Tests of QCD using jets at CMS

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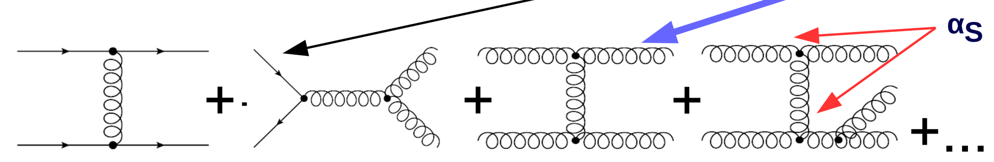
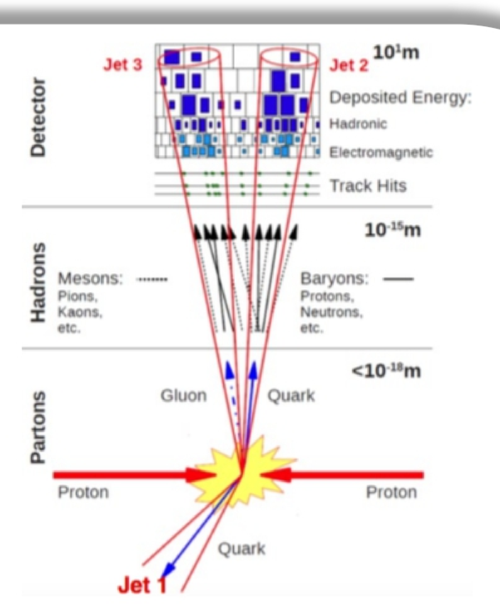
Introduction

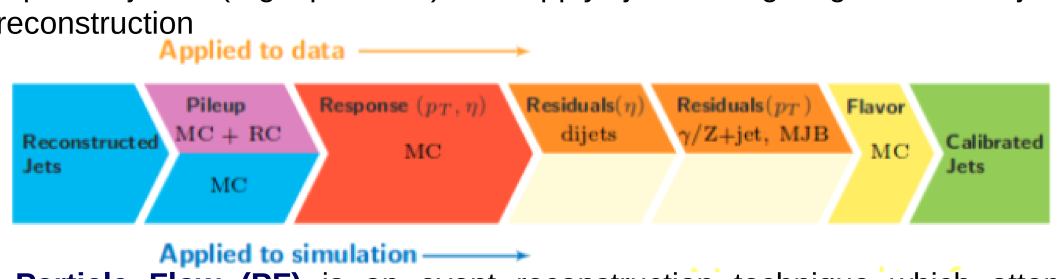
- Jets in *pp* collisions are described by QCD in terms of parton-parton scattering, where the outgoing scattered partons manifest themselves as hadronic jets.
- In this frame the partonic cross section is convoluted with PDFs
- Jet production in pp collisions directly sensitive to quark and gluon distributions (PDFs) and α_S



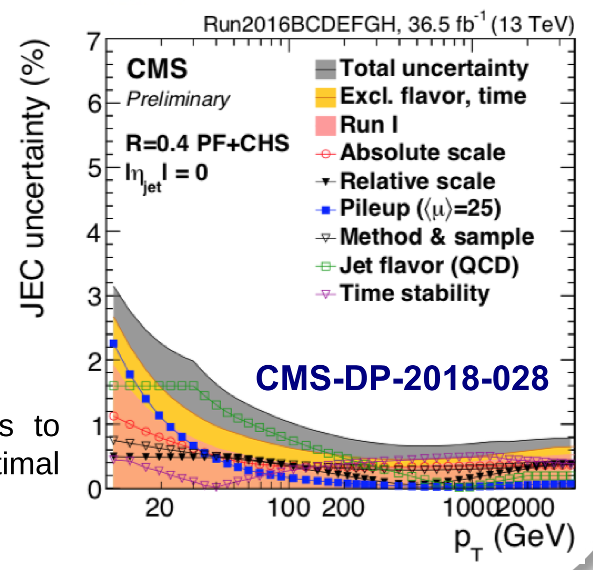


Jet reconstruction & calibration @ CMS

- Factorized approach to match energy of detector level jets to particle level jets (on average)
- Input objects (e.g. particles) → apply jet finding algorithm → jet reconstruction

