Universität Hamburg
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CMS

Federal Ministry of Education and Research

LHCPhysics
Belgrade, 22 - 26 May 2023

Jet measurements in pp collisions from CMS

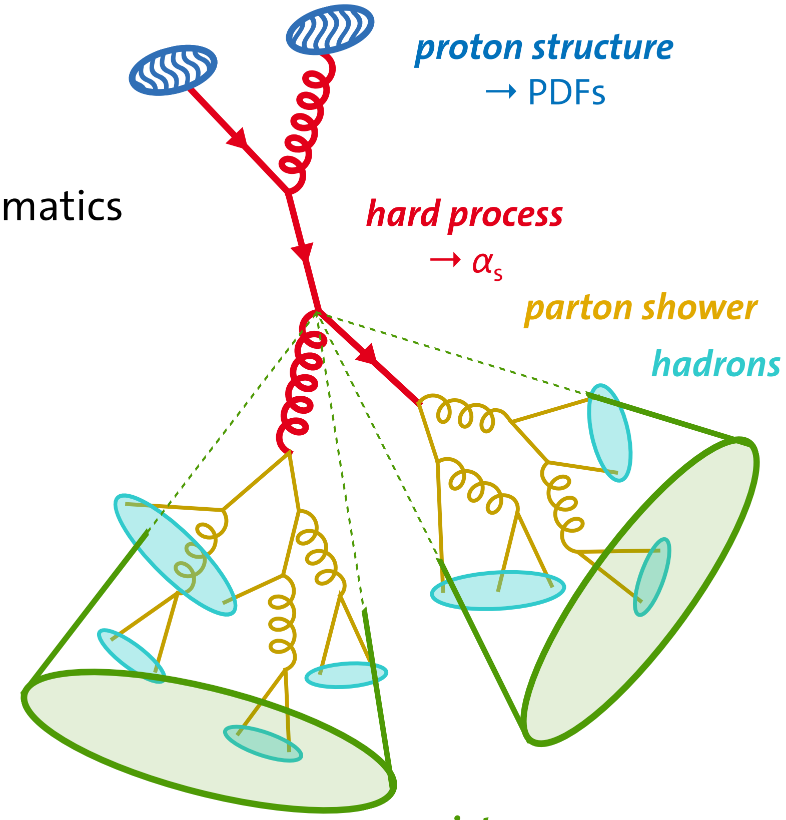
11th annual conference on Large Hadron Collider Physics | 22–26 May 2023 | Belgrade, Serbia

Daniel Savoiu on behalf of the CMS Collaboration

Why jets?

jet observables provide valuable experimental input for testing QCD & the Standard Model

- α_s and ***parton distributions*** of proton (PDFs)
  - ***inclusive jet*** cross sections → "counting jets"
  - ***dijet*** cross sections → topology provides handle on parton kinematics
- modeling of higher-order contributions
  - jet production known up to ***NNLO*** in pQCD
  - additional jets from hard radiation → ***multijet*** production
- improved understanding of perturbative & nonperturbative regimes
  - impact on *parton shower* & *hadronization* → jet ***substructure***



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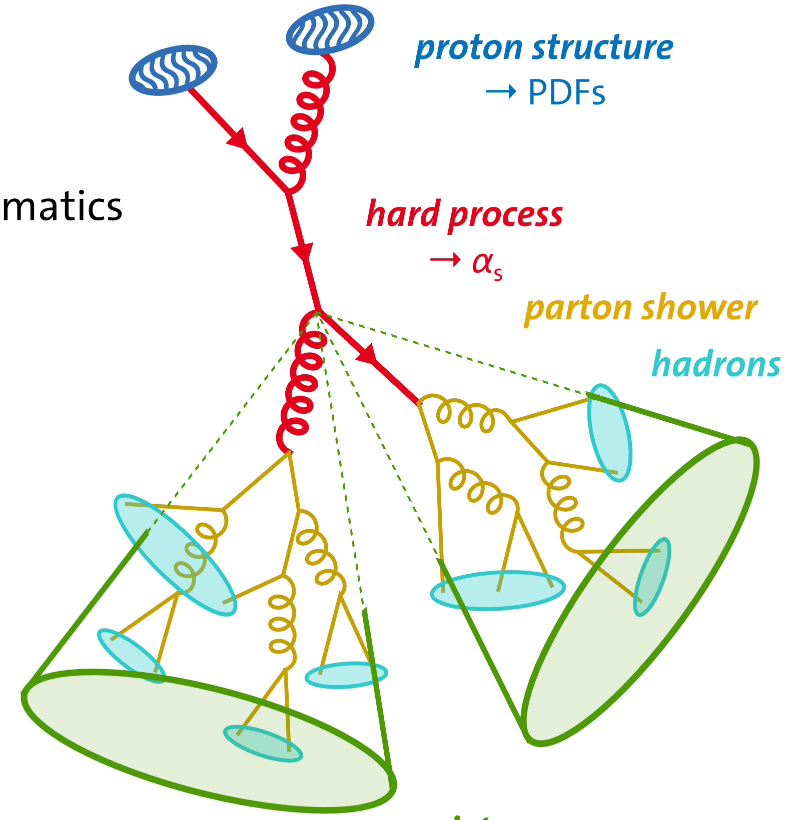
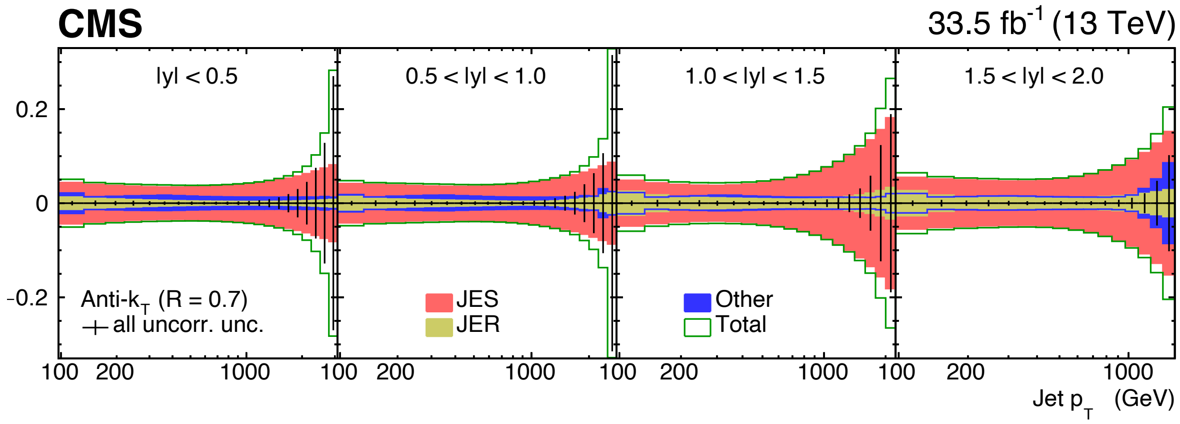
this talk: personal selection of recent results from CMS

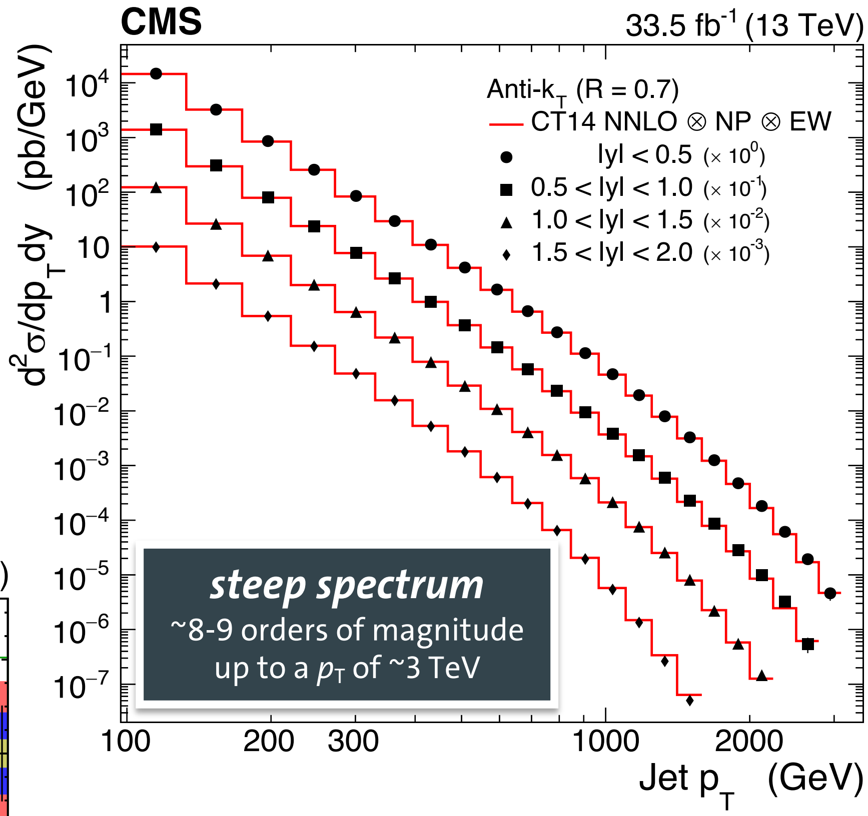


Inclusive jet production at $\sqrt{s}$ = 13 TeV

- ***double-differential*** cross section measured as a function of ***jet*** $\boldsymbol{p_T}$ & ***rapidity y*** for anti-k_T jets with R = ***0.4*** & ***0.7***

- good experimental precision, **<5% uncertainty** in main measurement region
  - dominant uncertainty contribution from jet energy scale (*JES*)



