Measurement of the double-differential dijet mass cross section at 13 TeV with CMS

PhD student
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Friday, 17th June 2022

Outline

- **Introduction**
  - Motivation
  - LHC & CMS
  - Jets
- Detector Level Spectrum
- Unfolding
- Experimental Uncertainties
- Theory
- Summary
- Back Up

Introduction - Motivation

1. Precise measurement
2. Comparison to NNLO pQCD predictions
3. Tune Monte Carlo event generators
4. Improve Parton Distribution Functions

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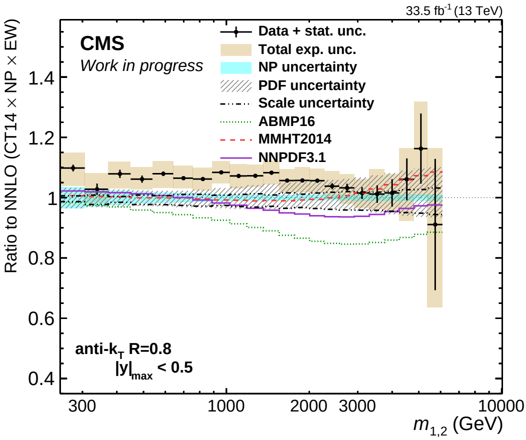

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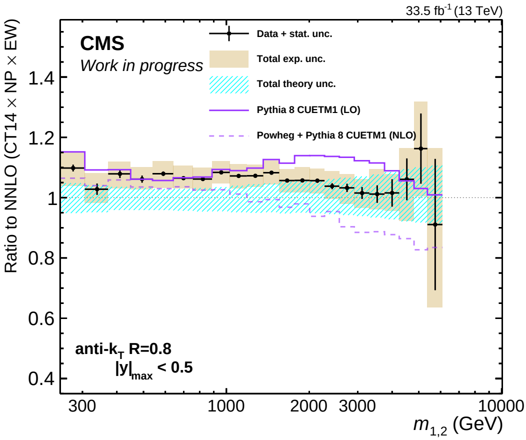

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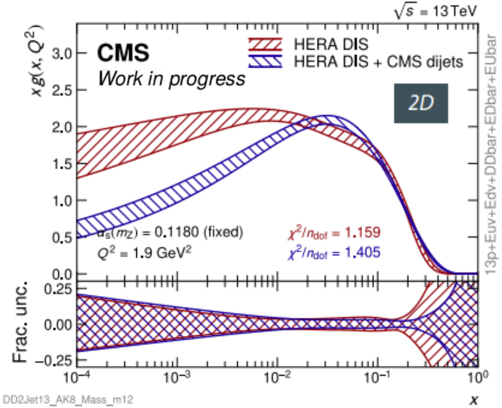
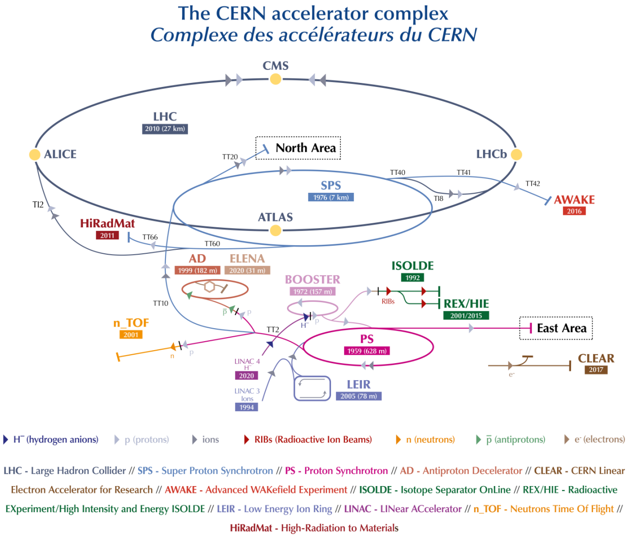
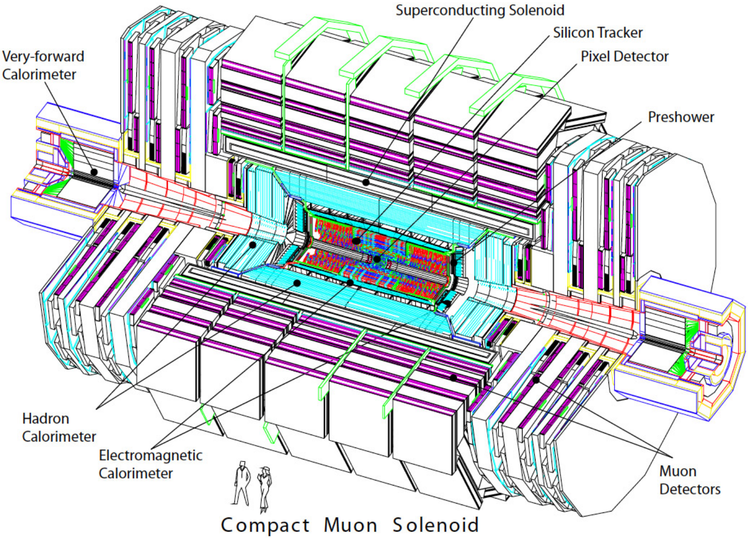


