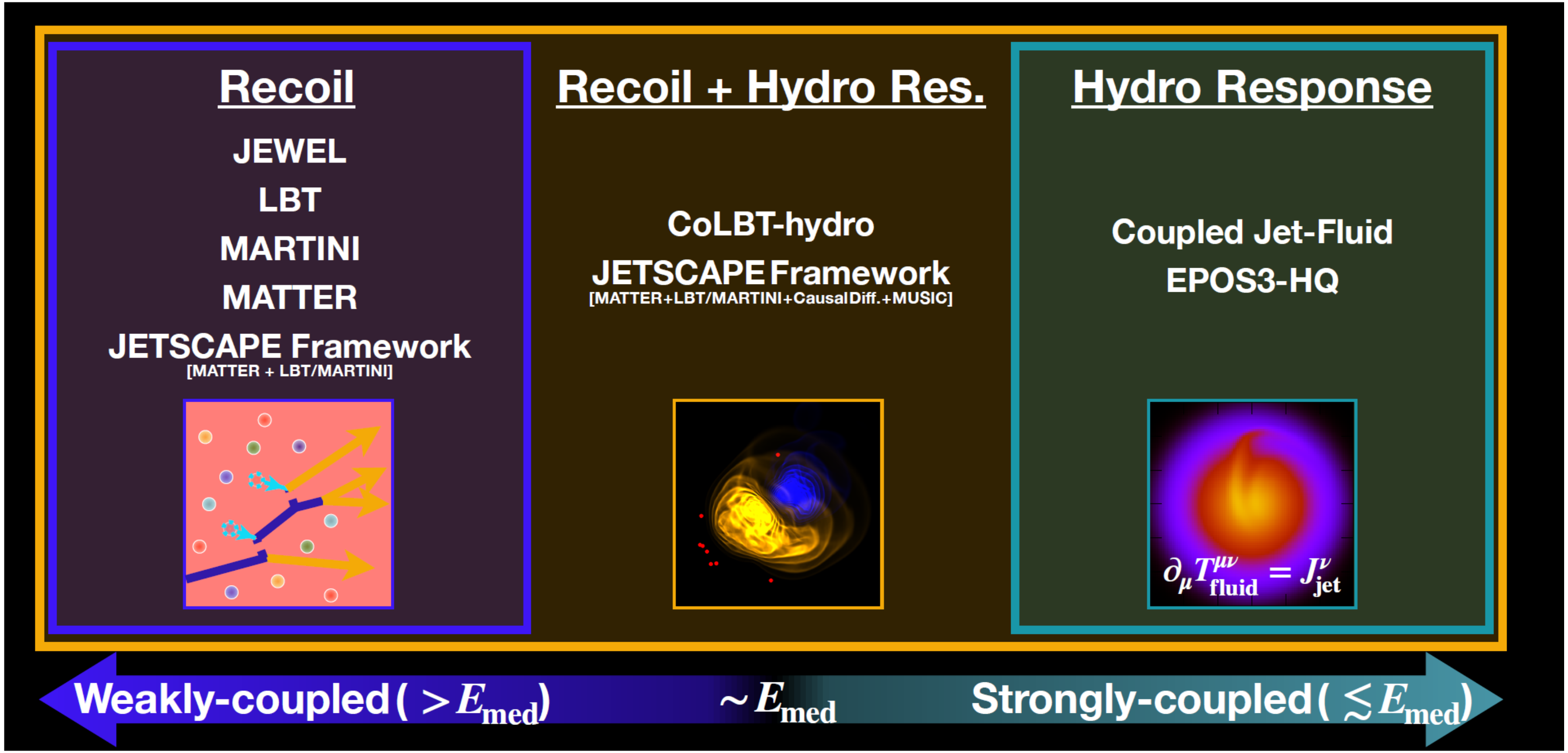
Summary: Jets and High-p_T

Jana Bielcikova
(Nuclear Physics Institute of the CAS)

10th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions

Models for medium response in a nutshell



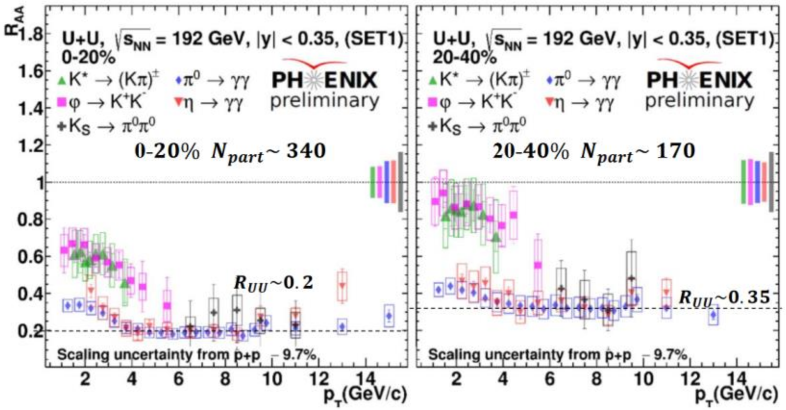
Slide courtesy Y. Tachibana, Plenary Wed 9:00

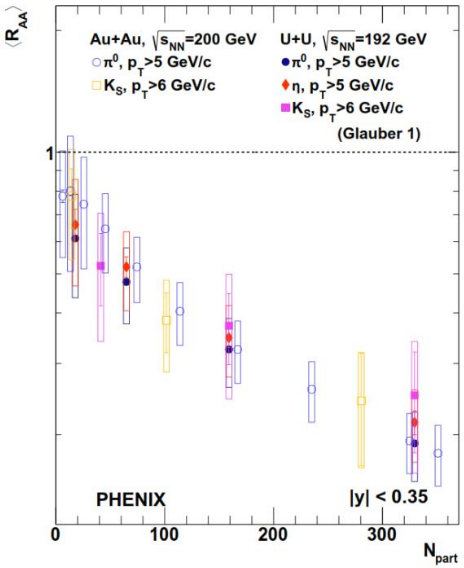
The R_{AA} …

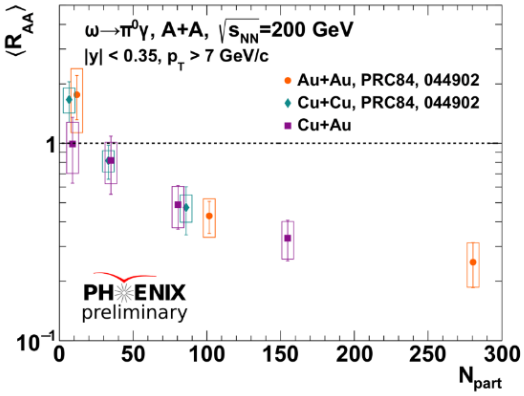
A. Drees, Thu 12:20

Hadron R_{AA} at RHIC: U+U collisions

central semi-central







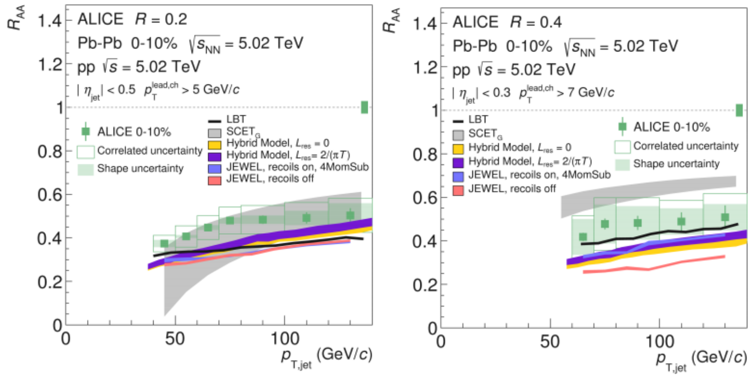
- $R_{AA}(p_T, N_{part})$ dependence qualitatively consistent between U+U and Au+Au
- Rich spectrum of meson species measured
- K*, ϕ less suppressed than π^0, η at lower p_T

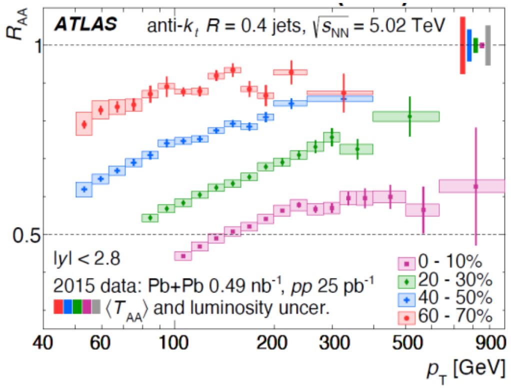
Universal high p_T suppression with N_{part} for light and strange quark mesons → Jet fragmentation not modified (or modified equally).

PHENIX, arXiv: 2005.14686

Jet R_{AA} measurements at LHC: going to large R

CMS, C. McGinn, Mon 12:20
ATLAS, W. Zou, poster

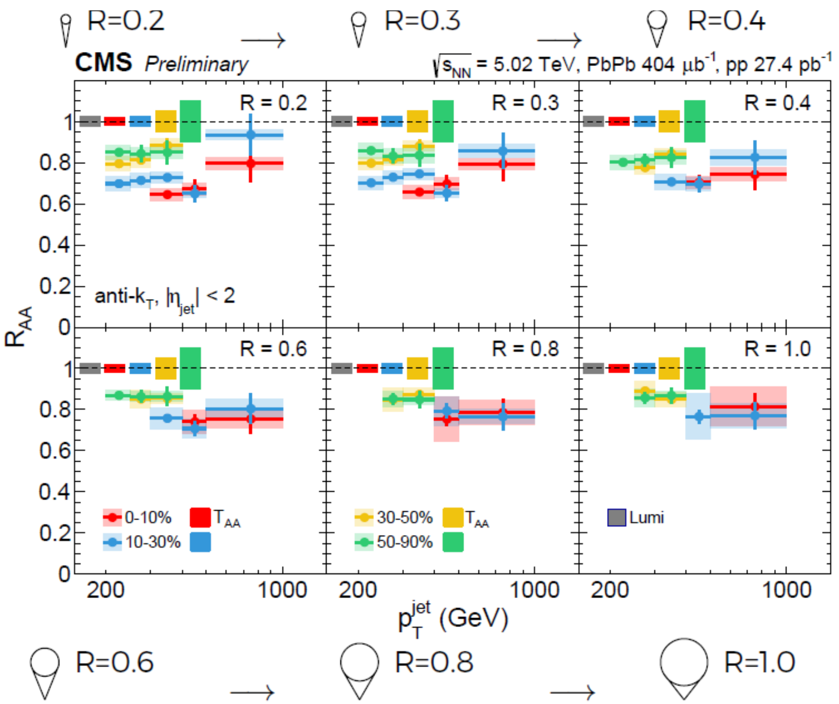




ALICE:
low p_T jets, moderate R

x

ATLAS, CMS:
high p_T jets, larger R

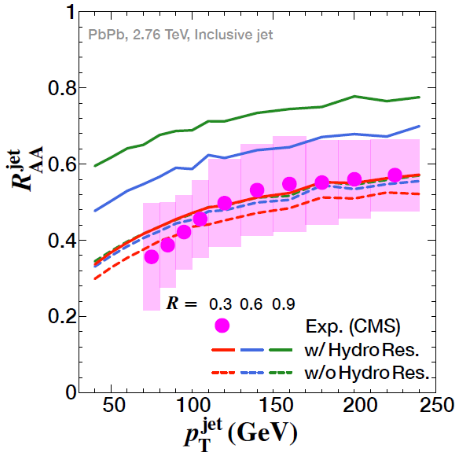


CMS measured jet R_{AA} in Pb+Pb at 5.02 TeV for large R > 0.6 in large background.
Only modest increase, R_{AA} never reaches 1.

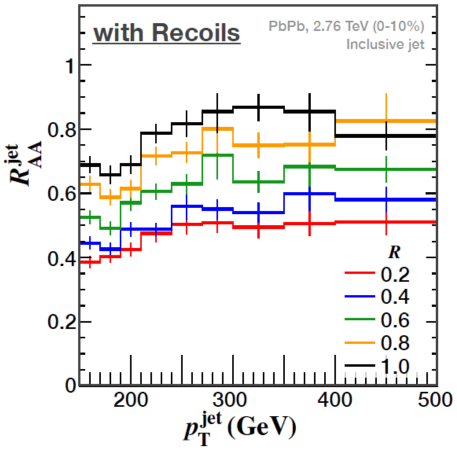
ALICE, PRC 101, 034911 (2020)
ATLAS, PLB 790 (2019) 108

Jet R_{AA} calculations: there are many …

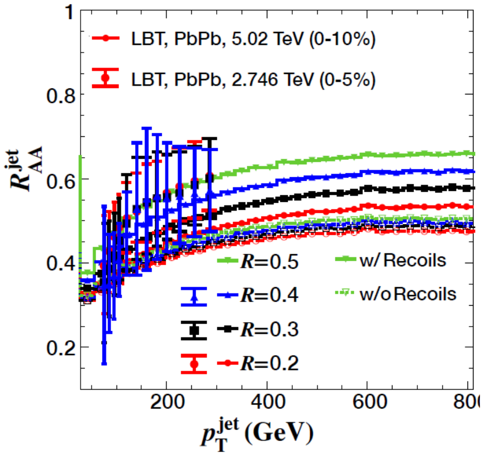
Coupled Jet-Fluid Hydro
YT, N.-B. Chang, G.-Y. Qin, PRC 95, 044909 (2017)

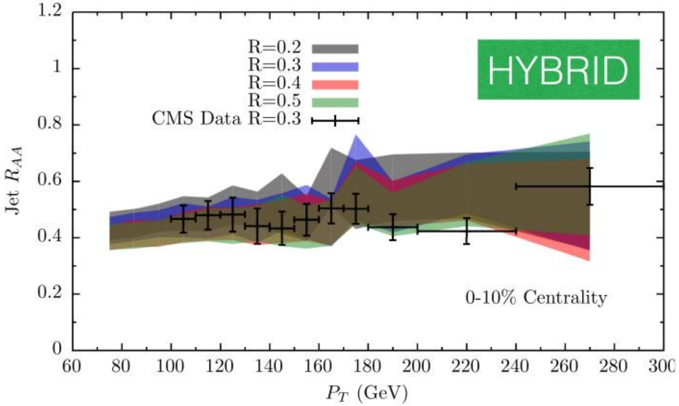


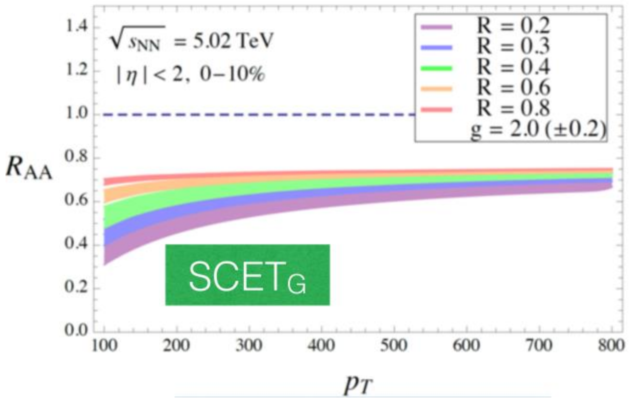
JEWEL Recoil
R. Kunnawalkam Elayavalli, K. C. Zapp, JHEP 1707, 141 (2017)



LBT Recoil
Y. He, et. al., PRC 99, 054911 (2019)







not all listed here …

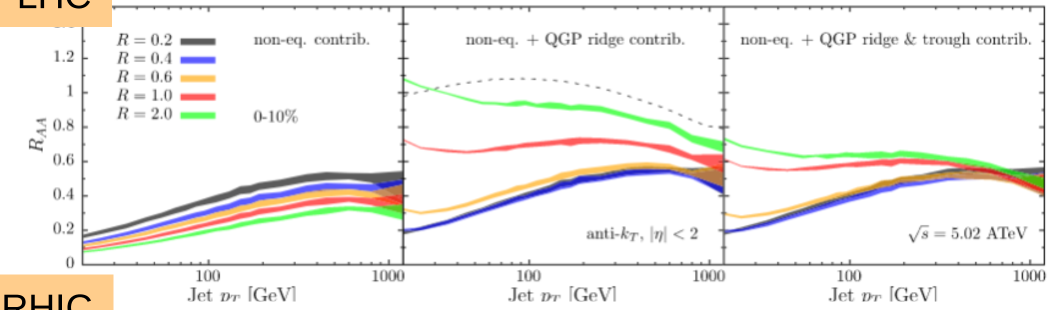
What new have we seen at HP2020?

