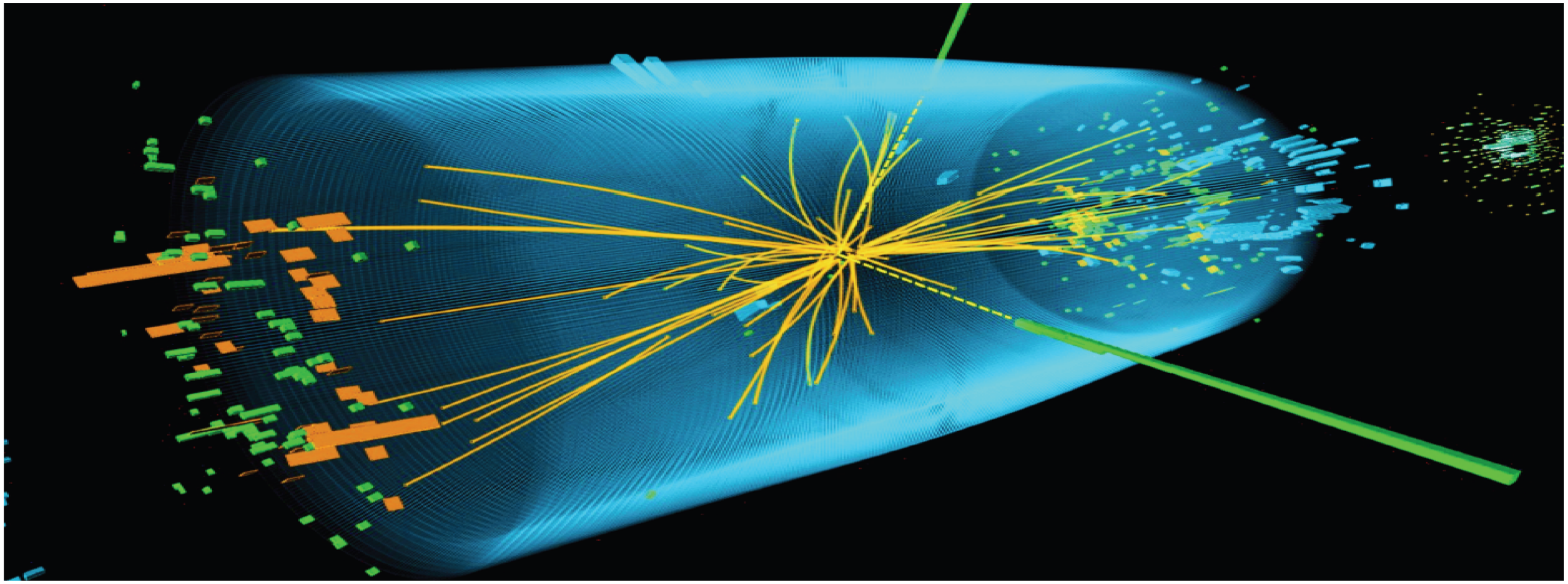
Top quark and electro-weak physics

María Moreno Llácer (IFIC, Uni.Valencia - CSIC)



XLVIII International Meeting on Fundamental Physics (IMFP21)

After the Higgs boson discovery, **Standard Model (SM) measurements** have two main goals:
- validate SM in new energy regime and **improve precision** of known SM parameters
- **test SM for new physics** (NP) contributions

Electro-weak and top quark physics have a great potential in both of these goals:
- unique signatures
- several rare processes predicted by SM, where the loop contributions (e.g. from NP particles) can give sizable effects, become sensitive tools to probe the NP models
- enough data for precision measurements of rare processes!
- theoretical predictions for most of the processes can be calculated with high precision

Very rich programme, only some recent analysis presented here.

All results are available in:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

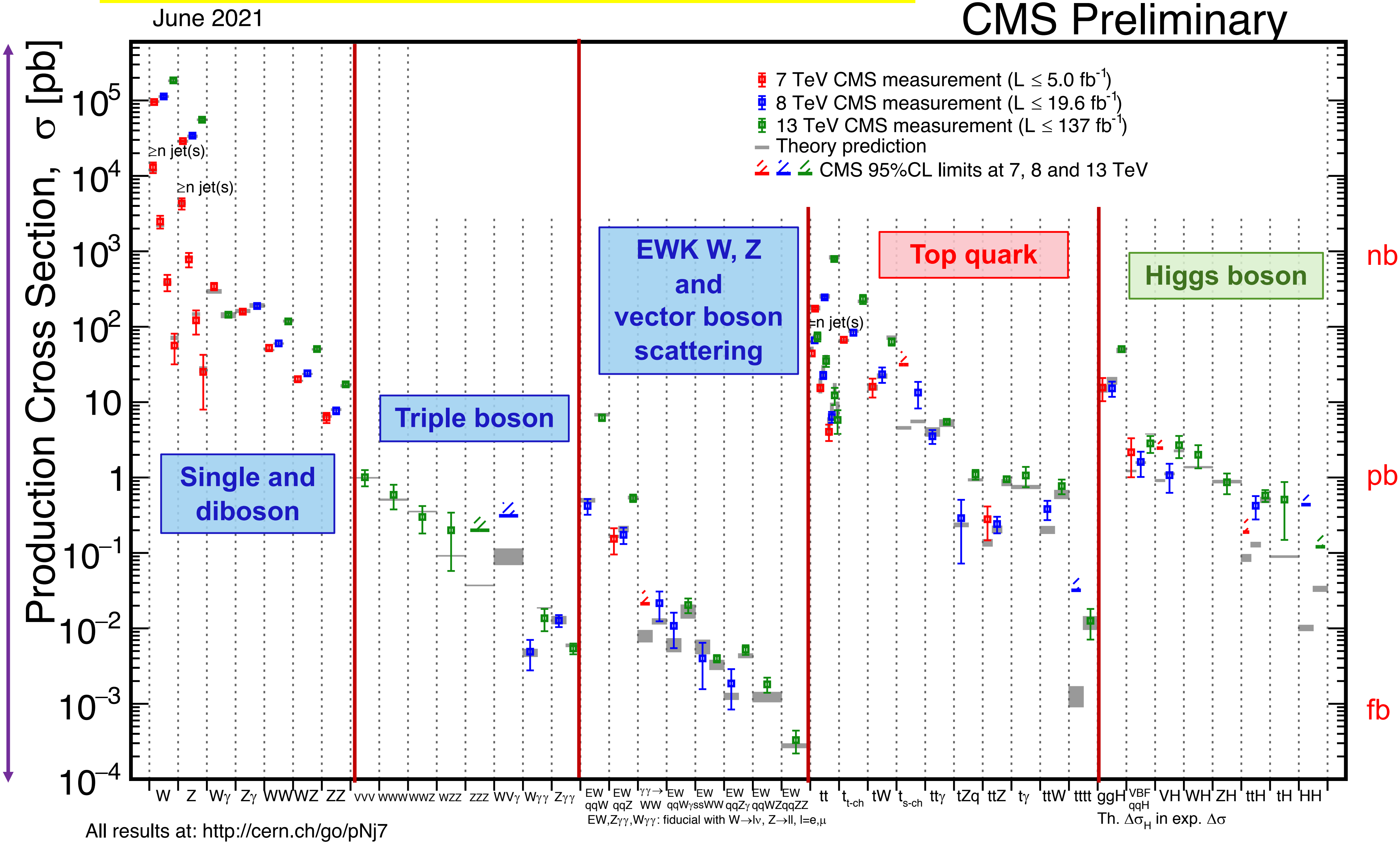
Events @ LHC Run 2 (140 fb^{-1})

W bosons	27000 10^6
Z bosons	8000 10^6
Top quarks	130 10^6
Higgs bosons	8 10^6

Thanks to LHC & the detectors!

Cross sections measured for several SM processes

New areas opening up as the luminosity increases



Electro-weak physics

Precision measurements

Single and diboson production cross sections

- Inclusive four-lepton differential cross sections
- WZ($\rightarrow$3l) and longitudinally polarized W bosons
- WWW observation

Vector boson fusion (VBF) & vector boson scattering (VBS)

- Polarisation of W bosons in $W^{\pm}W^{\pm} \rightarrow 2l^{\pm}2\nu$
- $\gamma\gamma \rightarrow WW$
- WV semileptonic
- EW $Z\gamma jj$ production

Top quark physics

Top mass

Production cross sections

Top couplings to W bosons (single top cross sections, V_{tb} and top polarisation)
to gluons (cross sections, spin corr., charge asymmetry, search for CPV)
to neutral bosons γ/Z/H (cross sections)

Global EFT fits

Searches for flavour changing neutral currents

Electro-weak physics

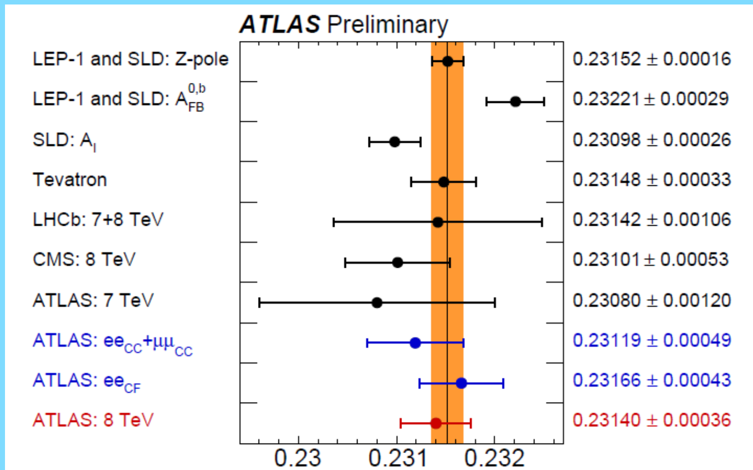
leptonic	hadronic
$W^+ \to l^+\nu$	$W^+ \to q\bar{q}$
$W^- \to l^-\bar{\nu}$	$W^- \to q\bar{q}$

hadronic	leptonic visible	leptonic invisible
$Z^0 \to q\bar{q}$	$Z^0 \to e^+e^-$	$Z^0 \to \nu\bar{\nu}$
	$Z^0 \to \mu^+\mu^-$	
	$Z^0 \to \tau^+\tau^-$	

Some EW precision measurements

Weak mixing angle (8 TeV data)

ATLAS-CONF-2018-037



$\sin^2\theta^l_{eff}$

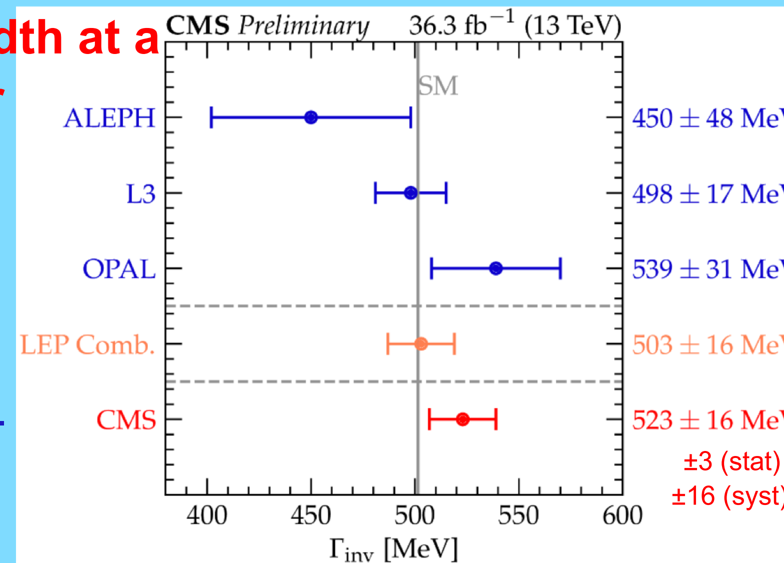
EW fit: $\sin^2\theta^l_{eff} = 0.23153 \pm 0.00006$

First measurement of Z→invisible width at a hadron collider

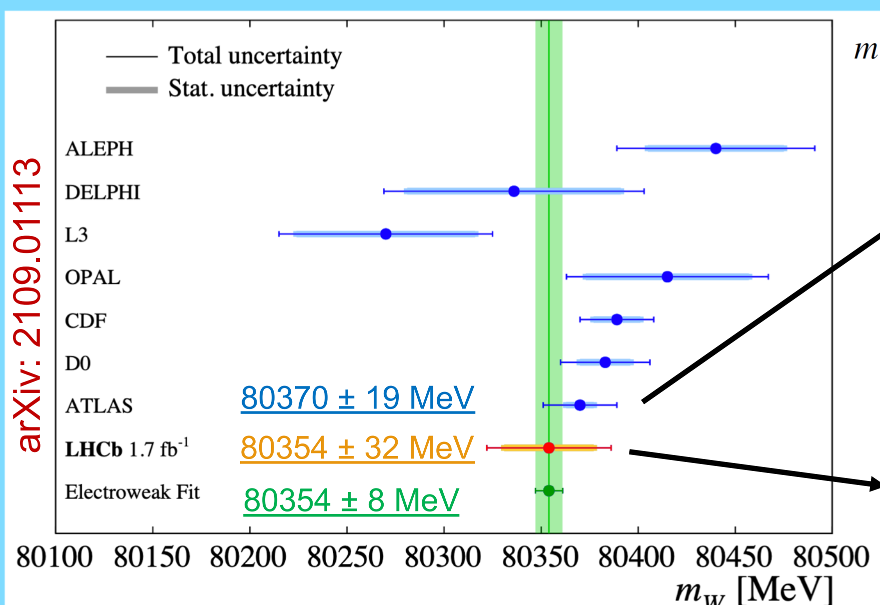
CMS-PAS-SMP-18-014

$\Gamma_{inv}/\Gamma_{\ell\ell}$ ratio from a simultaneous fit of $Z\to\nu\nu$ and $Z\to\ell\ell$

Single most precise direct measurement. Comparable precision to LEP.



arXiv: 2109.01113



$$m_W = 80369.5 \pm 6.8\text{ MeV(stat.)} \pm 10.6\text{ MeV(exp. syst.)} \pm 13.6\text{ MeV(mod. syst.)}$$
$$= 80369.5 \pm 18.5\text{ MeV},$$

ATLAS 7 TeV @ 4.1 fb^{-1} → $\delta m_W \sim$ **0.02%**

First measurement of m_W from LHCb

Simultaneous fit to q/p_T in $W\to\mu\nu$ and ϕ^* in $Z\to\mu\mu$

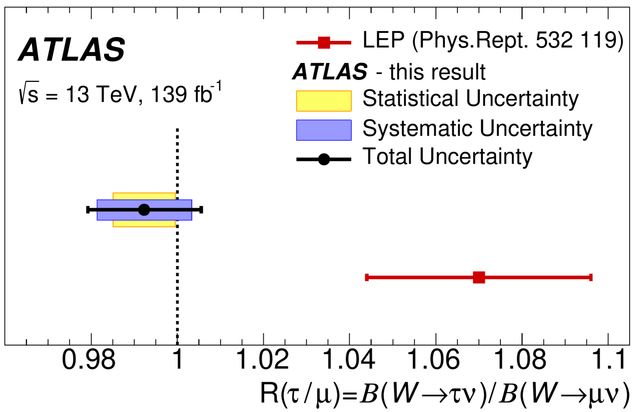
$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\text{ MeV}$$

LHCb (1/3 Run 2 data) → O(10) MeV stat. unc. with full Run 2

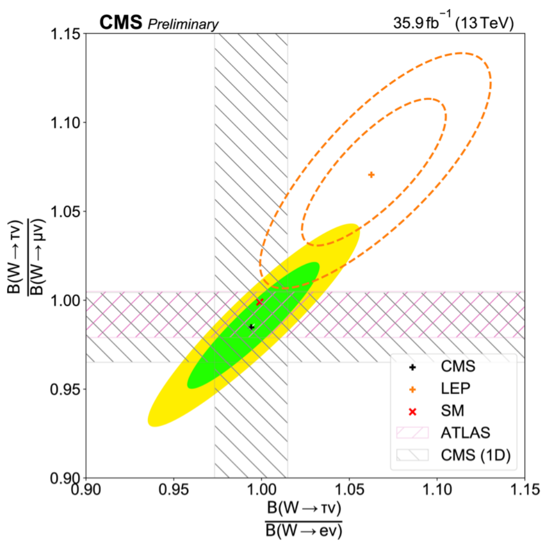
Lepton universality?

Measure W boson BRs in *tt* events

Nature Physics 17, p.813-818 (2021)

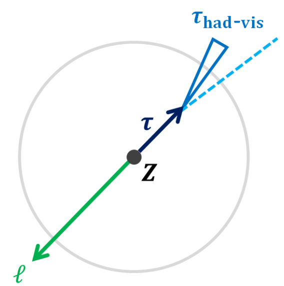


CMS-PAS-SMP-18-011

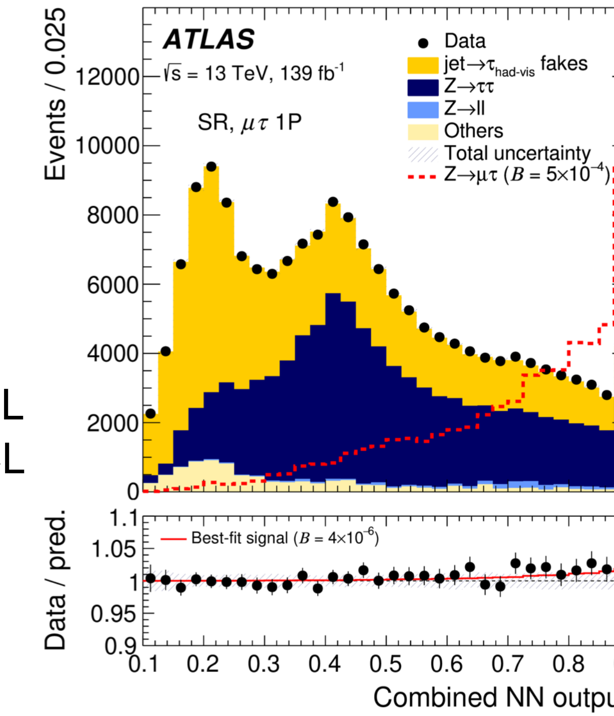


Charged lepton flavour violation?

Z→eτ/μτ decays?



BR(Z→eτ) < $5.0\cdot10^{-6}$ @95CL
BR(Z→μτ) < $6.5\cdot10^{-6}$ @95CL



Superseding LEP limits.

Limited by stat. unc
→improvements expected in next LHC runs

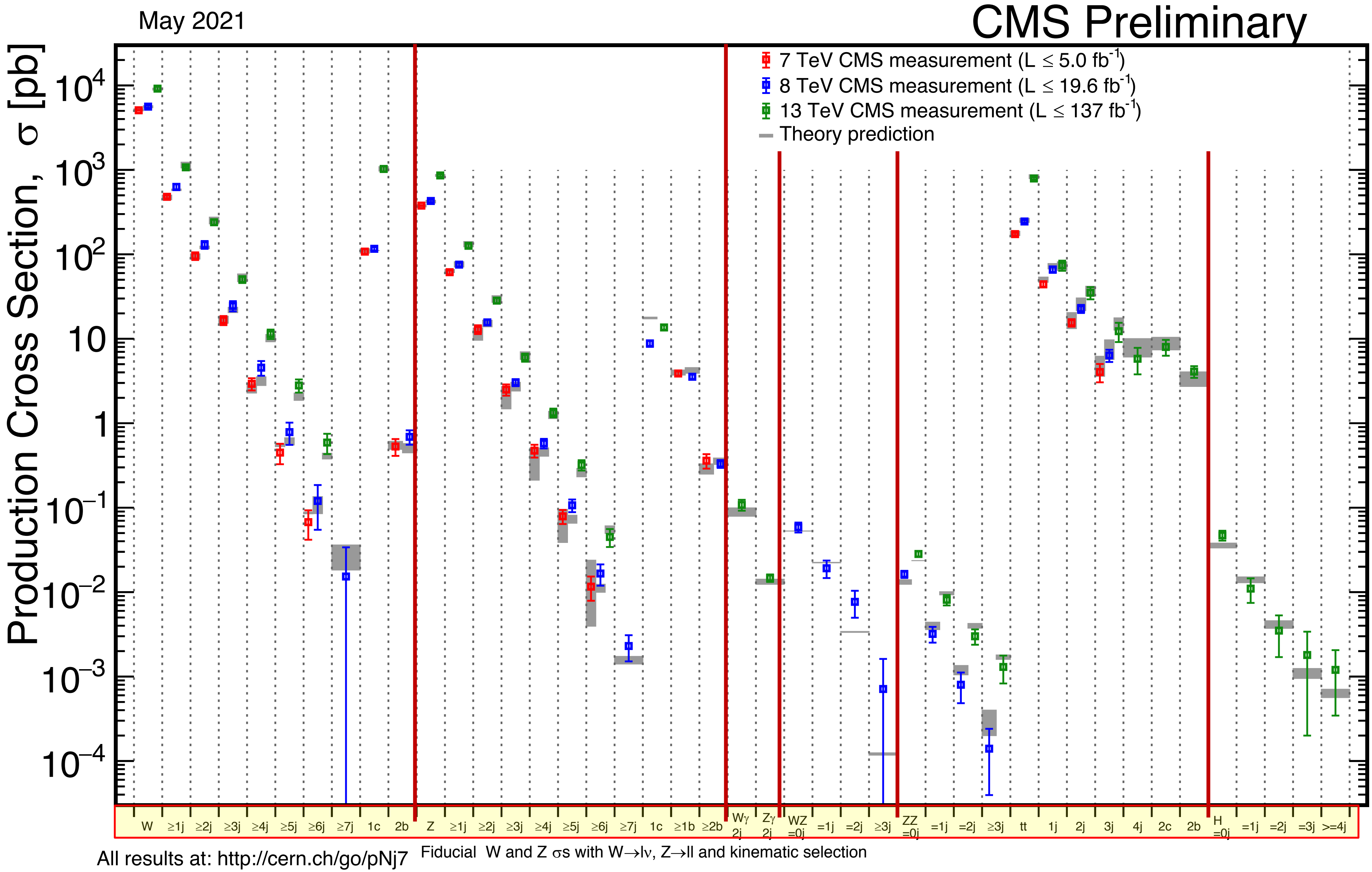
Nature Physics 17, p.819-825 (2021)
arXiv: 2105.12491

LEP: BR(Z→eτ) < $9.8\cdot10^{-6}$ (OPAL)
BR(Z→μτ) < $12\cdot10^{-6}$ (DELPHI)

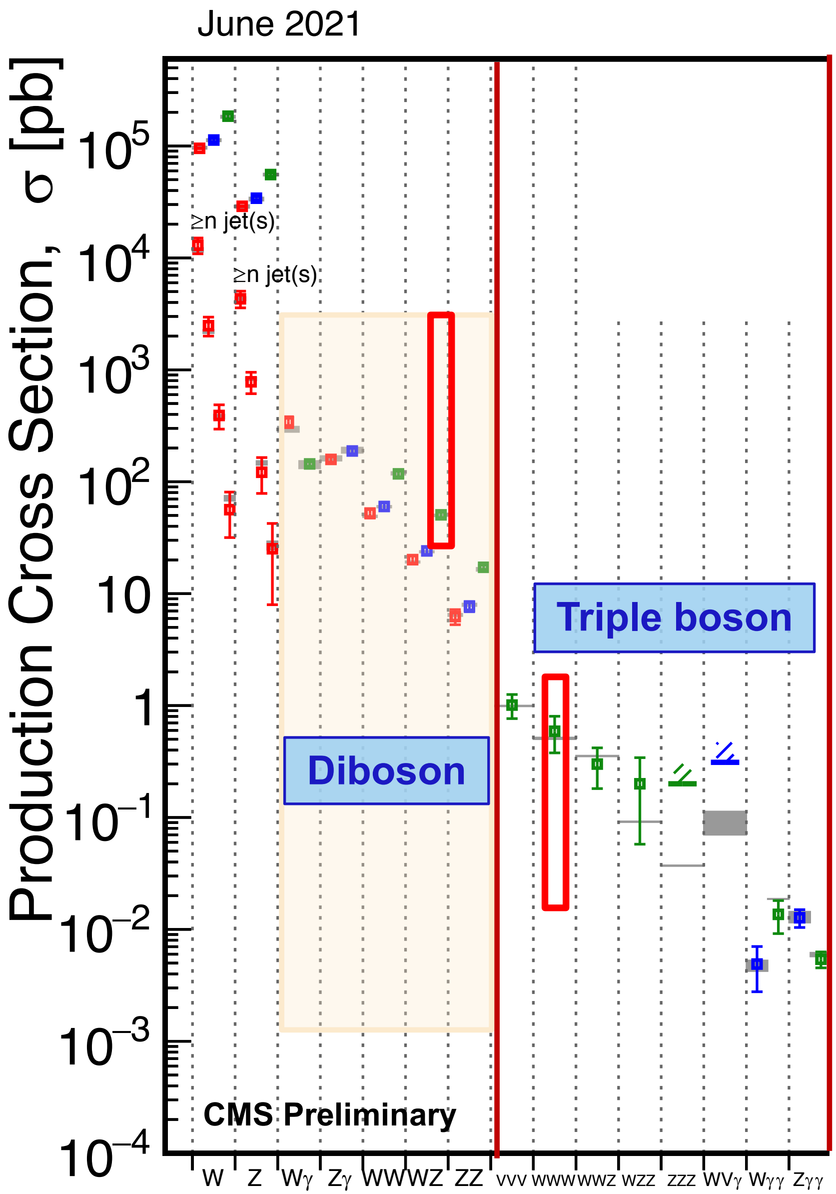
ATLAS: BR(Z→μe) < $3.04\cdot10^{-7}$ ATLAS-CONF-2021-042

Also cLFV studied in top quark (and Higgs boson) decays

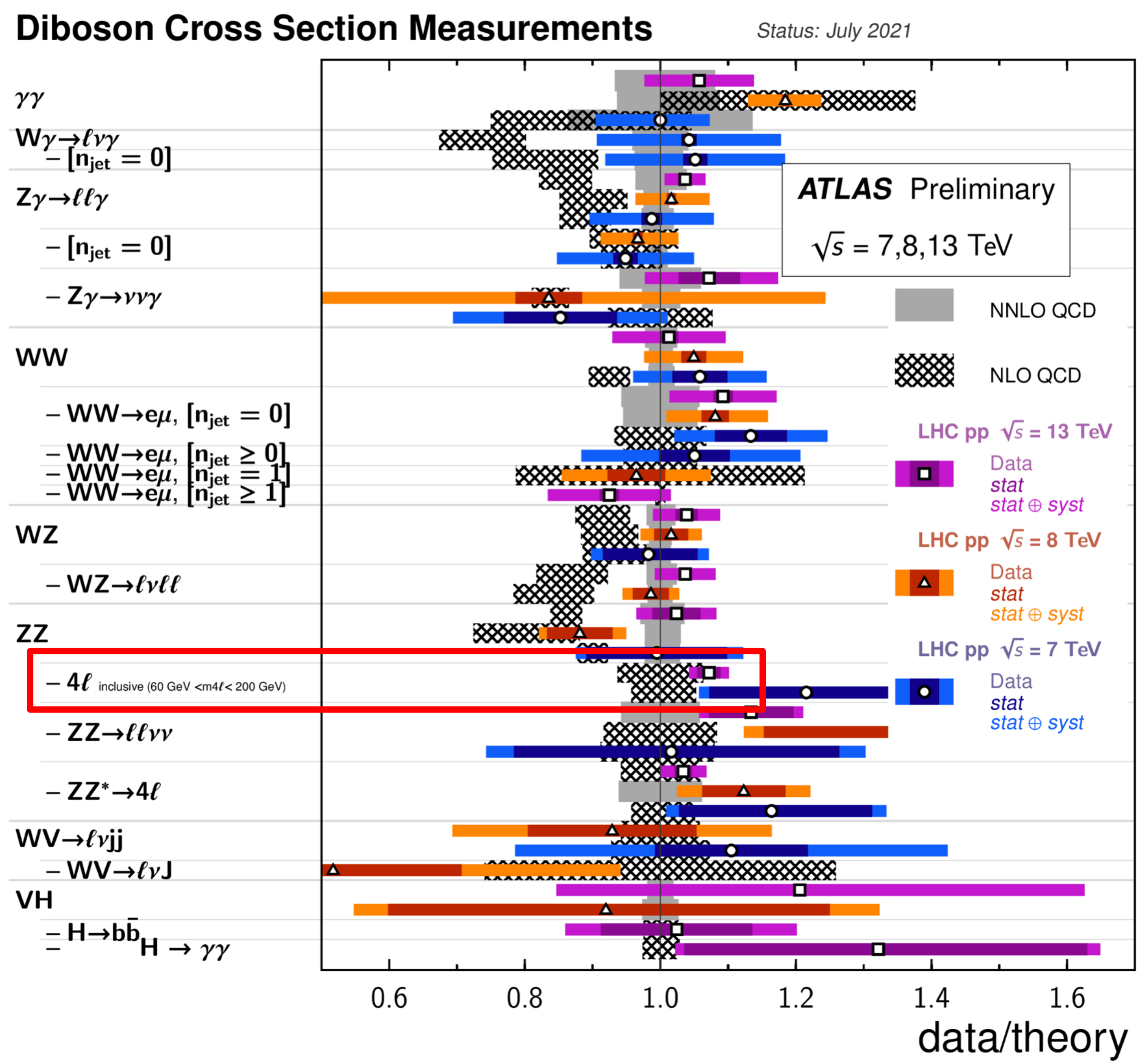
(Differential) cross sections with 1 or 2 vector bosons



Also WW and γγ differential cross sections.



All results at: http://cern.ch/go/pNj7

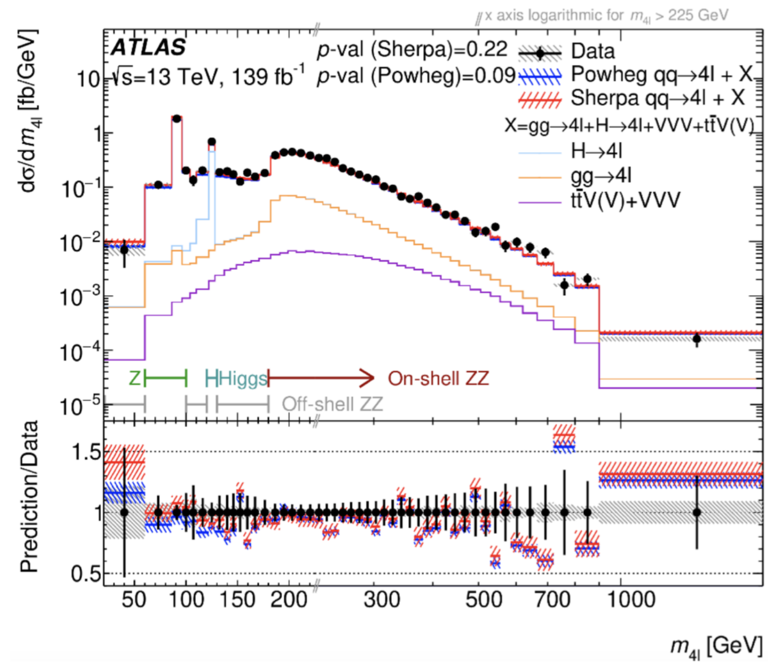


Cross section measurements (inclusive and differential) and limitis on anomalous triple gauge couplings (TGC).

