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Determination of α_S at CMS

Status & Prospects

Patrick L.S. Connor

on behalf of the CMS Collaboration

Universität Hamburg

7 February 2024

CDCS
CENTER FOR DATA AND COMPUTING
IN NATURAL SCIENCES

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Compact Muon Solenoid
Topologies

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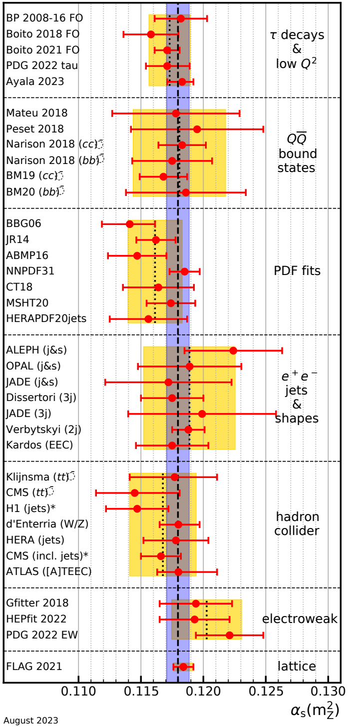
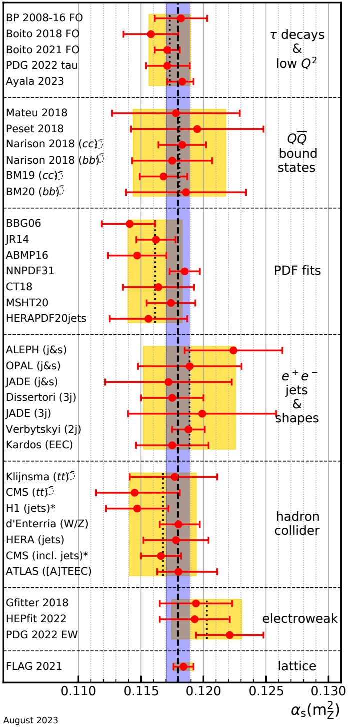
Goal



Goal



Goals of experimentalists

- Extract α_s directly from CMS data.
- Provide CMS data to the HEP community to include our data in global fits.

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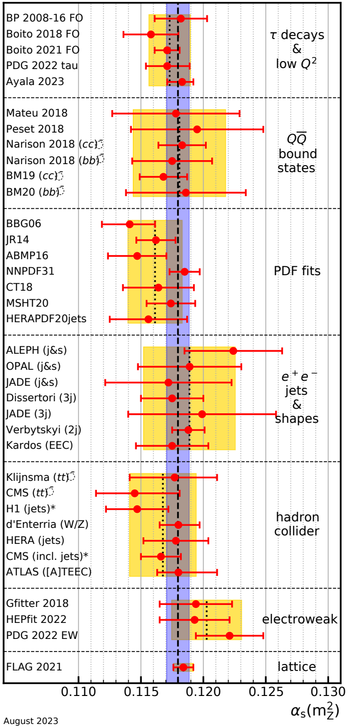

Goal

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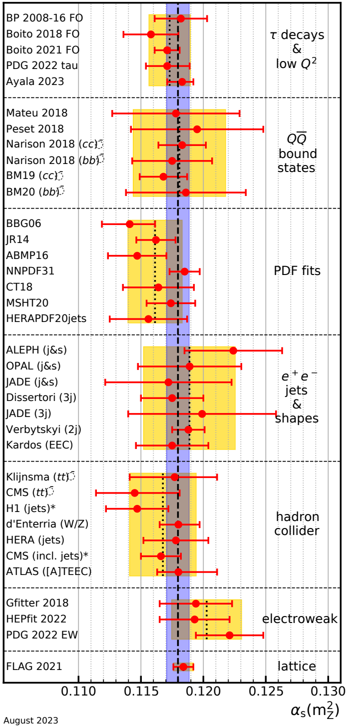
"The main scientific goals of this workshop are to bring together the current best experts in as determination, to critically discuss and understand the relevant merits and problems of each extraction method, and to consider new as studies and approaches. One important outcome should be to assess the **perspectives for systematic improvements of theoretical predictions and experimental methods** in order to resolve discrepancies, and improve the $\alpha_s(M_Z)$ world-average extraction."



August 2023

Goal

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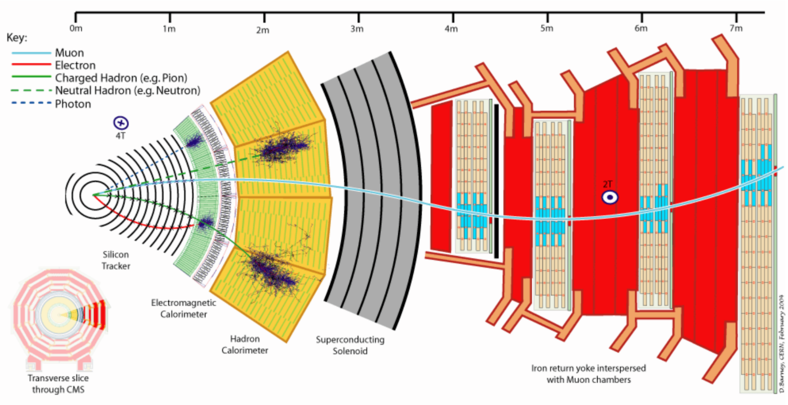
Disclaimer

The potential of jet substructure has been covered in dedicated presentations and will not be discussed here.

Compact Muon Solenoid



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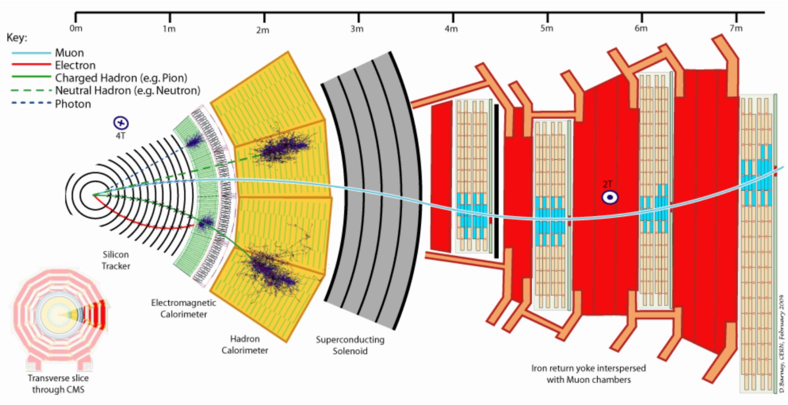
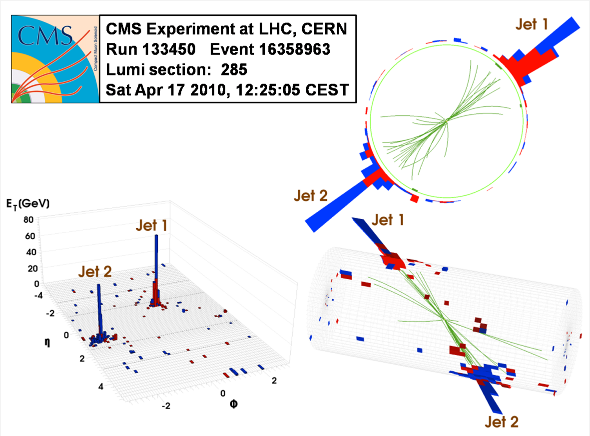


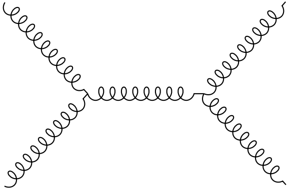
The key to precision & accuracy

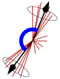
Explore and combine the different final states to exploit different subdetectors.

