CMS news on $\alpha_s(m_Z)$ and the PDFs using inclusive jets and $t\bar{t}$ cross sections

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LHC EWK meeting 29. November 2021
JET PRODUCTION AT LHC: PROBE OF SM

New CMS measurement: inclusive jets at 13 TeV:

2-differential cross sections vs jet $p_T$ and $y$

PDFs and $\alpha_s(m_Z)$

arXiv:2111.10431

CMS 33.5 fb$^{-1}$ (13 TeV)

CMS 36.3 fb$^{-1}$ (13 TeV)

used in the QCD analysis
New CMS measurement: inclusive jets at 13 TeV: 2-differential cross sections vs jet $p_T$ and $y$
JET PRODUCTION AT LHC: PROBE OF SM + CI

Contact Interactions

Cl expected to show up at high $p_T$ and central $y$:

[J. Gao, CJET arXiv:1301.7263]
JET PRODUCTION AT LHC vs QCD

**NNLO:**
- [Currie, Glover, Pires, PRL118 (2017) 072002]
- [Currie et al., JHEP 10 (2018) 155]

**NLOJet++**

**fastNLO**

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**Graph:**
- CMS, arXiv:2111.10431
- 33.5 fb⁻¹ (13 TeV)
- Ratio to NNLO CT14@NP@EW
- |y| < 0.5, 0.5 < |y| < 1.0, 1.0 < |y| < 1.5, 1.5 < |y| < 2.0
- Anti-\(k_T\) (R = 0.7)
- Total exp. unc., Data (stat unc.), NNLO PDF unc., NNLO scale unc.
- \(H_T\) scale
JET PRODUCTION AT LHC vs QCD

**Data vs NNLO**

**Data vs NLO+NLL**

**NLL resummation** [Liu, Moch, Ringer, arXiv:1801.07284]

[J. Gao et al., arXiv:1207.0513]

**Dominant uncertainty: PDF**

CMS [arXiv:2111.10431]

33.5 fb^{-1} (13 TeV)

Jet $p_T$ (GeV)

Ratio to NNLO CT14@NFW

Anti-$k_T$ (R = 0.7)

Total exp. unc.

Data (stat unc.)

NNLO PDF unc.

NNLO scale unc.

$H_T$ scale

CMS

36.3 fb^{-1} (13 TeV)

Jet $p_T$ (GeV)

Ratio to NLO+NLL CT14@NFW

Anti-$k_T$ (R = 0.4)

Total exp. unc.

Data (stat unc.)

NLO PDF unc.

HerAPDF2.0

NNPDF3.1

ABMP16

MMHT2014
• Investigate the impact of the measurement on the global PDF

• Perform a full QCD fit: extract simultaneously PDF and QCD parameters

• Perform a full SMEFT fit: extract simultaneously PDF and QCD parameters + CI coefficients

General idea of a full QCD analysis:

- parameterise PDFs at a starting scale $\mu^2_0$: $f(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$
  - **A**: normalisation, **B**: small-$x$ behaviour, **C**: $x \to 1$ shape
- evolve these PDFs to $\mu^2 > \mu^2_0$
- strong coupling, quark masses, can be added as parameters
- construct cross sections from PDFs and partonic cross sections:
  - SM/SMEFT predictions for every data point in ($x, \mu^2$) – plane
- $\chi^2$- fit to the experimental data $\to$ determine PDF parameters, $\alpha_s(m_Z), m_q, \ldots$
- NB: PDFs can not be obtained from LHC data alone, use DIS data as a basis

QCD analysis platform xFitter is used: [https://www.xfitter.org/xFitter/](https://www.xfitter.org/xFitter/)
**EXPLORE SENSITIVITY TO PDF**

- Investigate the impact of the measurement on the global PDF (here: CT14)

  “profiling” analysis [details e.g. J. Pumplin et al arXiv:1806.07950]

- minimise $\chi^2$ function, based on nuisances of experimental and theory uncertainties

- result: profiled PDFs with respect to the original ones

![Graphs showing the uncertainty in the original PDF](arXiv:2111.10431)
EXPLORE SENSITIVITY TO PDF

• Investigate the impact of the measurement on the global PDF (here: CT14)
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  • minimise $\chi^2$ function, based on nuisances of experimental and theory uncertainties
  • result: profiled PDFs with respect to the original ones

Significant improvements in PDF uncertainties expected for global PDF analyses
EXPLORE SENSITIVITY TO PDF + $\alpha_s$ at NNLO

- Full QCD fit at NNLO: basis data - $ep$ inclusive DIS cross sections (HERA) [arXiv:1506.06042]
  + CMS inclusive jets at 13 TeV [arXiv:2111.10431]: sensitivity to PDF and $\alpha_s$

