Standard Model Measurements

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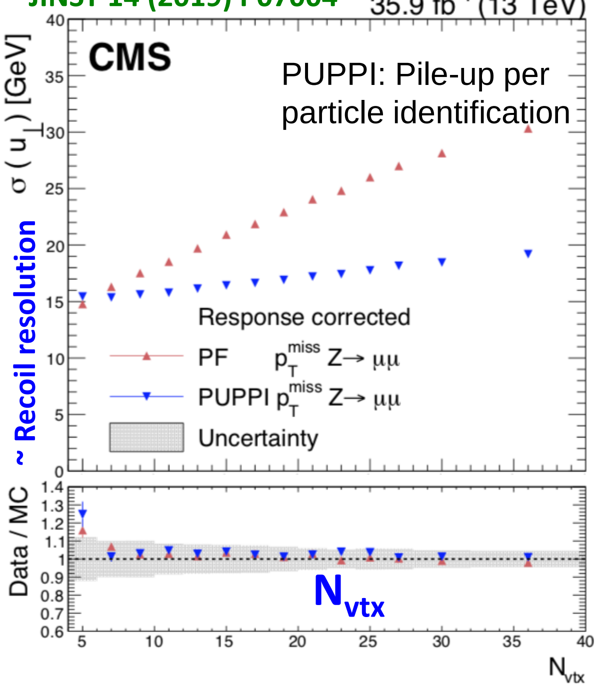
Presenting results from ATLAS, CMS, LHCb, D0 and HERA Collaborations

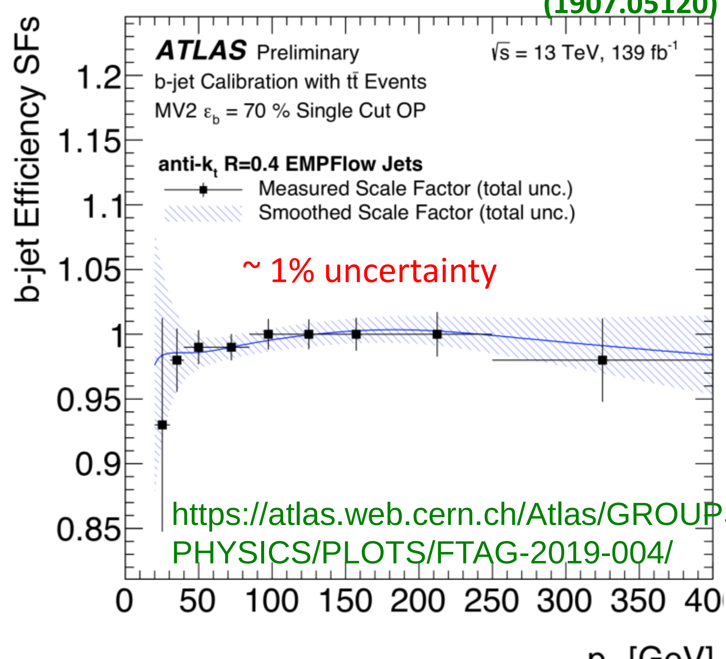
SM measurements: introduction

- **"SM everywhere" →** important to understand until which point it describes our world
  - Need to perform SM measurements as best we can
  - Need to look for "Beyond SM". Twofold interest in SM measurements:
    - look for deviations wrt SM
    - SM is a background for direct searches
- **LHC Run 2 (**2015-2018**) has ended**
  → additional ~ 140 (~ 6, LHCb) fb^{-1} @ 13 TeV being analysed
  - essential work in performance
  - steps forward in physics calculations and modelling

JINST 14 (2019) P07004



(1907.05120)



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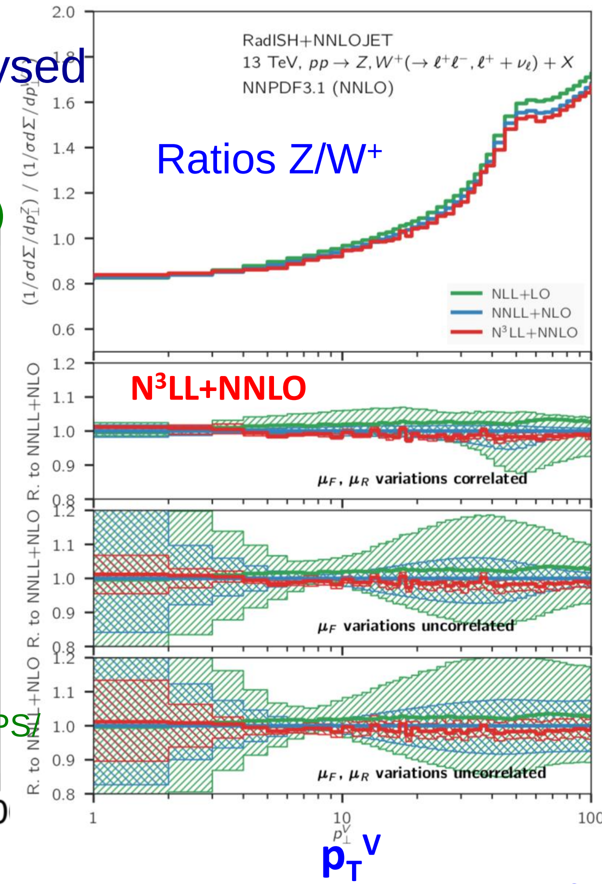
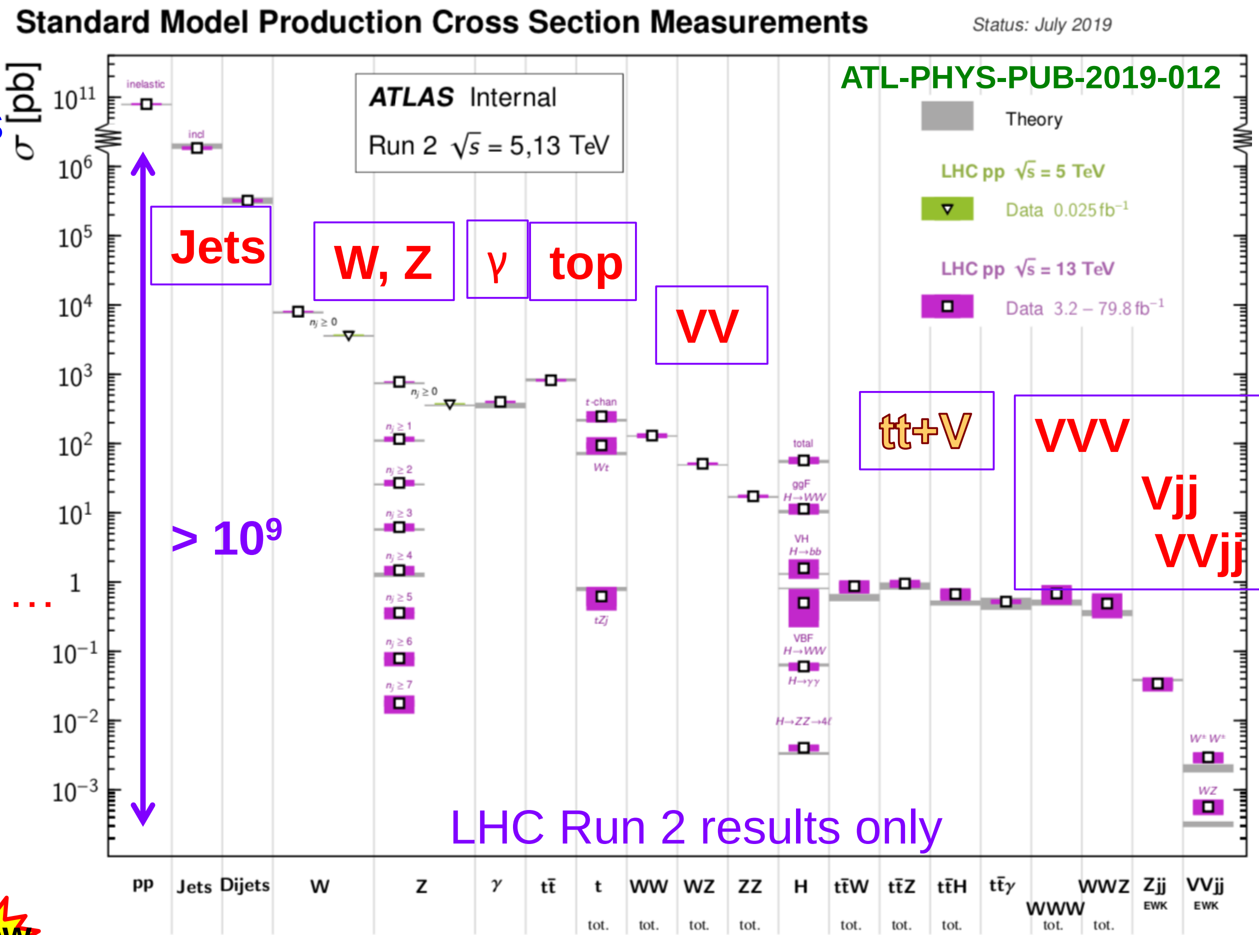


SM measurements: outline

- **Tests of QCD** new
  - V(V=W,Z) + Jets, Photons
  - p_T^V
- **E.w. precision tests**
  - m_W, $\sin^2\theta_W$, m_{top} new
- **Top couplings and more …**
  - ttZ, 4 tops, A_c^{top}, new
    single top
- **Gauge boson couplings**
  - VV, Vjj , VVjj & VVV new

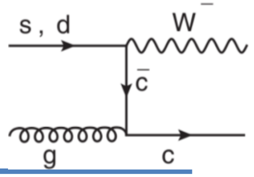


Standard Model is (nearly) everything (so far)

→ quick overview of new (10 !) & few recent resul

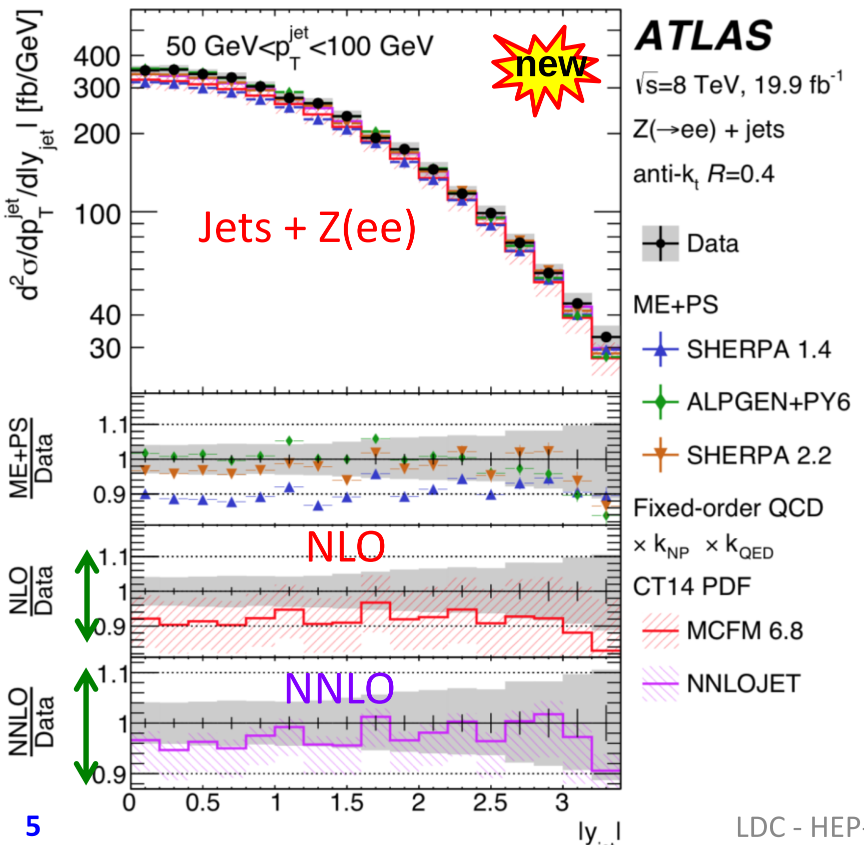
Tests of QCD

Probing QCD: V+jets (V=Z,W)



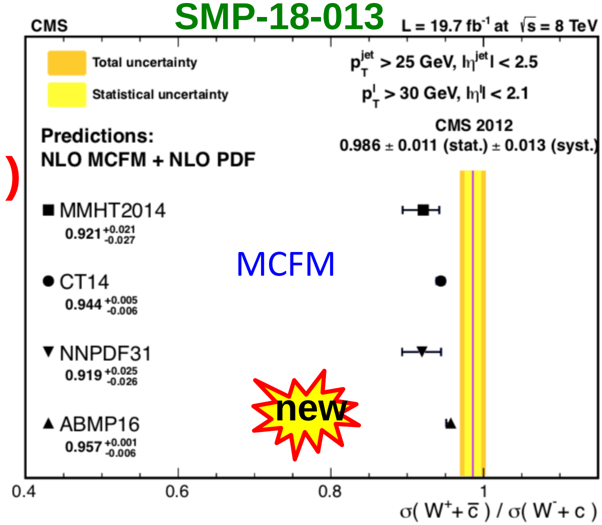
- Cross section measurements of V+jets test NLO & NNLO QCD predictions
- New ATLAS: **inclusive jets + Z(ee)** vs **jet |y| and |p$_T$|**
- **NNLO parton-level fixed-order predictions (corrected) improve agreement with data**

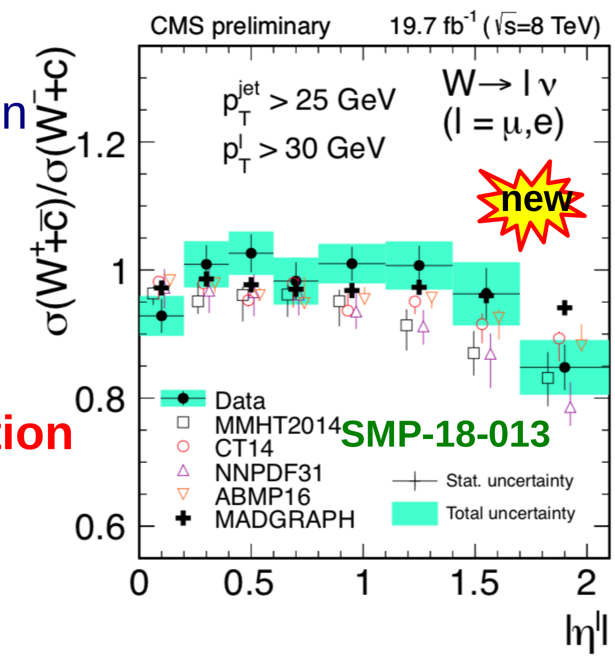
STDM-2016-11



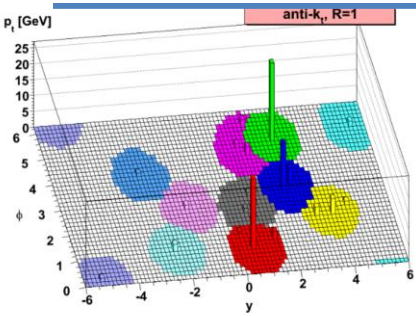
- New CMS: **W + c**
  Access to the strange quark content in proton @ Q ~ m$_W$
- **Potential to constrain the parton distribution functions**

SMP-18-013





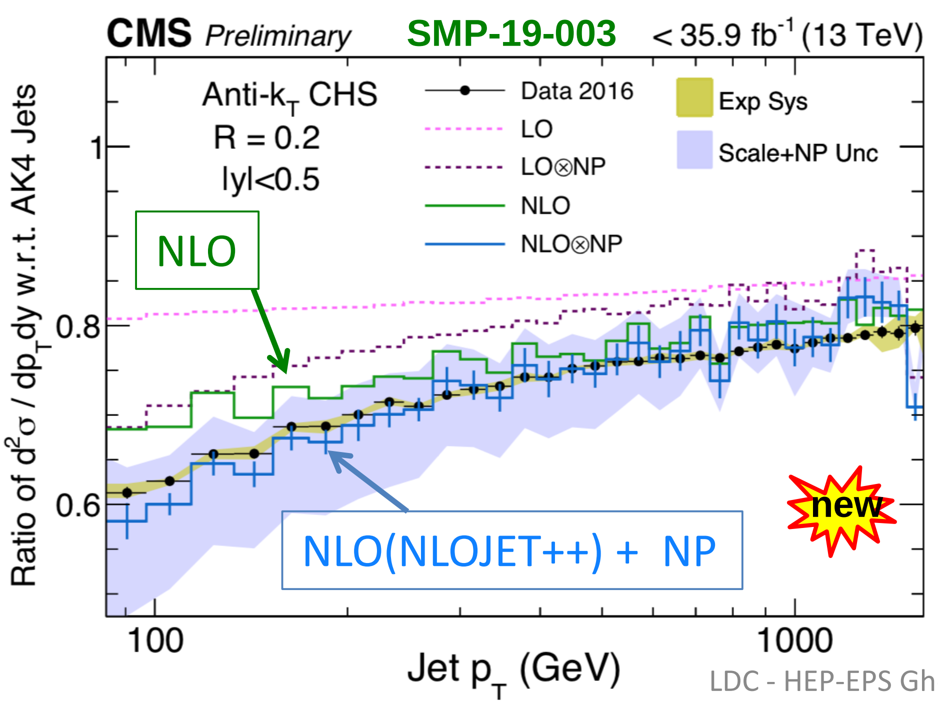
Probing QCD: cross section vs jet size



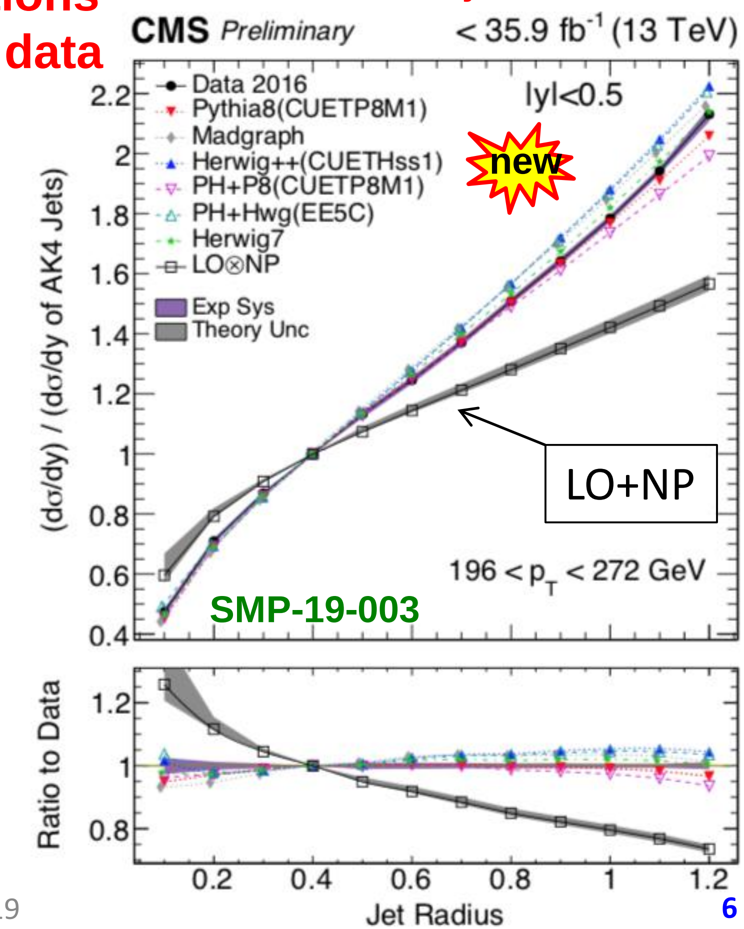
JHEP 0804:063,2008

- Dependence of the jet production cross section on the anti-k_T distance parameter R tests the modeling of the perturbative and nonperturbative (NP) processes in parton evolution
- New CMS: **NLO + NP corrections gives a good description of data**

