Search for jet quenching in small systems

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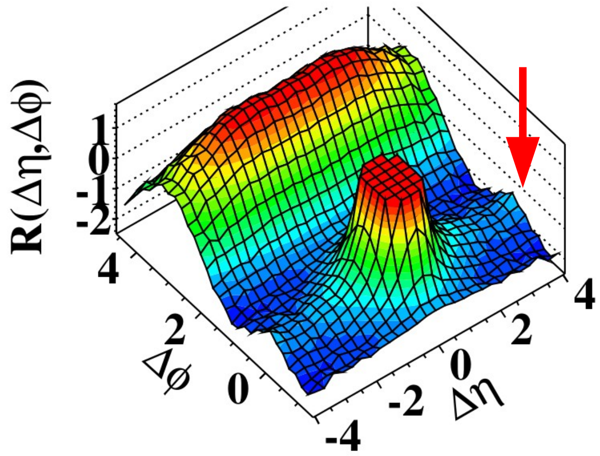
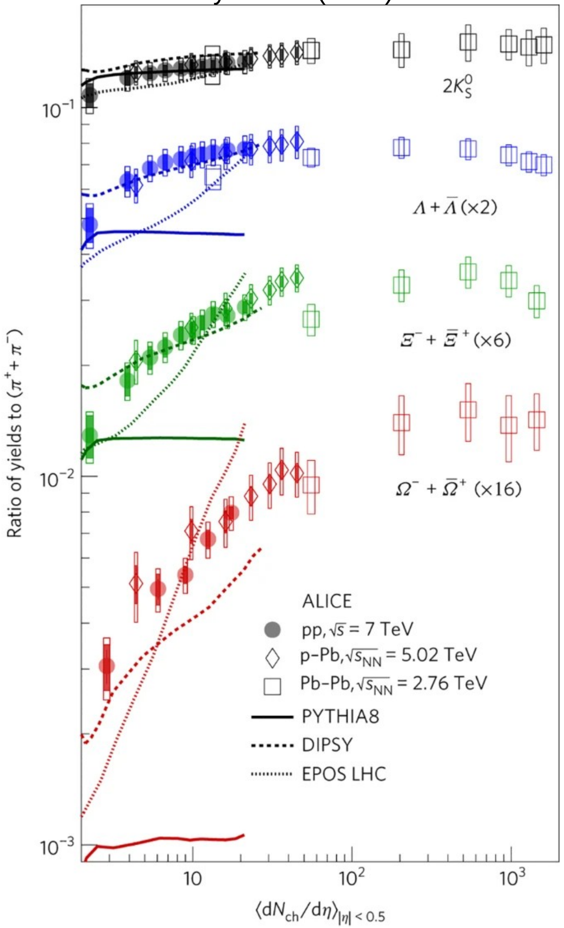
QGP in small collision systems?



CMS, JHEP 09 (2010) 091

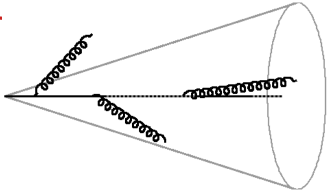
Nature Physics 13 (2017) 535–539



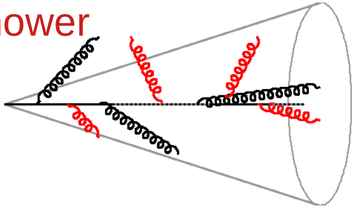
- QGP-like signatures in high-multiplicity pp and pA
- How do QGP signatures that we see in large collision systems evolve when decreasing system size?
- Jet quenching is necessary consequence of a hot and dense fireball. Can we see evidence of it?

Jet quenching observables

in-vacuum shower



in-medium shower



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

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

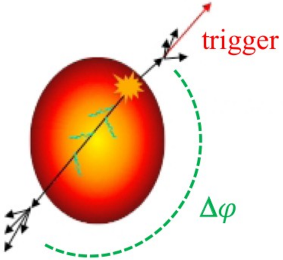
measurement of inclusive suppression R_{AA} requires Glauber scaling →

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

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

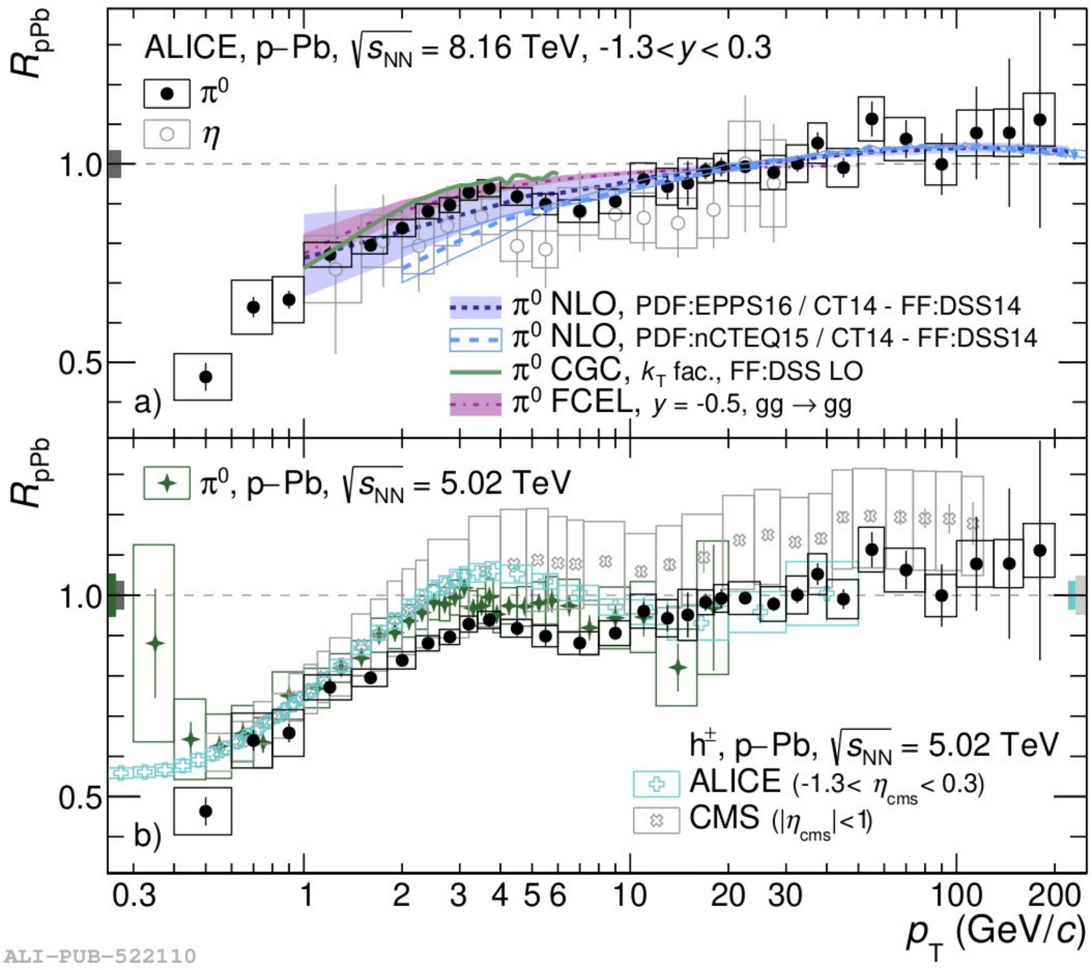
- not defined in high-multiplicity pp collisions

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



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

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



ALICE, PLB 827 (2022) 136943

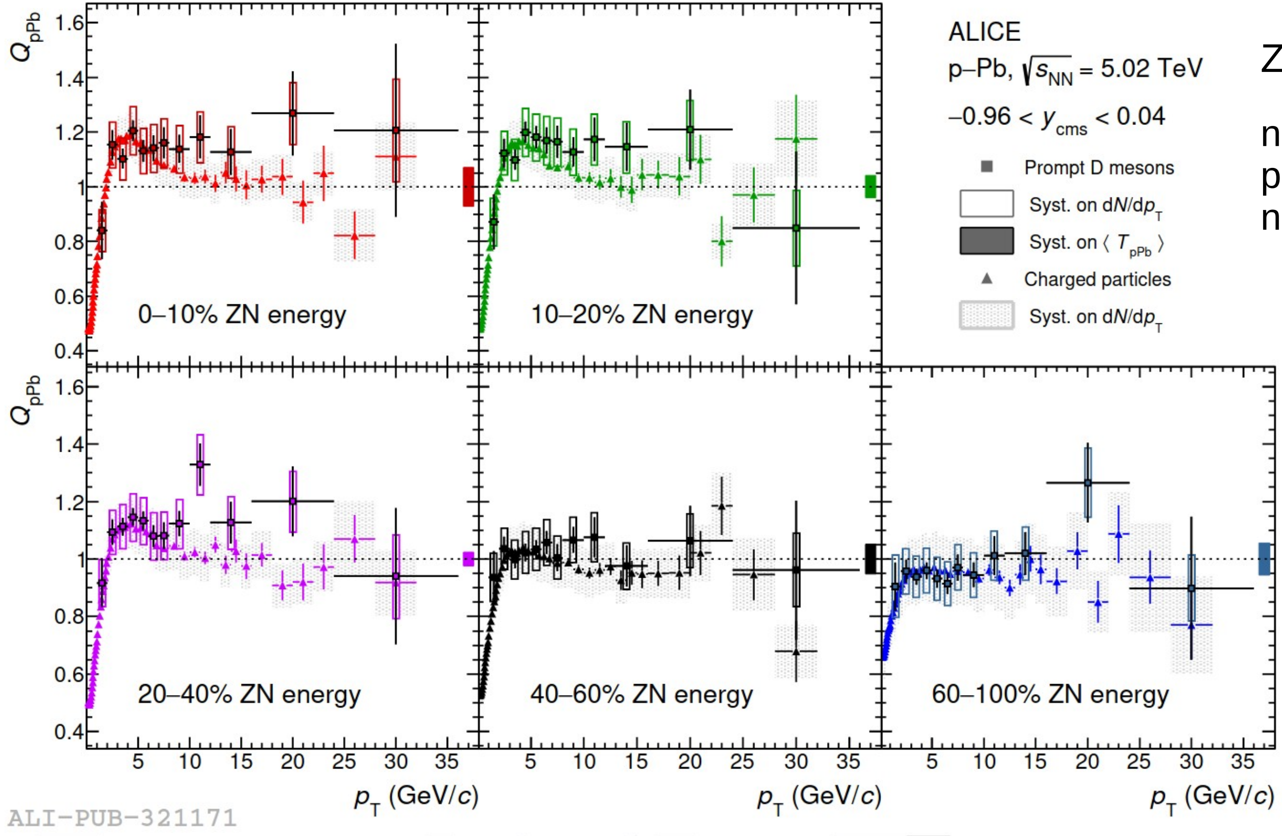
$$R_{pPb} = \frac{1}{A_{Pb}} \frac{d^2\sigma_{pPb}}{dp_T dy} \Big/ \frac{d^2\sigma_{pp}}{dp_T dy}$$

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

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

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

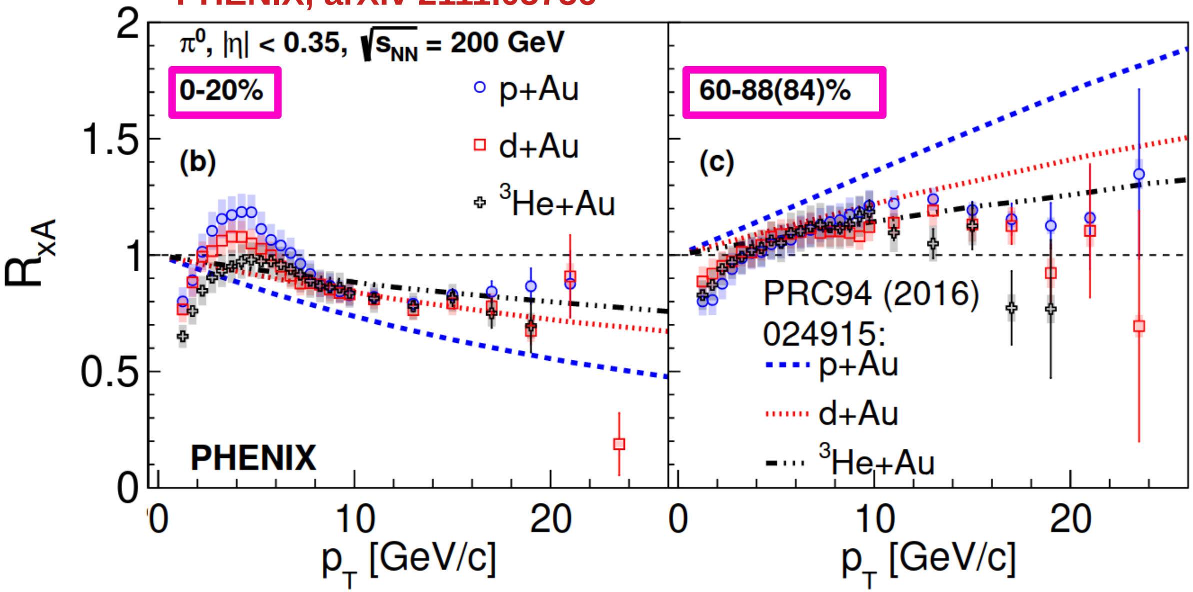
Assuming dN_{ch}/dη in mirapidity scales with N_{part}