Predictions for large R jets and di-jets

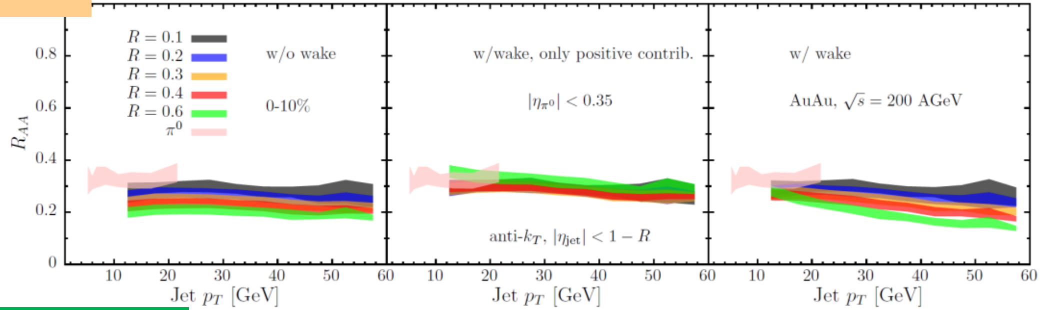
D. Pablos, Wed: 12:45

LHC

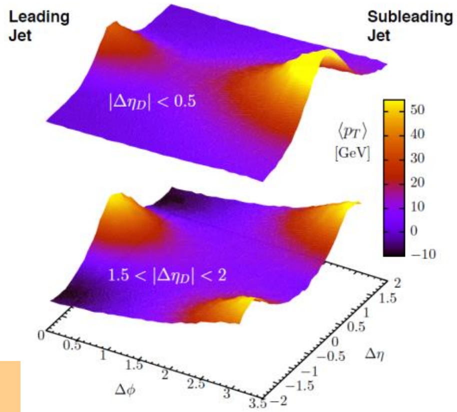
non-eq. …+QPG ridge …+QPG trough



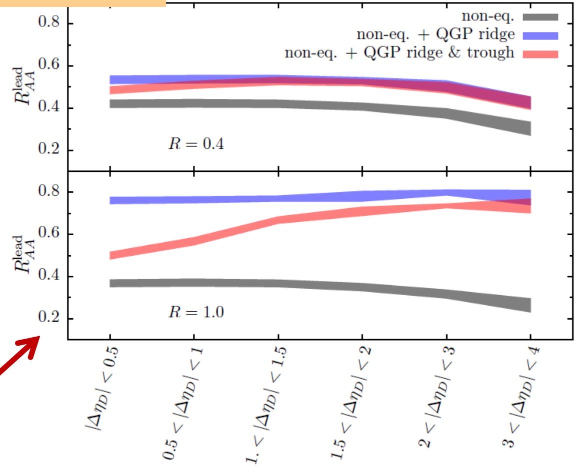
RHIC



Pablos, PRL 124 (2020) 5, 052301



dijet system

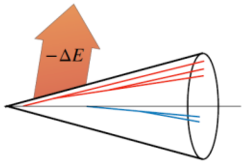


Hybrid strong/weak coupling

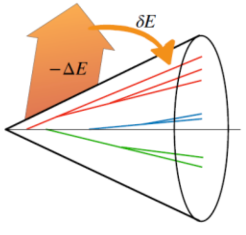
- Competition of effects results in a very mild evolution of R_{AA} from small to large R
- QGP trough effect more pronounced at RHIC
- Jet suppression due to QGP trough is from the wake of the recoiling jet → new observable

Analytical calculation of jet R_{AA}

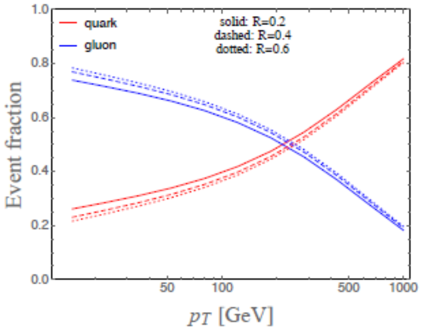
K. Tywoniuk, Wed 12:20

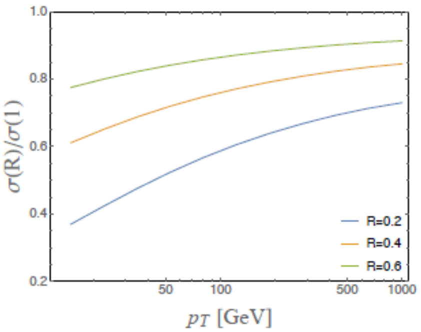


fewer color sources - less energy lost
easier for energy to flow out-of-cone



more color sources - more energy lost
recovery of lost energy

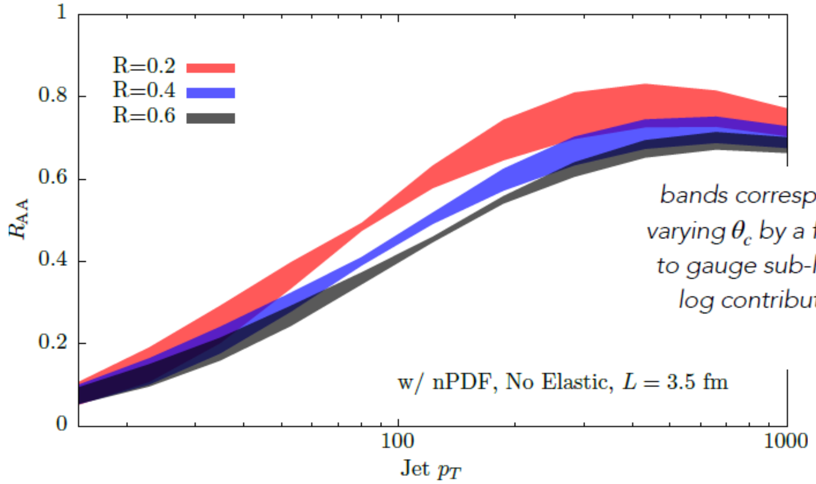




Analytical calculation in collinear factorization (LO+LL with nPDF) with medium effects on resummation

Recovery of energy at large angles is non-perturbative and strongly affected by choice of phase space for quenching

qhat: measure of energy lost + resolution parameter of the medium



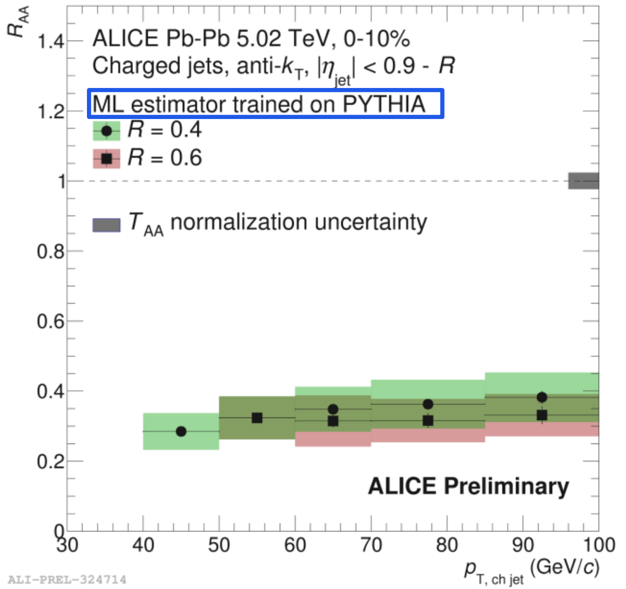
bands correspond to varying θ_c by a factor~2 to gauge sub-leading log contributions.

Tywoniuk, Mehtar-Tani, Pablos

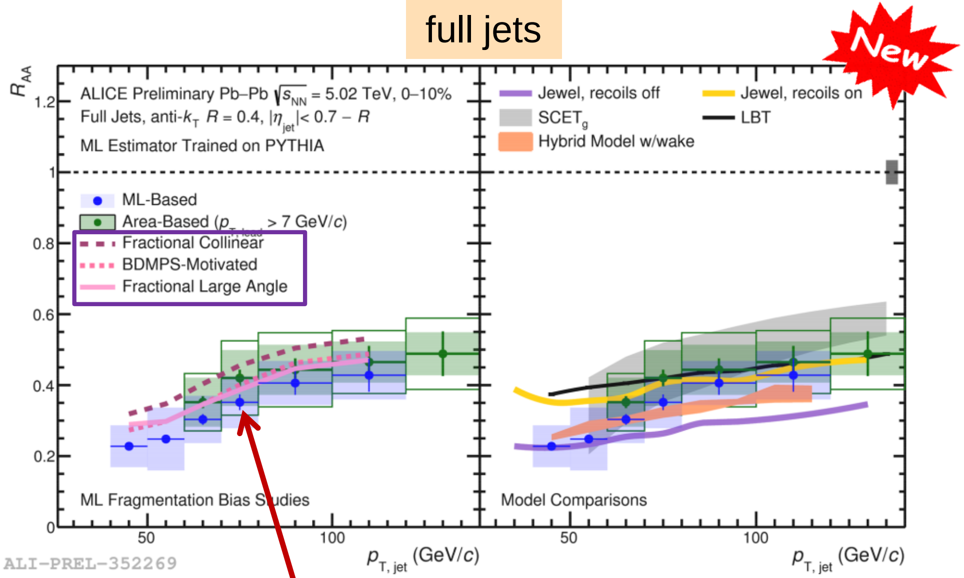
Machine learning: lower jet p_T and larger R?

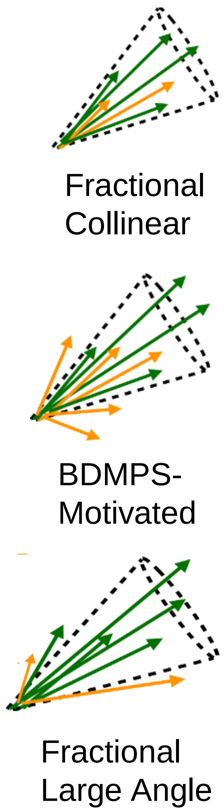
H. Bossi, Tue 12:20

charged jets



full jets





Caution: Although jet-by-jet fluctuations are significantly narrowed, ML training affected by assumed fragmentation model (~10-40%). Need to include quenched MCs …

Aim of ML: Improved precision and extended reach in p_T and R should help to constrain model predictions and allow for comparison with RHIC.

Models: JEWEL: *JHEP 1707 (2017) 141*
SCET$_G$: *PRD 80 (2009) 054022*
Hybrid Model: *PRL 124 (2020) 052301*
LBT: PRC 99 *(2019) 054911*

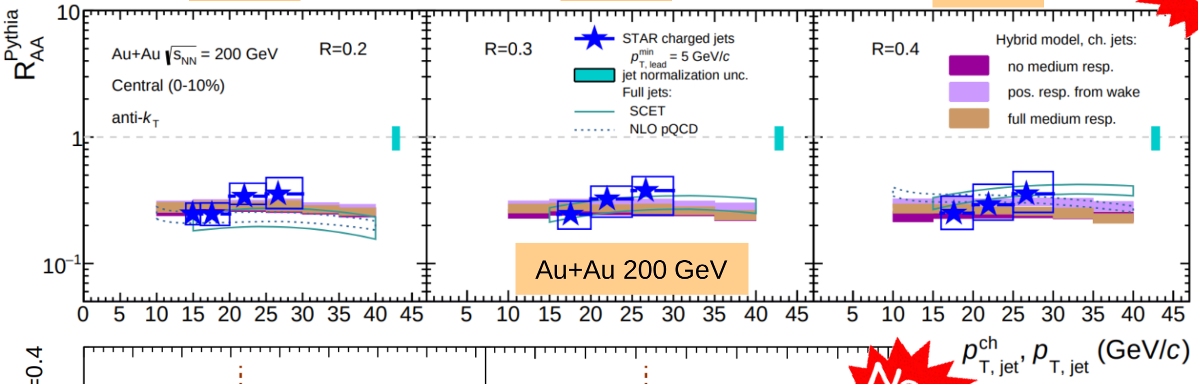
ML method: Haake, Loizides, PRC 99, 064904 (2019)

