La Fisica dei bosoni elettrodeboli a LHC

Vieri Candelise

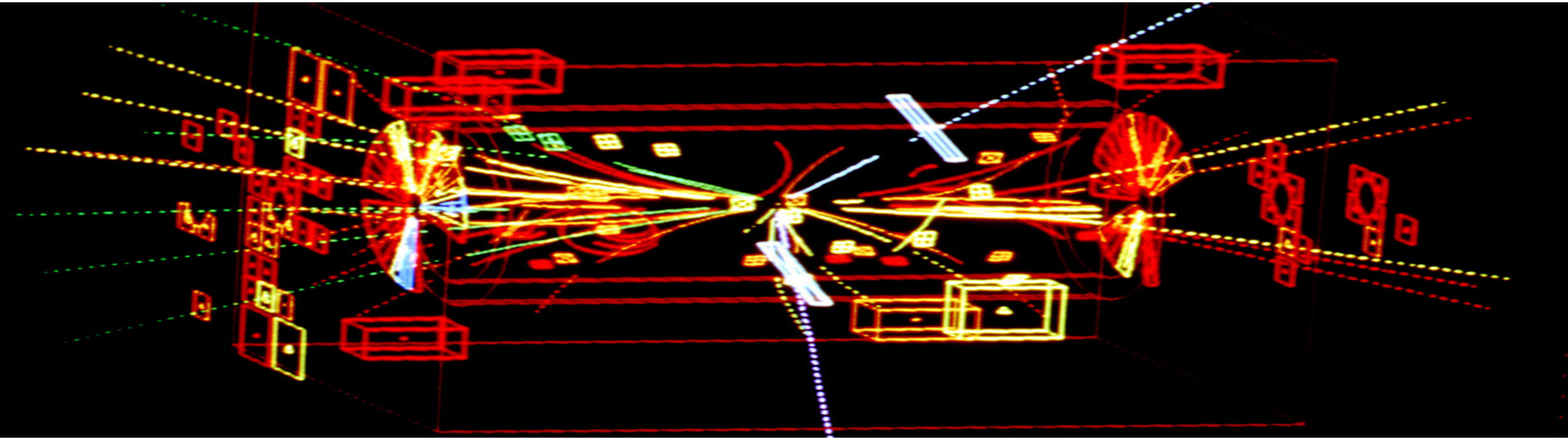
on behalf of the ATLAS and CMS Collaborations

106º Congresso Nazionale della Società Italiana di Fisica

Congresso Virtuale, 14-18 Settembre 2020

Overview

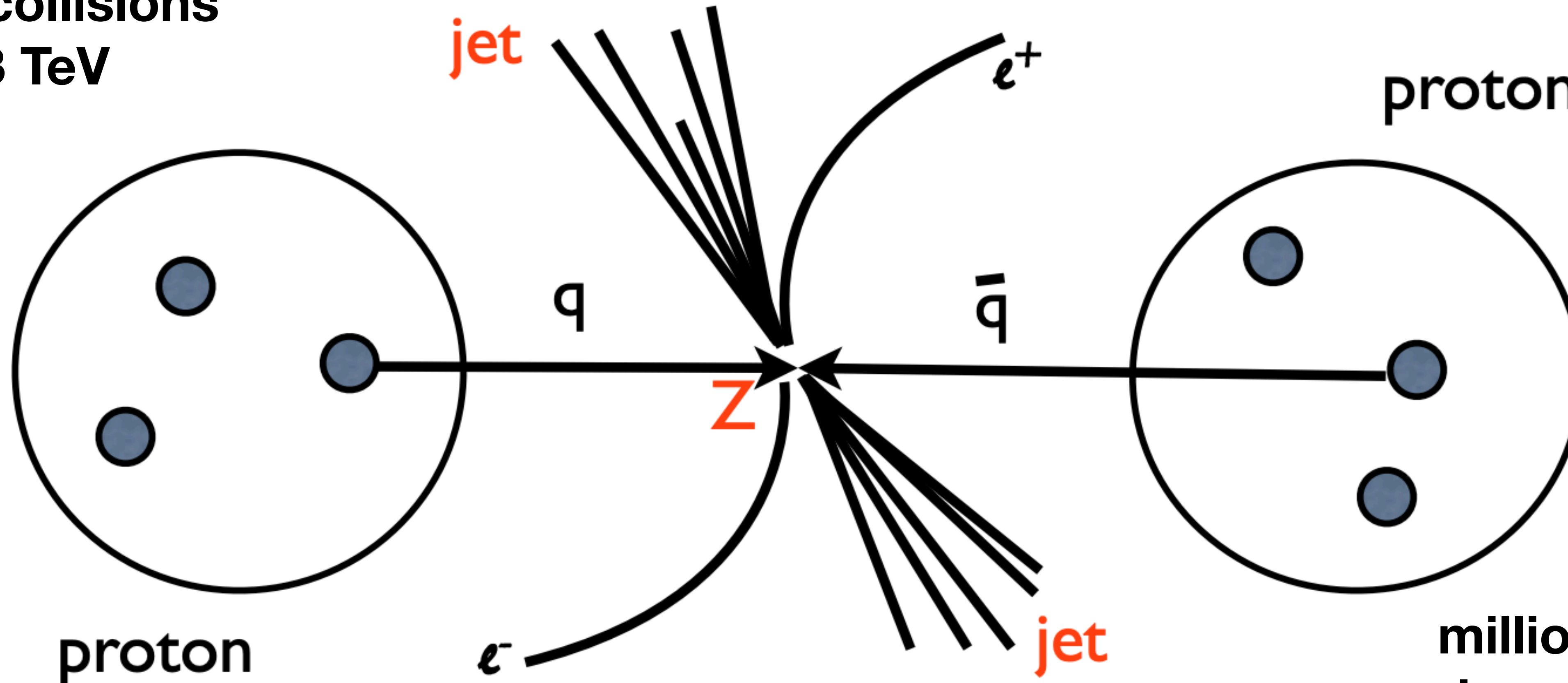
- Phenomenology of W and Z bosons physics at the LHC
- Measurements of the W and Z properties
- Associated production with jets and heavy flavours
- Electroweak W and Z production
- Vector Boson Fusions modes



June 1st, 1983. The first Z boson ever observed by humans

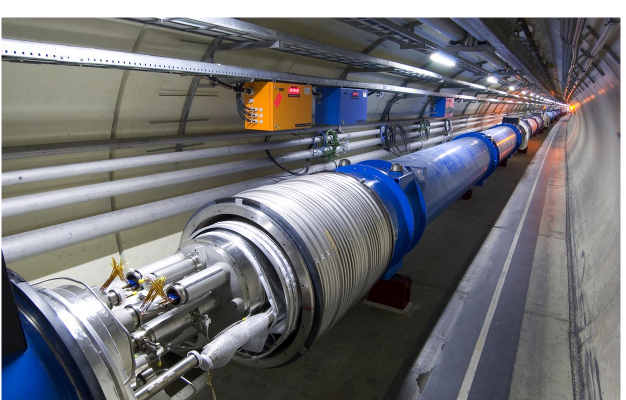
Phenomenology of W and Z bosons at LHC

LHC pp collisions
@ 13 TeV

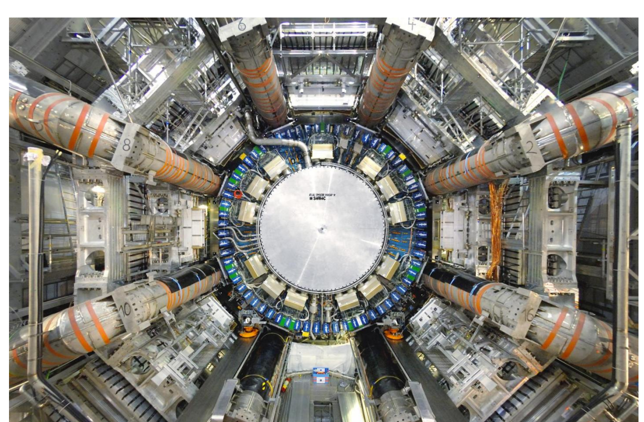


millions of W/Z boson events recorded

2.06 x 10^{34}cm^{-2}s^{-1},

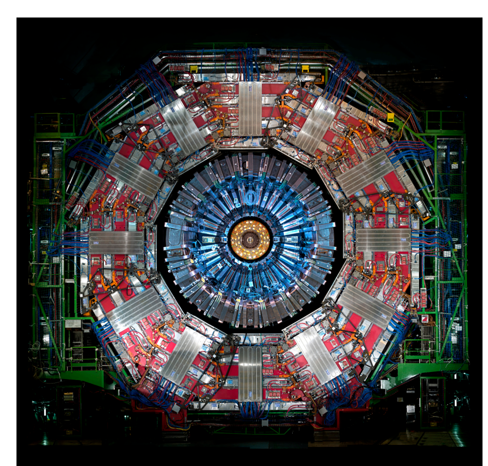


ATLAS

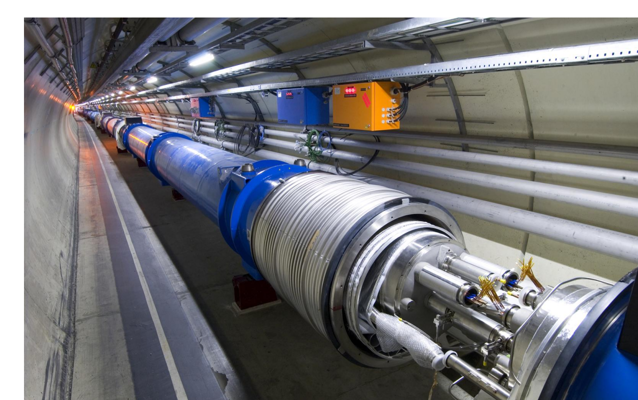


recorded 189.3 fb^{-1}

CMS

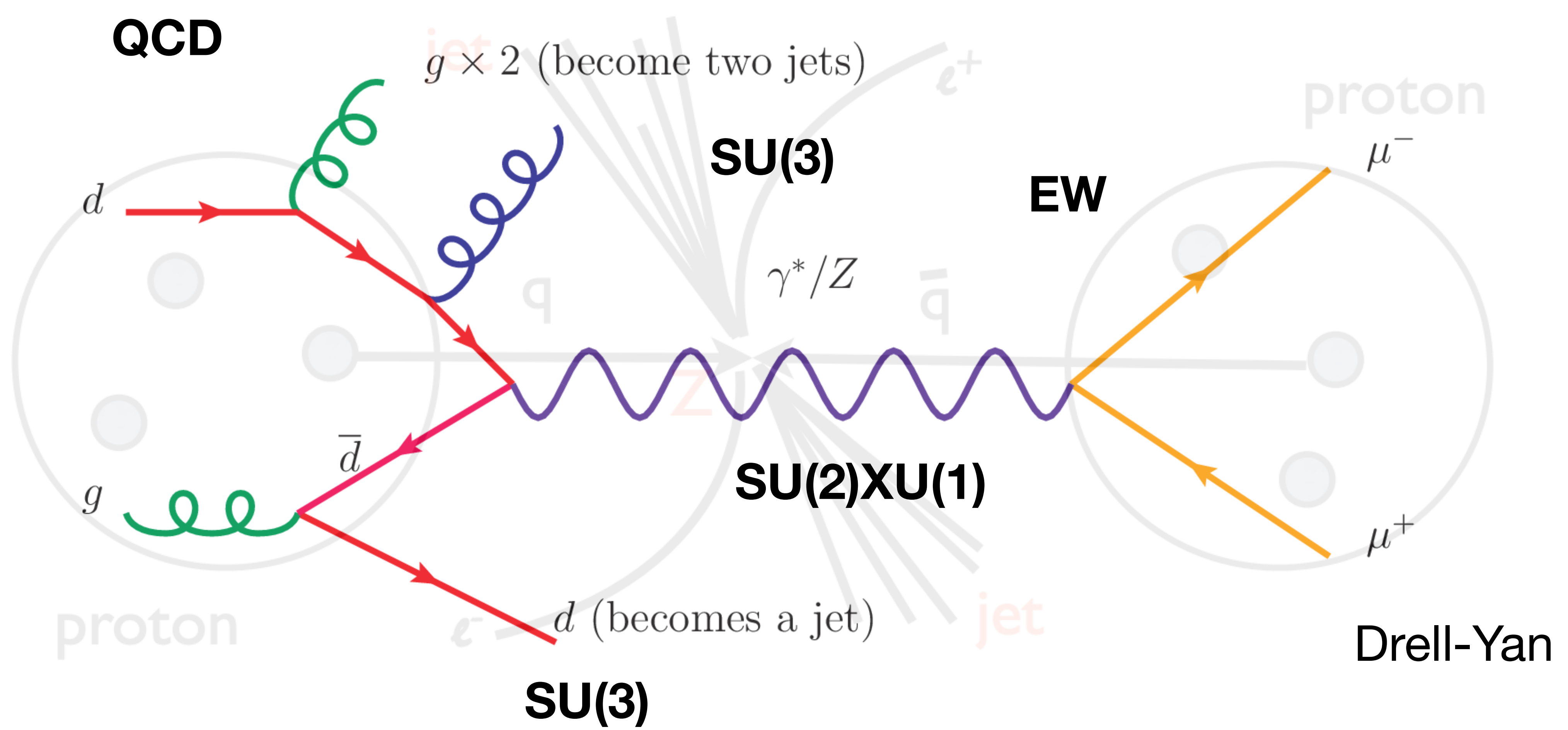


x2 design luminosity!



Phenomenology of W and Z bosons at LHC

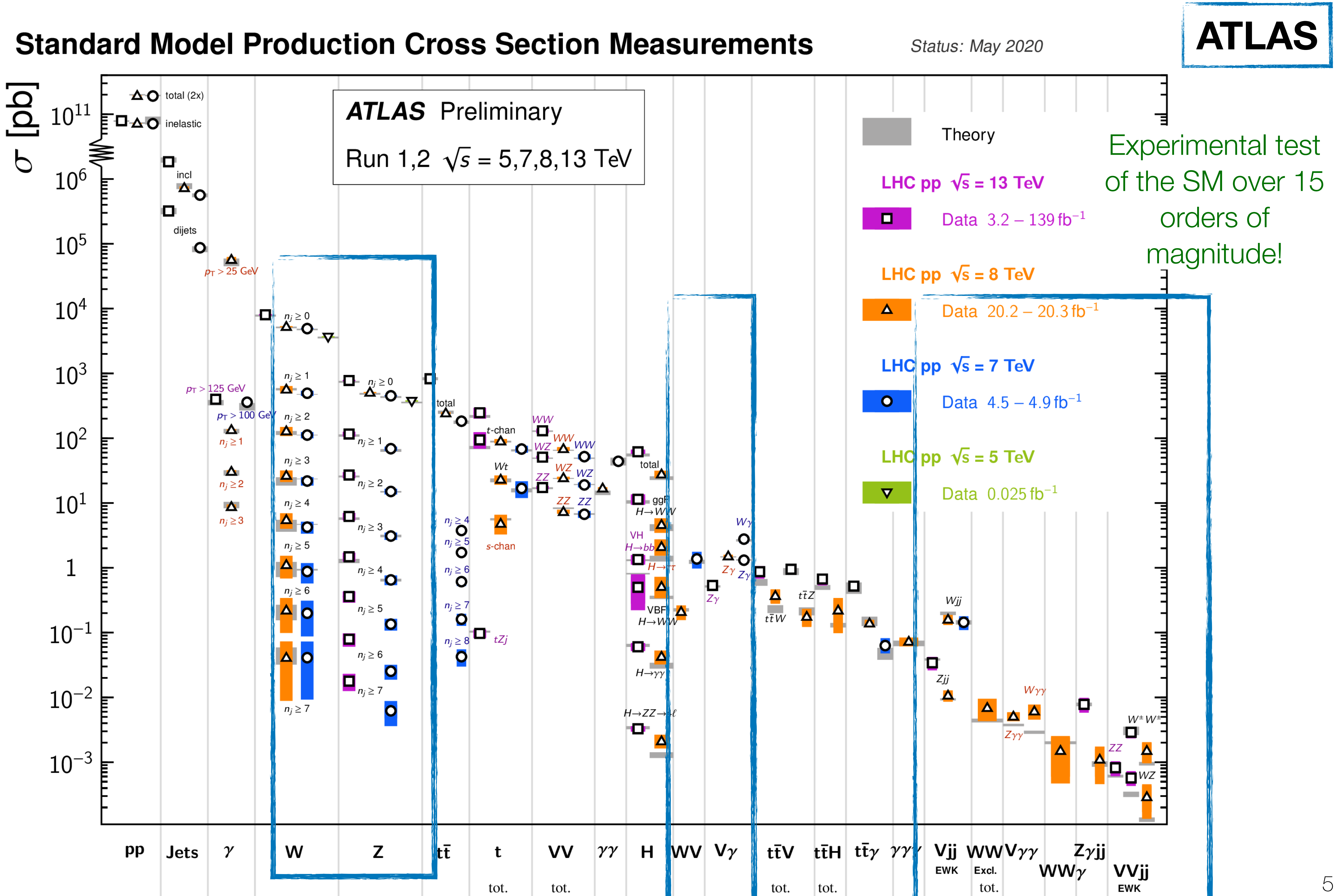
Z and W productions at LHC are sensitive to key aspects of the Standard Model



This is a laboratory for the experimental study and test of the Standard Model!

- QCD modelling plays a prime role: impact of the initial state (PDF, strong coupling, scales)
- Huge phenomenology: V+jets/HF, multiboson interactions, EW production (VBF/VBS)…
- Precision tests of the SM with W/Z: quark sea, PDFs, NNLL, higher orders in QCD
- Data-driven way to “tune” our simulation and improve perturbative calculations

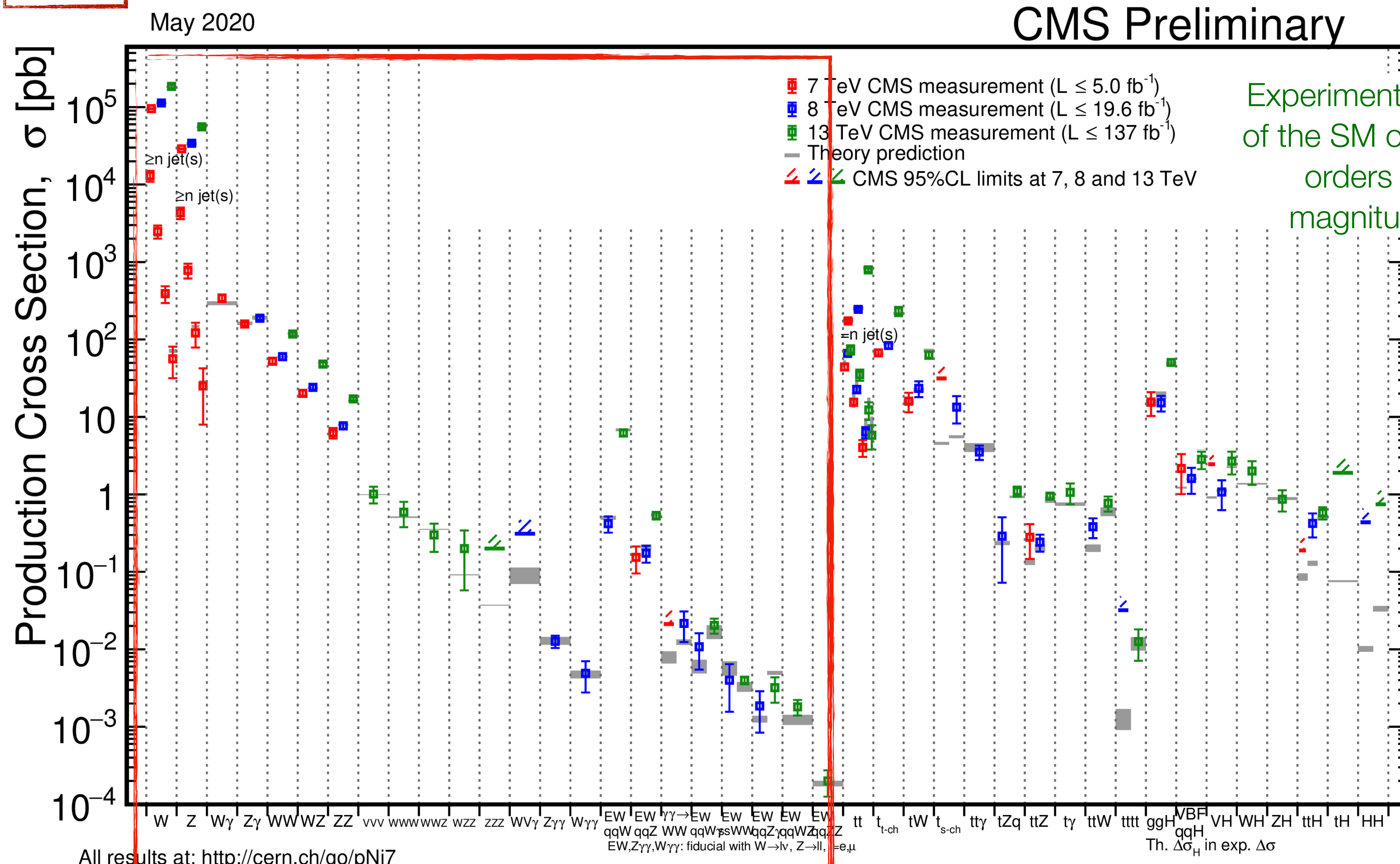
Standard Model measurements in 2020



Experimental test of the SM over 15 orders of magnitude!

Standard Model measurements in 2020

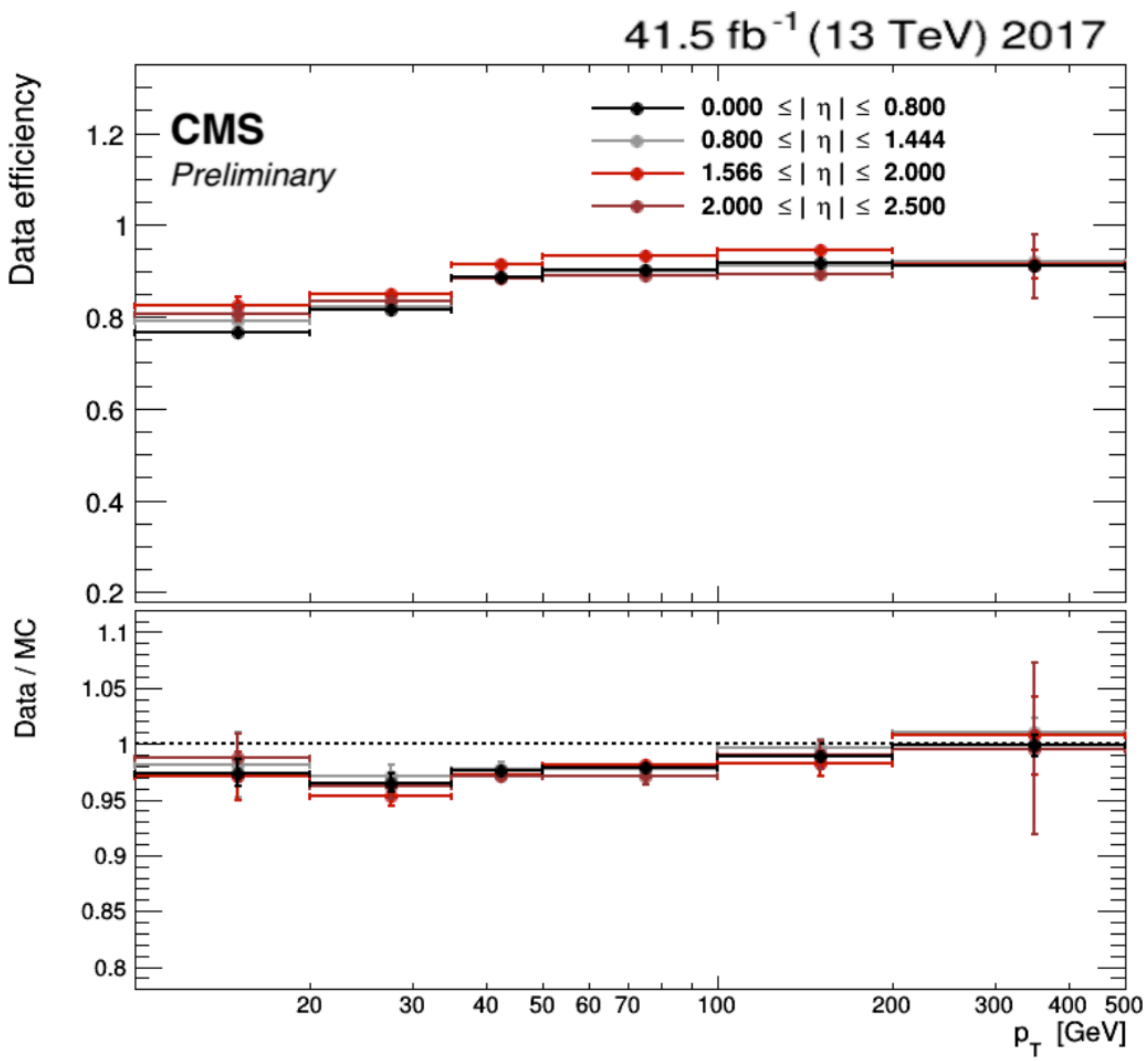
CMS

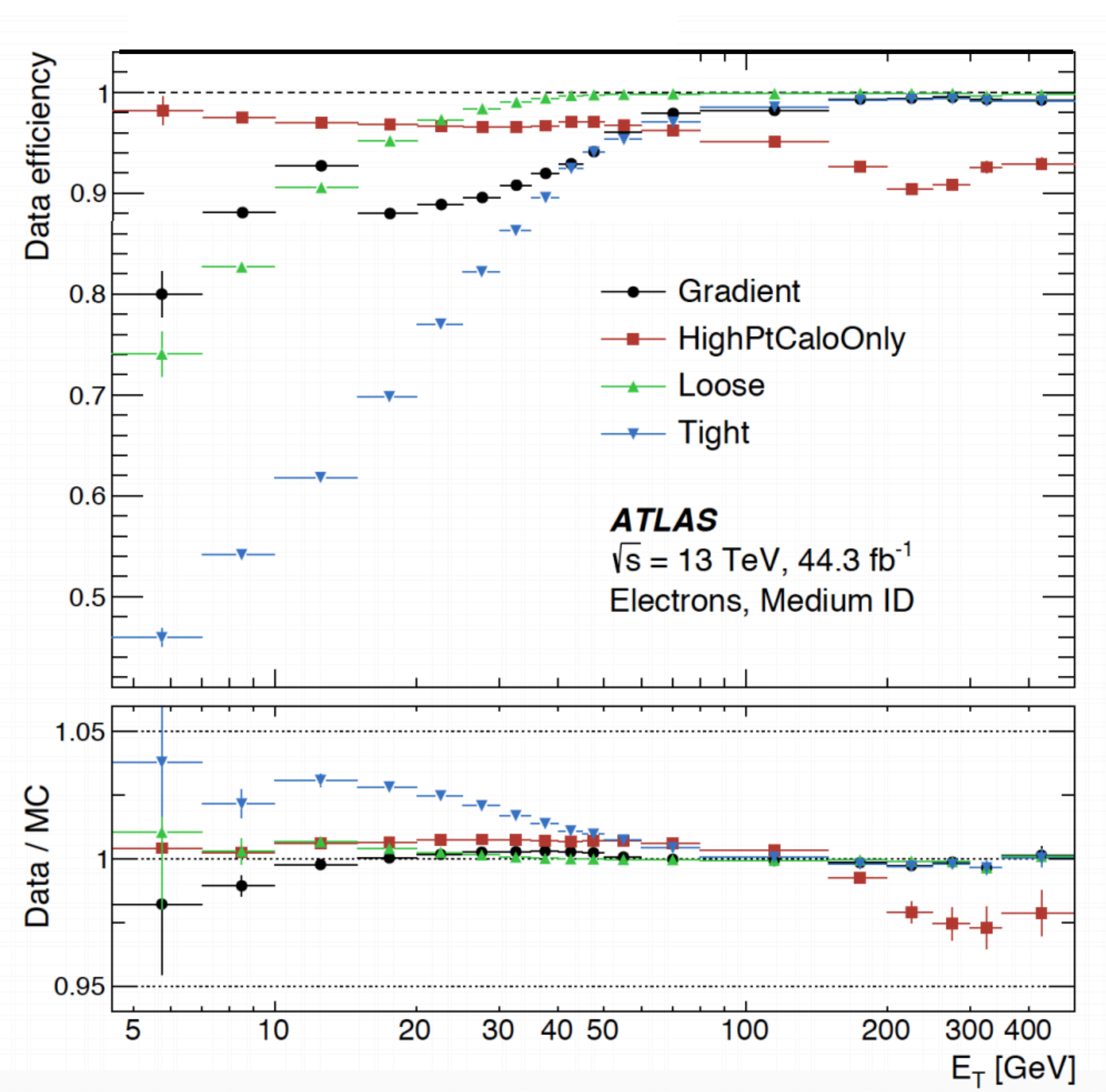


Experimental test of the SM over 15 orders of magnitude!

