Jet substructure on the Lund plane

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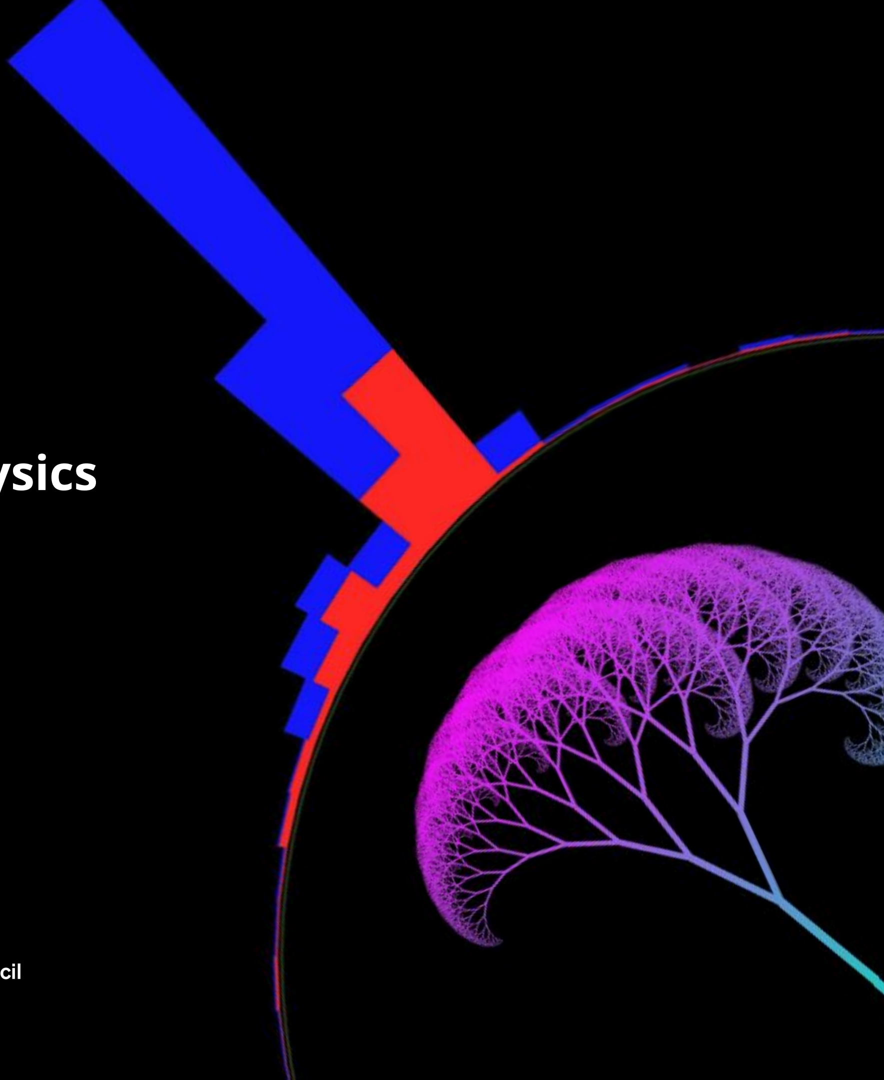
(Sapienza Università di Roma)

Workshop on medical and high energy physics
@ Sonora, Mexico
May 21st–24th



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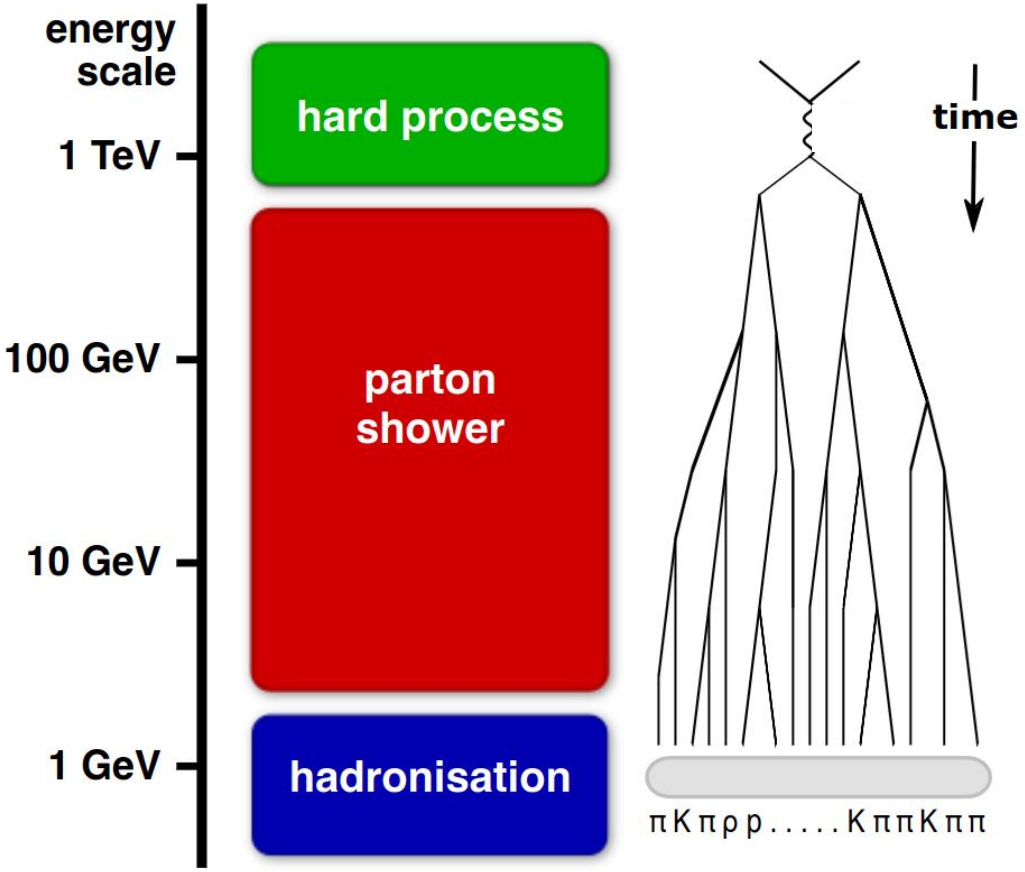
Jet formation is a multiscale probe of QCD evolution



G. Salam's sketch

From Q ~ 1 TeV to Λ_{QCD}~ 200 MeV

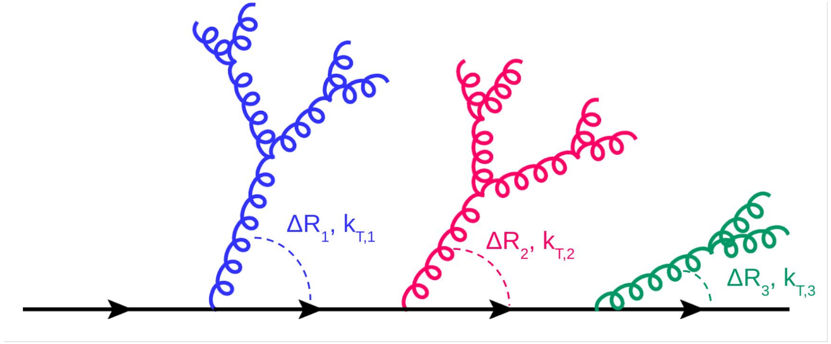
Depending on observable & jet p_T and R: sensitivity to parton shower, hadronization, underlying event, color reconnection, ...

Higher jet p_T ⇒ "longer" parton cascade

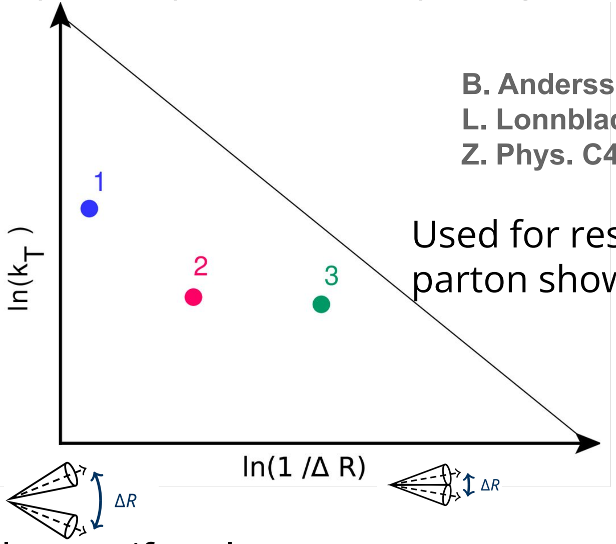
Results on jet fragmentation functions covered by ***Ezra Lesser*** *next*

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

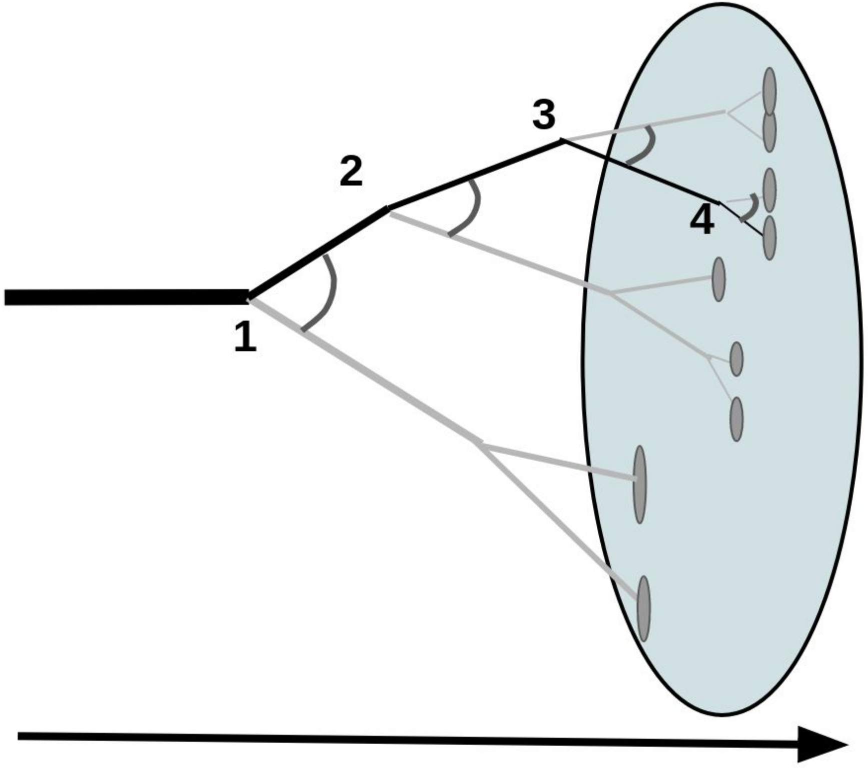
Used for resummation and parton shower development

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

$$\mathcal{P} \propto \alpha_s \frac{dk_T}{k_T}\frac{d\Delta R}{\Delta R} = \alpha_s d\ln(k_T) d\ln(\Delta R)$$ ← **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

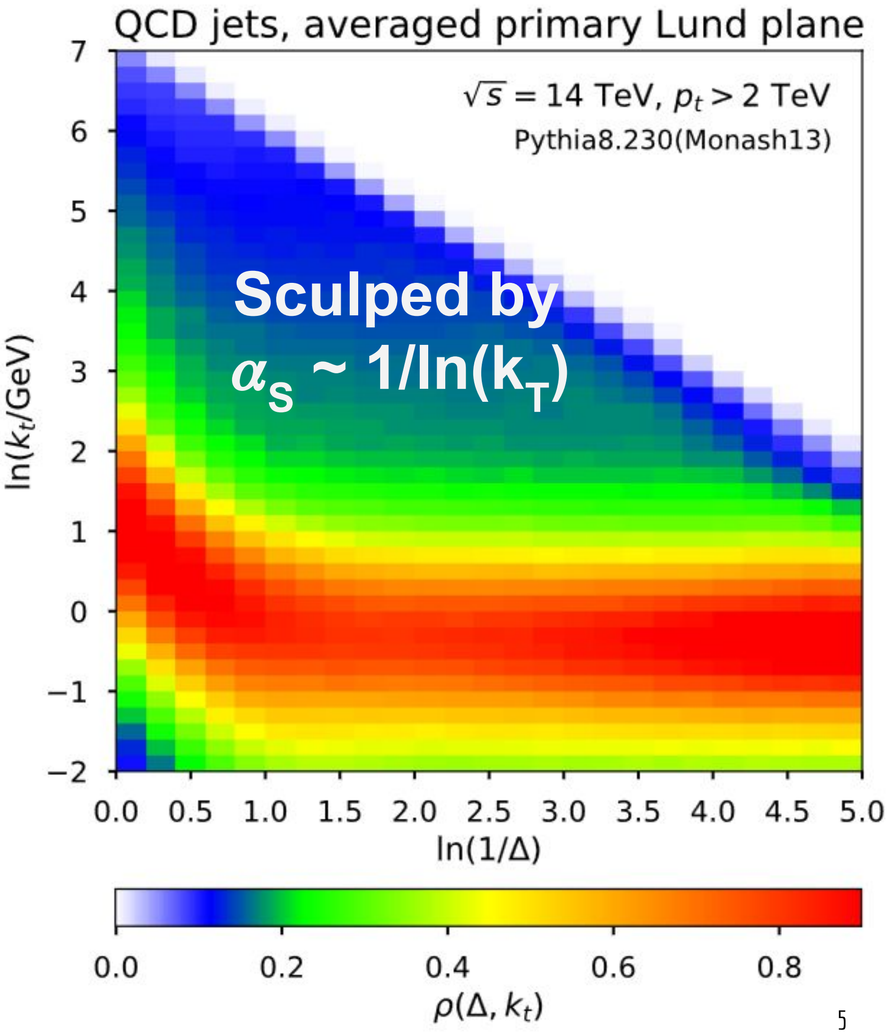
Define a *jet-averaged* number of emissions,
the ``primary" Lund jet plane density

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

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

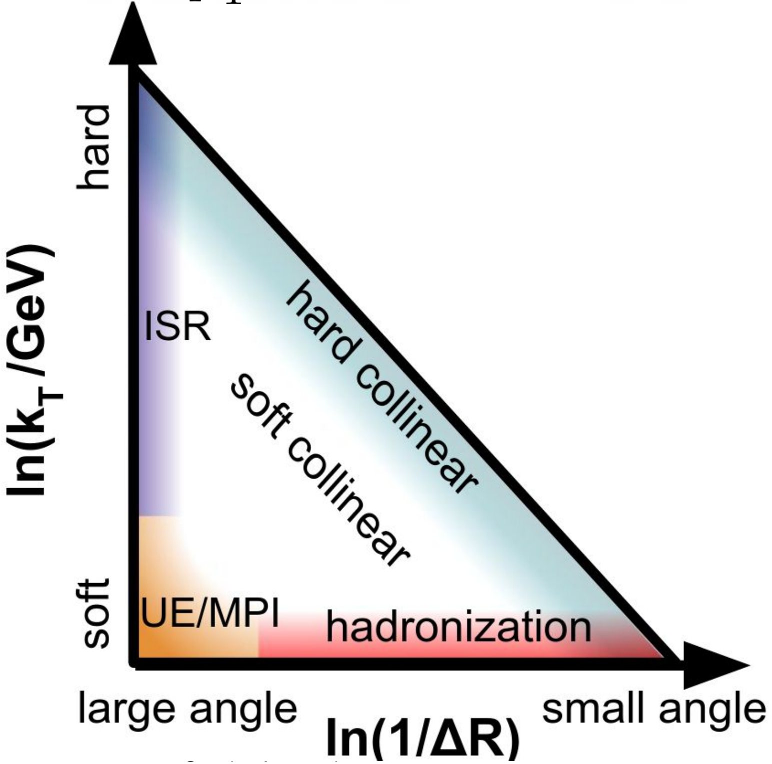


Mechanisms "factorize" in the Lund jet plane

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

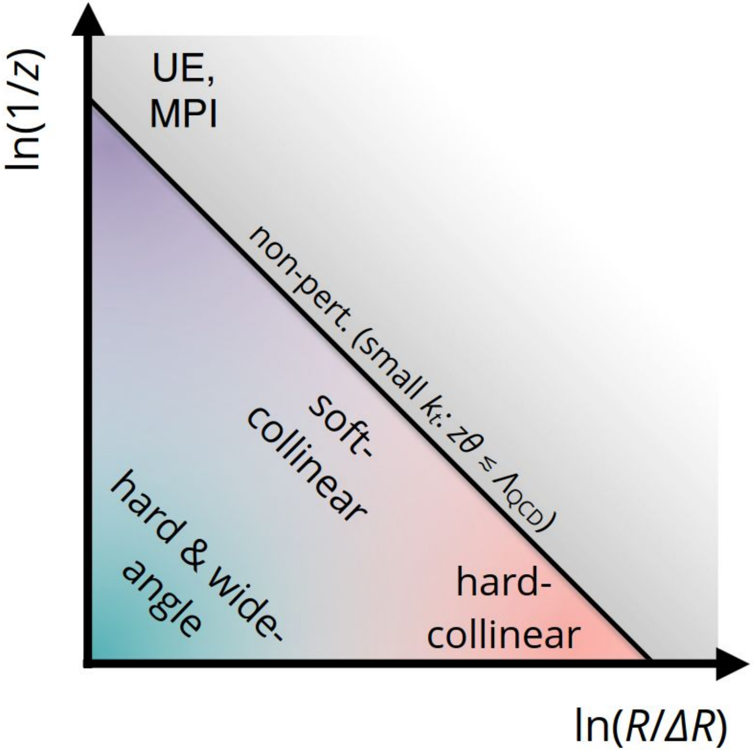
CMS Lund plane coordinates

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



ATLAS Lund plane coordinates

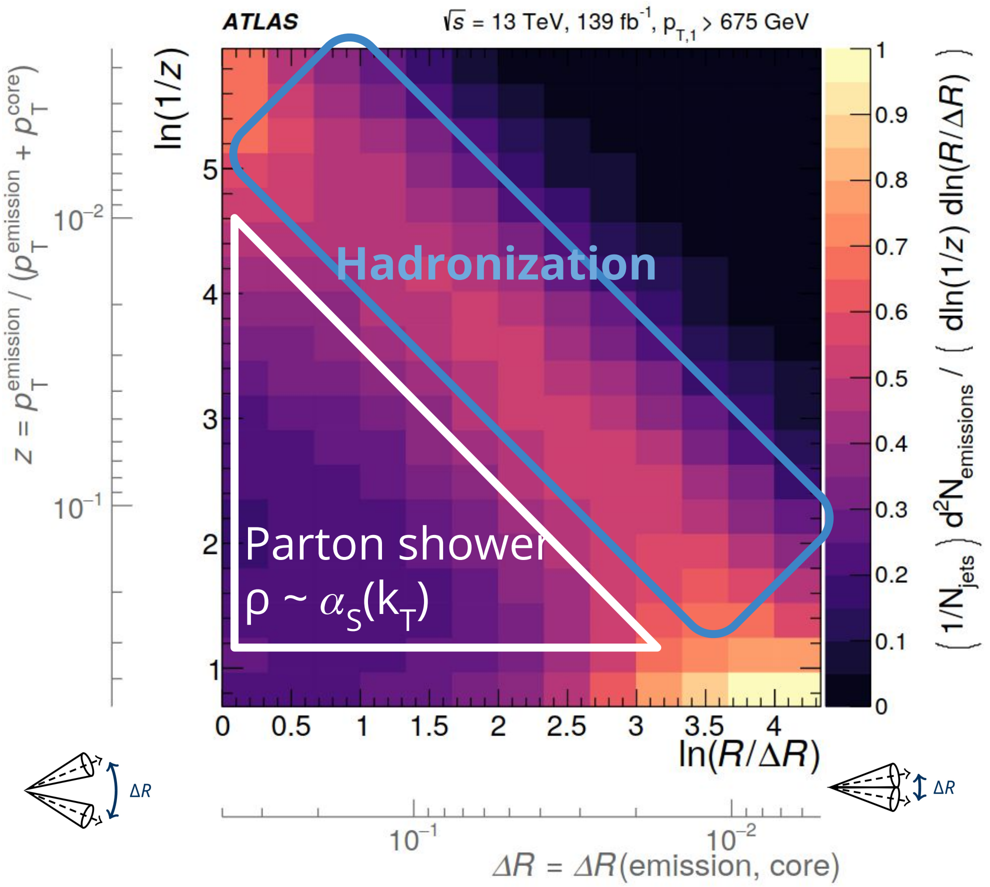
$z = p_{\mathrm{T}}^{\mathrm{softer}}/(p_{\mathrm{T}}^{\mathrm{harder}}+p_{\mathrm{T}}^{\mathrm{softer}})$ vs ΔR



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:

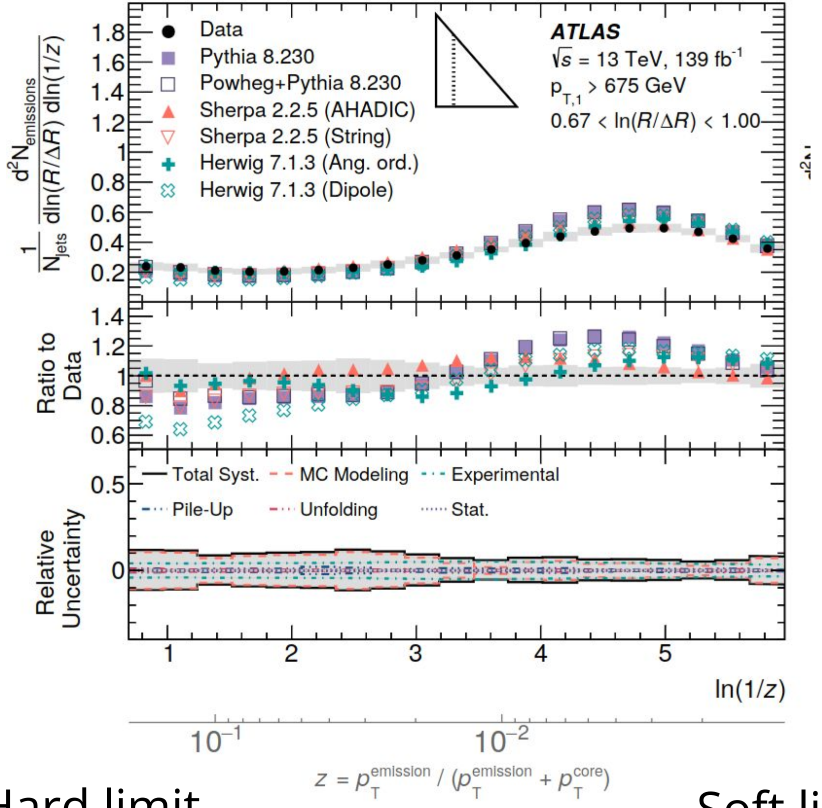
$$z = p_{T,softer}/(p_{T,softer}+p_{T,harder})$$

Multidimensional unfolding

Factorization properties in action (ATLAS)

Fixed-angle slize

PRL 124, 222002 (2020)



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**)