Inclusive jet suppression at RHIC

R. Licenik: Mo 11:20
M. Patel: Tue 11:40

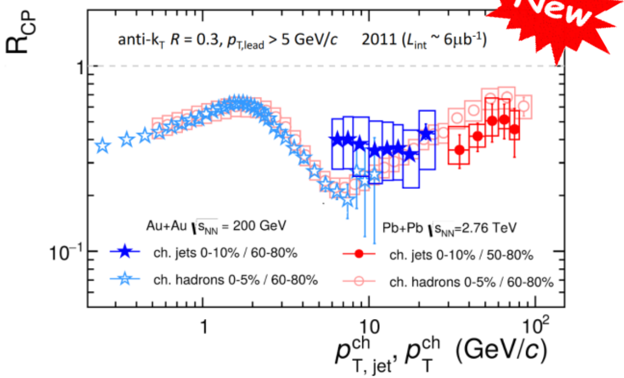
R=0.2 R=0.3 R=0.4

New

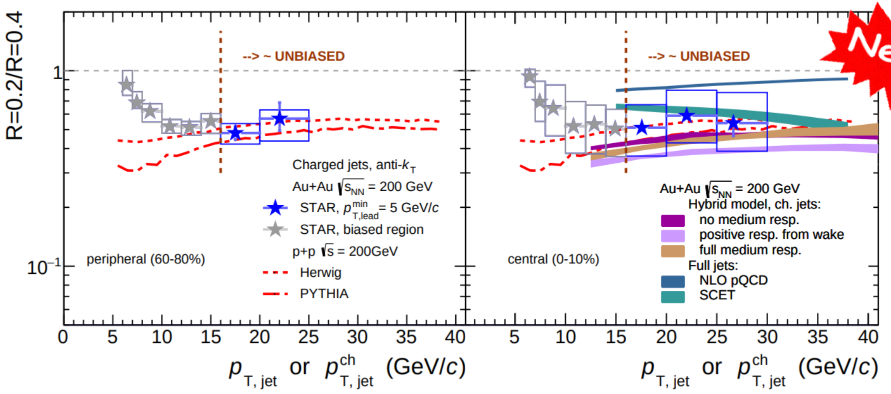


STAR. arXiv: 2006.00582

New

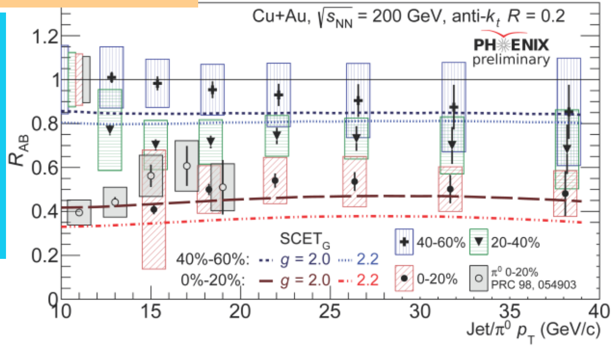


New



Cu+Au 200 GeV

R=0.2



Models generally agree with data, higher precision needed → ongoing analysis

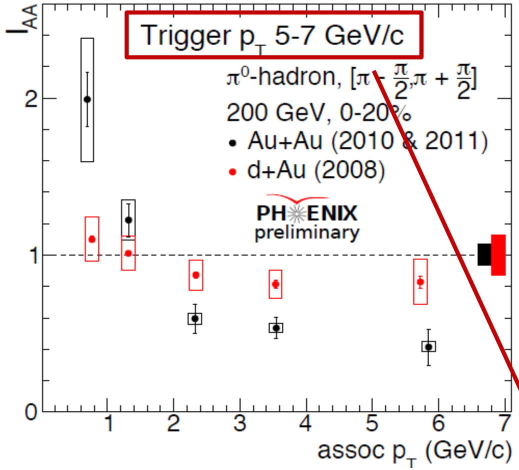
Jet yield suppression consistent with inclusive hadron suppression in Au+Au and Cu+Au collisions at RHIC, behavior similar to the LHC.

The correlations …

π^0/γ-hadron, h/γ+jet

π^0- hadron correlations in Au+Au at RHIC

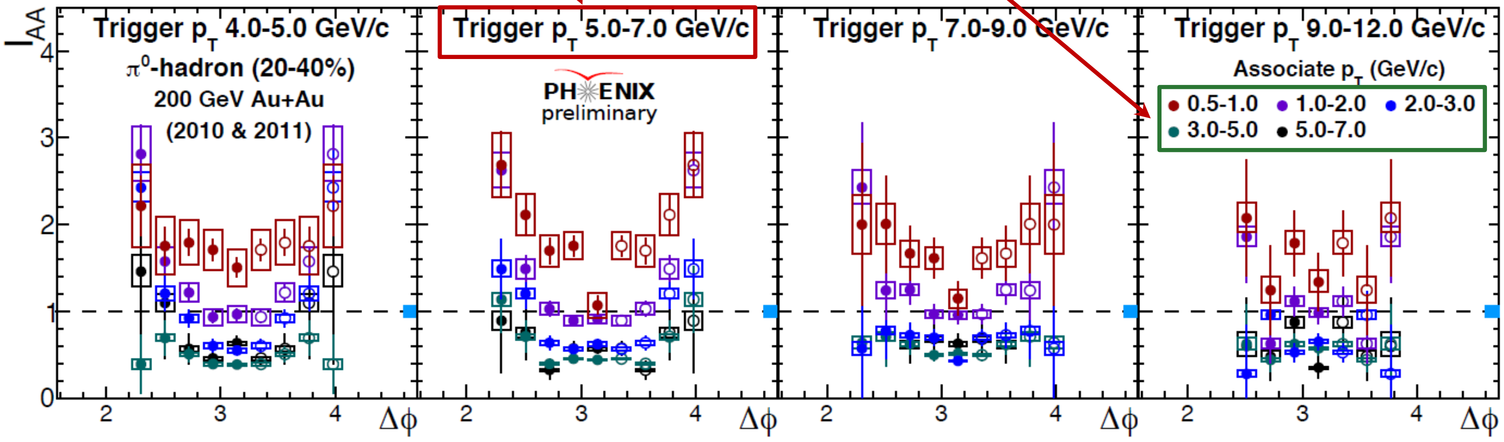
C.-P. Wong: Mo 13:55
M. Connors: poster 297
A. Hodges: poster 276

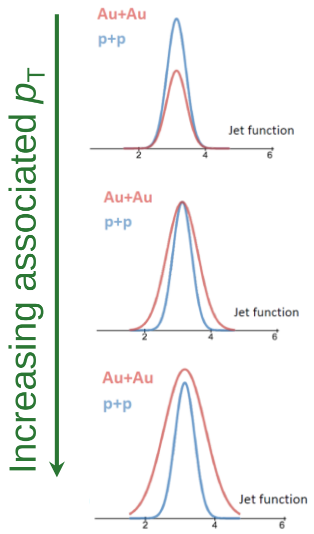


New observable: $I_{AA}(\Delta\phi)$
look for modification of associated particle yields on away-side of pion trigger
(„*jet substructure level*“)

p_T and angular dependent modification of away-side hadron yields measured

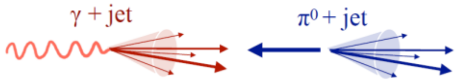
high p_T^{assoc} overall suppression
mid p_T^{assoc}: suppression at jet core and enhacement at jet skirt
low p_T^{assoc}: enhancement primarily at jet skirt





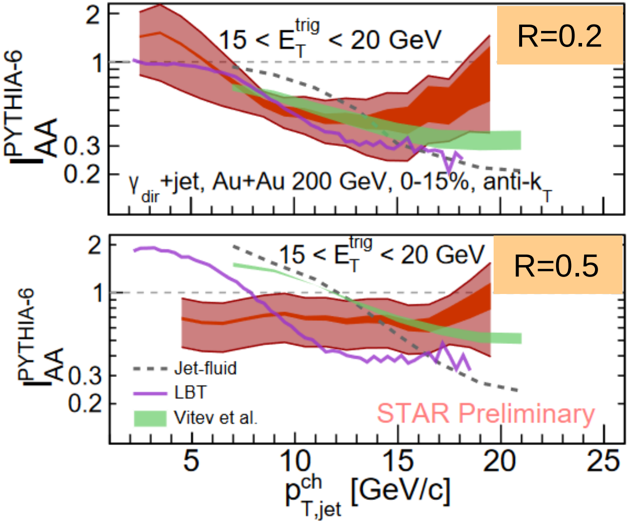
γ+jet and π^0+jet studies at RHIC

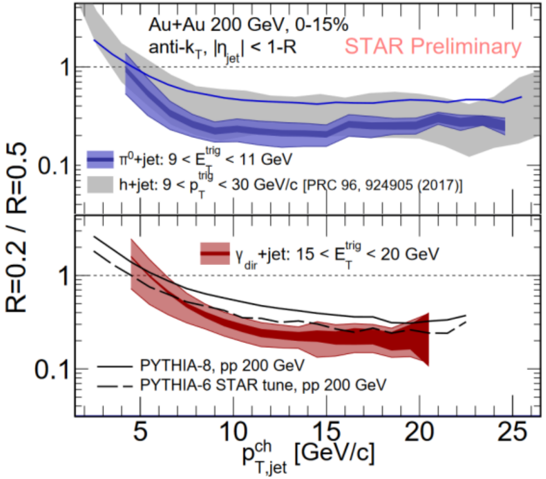
N. Sahoo, Tue 11:20



γ does not interact strongly
→ a calibrated probe

γ+jet data consistent with π^0+jet





Radius dependent I_{AA} suppression observed:
→ p_T behavior differs from models.
Jet radial profile: no significant in-medium broadening

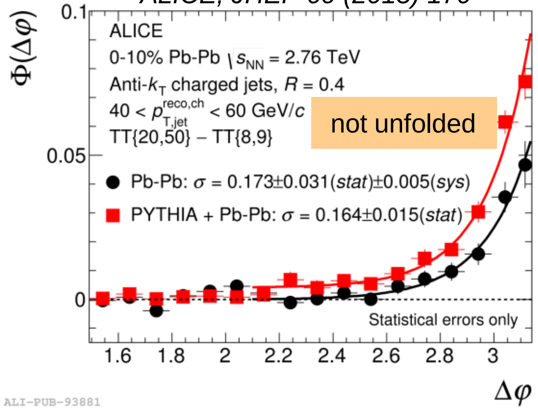
PYTHIA 6 and PYTHIA 8 give different pictures
→ pp data needed (analysis ongoing)

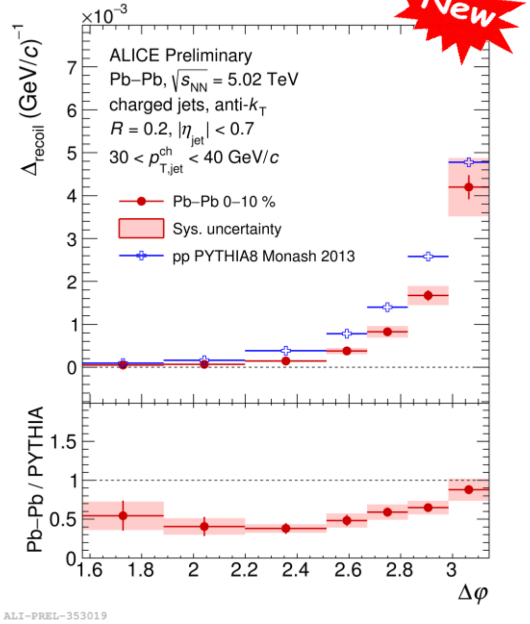
Models:
Jet-fluid: Chang, Qin, *PRC 94 (2016) 024902*
LBT: Chen, Cao, Luo, Pang, Wang, *PLB 777 (2018) 707*
Vitev et. al: Sievert, Vitev, Yoon, *PLB 795 (2019) 502*

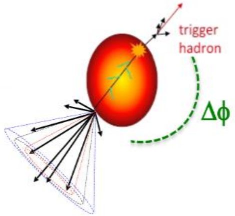
Jet acoplanarity in Pb+Pb collisions

J. Norman, Mon 12:55

ALICE, JHEP 09 (2015) 170

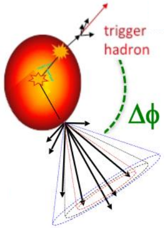






$\Delta\phi \sim \pi$:
vacuum: broadening (Sudakov radiation)
medium: interplay of multiple soft scattering(↑) and radiative corrections (↓)

Chen et al, PLB 773 (2017) 672
Gyulassy et al., arxiv:1808.03238
Zakharov, arxiv:2003.10182



$\Delta\phi \ll \pi$: large-angle deflection of hard partons off quasiparticles

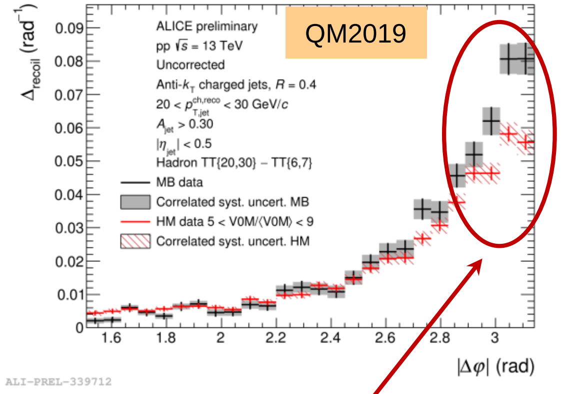
D'Eramo, Rajagopal, Yin, JHEP 01 (2019) 172

- First measurement of fully corrected acoplanarity down to low p_T recoil jets.
- Recoil jet yield suppressed with respect to PYTHIA + indication of $\Delta\phi$ narrowing.

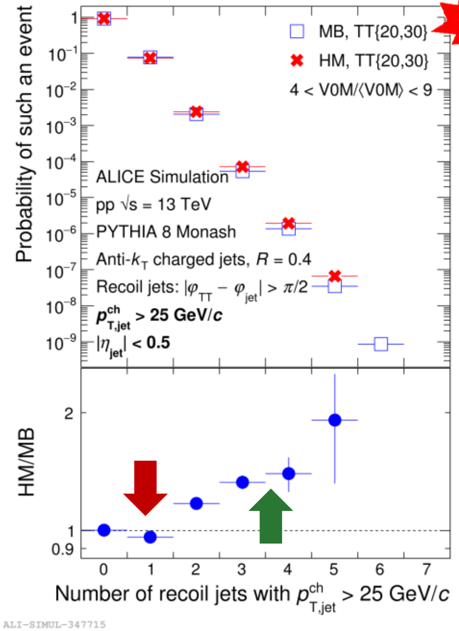
Jet acoplanarity in small systems: jet quenching?

F. Krizek: Thu 10:35
D. Stewart: Tue 12:55

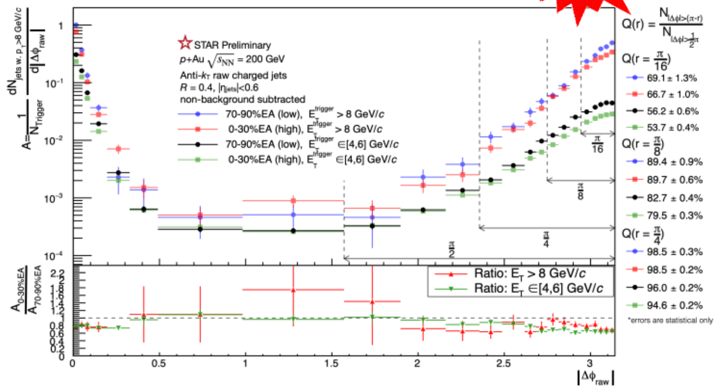
How to explore it?
Traditional R_{AA}: no, Glauber scaling undefined!
→ study acoplanarity instead



Is this jet quenching?



