Jet & jet substructure at ATLAS & CMS

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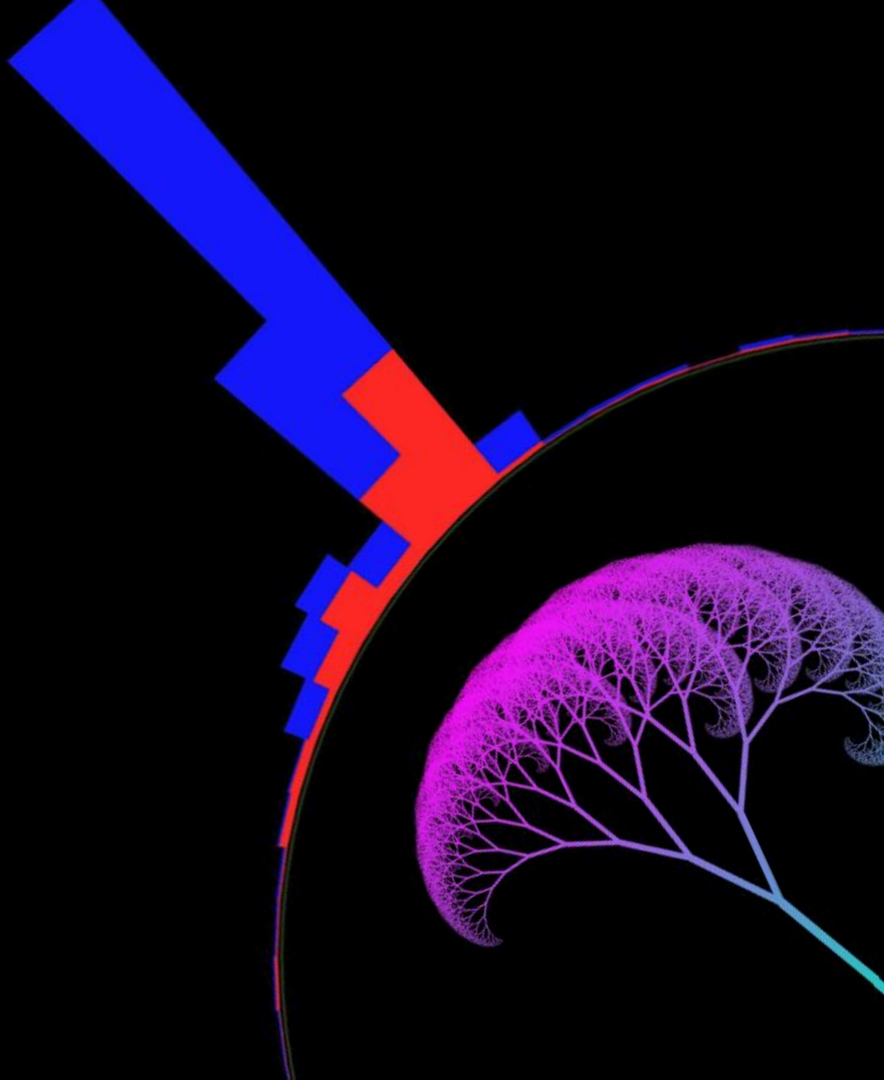
for the ATLAS & CMS Collaborations

Diffraction & Low-*x* 2024,
Palermo, Italy, Sep 8–14

ATLAS EXPERIMENT

CMS
Compact Muon Solenoid



Jet production at the LHC

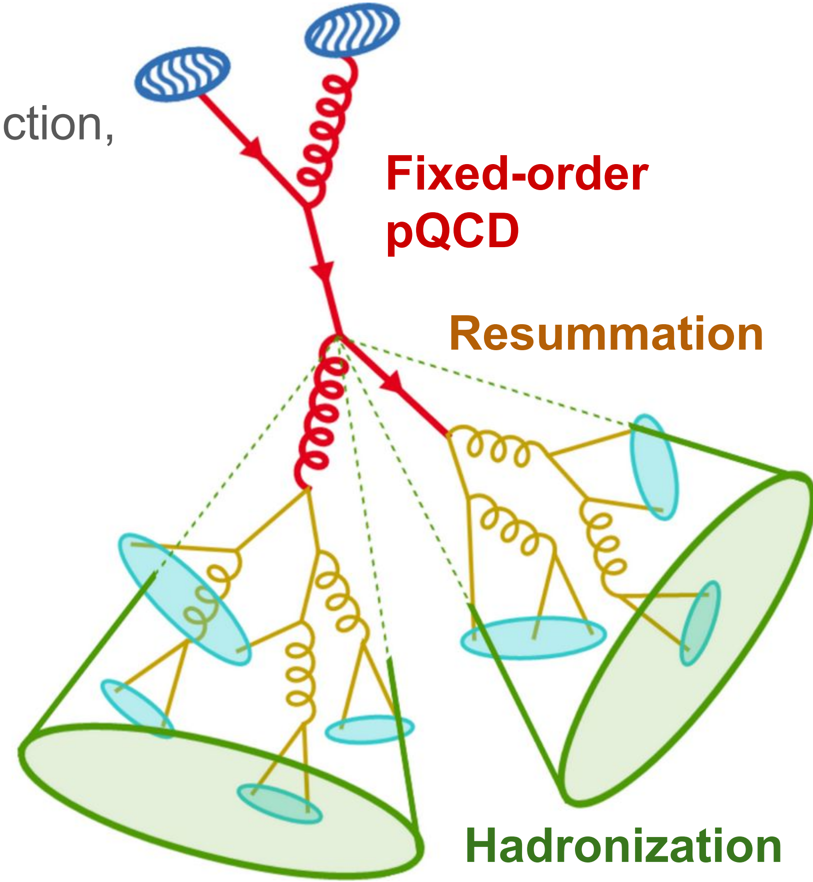
- Crucial to our understanding of the strong interaction, from the GeV to the TeV scale

- Essential input to improve theoretical models (parton showers, hadronization), PDFs, tests of resummation, α_s extractions…

- **Rich program at ATLAS and CMS!**

  Will focus on a selected set of recent multijet & jet substructure measurements **in pp collisions**

  (but there are lots of new results in heavy-ions as well!)



credits: *D. Savoiu*

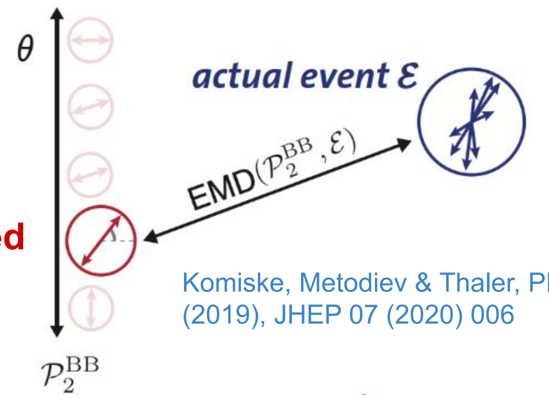
Multijet event isotropies

ATLAS, JHEP 10 (2023) 060

- **Energy-mover's distance (event shape observable),**

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

minimum "amount of work" it would take to transform a shape into an idealized reference radiation pattern