Topologies

Jets



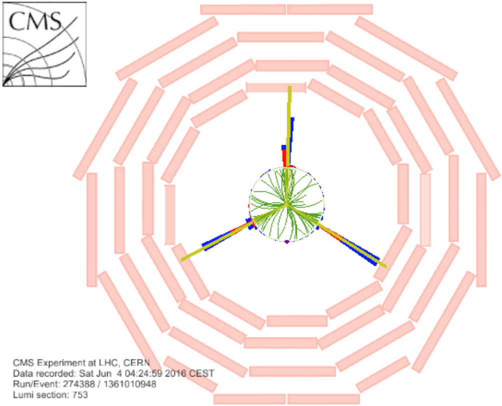


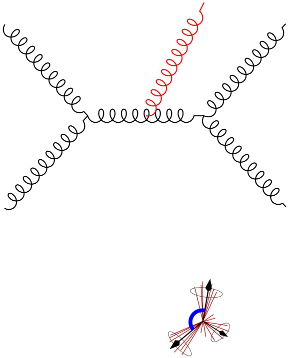


Sketches by M. Wobisch

Topologies

Jets





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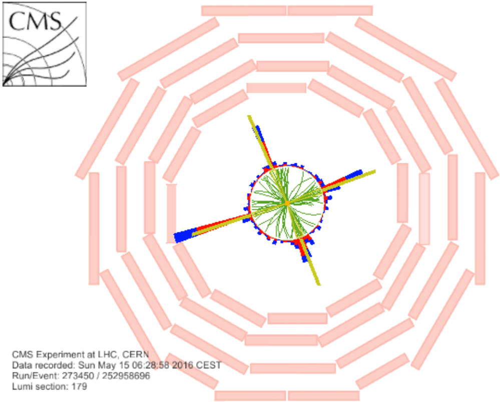

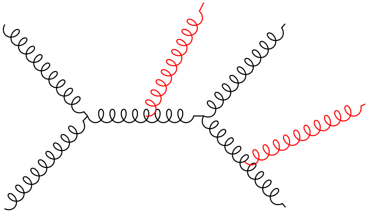

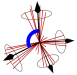

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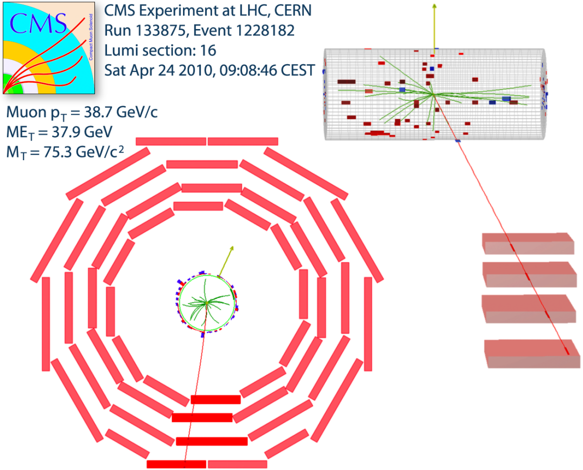
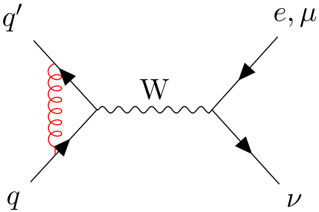
Topologies

Vector bosons





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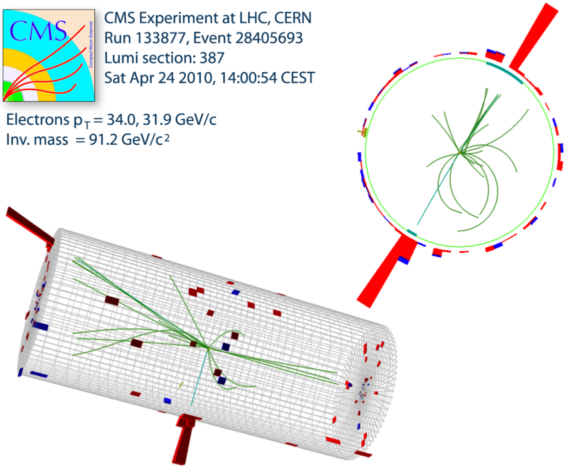

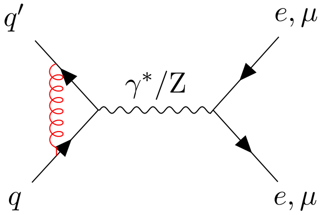

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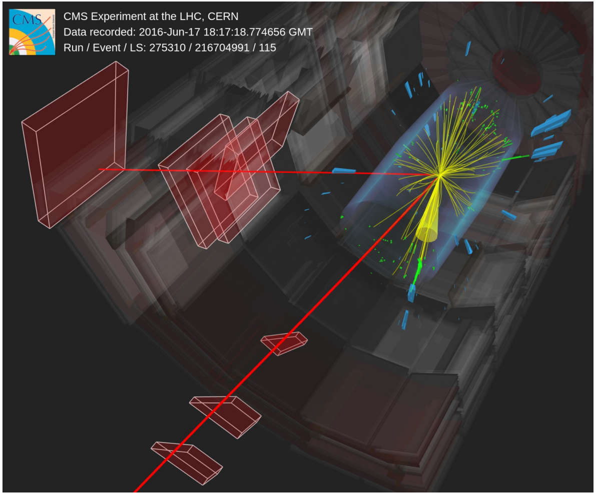
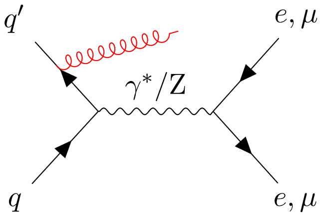
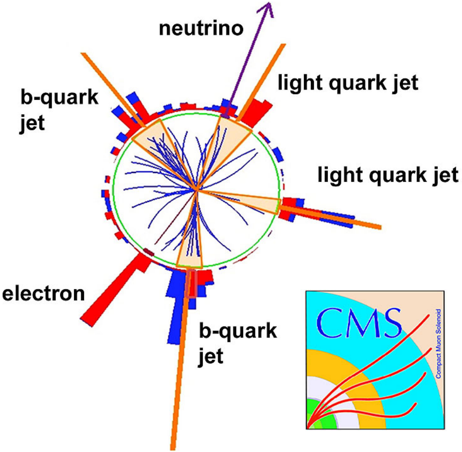
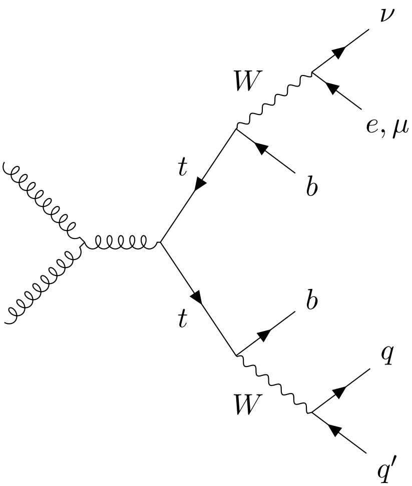




Topologies

Top quark pairs





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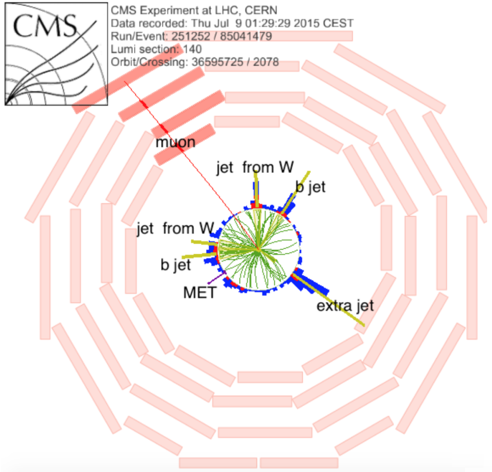

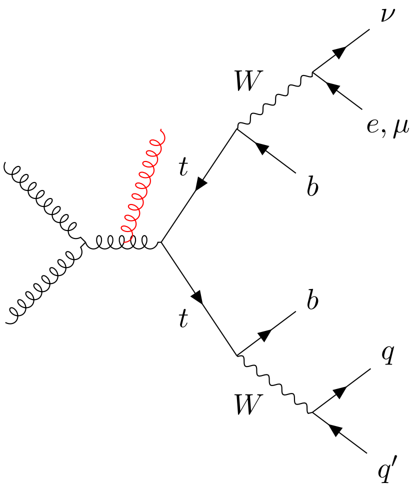

Methodology

Factorisation

α_s alone

α_s + PDFs

α_s + PDFs + more

Fixed-order predictions

Factorisation

Formulation for proton-proton collisions [1]

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

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Outline

- In earlier cross section measurements [2, 3, 4], as well as in measurements of cross section ratios [5, 6], only α_s was fitted for various PDF sets.

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- In most cross section measurements [3, 4, 7, 8, 9], α_s and PDFs have been extracted simultaneously. In that case, one must at least combine CMS with HERA DIS data.

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- Ideally, one also combines various final states from CMS data.

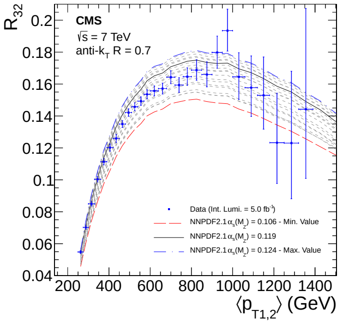
α_s alone

R_{32} observable [5]

- Cancellation of experimental effects
  $\longrightarrow$ e.g. luminosity
- Cancellation of theoretical effects
  $\longrightarrow$ e.g. NP corrections (PDFs?)

