learning about jet quenching from event generators

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TÉCNICO LISBOA

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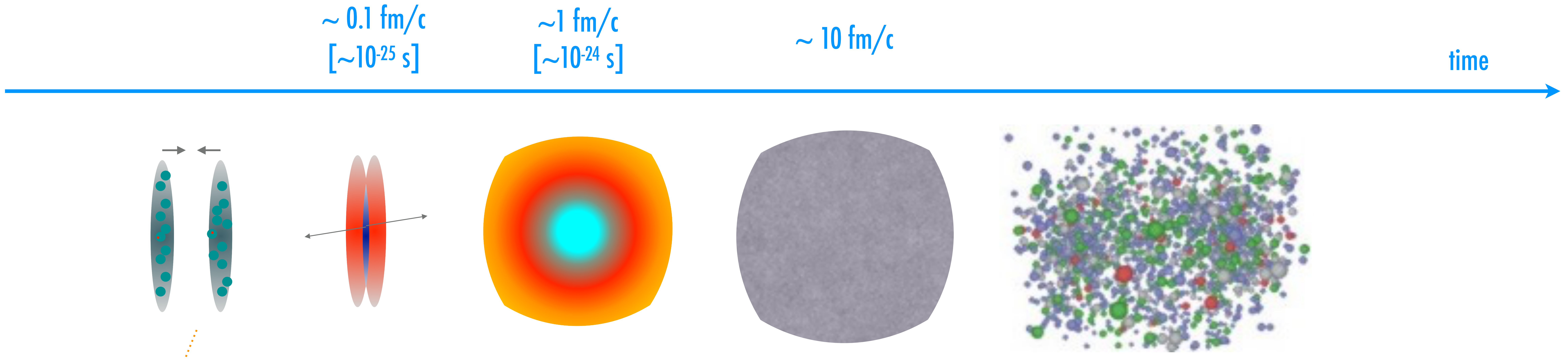
FROM NUCLEI TO QGP :: A HEAVY ION COLLISION



what we can ideally determine/constrain elsewhere
·electron-nucleus EIC/LHeC/FCC-eA
·proton-nucleus [to a lesser extent] LHC/RHIC–sPHENIX

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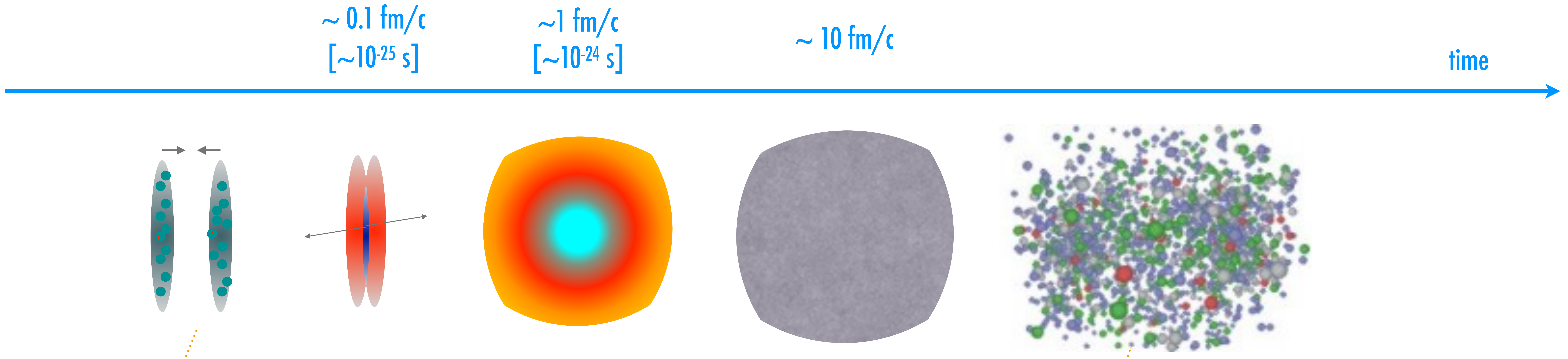

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all we have

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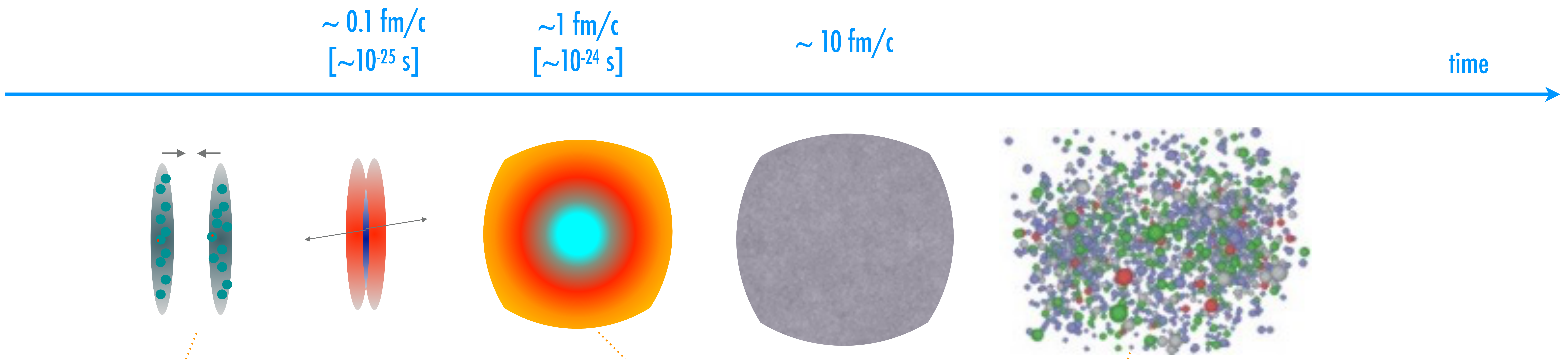

what we want to understand

- how we get here?
- what it is?
- how it stops being?

what we can ideally determine/constrain elsewhere

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HOW TO PROBE ANYTHING

scatter something off it

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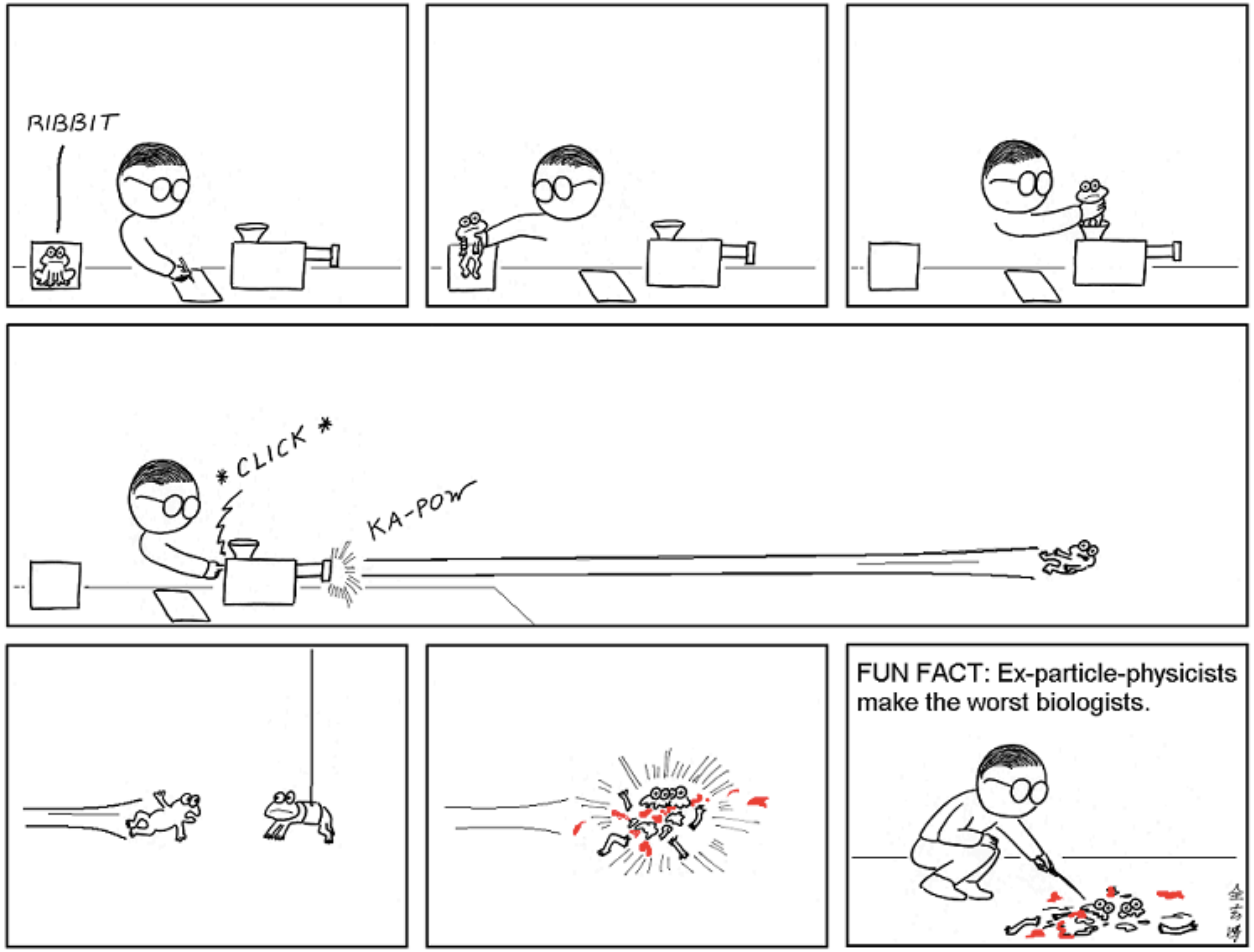
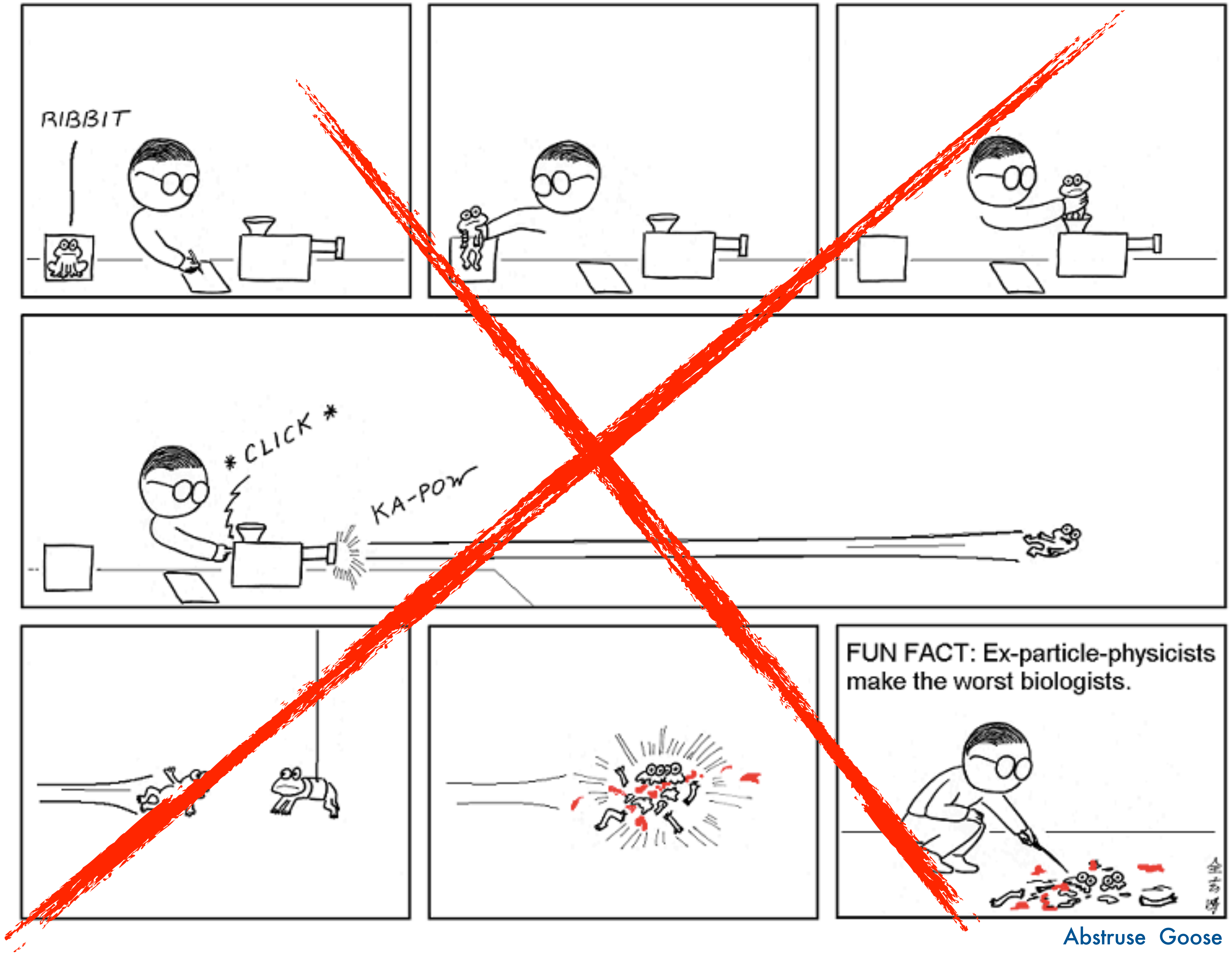


