Jet correlations

opportunities and pitfalls

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Introduction

- triggered soft vs. hard correlations

The bias problem

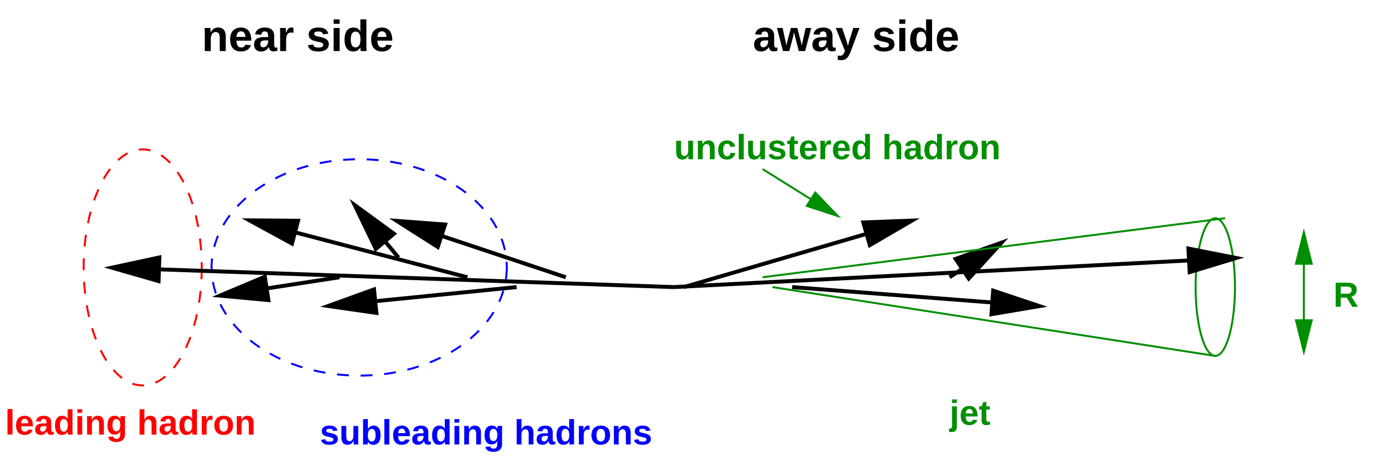
- how the trigger condition changes observations

Various jet correlations

- current phenomenology and what to learn from it

Conclusions

Jet correlations



- basic structure: hard event, back-to-back QCD jets
- select a trigger object:

$\longrightarrow$ unclustered: leading hadron, hard γ, Z^0, back-to-back hadron pair
$\longrightarrow$ clustered: jet, back-to-back jet pair

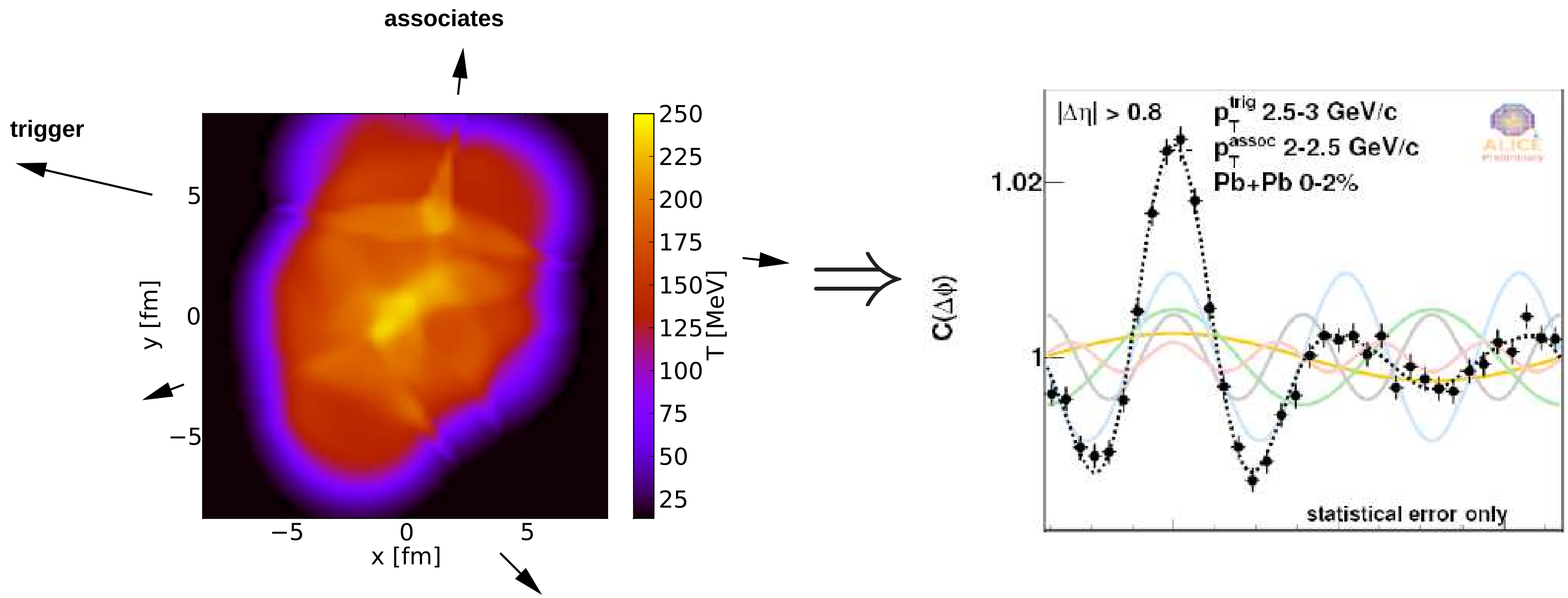
$\Rightarrow$ trigger defines event-by-event condition; observables are conditional probabilities

- select the observable

$\longrightarrow$ near side subleading yield, clustered yield,. . . directly biased by trigger condition
$\longrightarrow$ away side yield, clustered yield,. . . indirectly biased by trigger condition

- need to **understand biases** before interpreting results

NOT JET CORRELATIONS

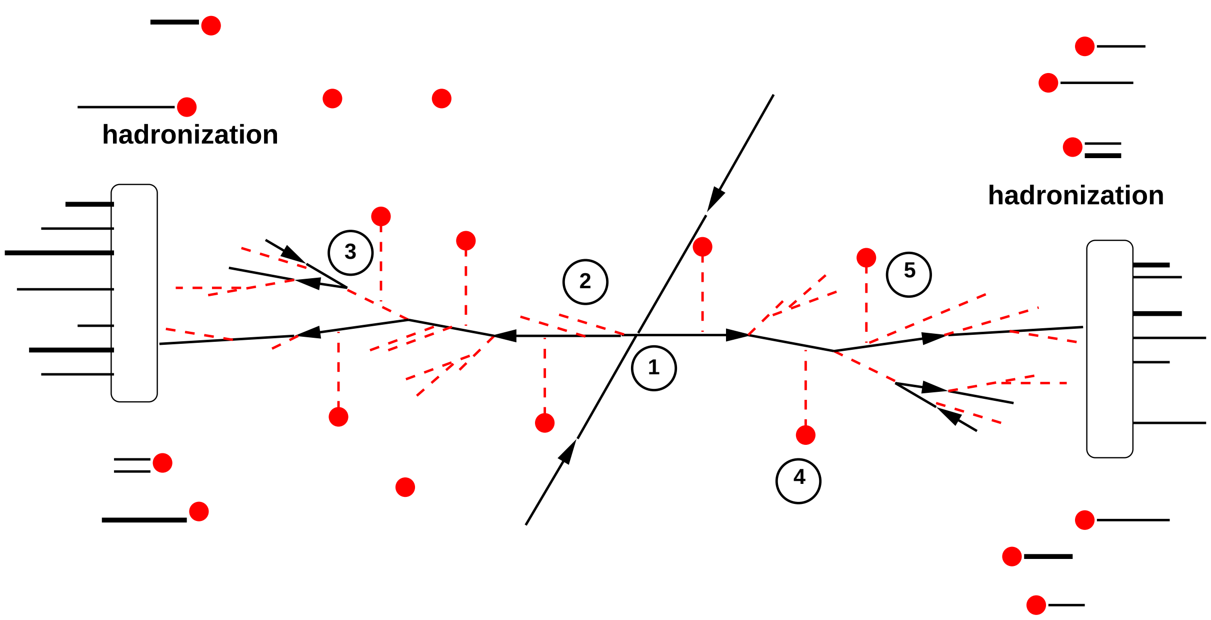


• triggering on hadrons below 6 GeV does not trigger back-to-back jet topologies
→ 3 GeV triggers predominantly select fluid dynamics modes

• in this case, angular distribution of associates is given by v_n pattern
→ powerful technique of v_n determination from correlations

Jet correlations are relevant where the hadron P_T spectrum and and PID differential yield is explained by pQCD and fragmentation. Typically, that happens for triggers above 6-8 GeV.

MEDIUM-MODIFIED JETS IN THE EYE OF A THEORIST



1) hard process 2) vacuum shower 3) medium-induced radiation 4) medium evolution 5) medium correlated with jet by interaction

- series of splittings $a \rightarrow bc$ with decreasing t

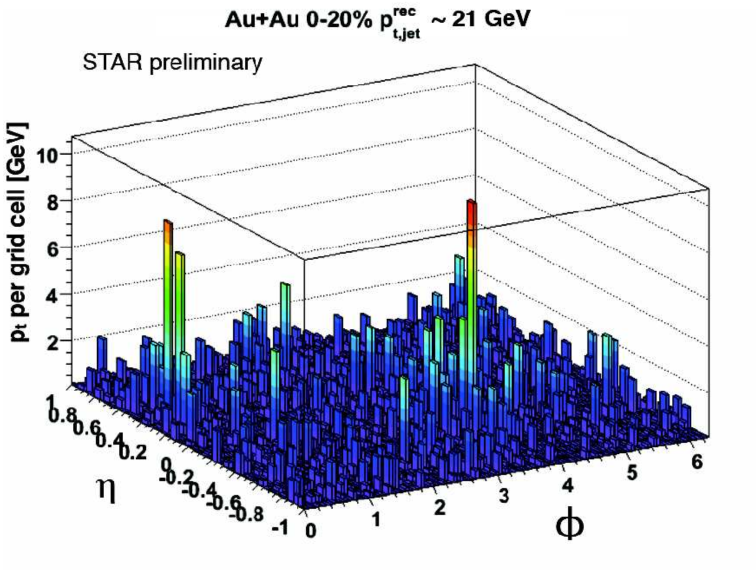
$$dP_a = \sum_{b,c} \frac{\alpha_s(t)}{2\pi} P_{a\rightarrow bc}(z) dt dz \quad \text{with} \quad t = \ln Q^2/\Lambda_{QCD} \quad \text{and} \quad z = E_d/E_p$$

$$P_{q\rightarrow qg}(z) = \frac{4}{3}\frac{1+z^2}{1-z} \quad P_{g\rightarrow gg}(z) = 3\frac{(1-z(1-z))^2}{z(1-z)} \quad P_{g\rightarrow q\overline{q}}(z) = \frac{N_F}{2}(z^2 + (1-z)^2)$$