Ratio of jet cross sections: R= 0.2 jets/R= 0.4 jet

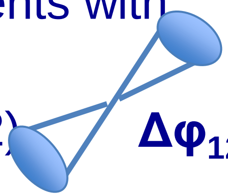


Ratio of jet cross section: w.r.t. R = 0.4 jet



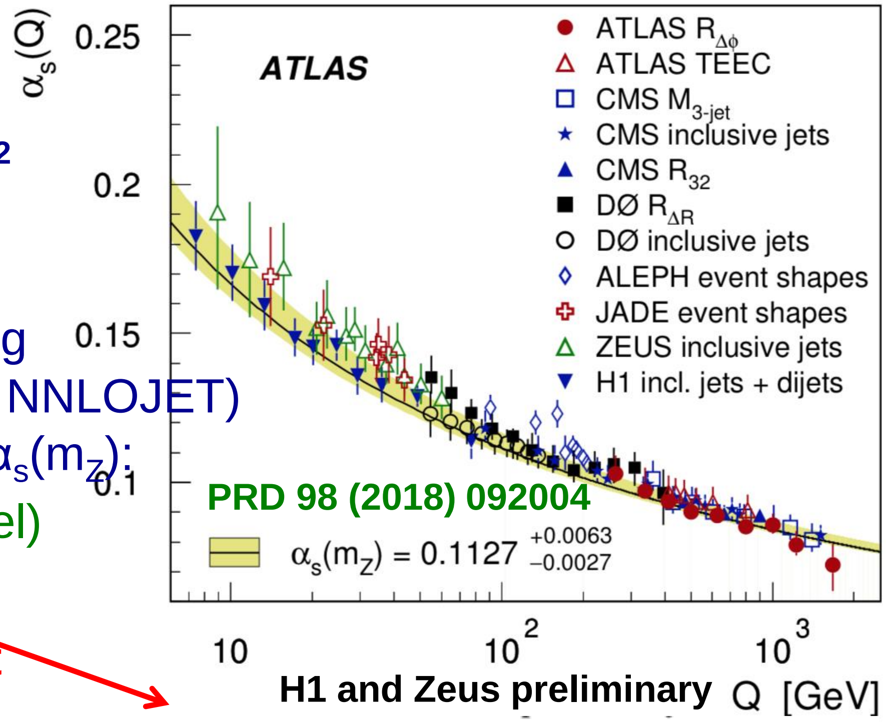
Recent α_s measurements

- α_s from fraction $R_{\Delta\varphi}$ of dijet events with $\Delta\varphi_{12} < \Delta\varphi_{max} = 7/8\pi$
  (use $0 < y^* < 1.0$, $y^* = |y_1 - y_2|/2$)



$\Delta\varphi_{12}$

→ **Test scale evolution of α_s up to 1.7 TeV**

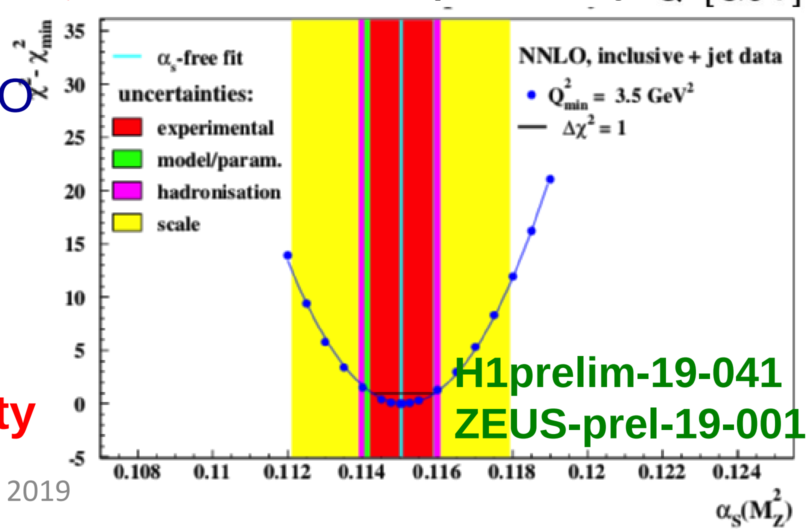


- $\alpha_s(m_Z)$ from a global NNLO QCD fit including inclusive DIS and jet data (jet predictions from NNLOJET)
  Simultaneous determination of the PDFs and $\alpha_s(m_Z)$:

$$\alpha_s(m_Z) = 0.1150 \pm 0.0008\,(\text{exp})\,^{+0.0002}_{-0.0005}\,(\text{model}) \pm 0.0006\,(\text{hadr}) \pm 0.0027\,(\text{scale})$$

→ **~ 30% reduction of scale uncertainty wrt NLO analysis**

H1 and Zeus preliminary

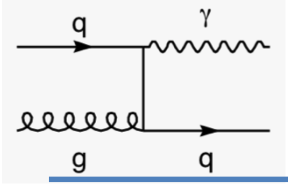


H1prelim-19-041
ZEUS-prel-19-001

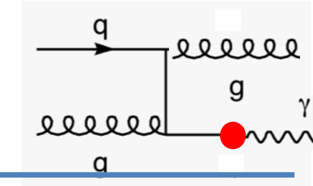
- $\alpha_s(m_Z)$ fit triple differential $t\bar{t}$ cross section @ NLO (CMS, **1904.0523**) including HERA DIS data for simultaneously α_s, m_t^{pole} and PDF extraction:

$$\alpha_s(m_Z) = 0.1135 \pm 0.0016(\text{fit})\,^{+0.0002}_{-0.0004}\,(\text{model})\,^{+0.0008}_{-0.0001}\,(\text{PDF param})\,^{+0.0011}_{-0.0005}(\text{scale})$$

→ **Value compatible with competitive uncertainty**

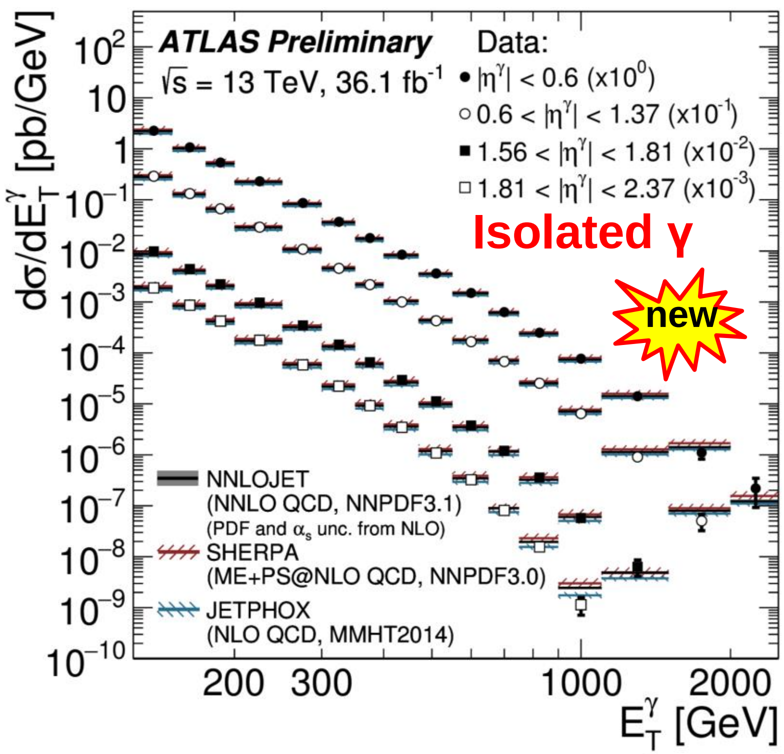


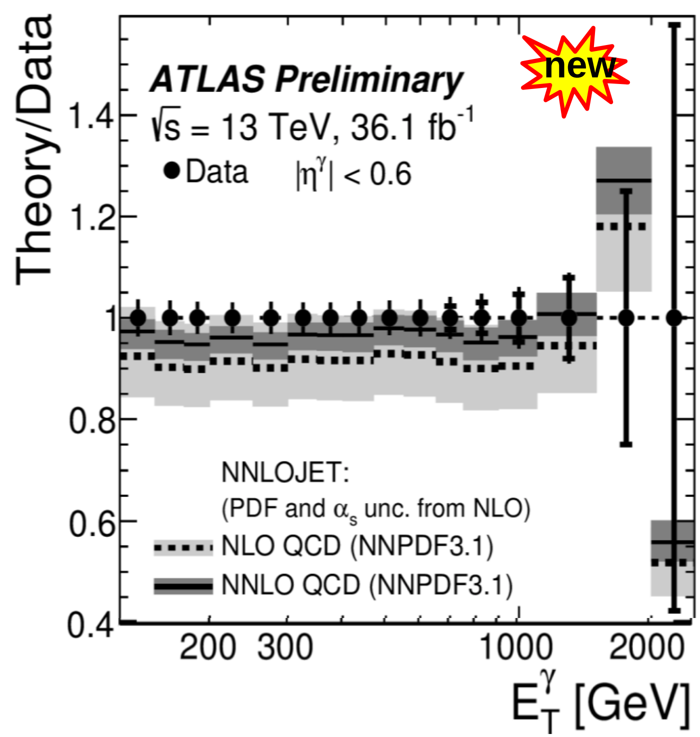
Photon (+ jet) cross sections



- **Test pQCD with a hard colorless probe + sensitivity to gluon density in the pro**
- New ATLAS result: better **γ** calibration & identification
  → reduced experimental systematic uncertainty (by up to ~ 40%)
- Cross sections vs E_T^γ & $|\eta^\gamma|$: good description of data already @ NLO QCD
- **Recent NNLO calculations (NNLOJET) lead to a reduction of the theory scale uncertainty, (< ~ 5%) and to an improved description of the measurements**

STDM-2017-29





Gauge boson p_T^V (V = W, Z)

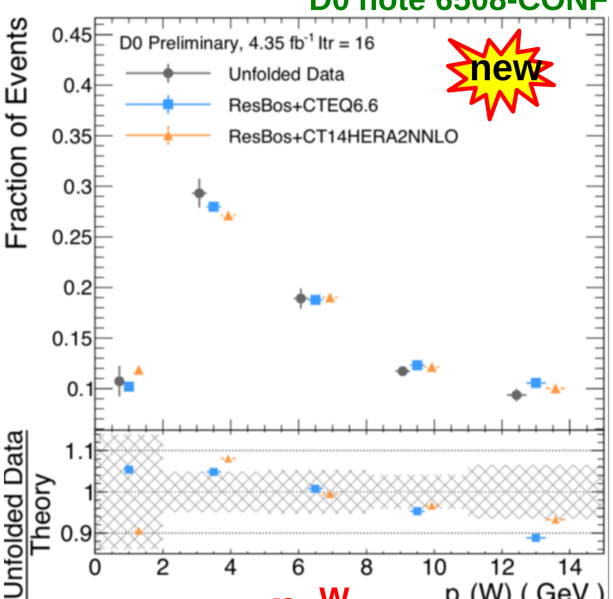
- **p_T^V distribution (V = W, Z): probes various aspects of the strong interactions** (fixed order, resummed, parton shower calculations)
- New D0 p_T^W: measurement where the production dominated by valence quarks
- CMS p_T^Z: for normalised σ, uncertainty < 0.5 % for p_T^Z < 50 GeV, ~ same as ATLAS
- **Predictions describe data within theory uncertainties:**

@ **low p_T:** RESBOS calculation (resummed NNLL) does a good job (but no uncertainties available)

@ **high p_T :** good description with MadG5_aMC@NLO; Z+j @ NNLO small uncertainti

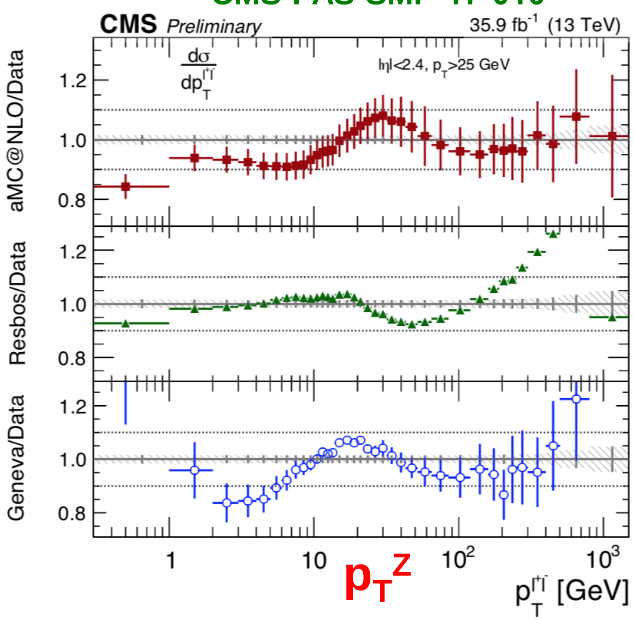
- Key ingredient for a precise measurement of the $W^{\pm}$ mass @ $p\overset{(-)}{p}$ colliders

D0 note 6508-CONF



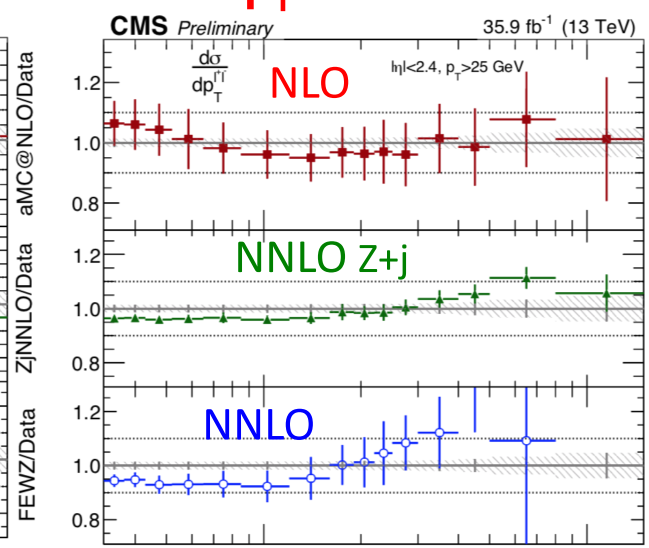
p_T^W

CMS-PAS-SMP-17-010



p_T^Z

p_T > 32 GeV



p_T^Z

E.w. precision measurements

Probe BSM via electroweak precision tests: m_W, $\sin^2\theta_W$, m_{top}

- m_W, $\sin^2\theta_W$: important parameters of SM.
  Can be calculated from 3 measured e.w. observables
  (ex. from 3 best measured: α_{em}, G_F and m_Z
  plus corrections including m_{top} & m_H)

$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}}\,\frac{1}{\sin\theta_W\sqrt{1-\Delta r}}$$

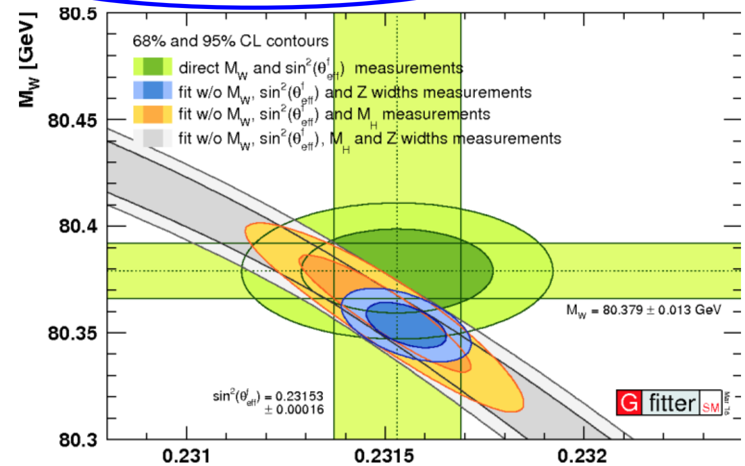
f (m_{top}^2, ln m_H) ~ few %

- **Comparing indirect to direct measurements**
  → tests SM internal consistency → BSM probe
  → Need to measure:
  $\Delta m_W \leq 8$ MeV,
  $\Delta\sin^2\theta_W \leq 7 \cdot 10^{-5}$
  $\Delta m_{top} \leq 1$ GeV

- PDF source of main systematics @ pp colliders (followed by QCD modelling)

- Projections from LHCb, 1808.08865:
  m_W measurement @ forward rapidities
  - complementary lepton acceptance $2 < \eta_l < 5$
    → partial anticorrelation of PDF w.r.t. existing measurements, Eur. Phys. J. C75 (2015) 601)

  → Δm_W^{PDF} ~ 2 MeV with LHeC



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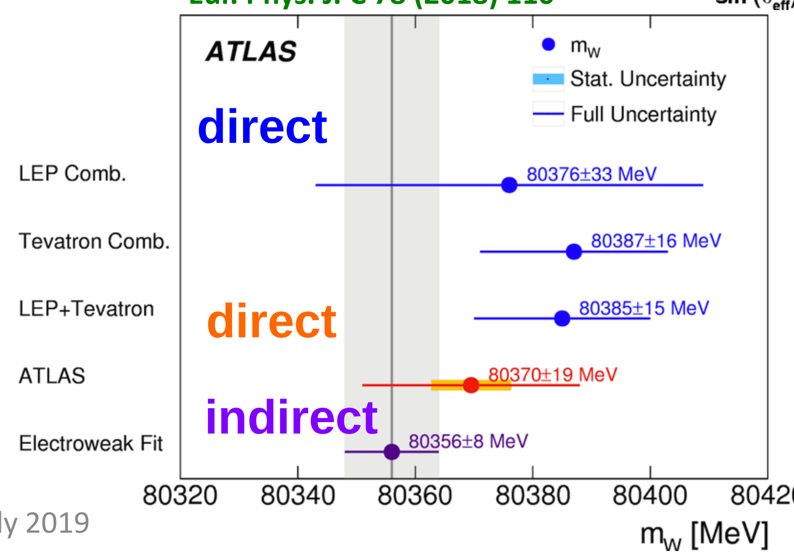
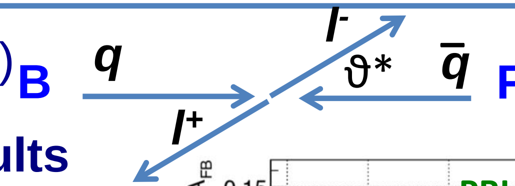


Probe BSM via electroweak precision tests (m_W, $\sin^2\theta_W$, m_{top})

$\sin^2 \theta^{lep}_{eff} = k_{lep} \sin^2 \theta_W$ (k_{lep} e.w. corrections)



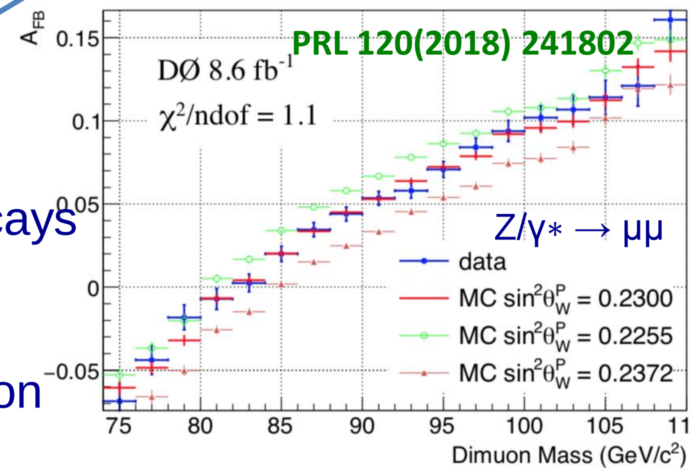
$A_{FB} = \dfrac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$

- **Tension between the most sensitive results**

Methods @ $p\overset{(-)}{p}$ colliders:

* Forward Backward Asymmetry (A_{FB}) in Z ($\rightarrow$ll) decays template fits (vs m_{ll}, in bins of y_{ll})

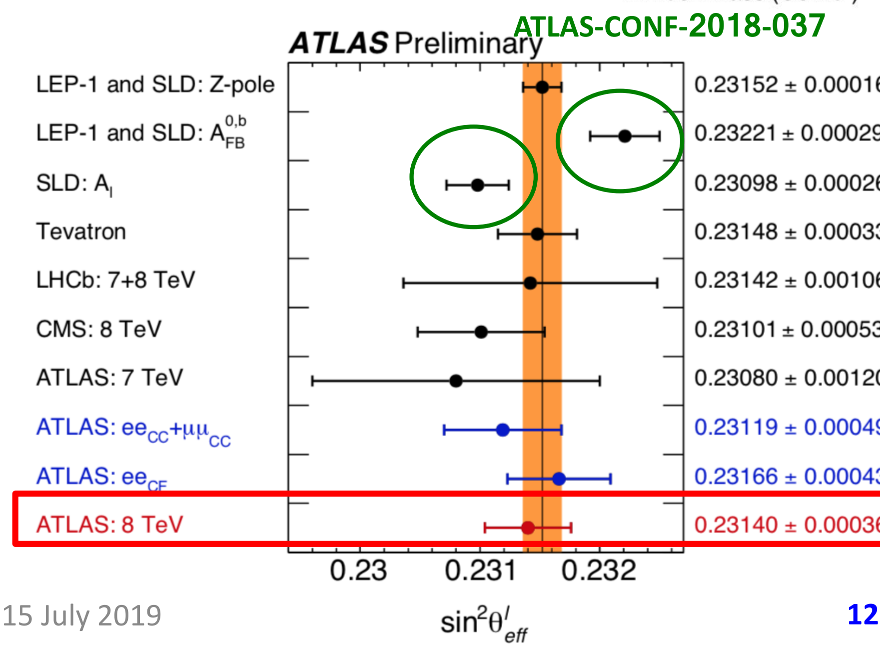
* Angular decomposition of the Drell-Yan cross-section $q\bar{q} \rightarrow Z/\gamma* \rightarrow ll$



