Measuring multi-body QCD

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Lecture 2: Using jets to probe the Quark-Gluon Plasma

Slides: https://tinyurl.com/JacobsICTS

Hard probes in non-equilibrium QCD matter
March 16-27, 2026

ICTS | INTERNATIONAL CENTRE for THEORETICAL SCIENCES
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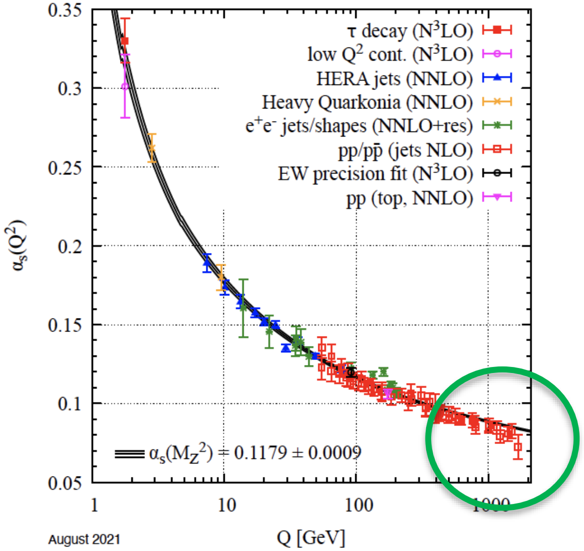
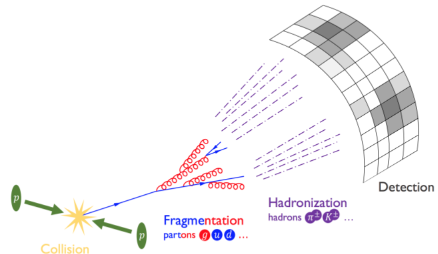
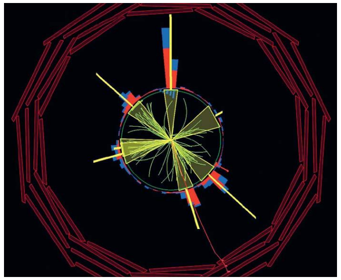
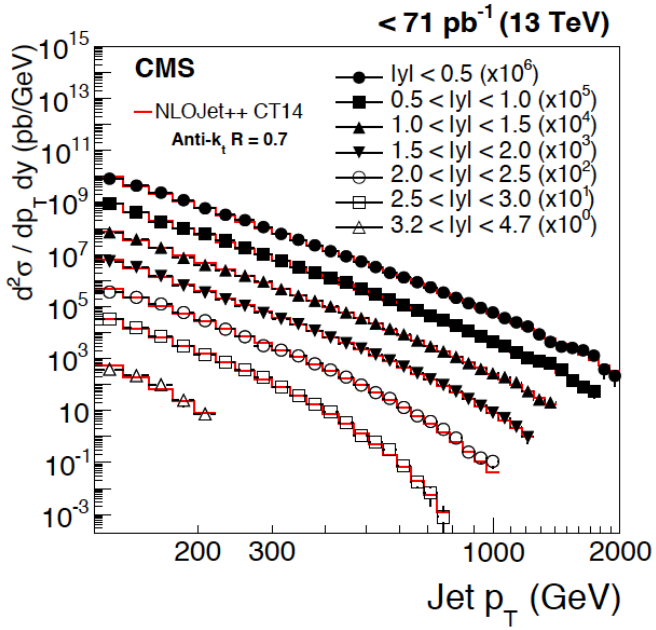
Lecture 1 recap

Jets measure partons



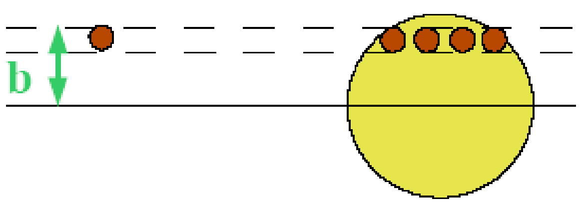






Coupling α_S small → asymptotic freedom → jets

Hard-process production rate in nuclear collisions



$$\sigma_{pA}^{hard} \simeq A \cdot \sigma_{NN}^{hard} \int d\vec{b}\, T_A(b) = A\sigma_{NN}^{hard}$$

4 August 1972, Volume 177, Number 4047 **SCIENCE**

More Is Different

Broken symmetry and the nature of the hierarchical structure of science.

P. W. Anderson

The reductionist hypothesis may still be a topic for controversy among philosophers, but among the great majority of active scientists I think it is accepted without question. The workings of our minds and bodies, and of all the animate or inanimate matter of which we have any detailed knowledge, are assumed to be controlled by the same set of fundamental laws, which except under certain extreme conditions we feel we know pretty well.

It seems inevitable to go on uncritically to what appears at first sight to be an obvious corollary of reductionism: that if everything obeys the same fundamental laws, then the only scientists who are studying anything really fundamental are those who are working on those laws. In practice, that amounts to some astrophysicists, some elementary particle physicists, some logicians and other mathematicians, and few others. This point of view, which it is

but they are clear in most cases. Solid state physics, plasma physics, and perhaps also biology are extensive. High energy physics and a good part of nuclear physics are intensive. There is always much less intensive research going on than extensive. Once new fundamental laws are discovered, a large and ever increasing activity begins in order to apply the discoveries to hitherto unexplained phenomena. Thus, there are two dimensions to basic research. The frontier of science extends all along a long line from the newest and most modern intensive research, over the extensive research recently spawned by the intensive research of yesterday, to the broad and well developed web of extensive research activities based on intensive research of past decades.

4 August 1972, Volume 177, Number 4047 SCIENCE

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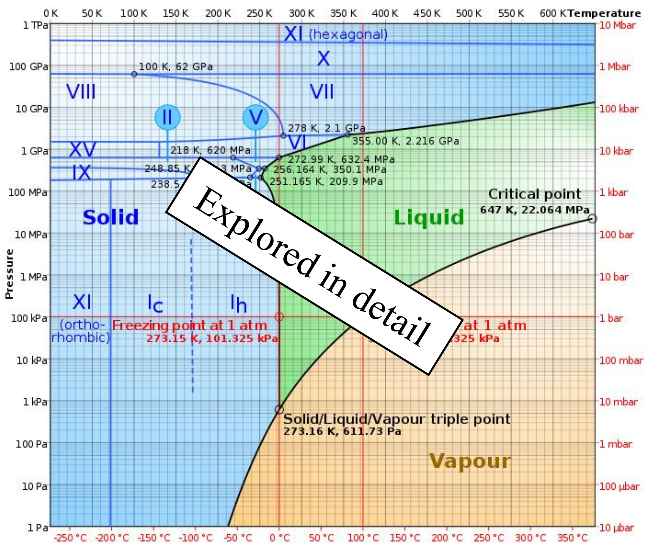
difficulties of scale and complexity. The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other. That is, it

Now consider "matter"

When you pack many particles tightly together, new things happen
➔"emergent" phenomena

Phase diagram of water

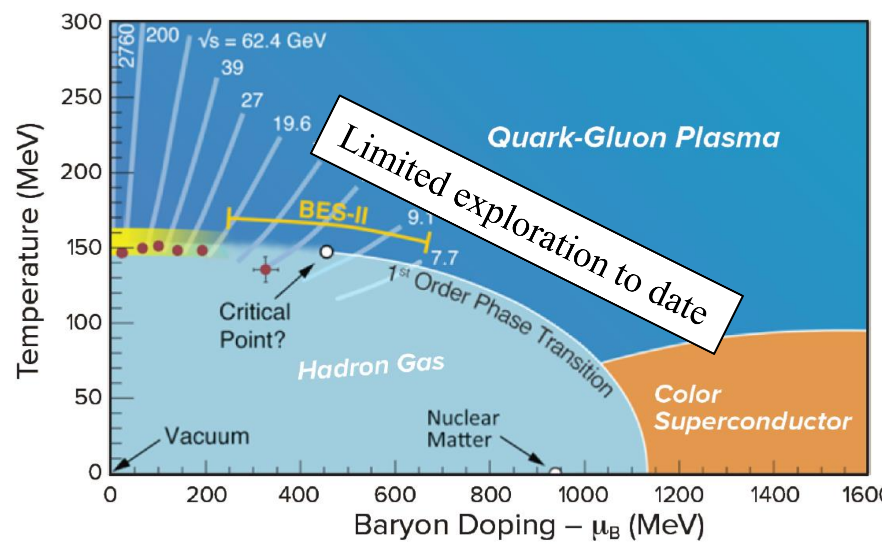
compress ➔



heat ➔

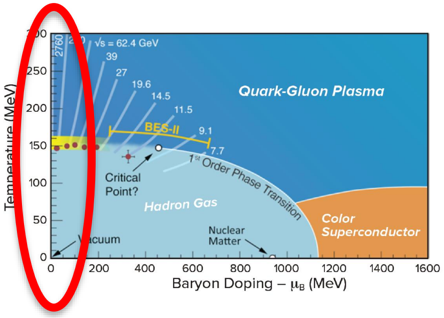
Phase diagram of QCD matter

heat ➔



compress ➔

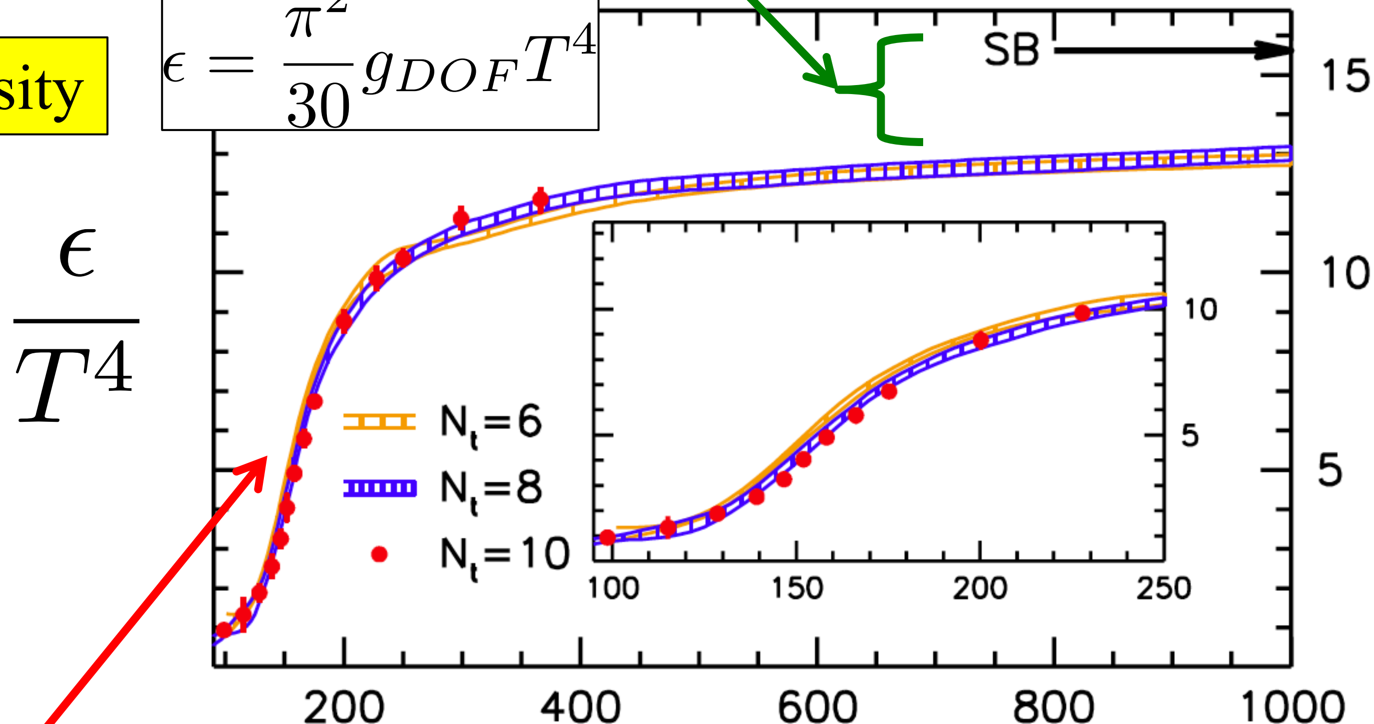
Finite Temperature QCD calculated numerically on the Lattice (μ_B=0)



Slow convergence to non-interacting Steffan-Boltzmann limit
What carries energy - complex bound states of q+g? "strongly-coupled" plasma?

Energy density

$$\epsilon = \frac{\pi^2}{30} g_{DOF} T^4$$

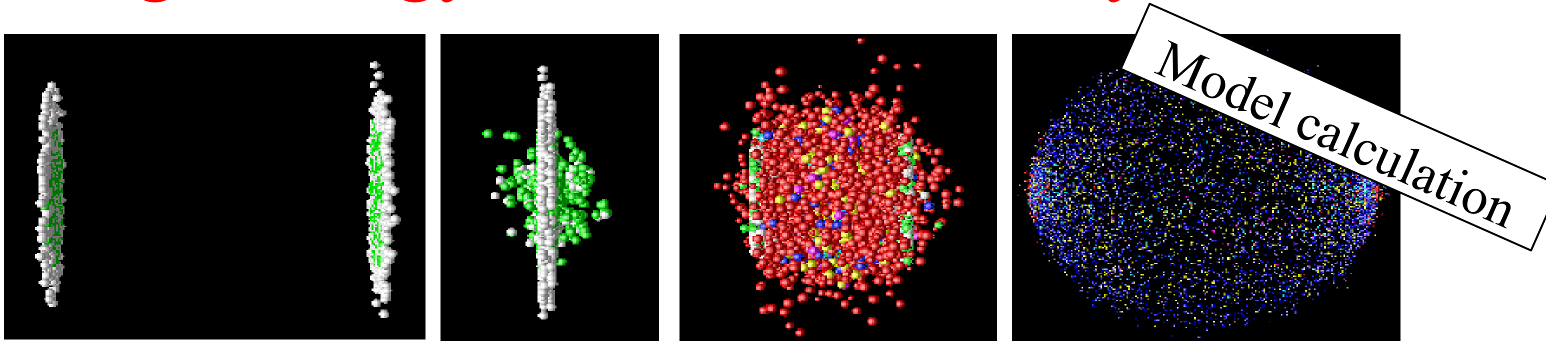


Temperature [MeV]

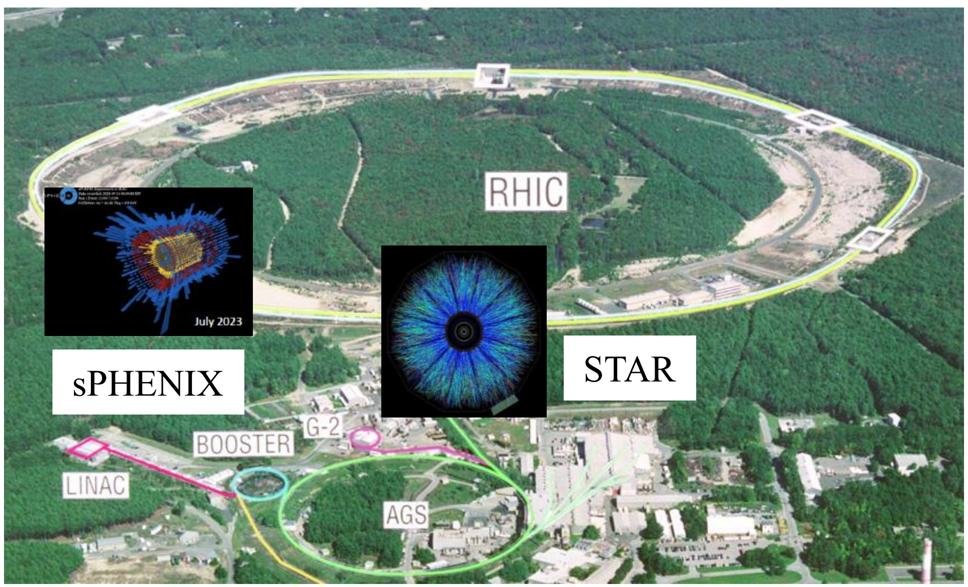
S. Borsanyi et al., JHEP 1011, 077 (2010)

Cross-over, not sharp phase transition
(like ionization of atomic plasma)

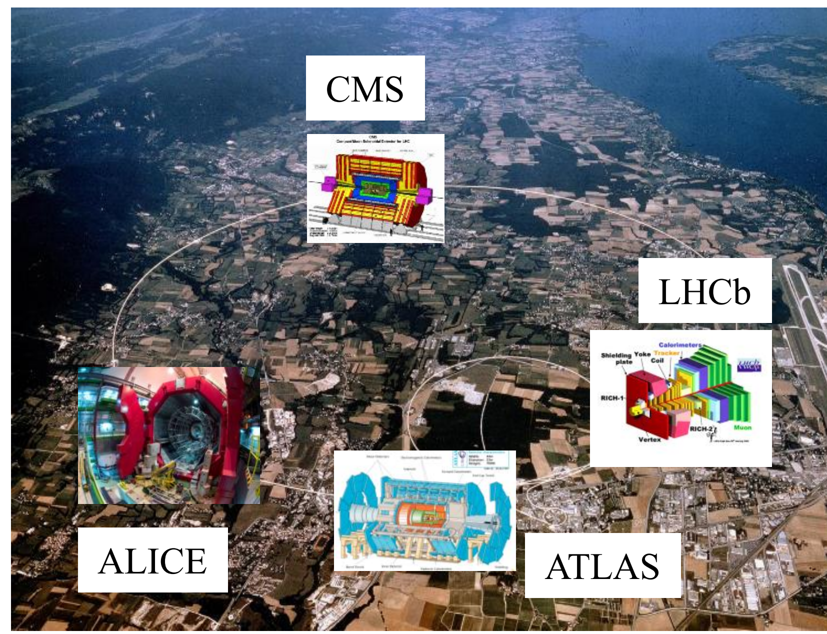
Quark-gluon plasma in the laboratory: high-energy collisions of heavy nuclei



RHIC @ BNL



LHC @ CERN



Thousands of particles in the final state

→ the most complex collisions ever studied in the laboratory

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.

First proposal of the concept of jet quenching

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Abstract

High energy quarks and gluons propagating through quark-gluon plasma 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

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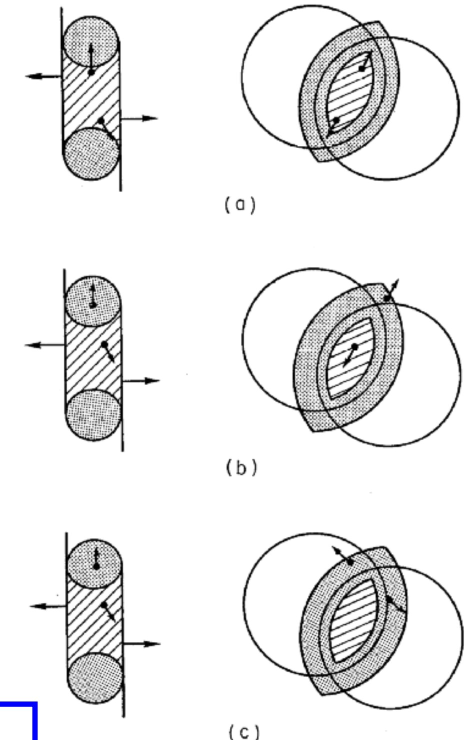
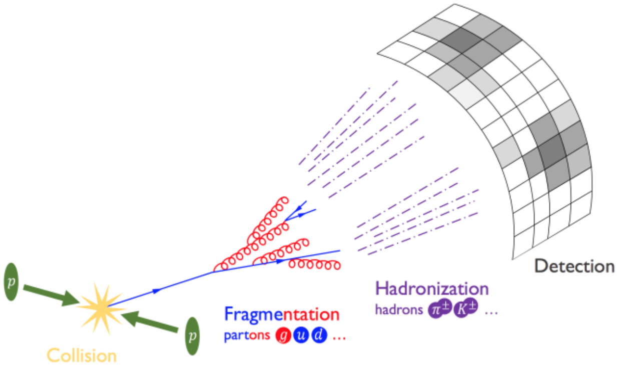
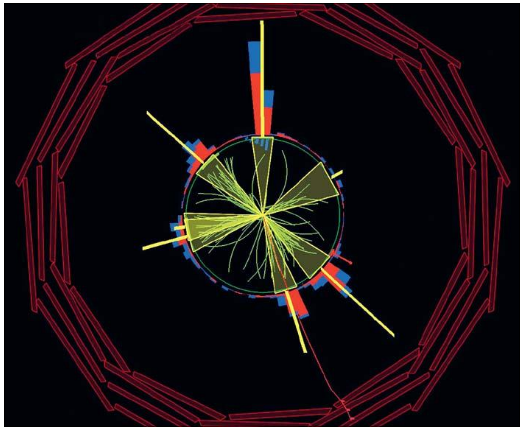
produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.



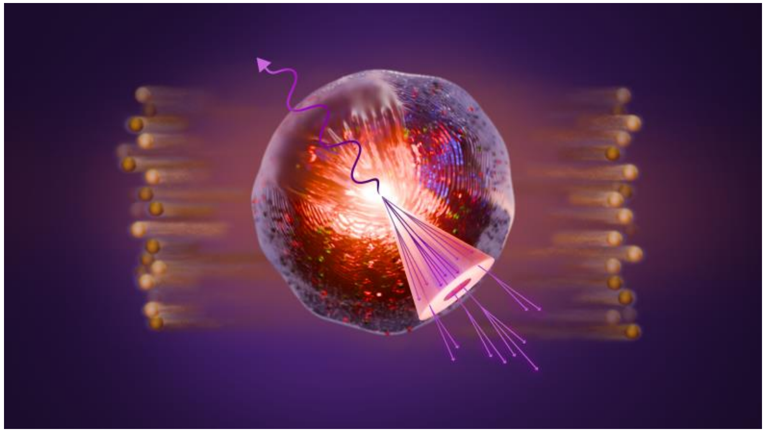
Jets probes of the QGP

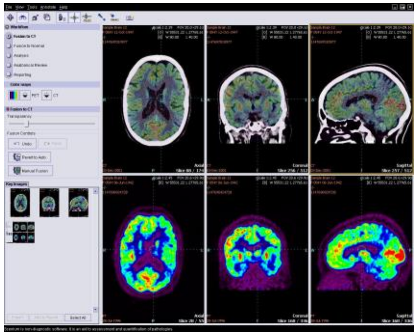
Jets in vacuum

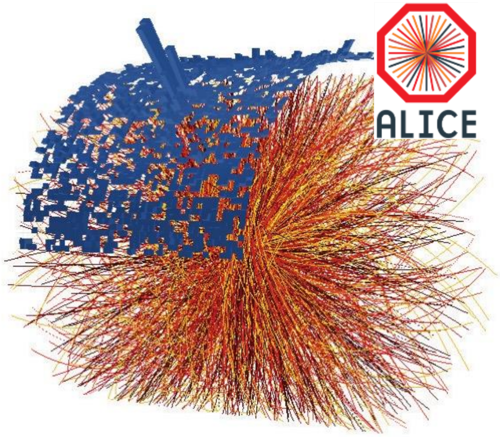




Jets in nuclear collisions







Energy loss in QED

Fractional energy loss of an (on-shell) electron or positron in Lead

http://pdg.lbl.gov/2017/reviews/rpp2016-rev-passage-particles-matter.pdf

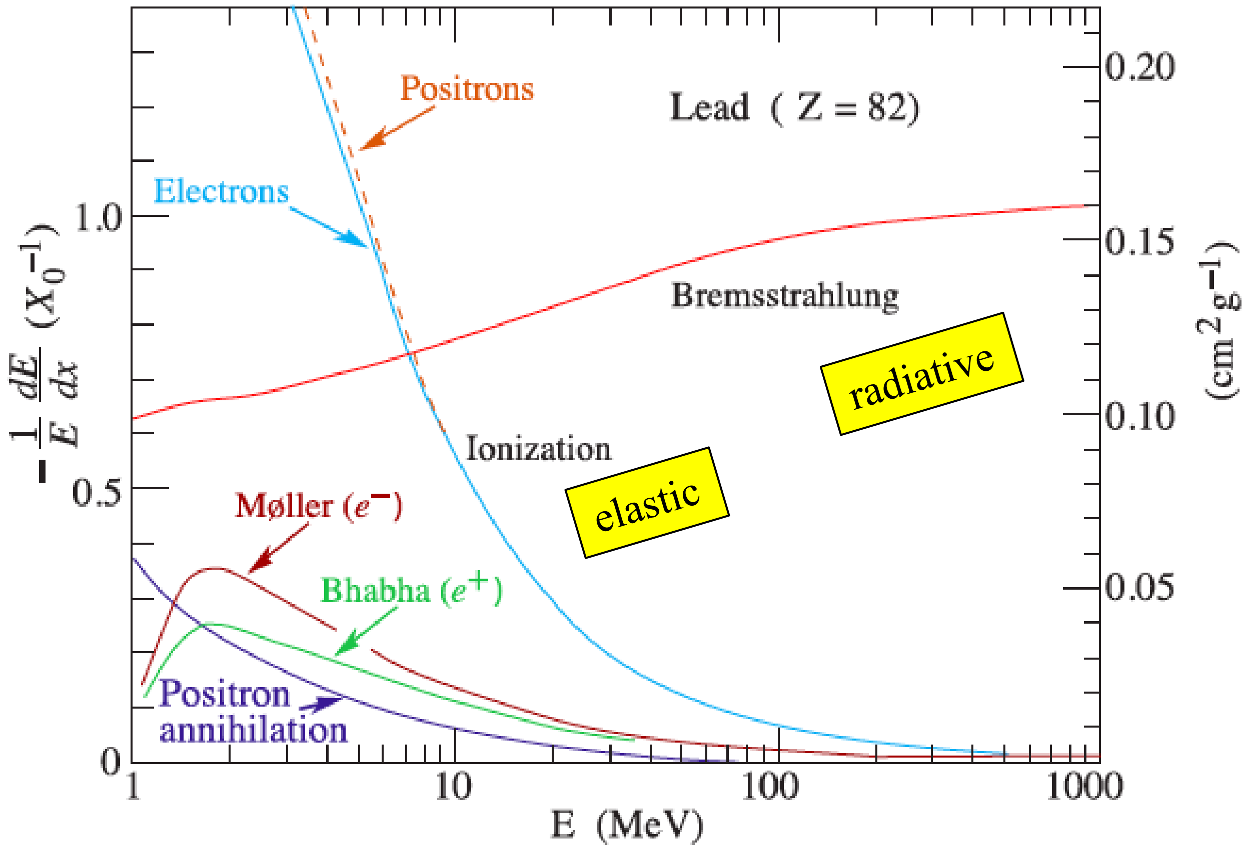


Figure 33.11: Fractional energy loss per radiation length in lead as a function of electron or positron energy. Electron (positron) scattering is considered as ionization

