Measurements of event properties and multi-differential jet cross sections and impact of CMS measurements on Proton Structure and QCD parameters

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On behalf of the CMS Collaboration

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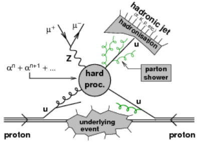
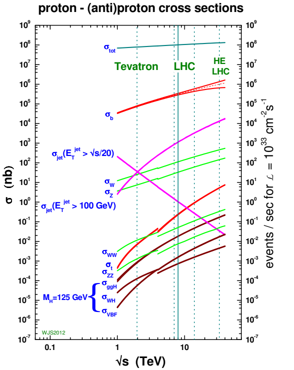
- Particle jets :
  - produced abundantly in the collisions of protons at the Large Hadron Collider (LHC)
  - provide an excellent opportunity for testing the predictions of perturbative Quantum Chromodynamics (pQCD) at high energies
  - important backgrounds for many new physics models
- Inclusive jet cross section measurement :
  - gives important information about the strong coupling constant α_S

$$\sigma_{\text{i-jet}} = \sigma(\text{pp} \rightarrow \text{i jets + X}) \propto \alpha_S^{\text{i}}$$

  - provides a deep insight to understand the proton structure by deriving constraints on the parton distribution functions (PDFs)
- Jet properties such as jet shapes, mass, charge etc. : key ingredients of Standard Model (SM) physics measurements and for beyond SM physics searches



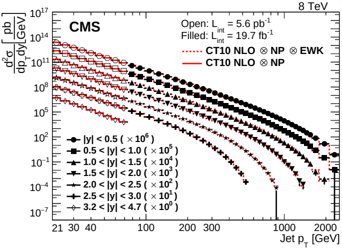


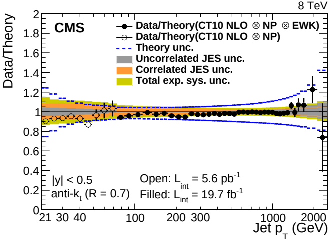
http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html

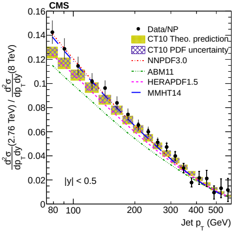
QCD multijet production

Double-differential cross-section in p_T and y :

$$\frac{d^2\sigma}{dp_T dy} = \frac{1}{\epsilon \times \mathcal{L}_{\text{int,eff}}} \frac{N_{\text{jets}}}{\Delta p_T (2\Delta|y|)}$$







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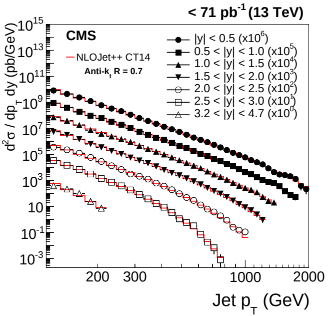
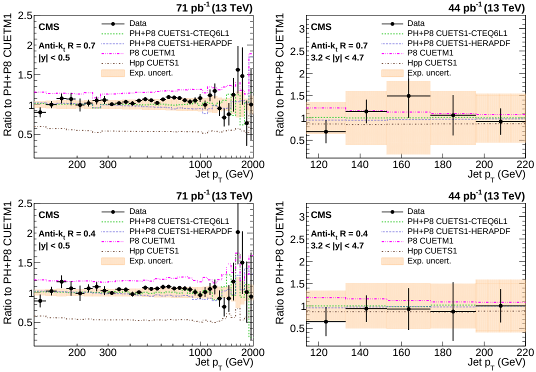
Measurement at 8 TeV :

- anti-k_t R = 0.7
- $21 < p_T < 74$ GeV, upto |y|= 4.7 ($\mathcal{L} = 5.6\ pb^{-1}$)
  $74 < p_T < 2500$ GeV, upto |y| = 3.0 ($\mathcal{L} = 19.7\ fb^{-1}$)
- Comparison to NLO parton-level calculations, including electroweak (EWK) and non-perturbative (NP) corrections
- Constraints on PDFs together with the fit of α_S [Slide no. 21, 22]
- Ratios between different energies 2.76/8 and 7/8 : partial reduction of uncertainties

Inclusive jet production

Double-differential cross-section in p_T and y :
$$\frac{d^2\sigma}{dp_T dy} = \frac{1}{\epsilon \times \mathcal{L}_{\text{int,eff}}} \frac{N_{\text{jets}}}{\Delta p_T \Delta y}$$





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Measurement at 13 TeV :

- anti-k_t R = 0.4 and R = 0.7
- p_T < 2 TeV; |y| < 3 ($\mathcal{L}$ = 71 pb^{-1}), 3.2 < |y| < 4.7 ($\mathcal{L}$ = 44 pb^{-1})
- P8+CUETM1 (LO) agrees in shape in |y| < 1.5
- Hpp+CUETS1 (LO) agrees in shape in all rapidity bins
- PH+P8 (NLO) shows good agreement

