Multi-differential jet cross sections in CMS

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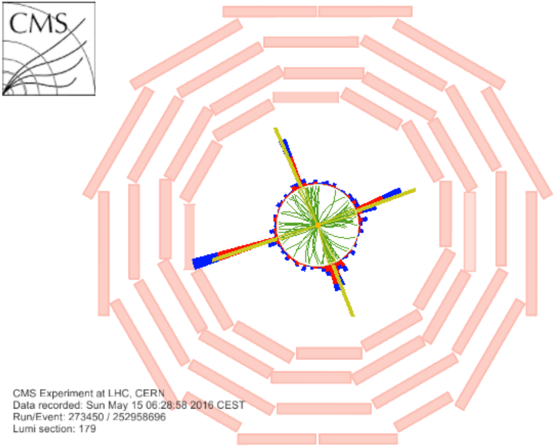
April 2017

QCD

- Main background to almost any interesting and rare event at a hadron collider.
- Understood in terms of factorization theorems.
- Extraction of α_s and PDFs.
- Many subtleties remain unclear (MM schemes, PS and resummation, factorization breaking and soft gluons color correlations...)

Jets measurements

- Partons express themselves through collimated streams of hadrons.



Double-differential inclusive jets cross sections
in pp collisions at $\sqrt{s} = 8$TeV
DOI: 10.1007/JHEP03(2017)156

Double-differential inclusive jet cross sections
in pp collisions at $\sqrt{s} = 13$TeV
DOI: 10.1140/epjc/s10052-016-4286-3

Inclusive jets cross sections @8TeV and 13TeV

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

- $p + p \to jet + X$ probes parton-parton interaction (Benchmark QCD test)

- Sensitive to α_s

- Provides important PDFs constraints

- QCD describes data within 14 orders of magnitude!!

- Experimental uncertainties dominated by JES, unfolding and the integrated luminosity.

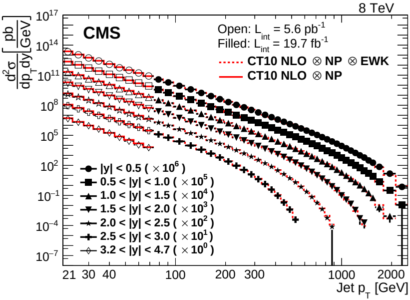
- Strongly p_T and y dependent PDF uncertainties (dominant)

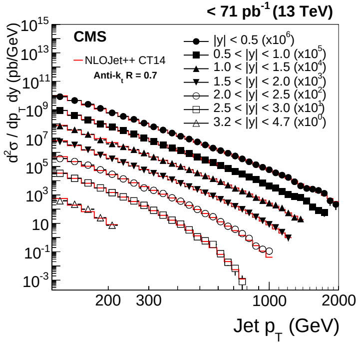
Inclusive jets cross sections @8TeV

- anti-k_t7, bins of rapidity $\in [0, 4.7]$

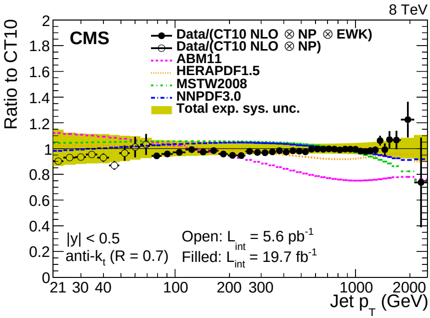
Inclusive jets cross sections @13TeV

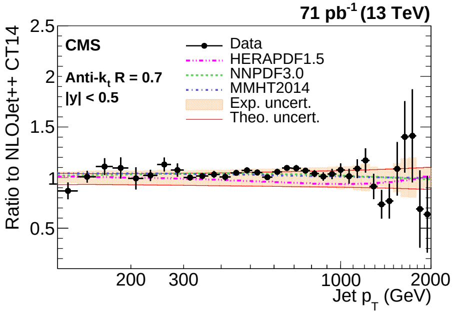
- anti-k_t4 and anti-k_t7, bins of rapidity $\in [0, 4.7]$





