Jet substructure at high-p_T

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On behalf of ATLAS & CMS Collaborations

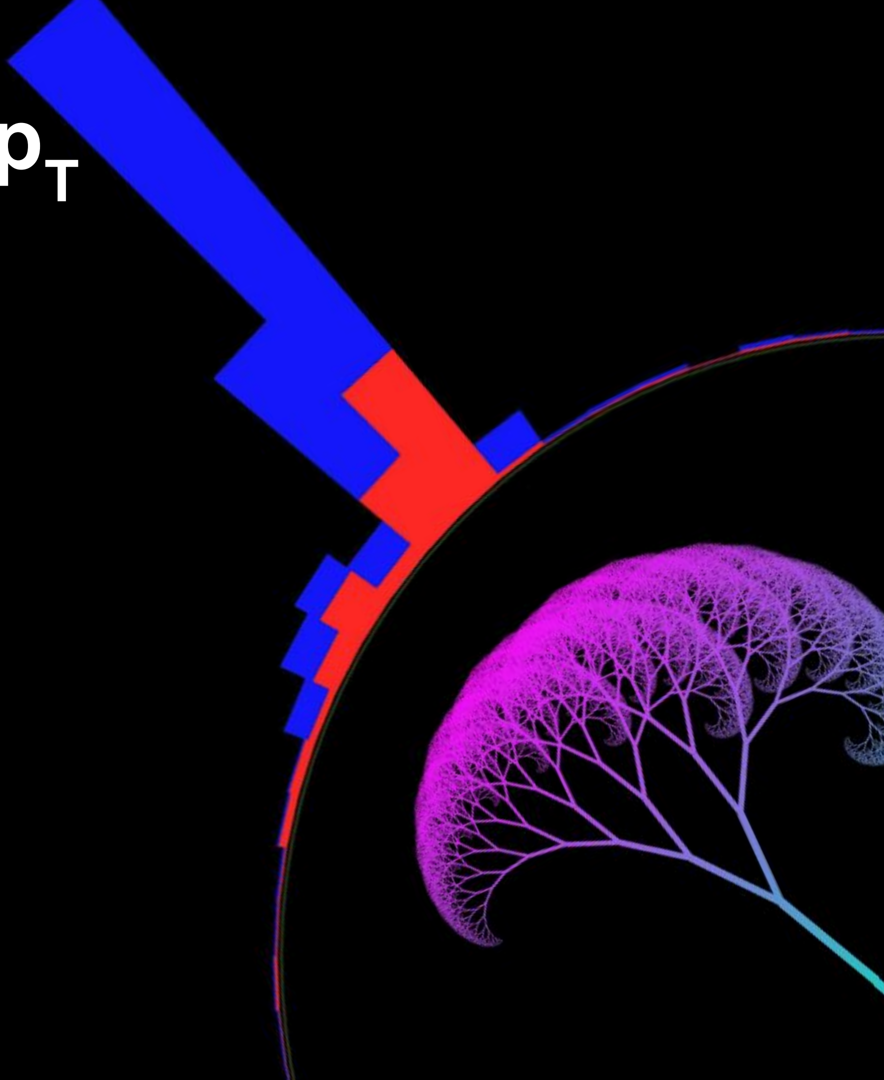
SM@LHC 2024
May 7th–10th

ATLAS EXPERIMENT

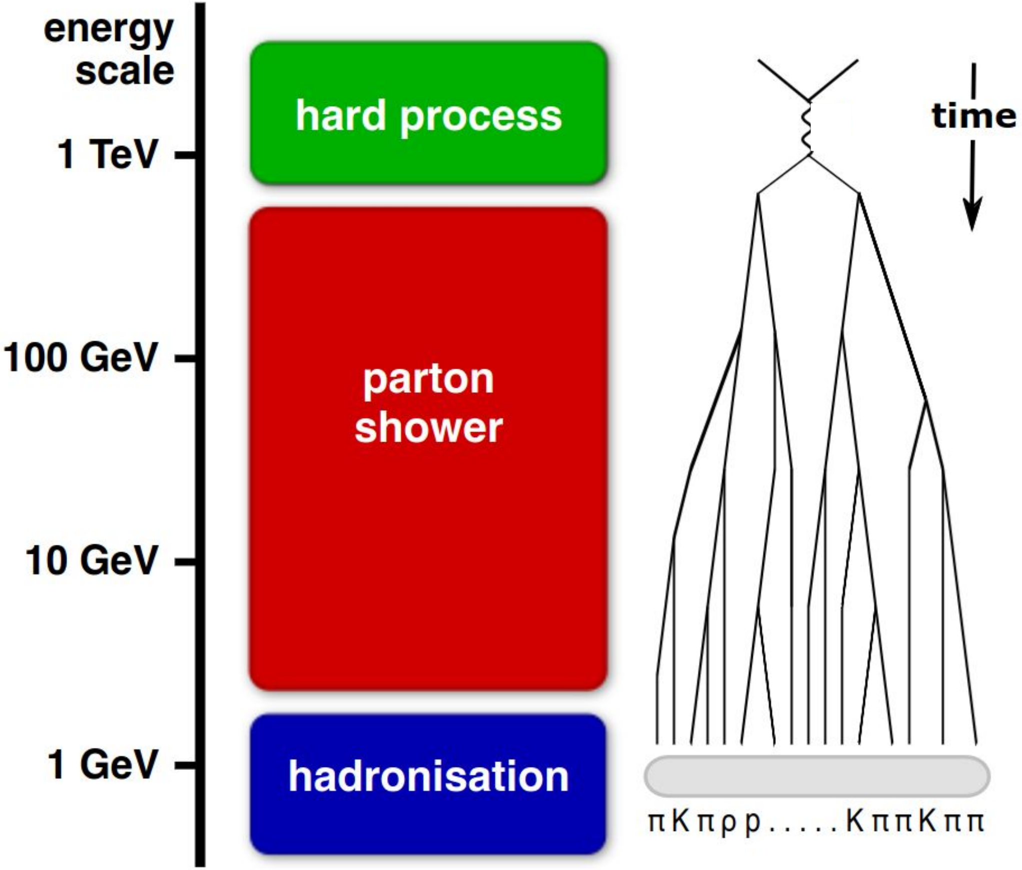
CMS
Compact Muon Solenoid

SAPIENZA
UNIVERSITÀ DI ROMA

European Research Council



Jet formation is a multiscale probe of QCD evolution



G. Salam's sketch

From $Q \sim$ 1 TeV to $\Lambda_{QCD} \sim$ 200 MeV

Depending on observable & jet p_T and R: sensitivity to parton shower, hadronization, underlying event, color reconnection, …

Higher jet p_T ⇒ "longer" parton cascade

Results on jet fragmentation functions covered by ***Ezra Lesser*** *next*

Focus on subset of recent results

CMS and ATLAS primary Lund jet plane densities

ATLAS: PRL 124, 222002 (2020)

CMS: arXiv:2312.16343, accepted by JHEP

ATLAS Lund subjet multiplicities

arXiv:2402.13052, *submitted to PLB*

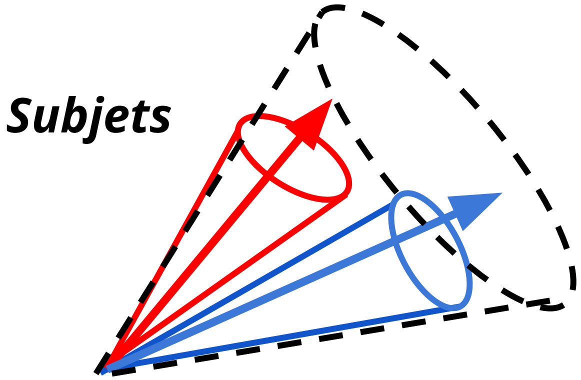
Energy-energy correlators in jets (CMS)

arXiv:2402.13864, submitted to PRL

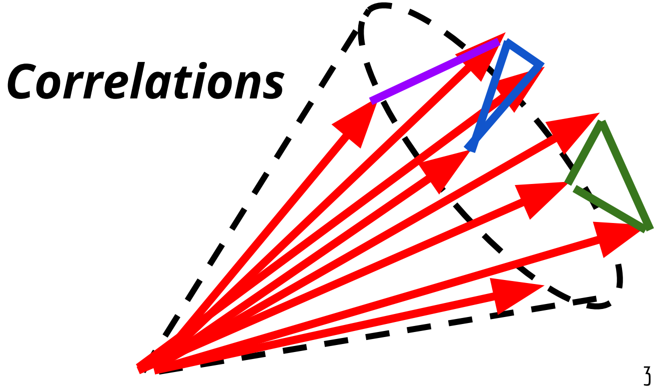
Collectivity in jets with high-particle multiplicities (CMS)

arXiv:2312.17103, submitted to PRL

Clustering-based observables

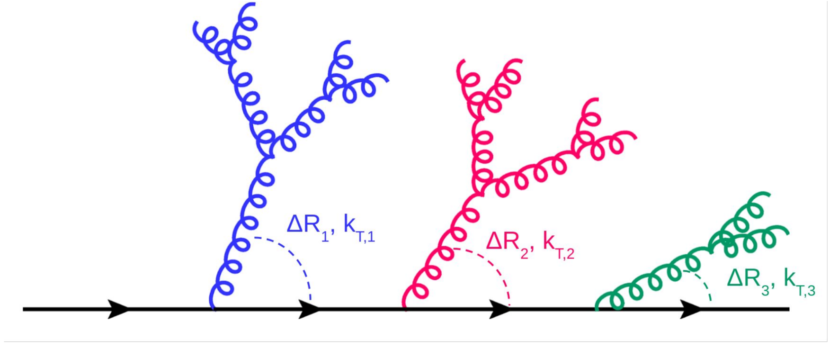


Energy-flow-based observables

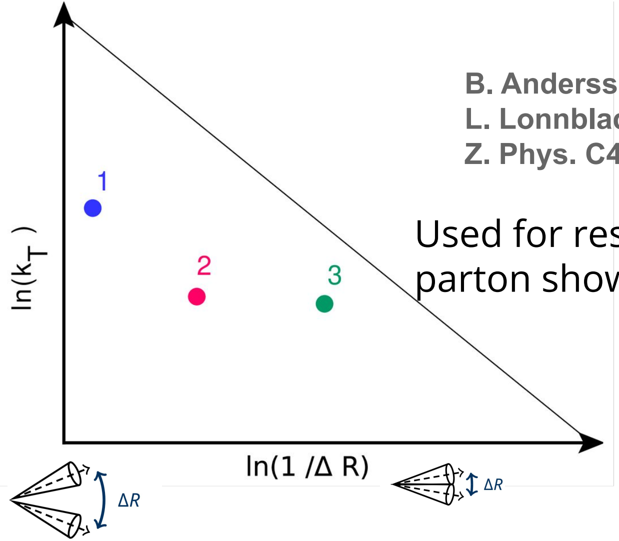


Phase-space of QCD branchings in the Lund plane

Lund planes (or diagrams) are a 2D representation of the phase-space of 1→2 splittings:



k_T : relative transverse momentum of emission
ΔR: angular opening of emission and core



**B. Andersson, G. Gustafson,
L. Lonnblad, and U. Pettersson,
Z. Phys. C43 (1989) 625**

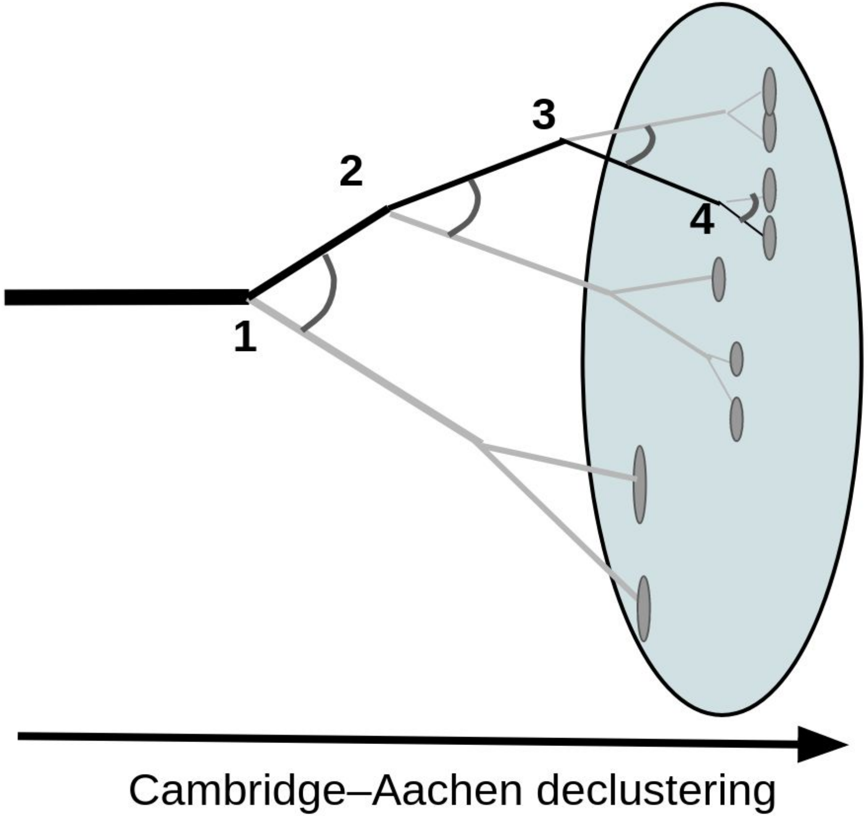
Used for resummation and parton shower development

In soft & collinear limit of QCD, emissions fill the Lund plane uniformly

$$\mathcal{P} \propto \alpha_{\mathrm{s}} \frac{\mathrm{d}k_{\mathrm{T}}}{k_{\mathrm{T}}} \frac{\mathrm{d}\Delta R}{\Delta R} = \alpha_{\mathrm{s}} \mathrm{d}\ln(k_{\mathrm{T}}) \mathrm{d}\ln(\Delta R)$$ ← **approximate self-similarity of QCD**

Constructing the ***primary*** Lund jet plane (LJP)

F. Dreyer, G. Salam, G. Soyez, JHEP12(2018)064



1. Jet is reclustered with Cambridge–Aachen algorithm (pairwise clustering with angular ordering)
2. Follow clustering tree in reverse (large → small angles), **along the hardest branch**
3. Register kinematics of branching at each step

$$\Delta R = \sqrt{(y^{\text{softer}} - y^{\text{harder}})^2 + (\phi^{\text{softer}} - \phi^{\text{harder}})^2}$$

$$k_{\mathrm{T}} = p_{\mathrm{T}}^{\text{softer}} \Delta R$$ **CMS**

$$z = p_T^{\text{softer}}/(p_T^{\text{harder}}+p_T^{\text{softer}})$$

Measured by ATLAS, CMS, ALICE (low p_T ~ 20 GeV)

F. Dreyer, G. Salam, G. Soyez, JHEP12(2018)064

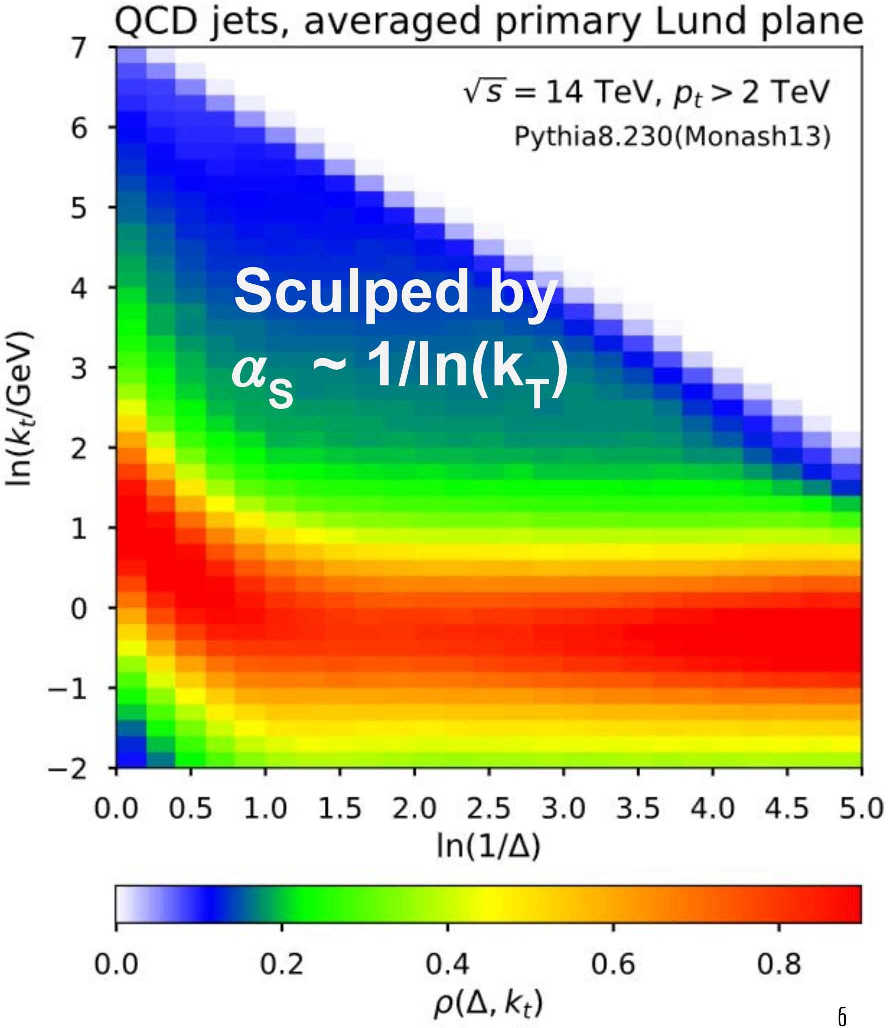
Define a *jet-averaged* number of emissions,
the ``primary" Lund jet plane density

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

At leading order, it's "sculpted" by $\alpha_S(k_T)$

$$\rho(k_\mathrm{T}, \Delta R)_\mathrm{LO} \approx \frac{2}{\pi} C_\mathrm{R}^\mathrm{eff} \alpha_\mathrm{S}(k_\mathrm{T})$$