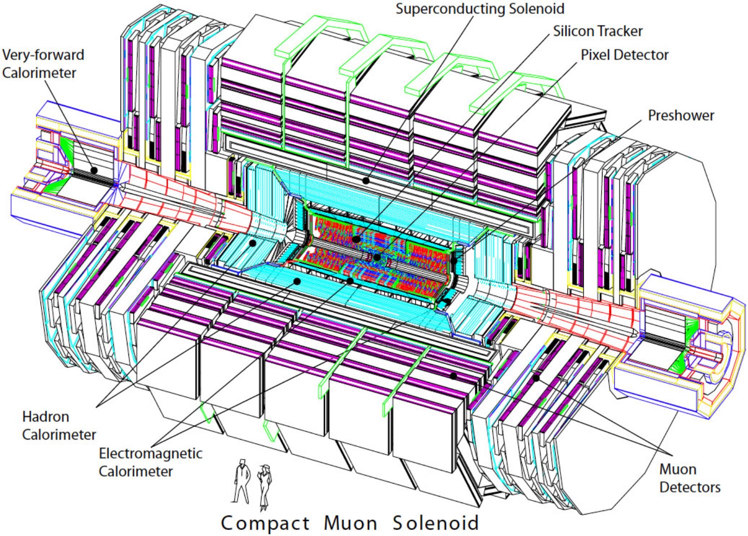
Large Hadron Collider

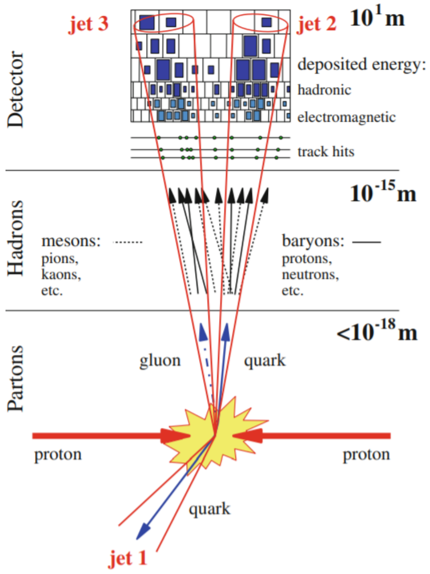


Compact Muon Solenoid



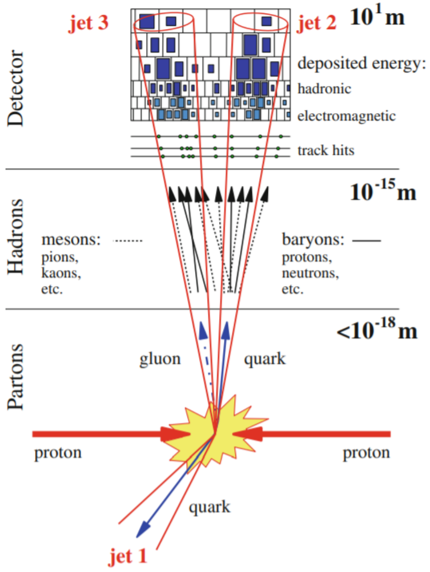
Compact Muon Solenoid + Trigger System





1. p $\longrightarrow \cdot \longleftarrow$ p Collision (hard process)
2. Parton production $\# \geq 2$ (asymptotic freedom)
3. Parton shower ($\alpha_S << 1$)
4. Bound states - Hadronization ($\alpha_S >> 1$)
5. Stream of hadrons $\longrightarrow$ Jet formation!

