Summary: Electroweak topics at SM@LHC

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Overview

Rough topological ordering

- **Drell-Yan**:
  giant data sets allow for stringent precision tests of SM
- **VV / Vγ / γγ / VVV**:
  EW+QCD precision allows for crucial tests of aT(Q)GCs
- **VBF/VBS** processes:
  Discovery → Measurements → EFT

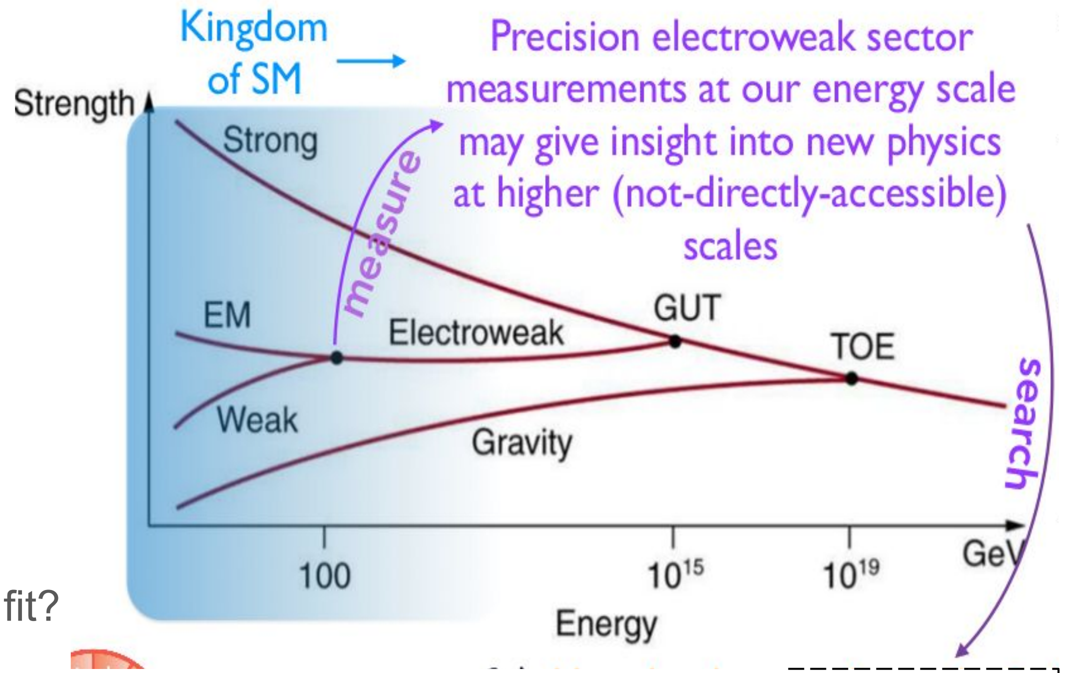
What is there for Run-2 ?

Now is time to shape the Run-2 legacy
→ What to measure?
→ What to compare to?
→ Consolidation between ATLAS and CMS

Why study the electroweak sector?

Test bed for higher scales

- The electroweak sector allows for most stringent tests of the Standard Model
- You can really have it all: Ultra-high precision (DY) and Processes accessible for the first time (VBS)
- VV / VBF-V: aTGC
  VVV / VBS-VV: aQGC → global EFT fit?