Energy loss in QED

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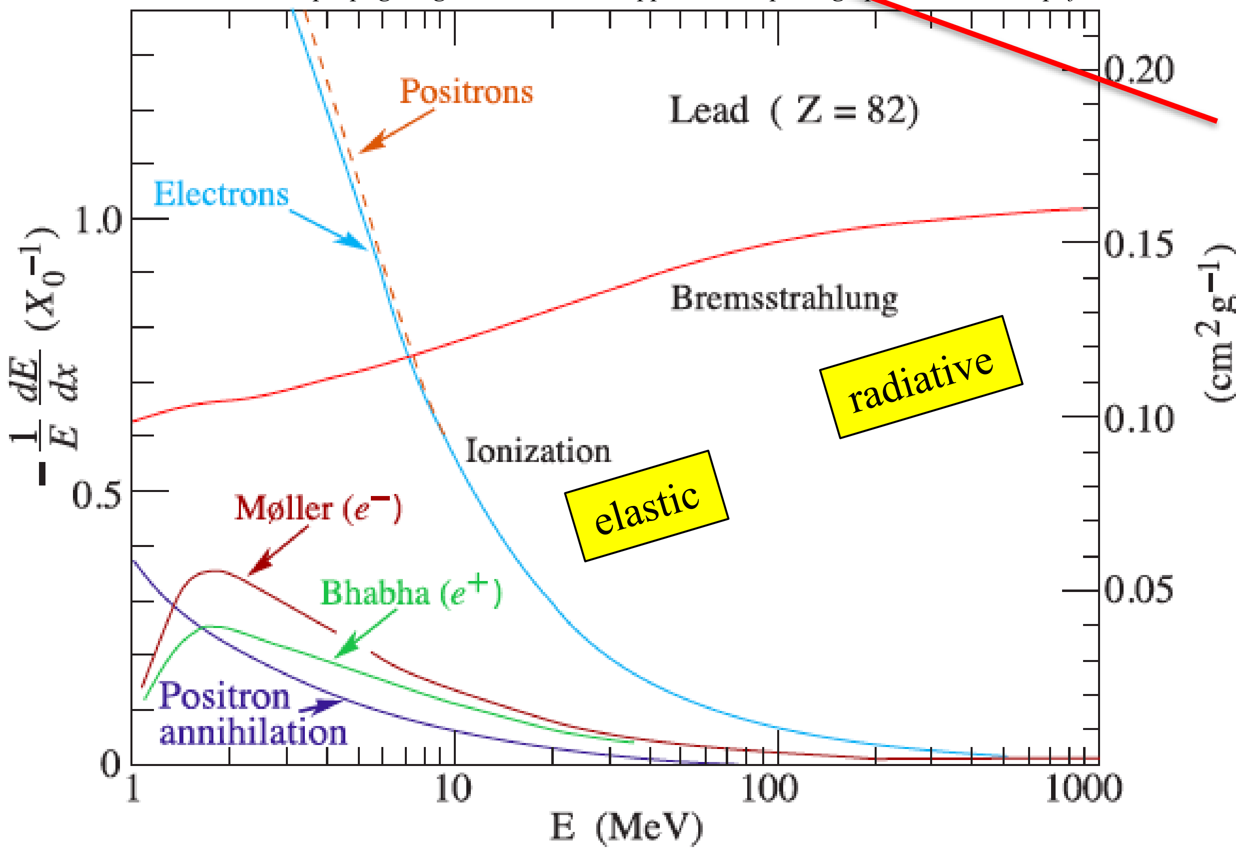
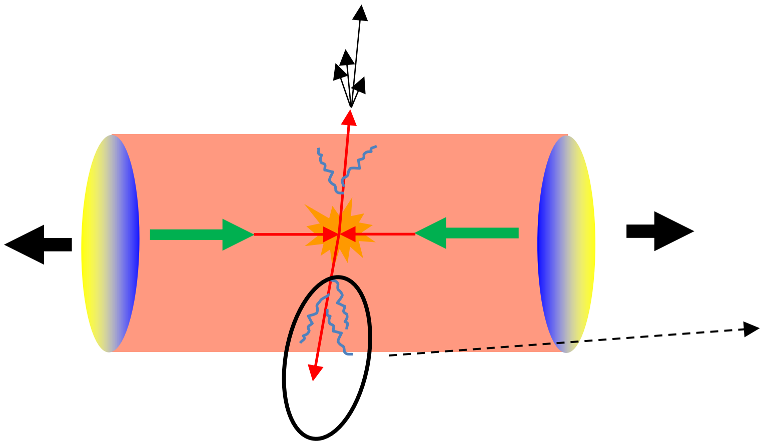


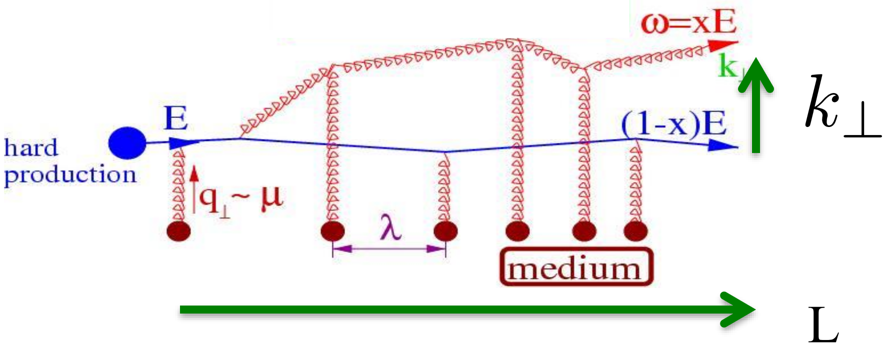
Not the case for QCD jets propagating in matter

Figure 33.11: Fractional energy loss per radiation length in lead as a function of electron or positron energy. Electron (positron) scattering is considered as ionization

Radiative energy loss in QCD



Medium-induced gluon radiation



Thermal field theory:

$$C(\mathbf{q}) = \frac{g_s^2 m_D^2 T}{\mathbf{q}^2 (\mathbf{q}^2 + m_D^2)}$$

$$m_D^2 = 3 g_s^2 T^2 / 2$$

$C(\mathbf{q})$ = Scattering kernel

$\mathbf{q}$ = Momentum transfer

T = Temperature

m_D = Debye mass

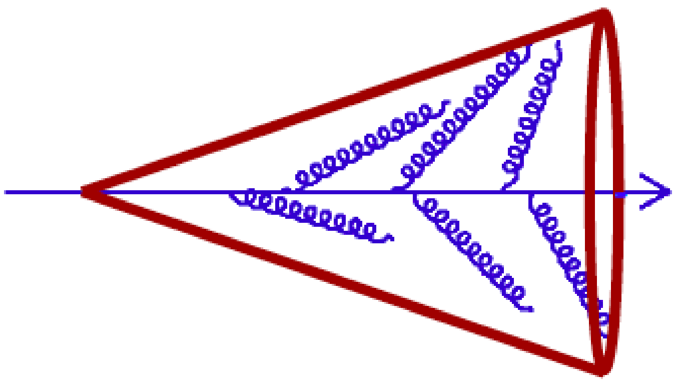
QGP properties

$$\hat{q} \equiv \frac{\langle k_\perp^2 \rangle}{L} \sim \frac{1}{L} \int d\mathbf{q}^2 \mathbf{q}^2 C(\mathbf{q})$$

Very useful parameter
Keep in mind; we will use it later

Jet quenching in one slide

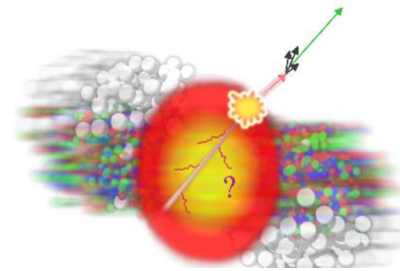
Jet shower in vacuum

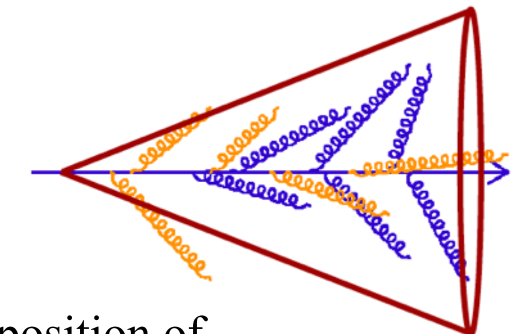


Evolution of highly virtual parton via gluon radiation

Quantum interference → angle-ordering
- hardest radiation is most collinear with jet axis
- Precise understanding in pQCD
- Accurately calculable with QCD-based Monte Carlo models

Jet shower in-medium



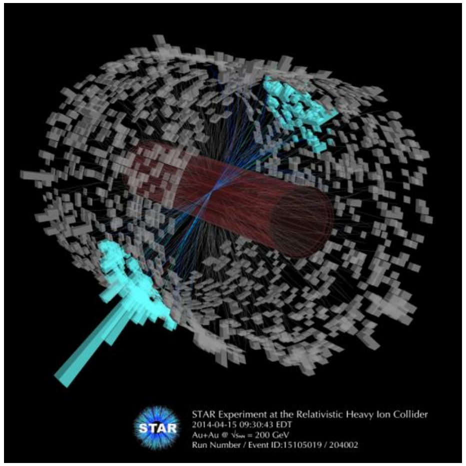


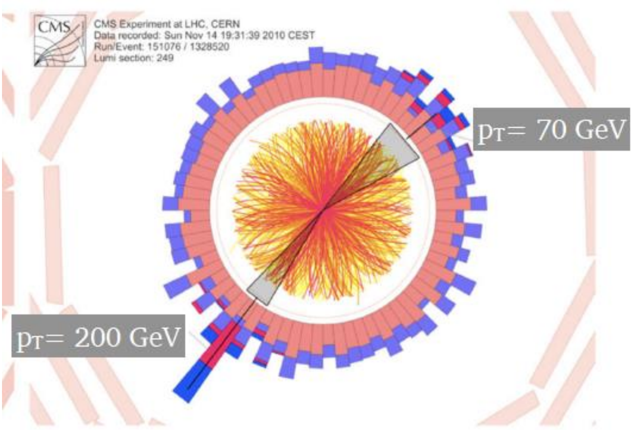
Superposition of
- vacuum shower
- medium-induced gluon emission

These processes happen simultaneously and interfere

Angle-ordering is modified or destroyed

The heavy-ion jet measurement challenge I



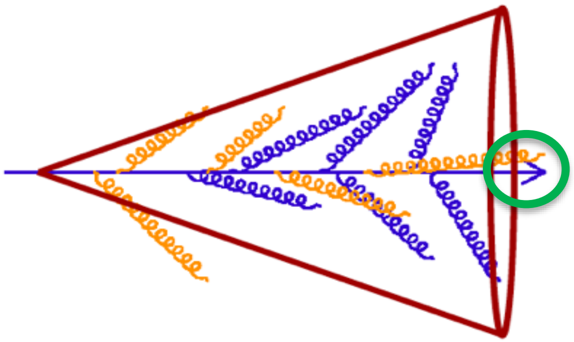


Very complex experimental environment

Huge background of particles not correlated with jet shower

How to make precise measurements?

First try simplifying the problem



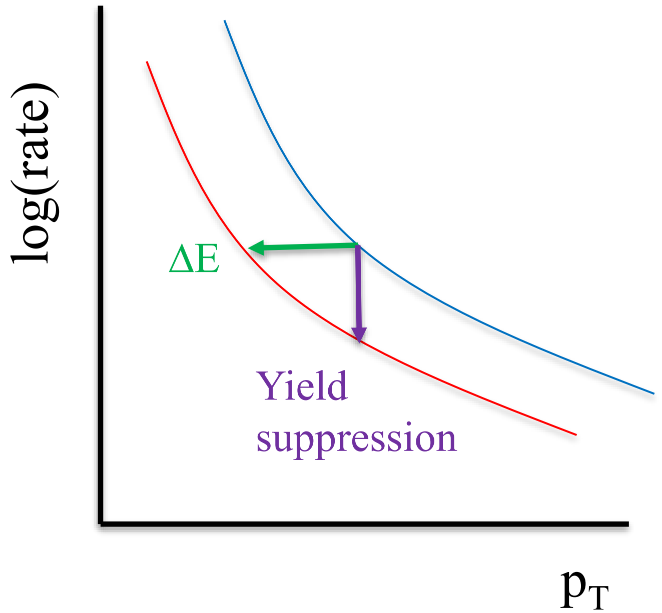
Particle spectrum of uncorrelated background is largely "soft" (low p_T)

→ measure only very high p_T hadrons ("leading hadrons" of jets)

Simplest energy loss measurement: inclusive yield of high p_T hadrons

Particle/jet spectrum falls rapidly with increasing transverse momentum p_T

Population-averaged energy loss generates a shift ΔE to lower p_T



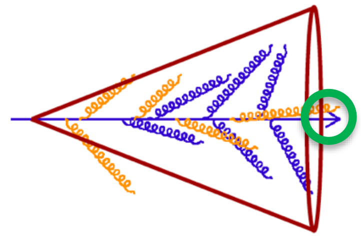
Equivalently: yield is suppressed at fixed p_T

$$R_{AA}(p_T) = \frac{\text{Observed rate in AA}}{\text{Expected rate in pp} \otimes \text{geometry}}$$

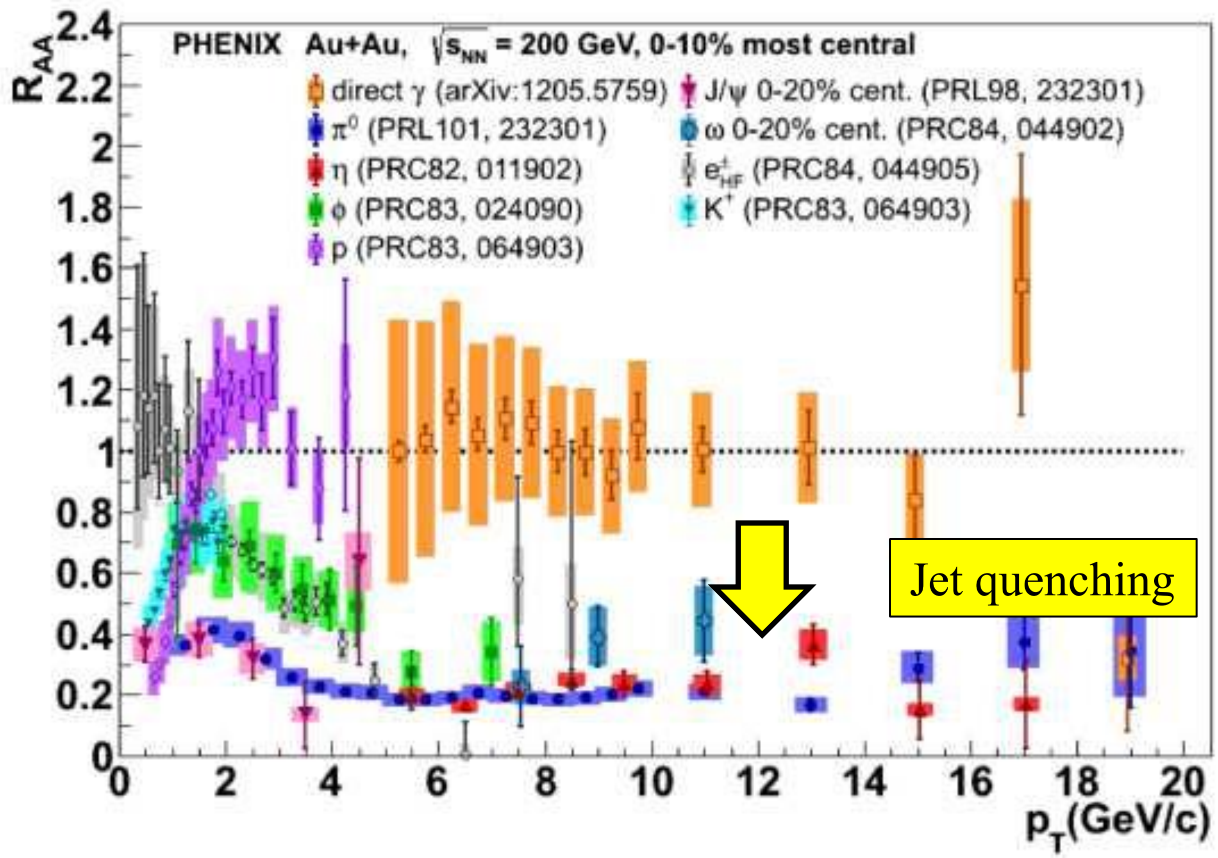
$$= \frac{dN_{AA}^{hard}/dp_T}{\langle T_{AA}\rangle d\sigma_{pp}^{hard}/dp_T}$$

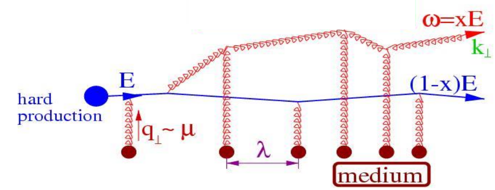
Initial evidence for jet quenching: inclusive hadron suppression

$$R_{AA} = \frac{dN_{AA}^{hard}/dp_T}{\langle T_{AA}\rangle d\sigma_{pp}^{hard}/dp_T}$$



Measure only very high p_T hadrons ("leading hadrons" of jets)

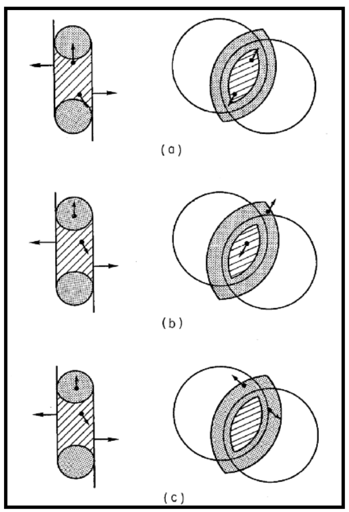


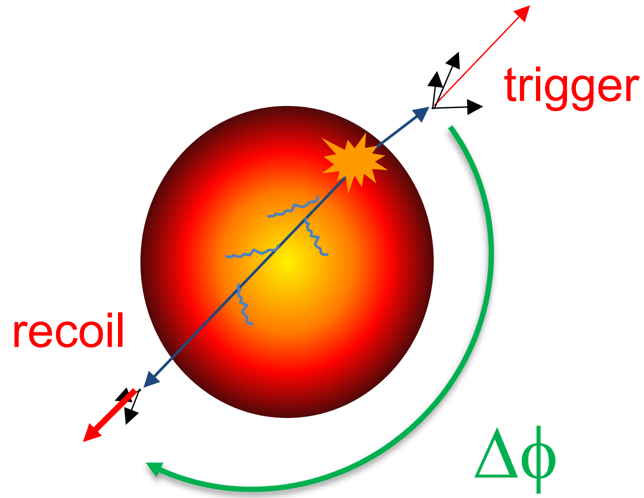


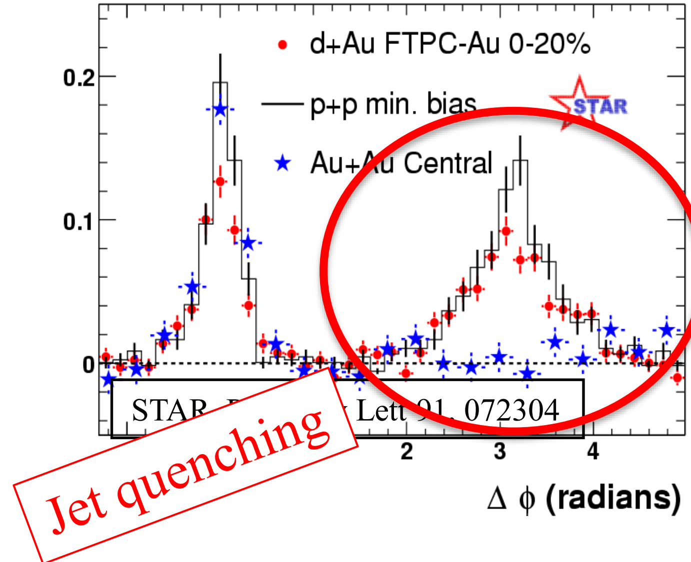
Photons (color-neutral)

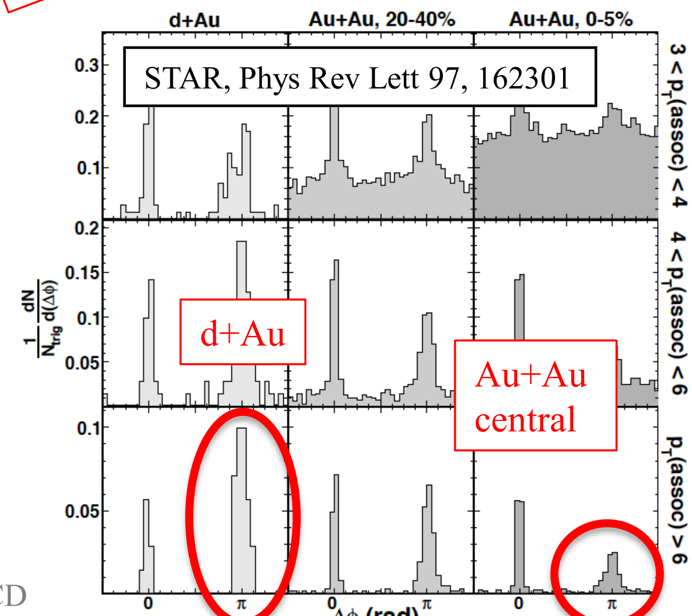
Jet fragments (color-charged)

Initial evidence for jet quenching: di-hadron suppression





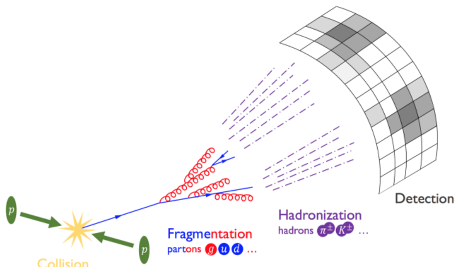


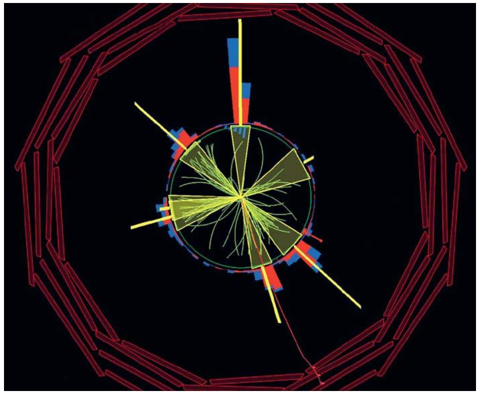


produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

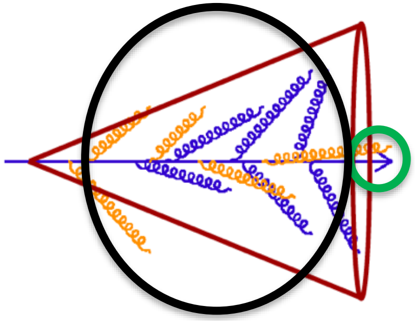
But high p_T hadrons are limited in scope: much richer physics in fully-reconstructed jets

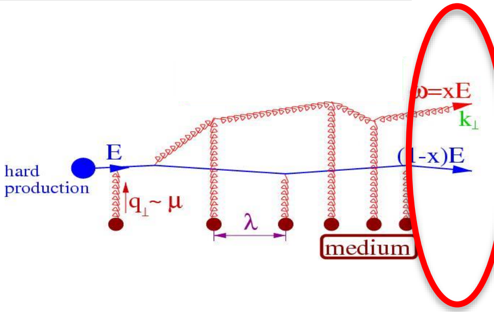
Jets in vacuum

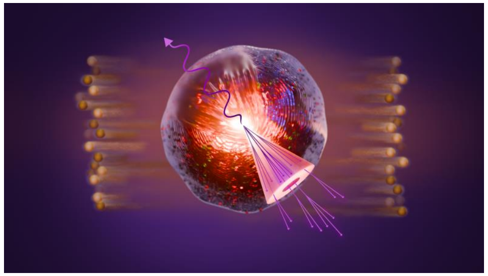


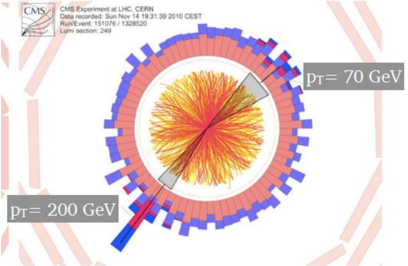


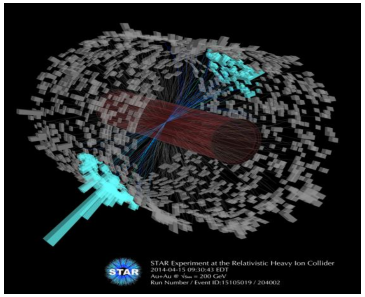
Jets in nuclear collisions

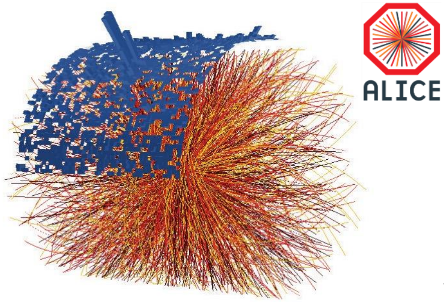






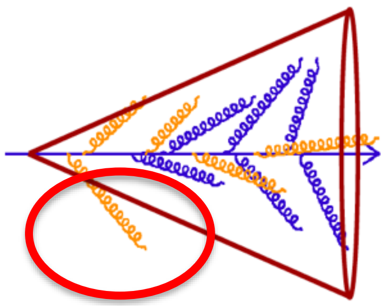


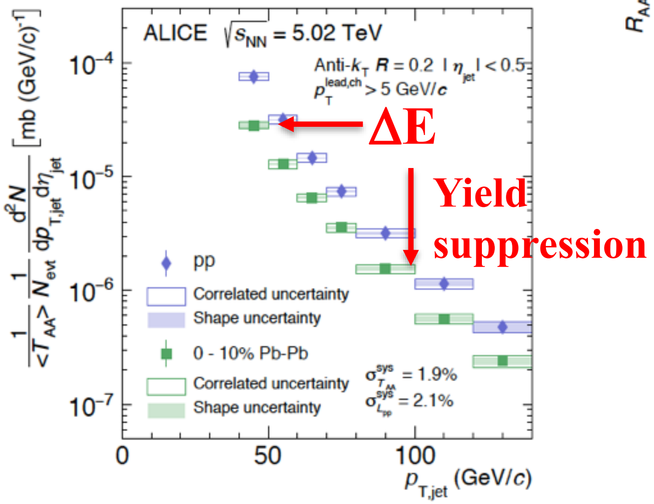


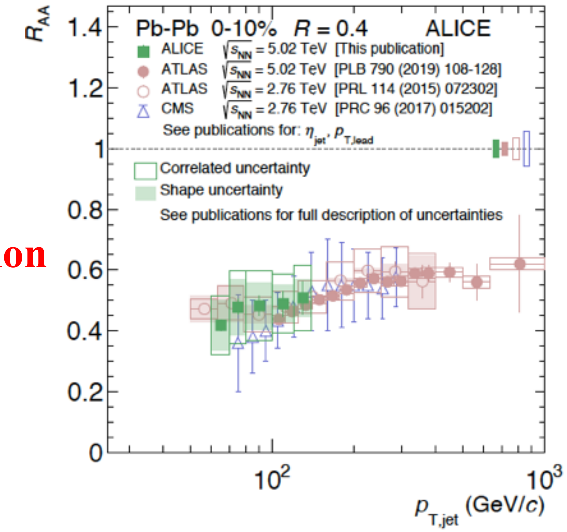


Jet quenching: observable consequences I

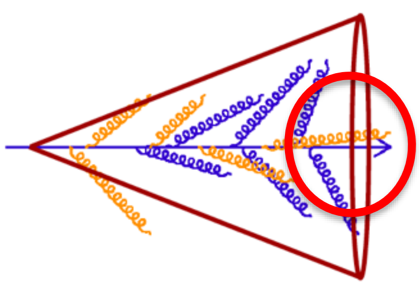
1. Energy loss

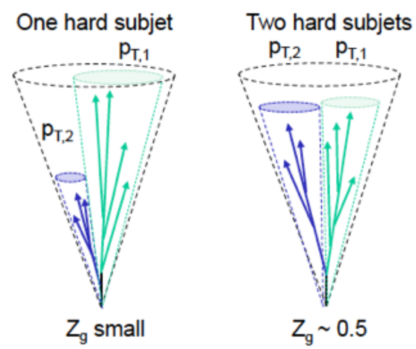




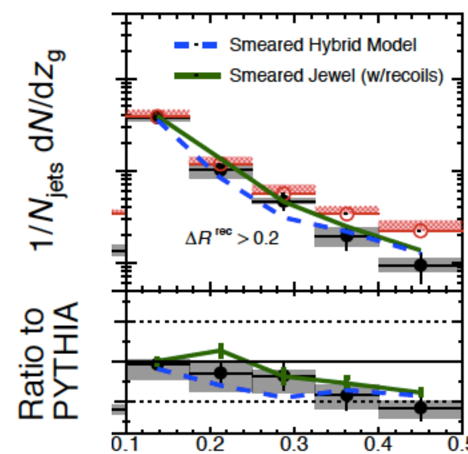


2. Modification of jet substructure



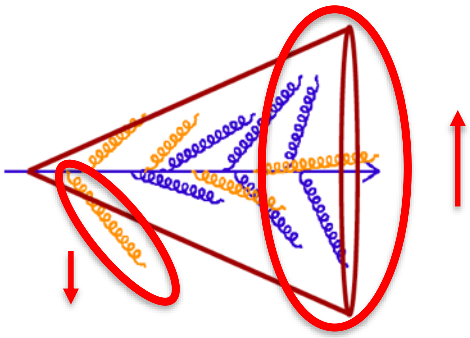


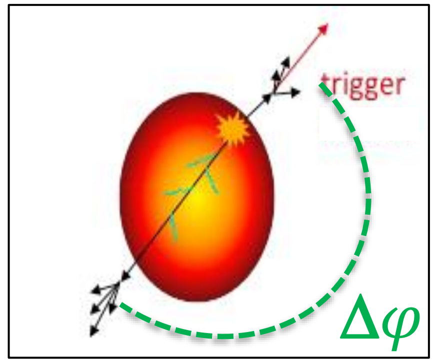
$$Z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$