- NNLO predictions obtained via fasNLO grids using NNLO k-factors

- PDF + uncertainties from:
  - uncertainties in exp. data
  - assumed $m_c, m_b, f_S$, scale variation
  - uncertainties in parametrisation
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  uncertainties in exp. data
  assumed $m_c, m_b, f_S$, scale variation
  uncertainties in parametrisation

- **Strong coupling constant**
  $\alpha_s(m_Z) = 0.1170 \pm 0.0019$

0.0014$_{fit}^{model} \pm 0.0007_{scale}^{param}$

**PDF and $\alpha_s(m_Z)$ obtained simultaneously!**
EXPLORE SENSITIVITY TO PDF + $\alpha_S$ at NNLO

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- Strong coupling constant
  $\alpha_S(m_Z) = 0.1170 \pm 0.0019$

- compared to HERA-only fit:

  Improved precision of the gluon at high $x$!
New $\alpha_s(m_Z)$ value on the landscape of earlier results

- ZEUS incl. jets in $\gamma p$ : NPB 864:1 (2012)
- H1 multijets at high $Q^2$ : arXiv 1406.4709 (2014)

- D0 incl. jets : PRD 80:111107 (2009)
- D0 ang. correl. : PLB 718:56 (2012)
- ATLAS TEEC 8TeV : EPJC 77:872 (2017)
- CMS $R_{32}$ 7TeV : EPJC 73:2604 (2013)
- CMS $t\bar{t}$ 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)
- CMS $t\bar{t}$ cross section 13TeV : EPJC 79:368 (2019)
- CMS multi-diff $t\bar{t}$ 13TeV : EPJC 80:658 (2020)

most precise single measurement (error 1.6%) mitigated dependence on PDFs

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined
EXPLORE SENSITIVITY TO PDF + $\alpha_s + m_q$ at NLO

- Full QCD fit at NLO: basis data - $ep$ inclusive DIS cross sections (HERA) [arXiv:1506.06042]
  + CMS inclusive jets at 13 TeV [arXiv:2111.10431]: sensitivity to PDF and $\alpha_s$
  + CMS 3-D $t\bar{t}$ cross sections [arXiv:1904.05237]: $m_t$ + additional sensitivity to $\alpha_s$

PDFs, $\alpha_s(M_Z)$, $m_t^{pole}$ extracted simultaneously:

$$\alpha_s(m_Z) = 0.1135 \pm 0.0016(\text{fit}) \pm 0.0002(\text{model}) \pm 0.0008(\text{param}) \pm 0.0011(\text{scale}) = 0.1135 \pm 0.0021(\text{total}),$$

$$m_t^{pole} = 170.5 \pm 0.7(\text{fit}) \pm 0.1(\text{model}) \pm 0.0(\text{param}) \pm 0.3(\text{scale}) \text{ GeV} = 170.5 \pm 0.8(\text{total}) \text{ GeV}.$$
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- **PDF + uncertainties from:**
  - uncertainties in exp. data
  - assumed $m_c, m_b, f_S$, scale variation
  - uncertainties in parametrisation

![Diagram showing sensitivity to PDF and $\alpha_s$](image)
EXPLORE SENSITIVITY TO PDF + $\alpha_s + m_q$ at NLO

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**PDF + uncertainties from:**

- uncertainties in exp. data
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- uncertainties in parametrisation

**QCD parameters:**

$\alpha_s(m_Z) = 0.1188 \pm 0.0026$

$m_t^{pole} = 170.4 \pm 0.7$ GeV

0.0017$_{fit} \pm 0.0025_{scale} \pm 0.0004_{mod} + 0.0001_{param}$

PDF, $\alpha_s(m_Z)$, $m_t^{pole}$ obtained simultaneously!
EXPLORE SENSITIVITY TO PDF + $\alpha_s + m_q + \text{CI}$

- **Full QCD fit at NLO:** basis data - $ep$ inclusive DIS cross sections (HERA) [arXiv:1506.06042]
  - + CMS inclusive jets at 13 TeV [CMS-SMP-PAS-20-011]: sensitivity to PDF, $\alpha_s + \text{CI}$
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**SMEFT Solution:**

PDFs in SM and SMEFT very similar → no risk of the BSM effects being absorbed in the SM PDF fit

only fit uncertainty shown

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**arXiv:2111.10431**
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**SMEFT Solution:**

- PDFs in SM and SMEFT very similar → no risk of the BSM effects being absorbed in the SM PDF fit
- Only fit uncertainty shown

- **QCD parameters**:
  - $\alpha_s(m_Z) = 0.1187 \pm 0.0033$
  - $m_t^{\text{pole}} = 170.4 \pm 0.7$ GeV

very similar to those in SM fit
EXPLORE SENSITIVITY TO PDF + $\alpha_s + m_q + \text{Cl}$