High-multiplicity trigger suppresses events with one hard recoil jet and enhances multi-jet events …

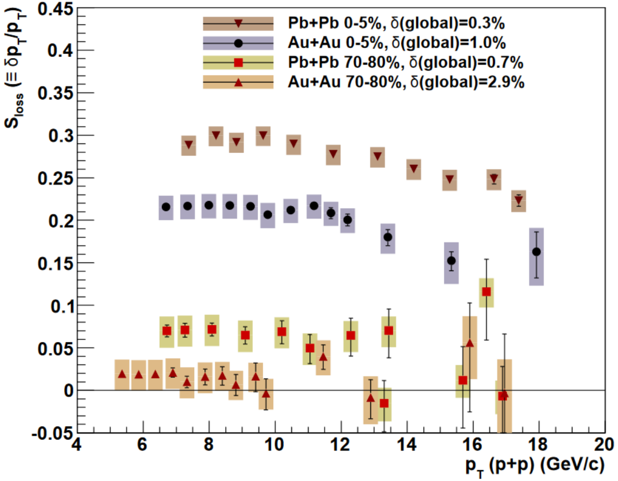


- High vs. low event activity spectra in p+Au suppressed, but acoplanarity minimally modified.
- Qualitatively reproduced by PYTHIA

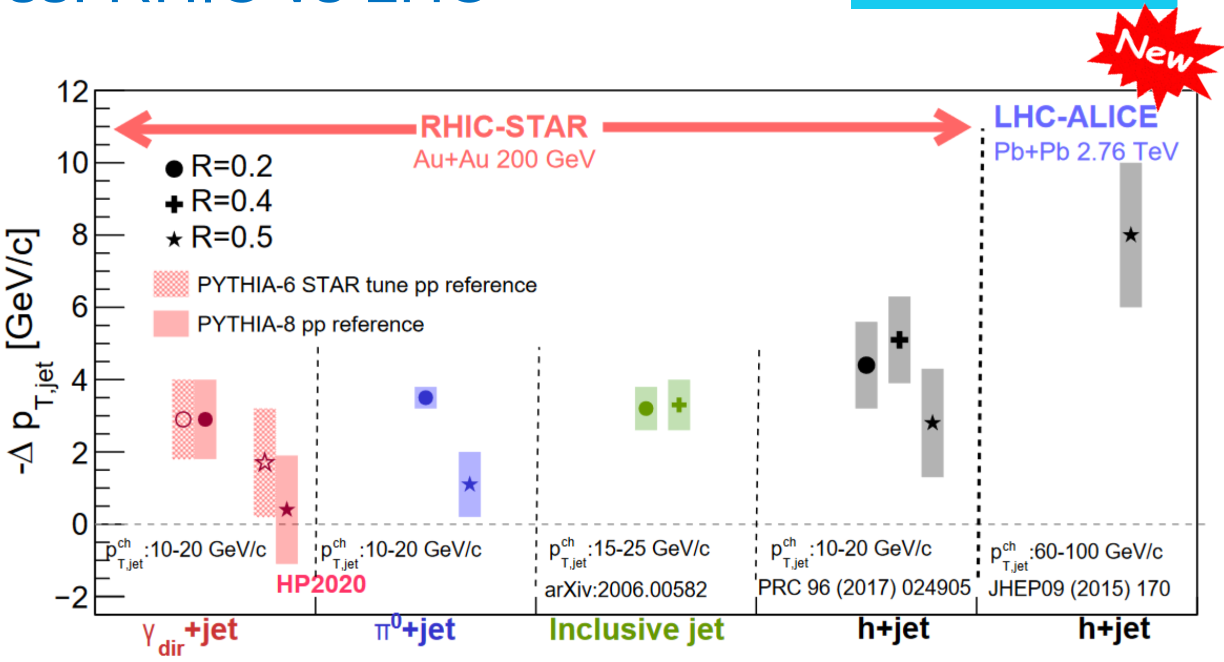
Out-of-cone energy loss: RHIC vs LHC

N. Sahoo, Tue 11:20

PHENIX, PRC 87, 034911 (2013)



Inclusive π^0
Δp_T =2-3 GeV/c

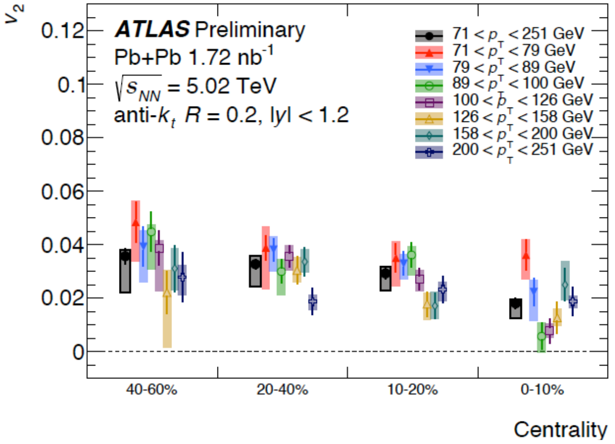


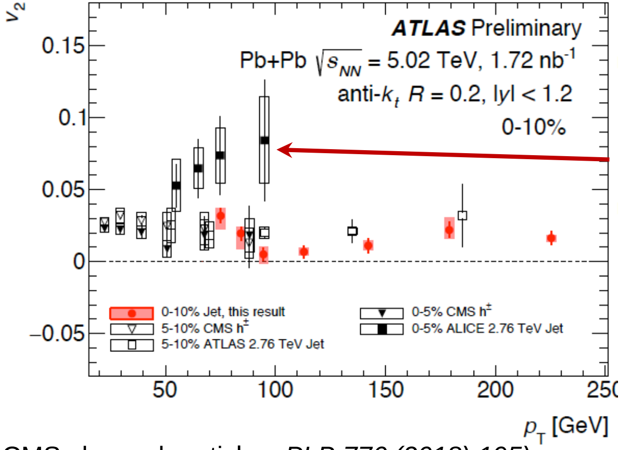
RHIC: various channels
consistent (π^0, jet, trigger+jet)

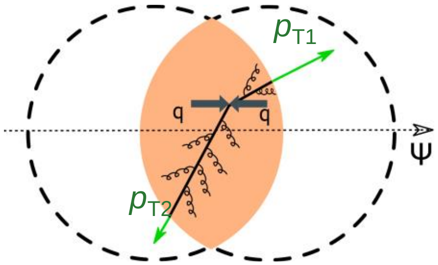
In-medium energy loss smaller at RHIC than at the LHC.

Path-length dependence of energy loss:

V. Bailey: Mo 11:00
T. Rinn (poster)

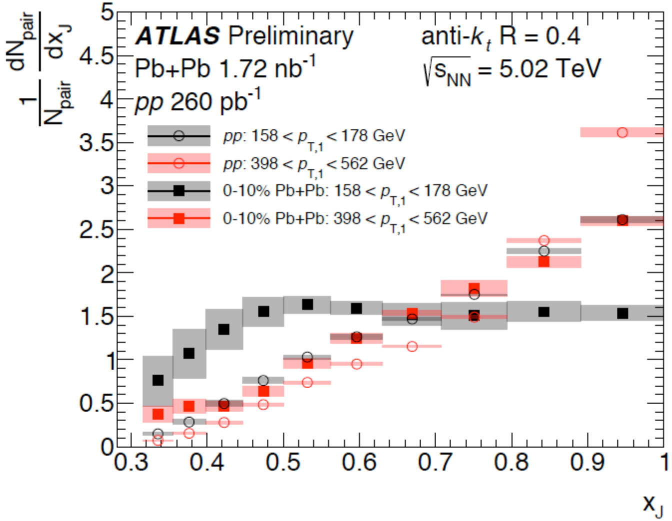






Observables studied:

- jet v_2
- dijet momentum imbalance $x_J = p_{T1}/p_{T2}$



Jet v_2: tension with ALICE
higher precision data needed

Central Pb+Pb collisions @ 5.02 TeV

- positive jet $v_2(p_T)$ ~ 2-3 %
- increased asymmetry of dijet pairs vs pp collisions persists even at leading jet p_T ~ 0.5 TeV

CMS charged particles: *PLB 776 (2018) 195);*
ATLAS 2.76 TeV: *PRL 111 (2013) 152301;* ALICE 2.76 TeV: *PLB 753 (2016) 511*

Let us look closer at jets

jet shapes
jet fragmentation
jet substructure
jet charge …

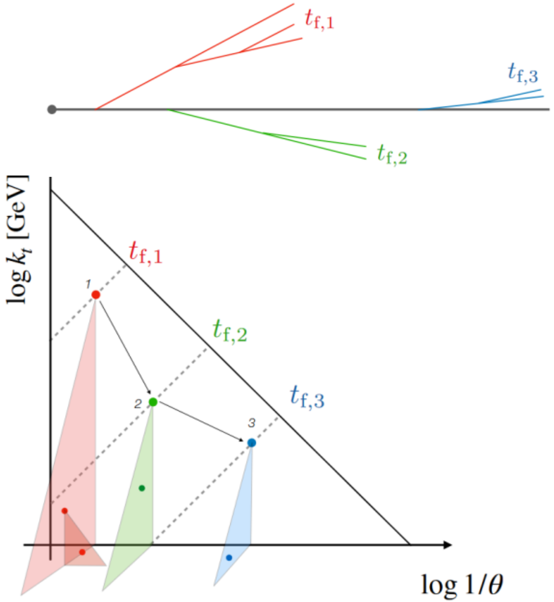
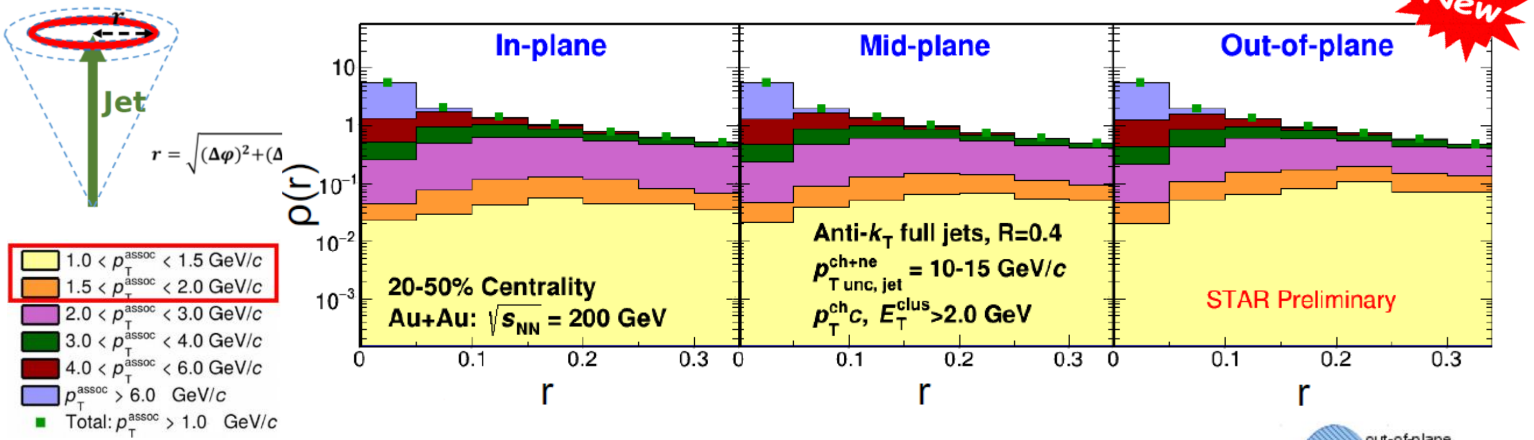


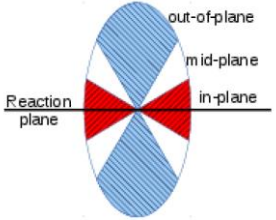
Figure courtesy: K. Tywoniuk

Jet shapes at RHIC

J. Mazer Thu 13:50

Radial distribution of momentum of jet constituents



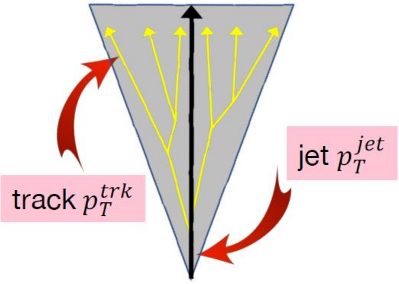


Low-p_T (< 2 GeV) particles pushed toward larger radii in the out-of-plane direction relative to the in-plane

Larger yields of low-p_T particles observed in the out-of-plane direction
→ inline with in-medium path length dependence

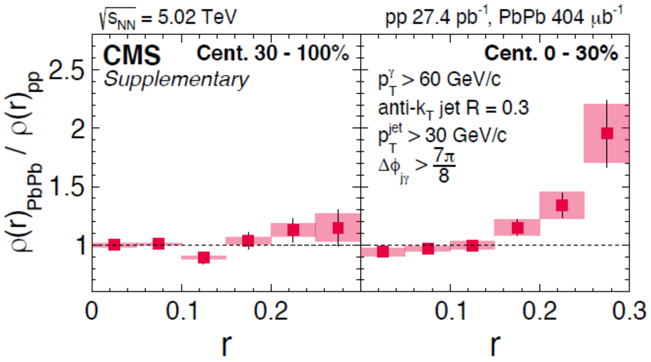
γ-tagged jet shapes at the LHC

M. Taylor, Mon 13:35
N.-B. Chang, Wed 11:30



$$r = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

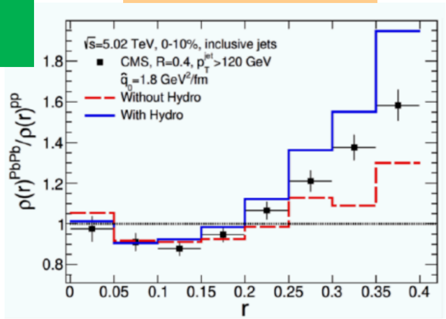
$$\boldsymbol{\rho(r)} = \frac{1}{\delta r} \frac{\sum_{jets} \sum_{r_a<r<r_b} p_T^{trk} / p_T^{jet}}{\sum_{jets} \sum_{0<r<r_f} p_T^{trk} / p_T^{jet}}$$



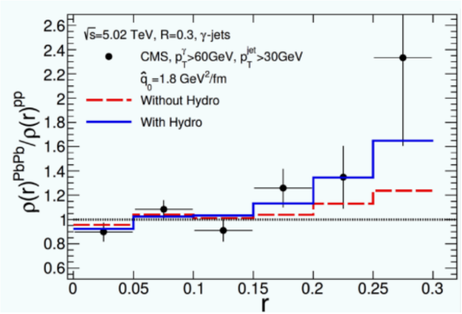
Almost no modification of the jet core in Pb+Pb relative to p+p, enhancement of particles at larger radii.

Coupled jet-fluid model

inclusive jets



γ - jets



Coupled jet-fluid model captures features observed in data.