Abstruse Goose

HOW TO PROBE ANYTHING

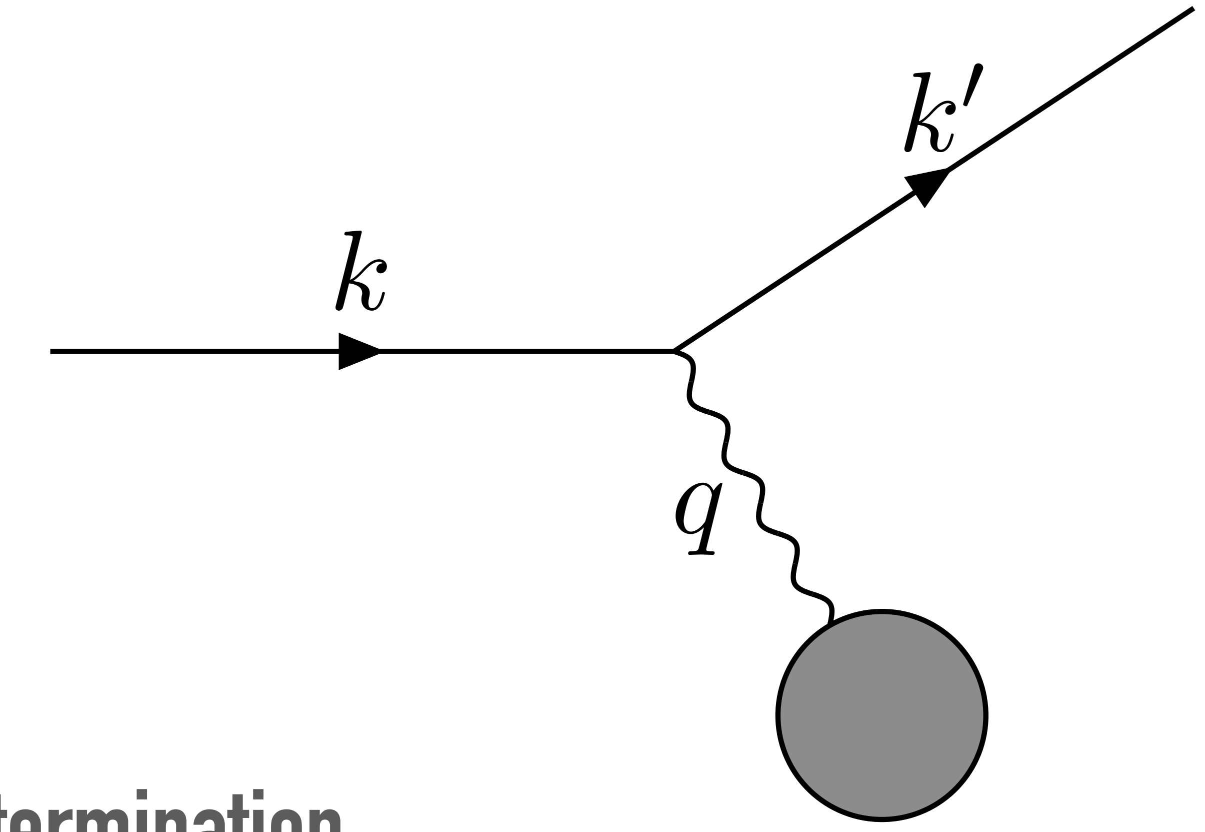
scatter something off it



cannot [easily] understand a frog from scattering it off another frog

HOW TO PROBE ANYTHING

scatter something you understand off it



deep inelastic scattering is the golden process for proton/nucleus structure determination

dial $Q^2 = -q^2 = -(k' - k)^2$ to probe distances $\lambda = \hbar/Q$

QGP too short-lived for external probes to be of any use

to mimic DIS paradigm need multi-scale probes produced in the same collision as the QGP

→ jets

WHY PROBING WITH JETS ?

UNIQUE AMONGST QGP PROBES

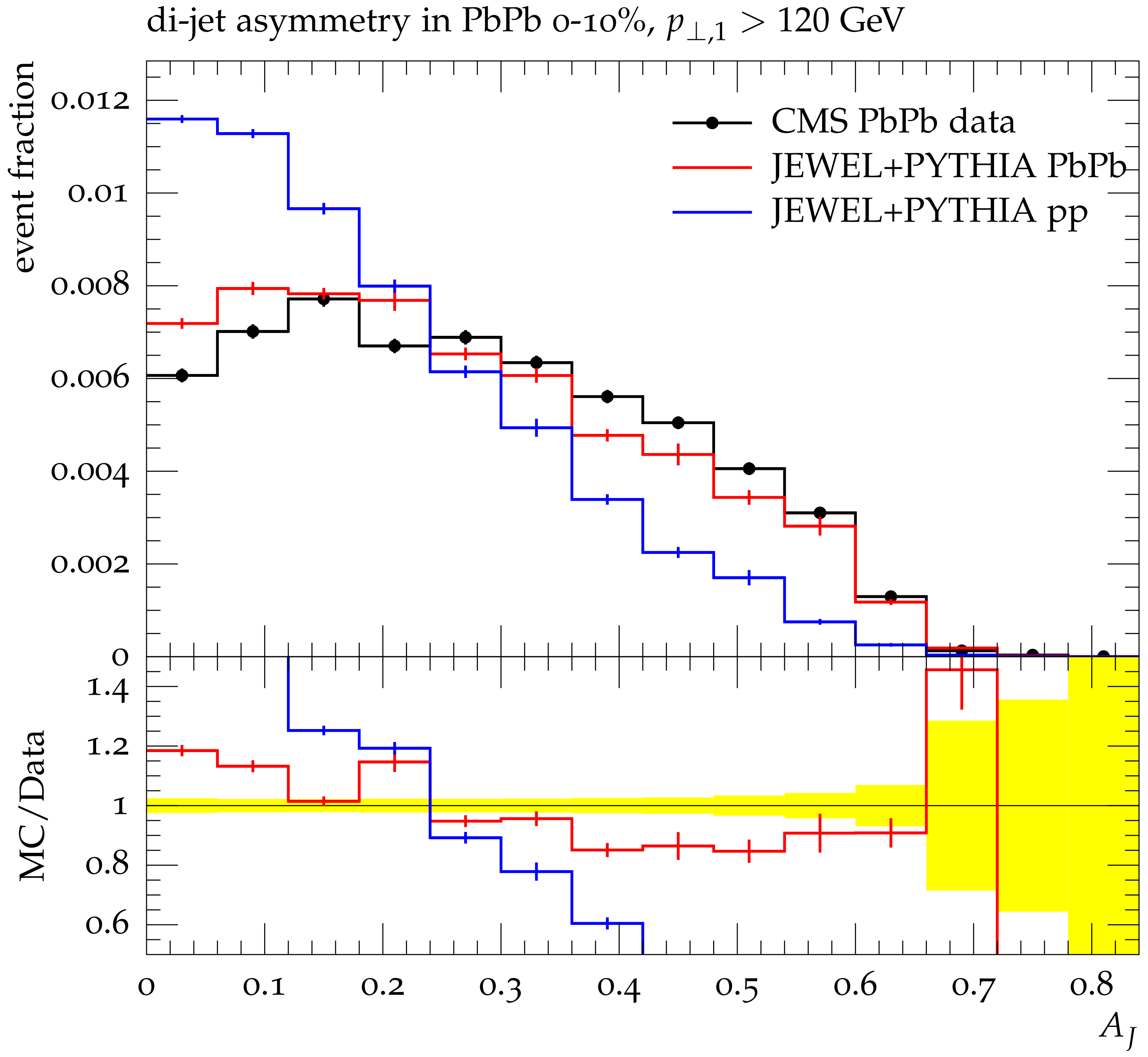
- multi-scale
  :: broad range of spatial and momentum scales involved in jet evolution in QGP
- multi-observable
  :: different observable jet properties sensitive to different QGP scales and properties
- very well understood in vacuum
  :: fully controlled benchmark
- feasible close relative of a standard scattering experiment

MC FOR JET QUENCHING

- several MC available for [semi]/public use
  - [very] diverse physical underpinnings
- two MC relevant for today
  - JEWEL :: grounded on pQCD :: vacuum parton shower dynamically modified by interaction with QGP :: QGP response modelled as recoiling QGP constituents :: joint hadronization of shower and QGP response [Lund strings]
  - HYBRID :: vacuum parton shower embedded in QGP modified by parton energy loss according to holographic prescription :: QGP response modelled as hydrodynamical wake :: separate hadronization of shower [Lund strings] and QGP response [Cooper-Frye]