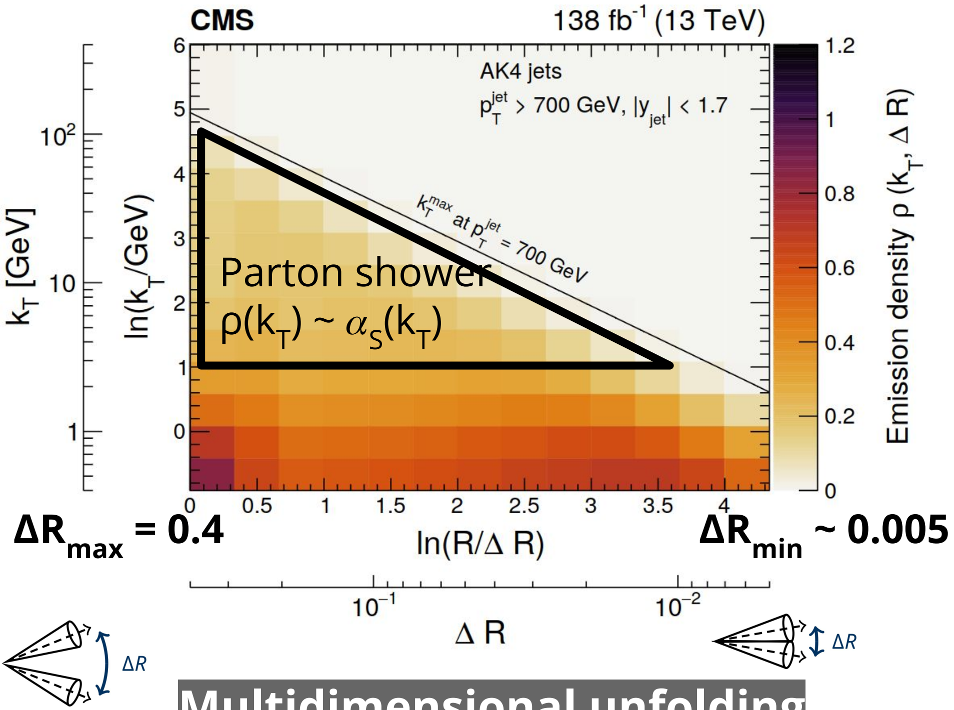
Best global description by **Herwig7.1 angle-ordered**

CMS primary Lund jet plane densities

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

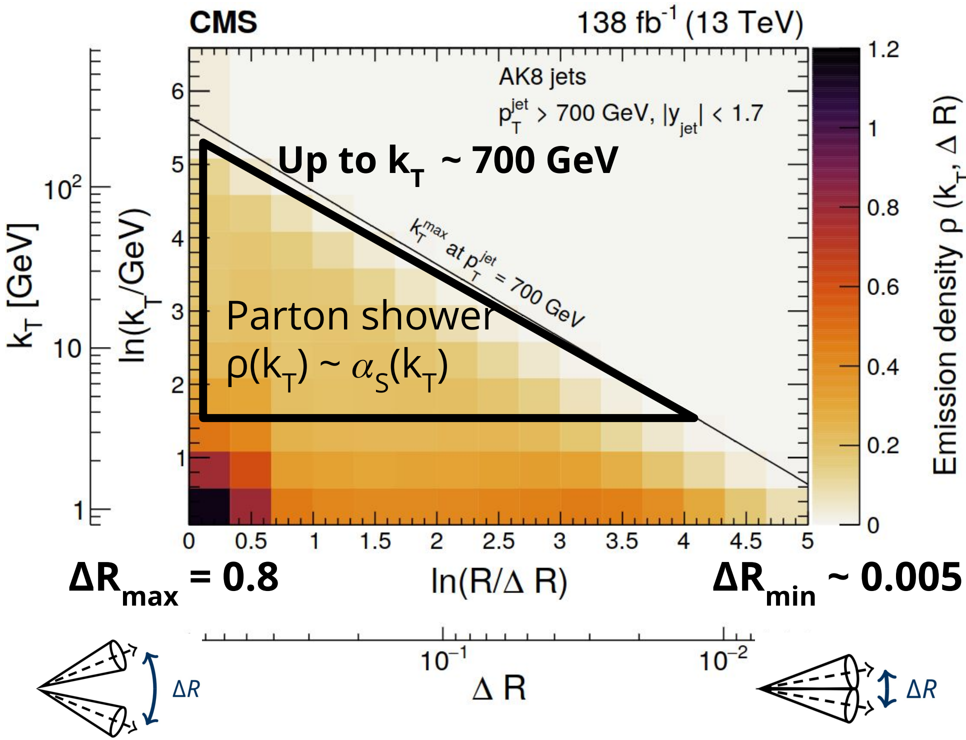
arXiv:2312.16343, accepted by JHEP

R=0.4 (standard R in Run-2)



Multidimensional unfolding

R=0.8 (large-angle & harder emissions)

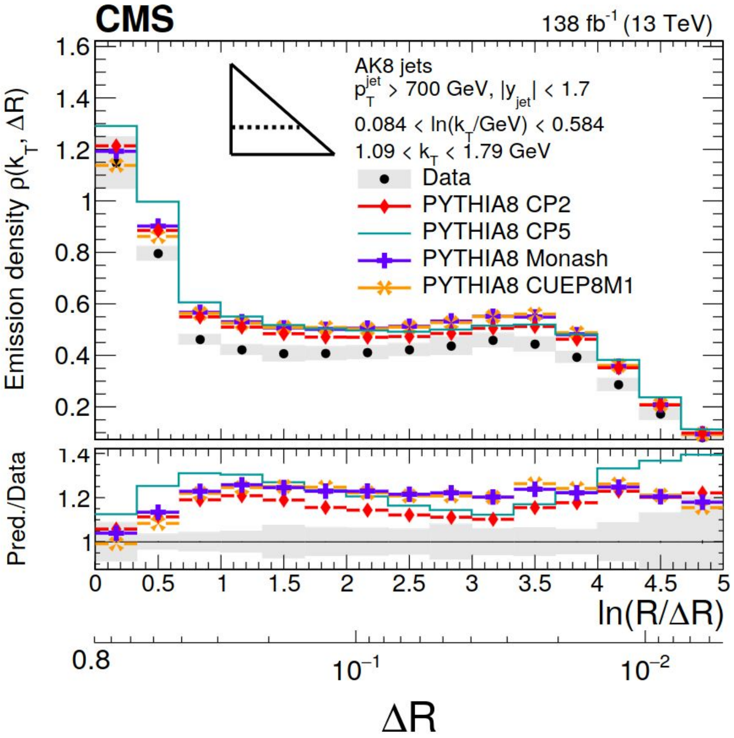


Emission density is flat for hard & collinear emissions due to $\alpha_S(k_T) \sim 1/\ln(k_T)$

arXiv:2312.16343, accepted by JHEP

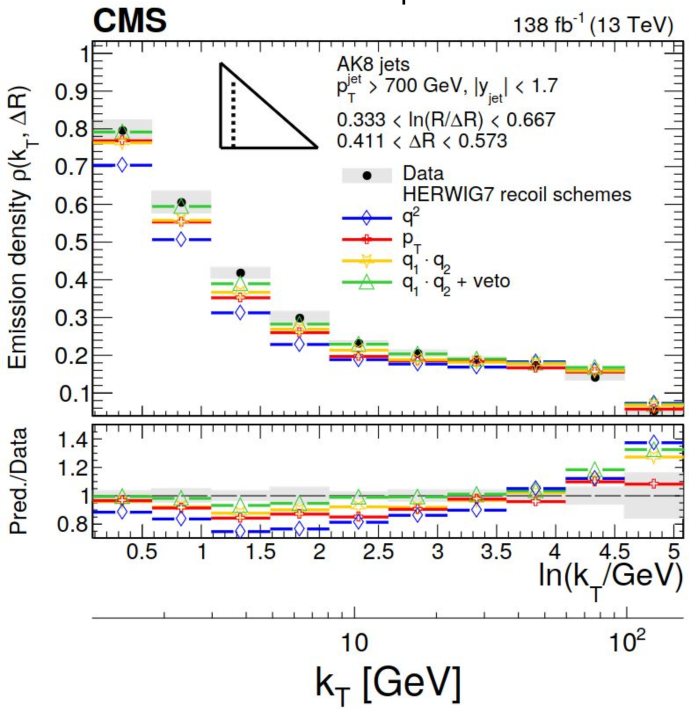
CMS Lund plane slices

Hadronization region ($k_T \sim 1$ GeV)



PYTHIA8 overshoots data by 15-20% in hadronization region

Large-angles (k_T = 1 – 200 GeV)

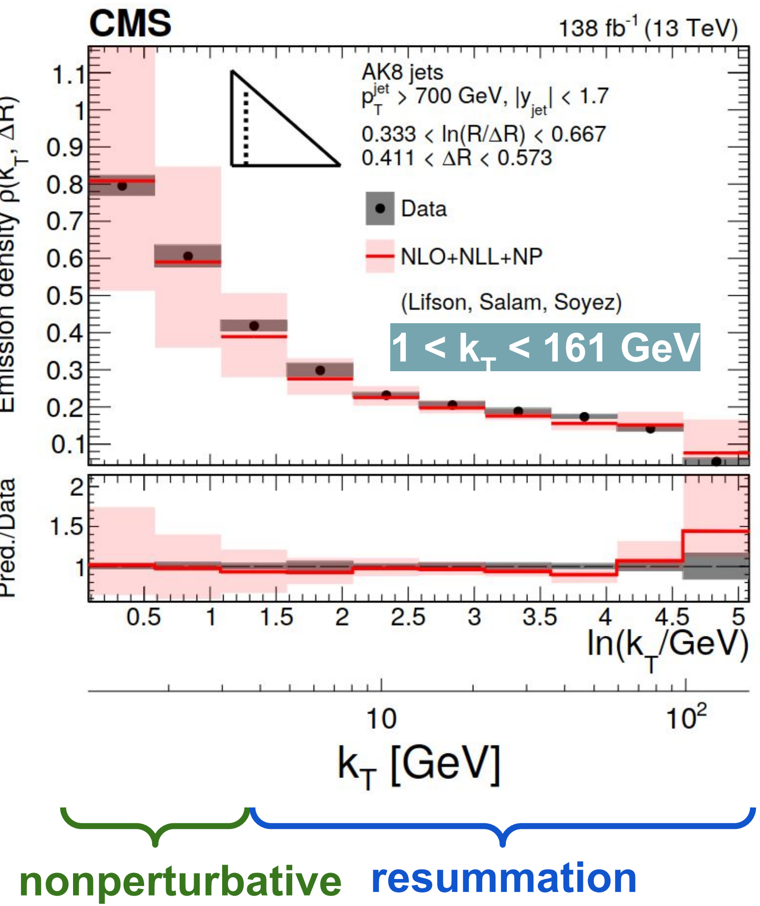


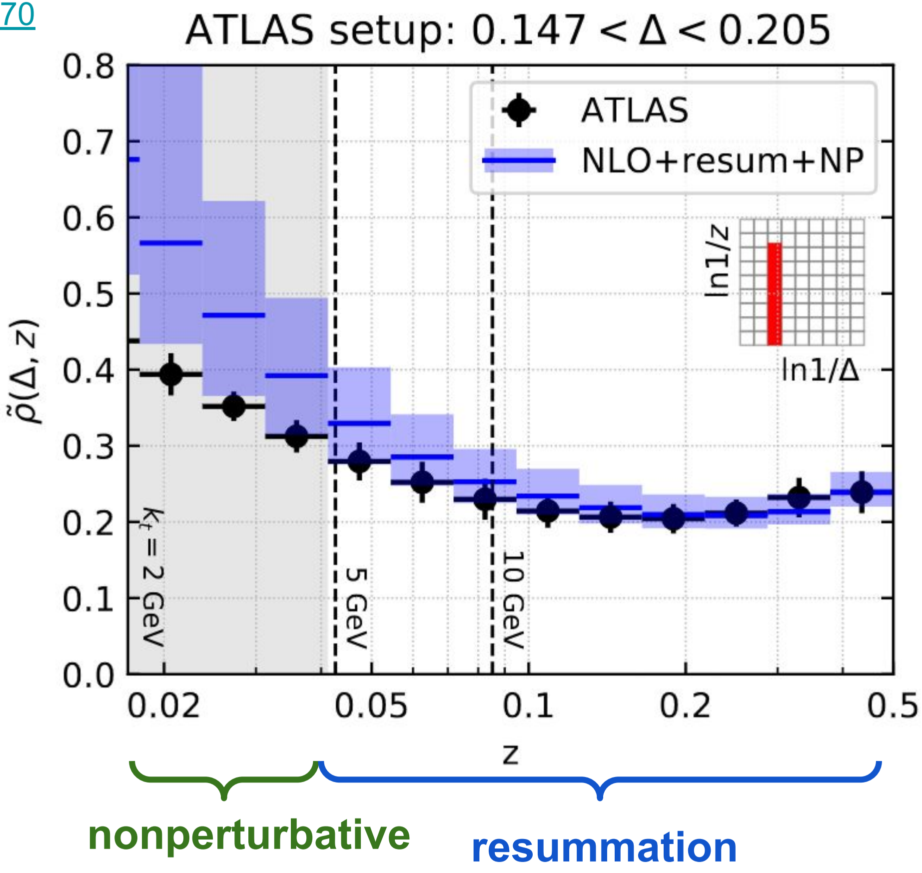
Sensitivity to parton shower recoil scheme (**Herwig7)**

Better description by Herwig7 angle-ordered with $q_1 q_2$+veto

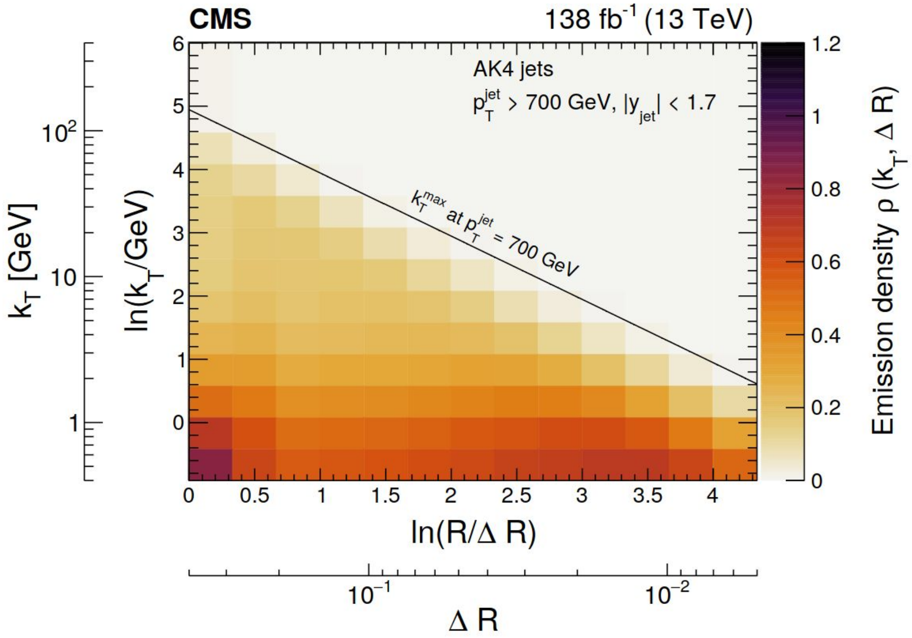
Described well by pQCD calculations (NLO+NLL+NP)

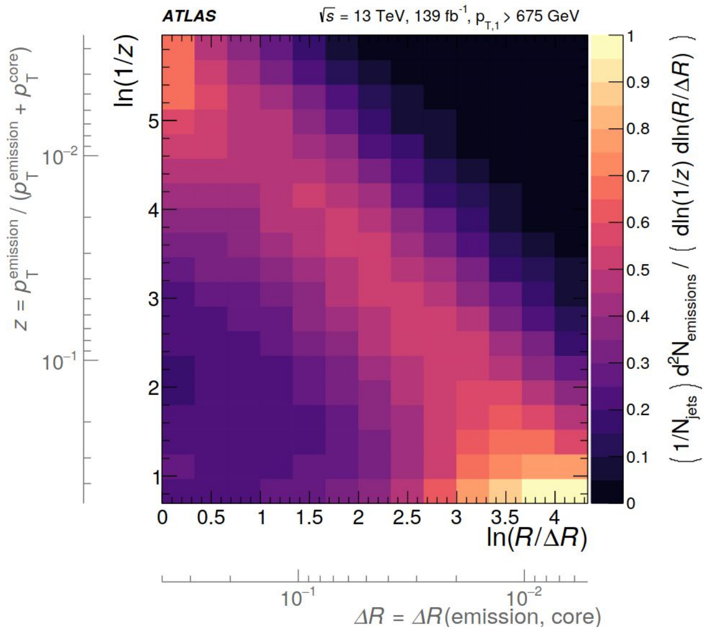
Calculations from A. Lifson, G. Salam, G. Soyez JHEP10(2020)170





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" ($k_T = z\, \mathbf{p_T^{mother}}\, \Delta R$)

ATLAS Lund subjet multiplicities

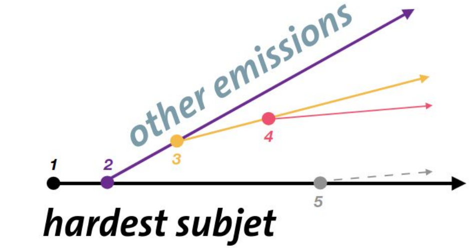
Proposed by [R. Medves, A. Soto-Ontoso, G. Soyez, JHEP04(2023)104]

[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 **($N^{primary}_{Lund}$)**

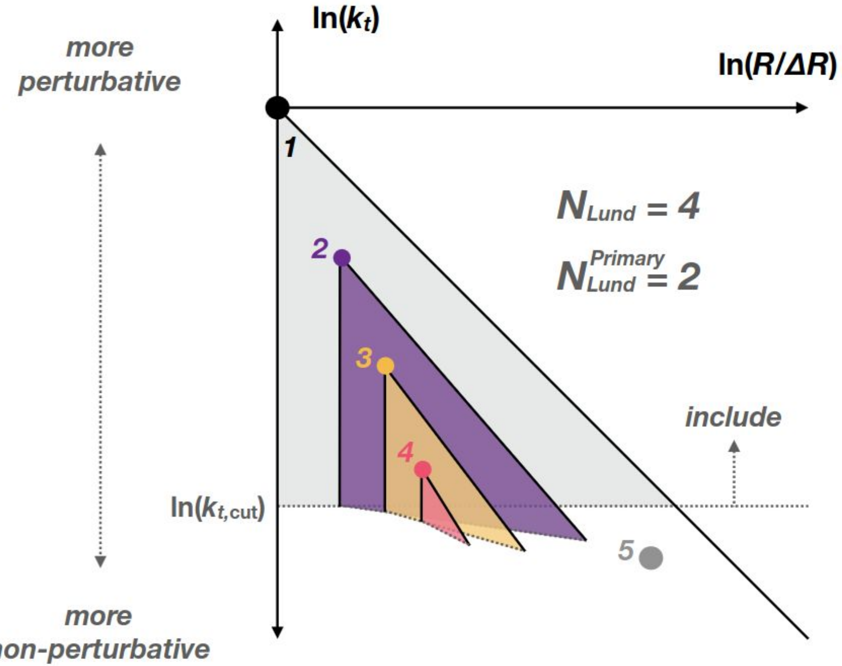


More inclusive observable, closely related to (sub)jet multiplicities at LEP

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



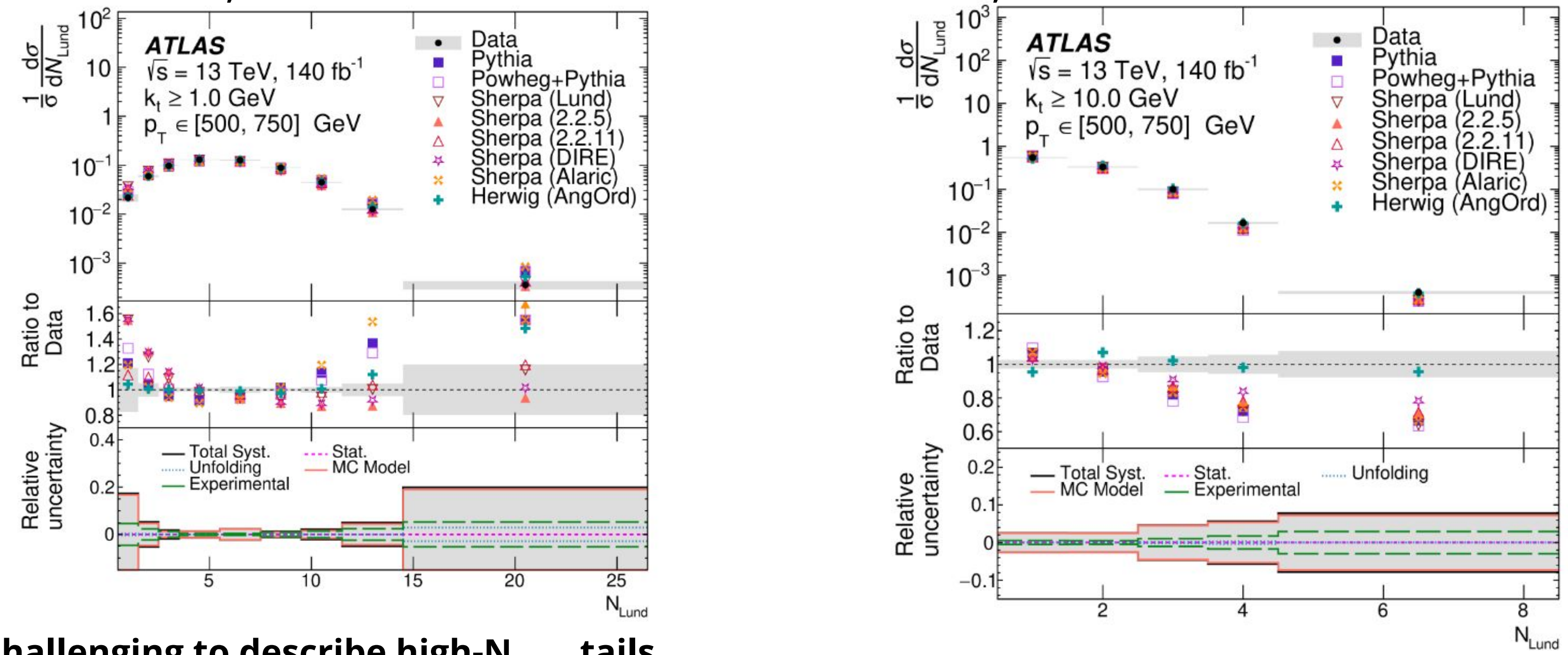
Sono

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)**



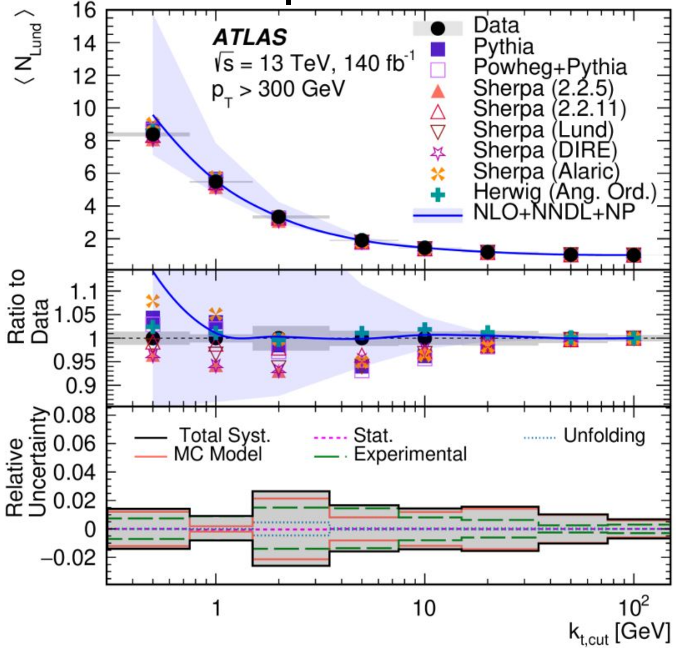
Challenging to describe high-N_{Lund} tails

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

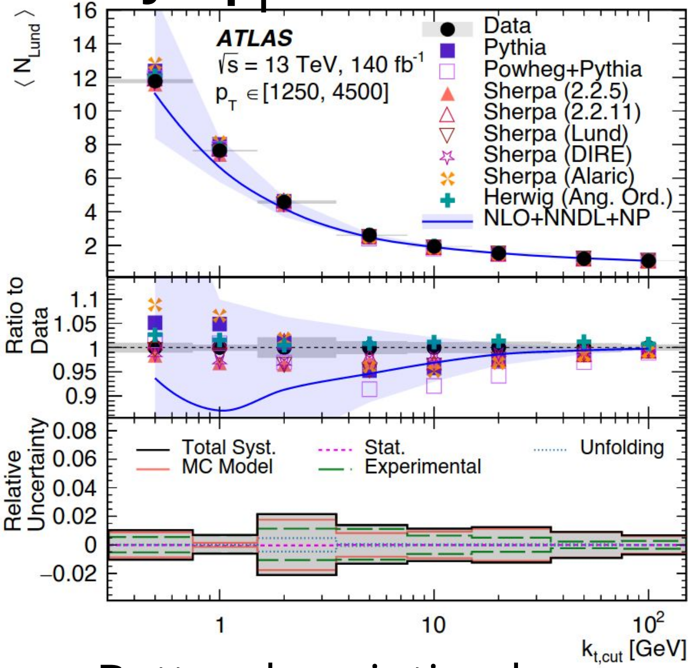
averaged Lund subjet multiplicities vs $k_{T,\,cut}$