Jet shape ratio Pb+Pb/pp:

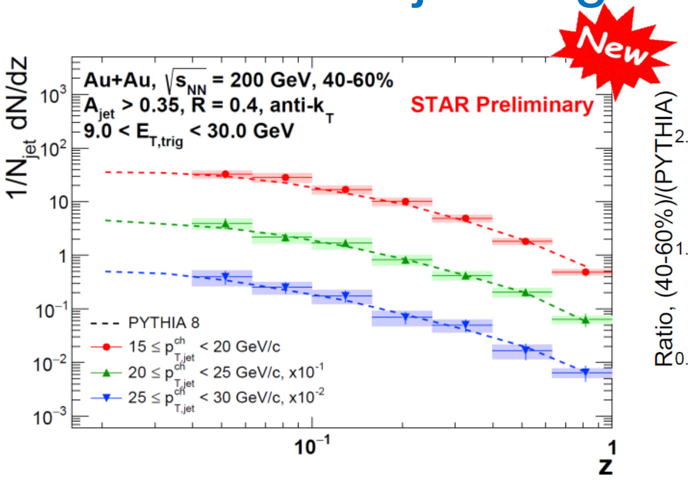
- Inclusive jets: non-monotonic function of radius
- γ-jets ratio increases monotonically with radius

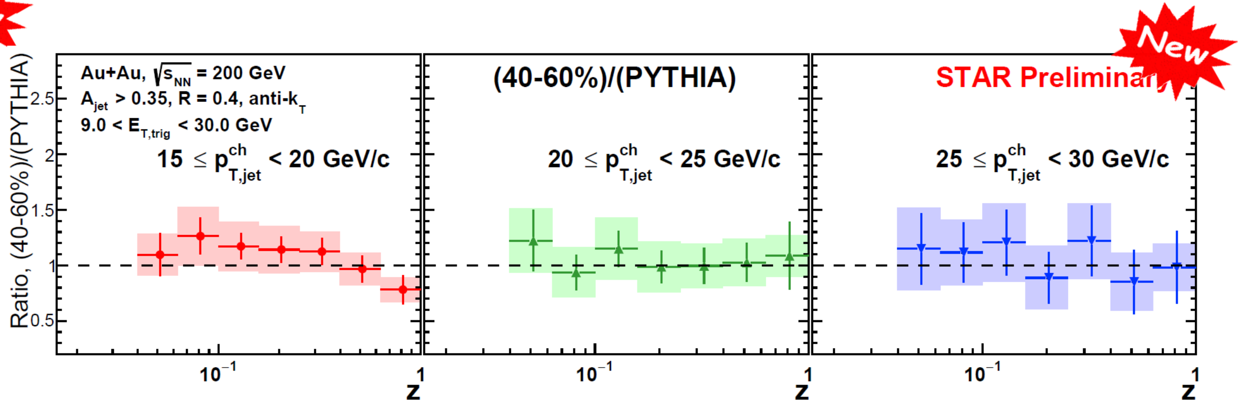
Chang, Tachibana, Qin, PLB 801 (2020) 135181

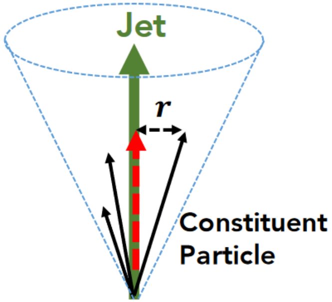
Jet fragmentation …

Semi-inclusive jet fragmentation function at RHIC

S. Oh, poster







$$z = \frac{p_{\mathrm{T,track}} \cos(r)}{p_{\mathrm{T,jet}}}$$

First fully corrected results of semi-inclusive jet fragmentation functions at RHIC
Data agree well with PYTHIA8

Possible tangential bias on jet selection by requiring high-p_T trigger particle?
→ pp data measurement and analysis in more central events ongoing

Jet fragmentation and substructure … the ATLAS way

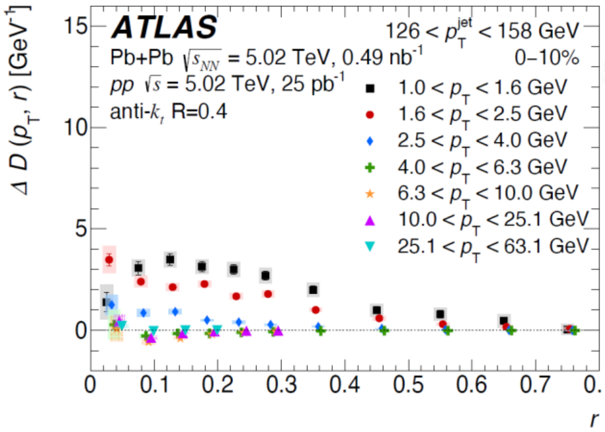
A. Sickles, Wed 10:30
W. Zou, poster

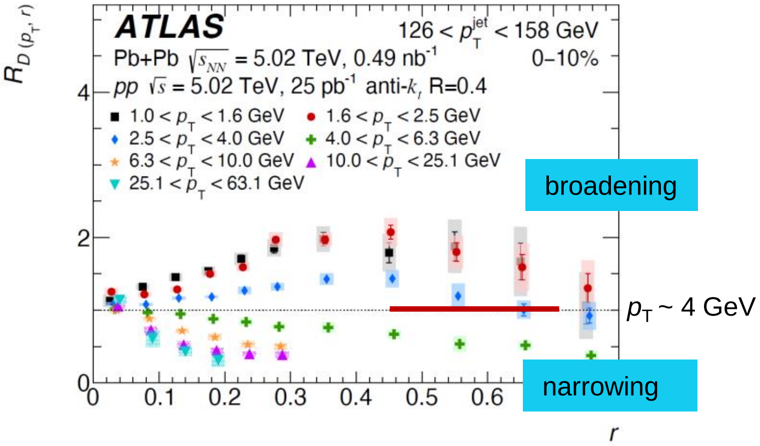
a 2D map of jet fragmentation

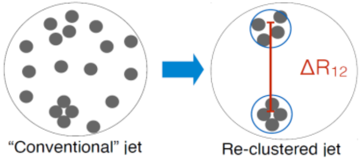
$$D(p_T, r) = \frac{1}{N_{\text{jet}}} \frac{1}{2\pi r\, dr} \frac{dn_{\text{ch}}(p_T, r)}{dp_T}$$

$$\Delta D(p_T, r) = D(p_T, r)_{\text{Pb+Pb}} - D(p_T, r)_{pp}$$

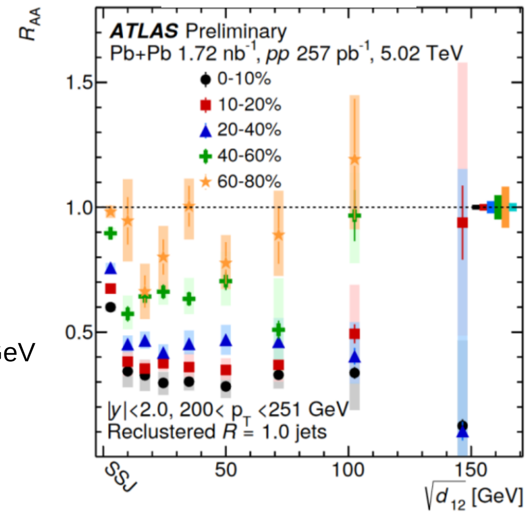
$$R_{D(p_T,r)} = \frac{D(p_T, r)_{\text{Pb+Pb}}}{D(p_T, r)_{pp}}$$







$$\sqrt{d_{12}} = \min(p_{T1}, p_{T2}) \times \Delta R_{12}$$



ATLAS-CONF-2019-056

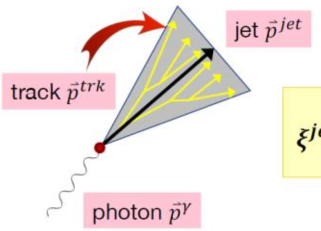
Significant modification of structure of jet fragments:
- qualitative change happens at $p_T \sim 4$ GeV
- most of the "extra" particles within the jet cone

Direct probe of the ability of medium to resolve parton fragments.
Jets with 1 subjet less quenched than multiple subjets.

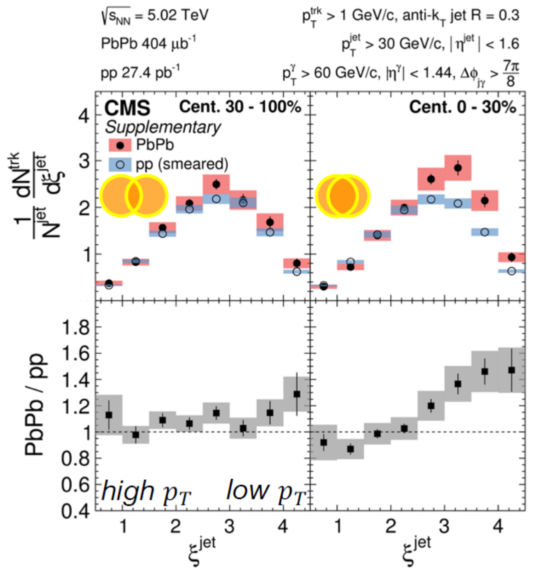
ATLAS, PRC100 (2019) 064901

γ-tagged jet fragmentation function

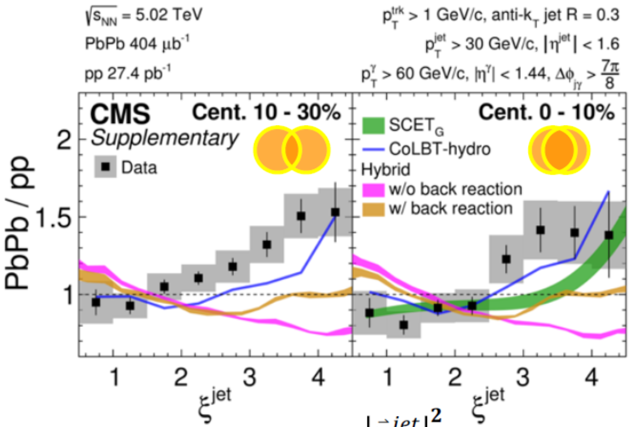
M. Taylor, Mon 13:35
C.-P. Wong, Mo 13:55



$$\xi^{jet} = \ln \frac{|\vec{p}^{jet}|^2}{\vec{p}^{trk} \cdot \vec{p}^{jet}}$$



[PRL 121 (2018) 242301](#)



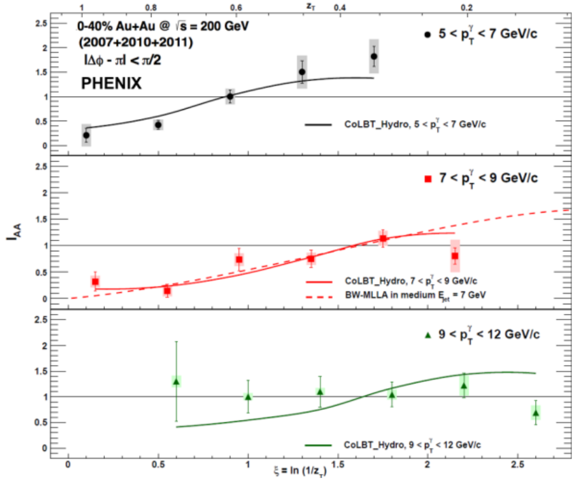
$$\xi^{jet} = \ln \frac{|\vec{p}^{jet}|^2}{\vec{p}^{trk} \cdot \vec{p}^{jet}}$$

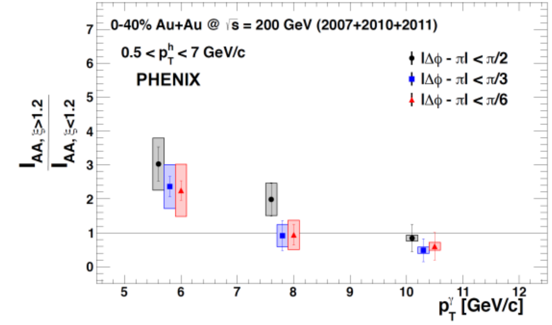
Excess of low p_T particles, depletion at high p_T in central collisions observed at the LHC. Similar trends observed at RHIC in γ-hadron correlations as well.

Hybrid model: back reaction needed, but not sufficient

SCET$_G$ and CoLBT-hydro qualitatively describe the trend

PHENIX arXiv:2005.14270



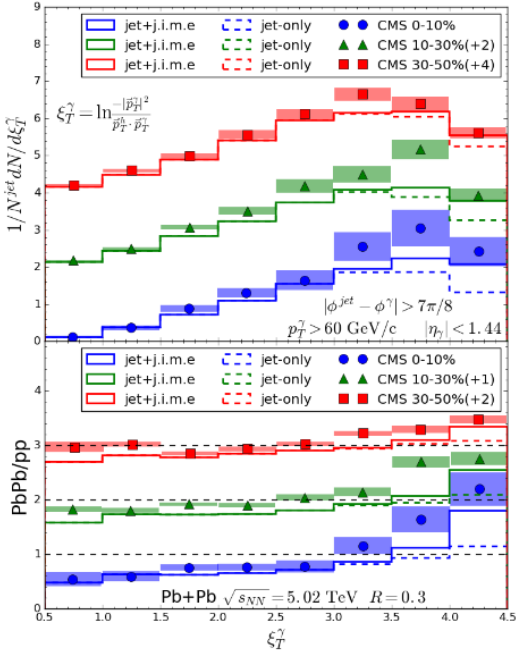


γ-tagged jet fragmentation function

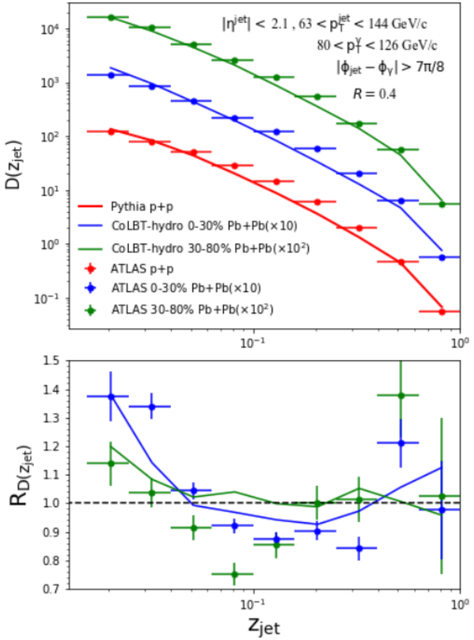
T. Luo, Wed 13:25

CoLBT-hydro model

Comparison with CMS



Comparison with ATLAS



W. Chen, S. Cao, T. Luo, L.-G. Pang, X.-N. Wang, 2005.09678

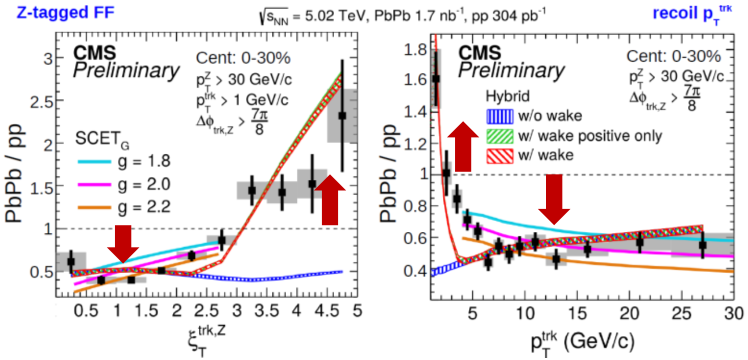
Measured centrality dependent enhancement of soft hadrons (large ξ) mainly due to medium response.

