Nonperturbative signals in jet observables

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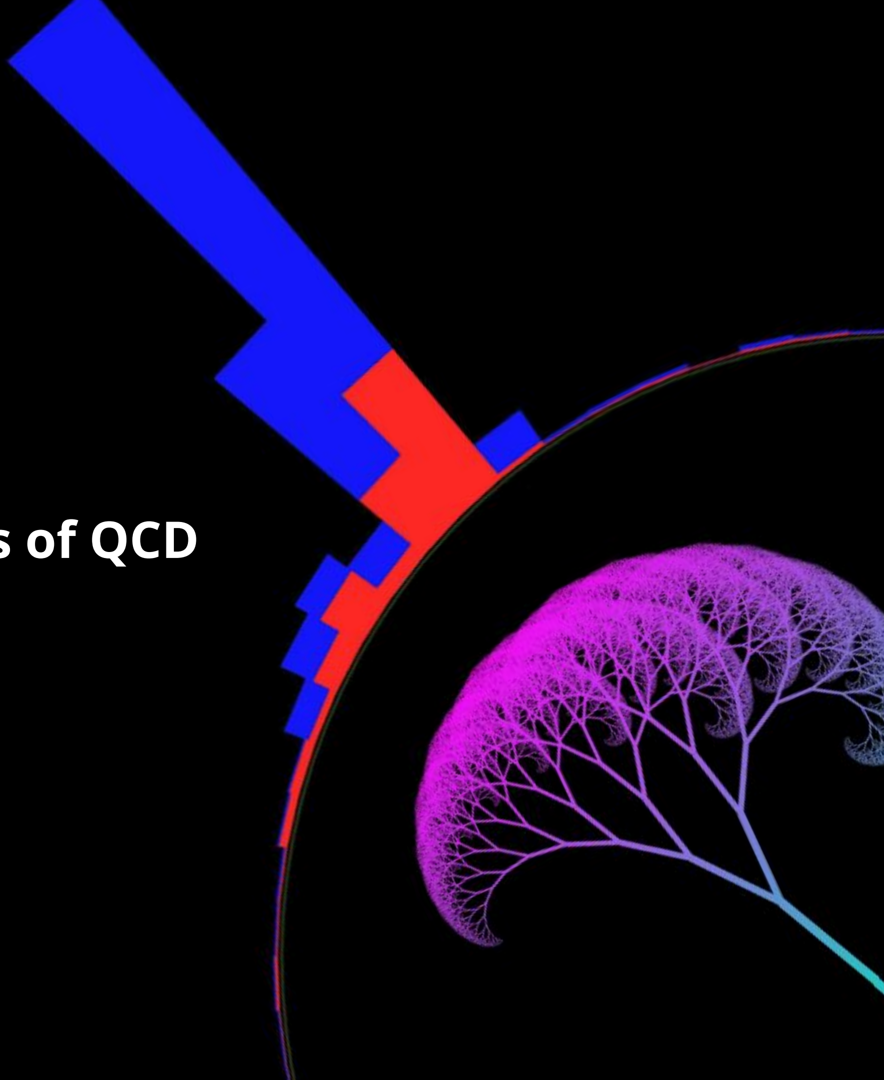
<u>Nonperturbative</u> and topological aspects of QCD

May 29th–30th



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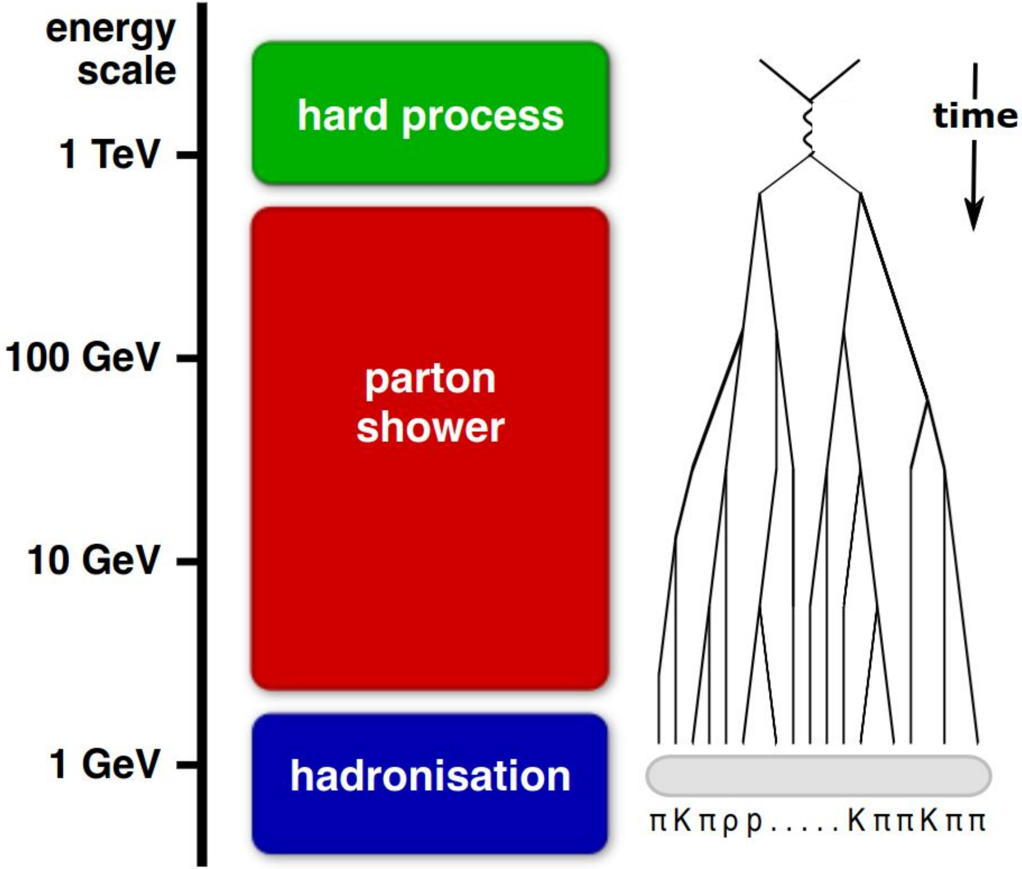
Jet formation is a multiscale probe of QCD evolution



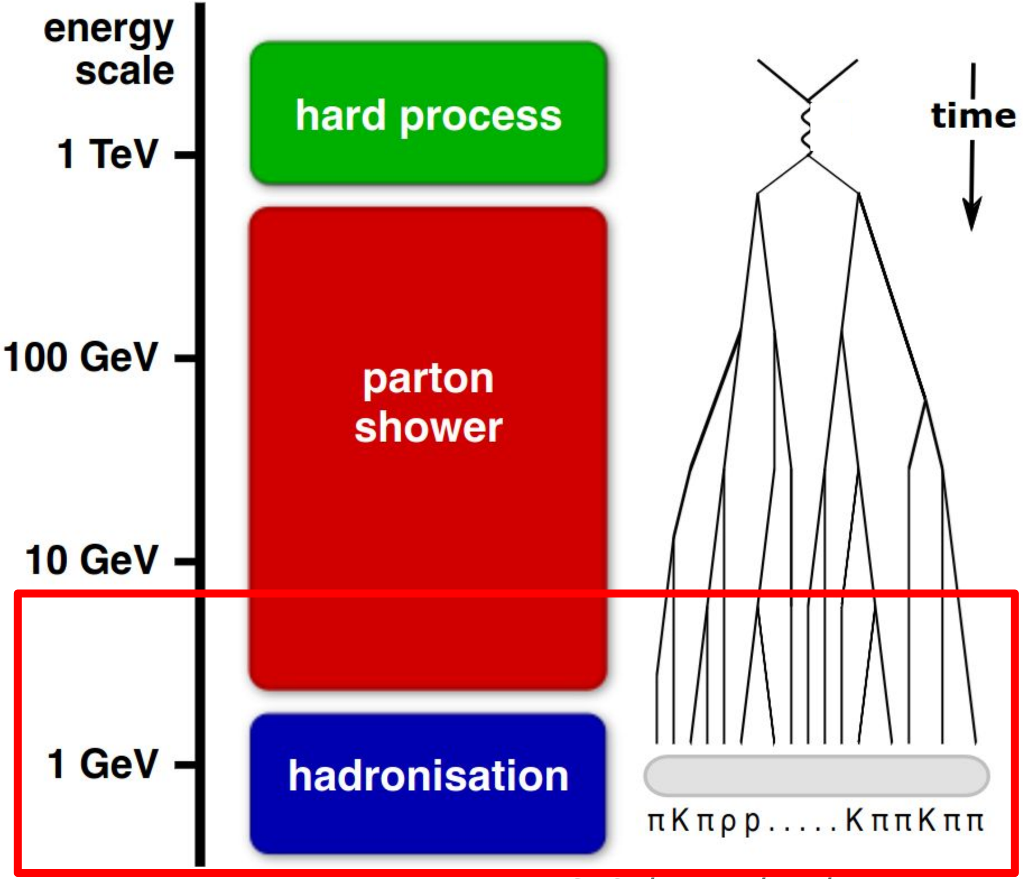
G. Salam's sketch

From Q ~ 1 TeV down to Λ_{QCD} ~ 200 MeV

Jet p_T ⇔ parton cascade "length"

Depending on observable, jet $p_{T,}$ and radius R: sensitivity to parton shower, hadronization, underlying event, color reconnection, …

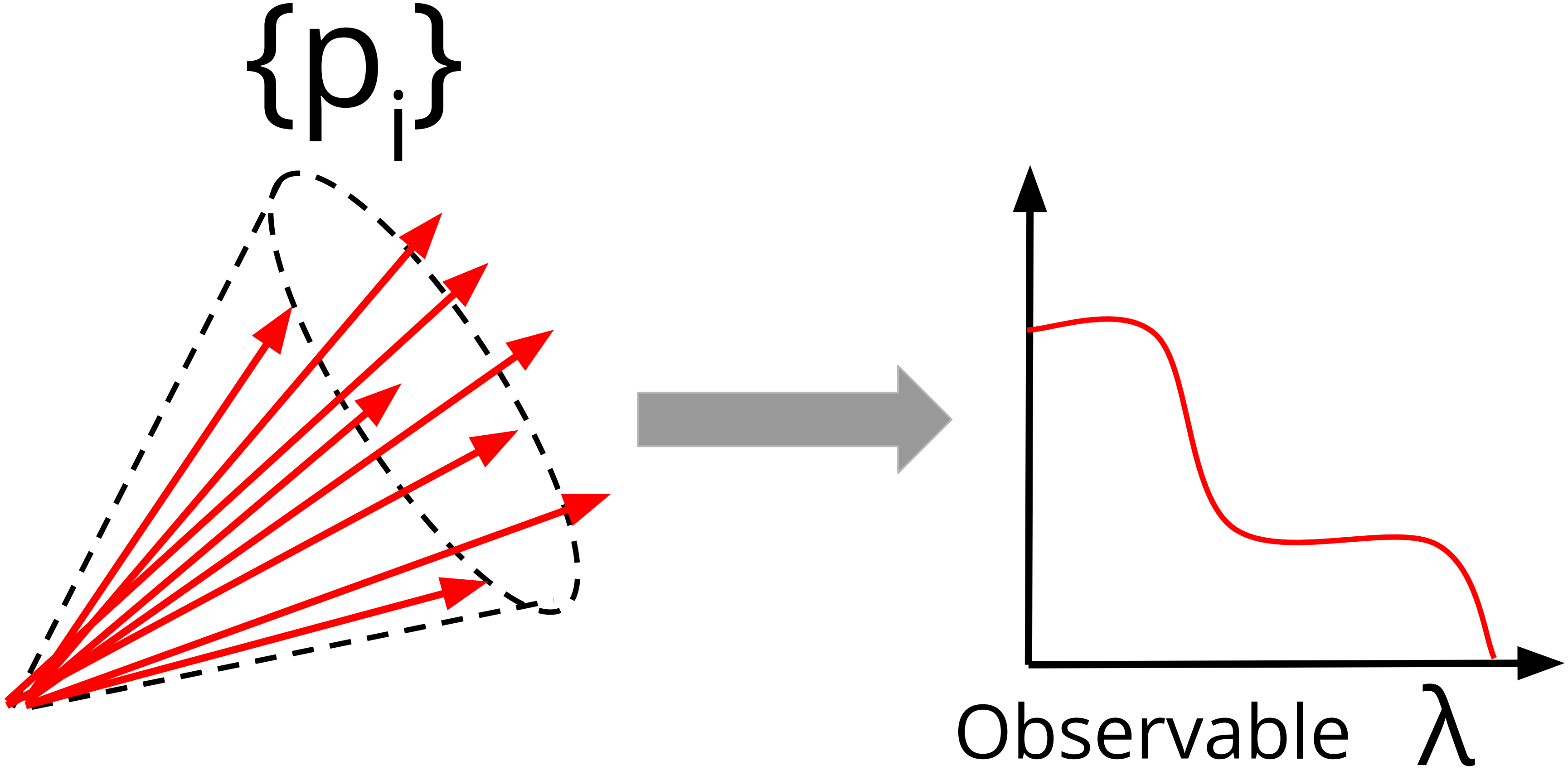
Jet formation is a multiscale probe of QCD evolution



G. Salam's sketch

focus on this

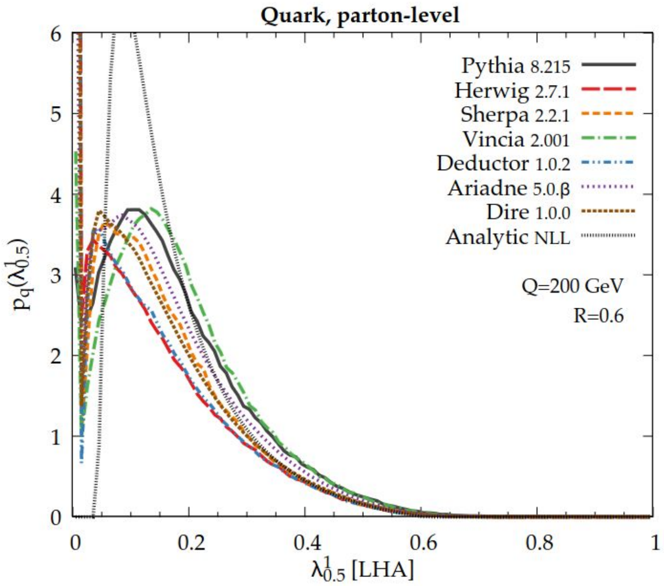
Jet substructure in a nutshell



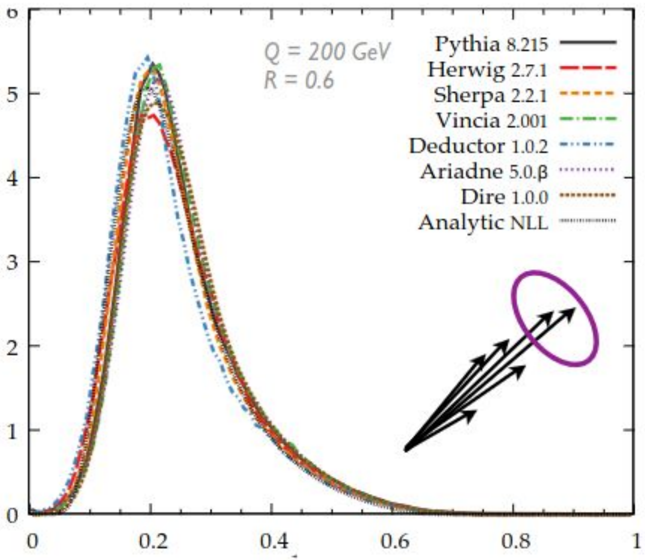
Identifying onset of hadronization in jet showers

Nontrivial to separate “perturbative” & “nonperturbative” components

Parton-level



Hadron-level



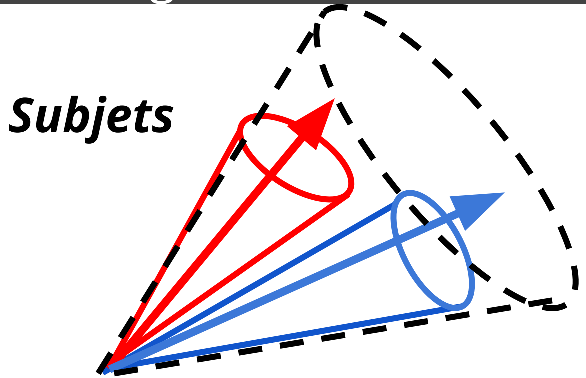
$$\mathrm{LHA} = \sum_i z_i \sqrt{\theta_i}$$

p_T-weighted angular distance

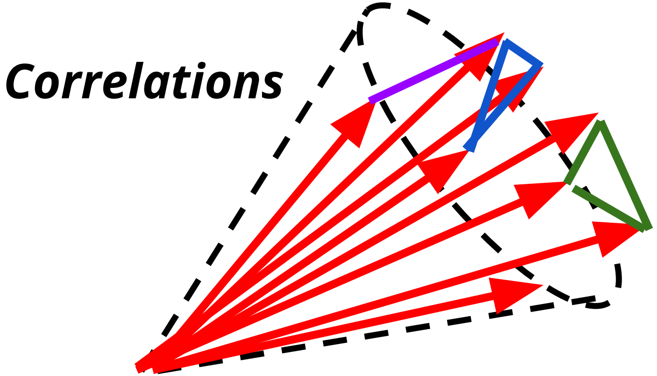
This talk:

Two approaches to understand jet showers in a **modular fashion**

Clustering-based observables

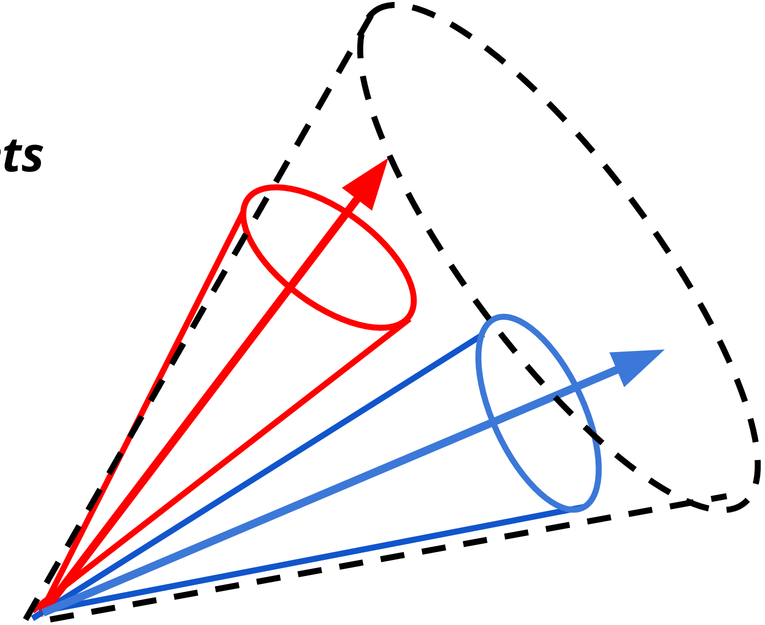


Energy-flow-based observables



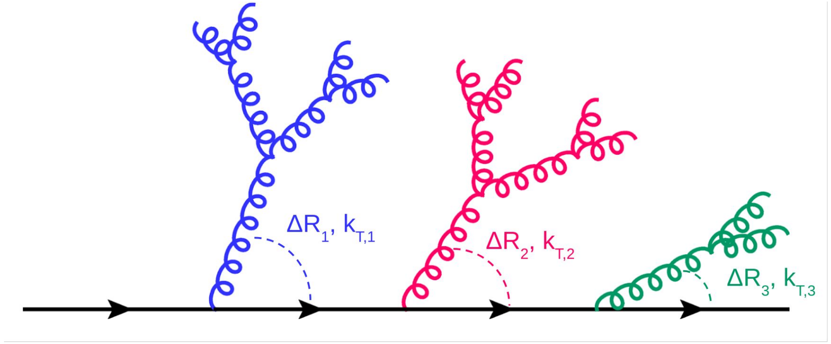
Clustering-based observables

Subjets

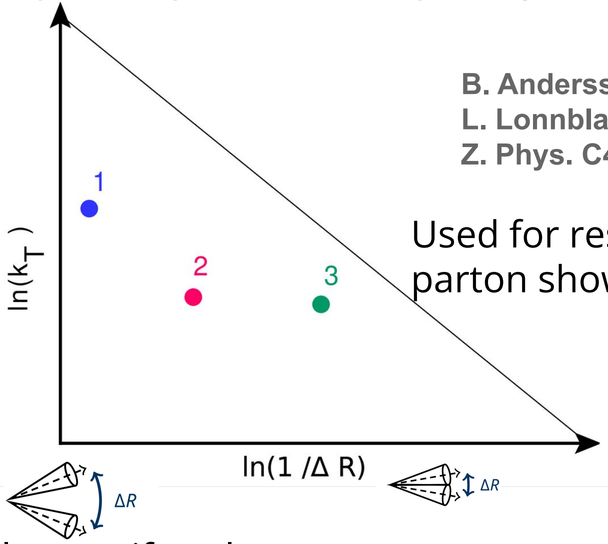


Phase-space of QCD branchings in the Lund plane

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

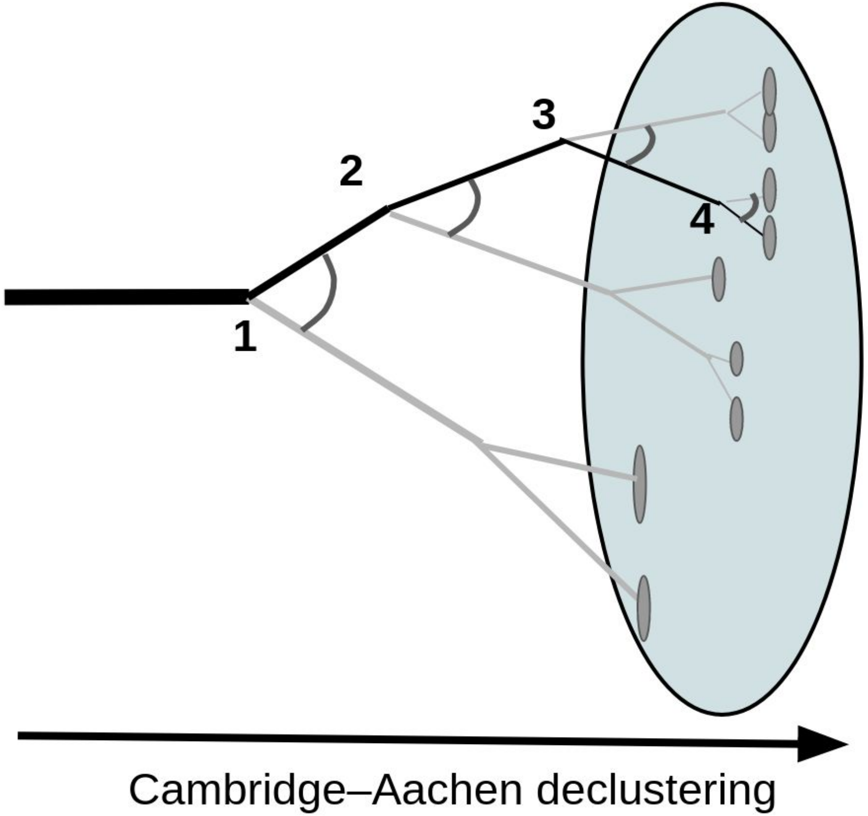
Used for resummation and parton shower development

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

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

Promoting the Lund plane to a tool: the Lund jet plane

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

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

CMS, ALICE $k_{\mathrm{T}} = p_{\mathrm{T}}^{\mathrm{softer}} \Delta R$

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

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

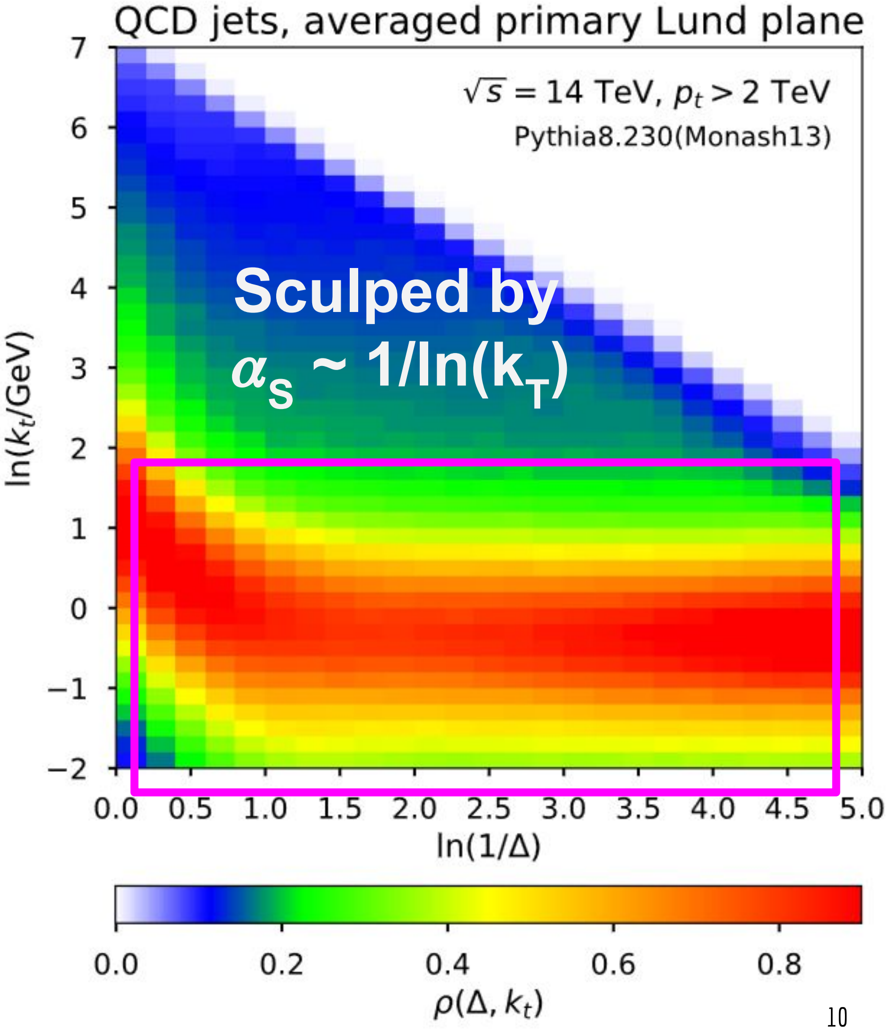
Define a *jet-averaged* number of emissions,
the ``primary" Lund jet plane density

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

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

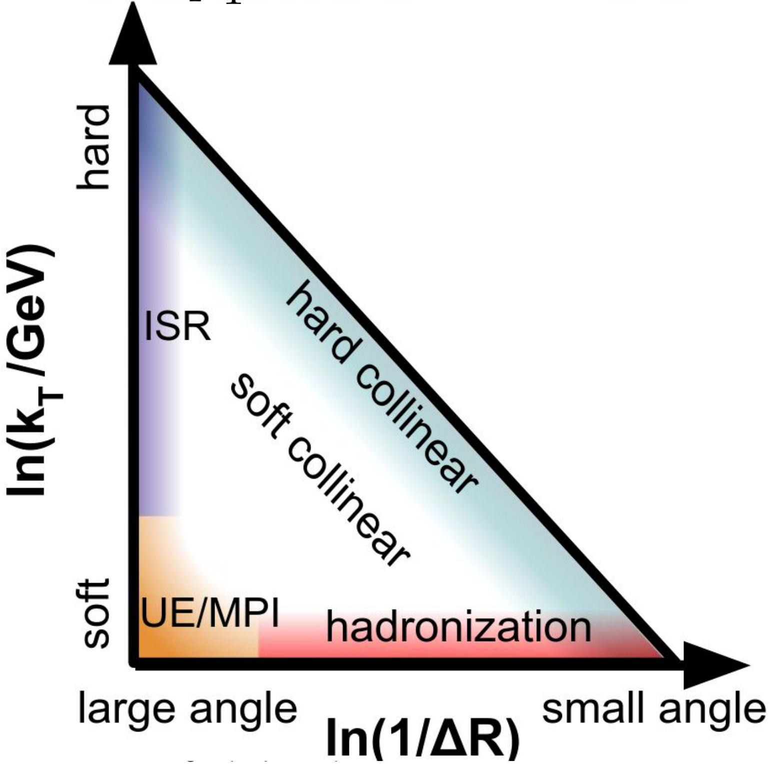


Mechanisms "factorize" in the Lund jet plane

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

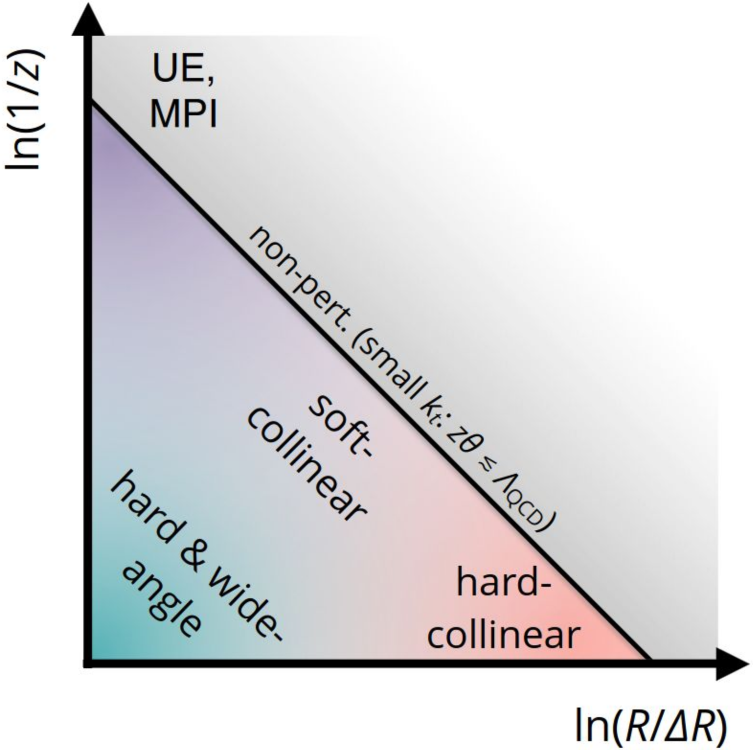
CMS Lund plane coordinates

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



ATLAS Lund plane coordinates

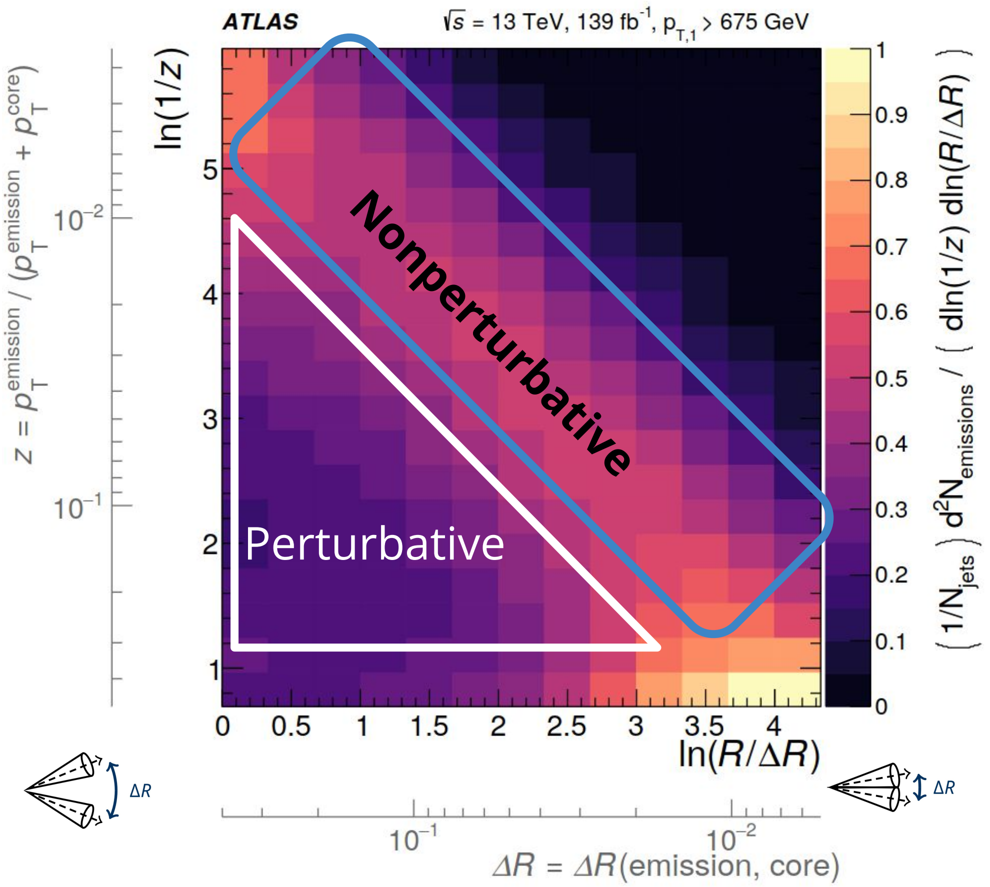
$z = p_{\mathrm{T}}^{\mathrm{softer}}/(p_{\mathrm{T}}^{\mathrm{harder}}+p_{\mathrm{T}}^{\mathrm{softer}})$ vs ΔR



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:

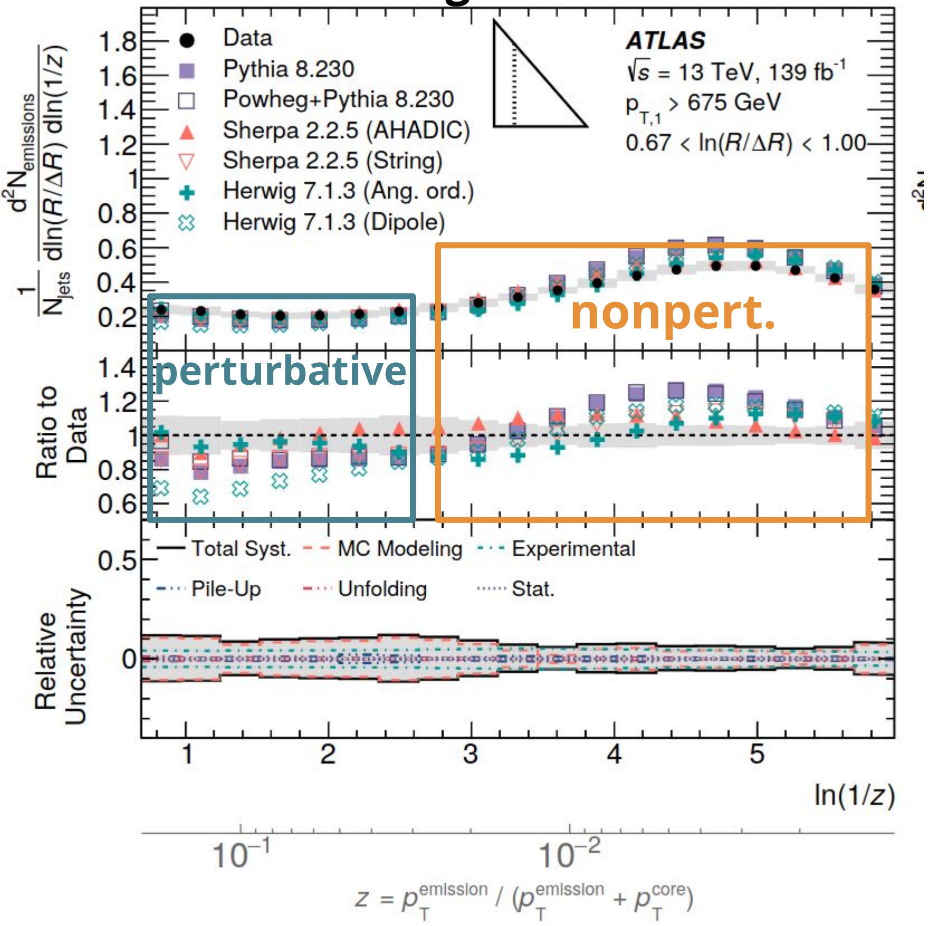
$$z = p_{T,softer}/(p_{T,softer}+p_{T,harder})$$

