also for polarisation studies
- did we squeeze all what we could from **machine learning** tools?

summary 2/4

- on the understanding and use of the **theory predictions**:
- **different generators** are not always compatible
- need to fully exploit the **existing precision calculations** in the data analysis
- understand how to **match them in EFT** and polarised studies
- experimental collaborations **not fully consistent** yet

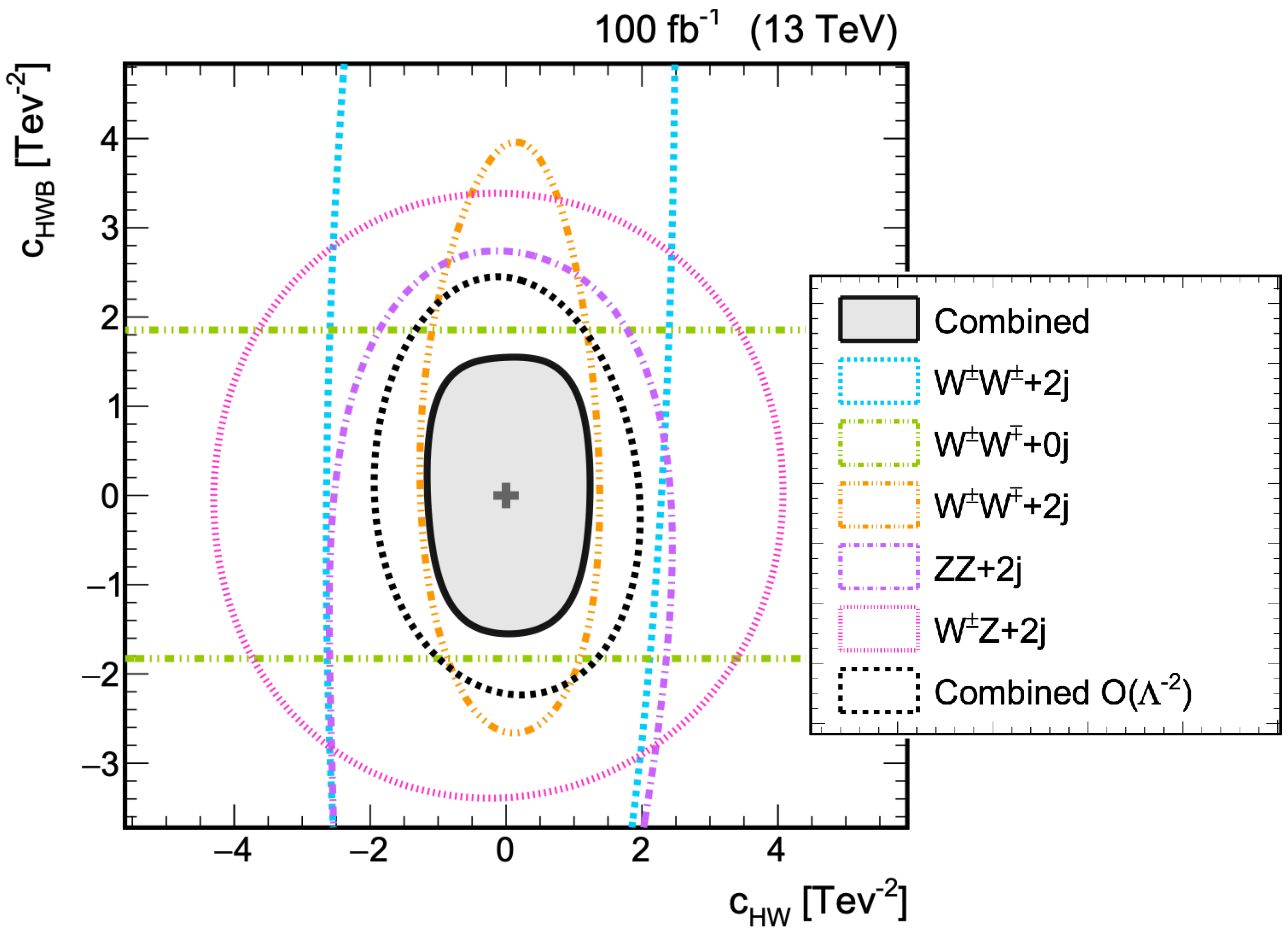


an **overall systematic comparison between measurements and predictions** across collaborations might be useful

summary 3/4

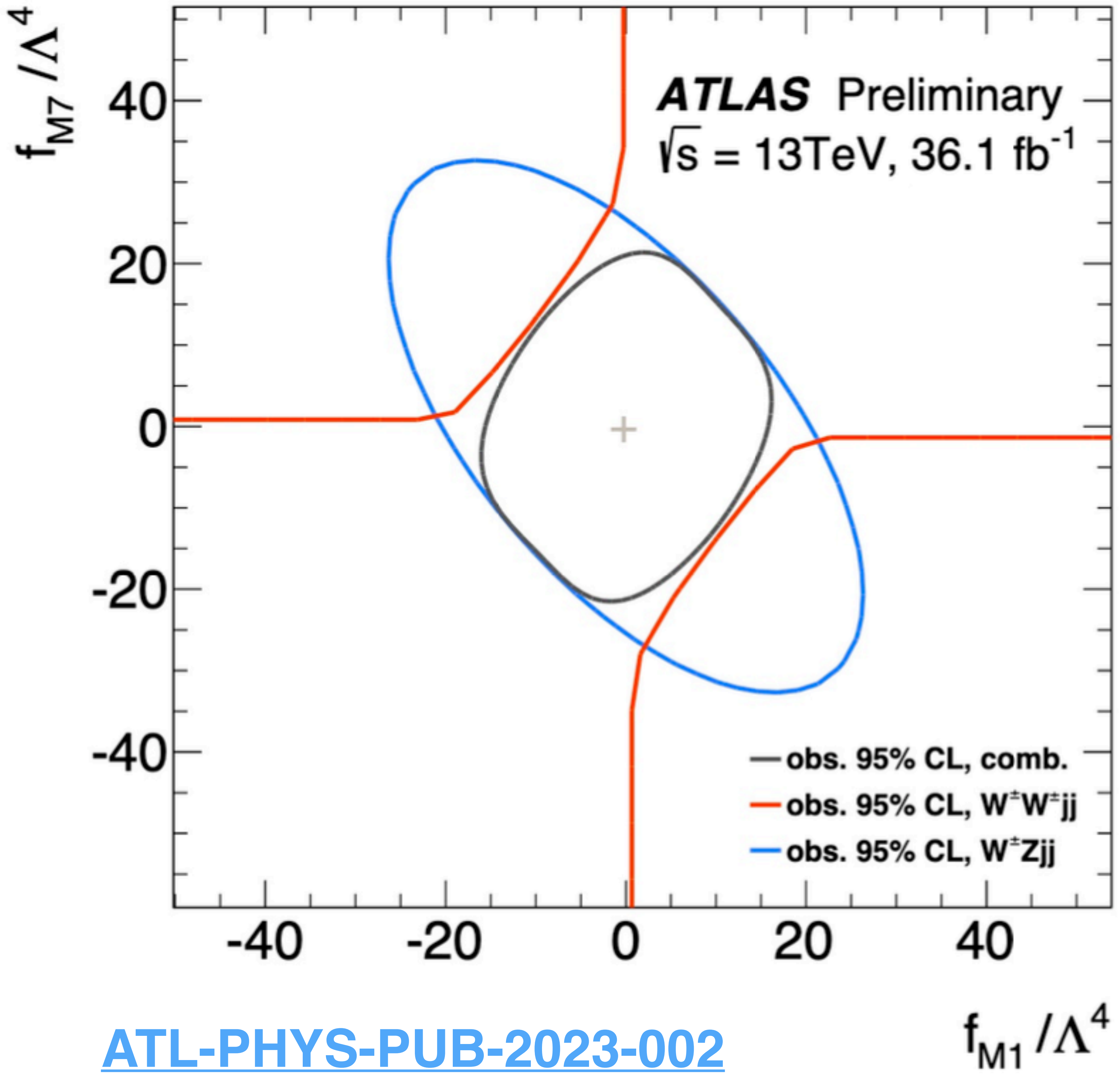
- constraining power still th be exploited in **global EFT fits**

dimension 6 SMEFT



arxiv:2108.03199

dimension 8 SMEFT



ATL-PHYS-PUB-2023-002

summary 4/4

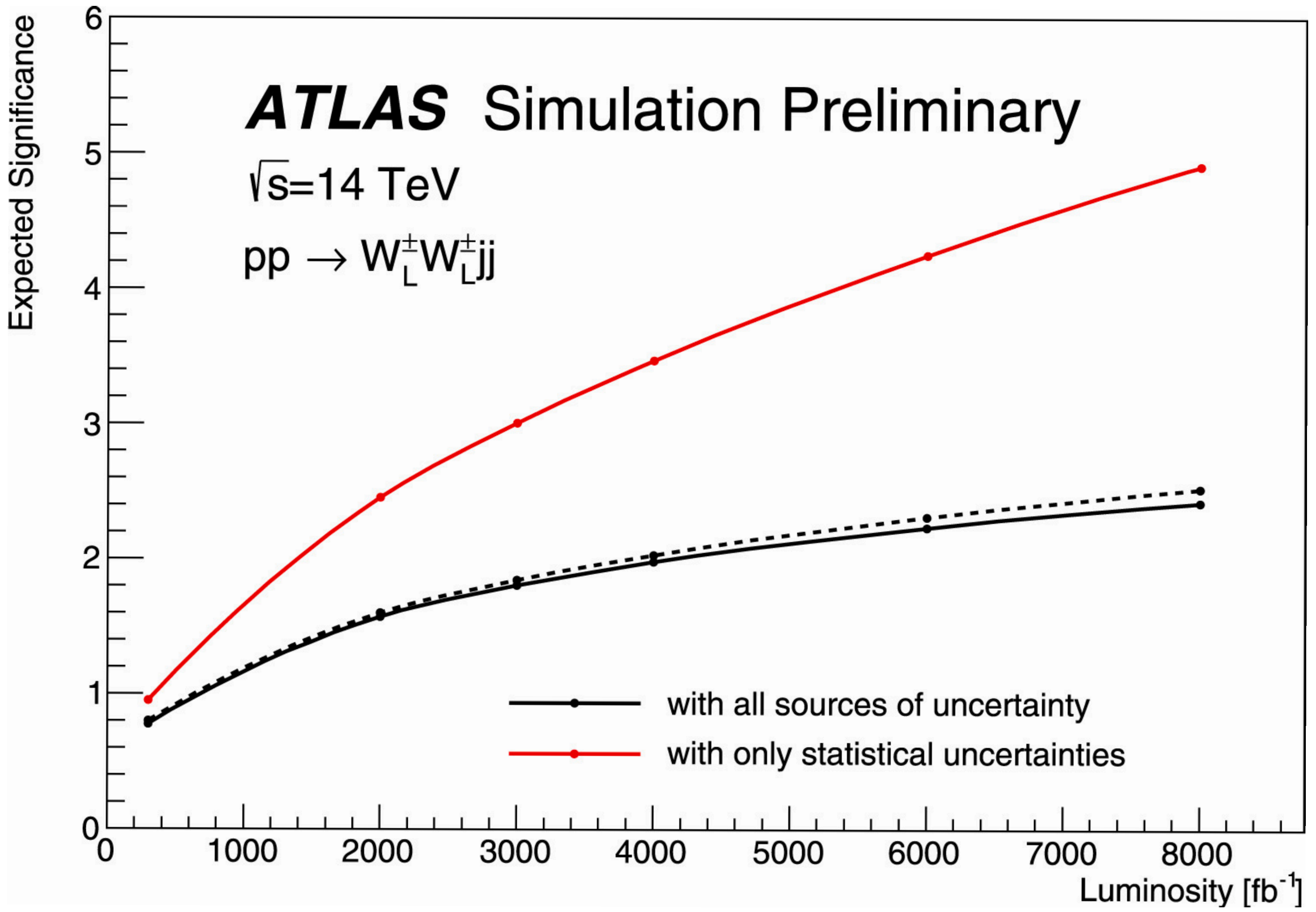
- the holy grail of the **VBS longitudinal component** measurement is still out of reach
  - **future detectors** expected to allow for a better control of the VBS topology

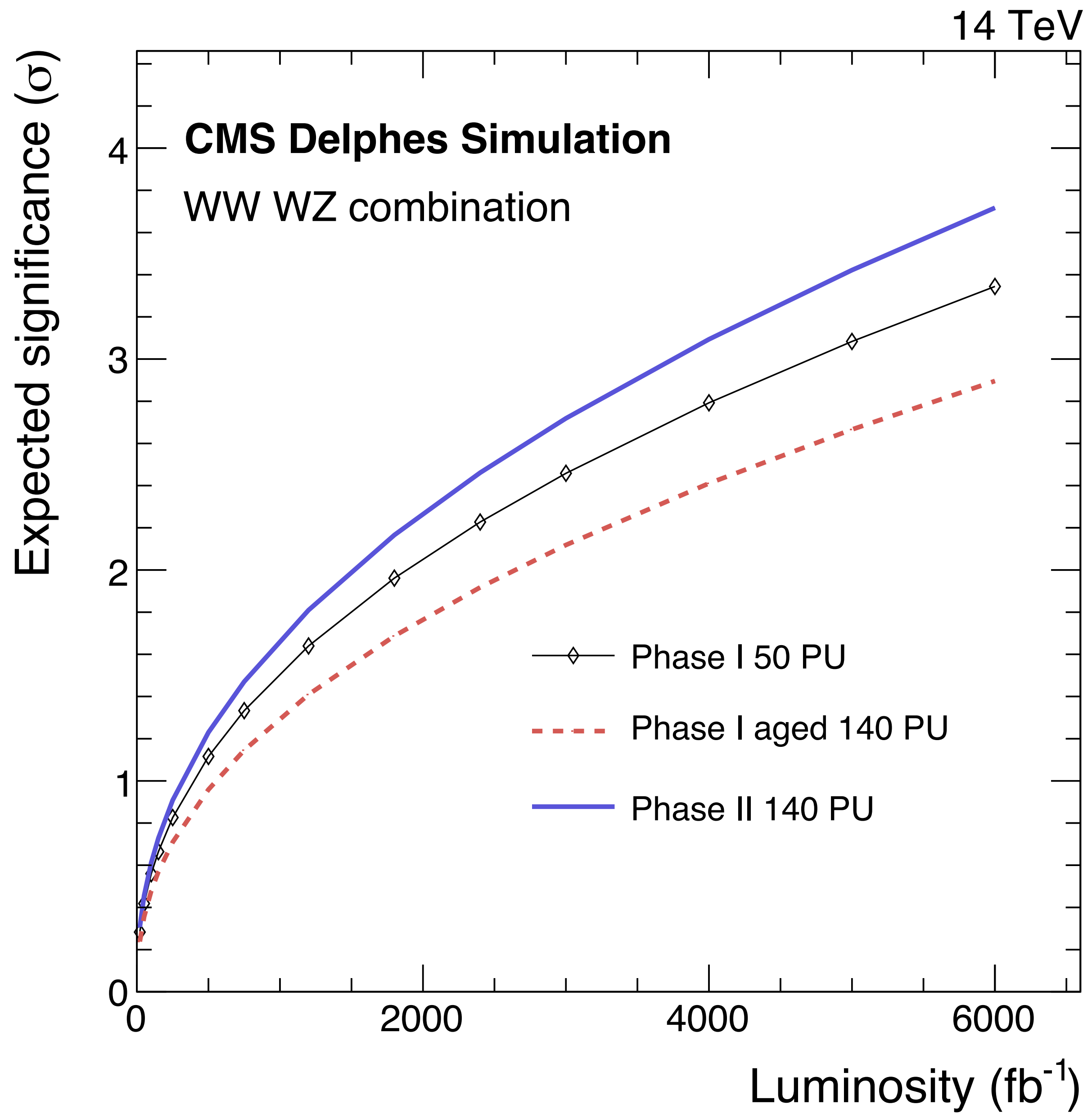
same-sign **longitudinal WW VBS projections**

[ATL-PHYS-PUB-2018-052](#)

[CMS-PAS-SMP-14-008](#)

[CMS-PAS-FTR-21-001](#)





- **Run3 measurements** still to be delivered!

The COMETA COST Action

https://cometa.web.cern.ch/

- **EU-funded initiative**
- one ideal place where to pursue these studies **across collaborations and communities**
- legacy of the VBSCan COST Action
- **freshly started** this year
- **everybody can join** the works

Funded by the European Union

COST EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

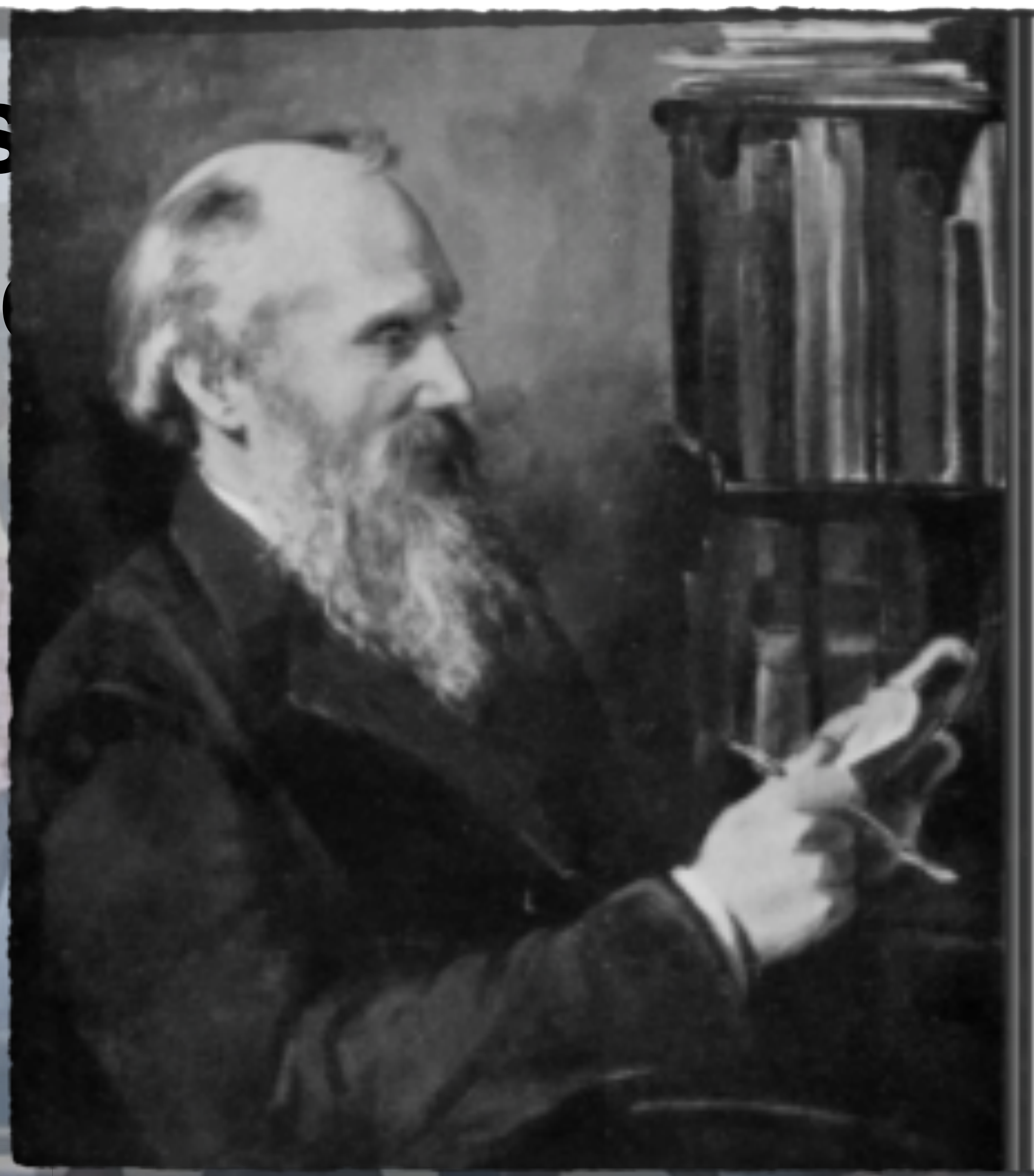
COMETA

The COMETA COST Action

https://cometa.web.cern.ch/

- **EU-funded initiative**
- one ideal place where to pursue these studies **across collaborations and comm**
- daugh
- **freshly s**
- **everybo**

and when you think that this is boring…



There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.

~ William Thomson (Lord Kelvin), 1900

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Funded by the European Union

COMETA

additional material

single vector boson results

- *CMS Coll.*, Measurement of electroweak production of a W boson and two forward jets in proton-proton collisions at 8 TeV **https://arxiv.org/abs/1607.06975**
- *ATLAS Coll.*, Measurements of electroweak Wjj production and constraints on anomalous gauge couplings with the ATLAS detector **https://arxiv.org/abs/1703.04362**
- *ATLAS Coll.*, Differential cross-section measurements for the electroweak production of dijets in association with a Z boson in proton-proton collisions at ATLAS **https://arxiv.org/abs/2006.15458**
- *CMS Coll.*, Electroweak production of two jets in association with a Z boson in proton-proton collisions at 13 TeV **https://arxiv.org/abs/1712.09814**
- *CMS Coll.*, Measurement of differential cross sections for the production of a Z boson in association with jets in proton-proton collisions at 13 TeV **https://arxiv.org/abs/2205.02872**

