Jets as a probe of QCD

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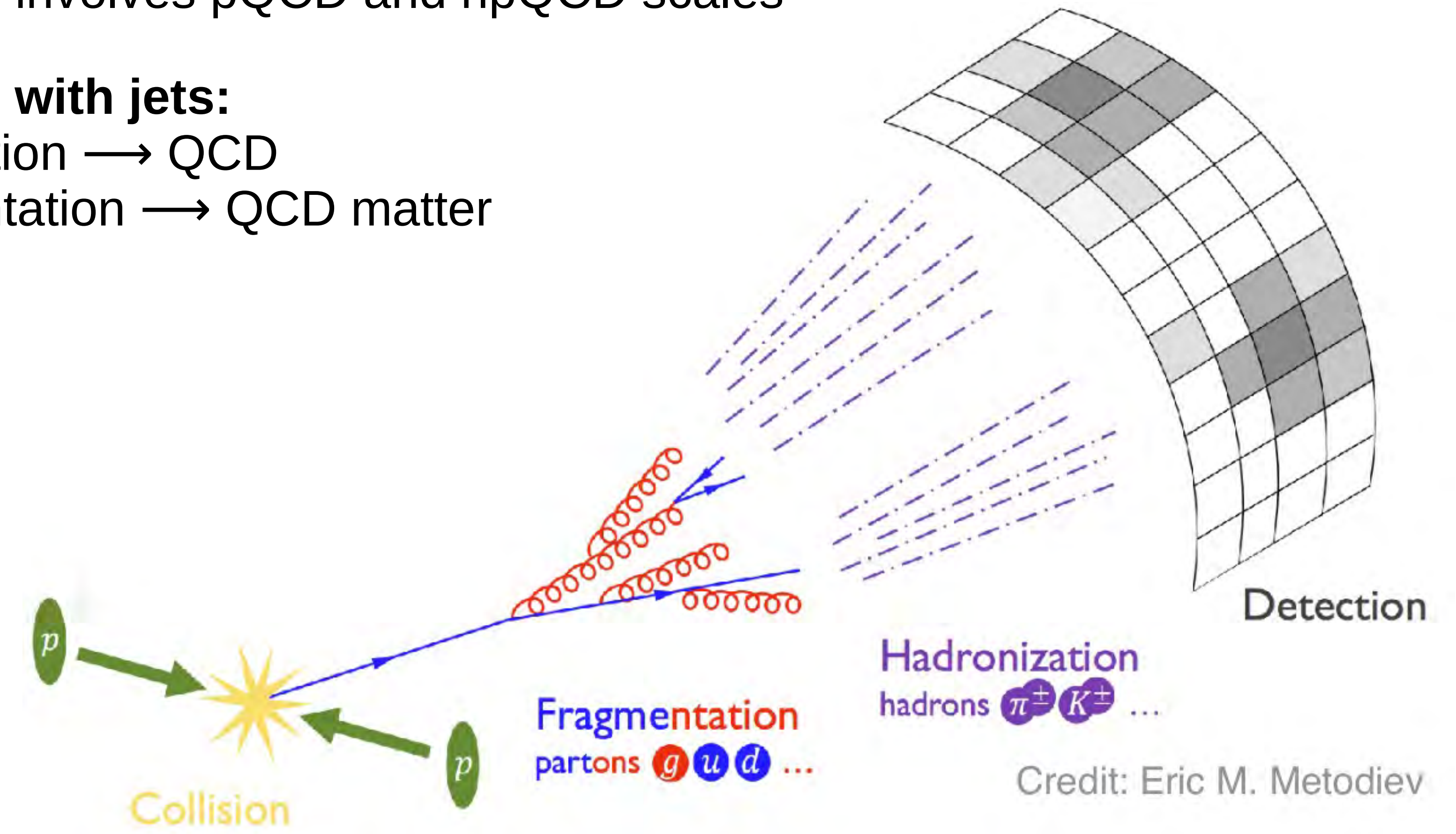
Jets and high-p_T hadrons as QCD probes

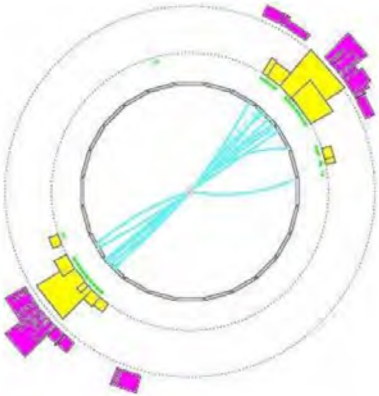
Jet shower evolution involves pQCD and npQCD scales

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



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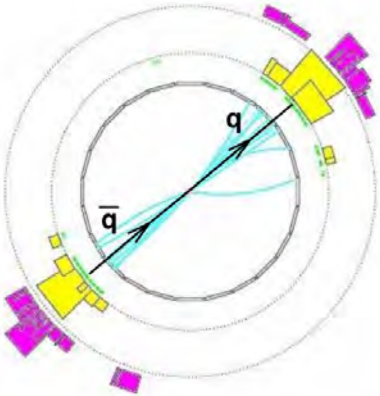

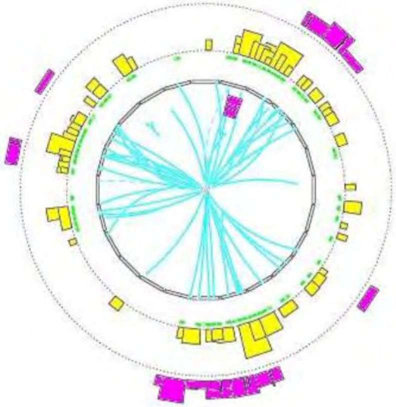

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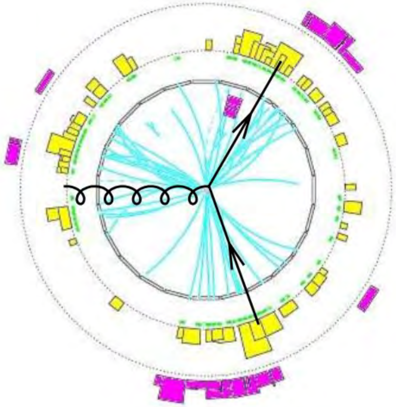
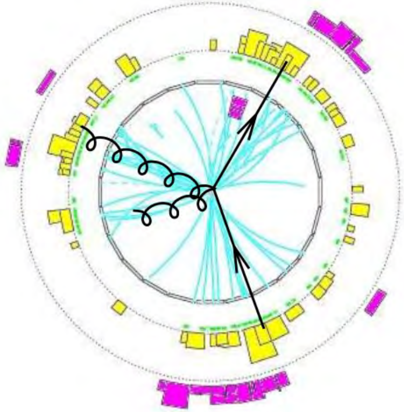


or



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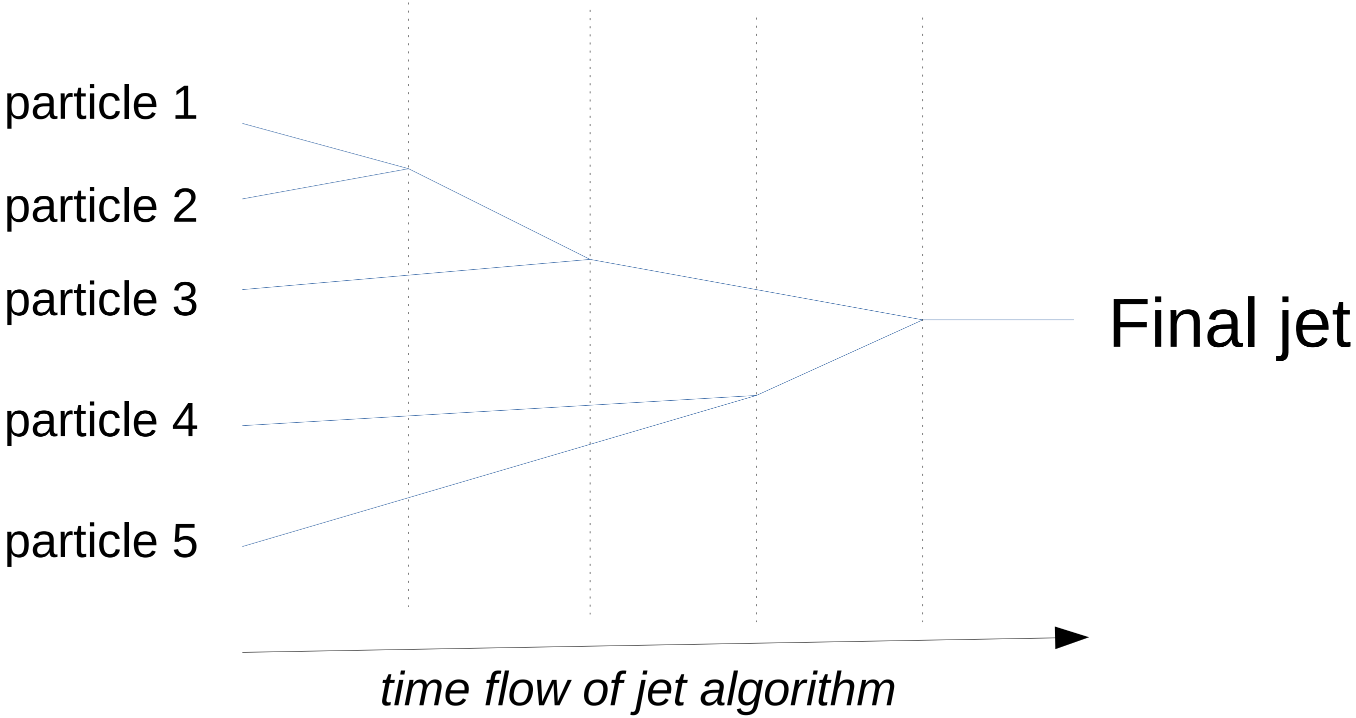
Definition of what jet actually is is needed !

Jet algorithm



Anti-k_T

p = -1, R = cone radius

1) for all particles i, j evaluate

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

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

2) Find minimal d_{ij} , d_{iB}

3) If d_{ij} is the minimum ⟶ merge i + j and go to 1)

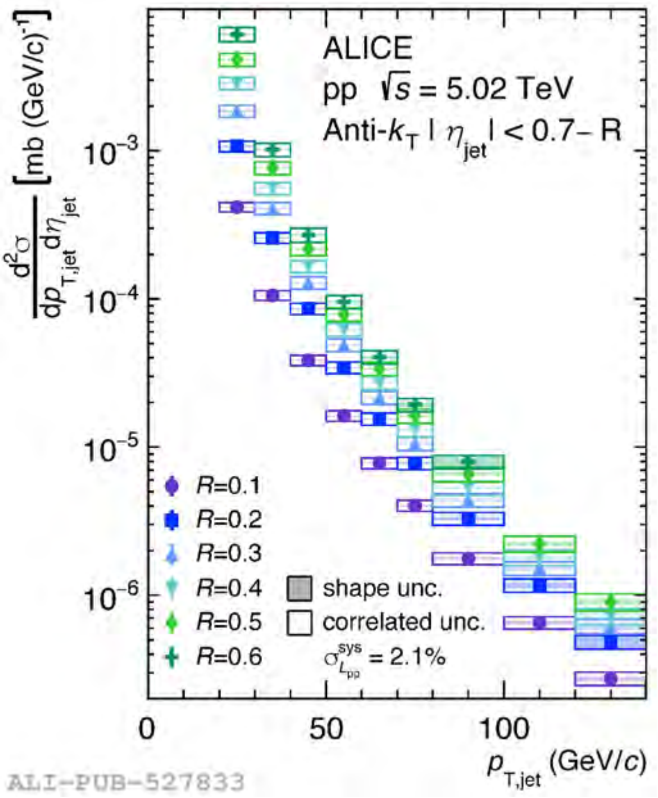
4) d_{iB} is the minimum ⟶ remove i from the list (final jet) and go to 1)

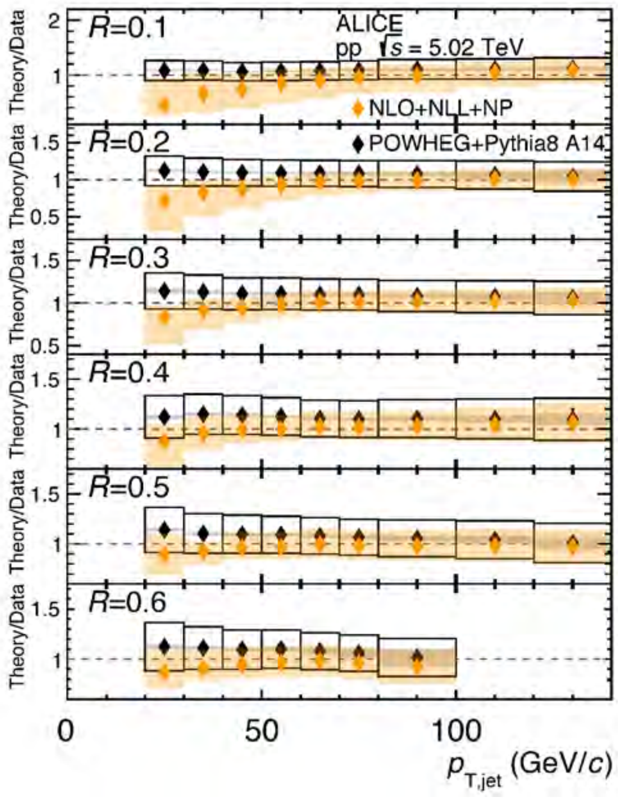
JHEP 0804 (2008) 063

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

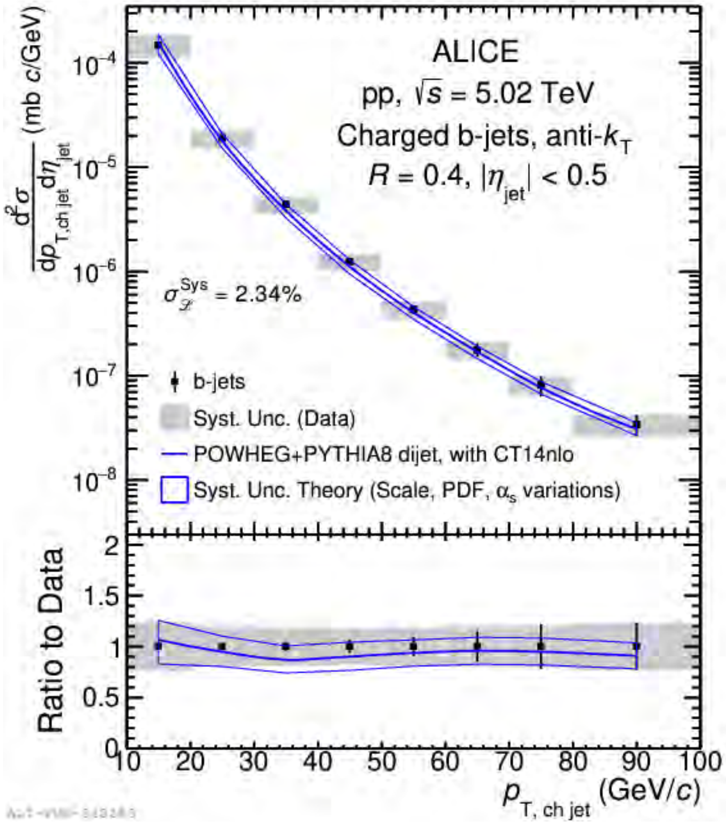
Salam, EPJ C67 (2010) 637

Jet cross section in pp @ √s = 5 TeV





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

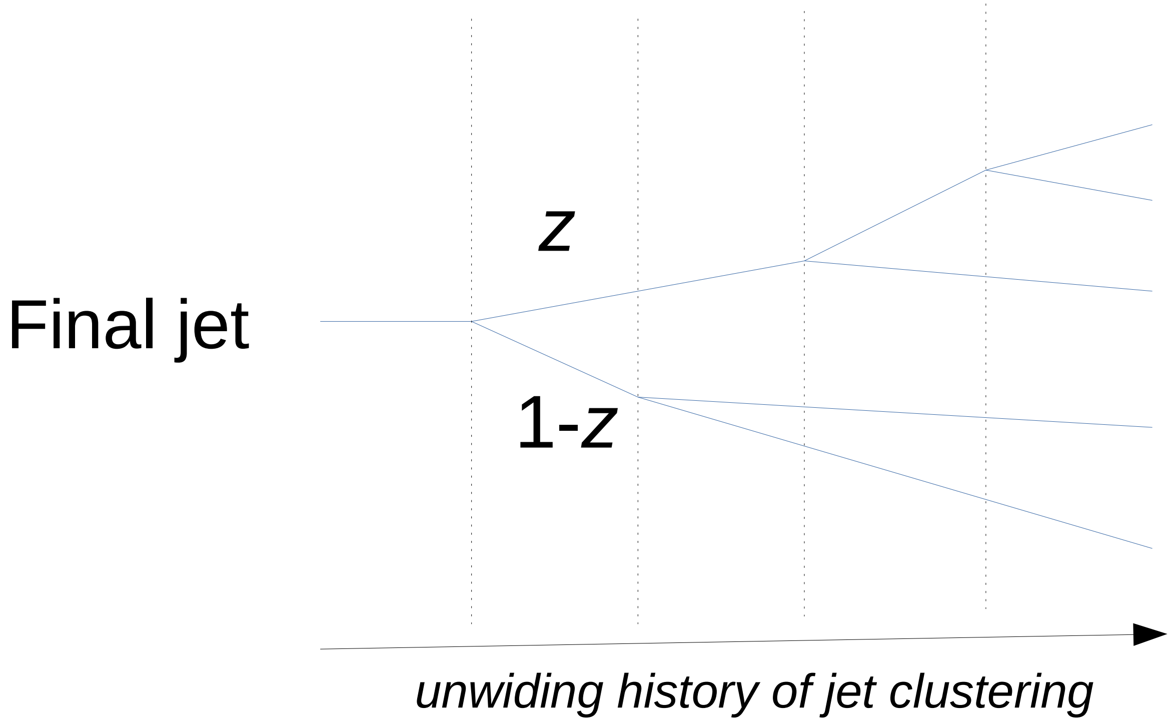


ALICE, JHEP 01 (2022) 178

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)

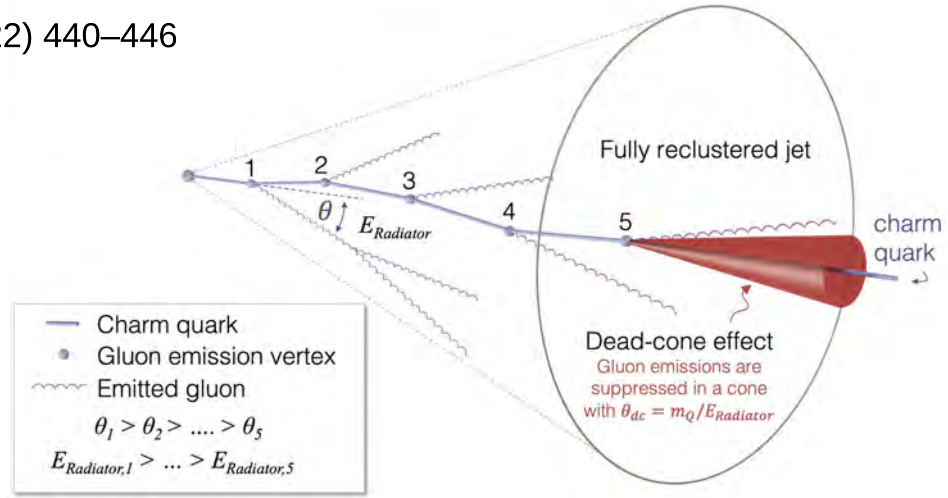
Uncovering the QCD dead cone effect

ALICE, Nature 605 (2022) 440–446

Gluon radiation is suppressed for angles

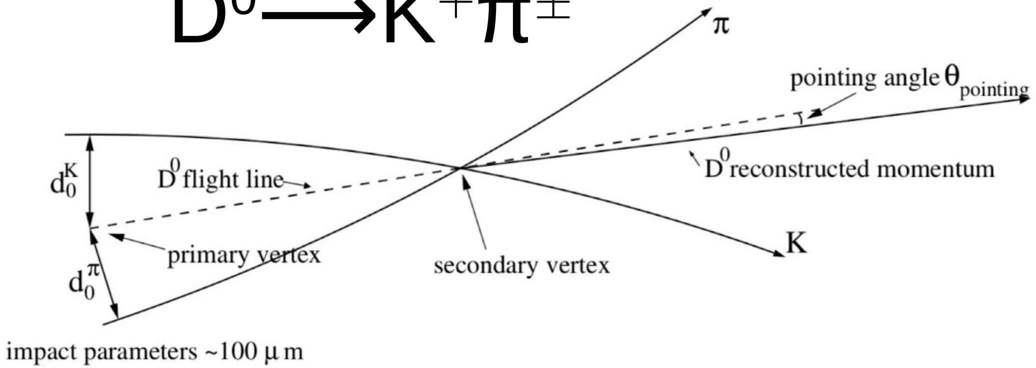
$$\theta_{gluon} < m/E_{radiator}$$

J. Phys. G17 (1991) 1602–1604

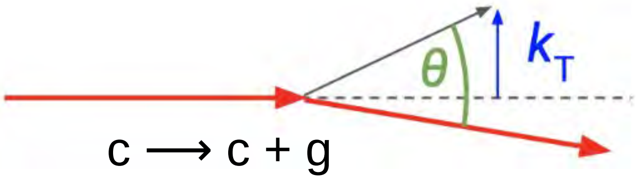


- c,b quarks from hard-scattering radiate, hadronize and decay
- D^0 from c fragmentation from:

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

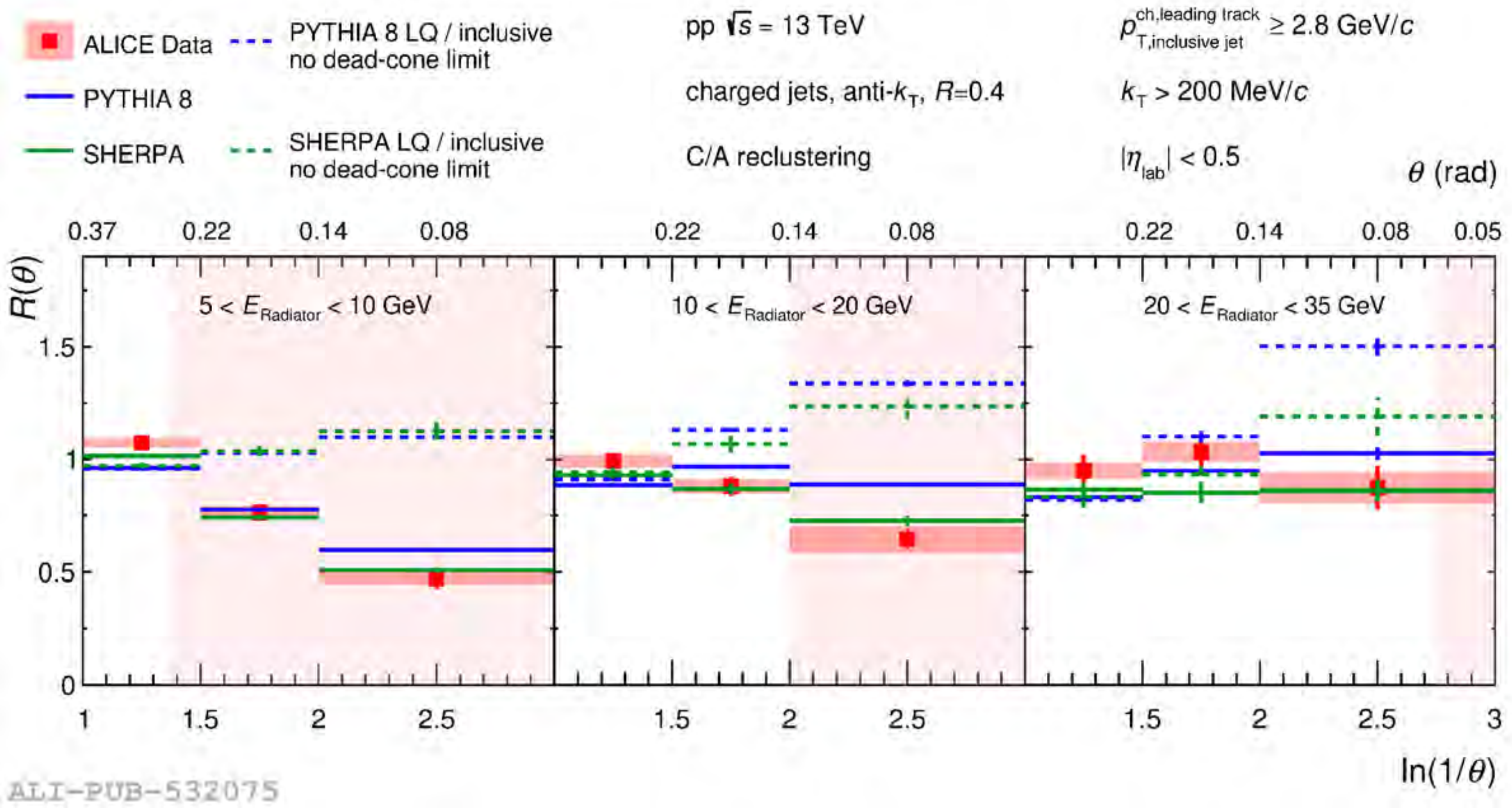


- Following the branch with D^0 coincides with the hadest branch in 99% cases
- Select splittings with $k_T > 200$ MeV
- Inclusive radiator same energy



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

$$R(\theta) = \frac{1}{N^{\mathrm{D^0\,jets}}} \frac{\mathrm{d}n^{\mathrm{D^0\,jets}}}{\mathrm{d}\ln(1/\theta)} \Big/ \frac{1}{N^{\mathrm{inclusive\,jets}}} \frac{\mathrm{d}n^{\mathrm{inclusive\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg|_{k_{\mathrm{T}}, E_{\mathrm{Radiator}}}$$

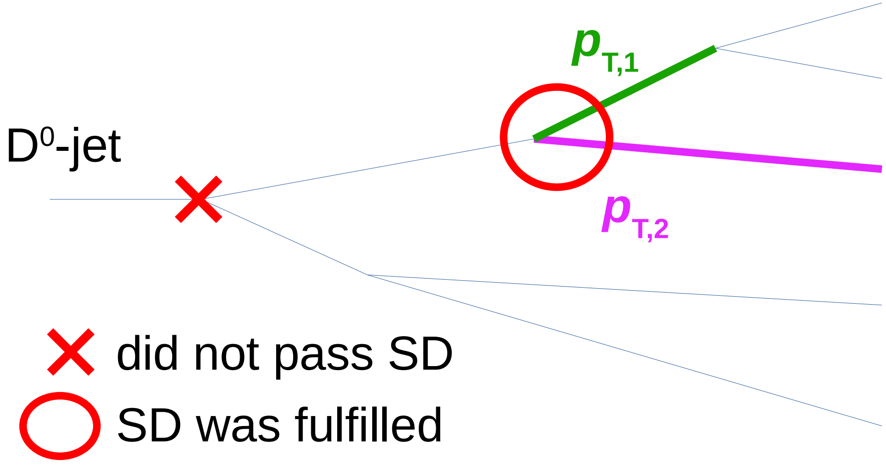
$$\theta_{\mathrm{gluon}} < m/E_{\mathrm{radiator}}$$

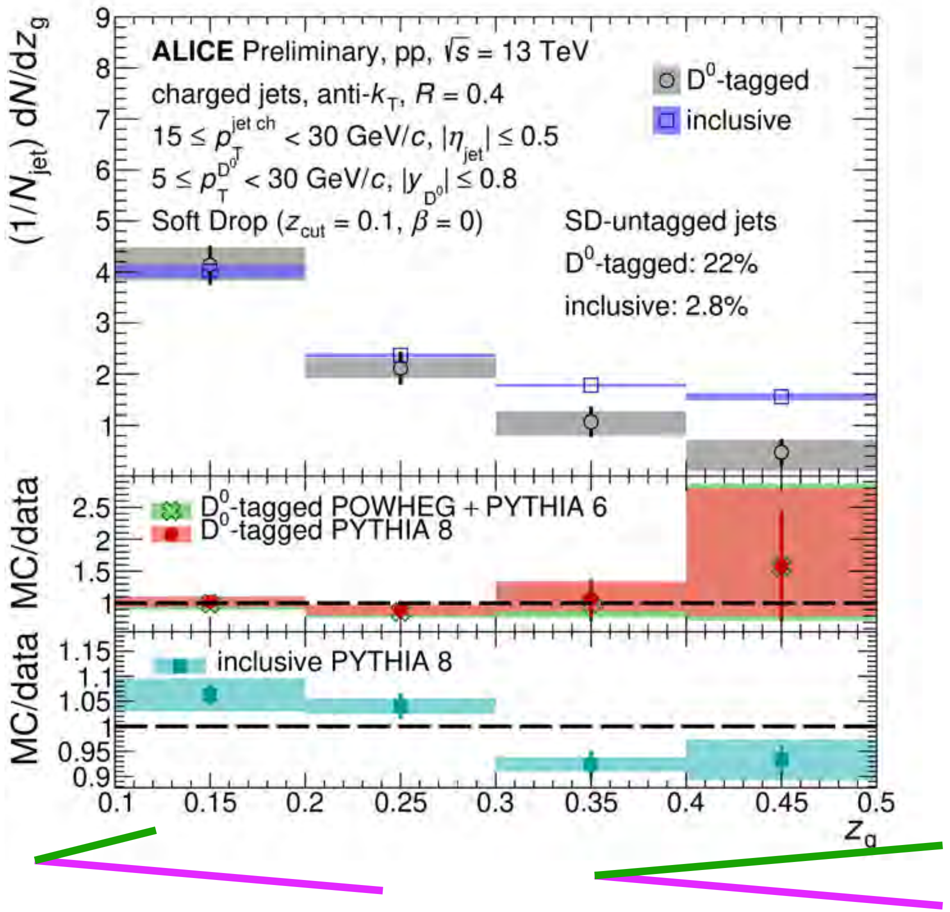
Momentum ballance of pQCD splittings

Soft-Drop (SD) grooming

- removal of soft radiation
- isolation of hard splittings

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



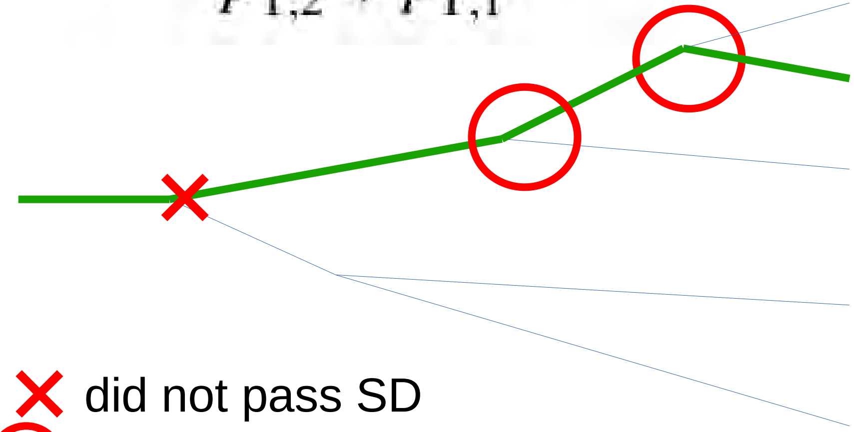


Fewer symmetric splits for D^0-tagged jets than untagged jets consistent with harder fragmentation

Count hard splits which fulfill SD

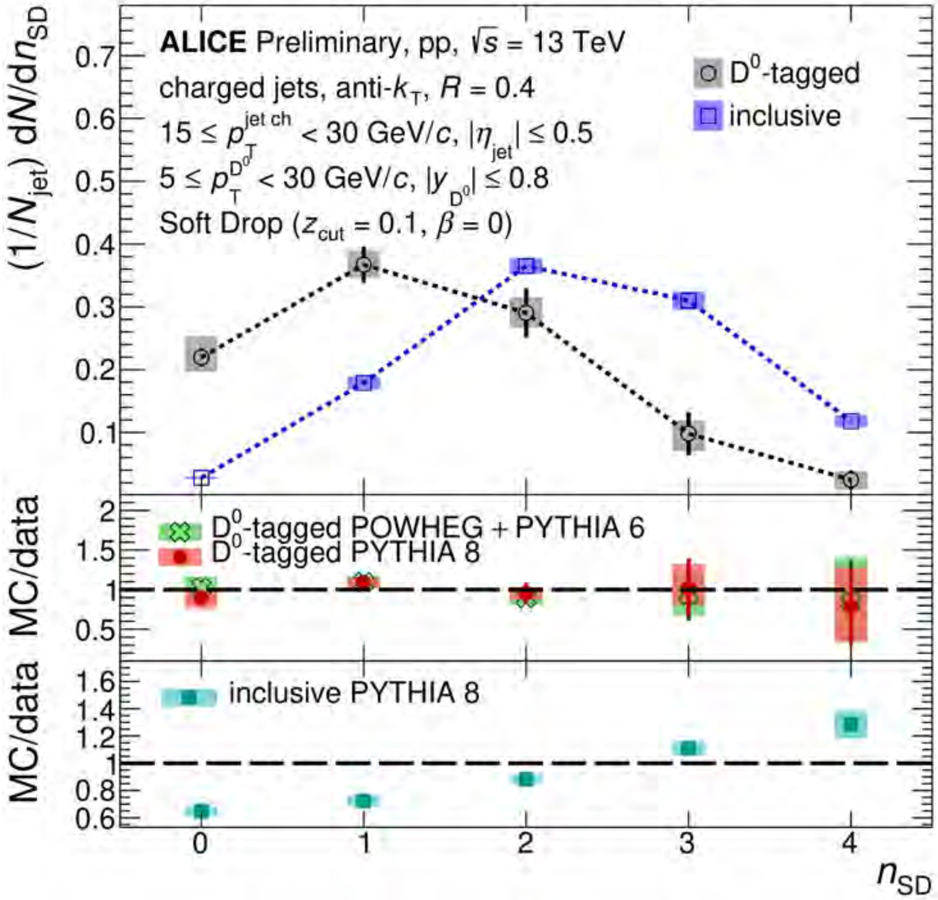
Soft-Drop (SD) grooming

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



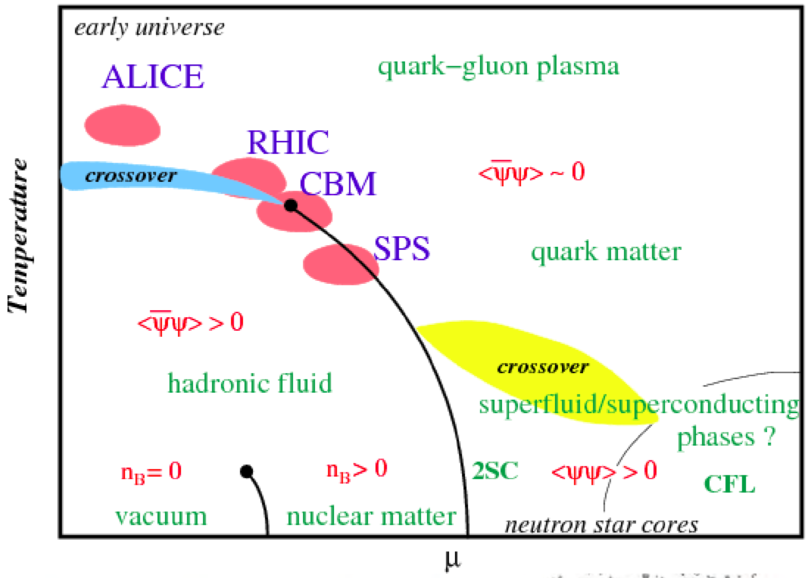
✕ did not pass SD

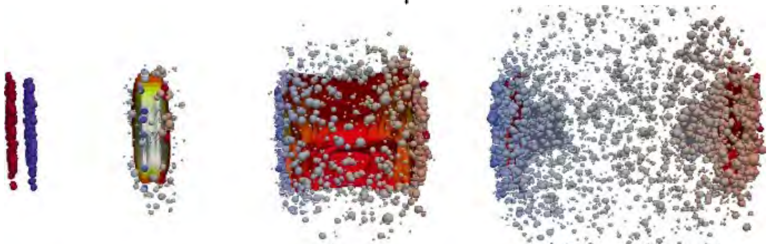
◯ SD was fulfilled



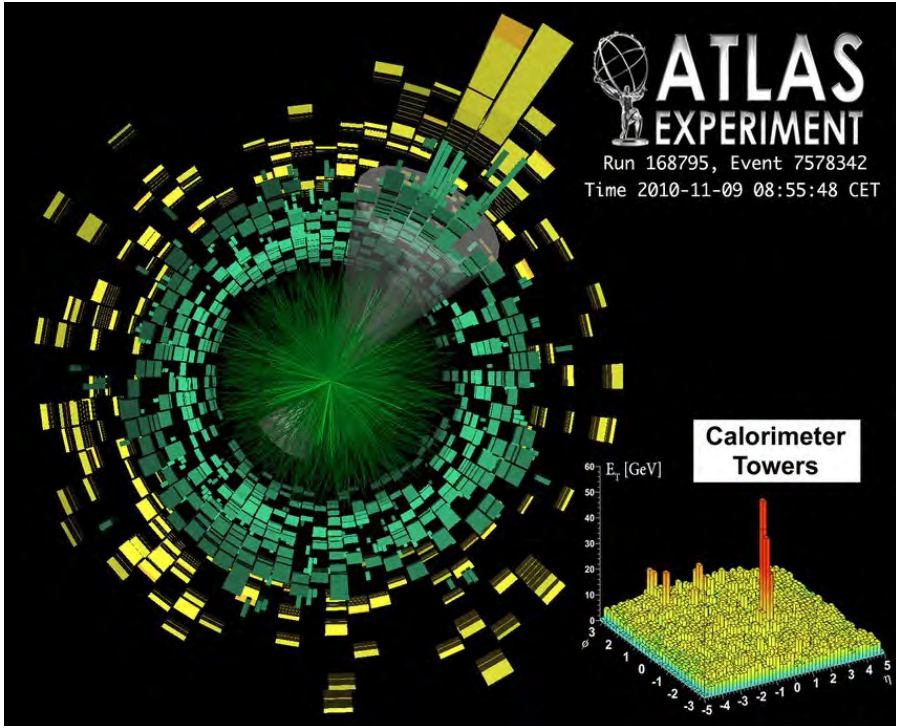
Fewer SD emissions in the D0-tagged jets compared to inclusive jets : consequence of both color factors and mass effects

Jets as a probe of QCD matter





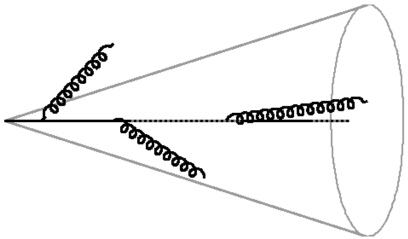
Bernhard, J.E. arXiv:1804.06469



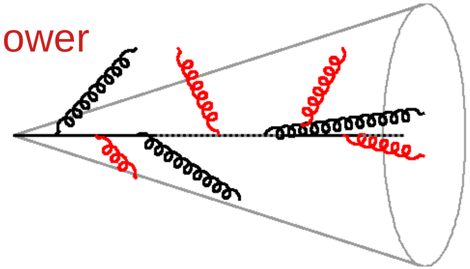
- Processes with high-Q^2 transfer occur early
- Medium created in heavy-ion collision dissipates energy of jet shower

Jet quenching observables

in-vacuum shower



in-medium shower

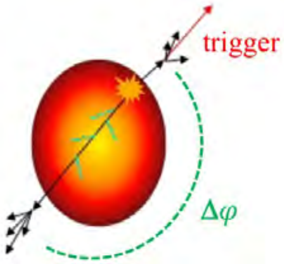


- **Yield suppression relative to min. bias pp** → energy transport out-of-cone

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

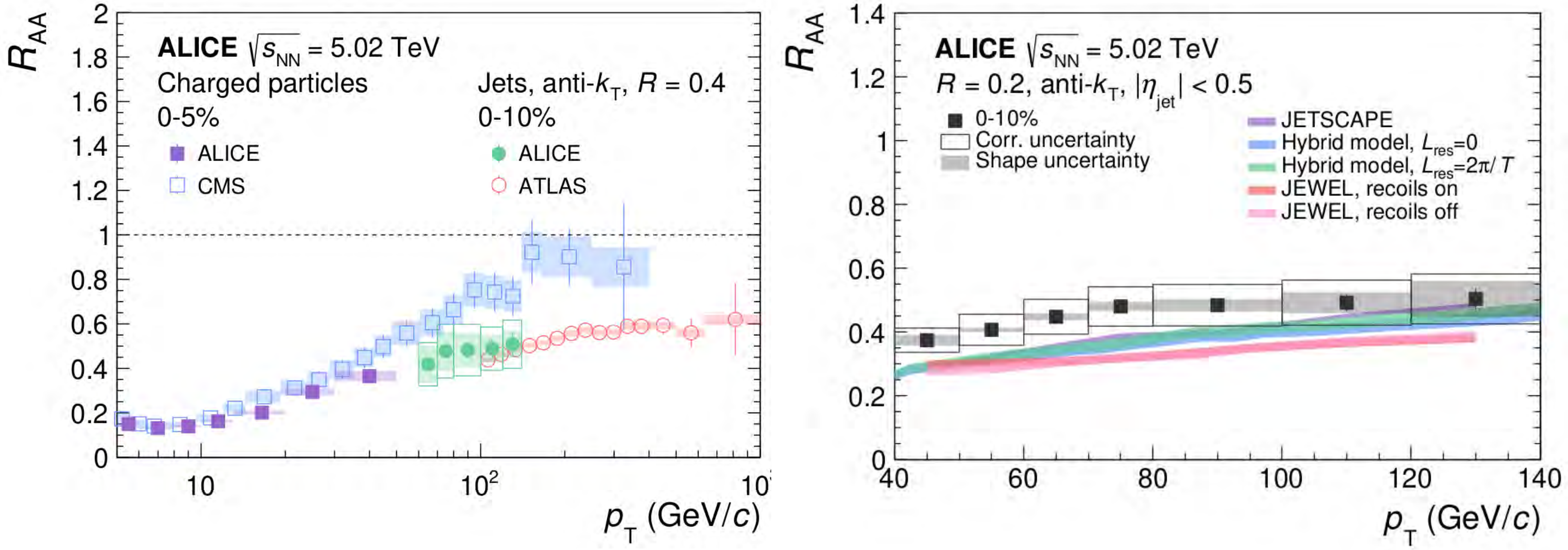
- **Jet substructure modification**
- **Jet deflection** → dijet acoplanarity

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



Suppression of hadrons and jes

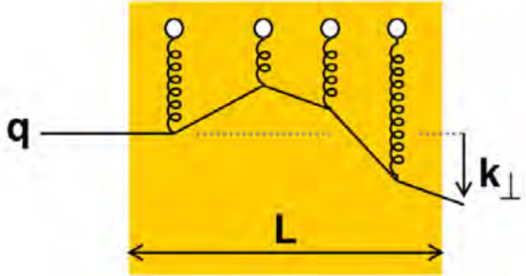
arXiv:2211.04384



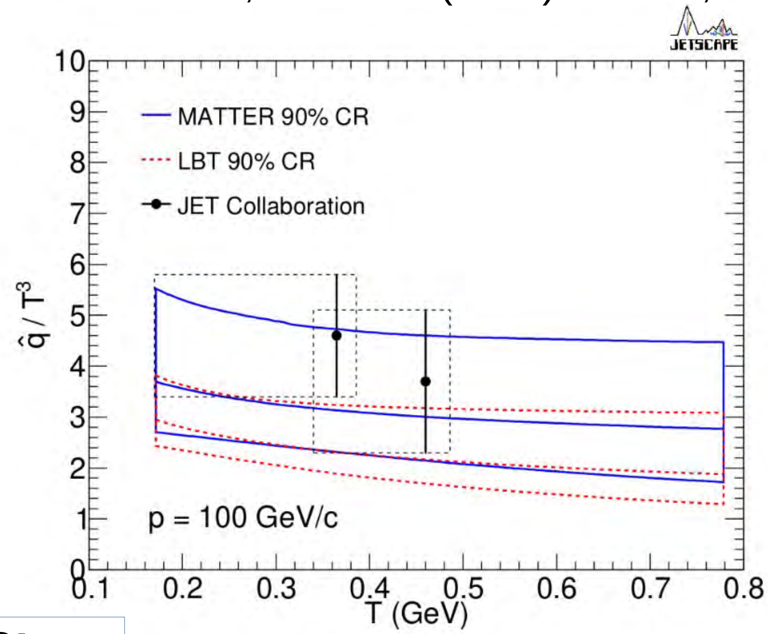
- Hadrons sensitive to energy loss in the hardest branch of the shower
- Energy loss for jets is the energy radiated out of cone
- Interpretation requires comparison with model

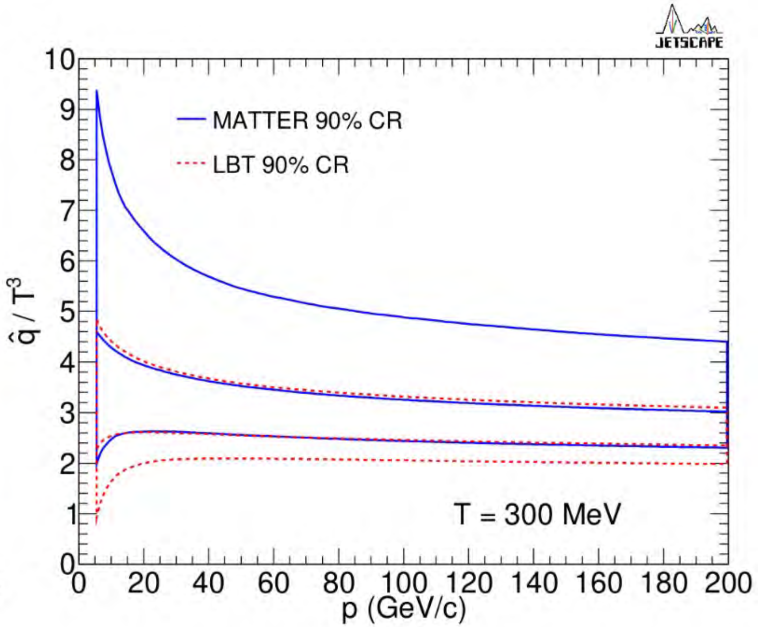
Bayesian estimate of jet transport coefficient q-hat from inclusive hadron suppression

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



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





Radiative energy loss:

