



# Measuring multi-body QCD

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

Slides: <https://tinyurl.com/JacobsICTS>

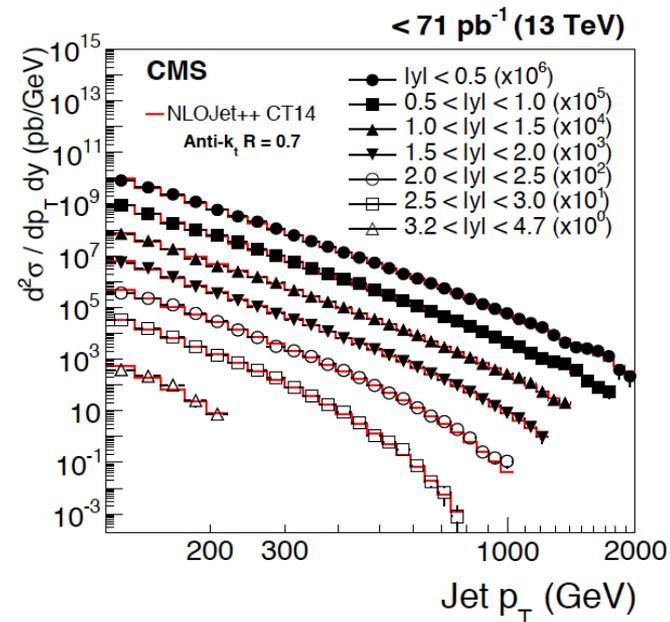
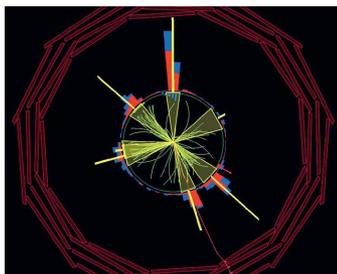
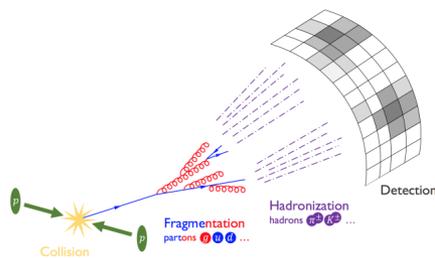
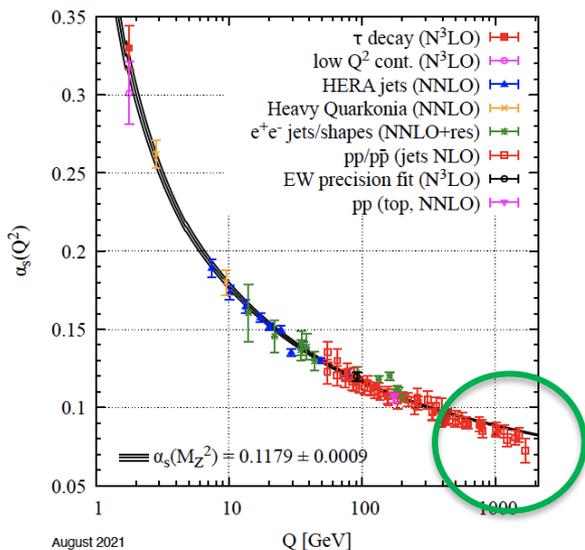
Hard probes in non-equilibrium QCD matter  
March 16-27, 2026



TATA INSTITUTE OF FUNDAMENTAL RESEARCH

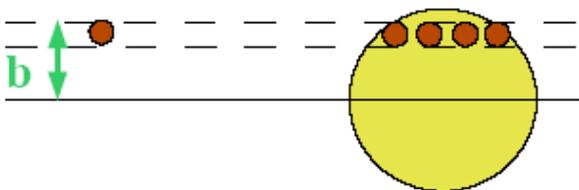
# Lecture 1 recap

## Jets measure partons



Coupling  $\alpha_s$  small  $\rightarrow$  asymptotic freedom  $\rightarrow$  jets

## Hard-process production rate in nuclear collisions



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

## 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.

## More Is Different

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

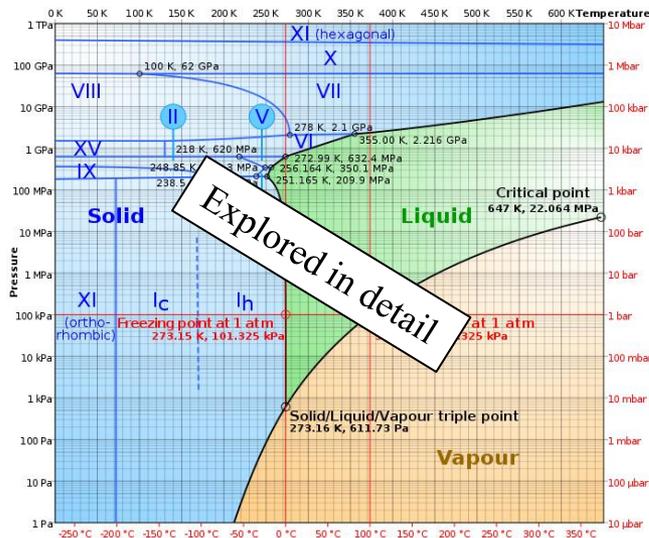
P. W. Anderson

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

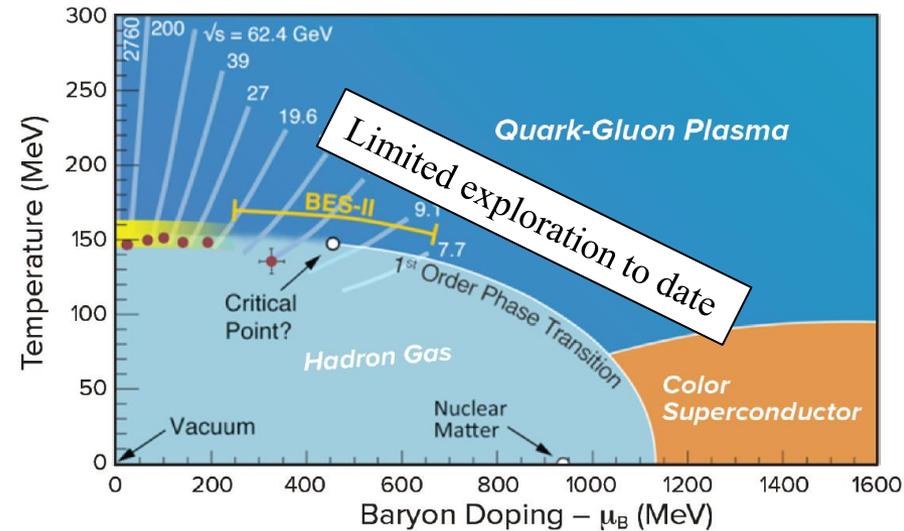
Phase diagram of water



compress ↑

heat →

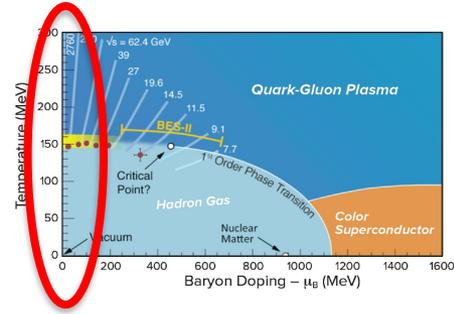
Phase diagram of QCD matter



heat ↑

compress →

# Finite Temperature QCD calculated numerically on the Lattice ( $\mu_B=0$ )

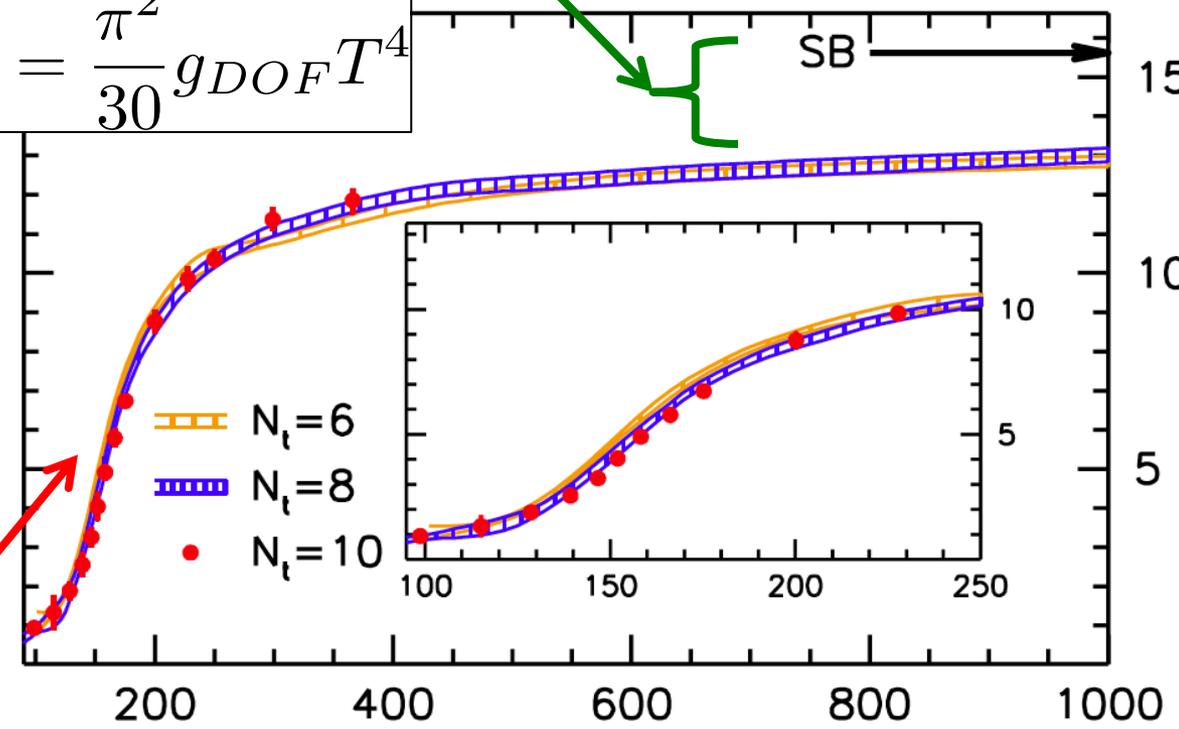


Slow convergence to non-interacting Steffan-Boltzmann limit  
 What carries energy - complex bound states of q+g? “strongly-coupled” plasma?

Energy density

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

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

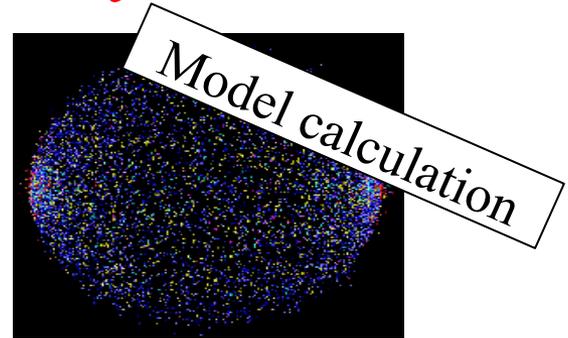
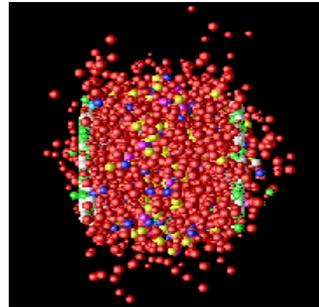
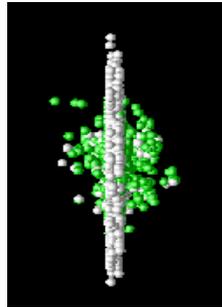
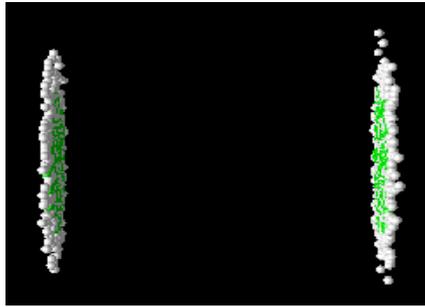


Temperature [MeV]

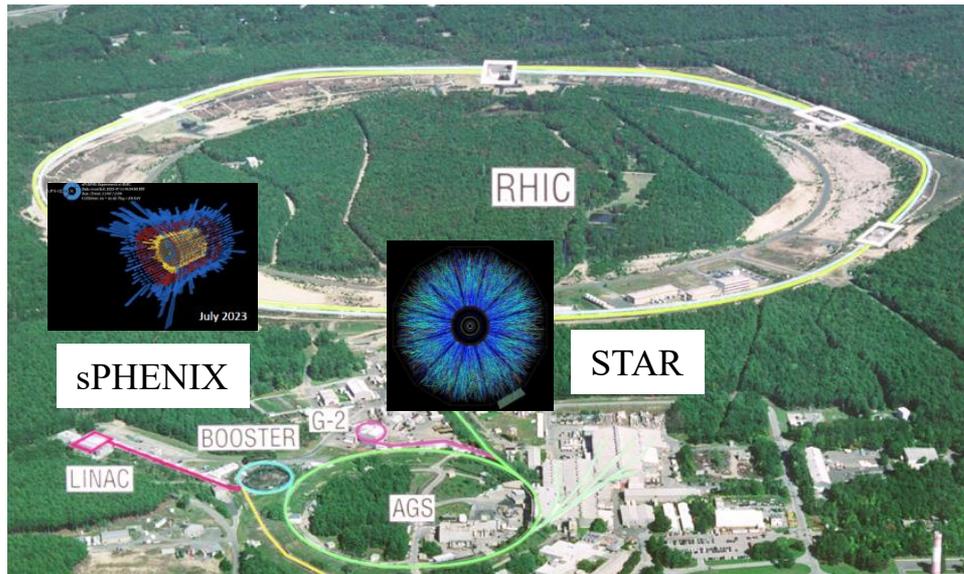
Cross-over, not sharp phase transition (like ionization of atomic plasma)

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

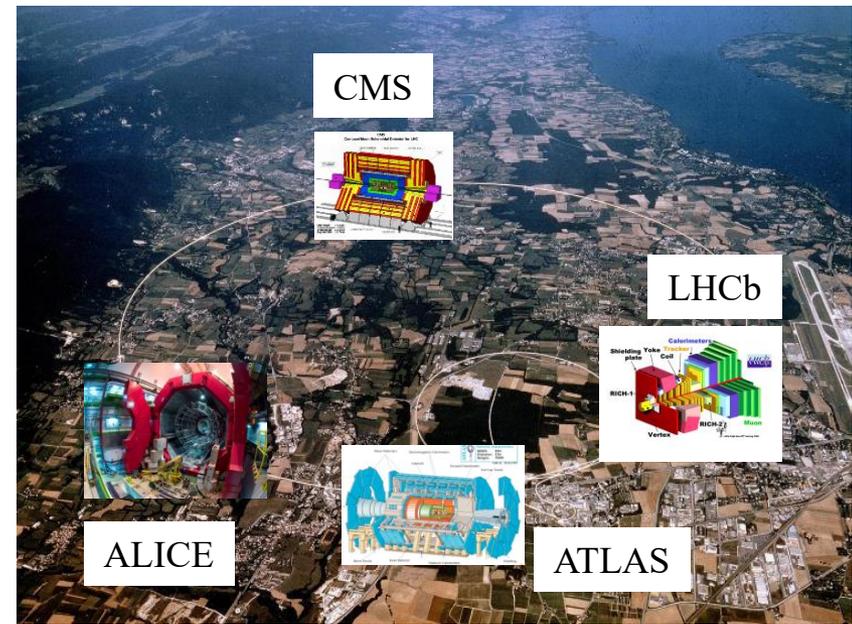
# Quark-gluon plasma in the laboratory: high-energy collisions of heavy nuclei



RHIC @ BNL



LHC @ CERN



Thousands of particles in the final state

→ the most complex collisions ever studied in the laboratory



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

First proposal of the  
concept of jet quenching

### Abstract

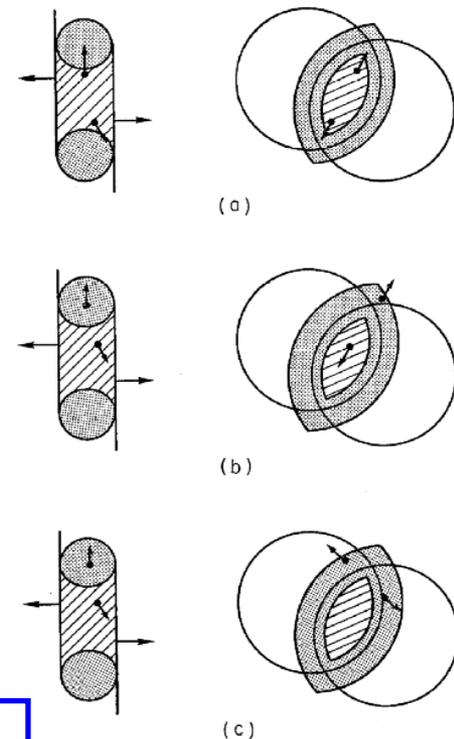
High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The  $dE/dx$  is roughly proportional to the square of the plasma temperature. For

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

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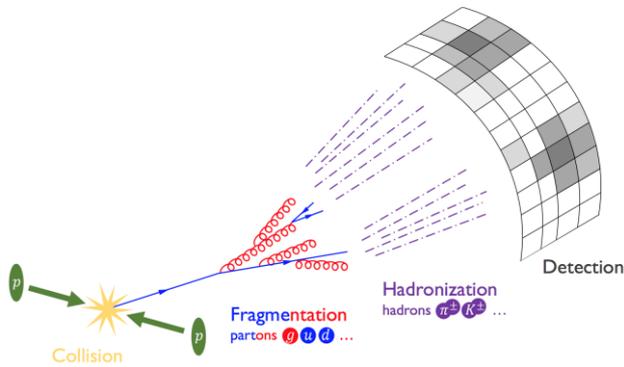
produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for

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.

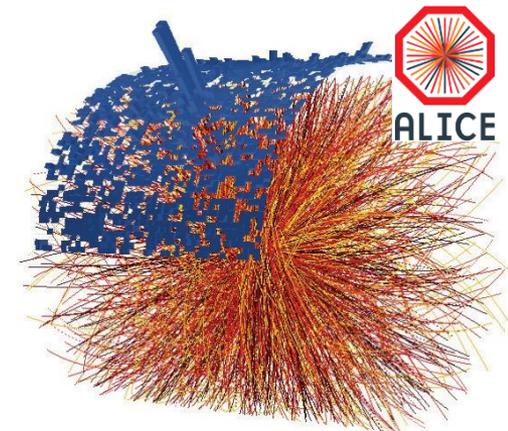
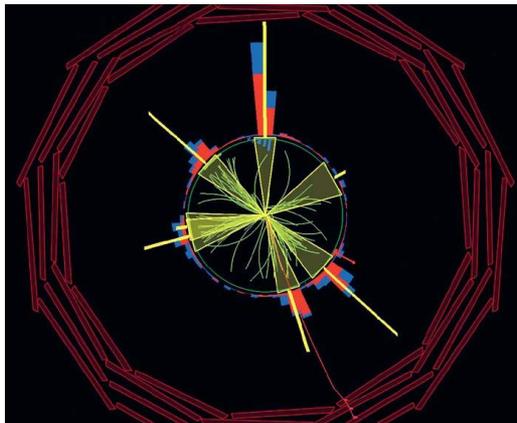
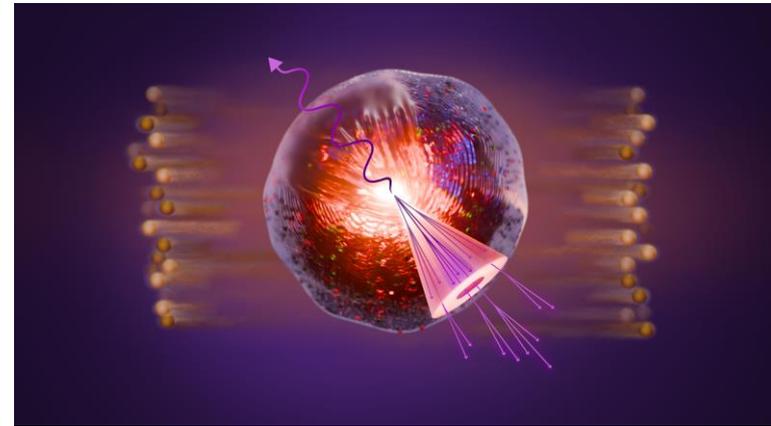


# Jets probes of the QGP

## Jets in vacuum

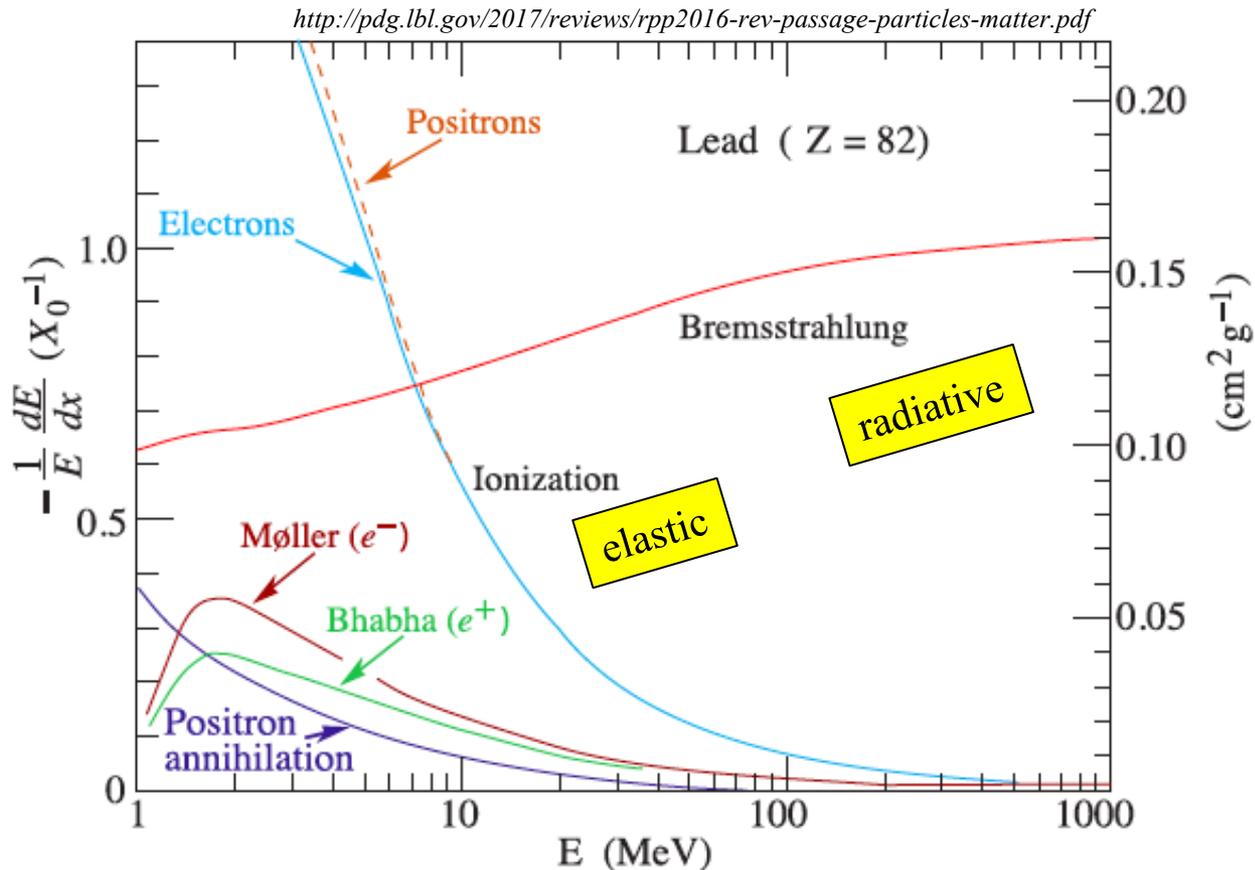


## Jets in nuclear collisions



# Energy loss in QED

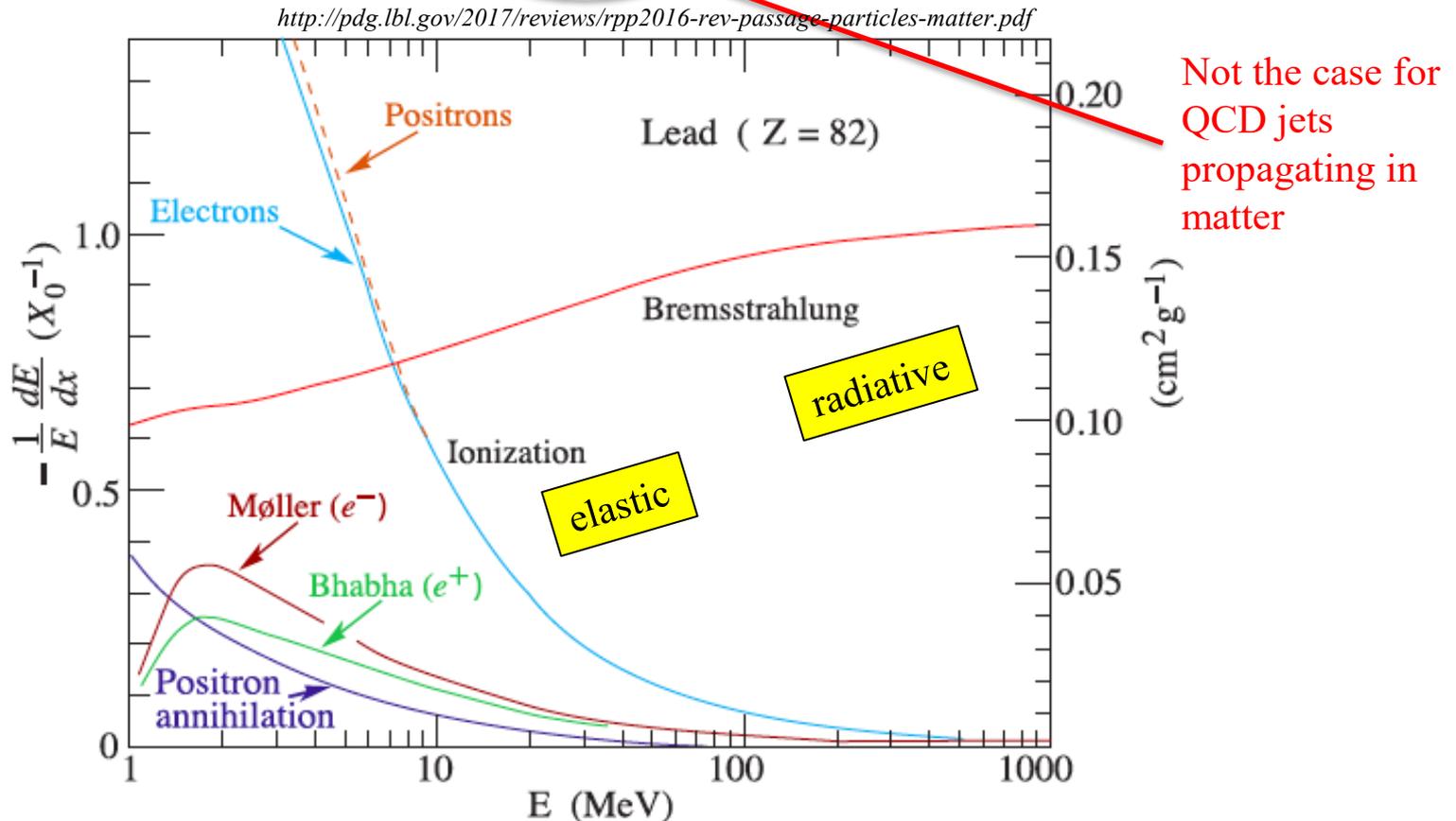
Fractional energy loss of an (on-shell) electron or positron in Lead