With $C_R = C_A = 3$ for g→gg or $C_F = 4/3$ for q→qg

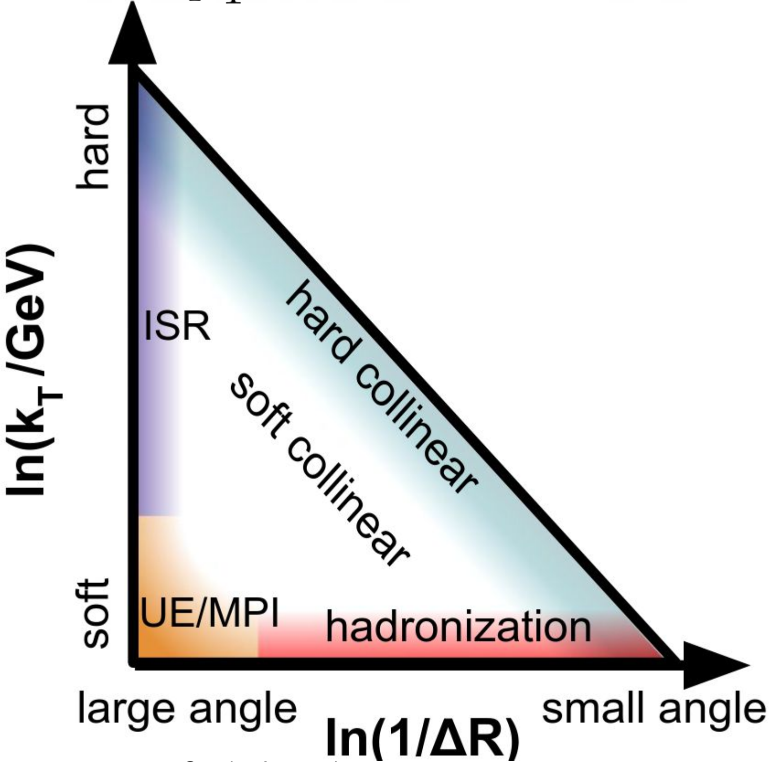


Mechanisms “factorize” in the Lund jet plane

F. Dreyer, G. Salam, G. Soyez, JHEP12(2018)064

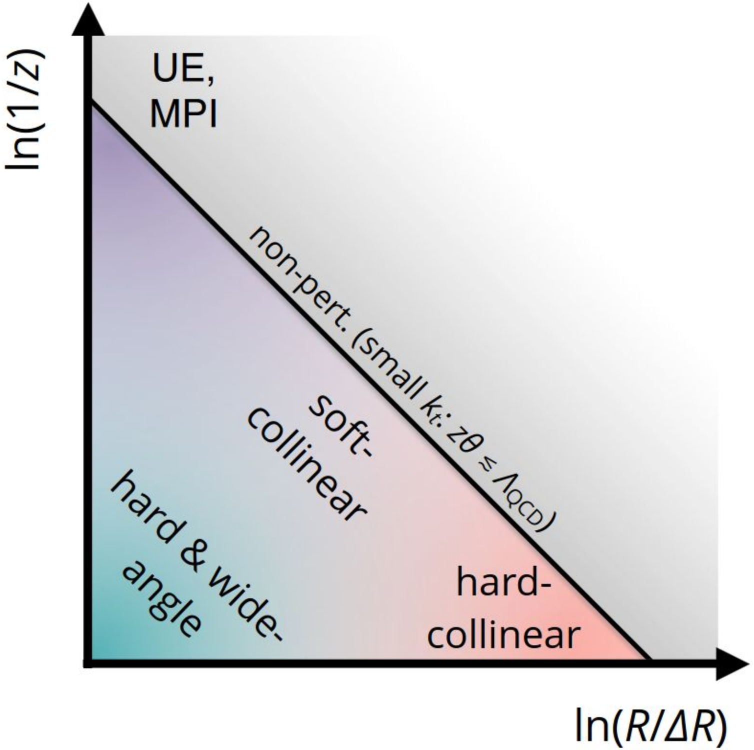
CMS Lund plane coordinates

$k_{\mathrm{T}} = p_{\mathrm{T}}^{\mathrm{softer}}\Delta R$ vs ΔR



ATLAS Lund plane coordinates

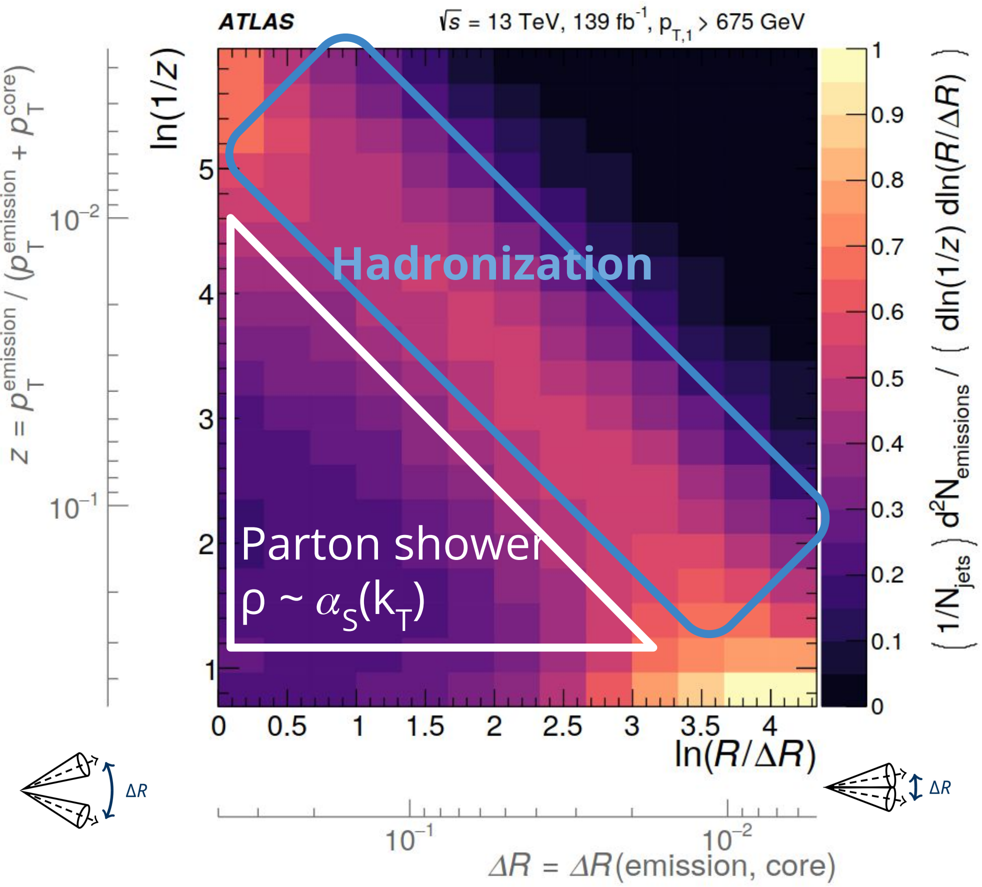
$z = p_T^{\mathrm{softer}}/(p_T^{\mathrm{harder}}+p_T^{\mathrm{softer}})$ vs ΔR



ATLAS primary Lund jet plane density

R=0.4 jets (standard R in Run-2)

PRL 124, 222002 (2020)



Dijet selection,

$p_{T,\,jet1} > 675$ GeV & $p_{T,jet2} > ⅔\ p_{T,jet1}$

Charged-particle tracks for substructure

Momentum fraction of the emissions for vertical axis of Lund plane:

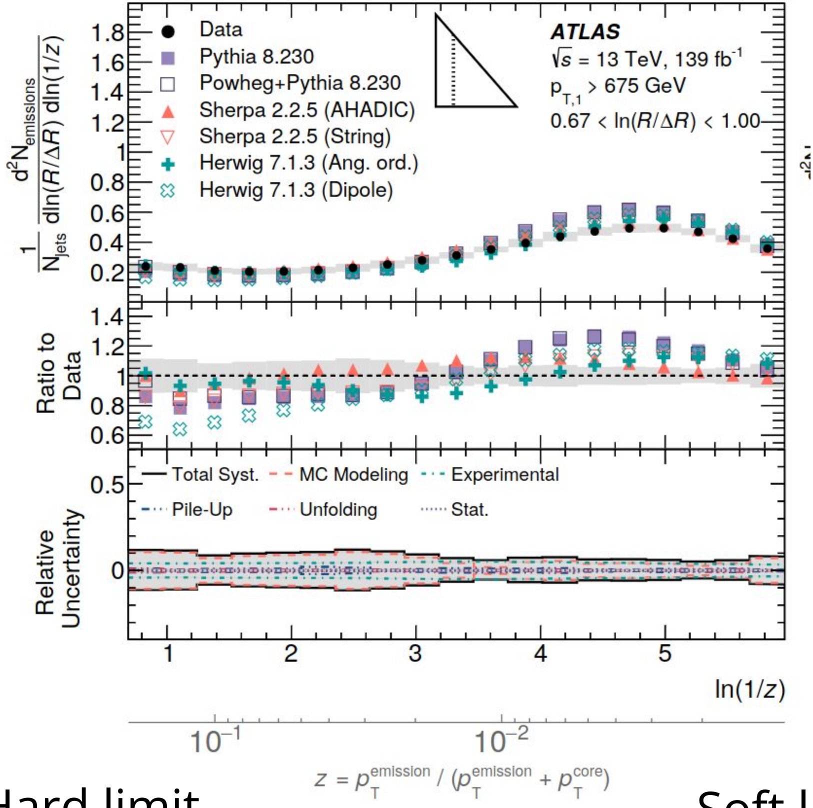
$$z = p_{T,softer}/(p_{T,softer}+p_{T,harder})$$

Multidimensional unfolding

Factorization properties in action (ATLAS)

Fixed-angle slize

PRL 124, 222002 (2020)



Hard limit
(high z)

Soft limit
(small z)

Variation of hadronization model, same parton shower (**Sherpa2 string vs hadronization**)

Variation of parton shower, same hadronization model (**Herwig7.1 angle vs dipole**)

Variation of matrix element (**Pythia8** vs **Powheg+Pythia8**)

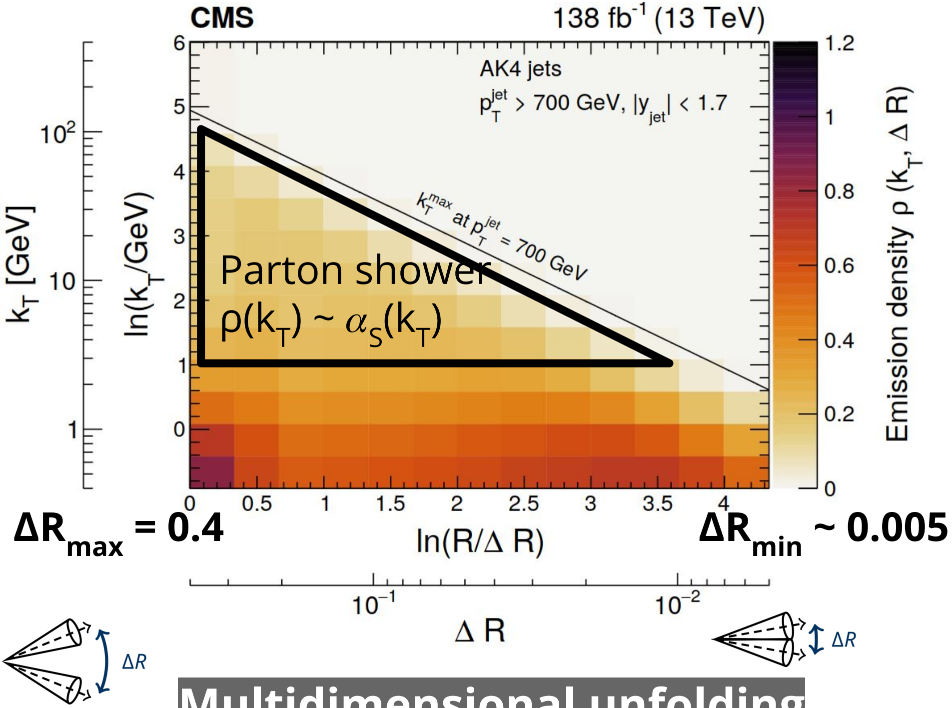
Best global description by **Herwig7.1 angle-ordered**

CMS primary Lund jet plane densities

arXiv:2312.16343, accepted by JHEP

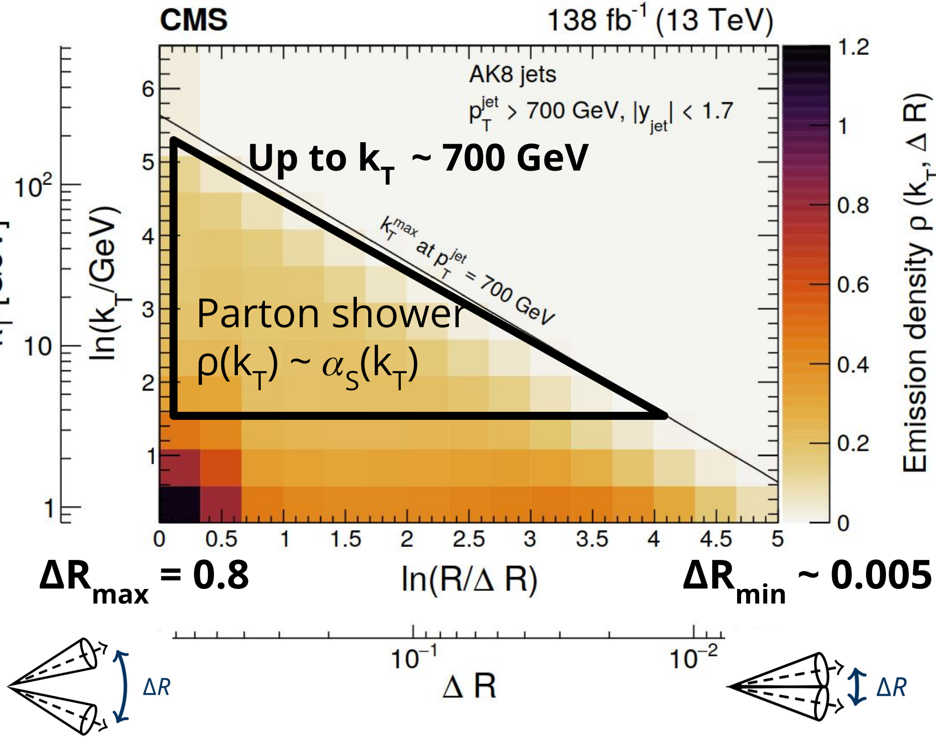
$p_T^{jet} > 700$ GeV,
charged particles for substructure

R=0.4 (standard R in Run-2)



ΔR_{max} = 0.4 **ΔR_{min} ~ 0.005**

R=0.8 (large-angle & harder emissions)



Up to k_T ~ 700 GeV

ΔR_{max} = 0.8 **ΔR_{min} ~ 0.005**

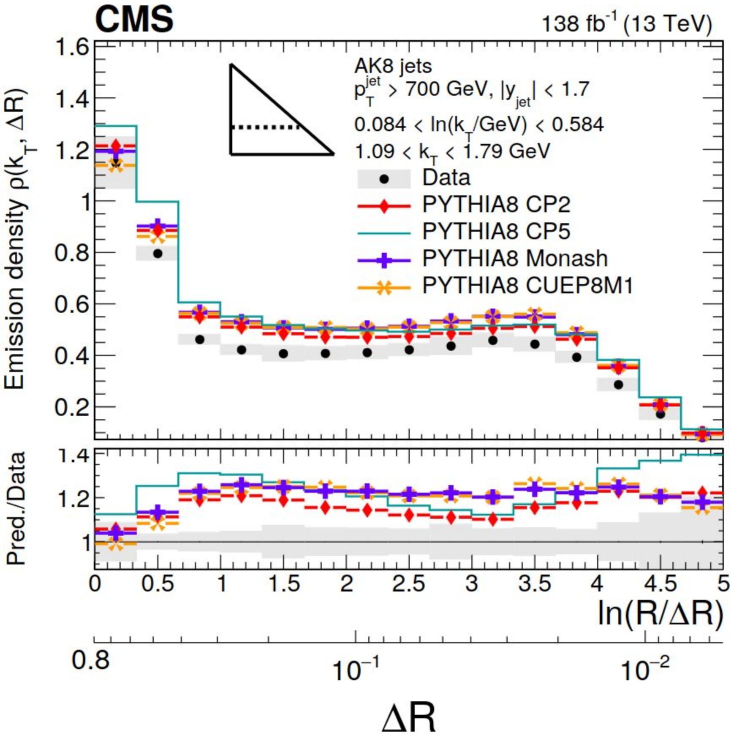
Multidimensional unfolding

Emission density is flat for hard & collinear emissions due to $\alpha_S(k_T) \sim 1/\ln(k_T)$

arXiv:2312.16343, accepted by JHEP

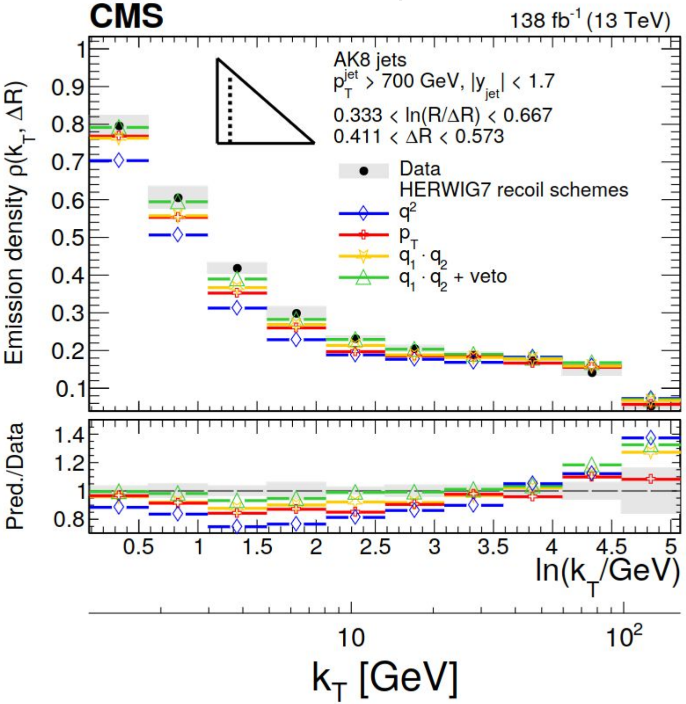
CMS Lund plane slices

Hadronization region ($k_T \sim 1$ GeV)



PYTHIA8 overshoots data by 15-20% in hadronization region

Large-angles (k_T = 1 – 200 GeV)

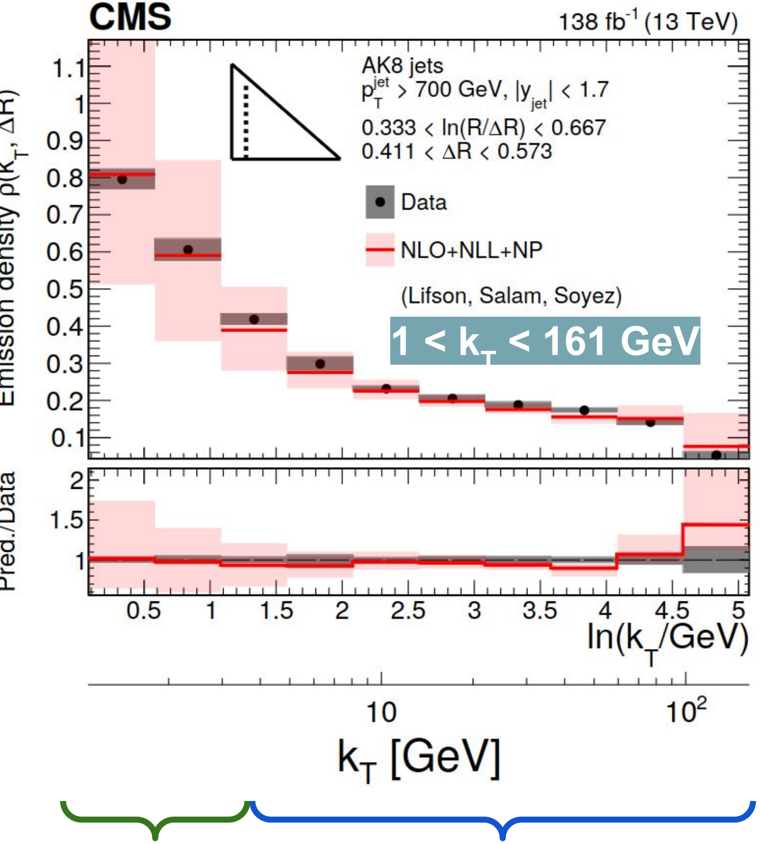


Sensitivity to parton shower recoil scheme (**Herwig7)**

Better description by Herwig7 angle-ordered with q_1q_2+veto

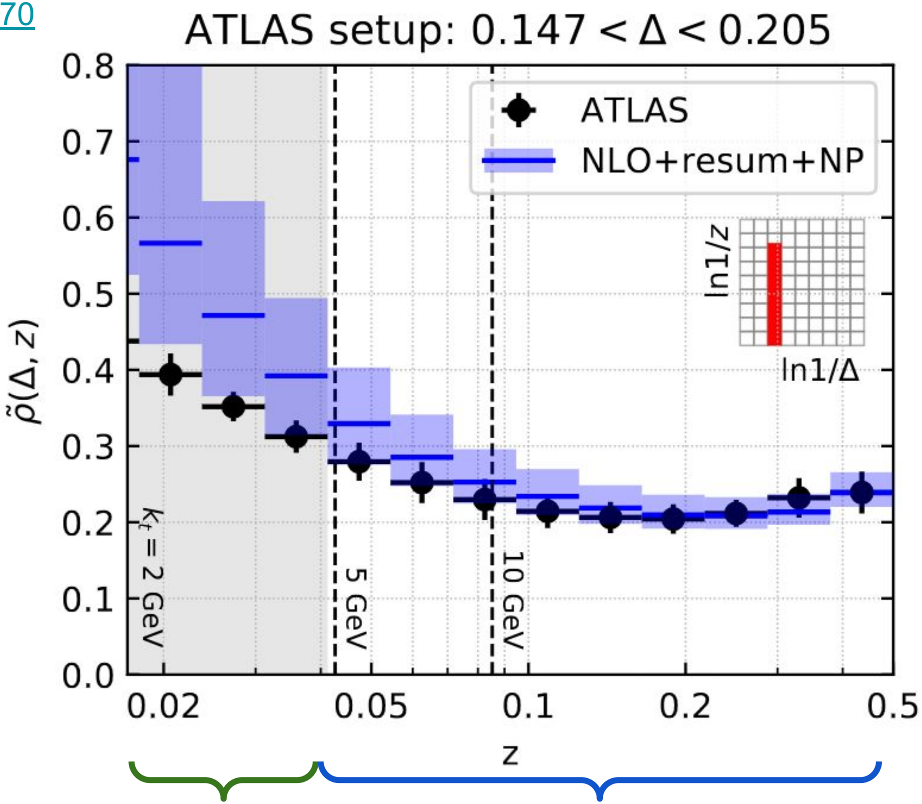
Described well by pQCD calculations (NLO+NLL+NP)