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

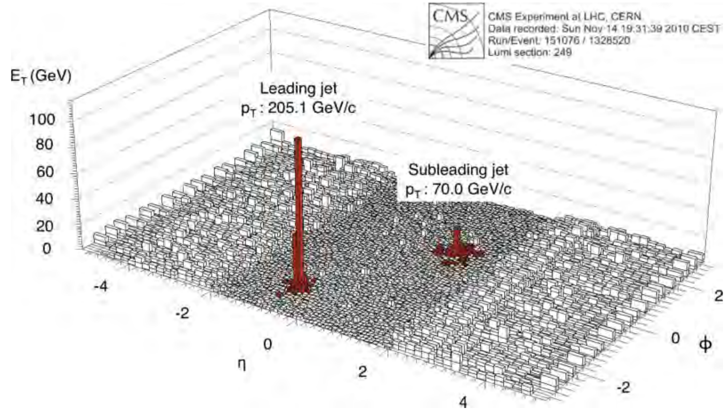
BDMPS, Nucl. Phys. B483 (1997) 291

$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \mathrm{GeV}^2/\mathrm{fm} \ \text{at} \ \begin{matrix} \mathrm{T{=}370\ MeV} \\ \mathrm{T{=}470\ MeV} \end{matrix}$$

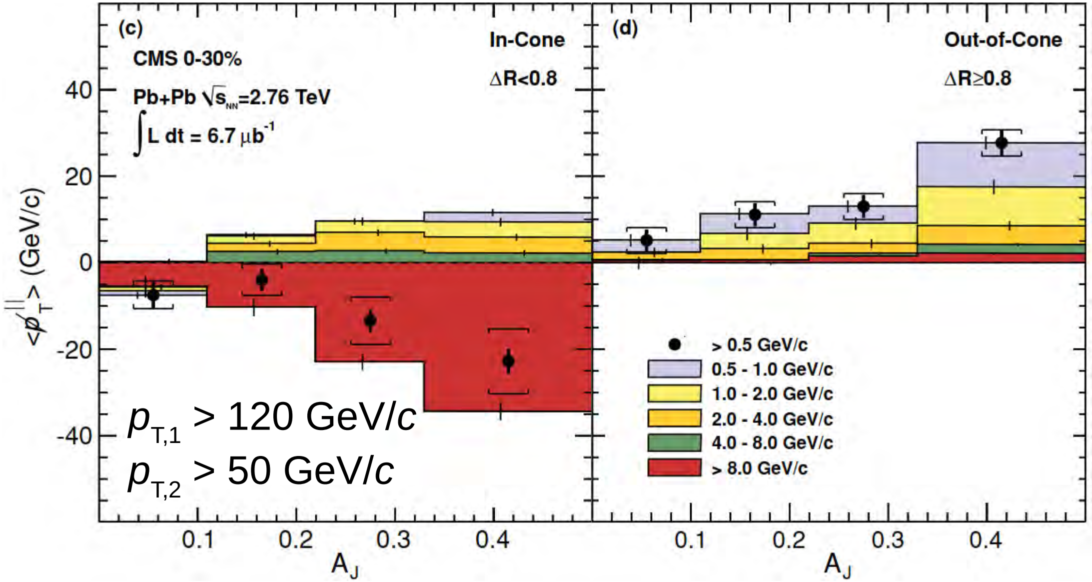
at an initial time $\tau_0 = 0.6\ \mathrm{fm}/c$

Momentum ballance measurement by CMS

CMS, PRC 84 (2011) 024906



in jet cones out of jet cones

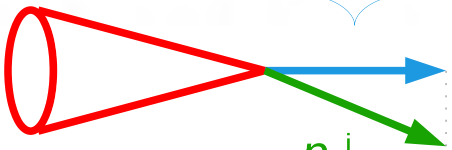


Jet momentum imballance

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

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

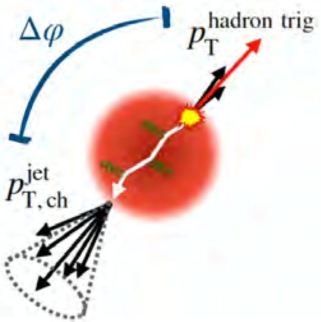
Leading jet



p_T^i

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

Hadron-jet acoplanarity

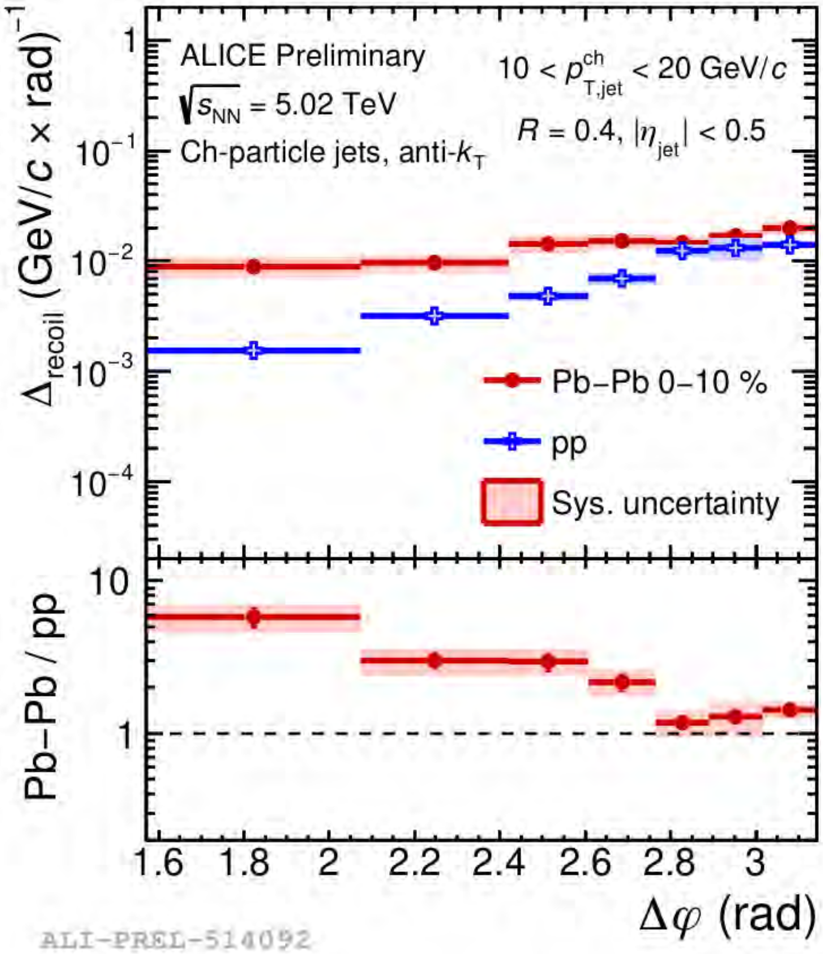


Data driven removal of uncorrelated jet yield

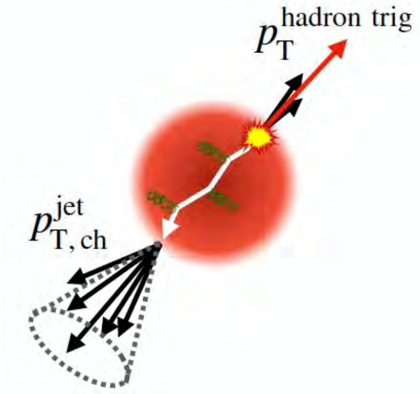
$$\Delta_{recoil}(p_{T,jet},\Delta\varphi) = \frac{1}{N_{trig}} \frac{d^2N_{jet}}{dp_{T,jet}d\Delta\varphi}\Bigg|_{p_T^{trig}\in TT_{sig}} - \frac{1}{N_{trig}} \frac{d^2N_{jet}}{dp_{T,jet}d\Delta\varphi}\Bigg|_{p_T^{trig}\in TT_{ref}}$$

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

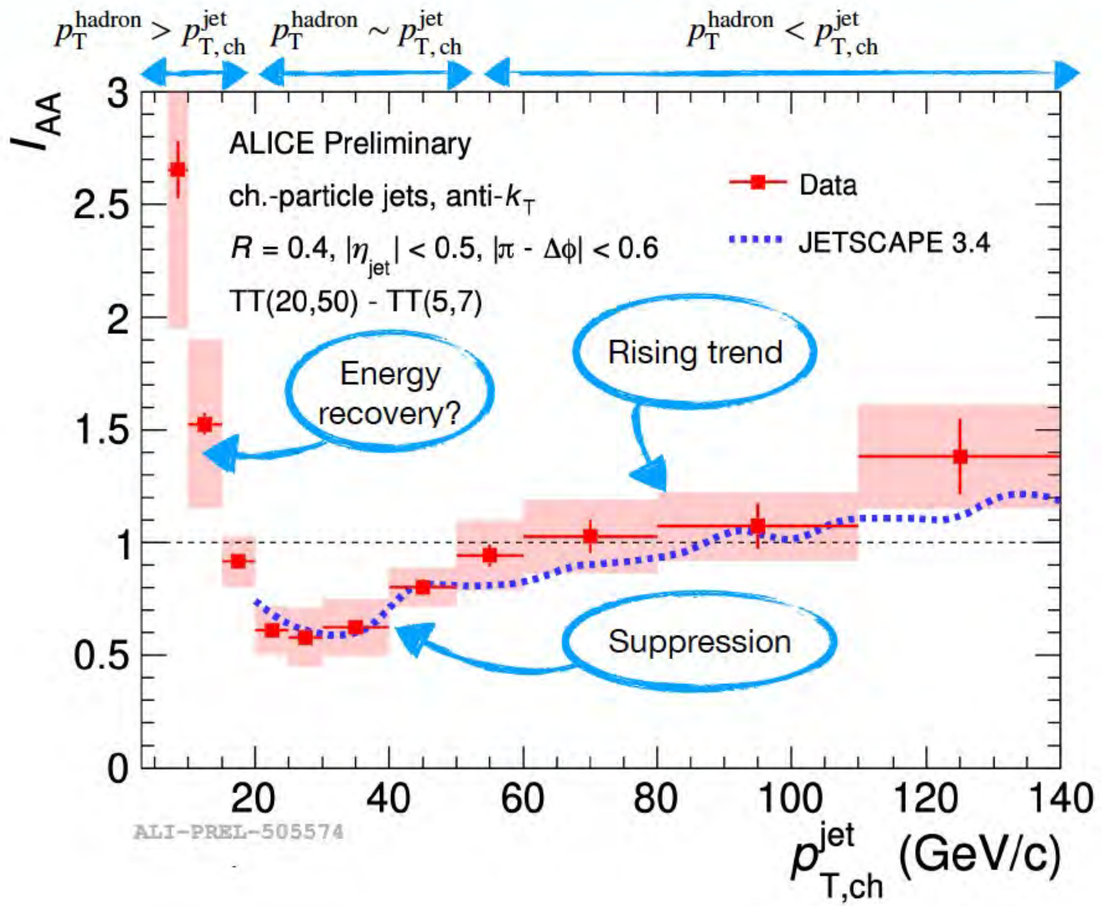


Recoil jet energy redistribution

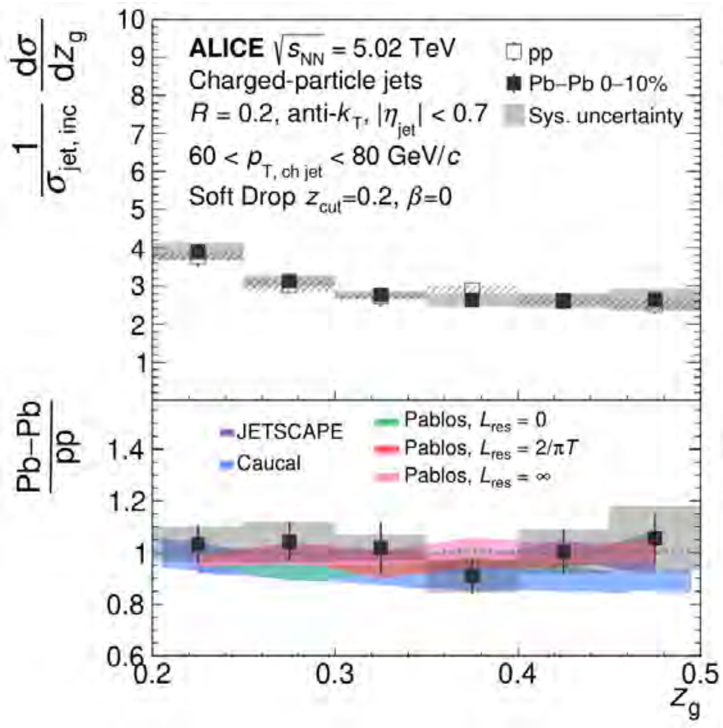


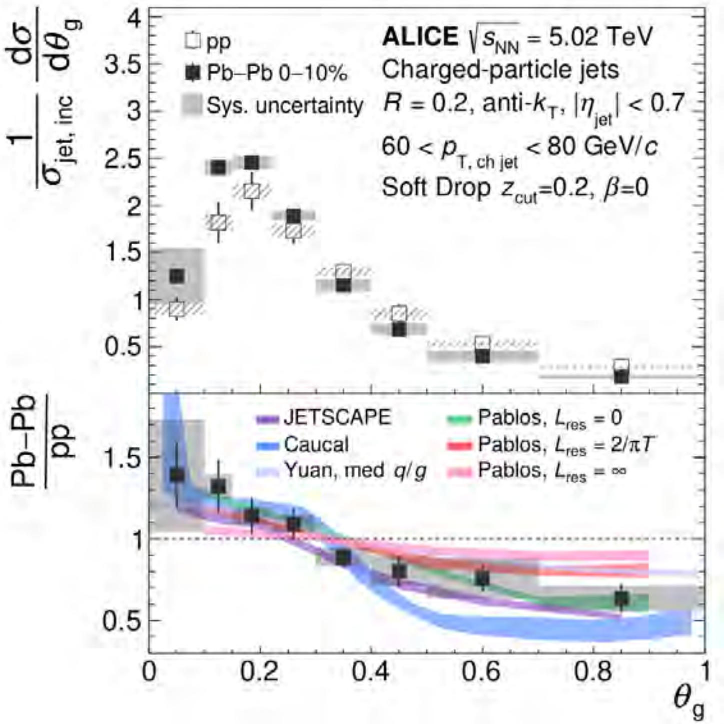
$$I_{AA} \equiv \frac{\Delta_{\text{recoil}}(\text{Pb}-\text{Pb})}{\Delta_{\text{recoil}}(\text{pp})}$$

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



Substructure of jets in PbPb





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

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

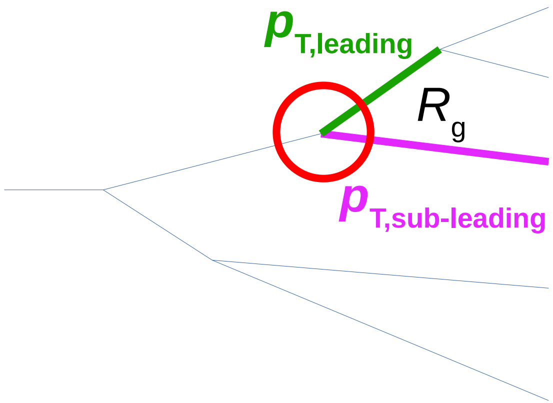
ALICE, PLB 128 (2022) 102001

arXiv:2211.04384

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

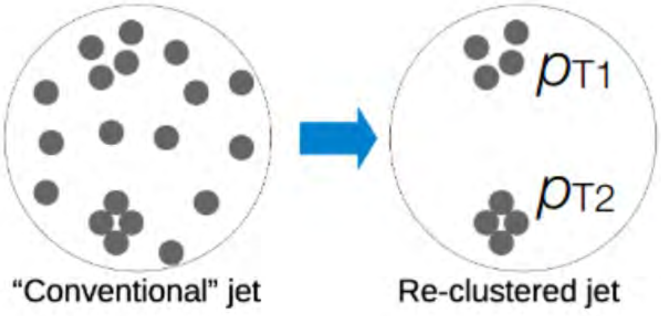
1) stronger suppression of wide fragmentation patterns

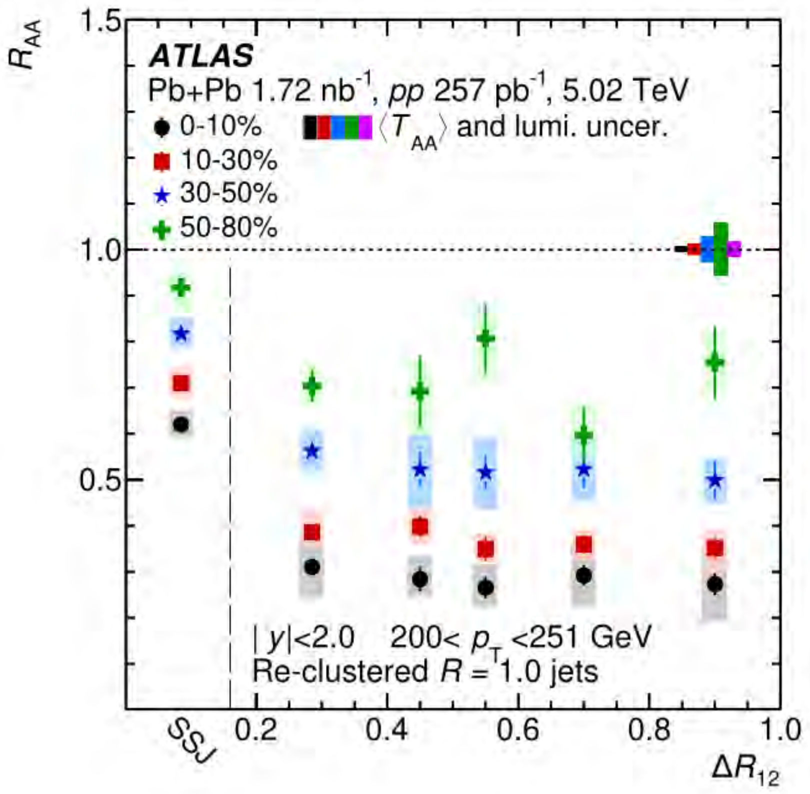
2) little to no modification of momentum splitting



Substructure of jets in ATLAS

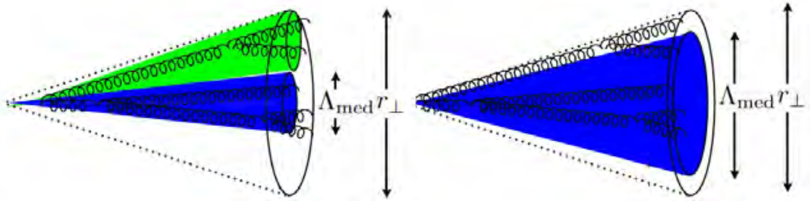
ATLAS, arXiv:2301.05606





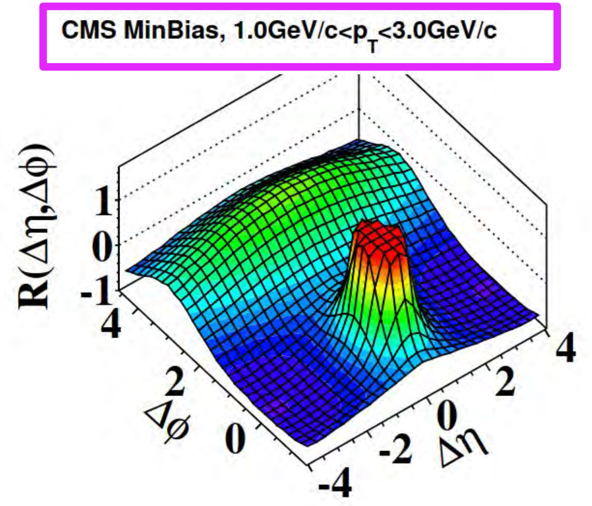
- Reconstruct first R = 0.2 jets (p_{Tjet} > 35 GeV/c)
- Recluster constituents of these jets to R = 1 jets
- Sort jets according to subjet angular distances
- Jets with substructure are more suppressed

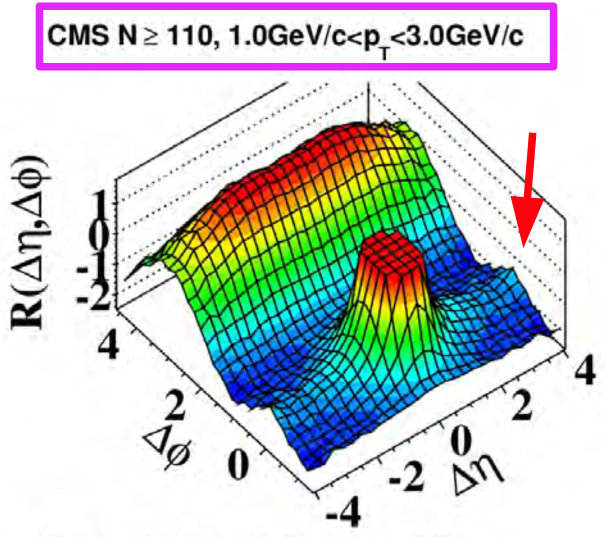
SSJ = jet with a single sub-jet



Casalderrey-Solana et al., arXiv:1210.7765v2

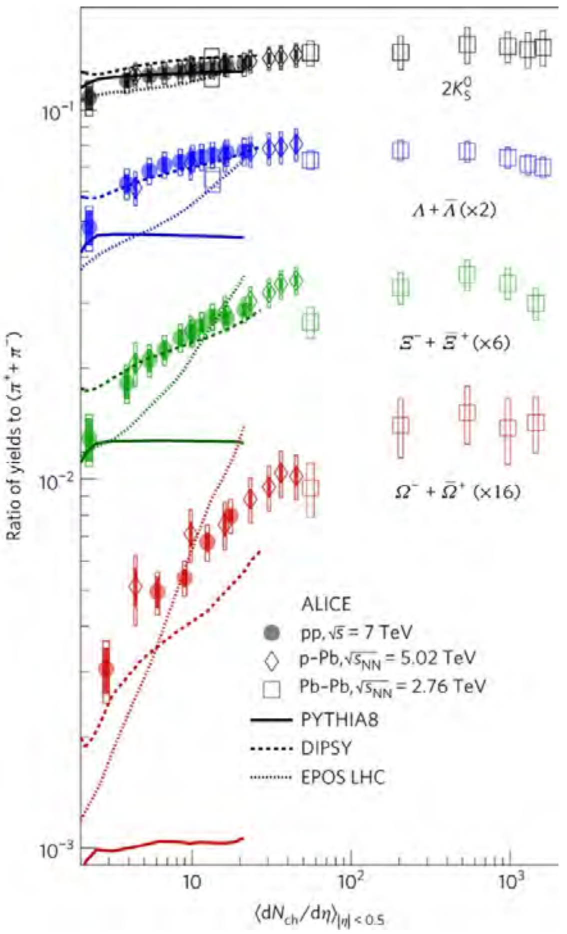
QGP in small collision systems?