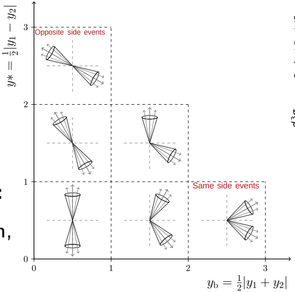
Triple-differential dijets

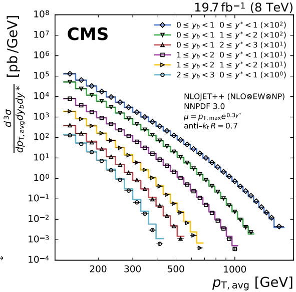
Triple differential cross-section :

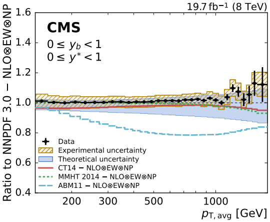
$$\frac{d^3\sigma}{dp_{T,avg}\,dy^{\star}\,dy_b} = \frac{1}{\epsilon\ \mathcal{L}_{\text{int,eff}}}\frac{N}{\Delta p_{T,avg}\Delta y^{\star}\Delta y_b}$$

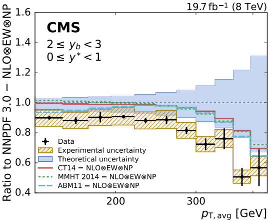
Measurement at 8 TeV :

- anti-k_t R = 0.7 ($\mathcal{L}$ = 19.7 fb^{-1})
- **Cross section as a function of the :**
  - average transverse momentum, $p_{T,avg} = \frac{1}{2}(p_{T,1} + p_{T,2})$
  - half the rapidity separation, $y^{\star} = \frac{1}{2}|y_1 - y_2|$
  - boost of the two leading jets, $y_b = \frac{1}{2}|y_1 + y_2|$
- Data are well described in most of the phase spaces but some differences at high $p_{T,avg}$ and y_b
- Best suited to constrain PDFs and extract α_S [Slide no. 21, 22]









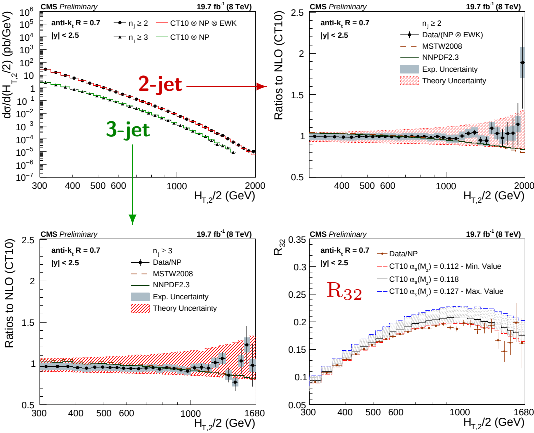
arXiv:1705.02628
(Submitted to EPJC)

Differential cross-section in $\mathrm{H}_{\mathrm{T},2}/2$:

$$\frac{d\sigma}{d(H_{T,2}/2)} = \frac{1}{\epsilon\ \mathcal{L}_{\text{int,eff}}}\frac{N_{\text{event}}}{\Delta\left(\mathrm{H}_{\mathrm{T},2}/2\right)}$$

Measurement at 8 TeV :

- anti-k_t R = 0.7 ($\mathcal{L}$ = 19.7 fb^{-1})
- **2-jet and 3-jet event cross sections as a function of** $\mathrm{H}_{\mathrm{T},2}/2 = \frac{1}{2}(p_{T,1} + p_{T,2})$
- Data are well described by theory predictions within uncertainty.
- EWK corrections explains the increasing excess of the 2-jet data w.r.t. theory (∼1 TeV)
- **3-jet to 2-jet cross section ratio** R_{32} **:** many uncertainties cancel and sensitive to α_S [Slide no. 22]



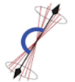
CMS-PAS-SMP-16-008

Normalized differential cross-section in ϕ :

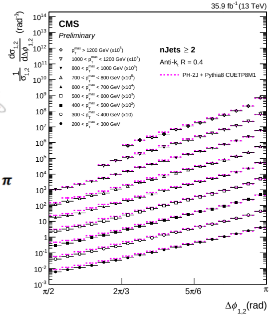
$$\frac{1}{\sigma_{1,2}}\frac{d\sigma_{1,2}}{d\Delta\phi_{1,2}}\text{(2-jet)},\quad \frac{1}{\sigma_{2j}^{\min}}\frac{d\sigma_{2j}^{\min}}{d\Delta\phi_{2j}^{\min}}\text{(3-jet and 4-jet)}$$