Calculations from A. Lifson, G. Salam, G. Soyez [JHEP10(2020)170]



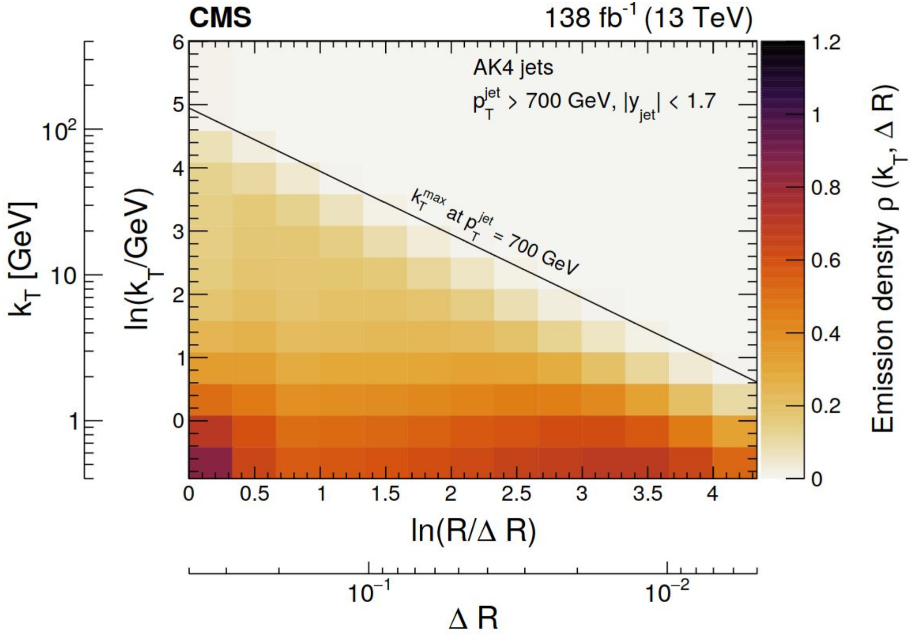
$1 < k_T < 161$ GeV

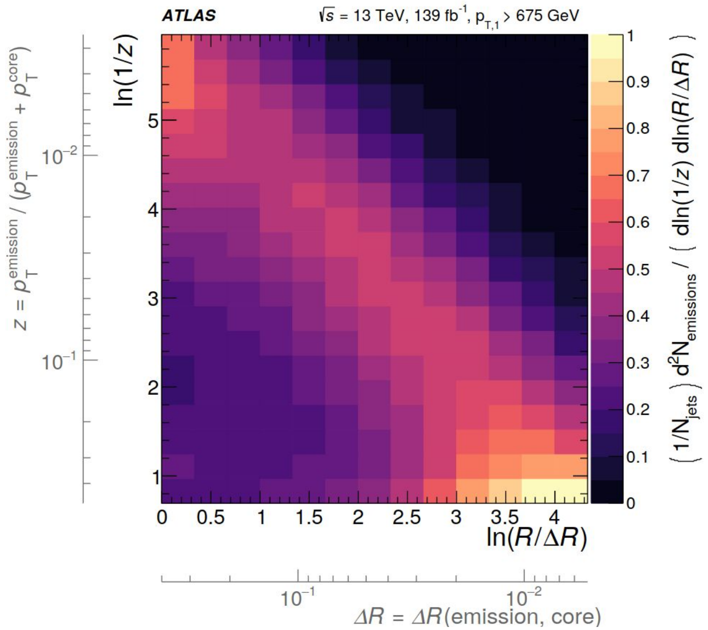
nonperturbative **resummation**


ATLAS setup: $0.147 < \Delta < 0.205$

nonperturbative **resummation**

Complementarity of ATLAS & CMS representations





k_T : hard-scale of 1→2 branching

Shower & hadronization regions separated via "horizontal" cuts

More sensitive to detector smearing effects

z : "core" and "emission" p_T-balance

More resilient to smearing effects (cancels in z ratio)

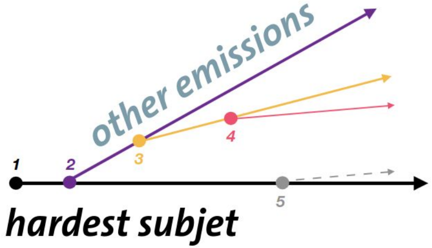
Hard-scale is "fuzzier" ($k_T = z\, p_T^{mother}\, \Delta R$)

ATLAS Lund subjet multiplicities

Proposed by [R. Medves, A. Soto-Ontoso, G. Soyez, JHEP04(2023)104]

[arXiv:2402.13052,](arXiv:2402.13052)
[submitted to PLB]

Count emissions with $k_T > k_{T,cut}$.
Using the ***full*** Lund jet tree **(N_{Lund})**
or for primary Lund emissions **($N^{primary}_{Lund}$)**

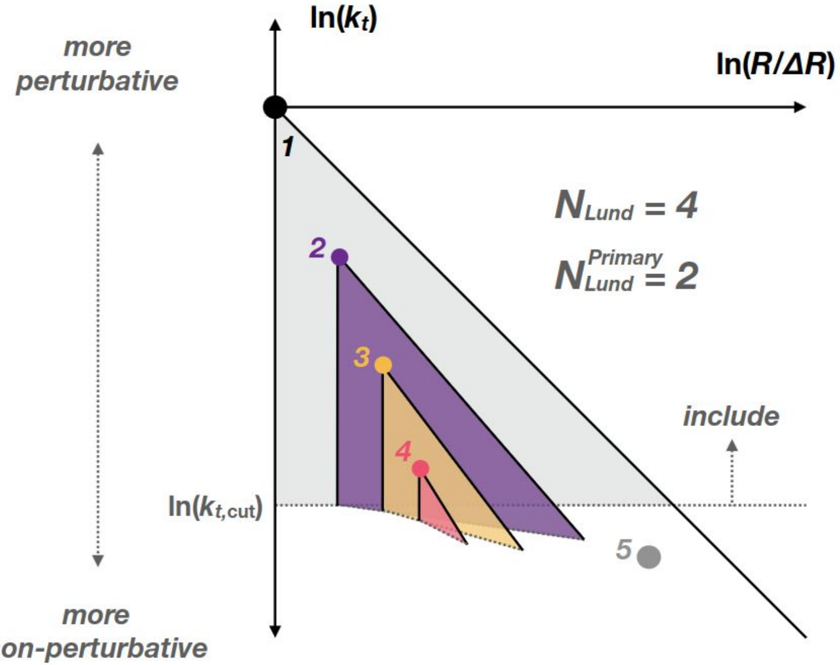


More inclusive observable, closely related to (sub)jet multiplicities at LEP

Charged-particles for substructure,
data-based rescaling for an effective full-particle k_T

$$k_{T,eff} = k_{T,ch} * (p_{T,jet}/p^{ch}_{T,jet})$$

charged-to-full rescaling factor

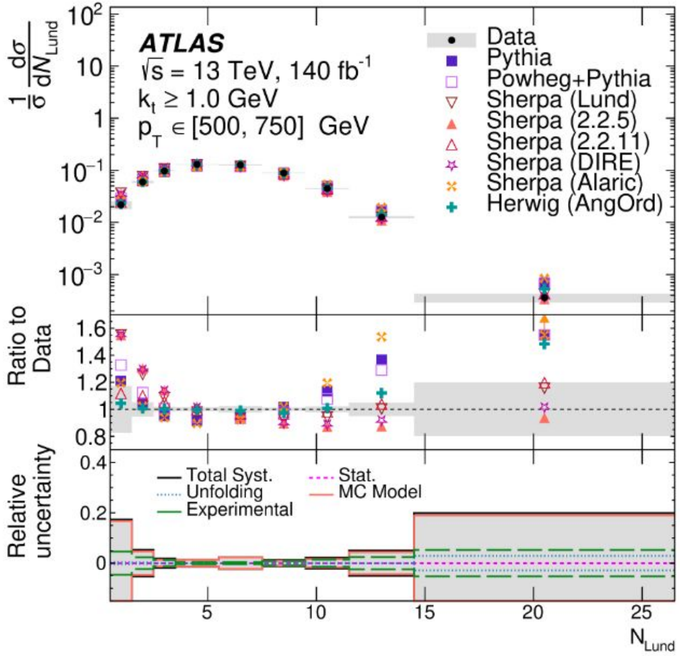


Lund subjet multiplicity distributions

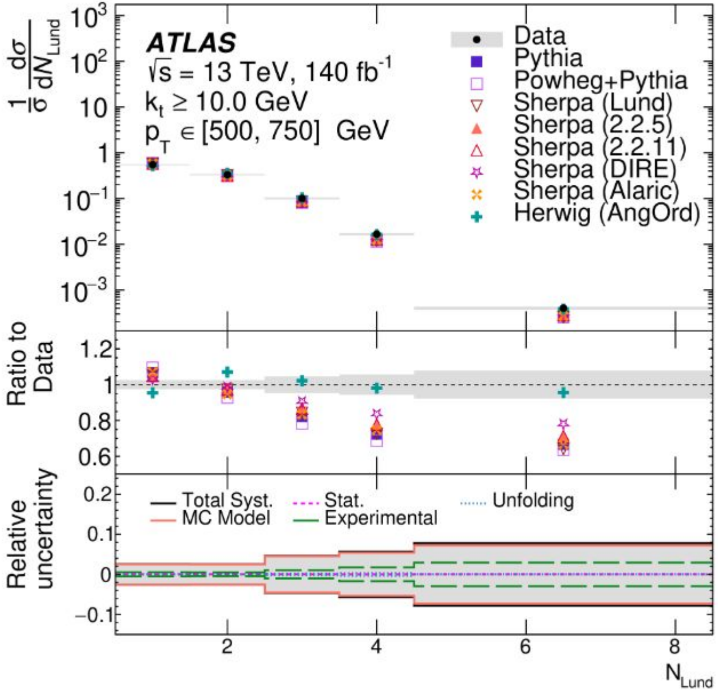
[arXiv:2402.13052, *submitted to PLB*](https://arxiv.org/abs/2402.13052)

Unfolded to the particle level, correcting jet p_T & subjet multiplicity for a given $k_{T,cut}$

$k_{T,cut}$ = 1 GeV (soft)



$k_{T,cut}$ = 10 GeV (hard)



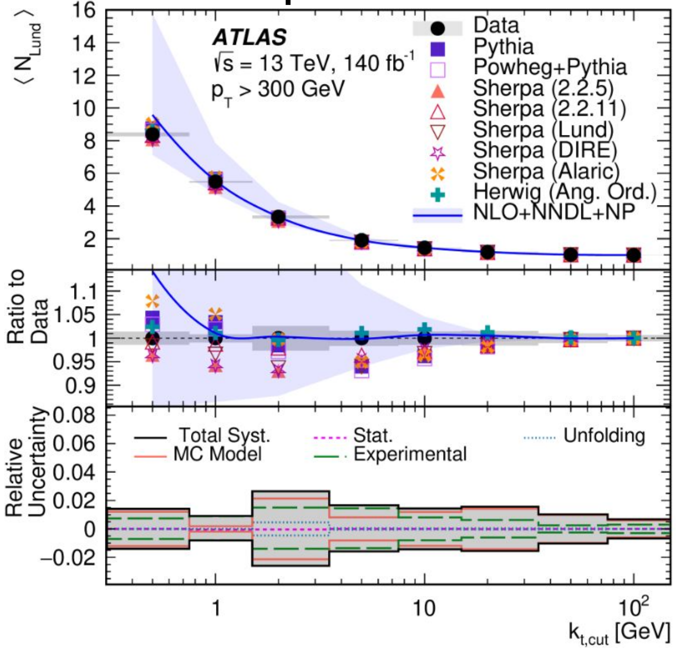
Challenging to describe high-N_{Lund} tails

Sherpa2 describes the $k_{T,cut}$ = 1 GeV category better. Better global description by **Herwig7 angle-ordered**

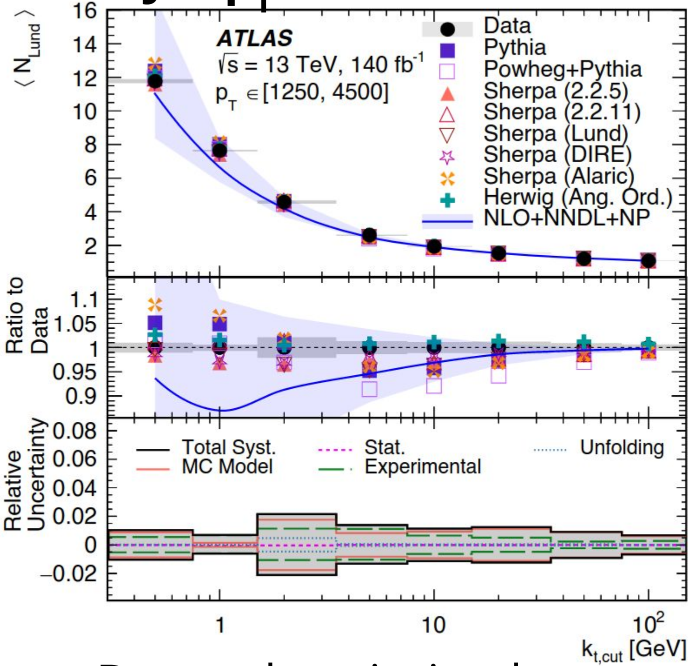
averaged **Lund subjet multiplicities vs $k_{T,\ cut}$**

arXiv:2402.13052,
submitted to PLB

Jet p_T > 300 GeV



Jet p_T > 1250 GeV



In good agreement with pQCD calculation (NLO+NNDL+NP), high-order resummation

Better description by **Herwig7 angle-ordered**

$$\langle N^{(\mathrm{Lund})}(\alpha_s;L)\rangle = \left[\underbrace{h_1(\alpha_s L^2)}_{\mathrm{DL}} + \underbrace{\sqrt{\alpha_s}h_2(\alpha_s L^2)}_{\mathrm{NDL}} + \underbrace{\alpha_s h_3(\alpha_s L^2)}_{\mathrm{NNDL}} + \ldots\right]$$

2024

Other MCs tend to ***undershoot***

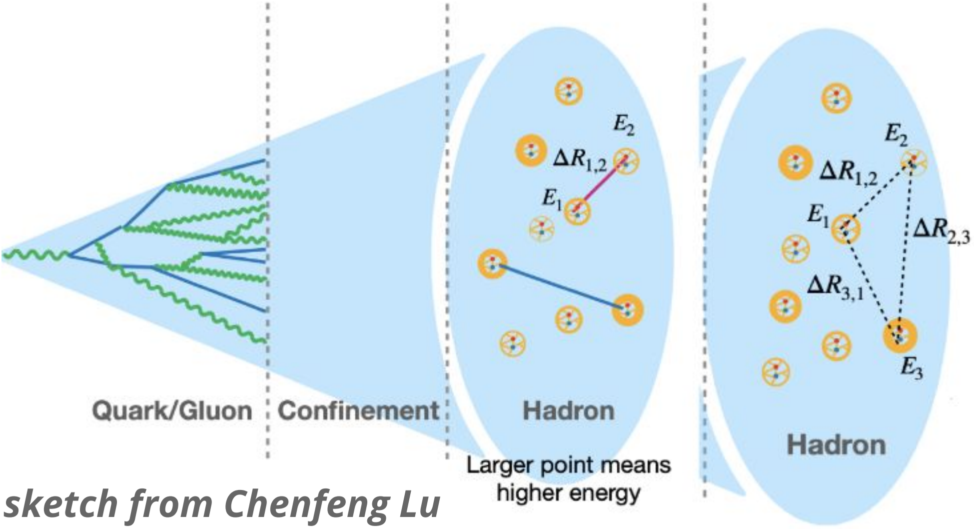
Energy-energy correlators (CMS)

Energy-weighted two-particle angular correlations

arXiv:2402.13864, submitted to PRL

$$C = \frac{d\sigma}{dx_L} = \sum_{i,j}^{n} d\sigma \boxed{\frac{E_iE_j}{E^2}} \delta(x_L - \Delta R_{i,j})$$

$$C = \frac{d\sigma}{dx_L} = \sum_{i,j,k}^{n} d\sigma \boxed{\frac{E_iE_jE_k}{E^2}} \times\ \delta(x_L - \max(\Delta R_{i,j}, \Delta R_{i,k}, \Delta R_{j,k}))$$



sketch from Chenfeng Lu

Angular separation x_L == $\Delta R_{ij} = \sqrt{\Delta y^2 + \Delta\varphi^2}$

Energy weights: soft contributions are penalized, hard contributions are rewarded

Preliminary results
also by ALICE and STAR

Mapping out different stages of jet formation

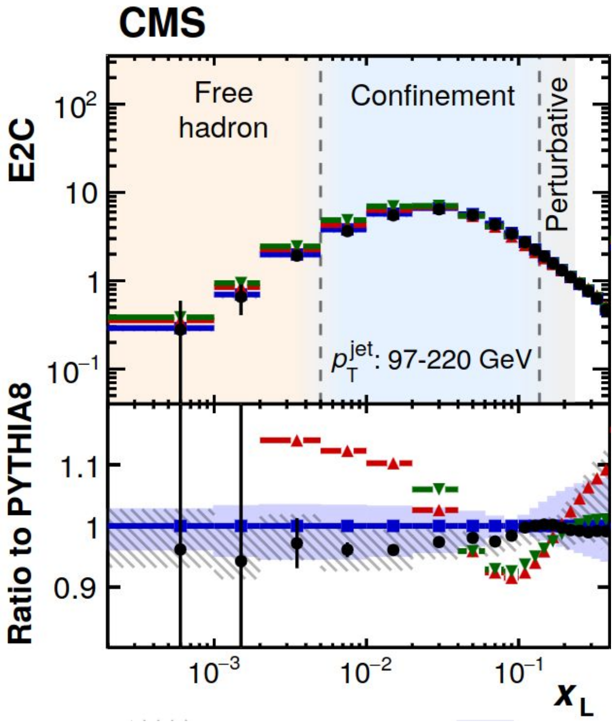
Energy-energy correlators (CMS)

arXiv:2402.13864, submitted to PRL

At least two anti-k_T $R = 0.4$ jets,
$p_{T,\,\mathrm{jet}}$ from 100 GeV – 2 TeV

Distributions unfolded to stable particle level
(x_L, p_T, & energy weights)