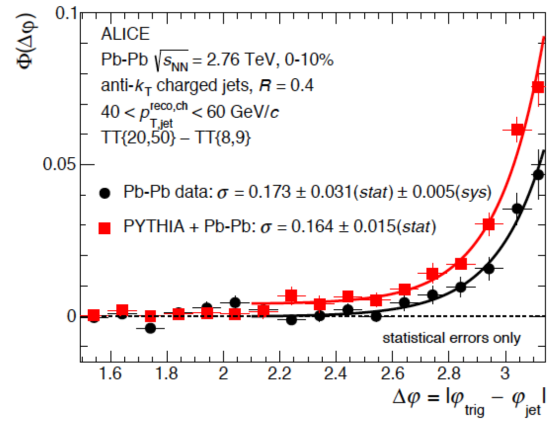


Jet quenching: observable consequences II

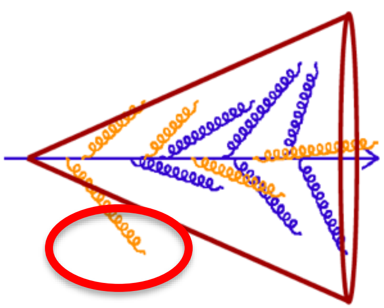
3. Jet deflection

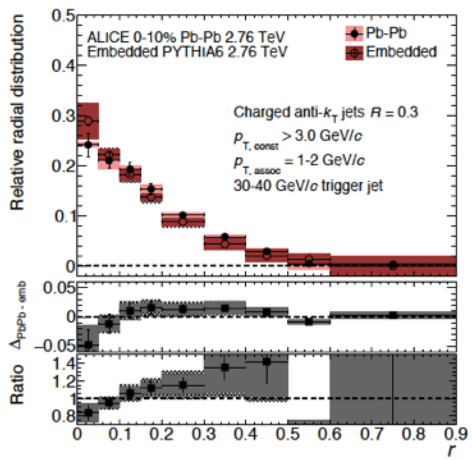


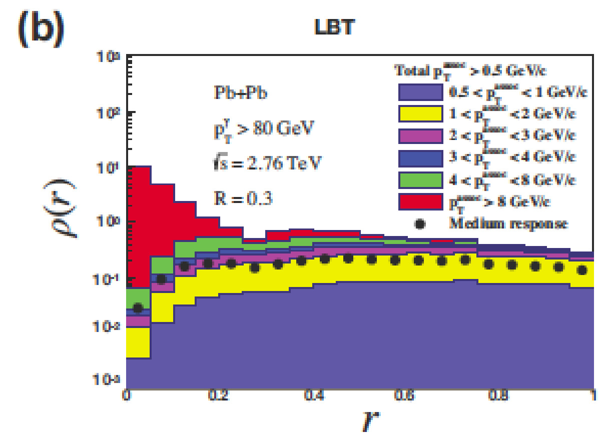




4. Recovery of
large-angle radiation







Jet quenching: observable consequences III

Four distinct manifestations of jet quenching:

- Jet energy loss
- Jet substructure modification
- Jet deflection
- Large-angle radiation

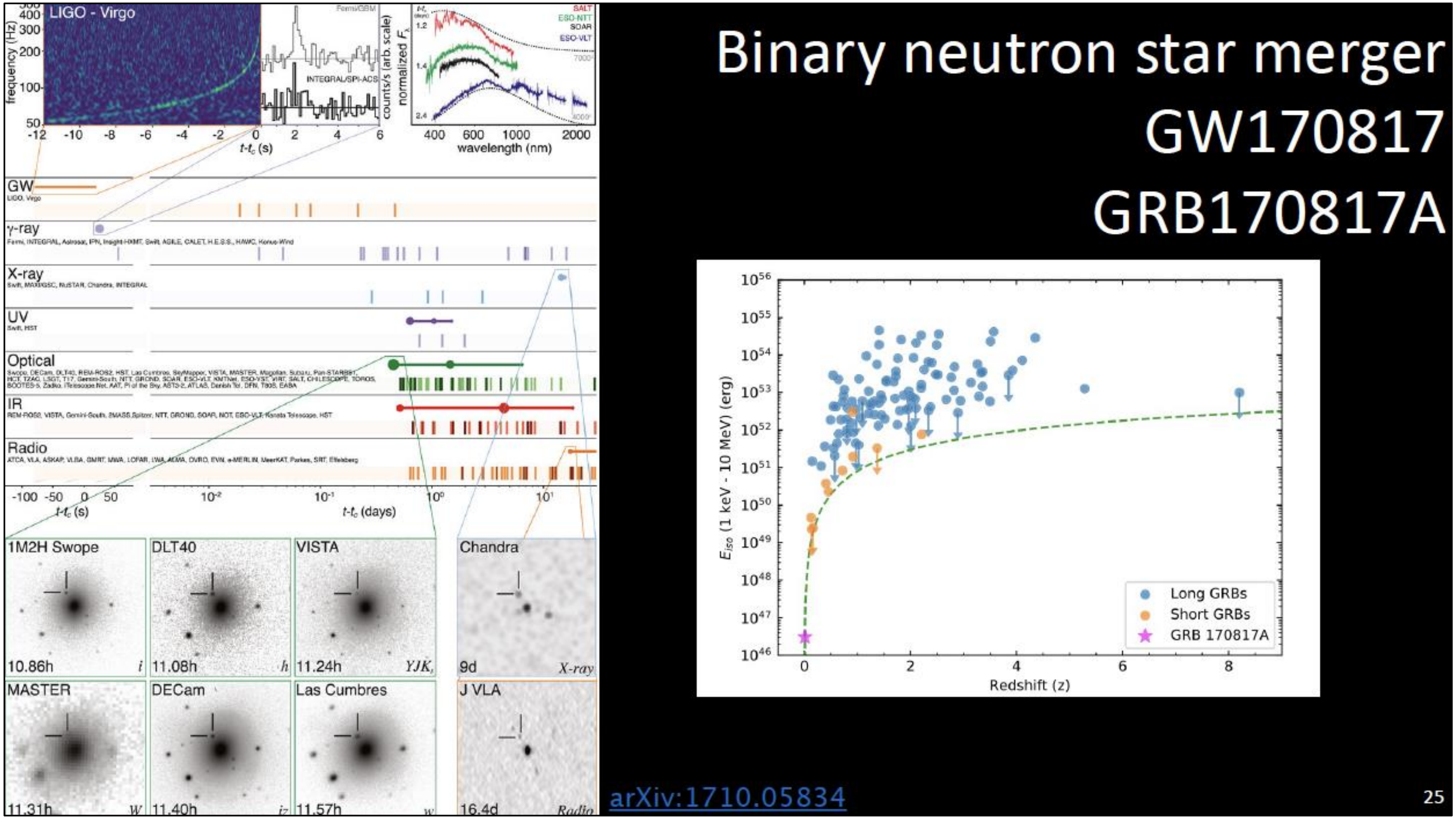
Different manifestations of same underlying physics

- All must occur if any of them does
- Probe different aspects of jet quenching
- Different experimental systematics as fn of kinematics and collision system
- Different theoretical sensitivity as fn of kinematics and collision system

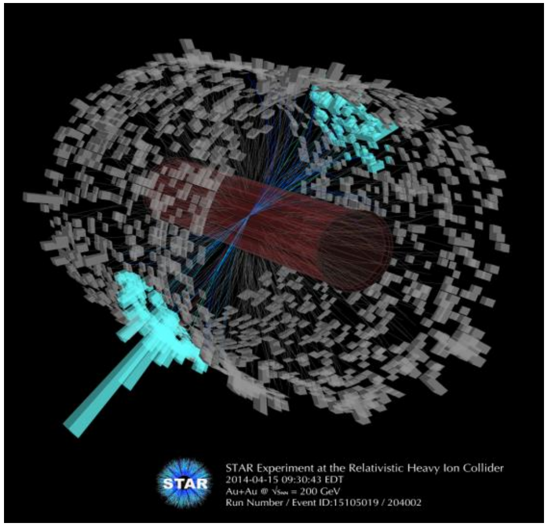
Jet quenching is multi-messenger physics!
Measure the same physics multiple ways and require a consistent picture

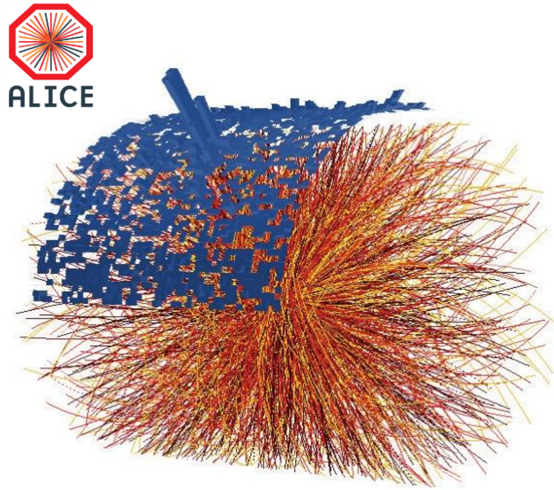
Multi-messenger physics: another example

G. De Wasseige, ICHEP 2022



The heavy-ion jet measurement challenge II





Very complex experimental environment

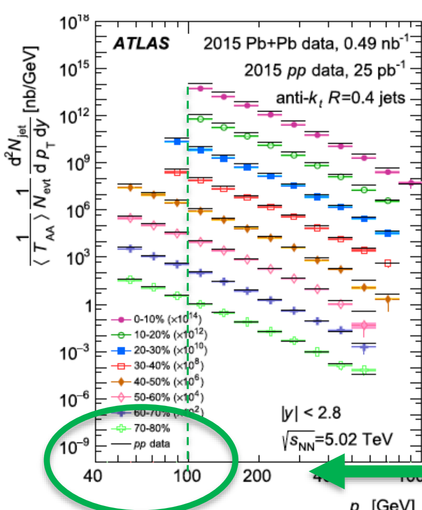
Huge background of particles not correlated with jet shower

How to make precise measurements?

True jet measurements in high bkgd environment: two distinct approaches

Limit jet measurements to high p_T /small R to avoid high bkgd region

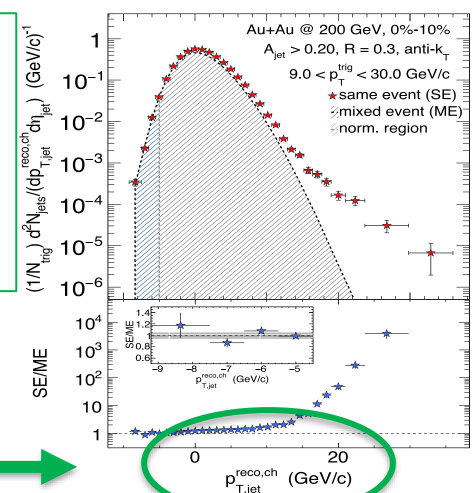
ATLAS/CMS/sPHENIX



PhysLett B790 108 (2019)

Statistical approach to measure and subtract bkgd → low p_T, large R

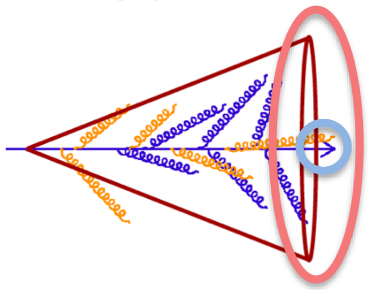
ALICE/STAR



Phys. Rev. C 96 (2017) 024905

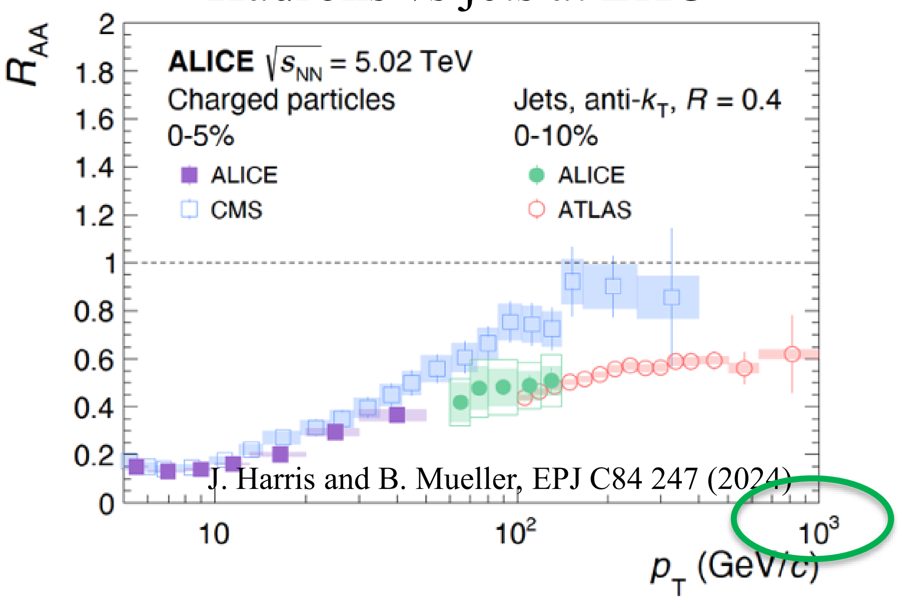
…ng multi-body QCD

Energy loss: hadrons vs jets (inclusive)



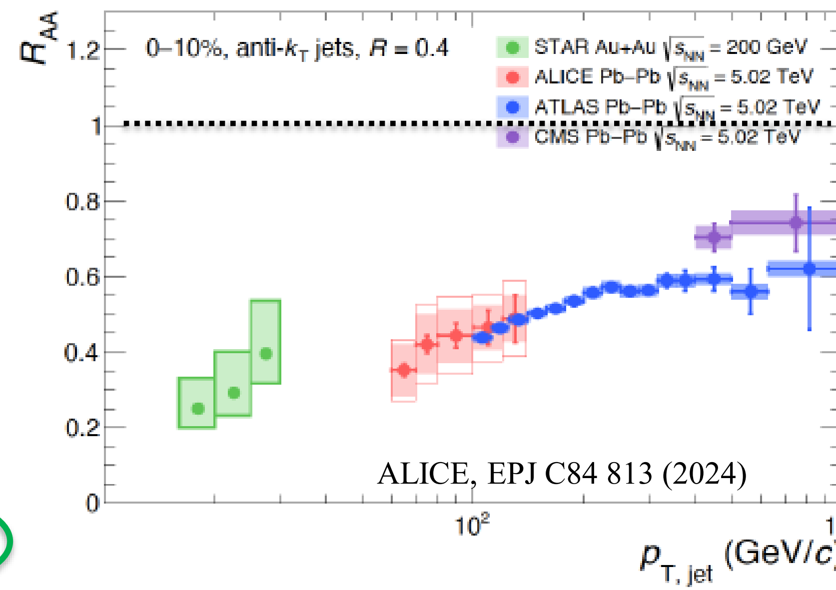
$$R_{AA} = \frac{dN_{AA}^{hard}/dp_T}{\langle T_{AA}\rangle d\sigma_{pp}^{hard}/dp_T}$$

Hadrons vs jets at LHC



J. Harris and B. Mueller, EPJ C84 247 (2024)

Jets at RHIC and LHC



ALICE, EPJ C84 813 (2024)

Jets probe much higher p_T

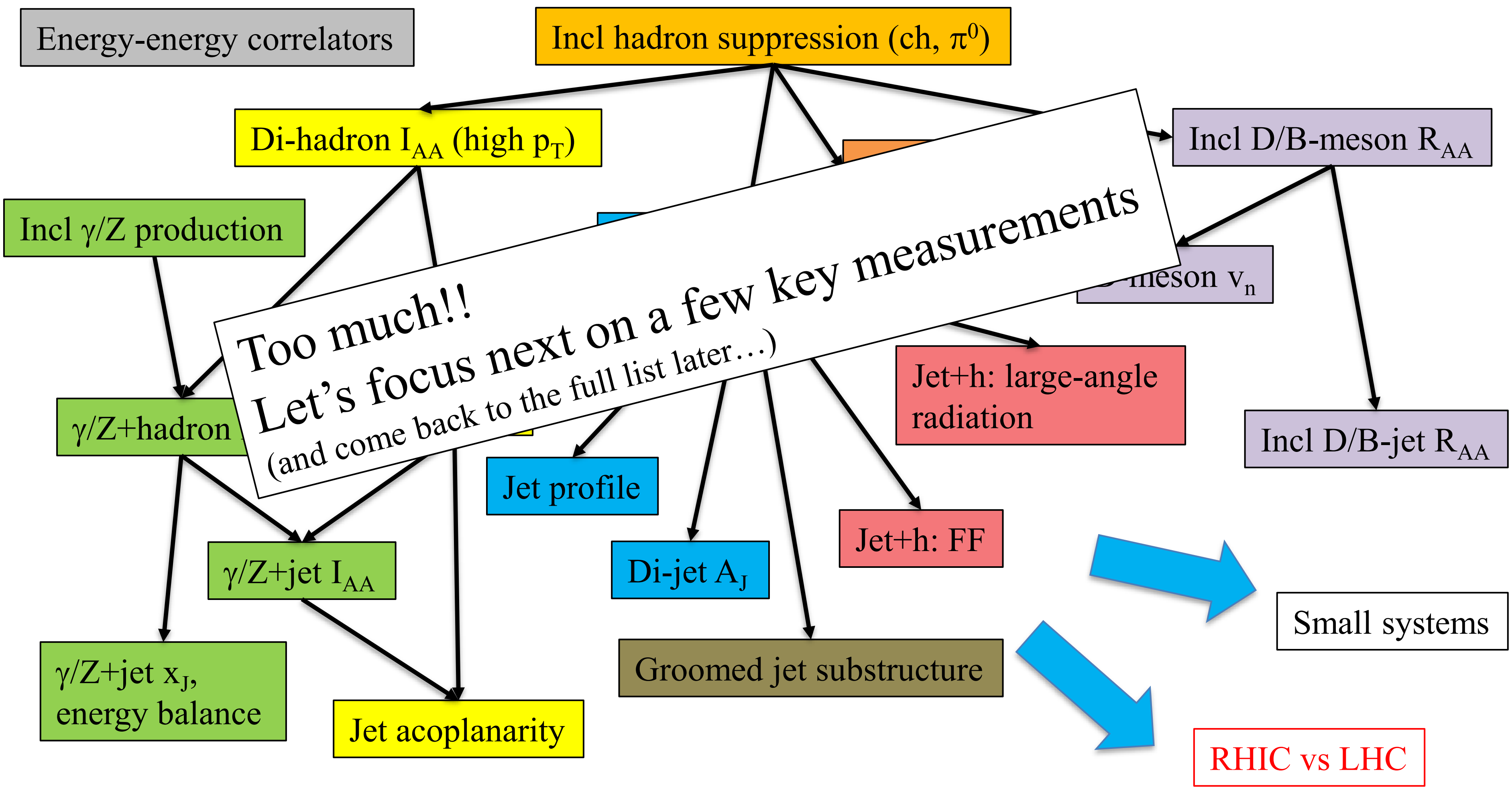
Phenomenology: broadly similar at RHIC vs LHC, hadrons vs jets

But quantitative differences: what do they teach us?

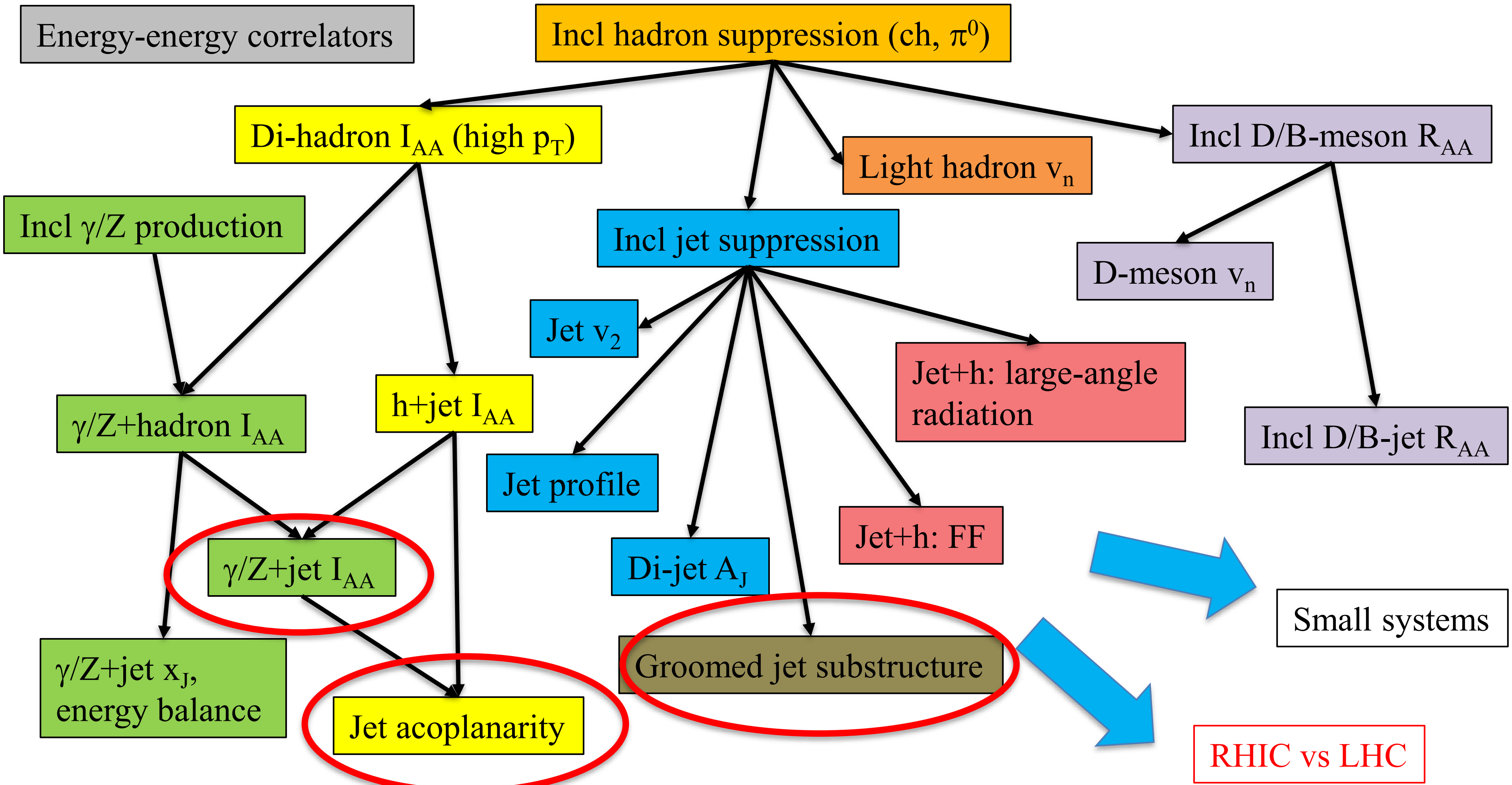
Let's table the question until the lecture on Bayesian Inference, when we will study it in detail

What's next? How do we explore jet quenching more deeply?

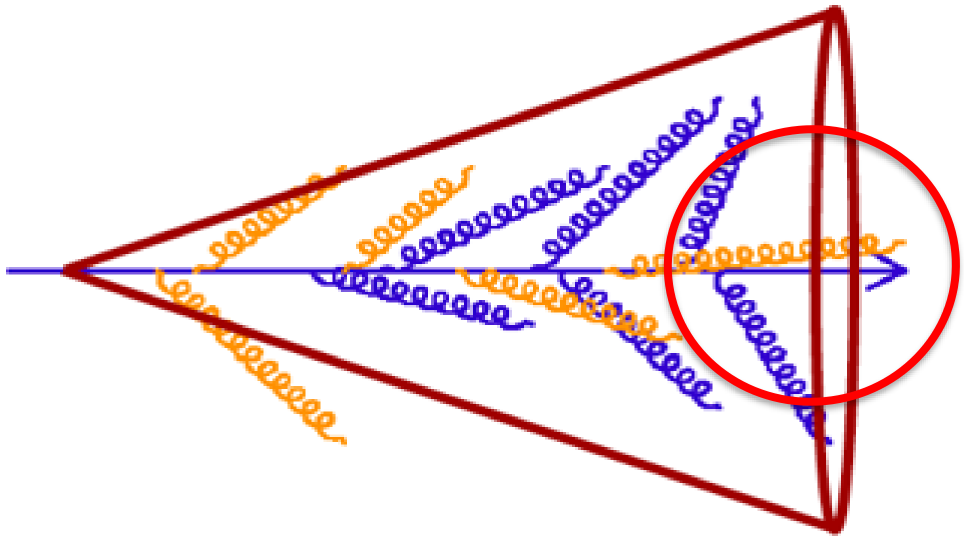
Topology driven by experimental considerations: arrows connect observables with just one thing changed



What's next? How do we explore jet quenching more deeply?