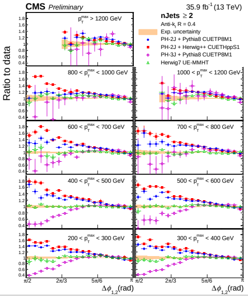
Measurement at 13 TeV :

- anti-k_t R = 0.4 ($\mathcal{L}$ = 35.9 fb^{-1})
- Normalized cross sections as a function of the :
  - **azimuthal angular separation** between the two highest leading p_T jets (2-jet, 3-jet and 4-jet)
  - **minimum azimuthal angular separation** between any two of the three or four leading p_T jets (3-jet and 4-jet)
- Spectrum gets flatter and become more sensitive to parton shower on moving from 2-jet to 3-jet to 4-jet
- Best agreement is given by Herwig7
- POWHEG-2J gives better results when matched with Pythia8 than Herwig++
- POWHEG-3J+Pythia8 is generally lower than POWHEG-2J+Pythia8
- An interesting tool to test the theoretical predictions of multijet production processes

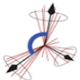


$\Delta\varphi_{\text{dijet}} = \pi$

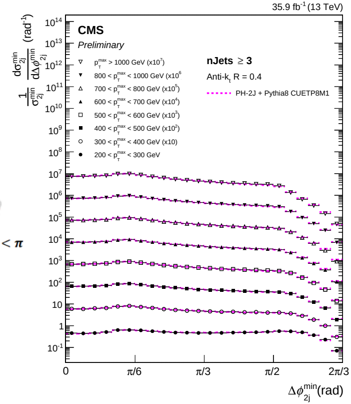


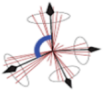


CMS-PAS-SMP-16-014

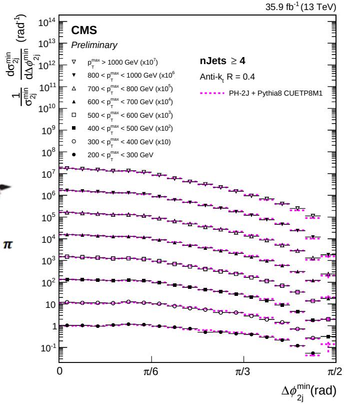


$2\pi/3 \leq \Delta\varphi_{dijet} < \pi$





$0 < \Delta\varphi_{dijet} \ll \pi$



- **Pythia8 (LO)** exhibits small deviations from the $\Delta\phi_{1,2}$ and fails to describe $\Delta\phi_{2j}^{min}$
- **Herwig++** exhibits the largest deviations from the $\Delta\phi_{1,2}$ but provides a reasonable description of the $\Delta\phi_{2j}^{min}$
- **MADGRAPH+Pythia8** provides a good overall description of the measurements except for $\Delta\phi_{2j}^{min}$ in 4-jet case

CMS-PAS-SMP-16-014

Measurement at 8 TeV :

- anti-k_t R = 0.5 ($\mathcal{L}$ = 19.7 fb^{-1})
- **p_T-weighted sum of the electric charges of the particles in a jet :**

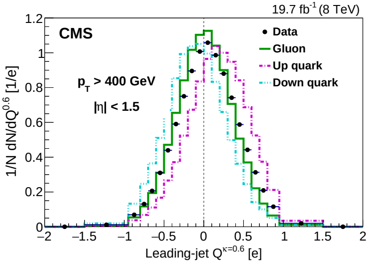
$$Q^\kappa = \frac{1}{(p_T^{jet})^\kappa} \sum_i Q_i (p_T^i)^\kappa$$

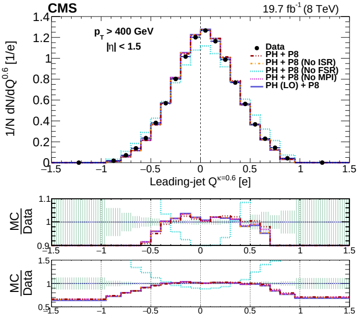
$$Q_L^\kappa = \sum_i Q_i \left(p_\parallel^i\right)^\kappa / \sum_i \left(p_\parallel^i\right)^\kappa$$

$$Q_T^\kappa = \sum_i Q_i \left(p_\perp^i\right)^\kappa / \sum_i \left(p_\perp^i\right)^\kappa$$

- Differentiate statistically jets from quarks of different electric charge, or between gluon or quark jets
- Three values of κ = 0.3, 0.6 and 1.0, provide different sensitivities to the softer and harder particles in the jet
- Broader jet charge distribution on disabling the simulation of FSR in Pythia8

arXiv:1706.05868
(Submitted to JHEP)



