Photo: World Atlas

Universität Hamburg
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ATLAS EXPERIMENT

CMS

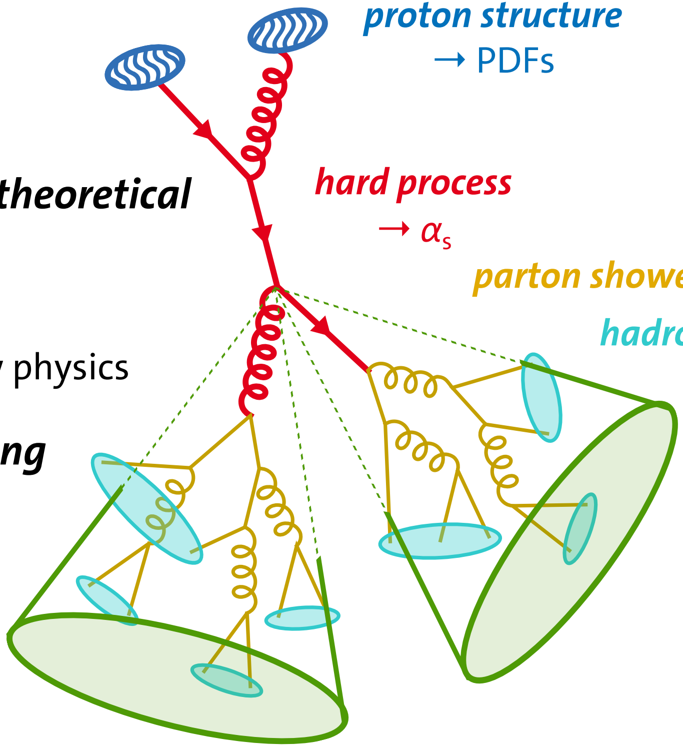
Jet measurements from CMS and ATLAS

New Trends in High-Energy and Low-*x* Physics | 2–5 September 2024 | Sfântu Gheorghe, Romania

Daniel Savoiu on behalf of the ATLAS and CMS collaborations

Why jets?

- jet production is dominant process at hadron colliders
- jet measurements provide essential input for improving ***theoretical models*** (perturbative QCD, parton showers, hadronization)
  - crucial for calculating any process at the LHC, precise modeling of background processes in searches for new physics
- esp. important for understanding ***proton structure*** & ***strong interaction*** (among theoretical components with largest uncertainties)
- rich measurement program at ATLAS & CMS + active theory community



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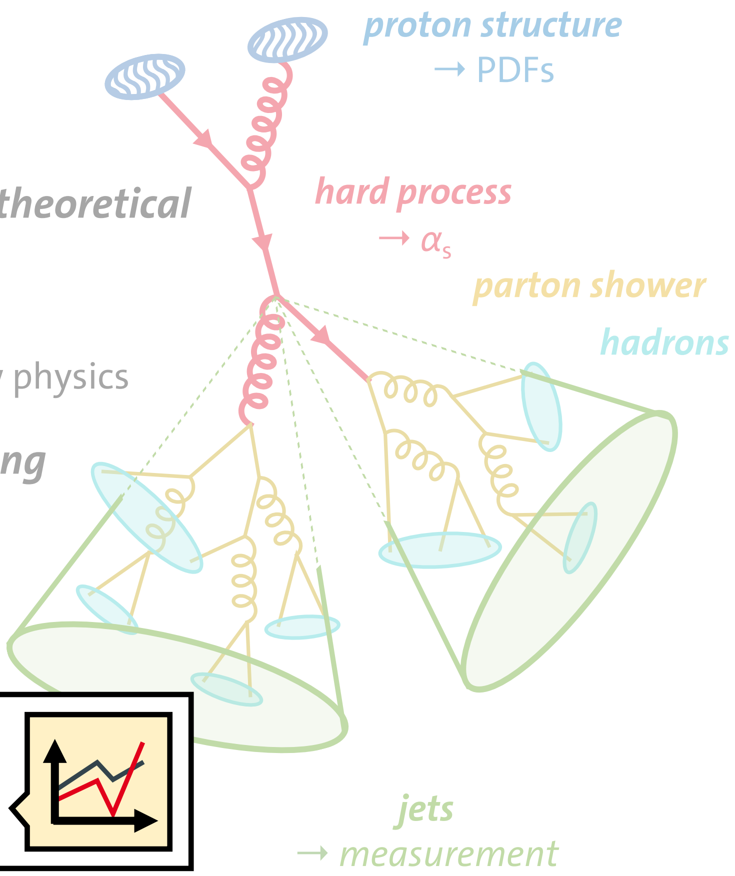
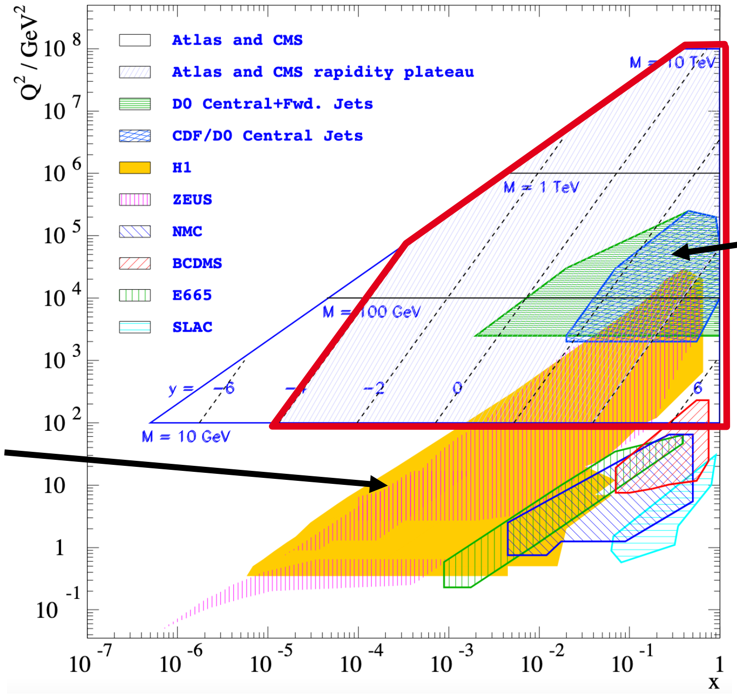
- *this talk*: personal highlights from recent results by both collaborations + attempt to identify ***old*** & ***new trends***



Experimental reach in *x* and *Q*²

phase spaces in parton momentum fraction *x* and energy scale Q^2 covered by experiments

HERA deep inelastic scattering (DIS) data



Tevatron

LHC

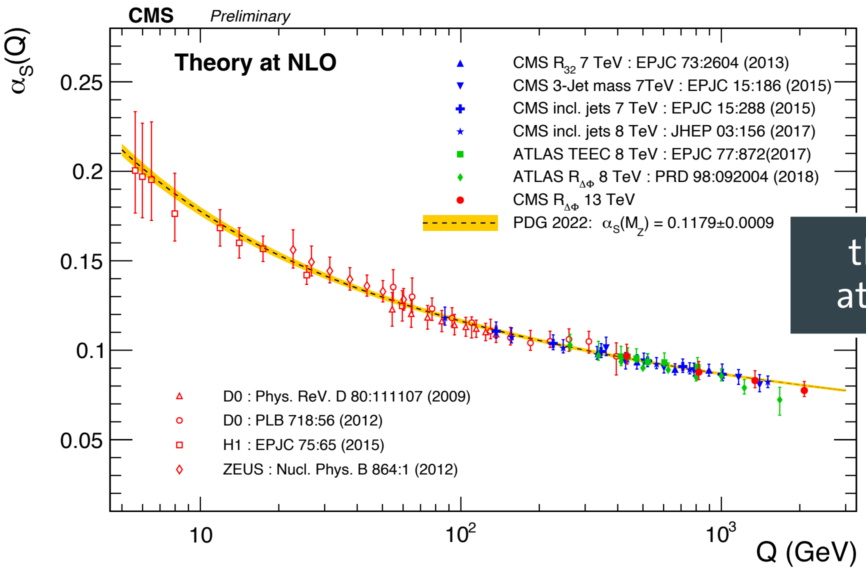
expansion in reach of experiments over time

[D. South et al. *"Review of Searches for Rare Processes and Physics Beyond the Standard Model at HERA"*, *EPJC C* **76** doi:10.1140/epjc/s10052-016-4152-3]

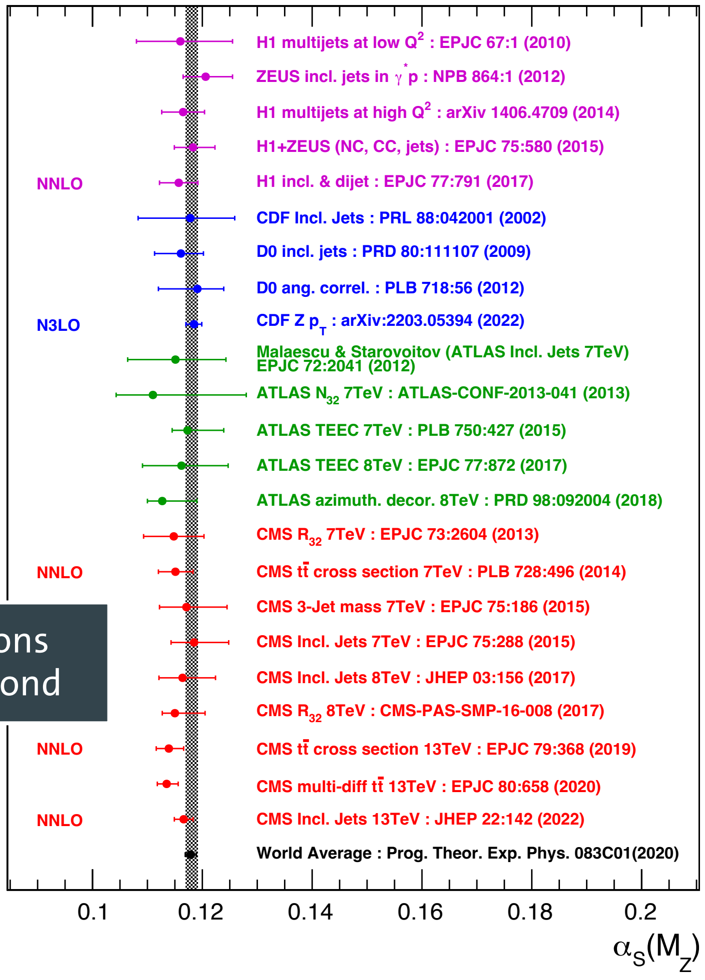
Sensitivity to the strong coupling

jet observables are naturally sensitive to ***strong coupling α_s***

- precise determination of $\boldsymbol{\alpha_s(m_Z)}$
- probe **running of strong coupling** at energies >1 TeV



theory calculations at NNLO and beyond



Selected results from ATLAS & CMS

Collab.	Title	Int. Lumi.	Energies (TeV)	Reference	arXiv
ATLAS	Measurement of **inclusive jet** and **dijet** production in pp collisions at √s = 7 TeV using the ATLAS detector	37 pb-1	7	PRD 86 (2012) 014022	1112.6297
CMS	Measurements of differential **jet cross sections** in proton-proton collisions at √s = 7 TeV with the CMS detector	5.0 fb-1	7	PRD 87 (2013) 112002	1212.6660
ATLAS	Measurement of the **inclusive jet cross-section** in proton-proton collisions at √s = 7 TeV using 4.5 fb^{-1} of data with the ATLAS detector	4.5 fb-1	7	JHEP 02 (2015) 153	1410.8857
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CMS	Measurement of the triple-differential **dijet cross section** in proton-proton collisions at sqrt(s) = 8 TeV and constraints on parton distribution functions	19.7 fb-1	8	EPJC 77 (2017) 11	1705.02628
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CMS	Measurement and QCD analysis of double-differential **inclusive jet cross sections** in proton-proton collisions at √s = 13 TeV	36.3 fb-1	13	JHEP 22 (2022) 142	2111.10431
CMS	Measurement of multidifferential cross sections for **dijet production** in proton-proton collisions at √s= 13 TeV	36.3 fb-1	13	Sub. EPJC	2312.16669
ATLAS	Measurements of **jet cross-section** ratios in 13 TeV proton-proton collisions with ATLAS	140 fb-1	13	Sub. PRD	2405.20206

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More results can be found on experiments' public information pages

ATLAS https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

CMS https://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html

Observables

inclusive jet **cross sections** ("every jet counts")

- direct probe of QCD at different scales and proton momentum fractions

dijet (+ trijet, ...) **cross sections**

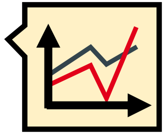
- exploit jet topology for additional handle on PDFs over wide range in x