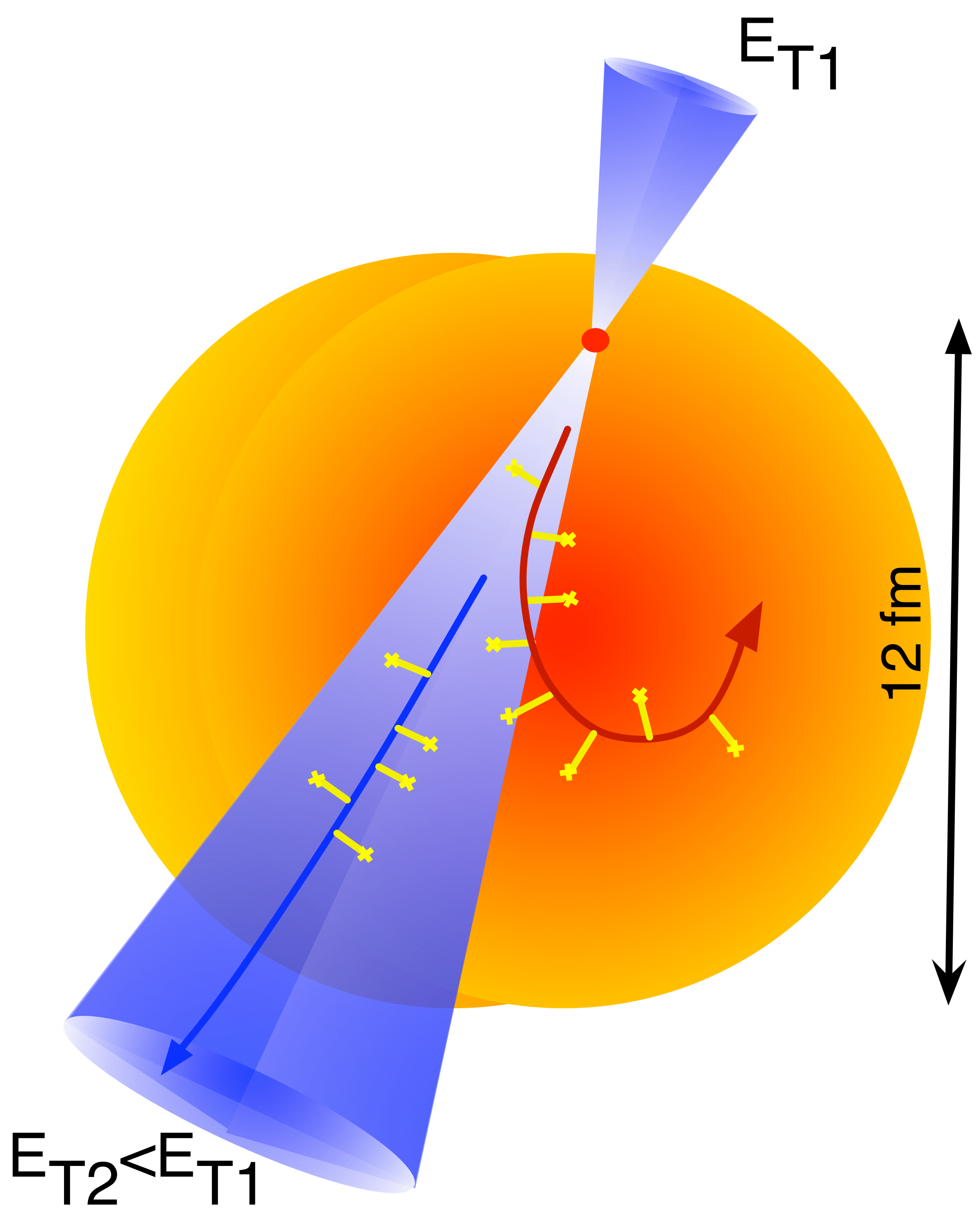
dijet asymmetry

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



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

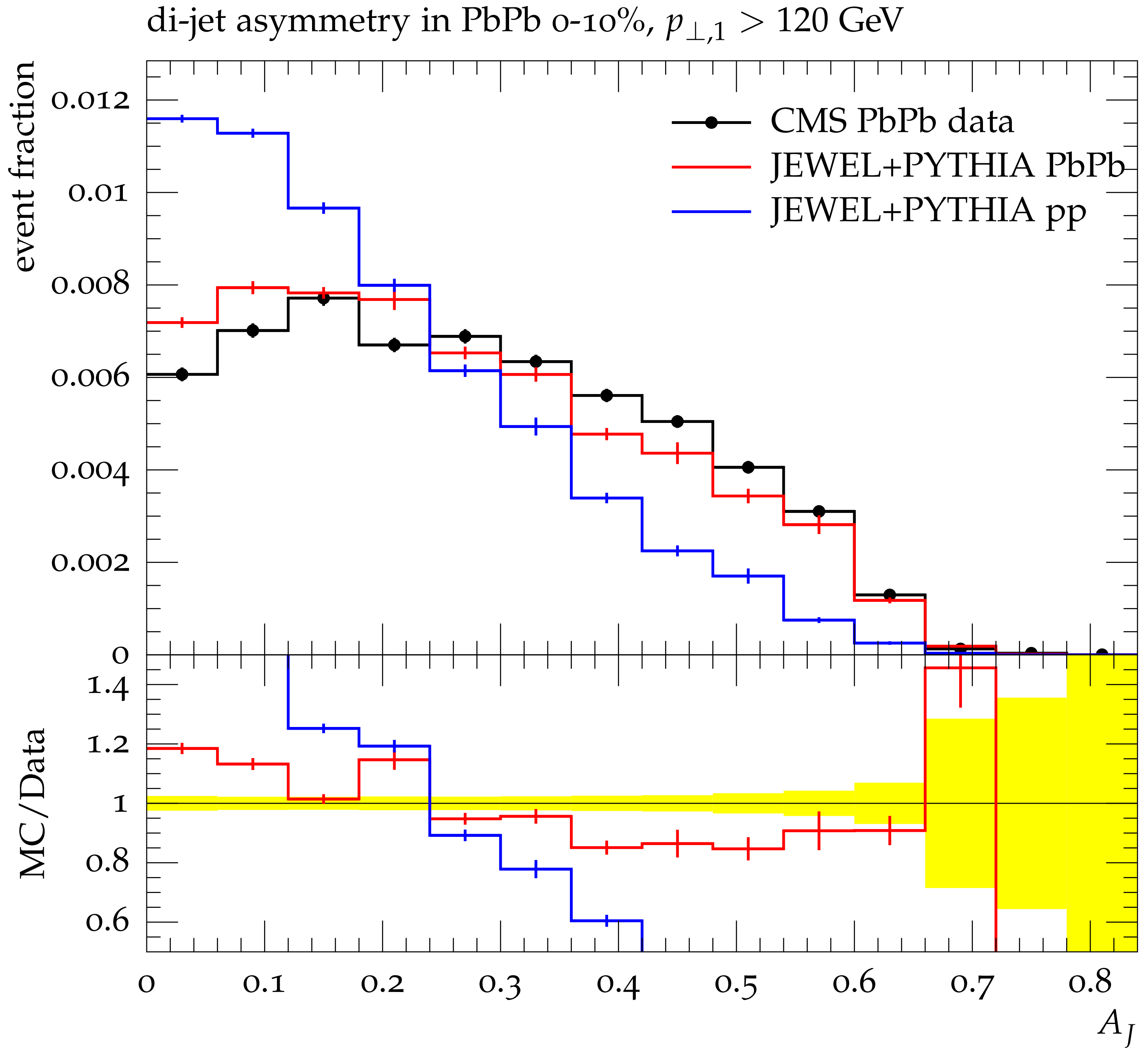
$$A_J = \frac{p_{\perp,1} - p_{\perp,2}}{p_{\perp,1} + p_{\perp,2}}$$



- 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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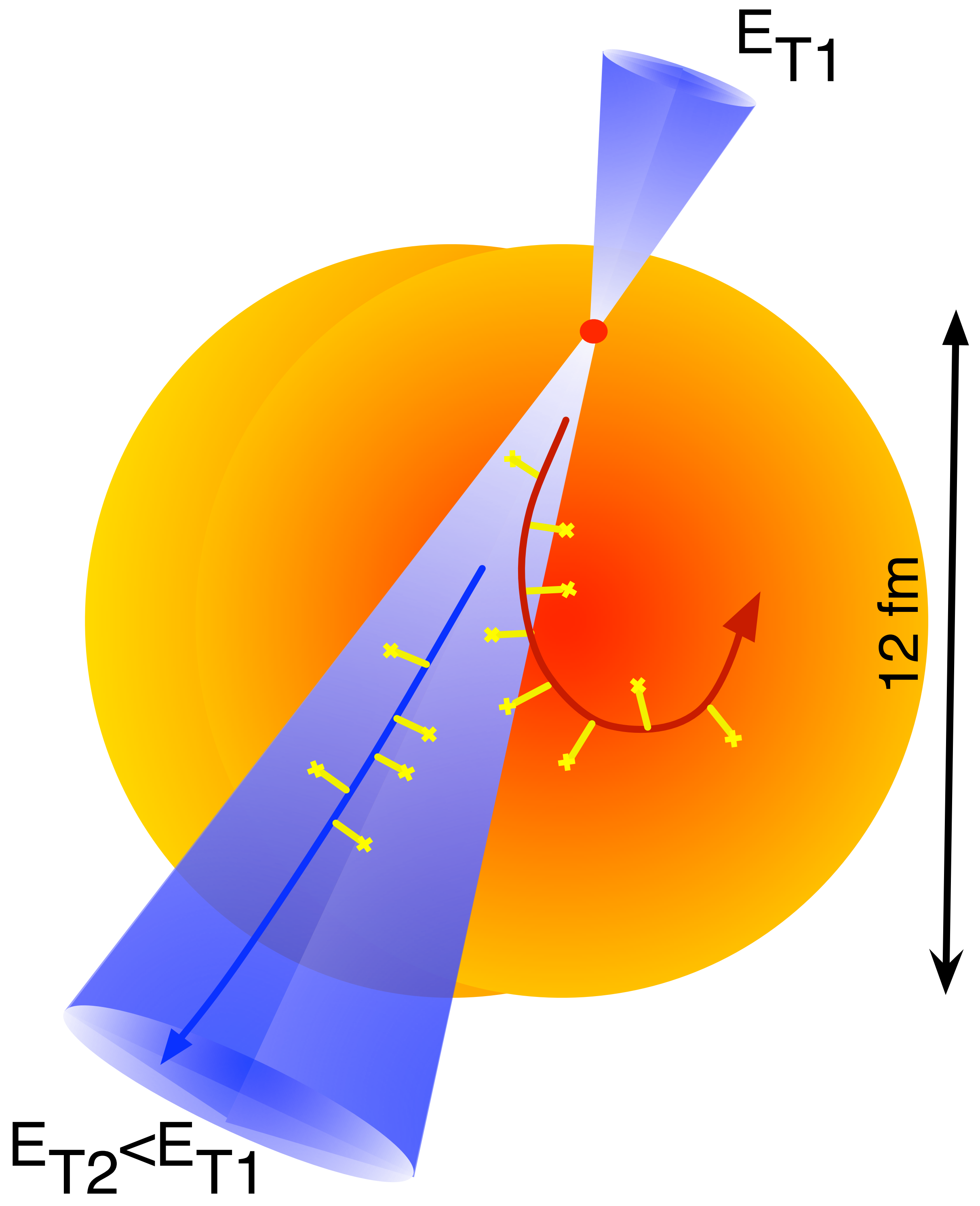