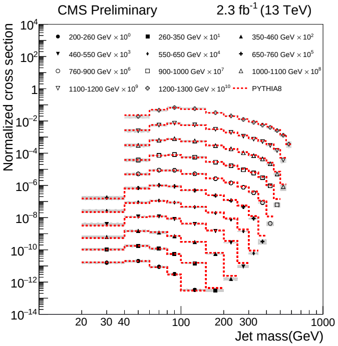


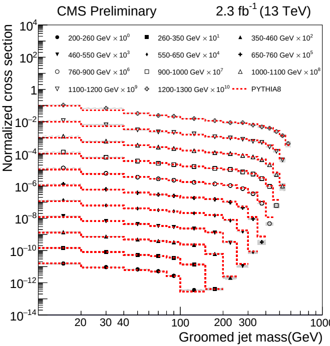
Dijet mass

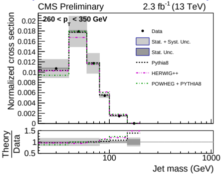
Measurement at 13 TeV :

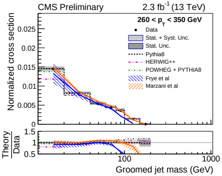
CMS-PAS-SMP-16-010

- anti-k_t R $= 0.8$ ($\mathcal{L} = 2.3$ fb^{-1})
- **Double-differential jet cross section as a function of the jet mass and jet p_T :**
  - **Soft drop (SD)** grooming algorithm removes low energetic constituents
  - For ungroomed jets : MC generators predictions agree with data within uncertainities for intermediate regions ($0.1 < m/p_T < 0.3$)
  - For groomed jets : the jet mass peak is suppressed and the precision in the low and intermediate regions improves
  - Sensitive to QCD parton showering; used in searches for new physics ("boosted" objects)









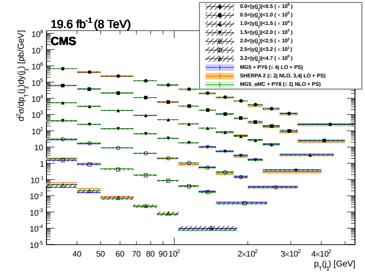
Electroweak production

Z + jets

Measurement at 8 TeV :

JHEP 04 (2017) 022

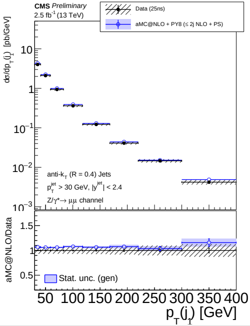
- anti-k_t R = 0.5 ($\mathcal{L} = 19.6$ fb^{-1})
- $p_T(\ell) > 20$ GeV, $|y(\ell)| < 2.4$,
  $71 < M(\ell\ell) < 111$ GeV; $\ell = e, \mu$
  $p_T(j) > 30$ GeV, $|y(j)| < 2.4$
- **Differential cross sections as functions of the jet H_T, p_T and $|y|$**
- **Double differential cross sections as a function of $|y|$ and p_T, for the leading jet**
- A large number of final-state partons should be included in the matrix element calculations in order to correctly describe the kinematics of the leading jets



Measurement at 13 TeV :

CMS-PAS-SMP-15-010

- anti-k_t R = 0.4 ($\mathcal{L} = 2.5$ fb^{-1})
- $p_T(\ell) > 20$ GeV, $|y(\ell)| < 2.4$,
  $71 < M(\ell\ell) < 111$ GeV; $\ell = \mu$
  $p_T(j) > 30$ GeV, $|y(j)| < 2.4$
- **Differential cross sections as a function of jet multiplicity, p_T and y for different jet multiplicities (upto 3 jets)**
- Good agreement with NLO and NNLO calculations

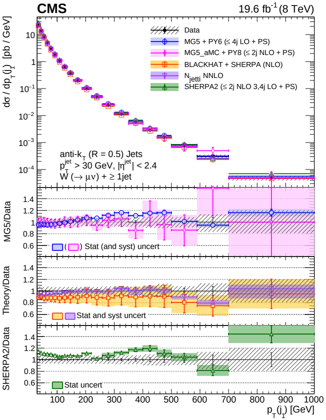


W → $\mu\nu$ + jets

Measurement at 8 TeV :

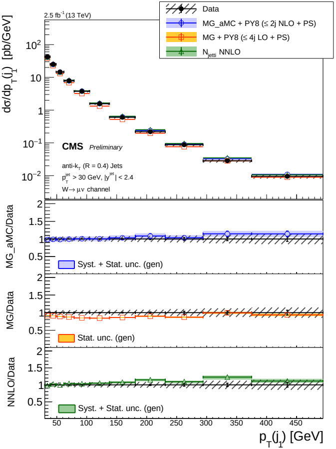
- anti-k_t R = 0.5 ($\mathcal{L} = 19.6\ \mathrm{fb}^{-1}$)
- **Differential cross sections as functions of the jet multiplicity, H_T, and p_T for different jet multiplicities**
- Very good agreement with NLO 0, 1, 2 jets FxFx and NNLO 1 jet
- Important background for other measurements

PRD 95 (2017) 052002



Measurement at 13 TeV :