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

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

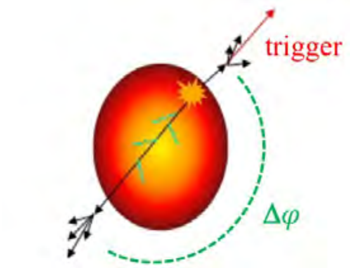
measurement of inclusive suppression R_{AA} requires Glauber scaling →

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

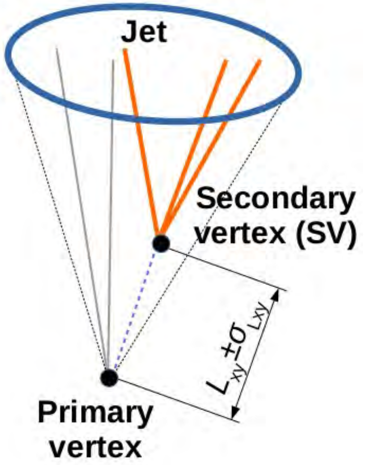
- Glauber model does not account for conservation laws, geometry information smeared by fluctuations

- not defined in high-multiplicity pp collisions

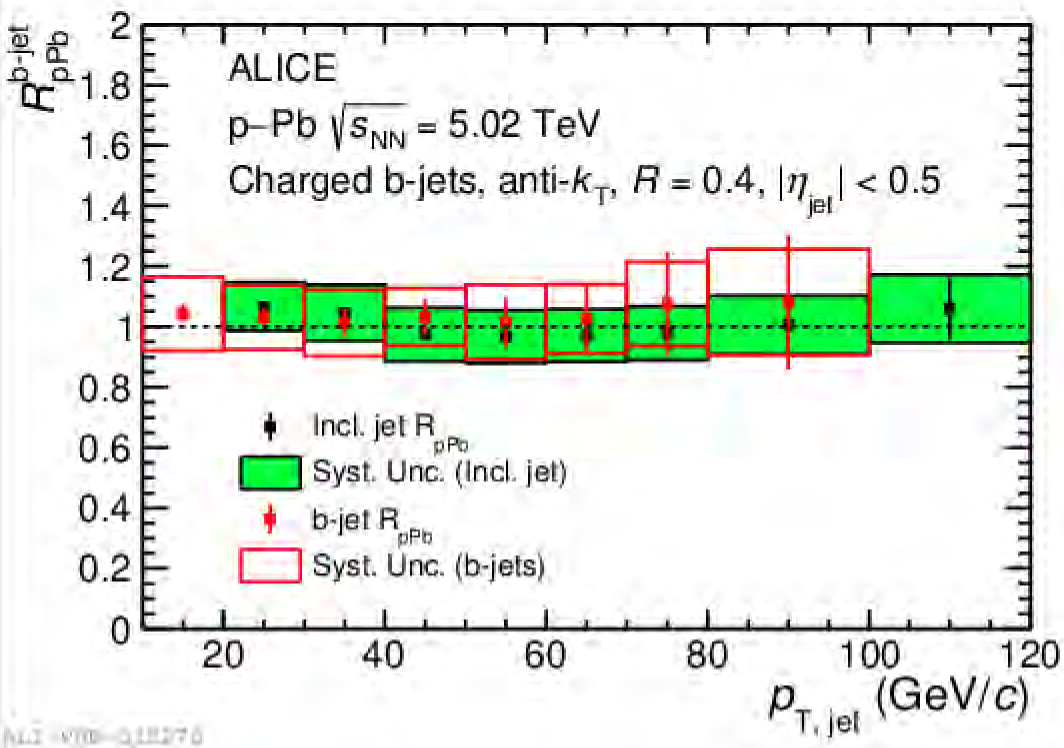
- **Jet substructure modification**
- **Jet deflection** → dijet acoplanarity



Production of jets associated with b quark fragmentation in p+Pb and p+p collisions



ALICE, JHEP 01 (2022) 178



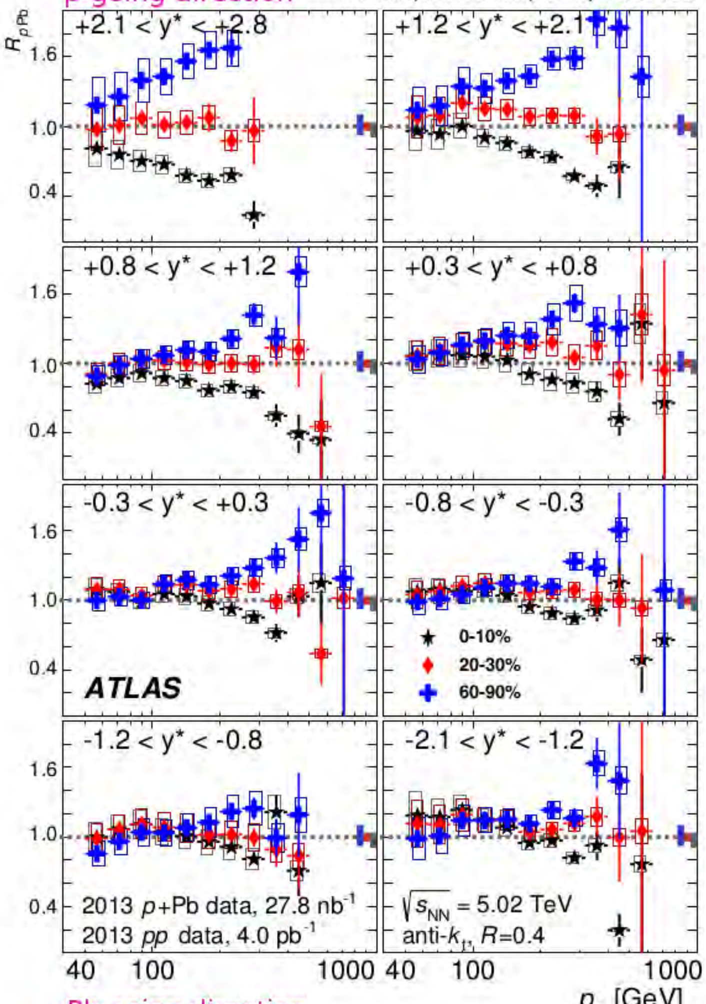
- Nuclear modification factor compatible with 1
- No sign of mass dependent effects

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

Jet R_{pPb} by ATLAS

p-going direction

ALTAS, PLB 748 (2015) 392-413



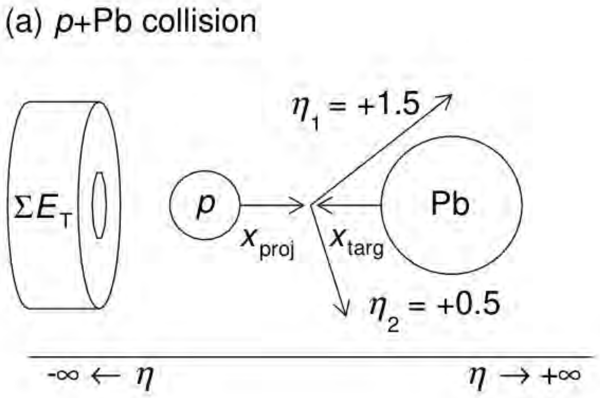
Pb-going direction

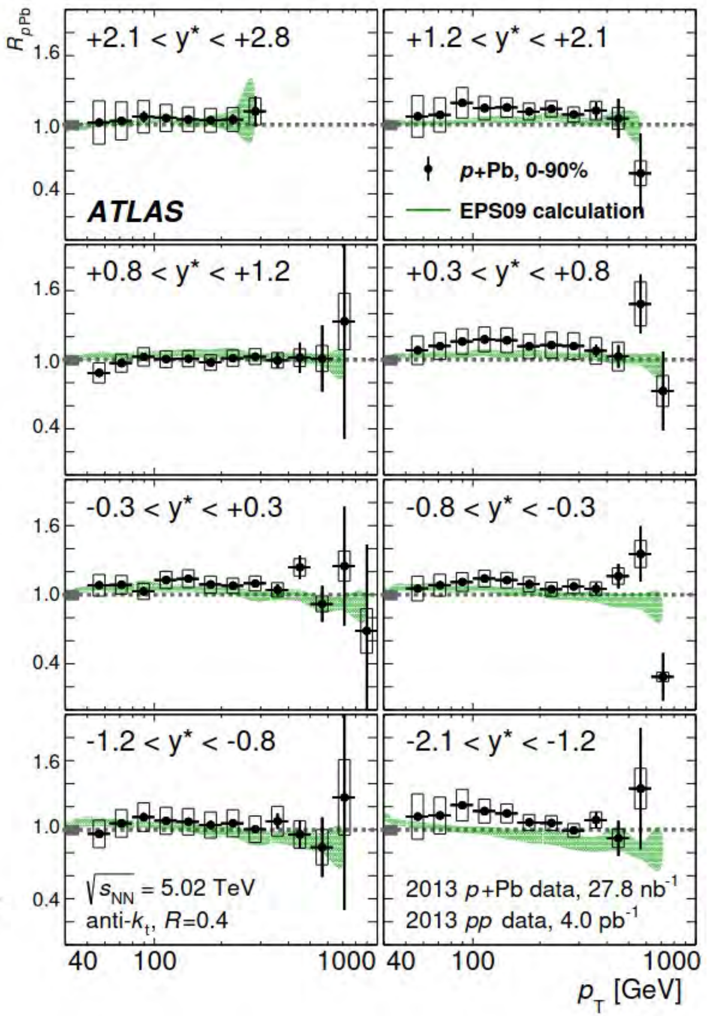
p-Pb 0-90%

p-Pb 0-10%

p-Pb 20-30%

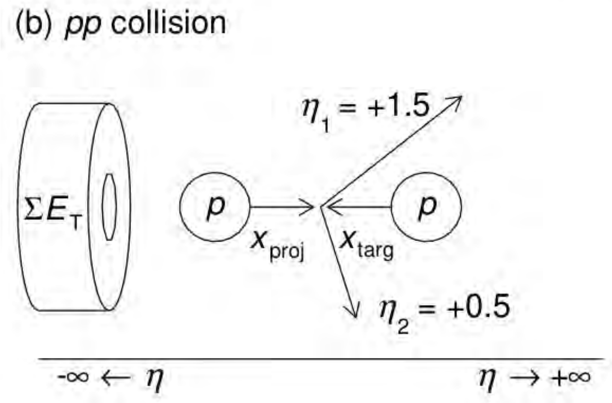
p-Pb 60-90%





ALTAS, PLB 748 (2015) 392

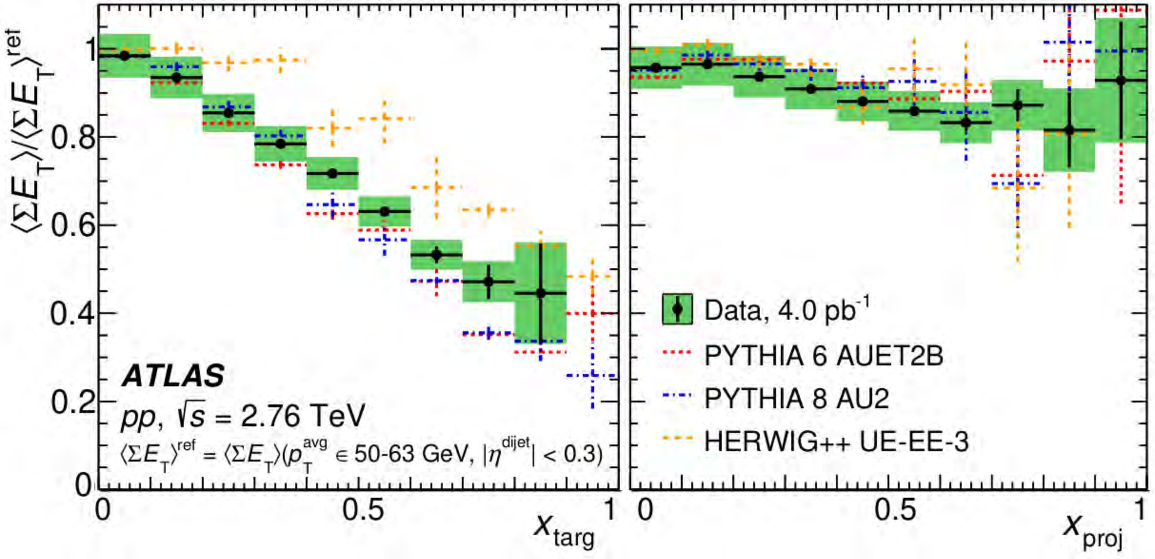
Corrlation of hard processes and soft particle production in pp by ATLAS



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

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

ATLAS, PLB 756 (2016) 10

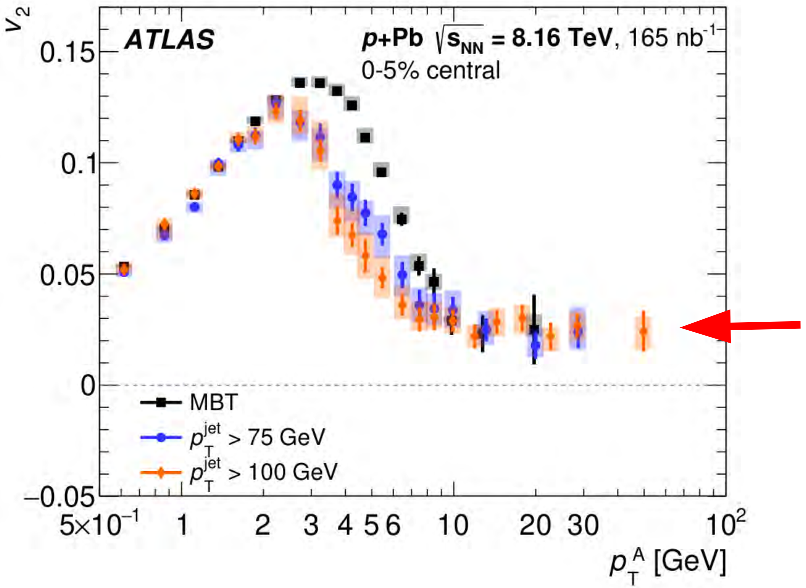


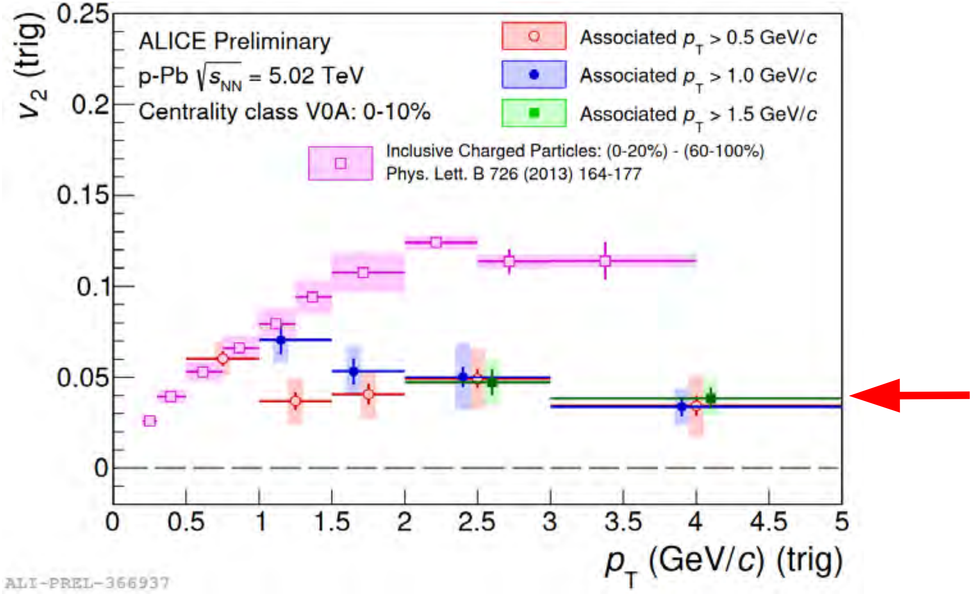
Hard scattering involving large x parton in Pb ⇒

The beam remnant has less longitudinal energy ⇒

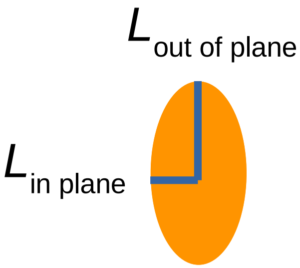
Reduction of E_T at large η

Flow of jet fragments in p-Pb

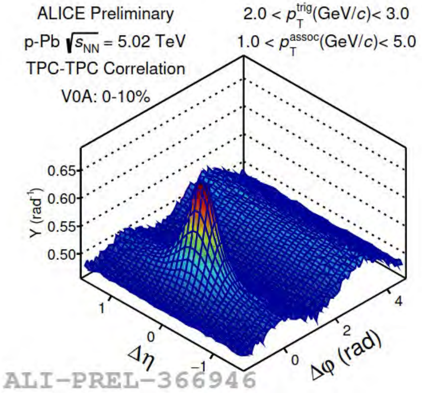


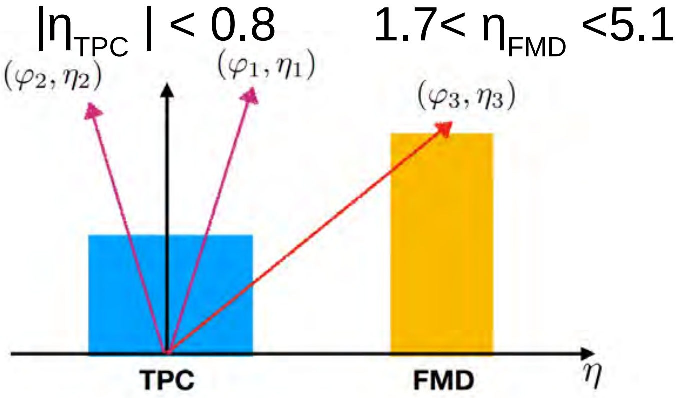


ATLAS, Eur. Phys. J. C 80 (2020) 73



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





Prospects for OO run at LHC

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

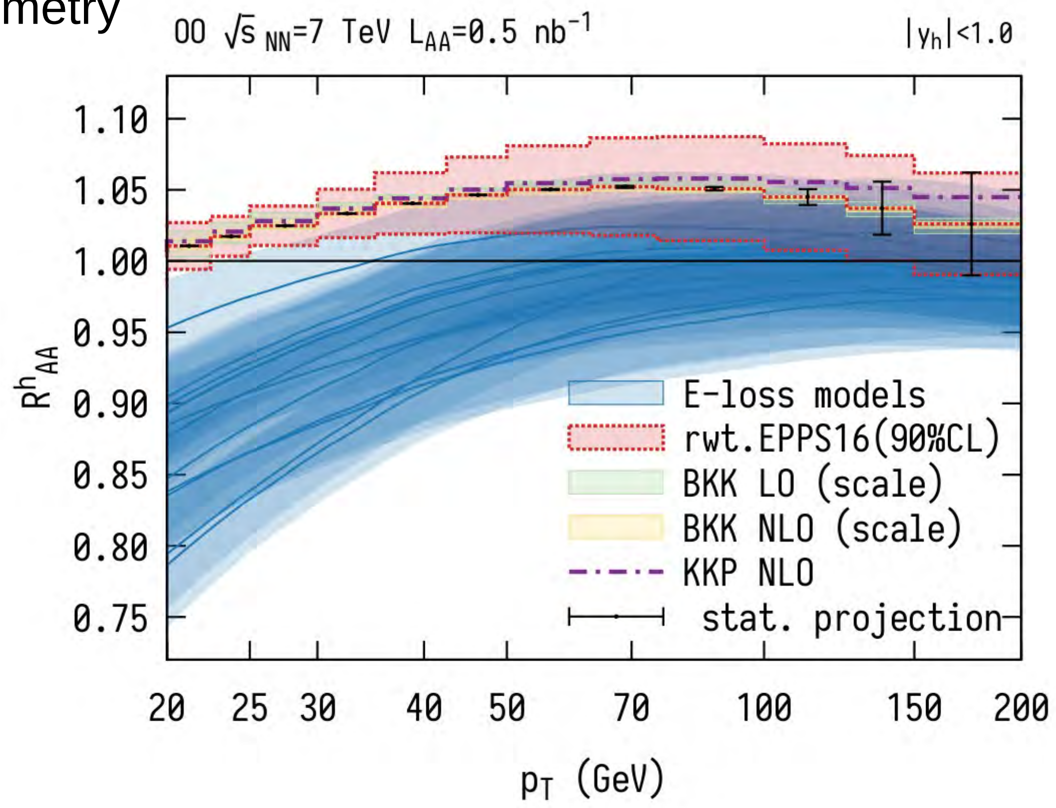
$$R^{h,j}_{AA}(p_T, y) = \frac{1}{\langle T_{AA} \rangle} \frac{(1/N_{ev})\, dN^{h,j}_{AA}/dp_T dy}{d\sigma^{h,j}_{pp}/dp_T dy}$$

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

$\Rightarrow$ MB provides better precision

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

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



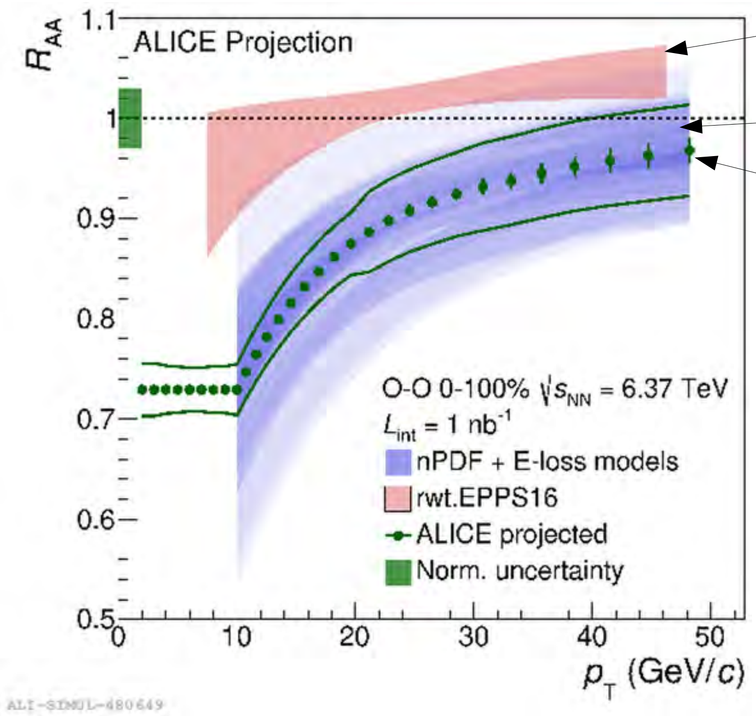
Projection of hadron R_{AA} for min bias OO

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

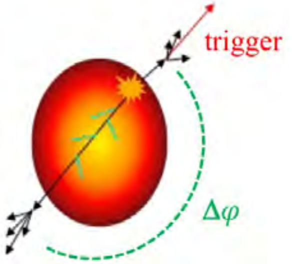
Calculations which assume energy loss models together with nuclear PDFs [Huss et al. arXiv 2007.13754]

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

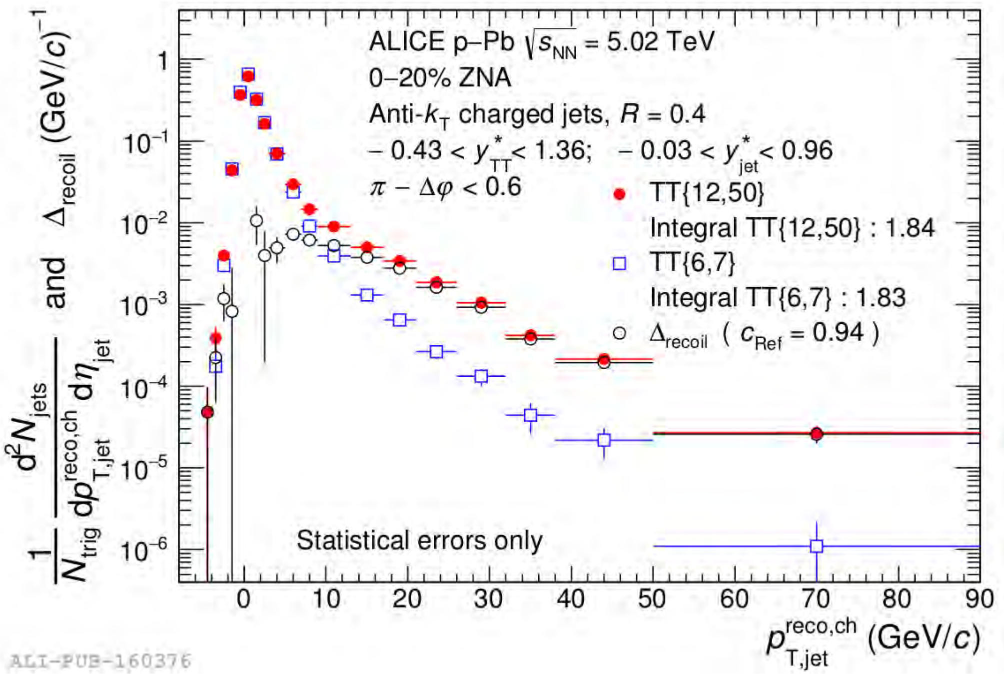
Search for jet quenching in p-Pb with h+jet correlations in ALICE



