Determination of the strong coupling from jet measurements at CMS

ICHEP2024

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on behalf of the CMS Collaboration

Universität Hamburg

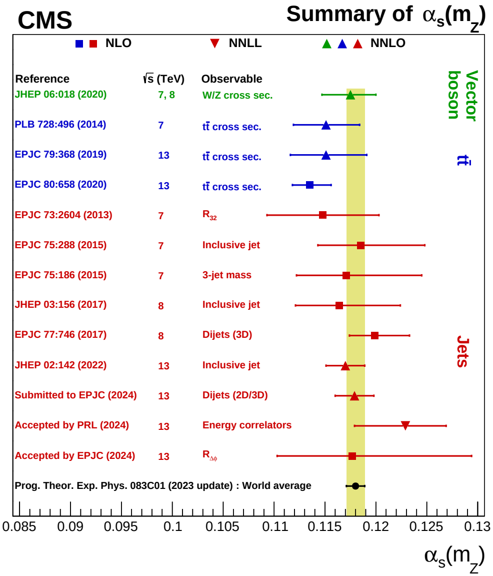
18 July 2024

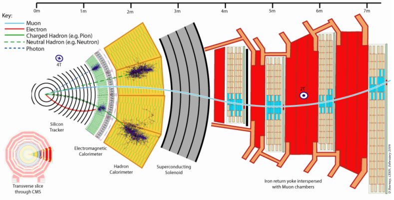
CDCS
CENTER FOR DATA AND COMPUTING
IN NATURAL SCIENCES

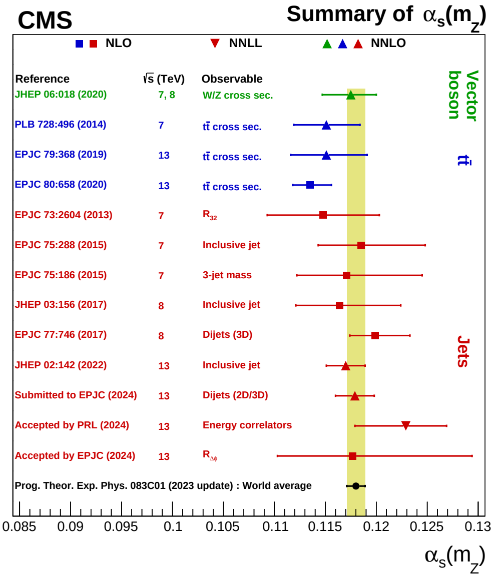
Introduction

Methodology

Introduction







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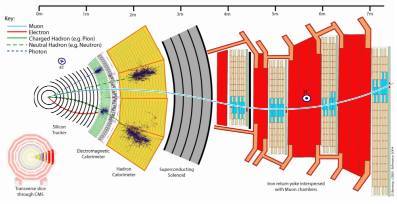

Motivation

Review the numerous determinations of $\alpha_s(m_Z)$ at CMS from **jet** measurements in LHC Run 1 and Run 2.

Methodology

Factorisation in proton-proton collisions [1]

$$\underbrace{\sigma_{pp}}_{\text{exp. data}} = \sum_{ij \in gq\bar{q}} \underbrace{f_i(x_i, \mu_F^2) \otimes f_j(x_j, \mu_F^2)}_{\text{PDFs}} \otimes \underbrace{\hat{\sigma}_{ij}\left(x_i, x_j, \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}, \alpha_S(\mu_R^2)\right)}_{\text{FO predictions}}$$

NP corrections are not included in the formula (more in Paris' talk).

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- Fit both PDFs and α_s simultaneously
- Follow the HERAPDF2.0 prescription with xFitter [9, 10]

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Beyond

- Take ratios of cross sections to reduce systematic effects [2, 6].
- Or exploit the jet substructure [11].

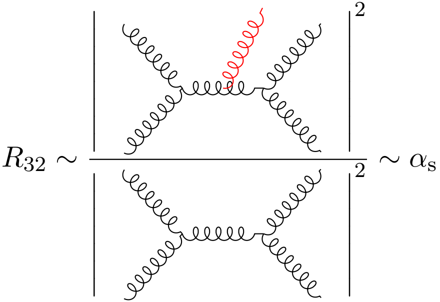
Review

First extraction
Inclusive jet
Dijet
Multijet
Energy correlators

Observable [2]

$$R_{32} = N^{\text{eff}}_{\text{incl. 3-jet}} / N^{\text{eff}}_{\text{incl. 2-jet}}$$

$\longrightarrow$ cancellation of systematic effects



First extraction

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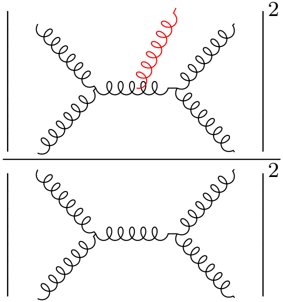
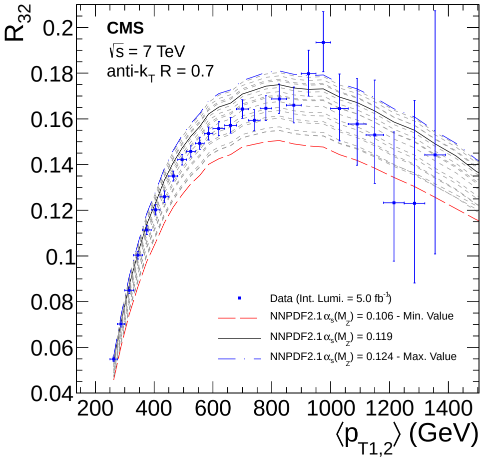
$R_{32} \sim$  $\sim \alpha_s$

Result with method #1 at NLO

$$\alpha_s(m_Z) = 0.1148 \pm 0.0014(\text{exp}) \pm 0.0018(\text{PDF}) \pm 0.0050(\text{theory})$$