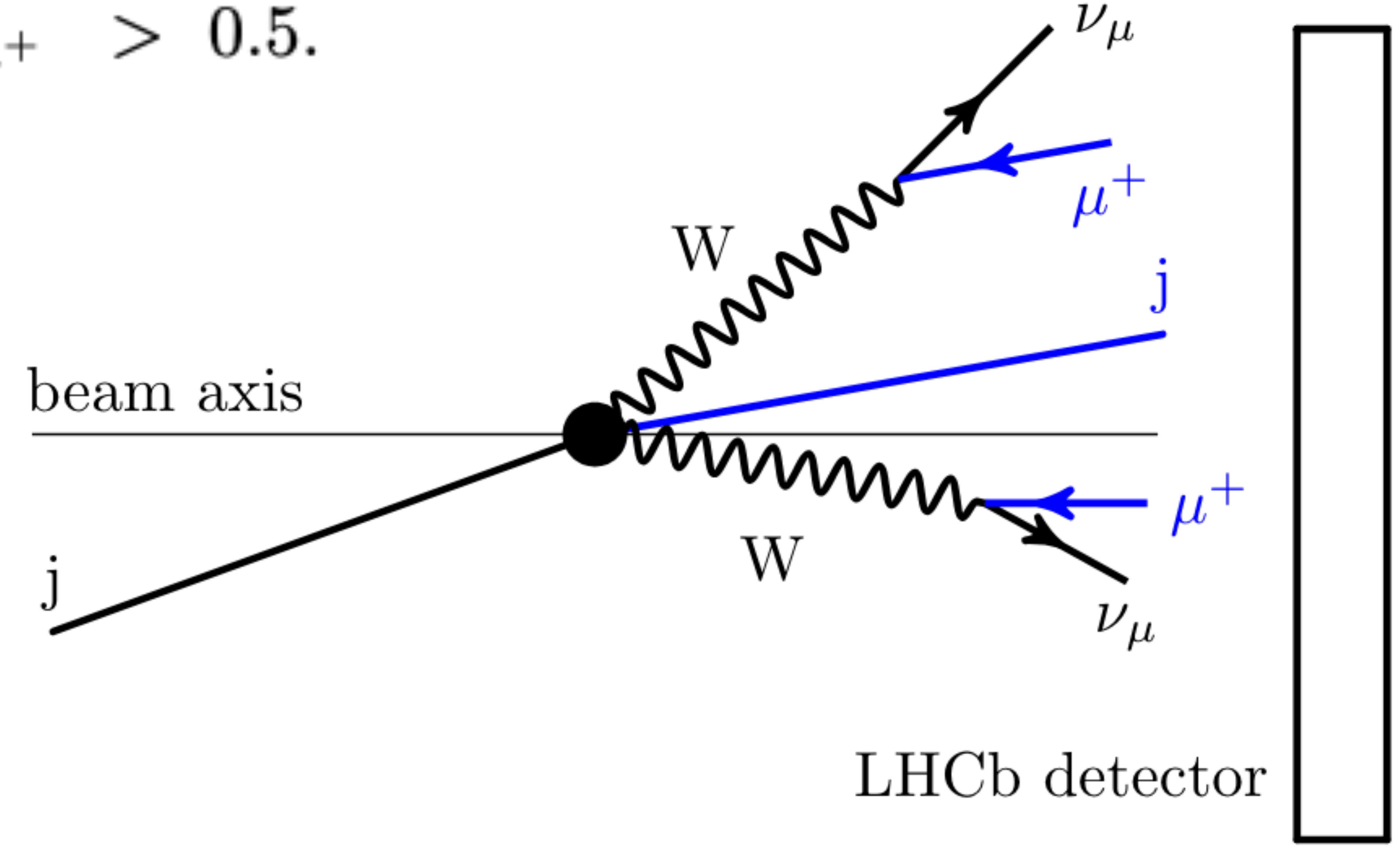
$W^\pm W^\pm \to \ell^\pm \nu \ell^\pm \nu$ in the LHCb detector

arxiv:1908.06805

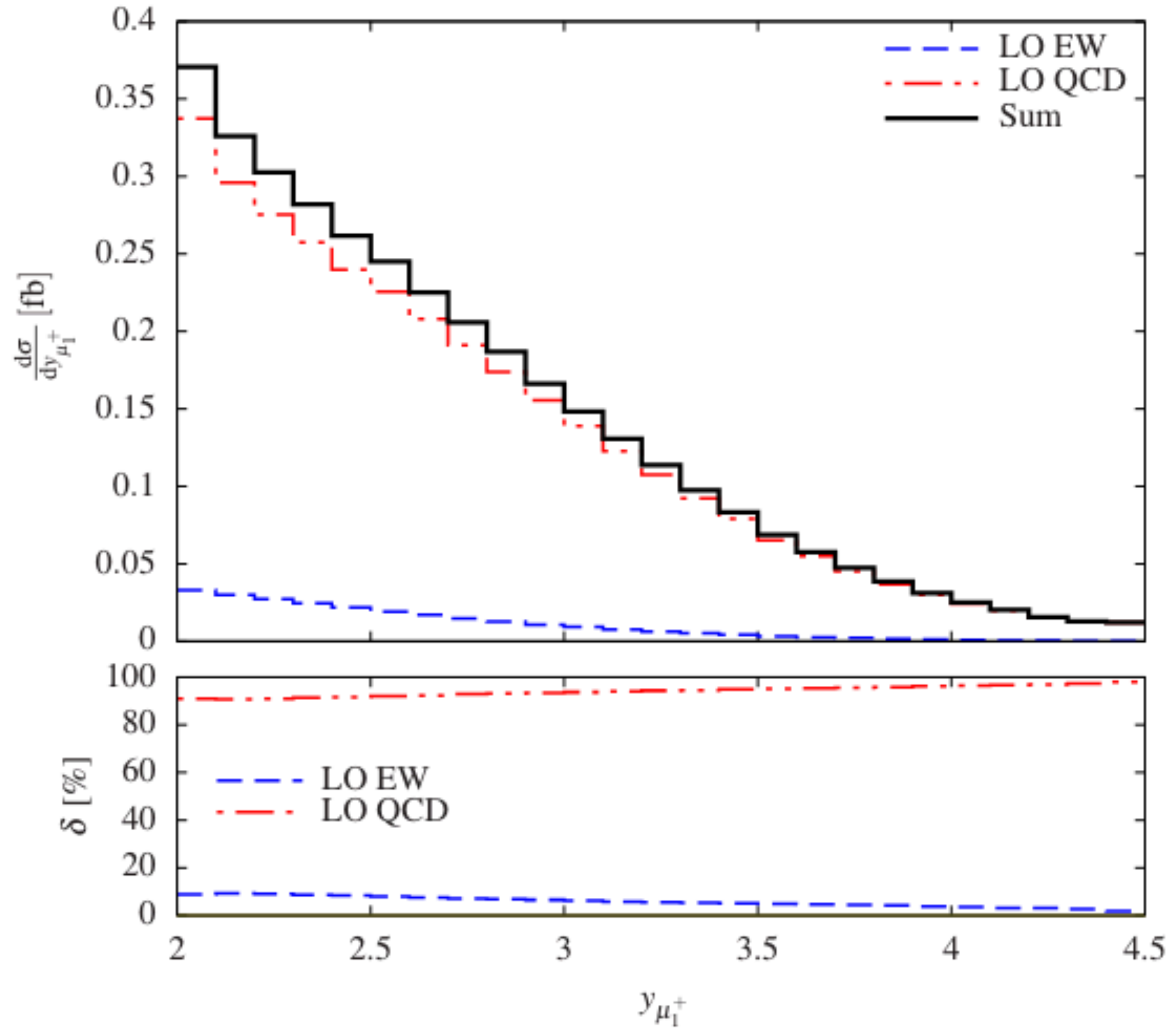
a parton level feasibility study

- signature with one jet and two anti-muons

$$p_{T,j} > 20\,\text{GeV}, \quad 2.2 < \eta_j < 4.2,$$
$$p_{T,\mu^+} > 20\,\text{GeV}, \quad 2.0 < y_{\mu^+} < 4.5,$$
$$\Delta R_{j\mu^+} > 0.5.$$



Channel	σ_{EW} [fb]	σ_{QCD} [fb]	σ_{EW}/σ_{QCD}
ss WW	0.0185(1)	0.0104(1)	1.78
WZ	0.0071(1)	0.2952(4)	0.02
ZZ	0.0003(1)	0.0161(1)	0.02
Sum	0.0258(1)	0.3217(4)	0.08



effective field theory

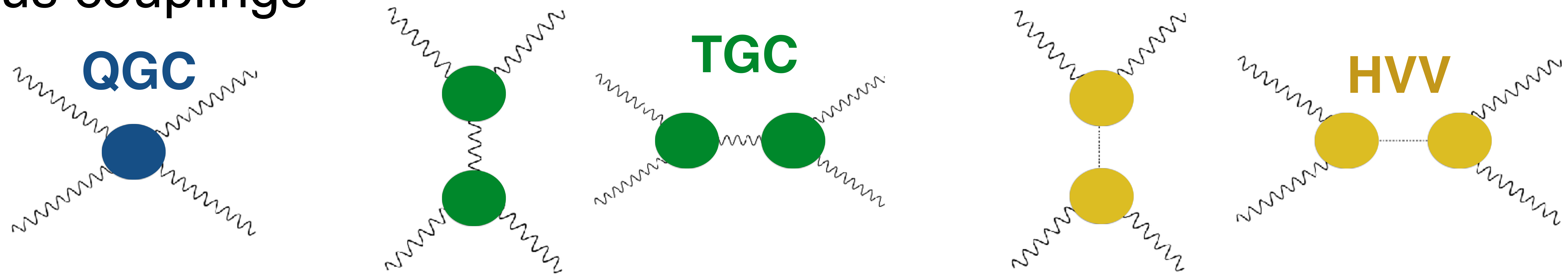
- add to the SM Lagrangian additional BSM terms
- generic **low-energy parameterisation of an unknown model** that would become apparent at (too) high energies

Dim 6 — Dim 8

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{i=WWW,W,B,\Phi W,\Phi B} \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_{j=1,2} \frac{f_{S,j}}{\Lambda^4}\mathcal{O}_{S,j} + \sum_{j=0,\ldots,9} \frac{f_{T,j}}{\Lambda^4}\mathcal{O}_{T,j} + \sum_{j=0,\ldots,7} \frac{f_{M,j}}{\Lambda^4}\mathcal{O}_{M,j}$$

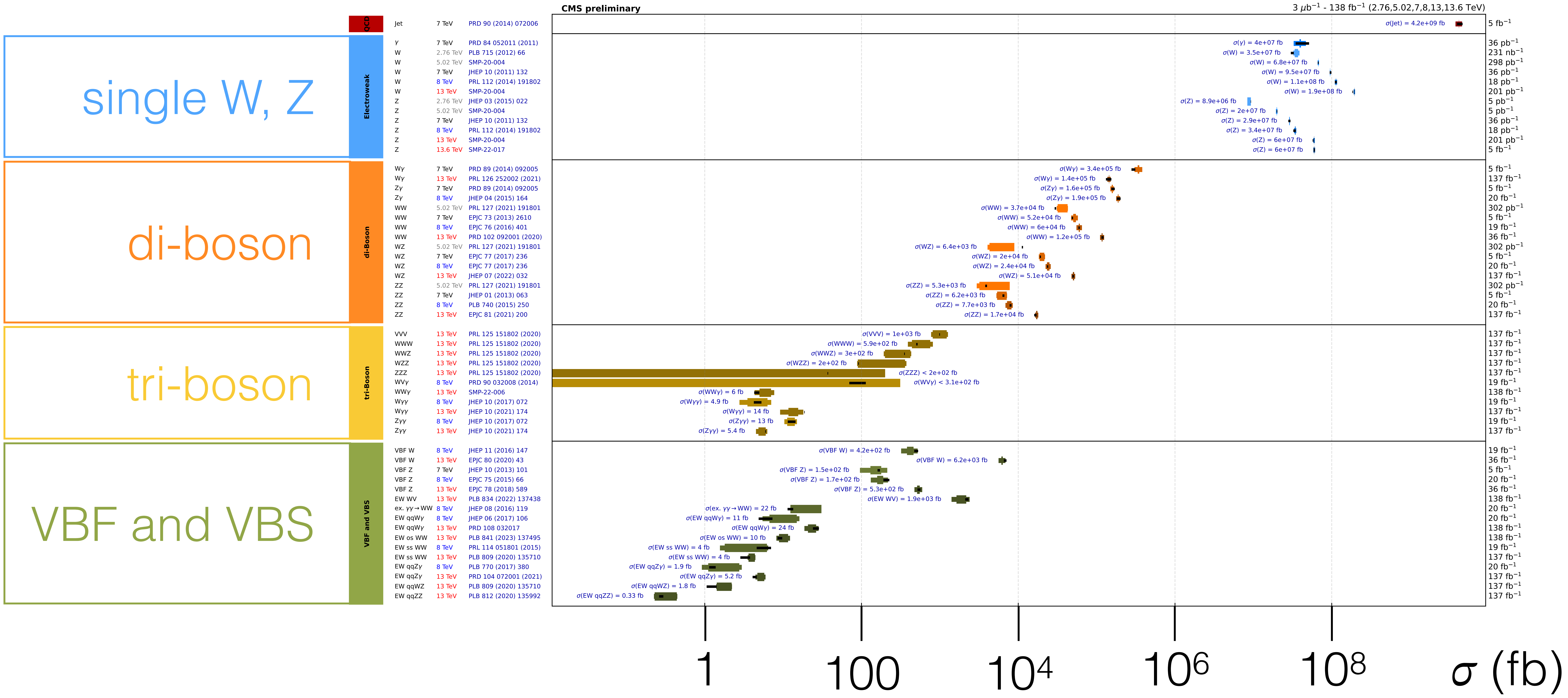
Pure Higgs field — Pure Field-strength tensor — Mixed Higgs-field-strength

- simplistic realisation: choose a basis and associate operators to vertices in form of anomalous couplings



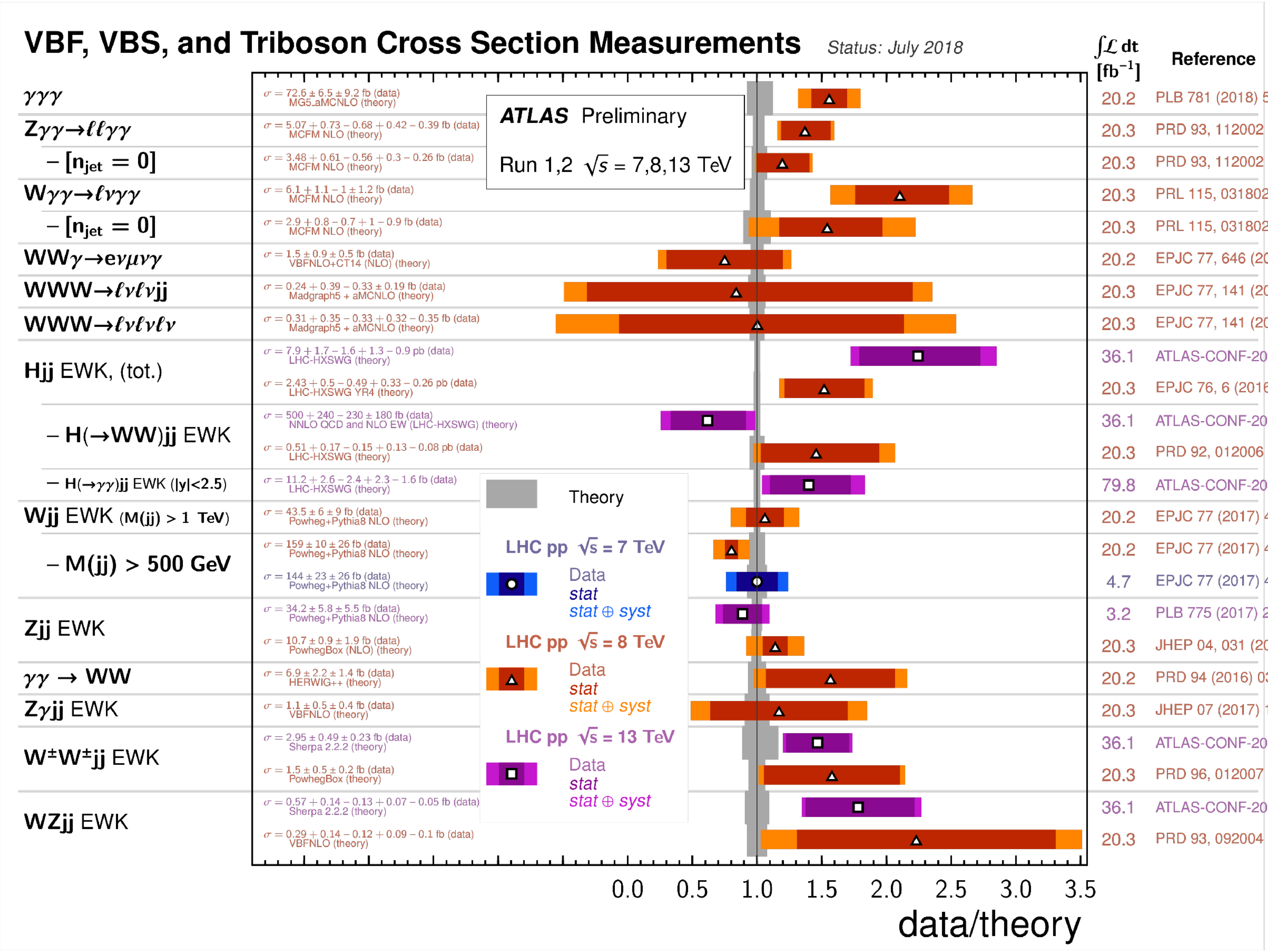
electroweak stairway to heaven

Overview of CMS cross section results



http://go.web.cern.ch/go/7LSN

measurements and predictions

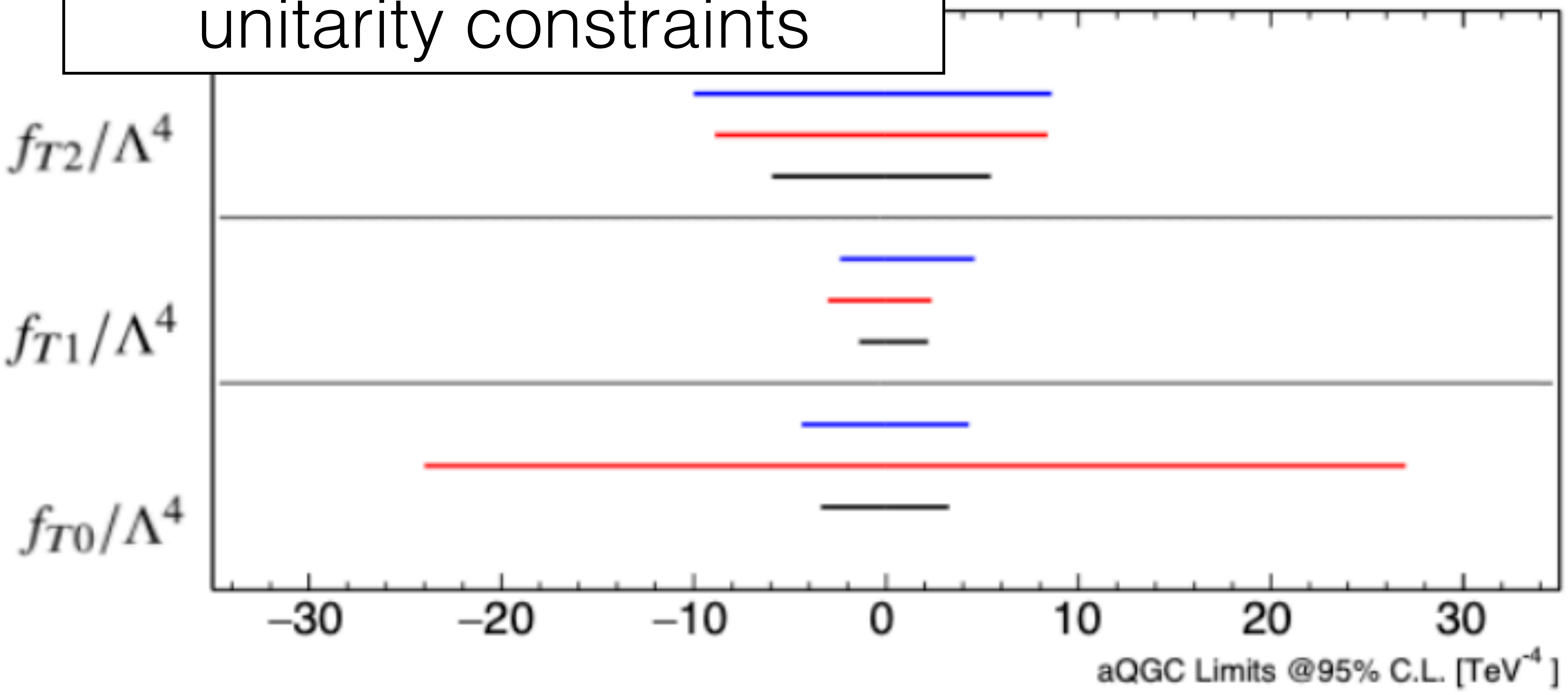


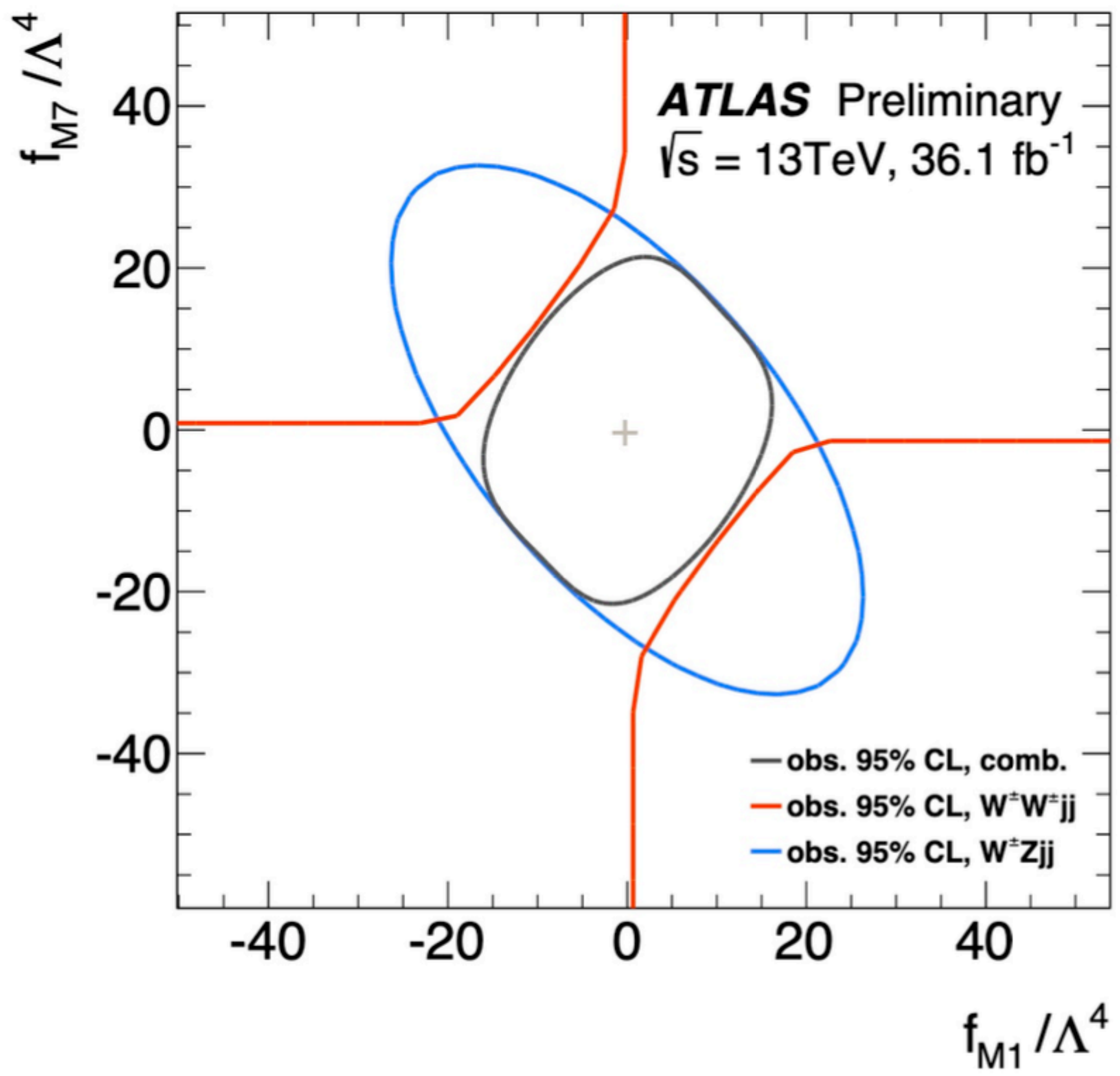
dimension-8 effects in vector boson scattering

- dimension-8 EFT interpretation of the fully leptonic *WZjj* and same-sign *WWjj* electroweak measurements
- joint fit on M_T^{WZ} and m_{ll}^{WW}

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{f_i^{(6)}}{\Lambda^2} O_i + \sum_j \frac{f_j^{(8)}}{\Lambda^4} O_j + \ldots$$

1 TeV clipping to cope with unitarity constraints



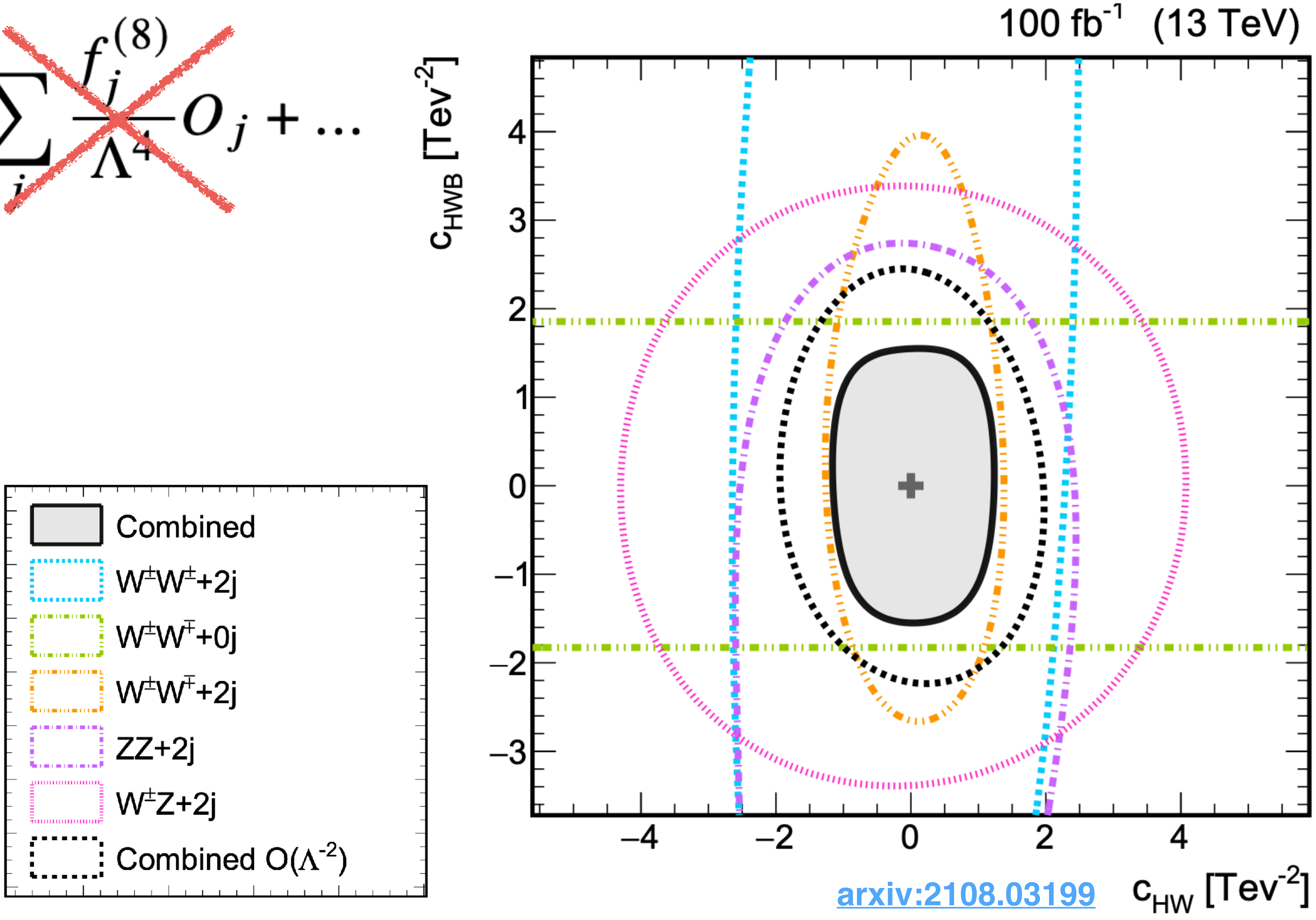


ATL-PHYS-PUB-2023-002

dimension-6 EFT global fits

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{f_i^{(6)}}{\Lambda^2} O_i + \sum_j \frac{f_j^{(8)}}{\Lambda^4} O_j + \ldots$$