- add medium perturbations, terminate at a soft virtuality scale t_0 or Q_0 and hadronize

$\Rightarrow$ compute the fate of the hard parton *forward* in time to get the final hadron shower

Medium-modified jets in the eye of an experimentalist



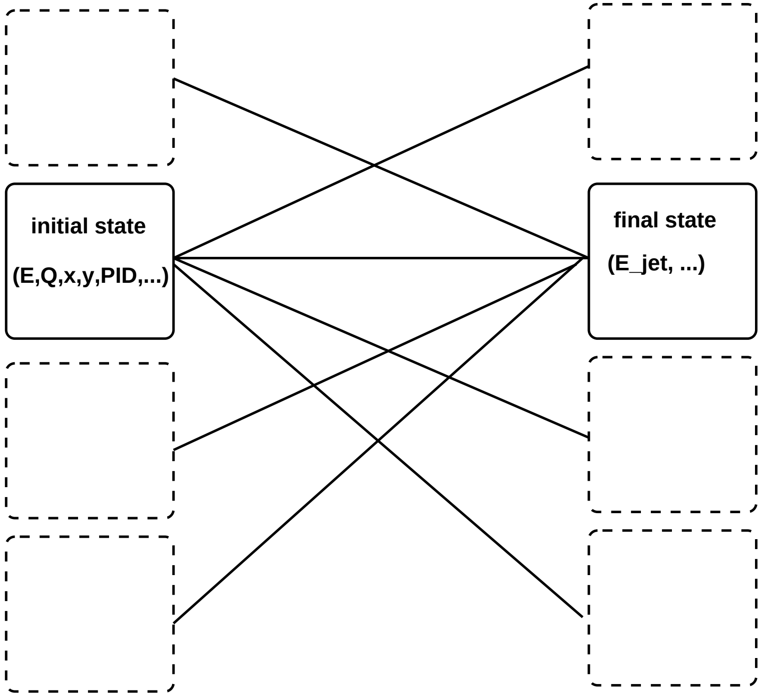
- 'Where is my jet, what belongs to it and what doesn't?'

→ triggered observables and background subtraction techniques

→ form 'modified over unmodified' ratios

⇒ conclude from the observed jet *backward* in time what the hard process and the modification might have been

Does this matter?



• initial state assumed by the theorist can lead to final states which are not triggered (and remain unobserved)

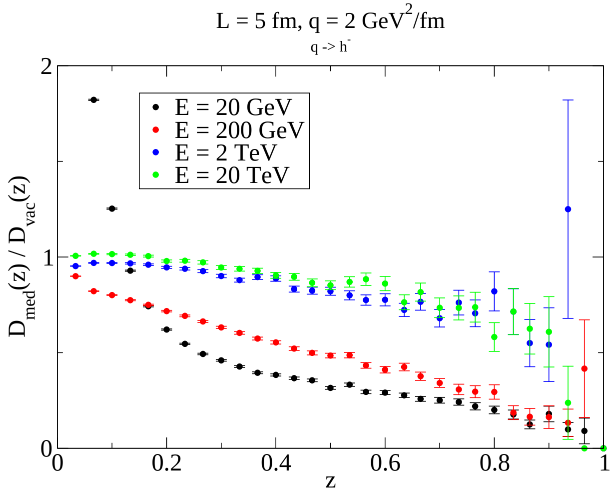
• experimental final state can come from initial states theory did not consider (background fluctuations, 'fake jets',. . .)

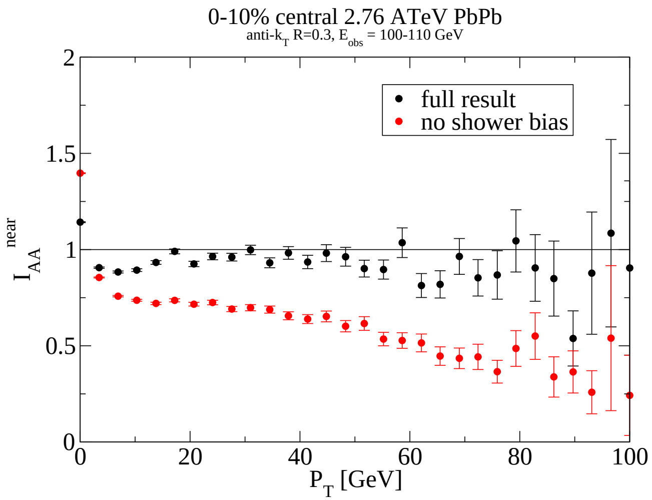
⇒ a correct comparison requires to compute for *all* initial states, taking the *biases* by the experimental observation into account

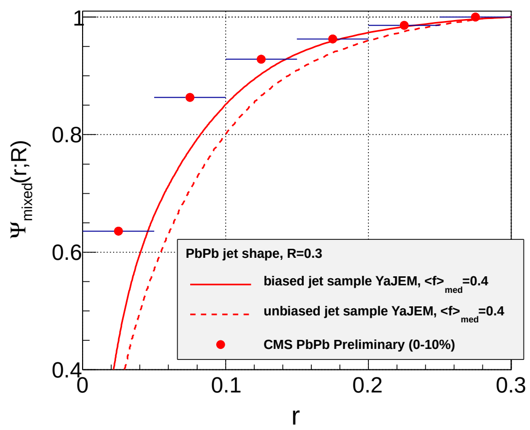
Case studies — biases matter!

Theoretical: shower from quark with fixed initial energy, fixed in-medium path (left)

Experimental: jets which clustered to fixed energy with anti-k_T, $R = 0.3$ (middle) (averaged over parton type, energy, medium geometry . . .)







- experimental observables are massive averages over possible initial states
$\longrightarrow$ information loss

- jet clustering represents a 'trigger' condition for the analysis
$\longrightarrow$ the observable is **always** biased (cf. also jet shape, right)

- biases can qualitatively change the picture and need to be understood

TR ,1212.0646 [hep-ph], R. Perez-Ramos and TR, in preparation

Types of biases

In dicussing high P_T reactions in heavy-ion collisions, 4 types of biases are relevant:

• **kinematic bias** — shift in the relation between hadron and parton kinematics
$\rightarrow$ occurs because the medium induces some extra radiation from partons

• **parton type bias** — shift in the mixture of quark to gluon jets
$\rightarrow$ occurs because gluons couple with a factor $C_F = 9/4$ more strongly to the medium

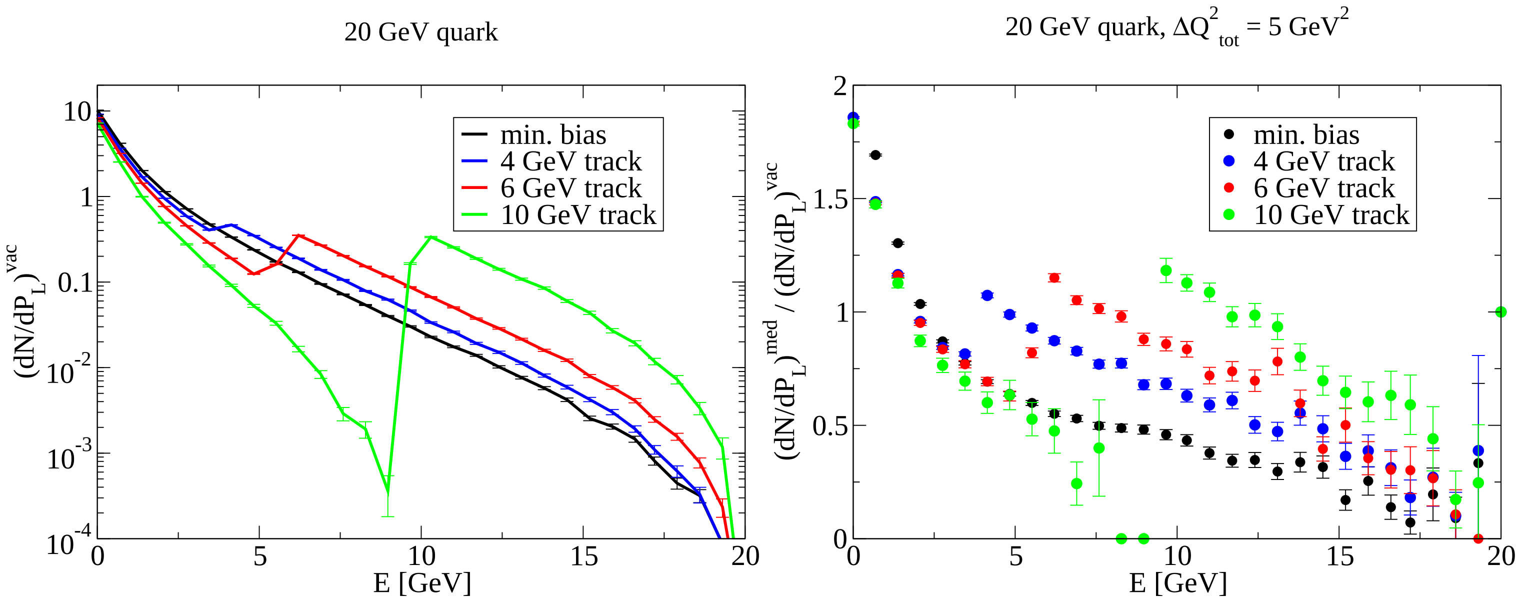
• **geometry bias** — observed hard reactions do not come from all vertices equally
$\rightarrow$ occurs because medium modification grows with medium density and pathlength

• **shower bias** — a trigger condition makes some shower structures unobservable
$\rightarrow$ occurs because of a direct selection effect

$\rightarrow$ shower bias directly affects analysis of clustered jet properties
$\Rightarrow$ look more closely

TR, 1212.0646 [hep-ph].