First extraction



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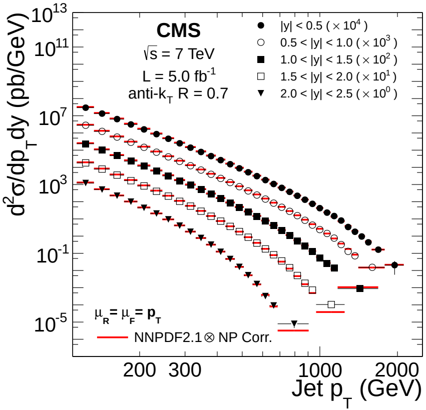


Observable [12, 4, 5, 8]

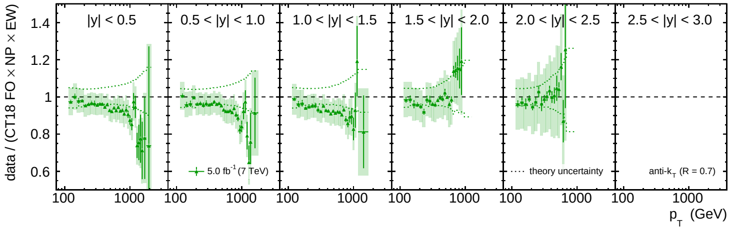
$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_\mathrm{T}\ \mathrm{d}y} = \frac{1}{\mathcal{L}} \frac{N^\mathrm{eff}_\mathrm{jets}}{\Delta p_\mathrm{T}\,\Delta y}$$

Result at NLO with method #1

$$\alpha_\mathrm{s}(m_\mathrm{Z}) = 0.1185 \pm 0.0019(\mathrm{exp}) \pm 0.0004(\mathrm{NP}) \pm 0.0028(\mathrm{PDF}) \pm^{0.0053}_{0.0024}(\mathrm{scale})$$

Data vs. NNLO

- NNLOJET interpolation grids [13]
- fastNLO [14]



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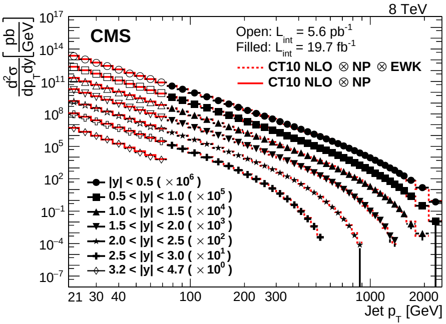

Observable [12, 4, 5, 8]

$$\frac{d^2\sigma}{dp_T\, dy} = \frac{1}{\mathcal{L}} \frac{N_{jets}^{eff}}{\Delta p_T\, \Delta y}$$

Result at NLO with method #2

$$\alpha_s(m_Z) = 0.1185 \pm^{0.0019}_{0.0021}(\text{fit}) \pm^{0.0002}_{0.0015}(\text{model}) \pm^{0.0000}_{0.0004}(\text{param}) \pm^{0.0022}_{0.0018}(\text{scale})$$

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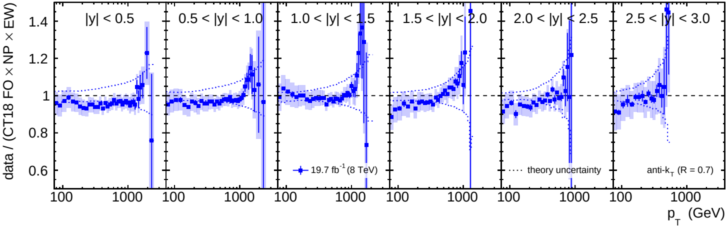

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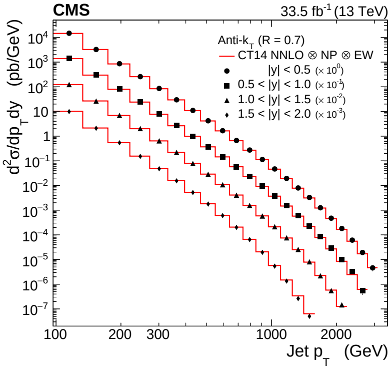

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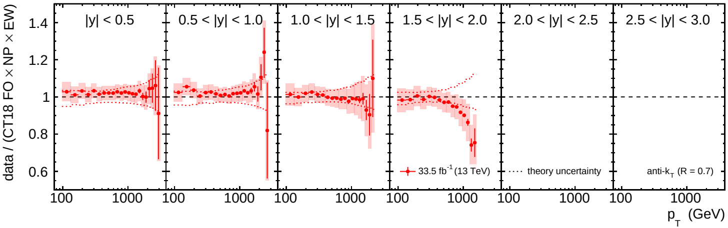

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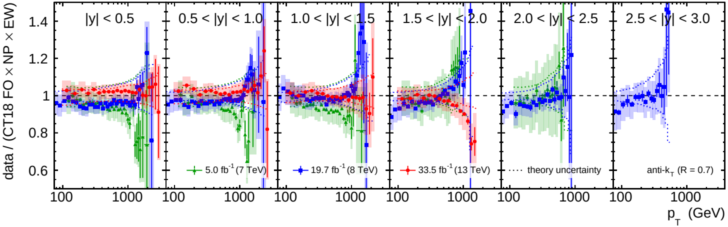
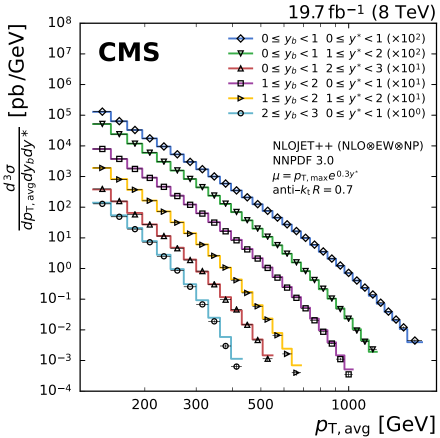
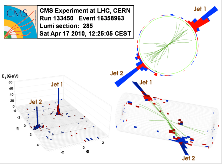