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- **QCD parameters:**
  
  \[
  \alpha_s(m_Z) = 0.1187 \pm 0.0033 \]
  
  \[
  m_t^{\text{pole}} = 170.4 \pm 0.7 \text{ GeV} \]

- **Cl parameters (for $\Lambda_{NP} = 10$ TeV):**
  
  \[
  c_1^L = -0.07 \pm 0.02_{\text{exp}} \pm 0.01_{\text{mod+par}} \]

SM +BSM obtained simultaneously !
EXPLORE SENSITIVITY TO PDF + $\alpha_s + m_q + \text{CI}$

**SMEFT fit: obtain PDFs, QCD parameters and CI Wilson coefficients simultaneously**

Compare to conventional studies: 
$\Lambda$ scan, fixed $c_1 = \pm 1$

### Compare to 95% exclusion limits for $\Lambda$ ($c_1 = -1$):

- **Left-handed**: $\Lambda > 24$ TeV
- **Vector-like**: $\Lambda > 32$ TeV
- **Axial-vector like**: $\Lambda > 31$ TeV

Agrees well with e.g. ATLAS result [arXiv:1703.09127]

$\Lambda$ (left-handed CI) $> 22$ TeV

No significant deviation from SM observed.

BSM constrained in a less QCD-biased way in a SMEFT analysis
SUMMARY

• New measurement of inclusive jet cross section at 13 TeV (2016 data) available

• NNLO result on strong coupling: most precise single result at a hadron machine

• pave the way towards global SMEFT fit

THANKS FOR LISTENING!
BACKUP
CORRECTIONS TO NLO/NNLO

EWK corrections:

average + envelope of PYTHIA and HERWIG used

\[ NP_i = \frac{\sigma_{MC}^{MC}(PS \ & MPI \ & HAD)}{\sigma_{i}^{MC}(PS)}, \]
Jets: profiling strong coupling:

Jets+top: NLO

tension in $\alpha_s(m_Z)$ between jet and top data observed in global PDFs

(no tensions in the data !)
**FIT RESULTS NNLO**

Parametrisation NNLO (HERA+CMS jets):

\[
\begin{align*}
  xg(x) &= A_g x^{B_g} (1-x)^{C_g} (1 + D_g x + E_g x^2), \\
  xu(x) &= A_u x^{B_u} (1-x)^{C_u} (1 + E_u x^2), \\
  xd(x) &= A_d x^{B_d} (1-x)^{C_d}, \\
  x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}} (1-x)^{C_{\bar{U}}} (1 + D_{\bar{U}} x), \\
  x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}} (1-x)^{C_{\bar{D}}} (1 + E_{\bar{D}} x^2).
\end{align*}
\]

Goodness of Fit NNLO:

<table>
<thead>
<tr>
<th>Data sets</th>
<th>HERA-only Partial $\chi^2/N_{\text{dp}}$</th>
<th>HERA+CMS Partial $\chi^2/N_{\text{dp}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERA I+II neutral current</td>
<td>$e^+p, E_p = 920\text{ GeV}$ 378/332</td>
<td>375/332</td>
</tr>
<tr>
<td>HERA I+II neutral current</td>
<td>$e^+p, E_p = 820\text{ GeV}$ 60/63</td>
<td>60/63</td>
</tr>
<tr>
<td>HERA I+II neutral current</td>
<td>$e^+p, E_p = 575\text{ GeV}$ 201/234</td>
<td>201/234</td>
</tr>
<tr>
<td>HERA I+II neutral current</td>
<td>$e^+p, E_p = 460\text{ GeV}$ 208/187</td>
<td>209/187</td>
</tr>
<tr>
<td>HERA I+II neutral current</td>
<td>$e^-p, E_p = 920\text{ GeV}$ 223/159</td>
<td>227/159</td>
</tr>
<tr>
<td>HERA I+II charged current</td>
<td>$e^+p, E_p = 920\text{ GeV}$ 46/39</td>
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<tr>
<td>HERA I+II charged current</td>
<td>$e^-p, E_p = 920\text{ GeV}$ 55/42</td>
<td>56/42</td>
</tr>
<tr>
<td>CMS inclusive jets 13 TeV</td>
<td>$0.0 &lt;</td>
<td>y</td>
</tr>
<tr>
<td></td>
<td>$0.5 &lt;</td>
<td>y</td>
</tr>
<tr>
<td></td>
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<td>y</td>
</tr>
<tr>
<td>Correlated $\chi^2$</td>
<td>66</td>
<td>83</td>
</tr>
<tr>
<td>Global $\chi^2/N_{\text{dof}}$</td>
<td>1231/1043</td>
<td>1321/1118</td>
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**FIT RESULTS NLO SM / SMEFT**

