Probing QCD with jets

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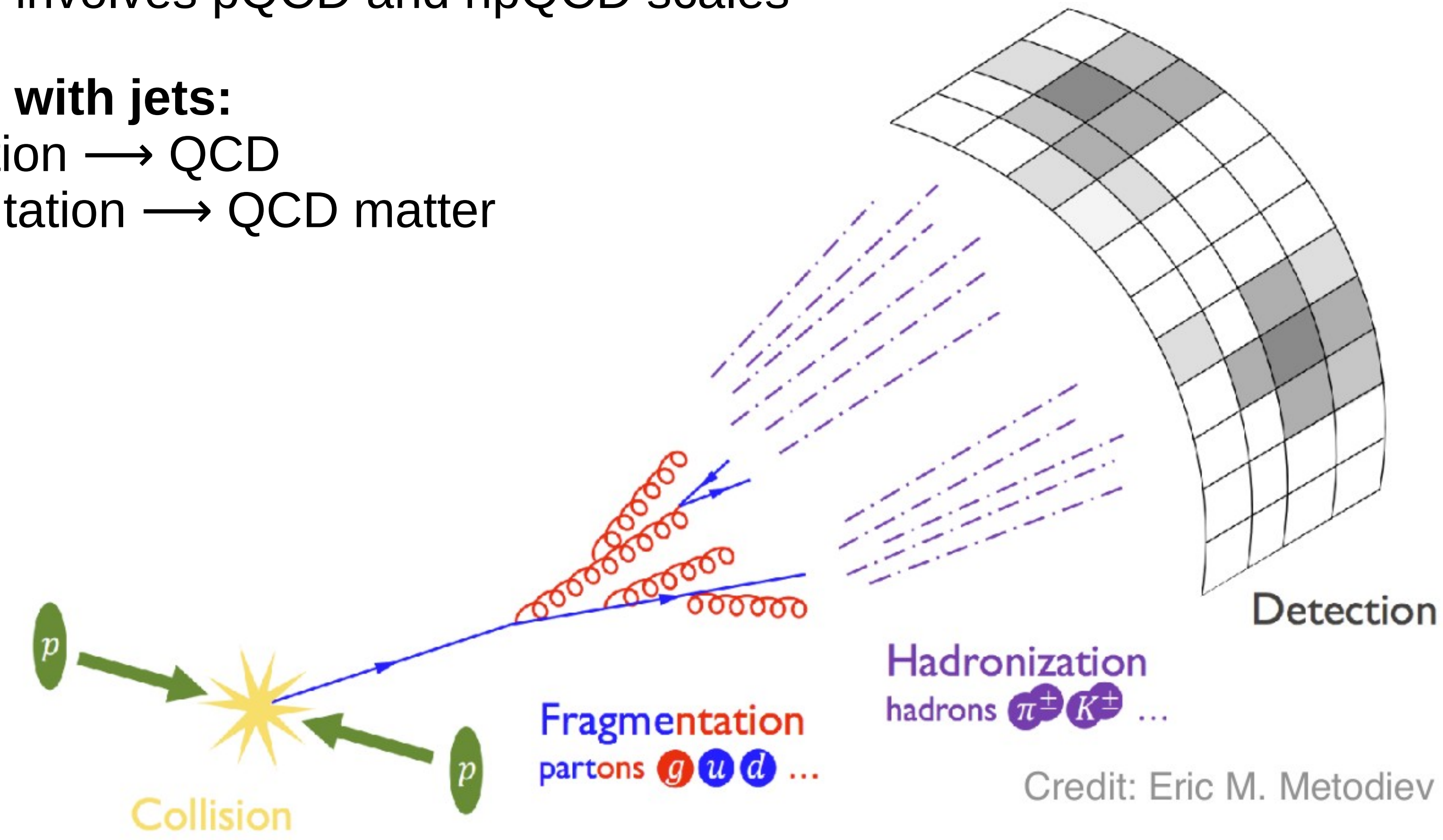
Jets and high-p_T hadrons as QCD probes

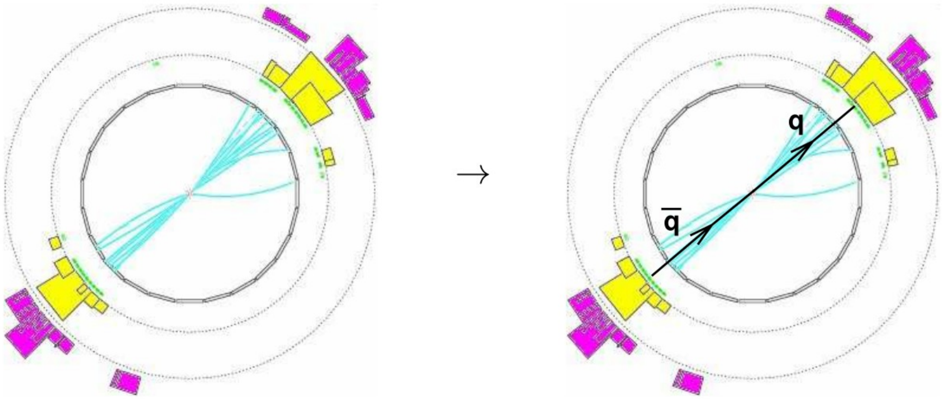
Jet shower evolution involves pQCD and npQCD scales

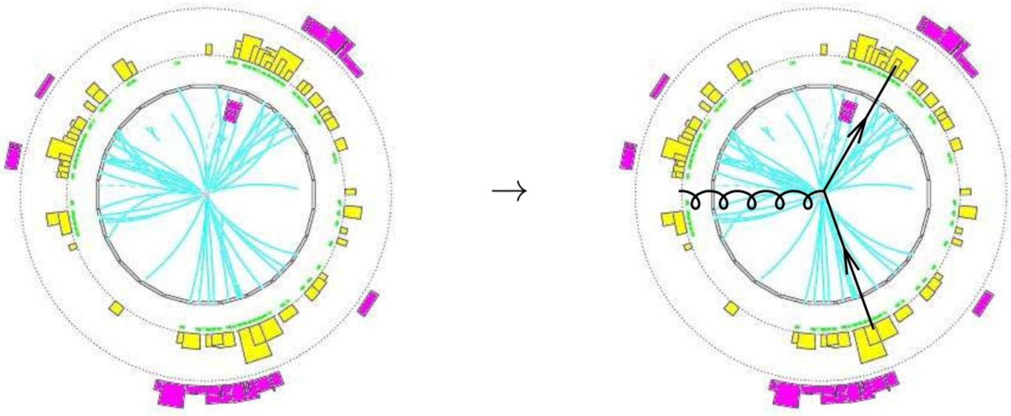
What can we probe with jets:
- vaccum fragmentation ⟶ QCD
- in medium fragmentation ⟶ QCD matter



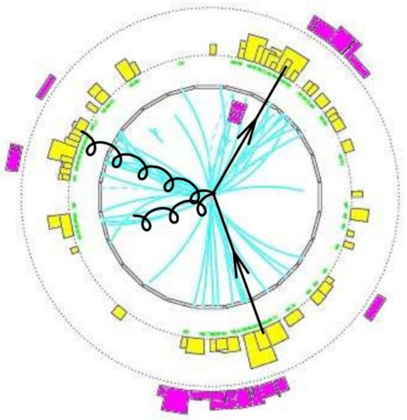
Jets ≡ bunch of collimated particles ≈ hard partons

Event displays with jets from e+e- collisions as measured by OPAL
taken from lecture by G. Soyez





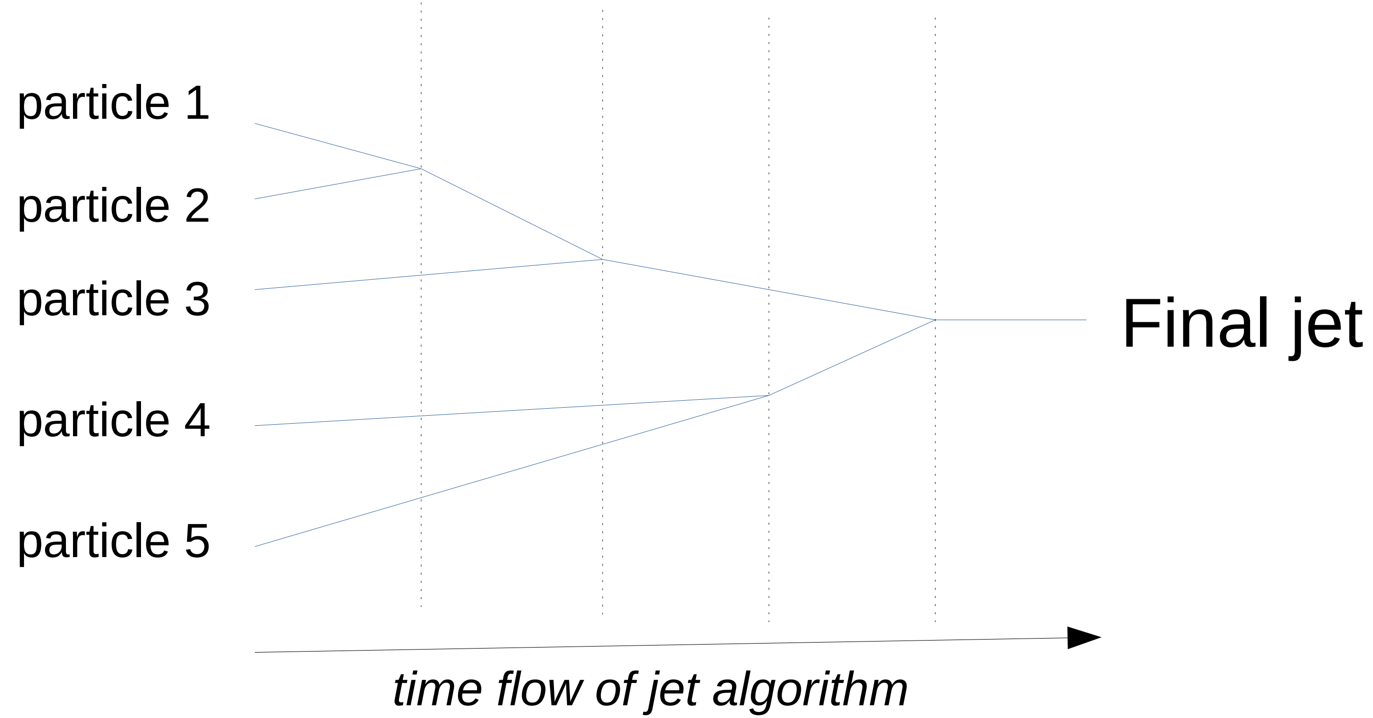
or



?

Definition of what a jet actually is is needed !

Jet algorithm



Anti-k_T p = -1
Cambridge-Aachen p = 0
k_T p = 1

1) for all particles *i*, *j* evaluate

$$d_{ij} = \min(p_{\mathrm{T,i}}^{2p}, p_{\mathrm{T,j}}^{2p}) \frac{\Delta_{ij}^2}{R^2}$$

$R \approx$ cone radius

$$d_{iB} = p_{\mathrm{T,i}}^{2p}$$

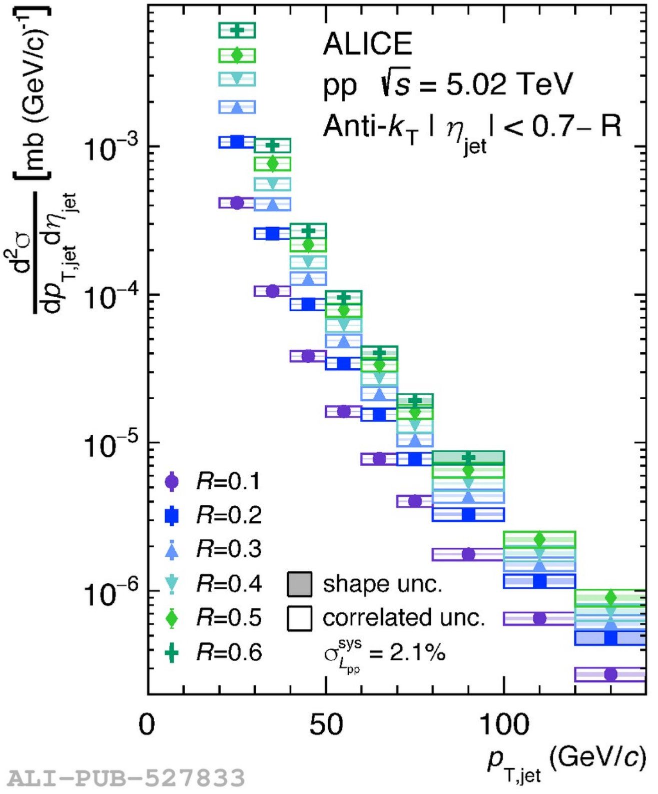
2) Find minimal d_{ij} , d_{iB}
3) If d_{ij} is the minimum ⟶
merge *i* + *j* and go to 1)
4) d_{iB} is the minimum ⟶
remove *i* from the list (final jet) and go to 1)

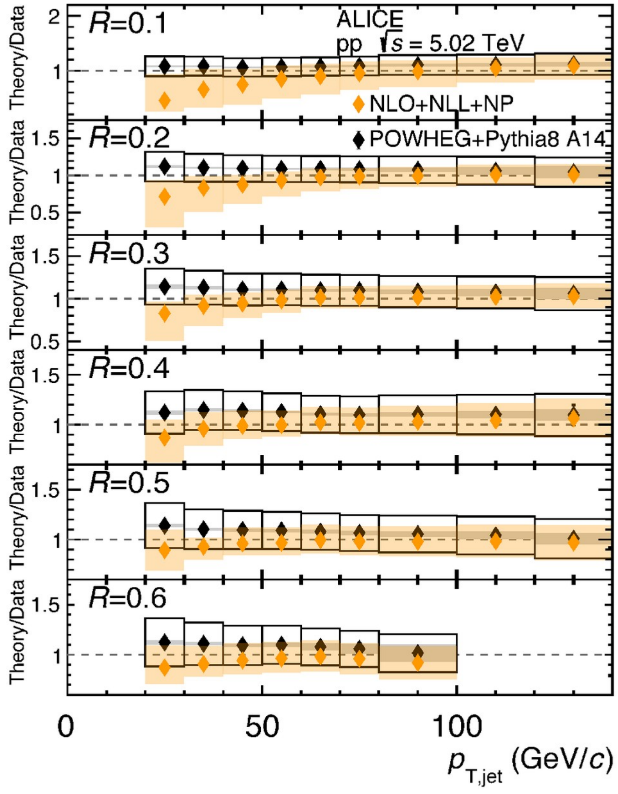
JHEP 0804 (2008) 063

- Measure of inter-particle distances & rule how to combine particle momenta
- Sequential recombination algorithms (infrared & collinear safety)