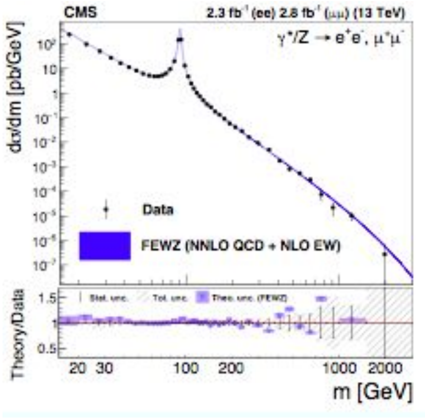
Raquel Gomez Ambrosio

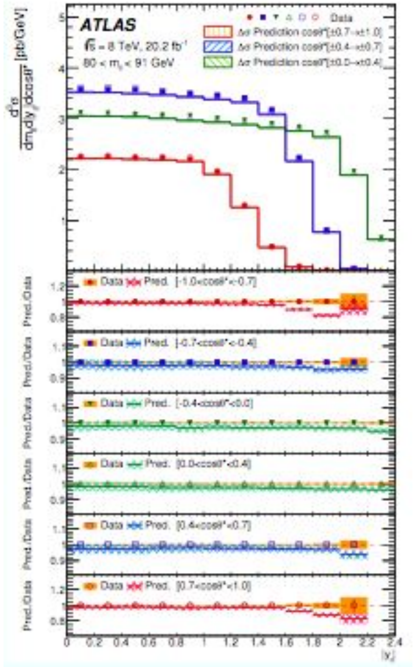
Claire Lee

see QCD summary!

Drell-Yan

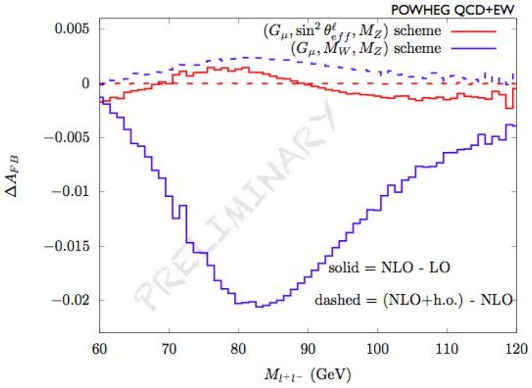
- Giant data sets allow for important of precision tests: MW, sin2θeff, PDFs
- Leave no stone unturned to push systematics further down (statistics is no issue!)
- Theory systematics often dominant
- Harness power of multi-dimensional measurements!





Oscar Gonzalez Lopez

What can we measure in a scattering process?



Cross sections and asymmetries are observables based on a counting procedure → always available

The determination of other parameters (masses, coupling constants) requires

- the choice of a model (e.g. the SM)
- the choice of an input scheme linking
  the renormalised lagrangian parameters to experimental observables

→ only the input parameters can be measured in a fit to the data, because they are the only quantities that can be freely varied

→ any derived quantity is computable in terms of the input param's
→ is fixed → can not be measured

New input scheme proposed:

$(G_\mu, M_Z, \sin^2\theta_{eff})$

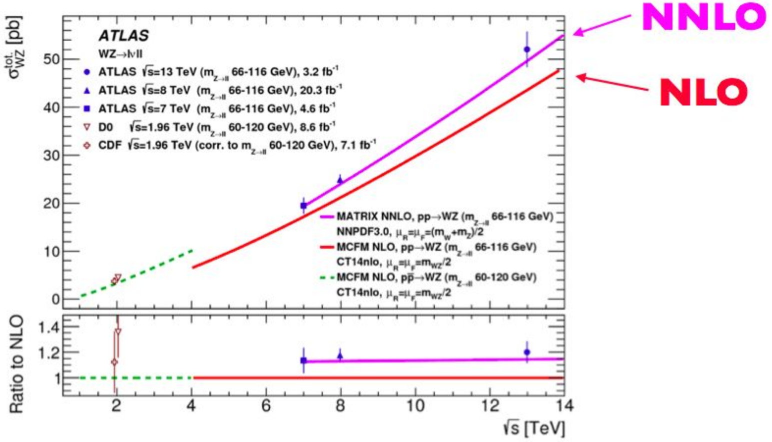
(Gmu, MZ, sin²θeff)

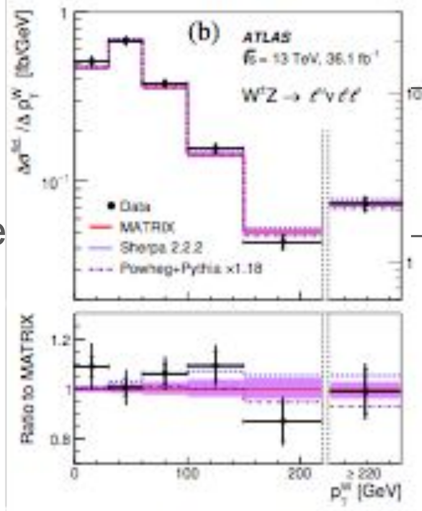
- Tailored for NC DY
- Allows for template fits of sin2θeff
- Results in small EW corrections to AFB