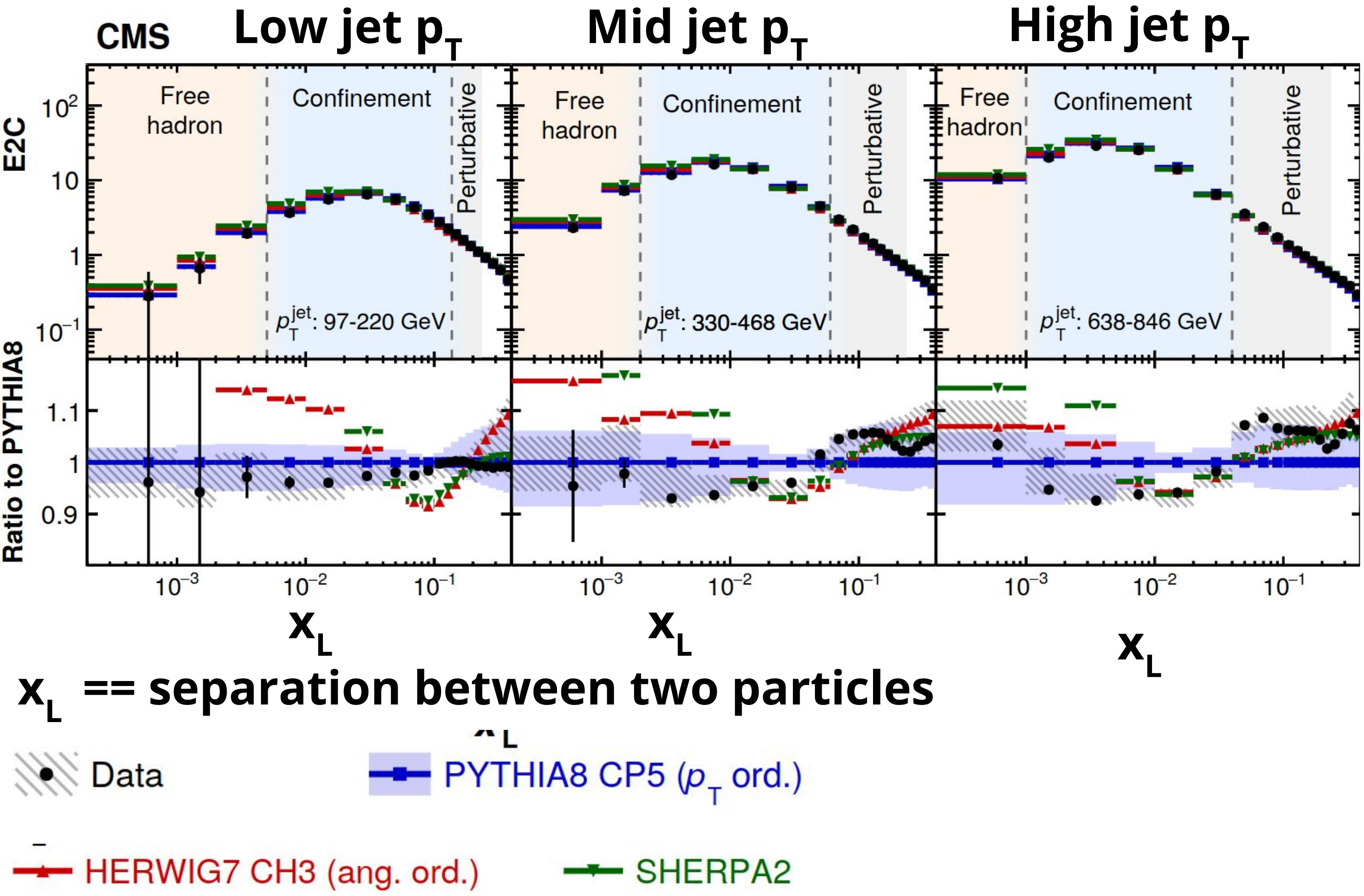
Parton shower and hadronization regimes
(similar to Lund plane factorization)



x_L == angular separation between two particles

Two-point correlators (E2C)

arXiv:2402.13864, submitted to PRL



x_L == separation between two particles

Free hadron region (low x_L)

PYTHIA8 CP5 describes data better than **HERWIG7 CH3**/**SHERPA2**

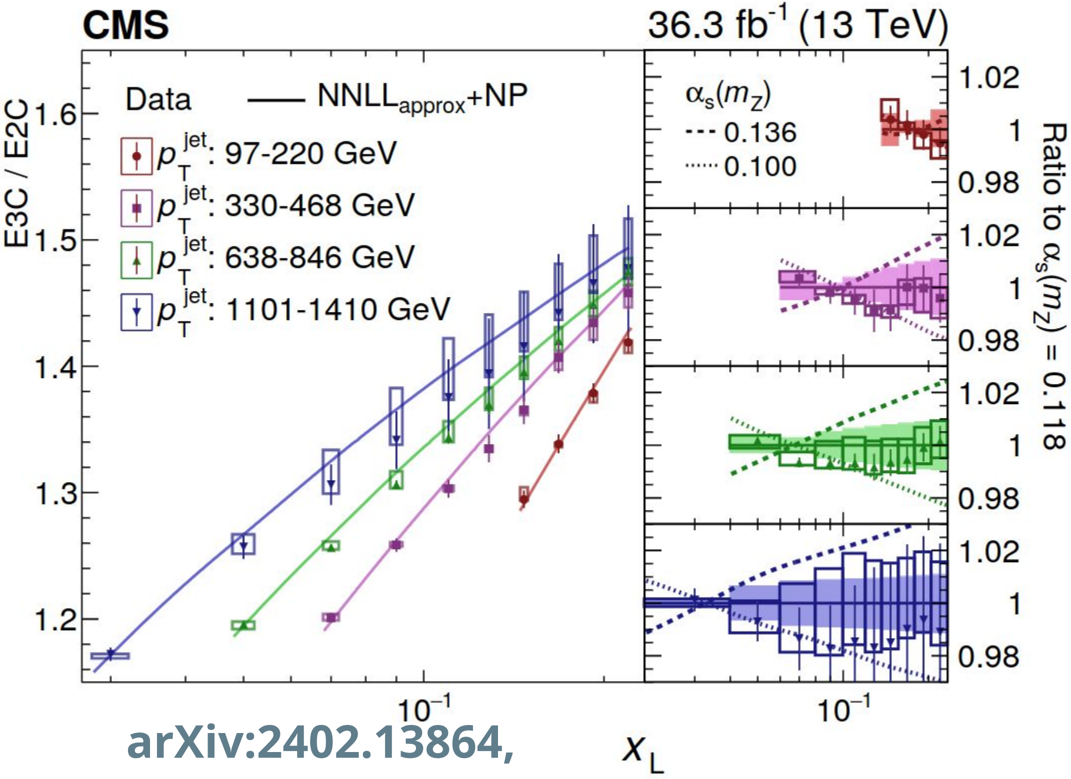
Perturbative region (high x_L)

PYTHIA8 CP5 undershoot data at higher jet p_T

HERWIG7 CH3 & SHERPA describe data better

Extraction of α_s from jet substructure

Ratio of three-point to two-point correlators (**E3C/E2C**)



arXiv:2402.13864, submitted to PRL

Using **NLO+NNLL$_{\text{approx}}$** pQCD calculation with nonperturbative corrections

$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050} \ (\sim 4\ \%)$$

Most precise extraction of $\alpha_s(m_Z)$ with jet substructure

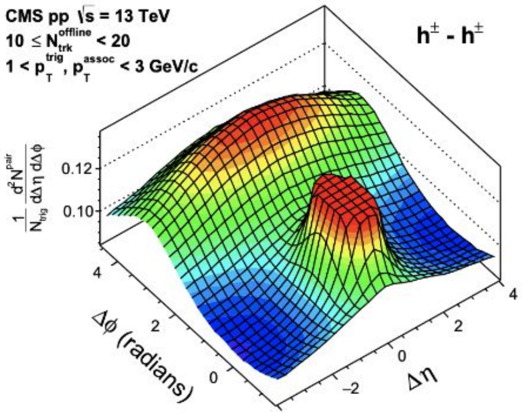
Quark/gluon degeneracy broken in E3C/E2C ratio, allows for breaking “10% uncertainty” barrier

Two-particle angular correlations

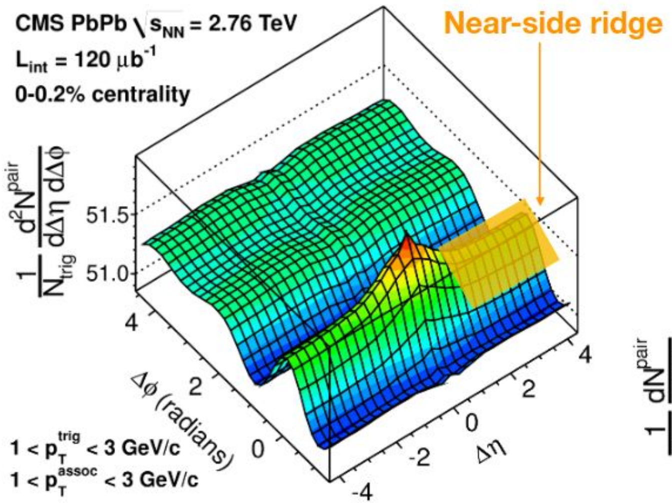
- **Near-side ridge** typical sign of collective behavior
- Fourier harmonics decomposition, nonzero $V_{2\Delta}$ associated with anisotropic expansi

$$\frac{1}{N_{\mathrm{ch}}}\frac{\mathrm{d}N^{\mathrm{pair}}}{\mathrm{d}\Delta\phi} \propto \sum_{n=1}^{\infty} \boxed{V_{\mathrm{n}\Delta}} \cos(\mathrm{n}\Delta\phi)$$

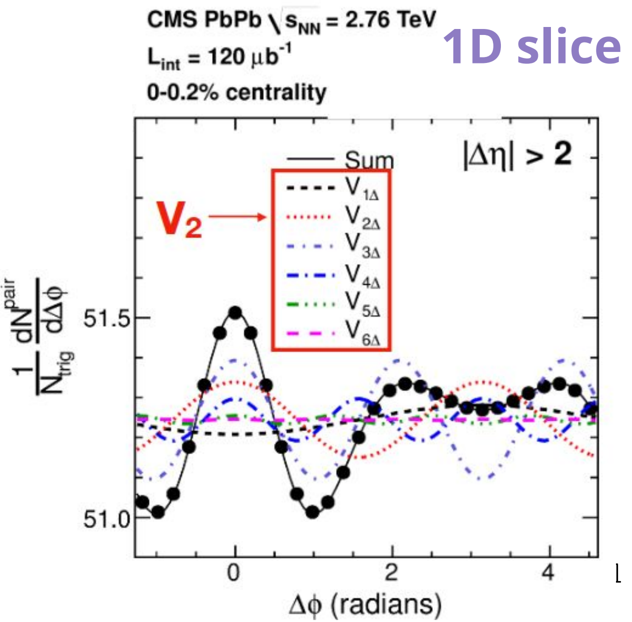
Inclusive pp



PbPb



1D slice



CMS, Phys. Lett. B 765 (2017) 193

What about smaller systems?

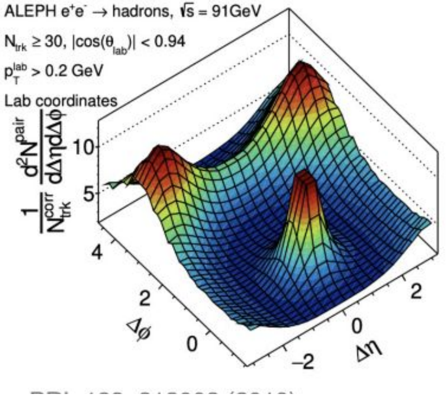
Unexpected nonzero v_2 in high-multiplicity pp and pPb by CMS (*PLB* 765 (2017) 193, *PLB* 718 (2013) 795)

→QGP droplet formation or emergent property of high-multiplicity QCD processes?

Since then, searches pushing the boundaries towards even smaller systems

e^+e^-

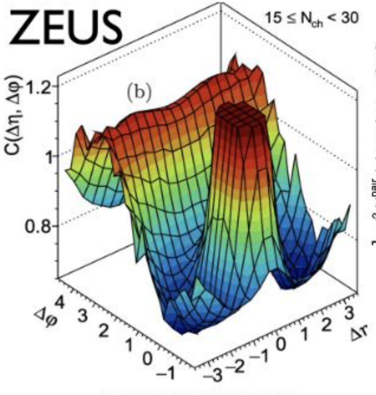
N_{ch}~30



PRL 123 212002 (2019)

ep

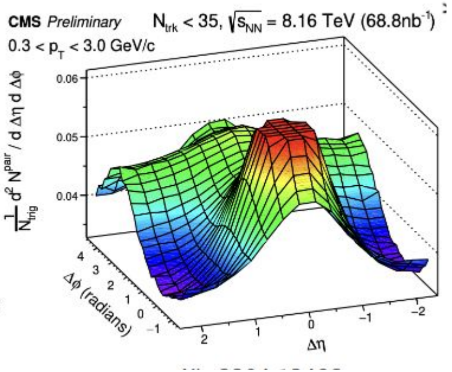
N_{ch}~30



JHEP 04 (2020) 070

γp

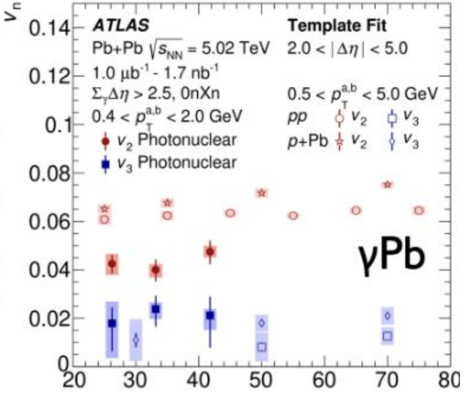
N_{ch}~20



PLB 844 (2023) 137905

γPb

N_{ch}~40



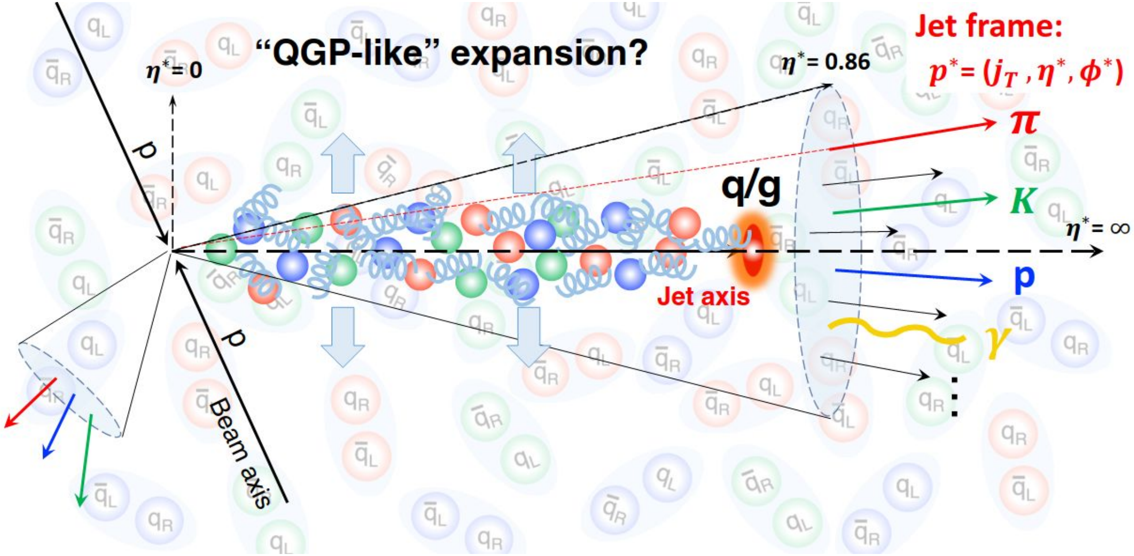
PRC, 104 014903 (2021)

Search for intrajet collective behavior in CMS

arXiv:2312.17103, submitted to PRL

$p_{T,jet}$ >550 GeV, anti-k_T R = 0.8, $|\eta^{jet}|$ < 1.6

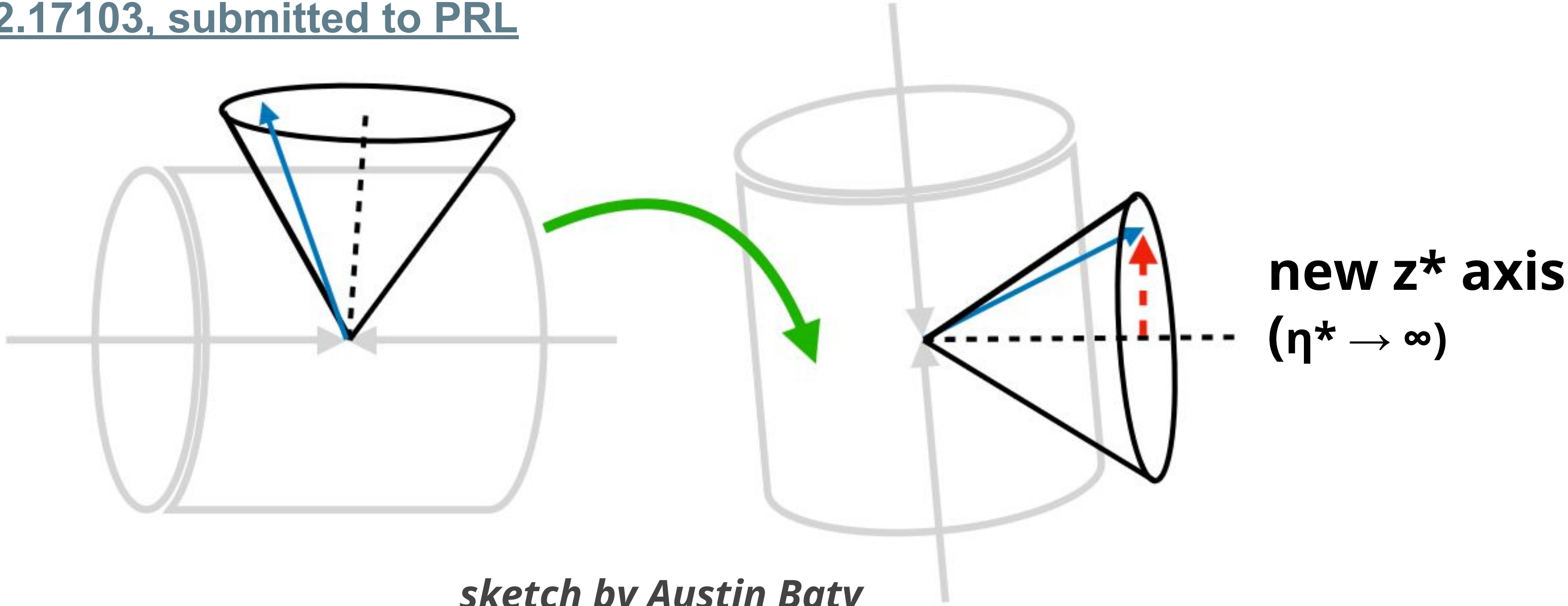
Charged-particle constituents used for two-particle correlations
(**pileup mitigation + low $p_{T,ch}$**)