[arXiv:2402.13052, *submitted to PLB*]

Jet p_T > 300 GeV



Jet p_T > 1250 GeV



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

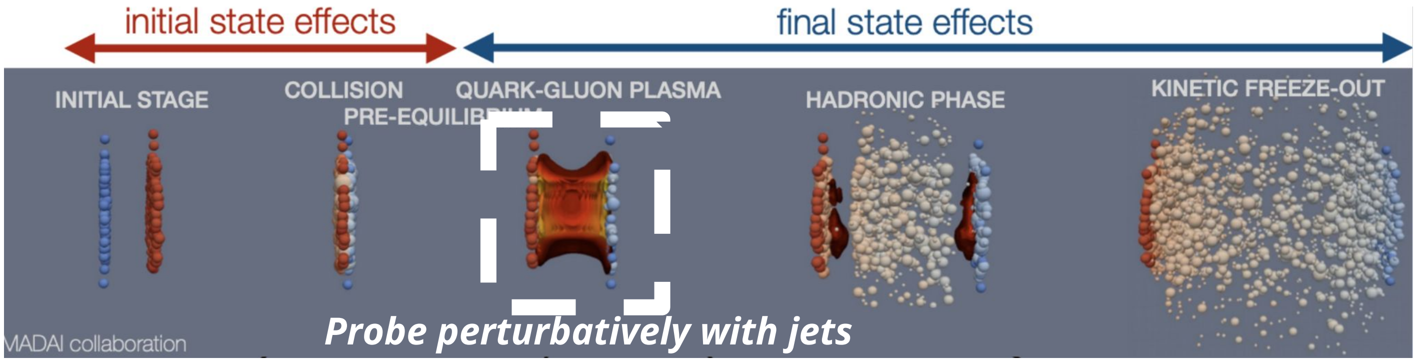
Better description by **Herwig7 angle-ordered**

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

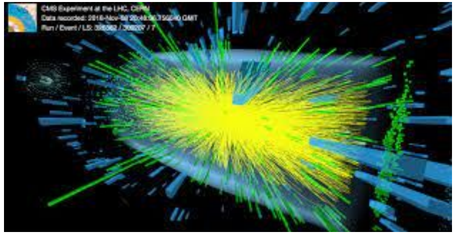
ntg, 2024

Other MCs tend to ***undershoot***

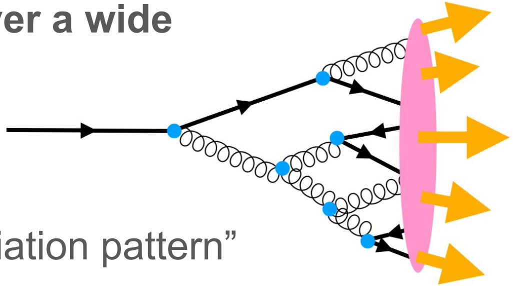
Probing QCD at high densities & high temperatures



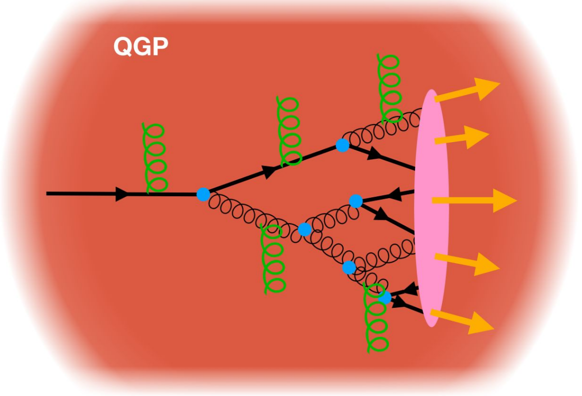
What we see



pp ("vacuum")



PbPb (in medium)



Jets are used to probe the medium over a wide range of momentum scales

Jet quenching == "modification of jet radiation pattern"

sketches from Rey Cruz

Spacetime picture of quark-gluon plasma evolution

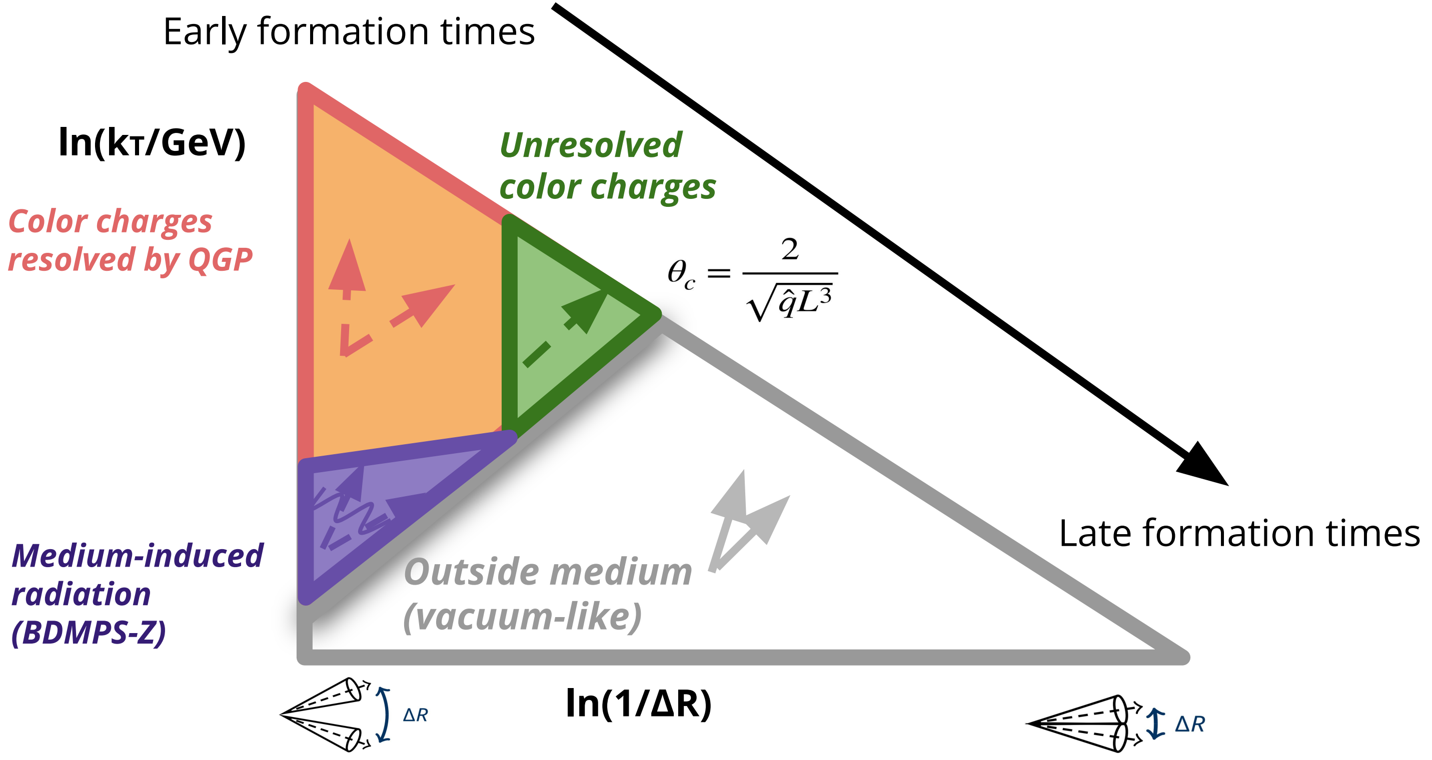
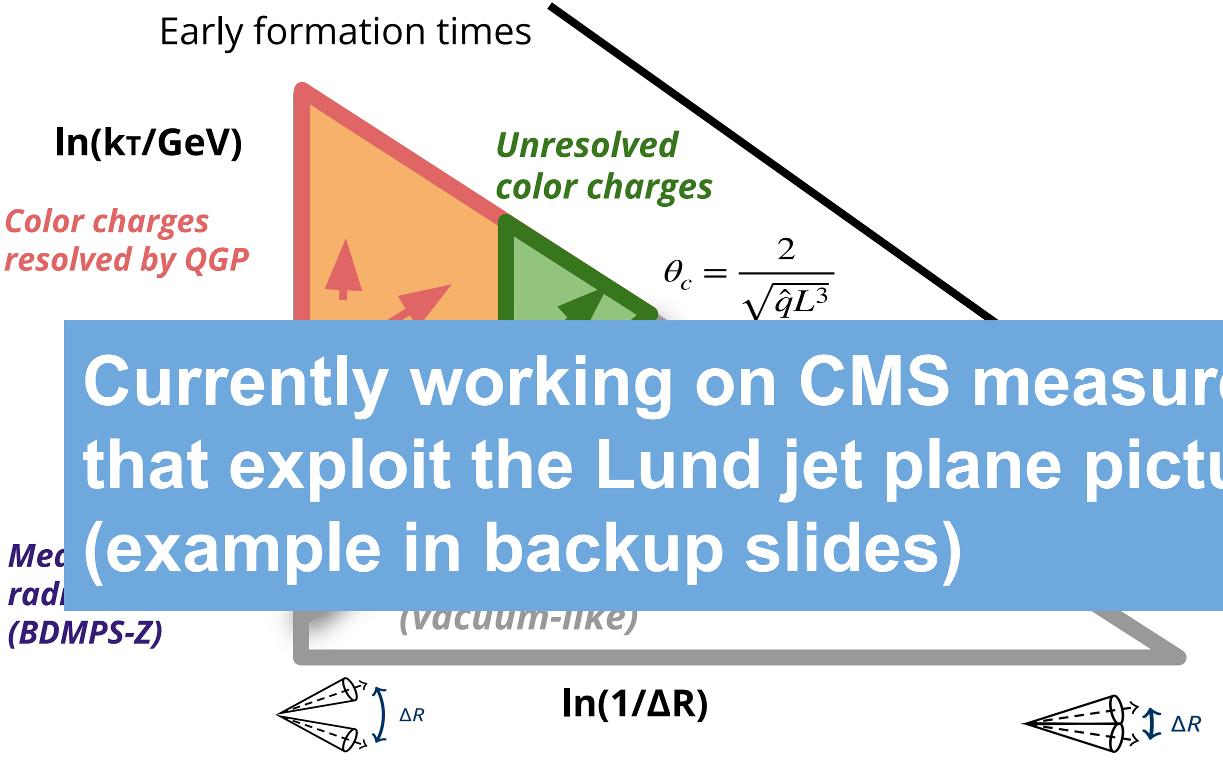


diagram inspired on regions from P. Caucal, A. Soto, A. Takacs, PRD 105, 114046 (2022)

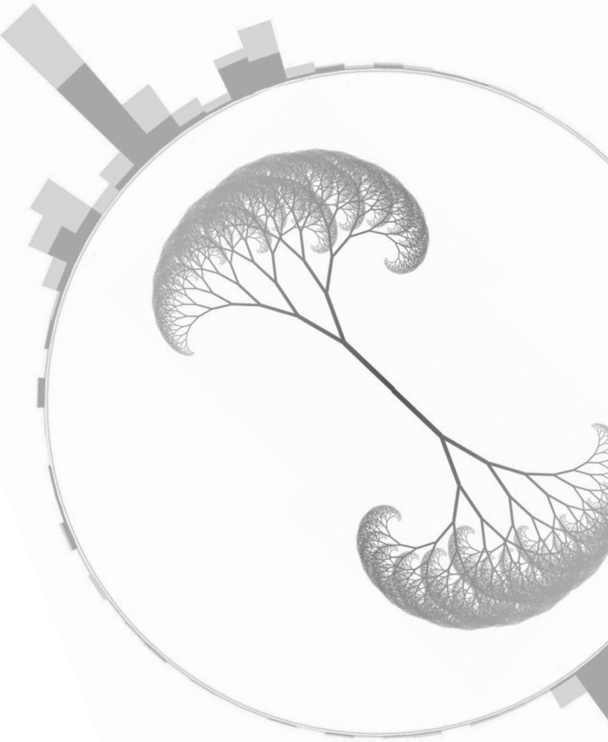
Spacetime picture of quark-gluon plasma evolution



Currently working on CMS measurements that exploit the Lund jet plane picture (example in backup slides)

diagram inspired on regions from [P. Caucal, A. Soto, A. Takacs, PRD 105, 114046 (2022)](https://doi.org/10.1103/PhysRevD.105.114046)

Summary



- Mapping out weakly- and strongly-coupled regimes via the **Lund jet plane picture**

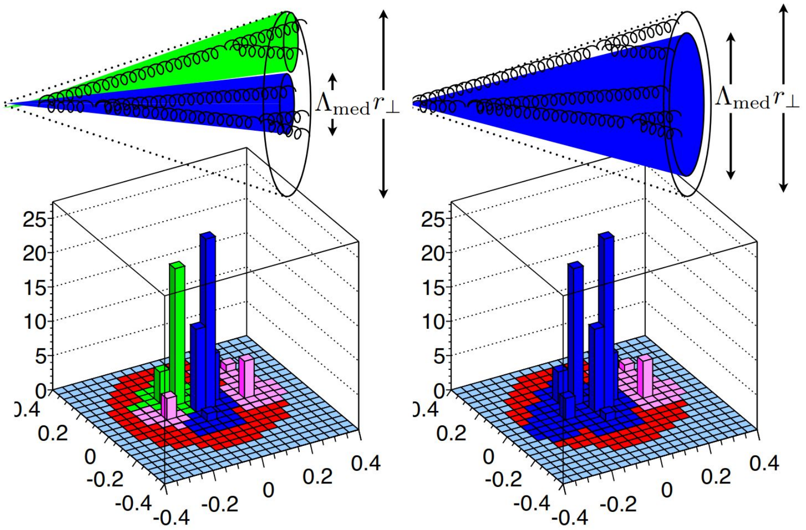
- Potential to map out spacetime evolution of quark-gluon plasma using Lund plane

- Other LHC substructure results can be found here

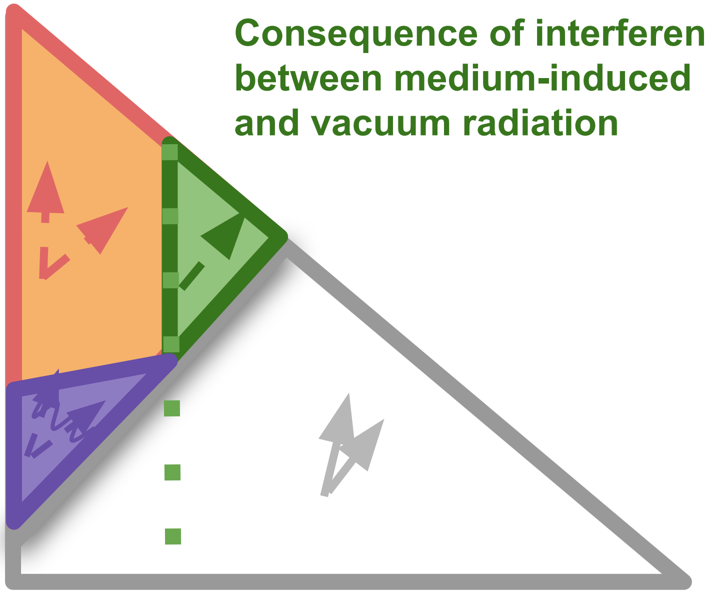
Medium resolution length (color decoherence)

Resolved as two charges → more quenching

Resolved as a single charge → less quenching



Diagrams from [J. Casalderrey-Solana, Y. Mehtar-Tani, C. A. Salgado, K. Tywoniuk, arXiv:1210.7765]



Consequence of interference between medium-induced and vacuum radiation

Is the critical angle large enough?

$\vartheta_c \sim O(10^{-2}–10^{-1})$?

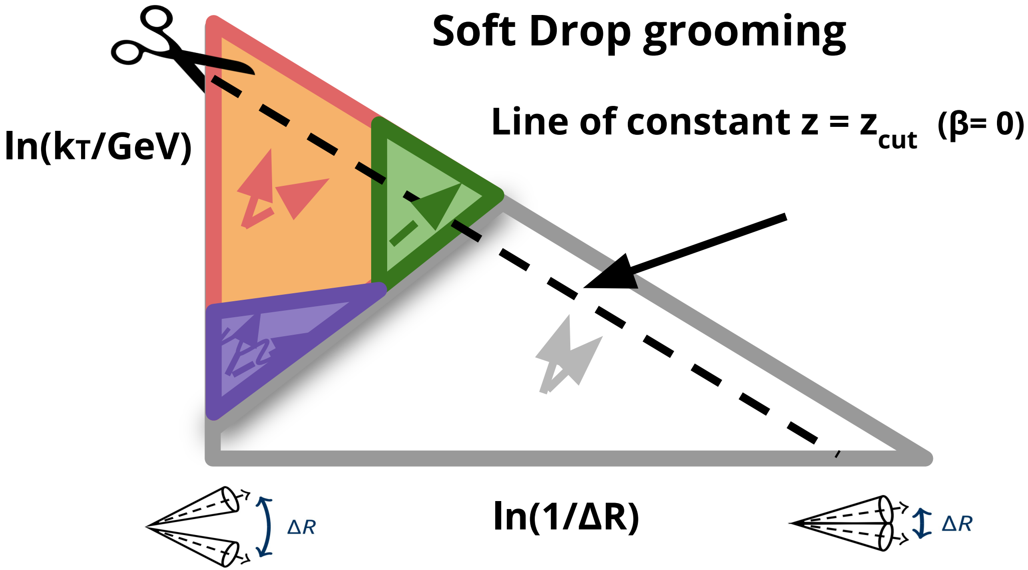
Soft-drop grooming

M. Dasgupta, A. Fregoso, S. Marzani, G. P. Salam, JHEP09 (2013) 029
A. J. Larkoski, S. Marzani, G. Soyez, J. Thaler, JHEP 1405 (2014) 146

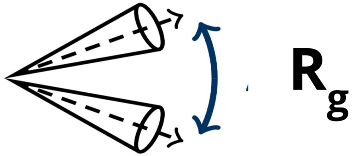
Soft Drop grooming to control ***large*** UE contribution:

$$z_g = \frac{\min(p_T^{(1)}, p_T^{(2)})}{p_T^{(1)} + p_T^{(2)}} > z_{cut}\left(\frac{\Delta R_{12}}{R}\right)^{\beta_{sd}},$$

(typical choice in heavy-ions is β_{SD} = 0, z_{cut} = 0.2)



Hard two-prong structure is exposed



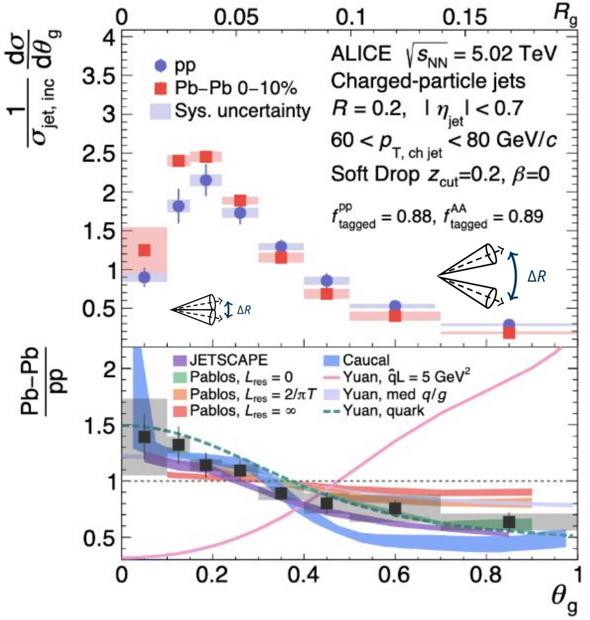
R_g is expected to be sensitive to color decoherence effects

Y. Mehtar-Tani, K. Tywoniuk, JHEP04(2017)125

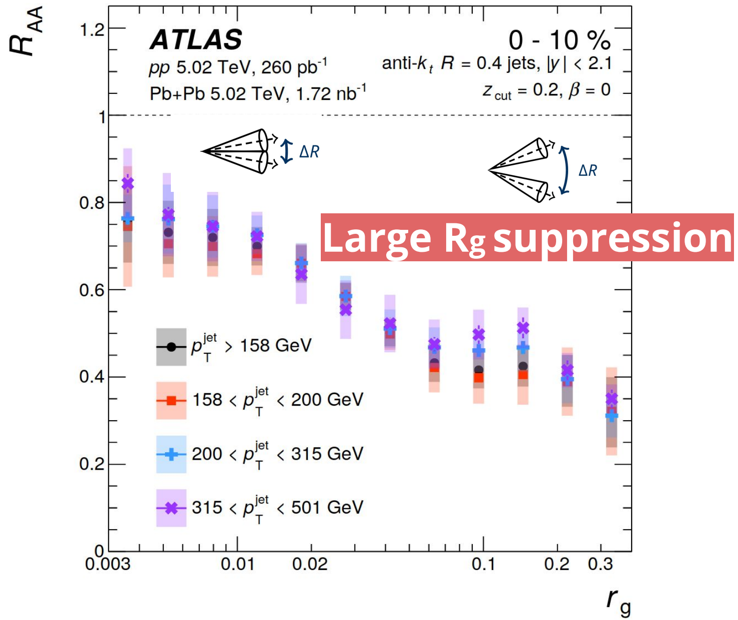
1-splitting per jet

Previous measurements in inclusive jet events

Groomed jet radius R_g

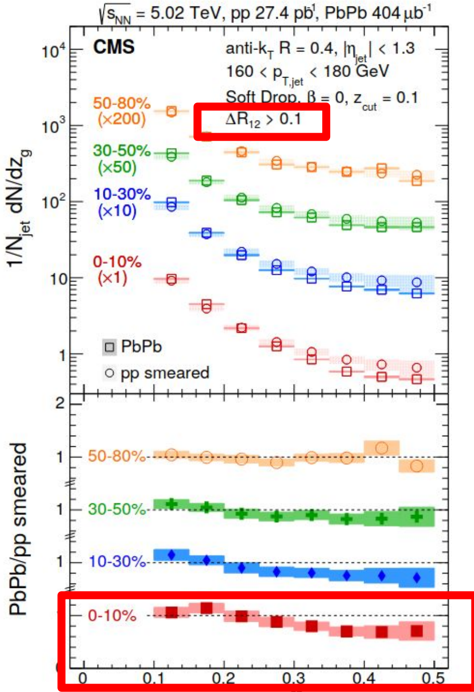


[ALICE, PRL 128.102001](#)



[ATLAS, PRC 107, 054909](#)

Splitting function



$$z_g = \frac{p_{T2}}{p_{T1} + p_{T2}}$$

CMS, [PRL 120, 142302 (2018)](#)

<u>Broad angular structures are more suppressed in PbPb.</u>

Consequence of color decoherence?

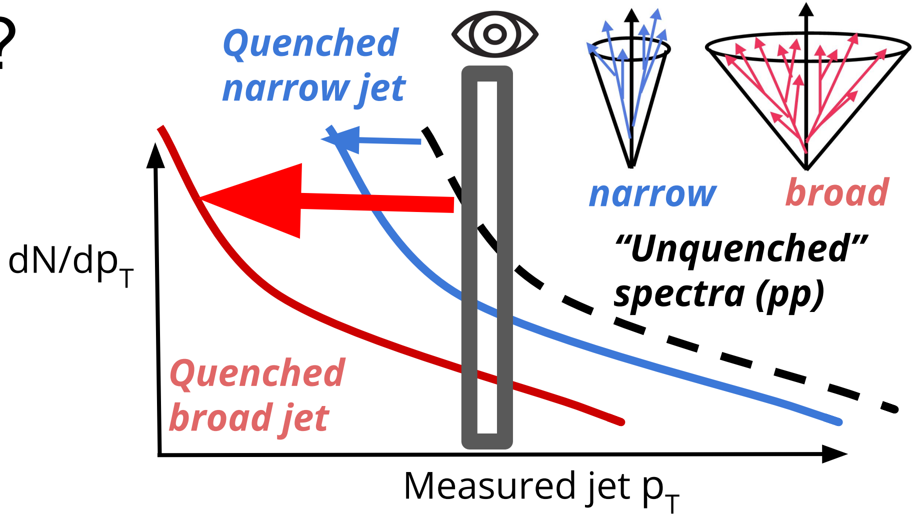
Is a finite critical angle necessary to describe jet quenching?