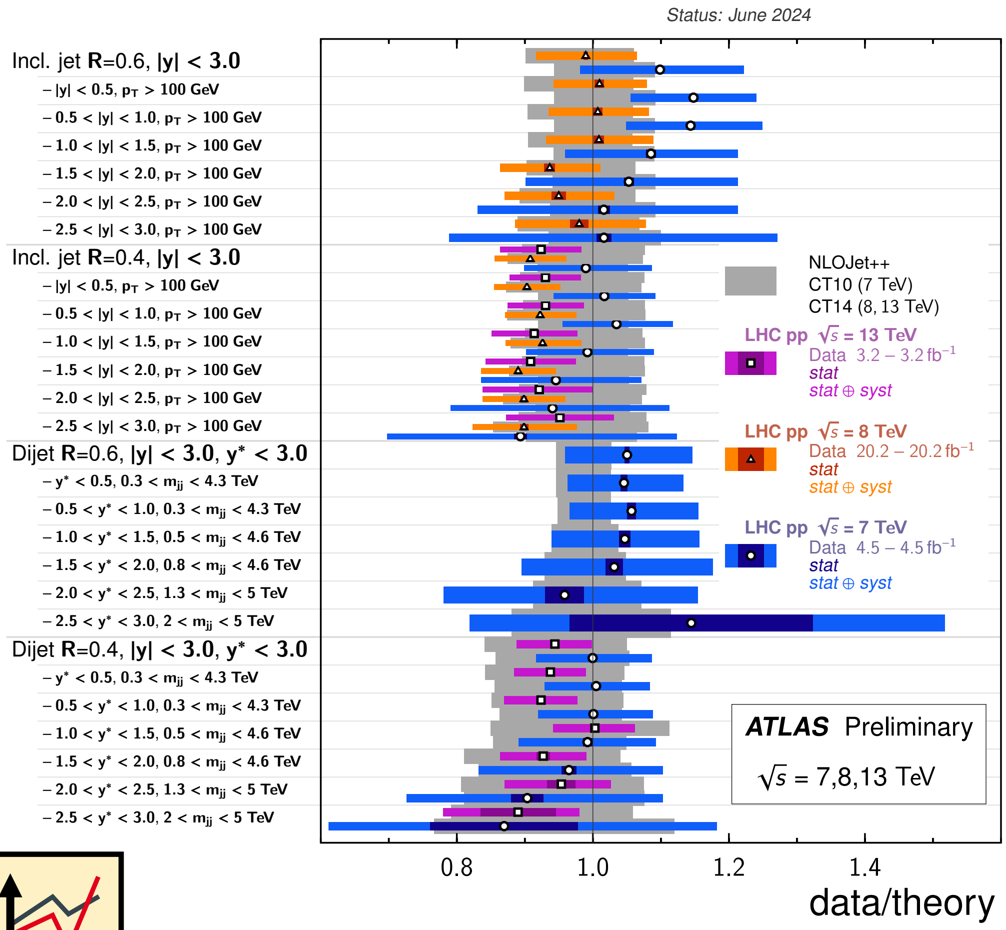
event shapes

- abstraction of topology beyond dijet allows constructing sensitive variables

jet substructure

- resolution of QCD processes inside jets

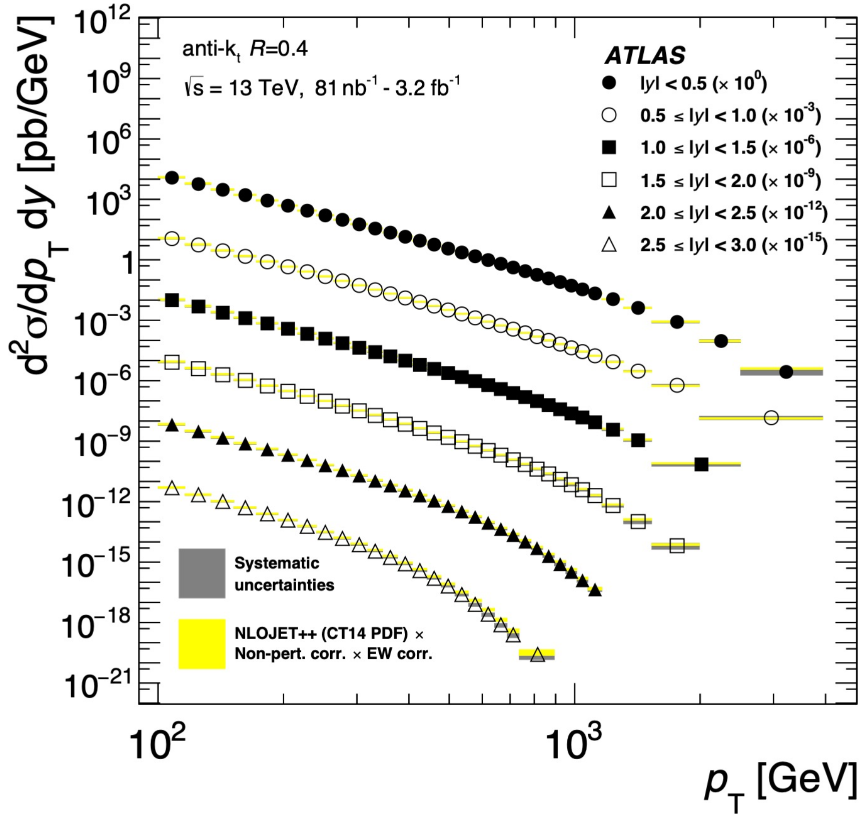




Inclusive jet production

first results at 13 TeV

[arXiv:1711.02692]
[JHEP 05 (2018) 195]

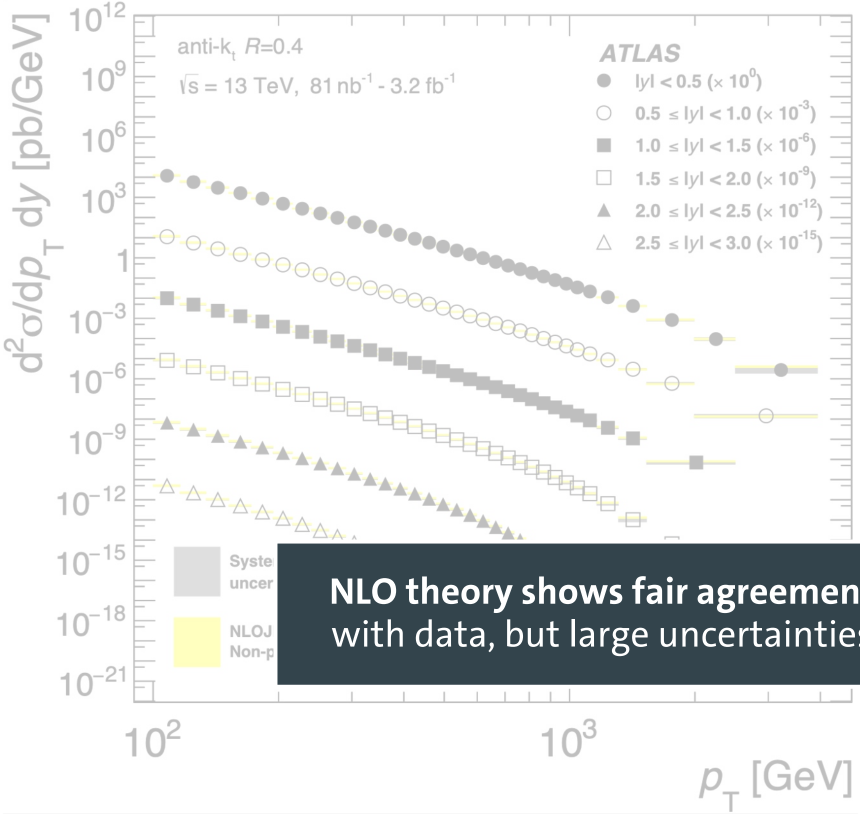


steeply falling spectrum
covering large p_T range

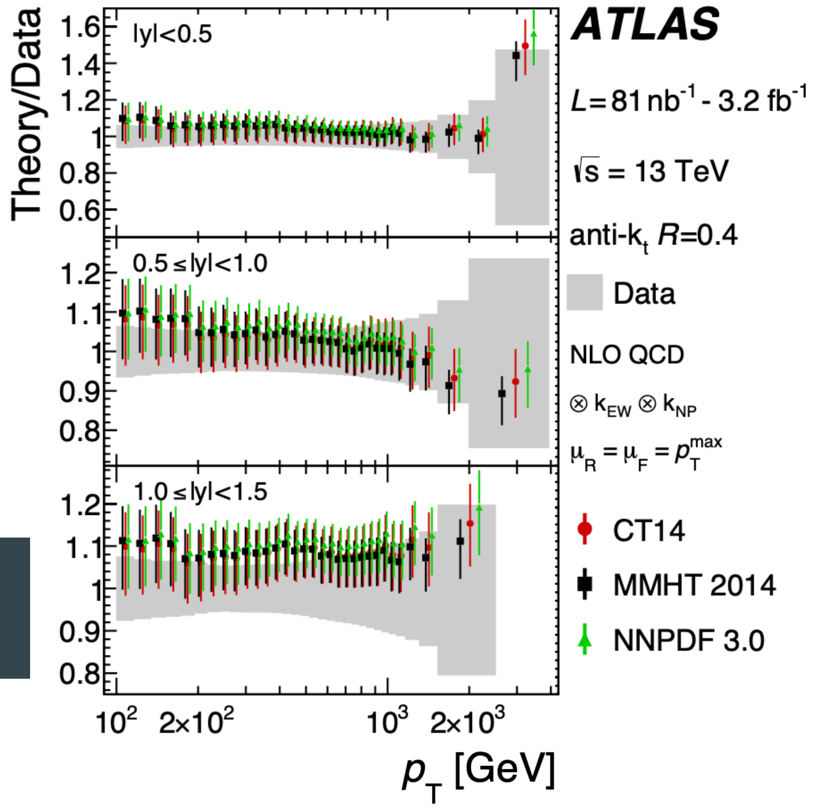
Inclusive jet production

first results at 13 TeV

[arXiv:1711.02692]
[JHEP 05 (2018) 195]



NLO theory shows fair agreement
with data, but large uncertainties



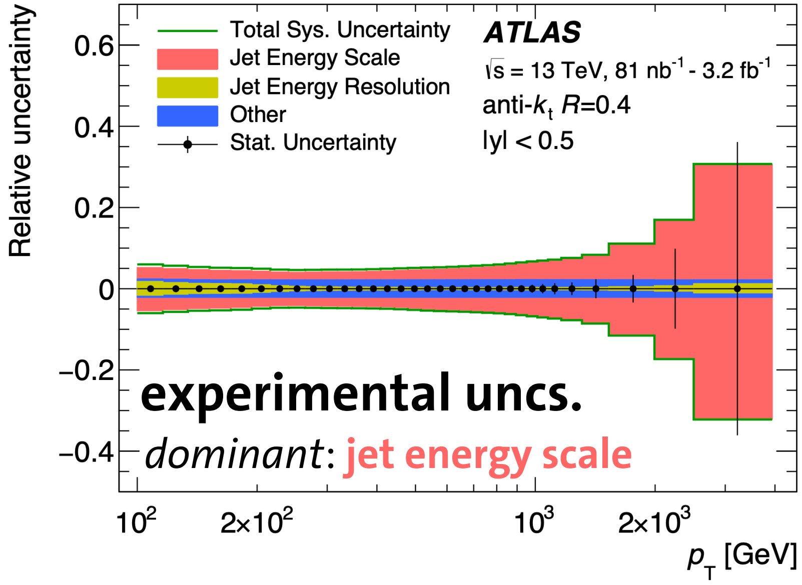
Inclusive jet production – uncertainties

first results at 13 TeV

[arXiv:1711.02692]
[JHEP 05 (2018) 195]