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

$\longrightarrow$ first α_s from CMS



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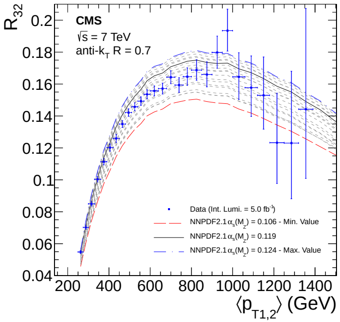
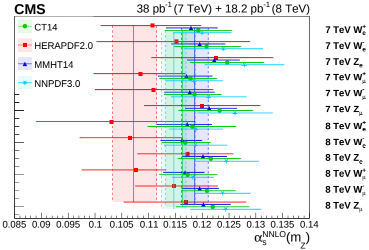


α_s alone

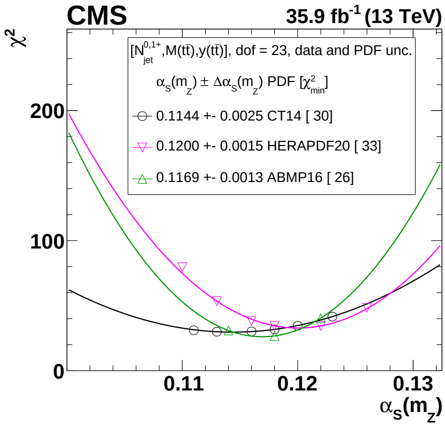


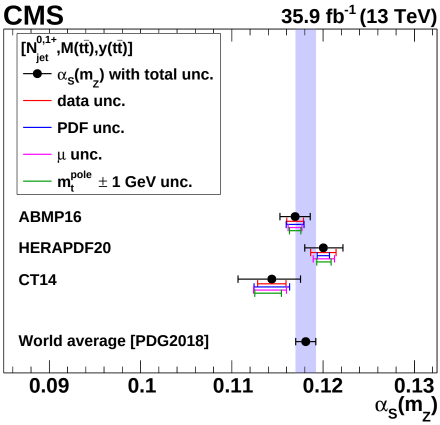
Vector boson production [10]

- Clear signatures at CMS.
- Complementary to jets.
- Predictions at NNLO.

$$\alpha_s(M_Z) = 0.1163 \pm 0.0007(\text{stat}) \pm 0.0013(\text{lumi}) \pm 0.0010(\text{syst})^{+0.0016}_{-0.0022}(\text{PDF}) \pm 0.0009(\text{scale}) \pm 0.0006(\text{num})$$

Methodology





$t\bar{t}$ production [7]

- The inclusive $t\bar{t}$ cross section is α_s and m_t.

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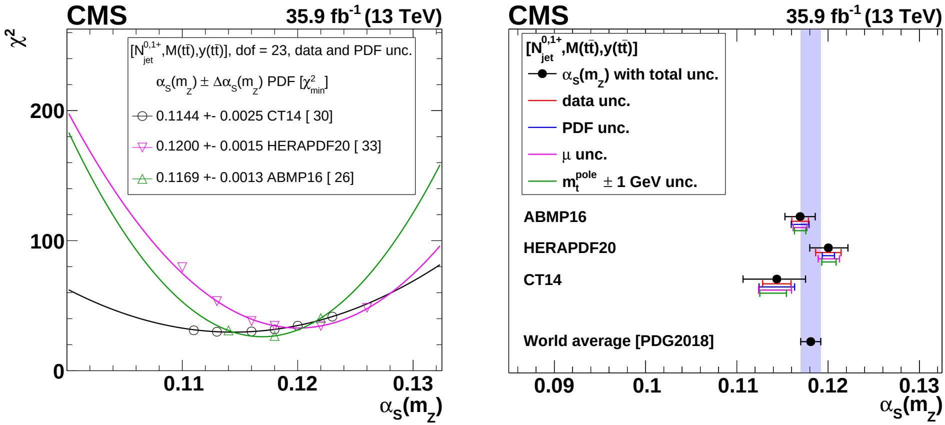
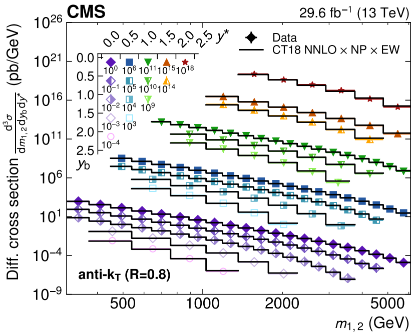


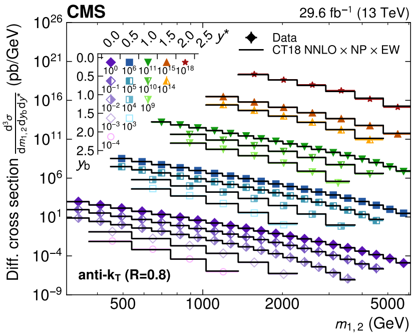
$t\bar{t}$ production [7]

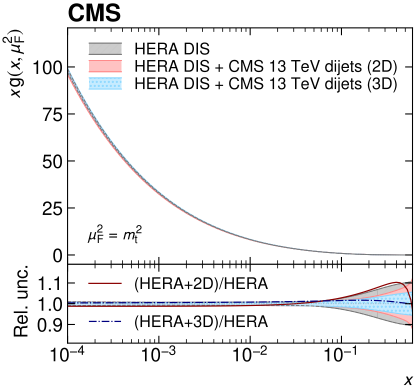
- The inclusive $t\bar{t}$ cross section is α_s and m_t.
- The presence of additional jets provides additional sensitivity to α_s.

α_s + PDFs


CMS
29.6 fb^{-1} (13 TeV)
Data
CT18 NNLO × NP × EW
anti-k$_T$ (R=0.8)
Diff. cross section $\frac{d^3\sigma}{dm_{1,2}dy_b dy^*}$ (pb/GeV)
$m_{1,2}$ (GeV)
y^*
y_b

α_s + PDFs





Dijet mass at 13 TeV [9]

- We use xFitter [11, 12] and FastNLO [13] with NNLO interpolation tables [14].
- We use charged- and neutral-current DIS cross section of HERA [15].
- We assume $f_i(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$ at starting scale.

  $\longrightarrow$ Actual number parameters to be adjusted

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

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α_s + PDFs + more

Combining inclusive jet and $t\bar{t} + X$ [7, 8] at NLO (+NLL)

- The respective measurements provide a better control on the gluon PDF and therefore improve the determinations of α_s and of m_t consequently:

$$\alpha_s(M_Z) = 0.1188 \pm 0.0017 \text{ (fit)} \pm 0.0004 \text{ (model)} \pm 0.0025 \text{ (scale)} \pm \mathbf{0.0001} \text{ (param)}$$

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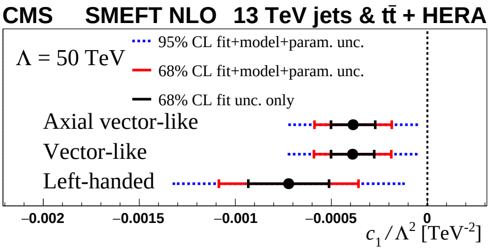

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$$\alpha_s(M_Z) = 0.1188 \pm 0.0017 \text{ (fit)} \pm 0.0004 \text{ (model)} \pm 0.0025 \text{ (scale)} \pm \mathbf{0.0001} \text{ (param)}$$

- Considering also possible BSM physics (c_1 Wilson coefficient):

$$\alpha_s(M_Z) = 0.1187 \pm 0.0016 \text{(fit)} \pm 0.0005 \text{(model)} \pm 0.0023 \text{ (scale)} \pm \mathbf{0.0018} \text{ (param)}$$