Multidimensional unfolding

Factorization properties in action (ATLAS)

Fixed-angle slize

PRL 124, 222002 (2020)



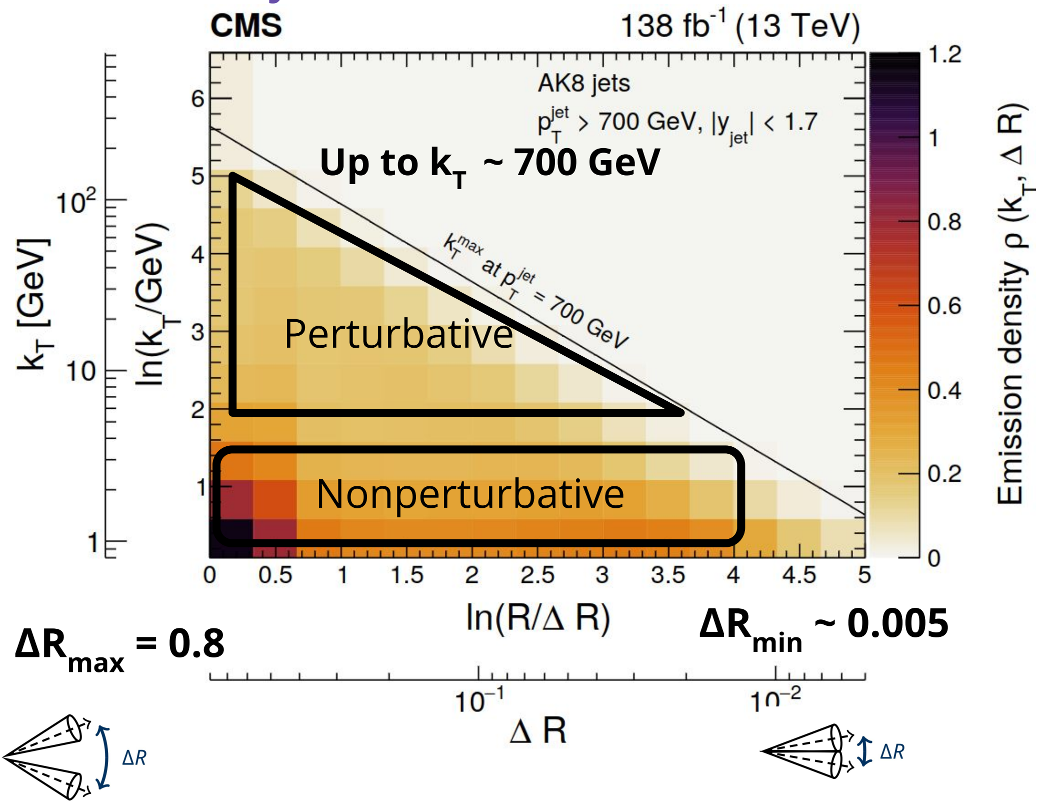
Variation of hadronization model, with the same parton shower (**Sherpa2 string vs hadronization**)

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

CMS primary Lund jet plane densities

arXiv:2312.16343, accepted by JHEP

R=0.8 jets



Probing k_T from ~1 GeV to 700 GeV, and 0.005 < ΔR < 0.8

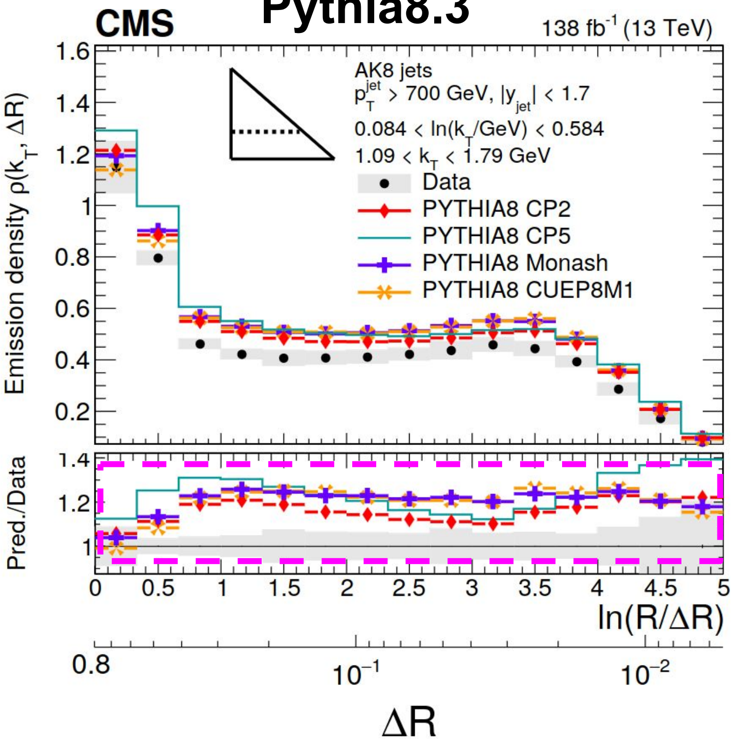
$$k_{\mathrm{T}} = p_{\mathrm{T}}^{\mathrm{softer}} \Delta R$$

Lund vs cluster fragmentation?

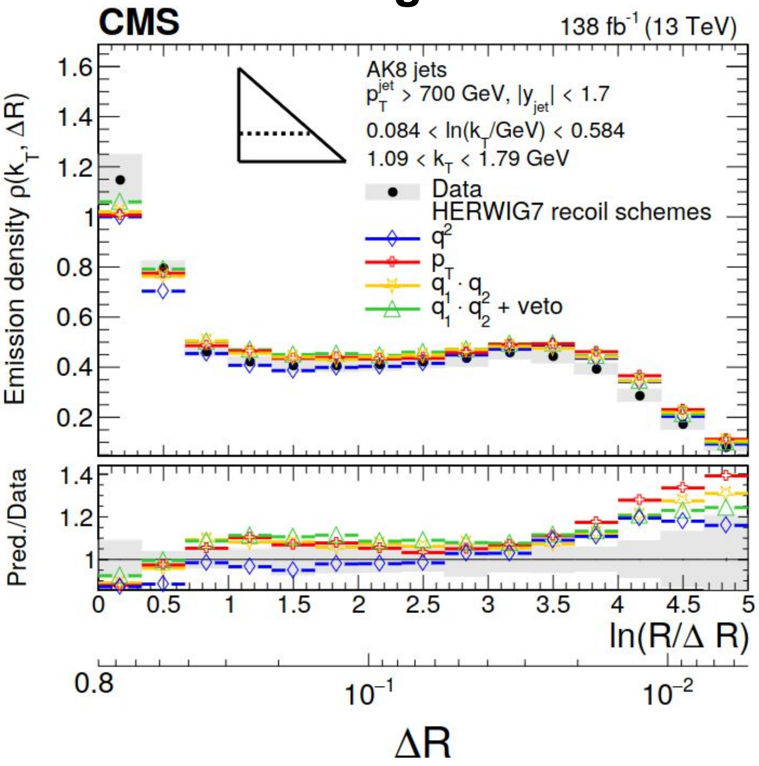
arXiv:2312.16343, accepted by JHEP

Hadronization region (**k_T ~ 1 GeV**)

Pythia8.3



Herwig7.2



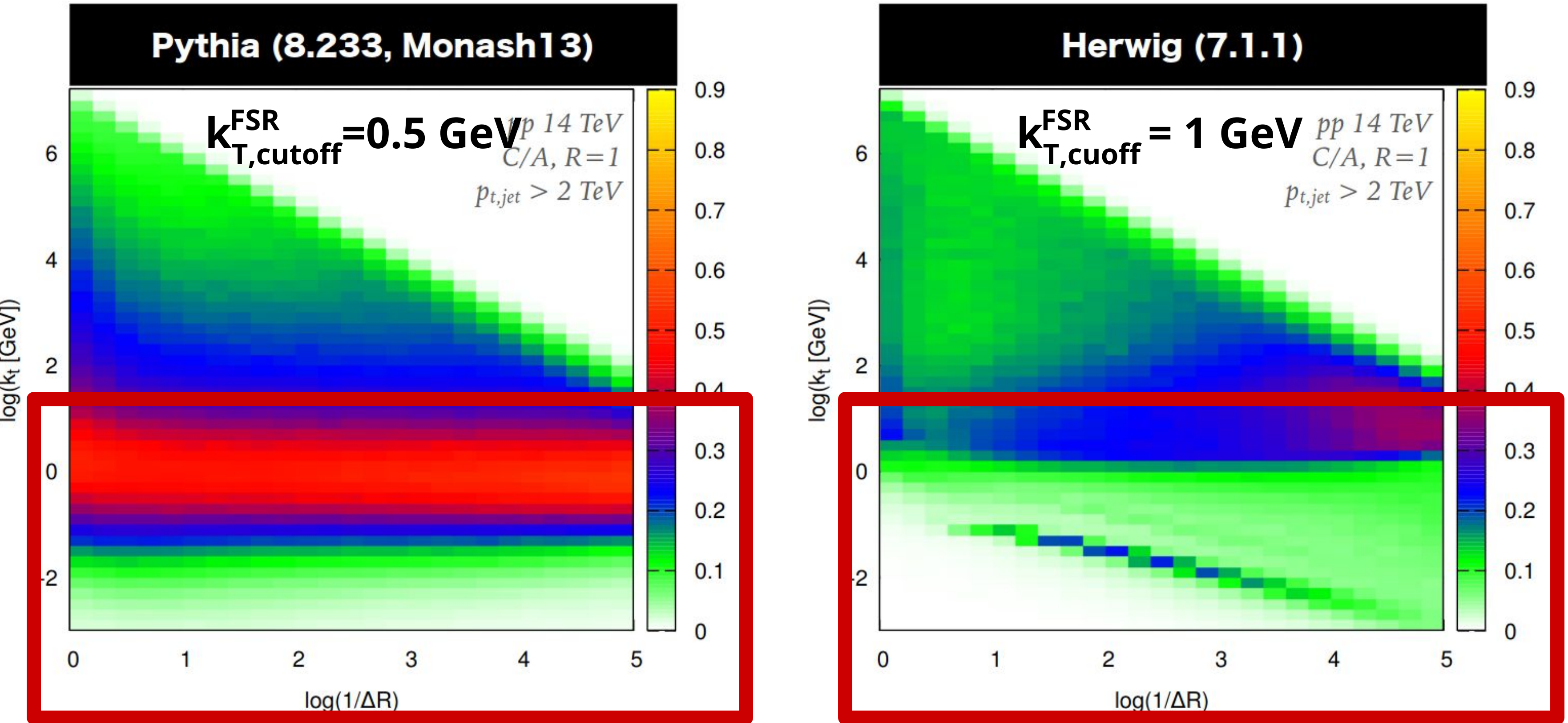
Lund string (**PYTHIA8** overshoots) data by 15-20% in hadronization region

Cluster model in better agreement… (**HERWIG7/SHERPA2**)

...Or could it be something else, e.g., the FSR k_T cutoff choice?