Introduction - Jets



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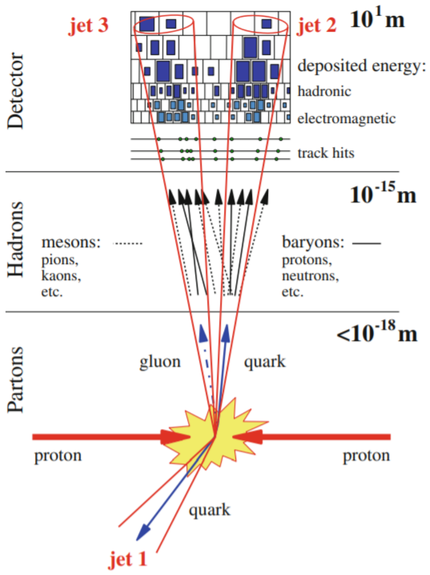

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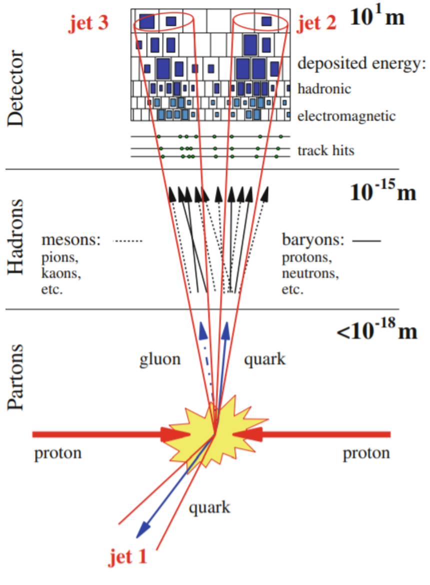

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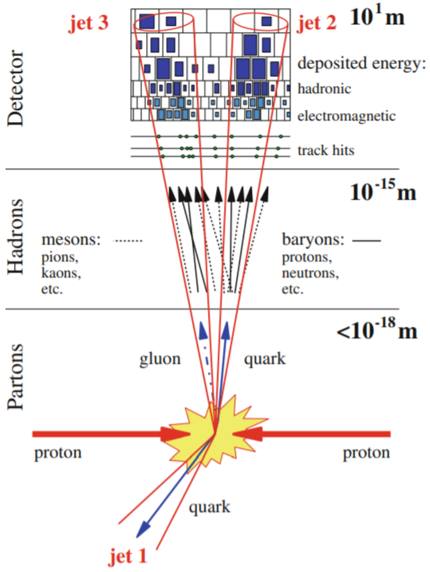

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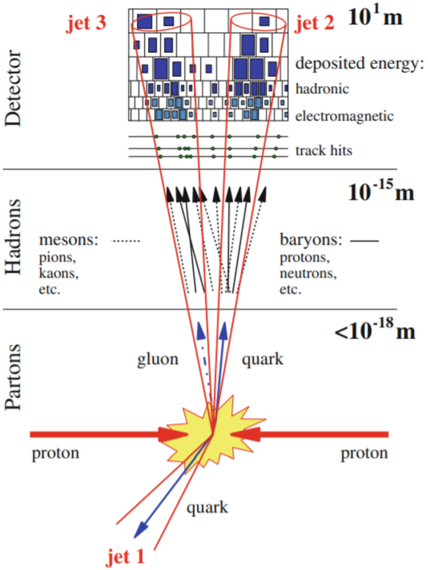

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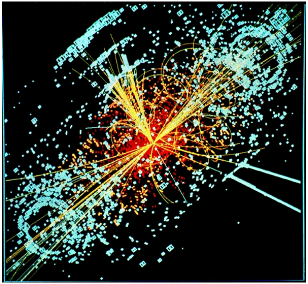

Outline

Detector Level Spectrum - Samples & Selection

- **Data Samples:** Use of 2016 Data $\longrightarrow$ $\mathcal{L}_{int} = 33.5\ fb^{-1}$
- **MC Samples:** Pythia8 $\hat{p_T}$ slices, Tune CUETM1 (15 Slices)
- **Corrections:** Following standard recommendations on both Data and MC
- **Selection:**
  - ∗ Jet Algorithm: $\mathbf{anti-k_t}$ with $R = \mathbf{0.8}$
  - ∗ Jet Type: PFchsJets
  - ∗ Events: At least **two jets** with $p_{T1} \geq 100\ GeV, p_{T2} \geq 50\ GeV$ and $|y_1| < 2.5$, $|y_2| < 2.5$