How all of this is possible

precision SM tests, differential spectra and sensitivity to very rare processes are possible exploiting the ATLAS and CMS excellent detector performances

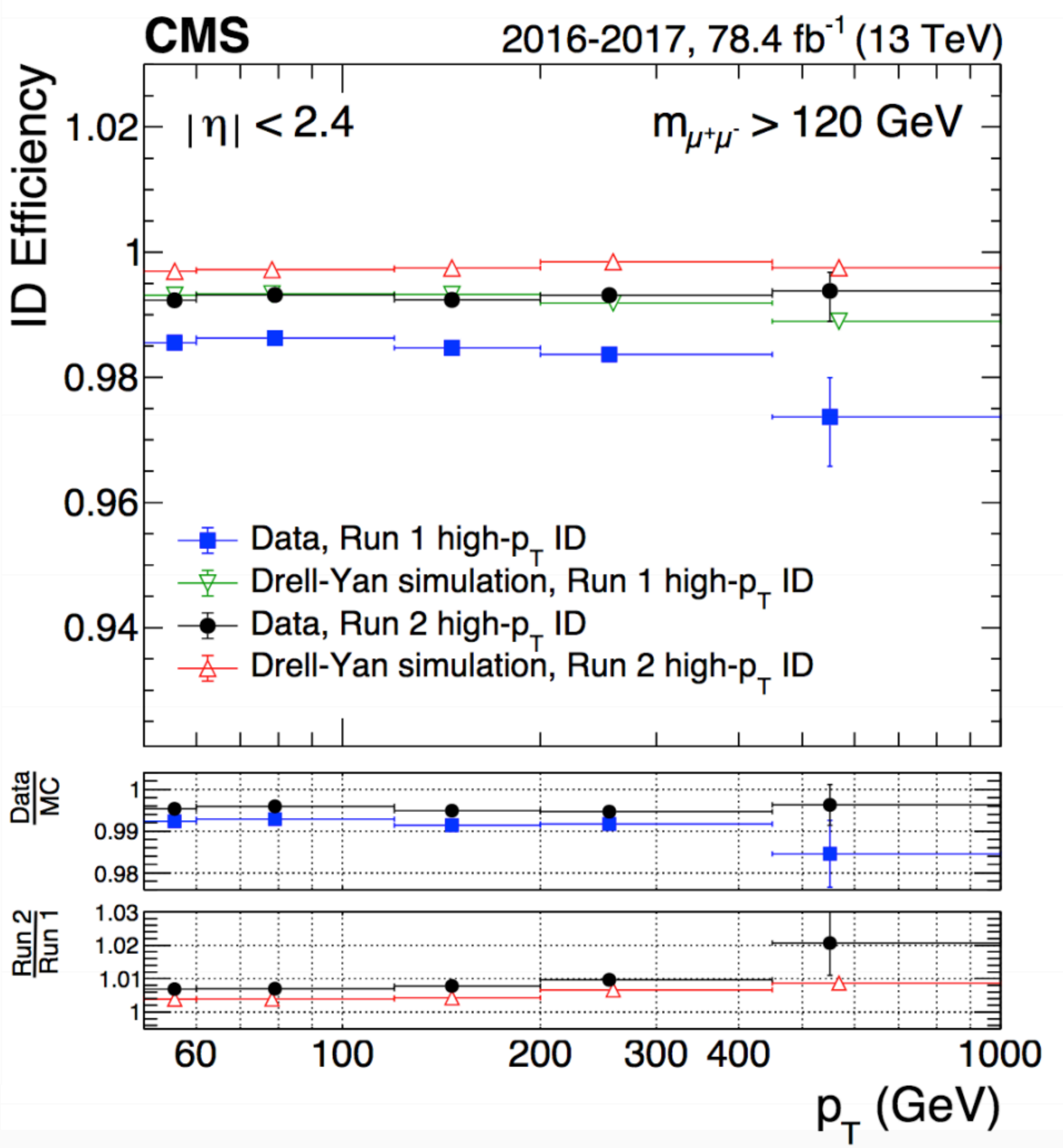


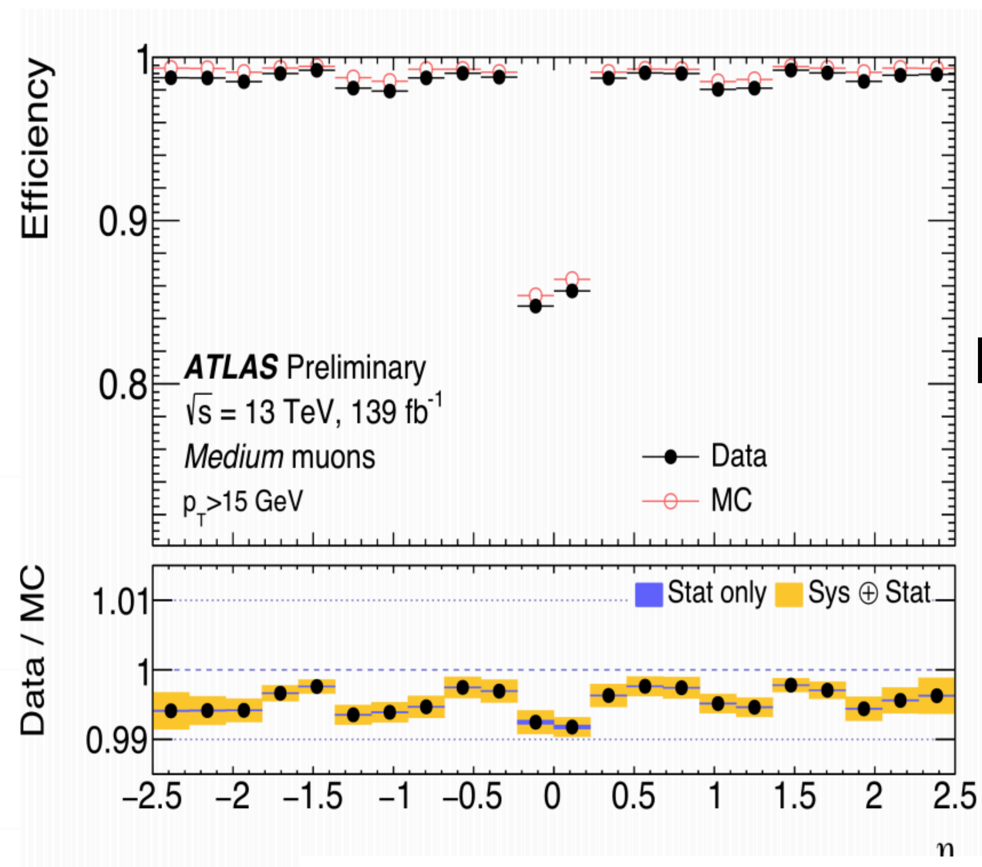


Electrons identification with $Z \to e^+e^-$ and $J/\psi \to e^+e^-$

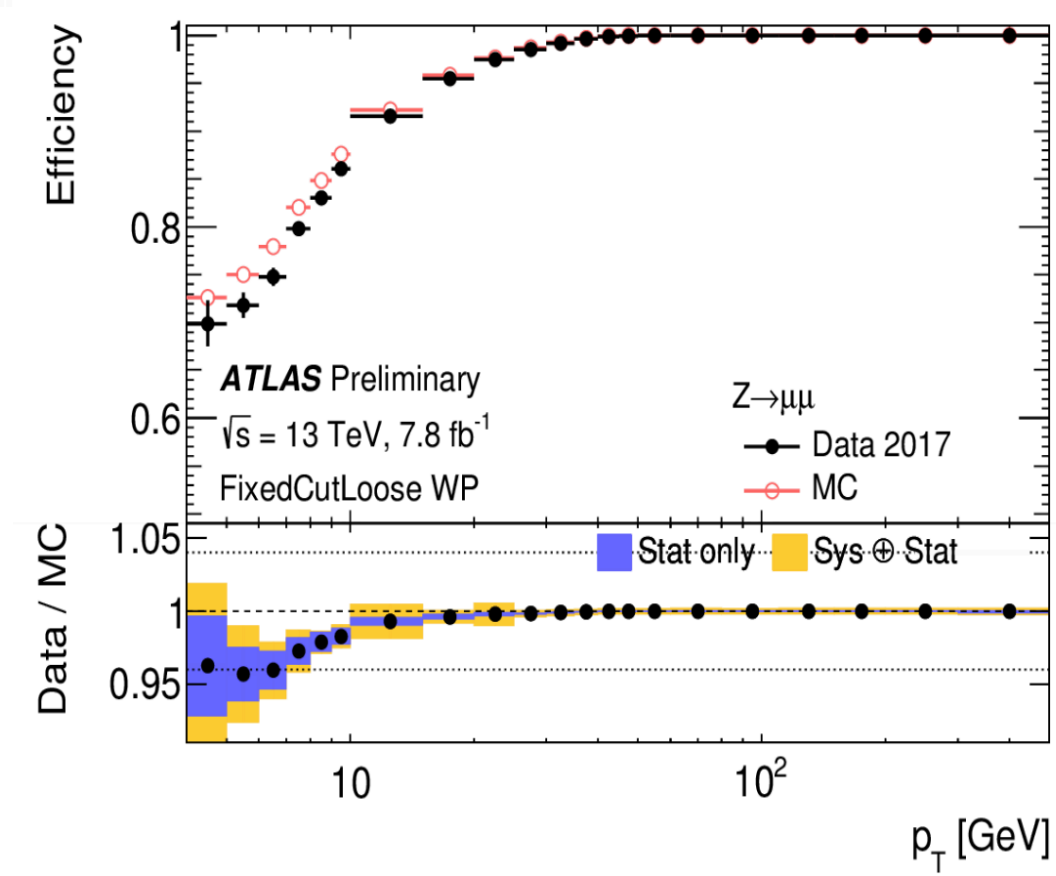
both ATLAS and CMS achieve sub-% precision

How all of this is possible





Muons Reconstruction and Isolation efficiency



Muons identification with $Z \to e^+e^-$ up to 1 TeV

Outstanding precision

DISCLAIMER!

Electroweak bosons physics at the LHC is a super productive factory of scientific results… a lot of amazing publications are available!

what comes next is my *personal overview* of the *most recent results at 13 TeV* from ATLAS and CMS

enjoy!

---

you can have a look at the full Standard Model gallery of results from the two experiments here:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic

http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html

ATLAS @ 13 TeV

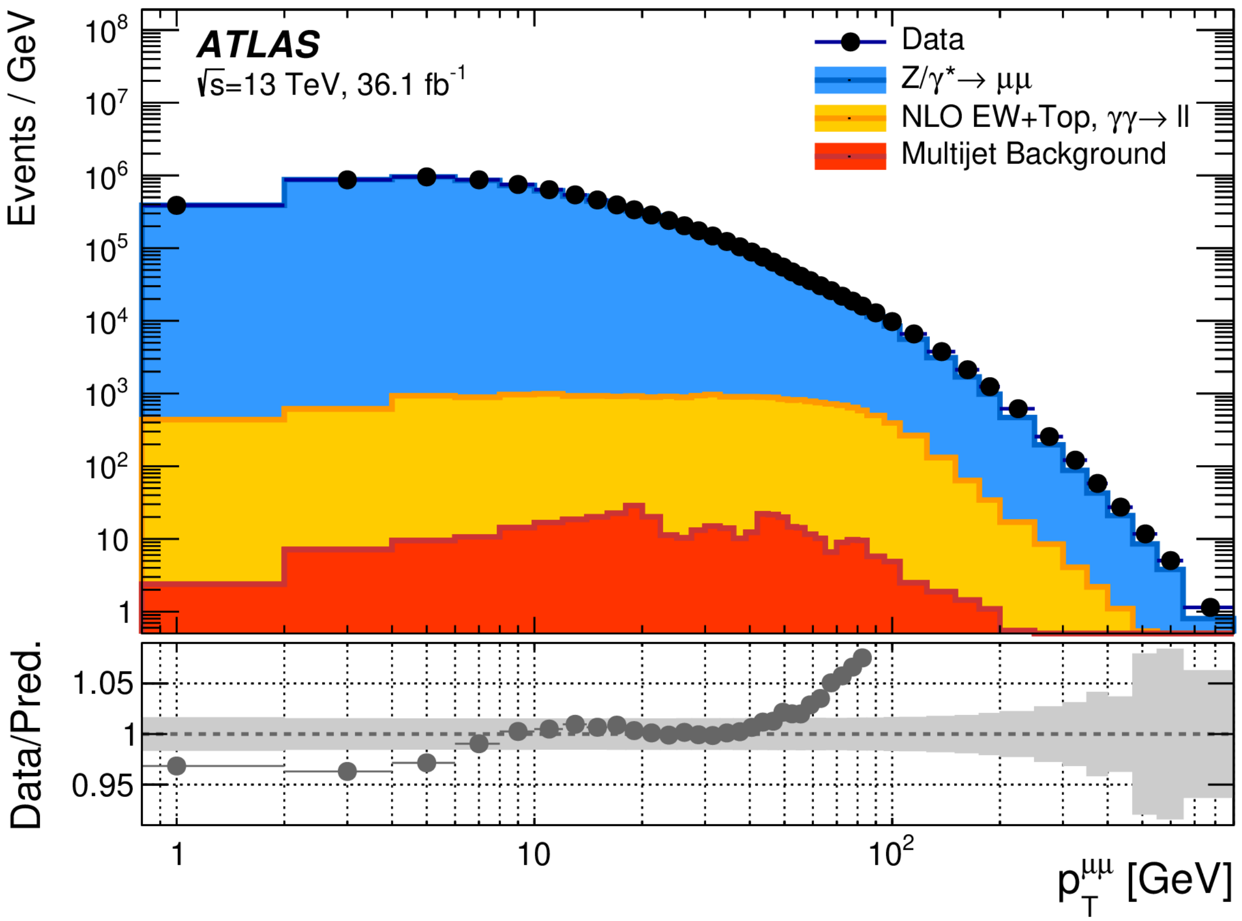
Eur. Phys. J. C 80 (2020) 616

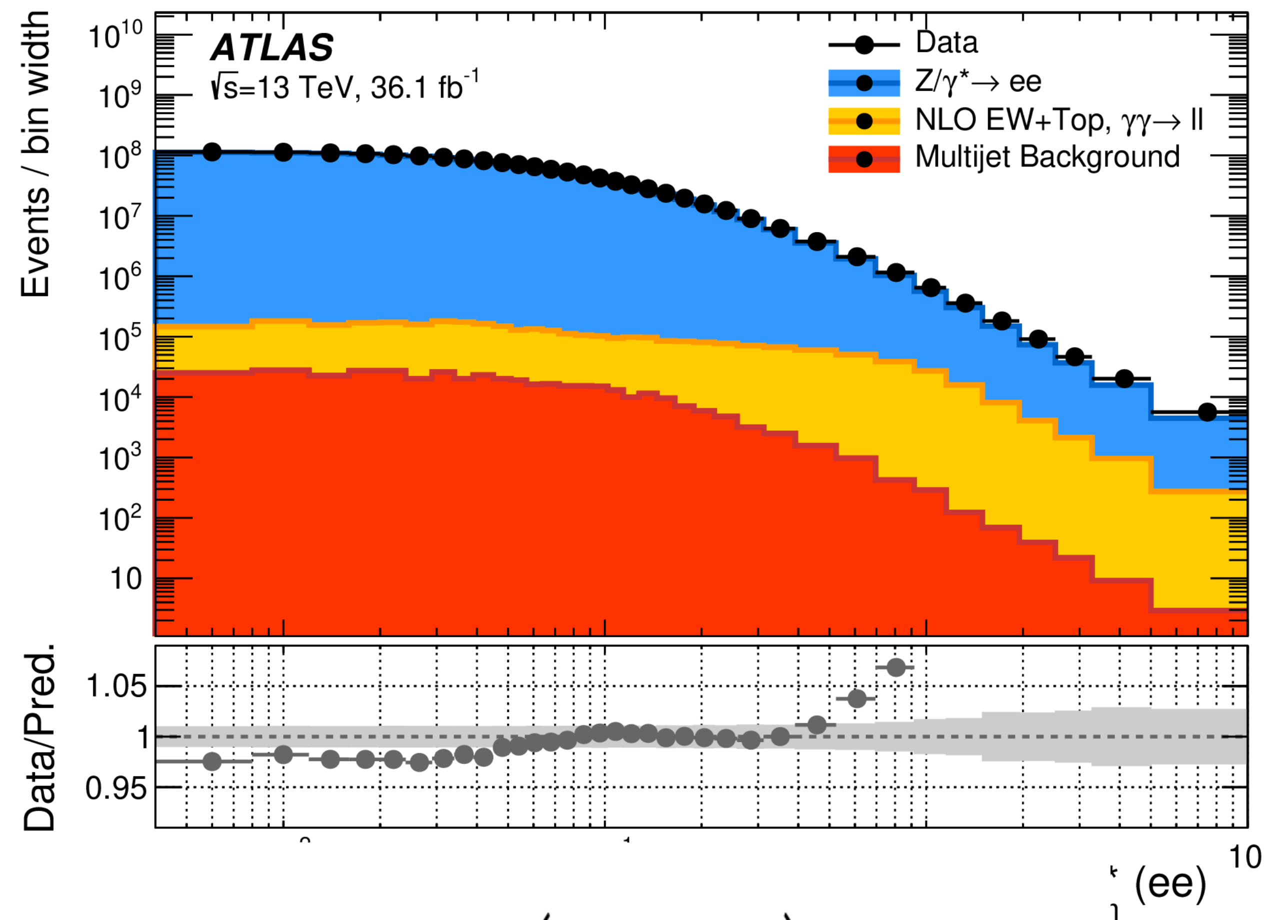
Z properties

Precision measurements of the Drell-Yan dilepton pair $p_T^{\ell\ell}$ and ϕ^*

$\ell = e, \mu$; pT > 27 GeV ; |η| < 2.5 and 66<m<116 GeV

fundamental measurement to understand pQCD at 13 TeV, initial state composition and crucial for the future W mass measurements





sensitive to the gluon resummation and parton intrinsic momentum through non-perturbative effects

$$\phi^*_\eta = \tan\left(\frac{\pi - \Delta\phi}{2}\right) \times \sin(\theta^*_\eta)$$

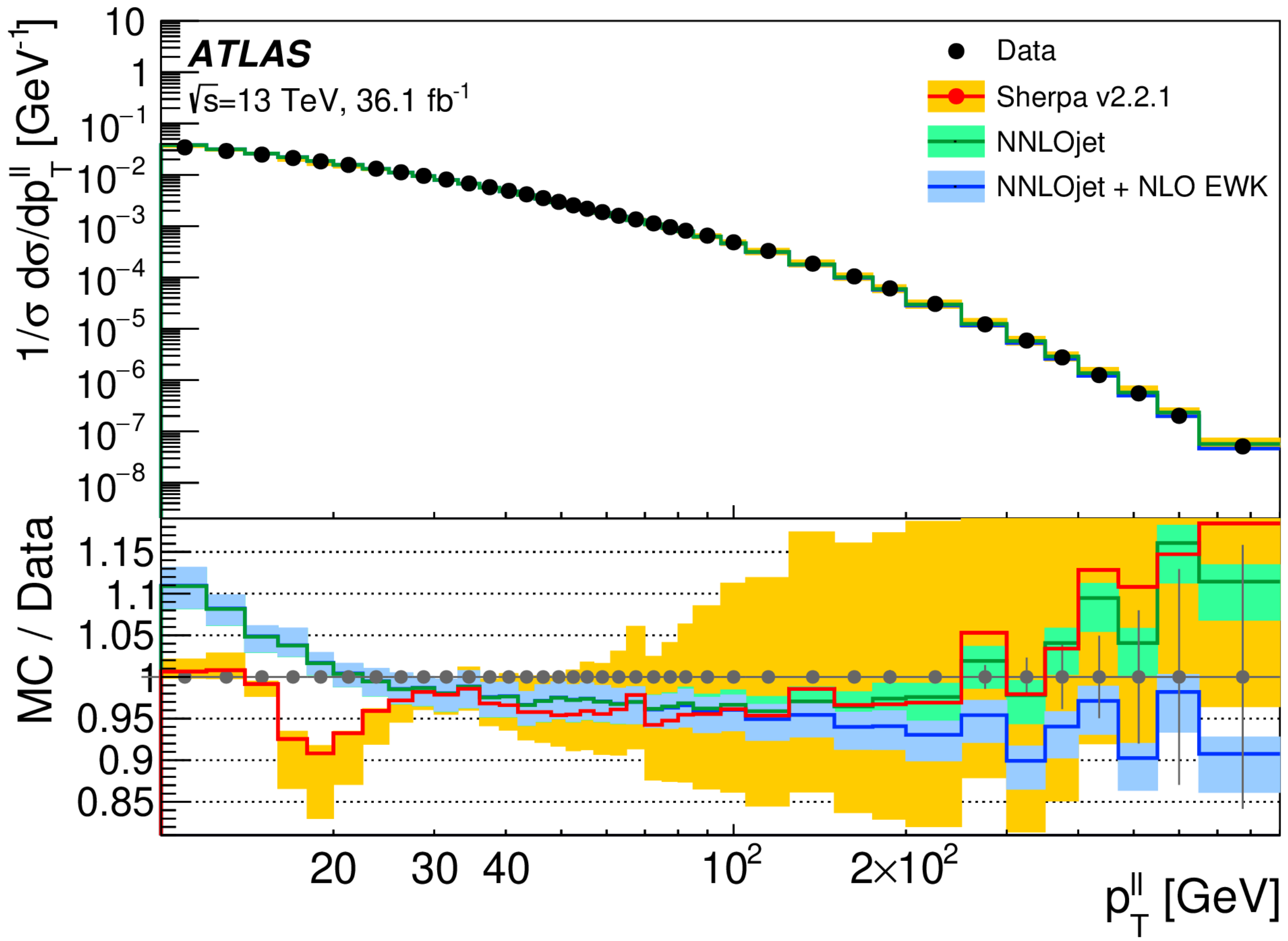
independent on the lepton scale and resolution (important at low dilepton momentum)

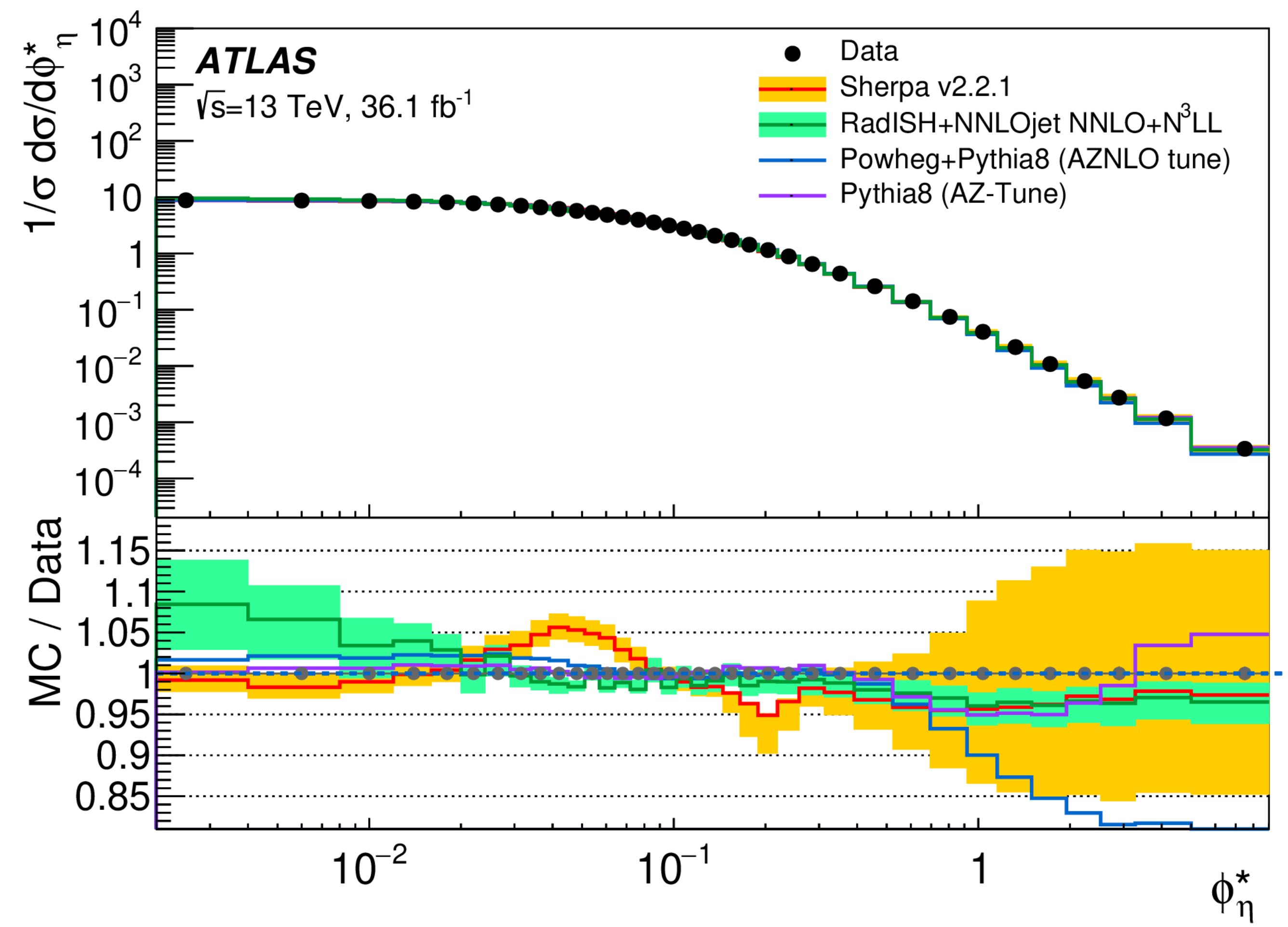
ATLAS @ 13 TeV

Z properties

Eur. Phys. J. C 80 (2020) 616

Unfolded results compared to Pythia8 with the AZ tune, Powheg+Pythia8 with the AZNLO tune, Sherpa v2.2.1 and RadISH with the Born level combined measurement.