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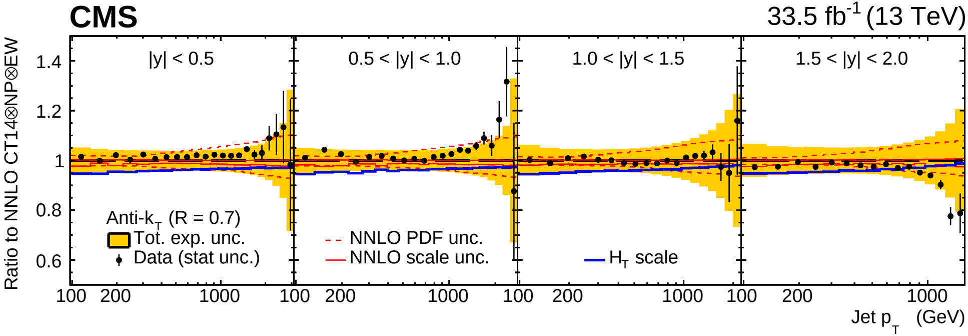
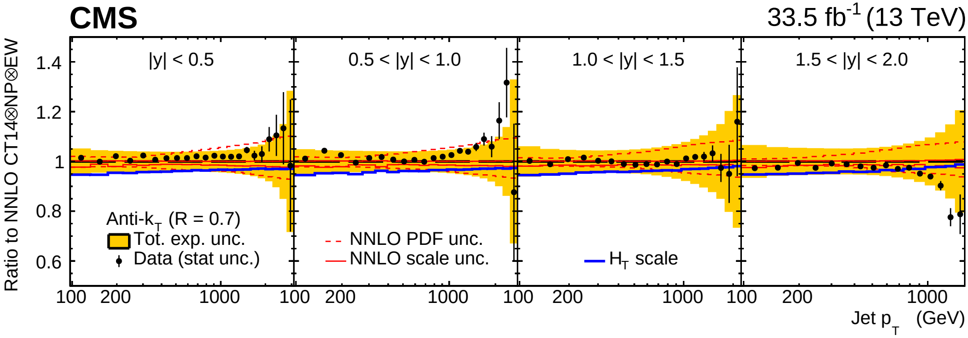


At NNLO using a k factor

$$\alpha_s(M_Z) = 0.1170 \pm 0.0014 \text{ (fit)} \pm 0.0007 \text{ (model)}$$
$$\pm \mathbf{0.0008} \text{ (scale)} \pm 0.0001 \text{ (param)}$$

Fixed-order predictions



At NNLO using interpolation tables [14]

$$\alpha_s(M_Z) = 0.1166 \pm 0.0014 \text{ (fit)} \pm 0.0007 \text{ (model)}$$
$$\pm \mathbf{0.0004} \text{ (scale)} \pm 0.0001 \text{ (param.)}$$

Remark

The statistical uncertainties of the FO predictions and of the data are of similar order at medium transverse momentum.

Lessons

Overview

Systematic effects

Smoothness

Refs.	$\sqrt{s}$	value	fit unc.	PDF unc.	scale unc.	other unc.	PDF	order
R_{32} [5]	7 TeV	0.1148	± 0.0014	± 0.0018		± 0.0050	NNPDF2.1	NLO
2D inclusive jet [16, 3]	7 TeV	0.1185	± 0.0019	± 0.0028	${}^{+0.0053}_{-0.0024}$	$\underbrace{\pm 0.0004}_{\text{NP}}$	—	NLO
inclusive 3-jet mass [2]	7 TeV	0.1171	± 0.0013	± 0.0024	${}^{+0.0069}_{-0.0040}$	$\underbrace{\pm 0.0008}_{\text{NP}}$	CT10	NLO
$t\bar{t}$ [17]	7 TeV	0.1151	${}^{+0.0017}_{-0.0018}$	${}^{+0.0013}_{-0.0011}$	${}^{+0.0009}_{-0.0008}$	$\underbrace{\pm 0.0013}_{m_t} \underbrace{\pm 0.0008}_{\sqrt{s}}$	NNPDF2.3	NNLO
2D inclusive jet [4]	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 [17]	8 TeV	0.1199	± 0.0015	$\underbrace{\pm 0.0002}_{\text{model}} \underbrace{{}^{+0.0002}_{-0.0004}}_{\text{param}}$	${}^{+0.0026}_{-0.0016}$		—	NLO
W/Z [10]	7–8 TeV	0.1163	± 0.0018	${}^{+0.0016}_{-0.0022}$	± 0.0009	$\underbrace{\pm 0.0006}_{\text{num}}$	CT14	NNLO
$t\bar{t}$ (dilepton) [18]	13 TeV	0.1151	± 0.0035		${}^{+0.0020}_{-0.0002}$		MMHT14	NNLO
normalised $t\bar{t}$ [7]	13 TeV	0.1135	± 0.0016	$\underbrace{{}^{+0.0002}_{-0.0004}}_{\text{model}} \underbrace{{}^{+0.0008}_{-0.0001}}_{\text{param}}$	${}^{+0.0011}_{-0.0005}$		—	NLO
2D inclusive jet [8]	13 TeV	0.1166	± 0.0014	$\underbrace{\pm 0.0007}_{\text{model}} \underbrace{\pm 0.0001}_{\text{param}}$	± 0.0004		—	NNLO
2D & 3D dijet mass [9]	13 TeV	0.1181	± 0.0013	$\underbrace{\pm 0.0006}_{\text{model}} \underbrace{\pm 0.0002}_{\text{param}}$	± 0.0009		—	NNLO
$R_{\Delta\phi}$ [6]	13 TeV	0.1177	± 0.0013	$\underbrace{\pm 0.0010}_{\text{NNPDF3.1}} \underbrace{\pm 0.0020}_{\text{choice}}$	${}^{+0.0114}_{-0.0068}$	$\underbrace{\pm 0.0011}_{\text{NP}} \underbrace{\pm 0.0003}_{\text{EW}}$	NNPDF3.1	NLO
EEC in jets [19]	13 TeV	0.1229	$\underbrace{{}^{+0.0014}_{-0.0012}}_{\text{stat}} \underbrace{{}^{+0.0023}_{-0.0036}}_{\text{syst}}$		${}^{+0.0030}_{-0.0033}$		—	aNNLL

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

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

Refs.	$\sqrt{s}$	value	fit unc.	PDF unc.	scale unc.	other unc.	PDF	order
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$\mathrm{t\bar{t}}$ (dilepton) [18]	13 TeV	0.1151	±0.0035		$^{+0.0020}_{-0.0002}$		MMHT14	NNLO
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$$\boldsymbol{\alpha_\mathrm{s}^{\text{PDG 2023}}(M_\mathrm{Z}) = 0.1180 \pm 0.0009}$$

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Overview

Lessons from our past publications

1. No tension observed among the different analyses
   $\longrightarrow$ although the agreement is hard to judge, because of subtle correlations and differences among conventions.
2. Ratios have smaller uncertainties than differential cross sections
   $\longrightarrow$ it would be ideal if one would combine them.
3. Model uncertainties matter, especially for jet substructure measurements.
   $\longrightarrow$ 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.

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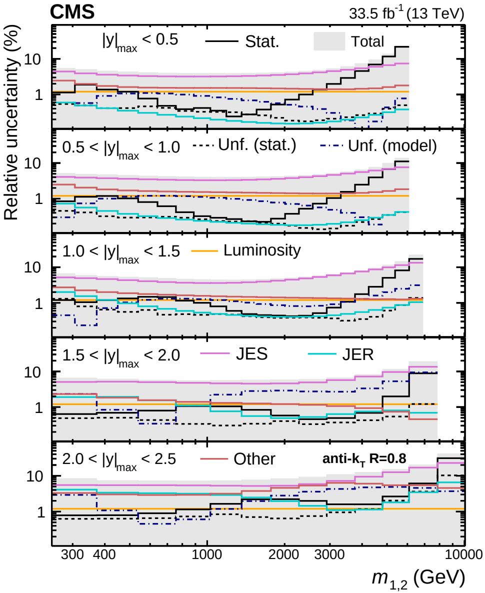
Possible roads

- Explore new observables ⟶ *e.g. novel cross section ratios*
- Combine existing measurements ⟶ *e.g. vector boson cross sections or inclusive jet* $+ t\bar{t}$
- Improve experimental uncertainties ⟶ *see next slides*
- Perform measurements simultaneously ⟶ *see next section*

Systematic effects

Overview



Overview (figure from Ref. [9])

- The JES uncertainty is the combination of ~ 25 uncertainties.
- The unfolding model uncertainty is obtained from the unfolding of the same data with another MC generator (not Gaussian).
- We reach $<1\%$ statistical precision.

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Systematic effects

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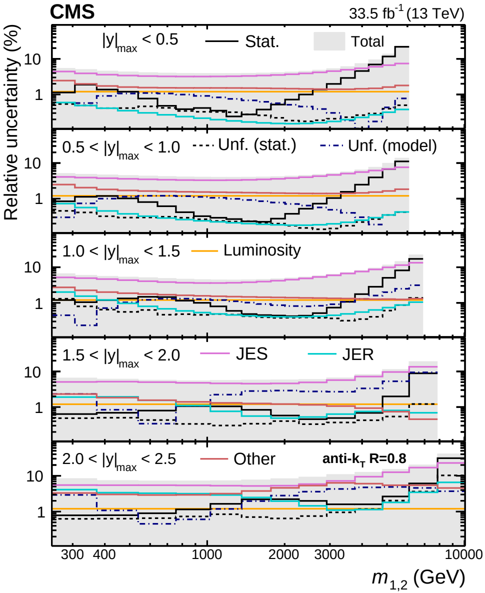

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- The JES uncertainty is the combination of ~ 25 uncertainties.
- The unfolding model uncertainty is obtained from the unfolding of the same data with another MC generator (not Gaussian).
- We reach $<1\%$ statistical precision.