Dibosons

- Immense progress in useable (parton-level) NNLO+X calculations (M. Wieseman → MATRIX).
  New:
  ggNLO+new qg contributions,
  NNLO-QCD+NLO-EW
  NNLOPS (for WW)

- Wealth of differential measurements are becoming more and more precise
  E. Baldin, P. Vischia
  → *How to best exploit this information?*



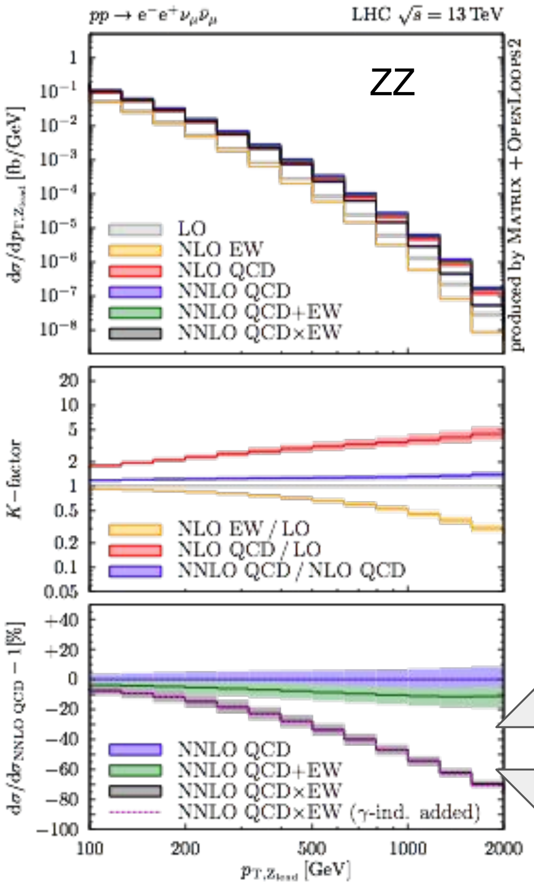


→ *explore tails of distributions for sensitivity to BSM*

→ *suggestions for additional measurements very welcome!*

Marius Wiesemann

VV: NNLO QCD+NLO EW

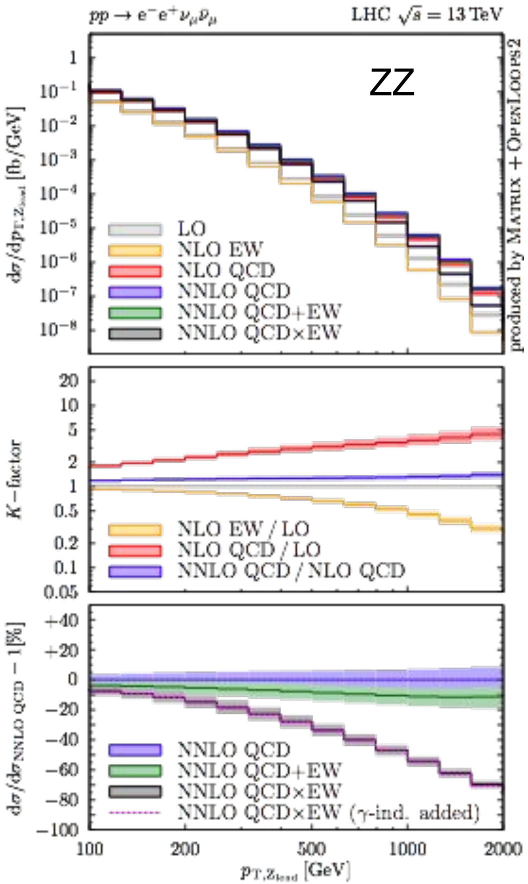


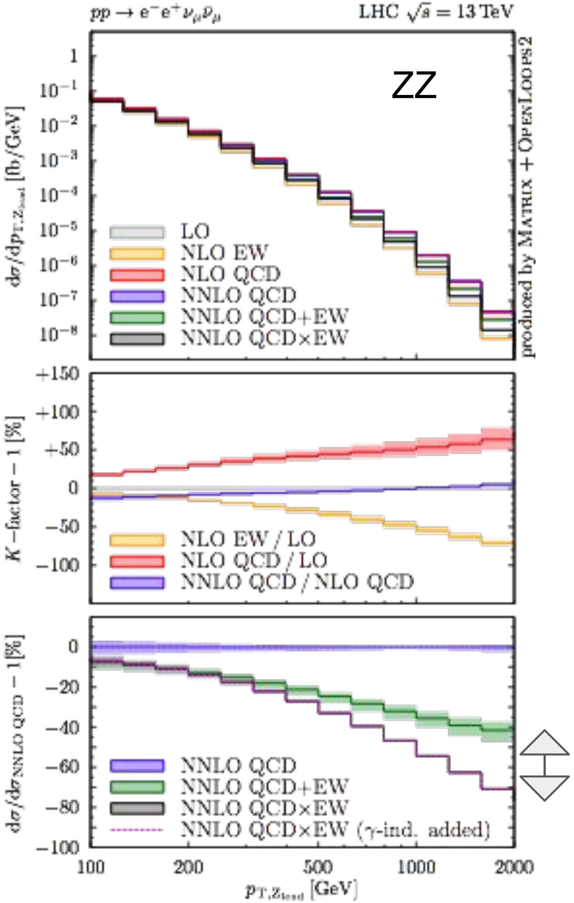
- **NLO/LO=2-5!** ("giant K-factor")
- at large pTV1 **VV is dominated by V+jets** (w/ soft V radiation)

- O(1) difference in
  NNLO QCD+NLO EW
  vs.
  NNLO QCDxNLOEW

Marius Wiesemann

VV: NNLO QCD+NLO EW





- NLO/LO=~<1.5 (normal K-factor)
- Reliable uncertainty from NNLO QCD+NLO EW vs. NNLO QCDxNLOEW

Question: how to obtain reliable inclusive prediction?

Some (self-)criticism

Too much is

- Inaccessible
- unuseable
- inconsistent (between experiments)

- We need precision measurements to improve constraints on aTGC/aQGC couplings
- Data set widly incoherent among and within collaborations
  - Soup of comparisons with 3, 13, 36, 70–80, 101 fb^{-1}: even a comparison of 3 vs 77 fb^{-1}!