Dijet





Observable [15, 6]

$$\frac{d^3\sigma}{dy^*\, dy_b\, d\langle p_T\rangle_{1,2}} = \frac{1}{\mathcal{L}} \frac{N_{\text{eff}}}{\Delta y^*\, \Delta y_b\, \Delta\langle p_T\rangle_{1,2}}$$

- $y^* = (y_1 - y_2)/2$
- $y_b = (y_1 + y_2)/2$

Result at NLO with method #2

$$\alpha_s(m_Z) = 0.1199 \pm 0.0015(\text{fit}) \pm 0.0002(\text{model}) \pm^{0.0002}_{0.0004}(\text{param}) \pm^{0.0026}_{0.0016}(\text{scale})$$

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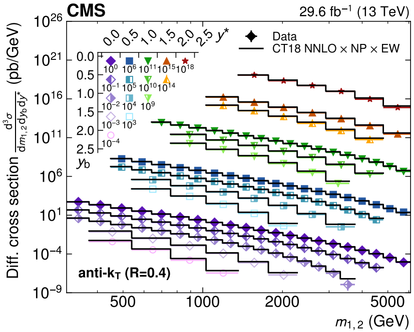
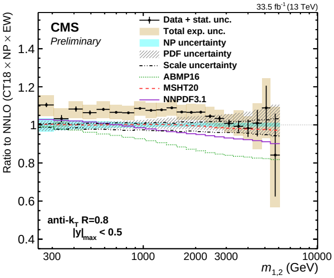




Observable [15, 6]

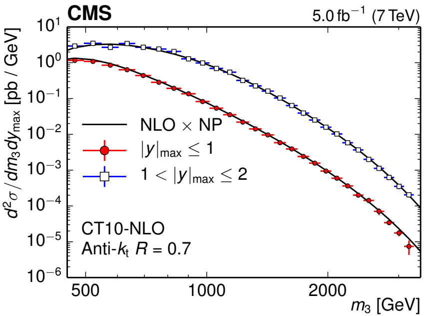
$$\frac{d^3\sigma}{dy^*\, dy_b\, dX} = \frac{1}{\mathcal{L}} \frac{N_{\text{eff}}}{\Delta y^*\, \Delta y_b\, \Delta X}$$

- $y^* = (y_1 - y_2)/2$
- $y_b = (y_1 + y_2)/2$
- Also in 2D
- $X = \langle p_T \rangle_{1,2}, m_{1,2}$

Result at NNLO with method #2

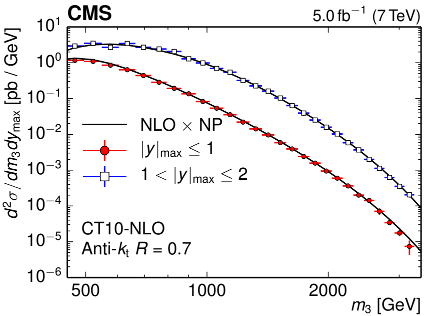
$$\alpha_s(m_Z) = 0.1181 \pm 0.0013(\text{fit}) \pm 0.0006(\text{model}) \pm 0.0002(\text{param}) \pm 0.0009(\text{scale})$$

Multijet



Trijet mass [3]

$$\frac{d^2\sigma}{d|y|_{\mathrm{max}}\, dm_3} = \frac{1}{\mathcal{L}} \frac{N_{\mathrm{eff}}}{\Delta|y|_{\mathrm{max}}\, \Delta m_3} \sim \alpha_s^2$$



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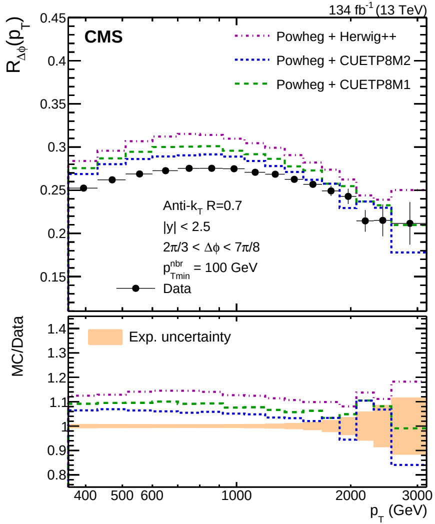

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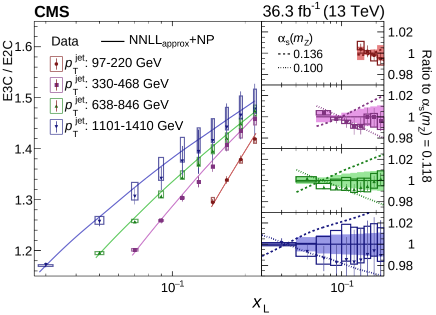
$R_{\Delta\phi}$ [6] (recently accepted)

$$R_{\Delta\phi} = \frac{\sum_{i=1}^{N_{\text{jet}}(p_T)} N^{(i)}_{\text{nbr}}(\Delta\phi, p^{\text{nbr}}_{\text{Tmin}})}{N_{\text{jet}}(p_T)}$$

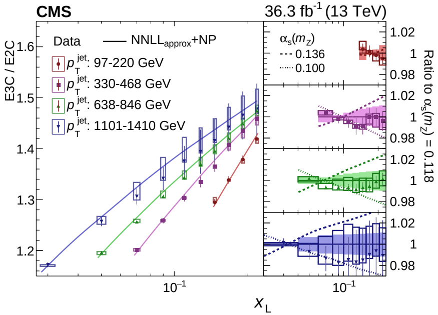
$\longrightarrow$ more in Paris' talk

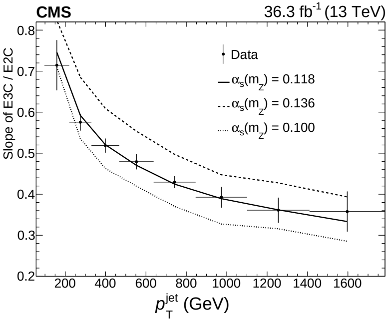


Energy correlators

α_s from jet constituents [11] (recently accepted)