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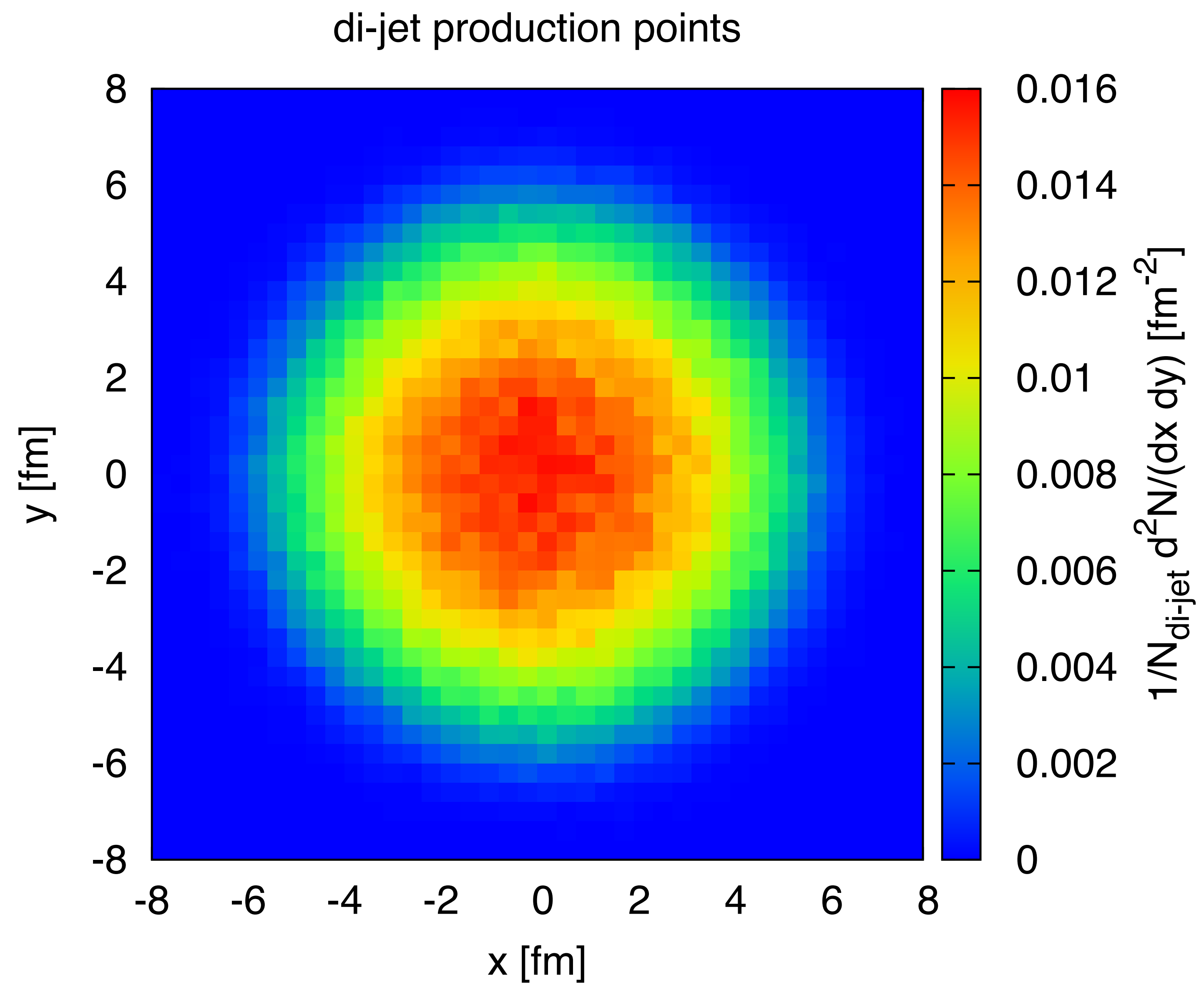
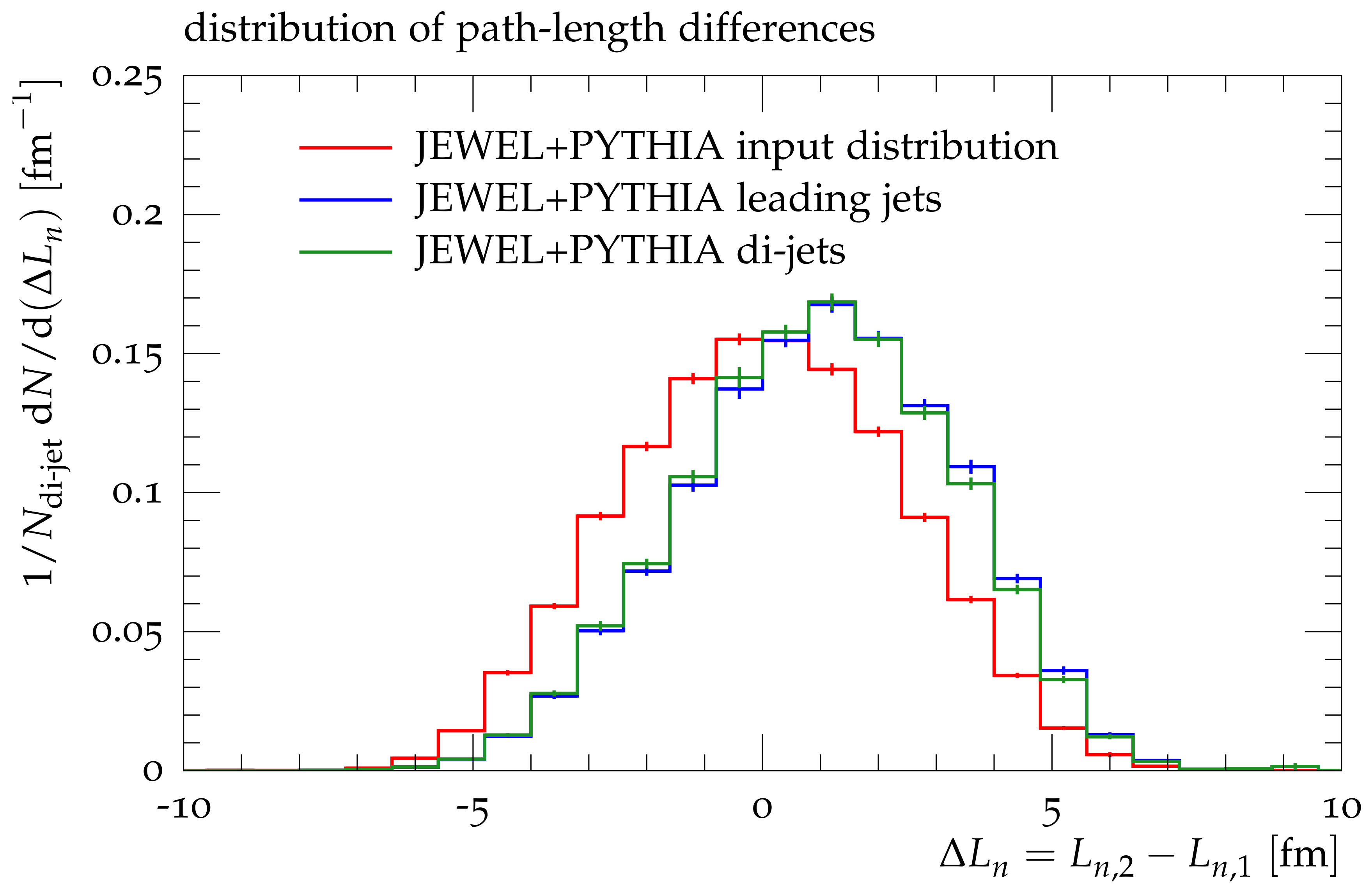
really not the case ...

dijet asymmetry

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





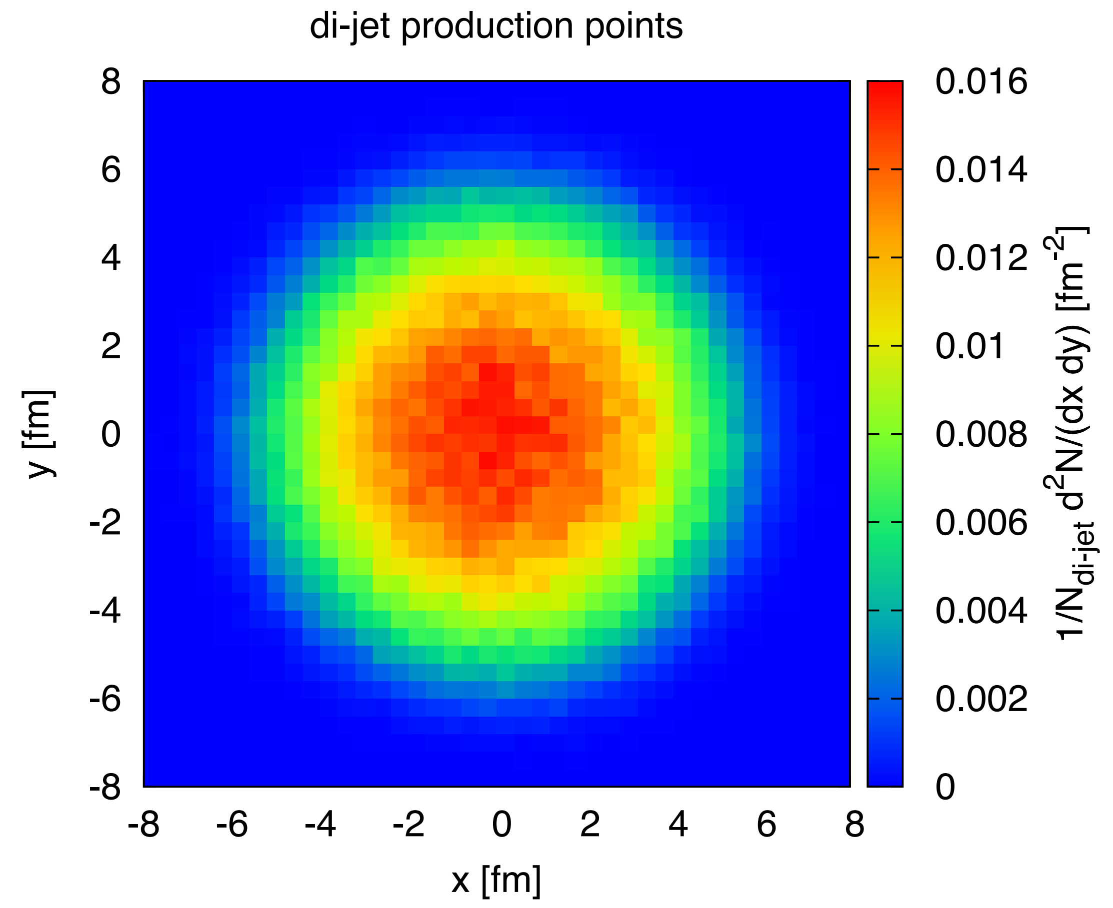
density weighted path-length
[accounts for medium expansion, rapidity independent for boost invariant medium]

