heavy ion physics [lecture II]

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TÉCNICO LISBOA

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

erc European Research Council
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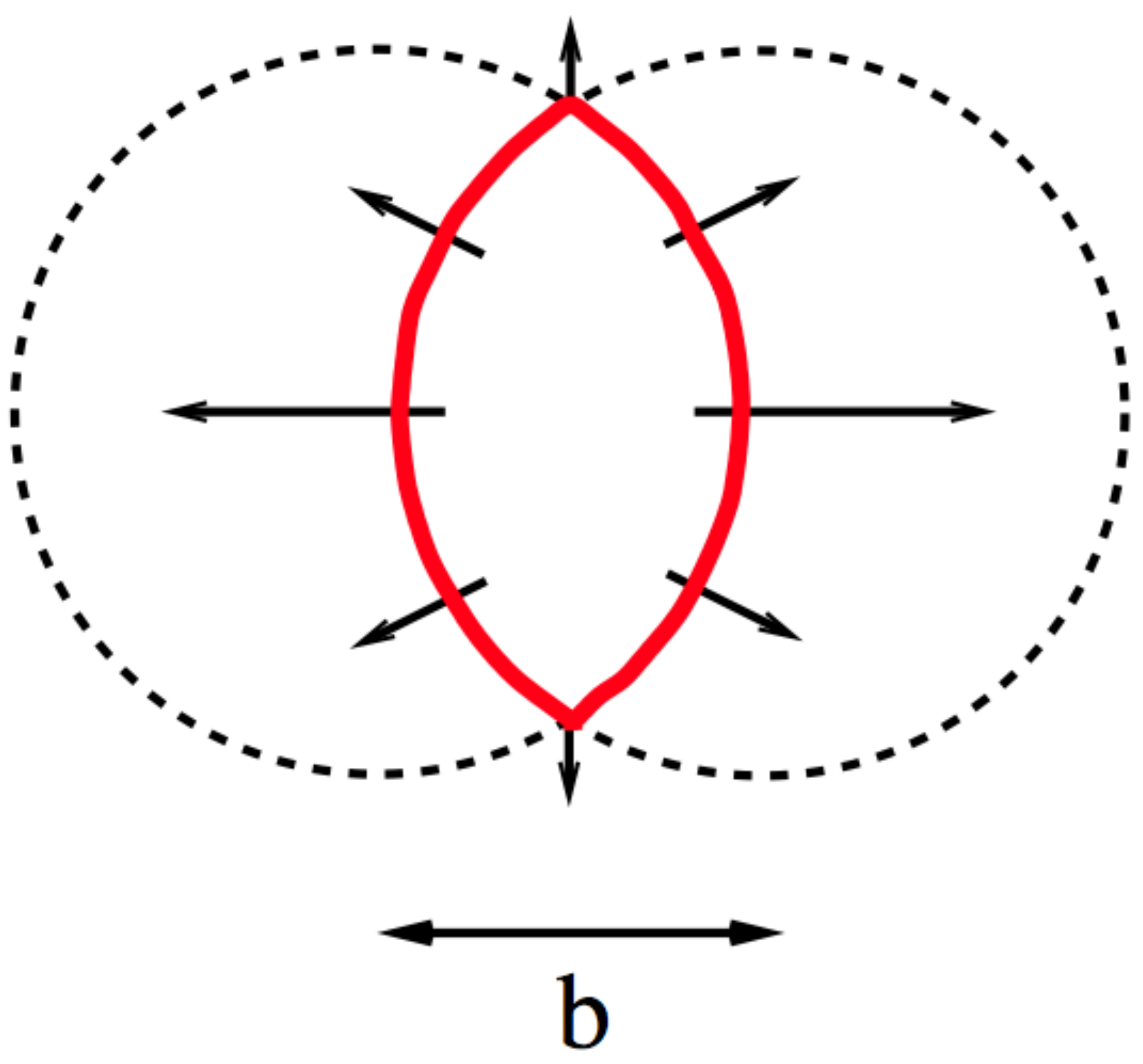
OUTLINE

- lecture I [yesterday]
  - general introduction
  - what is Quark Gluon Plasma
  - the states of a Heavy Collision

- **lecture II [today]**
  - **how do we know what we know about Quark Gluon Plasma**
  - **how do we get to know more**
  - **focus on two classes of observables: particle correlations and jet properties**

MEASURING FLOW



- pressure gradients larger in reaction plane
- larger fluid velocity along reaction plane
    - more particles fly in this direction

:: quantify effect by measuring particle distribution in azimuth

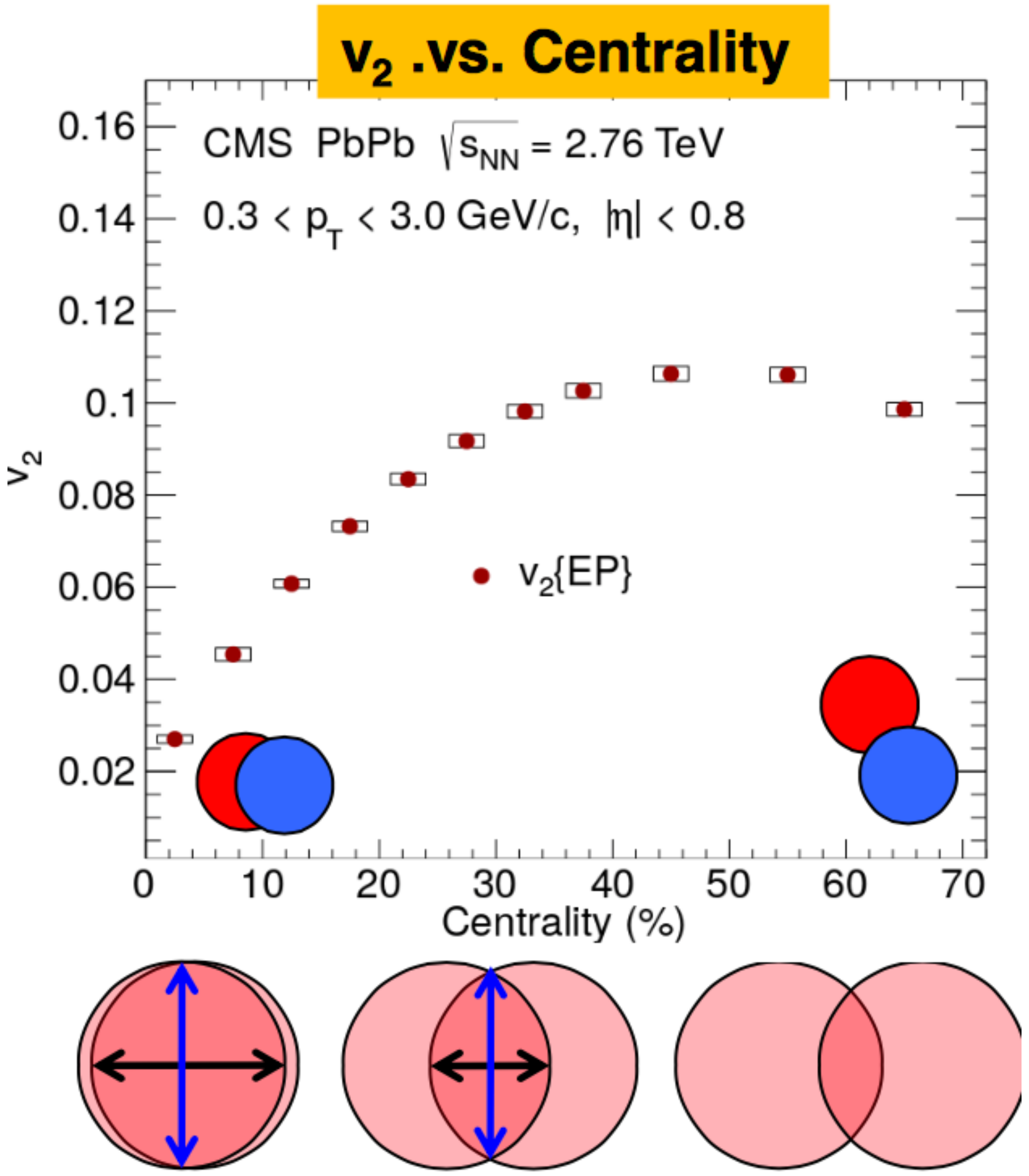
$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + 2\sum_n v_n \cos(n(\phi - \psi))\right]$$

:: $v_2(p_t, y)$ measures ellipticity of momentum distribution

:: odd-coefficients [v_3, ...] vanish by $\phi \rightarrow \phi + \pi$ symmetry

event plane angle: direction of maximum particle density

MEASURING FLOW



CMS, PRC 87(2013) 014902

- strong centrality dependence
  - small for central [small spatial asymmetry]
  - maximum for mid-central
  - smaller for very peripheral [small QGP]
- conversion of spatial asymmetry into momentum asymmetry is a key property of hydrodynamics

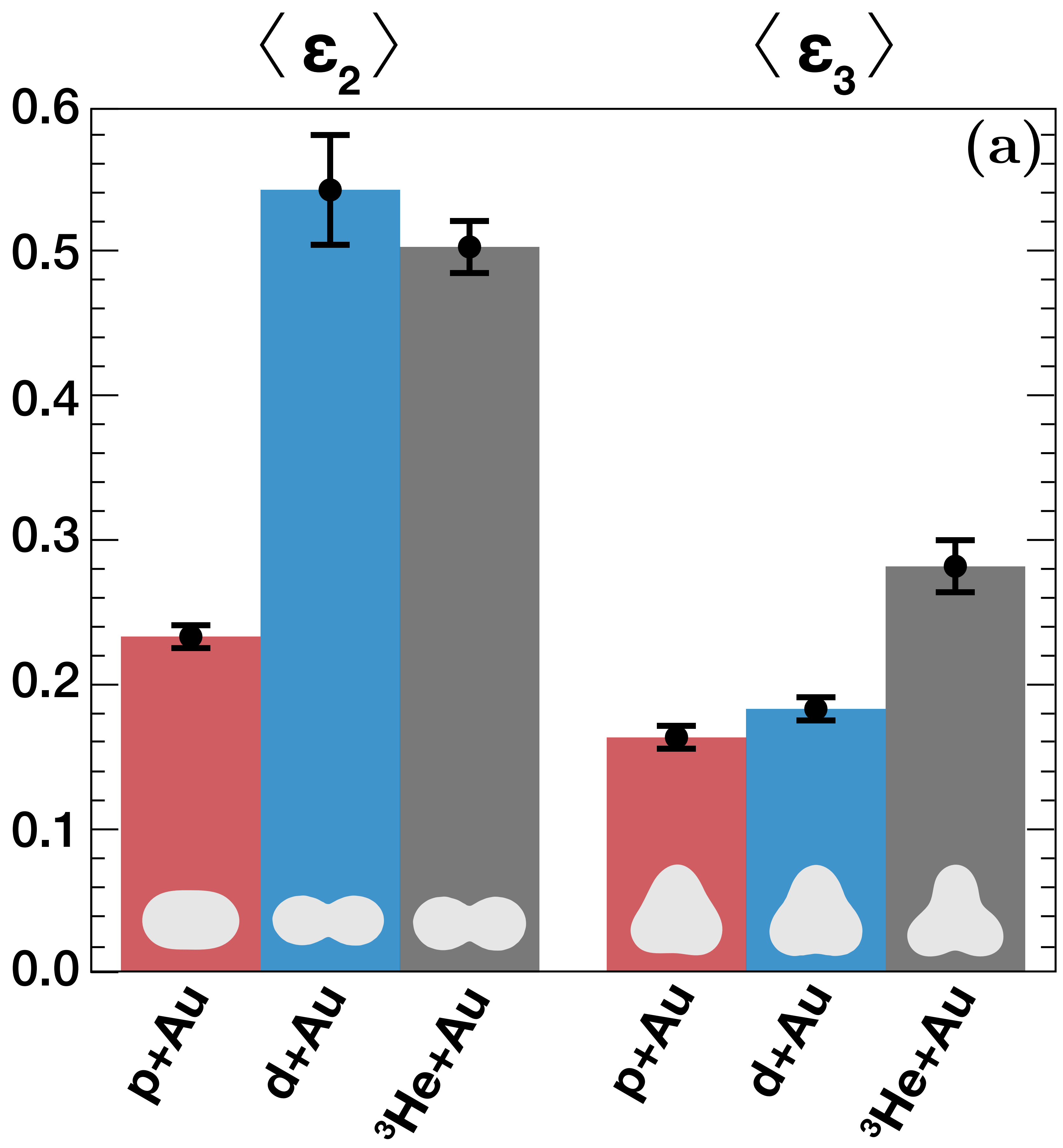
$$\varepsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle + \langle r^n \sin(n\phi)\rangle}}{\langle r^n \rangle} \longrightarrow v_n$$