- **two Wilson coefficients free to float simultaneously** (the others are set to zero)
- the **combination and complementarity of different analysis channels** allows for a narrower limit area definition



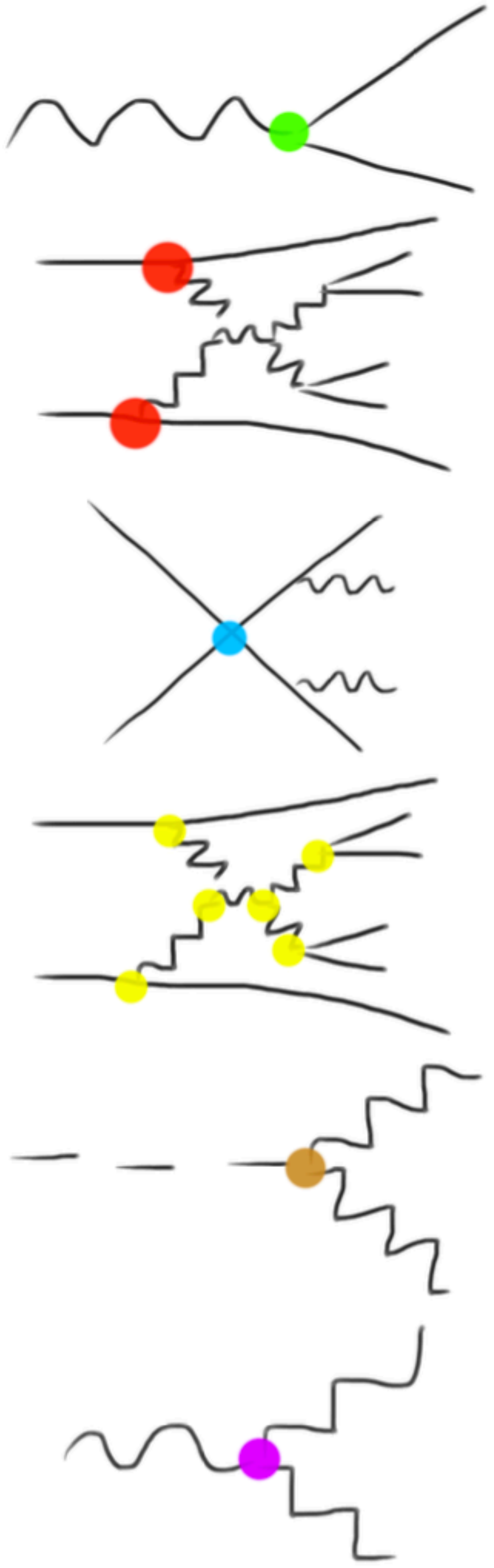
arxiv:2108.03199

dimension-6 operators

courtesy of G. Boldrini

Op.	SSWW+2j		OSWW+2j		WZ+2j		ZZ+2j		ZV+2j		WW	
	L	L+Q	L	L+Q	L	L+Q	L	L+Q	L	L+Q	L	L+Q
$c_{Hl}^{(1)}$	-	m_{ll}	-	MET	$m_{ee}{}^{\dagger}$	m_{WZ}	$p_{T,e^-\mu^-}{}^{\dagger}$	$p_{T,e^-\mu^-}{}^{\dagger}$	p^{V}_{T,j_1}	p^{V}_{T,j_1}	p_{T,l^1}	MET
$c_{Hq}^{(1)}$	p_{T,j^1}	p_{T,j^1}	m_{jj}	m_{ll}	m_{jj}	p_{T,j^1}	m_{jj}	p_{T,j^1}	m_{jj}^{VBS}	m_{jj}^{VBS}	MET	MET
$c_{Hq}^{(3)}$	$\Delta\phi_{jj}$	$\Delta\phi_{jj}$	m_{ll}	m_{ll}	$\Delta\phi_{jj}{}^{\dagger}$	p_{T,l^1}	$\Delta\phi_{jj}{}^{\dagger}$	p_{T,l^4}	p^{VBS}_{T,j_2}	p^{VBS}_{T,j_2}	p_{T,l^1}	p_{T,l^1}
$c_{qq}^{(3)}$	$m_{ll}{}^{\dagger}$	p_{T,j^2}	m_{jj}	p_{T,j^2}	m_{jj}	p_{T,j^2}	m_{jj}	p_{T,j^1}	$p_{T,l^1}{}^{\dagger}$	$\Delta\phi_{jj}^{VBS}$	-	-
$c_{qq}^{(3,1)}$	$\Delta\phi_{jj}$	p_{T,j^2}	m_{jj}	p_{T,j^2}	m_{jj}	p_{T,j^2}	m_{jj}	p_{T,j^1}	$\Delta\eta_{jj}^{V\dagger}$	$\Delta\phi_{jj}^{VBS}$	-	-
$c_{qq}^{(1,1)}$	$\Delta\phi_{jj}$	p_{T,j^1}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	p_{T,j^1}	p_{T,j^2}	p_{T,j^2}	$\Delta\phi_{jj}^{VBS}$	p^{VBS}_{T,j_1}	-	-
$c_{qq}^{(1)}$	p_{T,j^1}	p_{T,j^1}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	$\Delta\phi_{jj}^{VBS}$	p^{VBS}_{T,j_1}	-	-
$c_{Hl}^{(3)}$	$\Delta\eta_{jj}{}^{\dagger}$	$\Delta\eta_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	m_{jj}	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$\Delta\eta_{jj}^{V}$	$\Delta\eta_{jj}^{V}$	$m_{ll}{}^{\dagger}$	$m_{ll}{}^{\dagger}$
c_{HD}	p_{T,j^1}	m_{ll}	$\Delta\eta_{jj}$	$\Delta\eta_{jj}$	m_{ee}	$\Delta\eta_{jj}{}^{\dagger}$	$p_{T,e^+\mu^+}$	$p_{T,e^+\mu^+}{}^{\dagger}$	p_{T,l^2}	p_{T,l^2}	p_{T,l^1}	p_{T,l^1}
$c_{ll}^{(1)}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	m_{jj}	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$\Delta\eta_{jj}^{V\dagger}$	$\Delta\eta_{jj}^{V\dagger}$	$p_{T,ll}{}^{\dagger}$	p_{T,l^2}
c_{HWB}	p_{T,j^1}	p_{T,j^1}	$\Delta\eta_{jj}$	m_{ll}	m_{ee}	m_{WZ}	$m_{\mu\mu}{}^{\dagger}$	$\Delta\eta_{jj}$	$\Delta\eta_{jj}^{V}$	$\Delta\eta_{jj}^{V}$	p_{T,l^1}	MET
$c_{H\Box}$	p_{T,j^1}	m_{ll}	m_{ll}	m_{ll}	-	m_{WZ}	-	$\Delta\eta_{jj}$	p^{V}_{T,j_2}	p^{V}_{T,j_2}	-	-
c_{HW}	$\Delta\phi_{jj}$	m_{ll}	$\Delta\phi_{jj}$	m_{ll}	$\eta_{l^3}{}^{\dagger}$	m_{WZ}	m_{jj}	m_{4l}	p^{VBS}_{T,j_1}	p^{V}_{T,j_2}	-	-
c_{W}	$\Delta\phi_{jj}$	$p_{T,ll}$	$\Delta\phi_{jj}$	m_{ll}	p_{T,l^1}	m_{WZ}	$\Delta\phi_{jj}$	p_{T,l^4}	$\Delta\phi_{jj}^{VBS\dagger}$	$\Delta\phi_{jj}^{VBS\dagger}$	MET	MET

Observables ranking change from Lin to Lin+Quad.
Best observable group usually match prior knowledge about the operator.



CMS W^+W^-

event yields

Process	SR eμ $Z_{\ell\ell} < 1$	SR eμ $Z_{\ell\ell} > 1$	SR ee - $\mu\mu$ $Z_{\ell\ell} < 1$	SR ee - $\mu\mu$ $Z_{\ell\ell} > 1$
DATA	2441	2192	1606	1667
Signal + background	2396.8 ± 98.5	2239.6 ± 106.0	1590.4 ± 49.4	1660.5 ± 43.6
Signal	169.1 ± 20.2	69.9 ± 8.4	98.0 ± 6.5	38.3 ± 2.5
Background	2227.7 ± 96.4	2169.7 ± 105.6	1492.4 ± 48.9	1622.1 ± 43.5
$t\bar{t} + tW$	1629.4 ± 71.4	1452.5 ± 69.5	767.8 ± 14.5	642.5 ± 13.2
WW (QCD)	327.0 ± 61.6	409.3 ± 77.3	111.1 ± 16.6	121.5 ± 17.3
Nonprompt	107.0 ± 18.4	109.9 ± 16.4	30.0 ± 4.9	32.0 ± 4.2
DY no PU jets	—	—	259.5 ± 27.3	408.3 ± 17.1
DY + 1 PU jets	—	—	222.7 ± 33.3	337.4 ± 32.9
DY$\tau^+\tau^-$	69.2 ± 4.6	102.0 ± 5.8	—	—
Multiboson	67.7 ± 6.6	75.6 ± 7.3	60.9 ± 3.8	60.1 ± 4.8
Zjj	1.0 ± 0.2	0.4 ± 0.0	40.5 ± 4.2	20.3 ± 1.3
Higgs	26.6 ± 1.5	20.1 ± 1.0	—	—

uncertainties

Uncertainty source	Value
QCD-induced W^+W^- normalization	5.3%
$t\bar{t}$ scale variation	5.1%
VBS signal scale variation	5.0%
$t\bar{t}$ normalization	4.9%
b tagging	3.5%
Trigger corrections	3.3%
DY normalization	2.9%
Jet energy scale + resolution	2.6%
Unclustered p_T^{miss}	2.4%
QCD-induced W^+W^- scale variation	2.1%
Integrated luminosity	2.0%
Muon efficiency	2.0%
Pileup	1.8%
Electron efficiency	1.5%
Underlying event	1.3%
Parton shower	1.0%
Other	$<$1%
Total systematic uncertainty	13.1%
Total statistical uncertainty	14.9%
Total uncertainty	19.8%

impact on the cross-section

ATLAS W^+W^-

event yields

Process	Event yields $n_{\text{jets}} = 2$	Event yields $n_{\text{jets}} = 3$
EWK W^+W^-jj	158 ± 27	54 ± 13
$t\bar{t}$	2394 ± 194	1625 ± 125
Single top	491 ± 34	225 ± 21
Strong W^+W^-jj	1214 ± 256	514 ± 121
W+jets	37 ± 97	19 ± 48
Z + jets	216 ± 62	65 ± 25
Multiboson	101 ± 5	42 ± 3
SM prediction	4610 ± 77	2546 ± 48
Data	4610	2533

uncertainties

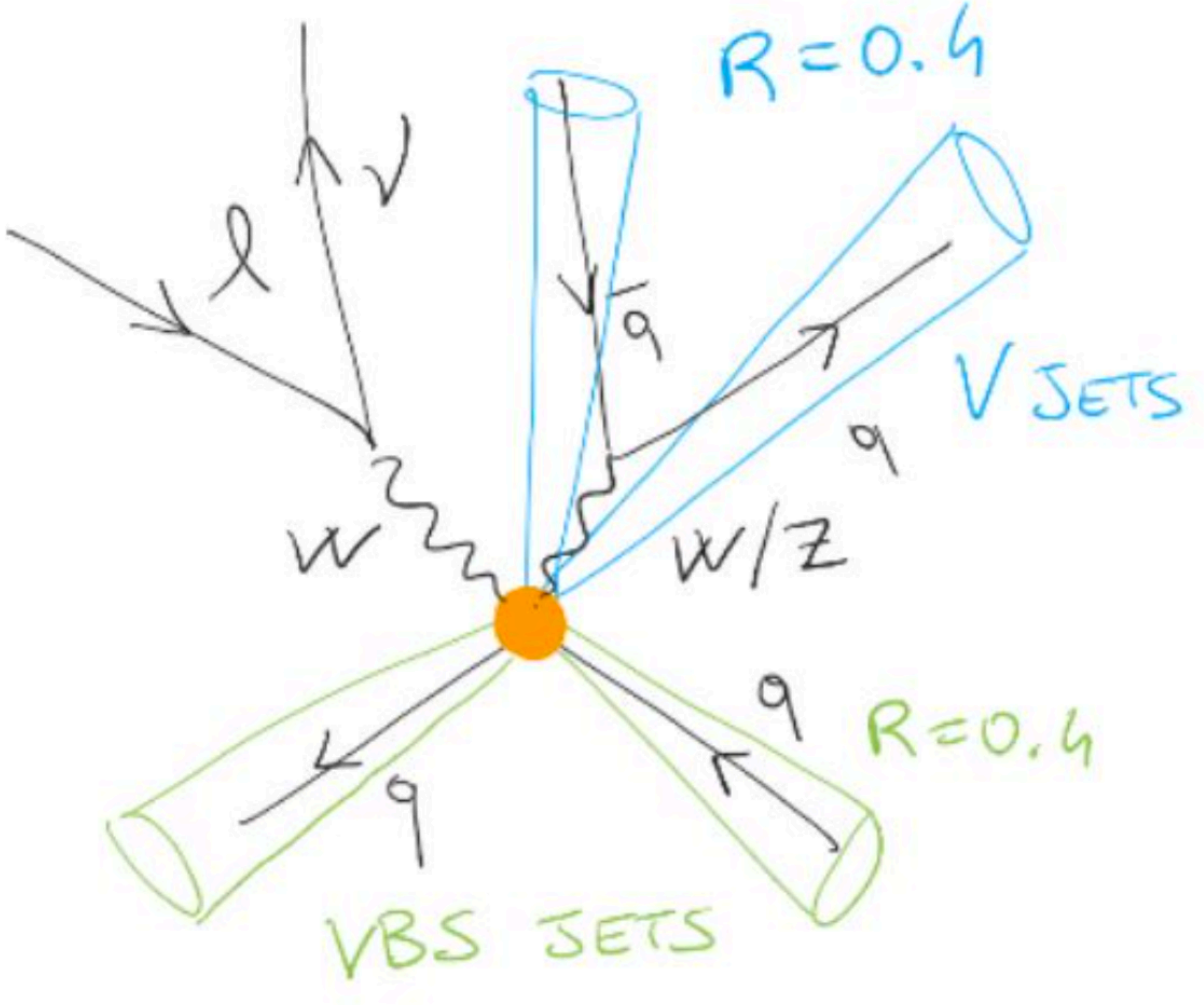
Sources	$\frac{\sqrt{(\Delta\mu)^2-(\Delta\mu')^2}}{\mu}$ [%]
MC statistical uncertainty	7.7
Top quark theoretical uncertainties	6.3
Signal theoretical uncertainties	5.8
Jet experimental uncertainties	4.9
Strong W^+W^-jj theoretical uncertainties	1.3
Luminosity	0.8
Misidentified lepton uncertainty	0.5
b-tagging	0.4
Lepton experimental uncertainties	0.1
Others	0.3
Data statistical uncertainty	12.3
Top quark normalisation uncertainty	4.9
Strong W^+W^-jj normalisation uncertainty	2.2
Total uncertainty	18.5

CMS semi-leptonic WV

vector boson identification

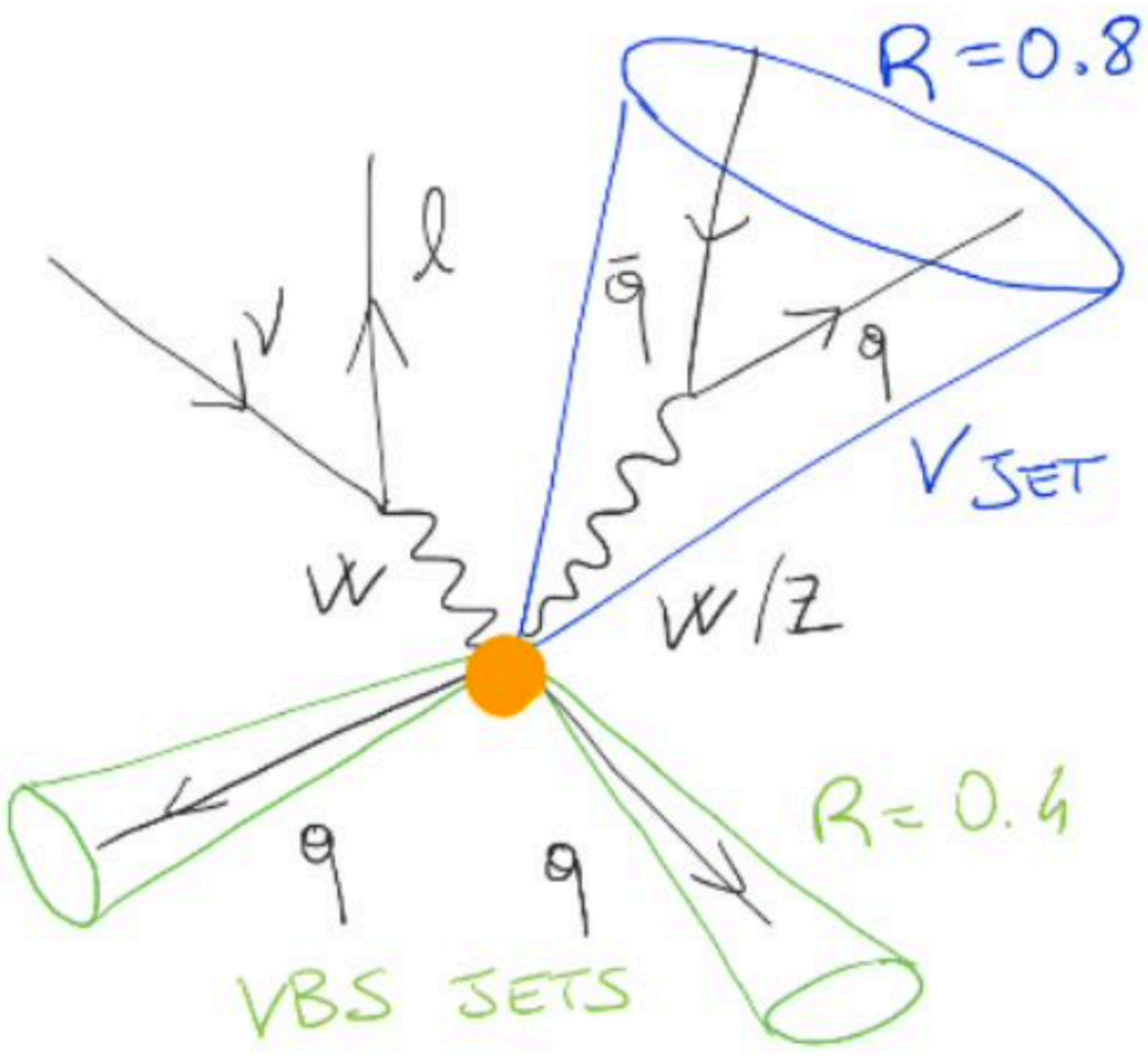
cartoons are courtesy of D. Valsecchi

RESOLVED CASE



the quarks due to the V decay originate **two jets**

MERGED CASE

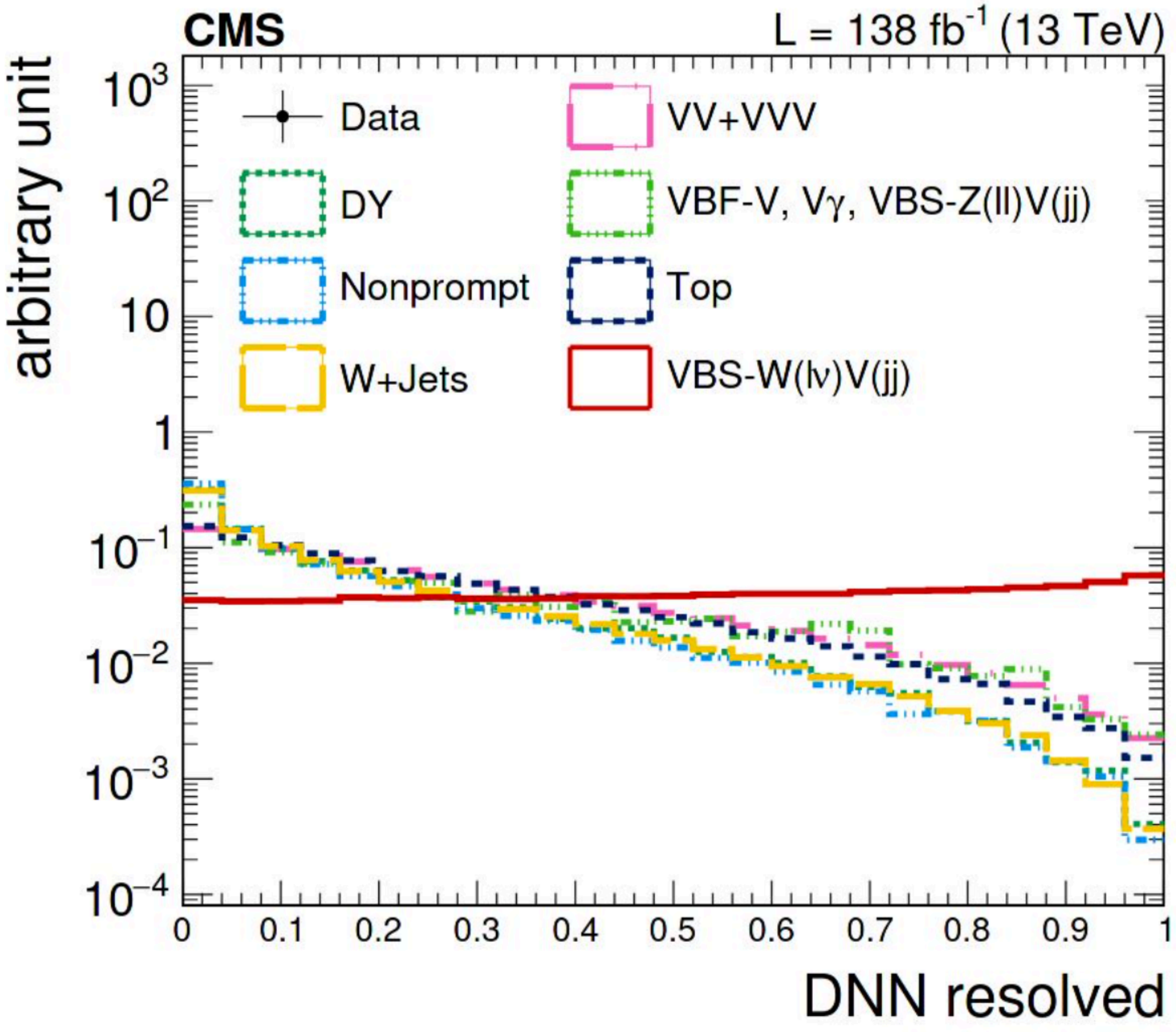


the quarks due to the V decay are close enough to originate **one single large jet**