Selection bias in inclusive jets?

Jets with a **broad** early vacuum shower are expected to be more quenched

Gluon jets (which are broad) are quenched more strongly than **quark jets** (which are narrow)

Potential effect in a jet p_T bin: ***a narrowing effect***



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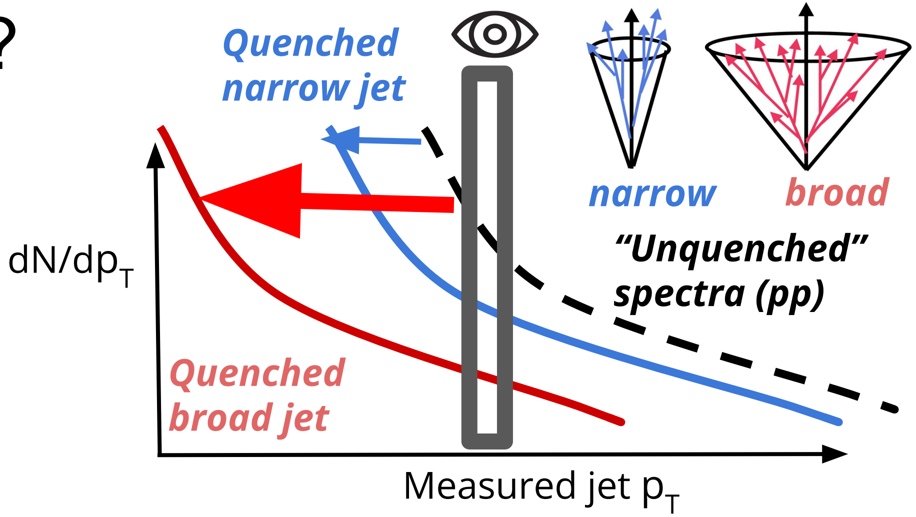


Gluon jets (which are broad) are quenched more strongly than **quark jets** (which are narrow)

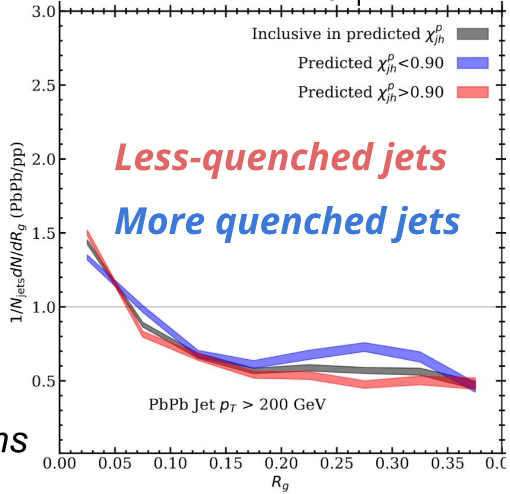
Potential effect in a jet p_T bin: ***a narrowing effect***

One way of controlling this effect is by selecting jets according to their **unquenched p_T**

J. Brewer, Q. Brodsky, K. Rajagopal, JHEP02(2022)175

J. Brewer, J. Milhano, J. Thaler PRL 122, 222301 (2019)

Final-state jet* p$_T$ *cut



Y.L. Du, D. Pablos, K. Tywoniuk, JHEP 21 (2020), 206

Hybrid model calculations

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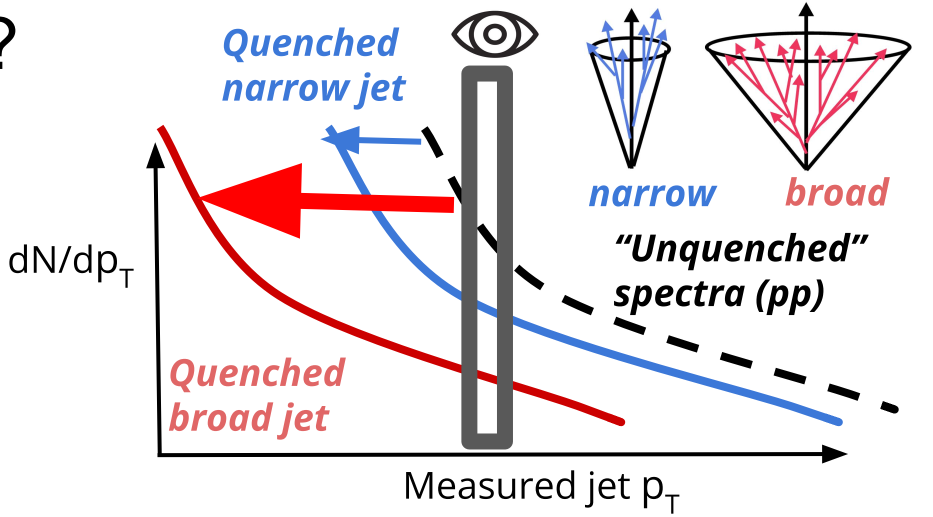
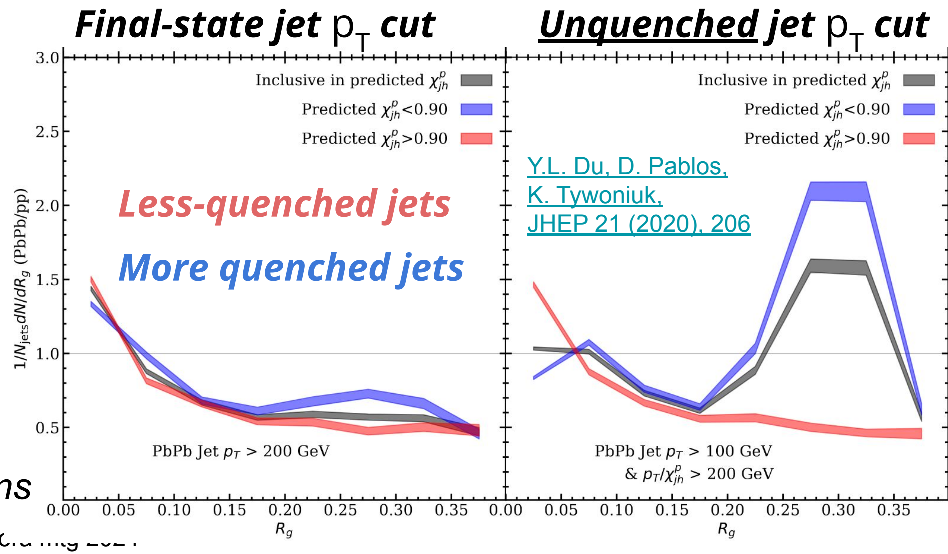


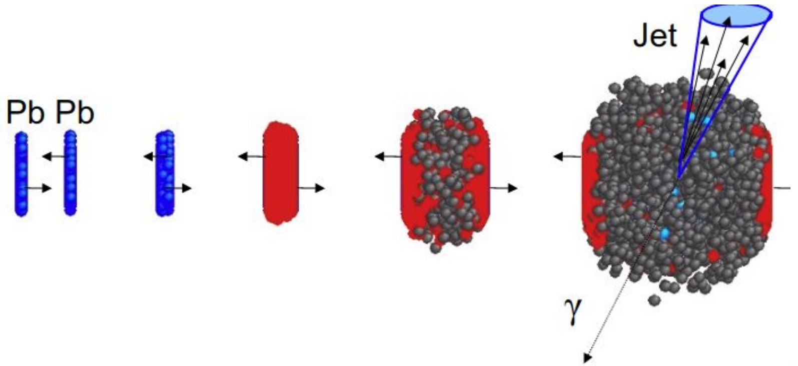


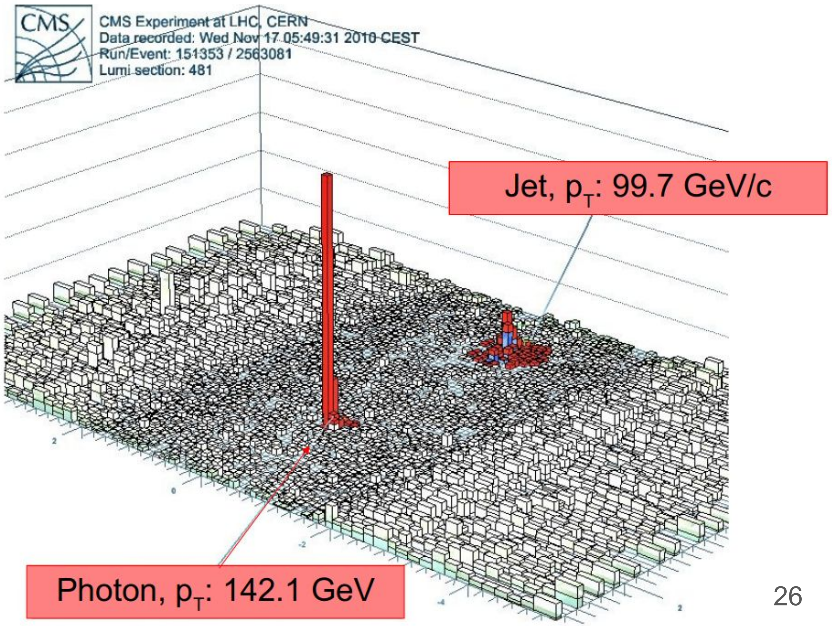
Hybrid model calculations

Jet substructure using photon-tagged jets

Photon p_T^γ can be used as a proxy for <u>unquenched</u> p_T^{jet}

Compare pp and PbPb with the same p_T^γ





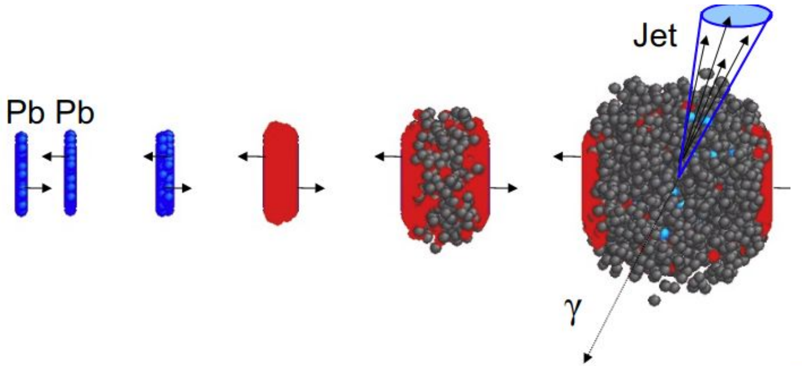
Jet substructure using photon-tagged jets

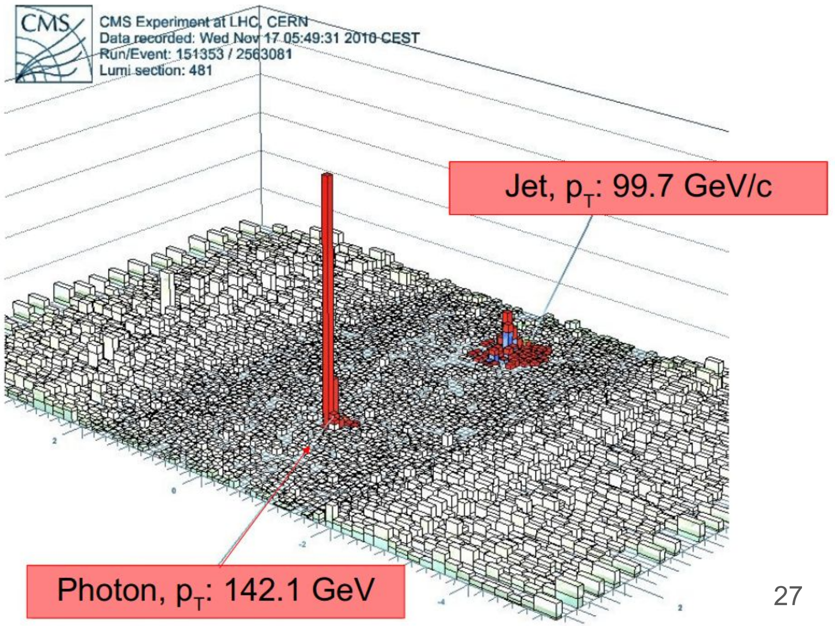
Photon p_T^γ can be used as a proxy for unquenched p_T^{jet}

Compare pp and PbPb with the same p_T^γ

Measurement setup:

- Isolated photon with $p_T^\gamma > 100$ GeV with $|\eta^\gamma| < 1.44$
- anti-k_T jets with R = 0.2, $\Delta\varphi_{\gamma,jet} > ⅔\,\pi$ and $|\eta^{jet}| < 2$
- R_g (z_{cut} = 0.2, β = 0) and jet girth $g = \frac{1}{p_T^{jet}} \sum_i p_T^i \Delta R_{i,jet}$





Jet substructure using photon-tagged jets

Photon p_T^{γ} can be used as a proxy for <u>unquenched</u> p_T^{jet}

Compare pp and PbPb with the same p_T^{γ}

Measurement setup:

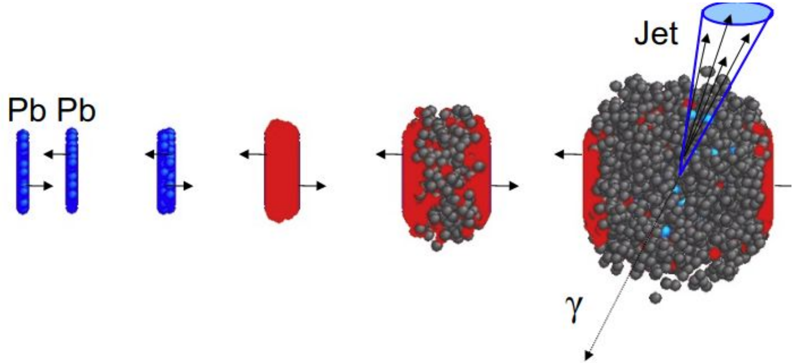
- Isolated photon with $p_T^{\gamma} > 100$ GeV with $|\eta^{\gamma}| < 1.44$
- anti-k_T jets with R = 0.2, $\Delta\varphi_{\gamma,jet} > \frac{2}{3}\pi$ and $|\eta^{jet}| < 2$
- R_g ($z_{cut} = 0.2$, $\beta = 0$) and jet girth $g = \frac{1}{p_T^{jet}} \sum_i p_T^i \Delta R_{i,jet}$

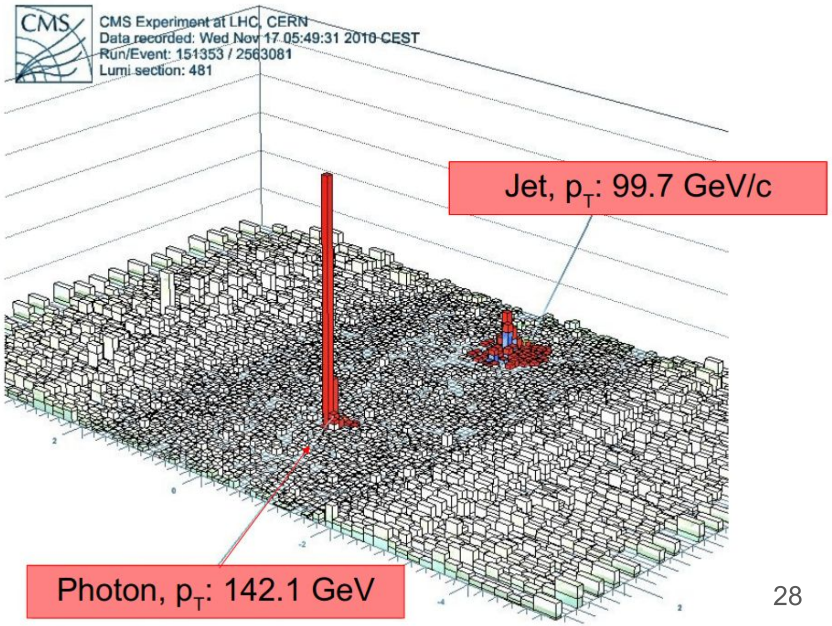
Two categories for measurement:

$p_T^{jet}/p_T^{photon} > 0.4$ (quenched and nonquenched jets)
$p_T^{jet}/p_T^{photon} > 0.8$ (less quenched jets)

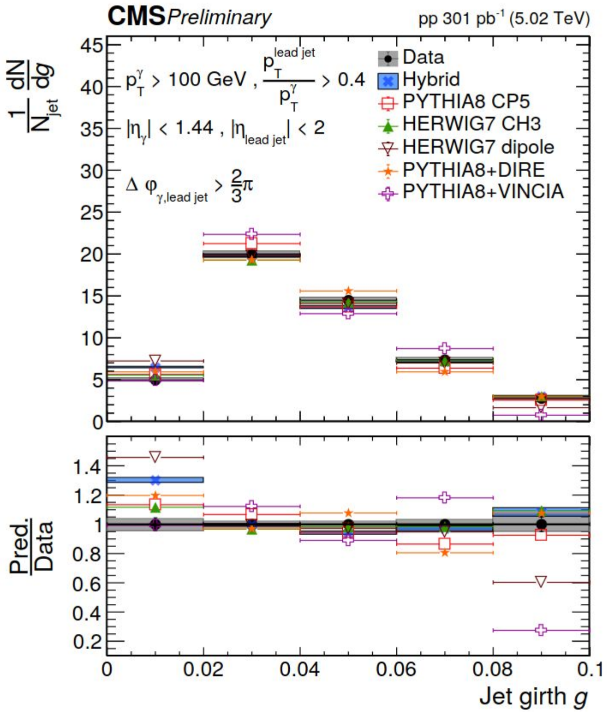
Bkg from neutral meson diphoton decays subtracted with template fits and ABCD method

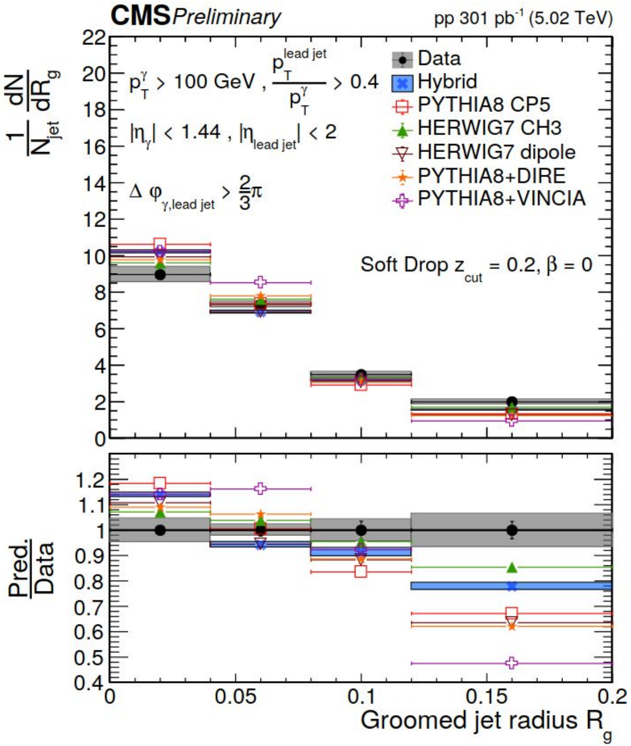
corrections with D'Agostini unfolding

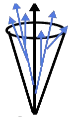


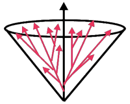


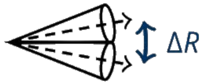
Photon-tagged jets with $p_T^{jet}/p_T^{\gamma} > 0.4$ (**proton-proton**) **CMS-PAS-HIN-23-001, *link soon***

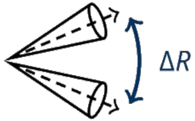








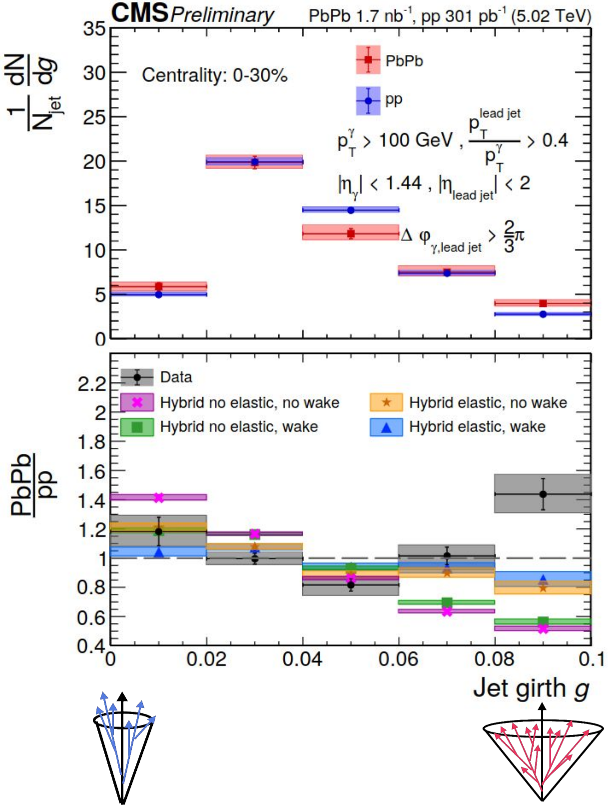


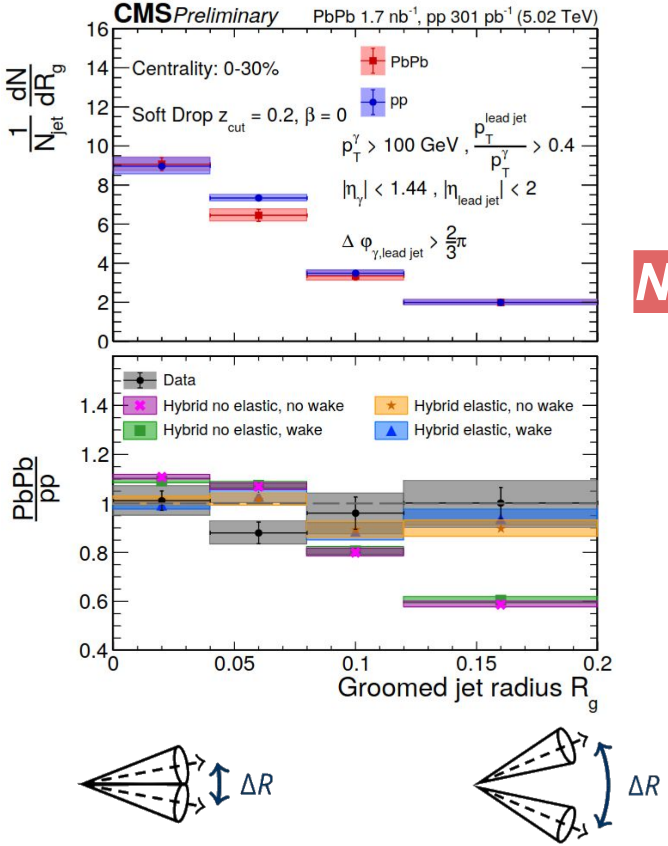


Differences of data and MC simulation of factors of up to 2
best global description by **HERWIG7 angular-ordered (CH3)**

Photon-tagged jets with $p_T^{jet}/p_T^{\gamma} > 0.4$ in PbPb and pp (selecting quenched and less quenched jets)