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

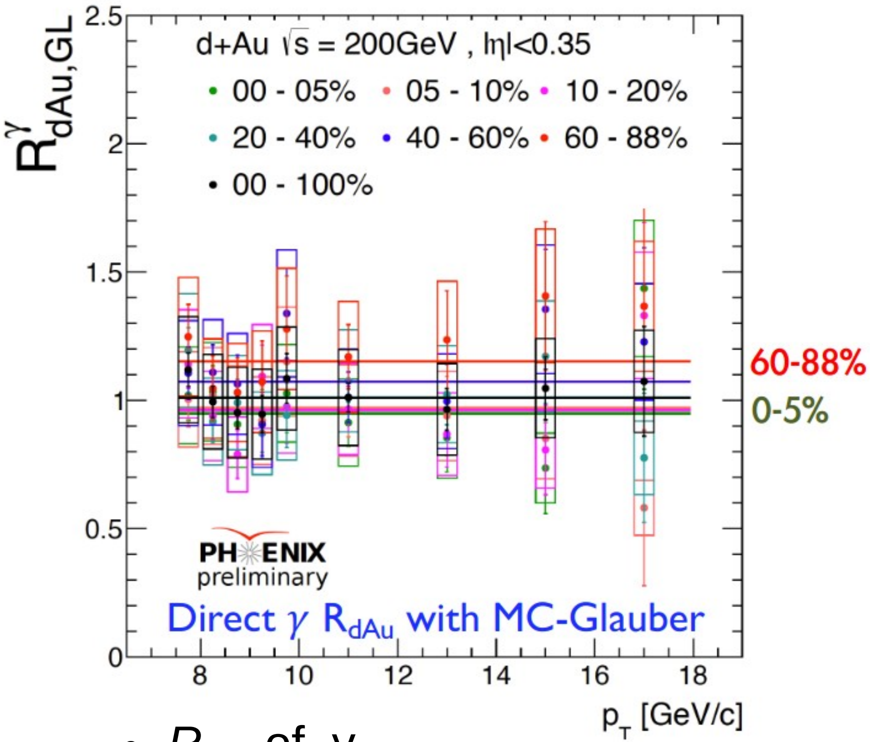
$$= \langle N^{\mathrm{MB}}_{\mathrm{part}}\rangle \cdot \left(\frac{\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta\rangle_{\mathrm{i}}}{\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta\rangle^{\mathrm{MB}}}\right)_{-1<\eta<0} - 1$$

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

PHENIX, arXiv 2111.05756



Sanghoon Lim talk at QM2022

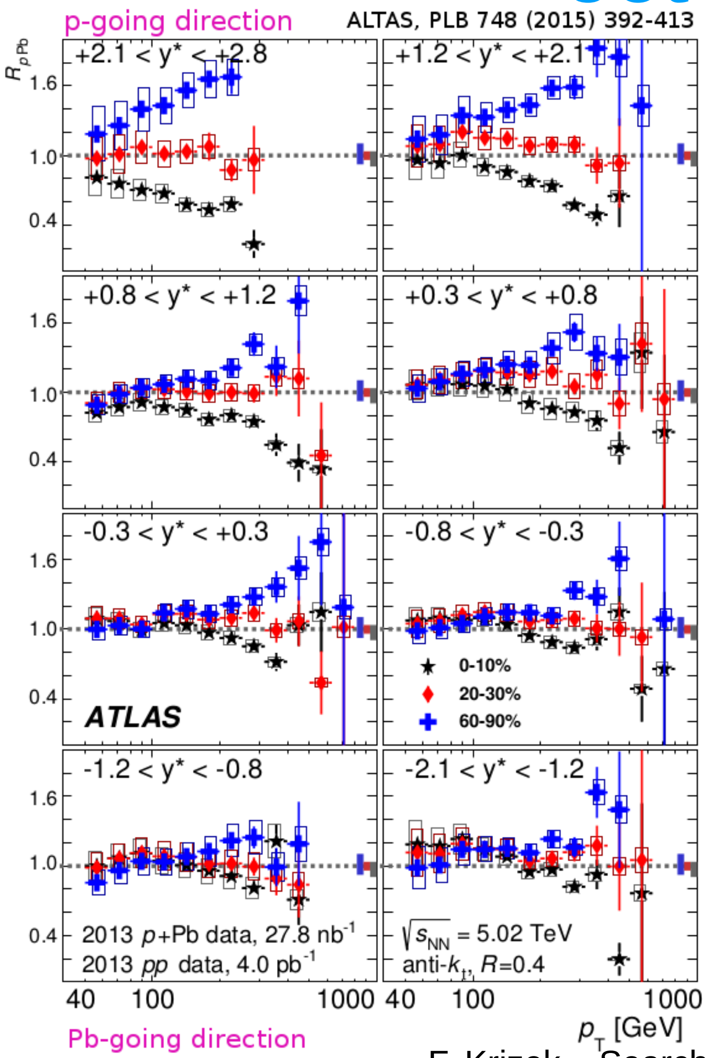


- Event activity (EA) dependence of R_{xA}
- Is suppression in central collisions due to jet quenching?

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 $\Rightarrow$
Enhancement of peripheral events & suppression of central

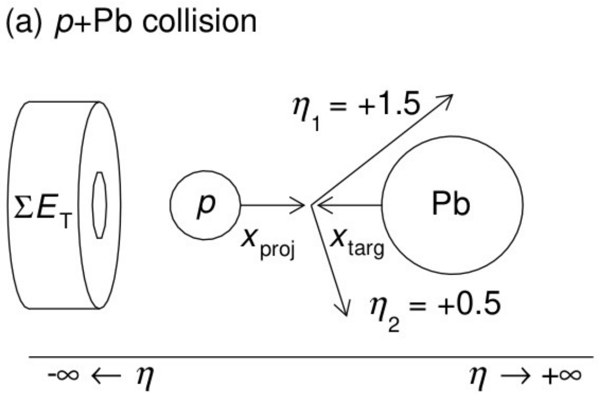
- R_{dAu} of γ_{direct}
  ≈ 1 in central and MB
  > 1 in peripheral

Jet R_{pPb} by ATLAS

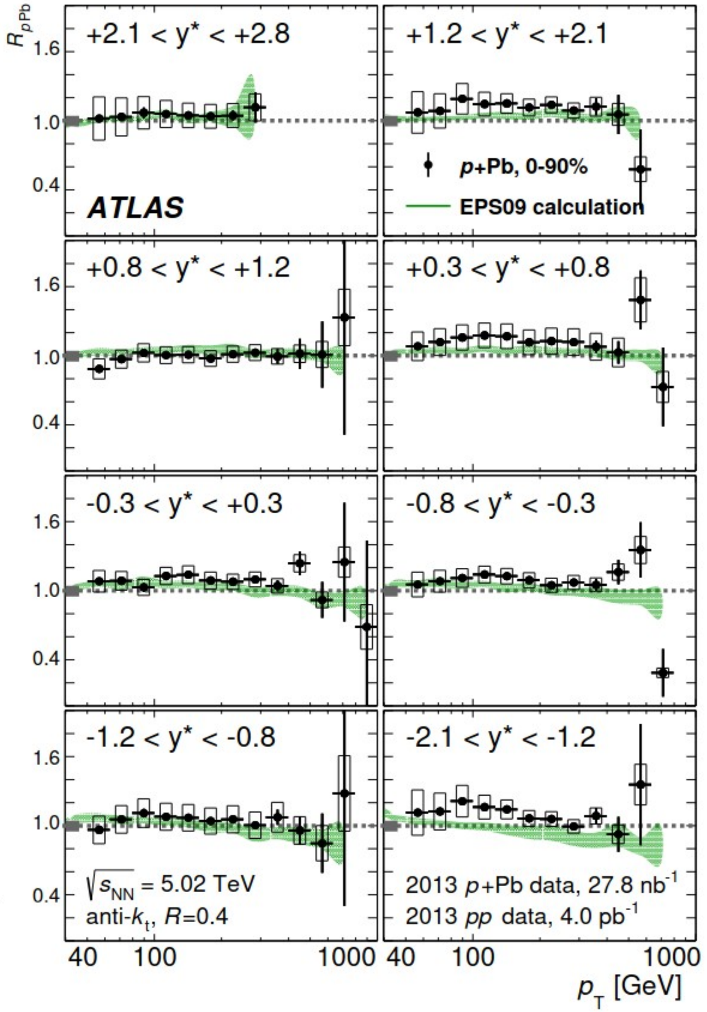


p-Pb 0-90%

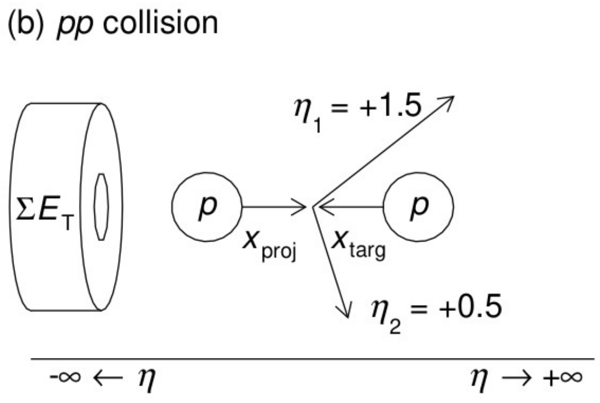
p-Pb 0-10%
p-Pb 20-30%
p-Pb 60-90%



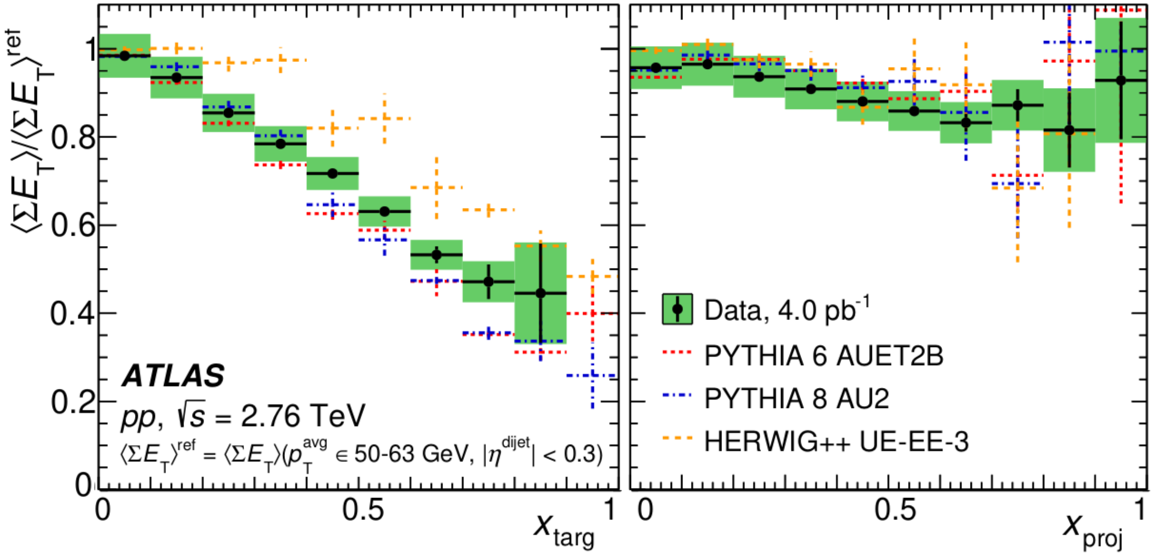
ALTAS, PLB 748 (2015) 392



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



ATLAS, PLB 756 (2016) 10



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

The beam remnant has less longitudinal energy $\Rightarrow$

Reduction of E_T at large η

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

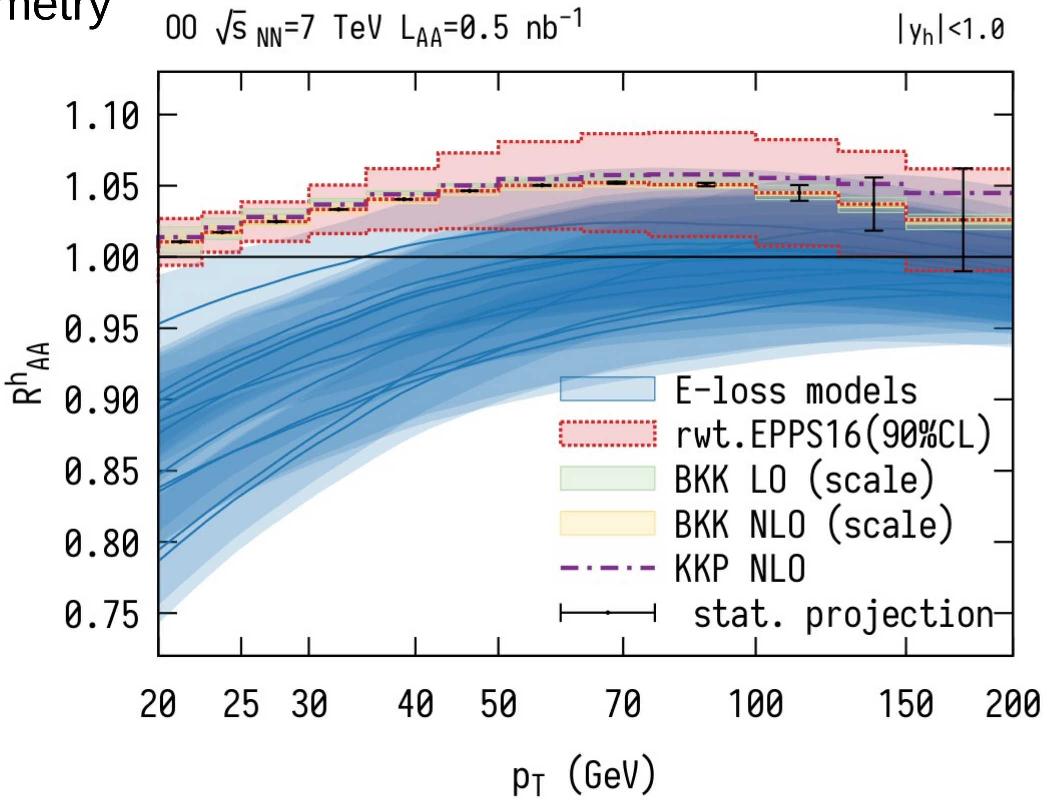
$$R^{h,j}_{\mathrm{AA}}(p_T, y) = \frac{1}{\langle T_{\mathrm{AA}}\rangle} \frac{(1/N_{\mathrm{ev}})\, dN^{h,j}_{\mathrm{AA}}/dp_T dy}{d\sigma^{h,j}_{pp}/dp_T dy}$$

$\langle T_{\mathrm{AA}}\rangle$ 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)



