The Cook, The Thief, His Wife & Her Lover *

* title borrowed from Peter Greenaway's 1989 film

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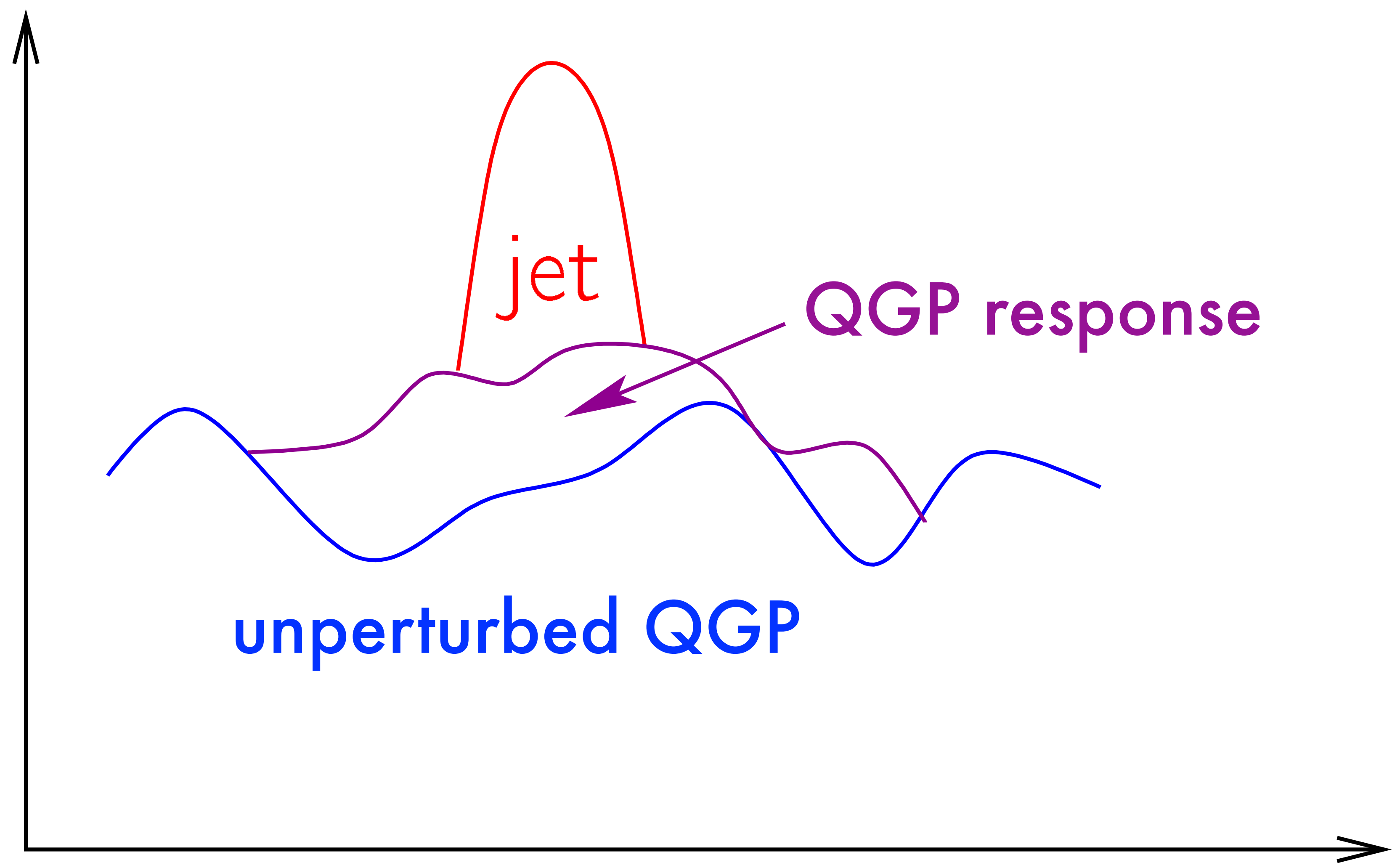
New jet quenching tools to explore equilibrium and non-equilibrium dynamics in heavy-ion collisions
Trento, 12 Nov 2023

The QGP, a Jet, QGP response & residual UE



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New jet quenching tools to explore equilibrium and non-equilibrium dynamics in heavy-ion collisions
Trento, 12 Nov 2023

The QGP, a Jet, QGP response & residual UE

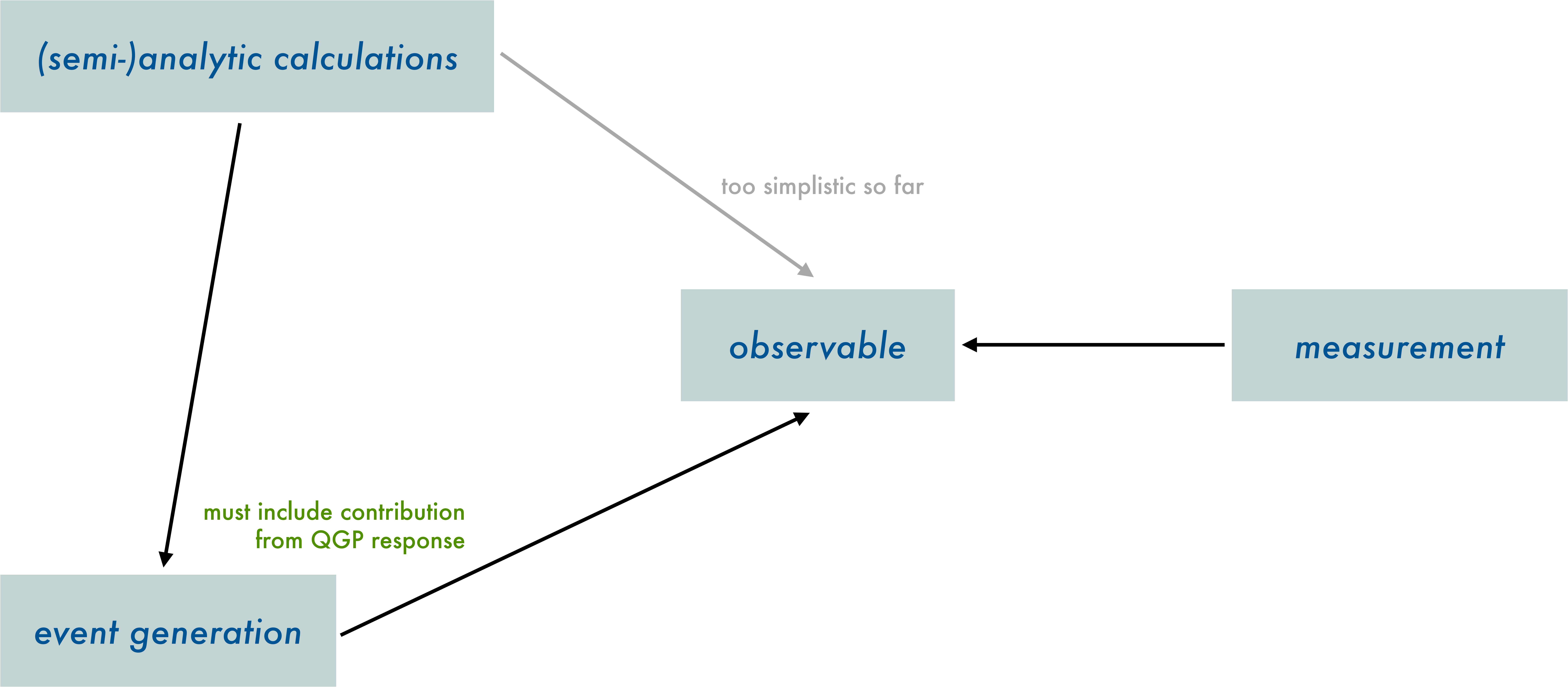
or more conventionally:

what we have, and what still have not, learnt about jets in QGP

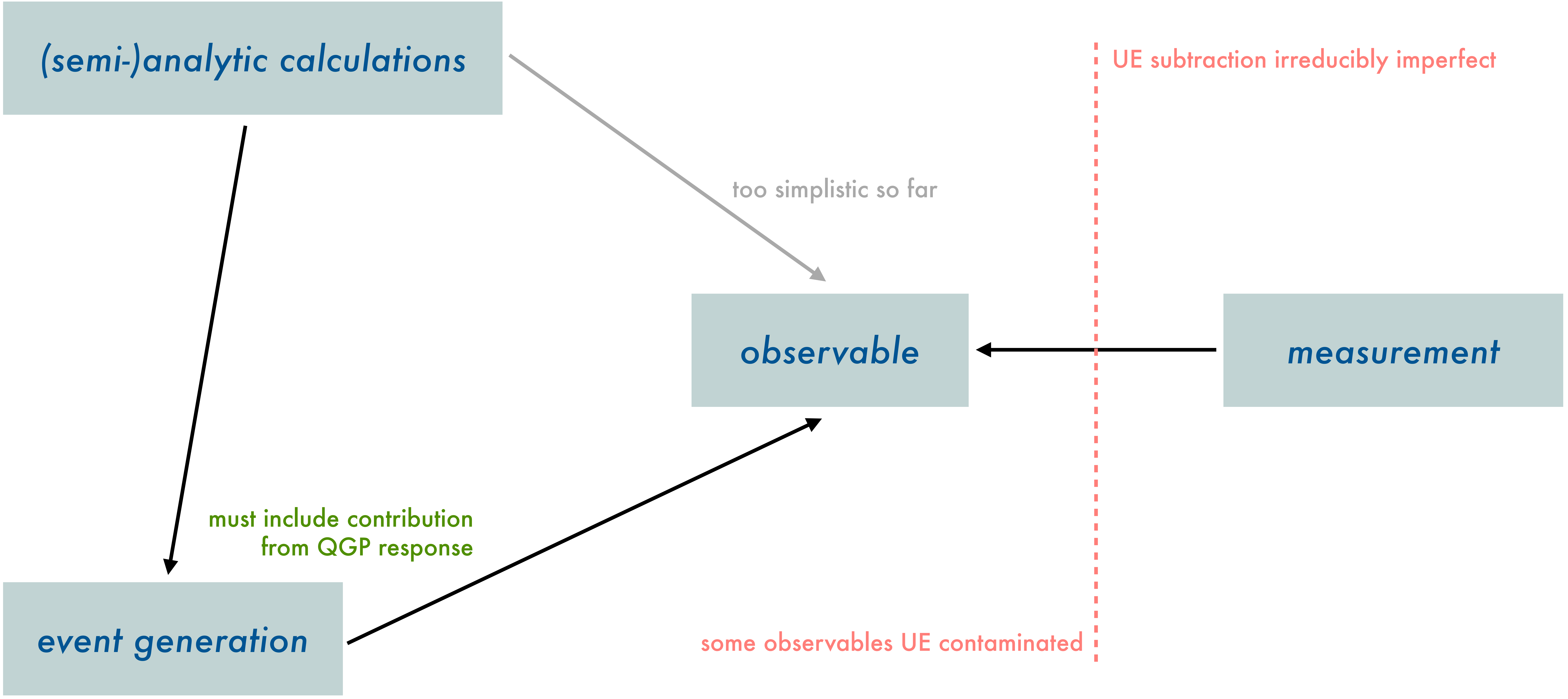
WHAT WE WANT TO UNDERSTAND

- jets in QGP
  - parton branching in presence of QGP
  - response of QGP to interaction with traversing partons and its contribution to jets
  - what is a fair comparison between theory and data
- jets as probes of QGP properties [assumes above is sufficiently understood]
  - observable properties of jets that can be robustly related to QGP properties
  - QGP response within jets as portal to understand hydrodynamization and how QGP forms