  - Collaboration strategy? Personpower?
- Agree on the choice of main/alternative generators?
  - Often different generators used (POWHEG vs SHERPA; etc)
- Level of detail provided as public material should be dramatically improved
  - Sometimes the collaborations push against <u>too much detail</u>
- Presentation of results
  - Same formulas, same comparisons
- Not only between ATLAS and CMS: even within ATLAS and CMS individually!!!

consequat.

- Differential measurements could profit from better reporting and agreements
  - Unfolding is an open topic, many discussions (ATLAS StatForum and CMS StatComm)
  - Use methods correctly (do not use defaults!)
    - Sometimes no unique "right" answer
    - Mostly we know what we should **not** do
  - Can we at least agree on this?
    - Publish the response matrix
    - Publish the tabulated results
    - Publish the details of the unfolding (e.g. number of iterations, choice of regularization, etc)
- Combinations: it is time, is it?
  - Cross section: wait for full Run-II?
  - Couplings: start combining current results, or wait for full Run-II?

Pietro Vischia

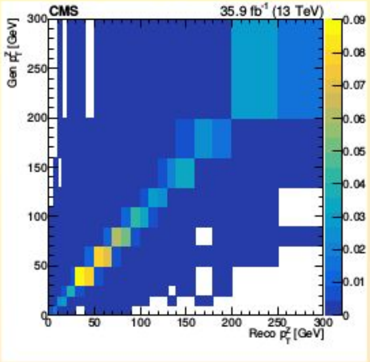
WZ production: differential cross section