The shower bias



- a trigger condition biases the shower in which the trigger is created (left)

$\longrightarrow$ suppresses medium-modifications — highly modified showers don't trigger (right)

$\longrightarrow$ similar if energy flux through a subcone is required — jet trigger condition

- leading cause for 'near-null effect' in FF and jet shape analysis

- this bias is unrelated to the hard process itself

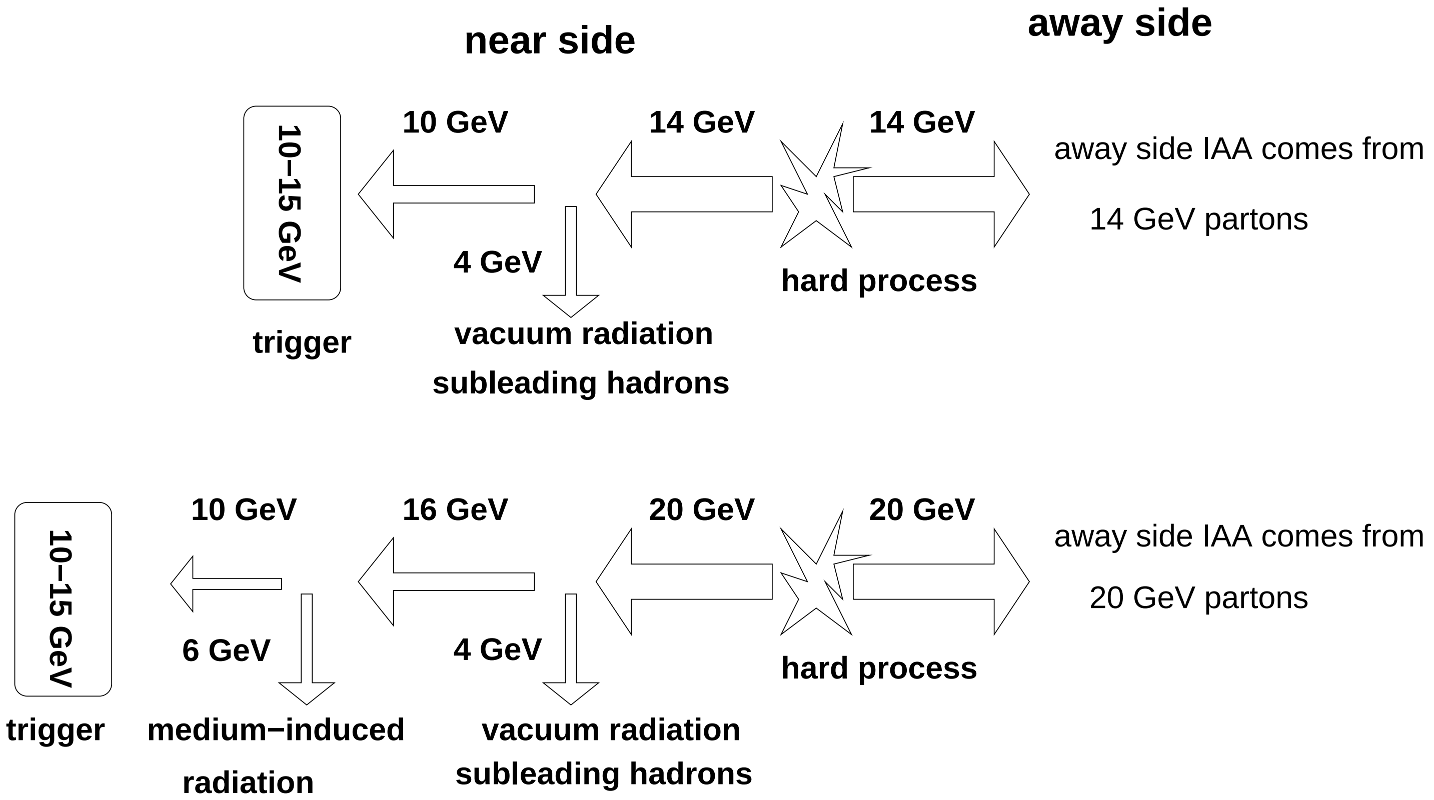
$\longrightarrow$ just affects the trigger side

$\longrightarrow$ strong advantage of back-to-back correlations: no shower bias on away side

TR, 1212.0646 [hep-ph].

The kinematic bias

- same trigger condition in vacuum and medium $\neq$ same initial kinematics



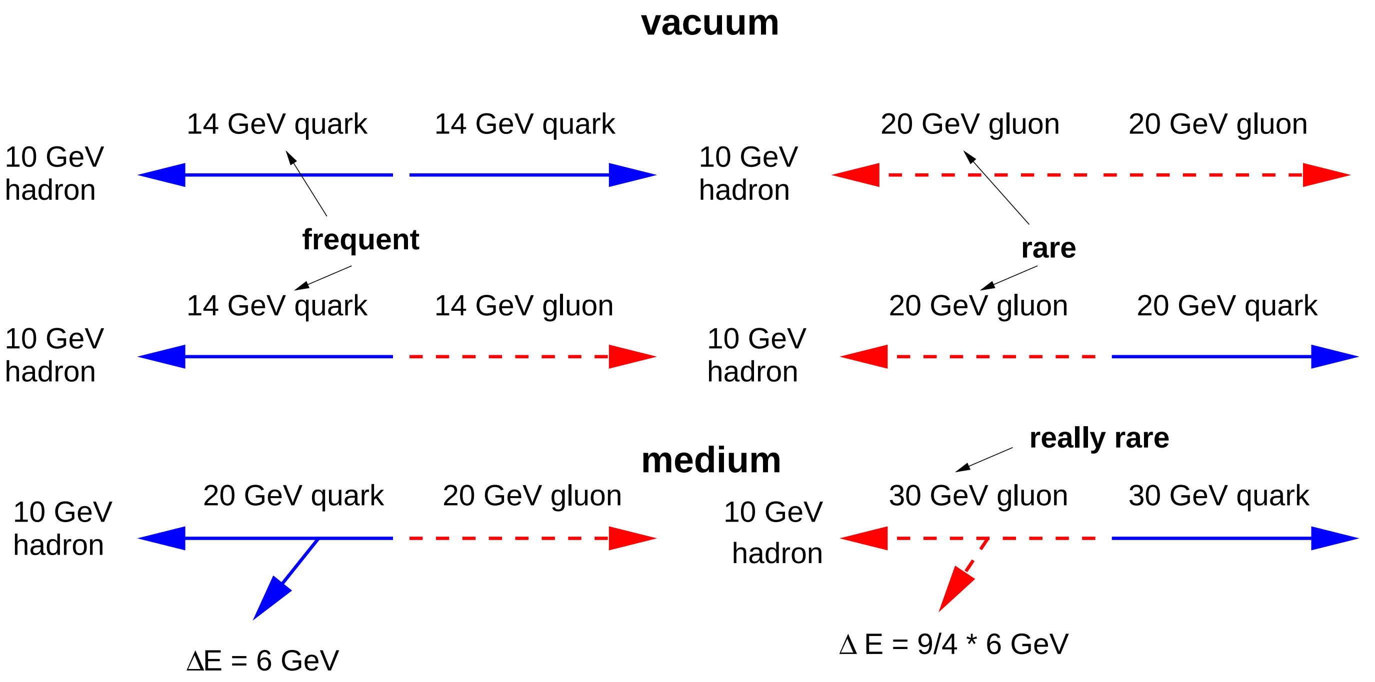
$\rightarrow$ counter-intuitively tends to *increase* I_{AA} in medium, naive argument misses this

- also other complications, intrinsic k_T points on average in trigger direction,. . .

The energy of a trigger object $\neq$ parton energy. This relation changes in a medium.

The parton type bias

- same trigger condition in vacuum and medium $\neq$ same parton types



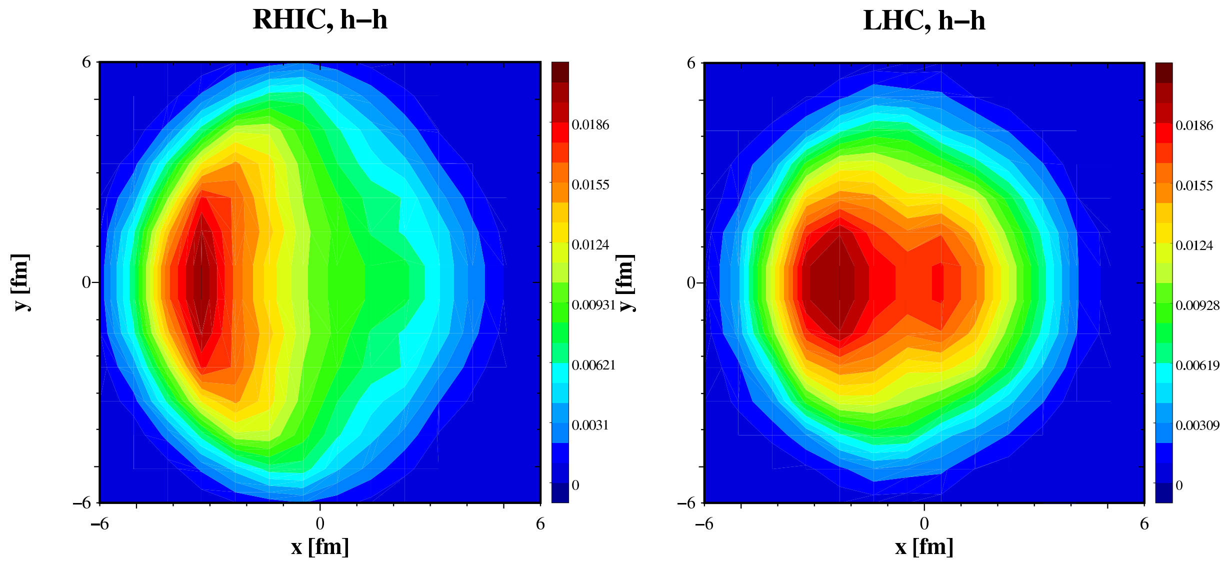
- most trigger conditions enhance the fraction of quark jets on the trigger side
$\rightarrow$ if $qg \rightarrow qg$ is important, this may enhance away side gluon fraction

- gluon jets in medium get additional penalty due to 9/4 higher interaction strength
$\rightarrow$ in-medium away side may have quite a different quark/gluon ratio than vacuum

Quark showers are more likely to trigger. The probability is changed by the medium.