- PDF source of main systematics

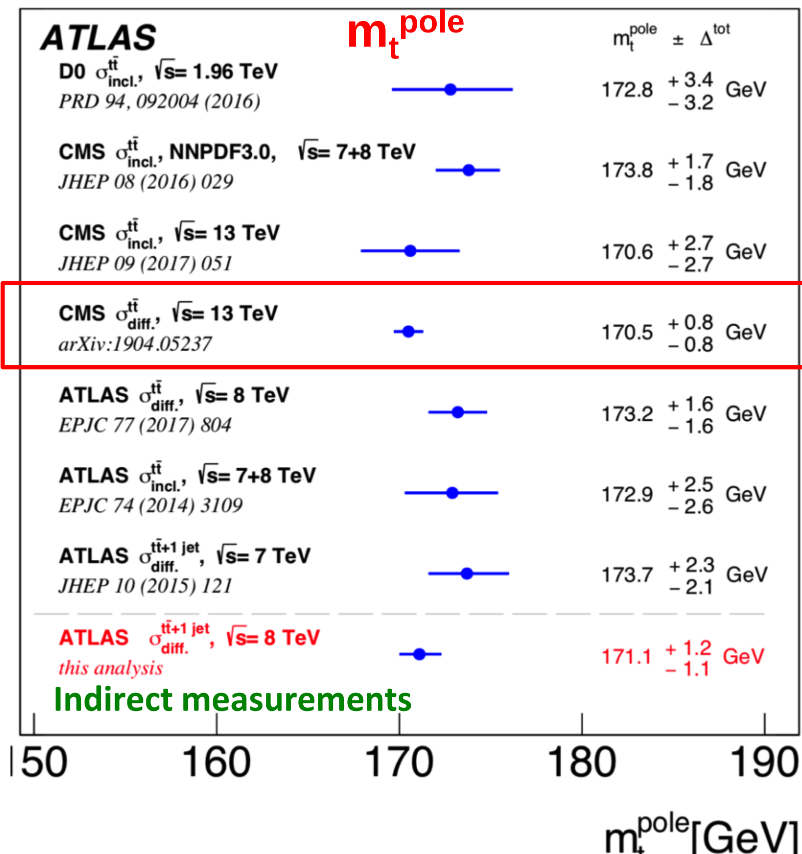
- Projections from LHCb (1808.08865): advantages @ higher Z rapidities:
  - the forward-backward asymmetry is larger
  - the parton direction is better known

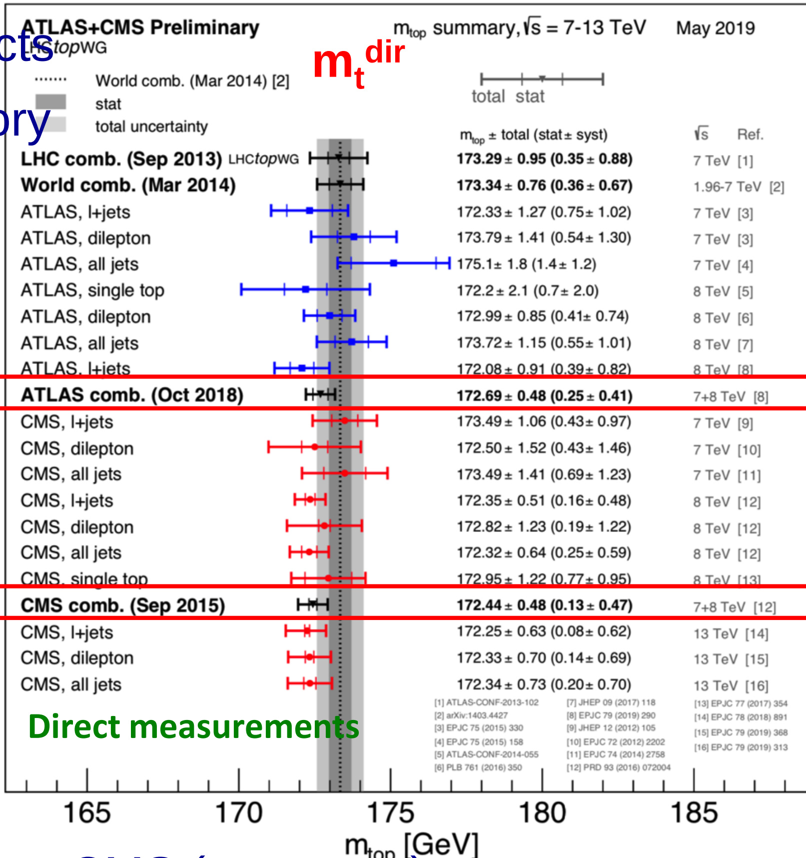
- A future e^+e^- collider may reach $\Delta \sin^2 \theta^{lep}_W \sim 5 * 10^{-6}$



Probe BSM via electroweak precision tests (m_W, $\sin^2\theta_W$, m_{top})

- Direct measurements: m_t^{dir} from decay products
- Indirect measurements: fit tt X-sections + theory
  - Extract the pole mass m_t^{pole}
- CMS (1904.05237): simultaneous α_S and m_t^{pole} extraction using NLO calculations
  Tot. uncertainty below 1 GeV





new

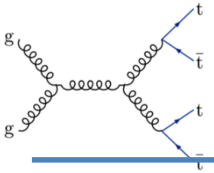
from CMS (TOP-19-005):

m_t @ **high Lorentz boosts**: a single jet include all t → bW → bqq'products

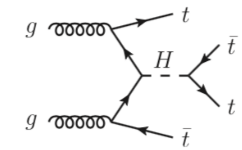
promising observable could calculated at particle level from theory

m_t^{boost} = 172.56 ± 2.47 GeV (36 fb^{-1} @13 TeV)

Top measurements for couplings & BSM



Rare processes: $t\bar{t}t\bar{t}$ (4 tops)

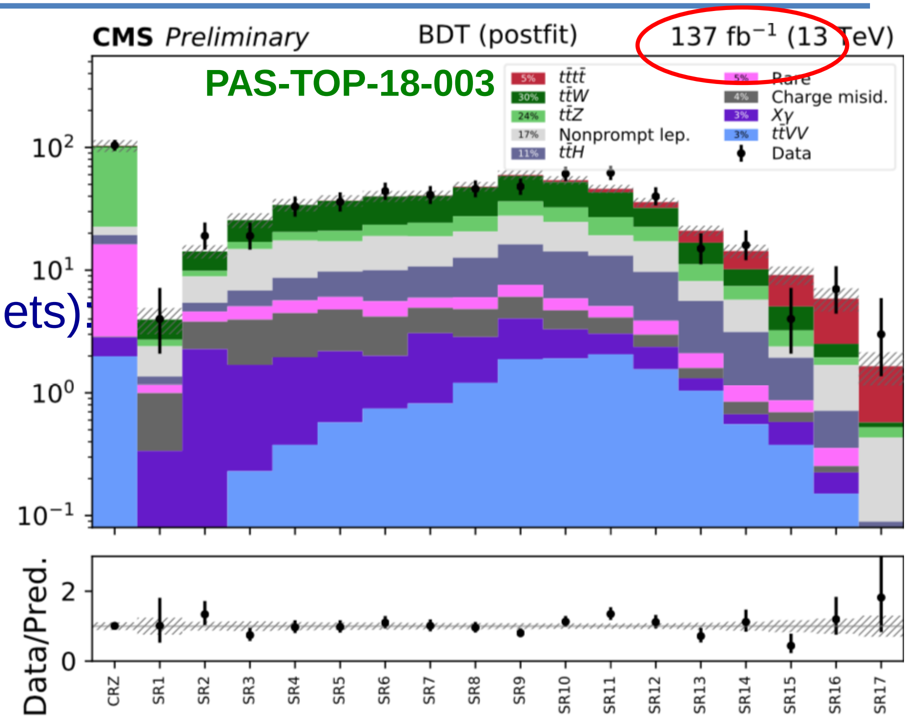


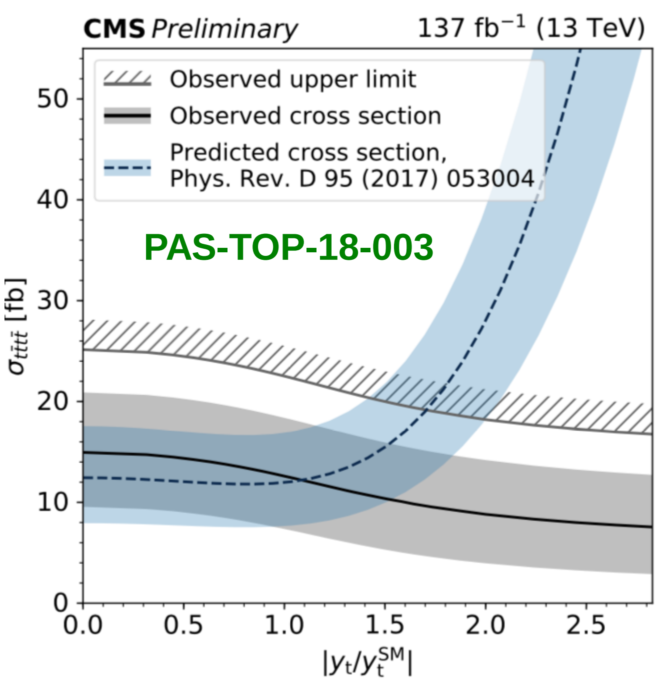
- Not yet observed : σ^{NLO}_{tttt} (SM) ~ 12 fb

- **Sensitive to BSM effects**
  way to assess the top Yukawa coupling

- **CMS full Run 2 data** (ss dileptons & ≥ 3 l+jets):
  fit many signal and control regions

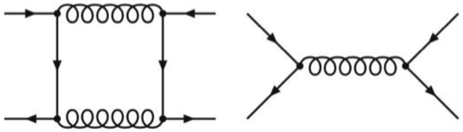
- Significance: **2.6 (2.7) σ** obs(exp.**)**
  → **Challenging !**





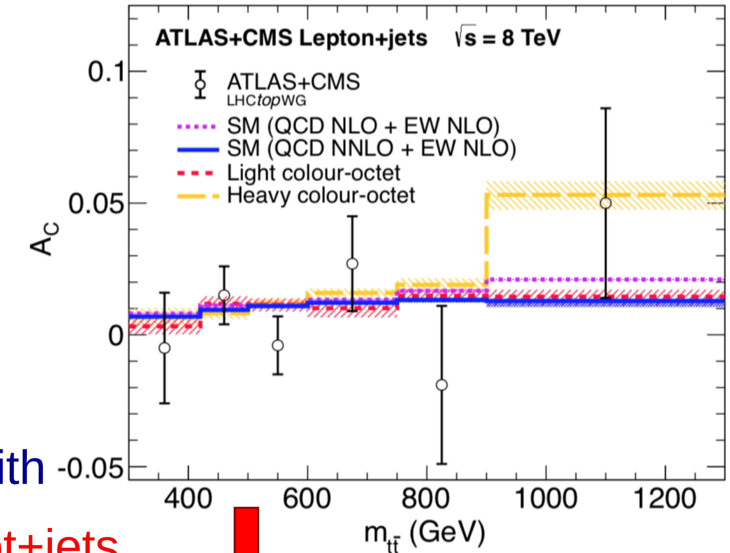
- **Top Yukawa coupling: $|y_t/y^{SM}_t|$ < 1.7 @ 95%**
  comparable with recent CMS limit from $t\bar{t}$ kinematic distributions in lepton+jet : $|y_t/y^{SM}_t|$ < 1.67 (**1907.01590**)
  complementary to coupling extraction in $t\bar{t}H$ & tH

- Limits on (pseudo) scalar A/H → $t\bar{t}$



Top properties in $t\bar{t}$: charge asymmetry, A_C

- In SM A_C results from the interference of HO amplitudes in $q\bar{q}$ and qg initial states
  → t prefers q direction
  Small effect, enhanced @ high $t\bar{t}$ mass (m_{tt}) and longitudinal $t\bar{t}$ boost (β_{tt})
- **Enhanced in some BSM theories**
- ATLAS + CMS results @ 8 TeV in agreement with NLO and NNLO but also compatible with zero A_C



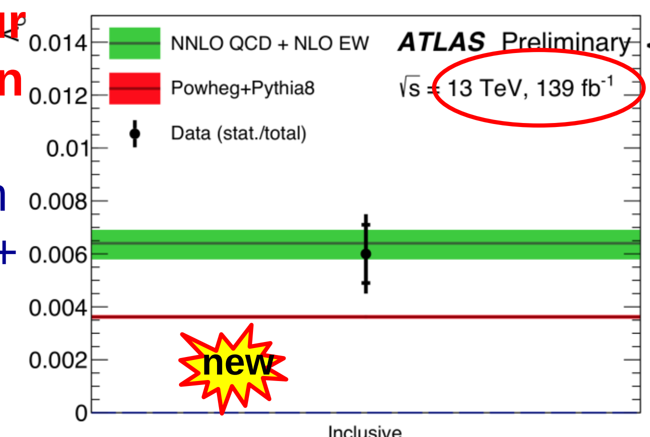
- New ATLAS result **full Run 2 data**: lepton + jet with resolved and boosted jet

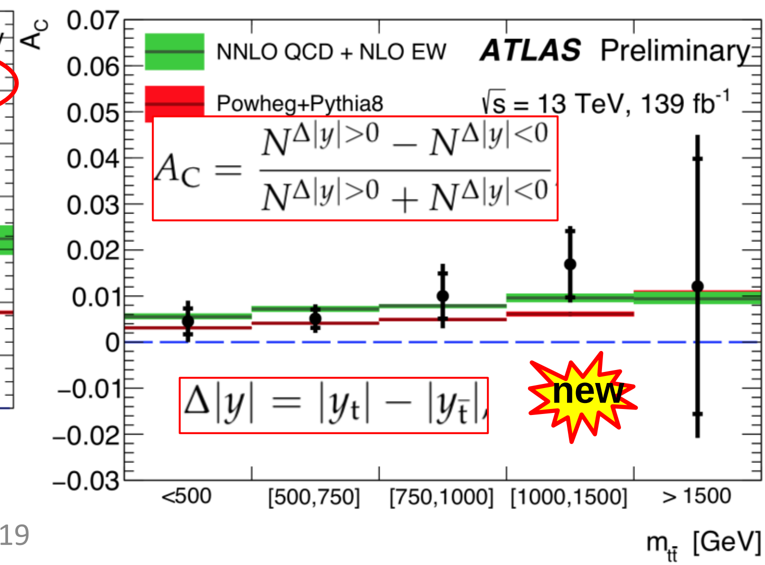
lept+jets

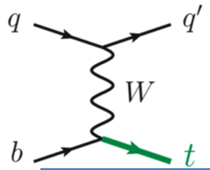
ATLAS-CONF-2019-026

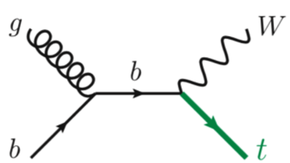
- **Inclusive A_C is four standard deviation from zero**
  & in agreement with NNLO predictions + EW NLO

→ Limits on coeff. dim-6 EFT operators C^-/Λ^2

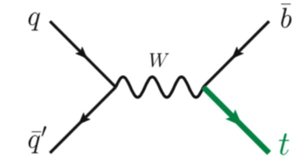






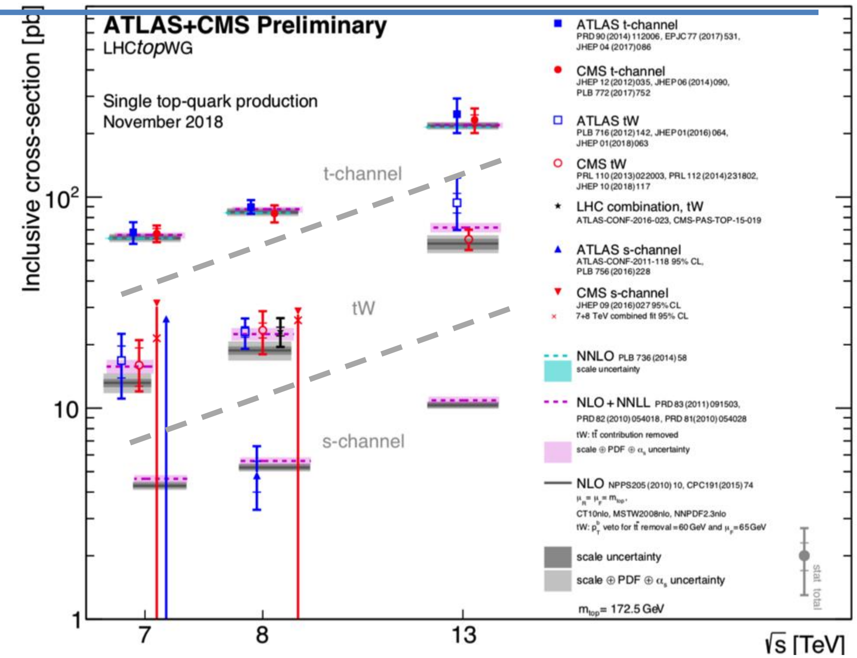


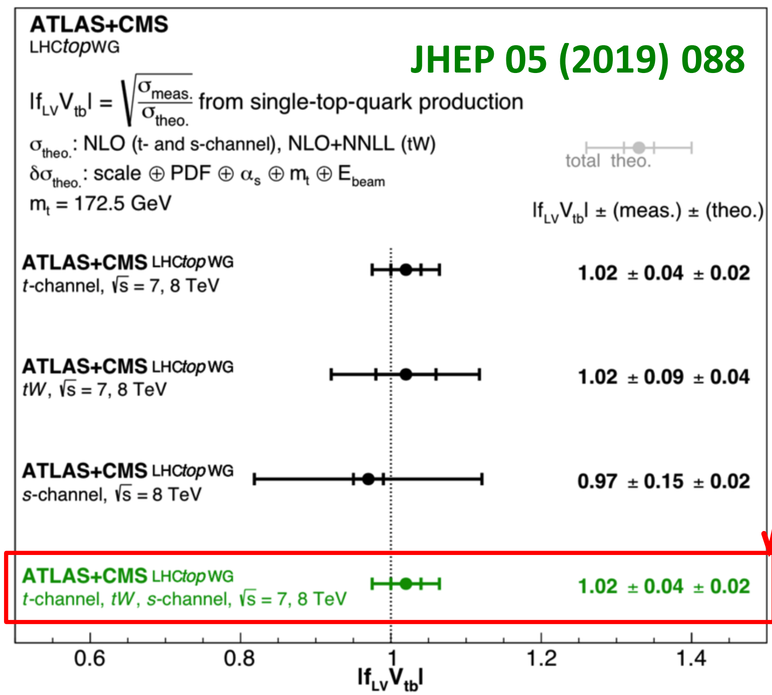
Single top cross section



- **Investigation of the Wtb vertex**

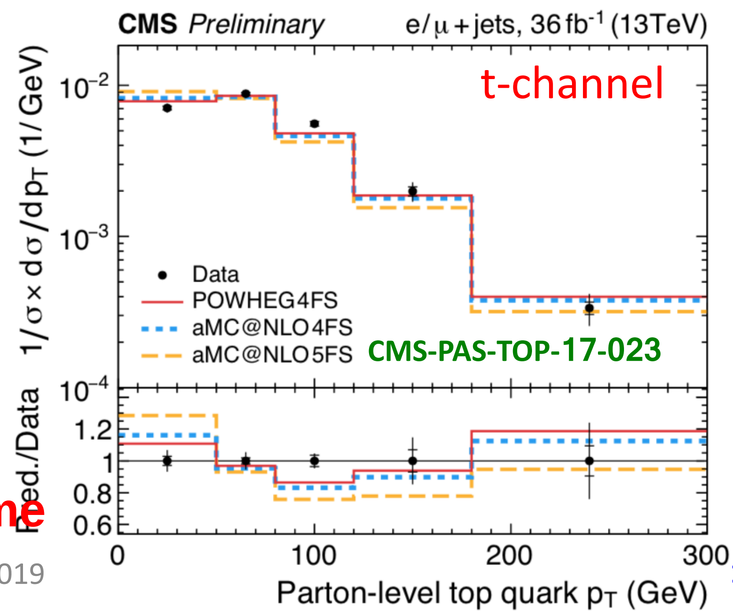
- LHC best combined precision 7@8TeV:
  ATLAS+CMS X-section: **~ 7%** (t-channel)
  NLO+NLL predictions **~ 3 %** (t-channel)