ALICE, PLB 783 (2018) 95

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

- 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



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

Hadron-jet observables and T_{AA}

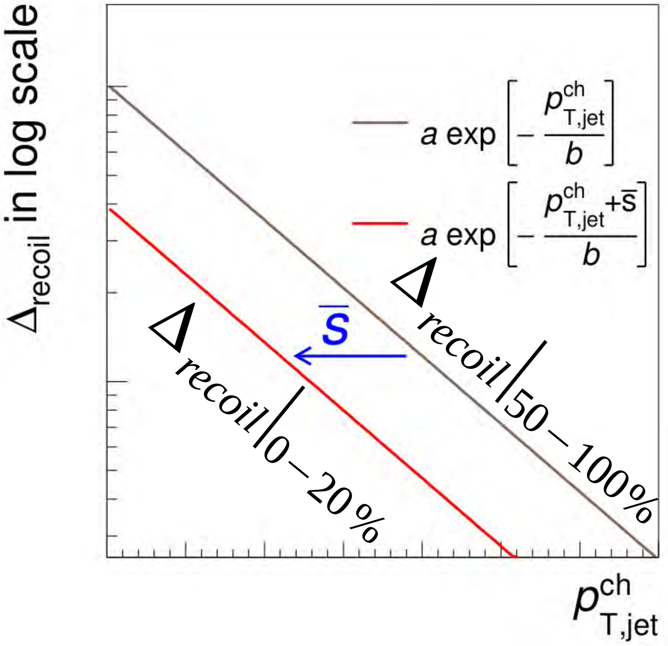
$$\frac{1}{N_{\rm trig}^{\rm AA}} \frac{{\rm d}^2 N_{\rm jet}^{\rm AA}}{{\rm d}p_{\rm T,jet}^{\rm ch}\,{\rm d}\eta_{\rm jet}}\Bigg|_{p_{\rm T,trig}\in{\rm TT}} = \left(\frac{1}{\sigma^{\rm AA\to h+X}} \cdot \frac{{\rm d}^2\sigma^{\rm AA\to h+jet+X}}{{\rm d}p_{\rm T,jet}^{\rm ch}\,{\rm d}\eta_{\rm jet}}\right)\Bigg|_{p_{\rm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

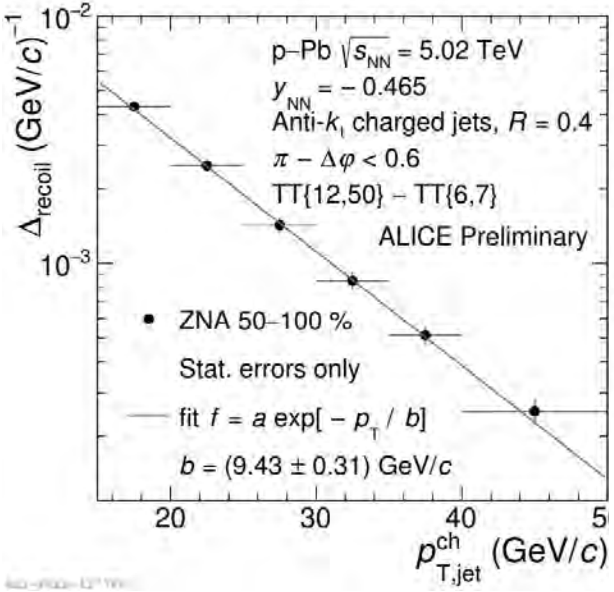
In case of no nuclear effects

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

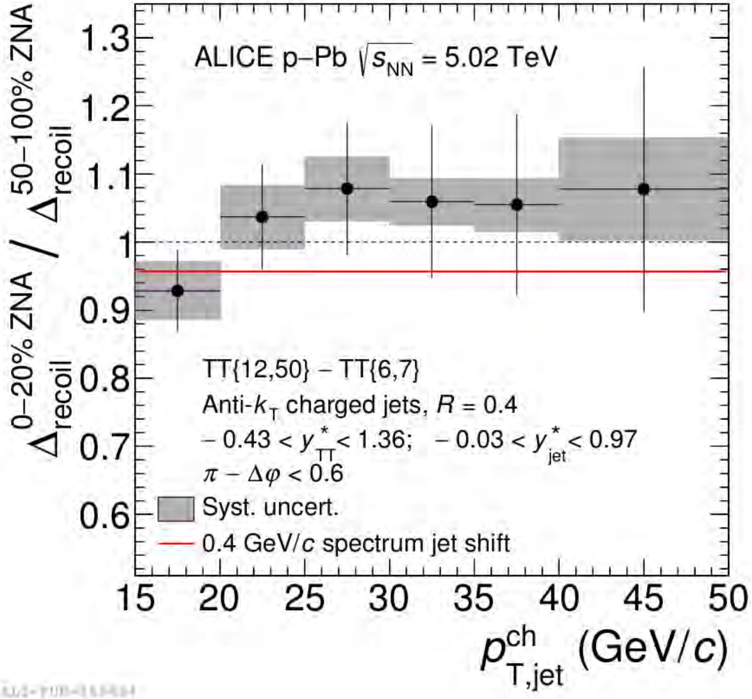
- This coincidence observable is self-normalized, no requirement of T_{AA} scaling
- No requirement to assume correlation between Event Activity and collision geometry

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





ALICE, PLB 783 (2018) 95



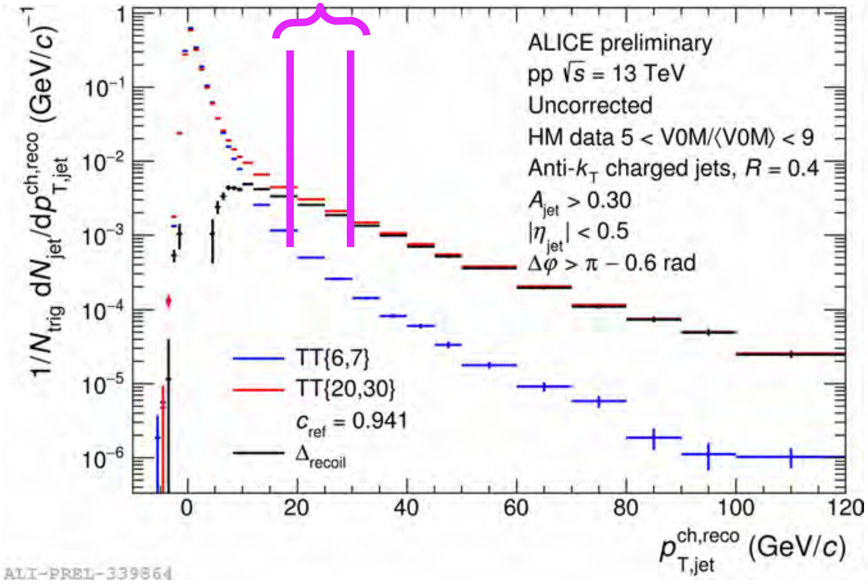
$$\frac{\Delta_{recoil}|_{0-20\,\%}}{\Delta_{recoil}|_{50-100\,\%}} = \exp\left(-\frac{\bar{s}}{b}\right)$$

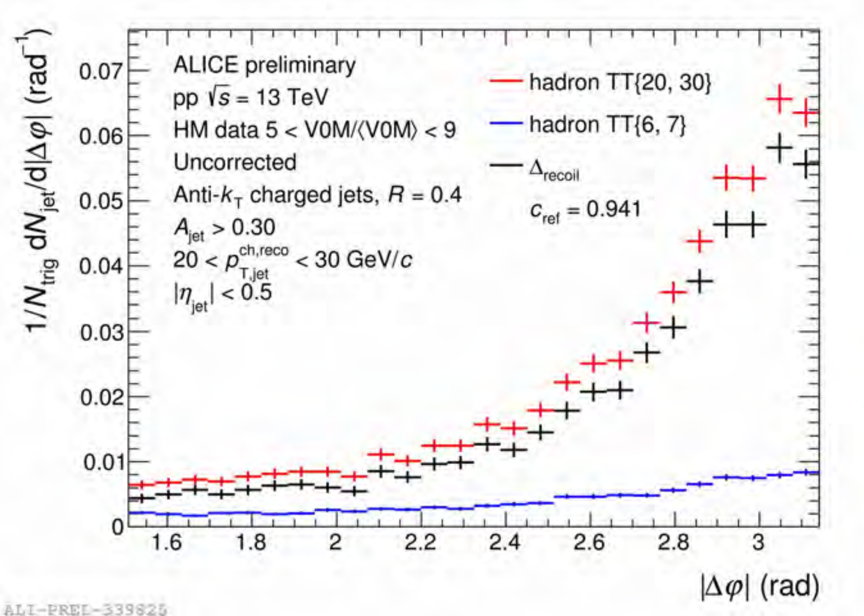
Medium-induced charged energy transport out of R = 0.4 cone is less than 0.4 GeV/c (90% CL)

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

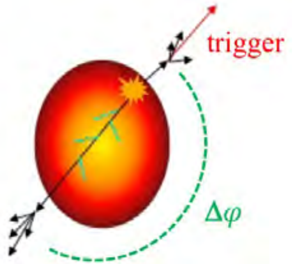
- pp minimum bias (MB)
- pp high-multiplicity (HM) : 5x larger multiplicity in V0 detector w.r.t. MB (0.1% of all events)

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

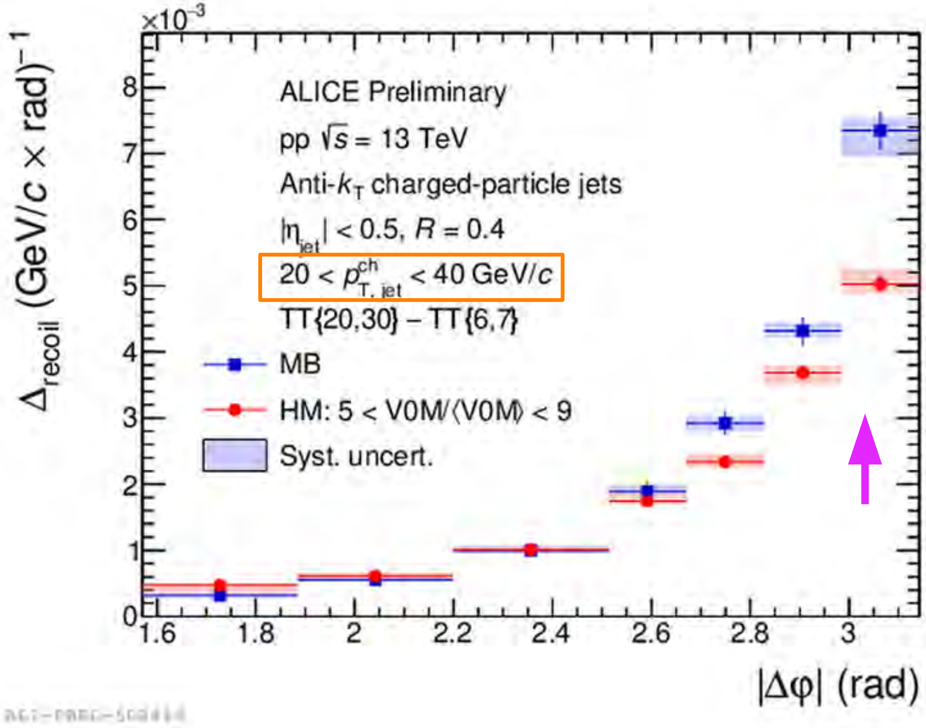


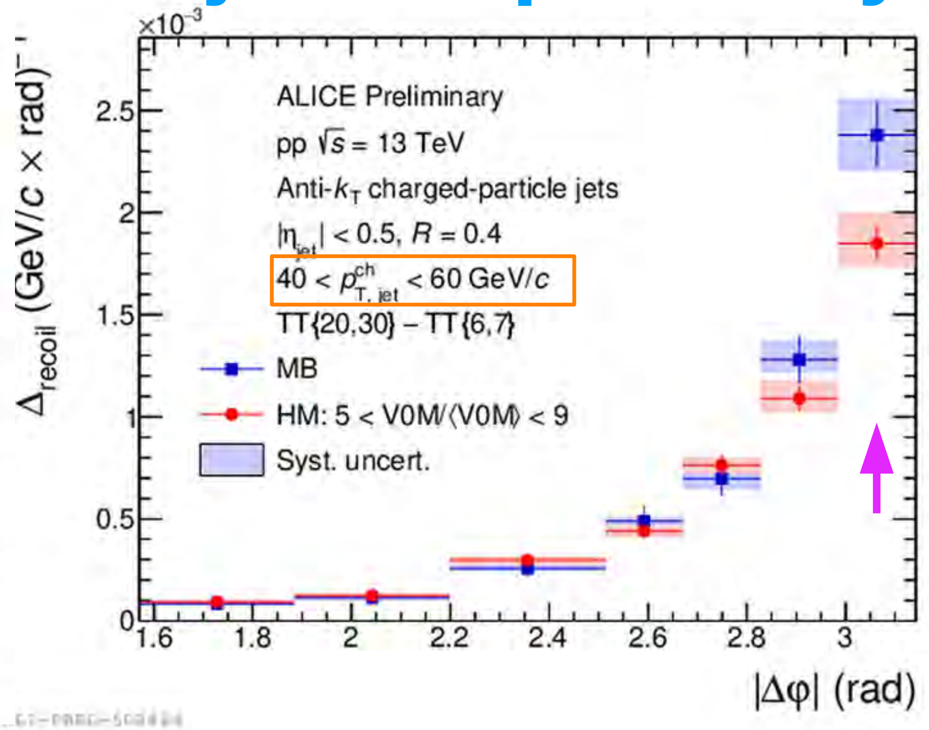


TT{X,Y} means X< $p_{\mathrm{T,trig}}$ < Y GeV/c



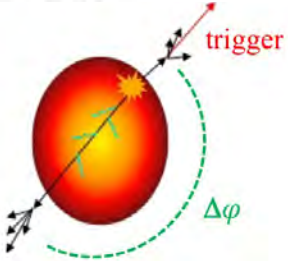
Distributions of hadron-jet acoplanarity





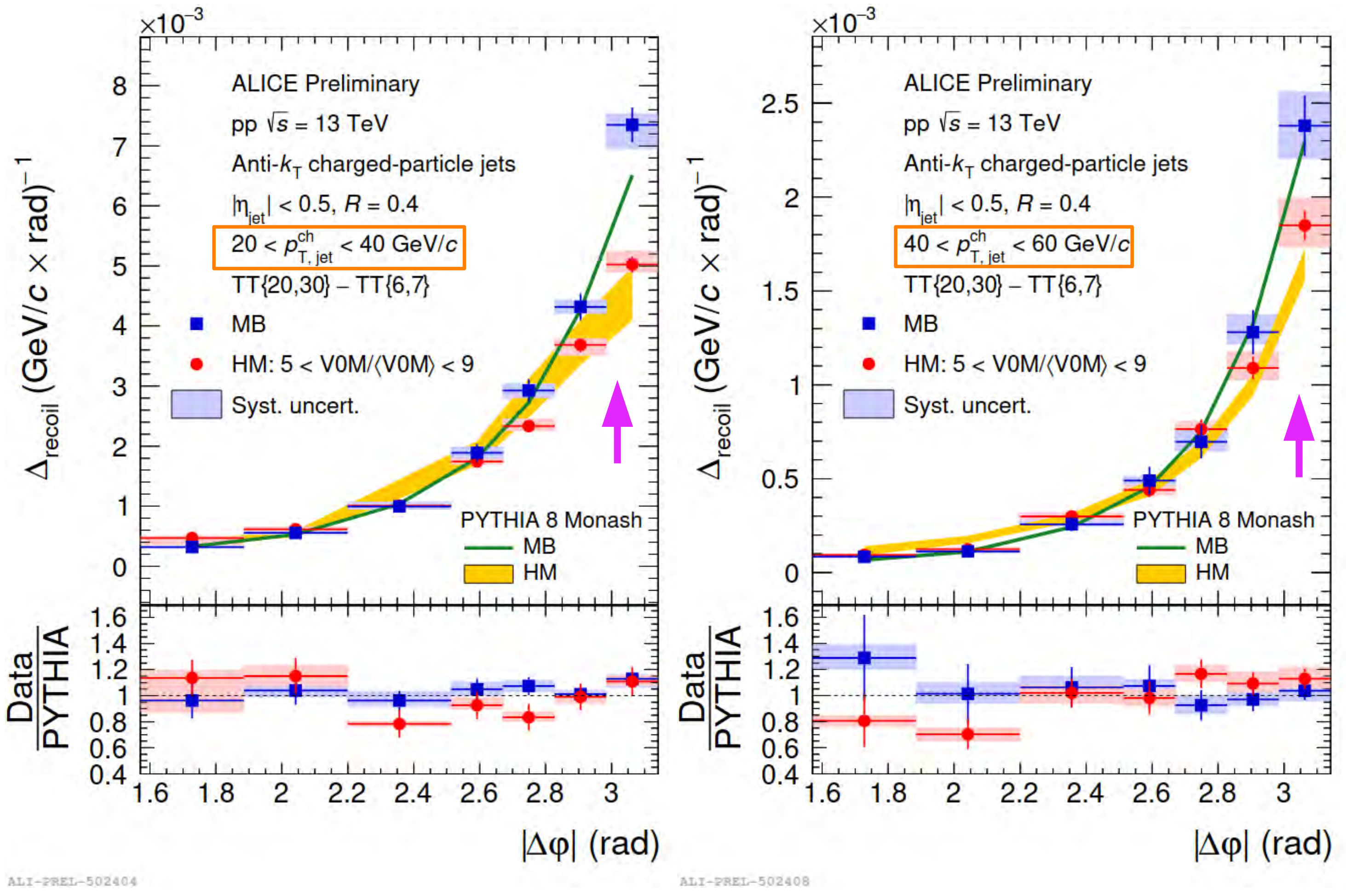
- HM acoplanarity distributions relative to MB
  - suppressed back-to-back correlation
  - broader

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

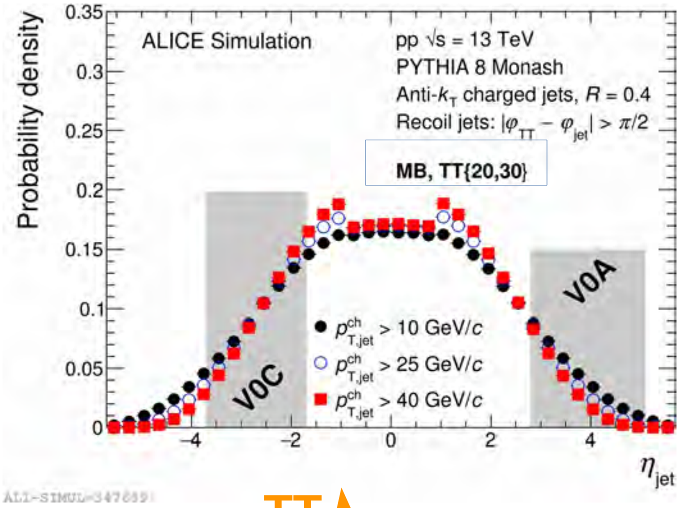


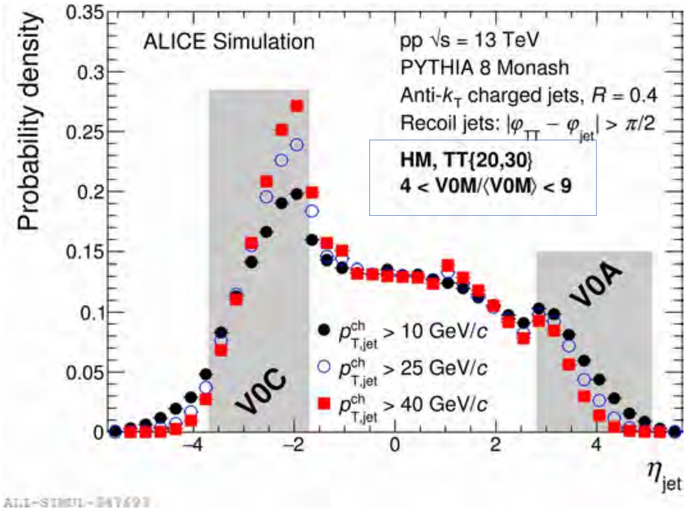
Quantitative comparison to PYTHIA 8 Monash shows similar suppression pattern

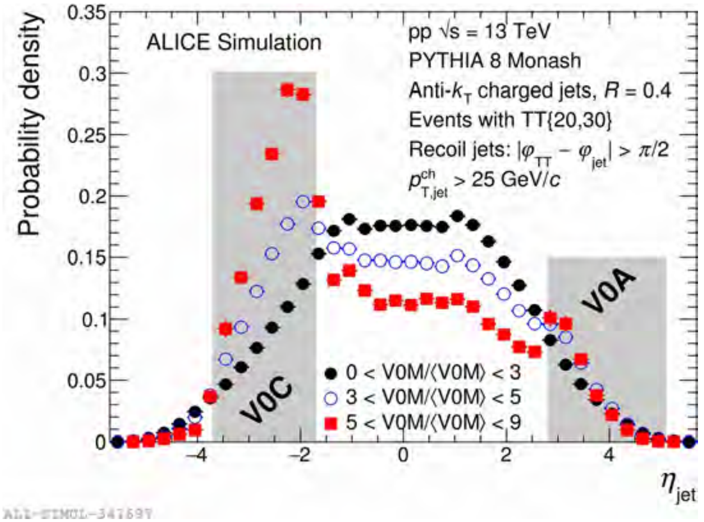
The effect is not due to jet quenching

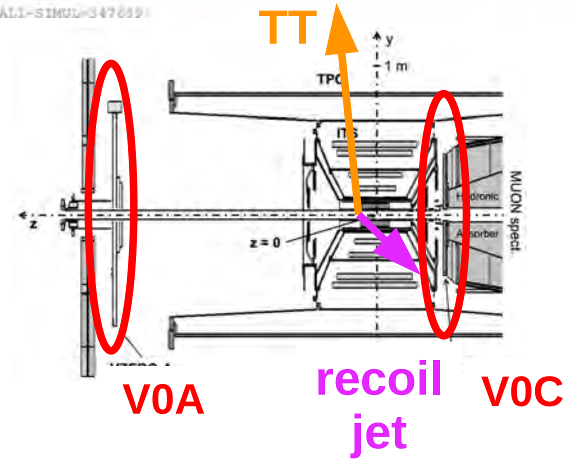
Use PYTHIA to explore the origin of the effect