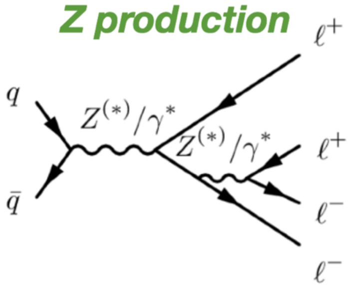
Inclusive four-lepton differential cross sections

JHEP 07 (2021) 005

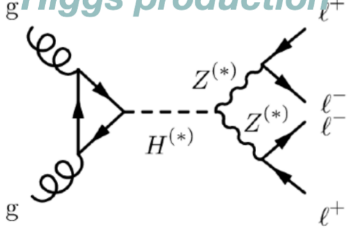
- Several interesting SM processes contribute to this final state
- Potencial new BSM effects interpreted using EFT formalism
- Differential cross sections measured
  - several variables: m_{12}, m_{34}, $p_{T,12}$, $p_{T,34}$, $\cos\theta^{*}_{12}$, $\Delta\phi_{ll}$, ...
  - in 4 ranges of m_{4l} phase space (in GeV):
    60-100 [Z], 120-130 [H], 180-2000 [on-shell ZZ] and off-shell ZZ
- Dominant unc.: data statistics and bkg. estimation

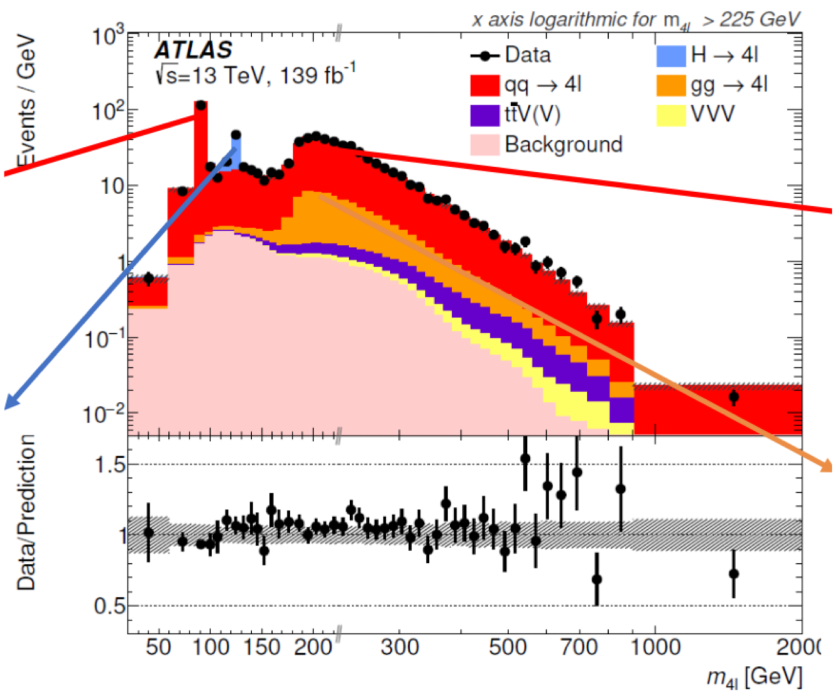


Z production

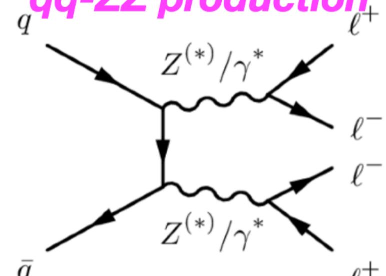


Higgs production

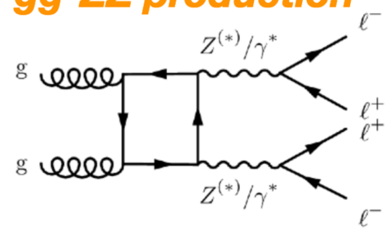




qq-ZZ production

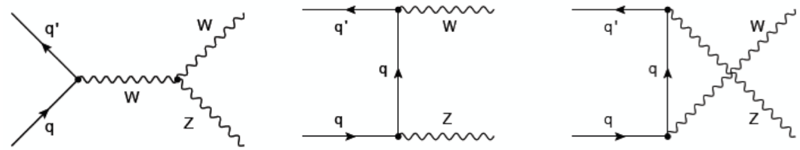


gg-ZZ production



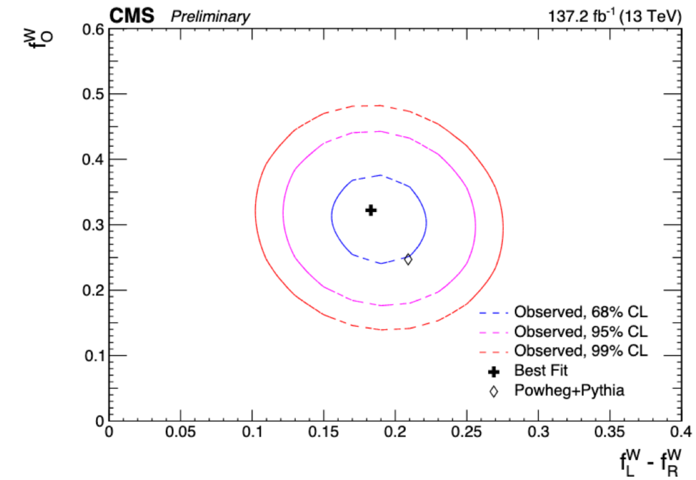
Z→4l branching ratio: $(4.41 \pm 0.30) \cdot 10^{-6}$
- compatible with SM
- most precise to date

CMS-PAS-SMP-20-014

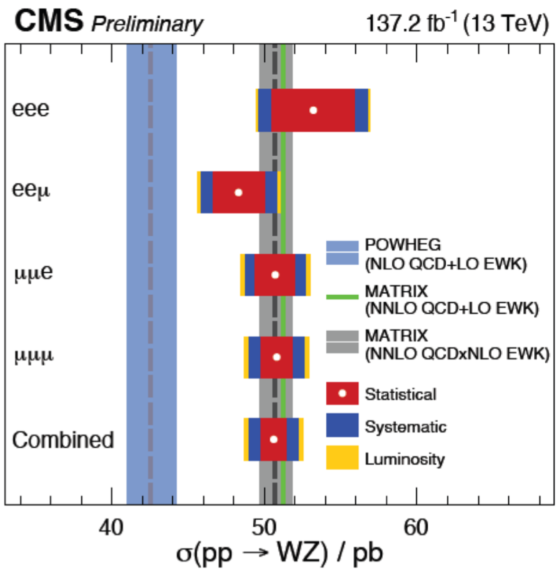


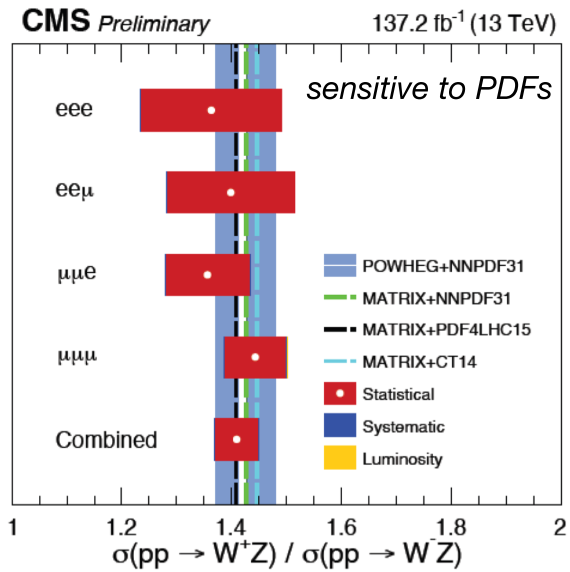
Measurements:

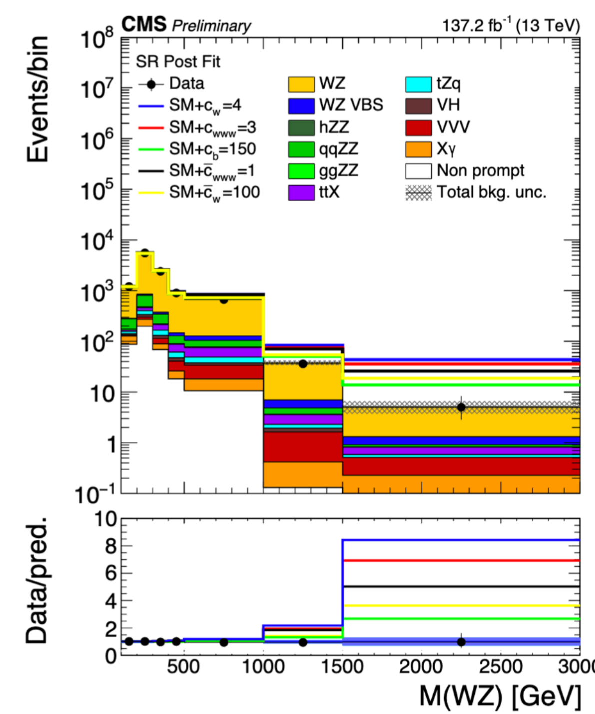
cross sections (inclusive & differential), charge asymmetry ratio, V polarisation and anomalous triple gauge coupling (TGC) WWZ



First observation of longitudinally polarized W bosons in WZ production







σ(WZ) Observed: σ = 50.6 ± 0.8 (stat) ± 1.5 (syst) ± 1.1 (lumi) ± 0.5 (theo) pb ~2%

MATRIX NNLO QCD × NLO EWK: $\sigma = 50.7^{+1.1}_{-1.0}$ (scale) pb

POWHEG NLO QCD: $\sigma = 42.5^{+1.6}_{-1.4}$ (scale) ± 0.6 (PDF) pb

$\sigma(W^+Z)/\sigma(W^-Z)$

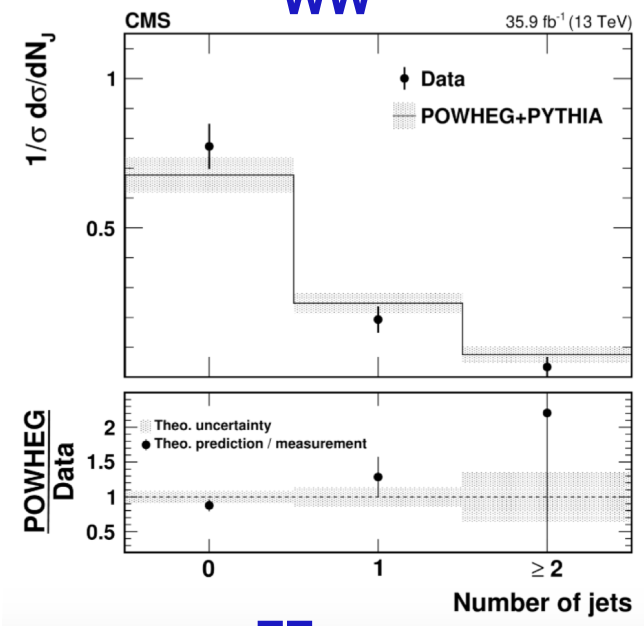
Measured: 1.41 ± 0.04 (stat) ± 0.01 (syst) ± 0.01 (lumi)

MATRIX NNLO QCD × NLO EWK: $1.427^{+0.002}_{-0.002}$(scale)

POWHEG NLO QCD: $1.42^{+0.06}_{-0.05}$(scale+PDF)

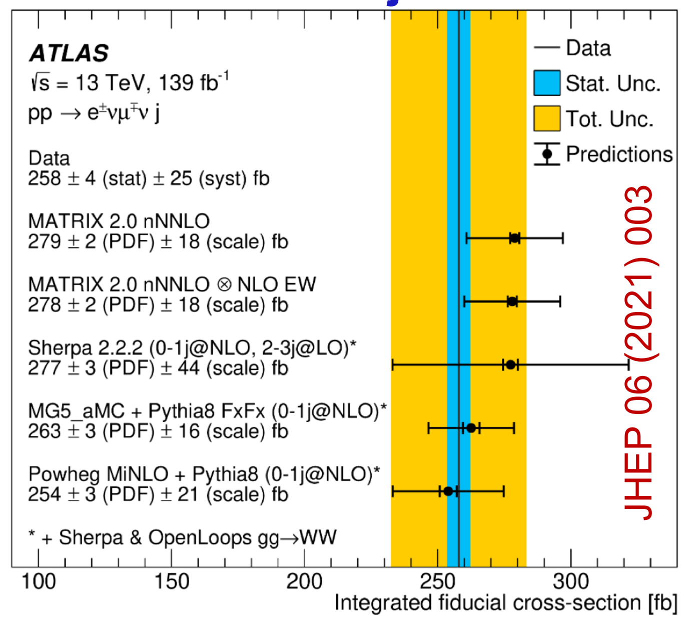
Other multiboson results: ZZ, WW, WW+≥1j, Wγ & WWW

WW



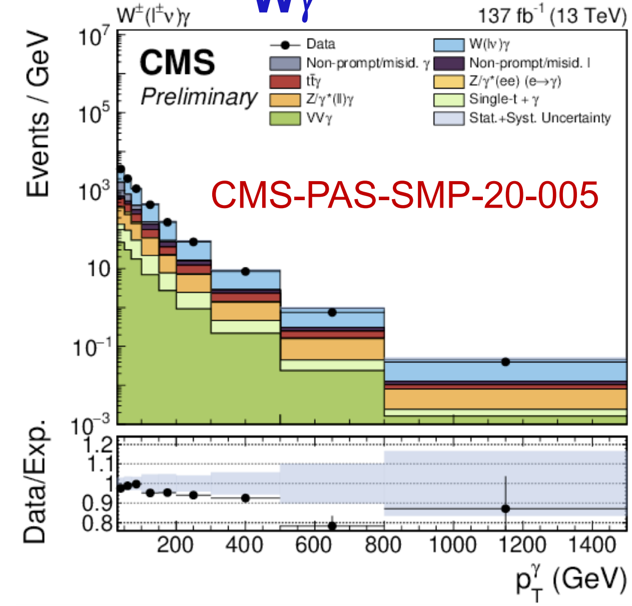
PRD 102 (2020) 092001

WW+ ≥1 jet



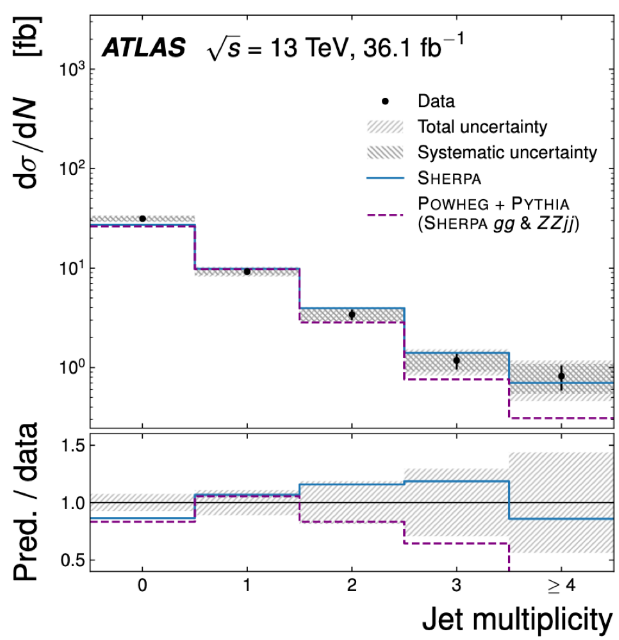
JHEP 06 (2021) 003

Wγ



CMS-PAS-SMP-20-005

ZZ



PRD 97 (2018) 032005

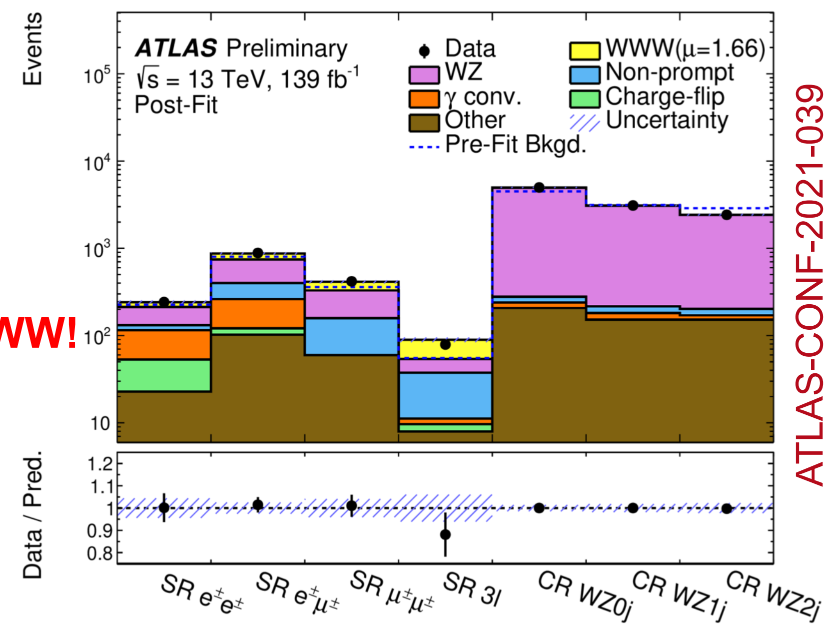
WWW

μ(WWW)~1.66±0.28

Limited by data stats.

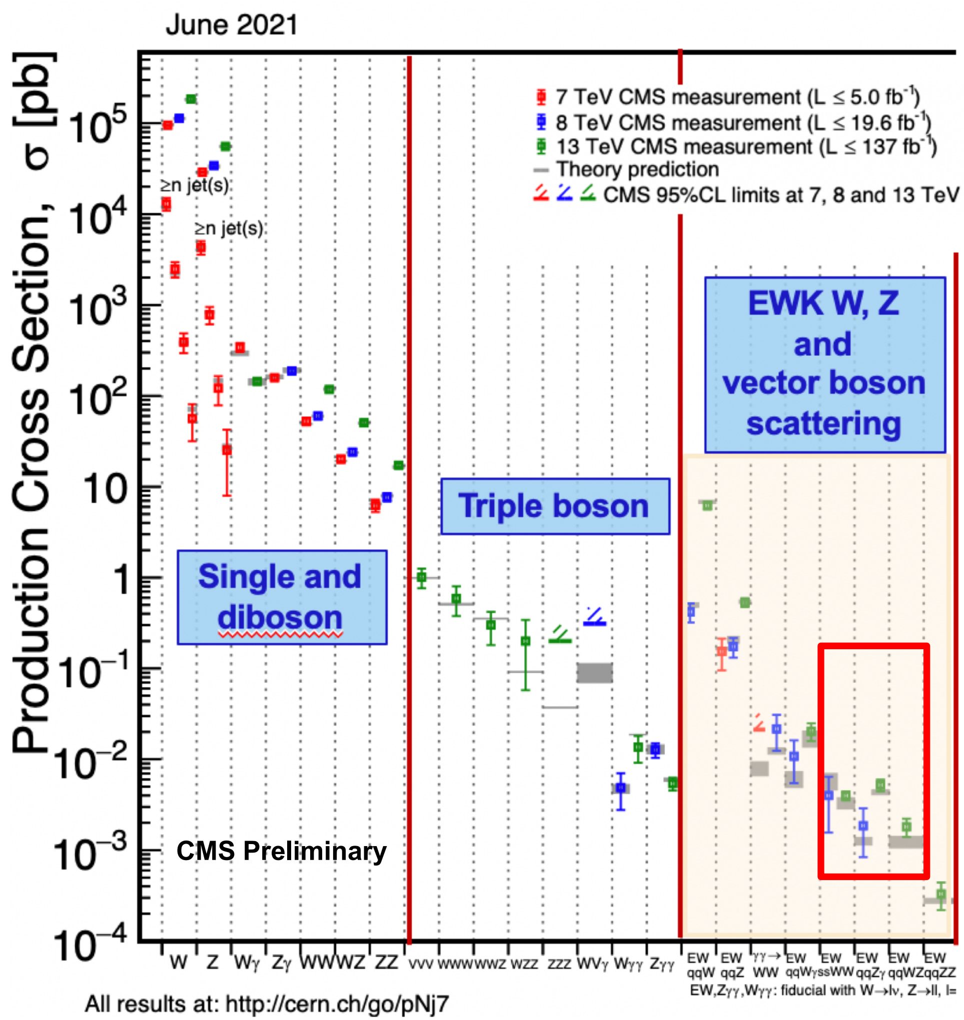
Significance: 8σ

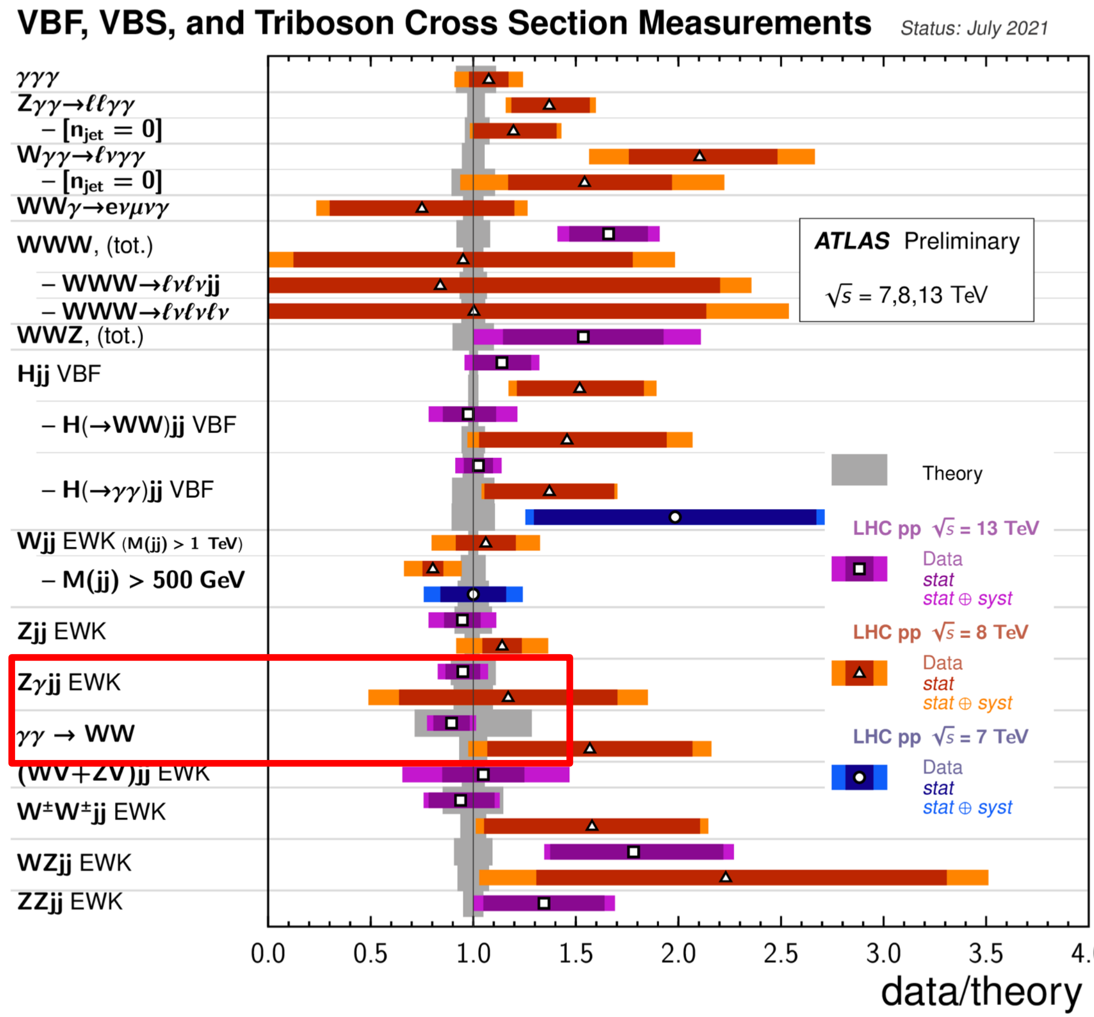
→ **Observation of WWW!**



ATLAS-CONF-2021-039

Vector boson fusion (VBF) & vector boson scattering (VBS)



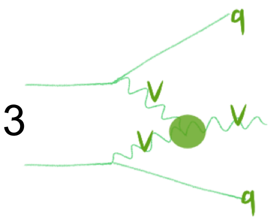


Although they are **very rare processes, all EW VVjj observed (~10% XS precision). Even first differential measurements available.**
Here, focus on recent results: polarised VBS ssWW, γγ→WW, WV semilep and EW Zγjj.

Mostly exploring fully-leptonic VBS. No fully-hadronic (all jets) VBS/F measured so far.

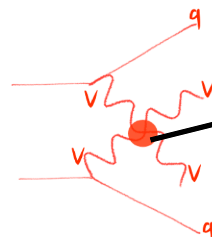
Also observed photon scattering in Pb-Pb coll.

V boson fusion (Vjj)

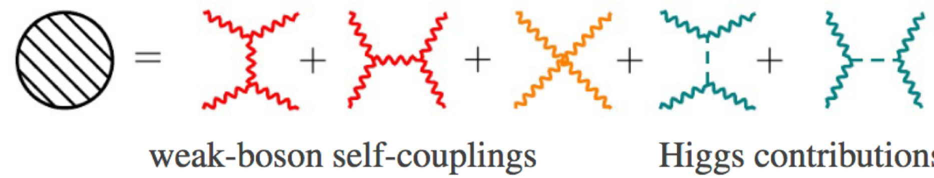


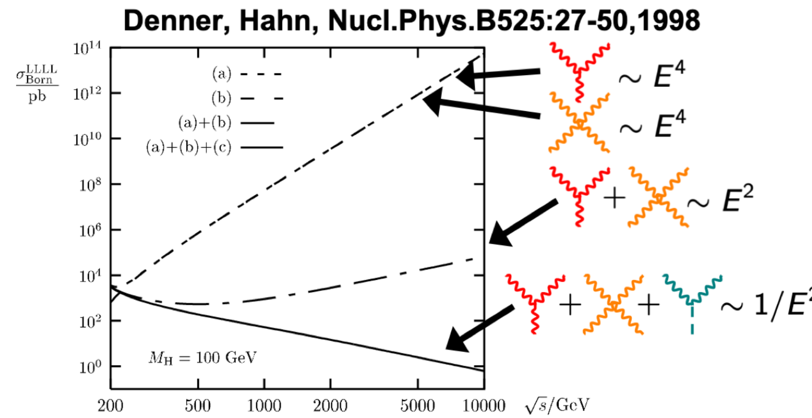
$\alpha_{EW}= 3$

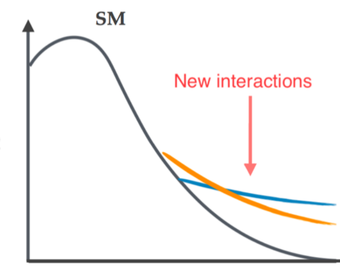
V boson scattering (VVjj)



$\alpha_{EW}= 4$

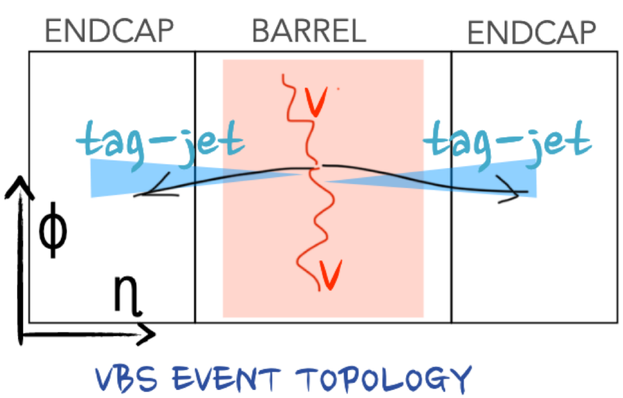






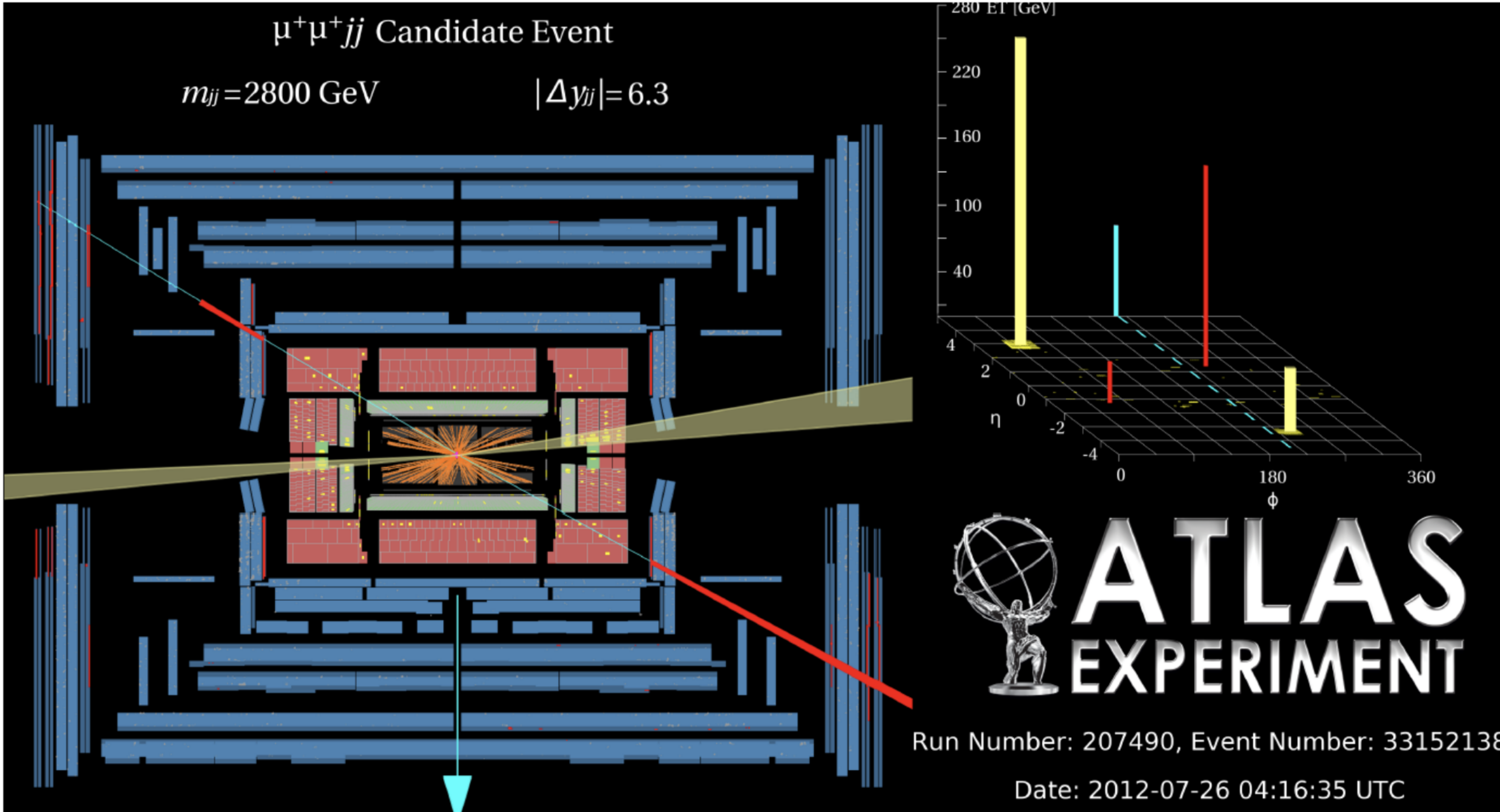
VBS are rare (but key) processes

- *The* crucial test of EW symmetry breaking
- Test V boson self int., TGC and QGC
- Large QCD background
- Typically look for 2 well-separated jets & gauge bosons produced in the central part
- W/Z: use semi/leptonic decay modes
- Photon: cleaner final states



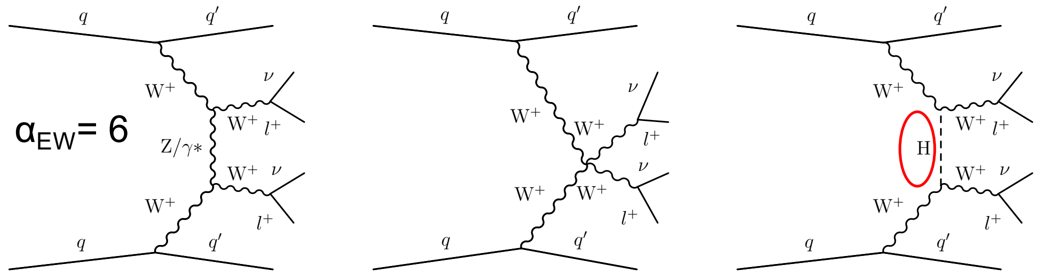
Experimental challenges:
- Missing neutrinos in W leptonic final states
- Jet systematic uncertainties in forward region
- Large QCD bkgs: matrix-element techniques or ML

Physics modelling:
- EW signals: large TH & EXP. efforts to cross-validate MC generators; parton-shower schemes very important
- VVjj QCD ($\alpha_S^2\,\alpha_{EW}^2$): very expensive computations at NLO and/or matched+merged; need careful validation in data CRs


$\mu^+\mu^+jj$ Candidate Event
m_{jj} =2800 GeV
$|\Delta y_{jj}|$=6.3
280 ET [GeV]
220
160
100
40
4
2
0
η
-2
-4
0
180
360
ϕ
ATLAS
EXPERIMENT
Run Number: 207490, Event Number: 33152138
Date: 2012-07-26 04:16:35 UTC

VBS $W^{\pm}W^{\pm} \rightarrow 2l^{\pm}2\nu$: longitudinally-polarised ?