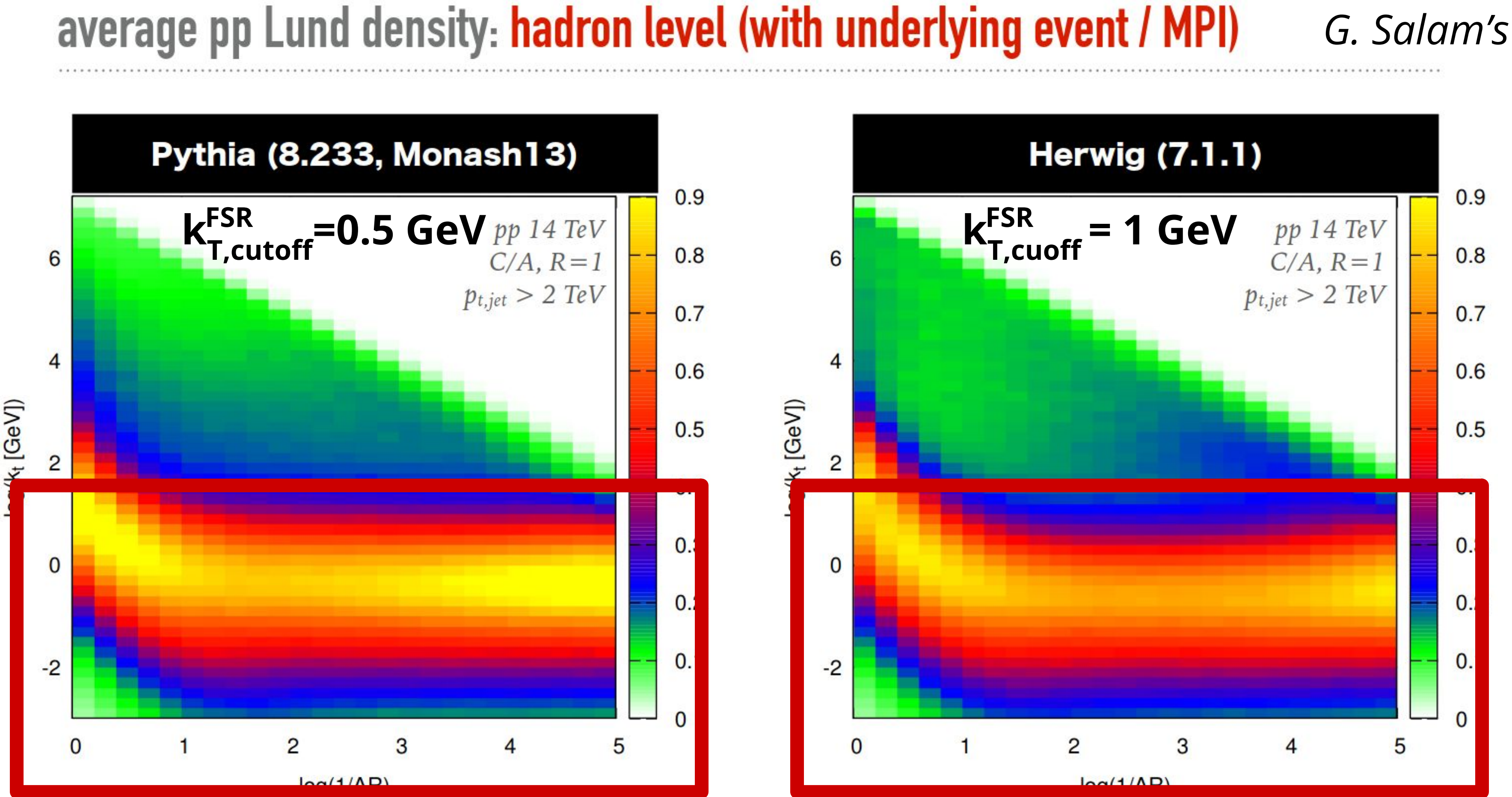
average pp Lund density: parton level

G. Salam's slide

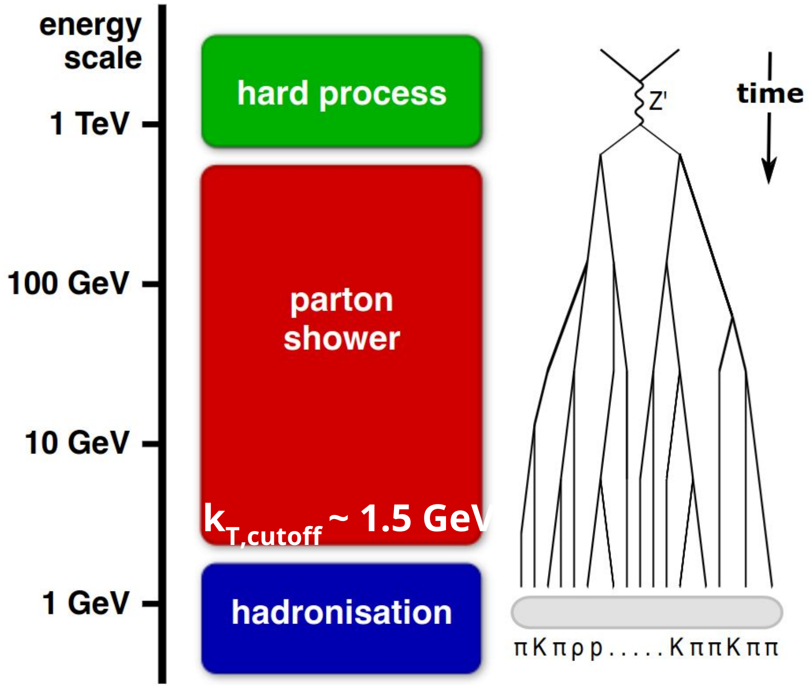


Hadron-level: FSR k_T cutoff choice shouldn't matter…

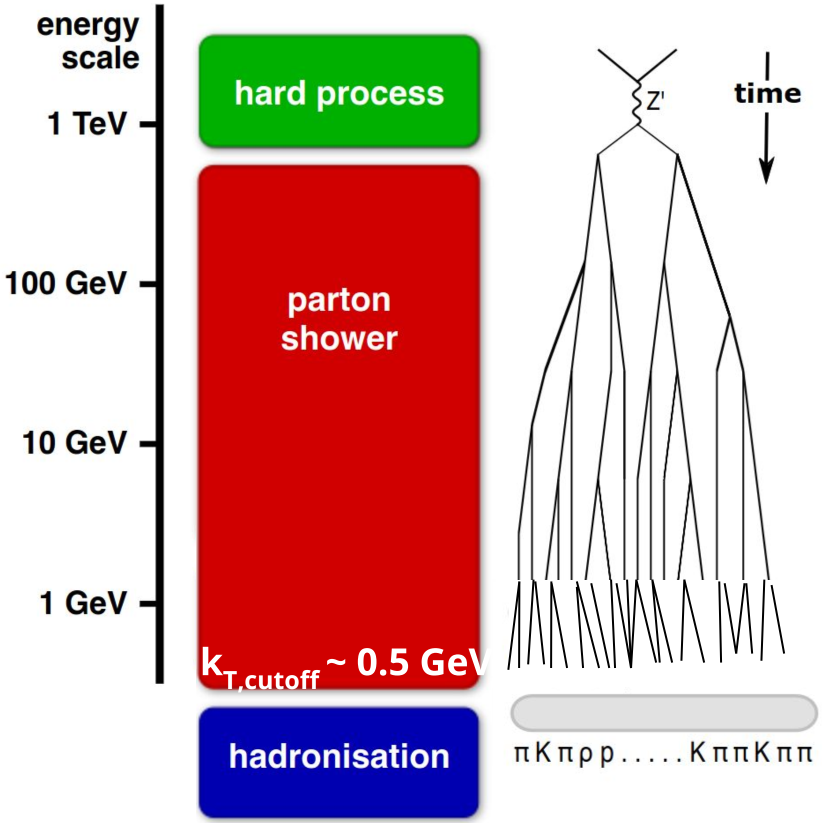
G. Salam's slide



Higher shower $k_{T,cutoff}$



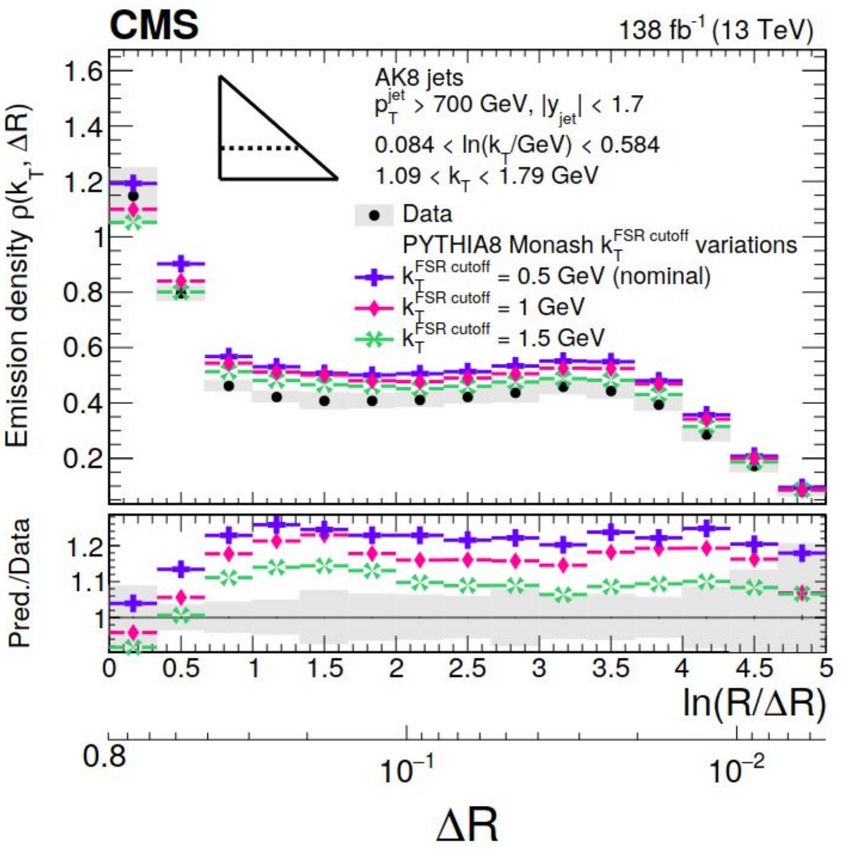
Lower shower $k_{T,cutoff}$



Could it lead to double counting?

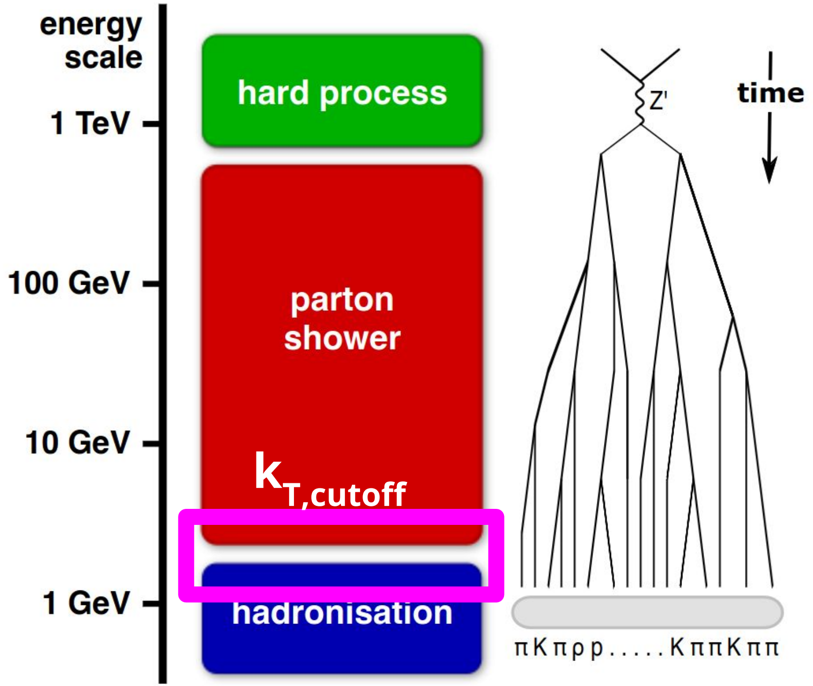
PYTHIA8 shower $k_{T,cutoff}$ variations ($k_T \sim 1$ GeV)

arXiv:2312.16343, accepted by JHEP



Larger FSR k_T cutoff ⇔ fewer Lund emissions

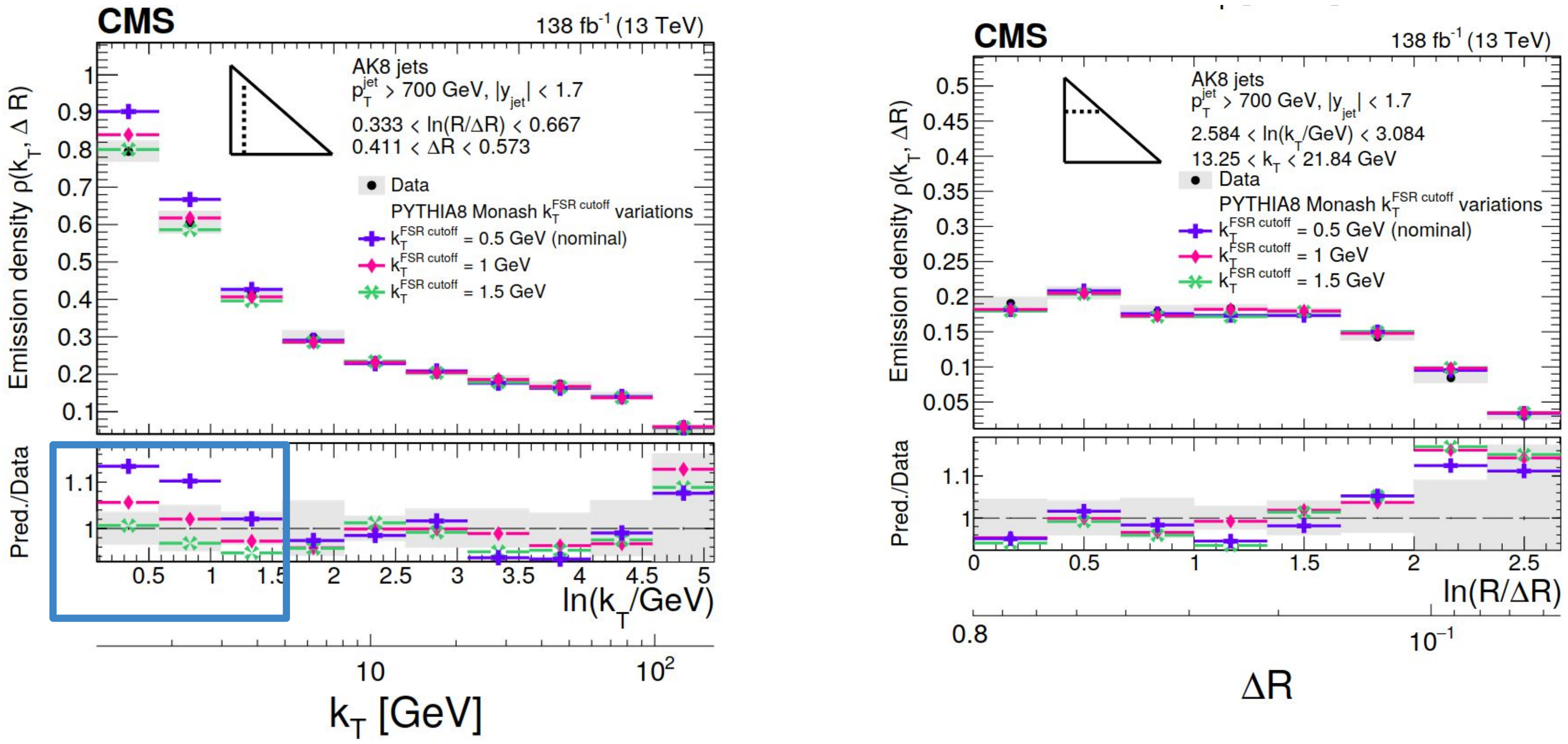
Data "prefers" higher FSR $k_{T,cutoff}$ = 1.5 GeV for PYTHIA8



Low shower $k_{T,cutoff}$ ⇒ "double counting"

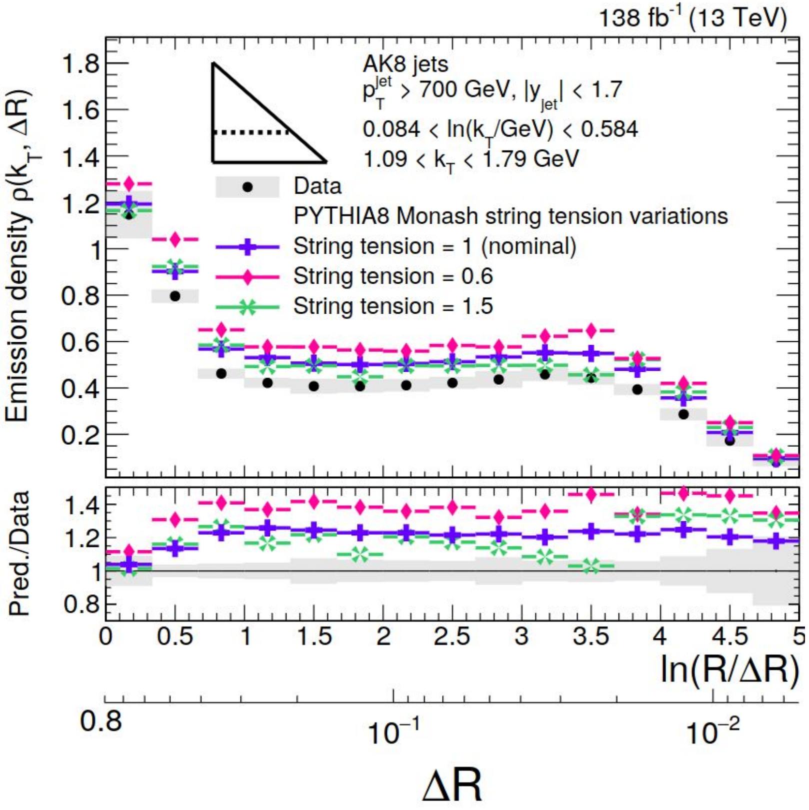
Shower $k_{T,cutoff}$ decouples at k_T ~ 4 GeV

arXiv:2312.16343, accepted by JHEP

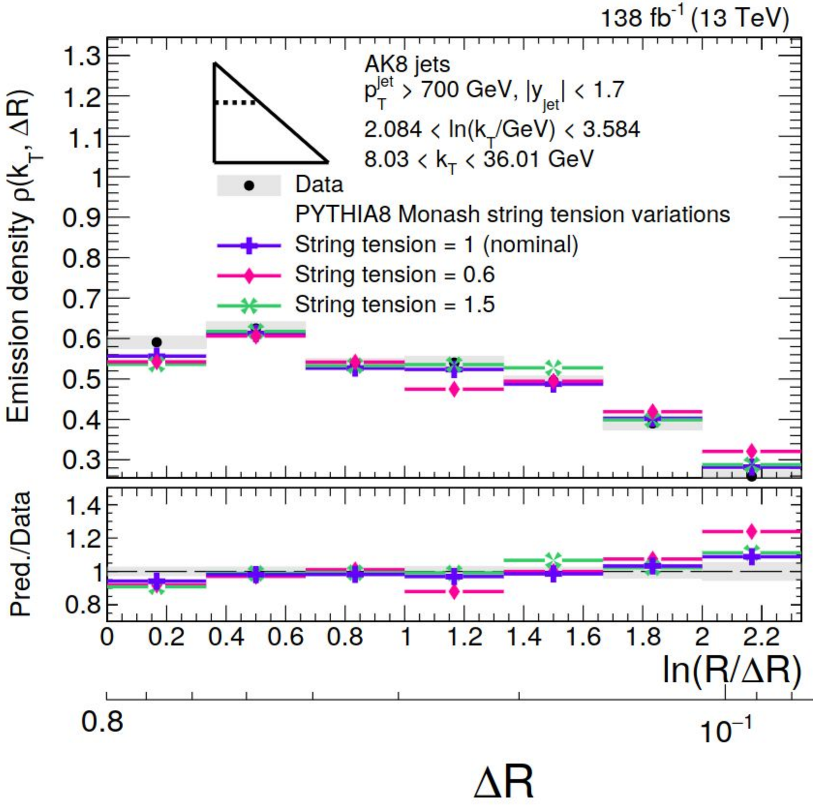


String tension sensitivity

Low $k_T \sim 1$ GeV

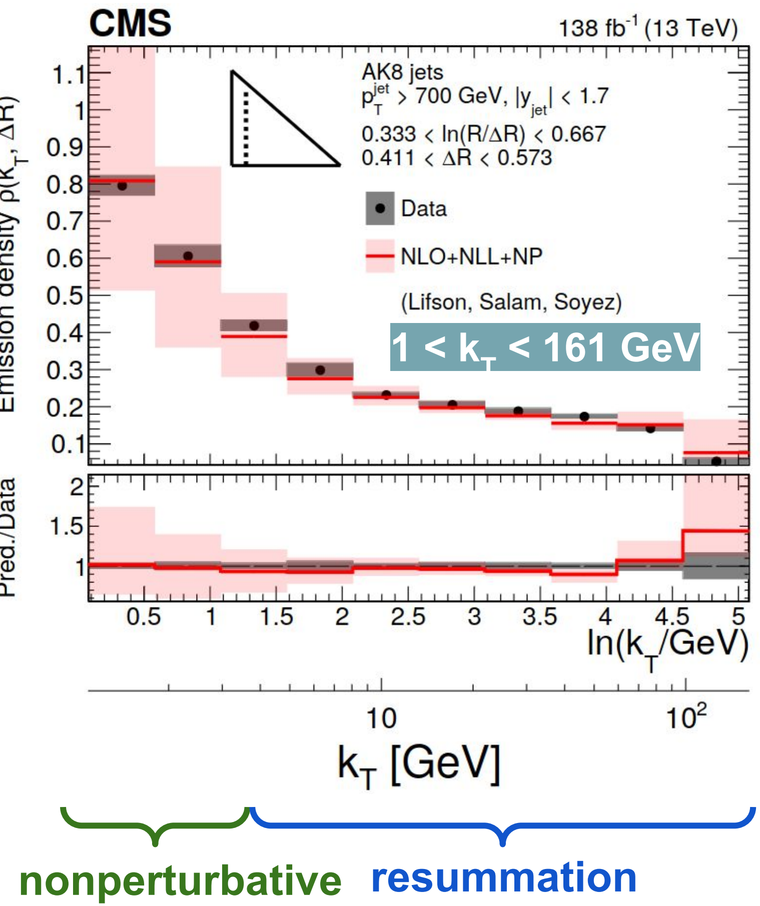


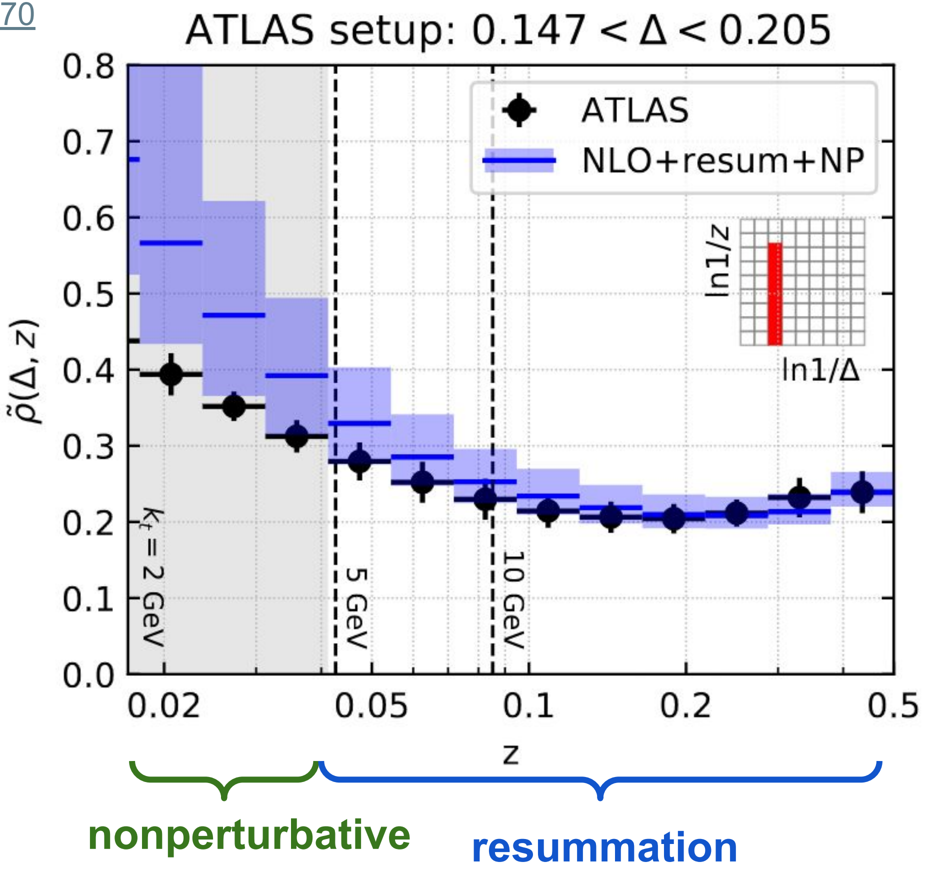
High k_T > 8 – 36 GeV



Similar onset for analytical calculations ($k_T \sim 3$ GeV)