The geometry bias

• if medium modification on average increases with medium length and density
$\longrightarrow$same trigger condition in vacuum and medium $\neq$ same geometry probed



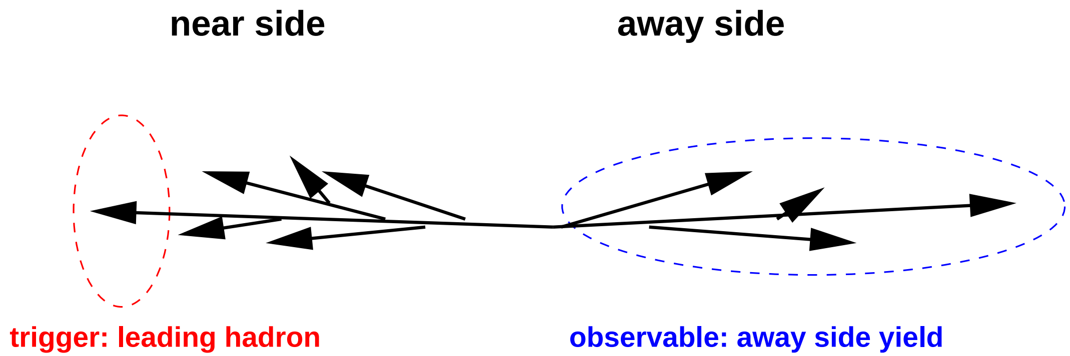
• partons with short in-medium paths have higher chance of fulfilling trigger condition
$\longrightarrow$ vertex distribution of triggered events is biased in a characteristic way

• interconnected with parton type and kinematical bias
$\longrightarrow$ harder parton spectra unbias geometry

Triggered objects in medium do not represent binary collision geometry.

A comparison of I_{AA}

Case study: compare away side I_{AA} for different trigger objects



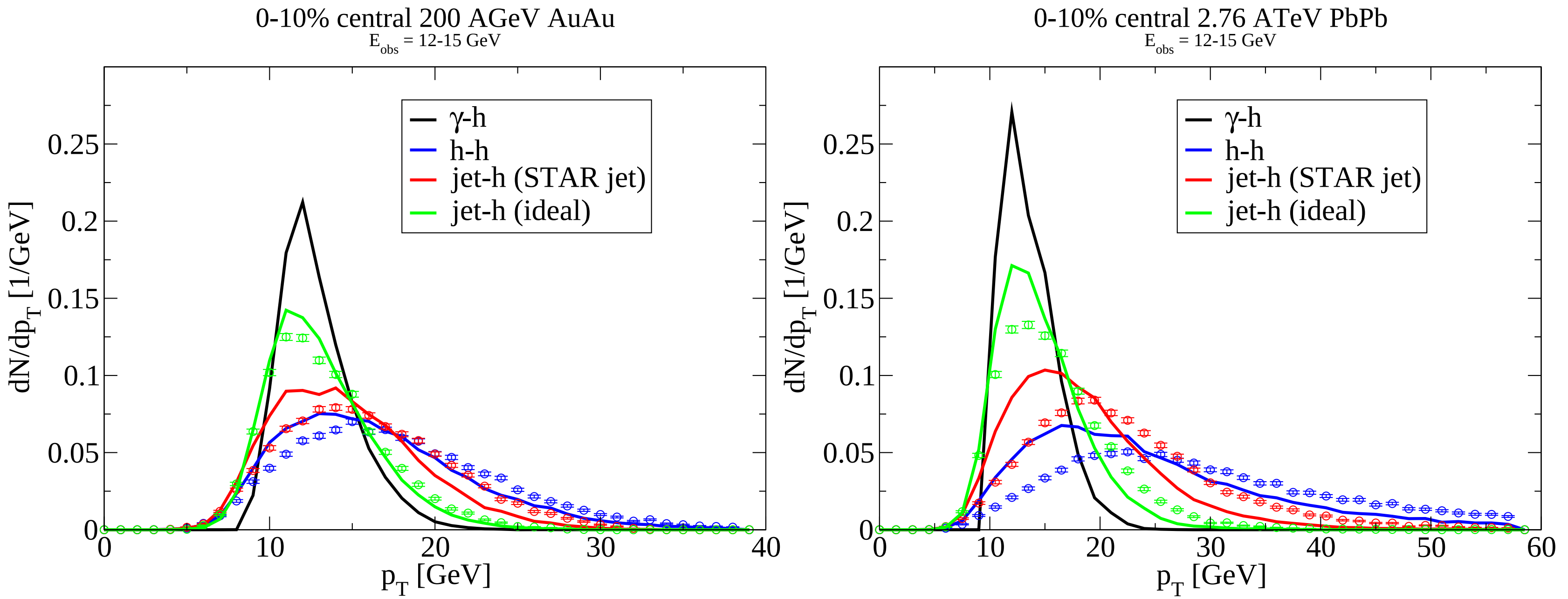
- the away side has no shower bias, because trigger is not from away side shower
- γ-h, h-h, jet-h (anti-k_T with $R = 0.4$, $P_T > 2$ GeV, STAR PID cuts), i(deal)jet-h (anti-k_T $R = 0.4$)
- trigger momentum range 12-15 GeV
- study away side charged hadron I_{AA}
- RHIC kinematics (steeply falling parton spectra, energetic partons strongly penalized)
- LHC kinematics (energetic partons accessible)

• *not* quantitative predictions, no attempt made to adjust model to data

TR, 1212.0646 [hep-ph].

A comparison of I_{AA}

- distribution of away side parton p_T ($\approx$ scale of back-to-back event)



- different trigger objects imply rather different kinematics for same trigger P_T

- also different response to medium

$\longrightarrow$ misleading to compare I_{AA} for same trigger kinematics

$\longrightarrow$ only for same parton type and kinematics a comparison becomes useful

TR, 1212.0646 [hep-ph].

A comparison of I_{AA}

RHIC

trigger	f^{vac}_{glue} near	f^{vac}_{glue} away	f^{med}_{glue} near	f^{med}_{glue} away
γ-h	N/A	0.03	N/A	0.03
h-h	0.04	0.69	0.04	0.69
jet-h	0.12	0.68	0.08	0.69
ijet-h	0.44	0.55	0.33	0.61

LHC

trigger	f^{vac}_{glue} near	f^{vac}_{glue} away	f^{med}_{glue} near	f^{med}_{glue} away
γ-h	N/A	0.04	N/A	0.04
h-h	0.33	0.79	0.32	0.78
jet-h	0.47	0.79	0.38	0.80
ijet-h	0.77	0.78	0.69	0.78

• moderately different parton type distribution, especially on near side

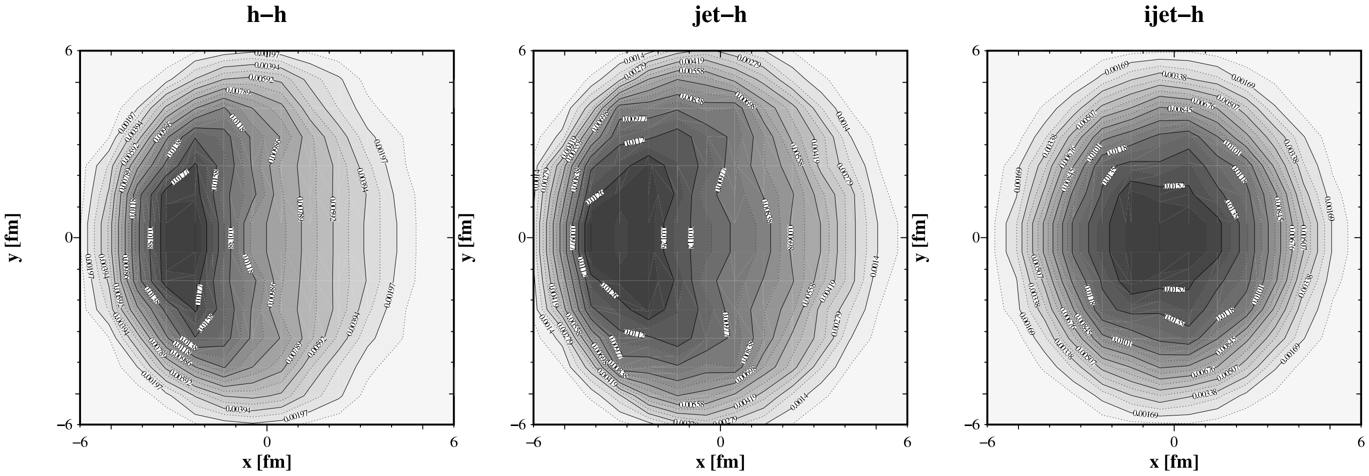
$\longrightarrow$ γ-h is really quite different in having quarks on the away side

$\longrightarrow$ also needs to be considered before comparison

TR, 1212.0646 [hep-ph].

A COMPARISON OF I_{AA}

RHIC:

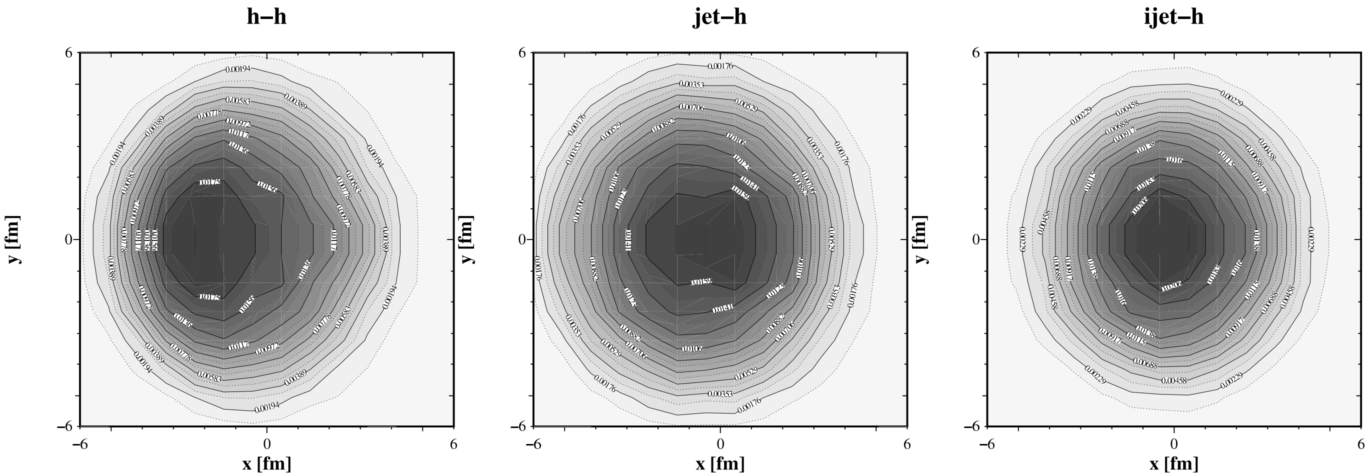


- completely different geometry bias

$\rightarrow$ unbiased for γ-h, nearly unbiased for ijet-h, highly biased for h-h