PLB 812 (2020) 136018



"Golden channel"

Measurements:

1) XS (~10% precision) + EFT limits

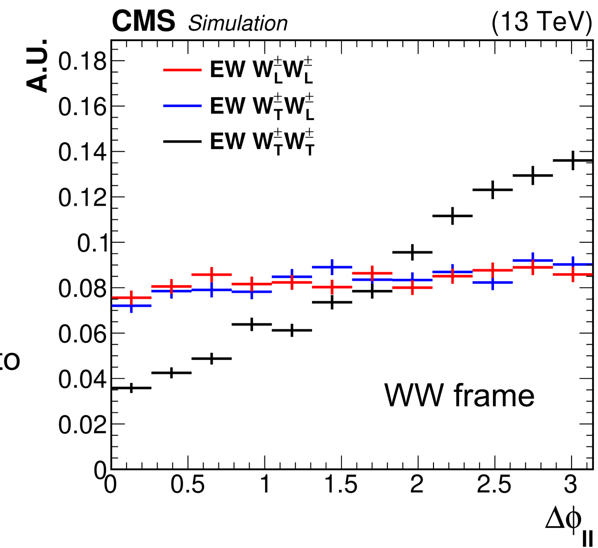
2) Differential cross sections (vs. m_{jj}, m_{ll} and $p_{T,lead.lep.}$)

3) **Polarisation states** (LL, LT or TT: 10, 30 or 60%)

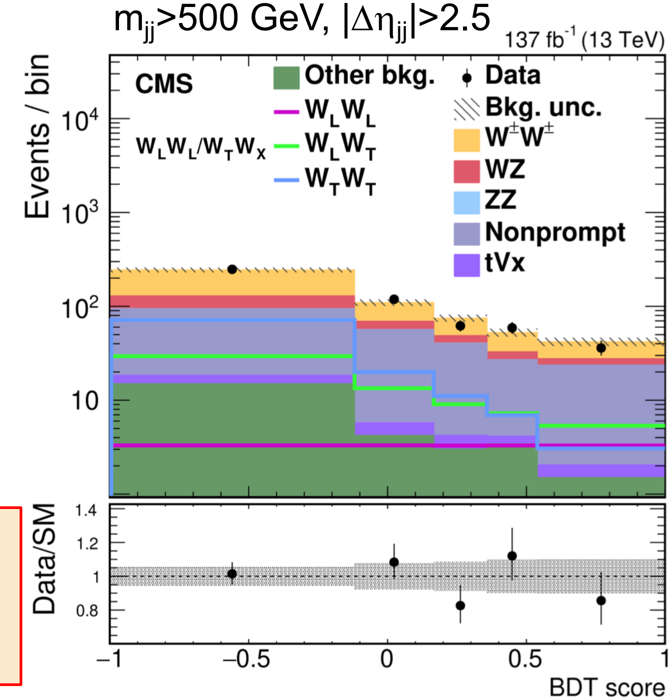
- very low expected WLWL yields → very challenging
- **measure (WLWL, WXWT) or (WLWX, WTWT) processes**
- reference-frame dependent: WW or parton-parton C.M.
- dedicated MC simulation (MG5_aMC@NLO)
- use two MVAs:
  - inclusive MVA: VBS vs. non-VBS
  - specific signal: separates polarisation states within VBS
- fit: 2D MVAs in SRs and m_{jj} in CRs
- measurements are statistically dominated

(520 data events, from which 16 are WLWL)

High sensitivity of angular variables to polarisation comp.



m_{jj}>500 GeV, $|\Delta\eta_{jj}|$>2.5

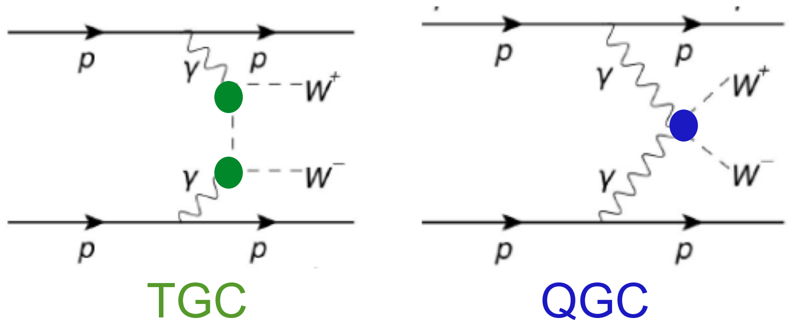


Not yet an evidence for a single-boson polarisation state

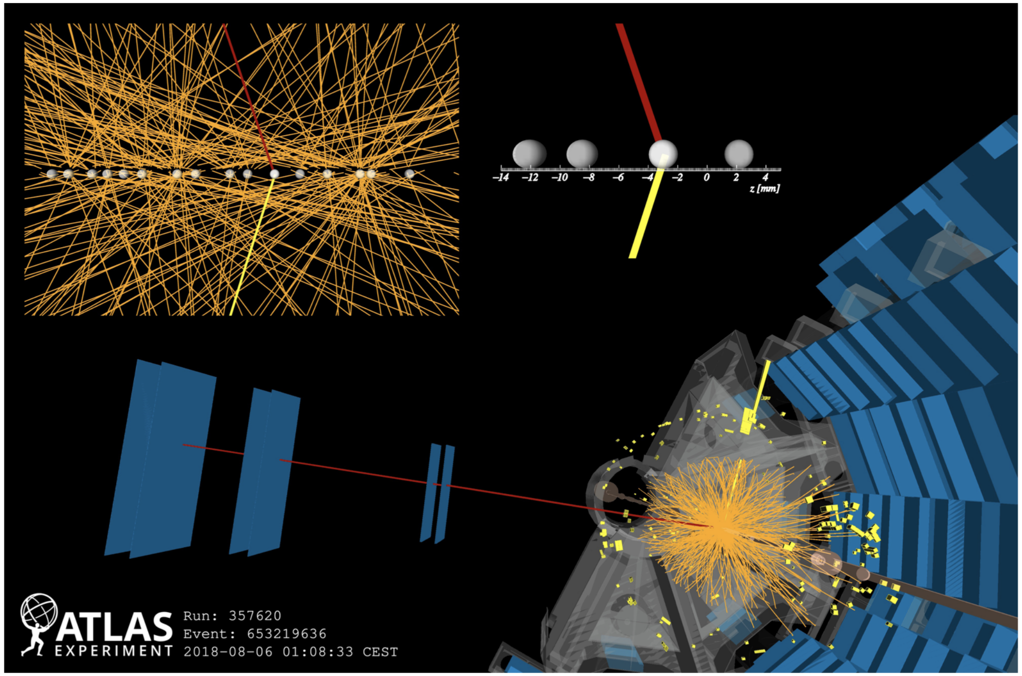
Observed (expected) significance for WLWL+WLWT: 2.3σ (3.1σ)

Obs. (exp.) significance for WLWL: 0.88σ (1.17σ)→ XS<1.17 (0.88) fb

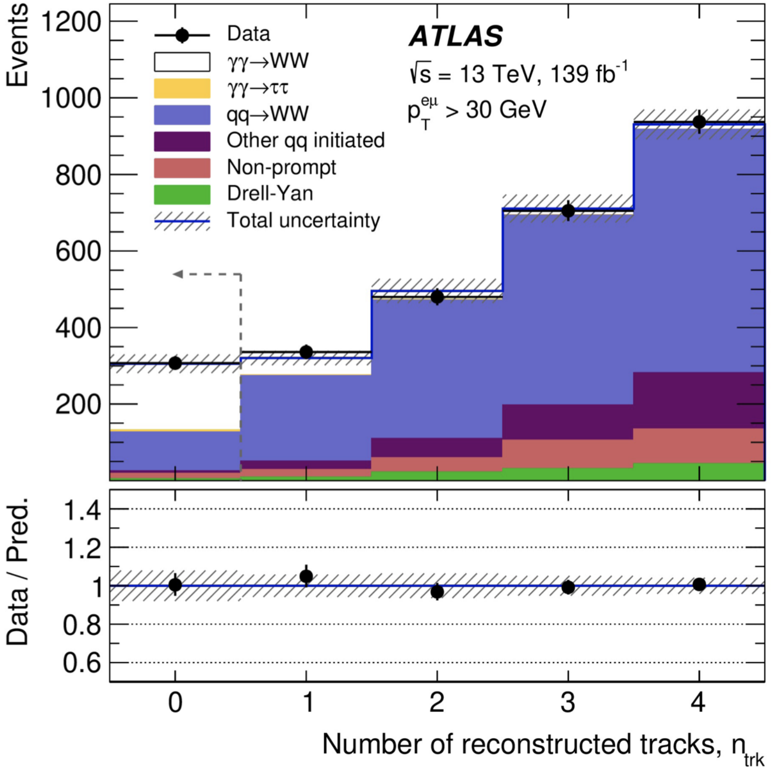
Observation of photon-induced WW production



PLB 816 (2021) 136190



At LO, it only involves self-couplings of EW gauge bosons. No forward jets. Very clean, but very rare…



- e/μ final state & NO additional charged particles in the vicinity of the selected interaction vertex (Δz=±1 mm)

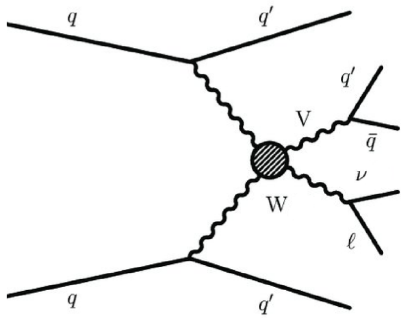
$$z_{vtx}^{\ell\ell} = \frac{z_{\ell_1}\sin^2\theta_{\ell_1} + z_{\ell_2}\sin^2\theta_{\ell_2}}{\sin^2\theta_{\ell_1} + \sin^2\theta_{\ell_2}}$$

- main challenge: determine production process in busy LHC environment (modelling of *additional pp interactions*)

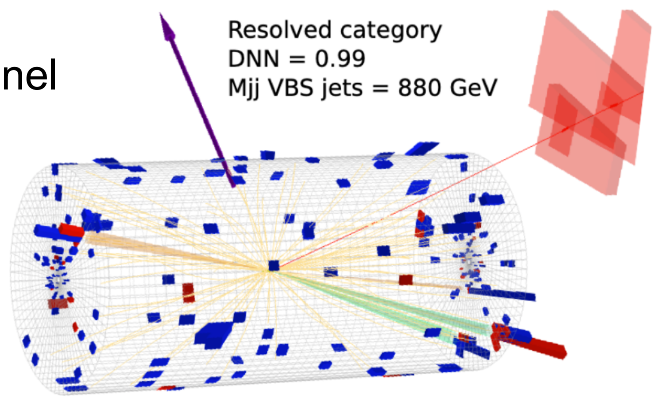
σ(γγ→WW) = 3.13 ± 0.31(stat) ± 0.28(sys) fb
Observation: 8.4σ

~300 data events in SR (~130 from bkg).
Normalisations of qq→WW and Drell-Yan bkg. free-floated.

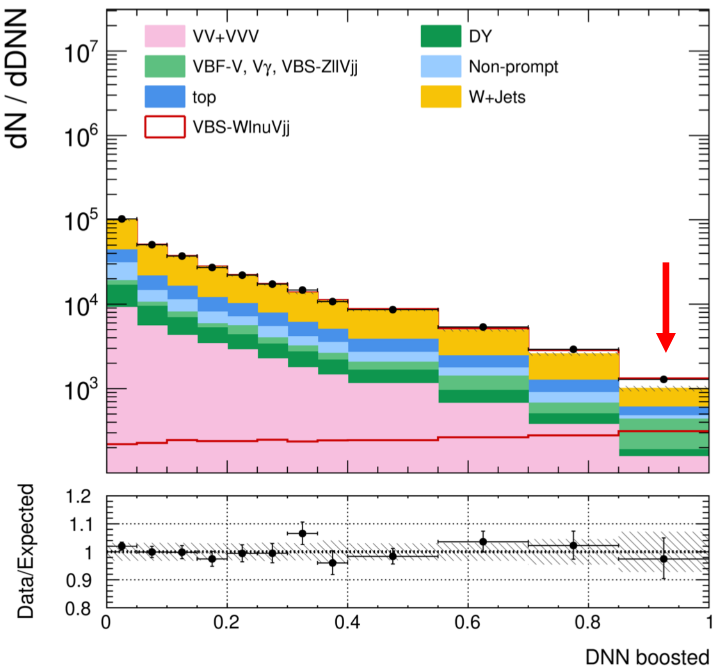
CMS-PAS-SMP-20-013



- signal: W_{lep} and V_{had} (W, Z)
- both resolved and boosted regimes of the V_{had} considered
- good balance between:
  - larger XS than fully leptonic decay channel
  - smaller bkg. than fully hadronic decay channel
- main bkgs: W+jets and top quarks
- objects/variables are exploited (and also MVAs):
  - boosted or resolved: large-R jet (AK8)
  - vs. W+jets bkg: V_{had} mass on- or off-shell
  - vs. top bkg.: *b*-jets



CMS event: Run 317640 event 954295051



Three main results:

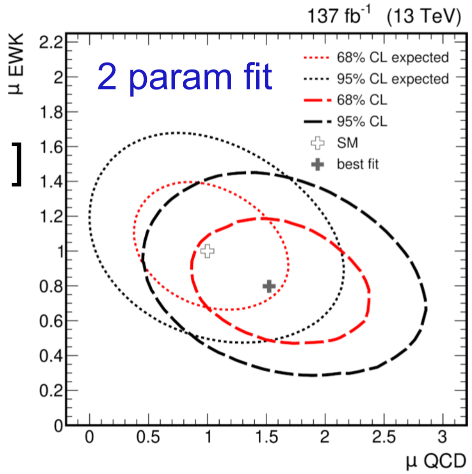
1) EW WV: $\mu_{EW} = \sigma^{obs}/\sigma^{SM} = 0.85^{+0.24}_{-0.20}[=^{+0.21}_{-0.17}\ (\text{syst.})\ ^{+0.12}_{-0.12}(\text{stat.})]$

First evidence of VBS in semilep. ch. @ LHC: 4.4σ (exp.: 5.1σ)

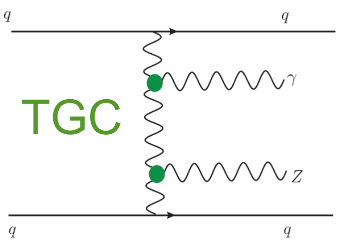
2) EW+QCD WV:

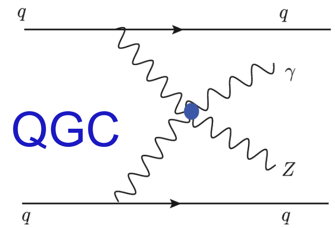
$$\mu_{EW+QCD} = 0.98^{+0.20}_{-0.17}\ [^{+0.19}_{-0.16}\ (\text{syst.})\ ^{+0.07}_{-0.07}(\text{stat.})\ ]$$

3) Simultaneous 2D fit: EW and QCD WV



Observation of Zγjj EW production



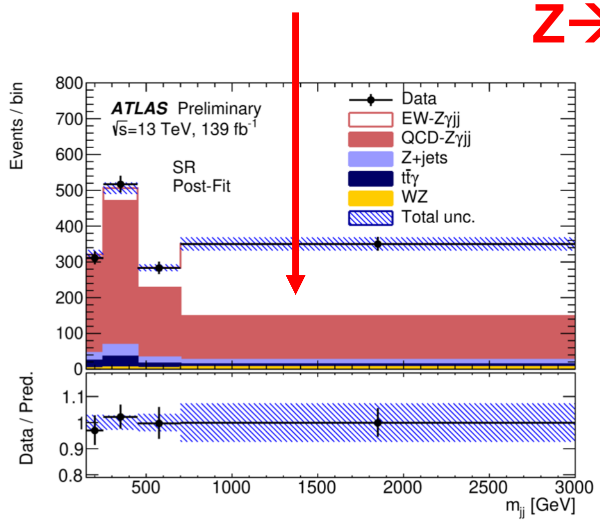


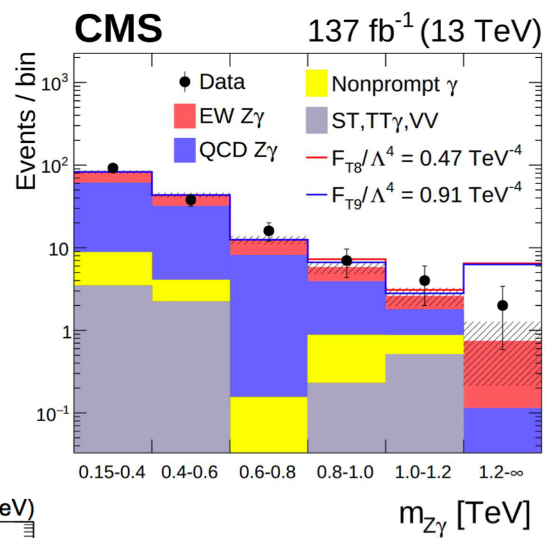
- very recent results!!
- sensitivity to pure neutral aQGC and NP

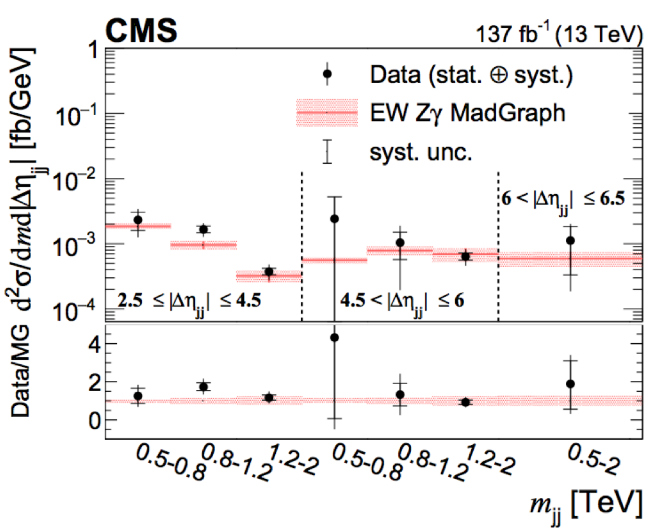
ATLAS-CONF-2021-038
arXiv: 2106.11082
arXiv: 2109.00925

Z→νν: reached 5σ
Z→ll: >10σ
Cross sections in agreement with SM, $\delta\sigma_{Z\gamma jj}$ <15%

Z→ll





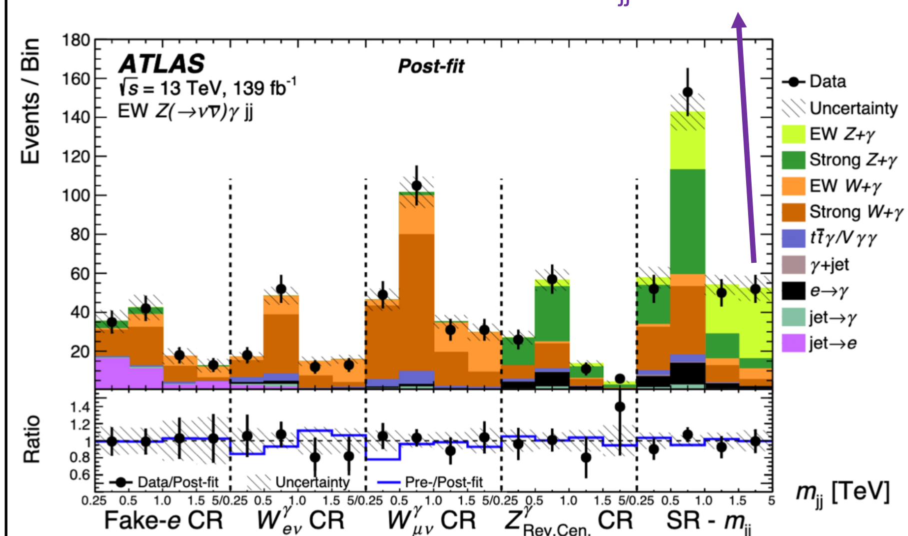


EW and EW+QCD Zγjj unfolded differential XS also measured.

Interpretation aQGC using $m_{Z\gamma}$: no obvious deviation from SM is observed.

Z→νν

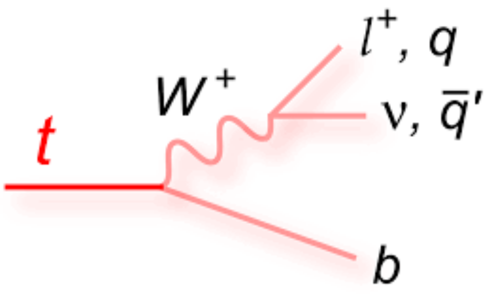
Data event with m_{jj}~4 TeV seen!



Interpretation H→inv or dark photon signals.
No significant excess.
Upper limits in BR or XS.

Top quark physics

- **most massive elementary particle**
- 'bare' quark: decays before hadronisation
- window into quark properties
- plays an important role in Higgs physics
- **interacts with all forces**

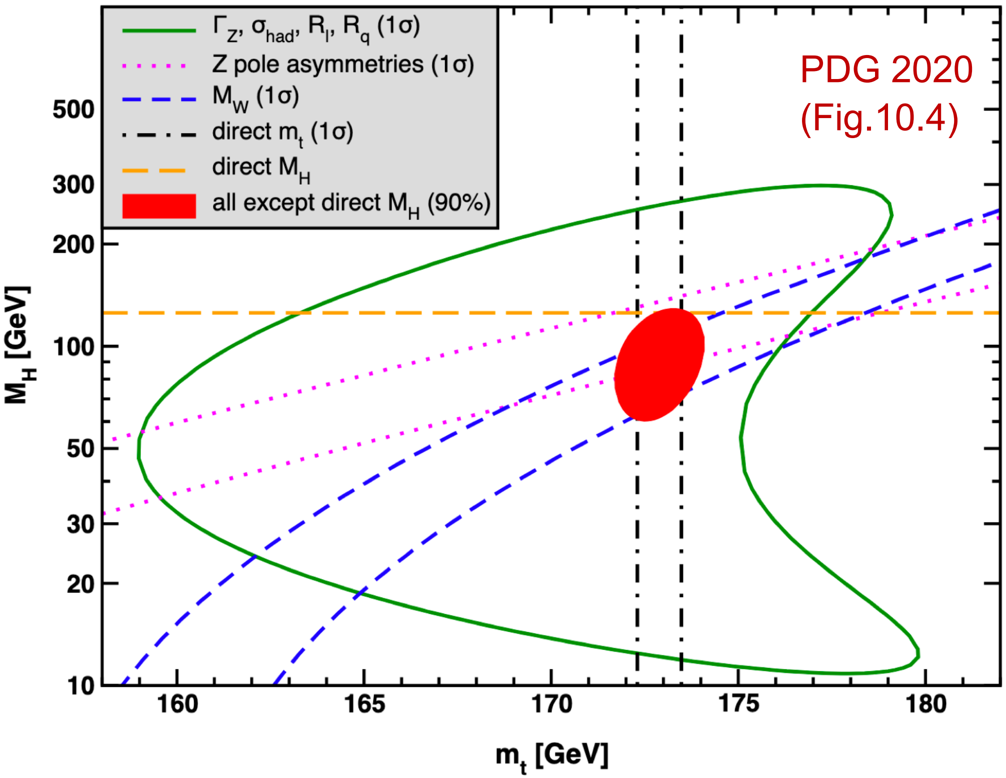


$t \to Wb$ ~100%

Main production modes:
- **Top and antitop pairs** (strong interaction, 800 pb): gg or qq initiated
- **Single top/antitop quarks** (EW interaction, 10-200 pb): t-ch, Wt, s-ch.

Associated production (< 1 pb): **tt+X or t+X**

Top quark mass: a very important parameter of the SM

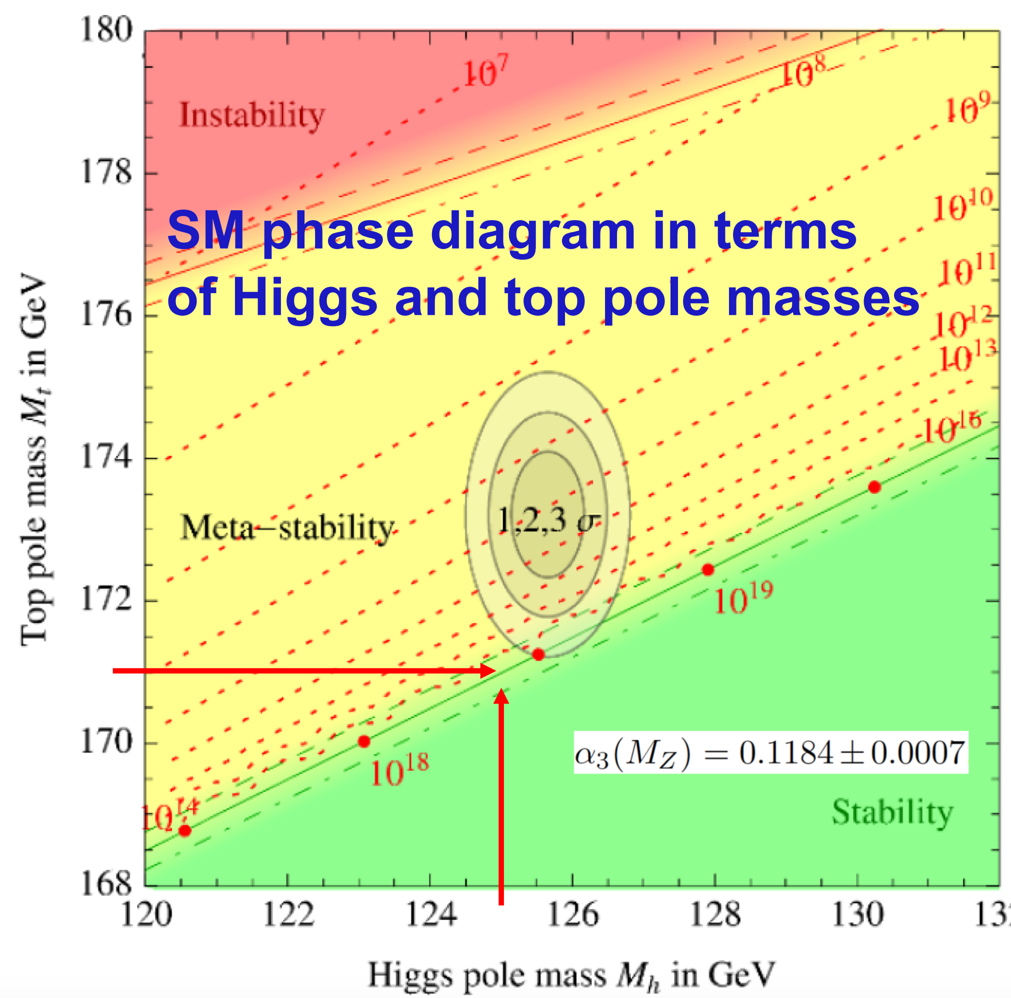


Global EW fits

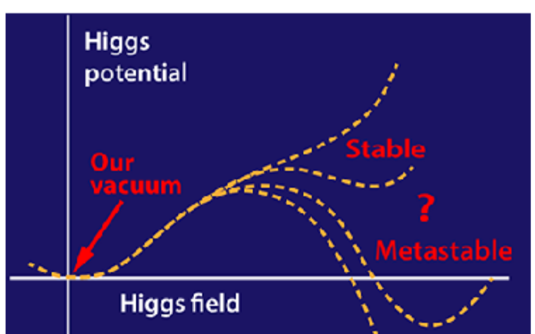
- important consistency test of the SM
- good agreement between measured and indirect predictions (*p*-value: 0.48, before FNAL g-2)

Recent measurements:
$\delta m_H \sim 0.11\%$, $\delta m_t \sim 0.3\%$

SM phase diagram in terms of Higgs and top pole masses

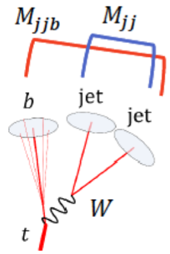


JHEP12(2013)089

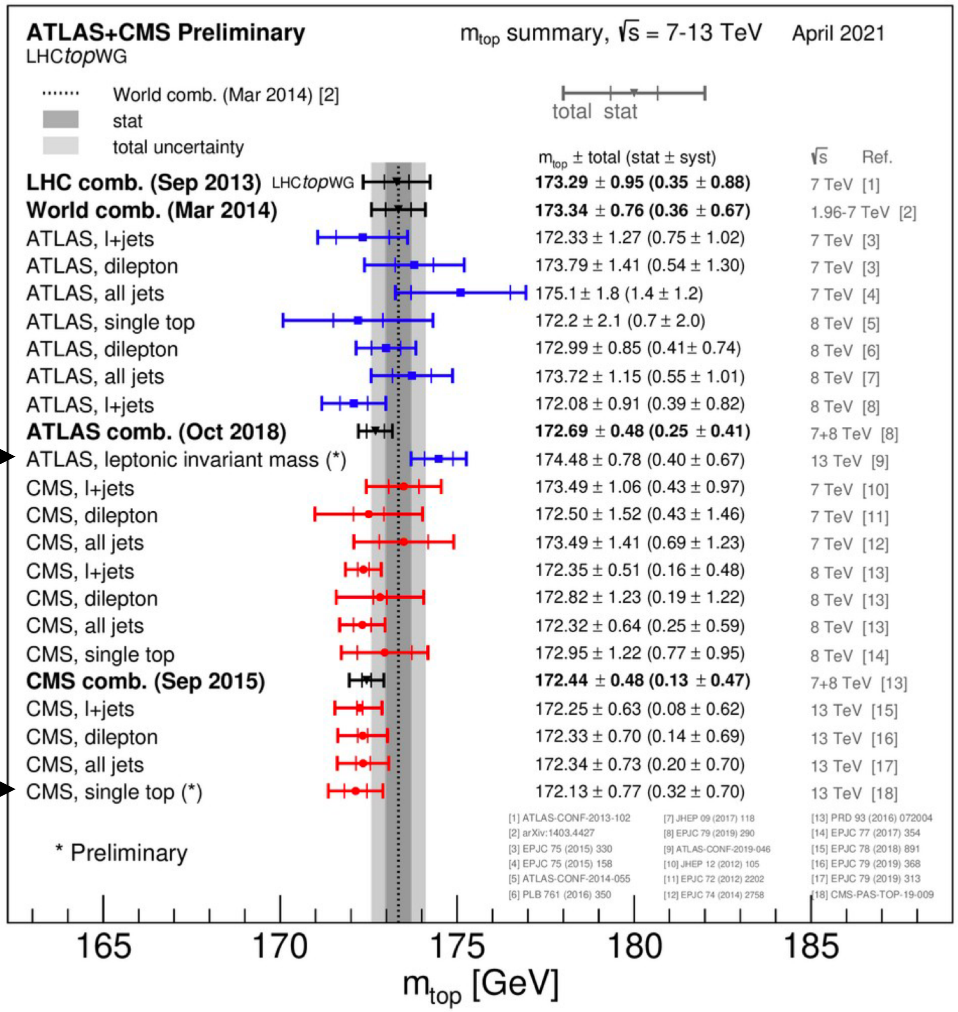


Top quark mass: two types of measurements

→ m_t^{MC}



Using decay products (kinematic reconstruction) → "direct" method

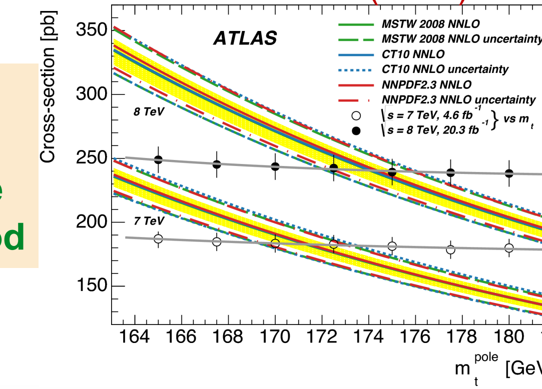


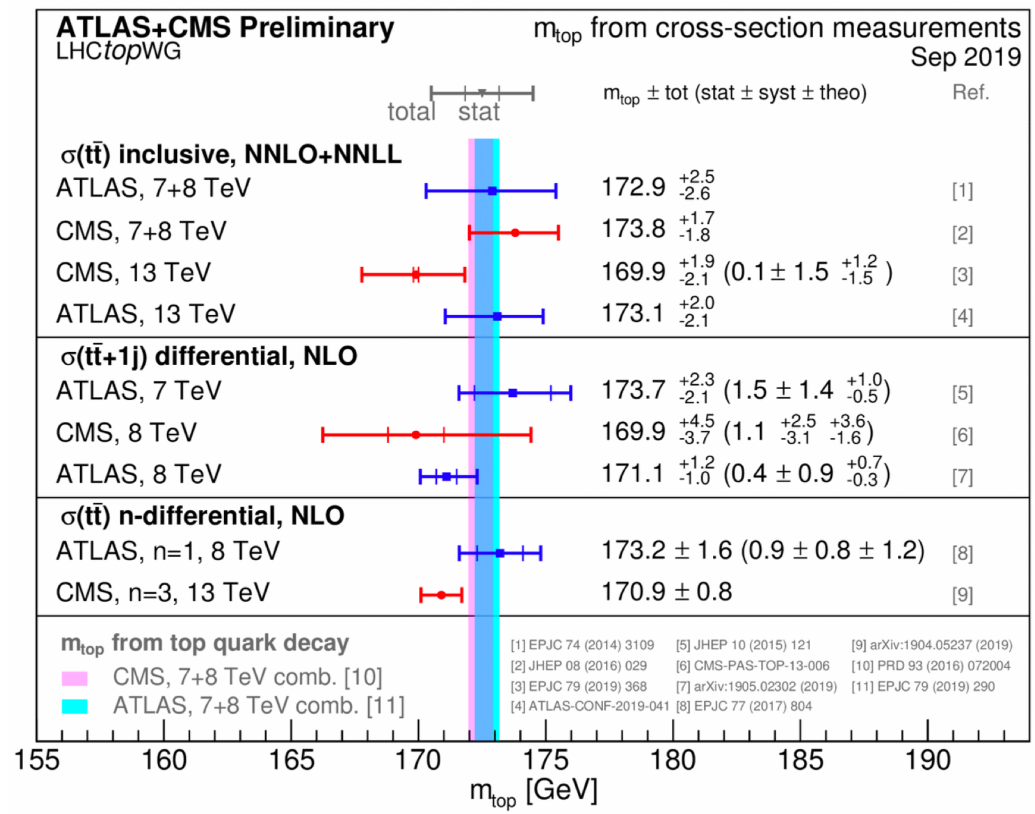
Recent measurements → $\delta m_t \sim 0.3\%$

→ m_t^{POLE}, $m_t^{\overline{MS}}$

EPJC 74 (2014) 3109
EPJC 76 (2016) 642

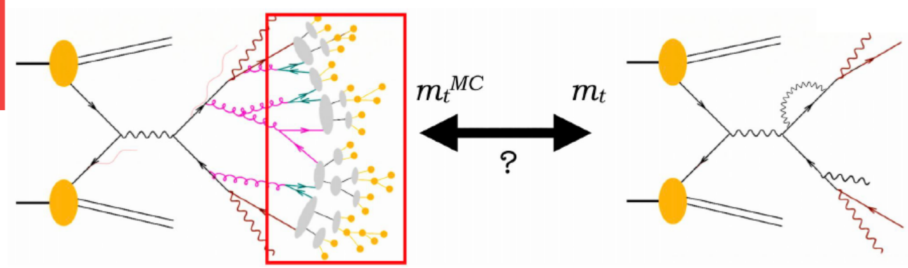
Using cross sections or unfolded dist. sensitive to the mass parameter in the model → "indirect" method





Recent measurements → $\delta m_t \sim 0.5\%$

MC/pole mass calibration



● Differences btw. m_t^{MC} and m_t^{POLE} expected of ~0.5 GeV, due to non-perturbative QCD effects that affect m_t determination

● Interpretation (calibration) of m_t^{MC} obtained by comparing MC dist. with calculations within well-defined theo. framework (m_t^{POLE}, m_t^{MSR})
- setting the scale to 1 GeV: $m_t^{MSR}(1\ GeV) \approx m_t^{POLE}$
- analytical calculation with non-pert. QCD effects at particle-level

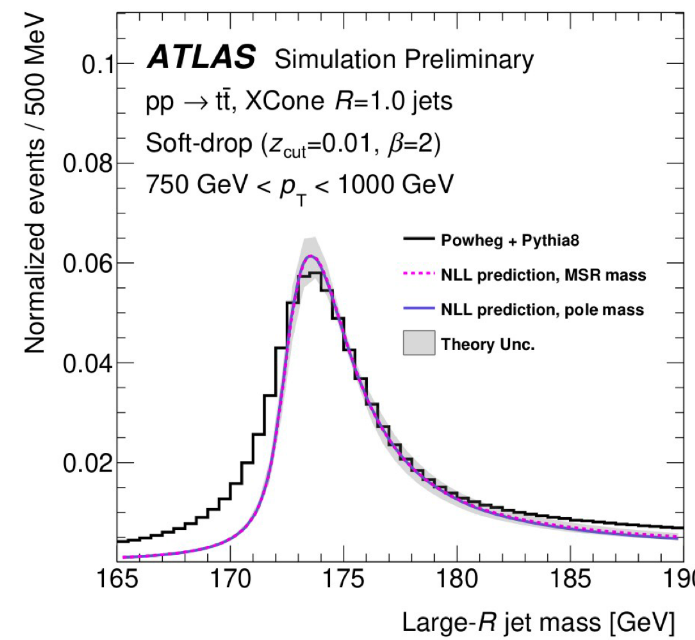
● Hadronically decaying top quarks fully reconstructed as lightly groomed large-R jets in boosted kinematic regime (jet p_T>750 GeV)
- *large-R jet with R=1 using XCone algorithm*

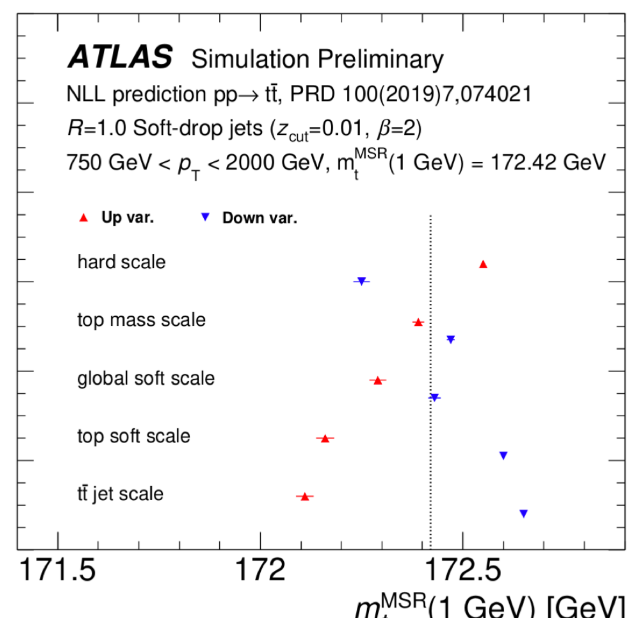
$$m_{top}^{MC} = m_{top}^{MSR}(1\ GeV) + \Delta m^{MSR} = m_{top}^{pole} + \Delta m^{pole}$$

$$m_t^{\text{MC}} = m_t^{\text{MSR}}(1\ \text{GeV}) + 80^{+350}_{-410}\ \text{MeV} = m_t^{\text{pole}} + 350^{+300}_{-360}\ \text{MeV}$$

$$m_t^{MSR}(R = 1\ \text{GeV}) = 172.42 \pm 0.10\ \text{GeV},$$

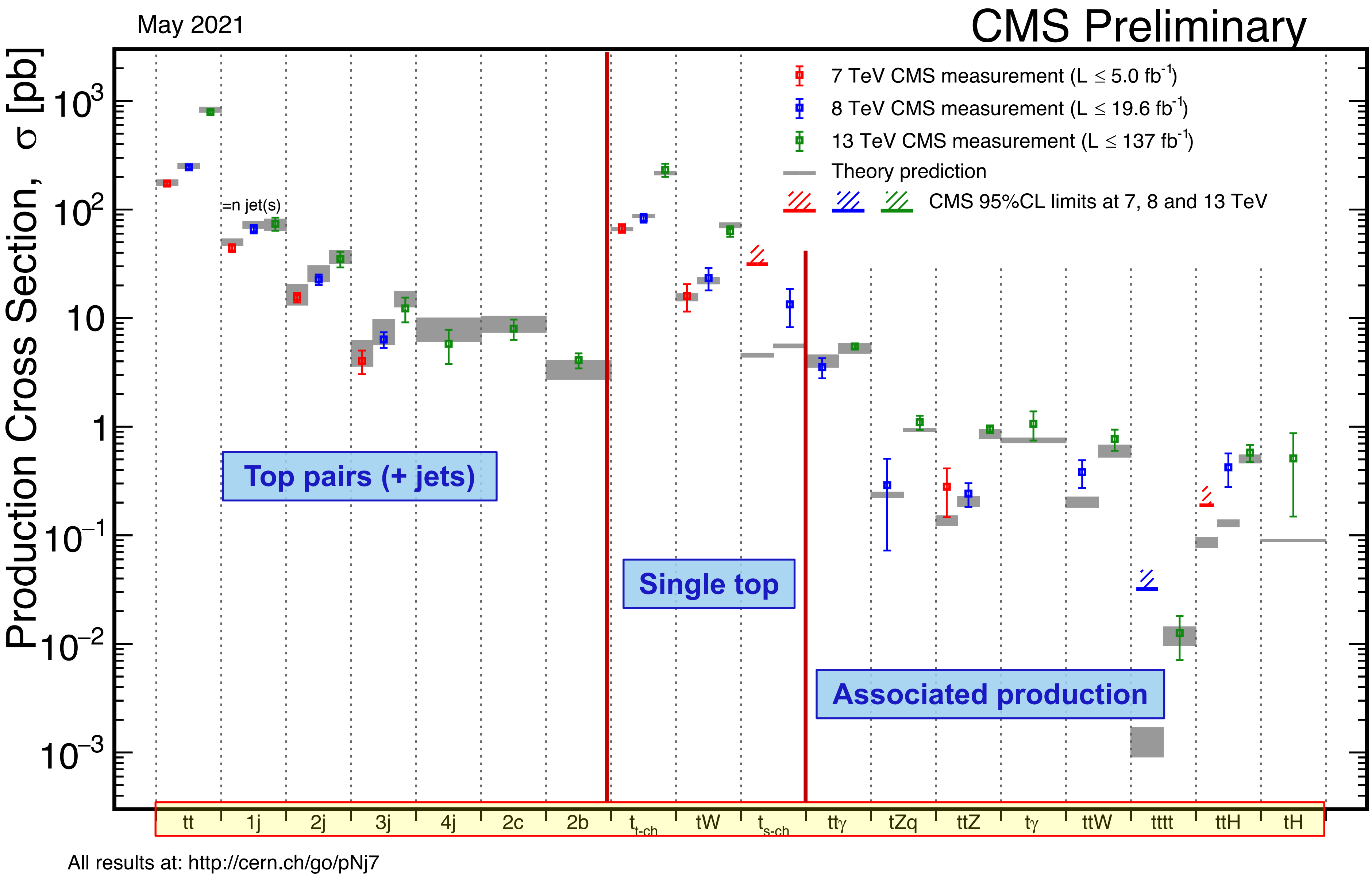
● Uncertainties dominated by theoretical ones (uncalculated higher orders in NLL calculation, fit methodology and UE modelling).