A. Baty, P. Gardner, W. Li,
Phys. Rev. C 107 (2023) 064908

Rotated reference frame such that z* axis is aligned with jet axis

arXiv:2312.17103, submitted to PRL

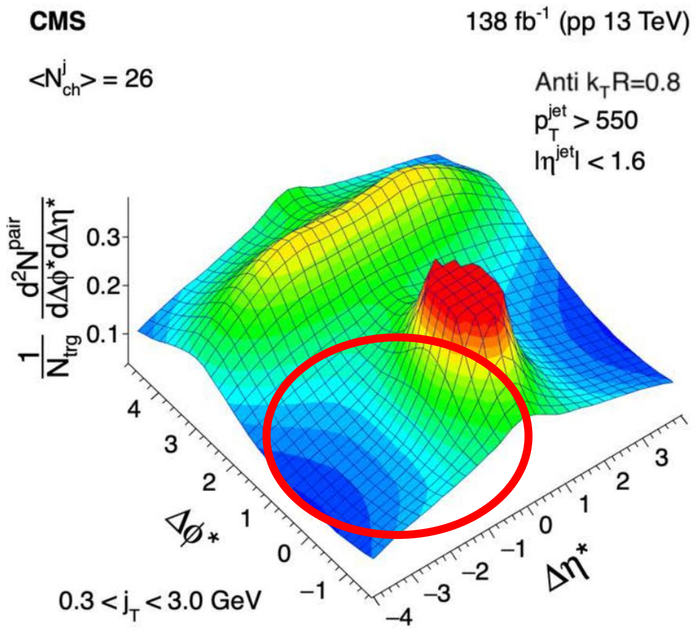


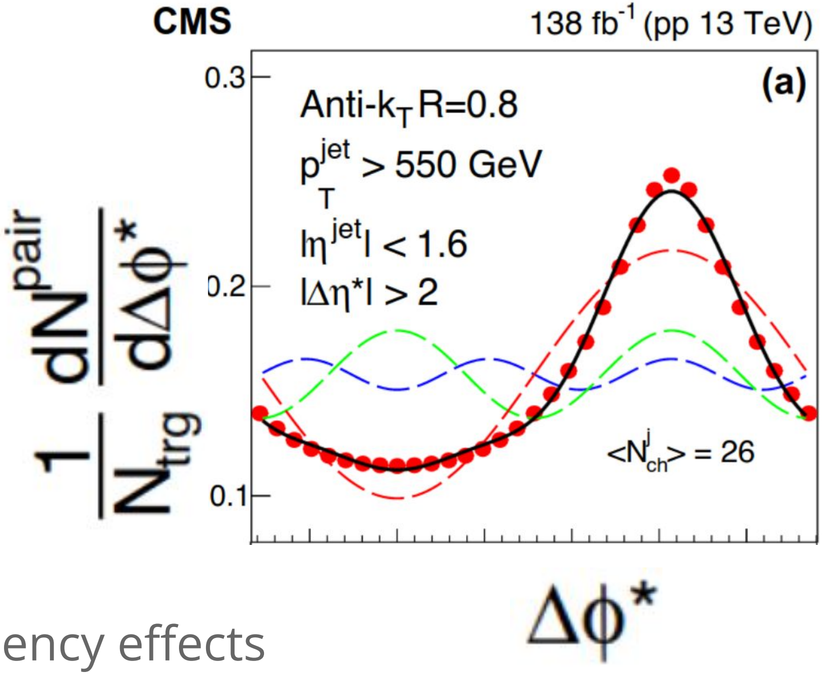
sketch by Austin Baty

Particle correlations using φ* and η* coordinates (restricted to $0.86 < |\eta^*| < 5$), transverse momentum relative to the jet axis j_T ($0.3 < j_T < 3$ GeV)

inclusive N_{ch} category

$$\frac{1}{N^{j}_{\mathrm{ch}}}\frac{\mathrm{d}N^{\mathrm{pair}}}{\mathrm{d}\Delta\phi^{*}} \propto \sum_{n=1}^{\infty} \boxed{V_{\mathrm{n}\Delta}} \cos(\mathrm{n}\Delta\phi^{*})$$





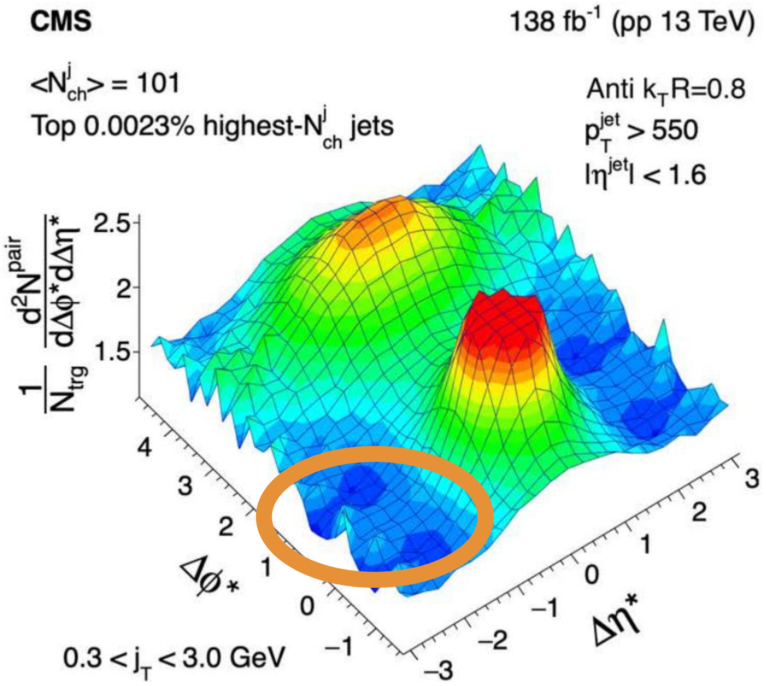
2D distributions corrected for acceptance/efficiency effects

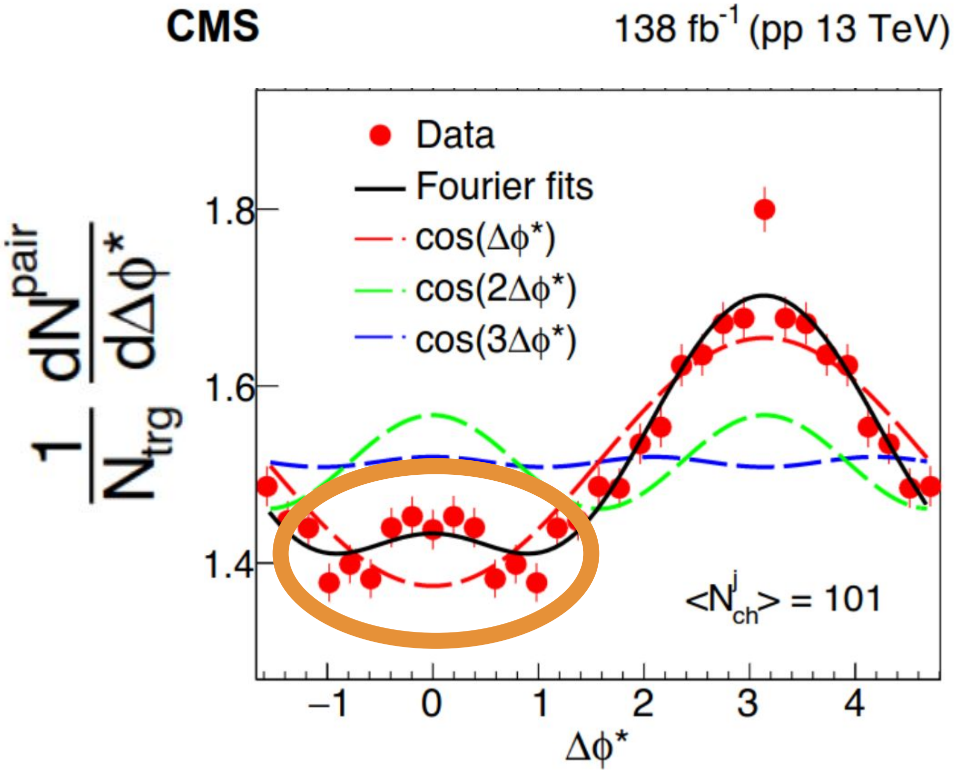
No near-side ridge at Δφ* ~ 0

arXiv:2312.17103, submitted to PRL

high N_{ch} category

arXiv:2312.17103, submitted to PRL

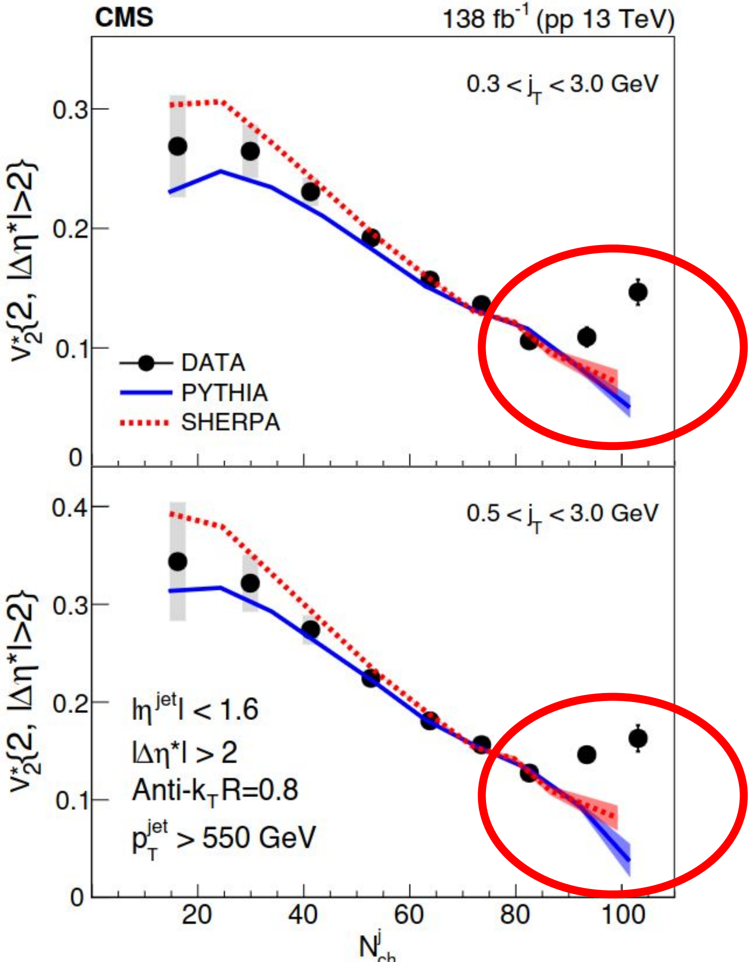




Near-side ridge-like structure at Δφ* ~ 0

single-particle $v_2 = \sqrt{V_2}$ vs N_{ch}

arXiv:2312.17103, submitted to PRL



Nonzero v_2 reproduced by **SHERPA2, PYTHIA8 CP5** up to $N_{ch} \sim 80$

Increasing v_2 with large N_{ch} not expected by these MC predictions

Summary

- Mapping out weakly- and strongly-coupled regimes via the **Lund jet plane picture** and with **N-point energy correlators**

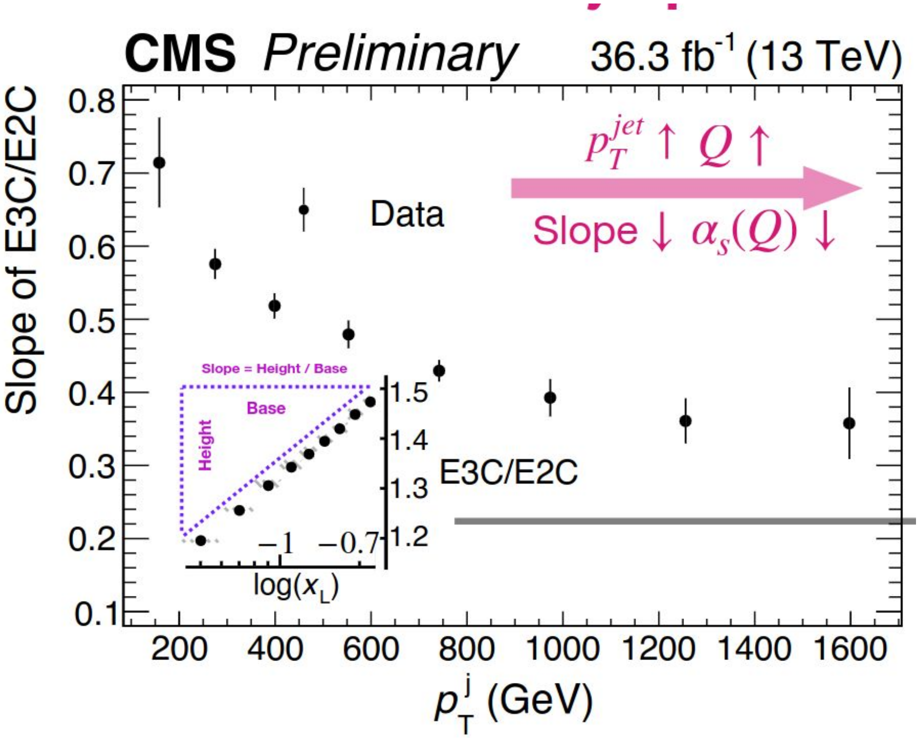
- Collective-like behavior in jets with high-N_{ch}

  Example of synergy between heavy-ion & high-energy communities

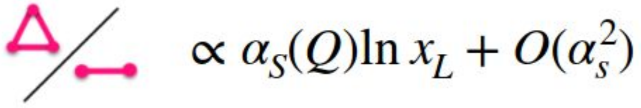
- Other LHC substructure results can be found here

E3C/E2C sensitive to running α_s

CMS-PAS-SMP-22-015



At LL, slope of E3C/E2C ratio sensitive to α_S(Q)

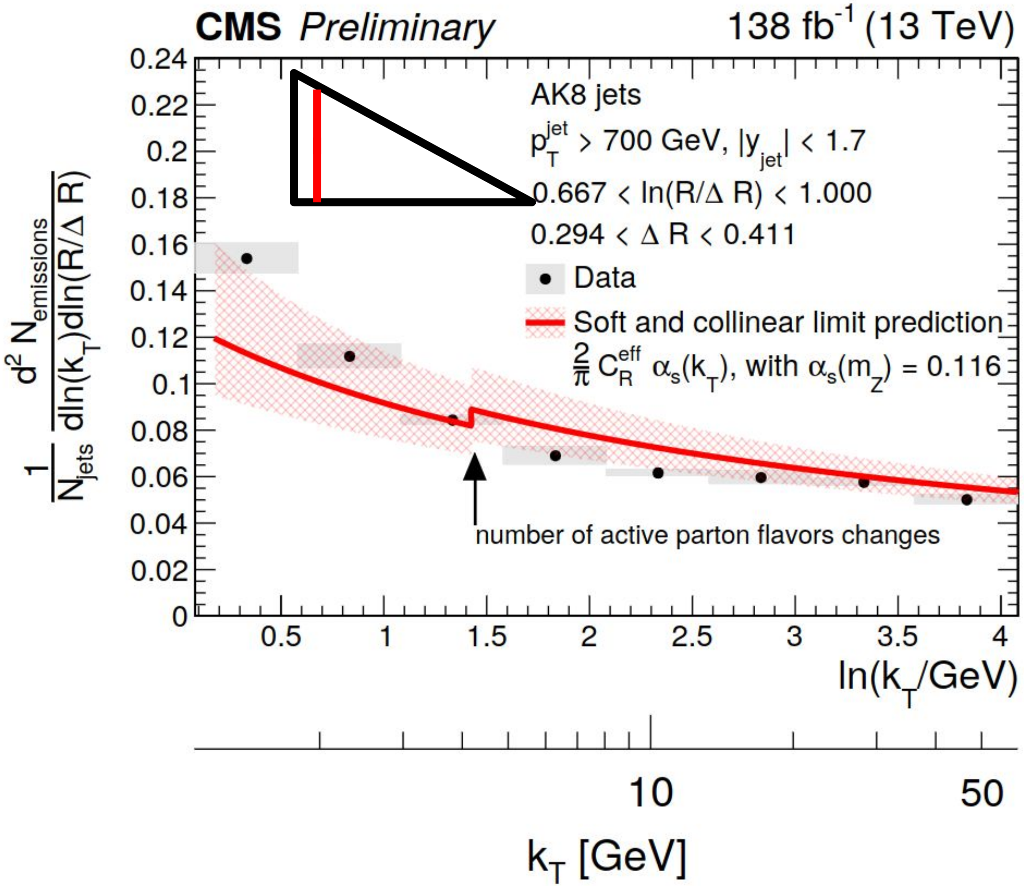


$$\propto \alpha_S(Q) \ln x_L + O(\alpha_s^2)$$

Quark/gluon fraction sensitivity is reduced in the E3C/E2C ratio, without losing sensitivity to α_S(Q) running

Running of α_s in the jet shower

CMS-PAS-SMP-22-007



Recall LO pocket formula for Lund density:

$$\frac{1}{N^{\text{jets}}} \frac{\mathrm{d}^2 N_{\text{emissions}}}{\mathrm{d}\ln(k_T)\mathrm{d}\ln(R/\Delta R)} \simeq \frac{2}{\pi} C_R \alpha_s(k_T)$$

Running $\alpha_s(k_T)$ from few GeV to ~60 GeV qualitatively describes the data

(Assuming q/g fractions from PYTHIA8)

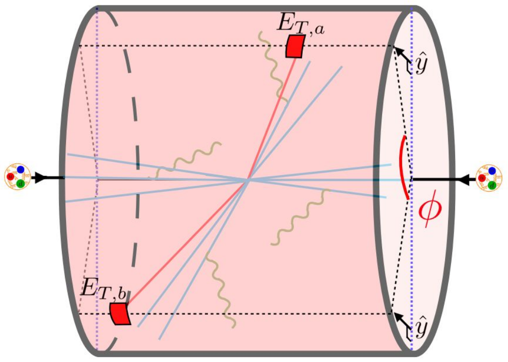
A. Larkoski, G. Salam, J. Thaler,
JHEP06(2013)108

energy-weighted cross section

$$\frac{d\sigma_{\mathrm{EEC}}}{dR_{\mathrm{L}}} = \sum_{i,j} \int d\sigma(R'_{\mathrm{L}}) \frac{p_{\mathrm{T},i}\, p_{\mathrm{T},j}}{p^2_{\mathrm{T,jet}}} \delta(R'_{\mathrm{L}} - R_{\mathrm{L},ij})$$

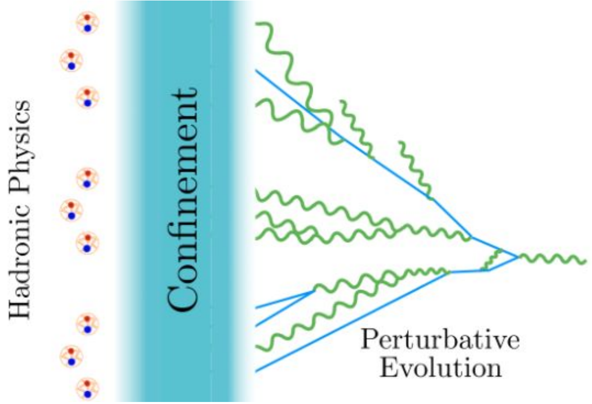
$$R_{\mathrm{L}} = \sqrt{\Delta\varphi^2_{ij} + \Delta\eta^2_{ij}}$$

Observable connected to conformal field theory approaches



sketch from Ian moult

$R_L << \Lambda_{QCD}/p_{T,jet}$ $\quad$ $R_L >> \Lambda_{QCD}/p_{T,jet}$



Soft particle pairs are "penalized" with small energy weights (typically at small R_L)

Hard radiation is "rewarded" with larger weights (typically at large R_L)

No jet grooming to suppress soft physics is required

$$\frac{d\sigma_{\mathrm{EEC}}}{dR_{\mathrm{L}}} = \sum_{i,j} \int d\sigma(R'_{\mathrm{L}}) \frac{p_{\mathrm{T},i}\, p_{\mathrm{T},j}}{p^2_{\mathrm{T,jet}}} \delta(R'_{\mathrm{L}} - R_{\mathrm{L},ij})$$

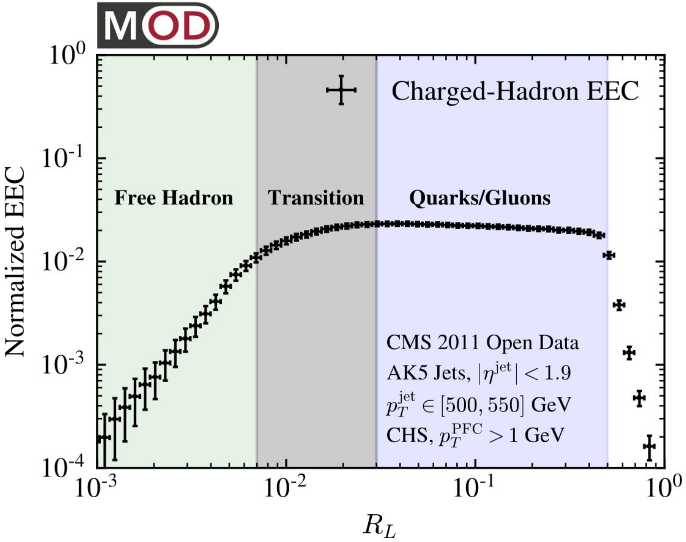
[P. Komiske, I. Moult, J. Thaler, H.X. Zhu, PRL 130, 051901](#)

How to measure these experimentally?