CMS-PAS-HIN-23-001, *link soon*



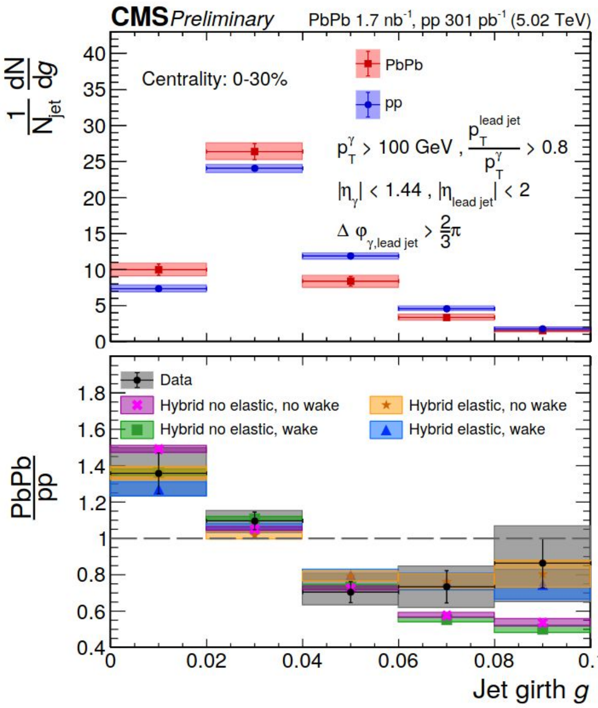


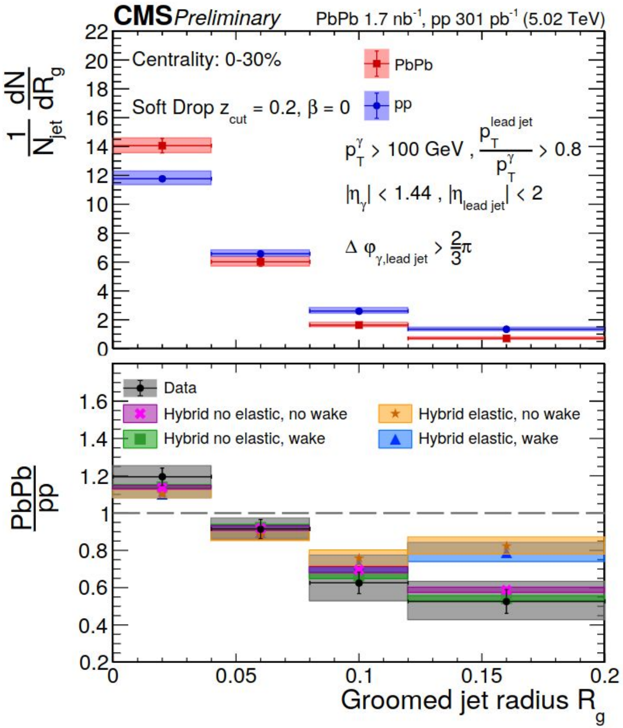
No narrowing

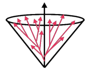
No angular narrowing observed in γ+jet events in contrast to inclusive jets

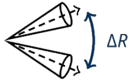
With stronger selection bias $p_T^{jet}/p_T^{\gamma} > 0.8$

CMS-PAS-HIN-23-001, *link soon*







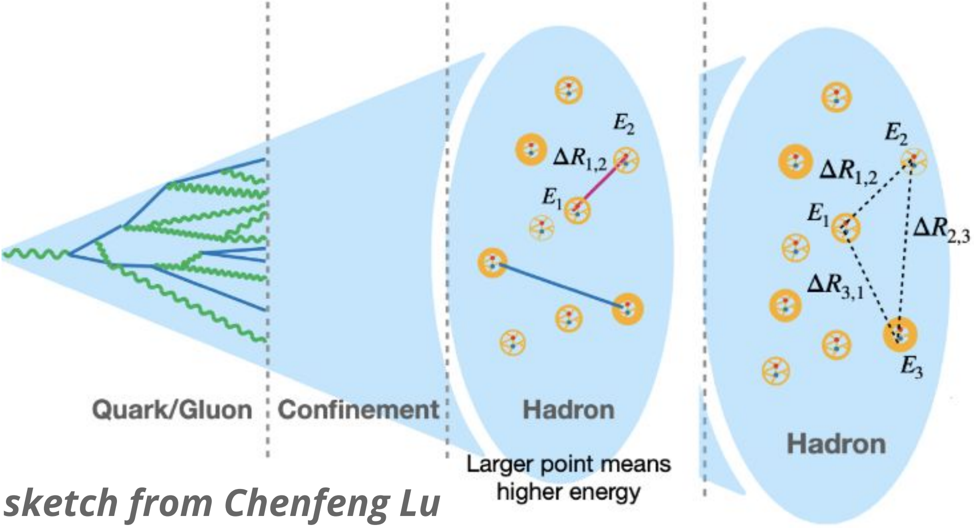


Narrowing

Predictions w/ Molière scatterings (large-angle deflections) give best global description (**ϑ_C = 0**). No sensitivity to wake effect. [J. Casalderrey-Solana et al, JHEP01(2020)044]

Energy-energy correlators (CMS)

arXiv:2402.13864, submitted to PRL



sketch from Chenfeng Lu

Energy-weighted two-particle angular correlations

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

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

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

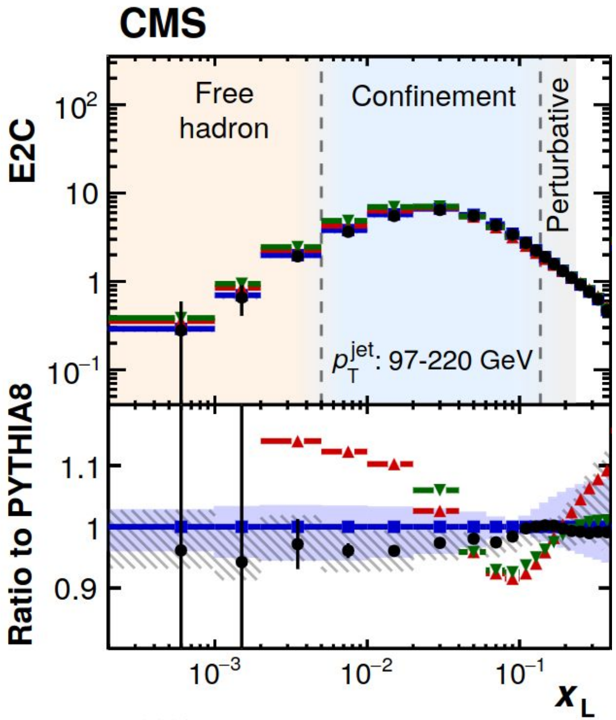
Energy-energy correlators (CMS)

arXiv:2402.13864, submitted to PRL

At least two anti-k_T R = 0.4 jets,
$p_{T,\,jet}$ 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)

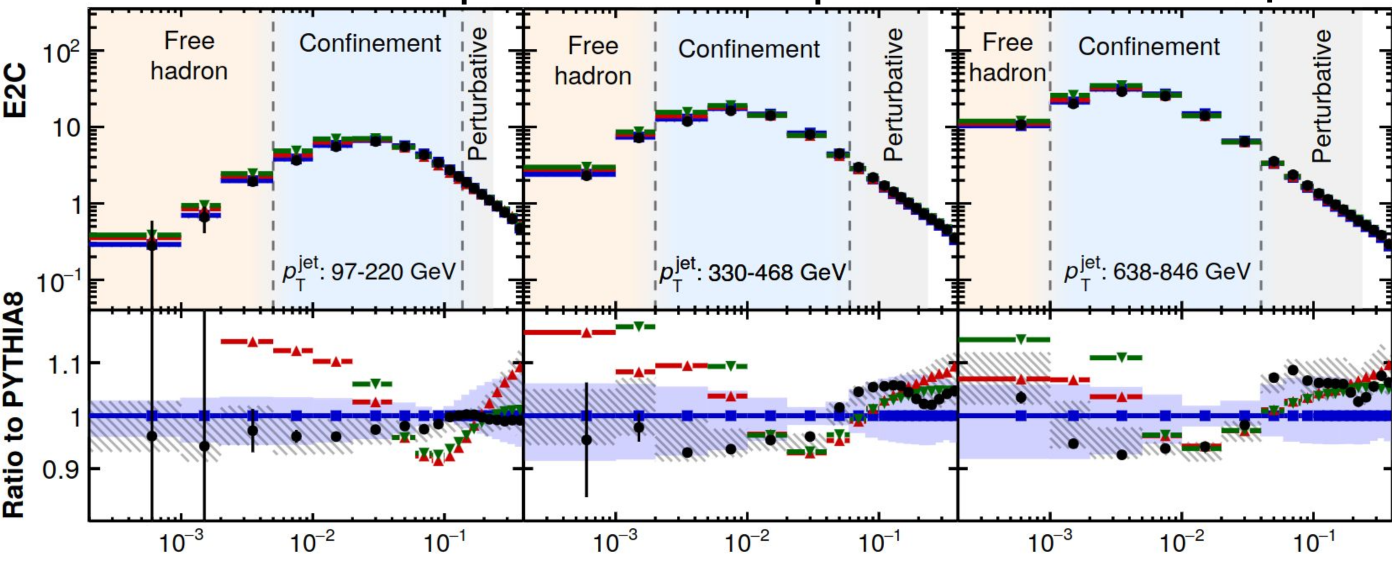


x_L == angular separation between two particles

Two-point correlators (E2C)

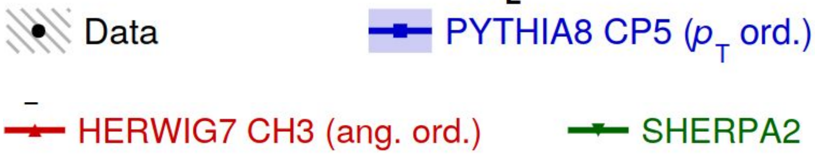
arXiv:2402.13864, submitted to PRL

Low jet p_T | Mid jet p_T | High jet p_T



x_L x_L x_L

x_L == separation between two particles



Free hadron region (low x_L)

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

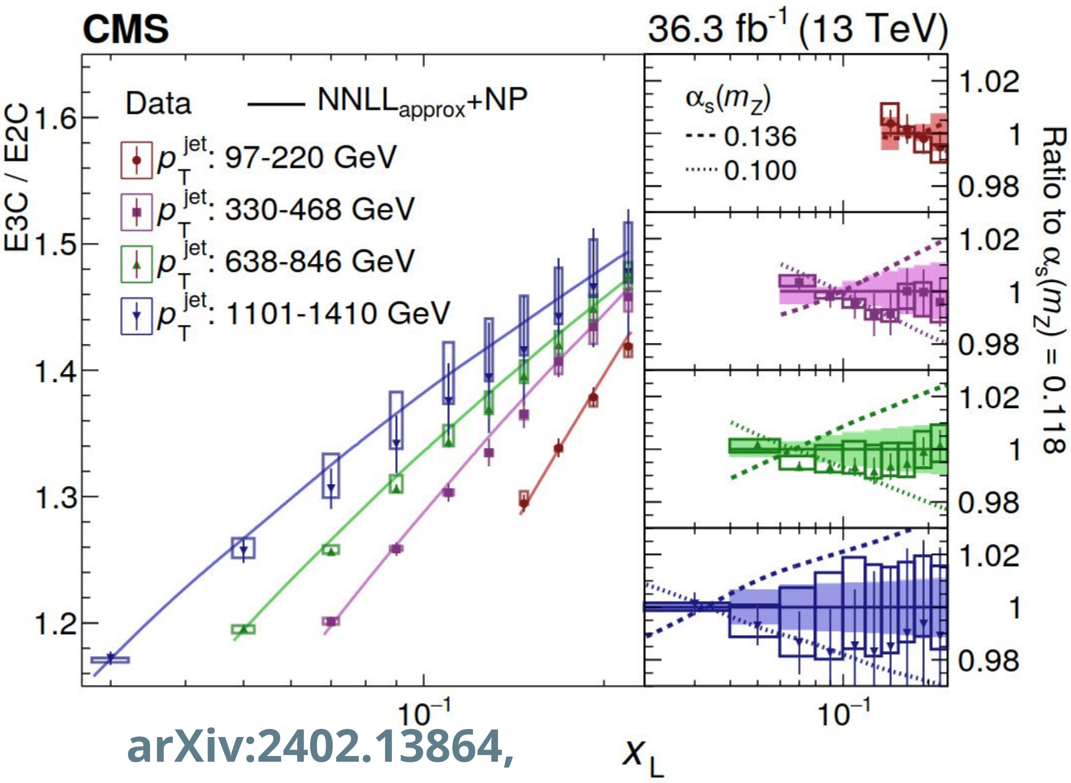
Perturbative region (high x_L)

PYTHIA8 CP5 undershoots data at higher jet p_T

HERWIG7 CH3 & SHERPA2 describe data better

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

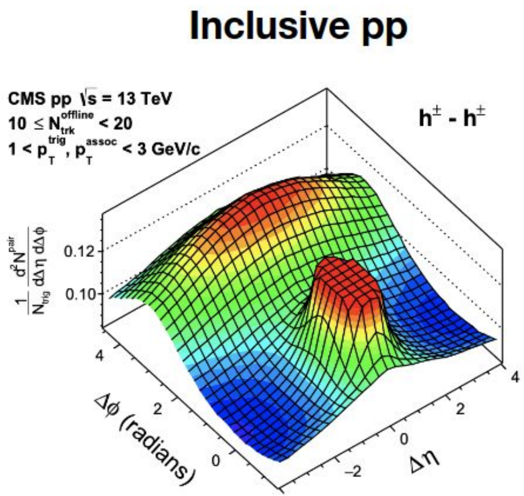
$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050} \; (\sim 4\ \%)$$

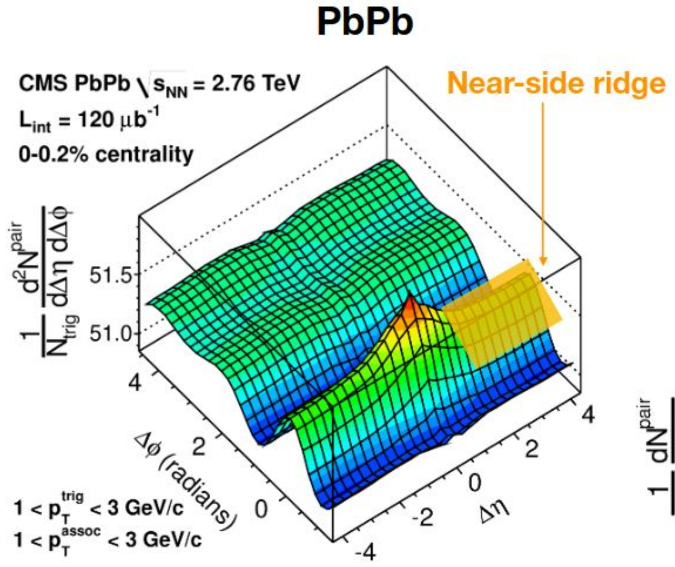
Most precise extraction of $\alpha_s(m_Z)$ with jet substructure

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

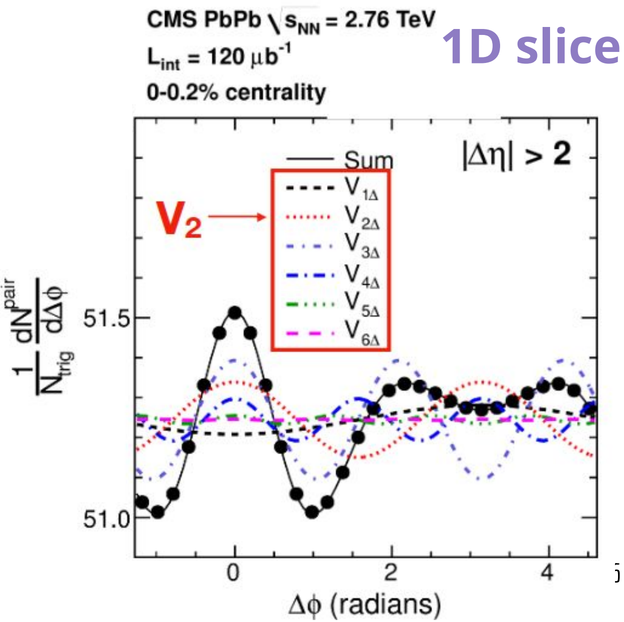
Two-particle angular correlations

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





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



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

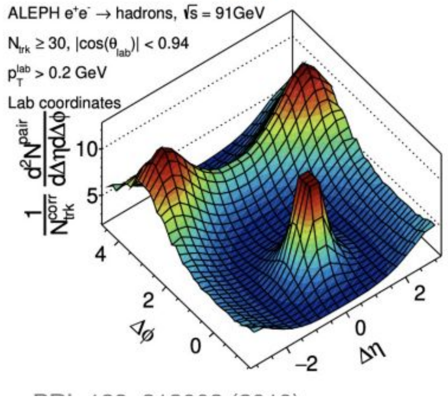
What about smaller systems?

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?

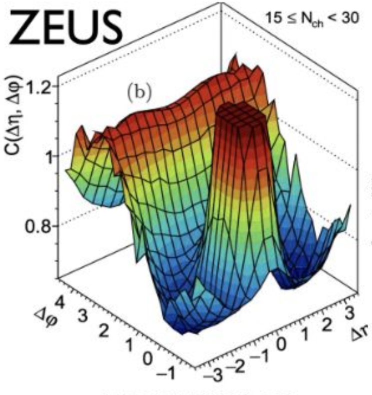
Since then, searches pushing the boundaries towards even smaller systems

e^+e^-
N_{ch}~30



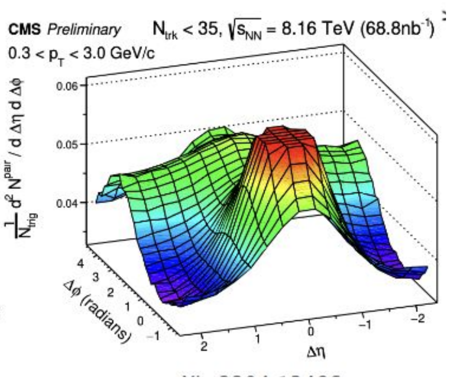
PRL 123 212002 (2019)

ep
N_{ch}~30



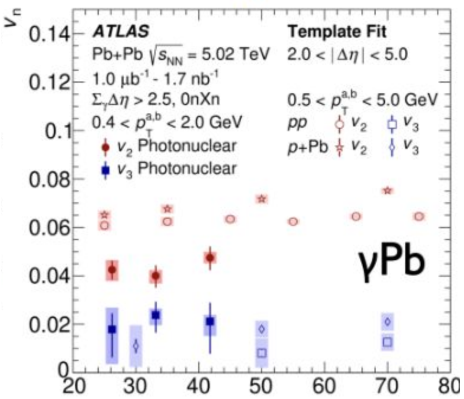
JHEP 04 (2020) 070

γp
N_{ch}~20



PLB 844 (2023) 137905

γPb
N_{ch}~40



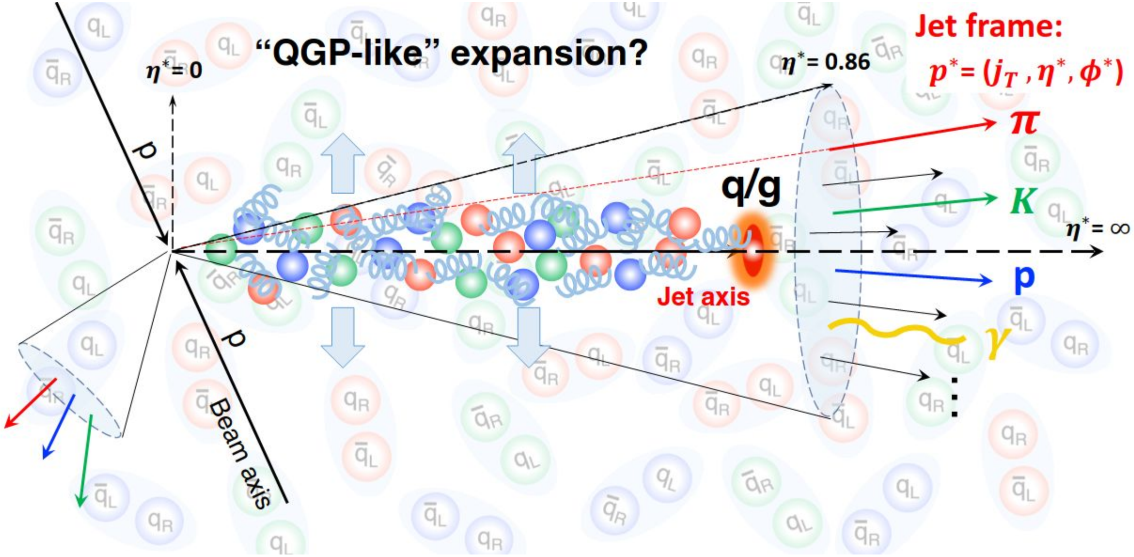
PRC, 104 014903 (2021)

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

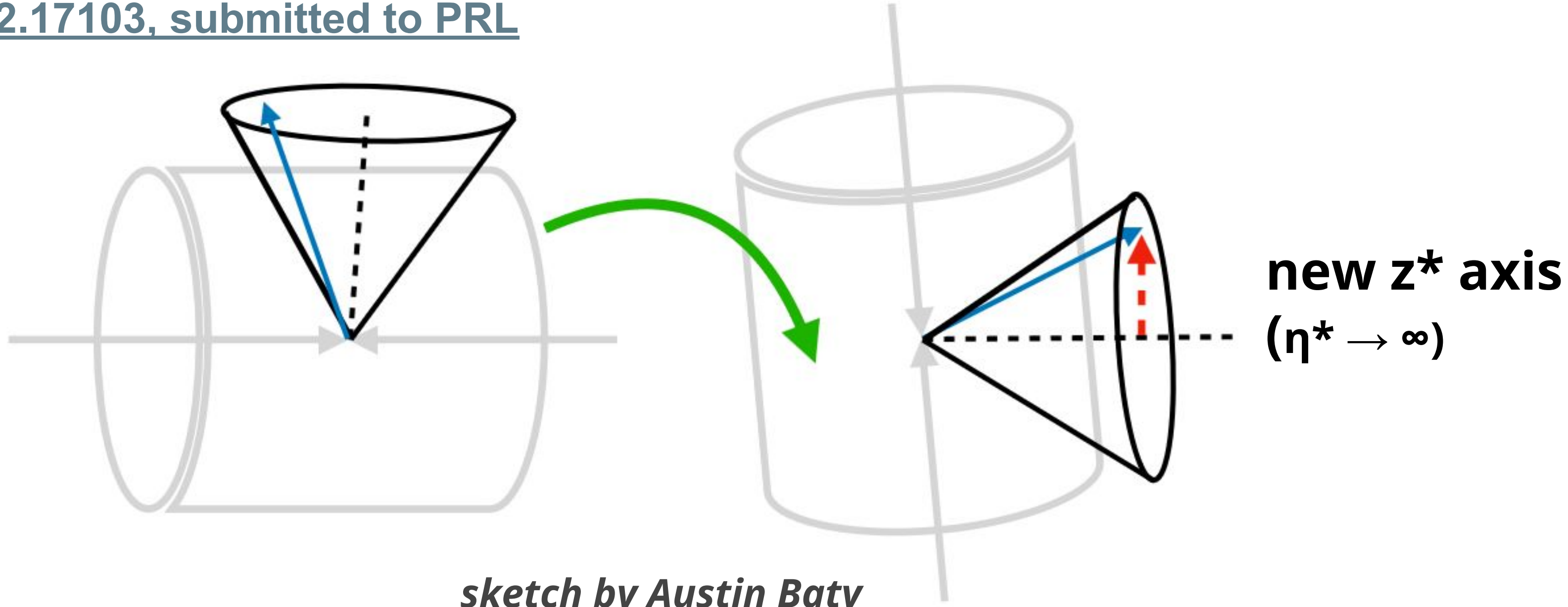
Charged-particle constituents used for two-particle correlations (**pileup mitigation + low $p_{T,ch}$**)