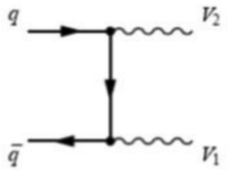
$|f_{LV} * V_{tb}| = 1$ within ~ 4%

(f_{LV} form factor for BSM contributions)

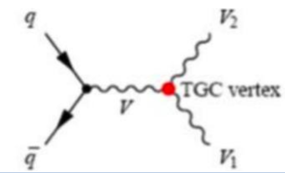


- **Differential cross-section measurements: better description with 4 Flavour than 5F scheme**

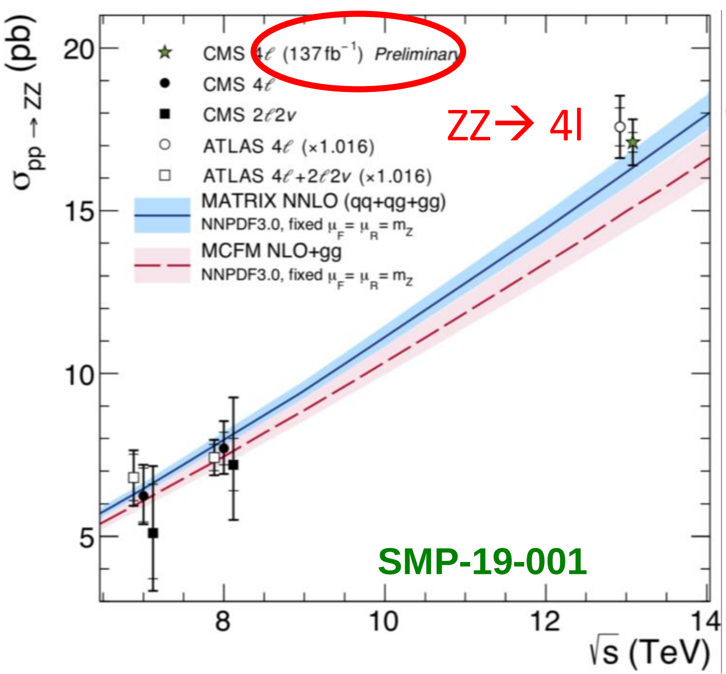
Gauge boson couplings

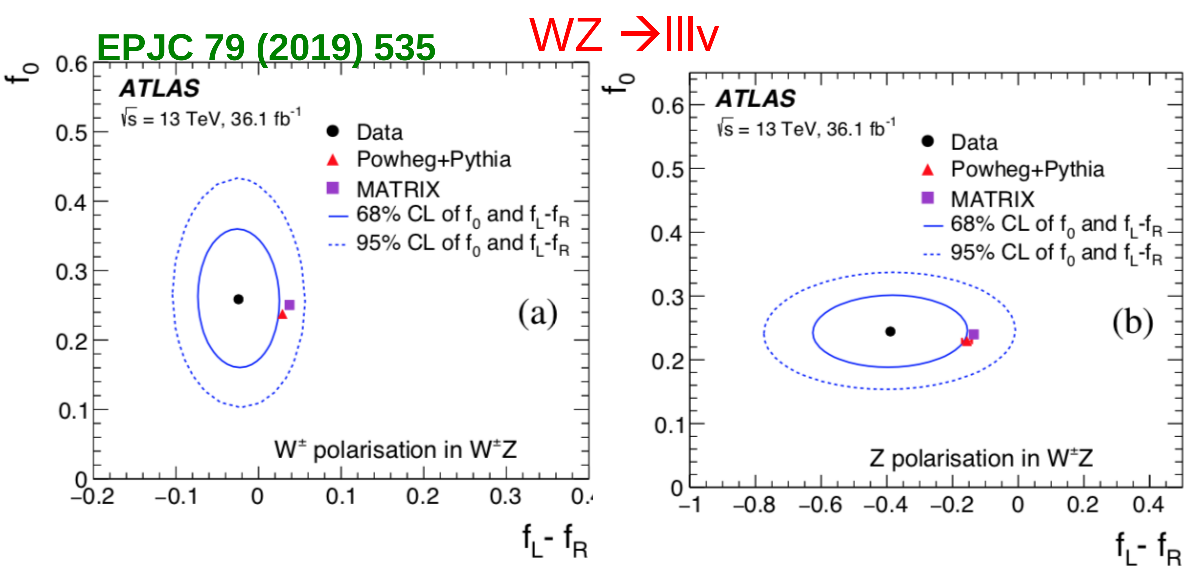


Multi gauge boson production



- **VV / Vγ / γγ / VVV (V=W, Z)**
  - **Investigate the non-abelian structure** of the SM at the highest energy
  - **Sensitive to new physics** via **a**nomalous Triple (Quartic) Gauge Couplings **(aTGC, a**
- Dibosons**:** many measurements, **NNLO necessary to describe data**
- CMS: σ_{tot} (ZZ) with **full Run 2 data**. Uncertainties: stat ~ syst ~ lumi
- ATLAS measures the helicity fractions of W± and Z in WZ events in agreement with SM predictions. First step on the way to perform polarization measurements in VBS proce





Multi gauge boson production

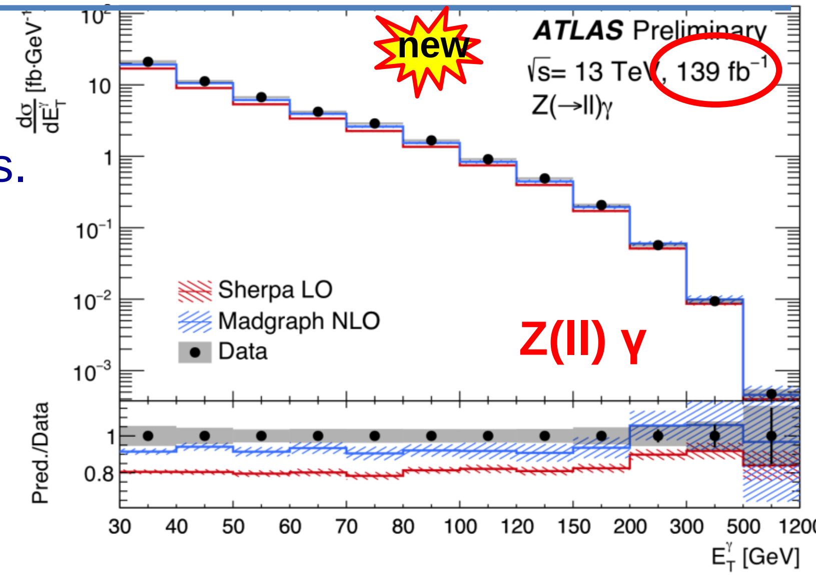
ATLAS-CONF-2019-034

- Di-boson Z(ll) γ : new ATLAS **full Run 2 data.**

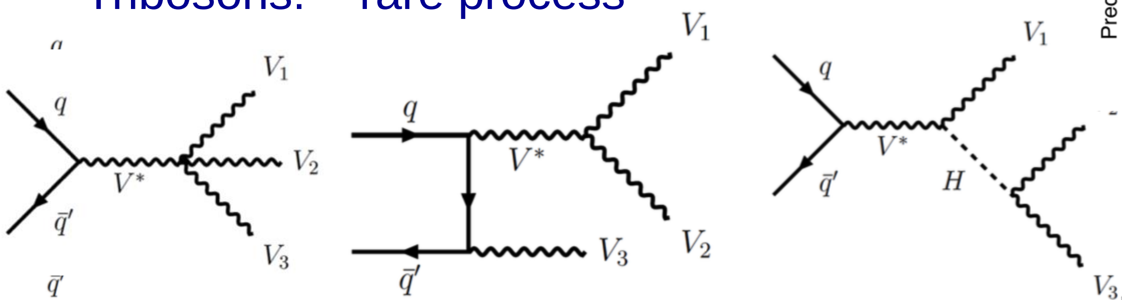
Differential X-sections vs E_T^{γ}, $|\eta_{\gamma}|$, $p_T^{ll\gamma}$, $m(ll\gamma)$

~ 5% experimental uncertainty in most of E_T^{γ} bins.

NNLO describes E_T^{γ} within uncertainties & improve data description

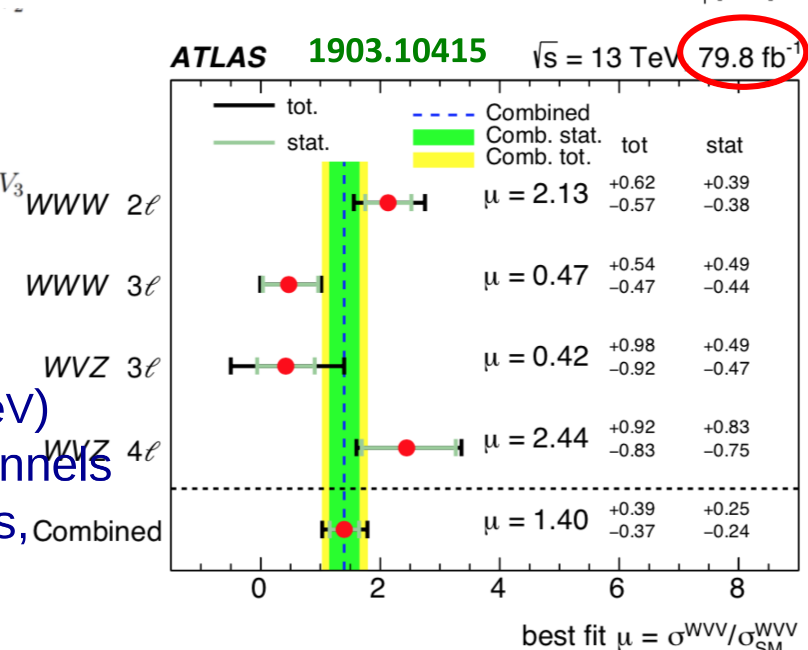


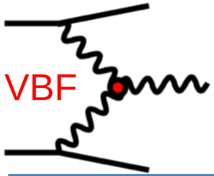
- Tribosons: rare process



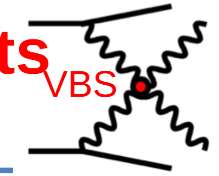
- Recent ATLAS result finds **4.1 σ evidence** (3.1 σ exp.) for WWW+WWZ+WZZ combined

- Recent CMS result (**1905.04246,** ~ 36 fb^{-1} @ 13 TeV) focuses on WWW in the 2ss- and 3-lepton channels Confidence intervals for **aQGC** (dim-8 operators, more later). Limits on axion-like particles

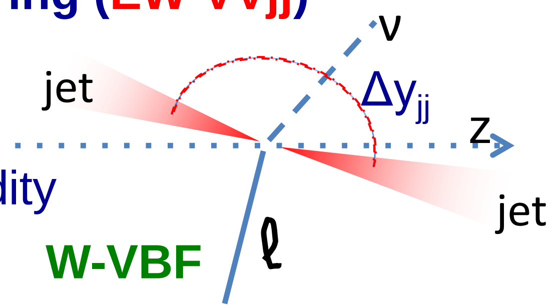




Single gauge bosons & di-bosons with dijets
(EW Vjj & EW-VVjj)



- **Vector Boson Fusion (EW-Vjj) and Vector Boson Scattering (EW-VVjj)**
  - **milestones studies of EW sector**
  - sensitive to new physics in the 3 or 4 boson vertex



- VBF and VBS tagged by 2 jets with large separation in rapidity
  - Large mjj for leading two jets
  - Low jet activity in the central region

- "QCD-mediated" V+jj and VV+jj (interference !). Often largest background
  → perform common fit to signal and contr regions

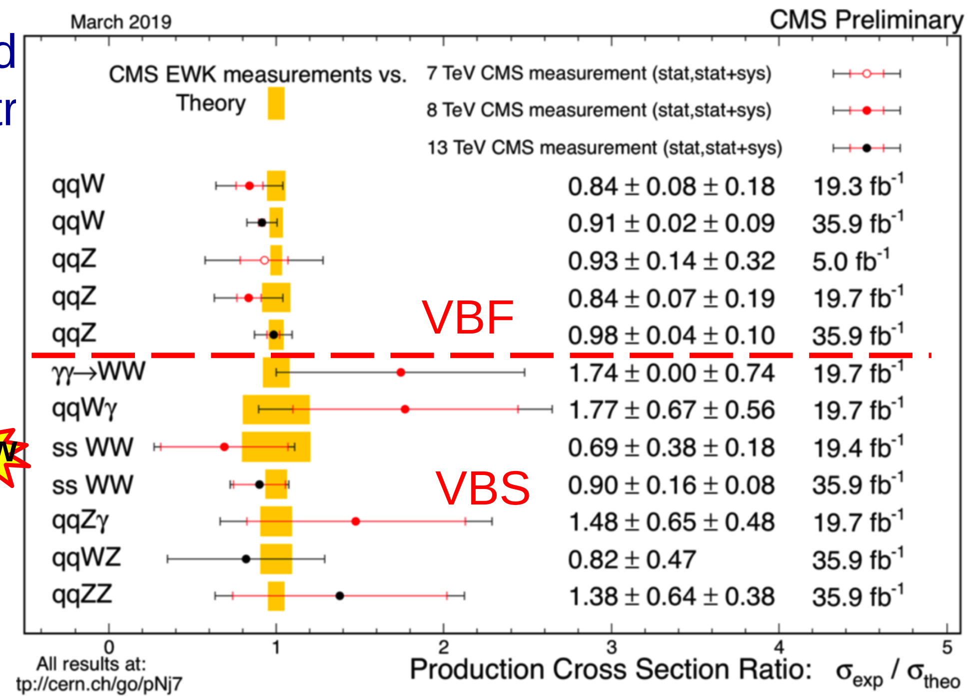
- **Observed :**

VBF: EW-Wjj and **EW-Zjj** (**ATLAS&CMS**)

VBS: EW-**ssWWjj(ATLAS&CMS**)
EW-**WZjj(ATLAS),EW-ZZjj (ATLAS)** new

- **Evidence:**
  VBS: EW-Zγjj (CMS) @ 8 TeV & 13 TeV new

- **Agreement with SM predictions**
  → limits on aTGC and aQGC



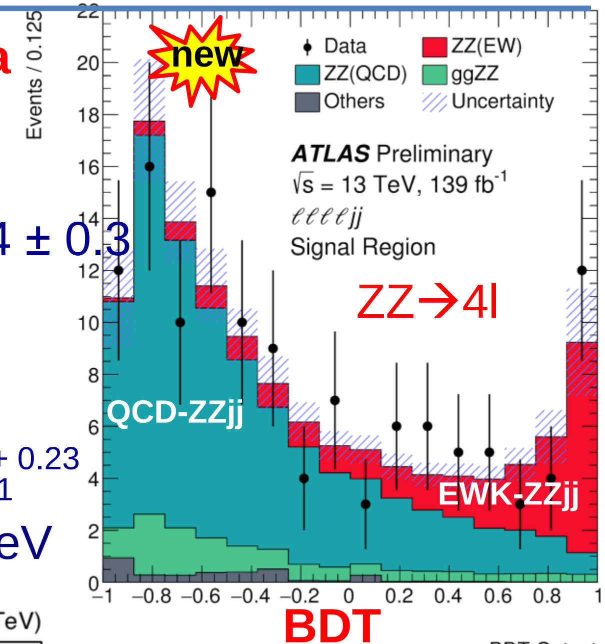
Observation of EWK-ZZjj & evidence EWK-Zγjj

CONF-STDM-2019-11

- **ATLAS: observation of EWK-ZZjj** with **full Run 2 data (4l and llvv)**
- Fit to a multi-variable combination (BDT):

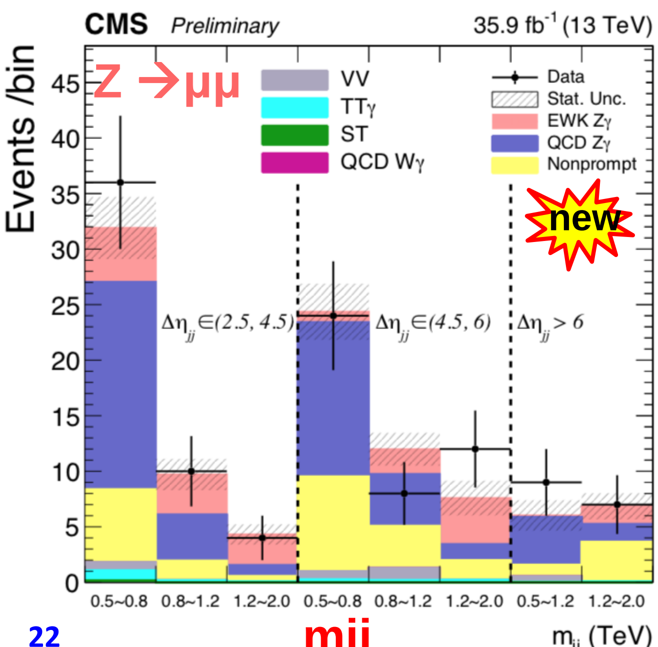
signal strength = 1.4 ± 0.3

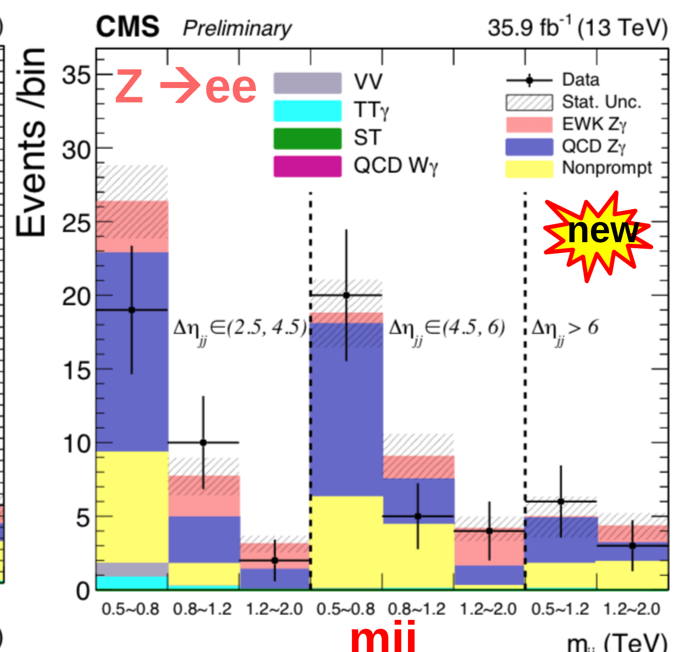
→ **Significance 5.5 (4.3) σ obs. (exp.)** σ_{fid} = 0.82 ± 0.21 fb

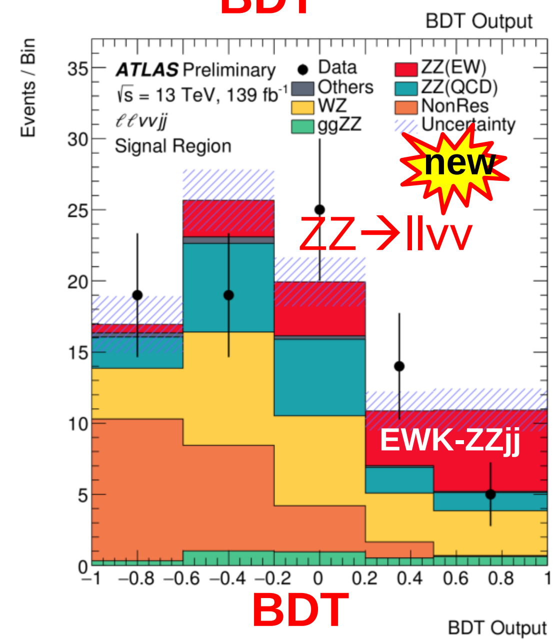


- **CMS: Evidence of EWK-Zγjj** 36 fb^{-1} @13 TeV **(Z → ll)**
- 2 D fit to mjj & Δηjj: signal strength = $0.64^{+0.23}_{-0.21}$