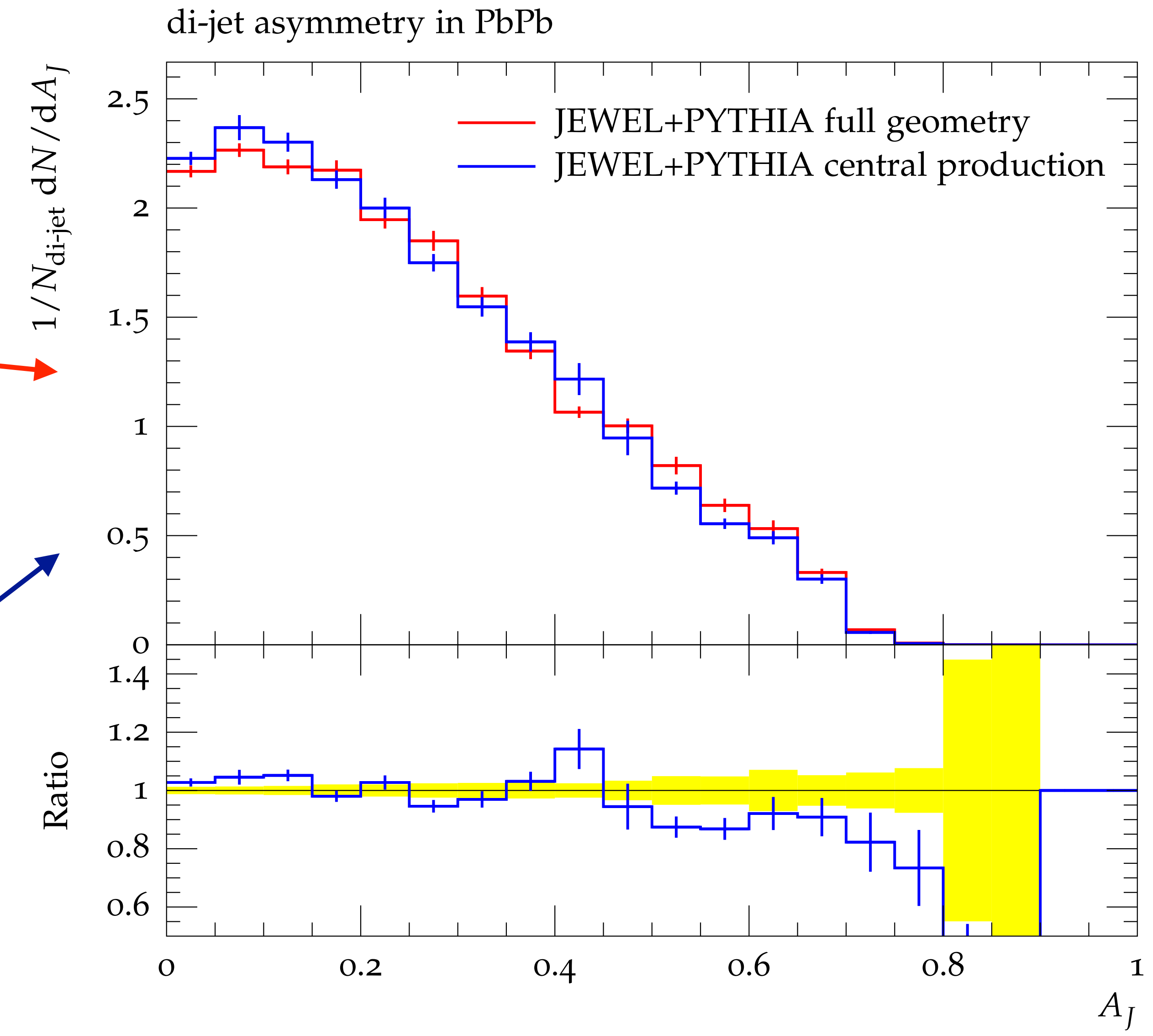
$$L_n = 2\frac{\int \mathrm{d}\tau\, \tau n(\mathbf{r}(\tau),\tau)}{\int \mathrm{d}\tau\, n(\mathbf{r}(\tau),\tau)}$$

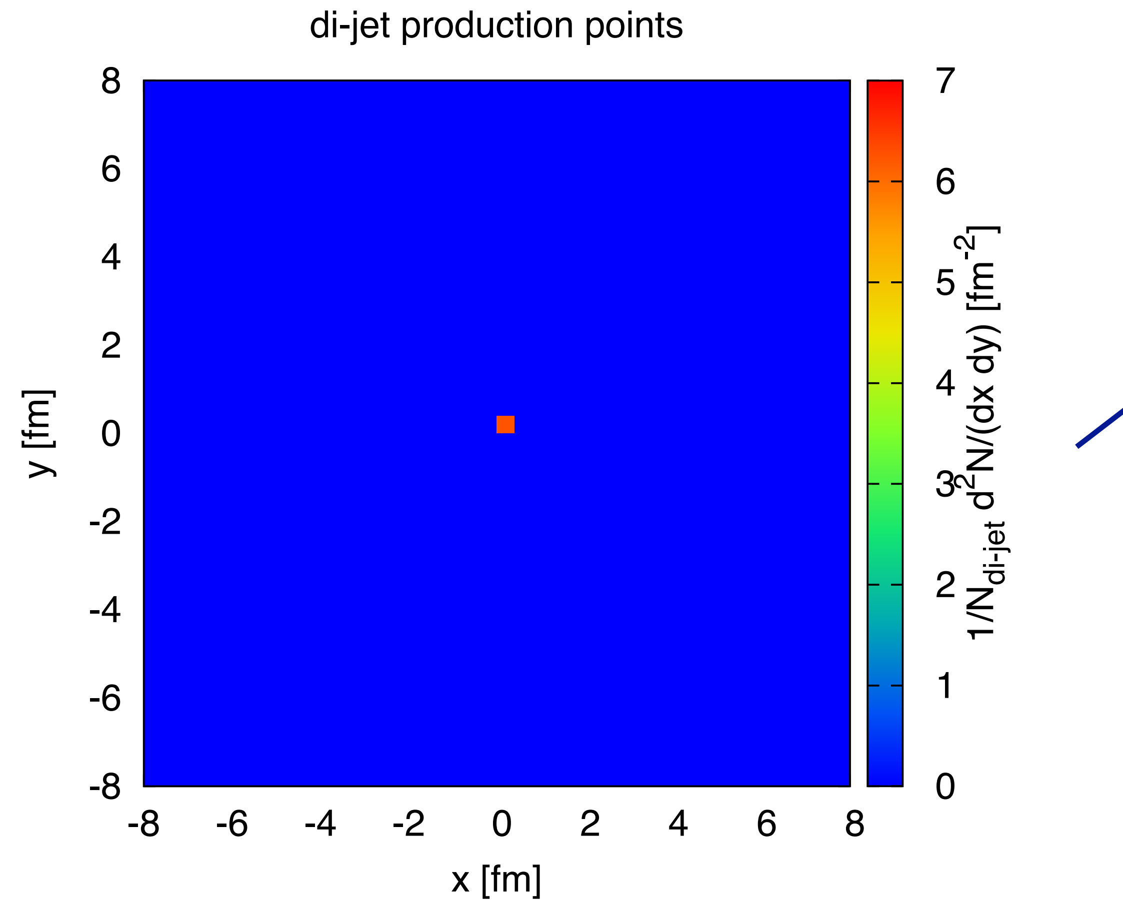
- small bias towards smaller path-length for leading jets
  - however, significant fraction [34%] of events have longer path-length for leading jet
  - consequence of fast medium expansion

dijet asymmetry

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





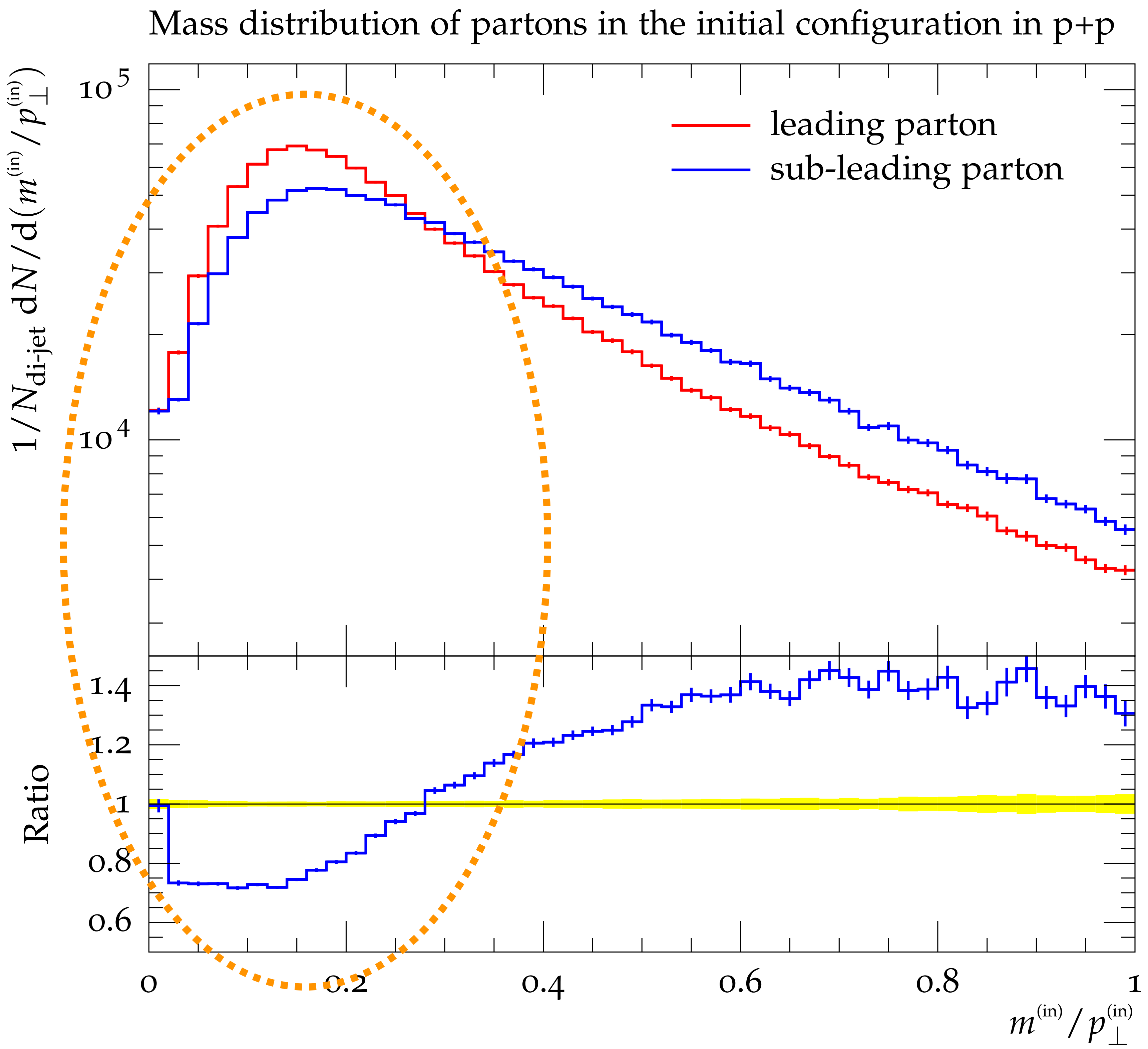


$$A_J = \frac{p_{\perp,1} - p_{\perp,2}}{p_{\perp,1} + p_{\perp,2}}$$

- 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
  - 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