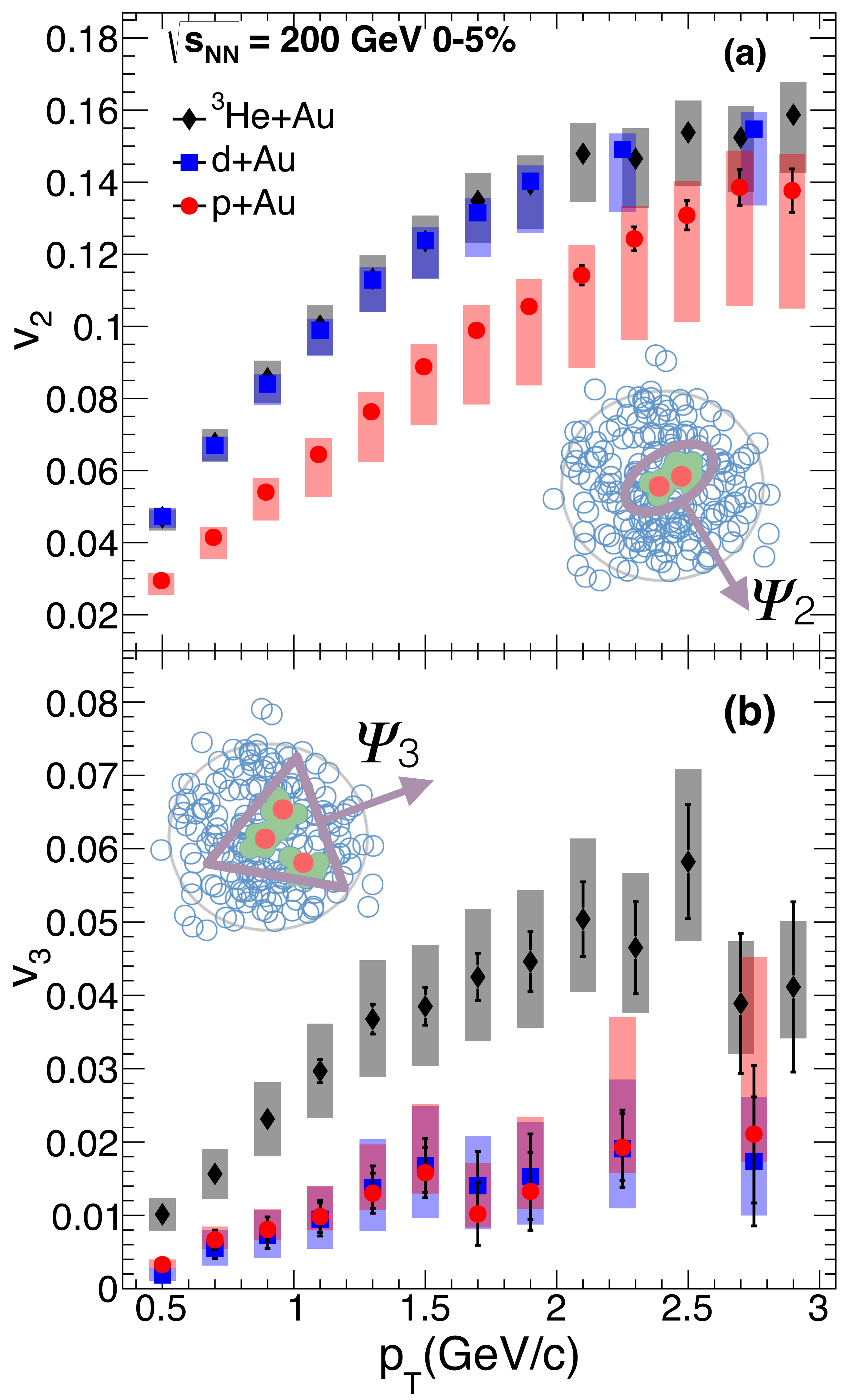
hydrodynamics

Momentum distribution remembers shape of collision

ENGINEERING THE SHAPE

PHENIX, Nature Phys. 15 (2019) 3, 214-220

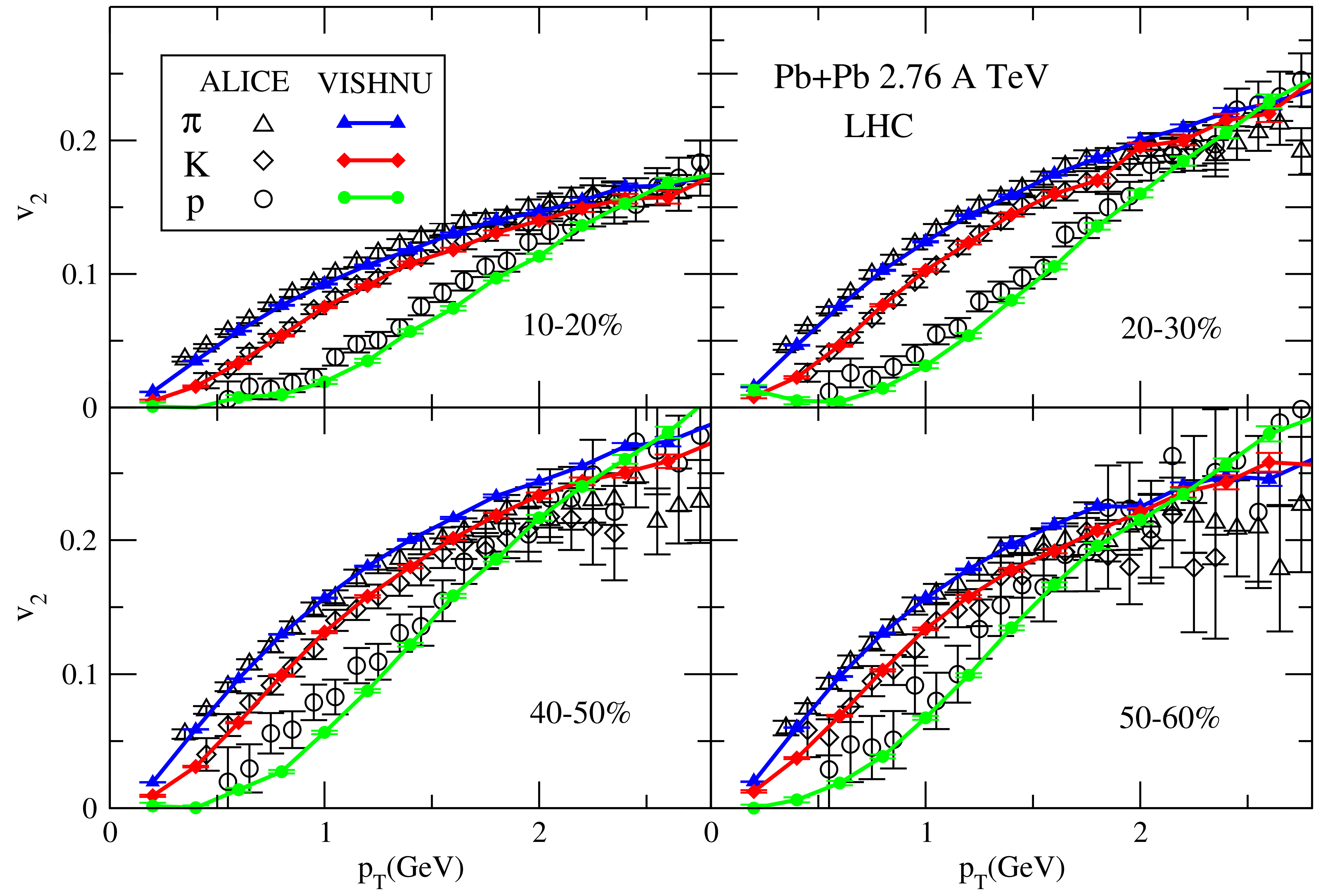




Momentum distribution remembers shape of collision

MASS DEPENDENCE OF FLOW

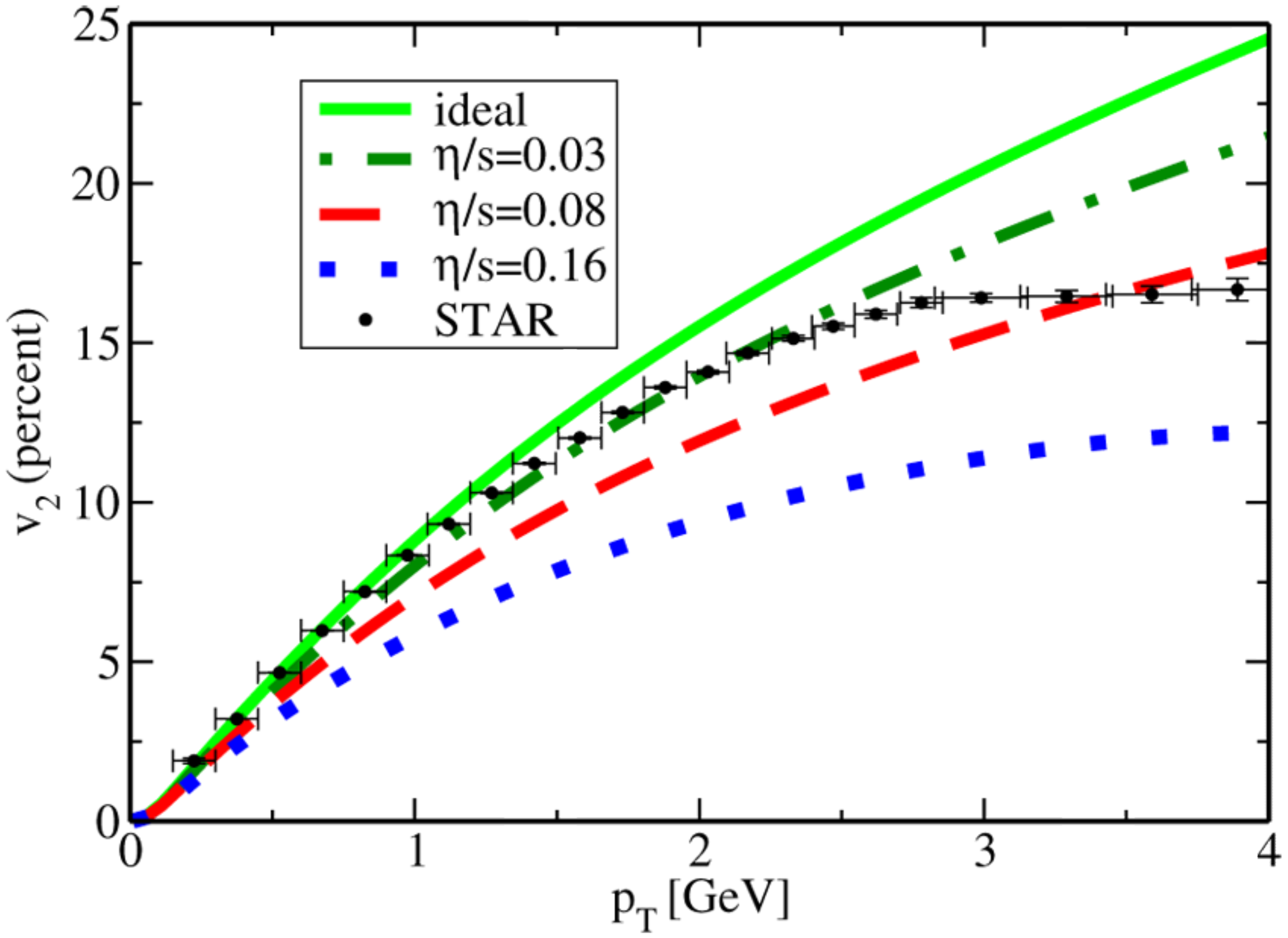
Phys.Rev. C89 (2014), no.3, 034919



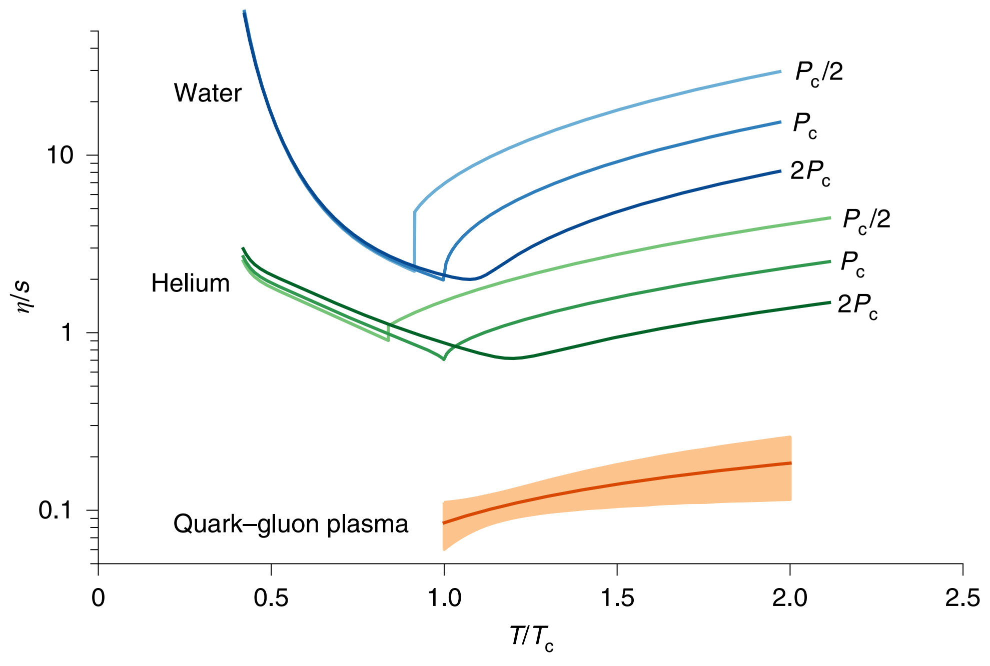
- heavier particles flow less
- hydrodynamics does an excellent jobs
  - mass ordering due to common fluid velocity

FLOW AND FLUID PROPERTIES

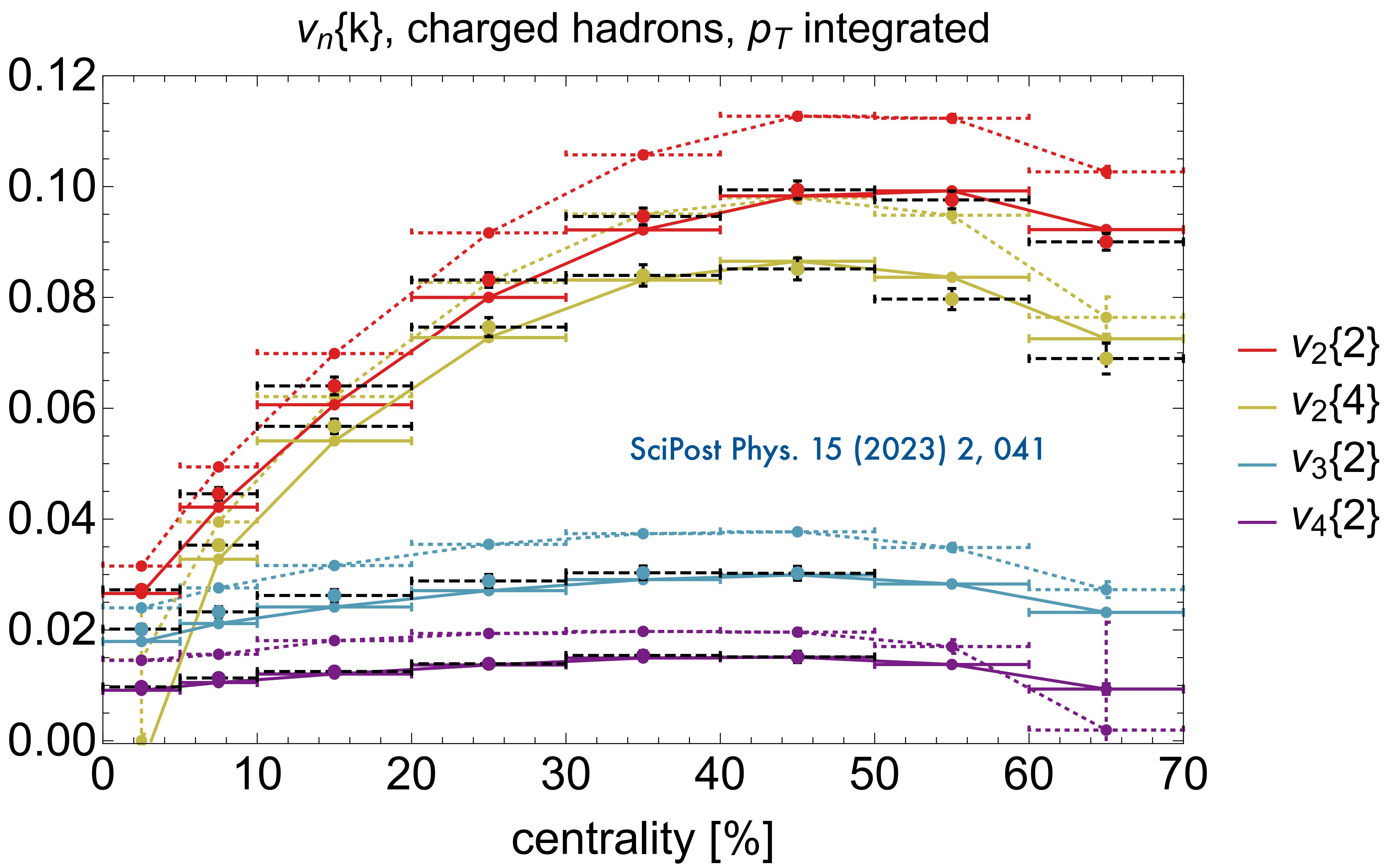
Phys.Rev. Lett. 99 (2007), 172301



- flow sensitive to fluid viscosity
  - [recall slide with global Bayesian extraction from yesterday]
  - ideal fluids flow more – perturbations propagate with no attenuation [note that an ideal gas has ∞ viscosity]
  - QGP is a nearly ideal fluid



HIGHER FLOW HARMONICS

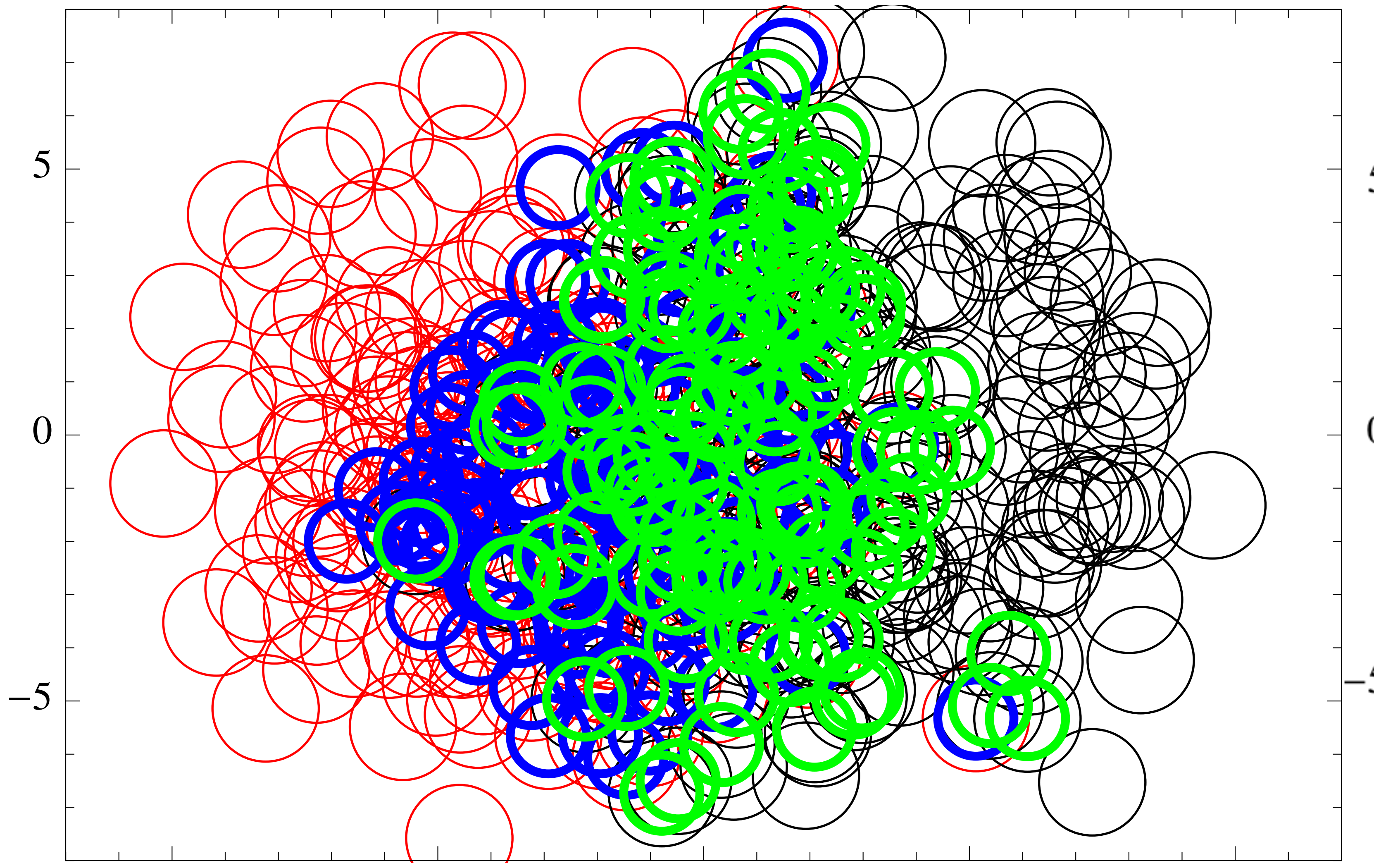


- higher flow harmonics are non-zero
  - flow is anisotropic
- importantly odd harmonics like v_3 are not zero as they should from the $\phi \to \phi + \pi$ symmetry of the definition
  - what is going on ?