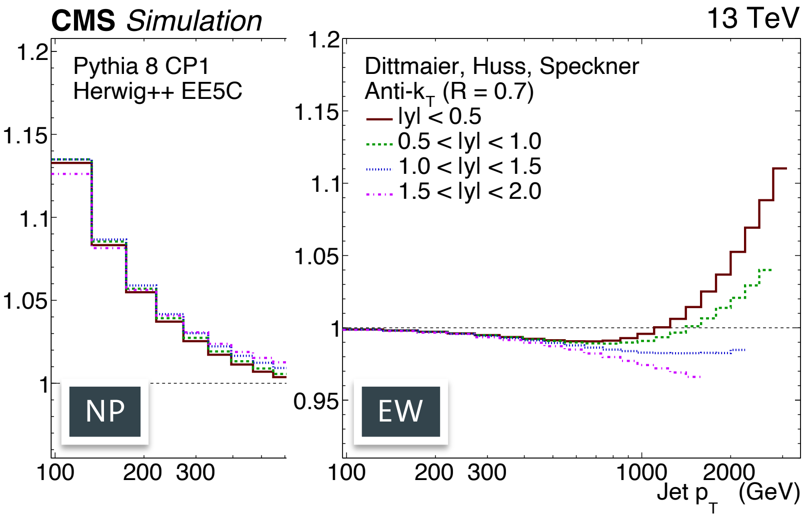


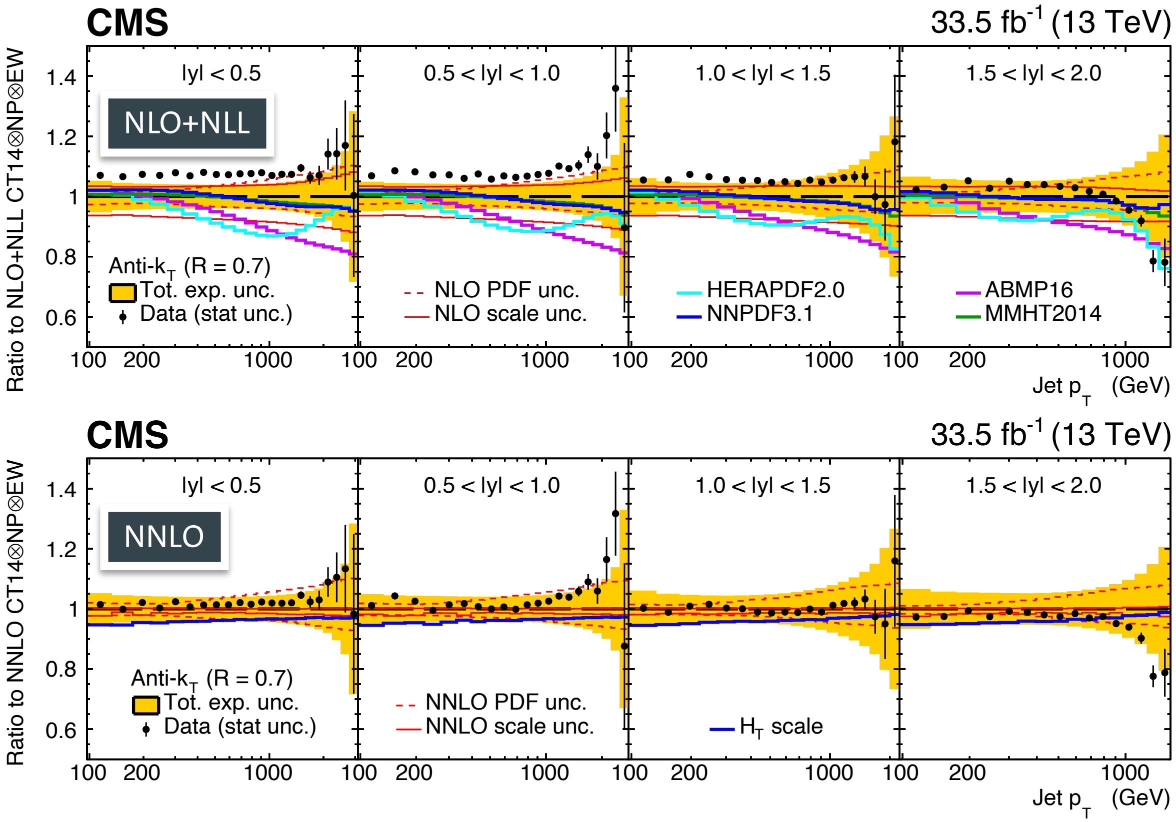
[1] CMS Collaboration, *"Measurement and QCD analysis of double-differential inclusive jet cross sections in proton-proton collisions at $\sqrt{s}$ = 13 TeV"*, CMS-SMP-20-011, JHEP 02 (2022) 142 [Addendum], arXiv:2111.10431

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

[1] JHEP 02 (2022) 142

- comparison to fixed-order pQCD theory at ***NNLO*** & ***NLO+NLL***
  + corrections for non-perturbative (***NP***) and electroweak (***EW***) contributions





- improved description of data at NNLO & reduced scale uncertainty
- some disagreement between global PDF sets, especially in high-p_T region

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

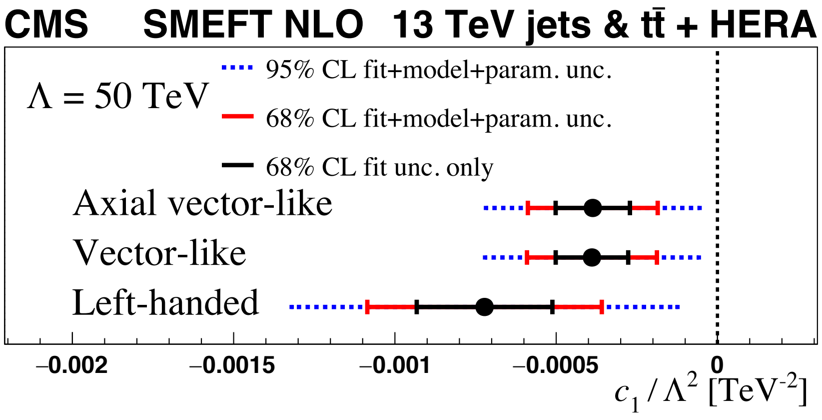
[1] JHEP 02 (2022) 142

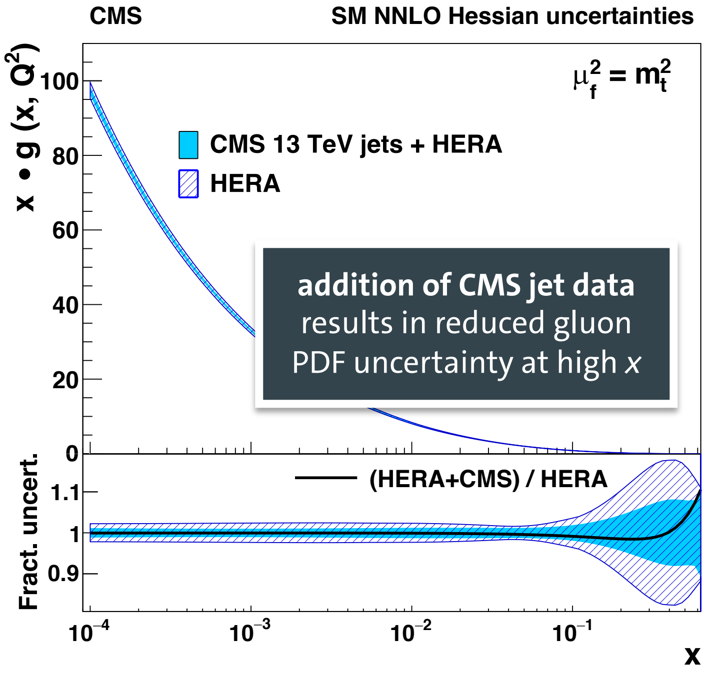
- determination of ***PDFs*** & **strong coupling constant** up to ***NNLO***

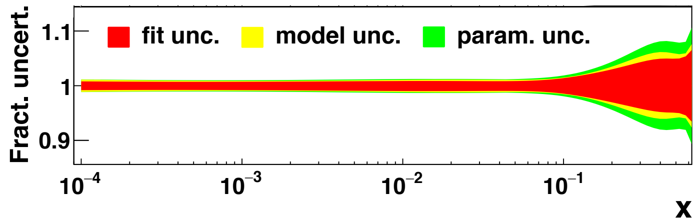
$$\boxed{\alpha_s(m_Z)_{\mathrm{NNLO}} = 0.1166\ \ (14)_{\mathrm{fit}}\ \ (7)_{\mathrm{model}}\ \ (4)_{\mathrm{scale}}\ \ (1)_{\mathrm{param.}}}$$

↳ $\chi^2\,/\,n_{\mathrm{dof}}$ = 1302 / 1118

- with $t\bar{t}$ data: limits on ***Wilson coefficients*** for four-quark contact interactions
  - multiple coupling structures probed, no significant deviations