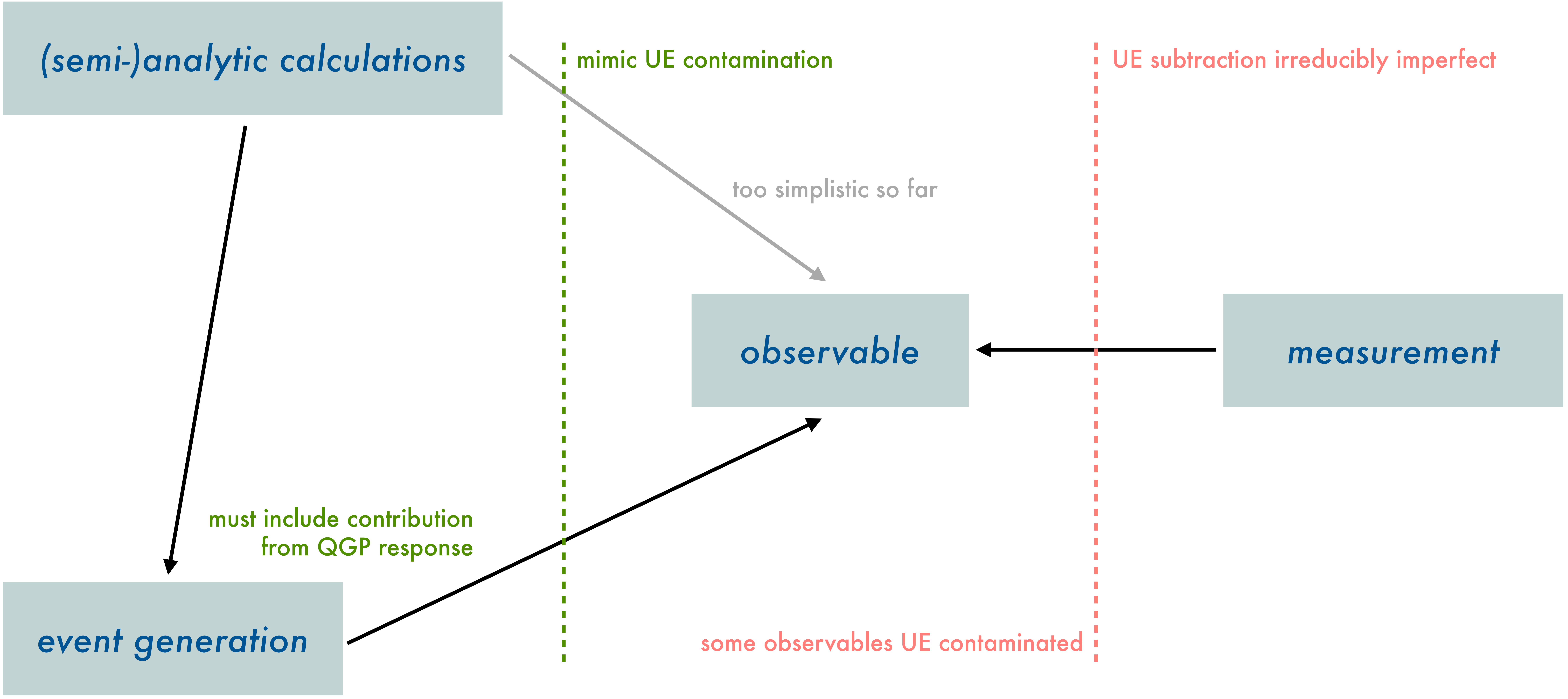
TOOLS


(semi-)analytic calculations
too simplistic so far
observable
measurement
must include contribution
from QGP response
event generation

TOOLS AND COFOUNDERS



TOOLS AND COFOUNDERS



lesson #0

jets are modified by the QGP

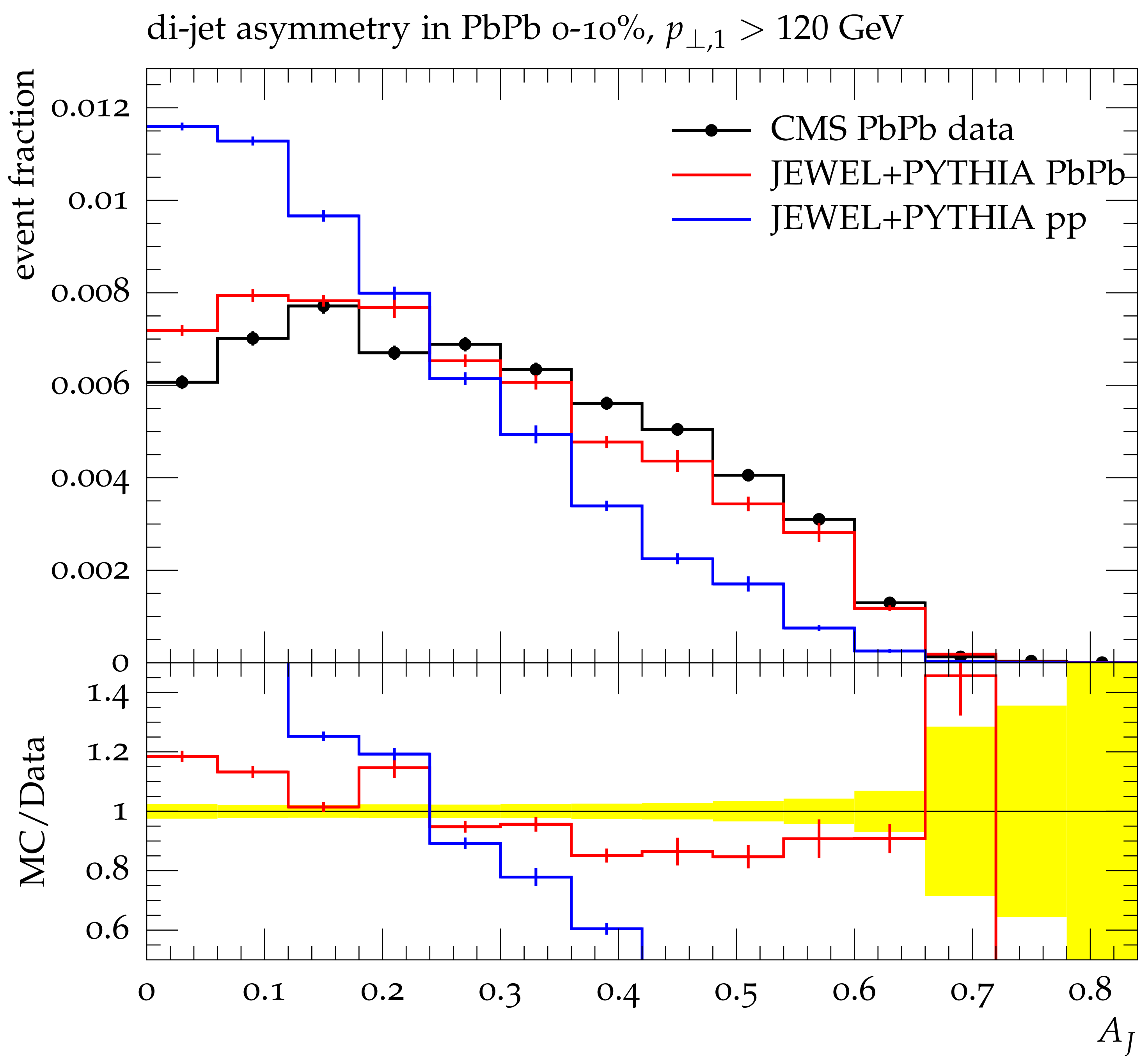
[almost] all observables computed for samples of AA jets differ from when computed in pp samples

criteria for establishing modification on a jet-by-jet basis remains elusive

lesson #1

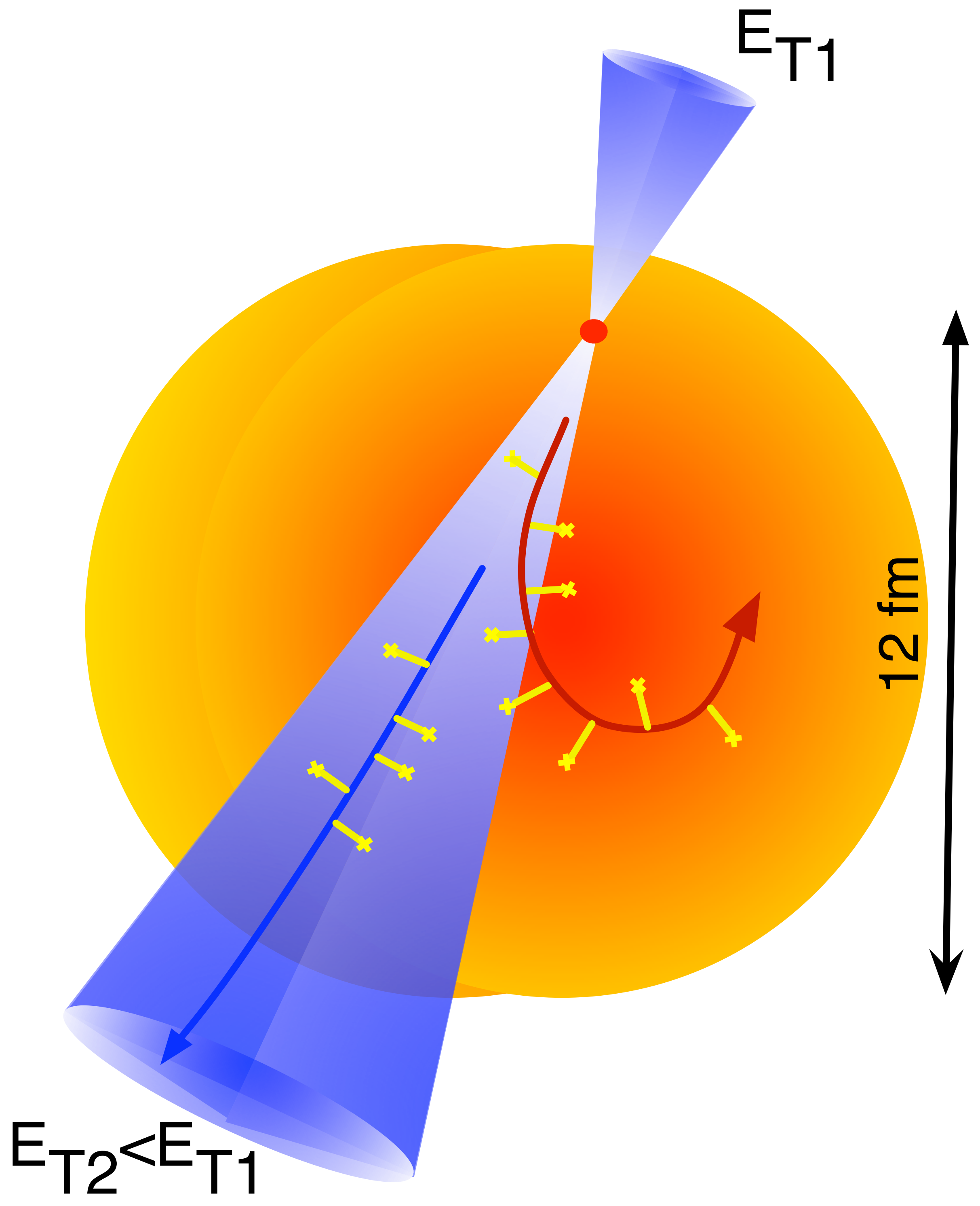
dijet asymmetry

Milhano and Zapp :: Eur.Phys.J. C76 (2016))



enhanced p_T imbalance in back-to-back dijet pairs in HI collisions

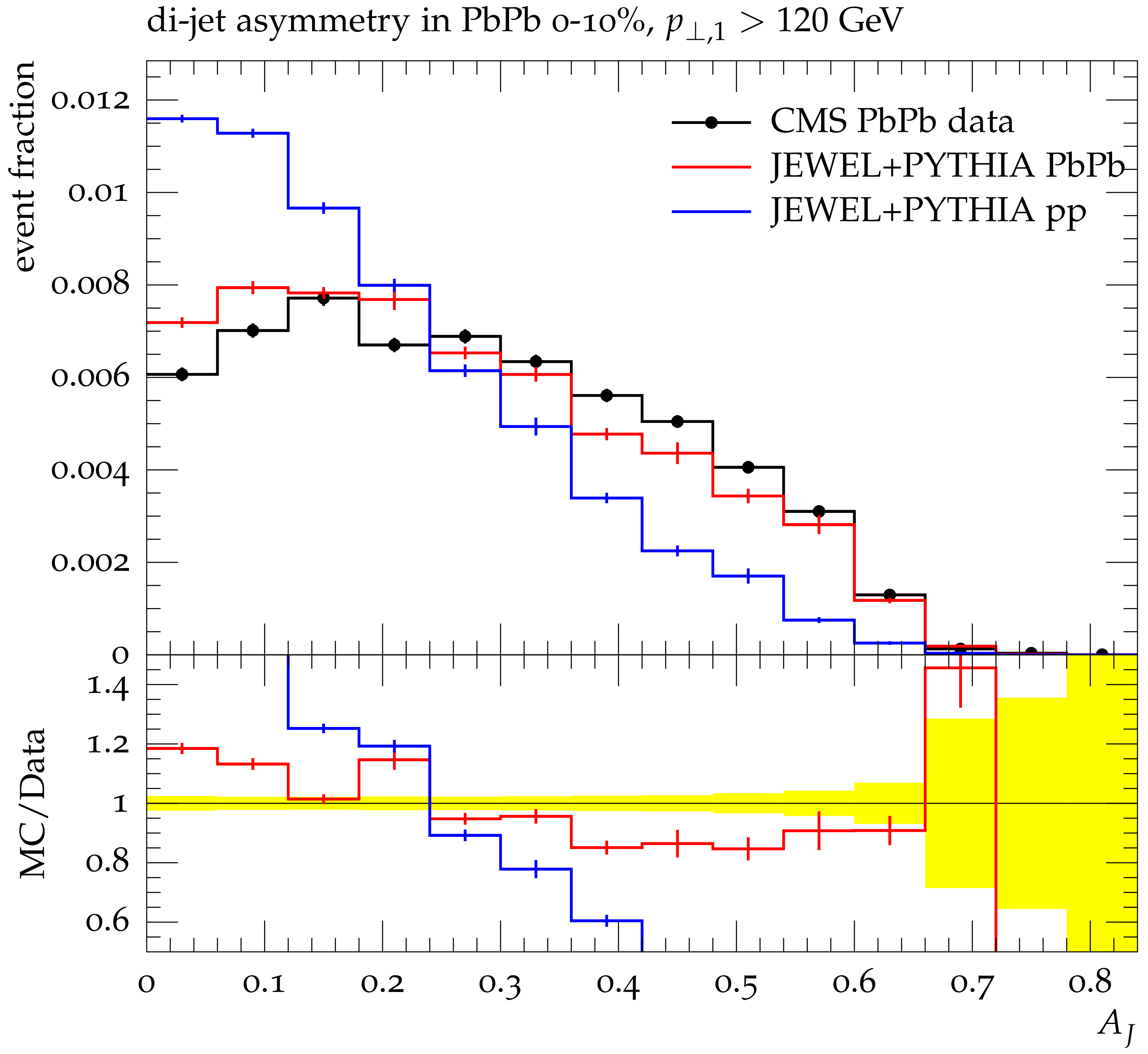
$$A_J = \frac{p_{\perp,1} - p_{\perp,2}}{p_{\perp,1} + p_{\perp,2}}$$