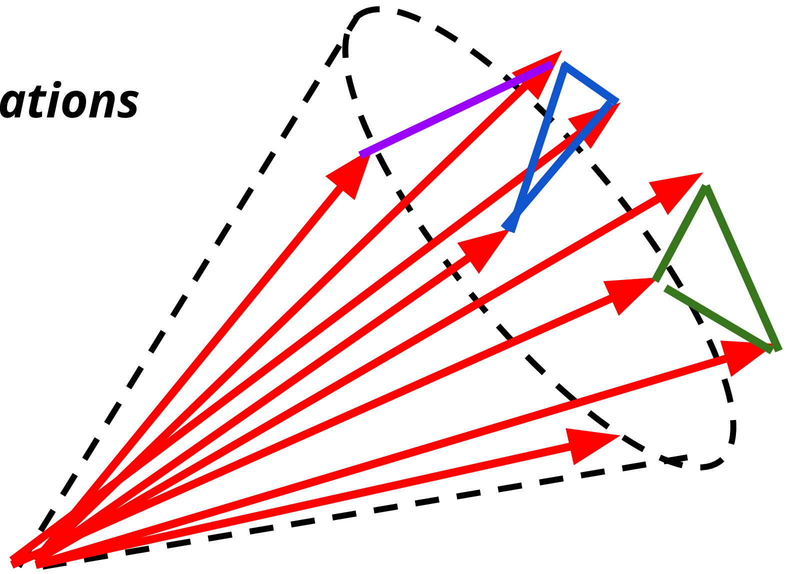
Calculations from A. Lifson, G. Salam, G. Soyez JHEP10(2020)170





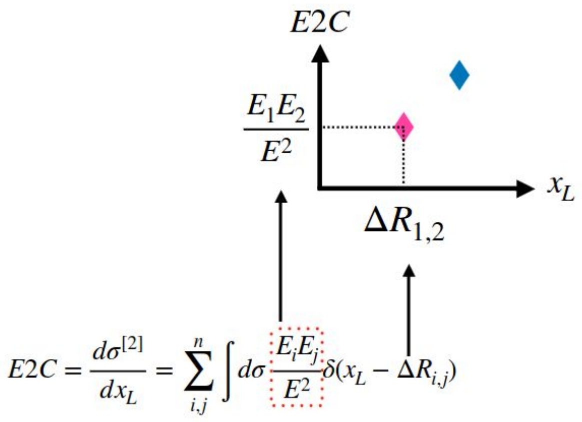
Energy-flow-based observables

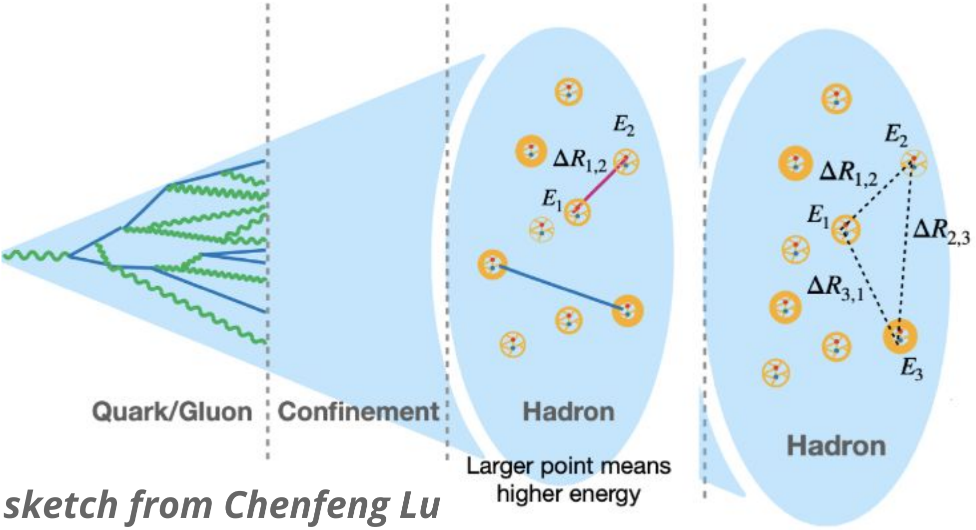
N-particle correlations



Energy-energy correlators

Energy-weighted two-particle correlations





sketch from Chenfeng Lu

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

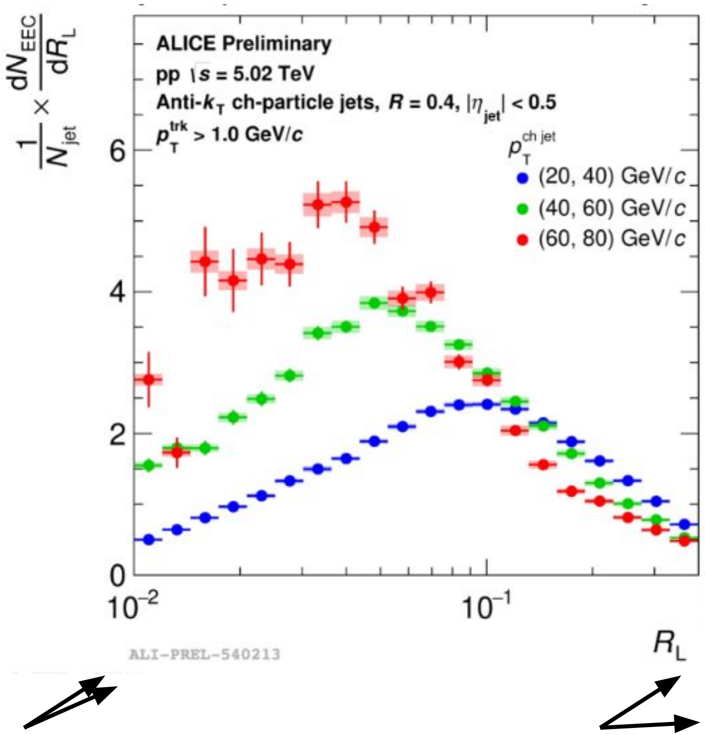
Energy weights $E_i E_j$: hard pairs are rewarded, soft pairs are penalized

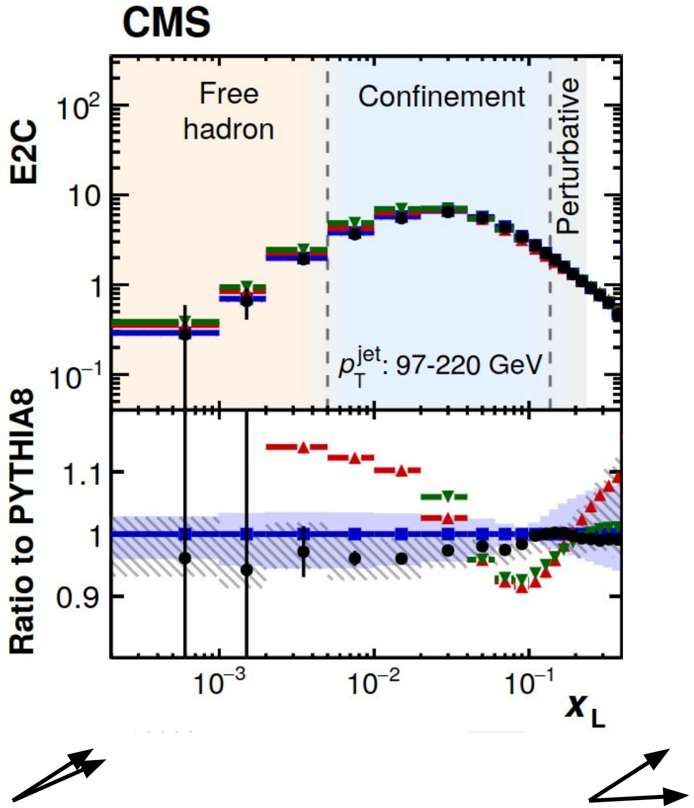
Mapping out different stages of jet formation

Proposed since the early days of QCD for e^+e^-, now explored specifically for jet substructure

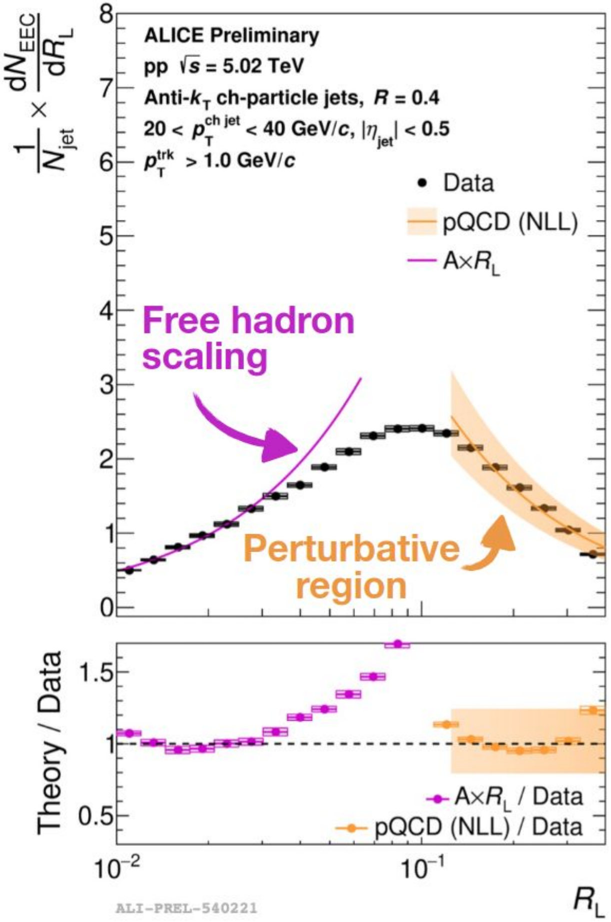
Energy-energy correlators

Separation of perturbative & nonperturbative regimes





Comparison to analytical calculations

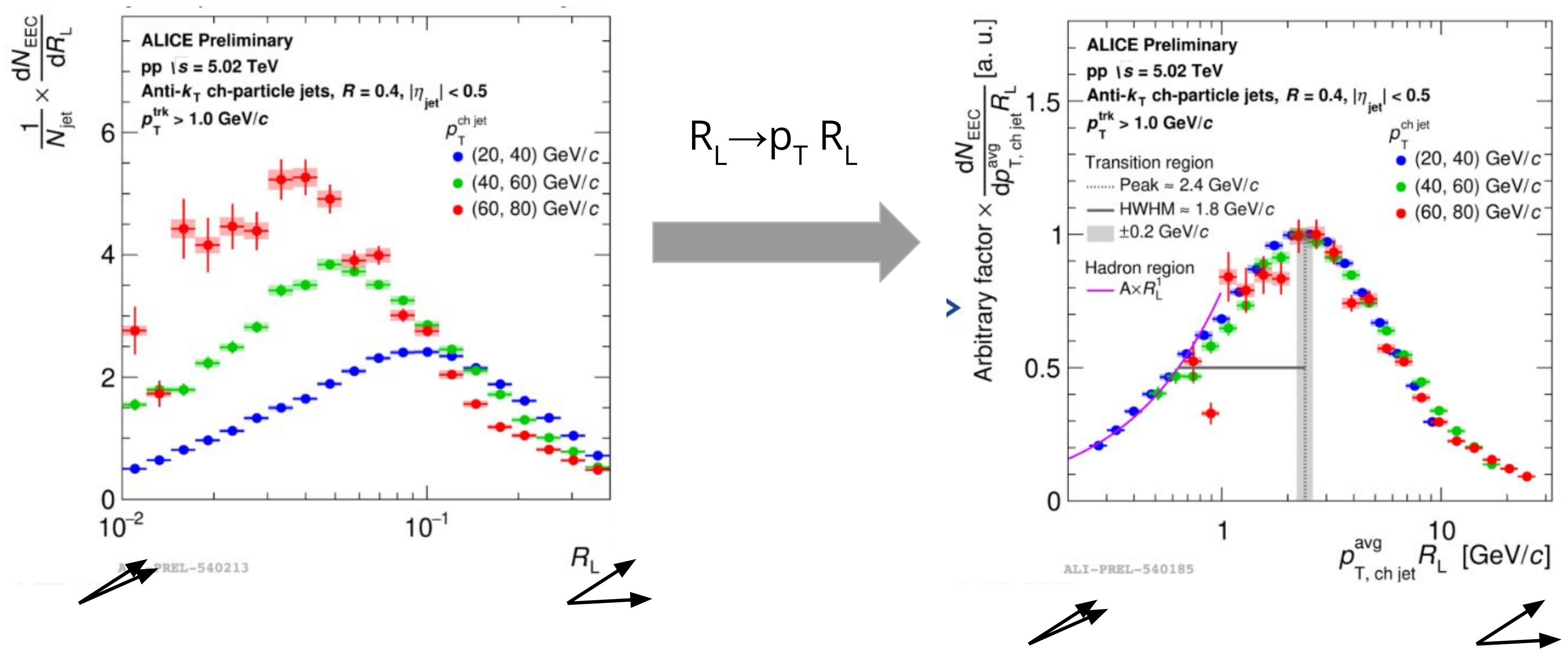


Based on K. Lee, B. Meçaj, I. Moult arXiv:2205.03414

Perturbative region at high-R_L (NLO+NLL+NP)

At small R_L, free-hadron scaling is followed,
deviation due to transition to short-distance physics

Scaling behavior with jet p_T

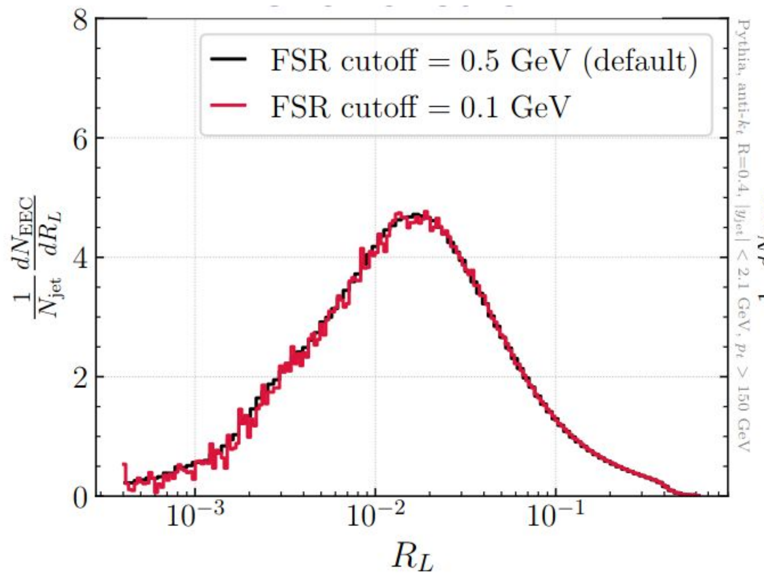


Peak of $p_T^{jet} R_L$ distribution suggests a characteristic universal scale **λ_{NP} ~ 2–3 GeV**