$\longrightarrow$ In practice, we still have to decorrelate certain uncertainties to obtain an acceptable fit performance.

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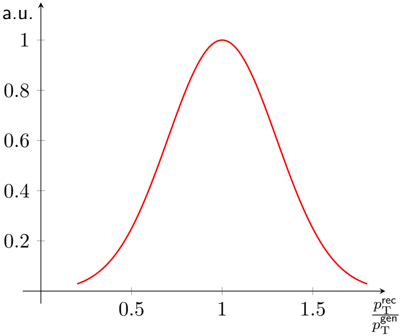
Systematic effects

Jet energy



Challenge

$$\delta\left(p_T^{rec}/p_T^{gen}\right) \sim 0.2\% \quad \Rightarrow \quad \delta\sigma \sim 1\%$$

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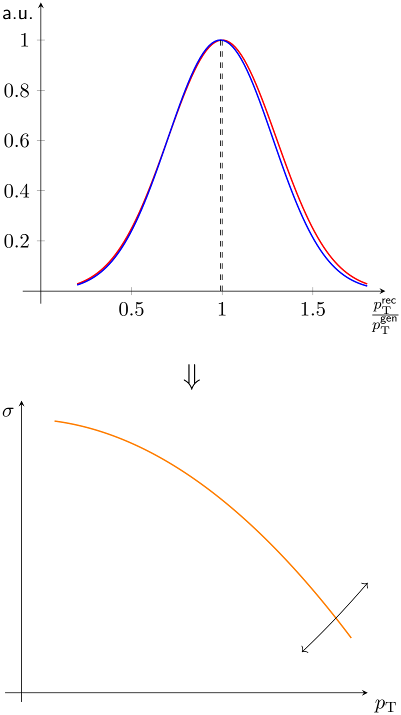

Systematic effects

Jet energy

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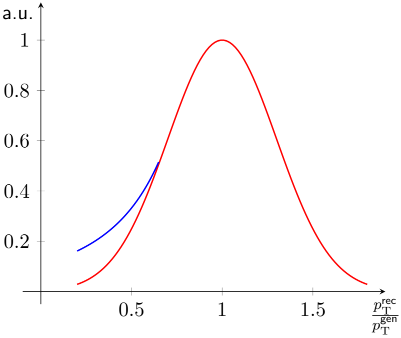
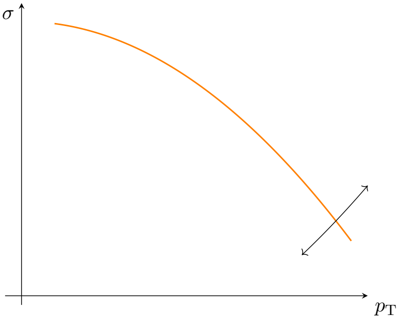
Flavour uncertainties

- The response of the detector depends on the flavour of the jet.
- One of the leading contributions to jet energy uncertainties.



$\Downarrow$



Systematic effects

Jet energy

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Flavour uncertainties

- The response of the detector depends on the flavour of the jet.
- One of the leading contributions to jet energy uncertainties.

Non-Gaussian tails

- The response of the detector is only approximately Gaussian.
- The nature of the large tails and the accuracy of their simulation is not totally under control.

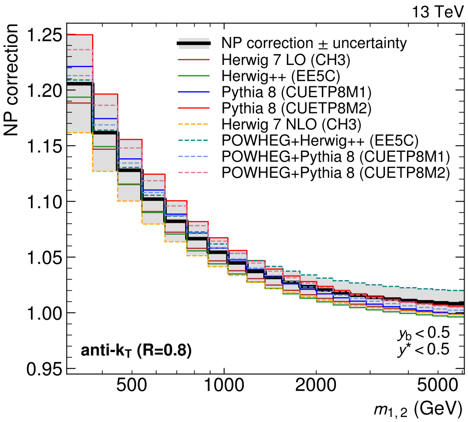
Systematic effects

Non-perturbative effects

Nature (figure from Ref. [9])

$$\mathrm{NP} = \frac{\sigma_{\mathrm{ME+PS+MPI+had}}}{\sigma_{\mathrm{ME+PS}}}$$

- Corrects for hadronisation and MPI.
- Usually obtained from the envelope of the results obtained with various MC generators and tunes.



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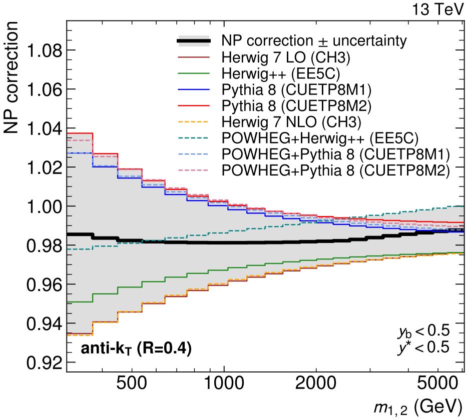

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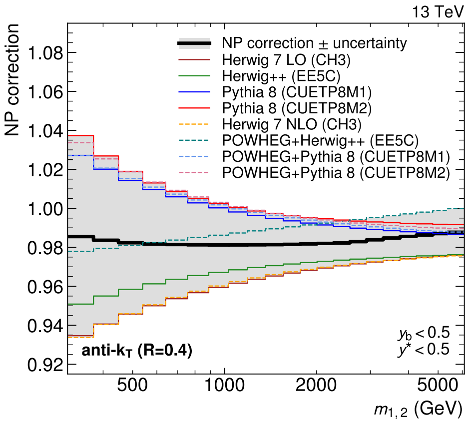
Limitations of the current approach

1. Arbitrary set of MC generators and tunes.
2. Not a Gaussian uncertainty.
3. Hardly interpretable shape.
4. No breakdown of uncertainties.



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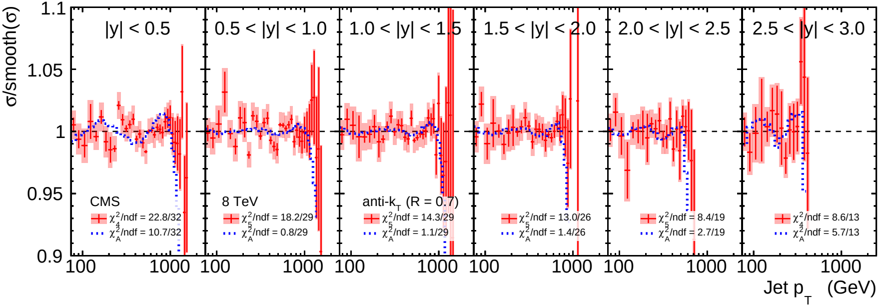
Smoothness



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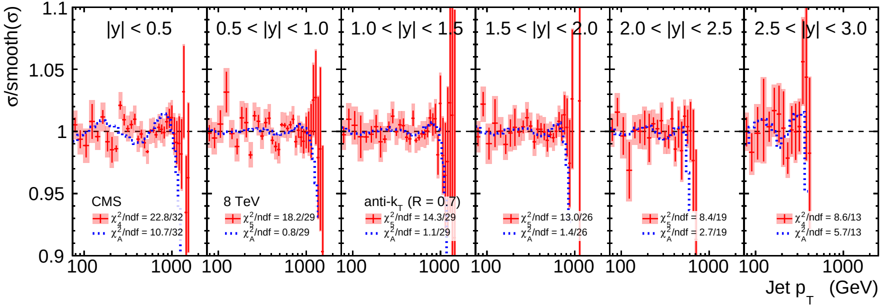
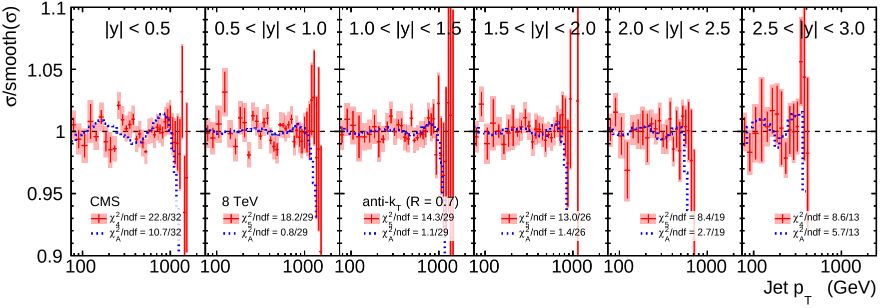


Steps & spurious fluctuations [20]

- Steps are usually not expected in differential cross sections.
- Relative variations may also suffer from spurious fluctuations, especially after the unfolding.
- Fluctuations in the variations will affect the QCD fits.