The relative precision of the combined result is better than 0.2% for pT<30 GeV

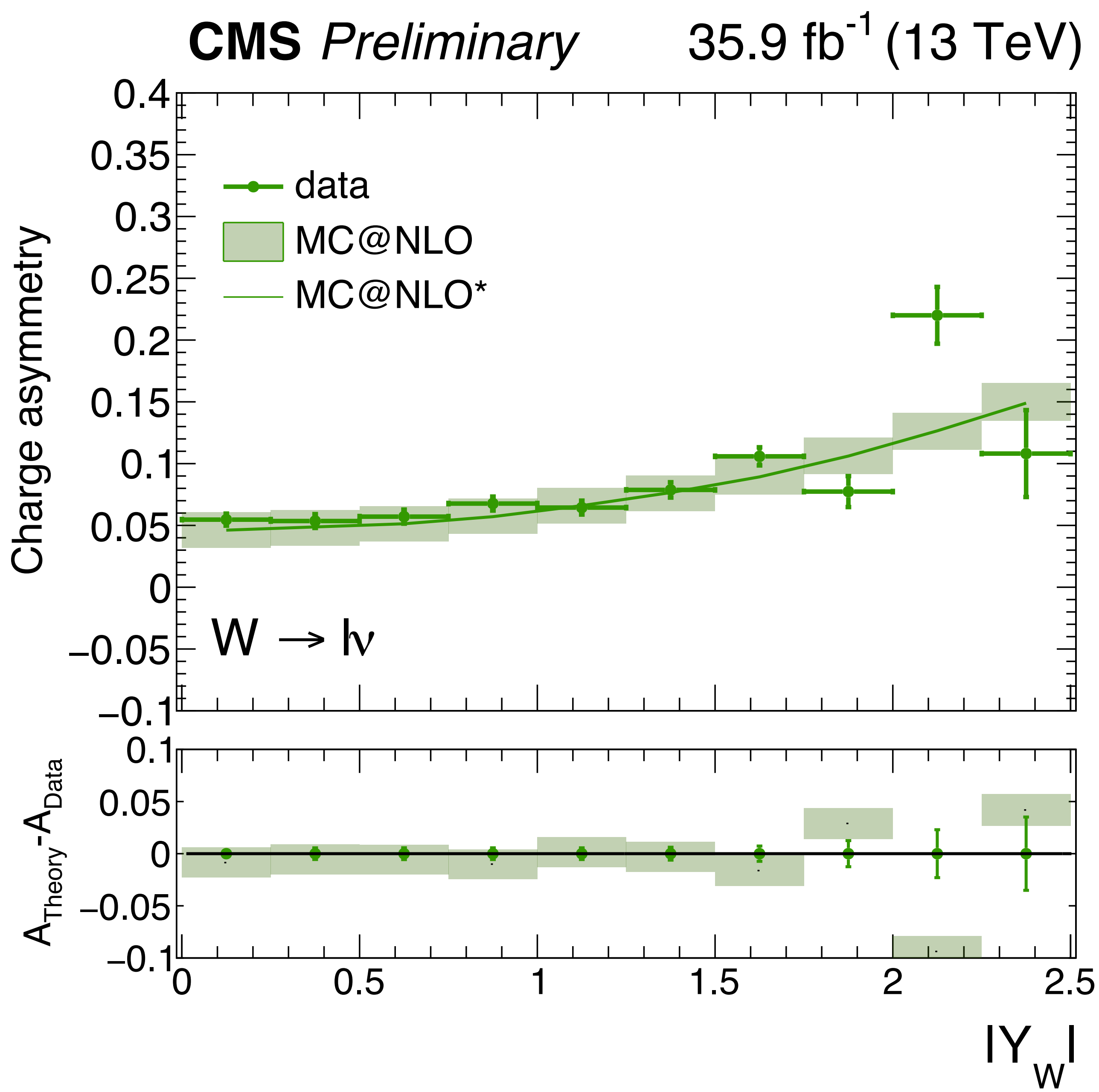
CMS @ 13 TeV

W properties

new!

W boson cross section as a function of the 3 helicity states

$$\frac{1}{N}\frac{dN}{d\cos\theta^* \, dp_T^W \, dY_W} = \frac{3}{8}(1 \mp \cos\theta^*)^2 \cdot f_L^{(p_T^W, Y_W)} + \frac{3}{8}(1 \pm \cos\theta^*)^2 \cdot f_R^{(p_T^W, Y_W)} + \frac{3}{4}\sin^2\theta^* \cdot f_0^{(p_T^W, Y_W)}$$



rapidity (in the three helicity states)
double differential cross section
charge asymmetry

- Trigger on $W \rightarrow \ell(=\mu, e)\nu$
- isolated hight pt leptons
- combined by Likelihood minimization
- fit data with simulated templates to measure YW for each W helicity state and charge

$$\mathcal{A}^{pol}(|Y_W|) = \frac{d\sigma^{pol}/dY_W(W^+ \rightarrow \ell^+\nu) - d\sigma^{pol}/dY_W(W^- \rightarrow \ell^-\bar{\nu})}{d\sigma^{pol}/dY_W(W^+ \rightarrow \ell^+\nu) + d\sigma^{pol}/dY_W(W^- \rightarrow \ell^-\bar{\nu})}$$

CMS-SMP-PAS-18-012
Submitted to Physical Review D

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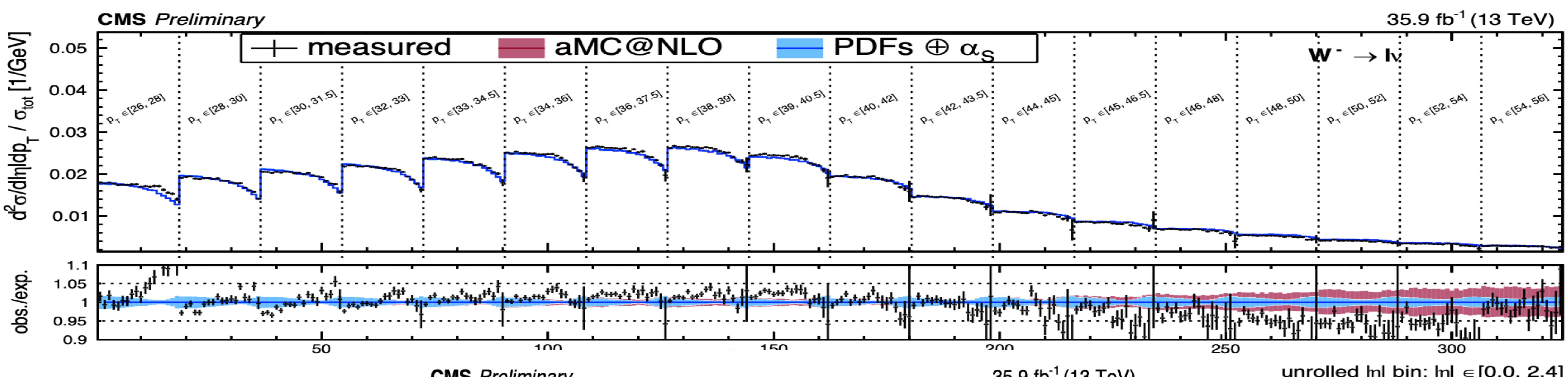
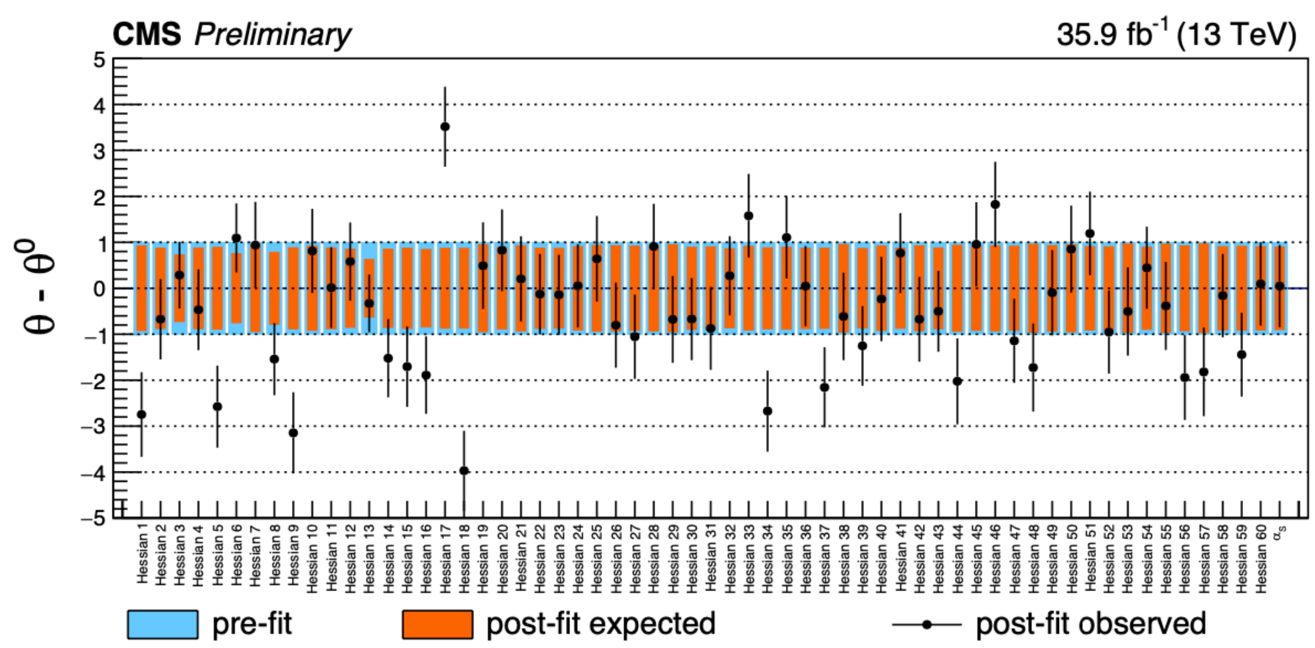
double-differential cross section $1/\sigma_{tot} d^2\sigma / dp_T |\eta|$



pQCD predictions test

powerful test of PDFs



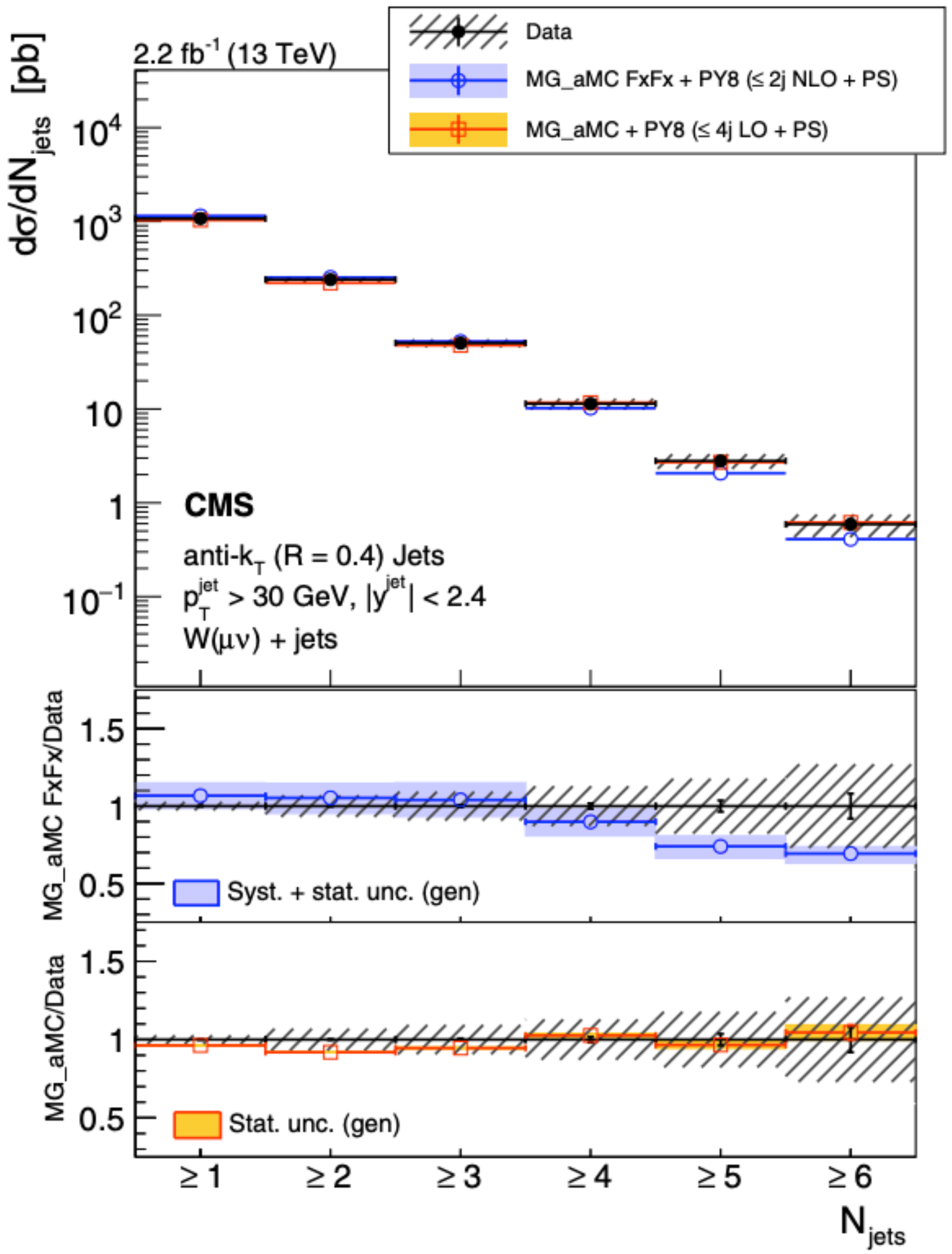
constraints of 60 Hessian variations of the NNPDF3.0 PDF+αs

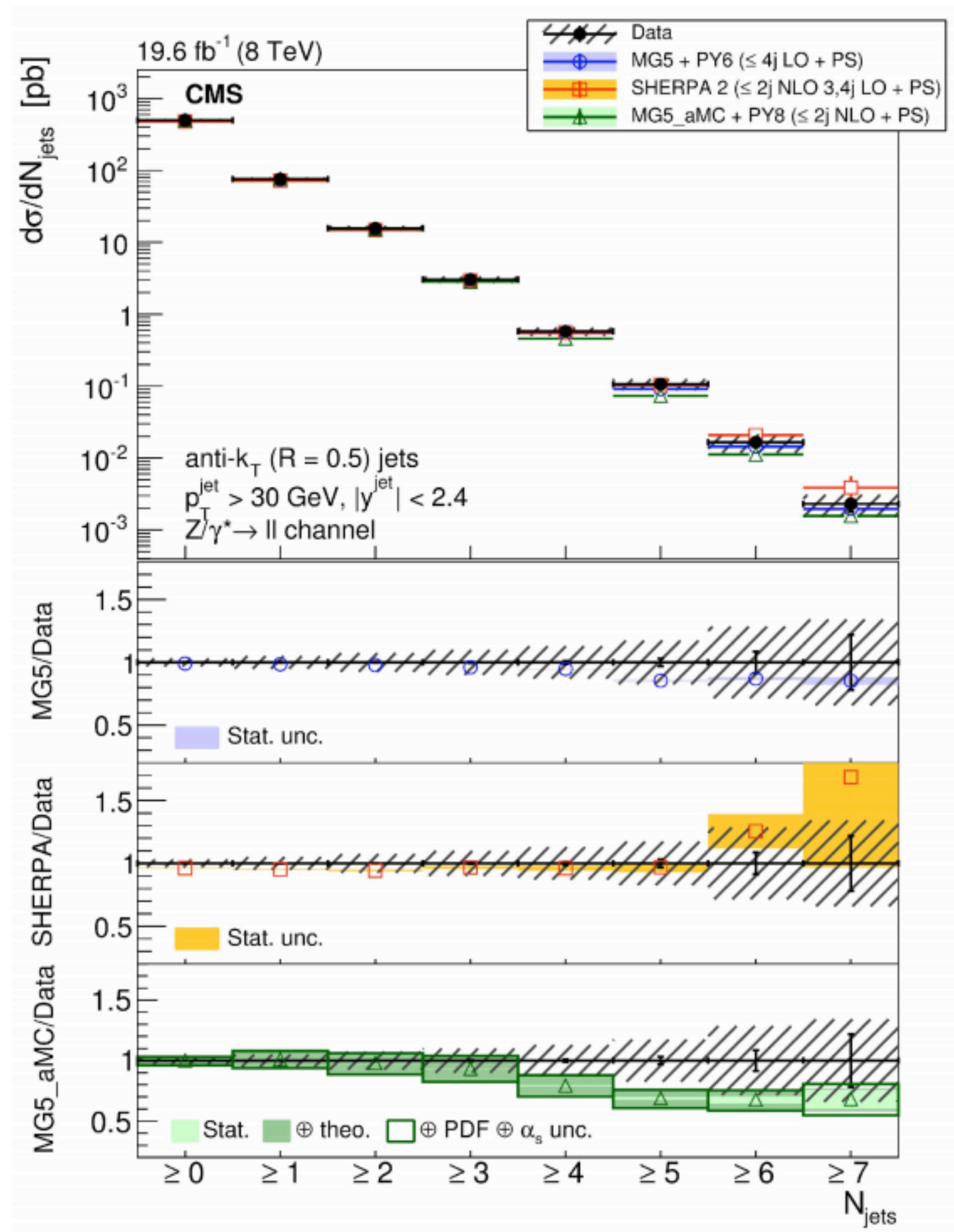
CMS-SMP-PAS-18-012
Submitted to Physical Review D

W and Z plus jets

EPJC 78 (2018) 965

PRD 96 (2017) 072005





anti-kt jets with pt>30 GeV

μμ/ee + N jets

unfolded to particle level (Bayes, SVD)

data VS NLO matrix element+parton shower predictions

unfolded differential cross sections provide benchmark comparisons for NNLO QCD calculation, generators tests, EW+QCD corrections

V+jets processes are basic backgrounds for Higgs and BSM with leptons+jets topologies

Z plus b quarks

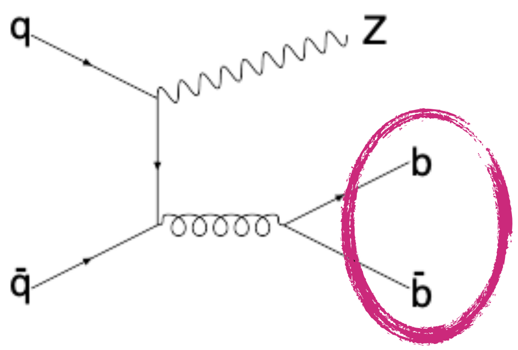
ATLAS @ 13 TeV

new!