- anti-k_t R = 0.4 ($\mathcal{L} = 2.5\ \mathrm{fb}^{-1}$)
- **Differential cross sections as a function of jet multiplicity, p_T, y and H_T for different jet multiplicities (upto at least 3 jets)**
- Good agreement with NLO and NNLO calculations



CMS-SMP-16-005 (Submitted to PRD)

V + b(b) production

Z $\to \ell$ + b jet at 8 TeV :

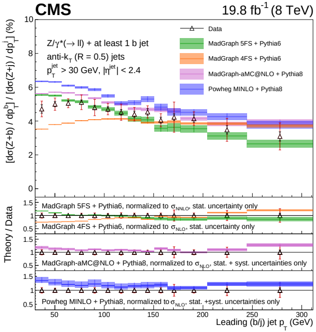
- anti-k_t R $= 0.5$ ($\mathcal{L} = 19.8$ fb^{-1})
- b tagging : combined secondary vertex (CSV) algorithm
- **Differential cross sections as a function of p_T and η of the highest-p_T b jet, Z boson p_T, H_T, and $\Delta\phi_{Zb}$**
- Ratios of the differential cross sections for Z(1b) and Z+jets
- Z($\geq$1b) low-p_T region not well described, Z(bb) generally agree with predictions

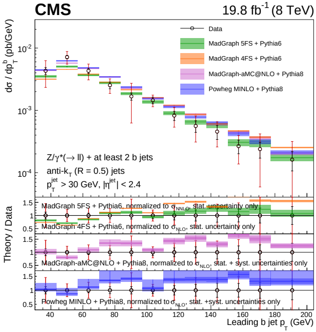
W $\to \ell$ + b jet at 8 TeV :

- anti-k_t R $= 0.5$ ($\mathcal{L} = 19.8$ fb^{-1})
- Exactly one ℓ with $p_T(\ell) > 30$ GeV, $|\eta_\ell| < 2.1$, Exactly two b jets with p_T(j) > 25 GeV, $|\eta_j| < 2.4$
- Cross-section in agreement with Standard Model predictions

$\sigma \to$ W($\ell\nu$+b$\bar{\text{b}}$) $= 0.64 \pm 0.03$(stat) ± 0.10(syst) ± 0.06(theo) ± 0.02(lumi)

arXiv:1611.06507 (Accepted in EPJC)





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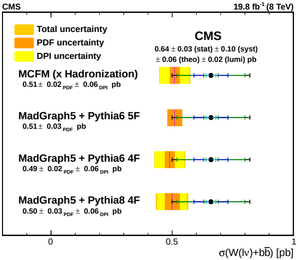


Z ($\rightarrow$ e or μ) + c

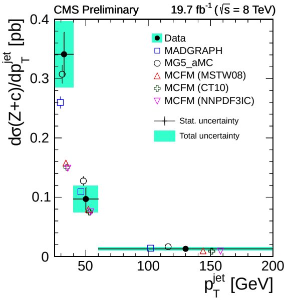
Measurement at 8 TeV :

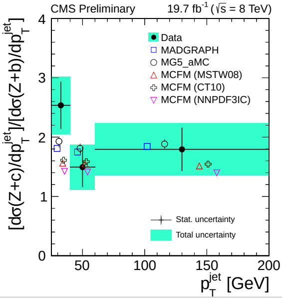
- anti-k_t R $= 0.5$ ($\mathcal{L} = 19.7$ fb^{-1})
- **Cross section $\sigma(\mathrm{pp} \rightarrow \mathrm{Z} + \mathrm{c} + \mathrm{X})$, Cross section ratio $\frac{\sigma(\mathrm{pp}\rightarrow\mathrm{Z} + \mathrm{c} + \mathrm{X})}{\sigma(\mathrm{pp}\rightarrow\mathrm{Z} + \mathrm{b} + \mathrm{X})}$, inclusively and differentially as a function p_T of Z boson and jet with heavy flavour content**
- Measurements are in agreement with the LO predictions from MADGRAPH and NLO predictions from MG5_aMC
- Predictions from the MCFM program are lower than the measured $\sigma(\mathrm{Z} + \mathrm{c})$, both inclusive and differentially
- Better description in terms of the Z + c/Z + b cross sections ratio

$$\sigma(\mathrm{pp} \rightarrow \mathrm{Z} + \mathrm{c} + \mathrm{X}) = 8.6 \pm 0.5(\mathrm{stat}) \pm 0.7(\mathrm{syst})\ \mathrm{pb}$$

$$\sigma(\mathrm{pp} \rightarrow \mathrm{Z} + \mathrm{c} + \mathrm{X})/\sigma(\mathrm{pp} \rightarrow \mathrm{Z} + \mathrm{b} + \mathrm{X}) = 2.0 \pm 0.2(\mathrm{stat}) \pm 0.2(\mathrm{syst})\ \mathrm{pb}$$