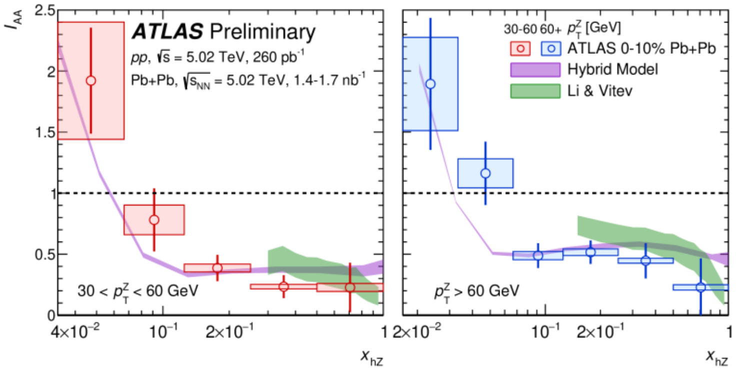
The lost energy is redistributed into soft hadrons by multiple scattering, gluon radiation and medium excitation from jet.

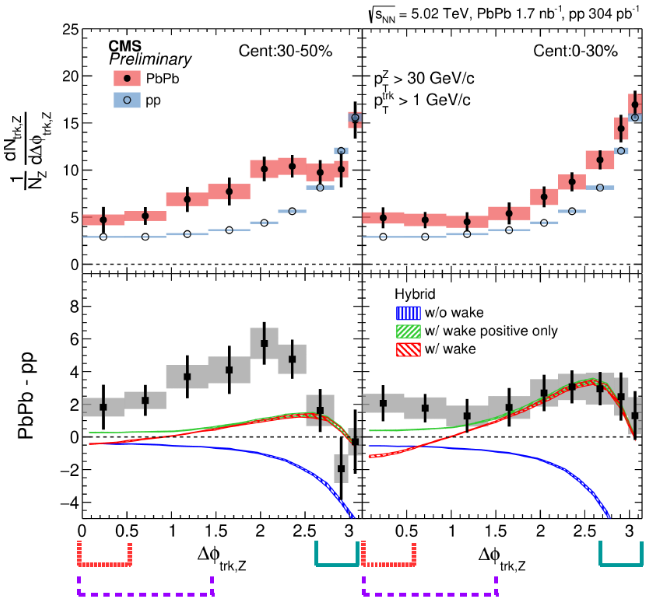
Note: In T. Luo's talk are shown further jet substructure observables confirming importance of medium response to describe data at the LHC.

Z-tagged fragmentation

K. Tatar, Thu 11:55
J. Ouellette, Thu 13:30







SCET$_G$ PRD 93 (2016) 074030,
PRD 101 (2020) 076020
Hybrid JHEP 1410 (2014) 019

- SCET$_G$ with g=2.0 reasonable description of data
- Hybrid model with medium wake undershoots intermediate p_T = 3-5 GeV, discrepancy even more pronounced in $\Delta\phi$ distributions

Similarly as for γ-tagged correlations excess (depletion) of low (high) momentum particles measured

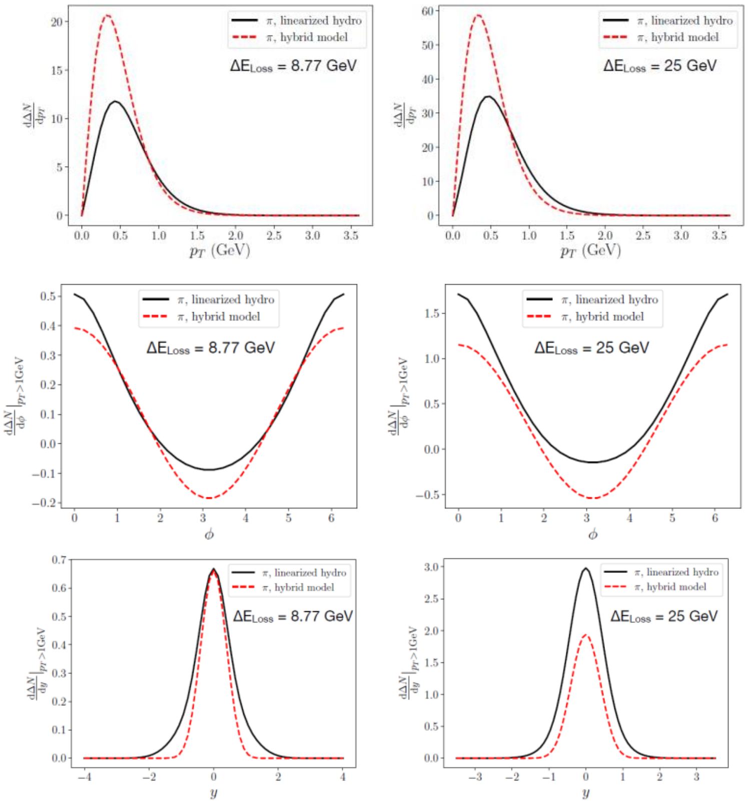
Need to improve medium response

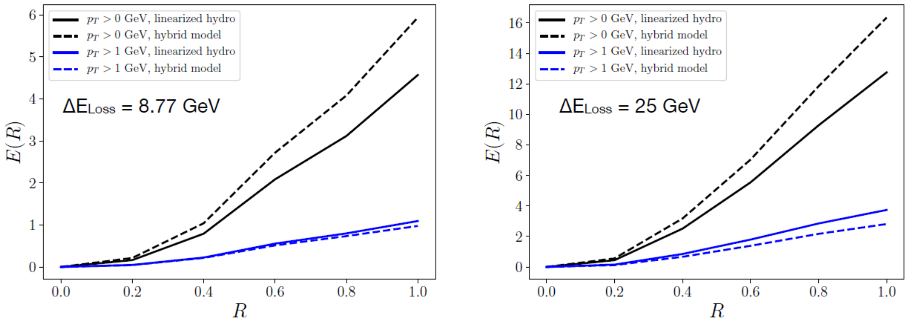
… see next slide

CMS-PAS-HIN-19-006, ATLAS-CONF-2019-052

Wake of jets in linearized hydrodynamics

J. Casalderrey-Solana, Tue 12:55





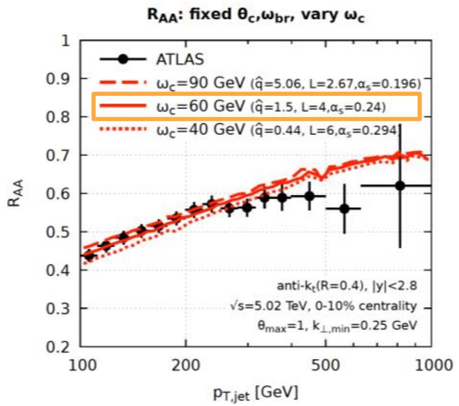
Linearized hydro provides improved description of medium back-reaction

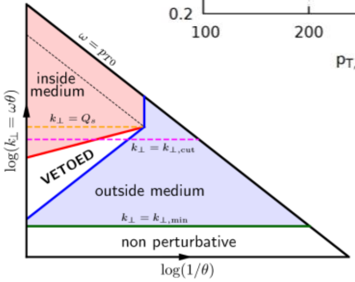
- → harder p_T spectrum of back-reaction particles
- → beaming of spectrum along jet azimuthal direction
- → wider rapidity distribution
- → larger fraction of semi-hard particles recovered around the jet
- → slower recovery of jet energy with R

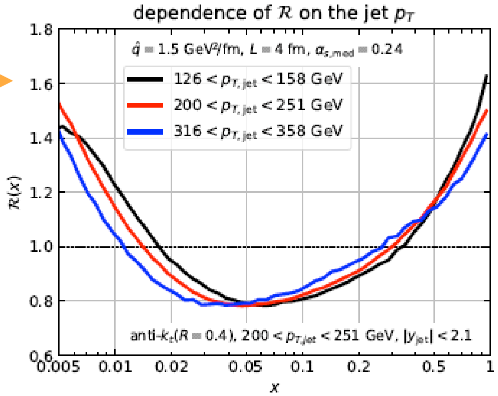
Casalderrey-Solana, Milhano, Pablos, Rajagopal, Yao, in preparation

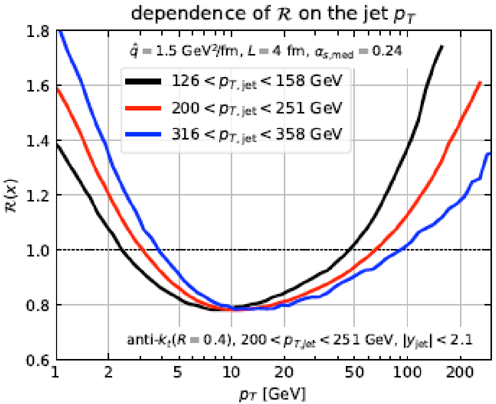
Medium modification of jet and subjet fragmentation

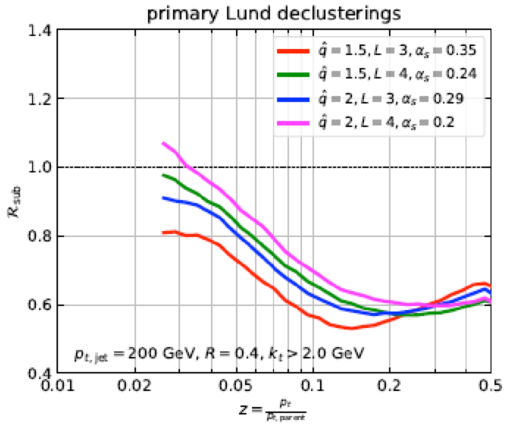
P. Caucal, Mo 11:40











pQCD based on factorized picture: vacuum-like and medium-induced emissions (BDMPS-Z)

medium: fixed brick of size L

Jet R_{AA} data described reasonably well.

Modification of jet fragmentation function, qualitatively agrees with the LHC data, but it is not IRC safe observable.

New observable:
Study modification of subjet FF which is IRC safe

$D_{sub}(z) = 1/N_{jets}\, dN_{sub}/dz$

Caucal, Iancu, Soyez, JHEP10 (2019) 273

Caucal, Iancu, Mueller, Soyez, arXiv:2005.05852

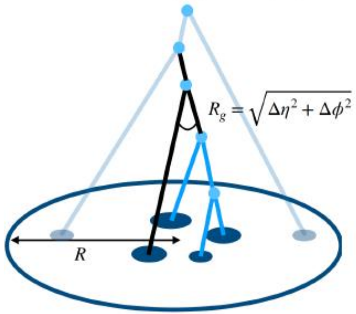
Let us groom the jets …

removing soft, wide-angle radiation from jets

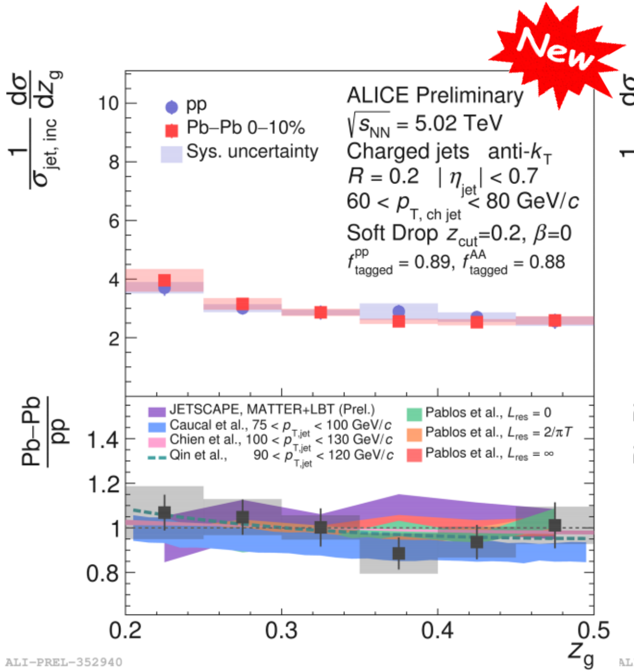
SoftDrop grooming in Pb+Pb collisions

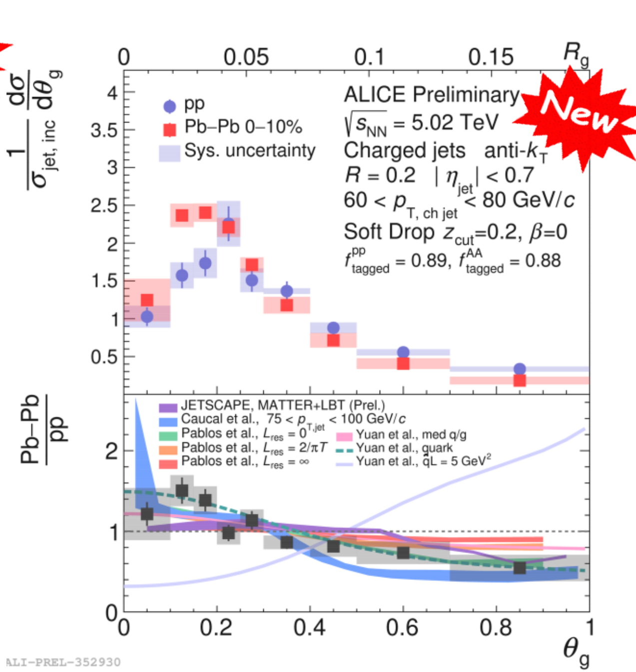
J. Mulligan, Wed 10:50
R. Ehlers, Wed 12:25

$$z_g \equiv \frac{p_{\mathrm{T,sublead}}}{p_{\mathrm{T,lead}} + p_{\mathrm{T,sublead}}}$$



$$\theta_g \equiv \frac{R_g}{R}$$





z_g: sensitive to modification of QCD splitting function, (in)coherent E_{loss}

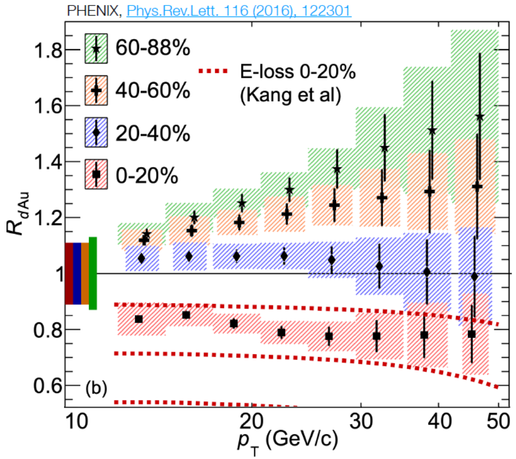
θ_g: medium-induced gluon radiation broadens jets, but E_{loss} narrows them, q-g fractions, path-length effects …

First fully corrected measurement of θ_g and z_g in A+A collisions:
- no significant modification of z_g distribution
- modification of θ_g → hint of collimation

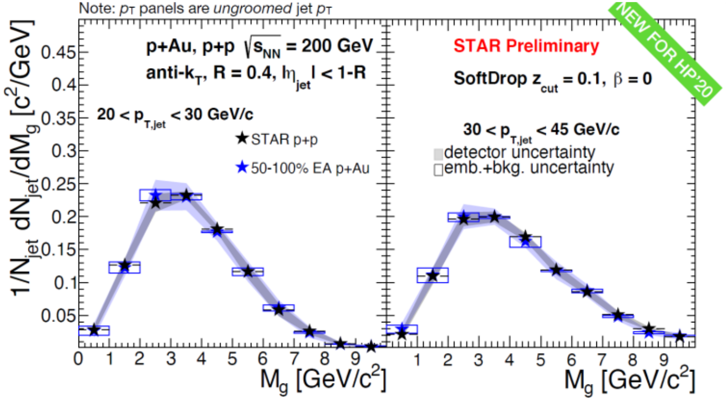
Alternative groomers? Which limitations they have?