1. For a given pair of jet constituents, fill a histogram with weight = $p_{T,i}\, p_{T,j}/p^2_{T,\mathrm{jet}}$ at entry $R_L = \Delta R_{ij}$

2. Iterate step 1 for all possible pairs in the jet (there will be multiple histogram entries per jet)

3. Do this for all jets, and you obtain an energy-weighted two-particle correlation distribution



Proof of concept using CMS OpenData

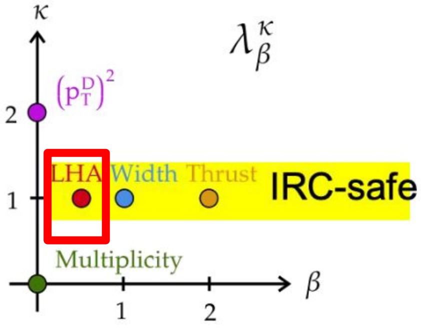
Access to scaling properties of QCD

Generalized angularities in dijet and Z+jet events

CMS, *arXiv:2109.03340*, ***JHEP 01 (2022) 188***

$$\lambda_{\beta}^{\kappa} = \sum_{\mathrm{i}\in\mathrm{jet}} z_{\mathrm{i}}^{\kappa} \left(\frac{\Delta R_{\mathrm{i}}}{R}\right)^{\beta} \quad z_i \equiv \frac{p_{Ti}}{\sum_{j\in\mathrm{jet}} p_{Tj}}$$

κ & β are parameters set by user

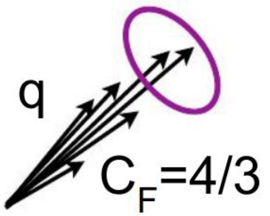


Will show a specific angularity (LHA)

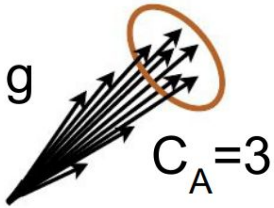
Sensitive to quark vs gluon differences
(subset of them are IRC-safe)

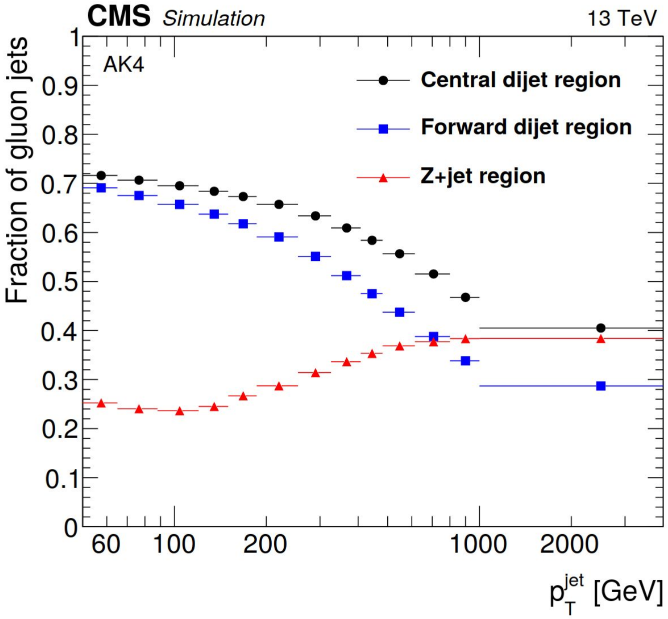
JHEP 1707 (2017) 091

Z+jet (quark-like)



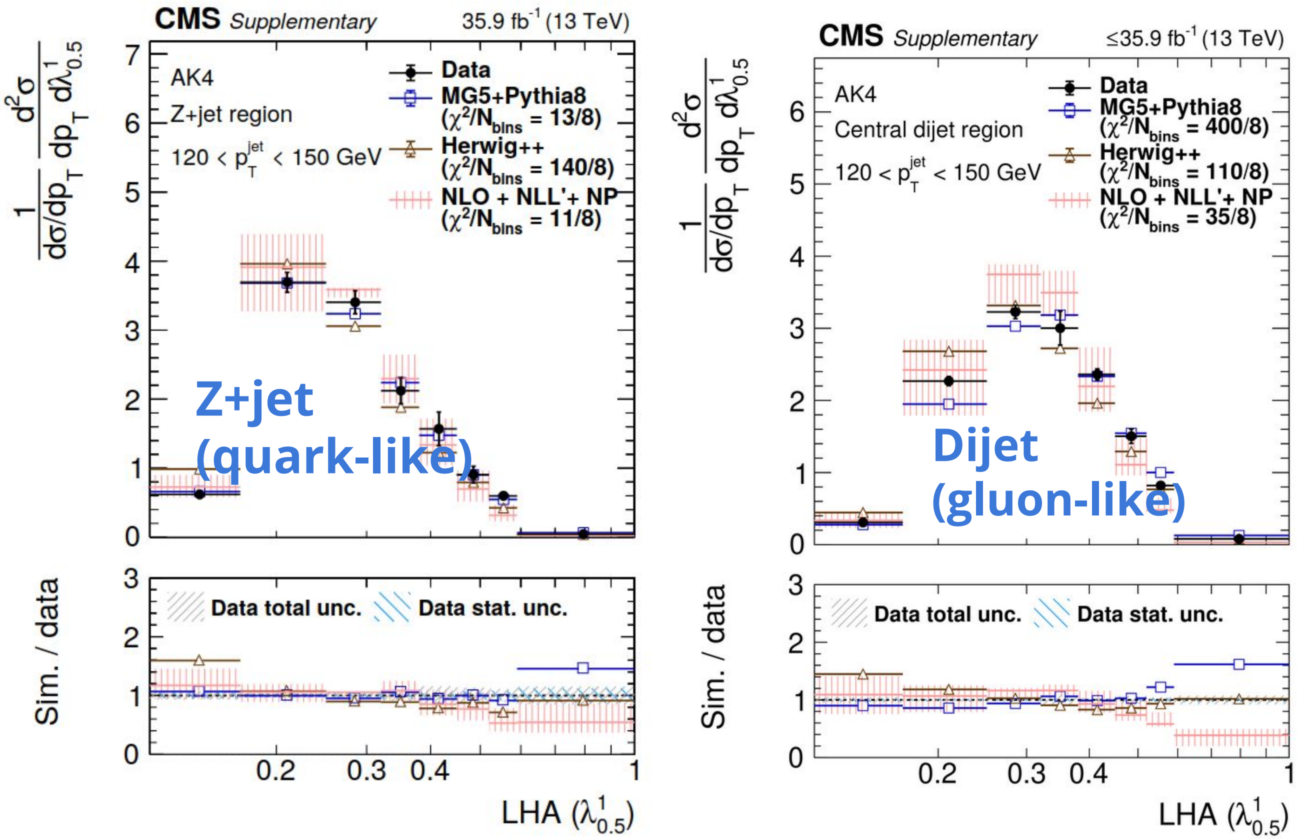
Dijet (gluon-like)





Ungroomed vs groomed with z_{cut} = 0.1, β_{SD} = 0,
R = 0.4 vs R =0.8
charged-only vs charged+neutrals

JHEP 01 (2022) 188



Z+jet (quark-like)

Dijet (gluon-like)

Jets in dijets (gluon-like) broader than Z+jets (quark-like)

More challenging to describe **gluon-enriched jets (dijet)**

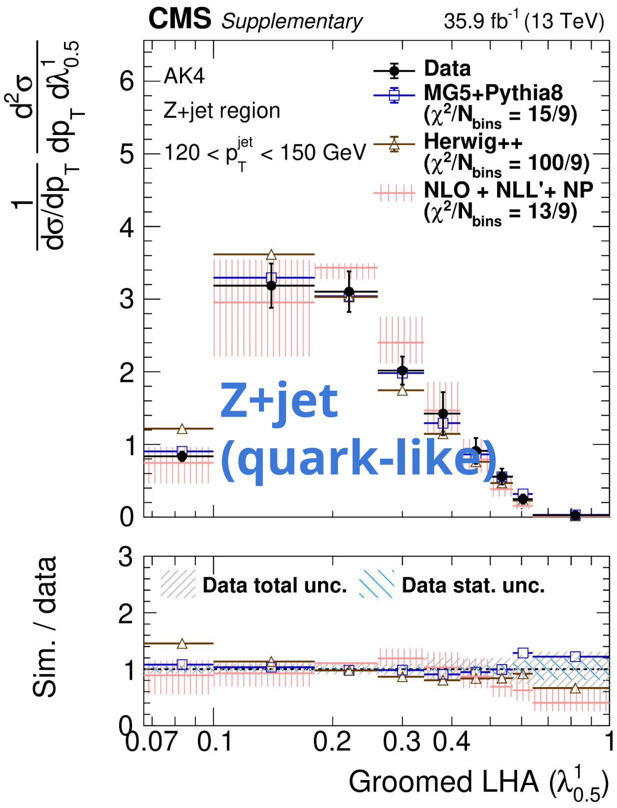
κ = 0.5, β = 1

$$\lambda^{\kappa}_{\beta} = \sum_{\mathrm{i}\in\mathrm{jet}} z_{\mathrm{i}}^{\kappa} \left(\frac{\Delta R_{\mathrm{i}}}{R}\right)^{\beta} \qquad z_i \equiv \frac{p_{Ti}}{\sum_{j\in\mathrm{jet}} p_{Tj}}$$

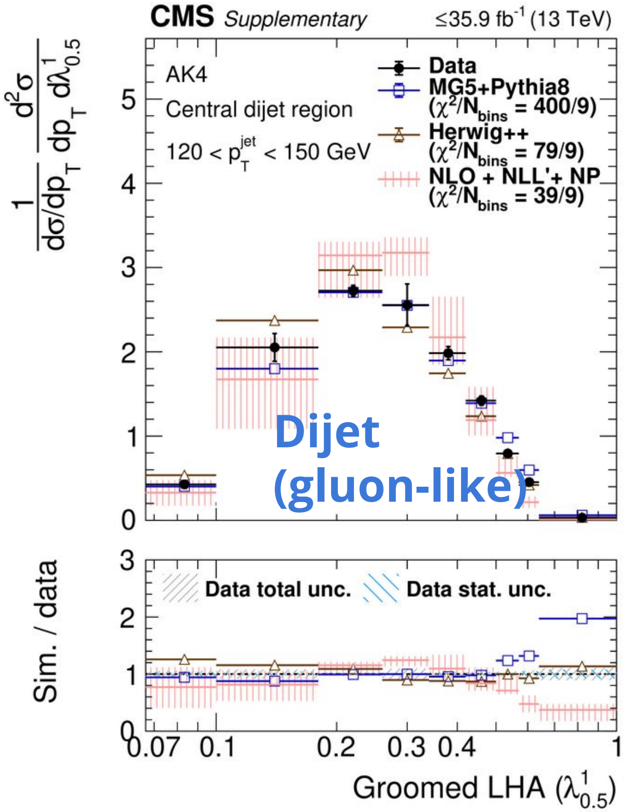
pQCD calculations D. Reichelt, S. Caletti, O. Fedkevych, S. Marzani, S. Schumann, G. Soyez, JHEP 03 (2022) 131

Groomed Les Houches Angularity in Z-jet and dijet events

JHEP 01 (2022) 188



Z+jet (quark-like)



Dijet (gluon-like)

Soft-drop grooming (z_{cut} = 0.1, β_{sd} = 0) to remove soft and wide-angle radiation

More challenging to describe **gluon-enriched jets**

Mismodeling at large LHA increase after removing soft&wide-angle radiation

$\kappa = 0.5, \beta = 1$

$$\lambda^\kappa_\beta = \sum_{i\in\text{jet}} z_i^\kappa \left(\frac{\Delta R_i}{R}\right)^\beta \qquad z_i \equiv \frac{p_{Ti}}{\sum_{j\in\text{jet}} p_{Tj}}$$

pQCD calculations D. Reichelt, S. Caletti, O. Fedkevych, S. Marzani, S. Schumann, G. Soyez, JHEP 03 (2022) 131

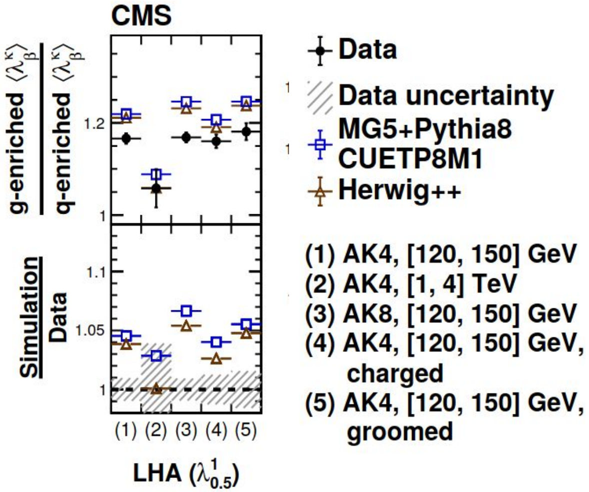
Dijet/Z+jet ratio (g-enriched/q-enriched)

CMS, [arXiv:2109.03340](https://arxiv.org/abs/2109.03340), *JHEP 01 (2022) 188*

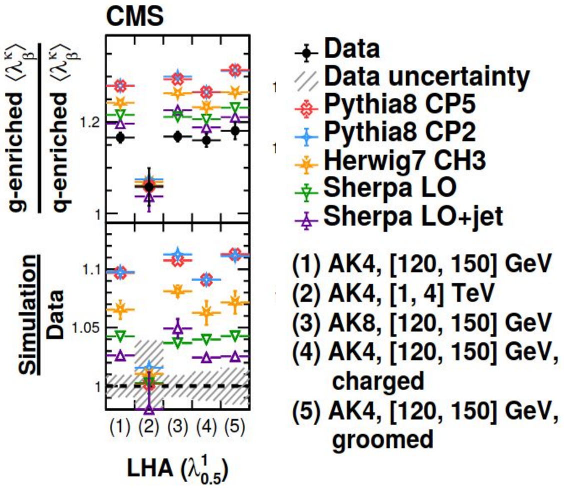
- uncertainties partially cancel in dijet/Z+jet ratio
- MC simulations overestimate g-enriched/q-enriched ratio
- g-enriched / q-enriched ratio is better modelled with “old” PYTHIA8/HERWIG7 tunes

gluon-LHA/quark-LHA > 1
(mostly due to $C_A > C_F$)

“old” CMS tunes
(<~ 5% off)



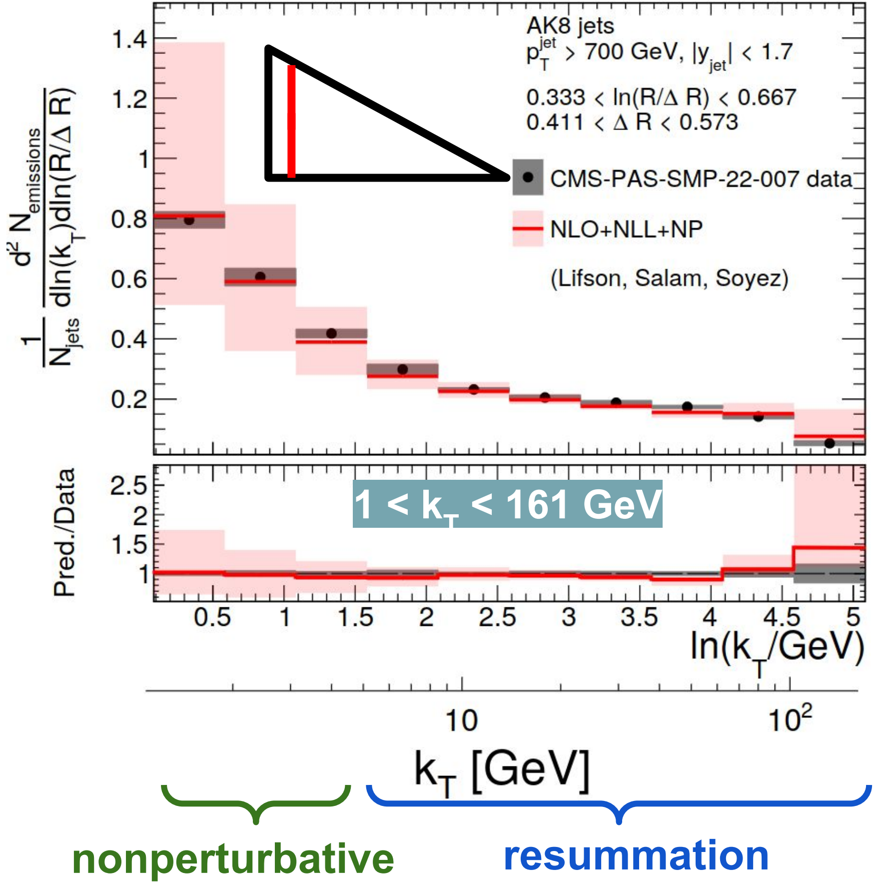
“new” CMS tunes
(up to ~10% off)

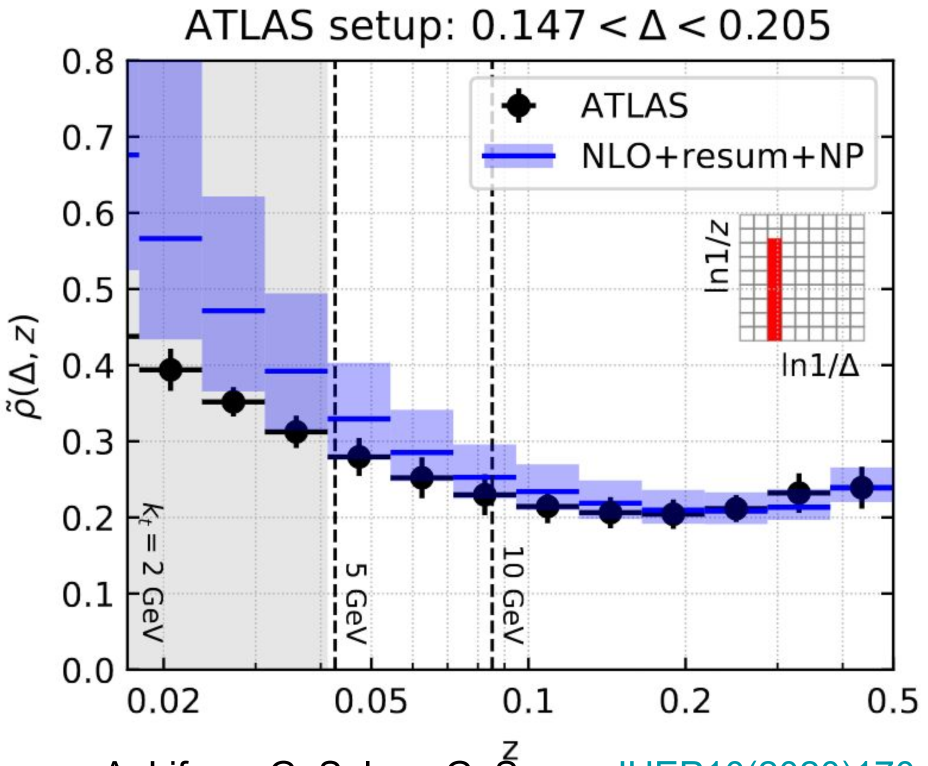


full summary plot in backup
(other angularities)