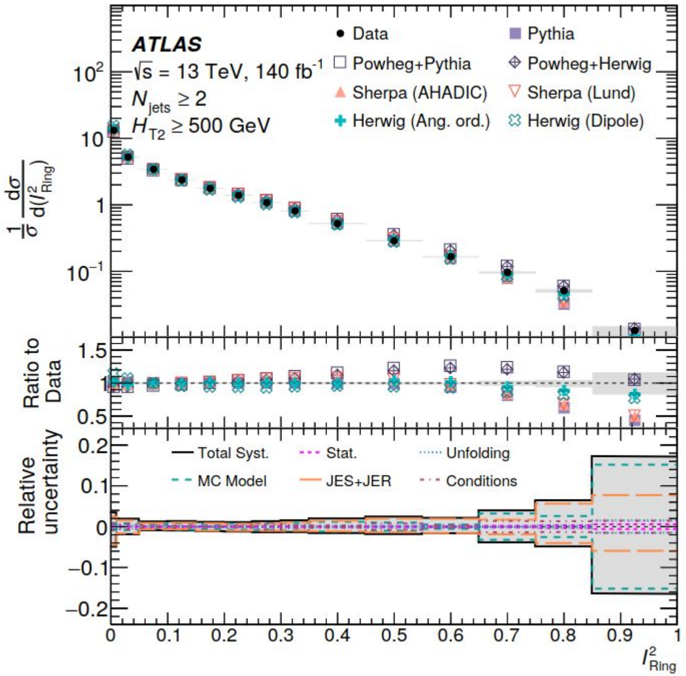


Closest idealized configuration

Komiske, Metodiev & Thaler, PRL 123, 041801 (2019), JHEP 07 (2020) 006

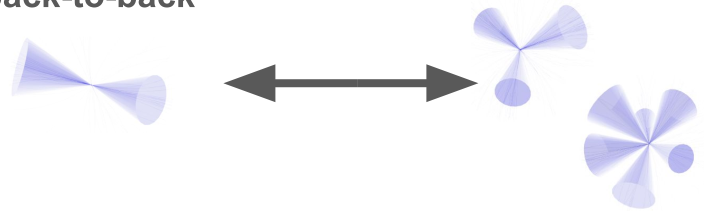
- Data/theory best for dijet-like, deteriorates for more isotropic configurations (**input for MC tuning**)

Example: I^2_{Ring} (thrust-like)



Back-to-back

Less back-to-back

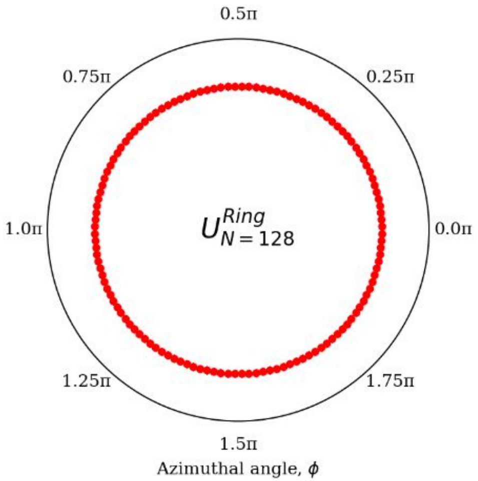


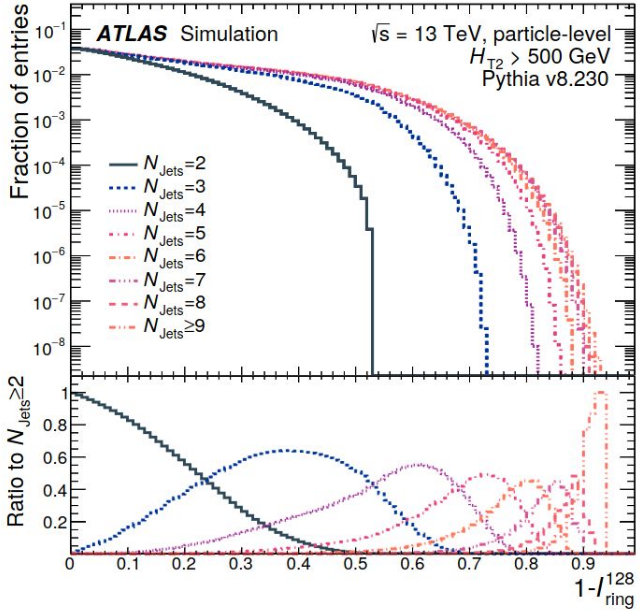
Ring-like isotropy

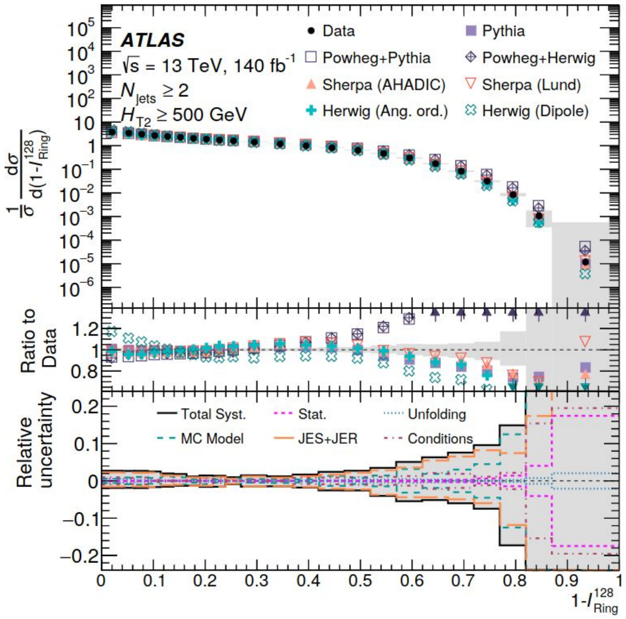
ATLAS, JHEP 10 (2023) 060

Larger N_{jet} multiplicity →more isotropic

Reference pattern

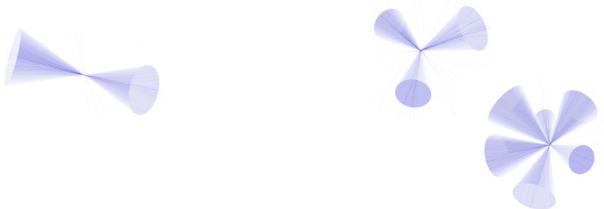






Less isotropic

More isotropic



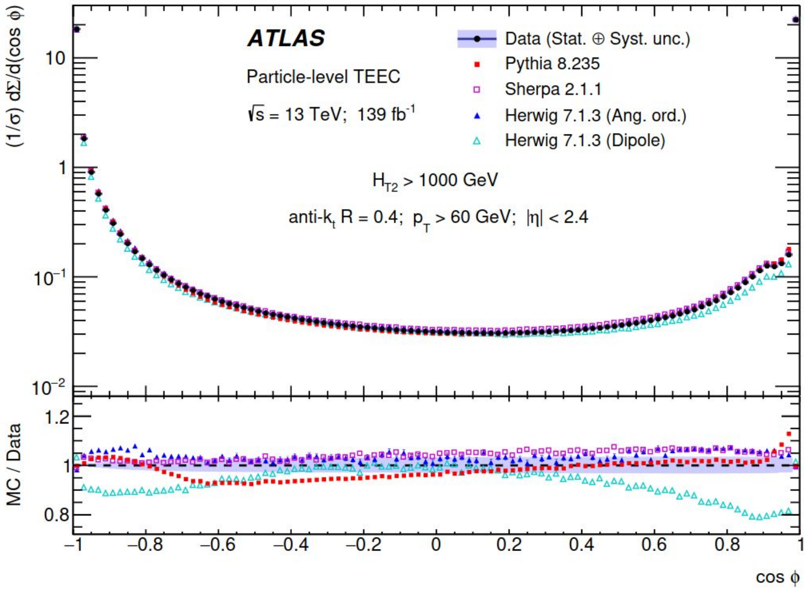
Transverse energy-energy correlators (TEEC)

ATLAS, JHEP 07 (2023) 85

Energy-weighted angular distribution of jet pairs:

$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} \equiv \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E^A_{\mathrm{T}i}E^A_{\mathrm{T}j}}{\left(\sum_k E^A_{\mathrm{T}k}\right)^2}\delta(\cos\phi-\cos\varphi_{ij})$$