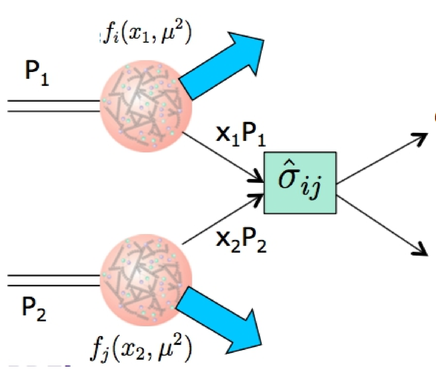


- **Particle Flow (PF)** is an event reconstruction technique which attempts to reconstruct and identify all stable particles in the event, through the optimal combination of all CMS sub-detectors.
- Anti-k_T jet clustering algorithm is used by CMS measurements



Hard QCD cross sections

- Parton density functions (PDFs)
  - evolution with DGLAP equations (Q^2 ordered)
- Hard scattering cross section
  - depend on process
  - valid in short distance
  - small coupling constant
  - calculable with pQCD



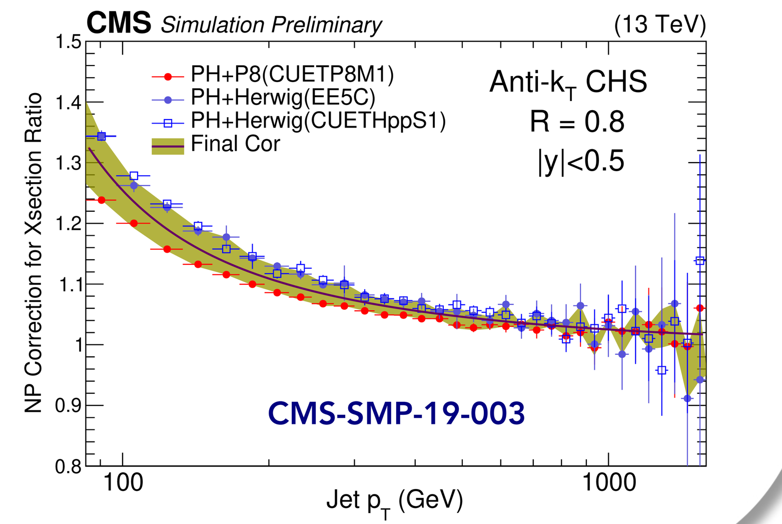
$$\sigma(P_1,P_2)=\sum_{i,j}\int dx_1 dx_2 f_i(x_1,\mu^2) f_j(x_2,\mu^2)\,\hat{\sigma}_{ij}(p_1,p_2,\alpha_S(\mu^2),Q^2/\mu^2) + \text{parton fragmentation}$$

$$\frac{d^2\sigma}{dp_T dy}=\frac{1}{\epsilon\cdot\mathcal{L}_{\mathrm{eff}}}\frac{N_{\mathrm{jets}}}{\Delta p_T(2\cdot\Delta|y|)} \propto \alpha_s^2$$

- Final-state hadronization (q,g,Q → π,k,p,D,B) or bound-state formation (ccbar,bbar):
  - Universal FFs fitted from data+DGLAP evolution