Comparison to pQCD analytical calculations (NLO+NLL+NP)

Calculations based on JHEP10(2020)170



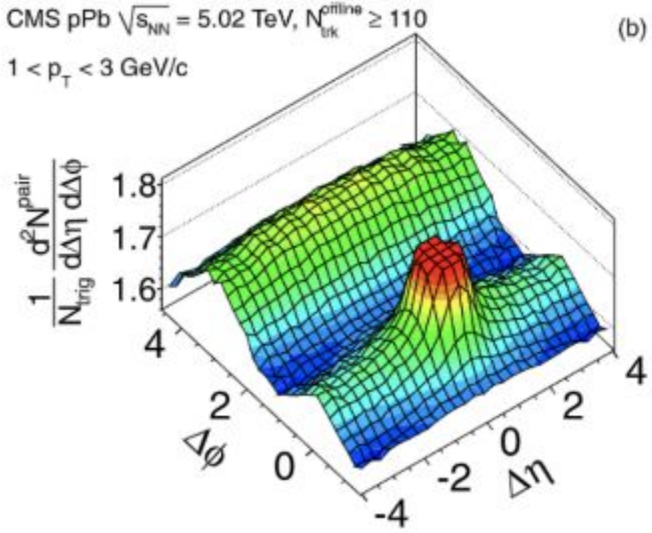


A. Lifson, G. Salam, G. Soyez JHEP10(2020)170

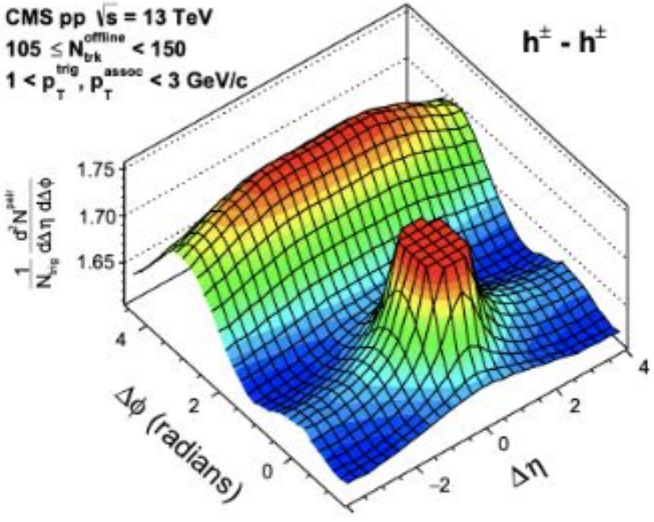
data from ATLAS Lund plane,
PRL 124, 222002 (2020)

Ridge in pPb and high-multiplicity pp

pPb

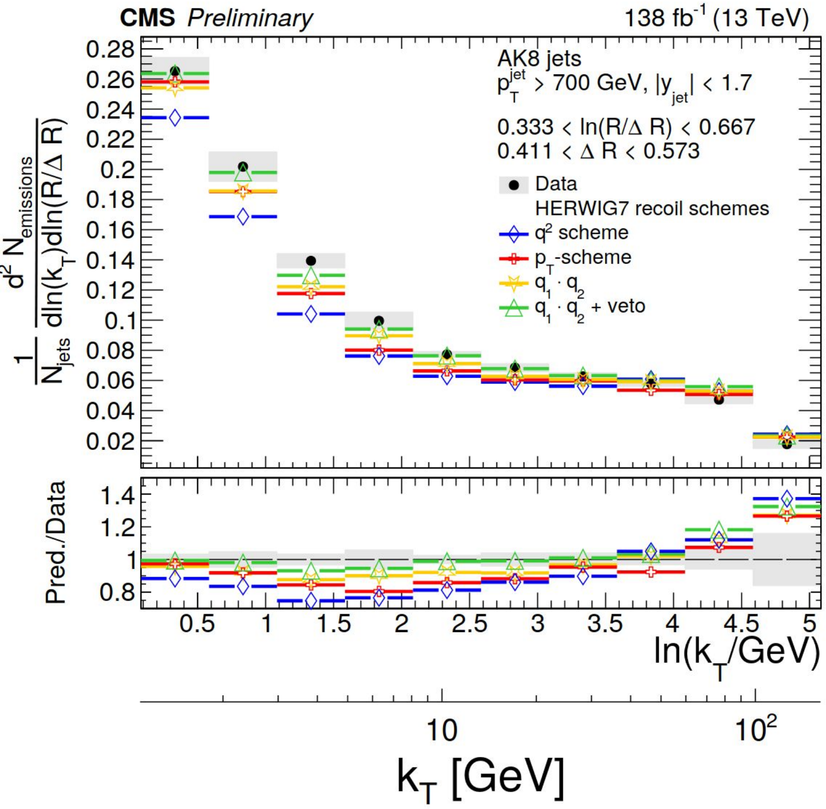


High-multiplicity pp

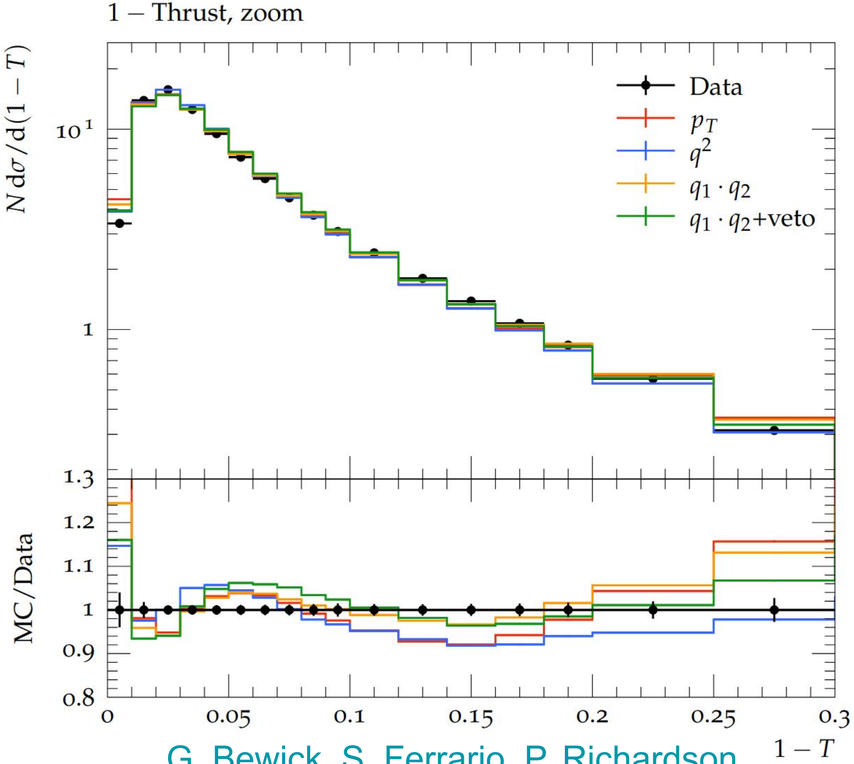


Sensitivity to recoil scheme choice, **important ingredient to reach NLL accuracy**

high-p_T quark and gluon jets



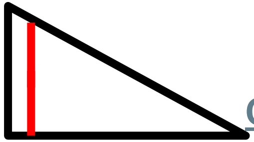
Thrust in e^+e^- at Z mass pole



G. Bewick, S. Ferrario, P. Richardson, M. H. Seymour, arXiv:1904.11866

LJP data favors **q_1q_2+veto** scheme, consistent with trends in event shape variables at LEP

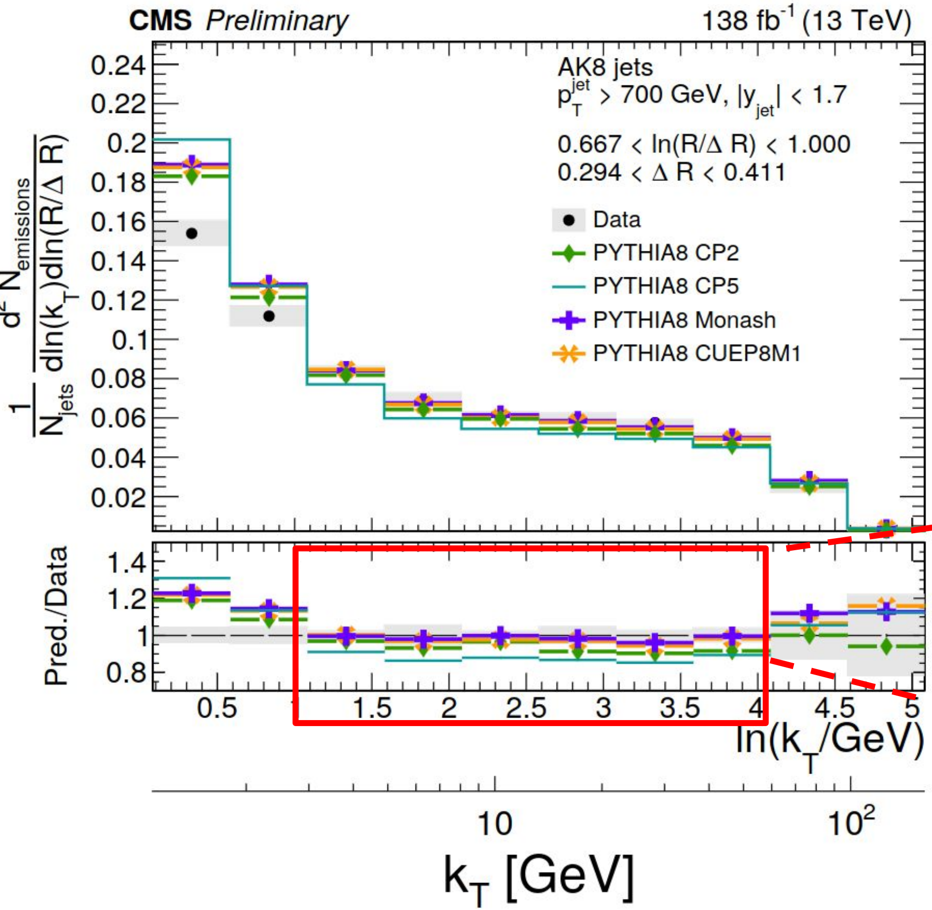
Large angle emissions



$R = 0.8$ Most important difference between PY8 tunes is α_S^{FSR}

CMS-PAS-SMP-22-007

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



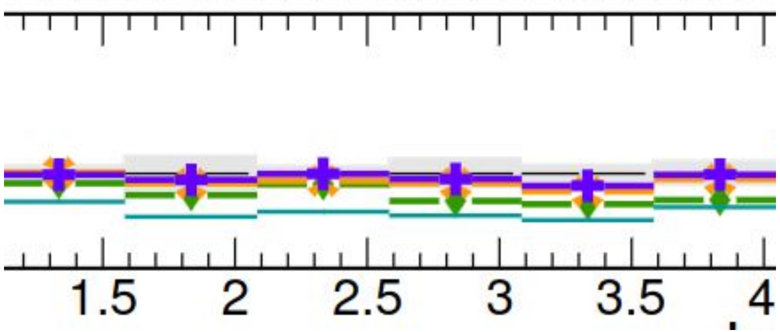
Monash/CUEP8M1: $\alpha_S^{FSR}(m_Z) = 0.1365$ **(best description)**

CP2: $\alpha_S^{FSR}(m_Z) = 0.130$

CP5: $\alpha_S^{FSR}(m_Z) = 0.118$

LJP data can be used to constrain $\alpha_S^{FSR}(m_Z)$ for MC tuning

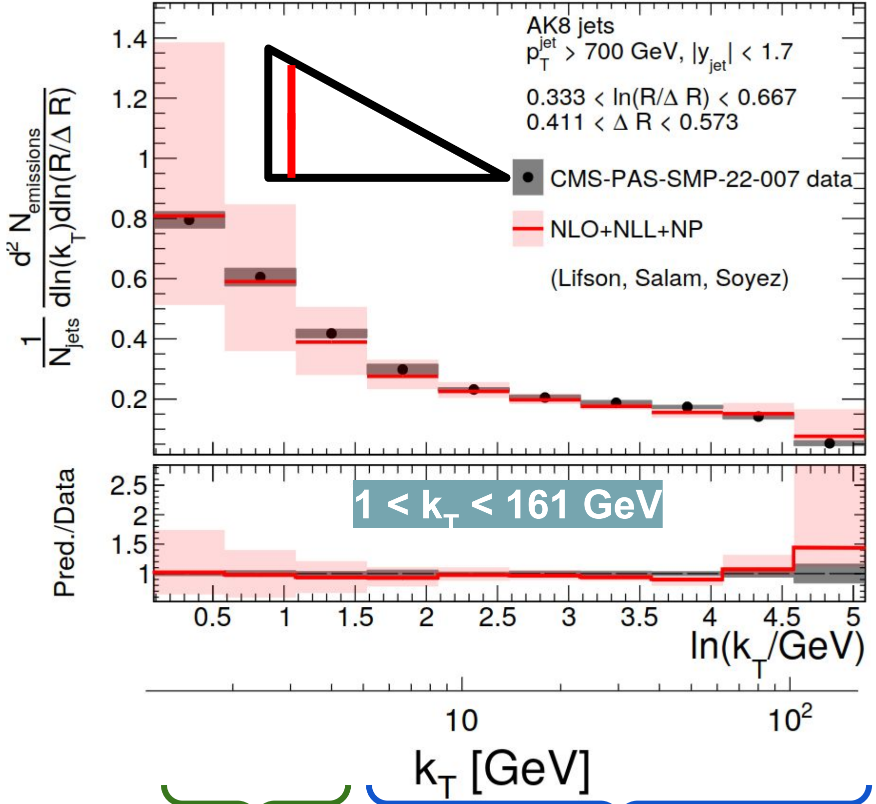
~15%



k_T between 3 – 50 GeV

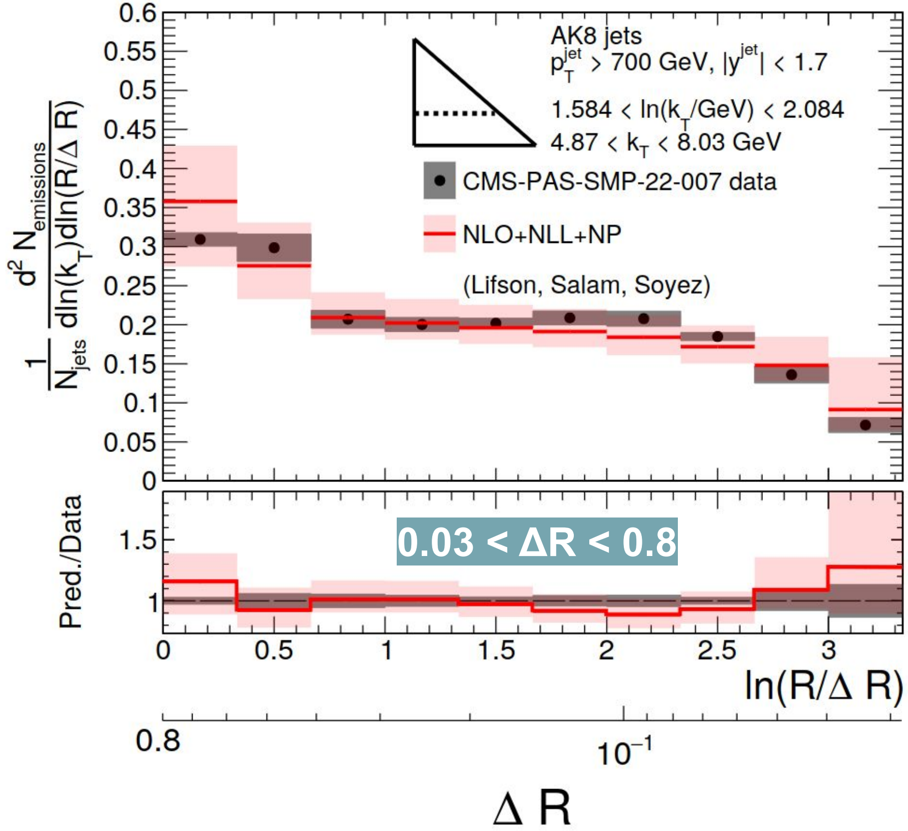
pQCD analytical calculations (NLO+NLL+NP)

based on A. Lifson, G. Salam, G. Soyez JHEP10(2020)170



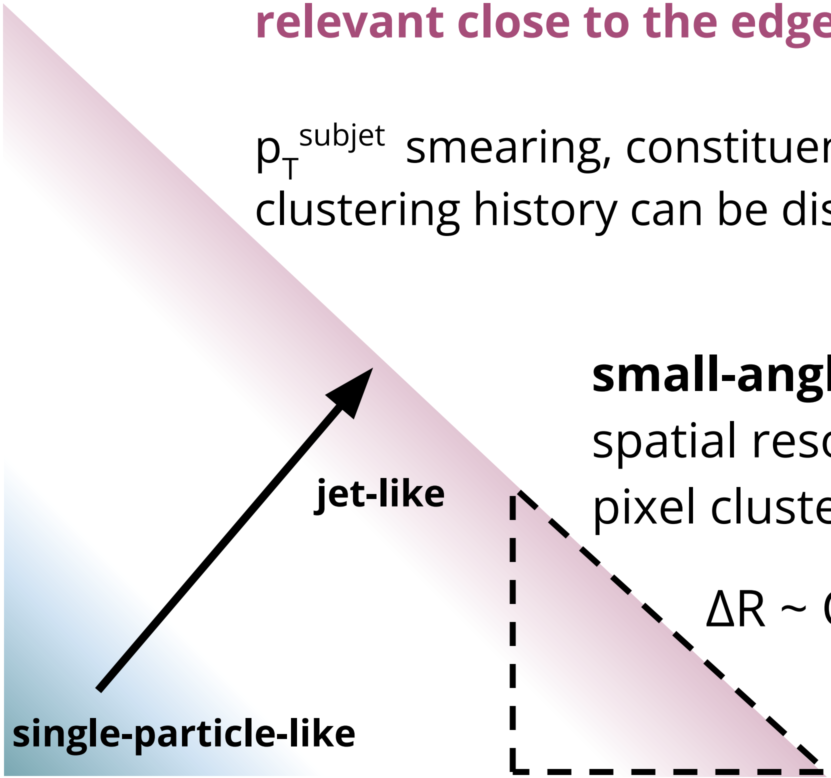
nonperturbative

resummation (unc. mostly perturbative)



Nonglobal logs, clustering logs

selected detector effects



relevant close to the edge ($p_T^{soft} \sim p_T^{hard}$):