ATL-PHYS-PUB-2021-034

Top quark production cross sections



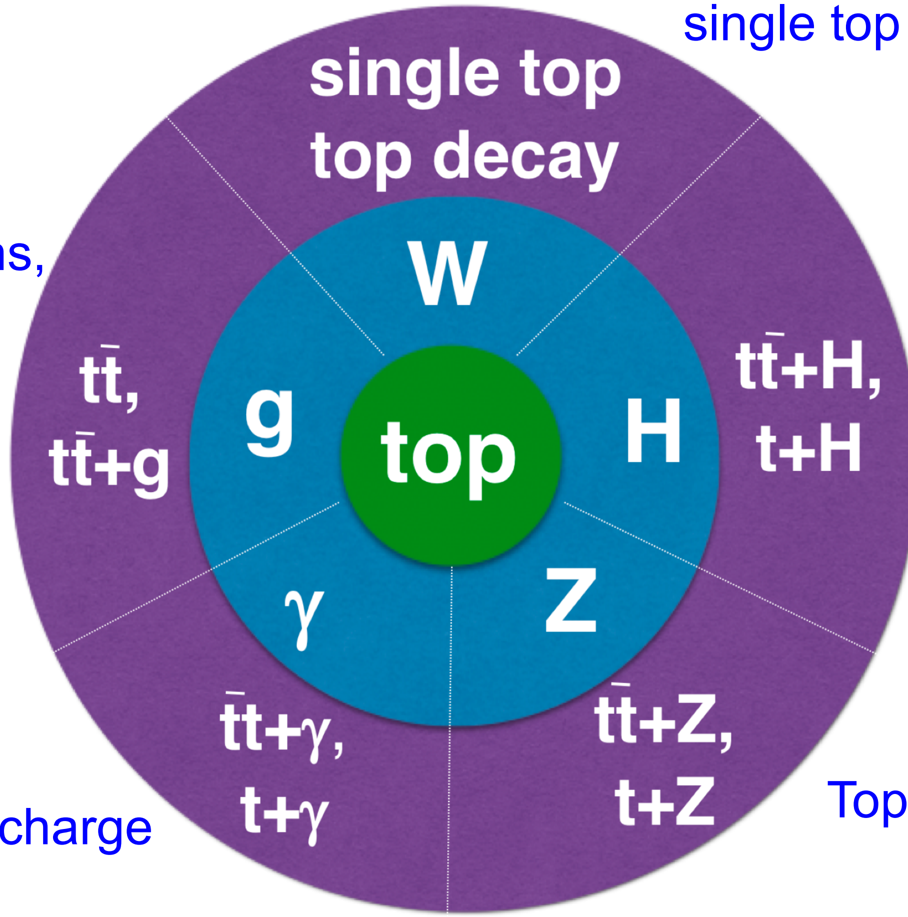
Increasing number of differential measurements, reaching very high precision, also EFT interpretations

Top quark couplings

Top quark couples to other SM fields through its **gauge and Yukawa interactions.**

W helicity and several single top quark measurements

Differential cross-sections, spin correlations, charge asymmetry, etc.



Top Yukawa coupling

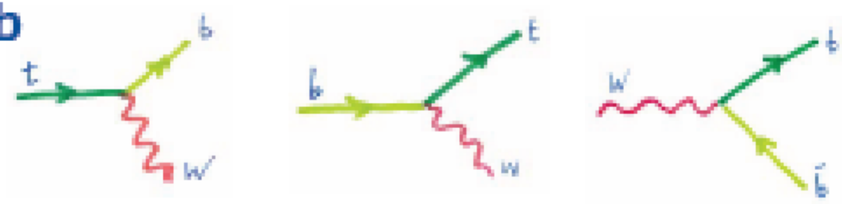
Top electric charge

Top weak isospin

top + X coupling: how to measure it?

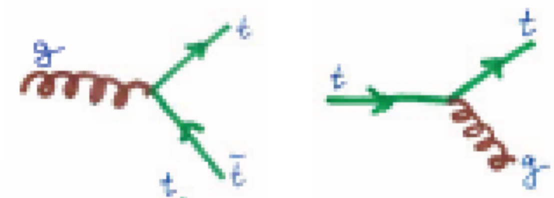
Flavour changing charged current

- Wtb

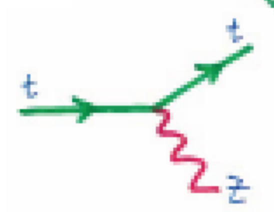


Flavour conserving neutral current

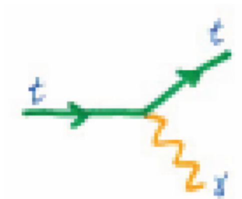
- tgt



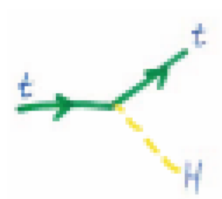
- tZt



- tγt

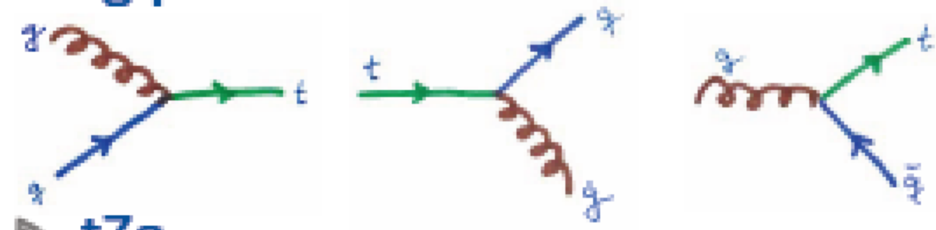


- tHt

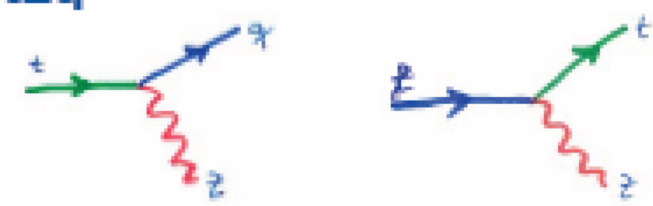


… and neutral current

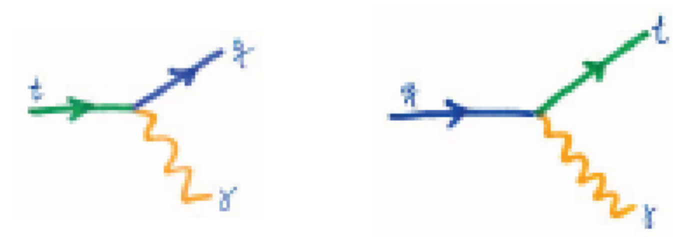
- tgq



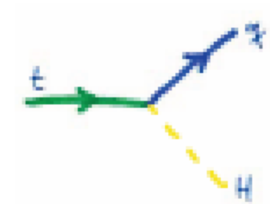
- tZq



- tγq



- tHq



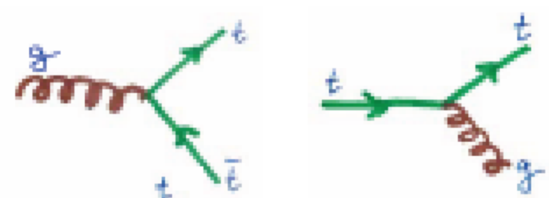
Top coupling to W bosons (*Wtb* vertex)

Flavour changing charged current

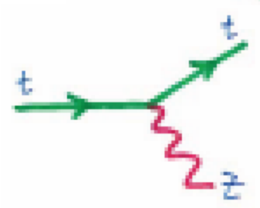
- Wtb

Flavour conserving neutral current

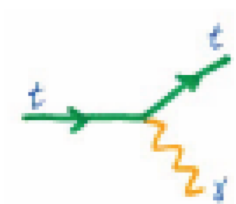
- tgt



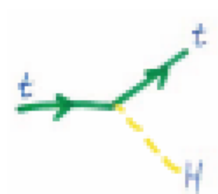
- tZt



- tγt

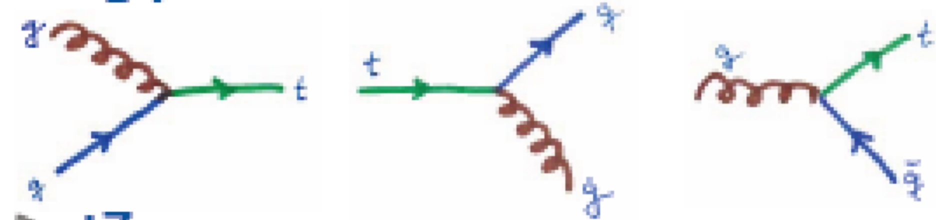


- tHt

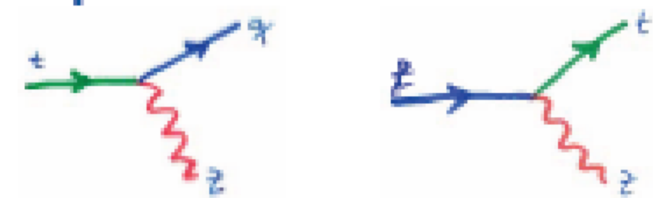


… and neutral current

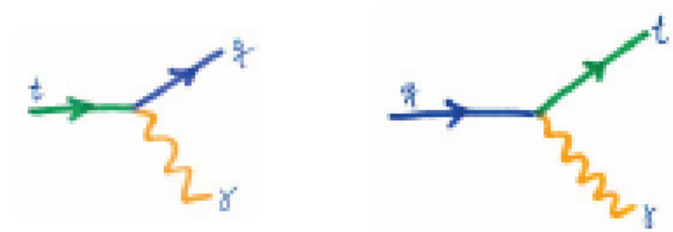
- tgq



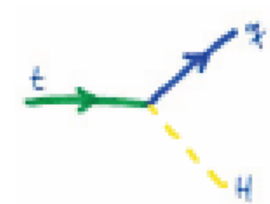
- tZq



- tγq



- tHq



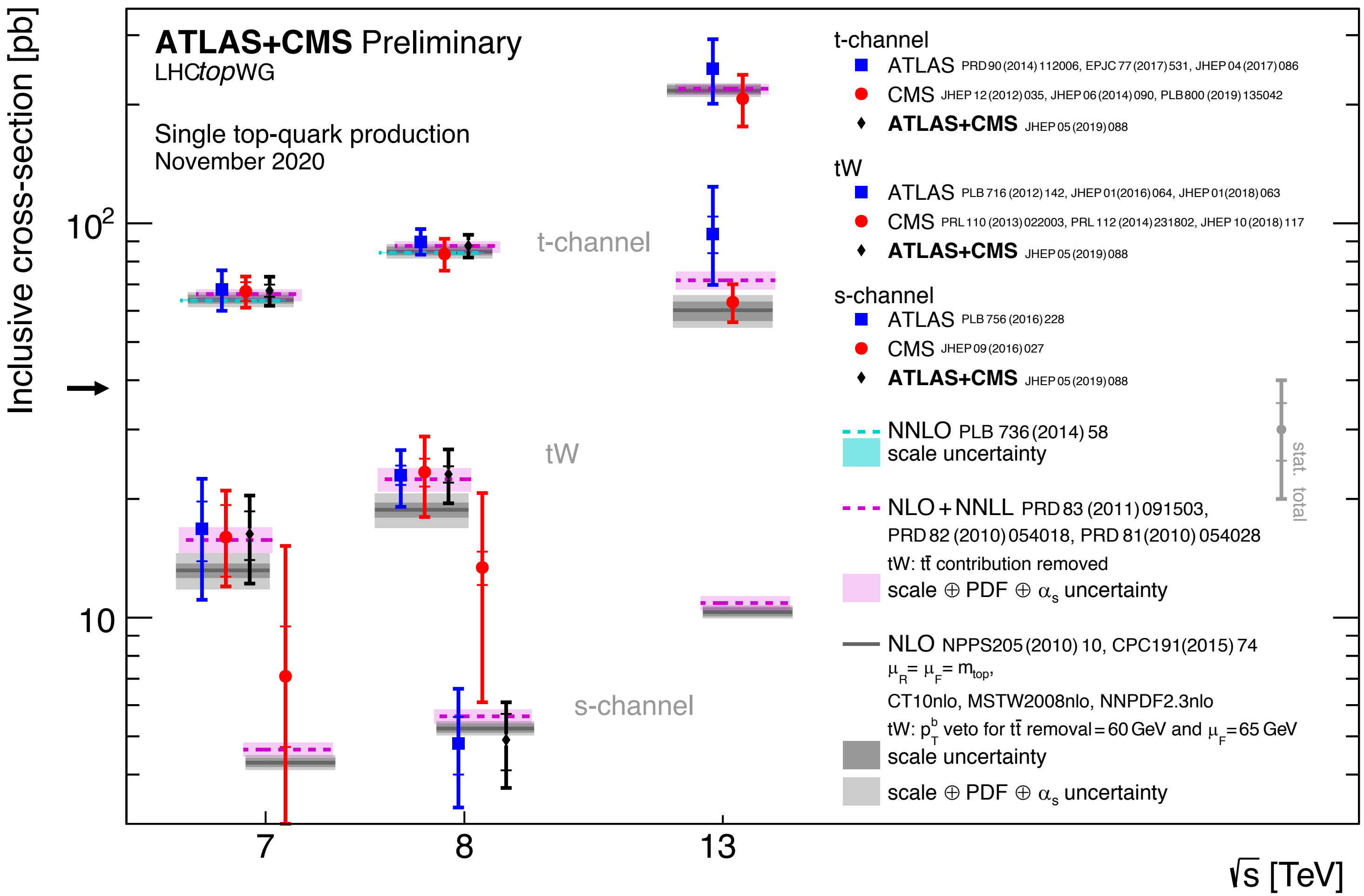
Top coupling to W bosons: single top production

The *Wtb* vertex has a V-A structure, described by $\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{\mathrm{L}}P_{\mathrm{L}}tW_{\mu}^{-} + \mathrm{h.c.}$

single top quark production cross sections

Combinations of ATLAS and CMS results using full Run 1 published

JHEP05(2019)088



→ (7 TeV) 8.4%
(8 TeV) 6.7%

→ (7 TeV) 25%
(8 TeV) 16%

→ (8 TeV) 30%

Exp. unc. larger than theory prediction unc. (4-8%)

s-ch. challenging, still not observed at LHC (only evidence)

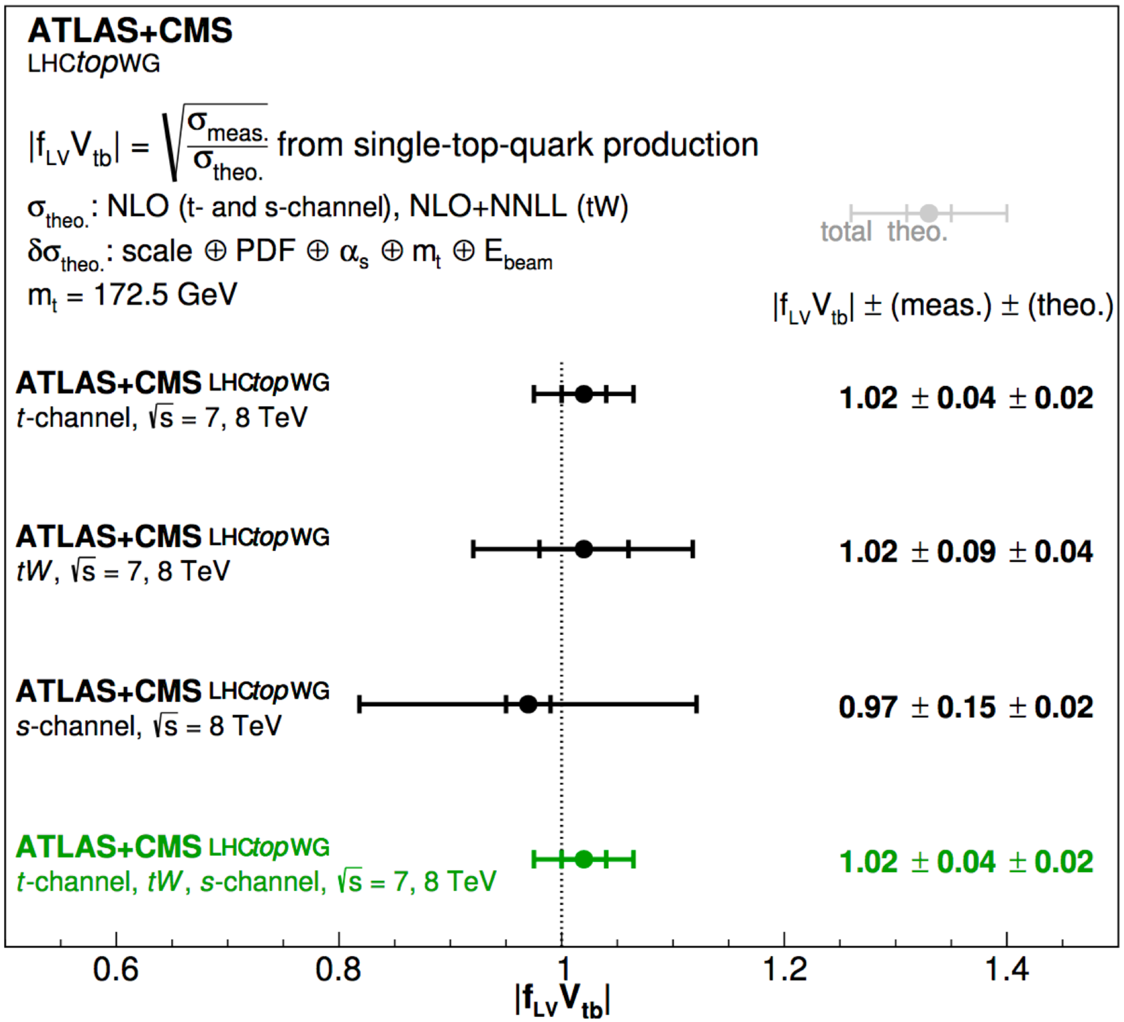
Top coupling to W bosons: V_{tb} measurement

The *Wtb* vertex has a V-A structure, described by $\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{\mathrm{L}}P_{\mathrm{L}}tW_{\mu}^{-} + \mathrm{h.c.}$

From single top quark production cross sections, **V_L can be extracted**: $|V_{\mathrm{L}}| \equiv |f_{\mathrm{LV}}V_{\mathrm{tb}}| = \sqrt{\frac{\sigma_{\mathrm{meas.}}}{\sigma_{\mathrm{theo.}}}}$

Combinations of ATLAS and CMS results using full Run 1 published

JHEP05(2019)088



3.9%

8.4%

15.0%

3.7%

Direct measurement

→ Assumptions:

Wtb has a SM-like left-handed weak coupling

$|V_{tb}| >> |V_{td}|, |V_{ts}|$

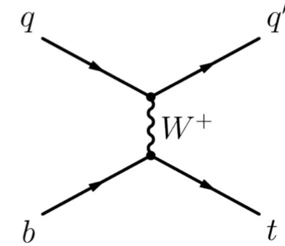
→ Independent of number of quark generations or unitarity of CKM matrix

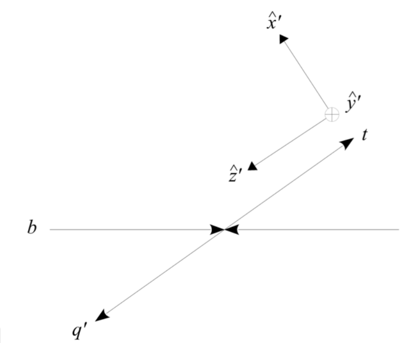
Dominant systematics:
theory modelling and normalisation

Top coupling to W bosons: top polarisation

ATLAS-CONF-2021-027

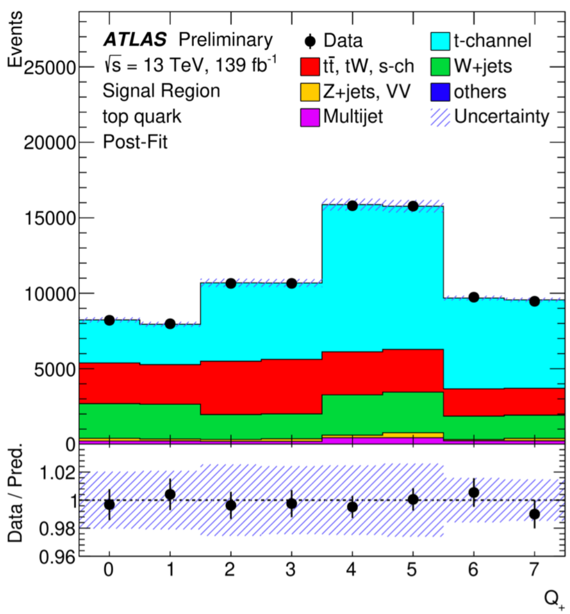
High polarisation expected from V-A structure of CC in single top.
Spin information transferred to the top quark decays.
1st measurement of full polarization vector via angular dist. of leptons for both top and antitop quarks.
3D space divided into 8 *octants* → fit rates in each of them

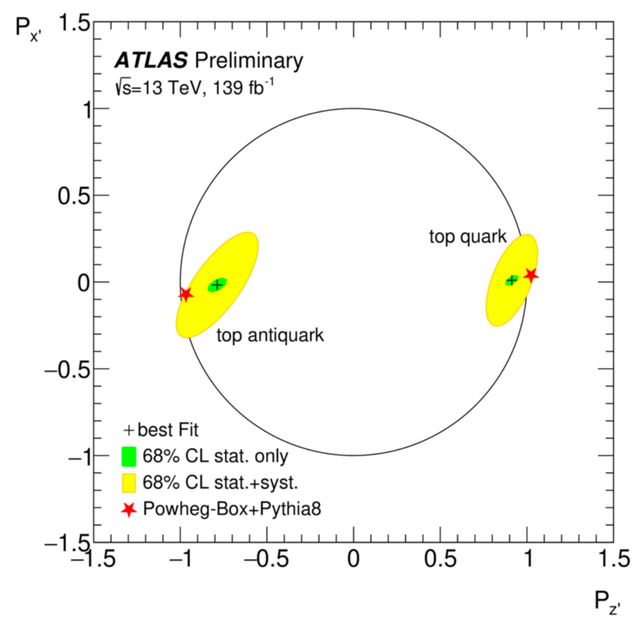


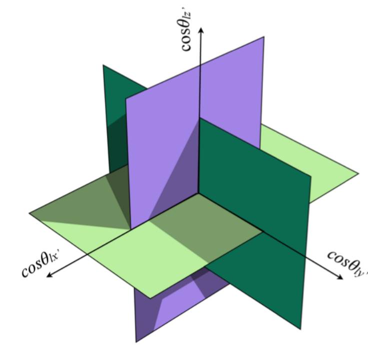


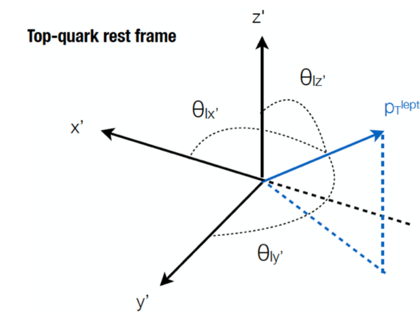
$$\hat{z}' = \vec{p}_{q'}/|\vec{p}_{q'}|$$

$$\hat{y}' = (\hat{z}' \times \vec{p}_q)/|\hat{z}' \times \vec{p}_q|$$





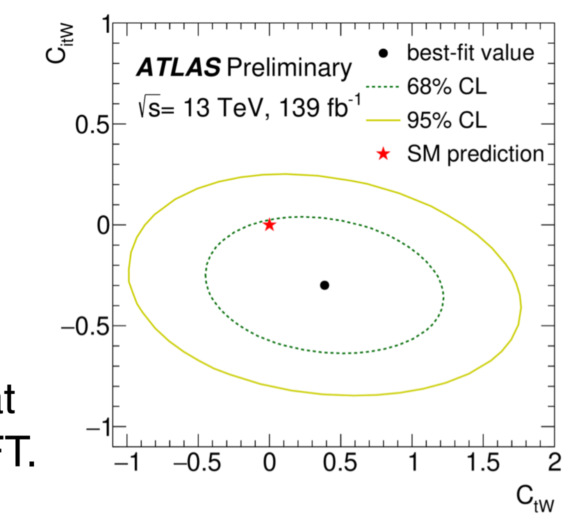




$P^{t}_{x'}$	$+0.01 \pm 0.18$	(± 0.02)
$P^{\bar{t}}_{x'}$	-0.02 ± 0.20	(± 0.03)
$P^{t}_{y'}$	-0.029 ± 0.027	(± 0.011)
$P^{\bar{t}}_{y'}$	-0.007 ± 0.051	(± 0.017)
$P^{t}_{z'}$	$+0.91 \pm 0.10$	(± 0.02)
$P^{\bar{t}}_{z'}$	-0.79 ± 0.16	(± 0.03)

$P_y=0$ → CP is conserved.
Mainly dominated by JER.

Unfolded angular distributions at particle level used to test SMEFT.

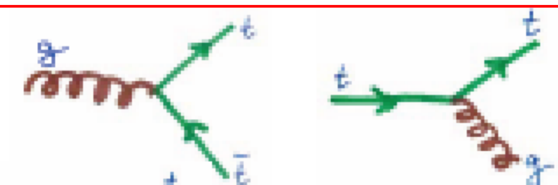


Flavour changing charged current

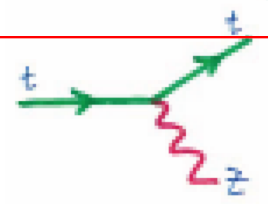
- Wtb

Flavour conserving neutral current

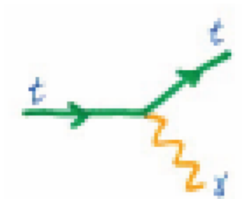
- tgt



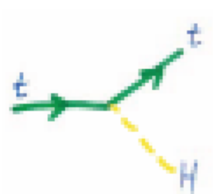
- tZt



- tγt

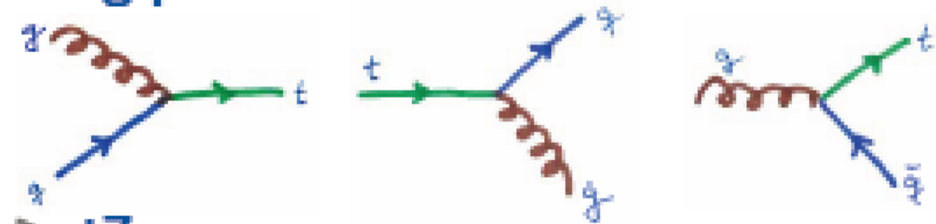


- tHt

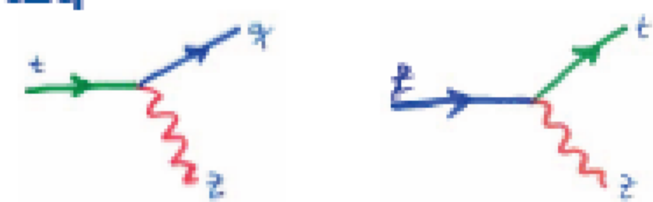


… and neutral current

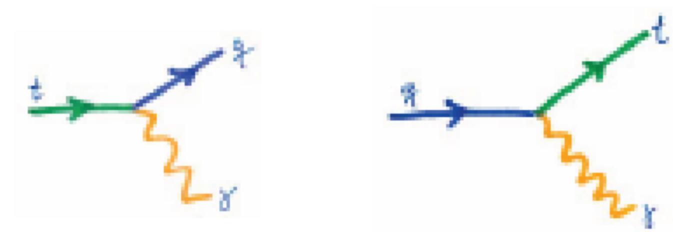
- tgq



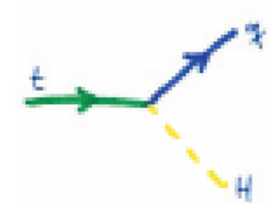
- tZq

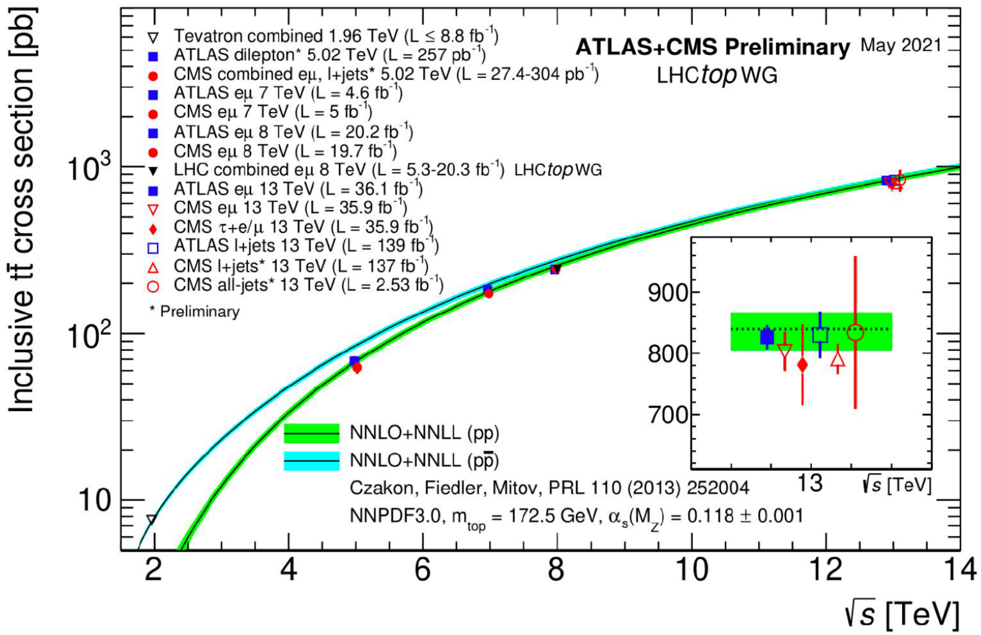


- tγq

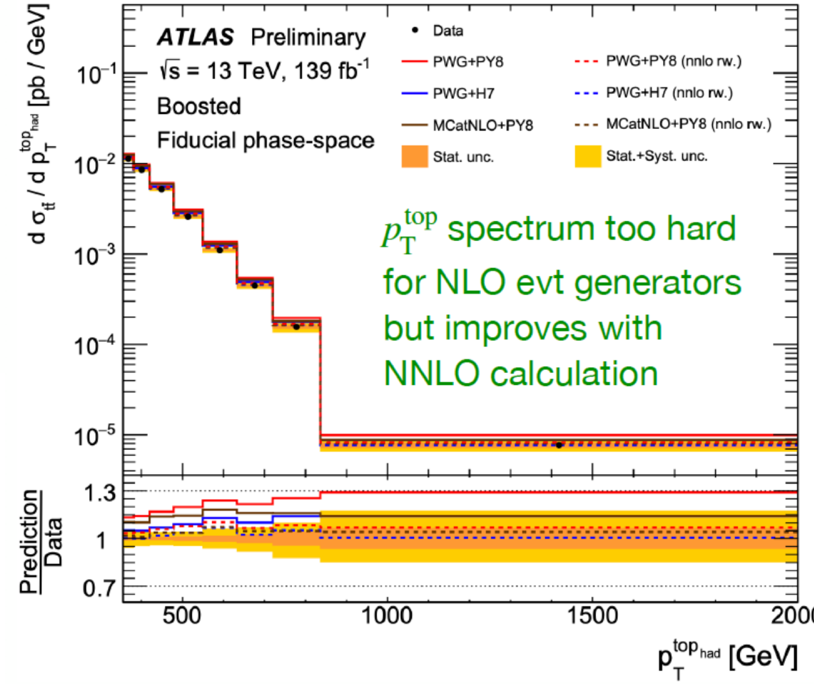


- tHq





ATLAS-CONF-2021-031

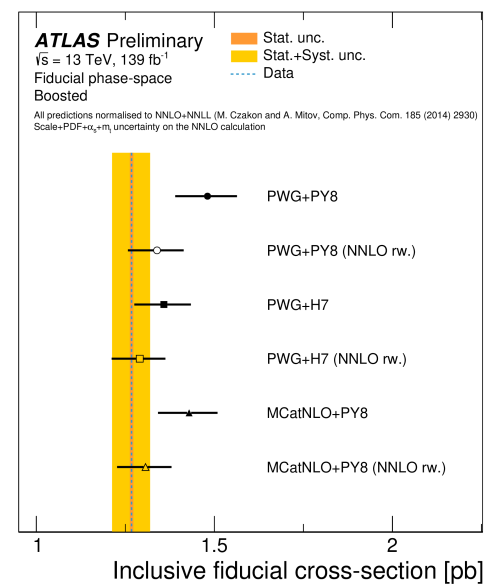


Inclusive cross sections

- reaching 2.4% exp. precision
- boosted: XS overestimated by several predictions NLO+PS; fiducial XS agrees significantly better after reweighting to NNLO(QCD)+NLO(EW) at parton level