Inclusive jets cross sections @8TeV and 13TeV



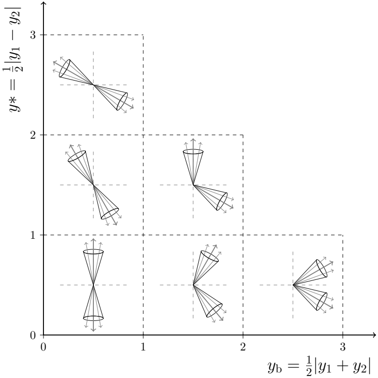


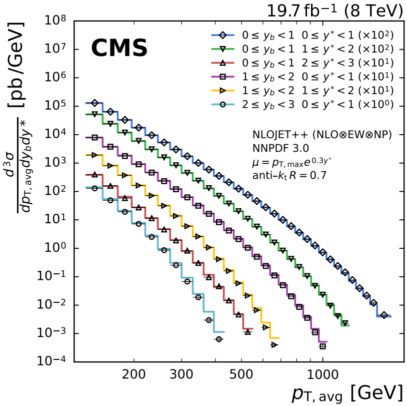
- Predictions are in good agreement with data
- More can be learnt from these measurements → see next slides

Measurement of the triple-differential dijet cross section in pp collisions at $\sqrt{s} = 8\text{TeV}$

arXiv: 1705.02628

Triple differential dijet cross section @8TeV



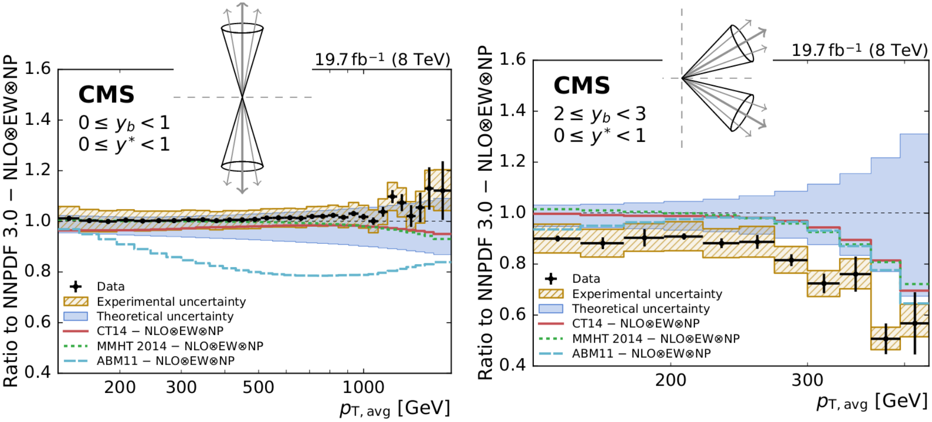


$$\frac{d^3\sigma}{dp_{T,avg}\, dy*\, dy_b} = \frac{1}{\epsilon \mathcal{L}_{\text{int,eff}}} \frac{N}{\Delta p_{T,avg} \Delta y* \Delta y_b}$$

- $p_{T,avg}$ leading jets average p_T
- $y* = |y_1 - y_2)|/2$
- $y_b = |(y_1 + y_2)|/2$

- Test of pQCD
- Determination of coupling constant
- Constraints on PDFs

Triple differential dijet cross section @8TeV



- For mid-x ($\sim$ partonic momentum fraction) regions data are well described
- Boosted topologies (large-x) lacks from PDF information
- Significantly small uncertainties at large-x $\rightarrow$ potential constraints on PDF

PDF constraints

- Largest impact on the high-x region

- PDF uncertainty from experimental, model, and parameterisation uncertainty

α_s extraction

$$\frac{d^2\sigma}{dp_T\,dy} \propto \alpha_s^2 \;(2\rightarrow 2 \text{ LO})$$

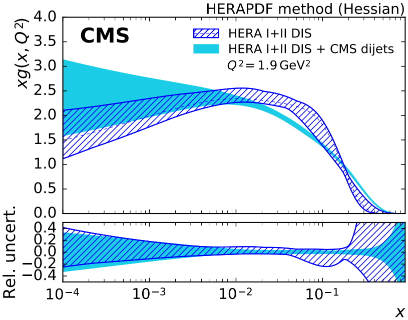
- α_s an additional free parameter in the PDF fit