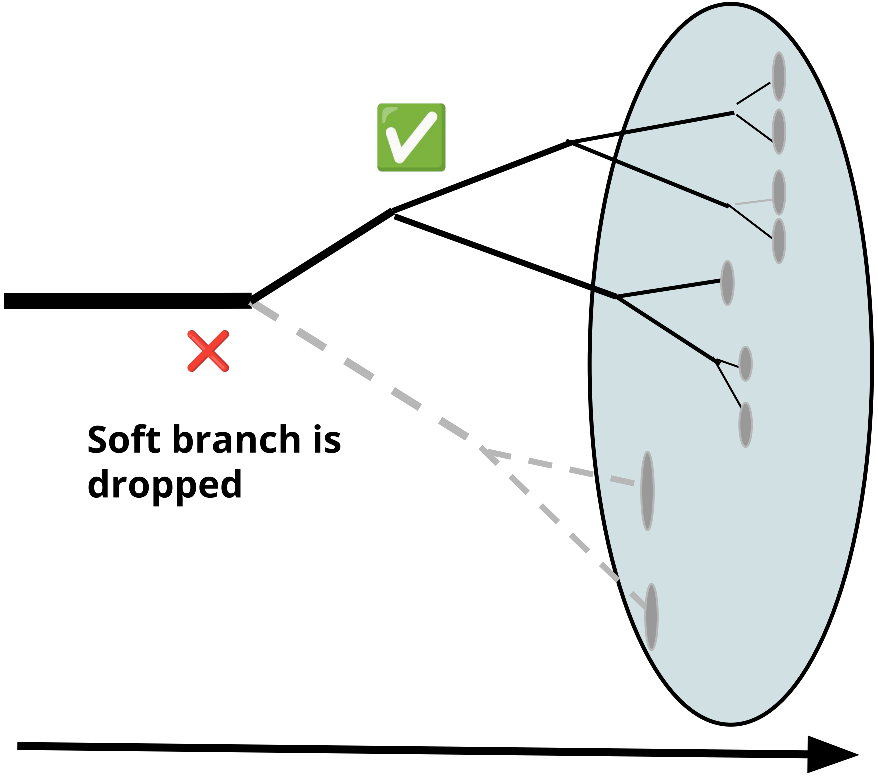
p_T^{subjet} smearing, constituents lost in reconstruction, clustering history can be distorted (e.g., branch swaps

small-angles:
spatial resolution,
pixel cluster merging

$\Delta R \sim O(10^{-3} – 10^{-2})$

residual PU contributions (large ΔR, low k_T)

(Intermezzo) soft-drop grooming algorithm



Soft branch is dropped

Cambridge–Aachen declustering

1. Jet is reclustered with Cambridge–Aachen (CA), which clusters particles with **angular ordering**

2. Follow the CA clustering history in reverse. Check if the branch satisfies the soft-drop condition:

   $z = p_T^{softer}/(p_T^{softer}+p_T^{harder}) > z_{cut} (\Delta R/R)^{\beta}$

   (a typical choice is $z_{cut} = 0.1$, $\beta = 0$)

   If the splitting fails the SD condition, the branch is removed

3. Repeat 2 until SD condition is satisfied, which yields a **soft-drop groomed jet**

Corrections to particle level

Sequential set of corrections:

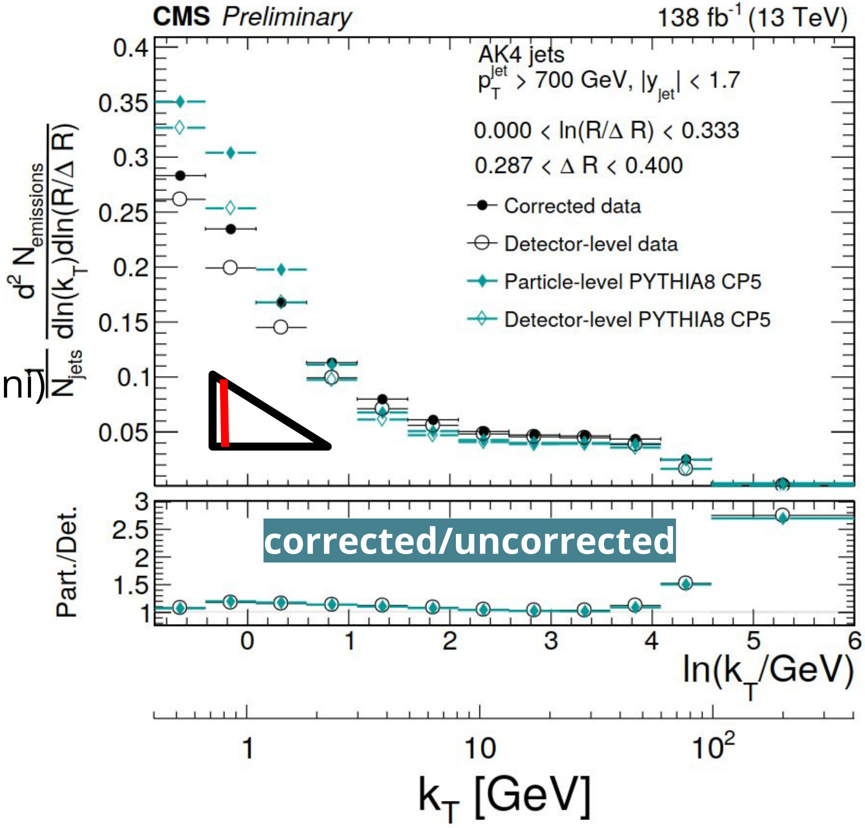
1. **Background:** bin-by-bin correction to account for det-level emissions not matched to truth-level emissions.

2. **Multidimensional regularized unfolding** (D'Agostini) of primary Lund jet plane (p_T^{jet}, k_T, ΔR).

3. **Efficiency:** bin-by-bin correction to account for hadron-level emissions without matching.

PYTHIA8 CP5 chosen as nominal to also propagate parton shower scale uncertainties

CMS-PAS-SMP-22-007

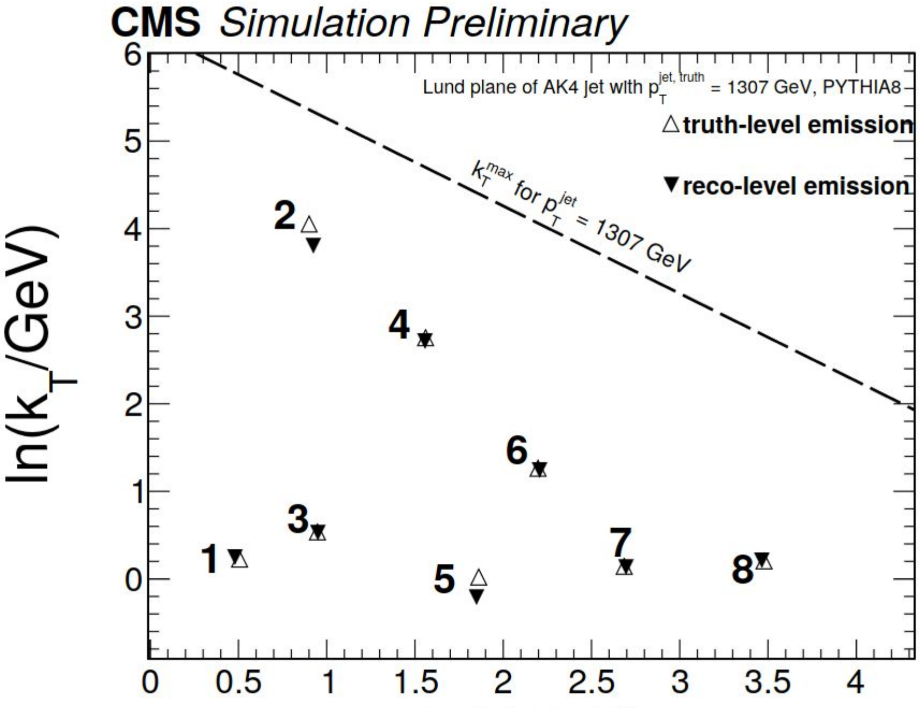


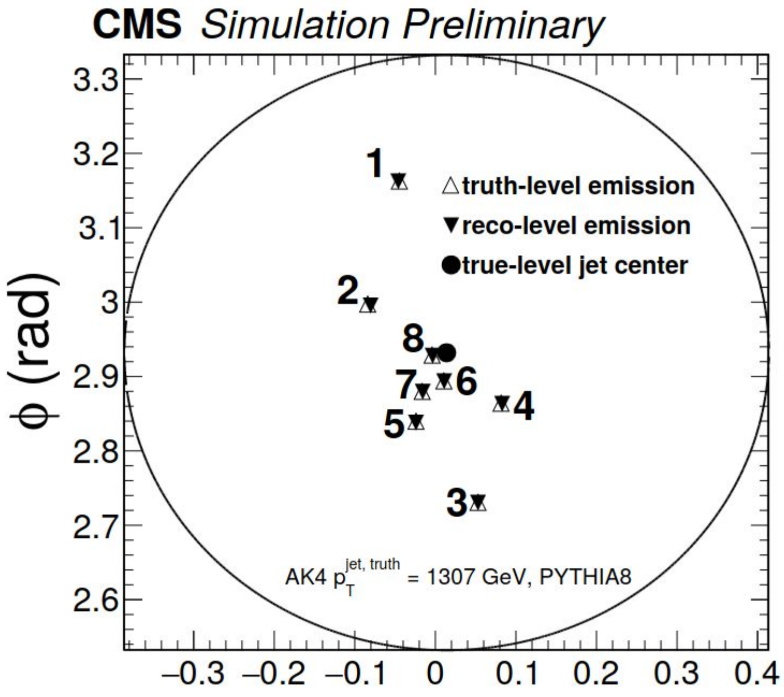
corrected/uncorrected

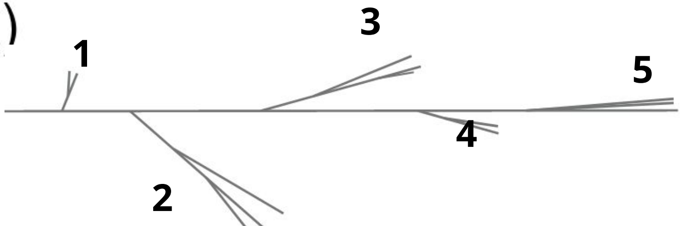
smearing becomes more important at high k_T

Matching emissions at detector level and particle level

Migration matrix and other MC-based corrections derived from matched part-level and det-level splittings.



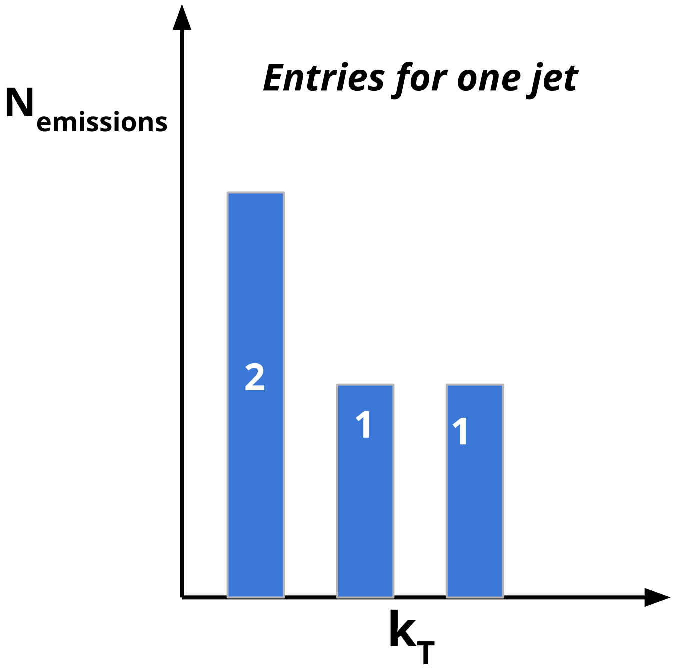


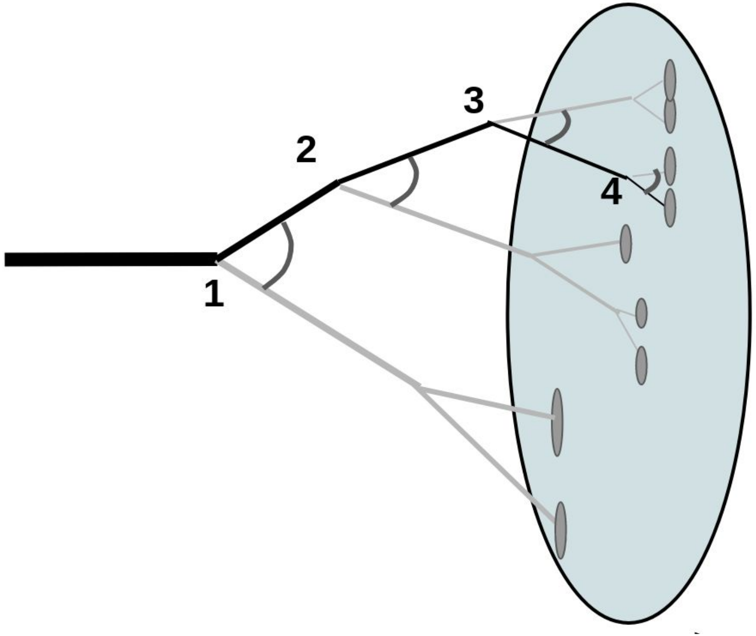


CMS-PAS-SMP-22-007

detector-level statistical correlations

LJP is a multicount observable (i.e., multiple entries per jet) → bins are statistically correlated at det level





bin-to-bin correlations of up to ~5–10%, measured covariance matrix used in unfolding

(can be important for other observables, e.g. Lund multiplicities, energy correlators, ...)

Systematic uncertainties

Shower & hadronization model uncertainty
(2–7% in the bulk, 10% at kinematical edge)

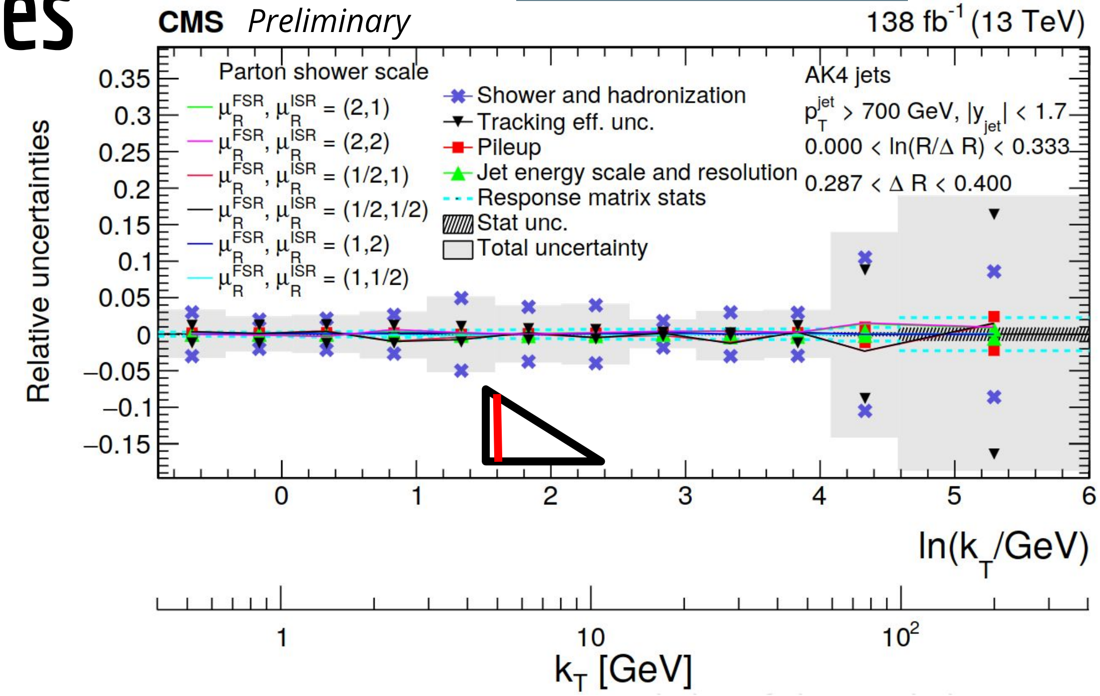
decorrelated into prior bias ⊗ response pieces

Tracking reco. efficiency model uncertainty,
1-2% in bulk, dominates at 10-20% at edge

Subleading components (<~ 1%):

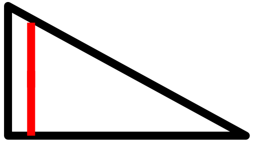
Parton shower scale
Response matrix stats
Jet energy scale **and** **resolution uncertainties**
Pileup modeling

CMS-PAS-SMP-22-007



Dominated by **shower & hadronization modeling** in bulk of Lund plane & by **tracking efficiency** at high k_T

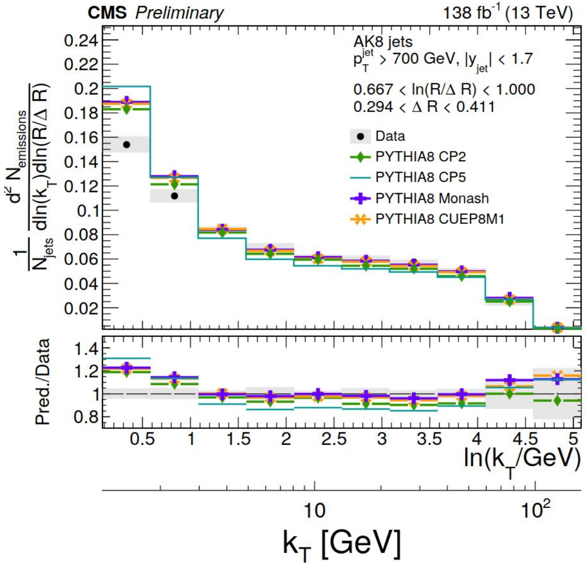
Large angle emissions



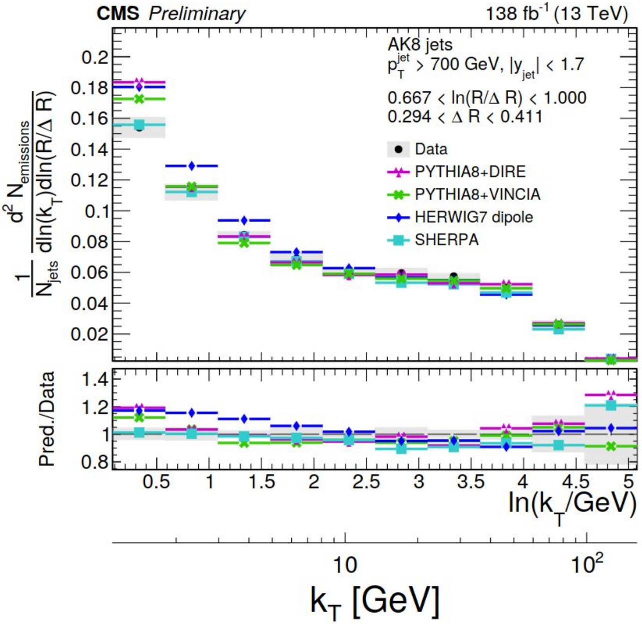
R = 0.8

Comparison to parton showers& tunes

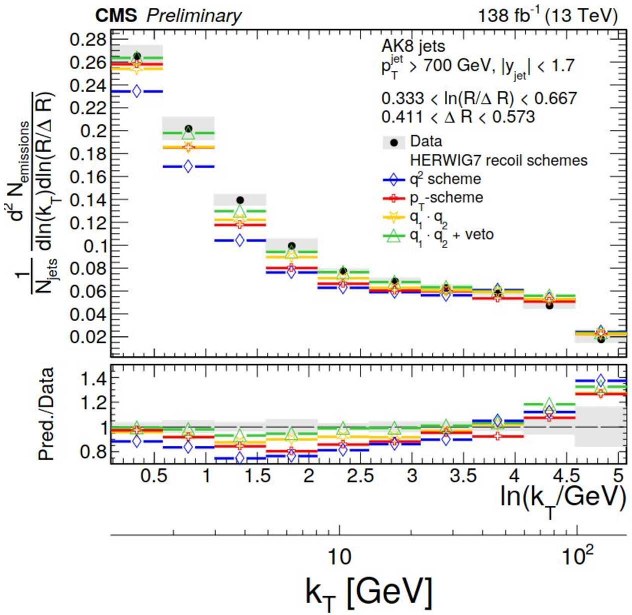
CMS-PAS-SMP-22-007



PYTHIA8 tunes
(CP2, CP5, Monash, CUEP8m1)



Dipole showers
(Vincia, Dire, Herwig7 dipole, Sherpa)



Herwig7 recoil schemes,
(angle-ordered showers)

Data/MC differences of 10–20%. Most important difference for PYTHIA8 tunes is the $\alpha_S^{FSR}(m_Z)$ value.

HERWIG7 angle-ordered describes better the data than **HERWIG7 dipole**

Factorization of effects can be exploited in MC tuning