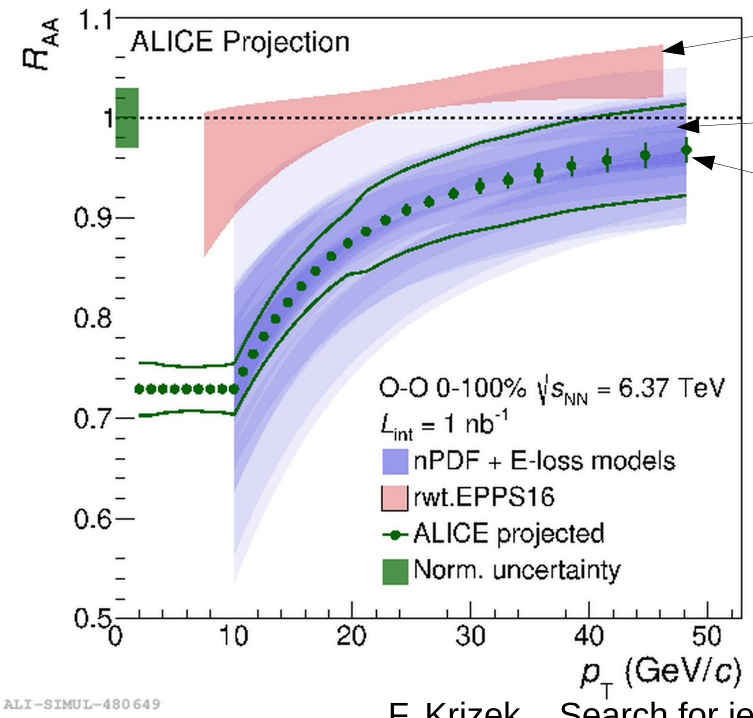
Projection of hadron R_{AA} for min bias OO

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 2024



ALICE-PUBLIC-2021-004

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

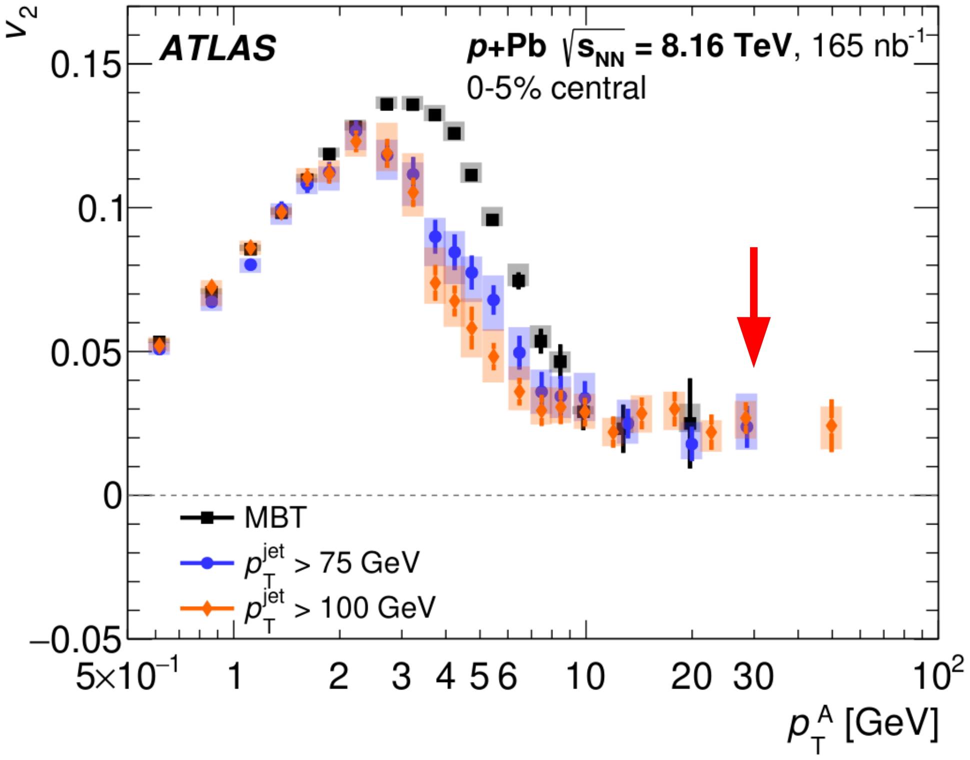
Calculations which assume energy loss models together with nuclear PDFs [Huss et al. arXiv 2007.13754]

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%
  - interpolation error ≤ 3%
  - cross section normalization 3%
  - other systematics 2–4%

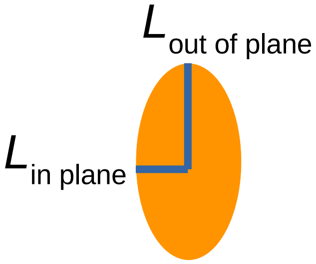
Measurement is potentially sensitive to the effect

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

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



Asymmetric collision zone

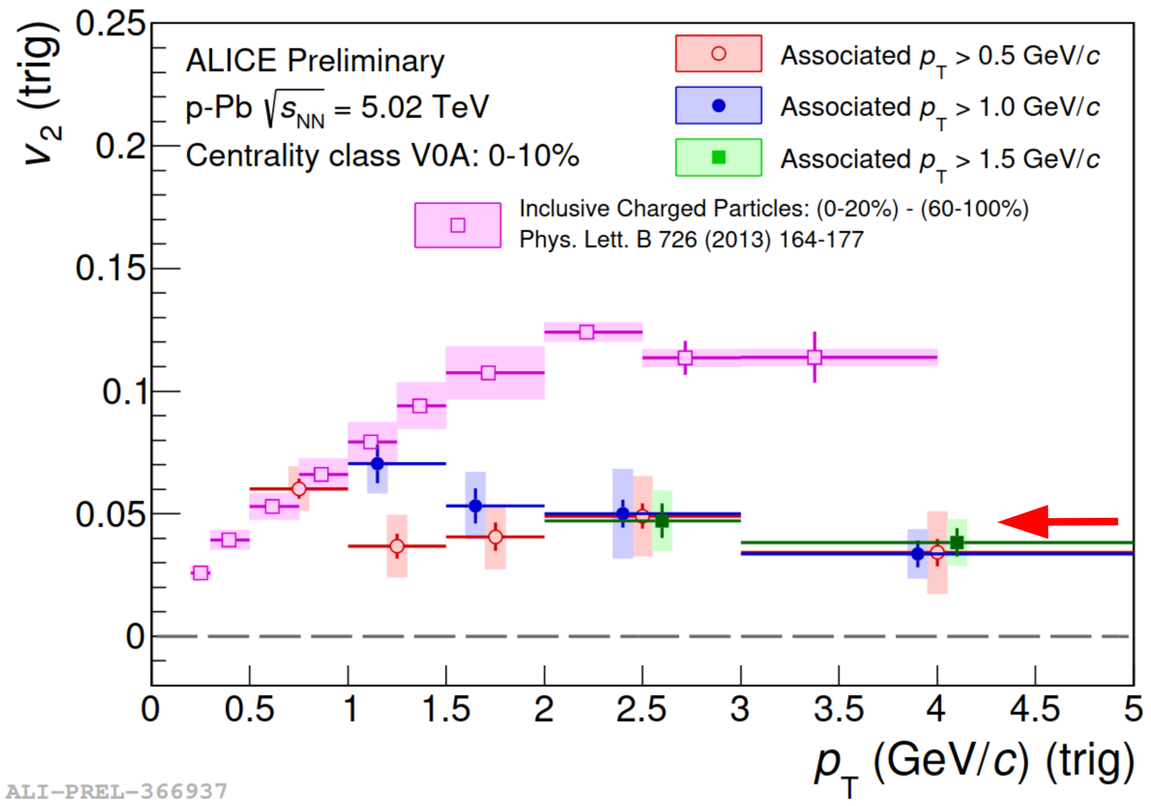


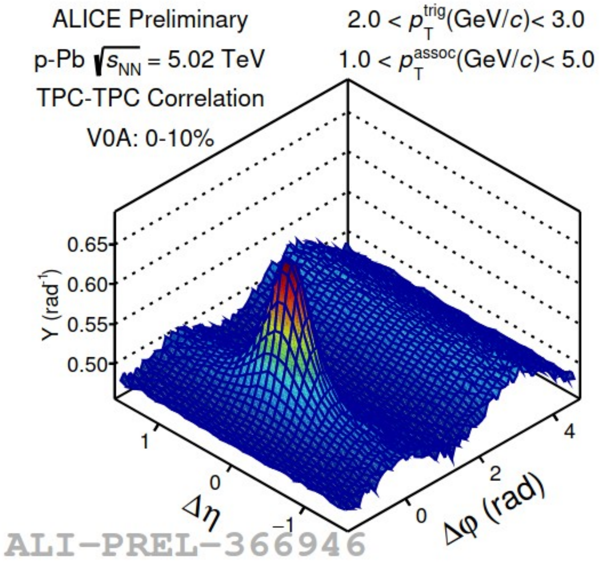
Radiative energy loss of partons

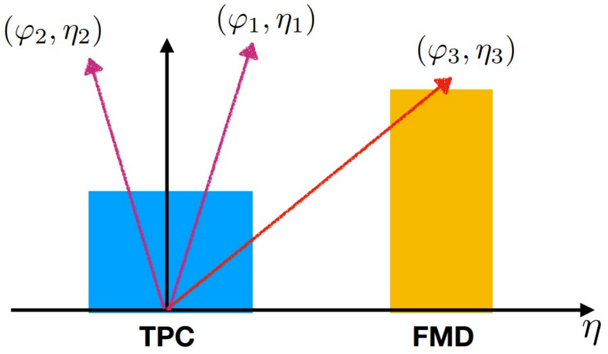
$$\Delta E \propto \hat{q} L^2$$

BDMPS, Nucl. Phys. B483 (1997) 291

Flow of jet fragments in p-Pb by ALICE





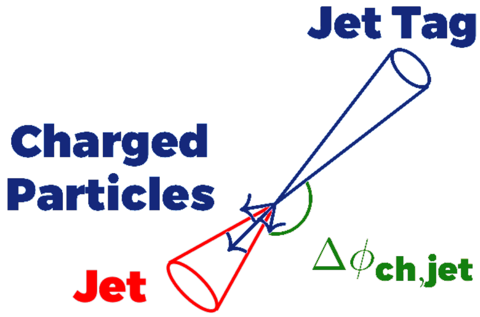


$|\eta_{TPC}| < 0.8$ $\quad$ $1.7 < \eta_{FMD} < 5.1$

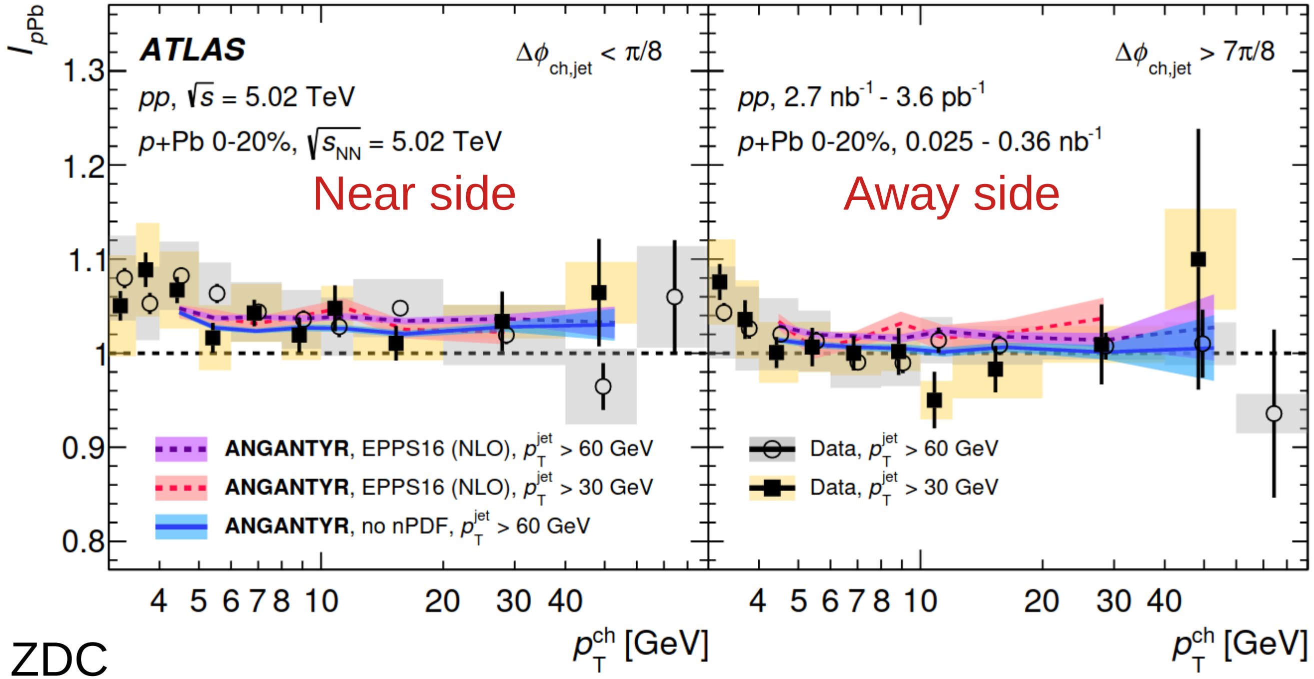
Jet fragmentation in p-Pb from ATLAS

Particle yield associated to jet tag

ATLAS, arXiv 2206.01138



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



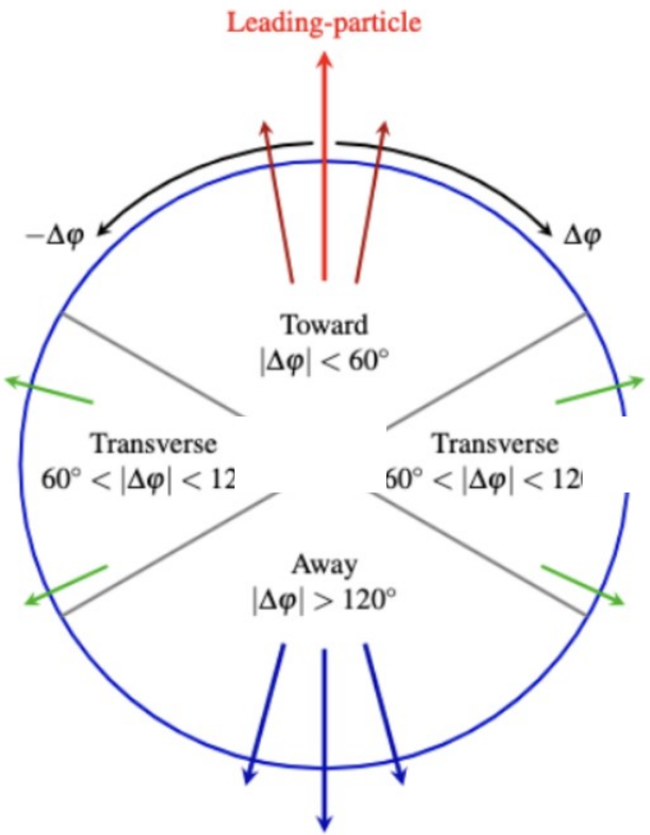
- Event activity measured with ZDC
- No modification in away-side
- Excess in near-side particle production
- Behavior of I_{pPb} is reproduced by PYTHIA ANGANTYR