- The measurement itself was presented in Jindrich's talk
- Exploit E3C/E2C $\propto \alpha_s \log x_L$ where x_L stands for the widest opening angle between the jet consistuents





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Result at NLO+aNNLL

$$\alpha_s(m_Z) = 0.1229 \pm^{0.0014}_{0.0012}(\text{stat}) \pm^{0.0030}_{0.0033}(\text{theo}) \pm^{0.0023}_{0.0036}(\text{exp})$$

Discussion

Overview
Lessons
Prospects

Overview

Refs.	$\sqrt{s}$	value	fit unc.	PDF unc.	scale unc.	other unc.	PDF	order
R_{32} [2]	7 TeV	0.1148	±0.0014	±0.0018		±0.0050	NNPDF2.1	NLO
2D inclusive jet [12, 4]	7 TeV	0.1185	±0.0019	±0.0028	$^{+0.0053}_{-0.0024}$	±0.0004 (NP)	—	NLO
2D trijet mass [3]	7 TeV	0.1171	±0.0013	±0.0024	$^{+0.0069}_{-0.0040}$	±0.0008 (NP)	CT10	NLO
2D inclusive jet [5]	8 TeV	0.1185	$^{+0.0019}_{-0.0021}$	$^{+0.0002}_{-0.0015}$ (model) $^{+0.0000}_{-0.0004}$ (param)	$^{+0.0022}_{-0.0018}$		—	NLO
3D dijet mass [15]	8 TeV	0.1199	±0.0015	±0.0002 (model) $^{+0.0002}_{-0.0004}$ (param)	$^{+0.0026}_{-0.0016}$		—	NLO
2D inclusive jet [8]	13 TeV	0.1166	±0.0014	±0.0007 (model) ±0.0001 (param)	±0.0004		—	NNLO
2D & 3D dijet mass [6]	13 TeV	0.1181	±0.0013	±0.0006 (model) ±0.0002 (param)	±0.0009		—	NNLO
$R_{\Delta\phi}$ [6]	13 TeV	0.1177	±0.0013	±0.0010 (NNPDF3.1) ±0.0020 (choice)	$^{+0.0114}_{-0.0068}$	±0.0011 (NP) ±0.0003 (EW)	NNPDF3.1	NLO
EEC in jets [11]	13 TeV	0.1229	$^{+0.0014}_{-0.0012}$ (stat) $^{+0.0023}_{-0.0036}$ (syst)		$^{+0.0030}_{-0.0033}$		—	aNNLL

$$\alpha_s^{\text{PDG 2023}}(M_Z) = 0.1180 \pm 0.0009$$

Whenever several values are given for a reference, only one value has been reported.

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Refs.	$\sqrt{s}$	value	fit unc.	PDF unc.	scale unc.	other unc.	PDF	order
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2D inclusive jet [12, 4]	7 TeV	0.1185	±0.0019	±0.0028	$^{+0.0053}_{-0.0024}$	$\underbrace{\pm0.0004}_{\text{NP}}$	—	NLO
2D trijet mass [3]	7 TeV	0.1171	±0.0013	±0.0024	$^{+0.0069}_{-0.0040}$	$\underbrace{\pm0.0008}_{\text{NP}}$	CT10	NLO
2D inclusive jet [5]	8 TeV	0.1185	$^{+0.0019}_{-0.0021}$	$\underbrace{^{+0.0002}_{-0.0015}}_{\text{model}}$ $\underbrace{^{+0.0000}_{-0.0004}}_{\text{param}}$	$^{+0.0022}_{-0.0018}$		—	NLO
3D dijet mass [15]	8 TeV	0.1199	±0.0015	$\underbrace{\pm0.0002}_{\text{model}}$ $\underbrace{^{+0.0002}_{-0.0004}}_{\text{param}}$	$^{+0.0026}_{-0.0016}$		—	NLO
2D inclusive jet [8]	13 TeV	0.1166	±0.0014	$\underbrace{\pm0.0007}_{\text{model}}$ $\underbrace{\pm0.0001}_{\text{param}}$	±0.0004		—	NNLO
2D & 3D dijet mass [6]	13 TeV	0.1181	±0.0013	$\underbrace{\pm0.0006}_{\text{model}}$ $\underbrace{\pm0.0002}_{\text{param}}$	±0.0009		—	NNLO
$R_{\Delta\phi}$ [6]	13 TeV	0.1177	±0.0013	$\underbrace{\pm0.0010}_{\text{NNPDF3.1}}$ $\underbrace{\pm0.0020}_{\text{choice}}$	$^{+0.0114}_{-0.0068}$	$\underbrace{\pm0.0011}_{\text{NP}}$ $\underbrace{\pm0.0003}_{\text{EW}}$	NNPDF3.1	NLO
EEC in jets [11]	13 TeV	0.1229	$\underbrace{^{+0.0014}_{-0.0012}}_{\text{stat}}$ $\underbrace{^{+0.0023}_{-0.0036}}_{\text{syst}}$		$^{+0.0030}_{-0.0033}$		—	aNNLL

$$\alpha_s^{\text{PDG 2023}}(M_Z) = 0.1180 \pm 0.0009$$

Whenever several values are given for a reference, only one value has been reported.

Lessons

From our past publications

1. No tension observed with world average

   $\longrightarrow$ a direct comparison is tricky, because of subtle correlations and differences among conventions and strategies.

2. Ratios have smaller uncertainties than differential cross sections

   $\longrightarrow$ it would be ideal if one would combine them.

3. Model & NP uncertainties matter

   $\longrightarrow$ not Gaussian + no clear prescription on how to handle them.

4. Determinations at NNLO are dominated by the fit uncertainties

   $\longrightarrow$ large (although not exclusive) contribution from experimental uncertainties.