- JEWEL provides good data description
- very tempting naive geometrical interpretation
  - one jet loses more energy than the other DUE TO different traversed amount of QGP matter

dijet asymmetry

Milhano and Zapp :: Eur.Phys.J. C76 (2016))



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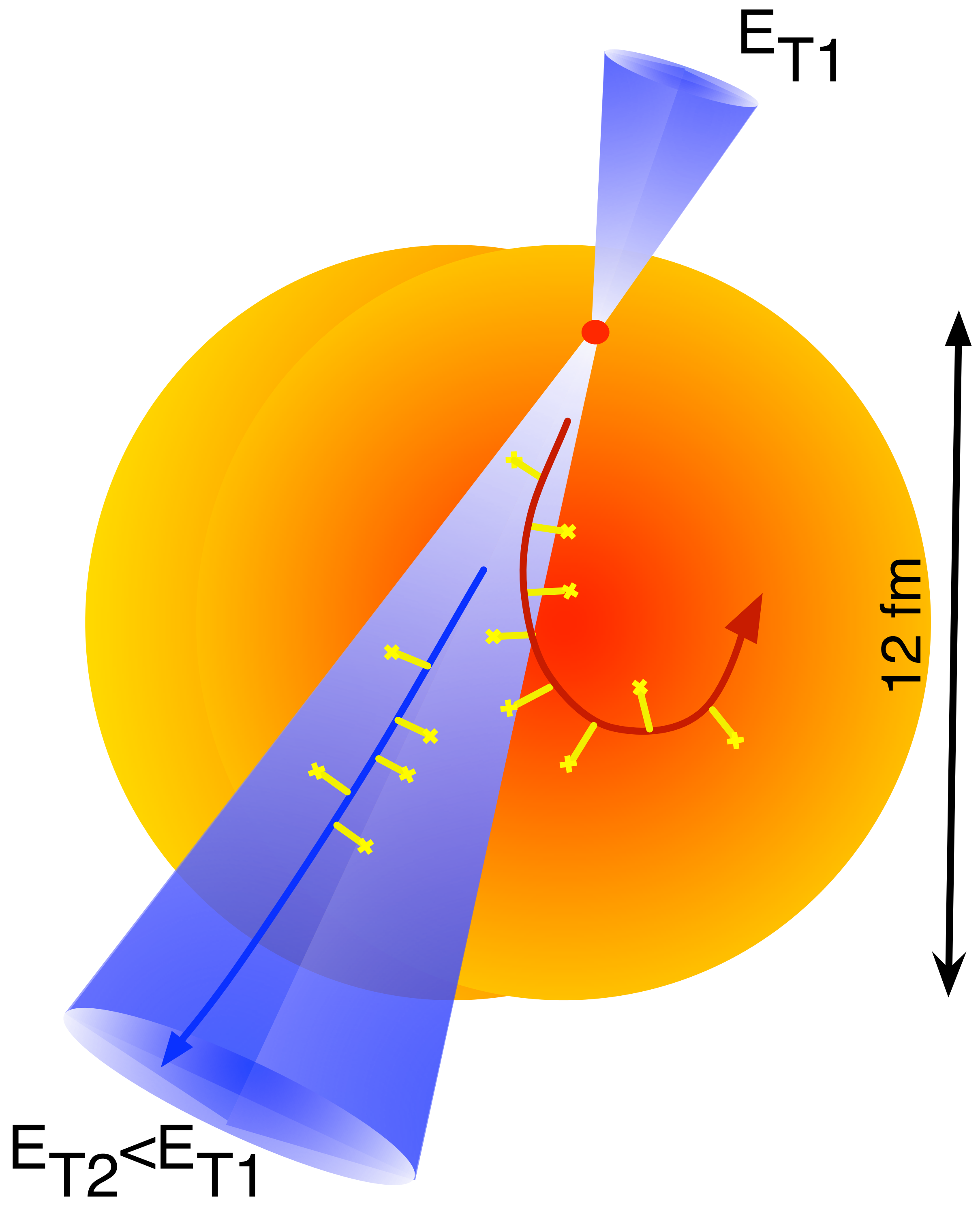
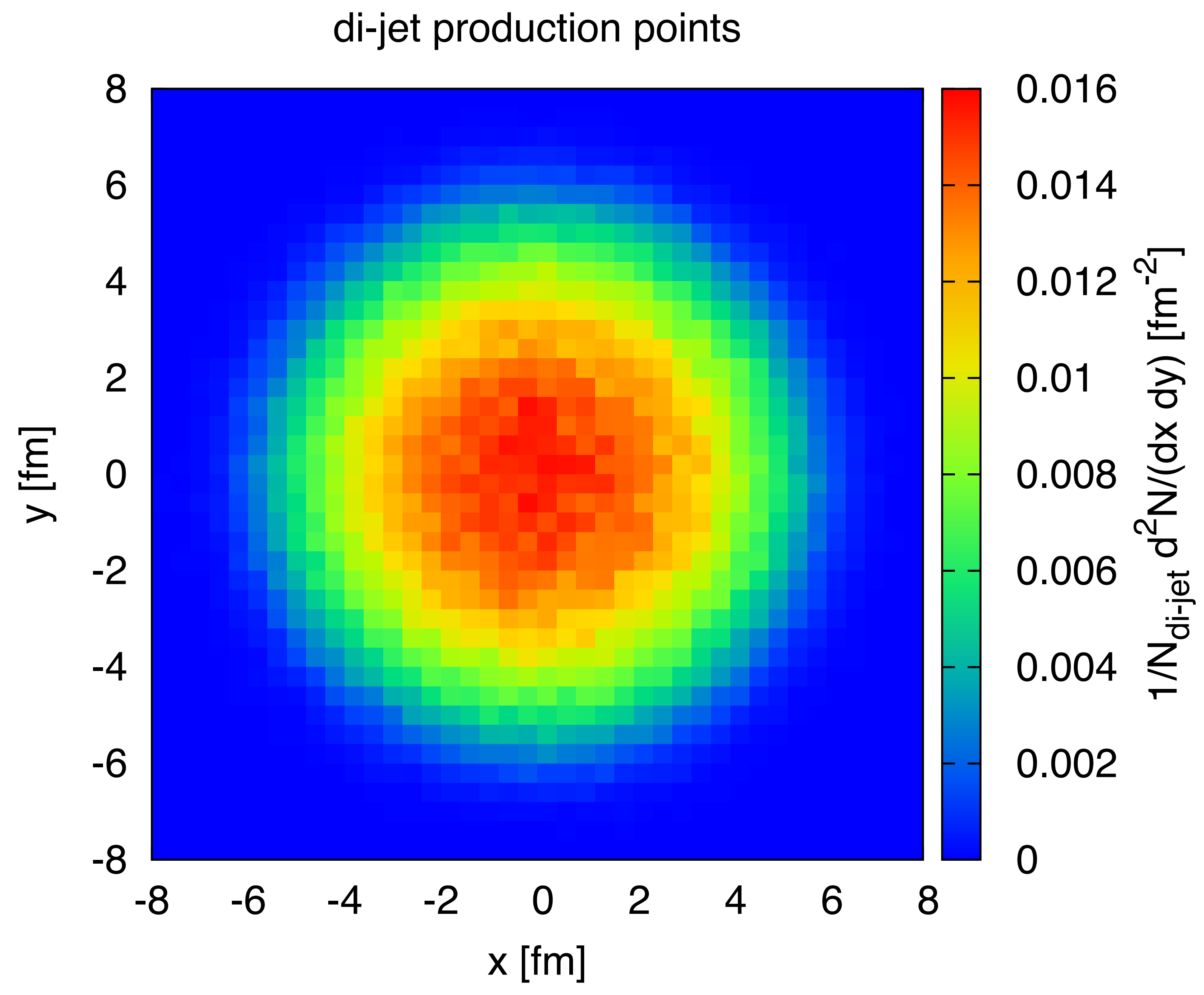


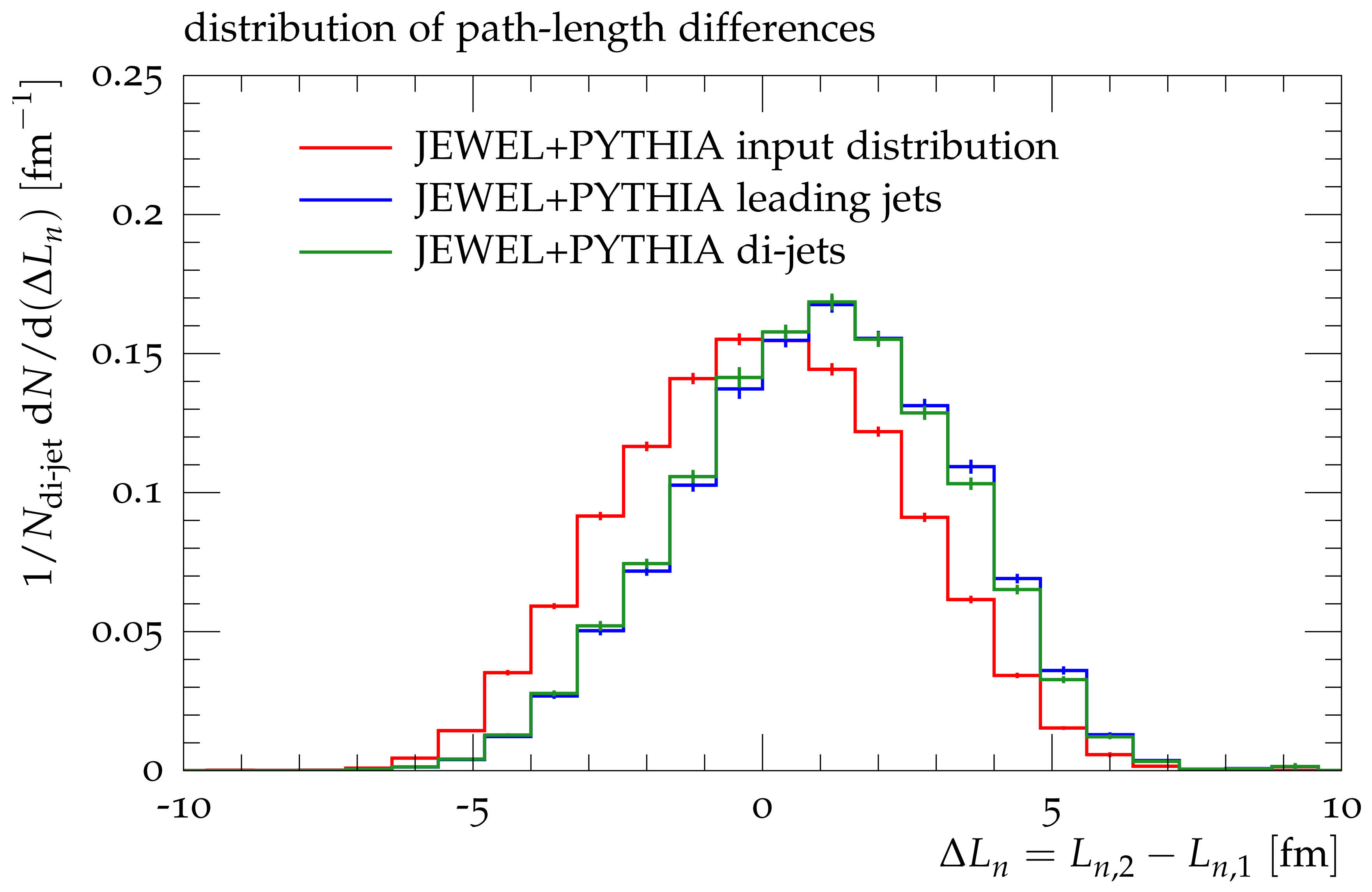
- JEWEL provides good data description
- very tempting naive geometrical interpretation
  - one jet loses more energy than the other DUE TO different traversed amount of QGP matter

really not the case ...