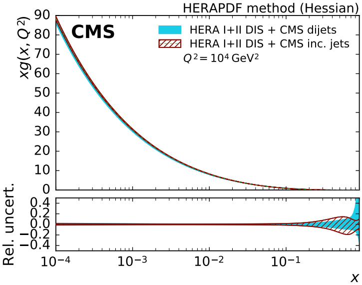
$\alpha_s(M_Z) = 0.1199 \pm 0.0015(exp)^{+0.0002}_{-0.0002}(mod)^{+0.0002}_{-0.0004}(par)$

$\Delta\alpha_s(M_Z) = ^{+0.0026}_{-0.0016}\;(scale, refit)$

- α_s measurement dominated by theory uncertainties

- World average value:
$\alpha_s(M_Z) = 0.1181 \pm 0.0011$





Strong coupling constant from the measurement of inclusive multijet event cross sections in pp collisions at $\sqrt{s} = 8$TeV

to be published

Inclusive 2-jets, 3-jets and R_{32}

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

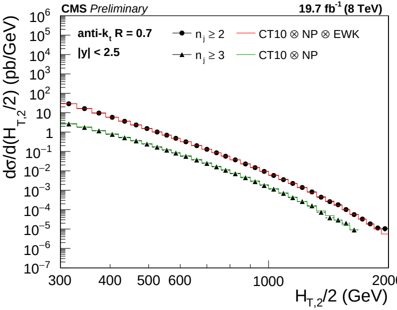
$H_{T,2}/2$: leading jets average p_T, and scale of the event

- Inclusive 3-jets, inclusive 2-jets were studied

$R_{32} = \frac{d\sigma_3}{d\sigma_2} \propto \alpha_s$

- JES is the dominant systematic uncertainty for σ_2 (3-10%) and σ_3 (3-8%)

- $R_{32} \to$ theoretical and experimental uncertainties partially cancel (exp. uncertainties $\sim$ 1%)

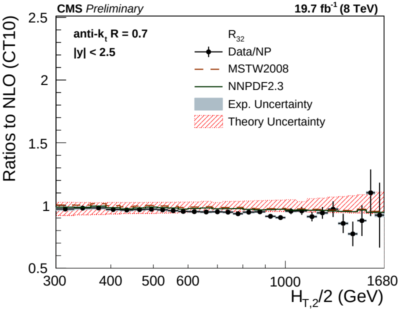


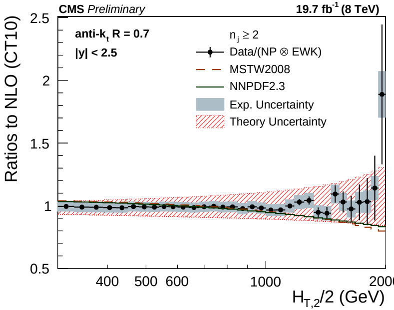
Inclusive 2-jets, 3-jets and R_{32}

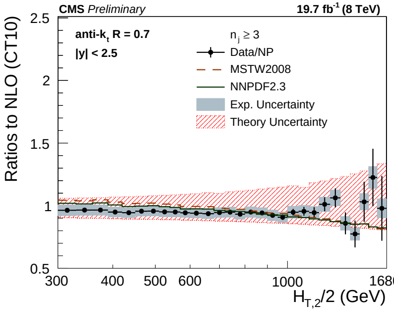
- Data are well described by the predictions

- Uncertainties: large $H_{T,2}/2 \rightarrow$ PDF dominates in the upward direction, scale uncertainties in the downward direction

- $R_{32} \rightarrow$ uncertainties significantly reduced.