Prospects

Possible ways forward

- Explore new observables
  $\longrightarrow$ e.g. novel cross section ratios
- Combine existing measurements
  $\longrightarrow$ e.g. vector boson, jet, $t\bar{t}$
- Improve calibration
  $\longrightarrow$ work in progress
- Perform measurements simultaneously
  $\longrightarrow$ see dedicated CMS note [16]

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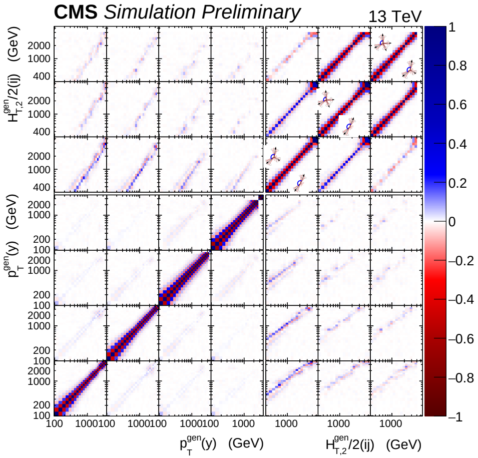
Teaser

3×3 upper right R_{32}, R_{42}, R_{43}

4×4 lower left 2D incl. jet cross section

$\longrightarrow$ statistical correlations in off-diagonal blocks



Summary & Conclusions

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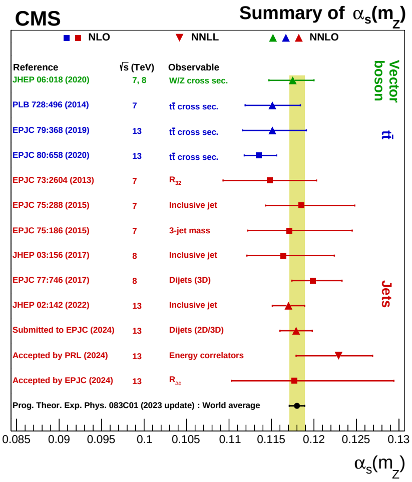
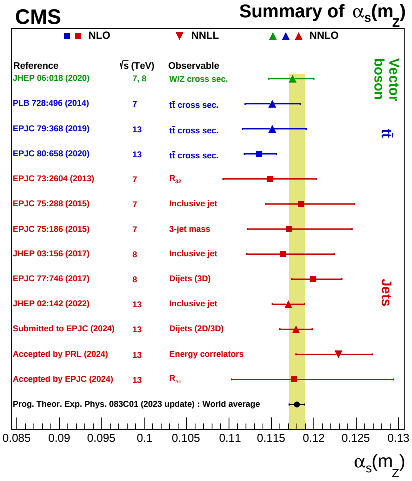


- The CMS Collaboration has provided numerous determinations of the strong coupling.
- With the advent of predictions at NNLO, the fit uncertainty has become dominant.
- Prospects have been discussed, in particular simultaneous measurements.
- Two more papers have just been accepted for publication [11, 6].

Summary & Conclusions



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Thank you for your attention!

Back-up

Inclusive jet

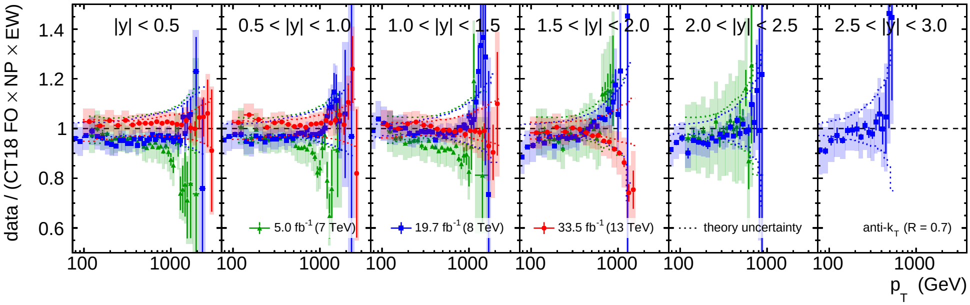
Summary

$\sqrt{s}$/TeV	$\mathcal{L}$	R	CADI	arXiv	HEPdata	xFitter
2.76	5.4/pb	7	SMP-14-017	1512.06212	1410826	
5.02	27.4/pb	4	SMP-21-009	2401.11355	2750408	
7	5.0/fb	7	SMP-12-018	1212.6660	1208923	
7	5.0/fb	5 & 7	SMP-13-002	1406.0324	1298810	
8	20/fb	7	SMP-14-001	1609.05331	1487277	
13	36.3/fb	4 & 7	SMP-20-011	2111.10431	1972986	

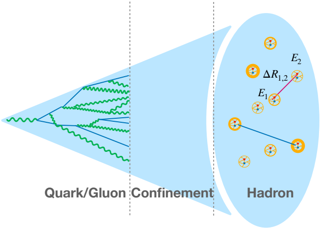
Integrated cross section for $p_T^{rec} > 97$ GeV and $|y| < 2.0$

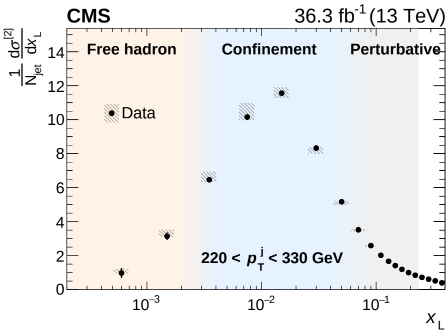
$\mathcal{L}$	$\sqrt{s}$	σ_{tot}^{theory} / pb	σ_{tot}^{data} / pb
5.0 fb^{-1}	7 TeV	8764.7 ± 9.0816(stat)$^{+388.28}_{-435.89}$(syst)	8519.3 ± 90.3722(stat)$^{+610.854}_{-612.47}$(syst)
19.7 fb^{-1}	8 TeV	11645.9 ± 4.6141(stat)$^{+269.196}_{-331.143}$(syst)	11217.2 ± 35.1583(stat)$^{+607.846}_{-597.06}$(syst)
33.2 fb^{-1}	13 TeV	14984.4 ± 16.9442(stat)$^{+424.457}_{-572.171}$(syst)	15234.8 ± 67.6377(stat)$^{+702.451}_{-702.451}$(syst)