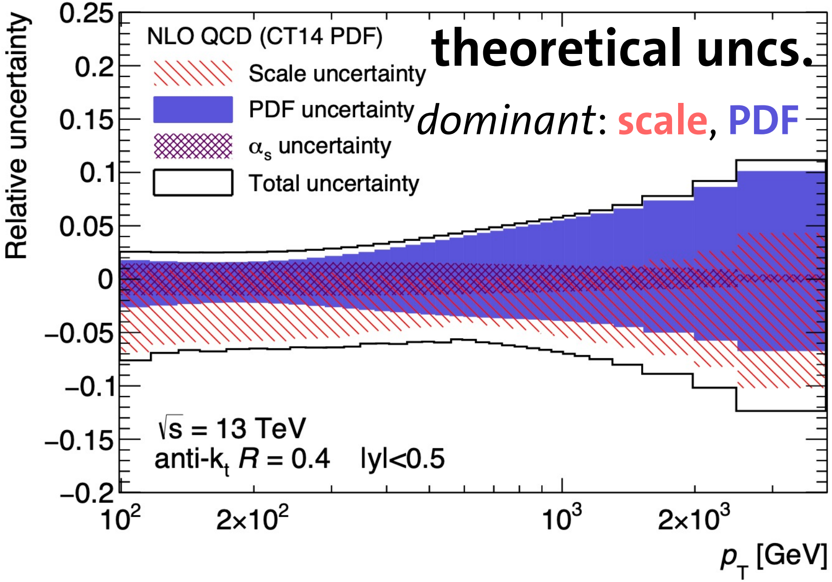
ATLAS EXPERIMENT

“scale” → missing higher orders in perturbation theory



experimental uncs.

dominant: **jet energy scale**



theoretical uncs.

dominant: **scale**, **PDF**

improvement in **experimental methods, calibration** to reduce uncertainties

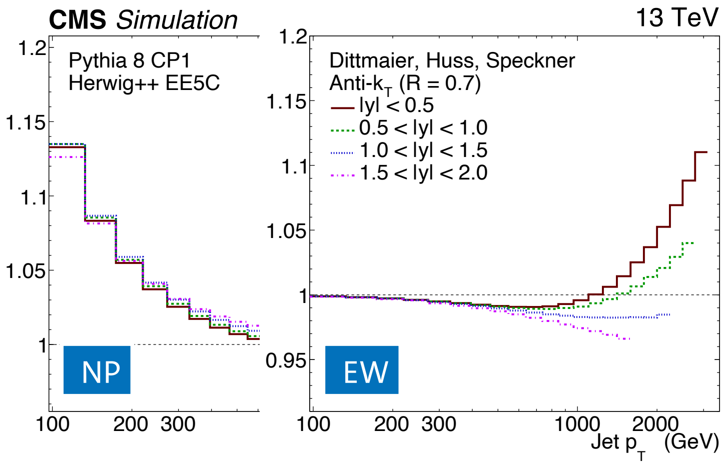
increase in accuracy of **theoretical calculations + models**

Inclusive jet production at $\sqrt{s}$ = 13 TeV

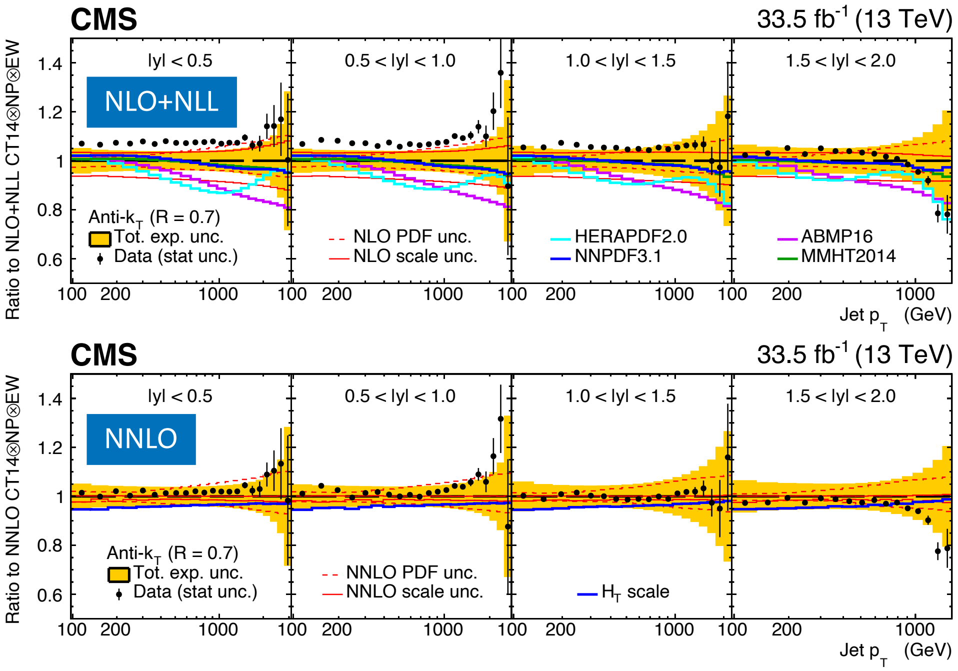
[arXiv:2111.10431]
[JHEP 02 (2022) 142]
+ addendum [JHEP 12 (2022) 035]

comparison to fixed-order pQCD theory at **NNLO** and **NLO+NLL**,
corrected for non-perturbative (***NP***)
and electroweak (***EW***) effects

improved agreement at NNLO



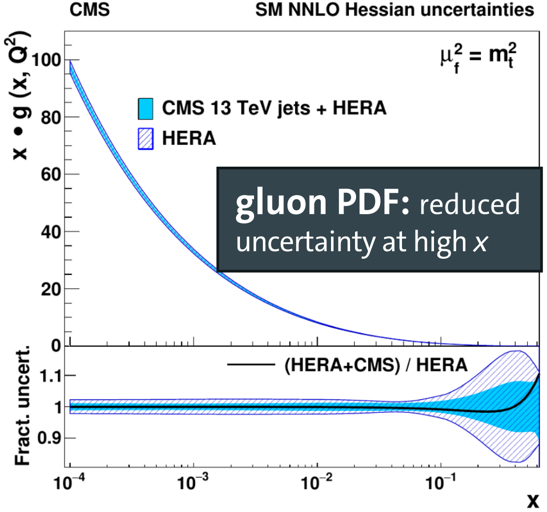
theory corrections of >10%
in certain phase space regions



Highlights

SM fits @ NNLO

PDFs + $\alpha_s(m_Z)$



gluon PDF: reduced uncertainty at high *x*

$\alpha_s(m_Z)$ = **0.1166** ± 0.0014 (fit)
± 0.0007 (model)
± 0.0004 (scale)
± 0.0001 (param.)

most precise NNLO result from jet cross sections

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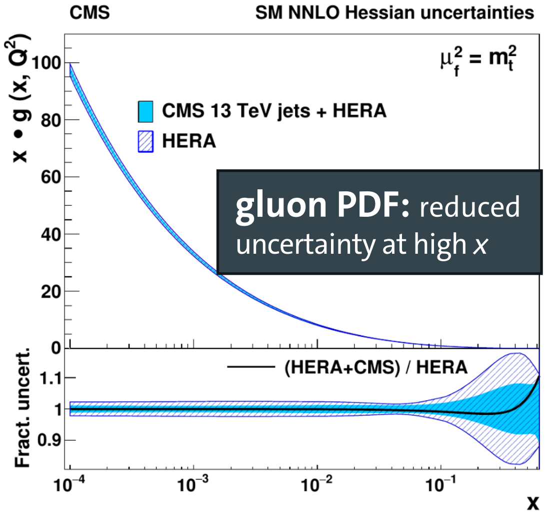

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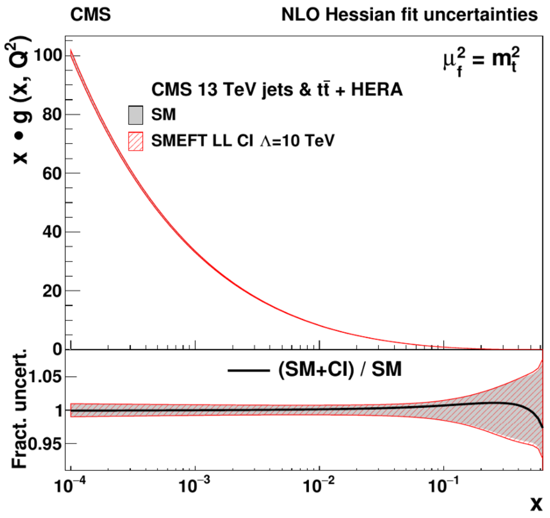
top quark mass in good agreement with previous CMS results using only $t\bar{t}$ data

$m_t^{(\text{pole})}$ [GeV] = **170.4** ± 0.6 (fit)
± 0.1 (model)
± 0.1 (scale)
± 0.1 (param.)

combined fits
with other data sets

PDFs + $\alpha_s(m_Z)$ + $m_t^{(\text{pole})}$



jet data "pins down" PDFs + $\alpha_s(m_Z)$
increased sensitivity to other parameters

$\alpha_s(m_Z)$ = **0.1188** ± 0.0017 (fit)
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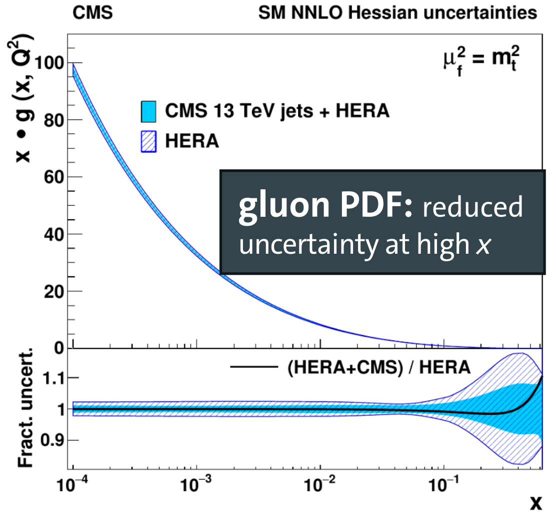

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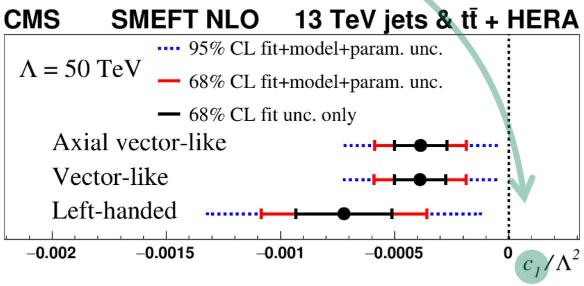
SMEFT constraints

constrain ***Wilson coefficients*** for SM extensions involving four-quark contact interactions

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{2\pi}{\Lambda^2} \sum_{n\in\{1,3,5\}} c_n O_n$$



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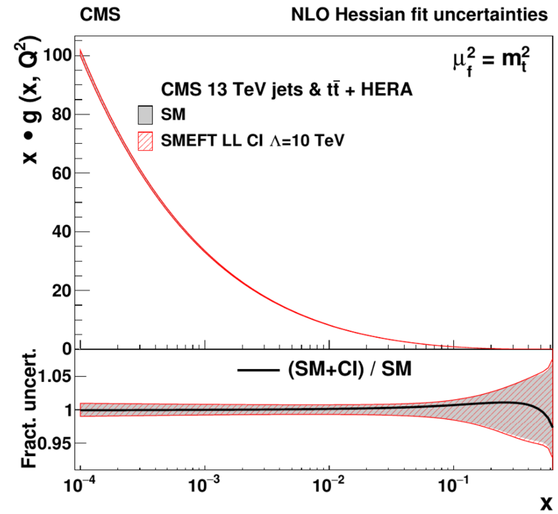

jet data "pins down" PDFs + $\alpha_s(m_Z)$
increased sensitivity to other parameters

$\alpha_s(m_Z)$ = **0.1188** ± 0.0017 (fit)
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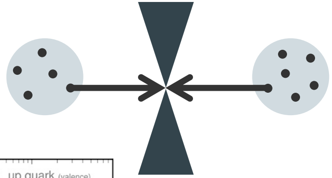
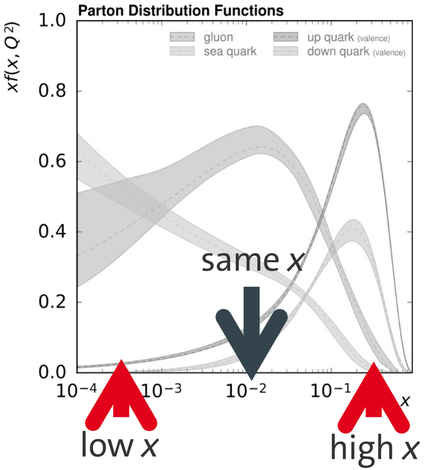
Dijet production