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

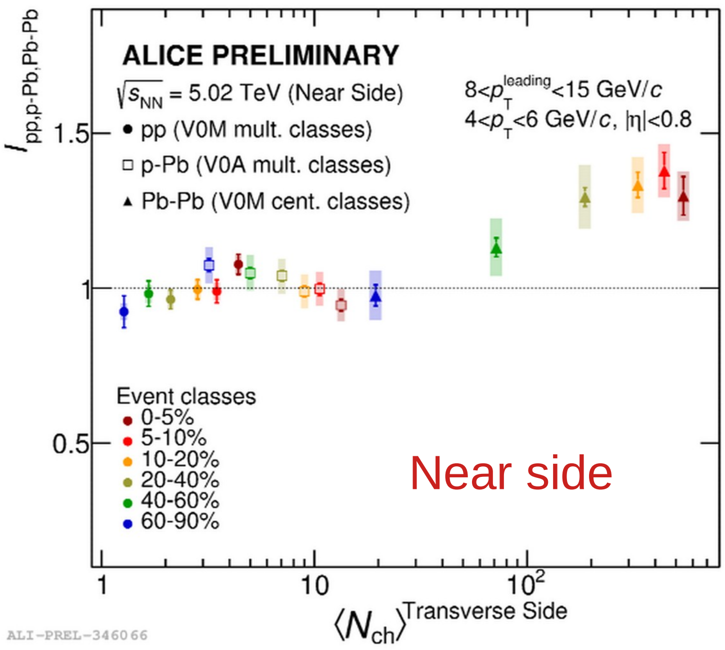
- Correlation of
  8-15 GeV/*c* leading particle
  4-6 GeV/*c* associated particle
  both in $|\eta| < 0.8$

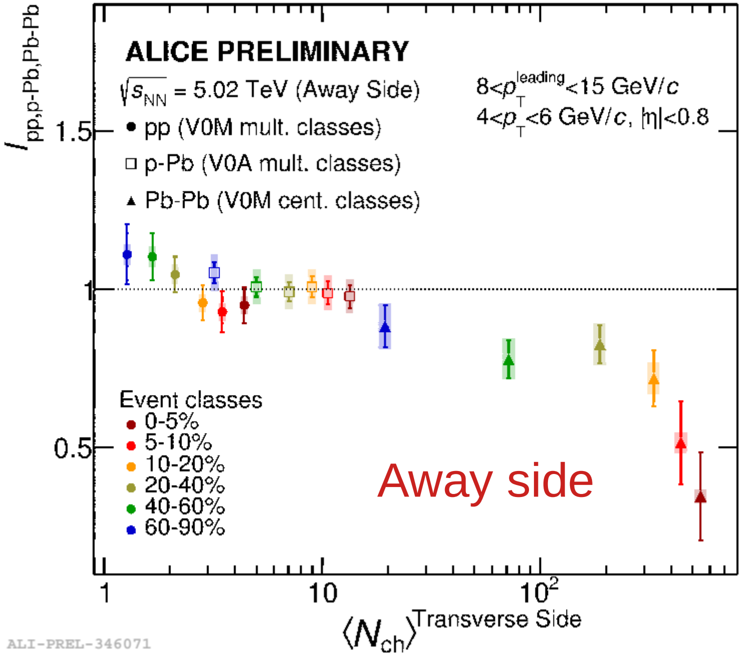
- Per trigger yield corrected for UE estimated in tranverse region relative to the leading particle

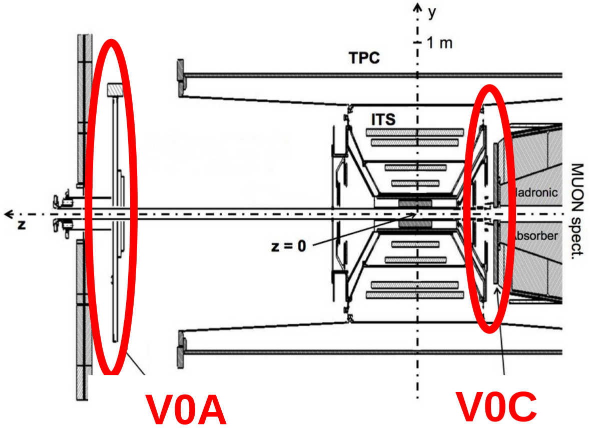
$$I_{\mathrm{pp,p-Pb,Pb-Pb}} = \frac{Y^{\mathrm{pp,p-Pb,Pb-Pb}} - Y_{\mathrm{TS}}^{\mathrm{pp,p-Pb,Pb-Pb}}}{Y^{\mathrm{pp\ min.bias}} - Y_{\mathrm{TS}}^{\mathrm{pp\ min.bias}}}$$



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







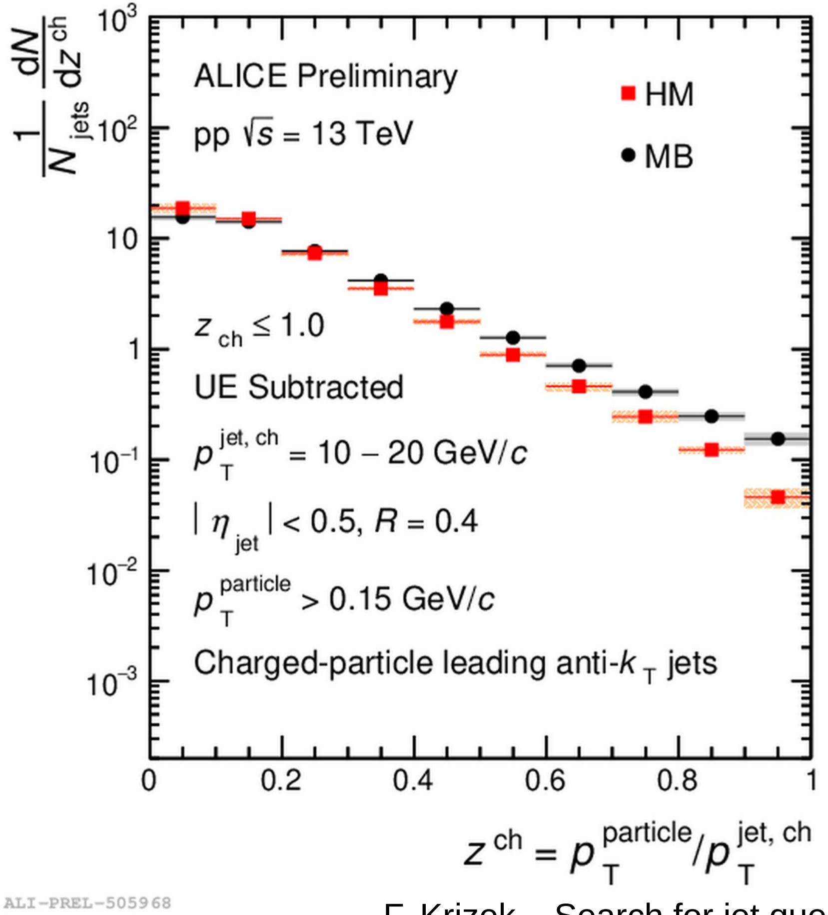
$2.8 < \eta < 5.1$

$-3.7 < \eta < -1.7$

- Event activity classified in forward V0 scintillator detector

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

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

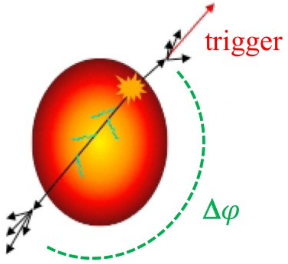


HM event activity selection:
5x larger multiplicity in V0 detector w.r.t min. bias
0-0.1% event activity percentile

HM event selection → softer jet fragmentation

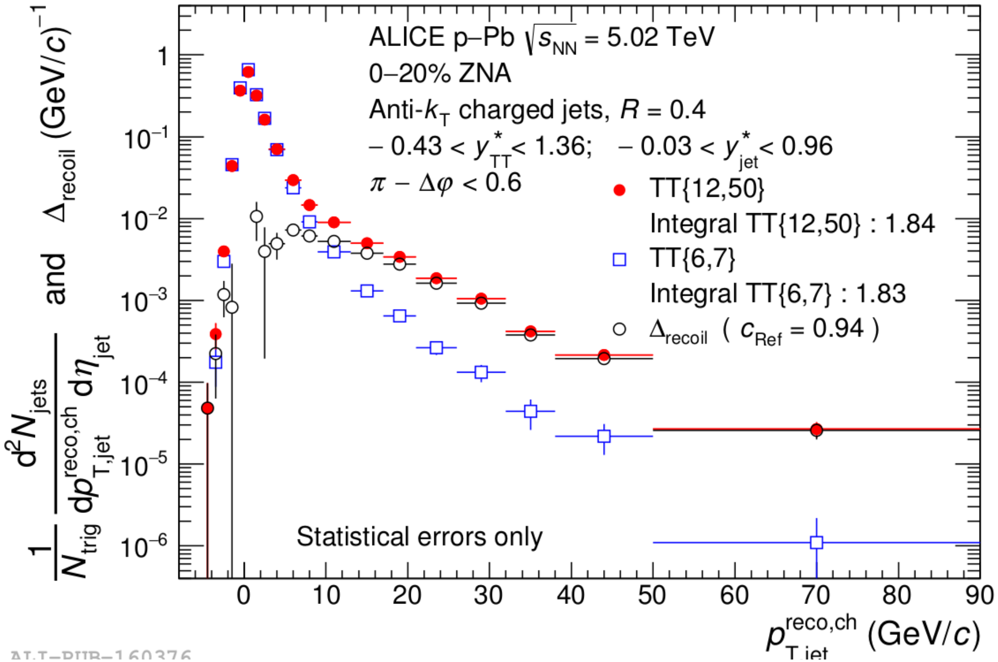
This is consistent with larger portion of jets comming from NLO processes

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



ALICE, PLB 783 (2018) 95

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

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

Hadron-jet observables and T_{AA}

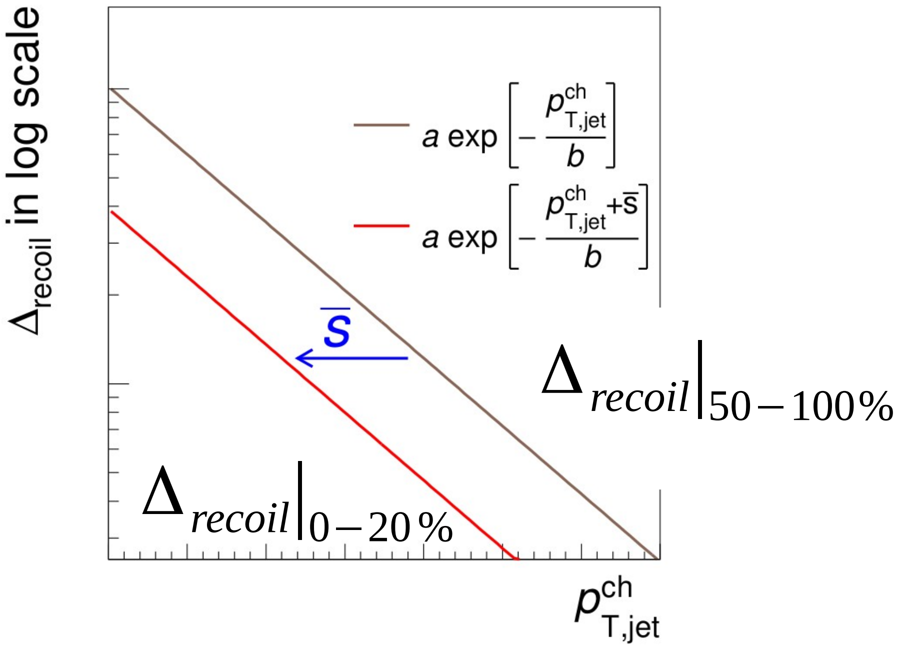
$$\frac{1}{N_{\mathrm{trig}}^{\mathrm{AA}}} \frac{\mathrm{d}^2 N_{\mathrm{jet}}^{\mathrm{AA}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}} \mathrm{d}\eta_{\mathrm{jet}}}\bigg|_{p_{\mathrm{T,trig}}\in \mathrm{TT}} = \left(\frac{1}{\sigma^{\mathrm{AA}\to\mathrm{h+X}}} \cdot \frac{\mathrm{d}^2\sigma^{\mathrm{AA}\to\mathrm{h+jet+X}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\ma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

In case of no nuclear effects

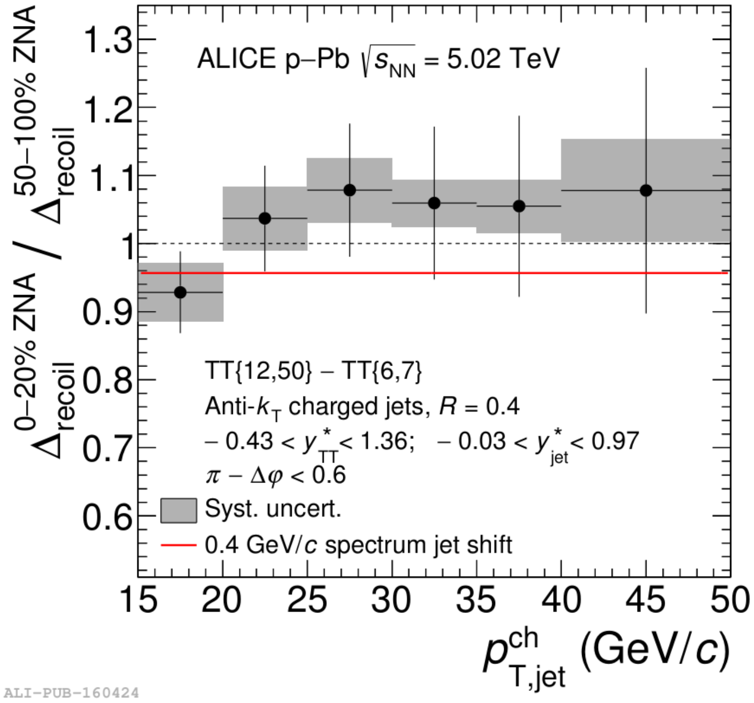
$$\frac{1}{N_{\mathrm{trig}}^{\mathrm{AA}}} \frac{\mathrm{d}^2 N_{\mathrm{jet}}^{\mathrm{AA}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\mathrm{ch}} \mathrm{d}\eta_{\mathrm{jet}}}\bigg|_{p_{\mathrm{T,trig}}\in \mathrm{TT}} = \left(\frac{1}{\sigma^{\mathrm{pp}\to\mathrm{h+X}}} \cdot \frac{\mathrm{d}^2\sigma^{\mathrm{pp}\to\mathrm{h+jet+X}}}{\mathrm{d}p_{\mathrm{T,jet}}^{\ma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