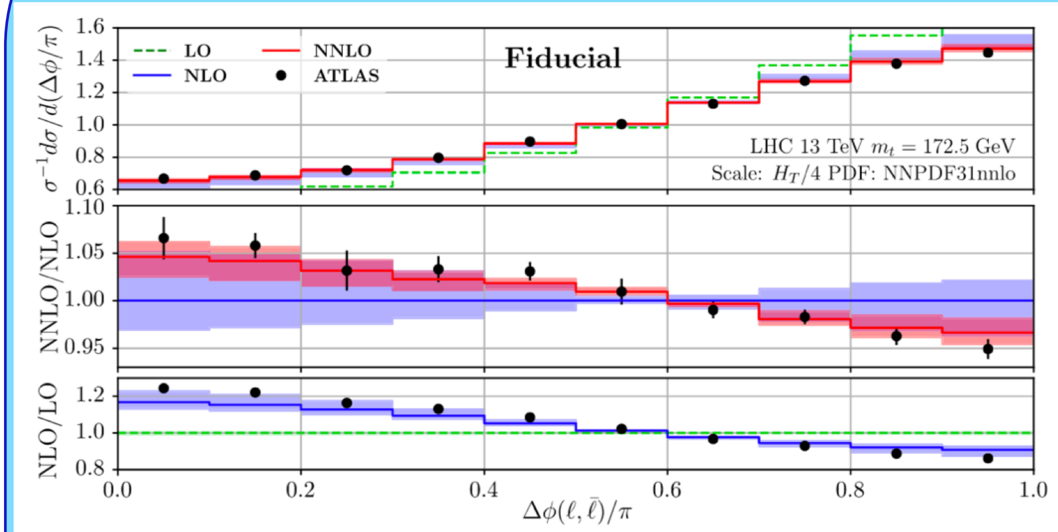
Differential measurements:

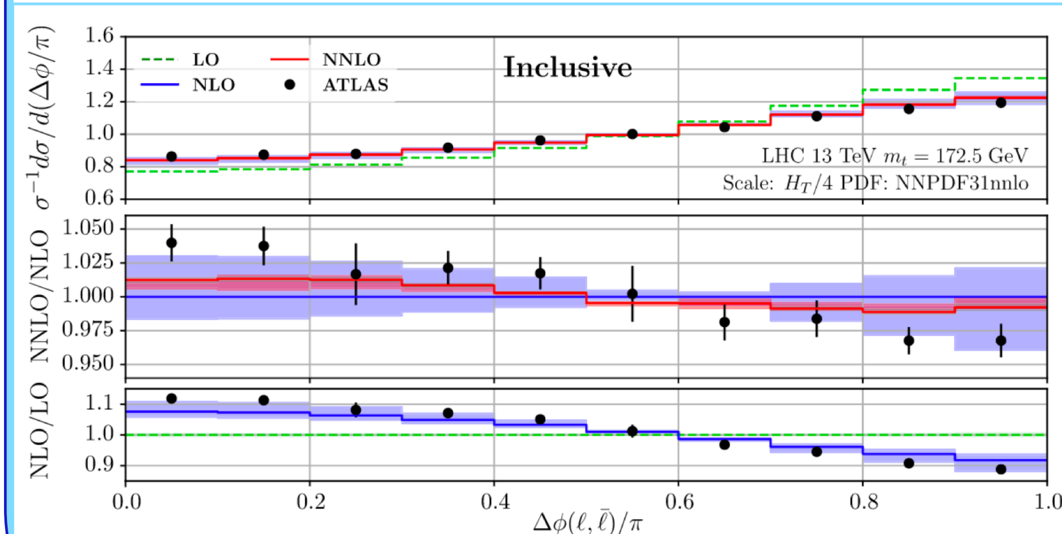
- increasing number of variables (16) in all ch. (all had, dilepton, single lepton; resolved, boosted); also 3D
- measure both *tt* and radiation
- test SM at high p_T top, where deviations expected from BSM
- agreement with SM: NLO MC reweighted to NNLO



Top coupling to gluons: asymmetries and angular dist.

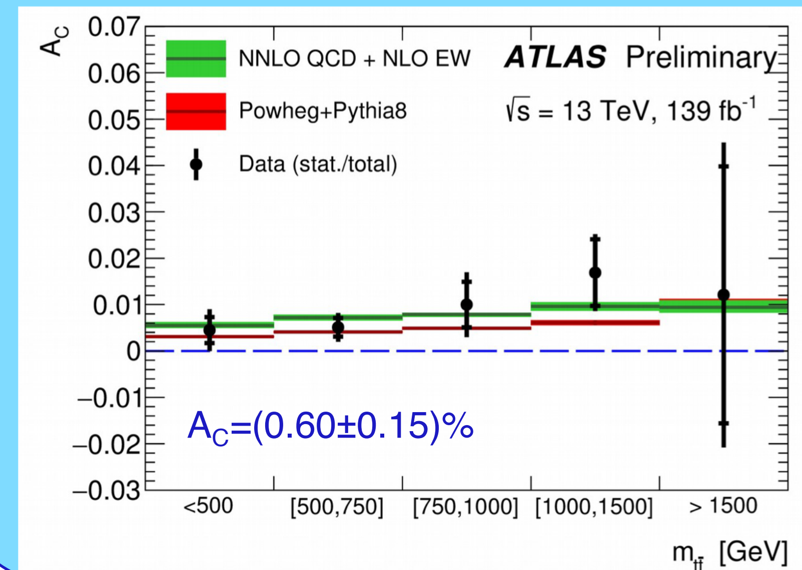
Spin correlations





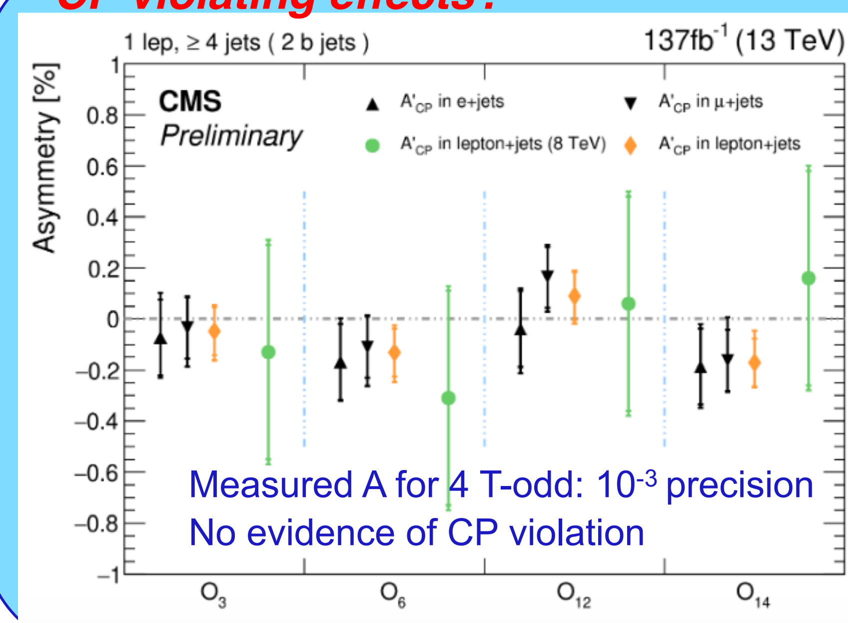
Theory paper PRL 123, 082001 (2019)
based on ATLAS-CONF-2018-02

Evidence of charge asymmetry (4σ)



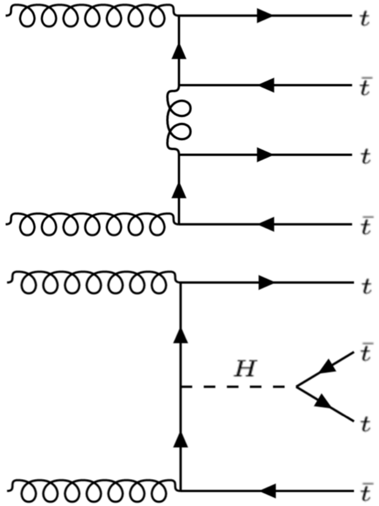
ATLAS-CONF-2019-026

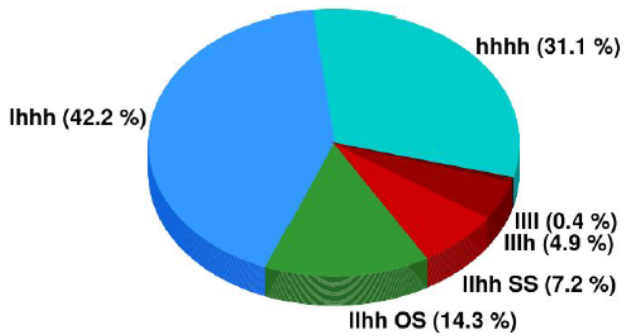
CP violating effects?



CMS-PAS-TOP-20-005

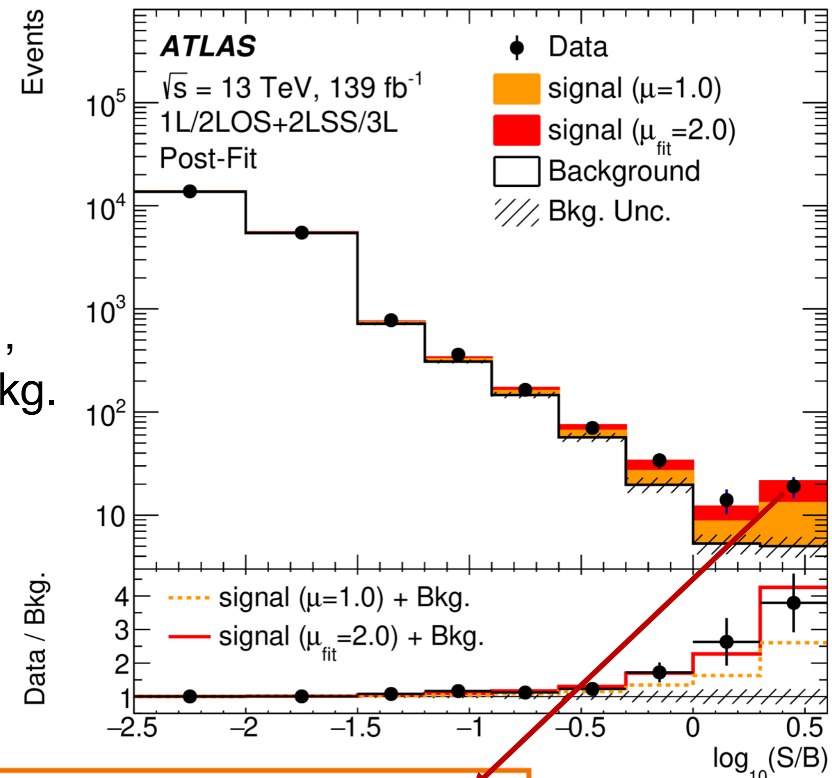
Production of four top quarks at once



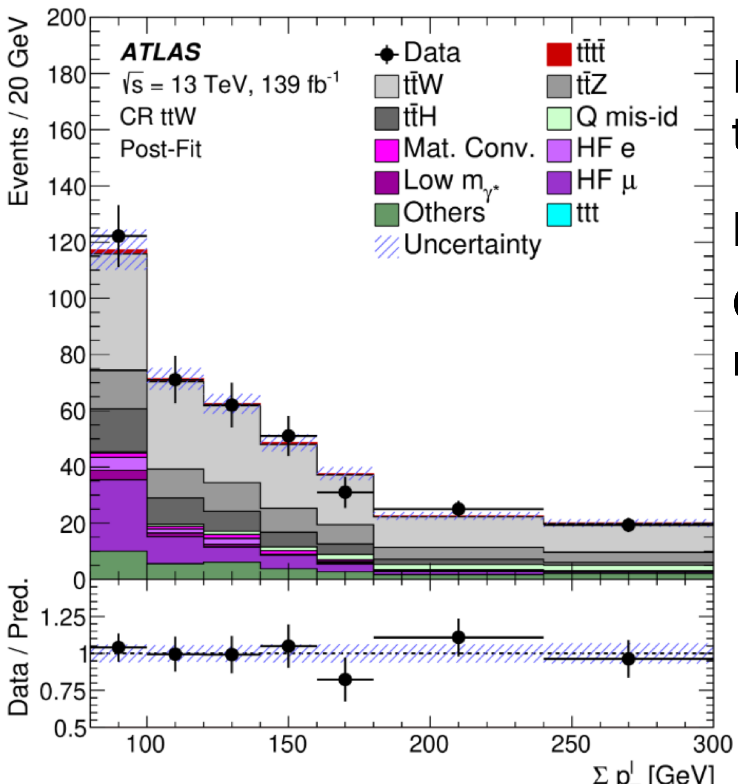


Exploit events with ≥1l.

One of the most spectacular mechanisms
- quite energetic $\sqrt{s} \geq 4m_{top} \sim 700$ GeV
- very challenging: 12 final state objects
- sensitive to new physics



arXiv: 2106.11683



For most sensitive ch., ttW+jets is the main bkg.

NF=1.6 ± 0.3

Good post-fit modelling

$$\sigma_{t\bar{t}t\bar{t}}^{1L2LOS/SSML} = 24\,^{+4}_{-4}\,(\text{stat.})\,^{+5}_{-4}\,(\text{syst.}) = 24\,^{+7}_{-6}\ \text{fb}$$

(ATLAS: μ~2, CMS: μ~1)

Significance: 4.7σ (expected: 2.6σ)

→ Very close to observation of 4-tops production

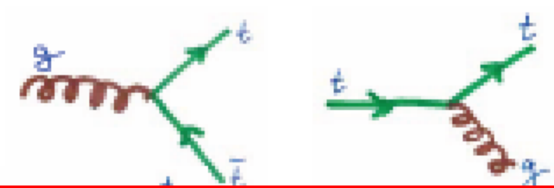
Top coupling to γ/Z/H bosons

Flavour changing charged current

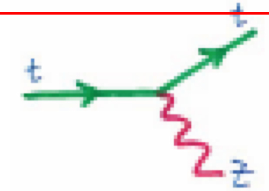
- Wtb

Flavour conserving neutral current

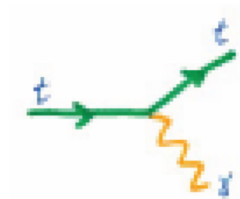
- tgt



- tZt



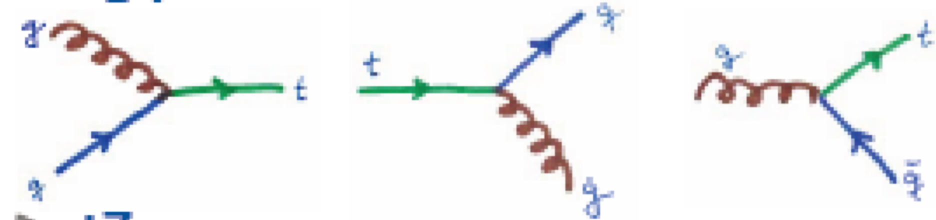
- tγt



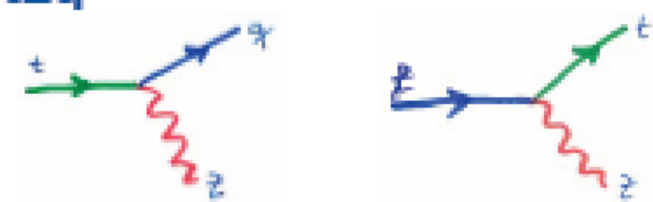
- tHt

… and neutral current

- tgq

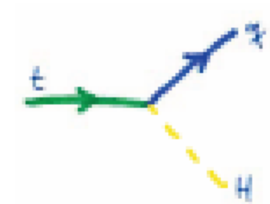


- tZq



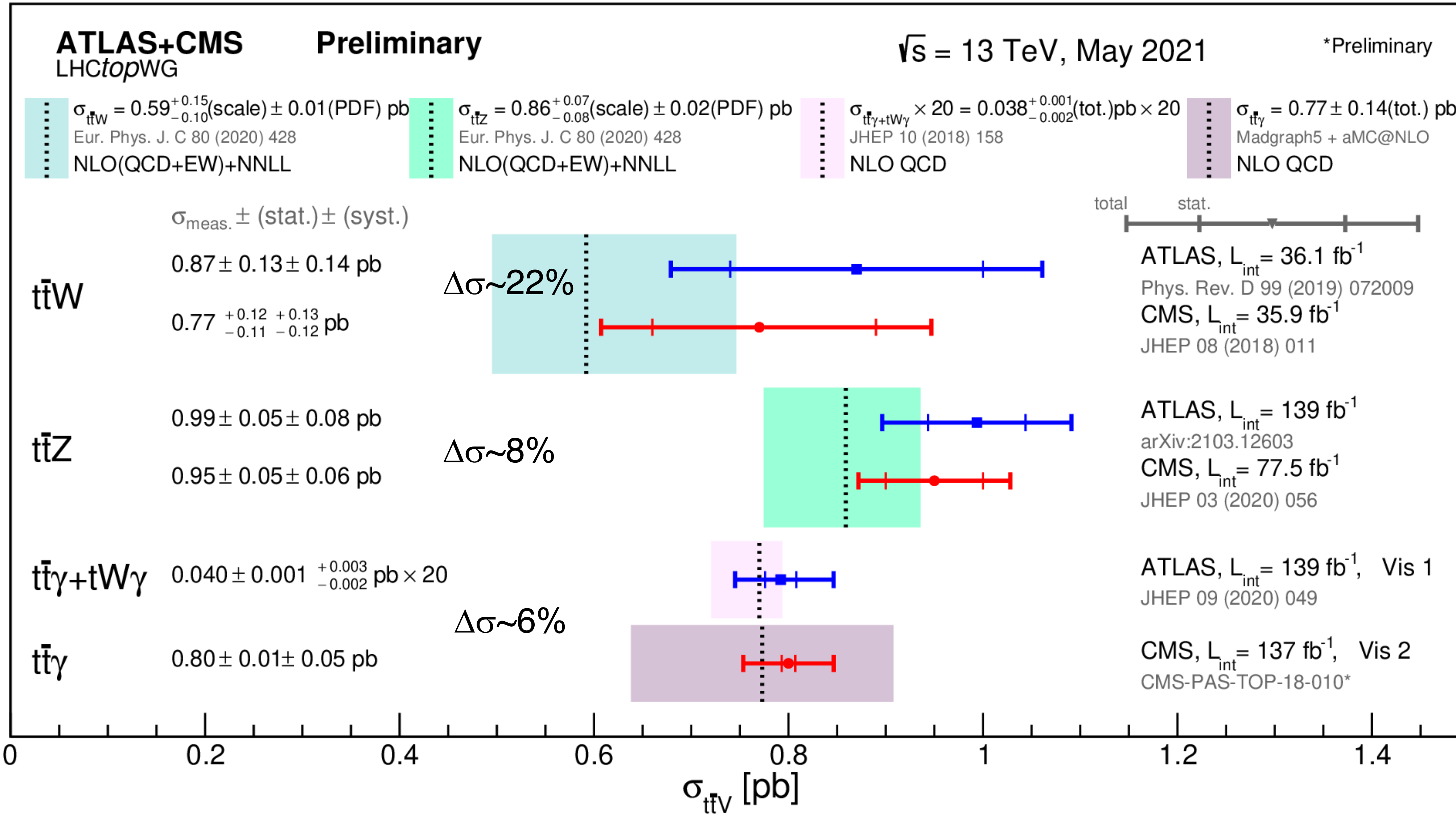
- tγq

- tHq



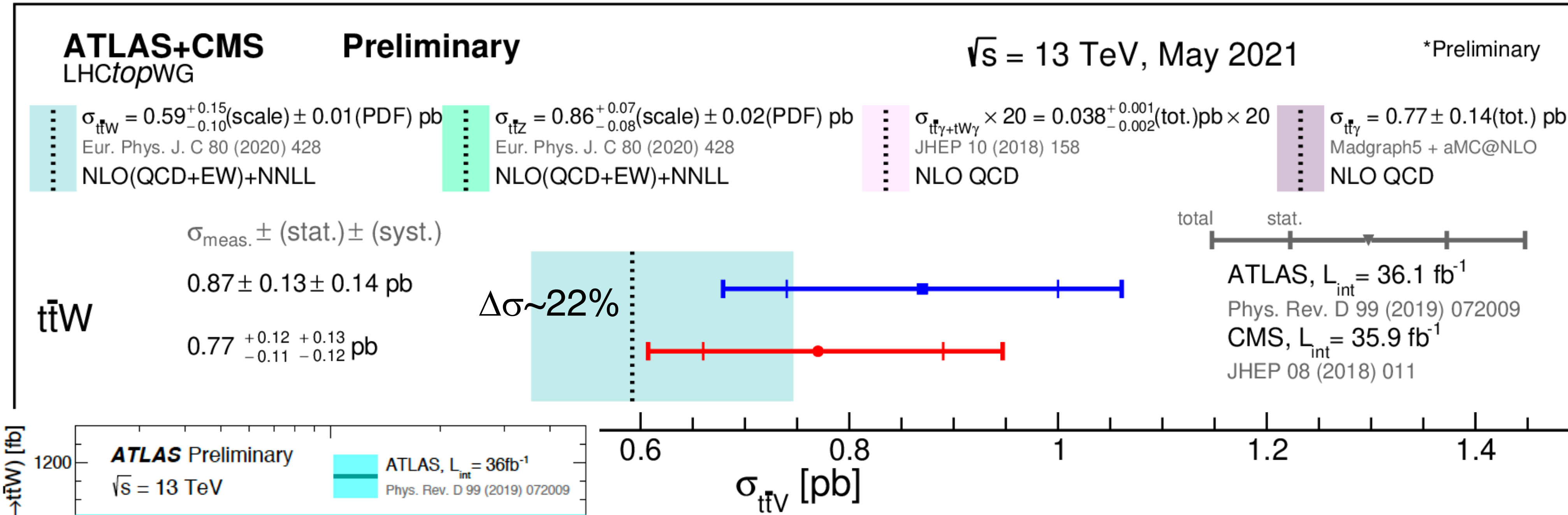
One of the highlights of LHC Run 2, but very challenging for both experimental and theoretical sides

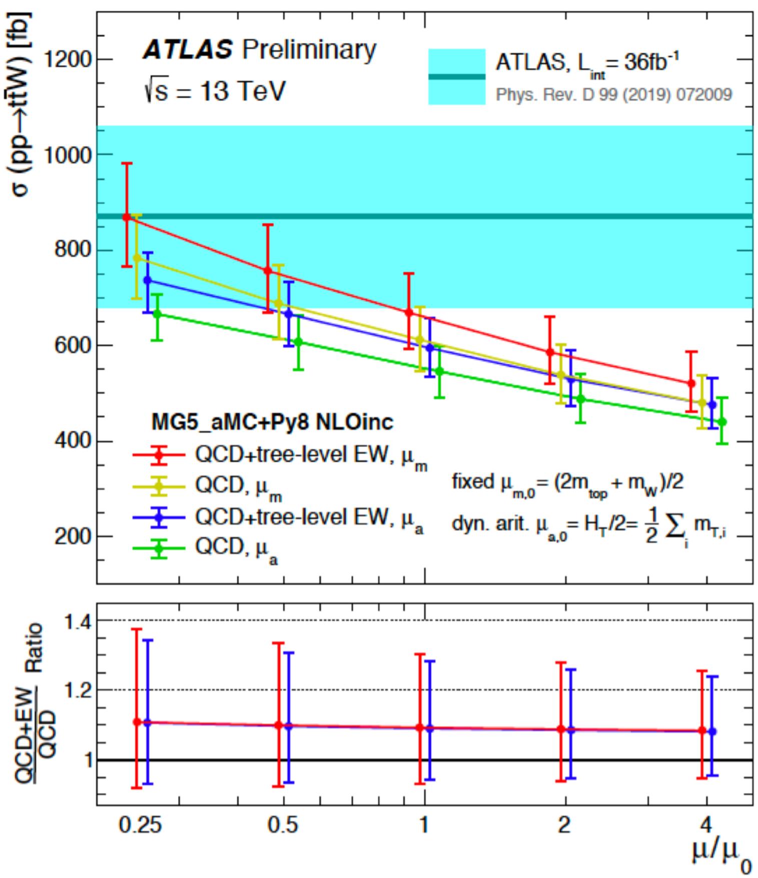
ttV production cross sections: summary

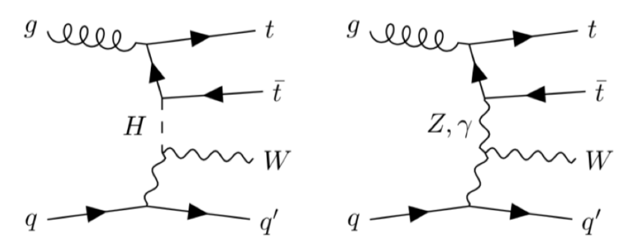


***ttW* measured consistently higher than SM reference in both experiments**

ttW production cross section: keep working!







Cross section vs. scale choice

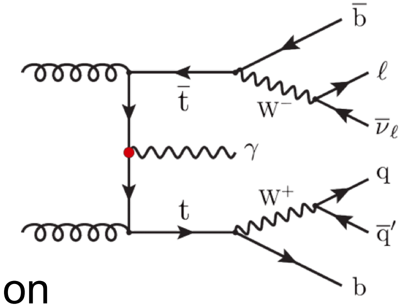
1) higher XS for fixed scales
2) 10% increase due to EW production
3) strong dependence

$$\sigma_{inc}(\mu_0/4)/\sigma_{inc}(\mu_0) \sim 1.4$$

factor 2 up/dw variation for the scale unc. might be conservative given the strong dependence …

ATL-PHYS-PUB-2020-024

ttγ - single lepton



- Signal: genuine γ from ISR, top or its decay products

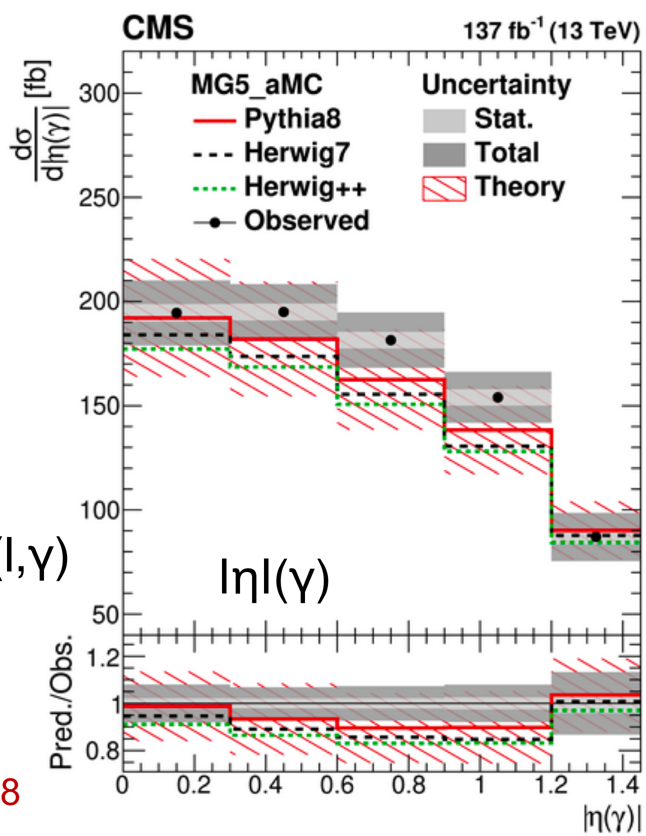
- Challenge: background estimation misId. electrons and non-prompt photons/leptons

Inclusive XS: in agreement with SM; δσ<6%

Dominated by syst unc.: bkg. norm., signal modeling, JES

Differential XS at particle level

$p_T(\gamma)$, $|\eta|(\gamma)$, $\Delta R(l,\gamma)$



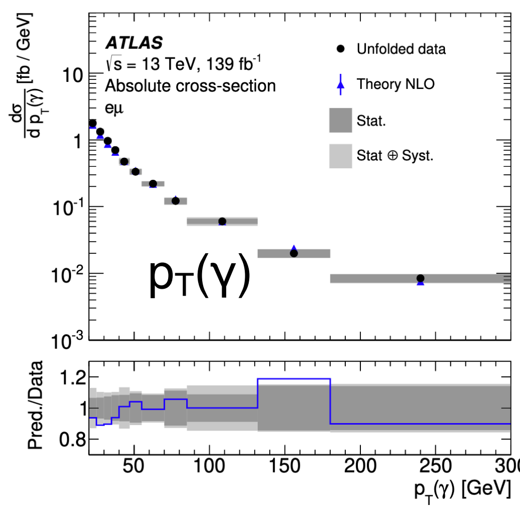
arXiv: 2107.01508

ttγ + tWγ - dilepton

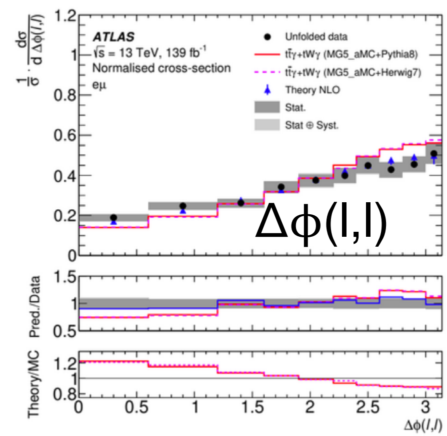
- Signal: γ from dif. sources (doubly resonant production)

$$pp \to b\ell\nu b\ell\nu\gamma$$
$$pp \to b\ell\nu\ell\nu\gamma$$
$$pp \to tW\gamma$$

Fiducial XS (δσ<7%) and **differential XS at parton level**



$p_T(\gamma)$, $|\eta|(\gamma)$, $\Delta R_{min}(l,\gamma)$, $\Delta\phi(l,l)$, $\Delta\eta(l,l)$



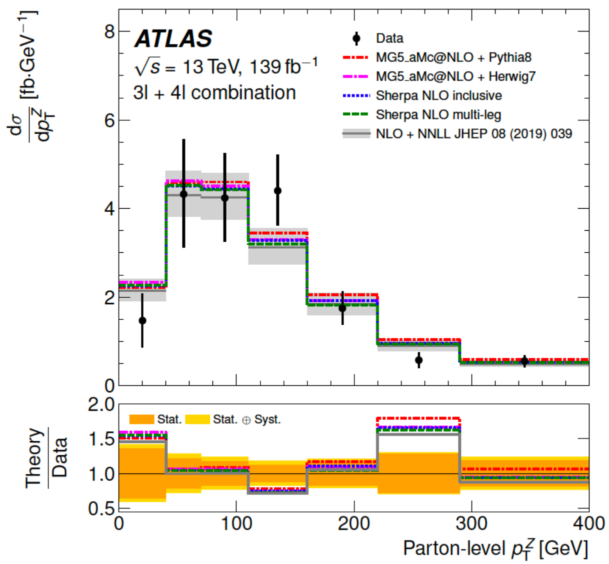
JHEP 09 (2020) 049

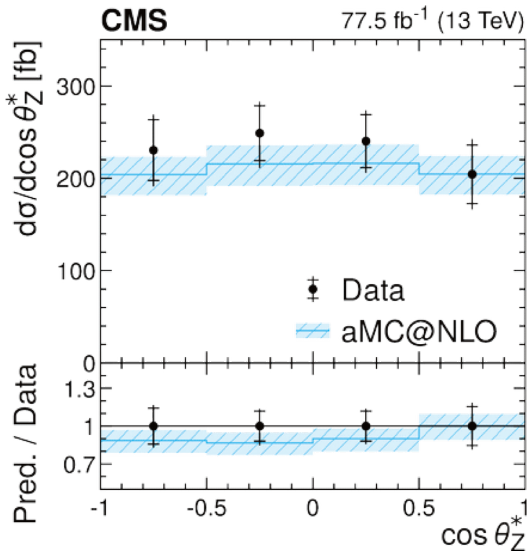
→ Also evidence of tγq process (δσ ~30%)

ttZ – 3ℓ+4ℓ

Inclusive XS: $\delta\sigma_{ttZ}$~8% (main syst: modelling, b-tag)

Differential XS measured **at parton & particle level**





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JHEP 03 (2020) 056

	Variable
$3\ell+4\ell$	p_T^Z $\lvert y^Z\rvert$
3ℓ	N_{jets} $p_T^{\ell,non-Z}$ $\lvert\Delta\phi(Z,t_{lep})\rvert$ $\lvert\Delta y(Z,t_{lep})\rvert$
4ℓ	N_{jets} $\lvert\Delta\phi(\ell_t^+,\ell_{\bar{t}}^-)\rvert$ $\lvert\Delta\phi(t\bar{t},Z)\rvert$ $p_T^{t\bar{t}}$

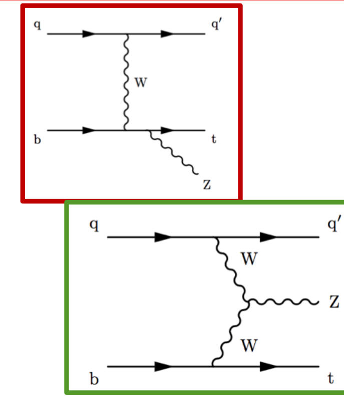
- Sensitive to generator modelling, BSM effects
- Probe QCD effects
- Top p_T modelling
- Probe t-Z vertex
- Spin correlation

tZ - 3ℓ

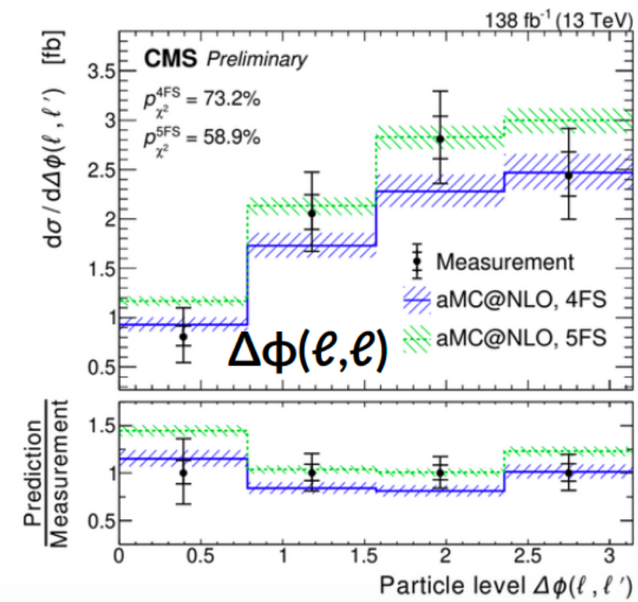
Inclusive XS: $\delta\sigma_{tZ}$<12%

stat. unc.~syst. unc.