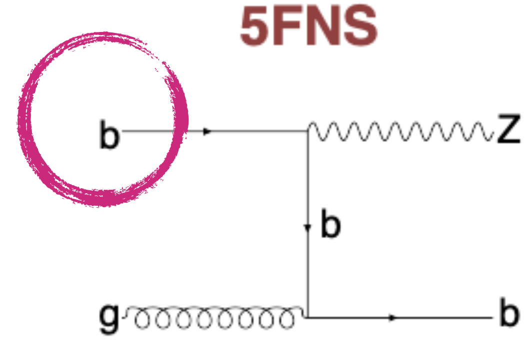
Inclusive unfolded Z+≥1 b-jet and Z+≥2 b-jets x-sections

JHEP 07 (2020) 44

4FNS



5FNS



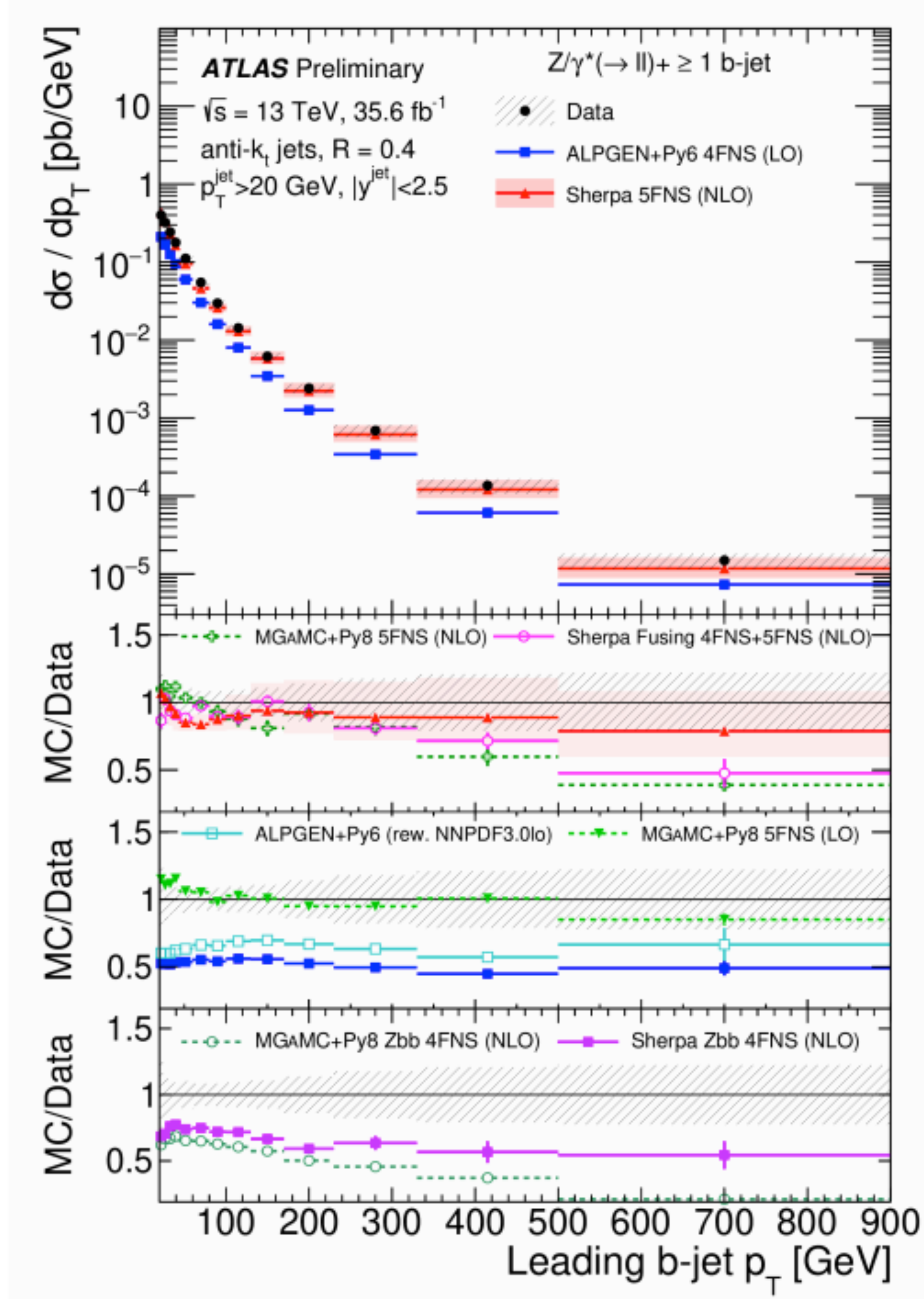
discriminate the effect of the b quark PDF of the proton (5/4-FS)

important test of pQCD: gluon splitting, HF mass, NLO effects

crucial background for VH->bbll, V'

combined MVA-based b-tagging reaching 70% efficiency for high pt jets

mistag rate c-quarks and light 8% and 0.26%



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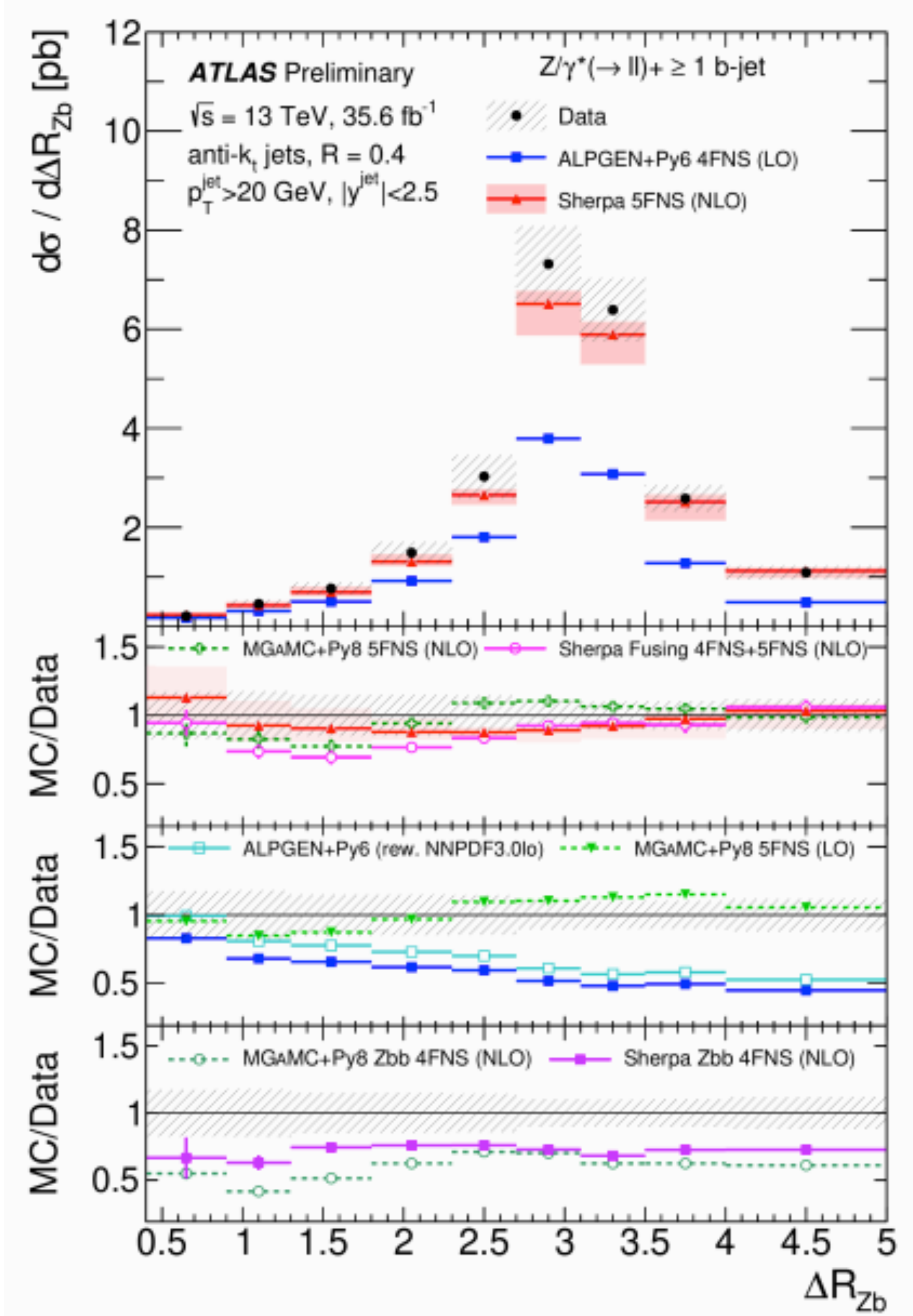

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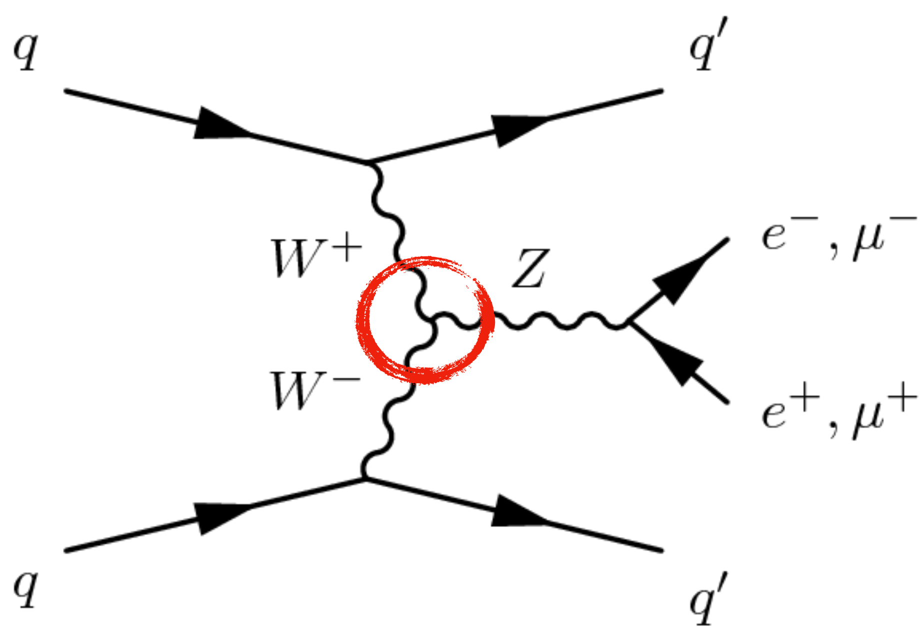
Phenomenology of EW production

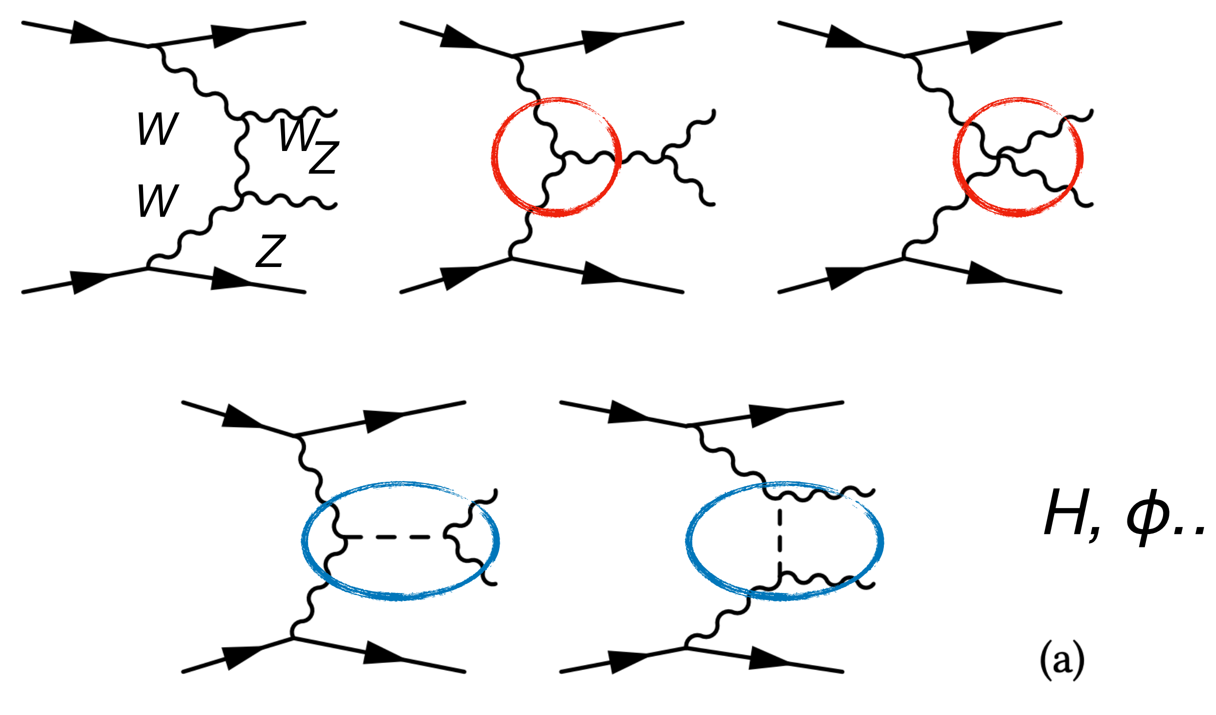
Exploiting the non-Abelian nature of the SU(2)XU(1) symmetry group: vector bosons interact!

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - ig f^a_{bc} A^b_\mu A^c_\nu$$

single boson



diboson



very clean signature at colliders: 2 isolated leptons + 2 high energy jet highly separated in Δη

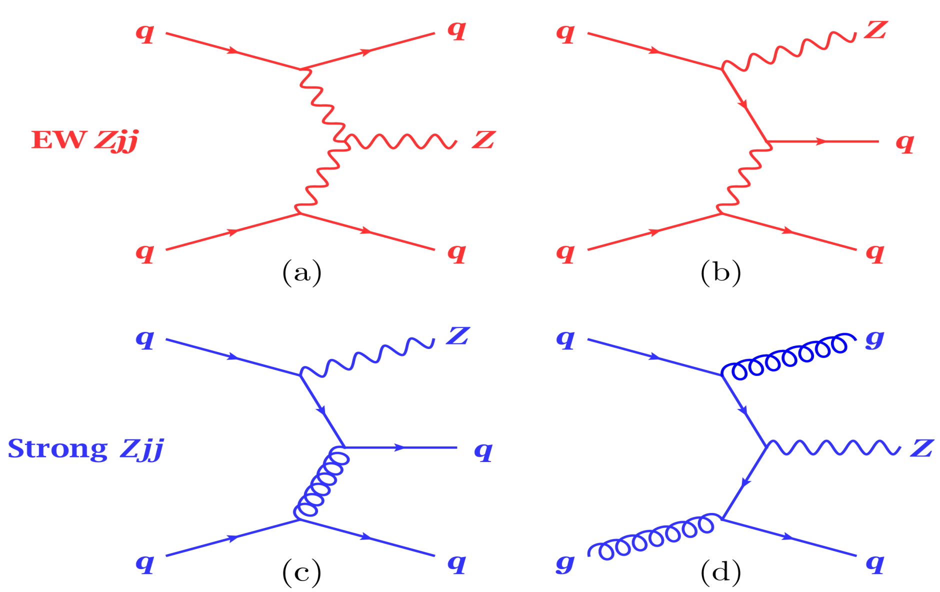
- pure EW production: order α^4_{EW} versus Drell-Yan order $\alpha^2_{QCD}\ \alpha^2_{EW}$
- includes diagrams with VBF processes: highly sensitive to EWSB and potential New Physics
- constrain SM-forbidden diagrams including higher order operators: anomalous triple/quartic gauge couplings

$$\mathscr{L}_{aQGC} = \mathscr{L}_{SM} + \sum_i \frac{f_i}{\Lambda^{d-4}} O_i + \ldots$$

A model-independent way of searching for New Physics

Electroweak Z+JJ

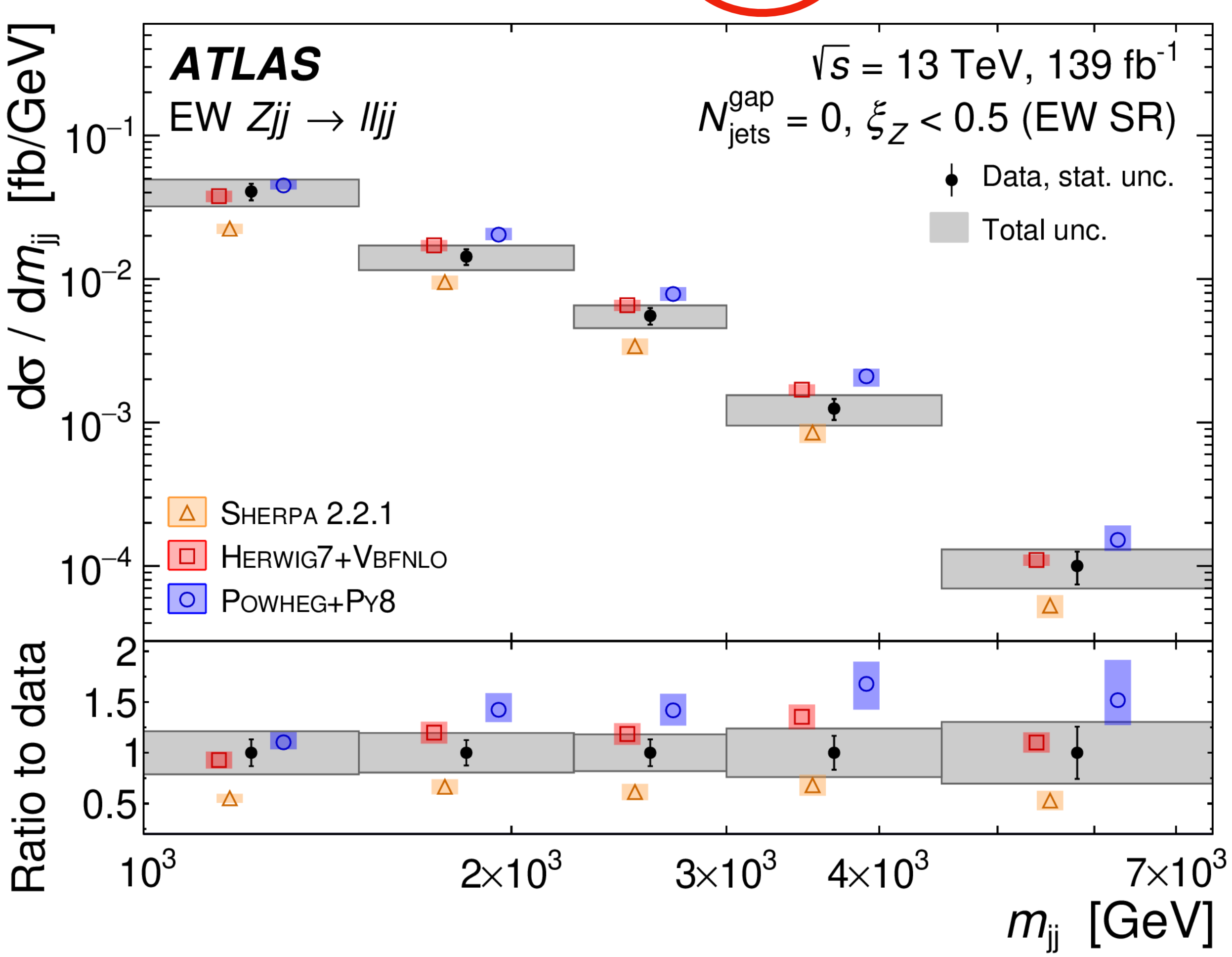
submitted to the EPJC
https://arxiv.org/abs/2006.15458

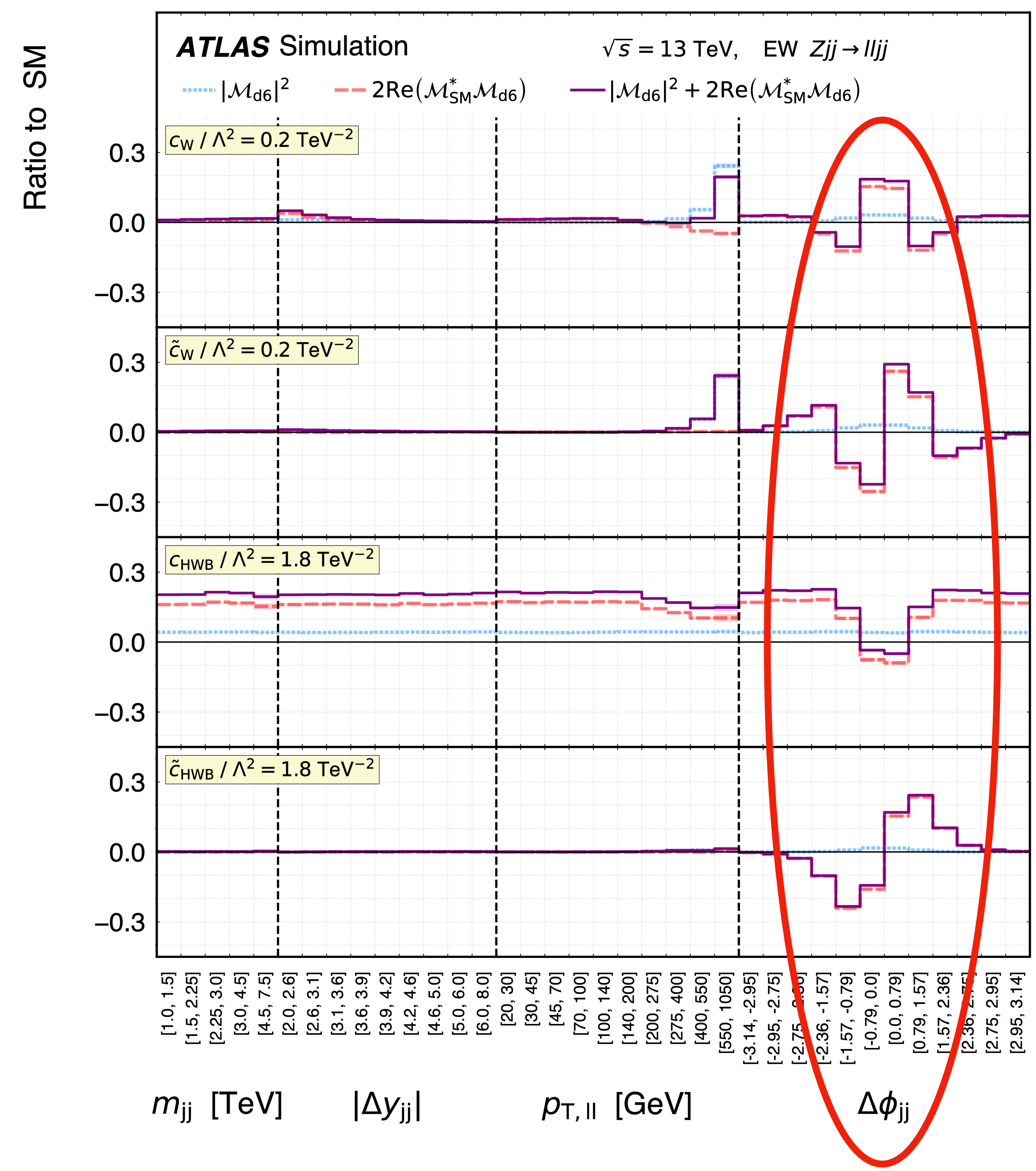


sensitive to the VBF production mechanism

test of potential anomalous weak bosons self-interactions using dim-6 operators EFT generated

Differential cross sections of $Z \to \ell\ell + jj$ VS dijet mass, y^{jj}, $\Delta\phi^{\ell\ell}$ and p_T^Z

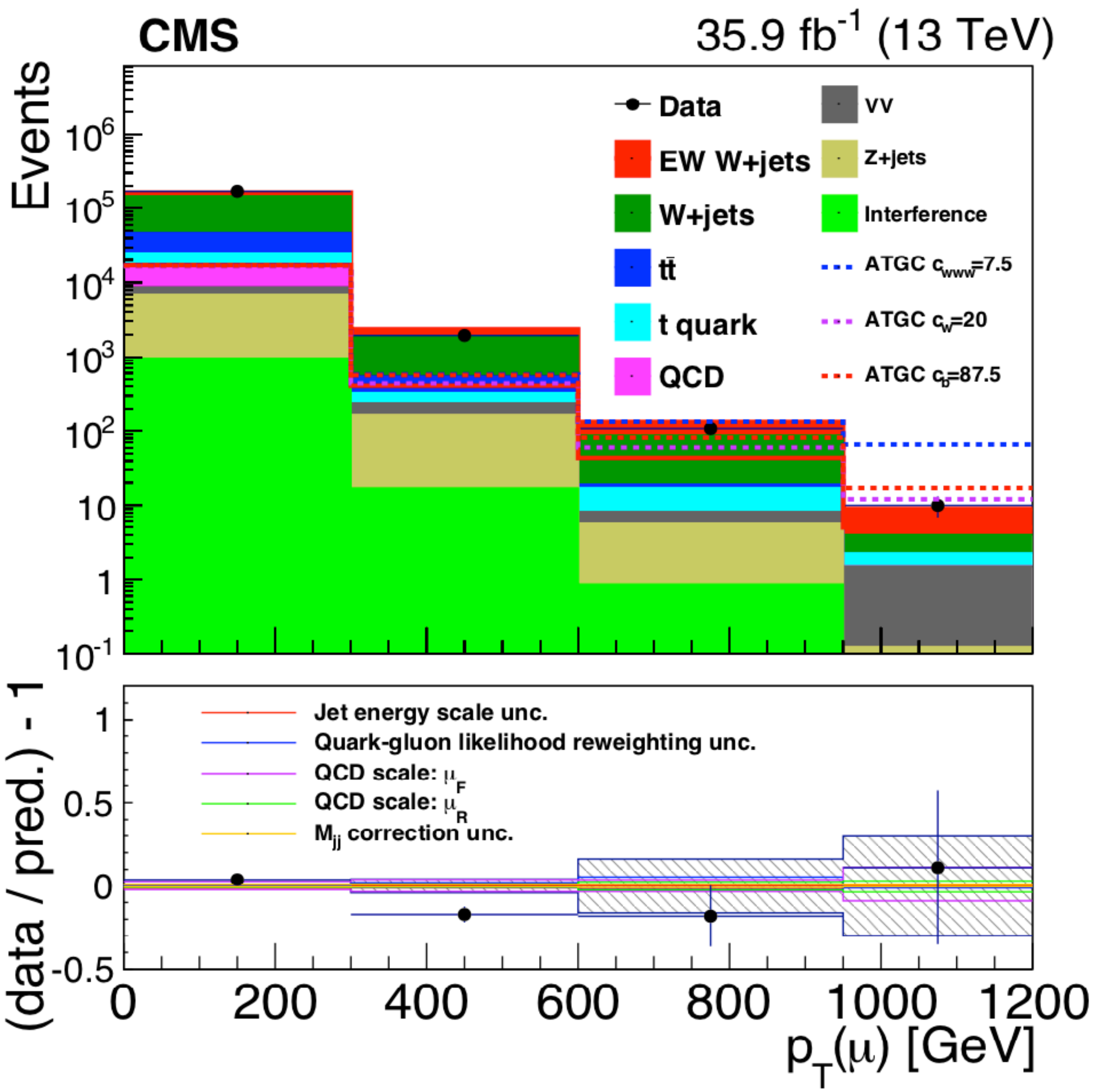




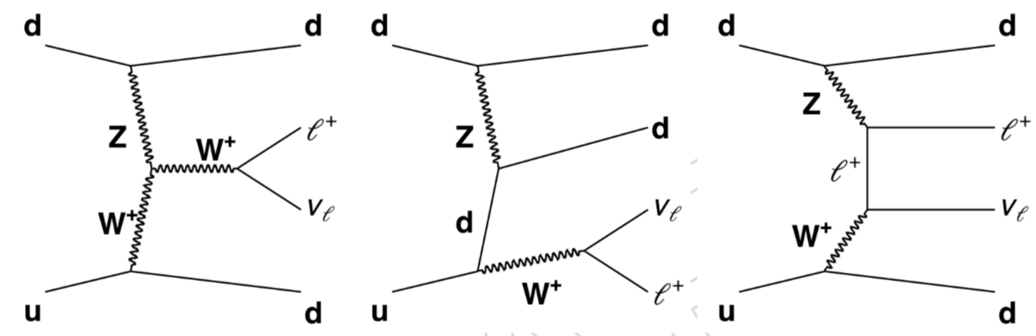
CMS @ 13 TeV

Electroweak W+JJ

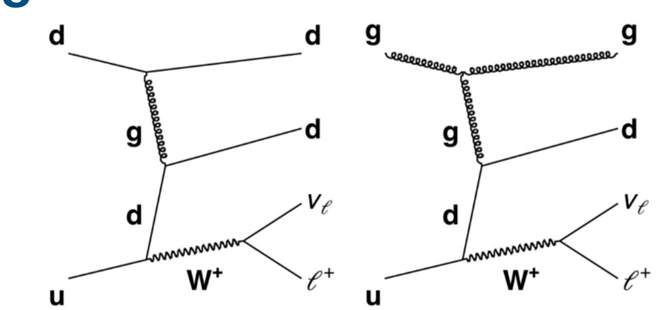
Eur. Phys. J. C 80, 43 (2020)



Signal VBF pure electroweak



Background



Drell-Yan

pure EW production: only q-jets initiated
DY production: ~50% jets produced are gluon-induced g-Gluon Likelihood discrimination (**QGL**)

Vector Boson Fusion Z topology:

- Central *W* decay plus 2 forward-backward jets
- Large dijet Δη separation
- Invariant dijet mass > 200 GeV
- Jet p_T > 50,30 GeV

- Limits on cWWW,cW, cB anomalous couplings from the sigle lepton p_T (with mild BDT>0.5 selection)

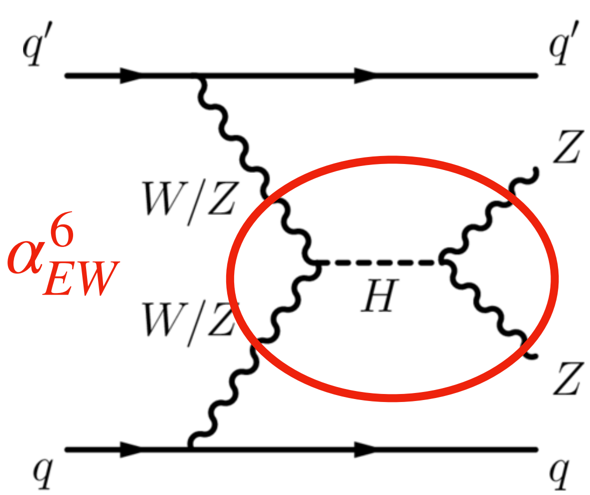
ATLAS @ 13 TeV
CMS @ 13 TeV
~140 fb^{-1}

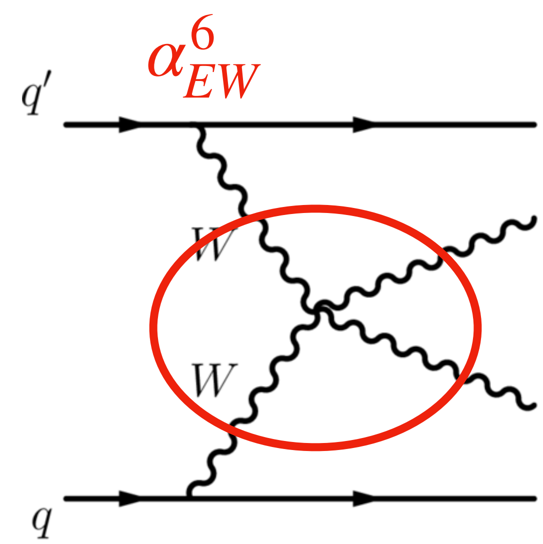
Electroweak ZZ+JJ

new!