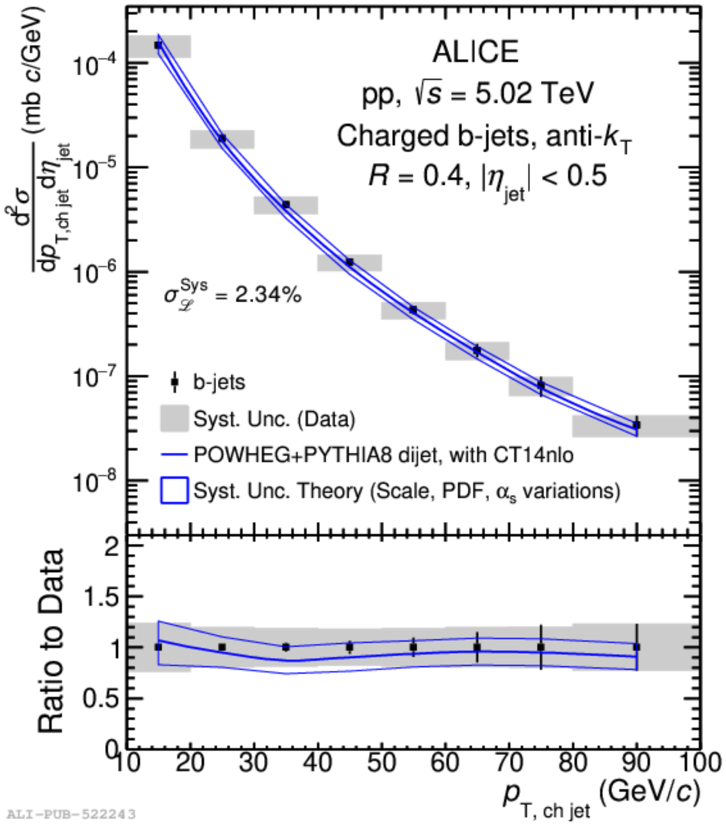
Salam, EPJ C67 (2010) 637

Jet cross section in pp @ √s = 5 TeV





ALICE, Phys. Rev. C 101 (2020) 034911

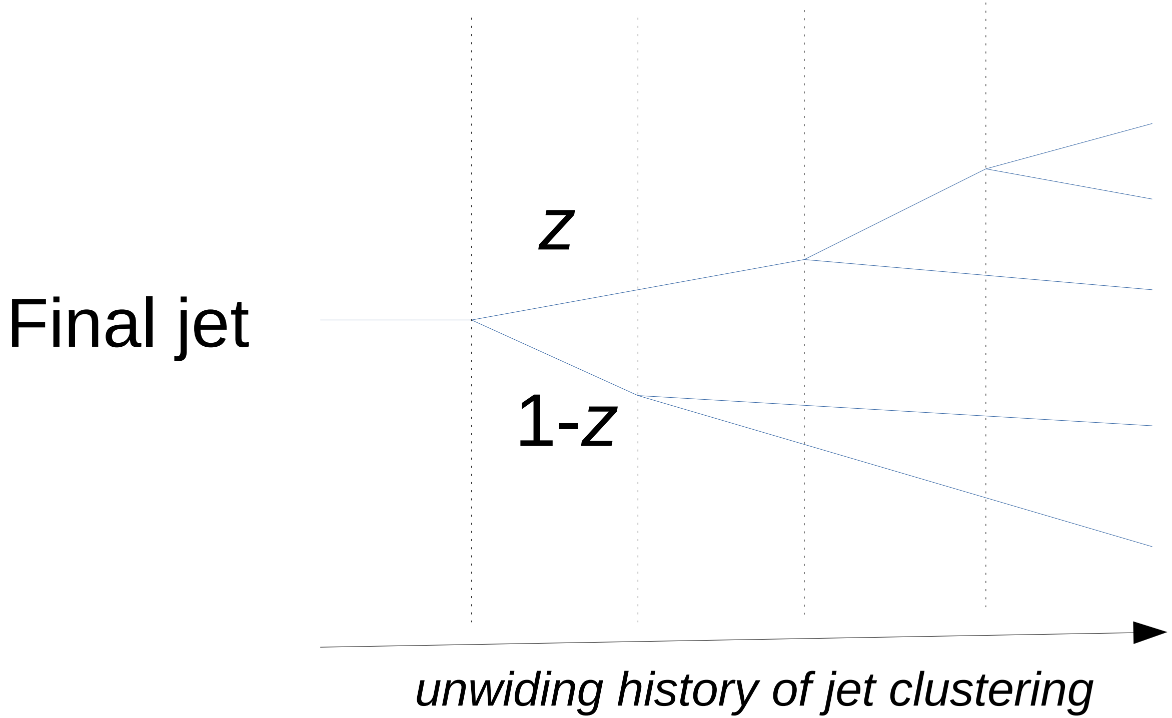


ALICE, JHEP 01 (2022) 178

NLO+NLL+NP: Z.-B. Kang, F. Ringer, I. Vitev, JHEP 2016 (2016) 125, PLB 769 (2017) 242

pQCD provides accurate desciption of jet production in pp

Jet substructure



- Use iterative declustering to search for a hard scale in course of splittings
- Search for a structure in terms of subjets ($W^- \longrightarrow \bar{u}\, d \longrightarrow$ jet)

Uncovering the QCD dead cone effect

ALICE, Nature 605 (2022) 440–446

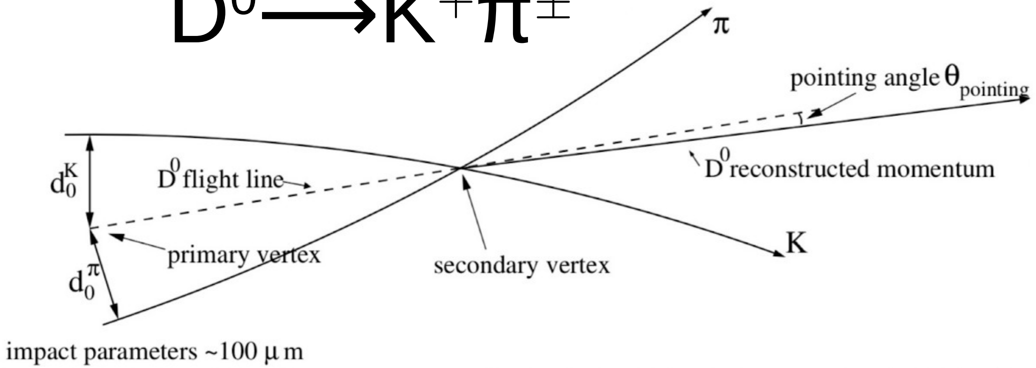
Gluon radiation is suppressed for angles

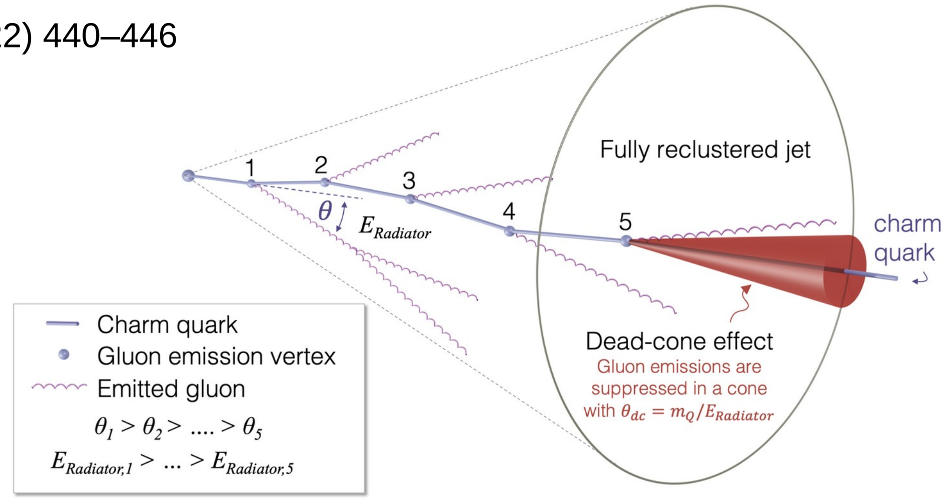
$$\theta_{gluon} < m/E_{radiator}$$

J. Phys. G17 (1991) 1602–1604

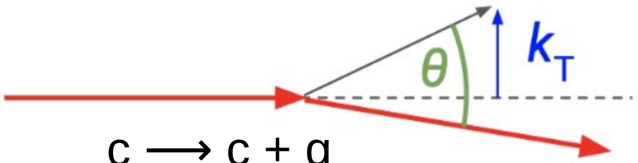
- c,b quarks from hard-scattering radiate, hadronize and decay
- D^0 from c fragmentation from:

$$D^0 \longrightarrow K^{\mp}\pi^{\pm}$$



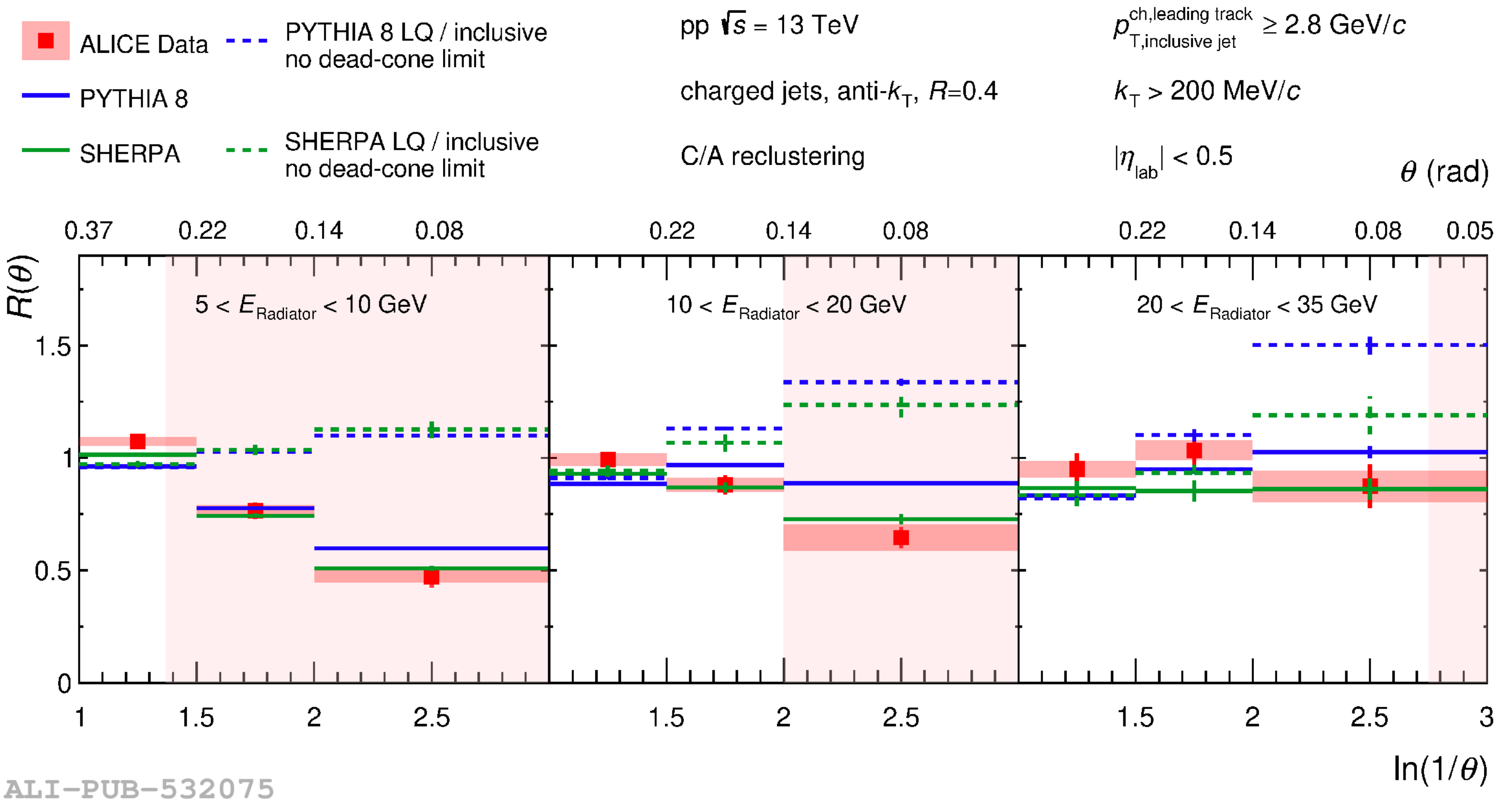


- Following the branch with D^0 coincides with the hadest branch in 99% cases
- Select splittings with k_T > 200 MeV
- Inclusive radiator same energy



Experimental access to dead cone

ALICE, Nature 605 (2022) 440–446



- Suppression of emissions at low angle for a D^0 jet compared to an untagged jet
- Smaller effects for higher splitting energy

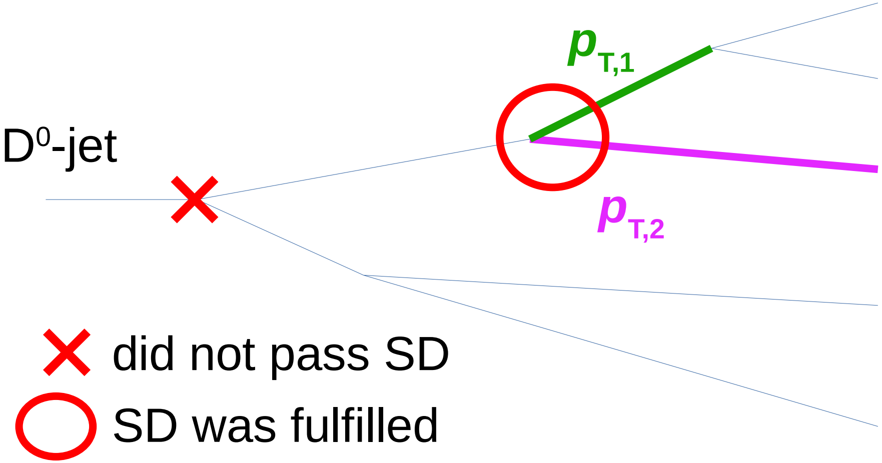
$$R(\theta) = \frac{1}{N^{D^0 \text{jets}}} \frac{dn^{D^0 \text{jets}}}{d\ln(1/\theta)} \Big/ \frac{1}{N^{\text{inclusive jets}}} \frac{dn^{\text{inclusive jets}}}{d\ln(1/\theta)} \Bigg|_{k_T, E_{\text{Radiator}}}$$

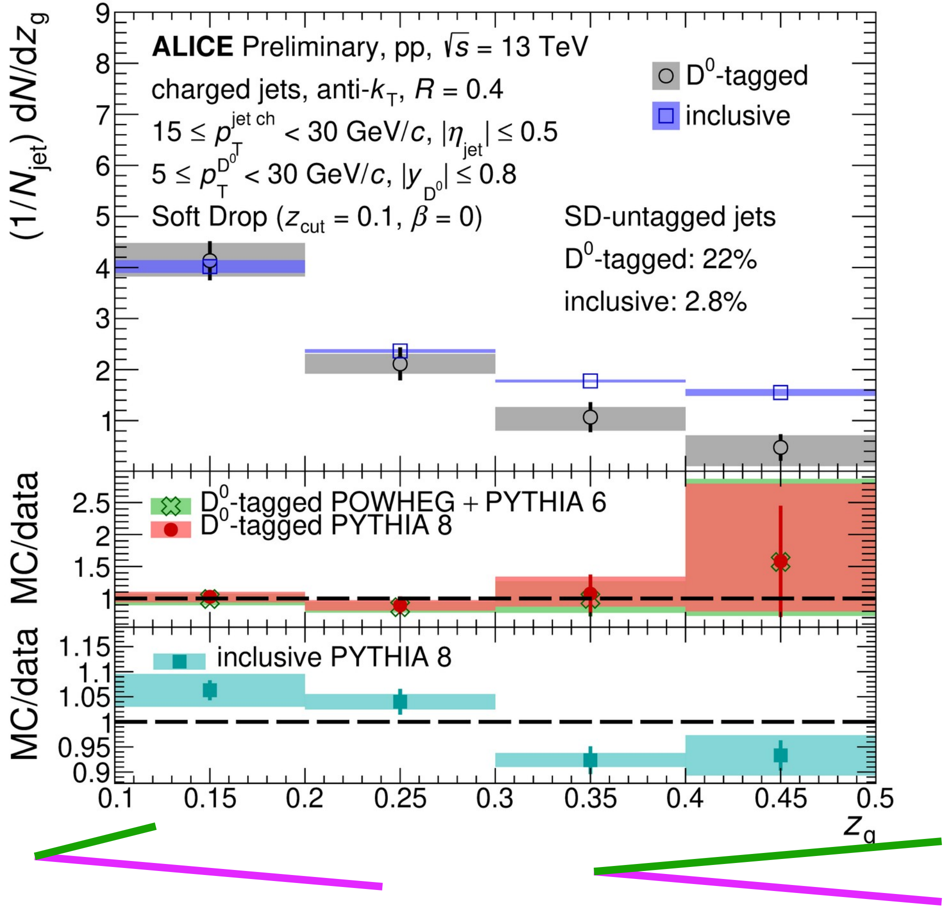
$$\theta_{gluon} < m/E_{radiator}$$

Momentum ballance of pQCD splittings

Soft-Drop (SD) grooming
- removal of soft radiation
- isolation of hard splittings

$$z_g = \frac{p_{T,2}}{p_{T,2} + p_{T,1}} > z_{cut}$$



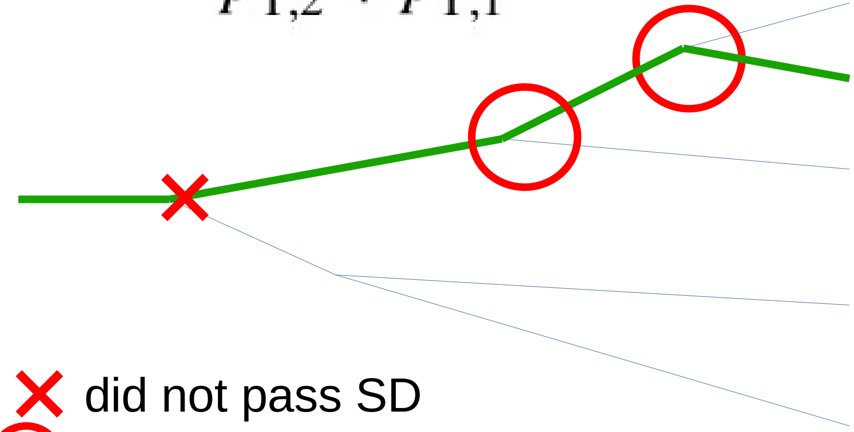


Fewer symmetric splits for D^0-tagged jets than untagged jets consistent with harder fragmentation

