Jet substructure with iterative declustering in CMS

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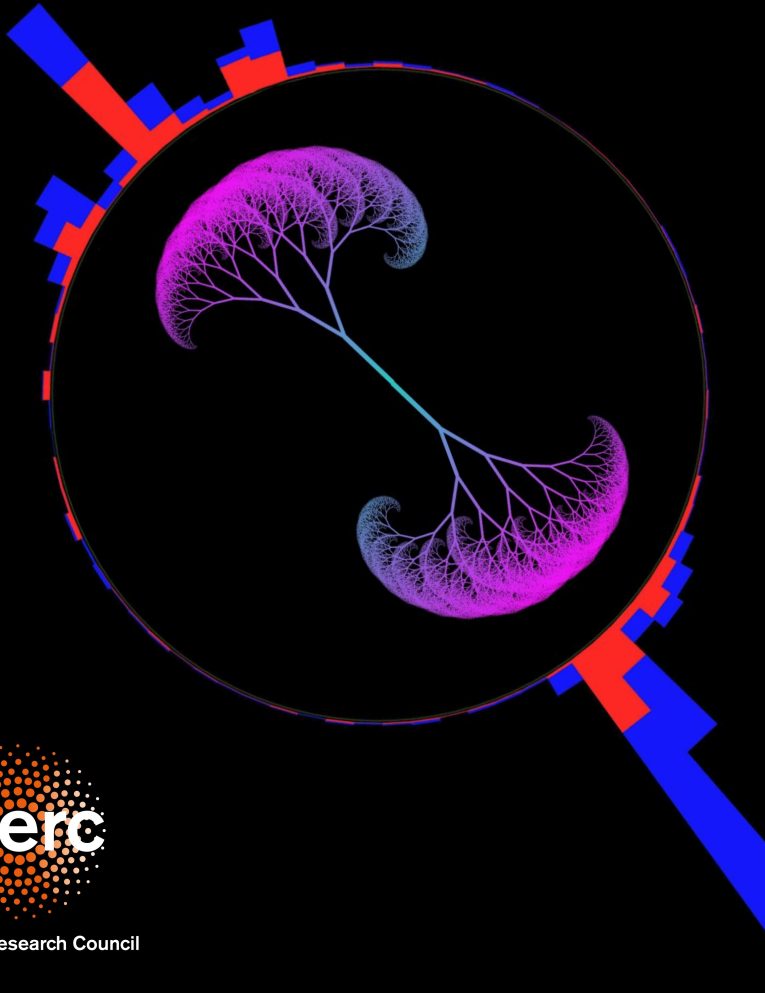
Laboratoire Leprince-Ringuet

BOOST 2023 at LBNL
July 31st – August 4th



CMS Compact Muon Solenoid

ÉCOLE POLYTECHNIQUE

European Research Council

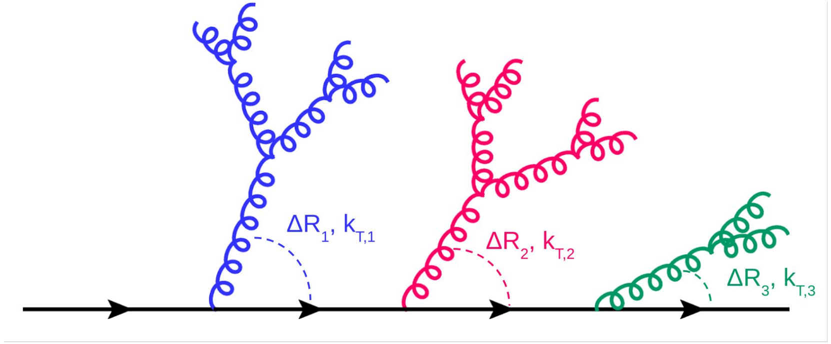
Focus on two recent CMS preliminary results:

CMS primary Lund jet plane density at 13 TeV
(**CMS-PAS-SMP-22-007**)

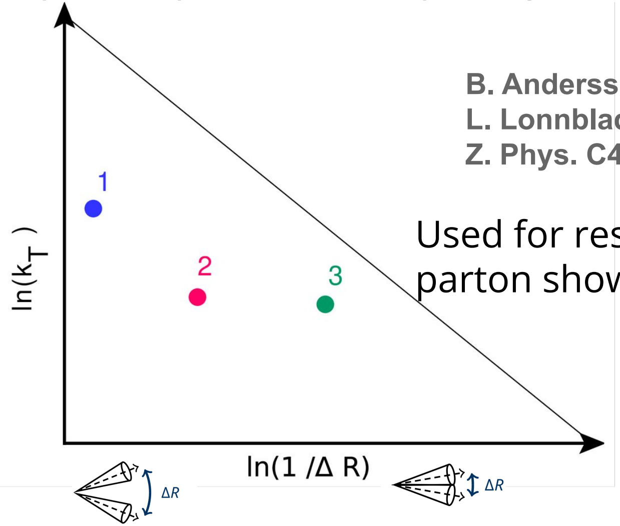
Jet substructure with photon-tagged jets in PbPb and pp at 5.02 TeV
(**CMS-PAS-HIN-23-001**, *link soon on CDS and CMS public page*)

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

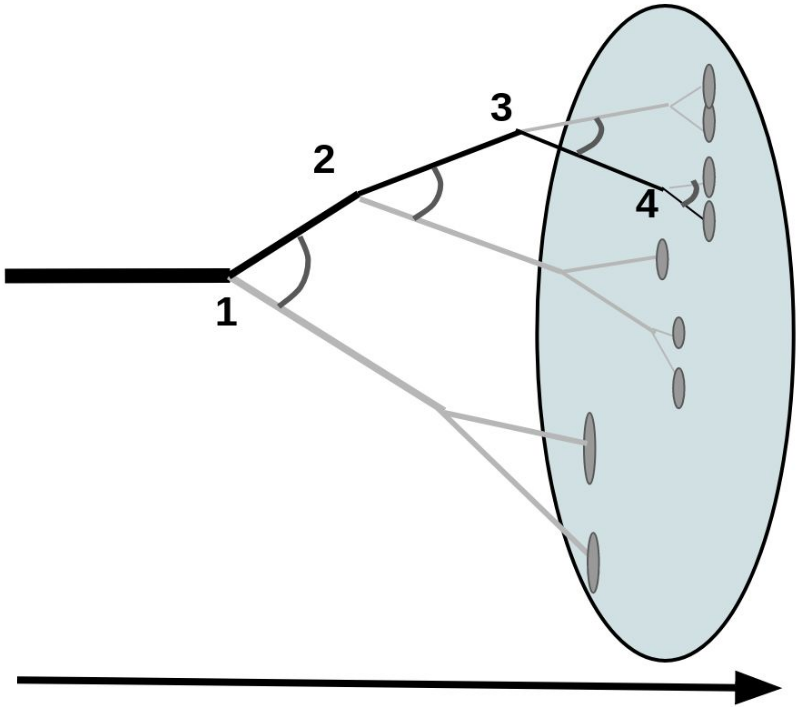
Used for resummation and parton shower development

In soft & collinear limit of QCD, emissions fill the double-logarithmic plane of k_T and ΔR 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**

Constructing the ***primary*** Lund jet plane

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



1. Jet constituents are reclustered with the CA algorithm.

2. Follow clustering tree in reverse (large → small angles), **along the hardest branch**

3. k_T and ΔR of the softer subjet relative to the harder subjet is registered at each step

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

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

4. Repeat until hard branch has a single constituent

   Previously measured by ATLAS PRL 124, 222002 (2020) and ALICE ALICE-PUBLIC-2021-002

Angular ordering privileges QCD collinear divergence & mimics color coherence effects

Primary Lund jet plane density

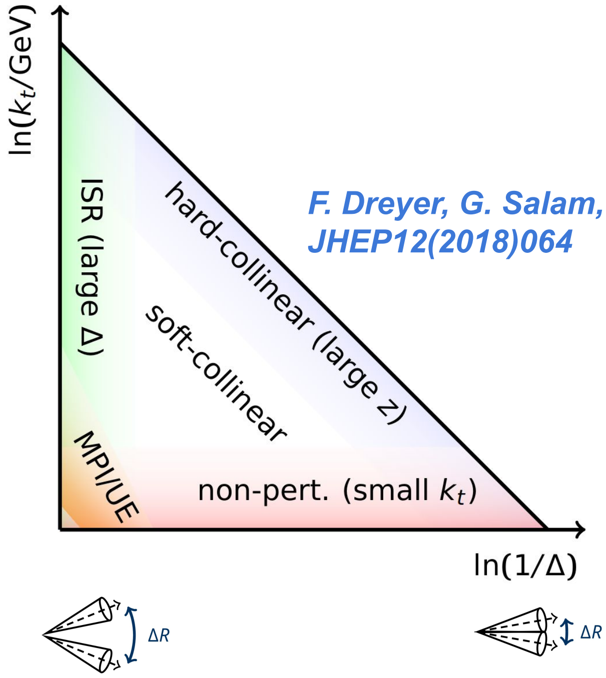
We measure the jet-averaged density of emissions:

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

soft & collinear limit

($C_R = C_A = 3$ for g→gg, $C_F = 4/3$ for q→qg)

Various mechanisms are separated



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

Can use Lund plane density to improve and test calculations in a “factorized” way

measured by ATLAS PRL 124, 222002 (2020)
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soft & collinear limit

($C_R = C_A = 3$ for g→gg, $C_F = 4/3$ for q→qg)

CMS full Run-2 setup CMS-PAS-SMP-22-007 :

- **Inclusive jet selection:**
  $p_T^{jet} > 700$ GeV, $|y^{jet}| < 1.7$,

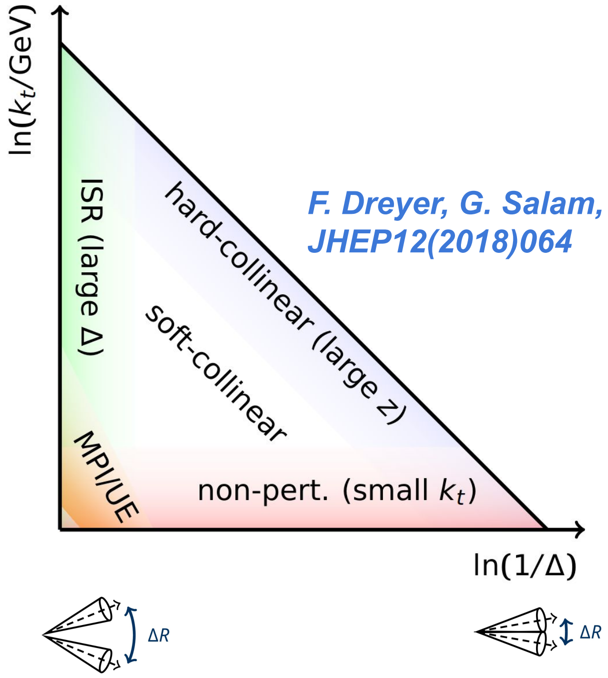
  anti-k_T with small R = 0.4 and large R = 0.8

- Charged-particles of the jet used for LJP

- Unfolding with D'Agostini to particle-level (p_T^{jet} , k_T, ΔR)

  # of iterations optimized based on χ^2 tests in smeared space

Various mechanisms are separated



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

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selected detector effects

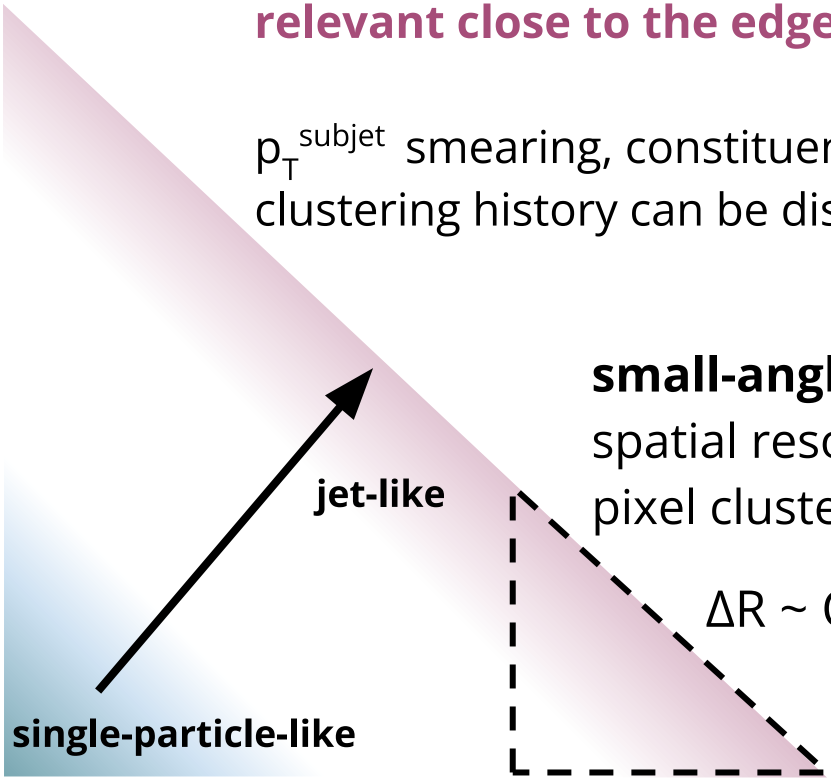
relevant close to the edge ($p_T^{soft} \sim p_T^{hard}$):