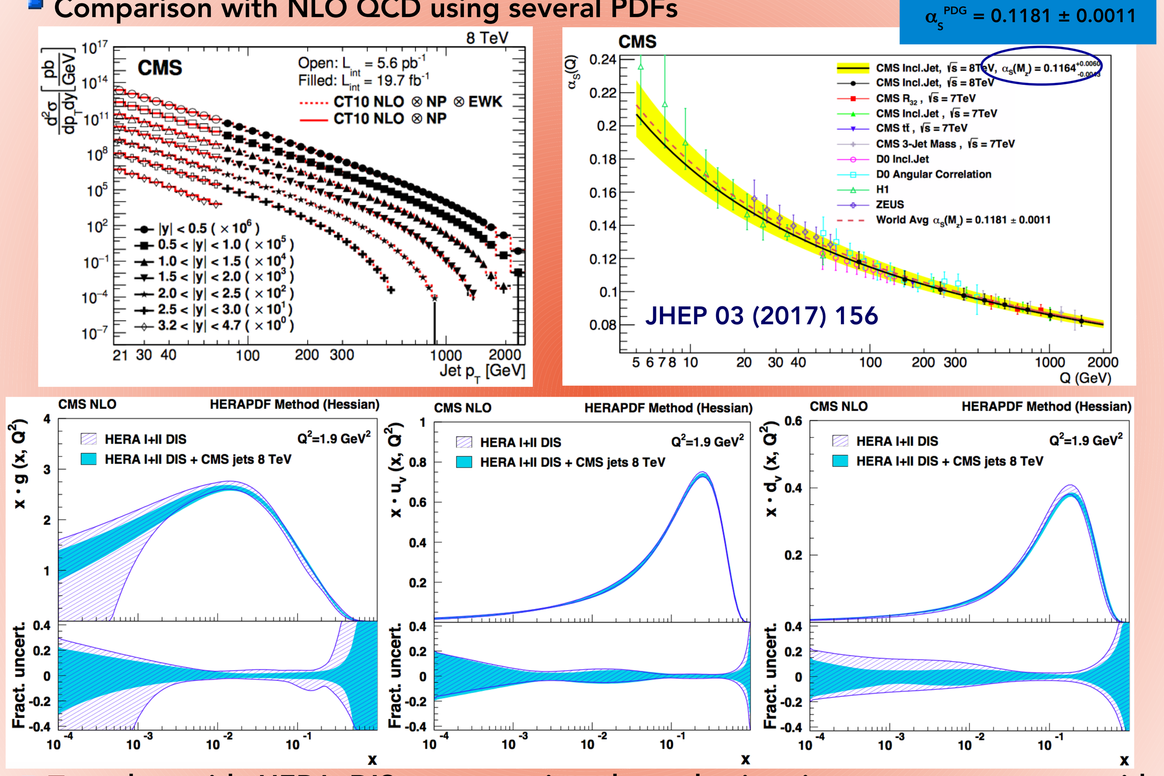
NP Corrections for fixed order predictions

- Fixed order calculation provides differential cross-section for parton level jets but jets in data are made from hadrons => needs additional correction
- Based on MC prediction from hadronization models & MPI tunes in parton shower
  - Hadronization correction is larger more small jet sizes
  - MPI correction has significant size for large jet radii



Inclusive Jets @ 8 TeV

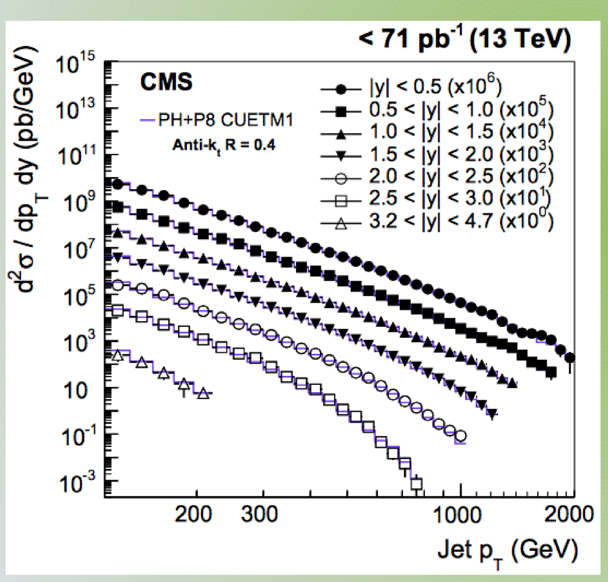
- Jet p_T range measured: [74,2500] GeV for |y| < 3 and [21,74] GeV for 3.2 <|y|< 4.7
- Good agreement over the whole p_T&y range for fixed-order calculations corrected for NP and EW effects
- Comparison with NLO QCD using several PDFs