Count hard splits which fulfill SD

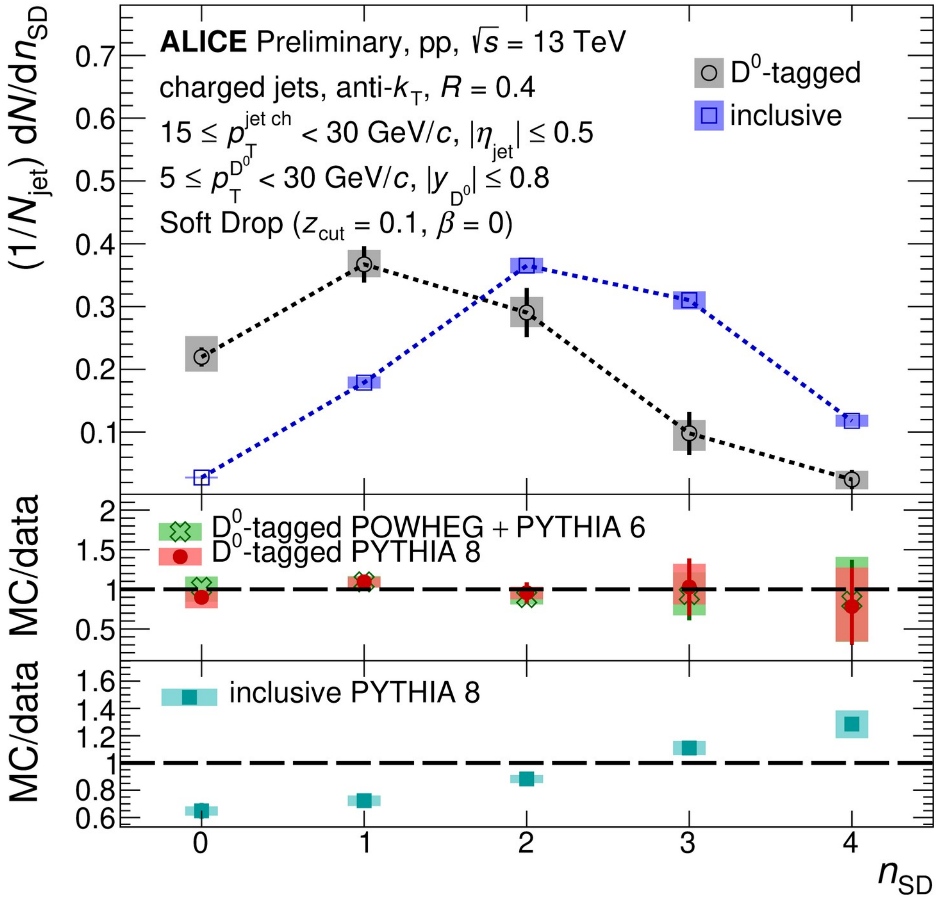
Soft-Drop (SD) grooming

$$z_g = \frac{p_{T,2}}{p_{T,2} + p_{T,1}} > z_{cut}$$



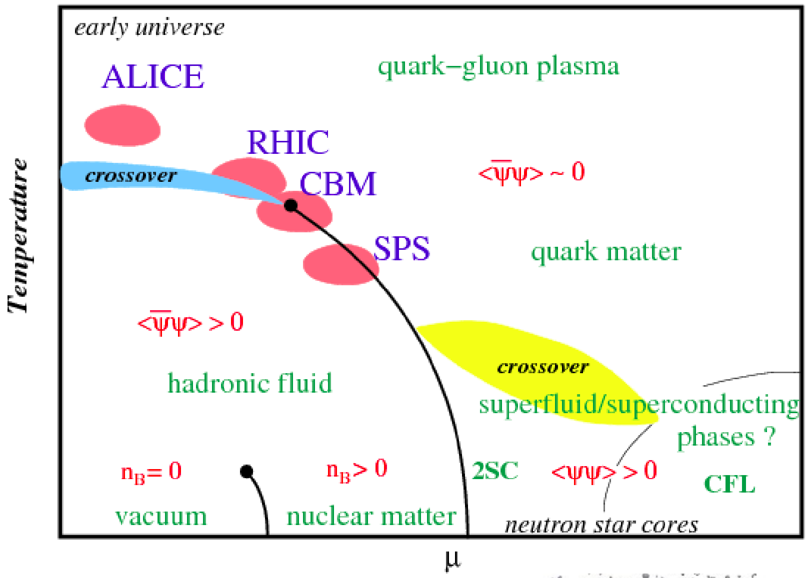
✕ did not pass SD

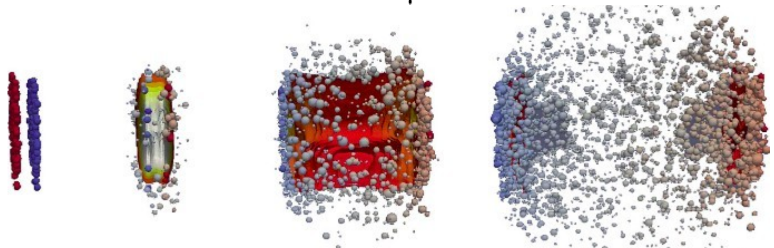
◯ SD was fulfilled



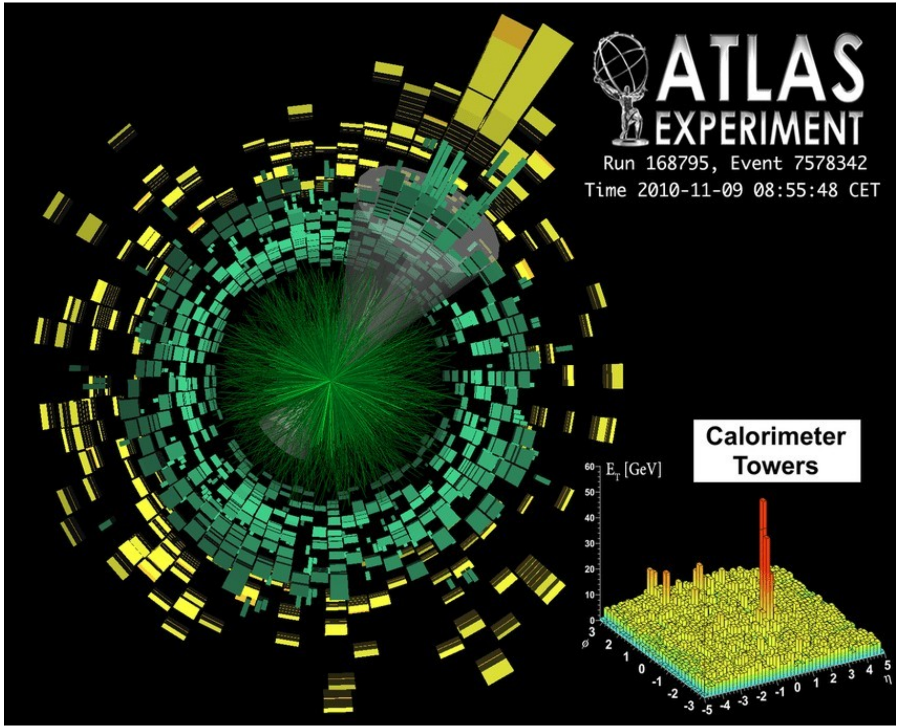
Fewer SD emissions in the D0-tagged jets compared to inclusive jets : consequence of both color factors and mass effects

Jets as a probe of QCD matter





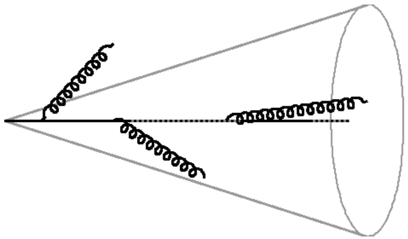
Bernhard, J.E. arXiv:1804.06469



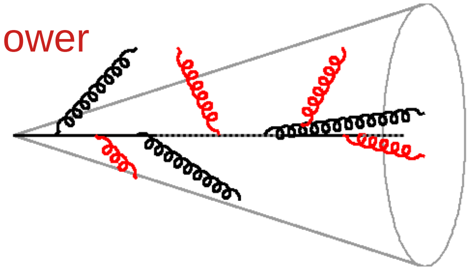
- Processes with high-Q^2 transfer occur early
- Medium created in heavy-ion collision dissipates energy of jet shower

Jet quenching observables

in-vacuum shower



in-medium shower

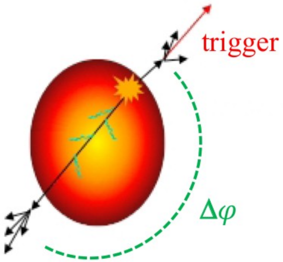


- **Yield suppression relative to min. bias pp** → energy transport out-of-cone

$$R_{\mathrm{AA}}^{h,j}(p_T, y) = \frac{1}{\langle T_{\mathrm{AA}} \rangle} \frac{(1/N_{\mathrm{ev}})\ dN_{\mathrm{AA}}^{h,j}/dp_T dy}{d\sigma_{pp}^{h,j}/dp_T dy}$$

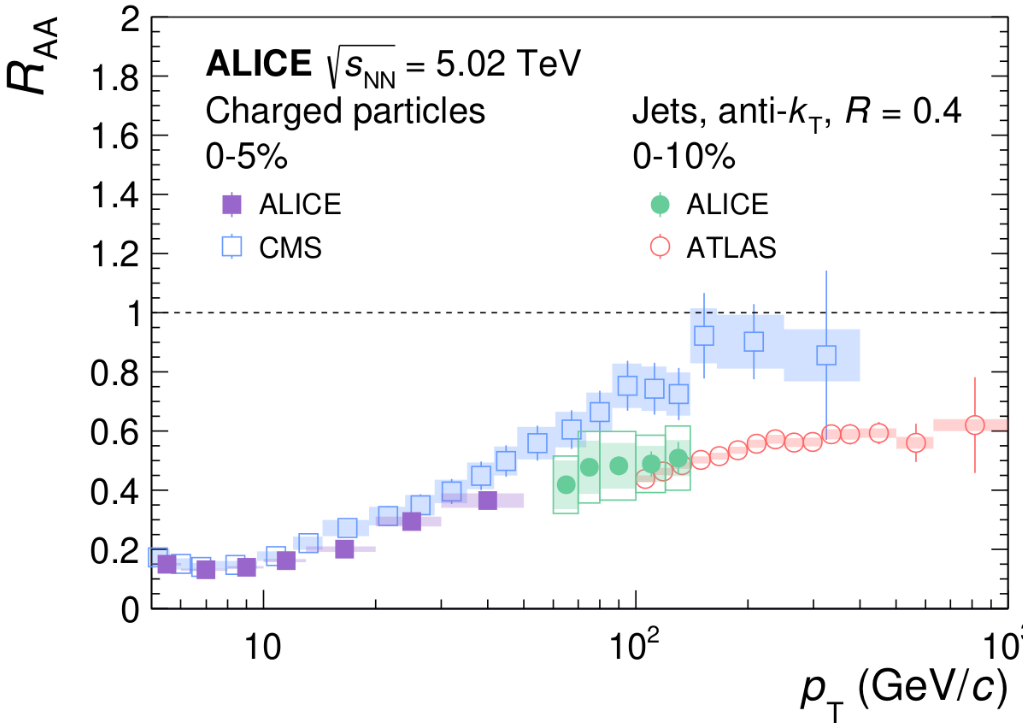
- **Jet substructure modification**
- **Jet deflection** → dijet acoplanarity

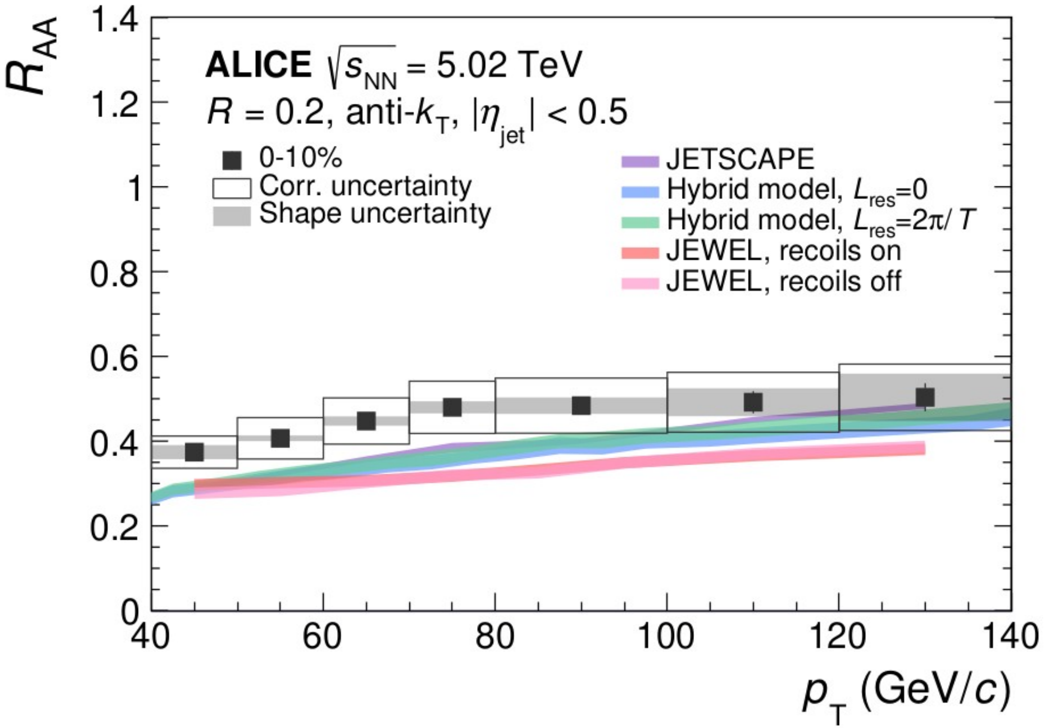
J.P. Blaizot and L. McLerran, PRD 34, 2739 (1986)



Suppression of hadrons and jes

arXiv:2211.04384

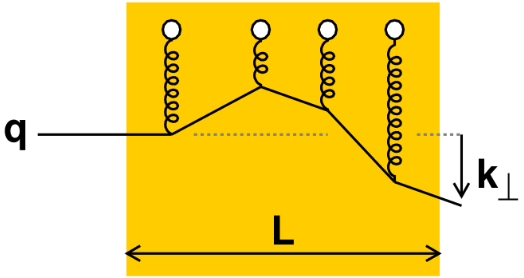




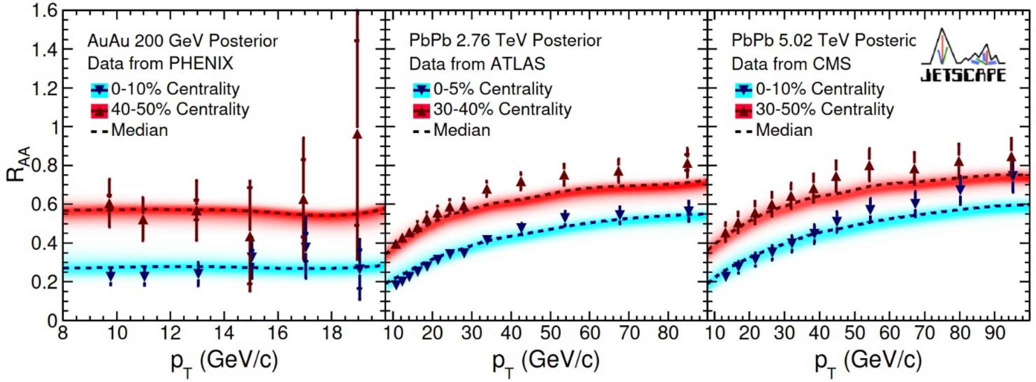
- Hadrons sensitive to energy loss in the hardest branch of the shower
- Energy loss for jets is the energy radiated out of cone
- Interpretation requires comparison with model