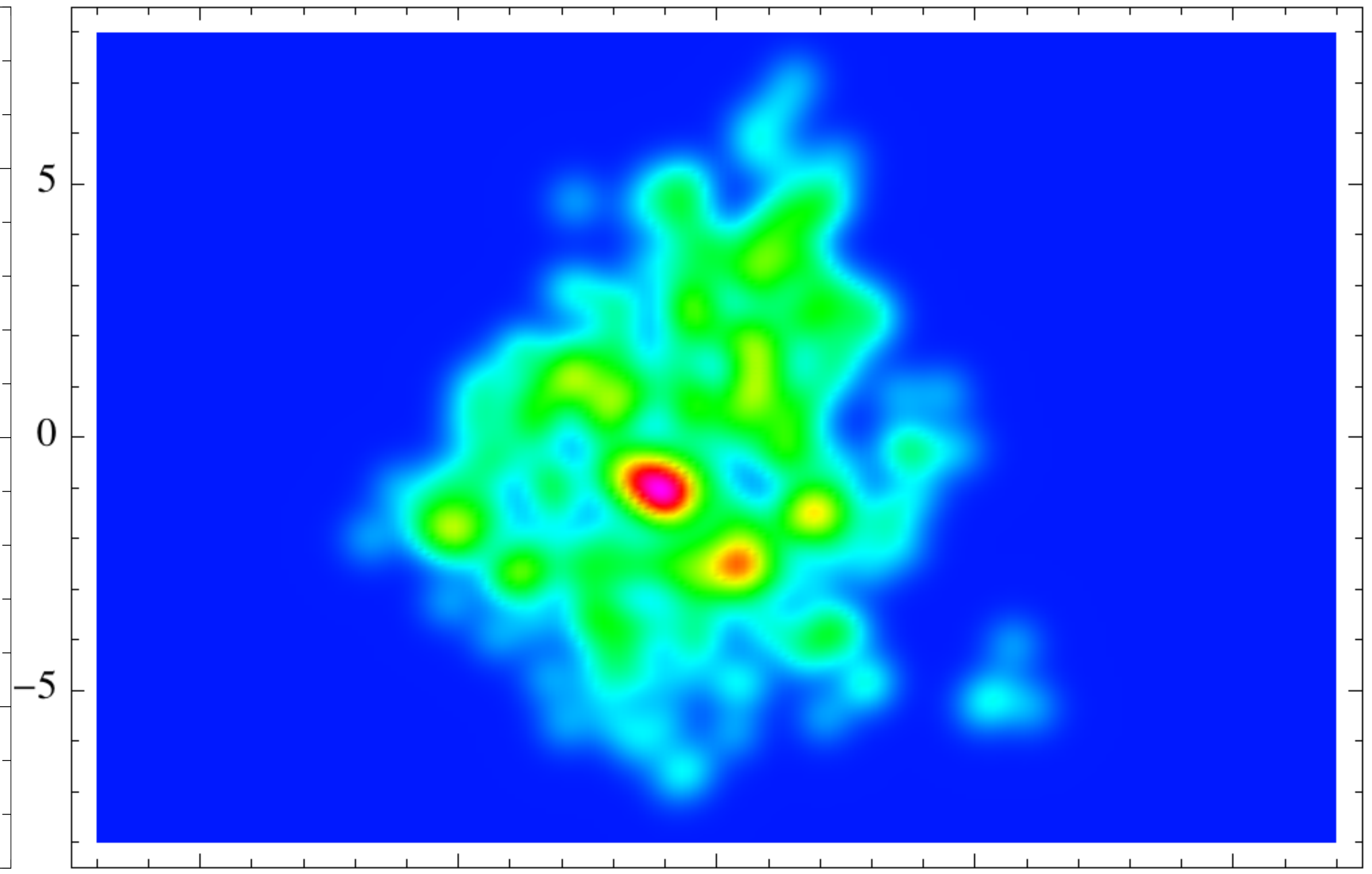
$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + 2\sum_n v_n \cos(n(\phi - \psi))\right]$$

ANISOTROPY FROM EVENT-BY-EVENT FLUCTUATIONS

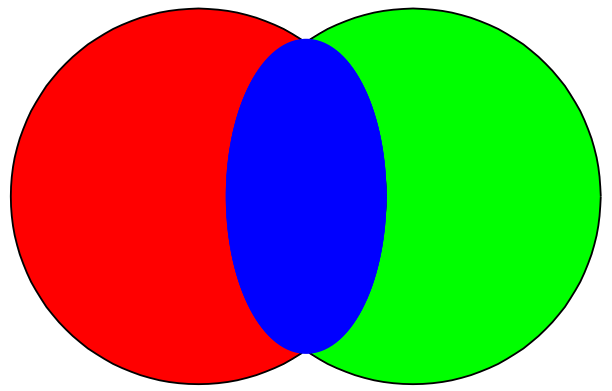
Phys.Rev.C 81 (2010) 054905



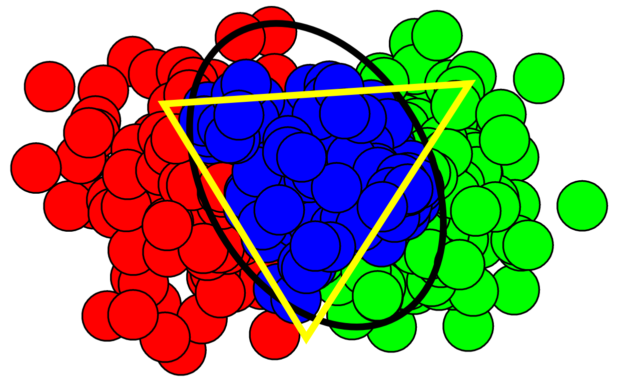
MCGlauber



IP-Glasma



no odd-harmonics

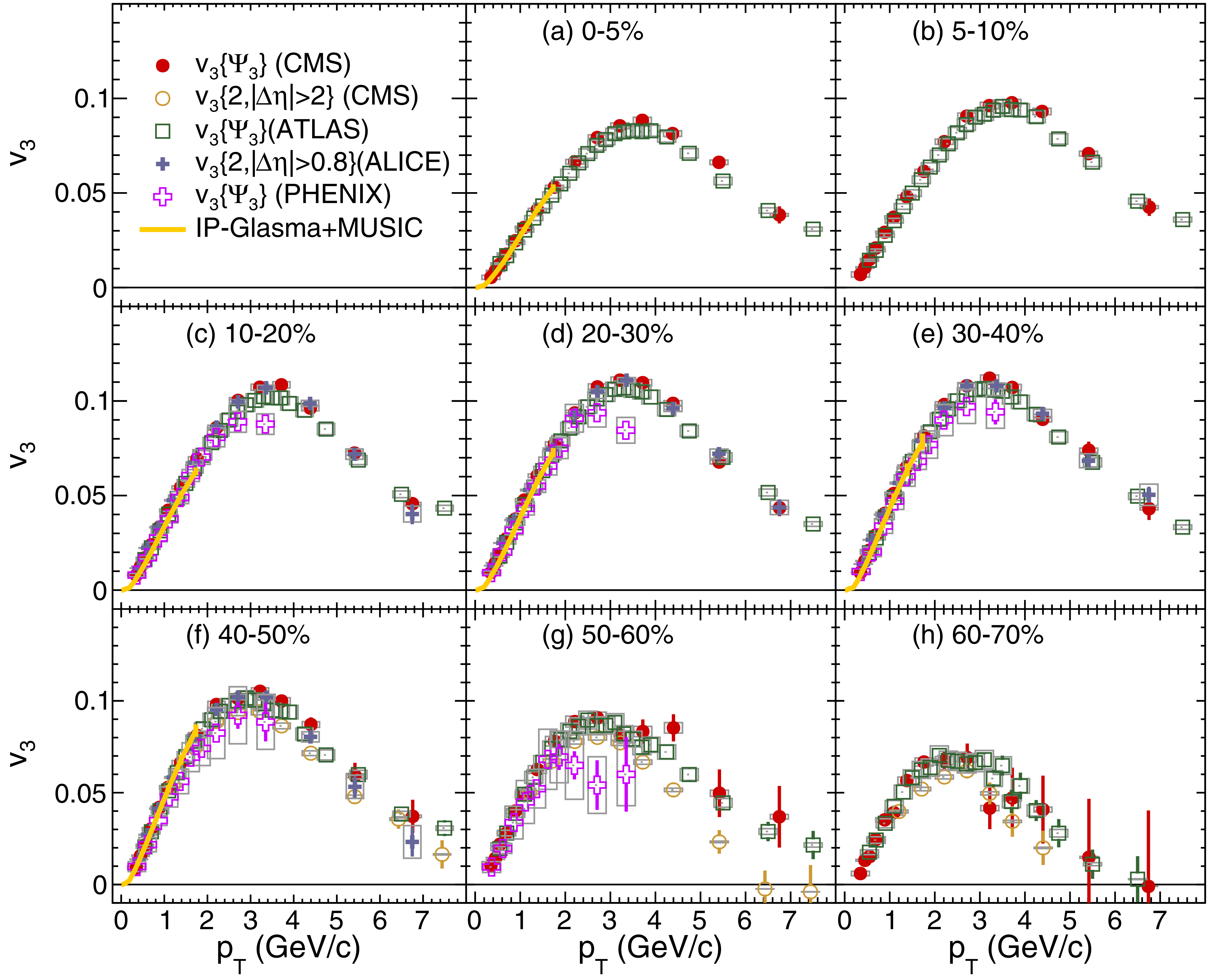


fluctuations generate odd-harmonics

- symmetry argument for vanishing odd harmonics only holds for event-averaged geometry
  - each event has a shape that cannot be described by eccentricity ε_2 alone
  - flow of average geometry is not the same as average of flow of all events

ODD-HARMONICS

CMS, Phys.Rev. C89, 044906 (2014)



- dominance of fluctuations implies centrality independence
    - same holds for also measured higher harmonics

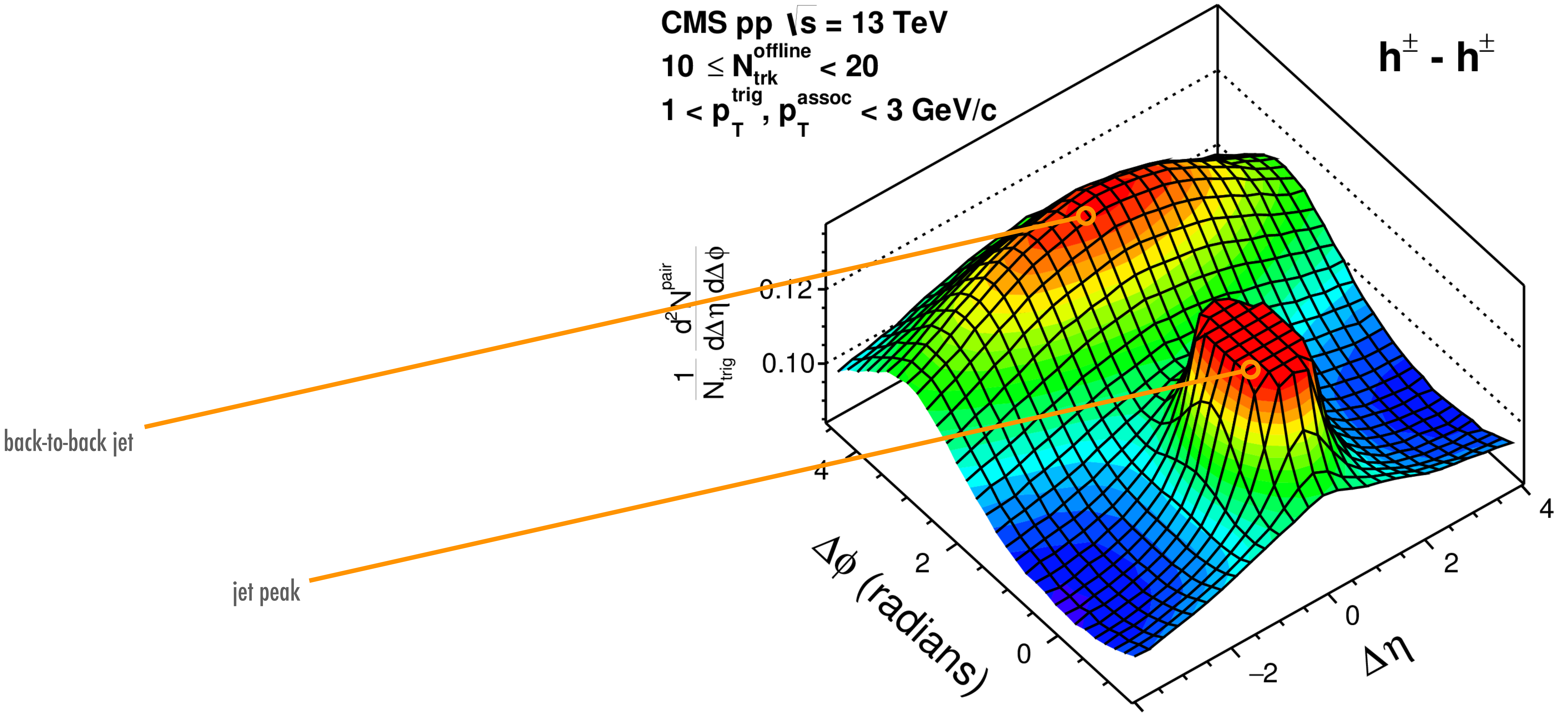
PARTICLE CORRELATIONS

- determination of event plane is not always easy, particularly so when multiplicity is low
  - same flow information [and more] can be obtained from particle-pair correlations

$$C(\phi_1, \phi_2) = \frac{\left\langle \frac{dN}{d\phi_1} \frac{dN}{d\phi_2} \right\rangle_{\text{events}}}{\left\langle \frac{dN}{d\phi_1} \right\rangle_{\text{events}} \left\langle \frac{dN}{d\phi_2} \right\rangle_{\text{events}}} = 1 + 2 \sum_n v_n^2 \cos(n(\phi_1 - \phi_2))$$