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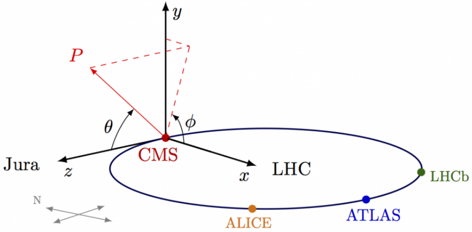
CMS coordinate system



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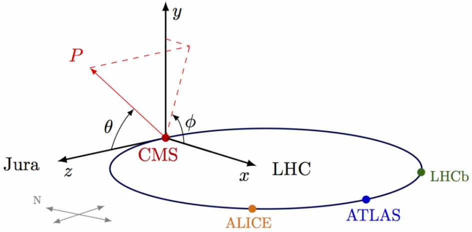
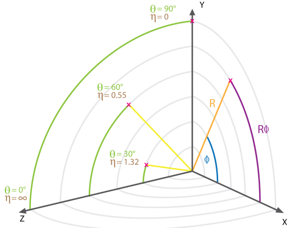




Detector Level Spectrum - About the Observable

- **Observable**: Measurement of the inclusive differential dijet cross-section as a function of the invariant mass of the two leading jets in the event.

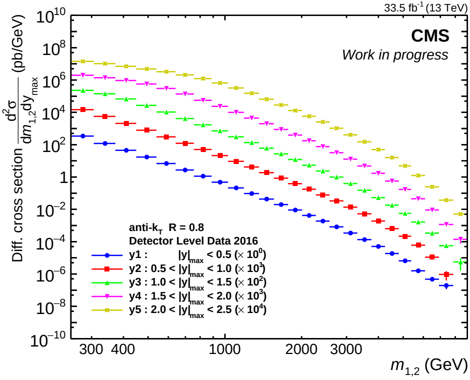
$$\frac{d^2\sigma}{dm_{1,2}\, dy_{max}} = \frac{1}{\mathcal{L}_{int}} \cdot \frac{N}{\Delta m_{1,2}(2 \cdot \Delta|y|_{max})},$$

$$m_{1,2} = \sqrt{(E_1 + E_2)^2 - (\vec{p_1} + \vec{p_2})^2},$$
$$|y|_{max} = max(|y_1|, |y_2|).$$

Measurement presented in five absolute regions of y_{max} $\longrightarrow [0.0, 0.5],\ [0.5, 1.0],\ [1.0, 1.5],\ [1.5, 2.0],\ [2.0, 2.5]$

- **Software**: DAS, based on CMS standard software

Detector Level Spectrum



Trigger Path	Turn on points (GeV)
HLT_AK8PFJet_40	74
HLT_AK8PFJet_60	97
HLT_AK8PFJet_80	114
HLT_AK8PFJet_140	196
HLT_AK8PFJet_200	272
HLT_AK8PFJet_260	330
HLT_AK8PFJet_320	395
HLT_AK8PFJet_400	507
HLT_AK8PFJet_450	592

- High Level single–jet Triggers
  $\longrightarrow$ HLT_AK8PFJet_X
- p_T turn on points (efficiency at 99.5%), same for all $|y|_{max}$ regions
- Event by event normalization with trigger prescales

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- **Unfolding**
- Experimental Uncertainties
- Theory
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Unfolding - Response Matrix

The Task

Particle Level Spectrum $\longleftarrow$ Detector Level Spectrum

Solution: Least-square minimization

$$\chi^2 = (y - Ax)^T (V_y)^{-1} (y - Ax)$$

- 2D−Unfolding (TUnfold) :
  - * Background (fakes)
  - * Unsmear
  - * Inefficiencies (misses)
- Response Matrix constructed by Pythia 8
- Condition Number < 10

CN: $\frac{max\_eigenvalue}{min\_eigenvalue}$

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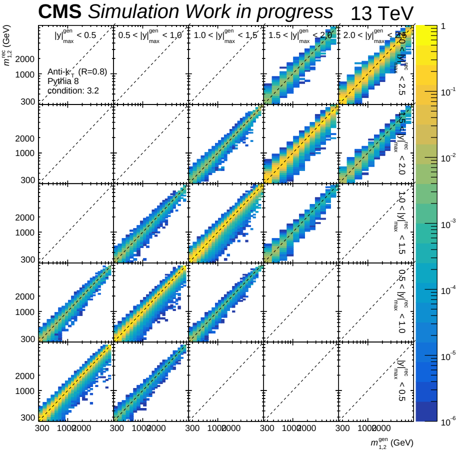