CMS-PAS-SMP-15-009



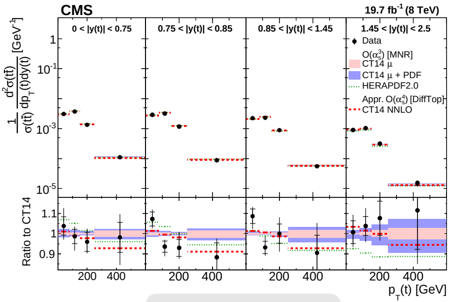


Top Physics

Measurement at 8 TeV :

- anti-k_t R = 0.5 ($\mathcal{L}$ = 19.7 fb^{-1})
- Dilepton $e^{\pm}\mu^{\mp}$ final state
- **Normalized double-differential cross section as a function of six different pairs of kinematic variables :**

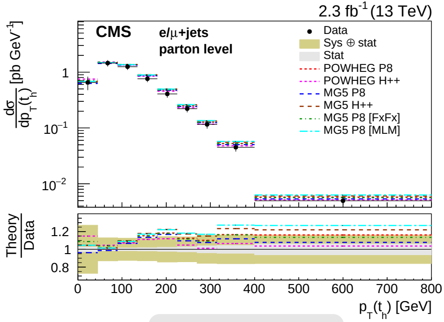
  $[p_T(t), y(t)]$, $[y(t), M(t\bar{t})]$, $[y(t\bar{t}), M(t\bar{t})]$, $[\Delta\eta(t,\bar{t}), M(t\bar{t})]$, $[p_T(t\bar{t}), M(t\bar{t})]$, $[\Delta\phi(t,\bar{t}), M(t\bar{t})]$)
- Significant improvement of g at high x as a function of $M(t\bar{t})$-$y(t\bar{t})$ [Slide no. 21]



EPJC 77 (2017) 459

Measurement at 13 TeV :

- anti-k_t R = 0.4 ($\mathcal{L}$ = 2.3 fb^{-1})
- ℓ+jets decay channels with a single μ or e in the final state
- **Differential and Double-differential cross sections as a function of jet multiplicity and of kinematic variables of the t and $t\bar{t}$ system**
- Measured $p_T(t)$ softer than expected except for Herwig++ MCs, as predicted by the NNLO and the NLO+NNLL' QCD calculation



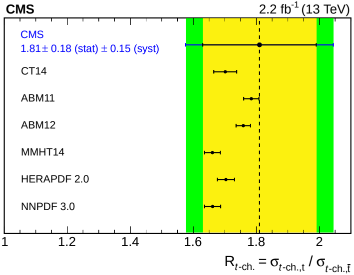
PRD 95 (2017) 092001

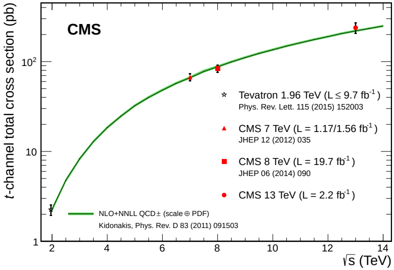
Measurement at 13 TeV :

- anti-k_t R = 0.4 ($\mathcal{L}$ = 2.2 fb^{-1})
- Exactly one muon and at least two jets with one b-tagged jet
- Separation between signal and background processes by a **MVA** technique
- Fit to the distribution of the discriminating variable yields a total cross section :

$\sigma(t\text{-}ch., t{+}\bar{t})$= 238 $\pm$ 13(stat) $\pm$ 29(syst) pb

- A ratio of top quark and top antiquark production :
  $R_{t\text{-}ch.} = 1.81 \pm 0.18(\mathrm{stat}) \pm 0.15(\mathrm{syst})$
- Absolute value of the CKM matrix element V_{tb} :
  $1.05 \pm 0.07(\mathrm{exp}) \pm 0.02(\mathrm{theo})$
- All results are in agreement with the Standard Model predictions.





arXiv:1610.00678
(Accepted in PLB)

Measurement at 8 TeV :

- Cambridge-Aachen R = 1.2 ($\mathcal{L} = 19.7\ \text{fb}^{-1}$)
- Vetoed > 2 jets with $p_T > 150$ GeV
- Highly boosted $t\bar{t}$ events :

  Semileptonic decay : t → bW with W → $\ell\nu_\ell$
  where $\ell = e$ or μ

  Fully hadronic decay : t → bW with W → $q\bar{q}'$

- **Differential cross section as a function of jet mass (m_{jet}) :**
  - Slight overestimation of cross section in simulation.
- **Normalized differential cross section as a function of jet mass (m_{jet}) :**
  - Consistent with other cross section measurements in boosted events.
- Peak position in the m_{jet} distribution is sensitive to the top quark mass m_t

$$m_t = 170.8 \pm 9.0\ \text{GeV}$$

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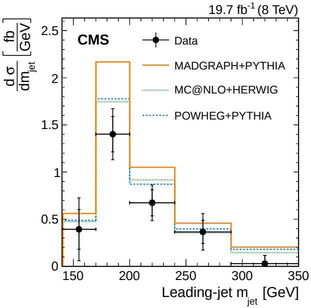
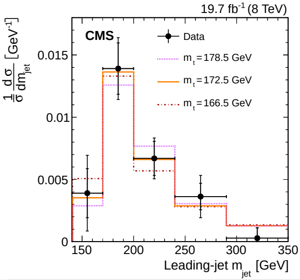