dijet asymmetry

Milhano and Zapp :: Eur.Phys.J. C76 (2016))





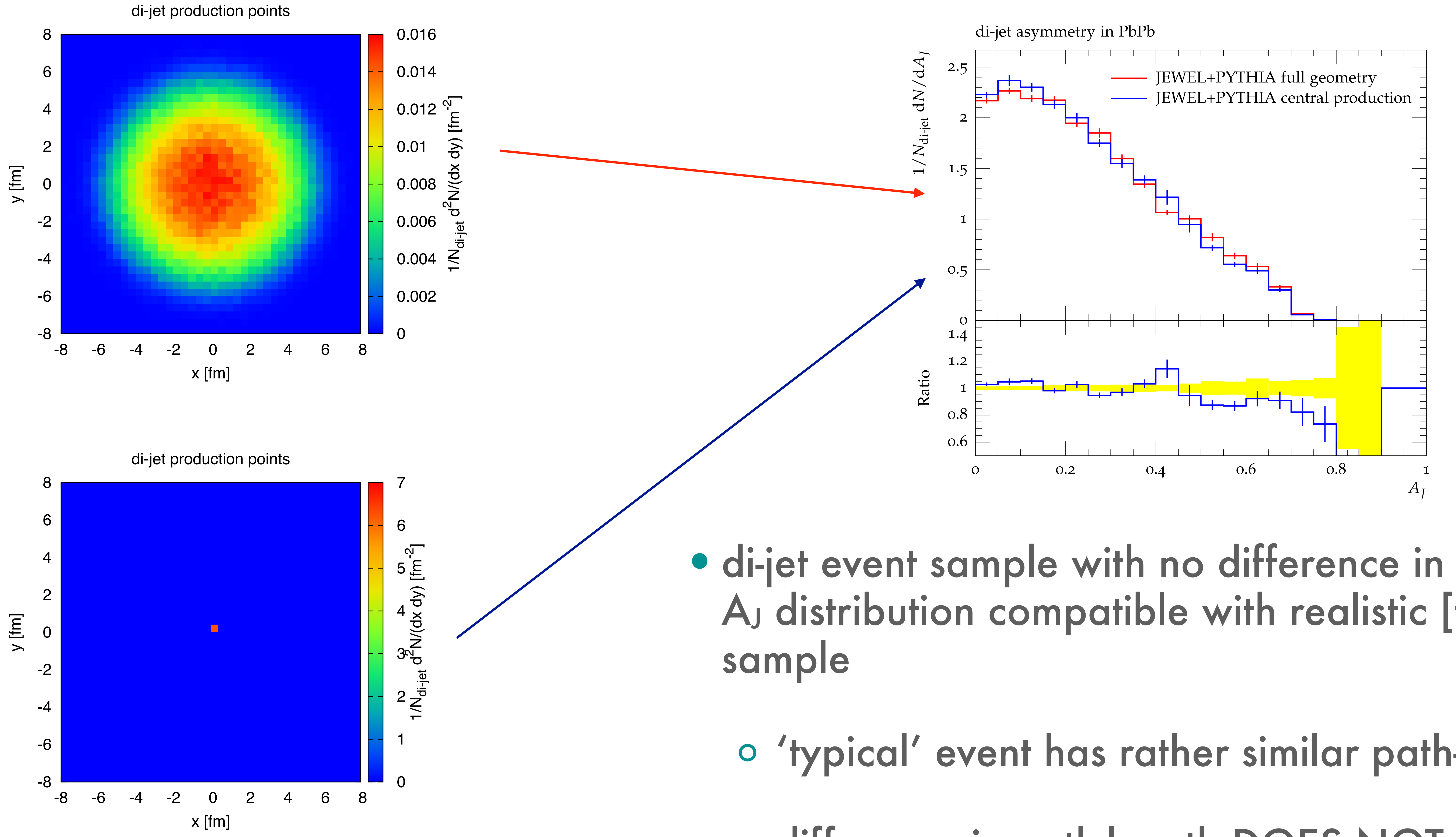
density weighted path-length
[accounts for medium expansion, rapidity independent for boost invariant medium]

$$L_n = 2\frac{\int d\tau\, \tau n(\mathbf{r}(\tau), \tau)}{\int d\tau\, n(\mathbf{r}(\tau), \tau)}$$

- small bias towards smaller path-length for leading jets
  - however, significant fraction [34%] of events have longer path-length for leading jet
  - consequence of fast medium expansion

dijet asymmetry

Milhano and Zapp :: Eur.Phys.J. C76 (2016))

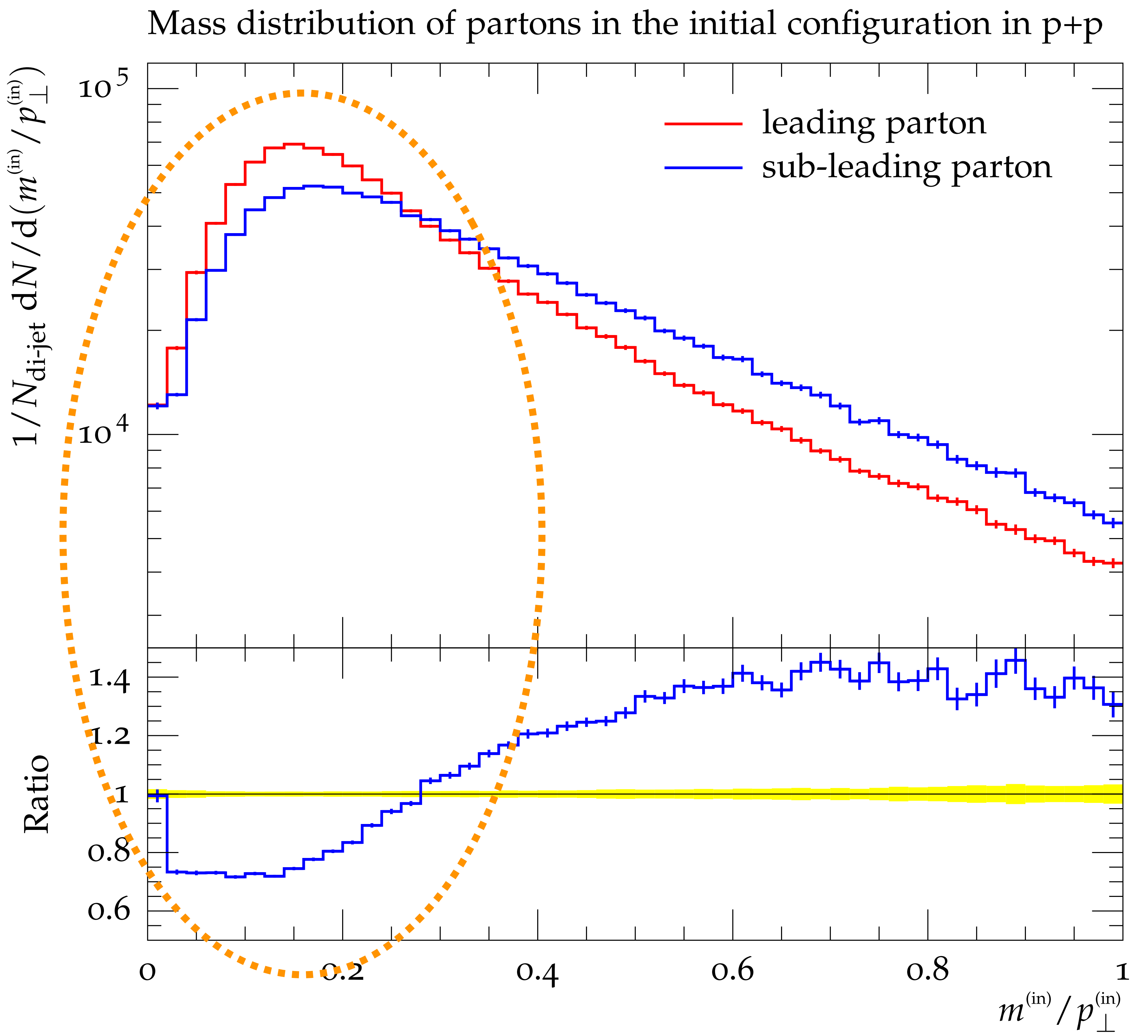


$$A_J = \frac{p_{\perp,1} - p_{\perp,2}}{p_{\perp,1} + p_{\perp,2}}$$

- di-jet event sample with no difference in path-length have A_J distribution compatible with realistic [full-geometry] sample
  - 'typical' event has rather similar path-lengths
  - difference in path-length DOES NOT play a significant role in the observed modification of A_J distribution

jet energy loss dominated by fluctuations

Milhano and Zapp :: Eur.Phys.J. C76 (2016))



- not all same-energy jets are equal
  - number of constituents driven by initial mass-to-p_t ratio :: vacuum physics
  - more populated jets have larger number of energy loss candidates
  - more populated jets lose more energy and their structure is more modified

[analogous results within other approaches]
Chesler, Rajagopal 1511.07567
Rajagopal, Sadofyev, van der Schee 1602.04187
Brewer, Rajagopal, van der Schee 1710.03237
Escobedo, Iancu 1609.06104 [hep-ph]

lesson #1

vacuum like parton showering very important driver of how much and how a jet ends up modified

supports common assumption that QGP induced modifications are a perturbation to vacuum physics

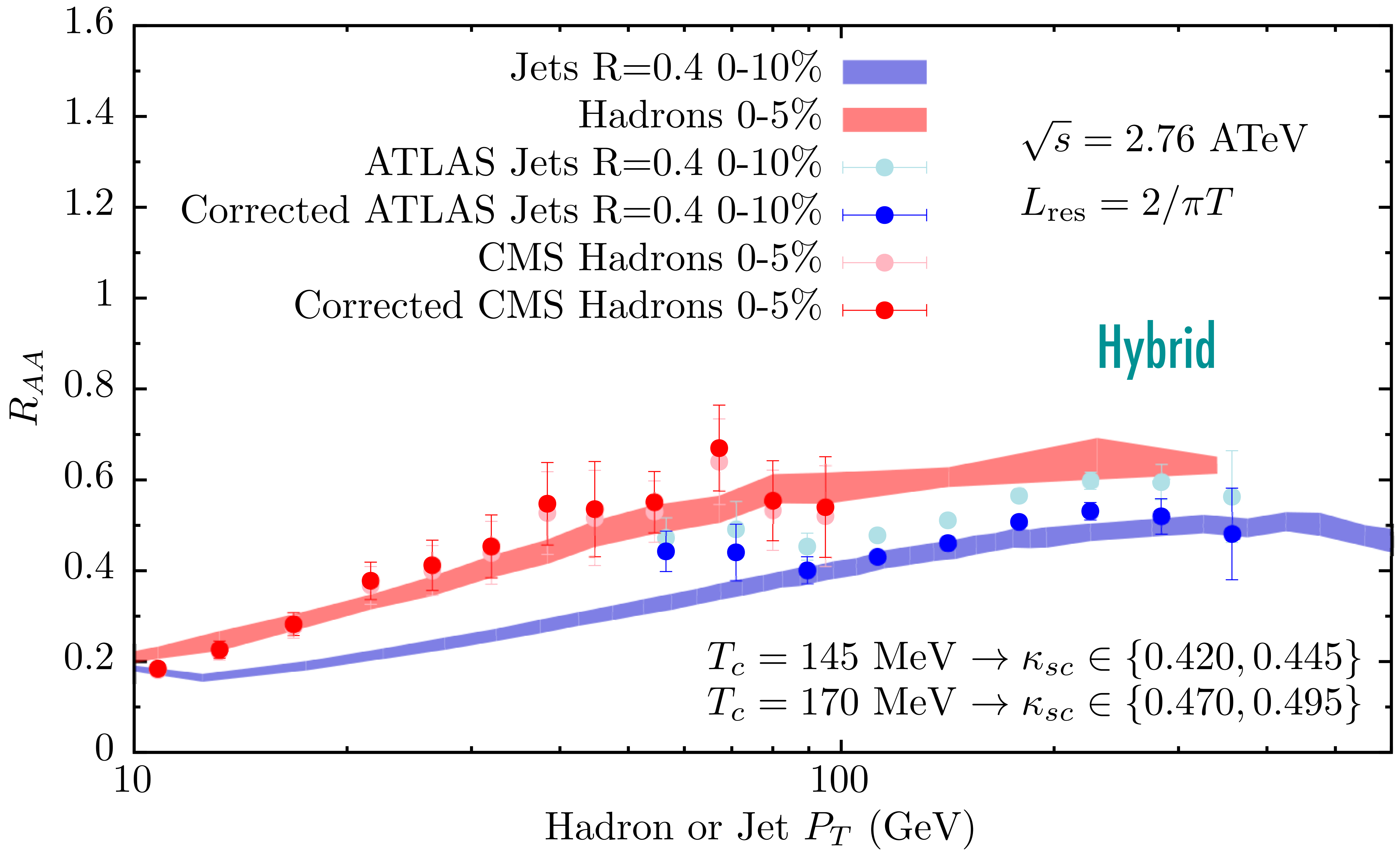
modifications depend on QGP size [centrality dependence], but 'surface bias' unimportant for [at least] many observables