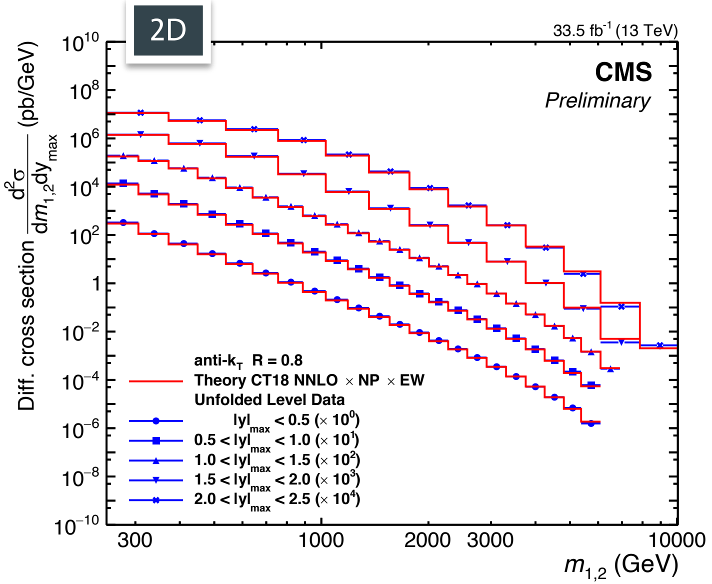


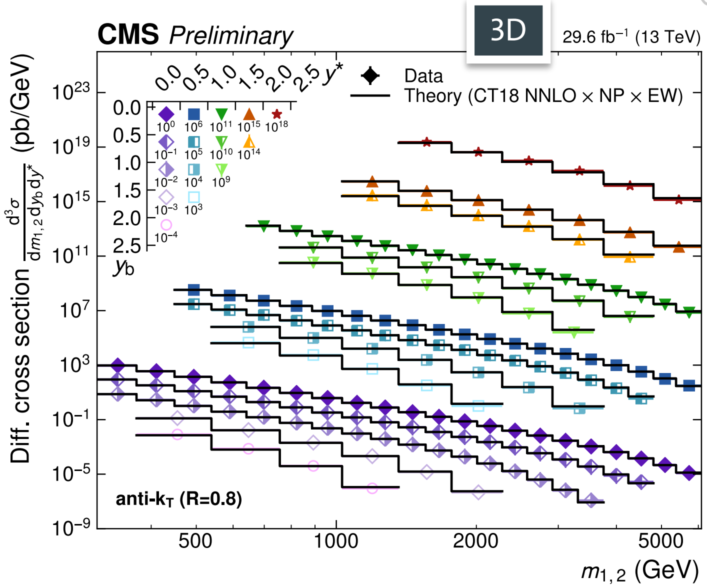


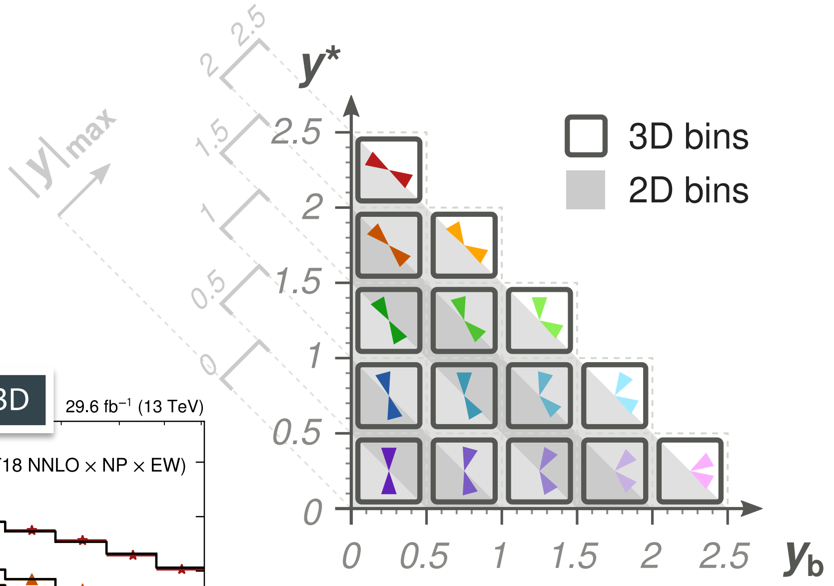


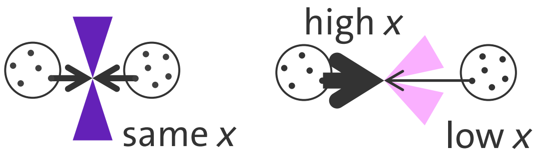
Dijet production at $\sqrt{s}$ = 13 TeV

- ***double-*** & ***triple-differential*** cross section measured as a function of **dijet invariant mass $m_{1,2}$** & rapidity for anti-k_T jets with R = ***0.4*** & ***0.8***









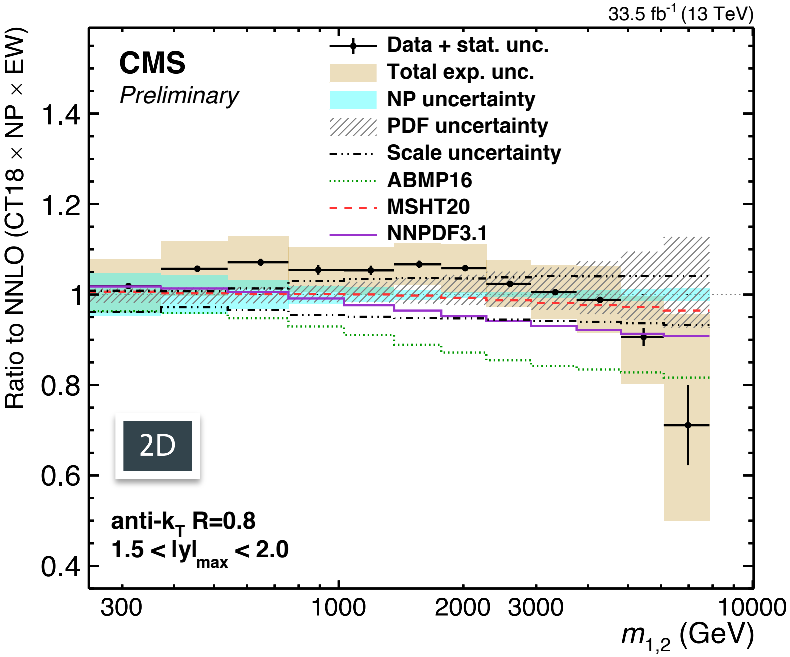
- disentangle regions of different momentum fractions x carried by partons → PDF fits

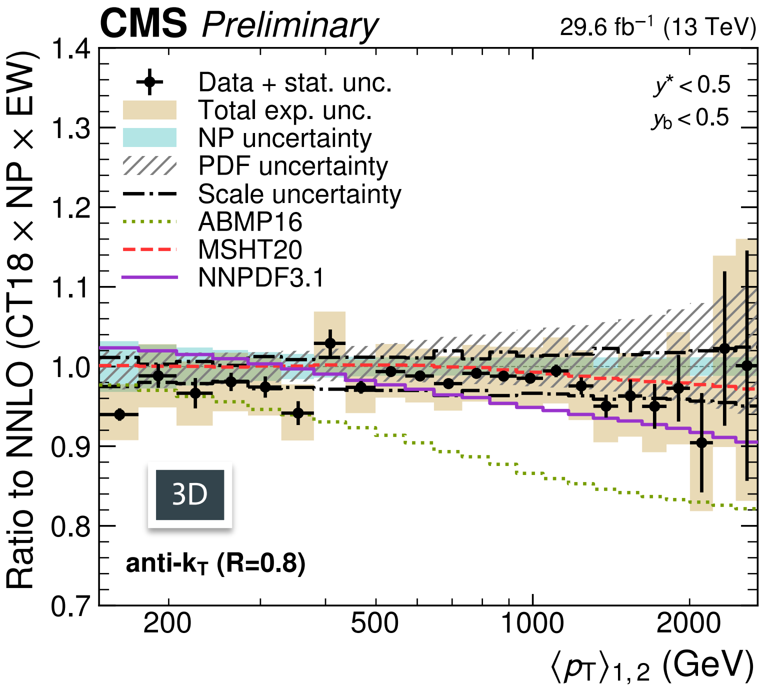
[2] CMS Collaboration, *"Multi-differential measurement of the dijet cross section in proton-proton collisions at $\sqrt{s}$ = 13 TeV"*, CMS-PAS-SMP-21-008

Dijet production at $\sqrt{s}$ = 13 TeV

[2] CMS-PAS-SMP-21-008

- comparison to fixed-order theory predictions @ ***NNLO*** × NP × EW
- data generally well described by theory (here: R = 0.8)

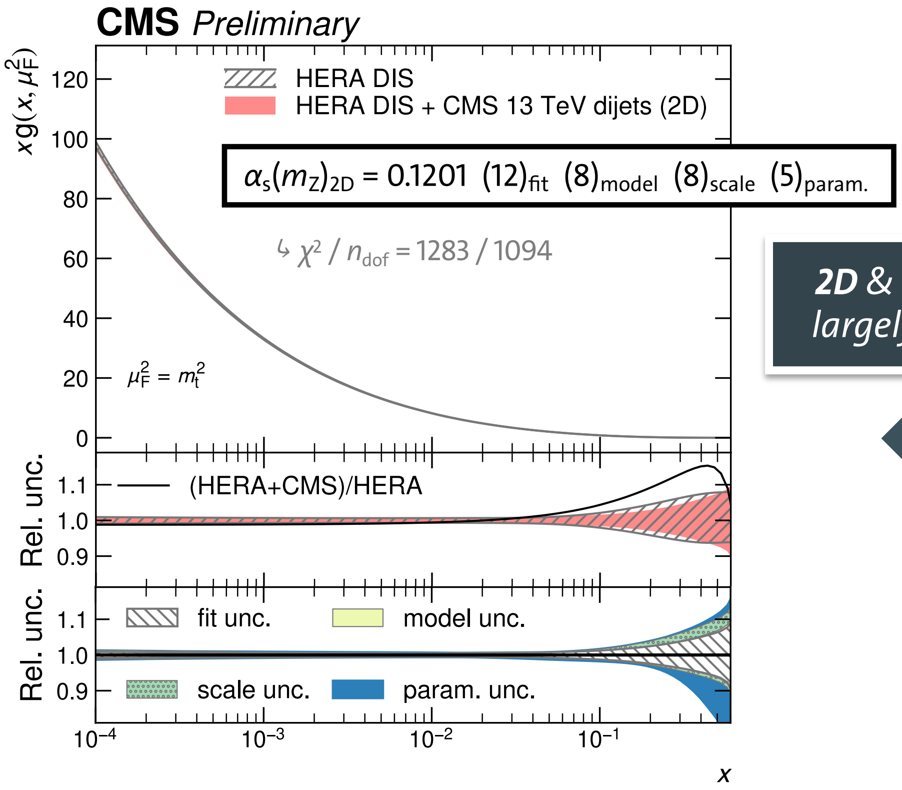




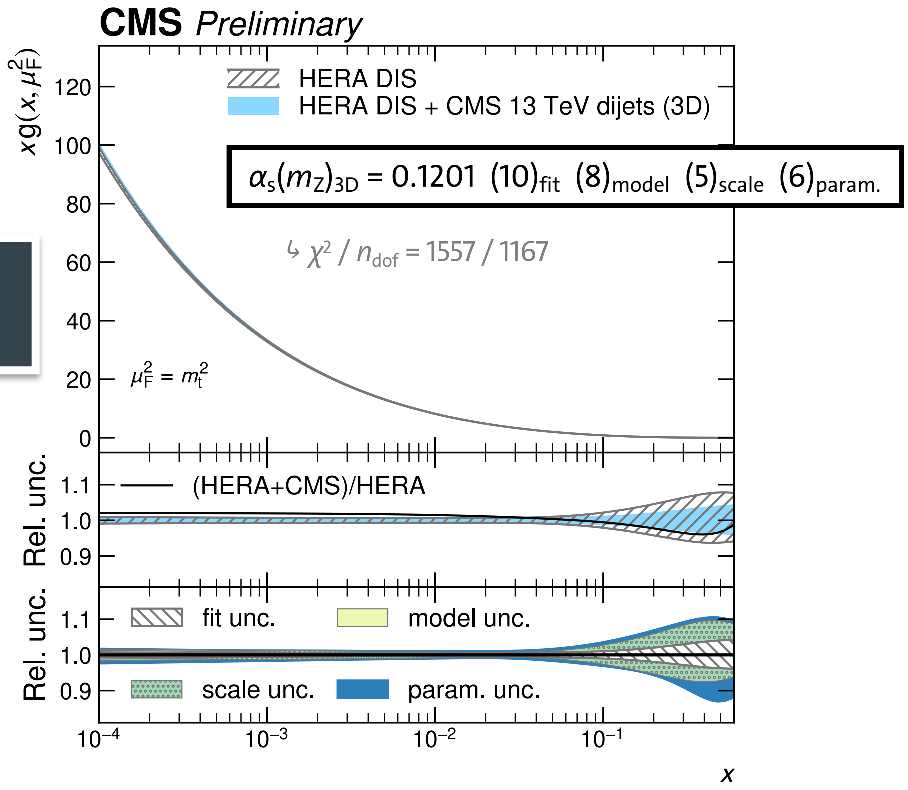
Dijet production at $\sqrt{s}$ = 13 TeV

[2] CMS-PAS-SMP-21-008

- determination of ***PDFs*** & **strong coupling constant** @ ***NNLO*** *(preliminary results)*