→ **Significance 4.7 (5.5) σ obs. (exp.)** combined with 8 TeV







Anomalous gauge boson couplings@ 13 TeV

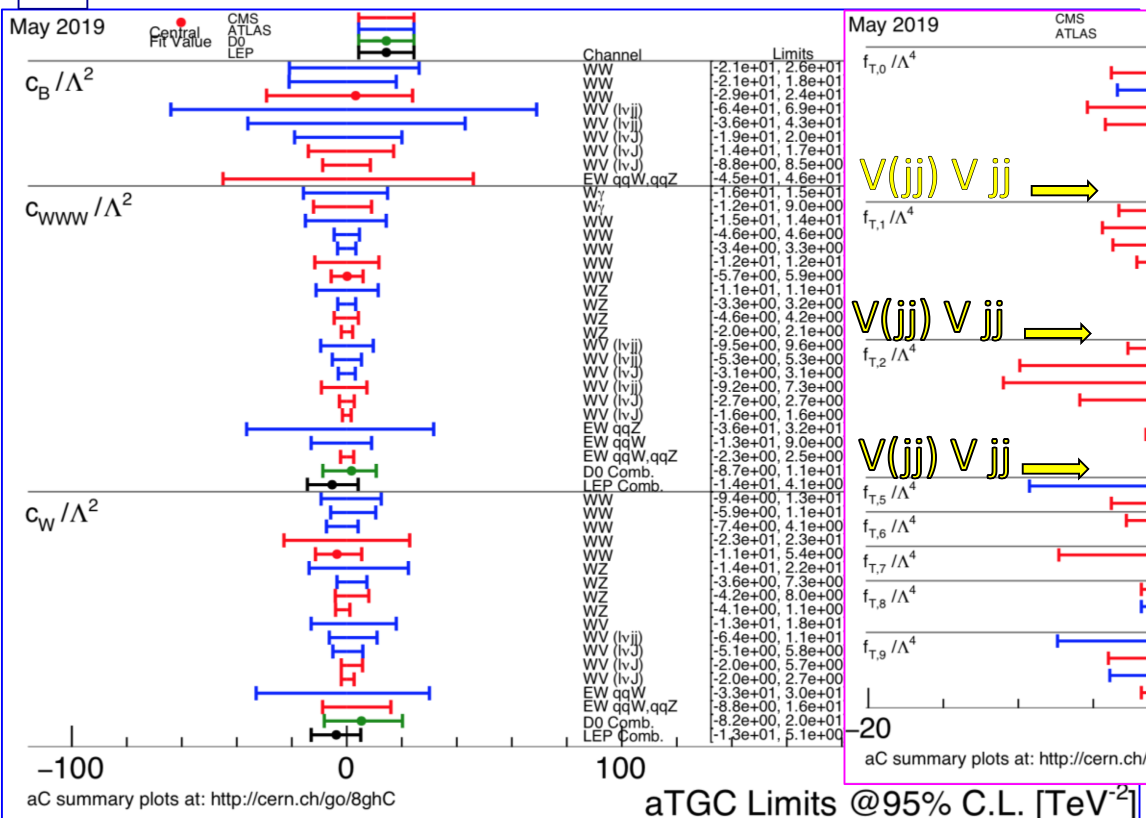
- New Physics added to the SM Lagrangian as higher dimensional operators:

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

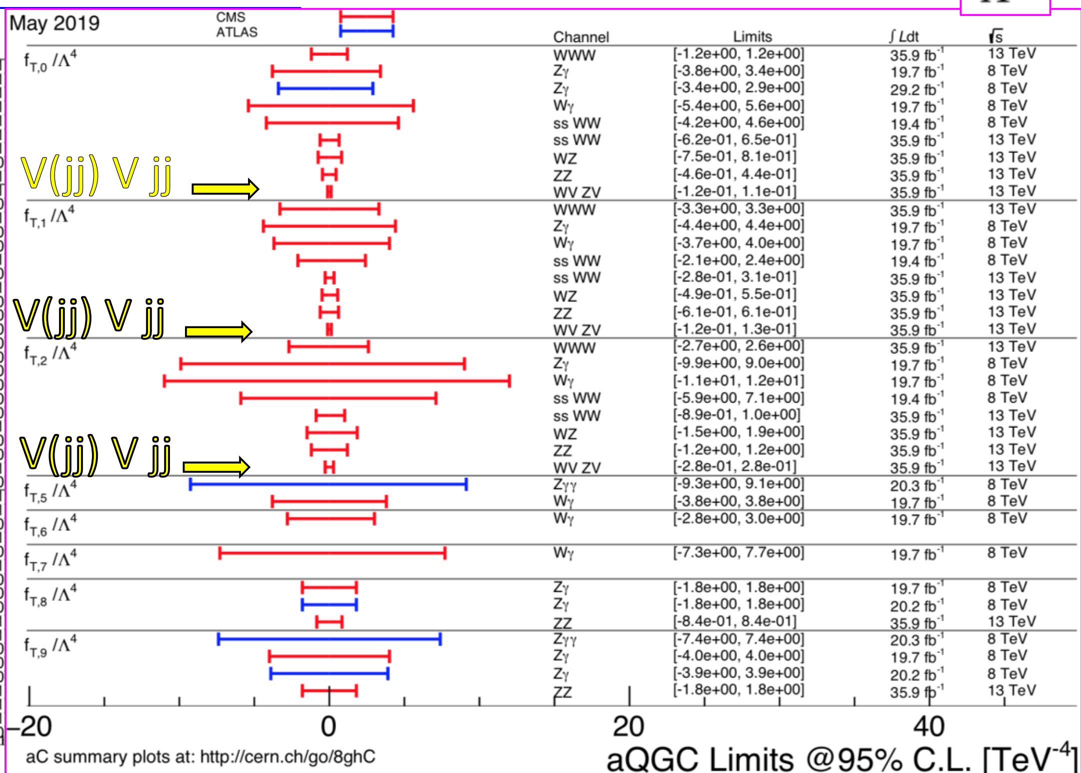
Dimension-6 operators
Give rise to charged aTGC & aQGC

Dimension-8 operators:
Give rise to aQGC

$\boxed{\frac{c_i}{\Lambda^2}}$



$\boxed{\frac{f_{T,j}}{\Lambda^4}}$



Conclusions

- LHC Run2 very successful → Large data sets available
- Improved performance
  - \+ Many important SM measurements with significantly increased precision
  - \+ Exploration of differential distributions in high p_T jet, photon, W, Z, top final state
  - \+ Many rare processes observed
- Major advances in techniques for theoretical calculations

  → stringent test of SM
- EFT: starting to be able to fit Wilson coefficients in multiple sectors simultaneously

  Rich interplay between EW precision + Higgs + top + diboson fits.
- **→ EW & EFT fits: important tools to search for BSM**

  Need theory guidance for the interpretation of experimental results

- **Solid basis for the future of the our discipline (colliders & beyond colliders)**

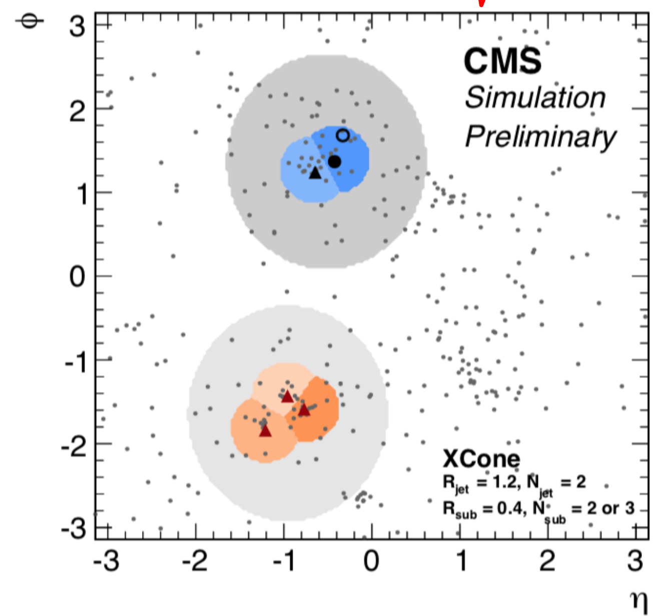
THANKS TO ALL MY ATLAS, CMS, LHCb, HERA & TEVATRON COLLEAGUES WHO PROVIDED ME WITH MATERIAL, COMMENTS & ANSWERS TO MY QUESTIONS

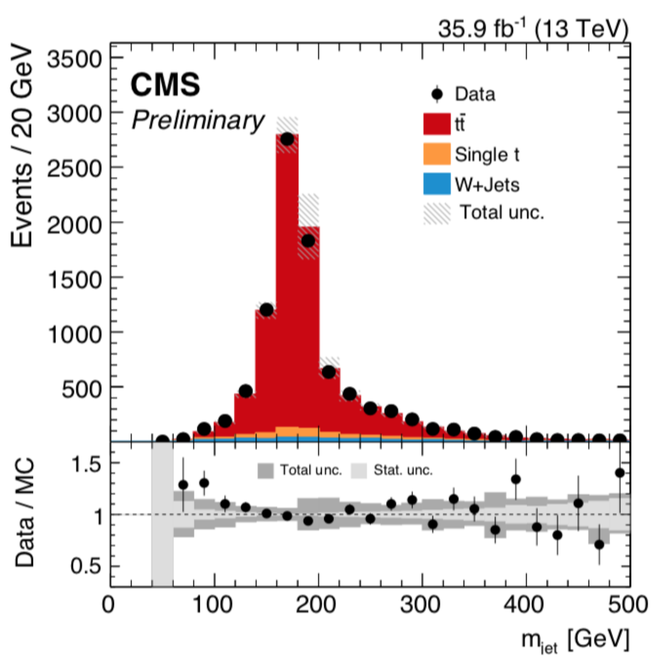
Additional recent results

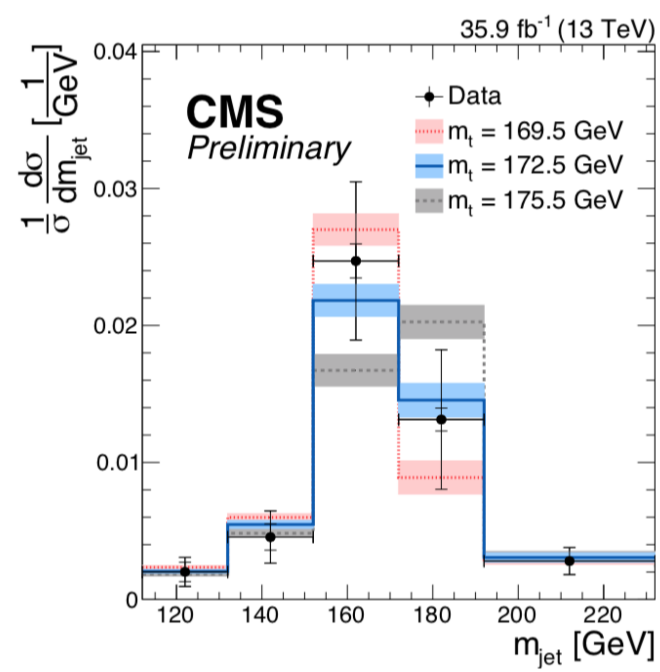
Slide from Maria, Florencia, Nadjieh (CMS): Top mass from boosted top

new

- differential $t\bar{t}$ cross section as function of m_{jet}
- boosted regime ($p_T > 400$ GeV)
- novel reconstruction using XCone
- $m_t = 172.56 \pm 2.47$ GeV



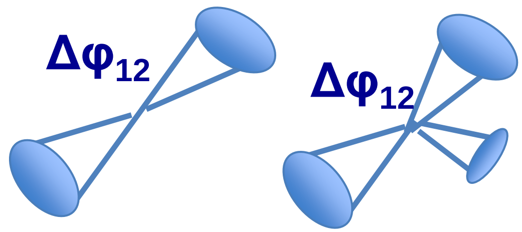


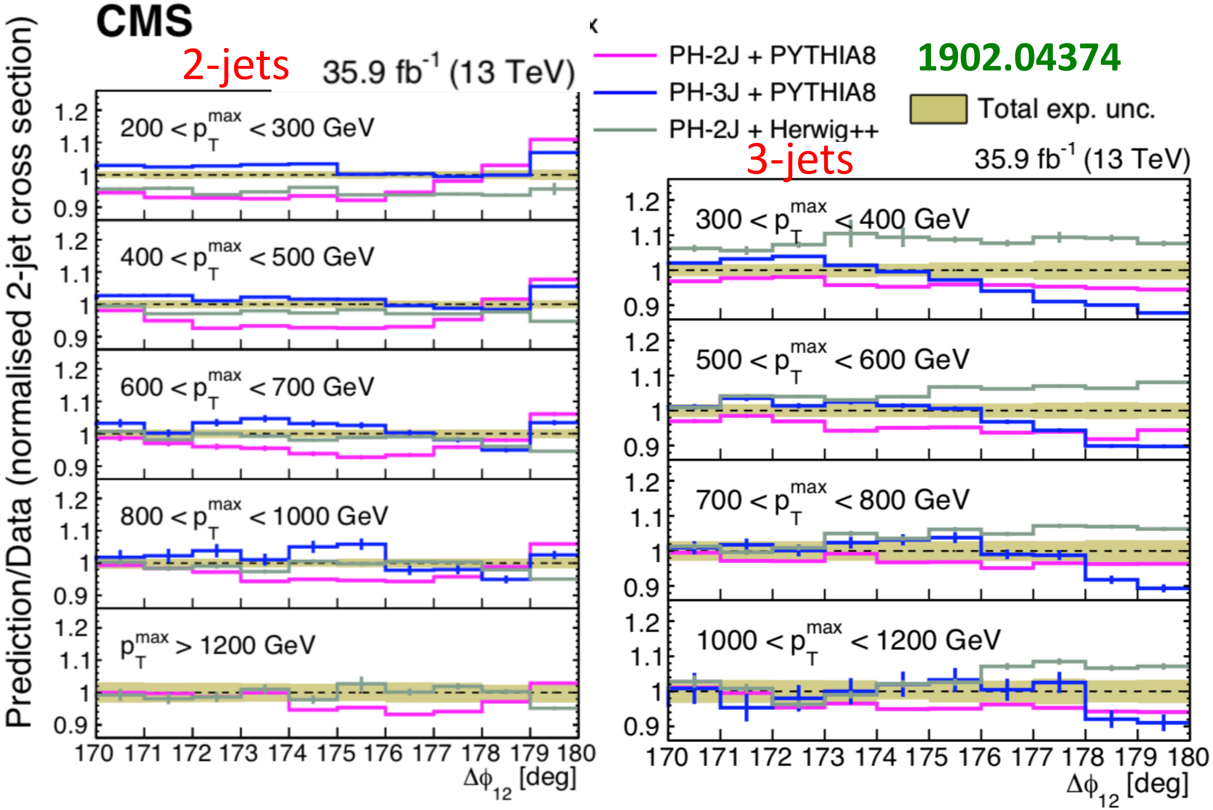


Jets & azimuthal decorrelations

- **Azimuthal decorrelations ($\Delta\varphi_{12}$): sensitive to higher orders, parton showering and resummation**
- pQCD fixed-order calculations unstable for $\Delta\varphi_{12} \approx \pi$,
  → resummation of soft parton emissions
  approximated with parton shower evolution
- Normalized differential cross section vs $\Delta\varphi_{12}$
  in 2 (and 3 jets) events in nearly back-to-back jet topologies in bins of leading jet p_T

$\Delta\varphi_1$ = azimuthal angular separatio
between the leading jets



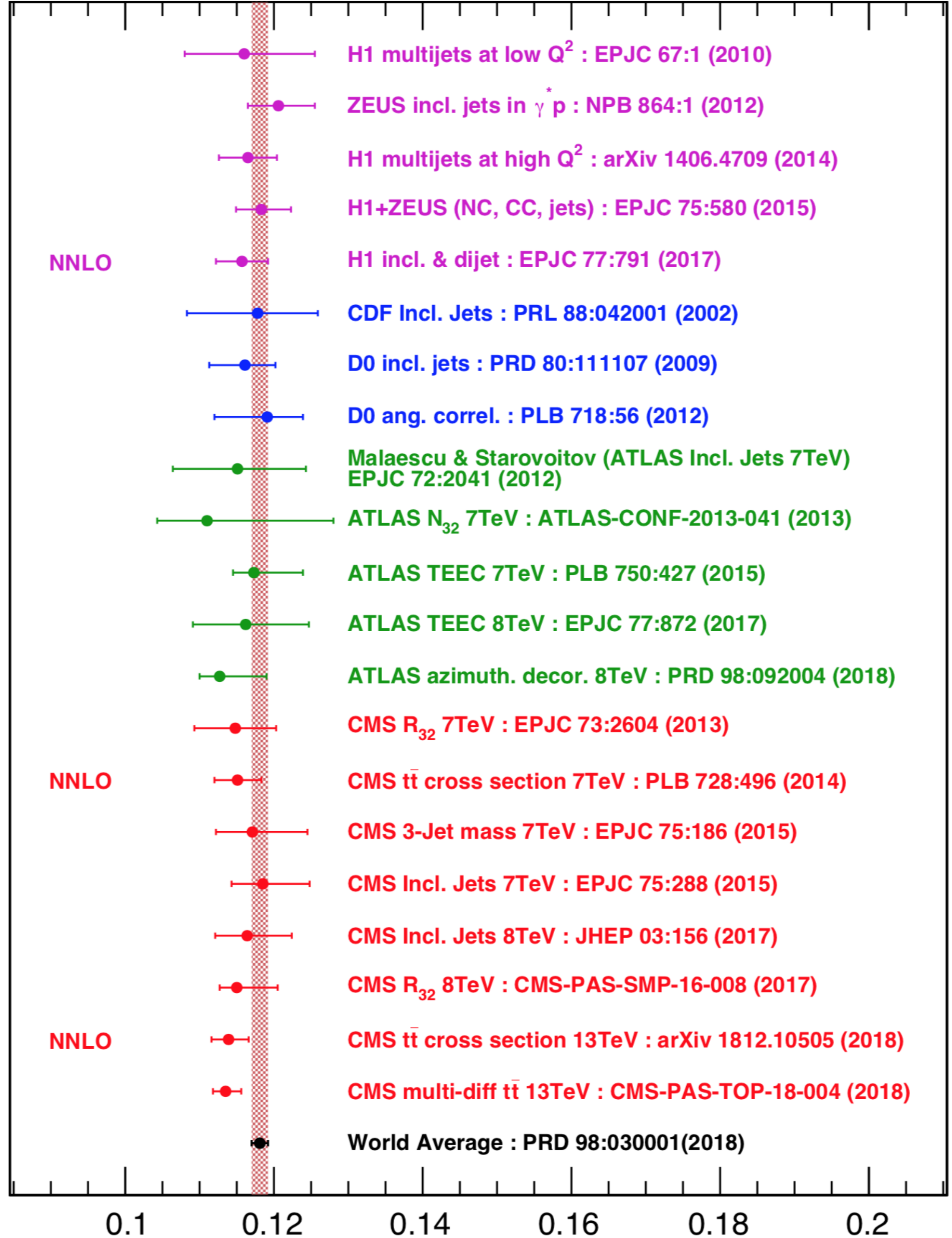


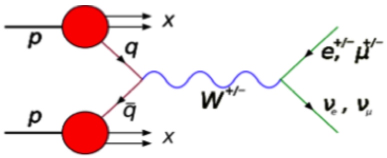
1902.04374

PH-2J PowHeg 2→2 NLO

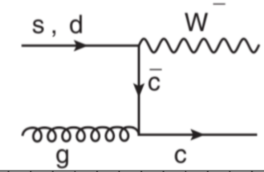
PH-3J Powheg 2→3 NLO

- Need **to improve the modelling of the accompanying soft parton radiation** because no model describes simultaneously the 2- and 3-jet measuremen (differences up to 15%)