signal extraction: a deep neural network

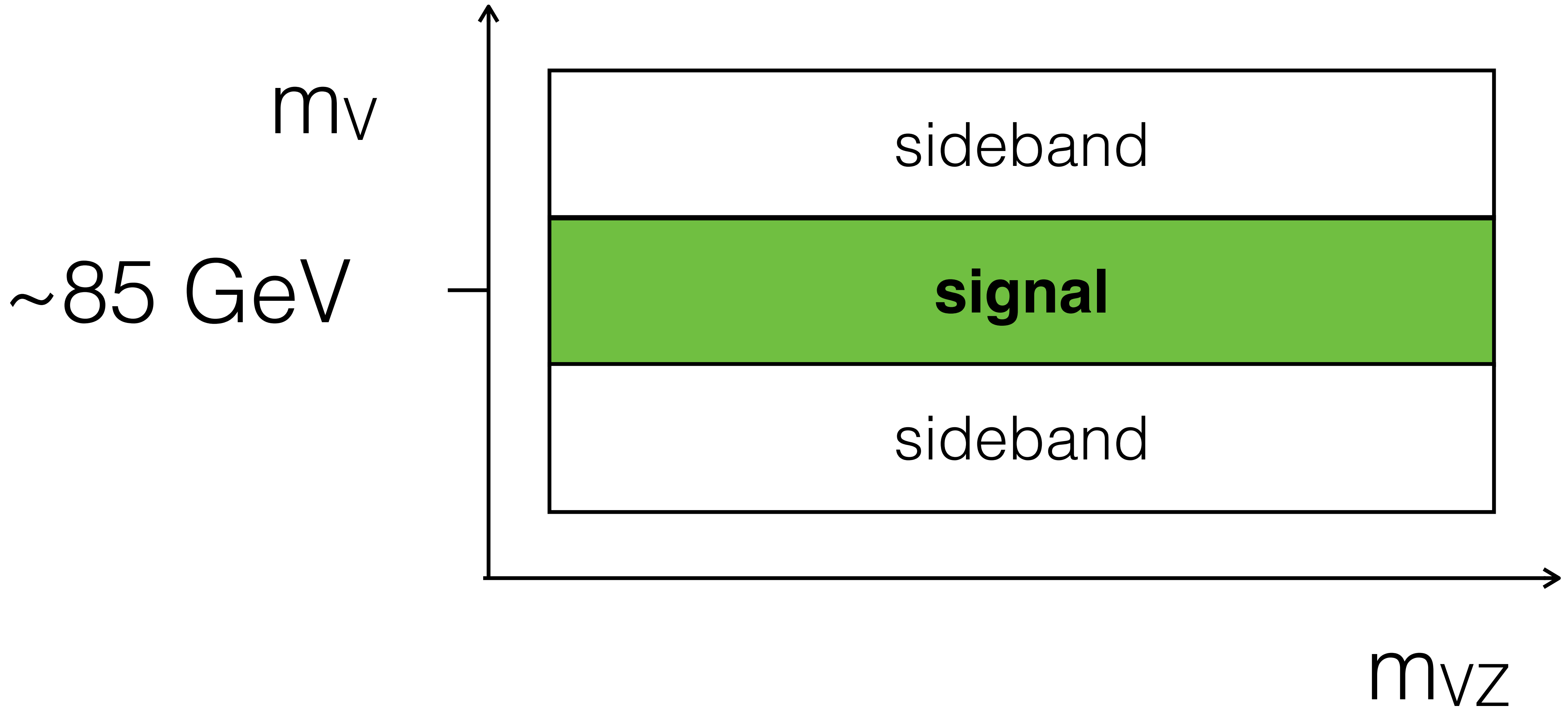
- many variables that characterise the signal **combined into a single discriminant**
- choose variables according to their importance (explainable AI)

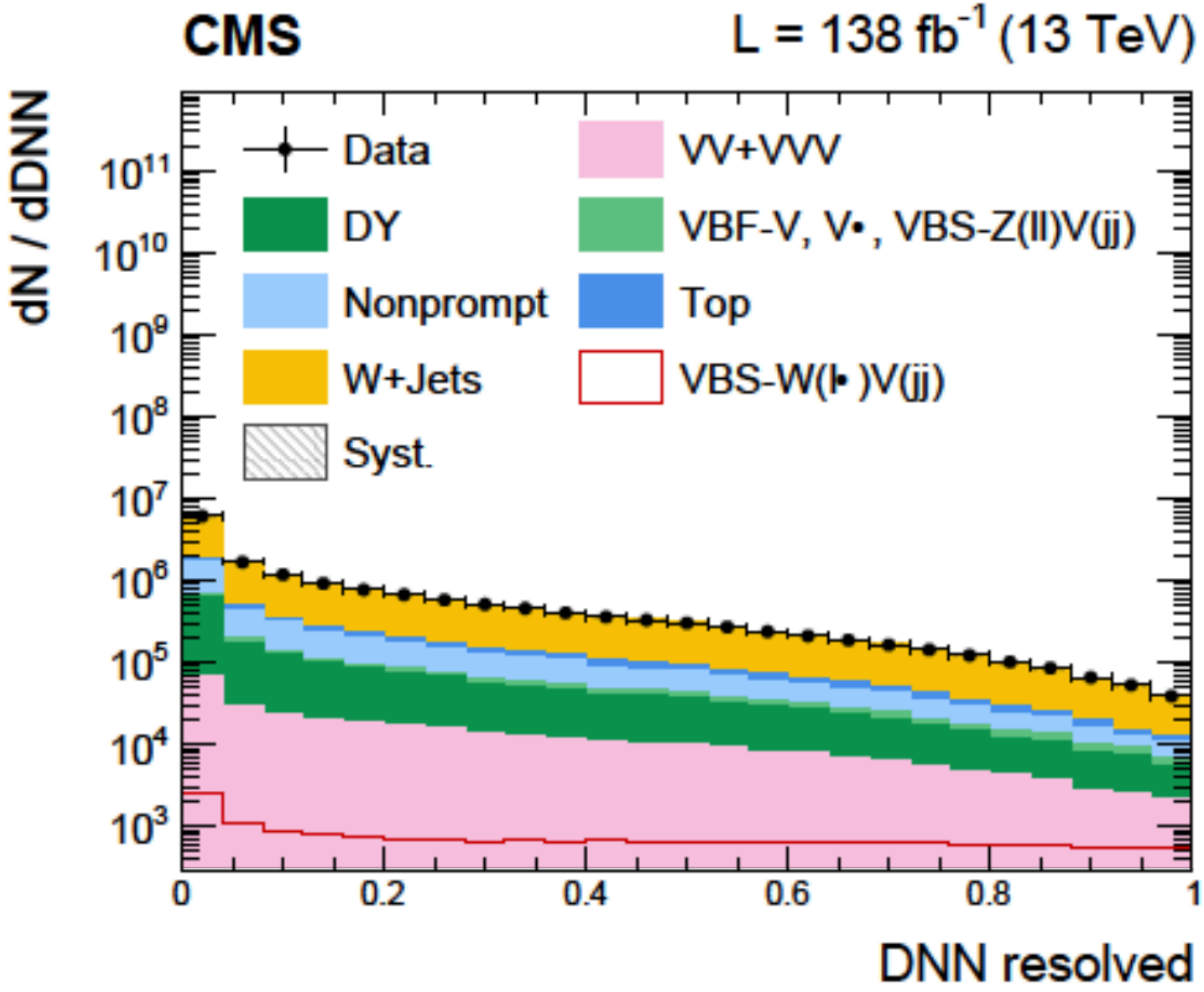
Variable	Resolved	Boosted	SHAP ranking Resolved	SHAP ranking Boosted
Lepton pseudorapidity	✓	✓	13	12
Lepton transverse momentum	✓	✓	16	10
Zeppenfeld variable for the lepton	✓	✓	2	2
Number of jets with $p_T > 30\,\mathrm{GeV}$	✓	✓	7	3
Leading VBS tag jet p_T	-	✓	-	11
Trailing VBS tag jet p_T	✓	✓	7	6
Pseudorapidity interval $\Delta\eta_{jj}^{VBS}$ between tag jets	✓	✓	4	4
Quark/gluon discriminator of leading VBS tag jet	✓	✓	9	7
Azimuthal angle distance between VBS tag jets	✓	-	10	-
Invariant mass of the VBS tag jets pair	✓	✓	1	1
p_T of the leading V_{had} jet	✓	-	14	-
p_T of the trailing V_{had} jet	✓	-	12	-
Pseudorapidity difference between V_{had} jets	✓	-	8	-
Quark/gluon discriminator of the leading V_{had} jet	✓	-	3	-
Quark/gluon discriminator of the trailing V_{had} jet	✓	-	5	-
p_T of the AK8 V_{had} jet candidate	-	✓	-	8
Invariant mass of V_{had}	✓	✓	11	5
Zeppenfeld variable for V_{had}	-	✓	-	9
Centrality	-	✓	15	13



W+jets estimate

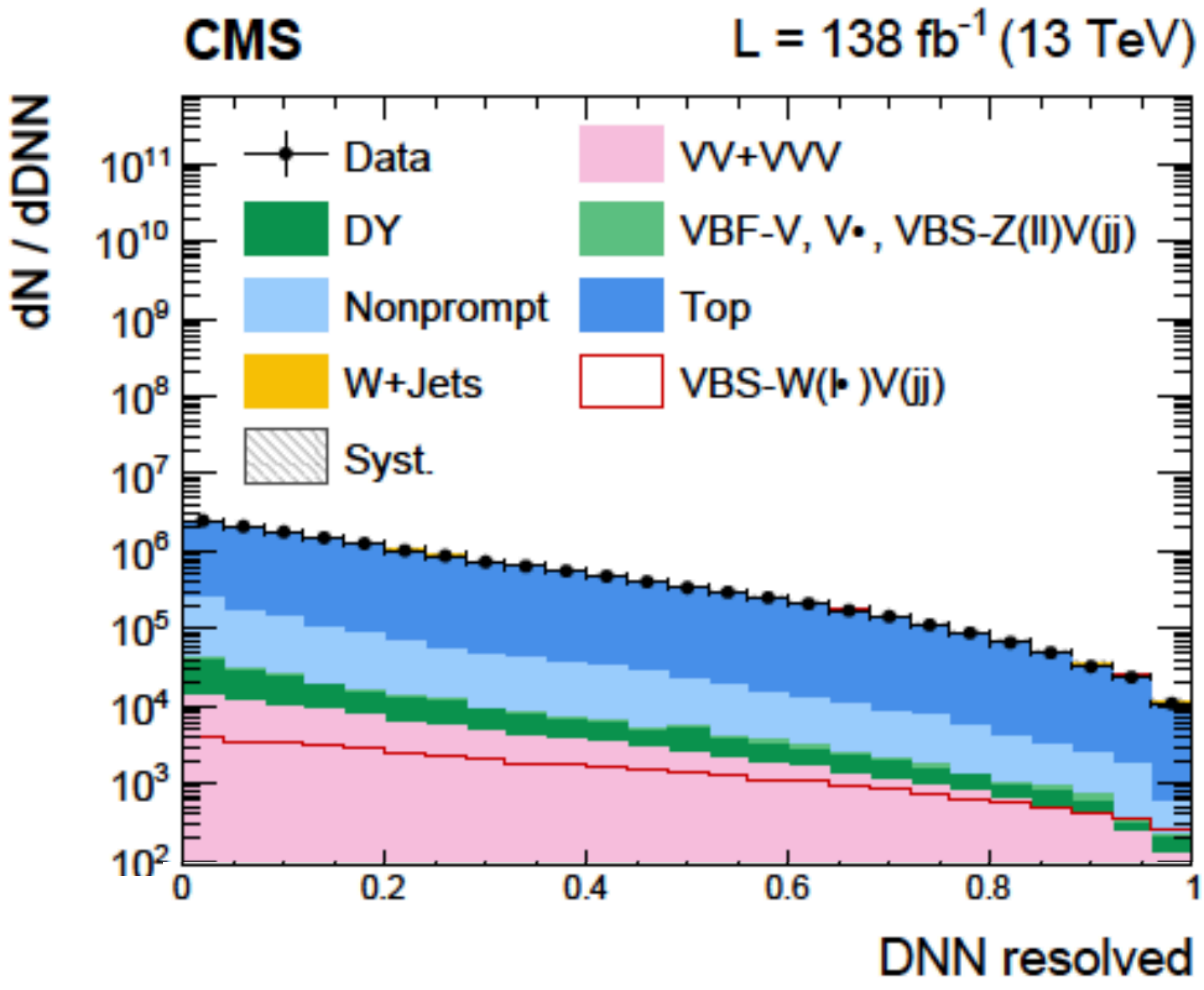
- measure the background cross-section **where no signal is expected**
- control region: sit **away from the hadronic W invariant mass**