Including charge ratio!



Differential XS at parton & particle level



CMS-PAS-TOP-20-010

First measurement of top quark spin asymmetry in tZ!

$A_\ell = 1/2 * P * a_\ell$

Sensitive to anomalous couplings

$$A_\ell = 0.58 \pm 0.06(\mathrm{syst})^{+0.15}_{-0.16}(\mathrm{stat})$$

→ In agreement with SM predictions!

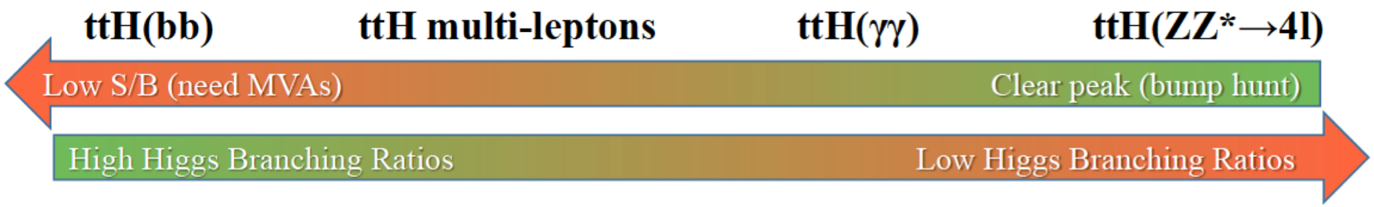
$$A_\ell^{\mathrm{MG5\_aMC@NLO}} = 0.437^{+0.004}_{-0.003}$$

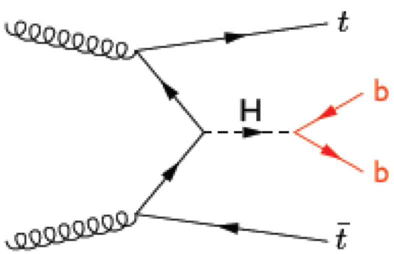
ttH spectroscopy

t t H → b W⁺ b W⁻ H → bb + (jjjj/lνjj/lνlν) + (bb/WW*/ττ/ZZ*/γγ)

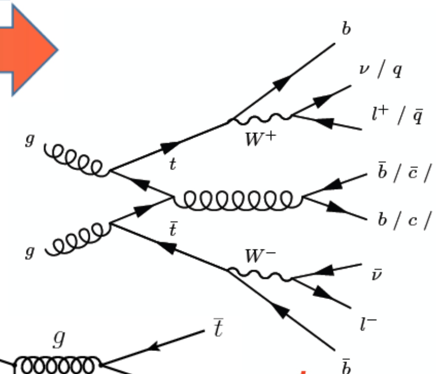
- Large number of final states which are typically very complex
- Different channels, different backgrounds and systematic uncertainties
- With the increased statistics, changes in leading channels

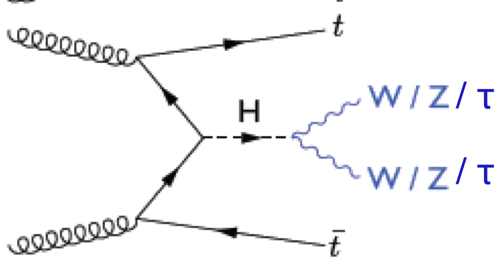
70k events in LHC Run 2



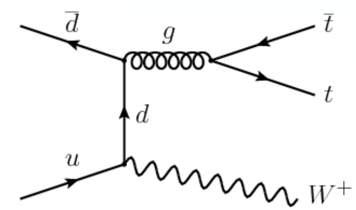


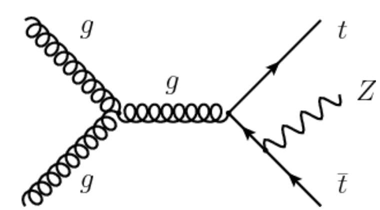
tt+H (H→bb) vs. *tt+jets (g→bb)*

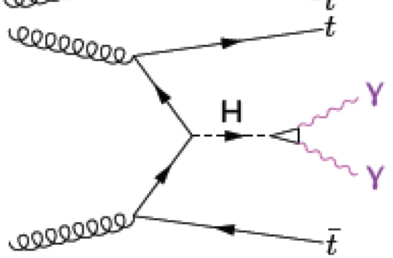




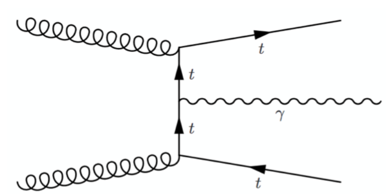
tt+H (H→WW,ττ, ZZ*)* vs. *tt+W/Z*



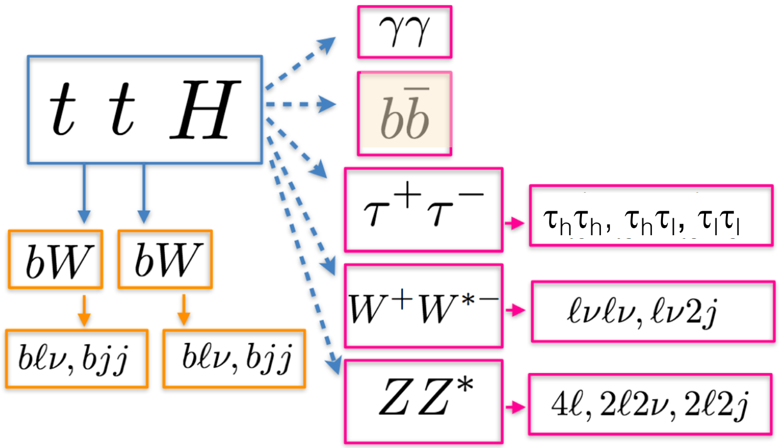


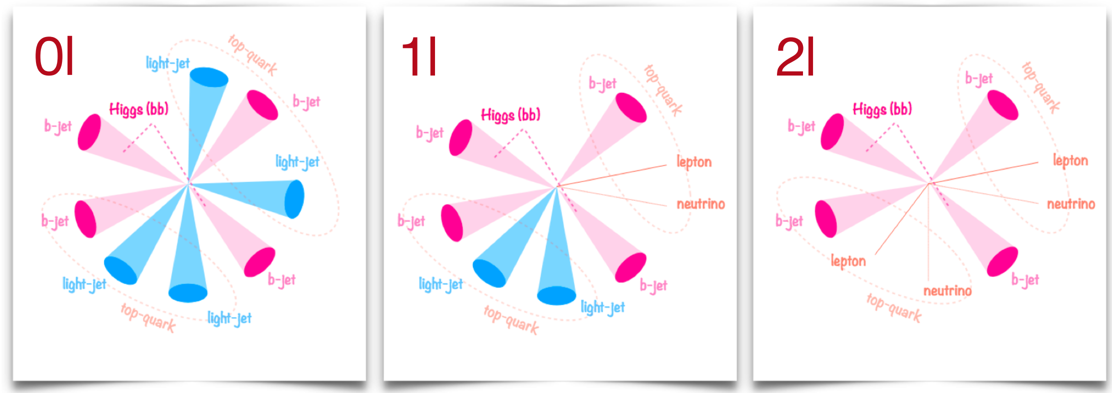


tt+H (H→γγ) vs. *tt+γ(γ)*



ttH (H→bb): large branching fraction but huge background



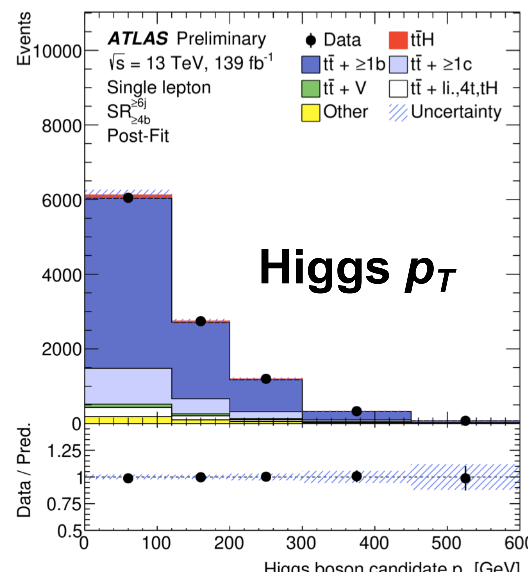


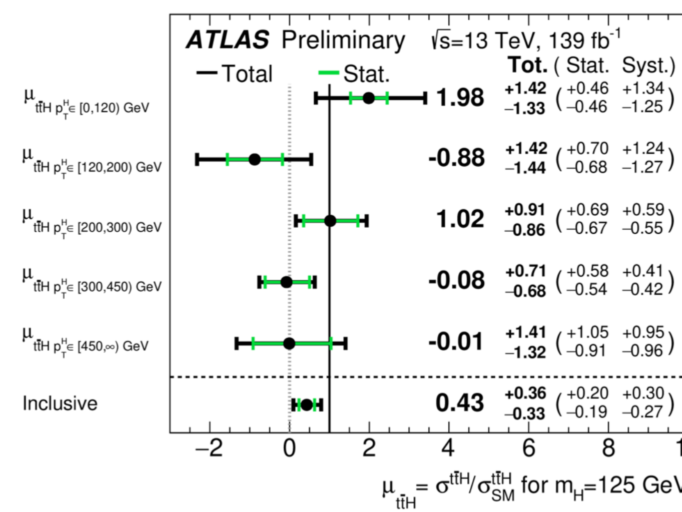
- Fermion-only production and decay
- Higgs boson reconstruction possible, but challenging due to large combinatorics
- **Biggest challenge**: tt+bb background with large theory uncertainty

Significance
ATLAS (139 fb^{-1}; ≥1l): 1.3σ (expected 3.0σ)
CMS (77.4 fb^{-1}): 3.9σ (expected 3.5σ)

- Event categorization based on # jets and b-tags
- Cascade of MVAs
- Systematically limited

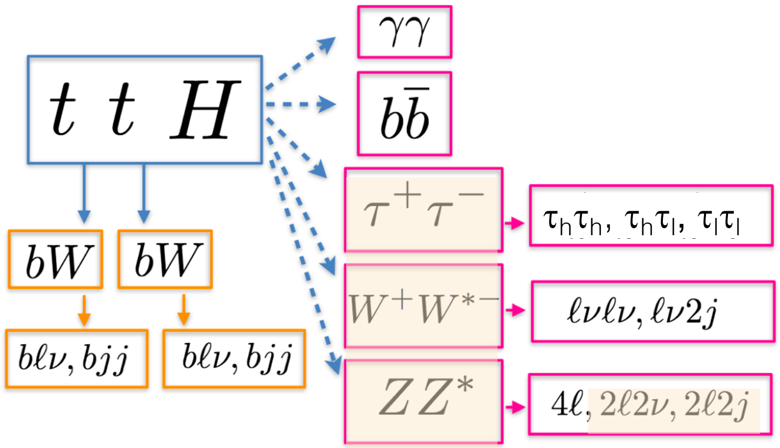
Also measurement of 5 STXS bins

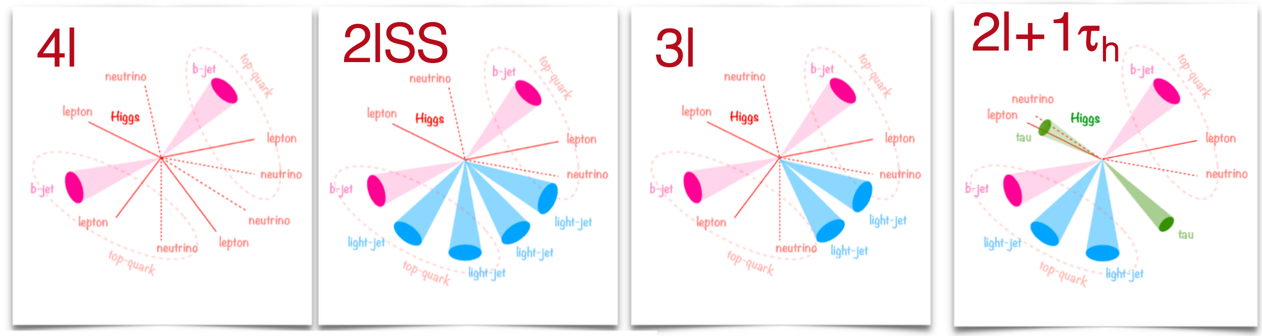




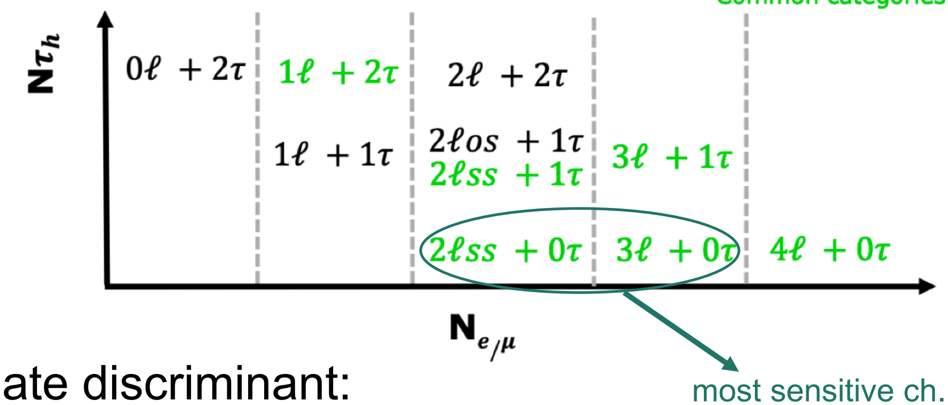
ATLAS-CONF-2020-058

ttH ($H \to WW^*, \tau\tau, ZZ^*$): suppressing ttW and non-prompt





Common categories



- Distinct multi-lepton signatures (up to 10 explored!)
- Higgs reconstruction is difficult

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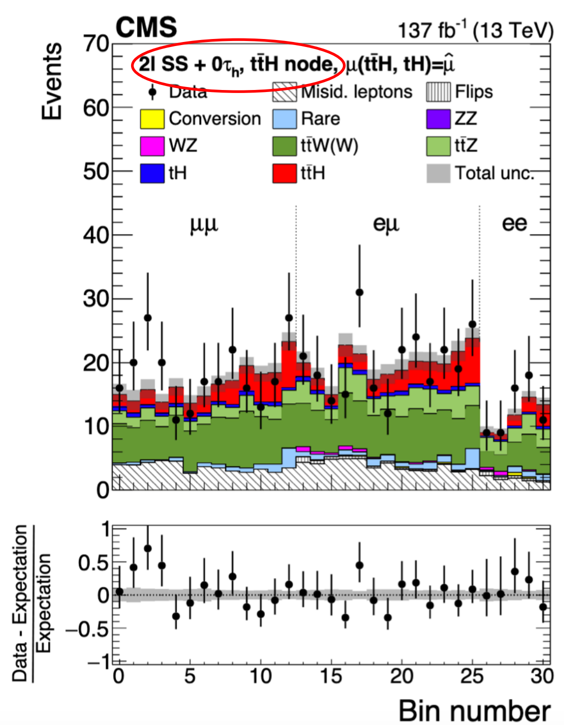


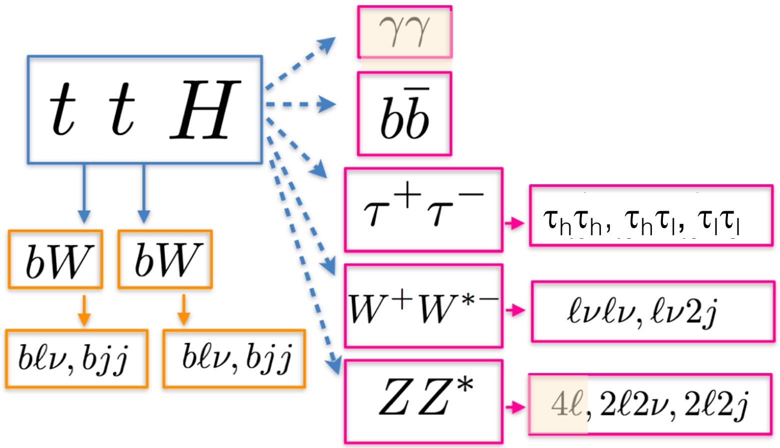
- Powerful multivariate discriminant:
  - object-level to reduce non-prompt leptons
  - event-level to discriminate ttH from main bkgs.
- Uncertainties: statistical ~ systematics

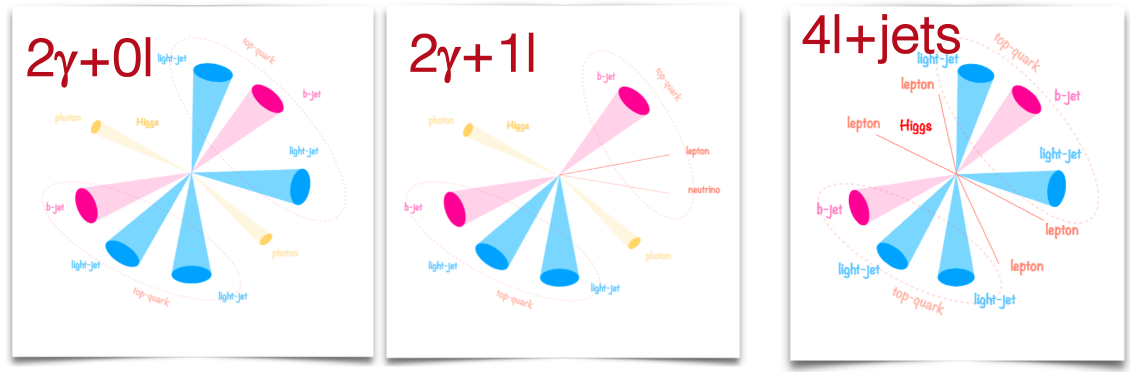
Significance
ATLAS (80 fb^{-1}; 6 ch): 1.8σ (expected 3.1σ)
CMS (137 fb^{-1}; 10 ch): 4.7σ (expected 5.2σ) → $\delta\sigma_{ttH}$~25%

CMS also studied tH signal:
μ_{tH} = 5.7 ± 2.7(stat) ± 3.0(syst)
1.4σ significance (0.3σ expected)

New ATLAS H→ττ analysis (137 fb^{-1}) includes 0l+2τ_h, obtaining 1σ significance

ttH (H→γγ, ZZ*→4l): very clean bumps



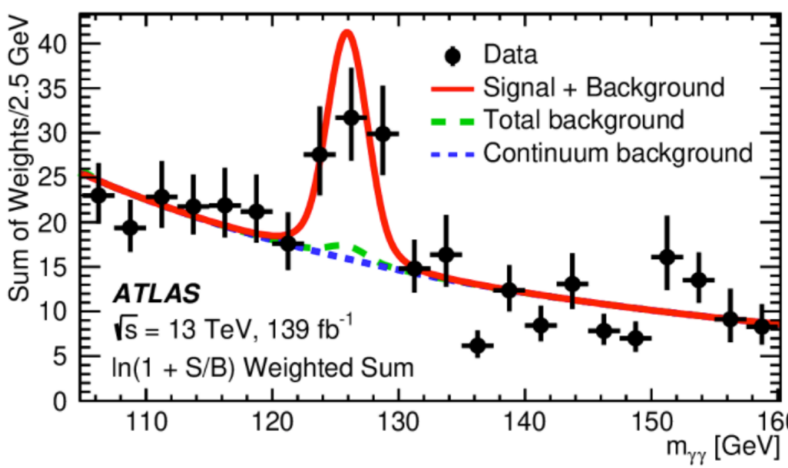


- Small rate
- Very clean final state with high S/B
- Clear Higgs peak

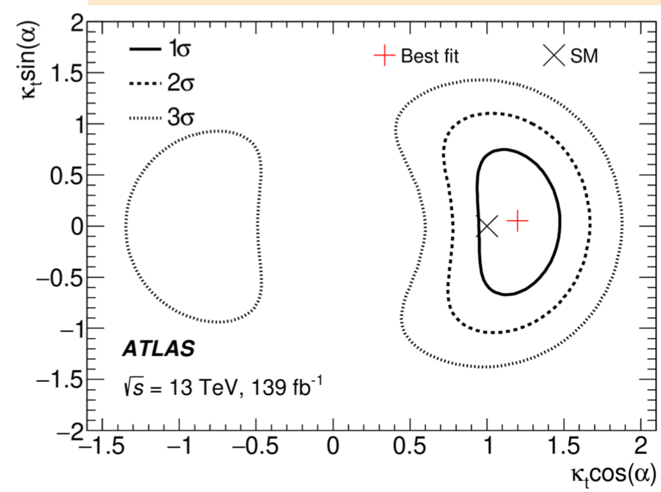
- Statistically limited

Significance (139 fb⁻¹):
γγ ➔ >5σ
ZZ*(4l) ➔ expected 1.2σ

For H→γγ, $\delta\sigma_{ttH}$~25% and also:
- measurement of 5 STXS bins
- CP analysis: mixing angle |α|< 43º @ 95% CL
a pure CP-odd coupling excluded >3σ



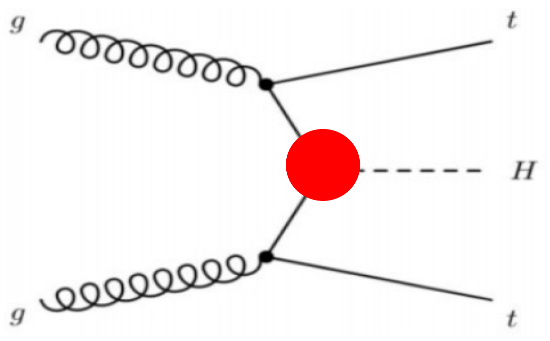
PRL 125 (2020) 061802

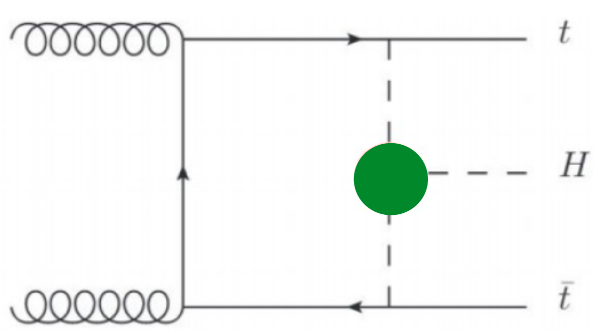


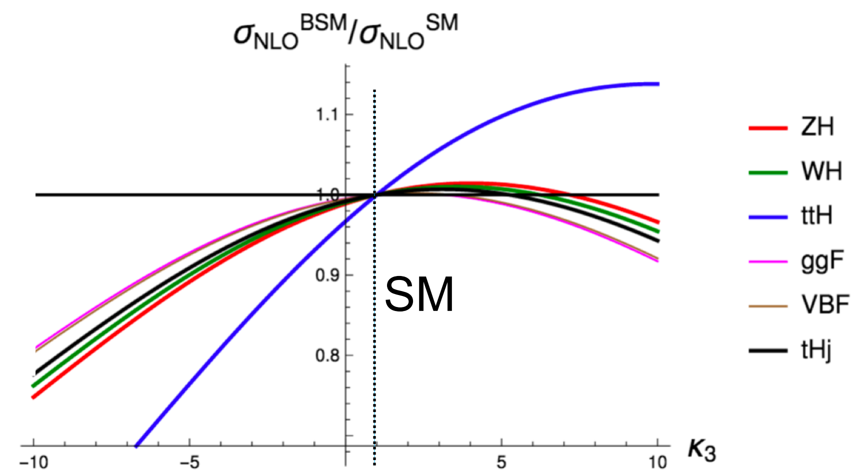
Also searches for tH, upper limits in XS: $\sigma_{tH} < 6\sigma_{SM}$

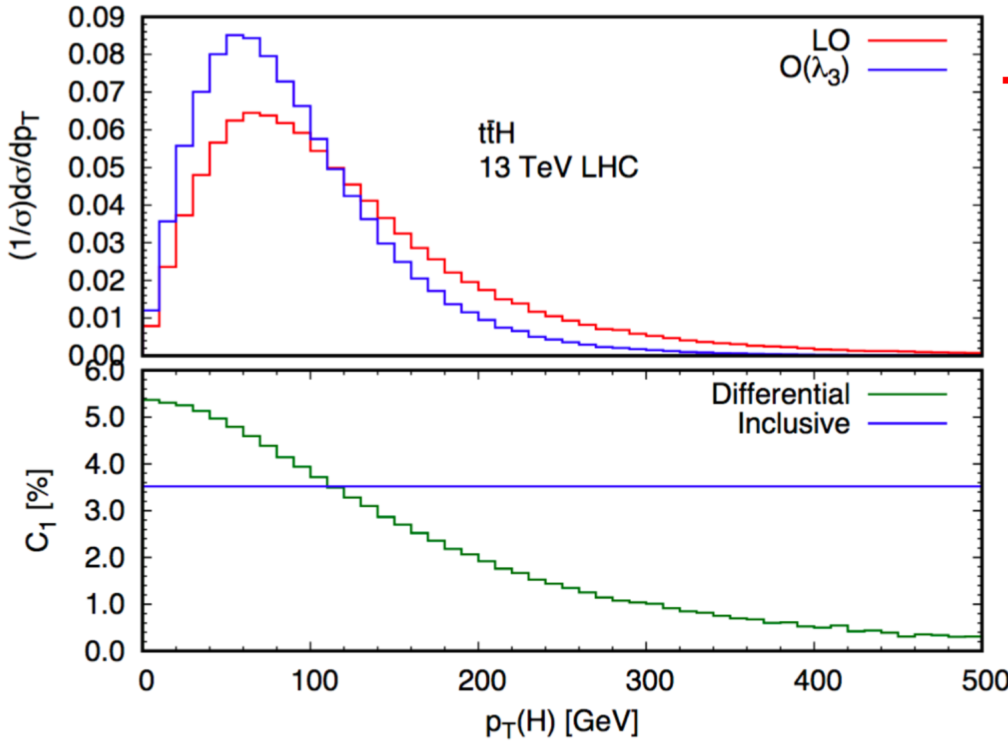
Who is the responsible ?

EPJC (2017) 77: 887









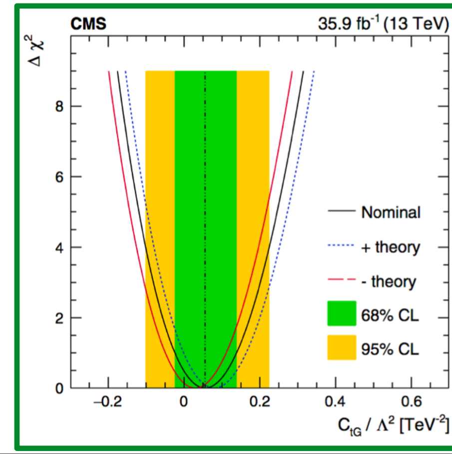
The power of differential measurements:

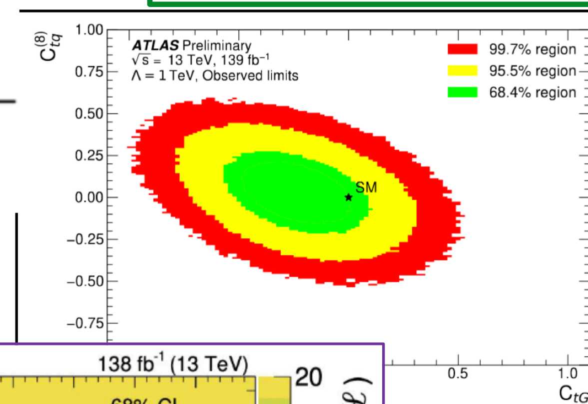
Variations in Higgs-self coupling (λ_3) will affect the shape of kinematic, e.g. low p_T(H) region would be highly affected while it is not deformed in the tail…

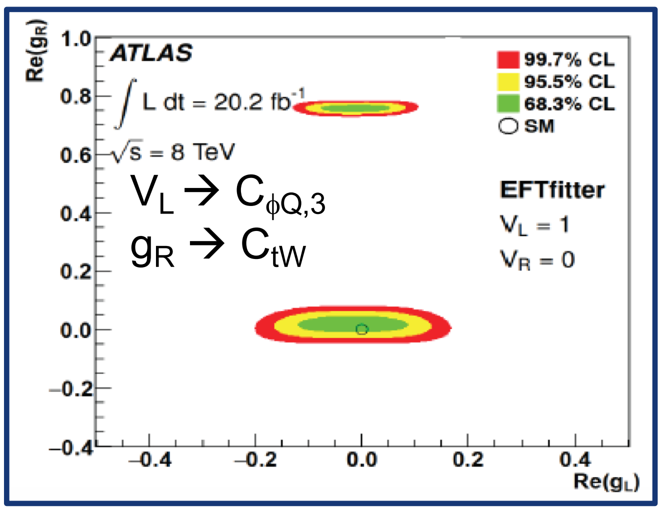
New Physics effects?