Parametrisation SMEFT NLO (HERA+CMS jets + $t\bar{t}$):

\[
\begin{align*}
x g(x) &= A_g x^B_g (1 - x)^C_g (1 + E_g x^2), \\
x u_v(x) &= A_{u_v} x^{B_{u_v}} (1 - x)^{C_{u_v}} (1 + D_{u_v} x + E_{u_v} x^2), \\
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<tr>
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<th>SMEFT fit</th>
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<td></td>
<td>23/23</td>
</tr>
<tr>
<td>CMS inclusive jets 13 TeV</td>
<td>0.0 &lt; $</td>
<td>y</td>
</tr>
<tr>
<td></td>
<td>0.5 &lt; $</td>
<td>y</td>
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<tr>
<td>Global $\chi^2/N_{dof}$</td>
<td></td>
<td>1411/1141</td>
</tr>
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</table>
THEORY PREDICTIONS

- **SM Jets**: NNLO computation: NNLOJet, in QCD analysis via K-factors
  NLO: NLOJet++/FastNLO improved by NLL (MEKS) via K-factors
  QCD predictions corrected for NP and EW effects
  Scales: $\mu_r = \mu_f = p_T$ (individual jet), variation up/down by factor 2 independently

- **3-differential $t\bar{t}$ cross section**: NLO MADGRAPH MC@NLO interfaced to APPLGRID
  Scale: $\mu_r = \mu_f = 1/2 \sum_{i} m_{T,i}, m_{T,i} \equiv \sqrt{m_i^2 + p_{T,i}^2}$;
  $i$—final-state partons $t, \bar{t}$ and max. 3 light partons for $t\bar{t} + \text{jet}$

- **CI**: CIJET interfaced to fastNLO / xFitter ; $L_{SMEFT} = L_{SM} + \frac{2\pi}{\Lambda^2} \sum_{n \in \{1,3,5\}} c_n \mathcal{O}_n$

studied non-renormalisable operators $\mathcal{O}_n$:
colour-singlet BSM-exchange between two quark lines integrated out

3 cases studied:
CI left-handed / vector-like / axial-vector-like

<table>
<thead>
<tr>
<th>Type of CI</th>
<th>$c_1$</th>
<th>$c_3$</th>
<th>$c_5$</th>
</tr>
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<tbody>
<tr>
<td>Purely left-handed</td>
<td>fitted</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Vector-like</td>
<td>fitted</td>
<td>$2c_1$</td>
<td>$c_1$</td>
</tr>
<tr>
<td>Axial-vector-like</td>
<td>fitted</td>
<td>$-2c_1$</td>
<td>$c_1$</td>
</tr>
</tbody>
</table>

c, d - generations     i,j,k - colour indices
HESSIAN PROFILING TECHNIQUE

Define a $\chi^2$ with theory uncertainties ($b_{th}$ are the PDF uncertainties)

$$
\chi^2(b_{exp}, b_{th}) = \sum_{i=1}^{N_{data}} \left( \frac{(\sigma_i^{exp} + \sum_\alpha \Gamma_{i\alpha}^{exp} b_{\alpha,exp} - \sigma_i^{th} - \sum_\beta \Gamma_{i\beta}^{th} b_{\beta,th})^2}{\Delta_i^2} \right) + \sum_\alpha b_{\alpha,exp}^2 + \sum_\beta b_{\beta,th}^2.
$$

Correlated experimental and theoretical uncertainties are included using the nuisance parameter vectors $b_{exp}$ and $b_{th}$, respectively.

Their influence on the data and theory predictions is described by $\Gamma_{i\alpha}^{exp}$ and $\Gamma_{i\alpha}^{th}$ matrices

index $\alpha$ ($\beta$) corresponds to the experimental (theoretical) uncertainty nuisance parameters

Minimisation of $\chi^2(b_{exp}, b_{th})$ leads to a system of linear equations.

The value at the minimum of the $\chi^2$ function provides a compatibility test of the data and theory.

The values at the minimum of the nuisance parameters $b_{\beta_{th}}^{min}$ are interpreted as optimisation ("profiling") of PDFs to describe the data. The shifted PDFs have reduced uncertainties.

In xFitter:
- Add the hessian PDF uncertainties as nuisance parameters $\beta$ in the $\chi^2$
- Minimise $\chi^2$ and profile the PDF shifts $\beta$ to the data $\chi^2(\beta_{exp}) \rightarrow \chi^2(\beta_{exp}, \beta_{th})$
- Propagate the shifts and the reduction of the uncertainties to the PDFs