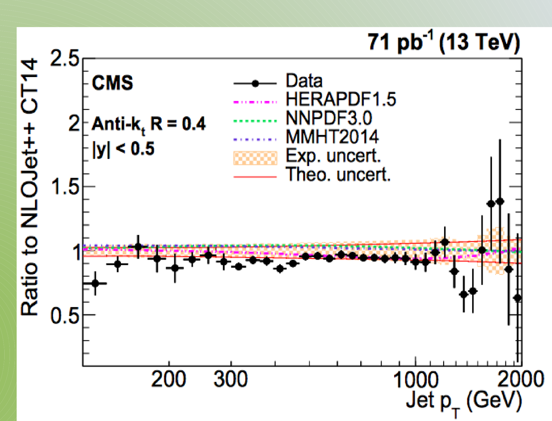


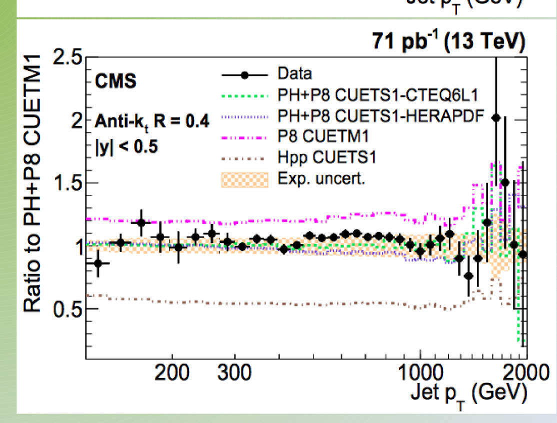
- Together with HERA DIS cross section data, the inc. jet measurements provide important constraints on the gluon and valence-quark distributions in the kinematic range studied.
- The parametrization unc. is significantly reduced once the CMS jet measurements are included.
  - No deviation from the QCD predictions is observed.
  - Improvement in the uncertainty of the gluon distributions at high-x

Inclusive Jets @ 13 TeV

- Jet p_T range measured: [74 , 2500] GeV for |y| < 4.7
- Results for ΔR = 0.7 and 0.4 up to |y| = 4.7
  - Smaller cone size, R=0.4, enables direct comparisons to ATLAS
- Excellent agreement with Powheg+Pythia8
  - p_T shape OK in Herwig++
  - Softer p_T in Pythia8 for larger |y|
  - Same results for both ΔR







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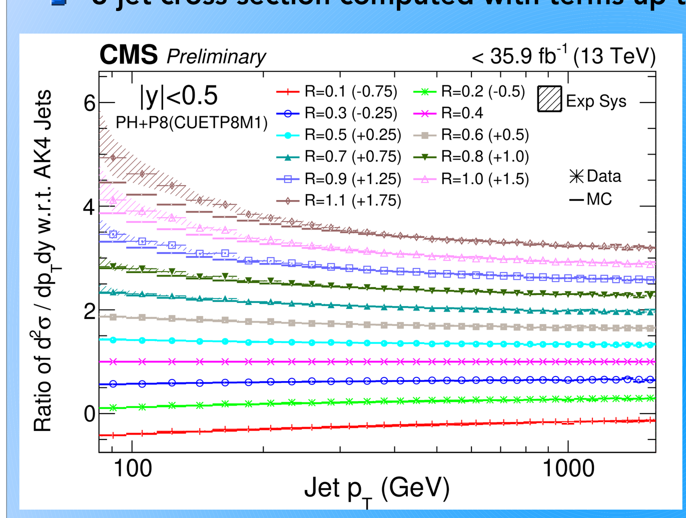
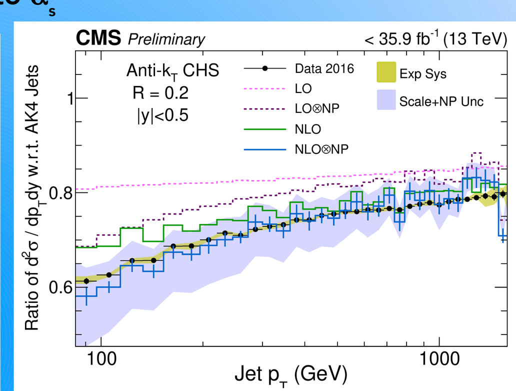
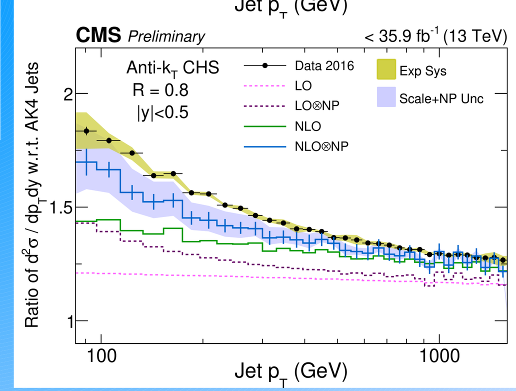
Ratio of Cross Sections