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

small-angles:
spatial resolution,
pixel cluster merging

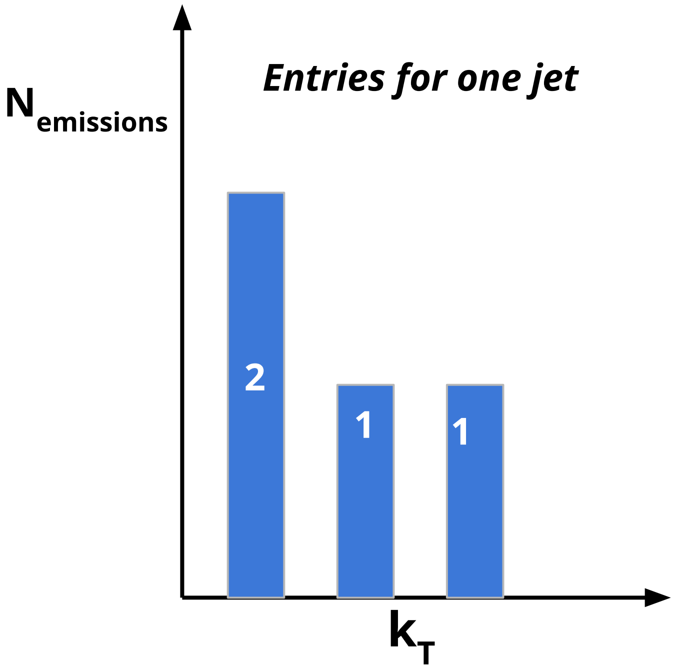
$\Delta R \sim O(10^{-3} – 10^{-2})$

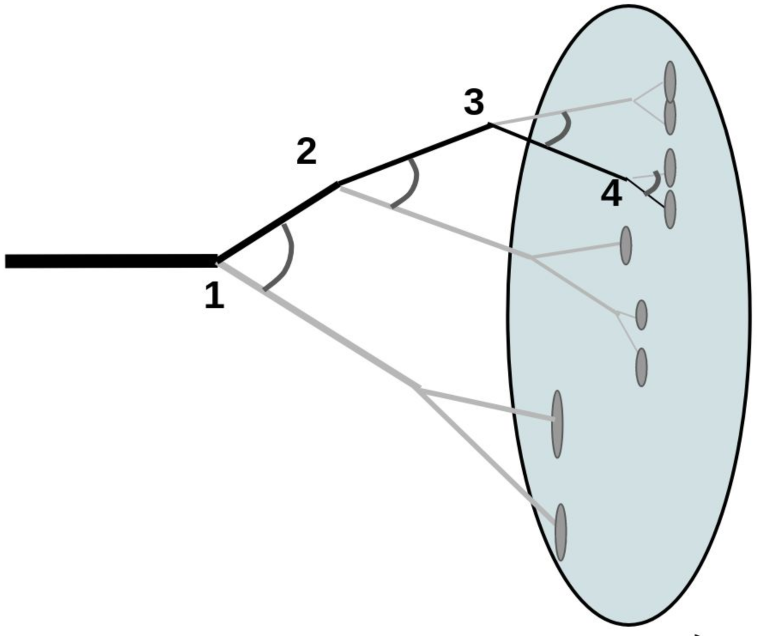
residual PU contributions (large ΔR, low k_T)



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)

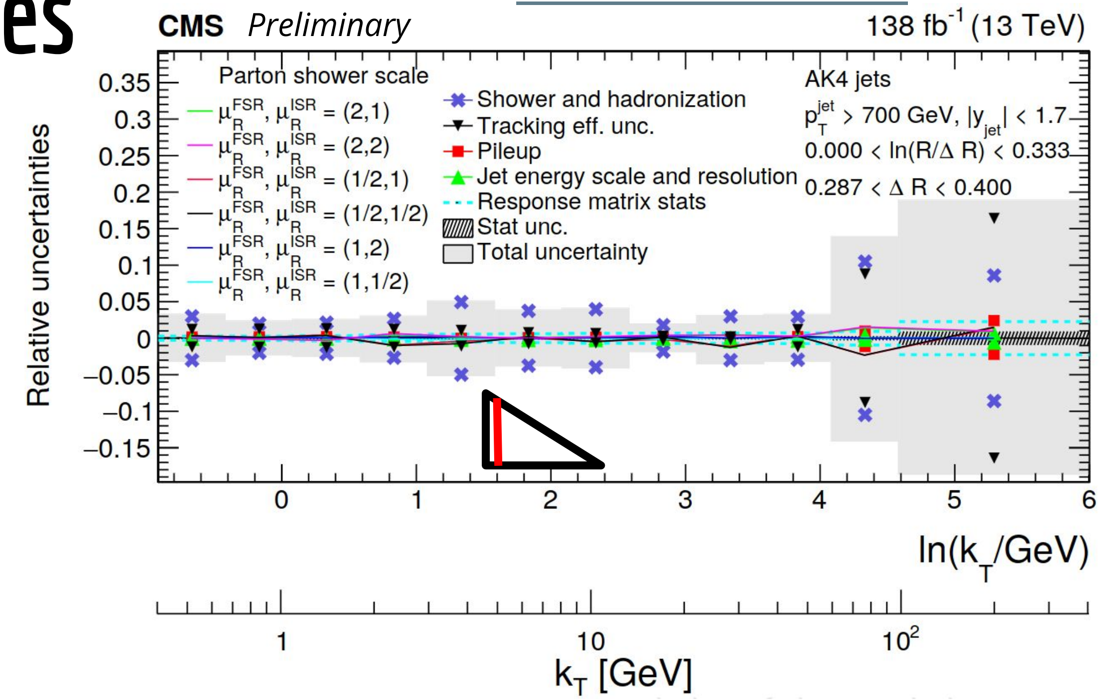
decorrelated into prior bias ⊗ response pieces

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

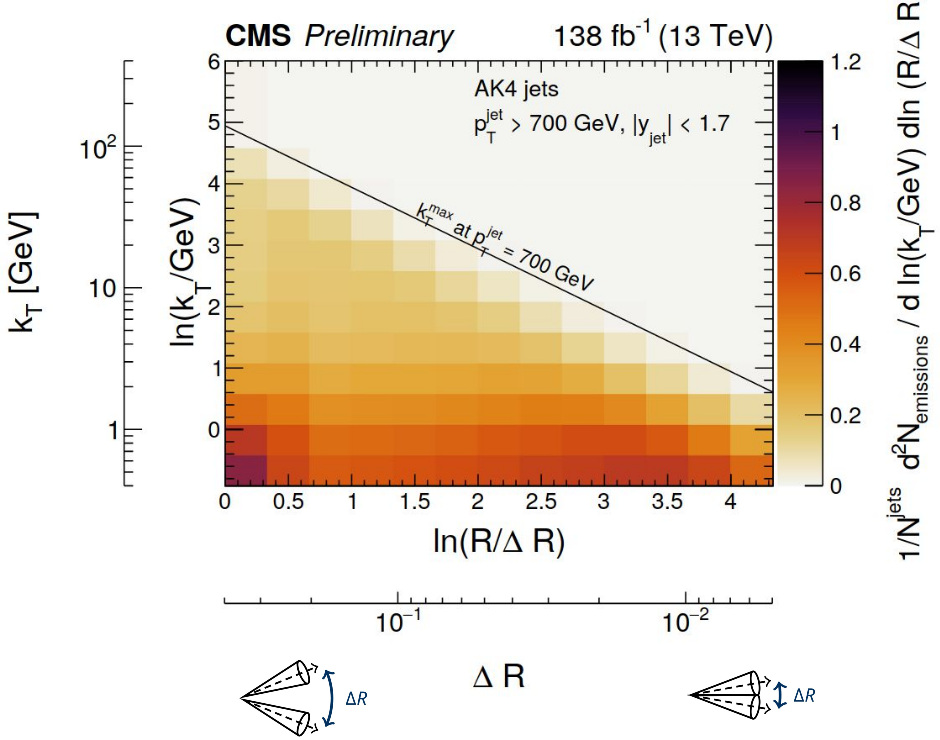


Dominated by **shower & hadronization modeling** in bulk of Lund plane & by **tracking efficiency** at high k_T

Unfolded primary Lund jet plane densities

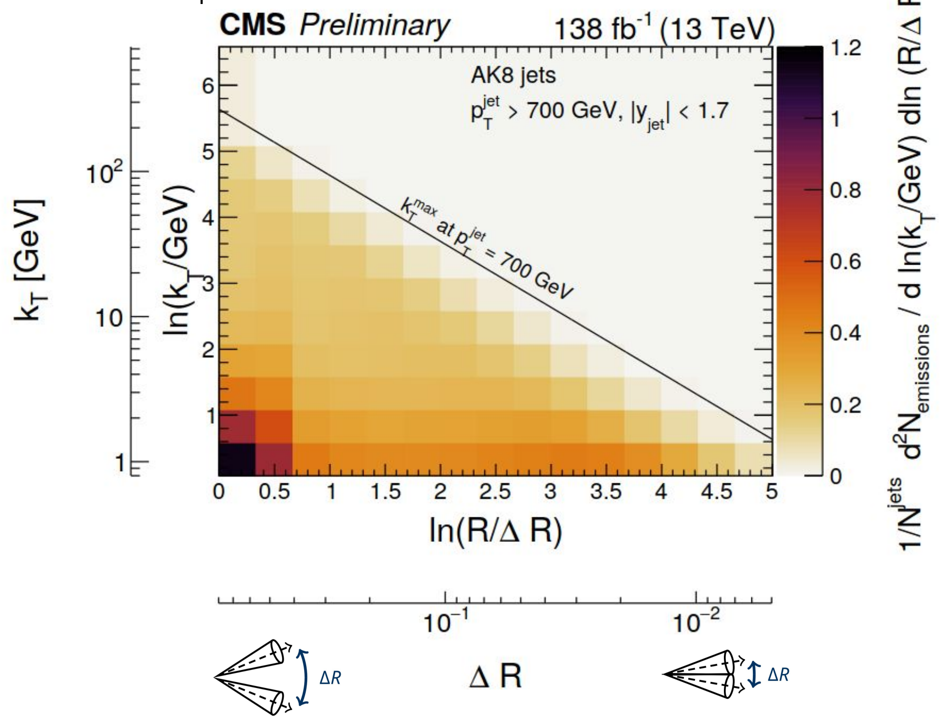
CMS-PAS-SMP-22-007

R=0.4 (standard R in Run-2)



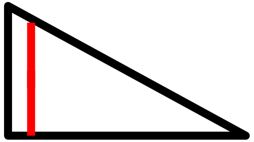
R=0.8 (wider & harder emissions)

Up to k_T ~ 700 GeV at large angles.



LJP density approximately flat for hard & collinear emissions due to $\alpha_S(k_T)$ ~ $1/\ln(k_T)$

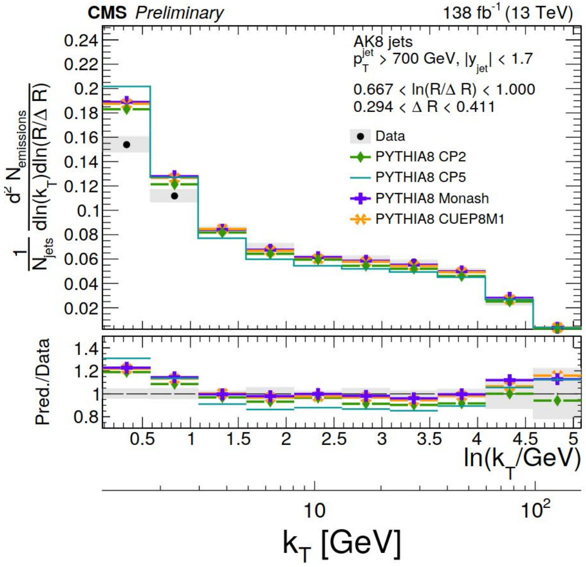
Large angle emissions



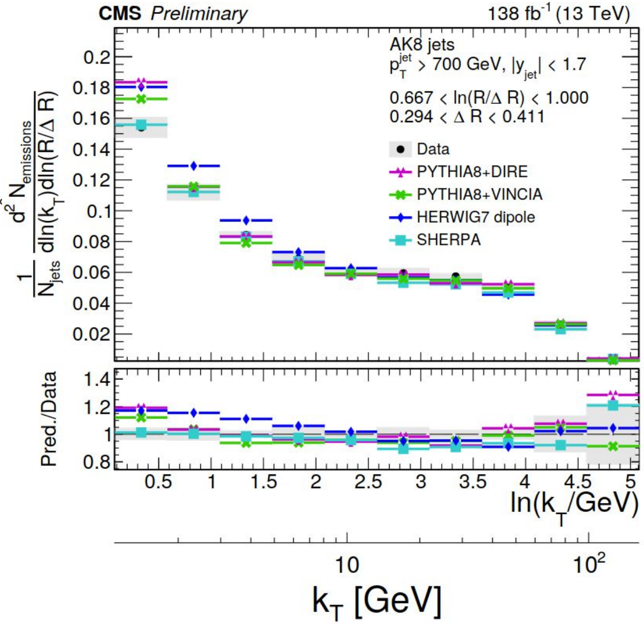
R = 0.8

Comparison to parton showers& tunes

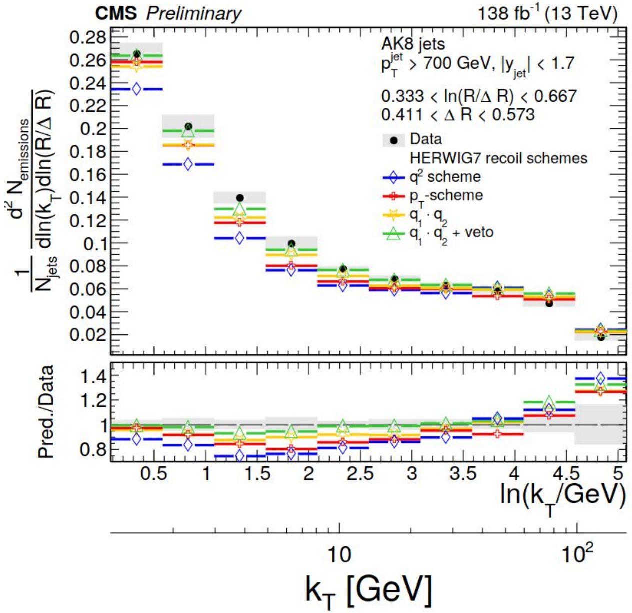
CMS-PAS-SMP-22-007



PYTHIA8 tunes
(CP2, CP5, Monash, CUEP8m1)