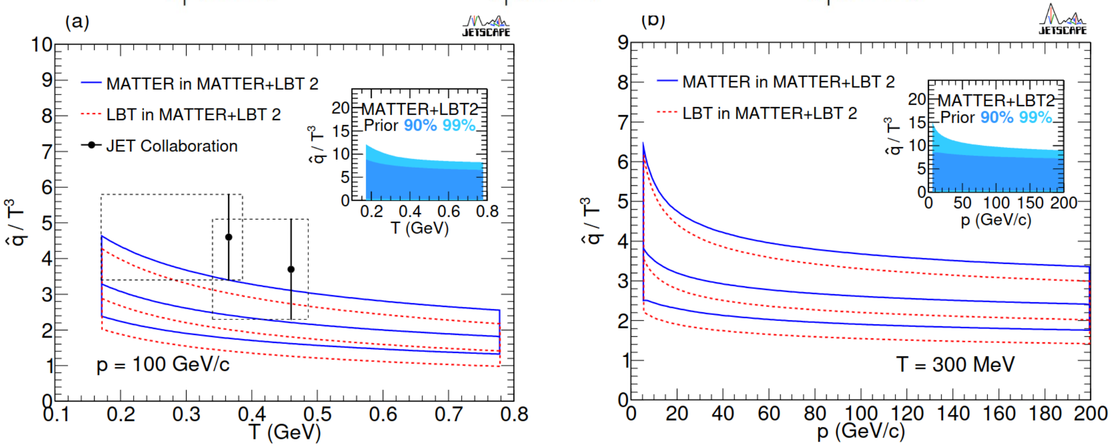
Bayesian estimate of jet transport coefficient $\hat{q}$ from inclusive hadron suppression

$$\frac{\hat{q}\left(Q,E,T\right)|_{Q_0,A,C,D}}{T^3} = 42 C_R \frac{\zeta(3)}{\pi}\left(\frac{4\pi}{9}\right)^2 \left\{ \frac{A\left[\ln\left(\frac{Q}{\Lambda}\right) - \ln\left(\frac{Q_0}{\Lambda}\right)\right]}{\left[\ln\left(\frac{Q}{\Lambda}\right)\right]^2}\theta(Q-Q_0) + \frac{C\left[\ln\left(\frac{E}{T}\right) - \ln(D)\right]}{\left[\ln\left(\frac{ET}{\Lambda^2}\right)\right]^2} \right\}$$



$$\hat{q} \equiv \frac{\langle k_\perp^2 \rangle}{L}$$





Radiative energy loss:

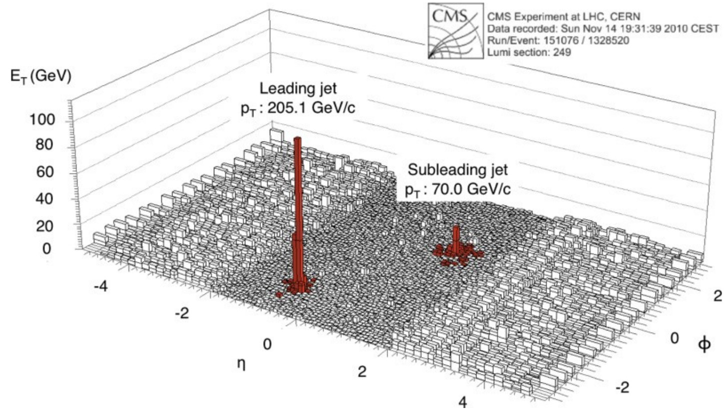
$$\Delta E \propto \hat{q} L^2$$

BDMPS, Nucl. Phys. B483 (1997) 291

JETSCAPE, PRC 104 (2021) 024905, arXiv: 2102.11337

Momentum ballance measurement by CMS

CMS, PRC 84 (2011) 024906

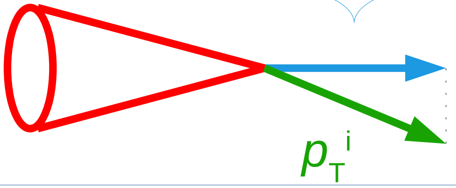


Jet momentum imballance

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

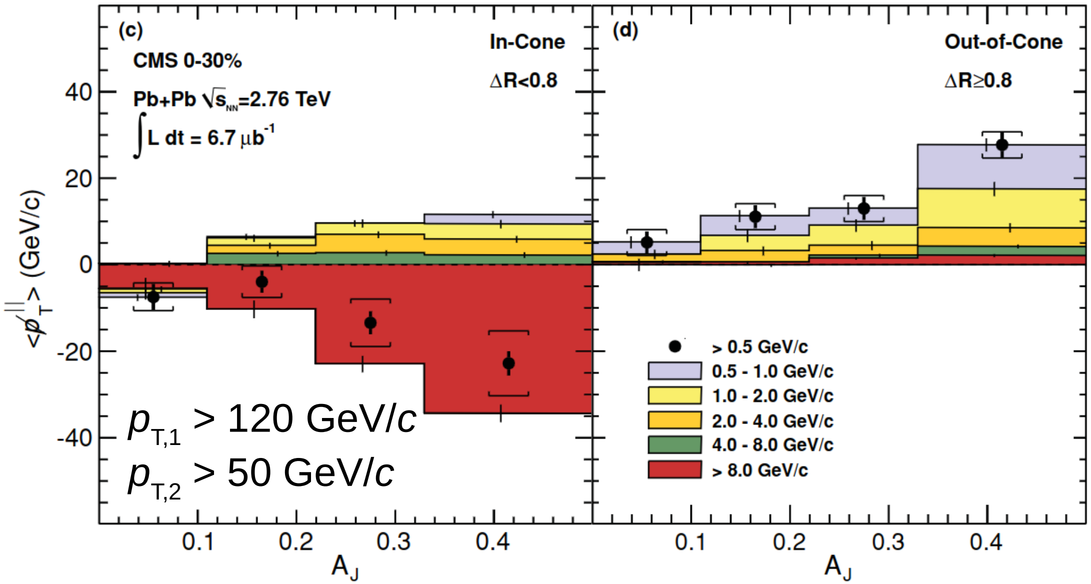
$$\not{p}_T^{\parallel} = \sum_i -p_T^i \cos\left(\phi_i - \phi_{\text{Leading Jet}}\right)$$

Leading jet



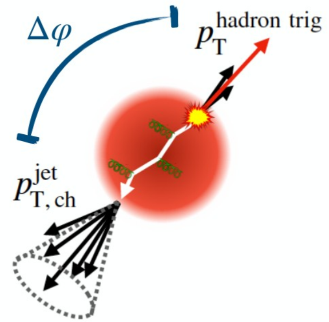
in jet cones

out of jet cones



Large contribution to the momentum balance in data arises from soft particles radiated at angles > 0.8 rad to the jets.

Hadron-jet acoplanarity

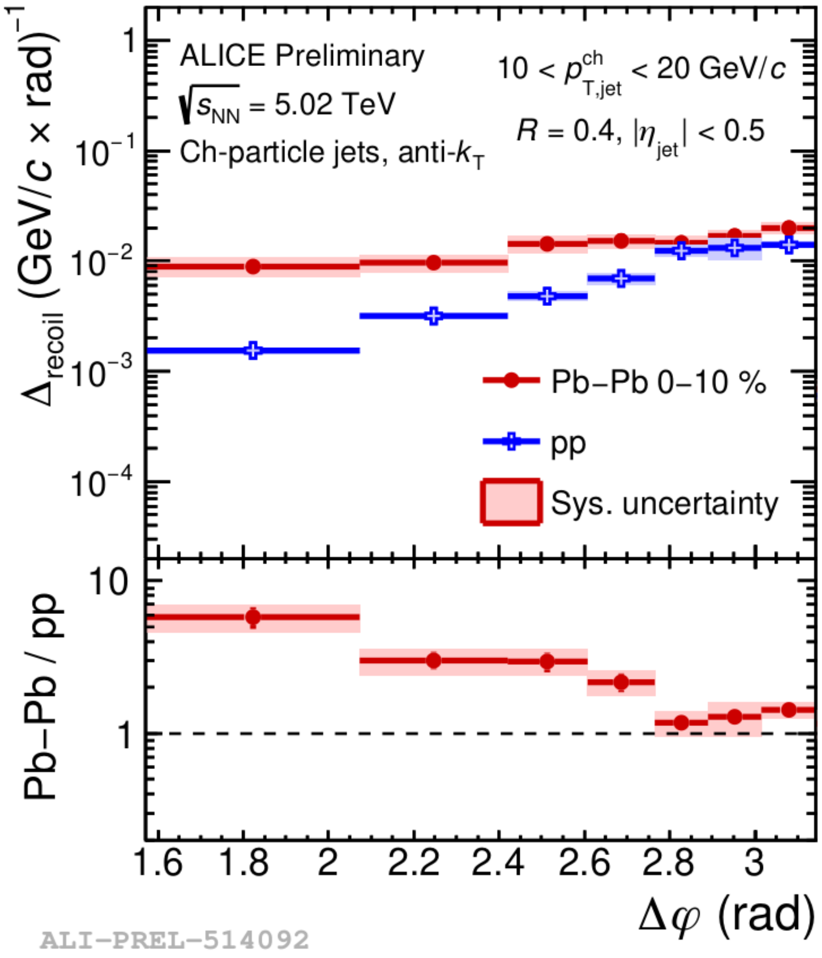


Data driven removal of uncorrelated jet yield

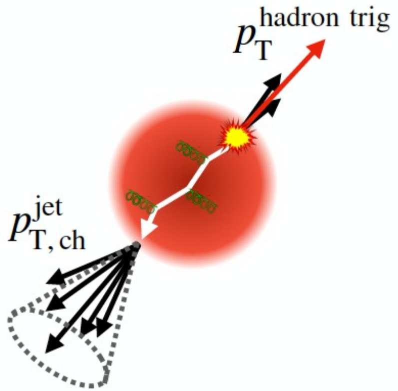
$$\Delta_{recoil}(p_{T,jet},\Delta\varphi) = \frac{1}{N_{trig}}\frac{d^2N_{jet}}{dp_{T,jet}d\Delta\varphi}\Bigg|_{p_T^{trig}\in TT_{sig}} - \frac{1}{N_{trig}}\frac{d^2N_{jet}}{dp_{T,jet}d\Delta\varphi}\Bigg|_{p_T^{trig}\in TT_{ref}}$$

TT_{sig}, TT_{ref} exclusive hadnon p_T bins

- Increase in acoplanarity of low-p_T, large R jets
- Models suggest this is due medium response rather than large angle scattering

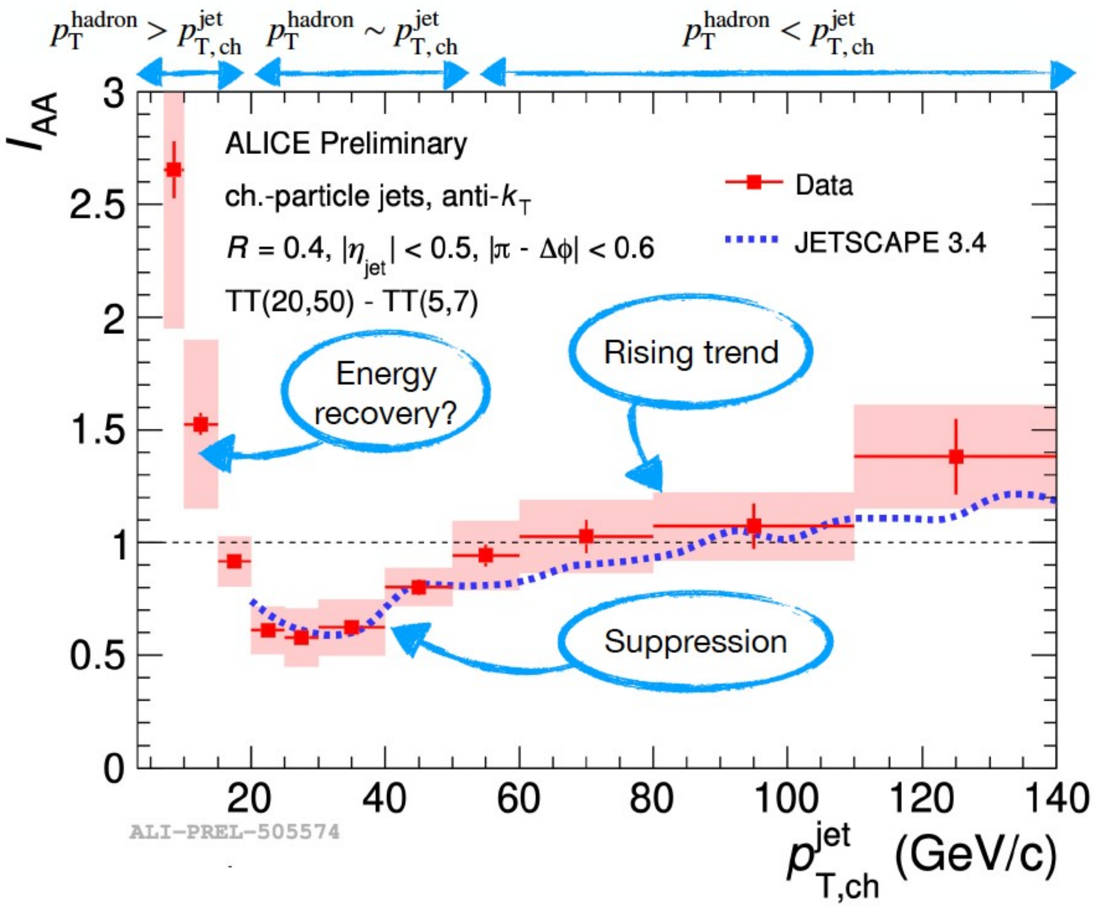


Recoil jet energy redistribution

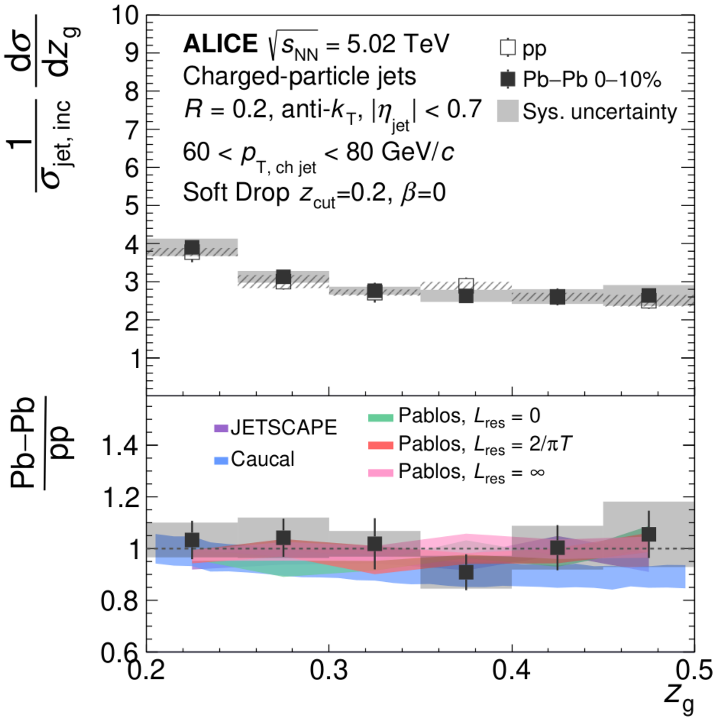


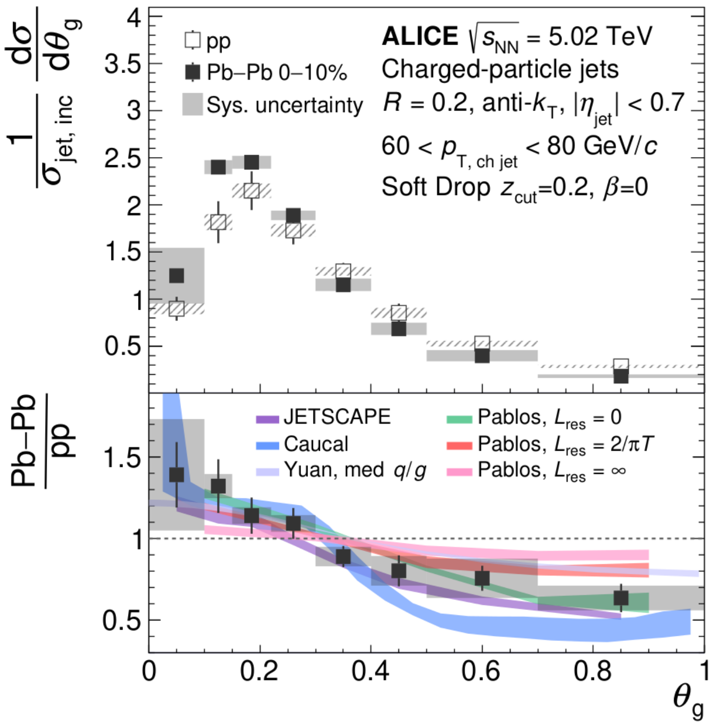
$$I_{AA} \equiv \frac{\Delta_{recoil}(Pb-Pb)}{\Delta_{recoil}(pp)}$$