**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

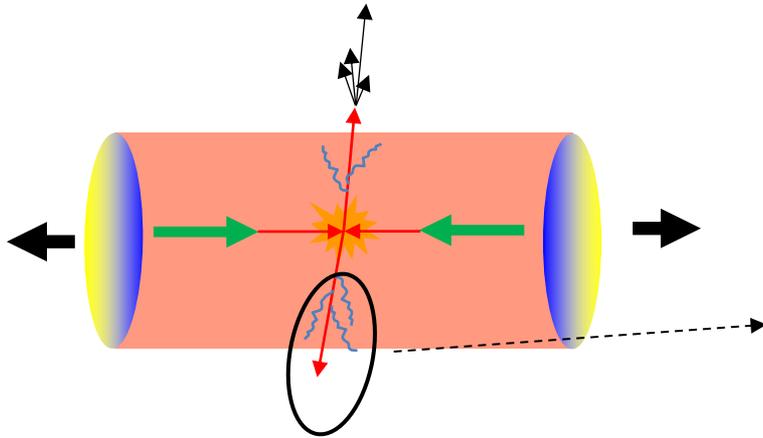
# Energy loss in QED

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

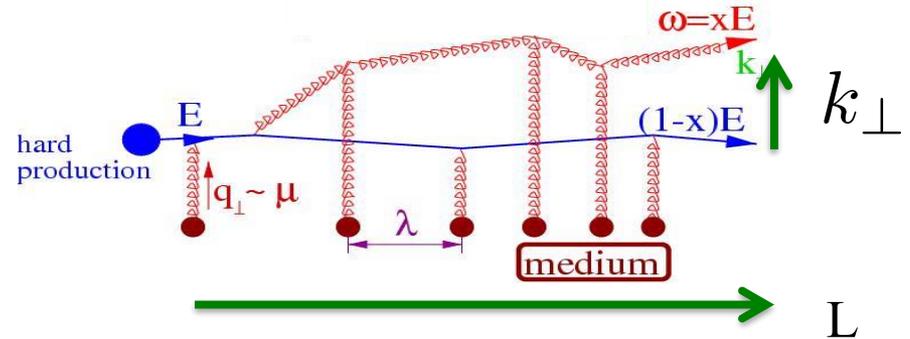


**Figure 33.11:** Fractional energy loss per radiation length in lead as a function of electron or positron energy. Electron (positron) scattering is considered as ionization

# Radiative energy loss in QCD



Medium-induced gluon radiation



Thermal field theory:

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

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

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

$\mathbf{q}$  = Momentum transfer

$T$  = Temperature

$m_D$  = Debye mass

} QGP properties

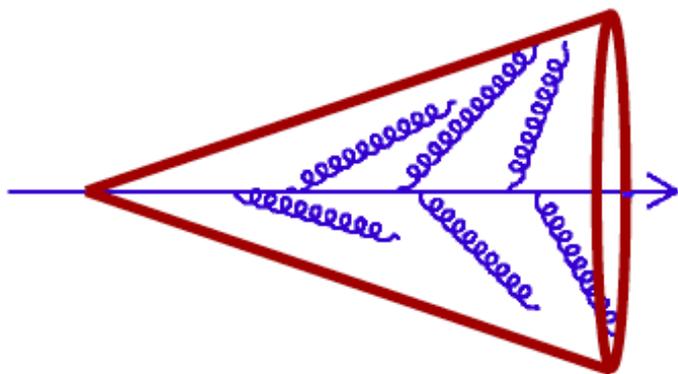
$$\hat{q} \equiv \frac{\langle k_{\perp}^2 \rangle}{L} \sim \frac{1}{L} \int d\mathbf{q}^2 \mathbf{q}^2 C(\mathbf{q})$$

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

# Jet quenching in one slide

## Jet shower in-medium

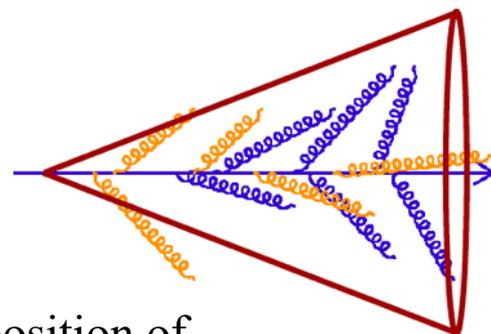
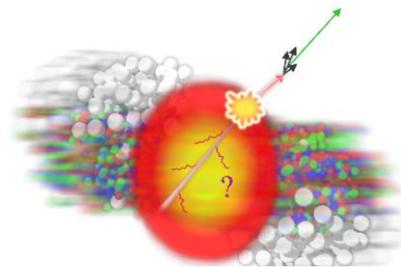
### Jet shower in vacuum



Evolution of highly virtual parton via gluon radiation

Quantum interference  $\rightarrow$  angle-ordering

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



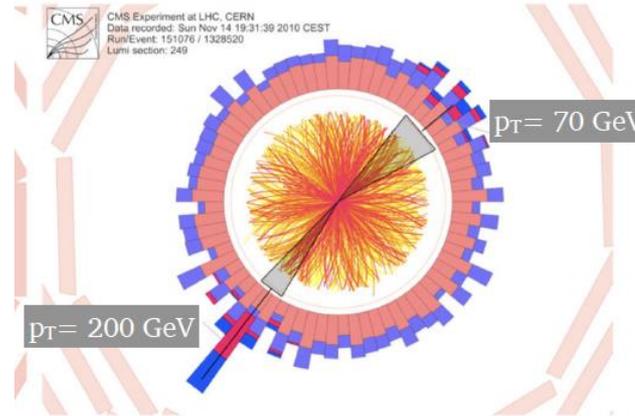
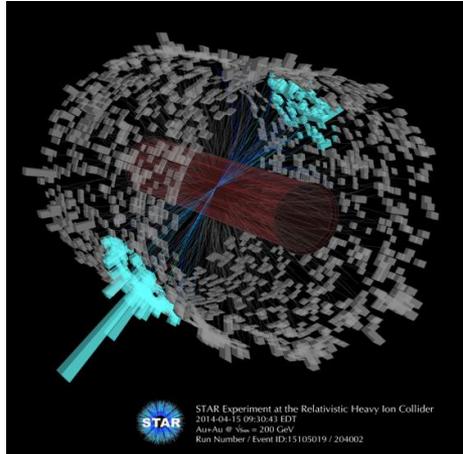
Superposition of

- 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

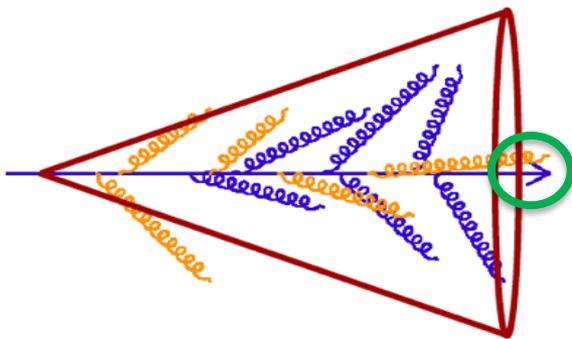


Very complex experimental environment

Huge background of particles not correlated with jet shower

How to make precise measurements?

First try simplifying the problem



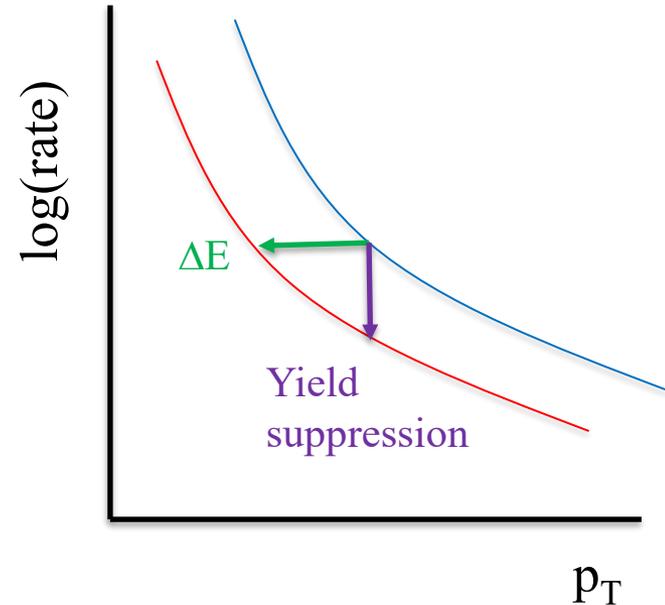
Particle spectrum of uncorrelated background is largely “soft” (low  $p_T$ )

→ 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  $\Delta E$  to lower  $p_T$

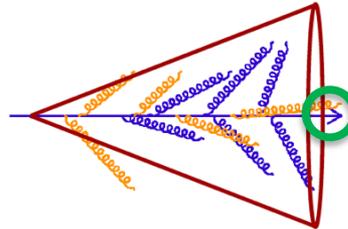


Equivalently: yield is suppressed at fixed  $p_T$

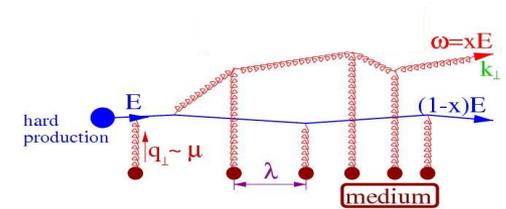
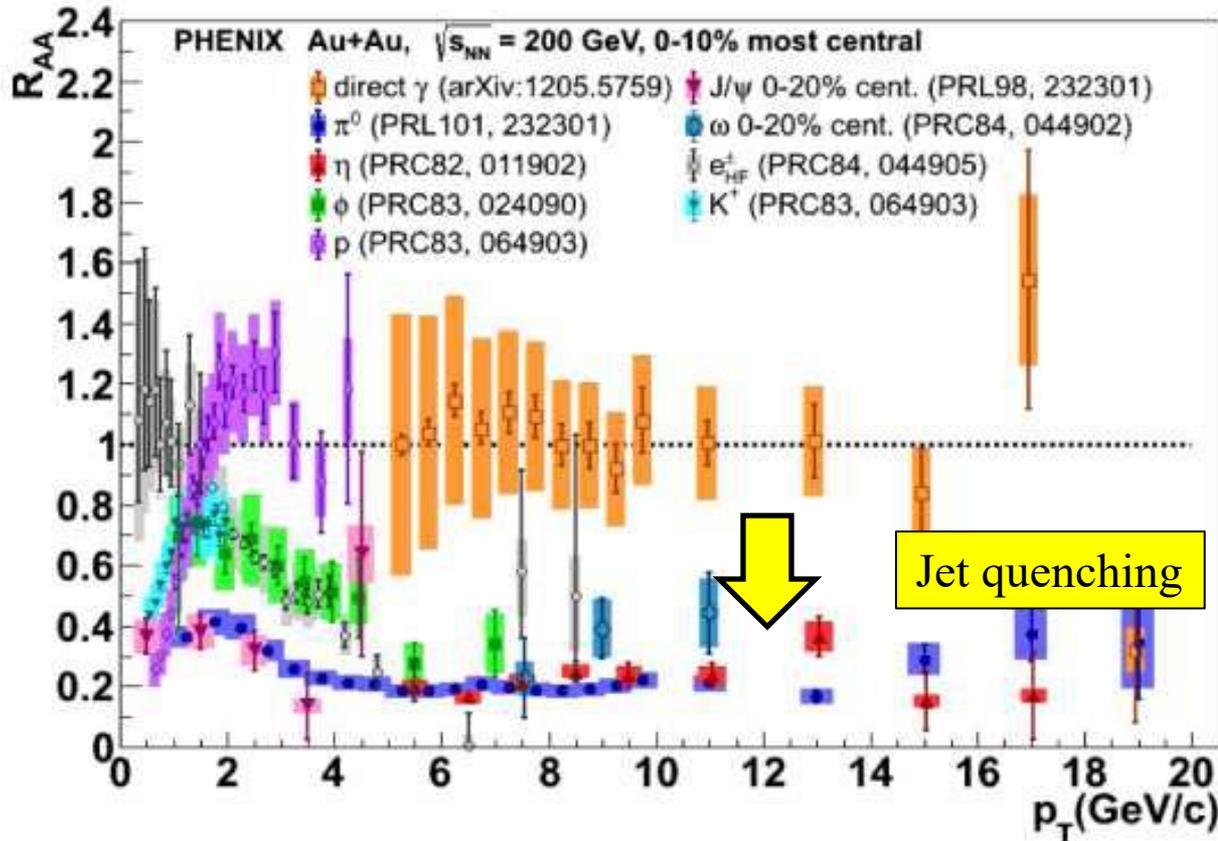
$$R_{AA}(p_T) = \frac{\text{Observed rate in AA}}{\text{Expected rate in pp} \otimes \text{geometry}}$$
$$= \frac{dN_{AA}^{hard}/dp_T}{\langle T_{AA} \rangle d\sigma_{pp}^{hard}/dp_T}$$

# Initial evidence for jet quenching: inclusive hadron suppression

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



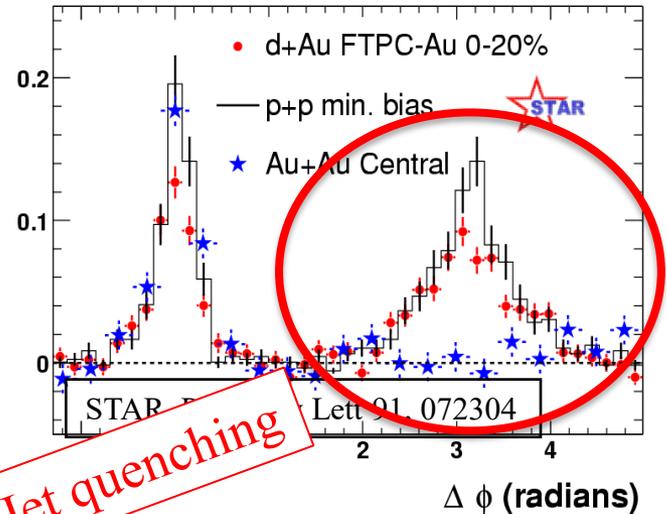
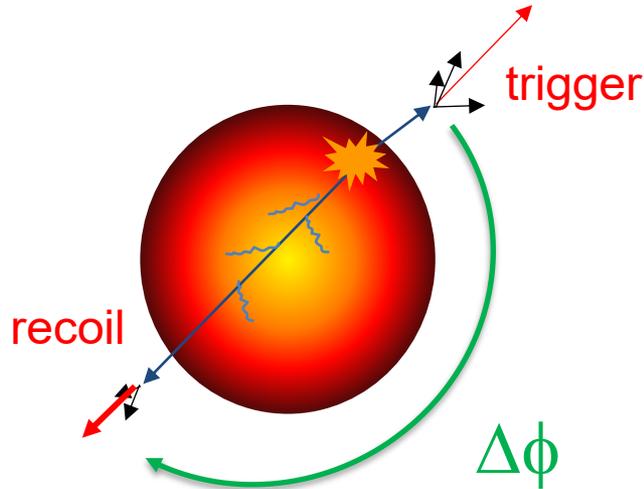
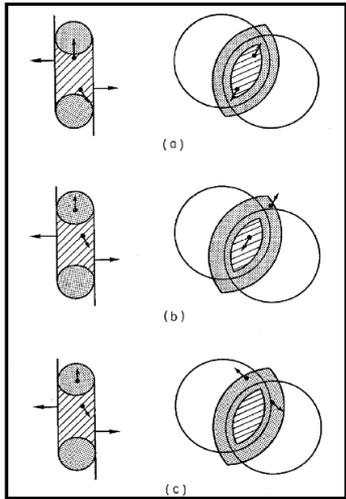
Measure only very high  $p_T$  hadrons (“leading hadrons” of jets)



Photons (color-neutral)

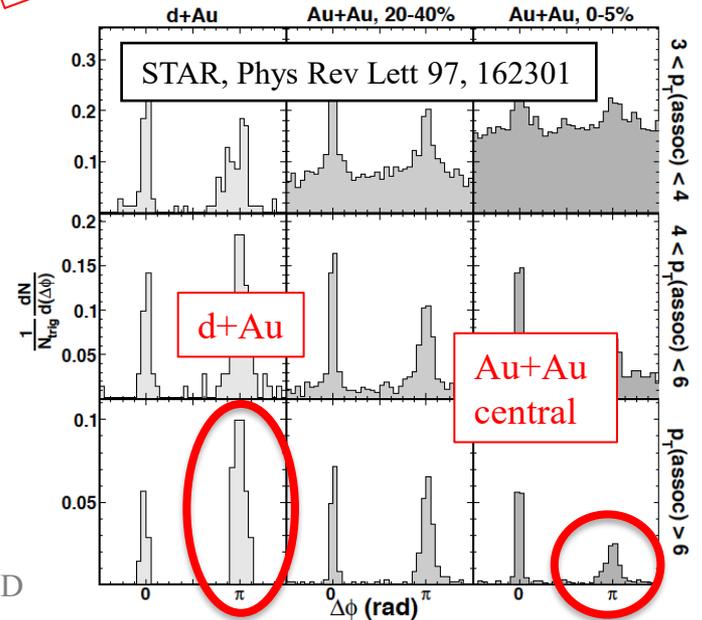
Jet fragments (color-charged)

# 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.

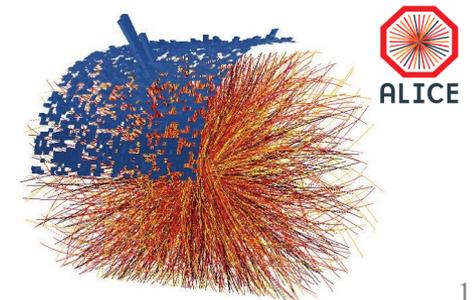
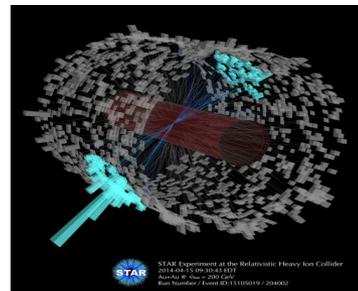
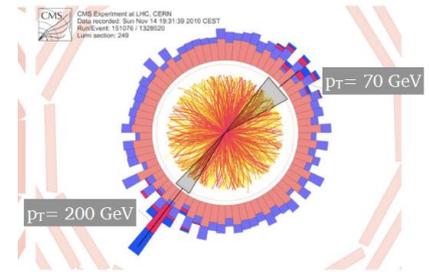
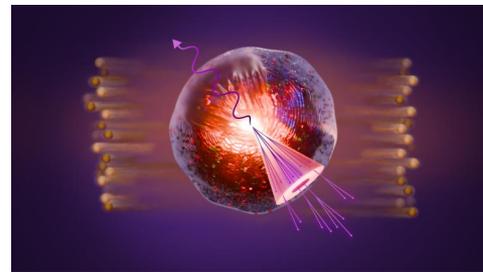
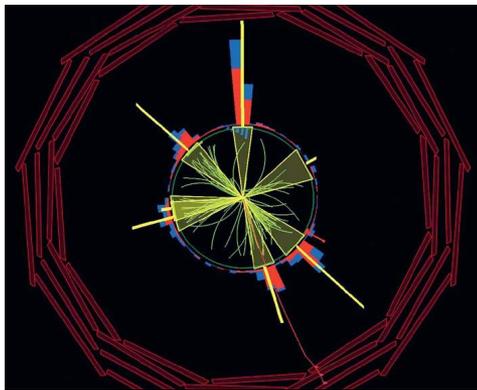
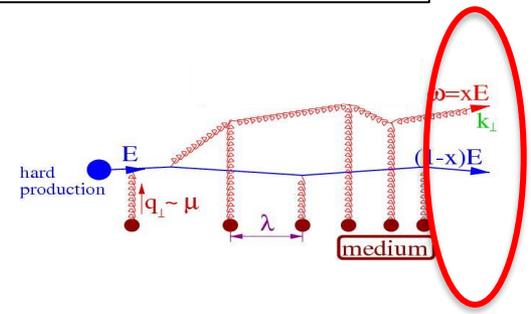
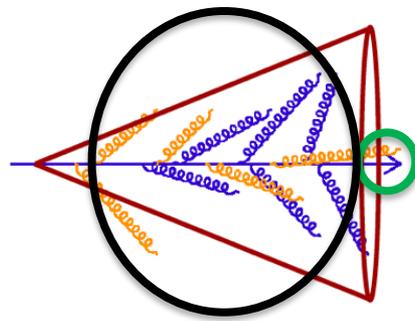
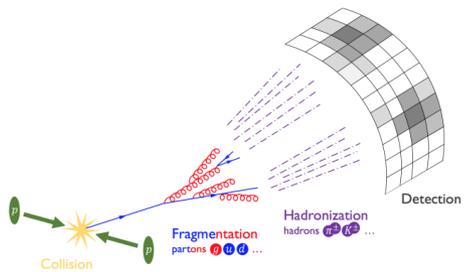
An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.