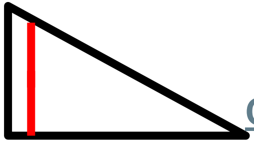
Dipole showers
(Vincia, Dire, Herwig7 dipole, Sherpa)



Herwig7 recoil schemes,
(angle-ordered shower)
approx. NLL accurate

Differences between data & MC of the order of 10–20%. “Factorization” of effects can be used for MC tuning

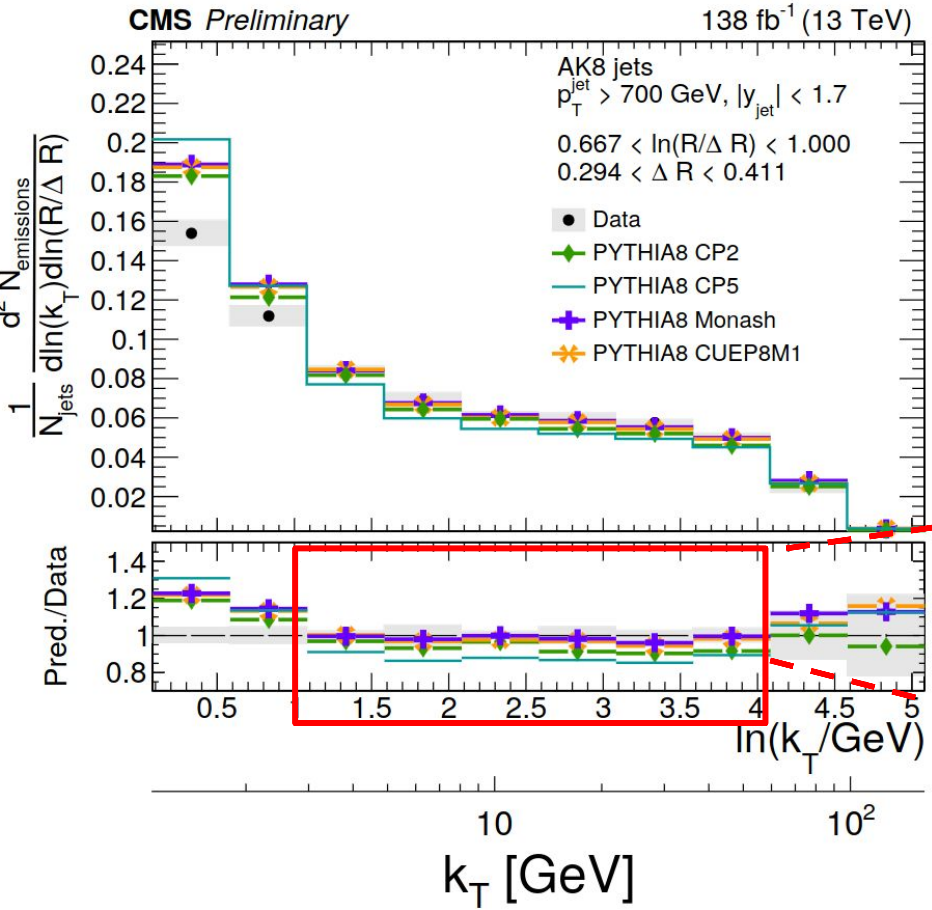
Large angle emissions



CMS-PAS-SMP-22-007

Most important difference between PY8 tunes is α_s^{FSR}

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

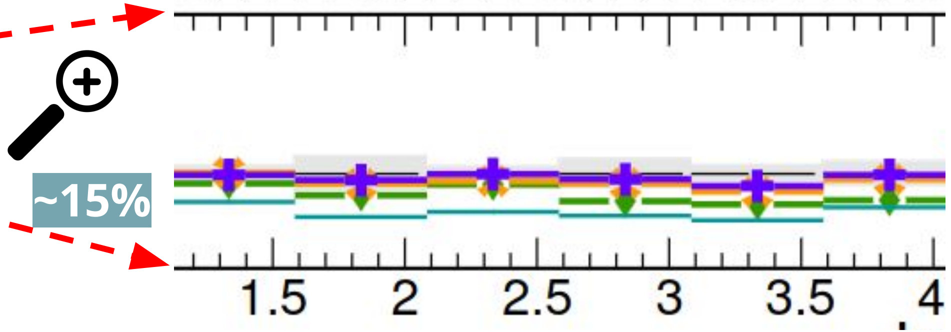


Monash/*CUEP8M1:* $\alpha_s^{FSR}(m_Z) = 0.1365$ (*best description*)

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

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

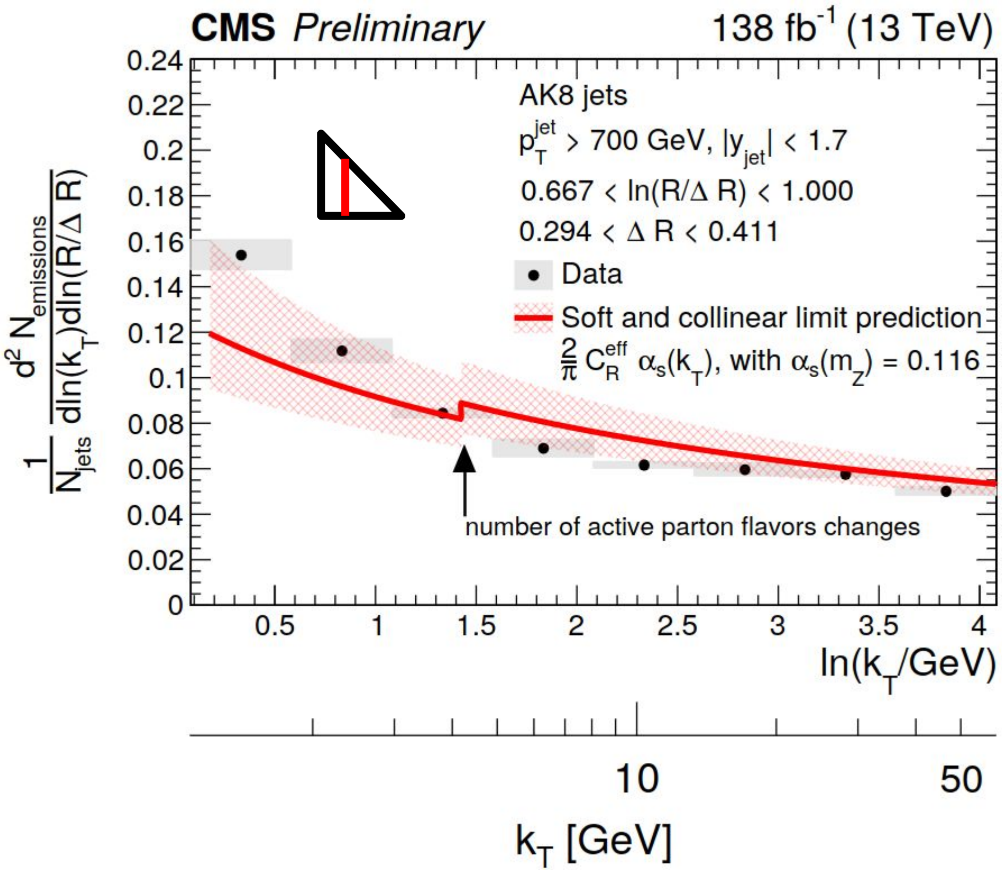
LJP data can be used to constrain $\alpha_s^{FSR}(m_Z)$ in MC tuning campaigns



k_T between 3 – 50 GeV

LJP data qualitatively described by running of $\alpha_S \sim 1/\ln(k_T)$

CMS-PAS-SMP-22-007

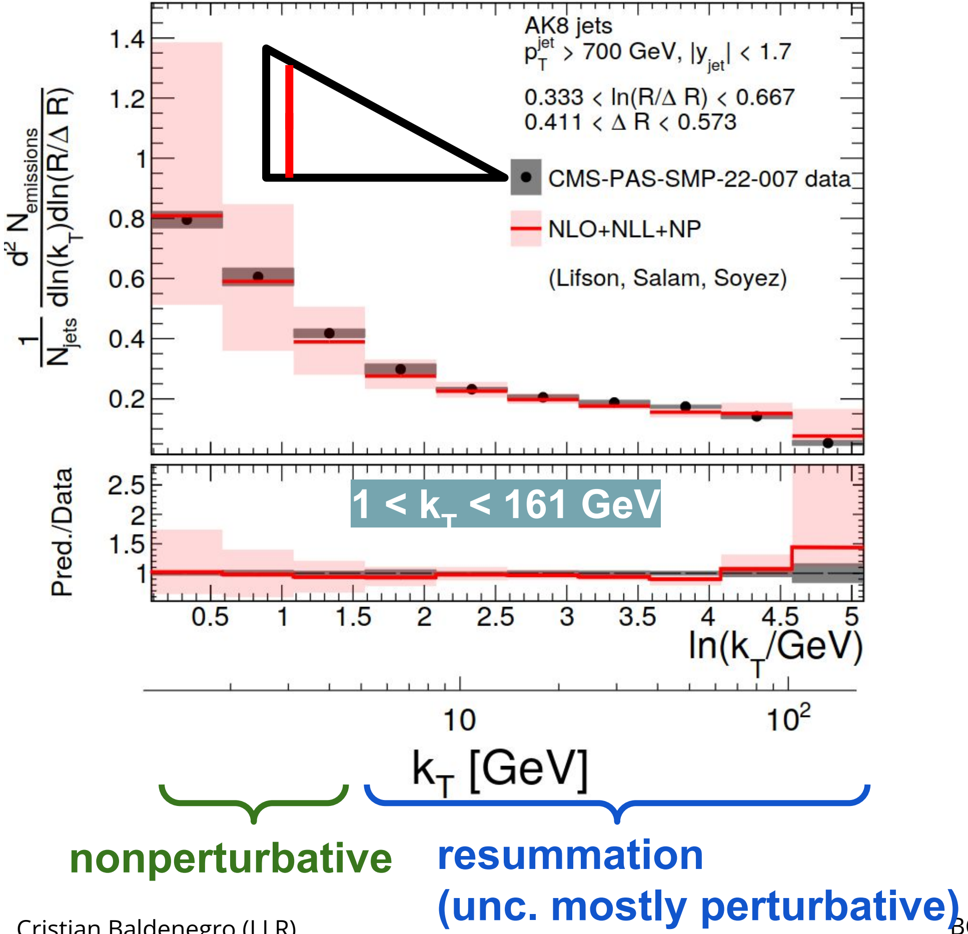


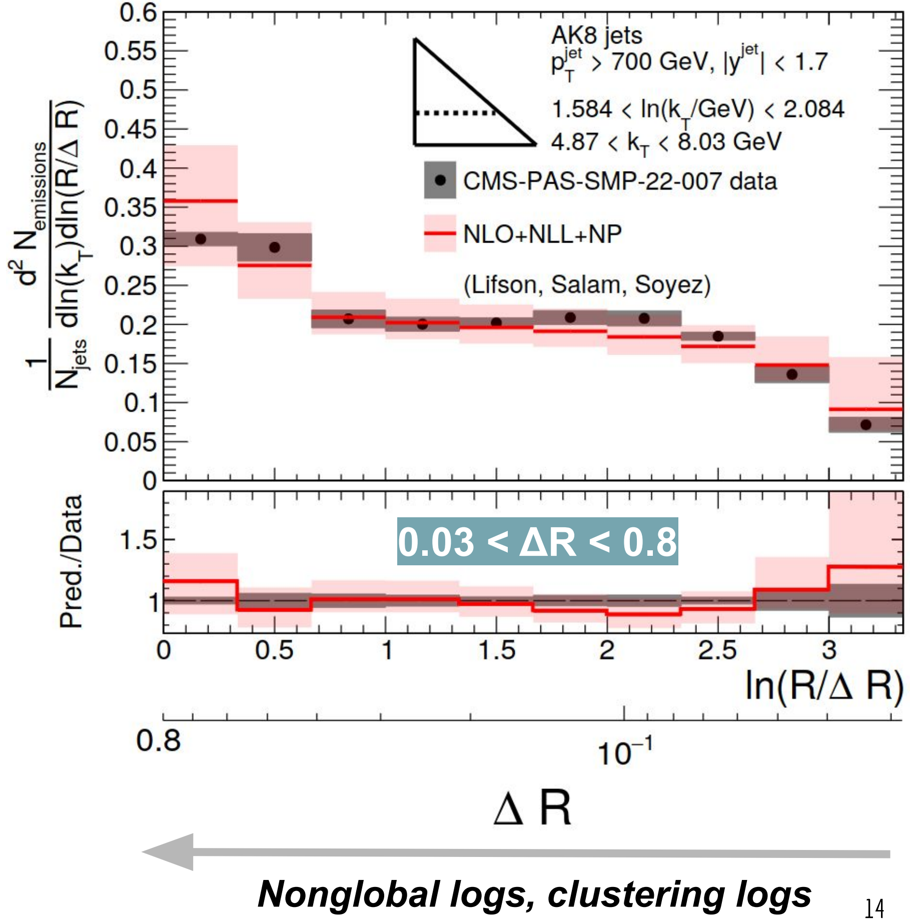
naïve pocket formula IRC limit

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

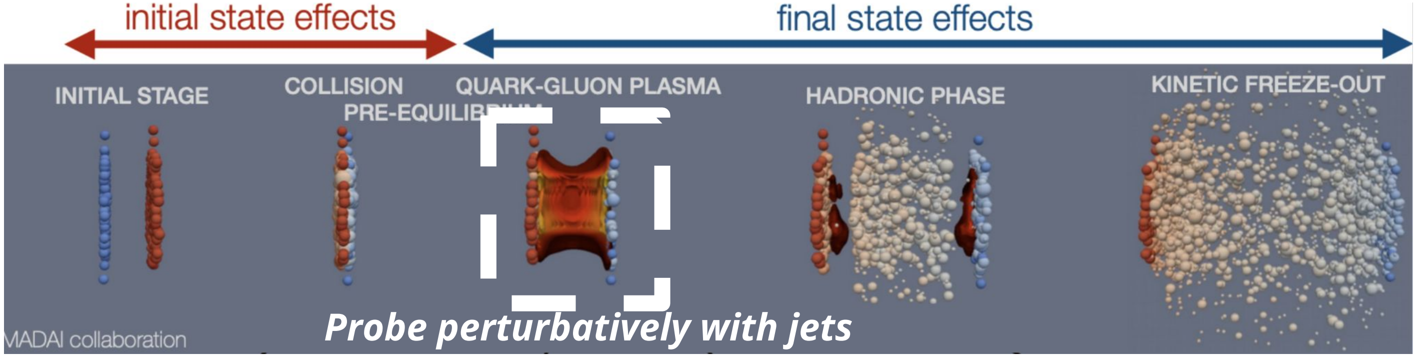
pQCD analytical calculations (NLO+NLL+NP)