Rising trend: interplay of jet quenching effects on hadron and jet production



Substructure of jets in PbPb





$$z \equiv \frac{p_{T,sub-leading}}{p_{T,leading} + p_{T,sub-leading}}$$

$$\theta_g \equiv \frac{R_g}{R} \equiv \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$

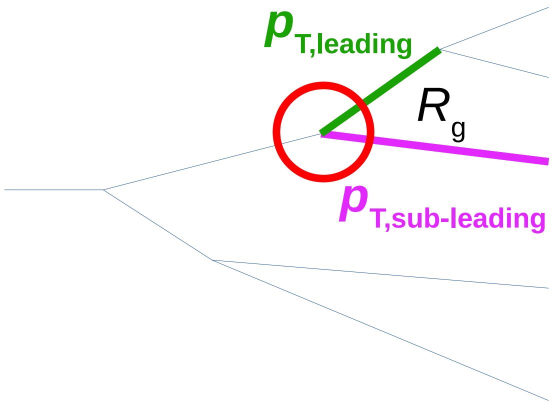
ALICE, PLB 128 (2022) 102001

arXiv:2211.04384

Splittings with $z > 0.2$ in PbPb relative to pp have on average

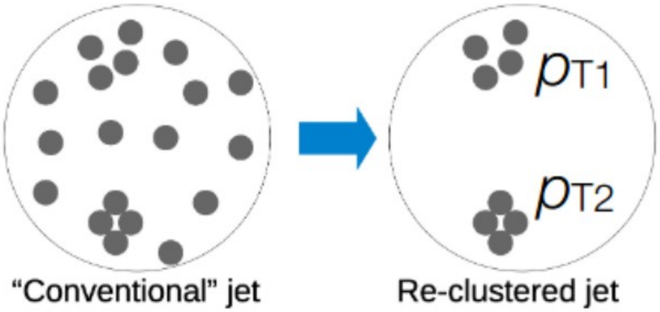
1) stronger suppression of wide fragmentation patterns

2) little to no modification of momentum splitting

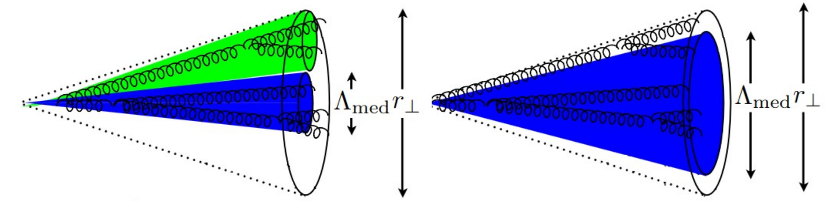


Substructure of jets in ATLAS

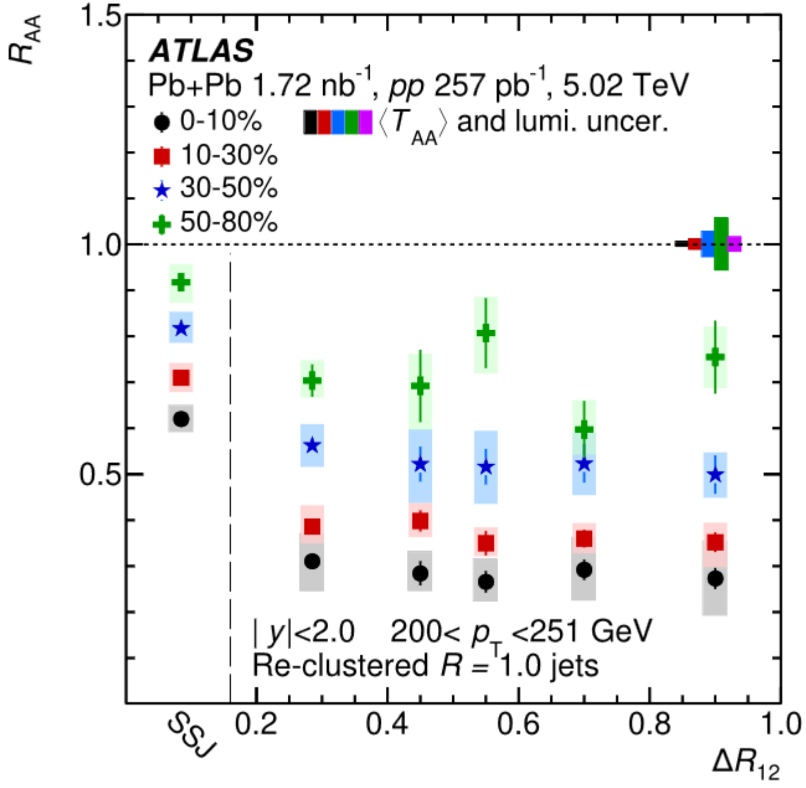
ATLAS, arXiv:2301.05606



- Reconstruct first R = 0.2 jets (p_{Tjet} > 35 GeV/c)
- Recluster constituents of these jets to R = 1 jets
- Sort jets according to subjet angular distances
- Jets with substructure are more suppressed

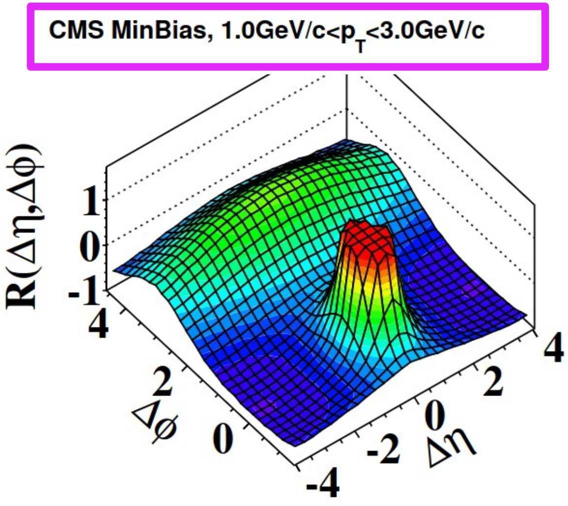


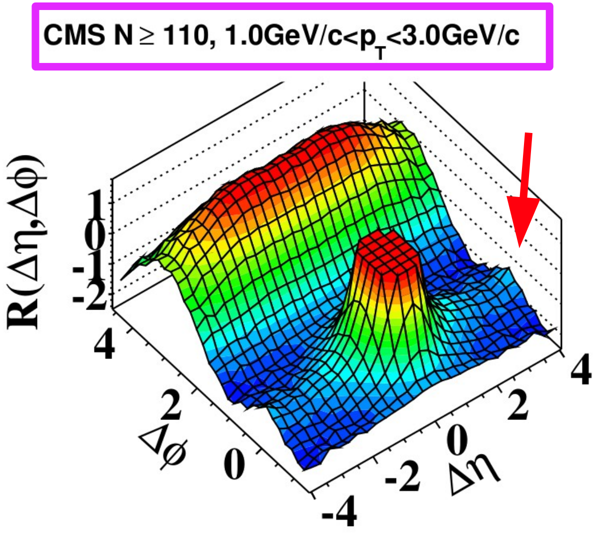
Casalderrey-Solana et al., arXiv:1210.7765v2



SSJ = jet with a single sub-jet

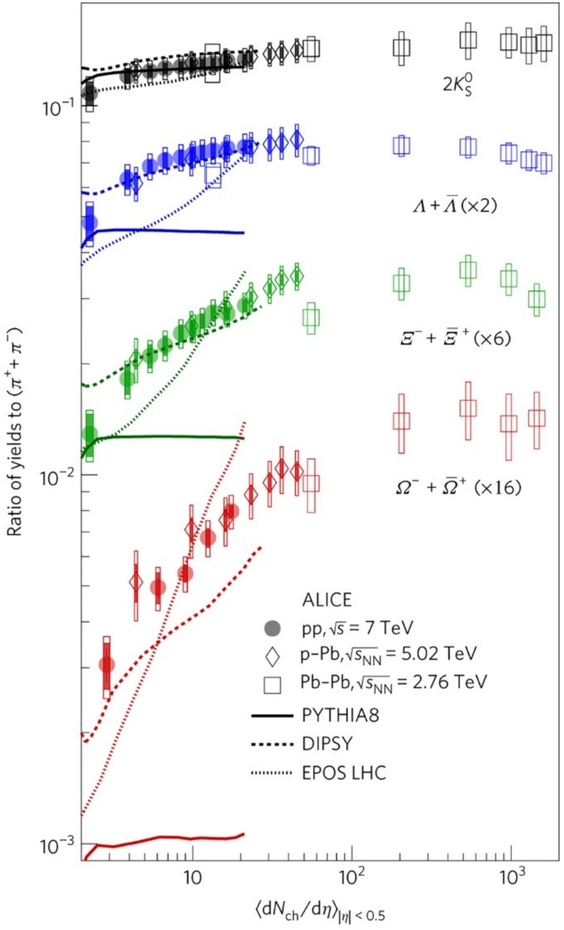
QGP in small collision systems?





CMS, JHEP 09 (2010) 091

ALICE Nat. Phys. 13 (2017) 535–539



- QGP-like signatures in high-multiplicity pp and pA
- How do QGP signatures that we see in large collision systems evolve when decreasing system size?
- Jet quenching is necessary consequence of a hot and dense fireball. Can we see evidence of it?

Considerations about jet quenching observables in small collision systems

- **Yield suppression relative to min. bias pp** → energy transport out-of-cone

$$R_{\mathrm{AA}}^{h,j}(p_T, y) = \frac{1}{\langle T_{\mathrm{AA}} \rangle} \frac{(1/N_{\mathrm{ev}})\, dN_{\mathrm{AA}}^{h,j}/dp_T dy}{d\sigma_{\mathrm{pp}}^{h,j}/dp_T dy}$$

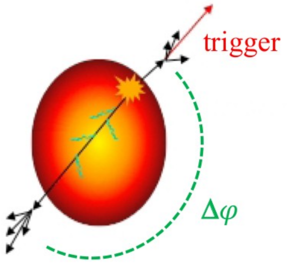
measurement of inclusive suppression R_{AA} requires Glauber scaling →

- limited precision of $\langle T_{AA} \rangle$ for centrality biased events

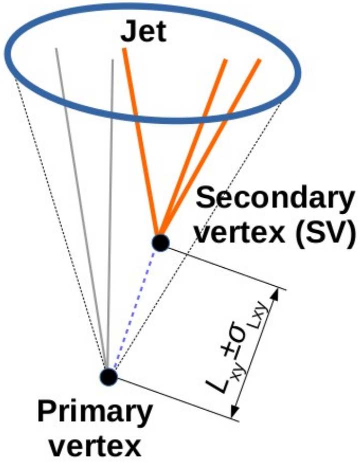
- Glauber model does not account for conservation laws, geometry information smeared by fluctuations

- not defined in high-multiplicity pp collisions

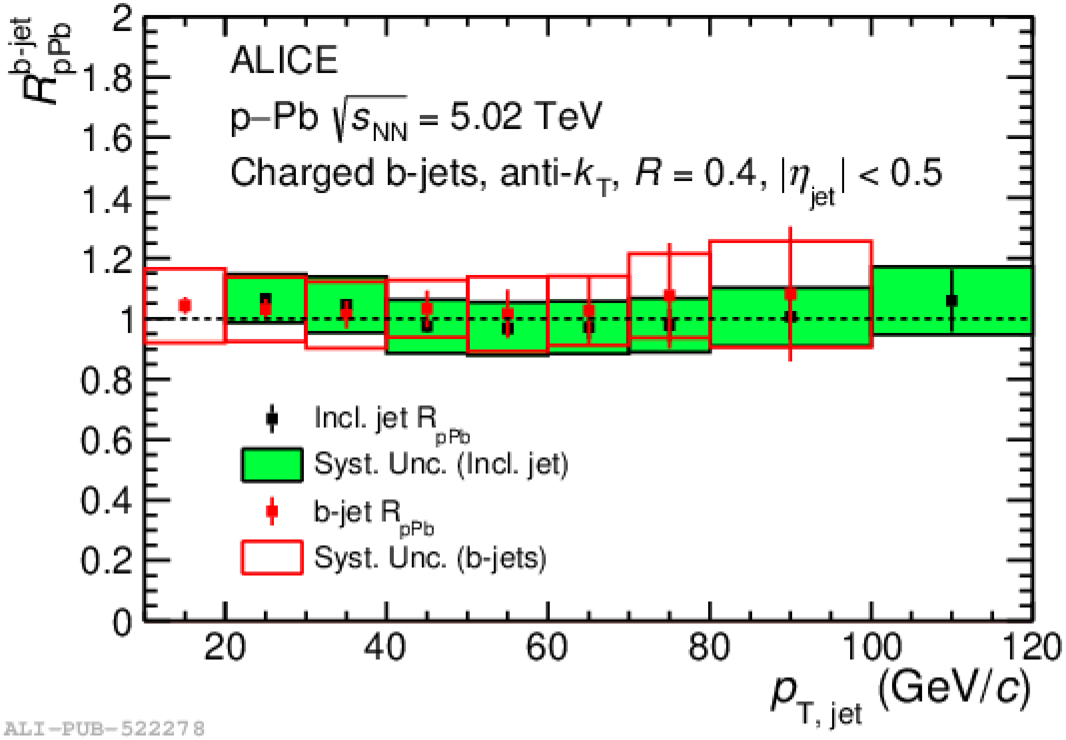
- **Jet substructure modification**
- **Jet deflection** → dijet acoplanarity



Production of inclusive jets and inclusive b-jets in minimum bias p+Pb



ALICE, JHEP 01 (2022) 178

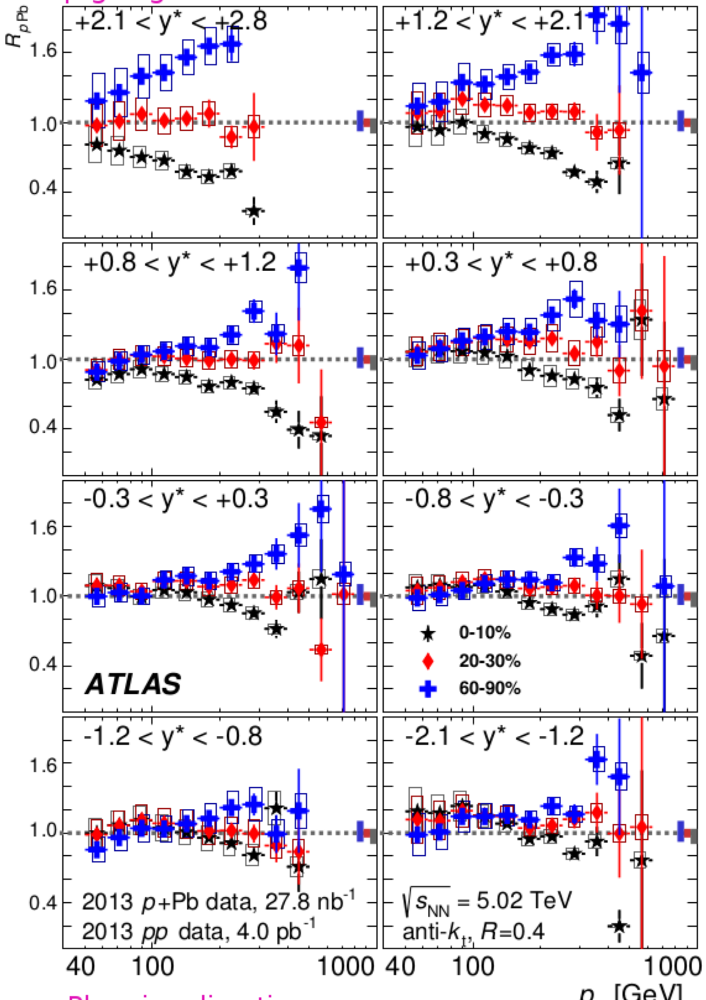


- Nuclear modification factor compatible with 1
- No sign of mass dependent effects

$$R^{\text{b-jet}}_{\text{pPb}} = \frac{1}{A} \frac{\mathrm{d}^2\sigma^{\text{b jet}}_{\text{pPb}} / \mathrm{d}p_{\text{T,ch jet}} \mathrm{d}\eta_{\text{jet}}}{\mathrm{d}^2\sigma^{\text{b jet}}_{\text{pp}} / \mathrm{d}p_{\text{T,ch jet}} \mathrm{d}\eta_{\text{jet}}}$$

