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

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CMS

PUPPI: Pile-up per particle identification

\[ \frac{\text{Response corrected}}{\text{Uncertainty}} \]

\[ \alpha (u) \text{(GeV)} \]

\[ \sigma (u) \text{(GeV)} \]

\[ \text{Data/MC} \]

\[ N_{\text{vtx}} \]

\[ \text{N}_{\text{vtx}} \]

\[ \text{Recoil resolution} \]

\[ \text{~ 1\% uncertainty} \]

1905.05171

Ratios Z/W+

1907.05120

ATLAS Preliminary

16 = 13 TeV, 139 fb\(^{-1}\)

b-jet Calibration with \(t\bar{t}\) Events

MV2 \(c_{\beta} = 70 \%\) Single Cut OP

anti-\(k_t\), \(R=0.4\) EMPFlow Jets

\[ \text{Measured Scale Factor (total unc.)} \]

\[ \text{Smoothed Scale Factor (total unc.)} \]

N\(^3\)LL+NNLO

\[ \mu_F, \mu_G \text{ variations correlated} \]

\[ \mu_F, \mu_G \text{ variations uncorrelated} \]

SM measurements: outline

- Tests of QCD
  - \( V(V=W,Z) + \text{Jets, Photons} \)
  - \( p_T^V \)

- E.w. precision tests
  - \( m_W, \sin^2\theta_W, m_{\text{top}} \)

- Top couplings and more …
  - \( \text{ttZ, 4 tops, } A_c^{\text{top}}, \text{single top} \)

- Gauge boson couplings
  - \( VV, Vjj, VVjj \text{ & } VVV \)

Standard Model is (nearly) everything (so far)
→ quick overview of (10 !) & few recent results

LDC - HEP-EPS Ghent, 15 July 2019
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 + $Z(\text{ee})$ vs jet $|y|$ and $|p_T|$
- NNLO parton-level fixed-order predictions (corrected) improve agreement with data

- New CMS: $W + c$
  Access to the strange quark content in proton @ $Q \sim m_W$
- Potential to constrain the parton distribution functions

LDC - HEP-EPS Ghent, 15 July 2019
Probing QCD: cross section vs jet size

- 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

CMS Preliminary SMP-19-003 < 35.9 fb$^{-1}$ (13 TeV)

Anti-$k_T$ CHS
- $R = 0.2$
- $|y| < 0.5$

NLO

NLO(NLOJET++) + NP

LO+NP

SMP-19-003
Recent $\alpha_s$ measurements

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

  $\rightarrow$ Test scale evolution of $\alpha_s$ 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 $\alpha_s(m_Z)$:
  \[
  \alpha_s(m_Z) = 0.1150 \pm 0.0008 \text{ (exp)} + 0.0002 \text{ (model)}
  \pm 0.0006 \text{ (hadr)} \pm 0.0027 \text{ (scale)}
  \]

  $\rightarrow$ $\sim 30\%$ reduction of scale uncertainty wrt NLO analysis

- $\alpha_s(m_Z)$ fit triple differential $t\bar{t}$ cross section @ NLO (CMS, 1904.0523) including HERA DIS data
  for simultaneously $\alpha_s$, $m_t^{\text{pole}}$, and PDF extraction:
  \[
  \alpha_s(m_Z) = 0.1135 \pm 0.0016 \text{ (fit)} \pm 0.0002 \text{ (model)}
  \pm 0.0008 \text{ (PDF param)} \pm 0.0011 \text{ (scale)}
  \]

  $\rightarrow$ Value compatible with competitive uncertainty
Photon (+ jet) cross sections

- Test pQCD with a hard colorless probe + sensitivity to gluon density in the proton
- New ATLAS result: better $\gamma$ calibration & identification
  → reduced experimental systematic uncertainty (by up to ~ 40%)
- Cross sections vs $E_T^\gamma$ & $|\eta^\gamma|$: 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
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 $\sigma$, 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 uncertainties