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

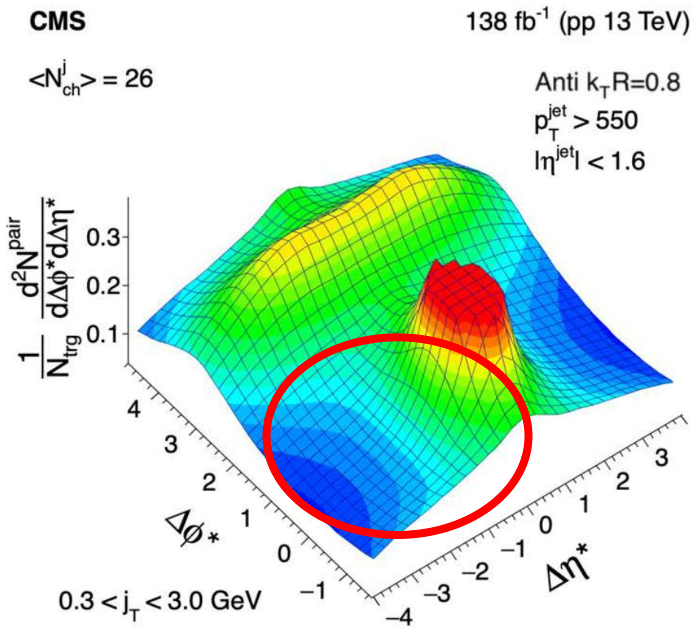


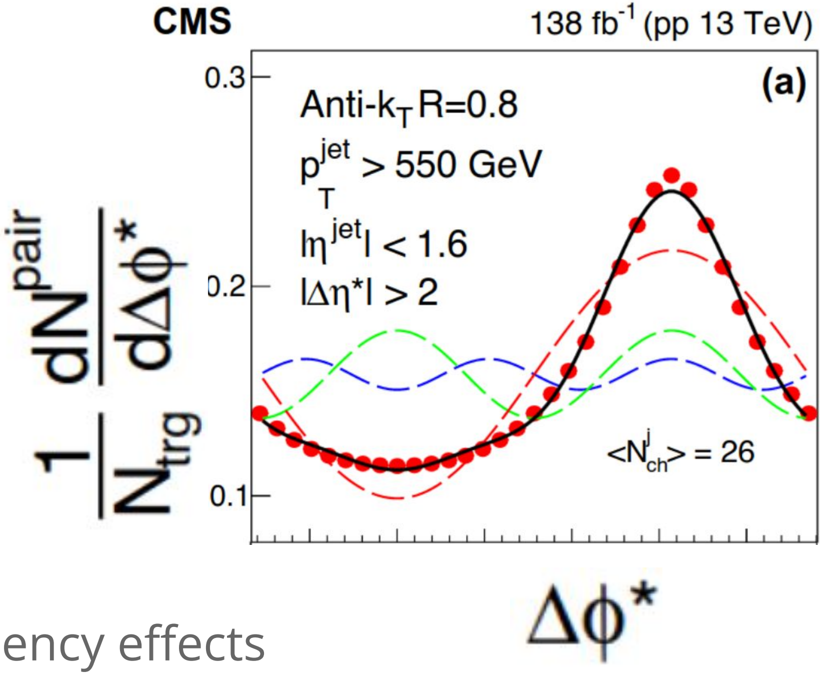
sketch by Austin Baty

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

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





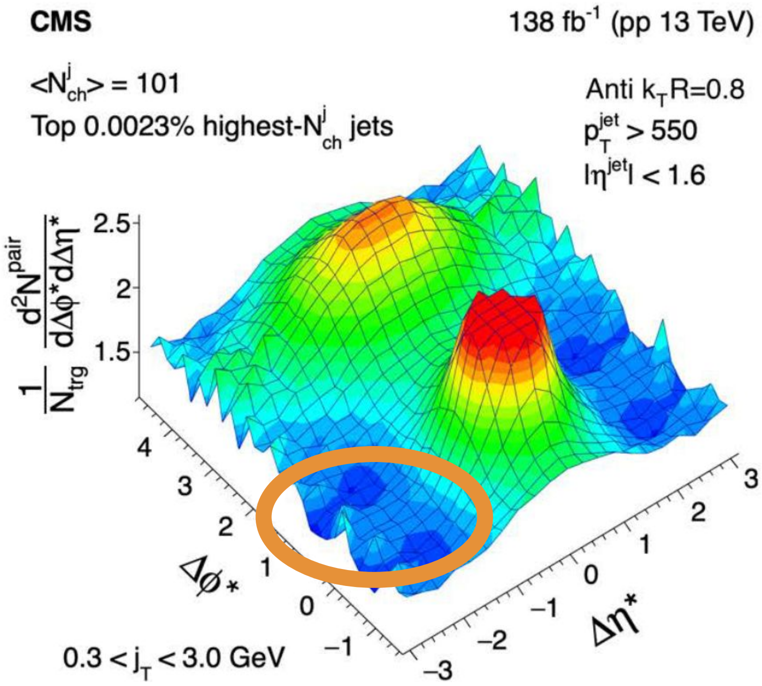
2D distributions corrected for acceptance/efficiency effects

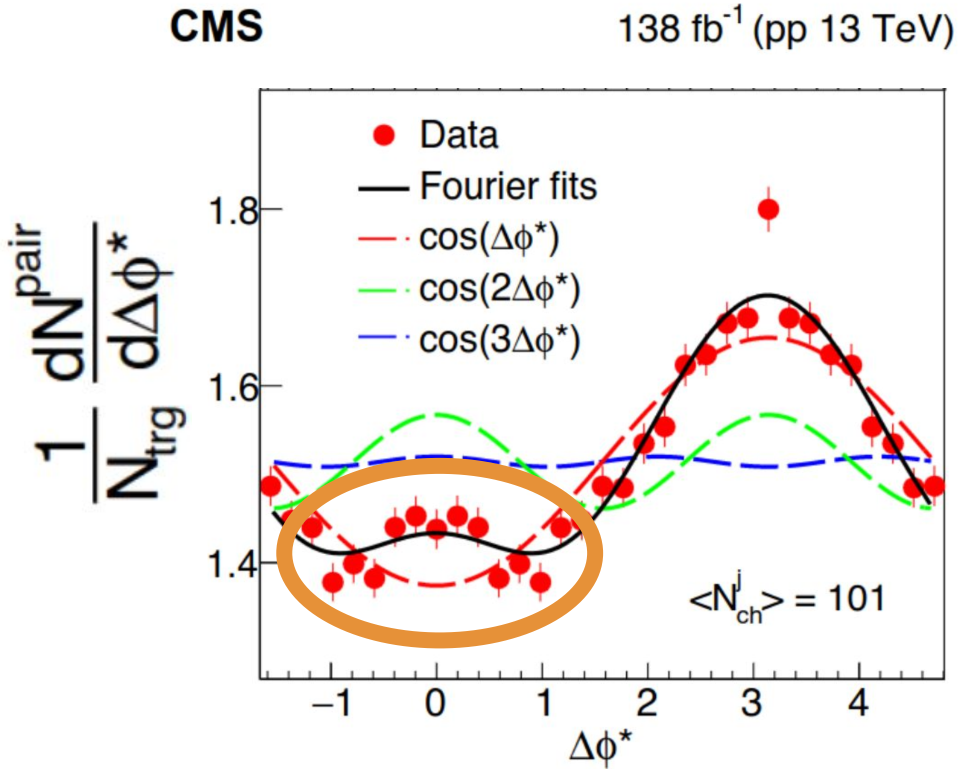
No near-side ridge at Δφ* ~ 0

arXiv:2312.17103, submitted to PRL

high N_{ch} category

arXiv:2312.17103, submitted to PRL

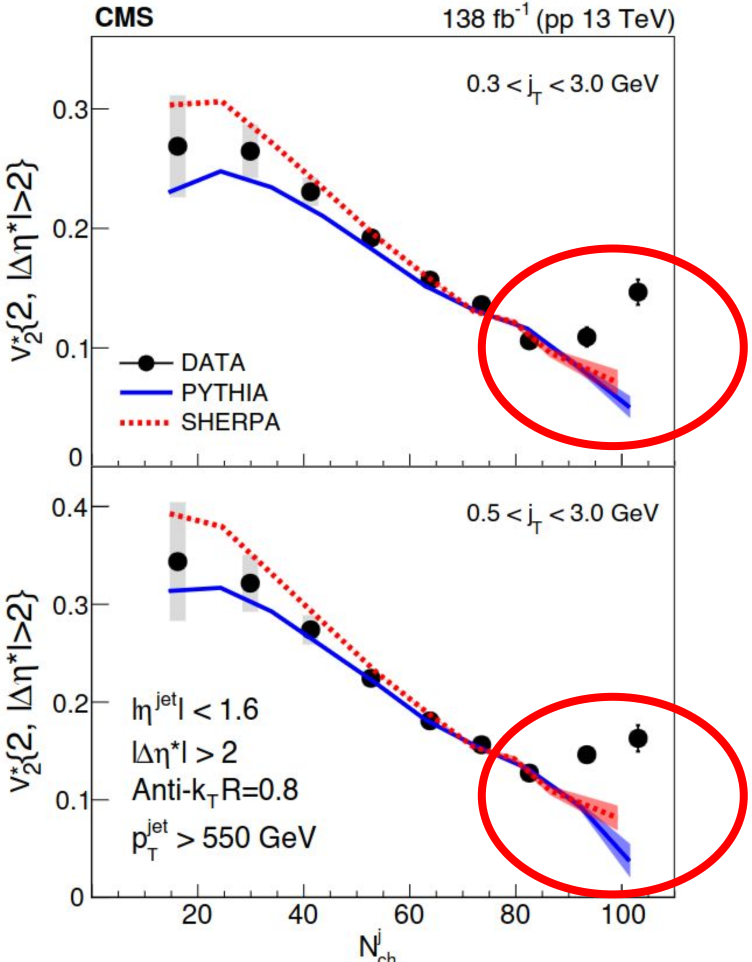




Near-side ridge-like structure at Δφ* ~ 0

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

arXiv:2312.17103, submitted to PRL

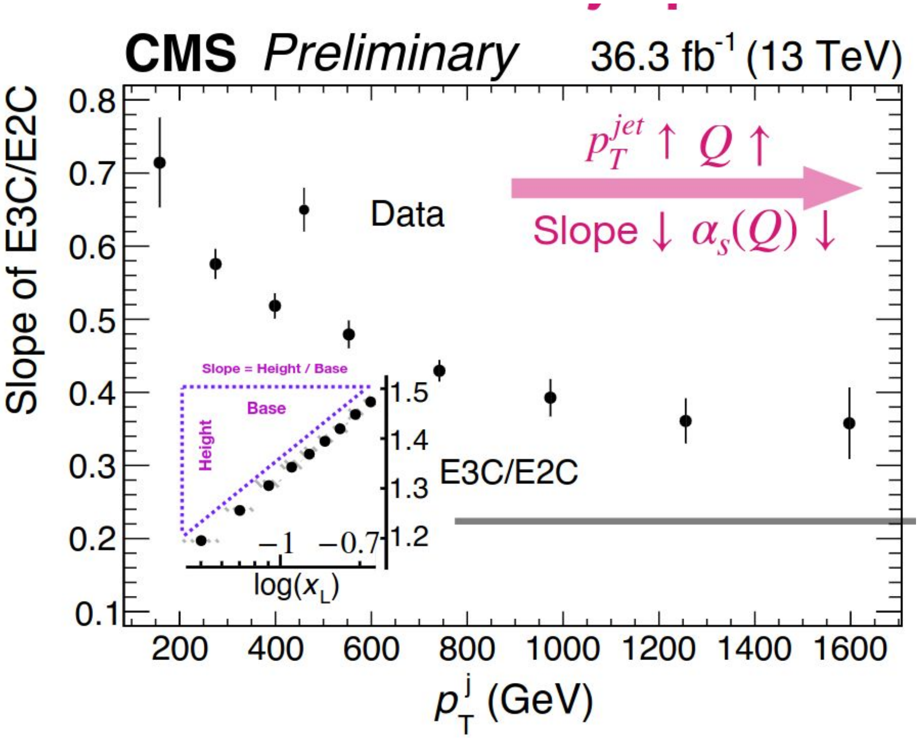


Nonzero v_2 reproduced by **SHERPA2**, **PYTHIA8 CP5** up to N_{ch}~ 80

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

E3C/E2C sensitive to running α_s

CMS-PAS-SMP-22-015



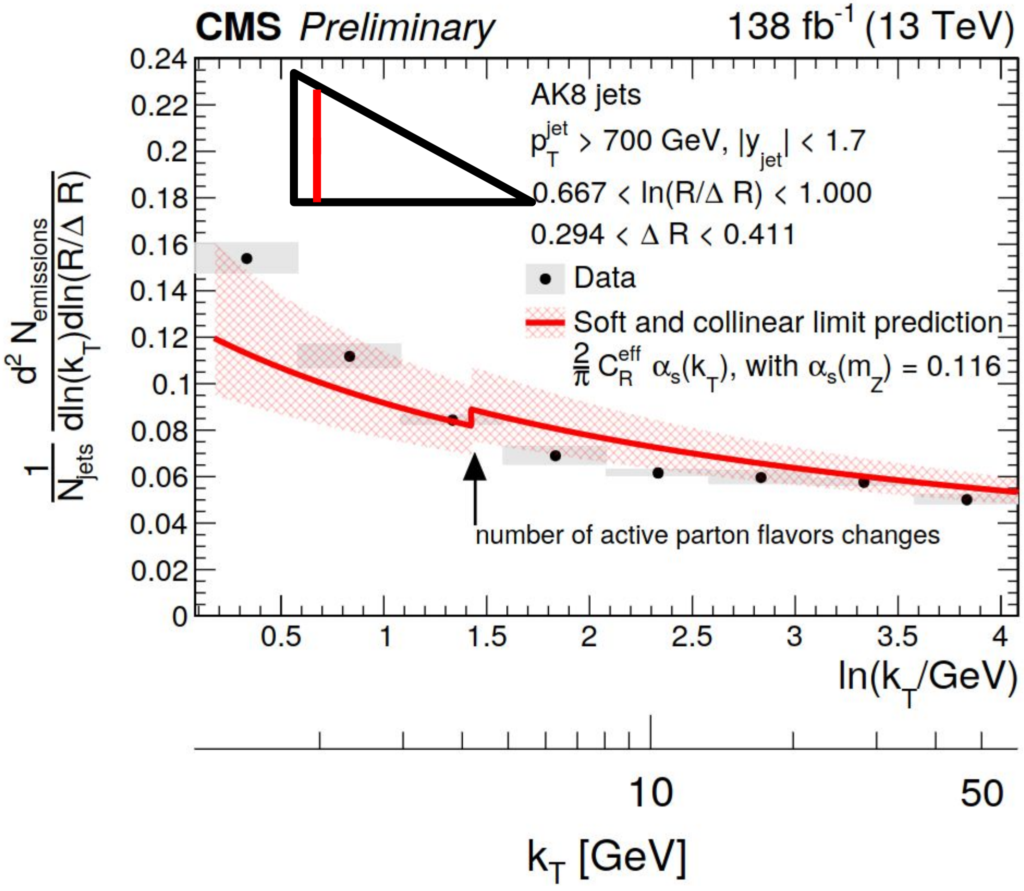
At LL, slope of E3C/E2C ratio sensitive to α_S(Q)

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

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)

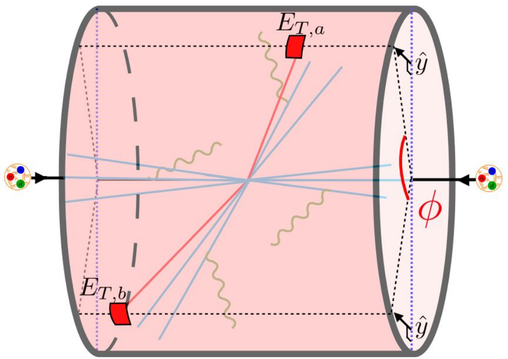
A. Larkoski, G. Salam, J. Thaler,
JHEP06(2013)108

energy-weighted cross section

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

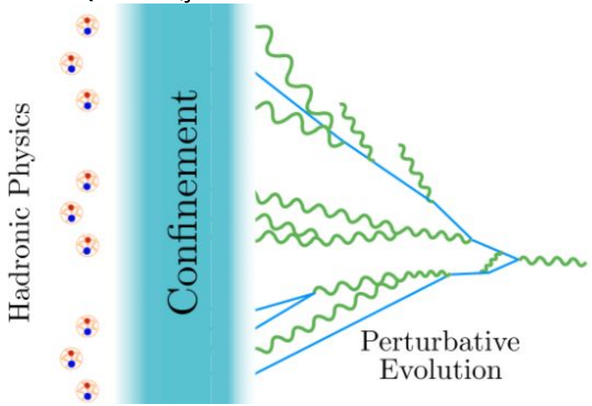
$$R_{\rm L} = \sqrt{\Delta\varphi^2_{ij} + \Delta\eta^2_{ij}}$$

Observable connected to conformal field theory approaches



sketch from Ian moult

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



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

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

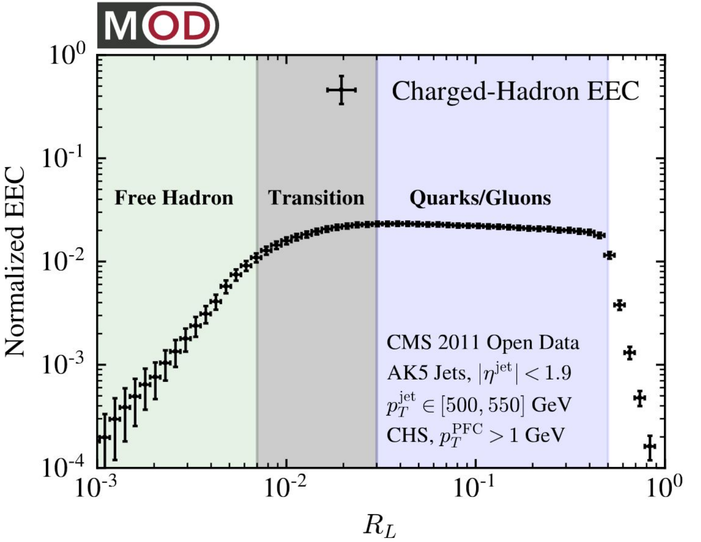
How to measure these experimentally?

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

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



Proof of concept using CMS OpenData

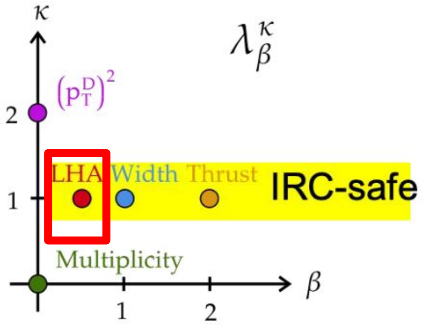
Access to scaling properties of QCD

Generalized angularities in dijet and Z+jet events

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

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

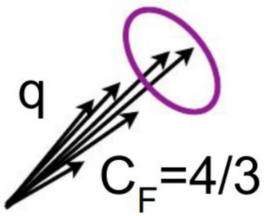
κ & β are parameters set by user



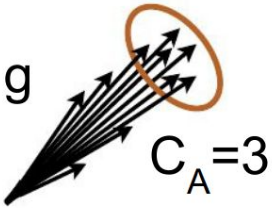
Will show a specific angularity (LHA)

Sensitive to quark vs gluon differences
(subset of them are IRC-safe)
JHEP 1707 (2017) 091

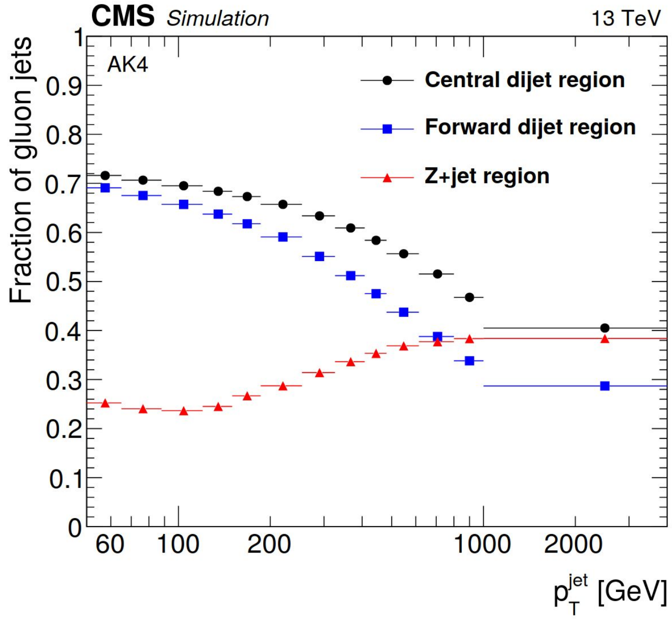
Z+jet (quark-like)



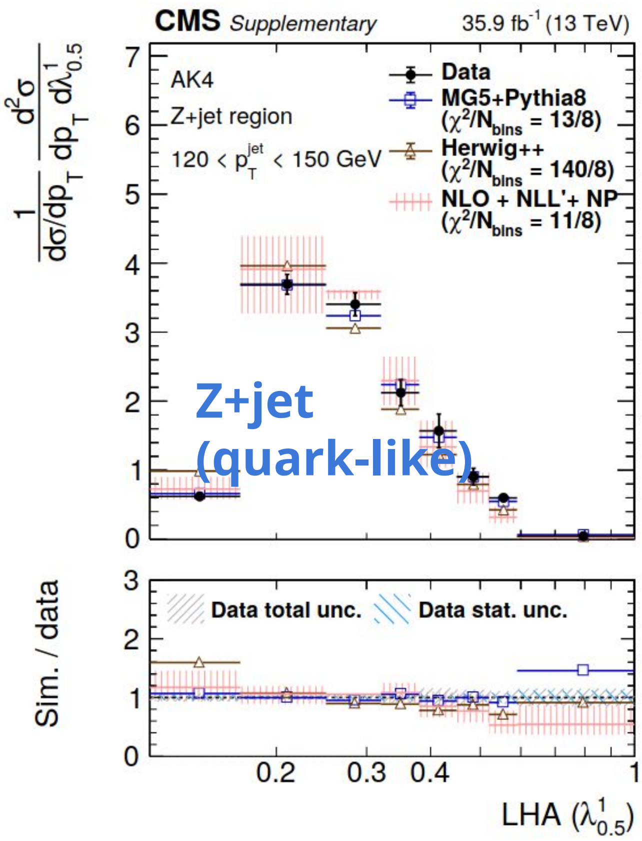
Dijet (gluon-like)

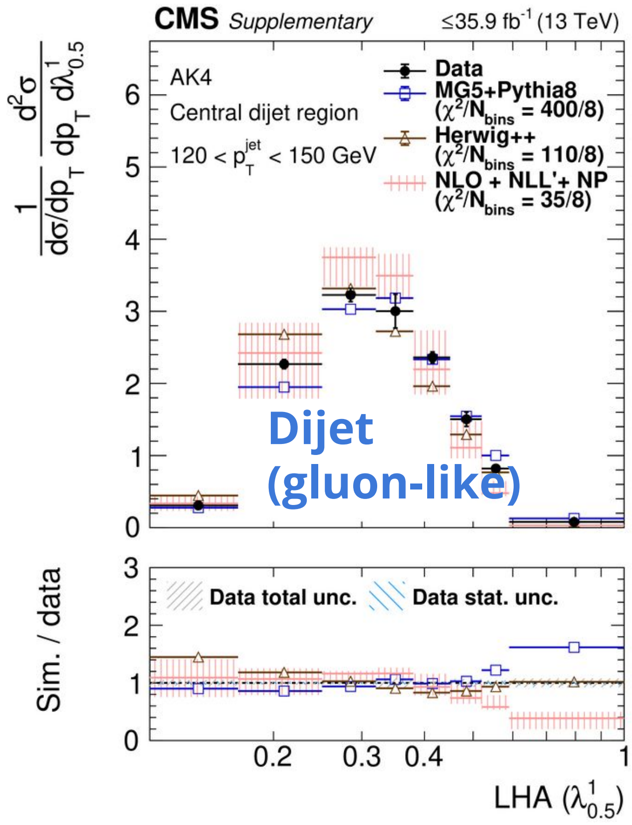


Ungroomed vs groomed with z_{cut} = 0.1, β_{SD} = 0,
R = 0.4 vs R =0.8
charged-only vs charged+neutrals