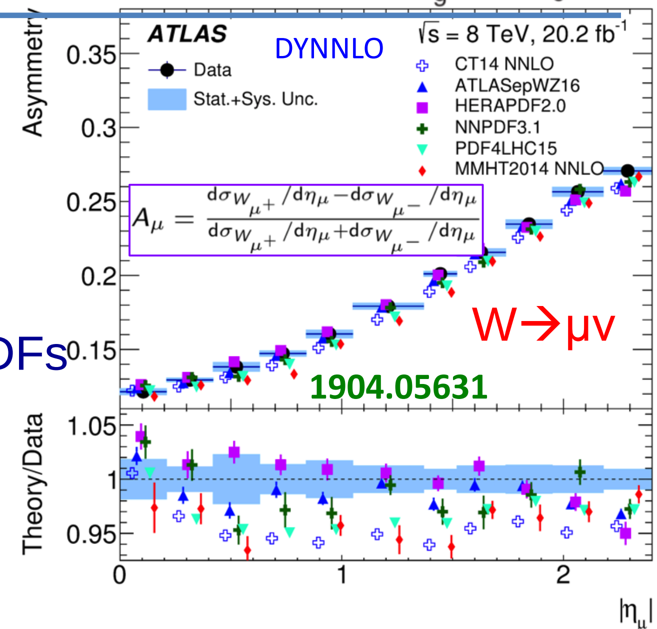

H1 multijets at low Q2 : EPJC 67:1 (2010)
ZEUS incl. jets in γ*p : NPB 864:1 (2012)
H1 multijets at high Q2 : arXiv 1406.4709 (2014)
H1+ZEUS (NC, CC, jets) : EPJC 75:580 (2015)
NNLO
H1 incl. & dijet : EPJC 77:791 (2017)
CDF Incl. Jets : PRL 88:042001 (2002)
D0 incl. jets : PRD 80:111107 (2009)
D0 ang. correl. : PLB 718:56 (2012)
Malaescu & Starovoitov (ATLAS Incl. Jets 7TeV)
EPJC 72:2041 (2012)
ATLAS N32 7TeV : ATLAS-CONF-2013-041 (2013)
ATLAS TEEC 7TeV : PLB 750:427 (2015)
ATLAS TEEC 8TeV : EPJC 77:872 (2017)
ATLAS azimuth. decor. 8TeV : PRD 98:092004 (2018)
CMS R32 7TeV : EPJC 73:2604 (2013)
NNLO
CMS tt̄ cross section 7TeV : PLB 728:496 (2014)
CMS 3-Jet mass 7TeV : EPJC 75:186 (2015)
CMS Incl. Jets 7TeV : EPJC 75:288 (2015)
CMS Incl. Jets 8TeV : JHEP 03:156 (2017)
CMS R32 8TeV : CMS-PAS-SMP-16-008 (2017)
NNLO
CMS tt̄ cross section 13TeV : arXiv 1812.10505 (2018)
CMS multi-diff tt̄ 13TeV : CMS-PAS-TOP-18-004 (2018)
World Average : PRD 98:030001(2018)
0.1
0.12
0.14
0.16
0.18
0.2

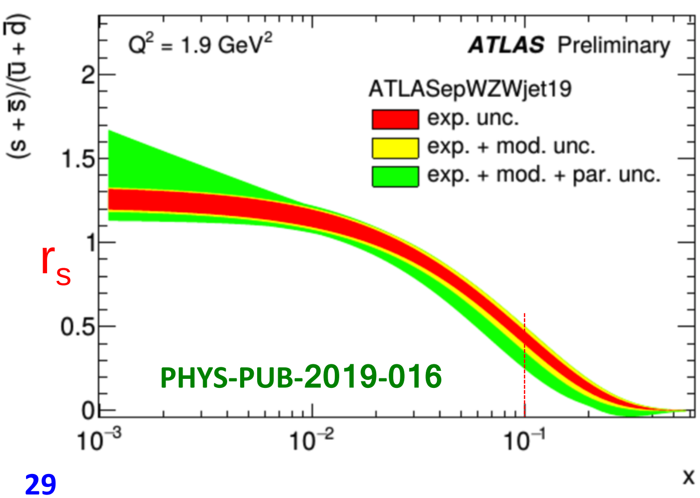


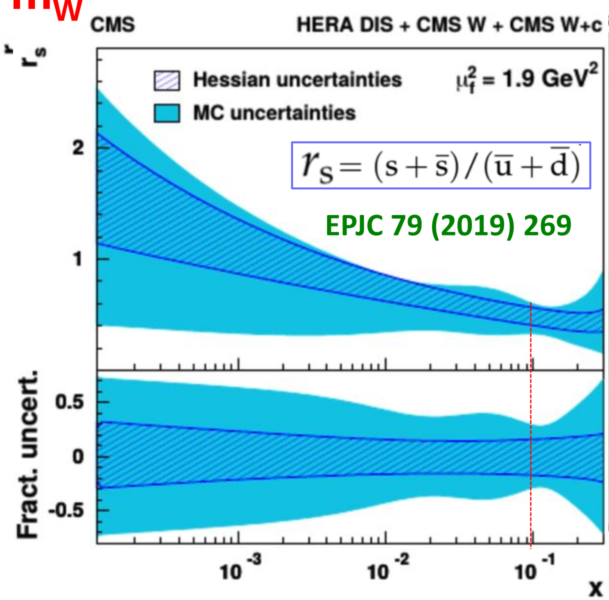
Single gauge boson production: W

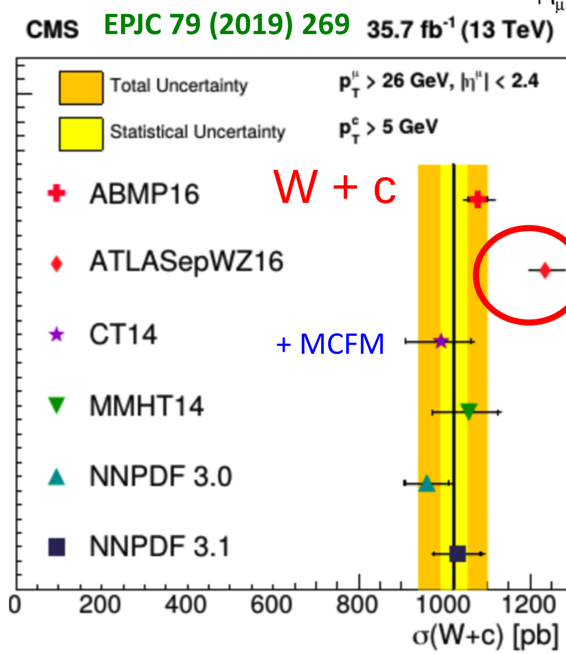


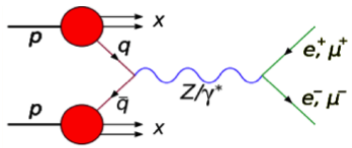
- **Large data sets and accurate predictions**
  → stringent SM measurements
- Recent results:
  - W charge asymmetry (ATLAS) vs $|\eta_\mu|$ discriminates among PDFs (asymm. uncertainty ~ 0.002 - 0.003)
  - W+c-jet (CMS) use D*: tension with *ATLASepWZ16* PDFs where strange-quark is unsuppressed @ at low x
- New PDF set: *ATLASepWZWjet19* include W+jet data r_s reduced @ high x but still enhanced at low x
- **To be followed: understanding the strange quark in proton important for the m_W measurement @ LHC**







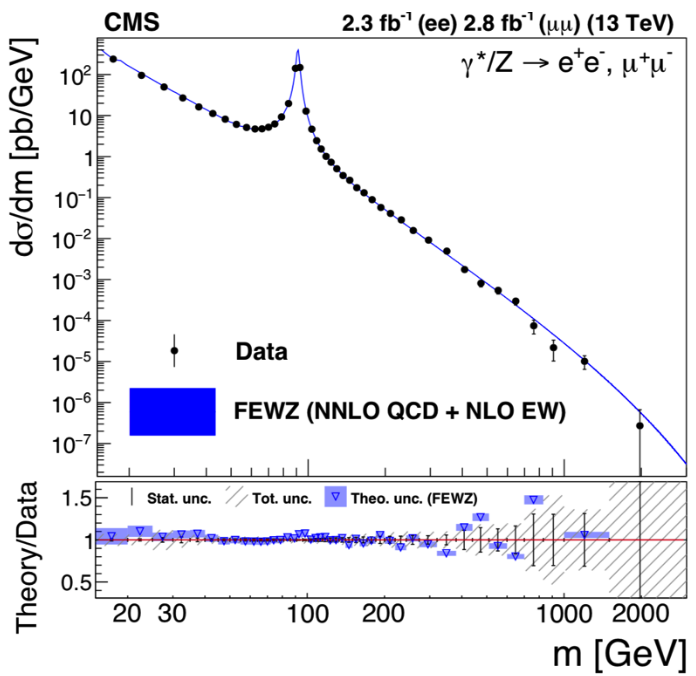


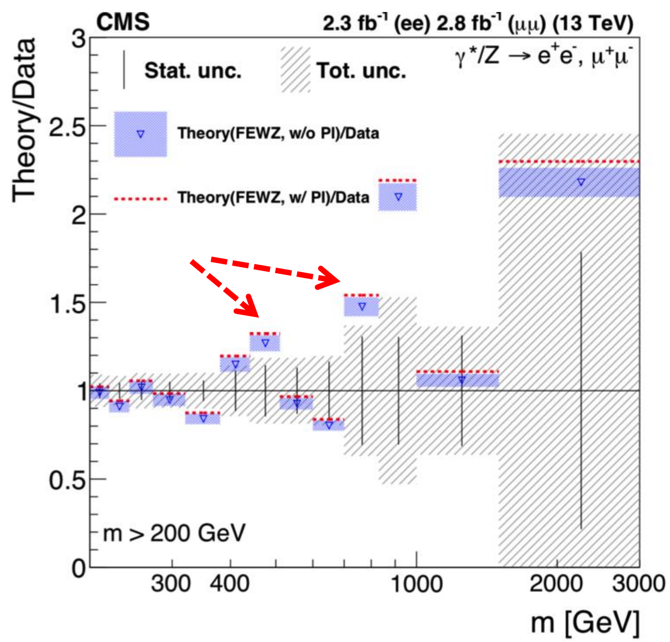


Single gauge boson production&decay: $Z/\gamma^* \rightarrow ll$

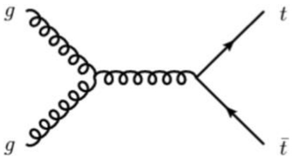
- **$d\sigma/dm_{ll}$ for 15 < m_{ll} < 3000 GeV (@ 13 TeV)** in full phase space, corrected for FSR
- Agreement with SM theoretical predictions (large stat. uncertainties at the highest mas

1812.10529

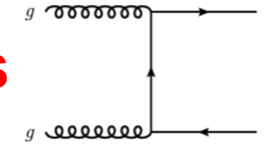




- **Sizable effect from Photon-Induced (PI) contribution** in the high- mass region (comparison with LUXqed PDF set)



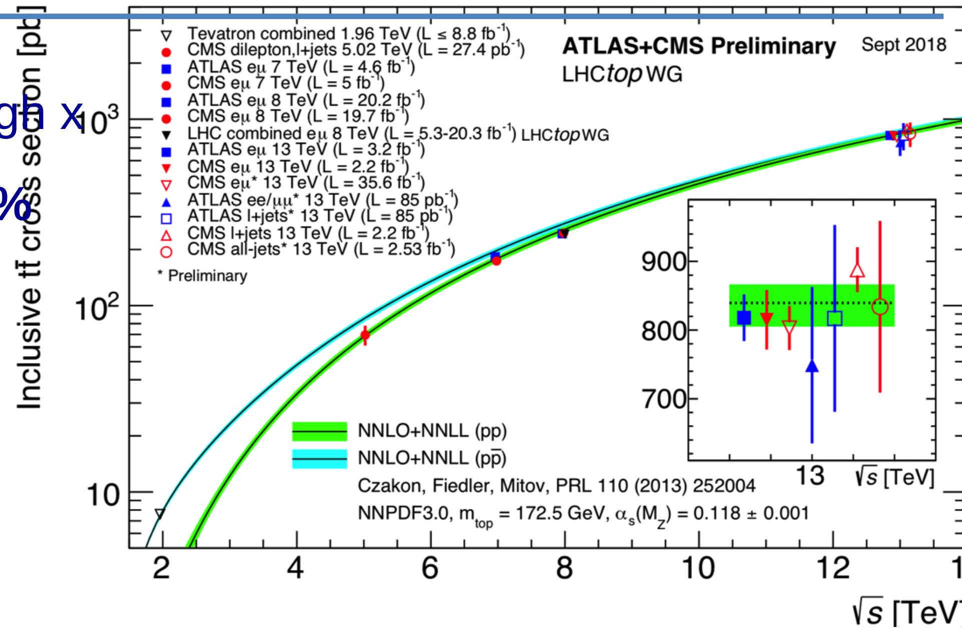
Top ($t\bar{t}$) cross section measurements



- **σ_{tt} provides information on:**

□ - Top mass, $\alpha_{s,}$ □ gluon PDF at high x

- **Most precise σ_{tt} measurements: ~ 4%** limited by luminosity & experimental systematics. Agreement with full NNLO+NNLL calculations

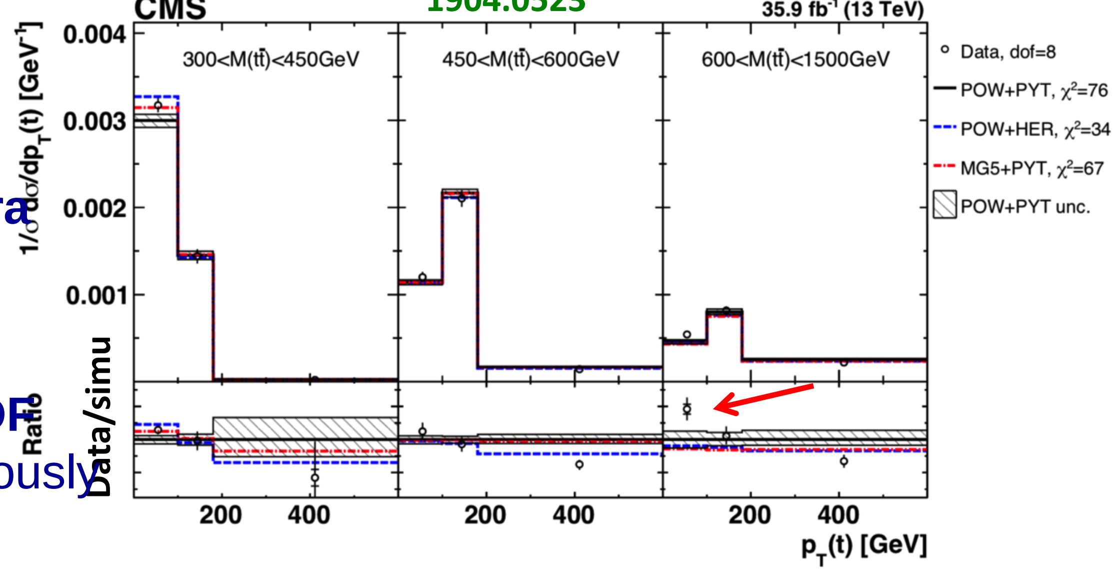


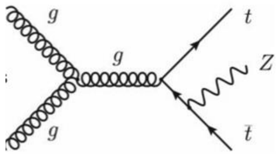
- **σ_{tt} (ee, eμ, μμ) multi-differential cross section :** normalised single, double & triple differential cross sections. Many variables unfolded to parton and particle level (p_T^t, y_T^t, $M_{tt,} p_T^{tt}$, ...)

- **MCs have harder top p_T spectra wrt data**, effect increases with higher **m($\bar{t}$t)** values

- **Significant impact on gluon PDF** at large x, when fitting simultaneously α_s , m_t^{pole}, and PDFs

1904.0523





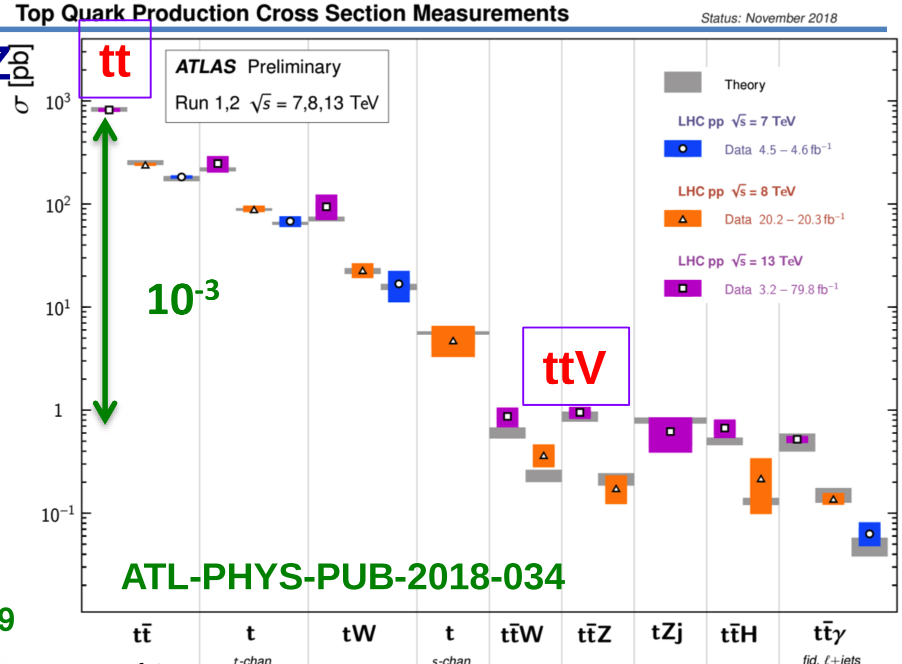
Associate production: $t\bar{t}$ + Z

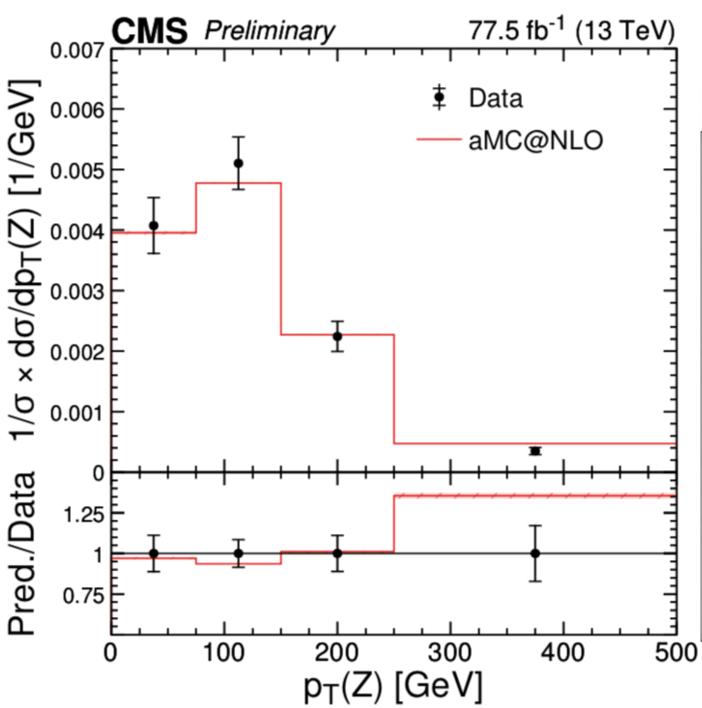
- **Rare process probing top coupling to Z**
- **Sensitive to BSM physics** (VLQ, 4/3 charged top, …)
- ttV, V= W, Z, observed already @ 8 TeV by ATLAS & CMS

@ 13 TeV:

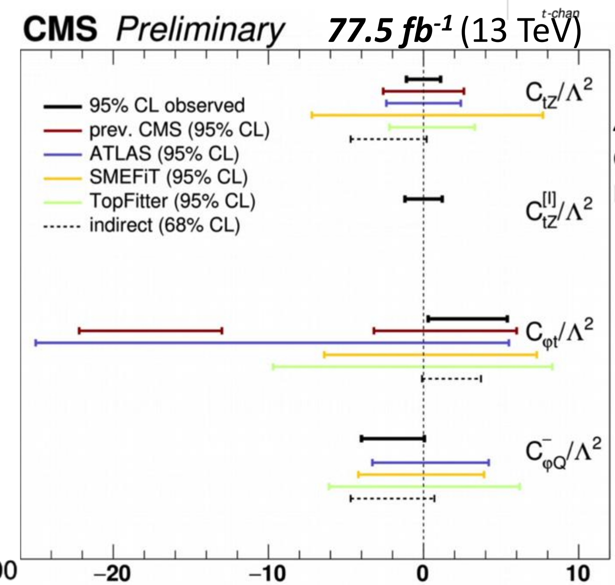
$$\sigma_{ttZ} = 1.00\,^{+0.06}_{-0.05}\,(\text{stat})\,^{+0.07}_{-0.06}\,(\text{syst})\text{ pb}$$

consistent with SM

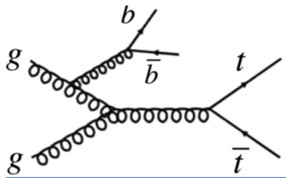




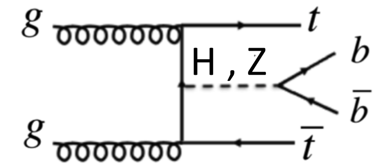
CMS-PAS-TOP-18-009



- **ttZ inclusive & differential cross sections:** 1-& 2-d fits to extract limits on coefficients of dimension-6 operators in an Effective Field Theory