Key ingredient for a precise measurement of the $W^\pm$ mass @ pp colliders

$p_T > 32$ GeV

D0 note 6508-CONF

CMS-PAS-SMP-17-010

p_T^W

p_T(W) (GeV)

p_T^Z

p_T^Z

p_T^Z

p_T^Z

p_T [GeV]

Fraction of Events

Unfolded Data

ResBos+CTEQ6.6

ResBos+CT14HERA2NNLO

NLO

NNLO Z+j

NNLO

CMS Preliminary

35.9 fb$^{-1}$ (13 TeV)

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35.9 fb$^{-1}$ (13 TeV)
E.w. precision measurements
Probe BSM via electroweak precision tests: \( m_W, \sin^2\theta_W, m_{\text{top}} \)

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

- Comparing indirect to direct measurements
  - Tests SM internal consistency \( \rightarrow \) BSM probe
    - \( \Delta m_W \leq 8 \text{ MeV}, \) \( \Delta \sin^2\theta_W \leq 7 \times 10^{-5} \)
    - \( \Delta m_{\text{top}} \leq 1 \text{ GeV} \)

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

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

  \( \rightarrow \Delta m_W^{\text{PDF}} \sim 2 \text{ MeV} \) with LHeC
Probe BSM via electroweak precision tests \((m_W, \sin^2\theta_W, m_{\text{top}})\)

\[ \sin^2 \theta_{\text{eff}} = k_{\text{lep}} \sin^2 \theta_W (k_{\text{lep}} \text{ e.w. corrections}) \]

- **Tension between the most sensitive results**

Methods @ pp 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
  \(\Delta \sin^2 \theta_W \sim 5 \times 10^{-6}\)
Probe BSM via electroweak precision tests ($m_W, \sin^2 \theta_W$)

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

Direct measurements
- $m_t^{\text{pole}}$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$m_t^{\text{pole}}$ [GeV]</th>
<th>$\Delta m_t$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS</td>
<td>172.8 ± 3.4</td>
<td>-3.2</td>
</tr>
<tr>
<td>CMS</td>
<td>173.8 ± 1.7</td>
<td>-1.8</td>
</tr>
<tr>
<td>CMS</td>
<td>170.6 ± 2.7</td>
<td>-2.7</td>
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<tr>
<td>CMS</td>
<td>170.5 ± 0.8</td>
<td>-0.8</td>
</tr>
<tr>
<td>ATLAS</td>
<td>173.2 ± 1.6</td>
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</tr>
<tr>
<td>ATLAS</td>
<td>172.9 ± 2.5</td>
<td>-2.6</td>
</tr>
<tr>
<td>ATLAS</td>
<td>173.7 ± 2.3</td>
<td>-2.1</td>
</tr>
<tr>
<td>ATLAS</td>
<td>171.1 ± 1.2</td>
<td>-1.1</td>
</tr>
</tbody>
</table>

Indirect measurements
- Probe BSM via electroweak precision tests ($m_W, \sin^2 \theta_W$)

**From CMS (TOP-19-005):**
- $m_t$ @ high Lorentz boosts: a single jet includes all $t \rightarrow bW \rightarrow bq'q'$ products
- Promising observable could be calculated at particle level from theory
- $m_t^{\text{boost}} = 172.56 \pm 2.47$ GeV (36 fb$^{-1}$ @ 13 TeV)
Top measurements for couplings & BSM
Rare processes: $t\bar{t}t\bar{t}$ (4 tops)

- Not yet observed: $\sigma_{t\bar{t}t\bar{t}}^{NLO} (\text{SM}) \sim 12 \text{ fb}$
- Sensitive to BSM effects, way to assess the top Yukawa coupling
- CMS full Run 2 data (ss dileptons & $\geq 3$ l+jets): fit many signal and control regions
- Significance: $2.6 (2.7) \, \sigma_{\text{obs(exp.)}} \rightarrow \text{Challenging !}$

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

- Limits on (pseudo) scalar $A/H \rightarrow t\bar{t}$
Top properties in $\bar{t}t$: charge asymmetry, $A_C$