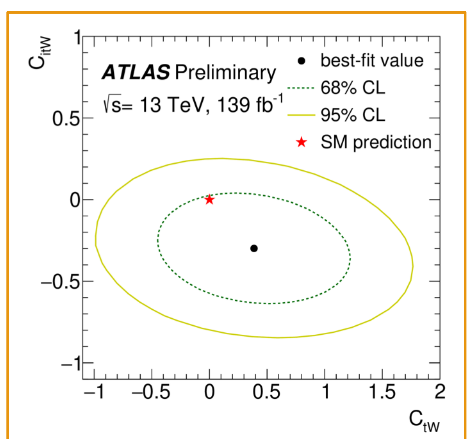
: differential measurements

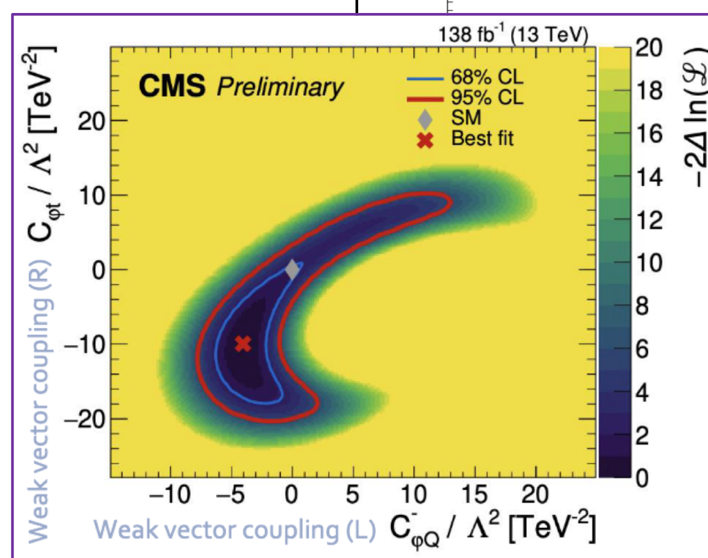
Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{bW}	$O_{\varphi tb}$	O_{4f}	O_G	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	N		L	L				L^2	L^2	$1L^2$		
$pp \to tj$	N		L	L				L^2	L^2	1L		
$pp \to tW$	L		L	L				L^2	L^2	1N	N	
$pp \to t\bar{t}$	L									2L-4N	L	
$pp \to t\bar{t}j$	L									2L-4N	L	
$pp \to t\bar{t}\gamma$	L	L	L							2L-4N	L	
$pp \to t\bar{t}Z$	L	L	L	L	L	L				2L-4N	L	
$pp \to t\bar{t}W$	L								L	1L-2L		
$pp \to t\gamma j$	N	L	L	L				L^2	L^2	1L		
$pp \to tZj$	N	L	L	L	L	L		L^2	L^2	1L		
$pp \to t\bar{t}t\bar{t}$	L									2L-4L	L	
$pp \to t\bar{t}H$	L						L			2L-4L	L	L
$pp \to tHj$	N		L	L			L	L^2	L^2	1L		N







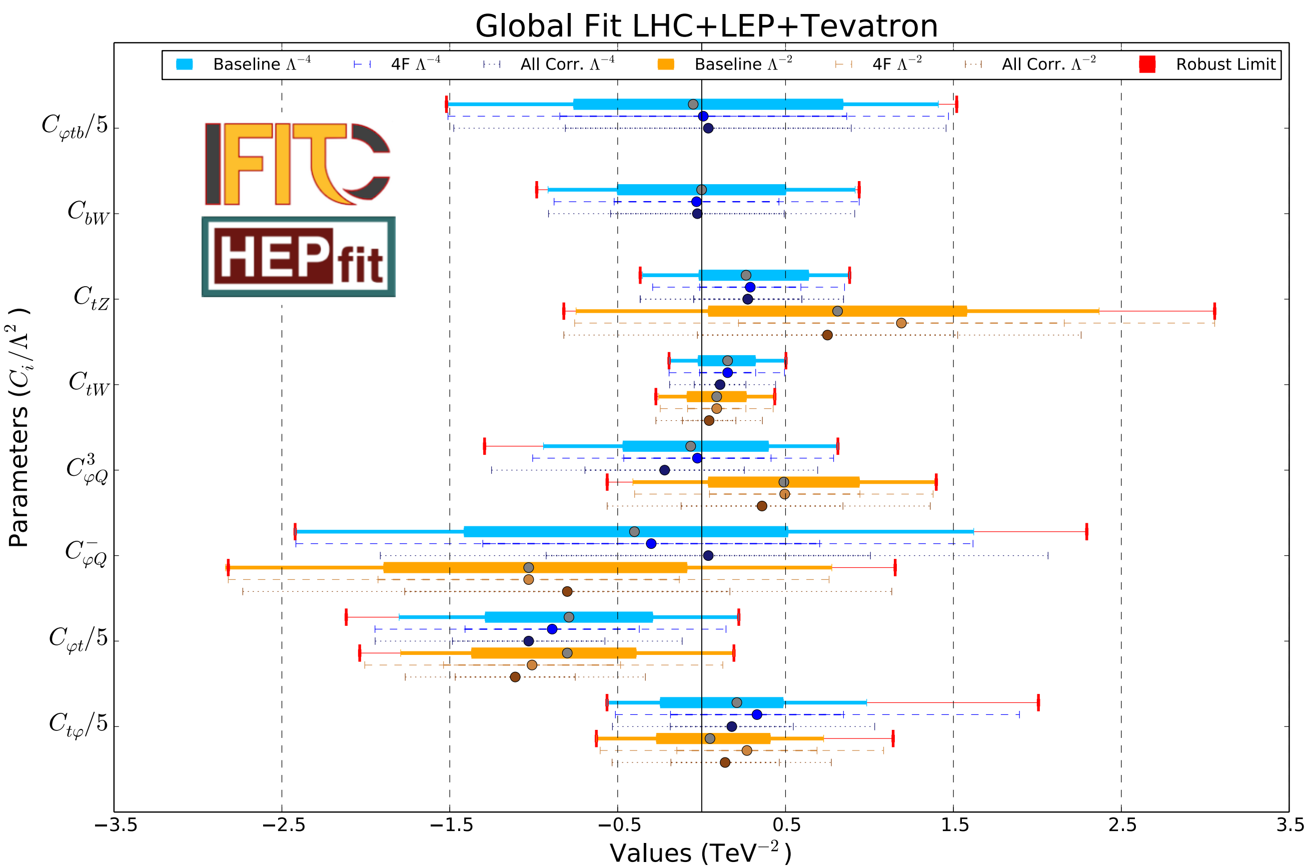




A recent global fit to top quark EW couplings

* Left/Right-handed couplings of top/bottom quarks to Z boson: $O_{\varphi t}, O^{-}_{\varphi Q}, O^{(3)}_{\varphi Q}$
* EW dipole operators: O_{tZ}, O_{tW}, O_{bW}
* Top Yukawa: $O_{t\varphi}$
* Charged current interaction: $O_{\varphi tb}$

Process	Observable	$\sqrt{s}$	$\int \mathscr{L}$	Experiment
$pp \to t\bar{t}H$ NLO	cross section	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}W$ NLO	cross section	13 TeV	36 fb^{-1}	CMS
$pp \to t\bar{t}Z$ NLO	(differential) x-sec.	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}\gamma$ NLO	(differential) x-sec.	13 TeV	140 fb^{-1}	ATLAS
$pp \to tZq$ NLO	cross section	13 TeV	140 fb^{-1}	CMS
$pp \to t\gamma q$ NLO	cross section	13 TeV	36 fb^{-1}	CMS
$pp \to tb$ (s-ch) NLO	cross section	8 TeV	20 fb^{-1}	ATLAS+CMS
$pp \to tW$ NLO	cross section	8 TeV	20 fb^{-1}	ATLAS+CMS
$pp \to tq$ (t-ch) NLO	cross section	8 TeV	20 fb^{-1}	ATLAS+CMS
$t \to W^{+}b$ NLO	F_0, F_L	8 TeV	20 fb^{-1}	ATLAS+CMS
$p\bar{p} \to t\bar{b}$ (s-ch) LO	cross section	1.96 TeV	9.7 fb^{-1}	Tevatron
$e^{-}e^{+} \to b\bar{b}$ LO	R_b , A^{bb}_{FBLR}	$\sim$ 91 GeV	202.1 pb^{-1}	LEP



- ✓ A **significant improvement** compared to other previous fits
- ✓ Bounds compatible with SM within 2σ
- ✓ 95% prob. bounds: ± 0.35 - 8 TeV^{-2}

arXiv: 2107.13917

A recent global fit to top quark EW couplings

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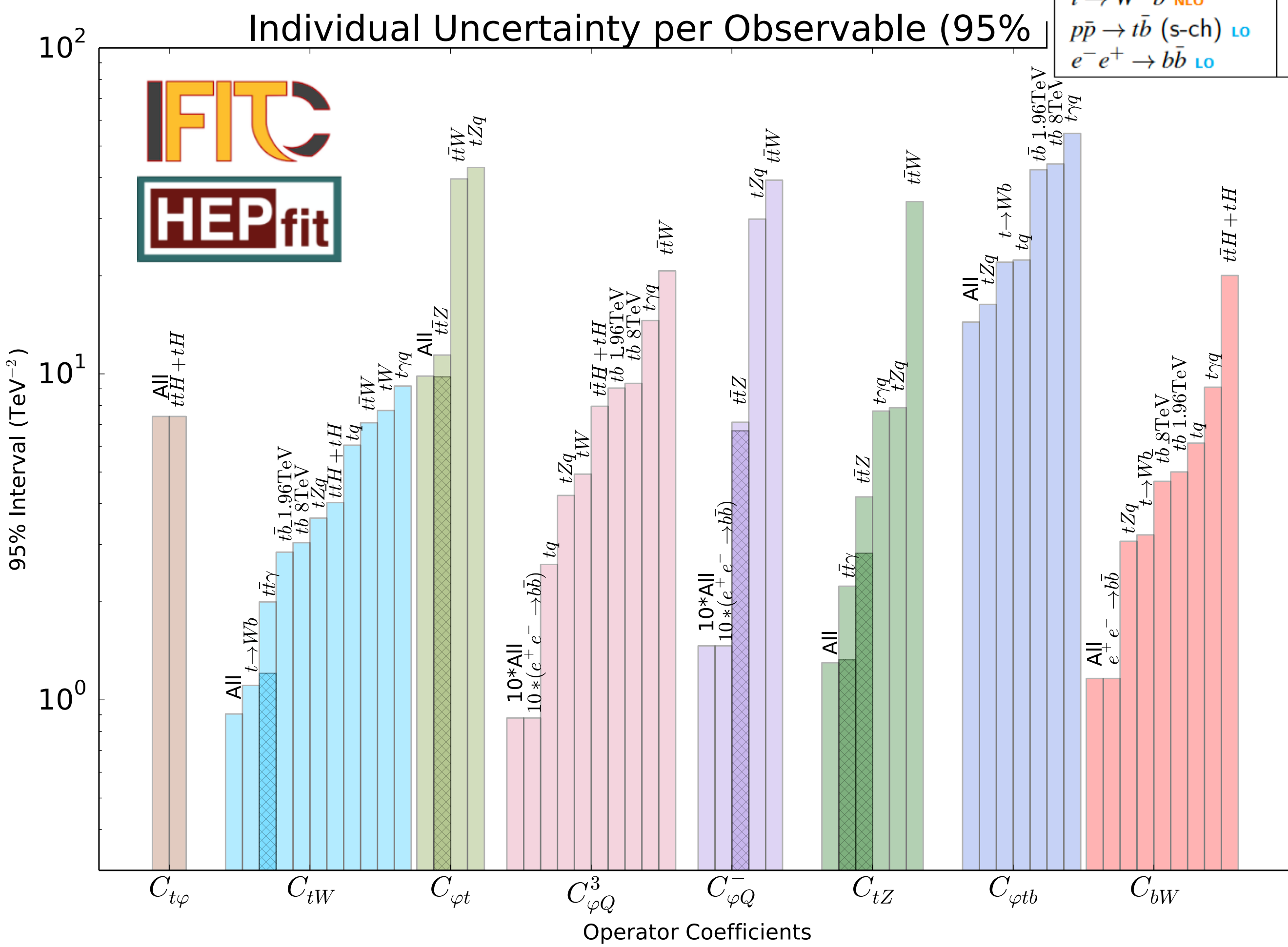

Sensitivity coming from:

C_{tW} → W helicity and $t\bar{t}\gamma$

$C_{\varphi t}$ → $t\bar{t}Z$

$C^{-}_{\varphi Q}$ & $C^{(3)}_{\varphi Q}$ → LEP/SLD

C_{tZ} → $t\bar{t}\gamma$ and $t\bar{t}Z$

$C_{\varphi tb}$ → tZ and W helicity

Significant improvement from $t\bar{t}Z$ and $t\bar{t}\gamma$ differential measurements ☺

arXiv: 2107.13917

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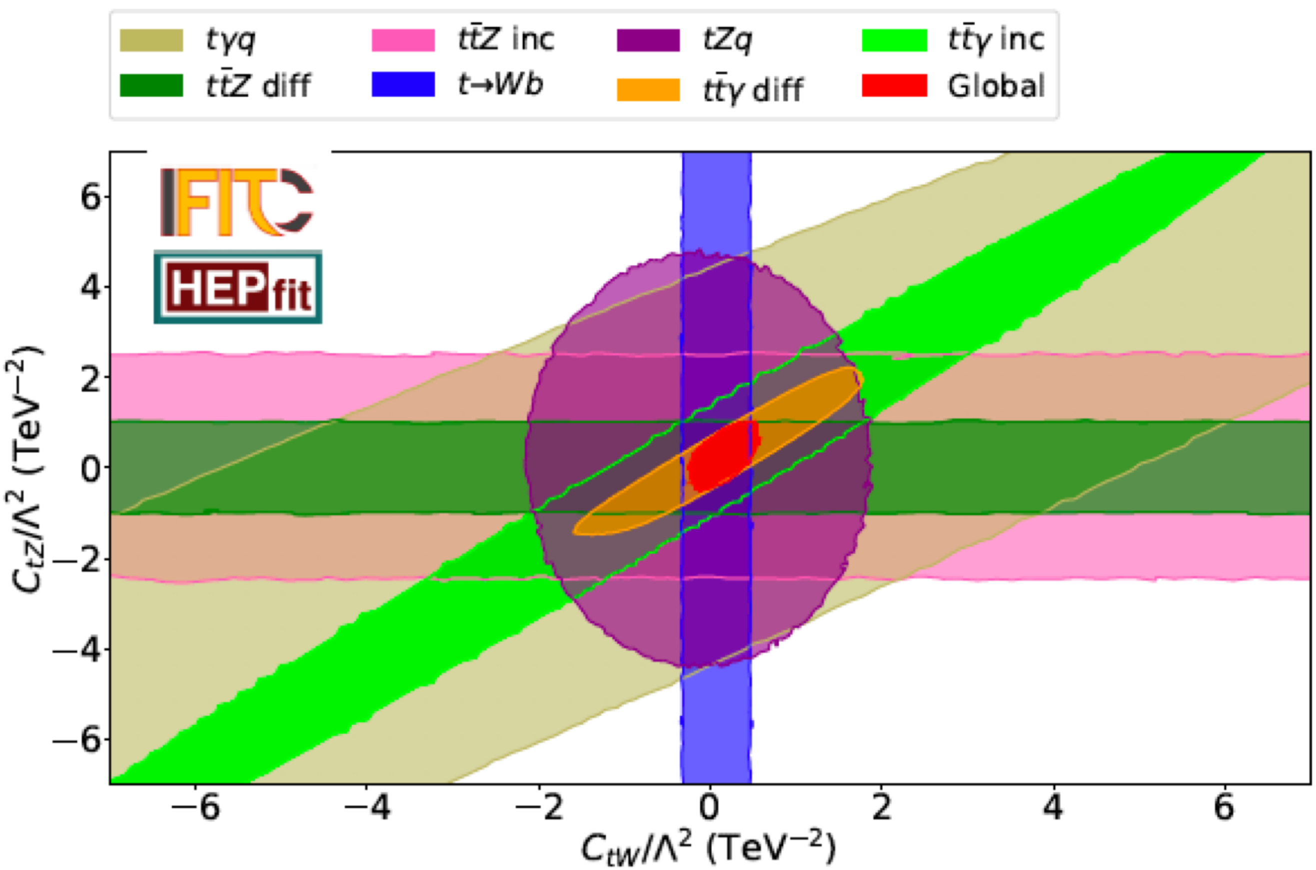
$e^-e^+ \to b\bar{b}$ LO	R_b , A_{FBLR}^{bb}	$\sim$ 91 GeV	202.1 pb^{-1}	LEP



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Significant improvement from $t\bar{t}Z$ and $t\bar{t}\gamma$ differential measurements ☺

Complementarity btw. measurements

arXiv: 2107.13917

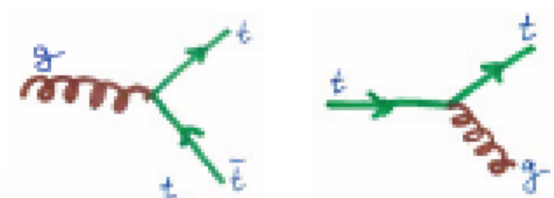
Flavour changing neutral currents

Flavour changing charged current

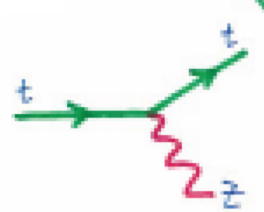
- Wtb

Flavour conserving neutral current

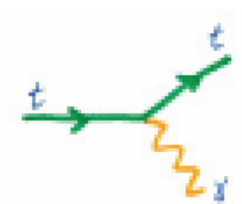
- tgt



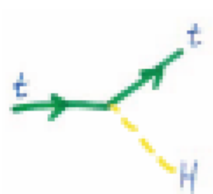
- tZt



- tγt

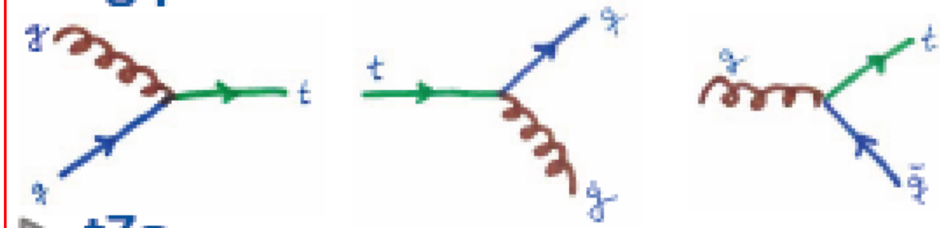


- tHt

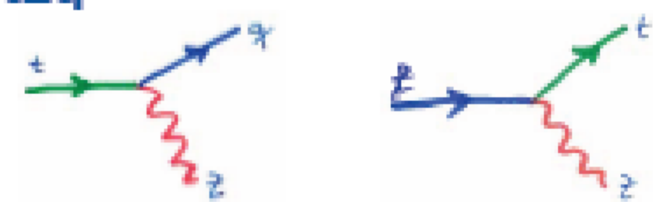


… and neutral current

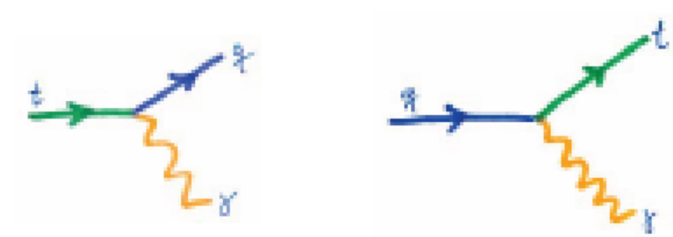
- tgq



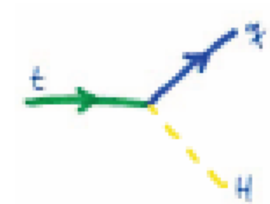
- tZq

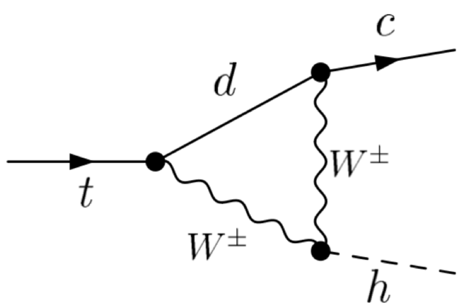


- tγq



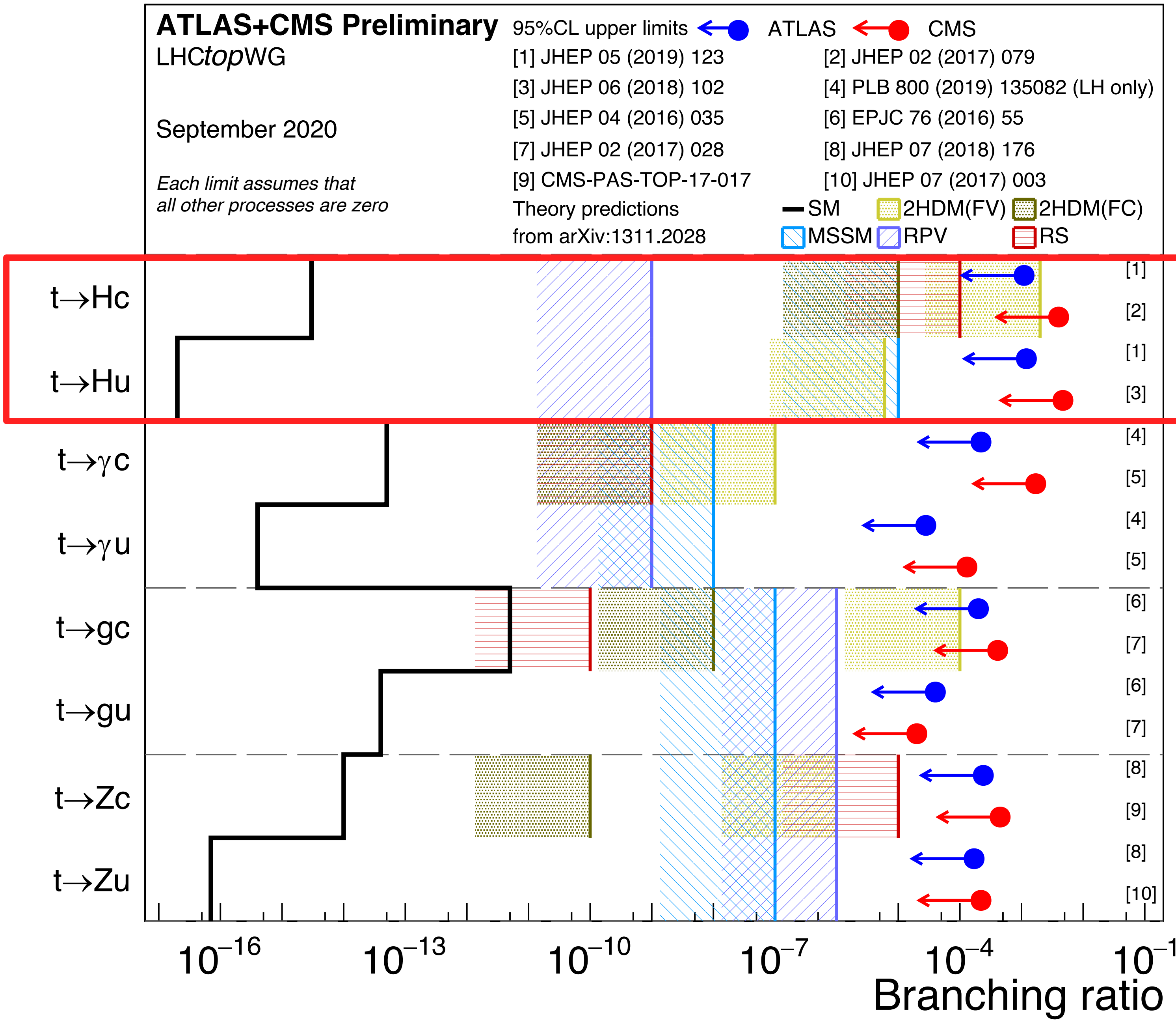
- tHq





BR(t→qH)< 10^{-4}

Most recent limits not included in this plot.



Summary

Many SM processes are explored for the first time at the LHC.
Recent results on EW and top quark physics have been summarized here.
Outstanding level of precision reached and continue pushing the limit.

Despite the enormous effort, **no new particles or significant deviations from SM**
[strong bounds on possible beyond-SM contributions]
No significant excesses seen (yet)…

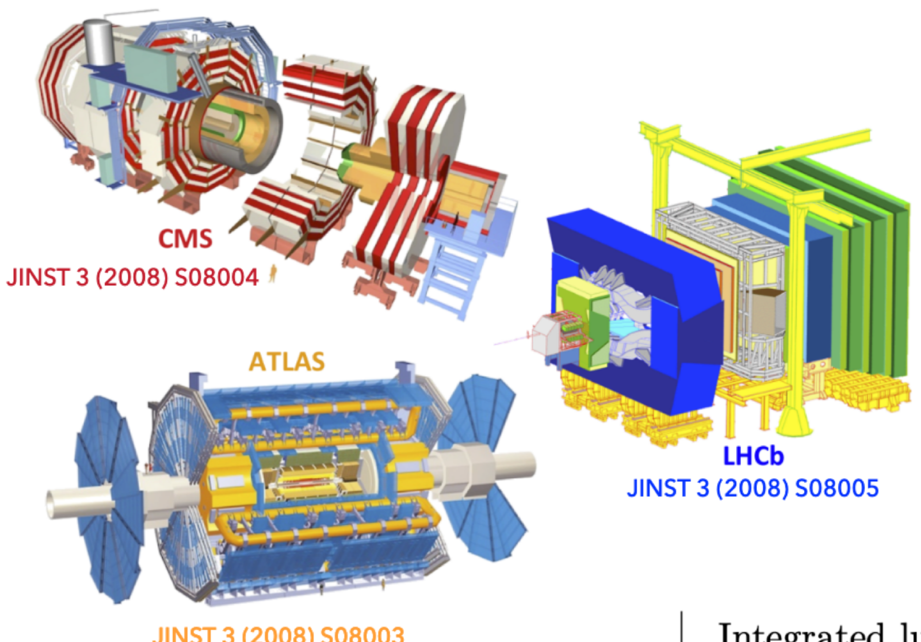
LHC will restart next year... and we have many challenges:

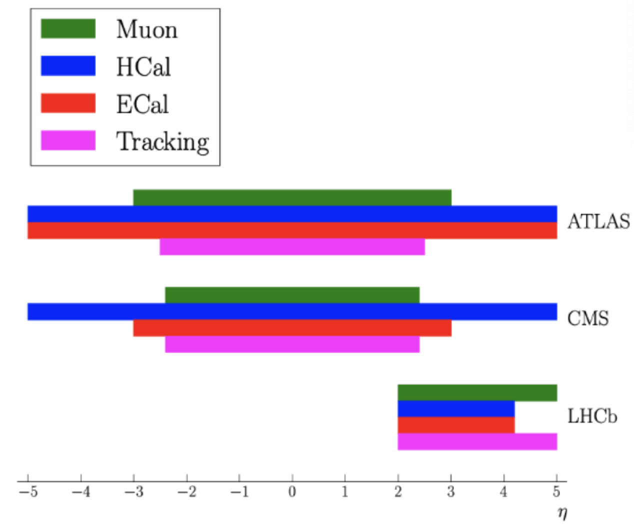
- Need to perform even more precise m_{top} / m_W measurements (also new calculations/observables, and improve experimental methods).
- Precision measurements of differential processes allow to test the theory advancements.
- Rare processes provide great insight towards BSM effects.
- Measurements of properties such polarizations, CP effects,… allow also BSM tests.
- The EFT extension of the SM allow for model independent searches of new physics.

A vast potential for discoveries! Exciting program with great opportunities.

THANKS FOR YOUR ATTENTION

BACK-UP





	Integrated luminosity (fb^{-1})		
$\sqrt{s}$ (TeV)	ATLAS	CMS	LHCb
7	5	6	1
8	21	23	2
13	147	150	6

Table 1 Input values and fit results for the observables used in the global electroweak fit. The first and second columns list respectively the observables/parameters used in the fit, and their experimental values or phenomenological estimates (see text for references). The third column indicates whether a parameter is floating in the fit. The fourth column gives the results of the fit including all experimental data. In the fifth column, the fit results are given without using the corresponding experimental or phenomenological estimate in the given row (indirect determination). The last column shows for illustration the result using the same fit setup as in the fifth column, but ignoring all theoretical uncertainties

Parameter	Input value	Free in fit	Fit result	Fit w/o exp. input in line	Fit w/o exp. input in line, no theo. unc.
M_H [GeV]	125.1 ± 0.2	Yes	125.1 ± 0.2	90^{+21}_{-18}	89^{+20}_{-17}
M_W [GeV]	80.379 ± 0.013	–	80.359 ± 0.006	80.354 ± 0.007	80.354 ± 0.005
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.091 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	Yes	91.1882 ± 0.0020	91.2013 ± 0.0095	91.2017 ± 0.0089
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4947 ± 0.0014	2.4941 ± 0.0016	2.4940 ± 0.0016
σ^0_{had} [nb]	41.540 ± 0.037	–	41.484 ± 0.015	41.475 ± 0.016	41.475 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.742 ± 0.017	20.721 ± 0.026	20.719 ± 0.025
$A^{0,\ell}_{FB}$	0.0171 ± 0.0010	–	0.01620 ± 0.0001	0.01619 ± 0.0001	0.01619 ± 0.0001
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1470 ± 0.0005	0.1470 ± 0.0005	0.1469 ± 0.0003
$\sin^2\theta^\ell_{eff}(Q_{FB})$	0.2324 ± 0.0012	–	0.23153 ± 0.00006	0.23153 ± 0.00006	0.23153 ± 0.00004
$\sin^2\theta^\ell_{eff}$(Tevt.)	0.23148 ± 0.00033	–	0.23153 ± 0.00006	0.23153 ± 0.00006	0.23153 ± 0.00004
A_c	0.670 ± 0.027	–	0.6679 ± 0.00021	0.6679 ± 0.00021	0.6679 ± 0.00014
A_b	0.923 ± 0.020	–	0.93475 ± 0.00004	0.93475 ± 0.00004	0.93475 ± 0.00002
$A^{0,c}_{FB}$	0.0707 ± 0.0035	–	0.0736 ± 0.0003	0.0736 ± 0.0003	0.0736 ± 0.0002
$A^{0,b}_{FB}$	0.0992 ± 0.0016	–	0.1030 ± 0.0003	0.1032 ± 0.0003	0.1031 ± 0.0002
R^0_c	0.1721 ± 0.0030	–	0.17224 ± 0.00008	0.17224 ± 0.00008	0.17224 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21582 ± 0.00011	0.21581 ± 0.00011	0.21581 ± 0.00004
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	Yes	$1.27^{+0.07}_{-0.11}$	–	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	Yes	$4.20^{+0.17}_{-0.07}$	–	–
m_t [GeV]$^{(\nabla)}$	172.47 ± 0.68	Yes	172.83 ± 0.65	176.4 ± 2.1	176.4 ± 2.0
$\Delta\alpha^{(5)}_{had}(M_Z^2)$ $^{(\dagger\Delta)}$	2760 ± 9	Yes	2758 ± 9	2716 ± 39	2715 ± 37
$\alpha_s(M_Z^2)$	–	Yes	0.1194 ± 0.0029	0.1194 ± 0.0029	0.1194 ± 0.0028

$^{(\star)}$Average of LEP ($A_\ell = 0.1465 \pm 0.0033$) and SLD ($A_\ell = 0.1513 \pm 0.0021$) measurements, used as two measurements in the fit. The fit without the LEP (SLD) measurement gives $A_\ell = 0.1470 \pm 0.0005$ ($A_\ell = 0.1467 \pm 0.0005$). $^{(\nabla)}$Combination of experimental (0.46 GeV) and theory uncertainty (0.5 GeV).$^{(\dagger)}$In units of 10^{-5}. $^{(\Delta)}$Rescaled due to α_s dependency

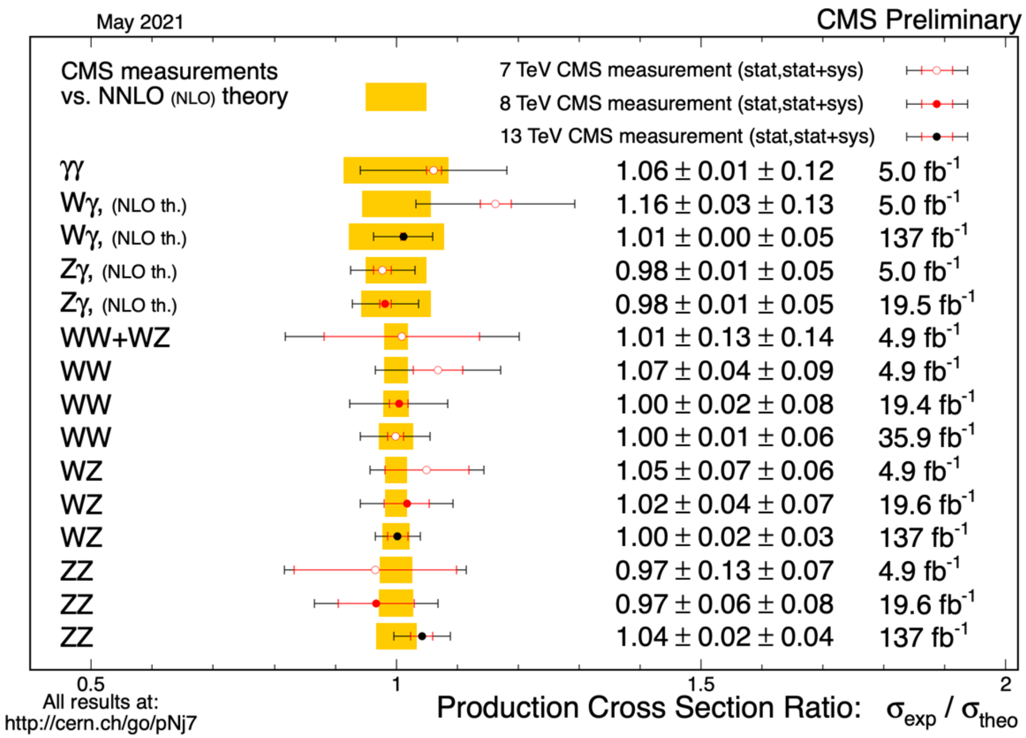
muon p_T based m_W measurement by LHCb

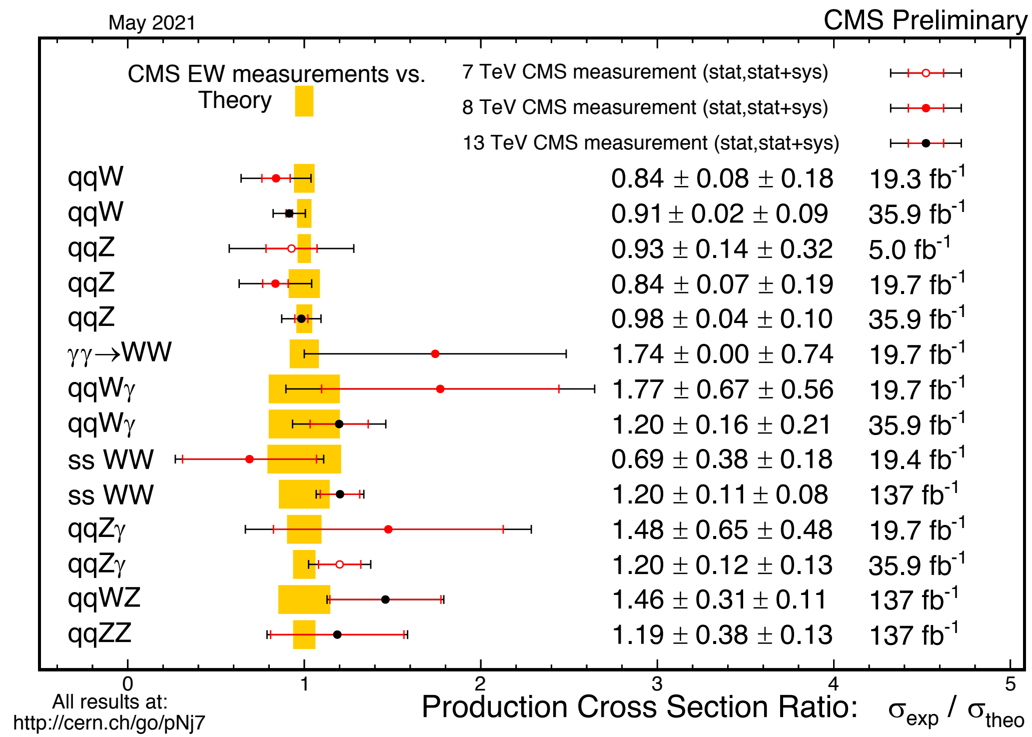
2016 dataset 1.7 fb^{-1}

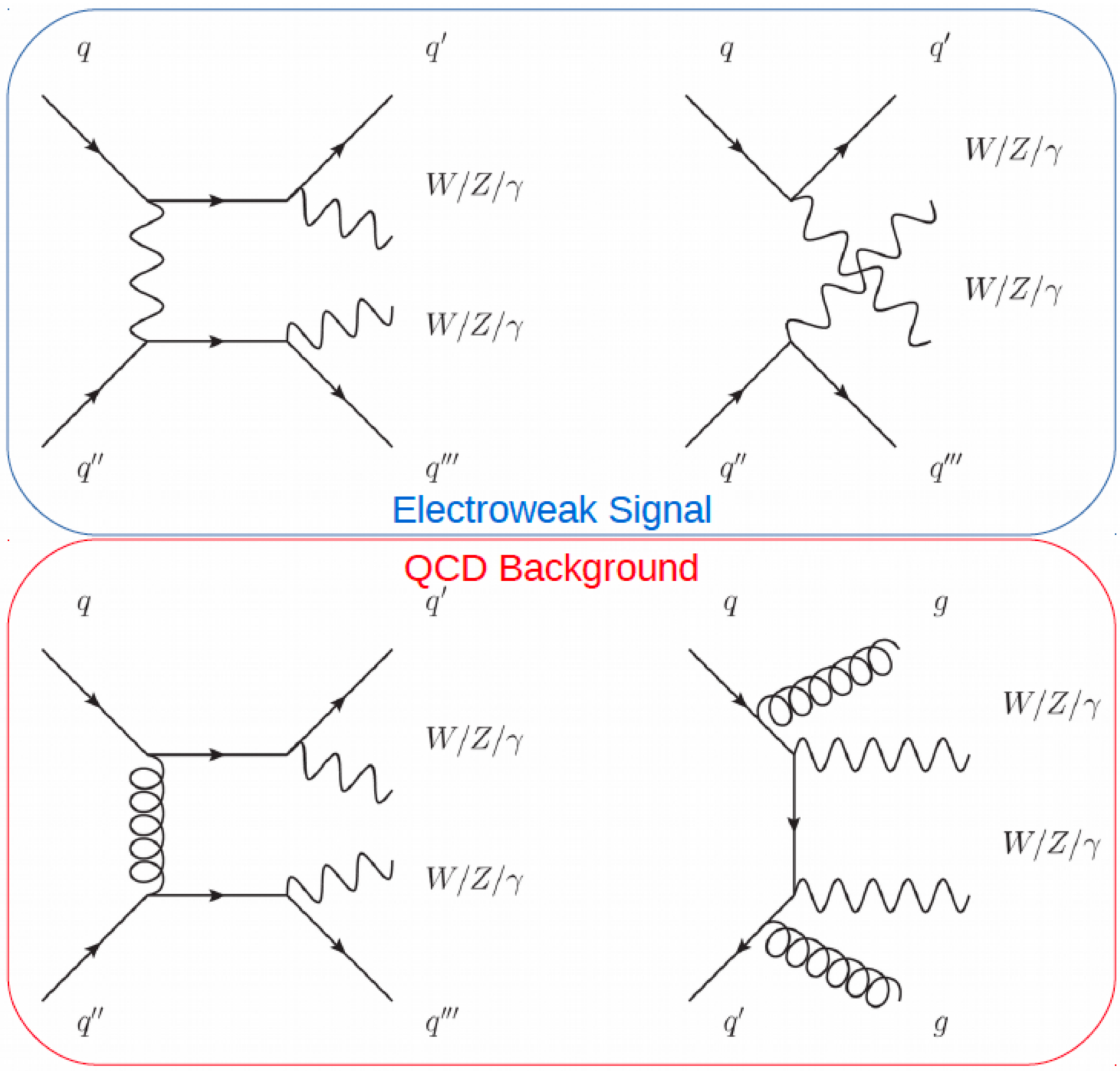
$$m_W = 80364 \pm 23_{stat} \pm 11_{exp} \pm 17_{theory} \pm 9_{PDF} \text{ MeV}$$