Smoothness



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- Fluctuations in the variations will affect the QCD fits.

⟶ We were able to reduce the 1% bin-to-bin uncorrelated systematic uncertainties in inclusive jet at 8 TeV [4] to 0.2% at 13 TeV [8].

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Motivation

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

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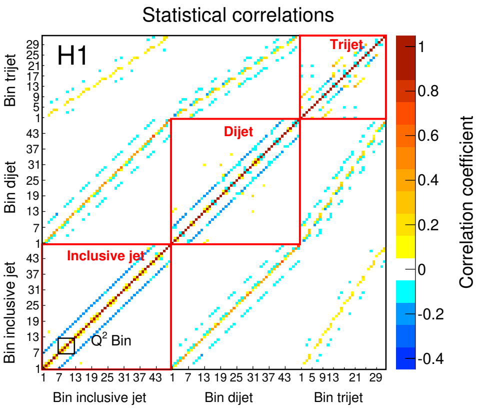
$\longrightarrow$ Follow and extend H1 approach [21]



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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).

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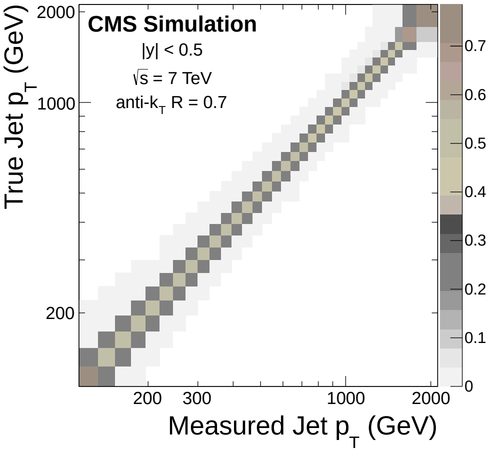
Unfolding

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

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

Reminder

Typical analysis strategy



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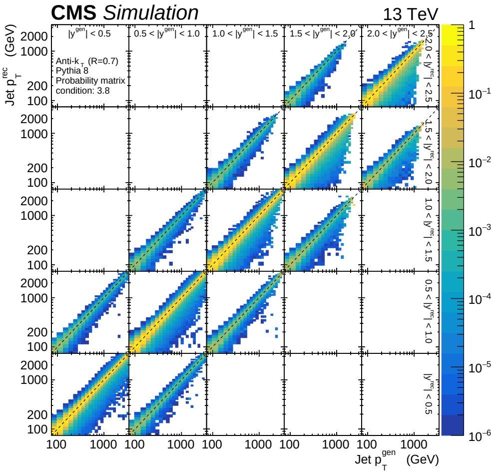
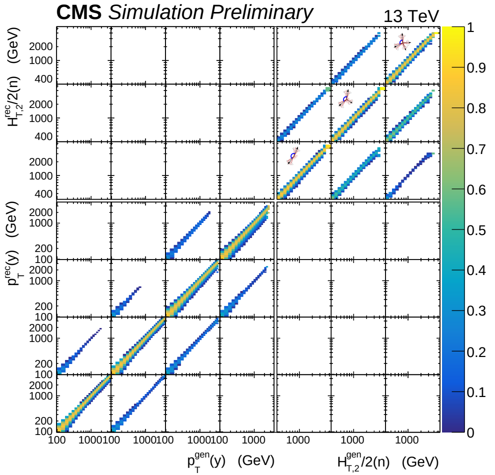


Remark

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

Example

Migrations



Inclusive jet (4×4 block)

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

Example

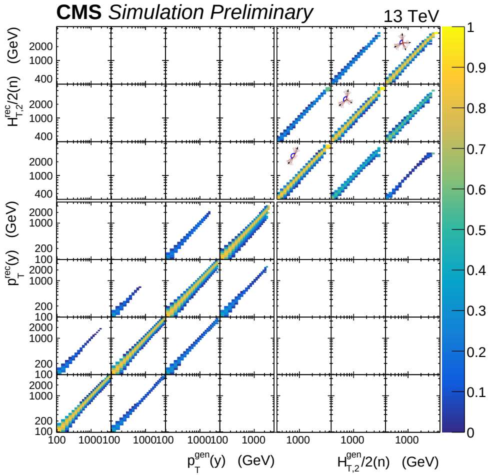
Migrations

$H_{\mathrm{T},2}$ spectra $(3 \times 3$ block$)$

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

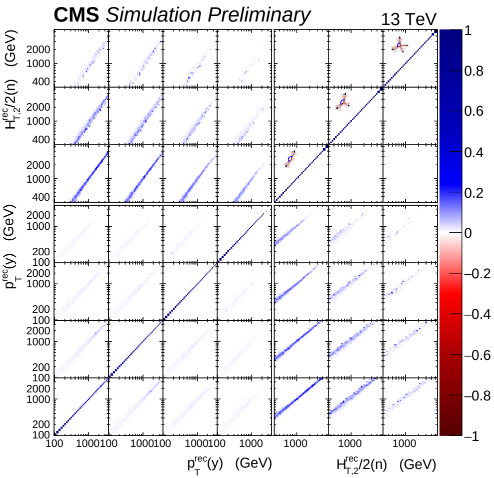
Inclusive jet $(4 \times 4$ block$)$

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



Example

Pre-unfolding correlations

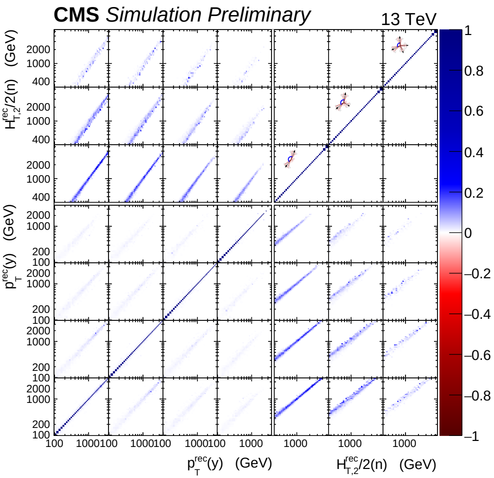


From the real data

- 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.

Example

Pre-unfolding correlations



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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

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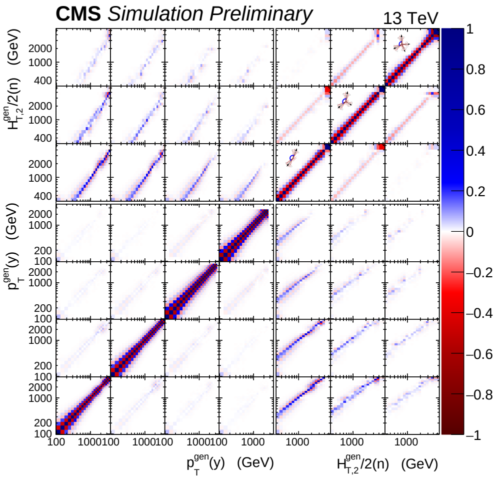
Post-unfolding correlations

Result (unless regularisation is needed)

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

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



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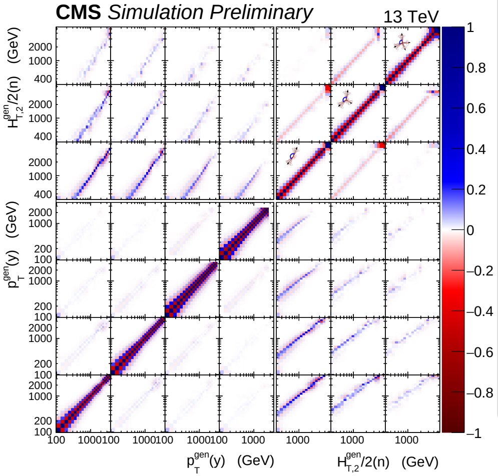

From the simulated data

- 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.

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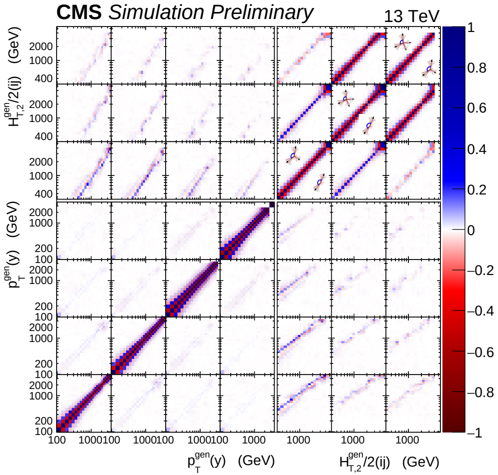
- Under the Gaussian hypothesis, the covariance may be obtained using the formula given on the last slices.