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

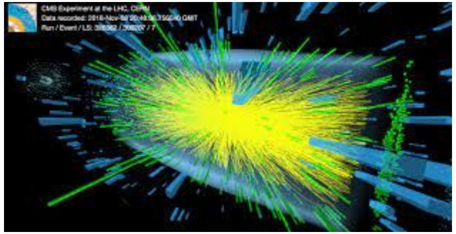




Probing QCD at high densities & high temperatures



What we see



sketches from Rey Cruz

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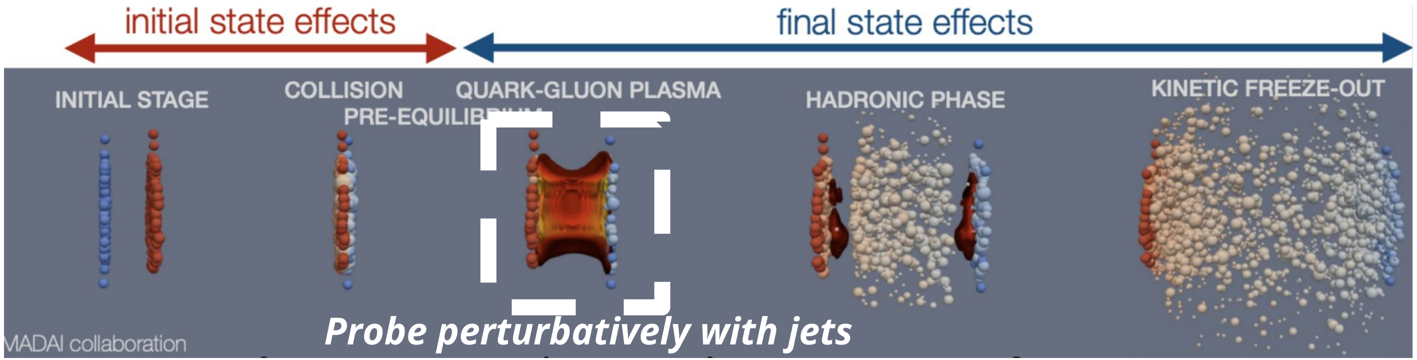

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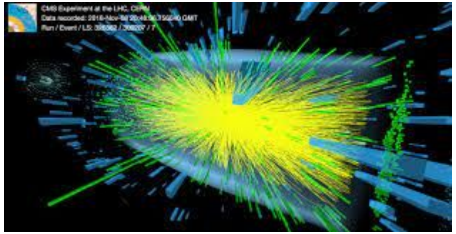
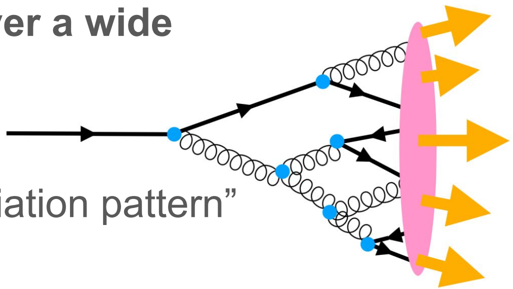
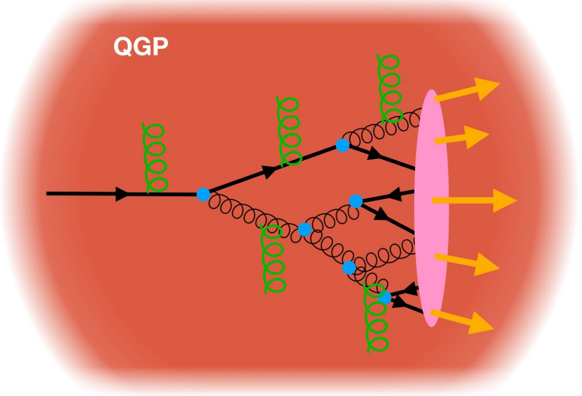


pp ("vacuum")

PbPb (in medium)

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





Jet quenching == "modification of jet radiation pattern"

More general introduction by J. Mulligan

sketches from Rey Cruz

Medium-induced modifications in the Lund plane

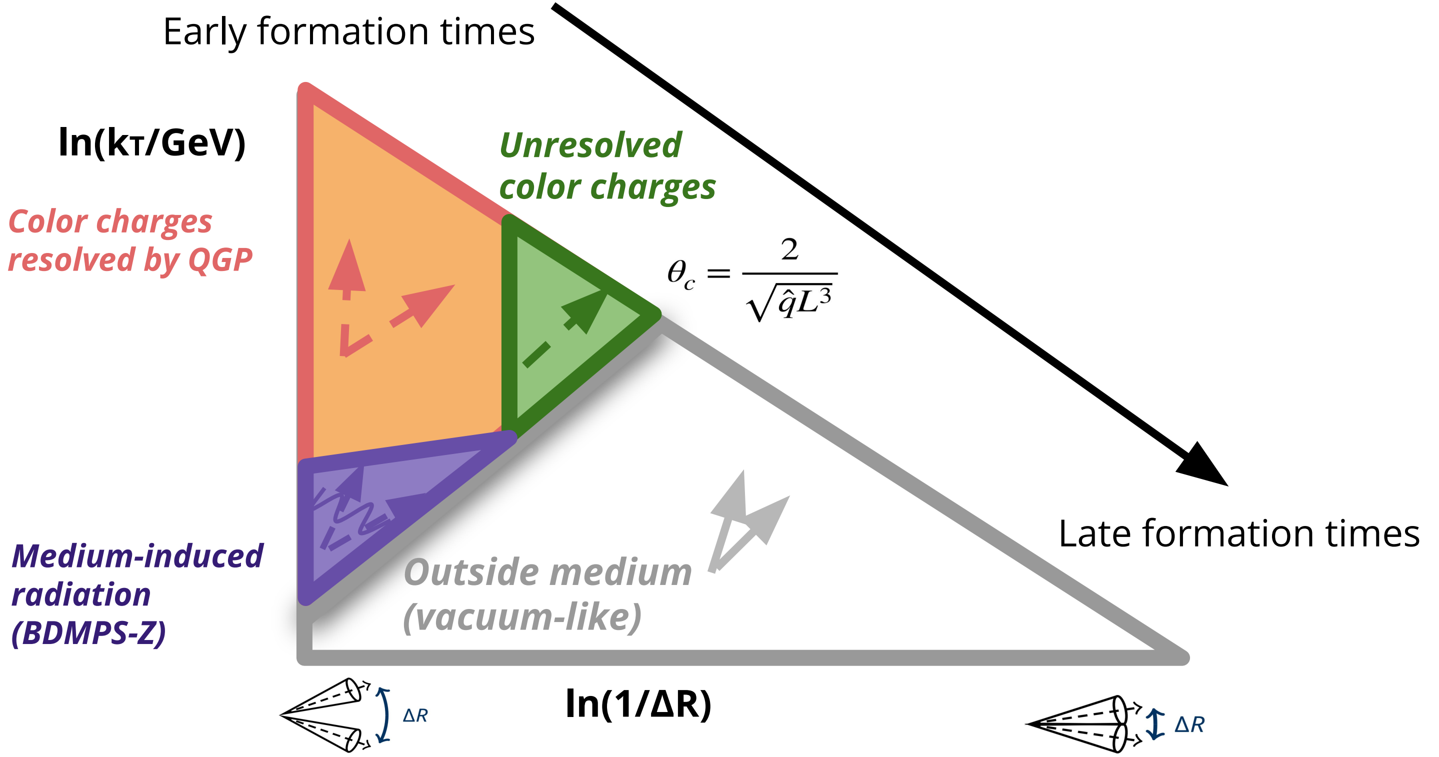
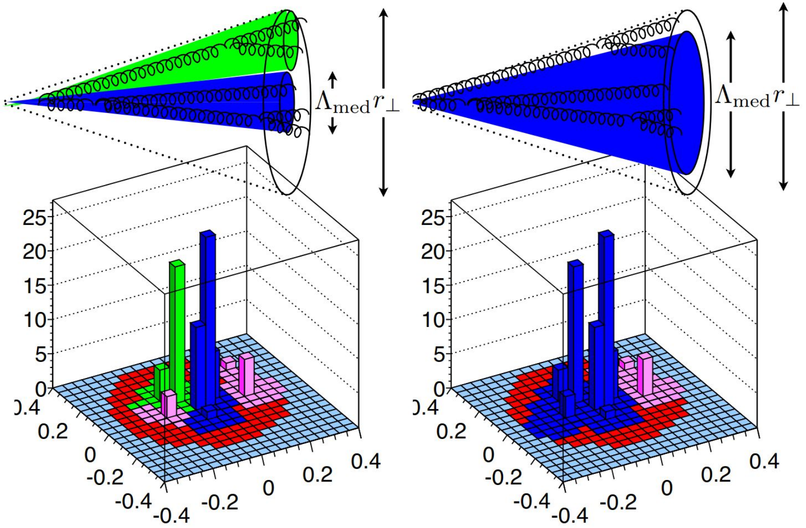


diagram inspired on regions from [P. Caucal, A. Soto, A. Takacs, PRD 105, 114046 (2022)]

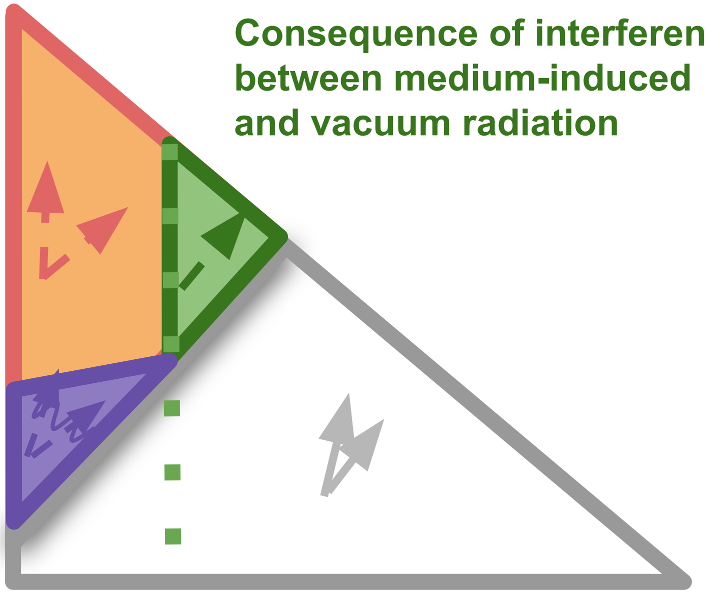
Medium resolution length (color decoherence)

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]



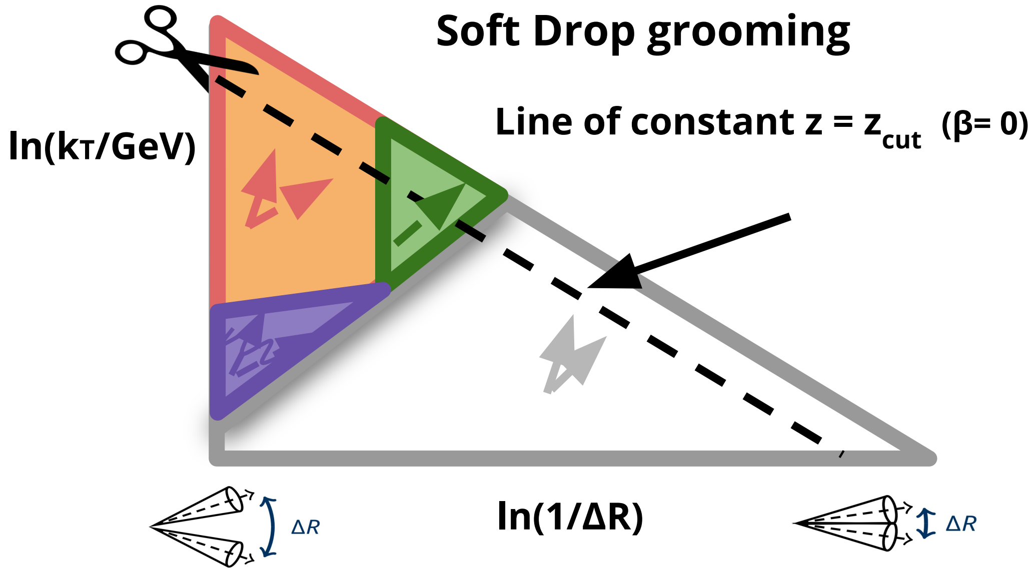
Consequence of interference between medium-induced and vacuum radiation