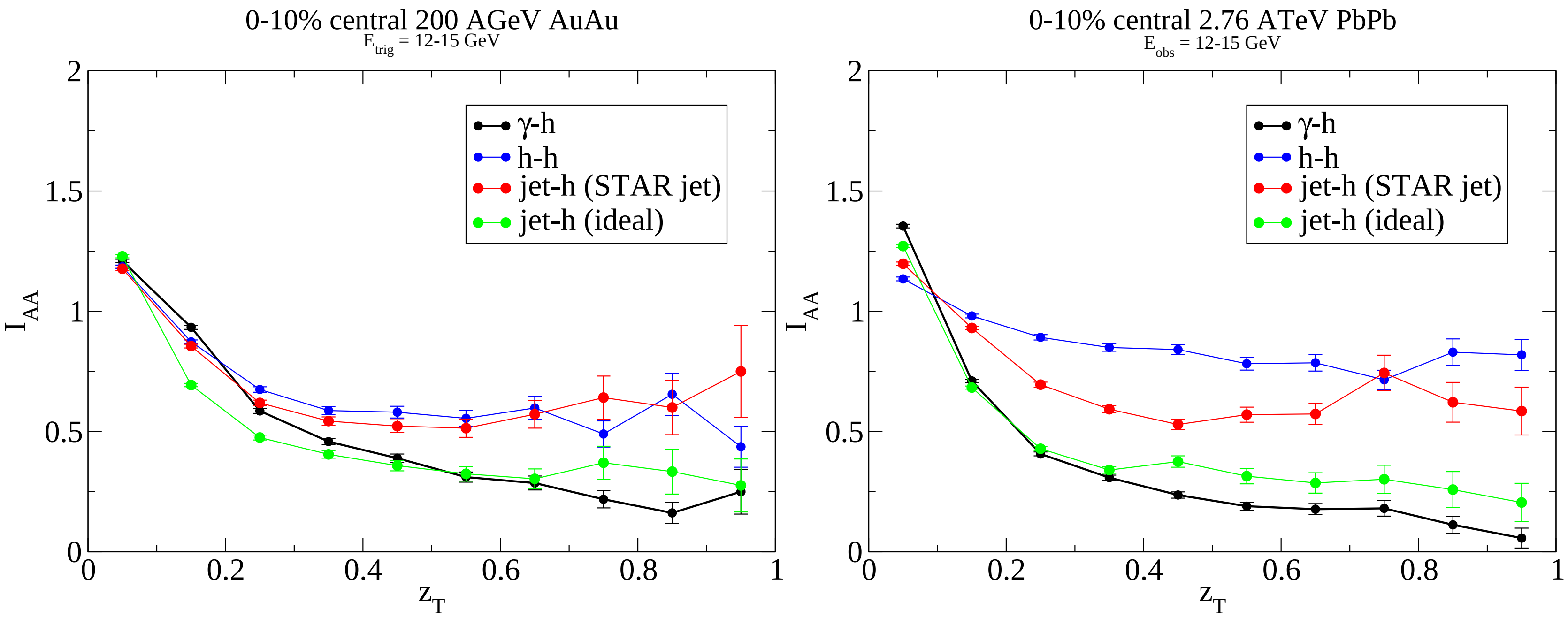
$\rightarrow$ note that bias depends on jet definition!

LHC:



- harder spectrum unbiases geometry

A comparison of I_{AA}



• at RHIC, results fairly similar — mere coincidence, completely different physics!

• at LHC, better separation, kinematic bias is seen to be very important
$\rightarrow$ pushed I_{AA} strongly up for h-h

• for seemingly similar trigger conditions, biases cause lots of variation in
- geometry
- parton type
- kinematics

TR, 1212.0646 [hep-ph].

Proposal

• experimental trigger cuts define a **filter** which controls the averaging
$\longrightarrow$ we see the theoretical shower through this filter

• different trigger conditions probe quite a range in geometry, parton type, kinematics
$\longrightarrow$ the filter is **controllable**

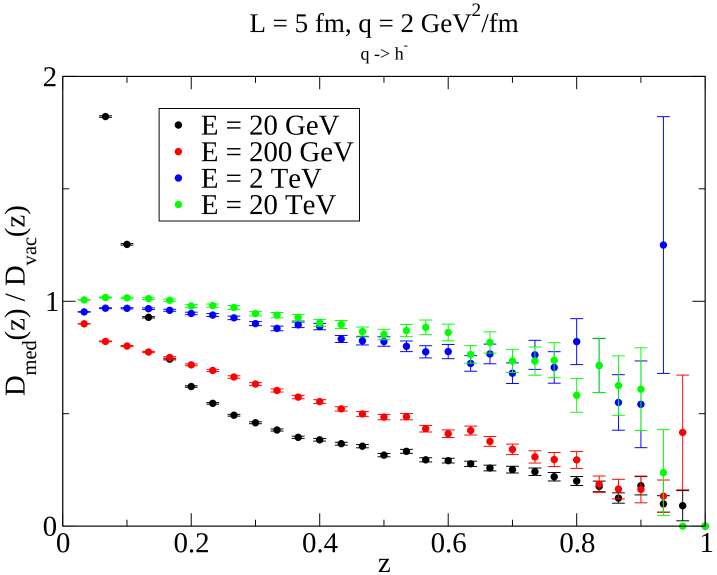
> Since we can't get clean kinematics and can't suppress biases, can we not actually *use* them to our advantage? More specifically, can biases not be designed such that they allow detailed tomography?

$\Rightarrow$ try understanding observables from the position
$\longrightarrow$ What is the trigger bias?
$\longrightarrow$ And thus what physics are we specifically sensitive to?

PROPOSAL

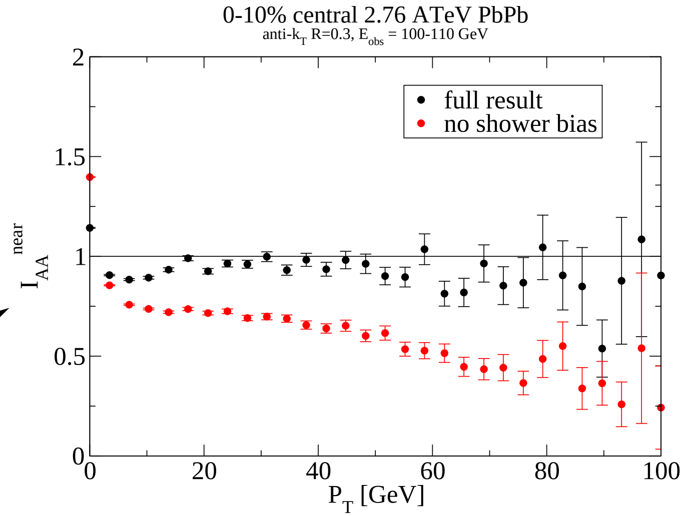
unfiltered distribution

(theoretical object)

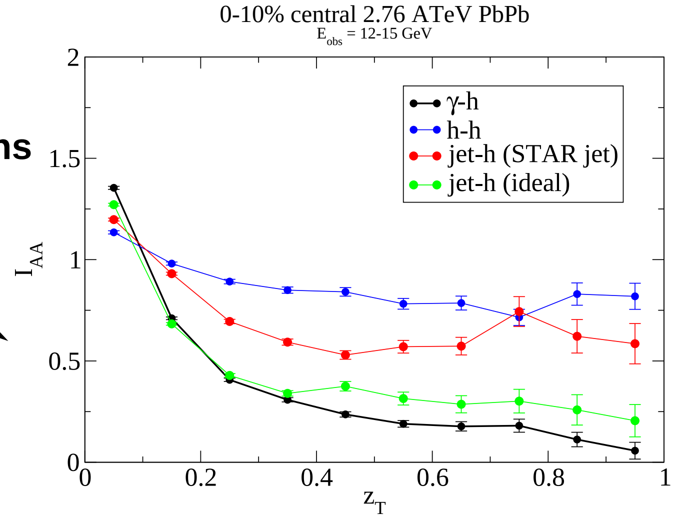


seen through

clustering

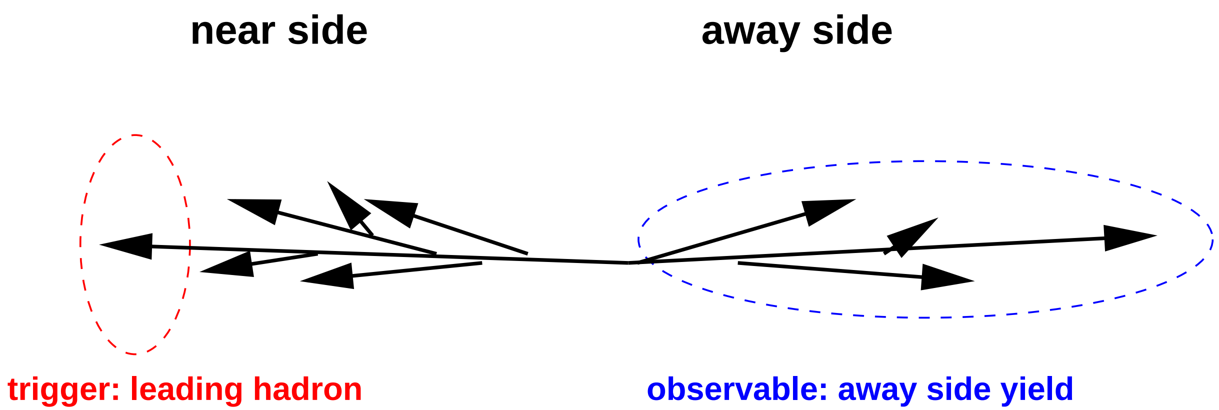


jet correlations



- different averaging process — filter set for different physics
- differently 'blurred' filter — γ-h is a cleaner trigger than h-h