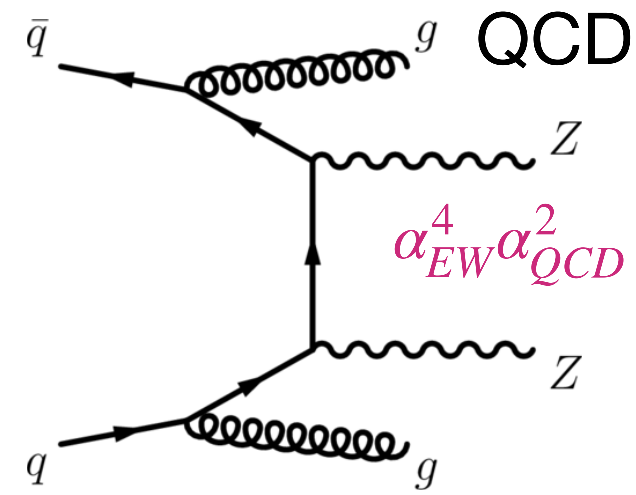
arXiv:2004.10612
arXiv:2008.07013
submitted to PLB
submitted to Nature Physics

first observation





QCD-induced

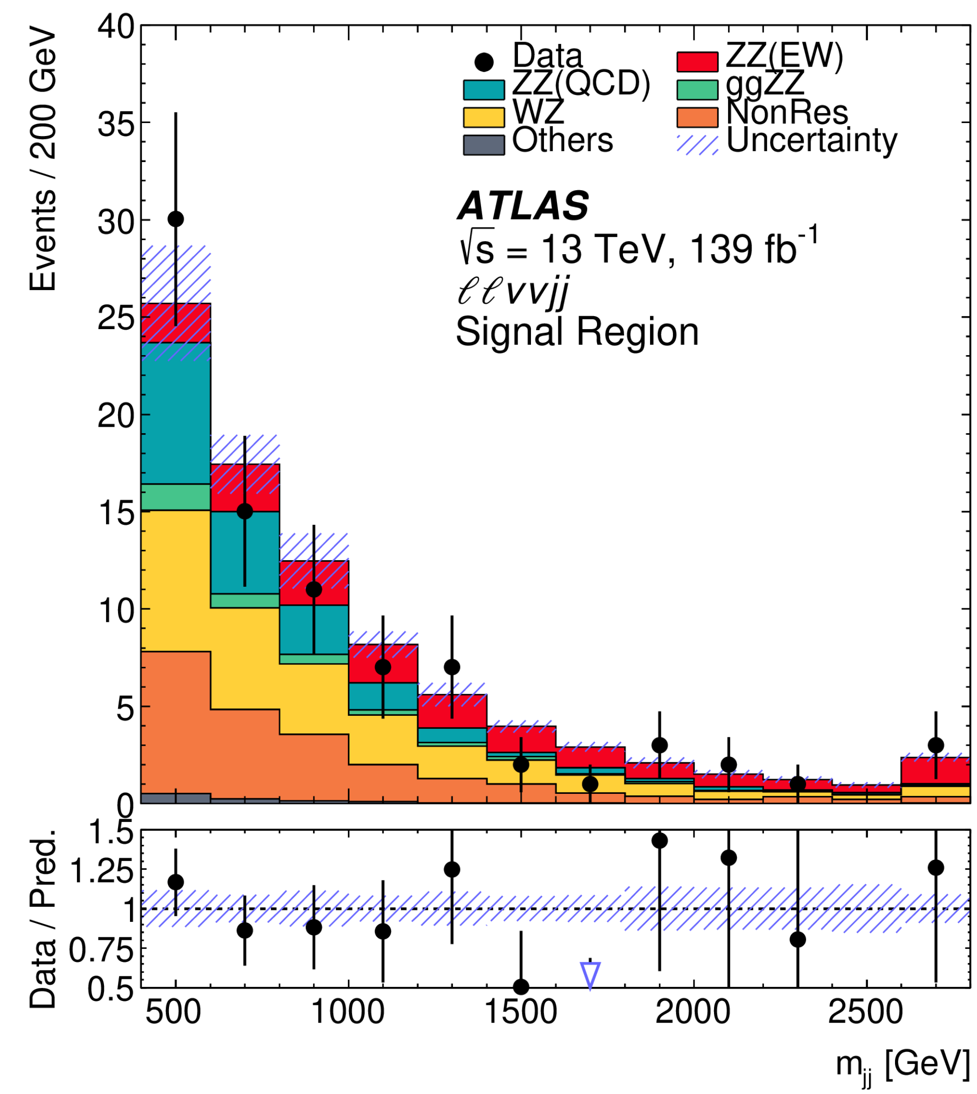


accessing the nature of electroweak symmetry breaking

ZZ+JJ is a rare process: α^6_{EW} - important test of the SM

testing anomalous quartic gauge couplings also possible

- final state with $4\ell + jj$ (e/μ)
- VBS sub-region with $\Delta\eta, m_{jj}$ cuts
- MVA/MELA to discriminate EW signal
- SM prediction: $\sigma = 0.275 \pm 0.021$



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~140 fb^{-1}

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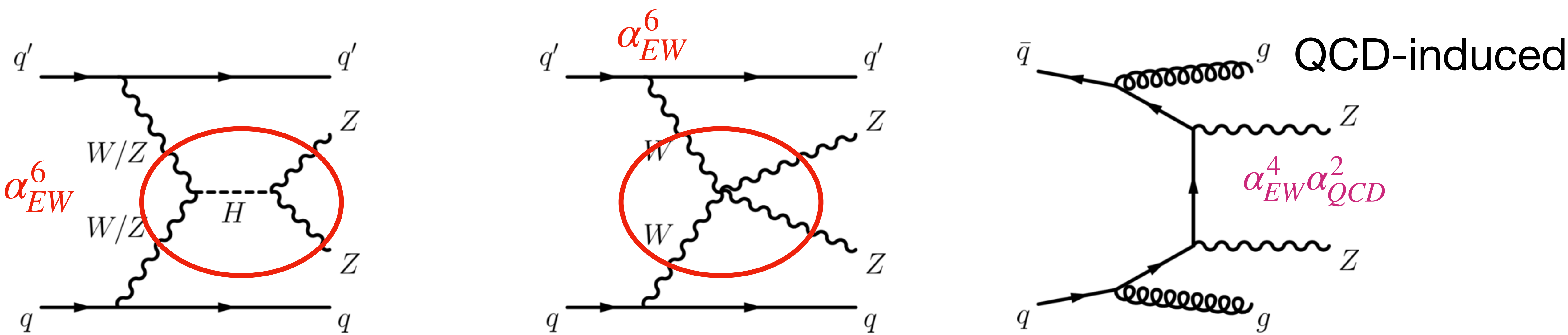

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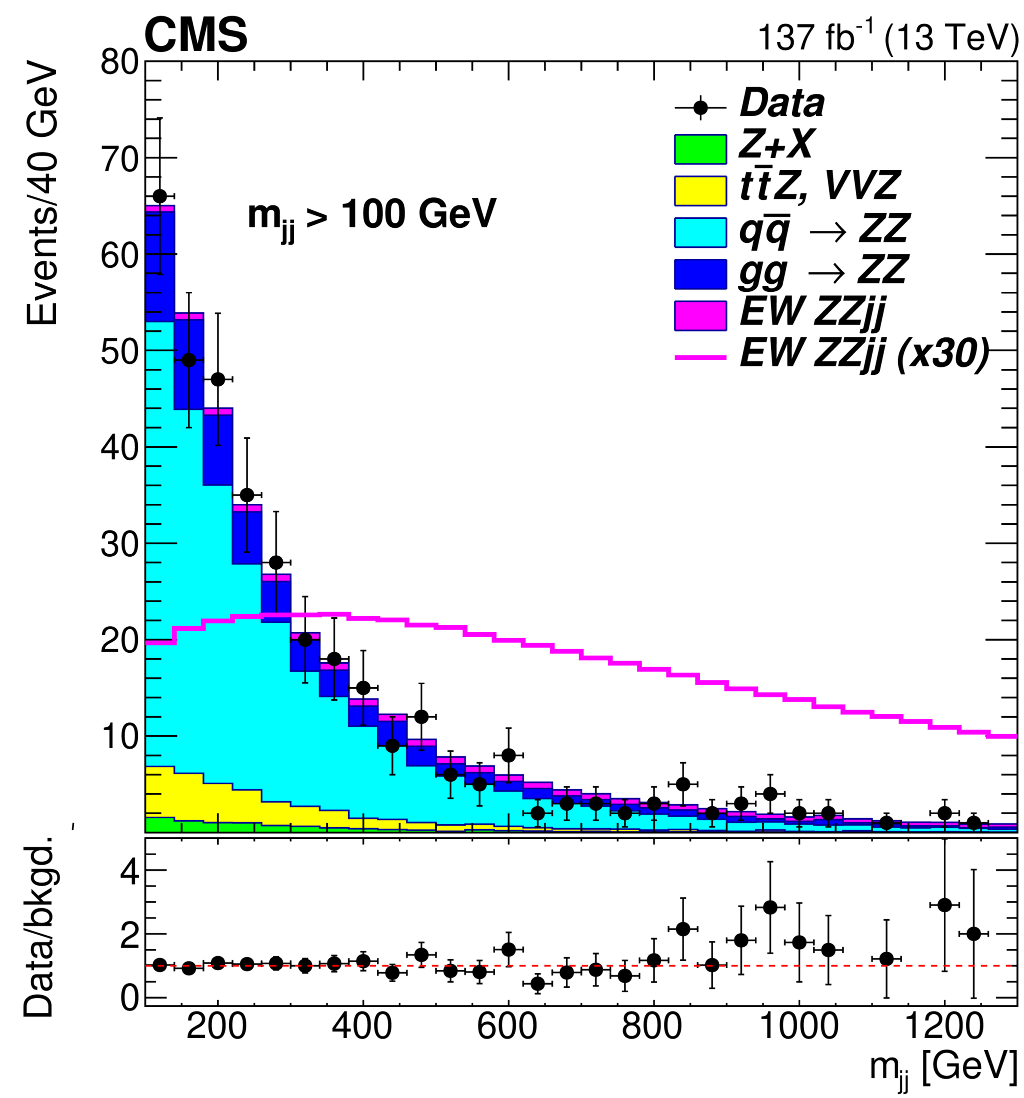

ATLAS @ 13 TeV
CMS @ 13 TeV
~140 fb^{-1}

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new!

arXiv:2004.10612
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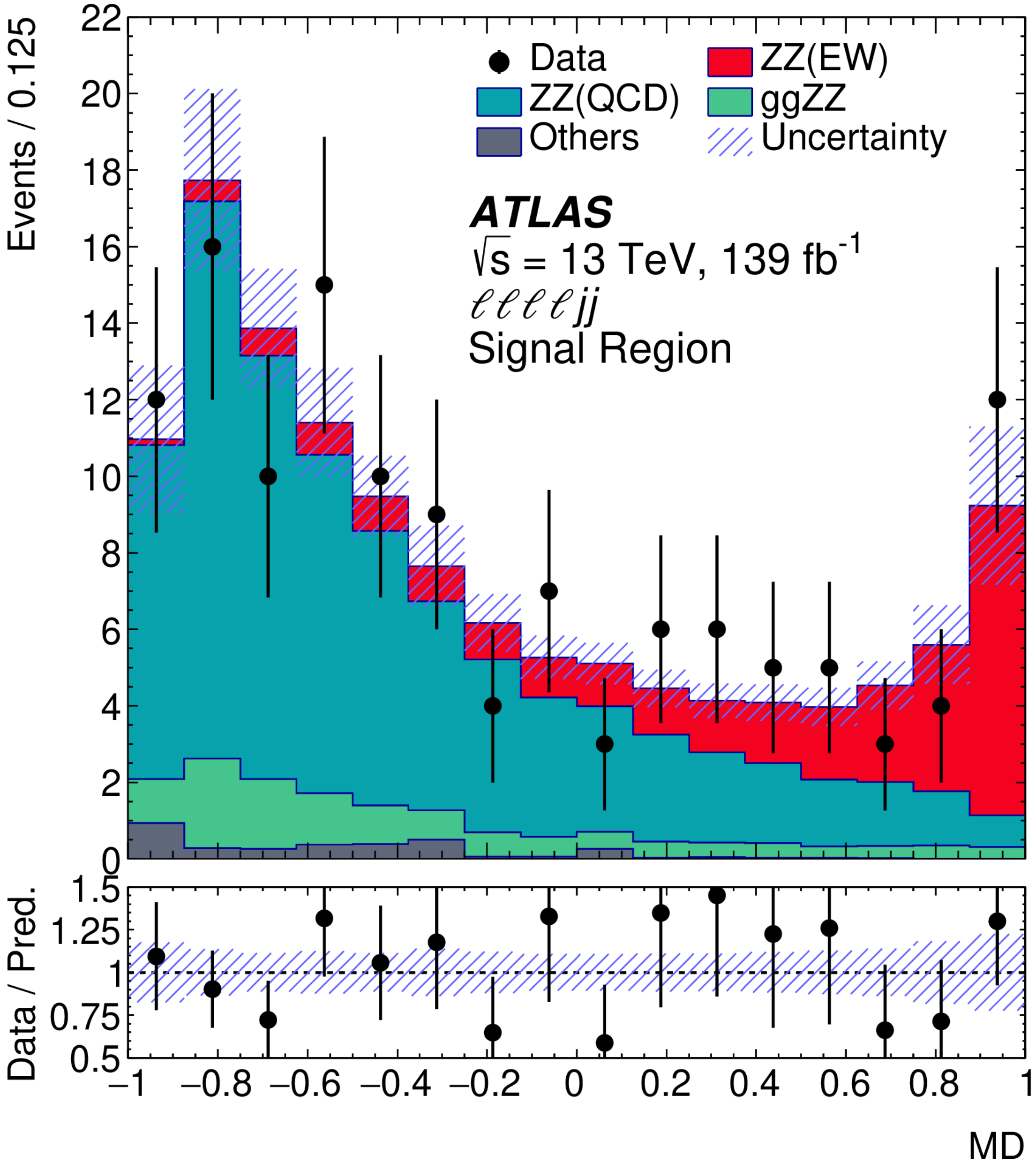
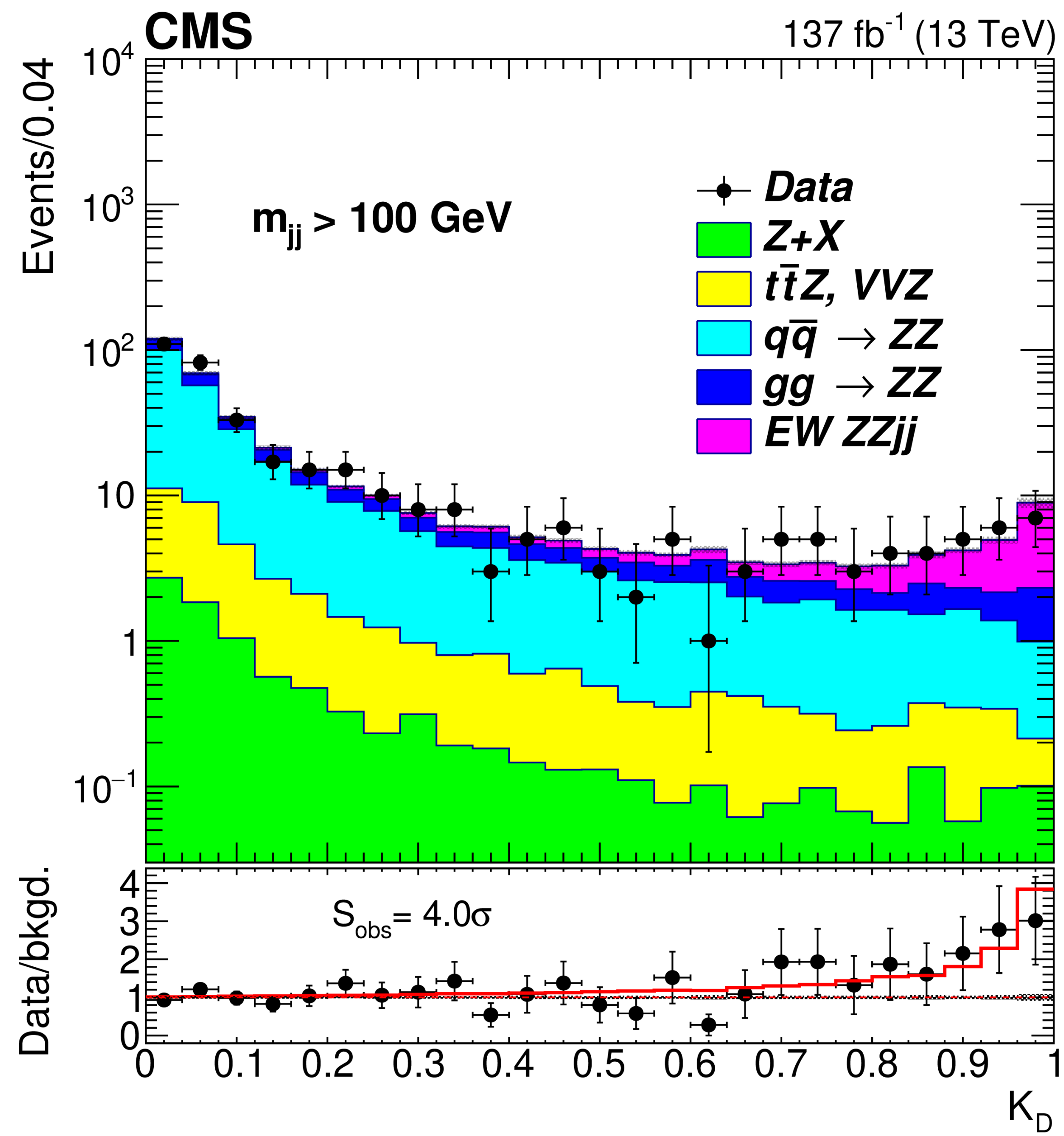




ATLAS: σ obs.(exp) =5.5 (3.9)

CMS: σ obs.(exp) = 4.0 (3.5)

CMS @ 13 TeV

Evidence of Triboson

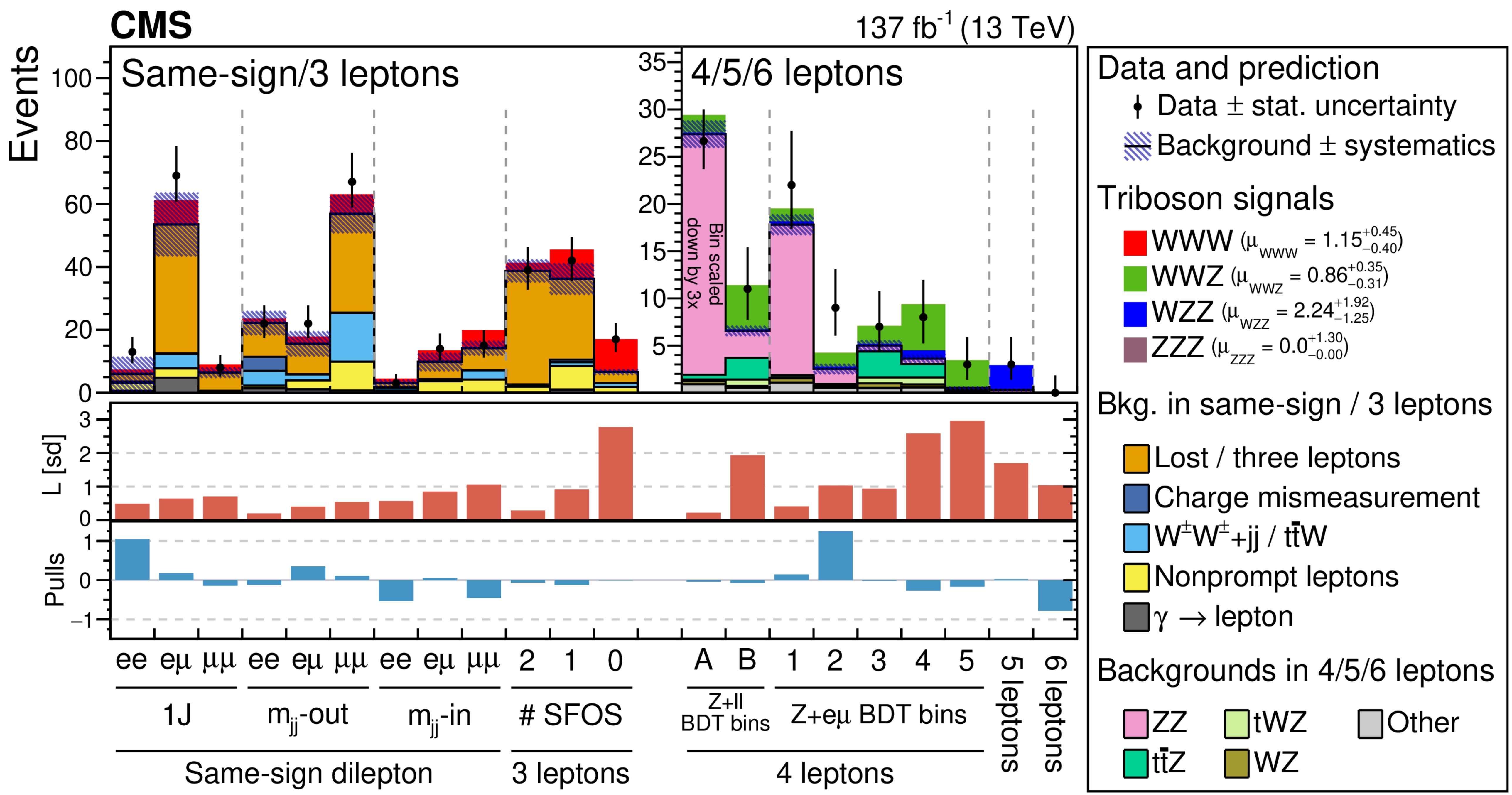
new!

first observation

http://arxiv.org/abs/2006.11191
accepted for publication Phy. Rev. Lett.

combined VVV production, V=W,Z

WWW, WWZ, WZZ, and ZZZ production are performed in final states with three, four, five, and six leptons (electrons or muons), or with two same-sign leptons plus one or two jets

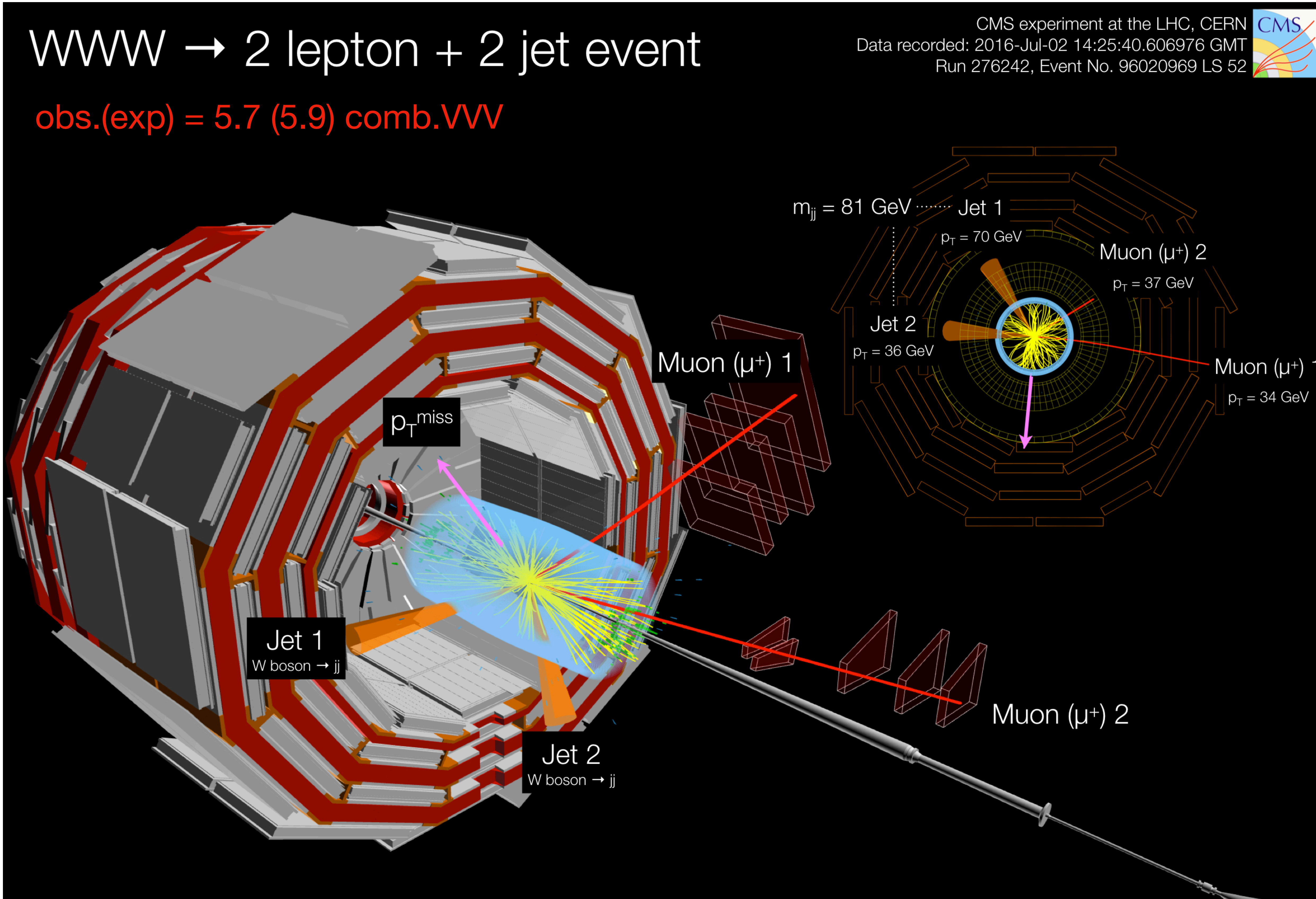


SM@NLO predicts 509, 354, 91.6, and 37.1 fb for WWW, WWZ, WZZ, and ZZZ

CMS @ 13 TeV

Evidence of Triboson

new!