2D & 3D fit results largely compatible



Multijet production

- ***jet multiplicity*** measured in bins of **leading jet p_T** & **azimuthal separation $\Delta\phi_{1,2}$**
  - access up to 7 jets, even in back-to-back region
- compare models using conventional parton showers & ***parton-branching*** approach (PB) + ***TMDs***
  - higher multiplicities not very well described
  - at low multiplicities, PB-TMD predictions @ NLO have similar accuracy as conventional models

Generator	PDF	ME
PYTHIA8 [23]	NNPDF 2.3 (LO) [25]	LO $2 \to 2$
MADGRAPH+PY8 [4]	NNPDF 2.3 (LO) [25]	LO $2 \to 2,3,4$
MADGRAPH+CA3 [4]	PB-TMD set 2 (NLO) [1]	LO $2 \to 2,3,4$
HERWIG++ [26]	CTEQ6L1 (LO) [27]	LO $2 \to 2$
MG5_aMC+Py8 (jj)	NNPDF 3.0 (NLO) [31]	NLO $2 \to 2$
MG5_aMC+CA3 (jj)	PB-TMD set 2 (NLO) [1]	NLO $2 \to 2$
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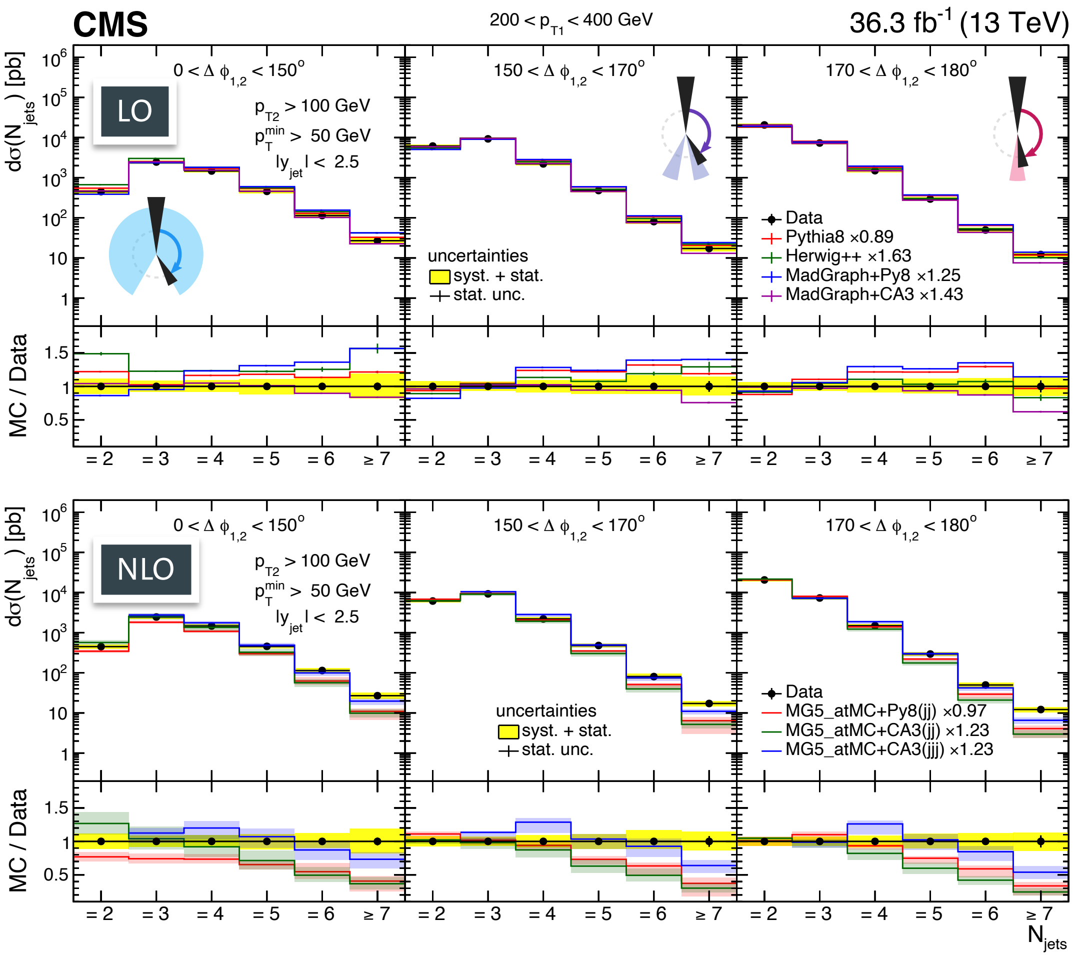
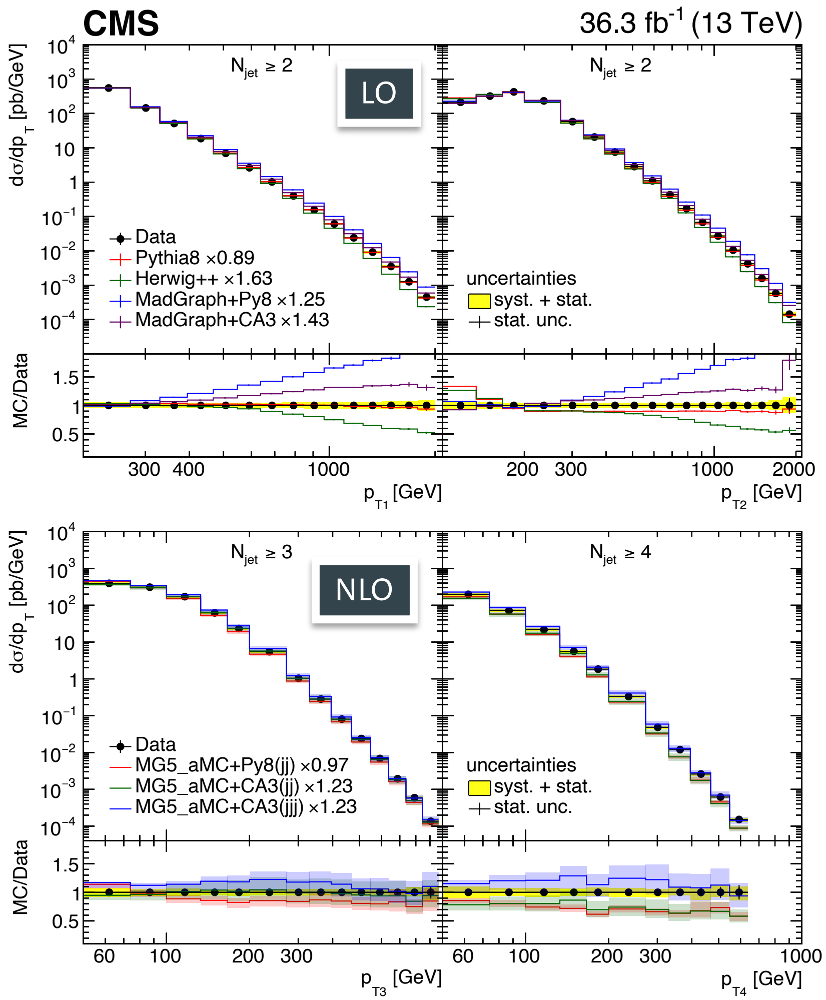


[3] CMS Collaboration, *"Measurements of jet multiplicity and jet transverse momentum in multijet events in proton-proton collisions at $\sqrt{s}$ = 13 TeV"*, *Submitted to Eur. Phys. J. C*, CMS-SMP-21-006, arXiv:2210.13557

Multijet production

[3] arXiv:2210.13557

- ***jet p_T*** measured for up to 4 leading jets
  - in general not well described by any model @ LO
  - better description for 3rd & 4th jet with NLO matrix elements



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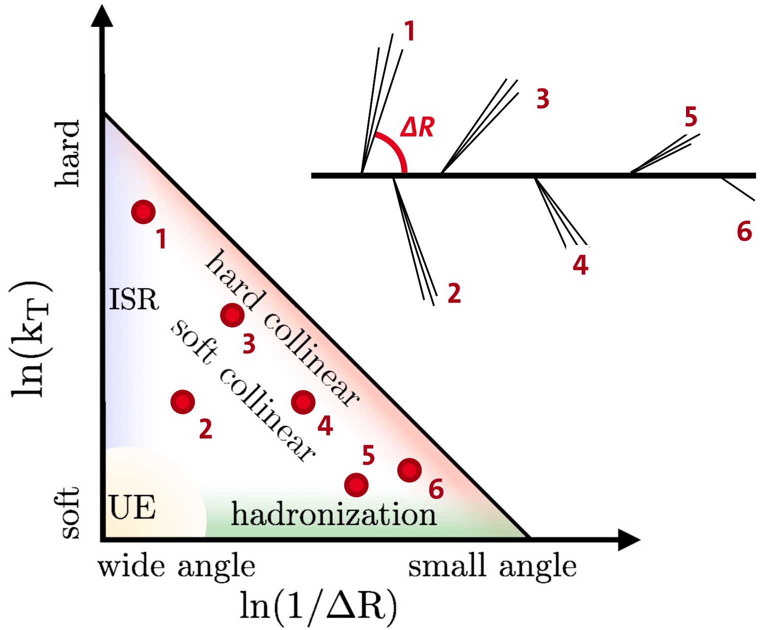
Measurement of the Lund jet plane density

[4] CMS-PAS-SMP-22-007

- ***Lund jet plane*** represents phase space of emissions inside jets
  - **anti-k_T** jets are declustered iteratively using the ***Cambridge–Aachen*** algorithm
  - the density of emissions is measured as a function of **$\ln(k_T$ / GeV)** and **$\ln(1 / \Delta R)$** as:

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



Applications

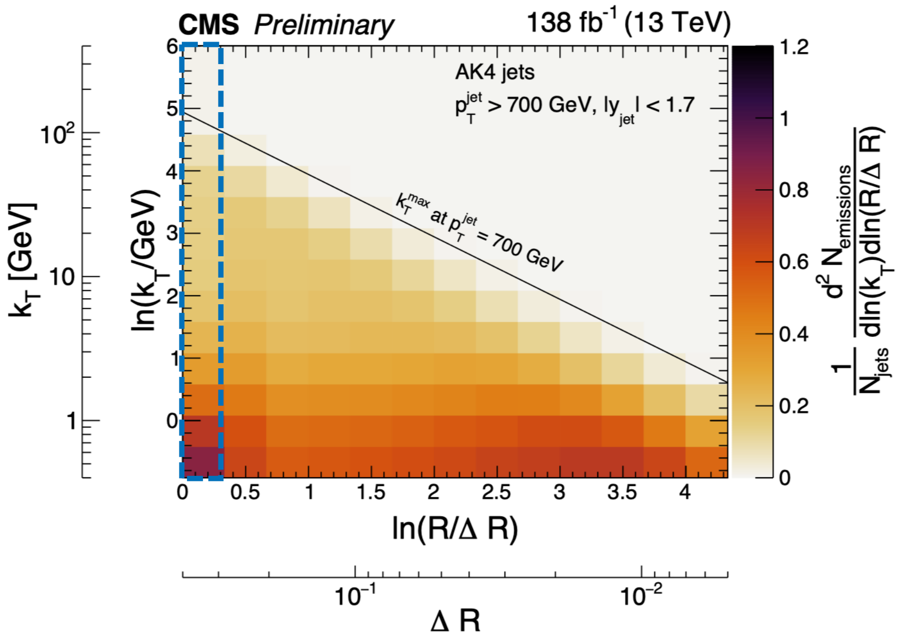
- improve modeling of parton shower, hadronization, underlying event
- heavy-flavor tagging due to unique signatures of highly boosted color-singlet particles
- test running of α_s via analytical predictions in perturbative QCD

[4] CMS Collaboration, *"Measurement of the primary Lund jet plane density in proton-proton collisions at $\sqrt{s}$ = 13 TeV"*, CMS-PAS-SMP-22-007

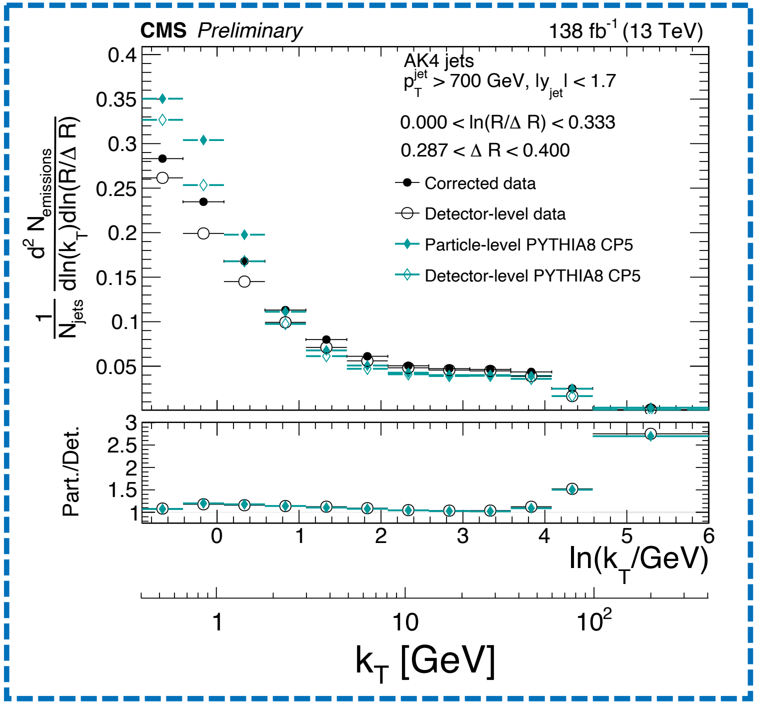
Measurement of the Lund jet plane density

[4] CMS-PAS-SMP-22-007

- measurement performed for both small (R = 0.4) and large-radius jets (R = 0.8)
- density measured for jets with p_T > 700 GeV & $|y|$ < 1.7
  - only charged-particle constituents of jets are used → increased resolution
- multi-dimensional ***unfolding*** to obtain density at particle level



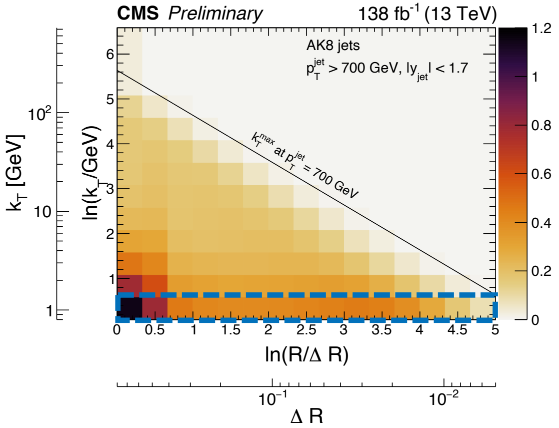
ΔR slice

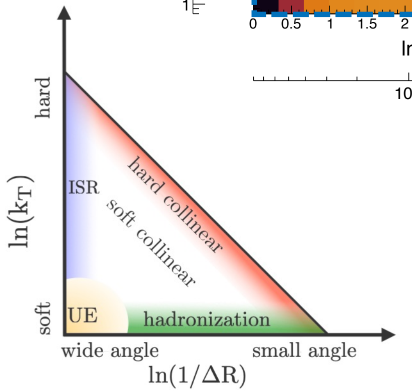


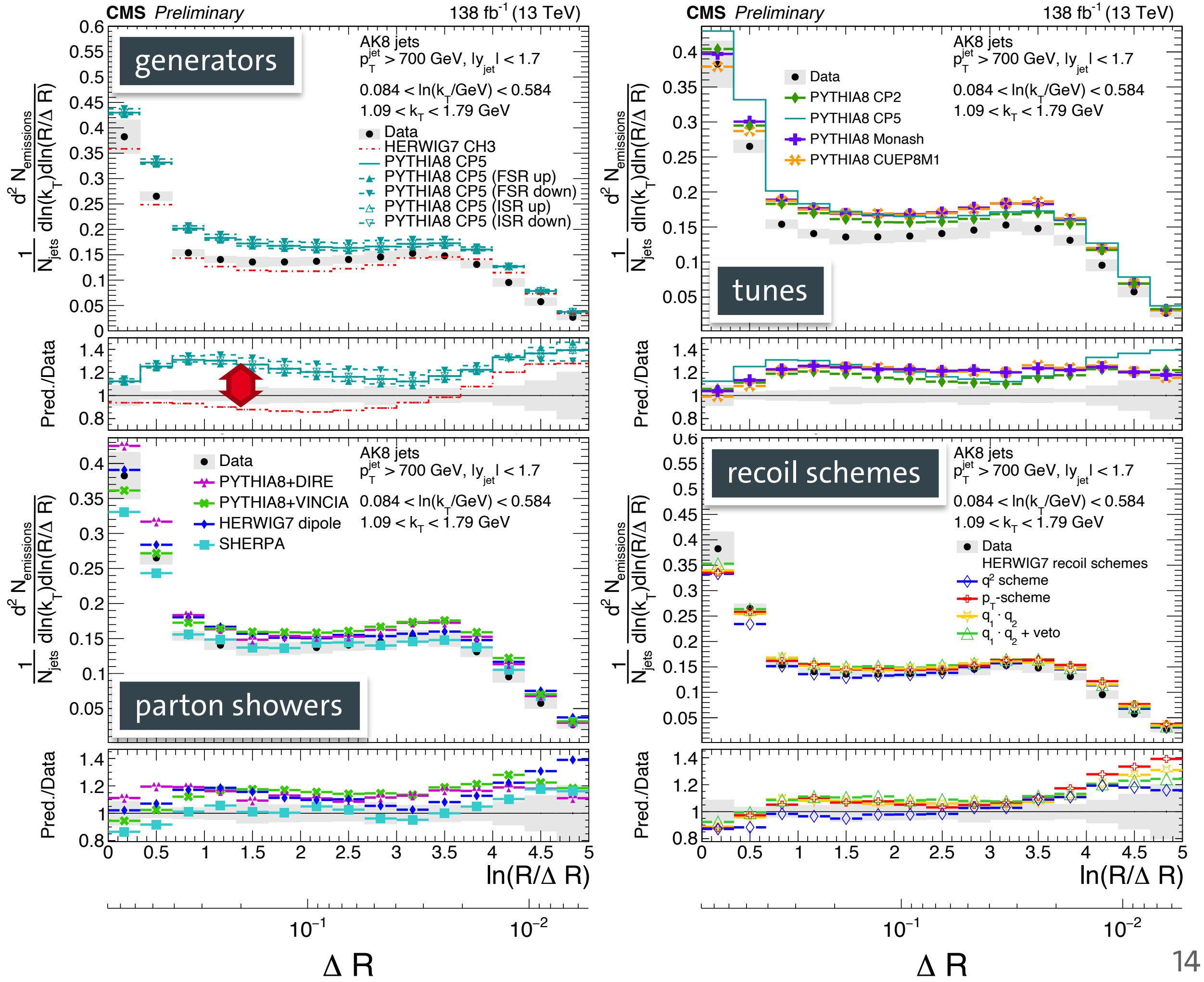
Measurement of the Lund jet plane density

[4] CMS-PAS-SMP-22-007

- performance of different **generators**, **tunes**, **parton showers**
- measurement can be used as input to further improve these models







Summary

- jet observables are an important experimental probe for SM at highest energy & precision

- many measurements from CMS at $\sqrt{s}$ = 13 TeV, targeting wide variety of jet observables
  - ***inclusive jet*** and ***dijet*** cross sections
  - jet ***multiplicity*** & ***transverse momentum spectra*** in multijet events
  - jet substructure → density of parton emissions in ***Lund jet plane***

- improved precision and extended kinematic reach, beneficial for:
  - determinations of the ***strong coupling constant*** $\alpha_s(m_Z)$ and ***parton distributions*** (PDFs)
  - probes of extensions to the SM in effective field theory
  - improvement of ***MC generator modeling*** of perturbative and non-perturbative effects

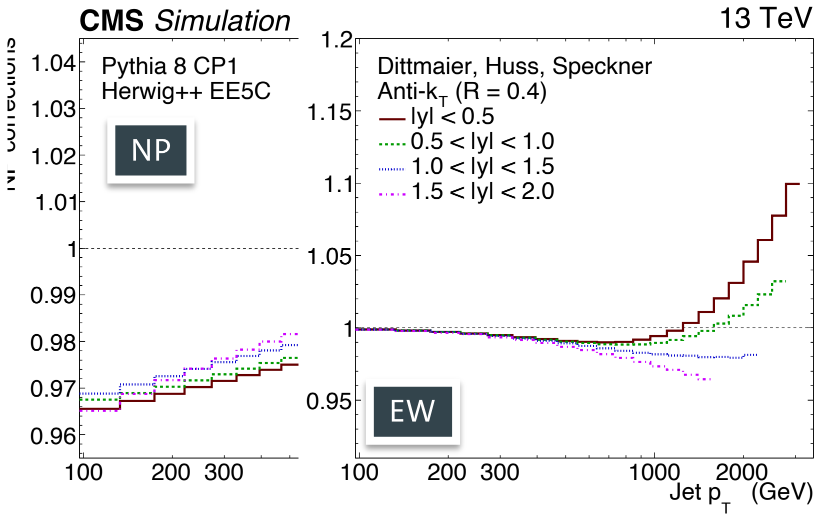
Thank you for your attention!