- 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



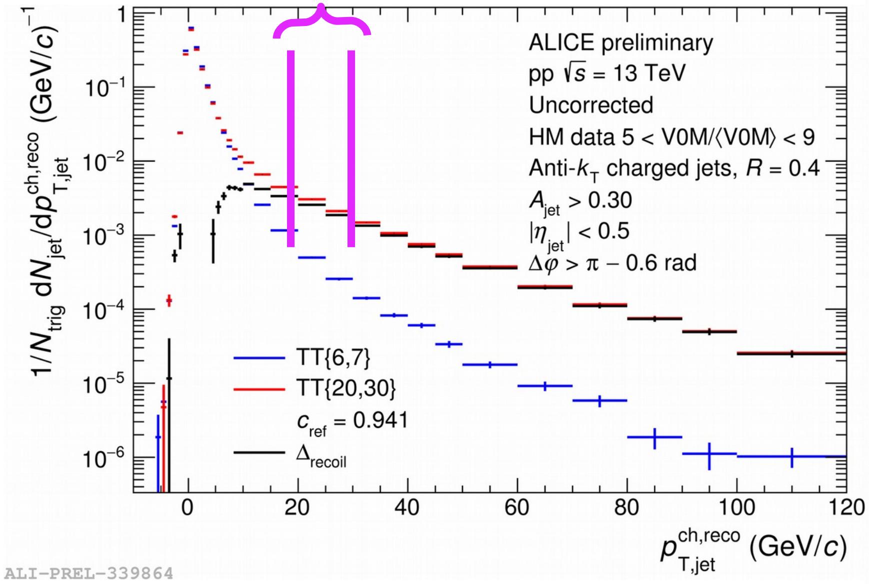
$$\frac{\Delta_{\mathrm{recoil}}\big|_{0-20\,\%}}{\Delta_{\mathrm{recoil}}\big|_{50-100\,\%}} = \exp\left(-\frac{\bar{s}}{b}\right)$$

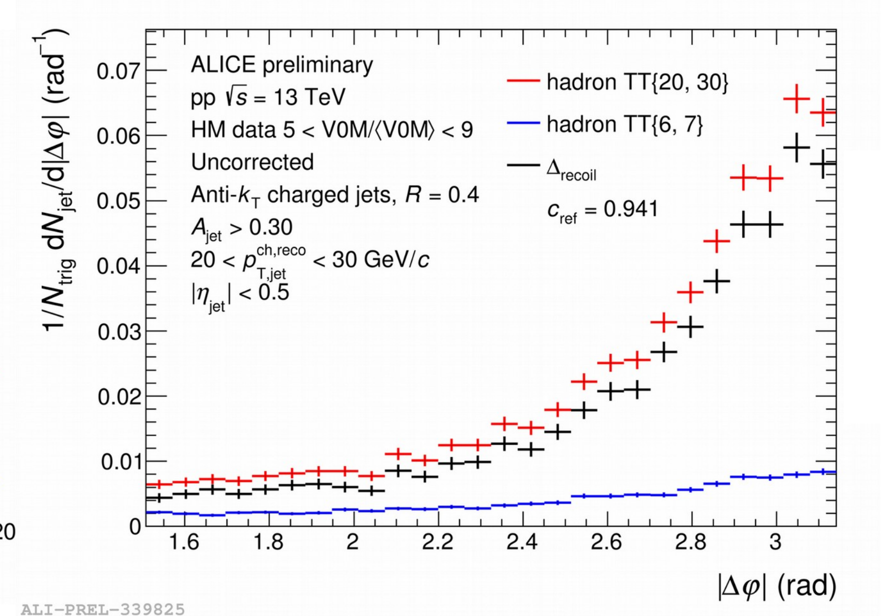
Medium-induced charged energy transport out of R = 0.4 cone is less than 0.4 GeV/c (90% CL)

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

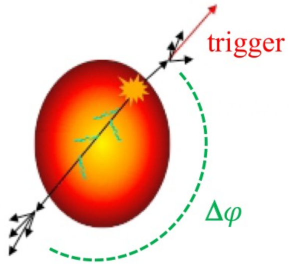
- pp minimum bias (MB)
- pp high-multiplicity (HM) : 5x larger multiplicity in V0 detector w.r.t. MB

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

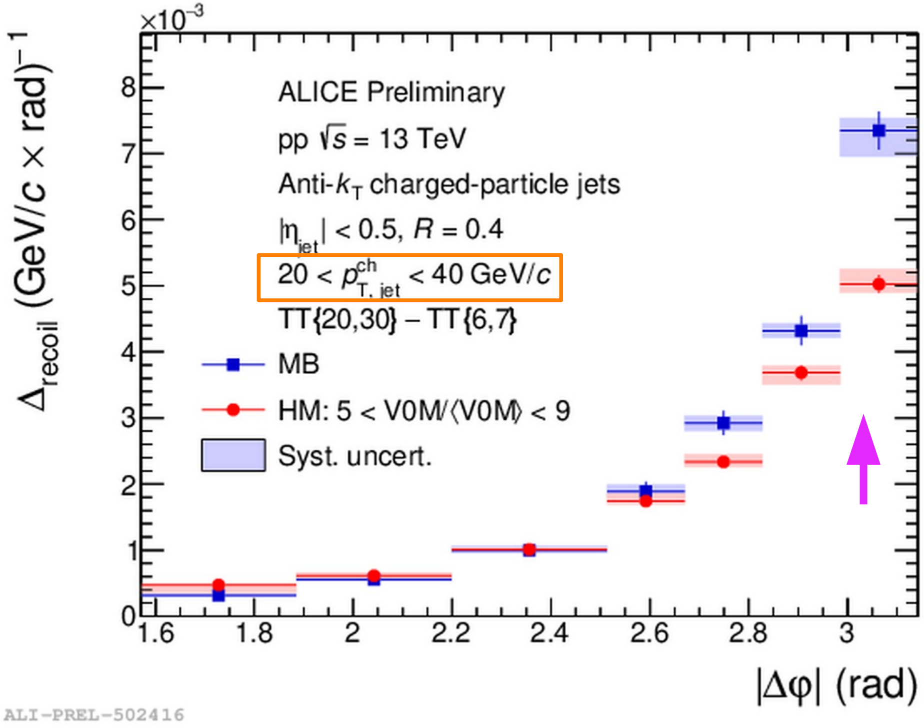


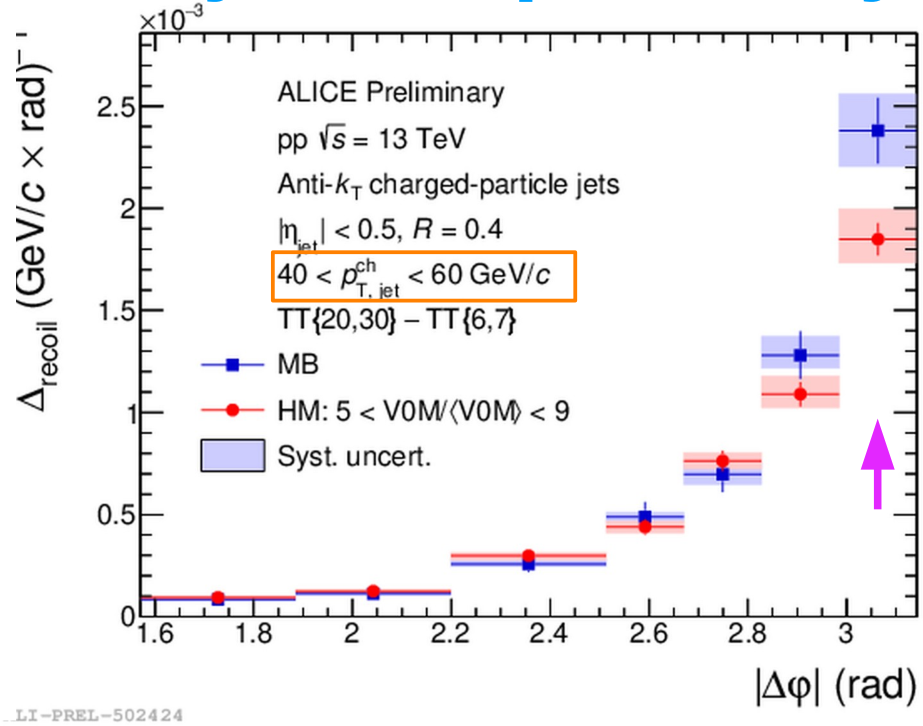


TT{X,Y} means X< $p_{T,trig}$ < Y GeV/c



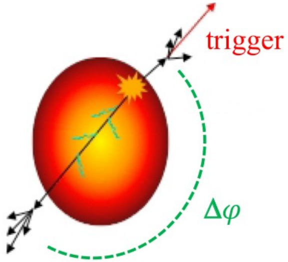
Distributions of hadron-jet acoplanarity





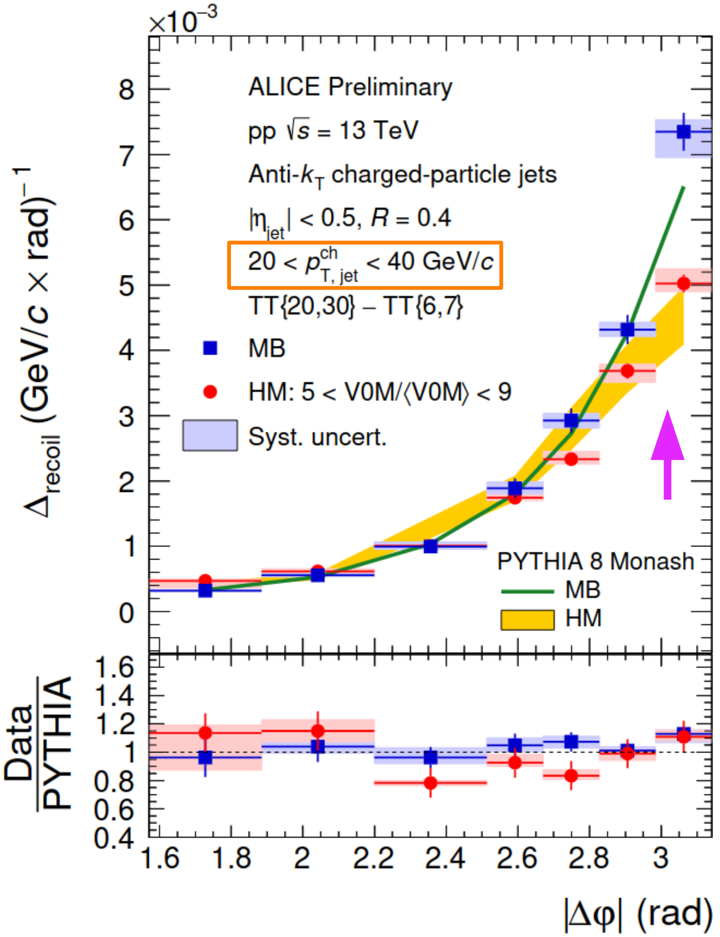
- HM acoplanarity distributions relative to MB
  - suppressed back-to-back correlation
  - broader

The effect is stronger for low p_T jets

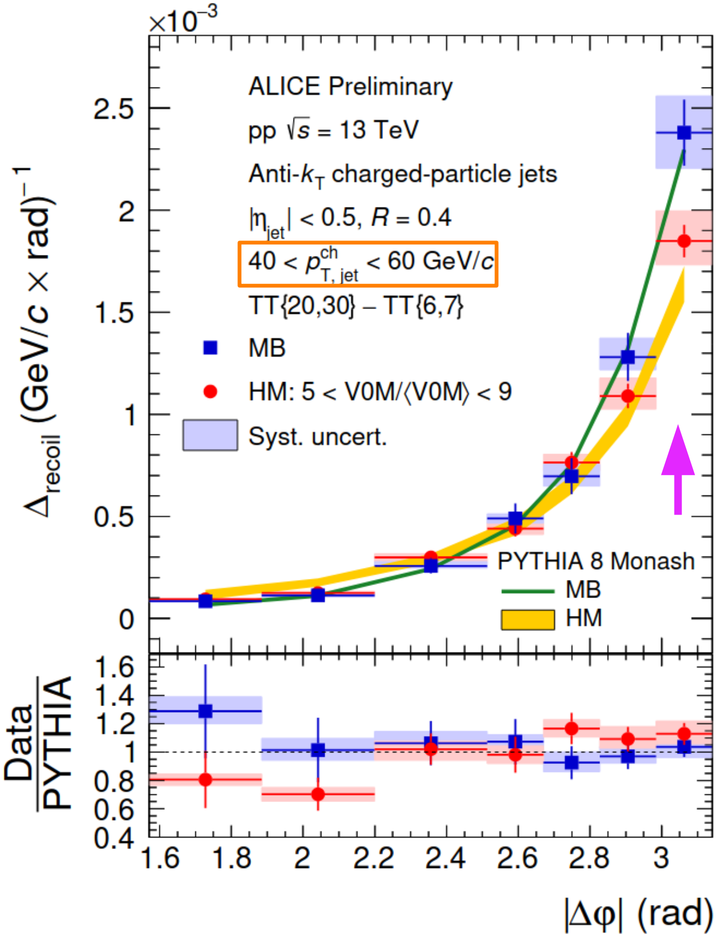


HM event activity selection:
$5 < \mathrm{V0M} / \langle \mathrm{V0M} \rangle < 9$
0.1% of MB cross section