Summary and conclusions

Impressive set of electroweak bosons results from LHC at 13 TeV!

- Selected measurement of cross sections for *V, V+jets, EW VJJ and VVV* in Run2 data presented

- Overall very good agreement with the Standard Model predictions at LO and NLO, first observations of processes such as ZZ+JJ and VVV

- Several EFT higher order operators describing anomalous couplings constrained with high precision using single and diboson channels

- A continuous effort of making new measurements with new ideas, new techniques exploring the most farthest corners of the SM

much more to come… stay tuned for the future of the Standard Model is here!

backup

Phenomenology of V+Jets production

adding jets to V production allows to precisely test pQCD at higher perturbative orders up to NNLO, test generators and improve modelling

adding heavy flavours tagging opens a new world of SM phenomenology

perturbative QCD

- *Wc* : access the strange quark content of the proton
- *Zb* : understand the production mechanism
  - tree level vs NLO
  - 4FS ($m_b \neq 0$) vs 5FS ($m_b = 0$)
- PDF studies, NLO effects

Electroweak Measurements

- Higgs background *HZ*, *HW*
- Differential Cross sections
- *Zb* polarization asymmetry
  $\sin^2\Theta_W^{eff}$, couplings

Beyond the Standard Model

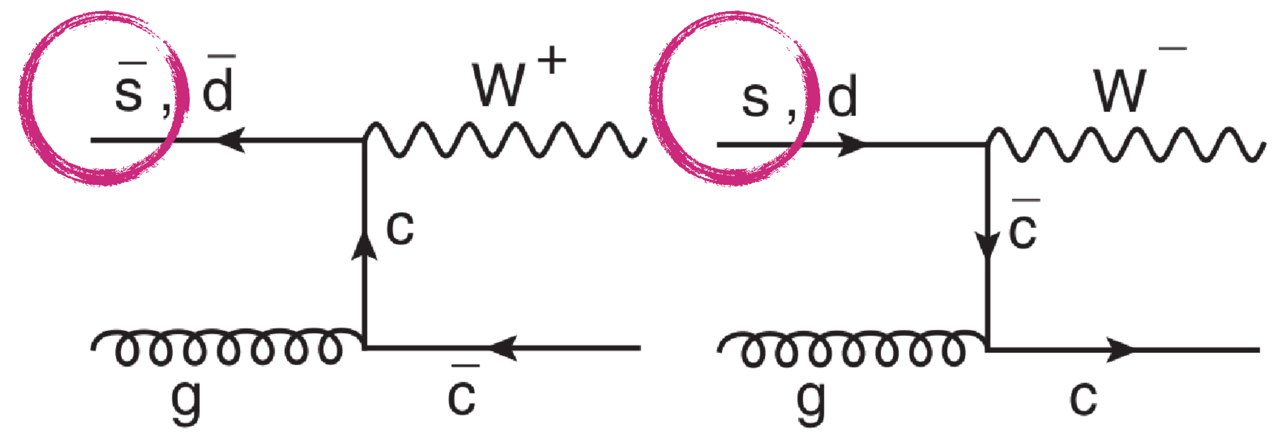
- 4th generation heavy *b',t'* quarks decaying to *Vb*
- Multi Higgs-doublets Models
- supersymmetry with *sbottoms*

W plus c quarks

CMS @ 13 TeV

Eur. Phys. J. C 79 (2019) 269

accessing the strange sea of the proton

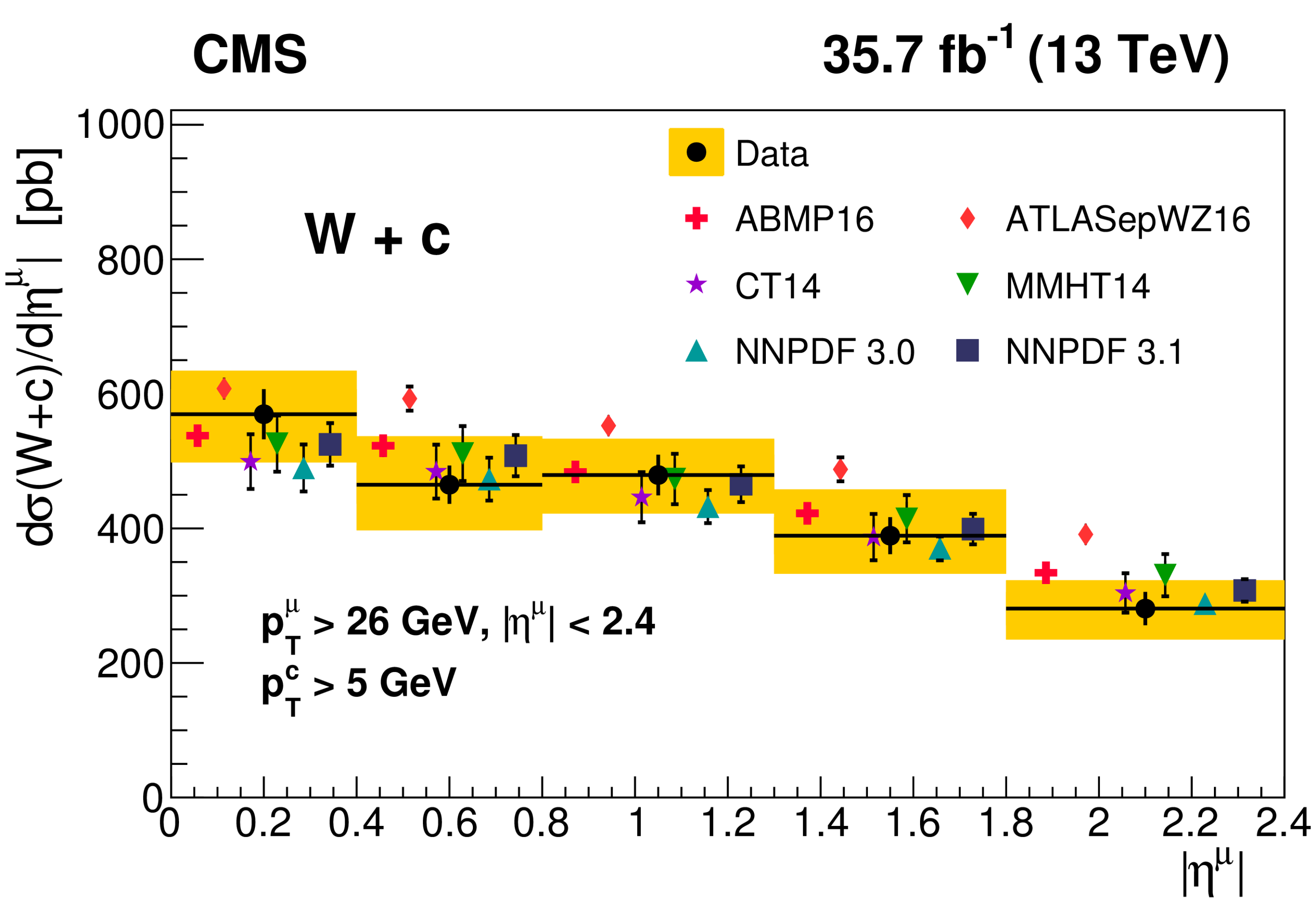


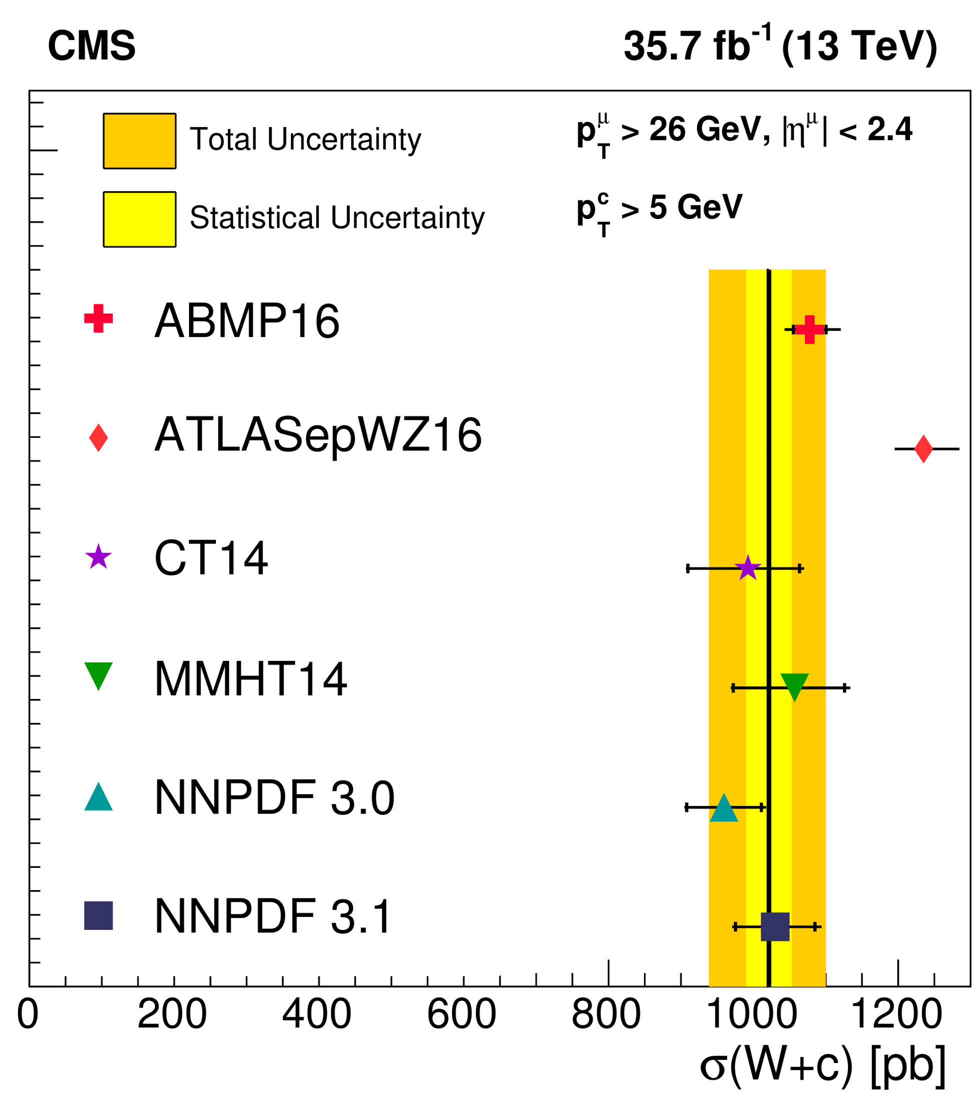
c quarks identified through

$$D^*(2010)^\pm \to D^0\pi^\pm \to K^\mp\pi^\pm\pi^\pm$$

fiducial cross section in

$$p_T^\mu > 26 GeV, |\eta_\mu| < 2.4, p_T^c > 5 GeV$$





ATLAS @ 13 TeV

Same-Sign VBF WW mode

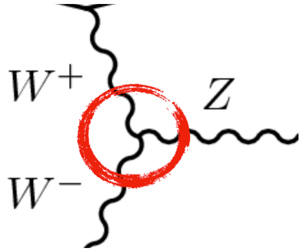
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2017-06/

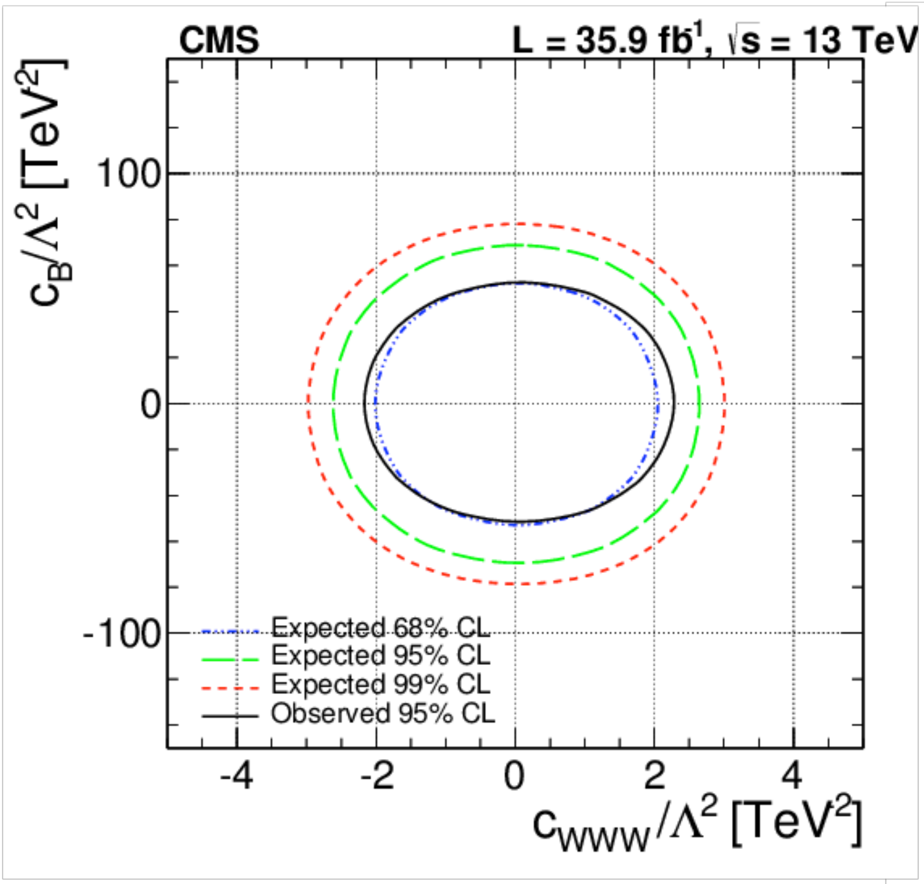
Electroweak production of W+JJ

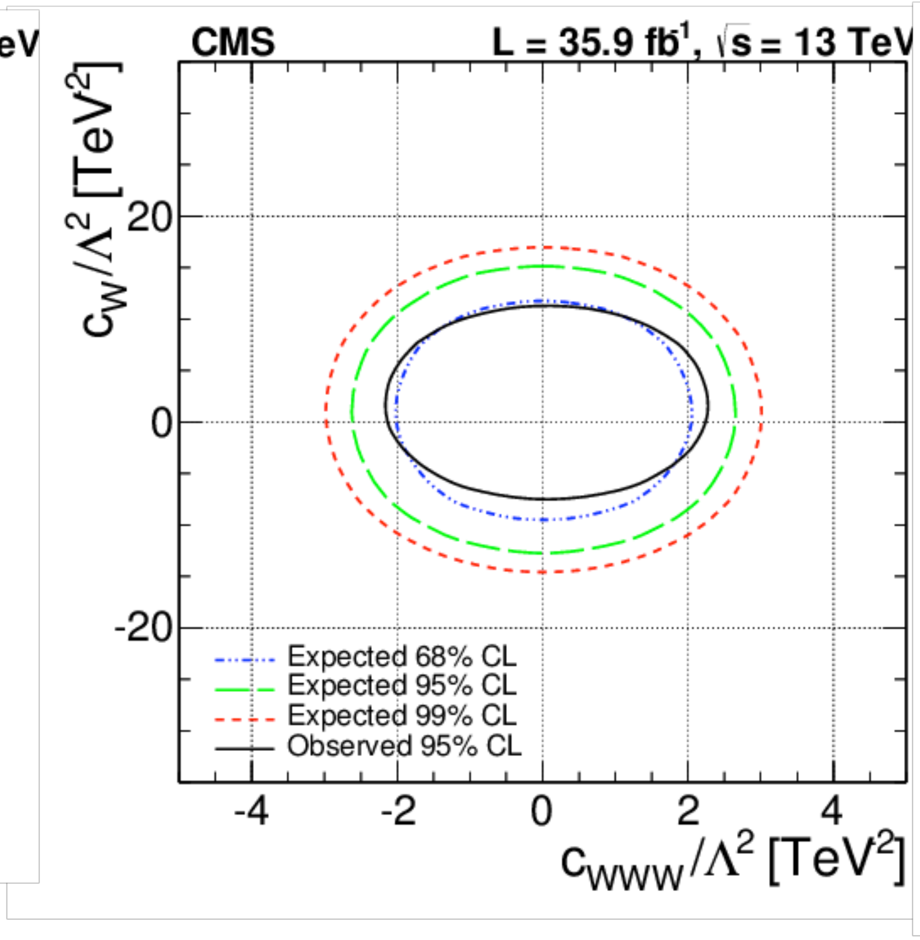
$\sqrt{s} = 13$ TeV
$\int L = 35.9$ fb^{-1}

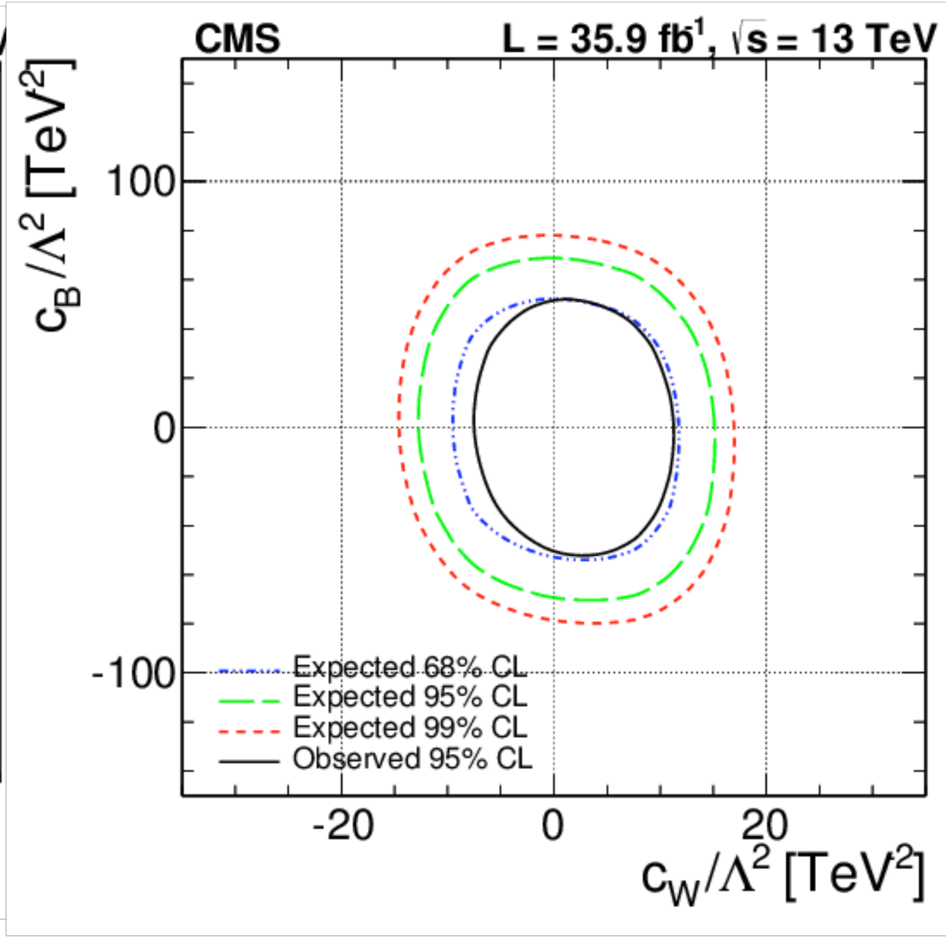
aTGC combination EW ZJJ + WJJ

enhancing sensitivity on the common WWZ vertex







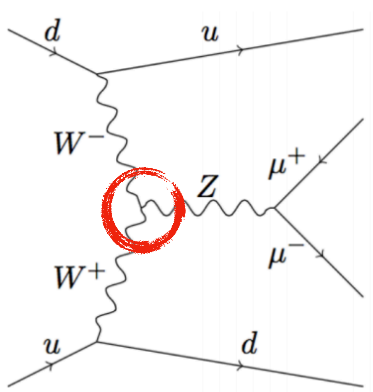


simultaneous fit to p_T^Z (EW-Z) and p_T^{lep} (EW-W)

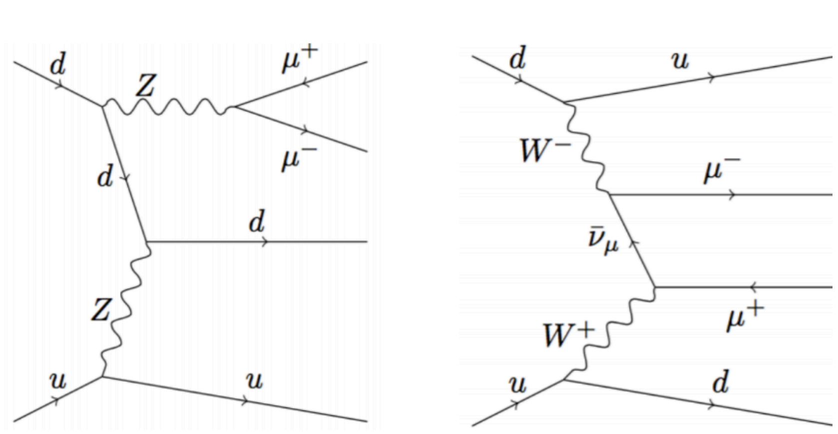
Most stringent experimental constrain on c_{WWW}/Λ^2 so far!