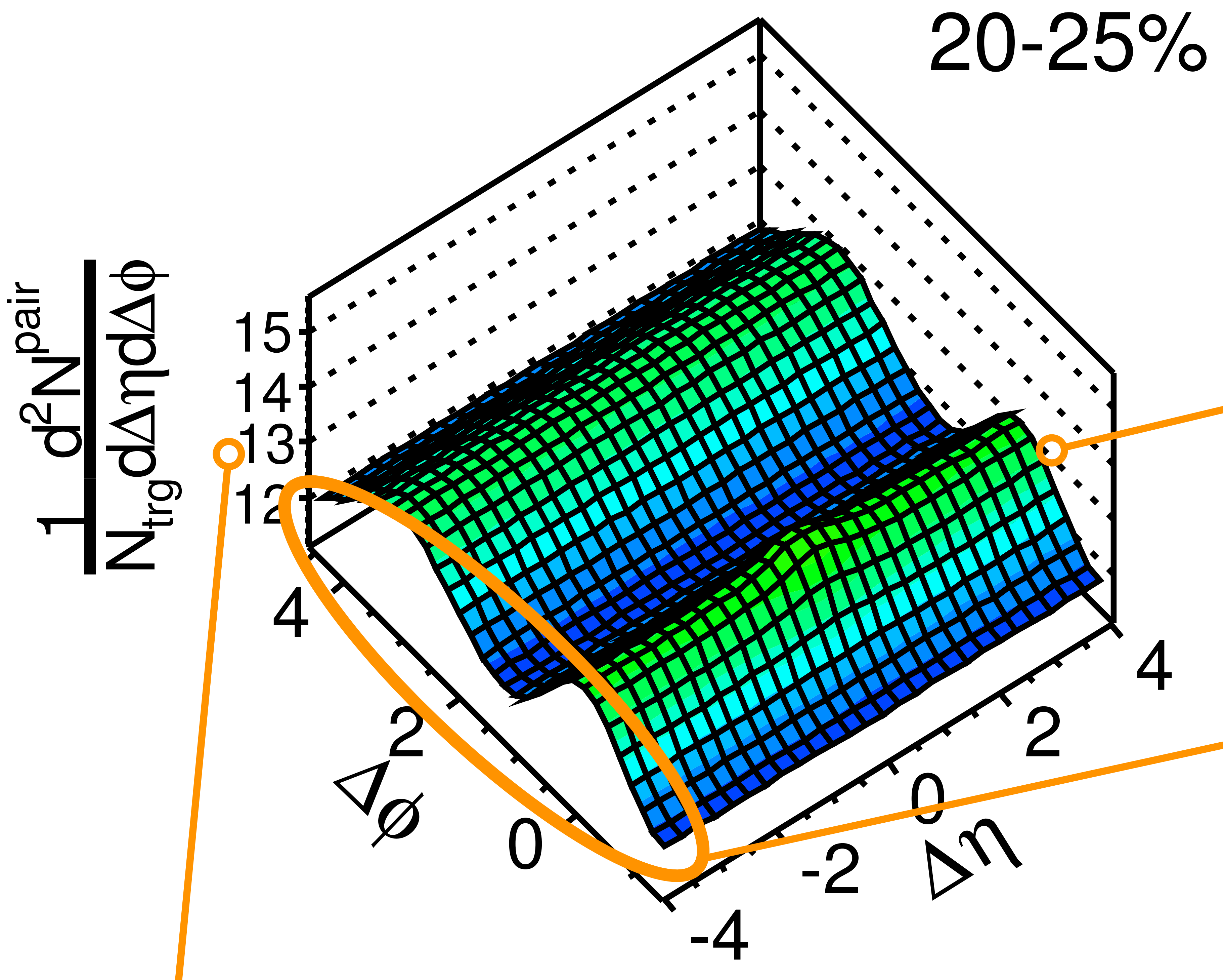
PARTICLE CORRELATIONS PROTON–PROTON

$$C(\phi_1,\phi_2) = \frac{\left\langle \frac{dN}{d\phi_1}\frac{dN}{d\phi_2}\right\rangle_{\text{events}}}{\left\langle \frac{dN}{d\phi_1}\right\rangle_{\text{events}} \left\langle \frac{dN}{d\phi_2}\right\rangle_{\text{events}}} = 1 + 2\sum_n v_n^2 \cos(n(\phi_1-\phi_2))$$



PARTICLE CORRELATIONS IN AA

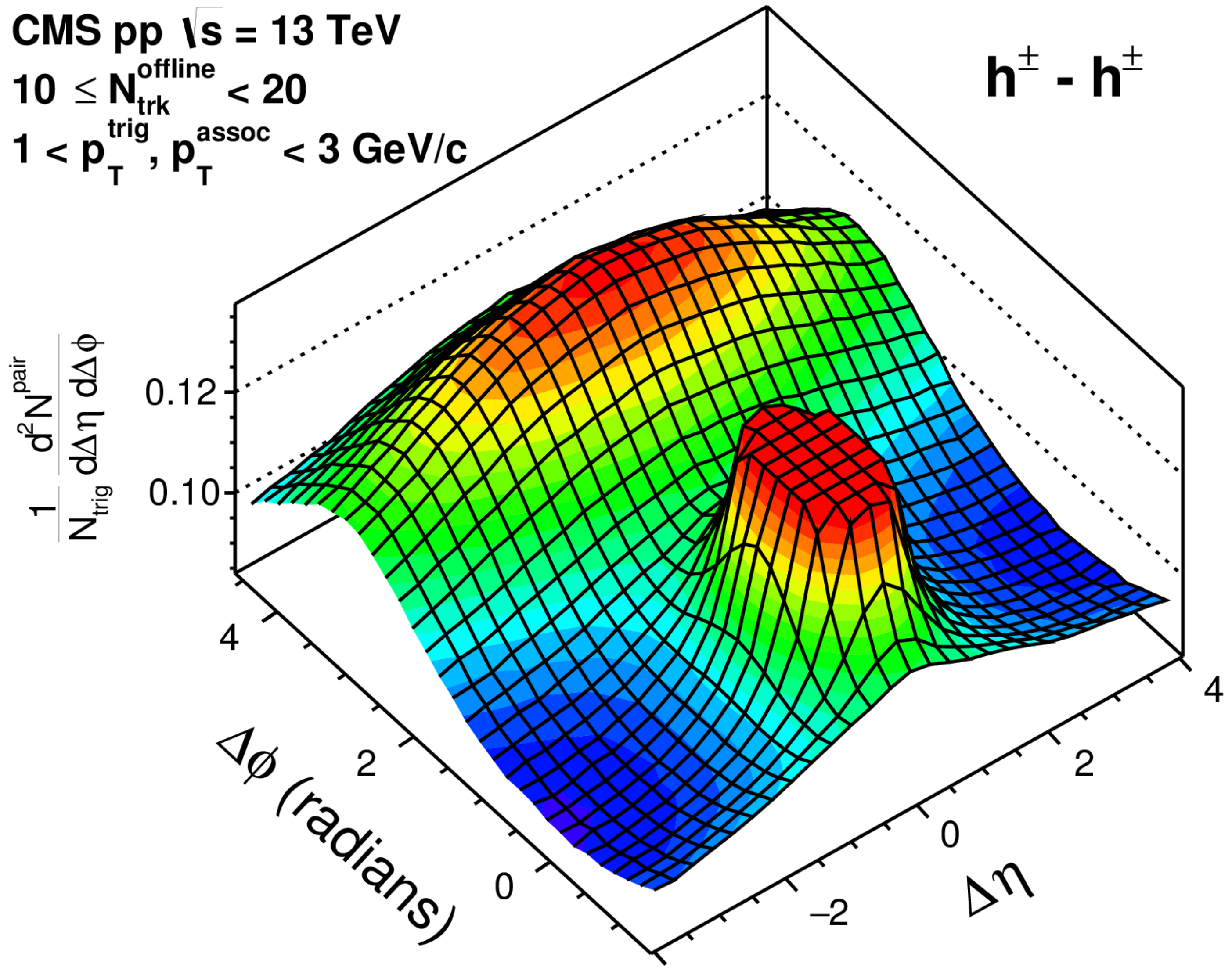
$$C(\phi_1,\phi_2) = \frac{\left\langle \frac{dN}{d\phi_1}\frac{dN}{d\phi_2}\right\rangle_{\text{events}}}{\left\langle \frac{dN}{d\phi_1}\right\rangle_{\text{events}}\left\langle \frac{dN}{d\phi_2}\right\rangle_{\text{events}}} = 1 + 2\sum_n v_n^2 \cos(n(\phi_1-\phi_2))$$



ridge: long range rapidity correlation [boost invariance]

azimuthal structure from flow

note the magnitude



IS THIS PICTURE, PICTURE PERFECT ?

- there is a slight complication …

IS THIS PICTURE, PICTURE PERFECT ?

Phys. Lett. B 774 (2017) 351-356

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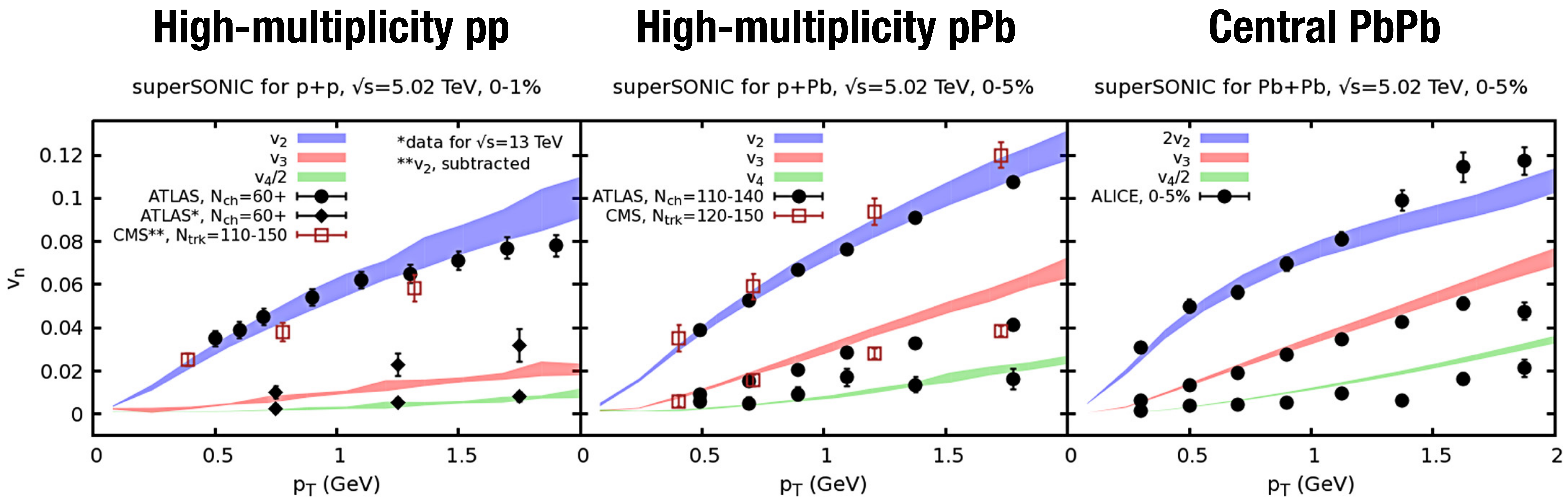
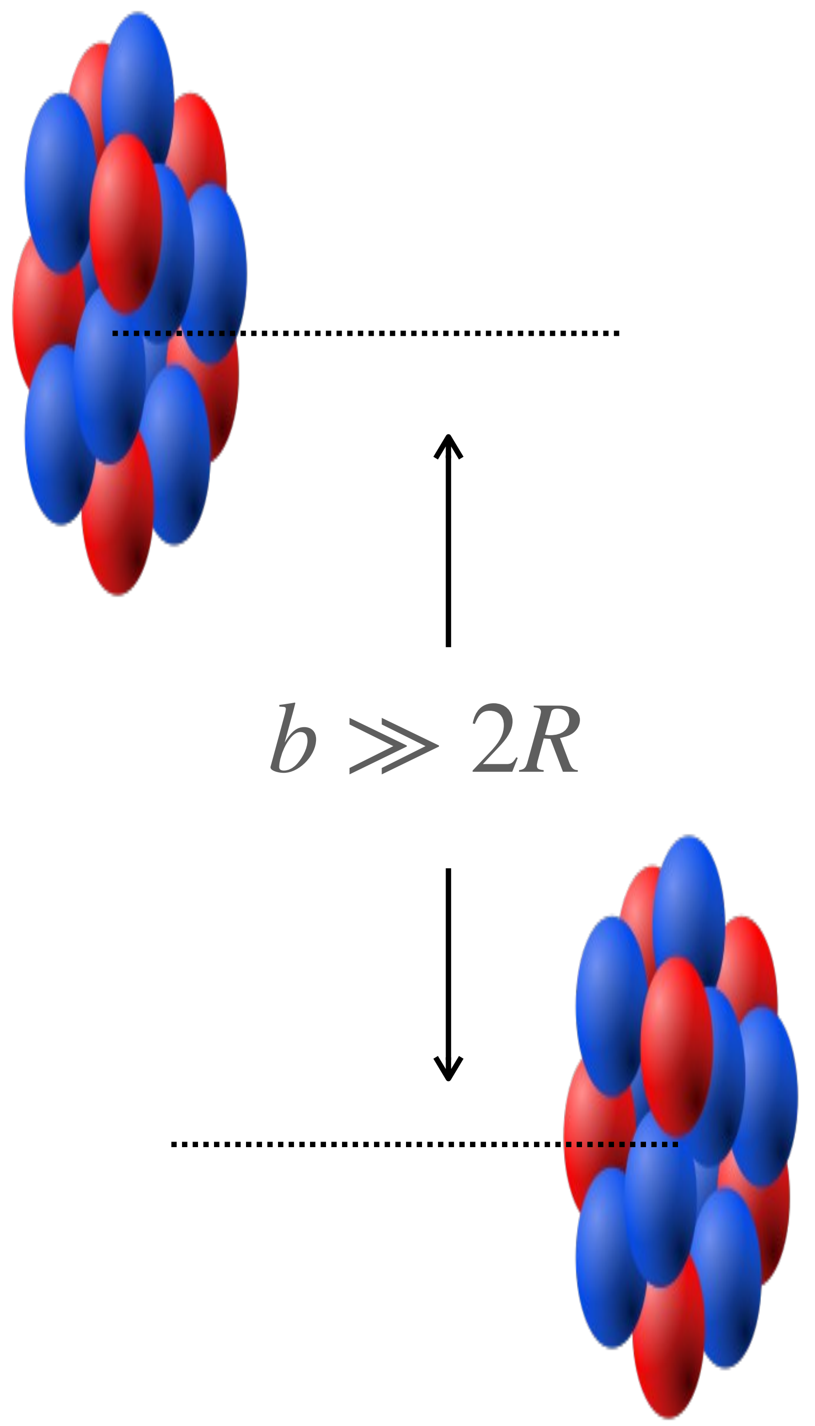