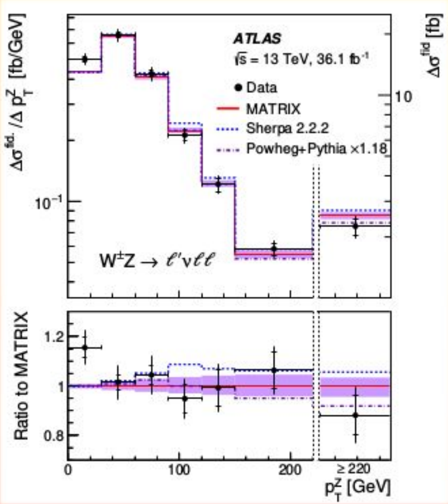
Pietro Vischia

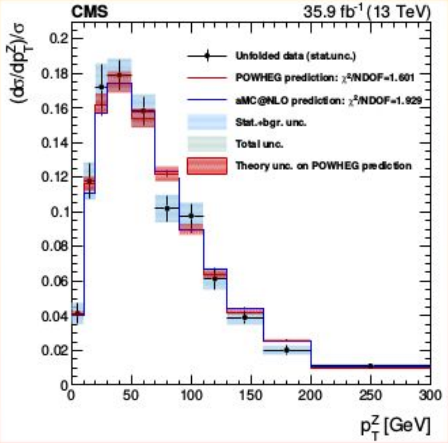
UCLouvain
Institut de recherche
en mathématique et physique

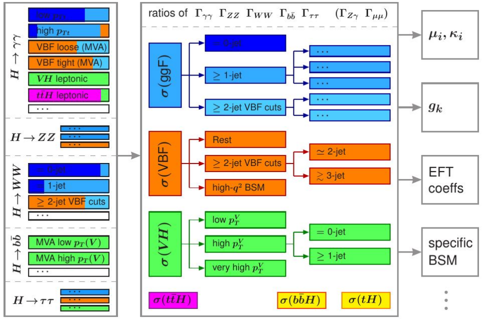
- Using available (NLO) MC
  - Constrain normalization to NNLO
- Different sets of observables
  - Somehow a failure of meetings done to agree on observables and such
  - ATLAS: , only for $W^{\pm}Z$
  - CMS: p_T^Z, p_T^{jet}, M_{WZ}, also split by W^+Z, W^-Z
- Different definitions of observables, e.g. $M_T(WZ)$
  - ATLAS: $\sim M(E_T^{miss}, \ell_1, \ell_2, \ell_3)$
  - CMS: $\sim M(E_T^{miss}, \ell\ell\ell)$
  - Headache for theoreticians (true story)
- Uncertainty on response matrix
  - ATLAS: data-driven (reweighting to data)
  - CMS: physics-driven (alternative MC sample)
- Statistical uncertainties dominate the measurement

- Unfolding
  - ATLAS: no detail on technique, response matrix not public
  - CMS: public response matrix, details on χ^2 fit (`TUnfold`) procedure, tabulated results









Inspired by Higgs STXS: Useful benchmarks!

LHC EWWG Working group proposal
https://indico.cern.ch/event/732057/

Step towards making global fits easier ?

- ***Keep just (differential) cross sections and measure (but in BSM phase space)***
- Profit from advantages of being **useful tool, interface, benchmark**

Multiboson Production

Final state	Object	Selection requirements
WW	**leptons**	p_T >25 GeV, $\lvert\eta\rvert < 2.5$
	neutrinos	$(\sum \vec{p}_\nu) > 30$ GeV
	jets	no jets with p_T >30 GeV and within $\lvert\eta\rvert < 5.0$
	final BSM region	$m_{\ell\ell}$: 380-600 GeV, >600 GeV
WZ	**leptons**	$p_{T,\text{lead}}$ >25 GeV, p_T >15 GeV, $\lvert\eta\rvert < 2.5$
	neutrinos	$(\sum \vec{p}_\nu) > 30$ GeV
	jets	no b-jets with p_T >30 GeV and within $\lvert\eta\rvert < 5.0$
	bosons	$m_{T,W}$ >30 GeV (see Eq. **??**), $\Delta(m_Z, m_{\ell\ell})$ <15 GeV
	final BSM region	$m_{T,WZ}$: 380-600 GeV, >600 GeV (see Eq. **??**)
ZZ	**leptons**	p_T >25 / 15 / 10 GeV (leading leptons), $\lvert\eta\rvert < 2.5$
	bosons	$\Delta(m_Z, m_{\ell\ell})$ <25 GeV
	final BSM region	m_{WZ}: 0.8-1.0 TeV, >1.0 TeV
$W\gamma$	**leptons**	p_T >35, $\lvert\eta\rvert < 2.5$
	photons	E_T >25, $\lvert\eta\rvert < 2.5$, $\Delta R(\ell,\gamma) > 0.7$
	neutrinos	$(\sum \vec{p}_\nu) > 30$ GeV
	bosons	$m_{T,W}$ >50 GeV
	final BSM region	$p_{T,\gamma}$: 25-60 GeV, 60-90 GeV, 90-150 GeV, >150 GeV
$Z(\to \ell\ell)\gamma$	**leptons**	p_T >35, $\lvert\eta\rvert < 2.5$
	photons	E_T >25, $\lvert\eta\rvert < 2.5$, $\Delta R(\ell,\gamma) > 0.4$
	bosons	$\Delta(m_Z, m_{\ell\ell})$ <10 GeV
	final BSM region	$p_{T,\gamma}$: 100-250 GeV, >250 GeV
$Z(\to \nu\nu)\gamma$	**photons**	E_T >25, $\lvert\eta\rvert < 2.5$, $\Delta R(\ell,\gamma) > 0.4$
	neutrinos	$(\sum \vec{p}_\nu) > 30$ GeV
	final BSM region	$p_{T,\gamma}$: 100-250 GeV, >250 GeV