- Data is compared to Powheg+Pythia8 prediction
- NLO + PS prediction describes data well till moderate values of jet radii and also at high jet pT
- Deviation occurs in low pT region for large jet sizes
- 3-jet cross-section computed with terms up to α_s^4







- Inclusive jet cross sections are determined in pT and y bins for all the jet sizes
- Ratio is taken with respect to the AK4 jet cross section in Herwig7 in the same pT and y bin
- Fixed order prediction shows a different trend of the ratio versus R as compared to MC predictions

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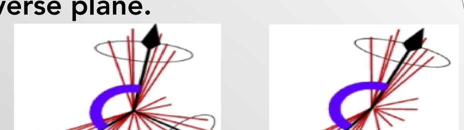
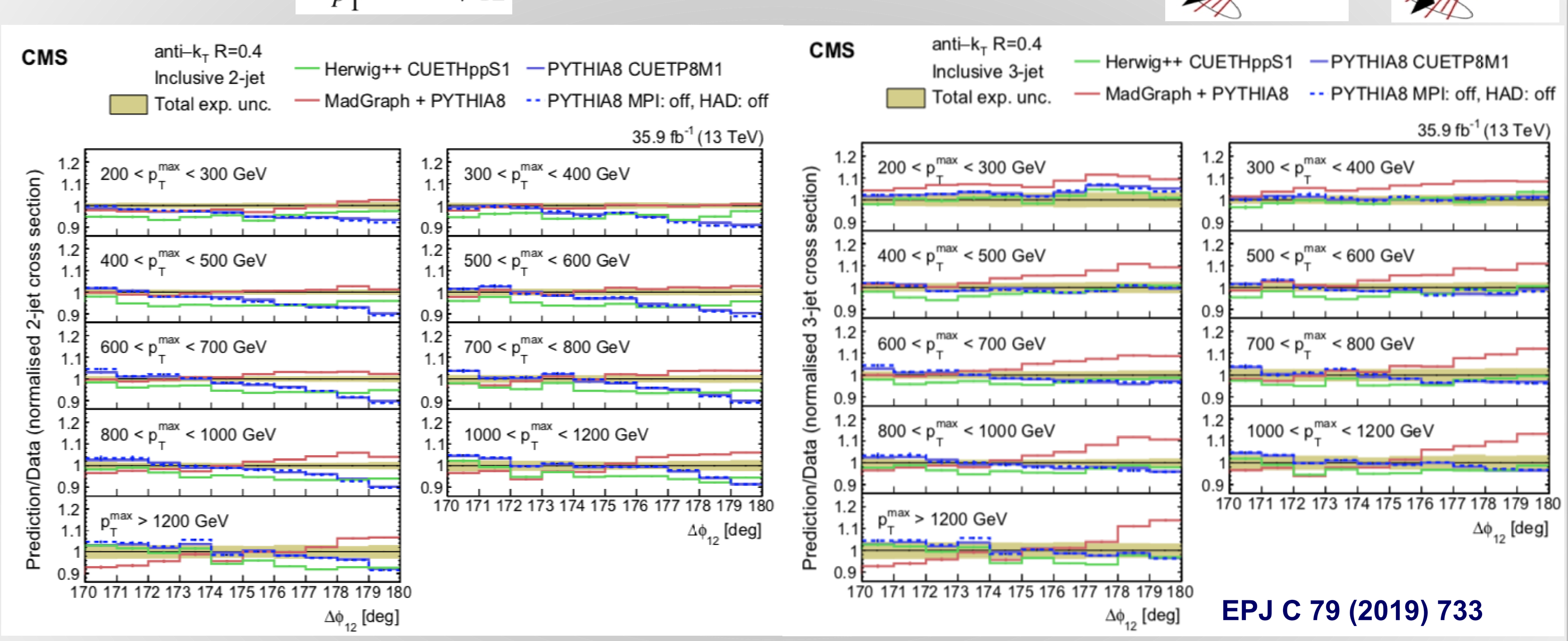
Azimuthal correlations in 2- and 3- jet events