Top ($t\bar{t}$) + heavy flavours



- **Background to $t\bar{t}H(b\bar{b})$ & $t\bar{t}t\bar{t}$**
- **Challenges:** multiple scale and many processes contribute
- **ATLAS: dilepton and lepton+jets**
  CMS: dilepton and all-jet
- **Measure integrated and (ATLAS) differential cross sections**
- **Dilepton and lepton+jets :**
  - cross sections higher than predicted still compatible within uncertainties
  - fair agreement for the shapes for m of the predictions
- **Tensions between all-jet cross section measurements and predictions**

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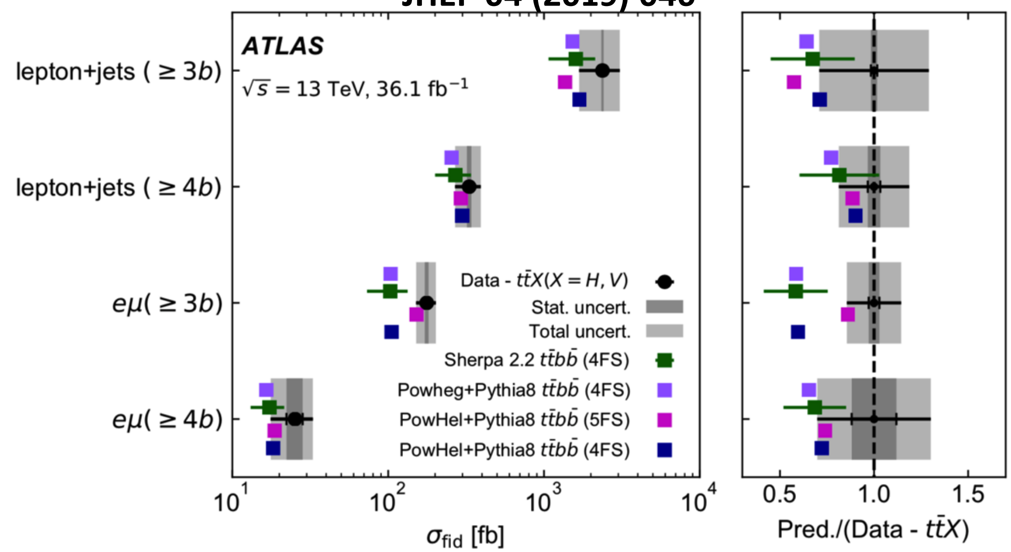
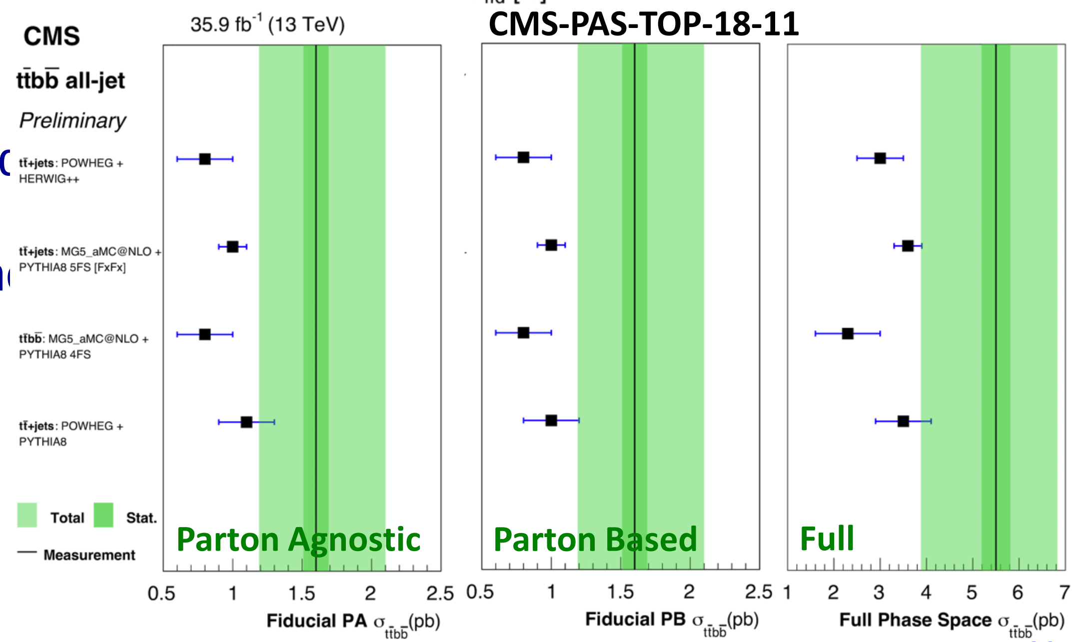
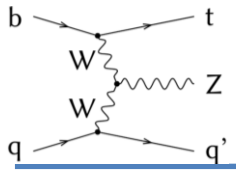
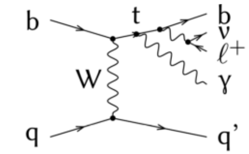


CMS-PAS-TOP-18-11

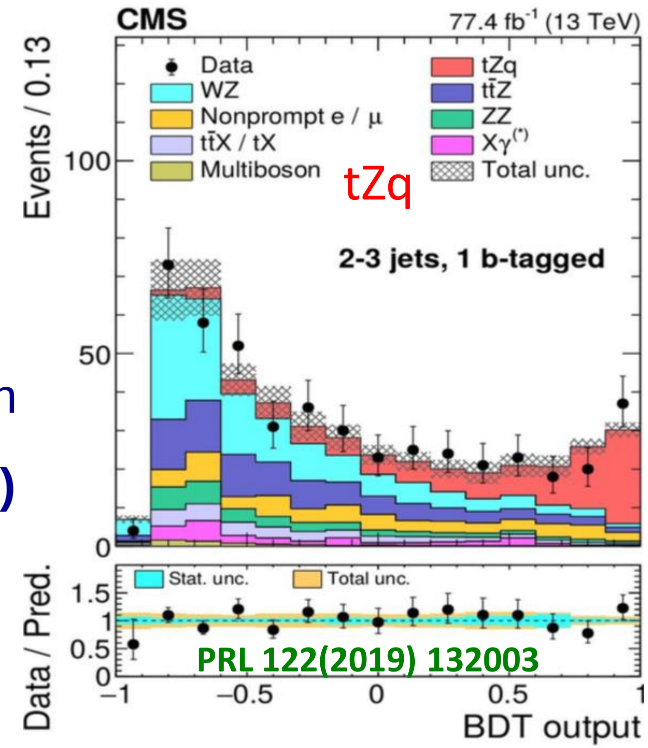




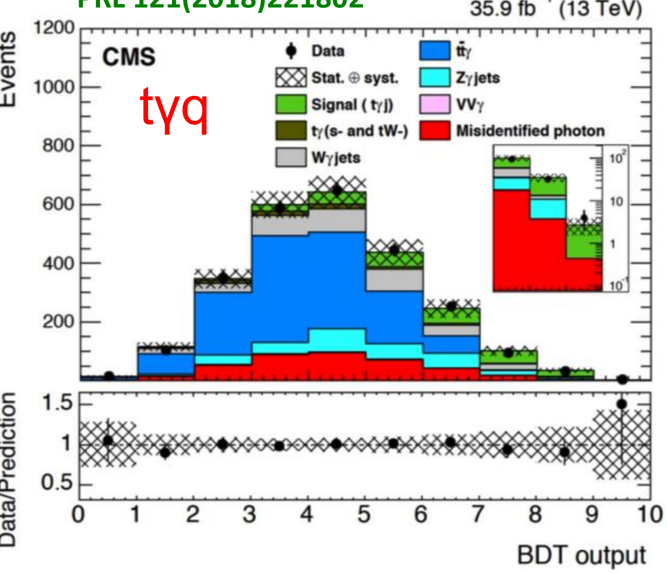
Rare processes with one top: tZq, tγq



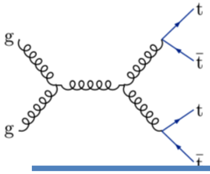
- **Sensitive to BSM effects**
  - **tZq & tγq** include TGC diagrams (WWZ & WW**γ**)
  - modified production could indicate FCNC
  - **tγq** sensitive to the top quark charge
- **pp → tZq** . Best signal region: 3 leptons, 2-3 jet (1b)
  Main bkg: diboson
  BDT (CMS), NN (ATLAS) trained in each signal region
- **ATLAS 36 fb^{-1}: first evidence : 4.2 (5.4) σ obs (expt)**
- **CMS 77.4 fb^{-1}: observation > 5 σ obs.**



PRL 121(2018)221802

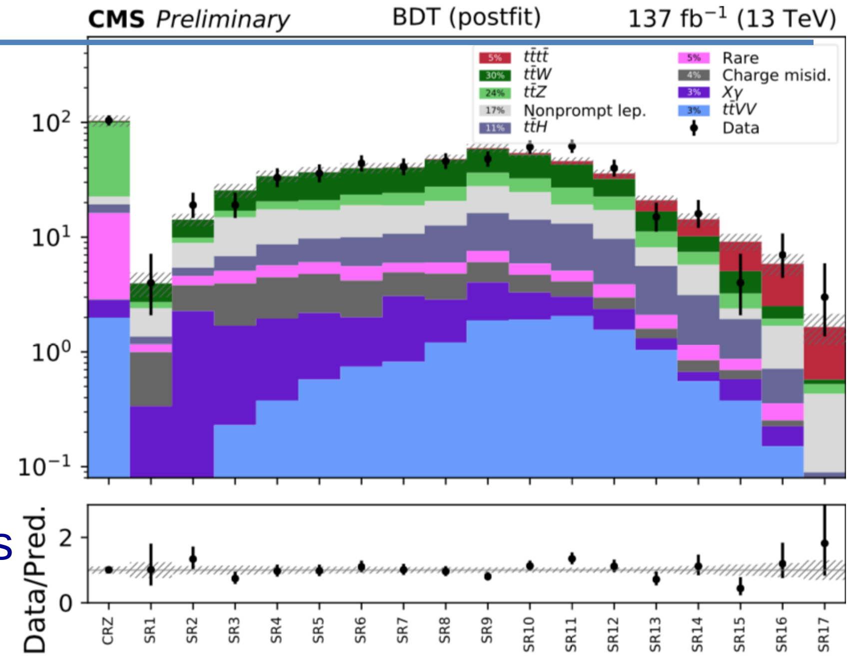


- **pp → tγq : first evidence for (4.4 σ obs., CMS)**
  Template fit to BDT distributions
- σ(pp → tγq) × B(t → μνb) = 115 ± 17(stat) ± 30(syst) f
- SM value: 81 ± 4 fb

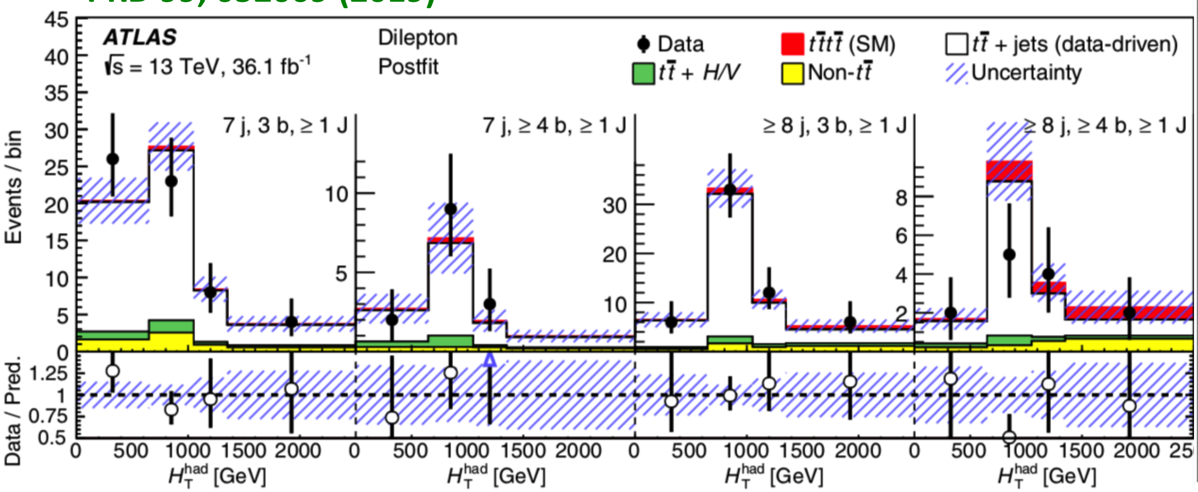


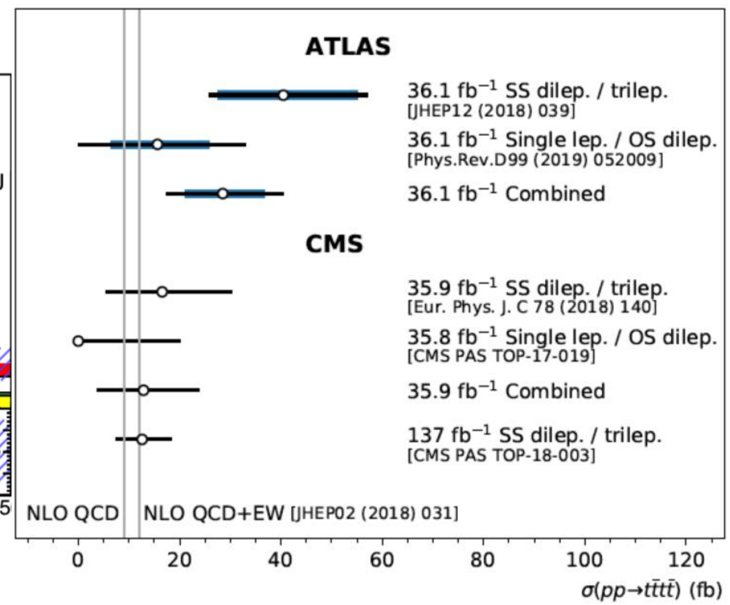
Rare processes: tttt (4 tops)

- σ^{NLO}_{tttt}(SM) = 9.2 fb (30% scale uncertainties)
- **Sensitive to Beyond SM effects**
  Way to asses the top Yukawa coupling
- **ATLAS 36 fb^{-1} :**
  Template fit to $H^{had} = \sum p_T^j$ in bins of b-jet multiplicity **2.8 (1.0) σ obs(exp.) significance**
- **CMS** 137 fb^{-1}: 2.6 (2.7) **σ**,
  BDT and cut base approach. Fit many regions
  2.6 (2.7) σ obs(exp.) significance
  $|y_t/y^{SM}_t|<1.7$



PRD 99, 052009 (2019)

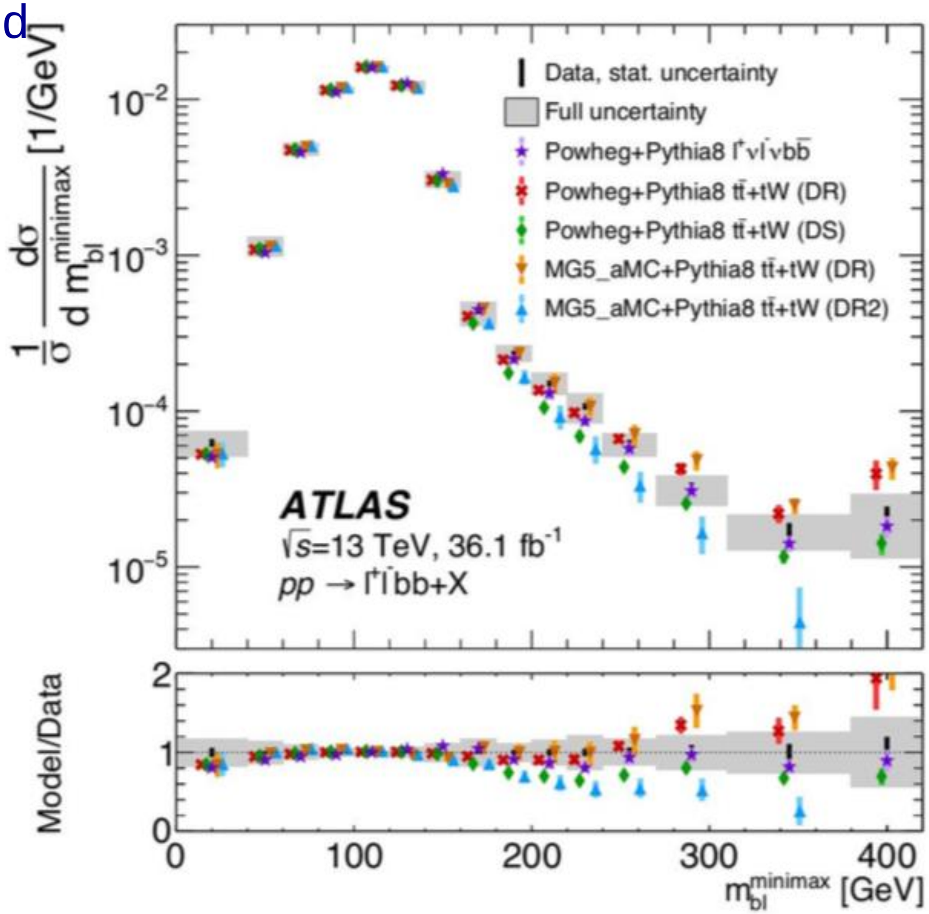




Quantum Interference Between Single and Doubly Resonant Top Quark

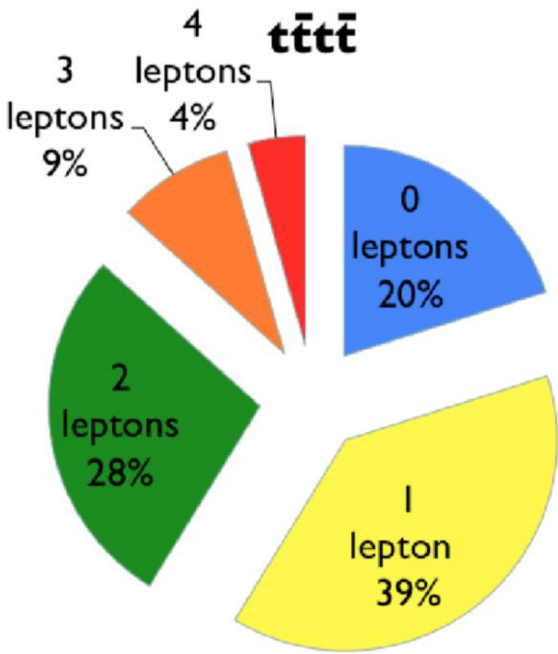
Phys. Rev. Lett. 121, 152002 (2018)