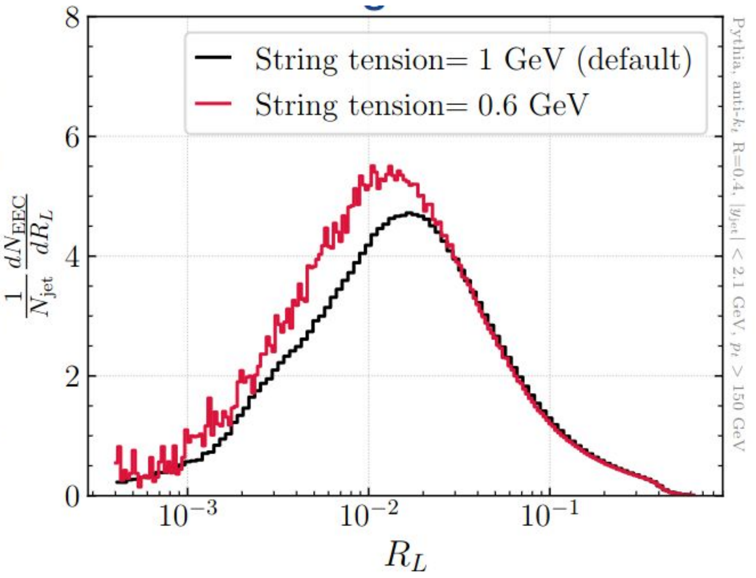
Sensitivity to infrared scales in MC

[A. Soto-Ontoso, ECT* 2024 workshop]

Shower $k_{T,cutoff}$



String tension



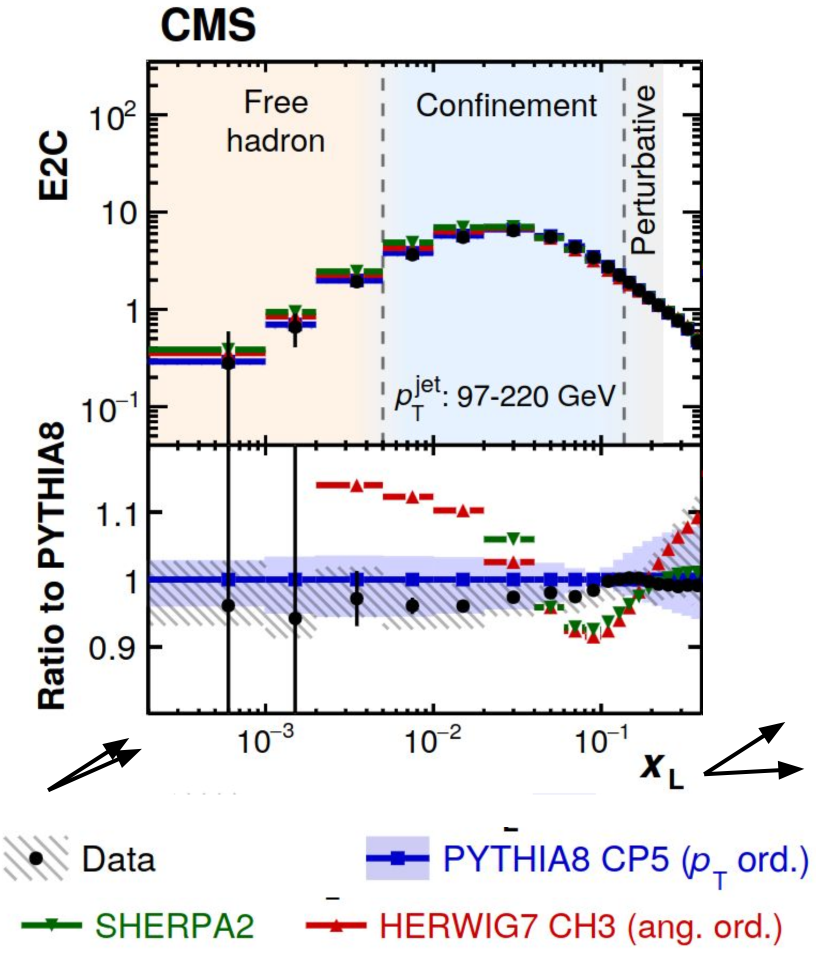
Not sensitive to FSR k_T cutoff (different from Lund plane), but sensitive to string tension

Comparison with MC generators

PYTHIA8 (string model) describes data in nonperturbative regions

HERWIG7/**SHERPA2** (cluster models) off by ~20% at small x_L

(Seemingly) opposite conclusions wrt the Lund plane analyses



arXiv:2402.13864, submitted to PRL

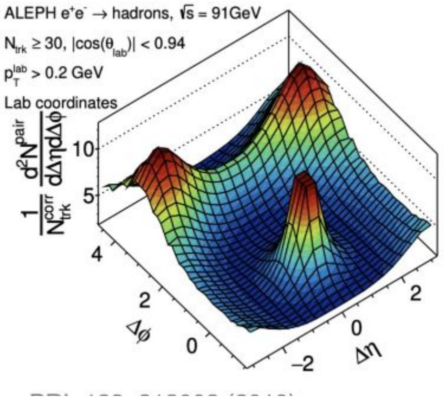
Two-particle angular correlations (*a la* heavy-ions)

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

Since then, searches pushing the boundaries towards even smaller systems

e^+e^-

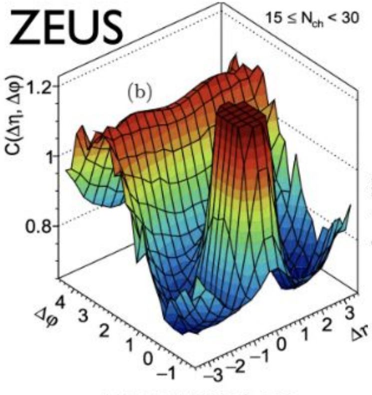
N_{ch}~30



PRL 123 212002 (2019)

ep

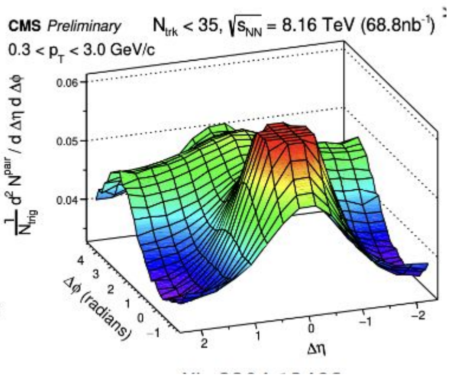
N_{ch}~30



JHEP 04 (2020) 070

γp

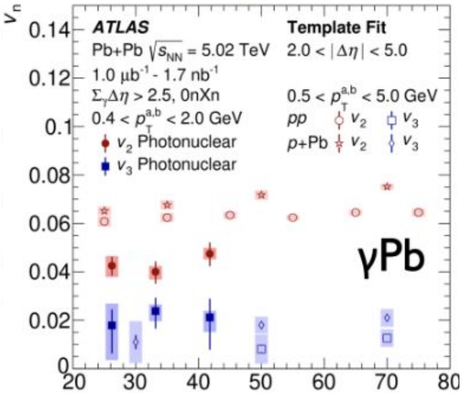
N_{ch}~20



PLB 844 (2023) 137905

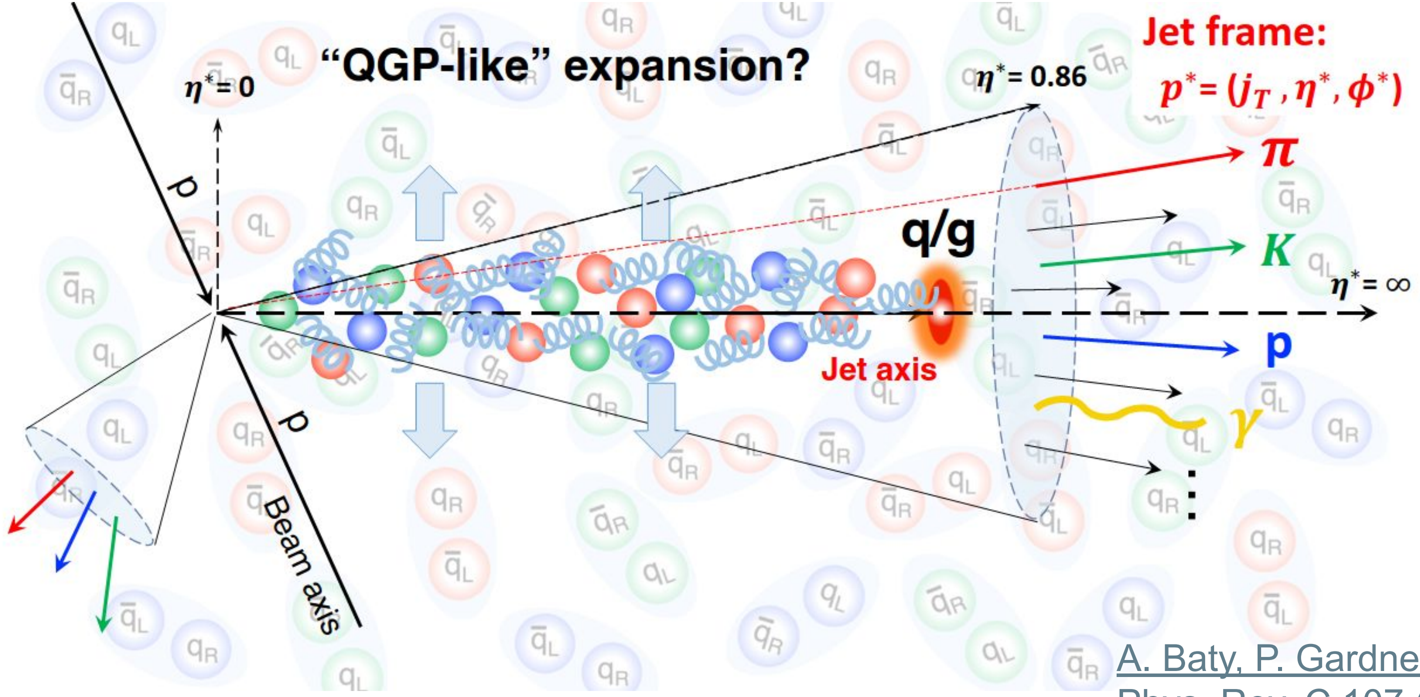
γPb

N_{ch}~40



PRC, 104 014903 (2021)

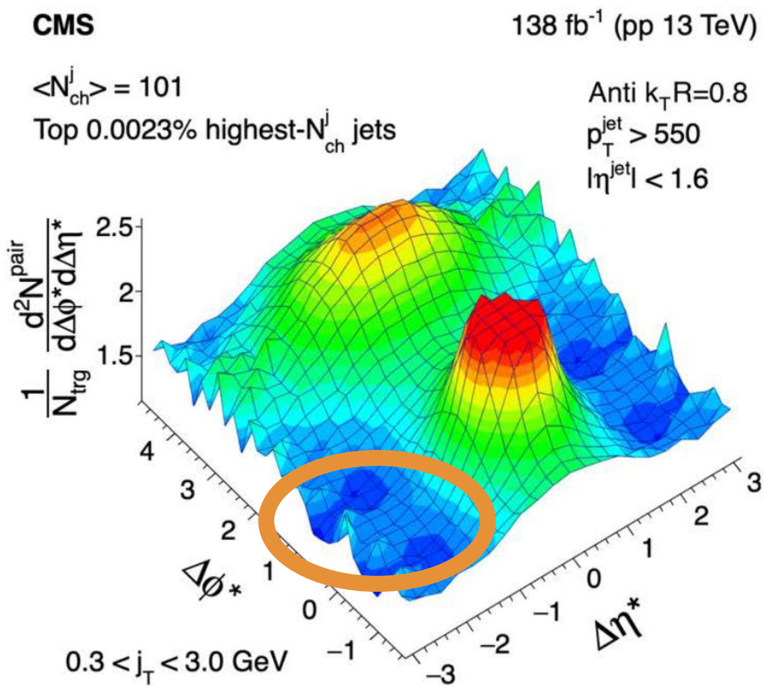
Search for intrajet collective behavior (small system?)

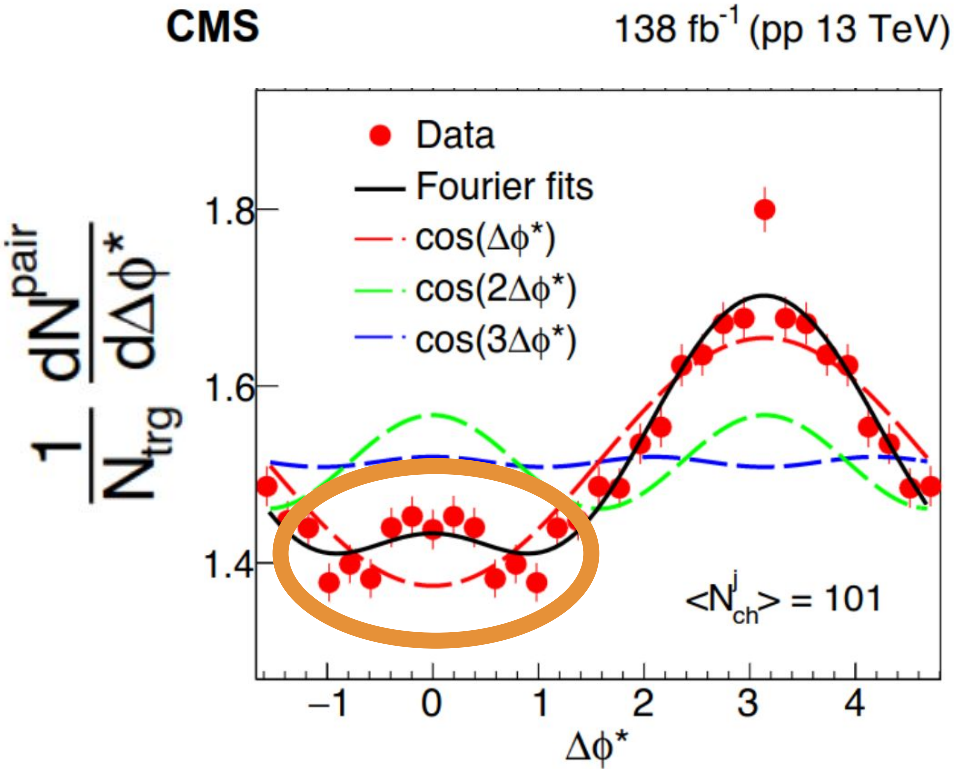


[A. Baty, P. Gardner, W. Li, Phys. Rev. C 107 (2023) 064908]

high N_{ch} category

arXiv:2312.17103, submitted to PRL

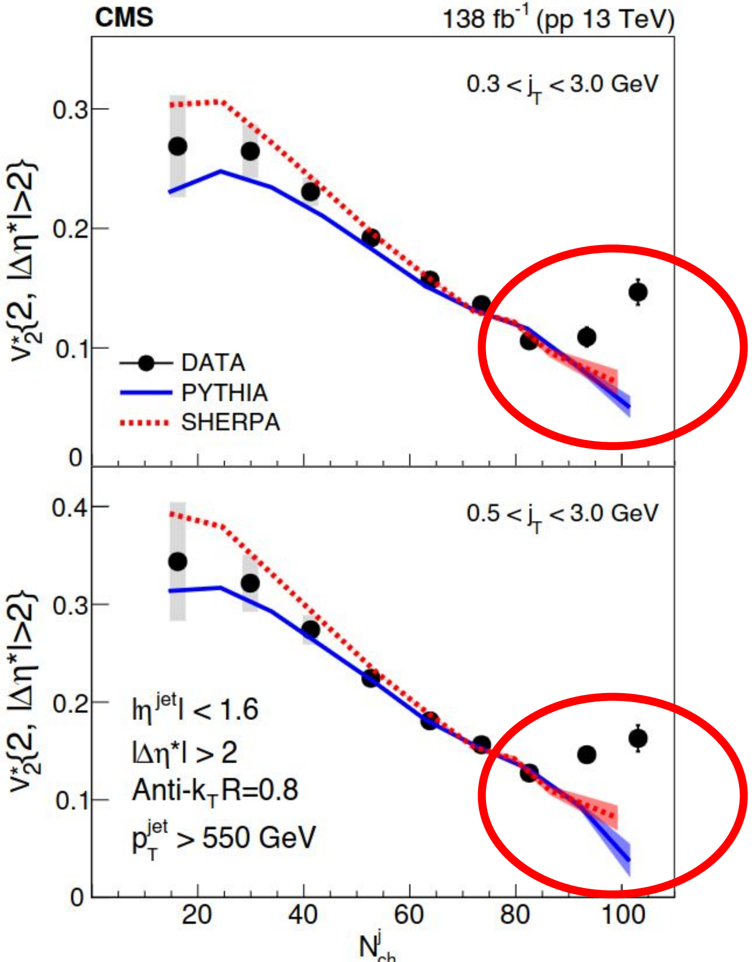




Near-side ridge-like structure at Δφ* ~ 0

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}~ 80

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

Could be extended (e.g., EEC in $\Delta\eta$–$\Delta\varphi$? Lund emissions as function of $k_{T,cut}$?)