- Inclusive 2- and 3-jet events of the azimuthal correlation between the two jets with the largest p_T
- Two leading jets are nearly collinear ("back-to-back") in the transverse plane
- The azimuthal separation, $\Delta\varphi_{12}=|\varphi_{jet1}-\varphi_{jet2}|$, between the two leading p_T jets in the transverse plane.

$$\frac{1}{\sigma}\frac{d\sigma}{p_T^{max}\, d\Delta\phi_{12}}$$





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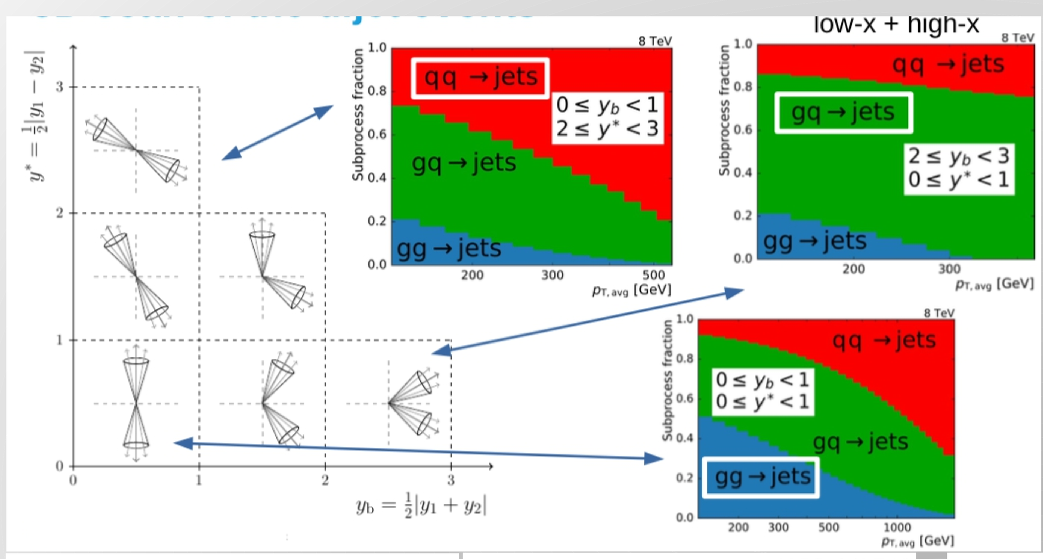
- \>= 2 Jets vs LO:
  - Best description by MadGraph + Pythia8 (CUETP8M1) up to 4 jets in ME, MLM matching
  - Pythia8 not steep enough
- \>= 3 Jets vs LO: The worst description by MadGraph + Pythia8 (CUETP8M1) up to 4 jets in ME, MLM matching
- Non of the generators is able to describe the 2- and 3-jet observables simultaneously
- The measurement of correlations for collinear back-to-back dijet configurations probes the multiple scales involved in the event and, therefore, the differences observed between predictions and the measurements illustrate the importance of improving the models of soft parton radiation accompanying the hard process.

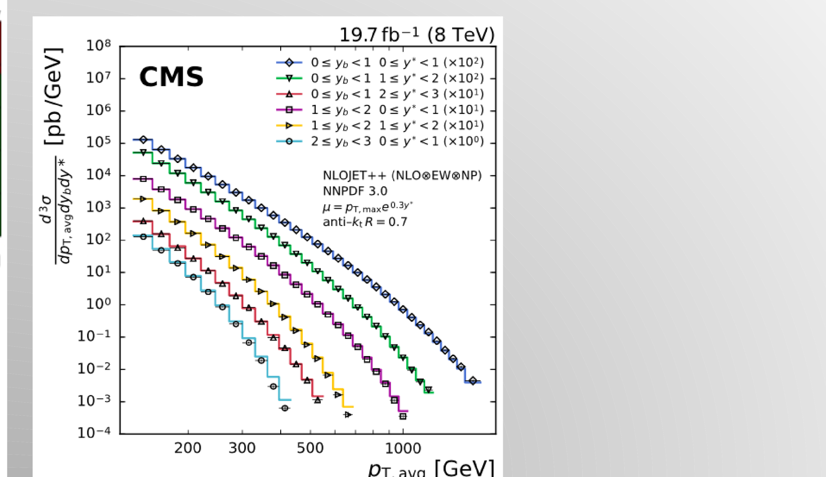
Triple-differential dijet cross sections