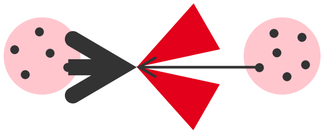
exploit topology of two hardest jets to enhance sensitivity to PDFs

back-to-back





boosted

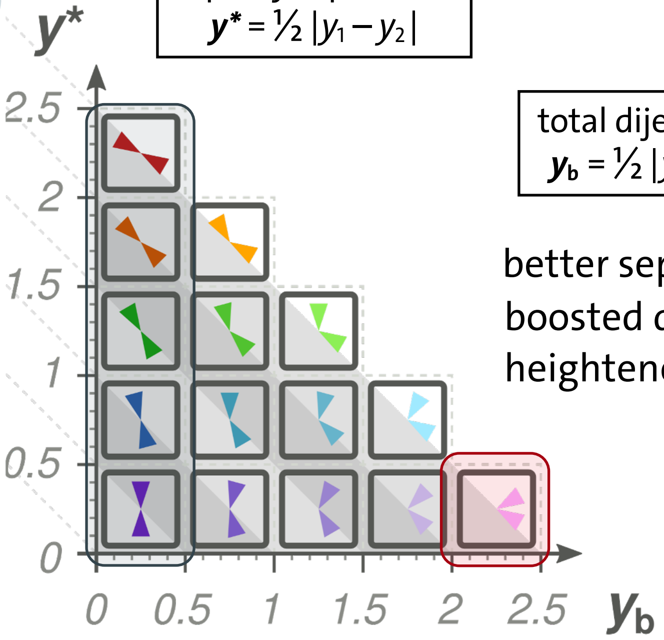


rapidity separation
$y^* = \frac{1}{2}\,|y_1 - y_2|$

triple-differential cross section

total dijet boost
$y_b = \frac{1}{2}\,|y_1 + y_2|$

$m_{1,2}$ or $\langle p_T \rangle_{1,2}$

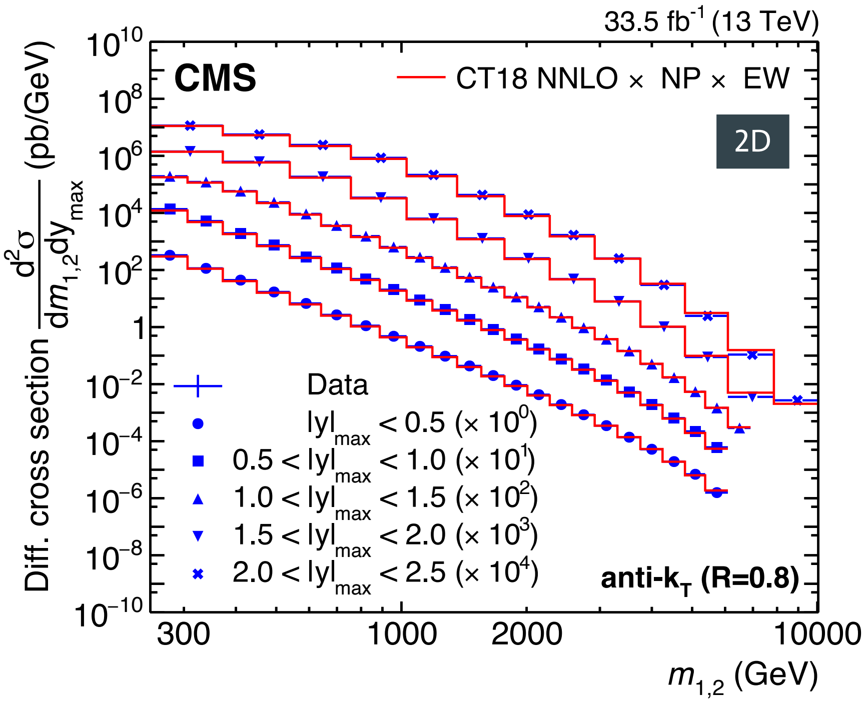


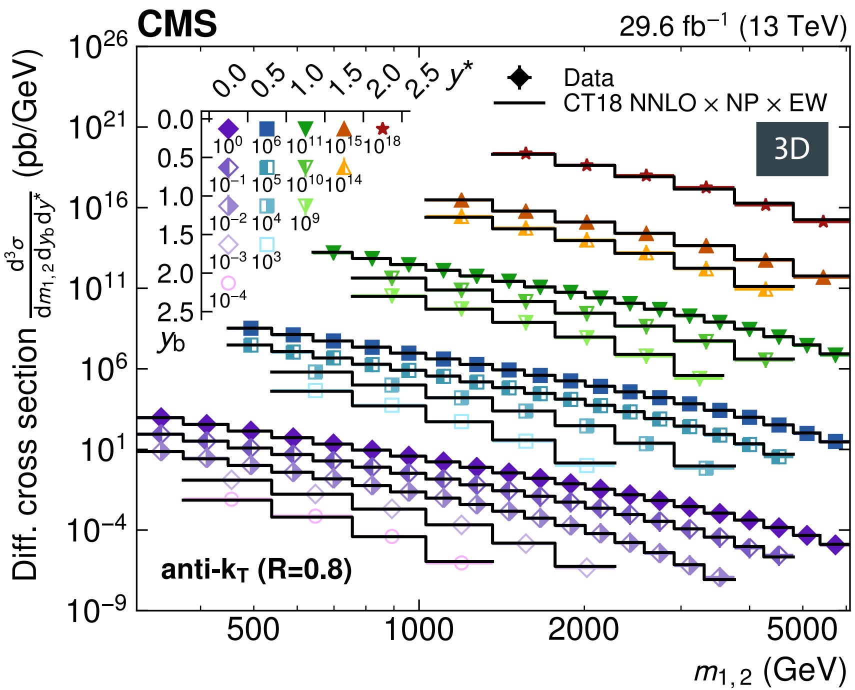
better separation of boosted and non-boosted dijet topologies → potentially heightened sensitivity to PDFs

Dijet cross sections at 13 TeV

[arXiv:2312.16669]
Submitted to *EPJC*

- **double-** (2D) & **triple-differential** (3D) cross section vs. **dijet invariant mass $m_{1,2}$**
- comparison to fixed-order theory at **NNLO** pQCD from ***NNLOJET*** + ***fastNLO***





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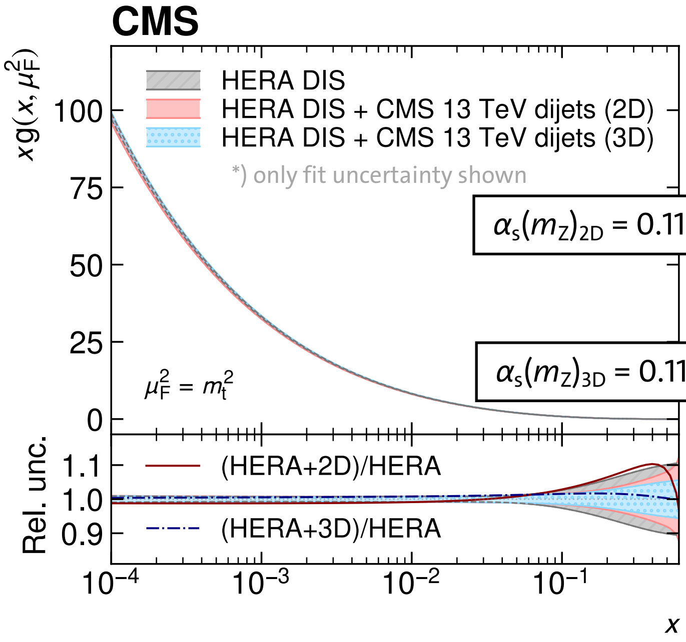
PDFs and $\alpha_s(m_Z)$ determined simultaneously in fits to CMS dijet & HERA DIS data



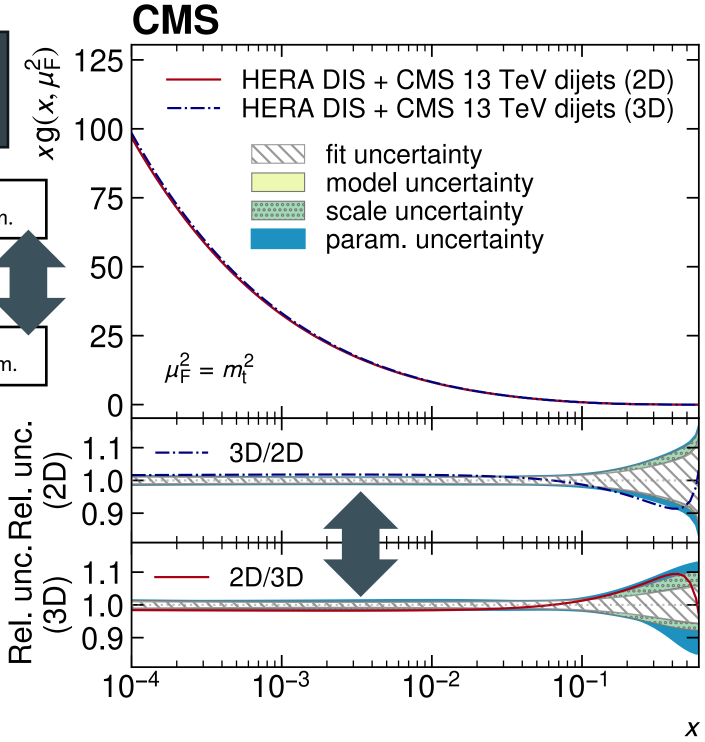
2D & 3D fits yield compatible results

$\alpha_s(m_Z)_{2D} = 0.1179\ (15)_{fit}\ (8)_{model}\ (8)_{scale}\ (1)_{param.}$

↳ $\chi^2 / n_{dof} = 1232 / 1081$

$\alpha_s(m_Z)_{3D} = 0.1181\ (13)_{fit}\ (9)_{model}\ (6)_{scale}\ (2)_{param.}$

↳ $\chi^2 / n_{dof} = 1339 / 1109$



gluon PDF uncertainty reduced at $x > 0.3$

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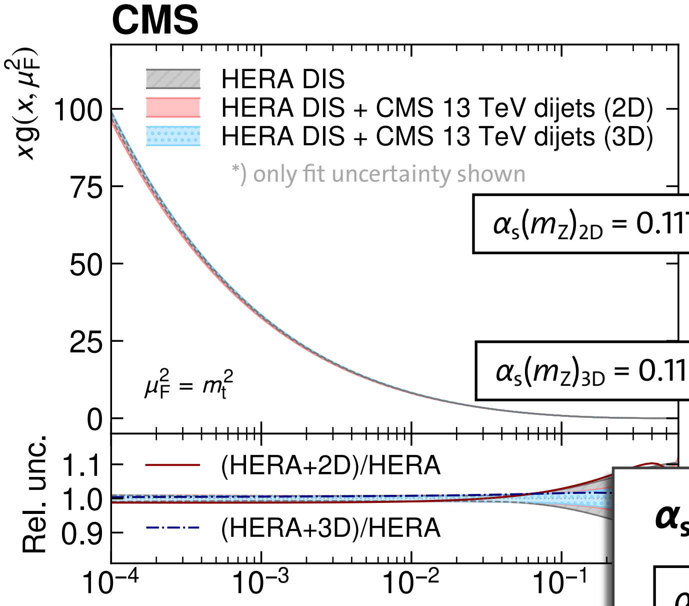

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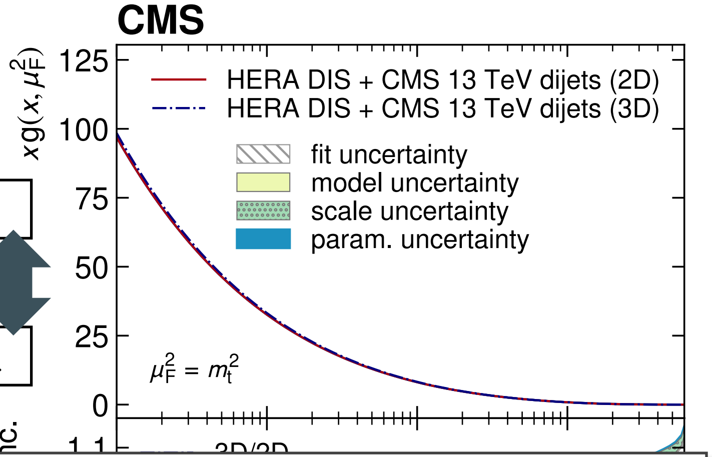


gluon PDF uncertainty reduced at $x >$

α_s from inclusive jet production at $\sqrt{s}$ = 13 TeV

[arXiv:2111.10431]
[JHEP 02 (2022) 142]
+ add. [JHEP 12 (2022) 035]

$\alpha_s(m_Z)_{incl.\ jet} = 0.1166\ (14)_{fit}\ (7)_{model}\ (4)_{scale}\ (1)_{param.}$