TEEC

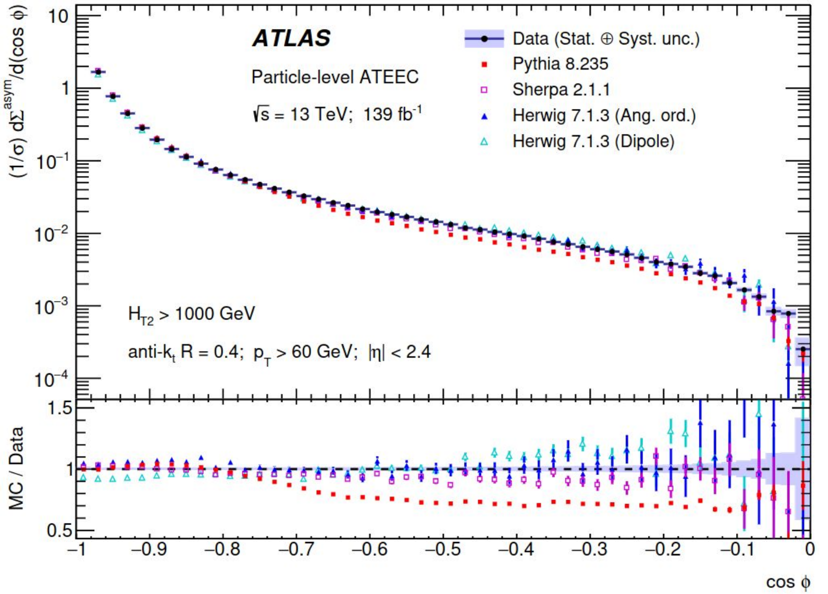


Back-to-back **Wide-angle** **Collinear**

Asymmetric TEEC (forward-backward)

$$\frac{1}{\sigma}\frac{d\Sigma^{\mathrm{asym}}}{d\cos\phi} = \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\pi-\phi}$$

ATEEC



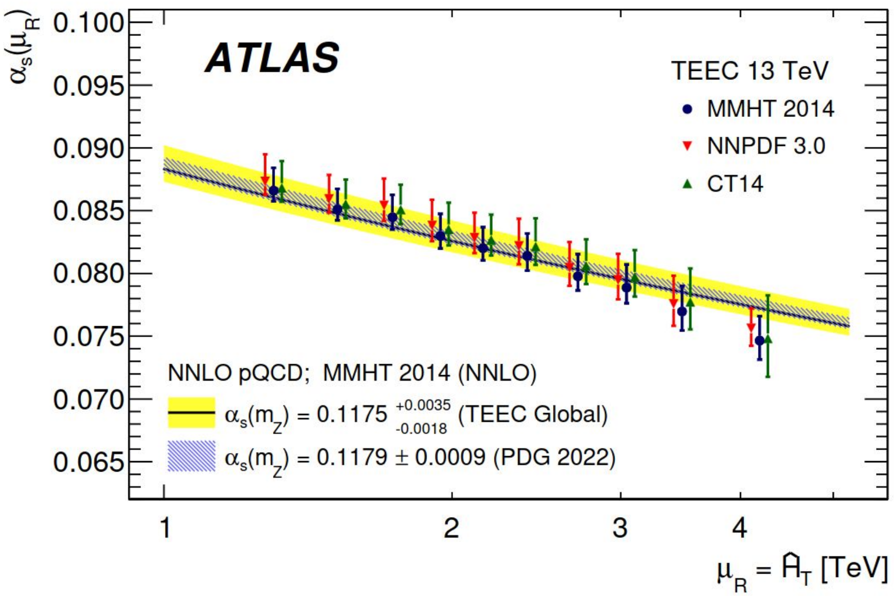
Transverse energy-energy correlators

ATLAS, JHEP 07 (2023) 85

TEEC and ATEEC observables can be used for **precision pQCD**, e.g., sensitive to running coupling $\alpha_s(Q^2)$ at high Q^2

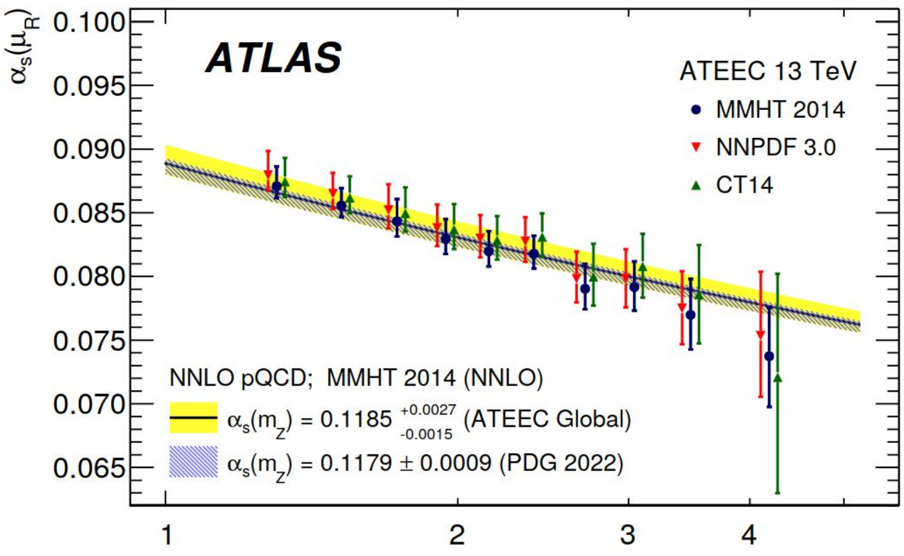
TEEC, NNLO pQCD

$$\alpha_s(m_Z) = 0.1175 \pm 0.0006\,(\text{exp.})^{+0.0034}_{-0.0017}\,(\text{theo.})$$



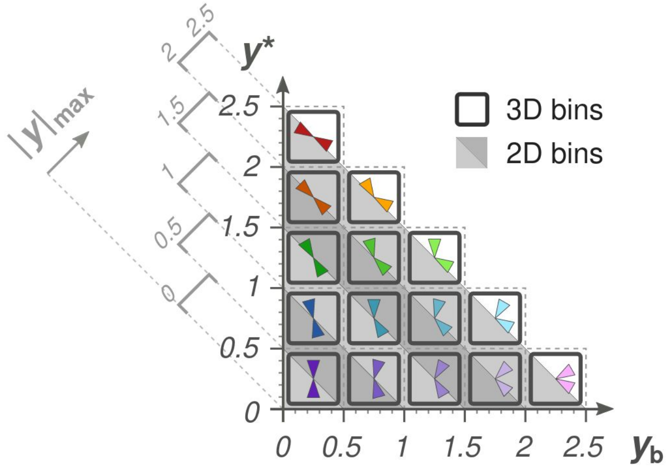
ATEEC, NNLO pQCD

$$\alpha_s(m_Z) = 0.1185 \pm 0.0009\,(\text{exp.})^{+0.0025}_{-0.0012}\,(\text{theo.})$$