[JHEP 01 (2022) 188]





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

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

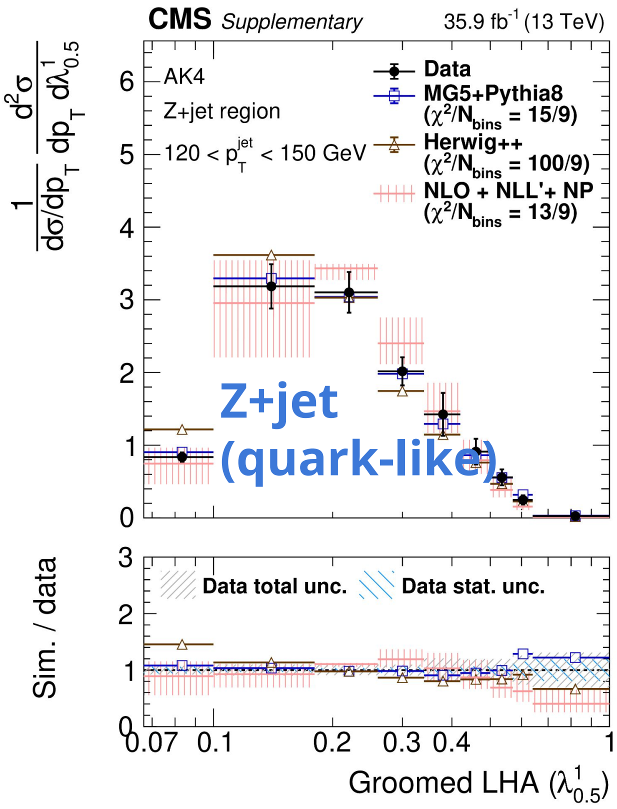
$\kappa = 0.5$, $\beta = 1$

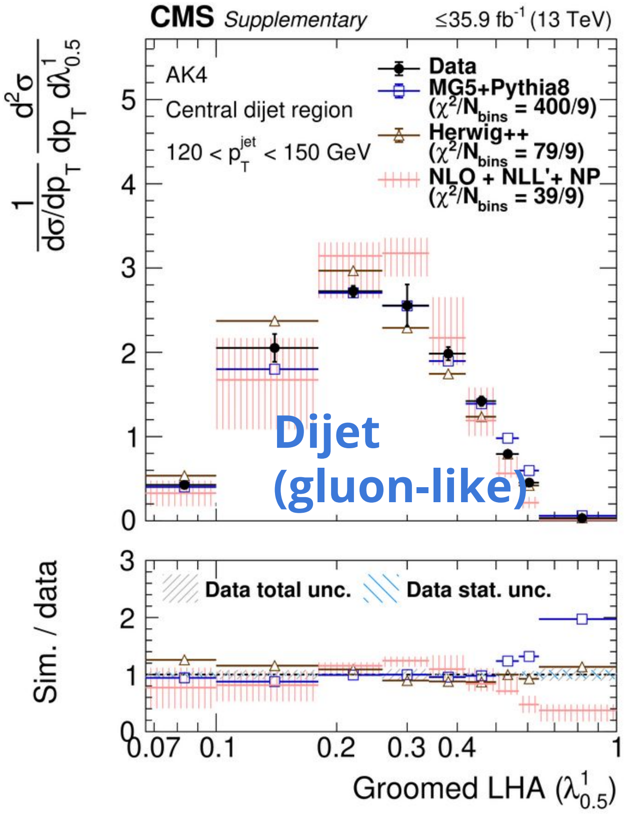
$$\lambda_\beta^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \left(\frac{\Delta R_i}{R}\right)^\beta \quad z_i \equiv \frac{p_{Ti}}{\sum_{j \in \text{jet}} p_{Tj}}$$

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

Groomed Les Houches Angularity in Z-jet and dijet events

JHEP 01 (2022) 188





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

κ = 0.5, β = 1

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

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

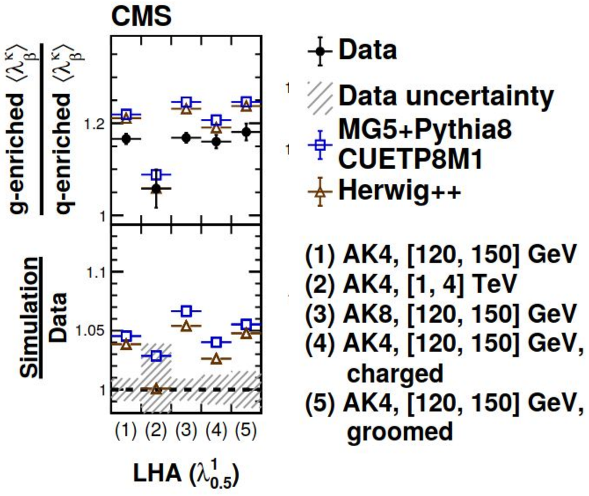
Dijet/Z+jet ratio (g-enriched/q-enriched)

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

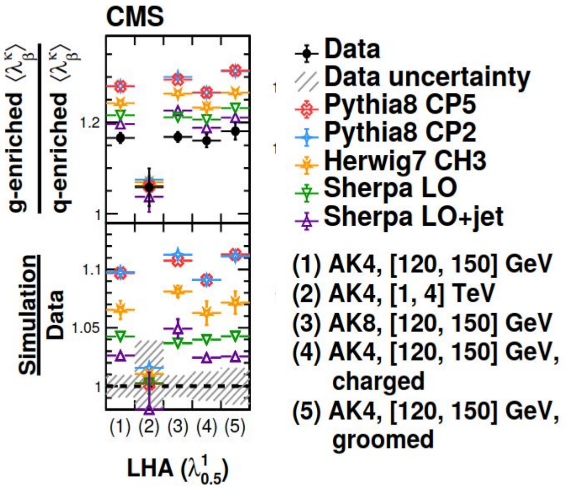
gluon-LHA/quark-LHA > 1
(mostly due to $C_A > C_F$)

- 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

"old" CMS tunes (<~ 5% off)



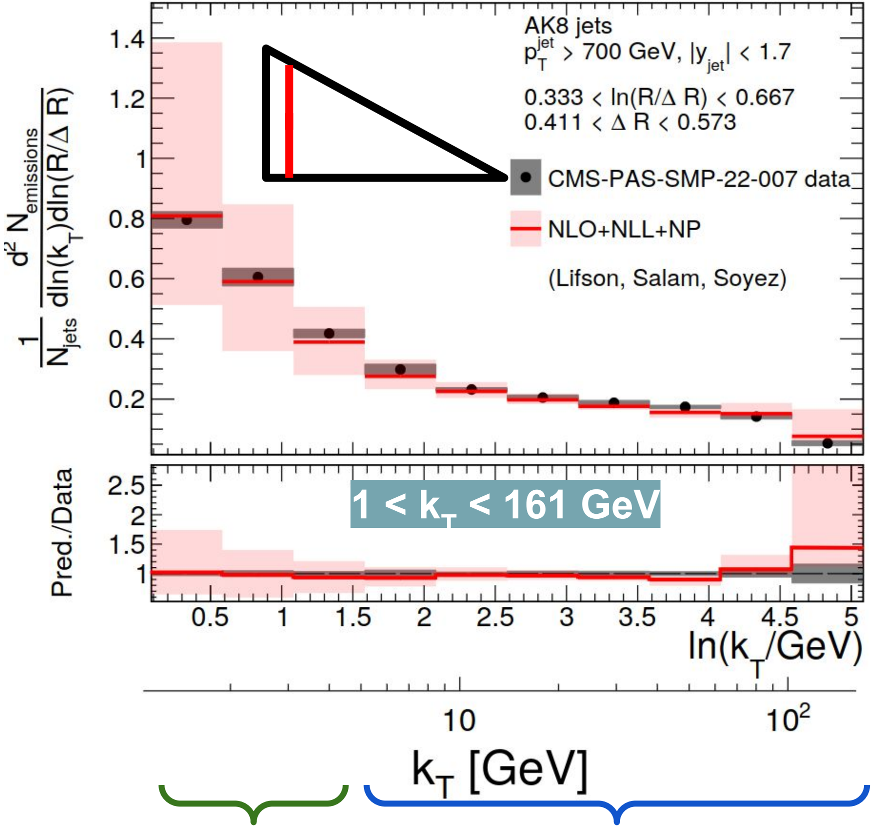
"new" CMS tunes (up to ~10% off)



full summary plot in backup (other angularities)

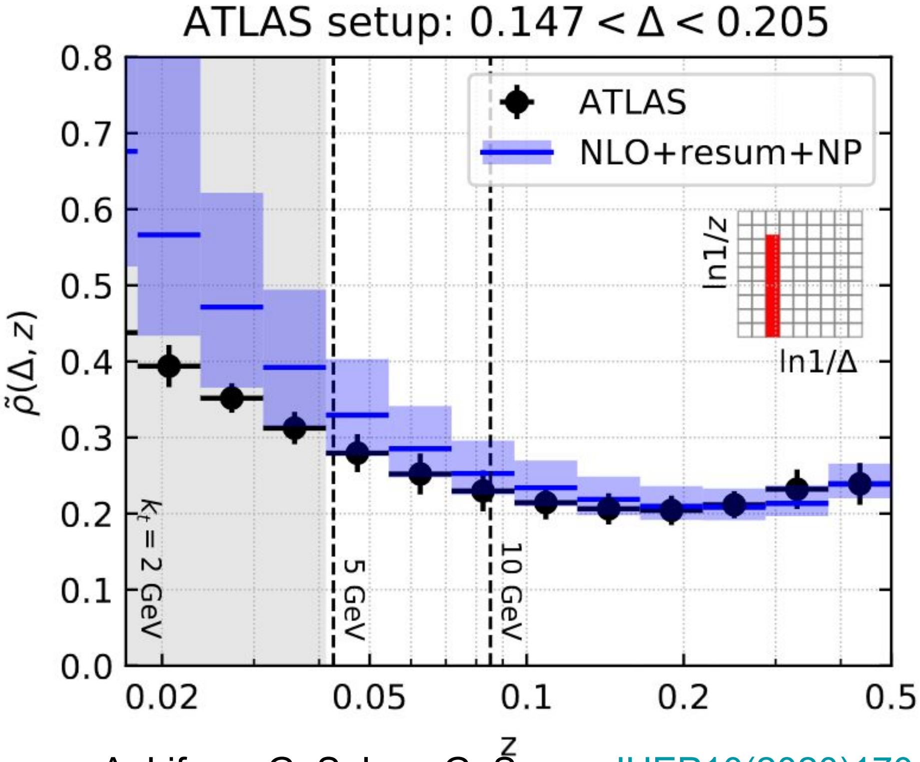
Comparison to pQCD analytical calculations (NLO+NLL+NP)

Calculations based on JHEP10(2020)170



nonperturbative

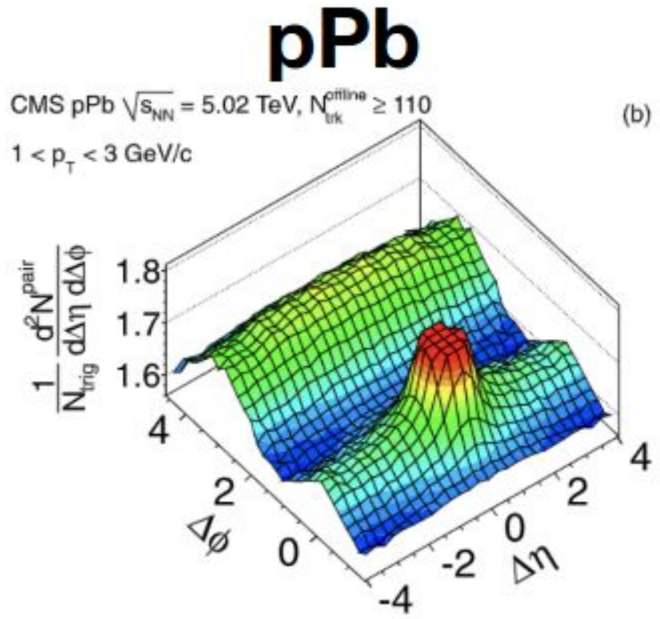
resummation

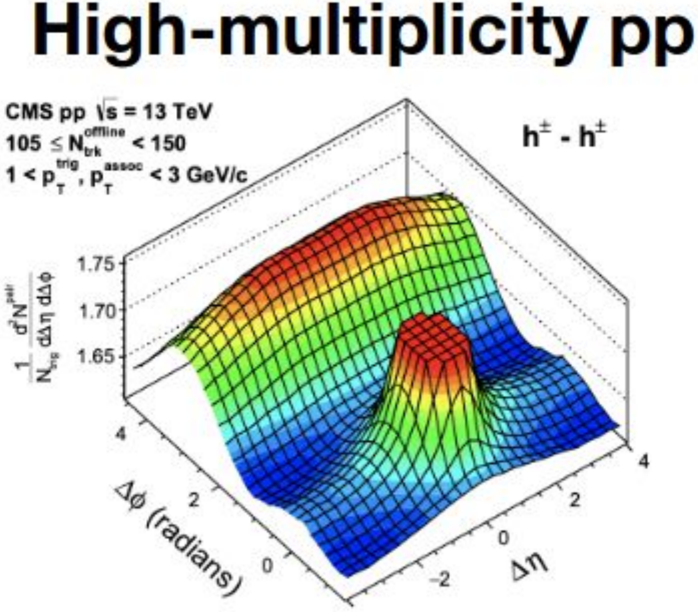


A. Lifson, G. Salam, G. Soyez JHEP10(2020)170

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

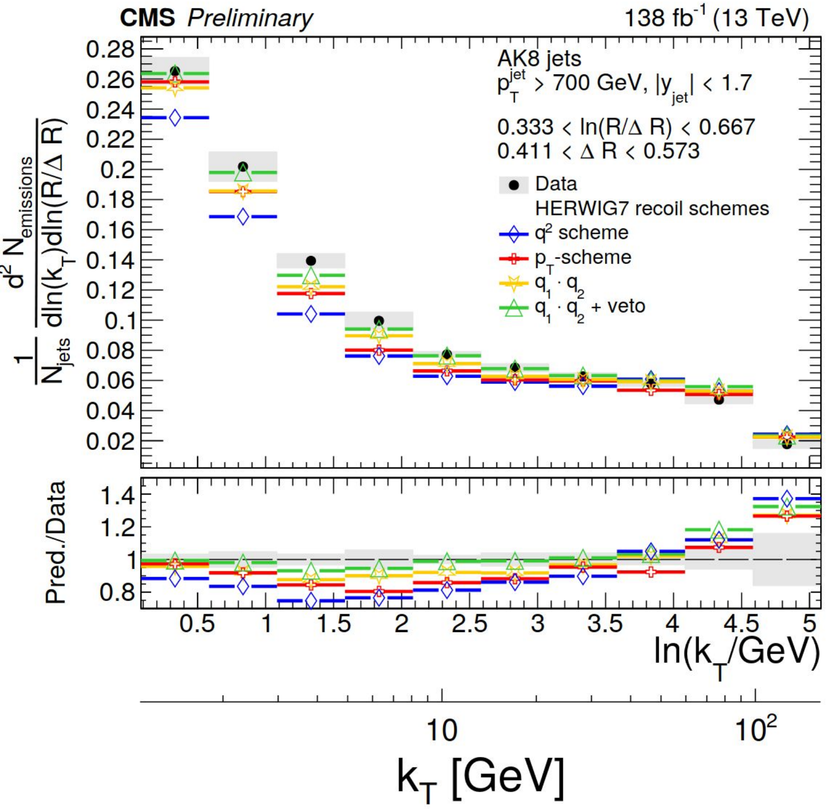
Ridge in pPb and high-multiplicity pp



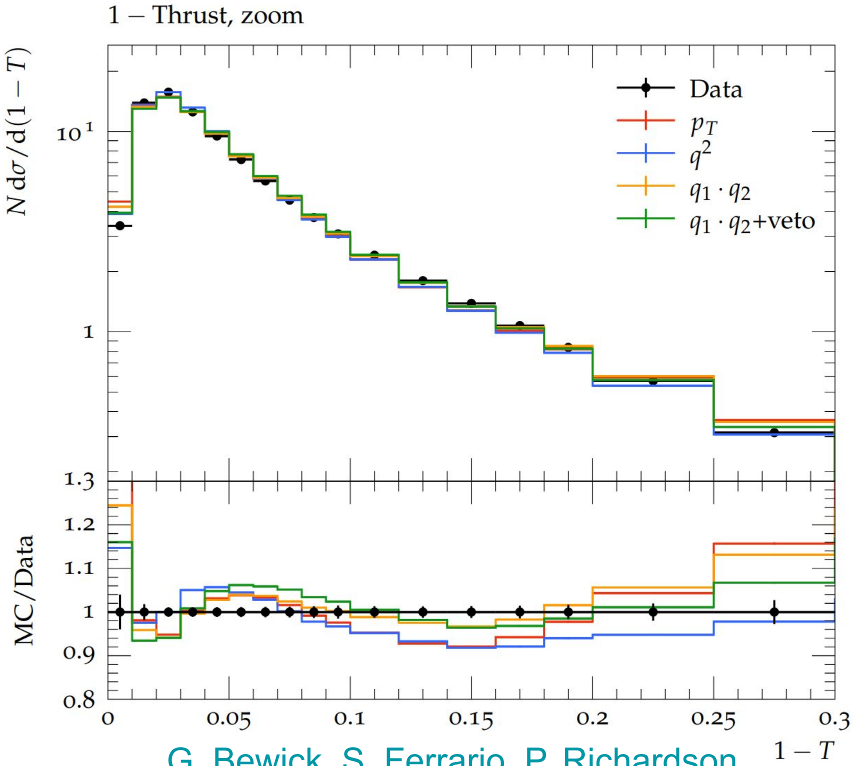


Sensitivity to recoil scheme choice, **important ingredient to reach NLL accuracy**

high-p_T quark and gluon jets



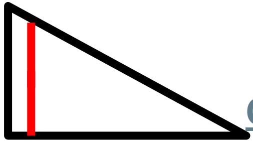
Thrust in e^+e^- at Z mass pole



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

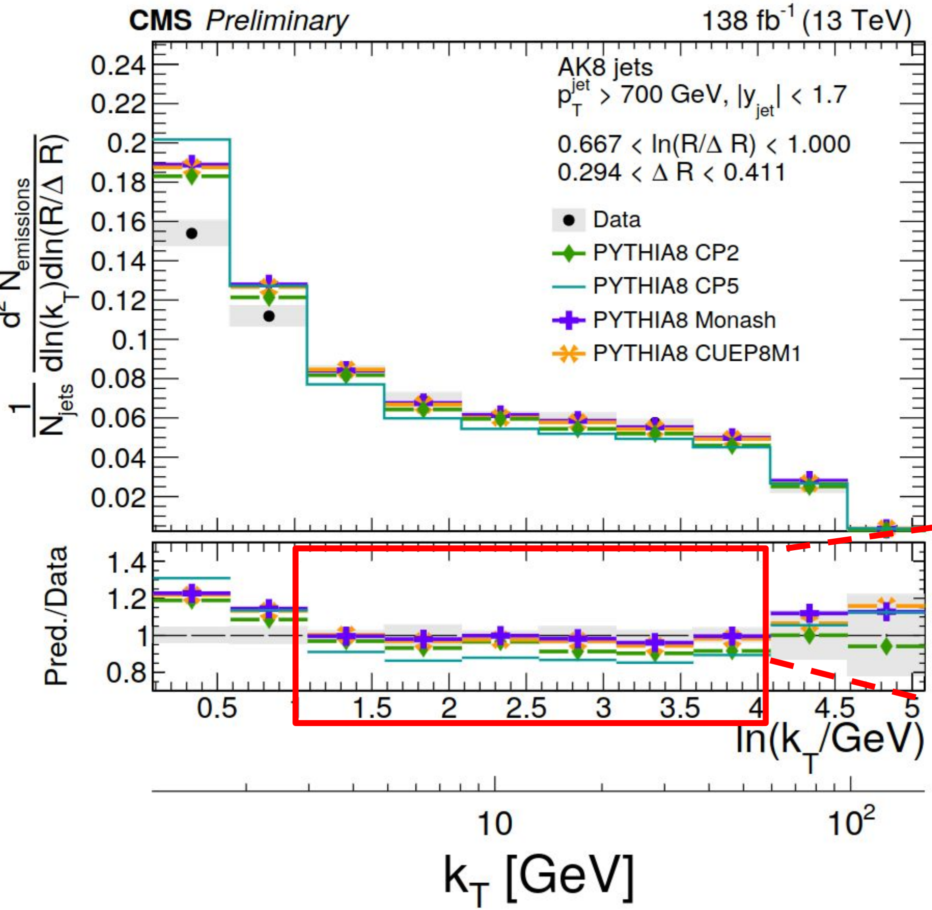
Large angle emissions



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

CMS-PAS-SMP-22-007

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

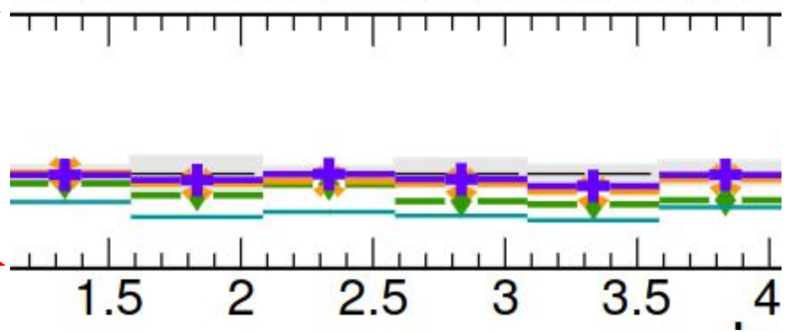


Monash/*CUEP8M1*: $\alpha_S^{FSR}(m_Z) = 0.1365$ (*best description*)

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

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

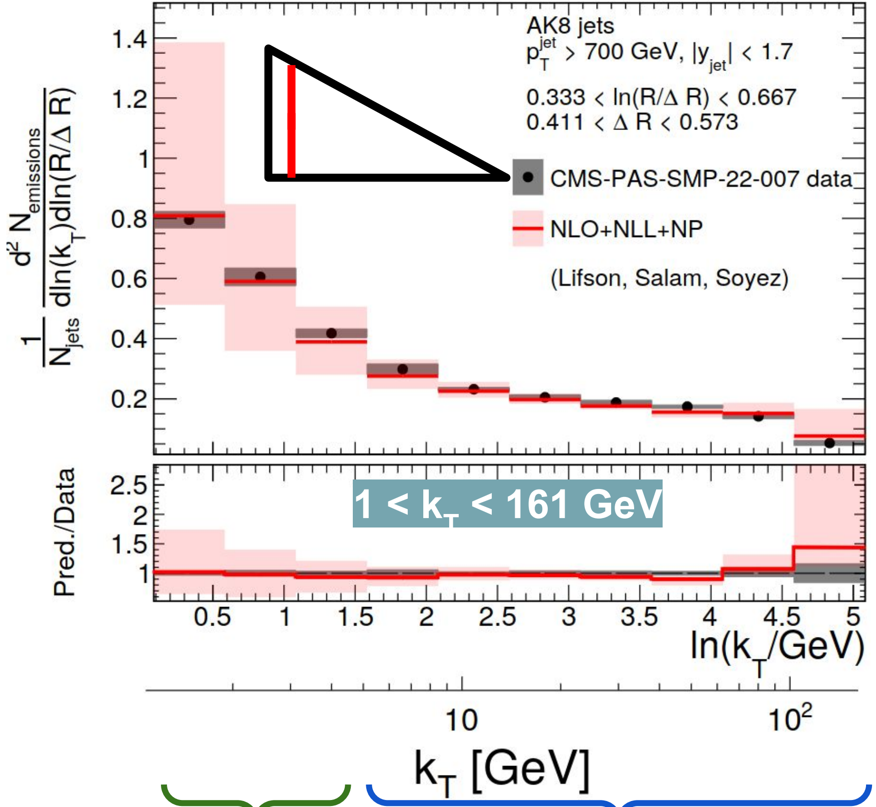
LJP data can be used to constrain $\alpha_S^{FSR}(m_Z)$ for MC tuning