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

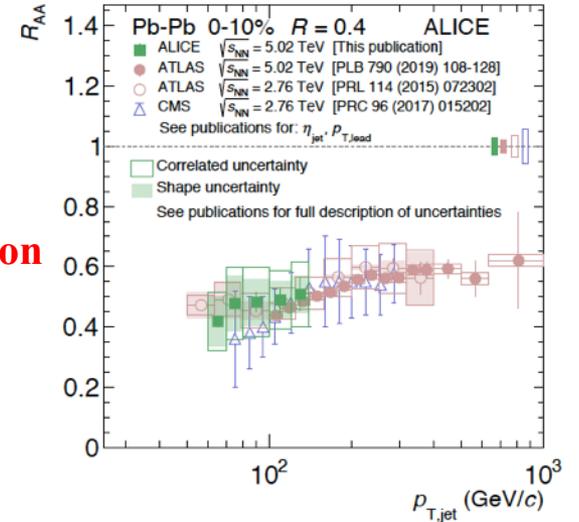
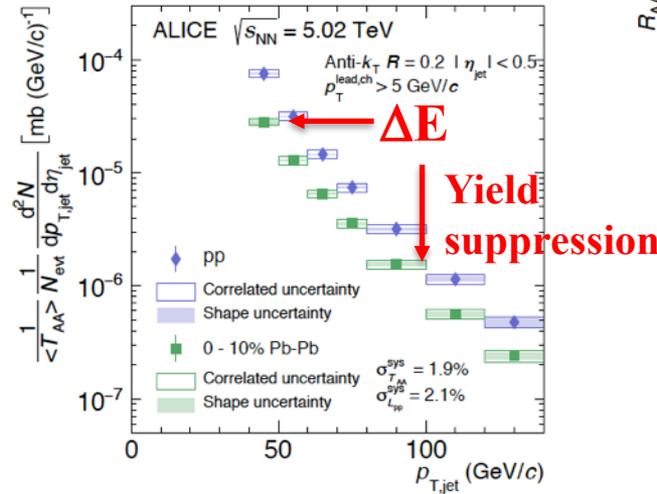
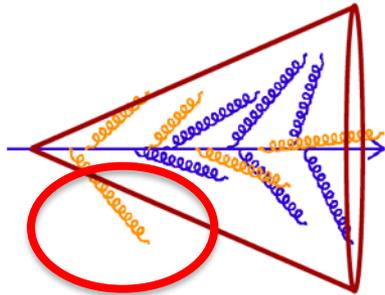
## Jets in nuclear collisions

### Jets in vacuum

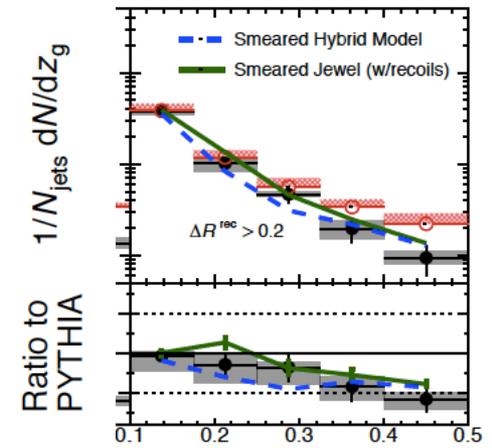
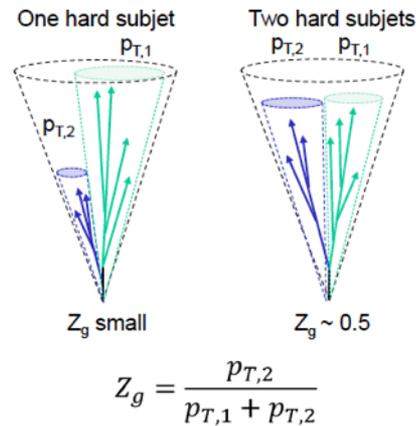
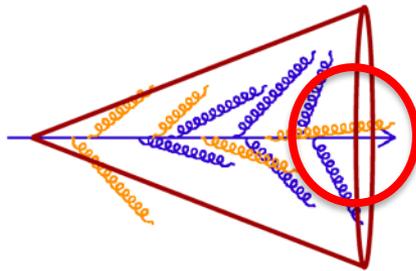


# Jet quenching: observable consequences I

## 1. Energy loss

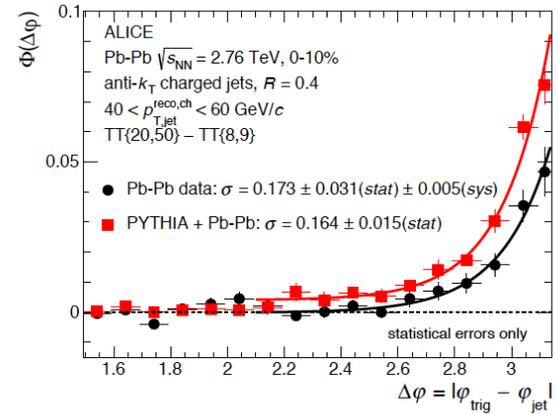
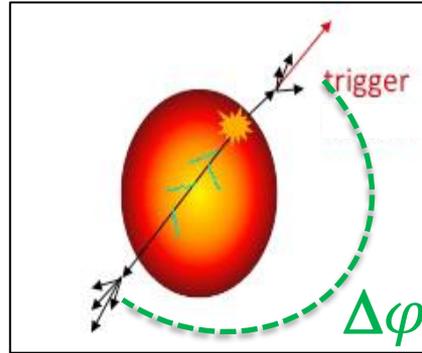
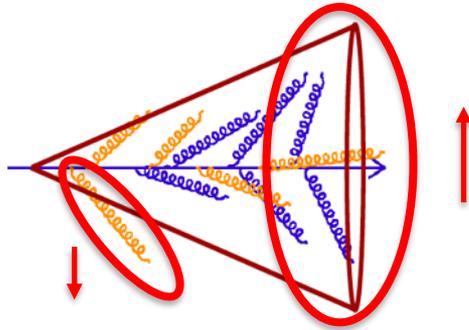


## 2. Modification of jet substructure

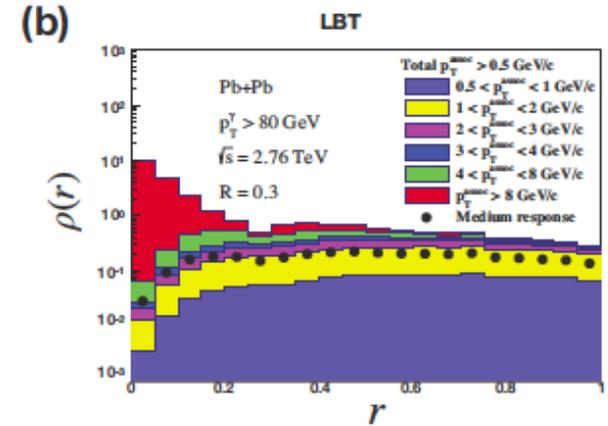
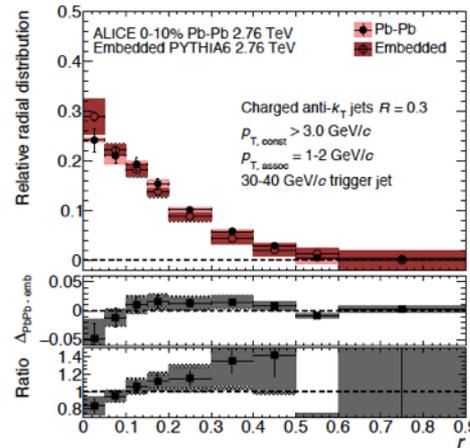
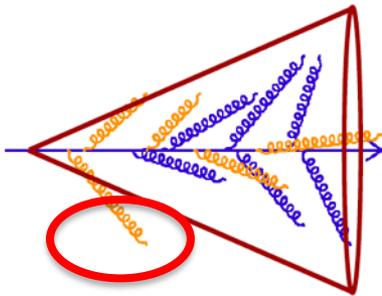


# Jet quenching: observable consequences II

## 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

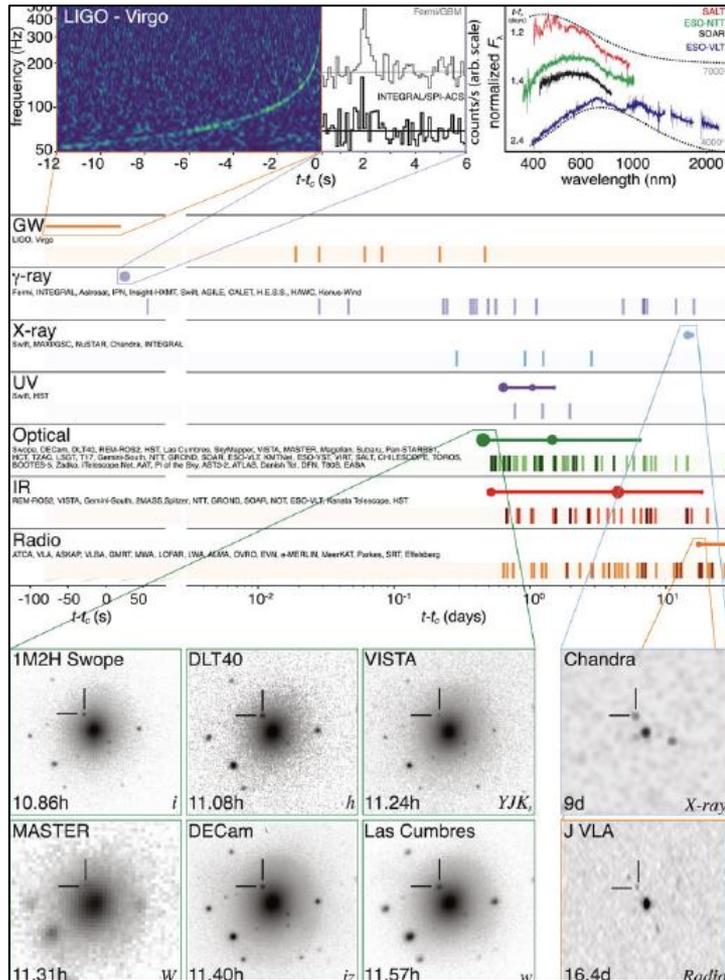
- All must occur if any of them does
- Probe different aspects of jet quenching
- Different experimental systematics as fn of kinematics and collision system
- Different theoretical sensitivity as fn of kinematics and collision system

Jet quenching is multi-messenger physics!

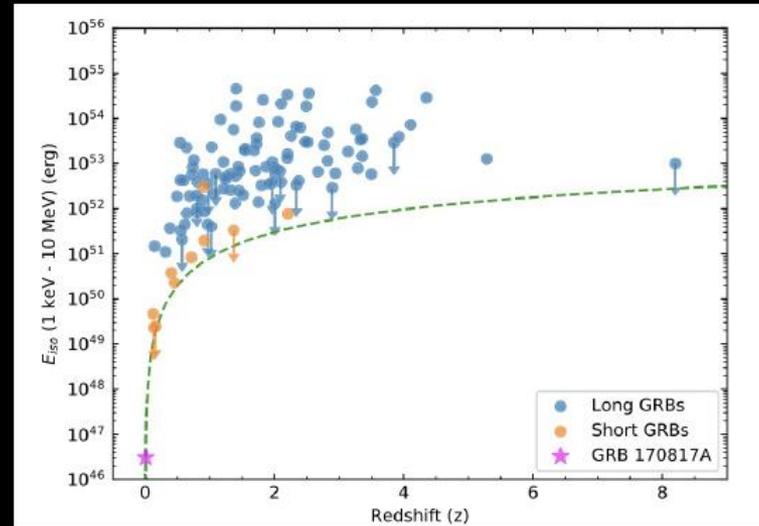
Measure the same physics multiple ways and require a consistent picture

# Multi-messenger physics: another example

G. De Wasseige, ICHEP 2022



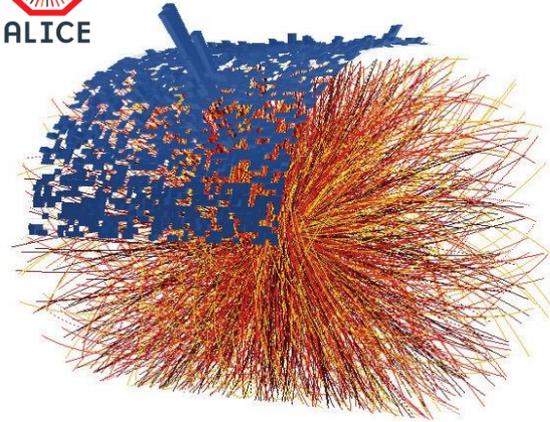
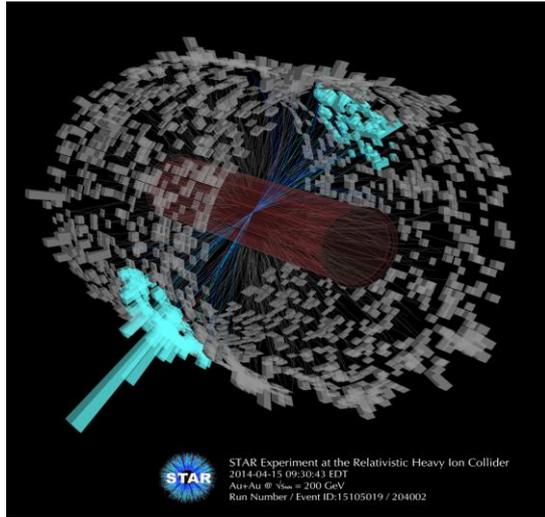
## Binary neutron star merger GW170817 GRB170817A



[arXiv:1710.05834](https://arxiv.org/abs/1710.05834)

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# The heavy-ion jet measurement challenge II



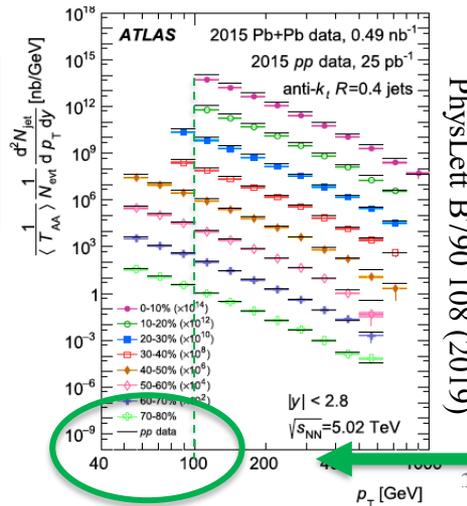
Very complex experimental environment

Huge background of particles not correlated with jet shower

How to make precise measurements?

True jet measurements in high bkgd environment: two distinct approaches

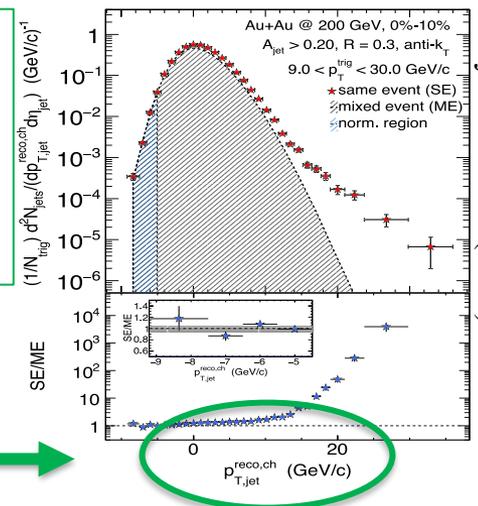
ATLAS/CMS/sPHENIX



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

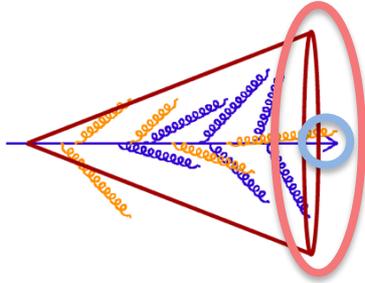
Statistical approach to measure and subtract bkgd  $\rightarrow$  low  $p_T$ , large  $R$

ALICE/STAR



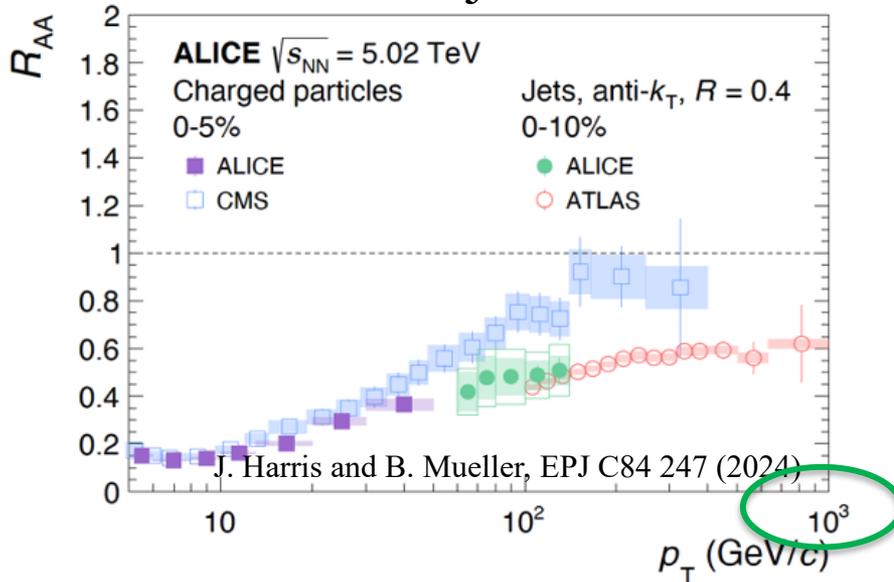
Phys. Rev. C 96 (2017) 024905

# Energy loss: hadrons vs jets (inclusive)

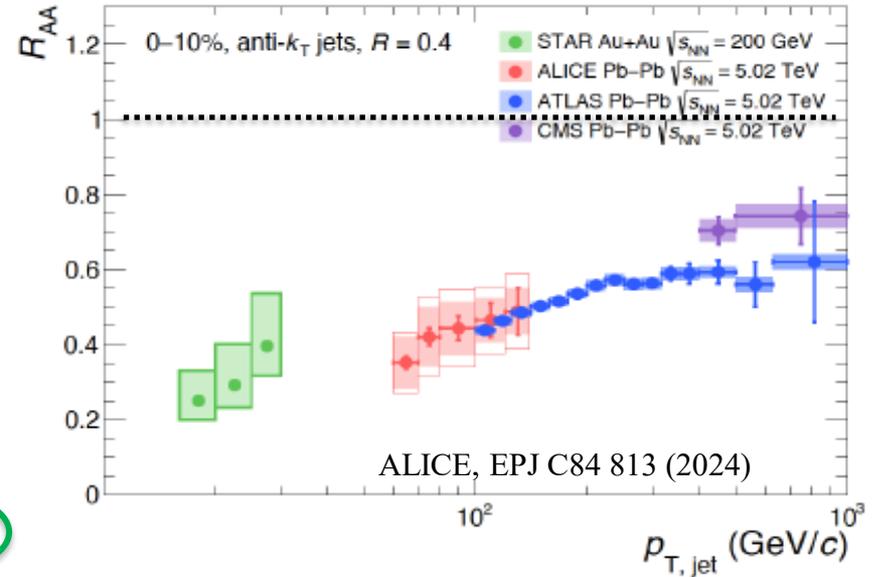


$$R_{AA} = \frac{dN_{AA}^{hard}/dp_T}{\langle T_{AA} \rangle d\sigma_{pp}^{hard}/dp_T}$$

### Hadrons vs jets at LHC



### Jets at RHIC and LHC



Jets probe much higher  $p_T$

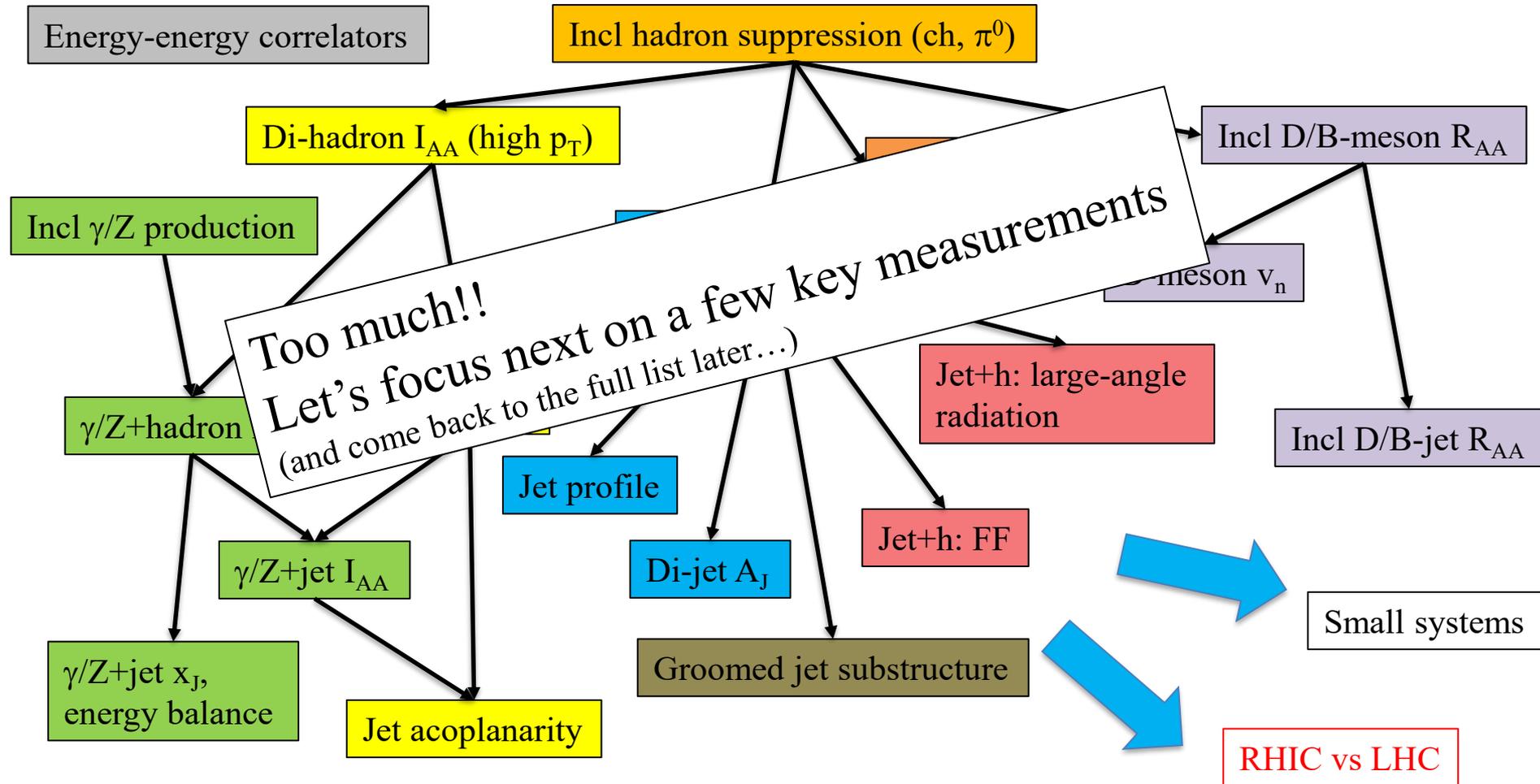
Phenomenology: broadly similar at RHIC vs LHC, hadrons vs jets

But quantitative differences: what do they teach us?

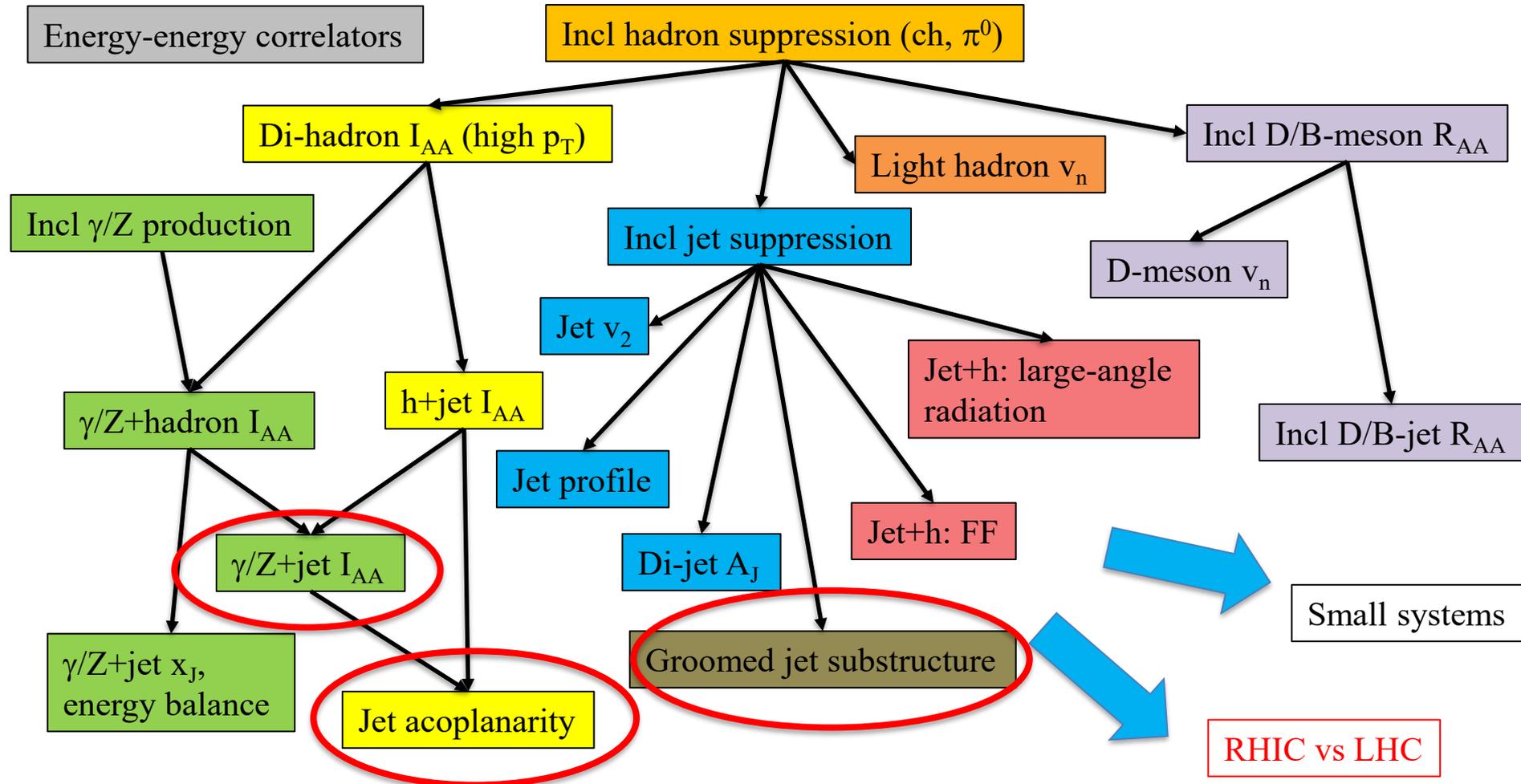
Let's table the question until the lecture on Bayesian Inference, when we will study it in detail

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

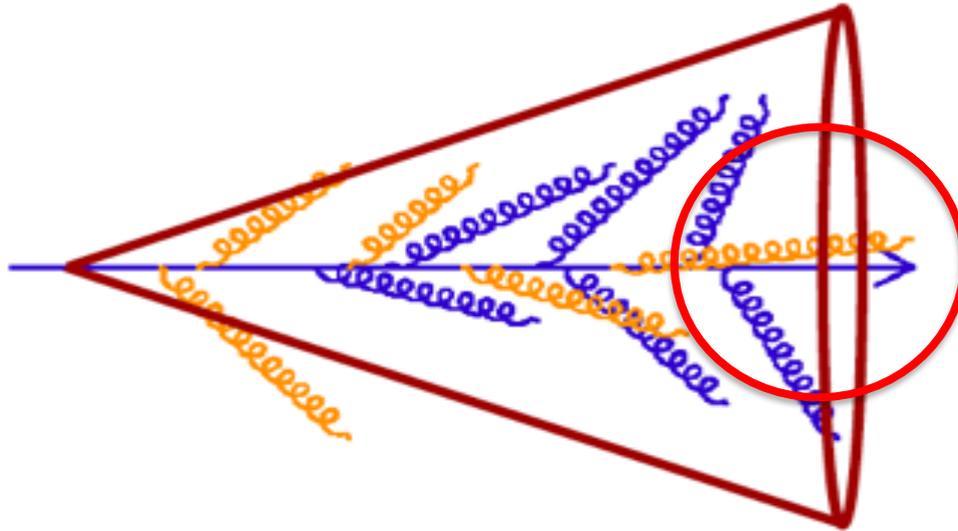
Topology driven by experimental considerations: arrows connect observables with just one thing changed