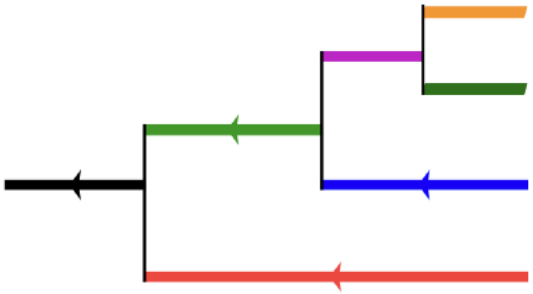


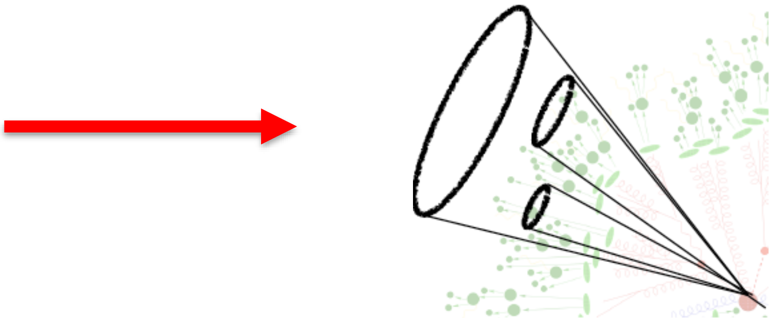
Jet substructure



Look at the structure of the jet shower and its in-medium modification

- Lund plane: full mapping of jet shower
- Groomed sub-structure: selected regions of Lund plane

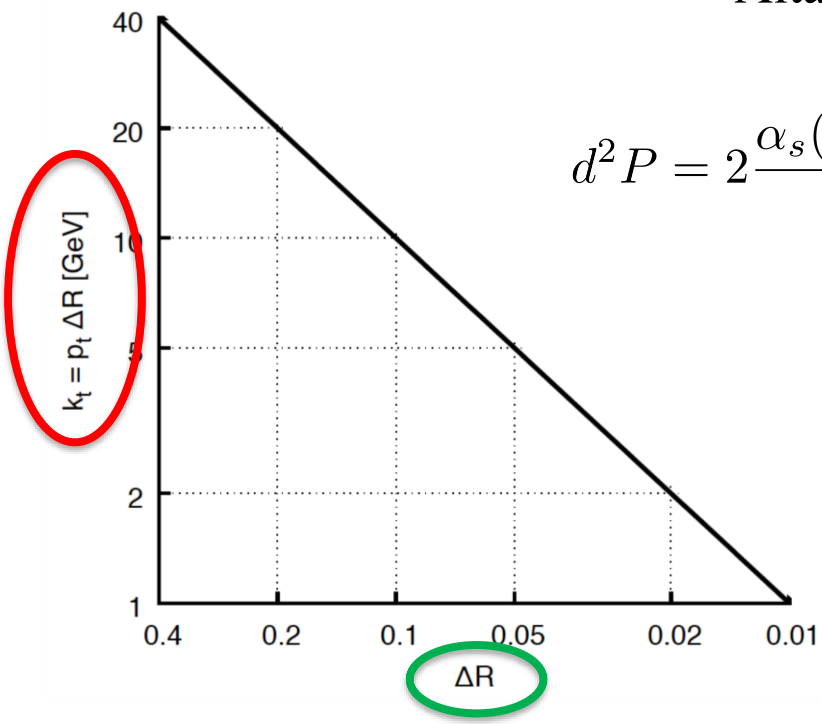


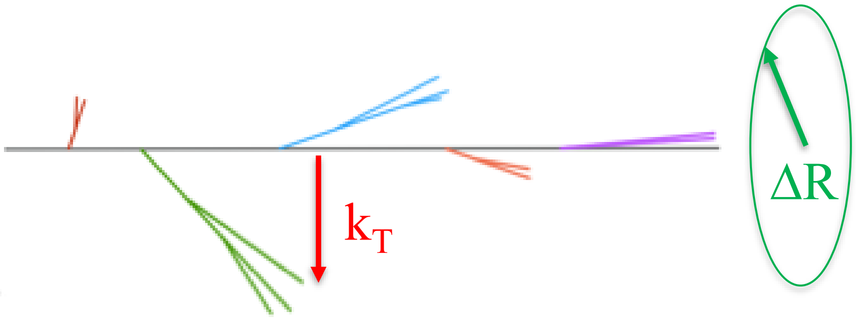


Lund Plane: jet shower map

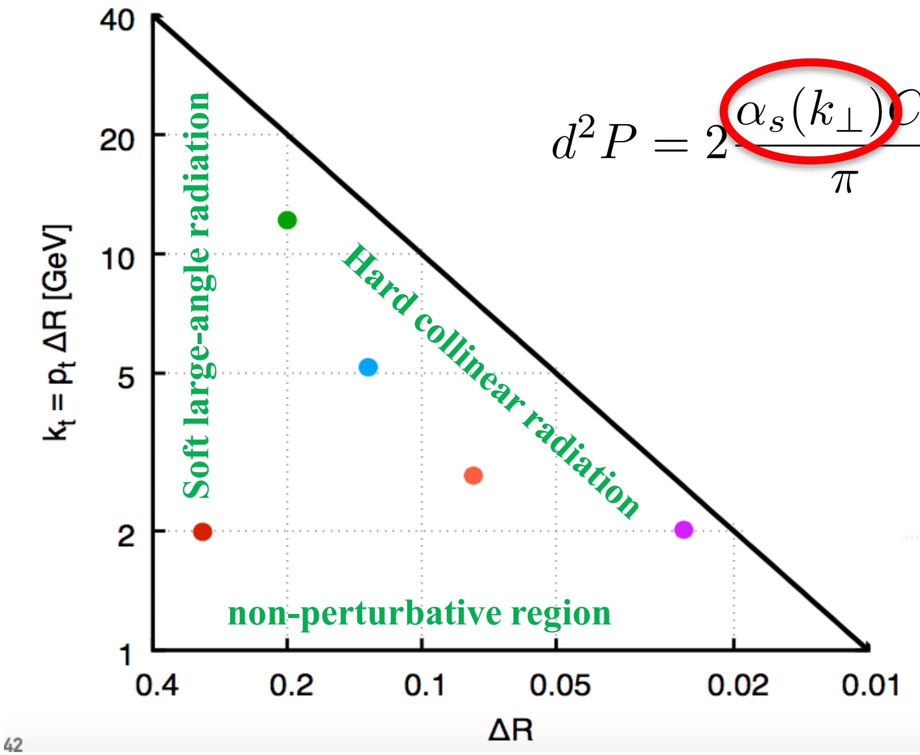
Altareli-Parisi splitting probability function

$$d^2P = 2\frac{\alpha_s(k_\perp)C_R}{\pi} d\ln\left(\frac{k_\perp}{p_T^{\rm jet}}\right) d\ln\left(\frac{1}{\Delta R}\right)$$





Lund Plane: jet shower map



Altareli-Parisi splitting probability function

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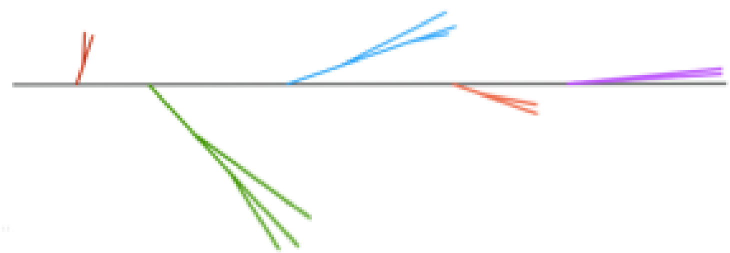


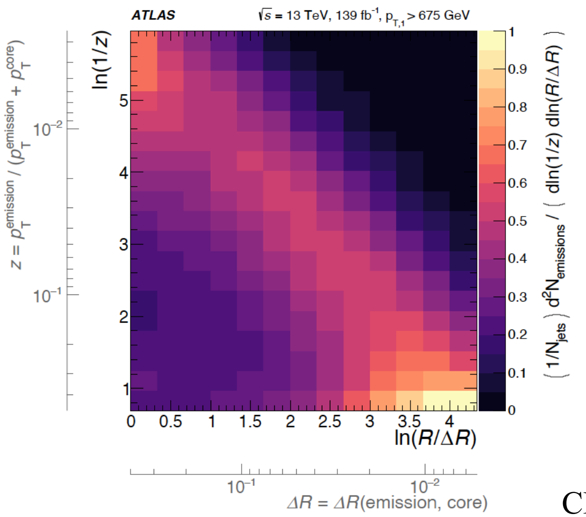
Each radiated gluon corresponds to a point in the Lund Plane

Fixed α_S: Lund diagram is populated uniformly
(note that axes are logarithmic)

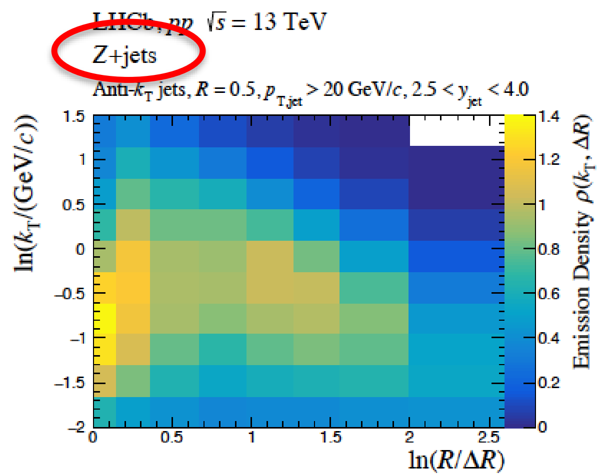
Measuring the Lund Plane in vacuum (pp@13 TeV)

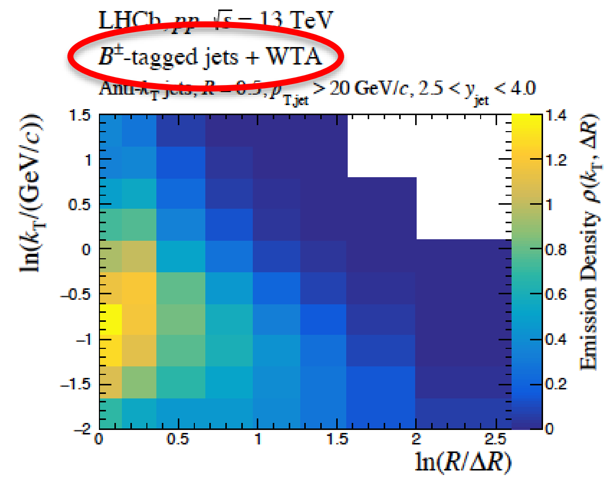
$$d^2P = 2\frac{\alpha_s(k_\perp)C_R}{\pi}\, d\ln\left(\frac{k_\perp}{p_T^{\text{jet}}}\right) d\ln\left(\frac{1}{\Delta R}\right)$$

ATLAS PRL 124 222002 (2020)

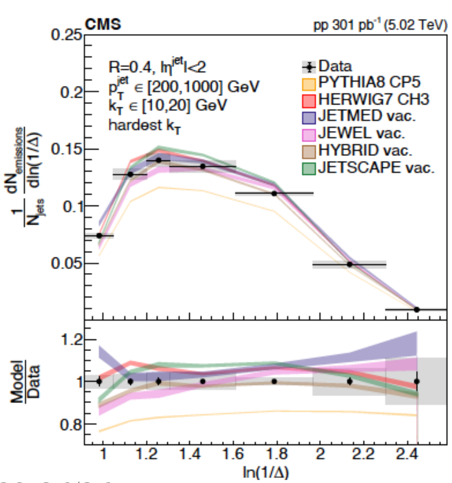


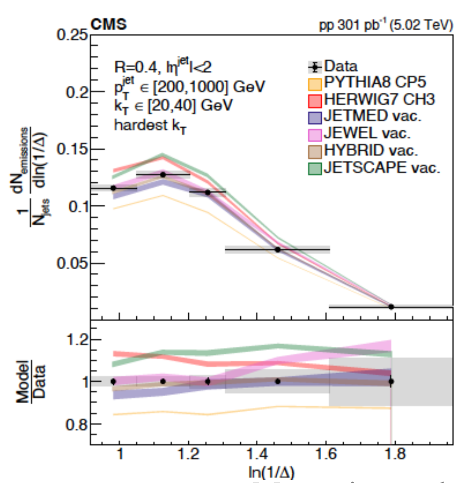
LHCb D112, 072015 (2025)





CMS arXiv:2602.09271



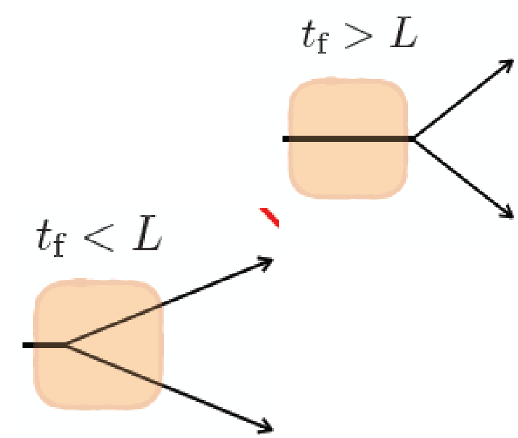


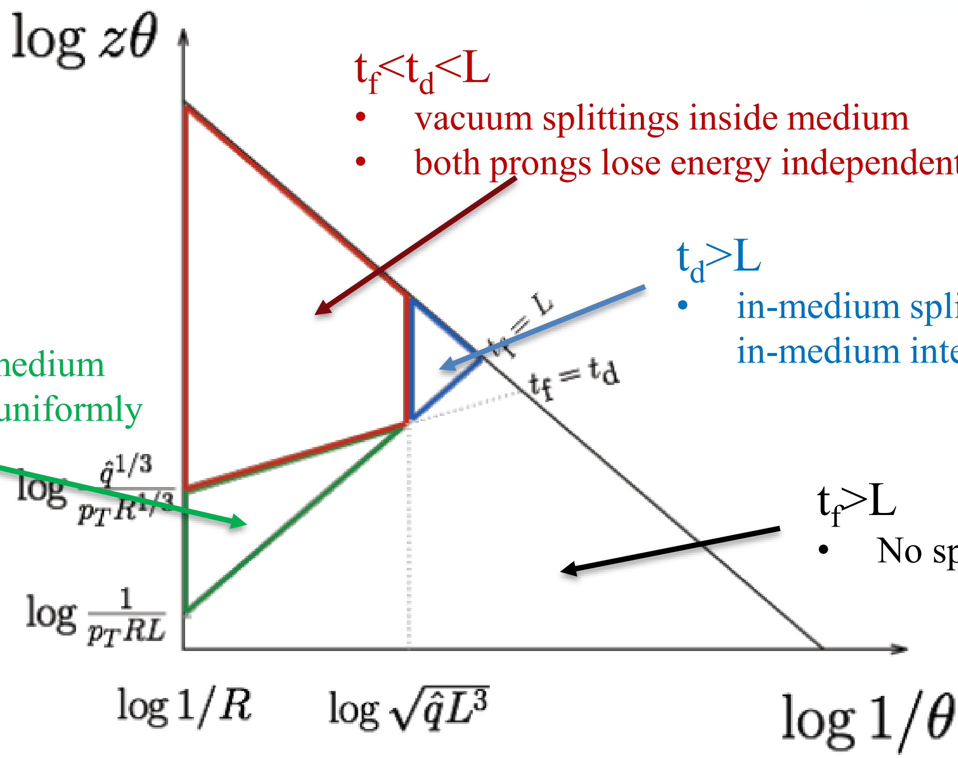
Non-uniform density
- running of α_S
- NP/hadronization effects

Lund Plane in medium (AA collisions)

Additional length/time scales:

- L: length of medium
- t_f: formation time of radiation
- t_d: "decoherence" time due to interaction with medium





$t_f < t_d < L$
- vacuum splittings inside medium
- both prongs lose energy independently

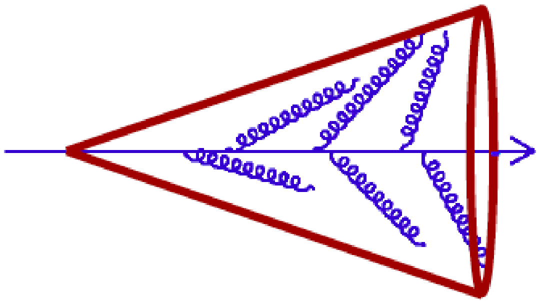
$t_d > L$
- in-medium splittings not resolved by in-medium interactions

$t_d \lesssim t_f$
- splitting affected by medium
- region not populated uniformly

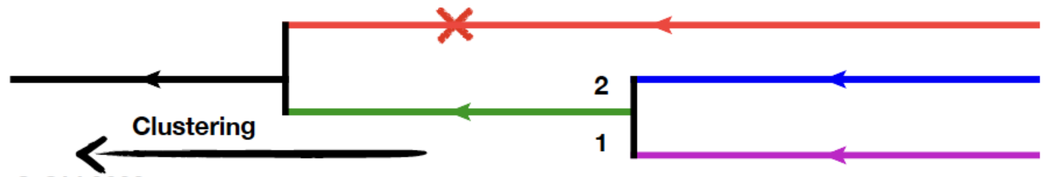
$t_f > L$
- No splitting in-medium

Jet grooming: softdrop

JHEP 09 (2013) 029
JHEP 05 (2014) 146



Clustering tree:



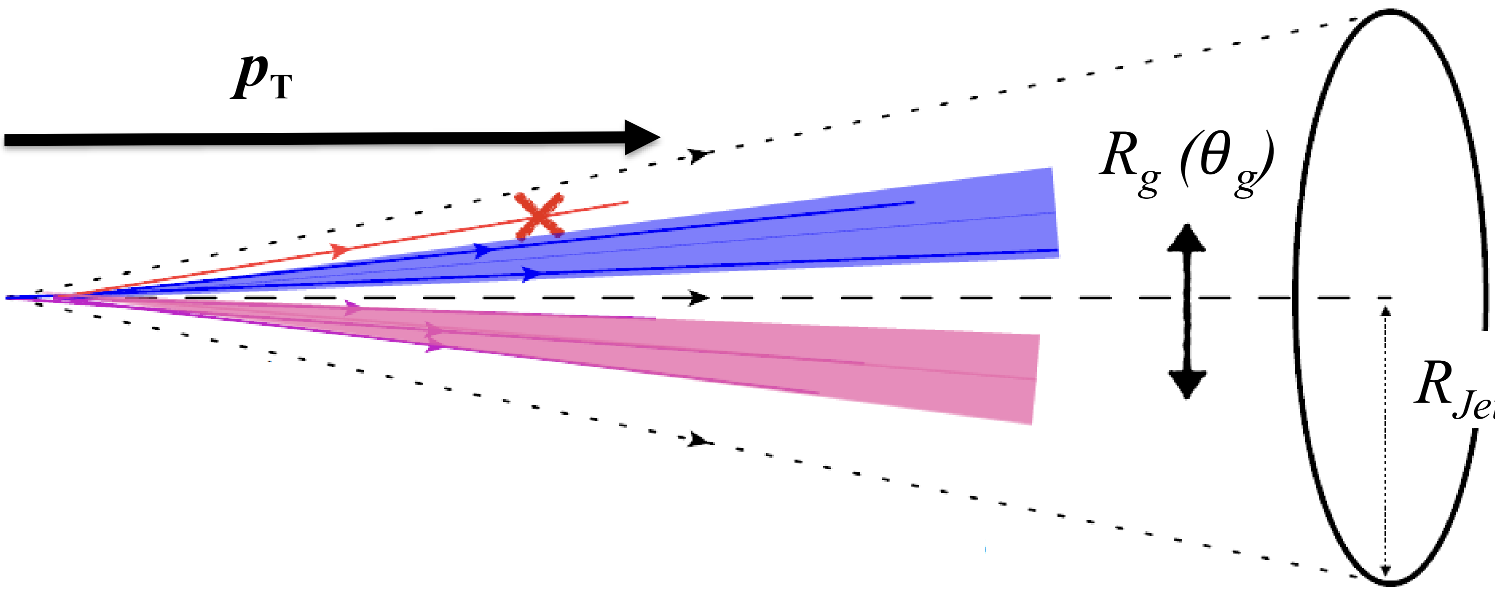
Iterate backwards through clustered jet tree, find first splitting that satisfies:

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

Common choices:

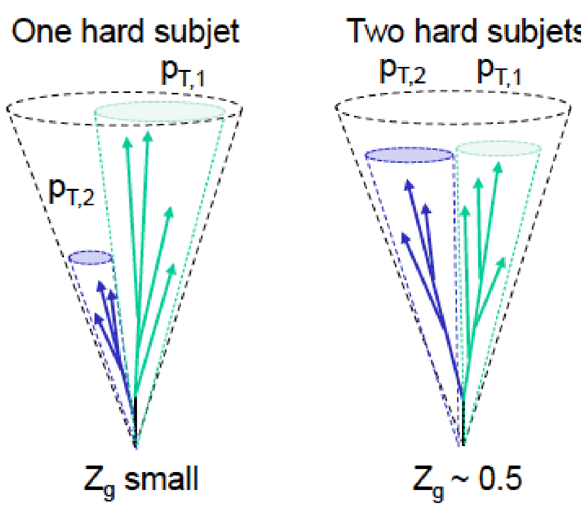
$z_{cut} = 0.1$

$\beta = 0$



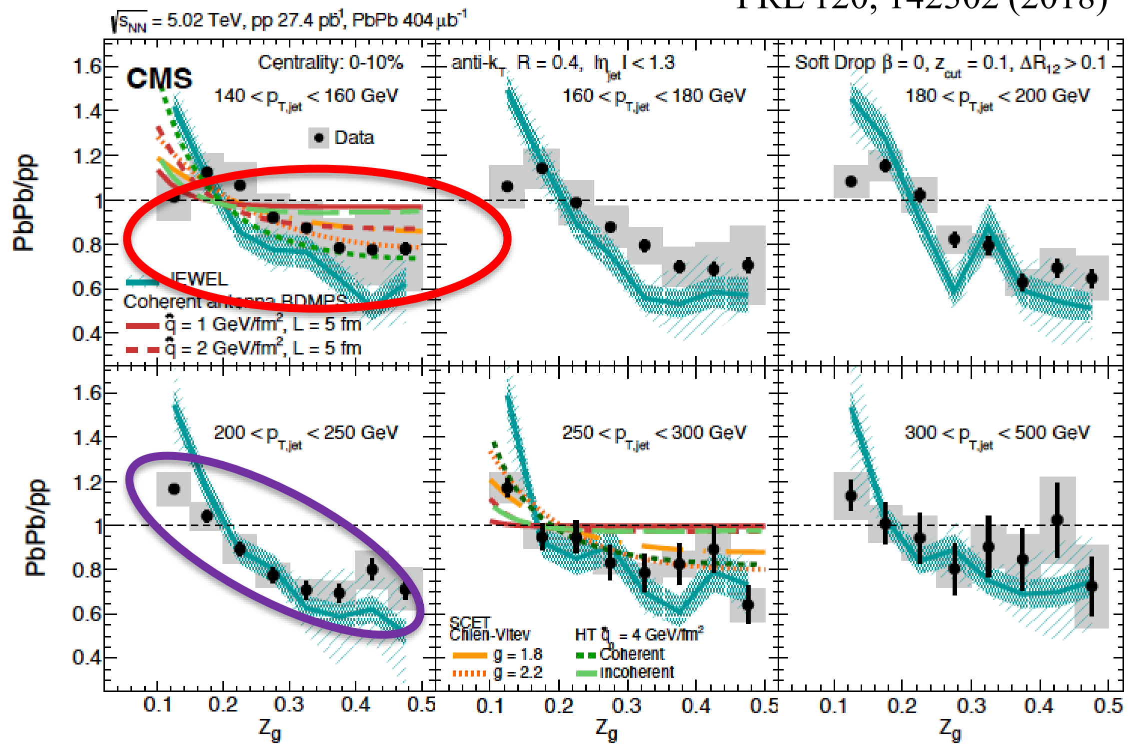
Longitudinal jet sub-structure: z_g

Momentum imbalance of the two leading subjets



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

PRL 120, 142302 (2018)

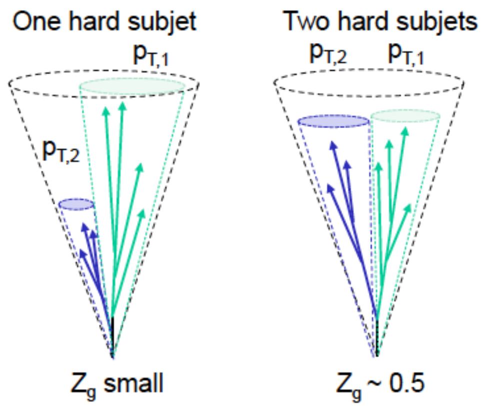


Data: in-medium interaction generates subjet momentum imbalance

Theory/models: small but non-zero difference between incoherent radiation (JEWEL) and coherent antennas –interesting!

- but current data uncertainty too large to discriminate. Need better measurements?

Measurement issue: selection bias!