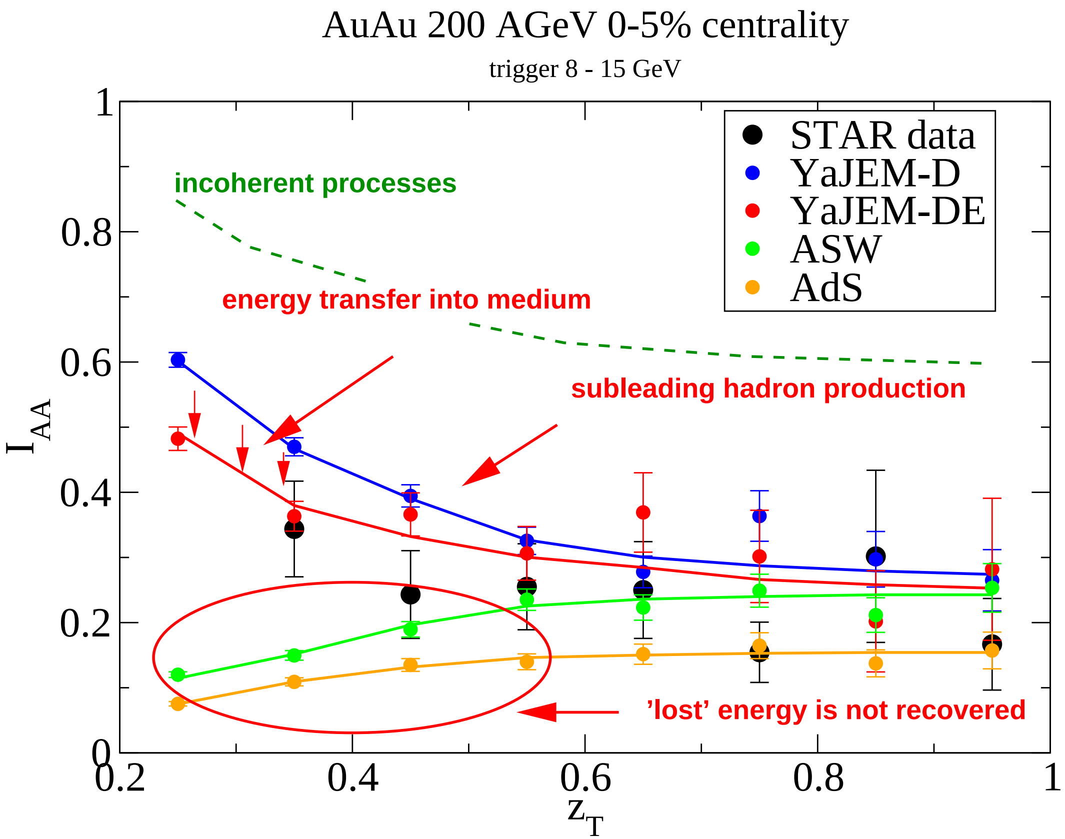
I_{AA} OF HADRONS



$$I_{AA} = \frac{\text{yield per trigger medium}}{\text{yield per trigger vacuum}}$$

(this is a conditional probability, and trigger biased)

I_{AA} OF HADRONS



- picture of the full MMFF

$\longrightarrow$ shows limits of leading parton energy loss picture

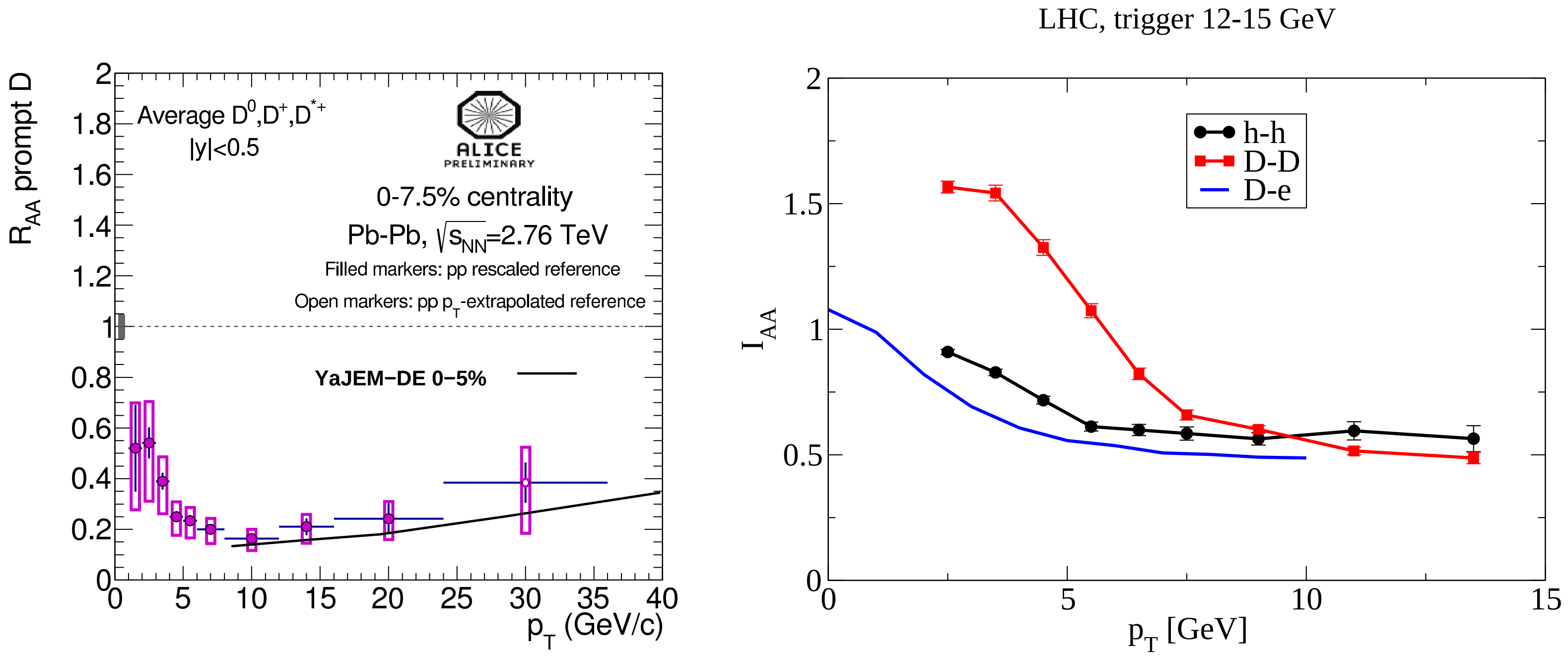
- constrains incoherent component from above with just 20% uncertainty
- constrains $\hat{e}$ from below to about 10% from subleading yield

TR, Phys. Rev. C **84** (2011) 067902

I_{AA} of charm mesons

- interesting idea (difficult experimentally) — how would heavy quarks be different?

$\rightarrow$ compute D-D and D-e correlations



- different parton type bias (always quark showers)
- different geometry bias (less coherent radiation, different pathlength dependence)
- different kinematical bias (harder fragmentation on the trigger side)

$\Rightarrow$ translate into significantly different result for I_{AA}

T. Renk, 1310.5458 [hep-ph].

I_{AA} of hadrons

- I_{AA} shows clearly that there is medium-induced radiation

$\longrightarrow$ outside the applicability of leading parton energy loss

- strong sensitivity to pathlength dependence

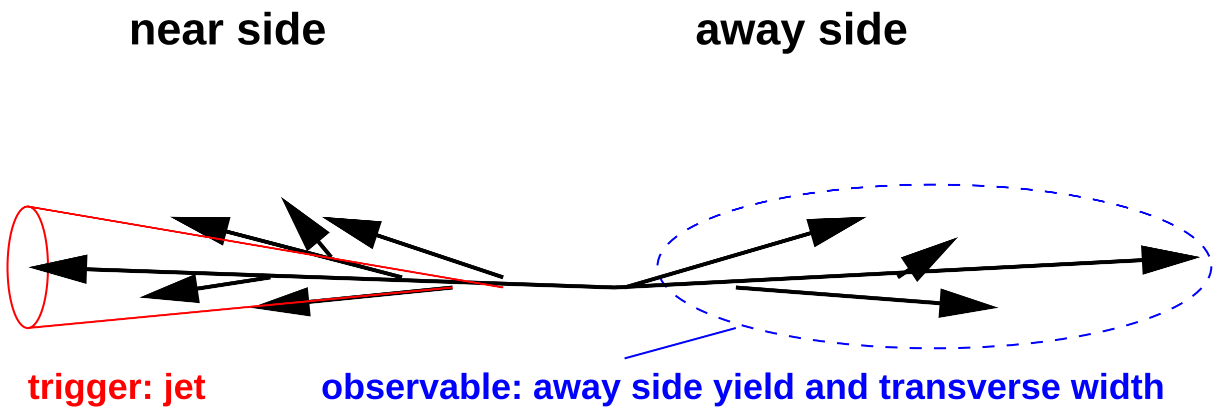
$\longrightarrow$ and modest uncertainty due to fluid dynamics background

- constrains elastic energy transfer into the medium from above and below

$\longrightarrow$ constraints both point to about 10%

Observes full longitudinal structure of the MMFF, but statistics insufficient to see transverse structure as well. Move to jet-h correlations instead!

I_{AA} IN JET-H CORRELATIONS



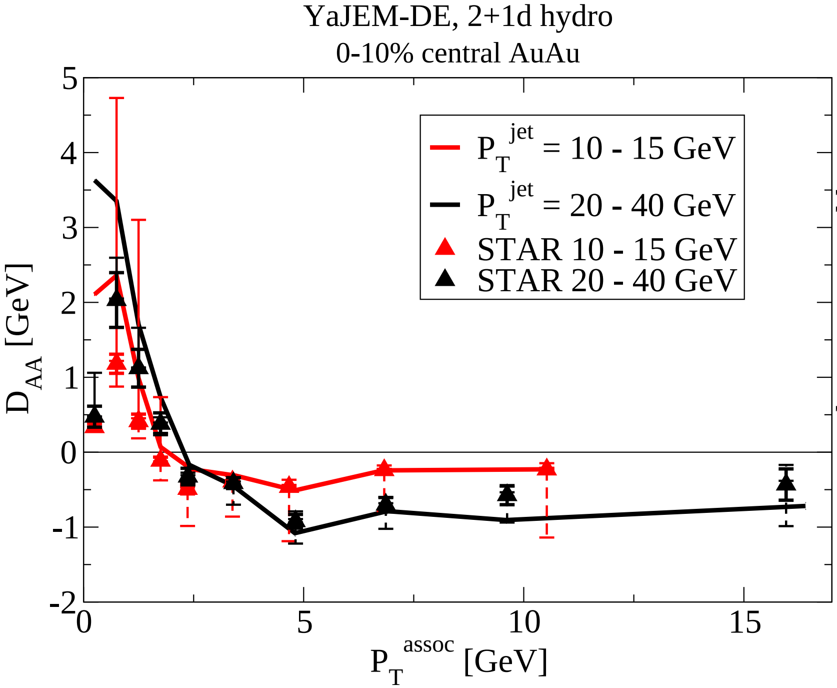
$$D_{AA} = \text{yield}_{AA}(P_T)\langle P_T\rangle - \text{yield}_{pp}(P_T)\langle P_T\rangle$$

