From high-momentum hadrons and correlations to jets

Jana Bielcikova (CTU in Prague, Czech Republic)

11th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions

A bit of history

2023: 50th anniversary of QCD

QCD: Quantum ChromoDynamics was born in 1973



VOLUME 30, NUMBER 26 PHYSICAL REVIEW LETTERS 25 JUNE 1973

Ultraviolet Behavior of Non-Abelian Gauge Theories*

David J. Gross† and Frank Wilczek
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 27 April 1973)

It is shown that a wide class of non-Abelian gauge theories have, up to calculable logarithmic corrections, free-field-theory asymptotic behavior. It is suggested that Bjorken scaling may be obtained from strong-interaction dynamics based on non-Abelian gauge symmetry.

Non-Abelian gauge theories have received much attention recently as a means of constructing unified and renormalizable theories of the weak and electromagnetic interactions.[1] In this note we report on an investigation of the ultraviolet (UV) asymptotic behavior of such theories. We have found that they possess the remarkable feature, perhaps unique among renormalizable theories, of asymptotically approaching free-field theory. Such asymptotically free theories will exhibit, for matrix elements of currents between on-mass-shell states, Bjorken scaling. We therefore suggest that one should look to a non-Abelian gauge theory of the strong interactions to provide the explanation for Bjorken scaling, which has so far eluded field-theoretic understanding.

The UV behavior of renormalizable field theories can be discussed using the renormalization-group equations,[2,3] which for a theory involving one field (say $g\varphi^4$) are

Nobel Prize 2004:
Gross, Politzer, Wilczek:

"for the discovery of asymptotic freedom in the theory of the strong interaction"

VOLUME 30, NUMBER 26 PHYSICAL REVIEW LETTERS 25 JUNE 1973

[14]Y. Nambu and G. Jona-Lasino, Phys. Rev. 122, 345 (1961); S. Coleman and E. Weinberg, Phys. Rev. D 7, 1888 (1973).
[15]K. Symanzik (to be published) has recently suggested that one consider a $\lambda\varphi^4$ theory with a negative λ to achieve UV stability at $\lambda=0$. However, one can show, using the renormalization-group equations, that in such theory the ground-state energy is unbounded from below (S. Coleman, private communication).
[16]W. A. Bardeen, H. Fritzsch, and M. Gell-Mann, CERN Report No. CERN-TH-1538, 1972 (to be published).
[17]H. Georgi and S. L. Glashow, Phys. Rev. Lett. 28, 1494 (1972); S. Weinberg, Phys. Rev. D 5, 1962 (1972).
[18]For a review of this program, see S. L. Adler, in Proceedings of the Sixteenth International Conference on High Energy Physics, National Accelerator Laboratory, Batavia, Illinois, 1972 (to be published).

Reliable Perturbative Results for Strong Interactions?*

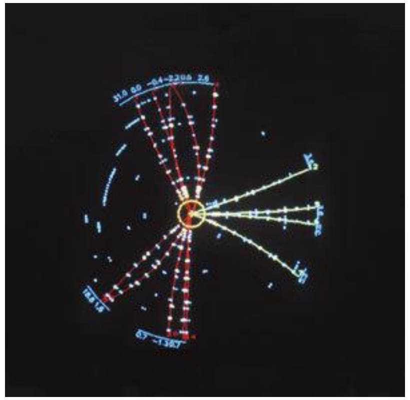
H. David Politzer
Jefferson Physical Laboratories, Harvard University, Cambridge, Massachusetts 02138
(Received 3 May 1973)

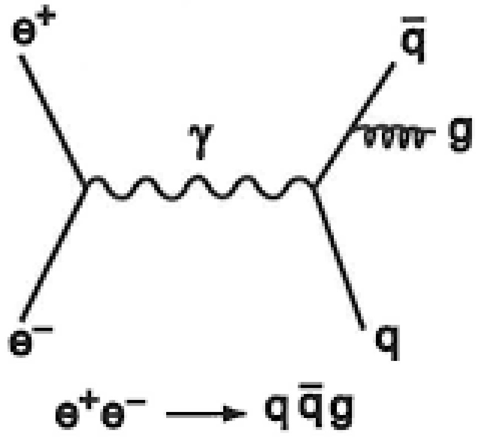
An explicit calculation shows perturbation theory to be arbitrarily good for the deep Euclidean Green's functions of any Yang-Mills theory and of many Yang-Mills theories with fermions. Under the hypothesis that spontaneous symmetry breakdown is of dynamical origin, these symmetric Green's functions are the asymptotic forms of the physically significant spontaneously broken solution, whose coupling could be strong.

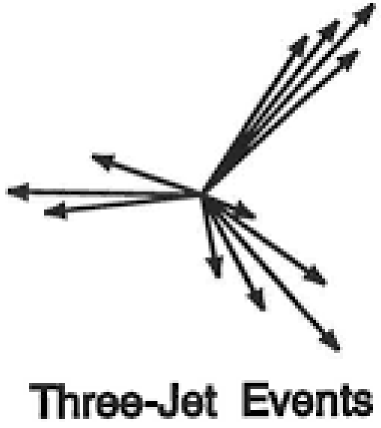
Renormalization-group techniques hold great promise for studying short-distance and strong-

goes to zero, compensating for the fact that there are more and more of them. But the large-

Gluon discovery (1979)





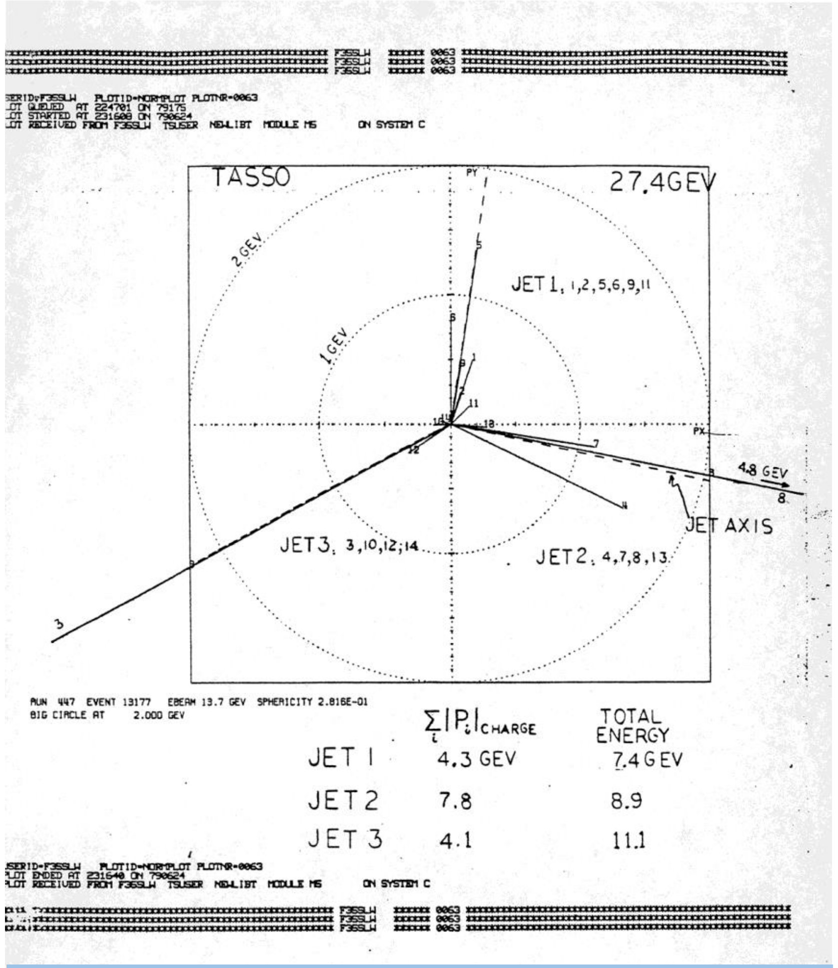


Physicists Sau Lan Wu and Georg Zobernig developed and programmed a method to search for planar three-jet events. At low collision energies, their searches produced no results. But when DESY's PETRA accelerator began to produce collisions at 27.4 GeV, they succeeded. A week later (Jun 18) Bjørn Wiik presented the first event on behalf of the TASSO collaboration at the "Neutrino 79" conference in Norway and he placed it on the overhead projector as the last transparency:

the gluon had seen the light of (the scientific) day

Shortly after (Jun 26), Wu and Zobernig distributed the figure in the internal TASSO Note No. 84.

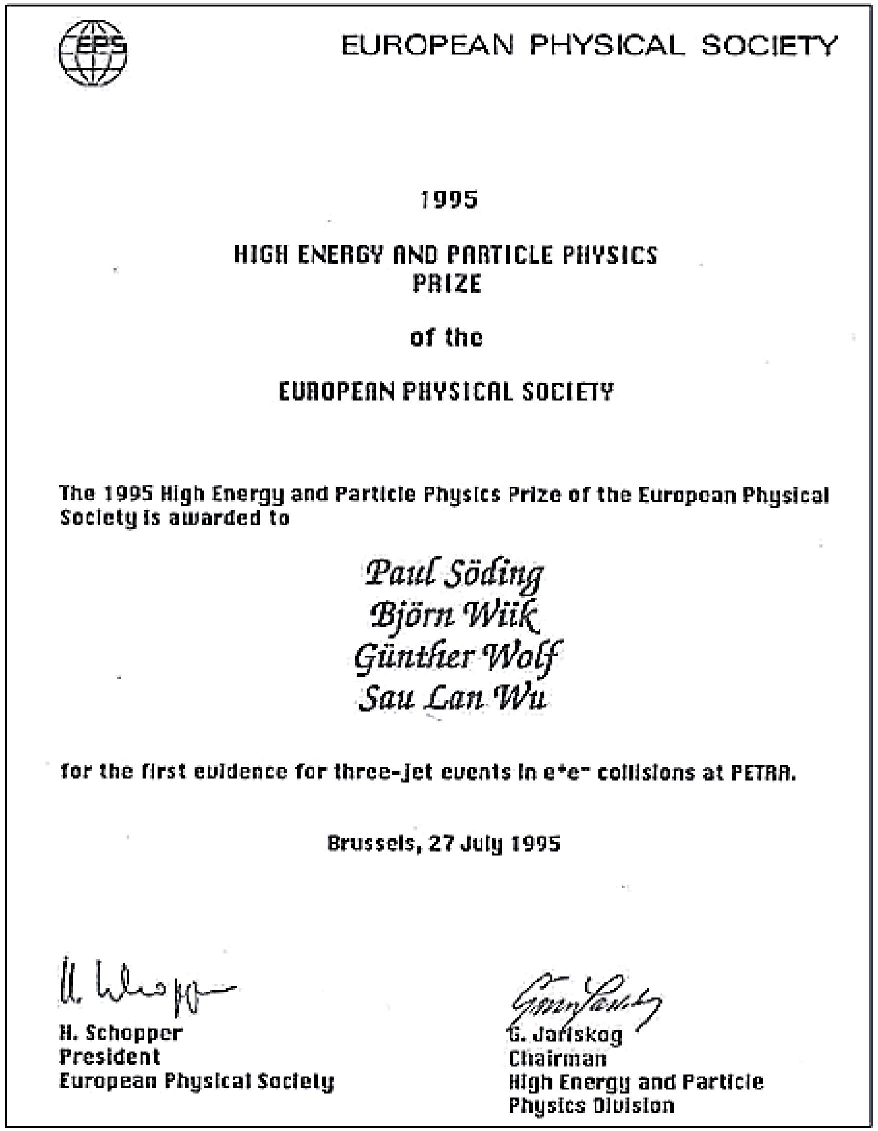
TASSO experiment: Event 13177, Run 447
the first evidence of the gluon



3 jets of particles produced in
an electron-positron collision

https://www.desy.de/news/backgrounders/40_years_of_gluon/index_eng.html
https://home.cern/news/news/physics/four-decades-gluons

Gluon discovery



EUROPEAN PHYSICAL SOCIETY

1995

HIGH ENERGY AND PARTICLE PHYSICS
PRIZE

of the

EUROPEAN PHYSICAL SOCIETY

The 1995 High Energy and Particle Physics Prize of the European Physical Society is awarded to

Paul Söding
Björn Wiik
Günther Wolf
Sau Lan Wu

for the first evidence for three-jet events in e^+e^- collisions at PETRA.

Brussels, 27 July 1995

H. Schopper
President
European Physical Society

G. Jarlskog
Chairman
High Energy and Particle Physics Division

European Physical Society High Energy and Particle Physics Prize, 1995.

The four prize recipients at the ceremony in Brussels (Belgium).

Front row: Günter Wolf and Sau Lan Wu
Second row: Bjørn Wiik and Paul Söding

UA1: observation of jets

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

CERN-EP/83-02
January 6th, 198

OBSERVATION OF JETS IN HIGH TRANSVERSE ENERGY EVENTS AT THE CERN PROTON ANTIPROTON COLLIDER

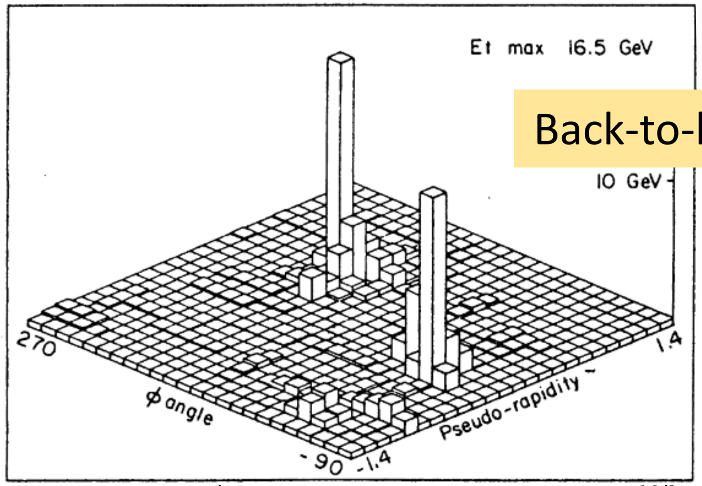
UA1 Collaboration, CERN, Geneva, Switzerland

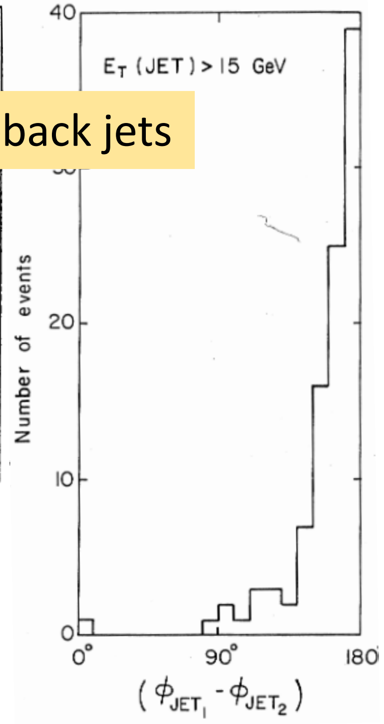
ABSTRACT

With a segmented total absorption calorimeter of large acceptance, we have measured the total transverse energy spectrum for $p\bar{p}$ collisions at $\sqrt{s}$=540 GeV up to ΣE_T=130 GeV in the pseudo-rapidity range $|\eta| < 1.5$. Using two different algorithms, we have looked for localized depositions of transverse energy (jets). For ΣE_T > 40 GeV, the fraction of events with two jets increases with ΣE_T; this event structure is dominant for ΣE_T > 100 GeV.

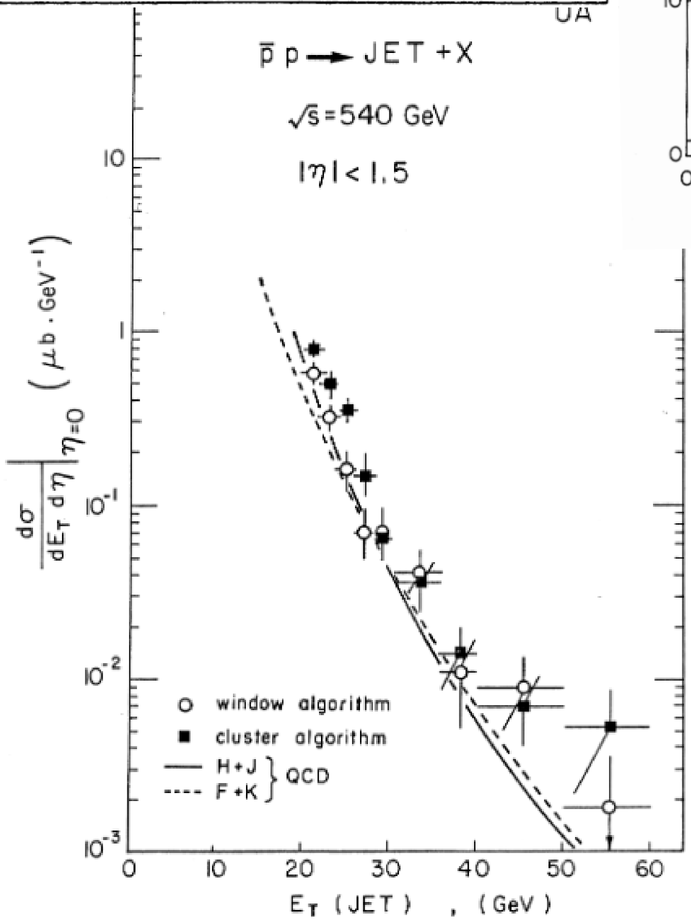
We measure the inclusive jet cross-section up to E_T(jet)=60 GeV and the two-jet mass distribution up to 120 GeV/c^2. The measured cross-sections are compatible with the predictions of hard scattering models based on QCD.

Phys. Lett. B 123 (1983) 115-122





Back-to-back jets

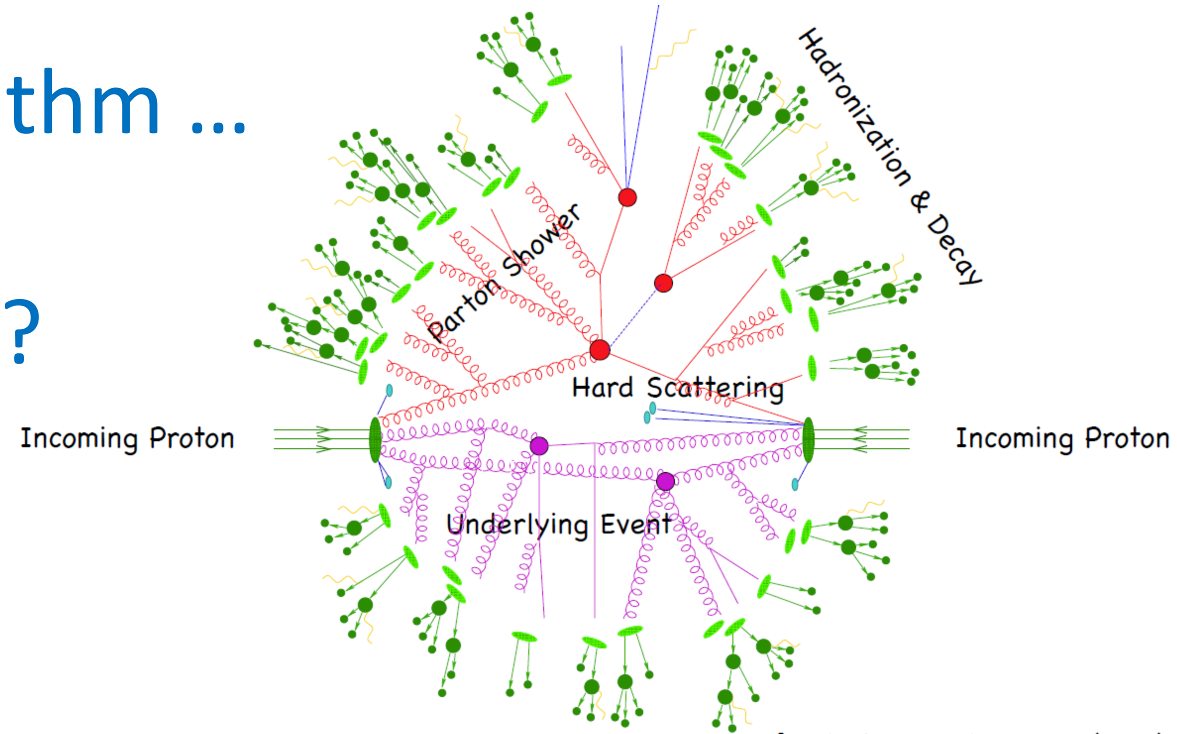


Q: What is a jet?

A: Jet is an image of the parent parton …

B: Jet is defined by an algorithm …

Hmm, but which one to use?



[T. Gleisberg et al., JHEP02 (2004) 05

1990: the proposed standard …

Fermi National Accelerator Laboratory

FERMILAB-Conf-90/249-E
[E-741/CDF]

Toward a Standardization of Jet Definitions *

John E. Huth and Naor Wainer
Fermi National Accelerator Laboratory
P.O. Box 500
Batavia, Illinois 60510

Karlheinz Meier
Deutsches Elektronen Synchrotron (DESY)
Hamburg 52, Germany

Nicholas Hadley
University of Maryland
College Park, Maryland 20742

F. Aversa and Mario Greco
Instituto Nazionale di Fiscia Nucleare (INFN)
Frascati, Italy

P. Chiappetta and J. Ph. Guillet
CTP-CRNS, Luminy
Marseille, France

Stephen Ellis
University of Washington
Seattle, Washington 98195

Zoltan Kunszt
Eidg. Technische Hochschule
Zurich, Switzerland

Davison Soper
University of Oregon
Eugene, Oregon 97403

December 1990

* To be published in the proceedings of the 1990 Summer Study on High Energy Physics, *Research Directions for the Decade*, Snowmass, Colorado, June 25 - July 13, 1990.

Until now, direct comparisons of jet cross sections in hadron collisions have been hindered by differences in jet definition adopted by various experiments.

Several important properties that should be met by a jet definition are [3]:

1. Simple to implement in an experimental analysis;
2. Simple to implement in the theoretical calculation;
3. Defined at any order of perturbation theory;
4. Yields finite cross section at any order of perturbation theory;
5. Yields a cross section that is relatively insensitive to hadronization.

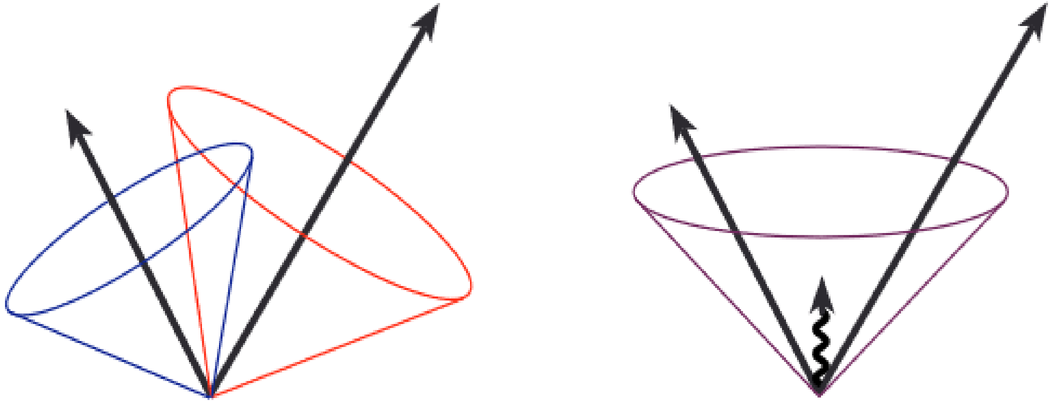
We propose to use a standard jet definition using cones in $\eta - \phi$ space. This has the advantage that it is related to the prescription for handling radiation in QCD introduced by Sterman and Weinberg [7]. The cone algorithms in $p\bar{p}$ collisions were first explored by the UA1 collaboration [8]. This technique is to be contrasted to nearest neighbor algorithms where clusters are formed from contiguous towers above some energy threshold. Clusters are defined as separate if some local minimum can be found between peaks of energy [9].

What should the jet algorithm fulfill?

From theoretical point of view:

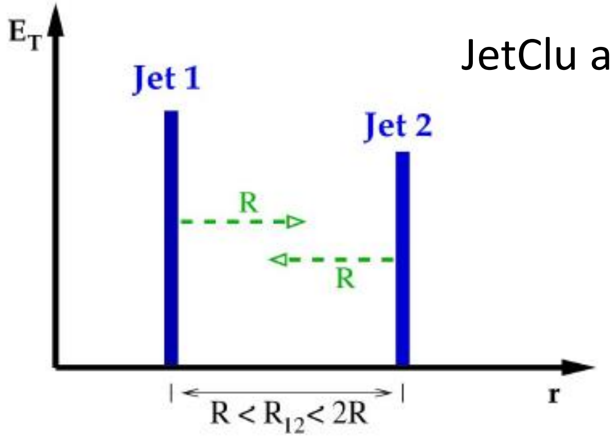
1. Infrared (IR) safety:

→ algorithm should find jets that are not sensitive to addition of soft gluons

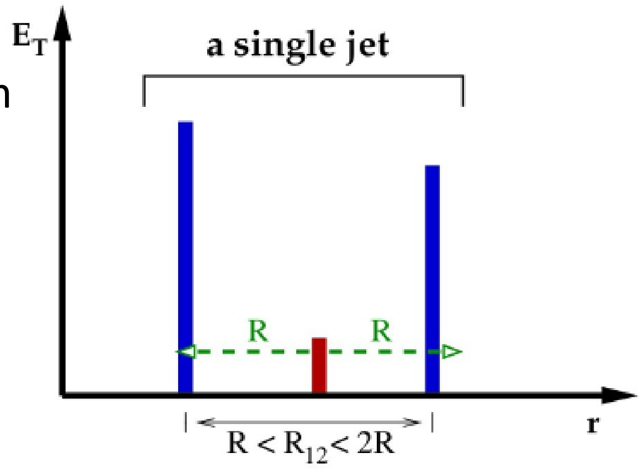


Cone clustering:
jet clustering begins around seed particles (arrows) with length proportional to energy.

JetClu algorithm



(Identified as 2 jets)



(Identified as 1 jet)

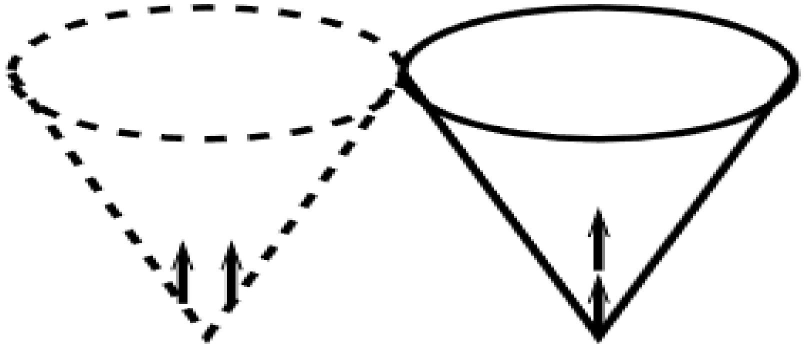
For example this potentialy dangerous configuration is identified as 2 jets but the addition of a soft gluon in the middle leads to a single jet!

courtesy Jay R. Dittmann
See also Blazey et al., hep-ex/0005012

What should the jet algorithm fulfill?

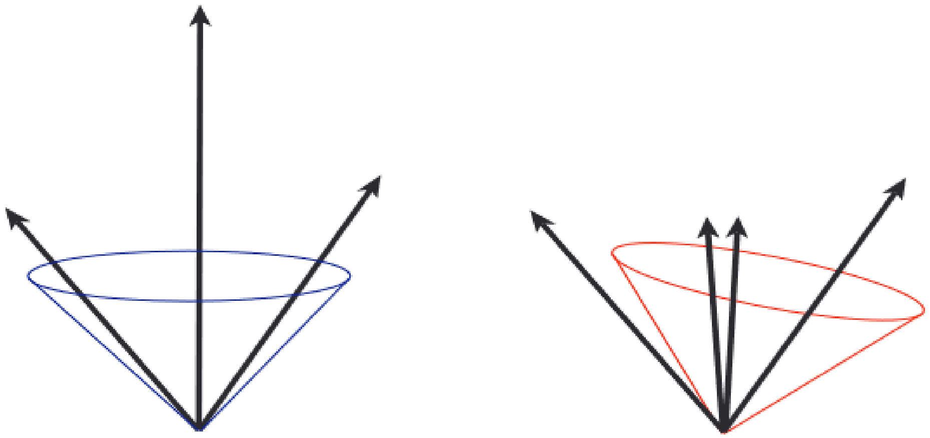
2. Collinear safety:

→ jets should not be sensitive to collinear gluon emission



Left: configuration fails to produce a seed because its energy is split among several detector towers.

Right: this configuration produces a seed because its energy is more narrowly distributed



Seed dependence:
we can observe sensitivity to E_T ordering of the particles that act as seeds.

courtesy Jay R. Dittmann
See also Blazey et al., hep-ex/0005012

What should the jet algorithm fulfill?

- „boost“ invariance : algorithm should find the same jets independently of the boost along the beam
- kinematic observables describing jets should be independent of details of the final state
- algorithm should be equivalent on parton, particle and detector level
- algorithm should be easily applicable in perturbative calculations

What about experimental aspects?

- independence on detectors (segmentation, resolution, response to energy deposited)
- algorithm should not increase effects of finite resolution of measurement (e.g. energy)
- algorithm should be immune against multiple hard scatterings at high luminosity (relevant for LHC and especially its high luminosity upgrade)
- easy implementation and reasonable computational speed
- possibility to identify all interesting jets

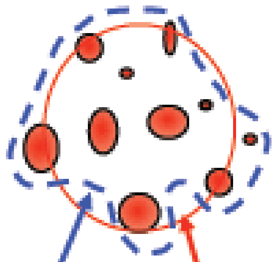
Jet reconstruction algorithms

In general, we divide jet algorithms to two classes“

A. Cone algorithms:

- JetClu
- Midpoint Cone
- SISCone (Seedles Infrared Safe Cone)
- Leading Order High Seed Cone (LOHSC)

typically with a „split-merge“ procedure



R: cone radius/resolution parameter

B. Sequential recombination algorithms:

- cluster pair of objects relatively close in p_T

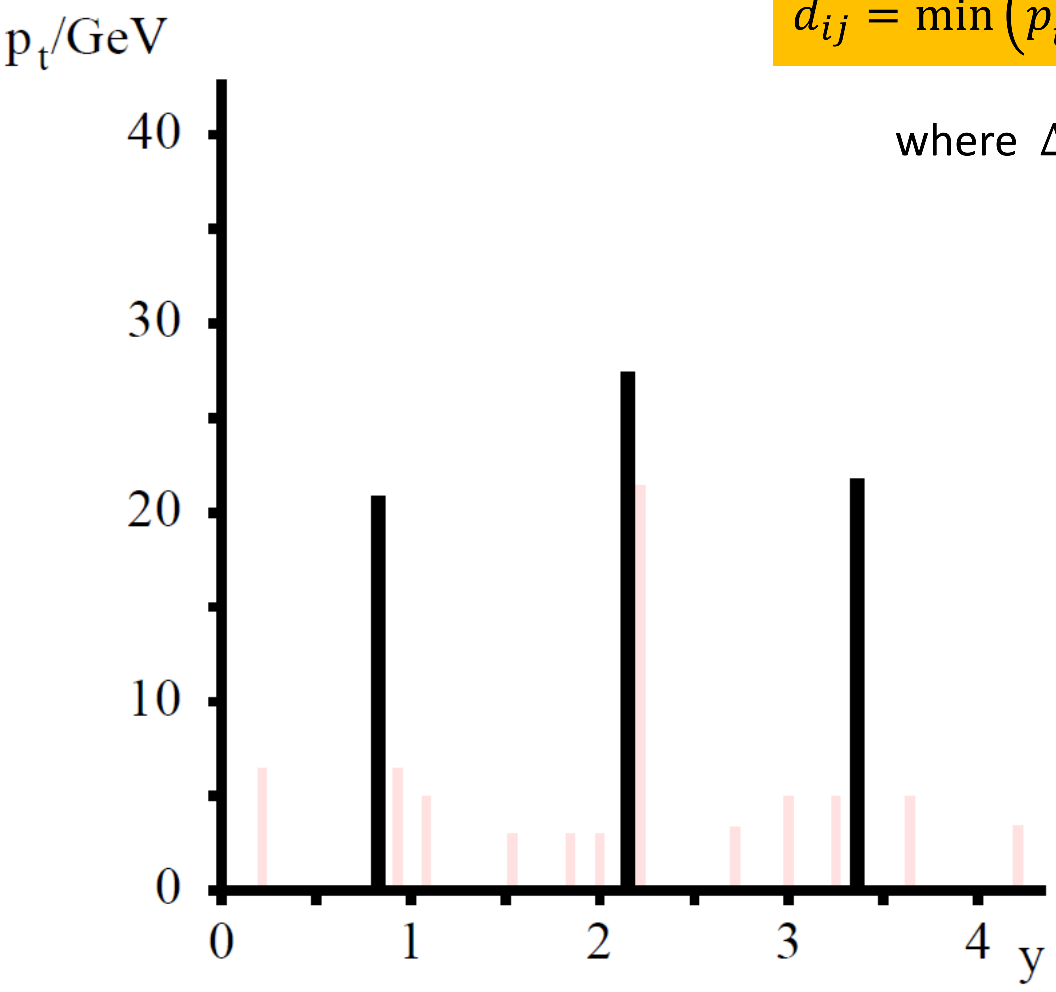
$$d_{ij} = min(p_{Ti}^n, p_{Tj}^n)\,(\Delta\eta^2+\Delta\varphi^2)/R^2, d_i = p_{Ti}^n$$

$min(d_i, d_{ij})$: d_i -> a new jet, d_{ij} -> combine i,j

- Recombination scheme needed:
  E-scheme: simply adds the four-vectors
  p-scheme: assumes zero particle mass

n = 2 : k_T (clustering starts from particles with small p_T)
n = -2: anti-k_T (clustering starts from particles with high p_T)
n = 0: Cambridge/Aachen (C/A)
(cares only about angular distance)

How does sequential recombination algorithm work?



$$d_{ij} = \min\left(p_{ti}^{2p}, p_{tj}^{2p}\right)\Delta R_{ij}/R^2 \quad \text{and} \quad d_{iB} = p_{ti}^{2p}$$

where $\Delta R_{ij}^2 = (y_i - y_j)^2 + (\varphi_i - \varphi_j)^2$

1. Find $d_{\min} = \min\{d_{ij}, d_{iB}\}$
2. $\exists i, j$: $d_{\min} = d_{ij}$, combine particles
3. $\exists i$: $d_{\min} = d_{iB}$, The particle is the final jet, remove it from the list
4. Start again from the top until no particles are left

Courtesy M. Cacciari

Do I need to write the code myself?

No, just use:

M. Cacciari, G.Salam and G.Soyez, JHEP0804 (2008) 005

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FastJet

http://fastjet.fr/

A software package for jet finding in pp and e^+e^- collisions. It includes fast native implementations of many sequential recombination clustering algorithms, plugins for access to a range of cone jet finders and tools for advanced jet manipulation.

Release of FastJet 3.4.0, (latest stable release) 25 June 2021 (release notes).
This is a main release of FastJet. The main new feature of FastJet-3.4.0 is the support for thread safety (through the --enable-thread-safety configure option). Other additions include facilities to get/set the seeds used to generate ghosts for jet area calculations and a new interface for background estimation. See the full release notes for details.

Download

Latest stable release of fjcore (v3.4.0), 25 June 2021
Lightweight access to the core FastJet functionality (PseudoJet, JetDefinition, ClusterSequence and Selector).
It consists of just two files, fjcore.hh and fjcore.cc, which can easily be included in 3rd party projects. Compile time: a few seconds. A fortran interface and basic examples are also included in the distribution. Download size: 75k.

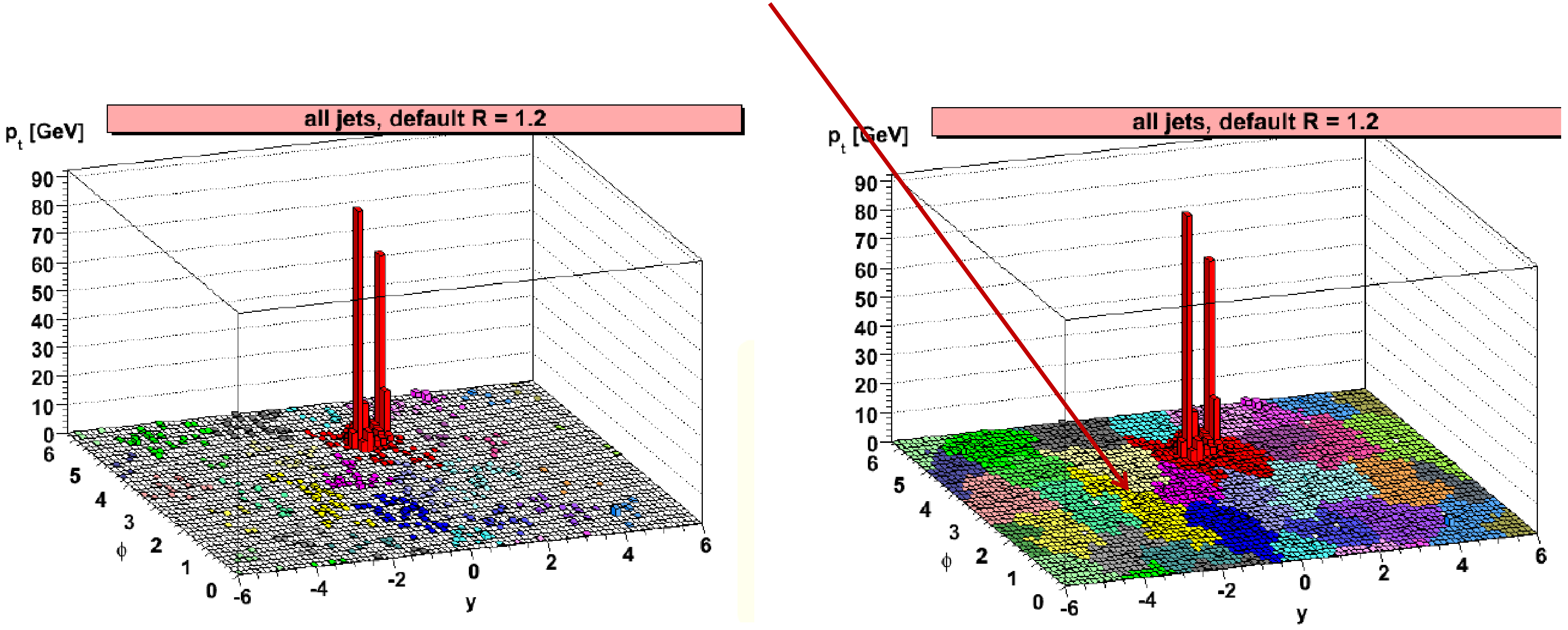
Release of FastJet Contrib 1.051, 1 March 2023.
A package of contributed add-ons to FastJet. This release brings the new KTClusCXX contrib, v.1.0.1 (a C++ reimplementation of the old Fortran KtClus package) and updates LundPlane to v.2.0.3 (fixing missing header installation). FastJet contrib 1.047 upwards now requires c++11 support in the compiler (if using g++ it should be version 5.1.0 or later). Direct download.

 - Bug report - Subscribe - Follow @fastjet_fr

How to define jet area?