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



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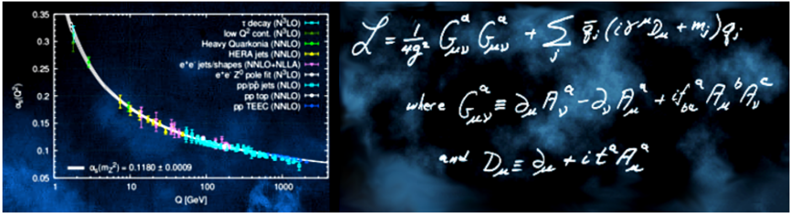
Summary & Conclusions

- The CMS Collaboration has provided numerous determinations of the strong coupling.
- With the advent of predictions at NNLO, the fit uncertainty has become dominant.
- A few of the improvements considered by CMS have been discussed, e.g. simultaneous measurements.



Summary & Conclusions

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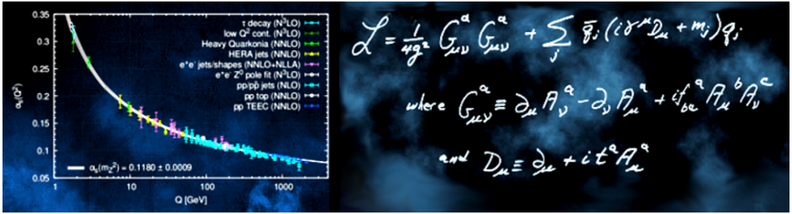
Thank you for your attention!



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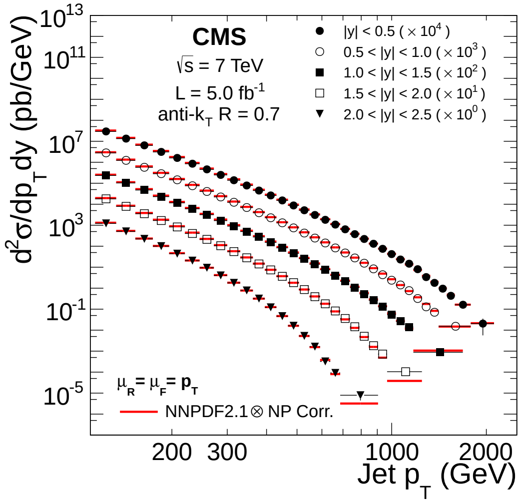
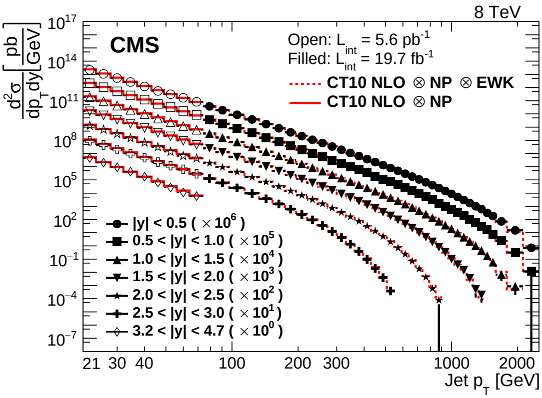
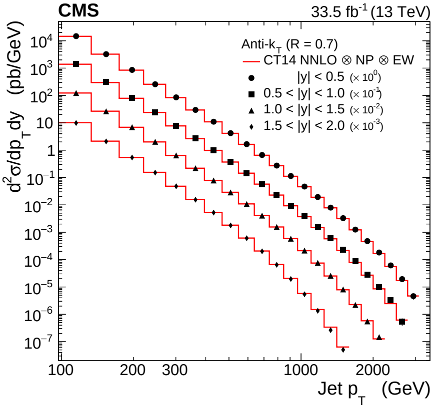


$\sqrt{s}$	lumi	CADI line
2.76 TeV	5.4 pb^{-1}	SMP-14-017
5.02 TeV	27.4 pb^{-1}	SMP-21-009
7 TeV	5.0 fb^{-1}	SMP-12-018
8 TeV	20 fb^{-1}	SMP-14-001
13 TeV	33.2 fb^{-1}	SMP-20-011

Inclusive jet





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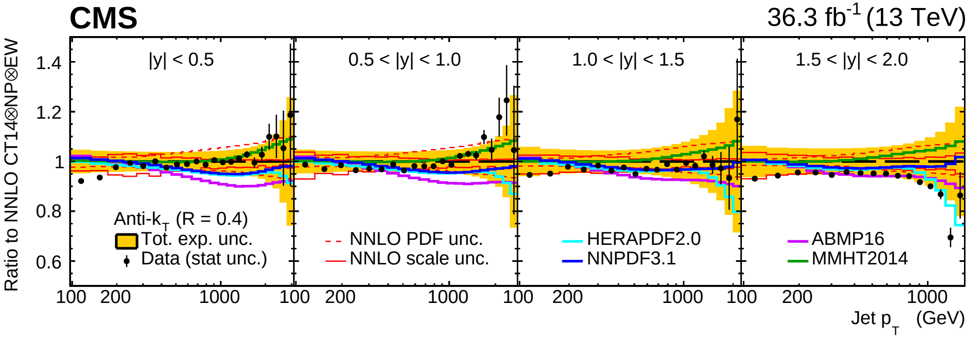
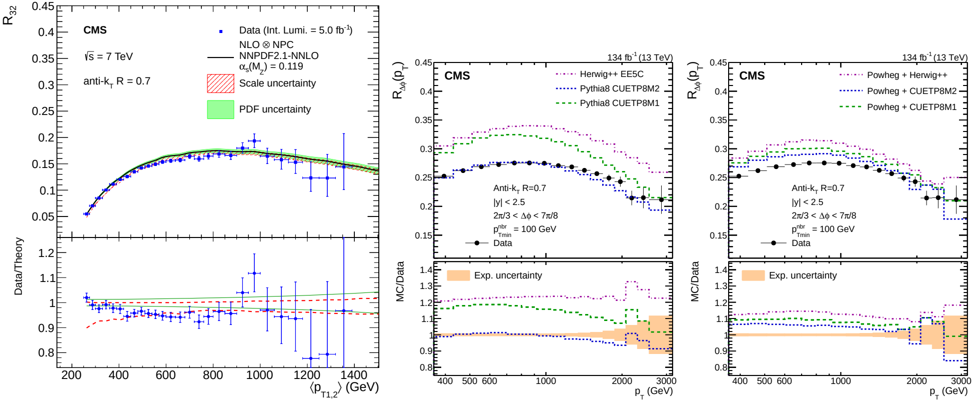


R_{32} and $R_{\Delta\phi}$



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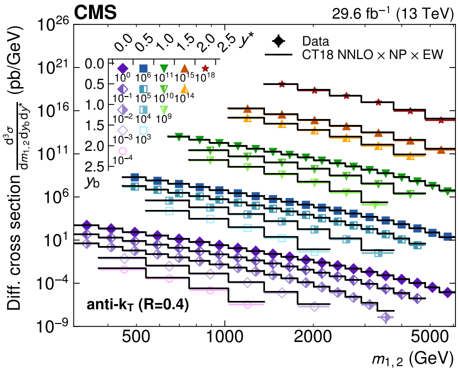
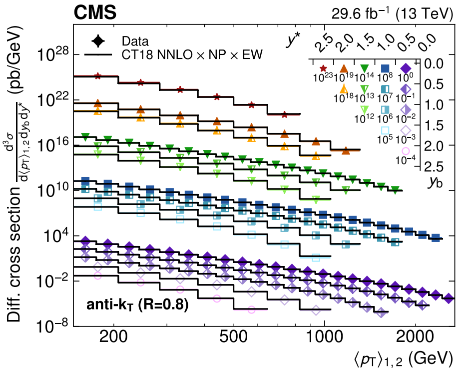
Dijet mass