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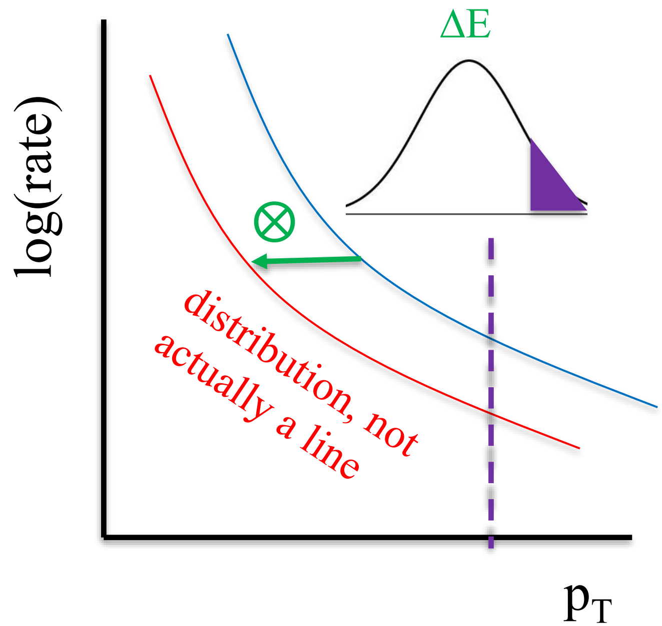
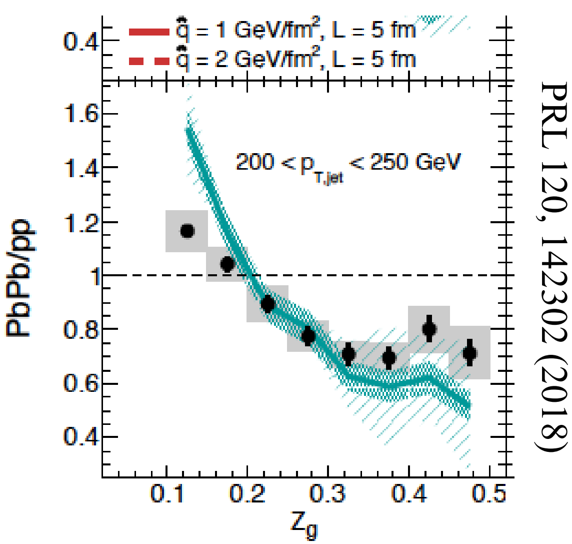
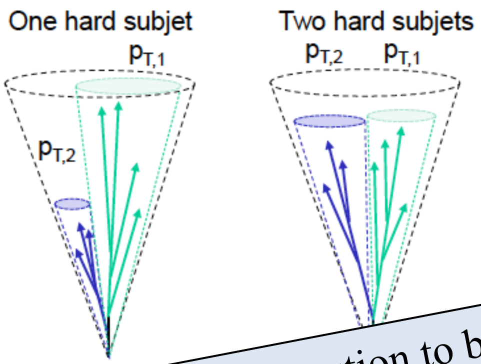


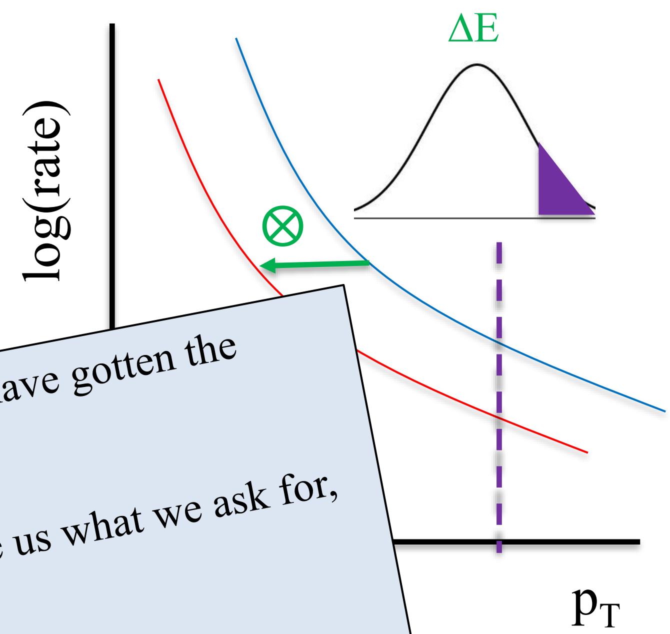


1. Jet spectrum falls with increasing p_T
2. Energy loss due to quenching is a distribution (!)
3. We compare jets in Pb+Pb and p+p at a fixed value of p_T (actually a finite-width bin but principle is the same)

Perhaps the Pb+Pb population being compared is dominated by that subset of jets which have lost relatively little energy? → "selection bias"

Measurement issue: selection bias!





If you find this question to be disturbing, you have gotten the point.

Heavy-ion physics is not easy. QCD will give us what we ask for, but not necessarily what we want.

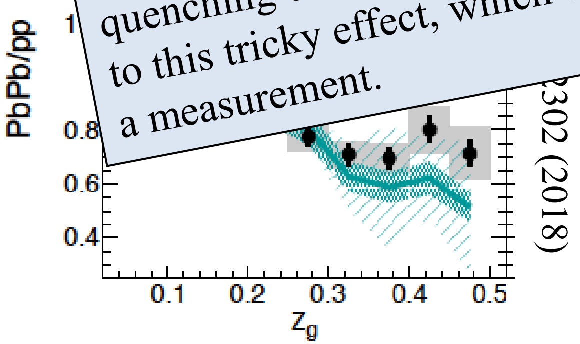
Always be on the lookout for selection bias. The best jet quenching observables are designed to be insensitive or immune to this tricky effect, which can badly confuse the interpretation of a measurement.

ncreasing p_T

ching is a distribution (!)

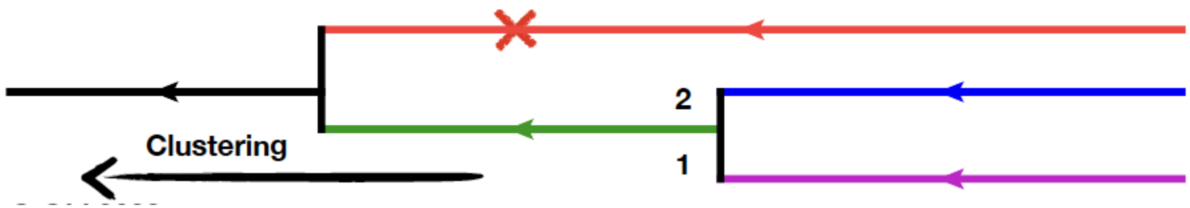
b and p+p at a fixed value

a finite-width bin but principle is the same)



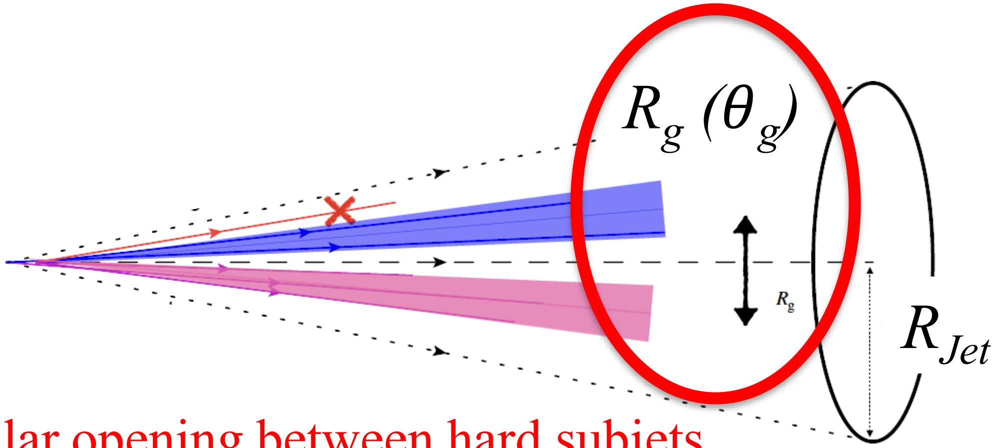
Perhaps the Pb+Pb population being compared is dominated by that subset of jets which have lost relatively little energy? → "selection bias"

Transverse jet sub-structure: R_g , θ_g



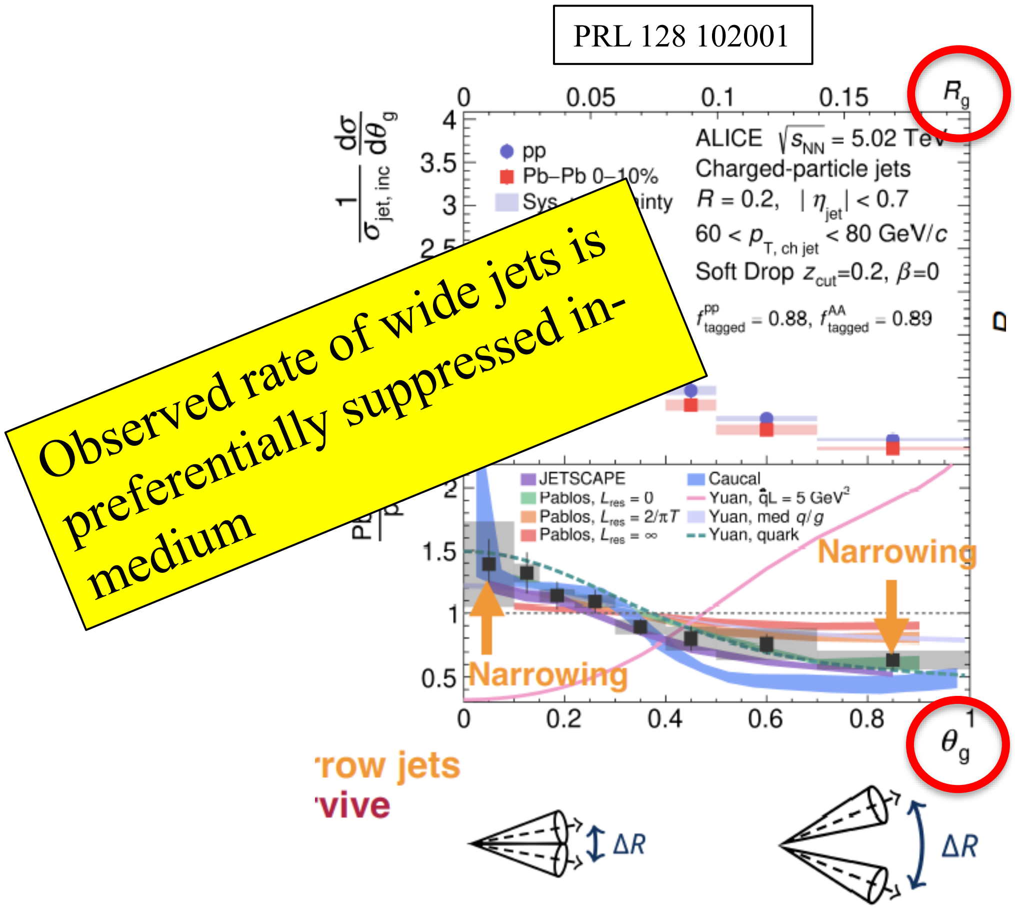
$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut} \left(\frac{R_g}{R_{jet}}\right)^{\beta}$$

$z_{cut} = 0.1$
$\beta = 0$

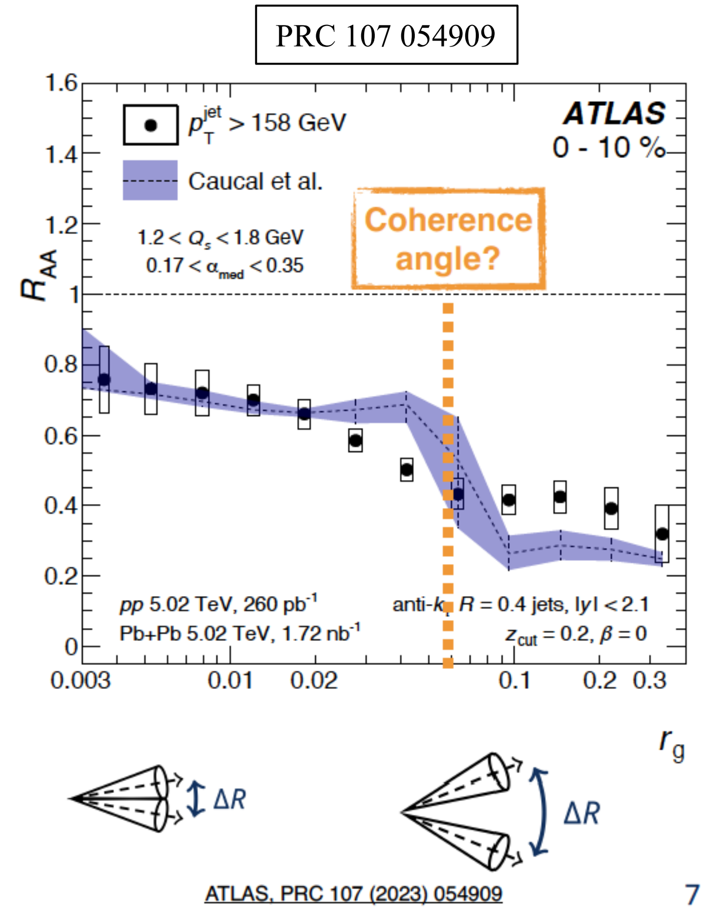


R_g: angular opening between hard subjets

Transverse jet sub-structure: R_g (θ_g)



Observed rate of wide jets is preferentially suppressed in-medium



- probe of QGP resolution scale (“color coherence”)?
- or selection bias, whereby narrow jets lose less energy?

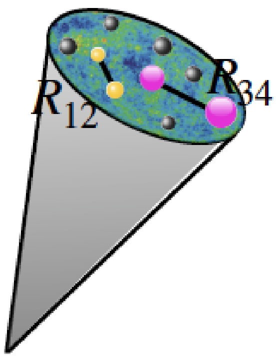
Interpretation under discussion; need additional measurements (but which?)

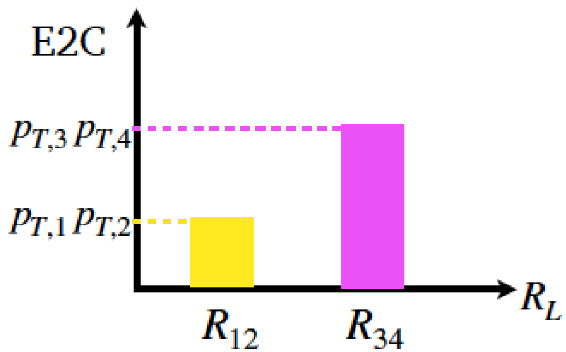
Energy-energy correlators (EECs)

E2C in p-p

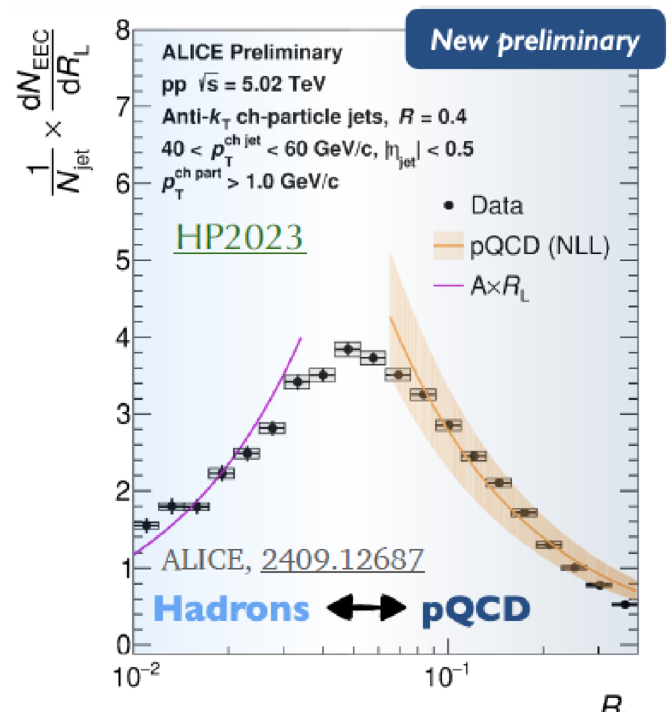
- Correlators of the **energy flux** $\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\cdots\mathcal{E}(\vec{n}_k)\rangle$

$$\text{E2C} = \frac{1}{N_{\text{jets}}}\sum_{\text{jets}}\sum_{i,j}\frac{P_{T,i}P_{T,j}}{P^2_{T,\text{jet}}}\,\delta(R_{ij}-R_L)$$





$$R_{ij} = \sqrt{\Delta\phi_{ij}^2 + \Delta\eta_{ij}^2}$$

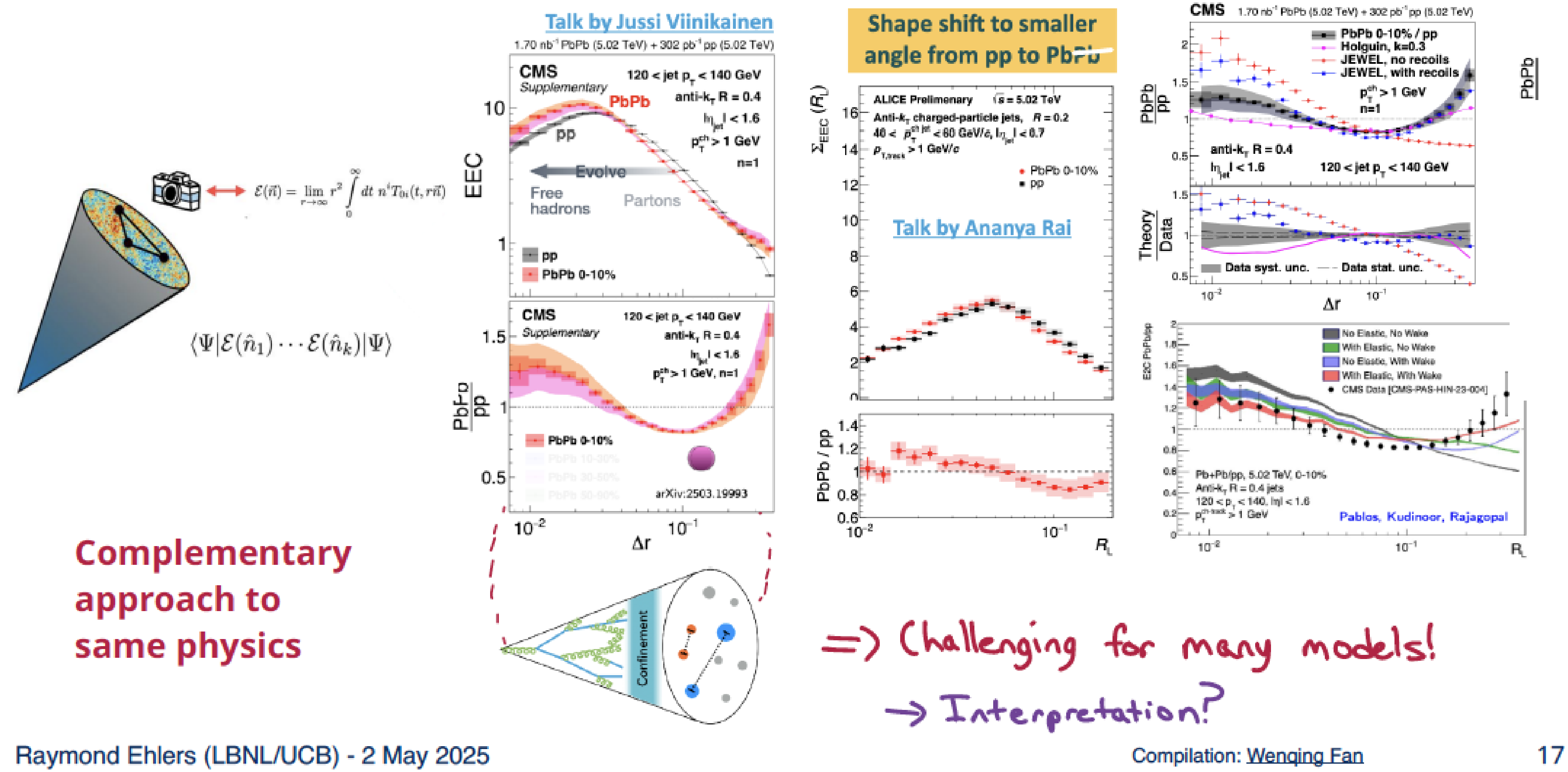


See also: STAR, 2502.15925

Carlota Andres 18

EECs in the QGP

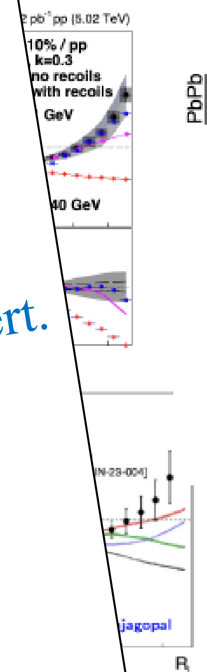
$$\text{E2C} = \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \sum_{i,j} \frac{P_{T,i} P_{T,j}}{P^2_{T,\text{jet}}} \delta(R_{ij} - R_L)$$



EECs in the QGP

$$\text{E2C} = \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \sum_{i,j} \frac{P_{T,i} P_{T,j}}{P^2_{T,\text{jet}}} \delta(R_{ij} - R_L)$$

Talk by



EECs are apparently simple, highly integrated hadronic correlators

Experiment:

- Straightforward in pp, extremely difficult in AA
- Only limited techniques to discriminate bkgd (because highly integrated)
- Measurements possible only in limited phase space, large sys uncert.

Theory:

- Predicted QGP effects are small
- Highly integrated: hard to discriminate different physics effects

Needs new ideas → work in progress

Con
appl
same

models!

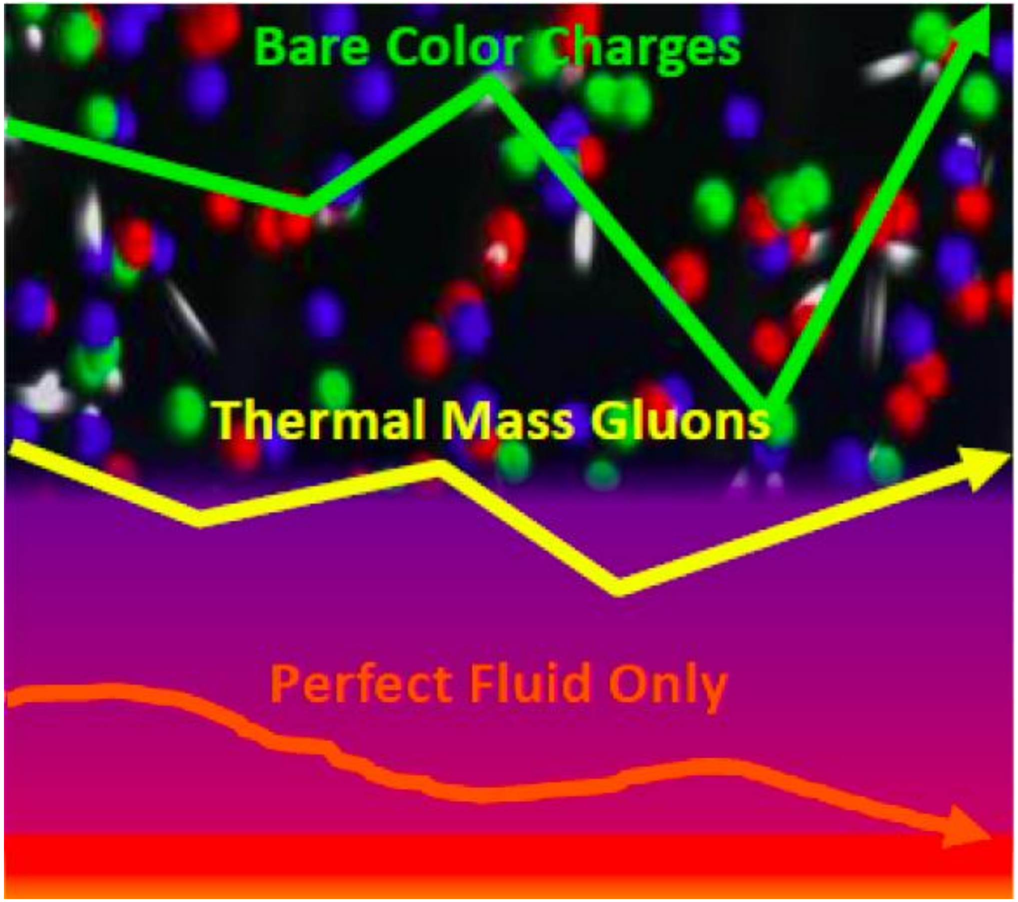
→ Interpretation?

Raymond Ehle

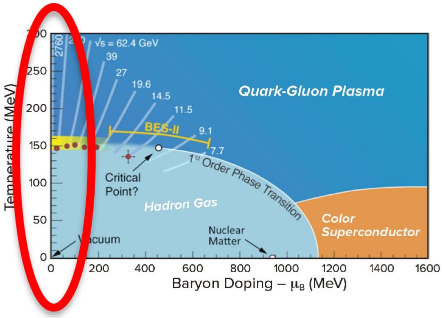
Compilation: Wenqing Fan

17

What is the QGP made up of?



Finite Temperature QCD calculated numerically on the Lattice (μ_B=0)

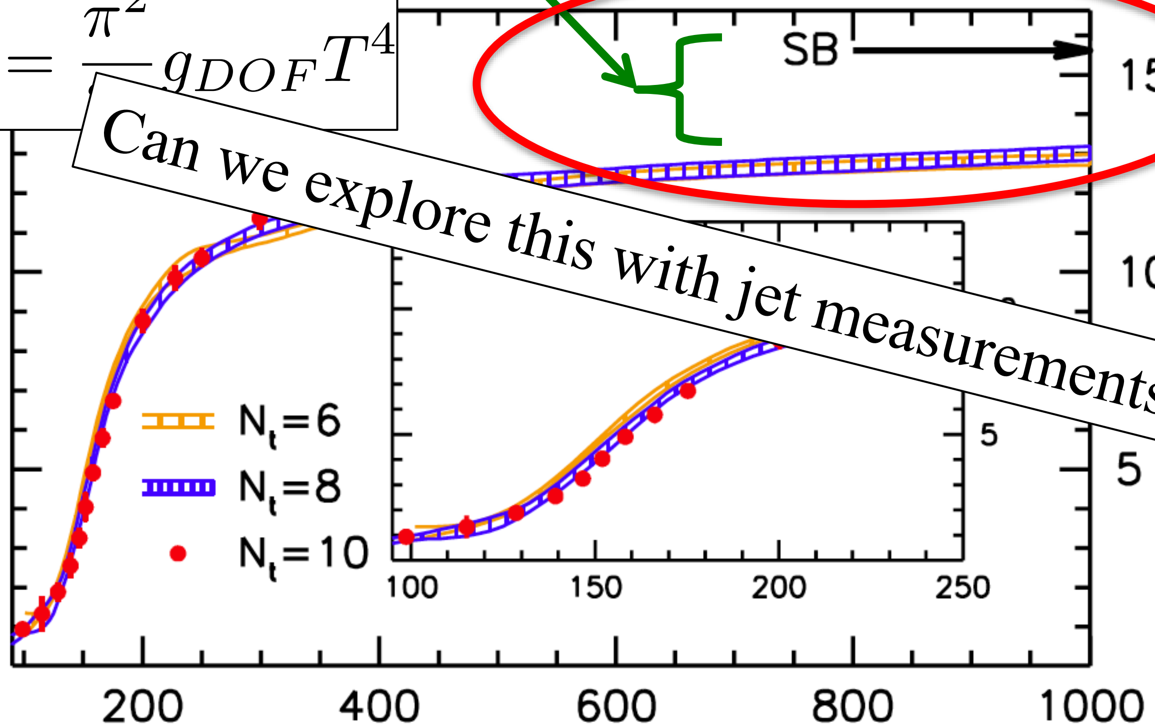


Slow convergence to non-interacting Steffan-Boltzmann limit
What carries energy - complex bound states of q+g? "strongly-coupled" plasma?

Energy density

$$\epsilon = \frac{\pi^2}{\ldots} g_{DOF} T^4$$

$$\frac{\epsilon}{T^4}$$



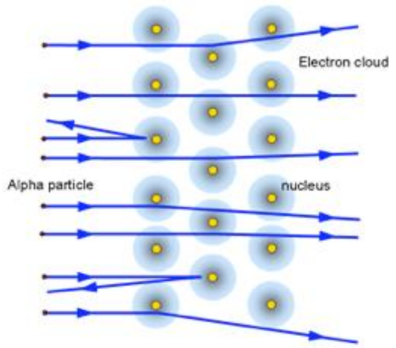
Temperature [MeV]

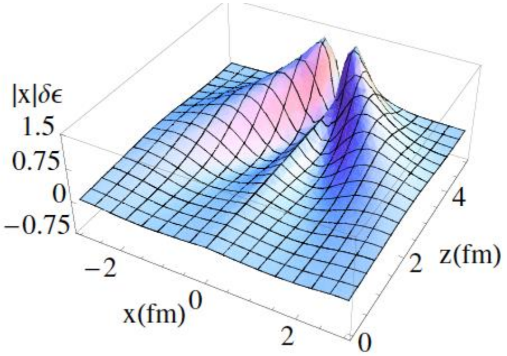
S. Borsanyi et al., JHEP 1011, 077 (2010)

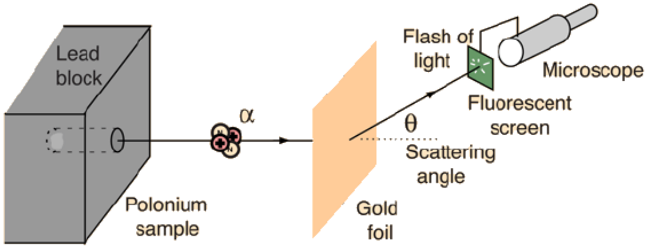
Can we explore this with jet measurements?