- In SM $A_C$ results from the interference of HO amplitudes in $qq$ and $qg$ initial states → $t$ prefers $q$ direction
  Small effect, enhanced @ high $tt$ mass ($m_{tt}$) and longitudinal $\bar{t}t$ boost ($\beta_{tt}$)
- 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
- Inclusive $A_C$ is four standard deviation from zero & in agreement with NNLO predictions + EW NLO
  → Limits on coeff. dim-6 EFT operators $C^-/\Lambda^2$

New ATLAS result for $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$
Single top cross section

- **Investigation of the Wtb vertex**

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

\[
\left| f_{LV} \right| V_{tb} = 1 \text{ within } \sim 4\%
\]

**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 anomalous Triple (Quartic) Gauge Couplings (aTGC, aQGC)

- Dibosons: many measurements, **NNLO necessary to describe data**

- CMS: $\sigma_{\text{tot}} (ZZ)$ with full Run 2 data. Uncertainties: stat ~ syst ~ lumi

- ATLAS measures the helicity fractions of $W^\pm$ and $Z$ in $WZ$ events in agreement with SM predictions. First step on the way to perform polarization measurements in VBS processes.
Multi gauge boson production

- **Di-boson $Z(\Pi)\gamma$:** new ATLAS full Run 2 data. Differential X-sections vs $E_T^\gamma$, $|\eta^\gamma|$, $p_T^{l\gamma}$, $m(l\gamma)$ ~ 5% experimental uncertainty in most of $E_T^\gamma$ bins.
  - NNLO describes $E_T^\gamma$ within uncertainties & improve data description

- **Tribosons:** rare process
  - Recent ATLAS result finds $4.1\sigma$ evidence (3.1 $\sigma$ 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

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LDC - HEP-EPS Ghent, 15 July 2019
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 $m_{jj}$ 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 control regions

- Observed:
  VBF: EW-Wjj and EW-Zjj (ATLAS&CMS)
  VBS: EW-ssWWjj (ATLAS&CMS)

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

- Agreement with SM predictions
  → limits on aTGC and aQGC

LDC - HEP-EPS Ghent, 15 July 2019
Observation of EWK-ZZjj & evidence EWK-Zγjj

- **ATLAS**: observation of EWK-ZZjj with full Run 2 data (4l and llνν)
- Fit to a multi-variable combination (BDT):
  - Significance $5.5 \ (4.3) \ σ_{\text{obs.}} \ (\text{exp.}) = 0.82 \pm 0.21 \ \text{fb}$
- **CMS**: Evidence of EWK-Zγjj $36 \ \text{fb}^{-1} @13 \ \text{TeV} \ (Z \rightarrow ll)$
- 2 D fit to $m_{jj} & Δη_{jj}$:
  - signal strength $= 0.64 \pm 0.21$
  - Significance $4.7 \ (5.5) \ σ_{\text{obs.}} \ (\text{exp.}) \ combined \ with \ 8 \ \text{TeV}$
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

May 2019

- **c_B/\Lambda^2**
- **c_{WWW}/\Lambda^2**
- **c_W/\Lambda^2**

May 2019

- **f_{T,j}/\Lambda^4**
- **f_{M,j}/\Lambda^4**
- **f_{S,j}/\Lambda^4**

V(jj) V jj

V(jj) V jj

V(jj) V jj

aTGC Limits @95% C.L. [TeV^2]
aQGC Limits @95% C.L. [TeV^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 states
  - 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
- differential $t\bar{t}$ cross section as function of $m_{\text{jet}}$
- boosted regime ($p_T > 400$ GeV)
- novel reconstruction using X Cone
- $m_t = 172.56 \pm 2.47$ GeV
Jets & azimuthal decorrelations

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

CMS

- 2-jets \(35.9 \text{ fb}^{-1} \) (13 TeV)
  - $200 < p_T^{\text{max}} < 300 \text{ GeV}$
  - $400 < p_T^{\text{max}} < 500 \text{ GeV}$
  - $600 < p_T^{\text{max}} < 700 \text{ GeV}$
  - $800 < p_T^{\text{max}} < 1000 \text{ GeV}$
  - $p_T^{\text{max}} > 1200 \text{ GeV}$