Electroweak production of Z+JJ

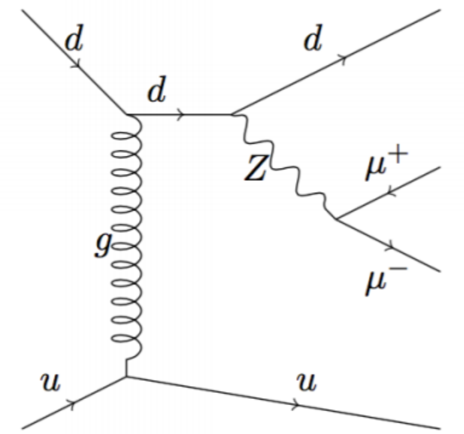
$\sqrt{s} = 13$ TeV
$\int L = 35.9\ fb^{-1}$



VBF Signal



Pure Electroweak



DY background

Signal definition

pT(j)>25 GeV, |η(j)|< 5, m(jj)>120 GeV, m(ll)>50 GeV and cross section

Vector Boson Fusion Z topology:

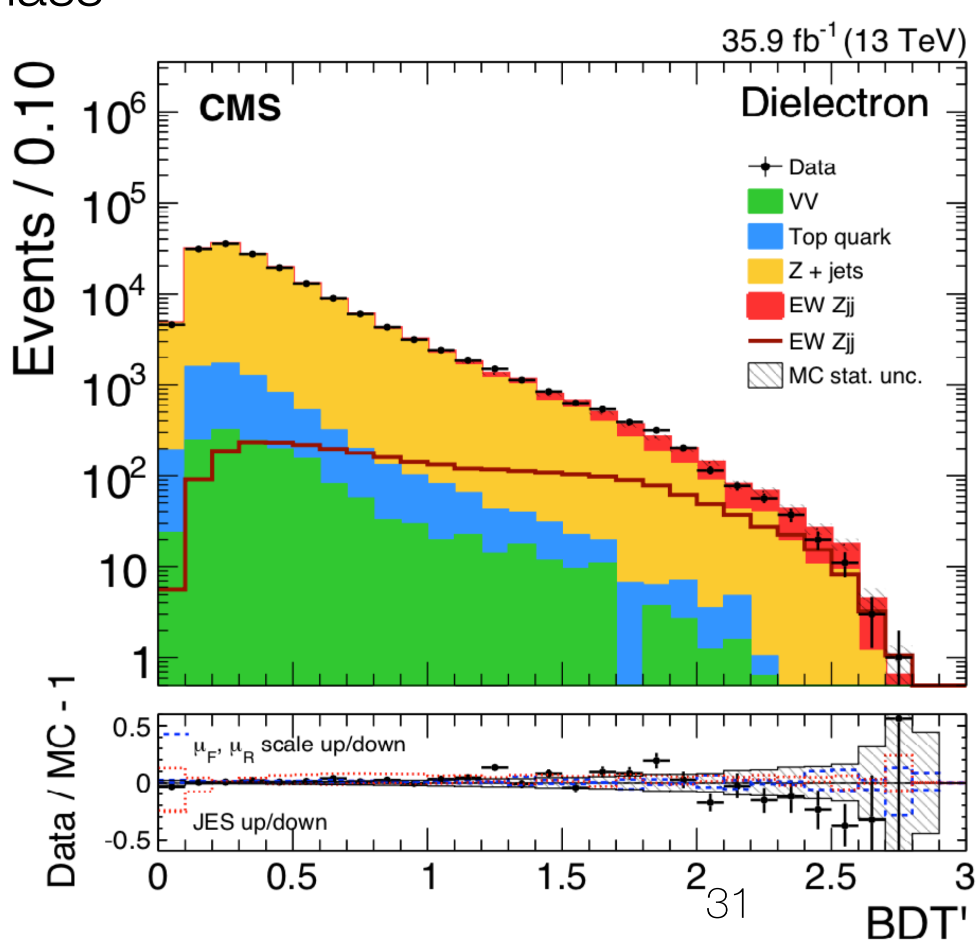
- Central Z decay +2 forward-backward jets
- Large dijet Δη separation
- Large invariant dijet mass

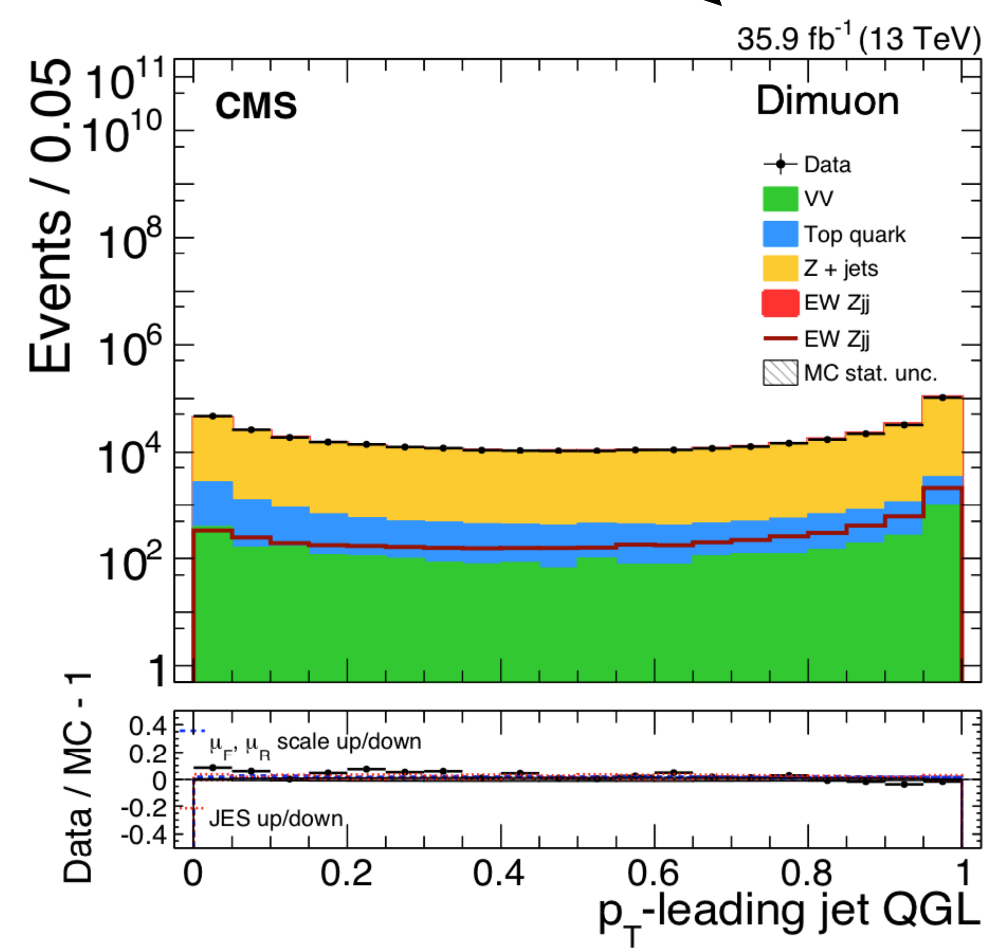
pure EW production: only q-jets initiated
DY production: ~50% jets produced are g-induced
Quark-Gluon Likelohood discrimination (**QGL**)

Signal is generally covered by the DY background

Signal Extraction:
Use multivariate analysis techniques to separate signal events from large DY background

- m(qq), Δη(qq),
- QGL,
- pT(qq),
- R(pThard),
- z*ll



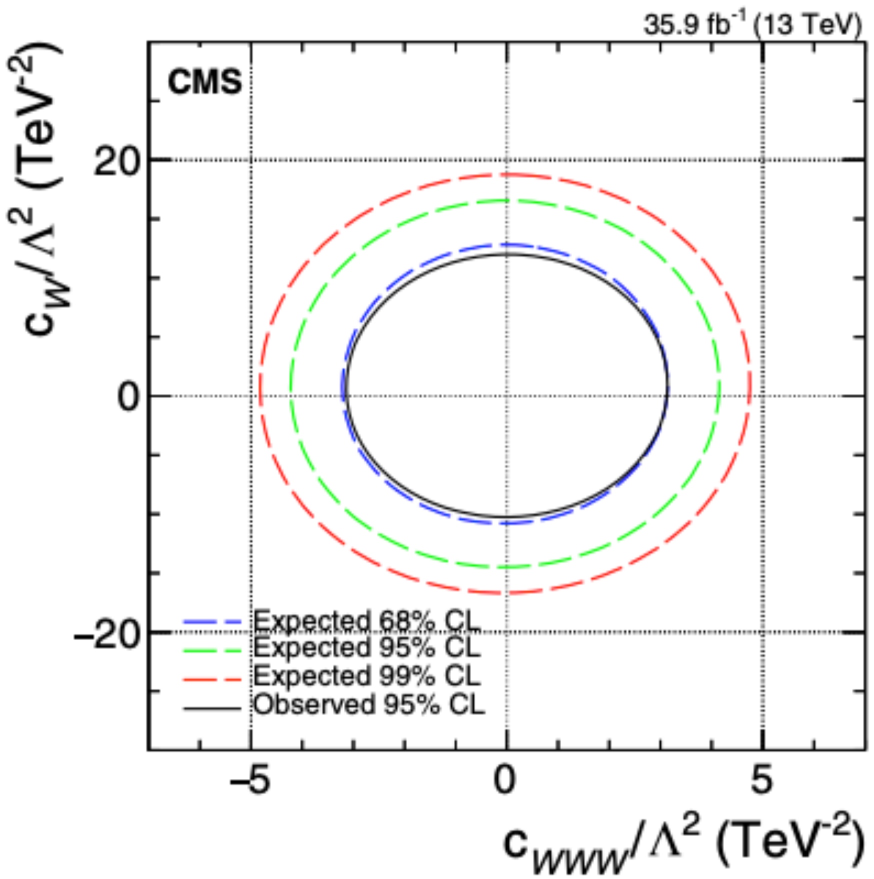


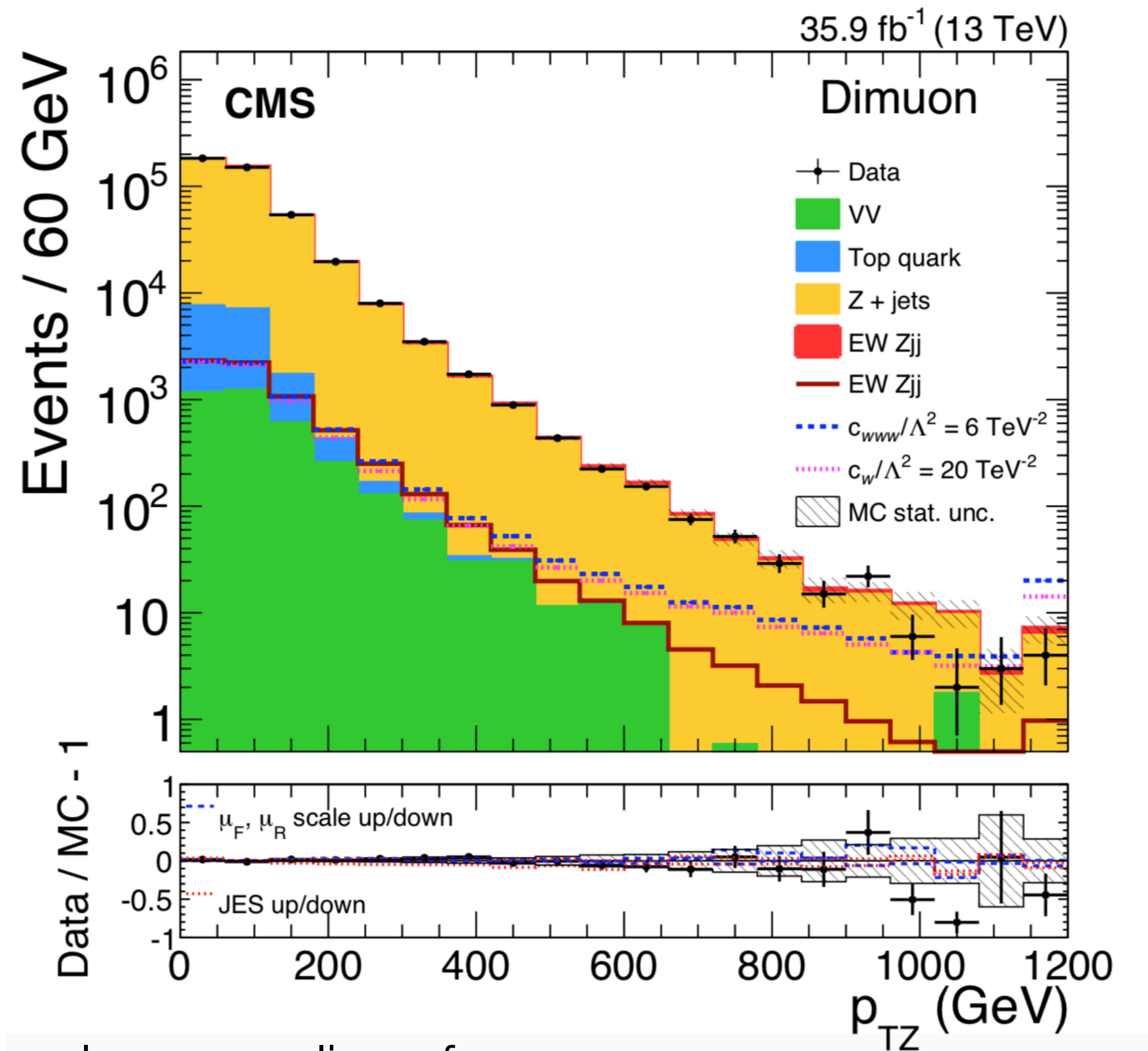
Electroweak production of Z+JJ

$\sqrt{s} = 13$ TeV
$\int L = 35.9\ fb^{-1}$

→ **σ(EW lljj) = 534 ± 20 (stat) ± 57 (syst) fb = 534 ± 60 (total) fb**

σ_{LO} (EW lljj) = 543 ± 24 fb





$$\mathcal{O}_{WWW} = \frac{c_{WWW}}{\Lambda^2} W_{\mu\nu} W^{\nu\rho} W^{\mu}_{\rho},$$
$$\mathcal{O}_{W} = \frac{c_{W}}{\Lambda^2} (D^{\mu}\Phi)^{\dagger} W_{\mu\nu} (D^{\nu}\Phi),$$
$$\mathcal{O}_{B} = \frac{c_{B}}{\Lambda^2} (D^{\mu}\Phi)^{\dagger} B_{\mu\nu} (D^{\nu}\Phi),$$
$$\widetilde{\mathcal{O}}_{WWW} = \frac{\widetilde{c}_{WWW}}{\Lambda^2} \widetilde{W}_{\mu\nu} W^{\nu\rho} W^{\mu}_{\rho},$$
$$\widetilde{\mathcal{O}}_{W} = \frac{\widetilde{c}_{W}}{\Lambda^2} (D^{\mu}\Phi)^{\dagger} \widetilde{W}_{\mu\nu} (D^{\nu}\Phi),$$

- Limits on anomalous couplings from dilepton p_T spectrum after preselection
- 6-dimensional EFT approximation
  simulated with MADGRAPH5 aMC@NLO

95%CL

$-8.4 < c_W/\Lambda^2 < 10.1 TeV^{-2}$

$-2.6 < c_{WWW}/\Lambda^2 < 2.6 TeV^{-2}$

most stringent constraints on ***cWWW*** to date with the *Z*

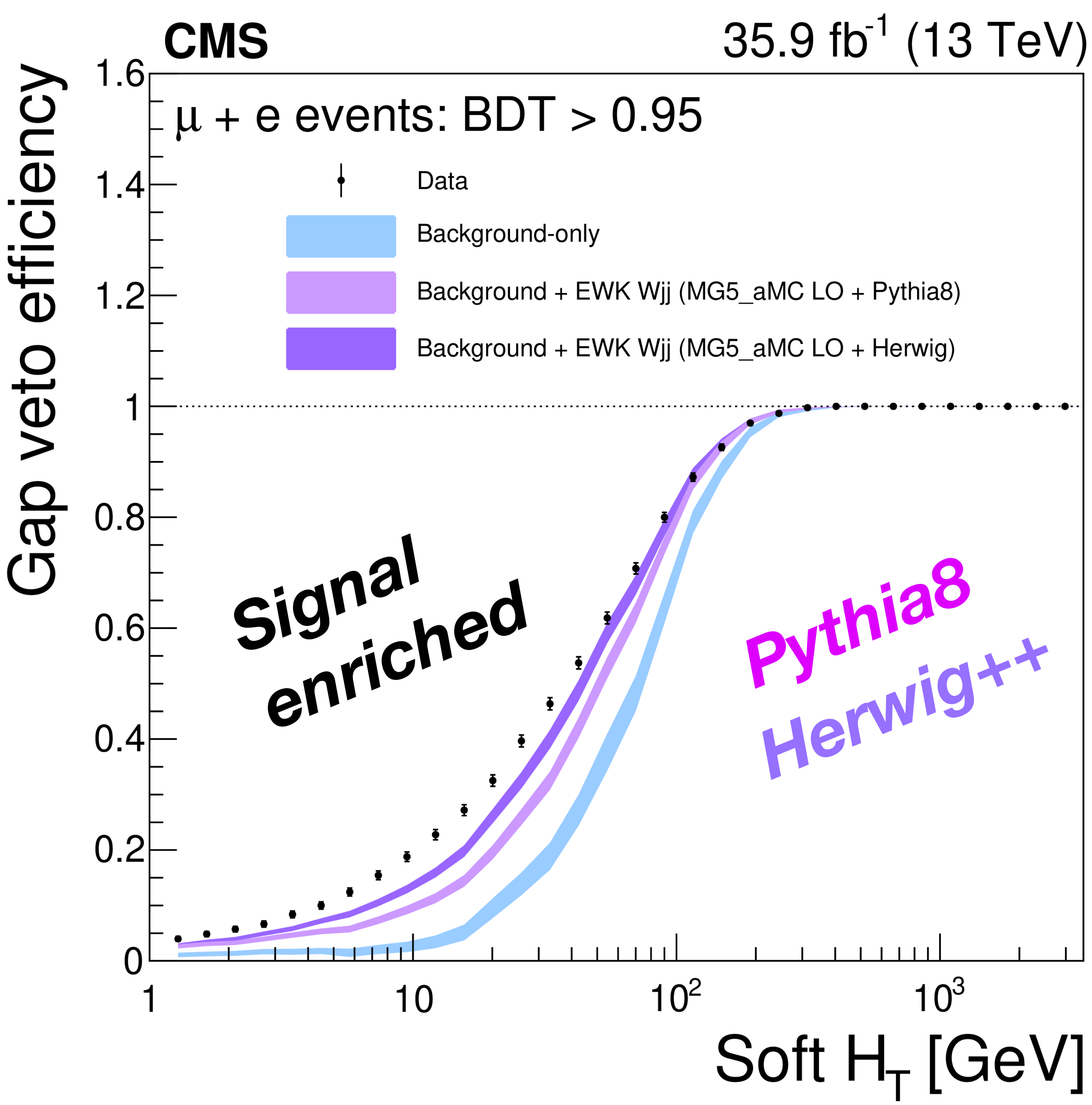
Rapidity Gap in VBF topologies

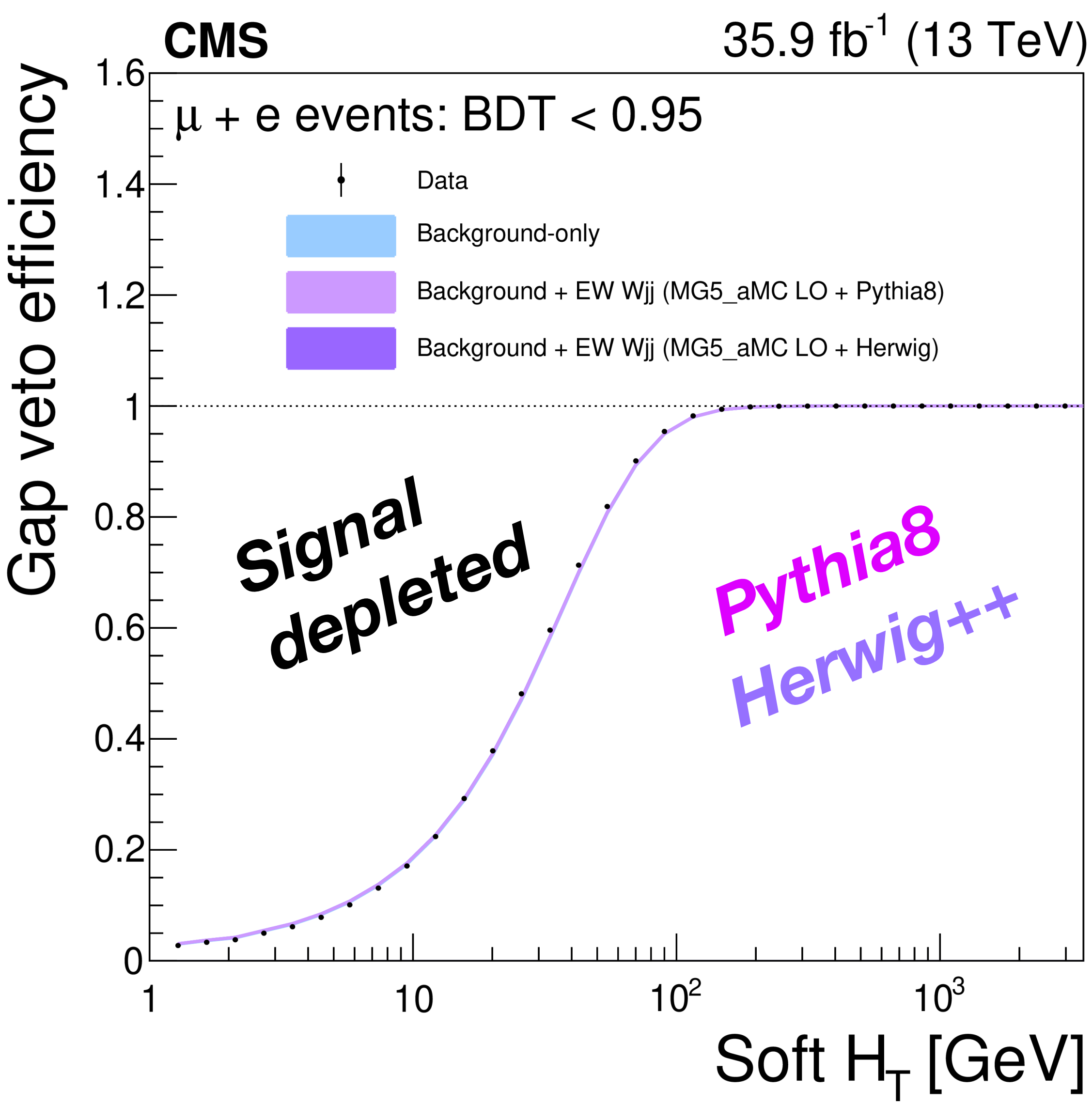
$\sqrt{s} = 13$ TeV
$\int L = 35.9$ fb^{-1}

Rapidity Gap

- Low hadronic activity is expected in the ΔηJJ region due to the pure EW nature of the interaction
- No color flow between the two tagged highly separated jets

additional jets produced and generated by the Parton Shower (Pythia and Herwig++) → powerful test of the Parton Shower model in Generators





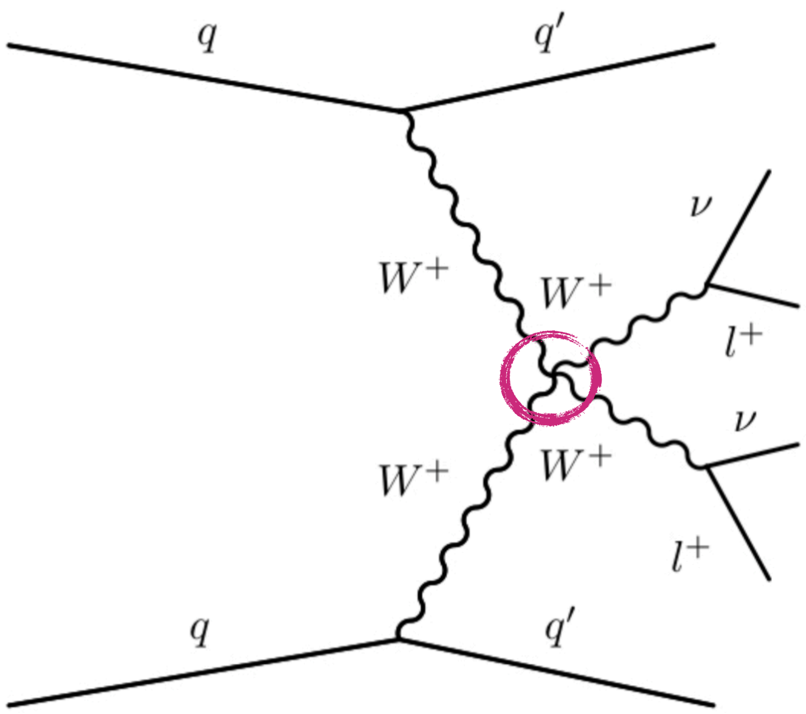
→ Pythia not describing the rapidity gap

→ good agreement

Same-Sign $W^{\pm}W^{\pm}$+JJ production

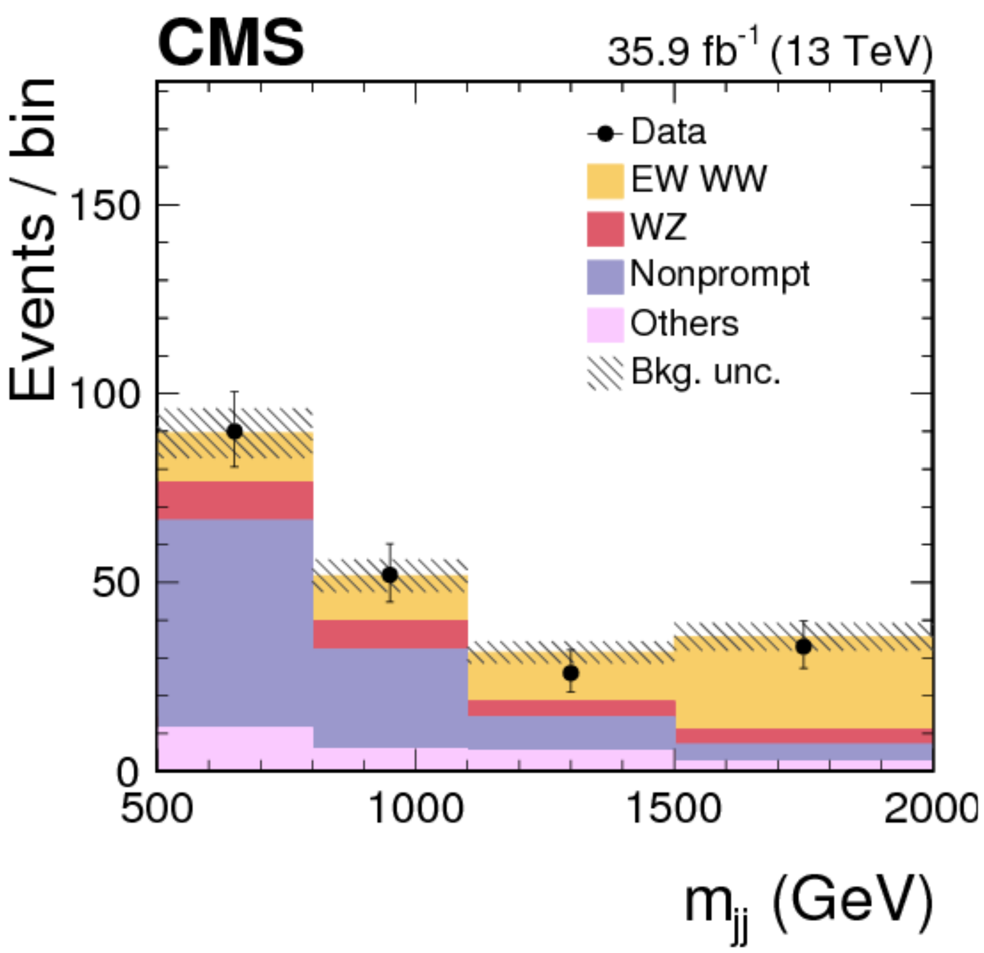
$\sqrt{s}$ = 13 TeV
$\int L$ =35.9 fb^{-1}