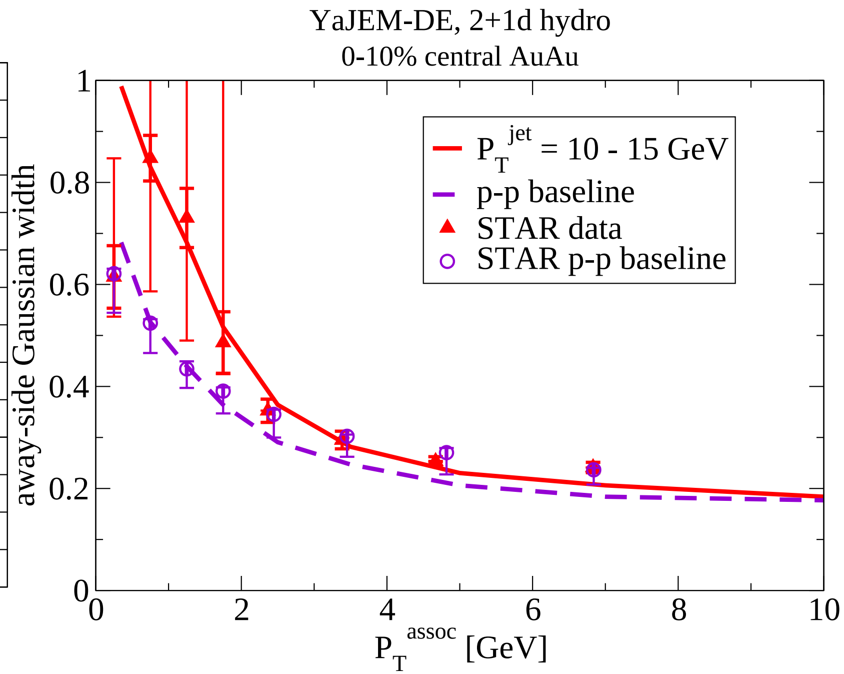
(this is also a conditional probability, and trigger biased)

I_{AA} IN JET-H CORRELATIONS

- differential long. and transverse picture of away side jet

$\longrightarrow$ correlation measurement can be carried down to few hundred MeV





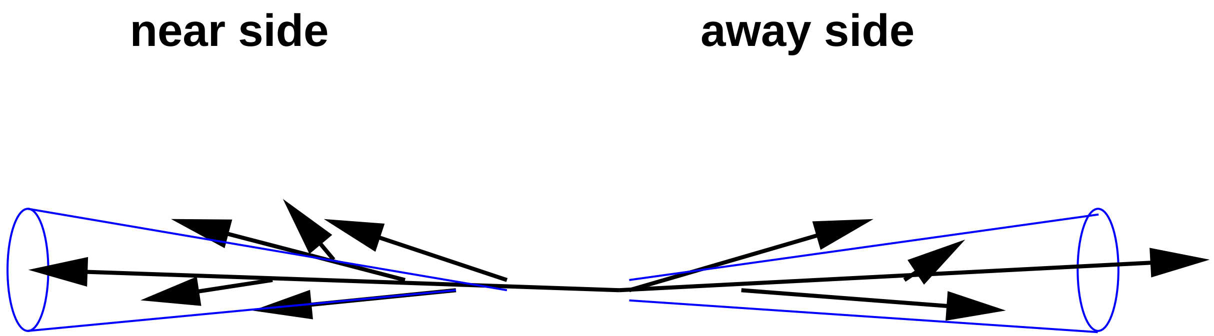
- 'upturn' of balance function around 3 GeV

- jet width increases over vacuum physics at the same scale

$\longrightarrow$ this happens independent of trigger energy (parton kinematics)

- crucial test for models, rules out fractional energy loss

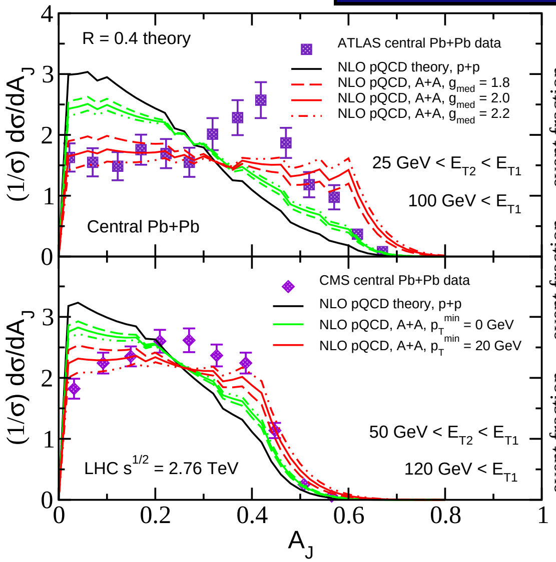
Dijet imbalance

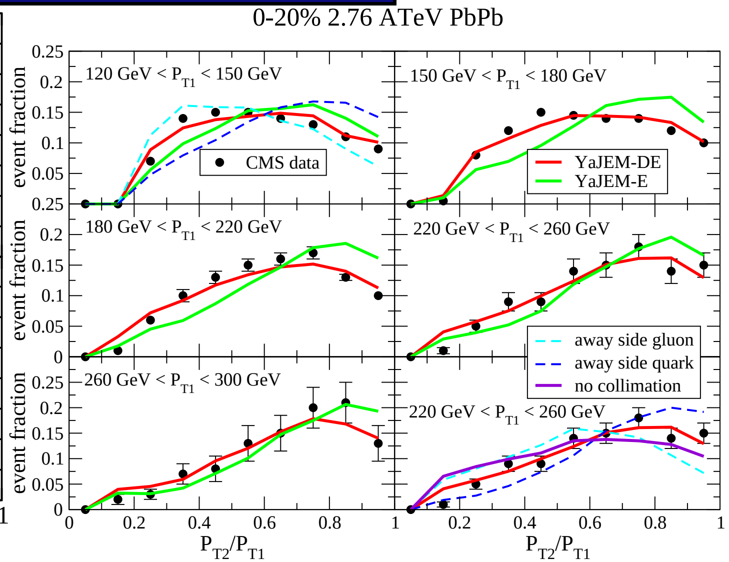


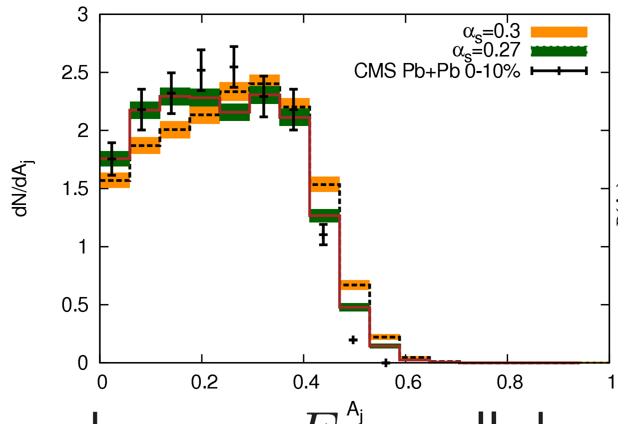
observable: momentum imbalance between jets

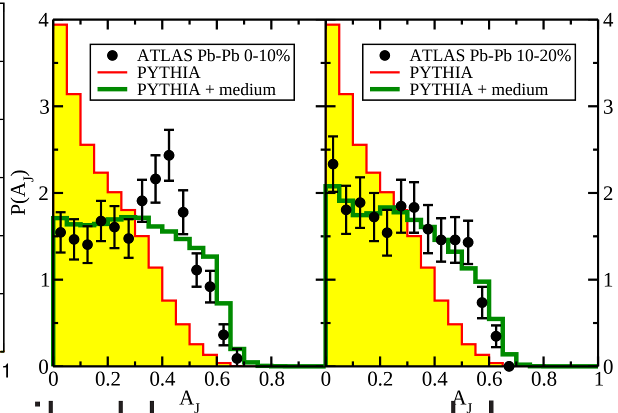
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} \quad \text{or} \quad E_{T2}/E_{T1}$$

Dijet imbalance









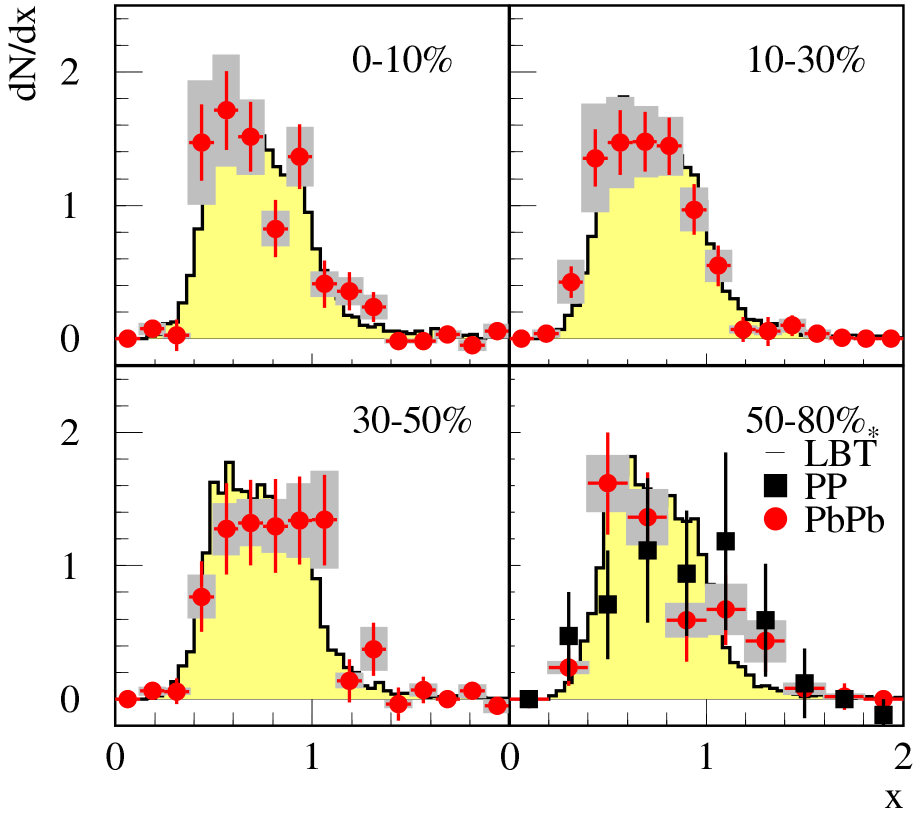
- shape and dependence on E_{jet} well described by many models
- contains lots of vacuum physics