Inclusive jet



Energy correlators

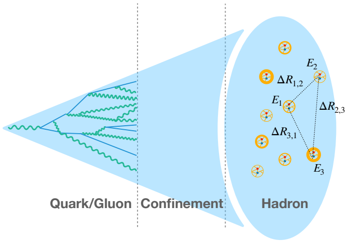


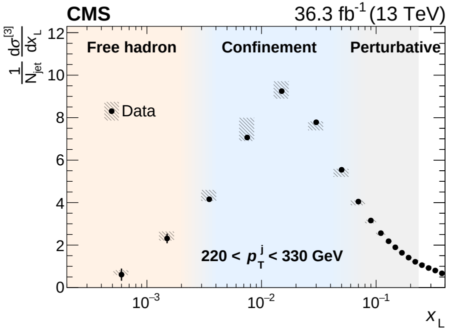


Energy-energy correlators

$$\text{E2C} = \sum_{ij}^{n} \int \mathrm{d}\sigma \, \frac{E_i E_j}{E^2} \delta(x_\mathsf{L} - \Delta R_{ij})$$

Energy correlators





Energy-energy correlators

$$\text{E3C} = \sum_{ijk}^{n} \int d\sigma \frac{E_i E_j E_k}{E^3} \delta(x_L - \max(\Delta R_{ij}, \Delta R_{ik}, \Delta R_{jk}))$$

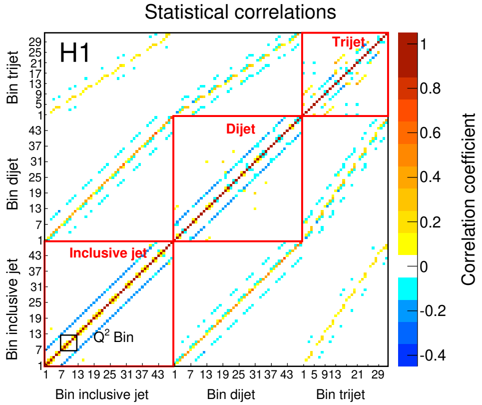
$\longrightarrow$ exploit E3C/E2C $\propto \alpha_s(Q^2) \log x_L$!

Limitations of the current strategy

1. Model dependence & uncertainties
   $\longrightarrow$ no clear procedure + various approaches
2. Backgrounds
   $\longrightarrow$ even the inclusive jet production is sensitive to backgrounds
3. Subtle differences among analyses
   $\longrightarrow$ e.g. choice of unfolding procedure, choice of initial model in QCD interpretation
4. Measurements based on the same data cannot be used in the same fit
   $\longrightarrow$ e.g. dijet mass and inclusive jet p_{T} with CMS 2016 data

$\longrightarrow$ Follow and extend H1 approach [17]

Motivation



Reminder

Typical analysis strategy

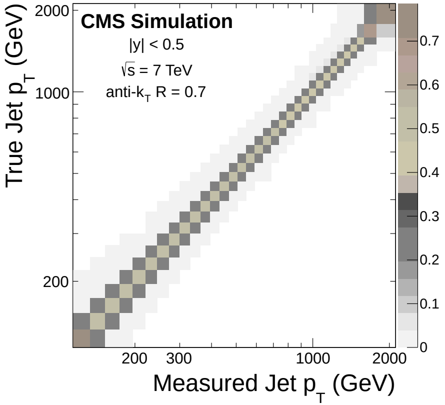
Data reduction in a nutshell

1. Apply a common selection to real and simulated samples.
2. Calibrate the samples.
3. Use simulated samples to construct a migration matrix.
4. Invert this migration matrix and apply to real data (unfolding).

Unfolding

$$\mathbf{A}\mathbf{x} = \mathbf{y}$$

- $\mathbf{x}$ (unknown) unbiased measurement
- $\mathbf{y}$ biased measurement
- $\mathbf{A}$ migration matrix



Remark

In principle, the order and nature of the bins are irrelevant.
$\longrightarrow$ One can always map a (series of) distribution(s) onto a 1D vector $\mathbf{y}$.

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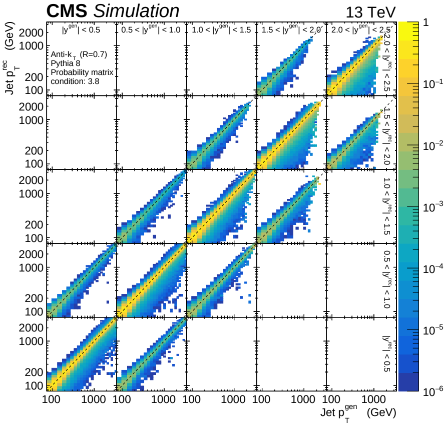