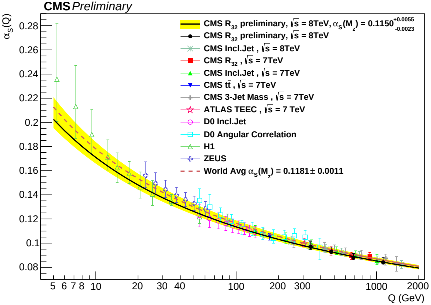


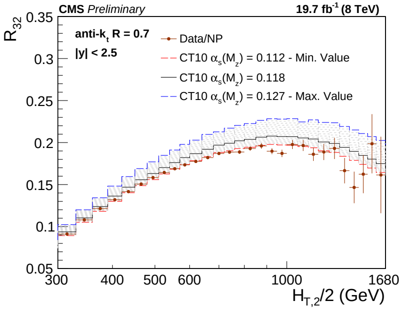
α_s extraction

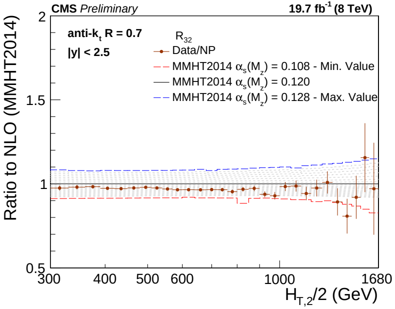
- Minimizing the χ^2 between the experimental measurement and the theoretical predictions

- Using MSTW2008 PDF:
$\alpha_s(M_Z) = 0.1150 \pm 0.0010(exp) \pm 0.0013(PDF) + \pm 0.0015(NP)^{+0.0050}_{-0.0000}(scale)$

- Result for $\alpha_s(M_Z)$ is in agreement with the world average value of $\alpha_s(M_Z) = 0.1181 \pm 0.0011$







Measurement of angular and momentum distributions in multi-jet final states at $\sqrt{s} = 8\text{TeV}$ and 13TeV

not yet released

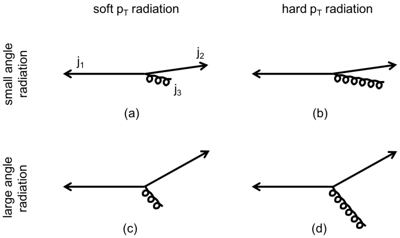
Multi-jets correlations @8TeV and 13TeV

- Interplay between parton showers and Matrix Elements

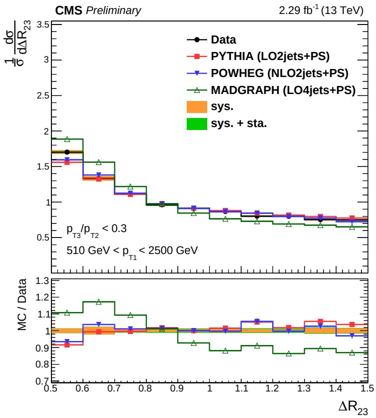
- Soft and hard radiation sensitivity $\rightarrow p_{T3}/p_{T2}$

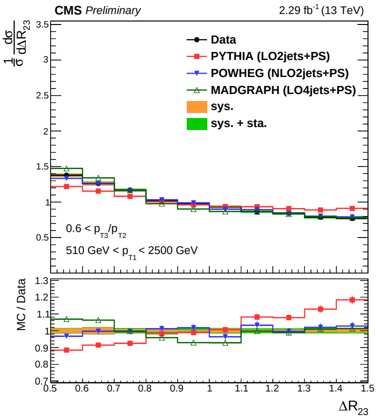
- Collinear and wide angle radiation sensitivity $\rightarrow \Delta R_{23}$

Criteria	Radiation type
$p_{T3}/p_{T2} < 0.3$	soft p_T radiation
$p_{T3}/p_{T2} > 0.6$	hard p_T radiation
$\Delta R_{23} < 1.0$	small angle radiation
$\Delta R_{23} > 1.0$	large angle radiation



Multi-jets correlations @8TeV and 13TeV





- All theoretical predictions show significant deviations from the measurements

- Contribution from higher order ME calculations supplemented with parton showers are necessary for describing the hard region