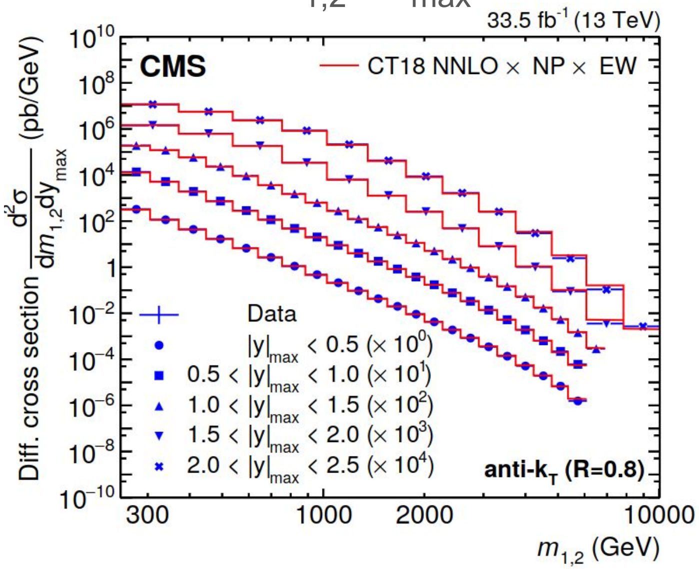
Multidifferential dijet cross section

CMS, arXiv:2312.16669, submitted to JHEP

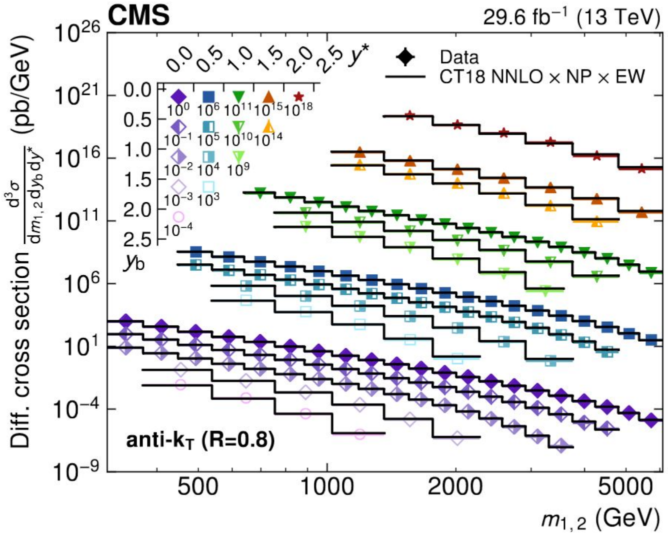


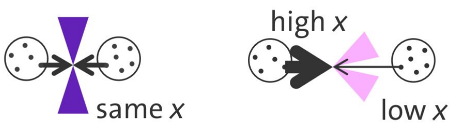
- Double- & triple-differential for anti-k_T jets with R = 0.4 & 0.8
- compared to fixed-order pQCD at NNLO pQCD from NNLOJET + fastNLO

2D: $m_{1,2}$, y_{max}



3D: $m_{1,2}$, y^*, y_b





Isolating different
x regions

QCD analysis (2D vs 3D dijet fits)

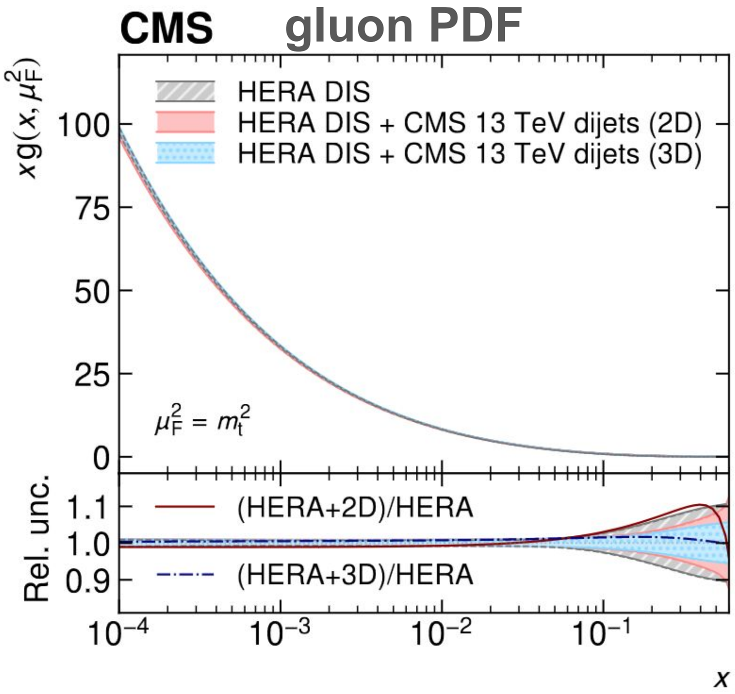
CMS, arXiv:2312.16669, submitted to JHEP

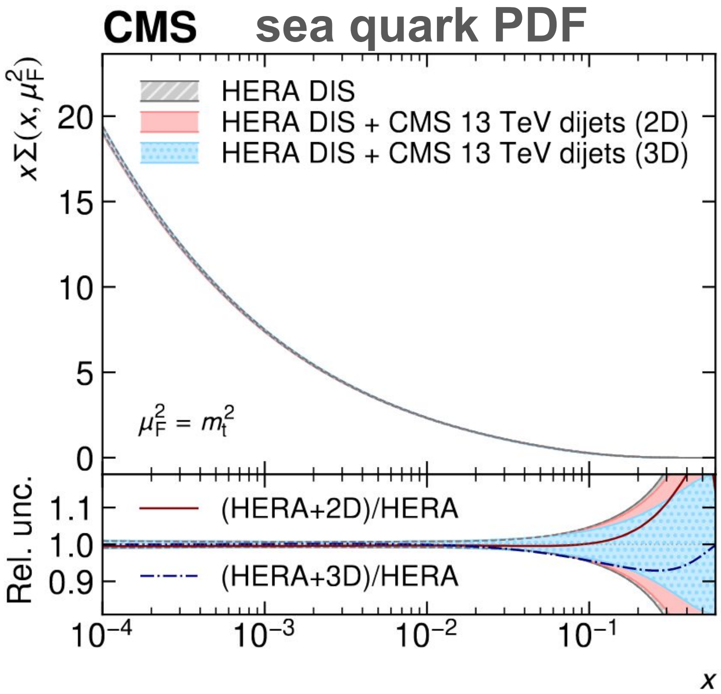
PDFs and $\alpha_s(m_Z)$ determined simultaneously in fits to CMS dijet & HERA data:

Reduction of gluon PDF uncertainty for *x* > 0.3 with **3D-dijet fit**

2D: $\alpha_S(m_Z) = 0.1179 \pm 0.0019$

3D: $\alpha_S(m_Z) = 0.1181 \pm 0.0022$ (compatible w/ **2D**)



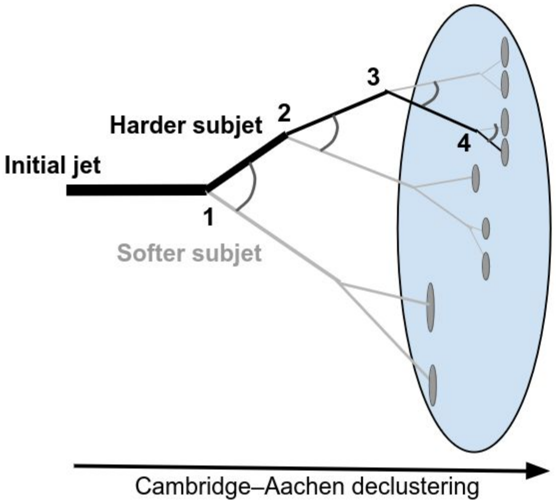


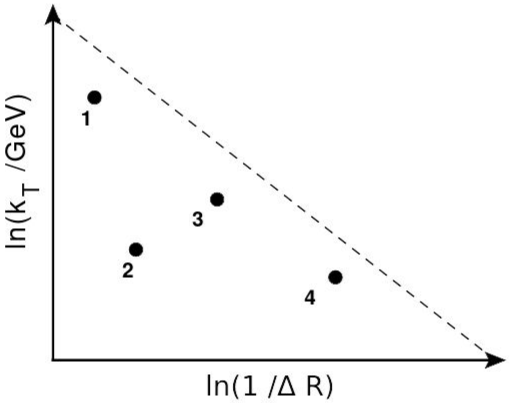
The Lund jet plane

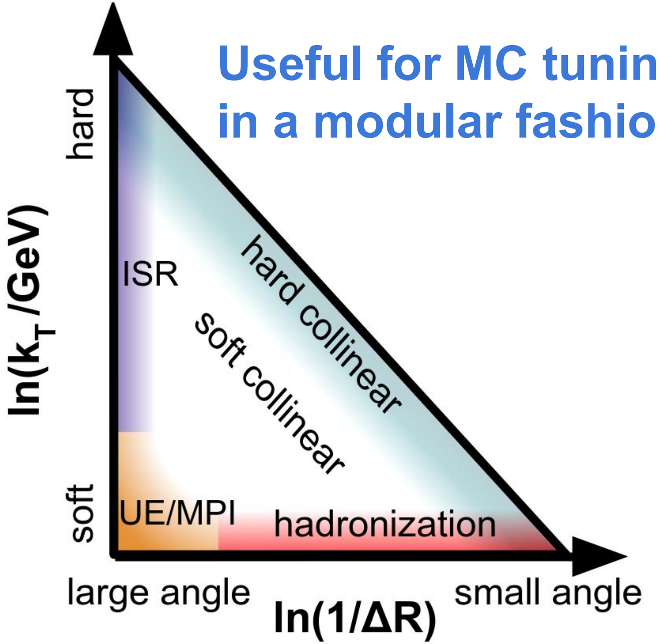
Dreyer, Salam, Soyez, JHEP12(2018)064

Representation of the phase space of 1→2 splittings:

- Recluster anti-k_T jets with the Cambridge–Aachen algorithm (angle-ordered tree)
- Undo clustering tree history, **use subjets as proxies for emissions**
- Register transverse momentum k_T and splitting angle ΔR







Useful for MC tuning in a modular fashion

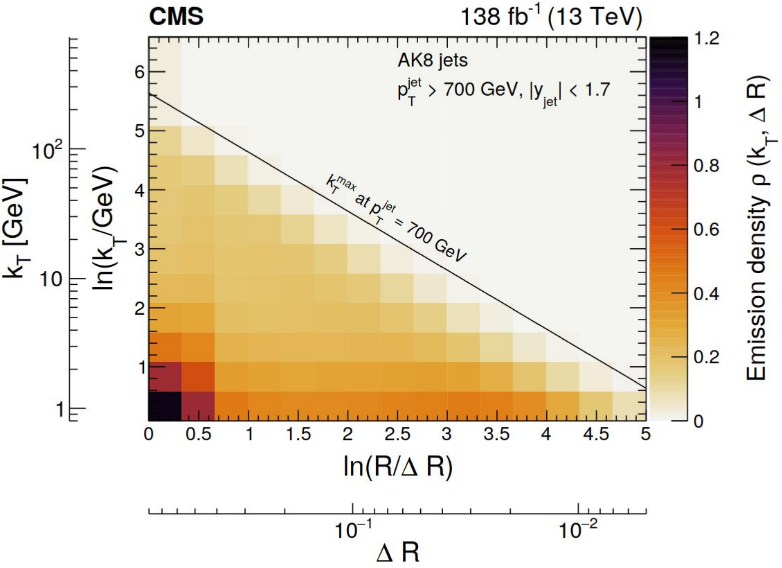
Primary Lund plane density

CMS, JHEP 05 (2024) 116

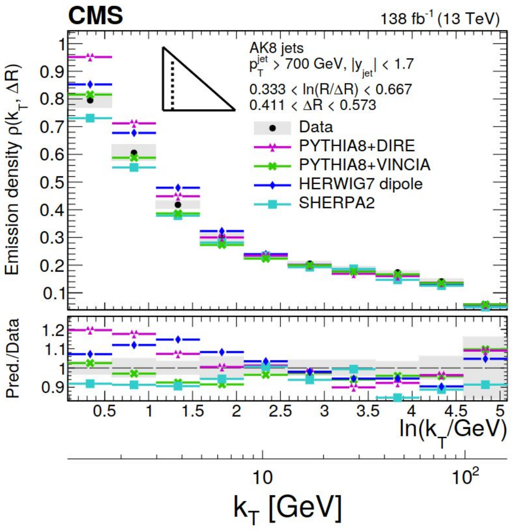
$$\rho(k_T, \Delta R) \equiv \frac{1}{N_{jets}} \frac{d^2 N_{emissions}}{d\ln(k_T/\text{GeV})\, d\ln(R/\Delta R)},$$

Measured for R = 0.4 and R = 0.8 with p_T > 700 GeV & |y| < 1.7

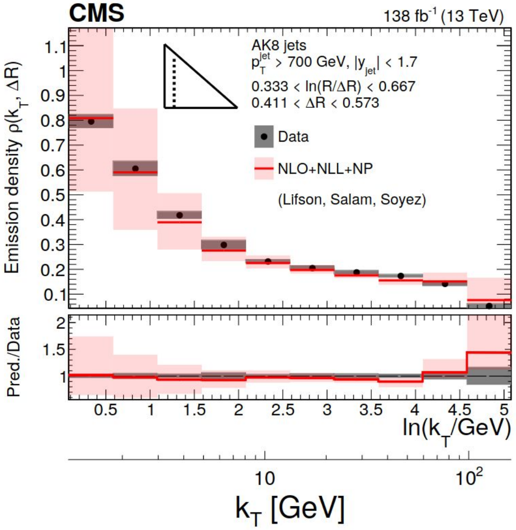
Flat density due to $\varrho(k_T, \Delta R) \propto \alpha_S(k_T)$



Testing parton showers, hadronization models



Testing resummation (NLO+NLL+NP)