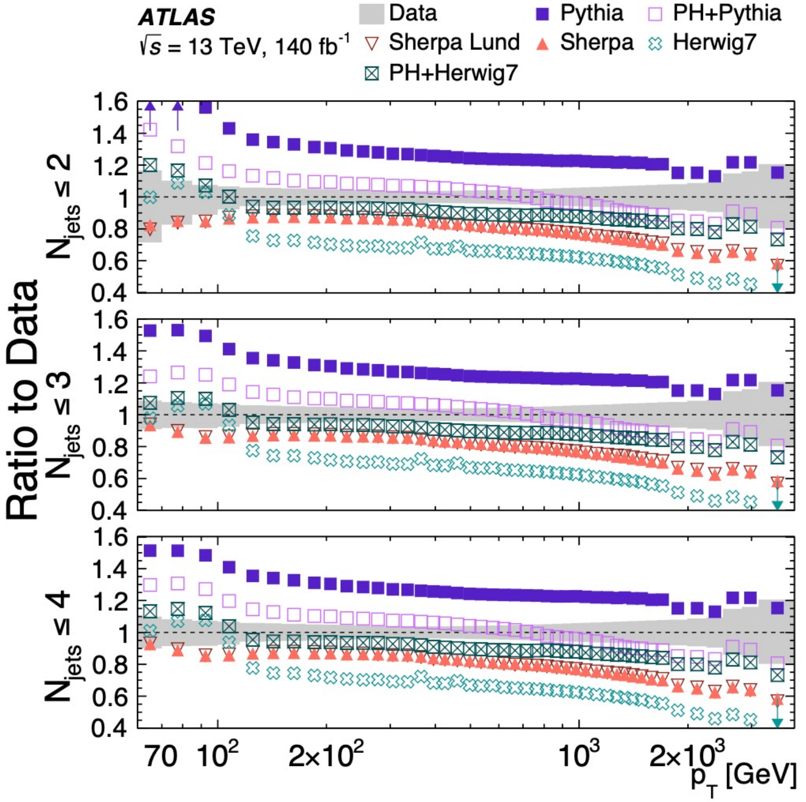
↳ $\chi^2 / n_{dof} = 1302 / 1118$

most precise value for $\alpha_s(m_Z)$ from jets

Jet cross sections vs. multiplicity

[arXiv:2405.20206]
Submitted to *PRD*

- differential cross section measured in bins of **jet multiplicity N_{jets}** from 140 fb^{-1} of data
- inclusive jet and dijet cross sections as a function of p_T and $H_{T2} = p_{T,1} + p_{T,2}$
- comparison to MC generators & fixed-order theory at NLO pQCD



no MC describes data in entire phase space,
best overall agreement from ***Sherpa***

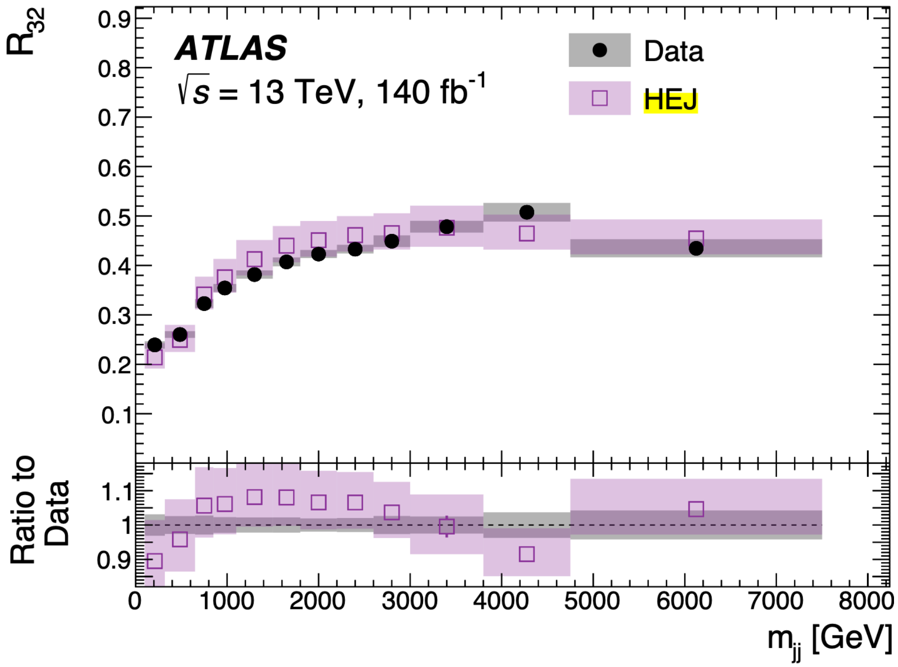
Jet cross section ratios

[arXiv:2405.20206]
Submitted to *PRD*

- ***ratios*** measured between multiplicity bins, benefit from cancellation of systematic uncertainties, e.g.

$$R_{32} = \frac{\sigma(N_{\text{jets}} \leq 3)}{\sigma(N_{\text{jets}} \leq 2)}$$

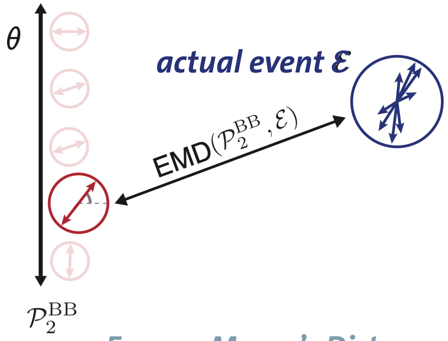
- comparison to NNLO theory using ***High Energy Jets*** theoretical framework for calculating logarithmic corrections to all orders in α_s



Multijet event isotropies

- ***isotropies*** = event shape variables that quantify the distance from a "symmetric radiation pattern"
- minimization of ***distance metric*** to ***reference geometries*** (dipole, cylinder, ring, etc.)

example: ***dipole***



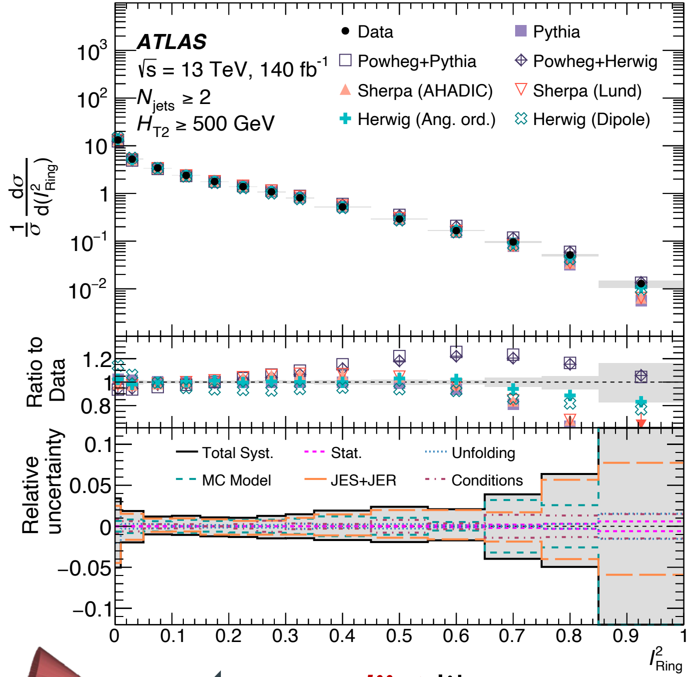
Energy-Mover's Distance

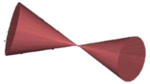
$$\mathrm{EMD}_\beta(\mathcal{E},\mathcal{E}') = \min_{\{f_{ij}\geq 0\}} \sum_{i=1}^{M}\sum_{j=1}^{M'} f_{ij}\theta_{ij}^{\beta},$$

- data/theory best for balanced ***dijet***-like configuration, ***deteriorates*** at high isotropy
- explore remote areas of QCD phase space, useful as input to ***MC tuning***

example: I^2_{Ring}

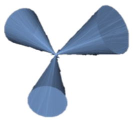
[arXiv:2305.16930]
[JHEP 10 (2023) 060]





more ***dijet***-like

more symm. ***trijet***-like



Jet azimuthal correlations

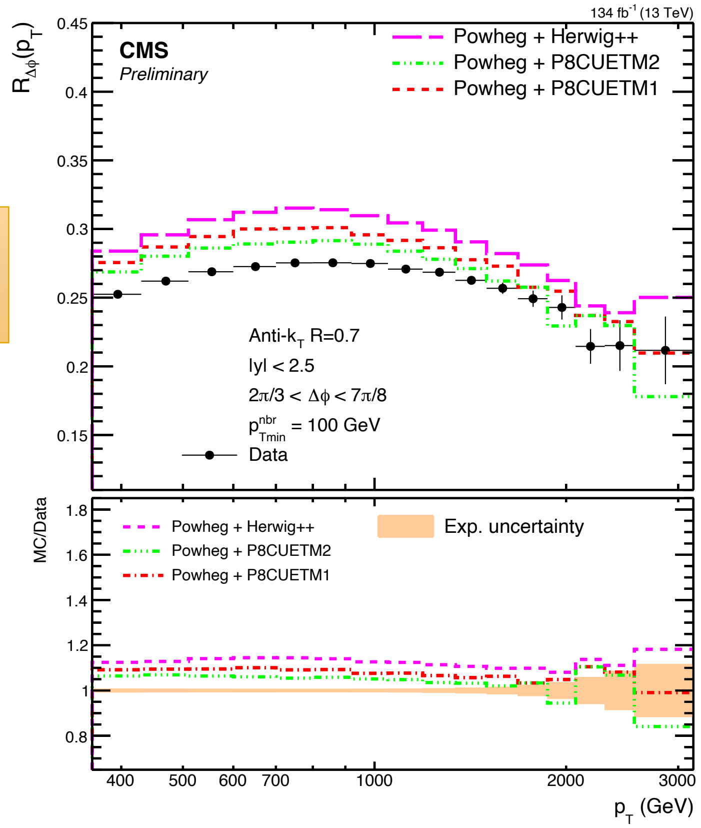
[arXiv:2305.16930]
[CMS-PAS-SMP-22-005]

- observable $R_{\Delta\phi}$ defined via the ***number of neighboring jets*** within a specified interval of ***angular distance Δφ***

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

ratio observable
→ many systematic uncertainties cancel

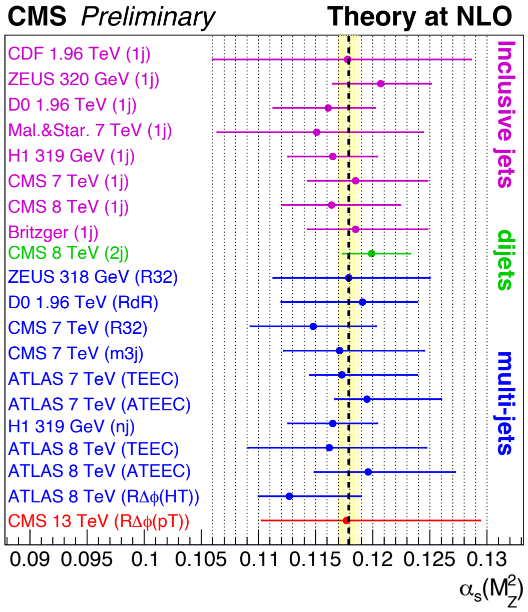
- interval $\left(\frac{2\pi}{3} < \Delta\phi < \frac{7\pi}{8}\right)$ separates dijet topologies from 3+ jets → ***sensitivity to $\alpha_s(m_Z)$***

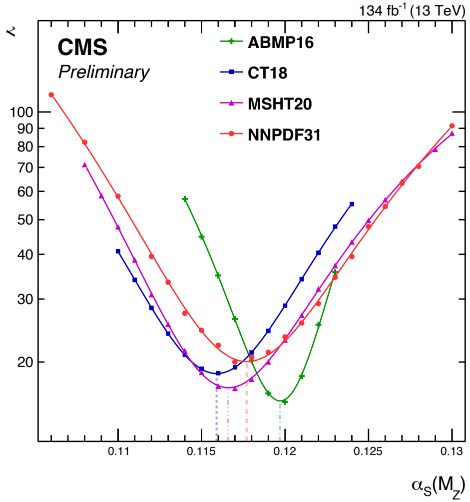


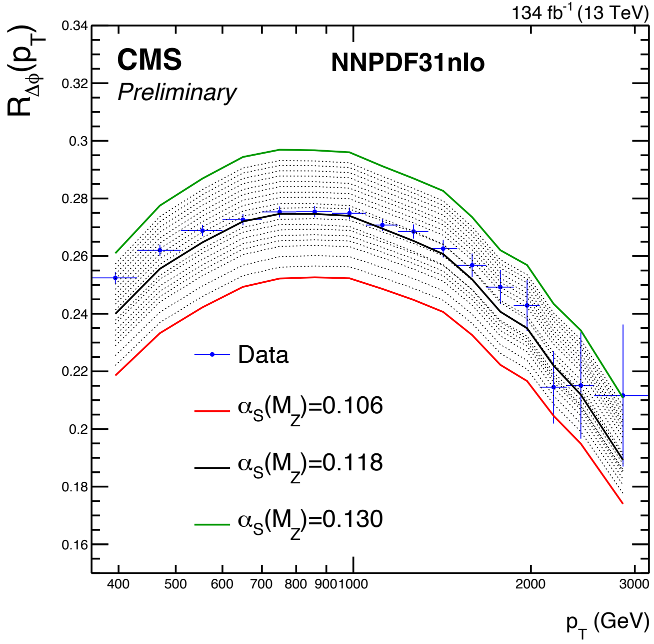
Jet azimuthal correlations

[arXiv:2305.16930]
[CMS-PAS-SMP-22-005]