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

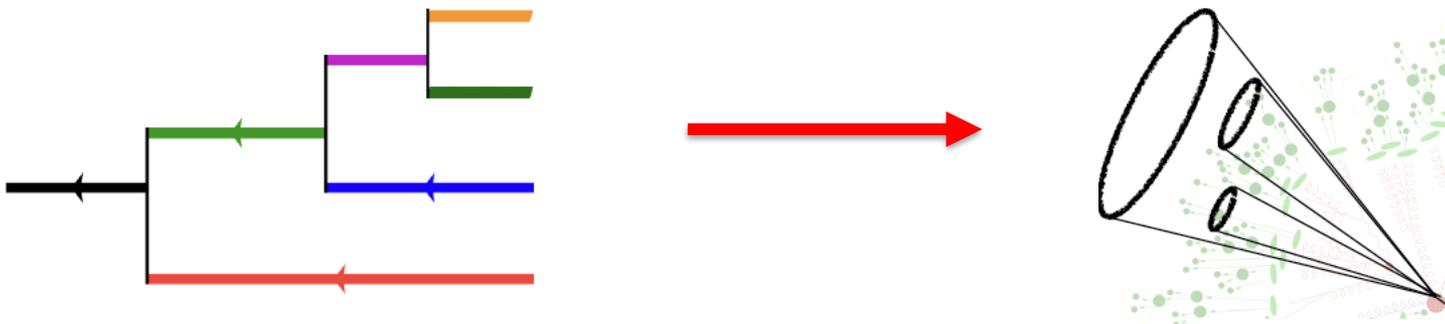


# Jet substructure



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

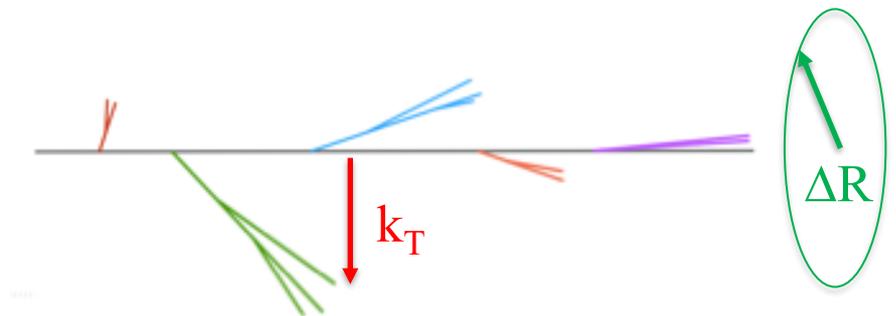
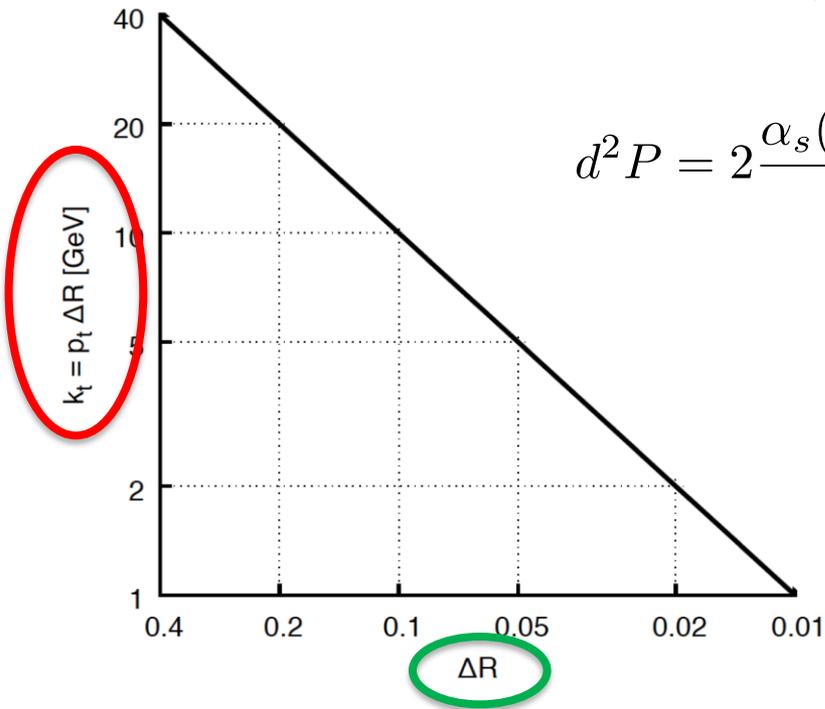
- Lund plane: full mapping of jet shower
- Groomed sub-structure: selected regions of Lund plane



# Lund Plane: jet shower map

Altareli-Parisi splitting probability function

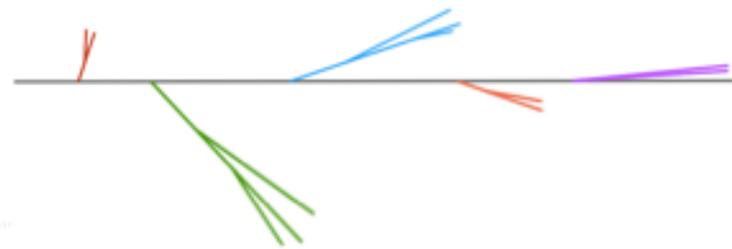
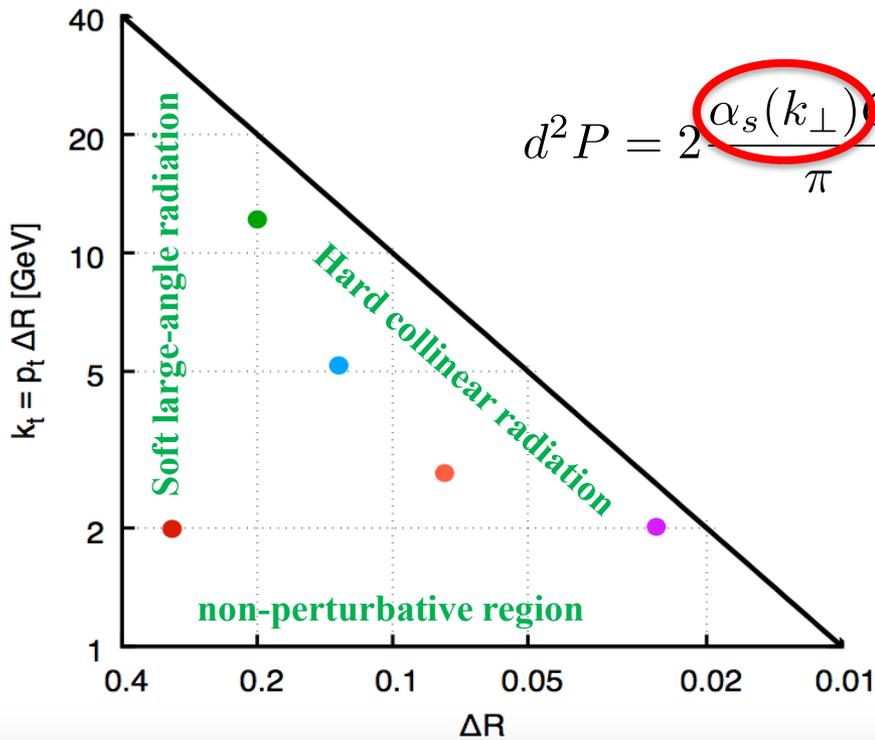
$$d^2 P = 2 \frac{\alpha_s(k_\perp) C_R}{\pi} d \ln \left( \frac{k_\perp}{p_T^{\text{jet}}} \right) d \ln \left( \frac{1}{\Delta R} \right)$$



# Lund Plane: jet shower map

Altareli-Parisi splitting probability function

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



Each radiated gluon corresponds to a point in the Lund Plane

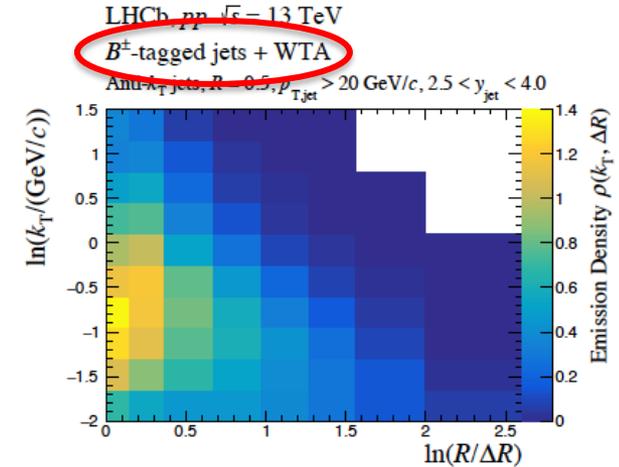
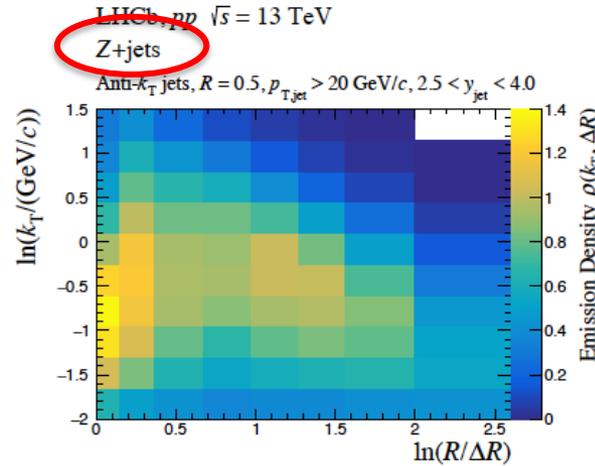
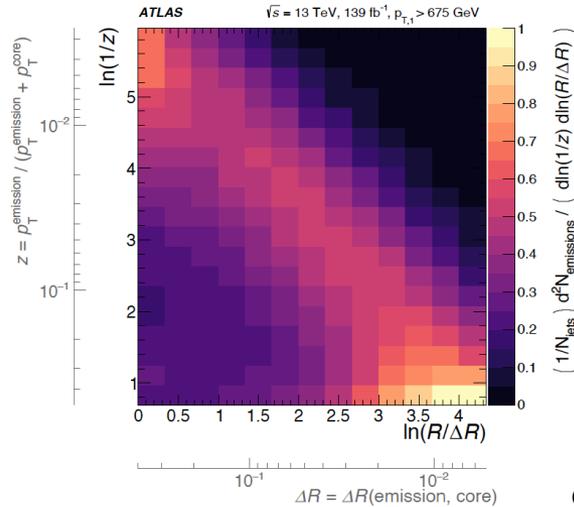
Fixed  $\alpha_s$ : Lund diagram is populated uniformly  
(note that axes are logarithmic)

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

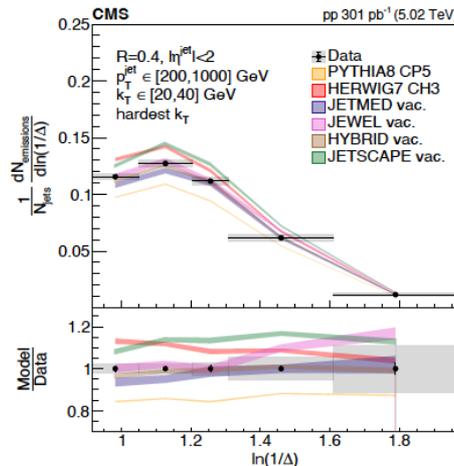
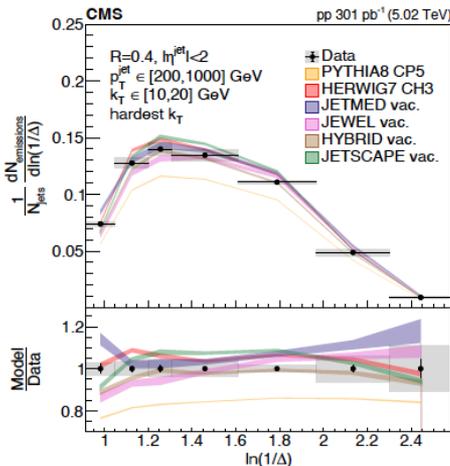
$$d^2P = 2 \frac{\alpha_s(k_\perp) C_R}{\pi} d \ln \left( \frac{k_\perp}{p_T^{\text{jet}}} \right) d \ln \left( \frac{1}{\Delta R} \right)$$

ATLAS PRL 124 222002 (2020)

LHCb D112, 072015 (2025)



CMS arXiv:2602.09271



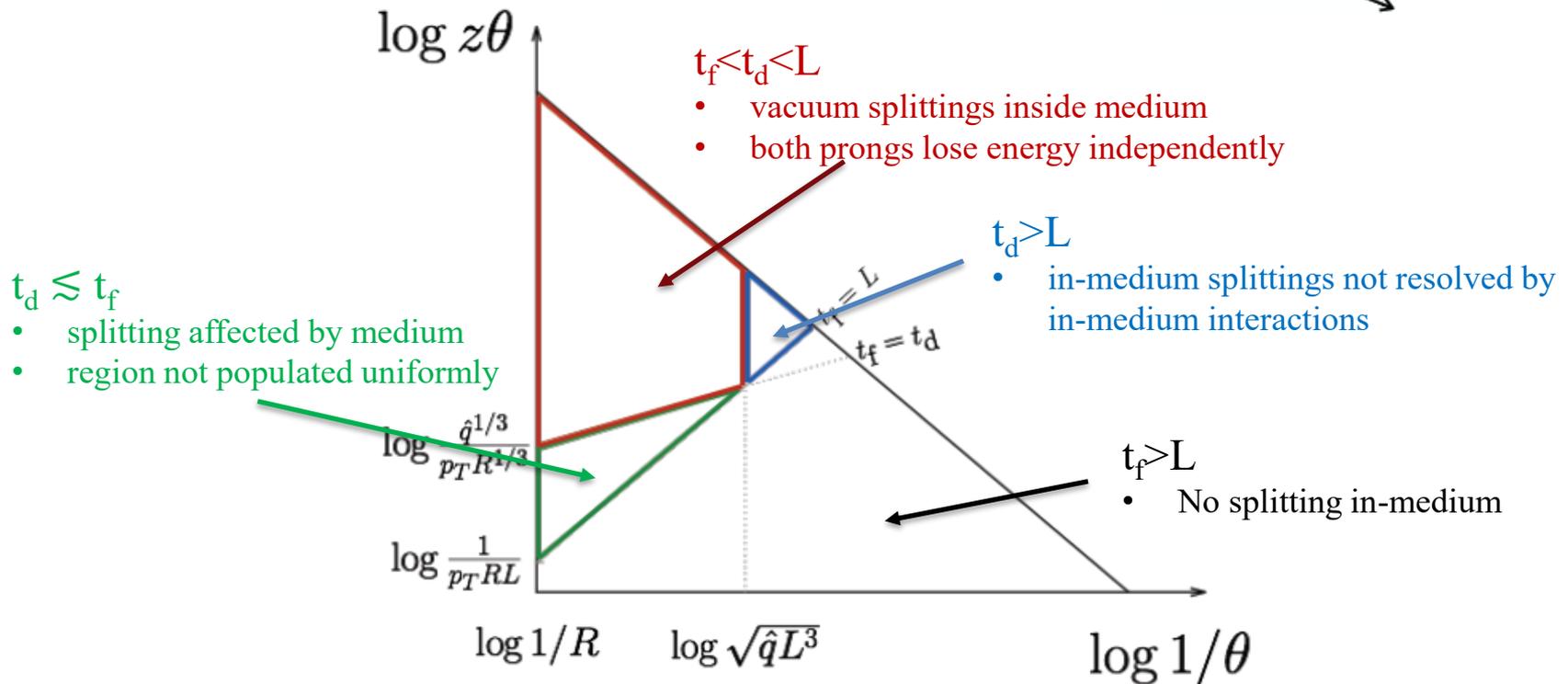
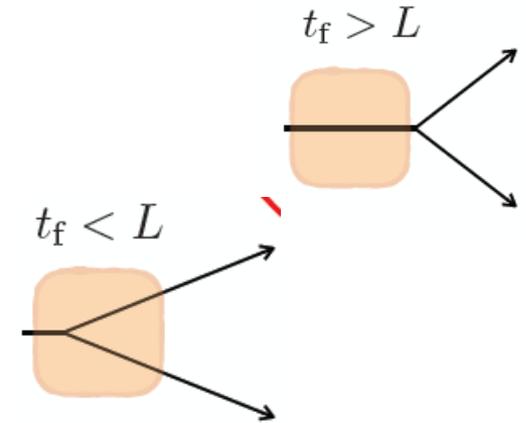
Non-uniform density

- running of  $\alpha_s$
- NP/hadronization effects

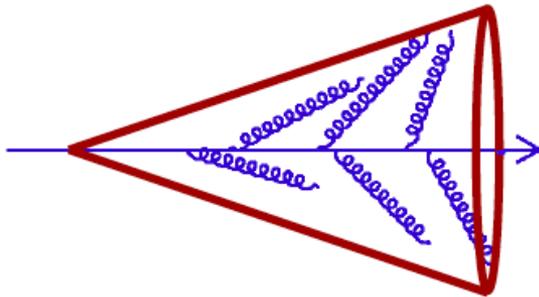
# Lund Plane in medium (AA collisions)

Additional length/time scales:

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



# Jet grooming: softdrop



Clustering tree:



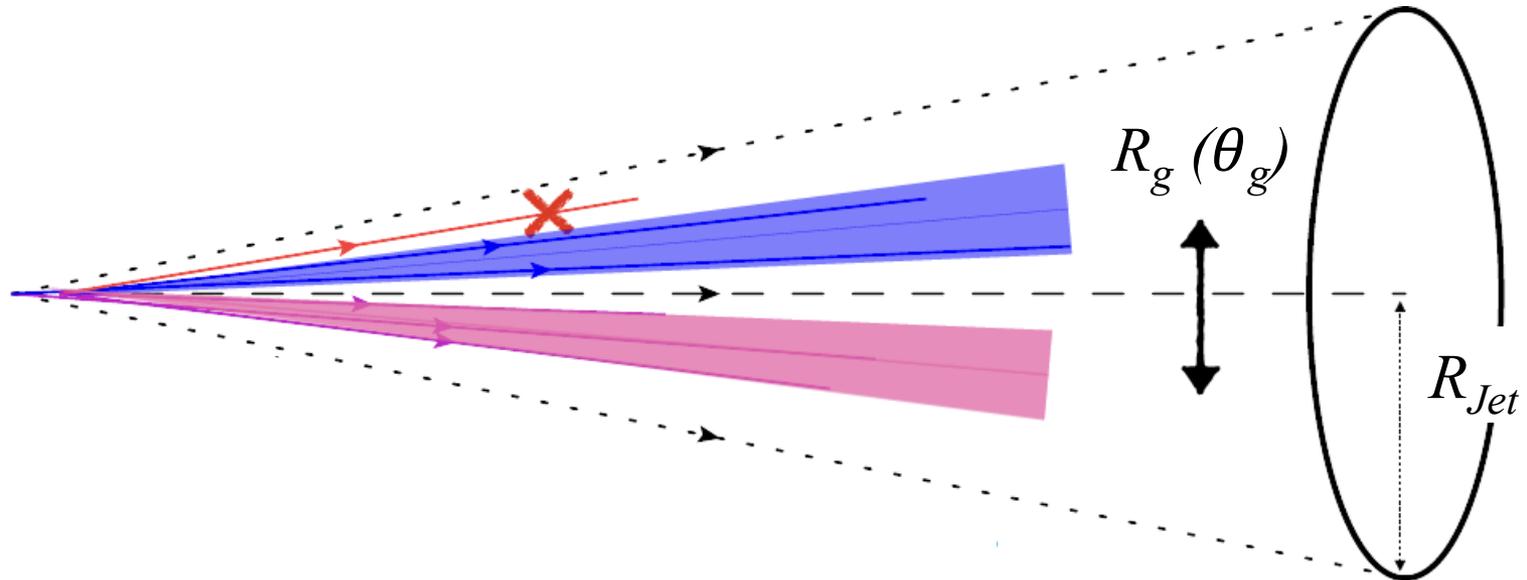
Iterate backwards through clustered jet tree, find first splitting that satisfies:

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

Common choices:

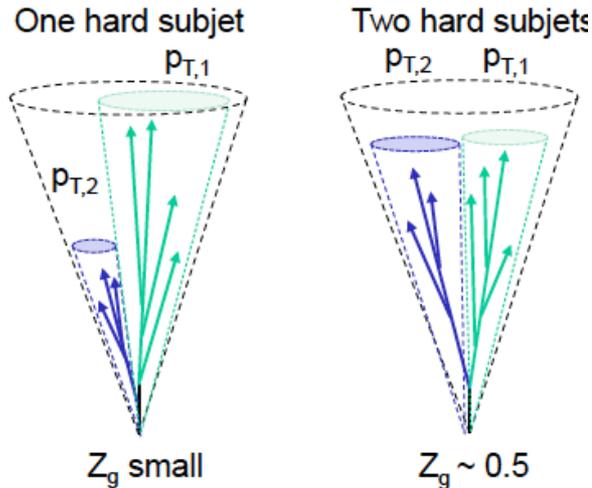
$$z_{cut} = 0.1$$

$$\beta = 0$$

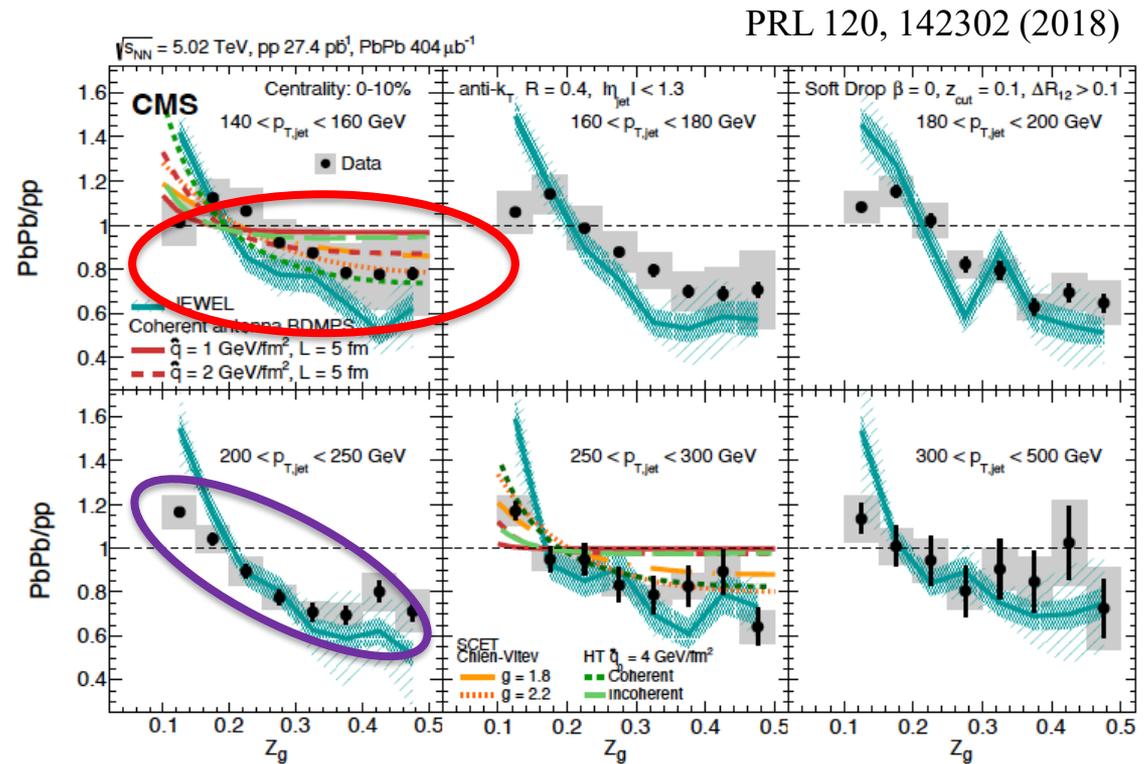


# Longitudinal jet sub-structure: $z_g$

Momentum imbalance of the two leading subjets



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

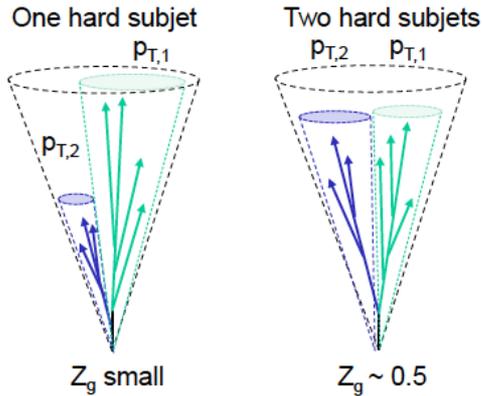


Data: in-medium interaction generates subjet momentum imbalance

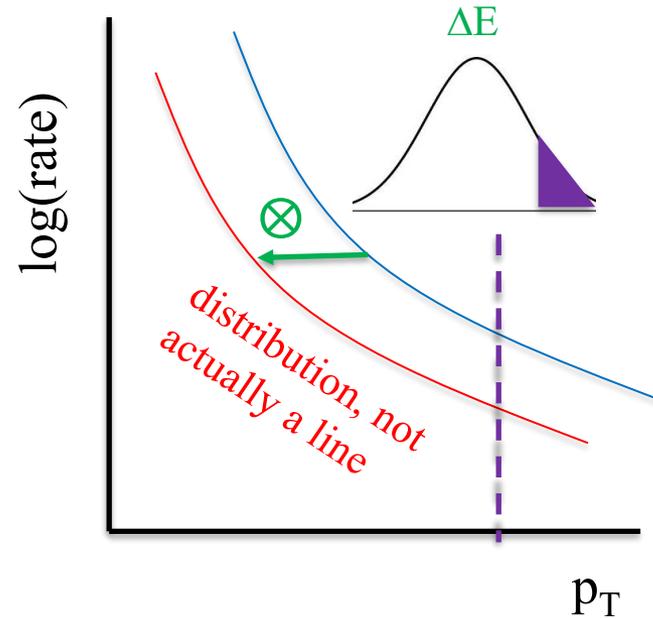
Theory/models: small but non-zero difference between incoherent radiation (JEWEL) and coherent antennas –interesting!