Jet R_{pPb} by ATLAS

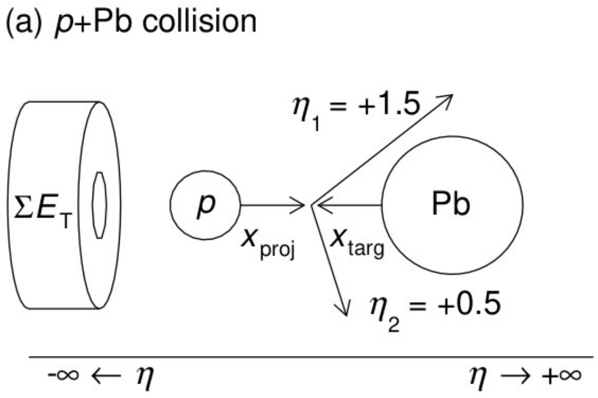
p-going direction   ALTAS, PLB 748 (2015) 392-413

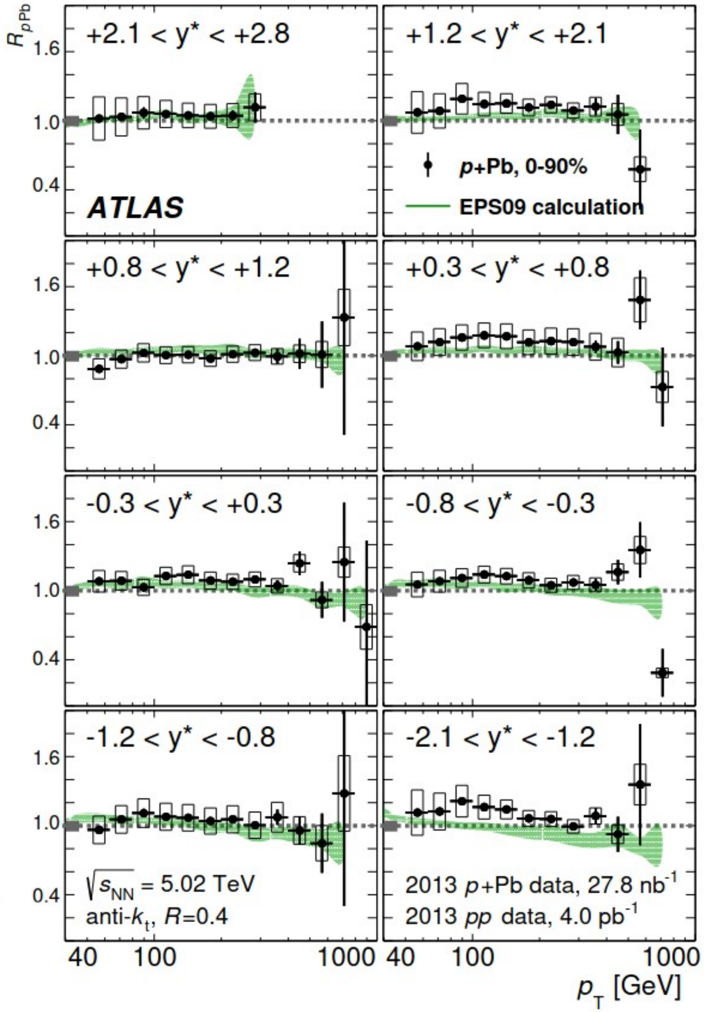


Pb-going direction

p-Pb 0-90%

p-Pb 0-10%
p-Pb 20-30%
p-Pb 60-90%

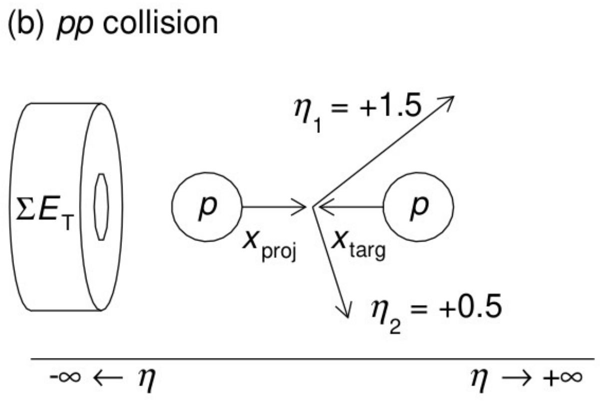




ALTAS, PLB 748 (2015) 392

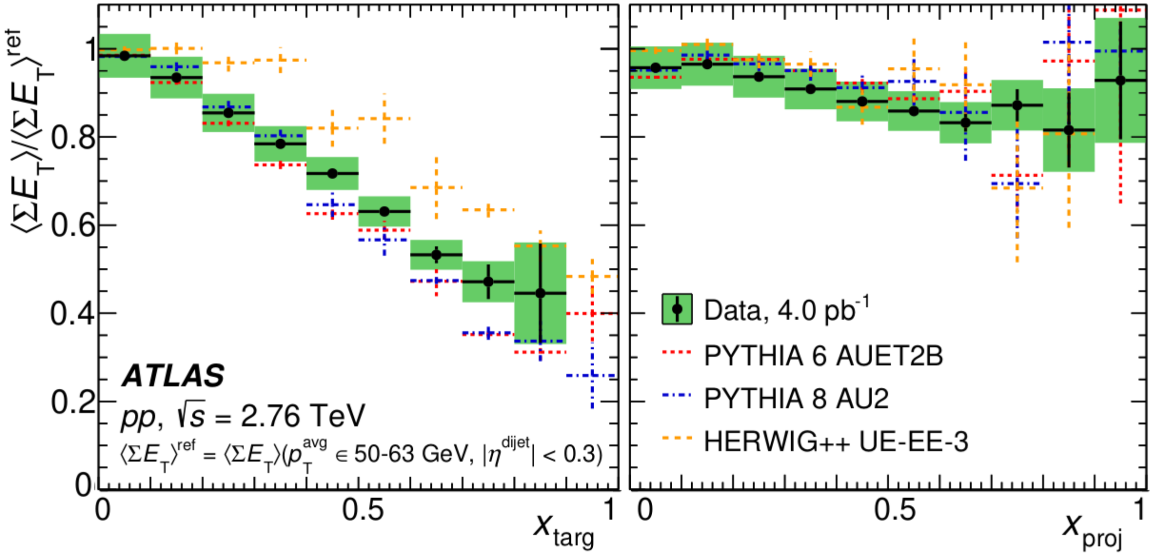
Corrlation of hard processes and soft particle production in pp by ATLAS

ATLAS, PLB 756 (2016) 10



$$x_{\text{proj}} = p_{\text{T}}^{\text{avg}}(e^{+\eta_1} + e^{+\eta_2})/\sqrt{s},$$
$$x_{\text{targ}} = p_{\text{T}}^{\text{avg}}(e^{-\eta_1} + e^{-\eta_2})/\sqrt{s}.$$

$$p_{\text{T}}^{\text{avg}} = (p_{\text{T},1} + p_{\text{T},2})/2$$

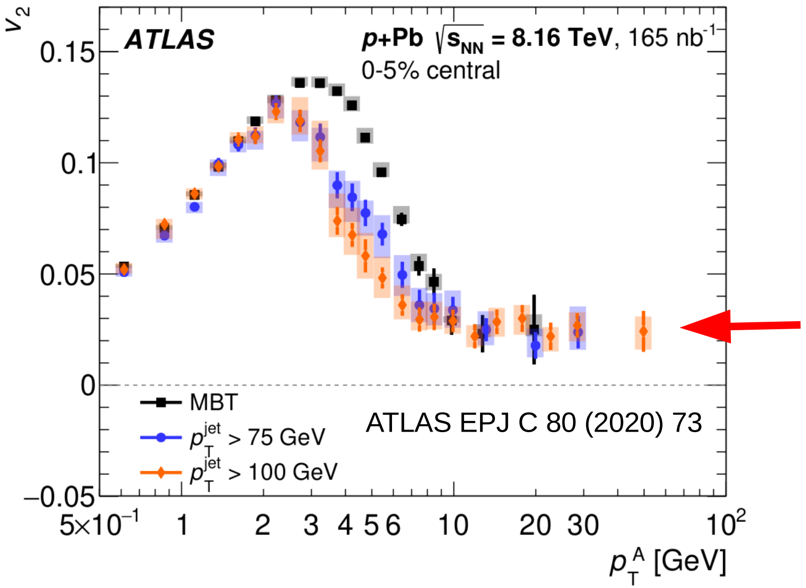


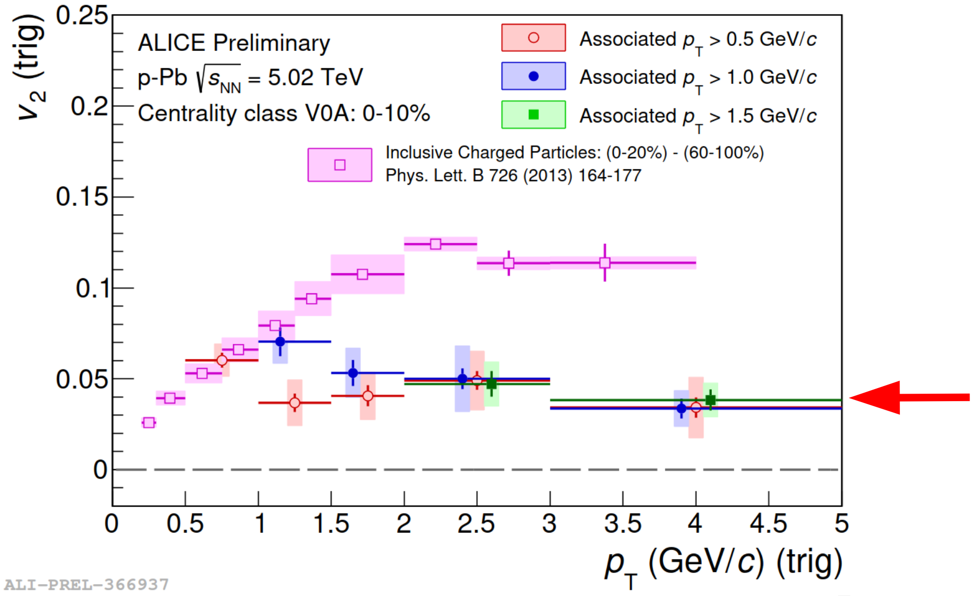
Hard scattering involving large x parton in Pb $\Rightarrow$

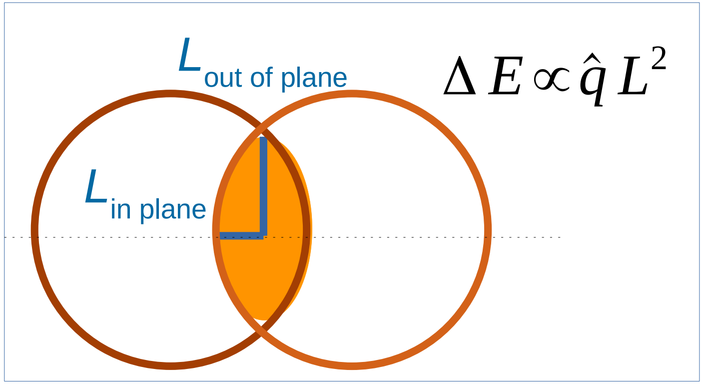
The beam remnant has less longitudinal energy $\Rightarrow$

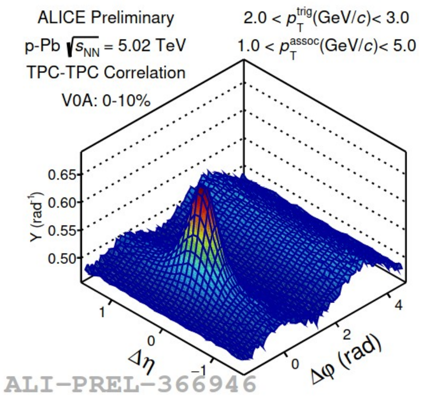
Reduction of E_T at large η

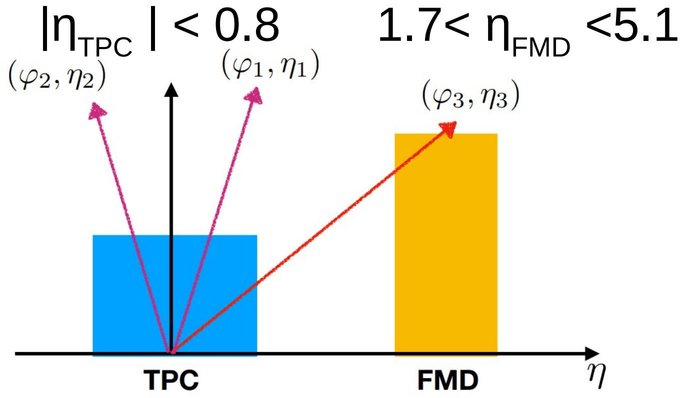
Flow of jet fragments in p-Pb











Prospects for OO run at LHC

Small system $\langle N_{\mathrm{ch}}\rangle_{\mathrm{OO}} \approx 2\ \langle N_{\mathrm{ch}}\rangle_{\text{p-Pb}}$ with AA geometry

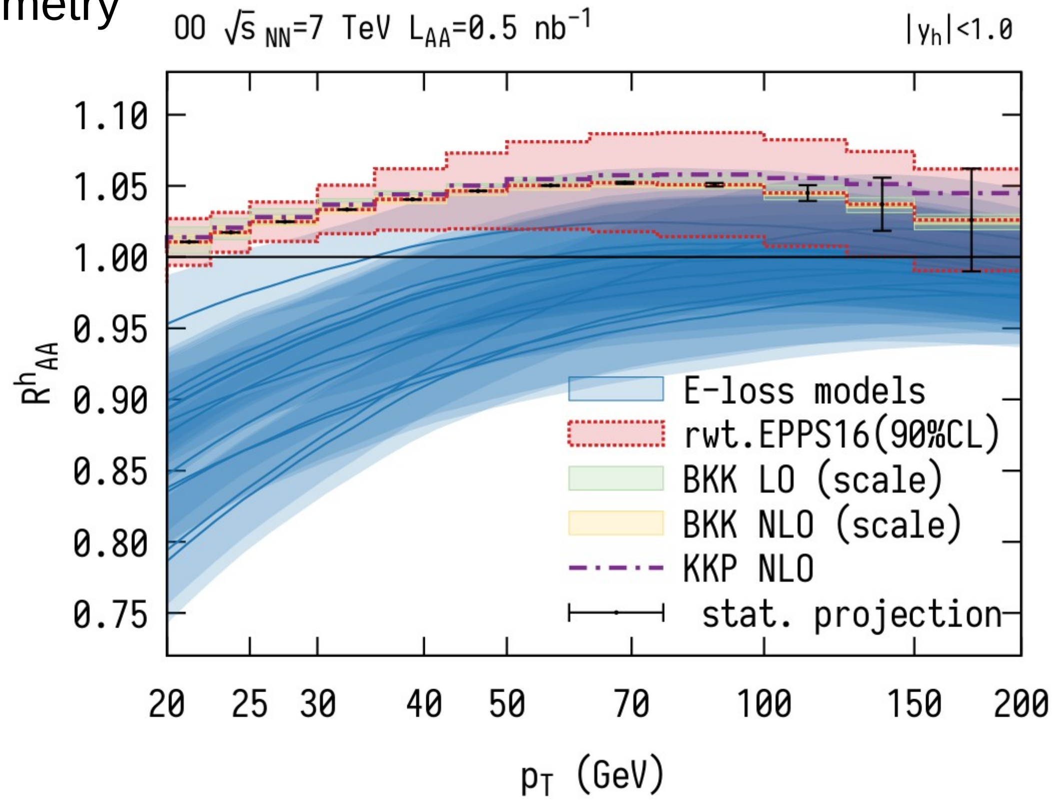
$$R^{h,j}_{\mathrm{AA}}(p_T, y) = \frac{1}{\langle T_{\mathrm{AA}}\rangle} \frac{(1/N_{\mathrm{ev}})\ dN^{h,j}_{\mathrm{AA}}/dp_T dy}{d\sigma^{h,j}_{pp}/dp_T dy}$$