lesson #2

jet and hadron R_{AA}

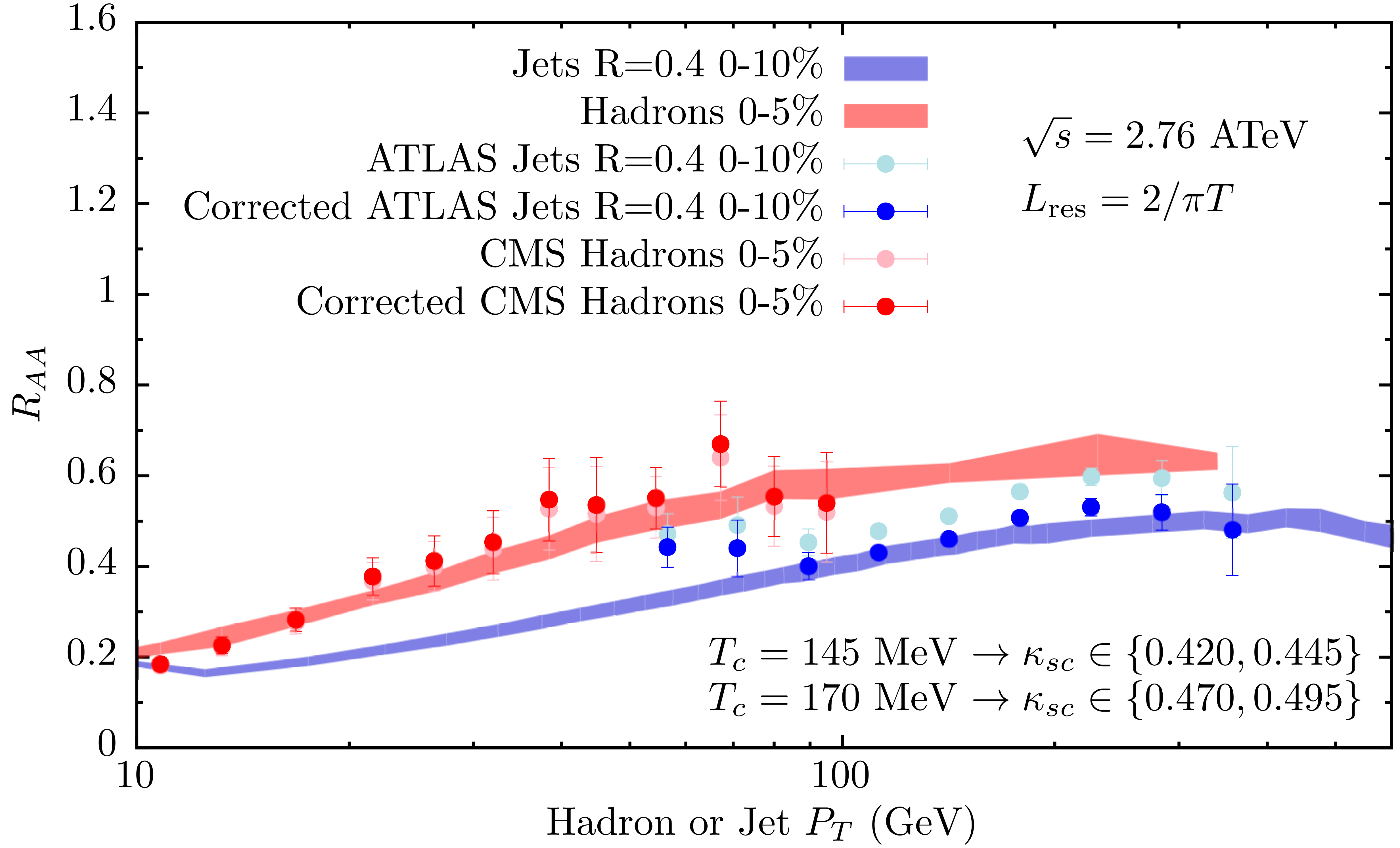
Casalderrey, Hulcher, Milhano, Pablos, Rajagopal :: 1808.07386 [hep-ph]

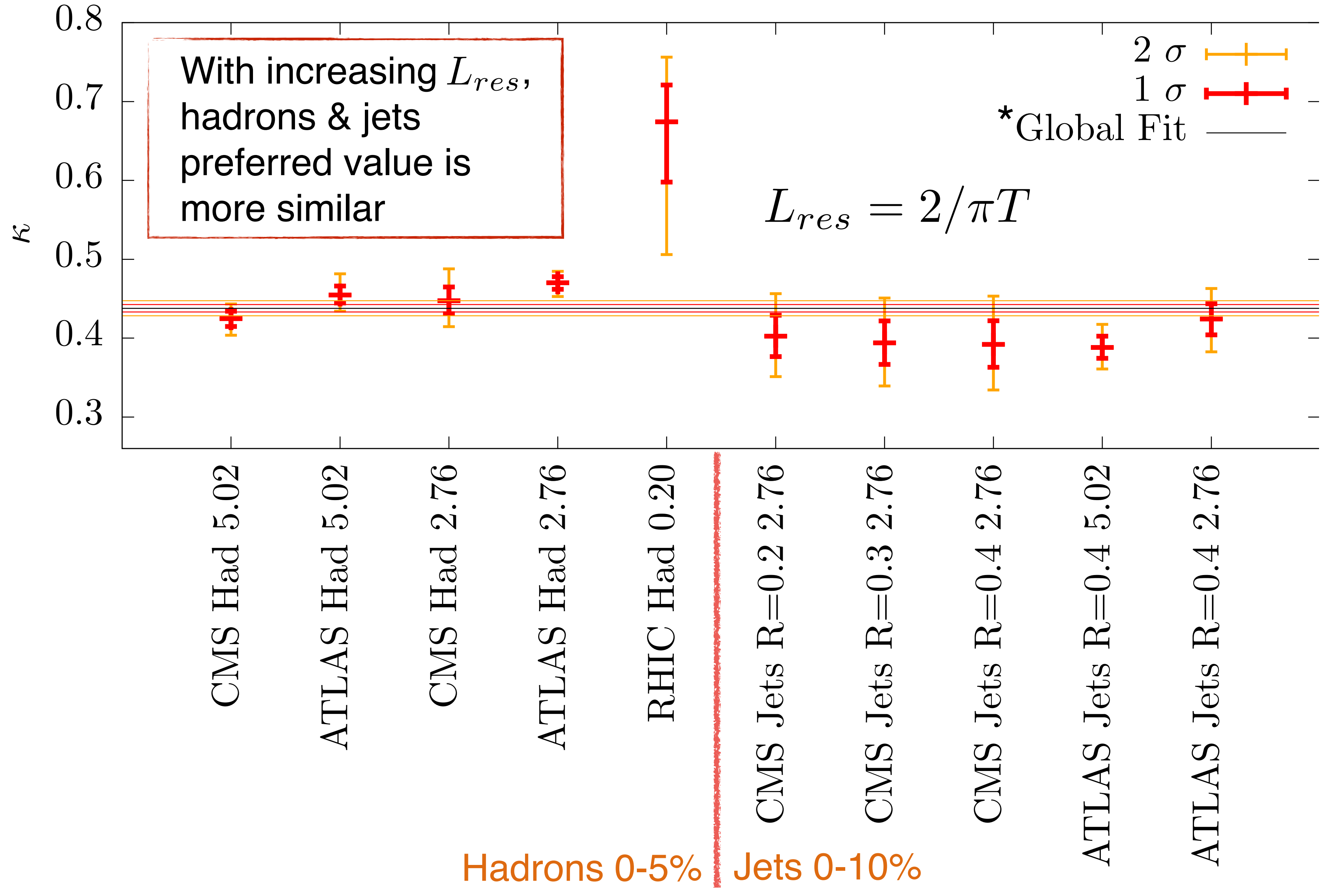
- different suppression of hadrons and jets was long seen as a 'puzzle'
  - all bona fide MC, and all analytical calculations that treat jets as resulting from evolution of a multiparticle state fully account for the different suppression



jet and hadron R_{AA}

Casalderrey, Hulcher, Milhano, Pablos, Rajagopal :: 1808.07386 [hep-ph]





- excellent global fit for LHC data :: some tension with RHIC data
- high p_T hadrons originate from narrow jets [fragmented less] which are less suppressed than inclusive jets
- simultaneous description of jet and hadron R_{AA} natural feature of any approach that treats jets as such [ie, objects resulting from evolution of state with internal structure]

lesson #2

QGP sees and interacts with constituents of evolving multi-parton state

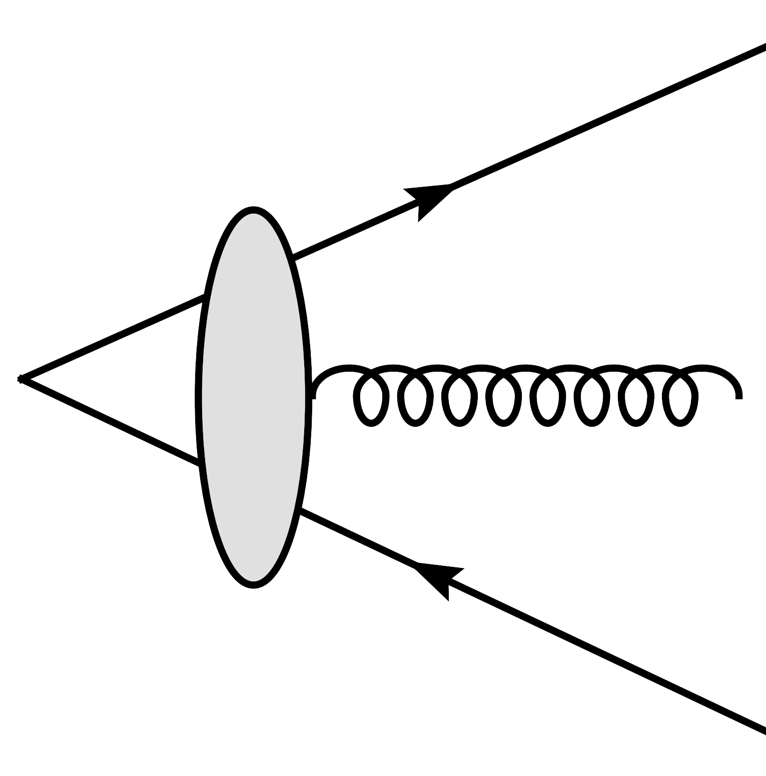
substructure modifications are a powerful tool to understand shower/QGP interaction

UE contamination can have significant effect in substructure observables

lesson #3

MULTIPLE EMISSIONS :: VACUUM ANTENNAS

- bona fide description of parton branching requires understanding of emitters interference pattern
  - qqbar antenna [radiation much softer than both emitters] as a TH lab



::vacuum::

- transverse separation at formation time

$$r_\perp \sim \theta_{q\bar{q}} \, \tau_f \sim \frac{\theta_{q\bar{q}}}{\theta^2 \omega}$$