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

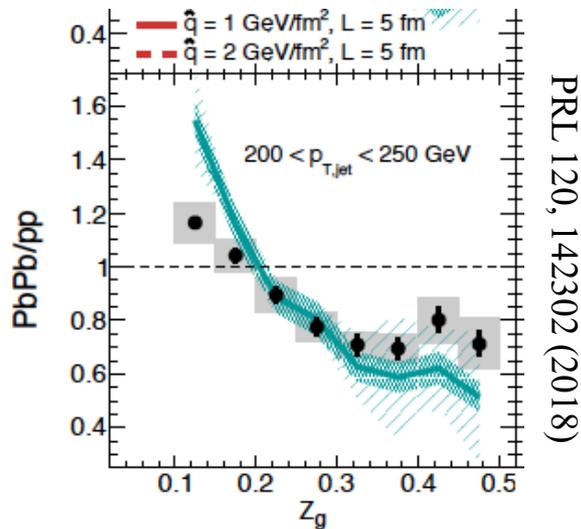
# Measurement issue: selection bias!



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

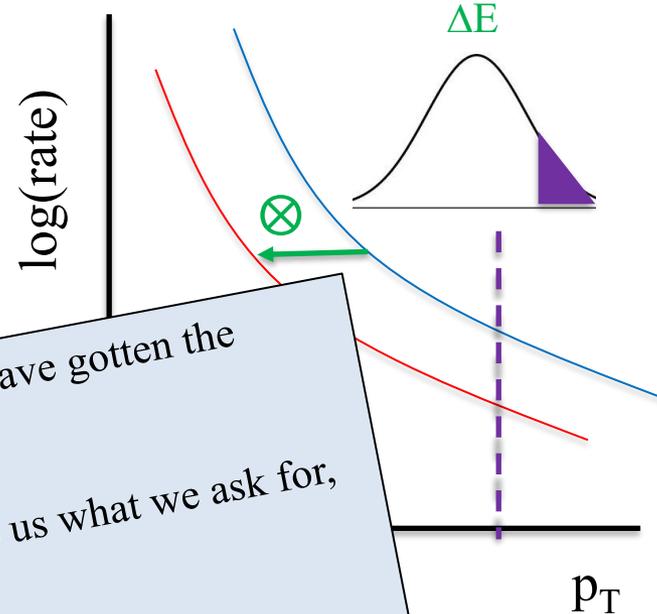
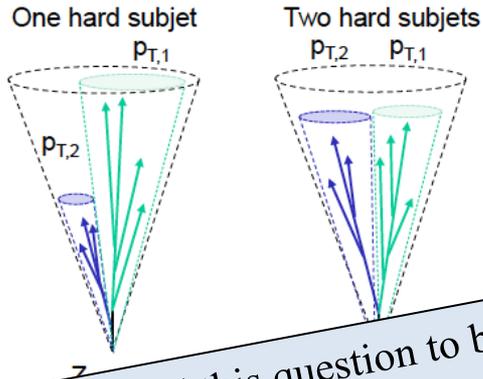


1. Jet spectrum falls with increasing  $p_T$
2. Energy loss due to quenching is a distribution (!)
3. We compare jets in Pb+Pb and p+p at a fixed value of  $p_T$  (actually a finite-width bin but principle is the same)



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

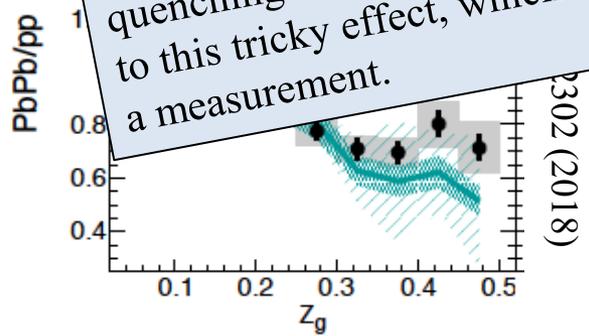
# Measurement issue: selection bias!



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.



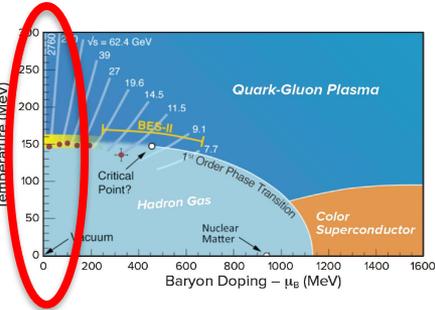
Increasing  $p_T$  is a distribution (!)

Pb and p+p at a fixed value

(same)

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

# Finite Temperature QCD calculated numerically on the Lattice ( $\mu_B=0$ )

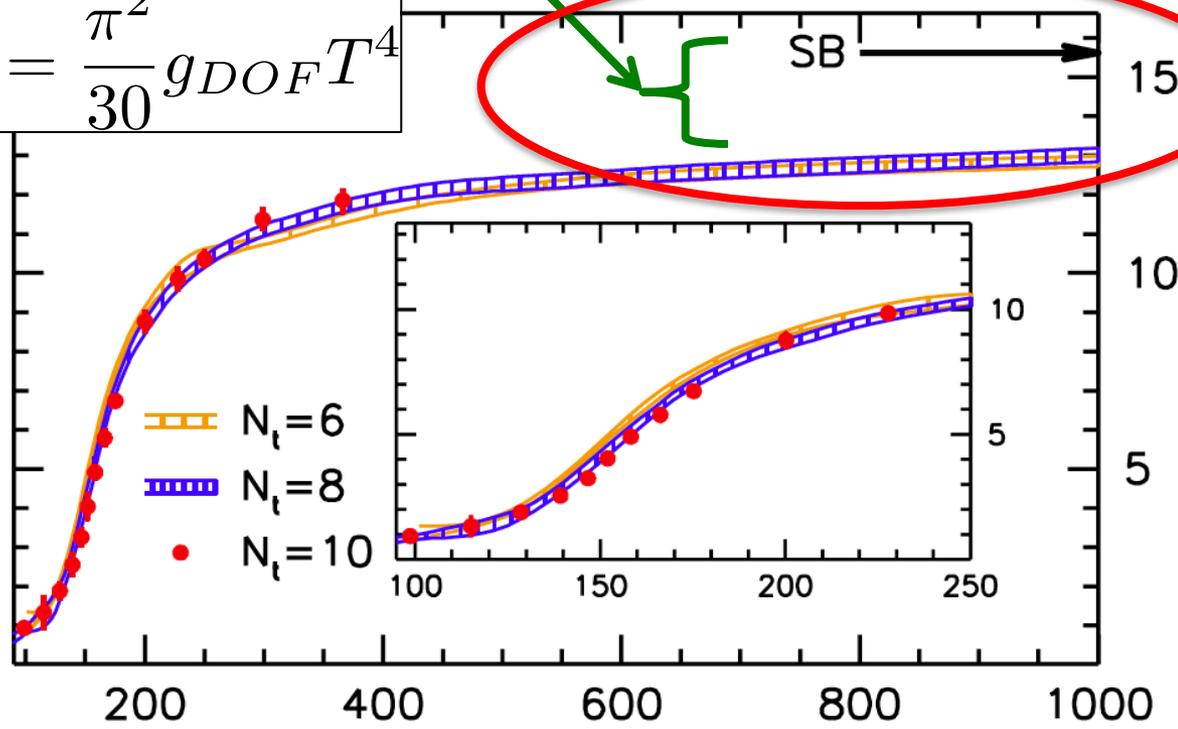


Slow convergence to non-interacting Steffan-Boltzmann limit  
 What carries energy - complex bound states of q+g? “strongly-coupled” plasma?

Energy density

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

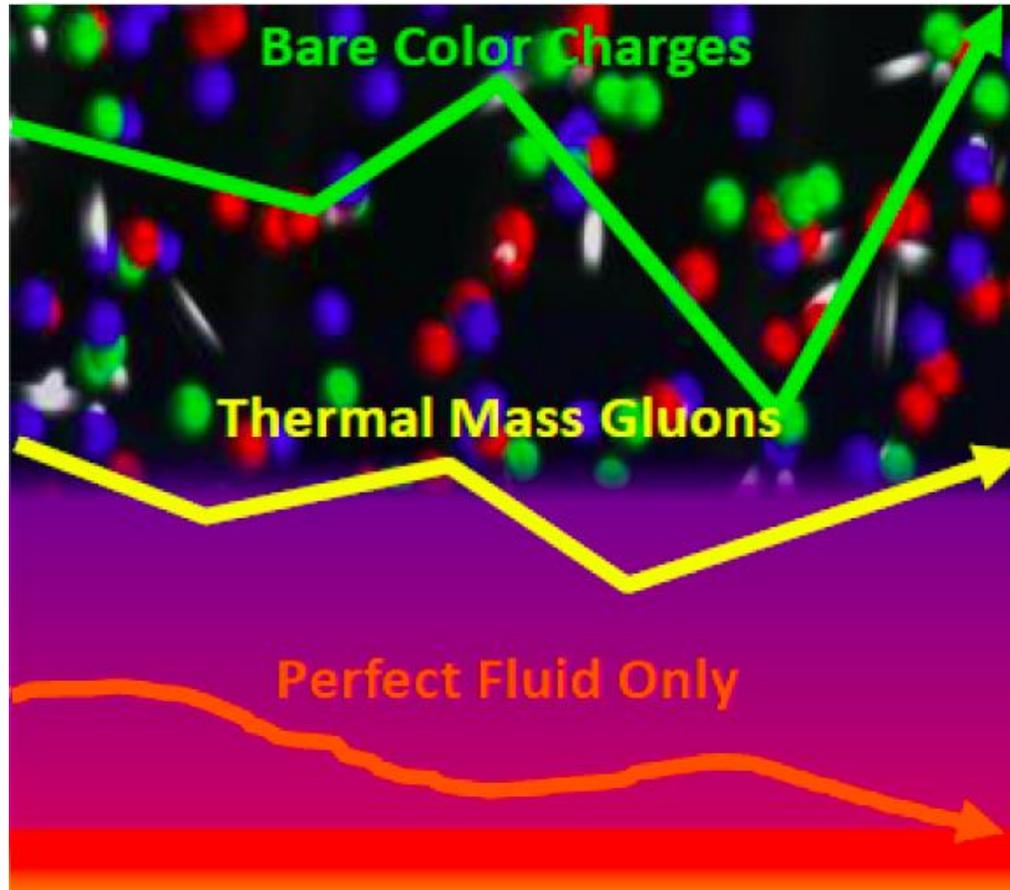
$$\frac{\epsilon}{T^4}$$



Temperature [MeV]

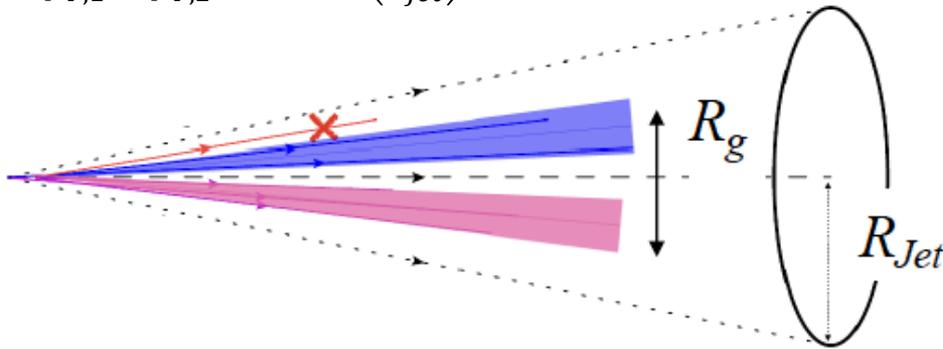
S. Borsanyi et al., JHEP 1011, 077 (2010)

# Can jet scattering measurements probe the microscopic structure of the QGP?



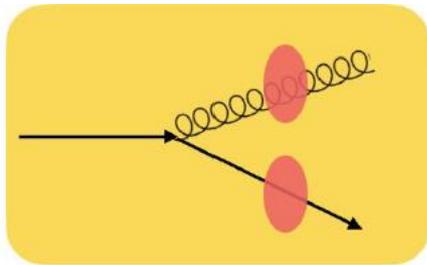
# Groomed subjet transverse distributions

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



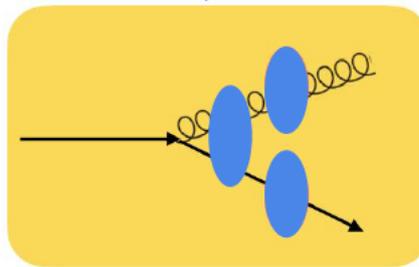
$$\theta_g = \frac{R_g}{R_{jet}}$$

Incoherent e-loss



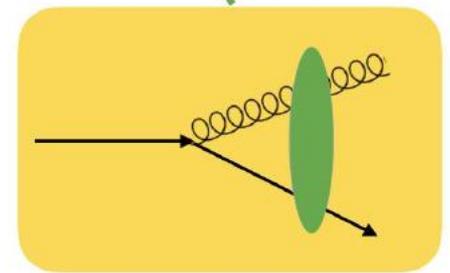
$$L_{res} = 0$$

Partially coherent e-loss



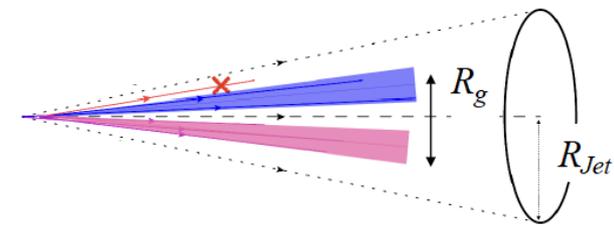
$$L_{res} = (1-2)/(\pi T)$$

Fully coherent e-loss

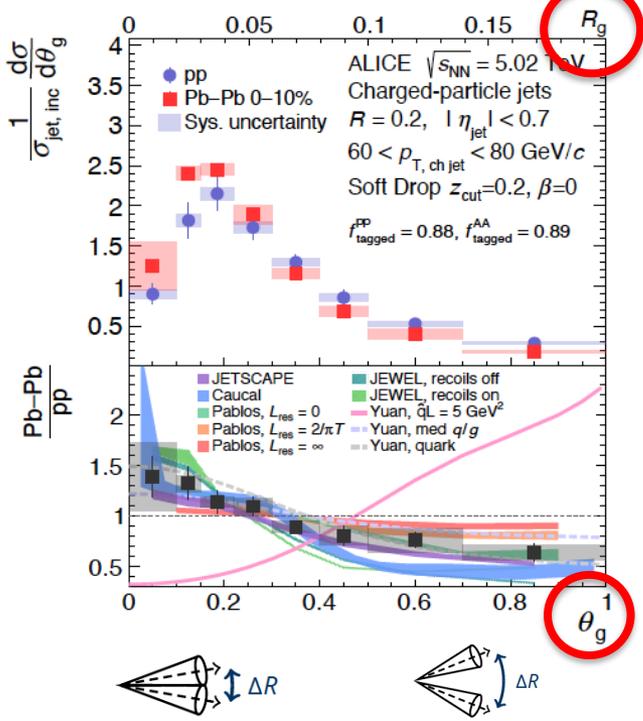


$$L_{res} = \infty$$

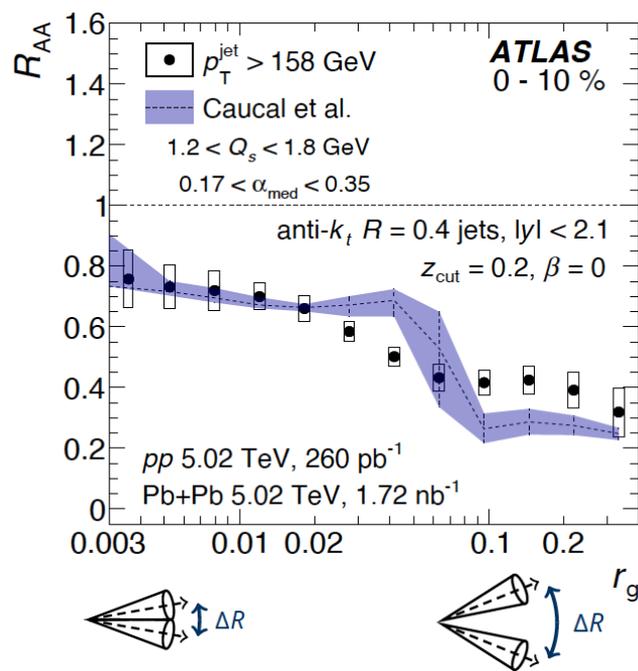
# Groomed subjet transverse distributions



PRL 128 102001



PRC 107 054909



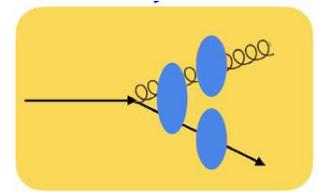
Wide jets  
 preferentially  
 suppressed in-  
 medium

Fully incoherent e-  
 loss models  
 (CAUCAL, JEWEL)  
 disfavored

This and other data: emerging picture favors partially coherent e-loss → promising path to uncovering QGP micro-structure

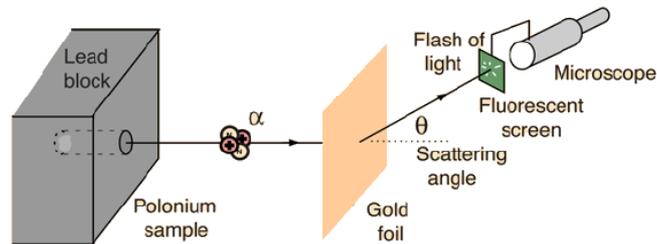
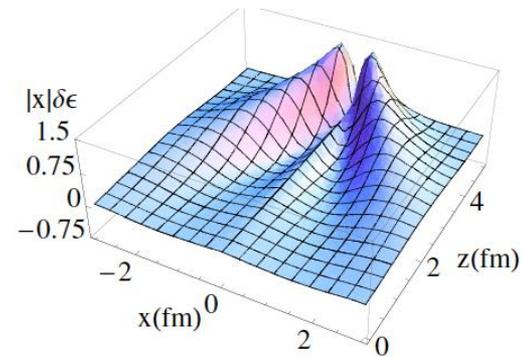
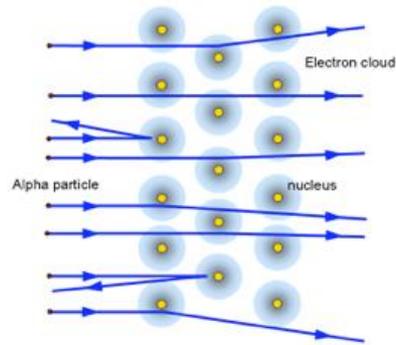
However: beware the selection bias!

- alternative picture: selective suppression of gluon jets (which are wider)



# Can we do a direct jet scattering measurement?

Discrete scattering centers or effectively continuous medium?



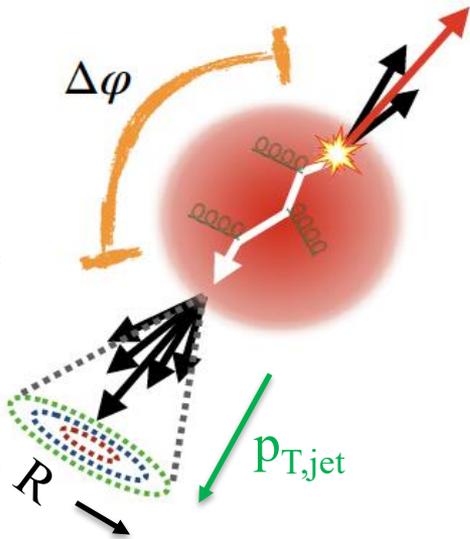
Picture depends on moment-transfer scale

Scattering measurement needs a broad kinematic range  
→ must measure jets with low  $p_T$  and large  $R$

# Correlation measurements of jet scattering

Semi-inclusive observables:

Trigger:  $\gamma/Z$ ,  $\pi^0$ , ch hadron



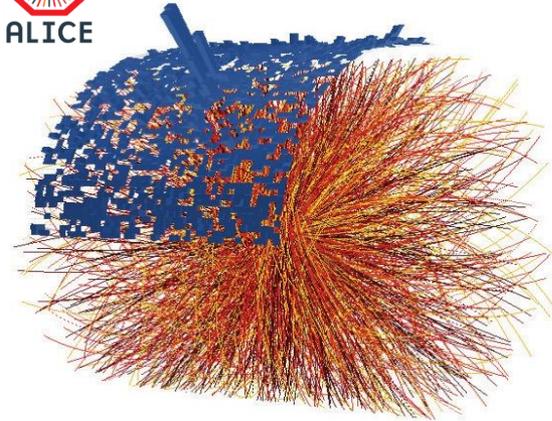
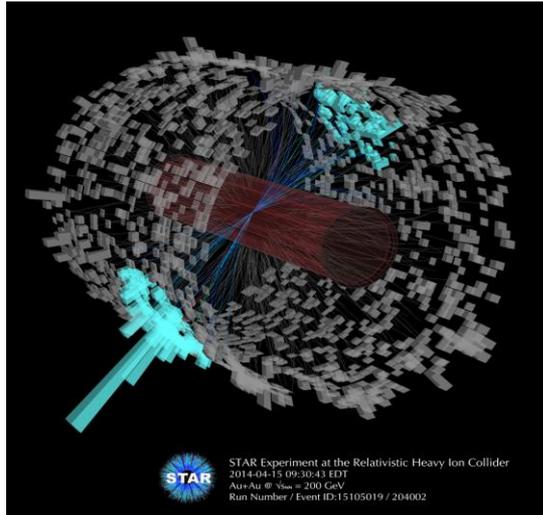
Recoil jet

1. Events are first selected for hard processes based on presence of a high  $p_T$  trigger
  - Because trigger selection is event-wise, must be cleanly measurable without large correction for bkgd
  - $\gamma/Z$ ,  $\pi^0$ , charged hadron; but not jet (!)
2. Jet reconstruction is then run on the full event
  - number of jets in recoil azimuth is simply counted

Trigger-normalized recoil yield = ratio of hard cross sections (excluding bkgd)

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

# The heavy-ion jet measurement challenge III



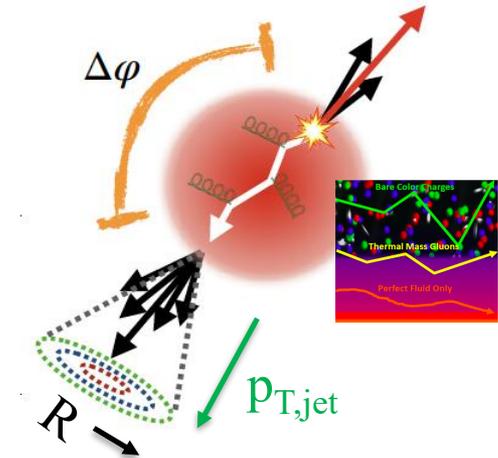
Very complex experimental environment

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

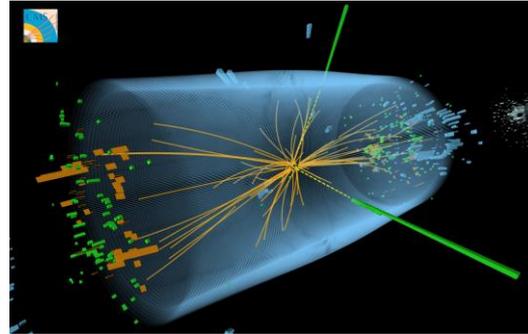
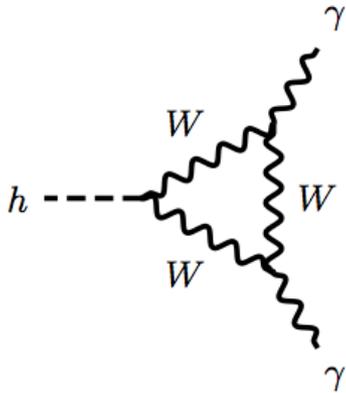
- “uncorrelated background” strictly has meaning only for ensemble-averaged (“statistical”) distributions



Low  $p_T$ /large  $R$  jet measurements

→ “statistical” correction of uncorrelated background yield

# Small signal/bkgd is a common problem in physics...



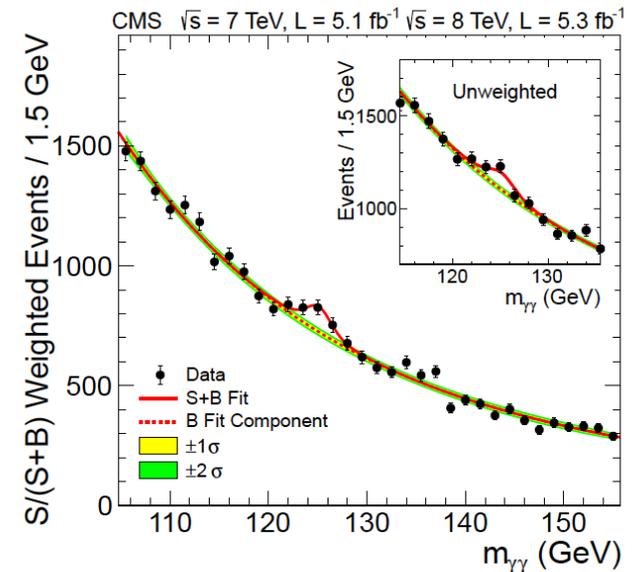
Complex experimental environment

Large background of particles not correlated with signal

Photons do not come labelled “Higgs” or “background”