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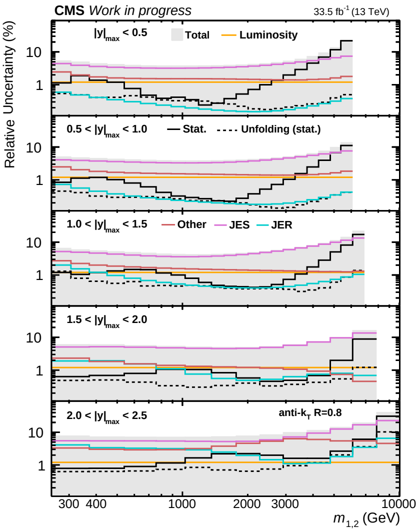
Experimental Uncertainties



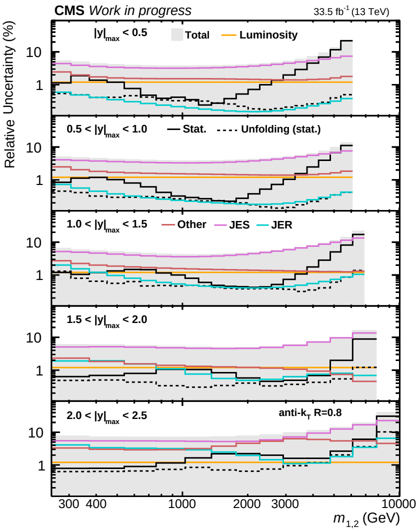
Uncertainty Sources:

1. JES dominant: 3% ⟶ 23%
2. JER: below 1% ⟶ 7%
3. Luminosity: at 1.2%
4. **Unfolding**: below 1% ⟶ 10%
5. Other (trigger and detector inefficiencies): generally ∼ 1%, but in forward region 3% ⟶ 6%
6. **Stat.** larger in high mass bins: below 1% ⟶ 31%

Remark: Total is the quadratic sum of all the contributions

4% ⟶ 41%

Experimental Uncertainties



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- **Theory**
  - Non-Perturbative (NP) Correction factors
  - Electroweak (EW) Correction factors
  - Comparison to Data
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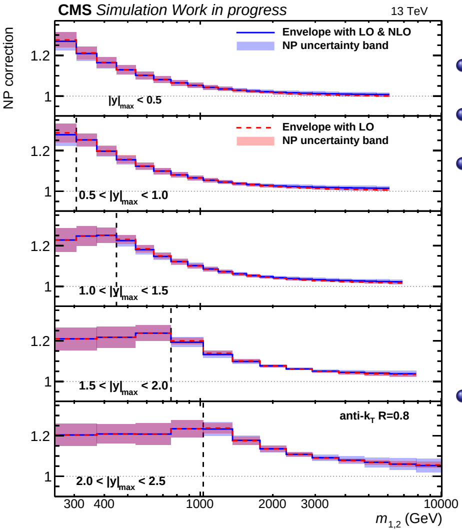
Theory - Non-Perturbative (NP) Corrections factors



- Theory $\longrightarrow$ at **Parton** Level
- Data $\longrightarrow$ at **Particle** Level
- Theory $\otimes$ C_{NPs} $\longrightarrow$ corrected for **NP effects** (*e.g.*, HAD and MPI)

  where,

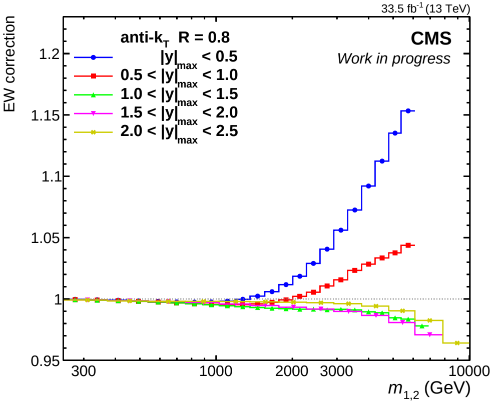
  $$C_{NPs} = \frac{MPI\_HAD\_on}{MPI\_HAD\_off} = \frac{\sigma^{PS+HAD+MPI}}{\sigma^{PS}}$$