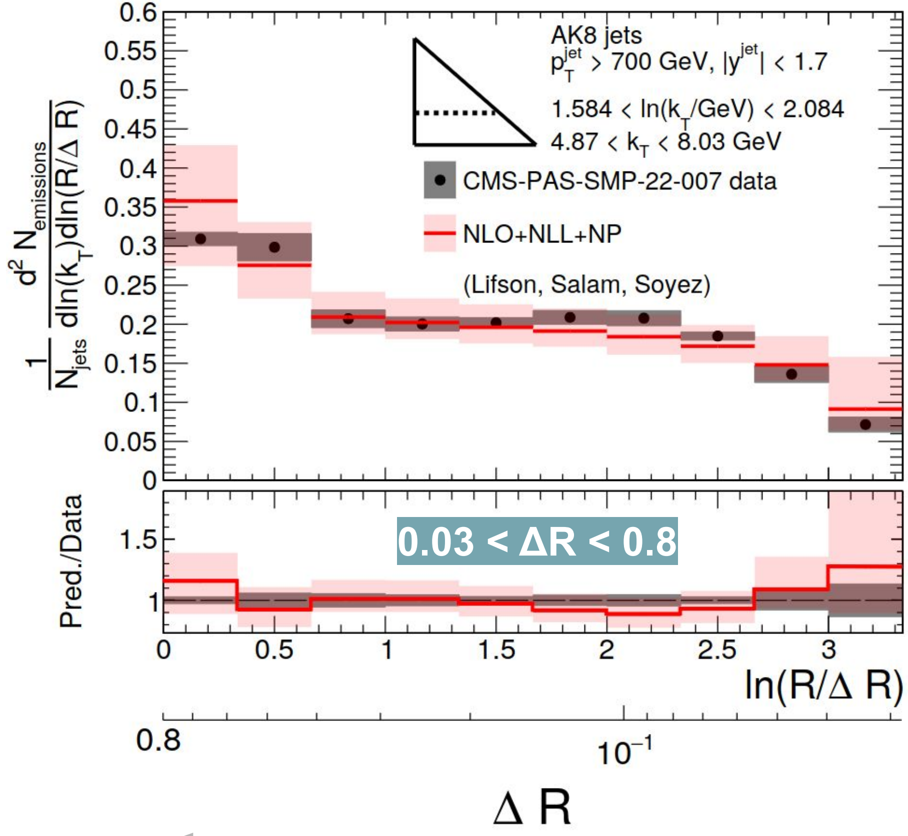


k_T between 3 – 50 GeV

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

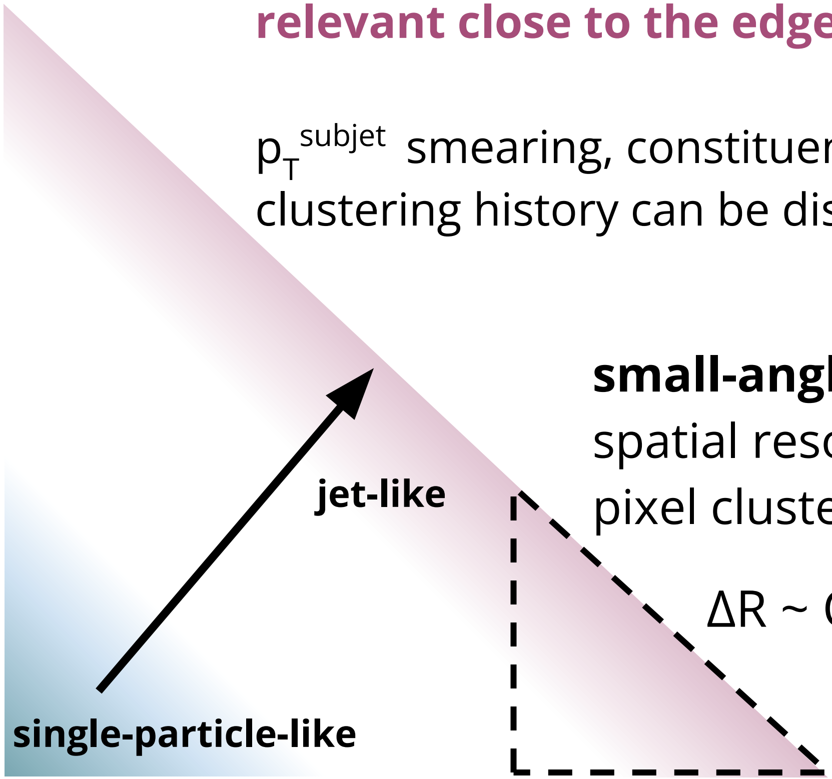
relevant close to the edge ($p_T^{soft} \sim p_T^{hard}$):

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

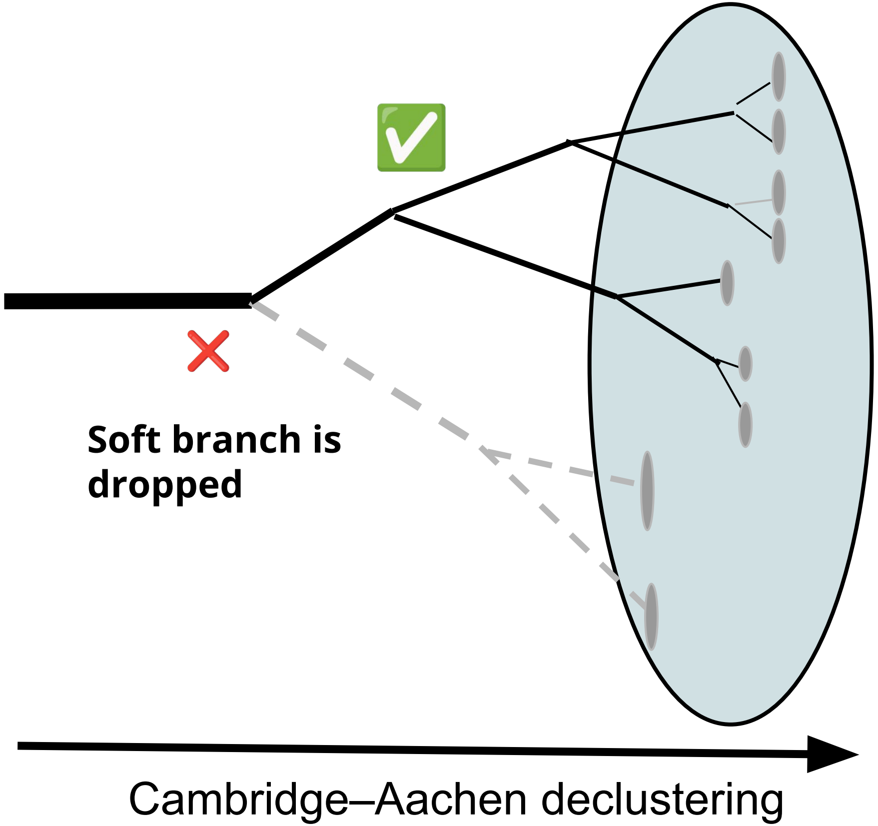
small-angles:
spatial resolution,
pixel cluster merging

$\Delta R \sim O(10^{-3} - 10^{-2})$

residual PU contributions (large ΔR, low k_T)



(Intermezzo) soft-drop grooming algorithm



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:

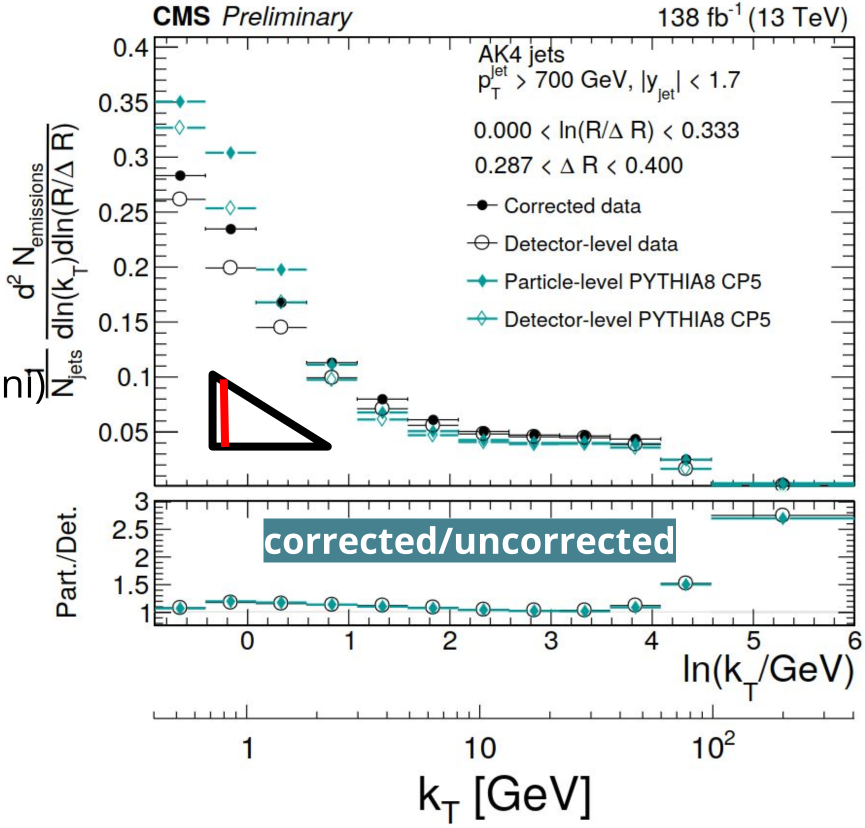
1. **Background:** bin-by-bin correction to account for det-level emissions not matched to truth-level emissions.

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

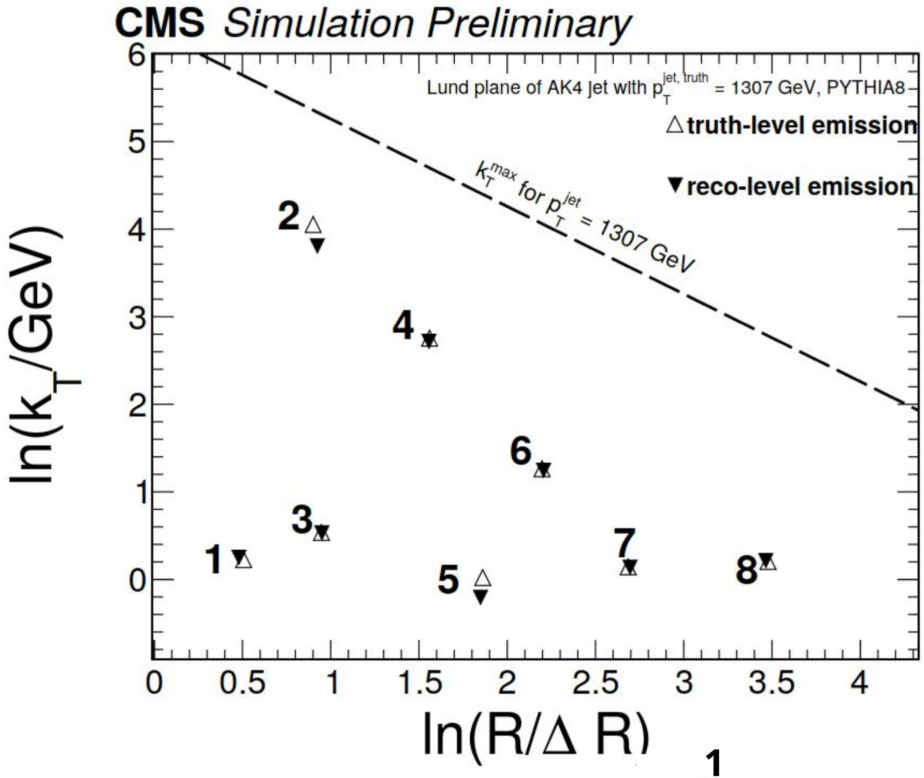
CMS-PAS-SMP-22-007

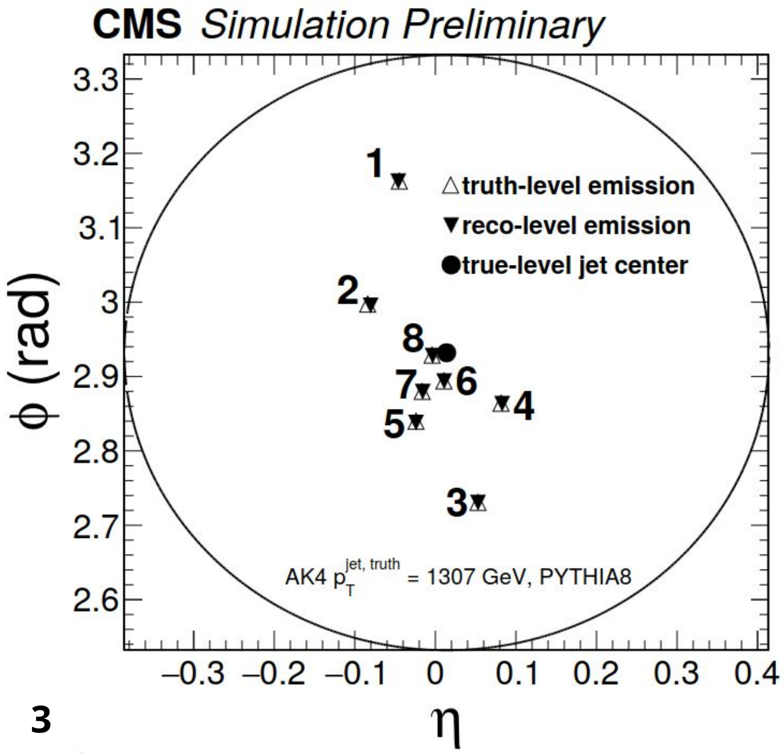


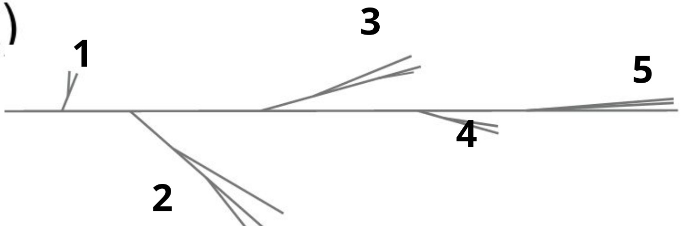
smearing becomes more important at high k_T

Matching emissions at detector level and particle level

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







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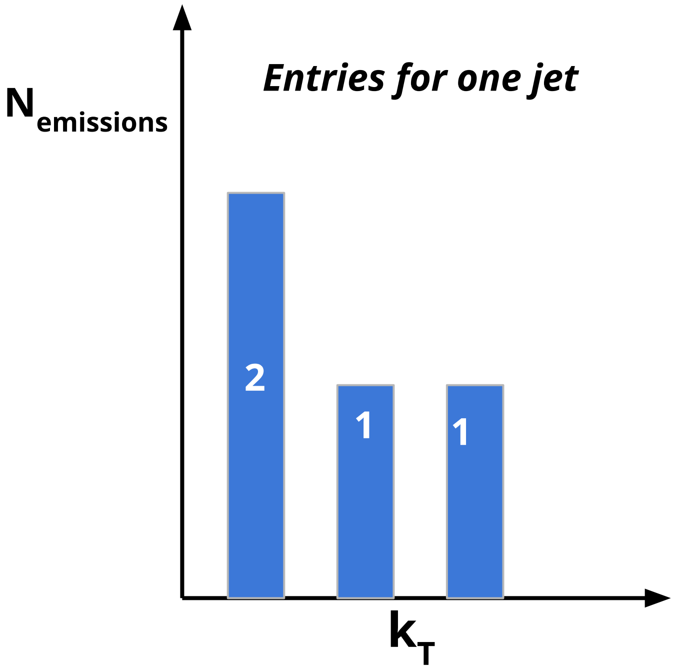
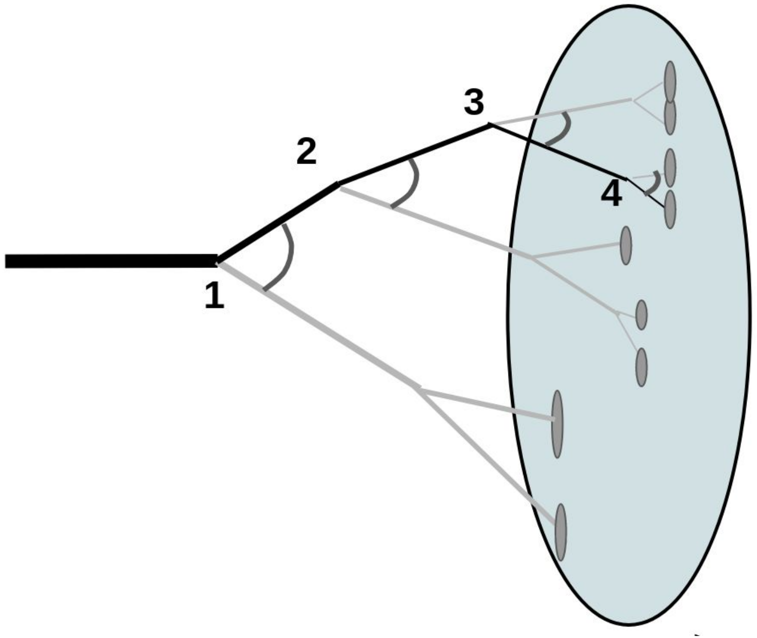
detector-level statistical correlations

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, …)

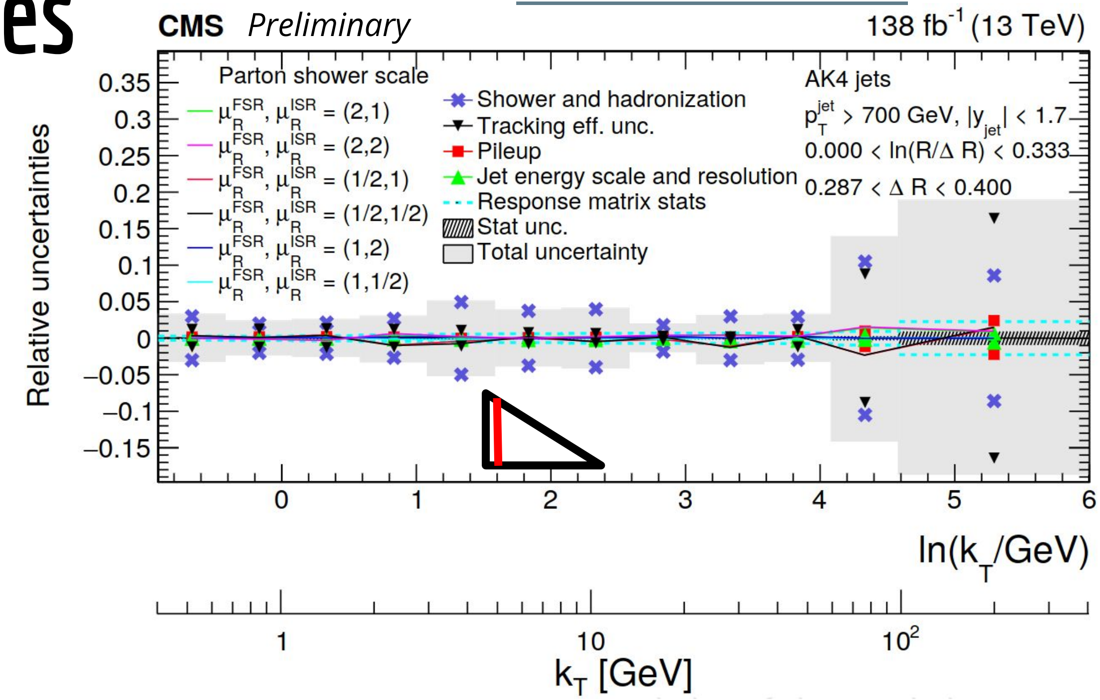
Systematic uncertainties

CMS-PAS-SMP-22-007

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

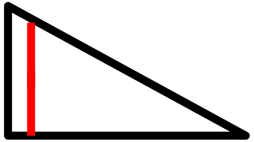


Dominated by **shower & hadronization modeling** in bulk of Lund plane & by **tracking efficiency** at high k_T

Subleading components (<~ 1%):

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

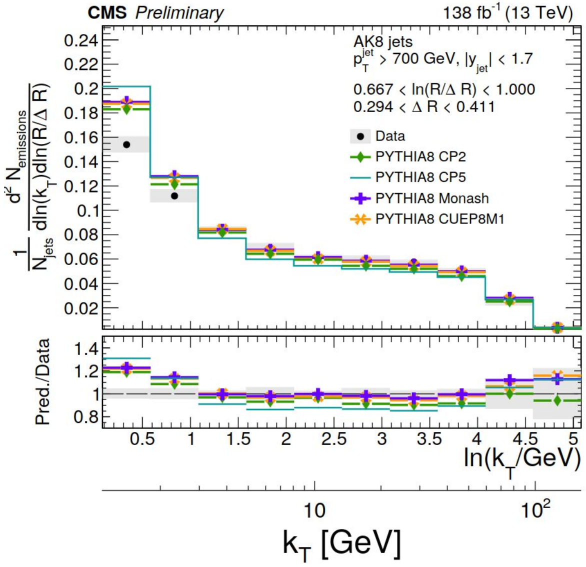
Large angle emissions



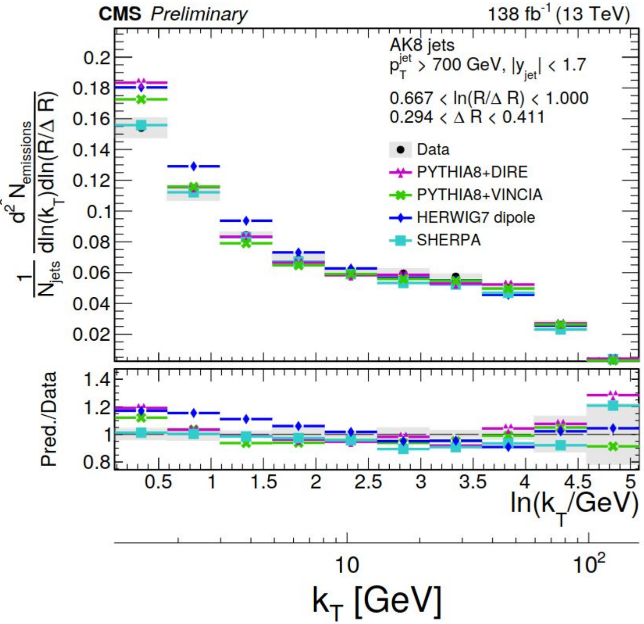
R = 0.8

Comparison to parton showers& tunes

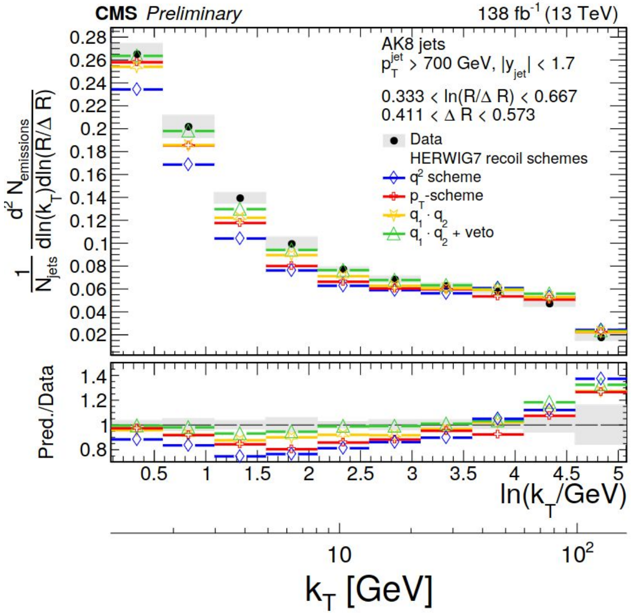
CMS-PAS-SMP-22-007



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