Vectorboson Fusion

Final state	Object	Selection requirements
Z VBF / Zjj	**leptons**	$p_{T,\text{lead}}$ >25 GeV, $\lvert\eta\rvert < 2.5$
	jets	$p_{T,j1}$ >55 GeV, $p_{T,j1}$ >40 GeV, $\lvert\eta\rvert < 4.5$
	bosons	$\Delta(m_Z, m_{\ell\ell})$ <10 GeV
	further jets	p_T >25 GeV, none in interval between leptons
	event	p_T^{balance} <0.15 (see Eq. **??**)
	final BSM region	m_{jj}: 0.8-1.2 TeV, >1.2 TeV

Vectorboson Scattering

Final state	Object	Selection requirements
WW VBS / $WWjj$	**leptons**	p_T >20 GeV, $\lvert\eta\rvert < 2.5$, same-sign
	jets	$p_{T,j1}$ >30 GeV, $p_{T,j1}$ >30 GeV, $\lvert\eta\rvert < 4.5$, $\Delta\eta_{jj}$ >2.5
same-sign	**final BSM region**	m_{jj}: 0.25-0.5 TeV, >0.5 TeV
$Z\gamma$ VBS / $Z\gamma jj$	**leptons**	p_T >35, $\lvert\eta\rvert < 2.5$
	photons	E_T >75, $\lvert\eta\rvert < 2.5$, $\Delta R(\ell/j,\gamma) > 0.4$
	bosons	$\Delta(m_Z, m_{\ell\ell})$ <10 GeV
	jets	$p_{T,j1}$ >30 GeV, $p_{T,j1}$ >30 GeV, $\lvert\eta\rvert < 4.5$, $\Delta\eta_{jj}$ >3.0
	final BSM region	m_{jj}>0.5 TeV
WZ VBS /	**leptons**	$p_{T,\text{lead}}$ >25 GeV, p_T >15 GeV, $\lvert\eta\rvert < 2.5$
	neutrinos	$(\sum \vec{p}_\nu) > 30$ GeV
	jets	$p_{T,j1}$ >55 GeV, $p_{T,j1}$ >40 GeV, $\lvert\eta\rvert < 4.5$
	bosons	$\Delta(m_Z, m_{\ell\ell})$ <25 GeV
	further jets	p_T >25 GeV, none in interval between leptons
	event	p_T^{balance} <0.15 (see Eq. **??**)
	final BSM region	m_{WZ}: 0.8-1.0 TeV, >1.0 TeV
ZZ VBS / $ZZjj$	**leptons**	p_T >25 / 15 / 10 GeV (leading leptons), $\lvert\eta\rvert < 2.5$
	jets	$p_{T,j1}$ >55 GeV, $p_{T,j1}$ >40 GeV, $\lvert\eta\rvert < 4.5$
	bosons	$\Delta(m_Z, m_{\ell\ell})$ <25 GeV
	further jets	p_T >25 GeV, none in interval between leptons
	event	p_T^{balance} <0.15 (see Eq. **??**)
	final BSM region	m_{WZ}: 0.8-1.0 TeV, >1.0 TeV