Observing QGP "quasi-particles"?

Discrete scattering centers or effectively continuous medium?



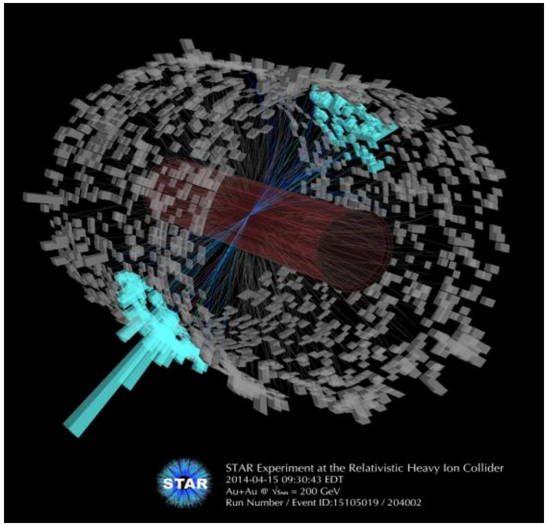




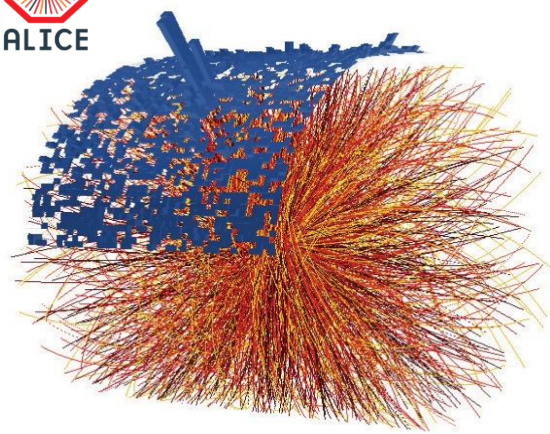
Picture depends on moment-transfer scale

Scattering experiments need a broad kinematic range
→ must measure jets with low p_T and large R

The heavy-ion jet measurement challenge III



ALICE



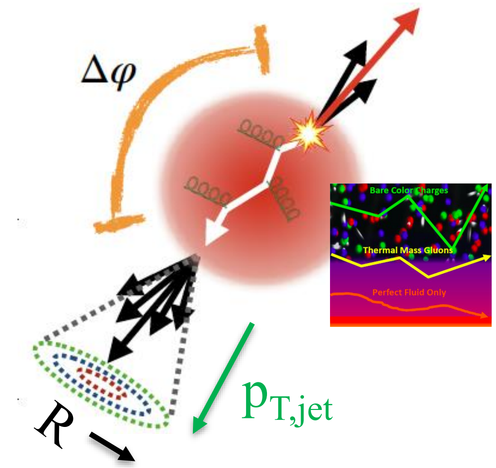
Very complex experimental environment

Huge background of particles not correlated with jet shower

Particles do not come labelled “jet” or “background”

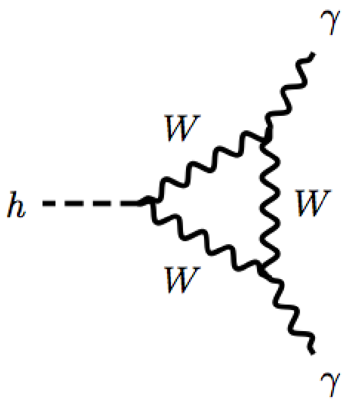
Correlation observables: cannot know with certainty whether a recoil hadron arises from the same high-Q^2 process as the trigger

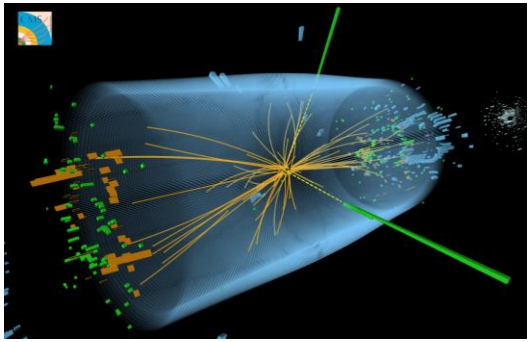
- “uncorrelated background” strictly has meaning only for ensemble-averaged (“statistical”) distributions



Low p_T/large R jet measurements
→ “statistical” correction of uncorrelated background yield

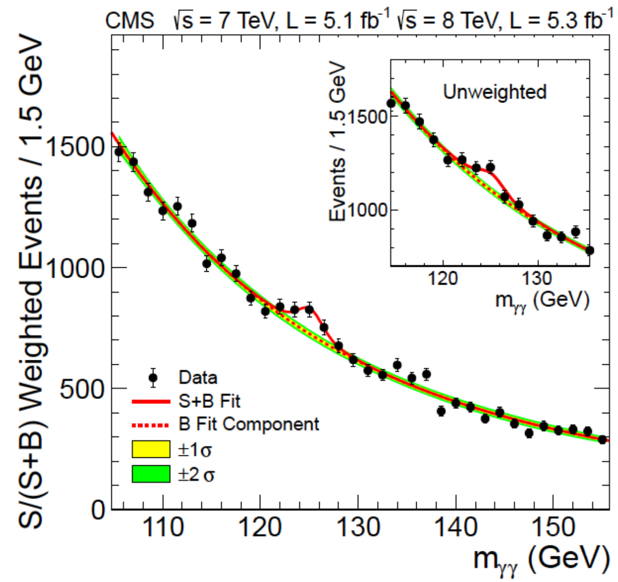
Small signal/bkgd is a common problem in physics…





Complex experimental environment

Large background of particles not correlated with signal



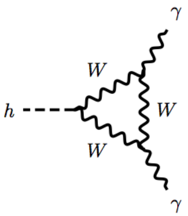
Photons do not come labelled "Higgs" or "background"

Cannot know with certainty whether a photon arises from Higgs decay or a background process

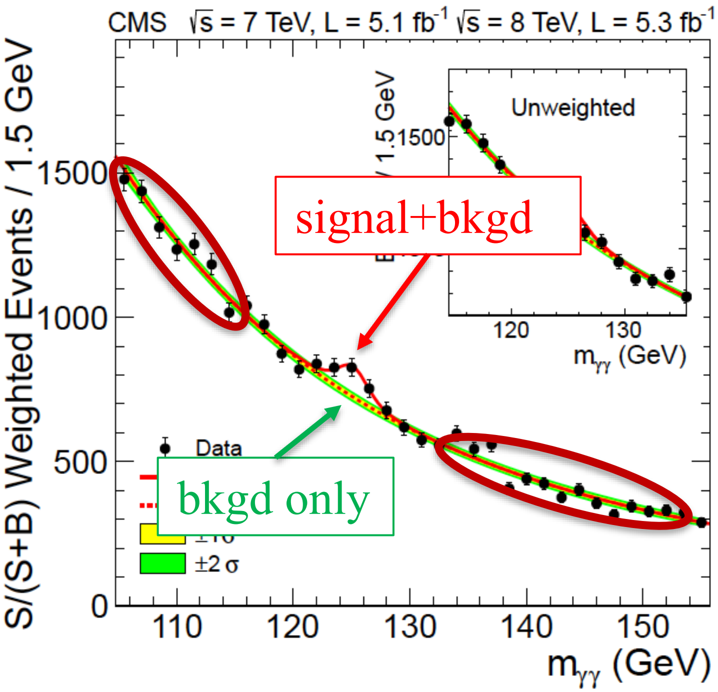
- "uncorrelated background" strictly has meaning only for ensemble-averaged distributions

Small S/B → "statistical" correction for uncorrelated background yield

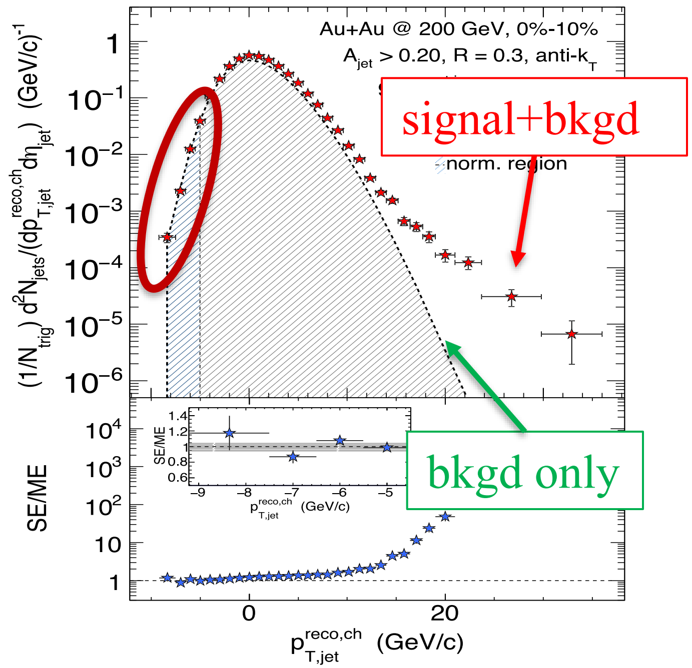
Statistical background correction

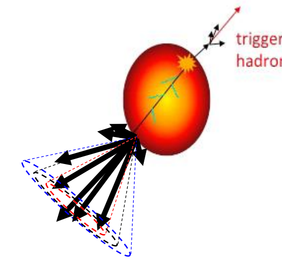


pp → Higgs → γγ



Au+Au → hadron + jet





Two distributions:

- S+B: Signal + background
- B: Background only

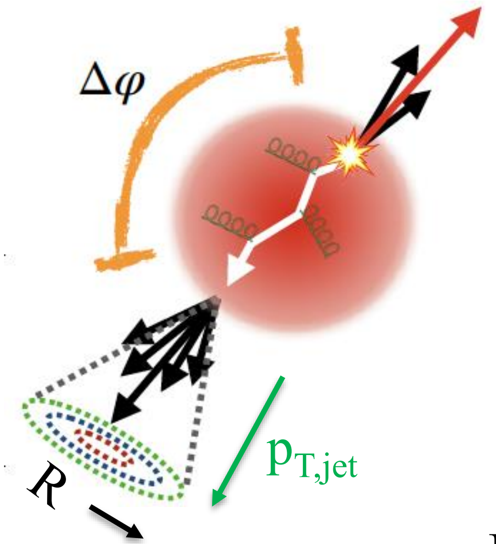
Normalize in B-dominated region

→ Subtract B from S+B

Fully data driven: no modeling of complex (even unknown) bkgd processes

Correlation measurements of jet scattering

Trigger: γ, π^0, ch hadron



Recoil jet

Statistical analysis of jet correlations requires semi-inclusive observables

1. Events are first selected for hard processes based on presence of a high p_T trigger
   - Because selection is event-wise trigger must be cleanly measurable without large correction for bkgd
   - γ/Z, π^0, charged hadron; but not jet (!)

2. Jet reconstruction is then run on the full event
→ number of jets in recoil azimuth is simply counted

Ratio of hard cross sections:

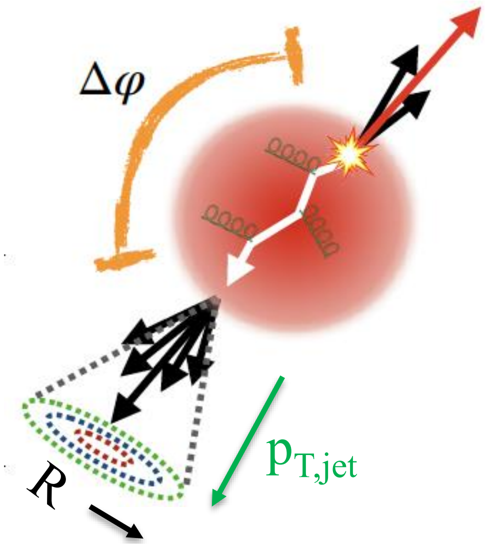
$$\frac{1}{N_{trig}^{AA}}\frac{d^2N_{jet}^{AA}}{dp_{T,jet}d\Delta\varphi}=\frac{1}{\sigma^{AA\to trig+X}}\frac{d^2\sigma^{AA\to trig+jet+X}}{dp_{T,jet}d\Delta\varphi}$$

Unbiased: no jet selection based on p_T^{jet} or other properties
→ can measure to very low p_T^{jet}/large R !!

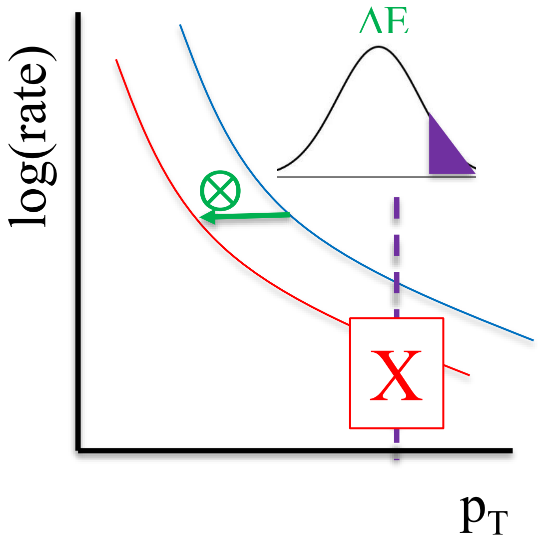
Semi-incl. observables and bias

1. Select for hard-process trigger
2. Count number of recoil jets

Trigger: γ, π^0, ch hadron



Recoil jet



No requirements on p_T^{jet}

No selection bias → unbiased jet distributions!

Unbiased jet measurements to very low p_T^{jet} and large R

Constructing uncorrelated background: event mixing

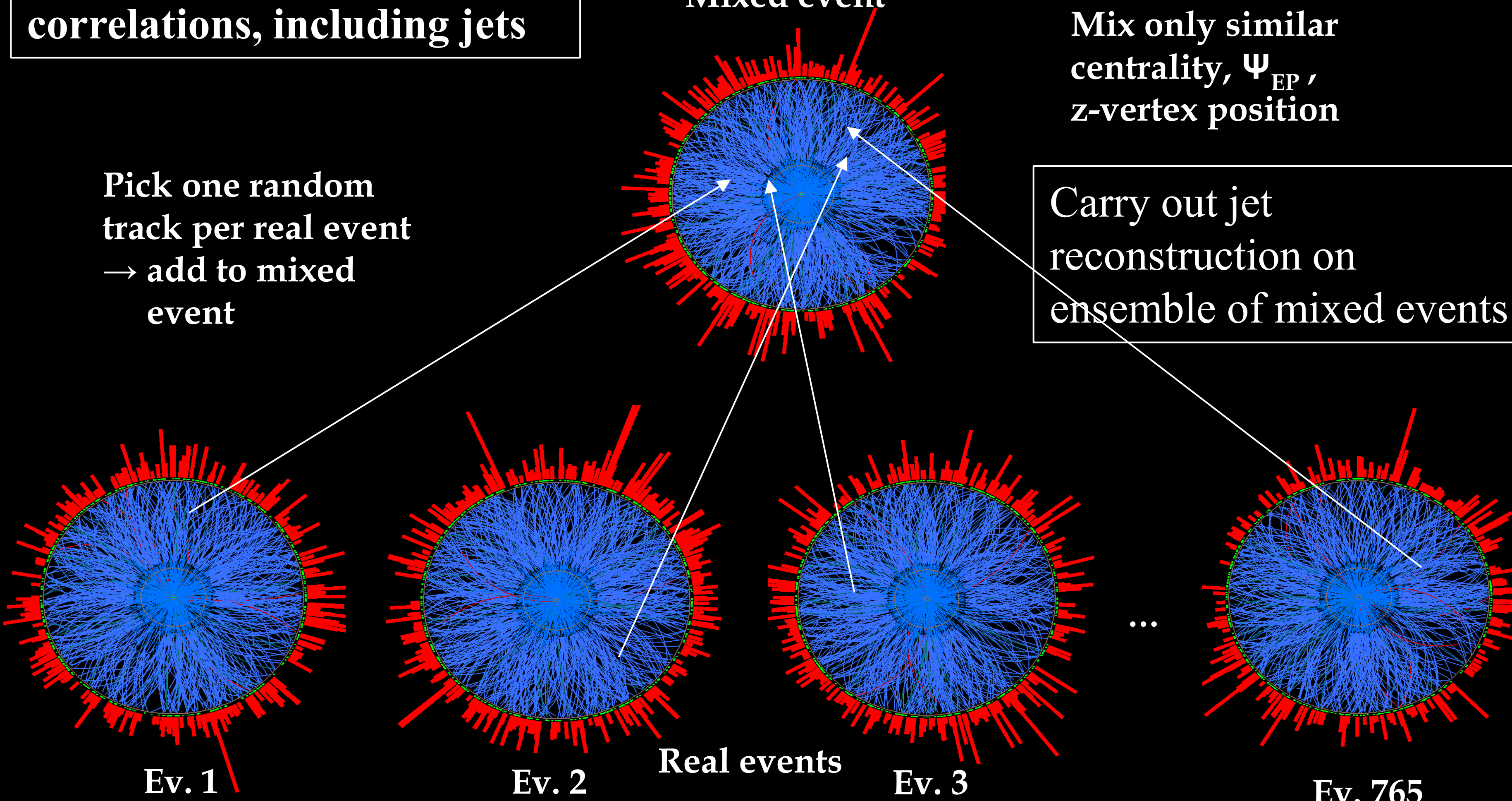
STAR Collaboration,
Phys. Rev. C 96 (2017), 024905

Destroys all multi-hadronic correlations, including jets

Mix only similar centrality, Ψ_{EP}, z-vertex position

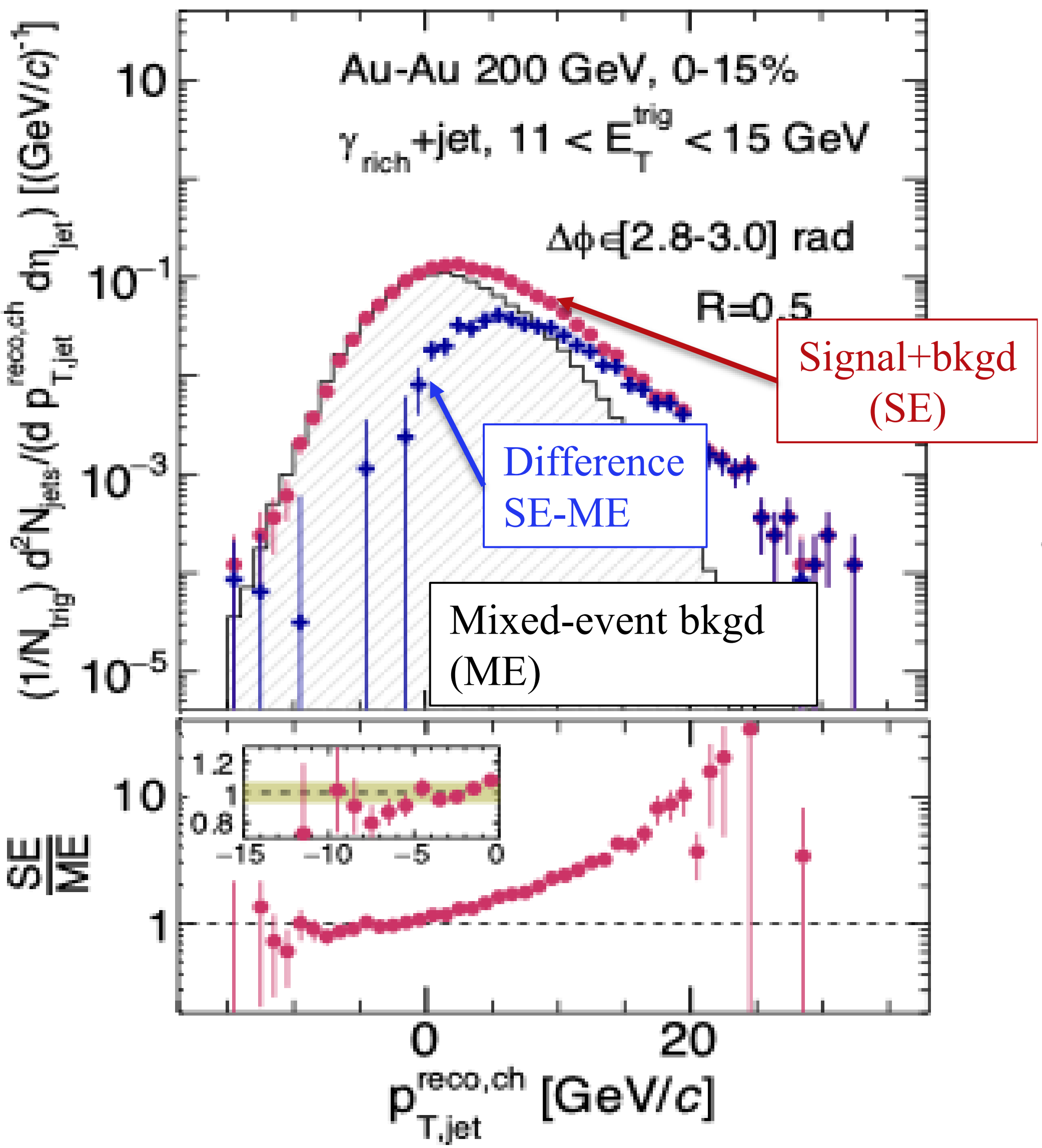
Pick one random track per real event → add to mixed event

Carry out jet reconstruction on ensemble of mixed events



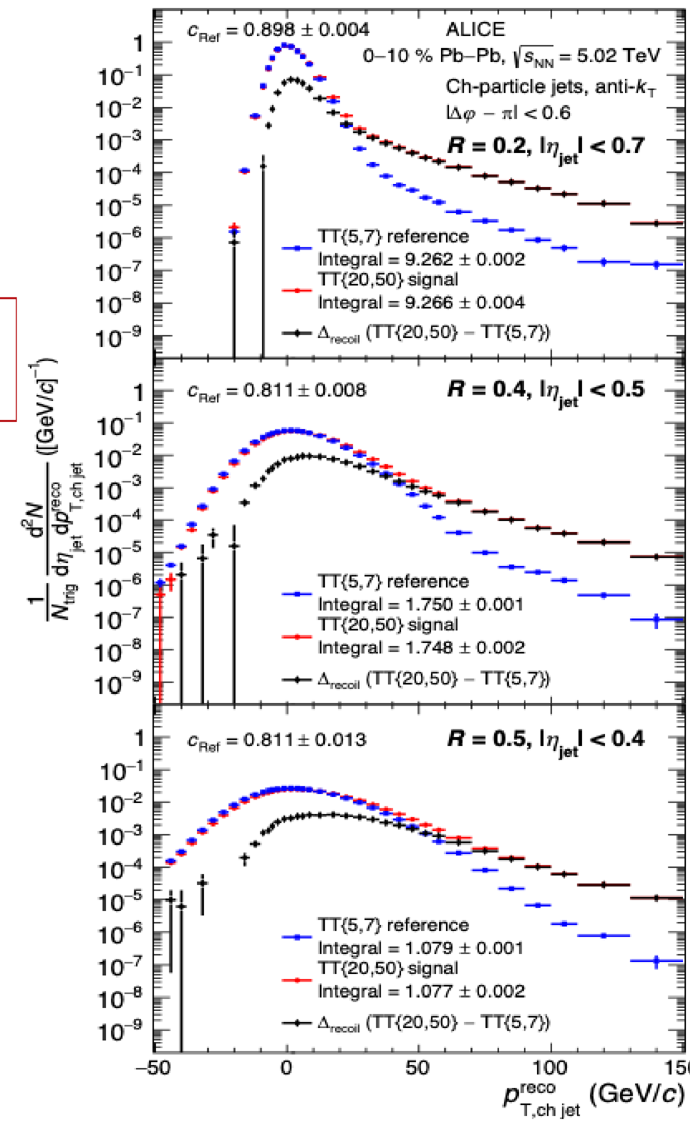
STAR: event-mixed bkgd

STAR Phys.Rev.C 111 (2025) 6, 064907

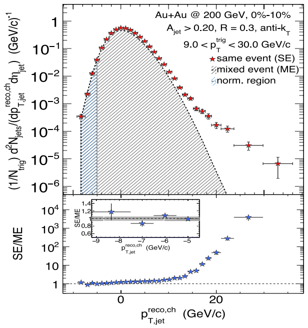


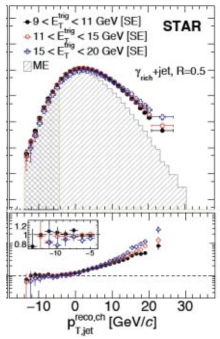
ALICE: trigger-difference bkgd

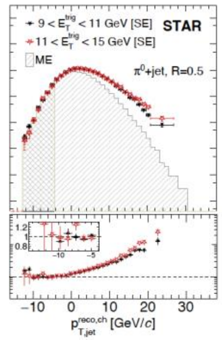
ALICE Phys.Rev.C 110 (2024) 1, 014906

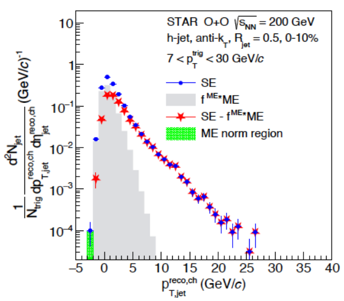


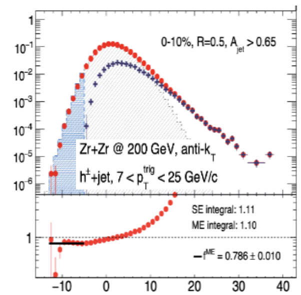
Statistical jet analysis: current results









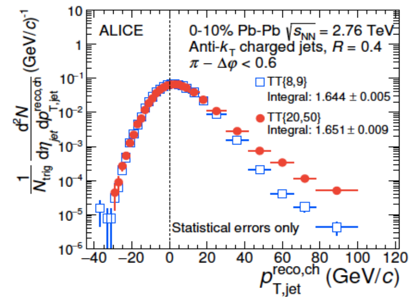


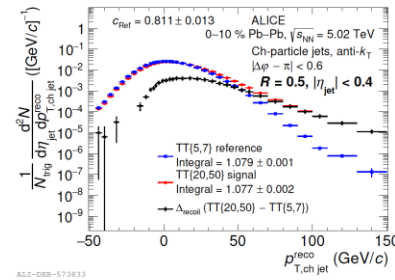
Au+Au; h+jet
- Phys. Rev. C 96 (2017) 024905