- Larger C_{NPs} at lower $m_{1,2}$

Theory - Electroweak (EW) Correction factors

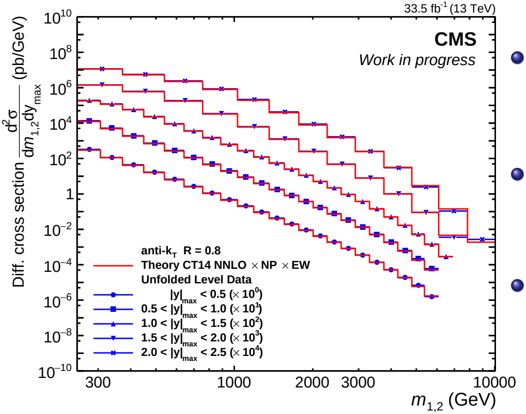
Above 1 *TeV* electroweak effects become important:

- Theory $\otimes$ C_{NPs} $\otimes$ C_{EW}



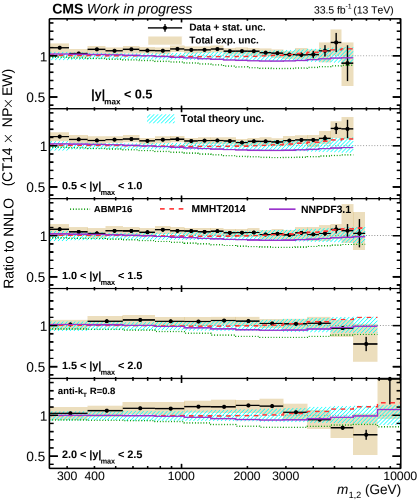
- EW factors dominant for large $m_{1,2}$ values and central $|y|_{max}$ regions
- At central $|y|_{max}$ regions up to $5-15\%$
- Change in sign for forward $|y|_{max}$ regions

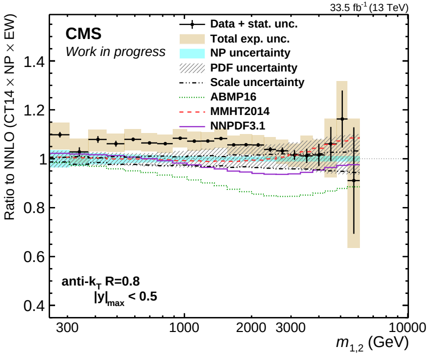
Theory - Comparison to Data



- Fixed order predictions at NNLO (NNLOJET within FASTNLO framework)
- Reference PDF set: CT14 NNLO
- Nice agreement between Data and Theory at NNLO combined with NNLO CT14 PDF set

Theory - Comparison to Data





- Good agreement in most phase space regions, mostly below 10%
- Additional PDF sets: ABMP16, MMHT2014, NNPDF3.1

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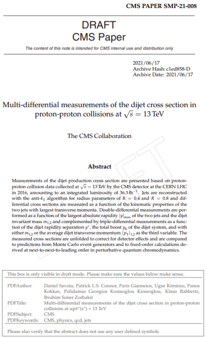
Summary

Actually this analysis is only one of the three analyses in total.
On going collaboration among 4 institutes across 3 countries.

1. Measurement of the 2D $m_{1,2}$ with $R = 0.8$
2. Measurement of the 2D $m_{1,2}$ with $R = 0.4$
3. Measurement of the 3D $m_{1,2}$ & $< p_T >_{1,2}$ with $R = 0.4$ & $R = 0.8$

Moving towards a collaborative paper publication.
Paper draft ready!

- Last item: QCD analysis



CMS PAPER SMP-21-008

DRAFT
CMS Paper

The content of this note is intended for CMS internal use and distribution only

2021/06/17
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Archive Date: 2021/06/17

Multi-differential measurements of the dijet cross section in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

Measurements of the dijet production cross section are presented based on proton-proton collision data collected at $\sqrt{s} = 13$ TeV by the CMS detector at the CERN LHC in 2016, amounting to an integrated luminosity of $36.3\,\mathrm{fb}^{-1}$. Jets are reconstructed with the anti-k_T algorithm for radius parameters of $R = 0.4$ and $R = 0.8$ and differential cross sections are measured as a function of the kinematic properties of the two jets with largest transverse momenta. Double-differential measurements are performed as a function of the largest absolute rapidity $|y|_{max}$ of the two jets and the dijet invariant mass $m_{1,2}$ and complemented by triple-differential measurements as a function of the dijet rapidity separation y^*, the total boost y_b of the dijet system, and with either $m_{1,2}$ or the average dijet transverse momentum $\langle p_T \rangle_{1,2}$ as the third variable. The measured cross sections are unfolded to correct for detector effects and are compared to predictions from Monte Carlo event generators and to fixed-order calculations derived at next-to-next-to-leading order in perturbative quantum chromodynamics.