- 3-jets \(35.9 \text{ fb}^{-1} \) (13 TeV)
  - $300 < p_T^{\text{max}} < 400 \text{ GeV}$
  - $500 < p_T^{\text{max}} < 600 \text{ GeV}$
  - $700 < p_T^{\text{max}} < 800 \text{ GeV}$
  - $1000 < p_T^{\text{max}} < 1200 \text{ GeV}$

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

$\Delta \phi_{12}$ = azimuthal angular separation between the leading jets

PH-2J PowHeg 2\(\rightarrow\)2 NLO
PH-3J Powheg 2\(\rightarrow\)3 NLO

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H1 multijets at low $Q^2$ : EPJC 67:1 (2010)

ZEUS incl. jets in $\gamma p$ : NPB 864:1 (2012)

H1 multijets at high $Q^2$ : arXiv 1406.4709 (2014)

H1+ZEUS (NC, CC, jets) : EPJC 75:580 (2015)

H1 incl. & dijet : EPJC 77:791 (2017)


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 $N_{32}$ 7TeV : ATLAS-CONF-2013-041 (2013)


ATLAS TEEC 8TeV : EPJC 77:872 (2017)


CMS $R_{32}$ 7TeV : EPJC 73:2604 (2013)

CMS tt cross section 7TeV : PLB 728:496 (2014)

CMS 3-Jet mass 7TeV : EPJC 75:186 (2015)


CMS $R_{32}$ 8TeV : CMS-PAS-SMP-16-008 (2017)


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: $Z/\gamma^* \rightarrow \ell\ell$

- $d\sigma/dm_{\ell\ell}$ for $15 < m_{\ell\ell} < 3000$ GeV ( @ 13 TeV ) in full phase space, corrected for FSR

- Agreement with SM theoretical predictions (large stat. uncertainties at the highest masses)

- Sizable effect from Photon-Induced (PI) contribution in the high- mass region (comparison with LUXqed PDF set)
Top (\(\bar{t}t\)) cross section measurements

- \(\sigma_{tt}\) provides information on:
  - Top mass, \(\alpha_s\), gluon PDF at high x

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

- \(\sigma_{tt}\) (ee, e\(\mu\), \(\mu\)\(\mu\)) multi-differential cross section:
  - normalised single, double & triple differential cross sections. Many variables unfolded to parton and particle level (\(p_T^t, y_T^t, M_{tt}, p_T^{tt}, \ldots\))

- 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 \(\alpha_s\), \(m_t^{pole}\), and PDFs
Associate production: \( tt + Z \)

- 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:
\[
\sigma_{ttZ} = 1.00 \pm 0.06 \text{ (stat)} \pm 0.07 \text{ (syst)} \text{ pb}
\]
consistent with SM

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

ATL-PHYS-PUB-2018-034

CMS Preliminary 77.5 fb\(^{-1}\) (13 TeV)

CMS-PAS-TOP-18-009

LDC - HEP-EPS Ghent, 15 July 2019
Top ($\bar{t}t$) + heavy flavours

- **Background to $t\bar{t}H(b\bar{b})$ & $t\bar{t}t$**

- **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 most of the predictions

- **Tensions between all-jet cross section measurements and predictions**
Rare processes with one top: $tZq$, $tyq$

- **Sensitive to BSM effects**
  - $tZq$ & $tyq$ include TGC diagrams ($WWZ$ & $WWγ$)
  - modified production could indicate FCNC
  - $tyq$ 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.

- **$pp → tyq$**: first evidence for ($4.4$ $σ$ obs., CMS)
  Template fit to BDT distributions

- $σ(pp → tyq) \times B(t → μνb) = 115 \pm 17$(stat) $\pm 30$(syst) fb

- SM value: $81 \pm 4$ fb
Rare processes: $tttt$ (4 tops)

- **NLO**
  - $\sigma_{tttt}^{\text{NLO}} (\text{SM}) = 9.2 \text{ fb} (30\% \text{ scale uncertainties})$