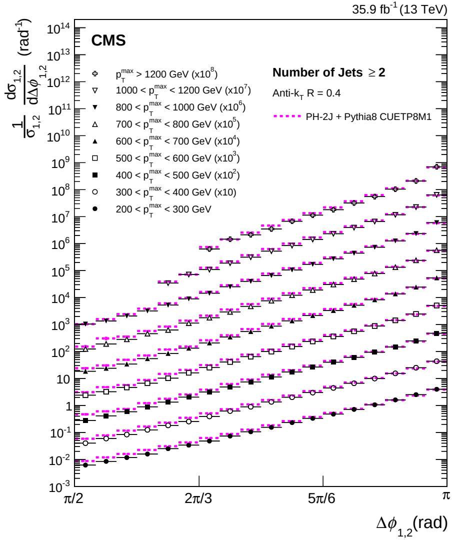
Measurements of inclusive 2-jet, 3-jet and 4-jet azimuthal correlations in pp collisions at 13TeV

to be published

Dijet cross section @13TeV

$$\frac{1}{d\sigma_{1,2}} \frac{d\sigma_{1,2}}{d\Delta\phi_{1,2}}$$

- Bin size 5° - Interesting tool to test theoretical predictions of multijet production processes
  - Region away from π is sensitive to hard radiation from ME
  - Region close to π is sensitive to resummed contributions from PS
- Overall description of the data is achieved and understood
  - JES is the dominant systematic uncertainty (from 3% at $\pi/2$ to 0.1% at π)



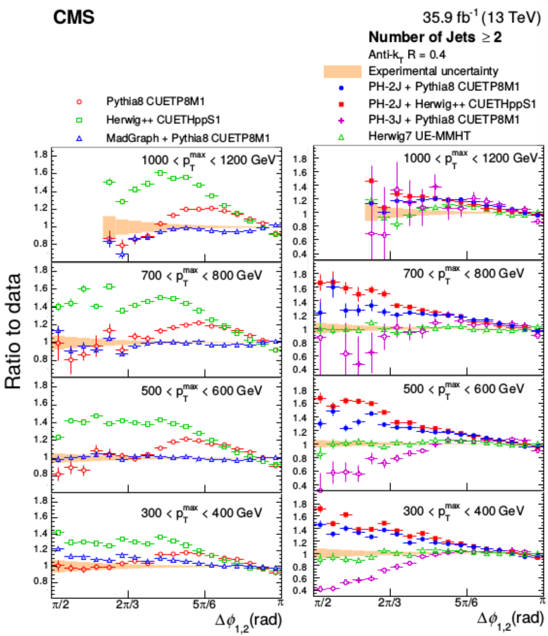
Dijet azimuthal angular correlations

- MadGraph (up to 2→4 LO) describes well the data whereas P8 and Herwig++ (2→2 LO) fail significantly

- Powheg 2J and Powheg 3J are not able to describe the data better than P8 and Herwig++, even though they provide multi-leg ME

- Herwig7, formally NLO but effectively 2→3 LO, gives a good description of the data

- For this observable MC@NLO method of combining parton shower with the NLO parton level calculations has advantages compared to the POWHEG method