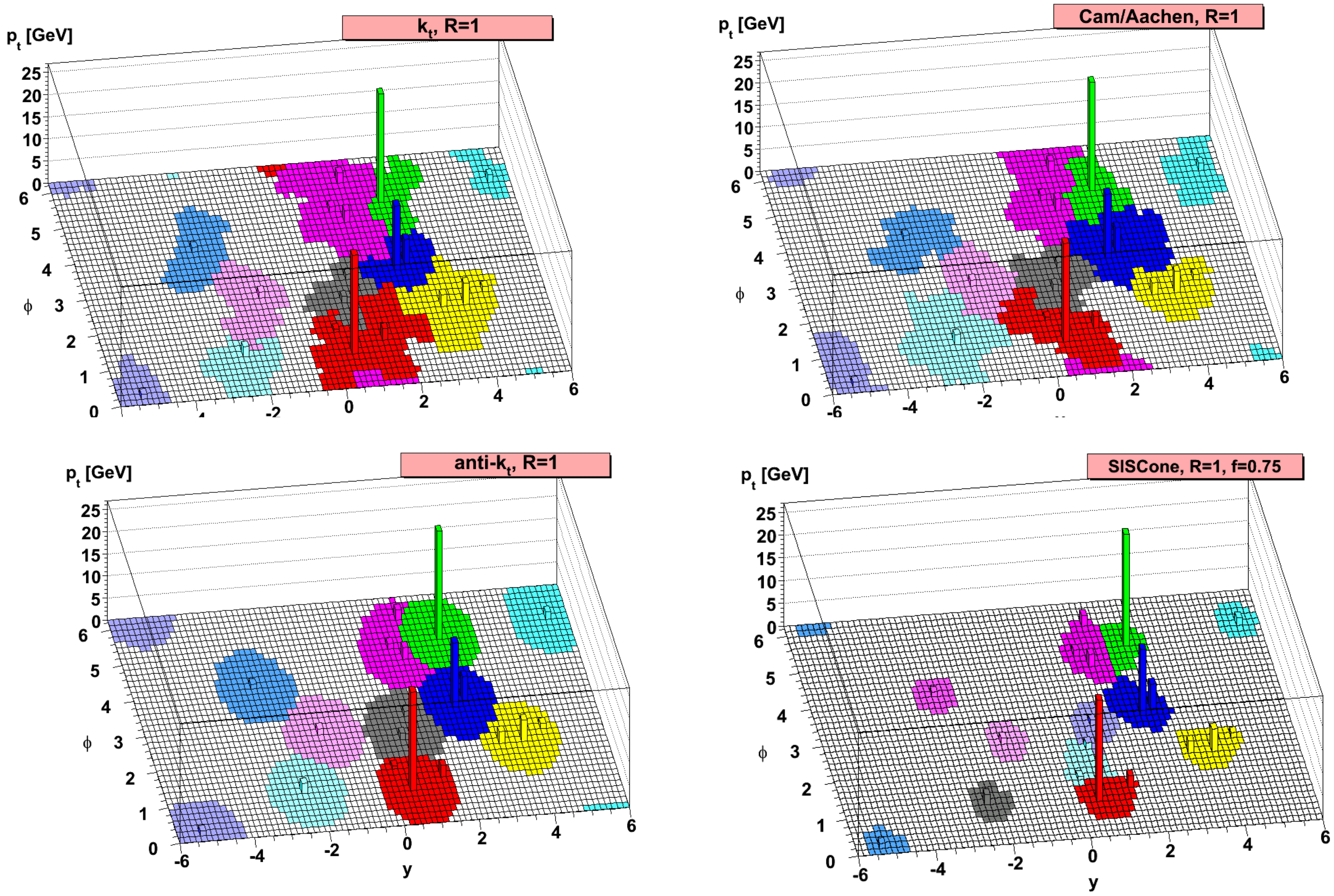
This is not that straightforward …

- let us add to each event many „soft particles – ghosts“ (10^{-100} GeV)
- the jet area A is proportional to the number of particles in jet



Cacciari, Salam, Soyez (2008)

The same event seen by different jet algorithms…

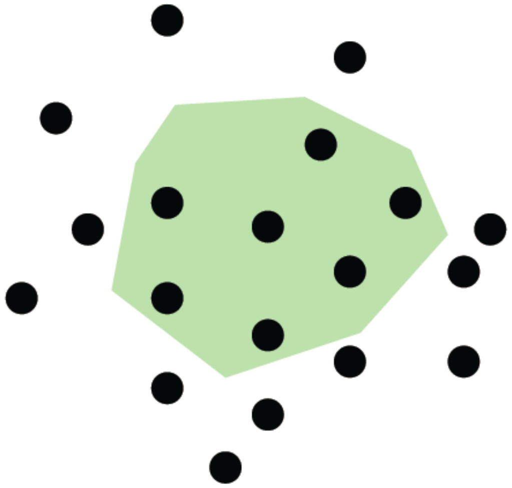


M. Cacciari, G. P. Salam, G. Soyez: The anti-kt jet clustering algorithm, JHEP 0804 (2008) 063, arXiv:0802.1189v2 [hep-ph]

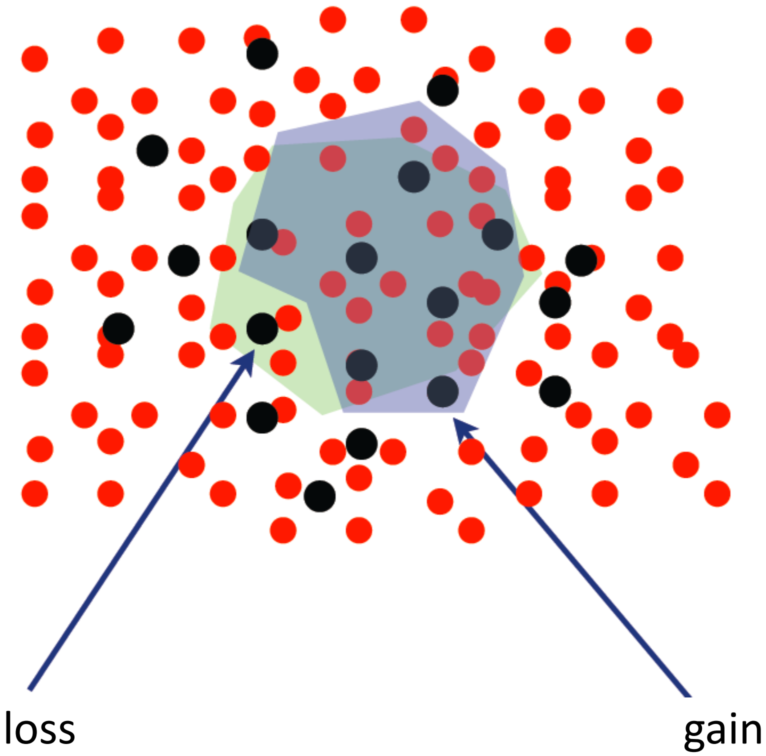
Does the background influence jet?

YES, it is the so called „back-reaction“

no background

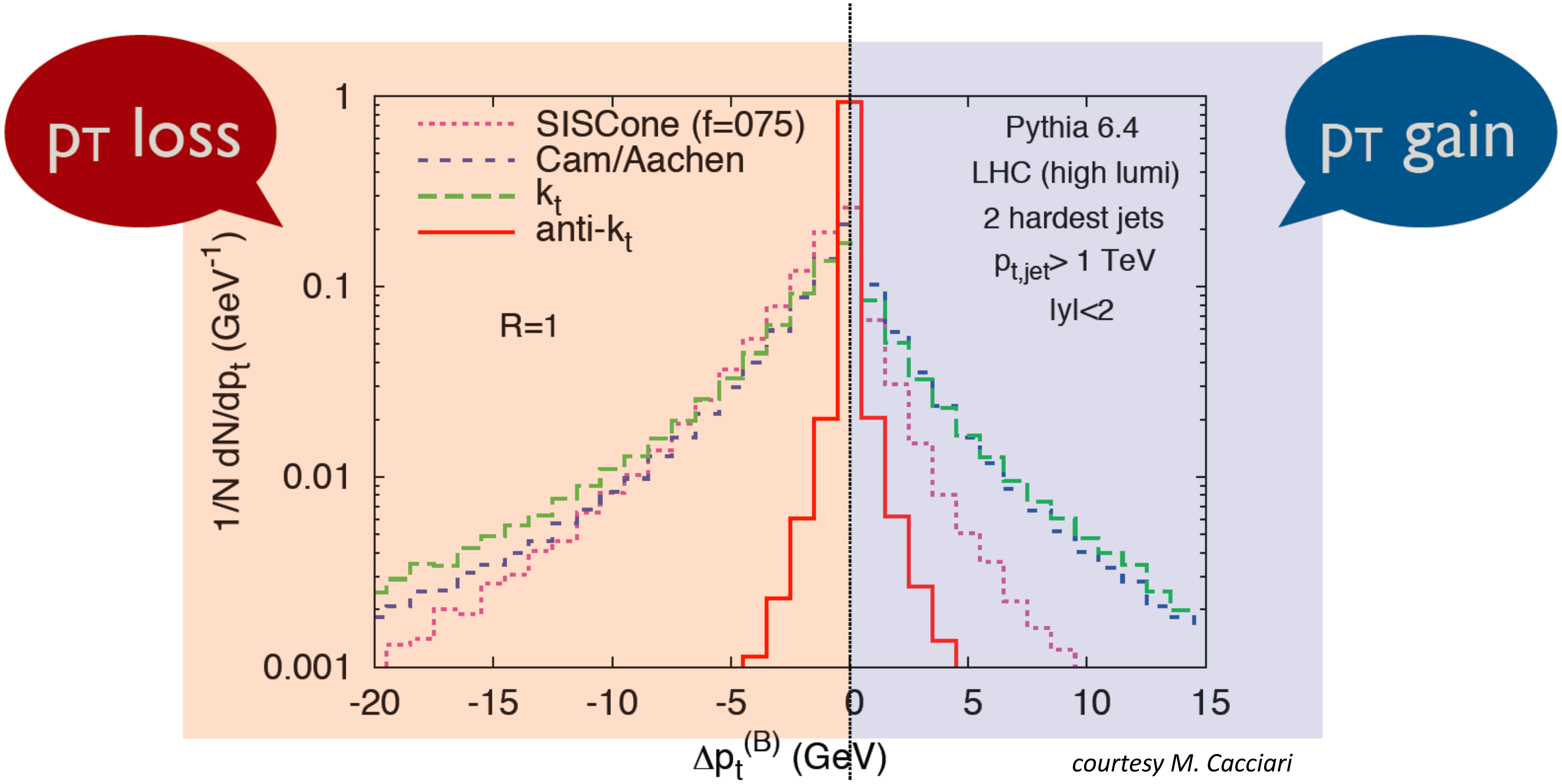


embedded in background



courtesy M. Cacciari

Sensitivity of jet algorithms to presence of background



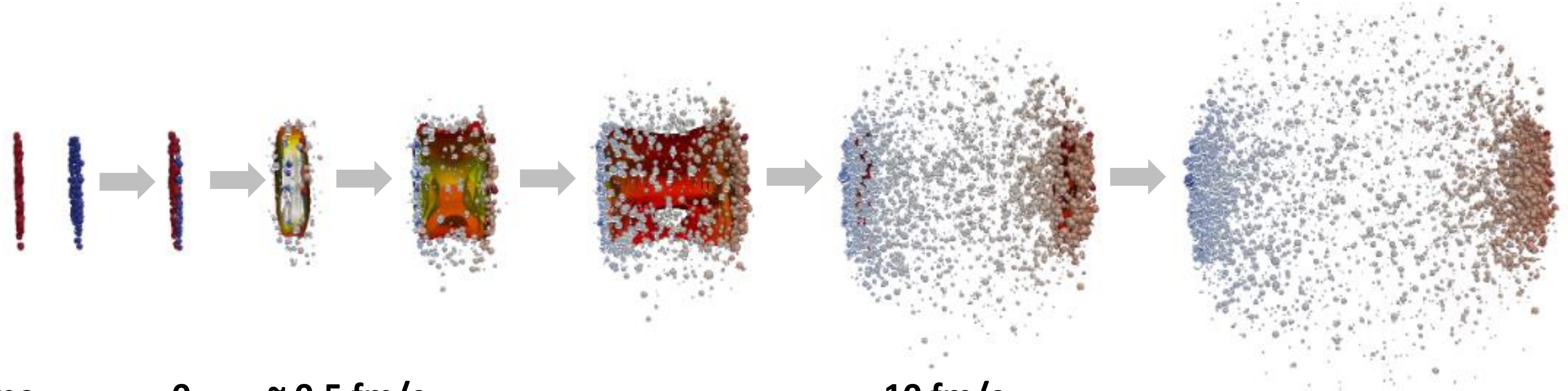
courtesy M. Cacciari

The anti-k_t algorithm is the least sensitive to the „back-reaction" from background → suitable to be used in A+A collisions

Cacciari, Salam, Soyez: Catchment Area of Jets, **JHEP 0804 (2008) 005,** *arXiv:0802.1188ss*

Let us now move to heavy-ion collisions and QGP exploration …

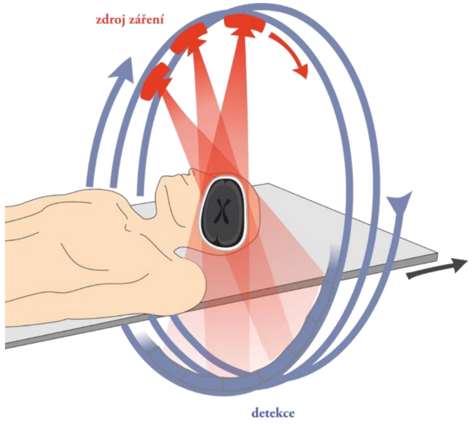
Tomography of QGP



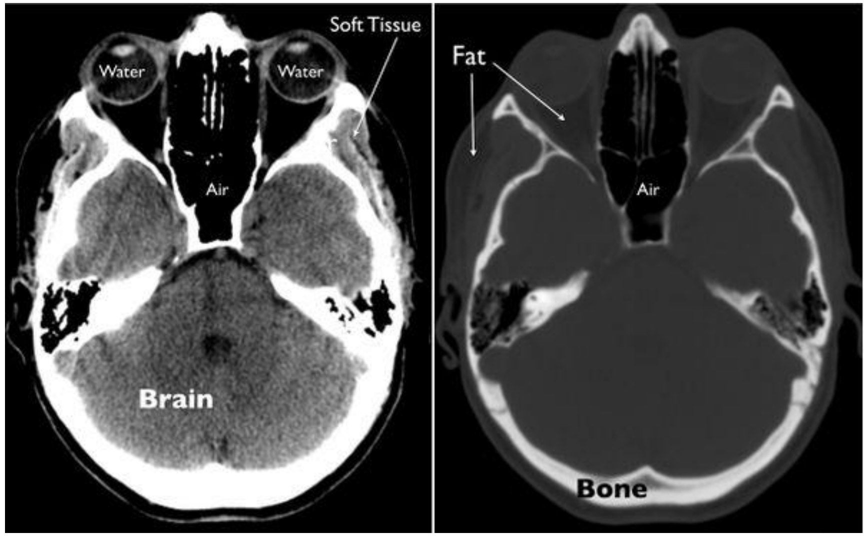
… the lifetime of QGP is very short

QGP tomography

CT (Computed Tomography) in medicine

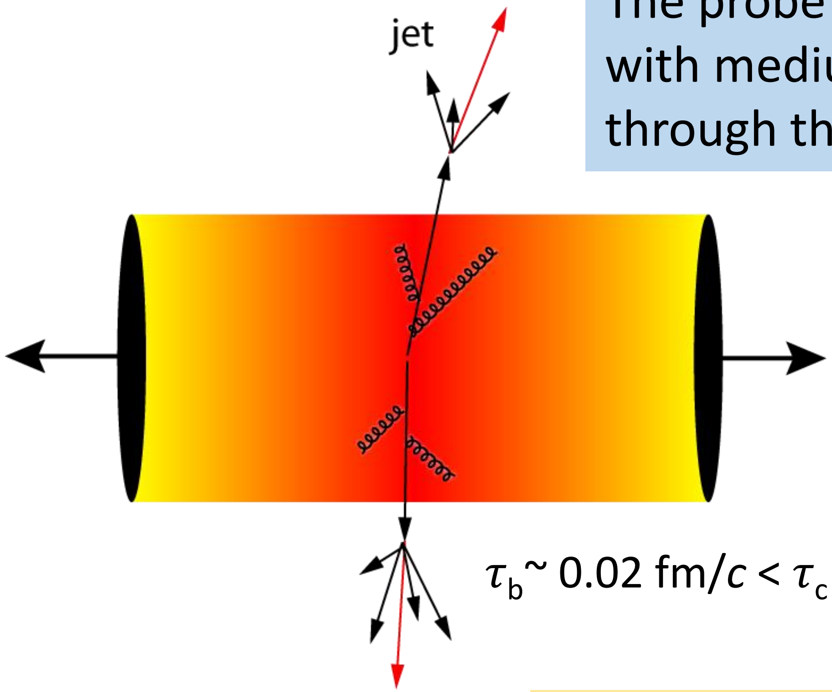


The probe enters to medium from outside



QGP lifetime is very short
→ in-situ probes needed

The probe is created together with medium and propagates through the medium



$\tau_b \sim 0.02$ fm/c < $\tau_c \sim 0.07$ fm/c < $\tau_{QGP} \sim 1$ fm/c

Photons, W and Z bosons: do not carry color charge, bring information about initial state

Jets, heavy quarks, quarkonia : originate from initial hard scattering of partons, which carry a color charge, interact with nuclear matter

High-p_T particle production pp collisions

p+p:

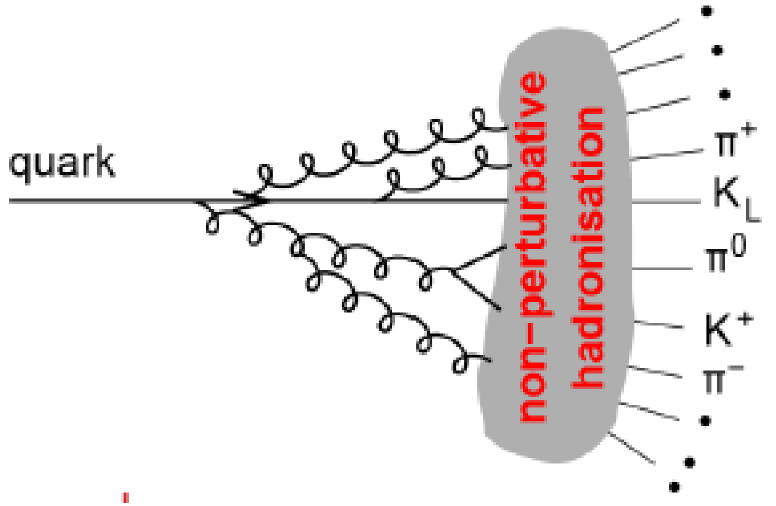
Hard parton scattering: *a large Q^2 process*

→ *initial phase of a collision << 1 fm/c*

can be calculated in perturbative QCD

It is followed by a parton shower

→ partons eventually hadronize and form jets



Collinear factorization:

$$\frac{d\sigma^h_{pp}}{dyd^2p_T} = K\sum_{abcd}\int dx_a dx_b f_a(x_a,Q^2) f_b(x_b,Q^2) \frac{d\sigma}{d\hat{t}}(ab\to cd)\frac{D^0_{h/c}}{\pi z_c}$$

Parton distribution function	Matrix element	Fragmentation function
measured in DIS	pQCD	e^+e^-
initial state (saturation?)		

High-p_T particle production A+A collisions

$$\frac{d\sigma_{pp}^{h}}{dyd^2p_T} = K\sum_{abcd}\int dx_a dx_b f_a(x_a,Q^2) f_b(x_b,Q^2) \frac{d\sigma}{d\hat{t}}(ab \to cd) \frac{D_{h/c}^0}{\pi z_c}$$

Parton distribution function — measured in DIS; initial state (saturation?)

Matrix element — pQCD

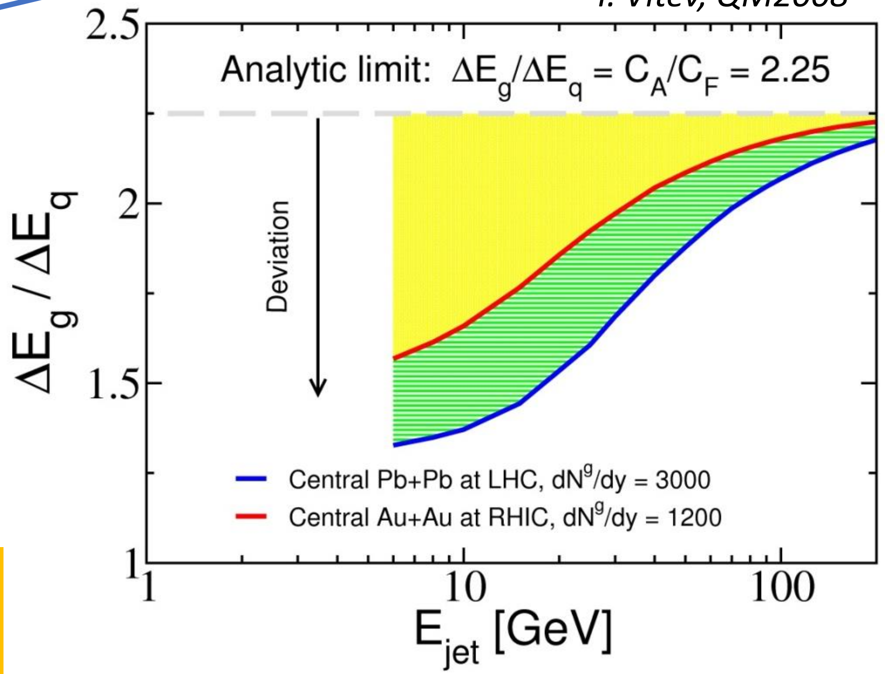
Fragmentation function — final state effects

Parton energy loss in medium:
- elastic scatterings
- gluon radiation

Depends on:
- color charge
- quark mass (dead cone effect)
- path length in medium

Goal: Use in-medium parton energy loss to quantify medium properties.

I. Vitev, QM2008



Parton interaction with medium not trivial, depends on strength of coupling, dynamics of fireball

… *challenge for theorists*

→ see talk by Carlos Salgado

Fermi National Accelerator Laboratory

FERMILAB-Pub-82/59-THY
August, 1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma: Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

Abstract

n energy quarks and gluons propagating through quark-gluon suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For hadron-hadron collisions with high associated multiplicity and with transverse energy dE_T/dy in excess of 10 GeV per unit rapidity, it is possible that quark-gluon plasma is produced in the collision. If so, a produced secondary high-p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

$$\frac{dE_T}{dy} = 10 \text{ GeV}$$

Then

$$\varepsilon_f \simeq 15 \text{ GeV/fm}^3$$

and

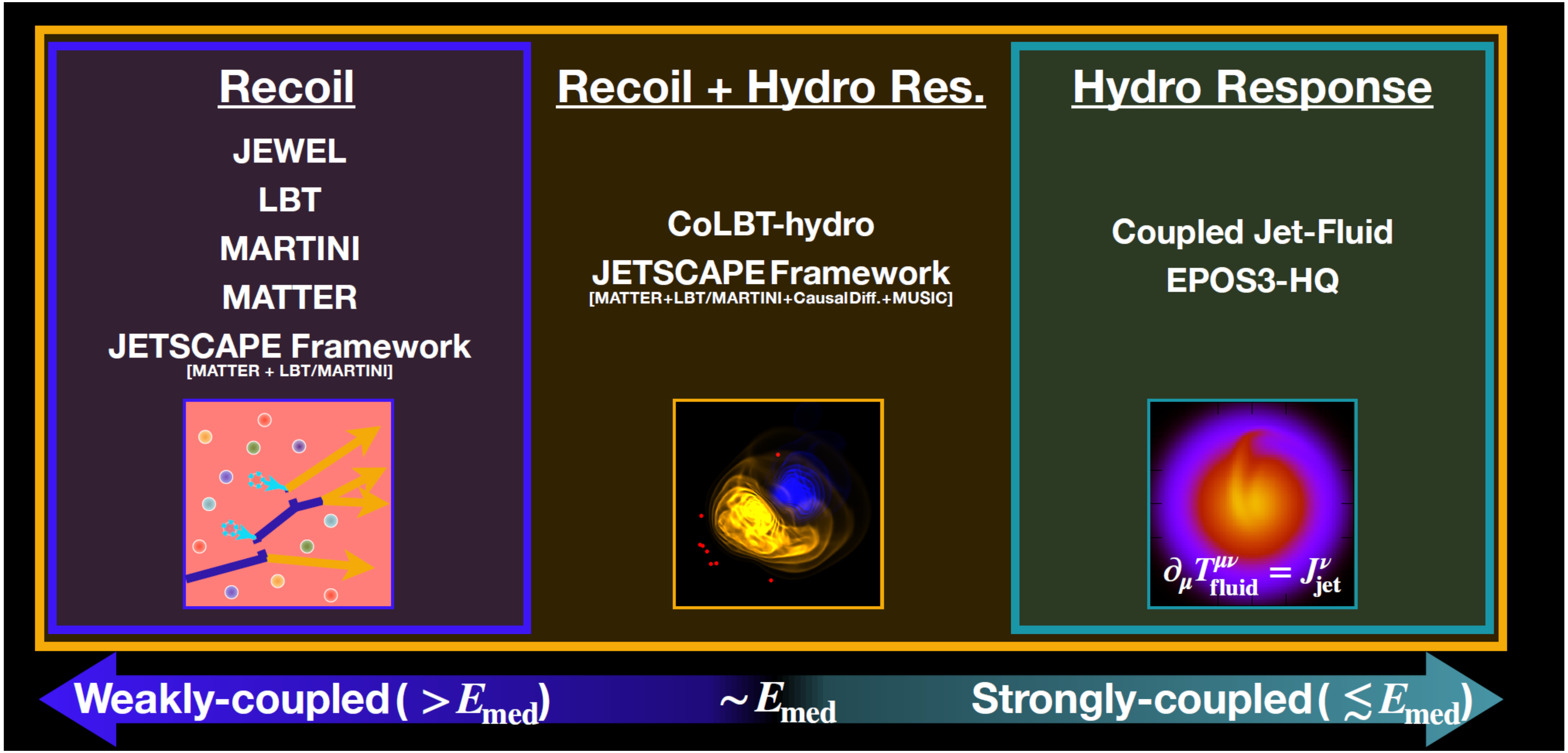
$$T_f \simeq 300 \text{ MeV}$$

For p_T=20 GeV

$$\Delta p_T = \begin{cases} 30 \text{ GeV} & \text{gluon} \\ 13 \text{ GeV} & \text{quark} \end{cases}$$

This is quite sufficient to quench low-p_T jets!!

Models for medium response in a nutshell



Slide courtesy Y. Tachibana

JETSCAPE

- 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

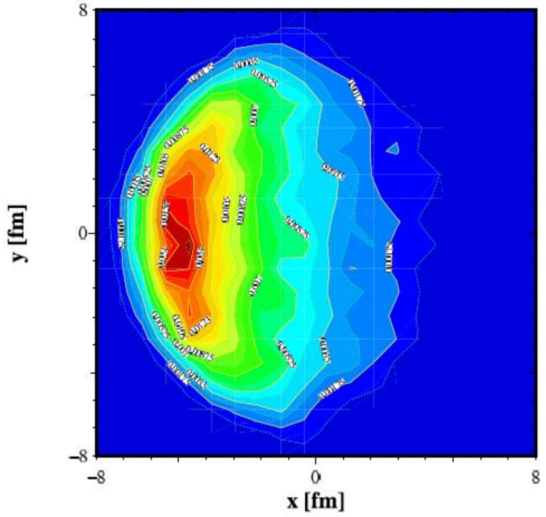
slide courtesy C. Park

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

Sensitivity of different observables

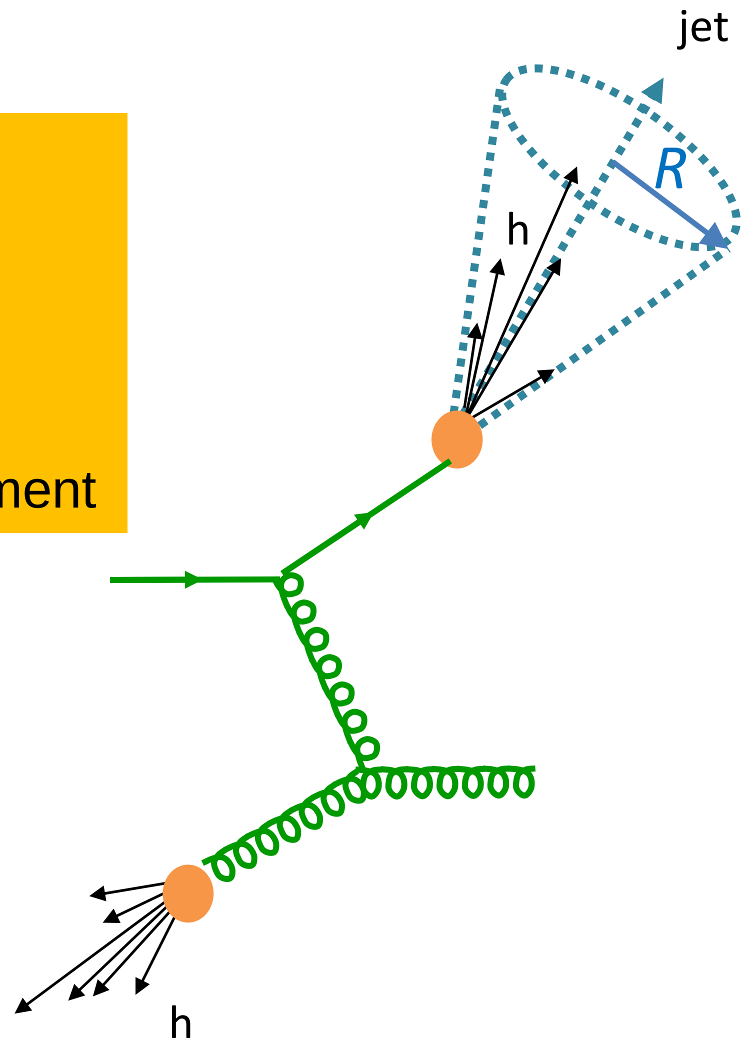
Renk, Eskola, PRC 75, 054910 (2007)

single h



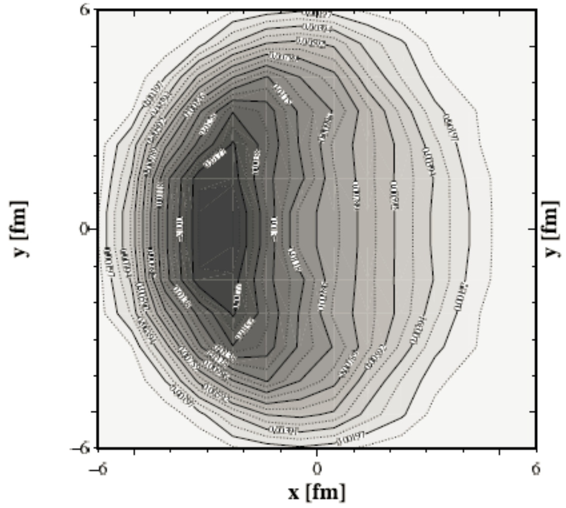
Surface bias dependence:

- single hadron and jet-hadron observables: strong surface bias
- di-hadron correlations: show less bias
- γ or Z triggered: offer unbiased measurement

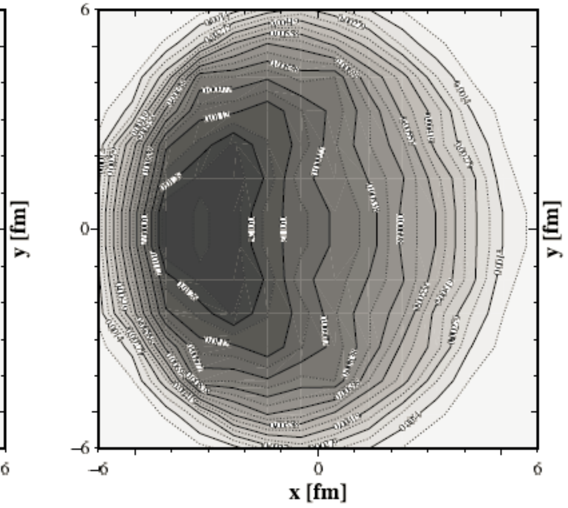


T. Renk, YaJEM

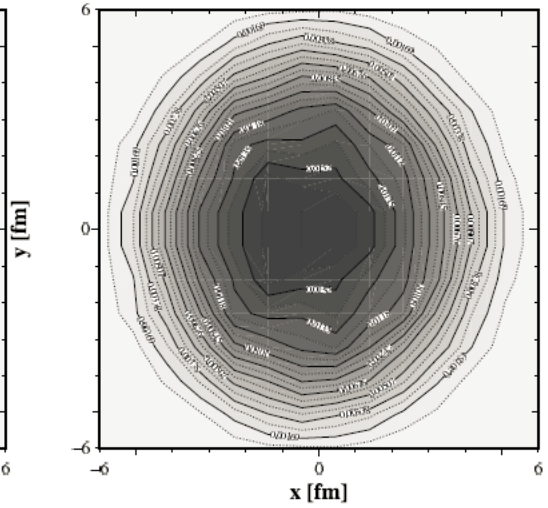
h - h



jet - h

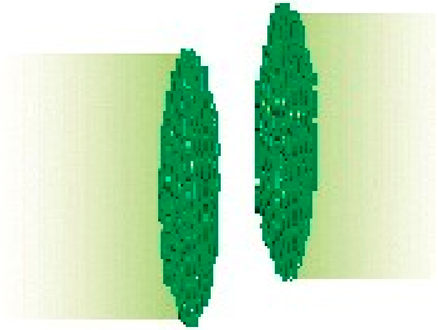


γ - h

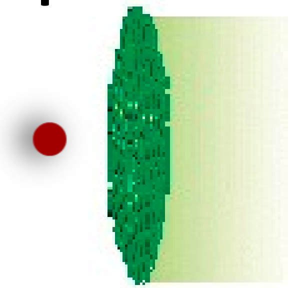


Dialing various physics phenomena: collision system size

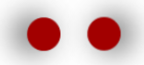
A + A



p + A



p + p



“hot/dense QCD matter”
final state effects
thermal and collective particle production (flow)

“cold nuclear matter”
initial state effects
shadowing and gluon saturation

“vacuum”
reference

Centrality:
level of overlap of the colliding Lorentz contracted nuclei

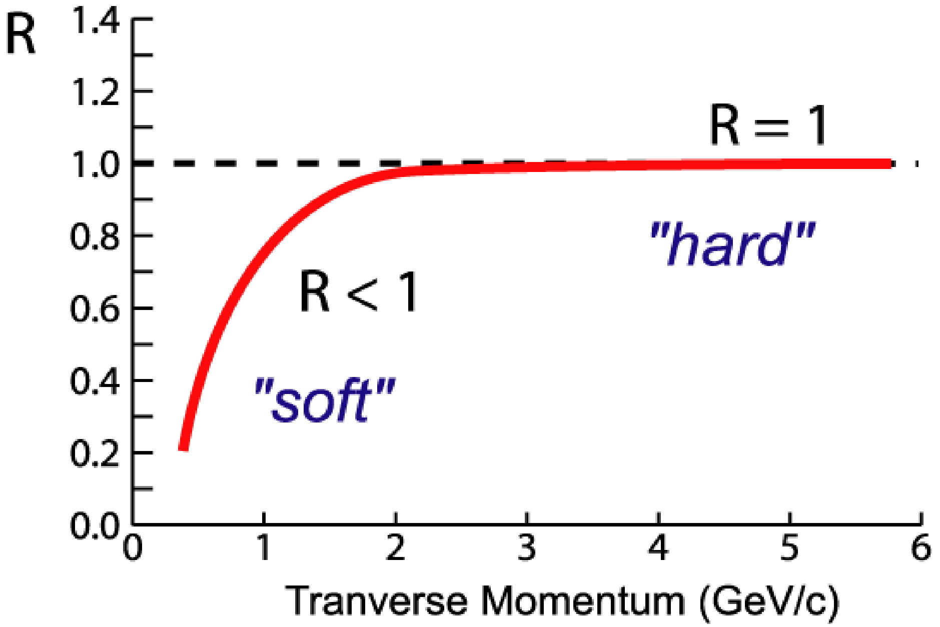
A very interesting physics program on its own:
high multiplicity pp collision studies
to look for onset of QGP formation

Nuclear modification factor (R_{AA})

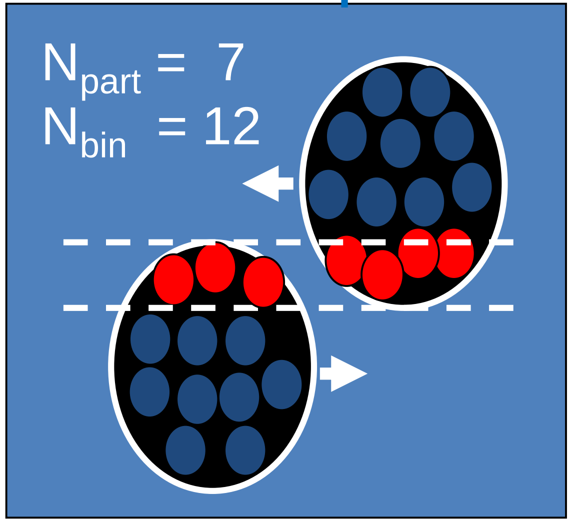
… the way to compare an observable in A+A collisions to the reference (pp or peripheral A+A)

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

$N_{bin}/\sigma_{inel}^{NN}$



Glauber's picture:



R = 1: A+A collision is a superposition of pp collisions

R < 1: suppression of particle production (quenching)

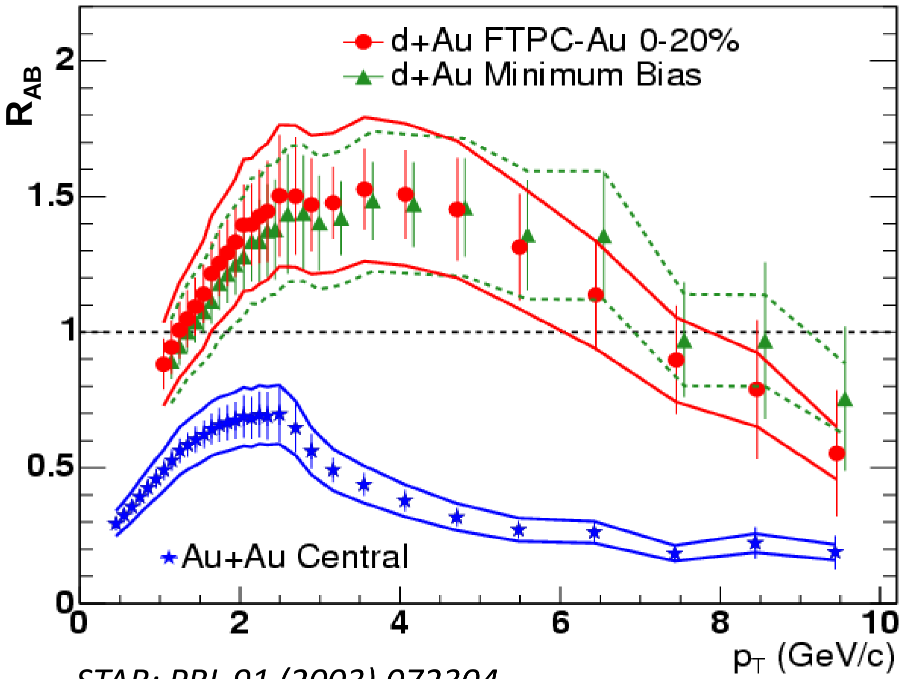
Soft processes scale with N_{part}
Hard processes scale with N_{bin}