- extraction of $\alpha_s(m_Z)$ from comparison to fixed-order pQCD predictions at ***NLO*** using several global PDF sets + nonperturbative & electroweak corrections





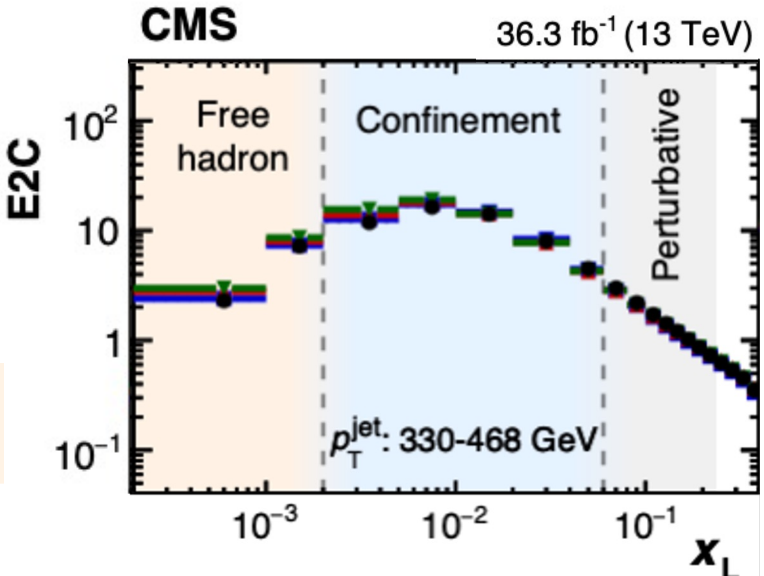


$$\alpha_s(m_Z)_{NLO} = 0.1177 \ (13)_{exp} \ \left({}^{+116}_{-73}\right)_{theo.}$$

Energy correlators (EECs)

[arXiv:2402.13864]
PRL 133 (2024) 7

- ***substructure observables*** that describe the correlations of kinematic properties of particles inside jets, weighted by energy → E_iE_j/E^2 or $E_iE_jE_k/E^3$
- calculated based on ***pairs*** (E2C) or ***triplets*** (E3C) of constituent particles
- ordered by ***angular separation*** x_L → probe timescale of hadron formation



$$= \sqrt{(\Delta\eta_{i,j})^2 + (\Delta\phi_{i,j})^2}$$

small angle splittings, non-interacting hadrons

wide angle splittings, perturbation theory

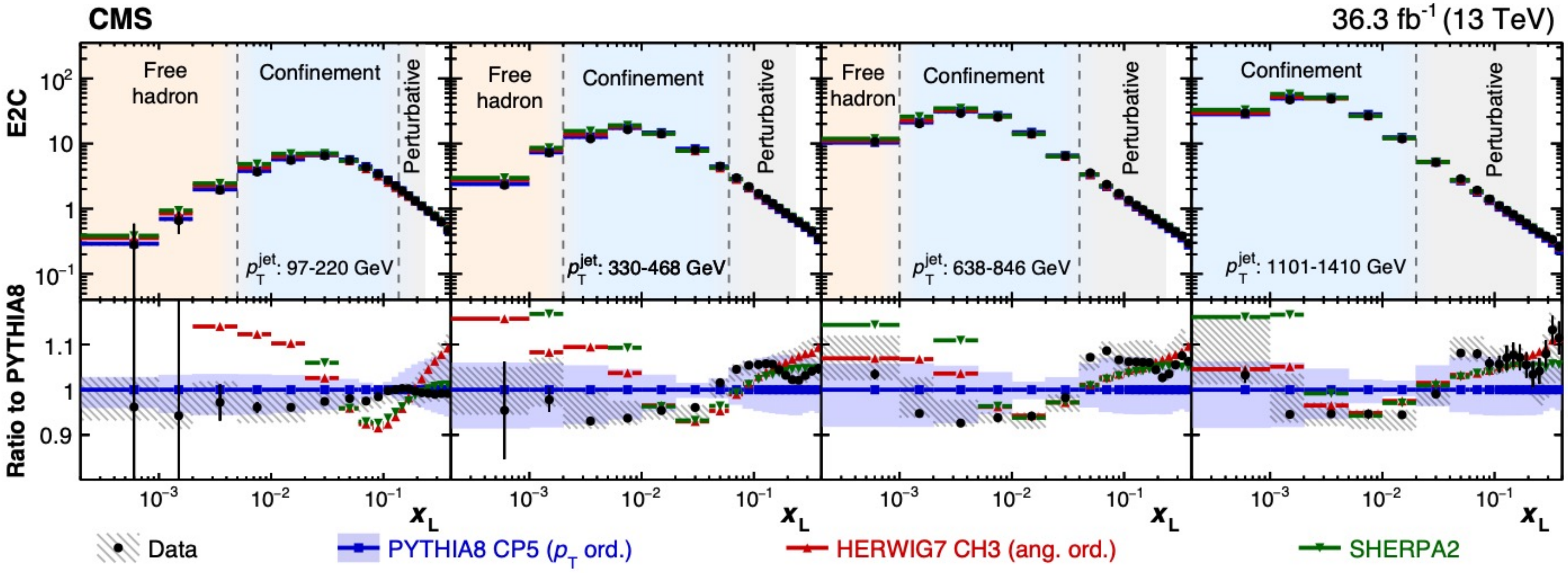
Energy correlators (EECs)

[arXiv:2402.13864]
PRL 133 (2024) 7

- EECs measured in bins of **jet p_T** and compared to predictions from MC generators ***PYTHIA 8***, ***Herwig 7*** and ***SHERPA 2***

best overall description (PYTHIA 8)

perform better in some regions (Herwig 7 and SHERPA 2)

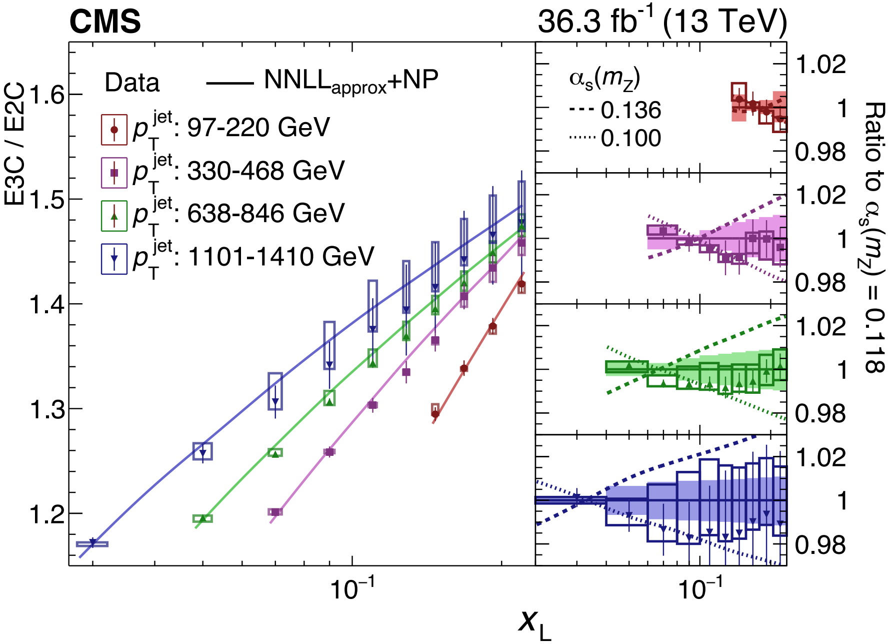


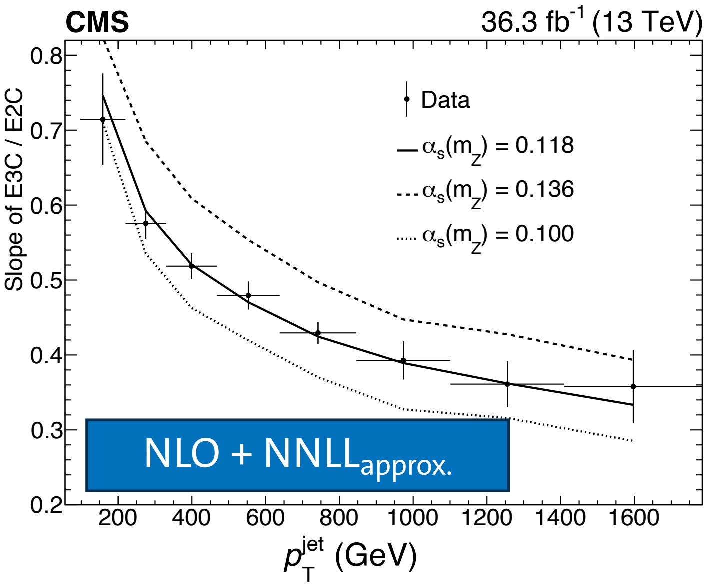
Strong coupling from EECs

[arXiv:2402.13864]
PRL 133 (2024) 7

ratio of E3C and E2C sensitive to $\alpha_s(m_Z)$:

- approx. linear in $\alpha_s \ln x_L$
- PDF dependence largely suppressed





$$\alpha_s(m_Z)_{EEC} = 0.1229 \; \left({}^{+14}_{-12}\right)_{stat.} \; \left({}^{+23}_{-36}\right)_{exp.} \; \left({}^{+30}_{-33}\right)_{theo.}$$

most precise $\alpha_s(m_Z)$ from substructure

Summary

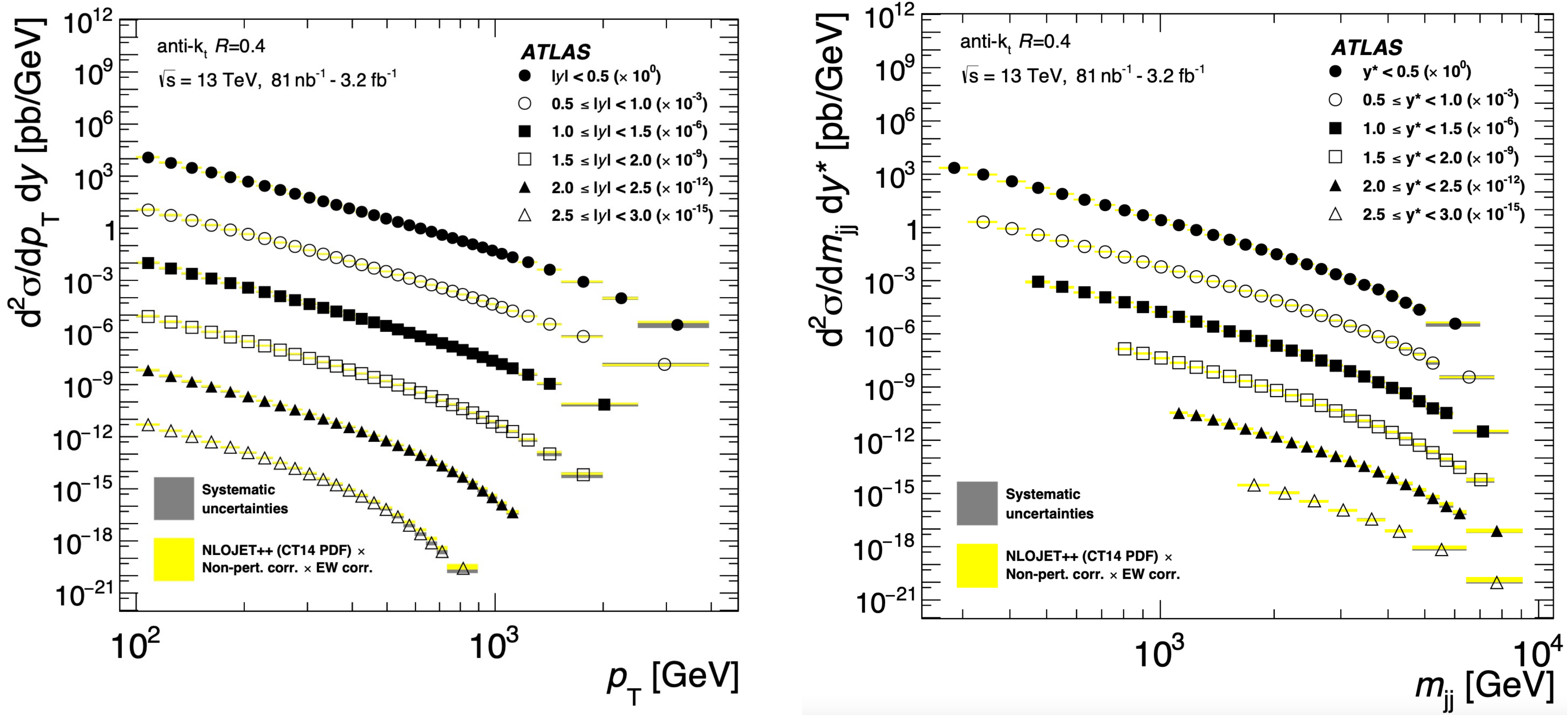
- presented recent results on **jet measurements** from the ***ATLAS*** & ***CMS*** collaborations
- diverse measurement programs, targeting various observables, e.g. **jet cross sections**, **event shapes, jet substructure**
- precision measurements provide essential input for improving our knowledge of the Standard Model, esp. for determinations of **strong coupling $\alpha_s(m_Z)$** and **parton distributions**
- large accessible phase space, useful for improvement and tuning of **MC models**
- improved experimental techniques + fixed-order predictions up to and beyond **NNLO** accuracy in pQCD are instrumental for improving precision and reducing systematic uncertainties