- wavelength of emitted gluon

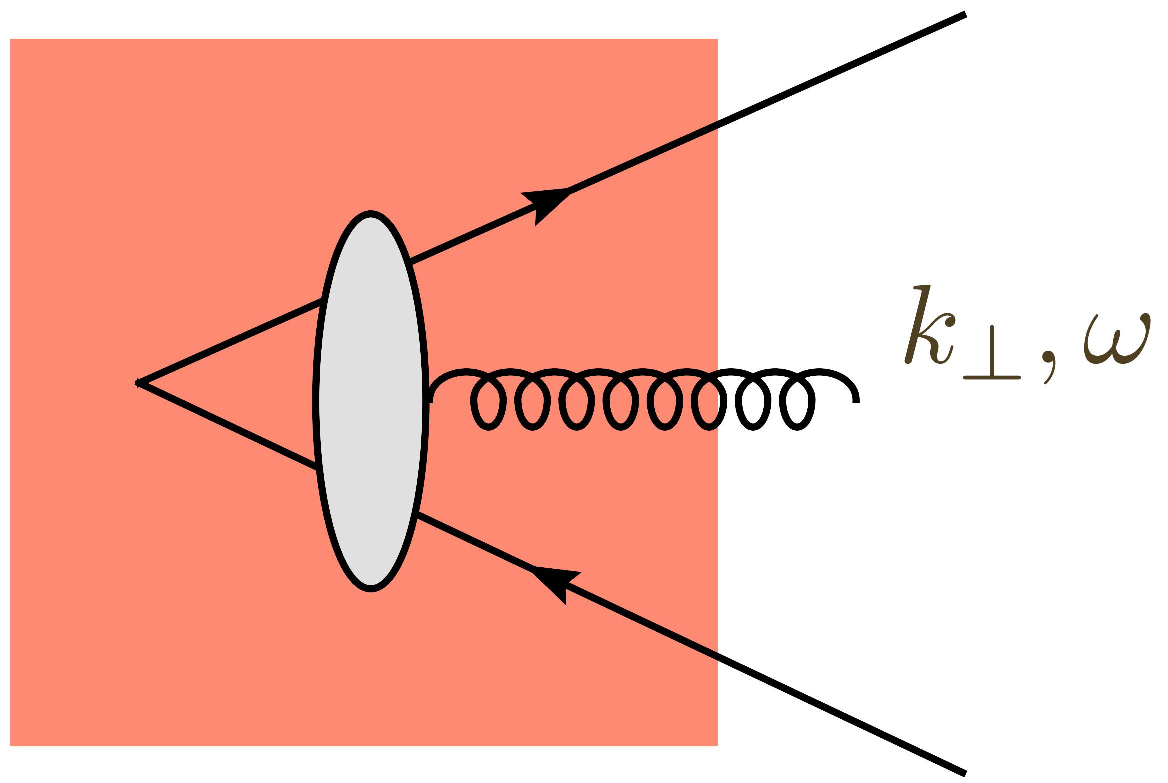
$$\lambda_\perp \sim \frac{1}{k_\perp} \sim \frac{1}{\omega\theta}$$

for $\lambda_\perp > r_\perp$ *emitted gluon cannot resolve emitters, thus emitted coherently from total colour charge*

large angle radiation suppressed :: angular ordering

MEDIUM ANTENNAS

Mehtar-Tani, Salgado, Tywoniuk :: 1009.2965 [hep-ph]
many, many papers thereafter...



- new medium induced colour decorrelation scale

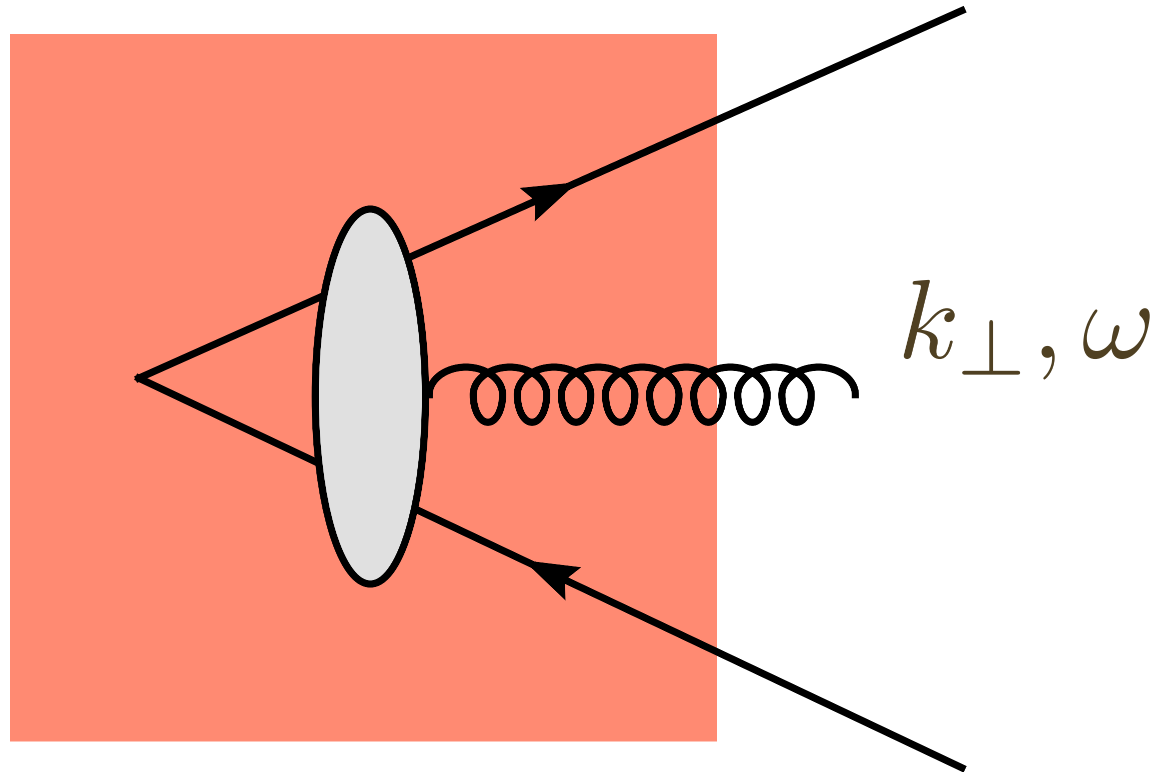
$$\Lambda_{med} \sim \frac{1}{k_\perp} \sim \frac{1}{\sqrt{\hat{q}L}}$$

- such that decorrelation driven by timescale

$$\tau_d \sim \left(\frac{1}{\hat{q}\theta_{q\bar{q}}^2}\right)^{1/3}$$

[DE]COHERENCE OF MULTIPLE EMISSIONS

Mehtar-Tani, Salgado, Tywoniuk :: 1009.2965 [hep-ph]
many, many papers thereafter…



- qqbar colour coherence survival probability

$$\Delta_{med} = 1 - \exp\left\{ -\frac{1}{12}\hat{q}\theta_{q\bar{q}}^2 t^3 \right\} = 1 - \exp\left\{ -\frac{1}{12}\frac{r_\perp^2}{\Lambda_{med}^2} \right\}$$

- time scale for decoherence

$$\tau_d \sim \left(\frac{1}{\hat{q}\theta_{q\bar{q}}^2} \right)^{1/3}$$

- total decoherence when $L > \tau_d$

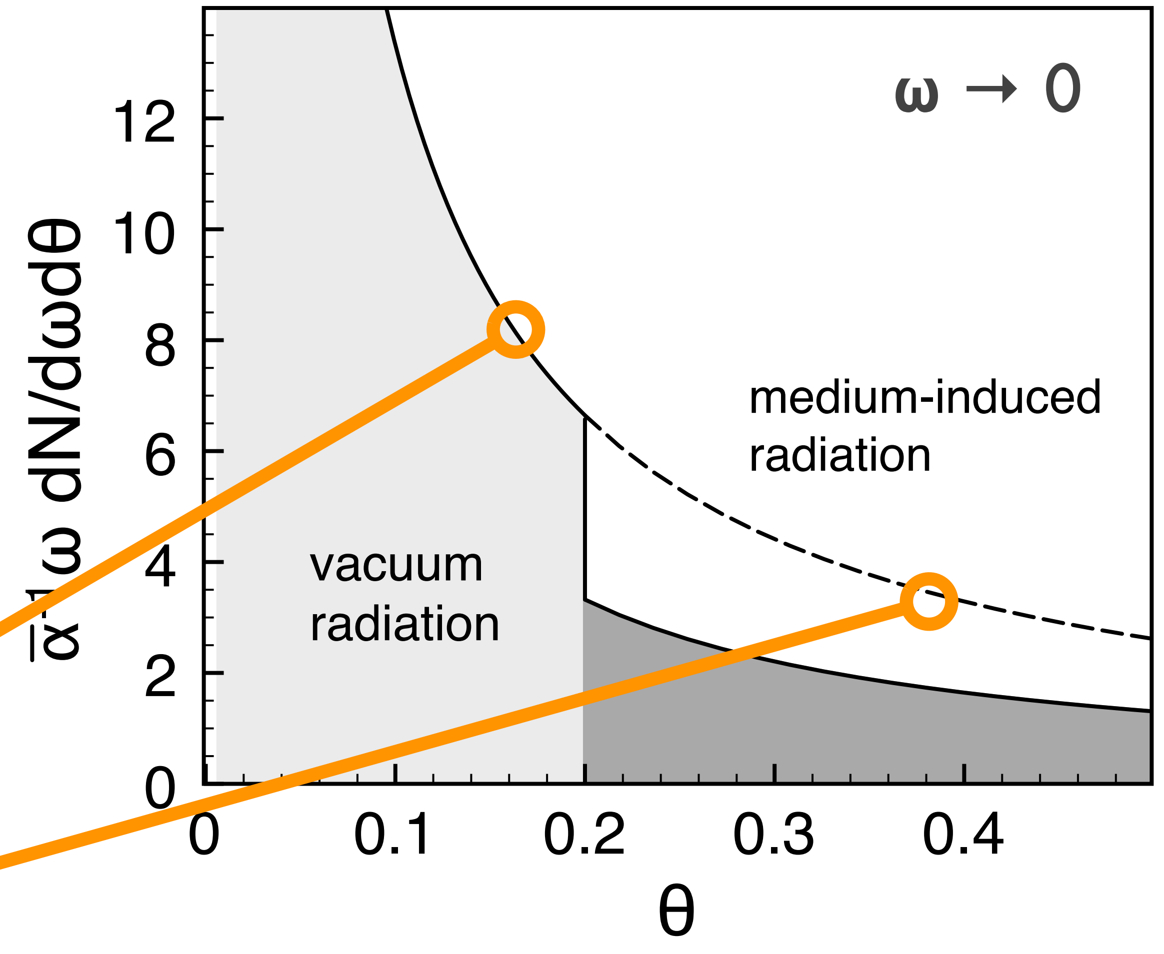
- colour decoherence opens up phase space for emission
  - large angle radiation [anti-angular ordering]

$$dN_{q,\gamma^*}^{\rm tot} = \frac{\alpha_s C_F}{\pi}\frac{d\omega}{\omega}\frac{\sin\theta\, d\theta}{1-\cos\theta}\left[\Theta(\cos\theta - \cos\theta_{q\bar{q}}) - \Delta_{\rm med}\,\Theta(\cos\theta_{q\bar{q}} - \cos\theta)\right]$$