- **Sensitive to Beyond SM effects**
  - Way to assess the top Yukawa coupling

- **ATLAS 36 fb$^{-1}$**
  - Template fit to $H^\text{had} = \sum p_T^j$ in bins of b-jet multiplicity $2.8 \ (1.0) \ \sigma_{\text{obs(exp.)}}$ significance

- **CMS 137 fb$^{-1}$**
  - $2.6 \ (2.7) \ \sigma$, BDT and cut base approach. Fit many regions $2.6 \ (2.7) \ \sigma_{\text{obs(exp.)}}$ significance $|y_t/y_t^{\text{SM}}|<1.7$

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**PRD 99, 052009 (2019)**

- **ATLAS**
  - $\sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1}$
  - Dilepton Postfit
  - $7 j, \geq 4 b, \geq 1 J$

- **CMS**
  - $35.9 \text{ fb}^{-1} \text{ SS dilep.} / \text{ trilep.}$
  - $35.9 \text{ fb}^{-1} \text{ Single lep.} / \text{ OS dilep.}$
  - $137 \text{ fb}^{-1} \text{ SS dilep.} / \text{ trilep.}$

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LDC - HEP-EPS Ghent, 15 July 2019
Quantum Interference Between Single and Doubly Resonant Top Quark


Identical $WWbb$ final states,

Good description by predictions including recent fixed-order calculations of the full next-to-leading-order (NLO) $pp \rightarrow l^+\nu l^-\nu \bar{b}b^- \bar{b}$ process
CMS Projection

$t\bar{t}t\bar{t}$ 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})

LDC - HEP-EPS Ghent, 15 July 2019
Top properties
Top properties: polarisation, spin correlations

- \( t \) 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

  - \( \Delta \phi_{ll} \) (\&\( \Delta \eta_{ll} \)) between leptons in \( tt \) (dilepton)

- A more direct study extracts 15 coefficients characterising spin dependence of \( tt \) production. Large uncertainties still.

- \( \Delta \phi_{ll} \) tension between NLO & data likely explained by missing higher order

- Polarisation, CMDM, in agreement with SM within uncertainties

CMS Preliminary

- CMS-PAS-TOP-17-023
- 35.9 fb\(^{-1}\) (13 TeV)

Data

- POWHEGv2 + PYTHIA8
- NLO calculation
- MG5_aMC@NLO + PYTHIA8 [FxFx]

Result \( \pm \) (stat) \( \pm \) (syst)
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 anomalous **Triple (Quartic) Gauge Couplings (aTGC, aQGC)**

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

- Larger samples allow for differential cross sections

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**ATLAS Internal**

**Run 1,2 \( \sqrt{s} = 7,8,13 \) TeV**

**STDM-2018-03**

**WZ** \( \rightarrow 3l\nu \)

**Diboson Cross Section Measurements**

- \( \gamma\gamma \)
  - \( Z\gamma \rightarrow \ell\nu\gamma \) \( [n_{jet} = 0] \)
  - \( Z\gamma \rightarrow \ell\nu\gamma \) \( [n_{jet} = 0] \)
- \( WV \rightarrow \ell\nu\gamma \)
- \( WV \rightarrow \ell\nu\gamma \)
- \( WW \)
  - \( WW \rightarrow \ell\nu\ell\nu \) \( [n_{jet} = 0] \)
  - \( WW \rightarrow \ell\nu\ell\nu \) \( [n_{jet} \geq 1] \)
  - \( WW \rightarrow \ell\nu\ell\nu \) \( [n_{jet} = 1] \)
- \( WZ \)
  - \( WZ \rightarrow \ell\nu\ell\nu \)
- \( ZZ \)
  - \( ZZ \rightarrow 4\ell \)
  - \( ZZ \rightarrow 4\ell \)
  - \( ZZ \rightarrow 4\ell \)
  - \( ZZ \rightarrow 4\ell \)
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 $W^±W^±jj \rightarrow l^±l^±jj$, most favorable EW/QCD production ratio)  
  - The former higher BR, probe higher energy tails where aQCG effects more prominent

- **Latest results (VZjj & VWjj)**: exploit boosted topology $V\rightarrow jj$ ($V$ 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$^±$)  
  - 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