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



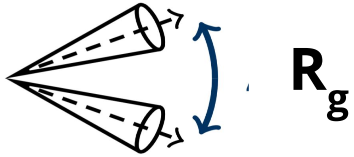
1-splitting per jet

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

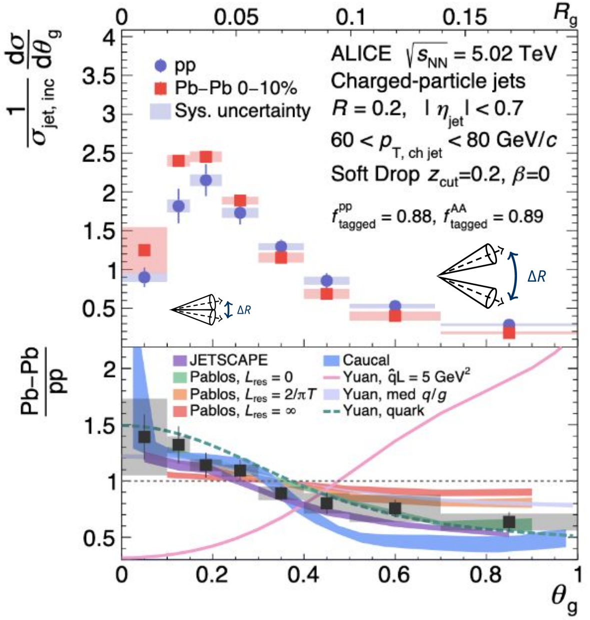


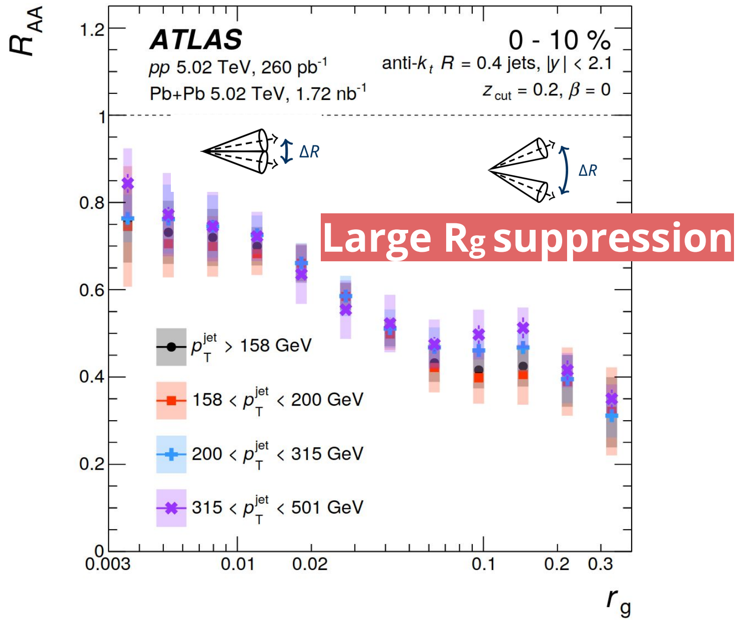
R_g is expected to be sensitive to color decoherence effects

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

Previous measurements in inclusive jet events

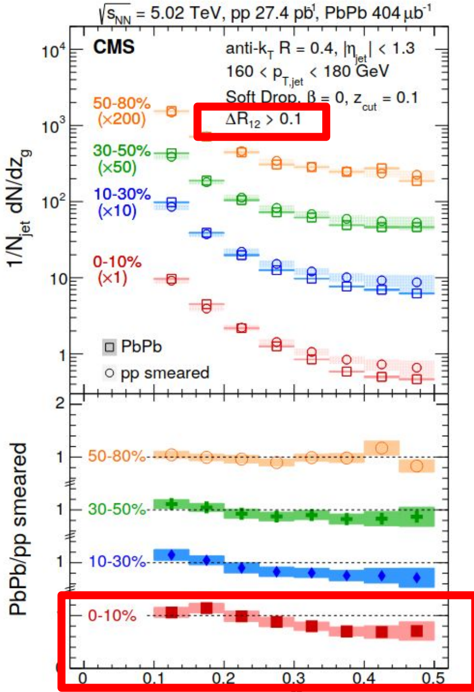
Groomed jet radius R_g





[ALICE, PRL 128.102001](#) [ATLAS, PRC 107, 054909](#)

Splitting function



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

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

Broad angular structures are more suppressed in PbPb.

Consequence of color decoherence?

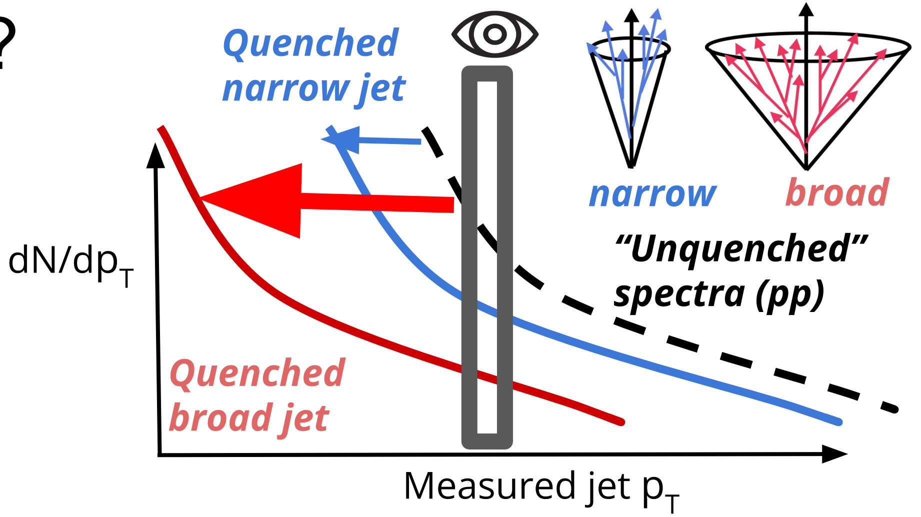
Is a finite critical angle necessary to describe jet quenching?

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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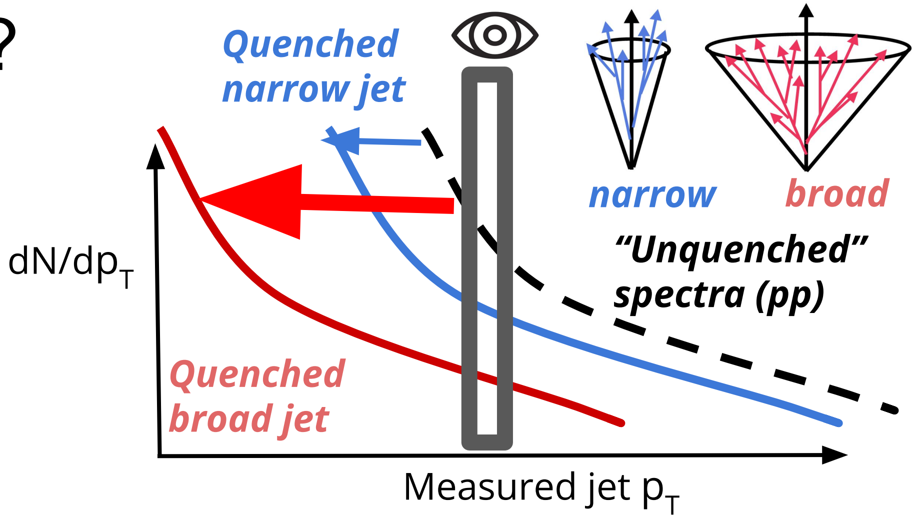
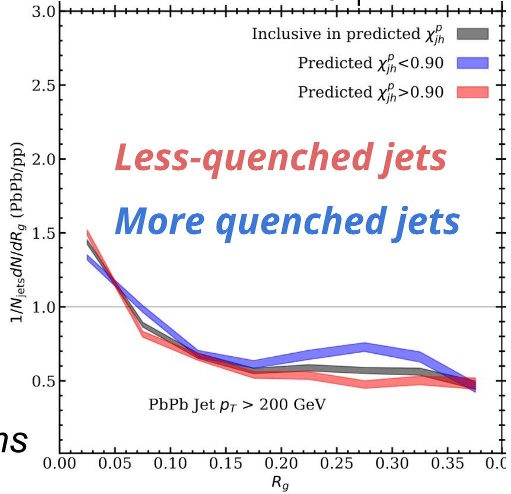
One way of controlling this effect is by selecting jets according to their **unquenched** $\mathbf{p_T}$

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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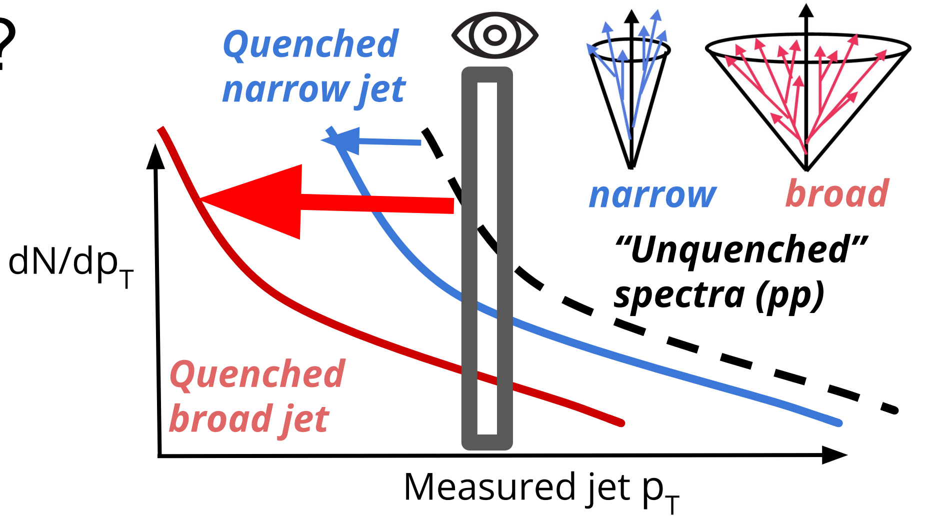

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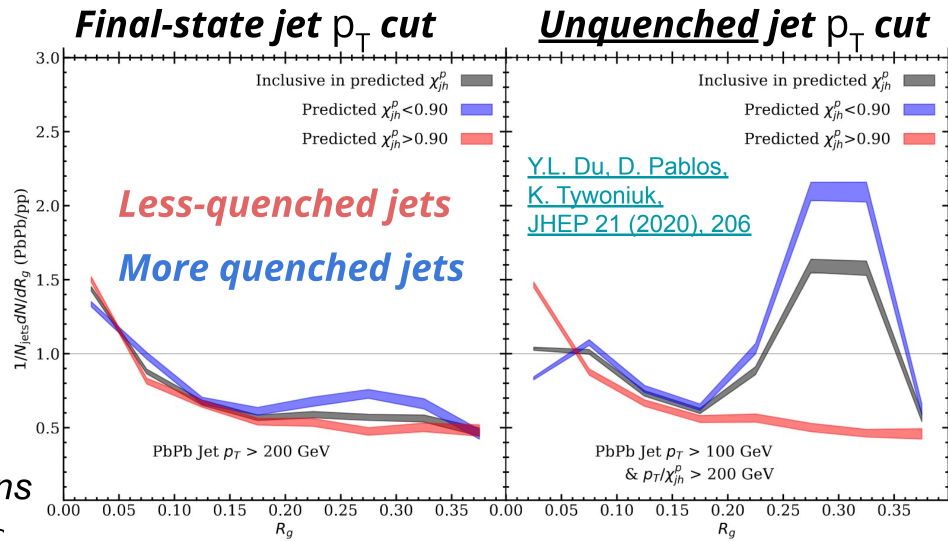
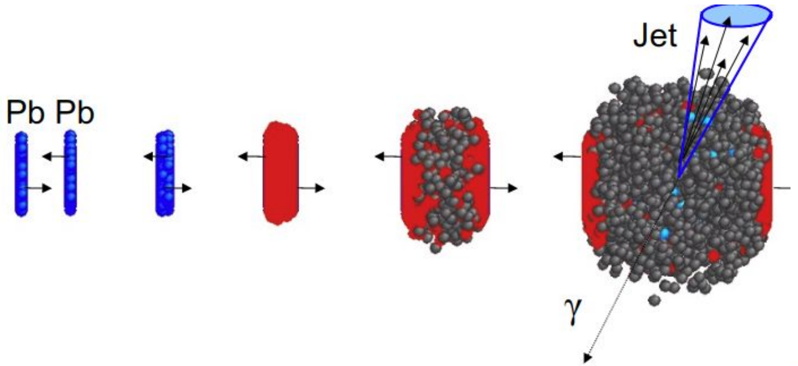