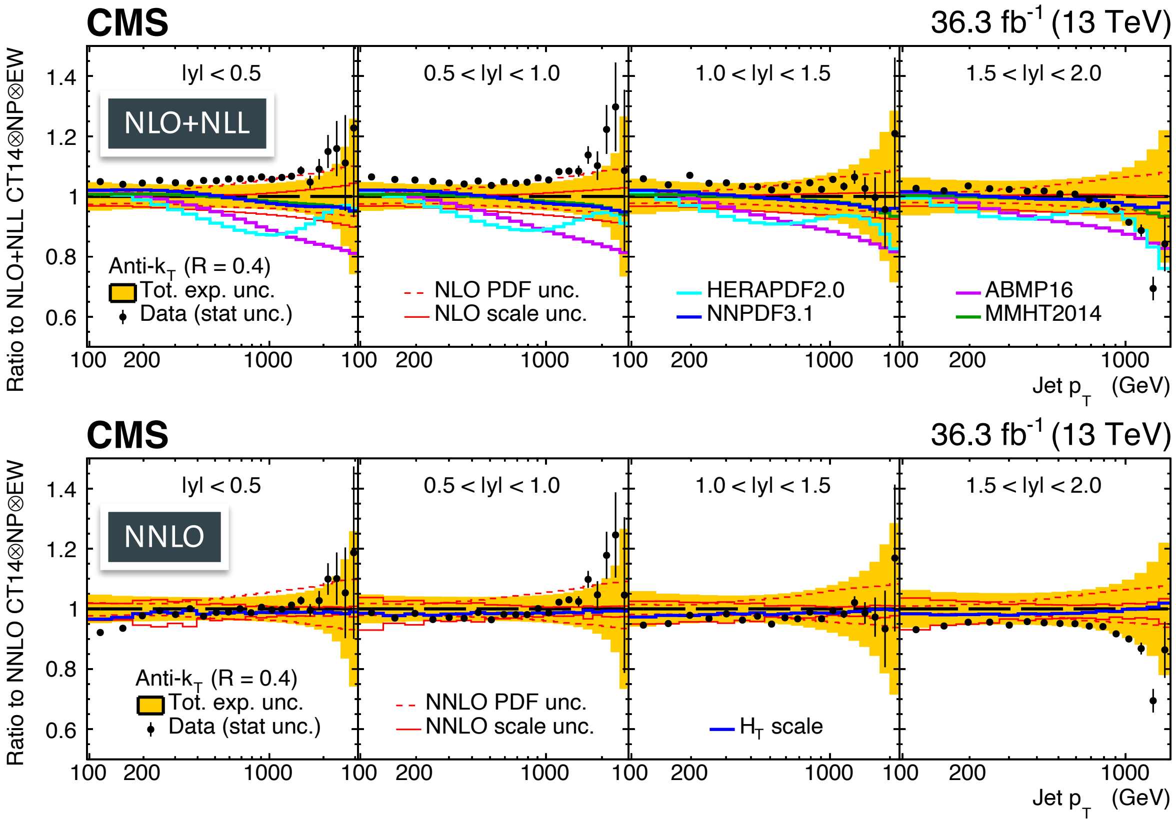
Backup

Inclusive jet production at $\sqrt{s}$ = 13 TeV (R = 0.4)

[1] JHEP 02 (2022) 142

- comparison to fixed-order pQCD theory at ***NNLO*** & ***NLO+NLL***
  + corrections for non-perturbative (***NP***) and electroweak (***EW***) contributions

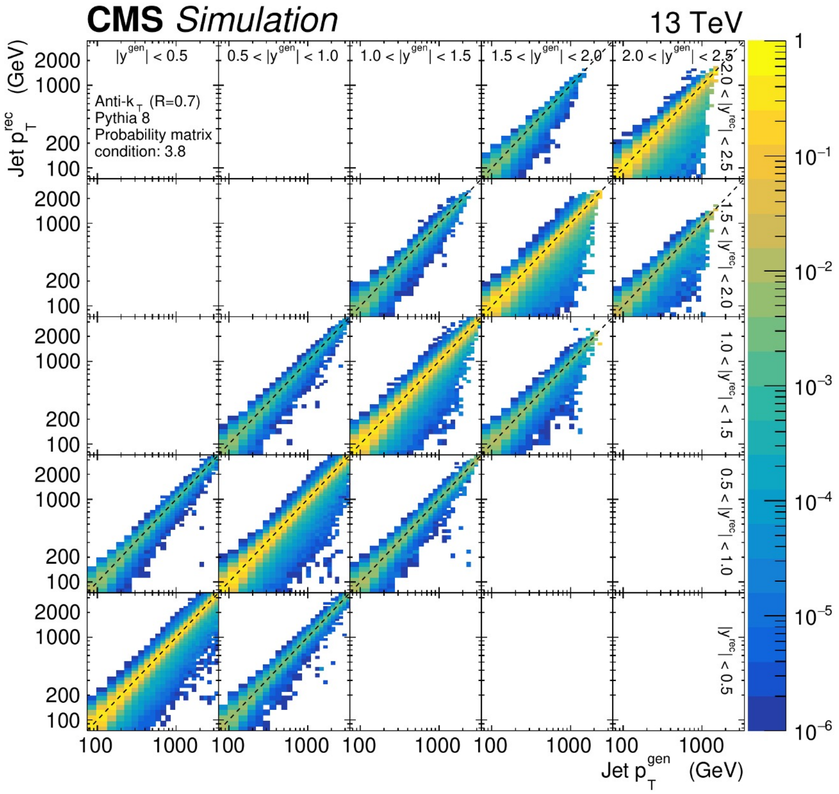




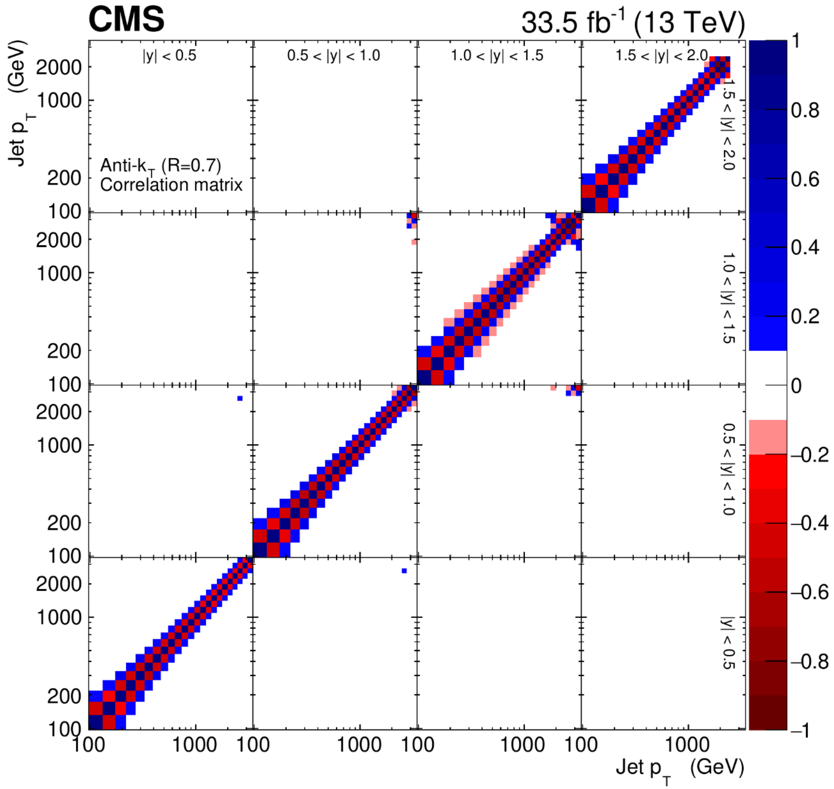
Inclusive jet production at $\sqrt{s}$ = 13 TeV (unfolding)

full 2D unfolding across jet p_T and $|y|$

response matrix depicts event migrations between the particle and detector levels

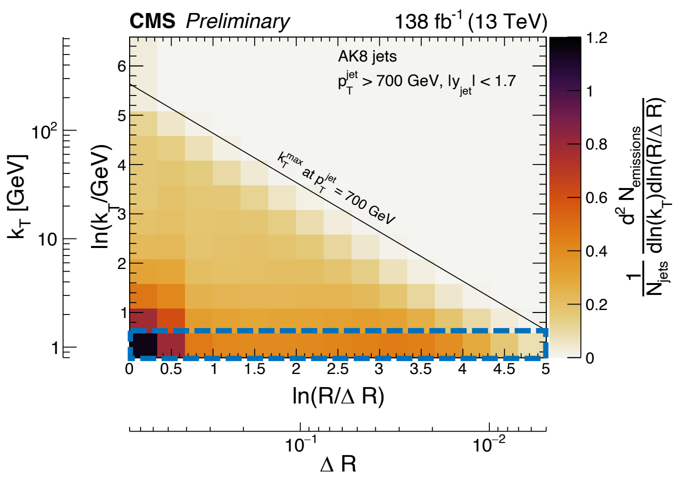


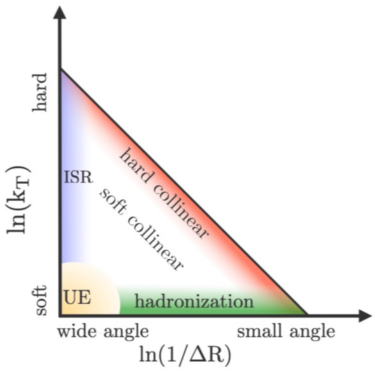
statistical correlations on particle-level spectra induced by the unfolding procedure