Thank you for your attention!

Backup

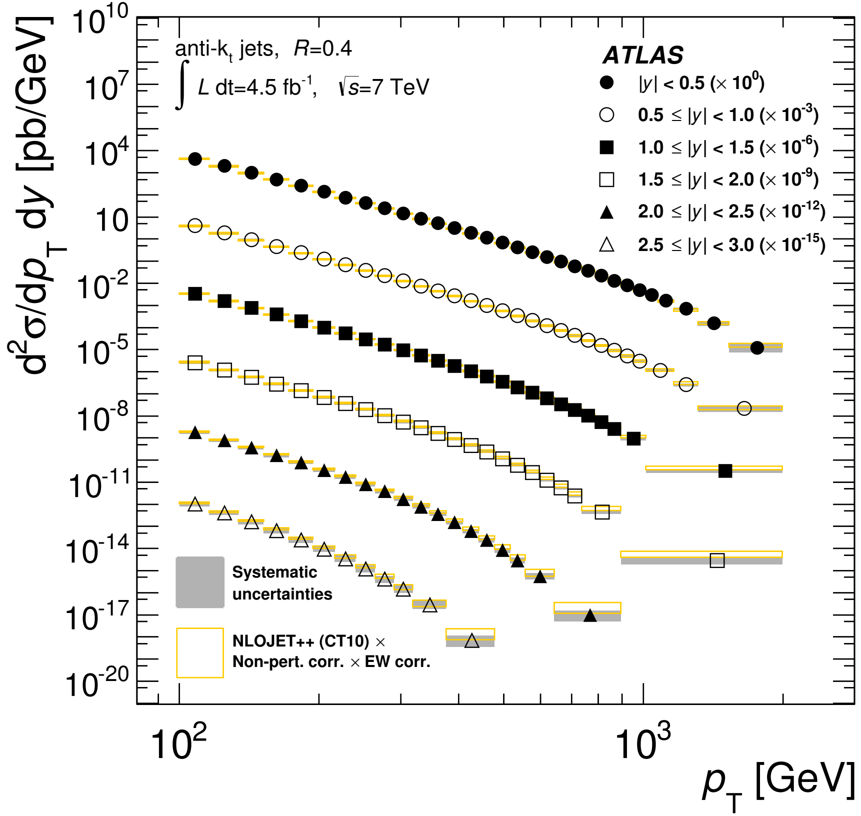
ATLAS inclusive jets 13 TeV

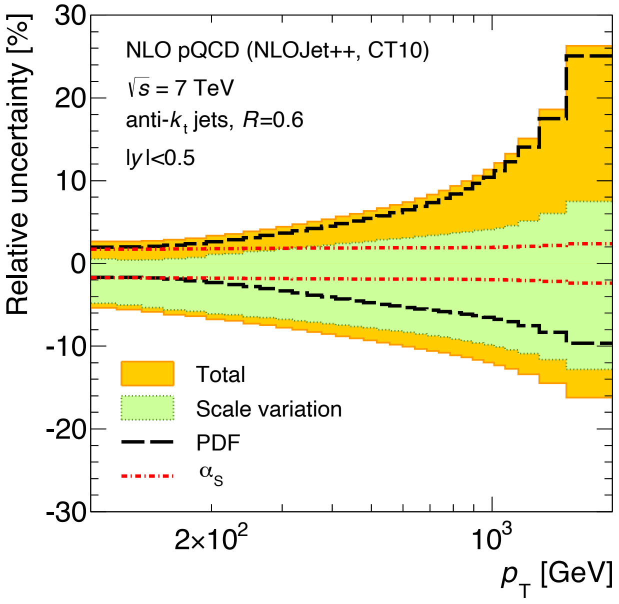
[arXiv:1711.02692]
[JHEP 05 (2018) 195]



ATLAS inclusive jets 7 TeV

[arXiv:1410.8857]
[JHEP 02 (2015) 153]



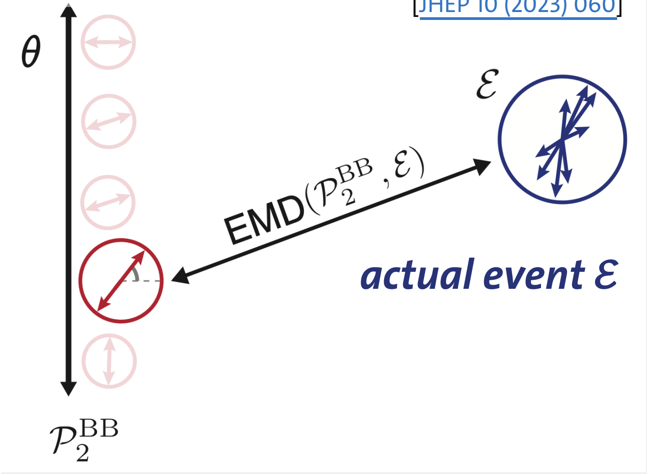


Multijet event isotropies

[arXiv:2305.16930]
[JHEP 10 (2023) 060]

- ***isotropies*** = event shape variables that quantify the distance from a "symmetric radiation pattern"
- infrared- and collinear-safe + complementary to traditional variables like ***thrust***, ***sphericity***, ***spherocity***
- obtained by minimization of ***distance metric*** to isotropic reference geometries (cylindrical, spherical)

example reference geometry: ***dipole***



Energy-Mover's Distance

$$\mathrm{EMD}_\beta(\mathcal{E}, \mathcal{E}') = \min_{\{f_{ij}\geq 0\}} \sum_{i=1}^{M} \sum_{j=1}^{M'} f_{ij}\theta_{ij}^{\beta},$$

angular weighting exponent

sum over object pairs

energy transfer

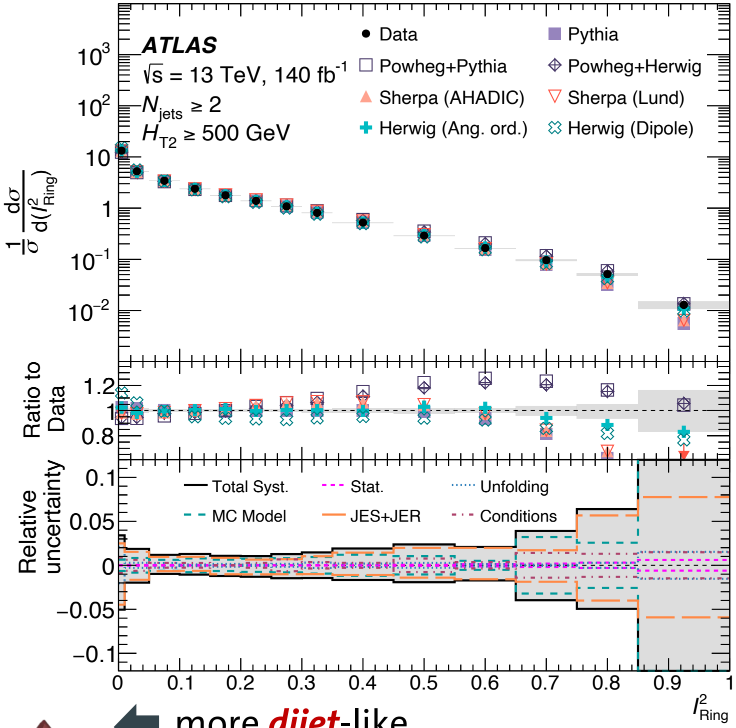
ground measure (e.g. angle)

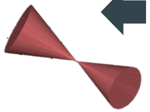
Multijet event isotropies

- measured in bins of **jet multiplicity** (N_{jet}) and **scalar sum of two leading jets' transverse momenta** (H_{T2})
- data best described by simulation in balanced, ***dijet***-like configuration (low isotropy), ***deterioration*** at high isotropy
- explore remote areas of QCD phase space, useful as inputs to ***MC tuning***

[arXiv:2305.16930]
[JHEP 10 (2023) 060]