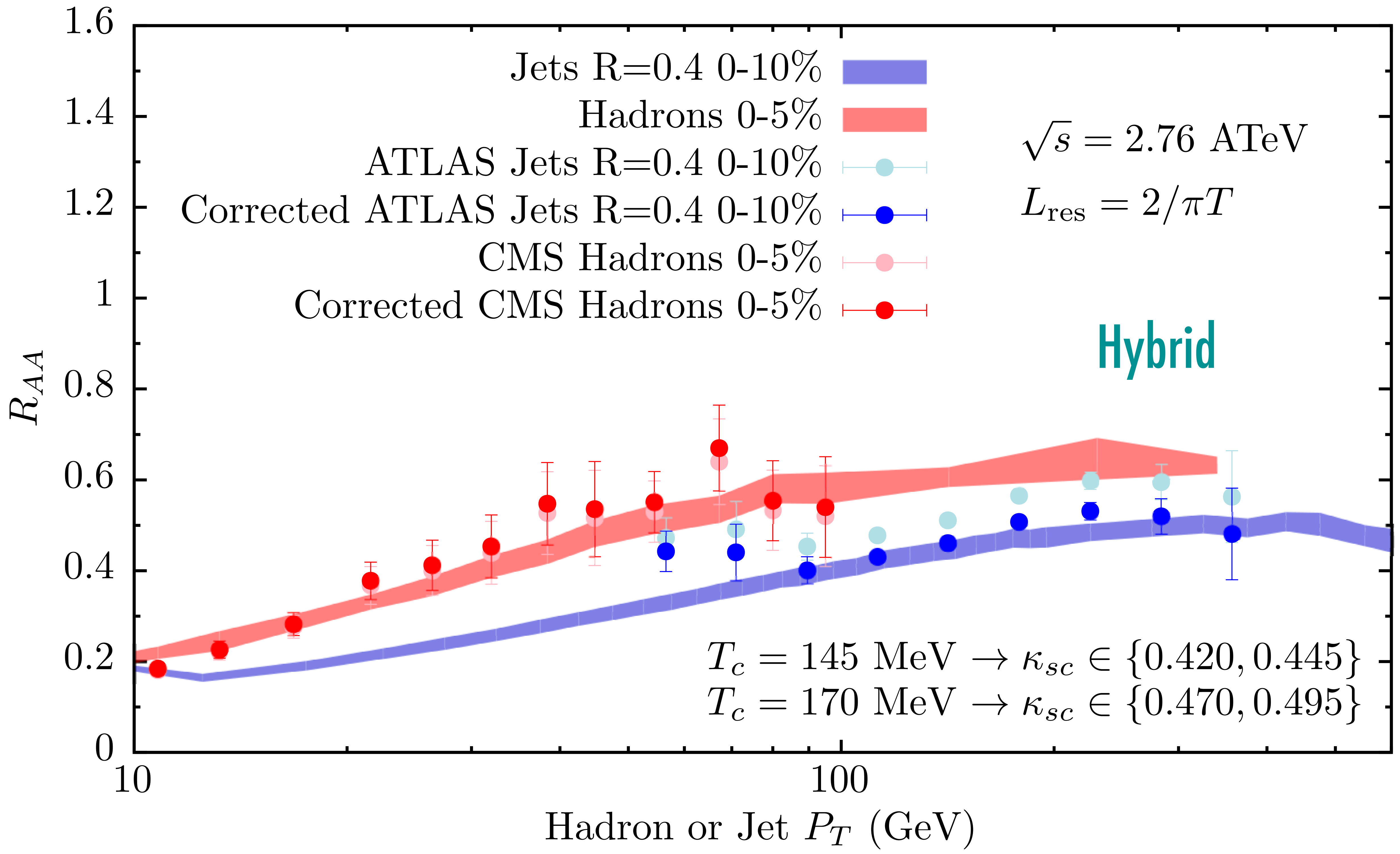
vacuum like jet fragmentation very important driver of how much and how a jet ends up modified

learning about jet quenching from MC requires careful analysis

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 treated jets as resulting from evolution of a multiparticle state fully account for the different suppression



jet and hadron R_{AA}

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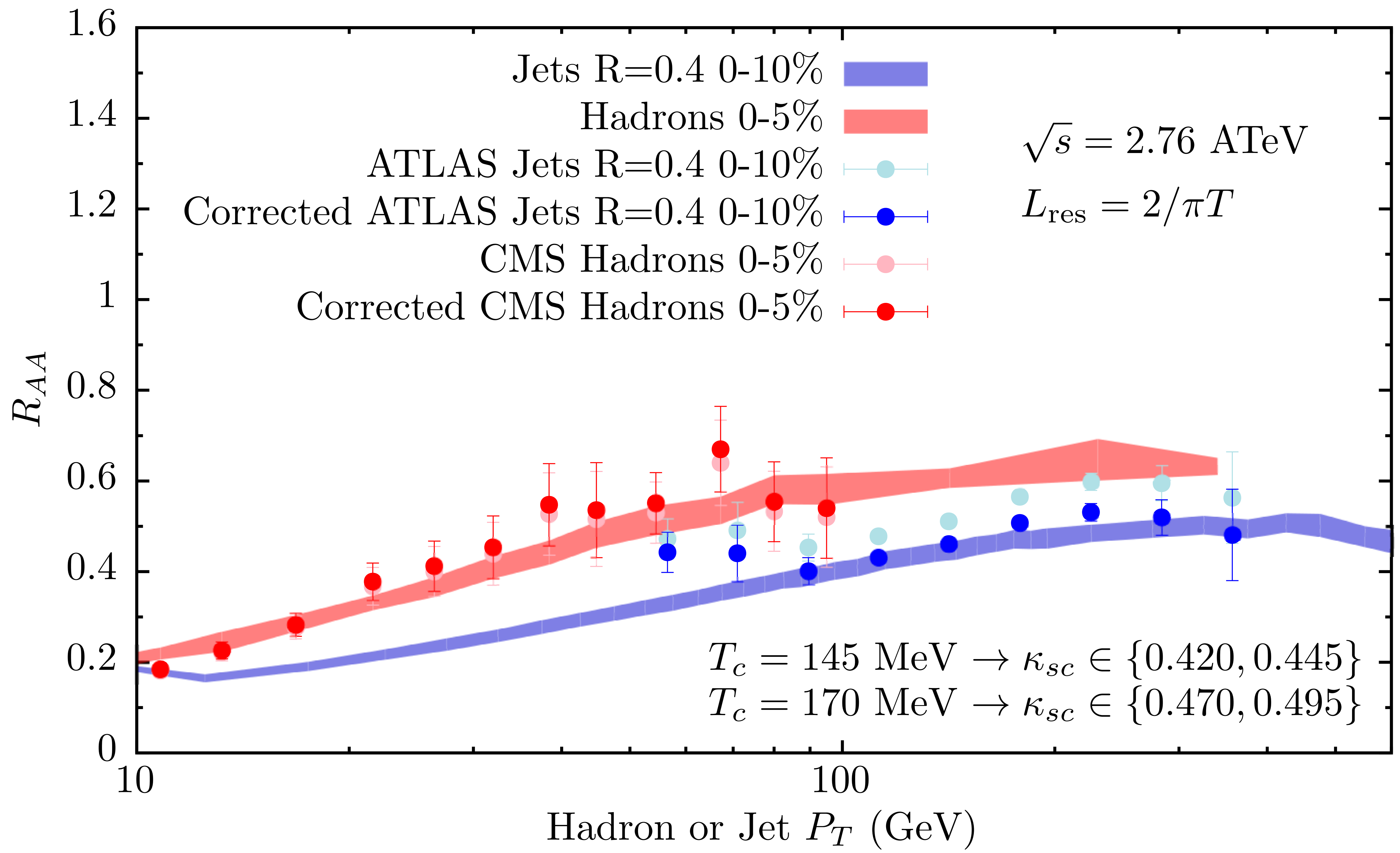
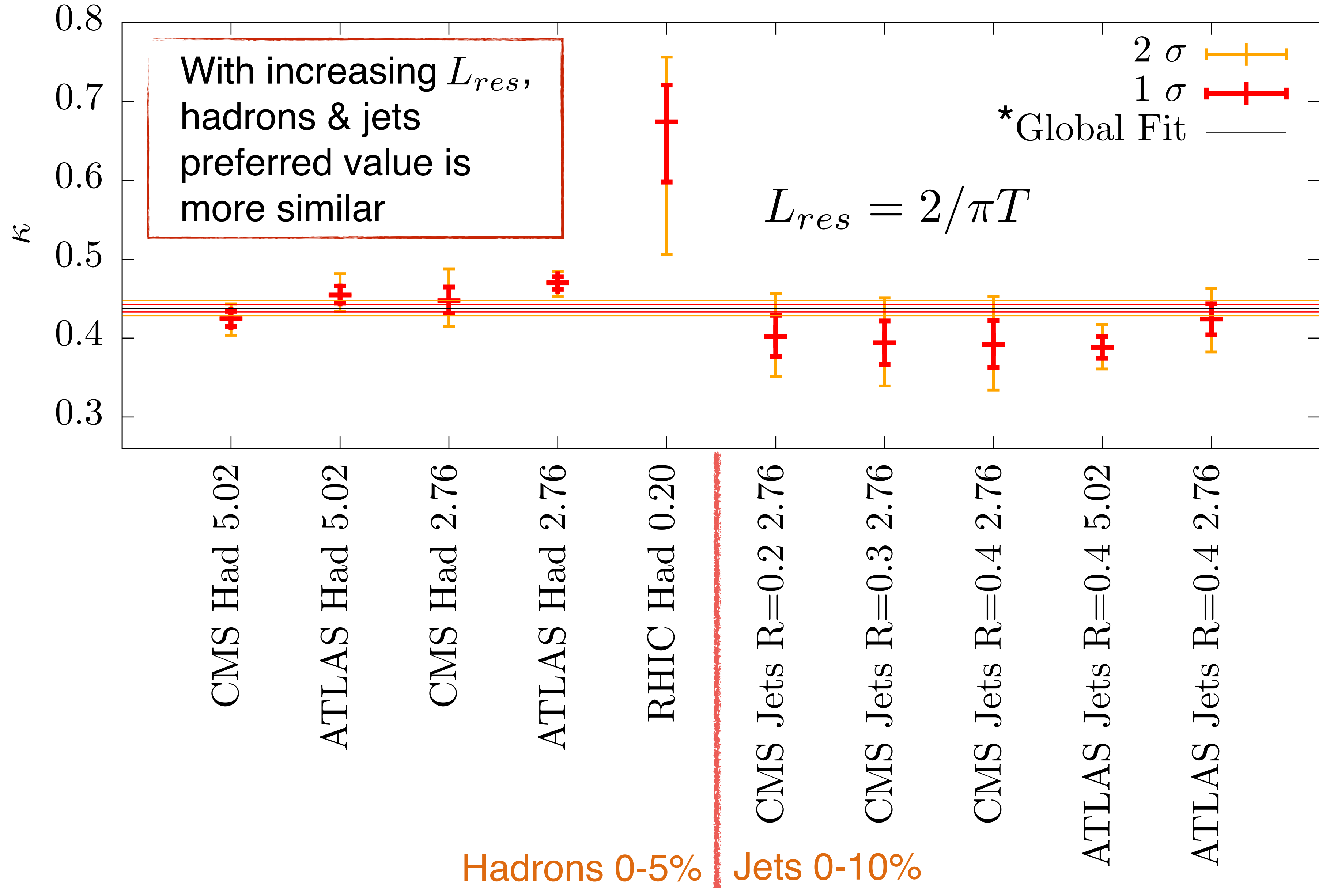