Inclusive jet :

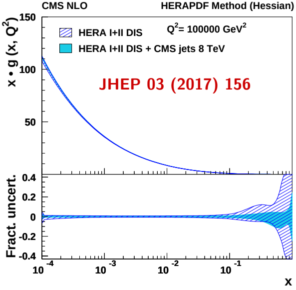
- 2D cross sections vs of jet p_T and rapidity
- Probes hadronic parton-parton interaction over a wide range of x and Q
- Constraints on PDFs : QCD analysis of data together with HERA DIS measurements, at NLO using HERAFfitter
- **Significant impact on the gluon distribution in a new kinematic regime**

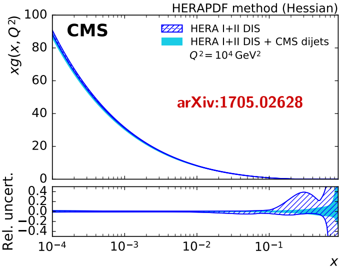
Triple differential dijets :

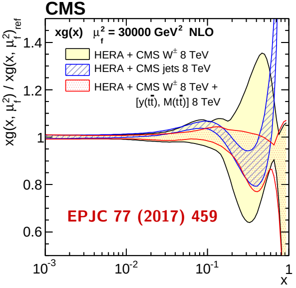
- 3D cross sections vs of jet average p_T, rapidity separation and boost
- Use dijet cross section in the QCD analysis in addition to HERA data
- Change in the gluon shape similar as observed in the case of inclusive jet data
- **Significant reduction of the uncertainty in g(x) at high x**

Double-differential cross sections for top quark pair production :

- 2d-differential $t\bar{t}$ cross sections
- QCD analysis of data along with HERA inclusive DIS data and CMS W asymmetry, using XFitter 1.2.2
- Best improvement comes from M($t\bar{t}$)-y($t\bar{t}$)
- **Recommend to use both data sets for further improvement of g(x) at high x**







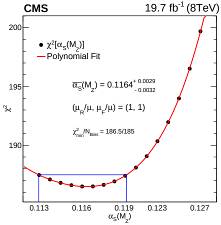
The strong coupling constant α_S

JHEP 03 (2017) 156

Inclusive jet [JHEP 03 (2017) 156] :

- Least square minimization on $p_T(y)$ spectrum using NLO parton level predictions
- Using the CT10 NLO PDF set

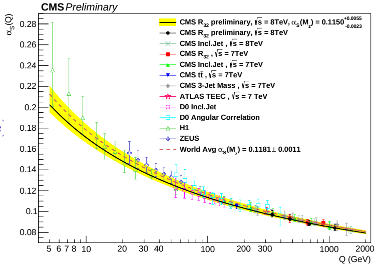
$$\alpha_S(M_Z) = 0.1164\,^{+0.0014}_{-0.0015}\,(\text{exp})\,^{+0.0025}_{-0.0029}\,(\text{PDF}) \pm 0.0001\,(\text{NP})\,^{+0.0053}_{-0.0028}\,(\text{scale})$$



Multijets [CMS-PAS-SMP-16-008] :

- 3-jet to 2-jet cross section ratio, $R_{32} \propto \alpha_S$
- Insensitive to many theoretical and experimental systematics
- Using the MSTW2008 PDF set

$$\alpha_S(M_Z) = 0.1150 \pm 0.0010\,(\text{exp}) \pm 0.0013\,(\text{PDF}) \pm 0.0015\,(\text{NP})\,^{+0.0050}_{-0.0000}\,(\text{scale})$$



Triple differential dijets [arXiv:1705.02628] :

- Precise α_S extraction together with PDF fit

$$\alpha_S(M_Z) = 0.1199 \pm 0.0015\,(\text{exp}) \pm 0.0002\,(\text{mod})\,^{+0.0002}_{-0.0004}\,(\text{par})\,^{+0.0031}_{-0.0019}\,(\text{scale})$$