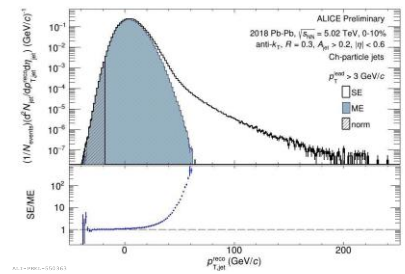
Au+Au, p+p; γ/π^0+jet
- Phys.Rev.Lett. 134 (2025) 232301
- Phys.Rev.C 111 (2025) 064907
- Phys.Rev.C 113 (2026) 014902

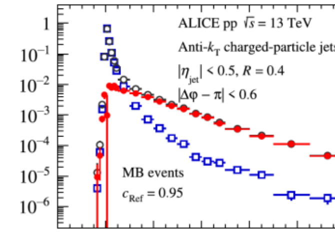
Zr+Zr, Ru+Ru; h+jet
- under collaboration review

O+O; h+jet
- under collaboration review









PbPb, pp; h+jet
- JHEP 09 (2015) 170
- Phys.Rev.Lett. 133 (2024) 2, 022301
- Phys.Rev.C 110 (2024) 1, 014906

Pb+Pb; inclusive jet
- EPJ Web Conf. 296 (2024) 11005

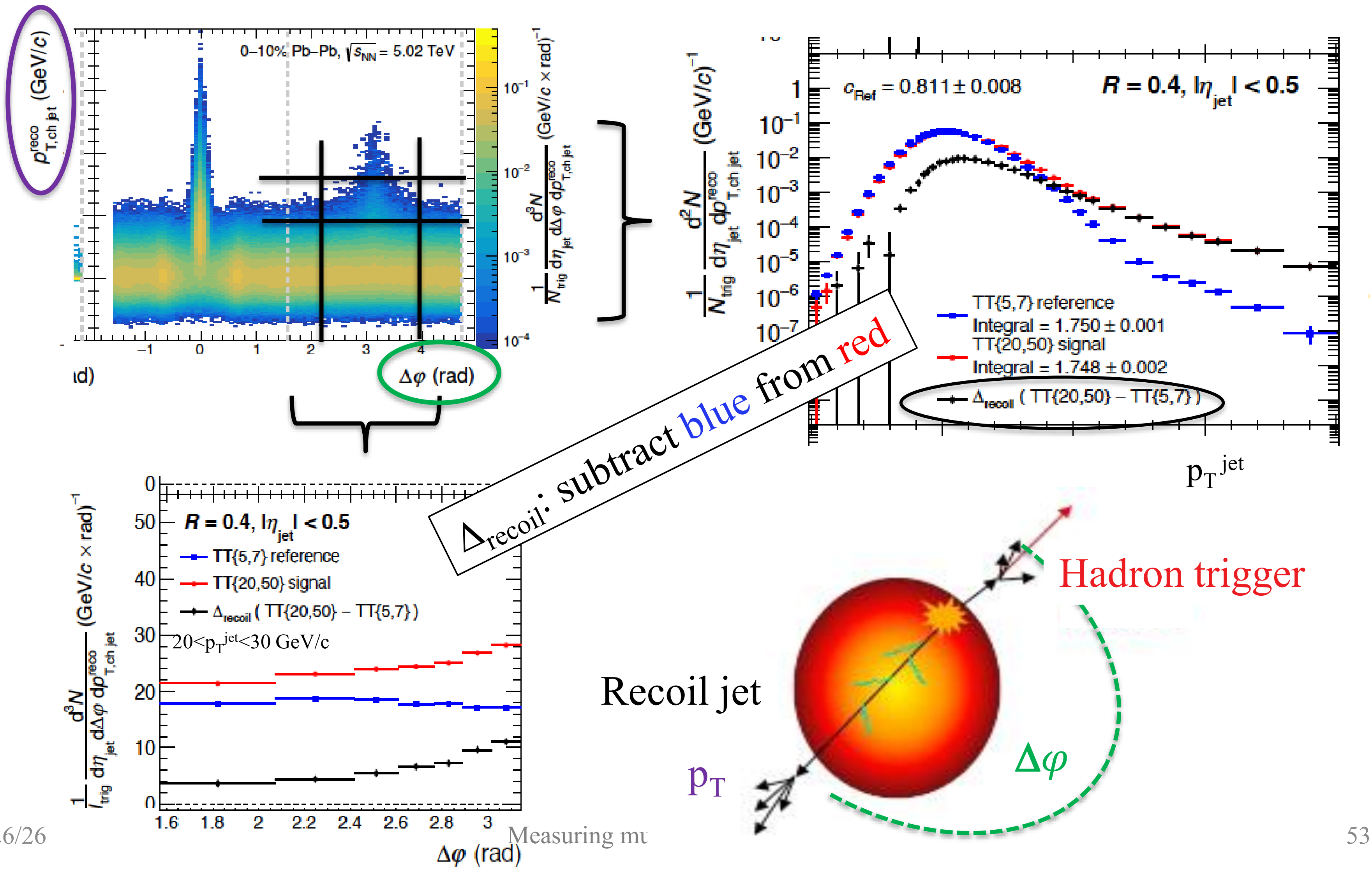
p+Pb, HM pp; h+jet
- JHEP 05 (2024) 229
- Phys.Lett.B 783 (2018) 95-113

O+O; h+jet
- in progress

Semi-inclusive hadron+jet measurements

$$\frac{1}{N_{trig}}\frac{dN_{jet}}{dp_{T,jet}d\Delta\varphi} = \frac{1}{\sigma^{AA\rightarrow h+X}}\frac{d\sigma^{AA\rightarrow h+jet+X}}{dp_{T,jet}d\Delta\varphi}$$

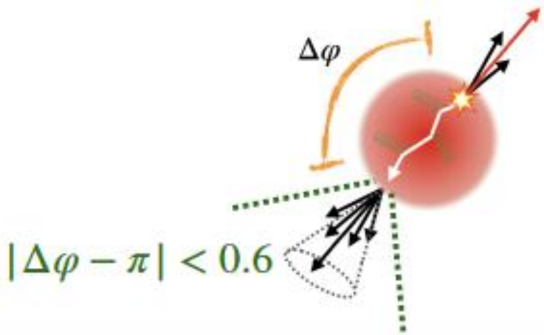
ALICE
Phys.Rev.Lett. 133 (2024) 2 022301
Phys.Rev.C 110 (2024) 014906



Semi-incl. jet quenching: p_T^{jet} dependence

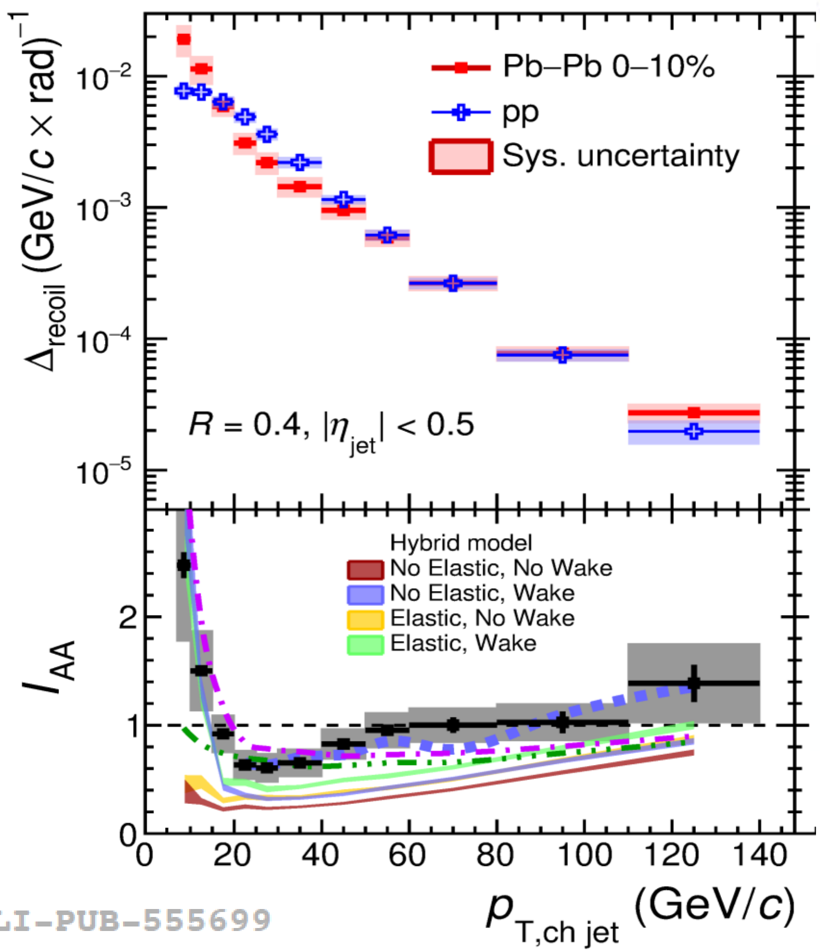
$$I_{AA} = \frac{\Delta_{recoil}(\mathrm{Pb-Pb})}{\Delta_{recoil}(\mathrm{pp})}$$

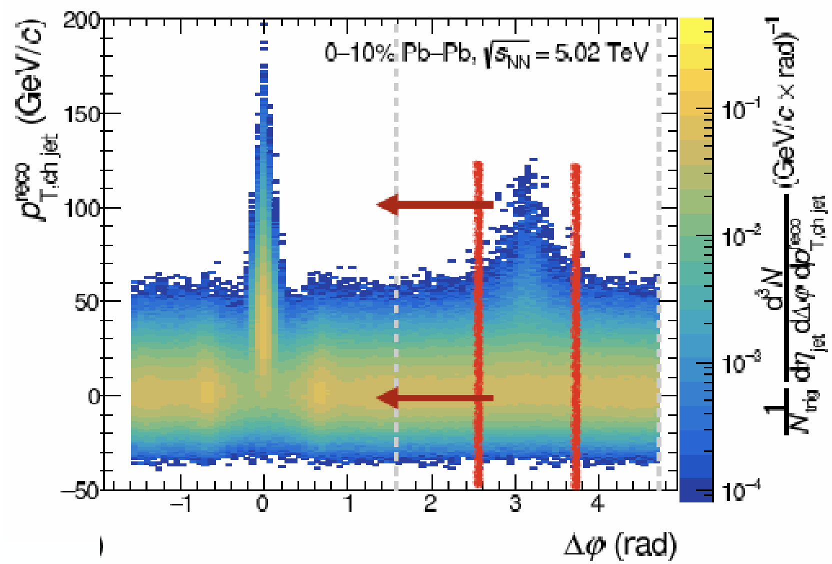
(corrected)



ALICE

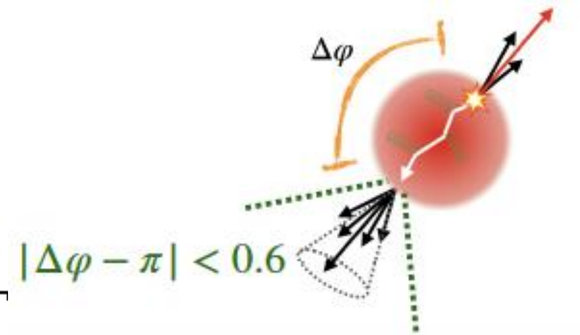
Phys.Rev.Lett. 133 (2024) 2 022301
Phys.Rev.C 110 (2024) 014906





Semi-incl. jet quenching: p_T^{jet} dependence

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



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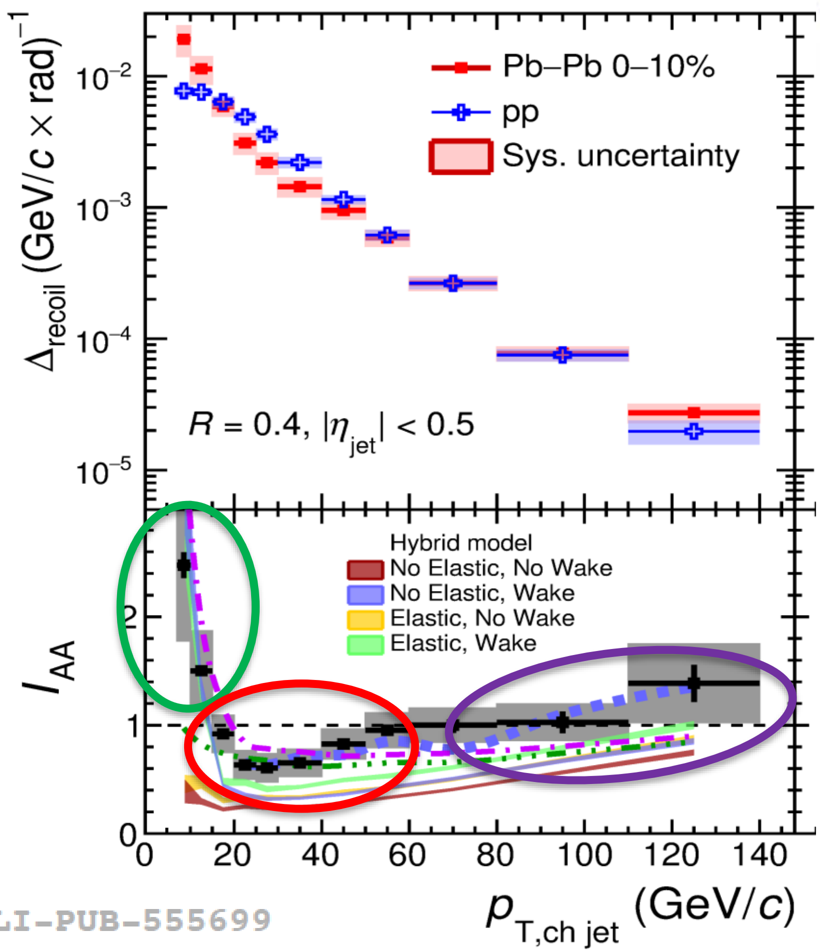
Phys.Rev.C 110 (2024) 014906

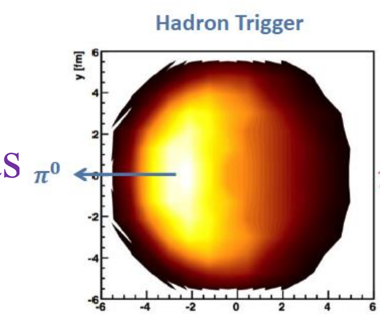
(corrected)



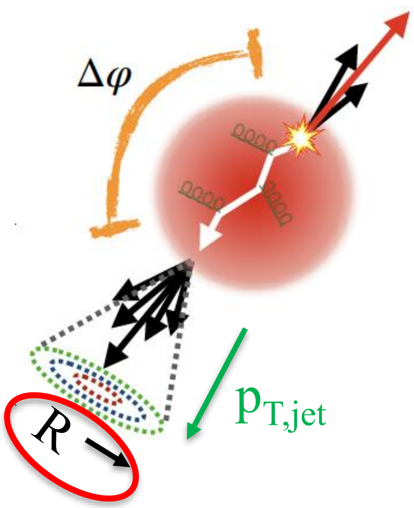
Energy loss

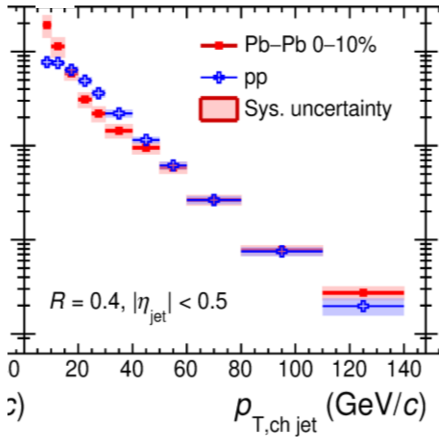
Energy recovery (!)

Change in geometric bias



In-medium jet shape modification: yield ratio R=0.2/R=0.5





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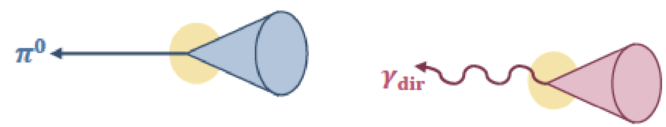
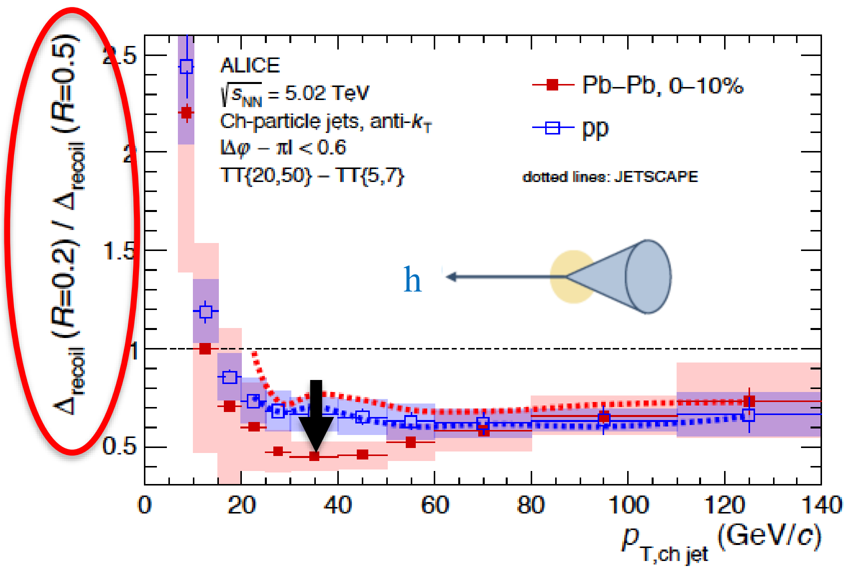
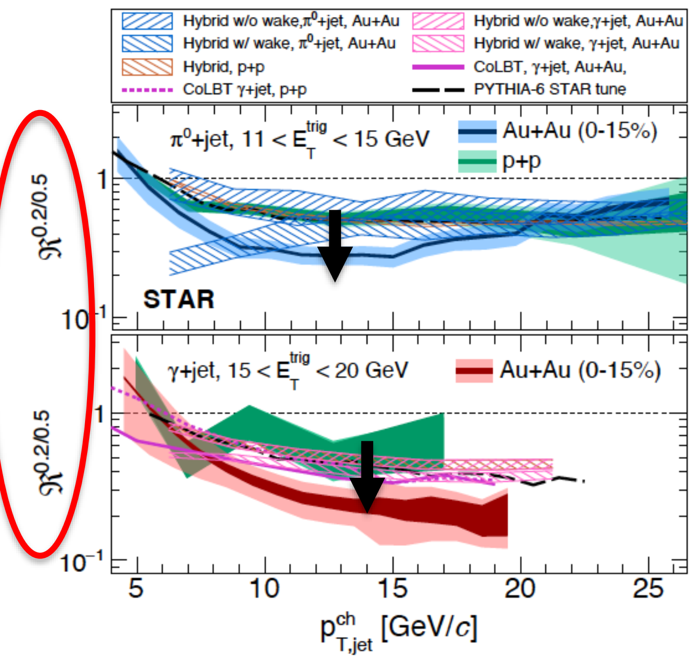
Phys.Rev.C 110 (2024) 1, 014906

Phys.Rev.Lett. 134 (2025) 232301
Phys.Rev.C 111 (2025) 064907







Medium-induced jet broadening
Seen at both LHC and RHIC!

In-medium azimuthal deflection

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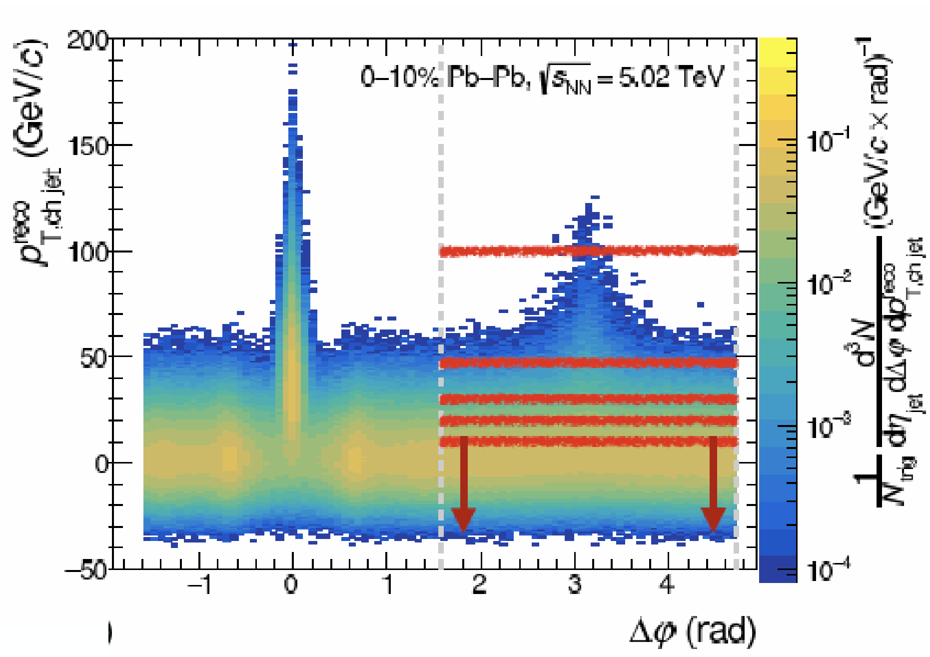
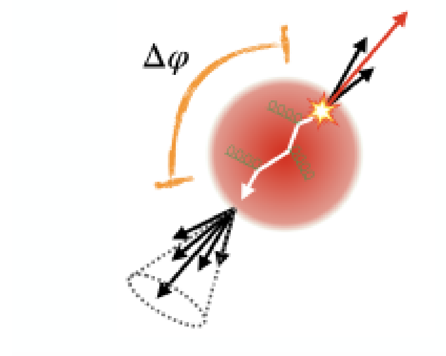
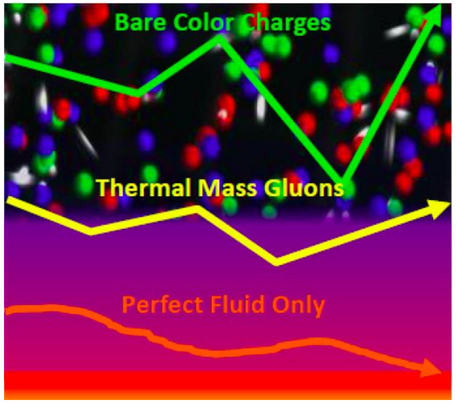
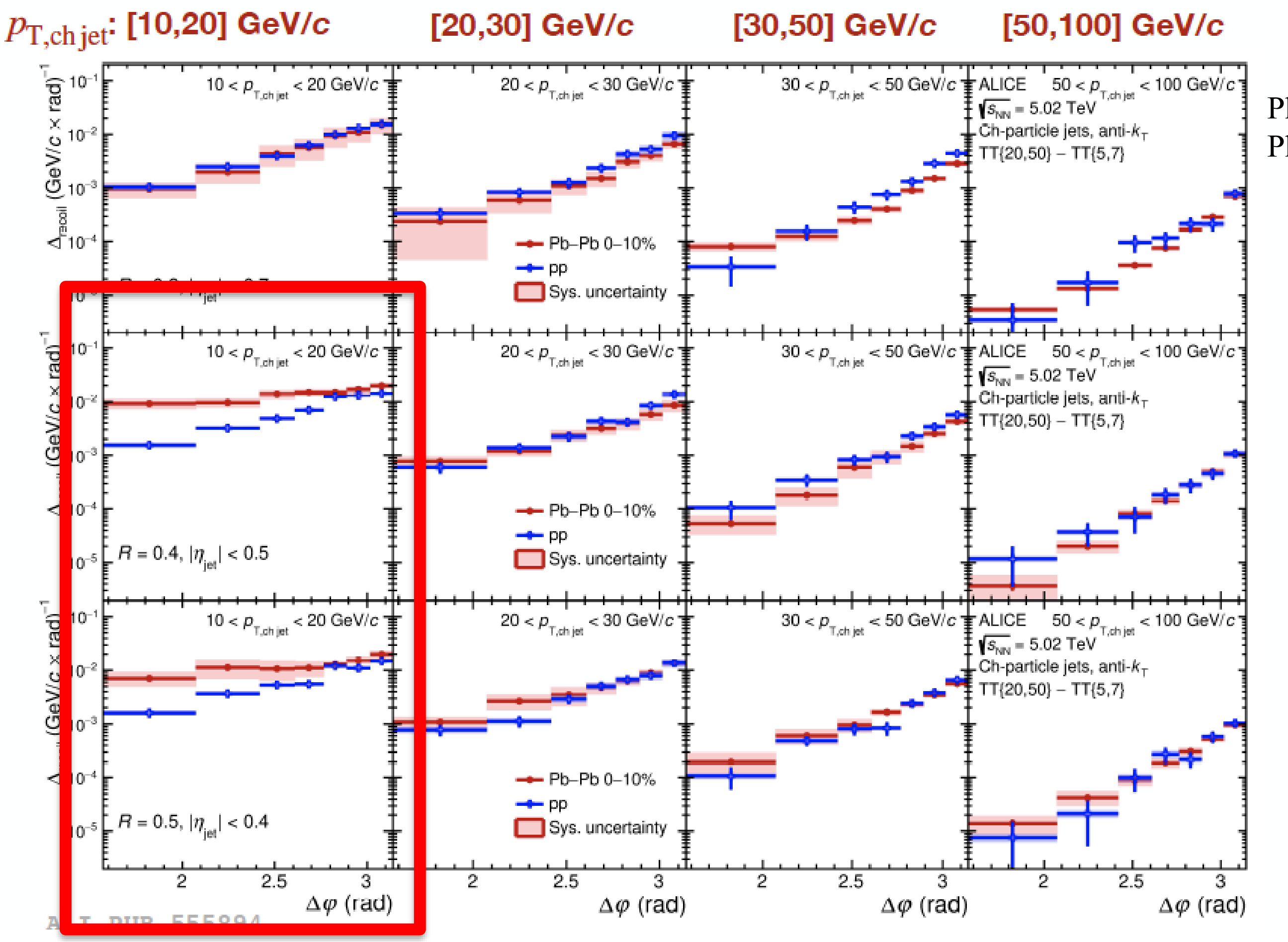
Phys.Rev.C 110 (2024) 014906







Semi-incl. jet quenching: angular dependence



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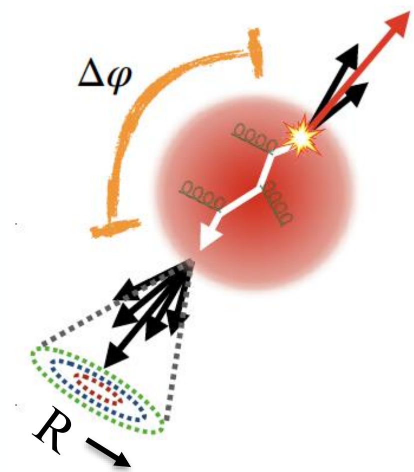
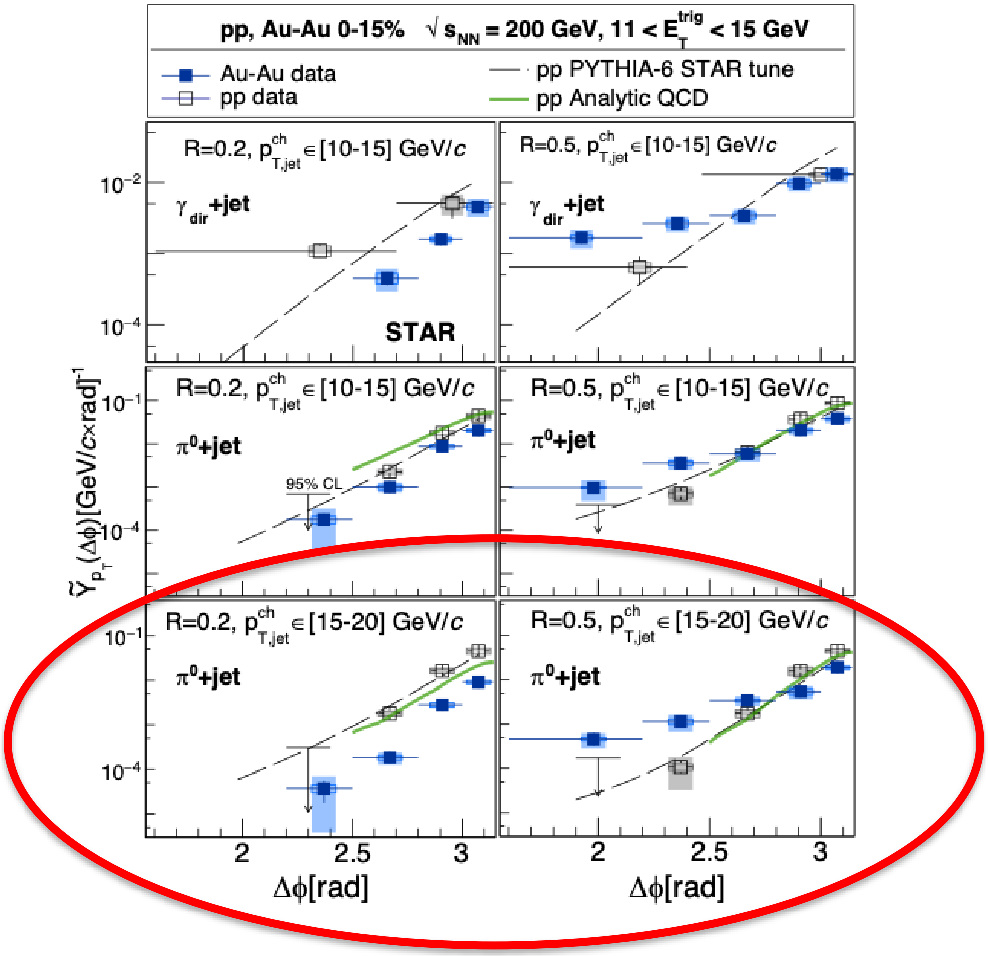
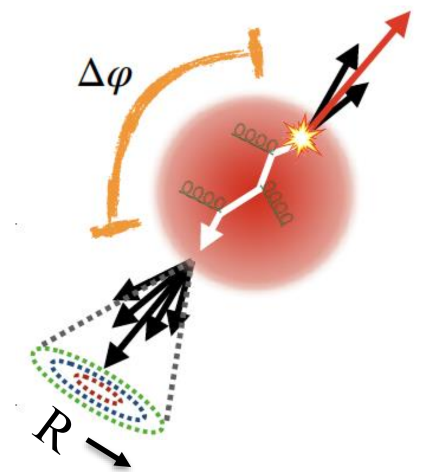


Large medium-induced azimuthal broadening for large-aperture recoil jets at low p_T^{jet} (!)