Comparison of hadron-jet acoplanarity with PYTHIA



ALI-PREL-502404



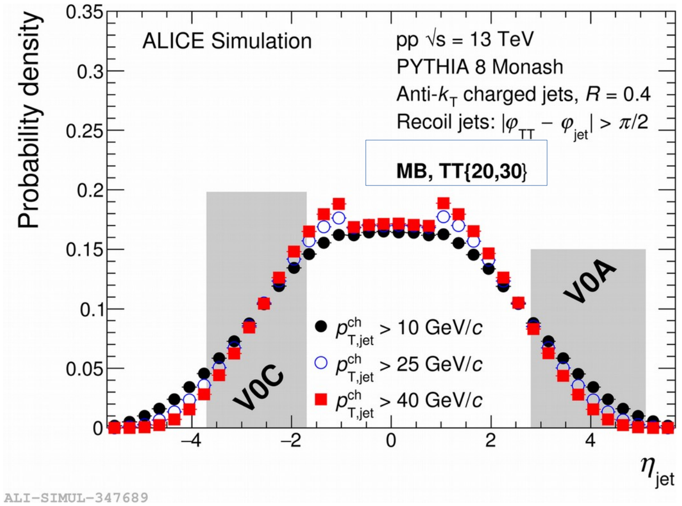
ALI-PREL-502408

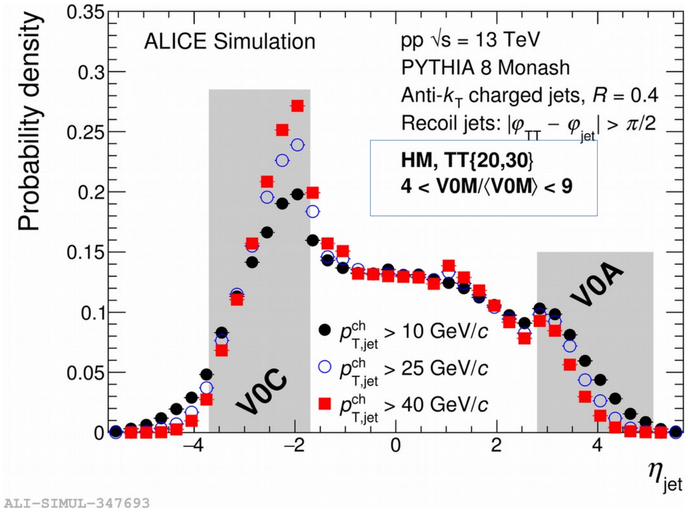
Quantitative comparison to PYTHIA 8 Monash shows similar suppression pattern

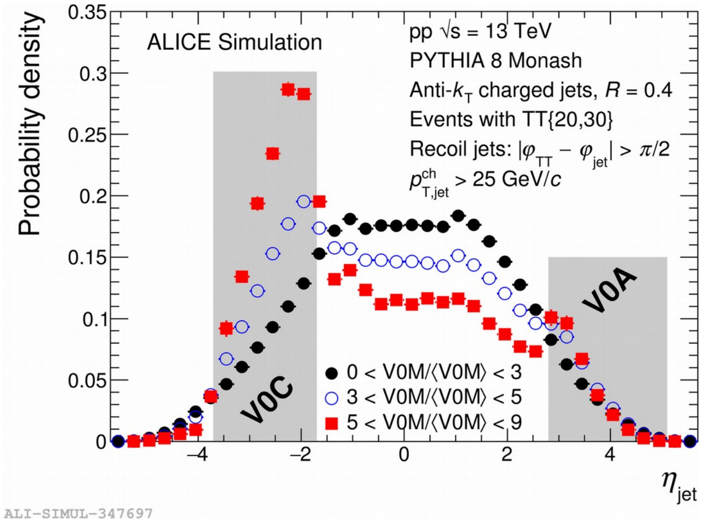
The effect is not due to jet quenching

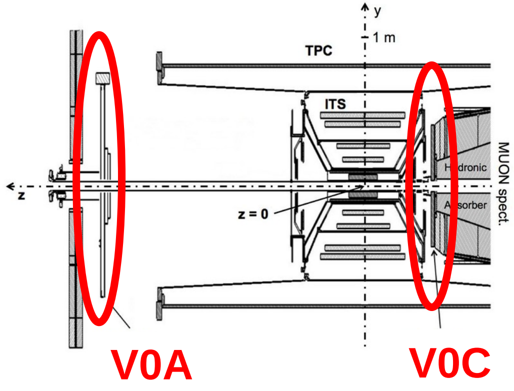
Use PYTHIA to explore the origin of the effect

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









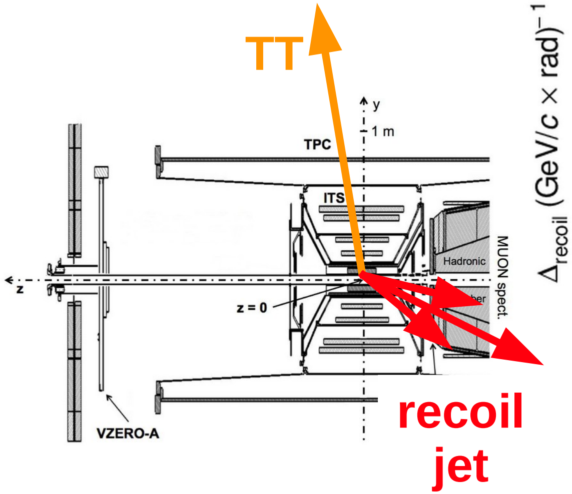
HM events:

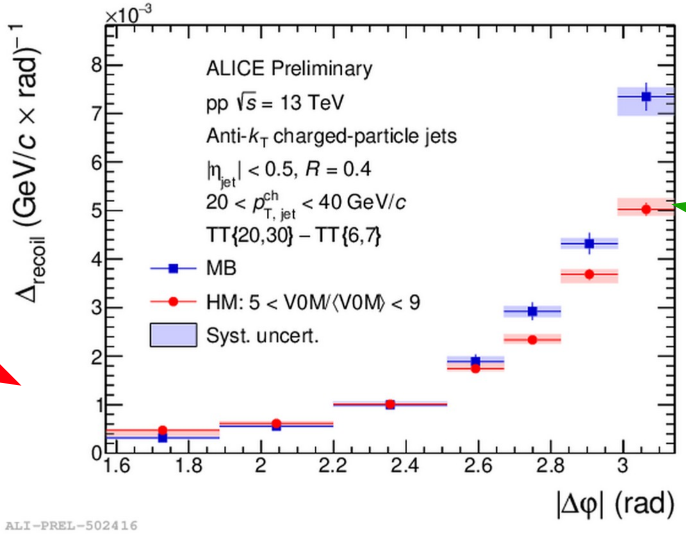
- significant bias in distribution of high-p_T recoil jets
- enhancement in forward trigger detector acceptance
- V0A and V0C have asymmetric coverage

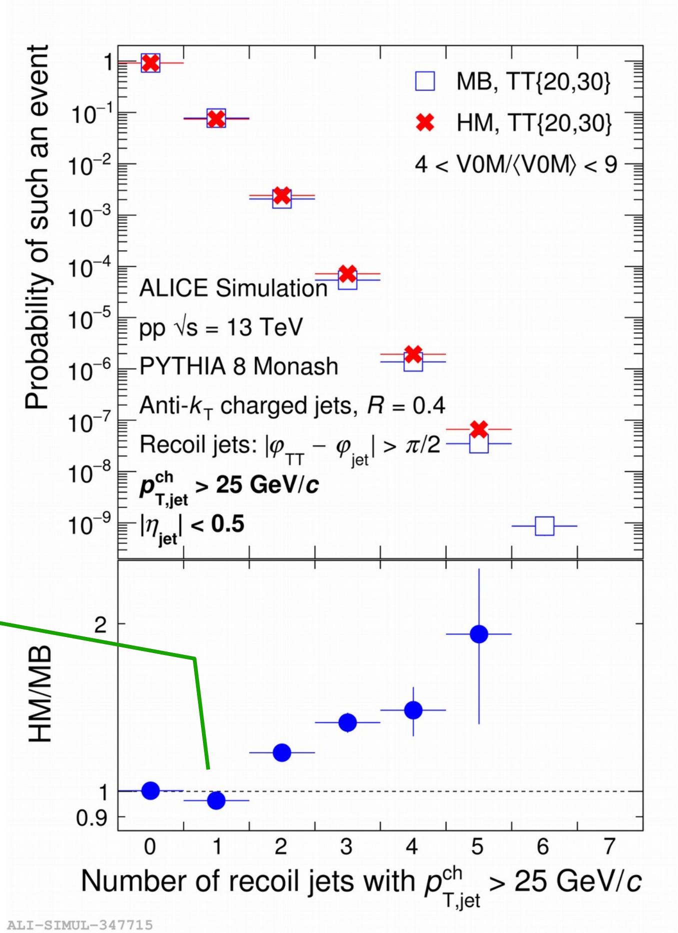
PYTHIA: Number of recoil jets versus event activity in ALICE acceptance

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







Summary

- Jet quenching in small collision systems is likely to be a small effect
- Jet quenching signatures can be created by event selection biases

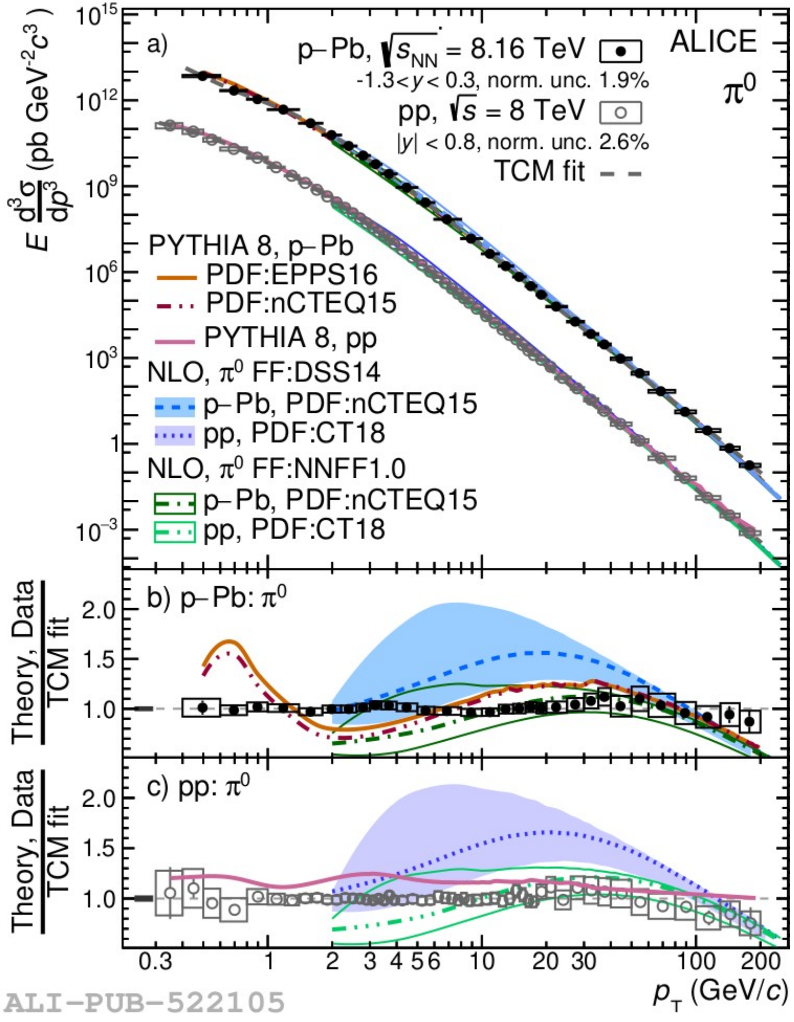
  - picking up fluctuations in particle wavefunction when imposing event activity bias

  - NLO processes with multi jet topology in final state, soft fragmentation

  - cold nuclear matter effects, CGC
- Need to understand positive v_2 of high-p_T particles in p-Pb.
  Would we see the same effect in HM pp?
- New systems comming soon OO, pO

Backup

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

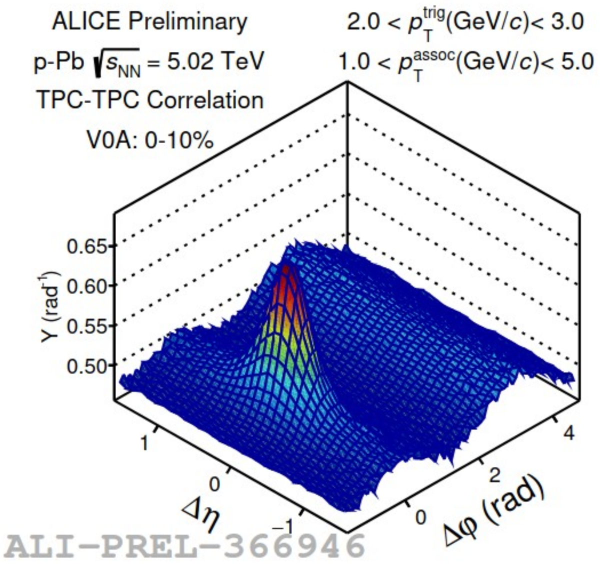


ALICE, PLB 827 (2022) 136943

- 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



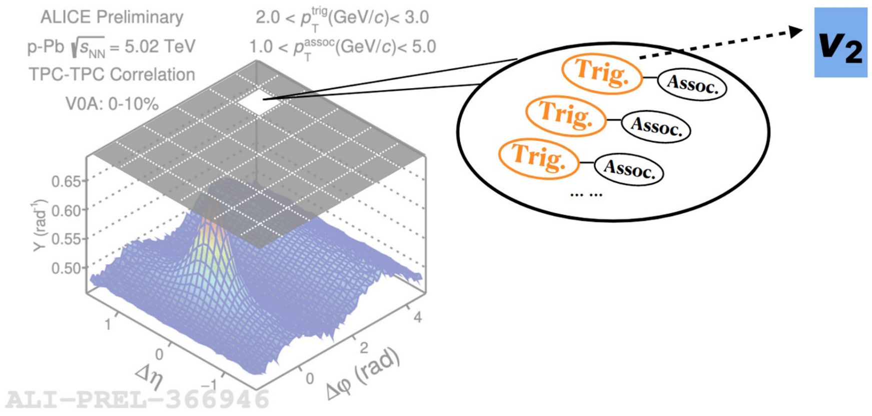
$$Y(\Delta\varphi,\Delta\eta) = \frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}^2N_{\mathrm{pair}}}{\mathrm{d}\Delta\varphi\mathrm{d}\Delta\eta} \approx \frac{S(\Delta\varphi,\Delta\eta)}{B(\Delta\varphi,\Delta\eta)}$$