- excellent global fit for LHC data :: some tension with RHIC data
- high p_T hadrons originate from narrow jets [fragmented less] which are less suppressed than inclusive jets
- simultaneous description of jet and hadron R_{AA} natural feature of any approach that treats jets as such [ie, objects resulting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

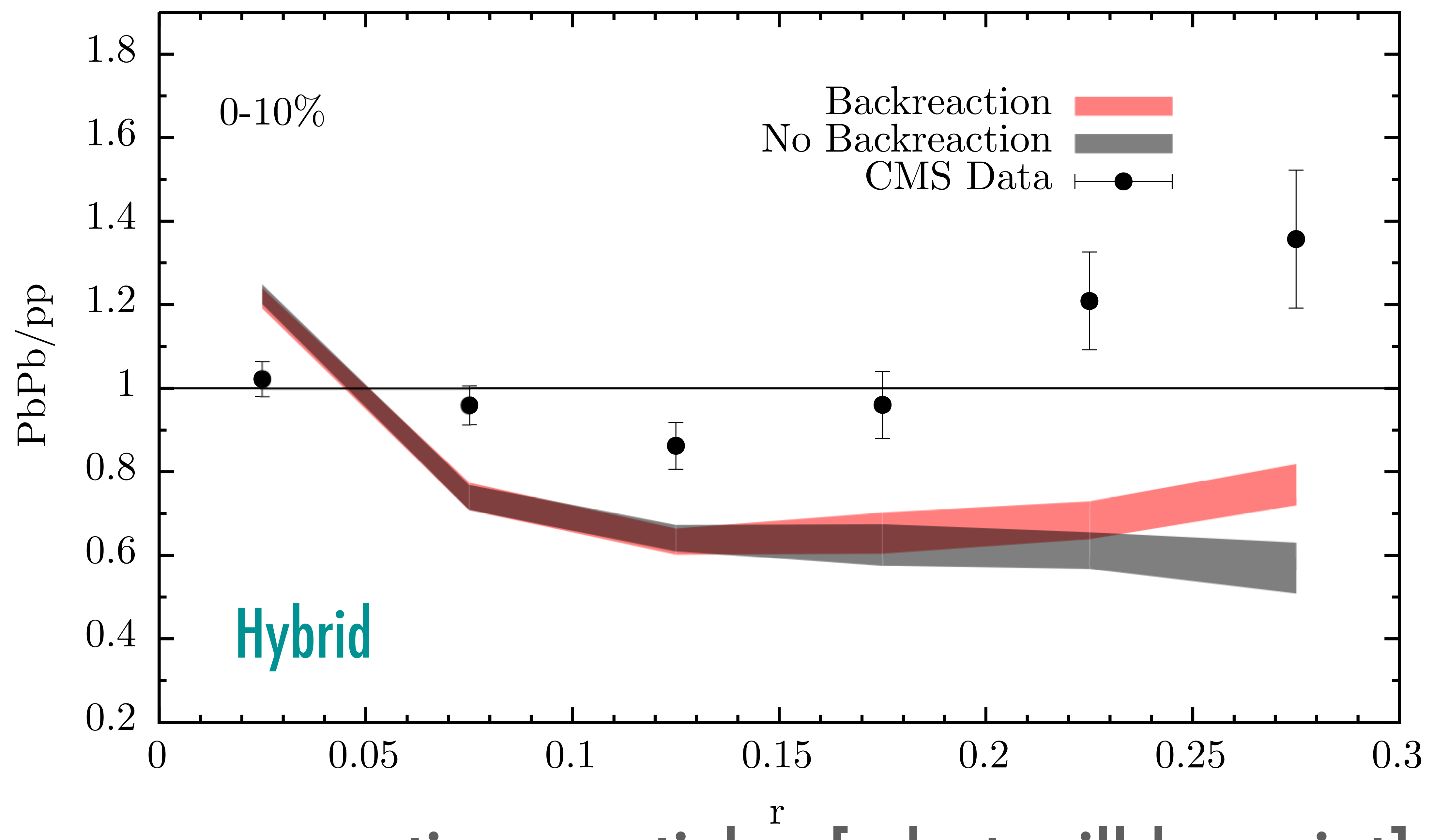
lesson #2

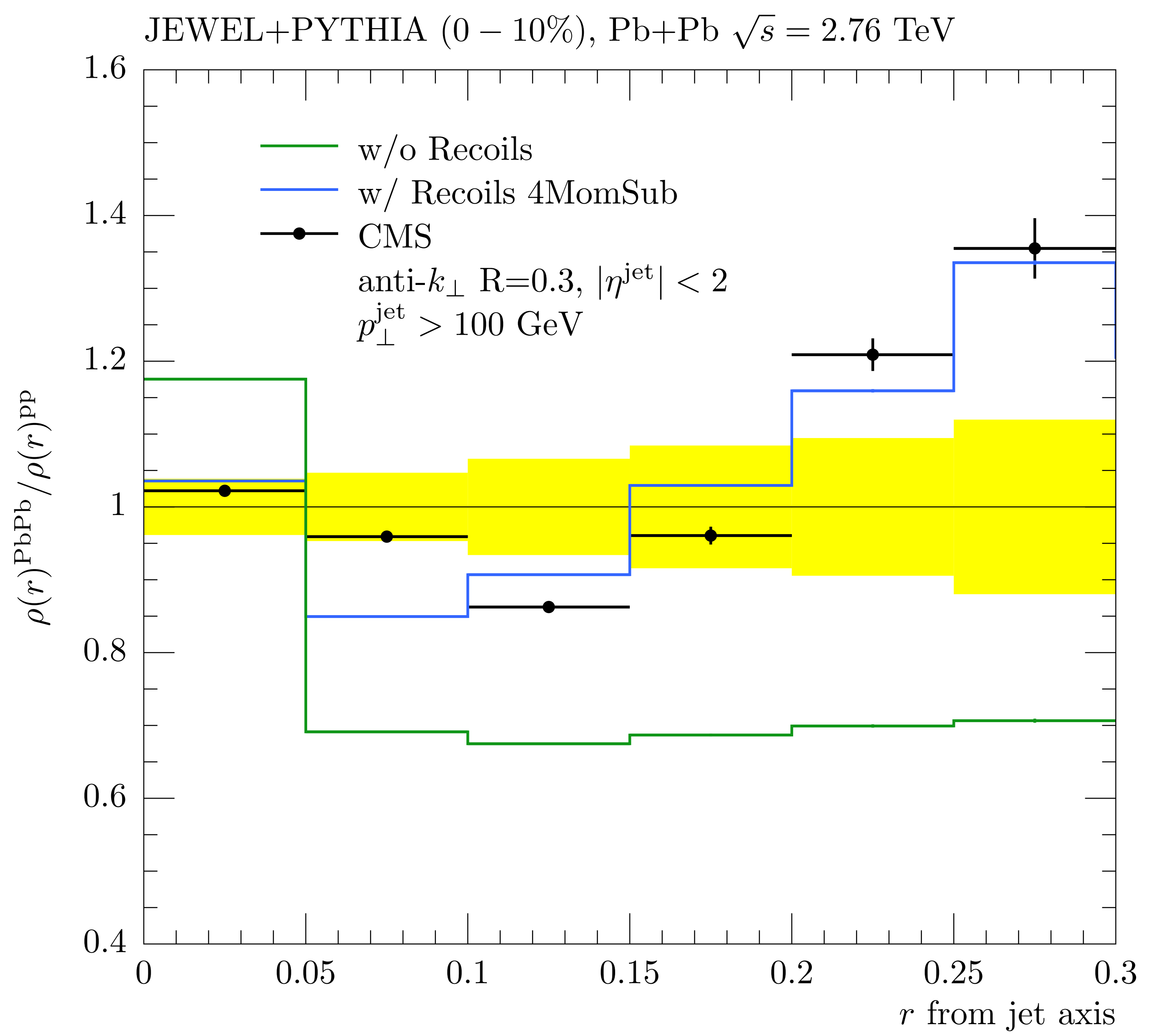
QGP sees and interacts with constituents of evolving shower

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

learning about jet quenching from MC requires careful analysis

'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 remains untractable in 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 #3