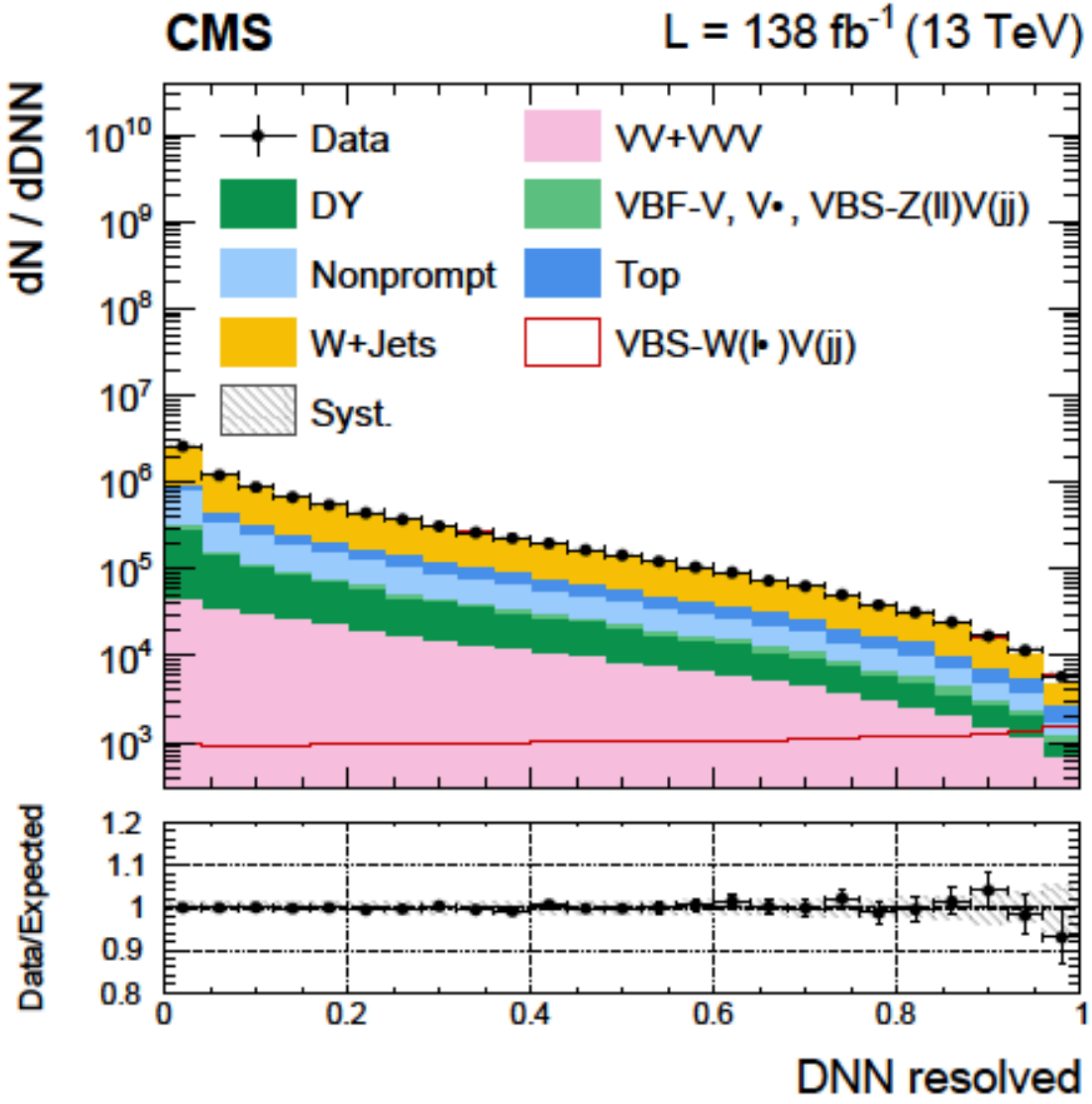


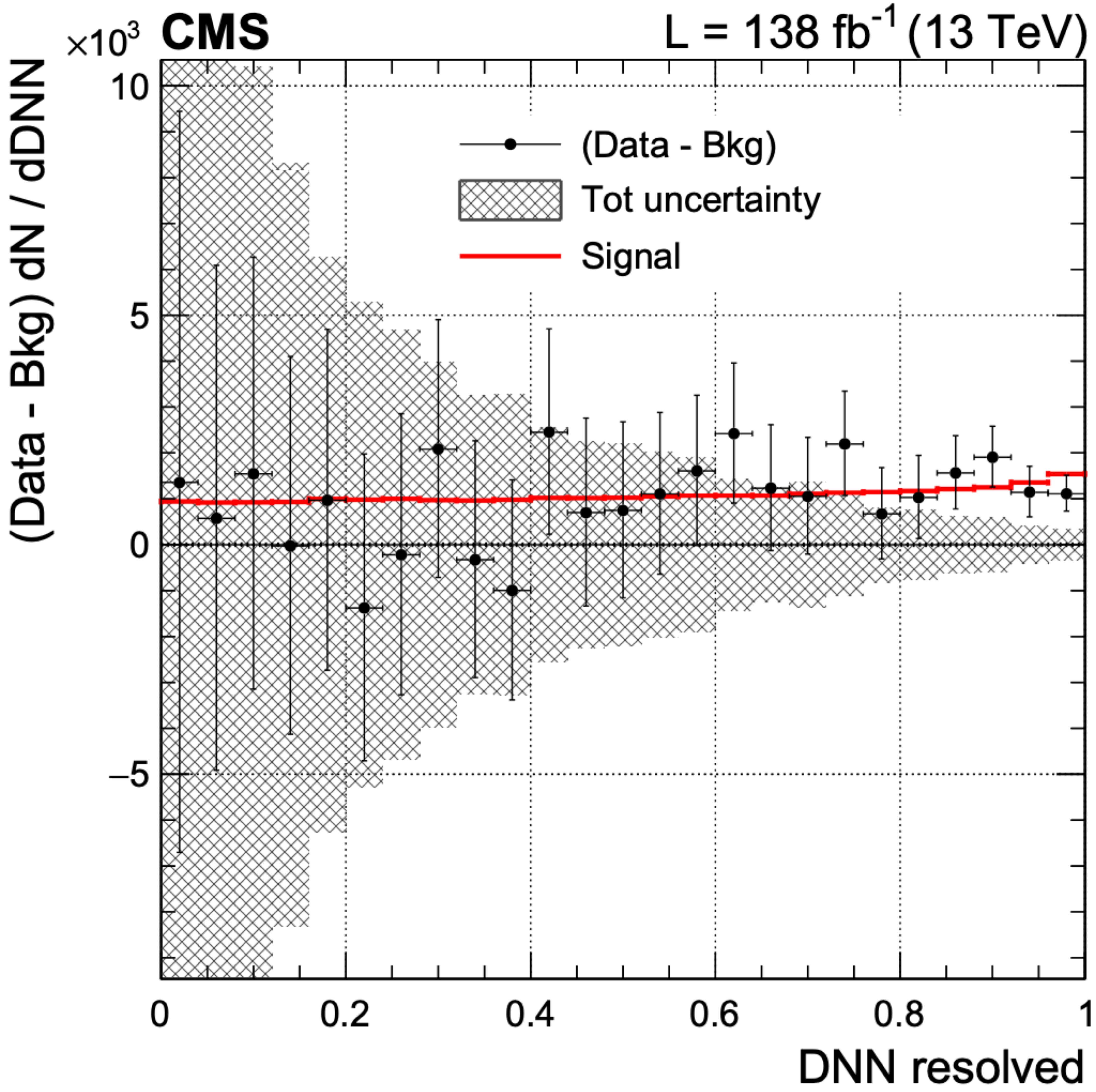
top background estimate

- select events with **at least one b-quark in the final state**

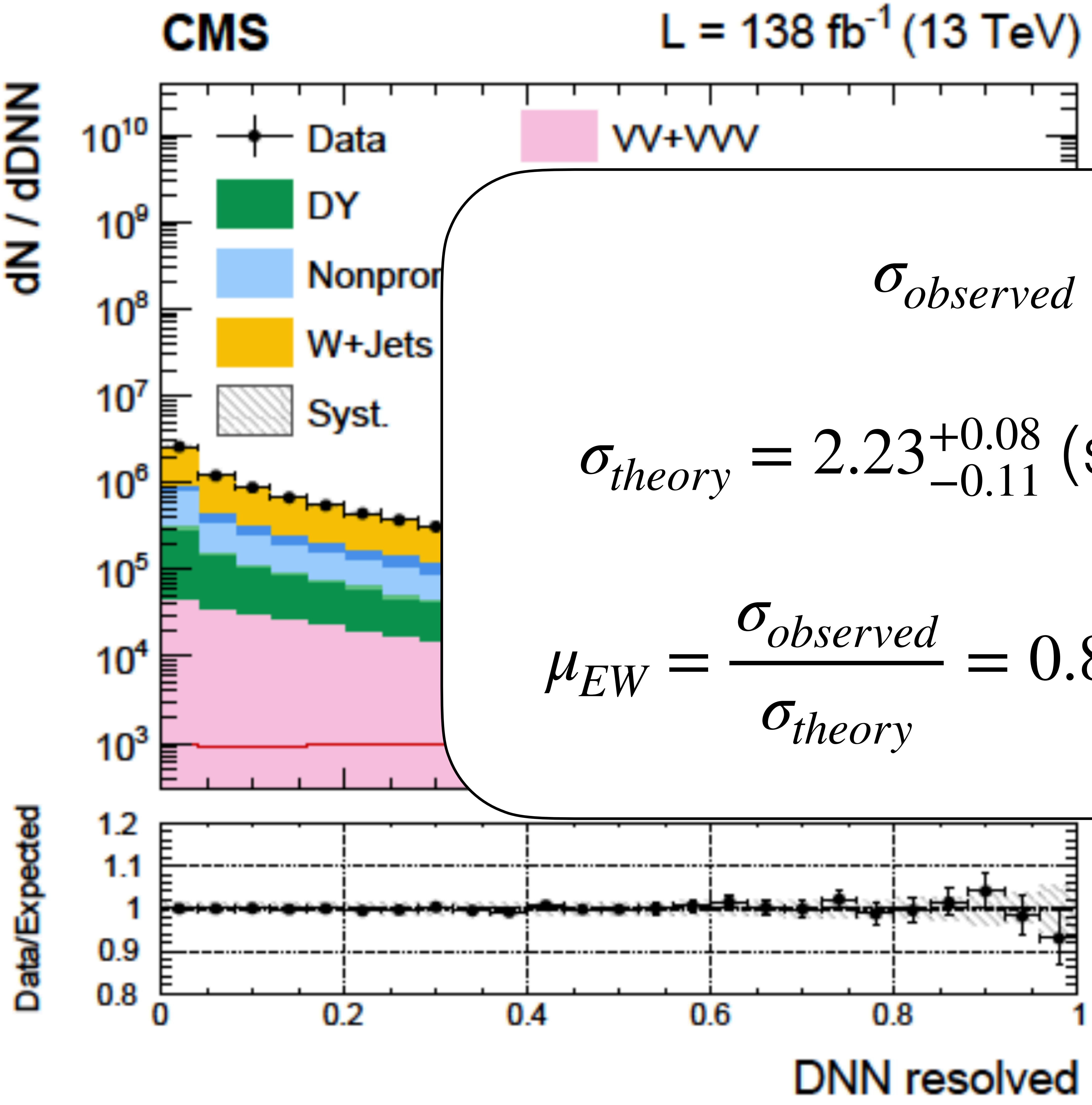


the fit result





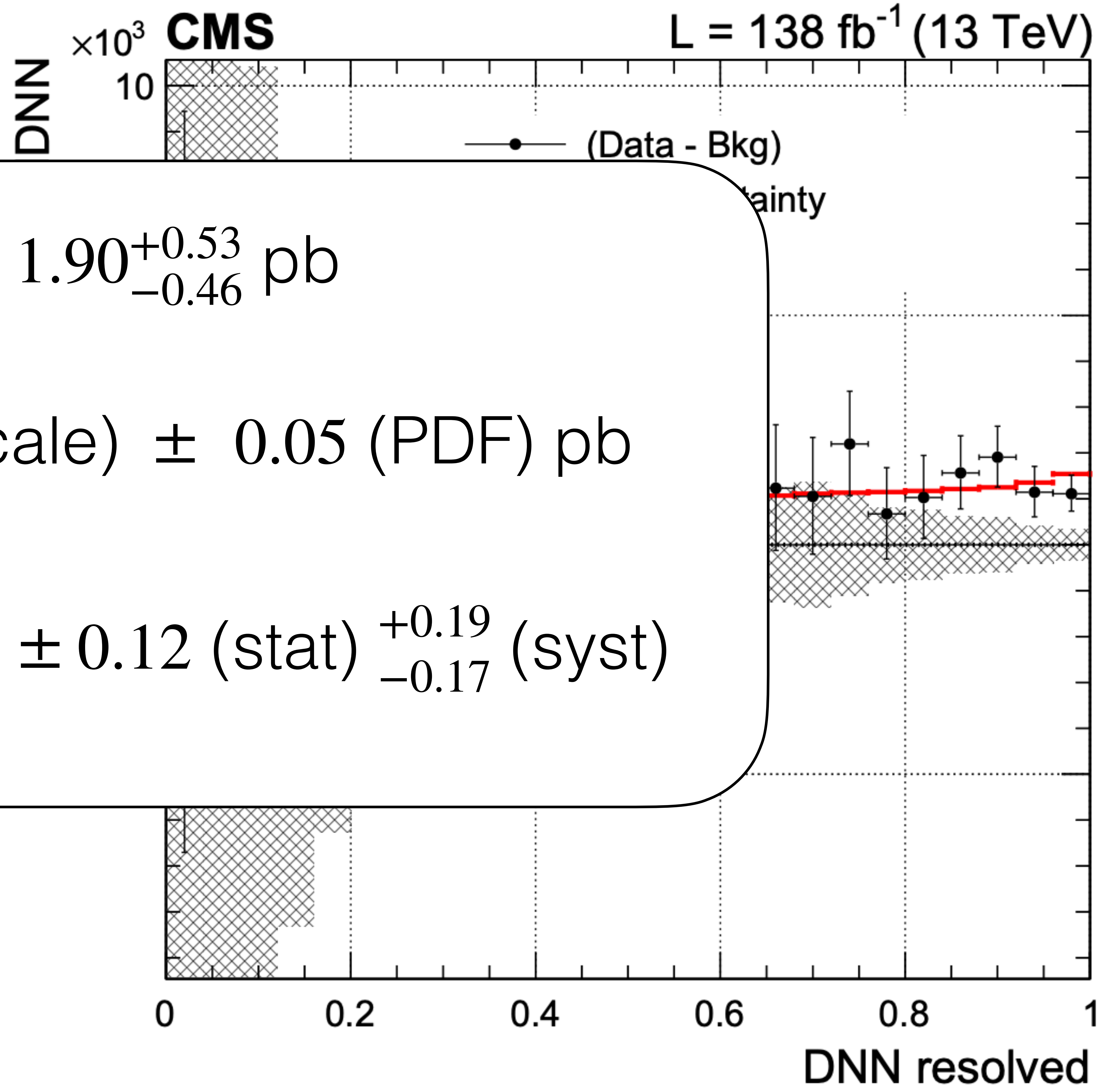
the fit result



$$\sigma_{observed} = 1.90^{+0.53}_{-0.46}\ \text{pb}$$

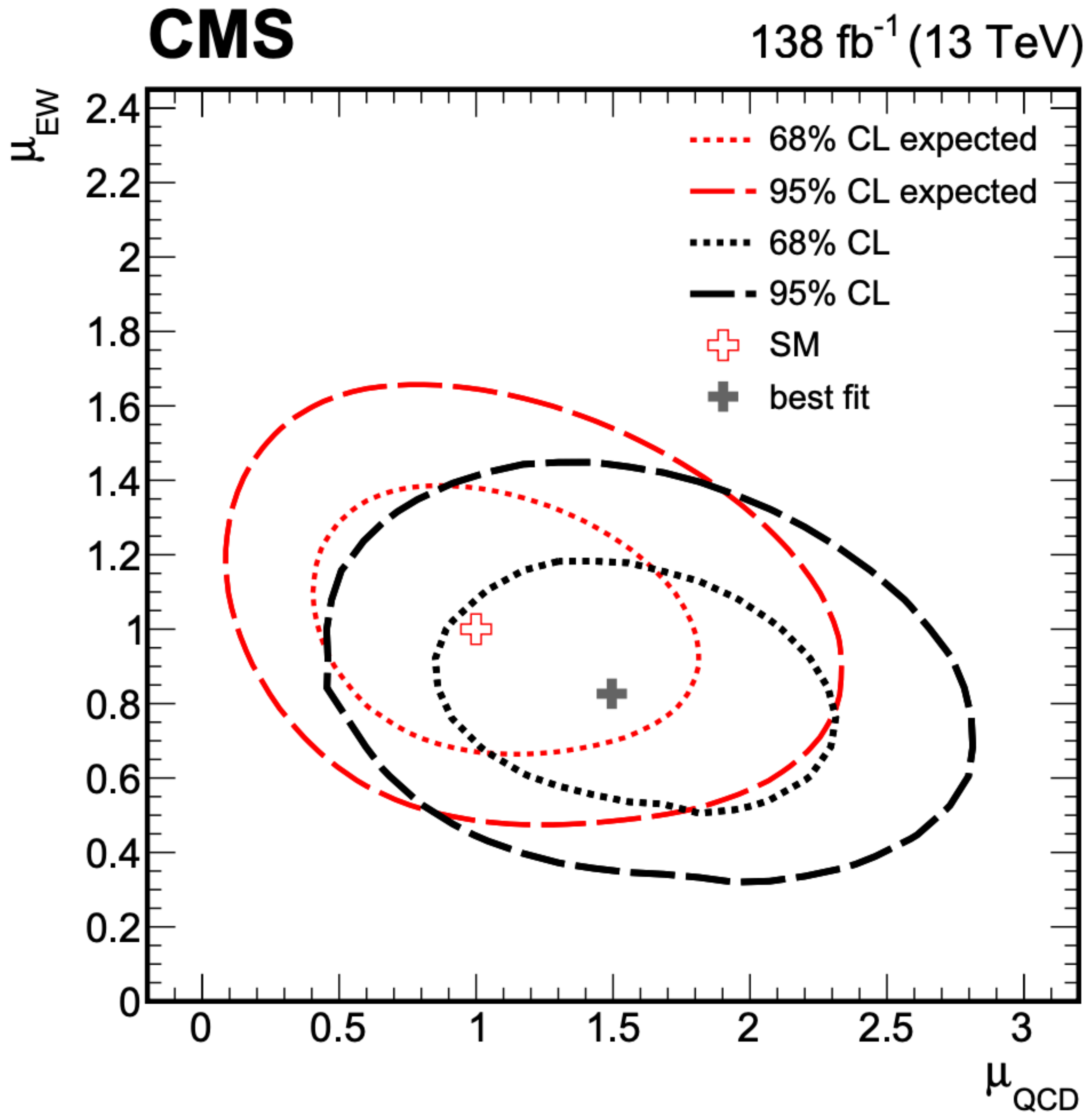
$$\sigma_{theory} = 2.23^{+0.08}_{-0.11}\ \text{(scale)} \pm 0.05\ \text{(PDF) pb}$$

$$\mu_{EW} = \frac{\sigma_{observed}}{\sigma_{theory}} = 0.85 \pm 0.12\ \text{(stat)}\ ^{+0.19}_{-0.17}\ \text{(syst)}$$



consistency of the Standard Model

- **two-dimensional fit**: QCD- and EW-induced VBS (at LO in perturbation theory) cross-sections fitted together



ATLAS $W\gamma$

selections and rates

ATLAS EXPERIMENT

Fiducial cross-section	SR^{fid}		CR^{fid}	
	$N_{jets}^{gap} = 0$		$N_{jets}^{gap} > 0$	
Differential cross-section	SR	CR_A	CR_B	CR_C
$m_{jj} > 1$ TeV	$N_{jets}^{gap} = 0$ $\xi_{l\gamma} < 0.35$	$N_{jets}^{gap} > 0$ $\xi_{l\gamma} < 0.35$	$N_{jets}^{gap} > 0$ $0.35 < \xi_{l\gamma} < 1$	$N_{jets}^{gap} = 0$ $0.35 < \xi_{l\gamma} < 1$

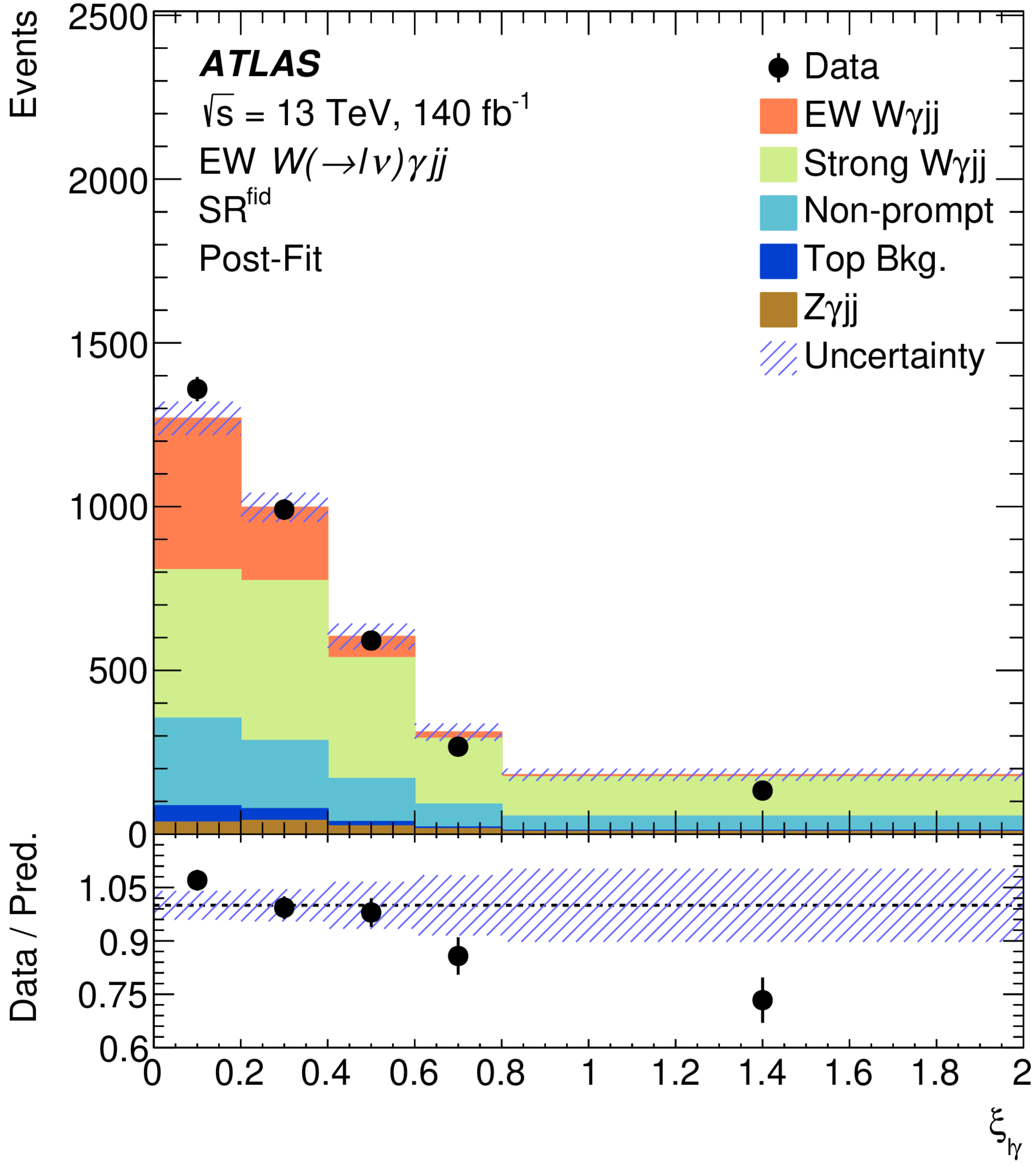
Expected number of events in the signal and control regions used for the fiducial cross-section measurement and observation of EW Wγ jj production.
Statistical and systematic uncertainties are included for each component.
The number of observed events in each region are included for comparison. The "non-prompt" background category includes non-prompt photons and fake leptons.

	$SR^{fid}\left(N_{jets}^{gap} = 0\right)$	$CR^{fid}\left(N_{jets}^{gap} > 0\right)$
EW $W\gamma jj$	520 ± 141	120 ± 49
Strong $W\gamma jj$	1550 ± 830	1970 ± 950
Non-prompt	692 ± 57	698 ± 58
Top quark processes	109 ± 18	183 ± 37
EW + strong $Z\gamma jj$	128 ± 34	163 ± 77
Total	3000 ± 830	3140 ± 960
Data	3341	3143

DNN input variable example

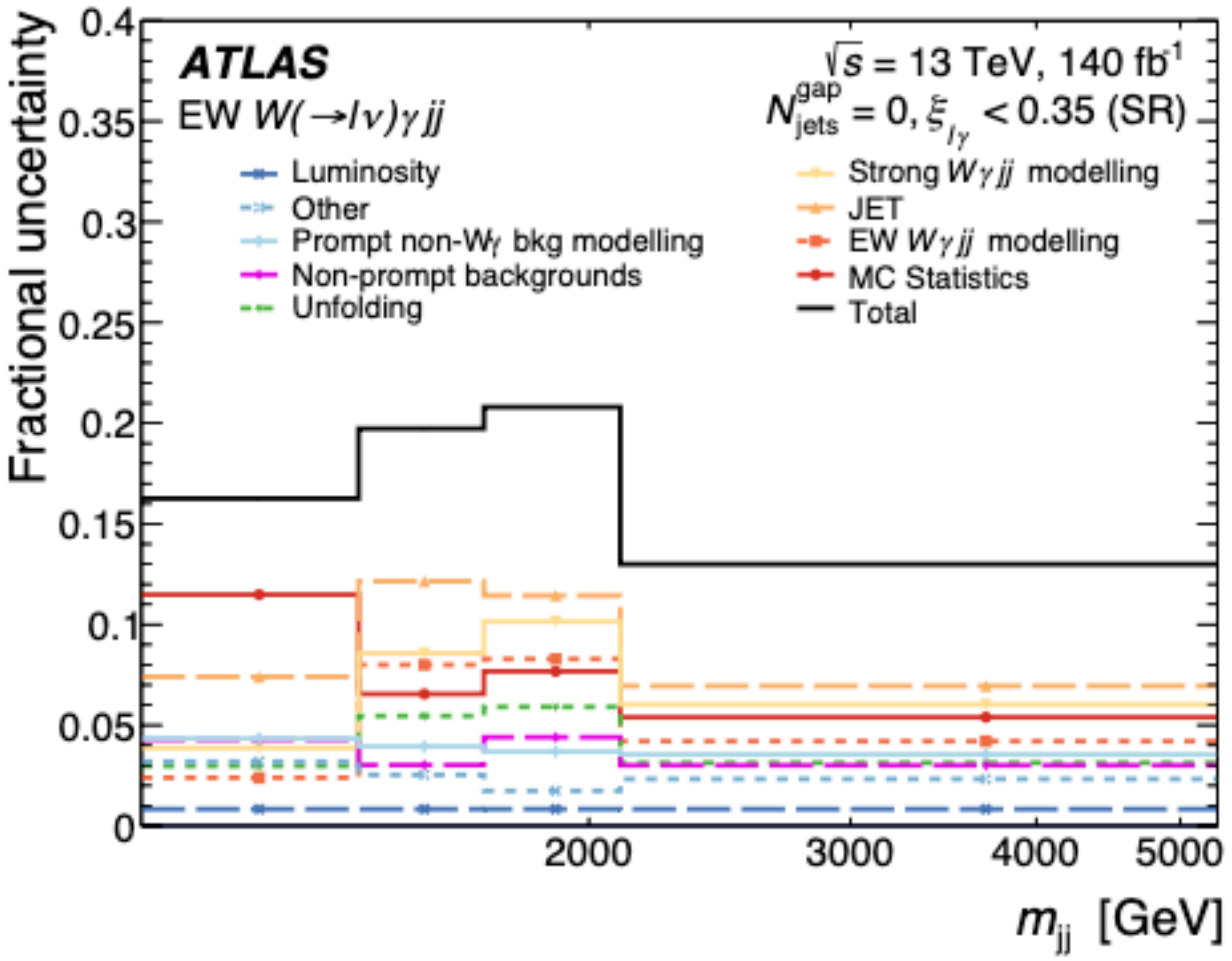
Distribution of the predicted and observed yields for one of the three highest ranked variables in the NN after performing the profile likelihood fit, **ξlγ**.
The observed data is represented by solid circles and the associated vertical error bar represents the statistical uncertainty of the data.
The predicted yields comprise simulated EW Wγ jj signal, backgrounds from non-prompt photons and leptons that are estimated by using data-driven methods, and backgrounds that are estimated with simulation.
The hashed band represents the quadrature sum of the statistical and systematic uncertainties.

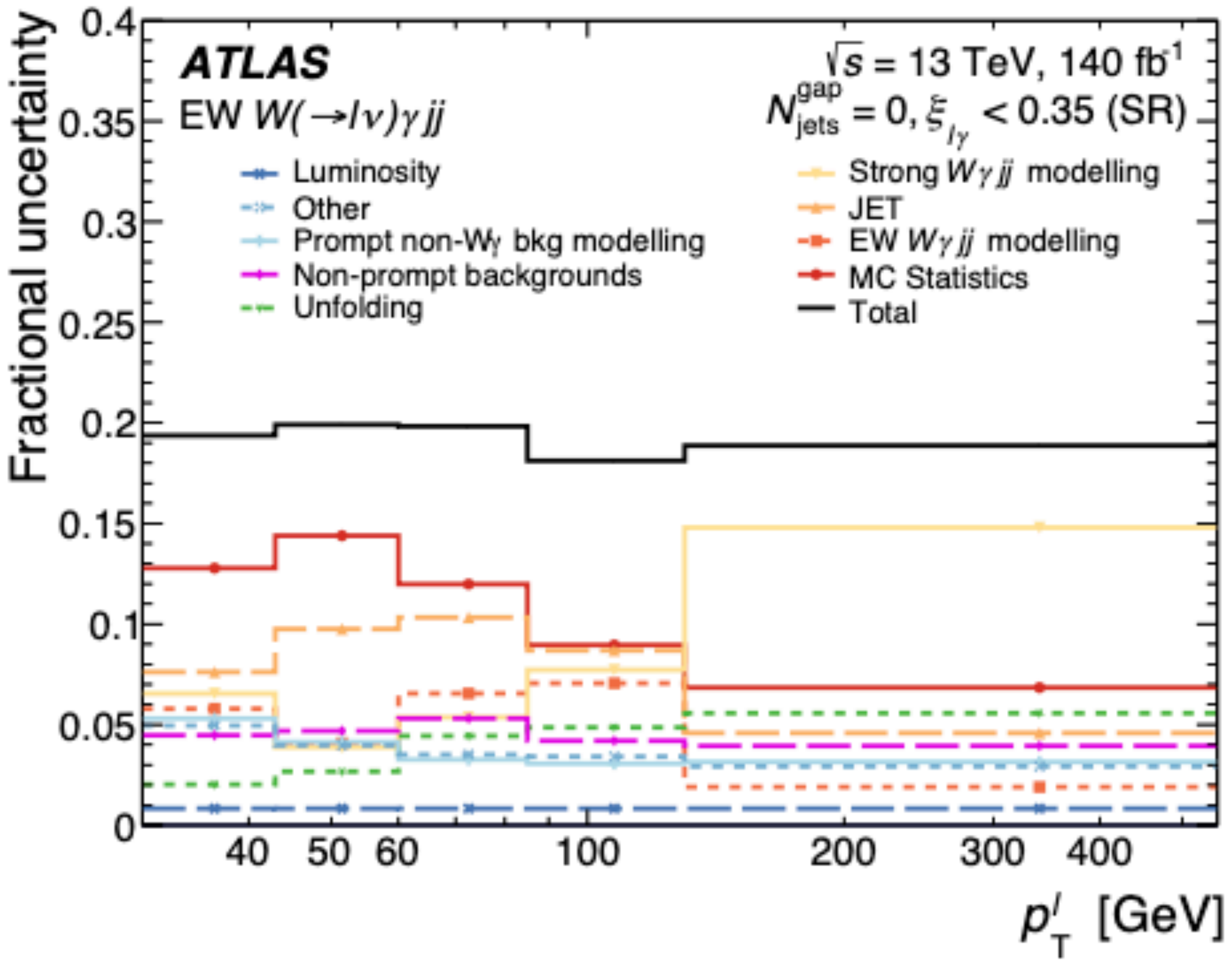
$$\xi_{l\gamma} = \left| \frac{y_{l\gamma} - \frac{y_{j_1} + y_{j_2}}{2}}{y_{j_1} - y_{j_2}} \right|$$



impact of uncertainties

Uncertainty Source	Fractional Uncertainty [%]
Statistics	11
Jets	8
Lepton, photon, pile-up	8
EW $W\gamma jj$ modelling	7
Strong $W\gamma jj$ modelling	6
Non-prompt background	2
Luminosity	2
Other Background modelling	2
E_T^{miss}	1

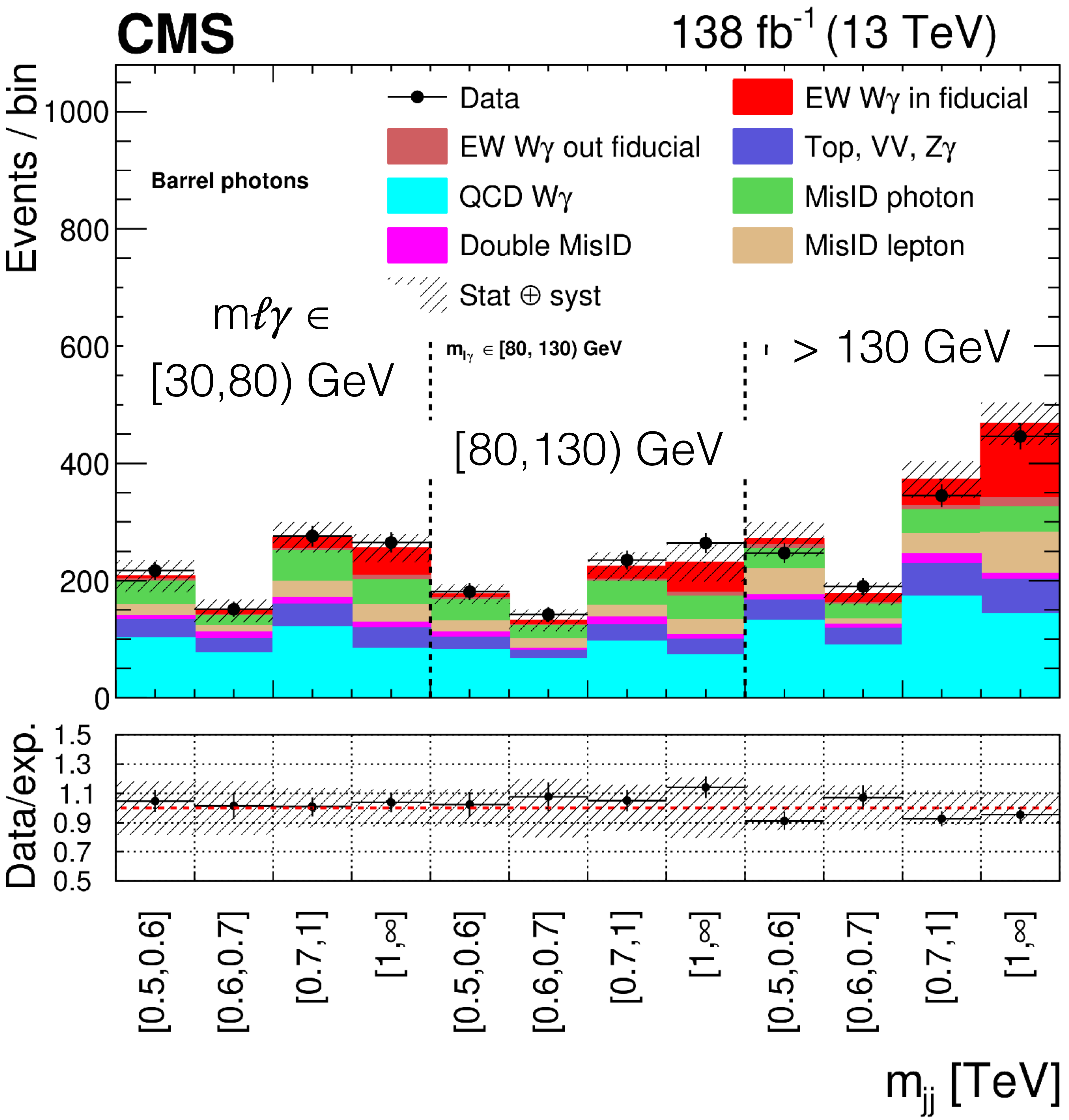




CMS Wγ

EW production of Wγ with two jets

- analysis based on a **2D fit** to maximise its sensitivity
- control region to constrain the QCD Wγjj production
- background due to **jets misidentified as photons or electrons** estimated from data with loose-to-tight ratios
- **irreducible backgrounds** estimated with the simulation