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

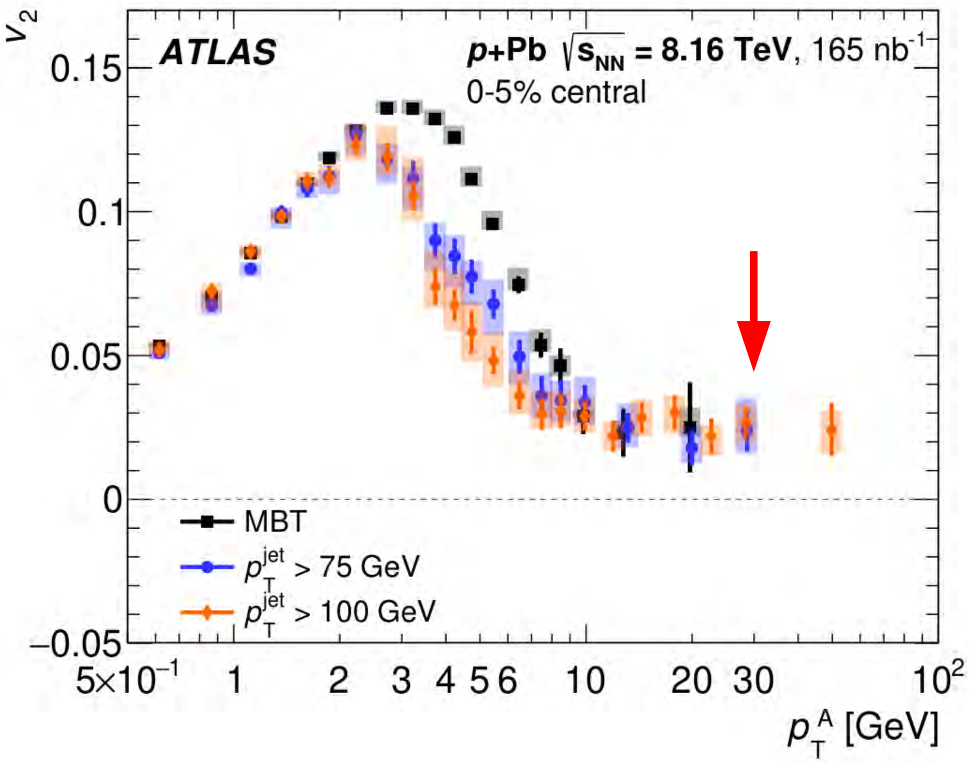
Summary

- 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

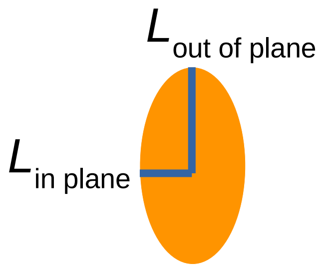
Backup

Flow of high-p_T particles in p-Pb from ATLAS

ATLAS, Eur. Phys. J. C 80 (2020) 73



Asymmetric collision zone



Radiative energy loss of partons

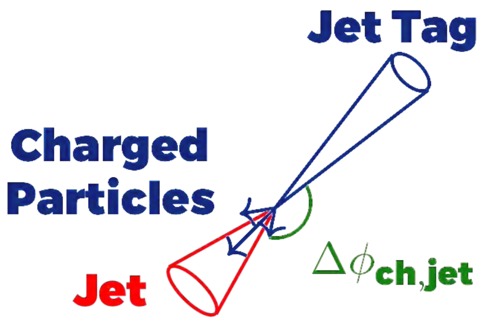
$$\Delta E \propto \hat{q} L^2$$

BDMPS, Nucl. Phys. B483 (1997) 291

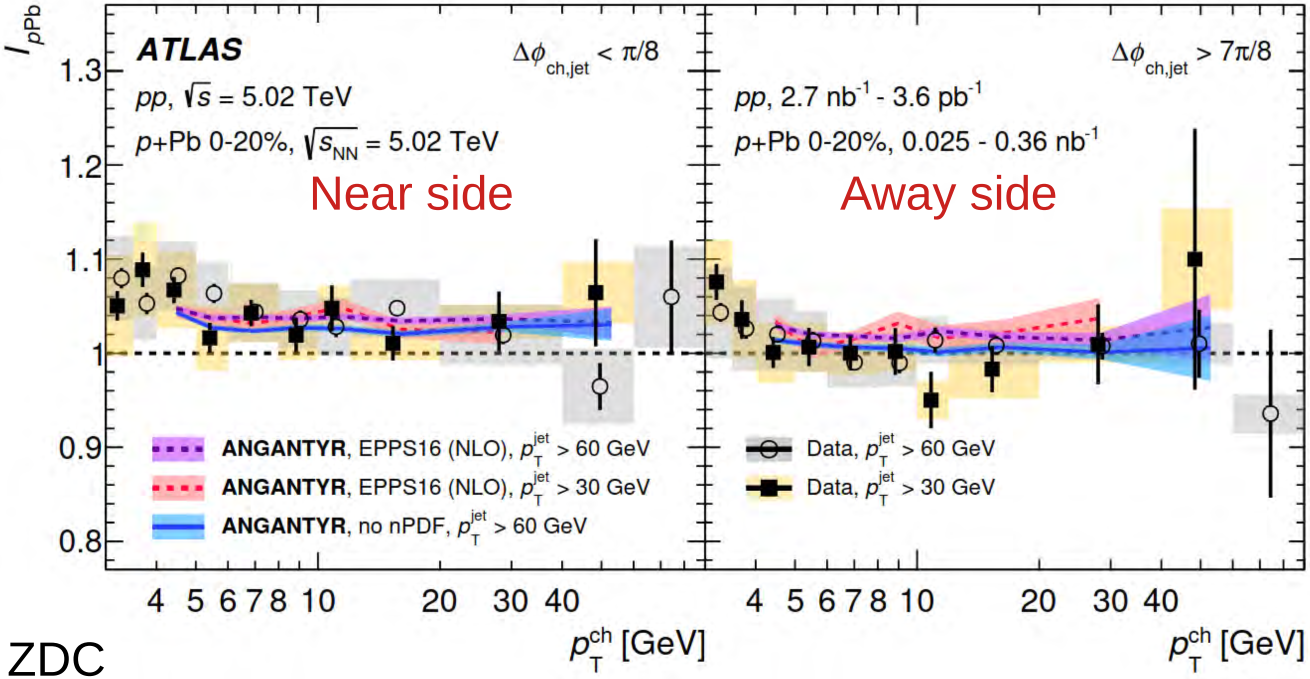
Jet fragmentation in p-Pb from ATLAS

Particle yield associated to jet tag

ATLAS, arXiv 2206.01138



$$I_{pPb} = \frac{Particles\ per\ jet|_{p+Pb}}{Particles\ per\ jet|_{p+p}}$$

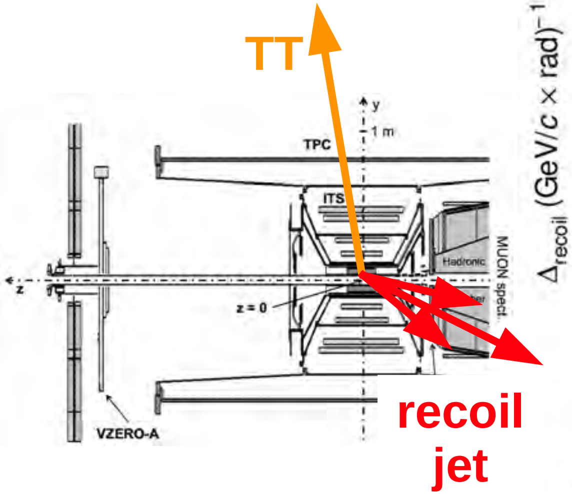


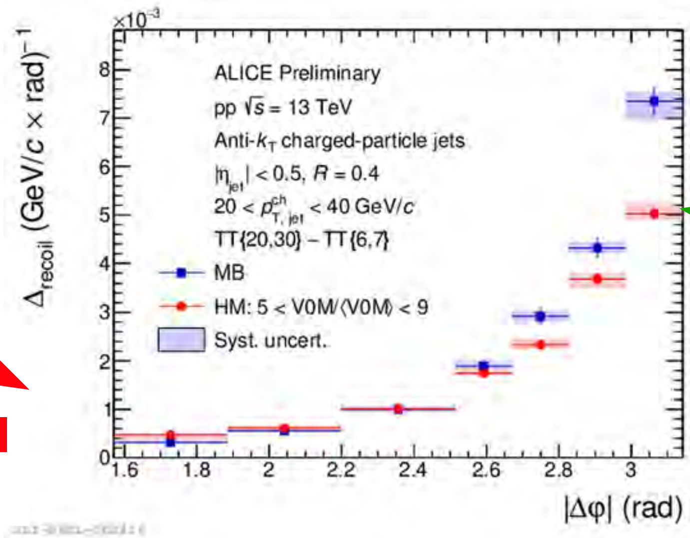
- Event activity measured with ZDC
- No modification in away-side
- Excess in near-side particle production
- Behavior of I_{pPb} is reproduced by PYTHIA ANGANTYR

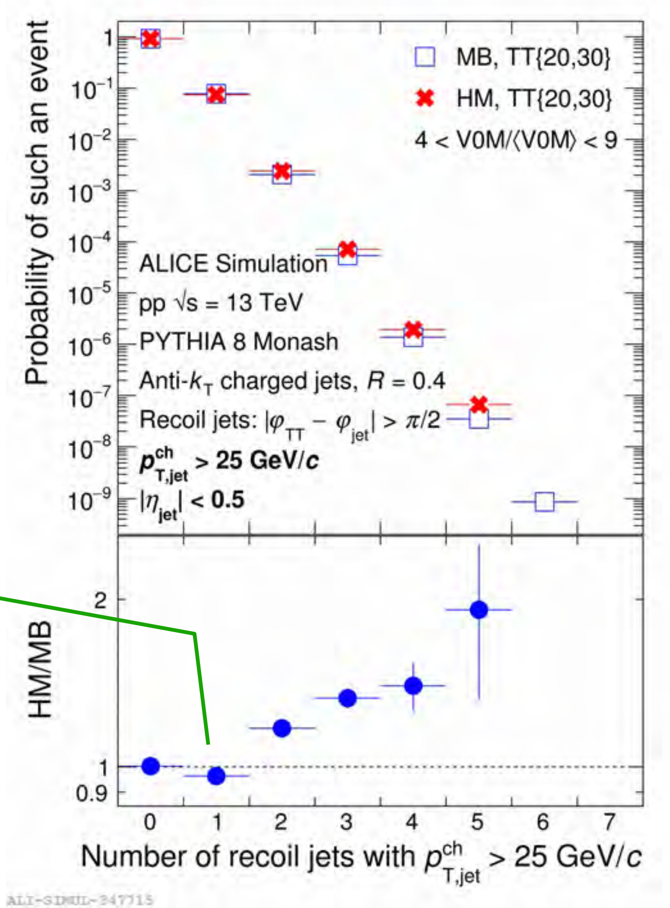
PYTHIA: Number of recoil jets versus event activity in ALICE acceptance

Distrib. of the number of recoil jets above p_T threshold:

- HM trigger suppresses events with 1 hard recoil jet in the ALICE central barrel
- HM trigger enhances multi-jet events in small system
- Signification issue for all HM analyses in small systems





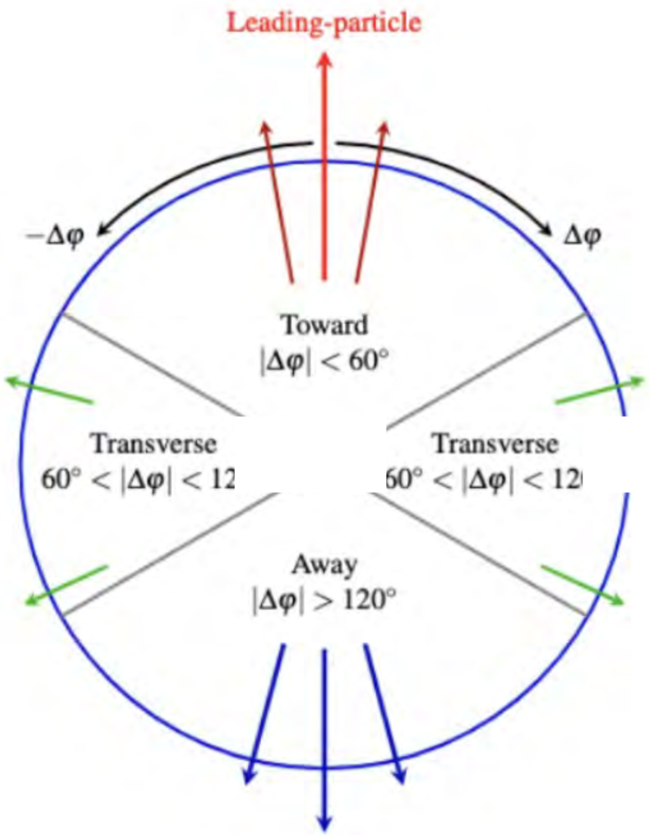


Measurement of jet particle yield in pp, p-Pb and Pb-Pb by ALICE

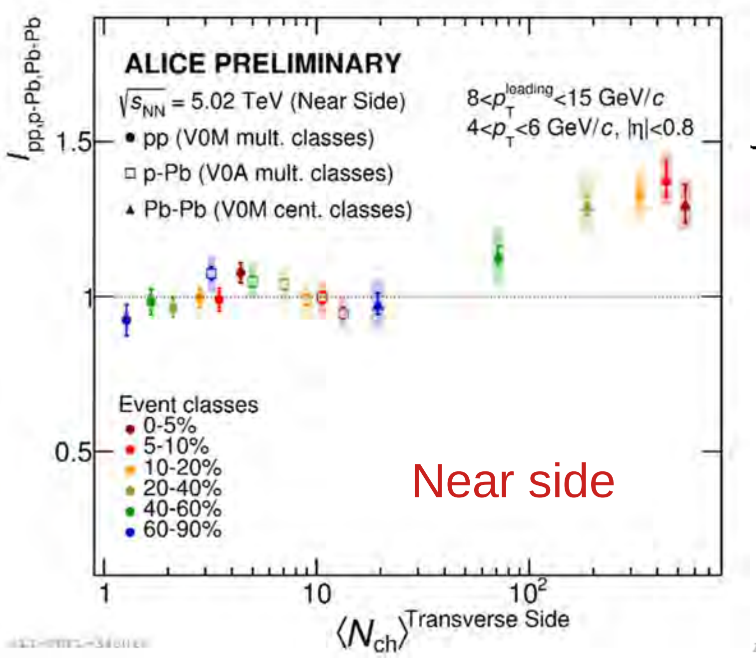
- Correlation of
  8-15 GeV/*c* leading particle
  4-6 GeV/*c* associated particle
  both in $|\eta| < 0.8$

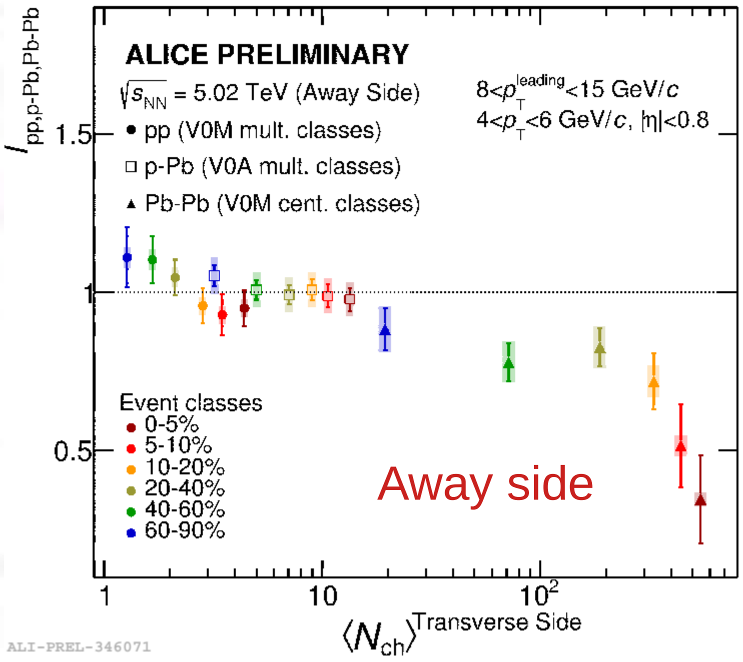
- Per trigger yield corrected for UE estimated in tranverse region relative to the leading particle

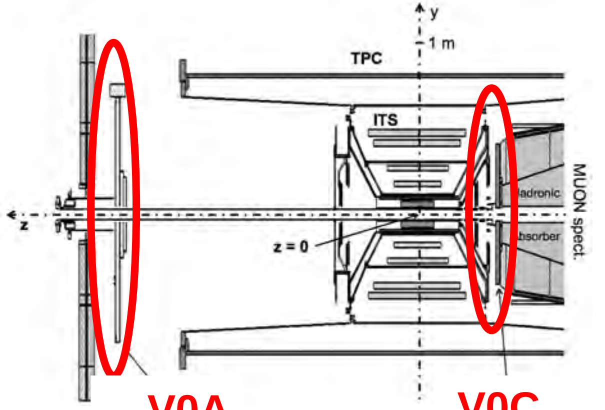
$$I_{\mathrm{pp,p-Pb,Pb-Pb}} = \frac{Y^{\mathrm{pp,p-Pb,Pb-Pb}} - Y_{\mathrm{TS}}^{\mathrm{pp,p-Pb,Pb-Pb}}}{Y^{\mathrm{pp\ min.bias}} - Y_{\mathrm{TS}}^{\mathrm{pp\ min.bias}}}$$



Measurement of jet particle yield in pp, p-Pb and Pb-Pb by ALICE



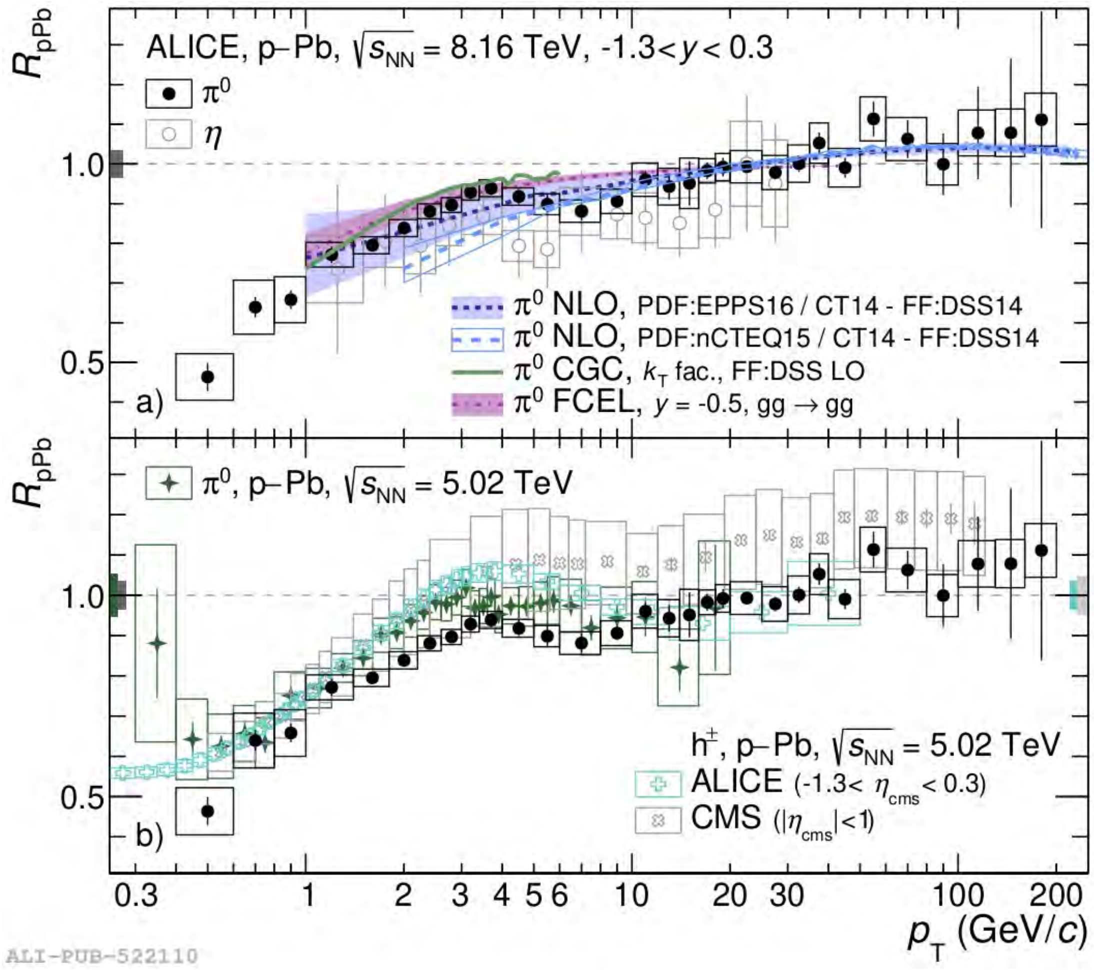




- Event activity classified in forward V0 scintillator detector

Absence of away side yield suppression for pp and pPb ⇒ absence of jet quenching

Minimum bias R_{pPb} for π^0 in p-Pb @ $\sqrt{s_{NN}}$ = 8 TeV



ALICE, PLB 827 (2022) 136943

$$R_{pPb} = \frac{1}{A_{Pb}} \frac{d^2\sigma_{pPb}}{dp_T dy} \bigg/ \frac{d^2\sigma_{pp}}{dp_T dy}$$

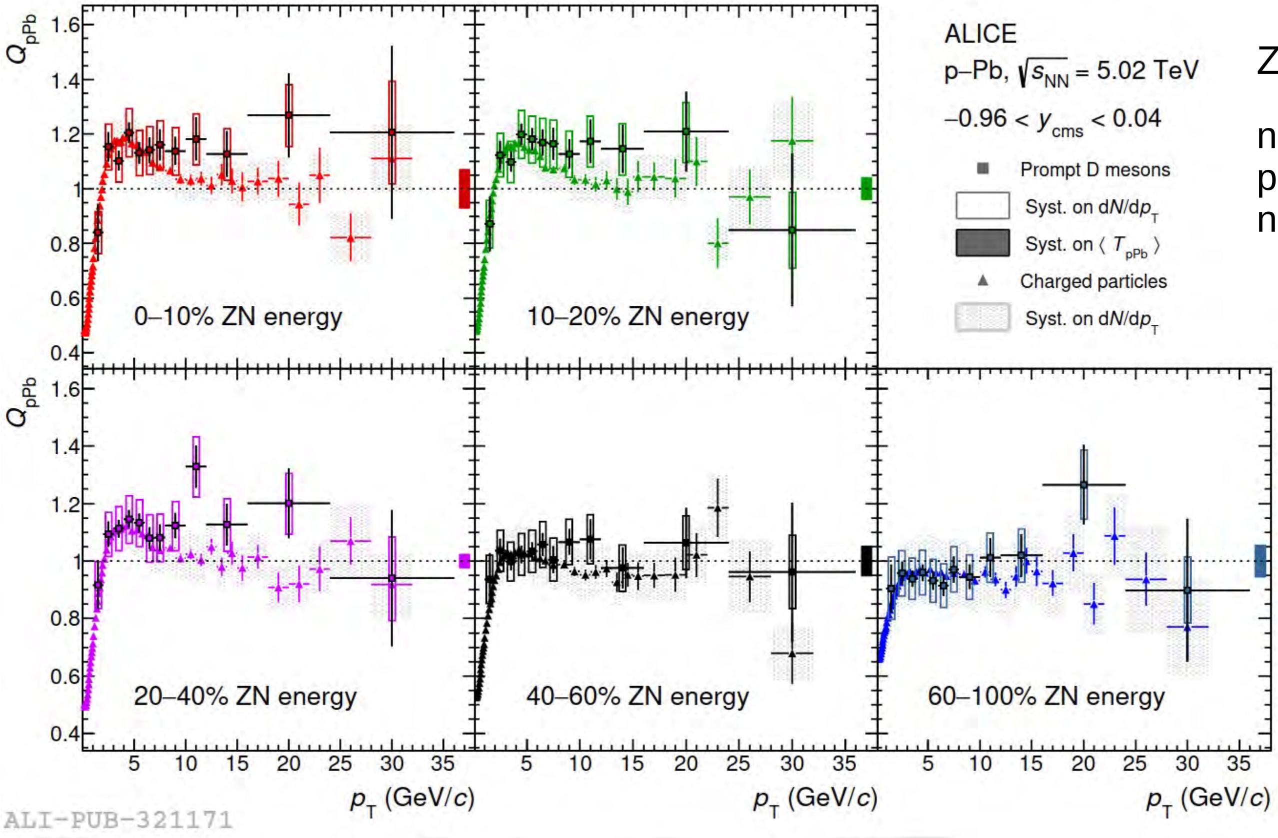
Data disfavor more than 1% relative energy loss or an induced p_T shift larger than 100 MeV in the range 10-20 GeV/*c*