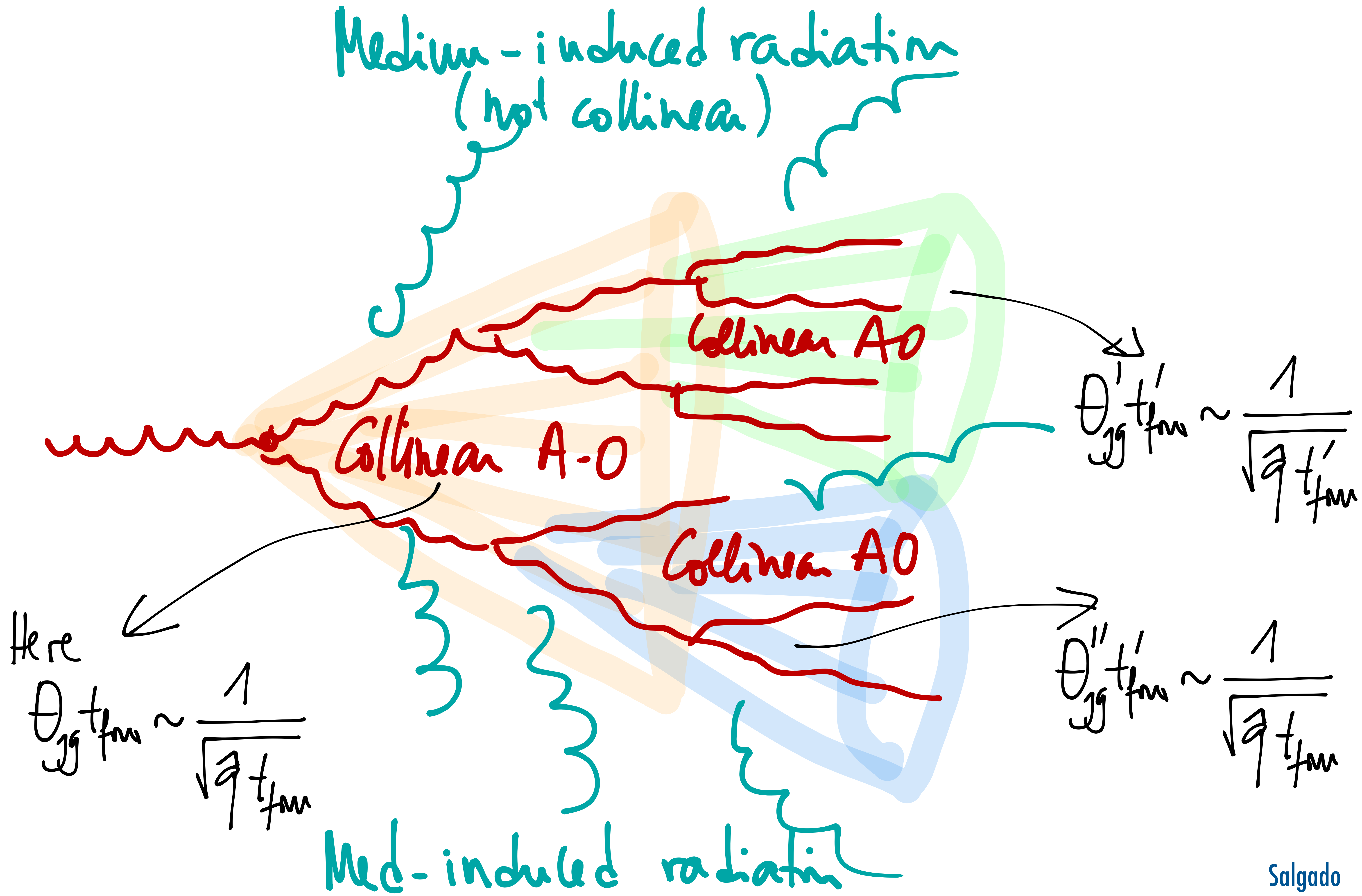
- *geometrical separation [in soft limit]*

$\Delta_{med} \to 0$ coherence

$\Delta_{med} \to 1$ decoherence



FROM ANTENNAS TO JETS



lesson #3

coherence properties of parton branching are modified by interaction with QGP

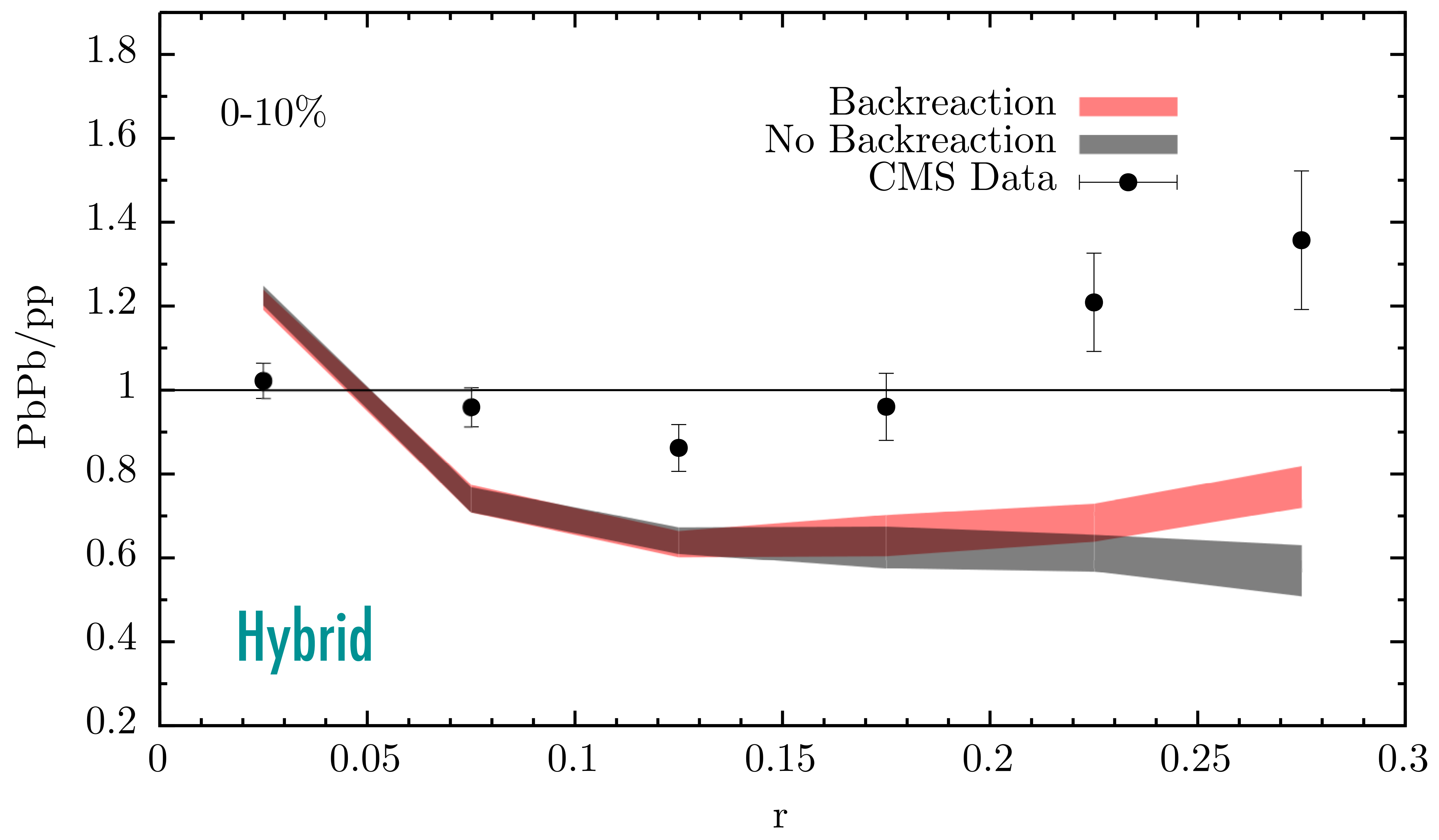
substructure modifications are a powerful tool to understand modifications of coherence

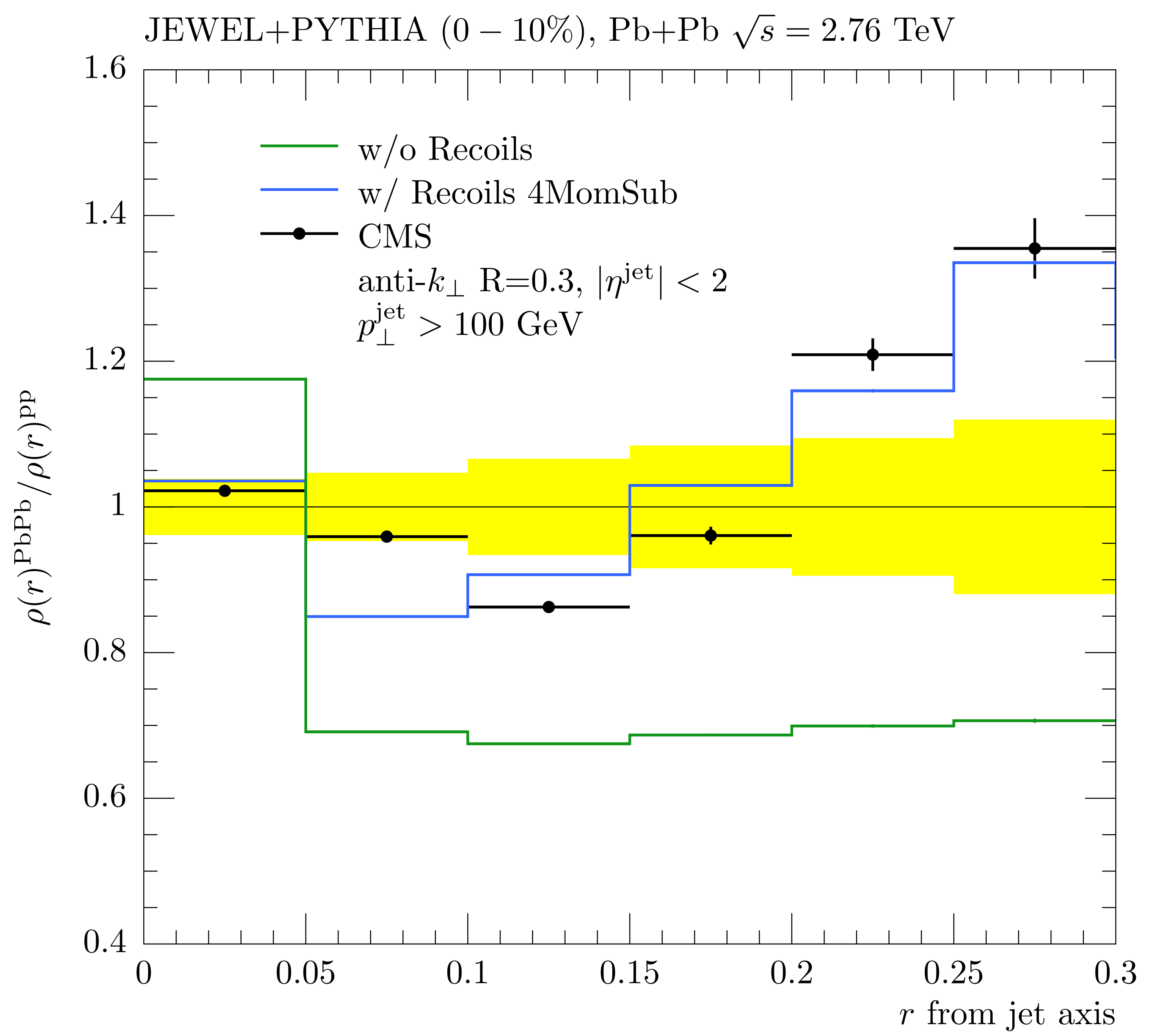
unequivocal observation of effect yet to happen; phenomenological importance of effect unknown; limited implementation in event generators

effect understood analytically in 2010 !

lesson #4

'discovery' of medium response





- propagating particles [what will be a jet] modify the QGP they traverse and modification of QGP reconstructed as part of jet
  - inclusion of QGP response in MC improves agreement with data
  - first evidence for importance of QGP response was seen in MC
  - QGP response of full shower remains untractable in [semi-]analytic calculations

$$\rho(r) = \frac{1}{p_\perp^{\rm jet}} \sum_{\substack{k \text{ with} \\ \Delta R_{kJ} \in [r, r+\delta r]}} p_\perp^{(k)}$$

lesson #4

QGP response to traversal by partons is an unavoidable and important component of jets in HI collisions