About 20 years ago at RHIC: jet quenching observed

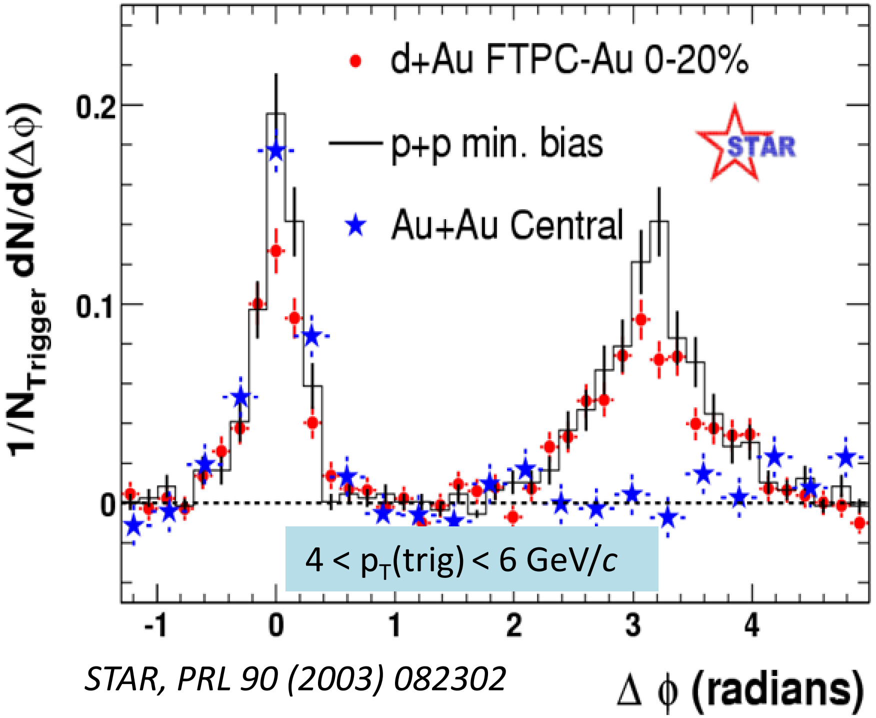
Single hadron

$\sqrt{s_{NN}}$ = 200 GeV

Di-hadron correlations

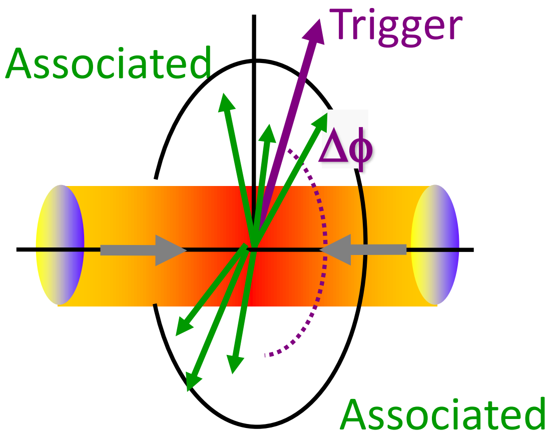


STAR: PRL 91 (2003) 072304



STAR, PRL 90 (2003) 082302

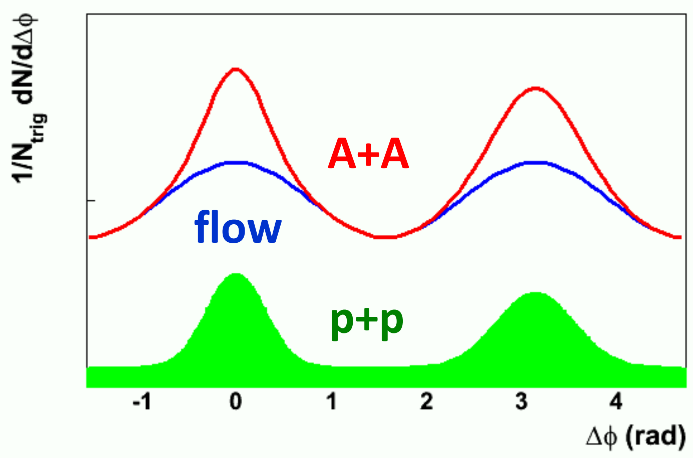
Azimuthal correlations of high-p_T particles as a proxy of jet reconstruction



Central Au+Au collisions at 200 GeV:

- particle production at high p_T is suppressed
- disappearance of away-side peak at intermediate p_T
- Suppression/disappearance not observed in d+Au
  → it is a final state effect

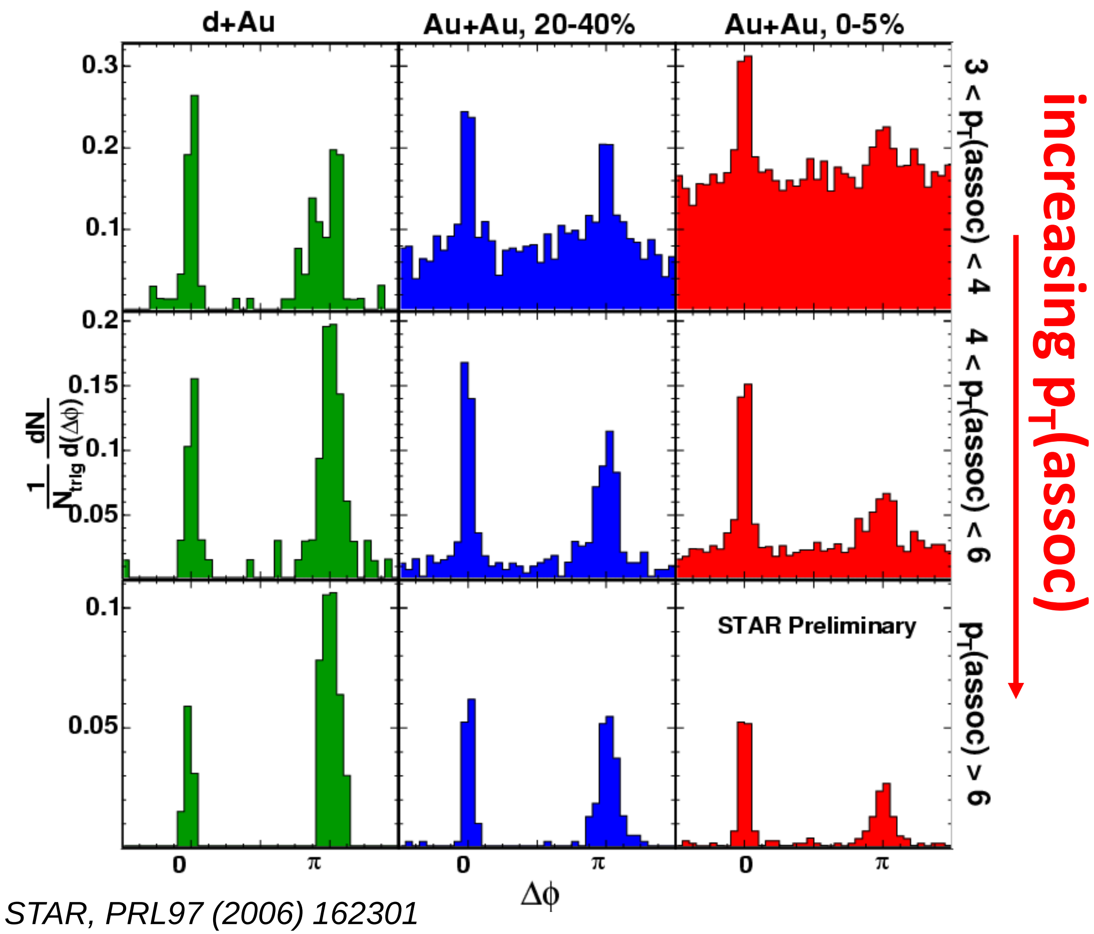
The matter created in central Au+Au collisions at RHIC is "opaque to jets"



Jet-like correlations at RHIC

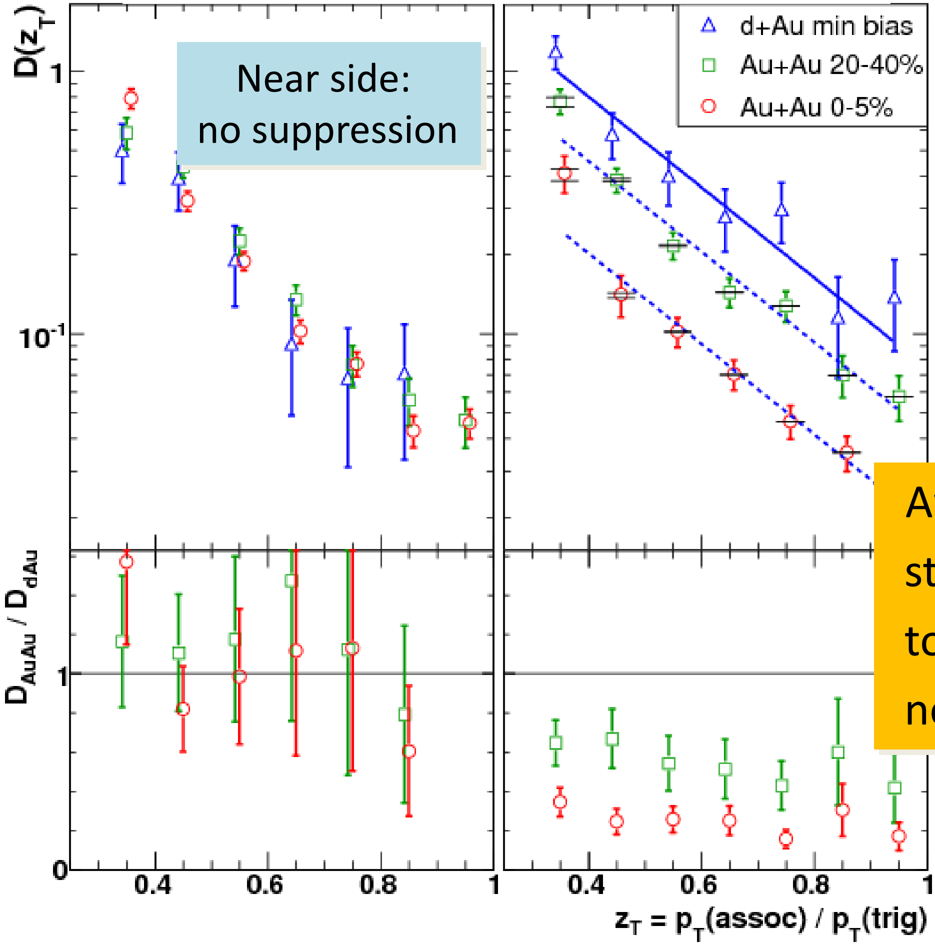
$$D^{h_1 h_2}(z_T, p_T^{trig}) = p_T^{trig} \frac{d\sigma_{AA}^{h_1 h_2}/dp_T^{trig} dp_T}{d\sigma_{AA}^{h_1}/dp_T^{trig}}$$

8 < p_T(trig) < 15 GeV/*c*



STAR, PRL97 (2006) 162301

8 < p_T(trig) < 15 GeV/*c*



Away side:
strongly suppressed
to level of R_{AA}
no dependence on z_T

R_{AA} ↓

$$I_{AA} = \frac{D_{AA}(z_T, p_T^{trig})}{D_{pp}(z_T, p_T^{trig})}$$

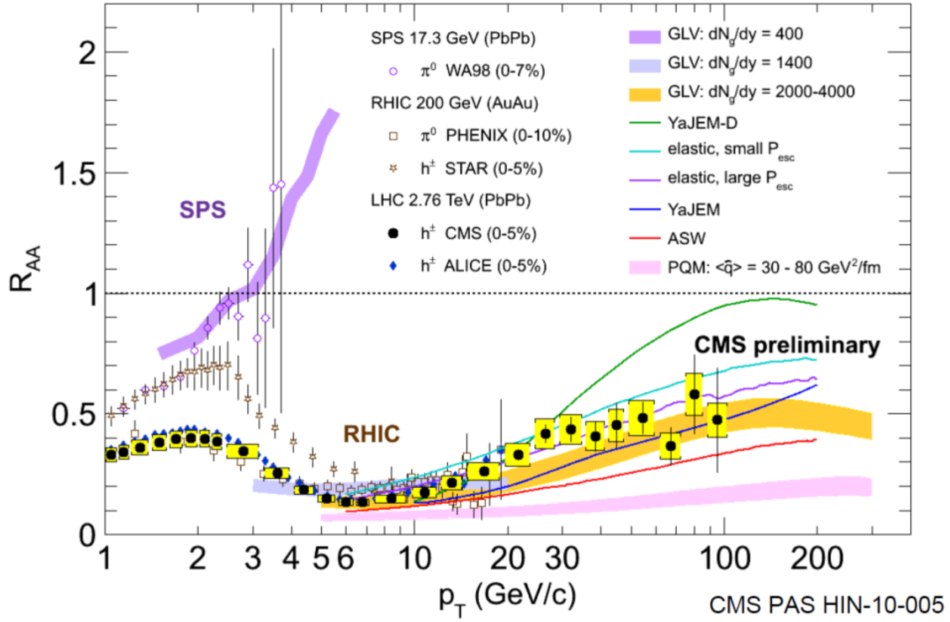
Is there a punch through? YES

- away-side yield is suppressed but finite and measurable
- suppression without angular broadening or medium modification

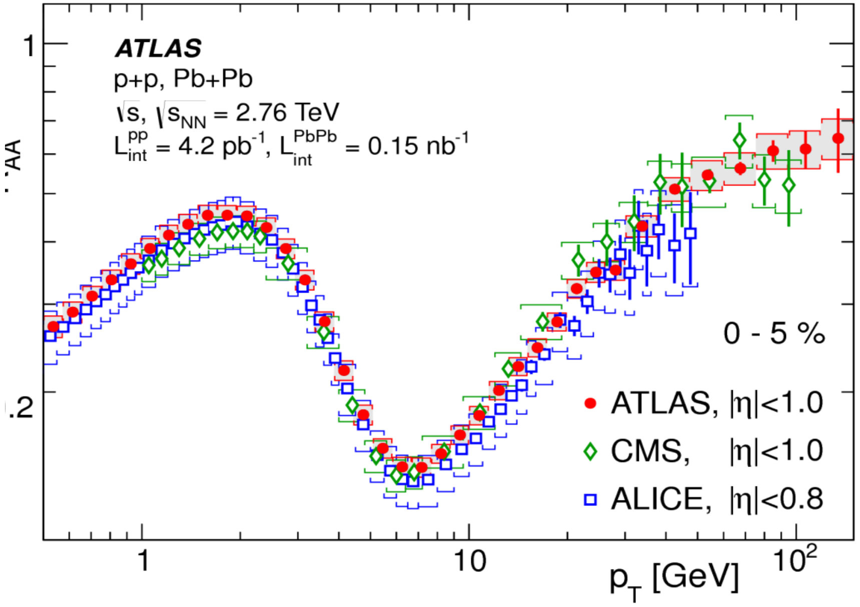
Correlated yield is related to ratio of di-hadron to single hadron fragmentation functions

Collision energy dependence of hadron R_{AA}

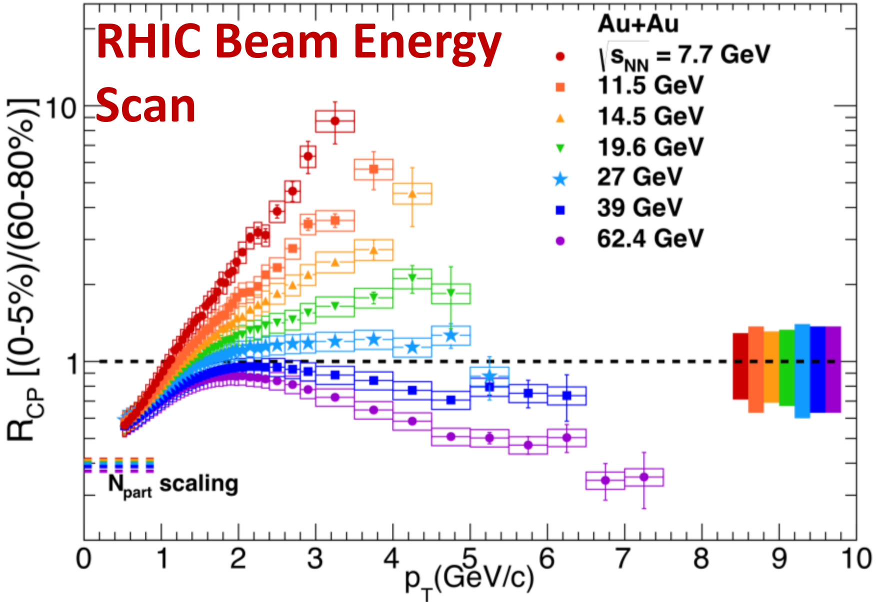
2010: SPS + RHIC + LHC



LHC Run1 FINAL



ATLAS: JHEP 1509 (2015) 050
ALICE: PLB 720 (2013) 52
CMS: EPJ C72 (2012) 1945S



Suppression of charged hadron production at large energies

R_{AA}(LHC) < R_{AA}(RHIC)

- increase of R_{AA} with p_T but even at $p_T \sim 100$ GeV/c $R_{AA} < 1$
- although R_{AA} is known to be limited in sensitivity to models of quenching, data excluded some of them

The quenching disappears around $\sqrt{s_{NN}}$ = 27 - 39 GeV

Di-hadron correlations at RHIC brought another surprise … existence of a ridge …

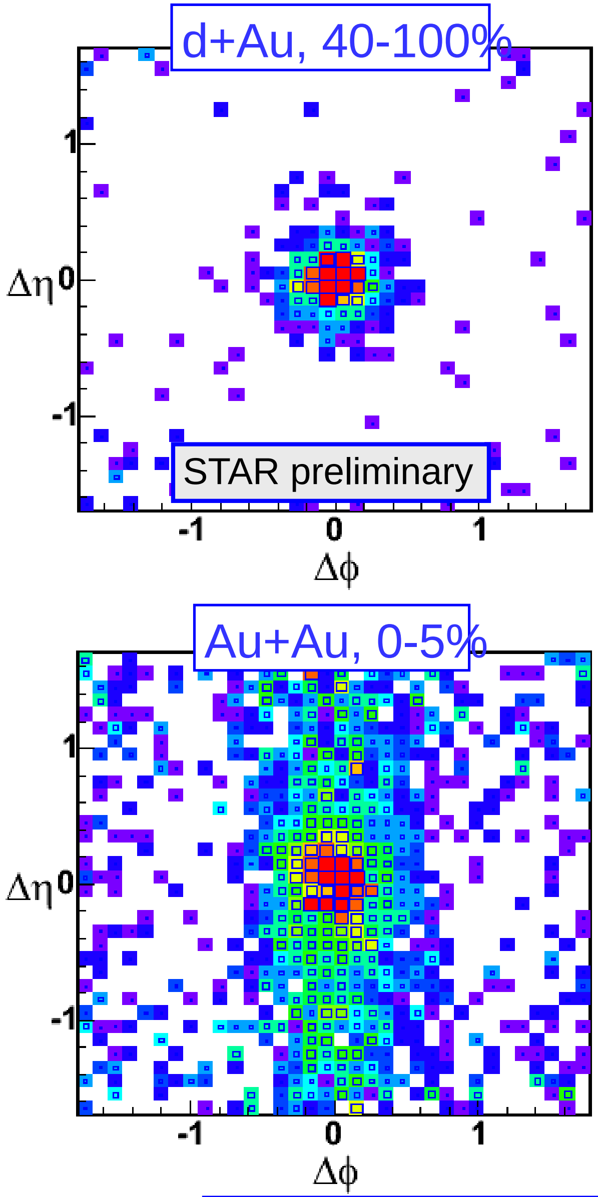
STRONG INTERACTIONS | FEATURE

Hard probes conference finds success in Portugal

6 June 2005

In November, more than 100 enthusiasts headed to a fishing village near Lisbon for the first international conference on hard probes of heavy-ion collisions, Hard Probes 2004.

1st Hard Probes conference: 2004

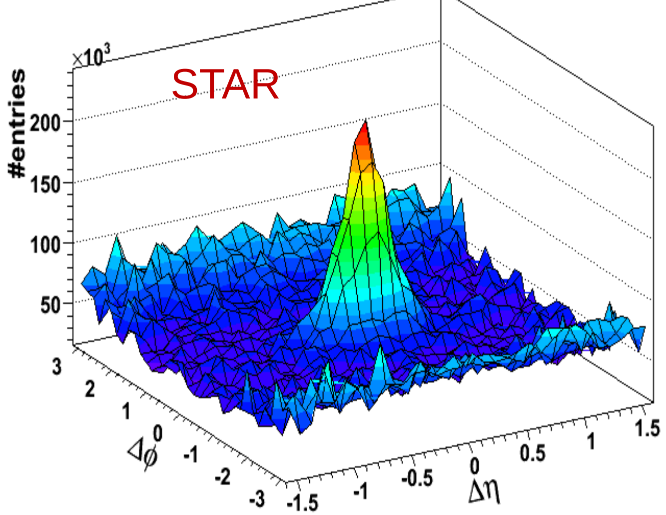


$3 < p_T(\text{trig}) < 6$ GeV
$2 < p_T(\text{assoc}) < p_T(\text{trig})$

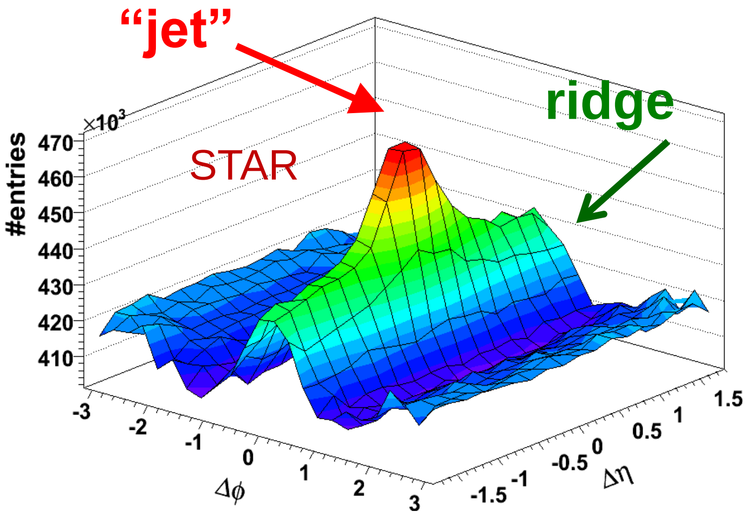
from D. Magestro (STAR) talk

The ridge phenomenon in Au+Au collisions

d+Au 200 GeV

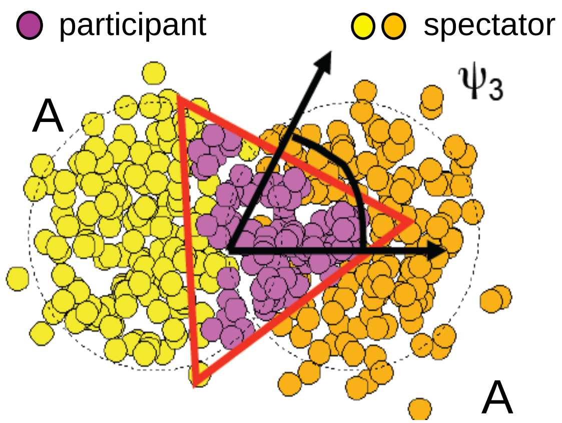


0-12% Au+Au 200 GeV



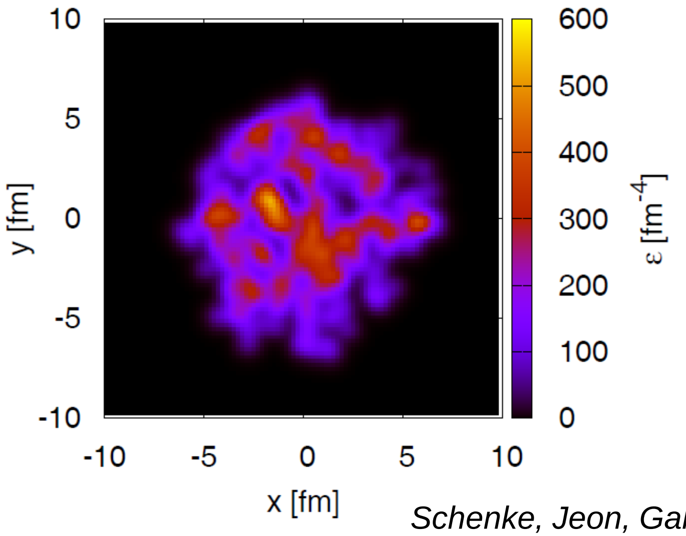
p_T^{trig}=3-4 GeV/c, 2 GeV/c <p_T^{assoc}< p_T^{trig}

STAR: PRC80 (2009) 064912



Alver, Roland,
PRC81 (2010) 054905

3+1D viscous hydro



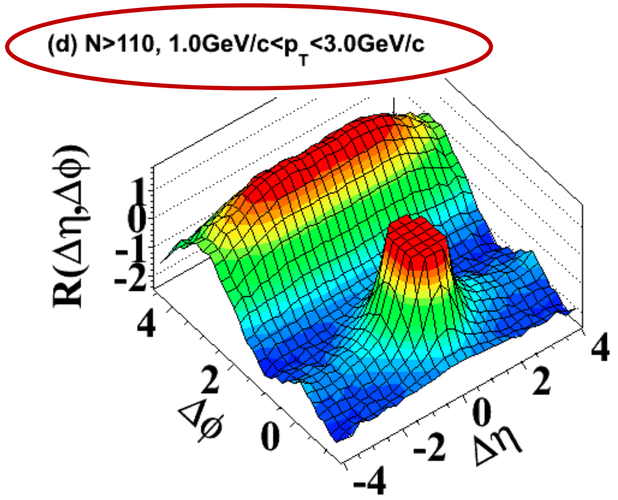
Schenke, Jeon, Gale,
PRL 106 (2011) 042301

Additional near-side correlation in pseudorapidity observed in central Au+Au collisions at RHIC in 2004.

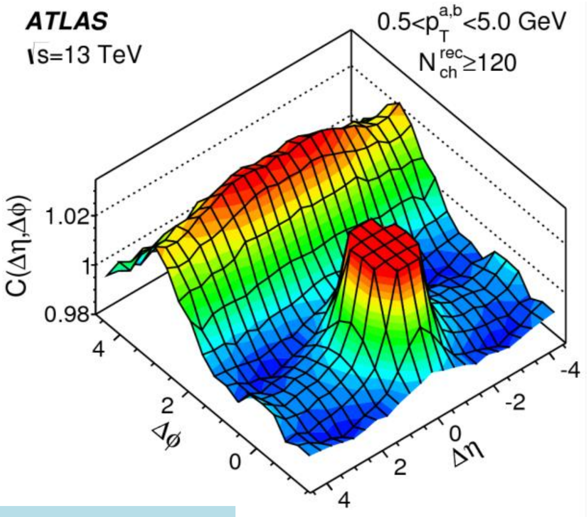
Many physics scenarios have been suggested (R. Hwa called it "ridgeology")
Current interpretation: initial state fluctuations give rise to a new „triangular flow" (v_3).

LHC: ridge is present also in small systems!

High multiplicity pp @ 7,13 TeV



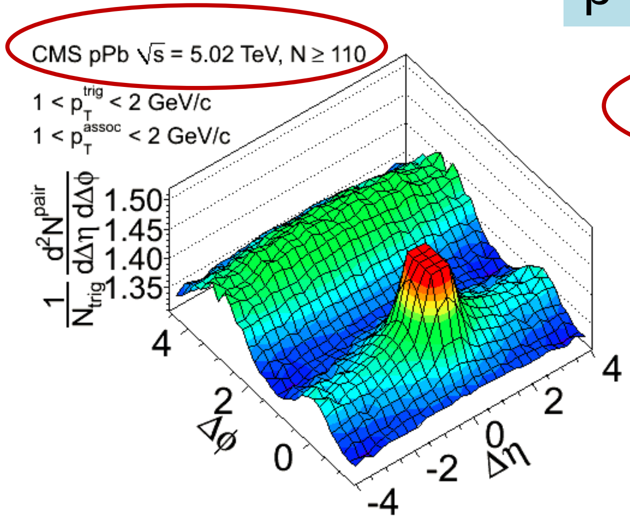
CMS, JHEP09 (2010) 091



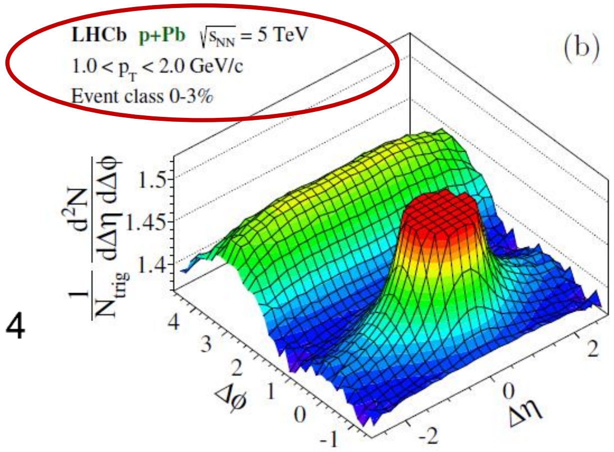
Common hydrodynamical origin?

But can hydrodynamical models be reliably applied in small systems?

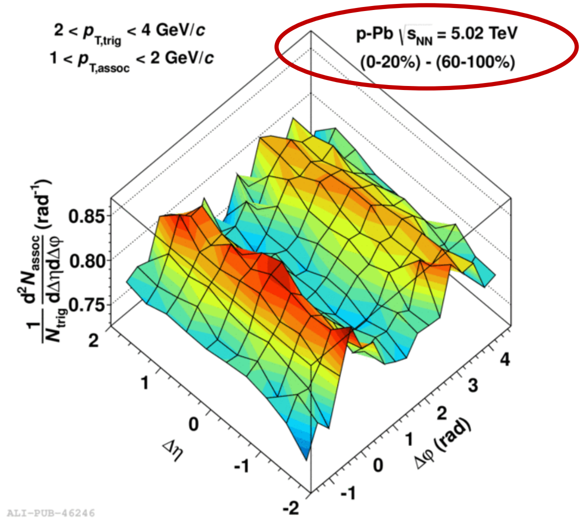
p+Pb @ 5.02 TeV



CMS, PLB 718 (2012) 795



LHCb, Phys. Lett. B762 (2016)



ALICE, PLB 719 (2013) 29

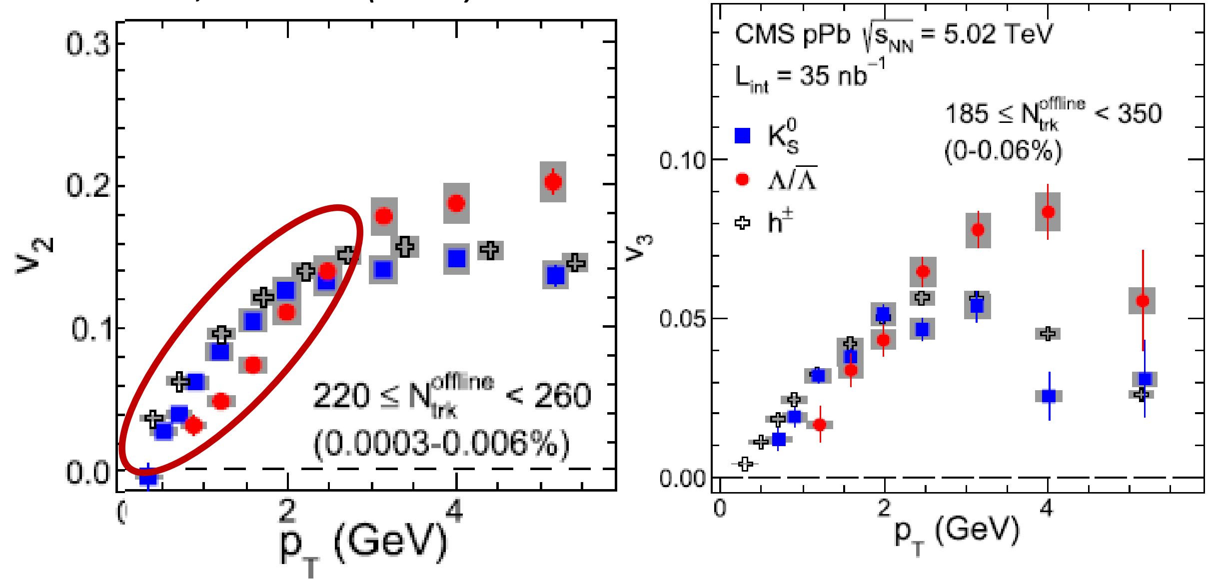
Initial state effects?
gluon saturation,
extended color connections
in longitudinal direction

Final-state parton-parton induced interactions?

Important are studies of multiparticle correlations

Evidence for collectivity in p-Pb?

CMS, PLB 742 (2015) 200

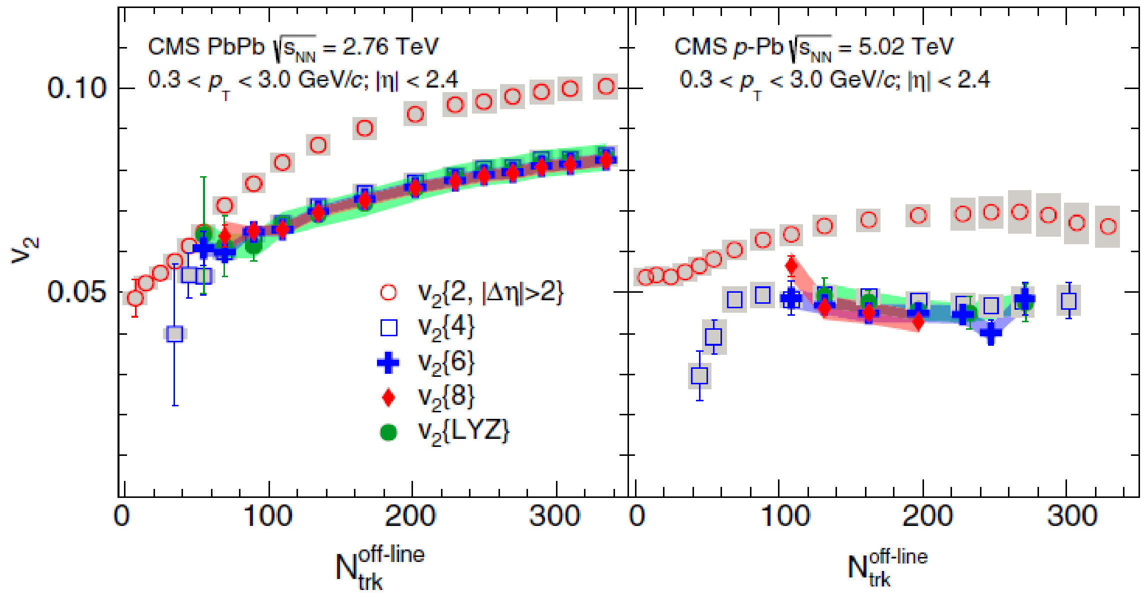


Mass ordering in v_2 resembling hydro picture observed earlier at low p_T in p, π and K by ALICE.

ALICE: PLB 726 (2013) 164

Confirmed by the CMS data for Λ and K^0_S.

CMS, PRL 115 (2015) 012301

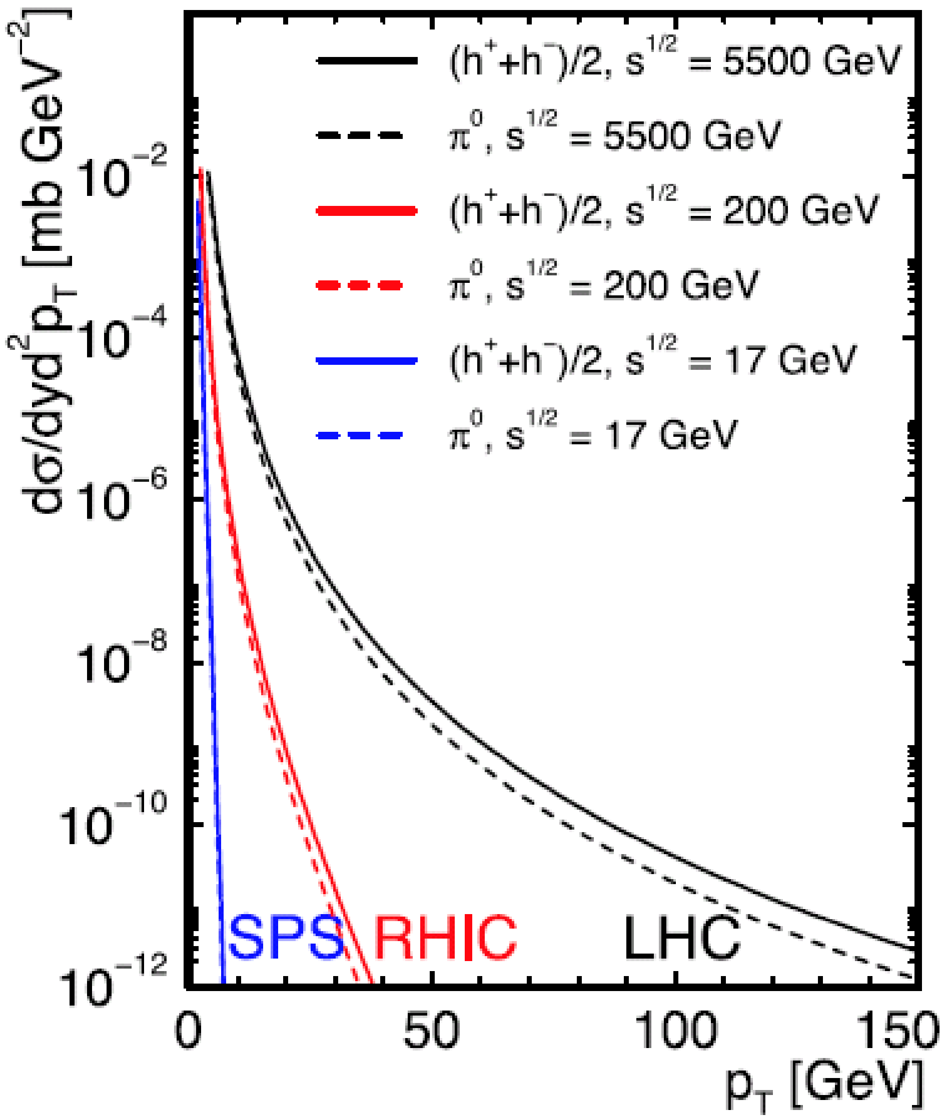


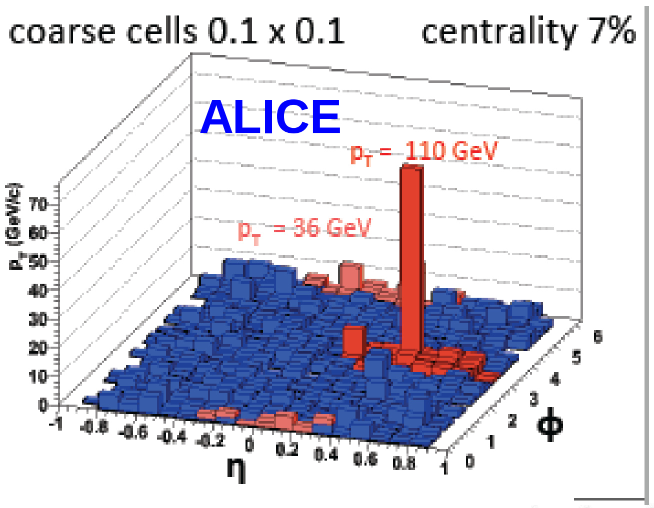
Multiparticle correlations (4-8) as well as Lee-Yang-Zero studies give consistent "v_2" values.
Proof of collectivity in small systems.