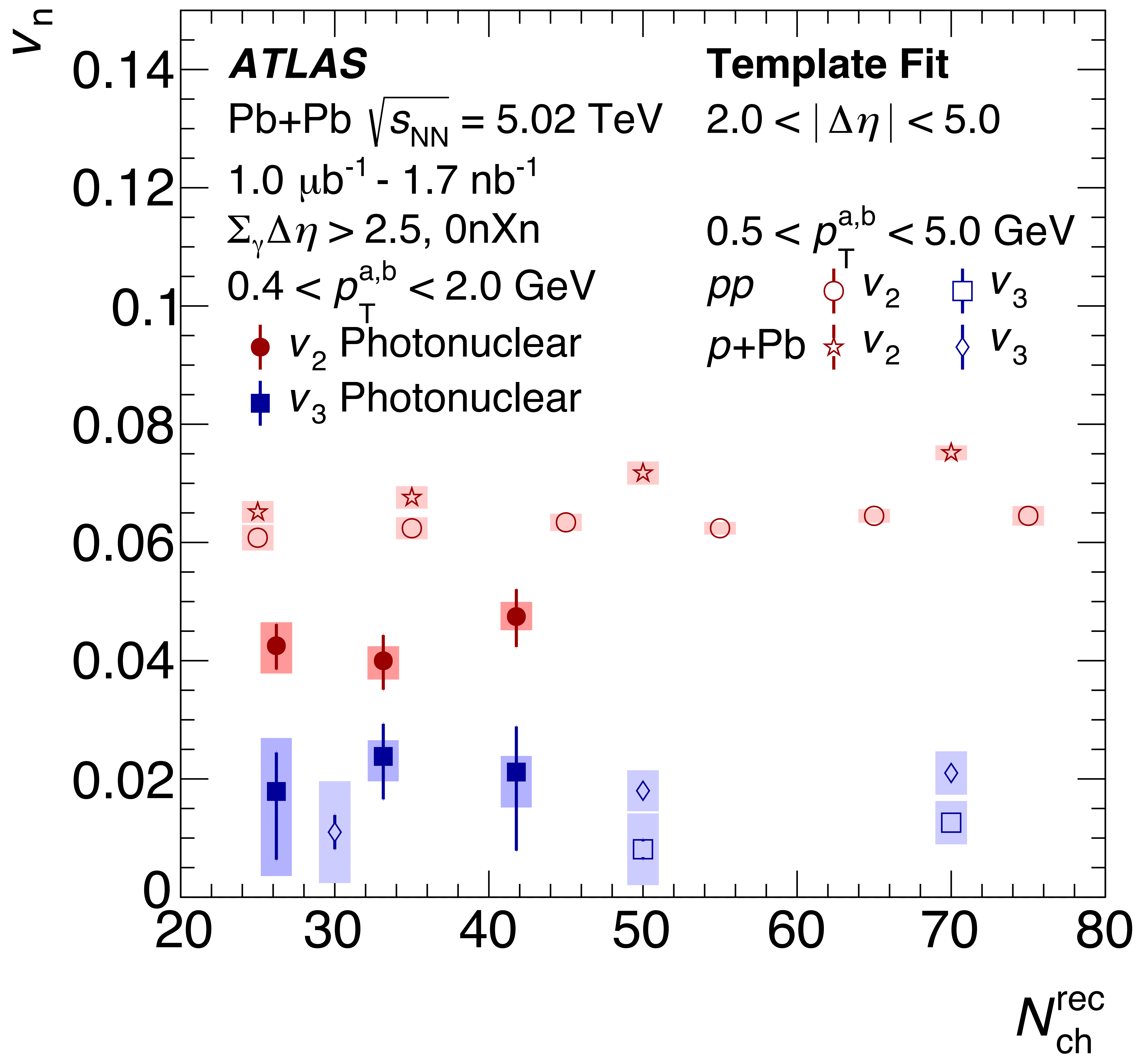
small systems also flow !

IS THIS PICTURE, PICTURE PERFECT ?

ATLAS, Phys.Rev.C 104 (2021) 1, 014903

- and a slightly bigger complication …



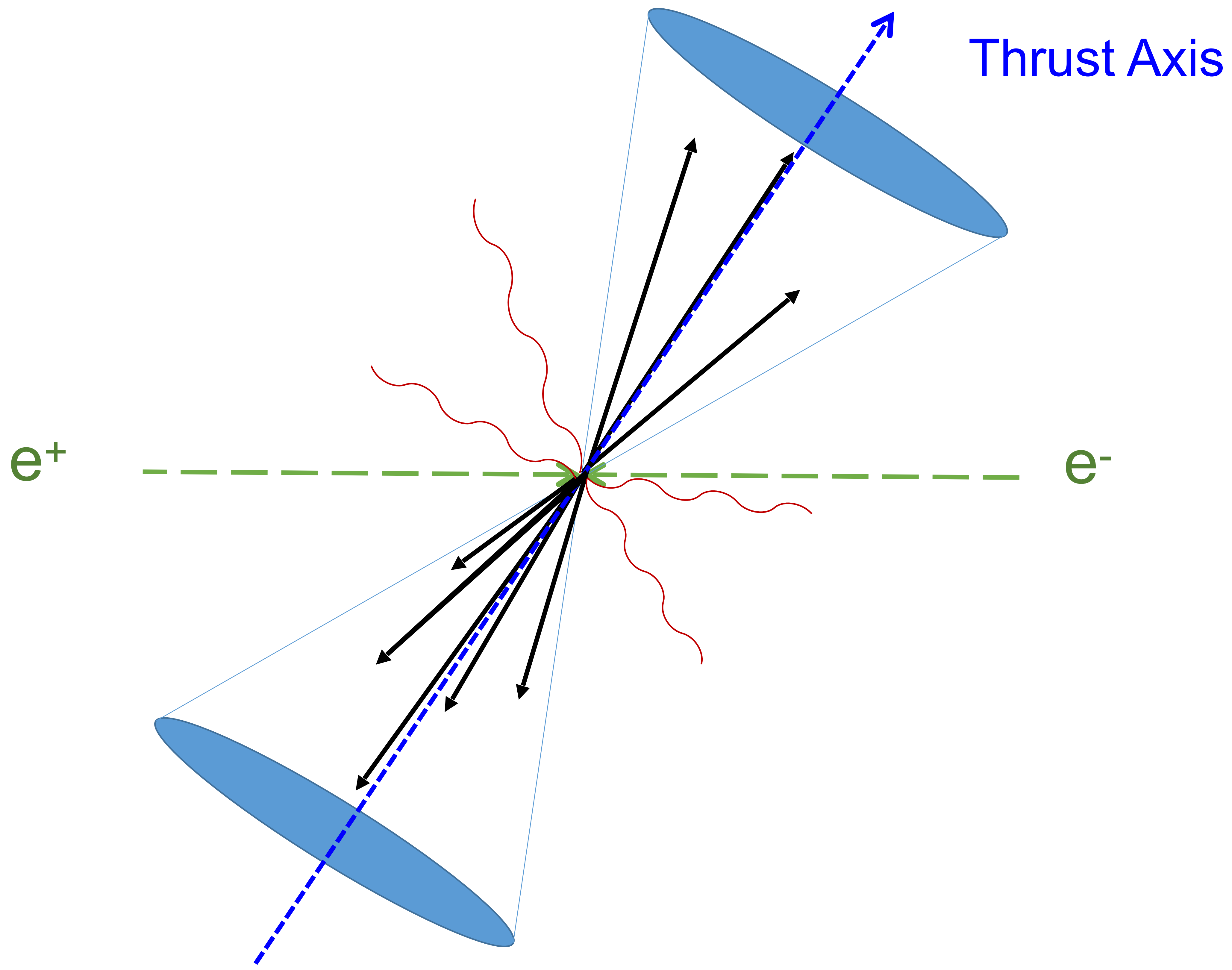


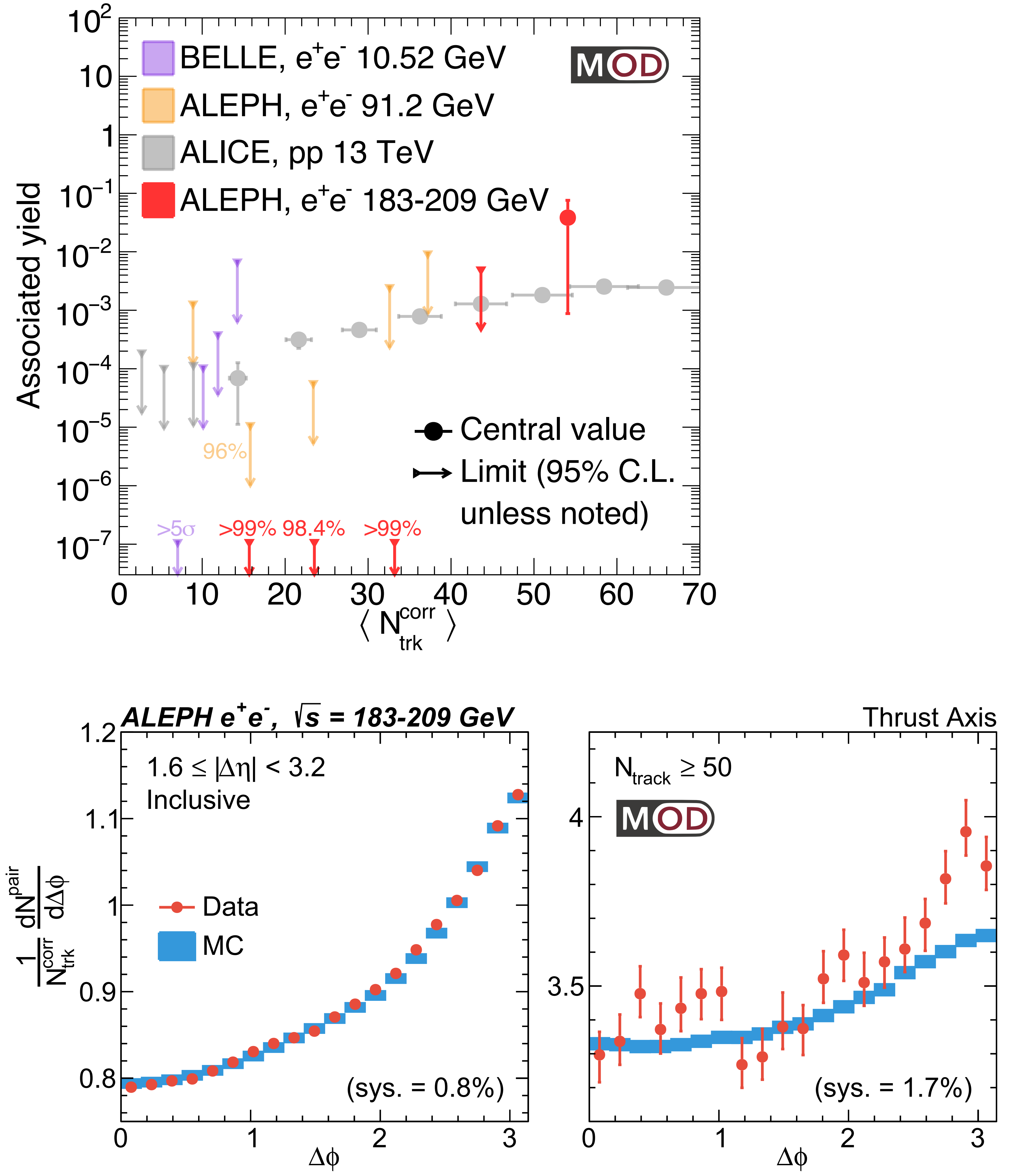
flow also in γPb collisions [ultra-peripheral HIC]

IS THIS PICTURE, PICTURE PERFECT ?

Phys.Lett.B 856 (2024) 138957

- and oddly ...