$\alpha_S^{PDG} = 0.1181 \pm 0.0011$

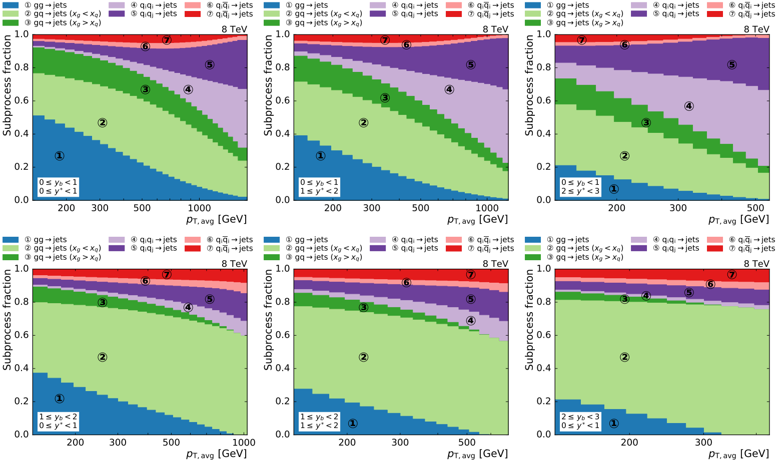
Summary

- Jet production in pp collisions is one of the main phenomenological predictions of pQCD.
- Measurements of characteristics of events with jets, from jet-charge over investigations of shapes to jet mass distributions are presented.
    - Compared to theoretical predictions including those matched to parton shower and hadronization.
- Multi-differential jet cross-sections over a wide range in transverse momenta from inclusive jets to multi-jet final states are measured.
    - Impact on the determination of the strong coupling constant α_S as well as on parton density functions (PDFs)
- Electroweak boson production : inclusive or associated with charm or beauty quarks give insight into the flavour separation of the proton sea.
- Measurements of cross sections of jet and top-quark pair production are in particular sensitive to the gluon distribution in the proton and α_S.

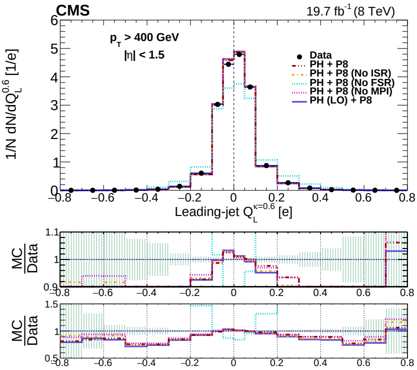
THANKS!!

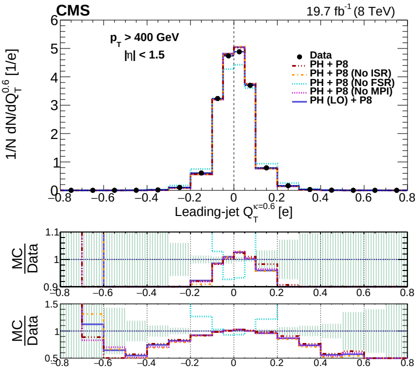
Back-Up Slides

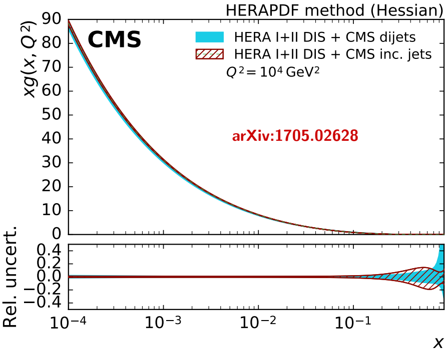
Triple-differential dijets

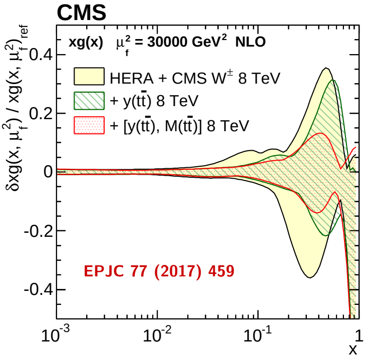


arXiv:1705.02628


CMS
19.7 fb-1 (8 TeV)
pT > 400 GeV
|η| < 1.5
Data
PH + P8
PH + P8 (No ISR)
PH + P8 (No FSR)
PH + P8 (No MPI)
PH (LO) + P8
1/N dN/dQ0.6L [1/e]
Leading-jet Qκ=0.6L [e]
MC/Data


CMS
19.7 fb-1 (8 TeV)
pT > 400 GeV
|η| < 1.5
Data
PH + P8
PH + P8 (No ISR)
PH + P8 (No FSR)
PH + P8 (No MPI)
PH (LO) + P8
1/N dN/dQ0.6T [1/e]
Leading-jet Qκ=0.6T [e]
MC/Data


HERAPDF method (Hessian)
CMS
HERA I+II DIS + CMS dijets
HERA I+II DIS + CMS inc. jets
$Q^2 = 10^4$ GeV^2
arXiv:1705.02628
$xg(x, Q^2)$
Rel. uncert.
x


CMS
xg(x) μ_f^2 = 30000 GeV^2 NLO
HERA + CMS W$^\pm$ 8 TeV
+ y(t$\bar{t}$) 8 TeV
+ [y(t$\bar{t}$), M(t$\bar{t}$)] 8 TeV
EPJC 77 (2017) 459
$\delta xg(x, \mu_f^2) / xg(x, \mu_f^2)_{ref}$
x