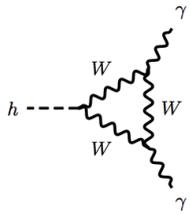
Cannot know with certainty whether a photon arises from Higgs decay or a background process

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

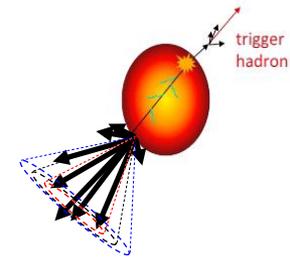
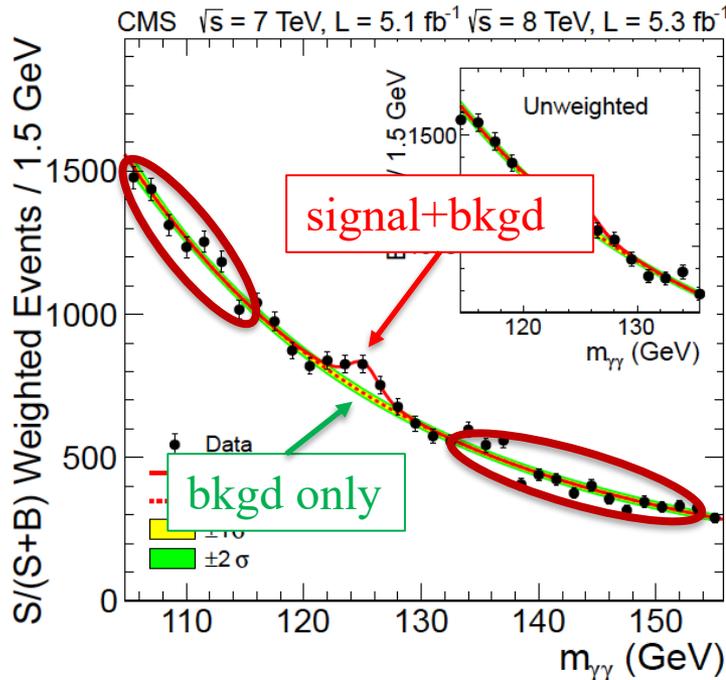


Small S/B  $\rightarrow$  “statistical” correction for uncorrelated background yield

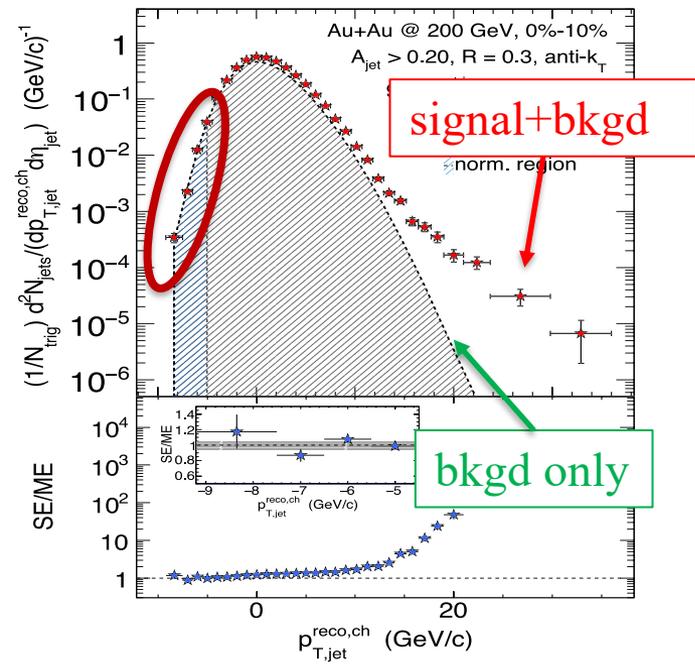
# Statistical background correction



$pp \rightarrow \text{Higgs} \rightarrow \gamma\gamma$



$\text{Au+Au} \rightarrow \text{hadron} + \text{jet}$



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 (generally unknown) bkgd processes

# Constructing uncorrelated background: event mixing

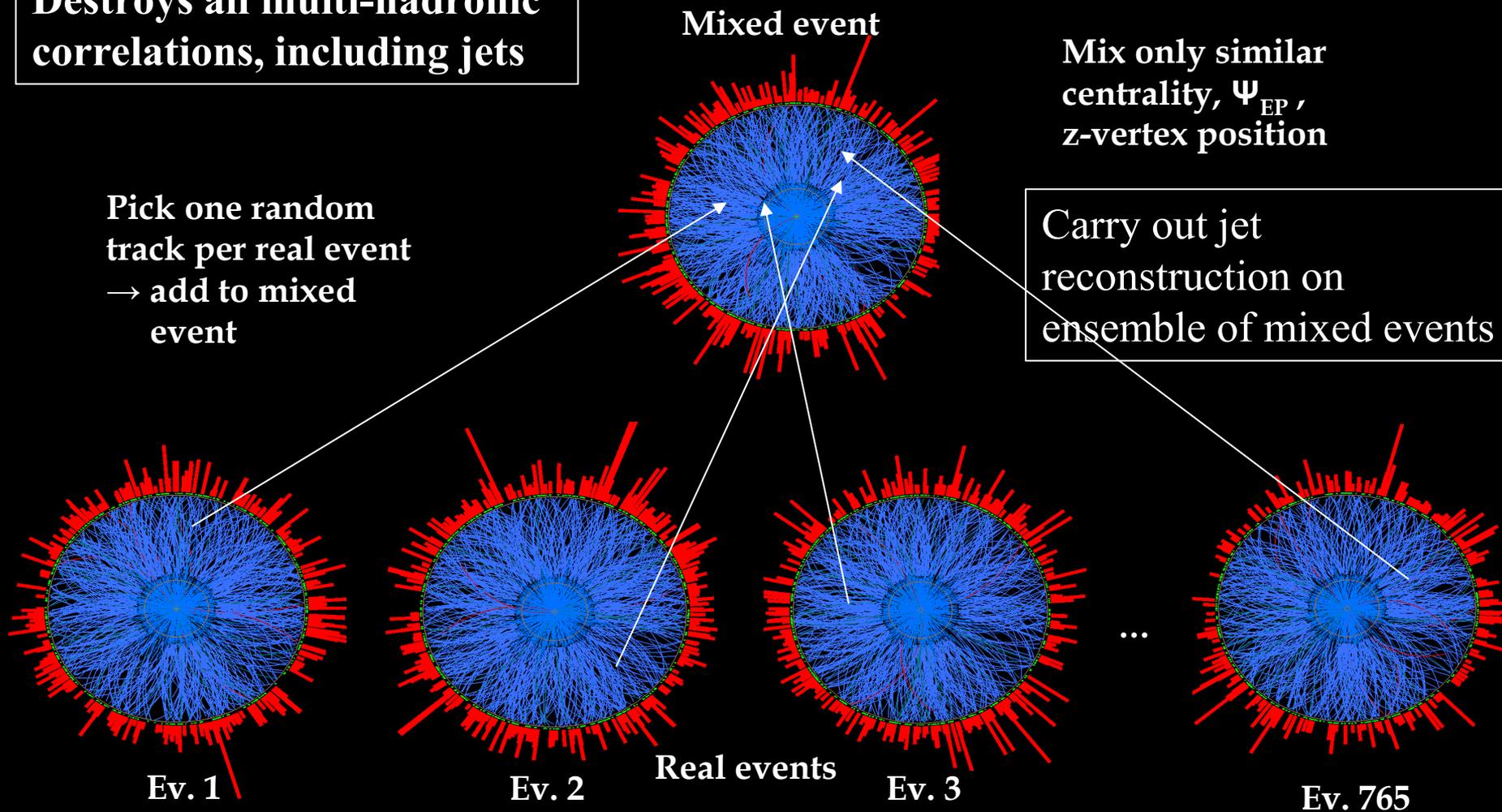
STAR Collaboration,  
Phys. Rev. C 96 (2017), 024905

Destroys all multi-hadronic correlations, including jets

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

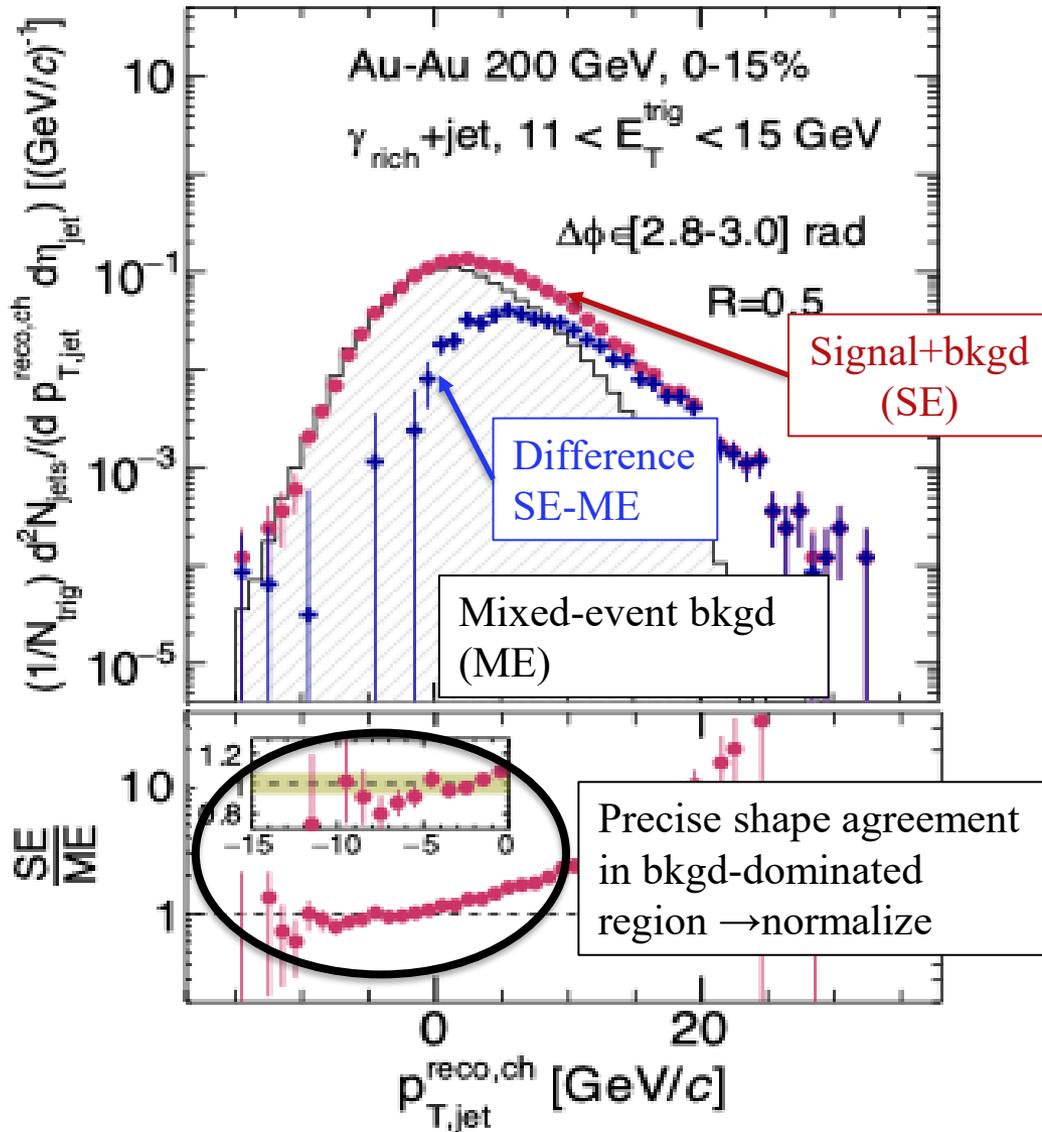
Mix only similar centrality,  $\Psi_{EP}$ ,  
z-vertex position

Carry out jet reconstruction on ensemble of mixed events



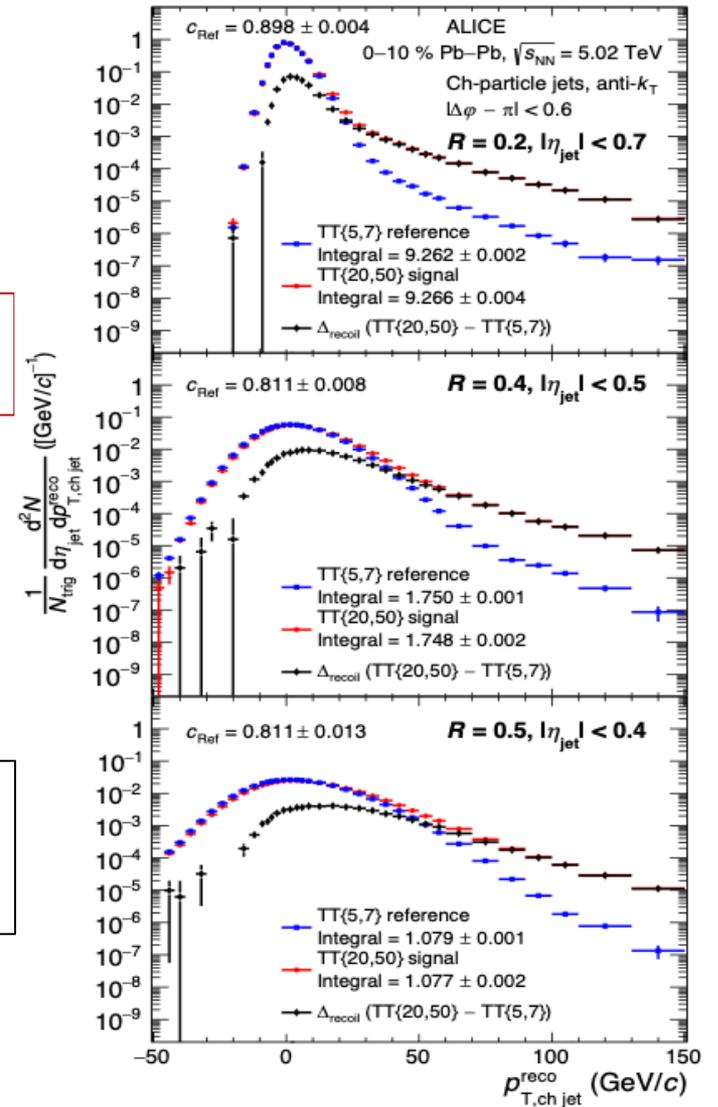
# STAR: event-mixed bkgd

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



# ALICE: trigger-difference bkgd

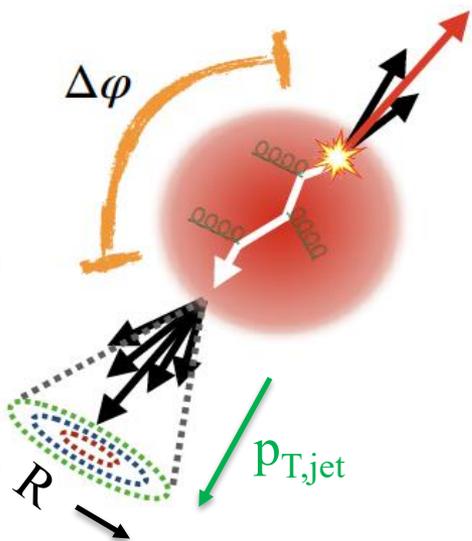
ALICE Phys.Rev.C 110 (2024) 1, 014906



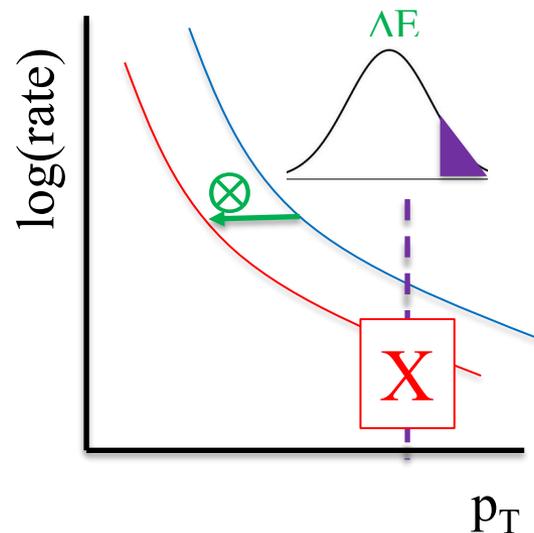
# Semi-incl. observables and bias

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

Trigger:  $\gamma$ ,  $\pi^0$ , ch hadron



Recoil jet

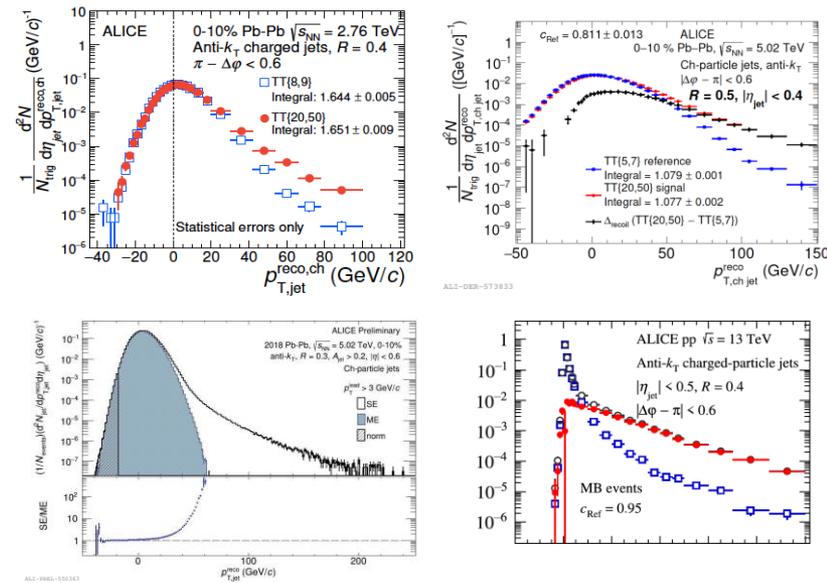
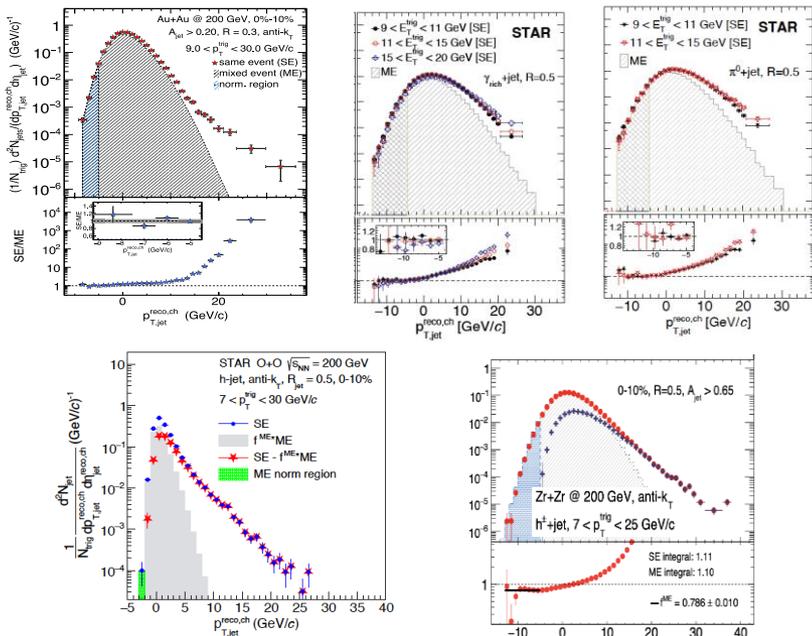


No requirements on  $p_T^{\text{jet}}$

No selection bias  $\rightarrow$  unbiased recoil jet distributions!

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

# Statistical jet analysis: current results



## Au+Au; h+jet

- Phys. Rev. C 96 (2017) 024905

## Au+Au, p+p; $\gamma/\pi^0$ +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

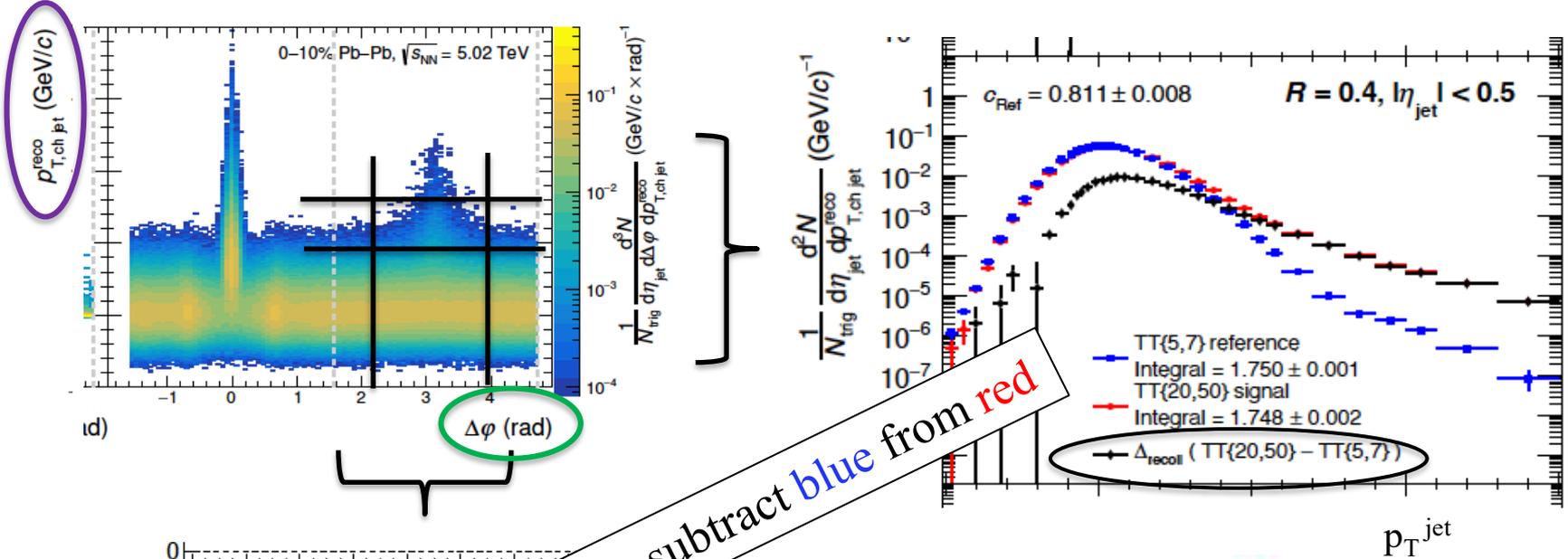
- in progress

# Semi-inclusive hadron+jet measurements

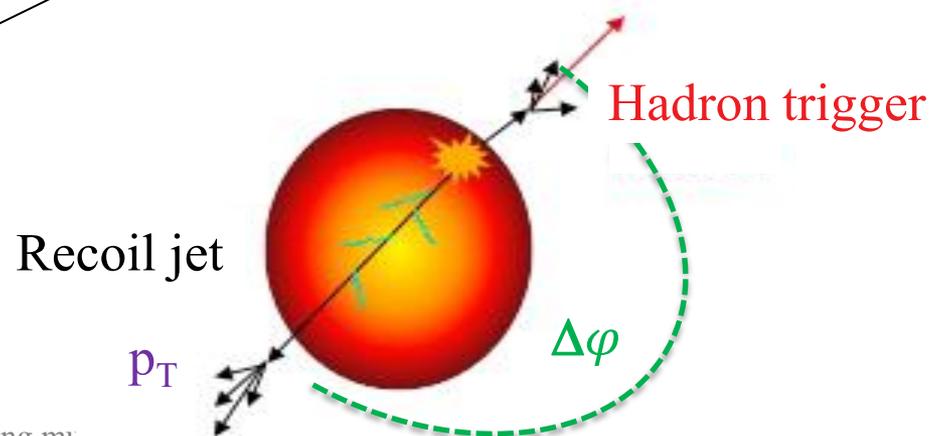
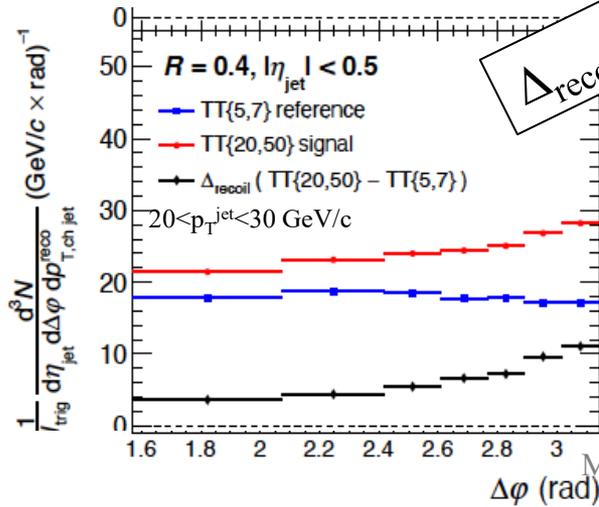