$\langle T_{\mathrm{AA}}\rangle$ nuclear overlap function depends on soft physics of tot. inel. pp Xsec. and $\langle N_{\mathrm{coll}}\rangle$

$\Rightarrow$ MB provides better precision

$$R^{h,j}_{\mathrm{AA,\ min\ bias}}(p_T, y) = \frac{1}{A^2} \frac{d\sigma^{h,j}_{\mathrm{AA}}/dp_T dy}{d\sigma^{h,j}_{pp}/dp_T dy}$$

Huss et al., PRL 126, 192301 (2021)



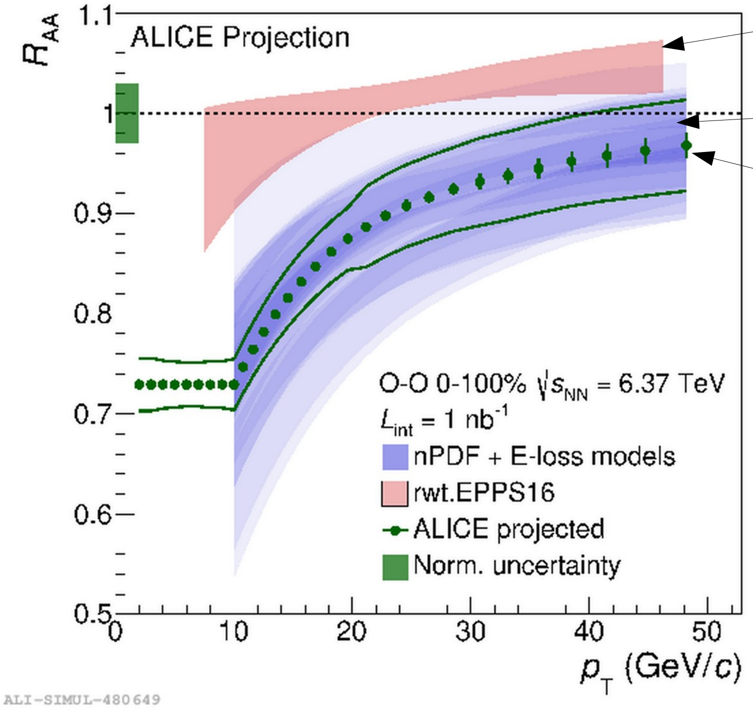
Projection of hadron R_{AA} for min bias OO

Luminosities used in the projection :

OO $\sqrt{s_{NN}}$ = 6.37 TeV $\mathcal{L}_{OO}$ = 1 nb^{-1}

pp $\sqrt{s}$ = 5.02 TeV $\mathcal{L}_{pp}$ = 3 pb^{-1}

OO run is planned in 2025



ALICE-PUBLIC-2021-004

Calculation which assumes no energy loss and which accounts just for nuclear PDFs

Calculations which assume energy loss models together with nuclear PDFs [Huss et al. arXiv 2007.13754]

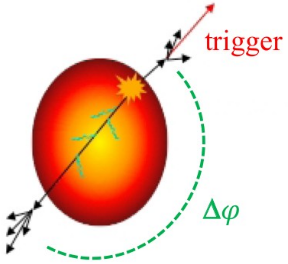
ALICE projection:
data points follow a mean energy loss model

In the range up to 50 GeV/*c*:

- statistical precision < 1.5%
- systematic precision 4–6%
  - $\sqrt{s}$ interpolation error ≤ 3%
  - cross section normalization 3%
  - other systematics 2–4%

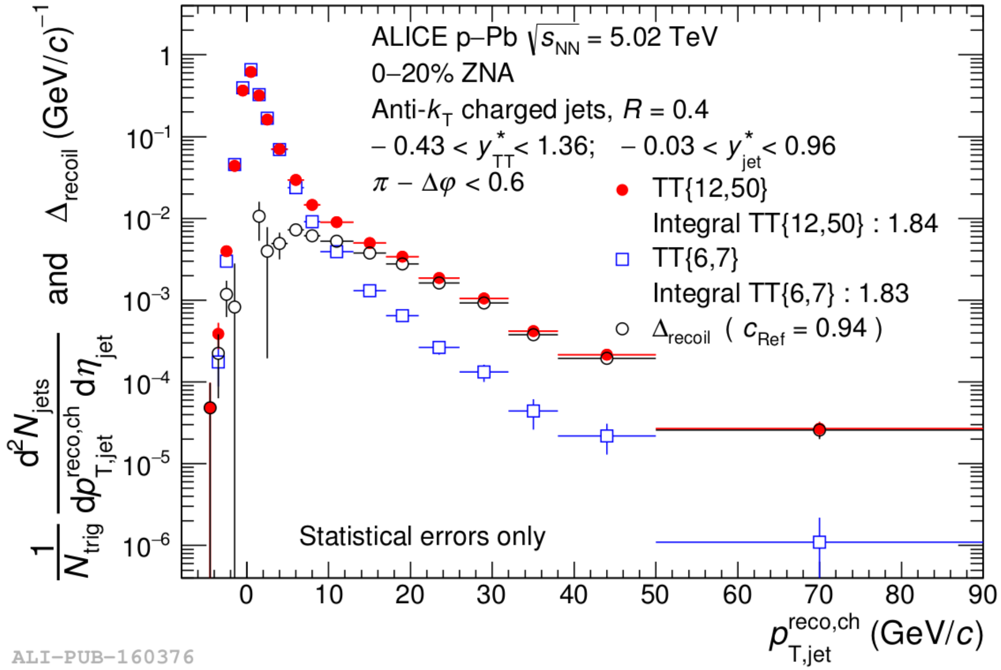
Measurement is potentially sensitive to the effect

Search for jet quenching in p-Pb with h+jet correlations in ALICE



TT{X,Y} means
X< $p_{T,trig}$ < Y GeV/*c*

ALICE, PLB 783 (2018) 95



- Event activity measured by ZDC
- Jets recoiling from high-p_T trigger hadron (TT)
- Data-driven statistical approach to remove recoil-jet yield uncorrelated to TT including MPI

$$\Delta_{recoil} = \frac{1}{N_{trig}} \frac{d^2 N_{jet}}{dp^{ch}_{T,jet} d\eta}\bigg|_{p_{T,trig} \in TT\{12,50\}} - \frac{1}{N_{trig}} \frac{d^2 N_{jet}}{dp^{ch}_{T,jet} d\eta}\bigg|_{p_{T,trig} \in TT\{6,7\}}$$

Hadron-jet observables and T_{AA}

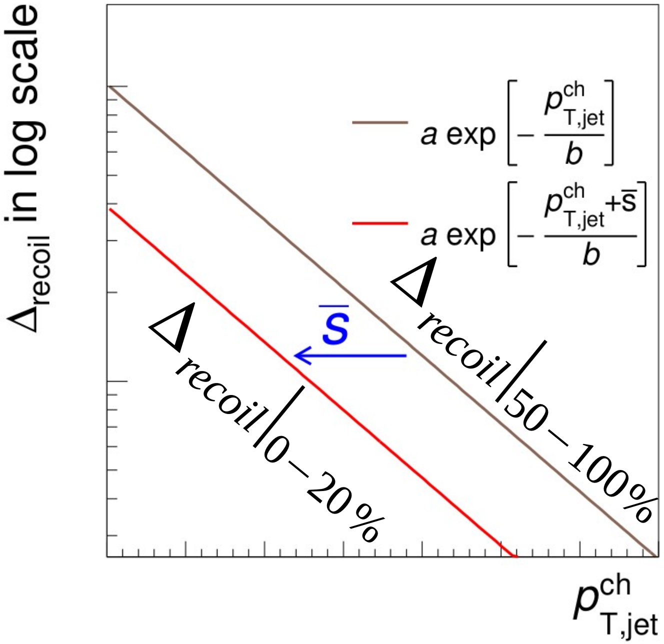
$$\frac{1}{N_{\mathrm{trig}}^{\mathrm{AA}}} \frac{\mathrm{d}^2 N_{\mathrm{jet}}^{\mathrm{AA}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}} \mathrm{d}\eta_{\mathrm{jet}}}\Bigg|_{p_{\mathrm{T,trig}} \in \mathrm{TT}} = \left(\frac{1}{\sigma^{\mathrm{AA}\rightarrow\mathrm{h+X}}} \cdot \frac{\mathrm{d}^2 \sigma^{\mathrm{AA}\rightarrow\mathrm{h+jet+X}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}} \mathrm{d}\eta_{\mathrm{jet}}} \right)\Bigg|_{p_{\mathrm{T,h}} \in \mathrm{TT}}$$

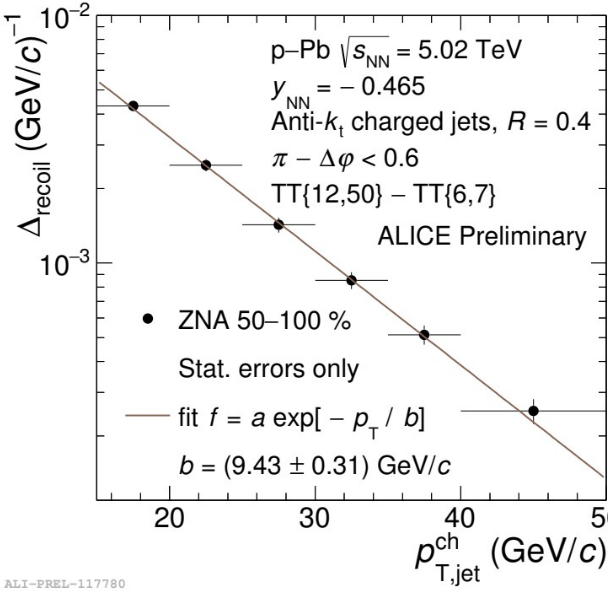
In case of no nuclear effects

$$\frac{1}{N_{\mathrm{trig}}^{\mathrm{AA}}} \frac{\mathrm{d}^2 N_{\mathrm{jet}}^{\mathrm{AA}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}} \mathrm{d}\eta_{\mathrm{jet}}}\Bigg|_{p_{\mathrm{T,trig}} \in \mathrm{TT}} = \left(\frac{1}{\sigma^{\mathrm{pp}\rightarrow\mathrm{h+X}}} \cdot \frac{\mathrm{d}^2 \sigma^{\mathrm{pp}\rightarrow\mathrm{h+jet+X}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}} \mathrm{d}\eta_{\mathrm{jet}}} \right)\Bigg|_{p_{\mathrm{T,h}} \in \mathrm{TT}} \times \frac{T_{\mathrm{AA}}}{T_{\mathrm{AA}}}$$

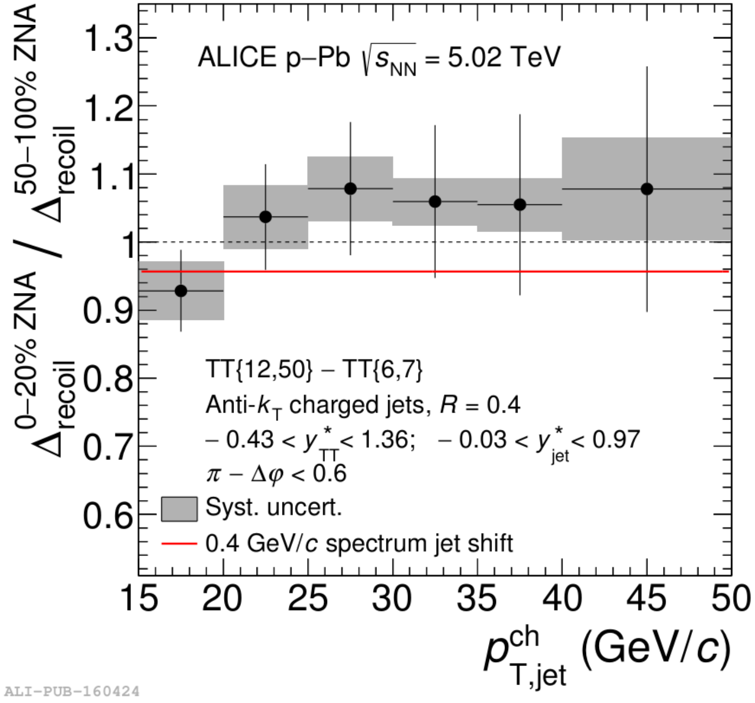
- This coincidence observable is self-normalized, no requirement of T_{AA} scaling
- No requirement to assume correlation between Event Activity and collision geometry

Limit on energy transport out of *R* = 0.4 in p-Pb





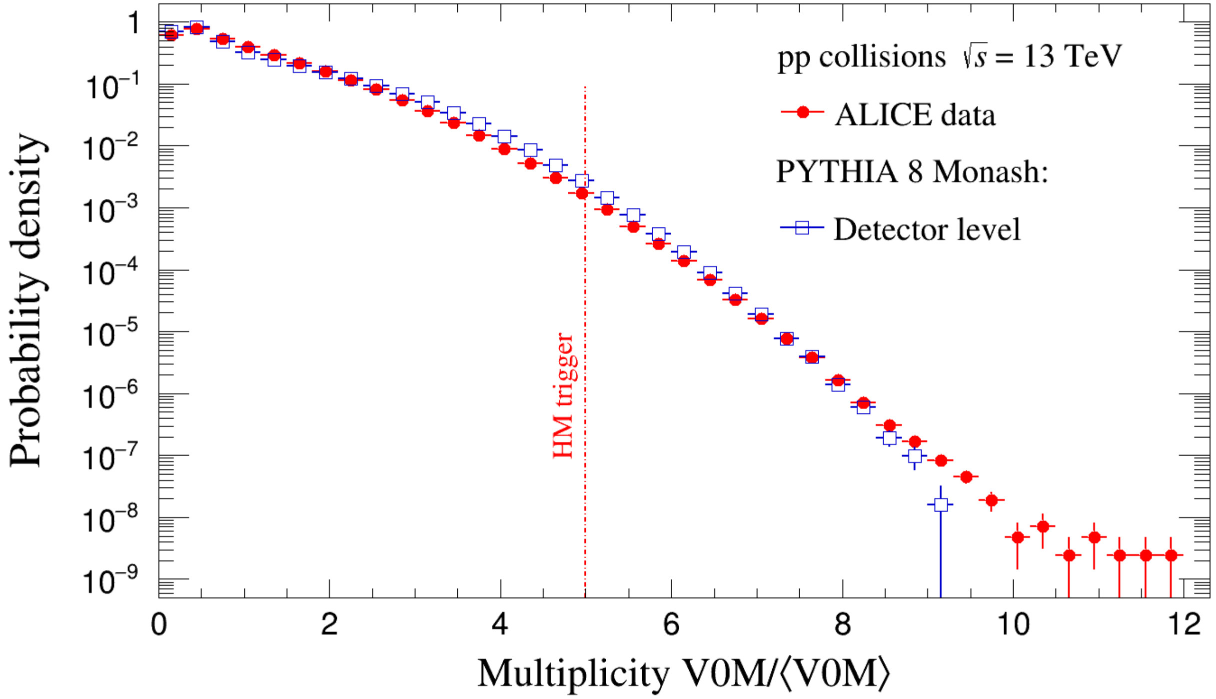
ALICE, PLB 783 (2018) 95

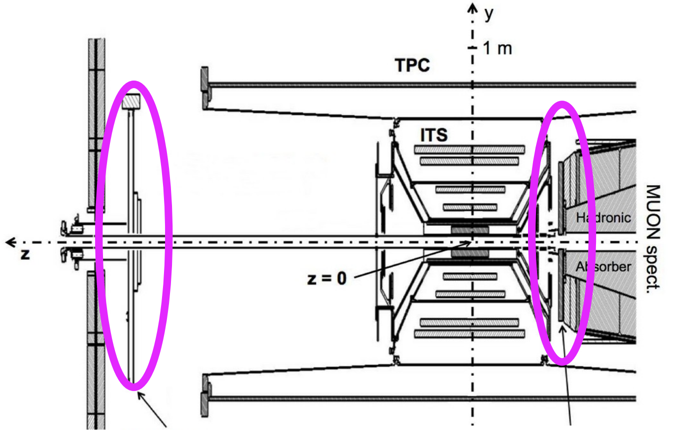


$$\frac{\Delta_{recoil}|_{0-20\,\%}}{\Delta_{recoil}|_{50-100\,\%}} = \exp\left(-\frac{\bar{s}}{b}\right)$$