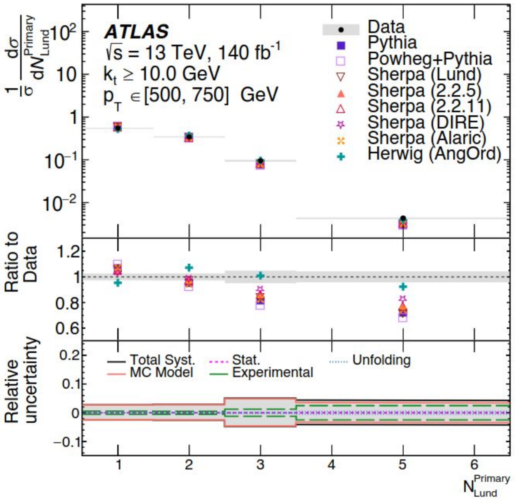


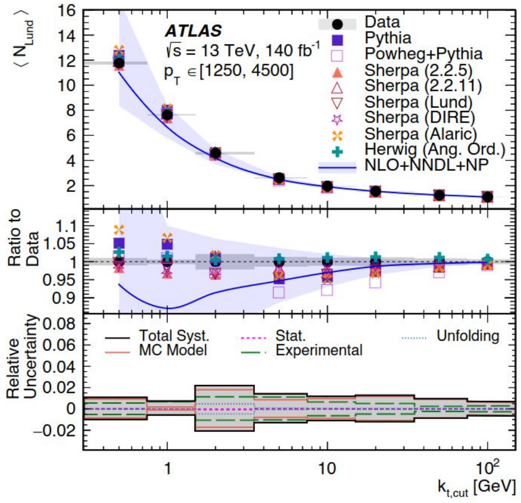
Lund subjet multiplicities

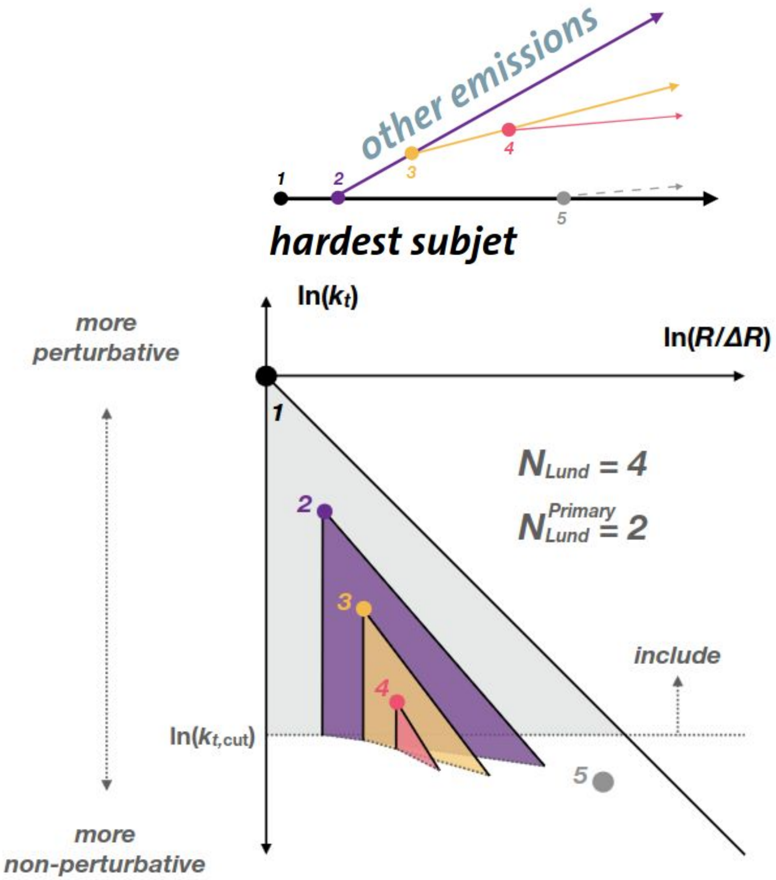
ATLAS, arXiv:2402.13052, submitted to PLB

Count subjets above a given $k_T > k_{T,cut}$ for different jet p_T

Computed for the full Lund tree (N_{Lund})
or only the primary Lund emissions ($N^{Primary}_{Lund}$)







Test resummation at **next-to-next-to-double-logarithmic accuracy (NLO+NNDL)**

Medves, Soto, Soyez
JHEP04(2023)104

Heavy-flavor quark jet substructure

Radiation pattern of light-quark & gluon-initiated jets is governed by soft & collinear divergences of QCD

Heavy quark mass term “regularizes” QCD divergences
→Harder fragmentation, dead cone effect, …

Massive splitting function

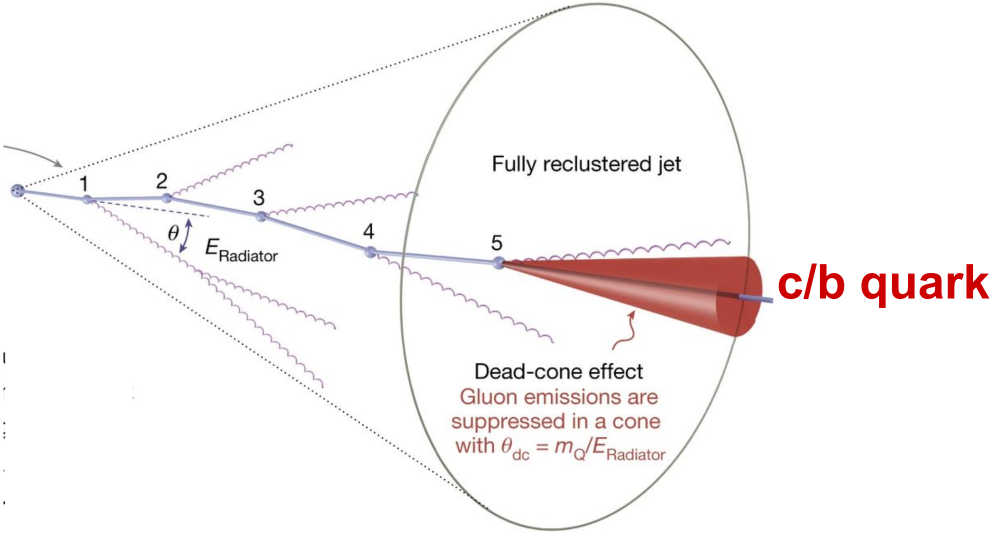
$$P_{Q\to Qg}(z) = \frac{1-z}{z} + \frac{z}{2} - 2\mu_{Qg}^2$$

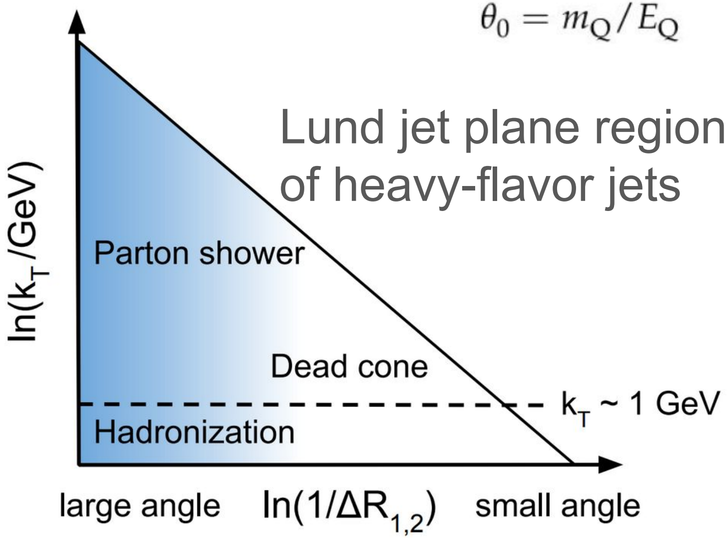
$$\mu_{Qg}^2 = \frac{m_Q^2}{m_{Qg}^2 - m_Q^2}$$

dead cone effect

$$d\mathcal{P}(\theta) \propto \frac{d\theta^2}{(\theta^2+\theta_0^2)^2}$$

$$\theta_0 = m_Q/E_Q$$





Lund jet plane regions of heavy-flavor jets

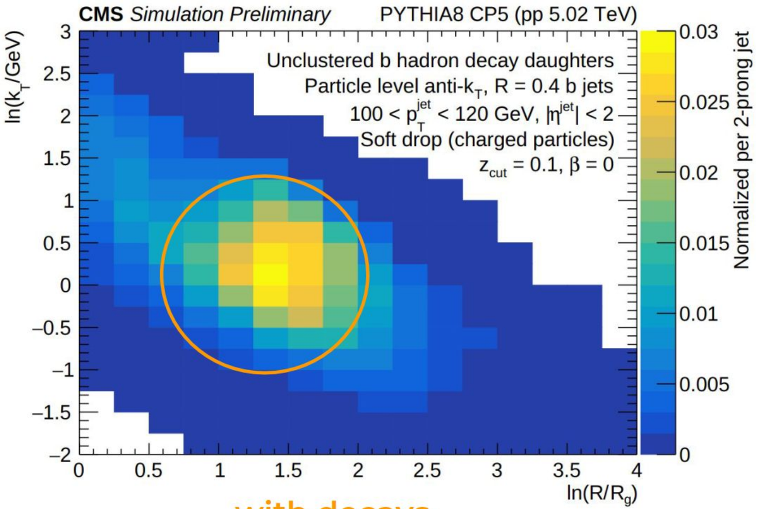
Nature **volume 605**, pages 440 (2022)

Contamination of heavy-flavor hadron decays

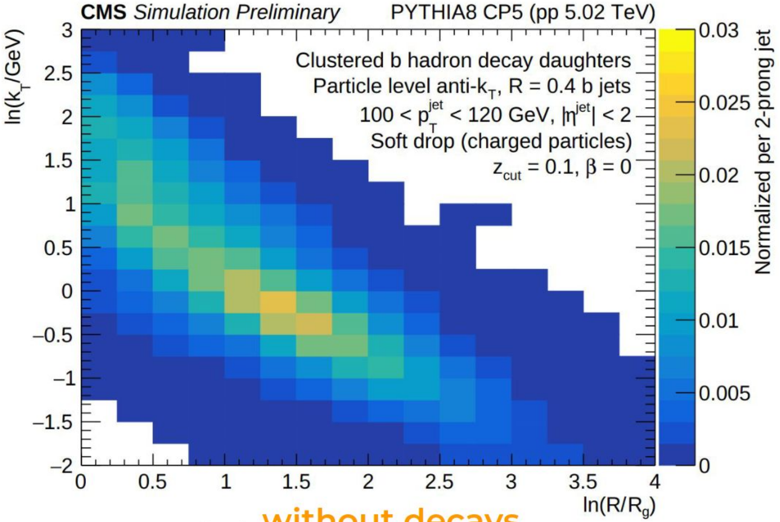
Decays **distort** the QCD radiation pattern of interest