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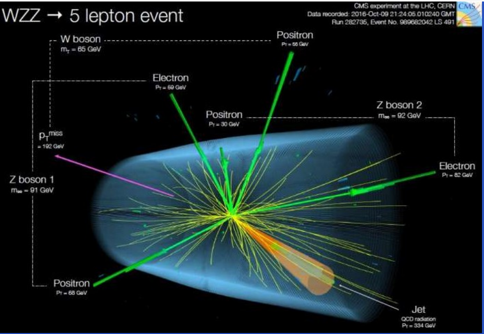
PDFAuthor:	Daniel Savoiu, Patrick L.S. Connor, Paris Gianneios, Ugur Kiminsu, Panos Kokkas, Polidamas Georgios Kosmoglou Kioseoglou, Klaus Rabbertz, Ibrahim Soner Zorbakir
PDFTitle:	Multi-differential measurements of the dijet cross section in proton-proton collisions at sqrt"(s") = 13 TeV
PDFSubject:	CMS
PDFKeywords:	CMS, physics, qcd, jets

Please also verify that the abstract does not use any user defined symbols

H.F.R.I.
Hellenic Foundation for Research & Innovation

The research work was supported by the Hellenic Foundation for Research and Innovation (HFRI) under the 3rd Call for HFRI PhD Fellowships (Fellowship Number: 83154).

The End



Thank you for you time!

Figure References

1. Slide 4: CERN accelerator complex
2. Slide 4: CMS subsystems
3. Slide 5: Jet formation
4. Slide 5: Collision example
5. Slide 7: CMS coordinate system
6. Slide 20: Collision event at CMS

Outline

Data and MC processing

On Data:

1. Raw n-tuple construction + apply basic filters
2. Jet Energy Correction
3. Normalization
4. Prefiring correction

On MC:

1. Raw n-tuple construction + apply basic filters
2. Normalization
3. Pileup removal
4. Jet Energy Correction
5. Jet Energy Resolution Correction
6. Pile Profile Reweighting Correction

θ to η and y

Relation between polar angle θ and pseudorapidity η:

$$\theta = -\ln(\tan(\theta/2))$$

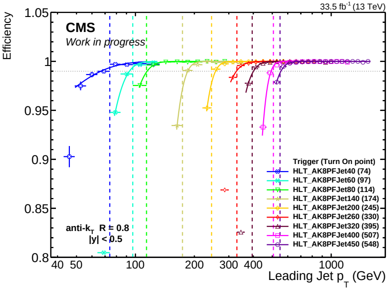
or

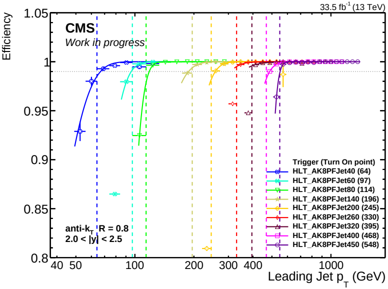
$$\theta = \frac{1}{2}\ln\left(\frac{|p|+p_z}{|p|-p_z}\right)$$