Medium-induced charged energy transport out of *R* = 0.4 cone is less than 0.4 GeV/c (90% CL)

High multiplicity pp events





V0A
2.8 < η < 5.1

V0C
-3.7 < η <-1.7

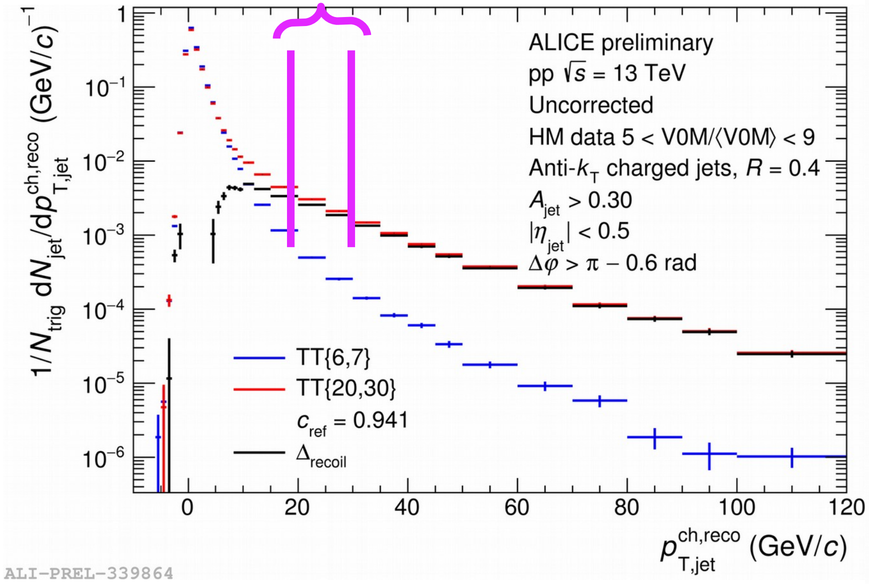
V0M = V0A + V0C

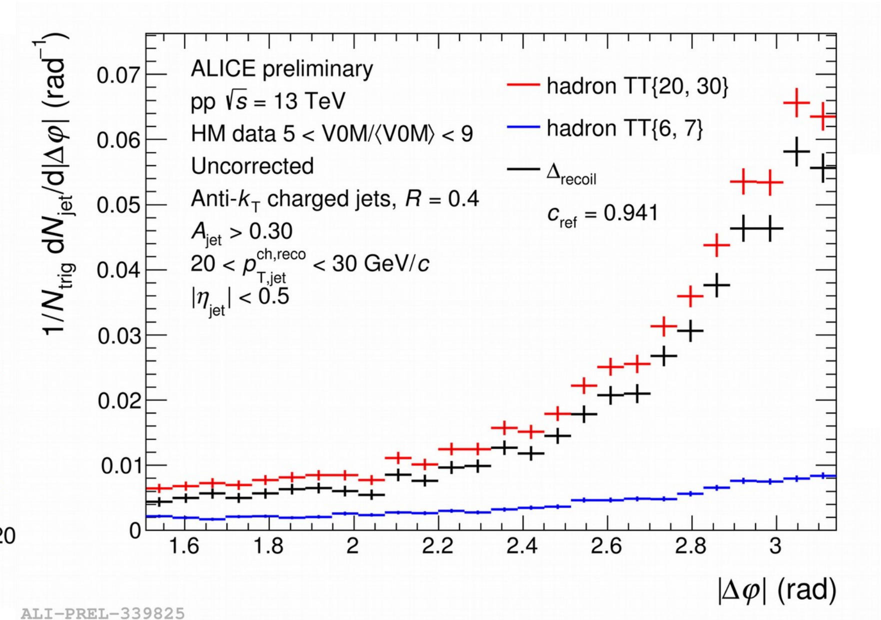
⟨V0M⟩ mean value in min. bias events

- pp minimum bias (MB)
- pp high-multiplicity (HM) : 5x larger multiplicity in V0 detector w.r.t. MB (0.1% of all events)

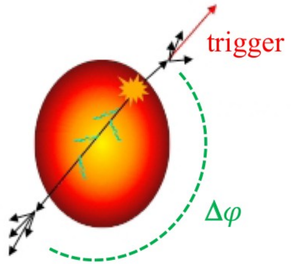
Search for jet quenching in high multiplicity pp collisions using hadron-jet acoplanarity

$$\Delta_{\mathrm{recoil}}(\Delta\varphi) = \frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}N_{\mathrm{jet}}}{\mathrm{d}\Delta\varphi}\bigg|_{\mathrm{TT}\{20,30\}\,\&\,p^{\mathrm{ch}}_{\mathrm{T,jet}}} - c_{\mathrm{ref}}\cdot\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}N_{\mathrm{jet}}}{\mathrm{d}\Delta\varphi}\bigg|_{\mathrm{TT}\{6,7\}\,\&\,p^{\mathrm{ch}}_{\mathrm{T,jet}}}$$

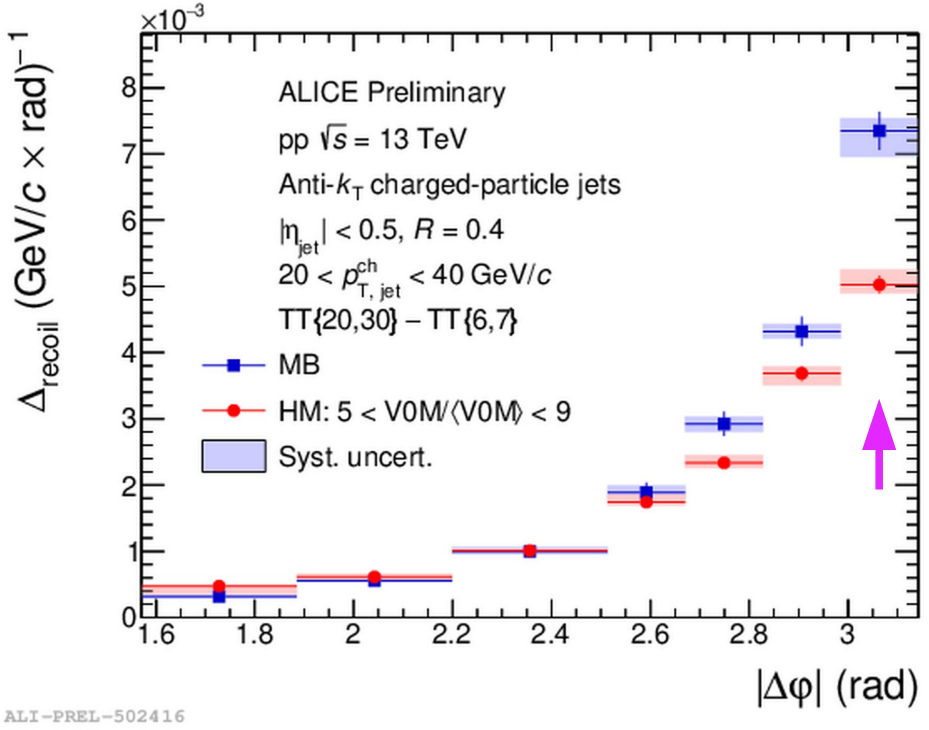




TT{X,Y} means X< $p_{\mathrm{T,trig}}$ < Y GeV/c

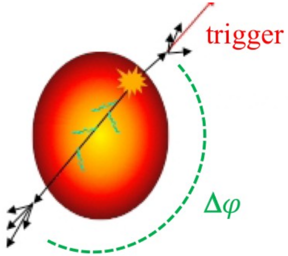


Distributions of hadron-jet acoplanarity



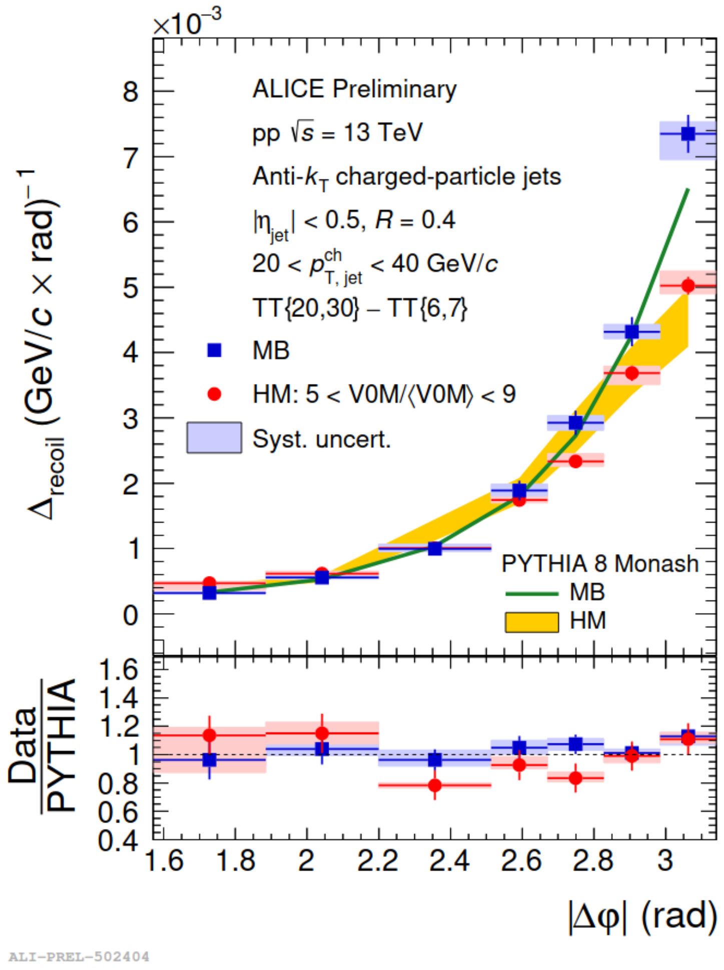
- HM acoplanarity distributions relative to MB
  - suppressed back-to-back correlation
  - broader

  The effect is stronger for low p_T jets



HM event activity selection:
5 < V0M / ⟨V0M⟩
0.1% of MB cross section

Comparison of hadron-jet acoplanarity with PYTHIA

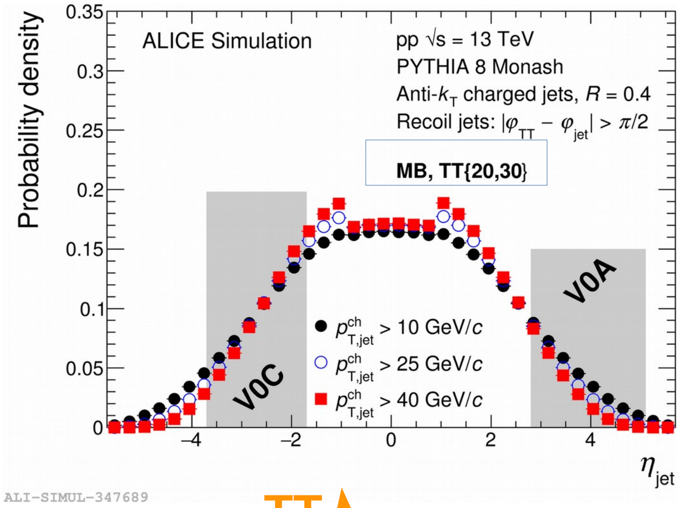


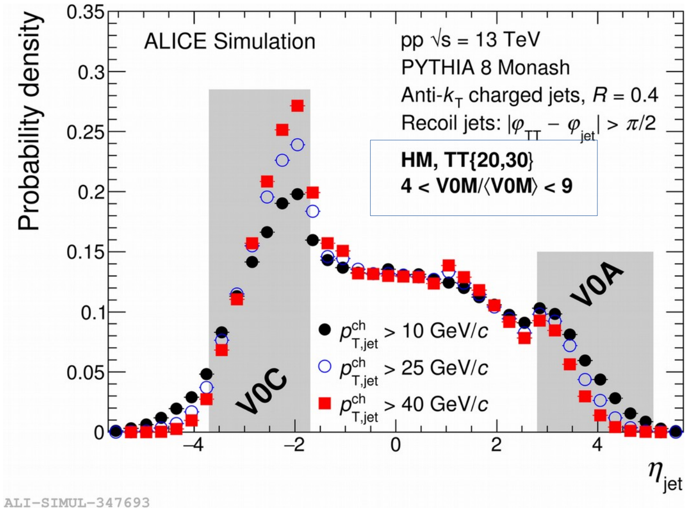
PYTHIA 8 Monash shows similar suppression pattern

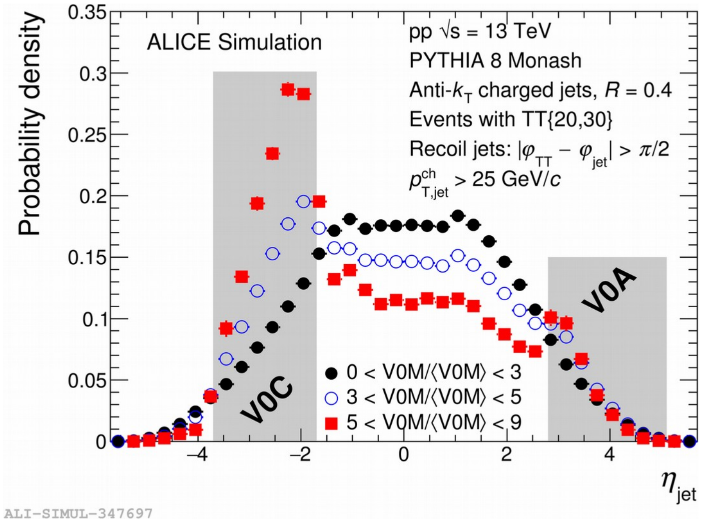
⇒ The effect is not due to jet quenching

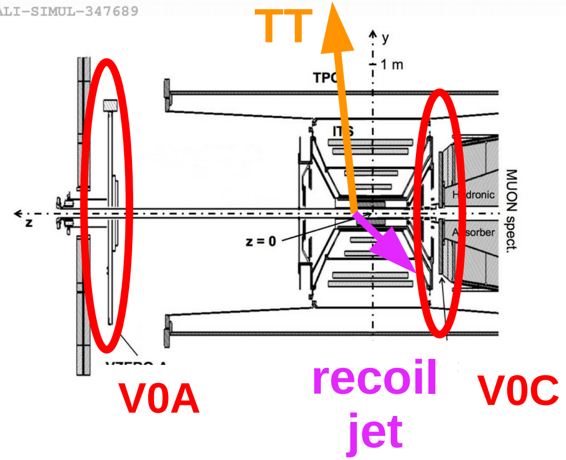
Use PYTHIA to explore the origin of the effect

PYTHIA : recoil jet η_{jet} versus $p_{T,jet}$









HM events:

- significant bias in distribution of high-p_T recoil jets
- enhancement in forward trigger detector acceptance
- V0A and V0C have asymmetric coverage

Summary

- Precise measurements of QCD with jets
- Jet shower interaction with QCD matter : wide angle radiation & jet core narrowing
- Jet quenching signatures in small systems can be created by event selection biases:
  - picking up fluctuations in particle wavefunction when imposing event activity bias
  - NLO processes with multi jet topology in final state
- We need to understand to $v_2 > 0$ of jet fragments in p-Pb
- New systems comming soon OO
- Physics summary of ALICE measurements from Run1 and Run2
  arXiv:2211.04384v1