Semi-incl. jet quenching: angular dependence



Phys.Rev.Lett. 134 (2025) 232301
Phys.Rev.C 111 (2025) 064907



Large medium-induced azimuthal broadening for large-aperture recoil jets at low p_T^{jet} (!)

Medium-induced angular broadening

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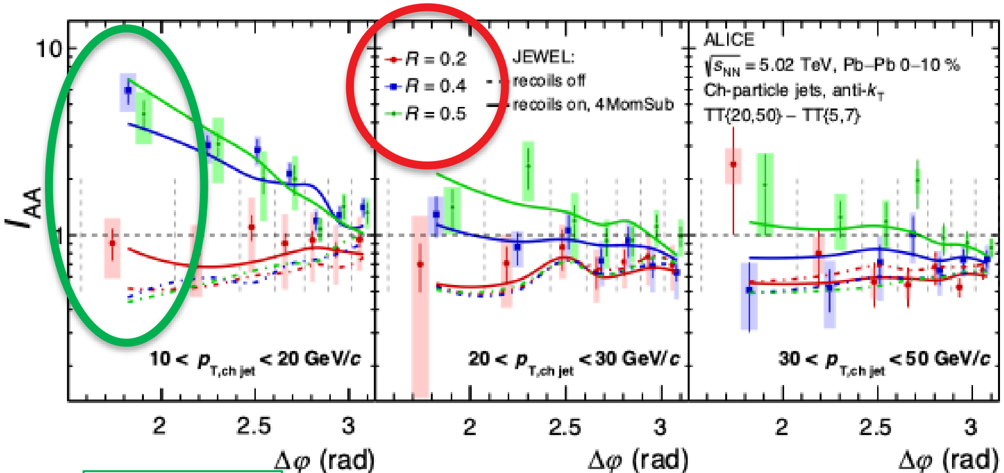
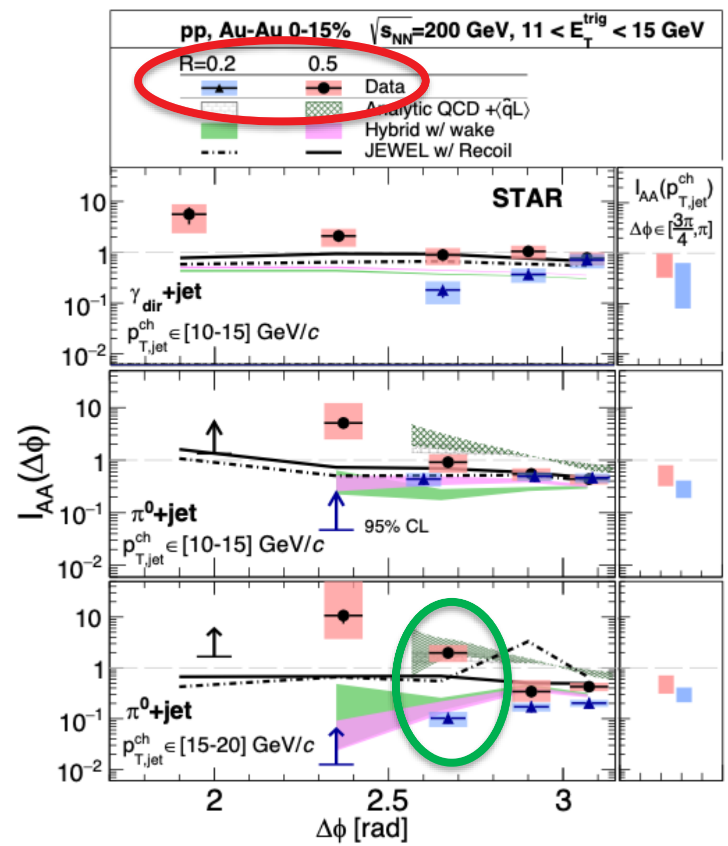
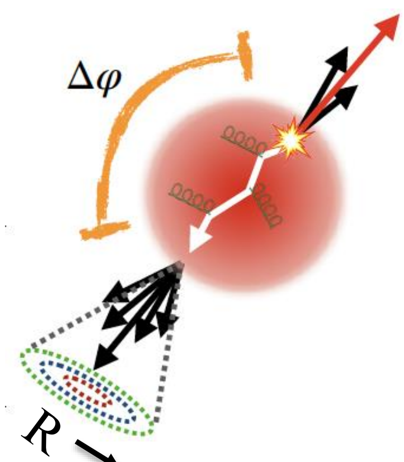




Factor 6



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

Factor 20±2; largest jet quenching signal ever observed

Semi-incl. jet quenching: angular and aperture (R) dependence

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Phys.Rev.Lett. 133 (2024) 2 022301
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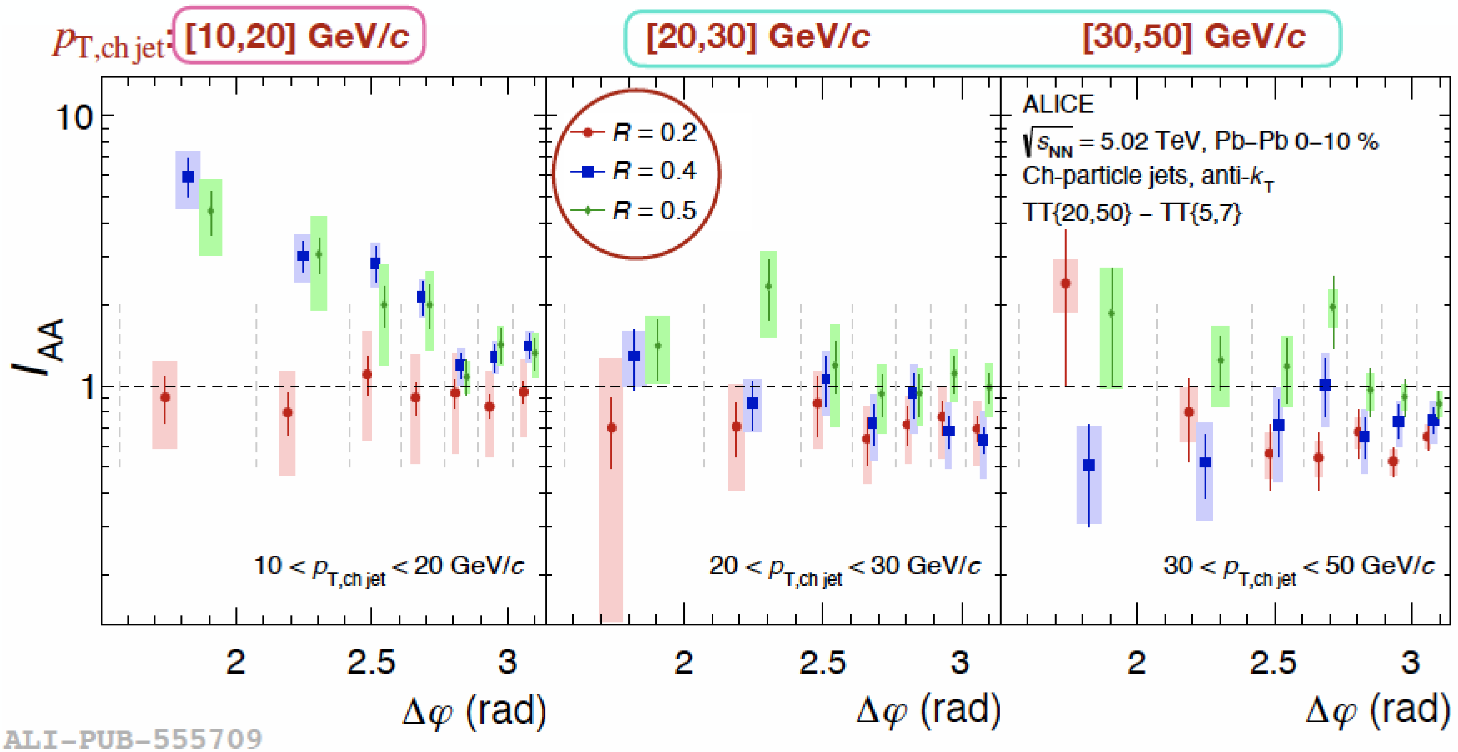
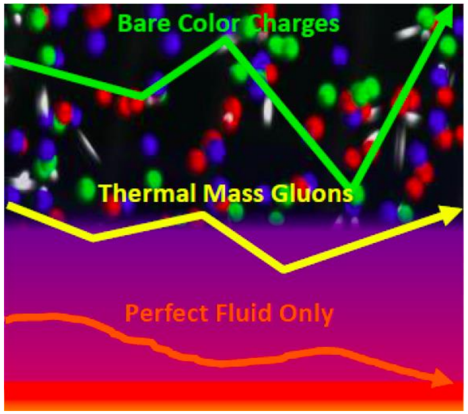
$$I_{AA} = \frac{\Delta_{recoil}(Pb-Pb)}{\Delta_{recoil}(pp)}$$

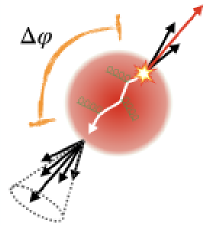


Large medium-induced azimuthal broadening

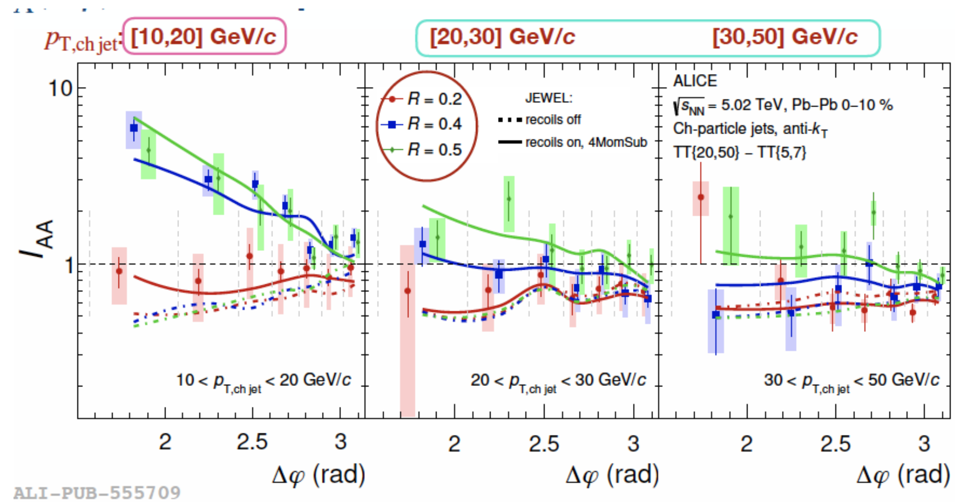
- **only** for large-aperture recoil jets
- **only** at low p_T^{jet}
- unexpected

Azimuthal broadening: what have we learned?



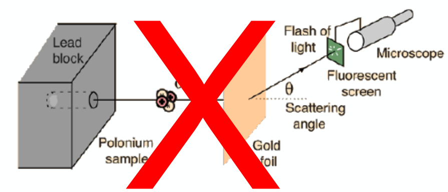


?

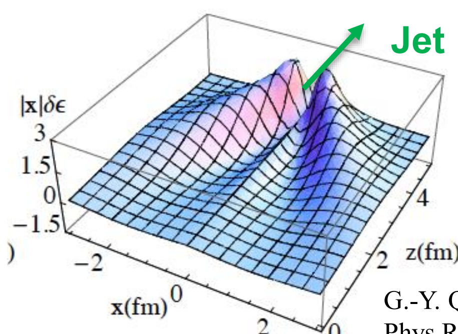


Why broadening only for large aperture recoil jets?

- not compatible with Rutherford scattering (should also affect small R jets)



Rather: characteristic of diffuse large-angle flow of QGP excited by the passage of an energetic reoil



G.-Y. Qin, A. Majumder, H. Song and U. Heinz
Phys.Rev.Lett. 103 (2009) 152303

New probe of the dynamical behavior of the QGP?

Compare to theory

arXiv:2512.12715

Emergence of thermal recoil jets in high-energy heavy-ion collisions

Peng Jing,[1] Yichao Dang,[1] Yang He,[2] Shanshan Cao,[1,*] Li Yi,[1,†] and Xin-Nian Wang[3,‡]

[1] *Institute of Frontier and Interdisciplinary Science, Shandong University, Qingdao, Shandong 266237, China*
[2] *Department of Modern Physics, University of Science and Technology of China, Anhui 230026, China*
[3] *Institute of Particle Physics and Key Laboratory of Quark and Lepton Physics (MOE), Central China Normal University, Wuhan, 430079, China*

(Dated: January 21, 2026)

In the established paradigm of jet quenching in relativistic heavy-ion collisions, jets from initial hard parton scatterings are suppressed due to their interaction with the quark-gluon plasma (QGP) as they traverse the hot medium, serving as crucial tomographic probes of QGP properties. The QGP is also capable of absorbing and reprocessing energy deposited by the hard jets into emergent jet-like objects, providing a novel production mechanism of thermal recoil jets. These emergent thermal recoil jets exhibit distinct transverse momentum (p_T) and jet-size (R) dependencies different from the hard jets, and naturally explain the puzzling observation of the enhanced yields of hadron or photon triggered jets at large azimuthal angle and solely at small p_T and large R. These thermal recoil jets are predicted to have unique substructures, such as their jet shape that increases with the radius and the thermal-like distribution of their constituents, which can be verified in future experimental analyses.

arXiv:2512.12715

Emergence of thermal recoil jets in high-energy heavy-ion collisions

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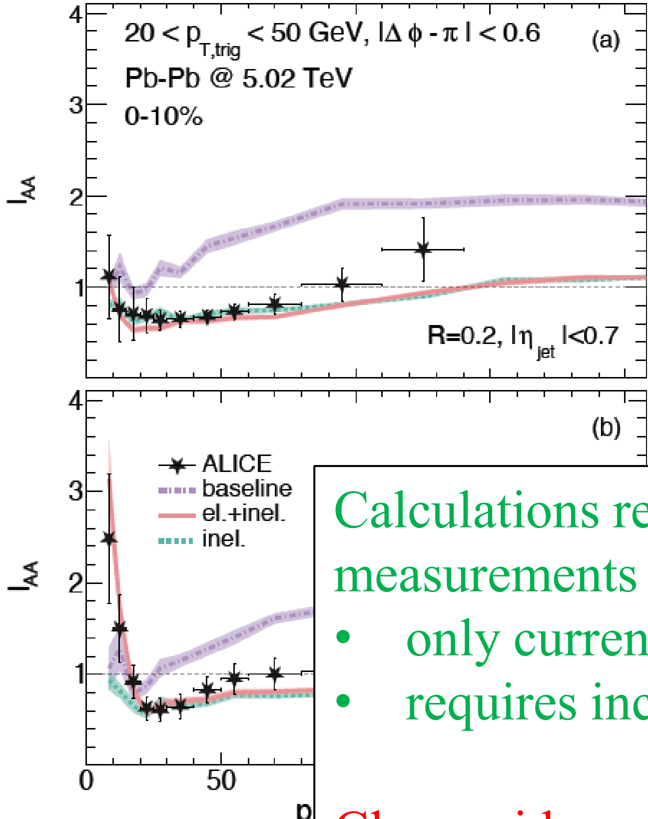
[1]*Institute of Frontier and Interdisciplinary Science, Shandong University, Qingdao, Shandong 266237, China*
[2]*Department of Modern Physics, University of Science and Technology of China, Anhui 230026, China*
[3]*Institute of Particle Physics and Key Laboratory of Quark and Lepton Physics (MOE), Central China Normal University, Wuhan, 430079, China*
(Dated: January 21, 2026)

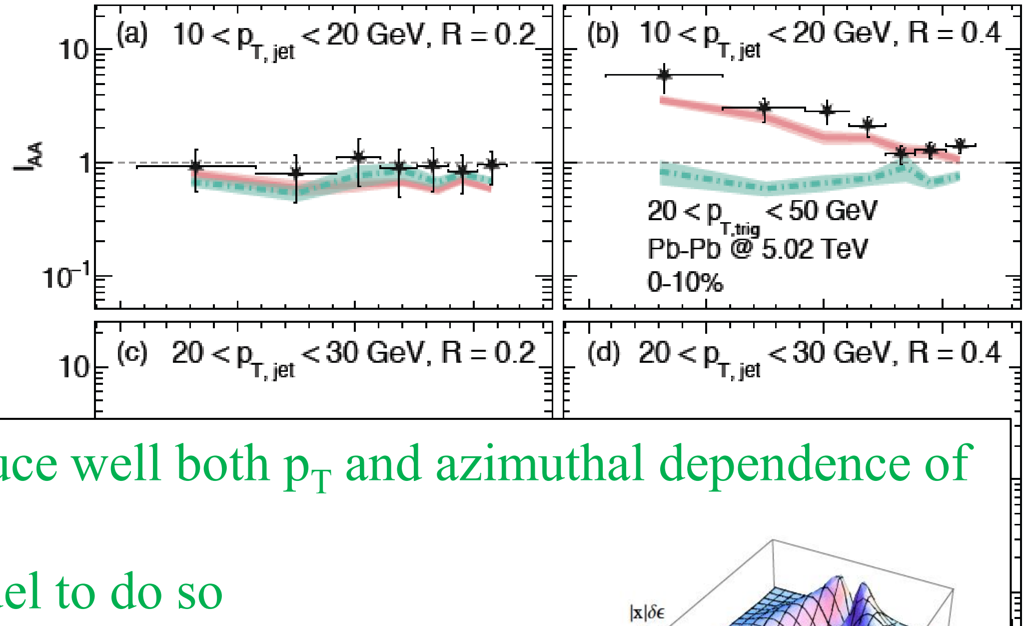
Linear Boltzmann Transport (LBT) model

- 3+1 dimensional hydrodynamics
- elastic and inelastic jet-medium scattering in Higher Twist (HT) approach
- generation of radiative and thermal recoil partons; further scattering and QGP back-reaction

Currently the most detailed and complete model of QGP response to excitation by a jet

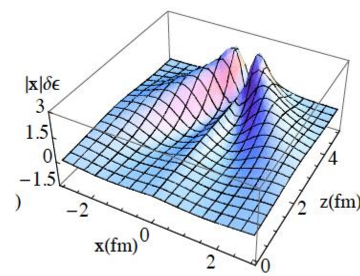
arXiv:2512.12715





Calculations reproduce well both p_T and azimuthal dependence of measurements

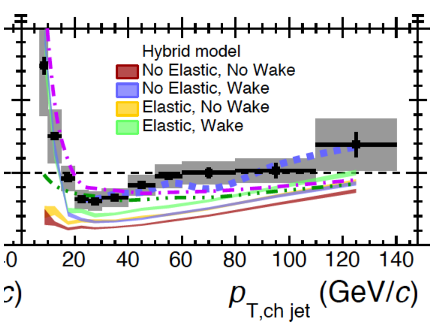
- only current model to do so
- requires inclusion of medium response

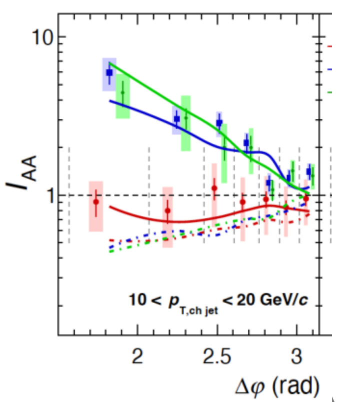


Clear evidence for “thermal jets” or jet wake

ALICE

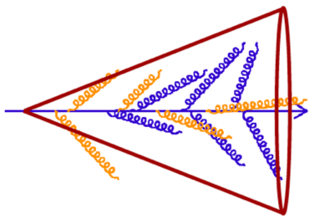
Phys.Rev.Lett. 133 (2024) 2 022301
Phys.Rev.C 110 (2024) 014906

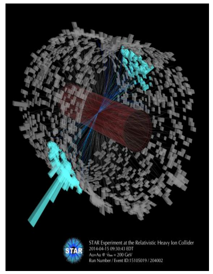


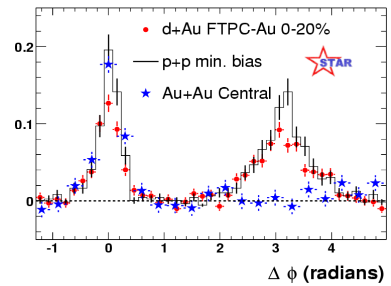


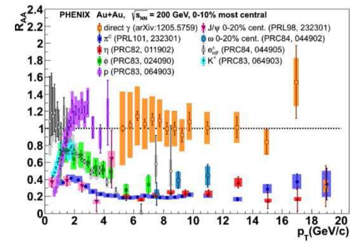
Opens a new chapter: study of the QGP response to excitation!

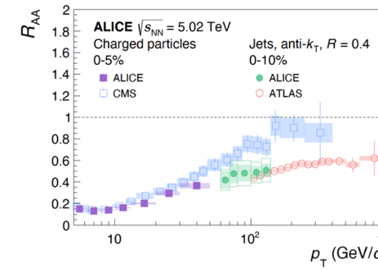
Summary of Lecture 2

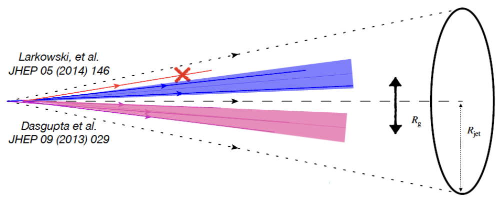


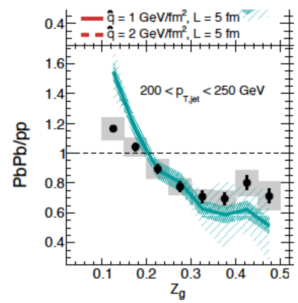


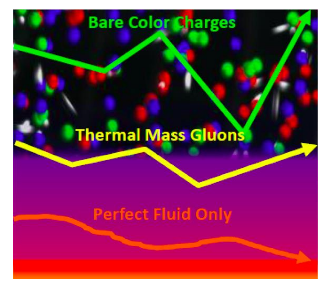


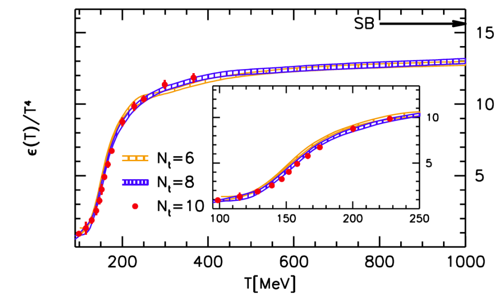


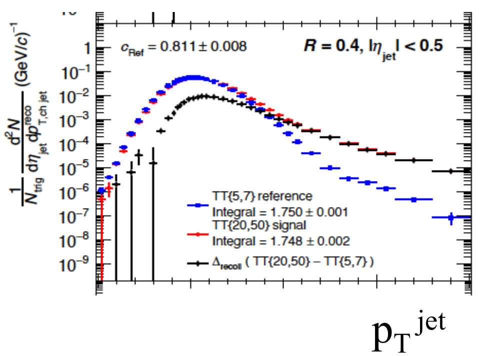


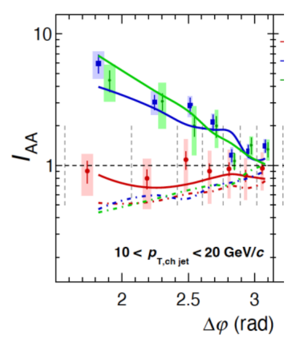


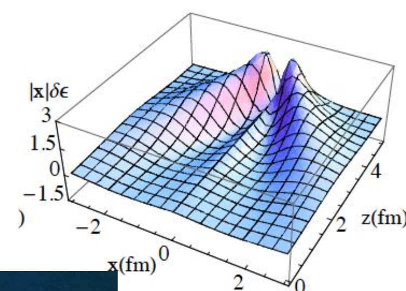


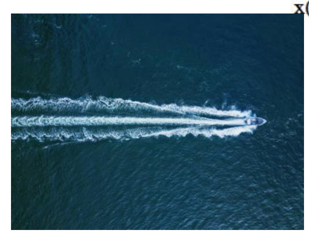












Opens a new chapter: study of the QGP response to excitation!

Extra slides

Azimuthal broadening: p_T^{jet} dependence

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