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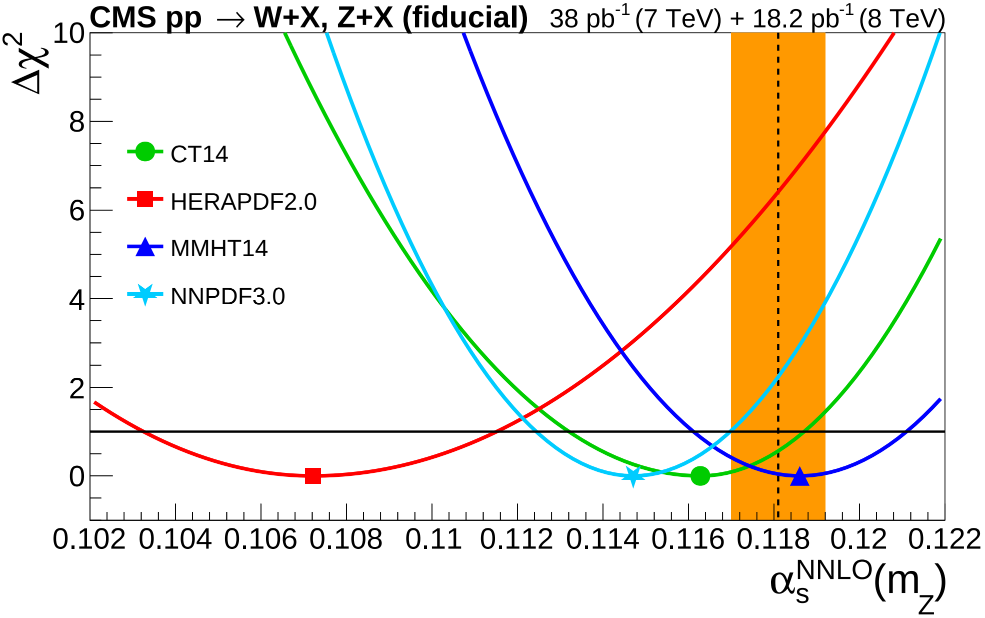
W/Z production



CMS
P. Connor

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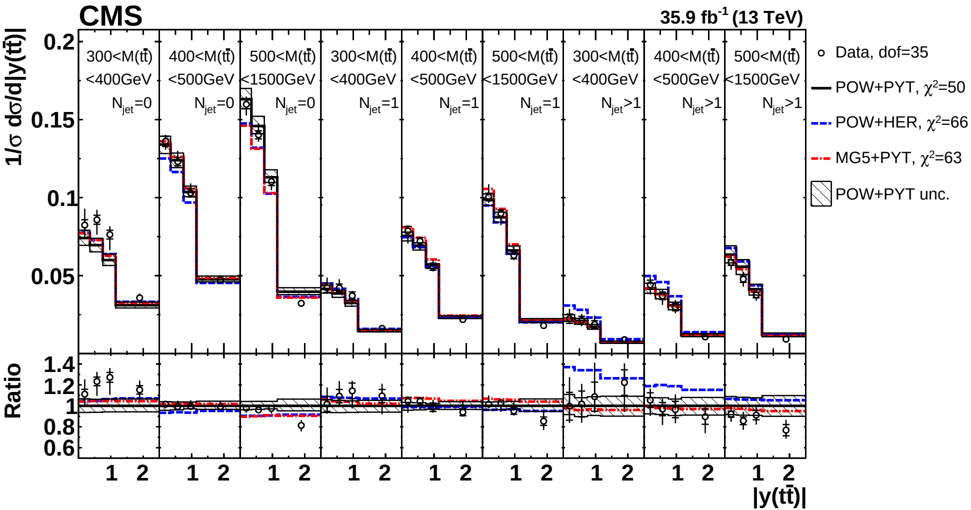
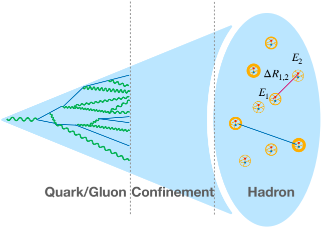
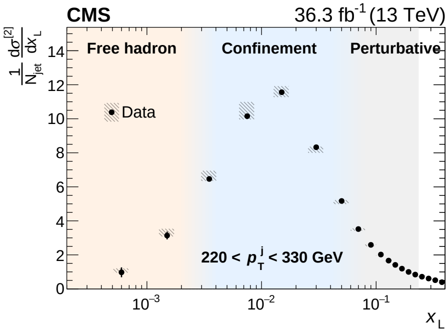
$t\bar{t}$ production



Energy correlators





Energy-energy correlators

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

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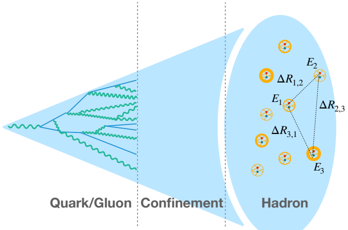
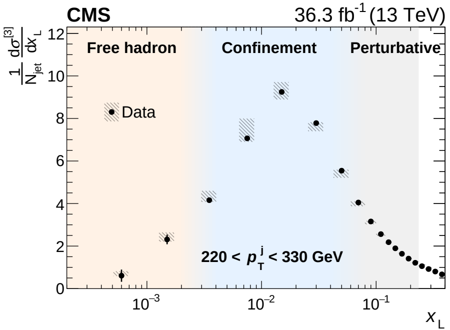
Energy correlators



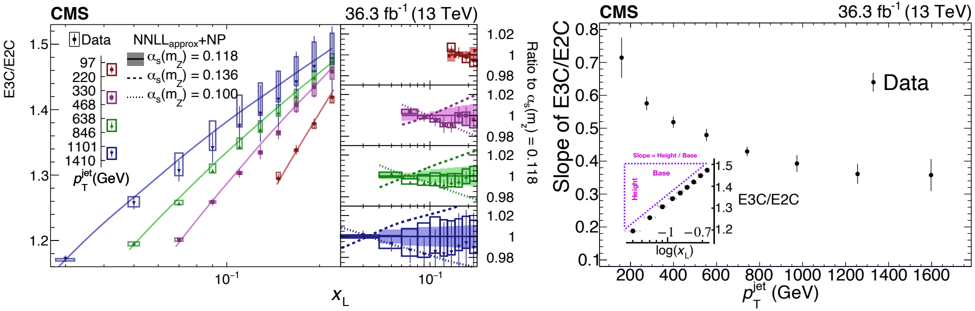


Energy-energy correlators

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

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

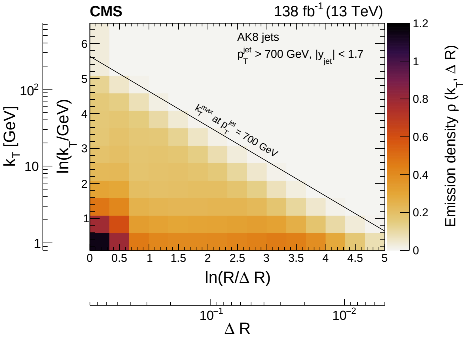
Energy correlators

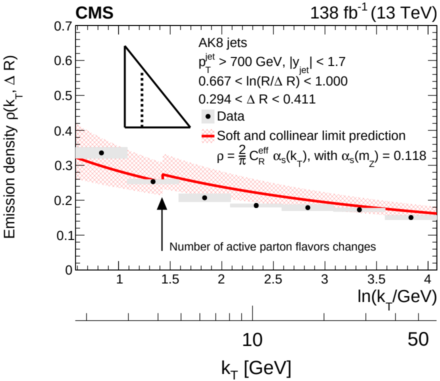


α_s from jet constituents (SMP-22-015)

$$\alpha_s(M_Z) = 0.1229^{+0.0040}_{-0.0050}$$

Lund jet plane





SMP-22-007

$$\rho(k_T, \Delta R) \equiv \frac{1}{N_{\text{jets}}} \frac{\mathrm{d}^2 N_{\text{emissions}}}{\mathrm{d}\log k_T \, \mathrm{d}\ln(R/\Delta R)} \approx \frac{2}{\pi} C_R \alpha_s(k_T),$$

Acronyms I

BSM	searches Beyond the SM. 29, 30
CMS	Compact Muon Solenoid. 3–6, 18–24, 53, 54, 67, 68
DIS	Deeply Inelastic Scattering. 18–22, 27, 28
EEC	energy-energy correlators. 34–38
FO	fixed order. 18–22, 31, 32
H1	HERA-1. 53, 54
HEP	High-Energy Physics. 3–6
HERA	**Hadron-Elektron-RingAnlage**. 18–22, 27, 28
JES	Jet Energy Scale. 41, 42
MC	Monte Carlo. 41, 42, 46–48
ME	Matrix Element. 46–48
MPI	Multi-Parton Interaction. 46–48
NLL	Next to Leading Logarithm. 29, 30
NLO	Next to Leading Order. 23, 24, 29, 30
NNLO	Next to Next to Leading Order. 23, 24, 27, 28, 31, 32, 39, 40, 67, 68
NP	Non-Perturbative. 18–24, 46–48
PDF	Parton Distribution Function. 18–24, 29, 30, 34–38
PS	Parton Shower. 46–48
QCD	Quantum Chromodynamics. 49–51, 53, 54

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