For c jets, one can use exclusive D meson decays (e.g., $D^0 \rightarrow K^- \pi^+$)

For b jets, exclusive decays (eg $B^+ \rightarrow J/\psi\ K^+$) are rarer,
need to use other approaches (TMVA-based "clustering" of b hadron)



with decays



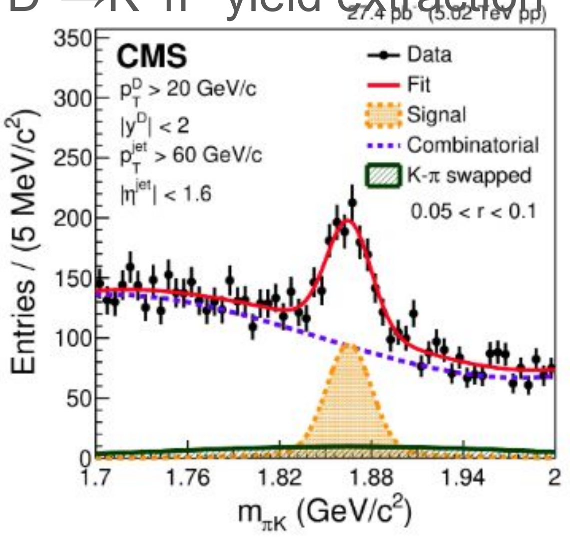
without decays

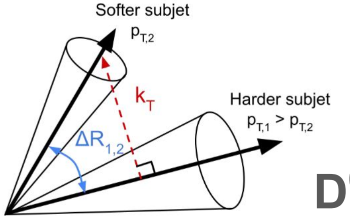
CMS-PAS-HIN-24-005

Collinear emissions are suppressed for D^0 -tagged jets

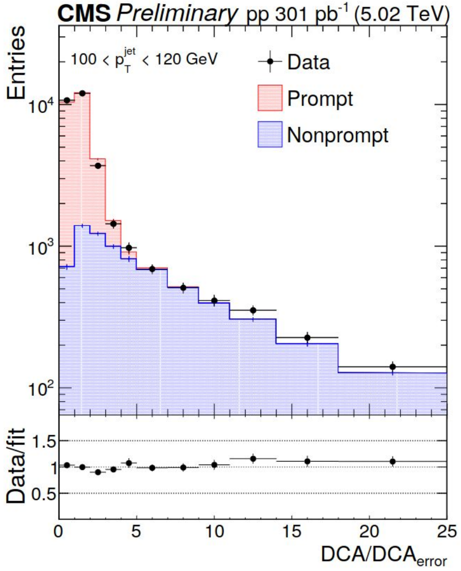
CMS-PAS-HIN-24-007

Substructure-dependent $D^0 \to K^- \pi^+$ yield extraction



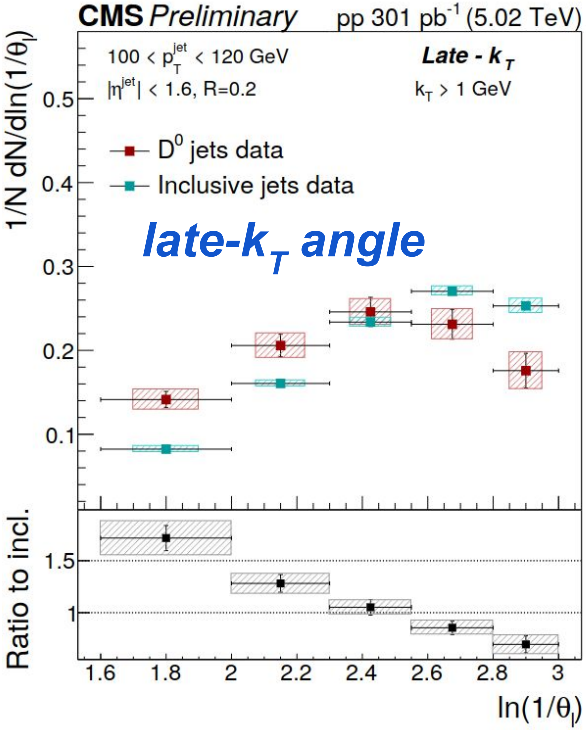


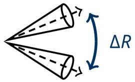
Prompt fraction

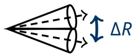


Distance of closest approach significance

D-jet vs inclusive jet







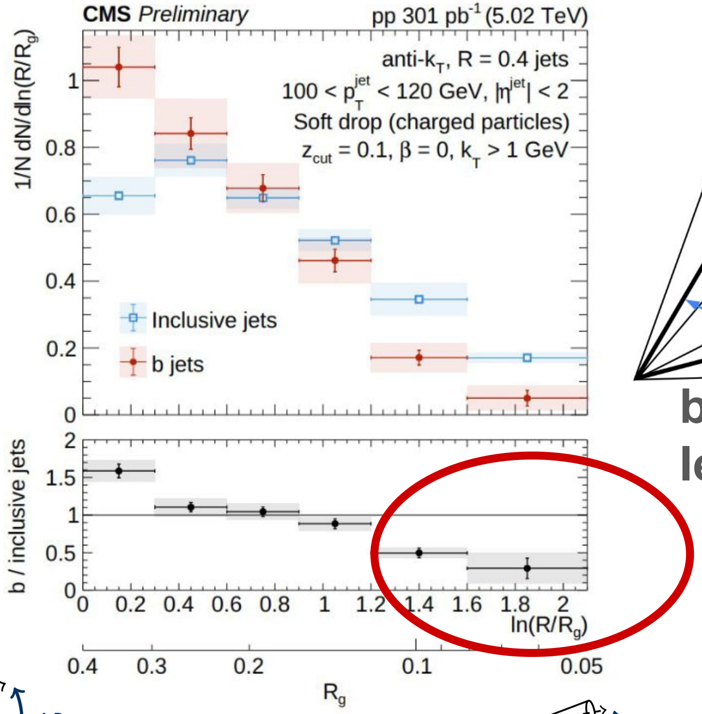
D^0 meson in leading subjet

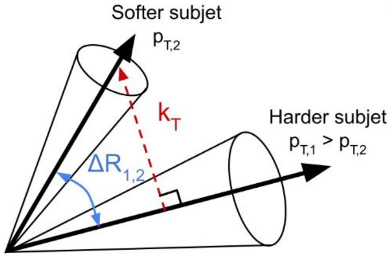
Bottom quark jet substructure

CMS-PAS-HIN-24-005

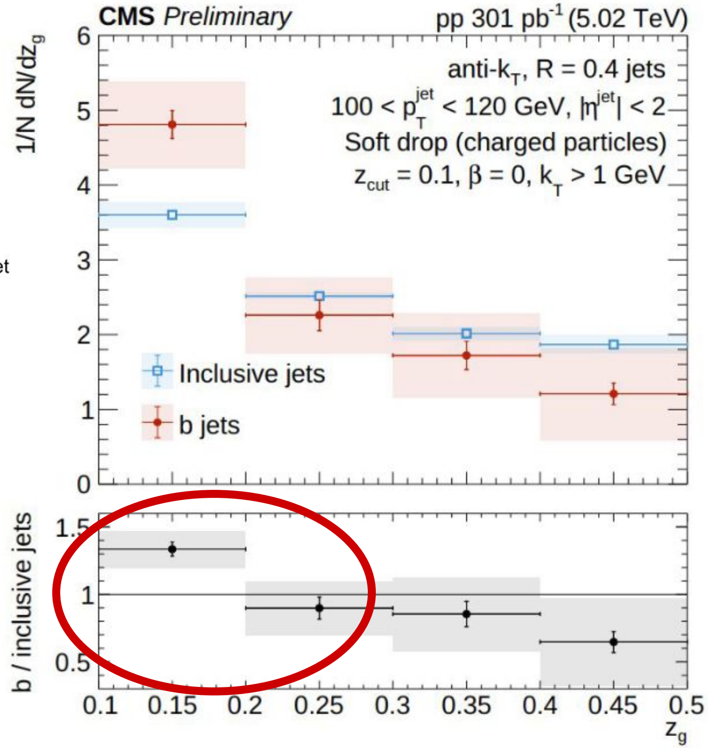
Collinear emissions are suppressed for **b jets** relative to **inclusive jets** (dead cone effect)