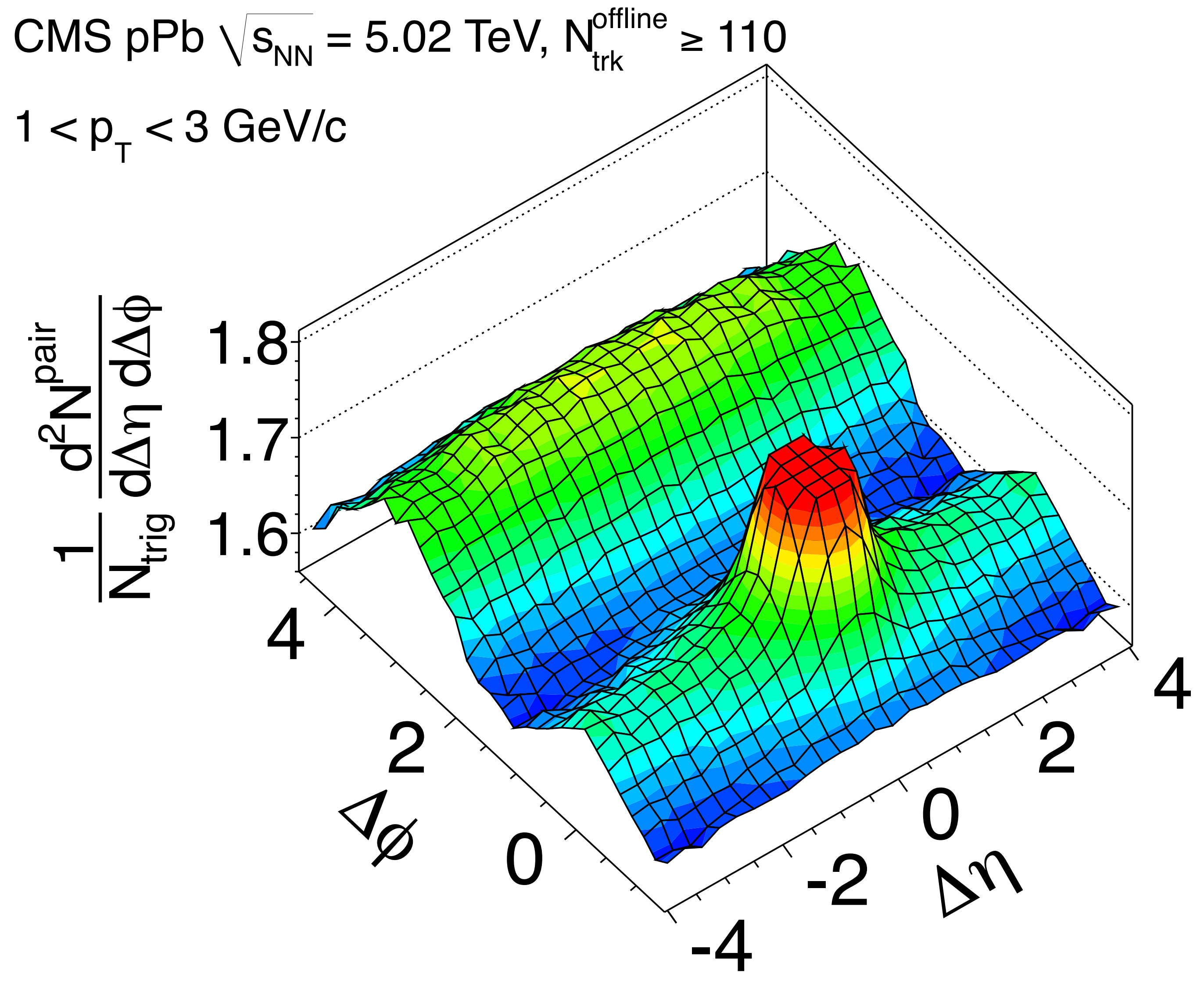


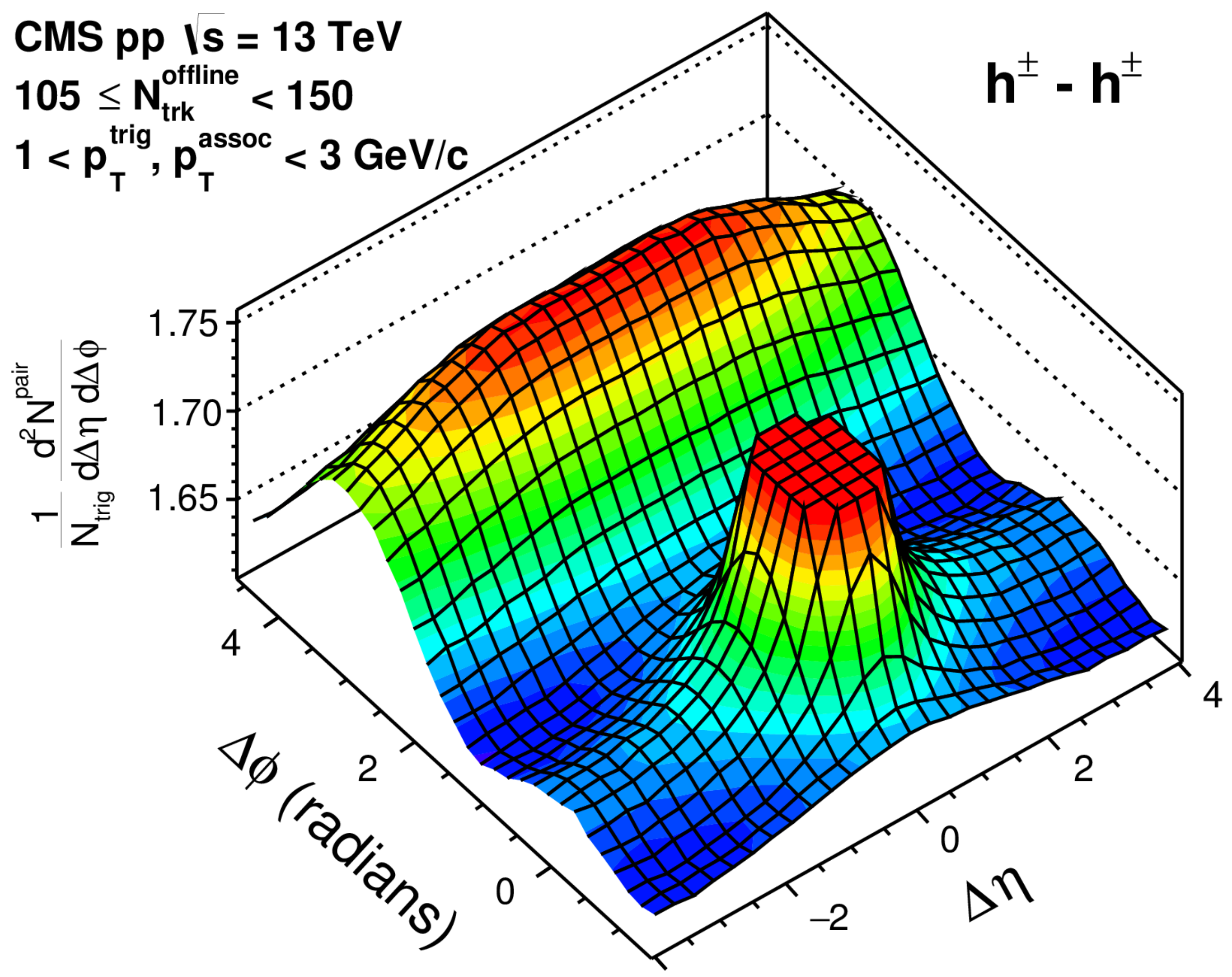


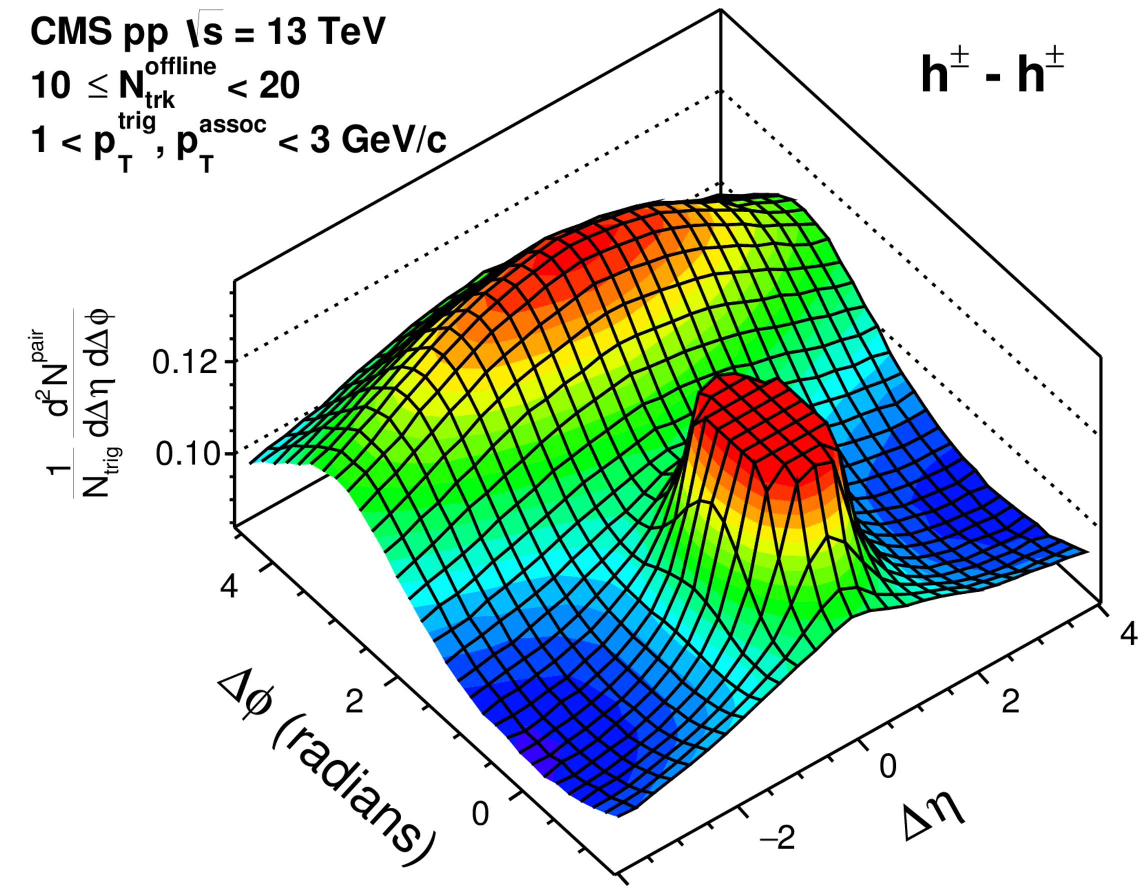
flow in e^+e^- collisions [high multiplicity]

IS THIS PICTURE, PICTURE PERFECT ?

- unsurprisingly similar message from particle correlations







AN ATTEMPT AT AN EXPLANATION WITH MANY OPEN QUESTIONS

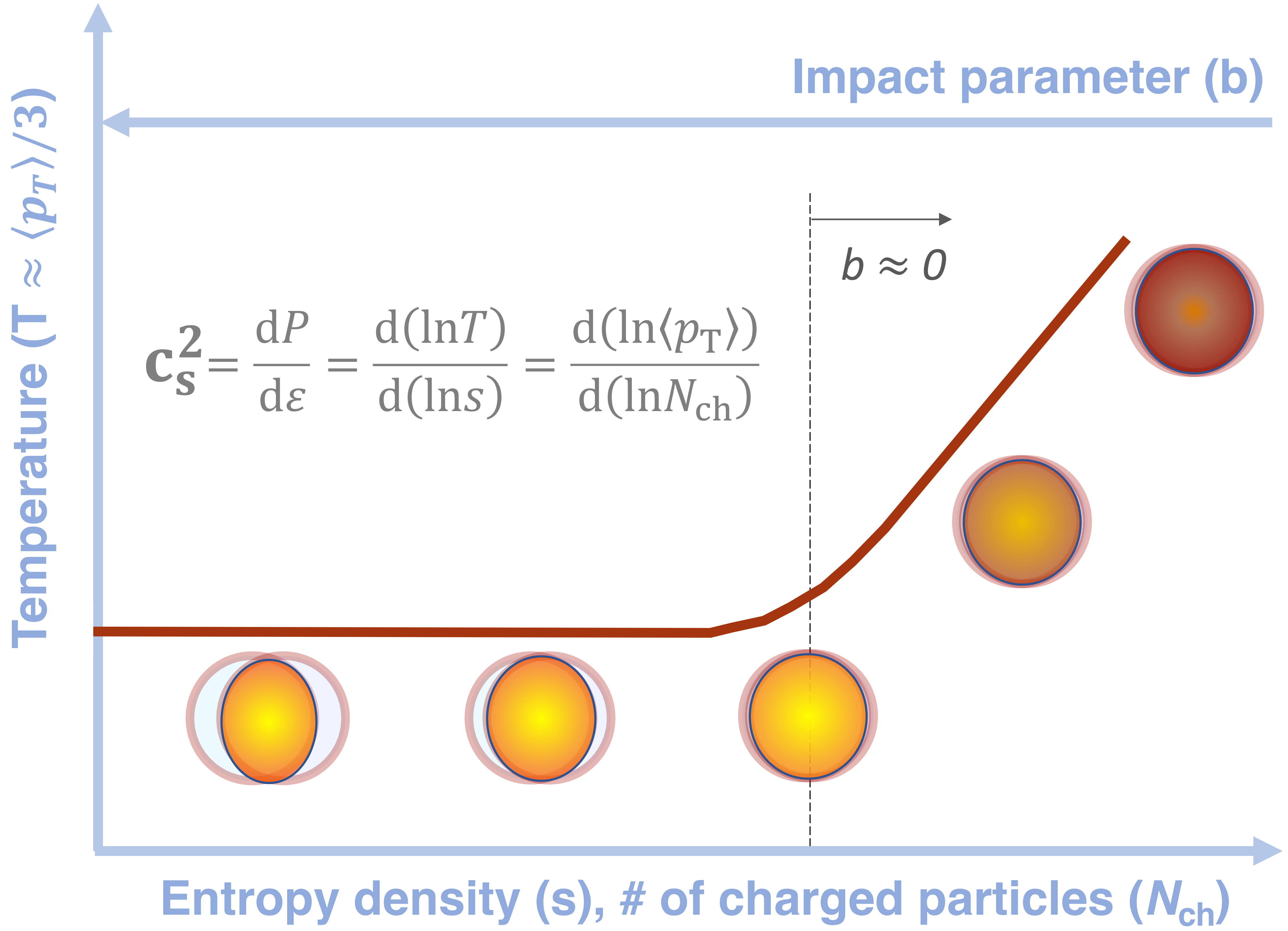
- in high-multiplicity pA and pp, correlations can be partly explained either as being remnants of correlations in the initial state [CGC-Glasma] or by dynamics [recombination and shoving] of Lund strings prior to hadronization. Nicely, these effects cannot explain the magnitude of correlations in AA
- or, by QGP being created in this systems and then explanation is analogous to AA
  - hydrodynamics is a gradient expansion. In pp the gradients are huge and thus hydro should not be applicable. That hydro appears to work well in high-multiplicity pp is [at least for me] very puzzling
  - search for other evidence of QGP in these systems
  - explore smaller [then PbPb] nuclear systems to determine how small a droplet of QGP can be [OO@LHC during Run 3]
- initial state correlations could possibly explain γA case [?????]
- all this obviously implausible in e^+e^-. origin of correlations has to be something else [?????]

THE SPEED OF SOUND IN QGP

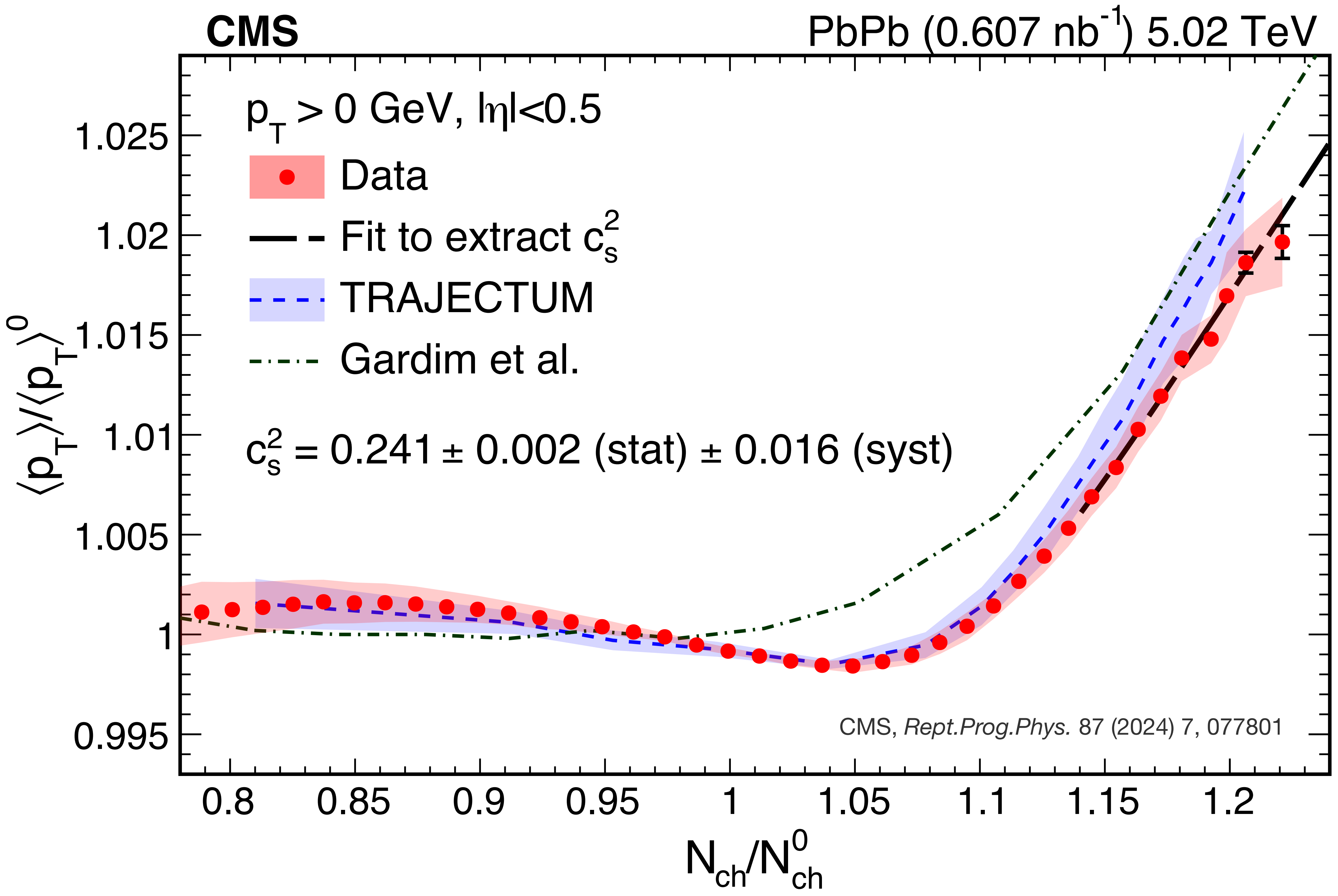
Phys.Lett.B 809 (2020) 1357497

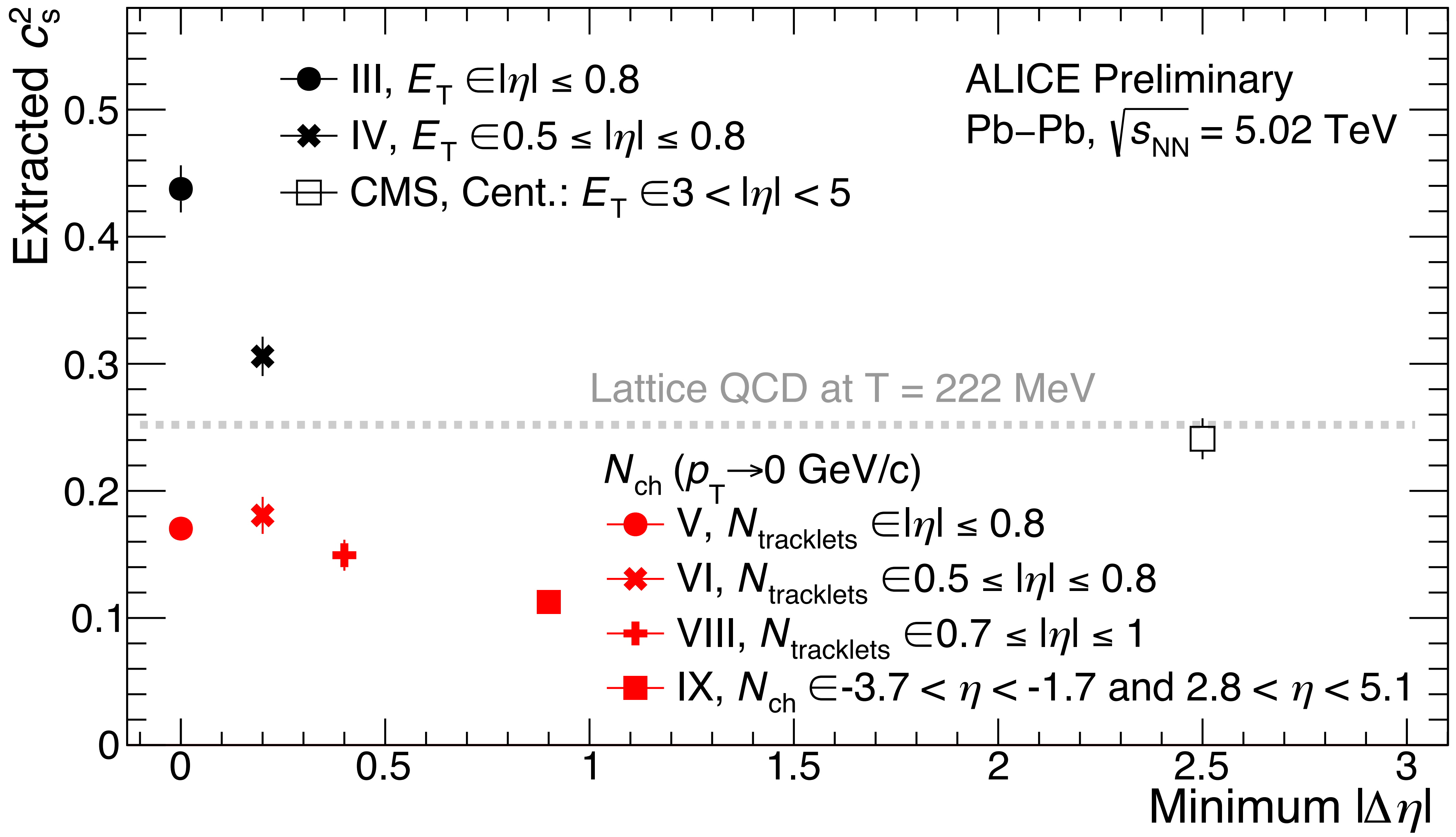
- the geometry of ultra-central collisions is essentially fixed [$b \simeq 0$] but multiplicity can vary by 10-15%
  - variation is due to quantum fluctuations and $\langle p_T \rangle$ increases as multiplicity increases if QGP is fluid
- the speed of sound is given by

$$c_s^2(T_{\text{eff}}) = \frac{d \ln \langle p_T \rangle}{d \ln N_{\text{ch}}}$$