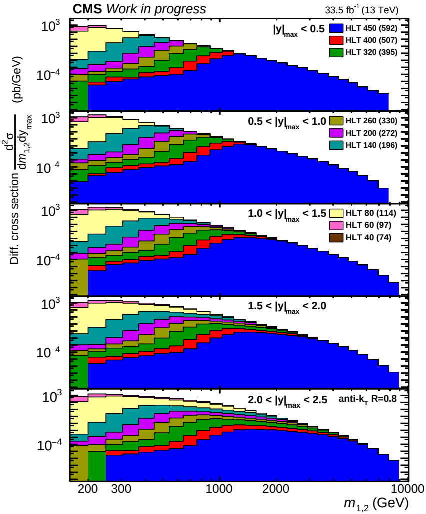
while when $m << p => E \approx p$

$$\eta \approx y \equiv \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

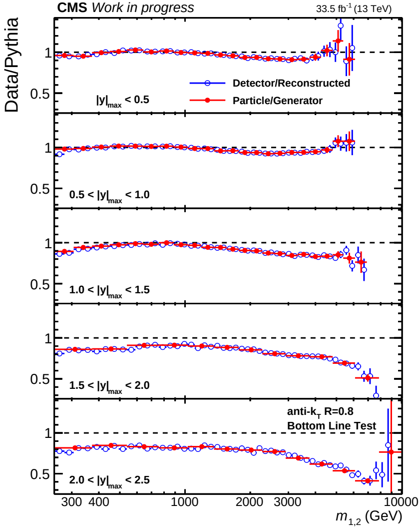
Trigger Efficiencies







Unfolding - Bottom Line Test

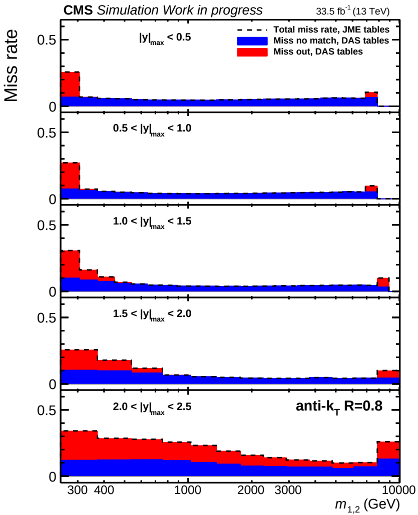


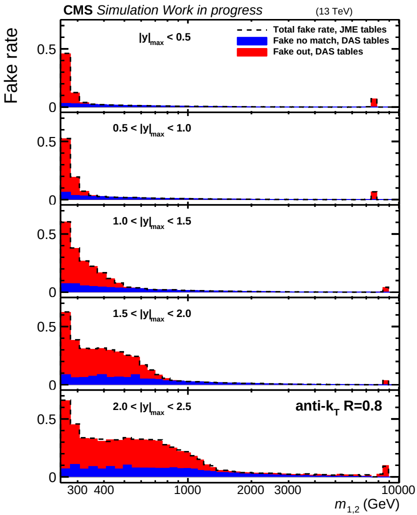
Aim

Check if any biased is introduced from the unfolding

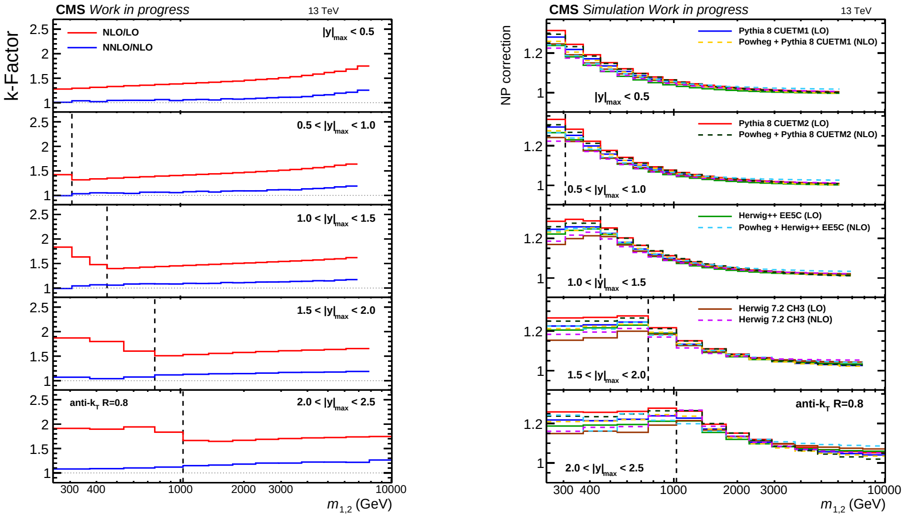
- Comparison of data/pythia before and after unfolding
- Agreement between the two shapes

Unfolding - Miss & Fake Rates

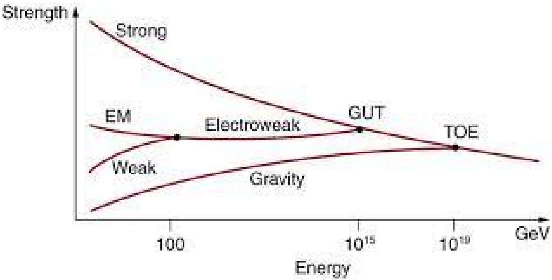




Theory k-factors and NPs detailed



Theory coupling constants



Ratio Data/Theory