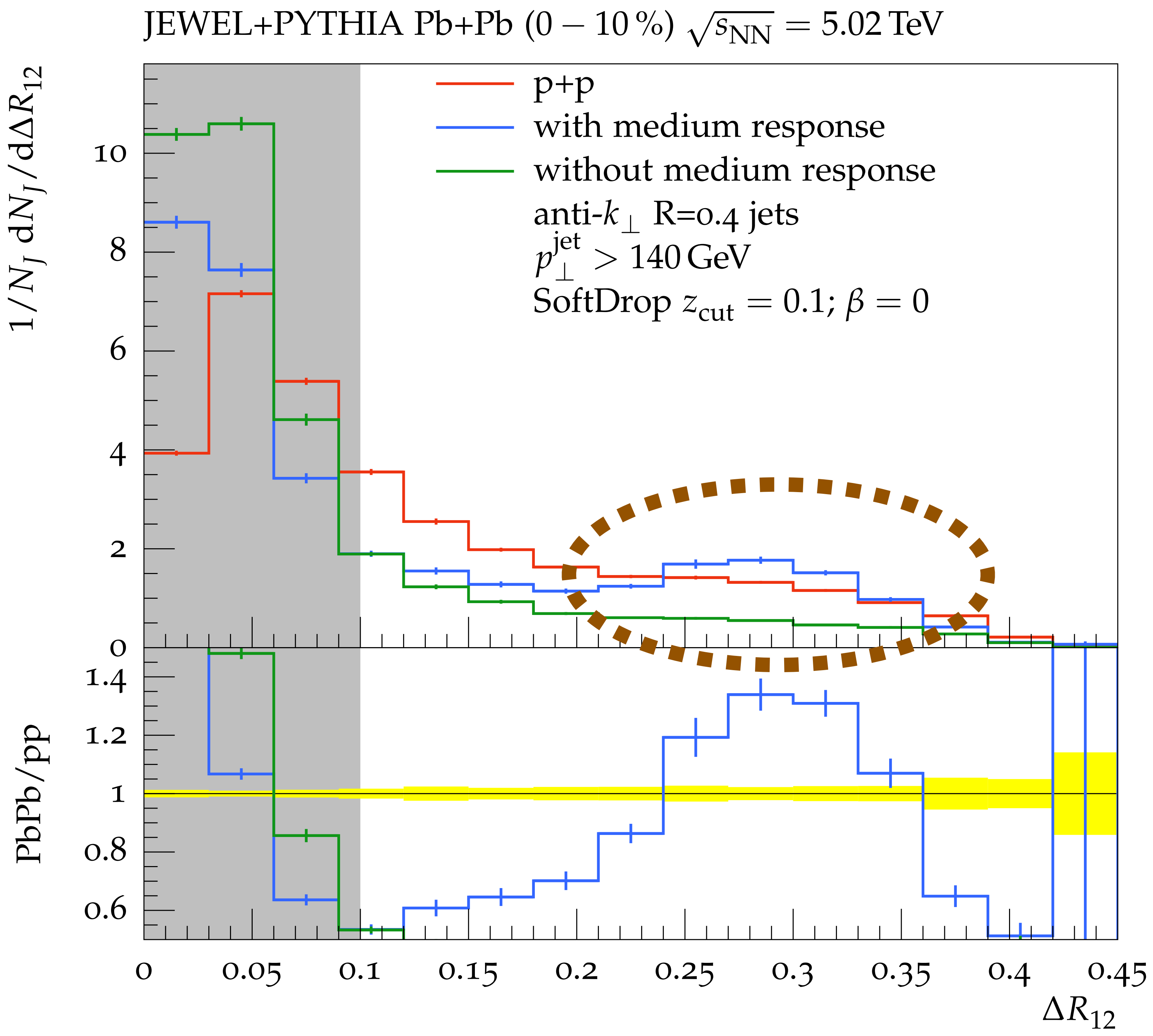
QGP response to traversal by partons is an important component of jets in HI collisions

contribution extremely important for jet substructure

MC essential to identify the physical mechanisms involved in jet quenching

QGP response in jet substructure

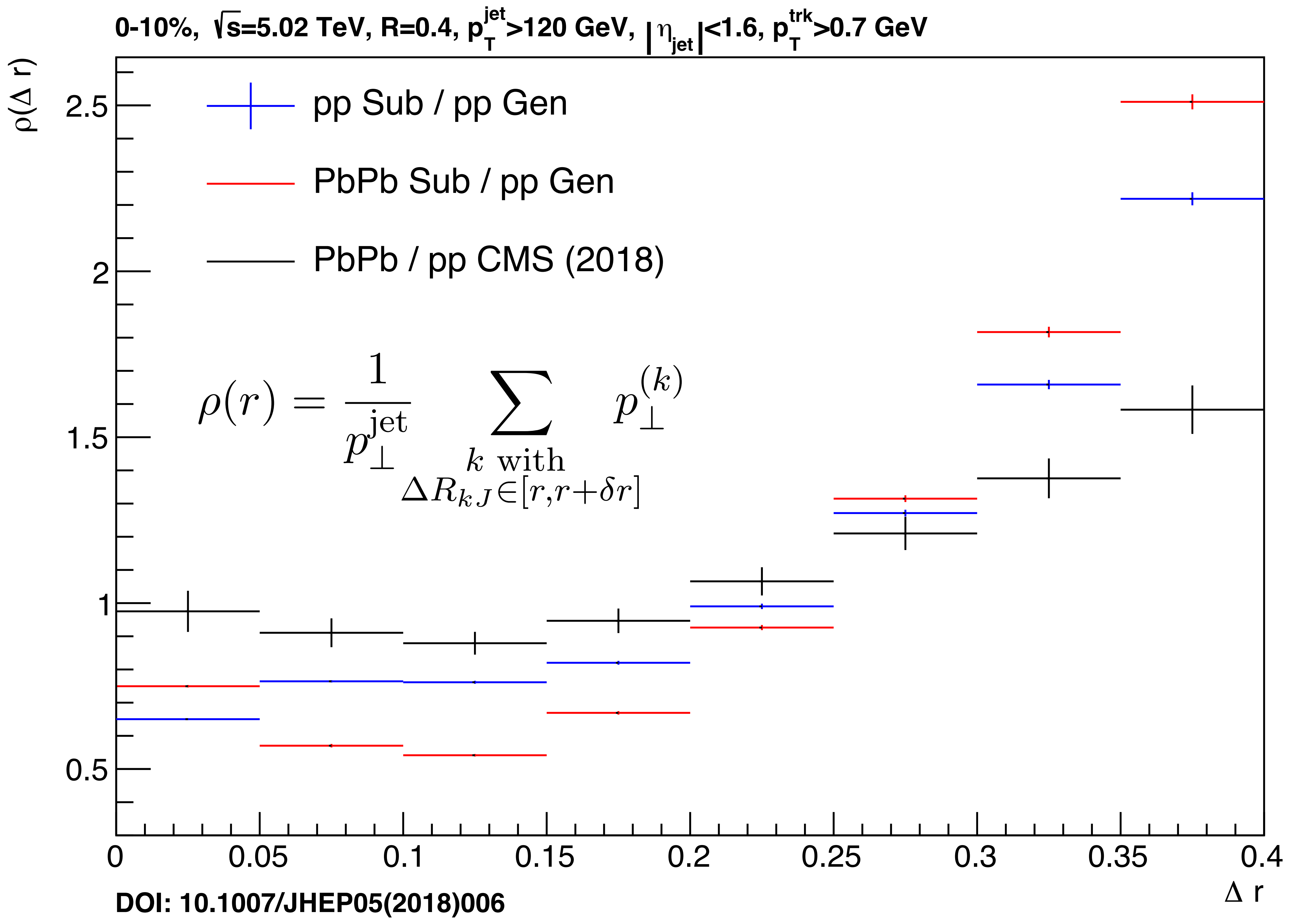
Milhano, Wiedemann, Zapp :: 1707.04142 [hep-ph]



- 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 #4

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

what i was asked to talk about

- what we learn from MC about:

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*

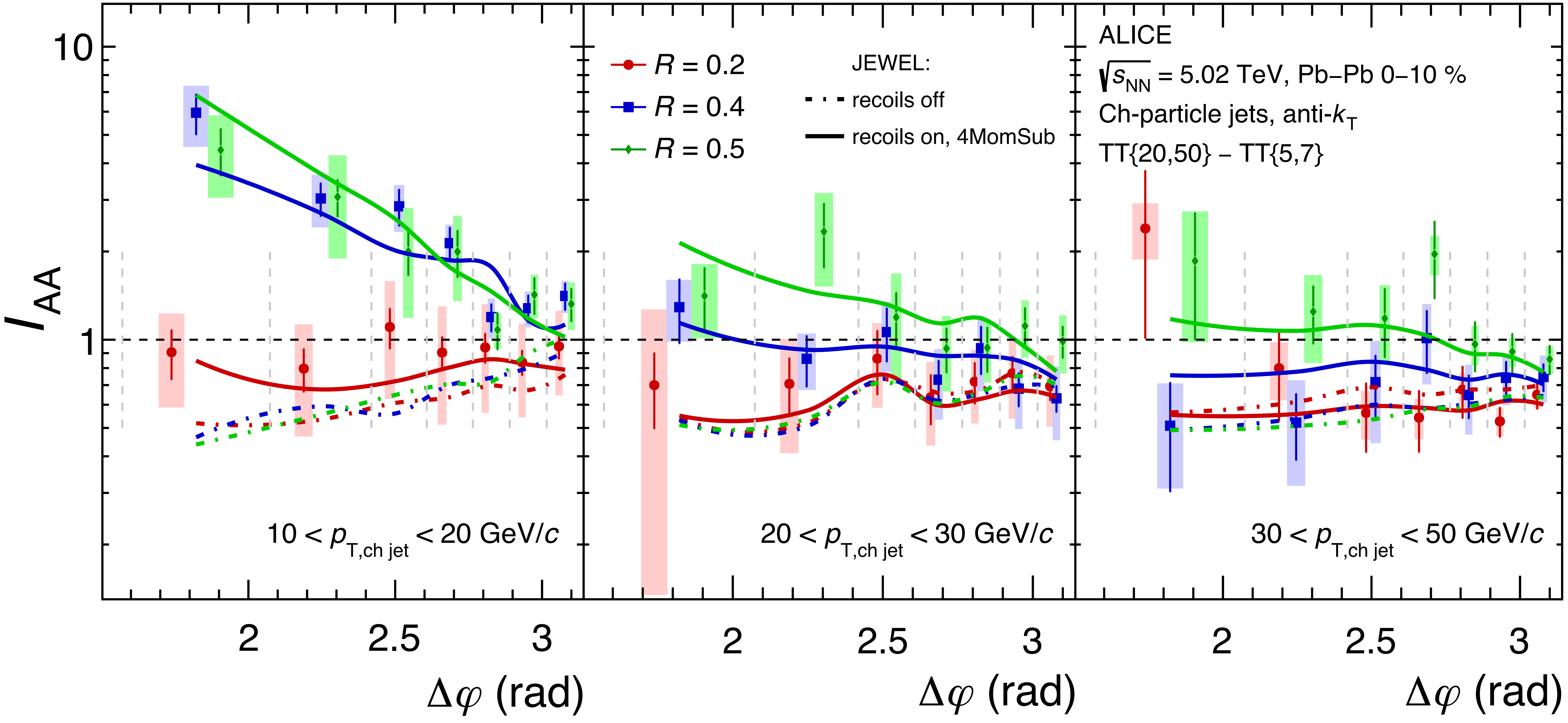
Abstract

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

this is a AA/pp ratio



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 #5

MC essential to learn about the QGP with jets

learning from scrutiny, not from MC/data agreement