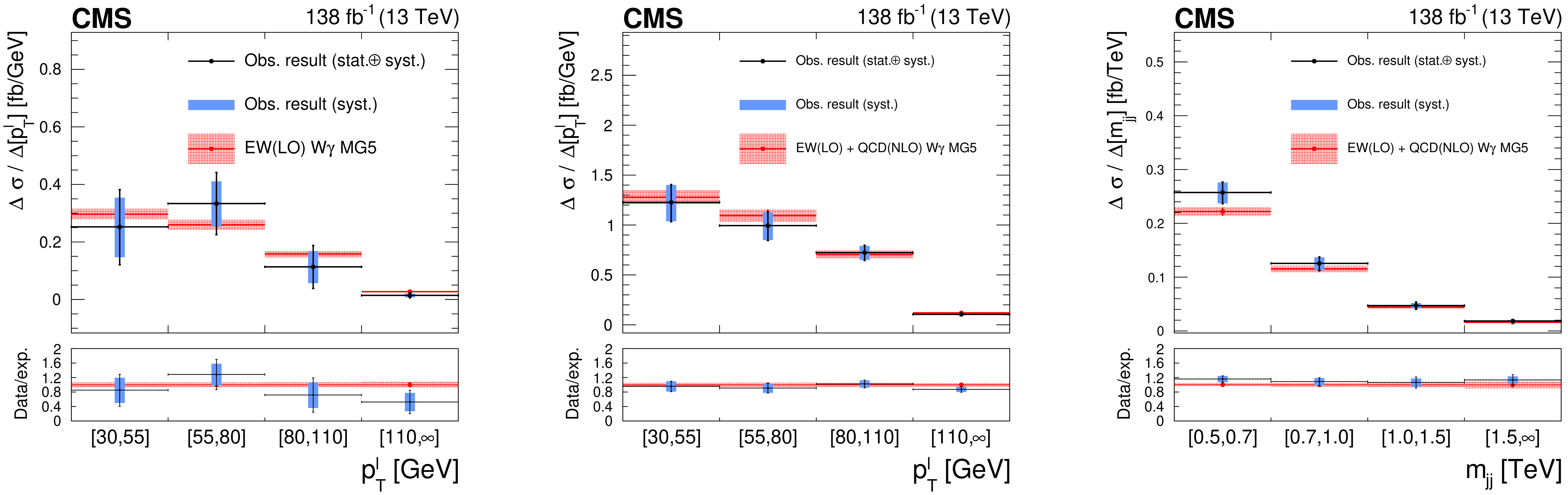
arxiv:2212.12592

measured unfolded cross-sections

observed significance of 6.0 s.d.

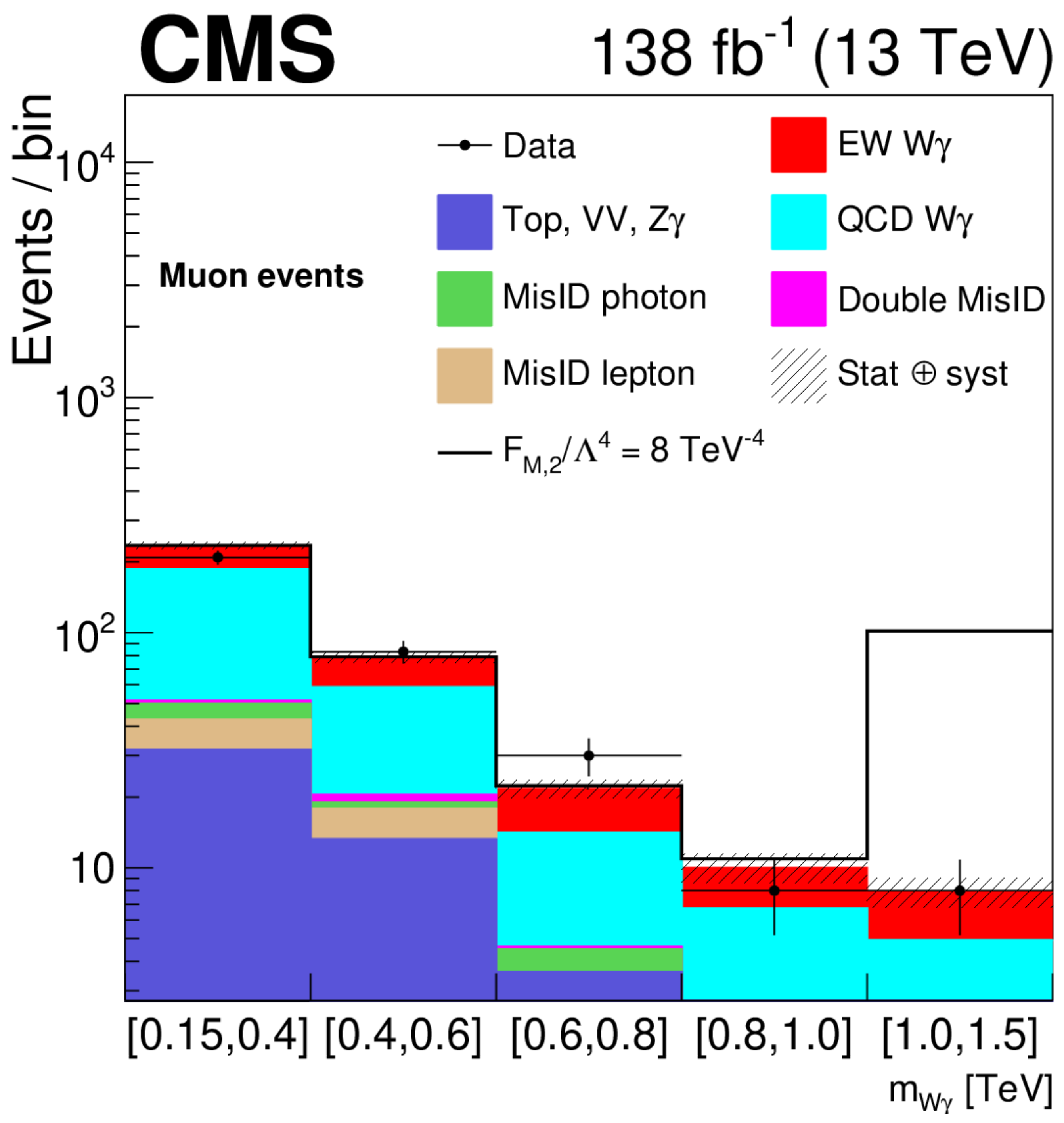
$$\sigma^{\text{fid}}_{\text{EW}} = 23.5 \pm 2.8\,(\text{stat})^{+1.9}_{-1.7}\,(\text{theo})^{+3.5}_{-3.4}\,(\text{syst})\,\text{fb} = 23.5^{+4.9}_{-4.7}\,\text{fb}$$

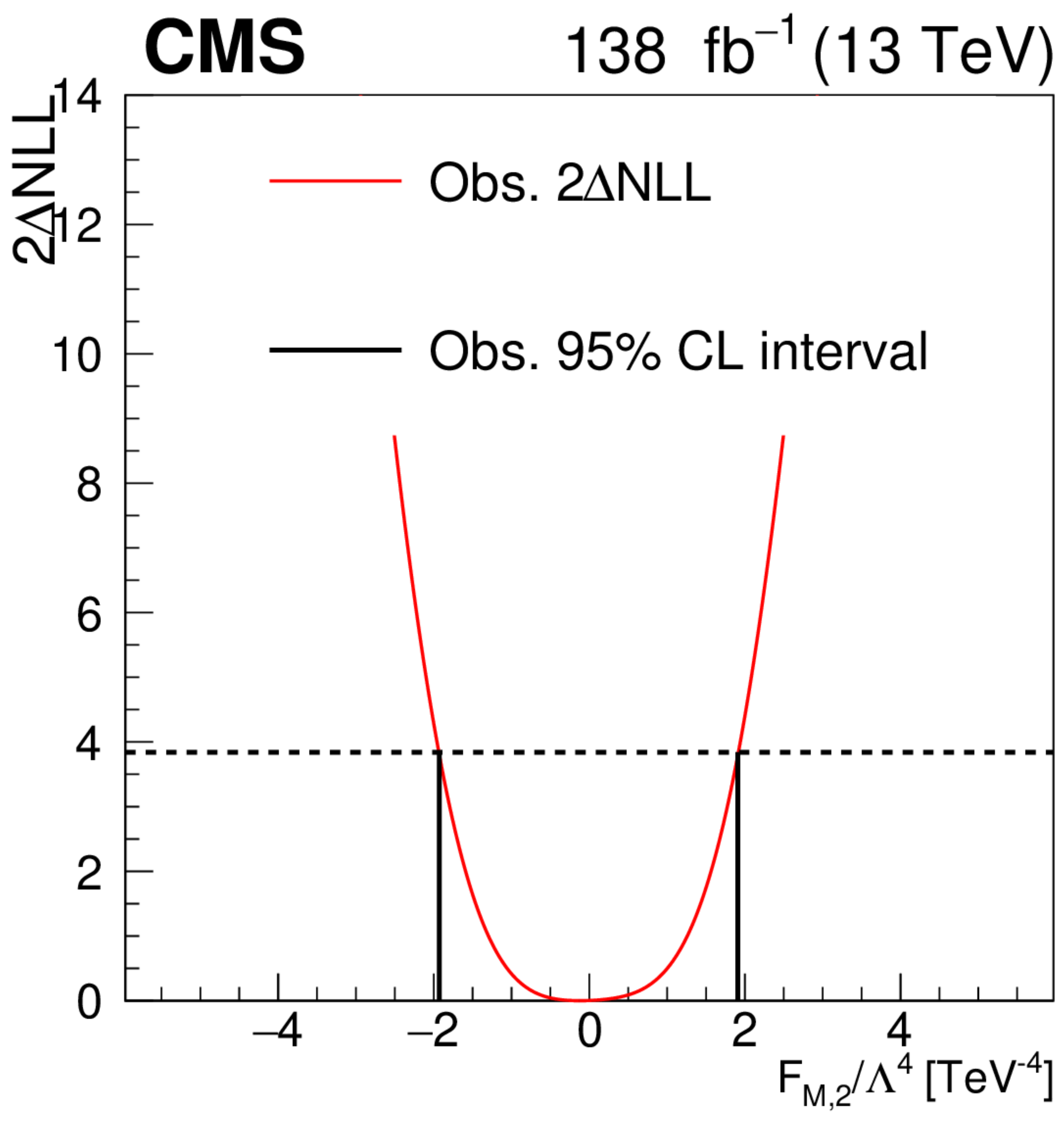
$$\sigma^{\text{fid}}_{\text{EW+QCD}} = 113 \pm 2.0\,(\text{stat})^{+2.5}_{-2.3}\,(\text{theo})^{+13}_{-13}\,(\text{syst})\,\text{fb} = 113 \pm 13\,\text{fb}$$



limits on new physics

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \cancel{\sum_i \frac{f_i^{(6)}}{\Lambda^2}O_i} + \sum_j \frac{f_j^{(8)}}{\Lambda^4}O_j + \ldots$$





Expected limit	Observed limit	$U_{\rm bound}$
$-5.1 < f_{M,0}/\Lambda^4 < 5.1$	$-5.6 < f_{M,0}/\Lambda^4 < 5.5$	1.7
$-7.1 < f_{M,1}/\Lambda^4 < 7.4$	$-7.8 < f_{M,1}/\Lambda^4 < 8.1$	2.1
$-1.8 < f_{M,2}/\Lambda^4 < 1.8$	$-1.9 < f_{M,2}/\Lambda^4 < 1.9$	2.0
$-2.5 < f_{M,3}/\Lambda^4 < 2.5$	$-2.7 < f_{M,3}/\Lambda^4 < 2.7$	2.7
$-3.3 < f_{M,4}/\Lambda^4 < 3.3$	$-3.7 < f_{M,4}/\Lambda^4 < 3.6$	2.3
$-3.4 < f_{M,5}/\Lambda^4 < 3.6$	$-3.9 < f_{M,5}/\Lambda^4 < 3.9$	2.7
$-13 < f_{M,7}/\Lambda^4 < 13$	$-14 < f_{M7}/\Lambda^4 < 14$	2.2
$-0.43 < f_{T,0}/\Lambda^4 < 0.51$	$-0.47 < f_{T,0}/\Lambda^4 < 0.51$	1.9
$-0.27 < f_{T,1}/\Lambda^4 < 0.31$	$-0.31 < f_{T,1}/\Lambda^4 < 0.34$	2.5
$-0.72 < f_{T,2}/\Lambda^4 < 0.92$	$-0.85 < f_{T,2}/\Lambda^4 < 1.0$	2.3
$-0.29 < f_{T,5}/\Lambda^4 < 0.31$	$-0.31 < f_{T,5}/\Lambda^4 < 0.33$	2.6
$-0.23 < f_{T,6}/\Lambda^4 < 0.25$	$-0.25 < f_{T,6}/\Lambda^4 < 0.27$	2.9
$-0.60 < f_{T,7}/\Lambda^4 < 0.68$	$-0.67 < f_{T,7}/\Lambda^4 < 0.73$	3.1

most stringent to date

ATLAS $Z\gamma$

event yields and systematics

ATLAS EXPERIMENT

Sample	SR, $m_{jj} > 150$ GeV	SR, $m_{jj} > 500$ GeV	CR, $m_{jj} > 500$ GeV
$N_{\mathrm{EW-Z\gamma jj}}$		269 ± 27	25 ± 6
$N_{\mathrm{QCD-Z\gamma jj}}$		245 ± 21	224 ± 18
$N_{\mathrm{Z\gamma jj}}$	1292 ± 50		
$N_{Z+\mathrm{jets}}$	78 ± 30	21 ± 8	16 ± 5
$N_{t\bar{t}\gamma}$	73 ± 11	16 ± 2	8 ± 1
N_{WZ}	17 ± 3	9 ± 2	4 ± 1
Total	1461 ± 38	560 ± 23	277 ± 17
N_{obs}	1461	562	274

	Data stat.	MC stat.	Background	Reco	EW mod.	QCD mod.	Total
$\Delta\sigma_{EW}/\sigma_{EW}$ [%]	± 9	± 1	± 1	± 4	$^{+8}_{-6}$	± 2	± 13
$\Delta\sigma_{Z\gamma}/\sigma_{Z\gamma}$ [%]	± 3	± 1	± 2	$^{+4}_{-3}$	$^{+7}_{-6}$	± 9	$^{+12}_{-11}$

CMS $Z\gamma$

systematic uncertainties

Systematic uncertainty	Impact [%]	
Jet energy correction	+7.9	−6.7
Theoretical uncertainties	+5.5	−4.7
MC statistical uncertainties	+4.7	−4.5
PU	+4.7	−4.1
Related to e, γ	+4.5	−3.6
PU jet ID	+3.7	−3.4
ECAL timing shift at L1	+3.5	−2.8
Nonprompt-γ bkg. estimate	+2.0	−1.6
Related to μ	+1.7	−1.4
Integrated luminosity	+0.8	−0.6
Total systematic uncertainty	+14	−12

event yields

Process	$\mu\mu\gamma_{\text{barrel}}$	$\mu\mu\gamma_{\text{endcap}}$	$ee\gamma_{\text{barrel}}$	$ee\gamma_{\text{endcap}}$
ST	0.7 ± 0.4	0.2 ± 0.2	0.6 ± 0.3	0.2 ± 0.2
TTγ	8.8 ± 1.3	2.1 ± 0.5	3.4 ± 0.6	0.2 ± 0.2
VV	6.0 ± 1.9	3.2 ± 1.2	4.1 ± 1.3	0.8 ± 0.3
Nonprompt photon	189 ± 9.2	143 ± 6.9	93.6 ± 6.5	74.3 ± 5.0
QCD Zγ	274 ± 10	108 ± 5.6	162 ± 7.4	62.4 ± 3.9
EW Zγ	133 ± 4.7	46.5 ± 1.7	84.5 ± 3.1	28.2 ± 1.1
Predicted yields	612 ± 13	303 ± 8	349 ± 9	166 ± 6
Data	584	320	375	174

CMS same-sign WW with a tau lepton

EFT limits

obtained with a fit on a DNN trained fo the dim-6 case

obtained with a fit on a DNN trained fo the dim-8 case

	Wilson coefficient	68% CL interval(s) Expected	68% CL interval(s) Observed	95% CL interval Expected	95% CL interval Observed
dim-6	$c_{ll}^{(1)}$	$[-12.9, -8.03] \cup [-2.95, 1.91]$	$[-11.6, 0.045]$	$[-14.6, 3.53]$	$[-13.5, 2.11]$
	$c_{qq}^{(1)}$	$[-0.501, 0.576]$	$[-0.341, 0.416]$	$[-0.742, 0.818]$	$[-0.605, 0.681]$
	c_W	$[-0.681, 0.669]$	$[-0.513, 0.481]$	$[-0.987, 0.974]$	$[-0.842, 0.818]$
	c_{HW}	$[-7.00, 6.09]$	$[-5.48, 4.31]$	$[-9.99, 9.05]$	$[-8.68, 7.60]$
	c_{HWB}	$[-41.7, 69.6]$	$[30.7, 89.2]$	$[-66.6, 96.4]$	$[-49.7, 110]$
	$c_{H\Box}$	$[-16.6, 18.1]$	$[-12.0, 14.0]$	$[-24.7, 26.3]$	$[-20.9, 22.7]$
	c_{HD}	$[-24.6, 34.7]$	$[-15.3, 31.5]$	$[-38.2, 48.8]$	$[-31.4, 45.5]$
	$c_{Hl}^{(1)}$	$[-28.8, 29.9]$	$[-38.2, 39.5]$	$[-49.4, 49.7]$	$[-69.3, 68.3]$
	$c_{Hl}^{(3)}$	$[-1.43, 2.23] \cup [5.88, 9.54]$	$[-0.045, 8.58]$	$[-2.64, 10.8]$	$[-1.59, 9.94]$
	$c_{Hq}^{(1)}$	$[-4.53, 4.42]$	$[-3.27, 3.44]$	$[-6.56, 6.44]$	$[-5.55, 5.60]$
	$c_{Hq}^{(3)}$	$[-2.39, 1.37]$	$[-1.88, 0.705]$	$[-3.24, 2.16]$	$[-2.82, 1.61]$
dim-8	f_{T0}	$[-1.02, 1.08]$	$[-0.774, 0.842]$	$[-1.52, 1.58]$	$[-1.32, 1.38]$
	f_{T1}	$[-0.426, 0.480]$	$[-0.319, 0.381]$	$[-0.640, 0.695]$	$[-0.552, 0.613]$
	f_{T2}	$[-1.15, 1.37]$	$[-0.851, 1.12]$	$[-1.75, 1.98]$	$[-1.51, 1.76]$
	f_{M0}	$[-9.89, 9.74]$	$[-8.07, 7.70]$	$[-14.6, 14.5]$	$[-13.1, 12.8]$
	f_{M1}	$[-12.5, 13.3]$	$[-9.54, 11.15]$	$[-18.7, 19.6]$	$[-16.4, 17.7]$
	f_{M7}	$[-20.3, 19.2]$	$[-17.6, 15.3]$	$[-29.9, 28.8]$	$[-27.6, 25.8]$
	f_{S0}	$[-11.6, 12.0]$	$[-9.60, 9.82]$	$[-17.4, 17.9]$	$[-15.9, 16.1]$
	f_{S1}	$[-37.4, 38.8]$	$[-40.9, 41.3]$	$[-57.2, 58.6]$	$[-60.9, 61.8]$
	f_{S2}	$[-37.4, 38.8]$	$[-40.9, 41.3]$	$[-57.2, 58.6]$	$[-60.9, 61.8]$

CMS same-sign WW and WZ

uncertainties

Source of uncertainty	$W^{\pm}W^{\pm}$ (%)	WZ (%)
Integrated luminosity	1.5	1.6
Lepton measurement	1.8	2.9
Jet energy scale and resolution	1.5	4.3
Pileup	0.1	0.4
btagging	1.0	1.0
Nonprompt rate	3.5	1.4
Trigger	1.1	1.1
Limited sample size	2.6	3.7
Theory	1.9	3.8
Total systematic uncertainty	5.7	7.9
Statistical uncertainty	8.9	22
Total uncertainty	11	23

event yields

Process	$W^\pm W^\pm$ SR		WZ SR	
	Asimov data set	Data	Asimov data set	Data
EW $W^\pm W^\pm$	209 ± 26	210 ± 26	—	—
QCD $W^\pm W^\pm$	13.8 ± 1.6	13.7 ± 2.2	—	—
Interference $W^\pm W^\pm$	8.4 ± 2.3	8.7 ± 2.3	—	—
EW WZ	14.1 ± 4.0	17.8 ± 3.9	54 ± 15	69 ± 15
QCD WZ	43 ± 6.7	42.7 ± 7.4	118 ± 17	117 ± 17
Interference WZ	0.3 ± 0.1	0.3 ± 0.2	2.2 ± 0.9	2.7 ± 1.0
ZZ	0.7 ± 0.2	0.7 ± 0.2	6.1 ± 1.7	6.0 ± 1.8
Nonprompt	211 ± 43	193 ± 40	14.6 ± 7.4	14.4 ± 6.7
tVx	7.8 ± 1.9	7.4 ± 2.2	15.1 ± 2.7	14.3 ± 2.8
$W\gamma$	9.0 ± 1.8	9.1 ± 2.9	1.1 ± 0.3	1.1 ± 0.4
Wrong-sign	13.5 ± 6.5	13.9 ± 6.5	1.6 ± 0.5	1.7 ± 0.7
Other background	5.0 ± 1.3	5.2 ± 2.1	3.3 ± 0.6	3.3 ± 0.7
Total SM	535 ± 52	522 ± 49	216 ± 21	229 ± 23
Data	524		229	