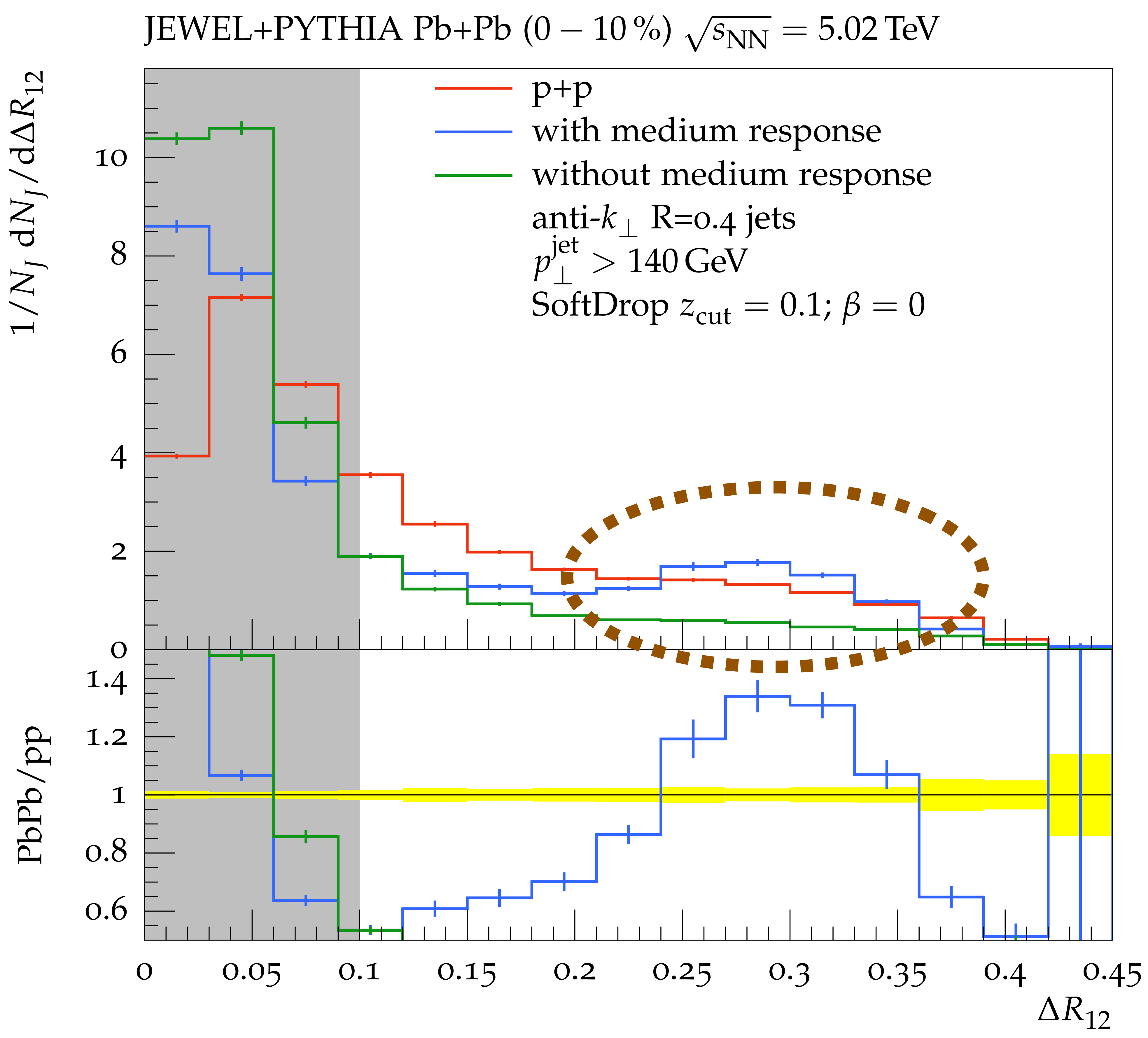
contribution extremely important for jet substructure

MC essential to study effects of QGP response given that analytical understanding remains limited

lesson #5

QGP response in jet substructure

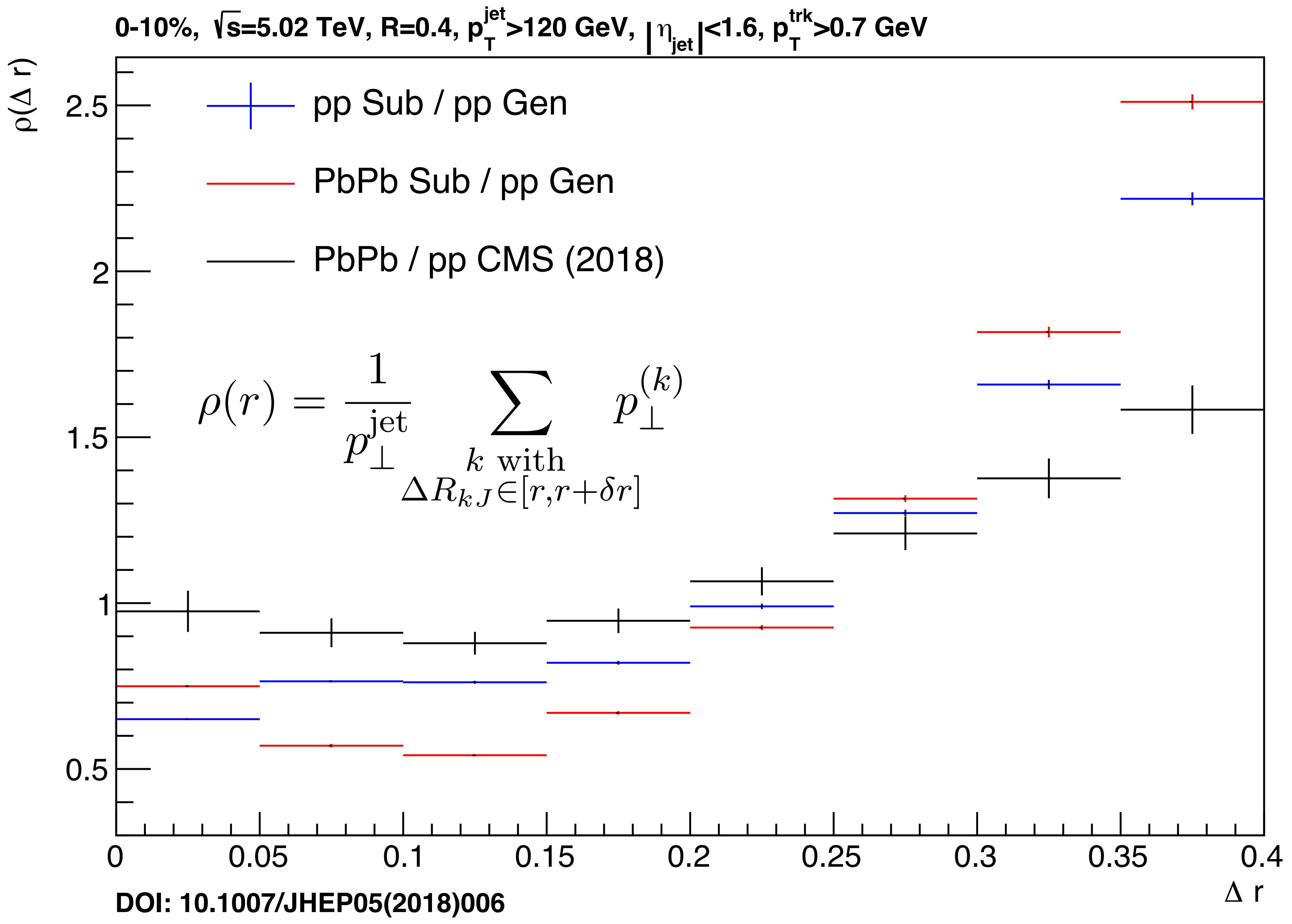
Milhano, Wiedemann, Zapp :: 1707.04142 [hep-ph]



- distance between main prongs of jet declustered with SoftDrop [largest hard splitting angle]
  - clear QGP response signal
  - HOWEVER: effect also present for unmodified jet [no interaction with QGP] embedded in HI event and background subtracted
  - QGP response signal overlaps with contamination from imperfect background subtraction :: effect is NOT observable

not all observed modifications are due to quenching

Gonçalves and Milhano :: in preparation



- imperfect background subtraction mimics many quenching-looking effects
  - here, true quenching predicted by JEWEL is blue/red difference

lesson #5

not all observed modifications of HI wrt pp
can be attributed to jet quenching

MC essential to decide what is quenching and what is not

lesson #6

the anatomy of a recent result *

* now borrowed from 'The anatomy of a Fall', Justine Triet's 2023 film

- observation of acoplanarity broadening due to QGP response

ALICE

CERN-EP-20223-189
29 August 20223

Observation of medium-induced yield enhancement and acoplanarity broadening of low-p_T jets from measurements in pp and central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

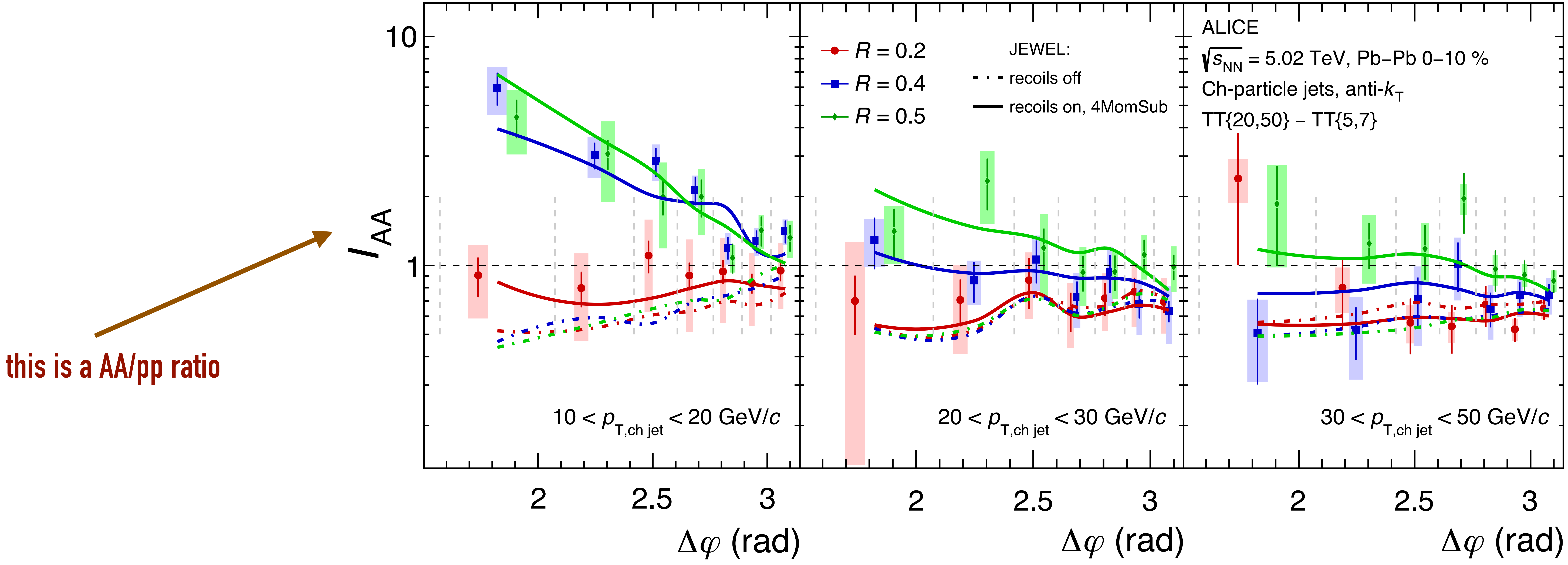
ALICE Collaboration*

Abstract

The ALICE Collaboration reports the measurement of semi-inclusive distributions of charged-particle jets recoiling from a high transverse momentum (high p_T) hadron trigger in proton–proton and central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. A data-driven statistical method is used to mitigate the large uncorrelated background in central Pb–Pb collisions. Recoil jet distributions are reported for jet resolution parameter $R = 0.2$, 0.4, and 0.5 in the range $7 < p_{T,jet} < 140$ GeV$/c$ and trigger–recoil jet azimuthal separation $\pi/2 < \Delta\varphi < \pi$. The measurements exhibit a marked medium-induced jet yield enhancement at low p_T and at large azimuthal deviation from $\Delta\varphi \sim \pi$. The enhancement is characterized by its dependence on $\Delta\varphi$, which has a slope that differs from zero by 4.7σ. Comparisons to model calculations incorporating different formulations of jet quenching are reported. These comparisons indicate that the observed yield enhancement arises from the response of the QGP medium to jet propagation.

azimuthal deviation of low p_T jets

- strong deviation of low p_T jets from back-to-back trigger hadron
  - effect consistent with being due to QGP response



my notes of caution

- interpretation of agreement of MC calculation with data requires detailed scrutiny
    - in hadron-jet coincidences, the trigger [the hadron] also loses energy
        - same cut for hadron p_T in pp and AA correspond to different hard process initial conditions :: observable is a ratio of samples born differently :: on-average correction possible but not done in experimental analysis
        - effects of imperfect background subtraction could be very sizeable for low p_T jets :: ALICE analysis very careful here :: check also with embedded pp
        - i am [very personal limitation] not very comfortable with such low p_T 'jets'

- i would only be comfortable with claiming the observation of azimuthal deviation of jets after excluding plausible confounding origins for observed effect

lesson #6

MC essential to learn about the QGP with jets

MC/data agreement insufficient to draw robust conclusions

very detailed scrutiny is essencial

WHAT WE HAVE, AND HAVE NOT YET, UNDERSTOOD

- jets in QGP
  - parton branching in presence of QGP [including effects of QGP gradients]
  - response of QGP to interaction with traversing partons and its contribution to jets
    - several implementations; few analytical results for inclusion in jets
  - what is a fair comparison between theory and data [but not yet doing it systematically]
- jets as probes of QGP properties [assumes above is sufficiently understood]
  - observable properties of jets that can be robustly related to QGP properties ?
  - QGP response within jets as portal to understand hydrodynamization and how QGP forms
    - how hydrodynamized is QGP response ?
- is there enough information in a modified jet to identify it as such jet-by-jet ?
  - how to use that information