Suppression for p_T < 10 GeV/*c* described by

- NLO calculations using nPDFs
  - EPPS16 [10] [Eskola et al. EPJC 77 (2017) 163]
  - nCETQ15 [Kovarik et al. PRD 93 (2016) 085037]
- CGC-based calculations [Lappi et al. PRD 88 (2013) 114020]
- parton energy loss in cold nuclear matter with fully coherent energy loss (FCEL)

[Arleo et al. JHEP 09 (2020) 190]

Q_{pPb} for h^{+-} and heavy flavor hadrons in p-Pb



ALICE, JHEP 2019 (2019) 92

ZDC in the Pb-going side

neutrons from nuclear de-excitation processes, or knocked out by wounded nucleon

$$Q_{\mathrm{pPb}} = \frac{(\mathrm{d}^2 N^{\mathrm{prompt\,D}}/\mathrm{d}p_\mathrm{T}\mathrm{d}y)^{\mathrm{i}}_{\mathrm{p-Pb}}}{\langle T_{\mathrm{pPb}}\rangle_{\mathrm{i}} \times (\mathrm{d}^2\sigma^{\mathrm{prompt\,D}}_{\mathrm{pp}}/\mathrm{d}p_\mathrm{T}\mathrm{d}y)}$$

$$\langle T_{\mathrm{pPb}}\rangle_{\mathrm{i}} = \frac{\langle N_{\mathrm{coll}}\rangle_{\mathrm{i}}}{\sigma_{\mathrm{NN}}}$$

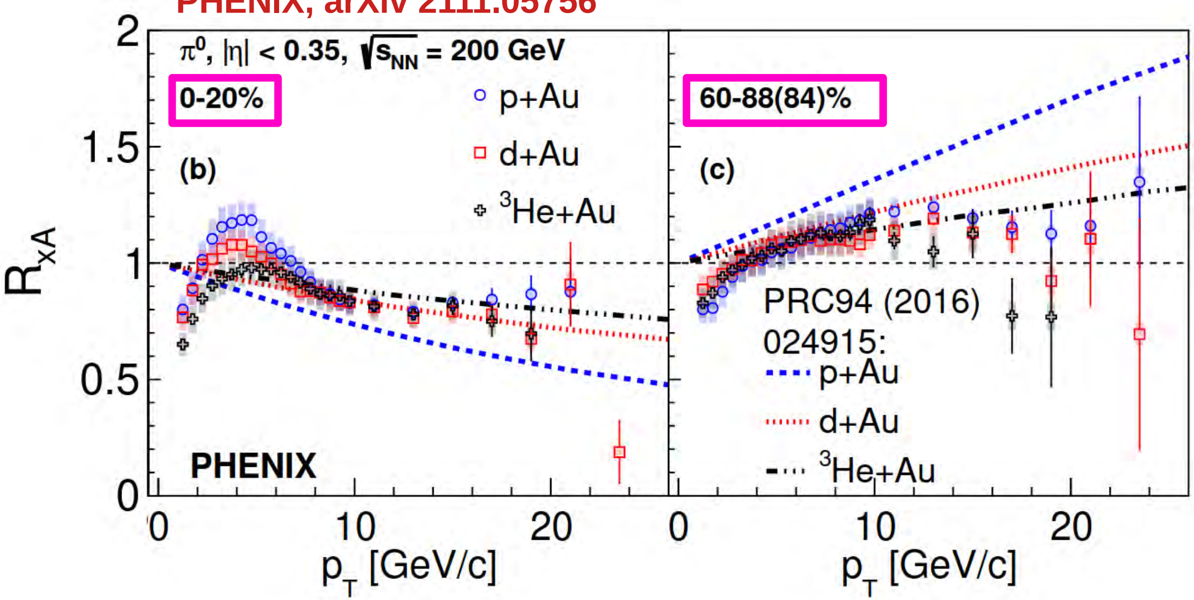
Assuming dN_{ch}/dη in mirapidity scales with N_{part}

$$\langle N_{\mathrm{coll}}\rangle_{\mathrm{i}} = \langle N_{\mathrm{part}}\rangle_{\mathrm{i}} - 1 =$$

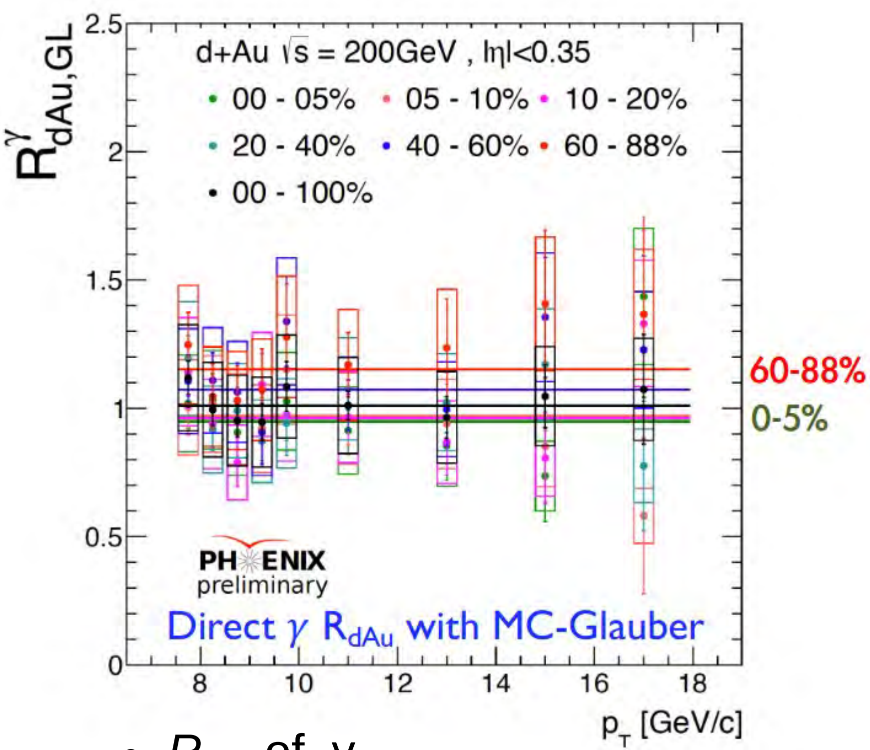
$$= \langle N^{\mathrm{MB}}_{\mathrm{part}}\rangle \cdot \left(\frac{\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta\rangle_{\mathrm{i}}}{\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta\rangle^{\mathrm{MB}}}\right)_{-1<\eta<0} - 1$$

R_{xA} of π^0 in EA biased collisions by PHENIX

PHENIX, arXiv 2111.05756



Sanghoon Lim talk at QM2022

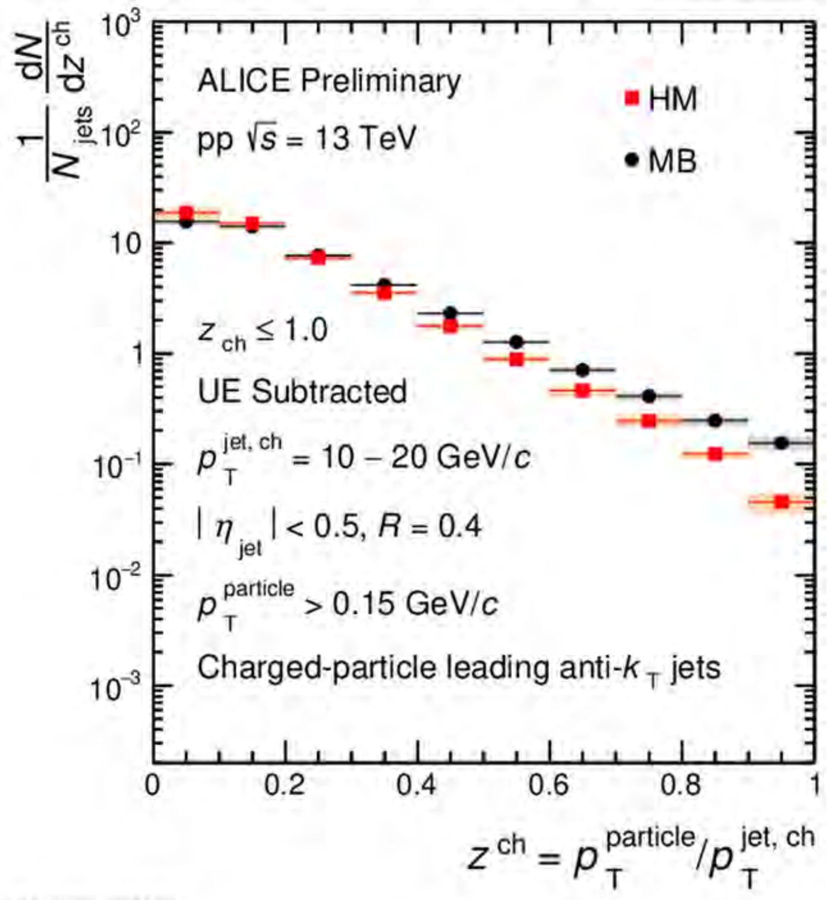


- Event activity (EA) dependence of R_{xA}
- Is suppression in central collisions due to jet quenching?

Model of proton size fluctuation: D. Mc Glinchey et al. PRC 94 (2016) 02415
protons with high-*x* partons are more compact and interact with less nucleons ⇒
Enhancement of peripheral events & suppression of central

- R_{dAu} of γ_{direct}
  ≈ 1 in central and MB
  > 1 in peripheral

Longitudinal fragmentation of jets in high-multiplicity pp events in ALICE

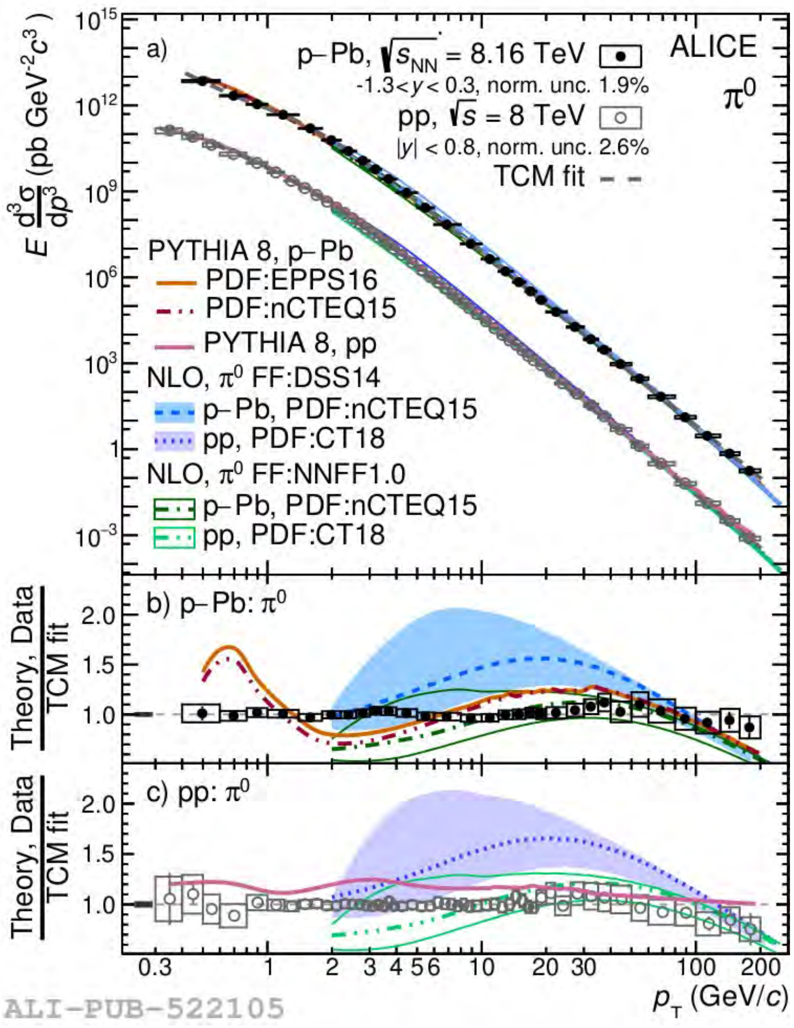


HM event activity selection:
5x larger multiplicity in V0 detector w.r.t min. bias
0-0.1% event activity percentile

HM event selection → softer jet fragmentation

This is consistent with larger portion of jets comming from NLO processes

π^0 production in min. bias p-Pb and pp @ $\sqrt{s_{NN}}$ = 8 TeV

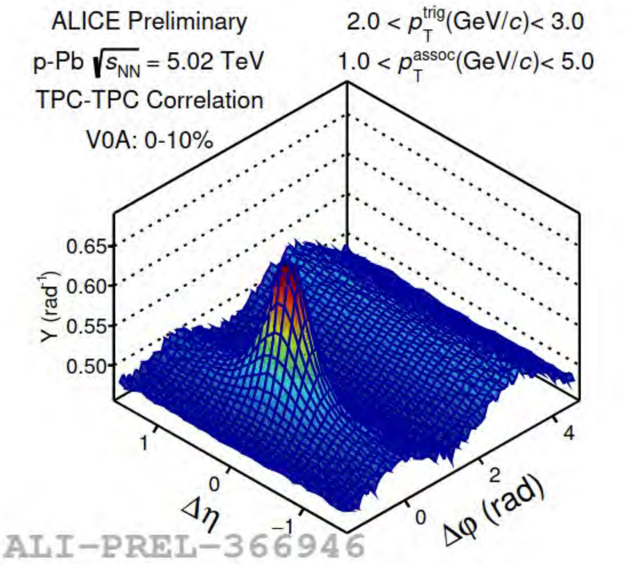


ALICE, PLB 827 (2022) 136943

- Reach up to 200 GeV/c
- pp reference corrected to 8.16 TeV using PYTHIA 8 Monash
- NLO with NNFF1.0 frag. functions
  [NNPDF EPJC 77 (2017) 516]
- NLO with DSS14 frag. functions
  [de Florian et al. PRD 91 (2015) 014035]

Elliptic flow of jet fragments in p-Pb

Two particle corrleations to measure yield assocated to jet fragments
- trig. and assoc. particles have same charge, measured in |η|<0.8
- signal/background as a function Δφ,Δη



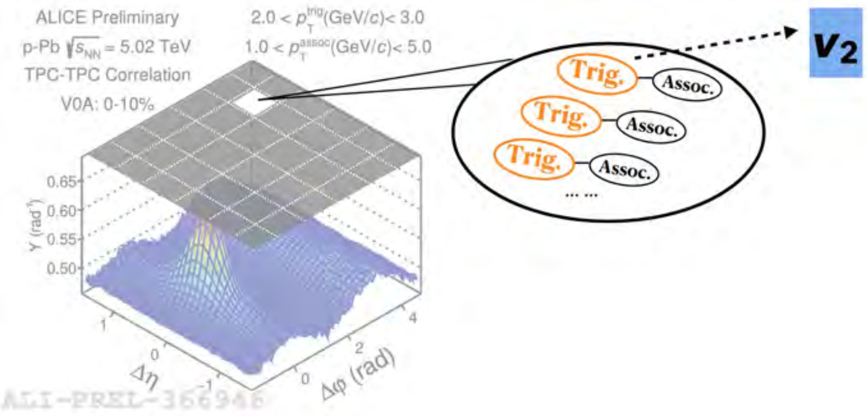
$$Y(\Delta\varphi,\Delta\eta) = \frac{1}{N_{\rm trig}}\frac{d^2N_{\rm pair}}{d\Delta\varphi d\Delta\eta} \approx \frac{S(\Delta\varphi,\Delta\eta)}{B(\Delta\varphi,\Delta\eta)}$$

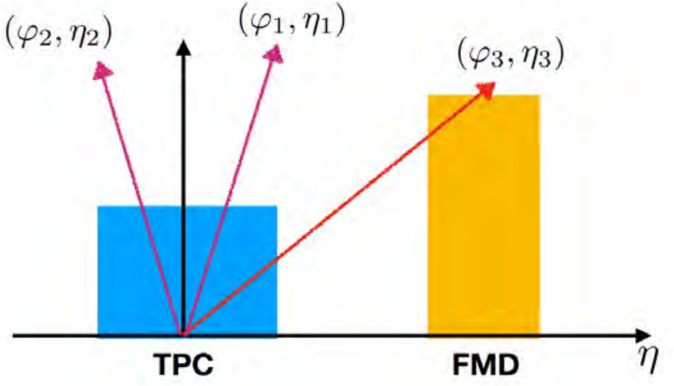
$$S(\Delta\varphi,\Delta\eta) = \frac{1}{N_{\rm trig}}\frac{d^2N_{\rm same}}{d\Delta\varphi d\Delta\eta}, \qquad B(\Delta\varphi,\Delta\eta) = \alpha\frac{d^2N_{\rm mix}}{d\Delta\varphi d\Delta\eta}$$

Elliptic flow of jet fragments in p-Pb

Correlate trigger particle with a hit in Forward Multiplicity Detector $1.7 < \eta_{FMD} < 5.1$

- Non flow removal : subtraction of correlations for high mult. and low mult. events



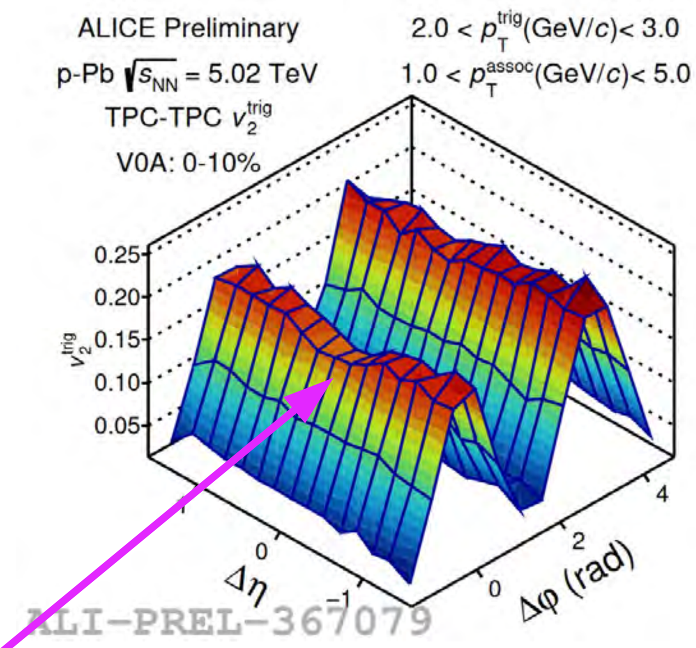


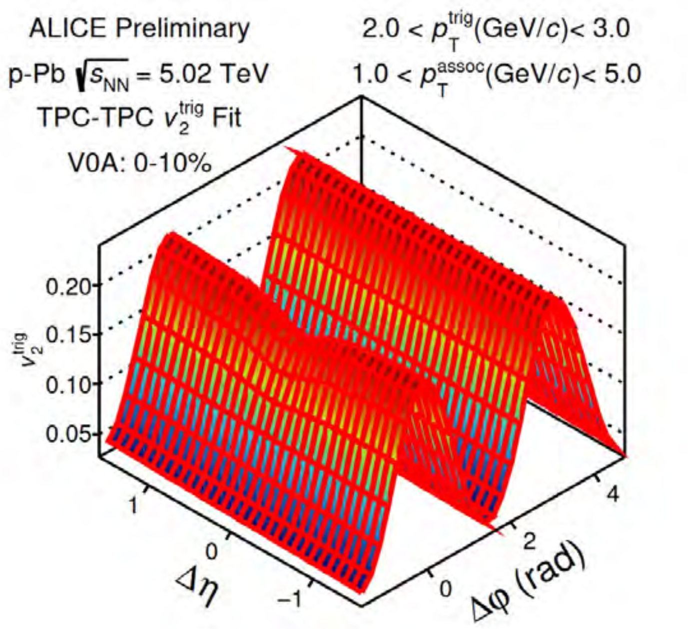
$$\frac{dN}{d\Delta\varphi'} \propto 1 + 2\sum_{n=1}^{3} \Delta V_n(\Delta\varphi, \Delta\eta)\cos(n\Delta\varphi'), |\Delta\eta| > 1$$

$$\Delta\varphi = \varphi_1 - \varphi_2 \quad \Delta\eta = \eta_1 - \eta_2$$
$$\Delta\varphi' = \varphi_1 - \varphi_3 \quad \Delta\eta' = \eta_1 - \eta_3$$

Factorization: $\Delta V_2(\Delta\varphi, \Delta\eta) = v_2(\Delta\varphi, \Delta\eta) v_2^{\mathrm{FMD}}$

Elliptic flow of jet fragments in p-Pb





Dip in v_2 of midrapidity pairs
at the position of the near-side peak

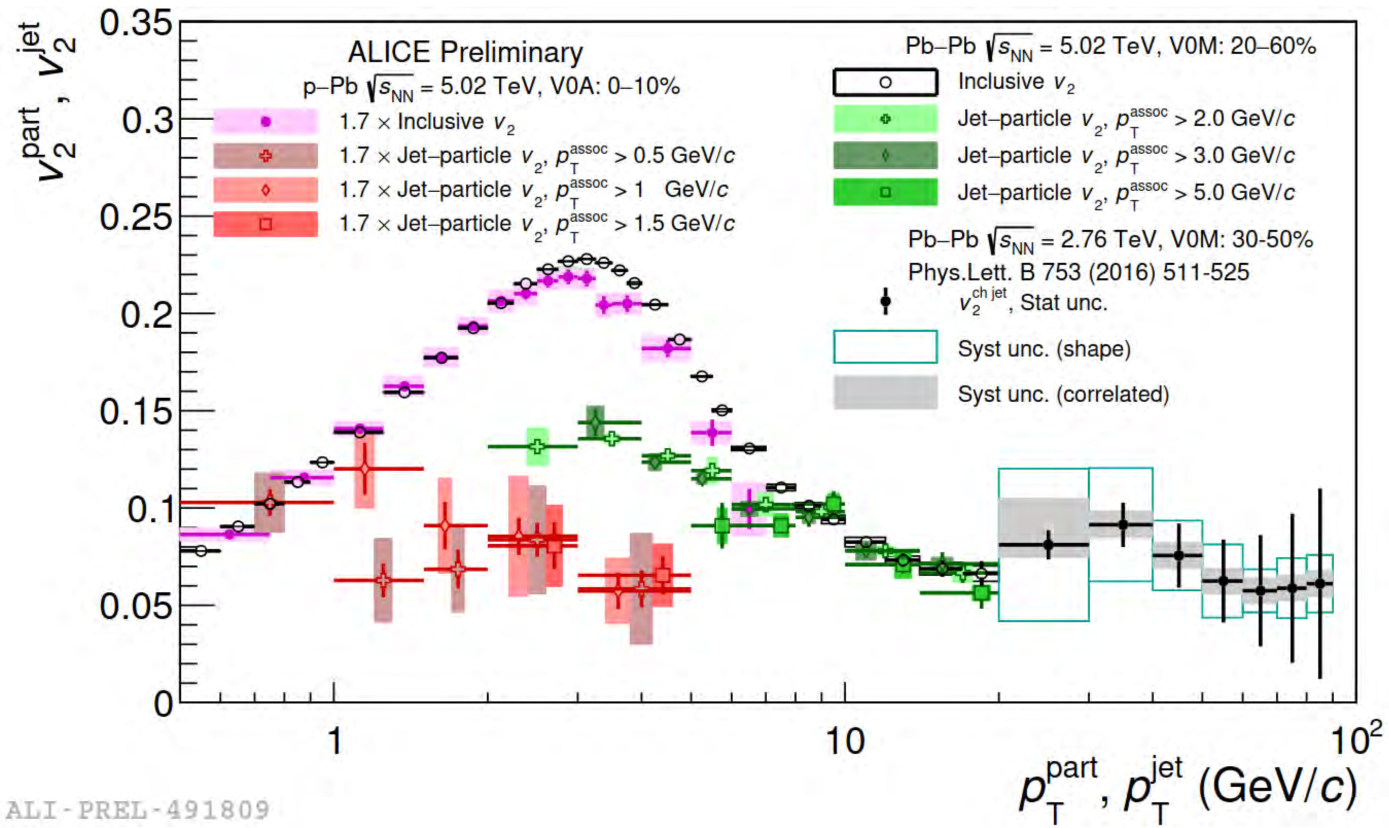
→

Extract $v_{2,jet}$ from fit by

$$v_2(\Delta\varphi,\Delta\eta)=\frac{S}{S+B}v_{2,jet}-\frac{B}{S+B}v_{2,bg}(\Delta\varphi,\Delta\eta)$$