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Example

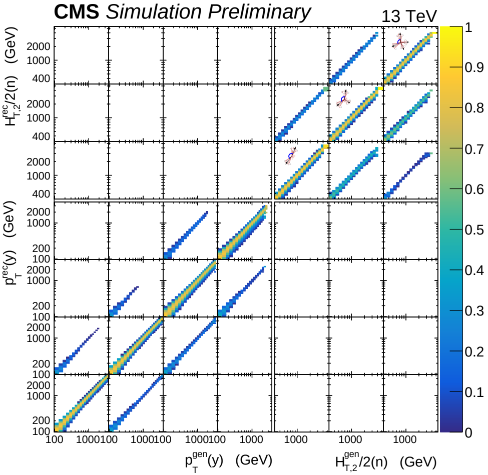
Migrations

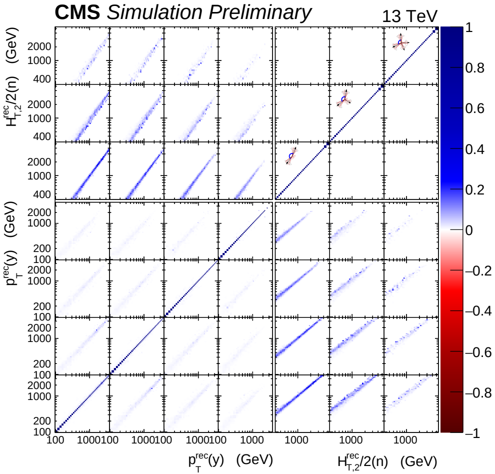
$H_{T,2}$ spectra (3×3 block)

$$\frac{d\sigma}{dH_{T,2}/2}(n) = \frac{1}{\mathcal{L}} \frac{N^{\text{eff}}_{n-\text{jets}}}{\Delta H_{T,2}/2}$$

Inclusive jet (4×4 block)

$$\frac{d^2\sigma}{dp_T\ dy} = \frac{1}{\mathcal{L}} \frac{N^{\text{eff}}_{\text{jets}}}{\Delta p_T\ \Delta y}$$





Example

Pre-unfolding correlations

From the real data

- Off-diagonal entries within the lower 4×4 block describe the statistical correlations among the kinematic bins of inclusive jet (multi-count observable).
- Off-diagonal entries in the 4×3 and 3×4 blocks describe the statistical correlations among the bins of the respective observables.

For the present exercise: simple least-square minimisation

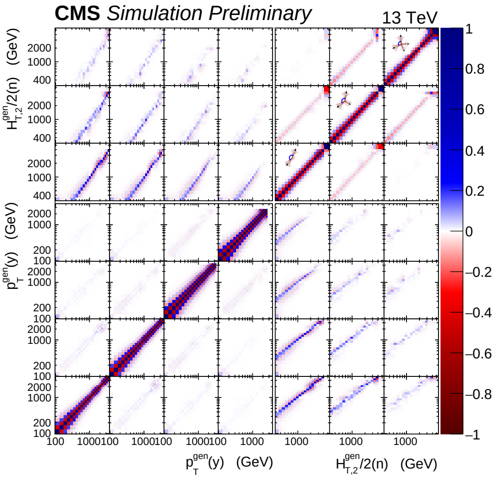
$$\chi^2 = \min_{\mathbf{x}} \left[(\mathbf{A}\mathbf{x} - \mathbf{y})^\intercal \mathbf{V_y}^{-1} (\mathbf{A}\mathbf{x} - \mathbf{y}) \right]$$

$\mathbf{V_y}$ covariance matrix from biased measurement

Result (unless regularisation is needed)

$$\mathbf{x} = \left(\mathbf{A}^\intercal \mathbf{V_y}^{-1} \mathbf{A}\right)^{-1} \mathbf{A}^\intercal \mathbf{V_y}^{-1} \mathbf{y}$$

$$\mathbf{V_x} = \mathbf{A}^{-1} \mathbf{V_y} \mathbf{A}^{\intercal\,-1}$$



Example

Post-unfolding correlations

From the simulated data

- With infinitely large statistics, one can use independent statistical samples to construct the different sectors of the migration matrix.
- Else repeat unfolding using alternative migration matrices with additional event weights $\sim \mathrm{Pois}(1)$:

$$\mathbf{V}'_\mathbf{x} = \left(\frac{1}{N}\sum_{n=1}^{N} \mathbf{x}_n \cdot \mathbf{x}_n^\intercal\right) - \frac{1}{N^2}\left(\sum_{n=1}^{N} \mathbf{x}_n\right) \cdot \left(\sum_{n=1}^{N} \mathbf{x}_n\right)^\intercal$$

From H_T spectra to R_{ij}

- Goal is to extract $\mathbf{z} = \mathbf{f}(\mathbf{x})$ and its correlations.
- Apply a rotation R to diagonalise $\mathbf{V_x}$ and generate N events $\mathbf{z}_n$:

$$\delta'_{n,i} \sim \mathcal{N}\left(0, \sqrt{\max(0, k_i)}\right)$$
$$\mathbf{z}_n = \mathbf{f}\left(\mathbf{x} + \mathbf{R}^{-1}\boldsymbol{\delta}'_n\right)$$

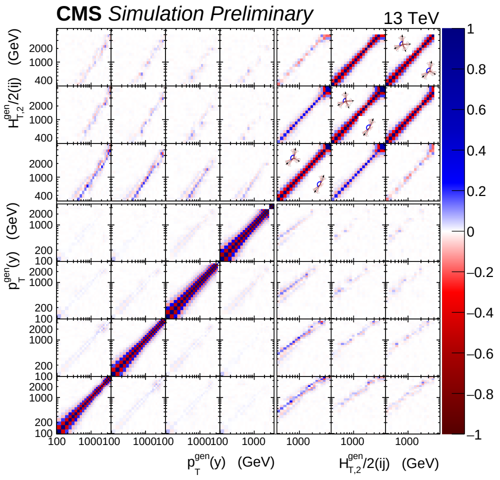
- Under the Gaussian hypothesis, the covariance may be obtained using the formula given on the last slices.

Gain

We now have two observables with distinct properties obtained from the same data.
$\longrightarrow$ R_{ij} offers additional control on α_s.