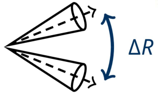
More asymmetric momentum imbalance for **b jets**

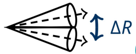




b hadron in leading subjet







Soft-drop angle R_g

CMS-PAS-HIN-24-005

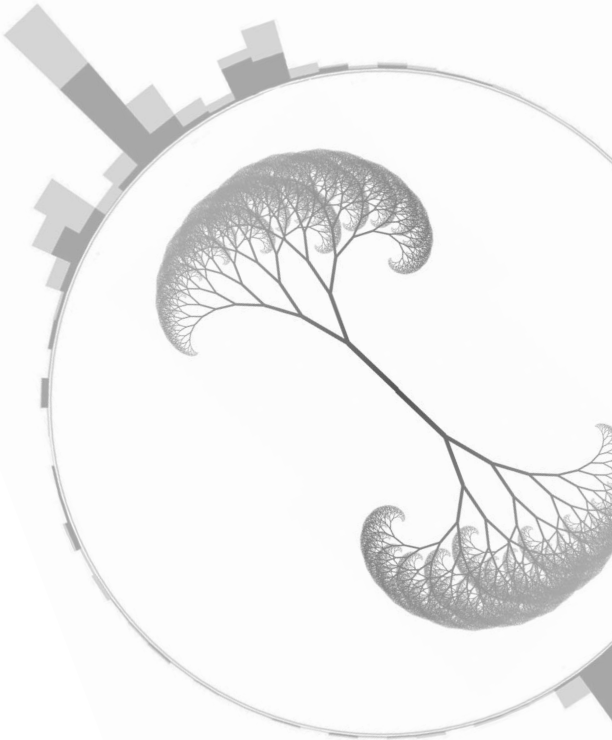
Splitting function

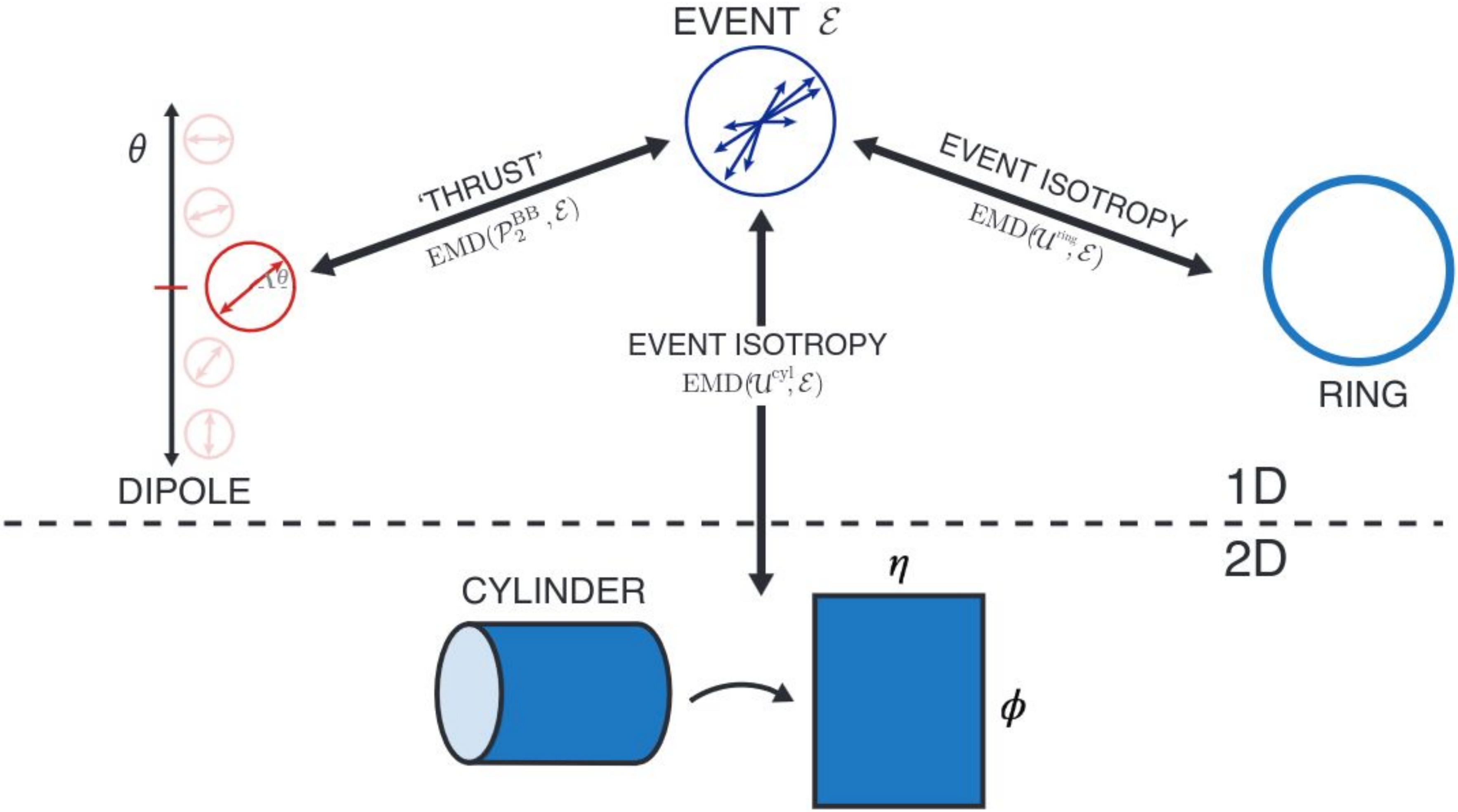
Summary

- Multijet measurements for precision physics (α_S & PDF extractions, MC generator input)

- Mapping out weakly- and strongly-coupled regimes via jet substructure.

  Sensitivity to heavy quark mass effects using the Lund tree of emission




EVENT $\mathcal{E}$
'THRUST'
$\mathrm{EMD}(\mathcal{P}_2^{\mathrm{BB}}, \mathcal{E})$
EVENT ISOTROPY
$\mathrm{EMD}(\mathcal{U}^{\mathrm{ring}}, \mathcal{E})$
θ
$\Delta\theta$
DIPOLE
EVENT ISOTROPY
$\mathrm{EMD}(\mathcal{U}^{\mathrm{cyl}}, \mathcal{E})$
RING
1D
2D
CYLINDER
η
ϕ

Cl

Geometry	Ground Measure	$\mathcal{U}$
Cylinder	$\theta_{ij}^{\text{cyl}} = \frac{12}{\pi^2+16y_{\text{max}}^2}\left(y_{ij}^2 + \phi_{ij}^2\right)$	$\mathcal{U}_N^{\text{cyl}}(\lvert y\rvert < y_{\text{max}})$
Ring	$\theta_{ij}^{\text{ring}} = \frac{\pi}{\pi-2}\left(1 - \cos\phi_{ij}\right)$	$\mathcal{U}_N^{\text{ring}}$
Ring (Dipole)	$\theta_{ij}^{\text{ring}} = \frac{1}{1-\frac{1}{\sqrt{3}}}\left(1 - \cos\phi_{ij}\right)$	$\mathcal{U}_2^{\text{ring}}$