Phys.Rev.Lett. 133 (2024) 2 022301  
Phys.Rev.C 110 (2024) 014906

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



$\Delta_{recoil}$ : subtract blue from red



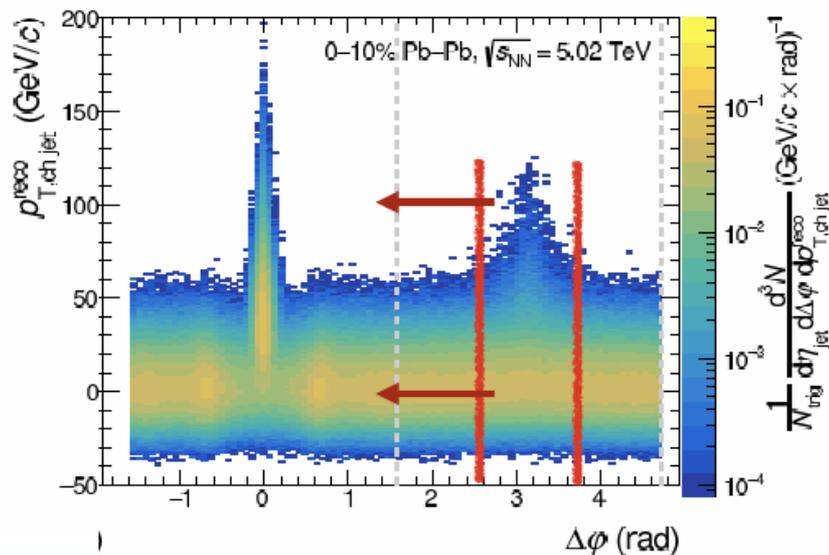
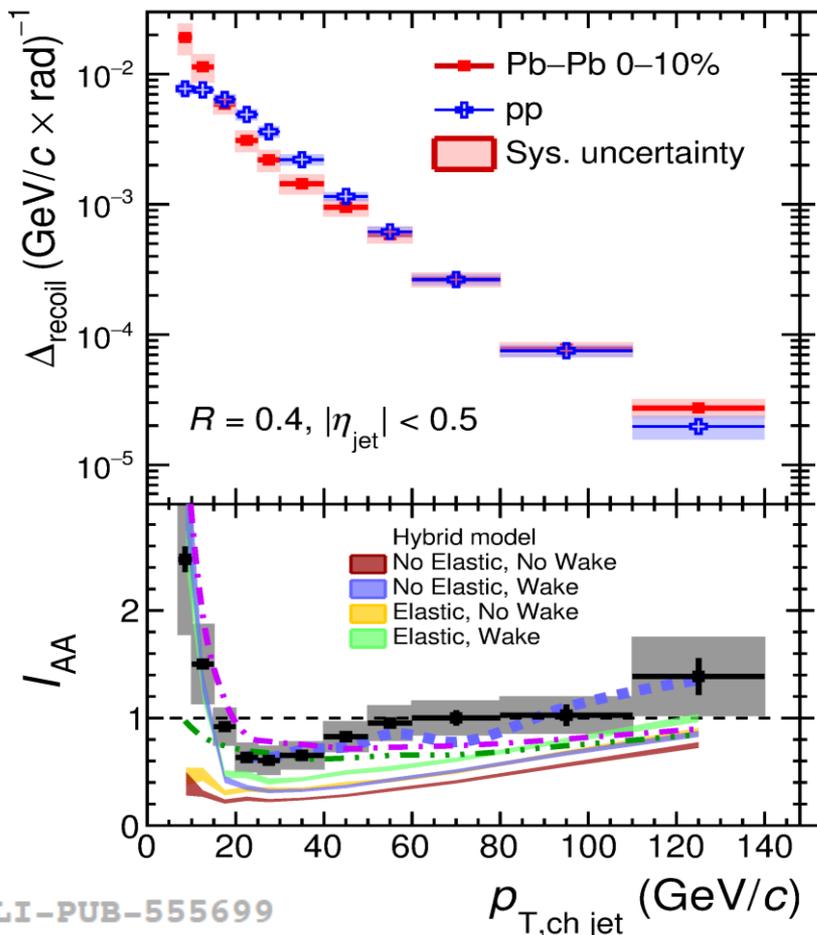
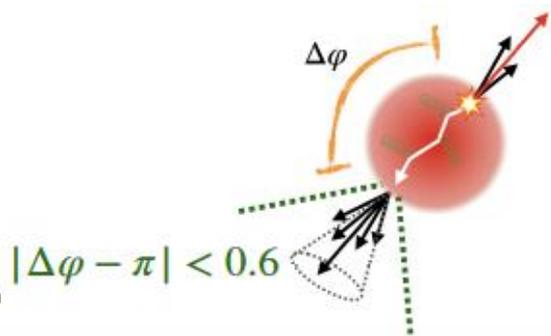
# Semi-incl. jet quenching: $p_{T}^{\text{jet}}$ dependence



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

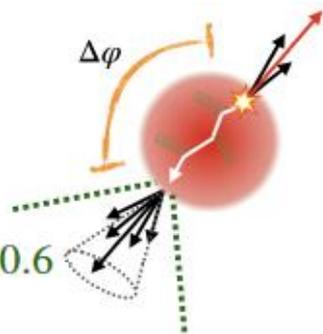
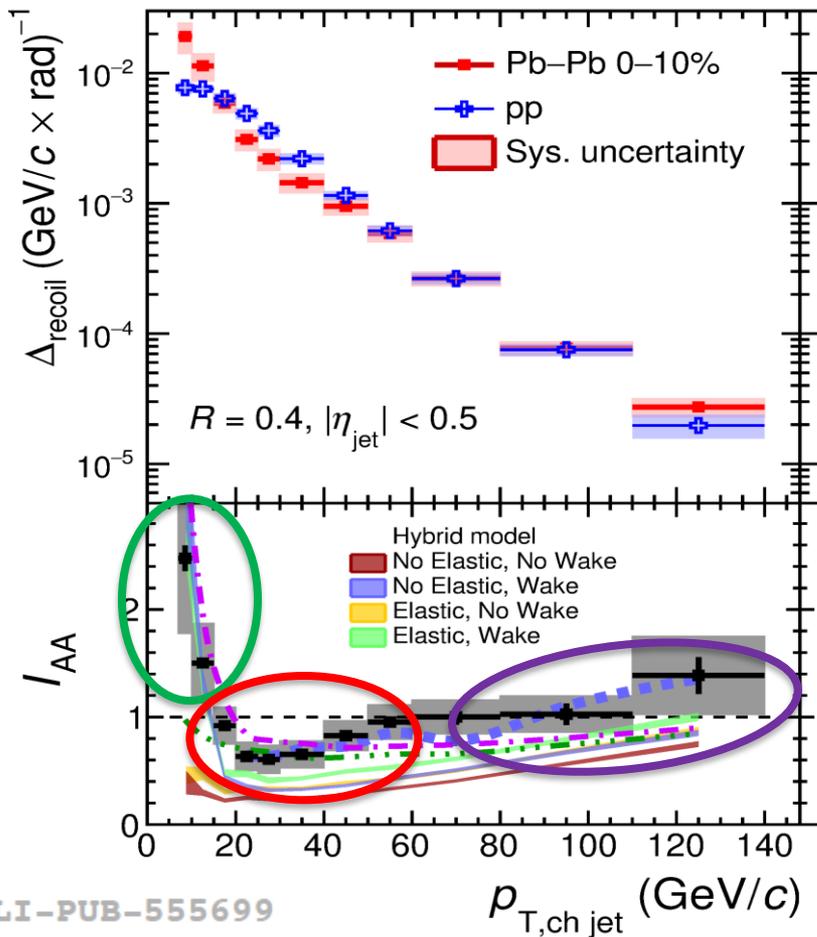
(corrected)



# Semi-incl. jet quenching: $p_T^{\text{jet}}$ dependence

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

(corrected)



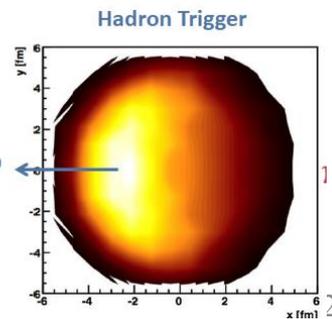
Phys.Rev.Lett. 133 (2024) 2 022301  
Phys.Rev.C 110 (2024) 014906

Energy loss

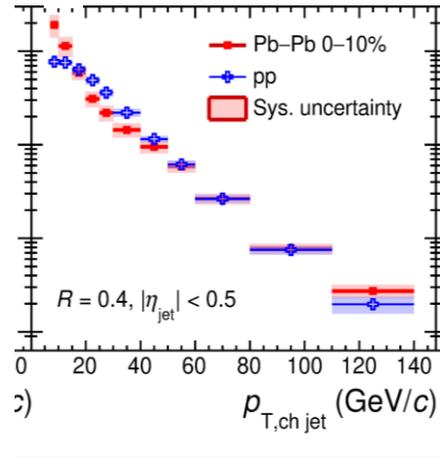
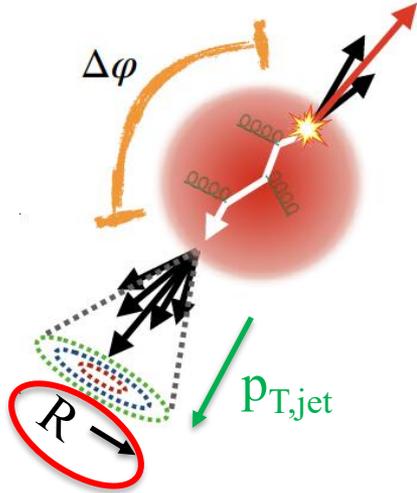
Energy recovery

- $R=0.4, p_T^{\text{jet}} \sim 10 \text{ GeV} (!)$

Change in geometric bias



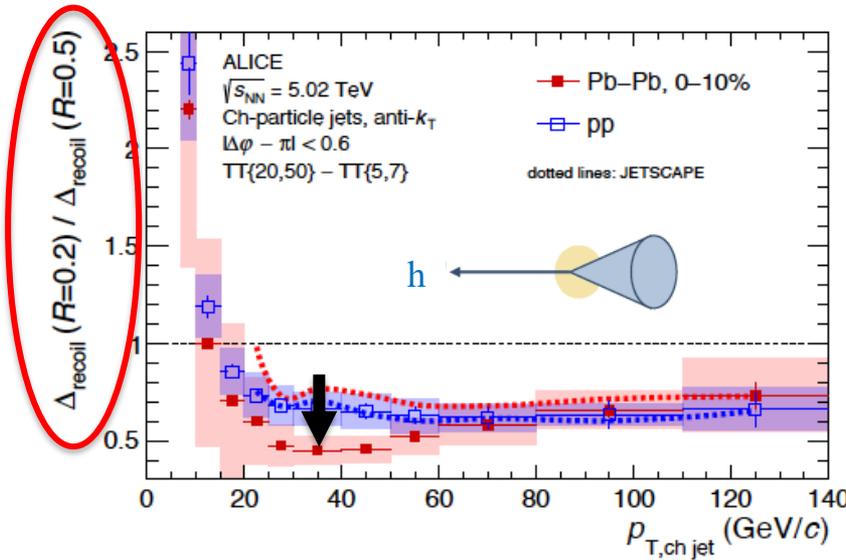
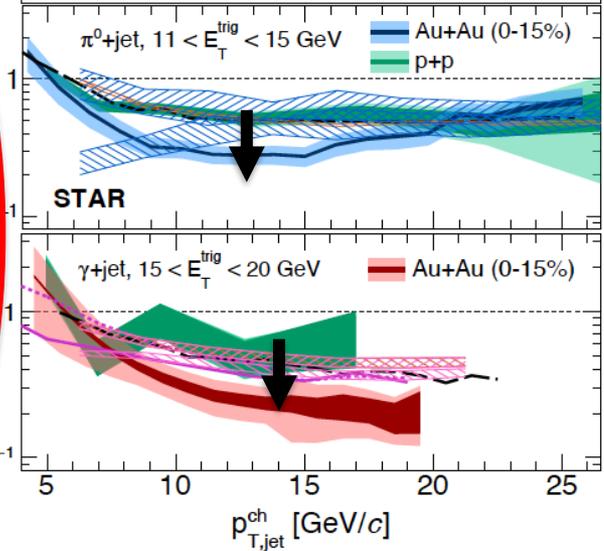
# In-medium jet shape modification: yield ratio $R=0.2/R=0.5$



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

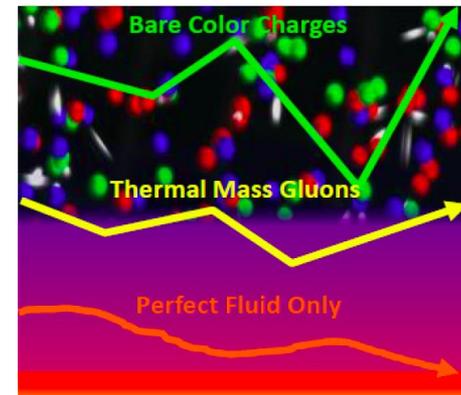
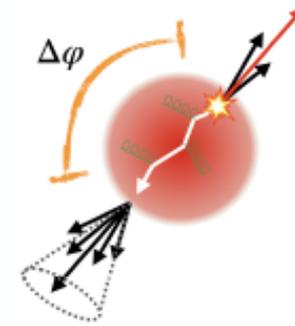
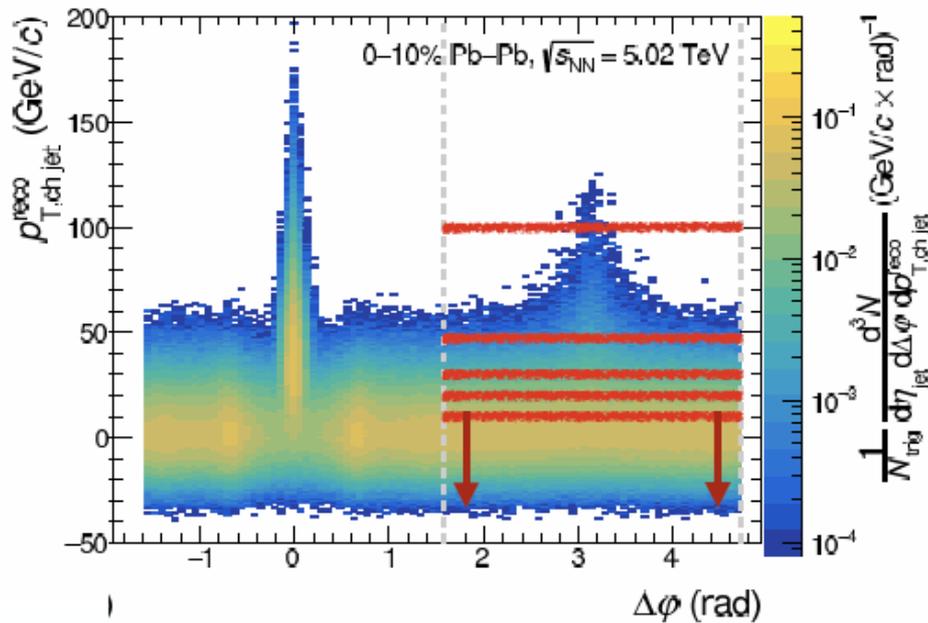


Medium-induced intra-jet broadening  
Seen at both LHC and RHIC

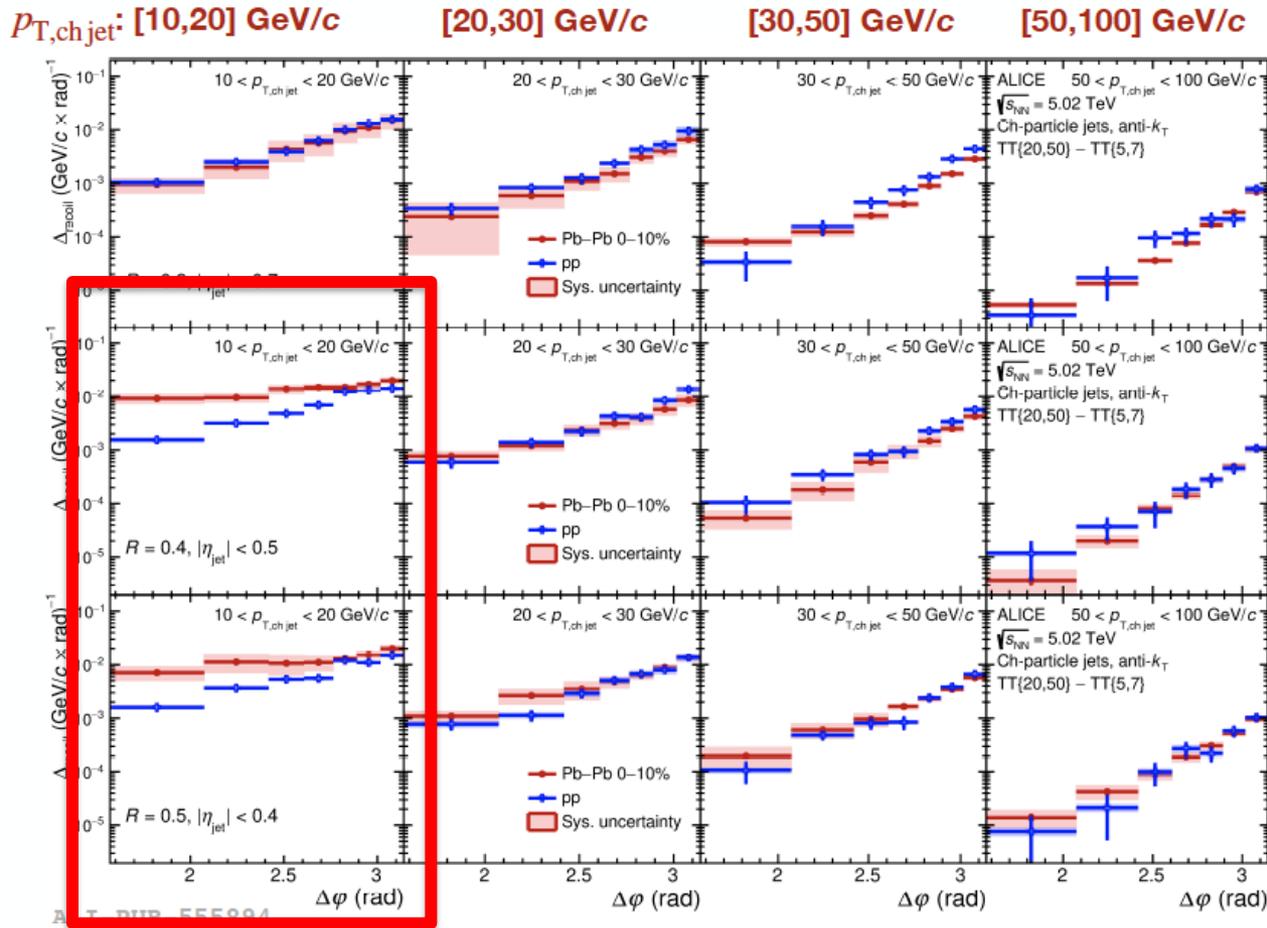
# In-medium azimuthal deflection



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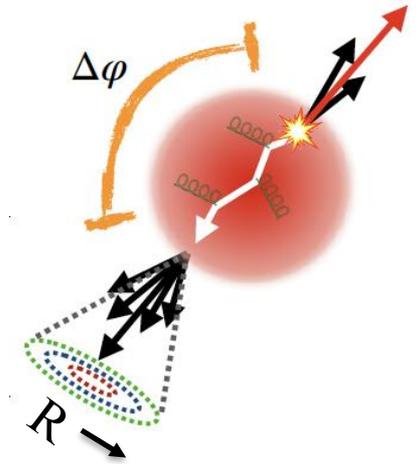


# Semi-incl. jet quenching: angular dependence



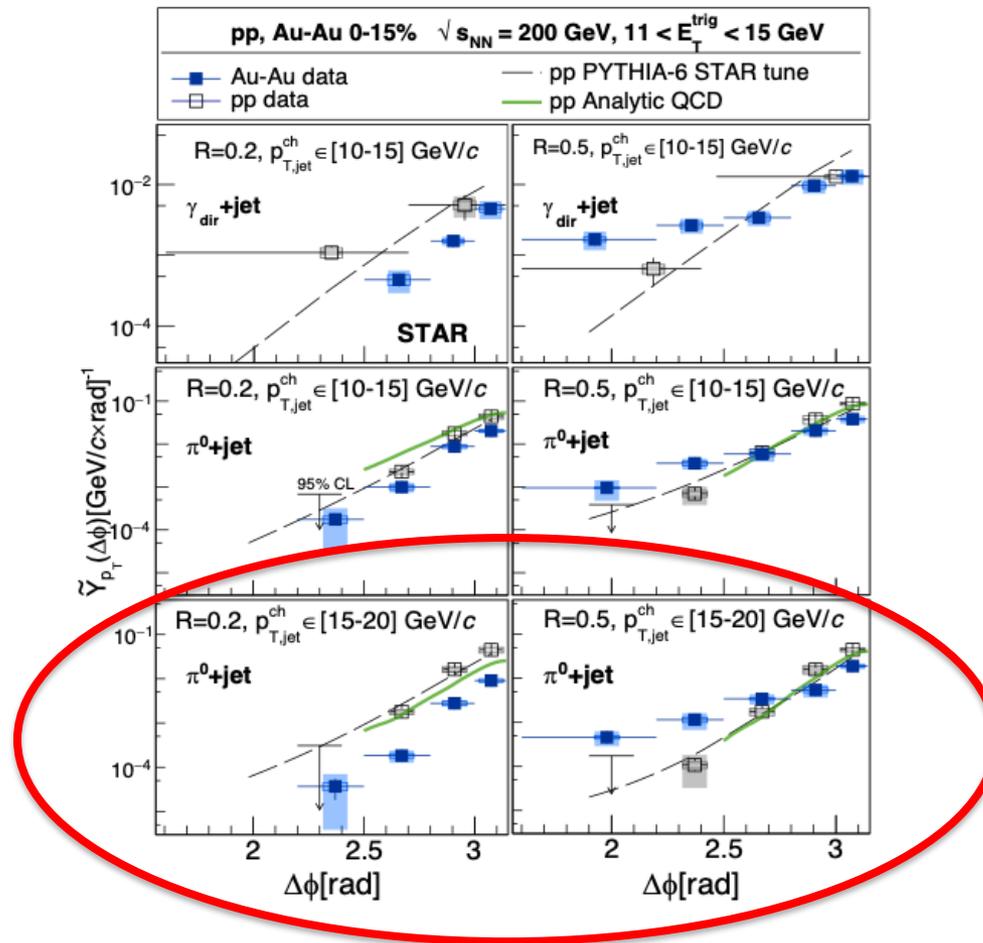
ALICE

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

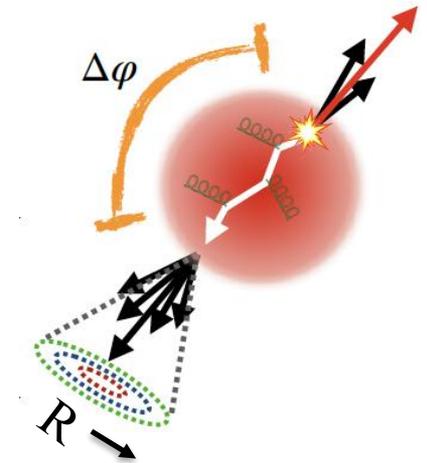


Large medium-induced azimuthal broadening for large-aperture recoil jets at low  $p_T^{\text{jet}}$  (!)