Example

Final correlations



Acronyms I

aNNLL approx. Next to Next to Leading Logarithm. 20, 21

CMS Compact Muon Solenoid. 3, 4, 29, 30, 32, 33, 39

EEC energy-energy correlators. 23–27

FO fixed order. 5–8

H1 HERA-1. 39

LHC Large Hadron Collider. 3, 4

NLO Next to Leading Order. 10–13, 16, 20, 21

NNLO Next to Next to Leading Order. 12–15, 17, 28, 32, 33

NP Non-Perturbative. 5–8, 28

PDF Parton Distribution Function. 5–8, 23–27

QCD Quantum Chromodynamics. 39

References I

[1] John C. Collins, Davison E. Soper, and George F. Sterman. "Factorization of Hard Processes in QCD". In: **Adv. Ser. Direct. High Energy Phys.** 5 (1989), pp. 1–91. DOI: 10.1142/9789814503266_0001. arXiv: hep-ph/0409313 [hep-ph].

[2] Serguei Chatrchyan et al. "Measurement of the ratio of the inclusive 3-jet cross section to the inclusive 2-jet cross section in pp collisions at $\sqrt{s} = 7$ TeV and first determination of the strong coupling constant in the TeV range". In: **Eur. Phys. J. C** 73 (2013), p. 2604. DOI: 10.1140/epjc/s10052-013-2604-6. hep-ex: 1304.7498. URL: http://cdsweb.cern.ch/record/1544428.

[3] Vardan Khachatryan et al. "Measurement of the inclusive 3-jet production differential cross section in proton-proton collisions at 7 TeV and determination of the strong coupling constant in the TeV range". In: **Eur. Phys. J. C** 75 (2015), p. 186. DOI: 10.1140/epjc/s10052-015-3376-y. hep-ex: 1412.1633. URL: http://cdsweb.cern.ch/record/1974165.

[4] Vardan Khachatryan et al. "Constraints on parton distribution functions and extraction of the strong coupling constant from the inclusive jet cross section in pp collisions at $\sqrt{s} = 7$ TeV". In: **Eur. Phys. J. C** 75 (2015), p. 288. DOI: 10.1140/epjc/s10052-015-3499-1. hep-ex: 1410.6765. URL: http://cdsweb.cern.ch/record/1957365.

References II

[5] Vardan Khachatryan et al. “Measurement and QCD analysis of double-differential inclusive jet cross sections in pp collisions at $\sqrt{s} = 8$ TeV and cross section ratios to 2.76 and 7 TeV”. In: **JHEP** 03 (2017), p. 156. DOI: 10.1007/JHEP03(2017)156. arXiv: 1609.05331 [hep-ex].

[6] Aram Hayrapetyan et al. “Measurement of multidifferential cross sections for dijet production in proton-proton collisions at $\sqrt{s} = 13$ TeV”. In: (Dec. 2023). Accepted by Eur. Phys. J. C. arXiv: 2312.16669 [hep-ex].

[7] Albert M Sirunyan et al. “Measurement of $\mathrm{t\bar{t}}$ normalised multi-differential cross sections in pp collisions at $\sqrt{s} = 13\,$TeV, and simultaneous determination of the strong coupling strength, top quark pole mass, and parton distribution functions”. In: **Eur. Phys. J. C** 80 (2020), p. 658. DOI: 10.1140/epjc/s10052-020-7917-7. arXiv: 1904.05237 [hep-ex].

[8] Armen Tumasyan et al. “Measurement and QCD analysis of double-differential inclusive jet cross sections in proton-proton collisions at $\sqrt{s} = 13$ TeV”. In: **JHEP** 02 (2022). [Addendum: JHEP 12, 035 (2022)], p. 142. DOI: 10.1007/JHEP02(2022)142. arXiv: 2111.10431 [hep-ex].

References III

[9] V. Bertone, M. Botje, D. Britzger, et al. "xFitter 2.0.0: An Open Source QCD Fit Framework". In: **PoS** DIS2017 (2018), p. 203. DOI: 10.22323/1.297.0203. arXiv: 1709.01151 [hep-ph].

[10] S. Alekhin et al. "HERAFitter, open source QCD fit project". In: **Eur. Phys. J. C** 75 (2015), p. 304. DOI: 10.1140/epjc/s10052-015-3480-z. arXiv: 1410.4412 [hep-ph].

[11] Aram Hayrapetyan et al. "Measurement of energy correlators inside jets and determination of the strong coupling $\alpha_S(m_Z)$". In: (Feb. 2024). Accepted by Phys. Rev. Letters. arXiv: 2402.13864 [hep-ex].

[12] Serguei Chatrchyan et al. "Measurements of Differential Jet Cross Sections in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV with the CMS Detector". In: **Phys. Rev. D** 87 (2013). [Erratum: Phys.Rev.D 87, 119902 (2013)], p. 112002. DOI: 10.1103/PhysRevD.87.112002. arXiv: 1212.6660 [hep-ex].

[13] D. Britzger et al. "NNLO interpolation grids for jet production at the LHC". In: **Eur. Phys. J. C** 82.10 (2022), p. 930. DOI: 10.1140/epjc/s10052-022-10880-2. arXiv: 2207.13735 [hep-ph].

References IV

[14] Daniel Britzger et al. "New features in version 2 of the fastNLO project". In: **20th International Workshop on Deep-Inelastic Scattering and Related Subjects**. 2012, p. 217. DOI: 10.3204/DESY-PROC-2012-02/165. arXiv: 1208.3641 [hep-ph].

[15] Albert M Sirunyan et al. "Measurement of the triple-differential dijet cross section in proton-proton collisions at $\sqrt{s} = 8$ TeV and constraints on parton distribution functions". In: **Eur. Phys. J. C** 77 (2017), p. 746. DOI: 10.1140/epjc/s10052-017-5286-7. arXiv: 1705.02628 [hep-ex].

[16] The CMS Collaboration. **Simultaneous determination of several differential observables with statistical correlations**. Tech. rep. Geneva: CERN, 2024. URL: https://cds.cern.ch/record/2888301.

[17] V. Andreev et al. "Measurement of multijet production in ep collisions at high Q^2 and determination of the strong coupling α_s". In: **Eur. Phys. J. C** 75.2 (2015), p. 65. DOI: 10.1140/epjc/s10052-014-3223-6. arXiv: 1406.4709 [hep-ex].

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