Azimuthal angular correlations in high transverse momentum dijet events

in high transverse momentum dijet events

not yet released

$$\frac{1}{d\sigma_{1,2}}\frac{d\sigma_{1,2}}{d\Delta\phi_{1,2}}$$

- In inclusive 2-jets and 3-jets events

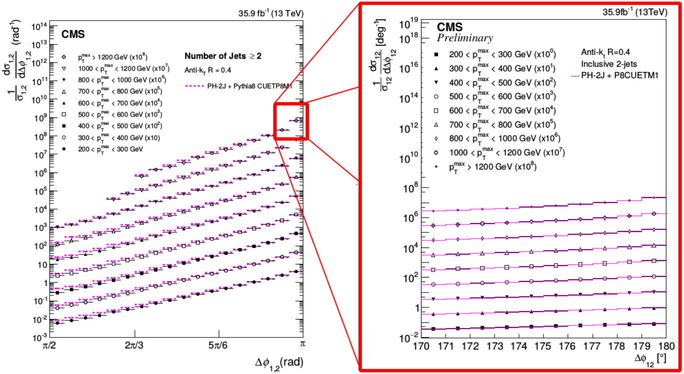
- Finer binning of 1°

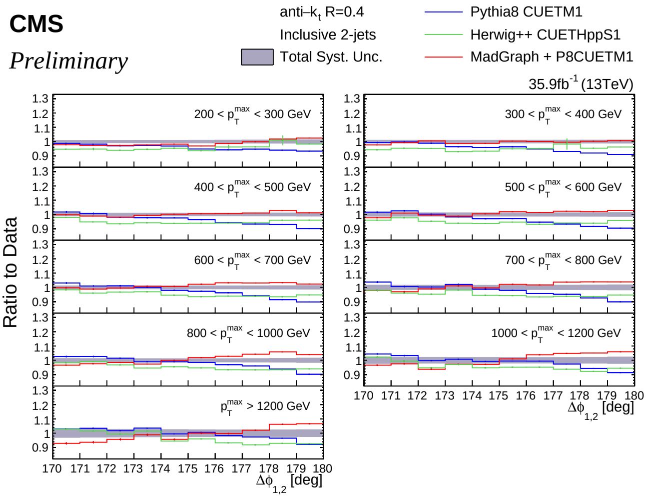
- Detailed investigation of the resummation region ($\Delta\phi \sim 180°$)

- Testing the resummed predictions coming from different Parton Shower models

- Studying matching and merging formalisms

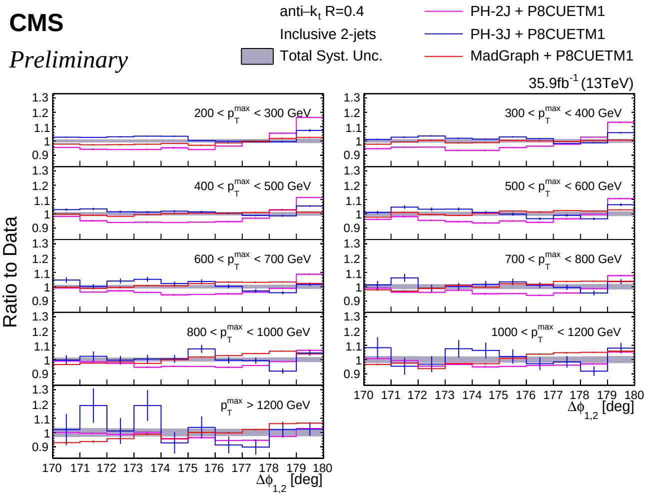
- Soft radiation interference and factorization breaking





- MadGraph gives the best description, and starts to fail towards high p_T^{max}
- P8 and Herwig++ perform similarly
- Differences of up to 10%

- Pythia8 and Herwig++ resum in the same way (only evolution variable differs)
- There are correlations towards high p_T^{max} which are not captured either by the parton shower nor the multi-leg final state ME from MadGraph



- MadGraph and Powheg 3J give the best description
- Powheg 2J fails to describe the data
- Biggest discrepancies in the last bin

- MadGraph and Powheg 3J, both go to up to $2 \to 4$ partons
- Powheg 2J is effectively $2 \to 3$ LO

Summary

Inclusive jet cross sections @$\sqrt{s} = 8$ and $\sqrt{s} = 13$TeV

- Sensitive to α_s
- Provides important PDFs constraints
- QCD describes data within 14 orders of magnitude!!
- Experimental uncertainties dominated by JES, unfolding and the integrated luminosity.

Measurement of the triple-differential dijet cross section

- Test of pQCD
- Determination of coupling constant and constraints on PDF

Strong coupling constant from inclusive multijet events

- Test of QCD
- R_{32} is used to access extract α_s

Multi-jets correlations @8TeV and 13TeV

- Interplay of ME and PS when dealing with soft and hard scales
- All theoretical predictions show significant deviations from the measurements

Dijet azimuthal angular correlations @$\sqrt{s} = 13$TeV

- Overall description of the data is achieved and understood
- For this observable MC@NLO method of combining parton shower with the NLO parton level calculations has advantages compared to the POWHEG method

Azimuthal angular correlations in high transverse momentum dijet events

- Multi-leg final state MC Powheg 3J and Madgraph provide a good description of the data
- They start to fail towards high p_T^{max} were presumably non-trivial correlations appears

Thank you for your attention.