K. Long

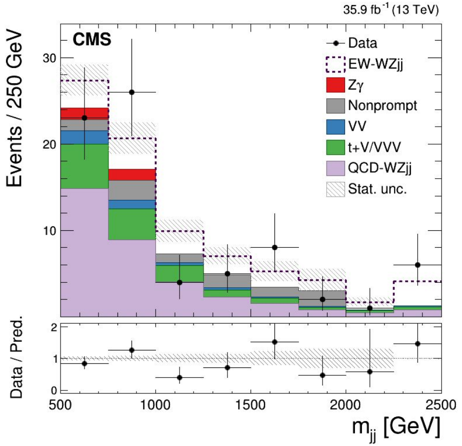
Precision VBF measurements

Improved description of VBF topology for other processes → **VBS modelling**

Modelling of the rapidity gap (color-flow,..)
→ **Significant differences in Sherpa vs. Herwig vs. Pythia (needs to be understood!)**

VBS-(ZZ, ssWW, WZ) processes observed!

General agreement with SM prediction.



VBF+VBS Measurements:

⟶ Always also perform common fit to SR and CR (at higher-orders no meaningful separation)

⟶ However (LO) separation necessary to tune selection/train BDTs (⟶Bias?)

The EFT Approach: QGCs

- A useful way to quantify the effects of new physics in a model-independent framework is to use an EFT description of the SM

- Define a scale of new physics Λ, and add higher-dimension operators to the SM Lagrangian:

$$\mathscr{L} = \mathscr{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathscr{O}_i + \sum_j \frac{f_j}{\Lambda^4}\mathscr{O}_j + \ldots$$

- Dimension-8 operators are the lowest-dimension operators inducing only QGCs without TGC vertices: 18 independent C,P conserving aQGC (dim 8) operators O:

S: Pure Higgs field, pure longitudinal
M: Mixed Higgs-field-strength, mixed long-transverse
T: Pure field-strength tensor, pure transverse

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

Allowed by SM

Test with VBS!

C. Lee

The EFT Approach: QGCs

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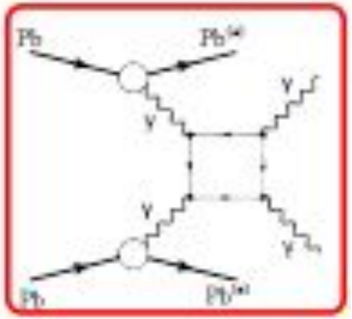
	$WWWW$	$WWZZ$	$WW\gamma Z$	$WW\gamma$	$ZZZZ$	$ZZZ\gamma$	$ZZ\gamma\gamma$	$Z\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$
$\mathcal{O}_{S,0}, \mathcal{O}_{S,1}$	✓	✓			✓				
$\mathcal{O}_{M,0}, \mathcal{O}_{M,1}, \mathcal{O}_{M,6}, \mathcal{O}_{M,7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2}, \mathcal{O}_{M,3},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

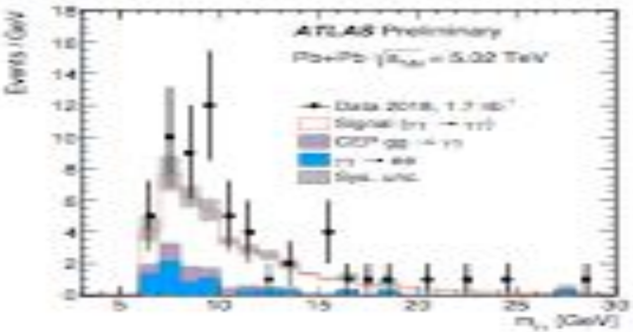
Allowed by SM

?

Light-by-light scattering

Similar to well known Delbrück scattering (γ diflection and photon splitting in nucleus Coulomb field).





$\sigma_{\text{fid.}} = 78 \pm 13\,(\text{stat.}) \pm 7\,(\text{syst.}) \pm 3\,(\text{lumi.})$ nb

$\sigma_{\text{th.}} = 50 \pm 5$ nb, experiment/prediction $= 1.53 \pm 0.33$

Light-by-light scattering ($\gamma\gamma \to \gamma\gamma$, left), QED dielectron ($\gamma\gamma \to e^+e^-$, centre), and central exclusive diphoton ($gg \to \gamma\gamma$, right) production in ultraperipheral Pb+Pb collisions.