EFT interpretation

no unitarisation

	Observed ($W^{\pm}W^{\pm}$) (TeV^{-4})	Expected ($W^{\pm}W^{\pm}$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-0.28, 0.31]	[-0.36, 0.39]	[-0.62, 0.65]	[-0.82, 0.85]	[-0.25, 0.28]	[-0.35, 0.37]
f_{T1}/Λ^4	[-0.12, 0.15]	[-0.16, 0.19]	[-0.37, 0.41]	[-0.49, 0.55]	[-0.12, 0.14]	[-0.16, 0.19]
f_{T2}/Λ^4	[-0.38, 0.50]	[-0.50, 0.63]	[-1.0 , 1.3]	[-1.4, 1.7]	[-0.35, 0.48]	[-0.49, 0.63]
f_{M0}/Λ^4	[-3.0, 3.2]	[-3.7, 3.8]	[-5.8, 5.8]	[-7.6, 7.6]	[-2.7, 2.9]	[-3.6, 3.7]
f_{M1}/Λ^4	[-4.7, 4.7]	[-5.4, 5.8]	[-8.2, 8.3]	[-11, 11]	[-4.1, 4.2]	[-5.2, 5.5]
f_{M6}/Λ^4	[-6.0, 6.5]	[-7.5, 7.6]	[-12, 12]	[-15, 15]	[-5.4, 5.8]	[-7.2, 7.3]
f_{M7}/Λ^4	[-6.7, 7.0]	[-8.3, 8.1]	[-10, 10]	[-14, 14]	[-5.7, 6.0]	[-7.8, 7.6]
f_{S0}/Λ^4	[-6.0, 6.4]	[-6.0, 6.2]	[-19, 19]	[-24, 24]	[-5.7, 6.1]	[-5.9, 6.2]
f_{S1}/Λ^4	[-18, 19]	[-18, 19]	[-30, 30]	[-38, 39]	[-16, 17]	[-18, 18]

with unitarisation

	Observed ($W^{\pm}W^{\pm}$) (TeV^{-4})	Expected ($W^{\pm}W^{\pm}$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-1.5, 2.3]	[-2.1, 2.7]	[-1.6, 1.9]	[-2.0, 2.2]	[-1.1, 1.6]	[-1.6, 2.0]
f_{T1}/Λ^4	[-0.81, 1.2]	[-0.98, 1.4]	[-1.3, 1.5]	[-1.6, 1.8]	[-0.69, 0.97]	[-0.94, 1.3]
f_{T2}/Λ^4	[-2.1, 4.4]	[-2.7, 5.3]	[-2.7, 3.4]	[-4.4, 5.5]	[-1.6, 3.1]	[-2.3, 3.8]
f_{M0}/Λ^4	[-13, 16]	[-19, 18]	[-16, 16]	[-19, 19]	[-11, 12]	[-15, 15]
f_{M1}/Λ^4	[-20, 19]	[-22, 25]	[-19, 20]	[-23, 24]	[-15, 14]	[-18, 20]
f_{M6}/Λ^4	[-27, 32]	[-37, 37]	[-34, 33]	[-39, 39]	[-22, 25]	[-31, 30]
f_{M7}/Λ^4	[-22, 24]	[-27, 25]	[-22, 22]	[-28, 28]	[-16, 18]	[-22, 21]
f_{S0}/Λ^4	[-35, 36]	[-31, 31]	[-83, 85]	[-88, 91]	[-34, 35]	[-31, 31]
f_{S1}/Λ^4	[-100, 120]	[-100, 110]	[-110, 110]	[-120, 130]	[-86, 99]	[-91, 97]

ATLAS same-sign WW

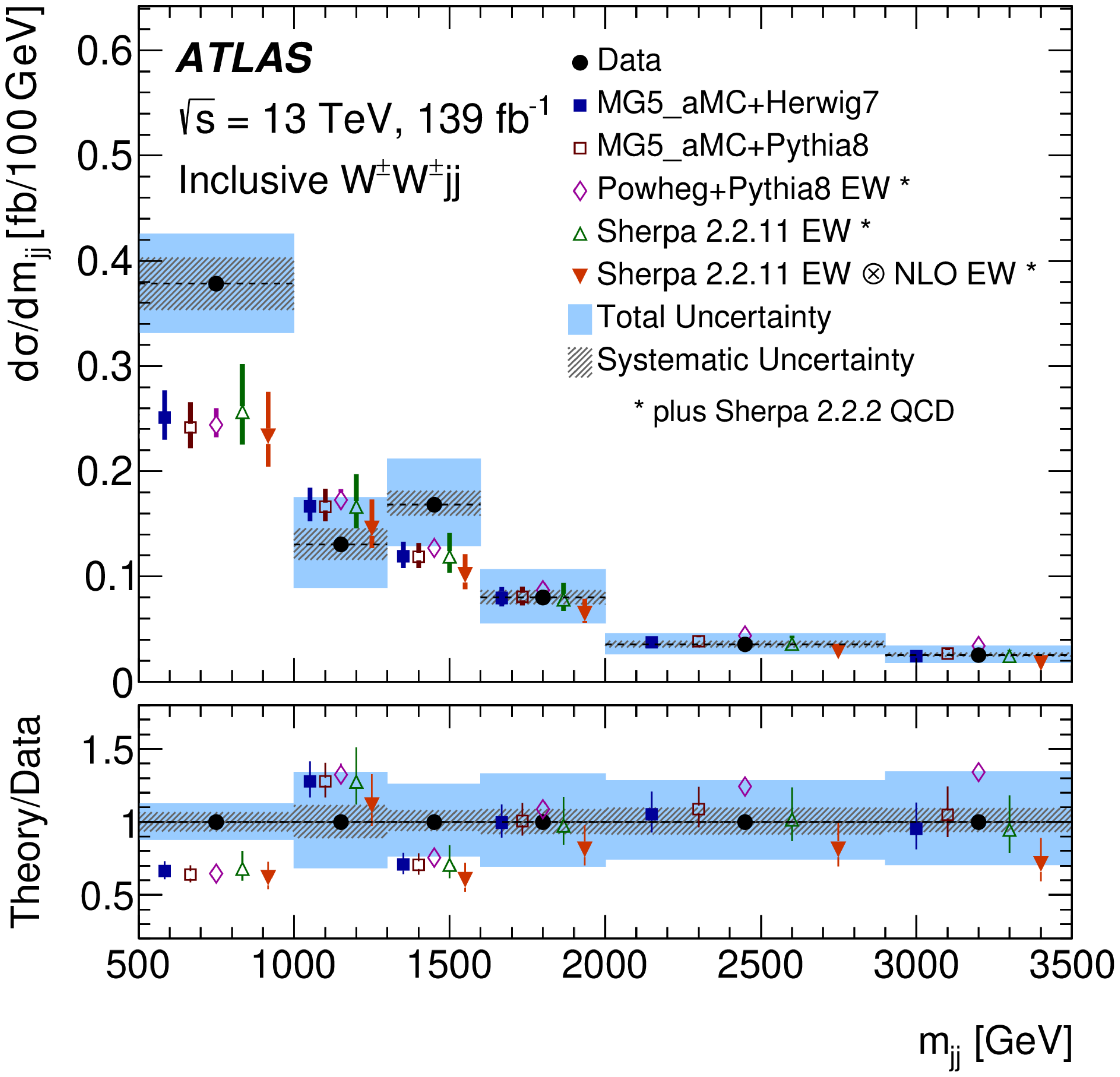
cross-section results

$$\sigma_{\text{fid}}^{\text{EW}} = 2.92 \pm 0.22\,(\text{stat}) \pm 0.13\,(\text{mod sys}) \pm 0.12\,(\text{exp sys}) \pm 0.06\,(\text{lum})\ \text{fb}$$

$$\sigma_{\text{fid}}^{\text{EW+QCD}} = 3.38 \pm 0.22\,(\text{stat}) \pm 0.11\,(\text{mod sys}) \pm 0.14\,(\text{exp sys}) \pm 0.06\,(\text{lum})\ \text{fb}$$

Description	$\sigma_{\text{fid}}^{\text{EW}}$ [fb]	$\sigma_{\text{fid}}^{\text{EW+Int+QCD}}$ [fb]	QCD	EW
Measured cross section	$2.92 \pm 0.22\,(\text{stat.}) \pm 0.19\,(\text{syst.})$	$3.38 \pm 0.22\,(\text{stat.}) \pm 0.19\,(\text{syst.})$	-	-
MG5_AMC+HERWIG7	$2.53 \pm 0.04\,(\text{PDF})\ ^{+0.22}_{-0.19}\,(\text{scale})$	$2.92 \pm 0.05\,(\text{PDF})\ ^{+0.34}_{-0.27}\,(\text{scale})$	LO	LO
MG5_AMC+PYTHIA8	$2.53 \pm 0.04\,(\text{PDF})\ ^{+0.22}_{-0.19}\,(\text{scale})$	$2.90 \pm 0.05\,(\text{PDF})\ ^{+0.33}_{-0.26}\,(\text{scale})$	LO	LO
SHERPA	$2.48 \pm 0.04\,(\text{PDF})\ ^{+0.40}_{-0.27}\,(\text{scale})$	$2.92 \pm 0.03\,(\text{PDF})\ ^{+0.60}_{-0.40}\,(\text{scale})$	LO	LO
SHERPA ⊗ NLO EW	$2.10 \pm 0.03\,(\text{PDF})\ ^{+0.34}_{-0.23}\,(\text{scale})$	$2.54 \pm 0.03\,(\text{PDF})\ ^{+0.50}_{-0.33}\,(\text{scale})$	NLO	LO
POWHEG BOX+PYTHIA	2.64	–	NLO	LO

tag jet pair invariant mass



EFT constraints

ATLAS EXPERIMENT

Coefficient	Type	No unitarisation cut-off [TeV^{-4}]	Lower, upper limit at the respective unitarity bound [TeV^{-4}]
f_{M0}/Λ^4	Exp.	[-3.9, 3.8]	-64 at 0.9 TeV, 40 at 1.0 TeV
	Obs.	[-4.1, 4.1]	-140 at 0.7 TeV, 117 at 0.8 TeV
f_{M1}/Λ^4	Exp.	[-6.3, 6.6]	-25.5 at 1.6 TeV, 31 at 1.5 TeV
	Obs.	[-6.8, 7.0]	-45 at 1.4 TeV, 54 at 1.3 TeV
f_{M7}/Λ^4	Exp.	[-9.3, 8.8]	-33 at 1.8 TeV, 29.1 at 1.8 TeV
	Obs.	[-9.8, 9.5]	-39 at 1.7 TeV, 42 at 1.7 TeV
f_{S02}/Λ^4	Exp.	[-5.5, 5.7]	-94 at 0.8 TeV, 122 at 0.7 TeV
	Obs.	[-5.9, 5.9]	–
f_{S1}/Λ^4	Exp.	[-22.0, 22.5]	–
	Obs.	[-23.5, 23.6]	–
f_{T0}/Λ^4	Exp.	[-0.34, 0.34]	-3.2 at 1.2 TeV, 4.9 at 1.1 TeV
	Obs.	[-0.36, 0.36]	-7.4 at 1.0 TeV, 12.4 at 0.9 TeV
f_{T1}/Λ^4	Exp.	[-0.158, 0.174]	-0.32 at 2.6 TeV, 0.44 at 2.4 TeV
	Obs.	[-0.174, 0.186]	-0.38 at 2.5 TeV, 0.49 at 2.4 TeV
f_{T2}/Λ^4	Exp.	[-0.56, 0.70]	-2.60 at 1.7 TeV, 10.3 at 1.2 TeV
	Obs.	[-0.63, 0.74]	–

phase space region definitions

Requirement	SR	Low-m_{jj} CR	WZ CR
Leading and subleading lepton p_T		> 27 GeV	
Electron $\|\eta\|$		< 2.47 (1.37 in ee), excluding $1.37 \leq \|\eta\| \leq 1.52$	
Muon $\|\eta\|$		< 2.5	
Leading (subleading) jet p_T		> 65 (35) GeV	
Additional jet p_T		> 25 GeV	
Jet $\|\eta\|$		< 4.5	
$m_{\ell\ell}$		> 20 GeV	
E_T^{miss}		> 30 GeV	
Charge misid. $Z \to ee$ veto	$\|m_{ee} - m_Z\| > 15$ GeV		–
b-jet veto		$N_{b\text{-jet}} = 0$, $p_T^{b\text{-jet}} > 20$ GeV, $\|\eta^{b\text{-jet}}\| < 2.5$	
$N_{\text{veto leptons}}$	$= 0$	$= 0$	$= 1$, $p_T > 15$ GeV
$m_{\ell\ell\ell}$	–	–	> 106 GeV
m_{jj}	> 500 GeV	$200 < m_{jj} < 500$ GeV	> 200 GeV
$\|\Delta y_{jj}\|$		> 2	

control background uncertainties

correct m_{jj} shape

$$\xi_{WZ} > 0.4$$

$$\xi_{WZ} = \left| \frac{y_{WZ} - (y_{j1} + y_{j2})/2}{y_{j1} - y_{j2}} \right|$$

event rates

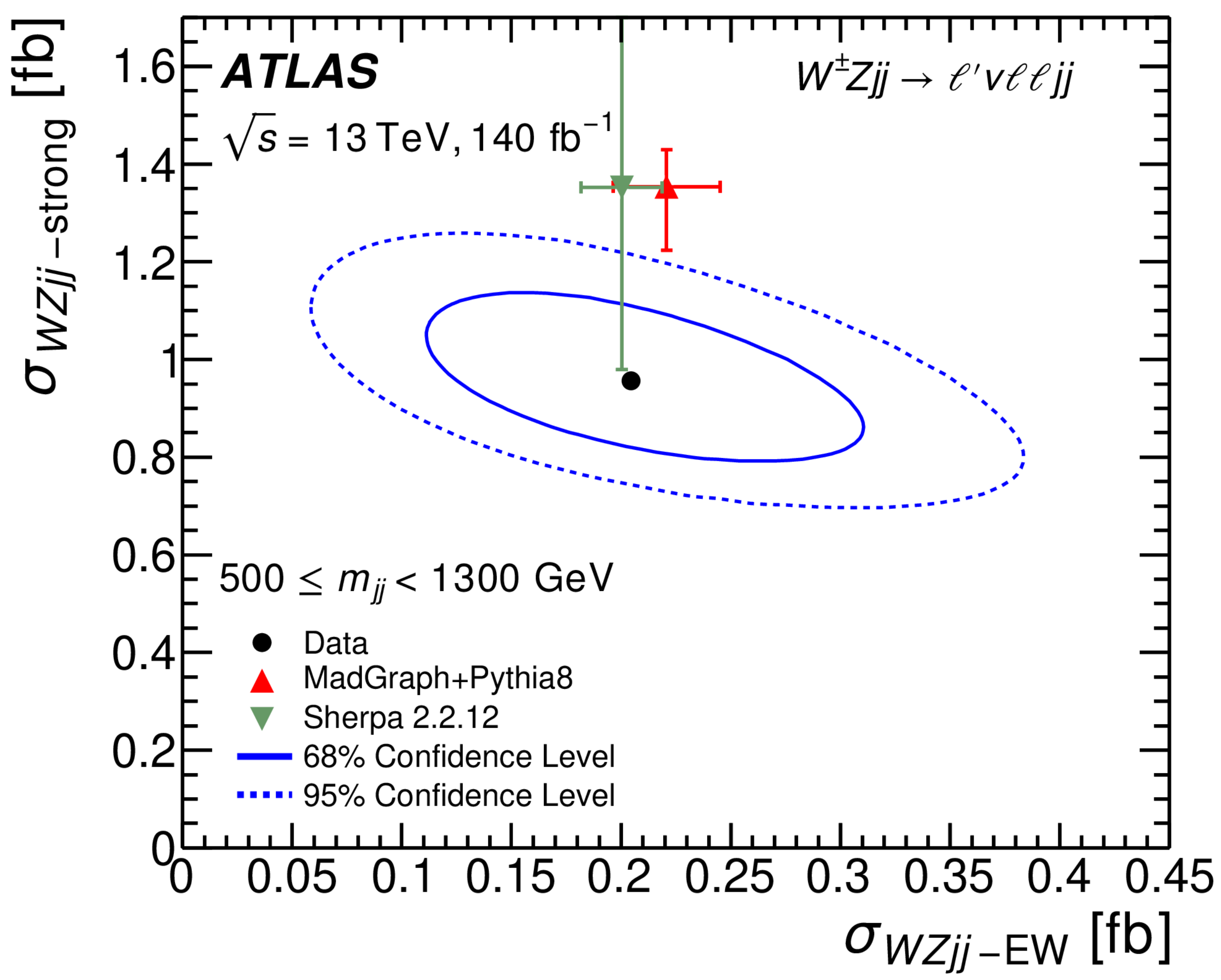
Process	ee	$e\mu$	μe	$\mu\mu$	Combined
$W^{\pm}W^{\pm}jj$ EW	27.6 ± 0.9	68.2 ± 1.6	61.3 ± 1.5	77.8 ± 1.7	235 ± 5
$W^{\pm}W^{\pm}jj$ QCD	1.6 ± 0.5	7.3 ± 2.2	6.4 ± 1.9	8.8 ± 2.5	24 ± 7
$W^{\pm}W^{\pm}jj$ Int	0.93 ± 0.20	2.2 ± 0.5	2.0 ± 0.4	2.5 ± 0.5	7.6 ± 1.6
$W^{\pm}Zjj$ QCD	8.4 ± 1.0	26.8 ± 3.0	26.7 ± 3.0	20.9 ± 2.2	83 ± 9
$W^{\pm}Zjj$ EW	1.71 ± 0.14	4.9 ± 0.4	4.1 ± 0.4	4.2 ± 0.4	14.9 ± 1.2
Non-prompt	8.9 ± 2.6	15 ± 4	10.2 ± 3.2	21 ± 7	56 ± 12
$V\gamma$	1.3 ± 0.8	5.1 ± 2.2	4.6 ± 2.6	—	11 ± 5
Charge misid.	3.8 ± 2.0	5.0 ± 1.3	1.2 ± 0.4	—	10 ± 4
Other prompt	1.02 ± 0.29	2.5 ± 0.6	1.8 ± 0.5	1.7 ± 2.2	7.1 ± 2.8
Total expected	55 ± 4	137 ± 7	118 ± 6	137 ± 8	448 ± 20
Data	52	149	127	147	475

systematic uncertainties

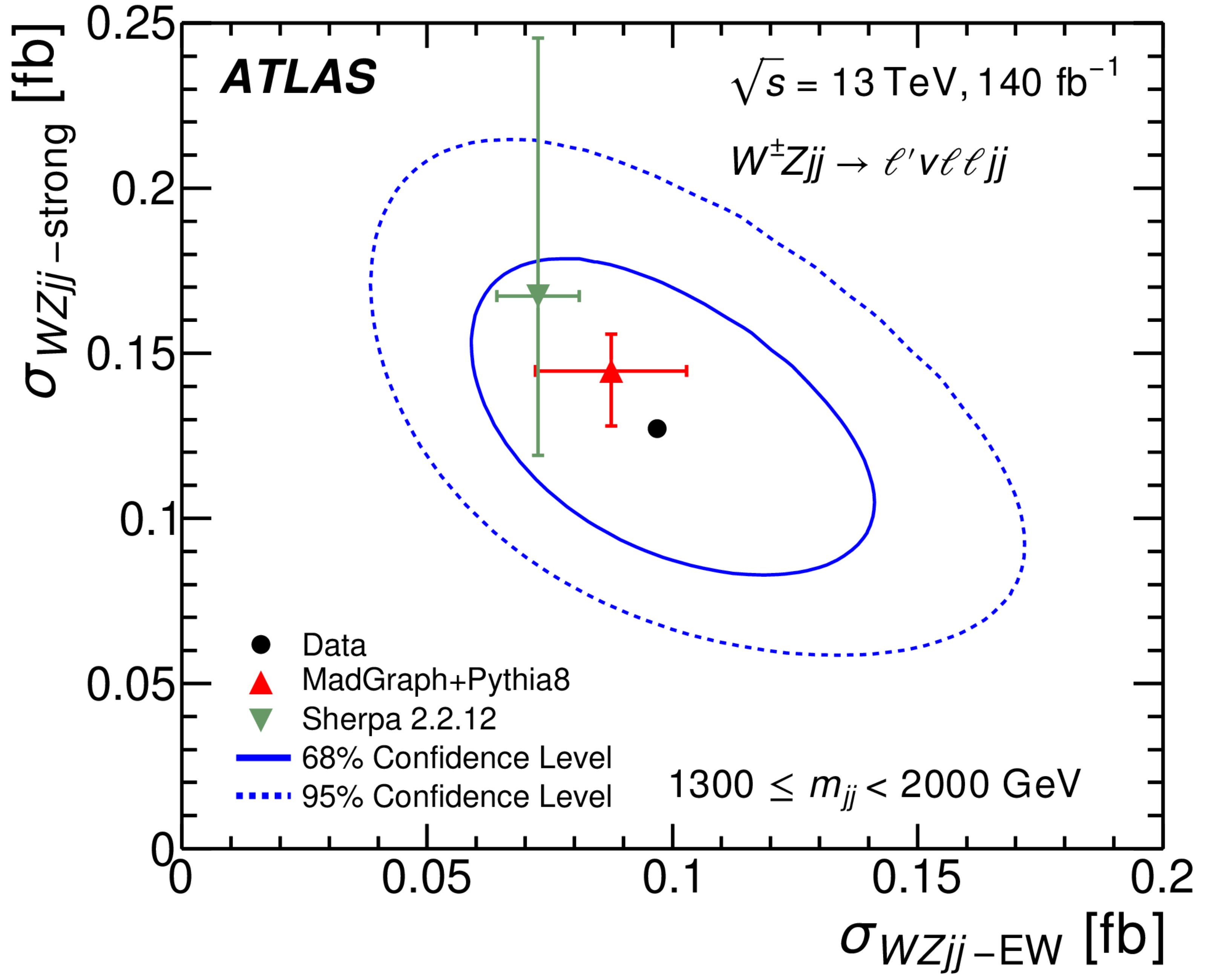
Source	Impact [%]
Experimental	4.6
Electron calibration	0.4
Muon calibration	0.5
Jet energy scale and resolution	1.9
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale and resolution	0.2
b-tagging inefficiency	0.7
Background, misid. leptons	3.4
Background, charge misrec.	1.0
Pile-up modelling	0.1
Luminosity	1.9
Modelling	4.5
EW $W^{\pm}W^{\pm}jj$, shower, scale, PDF & α_s	0.7
EW $W^{\pm}W^{\pm}jj$, QCD corrections	1.9
EW $W^{\pm}W^{\pm}jj$, EW corrections	0.9
Int $W^{\pm}W^{\pm}jj$, shower, scale, PDF & α_s	0.6
QCD $W^{\pm}W^{\pm}jj$, shower, scale, PDF & α_s	2.6
QCD $W^{\pm}W^{\pm}jj$, QCD corrections	0.8
Background, WZ scale, PDF & α_s	0.3
Background, WZ reweighting	1.5
Background, other	1.3
Model statistical	1.8
Experimental and modelling	6.4
Data statistical	7.4
Total	9.8