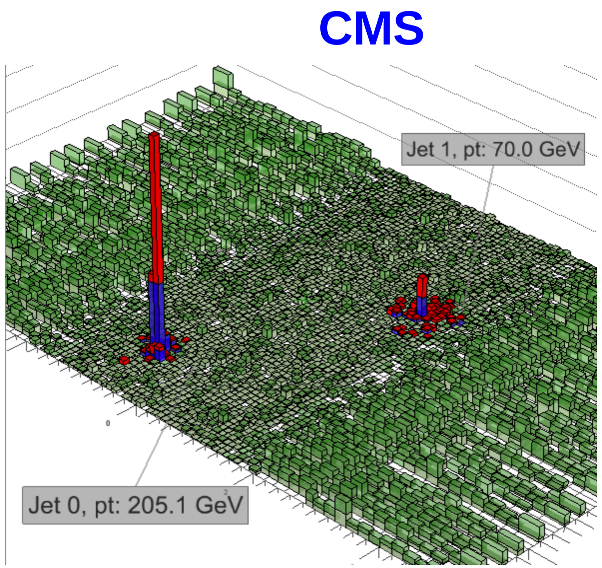
Studies of high-multiplicity pp and p+A Collisions remains still a very active area also to look for jet quenching effects so far no signals were found …

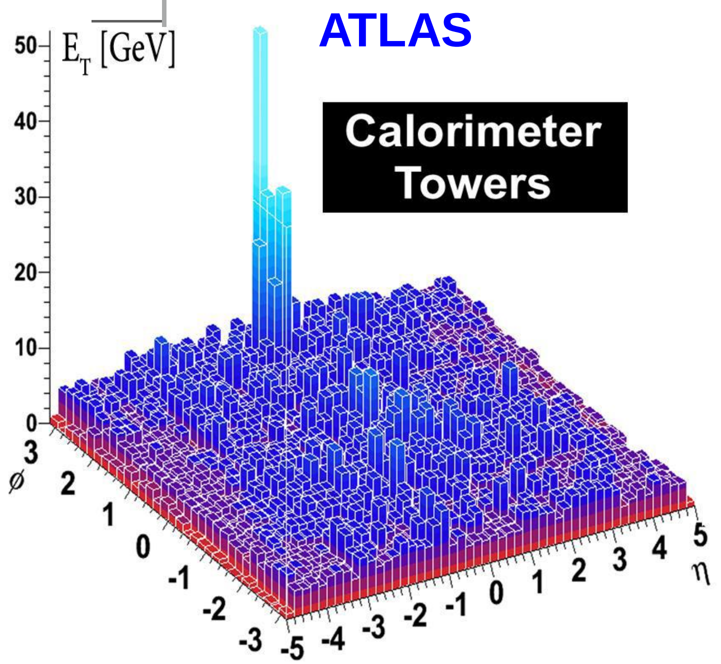
Reconstructed jets

LHC: the jet machine



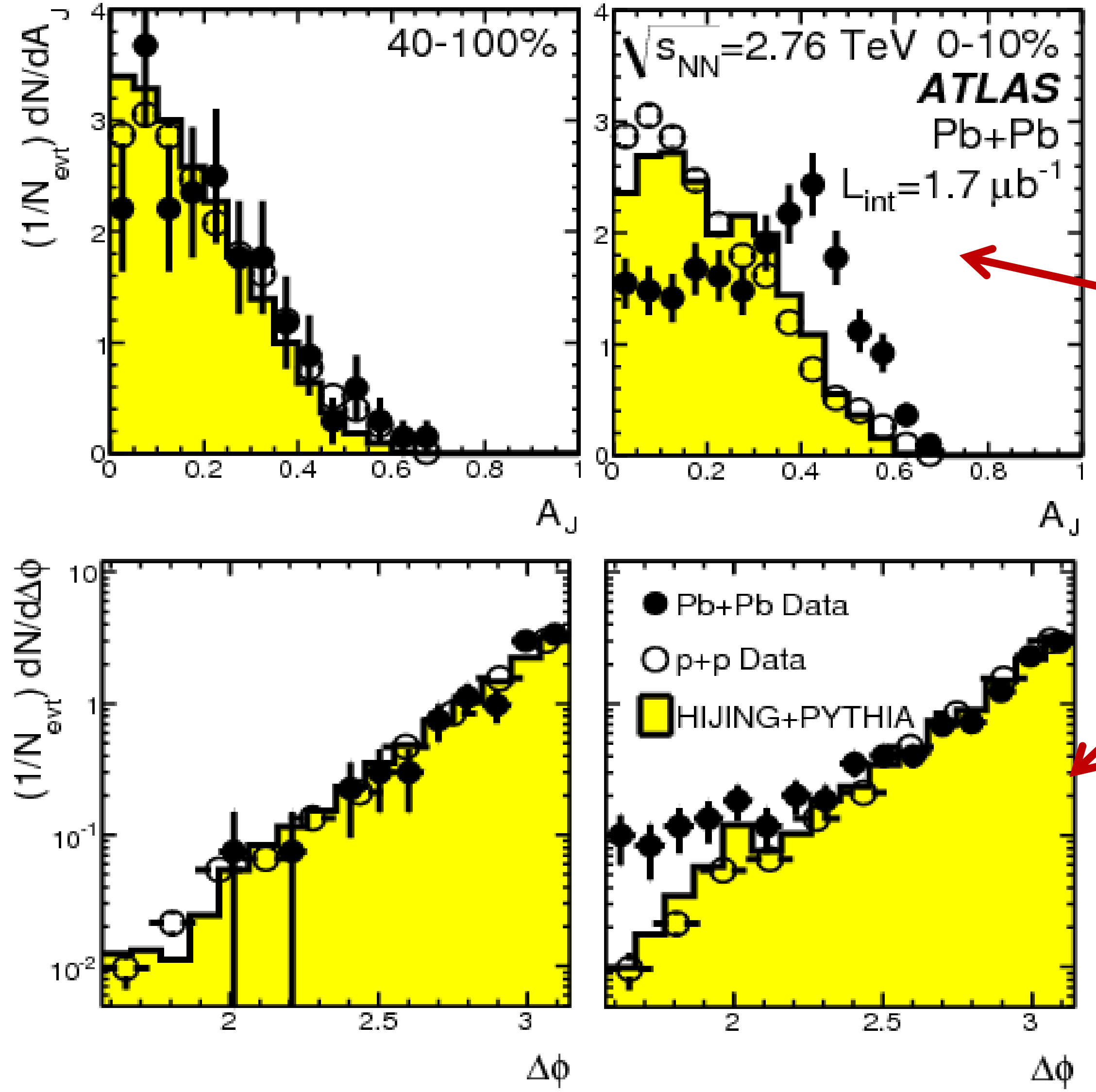






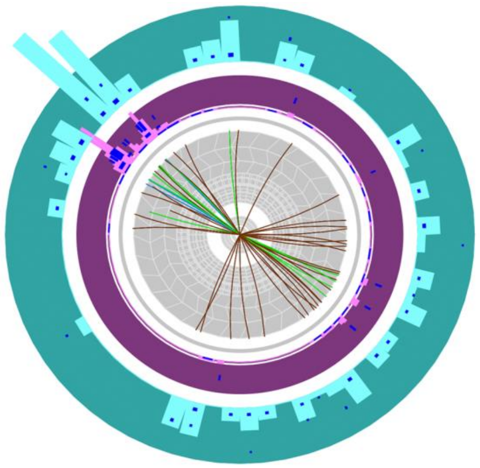
Dijet asymmetry in central Pb+Pb collisions

ATLAS: *PRL 105 (2010) 252303*



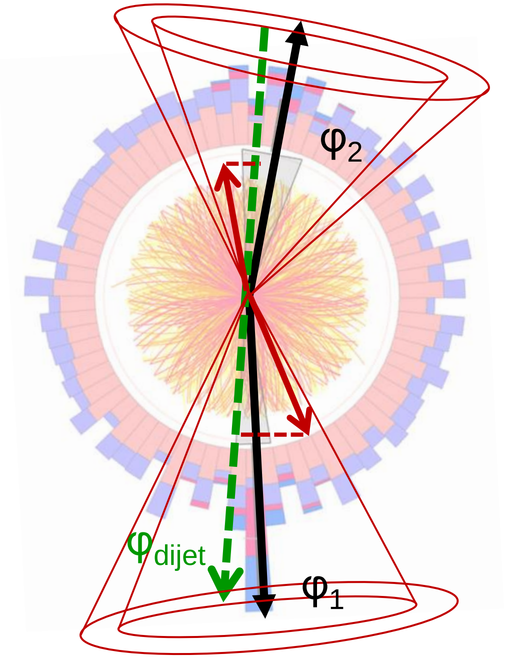
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta\phi > \frac{\pi}{2}$$

Dijet asymmetry observed in central Pb+Pb collisions, without angular decorrelation.

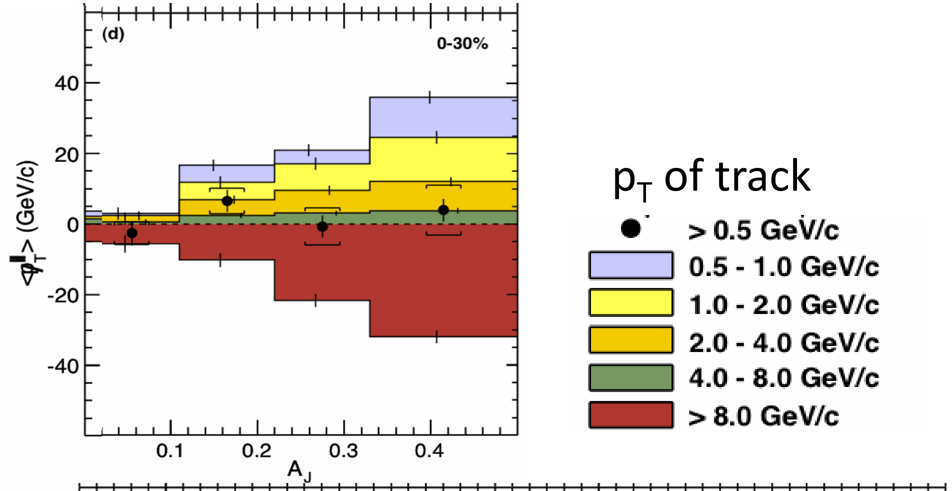


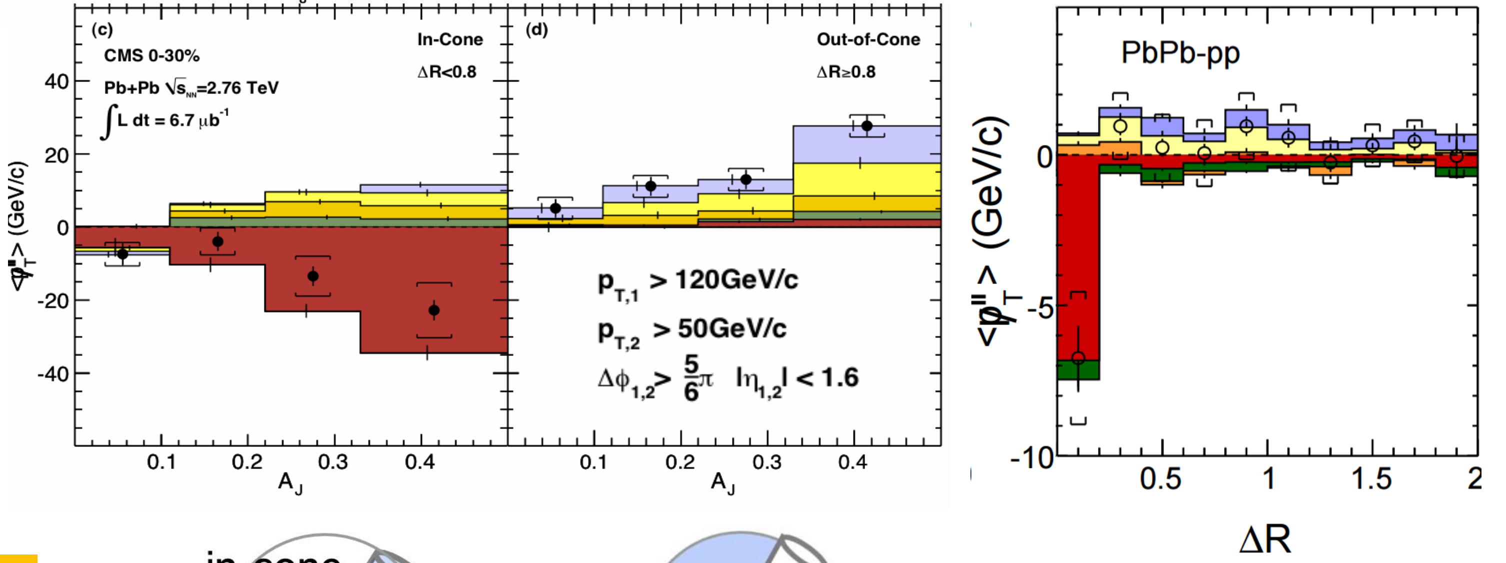
Where did the energy go?

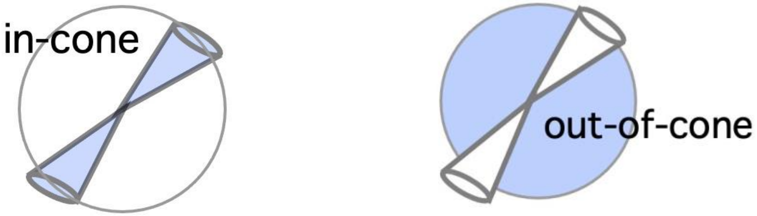
courtesy Y. J. Lee (CMS)



CMS, PRC 84 (2011) 024906







Missing p_T: $\not{p}_T^{\parallel} = \sum_i -p_T^i \cos(\phi_i - \phi_{Dijet})$

- increases with A_J
- in central Pb+Pb collisions is balanced by particles with $p_T < 2$ GeV/*c*

Lost energy is distributed to large angles ("out-of-cone") and low-p_T particles.

How much more we know since these early heavy-ion jet measurements?

… Let us start with inclusive jet production

Jet reconstruction in heavy-ion collisions

- jet reconstruction is performed with the anti-kt algorithm, background is estimated with the kt algorithm

$$\rho \cong \text{median}\left[\frac{p_{\mathrm{T,jet}}}{A_{\mathrm{jet}}}\right]$$

„Jets" from the background (majority in AA collision): $p_T \approx A_{jet}$

Challenge for experimentalists:

- large and **fluctuating** background:
  <ρ> ≈ 180 GeV/*c*
  in central Pb+Pb collisions at the LHC

→ limits jet resolution parameter R to modest values R ~ 0.2-0.4

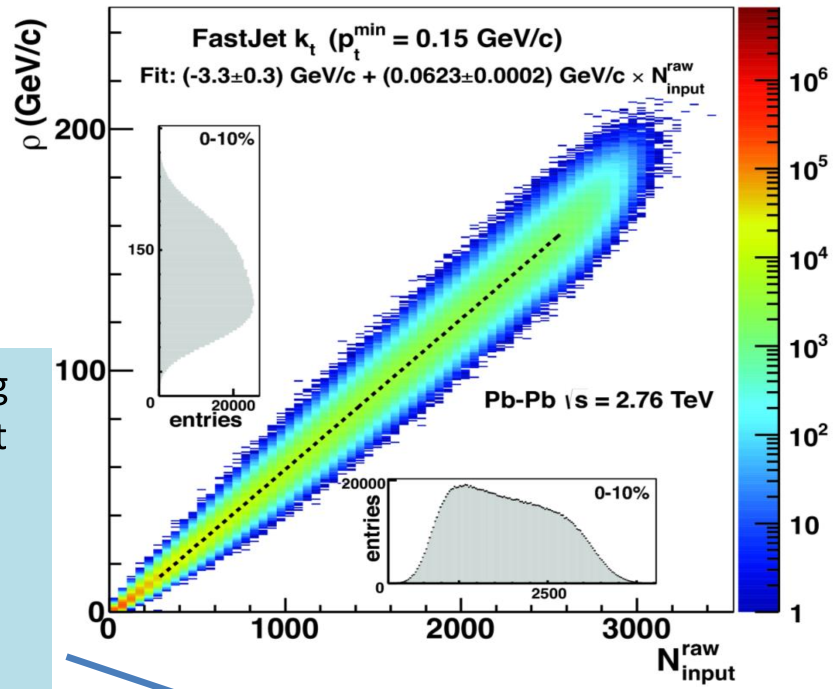
Experimentally more challenging is to deal with its event-by-event fluctuations.

p_T cut on jet constituents can suppress background BUT introduces a bias!

- average background subtracted on jet-by-jet basis and fluctuations together with instrumental effects unfolded on statistical basis

Unfolding methods: Bayesian, SVD, Omnifold …

ALICE, JHEP 1203 (2012), 053



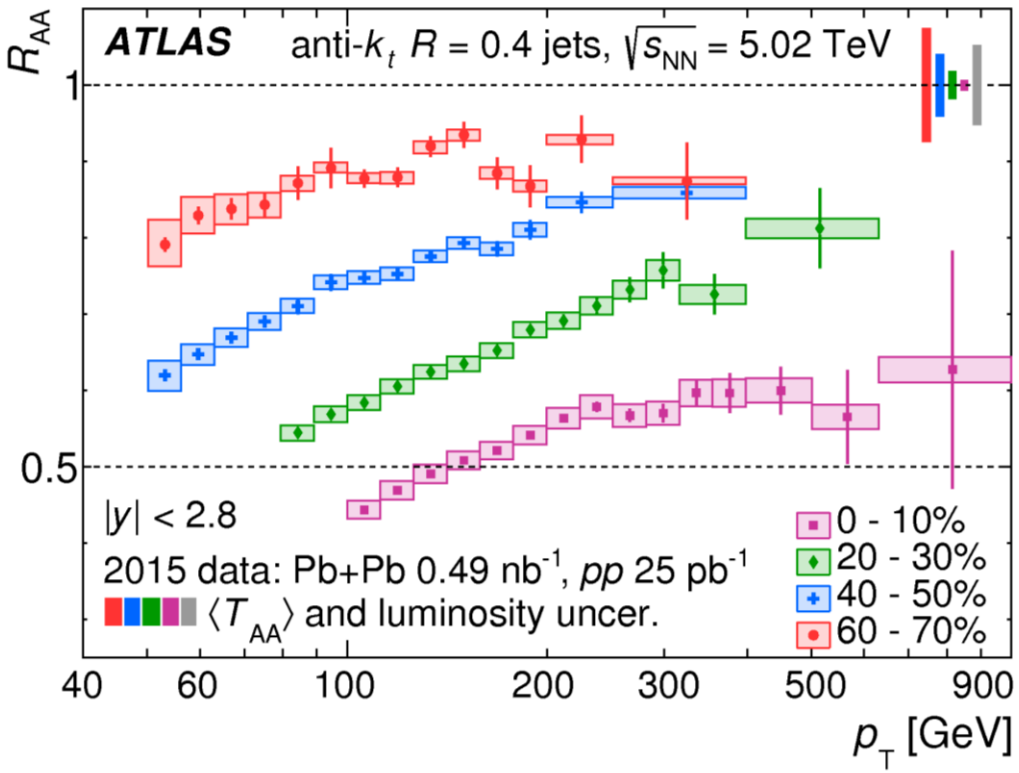
p_t^{min} (GeV/c)	$\langle\rho\rangle$ (GeV/c)	$\sigma(\rho)$ (GeV/c)
0-10%		
0.15	138.32 ± 0.02	18.51 ± 0.01
1.00	59.30 ± 0.01	9.27 ± 0.01
2.00	12.28 ± 0.01	3.29 ± 0.01

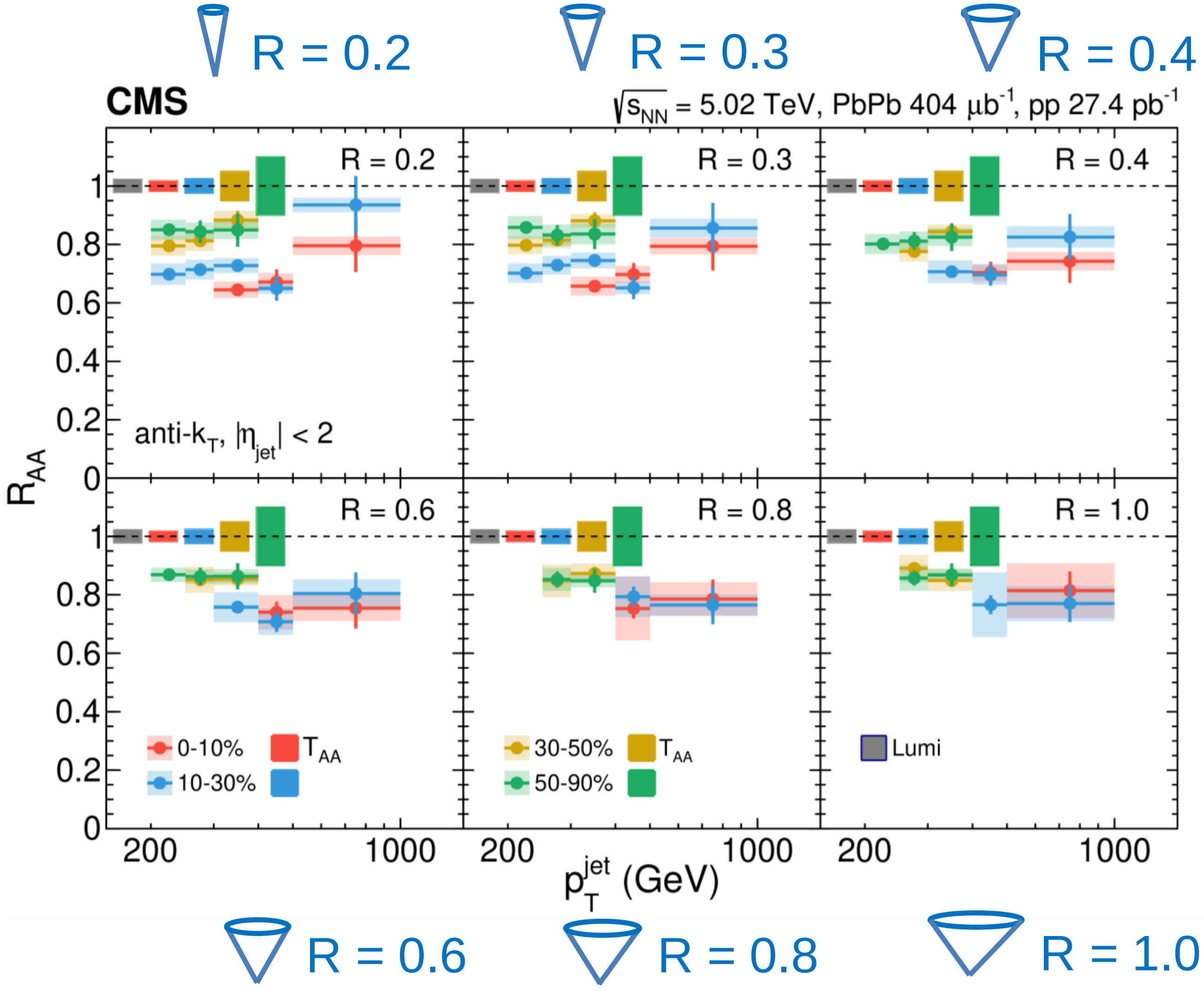
Inclusive jet suppression in medium

CMS, JHEP 05 (2021) 284

ATLAS, PLB 790 (2019) 108

R = 0.4





R_{AA} increases with jet p_T

R = 0.4 jets:

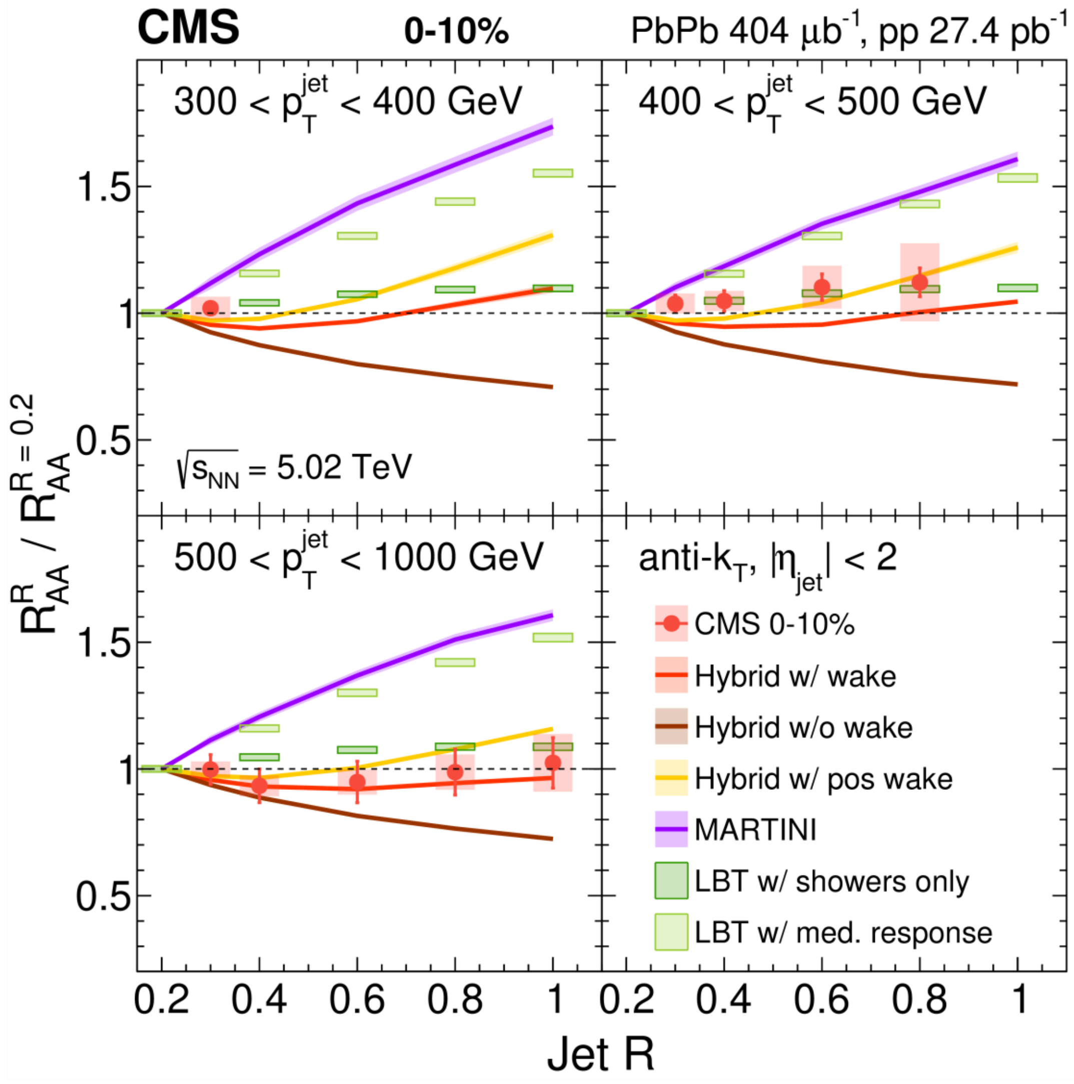
R_{AA} = 0.6 in central collisions at p_T = 1 TeV

Can we recover the lost energy?
→ study jets with larger radius R

Jet R_{AA} shows only a modest increase with R and never reaches unity.

Constraints from R_{AA} ratio of large/small jet radii

CMS, JHEP 05 (2021) 284



Significant constraints on models of jet quenching, medium response, wide angle radiation …

See the CMS paper for more comparisons not all models that get the jet R_{AA} ratio get also the inclusive jet R_{AA}

Models:

Hybrid: D. Pablos, PRL 124 (2020) 052301

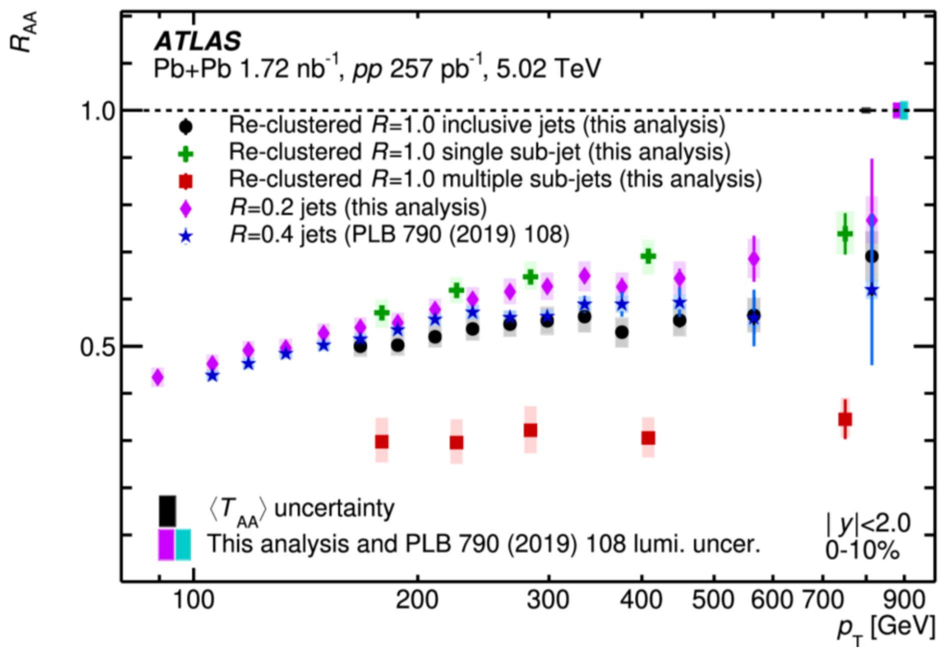
MARTINI: B. Schenke, C. Gale and S. Jeon, *PRC* **80** (2009) 054913

LBT: Y. He, S. Cao, W. Chen, T. Luo, L.-G. Pang, X.-N. Wang, *PRC* **99** (2019) 054911

Large R reclustered jets with multiple sub-jets

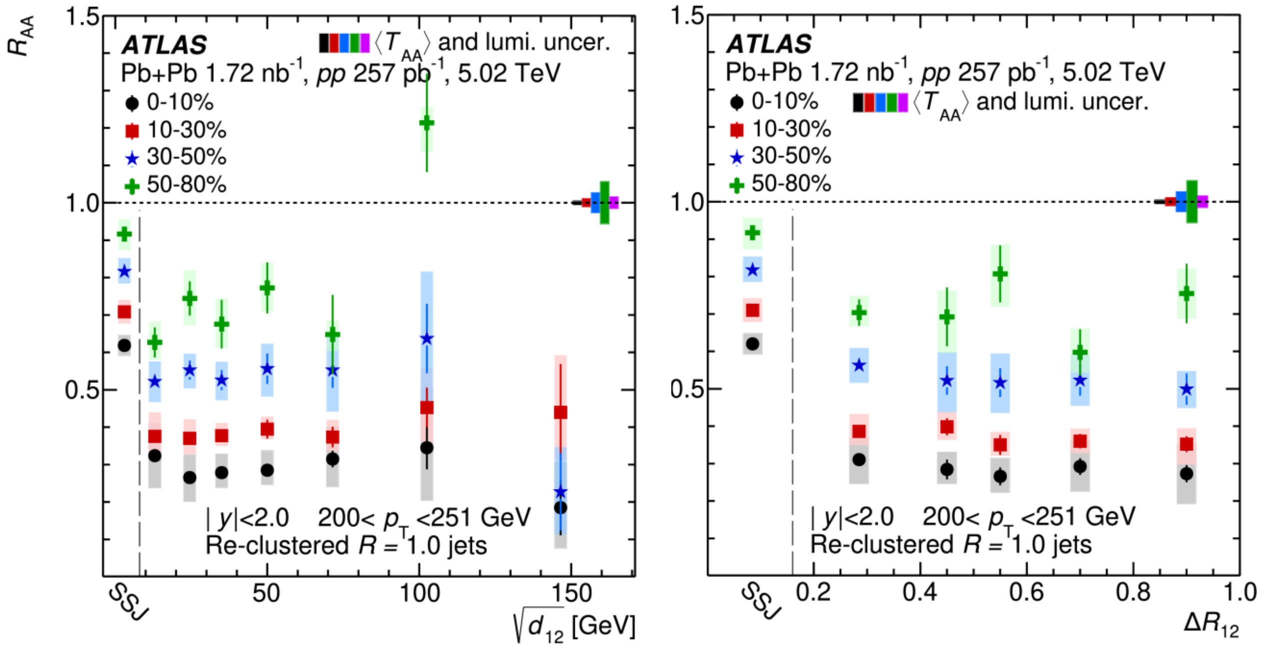
ATLAS, arXiV 2301.05606

1. Reconstruct anti-kt jets with R = 1 by re-clustering anti-kt R = 0.2 jets.
2. Large-R jet constituents are next re-clustered using kt.
3. Splitting parameters $\sqrt{d_{12}}$ (p_T scale) and ΔR_{12} (angular separation) for the hardest splitting in the jet are studied.



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

$$\Delta R_{12} = \sqrt{\Delta y_{12}^2 + \Delta \phi_{12}^2}$$



Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk, NPA 967 (2017) 564

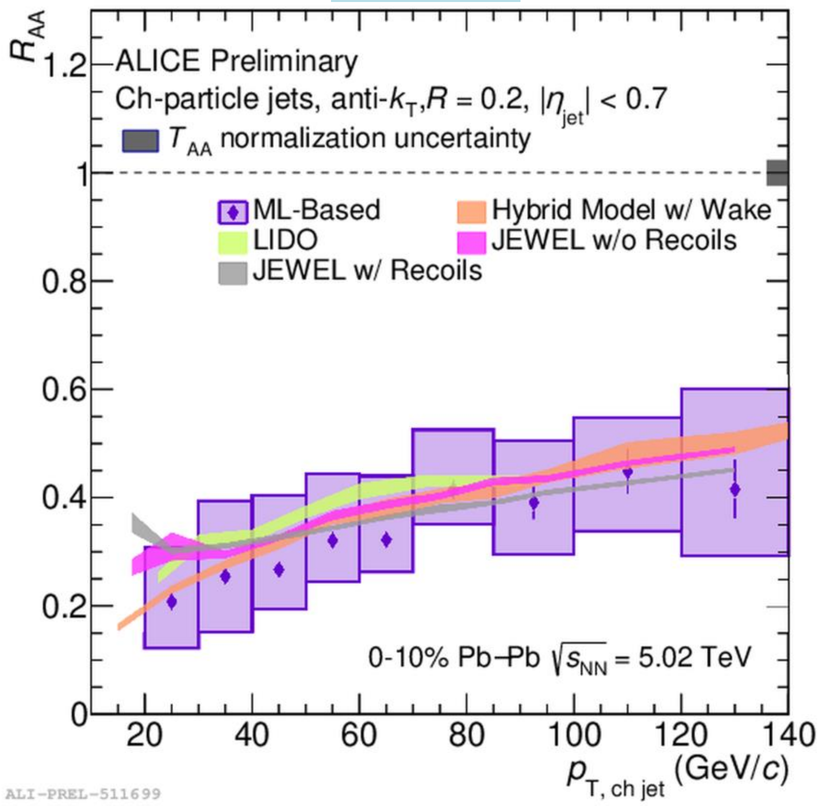
Significant difference in quenching of large-R jets with single sub-jet and those with more complex substructure:

- jets with hard internal splitings lose more energy
- medium is not able to resolve partonic fragments below a certain transverse scale

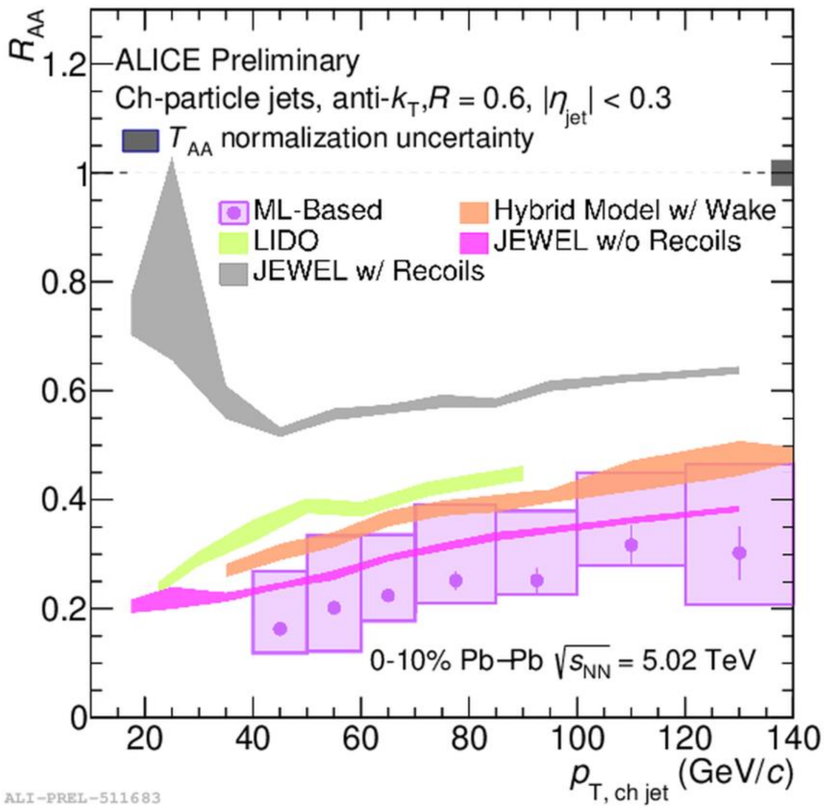
→ important input for understanding the role of color decoherence in jet quenching

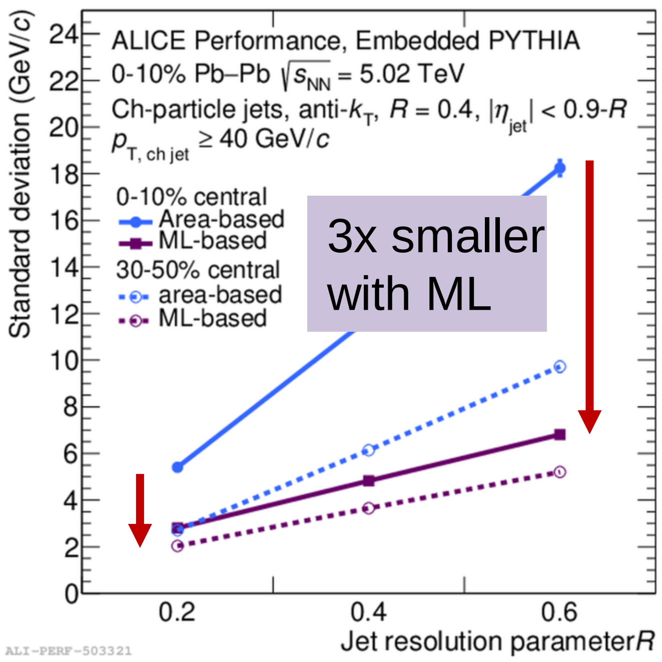
Larger R and lower jet p_T ?