THE SPEED OF SOUND IN QGP





extracted value in agreement with lattice QCD calculation, but precise value very dependent on definition of centrality class

TOWARDS MORE DETAILED PROBING OF QGP

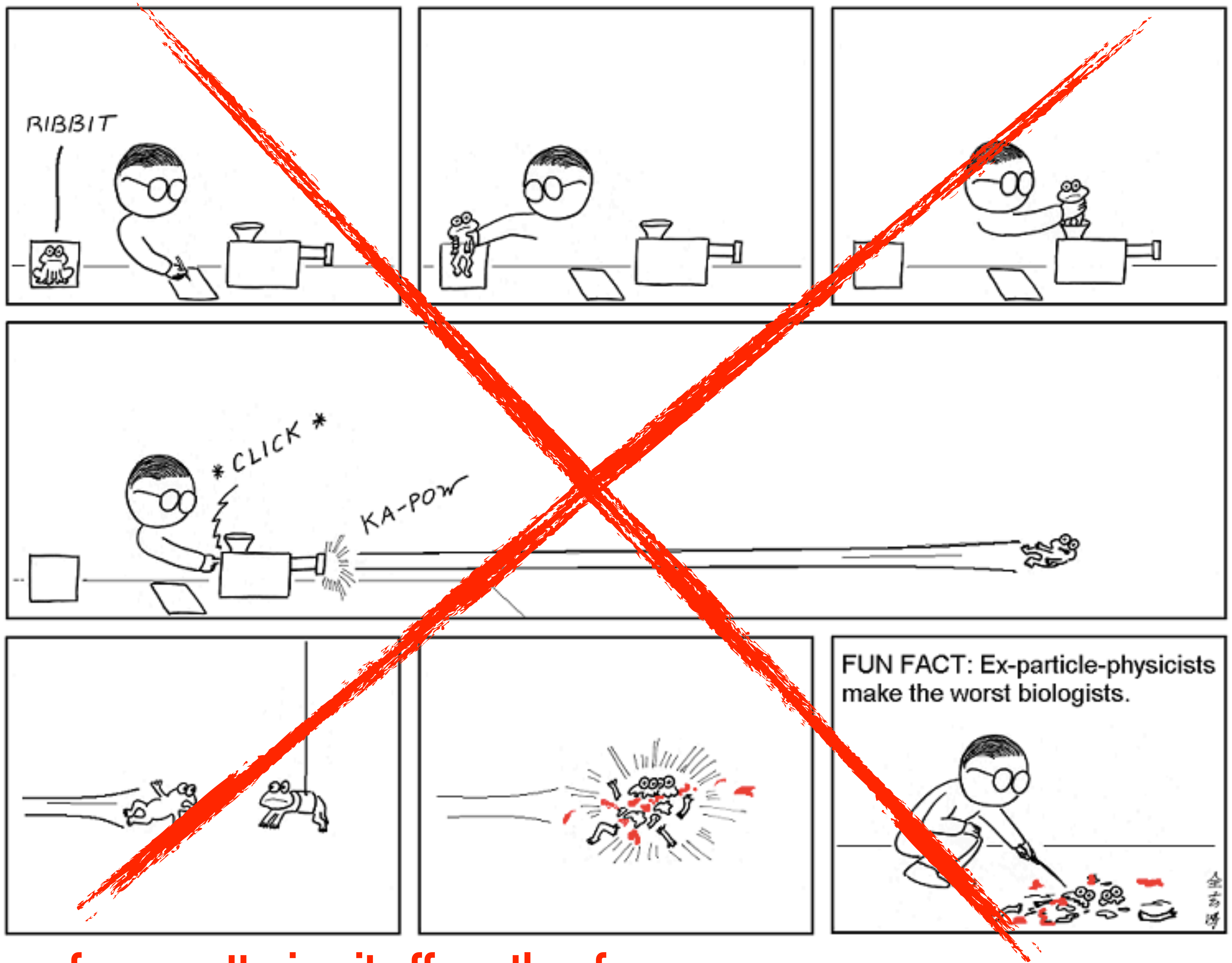
- all observables discussed so far are related to global [bulk] QGP properties
  - need further **probes** sensitive to diverse space, momentum and time scales of QGP

HOW TO PROBE ANYTHING

so far we haven’t invoked the best way of probing anything

HOW TO PROBE ANYTHING

scatter something off it

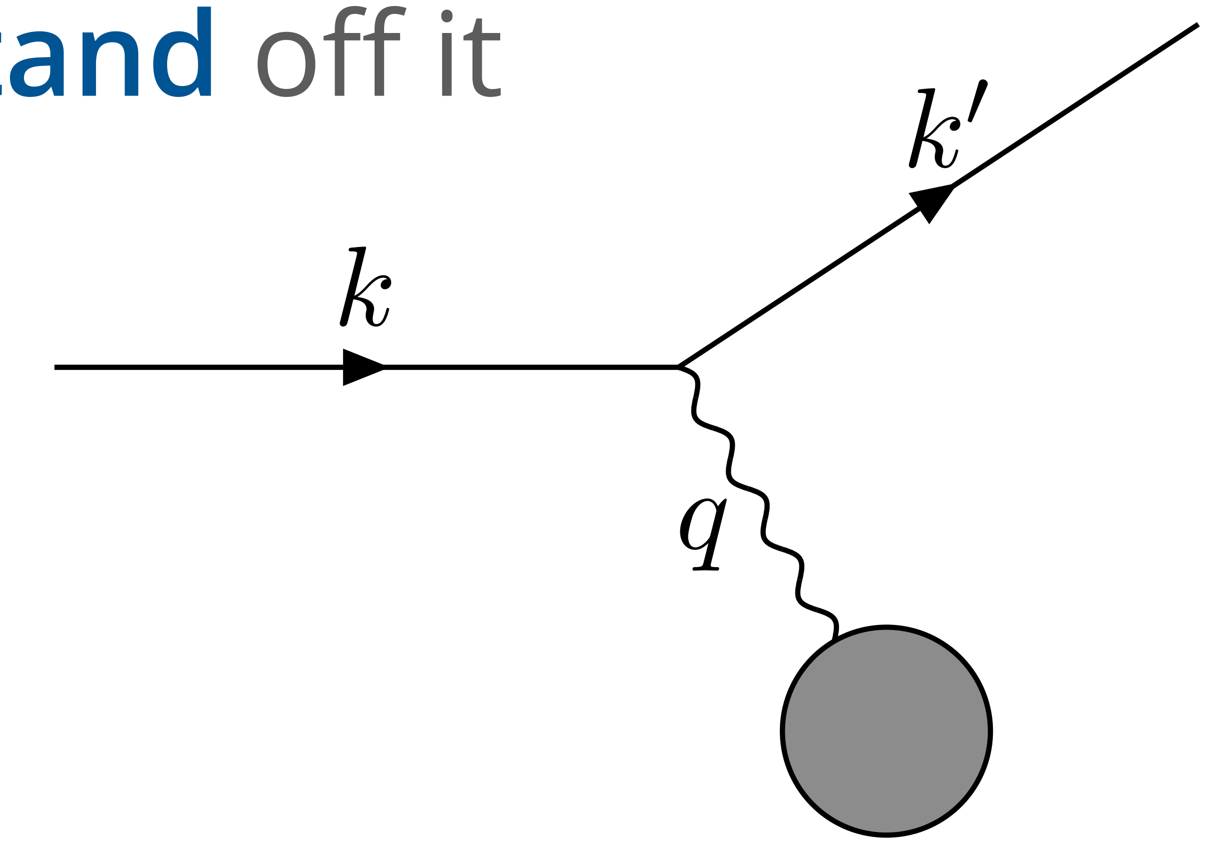


Abstruse Goose

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 $Q^2 = -(\mathbf{k}' - \mathbf{k})^2$ to probe distances $\lambda = 1/Q$

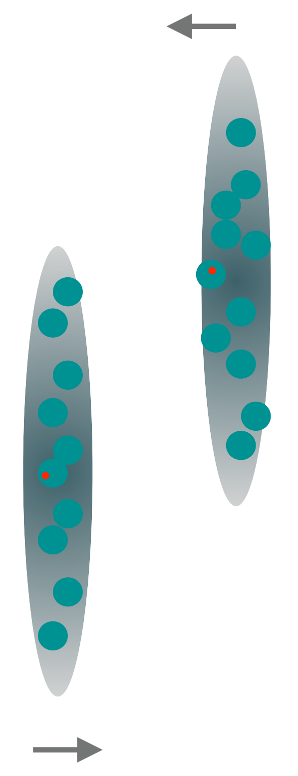
QGP too **short-lived** ($\sim 30\,\mathrm{ys}$) for **external probes** to be of **any use**

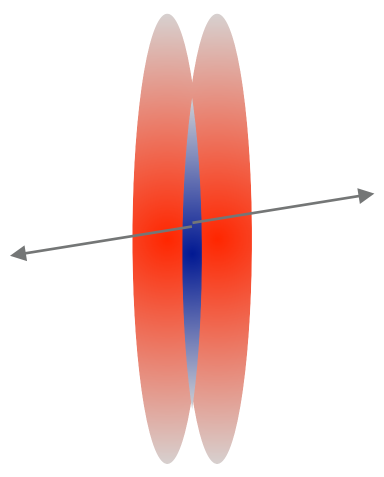
- to mimic DIS paradigm need **multi-scale probes produced concurrently with QGP**

TIMELINE OF A HEAVY ION COLLISION

~ 0.1 fm/c
[~10^{-25} s]

time





collision [out-of-equilibrium process]

- many soft [small momentum exchange] collisions
  - responsible for bulk low-momentum particle production
  - will quickly hydrodynamize
- **very few hard [large momentum exchange] collisions**
  - **off-spring will slowly relax toward hydrodynamization, yet remain out-of-equilibrium while traversing hot soup**

jets

jet definition [in elementary collisions]

*:: a jet is **defined** by a set of rules and parameters [a jet algorithm] specifying how to combine constituents and when to stop ::*

jet definition [in elementary collisions]

for an extensive discussion see G. Salam 0906.1832 [hep-ph]

*:: a jet is **defined** by a set of rules and parameters [a jet algorithm] specifying which particles are to be grouped together and when to stop, and how to combine properties of constituents into jet properties [a recombination scheme] ::*

e.g., generalized k_T family of sequential recombination jet algorithms

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p})\frac{\Delta R_{ij}^2}{R^2}\,, \qquad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2\,,$$

$$d_{iB} = p_{ti}^{2p}\,,$$

1. compute all distances d_{ij} and d_{iB}
2. find the minimum of the d_{ij} and d_{iB}
3. if it is a d_{ij}, recombine i and j into a single new particle and return to 1
4. otherwise, if it is a d_{iB}, declare i to be a jet, and remove it from the list of particles. return to 1
5. stop when no particles left

p = 1 :: k_T algorithm :: ordered in transverse momentum

p = 0 :: Cambridge/Aachen algorithm :: ordered in angle

p = -1 :: anti-k_T algorithm :: anti-ordered in transverse momentum

p = 1/2 :: τ algorithm :: ordered in inverse time

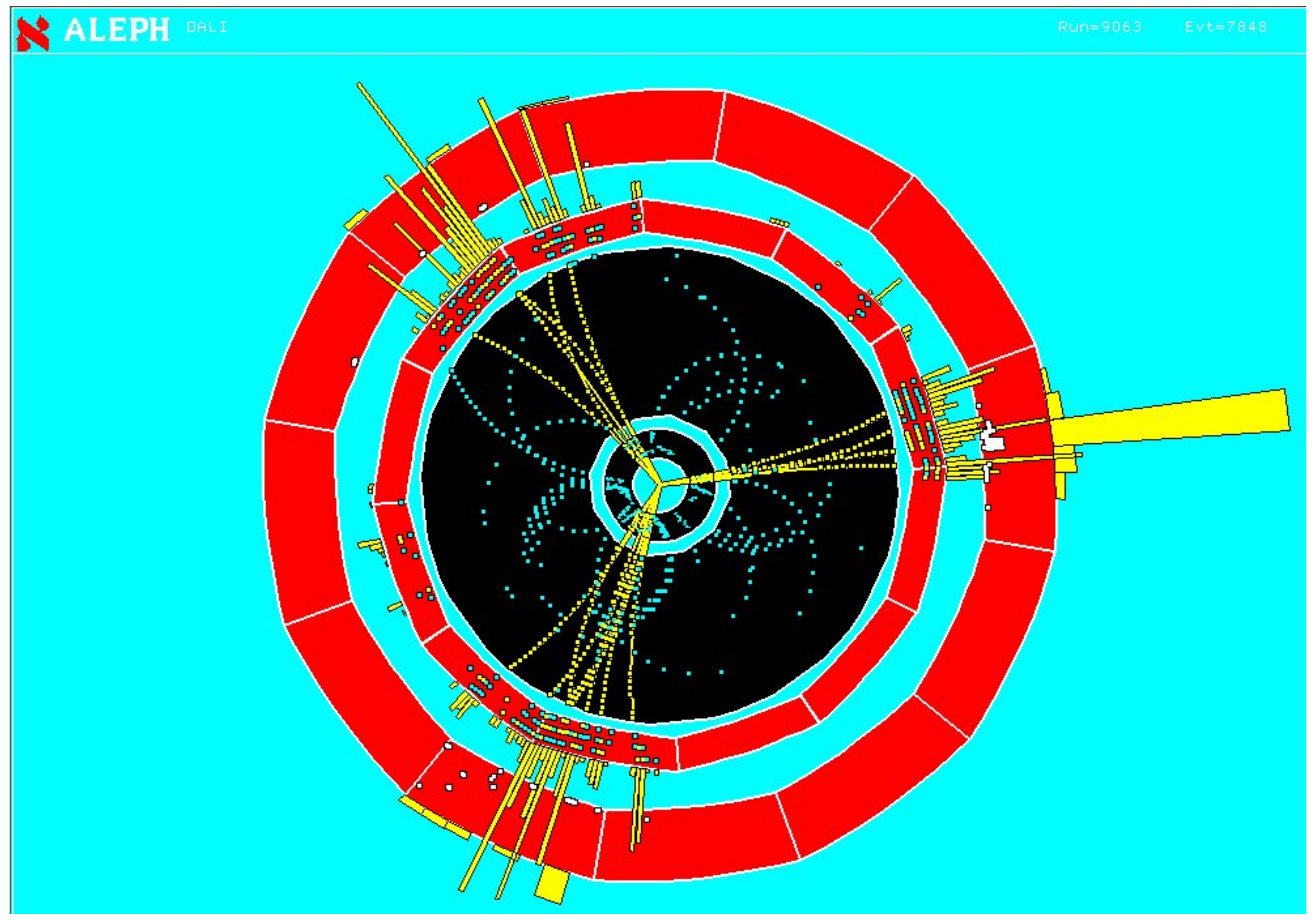
jet definition [in elementary collisions]