ATLAS WZ

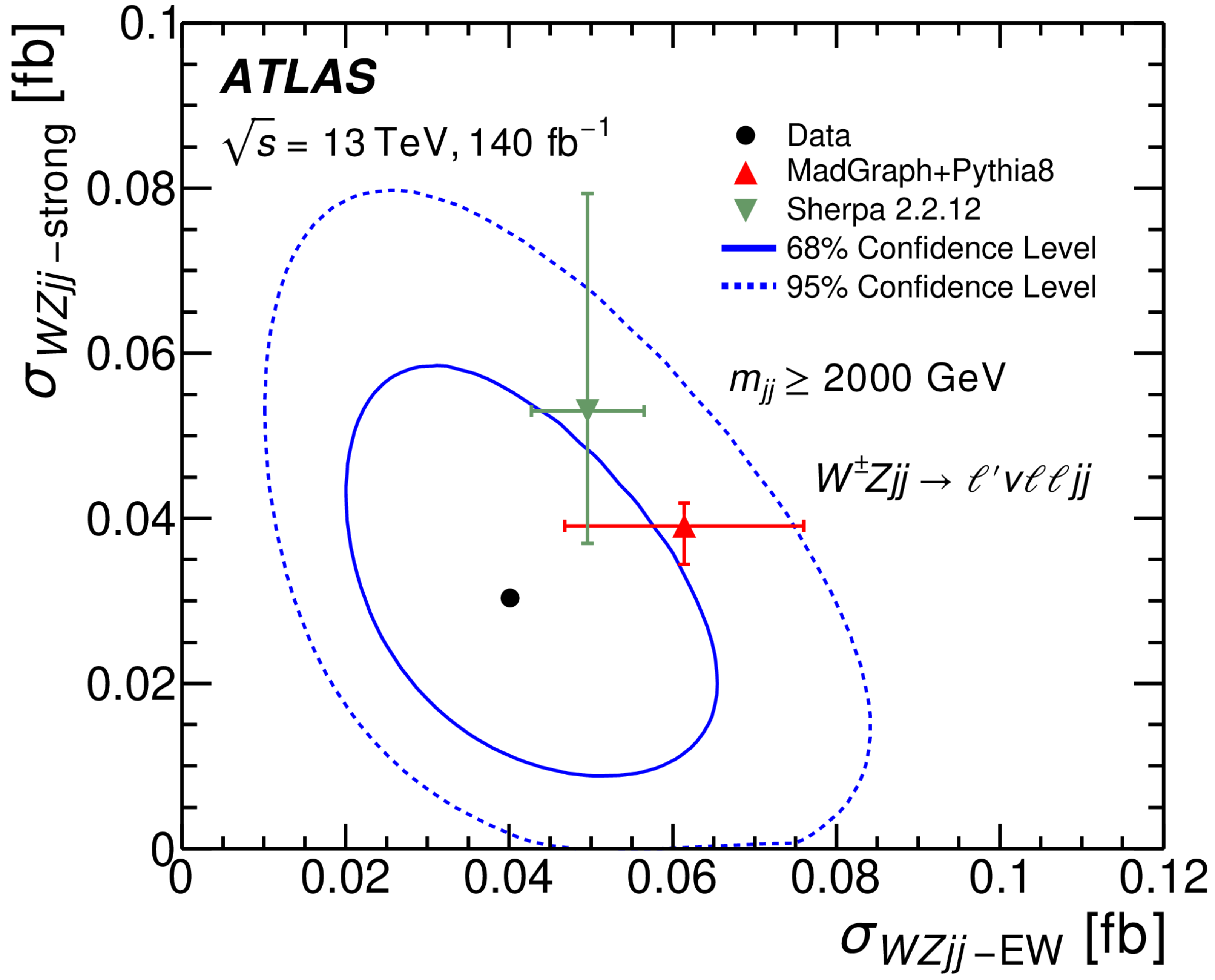
cross-sections in mjj bins



mjj ∈
500 - 1300 GeV



mjj ∈
1300 - 2000 GeV



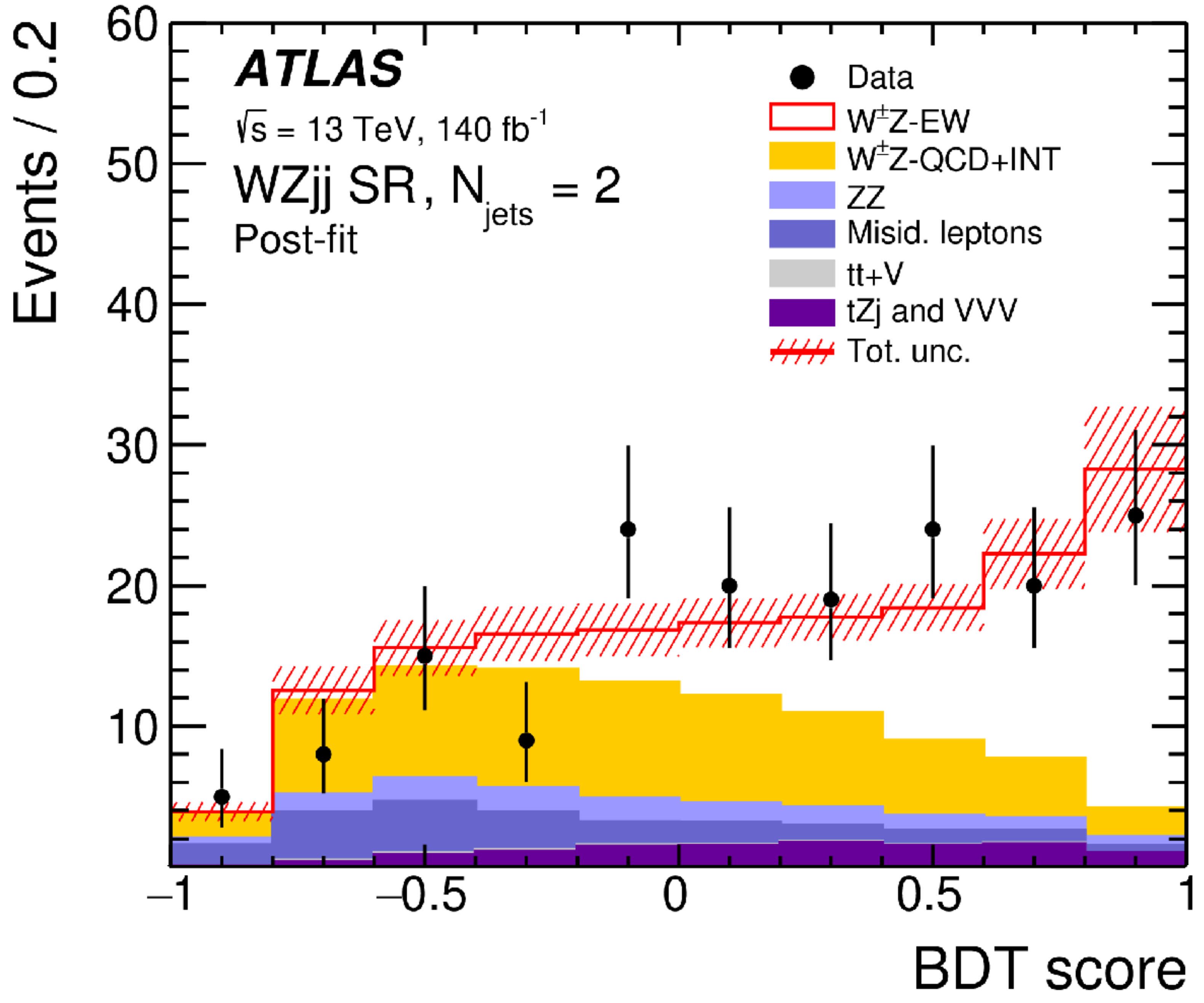
mjj ∈
2000 - ∞ GeV

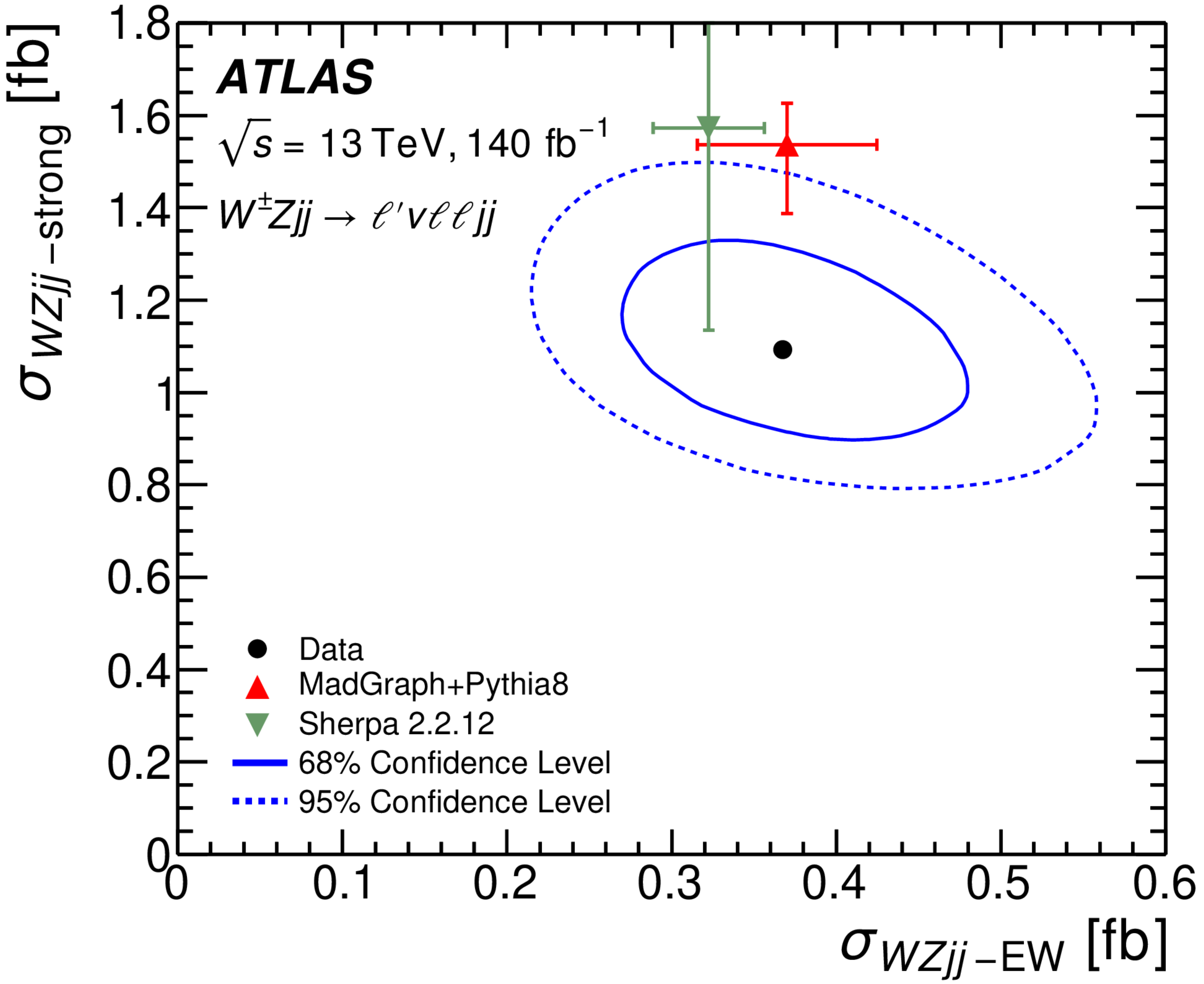
EW WZ → $3\ell\nu$ production

arxiv:2403.15296

- **MVA techniques** used in SR and CR's with non trivial uncertainty treatment
- **main uncertainties** from theory modelling and jet reconstruction

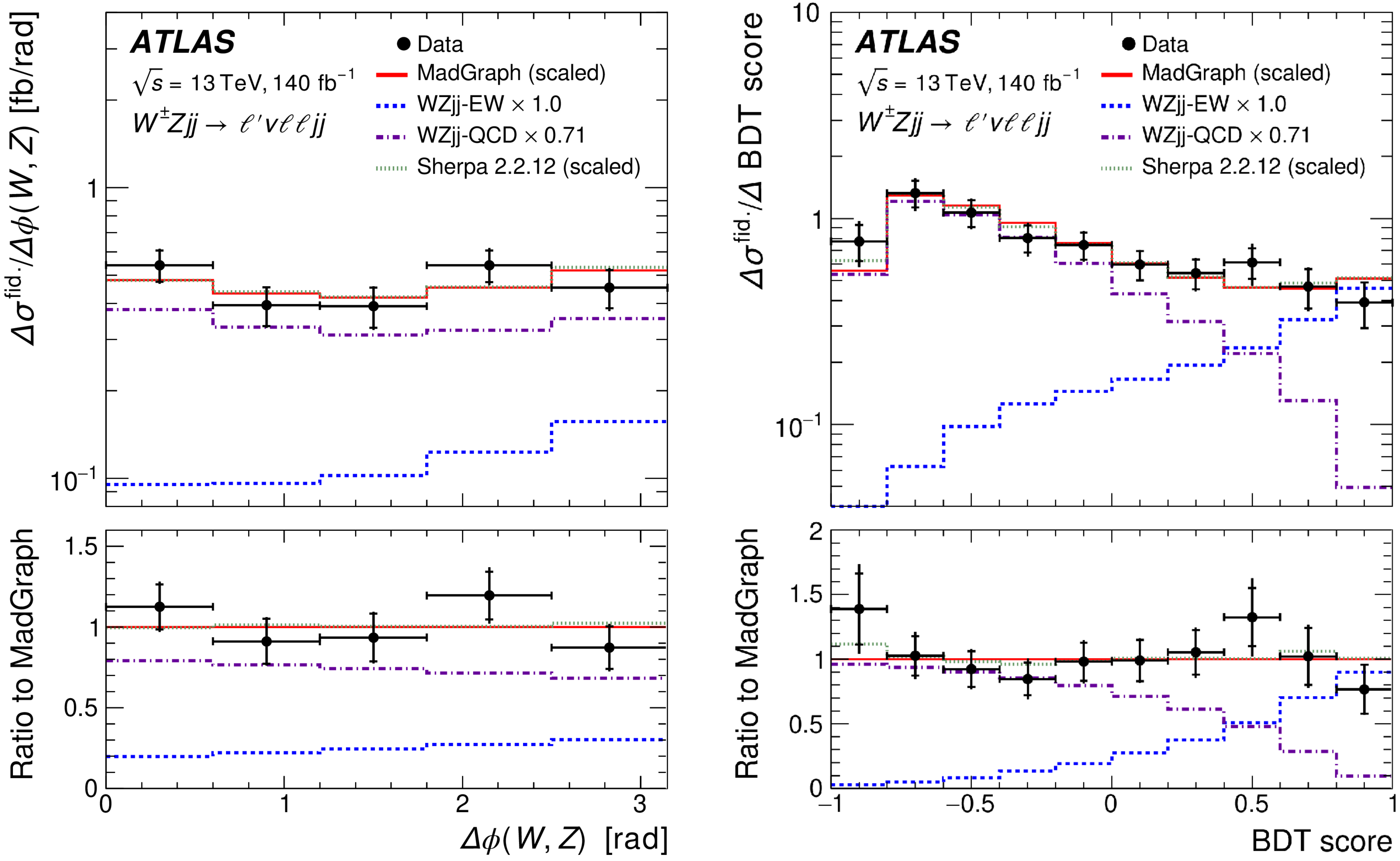
$$\sigma_{WZjj-\mathrm{EW}} = 0.368 \pm 0.037\,(\mathrm{stat.}) \pm 0.059\,(\mathrm{syst.}) \pm 0.003\,(\mathrm{lumi.})\ \mathrm{fb}$$
$$= 0.37 \pm 0.07\ \mathrm{fb},$$
$$\sigma_{WZjj-\mathrm{strong}} = 1.093 \pm 0.066\,(\mathrm{stat.}) \pm 0.131\,(\mathrm{syst.}) \pm 0.009\,(\mathrm{lumi.})\ \mathrm{fb}$$
$$= 1.09 \pm 0.14\ \mathrm{fb},$$





differential distributions and interpretation

- **statistically** dominated
- **unfolded BDT distribution**, obtained training the same BDT at particle level
- **dimension-8 EFT limits** (w/ and w/o unitarisation) comparable with CMS ones



arxiv:2403.15296

dimension-8 EFT operator limits

- dominated by **pure dimension-8 terms** in the cross-section calculation
- **unitarisation cut-off** set where the unitary bound and the experimental bound cross

	Expected [TeV^{-4}]	Observed [TeV^{-4}]
f_{T0}/Λ^4	[-0.80, 0.80]	[-0.57, 0.56]
f_{T1}/Λ^4	[-0.52, 0.49]	[-0.39, 0.35]
f_{T2}/Λ^4	[-1.6, 1.4]	[-1.2, 1.0]
f_{M0}/Λ^4	[-8.3, 8.3]	[-5.8, 5.6]
f_{M1}/Λ^4	[-12.3, 12.2]	[-8.6, 8.5]
f_{M7}/Λ^4	[-16.2, 16.2]	[-11.3, 11.3]
f_{S02}/Λ^4	[-14.2, 14.2]	[-10.4, 10.4]
f_{S1}/Λ^4	[-42, 41]	[-30, 30]

no unitarisation

	Expected [TeV^{-4}]	Observed [TeV^{-4}]
f_{T0}/Λ^4	[-7.0, 7.0]	[-1.5, 1.6]
f_{T1}/Λ^4	[-1.1, 1.0]	[-0.7, 0.6]
f_{T2}/Λ^4	[-12, 6]	[-2.4, 1.8]
f_{M0}/Λ^4	[-60, 60]	[-12, 12]
f_{M1}/Λ^4	[-32, 32]	[-15, 15]
f_{M7}/Λ^4	[-30, 30]	[-15, 15]
f_{S02}/Λ^4	[-41, 41]	[-18, 18]
f_{S1}/Λ^4	—	—

with unitarisation

expected and observed event number

	SR, $N_{\text{jets}} = 2$	SR, $N_{\text{jets}} \geq 3$	b-CR	ZZ-CR
Data	169	477	666	210
Total pred.	170 ± 13	476 ± 22	667 ± 26	212 ± 14
$WZjj$-EW	68 ± 14	55 ± 18	4.84 ± 0.27	0.724 ± 0.014
$WZjj$-QCD	58 ± 16	307 ± 27	77 ± 18	6.3 ± 0.7
$WZjj$-INT	0.9 ± 0.4	4.4 ± 2.3	0.57 ± 0.29	0.22 ± 0.11
$t\bar{t} + V$	0.59 ± 0.10	18.3 ± 2.4	262 ± 34	9.0 ± 1.3
tZj	11.0 ± 1.9	25 ± 5	169 ± 30	0.54 ± 0.09
ZZ-QCD	10.3 ± 1.0	34.6 ± 3.2	10.1 ± 0.5	171 ± 15
ZZ-EW	1.9 ± 0.4	3.7 ± 0.9	0.21 ± 0.05	19 ± 5
VVV	0.41 ± 0.10	2.0 ± 0.5	0.39 ± 0.10	4.2 ± 1.0
Misid. leptons	18 ± 4	27 ± 6	143 ± 35	1.7 ± 0.5

post-fit numbers
all sources of uncertainties included

systematic uncertainties

Source	$\frac{\Delta\sigma_{WZjj-\mathrm{EW}}}{\sigma_{WZjj-\mathrm{EW}}}$ [%]	$\frac{\Delta\sigma_{WZjj-\mathrm{strong}}}{\sigma_{WZjj-\mathrm{strong}}}$ [%]
$WZjj$–EW theory modelling	7	1.8
$WZjj$–QCD theory modelling	2.8	8
$WZjj$–EW and $WZjj$–QCD interference	0.35	0.6
PDFs	1.0	0.06
Jets	2.3	5
Pile-up	1.1	0.6
Electrons	0.8	0.8
Muons	0.9	0.9
b-tagging	0.10	0.11
MC statistics	1.9	1.2
Misid. lepton background	2.3	2.3
Other backgrounds	0.9	0.23
Luminosity	0.7	0.9
All systematics	16	12
Statistics	10	6
Total	19	13

ATLAS VBF WH

event yields

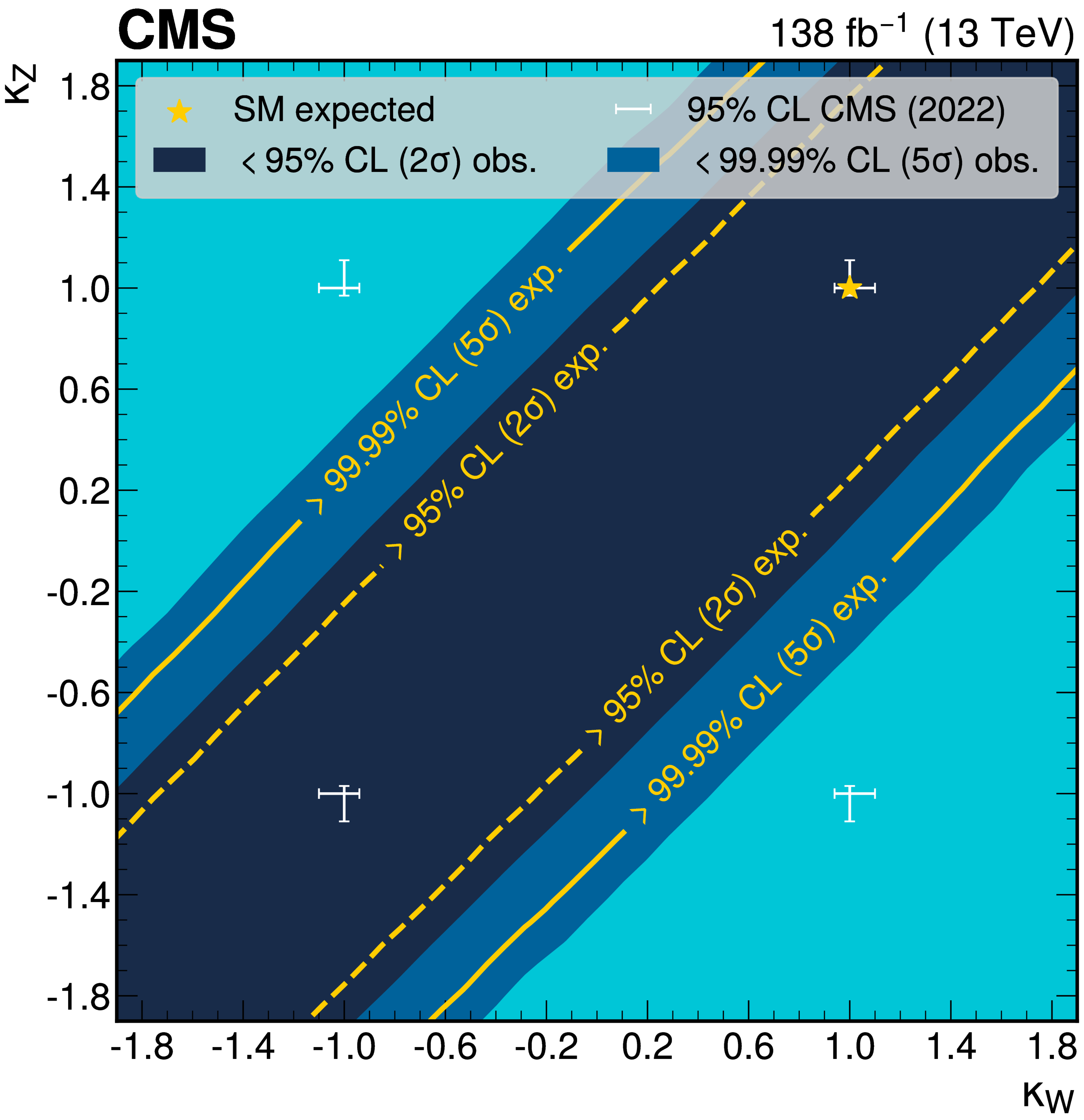
	Negative λ_{WZ}	Positive λ_{WZ}	
$k_{t\bar{t}}$	$0.88^{+0.30}_{-0.35}$	$0.96^{+0.21}_{-0.23}$	
k_W	$1.12^{+0.34}_{-0.25}$	$1.25^{+0.33}_{-0.24}$	
k_{Wt}	$0.32^{+0.39}_{-0.13}$	$0.31^{+0.37}_{-0.14}$	
$\mu = \sigma/\sigma_{\text{pred.}}$	$-0.027^{+0.054}_{-0.057}$	$0.9^{+4.0}_{-4.3}$	
	SR^-	SR^+_{loose}	SR^+_{tight}
$t\bar{t}$	42 ± 19	172 ± 35	15.0 ± 5.8
W+jets	26 ± 13	84 ± 32	14.1 ± 7.6
Wt	4.6 ± 7.0	8 ± 13	0.8 ± 1.5
Other background	5.4 ± 1.6	16.2 ± 4.2	3.0 ± 1.5
Total background	77.7 ± 8.6	279 ± 15	32.9 ± 5.8
VBF WH, pre-fit	285 ± 45	4.15 ± 0.56	2.30 ± 0.62
VBF WH, post-fit	-8 ± 17	4 ± 17	2.2 ± 9.8
Data	70	274	37

CMS VBF WH

The CMS result

Type	Yield	Stat. Unc.	Syst. Unc.
Signal	366	3	68
Background	108	14	14
Observed	130		

The background yield estimated from data and signal yield ($\kappa W=-1$, $\kappa Z=1$) predicted by MC simulation in the **BSM signal region**



ATLAS exclusive WW

systematics

Source of uncertainty	Impact [% of the fitted cross section]
Experimental	
Track reconstruction	1.1
Electron energy scale and resolution, and efficiency	0.4
Muon momentum scale and resolution, and efficiency	0.5
Misidentified leptons, systematic	1.5
Misidentified leptons, statistical	5.9
Other background, statistical	3.2
Modelling	
Pile-up modelling	1.1
Underlying-event modelling	1.4
Signal modelling	2.1
WW modelling	4.0
Other background modelling	1.7
Luminosity	1.7
Total	8.9

CMS exclusive $\gamma\gamma$

systematic uncertainties

Source	2016	2017	2018
Integrated luminosity	1.2%	2.3%	2.5%
Background estimation	23.3%	25.2%	20.9%
Photon ID scale factors	3.1%	7.0%	2.9%
Proton survival probability	10%	10%	10%
Particle shower reconstruction in PPS	—	—	1.7%

ATLAS ZZ

event yields

Process	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
EW $ZZjj$	31.4 ± 3.5	15.0 ± 0.8
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	–	24.6 ± 1.1
Others	3.2 ± 2.1	1.2 ± 0.9
Total	124 ± 26	82.9 ± 6.4
Data	127	82