Jet grooming at RHIC

I. Mooney Wed 11:50
D. Nemes (poster)

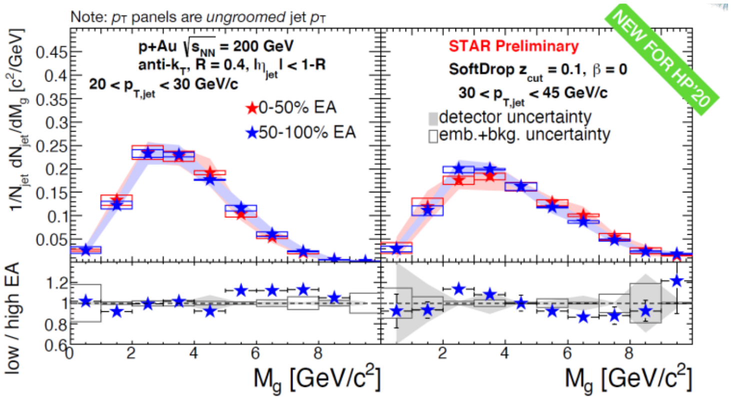


What is origin of the R_{d+Au} enhancement?
Jet quenching in d+Au?
Explore jet mass …



First inclusive p+p and p+Au (groomed) jet mass measurements at RHIC:

- No CNM effects on (groomed) jet mass …



Other groomed observables explored:

z_g and R_g p+p 200 GeV *STAR: arXiv: 2003.02114*

Au+Au 200 GeV *poster D. Nemes*

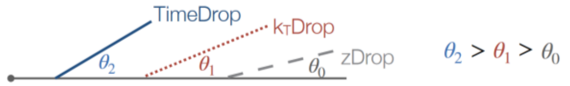
Jet substructure: dynamical grooming

A. Soto-Ontoso, Wed 11:10

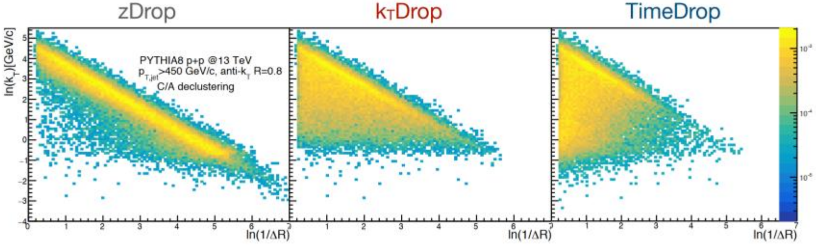
SoftDrop has flexibility to select splittings from different kinematic regions, but how to choose the parameters?

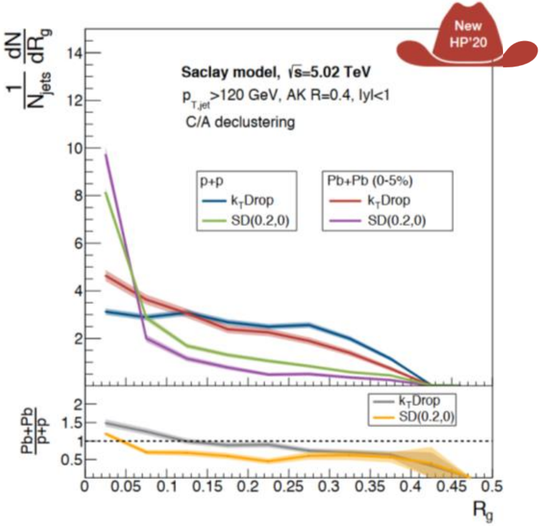
Saclay: P. Caucal et al
Hybrid w/wake: D. Pablos et al
JEWEL w/o recoil: K. Zapp et a

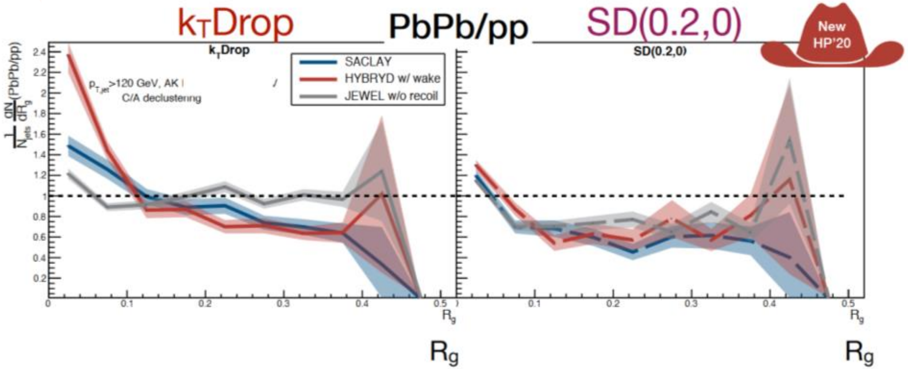
Physical interpretation: • a=2: TimeDrop • a=1: k_TDrop • a~0: zDrop



More aggressive grooming with decreasing ***a***







- Removal of soft radiation sensitive to total color charge
- Auto-generated grooming condition on a jet-by-jet basis
- k_TDrop is remarkably robust to hadronization.

Mehtar-Tani, Soto-Ontoso, Tywoniuk: PRD 101 (2020) 034004

Thermal background: Mulligan, Ploskon, arXiv:2006.01812

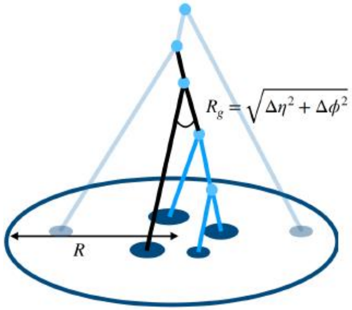
Jet substructure in p+p from ALICE

J. Mulligan, Wed 10:50
E. Lesser (poster)

First measurement of jet angularities and dynamically groomed distributions θ_g, z_g

$$z_g \equiv \frac{p_{T,\text{sublead}}}{p_{T,\text{lead}} + p_{T,\text{sublead}}}$$

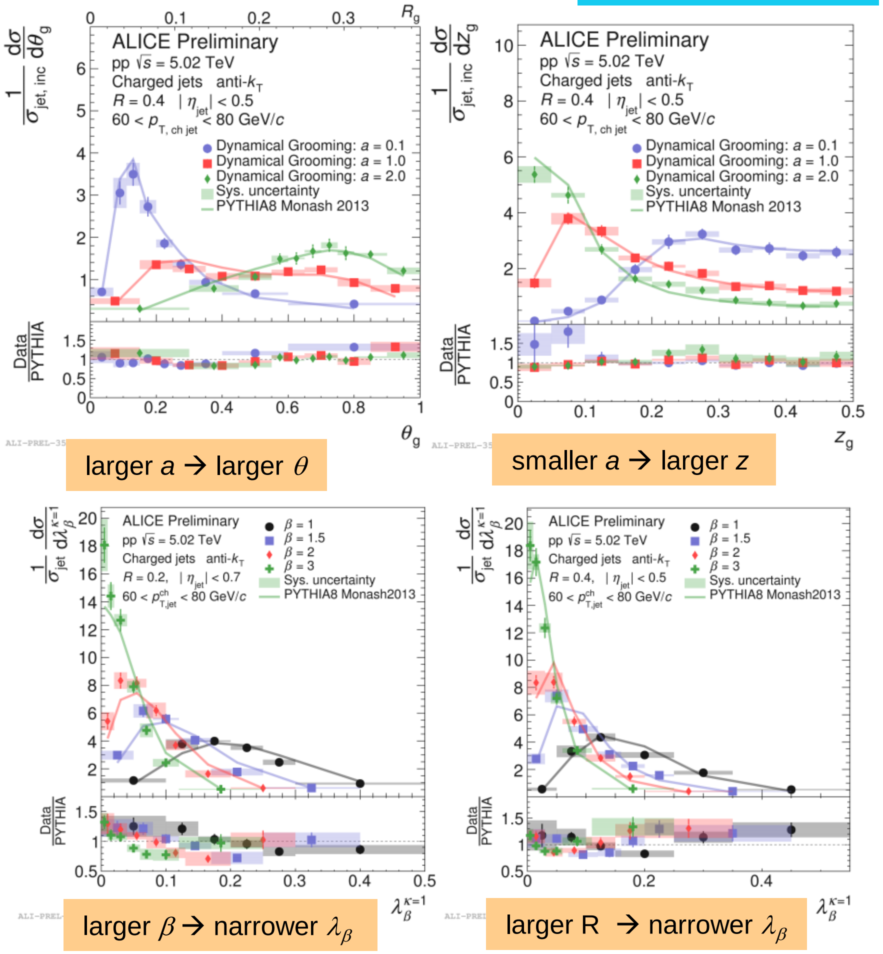
$$\lambda_\beta^\kappa \equiv \sum_{i \in \text{jet}} \left(\frac{p_{T,i}}{p_{T,\text{jet}}}\right)^\kappa \left(\frac{\Delta R_{jet,i}}{R}\right)^\beta$$



$$\theta_g \equiv \frac{R_g}{R}$$

PYTHIA provides reasonable description of measured distributions.

Test pQCD by systematic measurements for multiple R, β.



Jet charge …

Jet charge

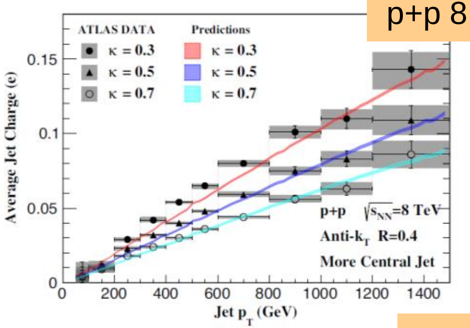
SCET$_G$

$$Q_{\kappa,\,\mathrm{jet}} = \frac{1}{\left(p_T^{\mathrm{jet}}\right)^{\kappa}} \sum_{\mathrm{h\ in\ jet}} Q_h \left(p_T^h\right)^{\kappa}$$

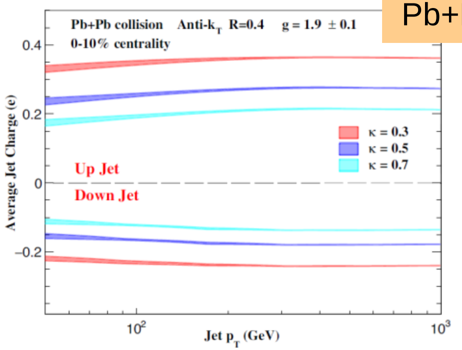
R. Field et al. (1978)

- in-medium modification jet flavor dependent
- separation important to advance understanding of medium effects

p+p 8 TeV



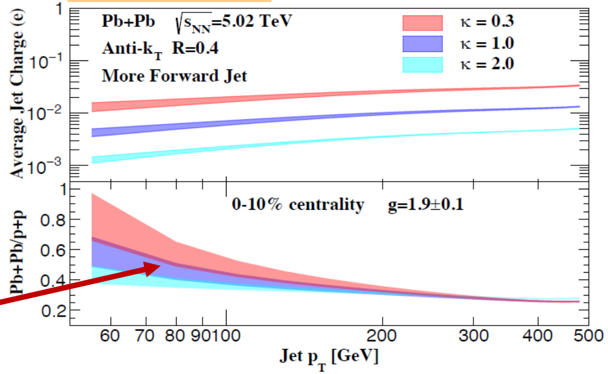
Pb+Pb



Different flavor jet charges remain distinct in HI collisions.

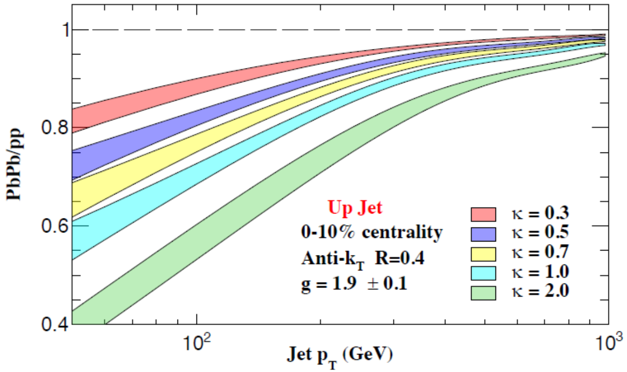
large p_T: isospin effects dominate
p_T < 200 GeV: effects of in-medium parton showers

Pb+Pb/pp



Proposed measurement: charge of individual jet flavors

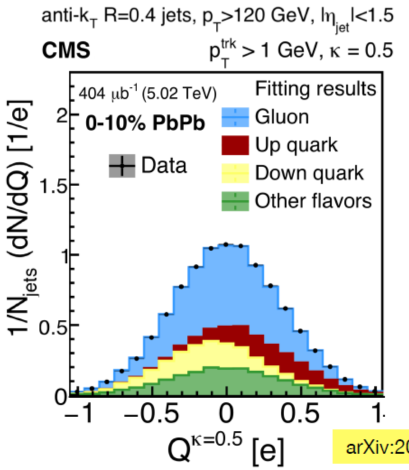
Pb+Pb/pp



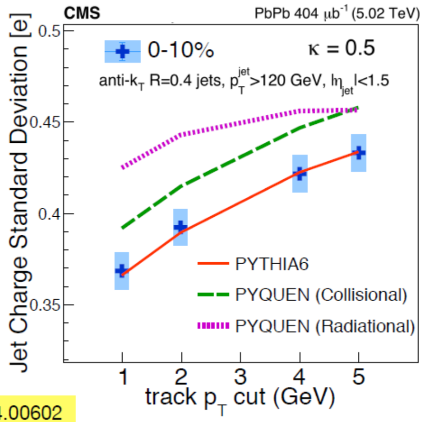
Li, Vitev, PRD 101, 076020 (2020)

Jet charge measurement: q/g contributions in jets

D. A. Hangal Thu 13:10
J. Brewer, Wed 7:55



arXiv:2004.00602



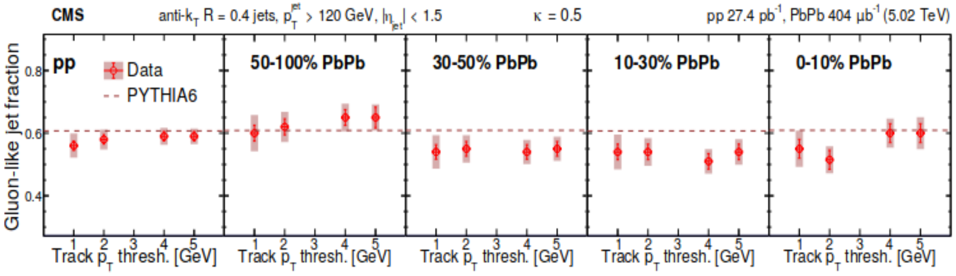
First jet charge measurements in HI collisions:

- no significant modification observed in the jet charge width (contrary to PYQUEN)
- quark and gluon-like fractions from template fitting centrality independent and in agreement with pp data

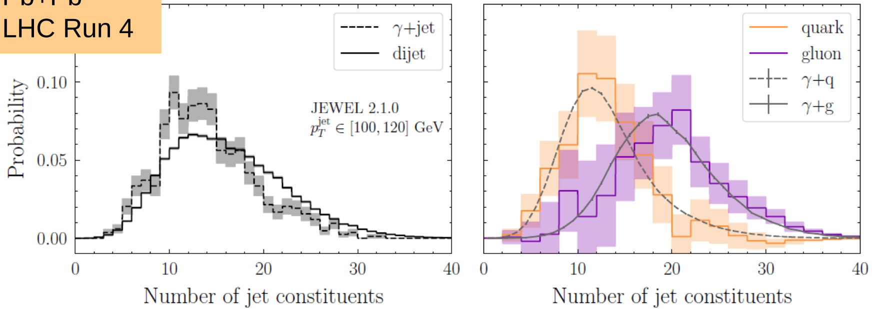
BUT: current analysis relies on PYTHIA template fitting

Going beyond templates → toward data driven measurement of q and g jet modification

pp: Metodiev, Thaler, *PRL* 120 (2018) 24, 241602
Komiske, Metodiev, Thaler, *JHEP* 11 (2018) 059



Pb+Pb
LHC Run 4

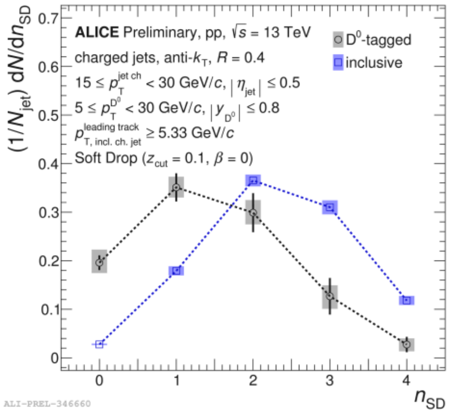


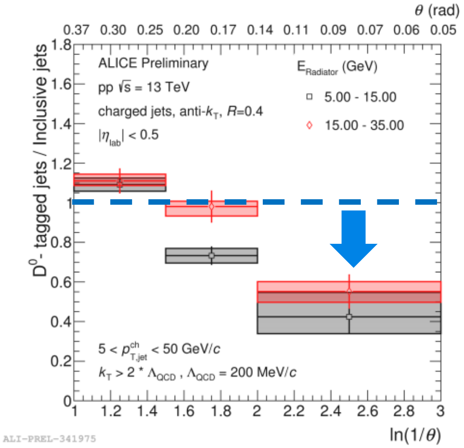
Brewer, Thaler, Turner, in preparation

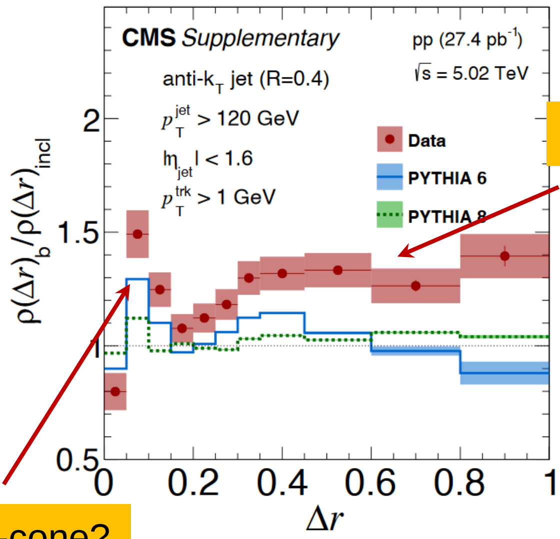
CMS arXiv: 2004.00602

Heavy-flavor jet substructure in p+p at the LHC

V. Kucera: Wed 13:05
X. Wang: Wed 13:45







mismodeling?

dead-cone?

c-jets:
D^0-tagged jets grooming via iterative declustering
n_{SD}: number of hard splittings in jet fragmentation

Less hard splittings for D^0-tagged jets than for inclusive
→ harder *c*-quark fragmentation

First direct measurement of the dead cone!
→ Suppression of radiation toward small angles

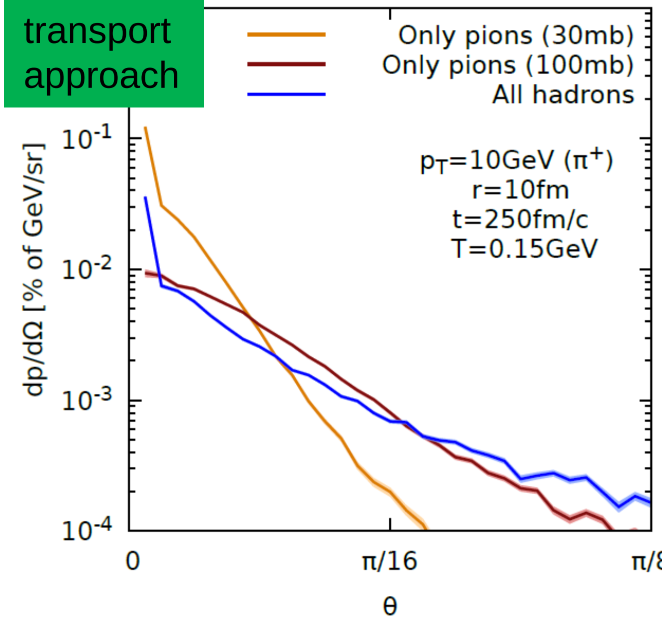
b-jet shape measurements:
data provide excellent opportunity to improve modeling of b-jet production and fragmentation
CMS, arXiv: 2005.14219

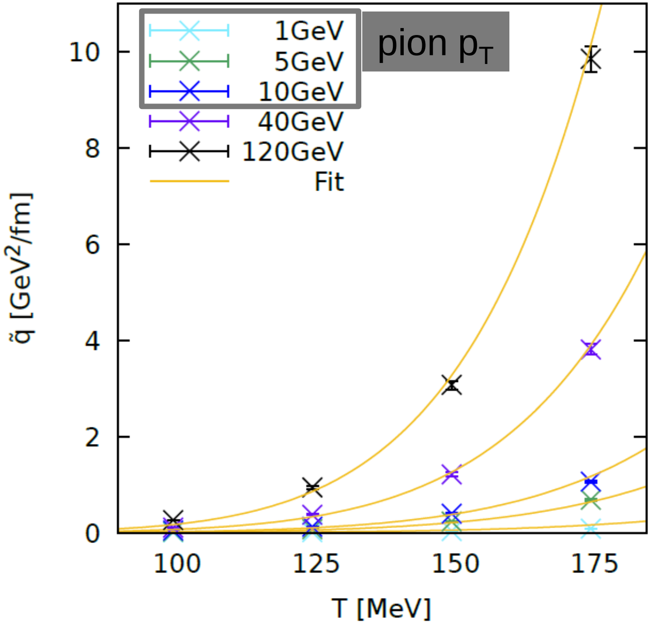
More on heavy-flavor in Roberta Arnaldi's talk

Jet quenching in the hadron gas

H. Elfner, Thu 10:35

Hadronic transport approach





Late stage hadronic interactions explored within SMASH, high-p_T particles in a radially expanding hadron gas

QGP:

$$\hat{q} = \frac{\langle q_\perp^2 \rangle_L}{L}, \qquad \hat{e} = \frac{\langle q_\parallel^2 \rangle_L}{L}$$

hadron gas:

$$\tilde{q} = \frac{\langle q_\perp^2 \rangle}{\lambda_{mfp}}, \qquad \tilde{e} = \frac{\langle q_\parallel^2 \rangle}{\lambda_{mfp}}$$

For reshuffling jet shapes the full hadron gas can be approximated with a pion gas and constant $\sigma = 100$ mb.

Reasonable to neglect E_{loss} in the hadronic stage for single-particle or even jet R_{AA}, but for sub-structure observables and disentangling medium effects, the hadronic phase might be important (up to particle p_T = 8-10 GeV)!

Dorau, Rose, Pablos, Elfner, PRC 101 (2020) 3, 035208

JETSCAPE

W. Fan, Mo 13:35
C. Sirimanna, Wed 11:30
C. Park, Wed 13:05
M. Kordell, Thu 10:55

- Modular framework, allows for study of different physics concepts in a consistent environment.
- Applicable to full range of HI phenomenology.
- Bayesian analysis enables systematic model-to-data comparison

JETSCAPE "PP19" tune provides reasonable agreement with experiments and PYTHIA at mid-rapidity |y|<2.

Hydrodynamics

- Event-by-event VISHNew Hydro (2+1D)
- TRENTO (2+1D) initial conditions with free streaming

Jet evolution

- MATTER + LBT
- Switching virtuality between MATTER and LBT shower, $Q_0 = 1, 2, 3\ \mathrm{GeV}$
- $\hat{q} \propto \alpha_s^2 T^3 \ln\left(\frac{cE}{\alpha_s T}\right)$ based on HTL where $\alpha_s = 0.25$

Medium response

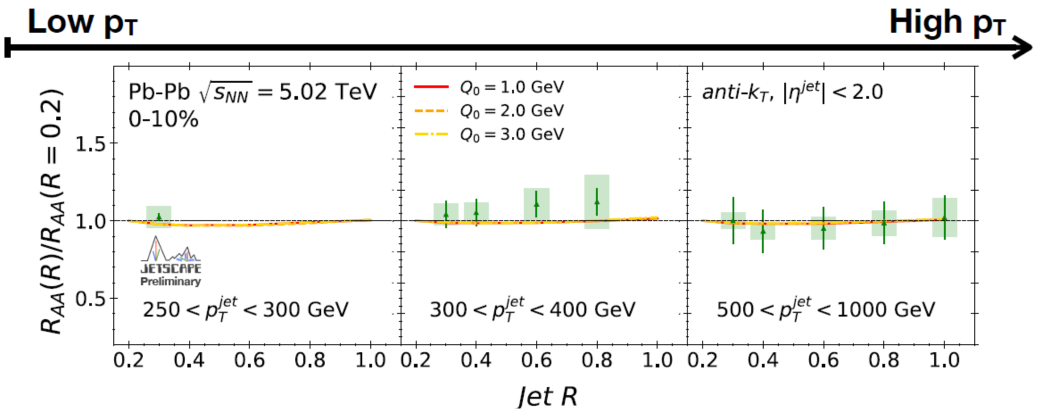
- Recoils: Kinetic theory based approach
- Medium constituents kicked out by jet propagate in jet shower
- Energy/momentum from medium subtracted from jet signals

slide courtesy C. Park

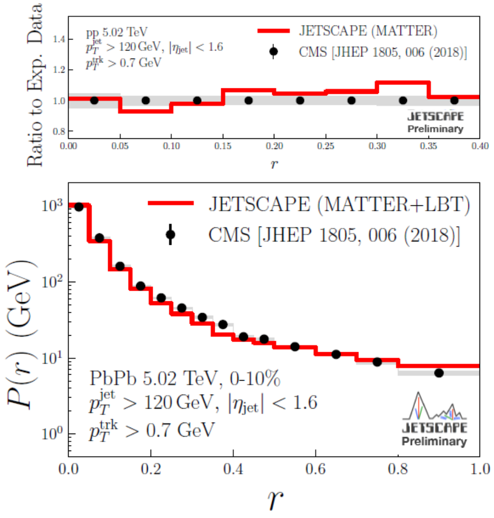
arXiv preprint arXiv:1903.07706 (2019), https://github.com/JETSCAPE/JETSCAPE

JETSCAPE

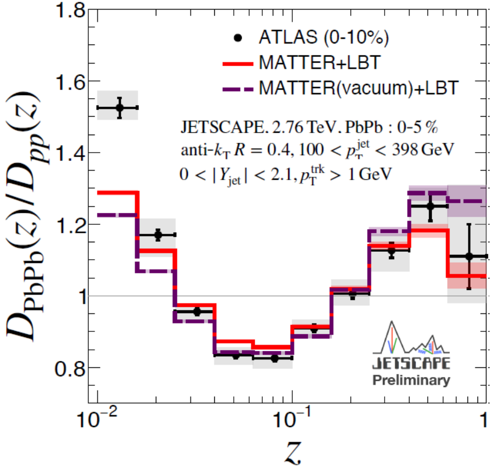
Double ratio of jet R_{AA} relative to R=0.2 close to unity well reproduced, as well as jet structure, v_2 …



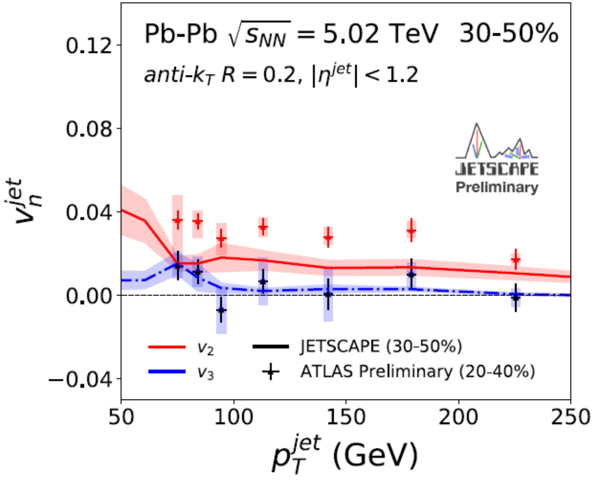
Jet shape function



Jet fragmentation function



Jet v_2, v_3



Instead of summarizing the summary …

1st Hard Probes conference (2004)
"Status and perspectives of jets and high-p_T physics" (given by P. Jacobs)

Summary and Outlook

Partonic energy loss in nuclear collisions at RHIC is firmly established

- broadly consistent with pQCD-based energy loss models
- present measurements supply significant lower bound to initial color charge density

But it promises much more: detailed study of interplay between fragmentation and thermalization may supply new and unique probes of the dynamics

- This is hard, we are only at the beginning
- Intermediate p_T~5-10 GeV/c appears to provide a laboratory in which we can isolate the various physics

Hard Probes '04 Jets and High pT 43

Instead of summarizing the summary …

1st Hard Probes conference (2004)
"Status and perspectives of jets and high-p_T physics" (given by P. Jacobs)

Summary and Outlo

and the LHC

Partonic energy loss in nuclear collisions at RHIC is firmly established

models really advanced

- broadly consistent with pQCD-based energy loss models
- present measurements supply significant lower bound to initial color charge density

rich spectrum of observables

But it promises much more: detailed study of interplay between fragmentation and thermalization may supply new and unique probes of the dynamics

Yes, still true. But we made a great progress!

- This is hard, we are only at the beginning
- Intermediate p_T~5-10 GeV/c appears to provide a laboratory in which we can isolate the various physics

We have a large reach in p_T now, but the "intermediate" p_T will probably teach us most …

Probes '04 Jets and High pT 43

Thank you for your attention