Measurement uncertainty summary

Source	Size [MeV]	
Parton distribution functions	**9.0**	Average of NNPDF31, CT18, MSHT20
Theory (excl. PDFs) total	**17.4**	
Transverse momentum model	12.0	Envelope from five different models
Angular coefficients	9.0	"Uncorrelated" 31 point scale variation
QED FSR model	7.2	Envelope of Pythia, Photos and Herwig
Additional electroweak corrections	5.0	Test with POWHEGew
Experimental total	**10.6**	
Momentum scale and resolution modelling	7.5	Includes simple statistical contributions, dependence on external inputs and details of the methods.
Muon ID, trigger and tracking efficiency	6.0	
Isolation efficiency	3.9	
QCD background	2.3	
Statistical	**22.7**	
Total	**31.7**	


May 2021
CMS Preliminary
CMS measurements
vs. NNLO (NLO) theory
7 TeV CMS measurement (stat,stat+sys)
8 TeV CMS measurement (stat,stat+sys)
13 TeV CMS measurement (stat,stat+sys)
γγ 1.06 ± 0.01 ± 0.12 5.0 fb-1
Wγ, (NLO th.) 1.16 ± 0.03 ± 0.13 5.0 fb-1
Wγ, (NLO th.) 1.01 ± 0.00 ± 0.05 137 fb-1
Zγ, (NLO th.) 0.98 ± 0.01 ± 0.05 5.0 fb-1
Zγ, (NLO th.) 0.98 ± 0.01 ± 0.05 19.5 fb-1
WW+WZ 1.01 ± 0.13 ± 0.14 4.9 fb-1
WW 1.07 ± 0.04 ± 0.09 4.9 fb-1
WW 1.00 ± 0.02 ± 0.08 19.4 fb-1
WW 1.00 ± 0.01 ± 0.06 35.9 fb-1
WZ 1.05 ± 0.07 ± 0.06 4.9 fb-1
WZ 1.02 ± 0.04 ± 0.07 19.6 fb-1
WZ 1.00 ± 0.02 ± 0.03 137 fb-1
ZZ 0.97 ± 0.13 ± 0.07 4.9 fb-1
ZZ 0.97 ± 0.06 ± 0.08 19.6 fb-1
ZZ 1.04 ± 0.02 ± 0.04 137 fb-1
0.5
1
1.5
2
All results at:
http://cern.ch/go/pNj7
Production Cross Section Ratio: σexp / σtheo


May 2021
CMS Preliminary
CMS EW measurements vs.
Theory
7 TeV CMS measurement (stat,stat+sys)
8 TeV CMS measurement (stat,stat+sys)
13 TeV CMS measurement (stat,stat+sys)
qqW 0.84 ± 0.08 ± 0.18 19.3 fb-1
qqW 0.91 ± 0.02 ± 0.09 35.9 fb-1
qqZ 0.93 ± 0.14 ± 0.32 5.0 fb-1
qqZ 0.84 ± 0.07 ± 0.19 19.7 fb-1
qqZ 0.98 ± 0.04 ± 0.10 35.9 fb-1
γγ→WW 1.74 ± 0.00 ± 0.74 19.7 fb-1
qqWγ 1.77 ± 0.67 ± 0.56 19.7 fb-1
qqWγ 1.20 ± 0.16 ± 0.21 35.9 fb-1
ss WW 0.69 ± 0.38 ± 0.18 19.4 fb-1
ss WW 1.20 ± 0.11 ± 0.08 137 fb-1
qqZγ 1.48 ± 0.65 ± 0.48 19.7 fb-1
qqZγ 1.20 ± 0.12 ± 0.13 35.9 fb-1
qqWZ 1.46 ± 0.31 ± 0.11 137 fb-1
qqZZ 1.19 ± 0.38 ± 0.13 137 fb-1
0
1
2
3
4
5
All results at:
http://cern.ch/go/pNj7
Production Cross Section Ratio: σexp / σtheo



q
q'
W/Z/γ
W/Z/γ
q''
q'''
q
q'
W/Z/γ
W/Z/γ
q''
q'''
Electroweak Signal
QCD Background
q
q'
W/Z/γ
W/Z/γ
q''
q'''
q
g
W/Z/γ
W/Z/γ
q'
g

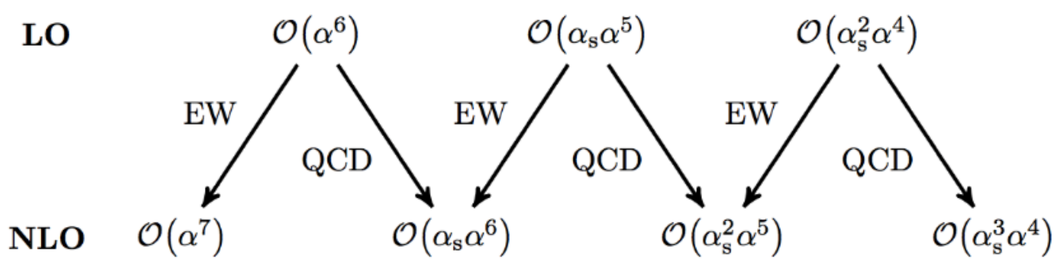
Experimental challenges per final states

channel	final state	comment *
Observed! VBF W	ℓν jj	statistics is not a problem, good modelling of W+jets needed
Observed! VBF Z	ℓℓ jj	statistics is not a problem, good modelling of Z+jets needed
Observed! VBS $W^{\pm}W^{\pm}$	$\ell^{\pm}\nu\ell'^{\pm}\nu$ jj	"golden channel": very good EW/QCD ratio, mainly experimental (charge misID) background, good statistics
VBS $W^{\pm}W^{\mp}$	$\ell^{\pm}\nu\ell'^{\mp}\nu$ jj	hard to investigate due to dileptonic ttbar background, Higgs group does also use this final state
Observed! VBS WZ	ℓℓℓ'ν jj	similar cross section as ssWW, but larger QCD background, fair reconstructibility of fs
Observed! VBS Wγ/Zγ	ℓνγ jj / ℓℓγ jj	photon brings higher stat. (and different experimental systematics), lacks sensitivity to BSM in Higgs sector
VBS WV	ℓνjj jj	large backgrounds (W+jets, ttbar), but promising boosted regime when looking for NP effects
VBS ZV	ℓℓjj jj	large backgrounds (Z+jets, ttbar), but promising boosted regime when looking for NP effects, no neutrinos in final state
VBS ZZ	ℓℓℓ'ℓ' jj	very clean channel, very good reconstructibility of final state and low background contamination, but small cross-section
Observed! VBS ZZ	ℓℓνν jj	challenging to measure invisible Z decay, combination with leptonic decay might help to suppress dileptonic ttbar background

P. Anger

Higher order corrections

- Full NLO computation have been done for same-sign unpolarized WW process



1708.00268

B. Biedermann
A. Denner
M. Pellen

All contributing orders at both LO and NLO

Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	Sum
$\delta\sigma_{\text{NLO}}$ [fb]	−0.2169(3)	−0.0568(5)	−0.00032(13)	−0.0063(4)	−0.2804(7)
$\delta\sigma_{\text{NLO}}/\sigma_{\text{LO}}$ [%]	−13.2	−3.5	0.0	−0.4	−17.1

- NLO EW and QCD [$\mathcal{O}(\alpha^7)$, $\mathcal{O}(\alpha_s\alpha^6)$] corrections are considered
- EW corrections are large and negative (~-15%) in the fiducial region and increasing with dijet and dilepton masses
- NLO corrections for the polarized samples are not known (α_s corrections expected to be the same for the 3 modes. α corrections expected to be small for the longitudinal modes).
  - Apply α_s corrections on LL, LT, and TT
  - Apply α corrections for TT
  - Take the size of α corrections as uncertainty for LL and LT

VBS $W^{\pm}W^{\pm} \rightarrow 2l^{\pm}2\nu$: longitudinally-polarised ?

Signal BDTs to improve the sensitivity to polarized scattering

- Train LL against (LT+TT) and train (LL+LT) against TT
- Use 15 discriminating variables
  - jet kinematics
  - vector boson kinematics
  - variables related to both lepton and jet kinematics

Variables	Definitions
$\Delta\phi_{jj}$	Difference in azimuthal angle between the leading and subleading jets
p_T^{j1}	p_T of the leading jet
p_T^{j2}	p_T of the subleading jet
$p_T^{\ell_1}$	Leading lepton p_T
$p_T^{\ell_2}$	Subleading lepton p_T
$\Delta\phi_{\ell\ell}$	Difference in azimuthal angle between the two leptons
$m_{\ell\ell}$	Dilepton mass
$p_T^{\ell\ell}$	Dilepton p_T
m_T^{WW}	Transverse WW diboson mass
$z^*_{\ell_1}$	Zeppenfeld variable of the leading lepton
$z^*_{\ell_2}$	Zeppenfeld variable of the subleading lepton
$\Delta R_{j1,\ell\ell}$	ΔR between the leading jet and the dilepton system
$\Delta R_{j2,\ell\ell}$	ΔR between the subleading jet and the dilepton system
$(p_T^{\ell_1} p_T^{\ell_2})/(p_T^{j1} p_T^{j2})$	Ratio of p_T products between leptons and jets
p_T^{miss}	Missing transverse momentum

Isolate EW $W^{\pm}W^{\pm}$ against nonVBS background

- Dominated by non-prompt ttbar events
- Use 10 discriminating variables

Variables	Definitions
m_{jj}	Dijet mass
$\lvert\Delta\eta_{jj}\rvert$	Difference in pseudorapidity between the leading and subleading jets
$\Delta\phi_{jj}$	Difference in azimuth angles between the leading and subleading jets
p_T^{j1}	p_T of the leading jet
p_T^{j2}	p_T of the subleading jet
$p_T^{\ell_1}$	Leading lepton p_T
$p_T^{\ell\ell}$	Dilepton p_T
$z^*_{\ell_1}$	Zeppenfeld variable of the leading lepton
$z^*_{\ell_2}$	Zeppenfeld variable of the subleading lepton
p_T^{miss}	Missing transverse momentum

VBS $W^{\pm}W^{\pm} \rightarrow 2l^{\pm}2\nu$: longitudinally-polarised ?

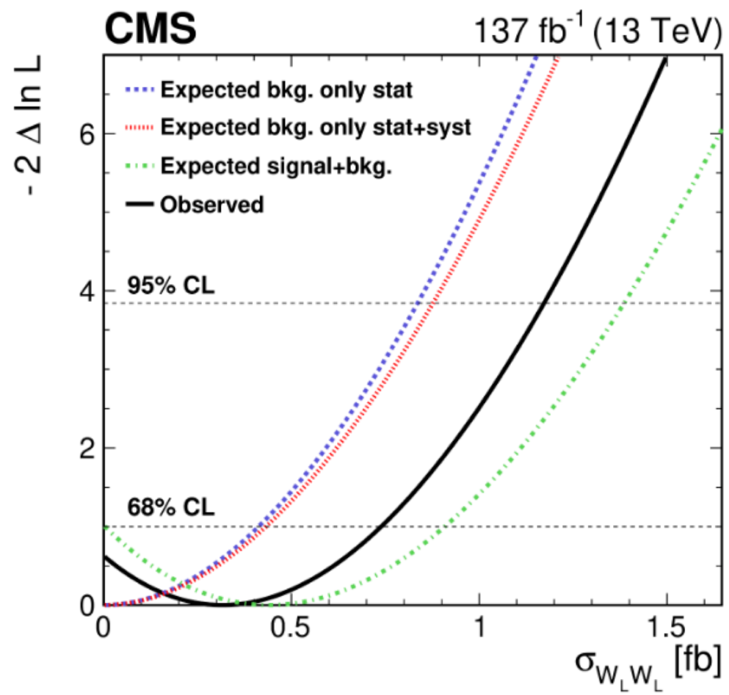
Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^{\pm}_{L}W^{\pm}_{L}$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W^{\pm}_{X}W^{\pm}_{T}$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W^{\pm}_{L}W^{\pm}_{X}$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W^{\pm}_{T}W^{\pm}_{T}$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

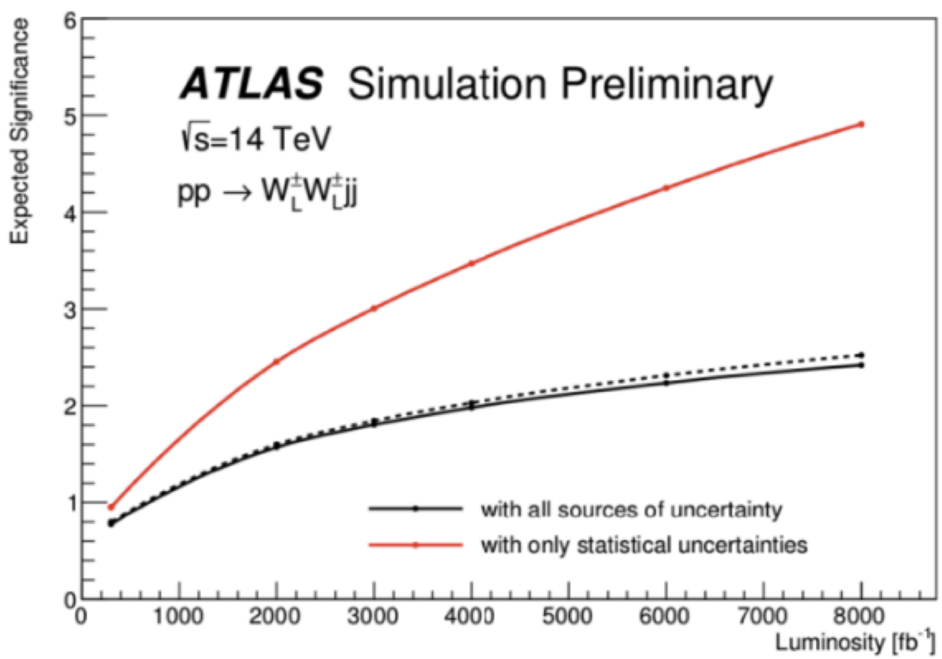
WW c.m. frame

Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^{\pm}_{L}W^{\pm}_{L}$	$0.24^{+0.40}_{-0.37}$	0.28 ± 0.03
$W^{\pm}_{X}W^{\pm}_{T}$	$3.25^{+0.50}_{-0.48}$	3.32 ± 0.37
$W^{\pm}_{L}W^{\pm}_{X}$	$1.40^{+0.60}_{-0.57}$	1.71 ± 0.19
$W^{\pm}_{T}W^{\pm}_{T}$	$2.03^{+0.51}_{-0.50}$	1.89 ± 0.21

Parton-parton c.m. frame

Not yet an evidence for a single-boson polarisation state
Observed (expected) significance for WLWL+WLWT: 2.3 (3.1)
Obs. (exp.) significance for WLWL: 0.88 (1.17)→ XS<1.17 (0.88) fb



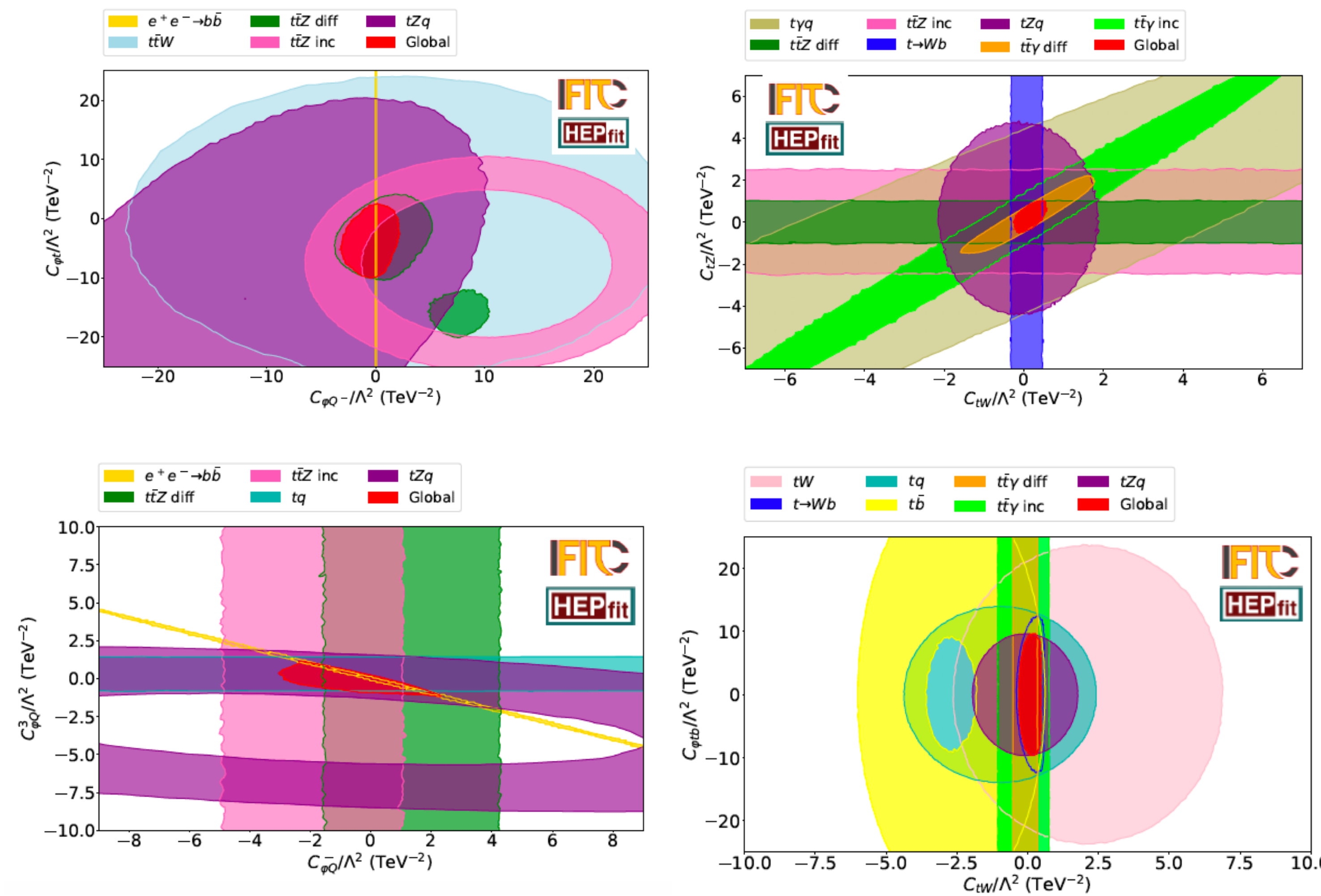


Top quark: experimental programme

- **Cross sections**
  - inclusive and (multi)-differential
  - tt, single top
  - boosted regime
- **Rare production & decay modes**
  - tt+Z,W,γ
  - t+Z,γ production
  - FCNC decays
  - tttt
- **Modelling**
  - b-fragmentation
  - tuning of underlying event
  - parton shower, hadronisation
- **Mass + properties**
  - mass, width, charge
  - spin, polarisation, W-helicity
  - lepton universality
  - charge asymmetries
- **Reinterpretations**
  - m_t^{POLE}, m_t, PDF and α_S
  - EFT constraints

* Left/Right-handed couplings of top/bottom to Z: $O_{\varphi t}, O_{\varphi Q}^{-}, O_{\varphi Q}^{(3)}$
* EW dipole operators: O_{tZ}, O_{tW}, O_{bW}
* Top Yukawa: $O_{t\varphi}$
* Charged current interaction: $O_{\varphi tb}$

2D 95% prob. contours showing complementarity btw. measurements
Watch out for:
LEP in $C_{\varphi Q}^{-}, C_{\varphi Q}^{(3)}$; $t\bar{t}Z$ in C_{tZ}, $C_{\varphi t}$; $t\bar{t}\gamma$ and W hel. in C_{tW}; tZq in $C_{\varphi tb}$



OPERATORS AND PHYSICS IMPLICATIONS

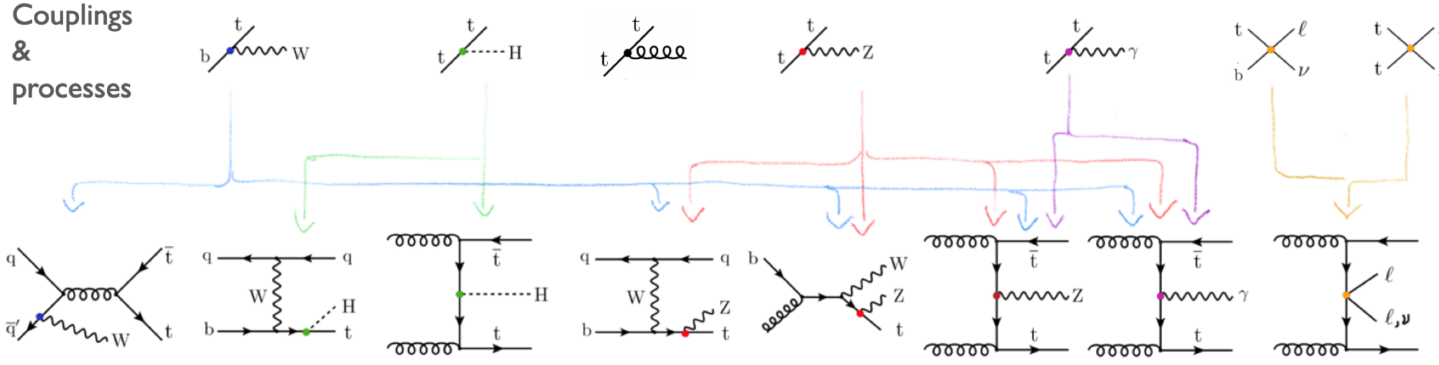
SMEFT Lagrangian

$$\mathcal{L} = \mathcal{L}_{4,\mathrm{SM}} + \frac{1}{\Lambda_{\delta L\neq 0}}\mathcal{L}_5 + \boxed{\frac{1}{\Lambda^2}\mathcal{L}_6} + \frac{1}{\Lambda^2_{\delta B\neq 0}}\mathcal{L}'_6 + \frac{1}{\Lambda^3_{\delta L\neq 0}}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \ldots$$

Operators

$\mathcal{O}_{\phi tb}$	$i(\tilde{\phi} D_\mu \phi)(\bar{t}_R\gamma^\mu b_R) + \mathrm{h.c.}$	$\mathcal{O}_{tB}$	$i(\bar{q}_L\sigma^{\mu\nu} t_R)\tilde{\phi} B_{\mu\nu} + \mathrm{h.c.}$	$\mathcal{O}^{(3)}_{\phi q_L}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \tau_I \phi)(\bar{q}_L\gamma^\mu \tau^I q_L)$	$\mathcal{O}^1_{qq}$	$(\bar{q}_L\gamma_\mu q_L)(\bar{q}_L\gamma^\mu q_L)$
$\mathcal{O}_{t\phi}$	$(\phi^\dagger\phi)\,\bar{q}_L t_R\tilde{\phi} + \mathrm{h.c.}$	$\mathcal{O}_{tG}$	$i(\bar{q}_L\sigma^{\mu\nu}\lambda^a t_R)\tilde{\phi} G^a_{\mu\nu} + \mathrm{h.c.}$	$\mathcal{O}^{(1)}_{\phi q_L}$	$i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{q}_L\gamma^\mu q_L)$	$\mathcal{O}^8_{qq}$	$(\bar{q}_L\gamma_\mu T^A q_L)(\bar{q}_L\gamma^\mu T^A q_L)$

Couplings & processes



Parametrized predictions

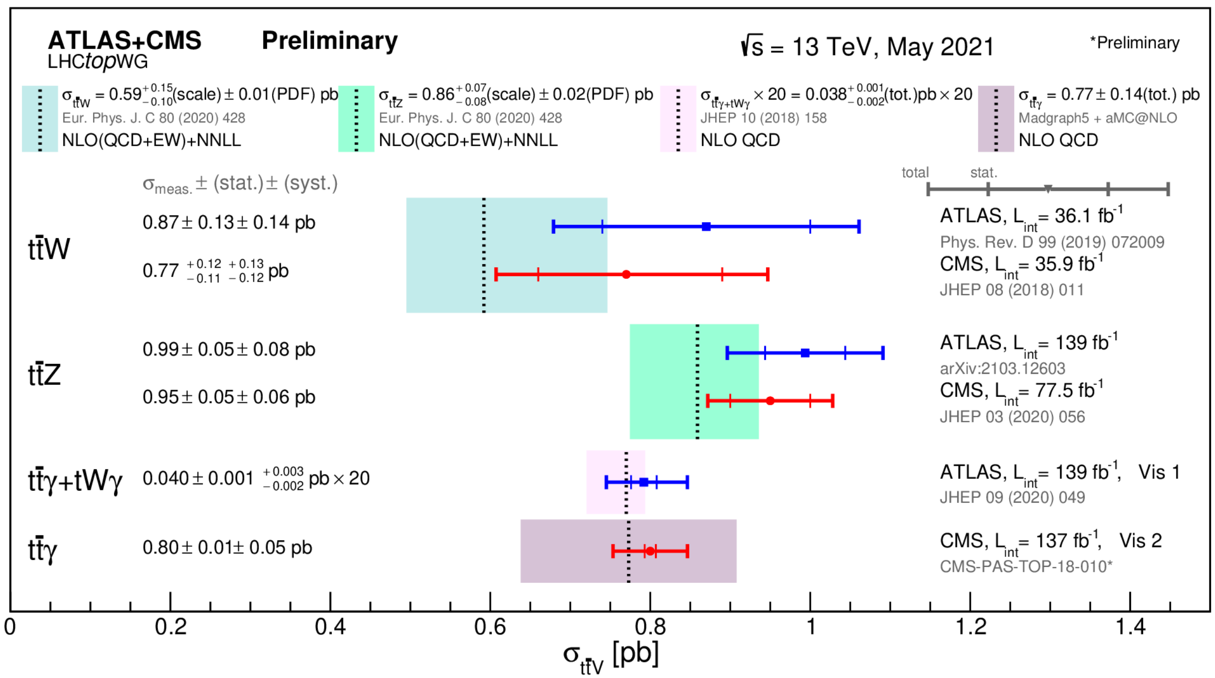
$$N\left(\frac{\vec{c}}{\Lambda^2}\right) = S_0 + \sum_j S_{1j}\frac{c_j}{\Lambda^2} + \sum_j S_{2j}\frac{c_j^2}{\Lambda^4} + \sum_{j,k} S_{3jk}\frac{c_j}{\Lambda^2}\frac{c_k}{\Lambda^2}$$

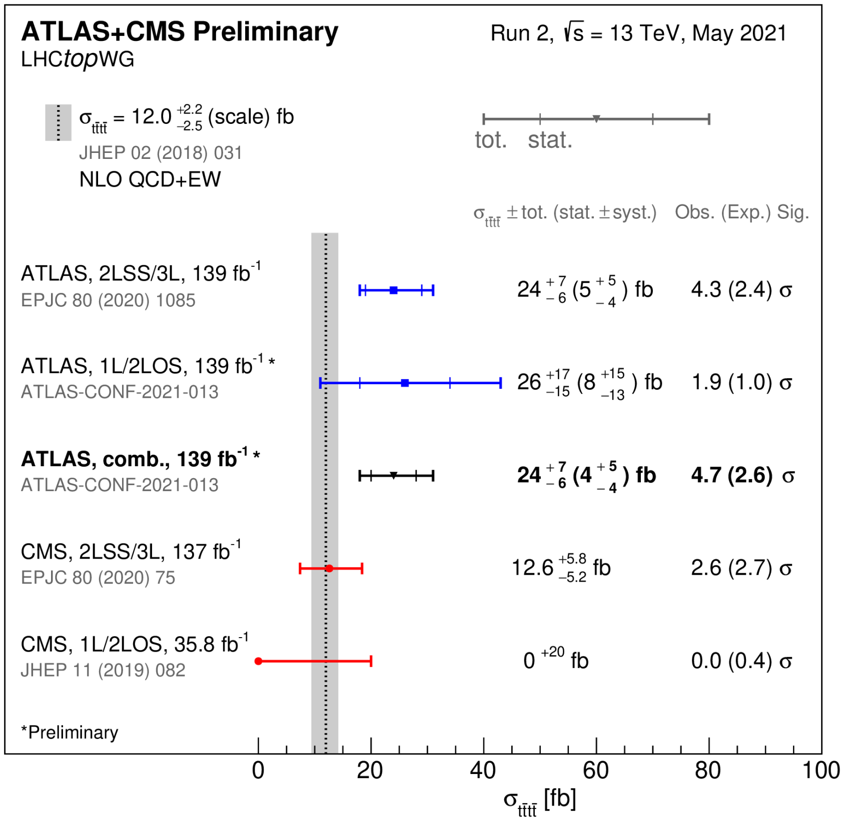
2 quarks + bosons

Operator	Definition	Lead processes affected
$^{\ddagger}O^{(ij)}_{u\varphi}$	$\bar{q}_i u_j \tilde{\varphi}\,(\varphi^\dagger\varphi)$	$t\bar{t}H$, tHq
$O^{1(ij)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_i\gamma^\mu q_j)$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$
$O^{3(ij)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_i\gamma^\mu\tau^I q_j)$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$
$O^{(ij)}_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_i\gamma^\mu u_j)$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, $tl\bar{l}q$
$^{\ddagger}O^{(ij)}_{\varphi ud}$	$(\tilde{\varphi}^\dagger iD_\mu\varphi)(\bar{u}_i\gamma^\mu d_j)$	$t\bar{t}H$, $tl\bar{l}q$, tHq
$^{\ddagger}O^{(ij)}_{uW}$	$(\bar{q}_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde{\varphi}W^I_{\mu\nu}$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$
$^{\ddagger}O^{(ij)}_{dW}$	$(\bar{q}_i\sigma^{\mu\nu}\tau^I d_j)\,\varphi W^I_{\mu\nu}$	$t\bar{t}H$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$
$^{\ddagger}O^{(ij)}_{uB}$	$(\bar{q}_i\sigma^{\mu\nu}u_j)\,\tilde{\varphi}B_{\mu\nu}$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$
$^{\ddagger}O^{(ij)}_{uG}$	$(\bar{q}_i\sigma^{\mu\nu}T^A u_j)\,\tilde{\varphi}G^A_{\mu\nu}$	$t\bar{t}H$, $t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, tHq, $tl\bar{l}q$

2 quarks + 2 leptons

Operator	Definition	Lead processes affected
$O^{1(ijkl)}_{\ell q}$	$(\bar{\ell}_i\gamma^\mu\ell_j)(\bar{q}_k\gamma^\mu q_\ell)$	$t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, $tl\bar{l}q$
$O^{3(ijkl)}_{\ell q}$	$(\bar{\ell}_i\gamma^\mu\tau^I\ell_j)(\bar{q}_k\gamma^\mu\tau^I q_\ell)$	$t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, $tl\bar{l}q$
$O^{(ijkl)}_{\ell u}$	$(\bar{\ell}_i\gamma^\mu\ell_j)(\bar{u}_k\gamma^\mu u_\ell)$	$t\bar{t}l\bar{l}$
$O^{(ijkl)}_{eq}$	$(\bar{e}_i\gamma^\mu e_j)(\bar{q}_k\gamma^\mu q_\ell)$	$t\bar{t}l\bar{l}$, $tl\bar{l}q$
$O^{(ijkl)}_{eu}$	$(\bar{e}_i\gamma^\mu e_j)(\bar{u}_k\gamma^\mu u_\ell)$	$t\bar{t}l\bar{l}$
$^{\ddagger}O^{1(ijkl)}_{\ell equ}$	$(\bar{\ell}_i e_j)\,\varepsilon\,(\bar{q}_k u_\ell)$	$t\bar{t}l\bar{l}$, $tl\bar{l}q$
$^{\ddagger}O^{3(ijkl)}_{\ell equ}$	$(\bar{\ell}_i\sigma^{\mu\nu}e_j)\,\varepsilon\,(\bar{q}_k\sigma_{\mu\nu}u_\ell)$	$t\bar{t}l\nu$, $t\bar{t}l\bar{l}$, $tl\bar{l}q$


ATLAS+CMS Preliminary
LHCtopWG
√s = 13 TeV, May 2021
*Preliminary
σmeas. ± (stat.) ± (syst.)
ttW
0.87 ± 0.13 ± 0.14 pb
ATLAS, Lint = 36.1 fb-1
Phys. Rev. D 99 (2019) 072009
CMS, Lint = 35.9 fb-1
JHEP 08 (2018) 011
ttZ
0.99 ± 0.05 ± 0.08 pb
0.95 ± 0.05 ± 0.06 pb
ATLAS, Lint = 139 fb-1
arXiv:2103.12603
CMS, Lint = 77.5 fb-1
JHEP 03 (2020) 056
ttγ+tWγ
ATLAS, Lint = 139 fb-1, Vis 1
JHEP 09 (2020) 049
ttγ
0.80 ± 0.01 ± 0.05 pb
CMS, Lint = 137 fb-1, Vis 2
CMS-PAS-TOP-18-010*
NLO(QCD+EW)+NNLL
NLO QCD
Eur. Phys. J. C 80 (2020) 428
JHEP 10 (2018) 158
Madgraph5 + aMC@NLO
σttV [pb]


ATLAS+CMS Preliminary
LHCtopWG
Run 2, √s = 13 TeV, May 2021
JHEP 02 (2018) 031
NLO QCD+EW
tot. stat.
Obs. (Exp.) Sig.
ATLAS, 2LSS/3L, 139 fb-1
EPJC 80 (2020) 1085
4.3 (2.4) σ
ATLAS, 1L/2LOS, 139 fb-1 *
ATLAS-CONF-2021-013
1.9 (1.0) σ
ATLAS, comb., 139 fb-1 *
ATLAS-CONF-2021-013
4.7 (2.6) σ
CMS, 2LSS/3L, 137 fb-1
EPJC 80 (2020) 75
2.6 (2.7) σ
CMS, 1L/2LOS, 35.8 fb-1
JHEP 11 (2019) 082
0.0 (0.4) σ
*Preliminary
σtttt [fb]