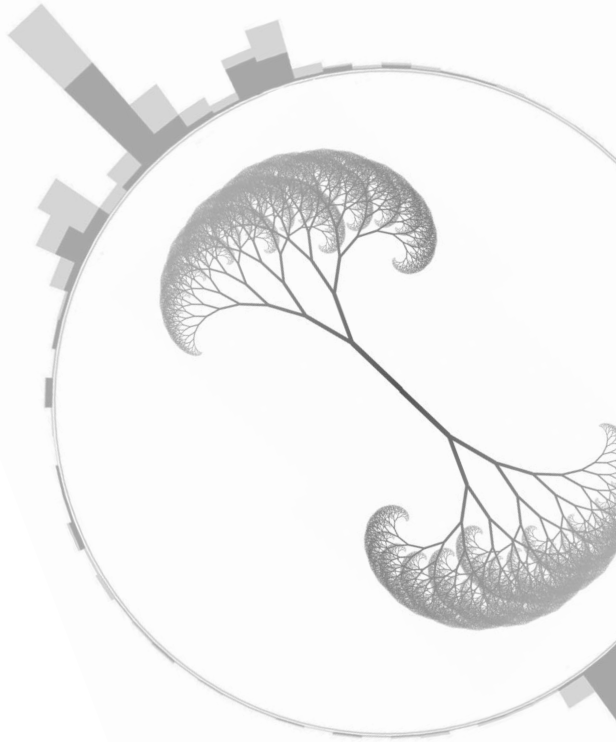
Summary

- 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

- Lund plane & EECs have complementary sensitivities to infrared scales

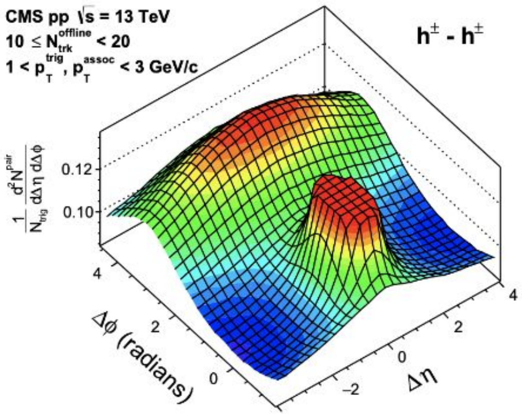


Two-particle angular correlations (*a la* heavy-ions)

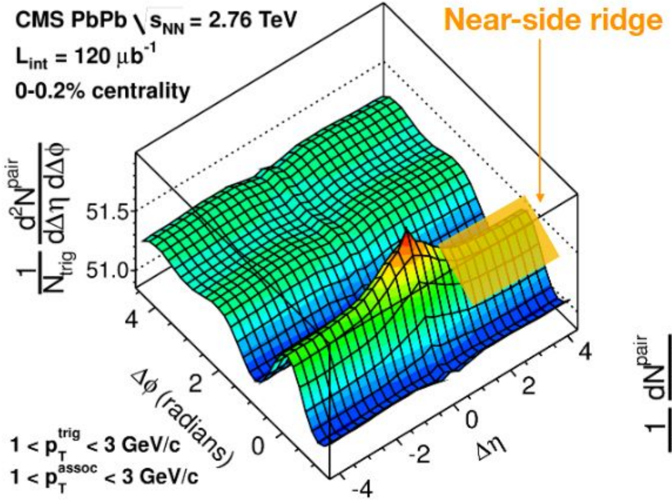
- **Near-side ridge** typical sign of collective behavior
- Fourier harmonics decomposition, nonzero $V_{2\Delta}$ associated with anisotropic expansio

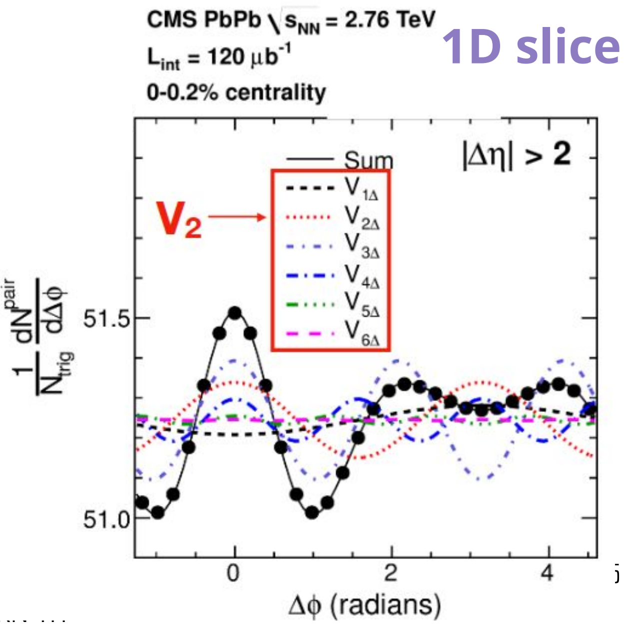
$$\frac{1}{N_{ch}}\frac{dN^{pair}}{d\Delta\phi} \propto \sum_{n=1}^{\infty} V_{n\Delta}\cos(n\Delta\phi)$$

Inclusive pp



PbPb

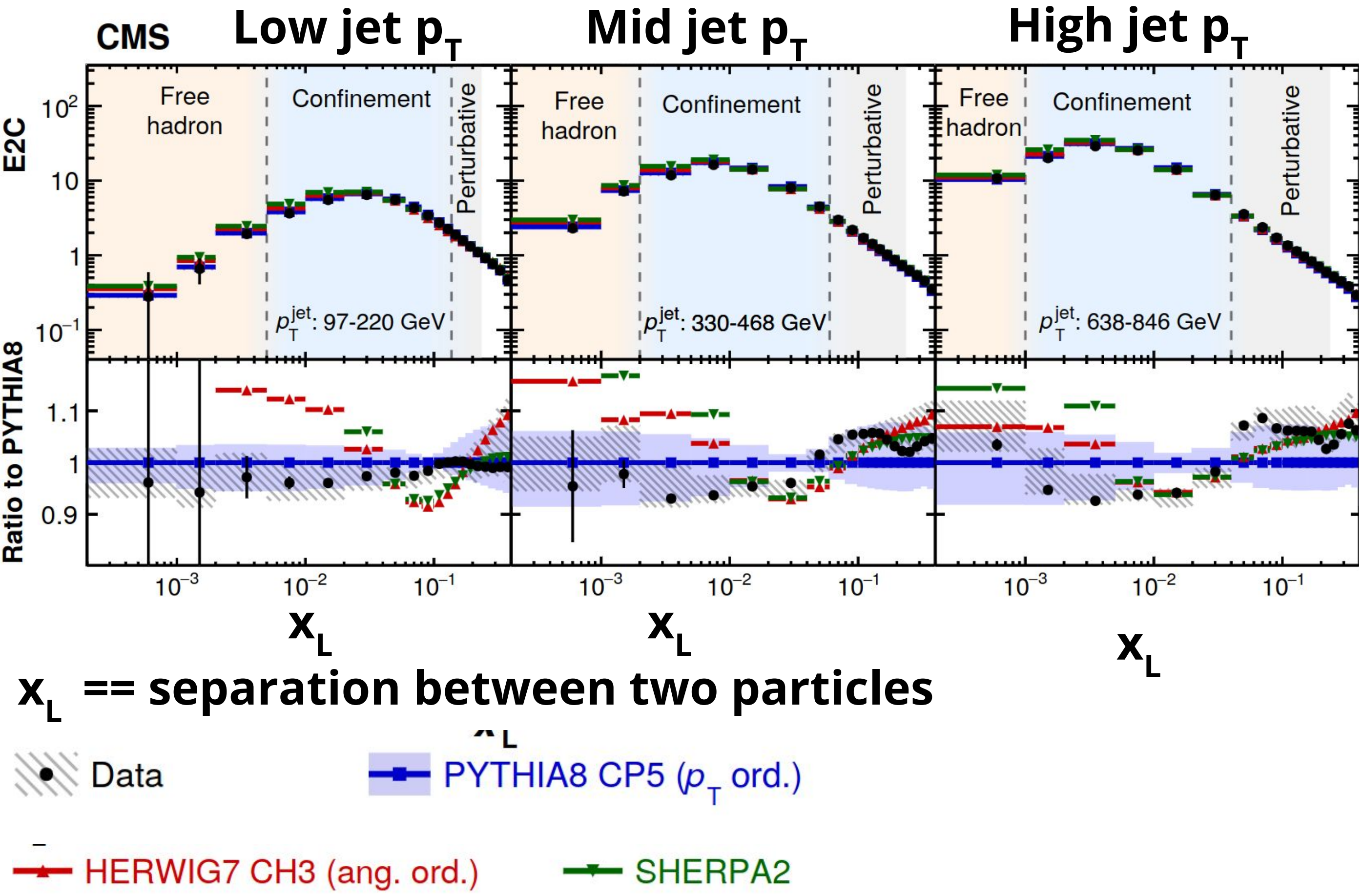




CMS, Phys. Lett. B 765 (2017) 193

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)

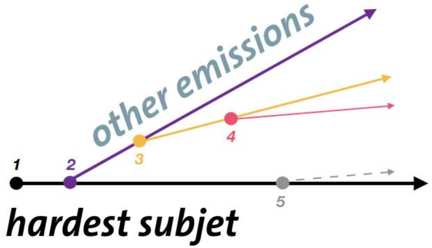
PYTHIA8 CP5 undershoots data at higher jet p_T

HERWIG7 CH3 & SHERPA2 describe data better

ATLAS Lund subjet multiplicities

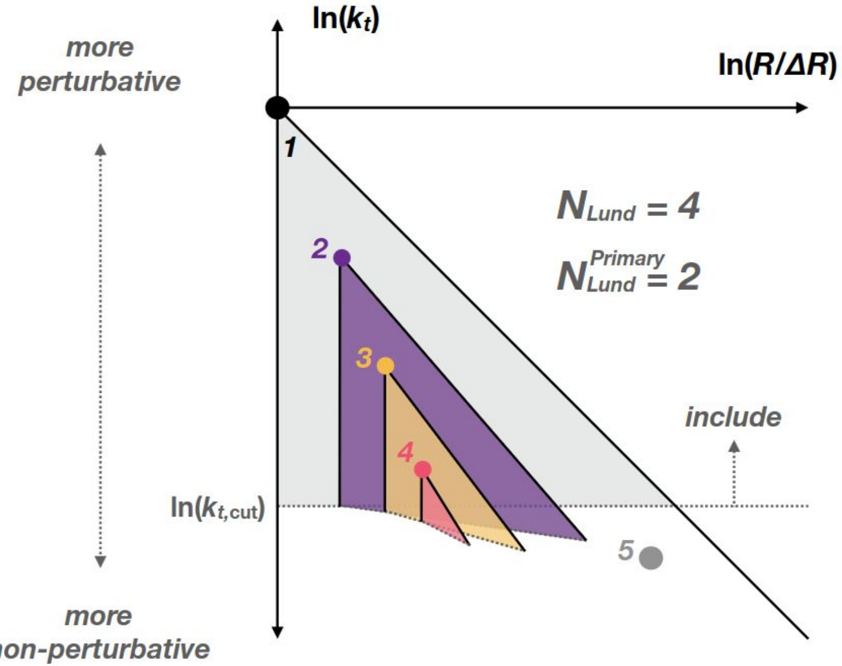
Proposed by *R. Medves, A. Soto-Ontoso, G. Soyez, JHEP04(2023)104*

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

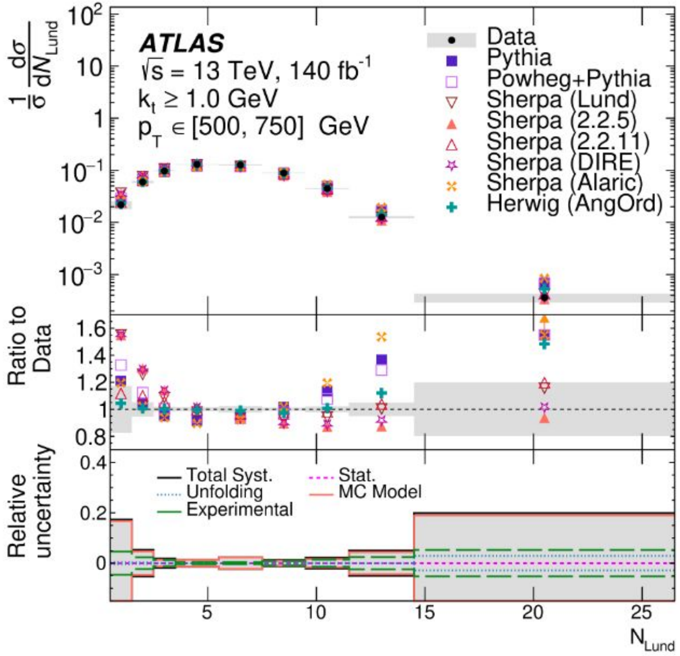
nonp

Lund subjet multiplicity distributions

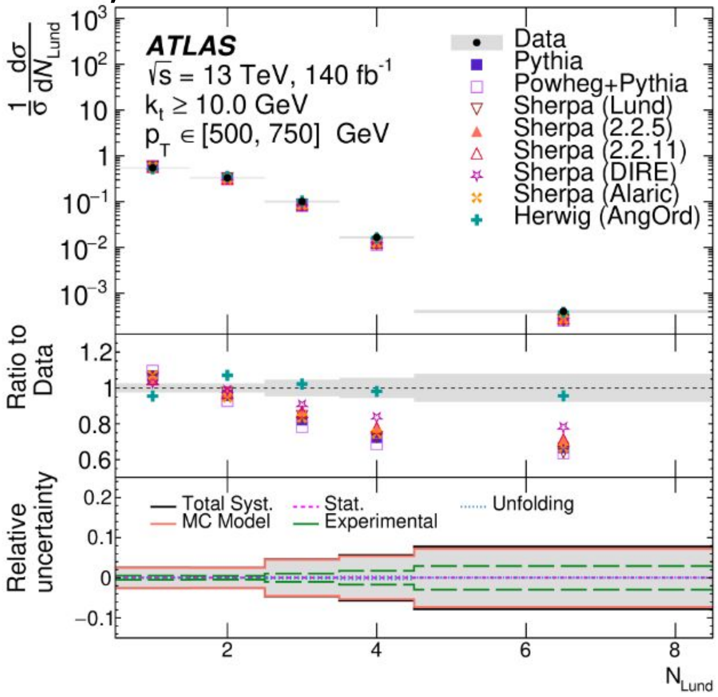
[arXiv:2402.13052, *submitted to PLB*]

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)



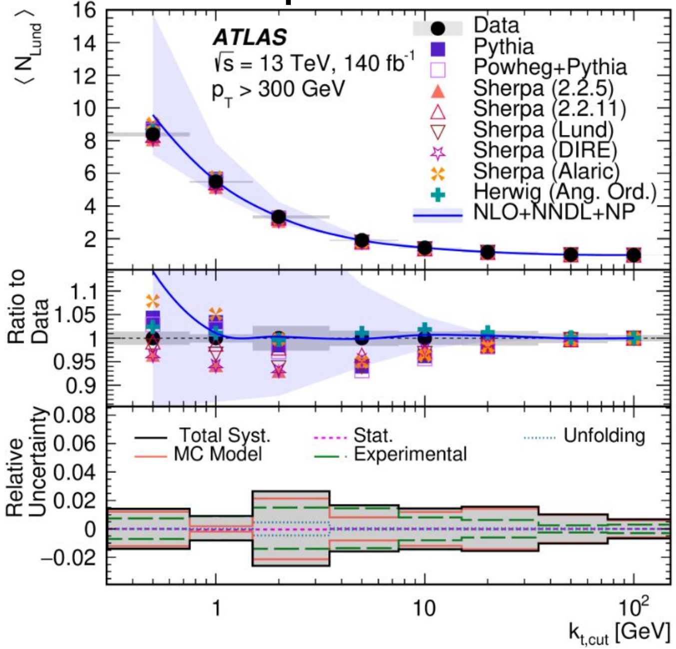
Challenging to describe high-N_{Lund} tails

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

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

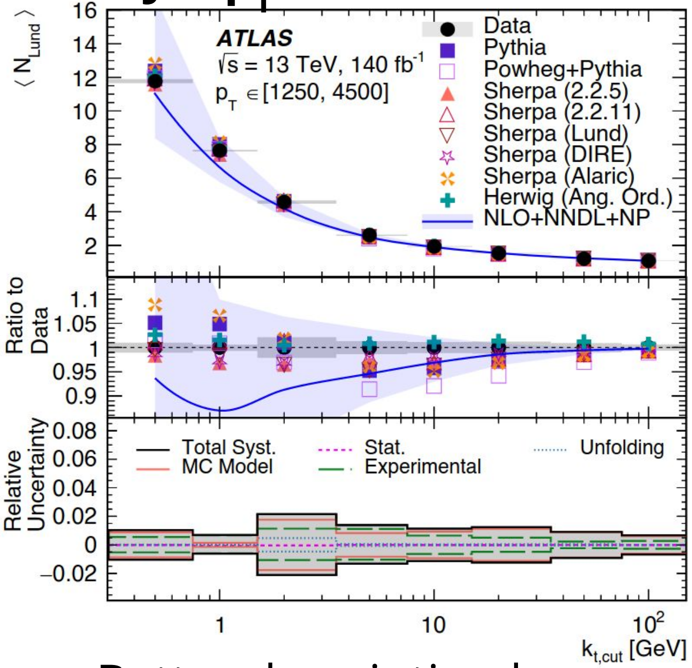
[arXiv:2402.13052, *submitted to PLB*]