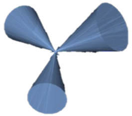
example: I^2_{Ring}



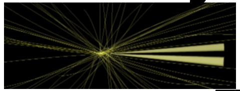


more ***dijet***-like

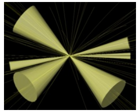
more symm. ***trijet***-like

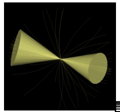


Multijet event isotropies

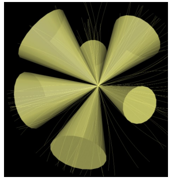


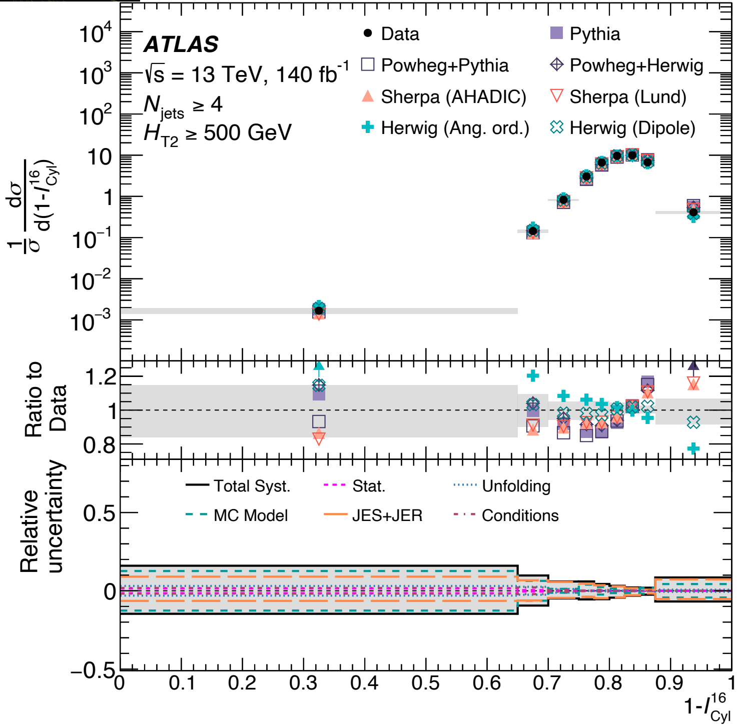
forward dijet ⟷ isotropic multijet

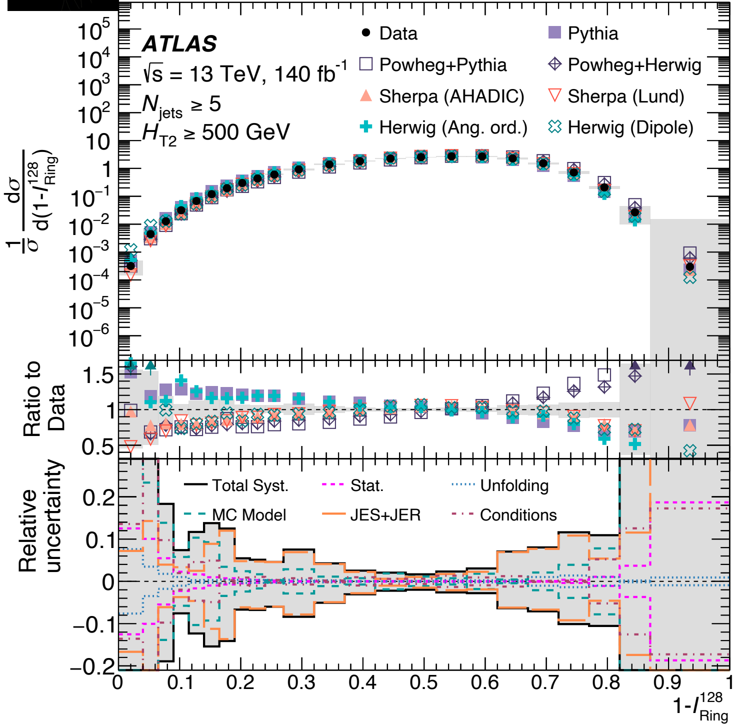




balanced dijet ⟷ isotropic multijet





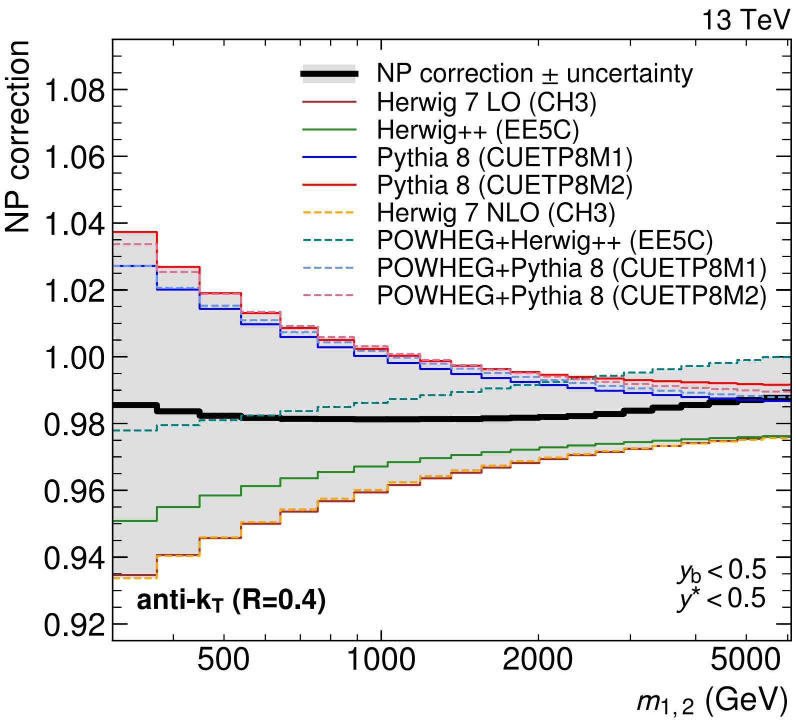


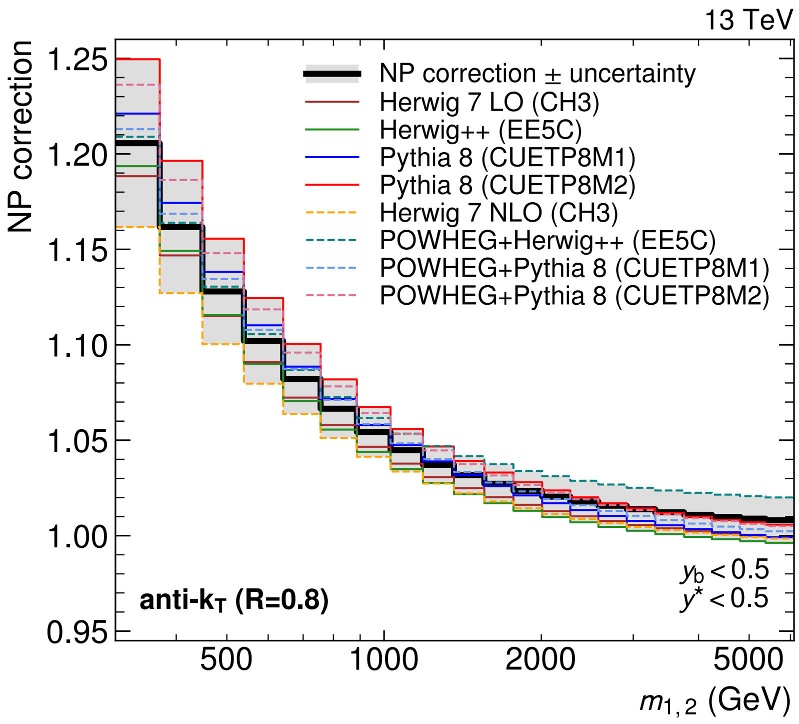
some isotropy shapes not described by any MC generator

Multidifferential dijet cross sections

[arXiv:2312.16669]
Submitted to *EPJC*

nonperturbative (NP) corrections

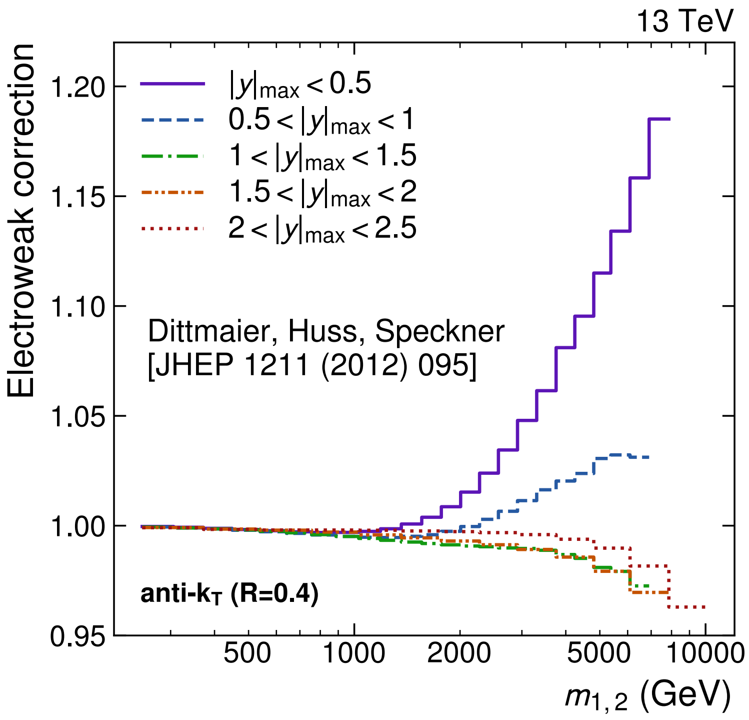


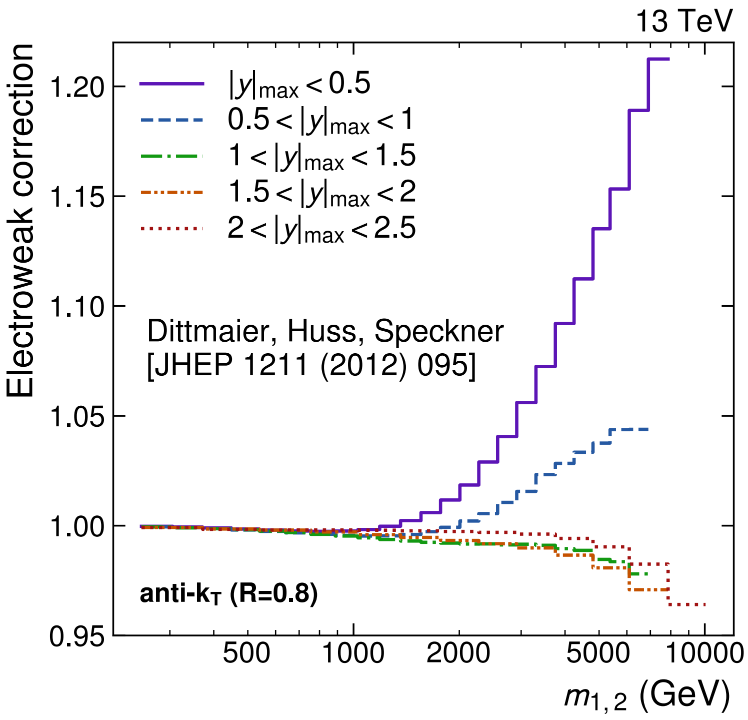


Multidifferential dijet cross sections

[arXiv:2312.16669]
Submitted to *EPJC*

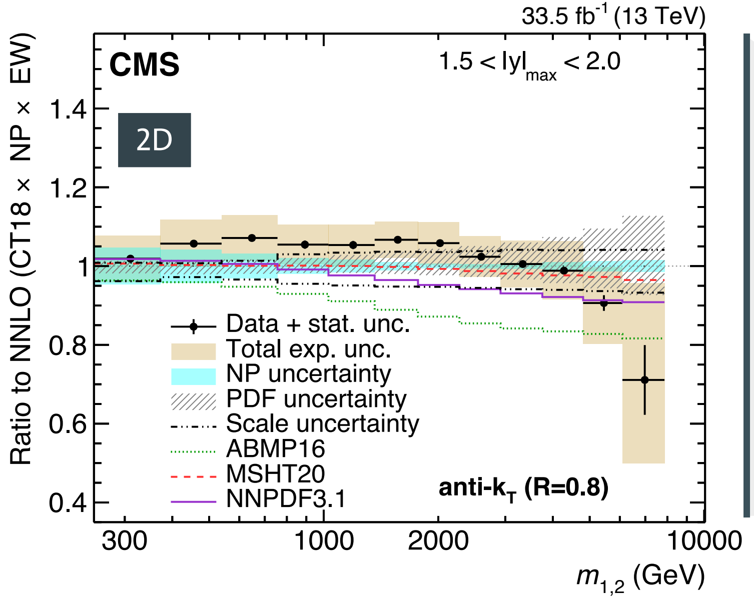
electroweak corrections

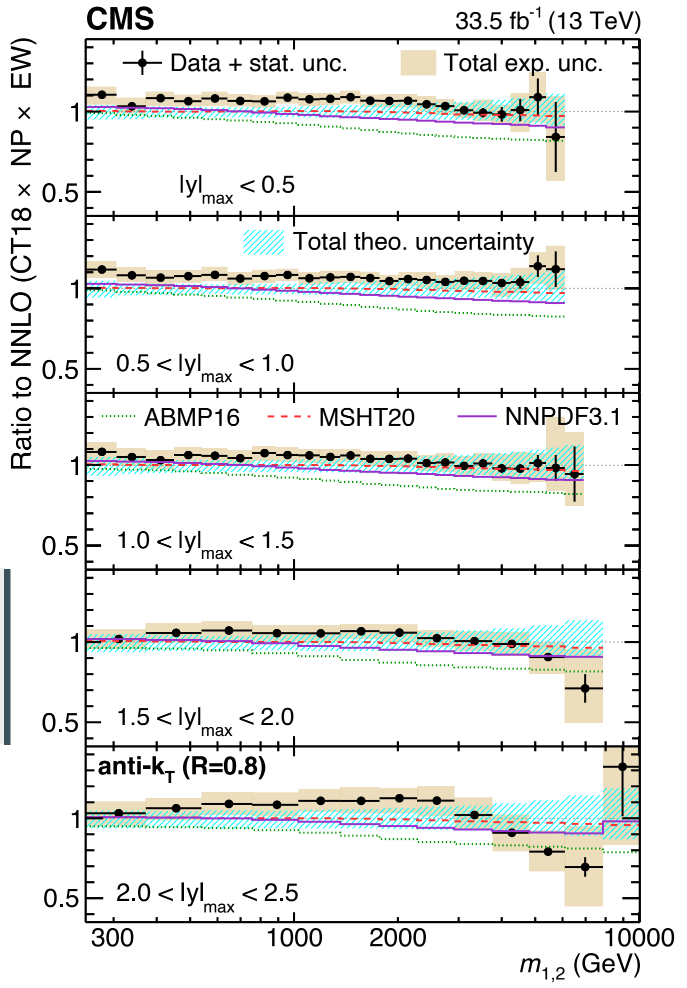




Multidifferential dijet cross sections

comparison to fixed-order theory predictions @ **NNLO** × nonperturbative, electroweak corrections





Multidifferential dijet cross sections

comparison to fixed-order theory predictions @ **NNLO** × nonperturbative, electroweak corrections