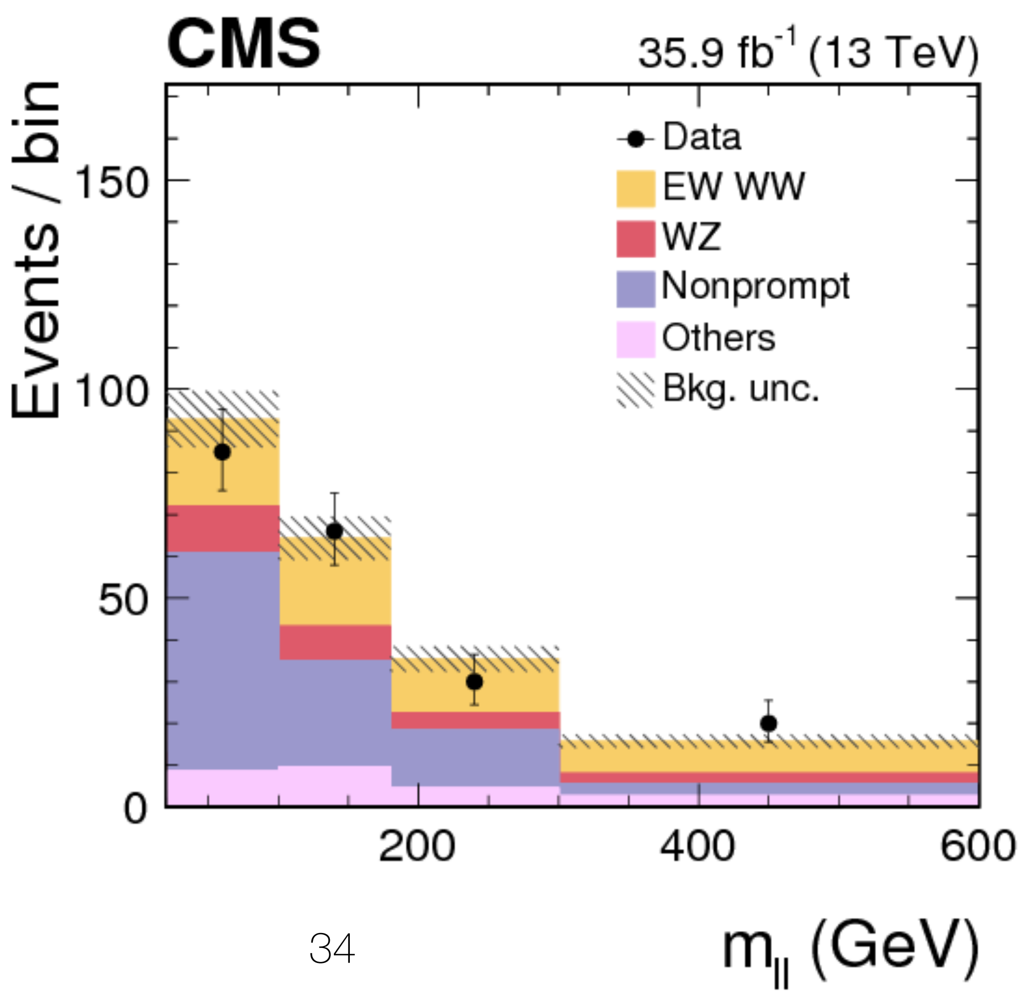
VBS EW production of same sign WW in ee,μe, μμ final states: probe of the quartic 4W coupling



selection criteria

- Exactly 2 S.S. isolated leptons pT>25,20 GeV and |η|<2.5
- VBS selection: 2 jets with p_T > 30 GeV
- m_{JJ} > 500 GeV $|\Delta\eta_{JJ}|$> 2.5
- b-jet veto + 3rd lepton veto for ttbar/WZ





- signal strength μ = σ/σSM from 2D fit to the dilepton and dijet distributions
- data driven estimation of WZ background (from non-prompt leptons)

Same-Sign $W^{\pm}W^{\pm}$+*JJ* production

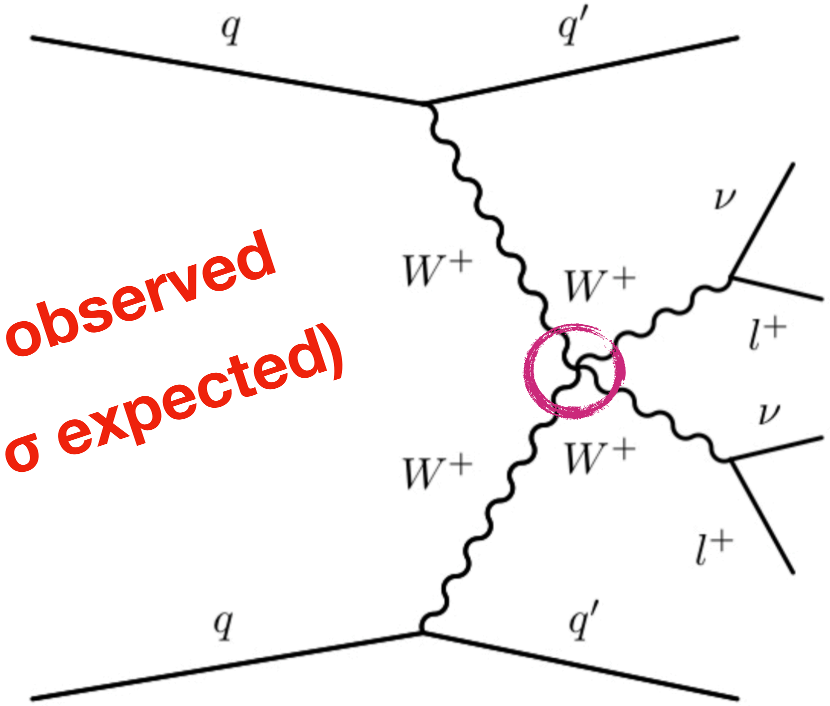
$\sqrt{s} = 13$ TeV
$\int L = 35.9\ \mathrm{fb}^{-1}$

dominant systematics:
jet energy scale (~7%)
non-prompt background (*WZ,* lepton mis-id, 30-40%)

$\sigma(W^{\pm}W^{\pm})^{\mathrm{meas.}} = 3.83 \pm 0.66(\mathrm{stat}) \pm 0.35(\mathrm{syst})$ fb

$\sigma(W^{\pm}W^{\pm})^{\mathrm{MadGraph\ LO}} = 4.25 \pm 0.27$ fb

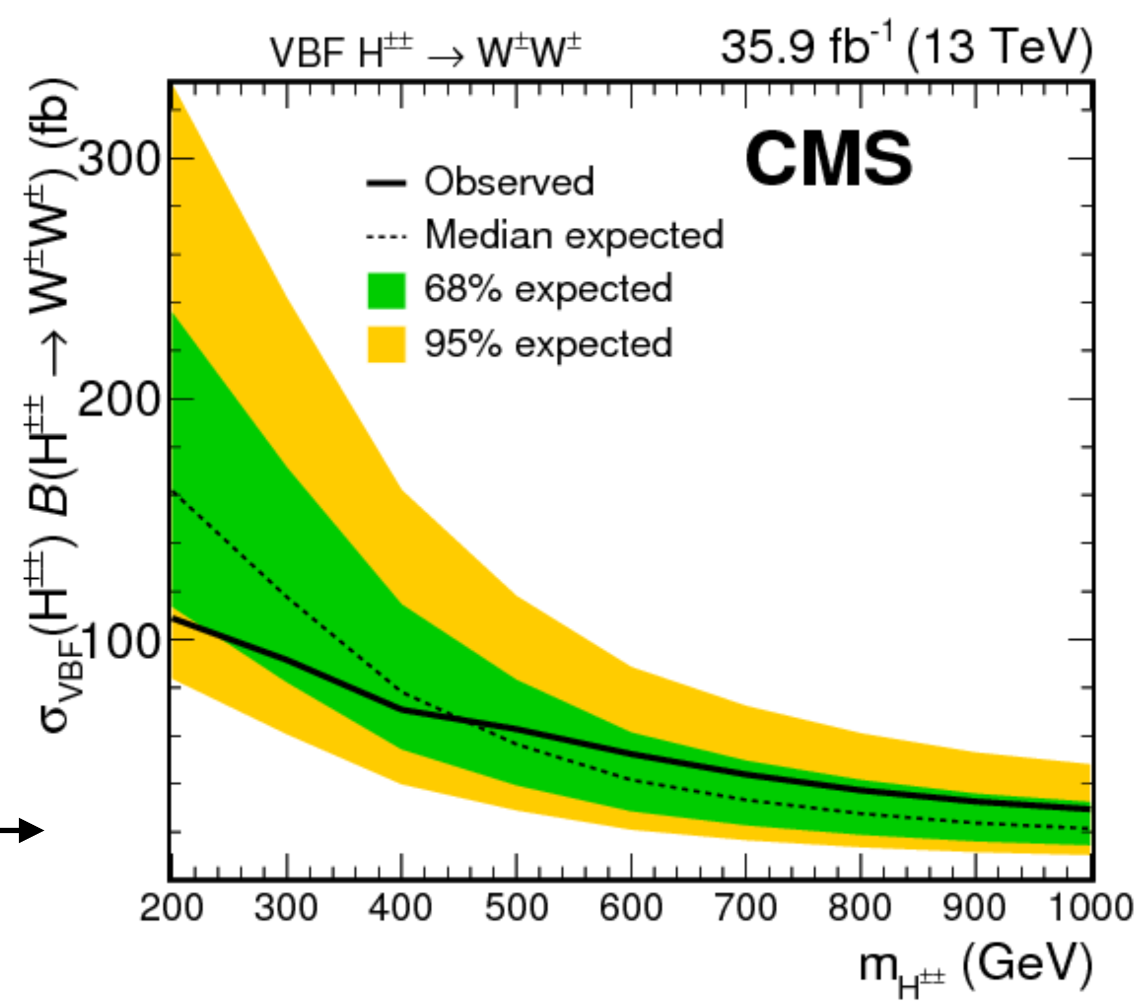
5.5σ observed
(5.7σ expected)



limits on dim-8 operators in aQGC EFT

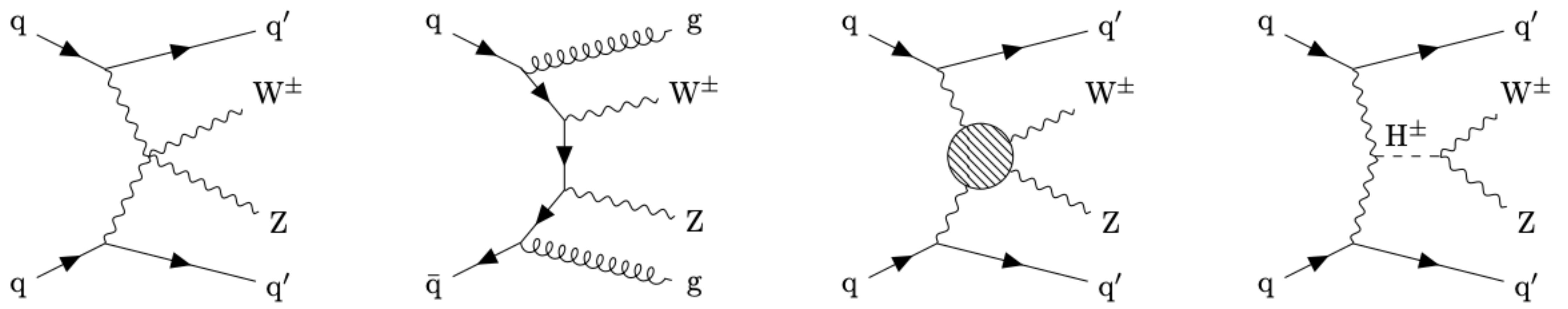
	Observed limits (TeV $^{-4}$)	Expected limits (TeV $^{-4}$)
f_{S0}/Λ^4	$[-7.7, 7.7]$	$[-7.0, 7.2]$
f_{S1}/Λ^4	$[-21.6, 21.8]$	$[-19.9, 20.2]$
f_{M0}/Λ^4	$[-6.0, 5.9]$	$[-5.6, 5.5]$
f_{M1}/Λ^4	$[-8.7, 9.1]$	$[-7.9, 8.5]$
f_{M6}/Λ^4	$[-11.9, 11.8]$	$[-11.1, 11.0]$
f_{M7}/Λ^4	$[-13.3, 12.9]$	$[-12.4, 11.8]$
f_{T0}/Λ^4	$[-0.62, 0.65]$	$[-0.58, 0.61]$
f_{T1}/Λ^4	$[-0.28, 0.31]$	$[-0.26, 0.29]$
f_{T2}/Λ^4	$[-0.89, 1.02]$	$[-0.80, 0.95]$

Georgi–Machacek Higgs Triplet Model →
95% CL limits on H± ⟶ W± W±



Electroweak $W^{\pm}Z+JJ$ production

$\sqrt{s} = 13$ TeV
$\int L = 35.9\ \mathrm{fb}^{-1}$



(a) (b) (c) (d)

probing the *WWZZ* coupling

3-lepton final state (*e*,*μ*)

main background: QCD-WZ+dijet, tri-bosons

strategy: from MC constrained in data sidebands

signal region	control region
$m_{JJ} > 500$ GeV, $\lvert\Delta\eta_{JJ}\rvert > 2.5$, $\lvert\eta^*\rvert < 2.5$	$m_{JJ} > 100$ GeV, fail $\lvert\Delta\eta_{JJ}\rvert$ or $\lvert\eta^*\rvert < 2.5$

selection criteria

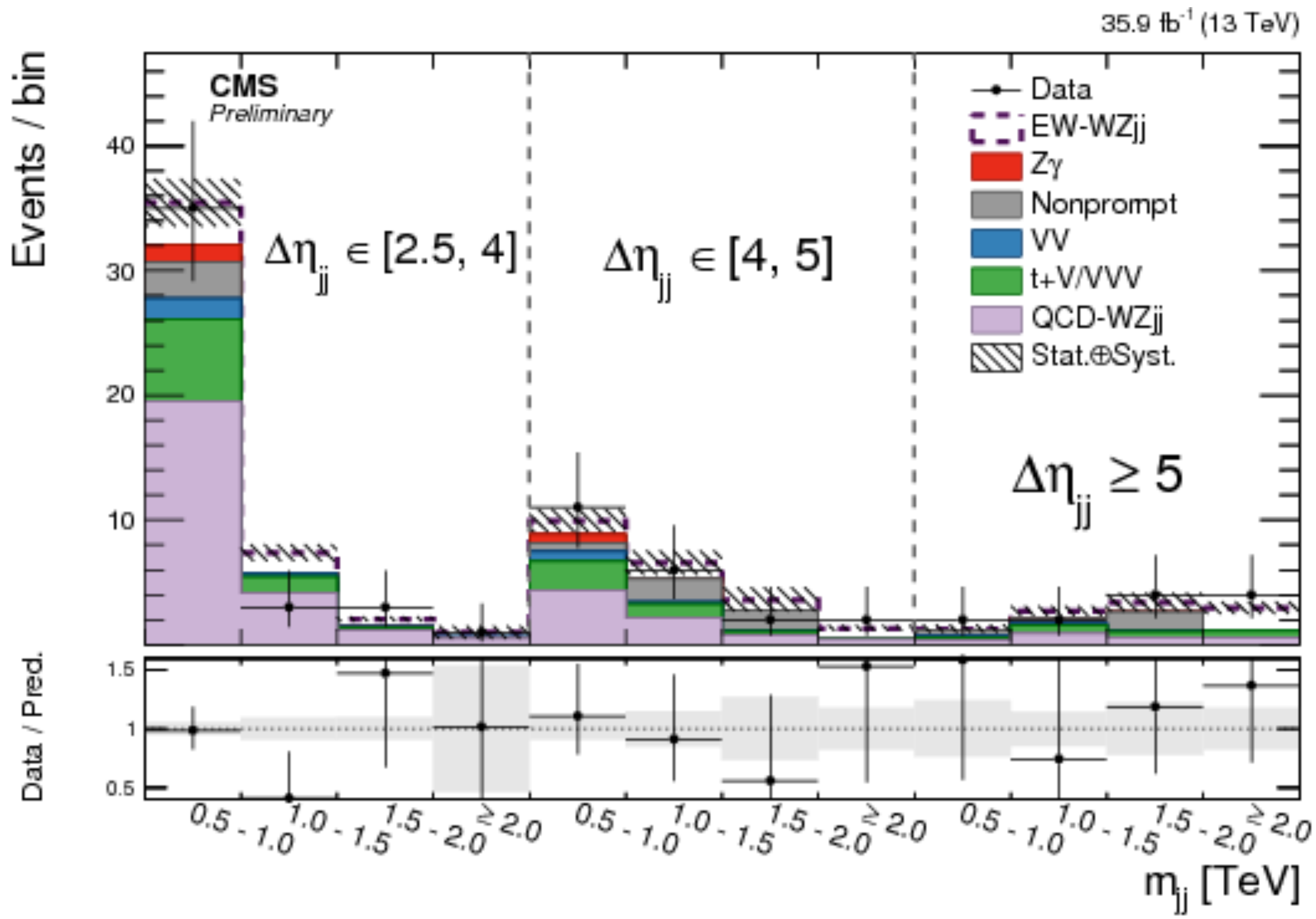
	Electroweak Signal	Loose Fiducial
$p_T(\ell_{Z,1})$ [GeV]	> 25	> 20
$p_T(\ell_{Z,2})$ [GeV]	> 15	> 20
$p_T(\ell_W)$ [GeV]	> 20	> 20
$\lvert\eta(\mu)\rvert$	< 2.4	< 2.5
$\lvert\eta(e)\rvert$	< 2.5	< 2.5
$\lvert m_Z - m_Z^{PDG}\rvert$ [GeV]	< 15	< 15
$m_{3\ell}$ [GeV]	> 100	> 100
$m_{\ell\ell}$ [GeV]	> 4	> 4
p_T^{miss} [GeV]	> 30	-
$\lvert\eta(j)\rvert$	< 4.7	< 4.7
$p_T(j)$ [GeV]	> 50	> 30
$\lvert\Delta R(j,\ell)\rvert$	> 0.4	> 0.4
n_j	≥ 2	≥ 2
$p_T(b)$ [GeV]	> 30	-
n_{b-jet}	$= 0$	-
m_{jj}	> 500	> 500
$\lvert\Delta\eta(j_1, j_2)\rvert$	> 2.5	> 2.5
$\lvert\eta_{3\ell} - \frac{1}{2}(\eta_{j_1} + \eta_{j_2})\rvert$	< 2.5	-

Signal extraction:

2-D m_{JJ} vs. $\lvert\Delta\eta_{JJ}\rvert$ combined fit w/ control region

Electroweak $W^{\pm}Z$+JJ production

$\sqrt{s} = 13$ TeV
$\int L = 35.9\ fb^{-1}$



Signal extraction:

2-D m_{JJ} vs. $|\Delta\eta_{JJ}|$

combined fit w/ control region

Systematics

biggest contribution from JES, non prompt statistics

$$\mu_{EW} = 0.64^{+0.45}_{-0.37}$$

$$\sigma_{WZjj} = 4.01^{0.72}_{-0.68}(stat)^{0.57}_{-0.47}(syst)$$ **Measured**

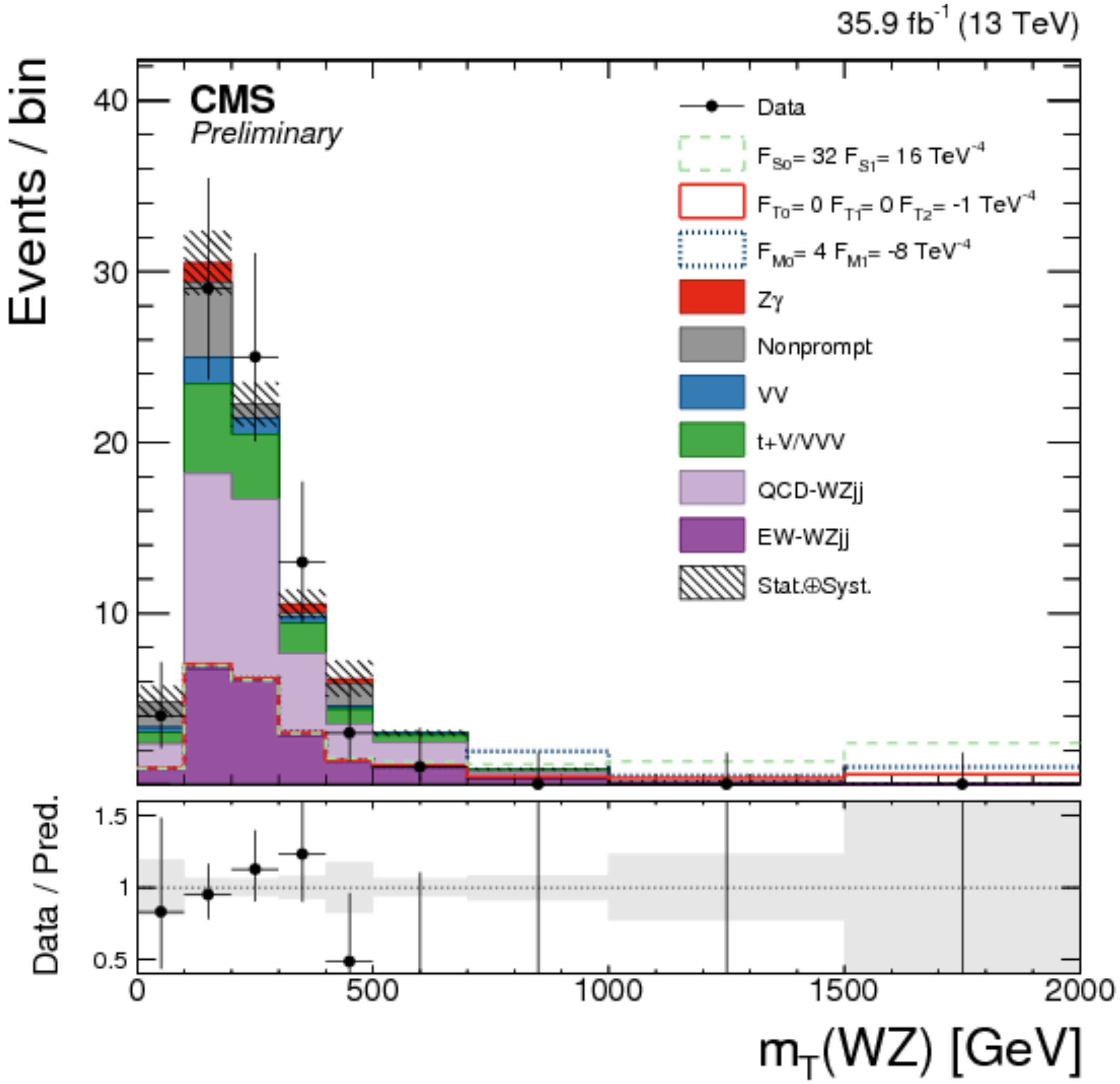
$$\sigma_{LO} = 4.51^{+0.59}_{-0.45}(scale) \pm 0.18(PDF)$$ **MadGraph5_aMC@NLO @LO**

expected significance: 2.7σ, observed: 1.9σ

EW+QCD NLO corrections not included

Electroweak $W^{\pm}Z+JJ$ production

$\sqrt{s} = 13$ TeV
$\int L = 35.9\ fb^{-1}$



$$m_T(WZ) = \sqrt{(E_T(W) + E_T(Z))^2 - (p_T(W) + p_T(Z))^2}$$

Parameters	Expected limit (TeV^{-4})	Observed limit (TeV^{-4})
f_{M0}/Λ^4	[-10.7, 10.7]	[-8.80, 8.55]
f_{M1}/Λ^4	[-10.1, 10.6]	[-8.25, 8.85]
f_{S0}/Λ^4	[-31.5, 33.5]	[-25.7, 27.5]
f_{S1}/Λ^4	[-50.5, 51.5]	[-40.5, 41.5]
f_{T0}/Λ^4	[-0.85, 0.85]	[-0.72, 0.75]
f_{T1}/Λ^4	[-0.55, 0.55]	[-0.48, 0.52]
f_{T2}/Λ^4	[-2.98, 2.92]	[-1.42, 1.83]

constraining aQGC in EFT with dim-8 operators: sensitive to

T0,T1,T2 -> SU(2) structure
S0,S1 -> Higgs field
M0,M1 -> Higgs-gauge interaction