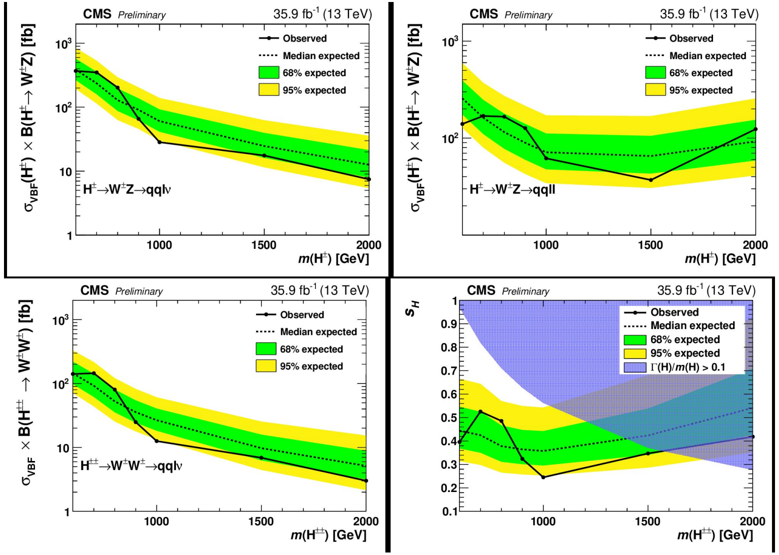
Constrain →aQGC/EFT!

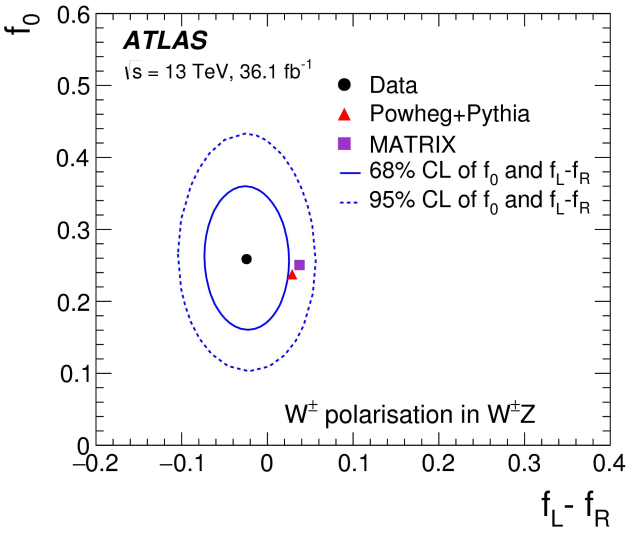
Interest: Sensitive to new physics in charged loops.

Problems: $\sim O(\alpha^4)$, high η for products, pileup, relatively low γ energies for trigger and reconstruction, QED dielectron and QCD backgrounds.

Not only limits in EFT coefficients

Mass limits on new particles:
single- and doubly-charged Higgs production





Scrutinizing angular variables:
different polarisation behaviour ??

Claire Lee

GLOBAL SMEFT FITS FOR VBS

Raquel Gomez Ambrosio

TRADITIONAL VBS INTERPRETATION: DIM 8

- VBS has traditionally been associated with Quartic Gauge Couplings, and the former have traditionally been described in terms of dim-8 operators only
- QGC can be parametrised in terms of "non-TGC EFT operators"

DIM 6: TGC AND QGC IN THE WARSAW BASIS

For the previous reasons, a description in terms of Dim-6 is more general and consistent. In terms of dim-6 operators, QGCs and TGCs can be written as:

To the exp.: specify the basis you are using

Not only total cross-sections... Differential observables shed light on the EFT effects

Notes:
Important to understand TH and EXP correlations across observables
Background may also be affected by EFT effects

Thank you!

1. Interesting presentations and discussions

2. Great progress in theoretical understanding, but still gaps and a lot of room for better collaboration between collaborations (and better practice!)

3. Ultimately this needs to be implemented before Run-2 final measurements

Now is the time!