R = 0.2



R = 0.6

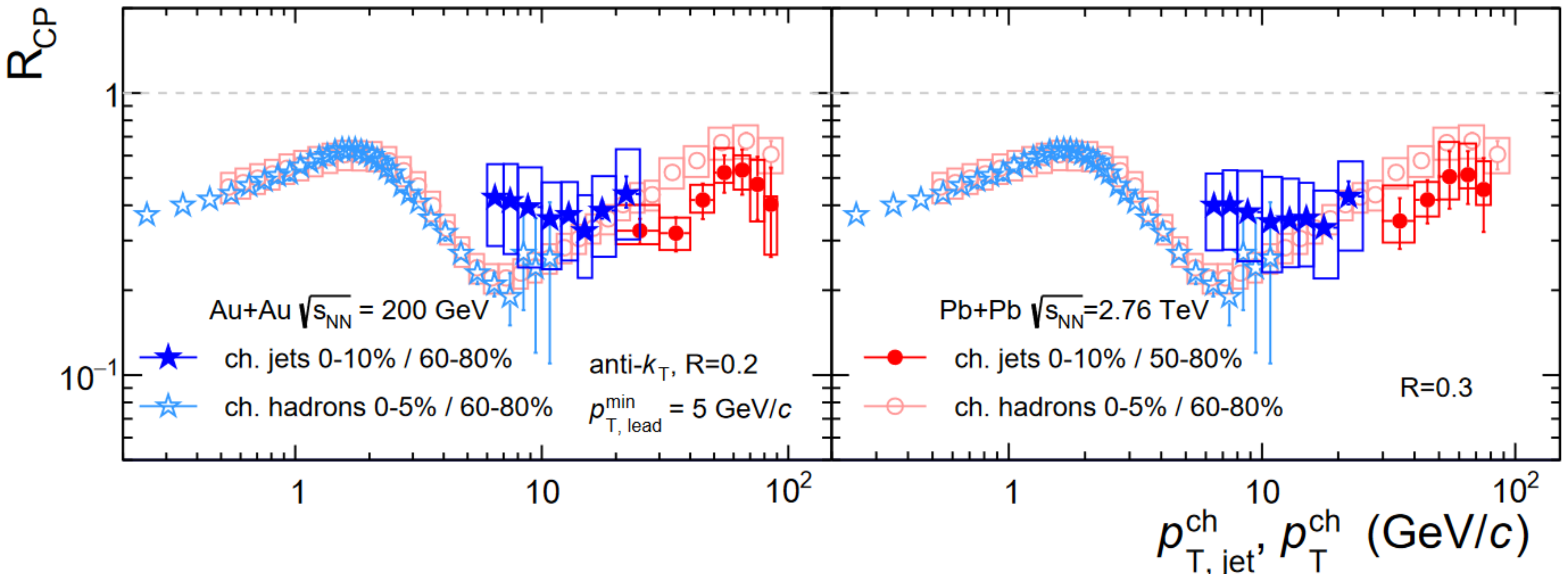




ML method: Haake, Loizides, PRC 99, 064904 (2019)

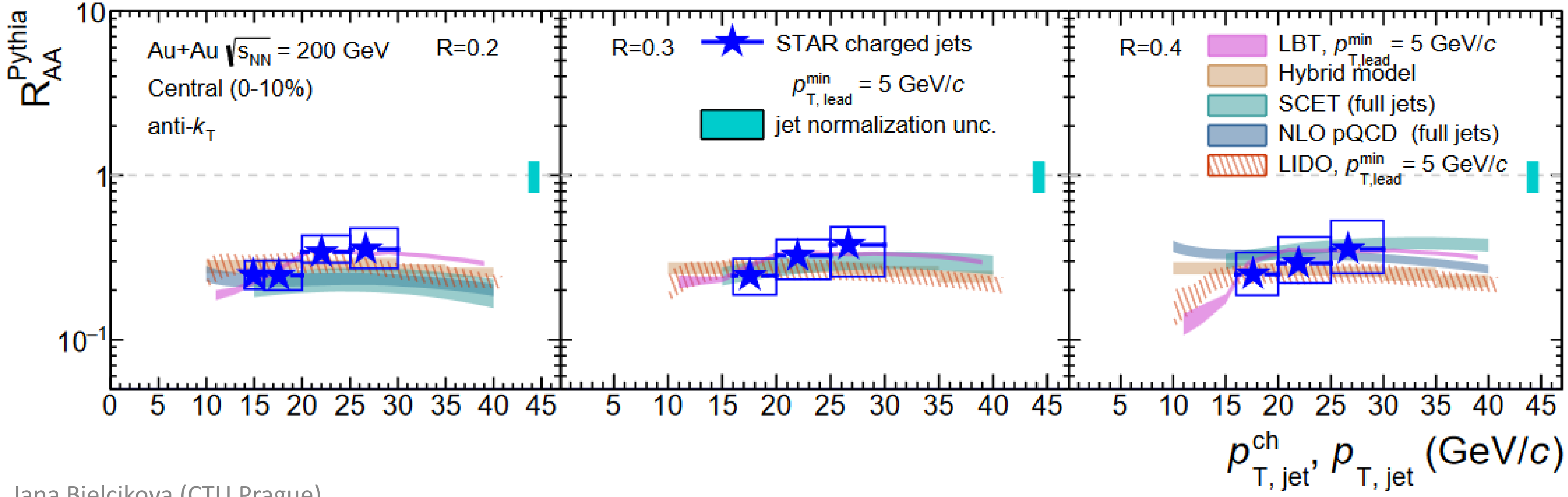
Encouraging results using ML reported by ALICE:
- improved precision and extended reach in p_T and R
- data will enable to constrain model predictions and allow for comparison with RHIC … see next slide

Jet suppression at RHIC energies



Jet suppression at RHIC is similar to that at LHC energy

Current precision of R_{AA} at RHIC does not allow to discriminate between models
→ ongoing STAR studies + future data from sPHENIX

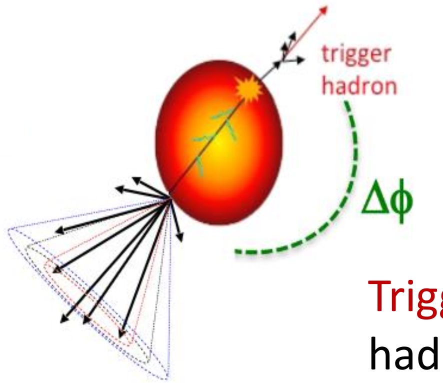


STAR, PRC 102 (2020) 054913

Semi-inclusive recoil jet studies

Semi-inclusive recoil jet studies

$$\Delta_{\mathrm{recoil}} = \frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}N_{\mathrm{jet}}}{\mathrm{d}p_{\mathrm{T}}}\bigg|_{p_{\mathrm{T,trig}}\in \mathrm{TT}_{\mathrm{Sig}}} - \frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}N_{\mathrm{jet}}}{\mathrm{d}p_{\mathrm{T}}}\bigg|_{p_{\mathrm{T,trig}}\in \mathrm{TT}_{\mathrm{Ref}}}$$

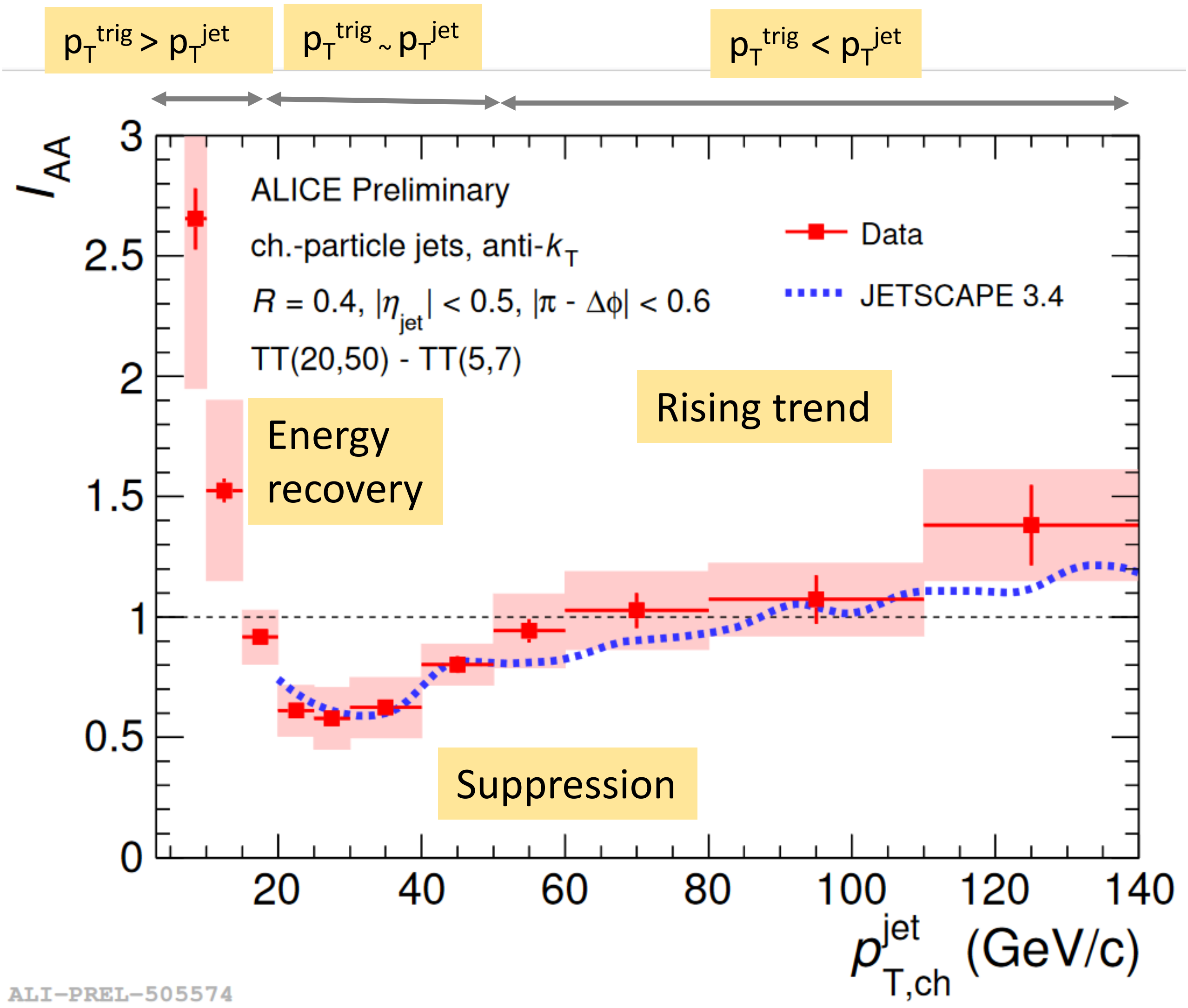


$$I_{\mathrm{AA}} \equiv \frac{\Delta_{\mathrm{recoil}}(\mathrm{Pb-Pb})}{\Delta_{\mathrm{recoil}}(\mathrm{pp})}$$

Trigger particle:
hadron, π^0, γ_{dir} …

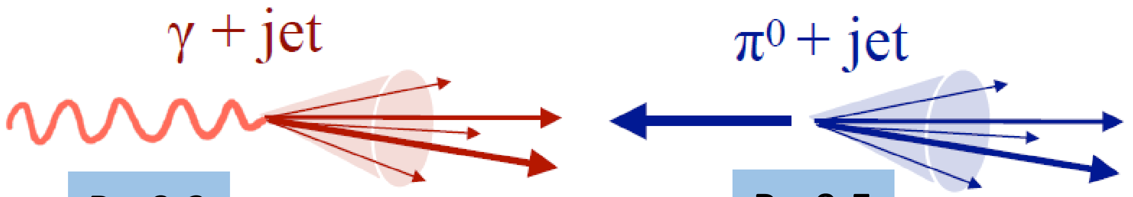
A unique observable:
- enables study of intra and inter-jet angular broadening
- directly comparable to analytic pQCD calculation
- large-angle jet deflection studies can probe the nature of quasi-particles in hot QCD matter (”QCD Molière scattering”)

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



Interplay between hadron and jet energy loss?

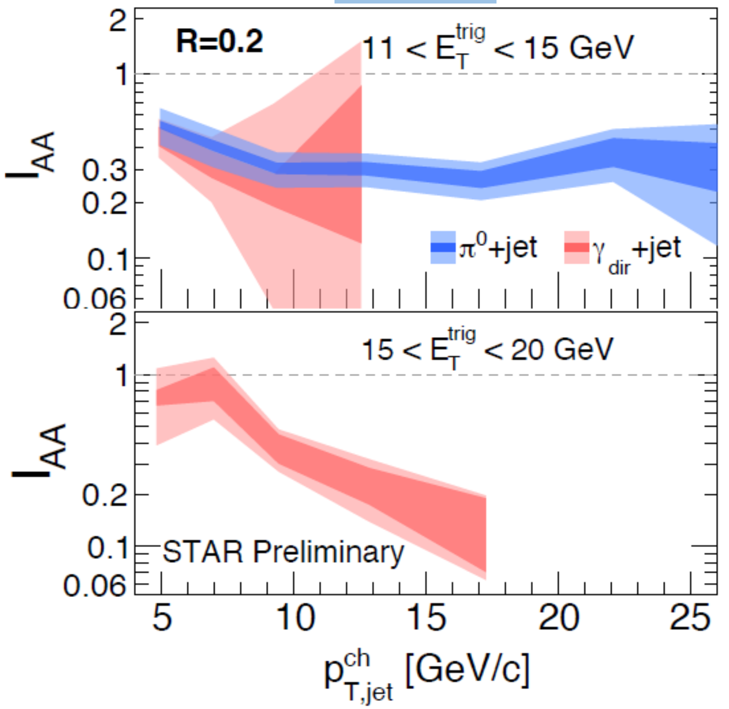
R-dependence of jet yield suppression at RHIC

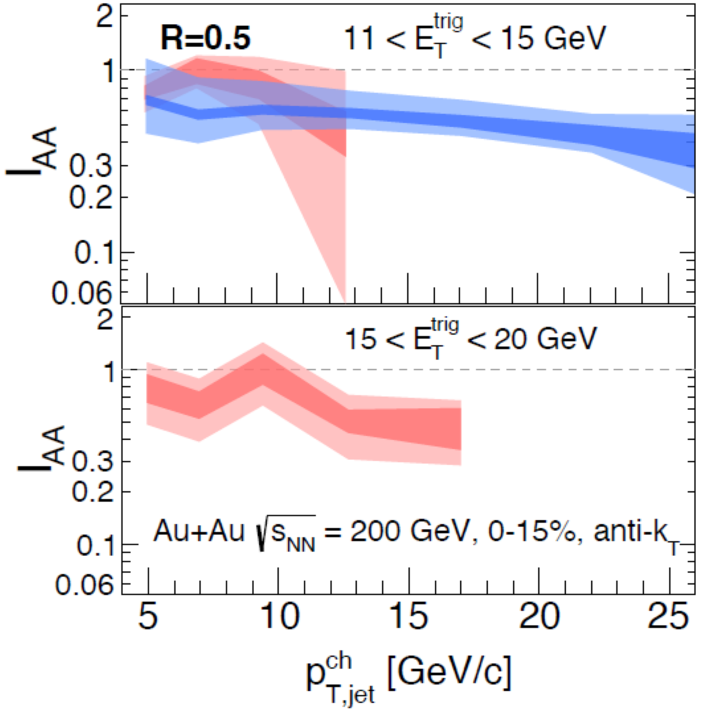


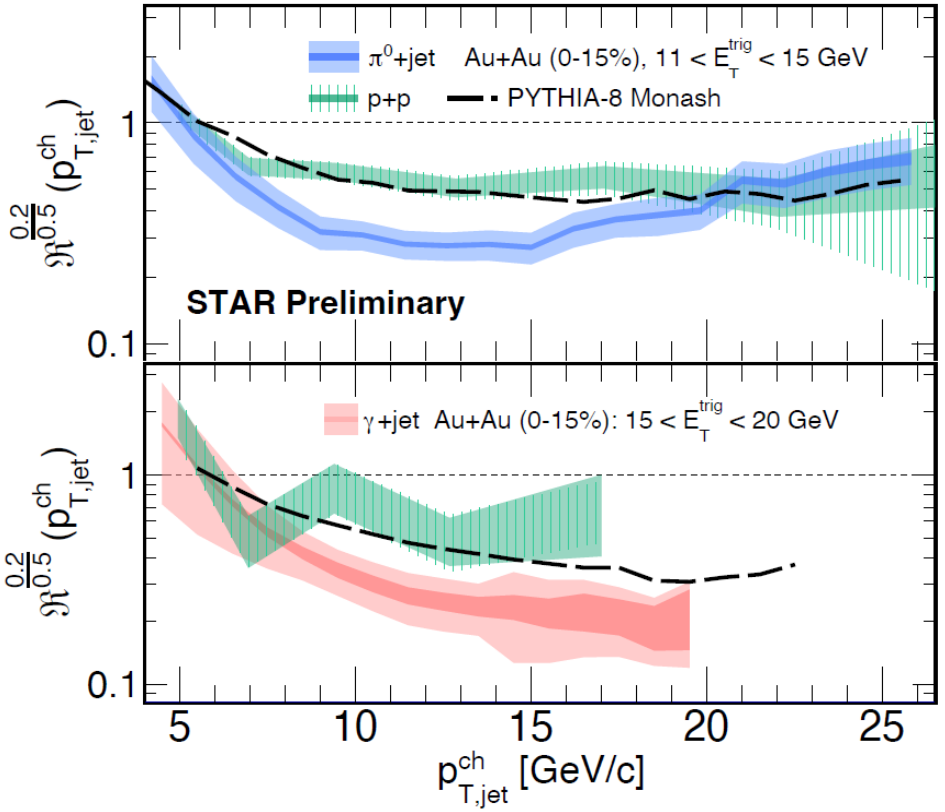
R= 0.2

R= 0.5

R=0.2/R=0.5







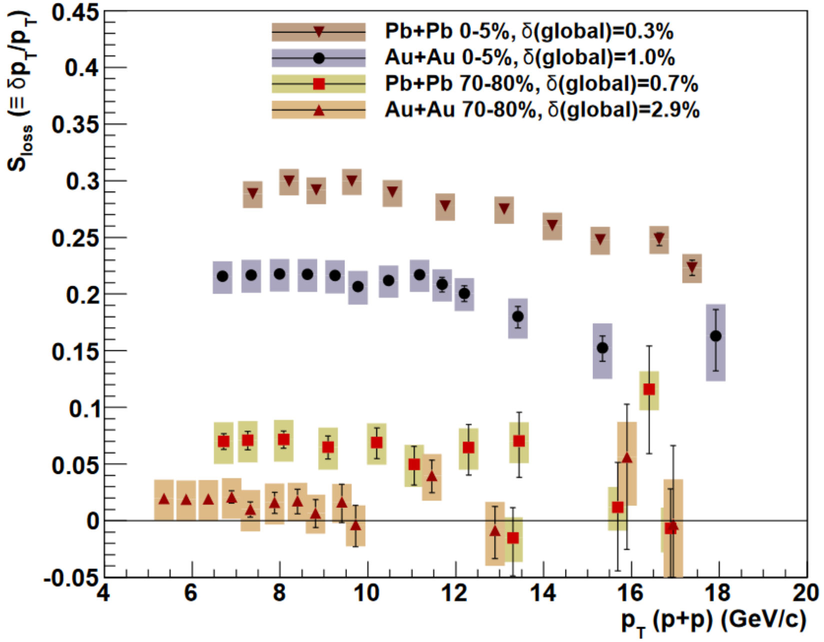
Semi-inclusive π^0+jet and γ+jet suppression I_{AA}

- suppression decreases with R
- no difference between π^0+jet and γ+jet within uncertainties observed

Intra-jet broadening in Au+Au collisions at RHIC energy present

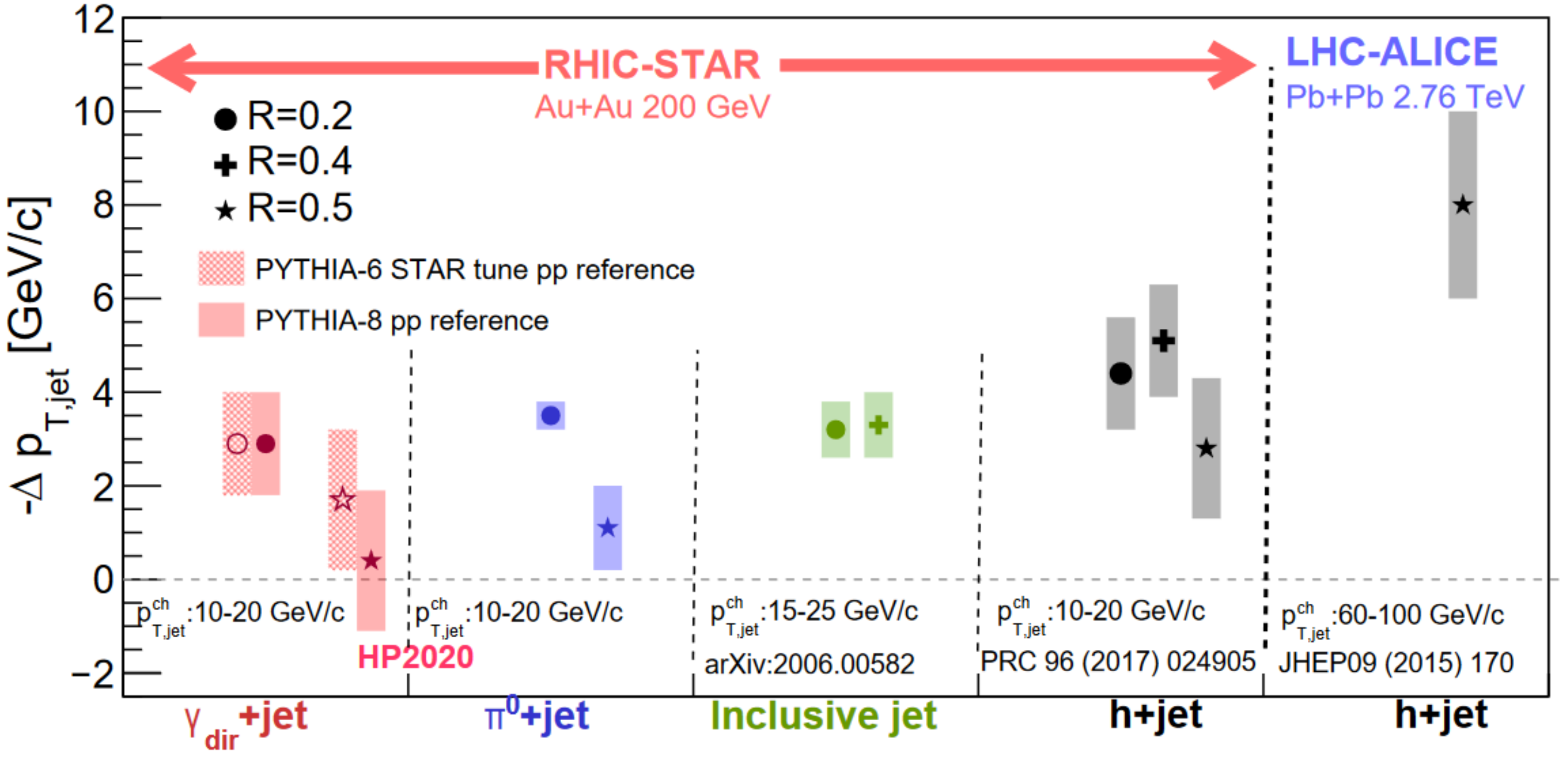
Out-of-cone energy loss: RHIC vs LHC

PHENIX, PRC 87, 034911 (2013)



Inclusive π^0
Δp_T =2-3 GeV/c

$-\Delta p_T$ refers to suppression in p_T



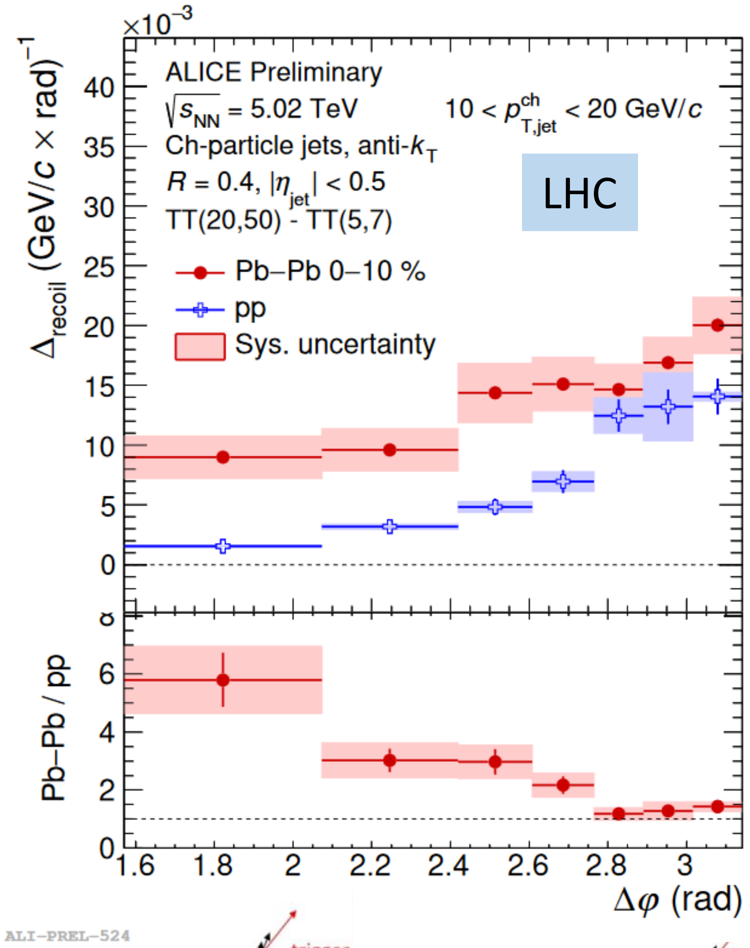
RHIC: various channels
consistent (π^0, jet, trigger+jet)

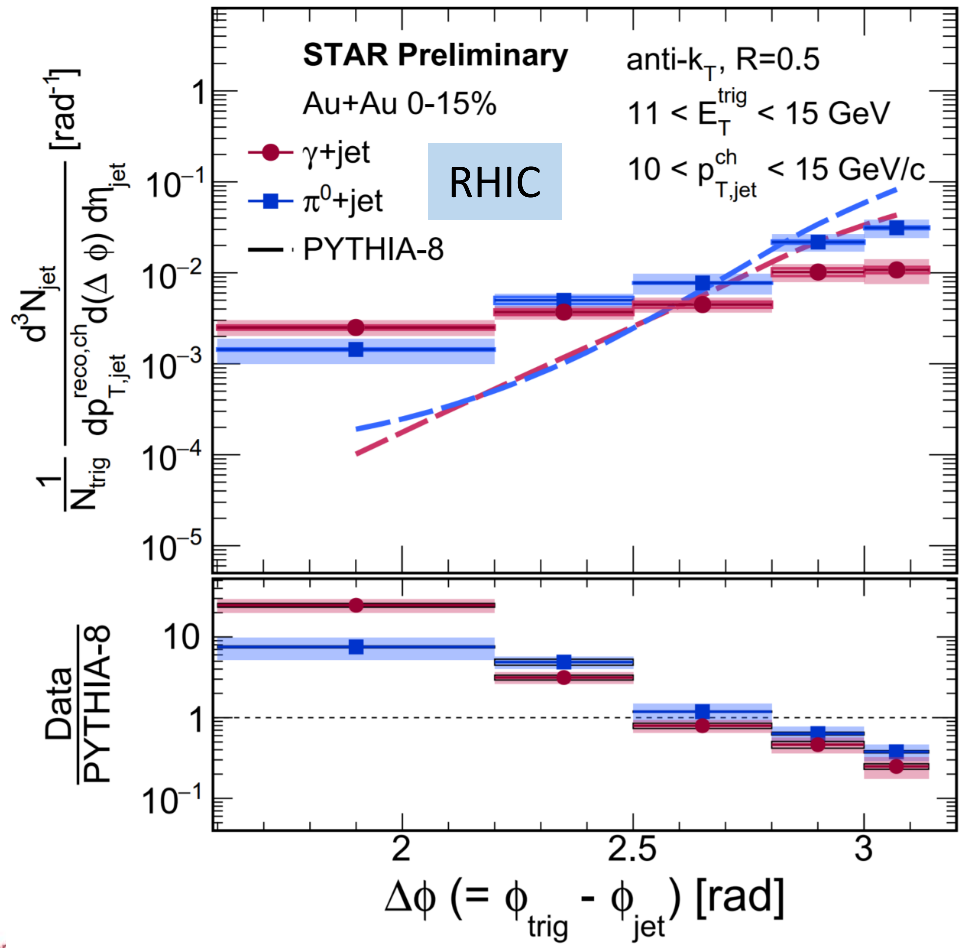
In-medium energy loss smaller at RHIC than at the LHC.

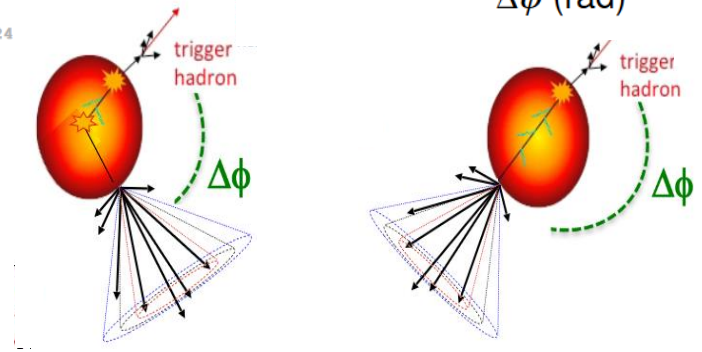
Exploring microscopic structure of QGP: acoplanarity

"QCD Molière scattering": large-angle jet deflection studies probe the nature of the quasi-particles in hot QCD matter

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



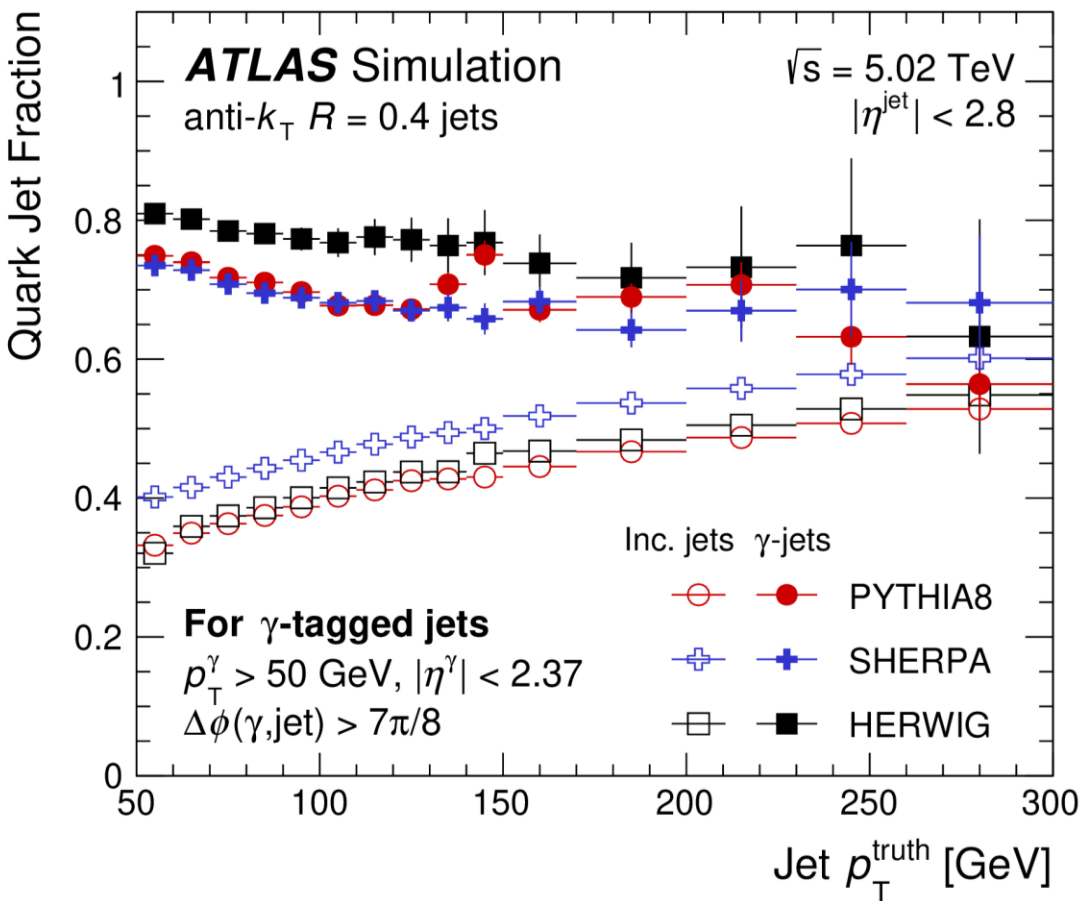


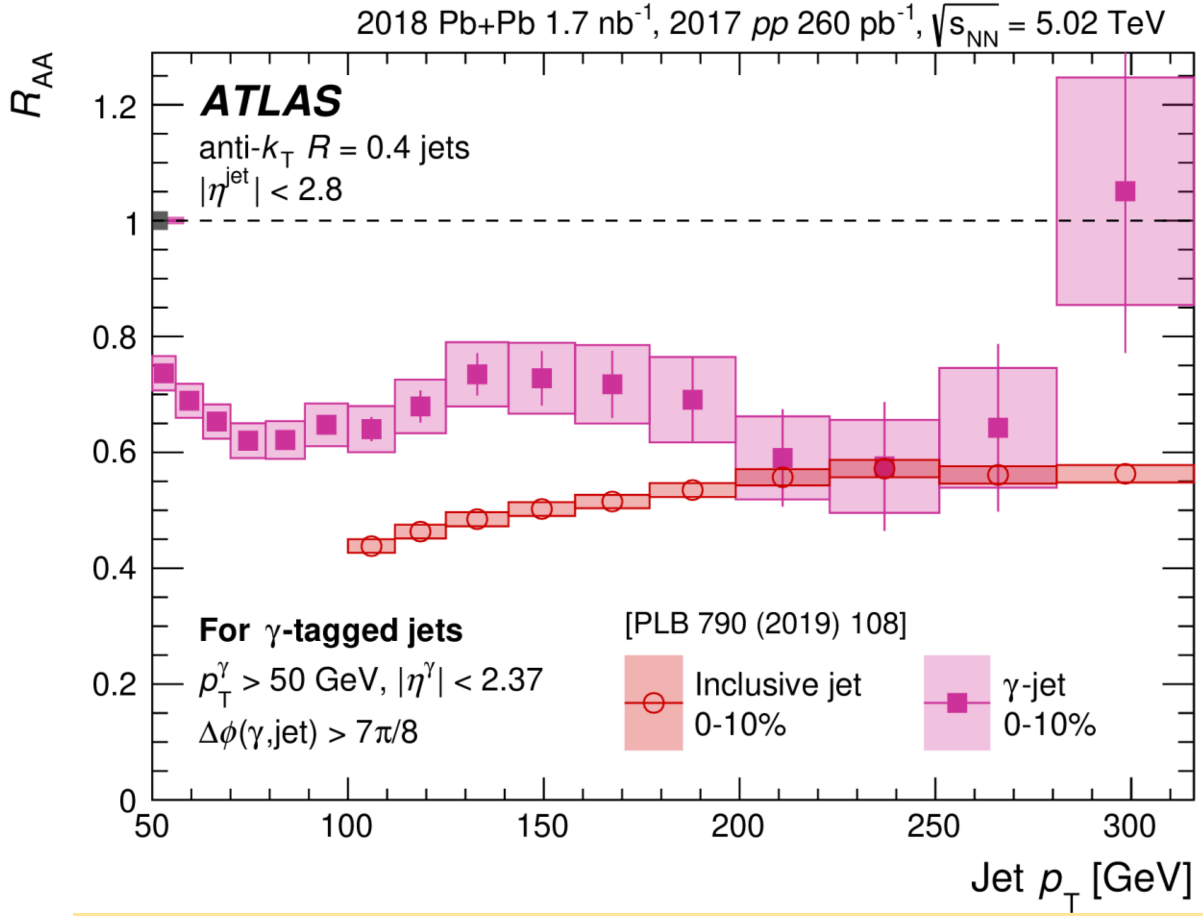


First measurements of acoplanarity down to low p_T of recoil jets.
$\Delta\phi$ broadening for larger R and small jet p_T observed at LHC and RHIC!