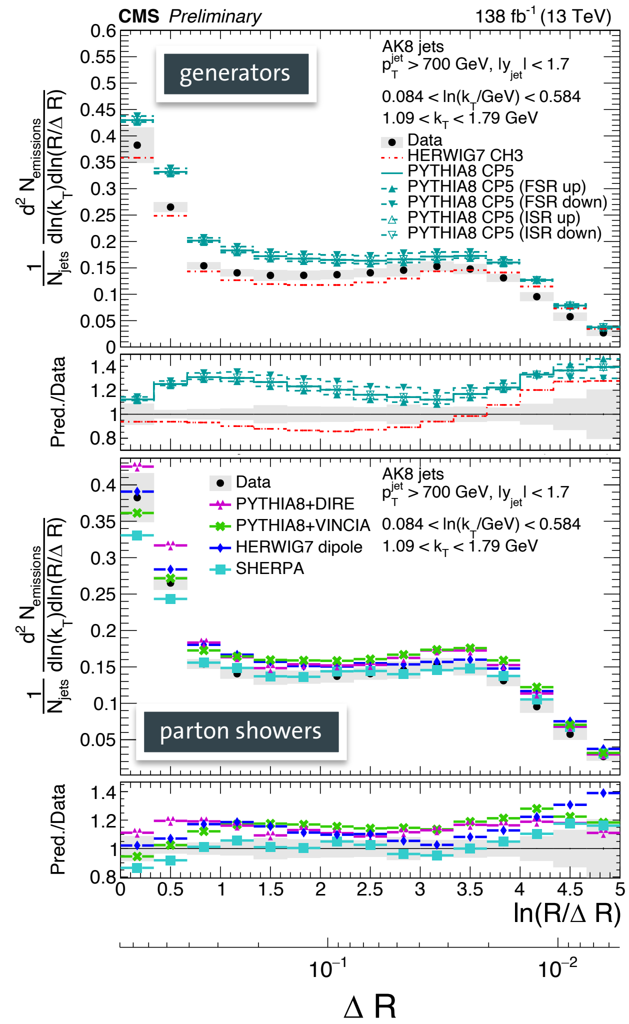


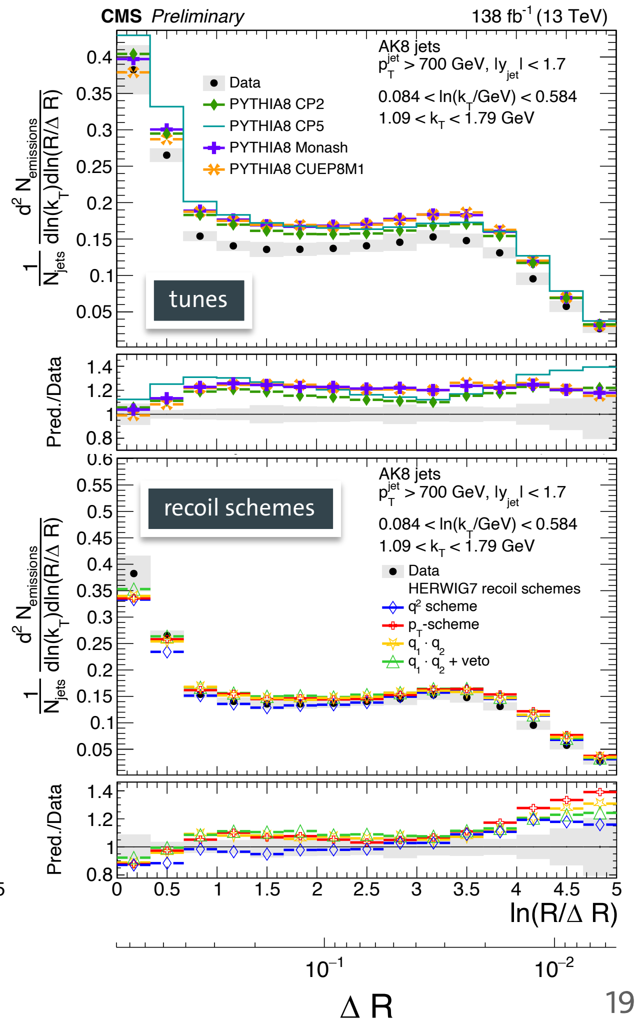
Measurement of the Lund jet plane density

[4] CMS-PAS-SMP-22-007









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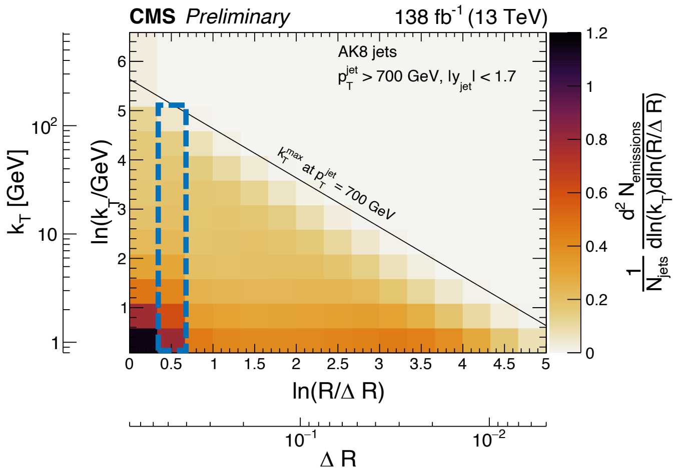