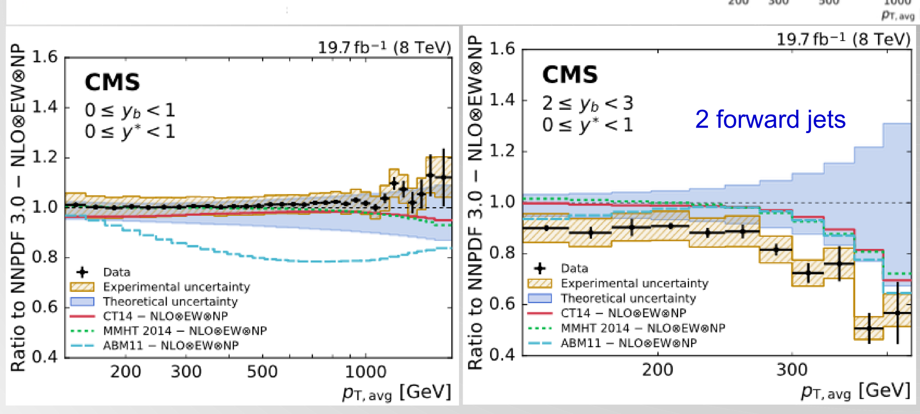
- Cross sections measured as a function of: $<p_T>$, half the rapidity separation: $y^*=1/2|y_1y_2|$ and boost of the two leading jets $y_b=1/2|y_1+y_2|$
- Apart from the boosted region, the data are well described by the predictions at NLO accuracy over many orders of magnitude.

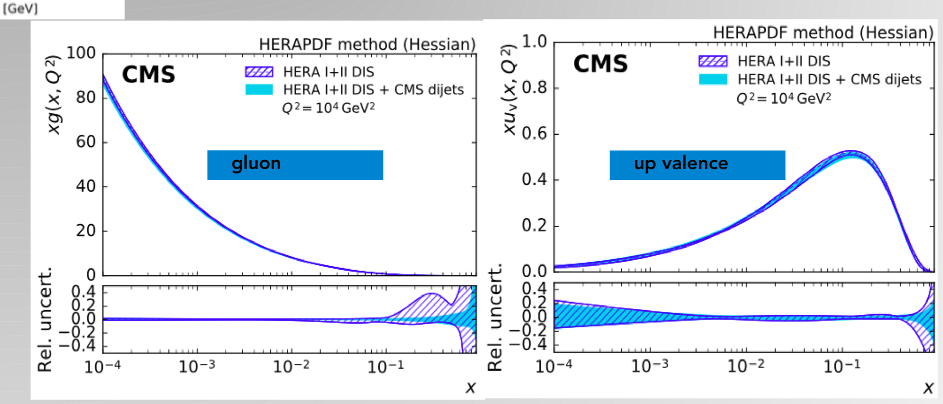
Triple differential dijet cross section

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









- PDF sensitivity + PS matching effects. (POWHEG vs HERWIG7 vs NLOJET++)
- Dominated by PDF uncertainty

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- This measurement is very well suited to extract PDFs and α_s:
  - central region most suited for α_s extraction at high energy scales
  - boosted region high-x region of PDFs can be better constrained
  - large rapidity separation PDF and detector effects can be better disentangled
- Fit combines HERA and CMS data

Summary

- CMS has a rich physics program which is the perfect testing ground for QCD models and theory
  - Wealth of jet data
  - Significant ongoing effort to improve our understanding of QCD
- Results provide new constraints for non-perturbative and semi-hard QCD dynamics on MC precision measurements
- Ranging from low p_T to high p_T and from inclusive to exclusive observables a large amount of QCD precision measurements
- Still more measurements and efforts on-going
  - Jets become even more interesting with available NNLO calculations
  - Stay tuned!

15th Vienna Central European Seminar on Particle Physics and Quantum Field Theory

Precision Physics at the LHC

References

- CMS Collaboration: CMS-DP-2018-028
- CMS Collaboration: CMS-PAS-SMP-19-003
- JHEP 03 (2017) 156
- EPJ C 76 (2016) 451
- EPJ C 79 (2019) 733
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