γ-tagged jets

ATLAS, arXiv:2303.10090



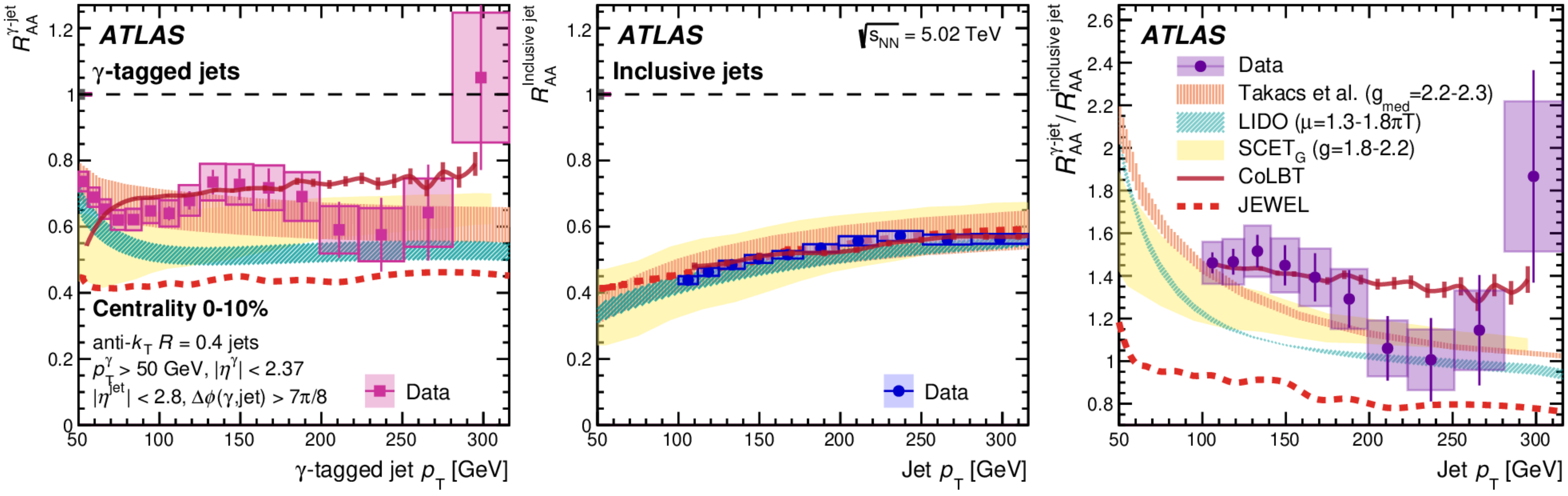


Dialing q/g fraction with γ-tagging:
p_T^γ > 50 GeV/c → q/g fraction ~ 80%

R_{AA} for γ-tagged jets is significantly higher than that for inclusive jets
→ clear demonstration of sensitivity of energy loss to the color-charge of the initiating parton (quarks lose less energy than gluons)

γ-tagged jets

ATLAS, arXiv:2303.10090

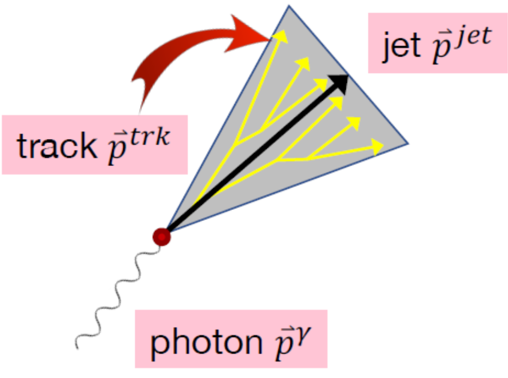


The ratio of R_{AA}(γ-tagged jet)/R_{AA}(inclusive jet) has a good discriminating power!

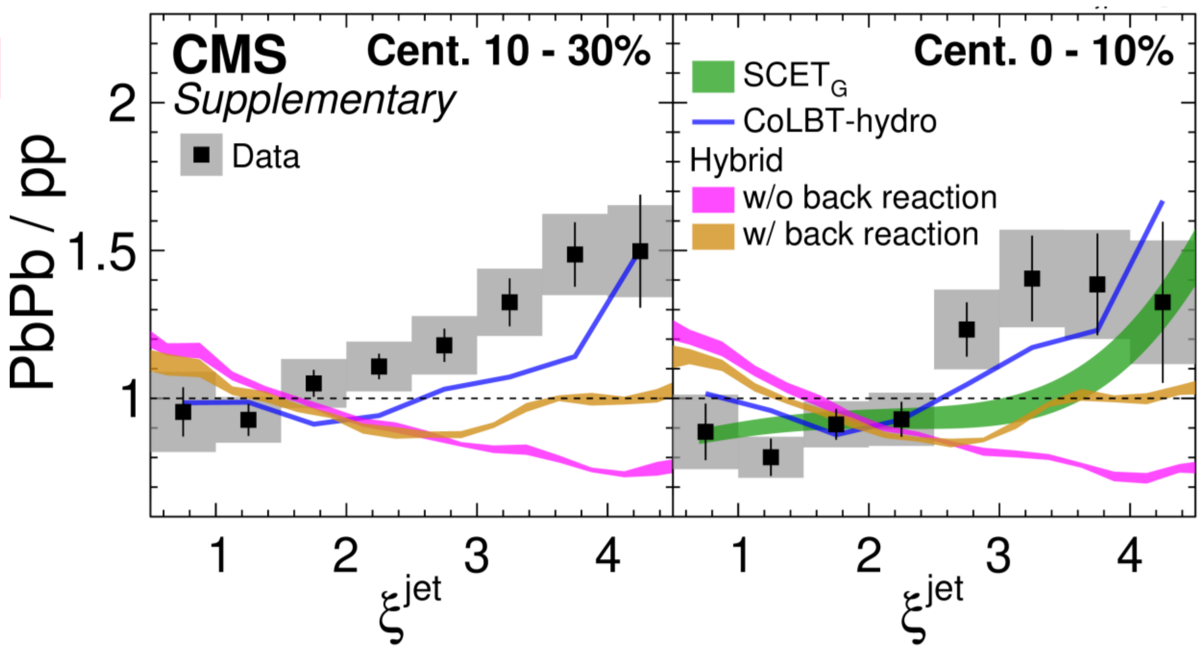
Most calculations underpredict the R_{AA} ratio of γ-tagged jet/inclusive jet.

Calculations:
Takacs, Tywoniuk, JHEP 10 (2021) 038
Ke, Xu, Bass, PRC 100 (2019) 064911, PRC 98 (2018) 064901
Ke, Wang, JHEP 05 (2021) 041
Kang, Vitev, Xing, PRC 96 (2017) 014912,
Li, Vitev, JHEP 07 (2019) 148, PRD 101 (2020) 076020
He et al., PRC 99 (2019) 054911
Zapp, JEWEL, Eur. Phys. J. C 76 (2016) 695

γ-tagged jets: fragmentation, radial density



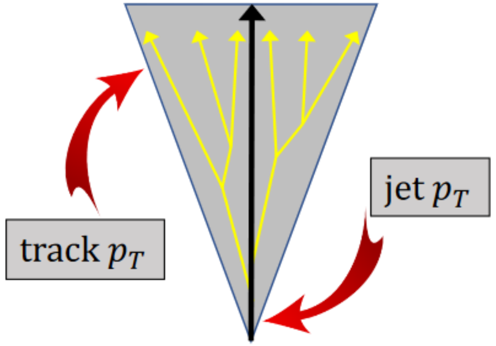
$$\xi^{jet} = \ln \frac{|\vec{p}^{jet}|^2}{\vec{p}^{trk} \cdot \vec{p}^{jet}}$$



$\sqrt{s_{NN}}$ = 5.02 TeV — p_T^{trk} > 1 GeV/c, anti-k_T jet R = 0.3
PbPb 404 μb^{-1} — p_T^{jet} > 30 GeV/c, $|\eta^{jet}|$ < 1.6
pp 27.4 pb^{-1} — p_T^{γ} > 60 GeV/c, $|\eta^{\gamma}|$ < 1.44, $\Delta\phi_{j\gamma} > \frac{7\pi}{8}$

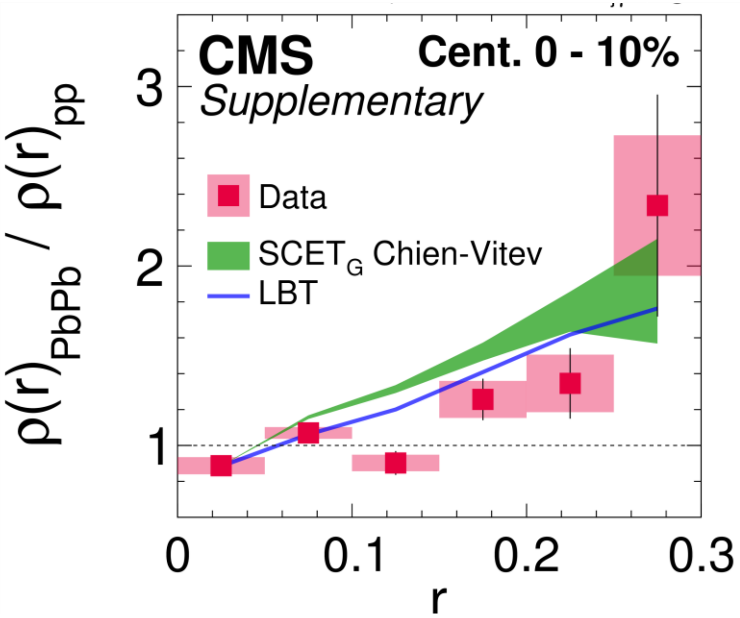
Small excess of low-p_T and depletion of high-p_T particles. Medium back-reaction in models improves data description.

CMS, PRL (2018) 242301



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

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



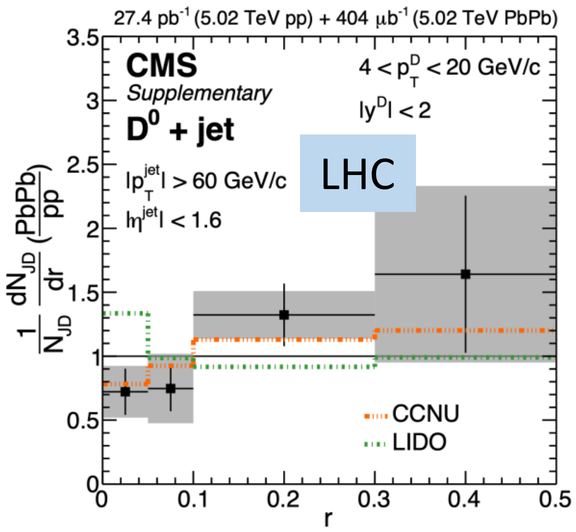
$\sqrt{s_{NN}}$ = 5.02 TeV — p_T^{γ} > 60 GeV/c
PbPb 404 μb^{-1} — anti-k_T jet R = 0.3
pp 27.4 pb^{-1} — p_T^{jet} > 30 GeV/c, $\Delta\phi_{j\gamma} > \frac{7\pi}{8}$

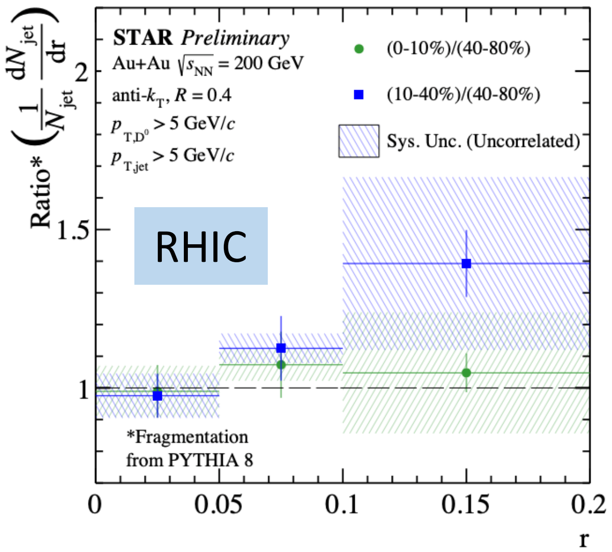
Small relative modification of jet core and enhancement of particles away from jet axis.

CMS, PRL 122 (2019) 152001

Flavor dependence of jet-medium interaction

p_T^D = 4 - 20 GeV/c

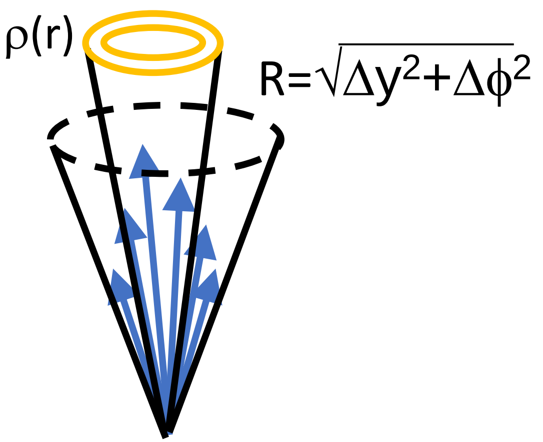


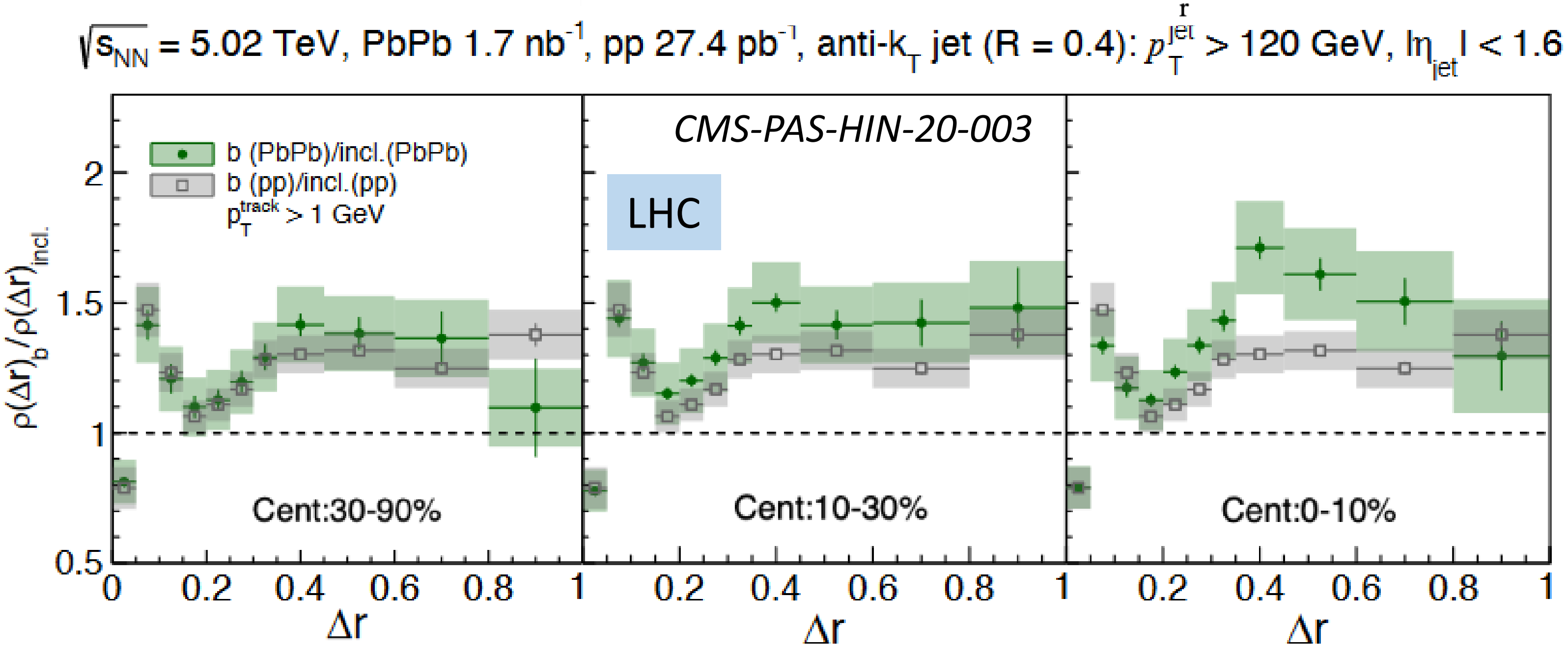


First measurements of the radial profile of heavy quarks in jets in heavy ion collisions.

Charm: hint of enhancement of D^0 at large angles and at lower p_T.

CMS, PRL 125 (2020) 102001



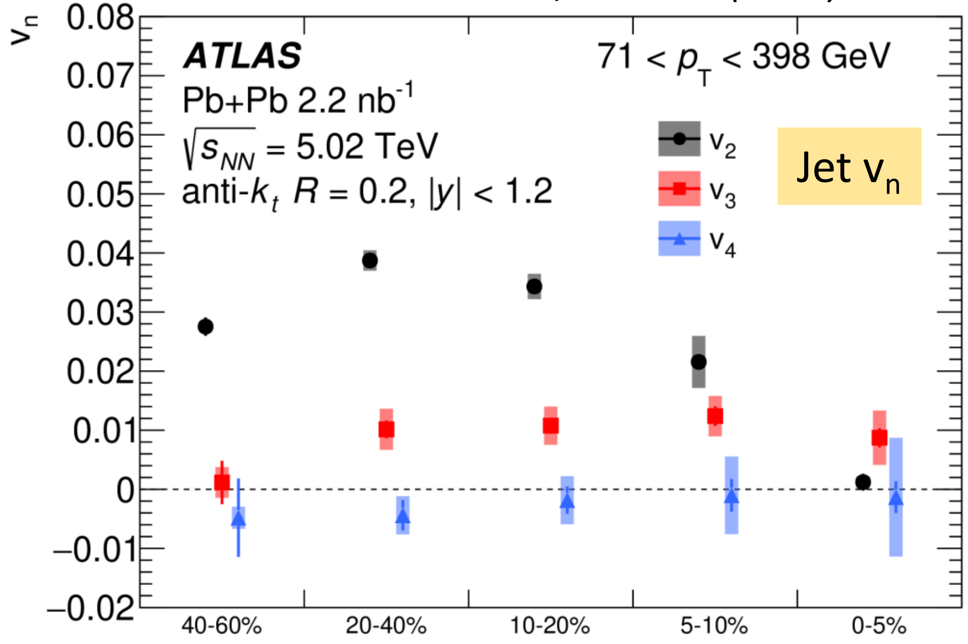


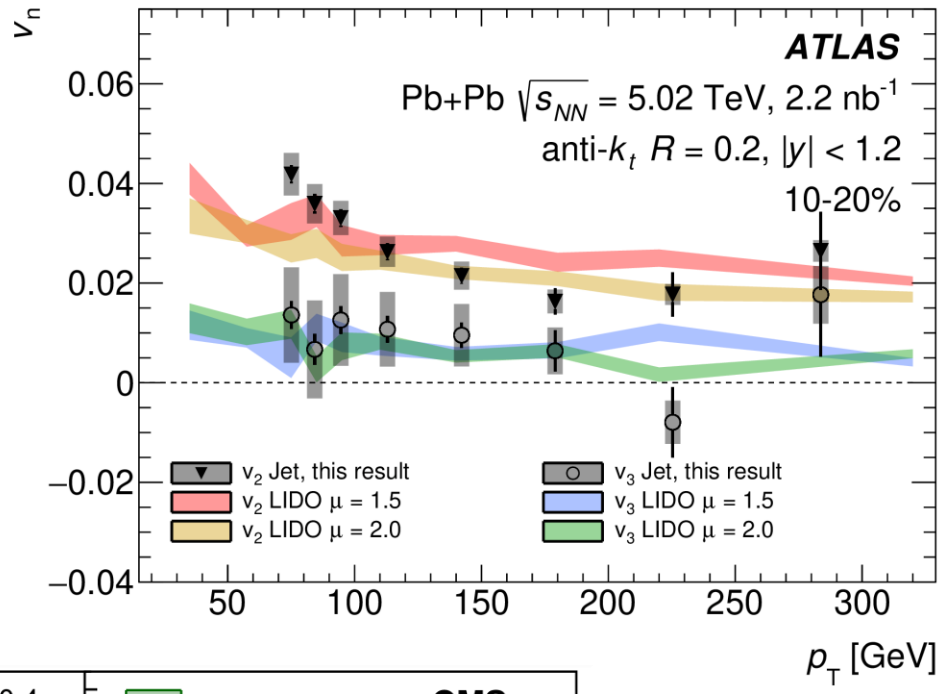
Quenching modifies b-jet shapes differently than inclusive jets:
→ relatively larger degree of transverse momentum shifted to large angles.

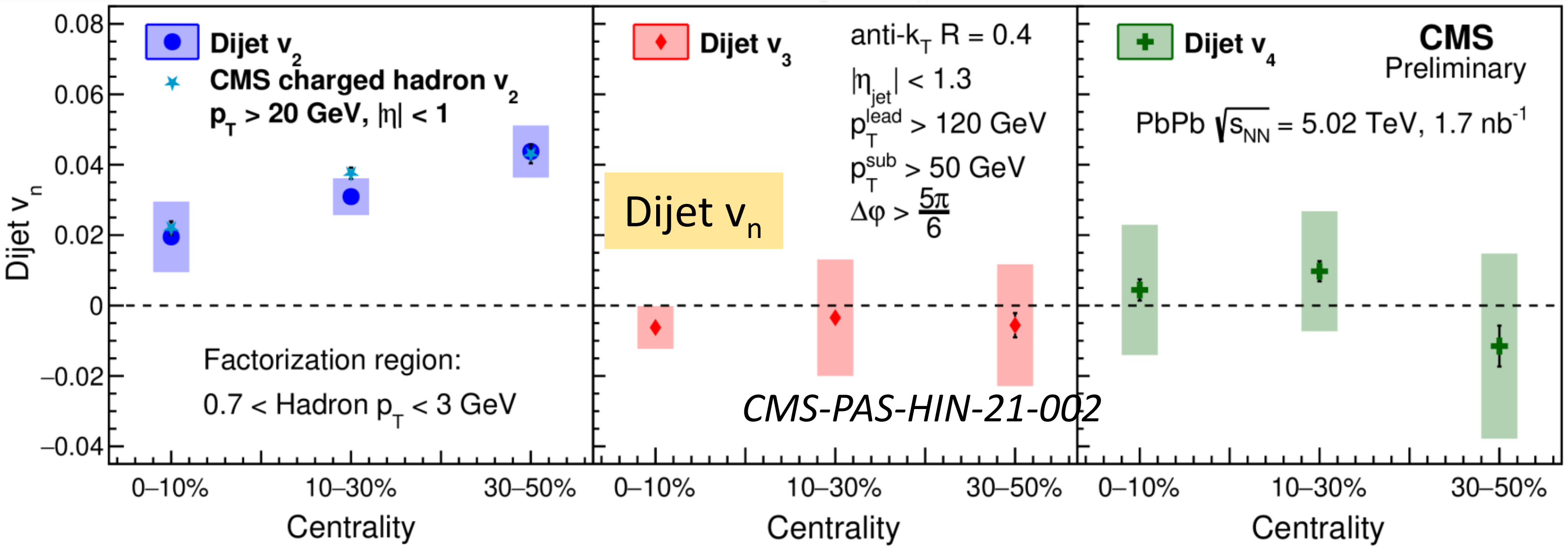
Path-length effects

Path-length dependence of jet energy loss

ATLAS, PRC 105 (2022) 064903





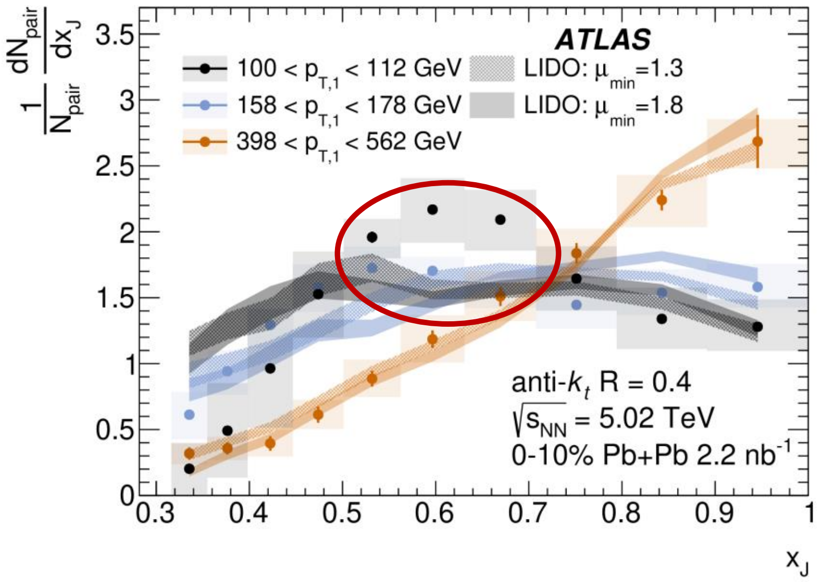


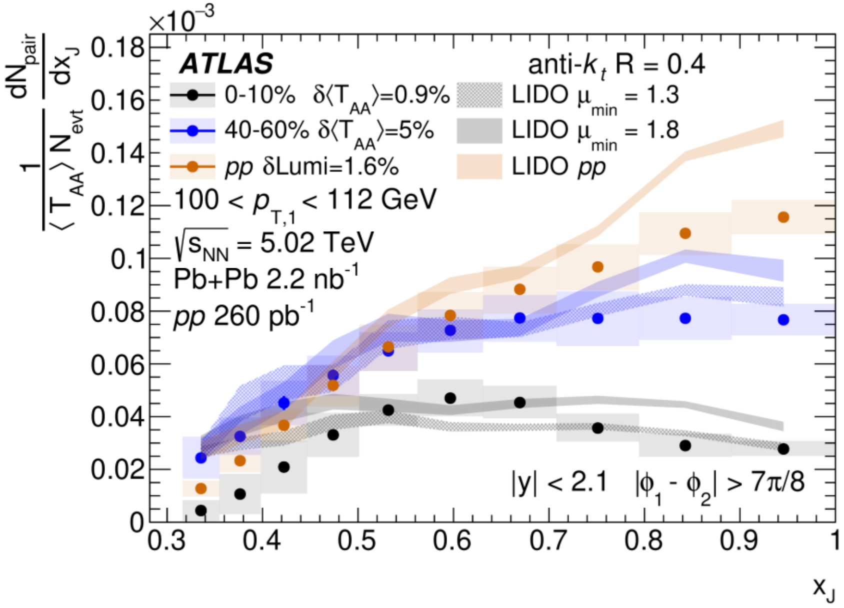
v_2: maximal at ~0.05 in mid-central collisions, slow decrease with p_T

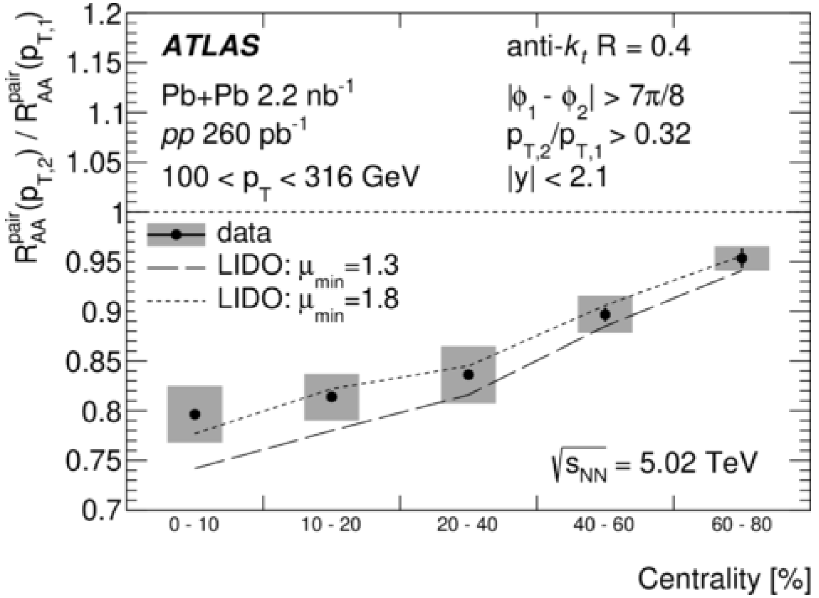
v_3, v_4 measured for the first time set limits on initial-state fluctuations of energy loss

Di-jet asymmetry

ATLAS, arXiv:2205.00682







Dijet-yield-normalized x_J distributions:
increased fraction of imbalanced jets in PbPb compared to pp collisions.

Absolutely-normalized dijet rates:
balanced dijets significantly more suppressed than imbalanced ones.

R_{AA} pair: subleading jets more suppressed than leading jets

- central PbPb : 20% effect
- peripheral PbPb: smaller, but still significant suppression of subleading jets

leading di-jet momentum balance

$$x_J \equiv p_{T,2}/p_{T,1}$$

New information about path-length dependence and fluctuations in jet energy loss.

Jet substructure

Jet grooming

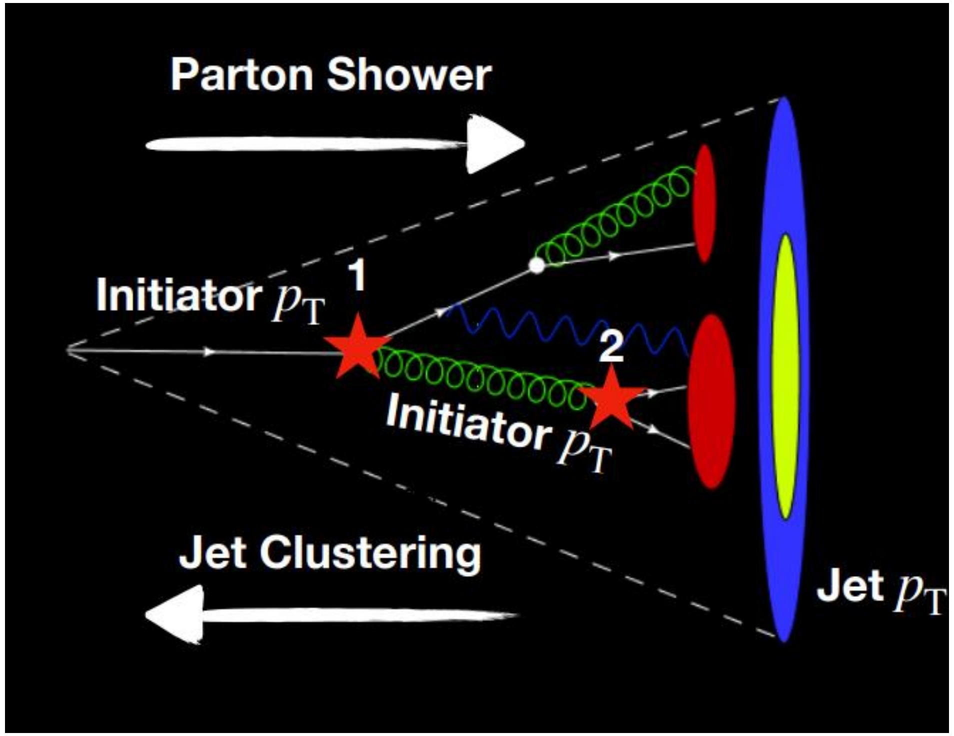


Figure courtesy R. Kunnawalkam Elayavalli

Vacuum:
Parton shower is a multi-scale process with a given momentum and angular/virtuality scale.

Medium:
Angular/virtuality scale can be related to a "resolution scale" at which the jet probes the medium.

Jet grooming algorithms:
Provide access to the hard parton splittings inside a jet by removing soft wide-angle radiation
→ mitigates non-perturbative effects
→ access to hard splittings in HI collisions
may help to constrain jet quenching effects
(color coherence, energy loss and p_T broadening)

Soft Drop:
Larkoski et al. JHEP 05 (2014) 146

Recursive Soft Drop:
Dreyer et al. JHEP 06 (2018) 093

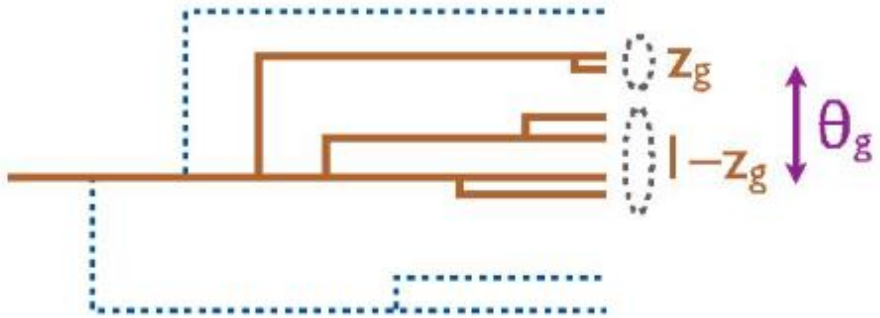
Dynamical grooming:
Mehtar-Tani, Soto-Ontoso, Tywoniuk, PRD 101 (2020) 034004

Soft Drop

- momentum scale: shared momentum fraction z_g,
- virtuality/angular scale: groomed radius R_g
  - it is the first ΔR_{12} that satisfies the SD grooming condition

Grooming condition:

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut} \left(\frac{R_g}{R_{jet}}\right)^{\beta}$$



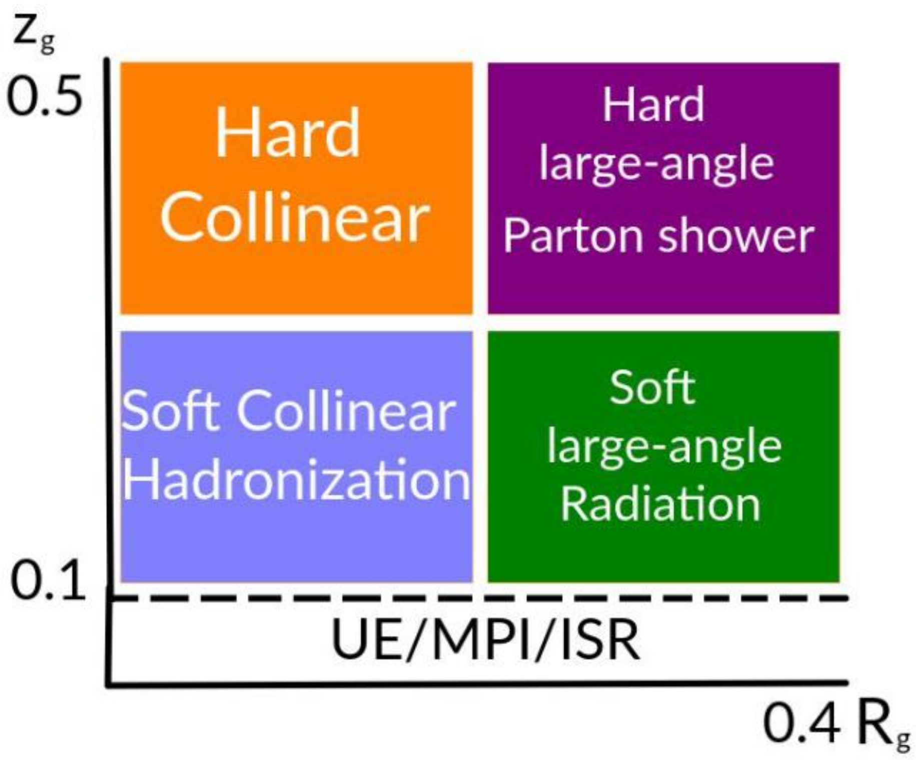
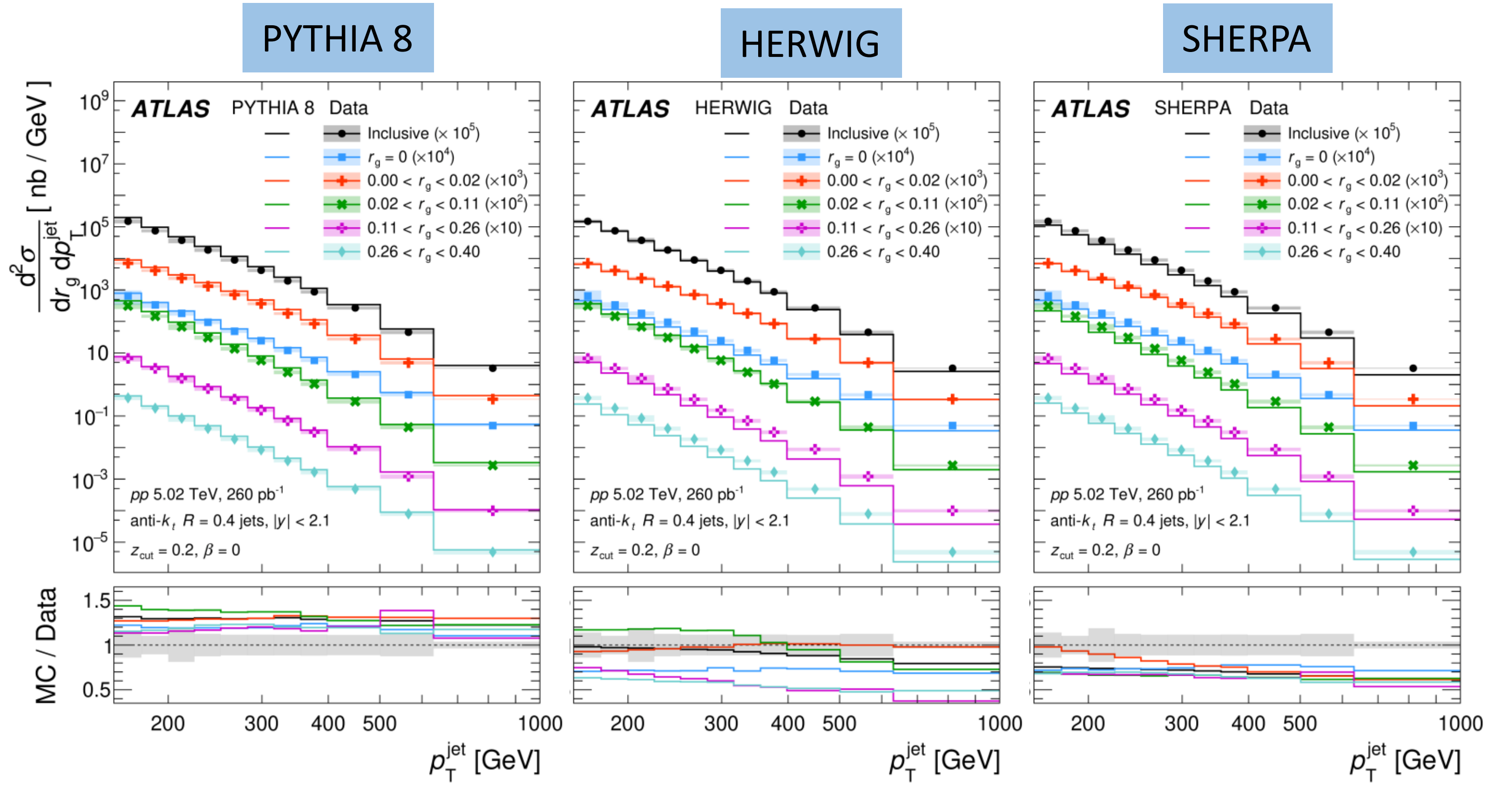
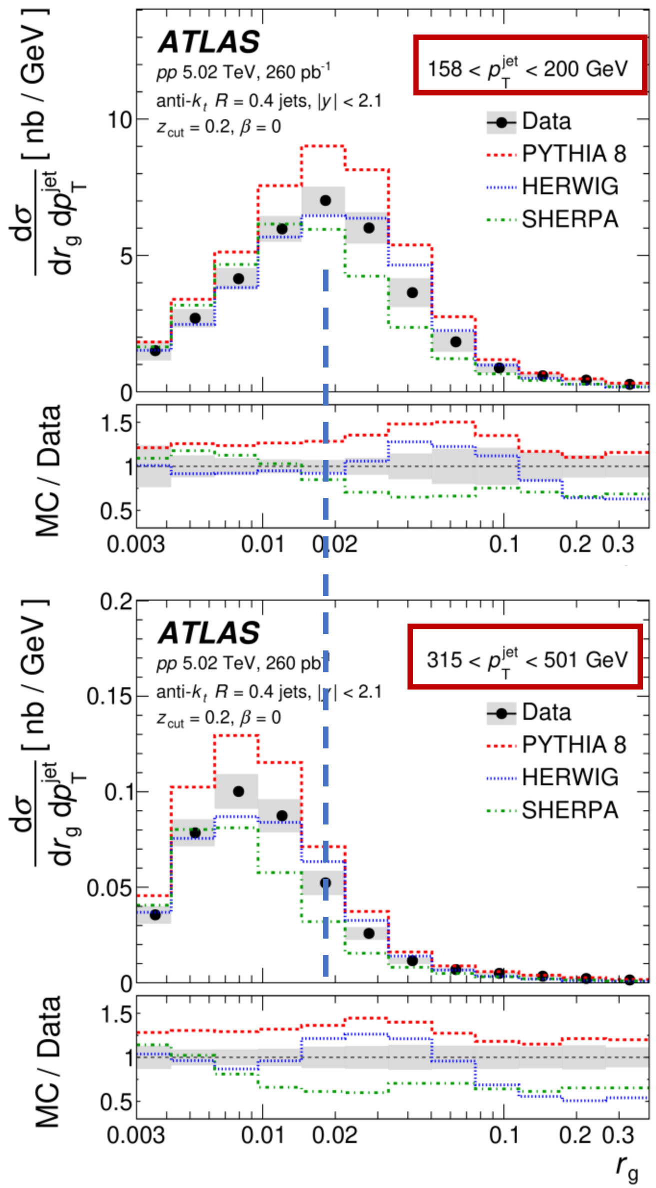