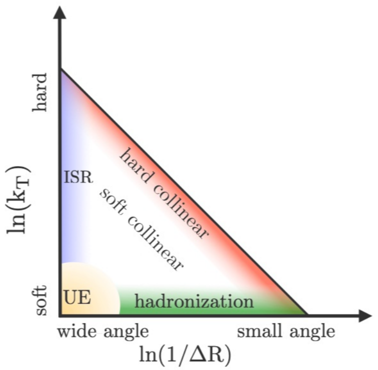

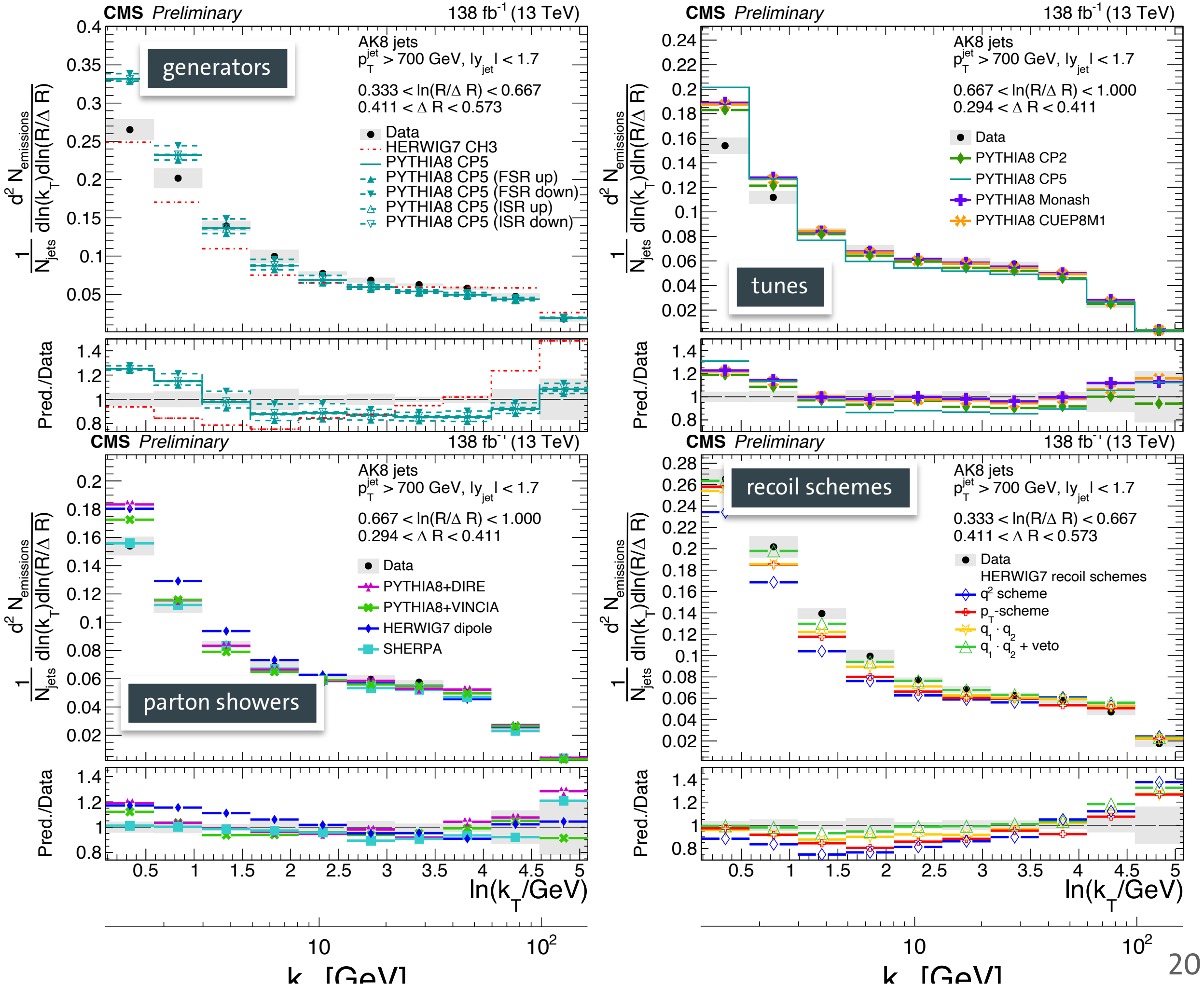

Measurement of the Lund jet plane density

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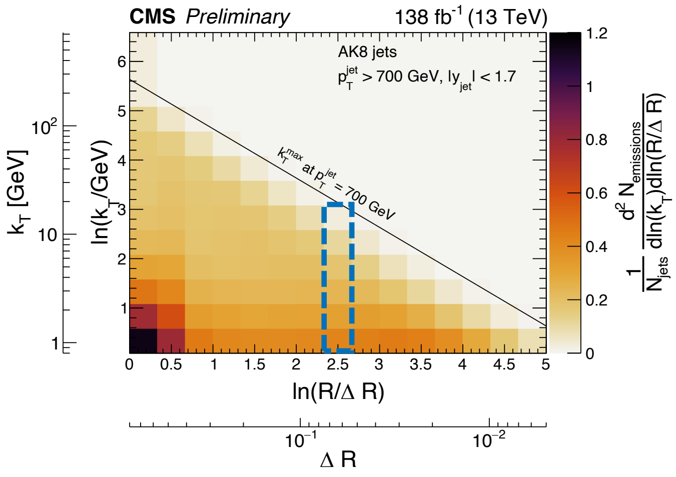
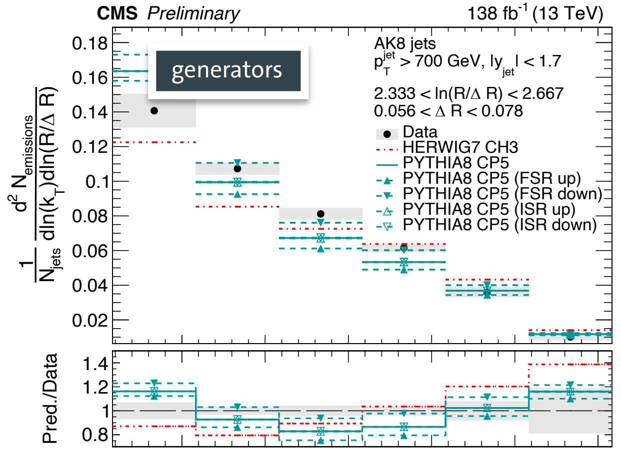
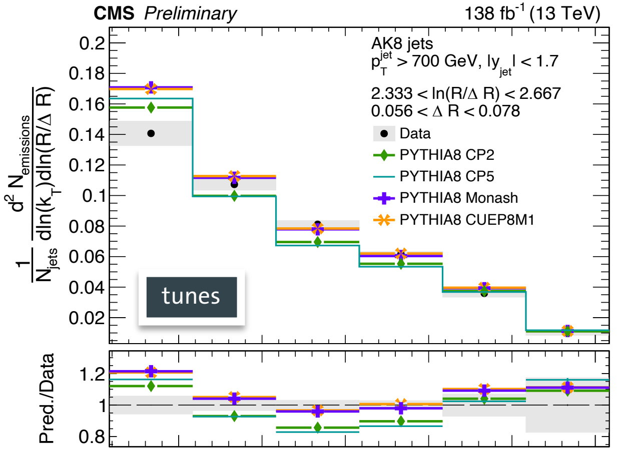
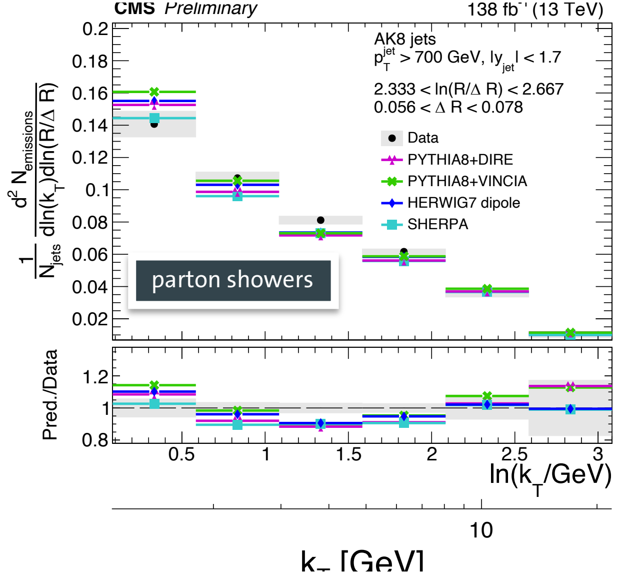
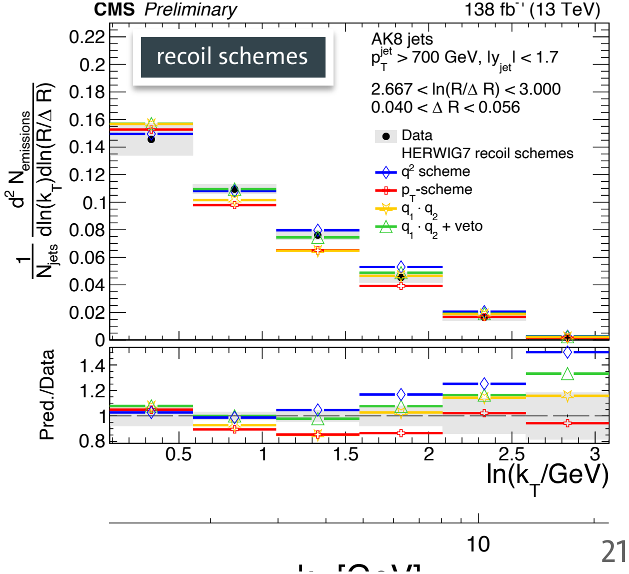
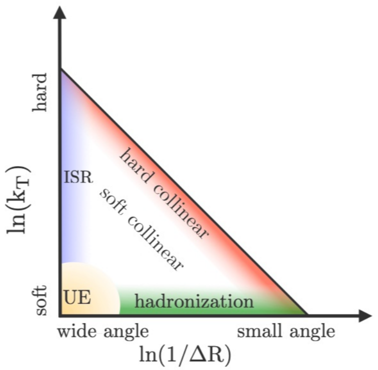






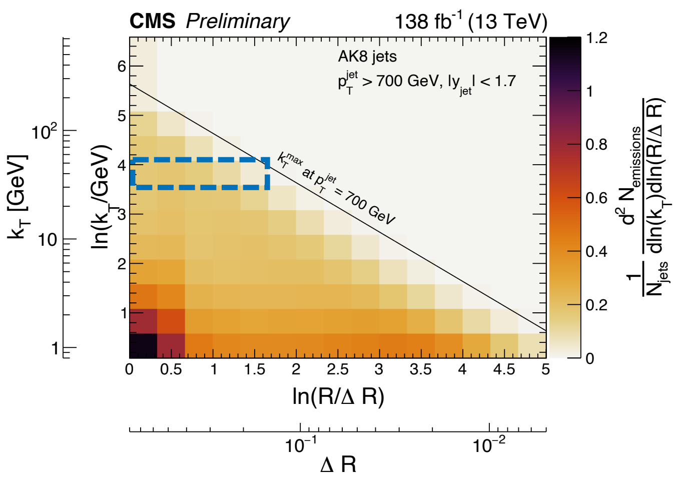


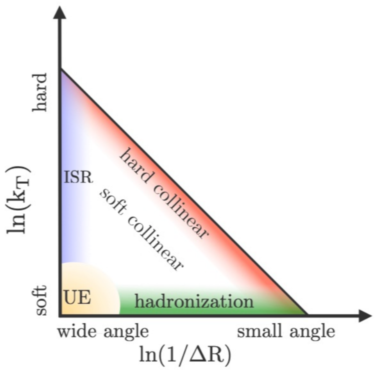


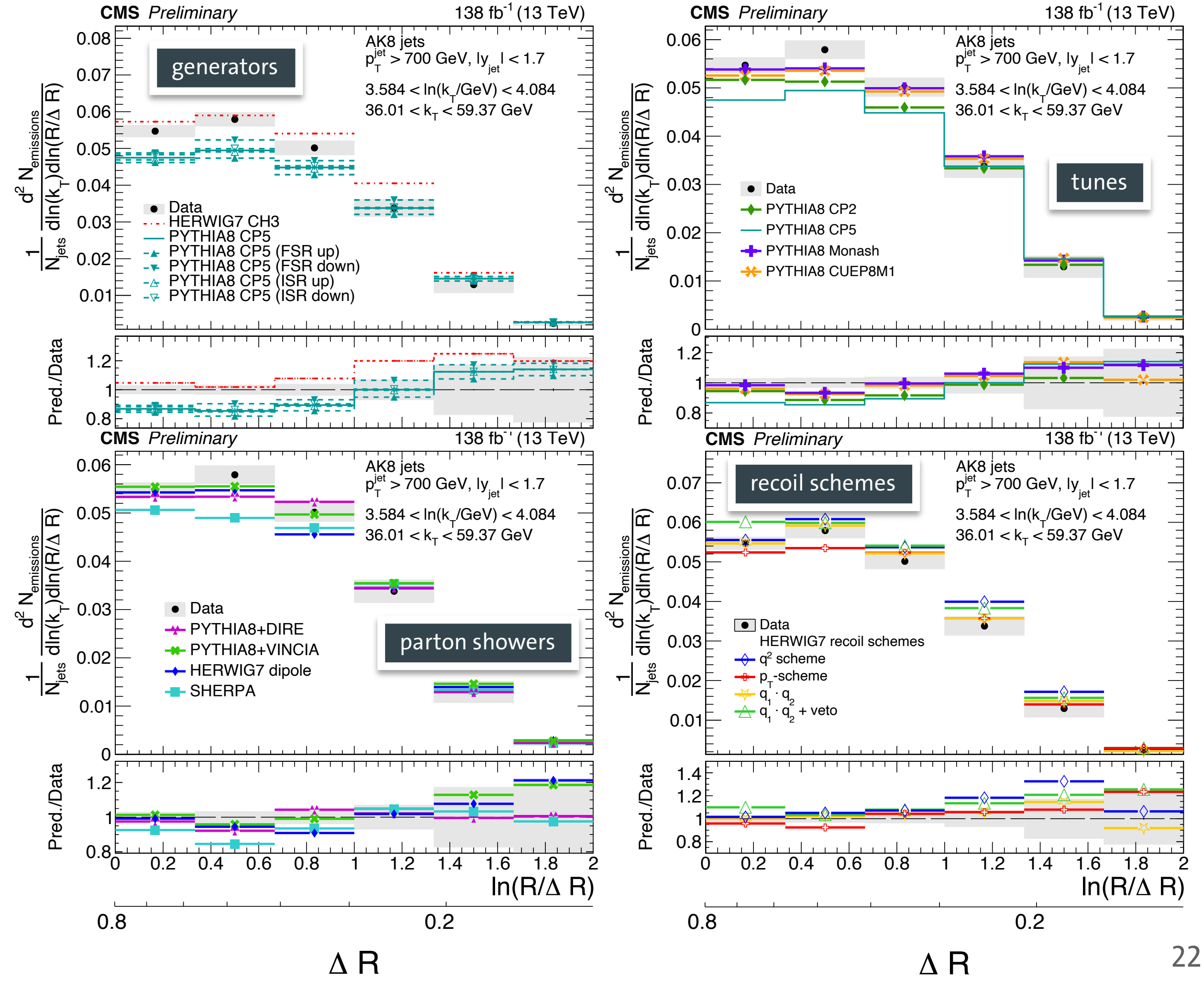


Measurement of the Lund jet plane density

[4] CMS-PAS-SMP-22-007







Measurement of the Lund jet plane density

[4] CMS-PAS-SMP-22-007

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

- comparison to predictions in the soft and collinear limit using the one-loop β function for the running of α_s
- qualitative description of emission density as a function of emission k_T