# Semi-incl. jet quenching: angular dependence



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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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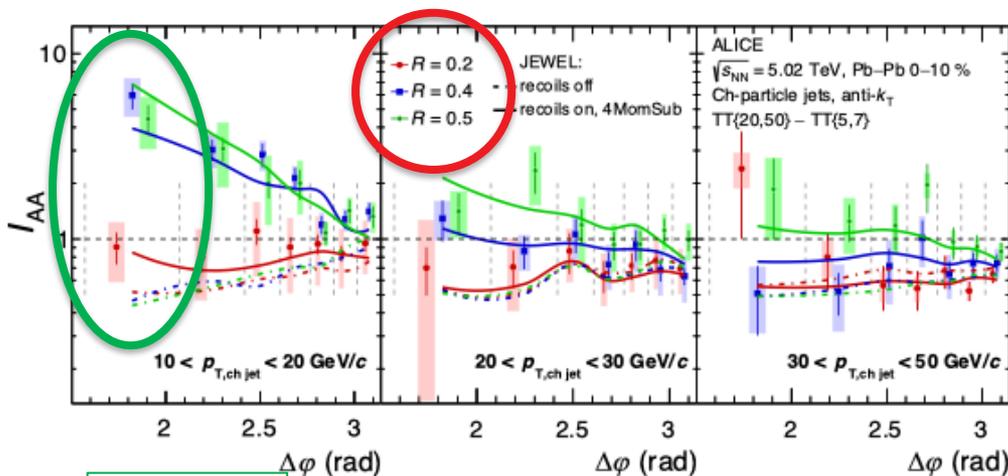
Phys.Rev.Lett. 133 (2024) 2 022301

Phys.Rev.C 110 (2024) 014906

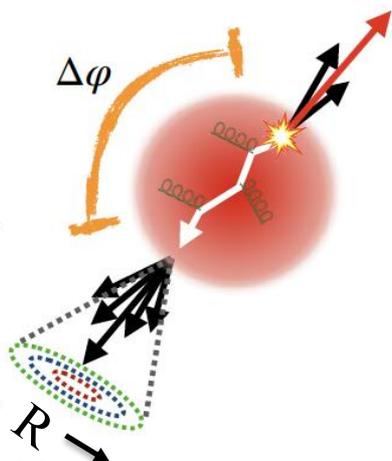


Phys.Rev.Lett. 134 (2025) 232301

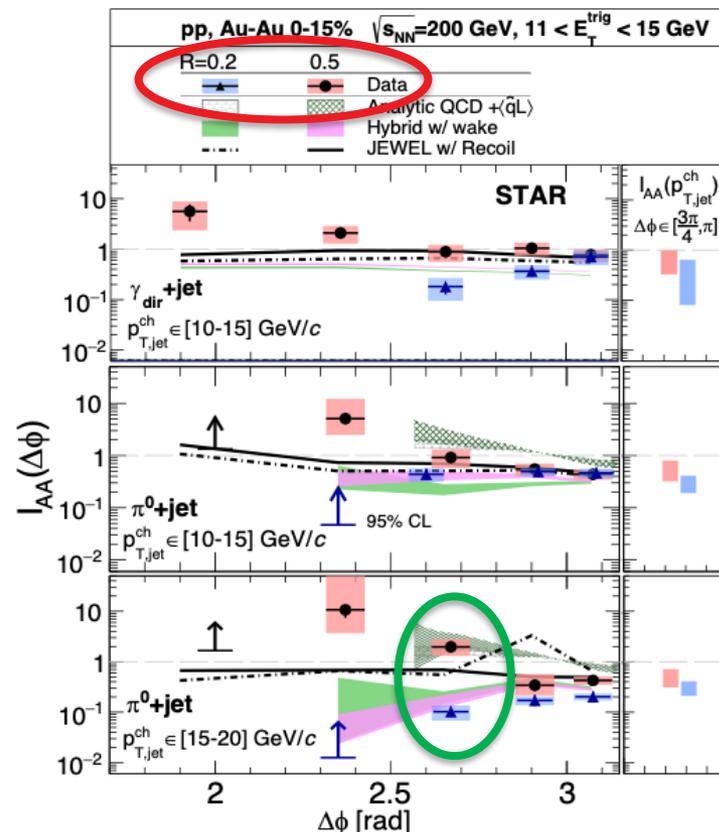
Phys.Rev.C 111 (2025) 064907



Factor 6

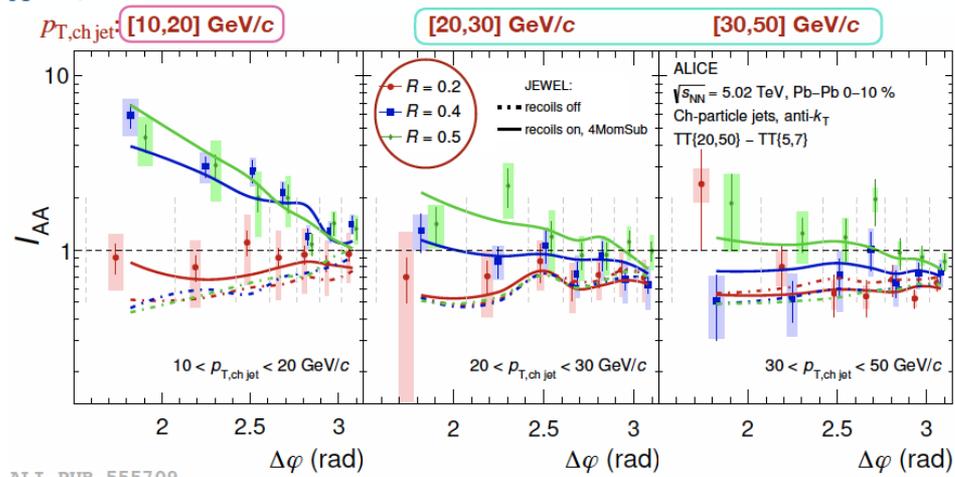
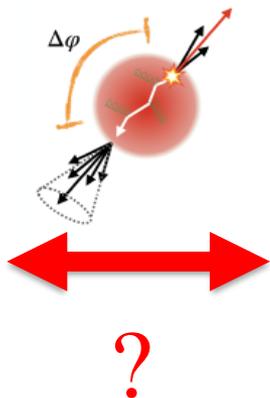
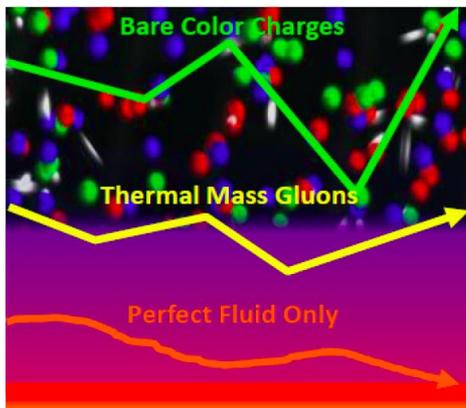


$$I_{AA} = \frac{\Delta_{\text{recoil}}(\text{Pb-Pb})}{\Delta_{\text{recoil}}(\text{pp})}$$

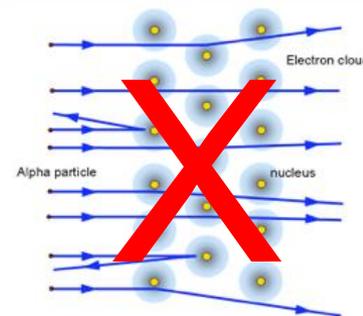


Factor  $20 \pm 2$ ; largest jet quenching signal ever observed

# Azimuthal broadening: what does it mean?



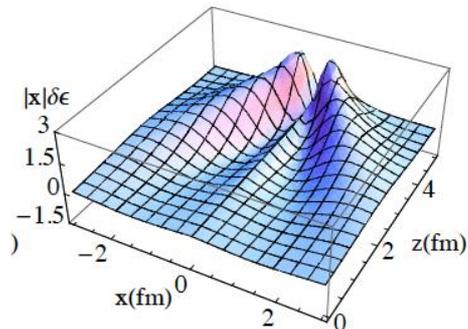
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Why broadening only for large aperture recoil jets?

- 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 recoil (“jet”  $p_T \sim R^2$ )



New probe of the dynamical behavior of the QGP?

Compare to theory

body QCD

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

Peng Jing,<sup>1</sup> Yichao Dang,<sup>1</sup> Yang He,<sup>2</sup> Shanshan Cao,<sup>1,\*</sup> Li Yi,<sup>1,†</sup> and Xin-Nian Wang<sup>3,‡</sup>

<sup>1</sup>*Institute of Frontier and Interdisciplinary Science,  
Shandong University, Qingdao, Shandong 266237, China*

<sup>2</sup>*Department of Modern Physics, University of Science and Technology of China, Anhui 230026, China*

<sup>3</sup>*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.

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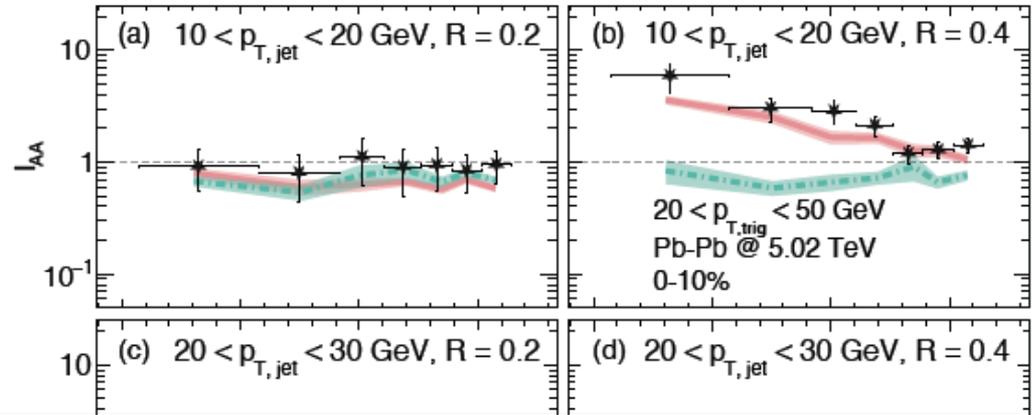
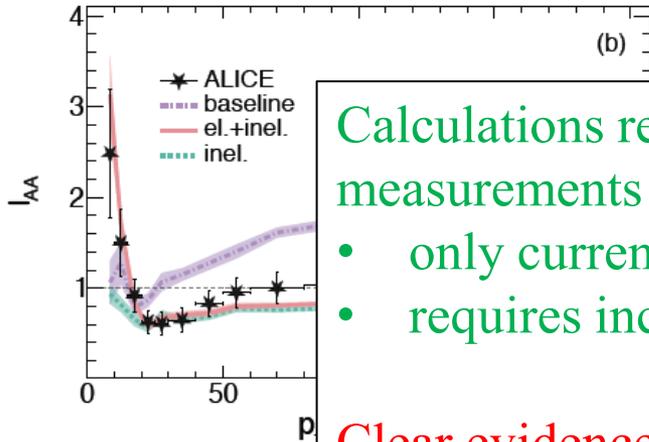
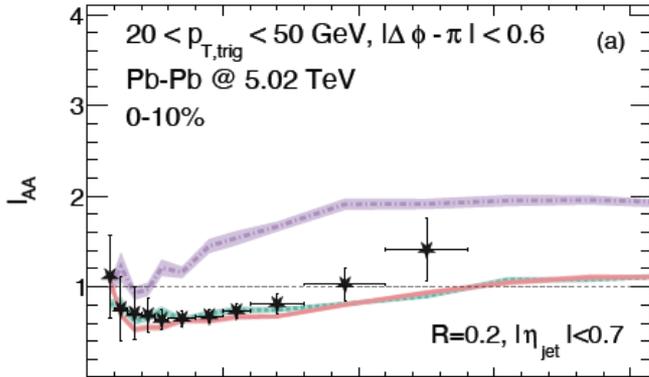
<sup>3</sup>*Institute of Particle Physics and Key Laboratory of Quark and Lepton Physics (MOE),  
Central China Normal University, Wuhan, 430079, China*

(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

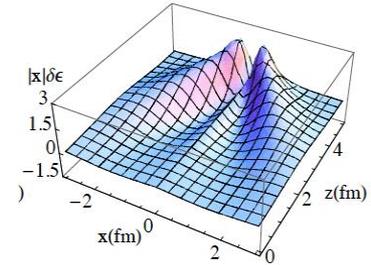
Currently the most detailed and complete model of QGP response to excitation by a jet



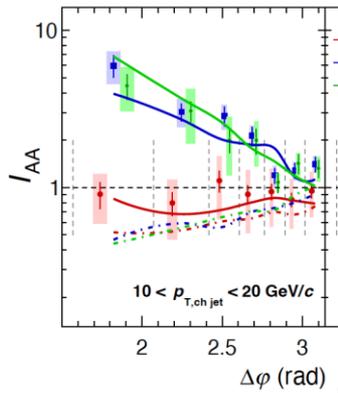
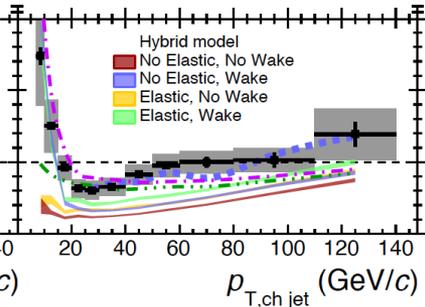
Calculations reproduce well both  $p_T$  and azimuthal dependence of measurements

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

Clear evidence for “thermal jets” or jet wake

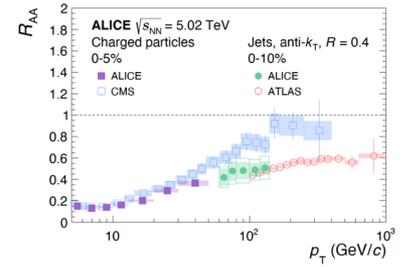
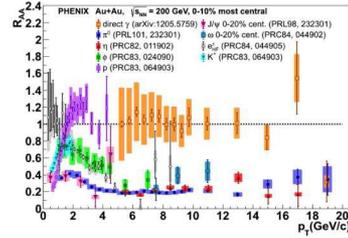
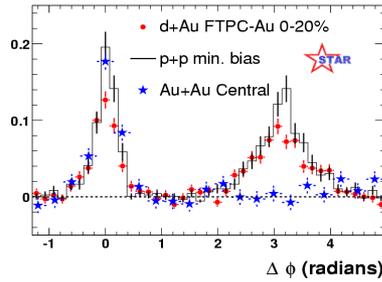
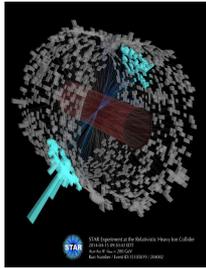
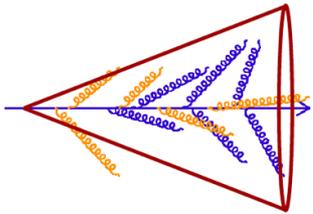


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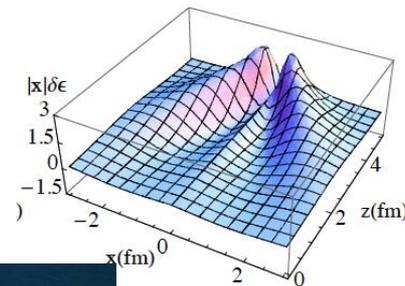
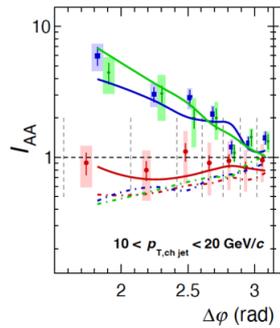
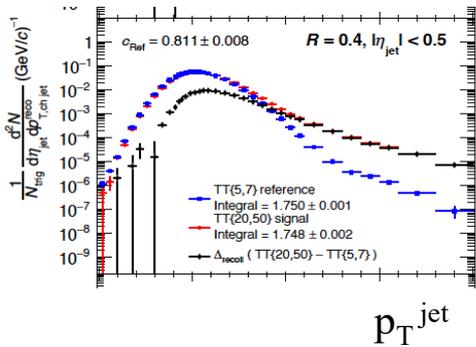
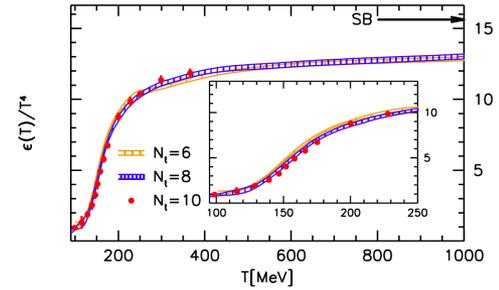
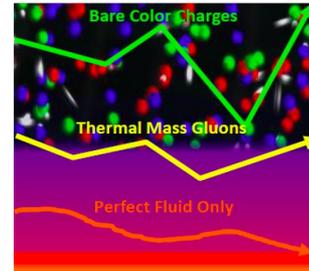
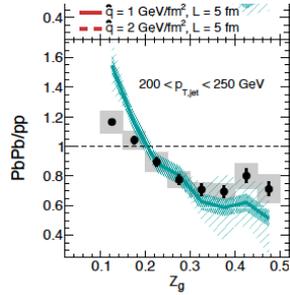
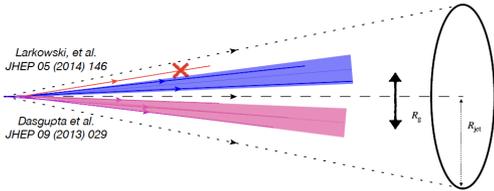
Opens a new chapter: study of the QGP response to excitation!

# Summary of Lecture 2



Larkowski, et al. JHEP 05 (2014) 146

Dasgupta et al. JHEP 09 (2013) 029

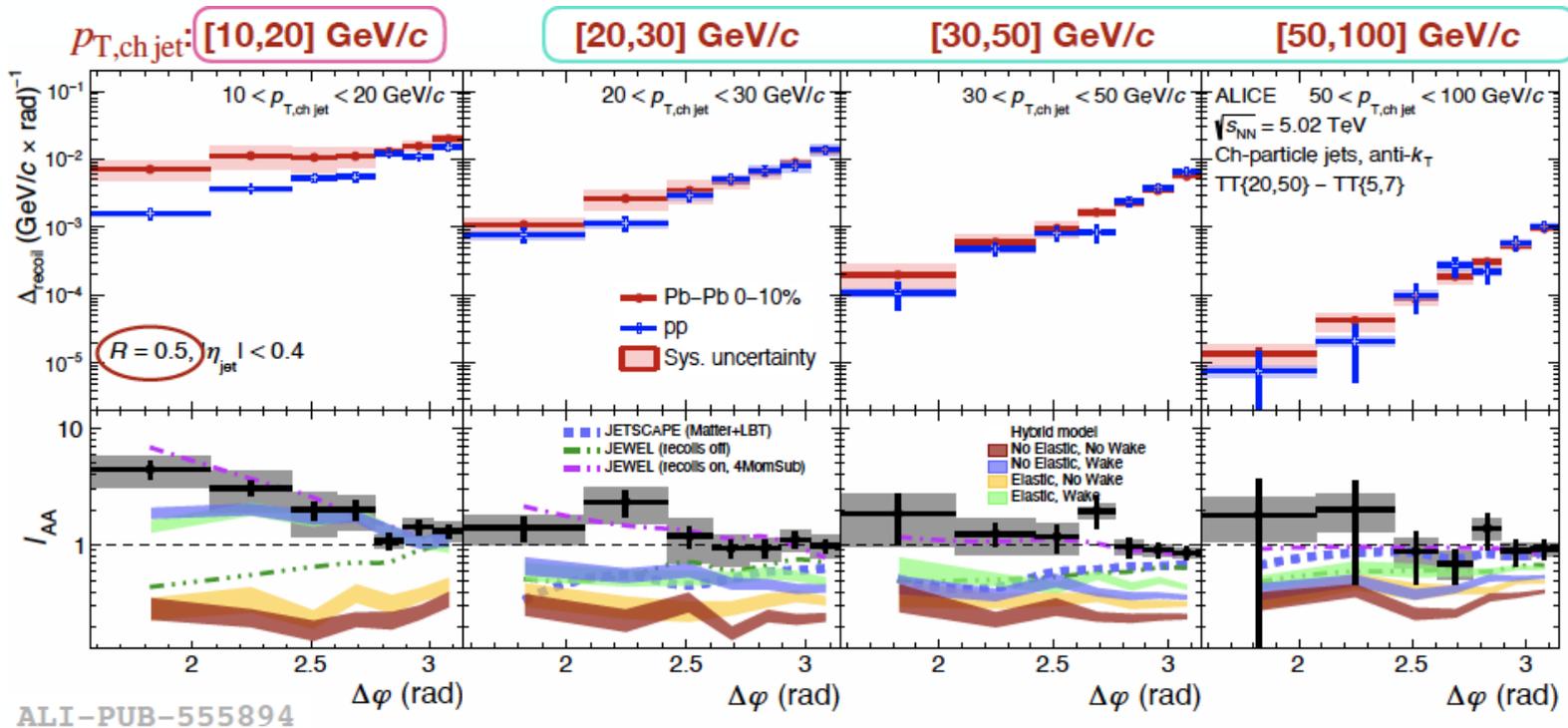
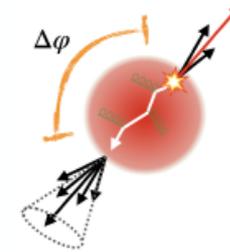


Opens a new chapter: study of the QGP response to excitation!

# Extra slides

# Azimuthal broadening: $p_T^{\text{jet}}$ dependence

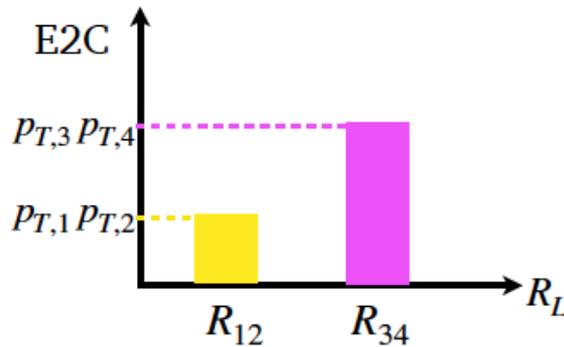
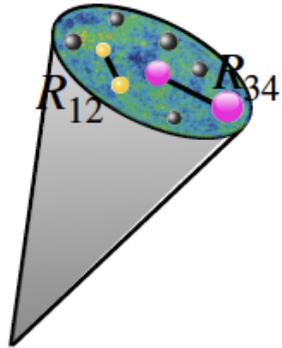
$$I_{AA} = \frac{\Delta_{\text{recoil}}(\text{Pb} - \text{Pb})}{\Delta_{\text{recoil}}(\text{pp})}$$



# Energy-energy correlators (EECs)

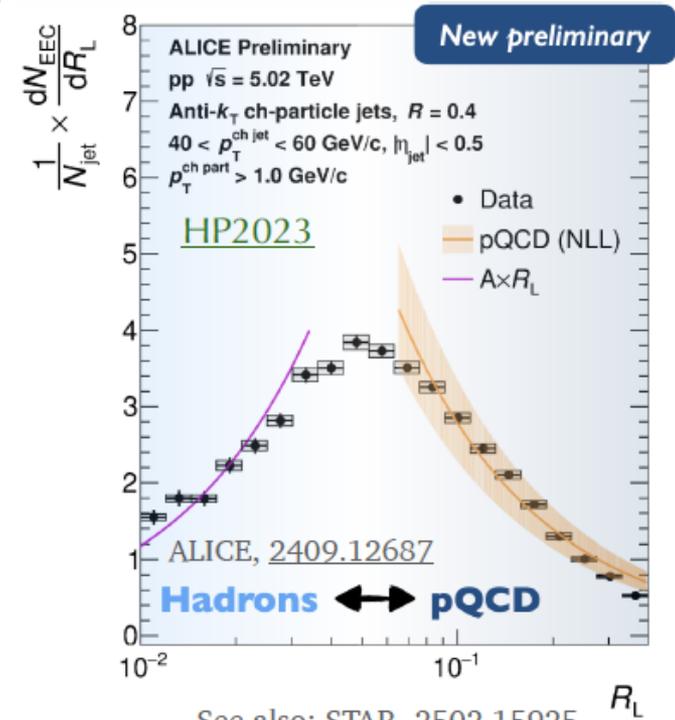
- Correlators of the **energy flux**  $\langle \mathcal{E}(\vec{n}_1) \mathcal{E}(\vec{n}_2) \cdots \mathcal{E}(\vec{n}_k) \rangle$

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



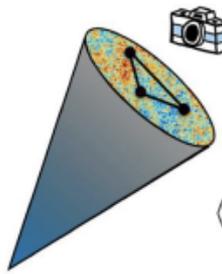
$$R_{ij} = \sqrt{\Delta\phi_{ij}^2 + \Delta\eta_{ij}^2}$$

E2C in p-p



# EECs in the QGP

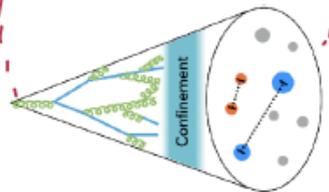
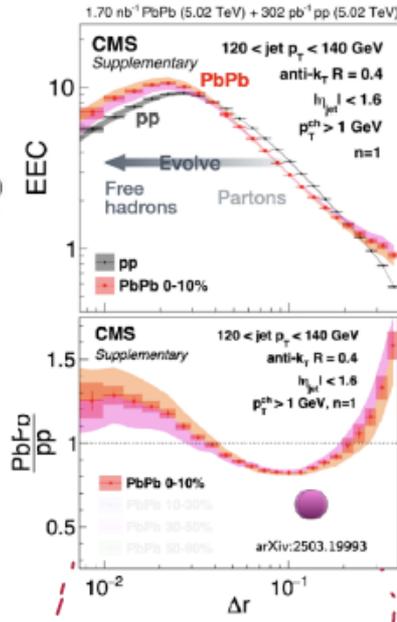
$$E2C = \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \sum_{i,j} \frac{P_{T,i} P_{T,j}}{P_{T,\text{jet}}^2} \delta(R_{ij} - R_L)$$



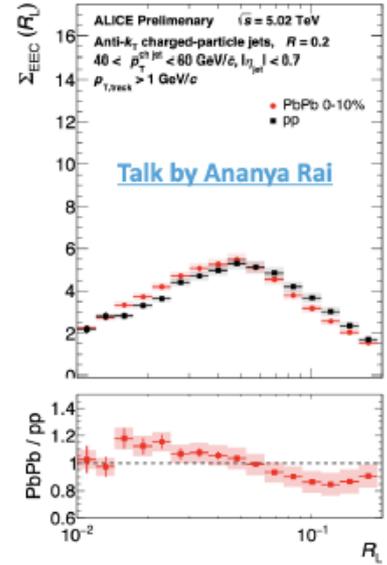
$$\langle \Psi | \mathcal{E}(\hat{n}_1) \cdots \mathcal{E}(\hat{n}_k) | \Psi \rangle$$

Complementary approach to same physics

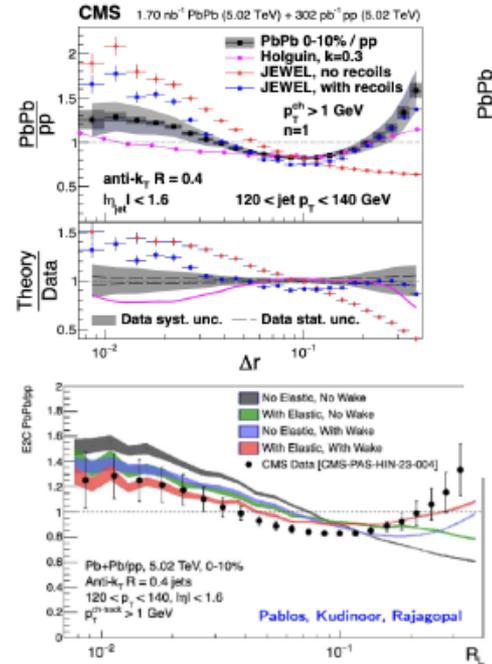
Talk by Jussi Viinikainen



Shape shift to smaller angle from pp to PbPb



=> (challenging for many models!)  
-> Interpretation?



# EECs in the QGP

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

EECs are apparently simple, highly integrated hadronic correlators

Experiment:

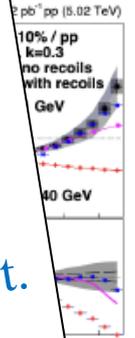
- highly integrated → only limited techniques to discriminate bkgd
- straightforward in pp, extremely difficult in AA
- measurements possible only in limited phase space, large sys uncert.

Theory:

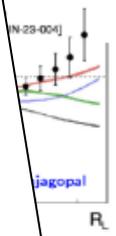
- Predicted QGP effects are small
- Highly integrated: hard to discriminate different physics effects

Needs new ideas → work in progress

→ Interpretation?



PbPb



R<sub>L</sub>