Sum of 5 harmonics

Elliptic flow of jet fragments in p-Pb



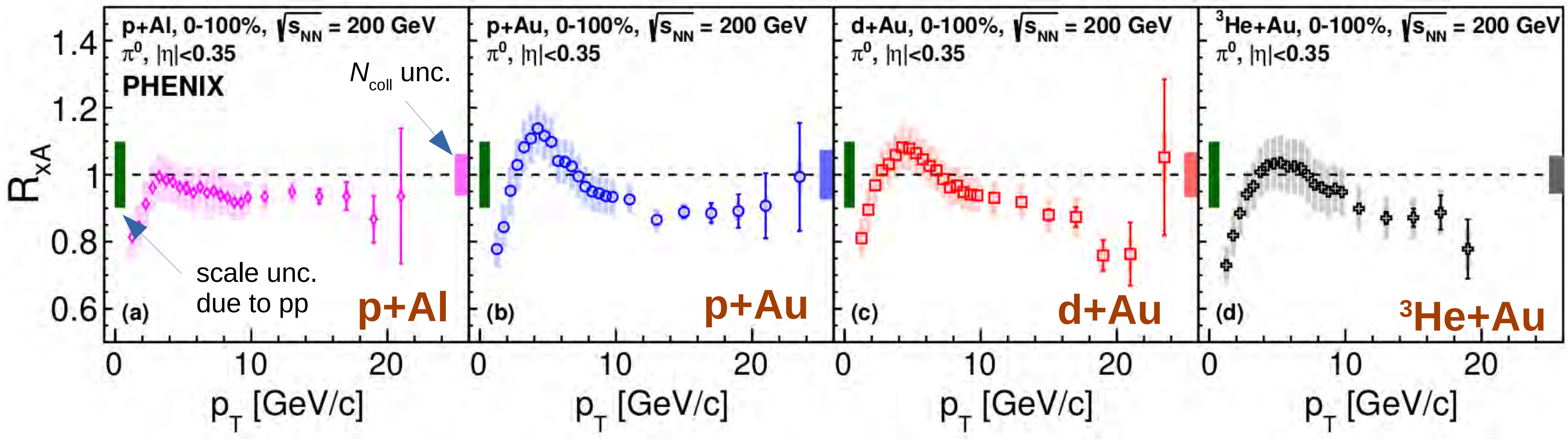
Pb-Pb:
- Jet particle v_2 is compatible with v_2 of charged-particle jets for p_T^{trig} > 7 GeV
- Both interpreted by pathlength dependnece of energy loss

p-Pb:
- Inclusive v_2 in Pb-Pb is about 1.7 greater w.r.t. p-Pb.

- Nonzero v_2 for jet fragments Initial-state effects (CGC) or final-state scatterings

R_{xA} of π^0 in min. bias collisions by PHENIX

PHENIX, arXiv 2111.05756



- $R_{xA} \approx 0.9$ but still compatible with unity within uncertainties
- No system size dependence at high p_T → little or no modification of hard scatteing

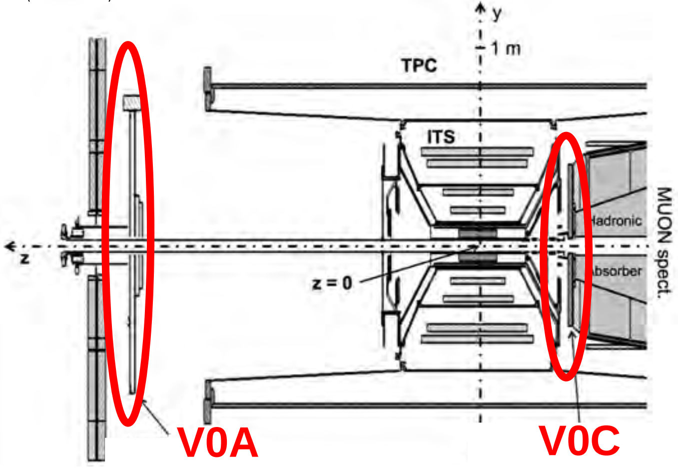
Event activity selection in pp at √s = 13 TeV

- Trigger:
  - Minimum bias (MB) $L_{int} \approx 32\ nb^{-1}$
  - High multiplicity (HM) $L_{int} \approx 10\ pb^{-1}$
- Event activity (EA) selection:

  V0M = V0A + V0C
- **HM is 0.1% of MB cross section**

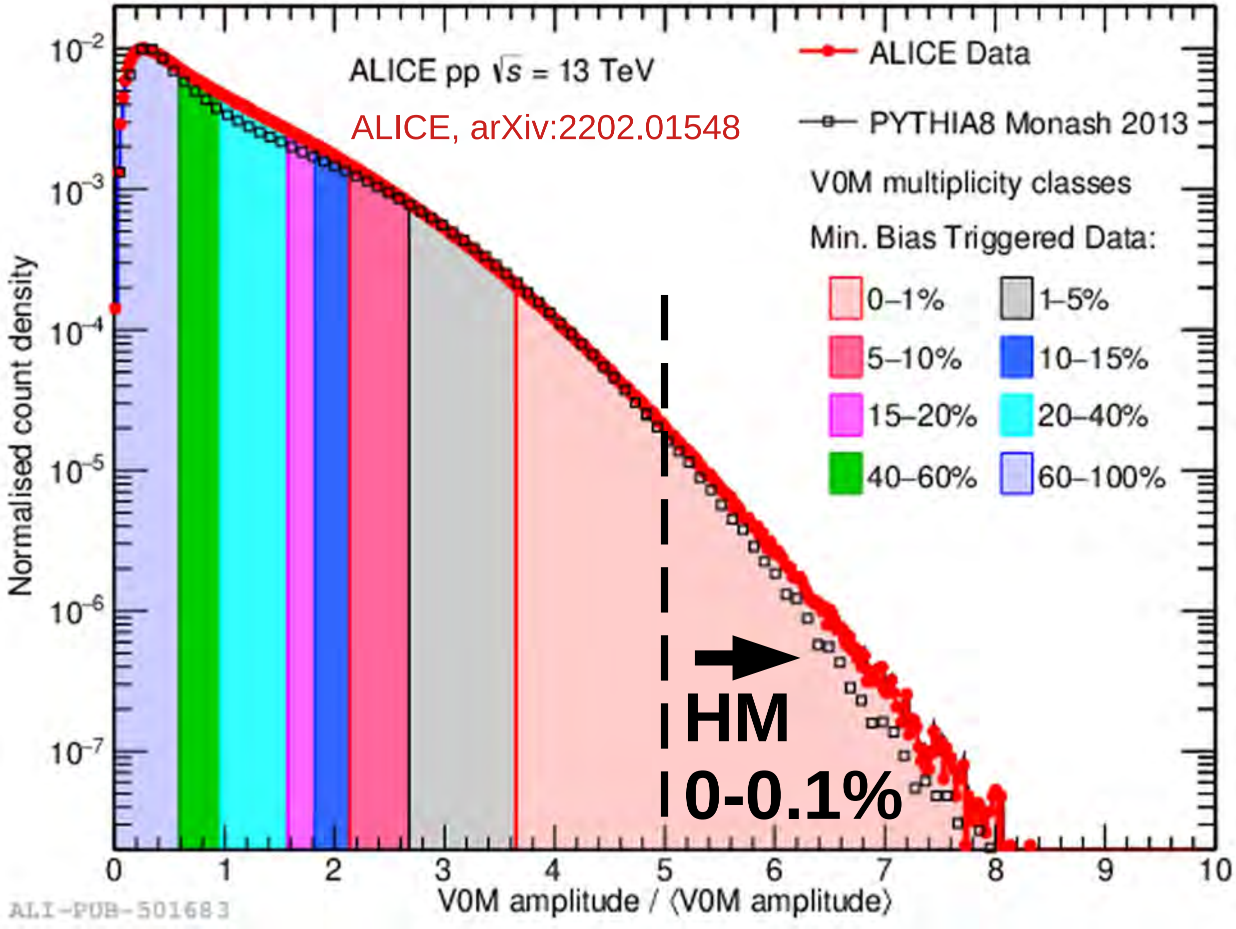
  $5 < V0M / \langle V0M \rangle < 9$

  $\langle V0M \rangle$ = mean of V0M in MB



2.8 < η < 5.1

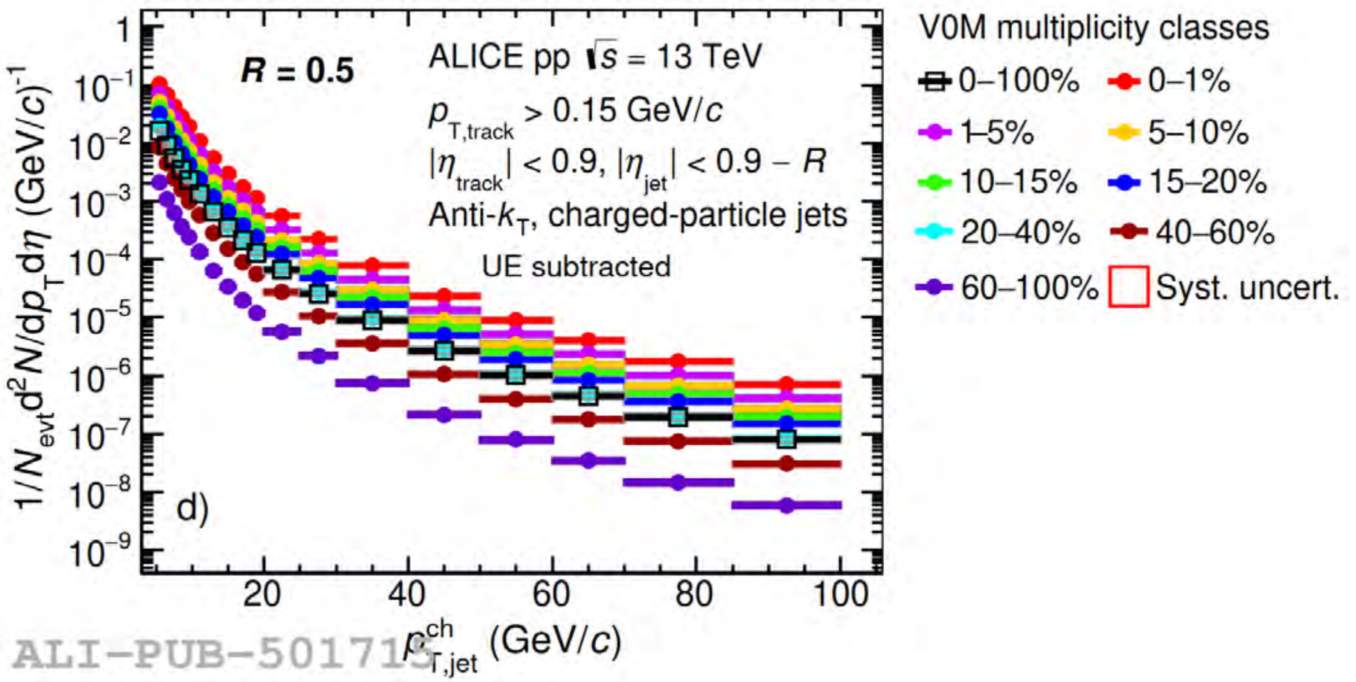
-3.7 < η < -1.7



Charged-particle jets in MB and event activity biased pp collisions at √s = 13 TeV

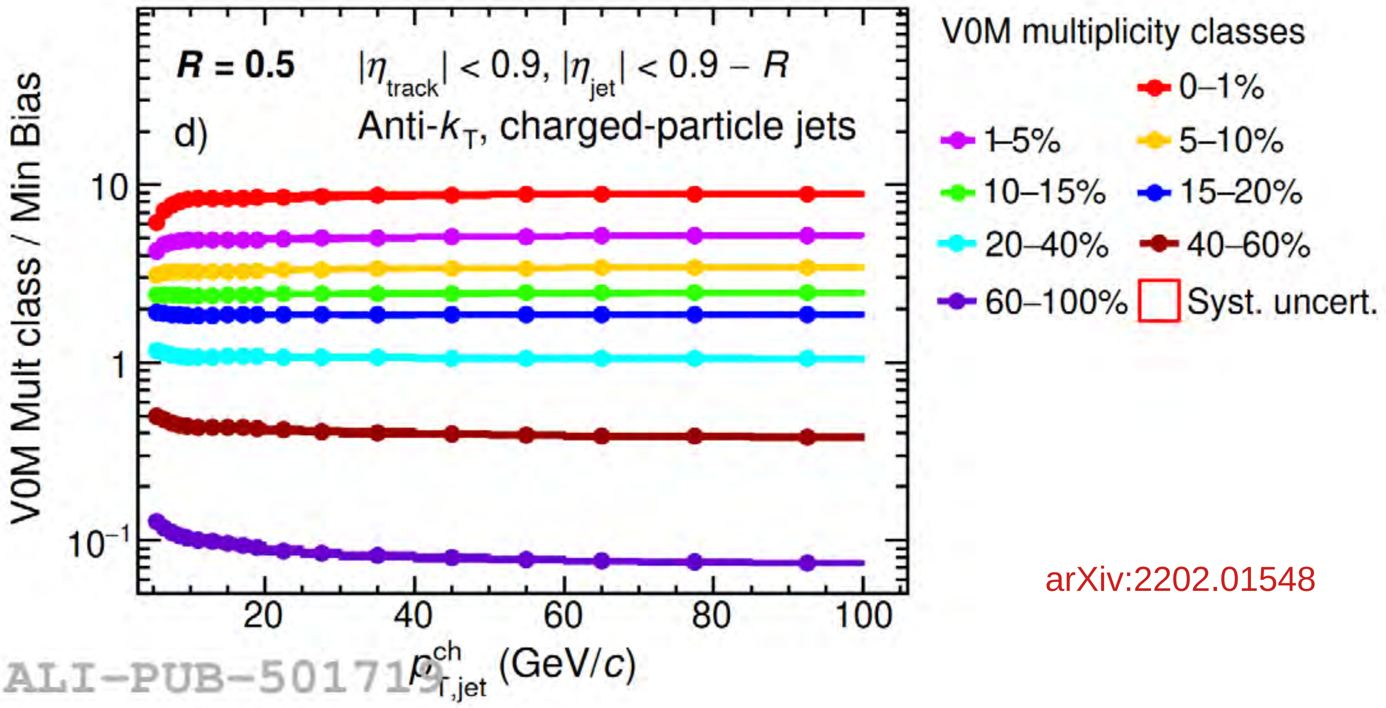
arXiv:2202.01548

- Tracks
  $|\eta_{track}| < 0.9$
  $0 < \varphi_{track} < 2\pi$
  $p_{T,track} > 150$ MeV/c
- Charged-particle jets
  Anti-k_T algorithm
  $|\eta_{jet}| < 0.9 - R$
  ***R* = 0.2 – 0.7**
- $p_{T,ch\ jet} = p^{raw}_{T,ch\ jet} - \rho A_{jet}$



How does the imposed event activity selection bias the spectrum shape?

Ratios of EA-biased jet p_T spectra to MB



arXiv:2202.01548

- Event activity (EA) bias affects the shape mostly for $p_{T,\text{ch jet}} < 20$ GeV/c
- Bias on high-EA causes increase of jet yield per event

May arise from increase in average number of hard scatterings per event

Self-normalized jet yield versus self-normalized multiplicity

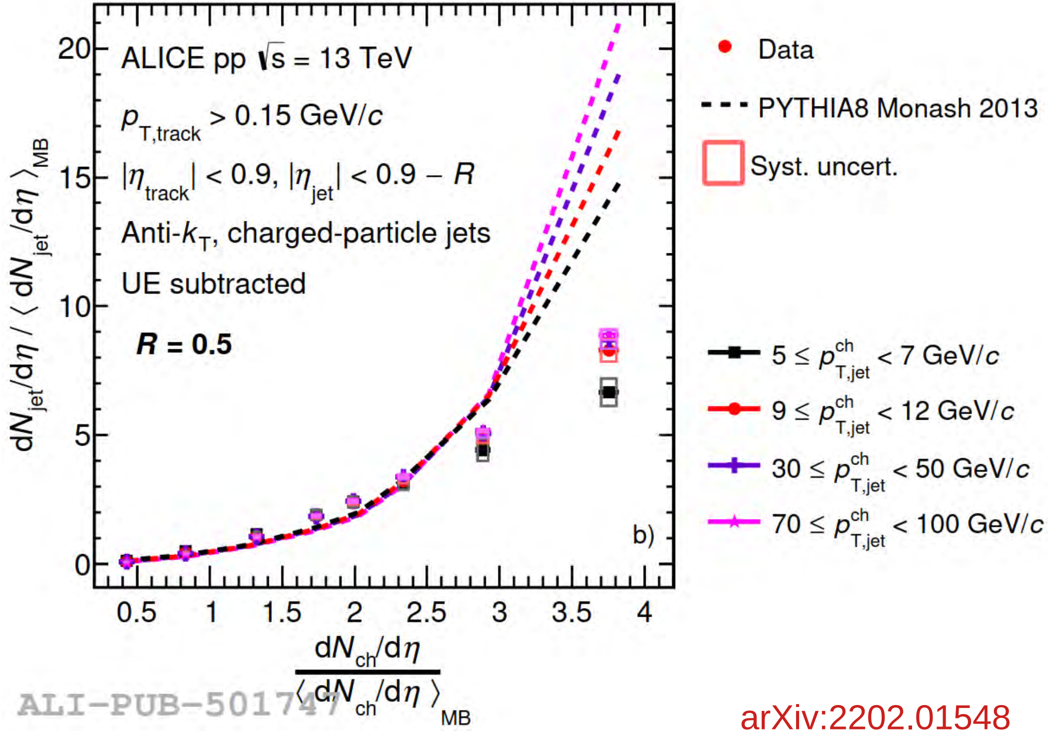
- Jets with $p^{\text{ch}}_{\text{T, jet}} > 9$ GeV/c follow non-linear trend similar to J/ψ in midrapidity

  Phys. Lett. B 810 (2020) 135758

  and heavy-flavor electrons and prompt D

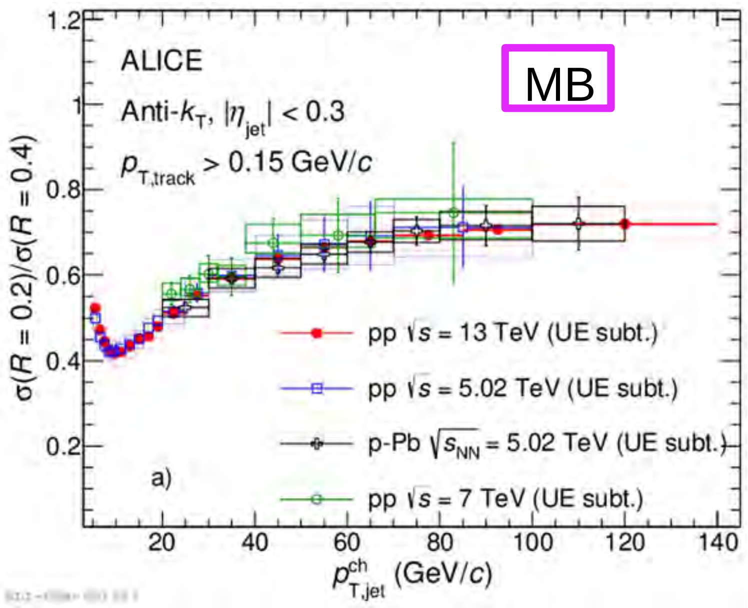
- Electrons from W decay follow linear trend

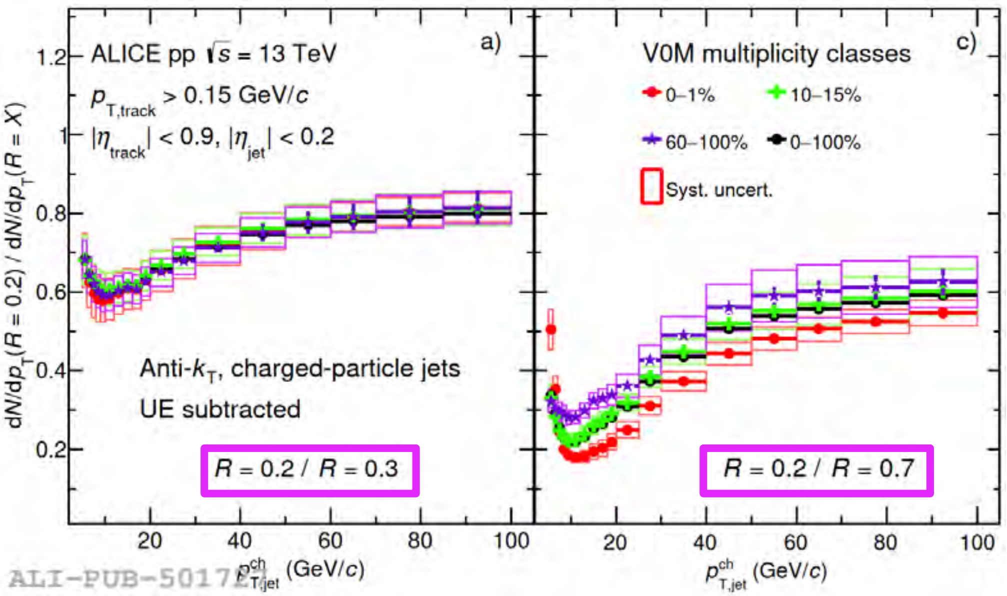
- Overshoot of the trend by PYTHIA at high charged-particle multiplicities



arXiv:2202.01548

Ratios of jet p_T spectra with different R





MB ratio of p_T-differential cross section spectra:

independent of $\sqrt{s}$

EA-selected ratio of spectra:
- small R : independent of EA
- large R : hint of EA dependence

arXiv:2202.01548