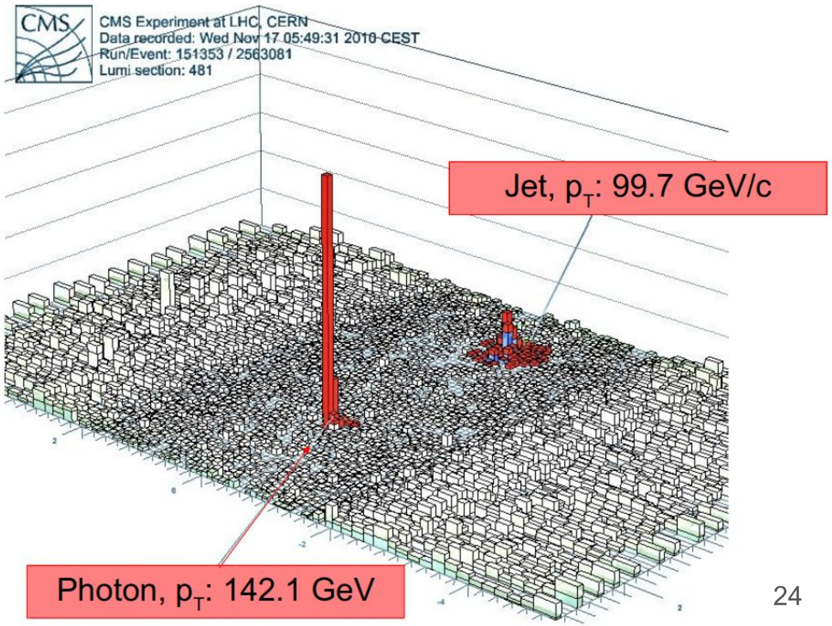
Hybrid model calculations

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}





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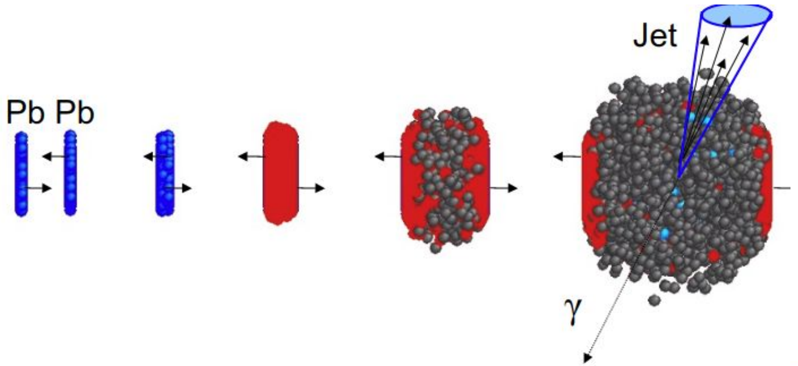
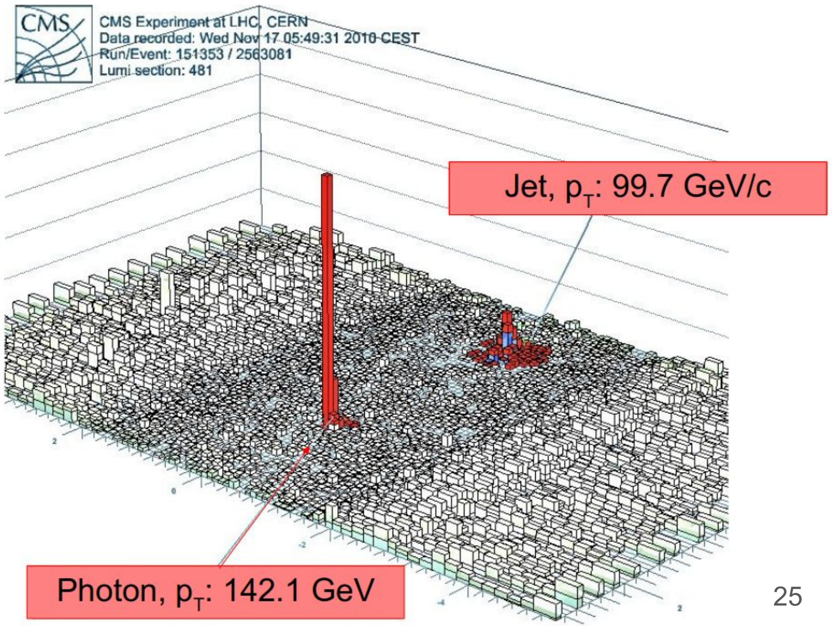
Compare pp and PbPb with the same p_T^{γ}

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, β = 0) and jet girth $g = \frac{1}{p_T^{jet}} \sum_i p_T^i \Delta R_{i,jet}$





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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, $\Delta\varphi_{\gamma,jet} > ⅔ \pi$ and $|\eta^{jet}| < 2$
- R_g (z_{cut} = 0.2, β = 0) and jet girth $g = \frac{1}{p_T^{jet}} \sum_i p_T^i \Delta R_{i,jet}$

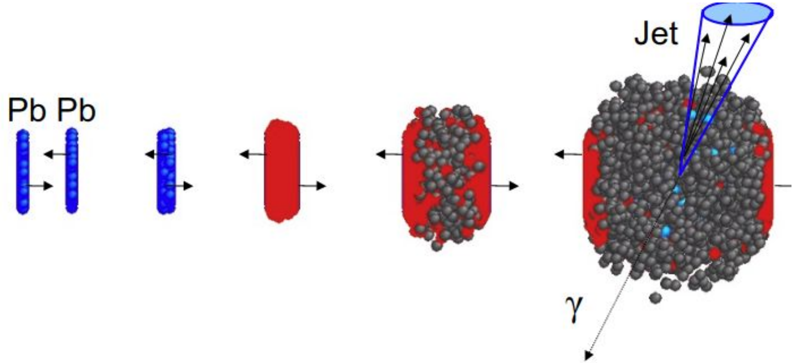
Two categories for measurement:

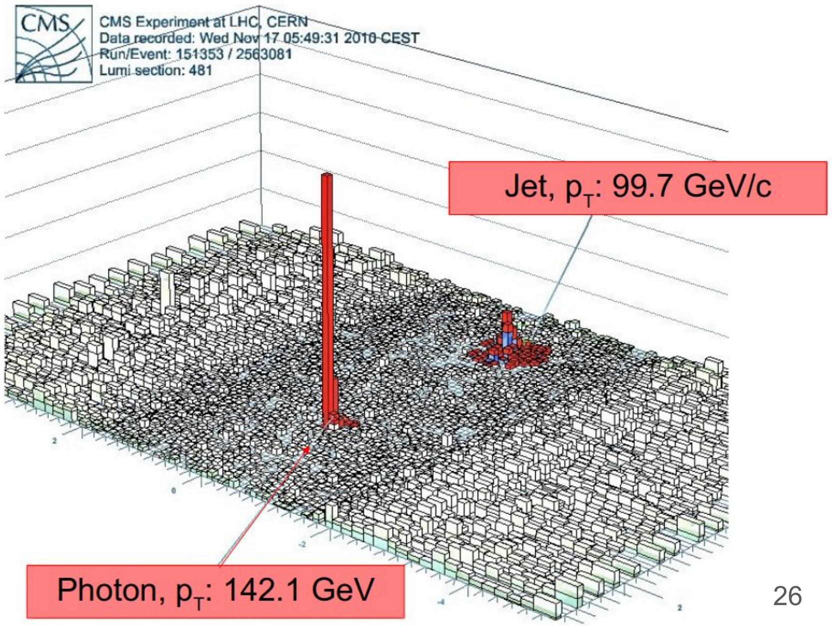
$p_T^{jet}/p_T^{photon} > 0.4$ (quenched and nonquenched jets)

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

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

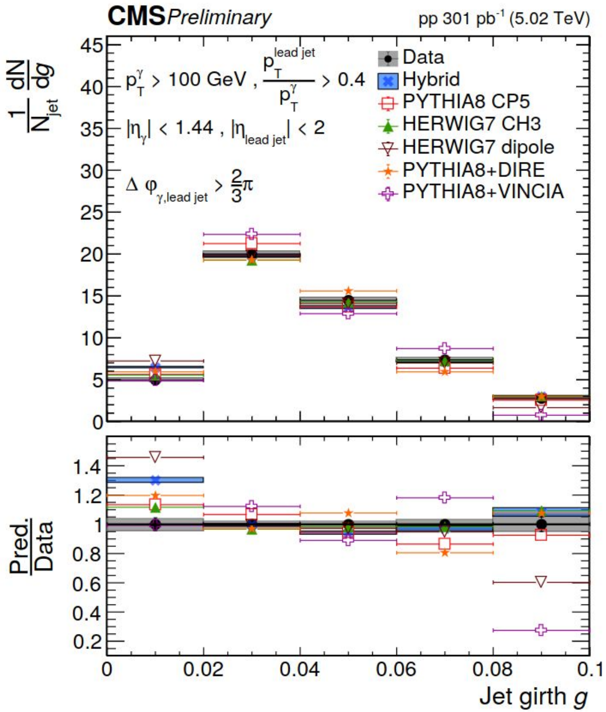
corrections with D'Agostini unfolding

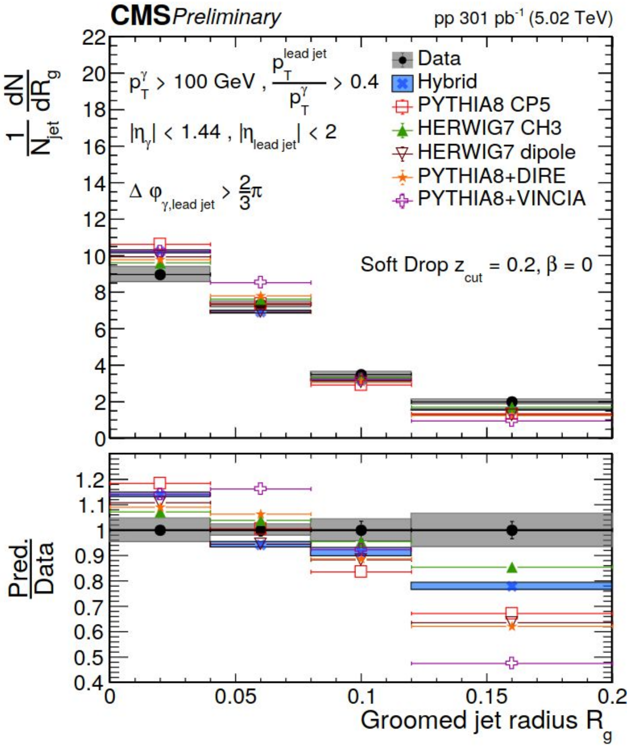


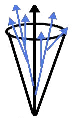


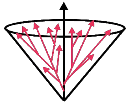
Photon-tagged jets with $p_T^{jet}/p_T^{\gamma} > 0.4$ (**proton-proton**)

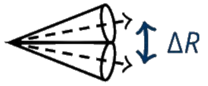
CMS-PAS-HIN-23-001, *link soon*

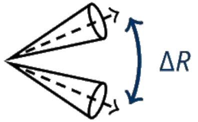








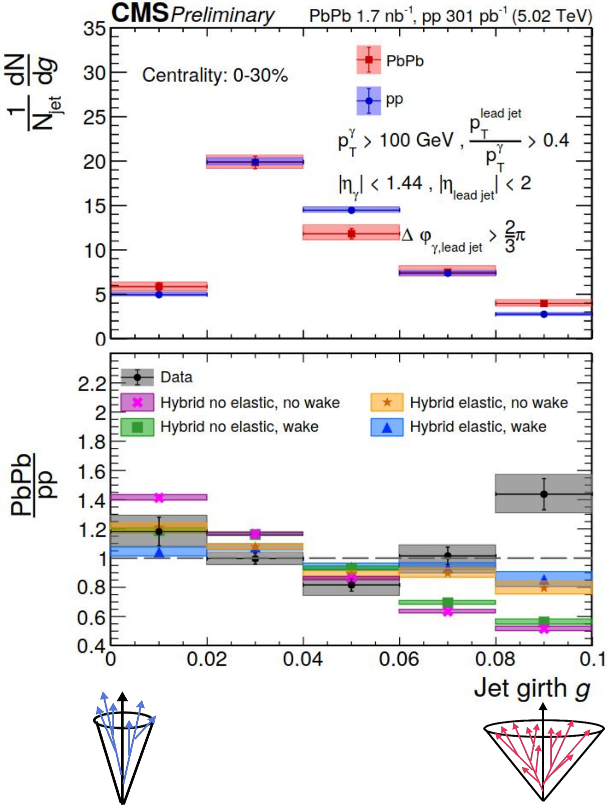


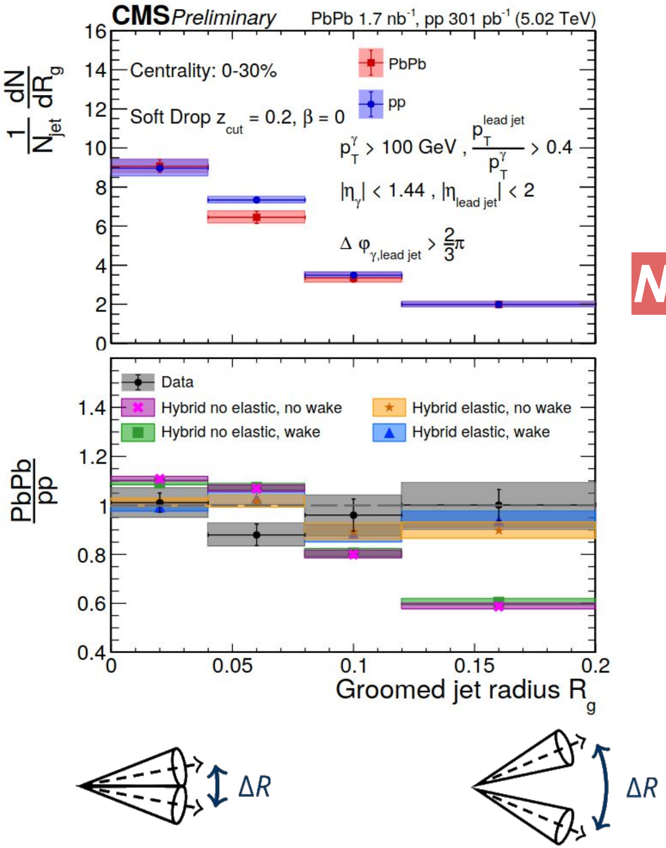


Differences of data and MC simulation of factors of up to 2
best global description by **HERWIG7 angular-ordered (CH3)**