Figure courtesy M. Robotkova

Soft Drop:
Larkoski et al. JHEP 05 (2014) 146
Recursive Soft Drop:
Dreyer et al. JHEP 06 (2018) 093

Jet substructre in pp at the LHC



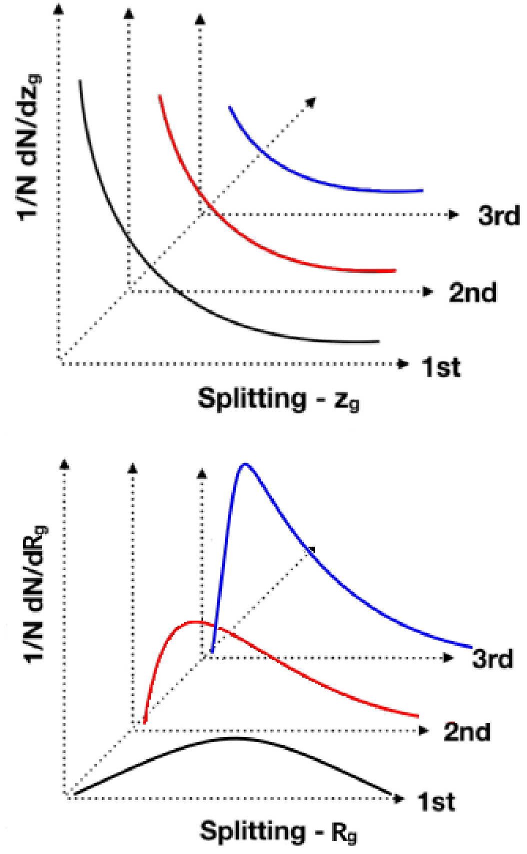


MC event generators (PYTHIA 8, HERWIG, SHERPA):
PYTHIA 8 predictions describe best both the shape of inclusive and differential distributions

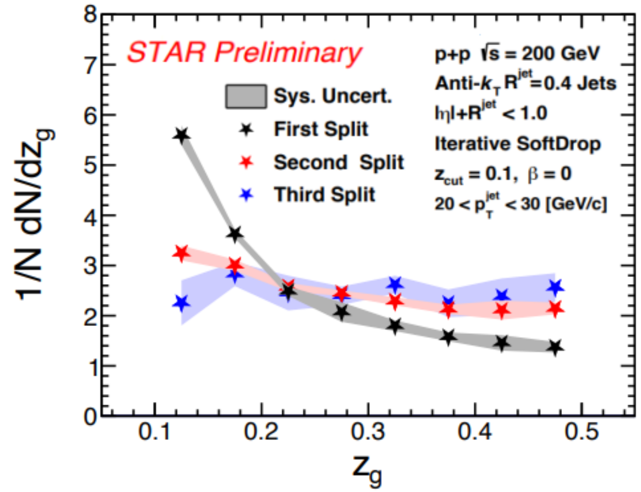
r_g distributions in pp collisions peak at lower values of r_g with increasing jet p_T
→ indicates stronger collimation with increasing jet p_T

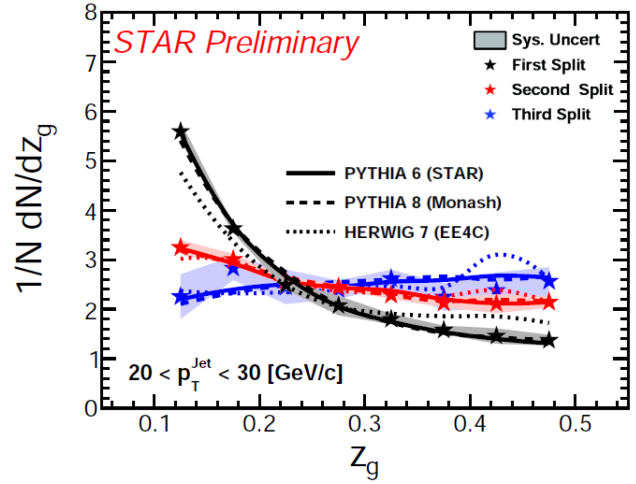
ATLAS, arXiv 2211.11470

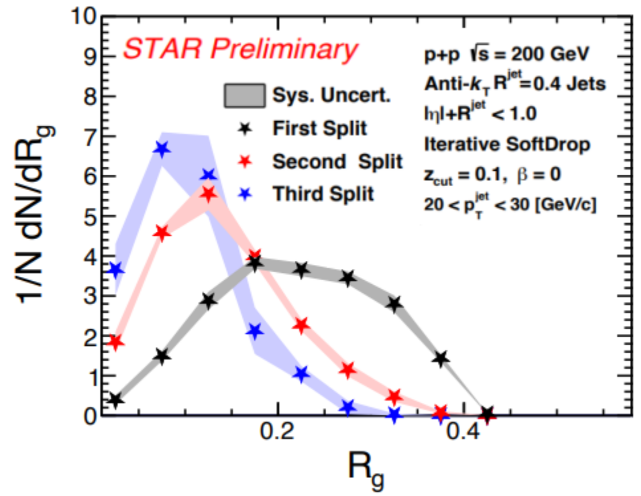
Jet substructre in pp at RHIC as a function of split

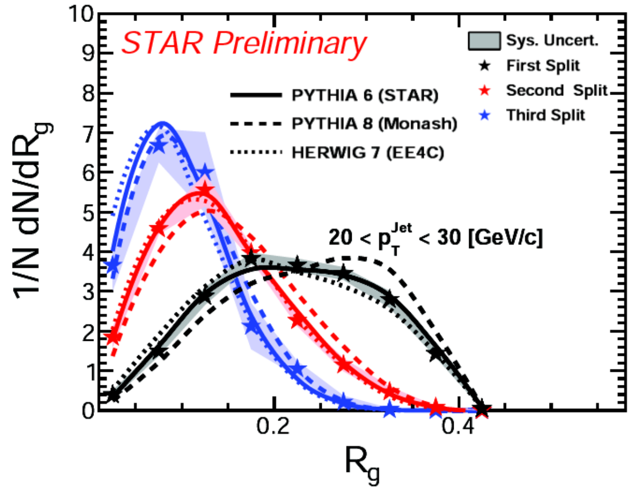


Cartoon courtesy M. Robotkova





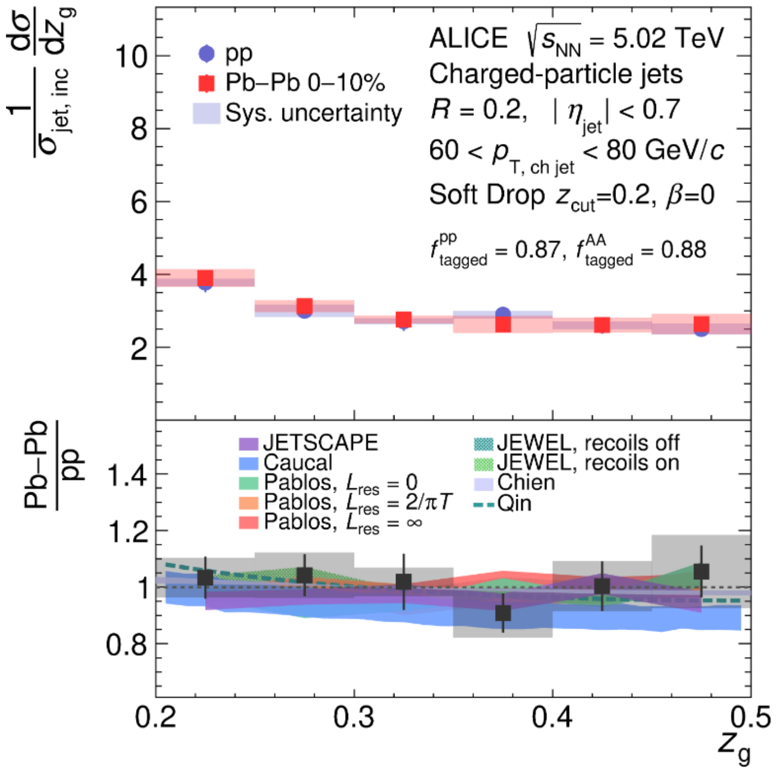




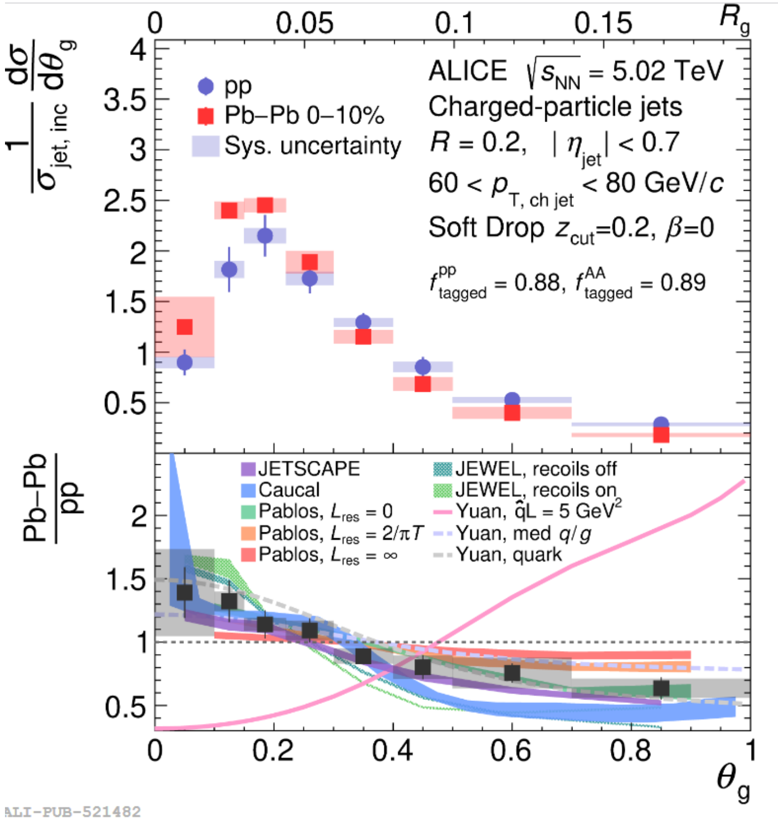
With the increased split number along the shower:
z_g becomes flatter and R_g becomes narrower
→ collinear emissions get enhanced

The observed evolution is well captured by MC models in the accessible kinematic region at RHIC.

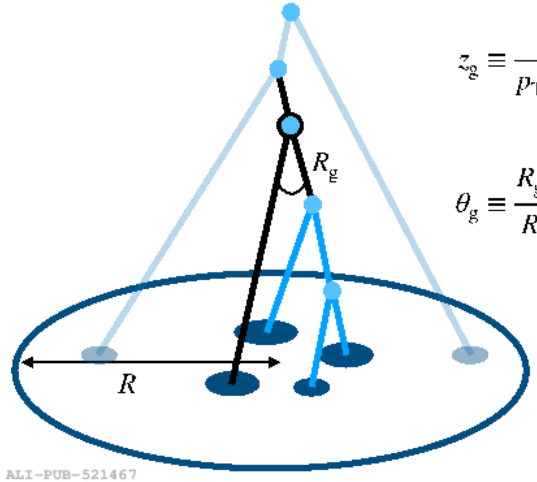
Jet substructure as a microscope: ALICE



ALI-PUB-521472



ALI-PUB-521482



$$z_g \equiv \frac{p_{T,subleading}}{p_{T,leading} + p_{T,subleading}}$$

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

ALI-PUB-521467

z_g : no modification

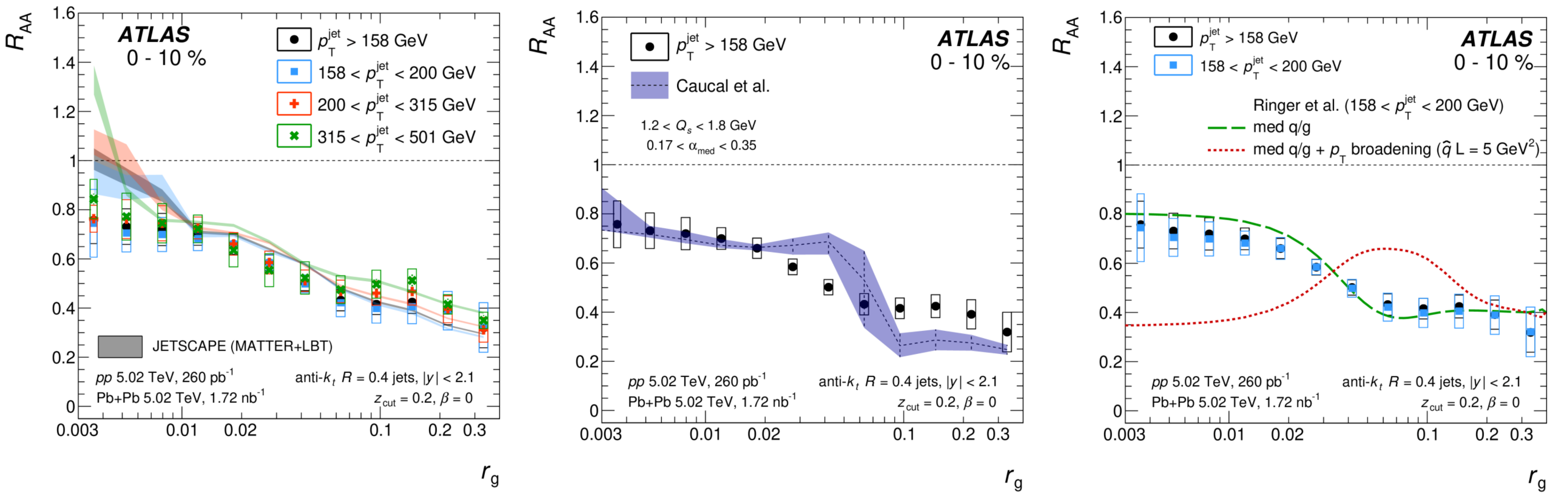
θ_g : narrowing in Pb-Pb compared to pp observed

→ direct evidence of the modification of jet angular structure in QGP.

ALICE: *PRL* 128 (2022) 10, 102001

Medium has resolving power for splittings (promotes narrow splittings, filters out wider subjets).

Jet substructure as a microscope: ATLAS



JETSCAPE (MATTER+LBT): captures r_g-dependent suppression but overestimates the R_{AA} for jets in the low r_g region, especially at higher jet p_T

pQCD (Caucal et al.): qualitatively describes the r_g dependent suppression, but predicts a sharper drop in R_{AA} around the critical angle beyond which incoherent jet energy loss sets in.

Medium q/g quenching effects (Ringer et al.): describes the r_g-dependent jet suppression

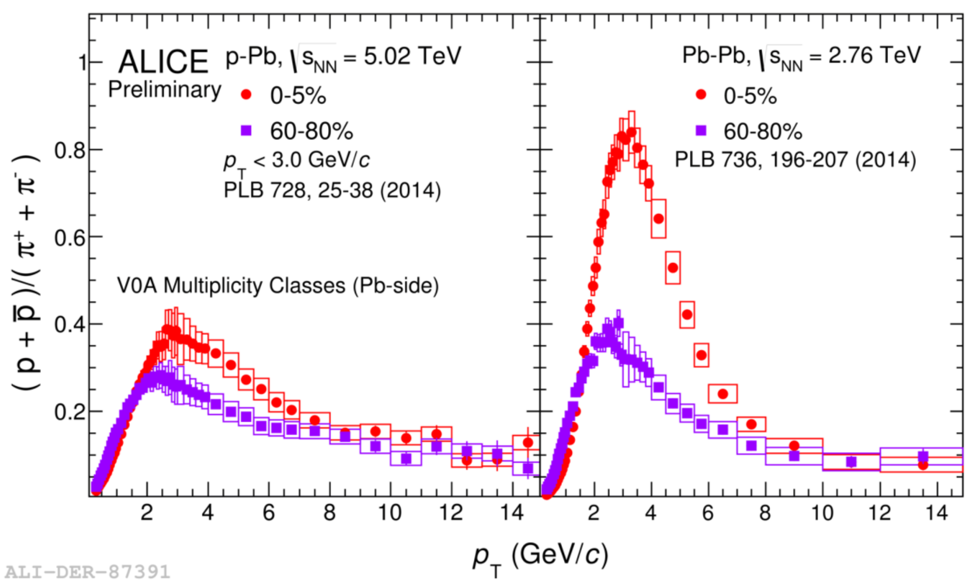
q/g + p_T-broadening effects
→ significant suppression at low r_g + peak in R_{AA} at mid-r_g values, not observed in data

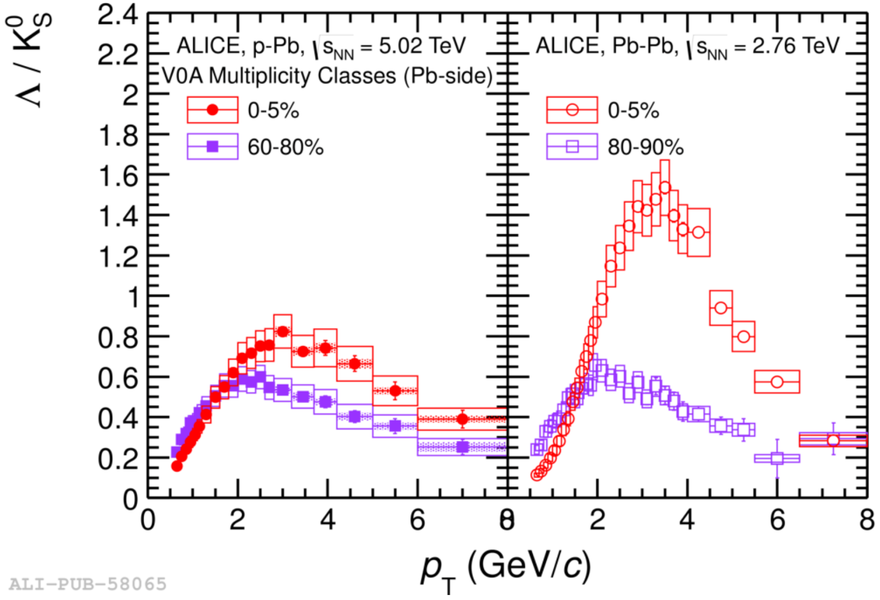
ATLAS, arXiv 2211.11470

Studies of hadronization mechanisms with jets

Baryon/meson enhancement in p-Pb and Pb-Pb relative to pp collisions

ALICE, PLB 728 (2014) 25, PLB 736 (2014) 196
arXiV: 1506.07287



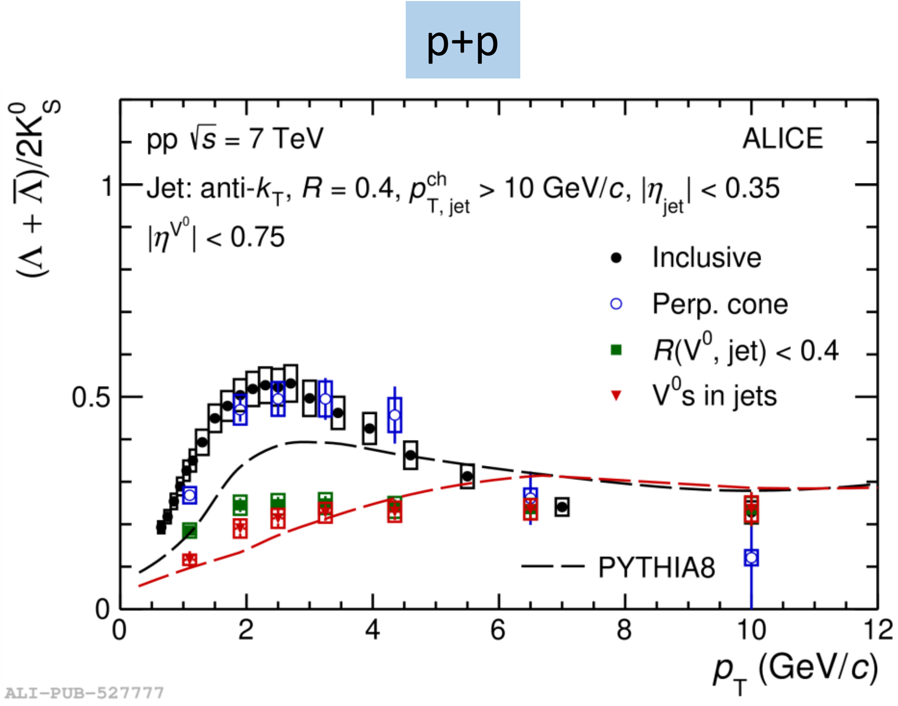


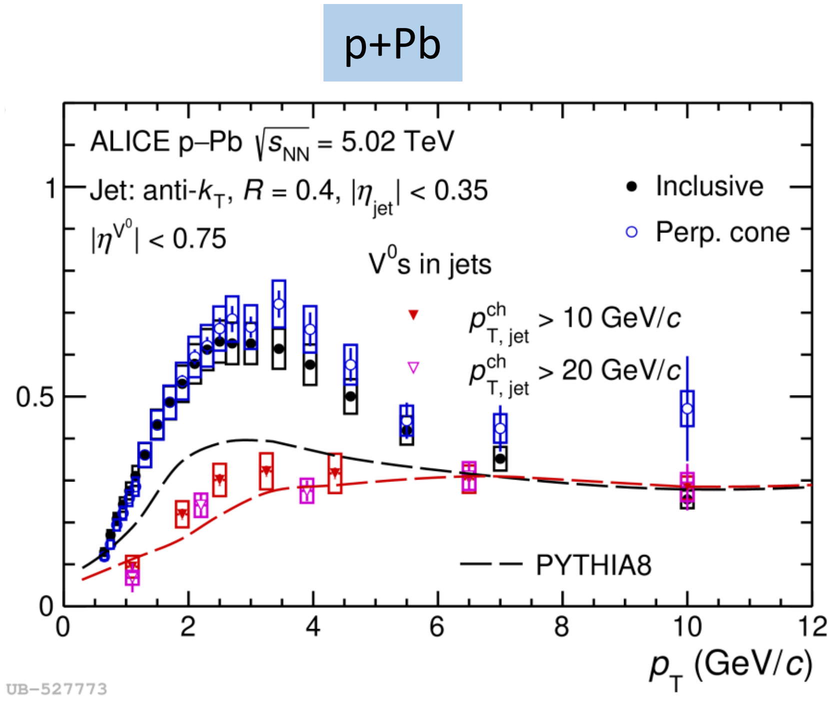
High multiplicity p–Pb and Pb–Pb collisions have many similarities (see earlier slides) including also an enhanced baryon-to-meson ratio (e.g. p/π and Λ/K^0_S ratio)

What is physics origin of this enhancement?
- radial flow
- coalescence/recombination vs fragmentation

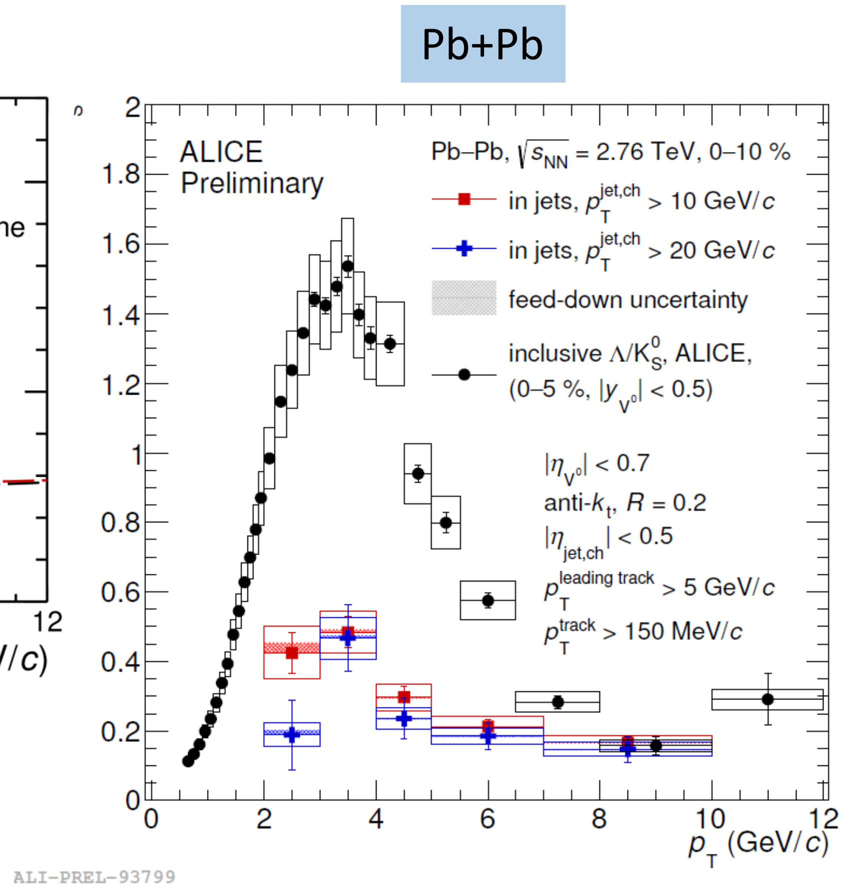
Measure baryon-to-meson ratios in jets and compare to that in bulk …

Is baryon/meson composition different in jets?





ALICE, *PLB* 827 (2022) 136984



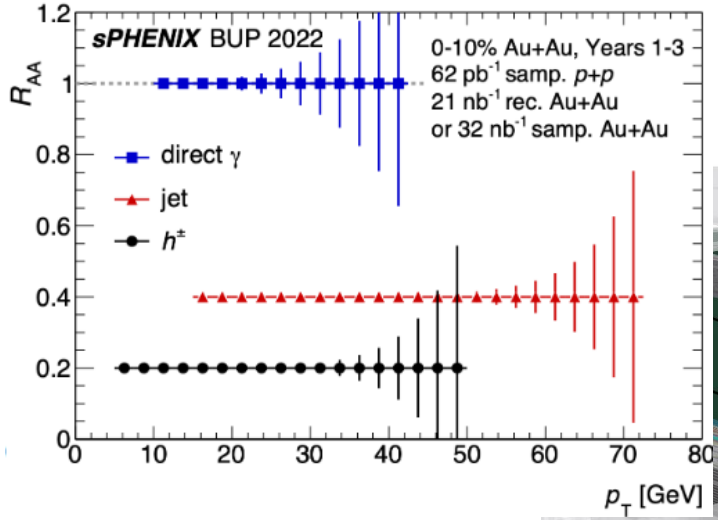
Λ/K^0_S ratio in charged-particle jets in p-p, p-Pb and Pb-Pb collisions is significantly lower than the inclusive one.

Jet composition is within uncertainties not influenced by the enhanced baryon/meson production in the bulk.

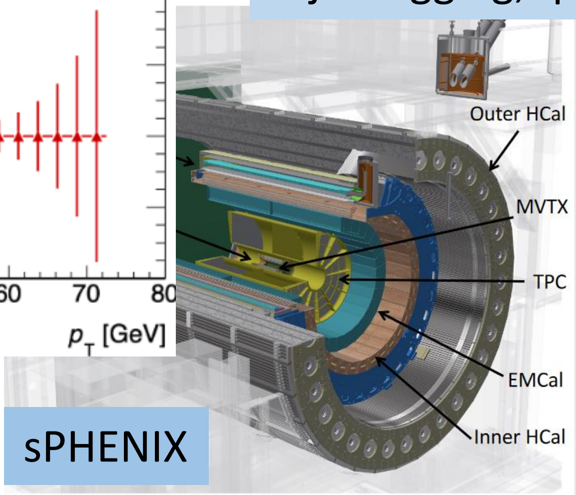
The future is bright …

more in L. Musa's talk

RHIC in 2023-2025:
Simultaneous data taking for STAR (with new forward capabilities) and a new sPHENIX experiment
- unprecedented statistics to be collected for pp, pAu and AuAu collisions at 200 GeV
  → completion of RHIC mission



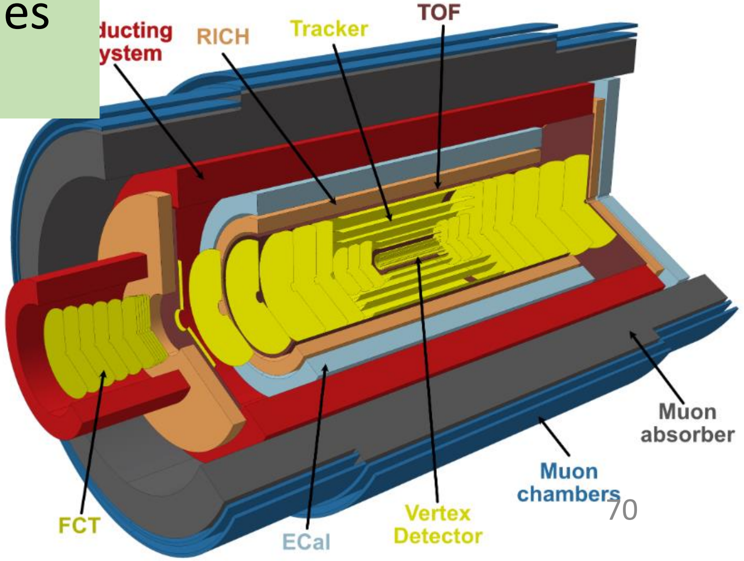
full jet reconstruction, b-jet tagging, quarkonia



sPHENIX

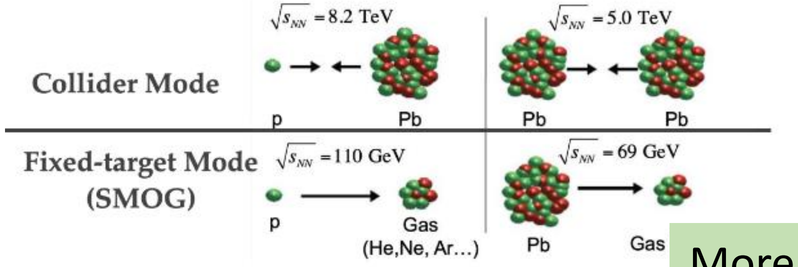
LHC:
Run 3 and Run 4 will enable to perform microscopic studies of QGP properties with upgraded LHC experiments

ALICE 3 Run5+



LoI: CERN-LHCC-2022-009

LHCb



More PbPb data
+ Fixed-target mode (SMOG)

Disclaimer:
Jets are rich objects and so are their studies, my apologies if you did not see your favourite observable being presented.

Thank you for your attention and enjoy the conference!

CTU
CZECH TECHNICAL UNIVERSITY IN PRAGUE

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"Center of Advanced Applied Science"

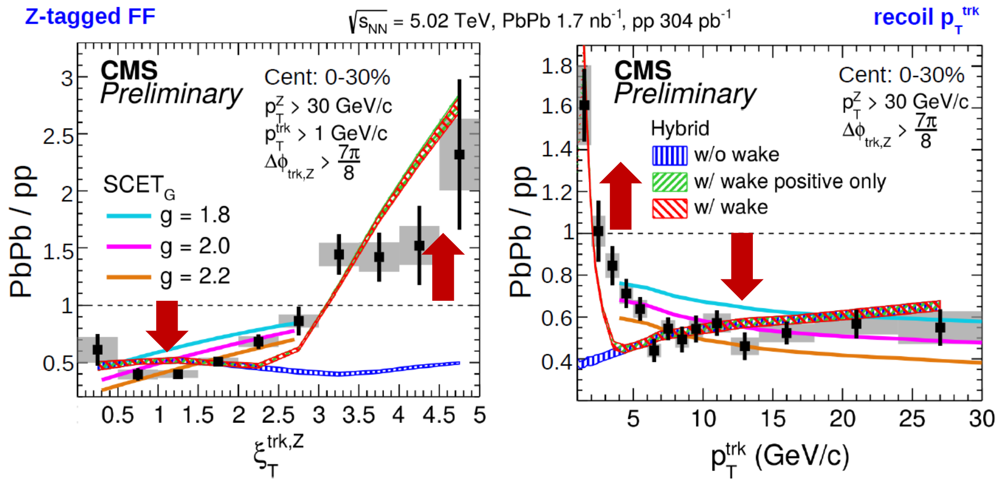
No. CZ.02.1.01/0.0/0.0/16-019/0000778.

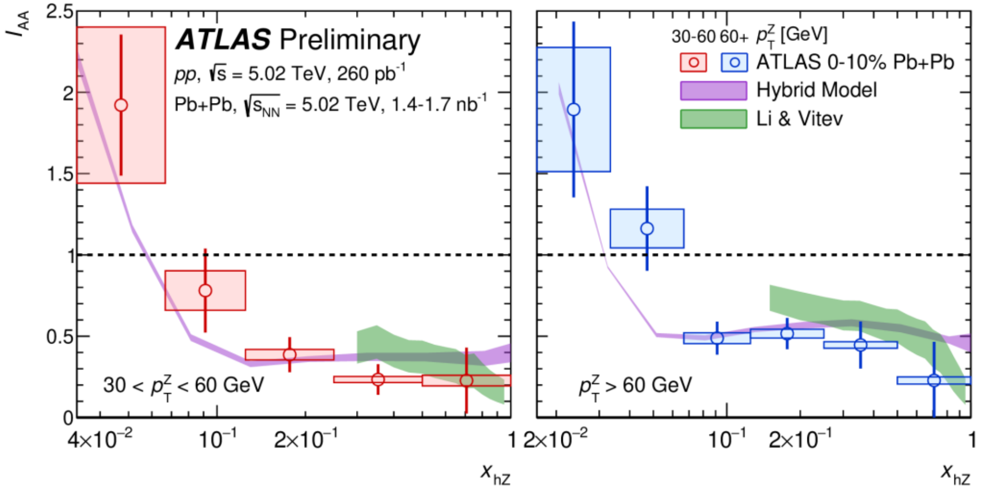
EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research, Development and Education

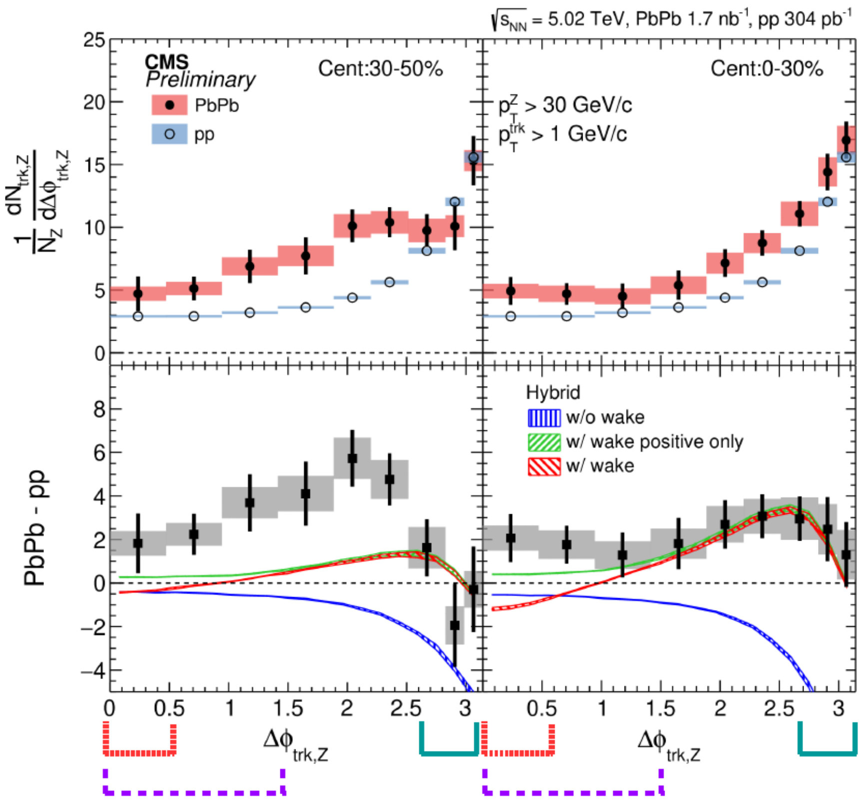
MINISTRY OF EDUCATION, YOUTH AND SPORTS

BACKUP SLIDES with more details

Z-tagged fragmentation







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

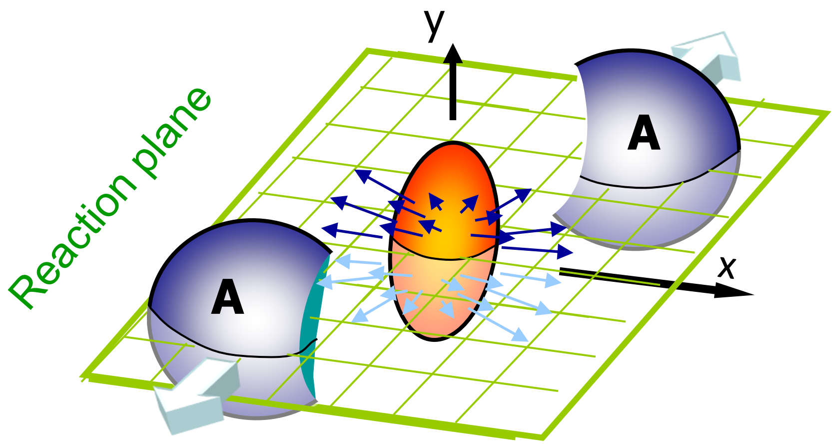
- SCET$_G$ with g=2.0 reasonable description of data
- Hybrid model with medium wake undershoots intermediate p_T = 3-5 GeV, discrepancy even more pronounced in $\Delta\phi$ distributions

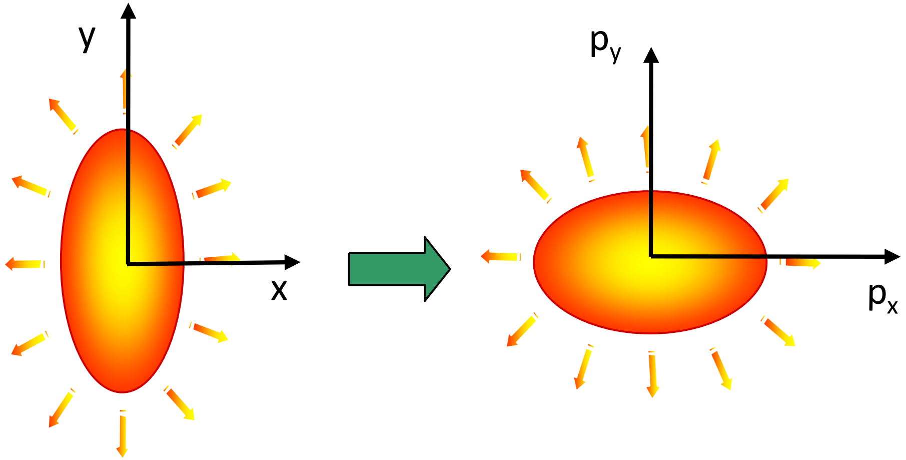
Similarly as for γ-tagged correlations excess (depletion) of low (high) momentum particles measured