Jet p_T > 300 GeV



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

Jet p_T > 1250 GeV



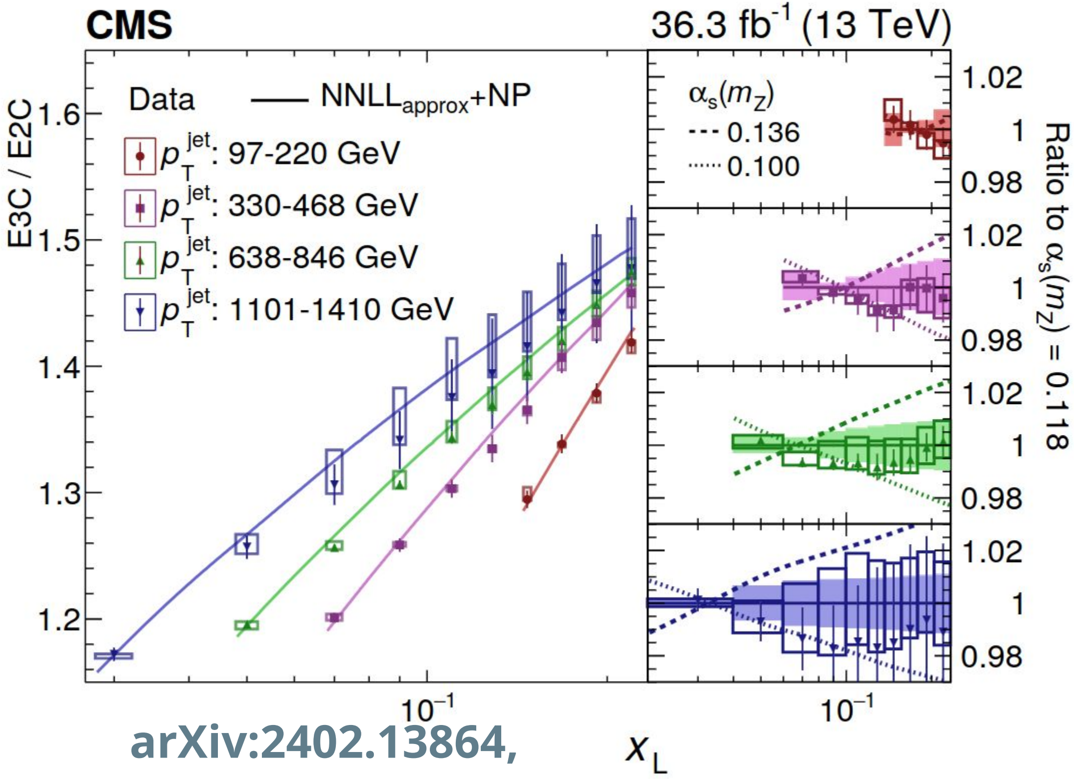
Better description by **Herwig7 angle-ordered**

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

Other MCs tend to ***undershoot***

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$_{approx}$** pQCD calculation with nonperturbative corrections

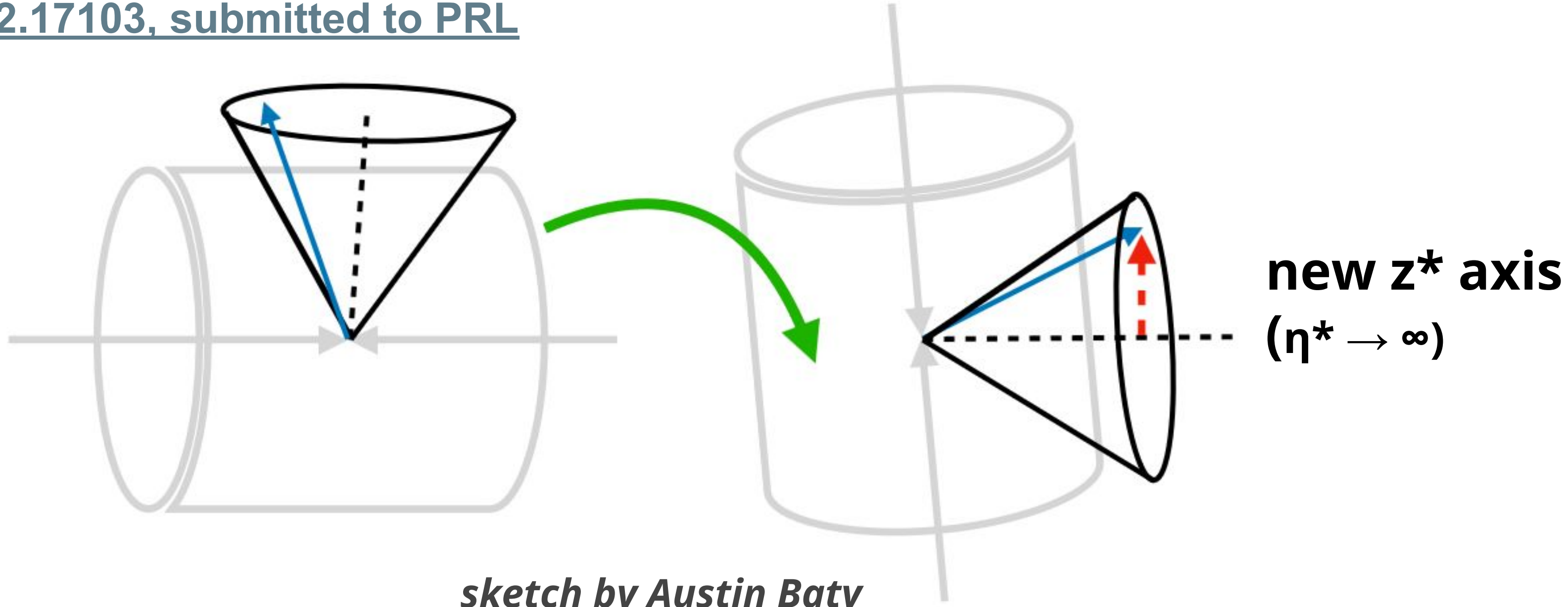
$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050} \ (\sim 4\ \%)$$

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

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

arXiv:2312.17103, submitted to PRL

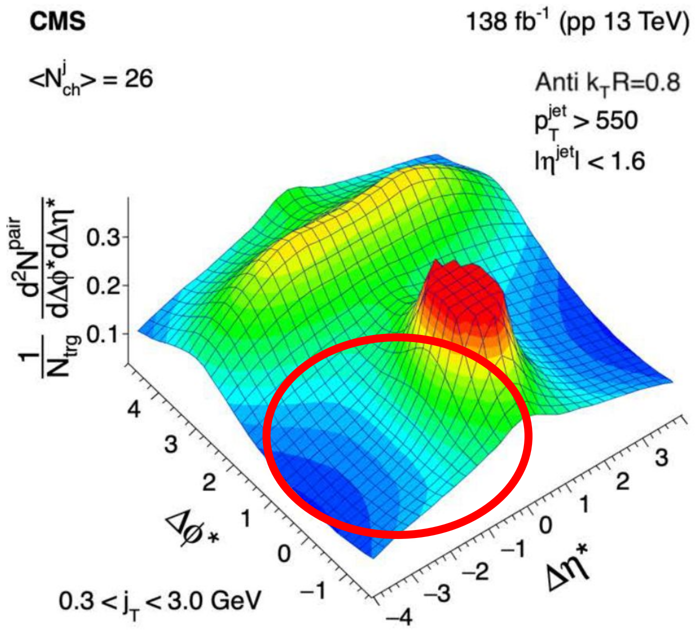


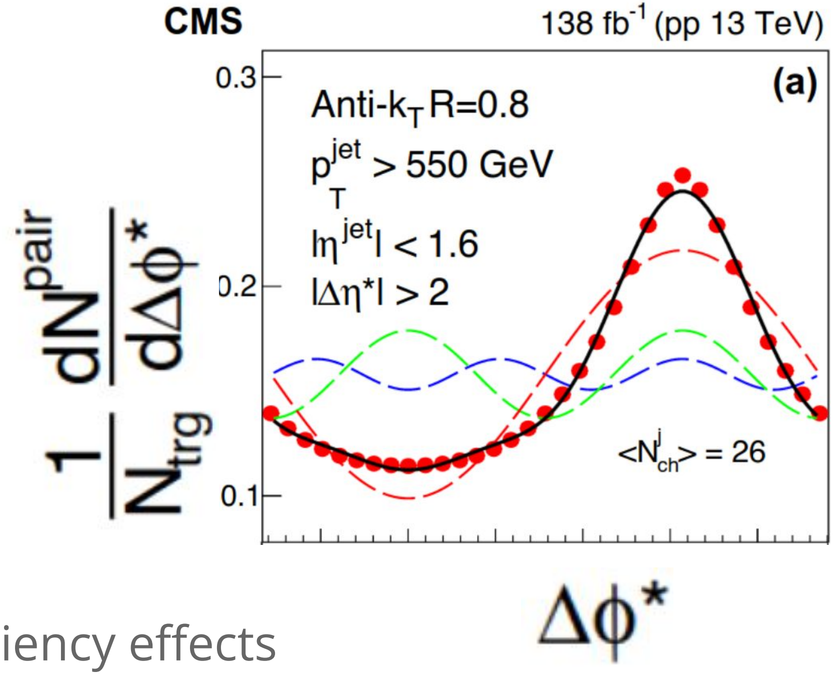
sketch by Austin Baty

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

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





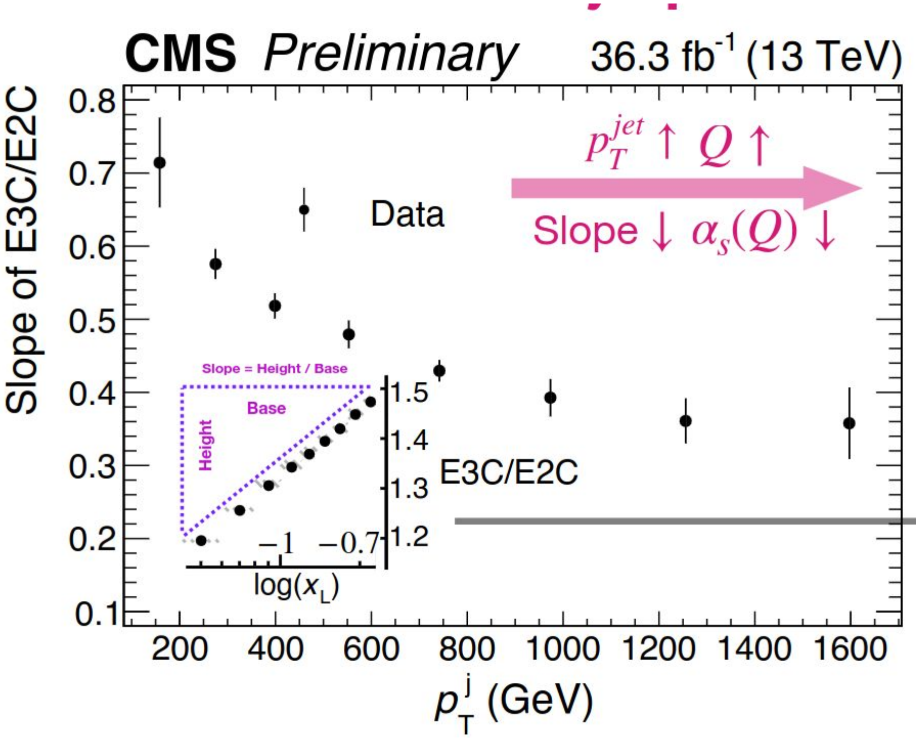
2D distributions corrected for acceptance/efficiency effects

No near-side ridge at Δφ* ~ 0

arXiv:2312.17103, submitted to PRL

E3C/E2C sensitive to running α_s

CMS-PAS-SMP-22-015



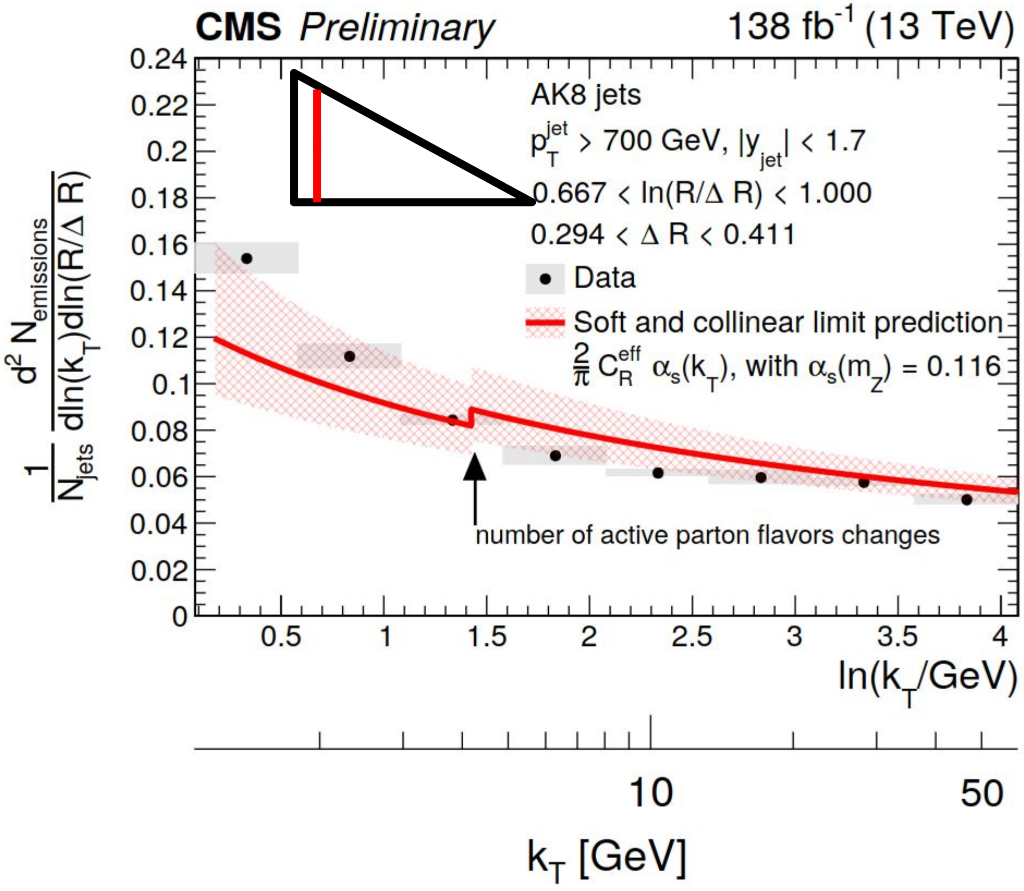
At LL, slope of E3C/E2C ratio sensitive to α_S(Q)

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

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



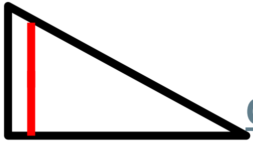
Recall LO pocket formula for Lund density:

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

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

(Assuming q/g fractions from PYTHIA8)

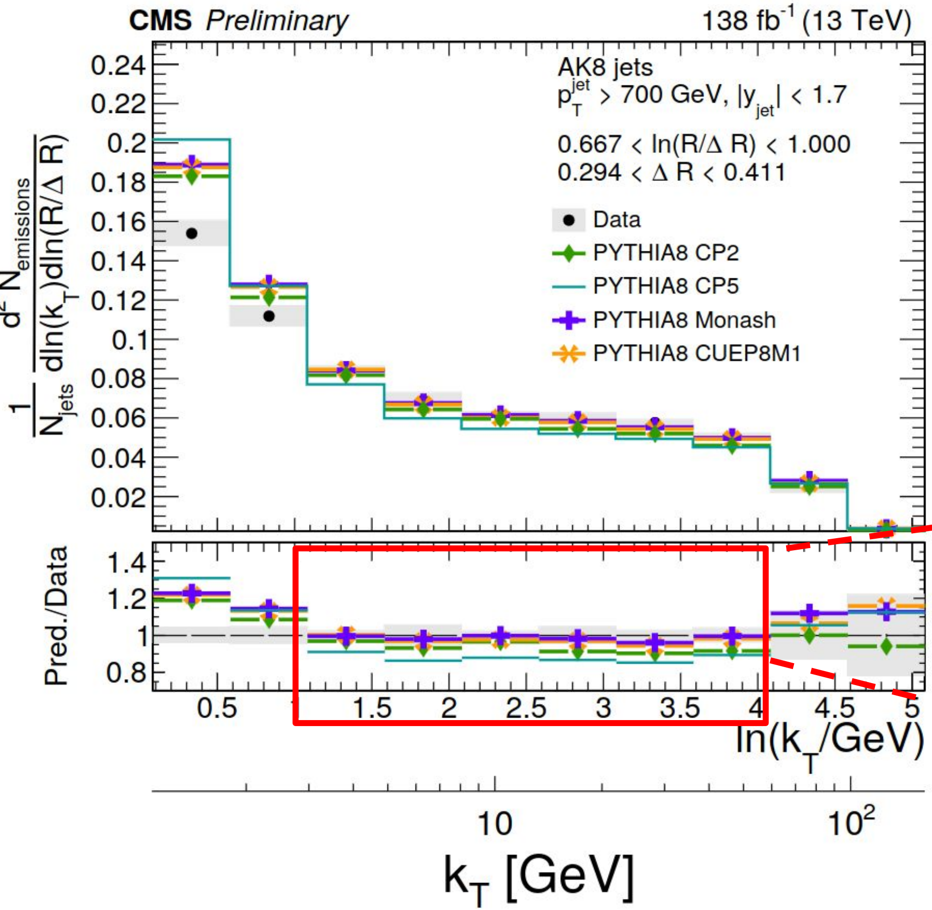
Large angle emissions



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

CMS-PAS-SMP-22-007

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

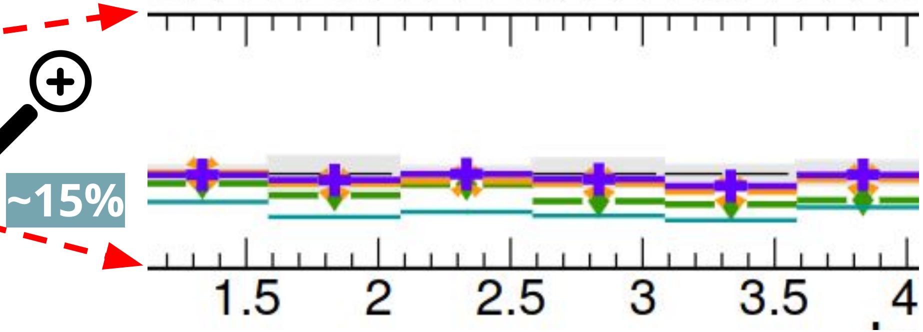


Monash/CUEP8M1: $\alpha_S^{FSR}(m_Z) = 0.1365$ ***(best description)***

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



k_T between 3 – 50 GeV