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*



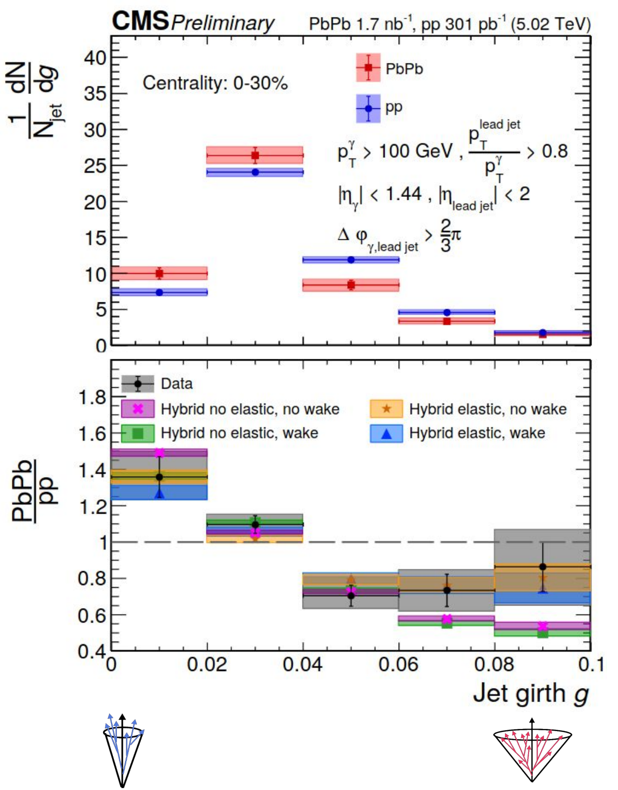


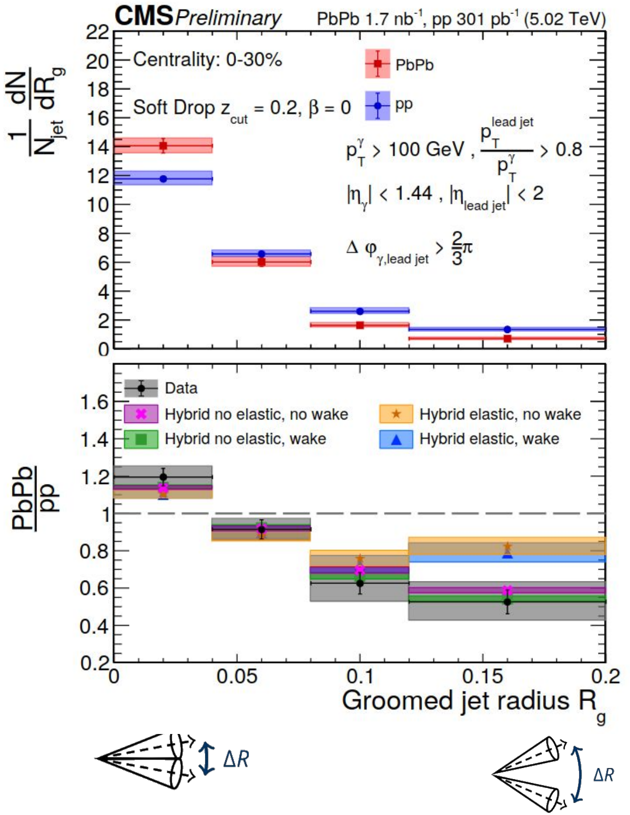
No narrowing

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 ($\boldsymbol{\vartheta_C = 0}$). No sensitivity to wake effect. [J. Casalderrey-Solana et al, JHEP01(2020)044]

Summary

- Accessing internal dynamics of jets via the **primary Lund jet plane** (**CMS-PAS-SMP-22-007**)

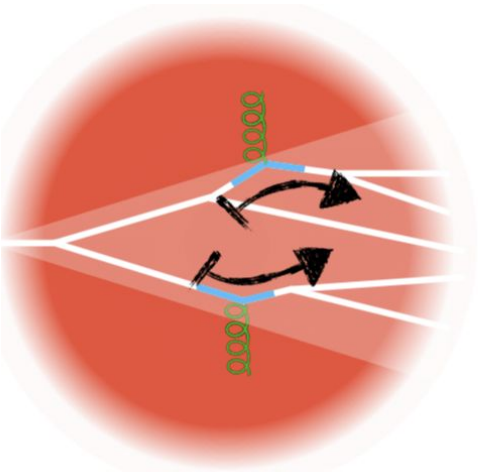
- For substructure in heavy ions, it's crucial to mitigate selection biases

  One path is via photon-tagged jets

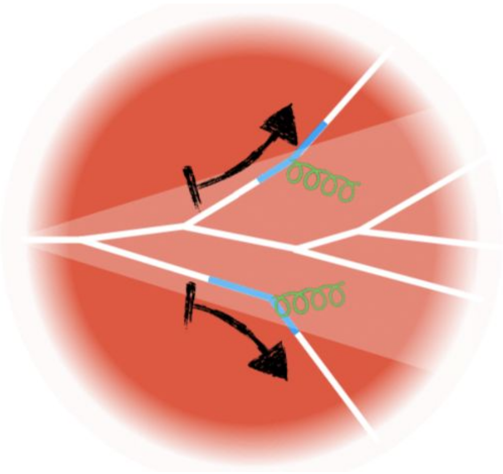
  (CMS-PAS-HIN-23-001, *link soon on CDS and CMS public pages*)

Looking deeper into the jet shower itself

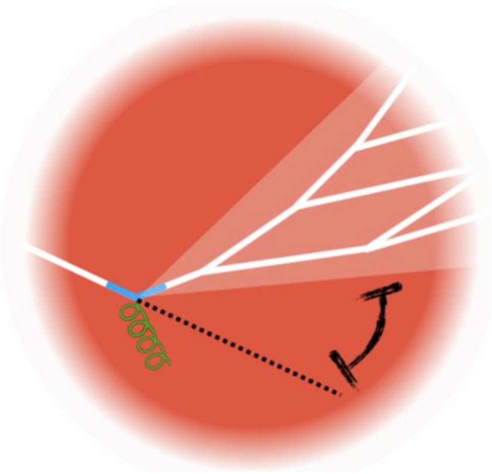
Medium induced radiation



Energy redistribution (“loss”)



Point-like scatterers
in the QGP (Quasi-particles)



sketch from Rey Cruz

jet substructure techniques can be used to expose these and other effects

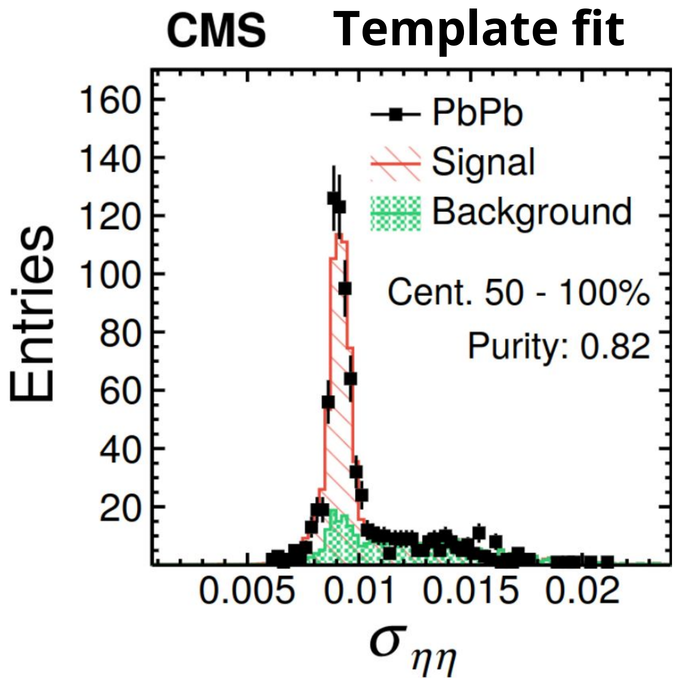
Systematic uncertainties in photon-tagged events

Dominant:
Shower & hadronization model uncertainty

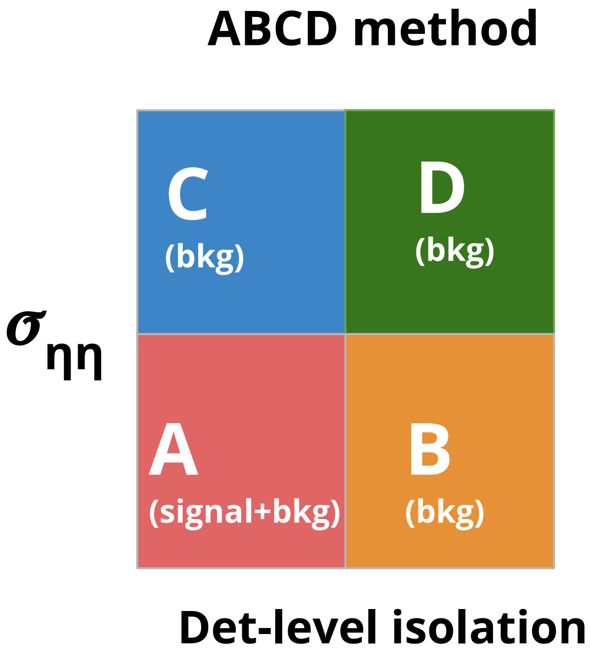
PF scale uncertainties (using all PF candidates)

Subdominant:
Decay photons bkg subtraction
Response matrix stats
Jet energy scale and resolution uncertainties
UE modeling (PbPb)

Photon bkg. subtraction ($h^0 \to \gamma\gamma$)



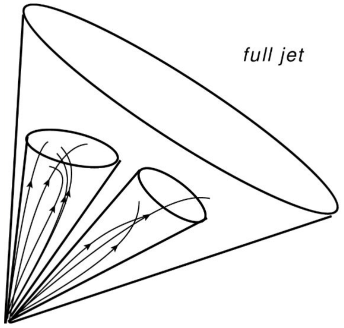
Plot from Phys. Lett. B 785 (2018) 14



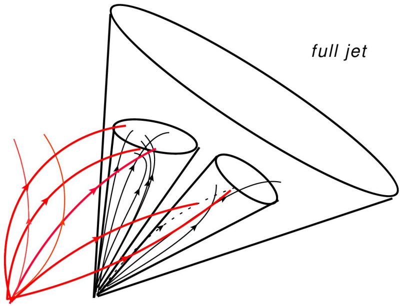
$I^{part} < 5$ GeV, I^{part} scalar sum of p_T in a cone of 0.4 with respect to the photon

Primary emissions in PbPb collisions

Subjets w/o UE (no embedding)



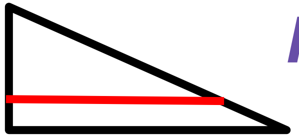
Subjets w/ UE (embedded)



Large UE in PbPb reduces purity of hard splittings at large ΔR

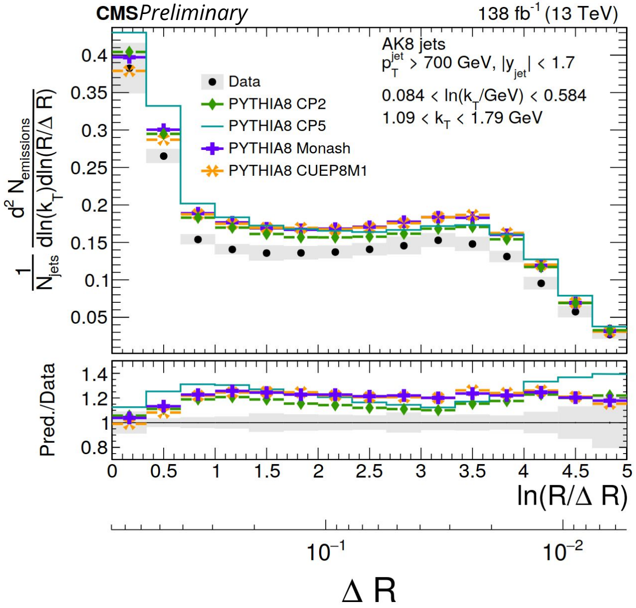
→ harder to interpret and to correct

In PbPb, one strategy is to measure one-splitting observables and use small R jets (or higher p_T^{jet})

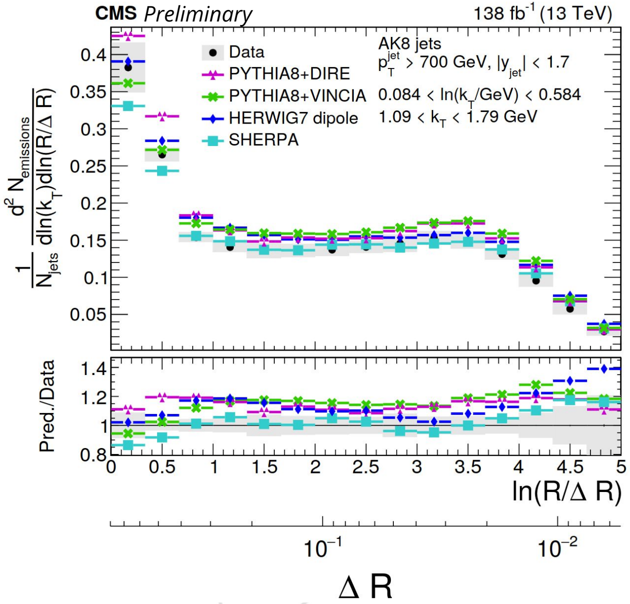


R=0.8   Low-k_T (hadronization + MPI)

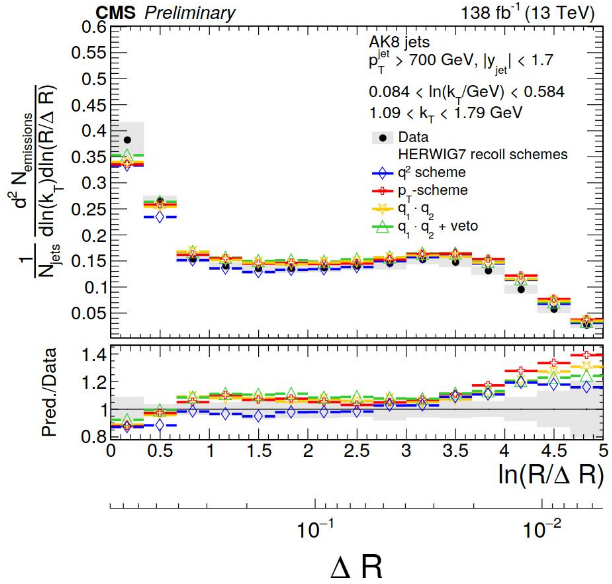
[CMS-PAS-SMP-22-007]



PYTHIA8 tunes
(CP2, CP5, Monash, CUEP8m1)



Dipole showers
(Vincia, Dire, Herwig7Dipole, Sherpa)



Herwig7.2 recoil schemes
(angle-ordered)