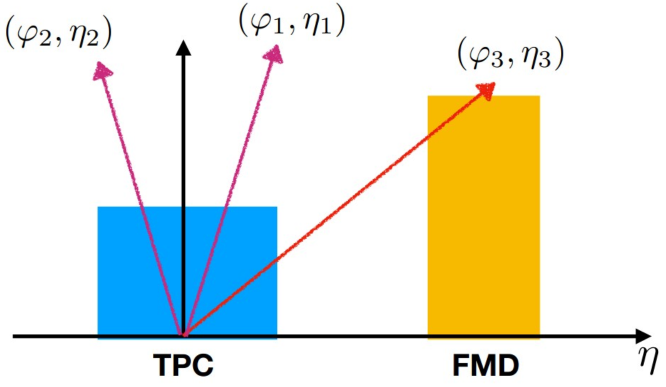
$$S(\Delta\varphi,\Delta\eta) = \frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}^2N_{\mathrm{same}}}{\mathrm{d}\Delta\varphi\mathrm{d}\Delta\eta}, \qquad B(\Delta\varphi,\Delta\eta) = \alpha\frac{\mathrm{d}^2N_{\mathrm{mix}}}{\mathrm{d}\Delta\varphi\mathrm{d}\Delta\eta}$$

Elliptic flow of jet fragments in p-Pb

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

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



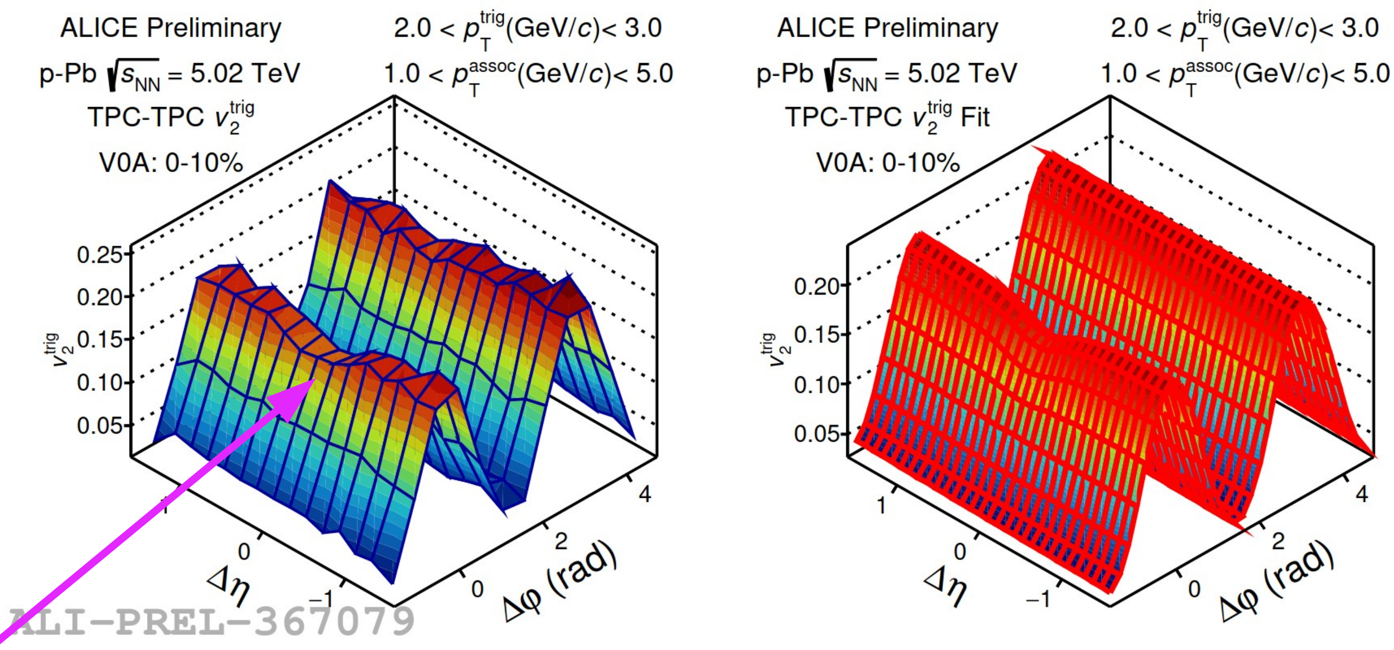


$$\frac{dN}{d\Delta\varphi'} \propto 1 + 2\sum_{n=1}^{3} \Delta V_n(\Delta\varphi, \Delta\eta)\cos(n\Delta\varphi'), |\Delta\eta| > 1$$

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

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

Elliptic flow of jet fragments in p-Pb



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

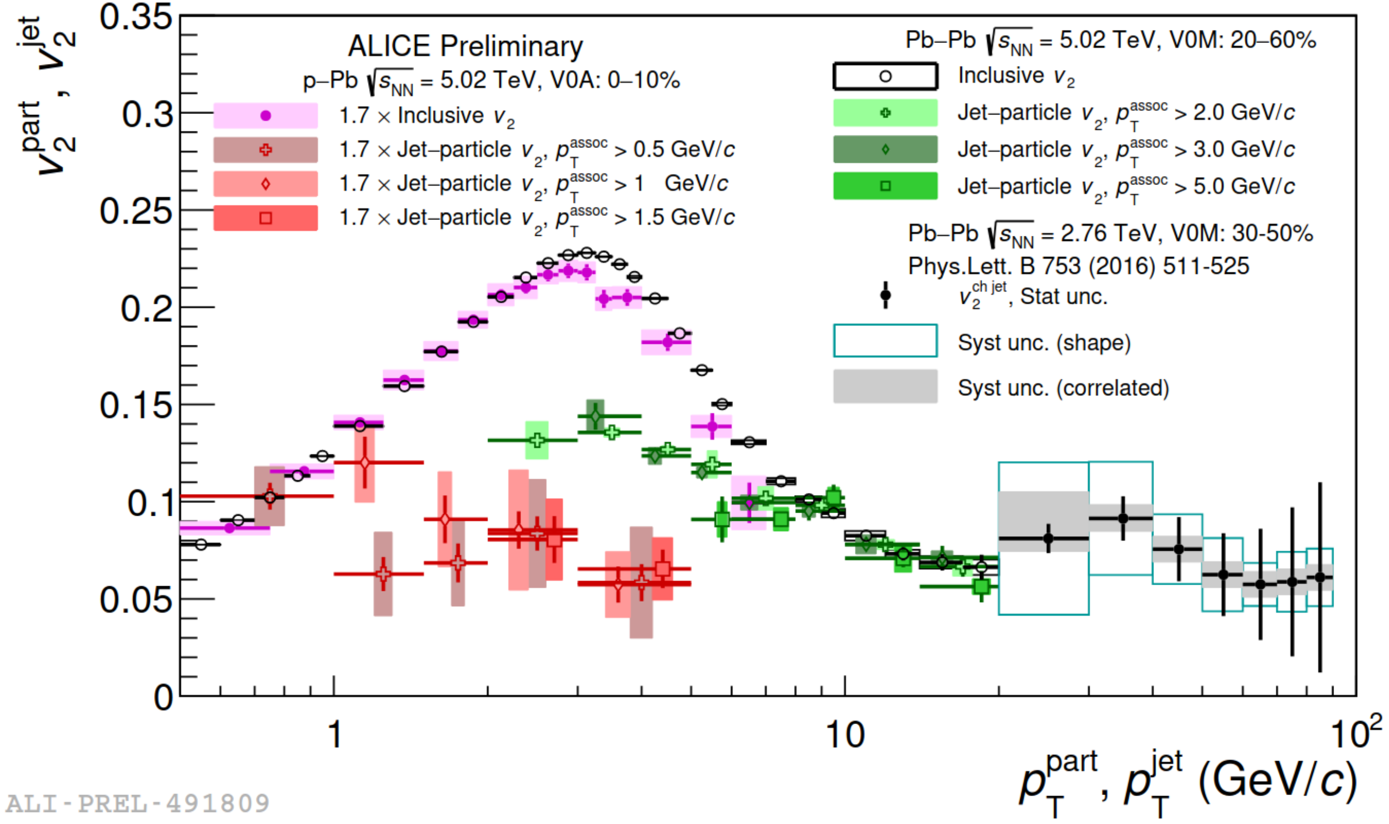
→

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

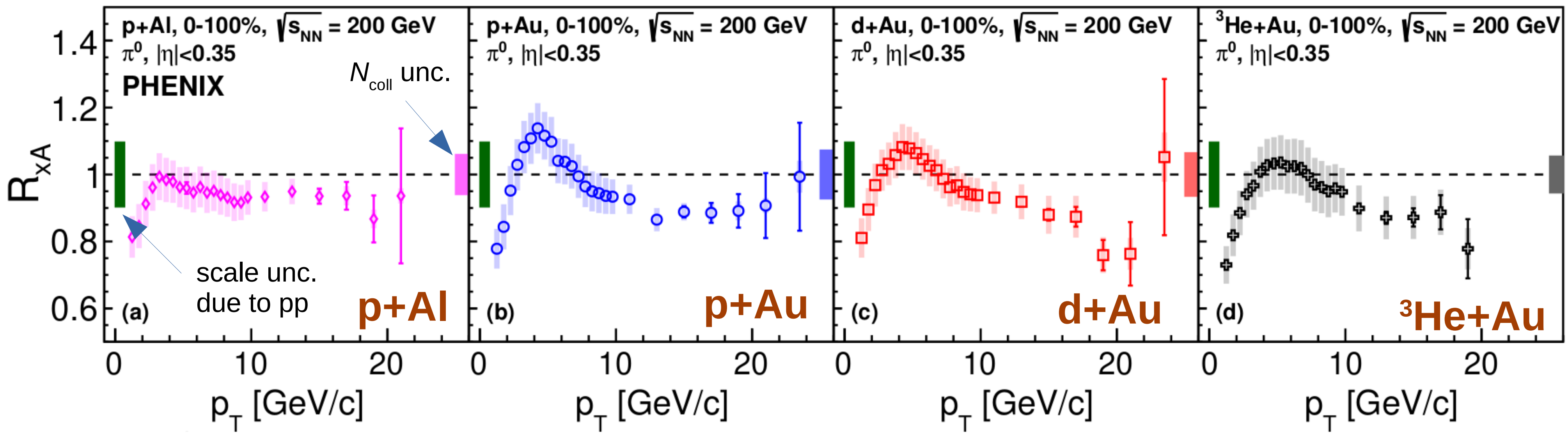
p-Pb:

- 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

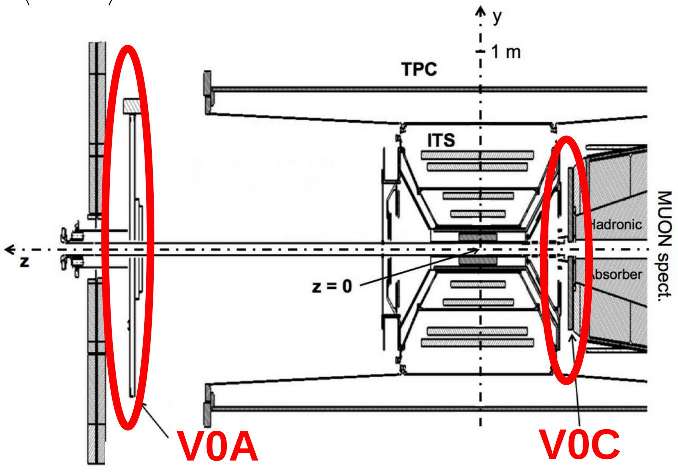
Event activity selection in pp at √s = 13 TeV

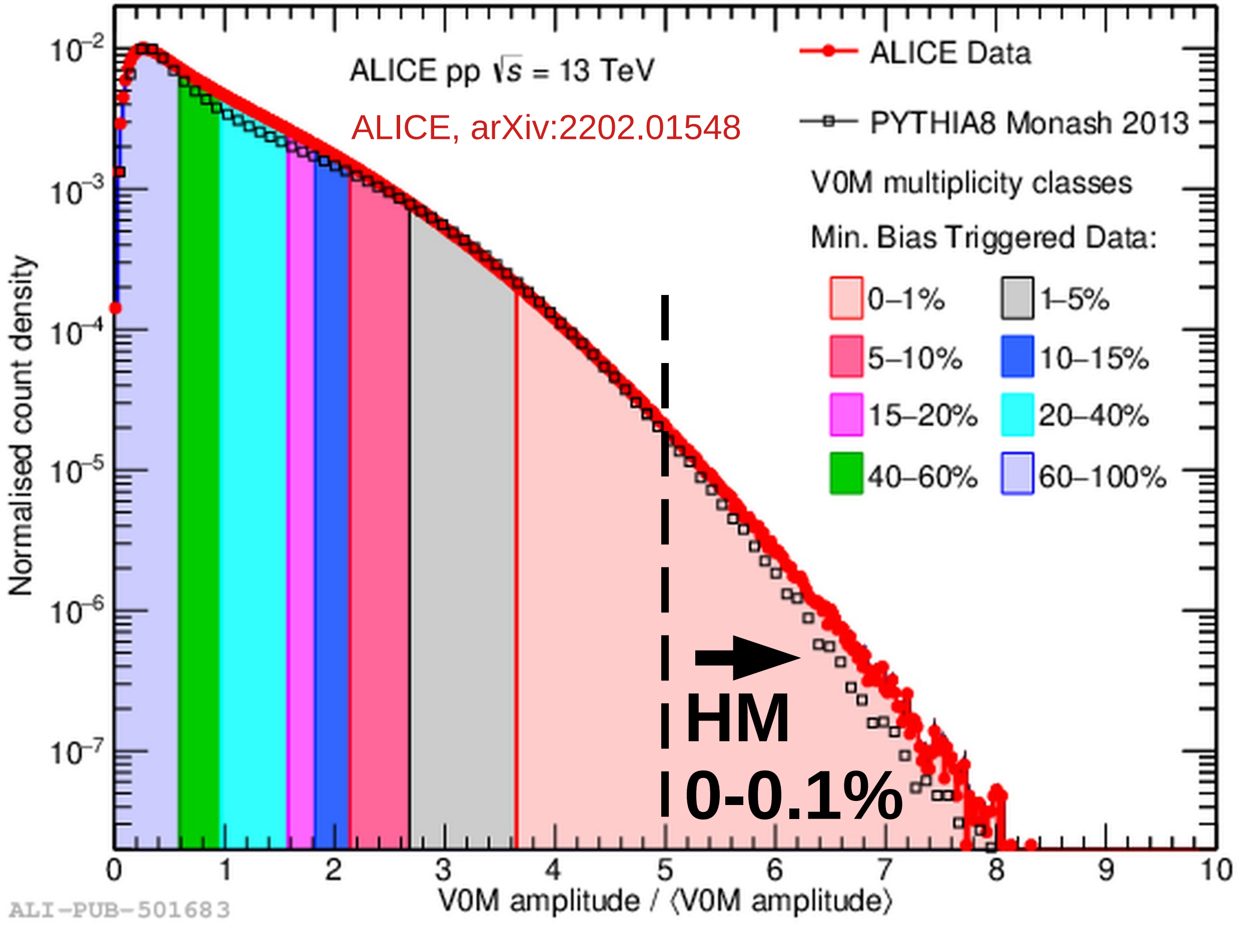
- Trigger:
  - Minimum bias (MB) $L_{int} \approx 32\ nb^{-1}$
  - High multiplicity (HM) $L_{int} \approx 10\ pb^{-1}$
- Event activity (EA) selection:

  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





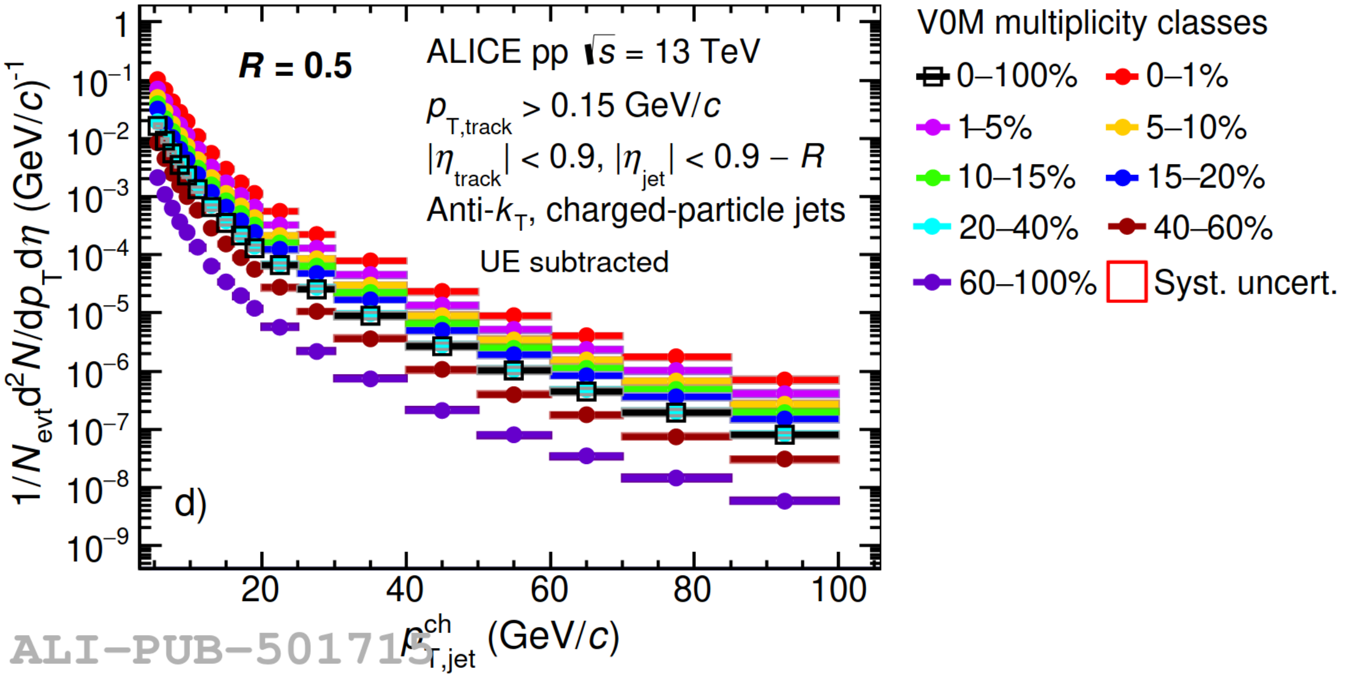
Charged-particle jets in MB and event activity biased pp collisions at √s = 13 TeV

arXiv:2202.01548

- Tracks
  $|\eta_{track}| < 0.9$
  $0 < \varphi_{track} < 2\pi$
  $p_{T,track} > 150$ MeV/c

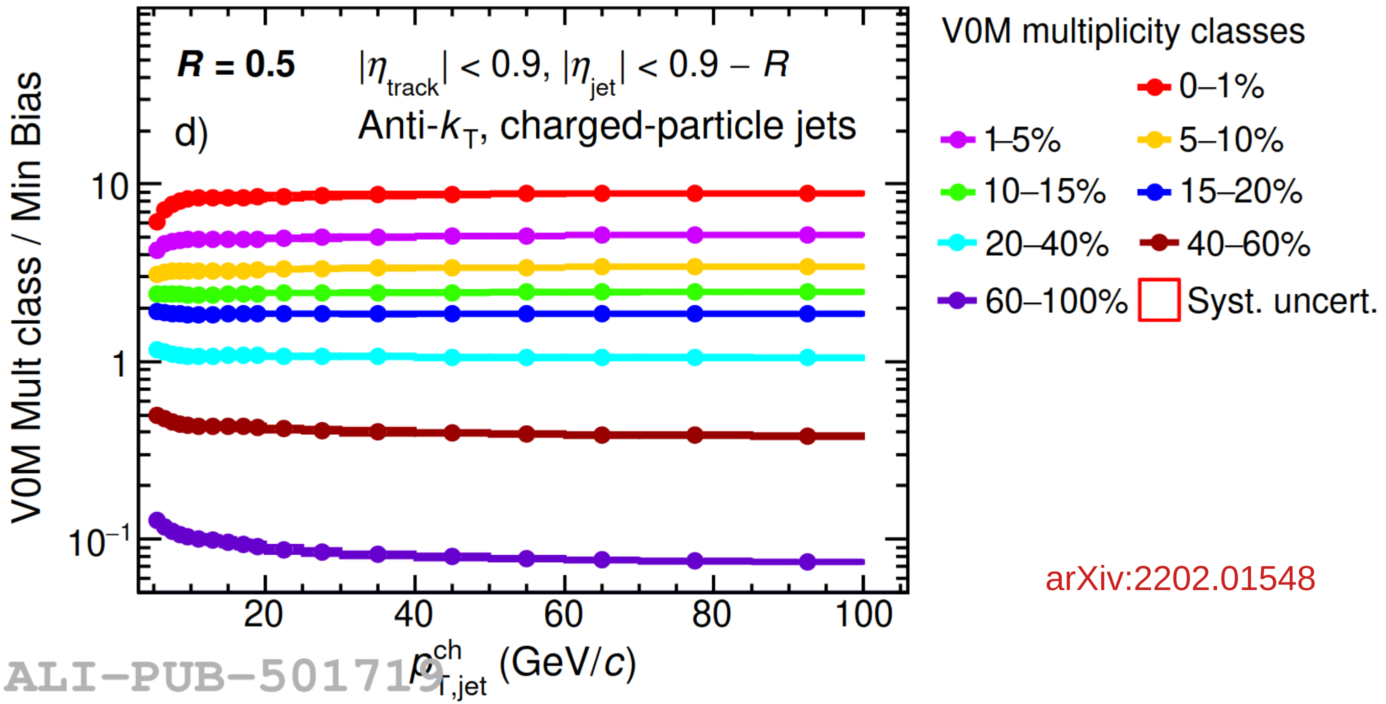
- Charged-particle jets
  Anti-k_T algorithm
  $|\eta_{jet}| < 0.9 - R$
  $\boldsymbol{R = 0.2 – 0.7}$

- $p_{T,ch\ jet} = p^{raw}_{T,ch\ jet} - \rho\, A_{jet}$



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

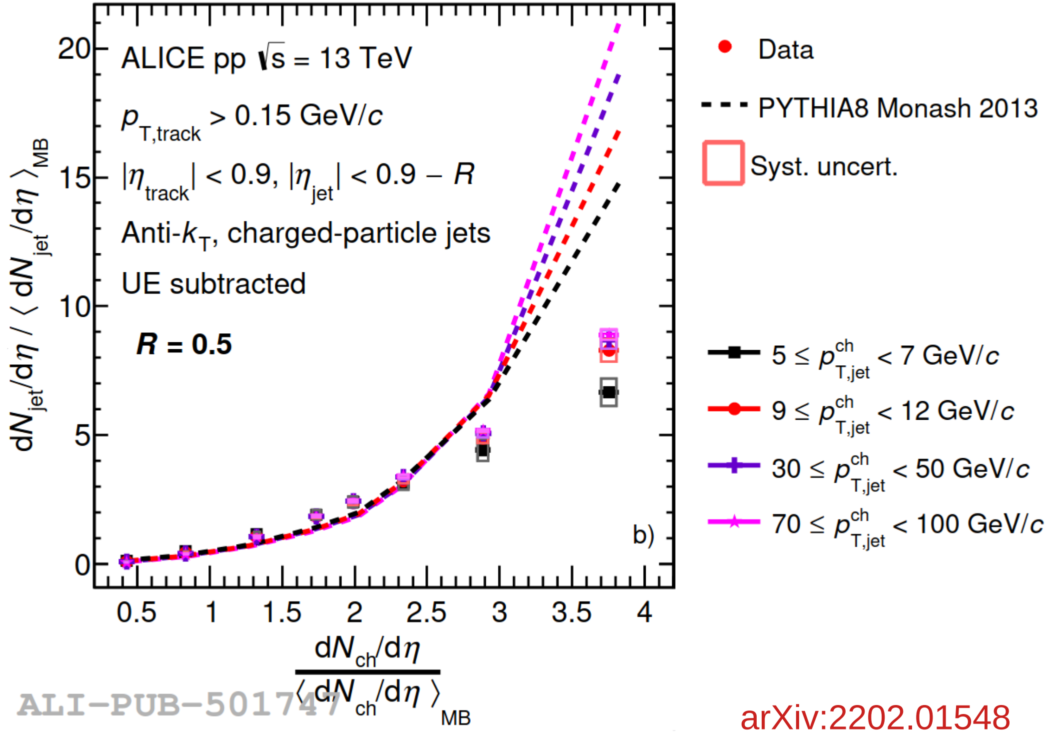
- Jets with $p_{\mathrm{T,\,jet}}^{\mathrm{ch}} > 9$ GeV/c follow non-linear trend similar to J/ψ in midrapidity

  Phys. Lett. B 810 (2020) 135758

  and heavy-flavor electrons and prompt D

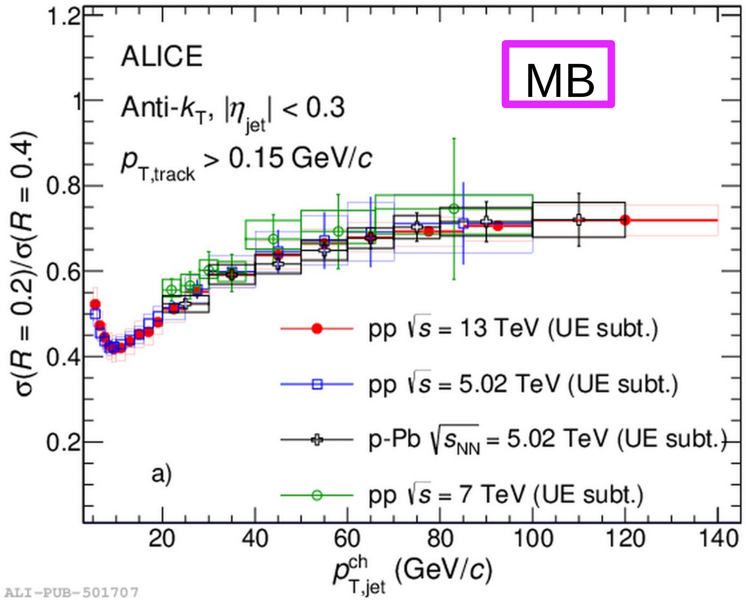
- Electrons from W decay follow linear trend

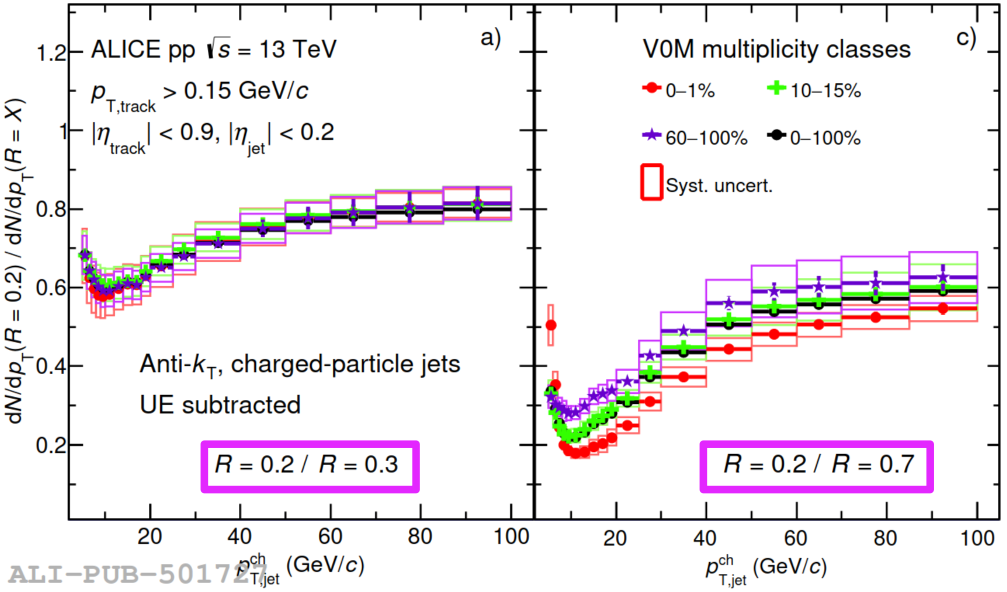
- Overshoot of the trend by PYTHIA at high charged-particle multiplicities



arXiv:2202.01548

Ratios of jet p_T spectra with different R





arXiv:2202.01548

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