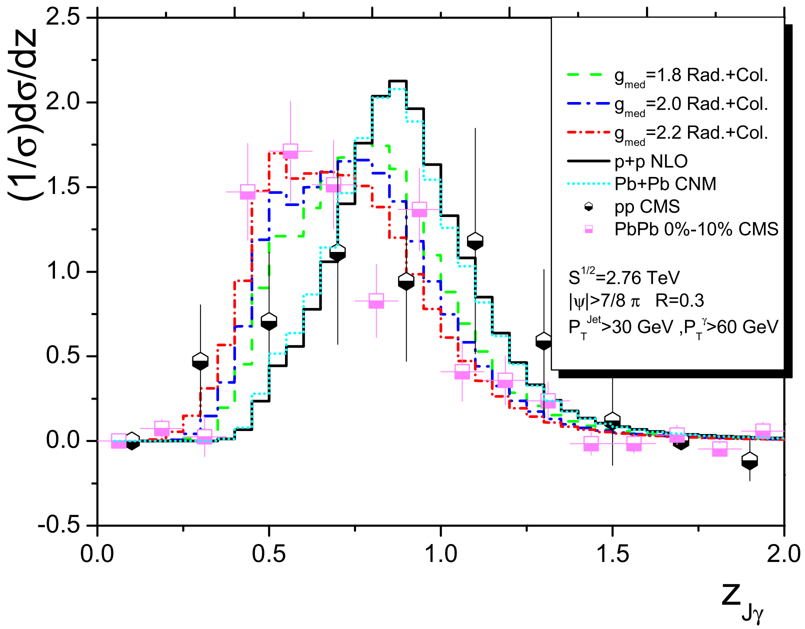
→ kinematical collimation, ratio of quark to gluon jets, EbyE jet mass distribution. . .

Y. He *et al.*,1105.2566; T. Renk, 1204.5572; C. Young *et al*, Phys. Rev. C **84** (2011) 024907, G. -Y. Qin and B. Muller, Phys. Rev. Lett. **106** (2011) 162302

γ-JET

- cleaner parton kinematics in γ-jet, away side is dominantly quark jet





- also well described by models

$\Rightarrow$ conceptually similar to A_J, but different kinematical and parton type bias

X. -N. Wang and Y. Zhu, Phys. Rev. Lett. **111** (2013) 062301; W. Dai, I. Vitev and B. -W. Zhang, Phys. Rev. Lett. **110** (2013) 142001

Dijet imbalance

• medium-induced angular decorrelation expected to be small
→ compare 100 GeV jet with $T = 300$ MeV thermal scale — ∼ 0.17° deflection
⇒ random kicks from a thermal medium can't significantly alter a 100 GeV jet axis
⇒ (neither can they change radiation phase space to create a hard gluon emission)

• beyond vacuum physics, A_J has little sensitivity to precise jet quenching mechanism
→ reason: the observable is a clustered quantity

Purpose of clustering in e^+e^- or p-p collisions: Get an observable which is sensitive only to hard physics (which we can do with pQCD) and not to soft physics (soft gluon emission, hadronization, . . .) which we can't.

jet ↔ good proxy for original parton (and hard physics)

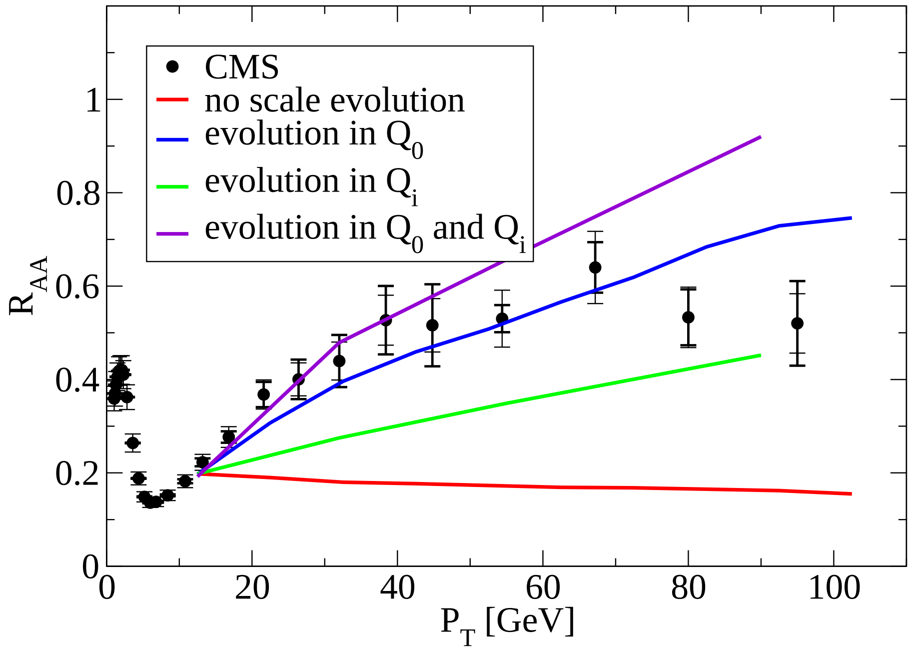
This really means:

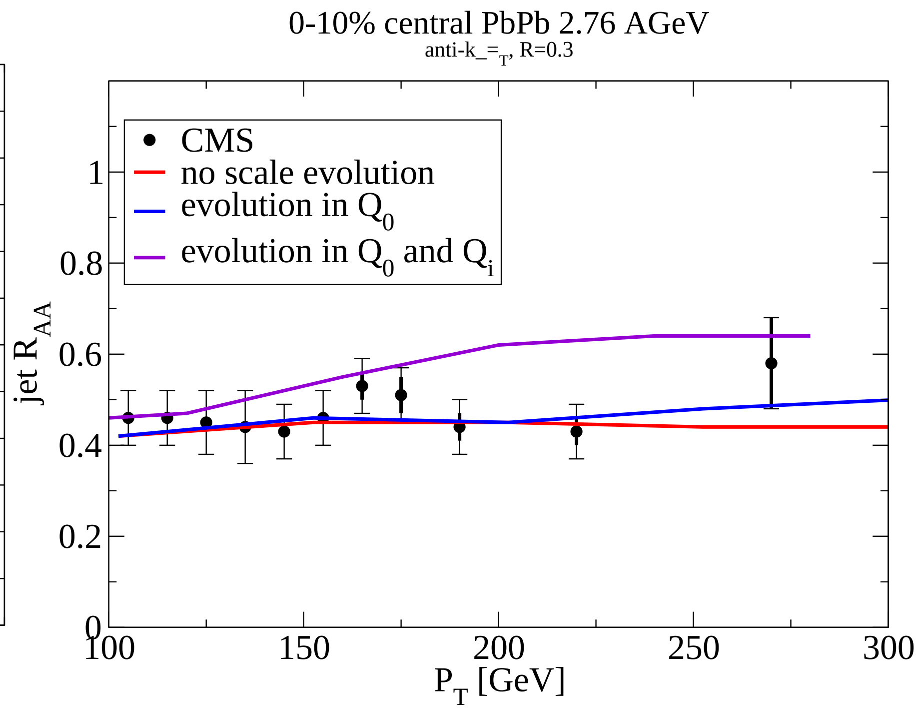
• clustering suppresses physics effects around $\Lambda_{QCD} \sim 300$ MeV
→ it also suppresses physics around $T \sim 300$ MeV

• clustering tends to undo the branching cascade of a shower
→ clustering also tends to undo the medium modification of a shower

Hadron vs. Jet R_{AA}

- compare the effect of QCD scale evolution and out of medium evolution





$\Rightarrow$ clustering removes the sensitivity to model details (as it should)

Clustered observables are less constraining for models than unclustered ones.

TR, Phys. Rev. C **88** (2013) 014905

Conclusions

We know how medium-modified jets look like.

• they've been observed through a number of different filters with consistent results
$\longrightarrow$ above ~ 3 GeV, structure resembles vacuum jets, but distributions are depleted
$\longrightarrow$ below ~ 3 GeV, broad and soft pedestal by hadronizing induced radiation
• this structure can be measured and plotted in many different ways
$\longrightarrow$ efforts should perhaps move towards detailed quantitative understanding

Not all observables are equally constraining.

• biases can be used to make an observable (in)sensitive to a physics question
$\longrightarrow$ designed biases may be the future generation of measurements

The results do not make a 'new physics' story.

• counter-intutive findings can usually be understood by complicated biases
$\longrightarrow$ no comparison with data should be made without modelling realistic biases
• results are consistent with 'simple' kinematical broadening of radiation phase space
$\longrightarrow$ some evidence for elastic energy transfer into medium
$\longrightarrow$ color coherence breakdown, modified color flow, . . . may be there, but not required

Conclusions

Implications for p-A

• jet correlations are a bad place to see initial state physics
$\rightarrow$ Q^2 evolution erases signals of nPDFs or CGC at high P_T

• some evidence for medium formation in p-A
$\rightarrow$ but medium is small-sized, many hard partons get out before medium forms
$\rightarrow$ LPM interference suppresses radiation for short paths
$\Rightarrow$ even if a medium exists, no strong effects on jets are expected

Urgently needed

• jet correlation results (h-h, jet-h,. . .) from other jet quenching codes
$\rightarrow$ **much** more constraining than popular observables R_{AA}, A_J

• experimental agreement on how things are plotted
$\rightarrow$ D_{AA}, I_{AA} and A_J medium vs. vacuum do not contain different information
$\rightarrow$ but it's very hard to see what the message is right now

Conclusions

Medium tomography is becoming possible.

- original idea: use jets as calibrated probes to study medium density

$\longrightarrow$ jet observables can probe ϵ_n from hydro with good sensitivity
$\longrightarrow$ no clear message, higher ϵ_2 preferred than hydro codes give
$\longrightarrow$ is jet pathlength dependence or hydro density evolution not quite right?

Things that do not work

- large ($> 20\%$) incoherent (elastic) component to energy loss

$\longrightarrow$ ruled out by geometry bias effect in correlation I_{AA}

- fractional energy loss

$\longrightarrow$ ruled out by the relative independence of upturn point in trigger momentum

- AdS/CFT strong coupling scenarios for jet quenching

$\longrightarrow$ rules out by $\sqrt{s}$ scaling and observed predictable pQCD radiation pattern