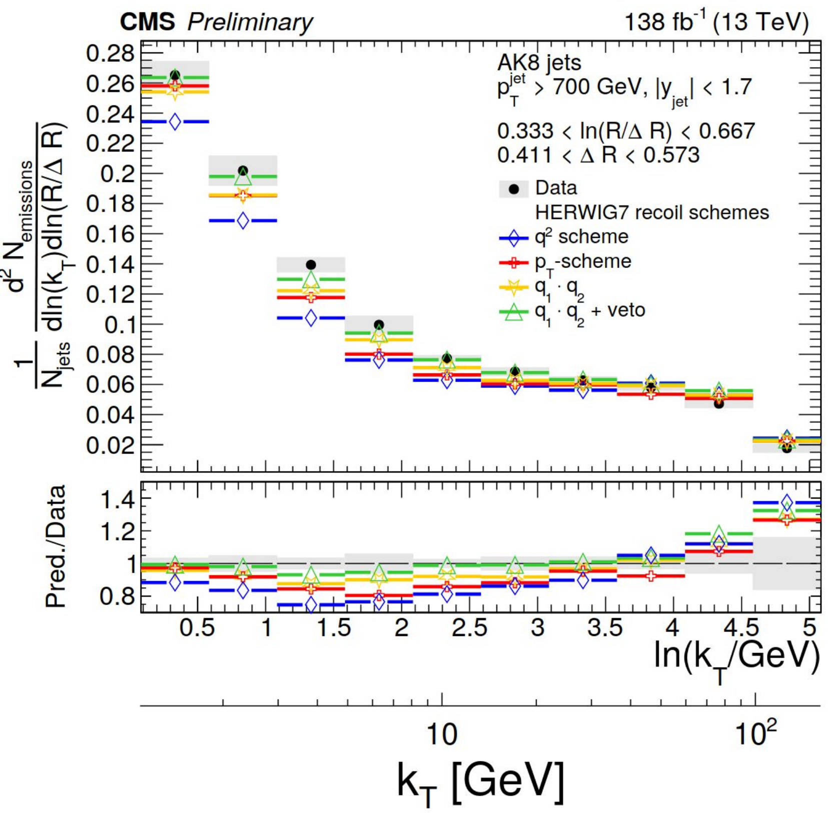
PYTHIA8 systematically overshoots LJP at low k_T by 15-20%, **regardless of tune or parton shower option**

HERWIG7 & **Sherpa** generally do better. **Cluster vs string fragmentation?**

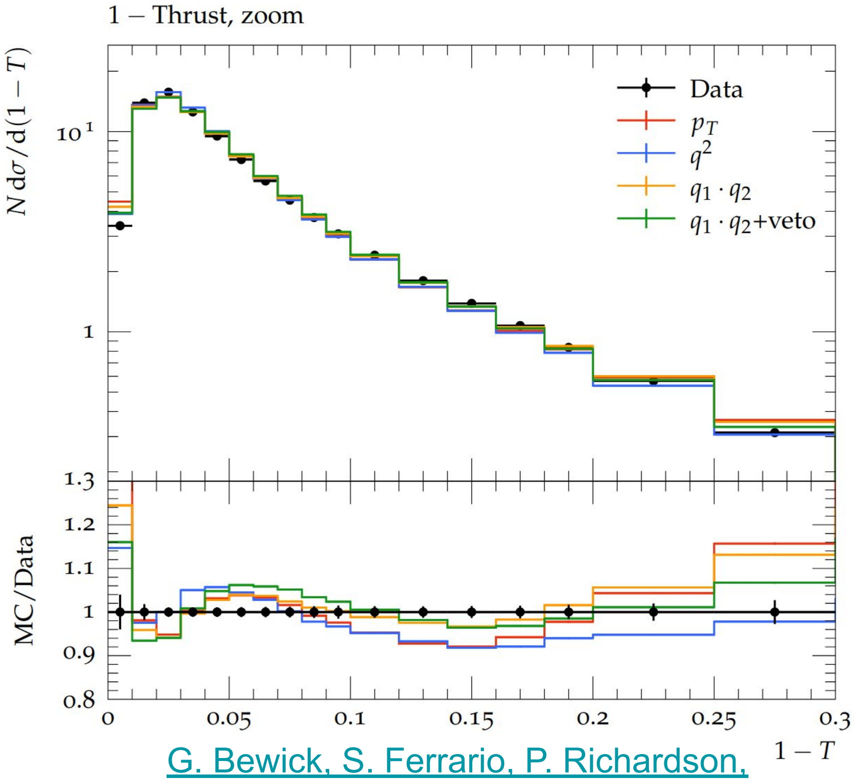
NB: different $p_T^{FSR, cutoff}$ between MCs

Sensitivity to recoil scheme choice, **important ingredient to reach NLL accurate showers**

high-p_T quark and gluon jets



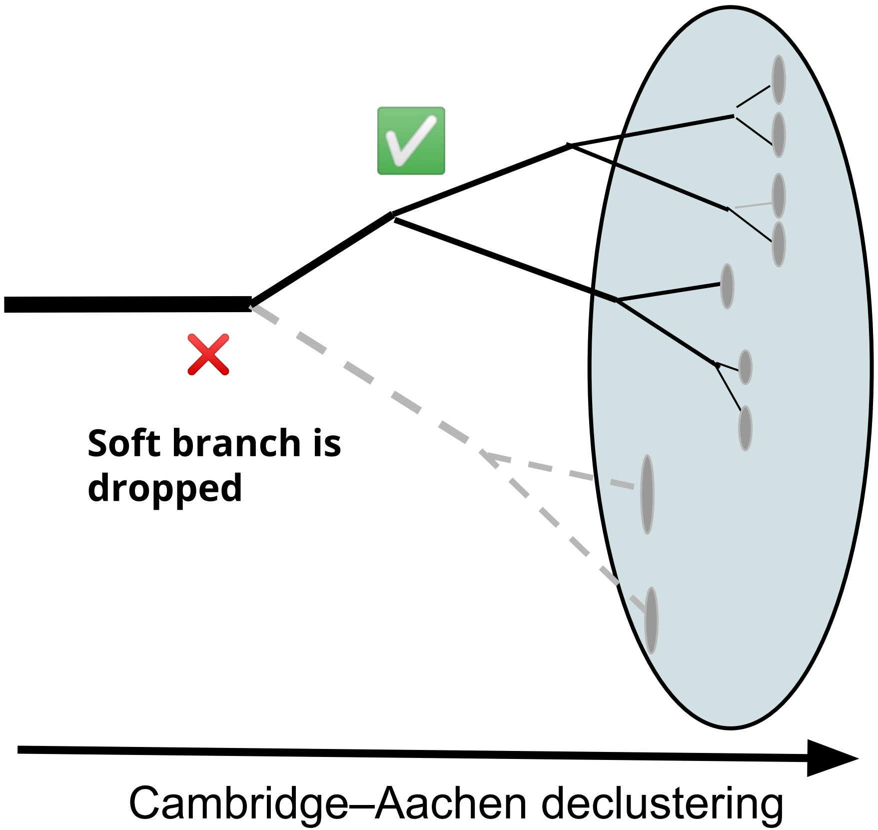
Thrust in e^+e^- at Z mass pole



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

(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:

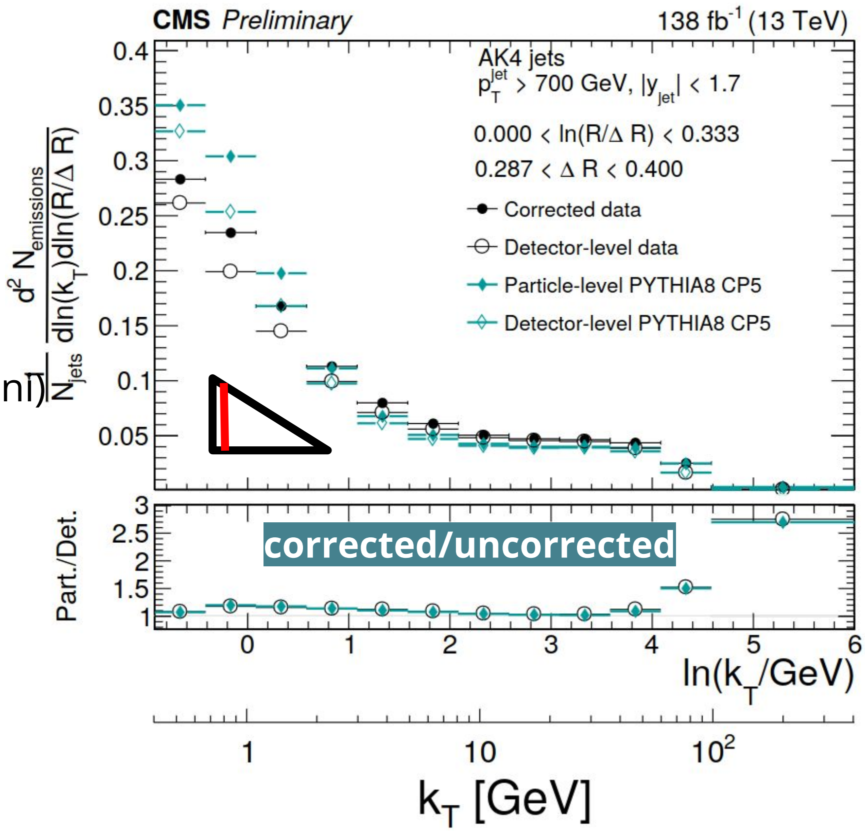
1. **Background:** bin-by-bin correction to account for det-level emissions not matched to truth-level emissions.

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

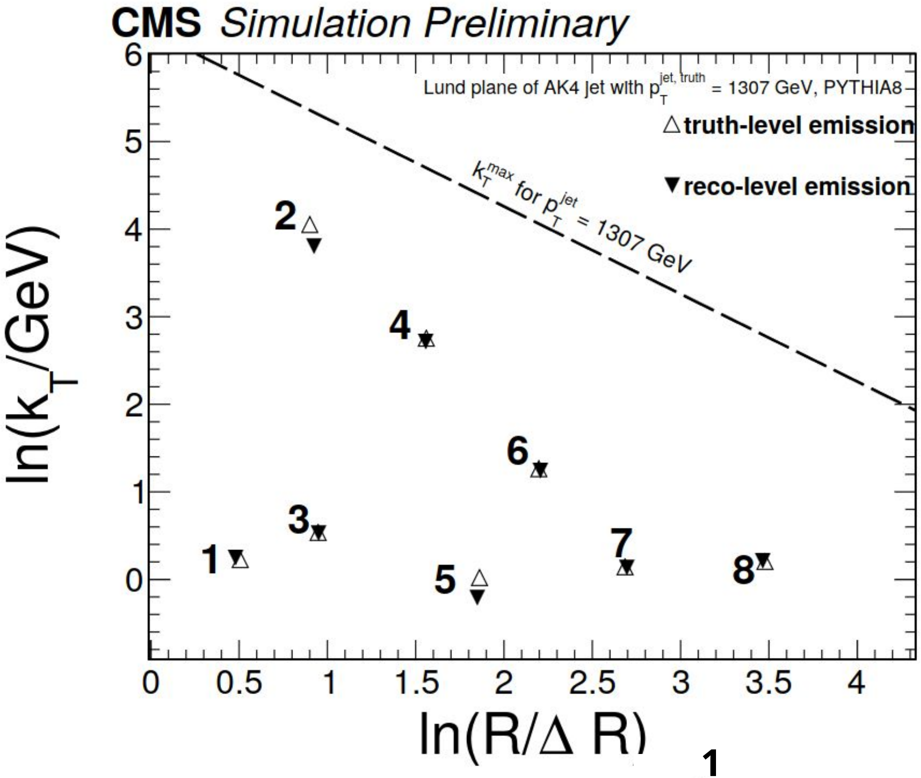
CMS-PAS-SMP-22-007

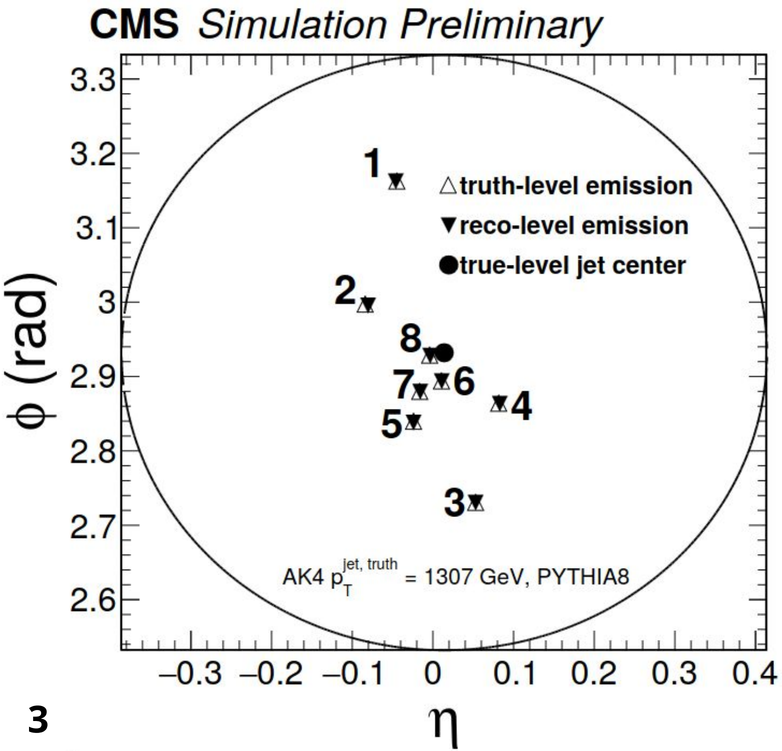


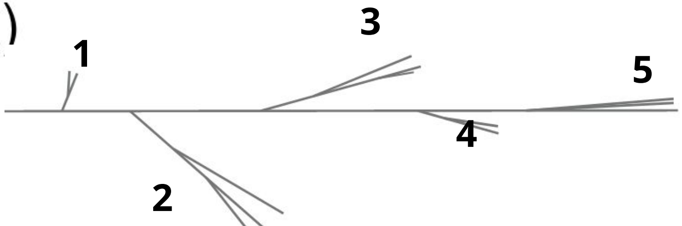
smearing becomes more important at high k_T

Matching emissions at detector level and particle level

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







CMS-PAS-SMP-22-007