Identical *WWbb* final states,

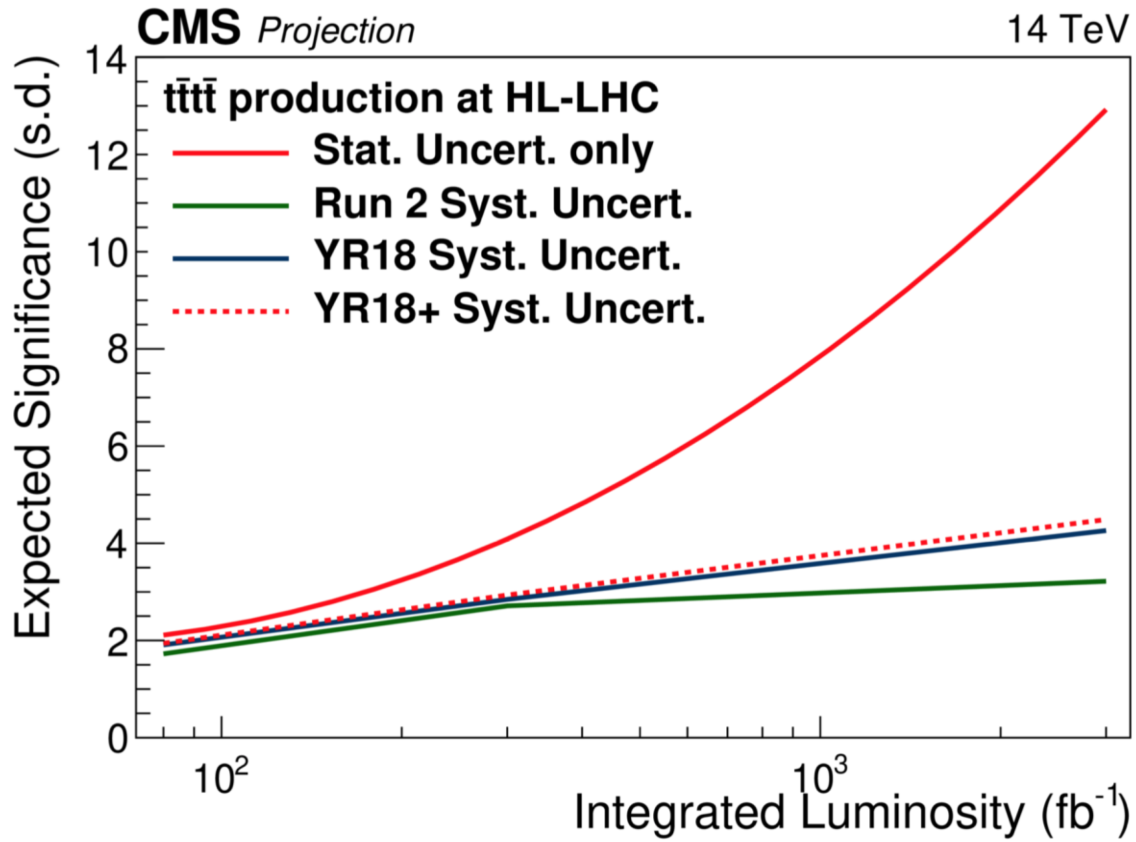


tt-tW interference

Good description by predictions including recent fixed-order calculations of the full next-to-leading-order (NLO) pp → l+νl−ν̄bb̄ process



$t\bar{t}t\bar{t}$
4 leptons 4%
3 leptons 9%
0 leptons 20%
2 leptons 28%
1 lepton 39%



CMS Projection
14 TeV
$t\bar{t}t\bar{t}$ production at HL-LHC
Stat. Uncert. only
Run 2 Syst. Uncert.
YR18 Syst. Uncert.
YR18+ Syst. Uncert.
Expected Significance (s.d.)
Integrated Luminosity (fb^{-1})

Top properties

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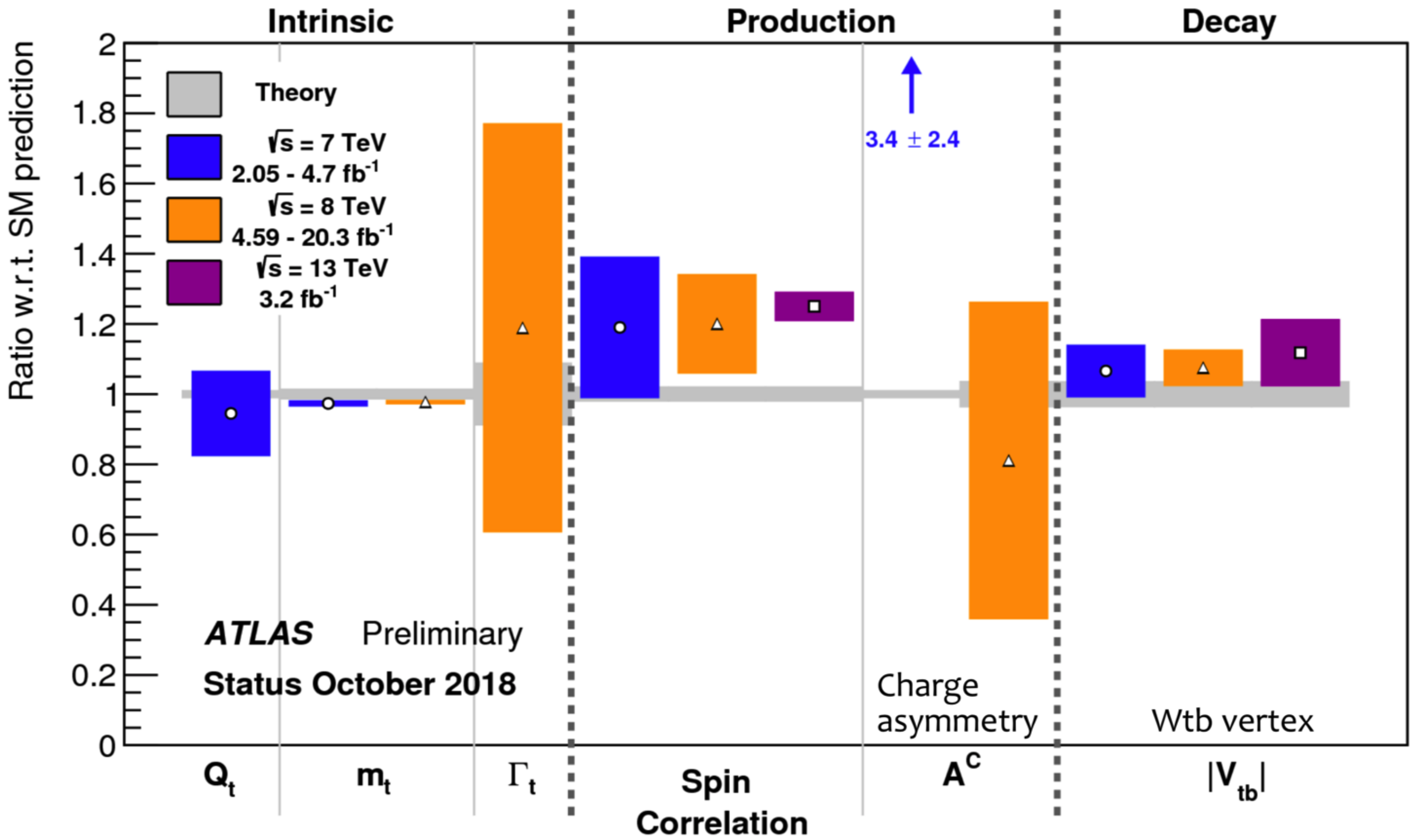
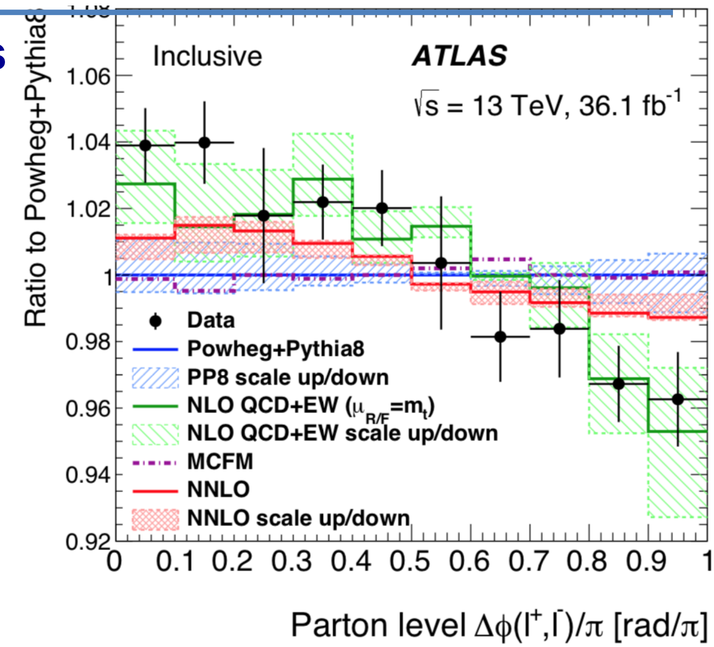


Top properties: polarisation, spin correlations

1903.07570

- **t and $\bar{t}$ produced non polarised (QCD conserves C and P) with t and $\bar{t}$ spins correlated.**

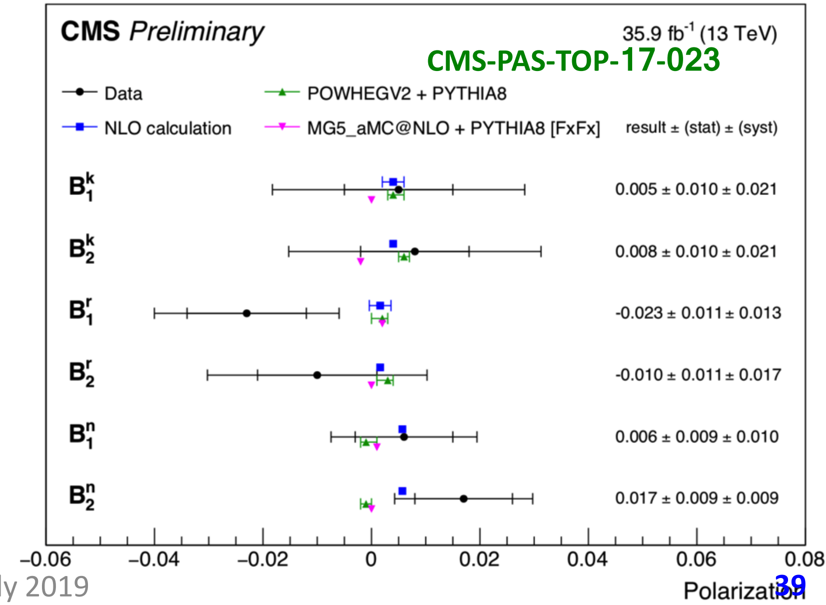
→ Test of BSM effects via EFT, (ChroMagnetic Dipole Moment ..)



- Top decays before hadronisation
  → Spin information preserved in the decay products

use $\boldsymbol{\Delta\varphi_{ll}}$ (&$\Delta\eta_{ll}$) between leptons in $\bar{t}$t (dilepton)

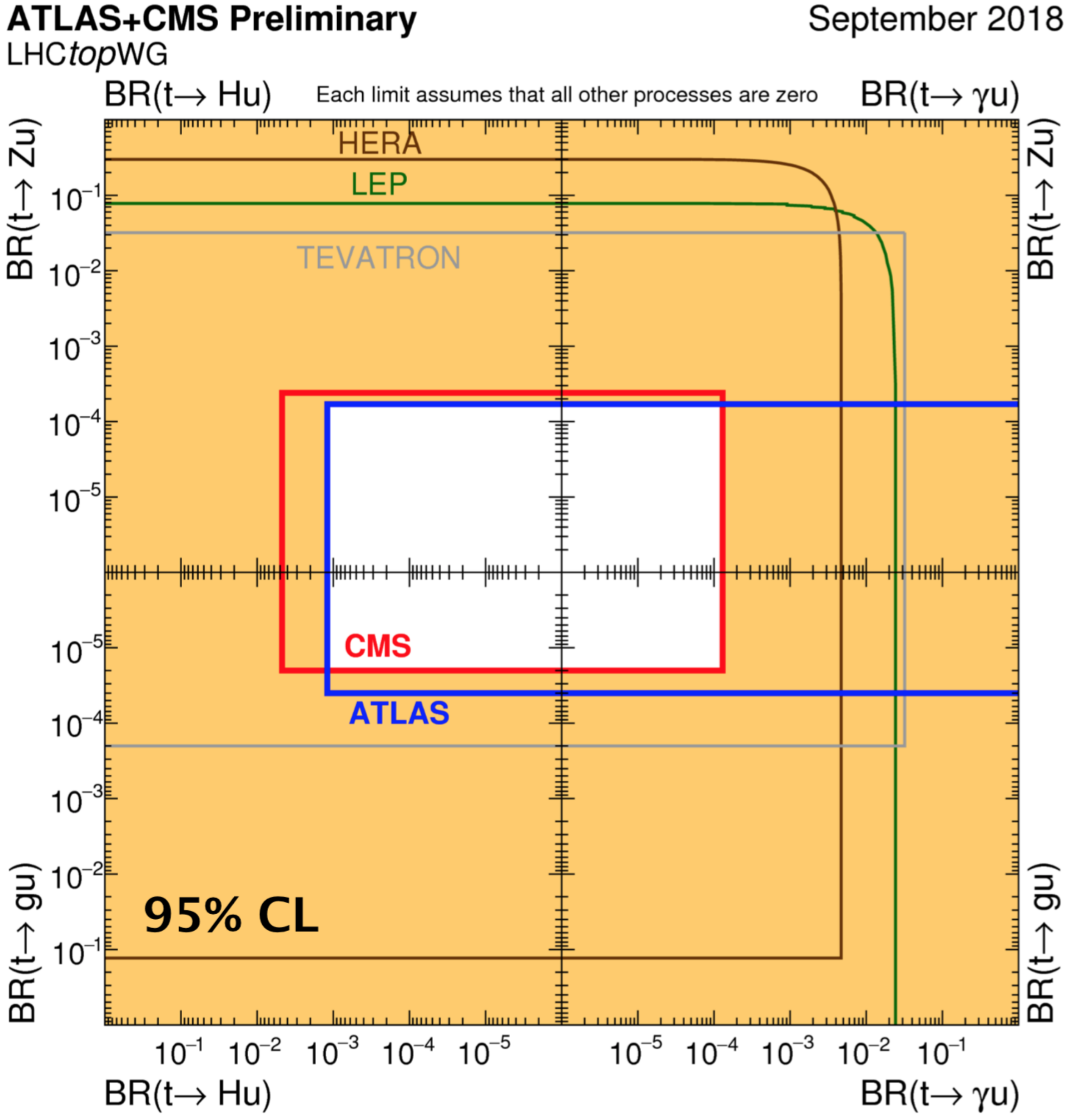
- A more direct study extracts 15 coefficients characterising spin dependence of $\bar{t}$t production. Large uncertainties still.

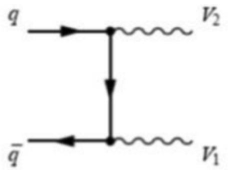


- **$\Delta\varphi_{ll}$ tension between NLO & data likely explained by missing higher order**

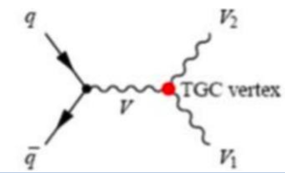
- **Polarisation, CMDM, in agreement with SM within uncertainties**

Slide from Christian Schwanenberger





Multi gauge boson production



- **VV / Vγ / γγ / VVV (V=W, Z)**
  - Investigate the non-abelian structure of the SM at the highest energy
  - Sensitive to new physics via **a**nomalous **T**riple (**Q**uartic) **G**auge **C**ouplings (**aTGC, a**

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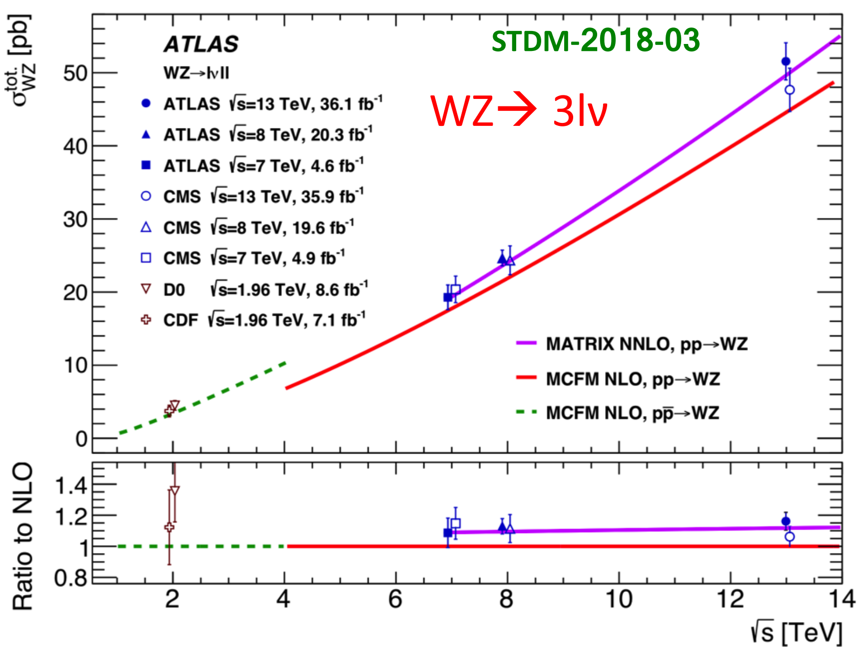
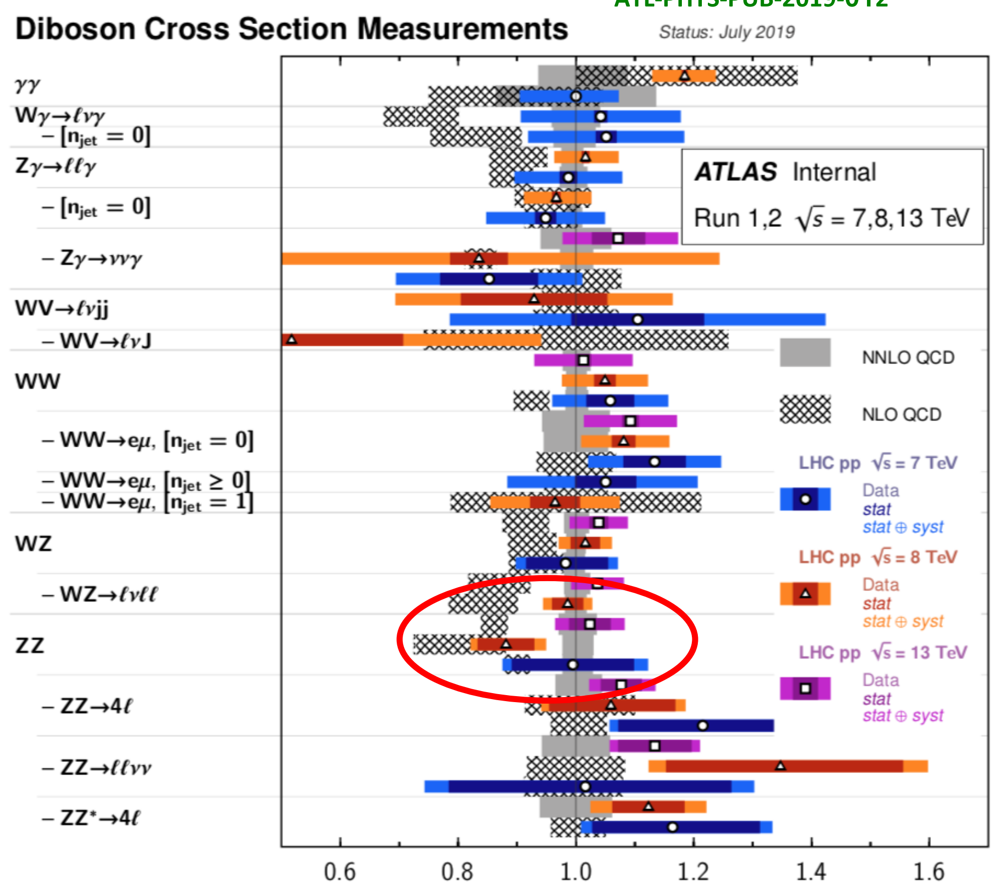
- **Dibosons:**
  - Many measurements
  - NNLO necessary to describe data





Ratio with respect to NNLO

- Larger samples allow for differential cross sections

VBS with semileptonic final states: V(jj) V(lν/l)+jj

- **Semi-leptonic final states complementary to fully-leptonic** :
  - The latter less background, good for observation (first VBS observation, 2017, in $W^{\pm}W^{\pm}jj \longrightarrow l^{\pm}l^{\pm}jj$, most favorable EW/QCD production ratio)
  - The former higher BR, probe higher energy tails where **aQCG** effects more promine

- **Latest results (VZjj & VWjj):** exploit boosted topology V→jj (V as large merged jet)

- **Recent ATLAS (1905.07714)** ~ 36 fb^{-1} @ 13 TeV: also resolved jets. 0/1/2 leptons
  - Use MVA including quark-gluon separation
  - **2.7 σ significance** (2.5 **σ** exp.)

- **Recent CMS (1905.07445):**
  - Main aim: search for aQGCs (& Higgs$^{\pm}$)
  - Fit to m_{WV} and m_{ZV} distributions
  - Uncertainties: QCD scale, PDF uncertainties, V+jets background shape
  - **Stringent constraints on parameters for dimension 8 operators**