Need to improve medium response

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

Anisotropic flow





Initial spatial anisotropy → Strong pressure gradients → Anisotropy of produced particles

Sensitivity to early expansion

Fourier analysis of particle distribution:

v_1 : directed flow

v_2: elliptic flow

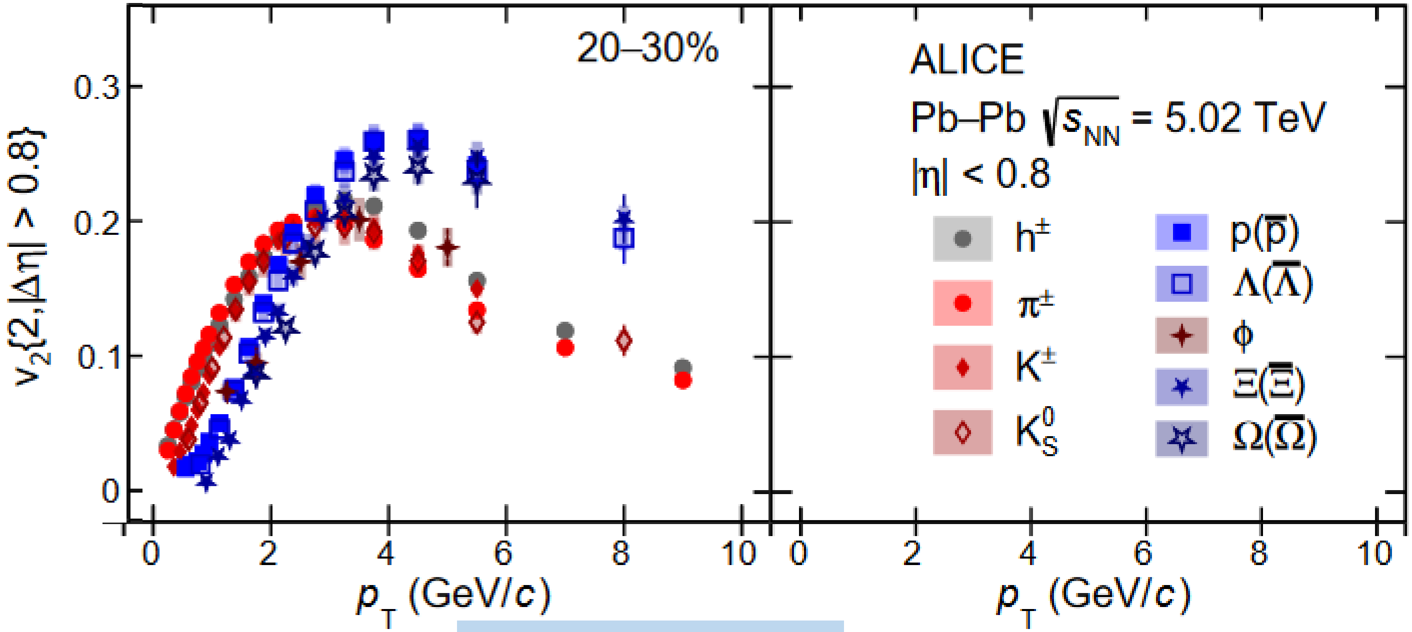
v_3: triangular flow ...

$$\frac{dN}{d(\phi - \Psi_R)} = A\left[1 + \sum_n 2\mathbf{v}_n \cos(n(\phi - \Psi_R))\right]$$

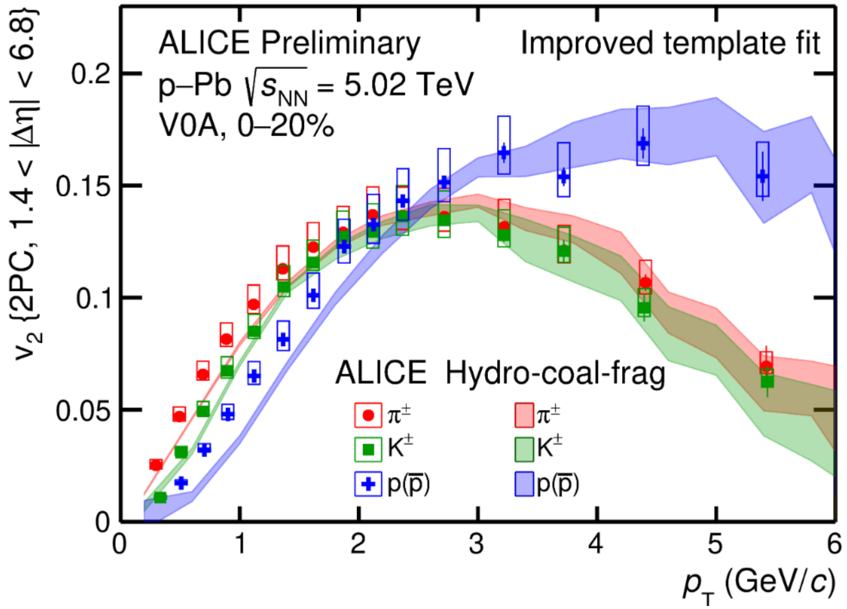
Anisotropic elliptic flow

ALICE, arXiv:2206.04587

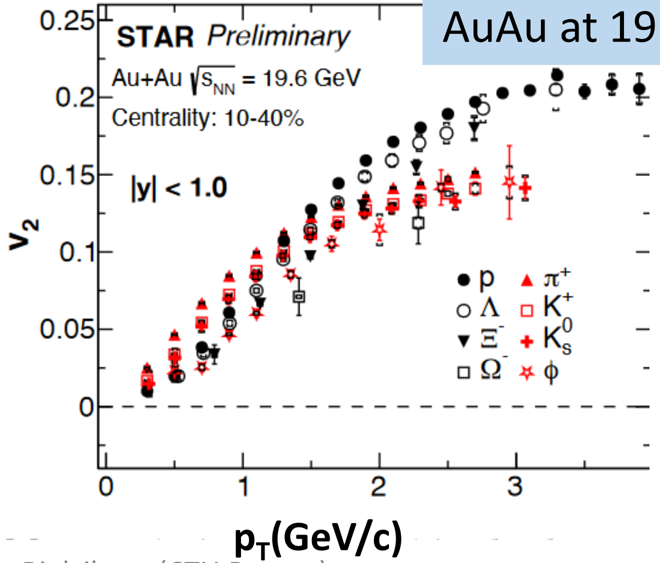
PbPb at 5.02 TeV



pPb at 5.02 TeV



AuAu at 19.6 GeV



Low p_T: mass ordering in line with hydrodynamics

High p_T: baryon and meson grouping

→ flow develops on quark level

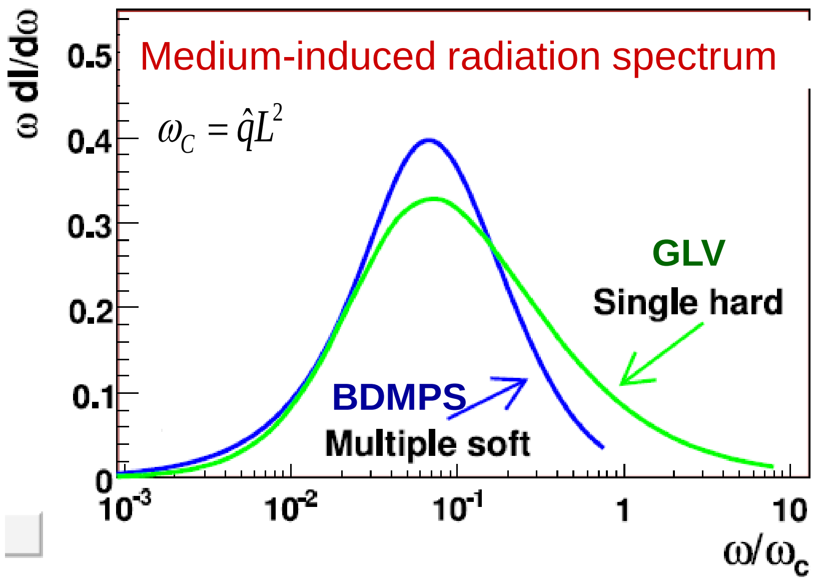
The baryon/meson grouping is observed down to low collision energies of RHIC + similar observation also in pPb collisions at the LHC!

Radiative energy loss in QCD

4 jet quenching schemes:

- higher twist expansion
  Qiu, Sterman, Wang, Wang, Zhang, Majumder,…
- finite temperature field theory
  Arnold, Moore, Yaffe (AMY)
- opacity expansion:
  - thin medium/single hard scattering
    Gyulassy, Levai, Vitev, Djordjevic,… (GLV)
  - thick medium/multiple soft scatterings
    Baier, Dokshitzer, Mueller, Peigne, Schiff (BDMPS)
    Armesto, Salgado, Wiedemann (ASW)

Salgado, Wiedemann PRD68 (2003) 014008



$$\frac{d\sigma^{h_1}}{dy\,dp_{T_1}} \sim \int dx_a dx_b G(x_a) G(x_b) \frac{d\hat{\sigma}}{d\hat{t}} D_q^{h_1}(z_1)$$

energy loss

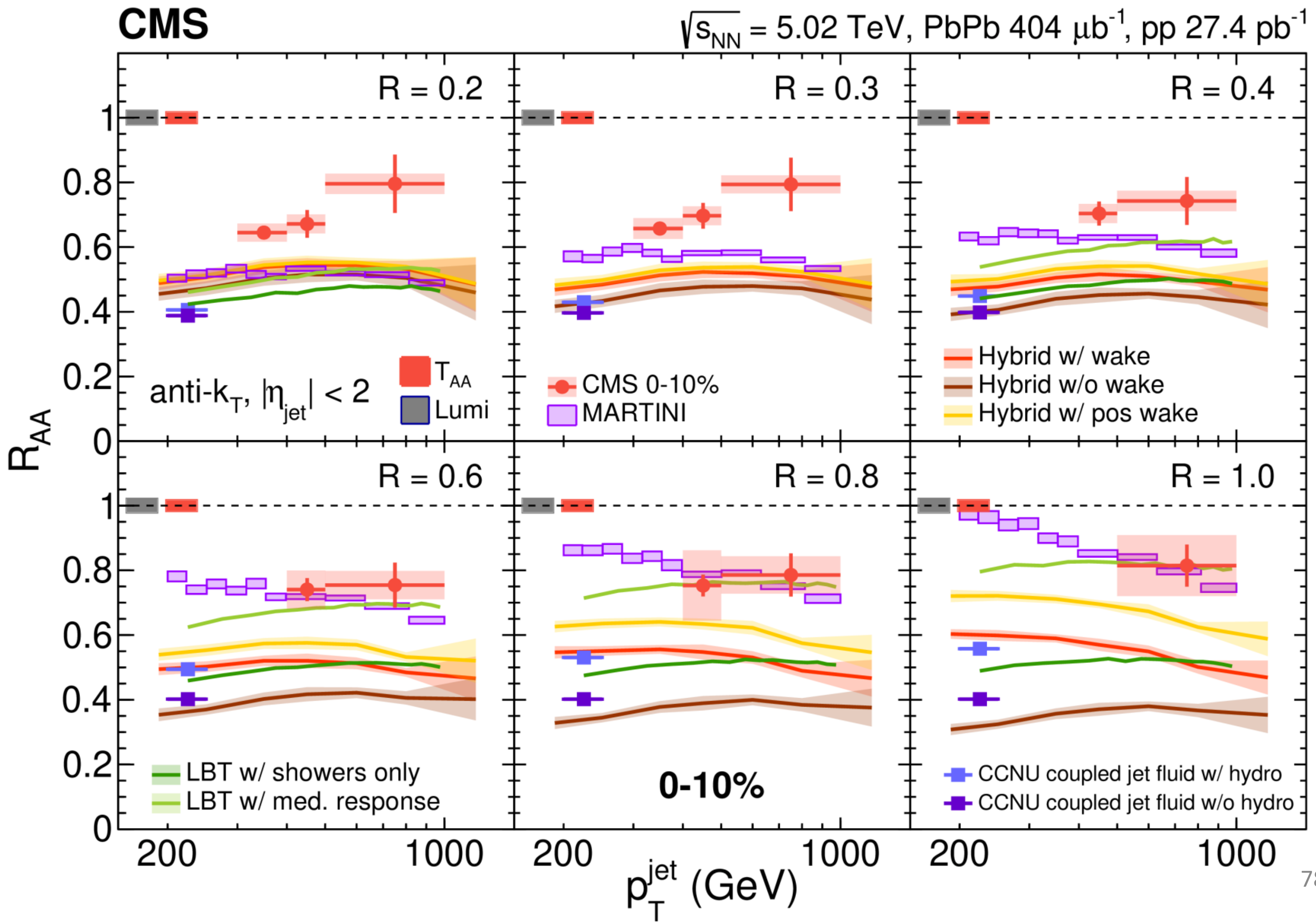
- medium properties can be characterized by a single constant:

e.g. transport coefficient $\hat{q} \equiv \frac{\mu^2}{\lambda}$ 'average k_T-kick per mean-free-path'

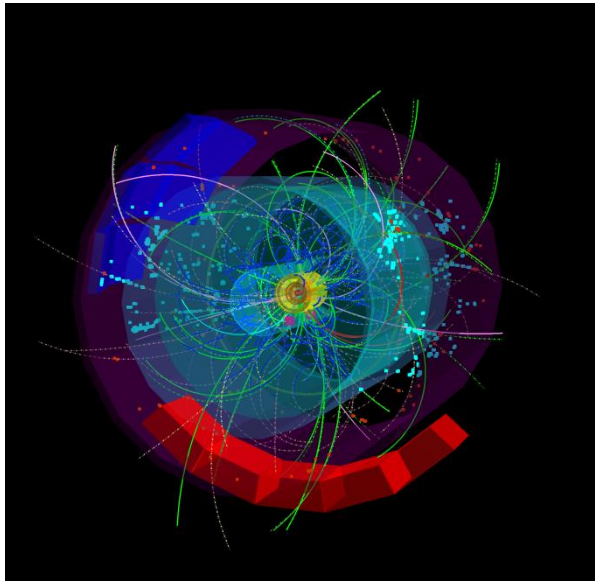
- static medium: $\Delta E \propto L^2$ due to interference effects, expanding medium: $\Delta E \propto L$

Constraints from large jet R_{AA}

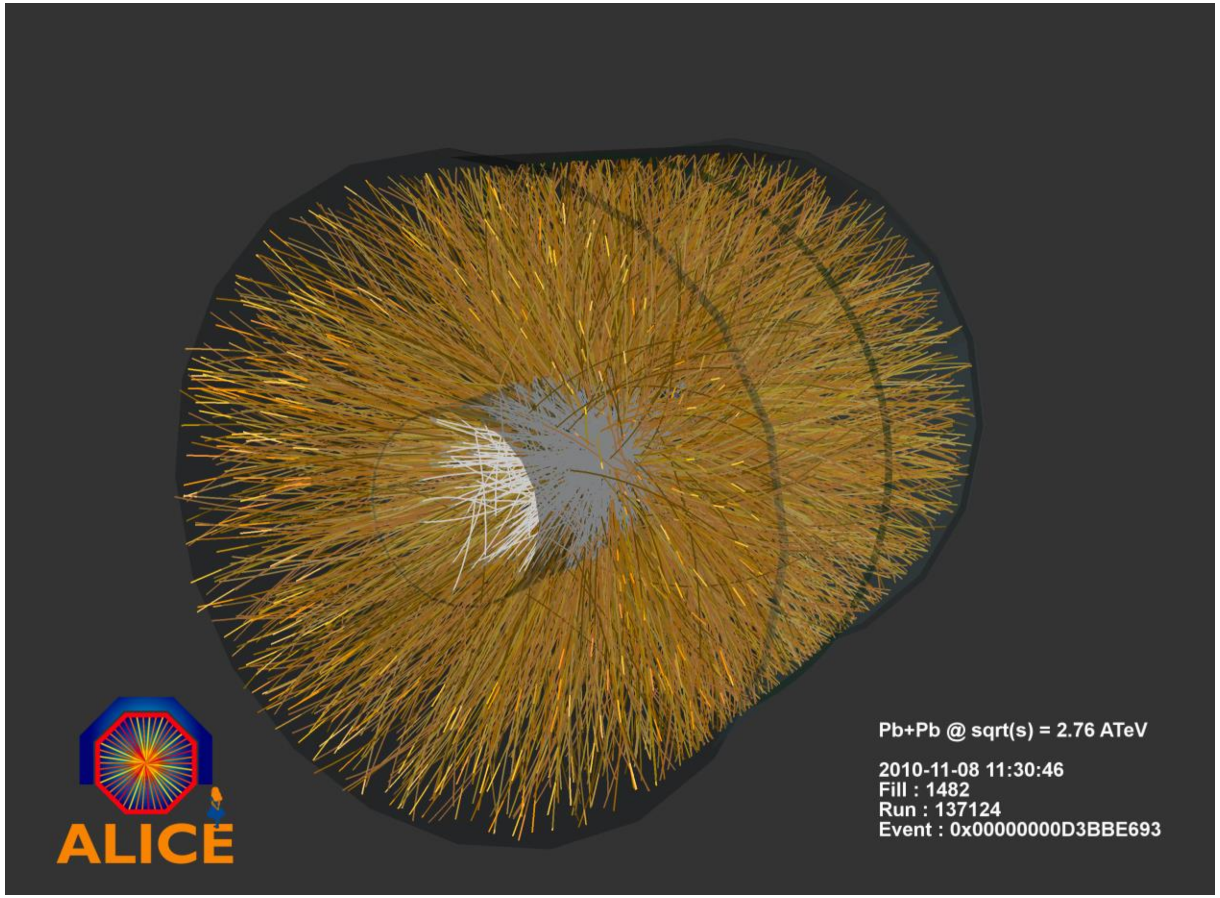
CMS, JHEP 05 (2021) 284



Collision of two protons or two Pb ions as seen by ALICE

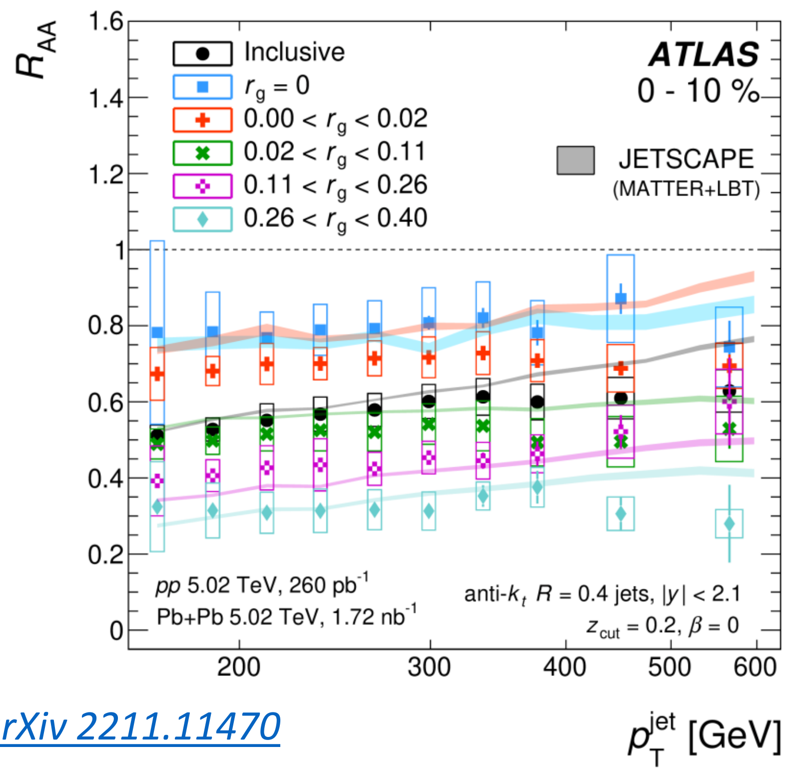


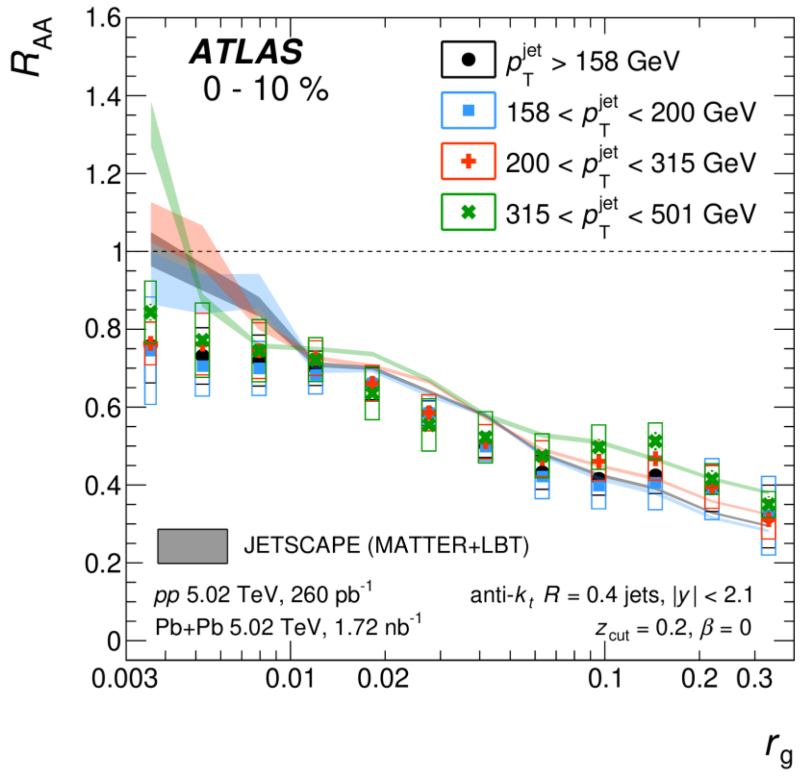
An almost empty pp collision at 7 TeV …



It is a very challenging task to reconstruct tracks of individual particles, but even more to quantify properties of the matter that is created.

Jet substructure as a microscope





ATLAS, [arXiv 2211.11470]

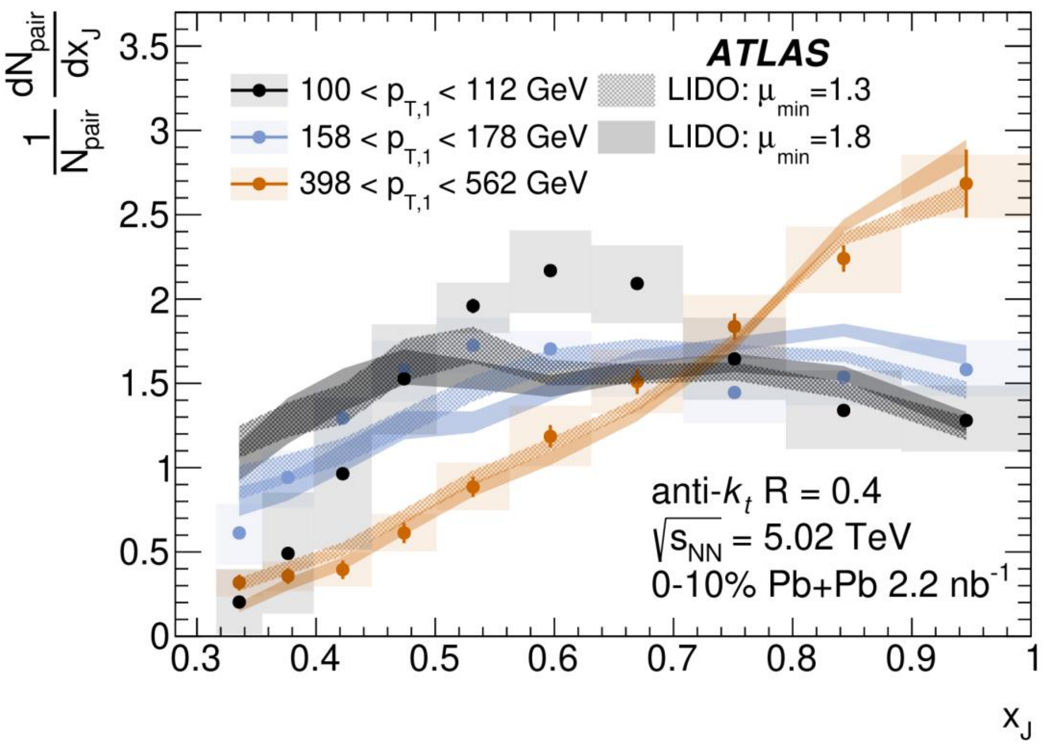
Jet suppression does not exhibit a strong variation with jet p_T but increases steeply with r_g:
→ consistent with a picture of jet quenching arising from coherence
→ provides direct evidence in support of this approach

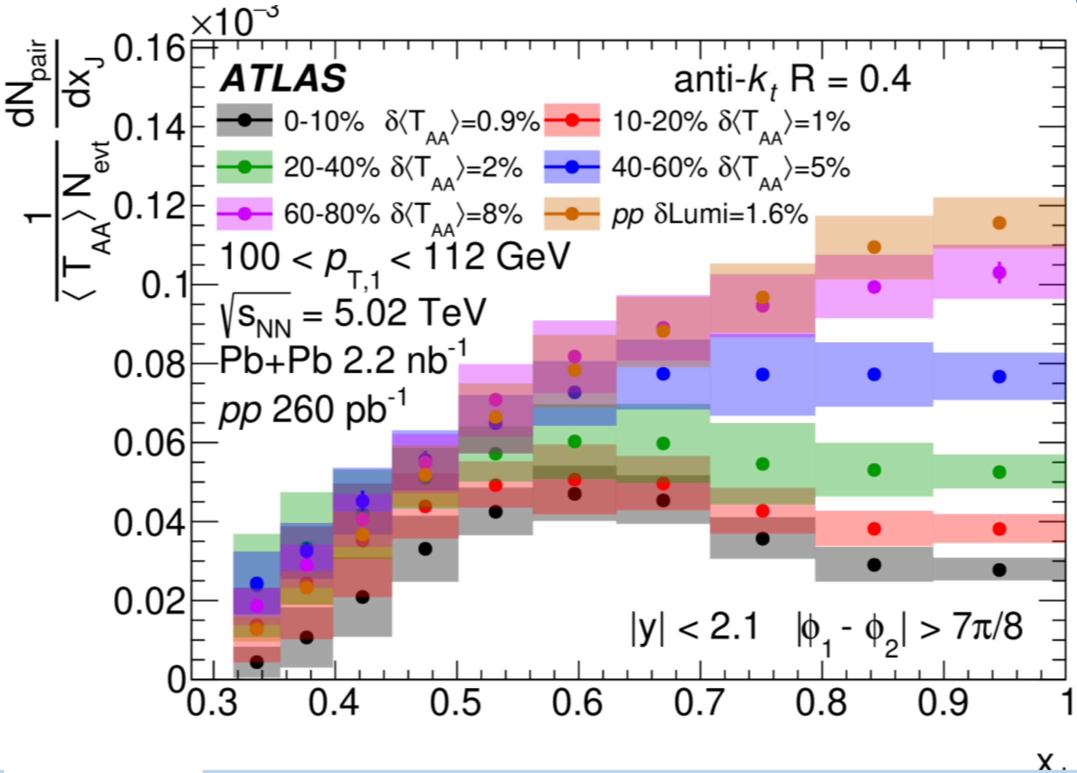
Di-jet asymmetry

ATLAS, arXiv:2205.00682

leading di-jet momentum balance

$x_J \equiv p_{T,2}/p_{T,1}$





Dijet-yield-normalized x_J distributions: increased fraction of imbalanced jets in PbPb compared to pp collisions.

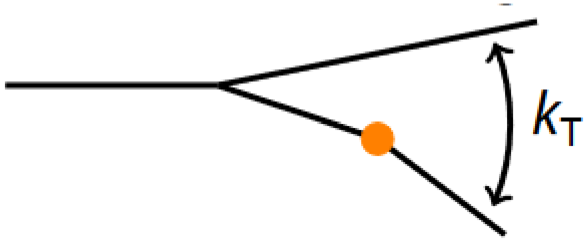
Absolutely-normalized dijet rates: balanced dijets are significantly more suppressed than imbalanced ones.

Central PbPb collisions: a broad maximum around $x_J = 0.6$ for “low” p_T = 100 -112 GeV

→ challenge for models to describe it … it would be interesting to see even lower p_T

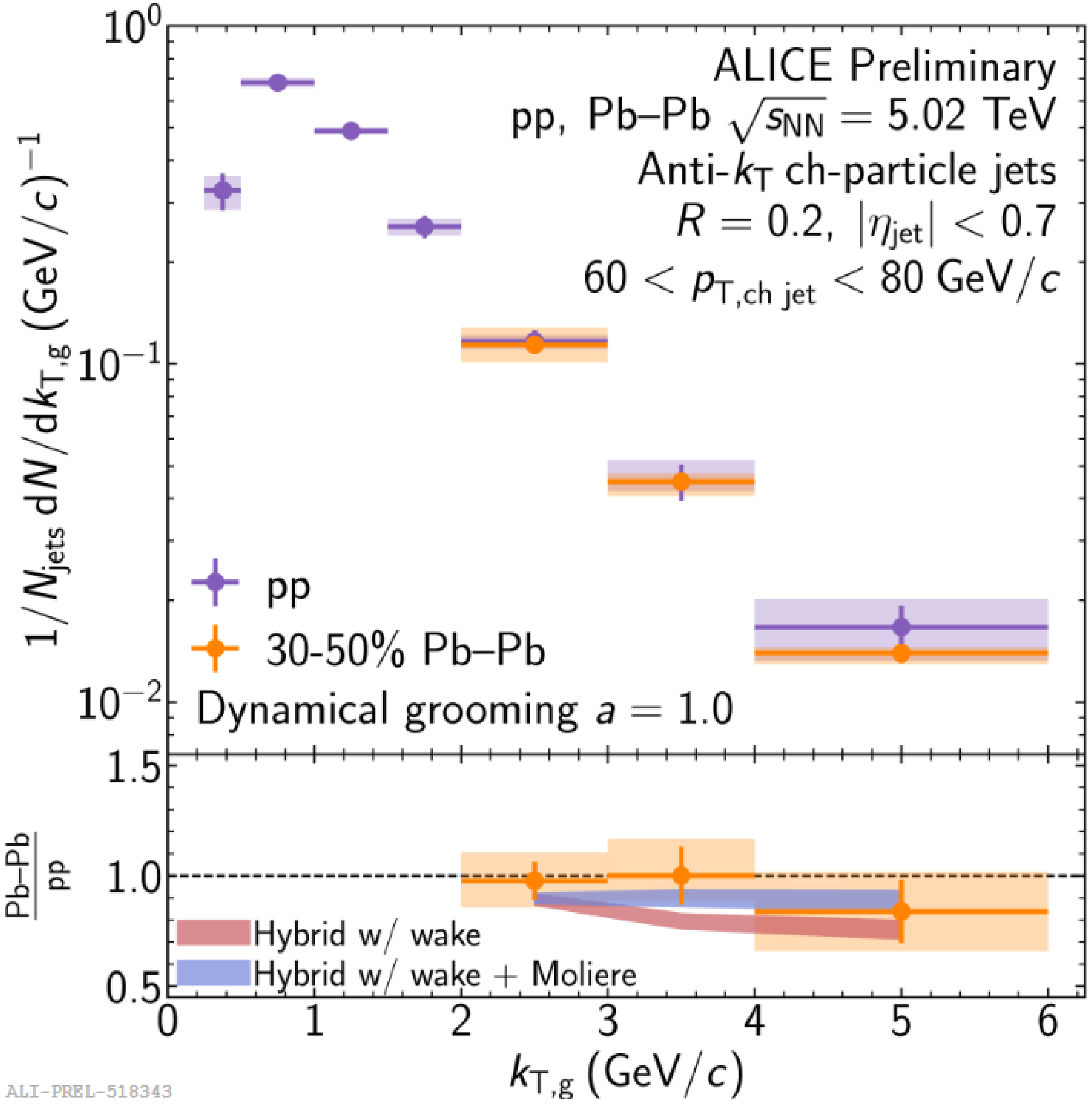
Exploring microscopic structure of QGP: hardest $k_{T,g}$ splittings

Search for high k_T emissions as signature of "Moliere" scattering



Use dynamically groomed jet substructure (1st time in PbPb collisions)

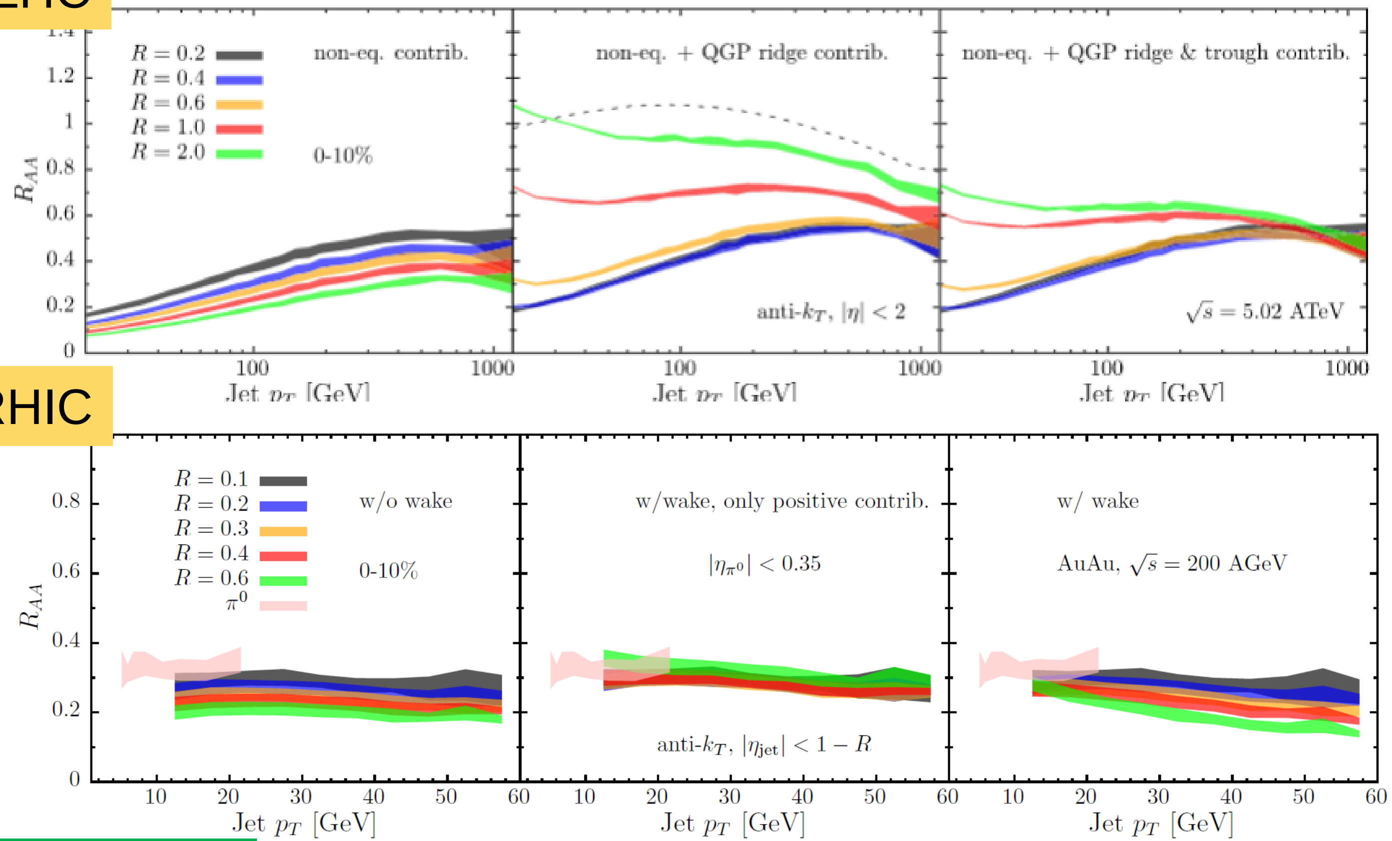
SD *zcut* = 0.2 removes soft component



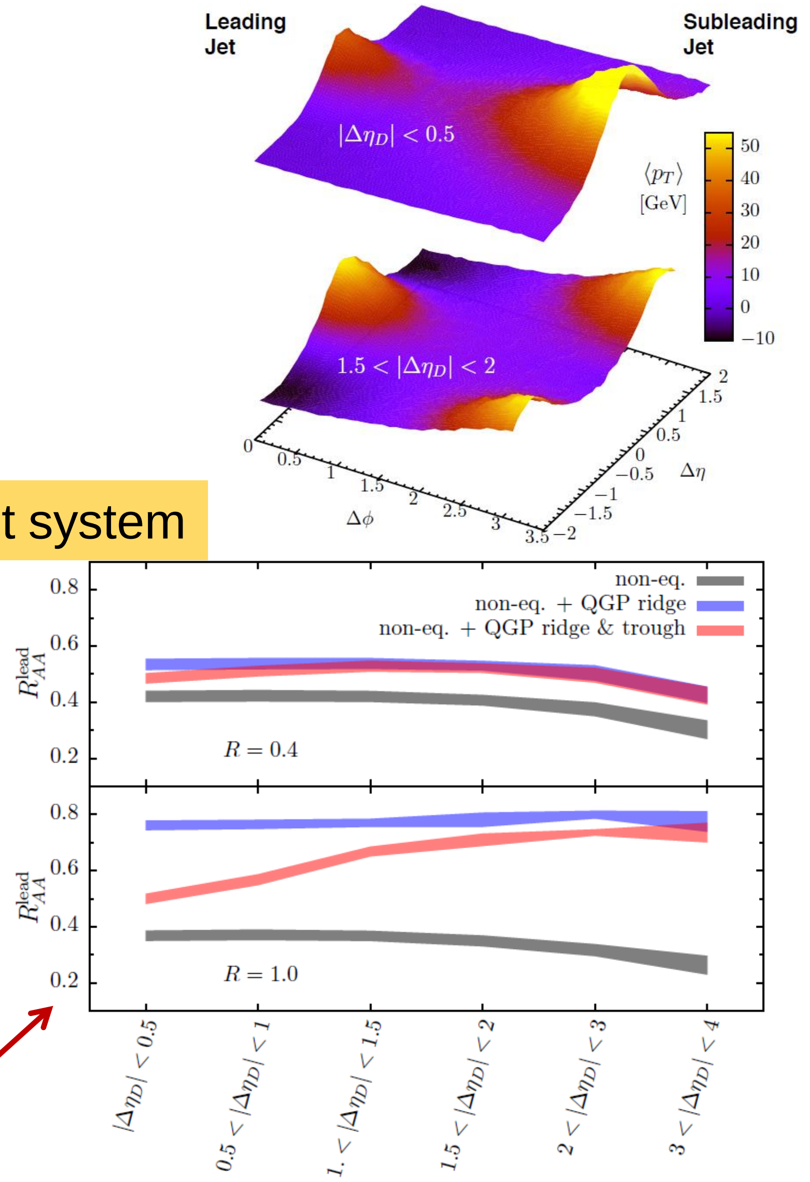
Deflections off scattering centers are expected to increase the relative k_T of subjets within a jet in PbPb compared to pp collisions

→ data do not yet have the sensitivity

Predictions for large R jets and di-jets



Pablos, PRL 124 (2020) 5, 052301



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