:: a jet is ***defined*** *by a set of rules and parameters [a jet algorithm] specifying how to combine constituents and when to stop ::*

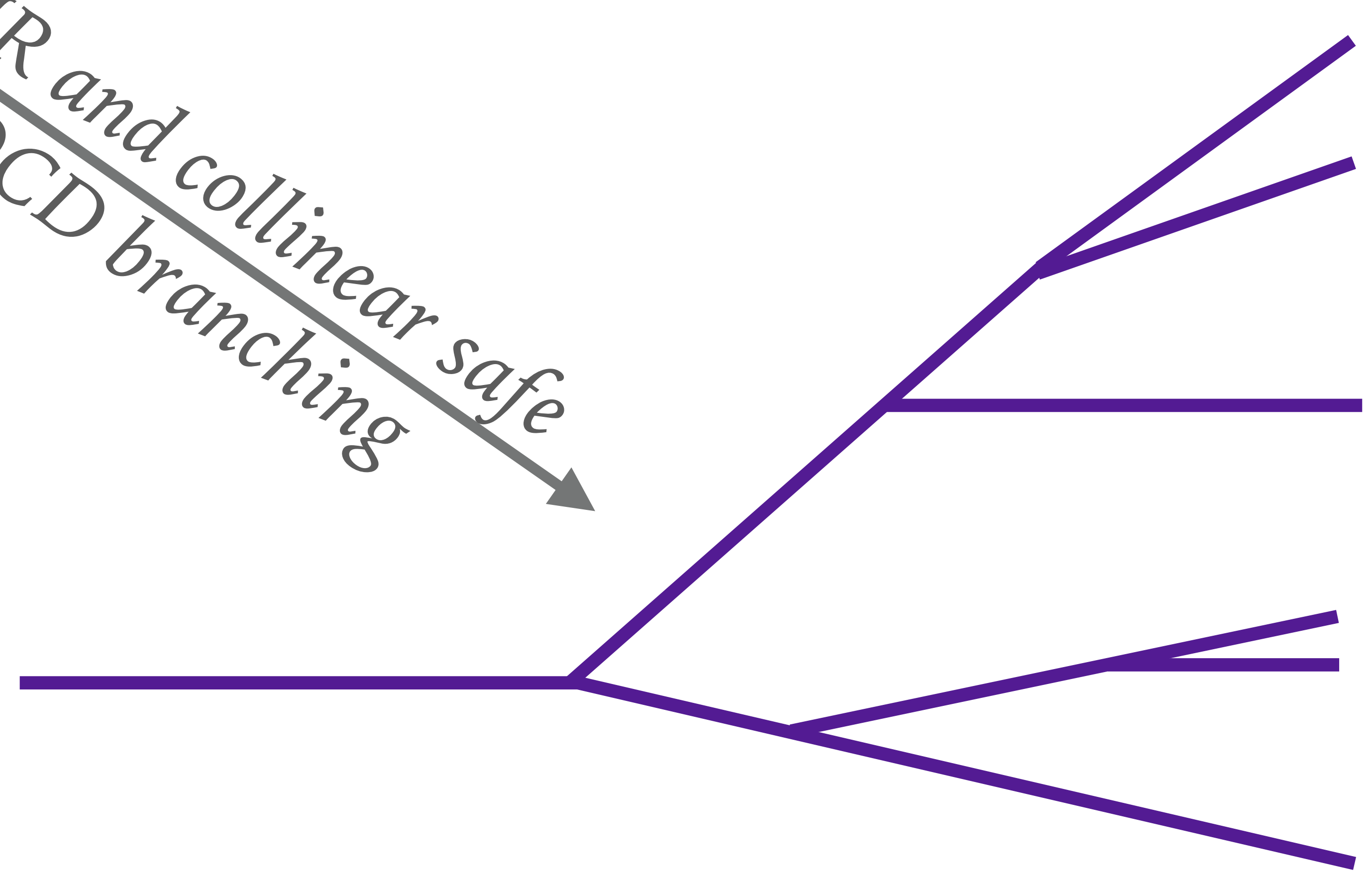
jet algorithm

robust and efficient
IR and collinear safe

IR and collinear safe
QCD branching



experimentally measurable
collimated spray of hadrons

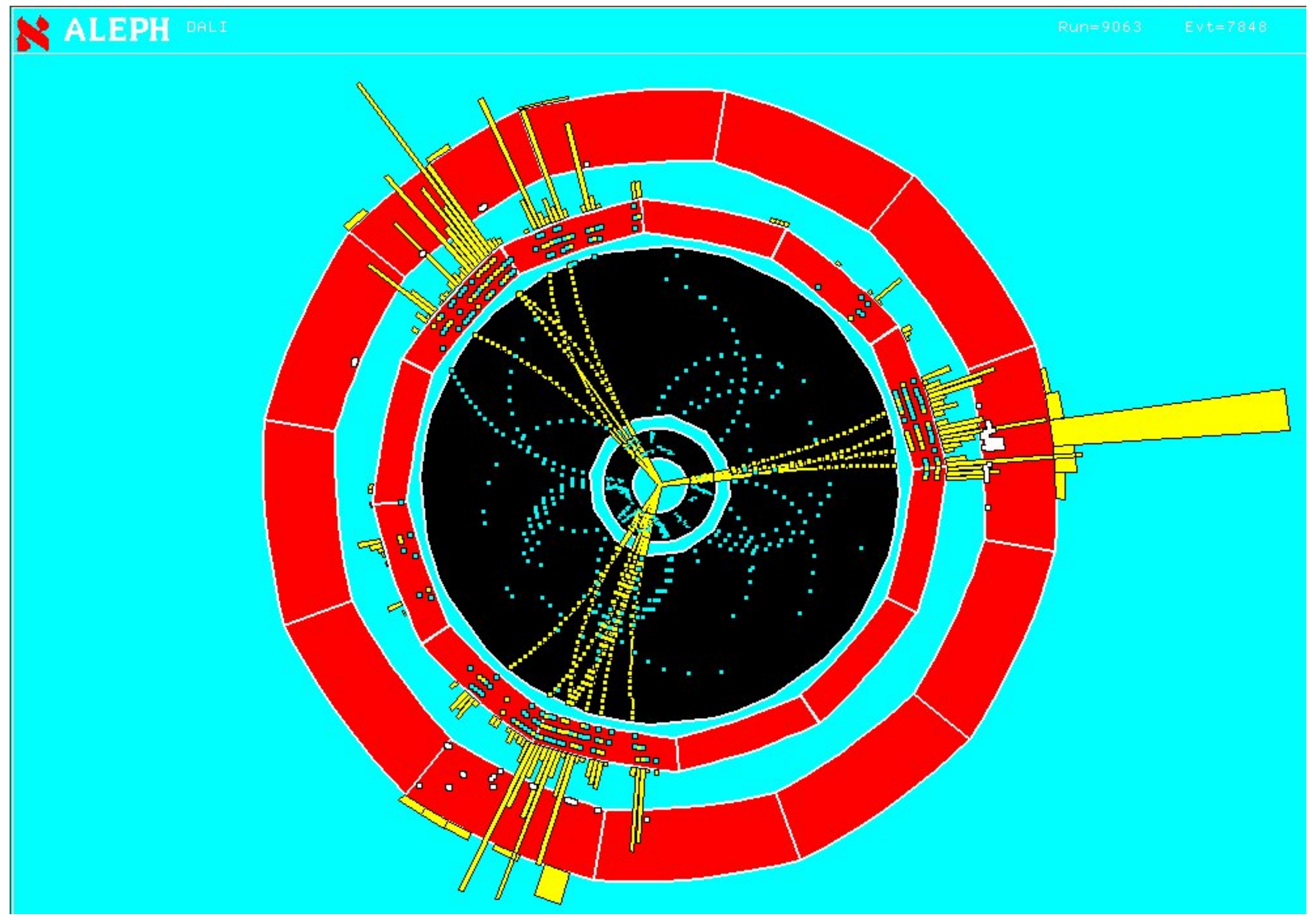


theoretically calculable
fragmentation of energetic parton

jet definition [in elementary collisions]

*:: a **jet** is **defined** by a set of rules and parameters [a jet algorithm] specifying how to combine constituents and when to stop ::*

experimental jet



experimentally measurable
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robust and efficient
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jet algorithm

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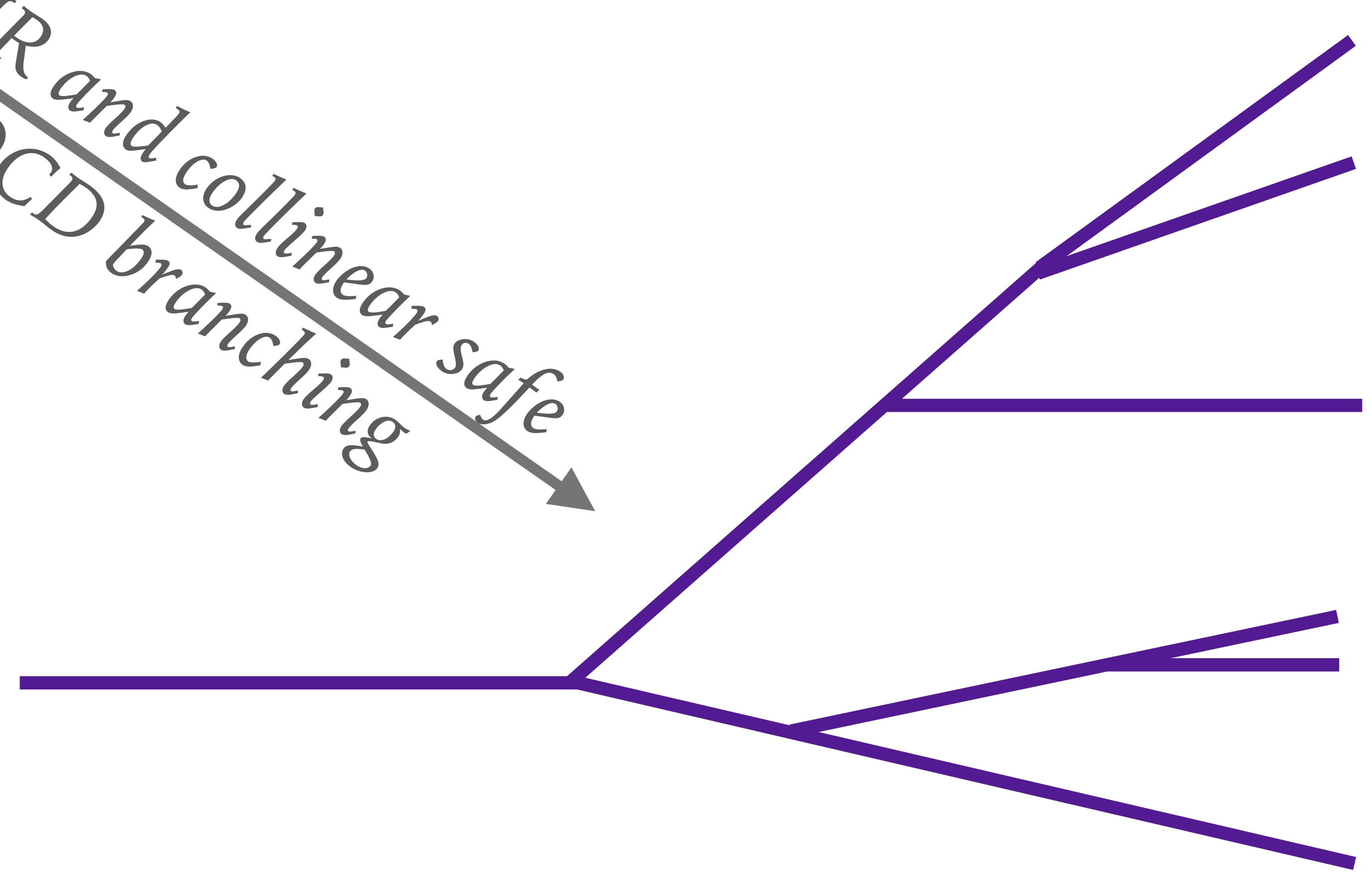
QCD branching

theory jet

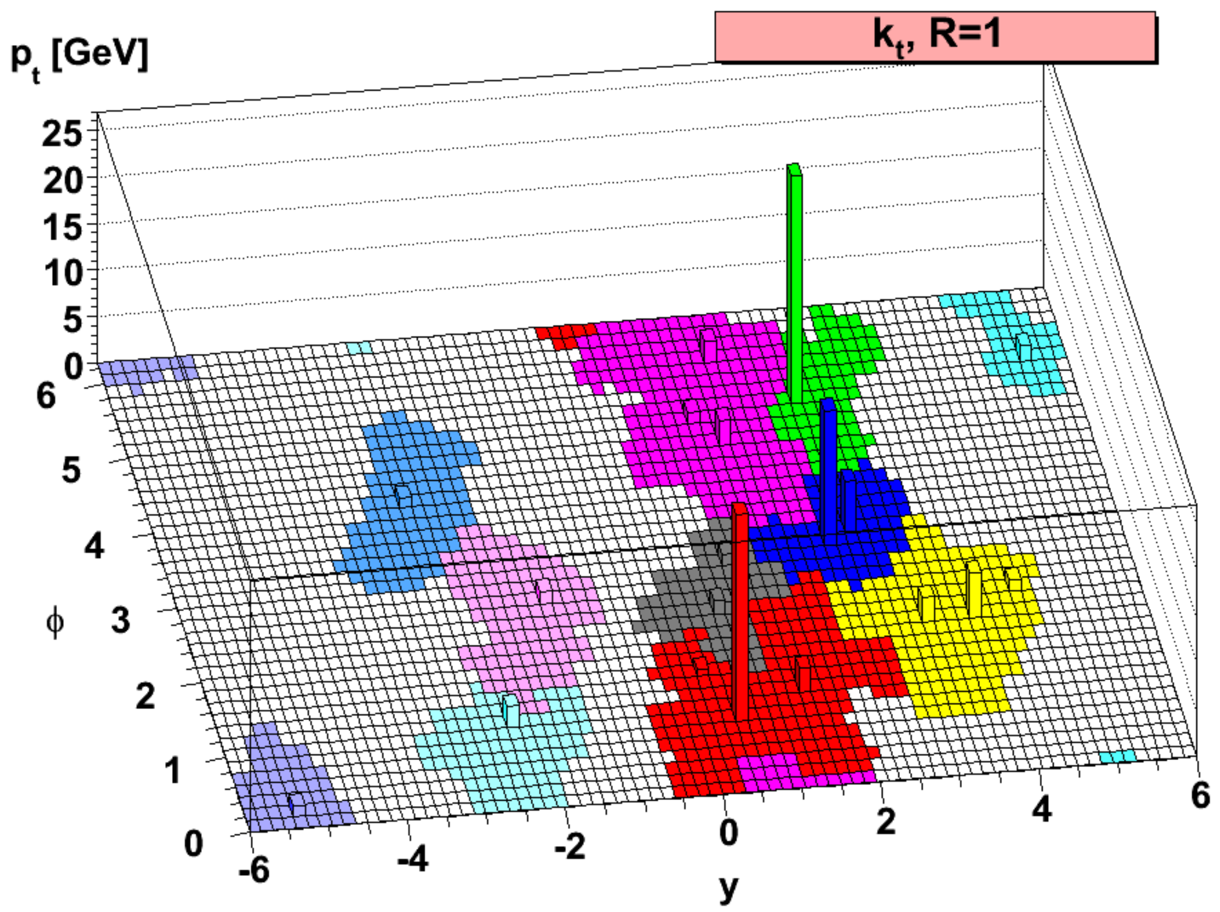


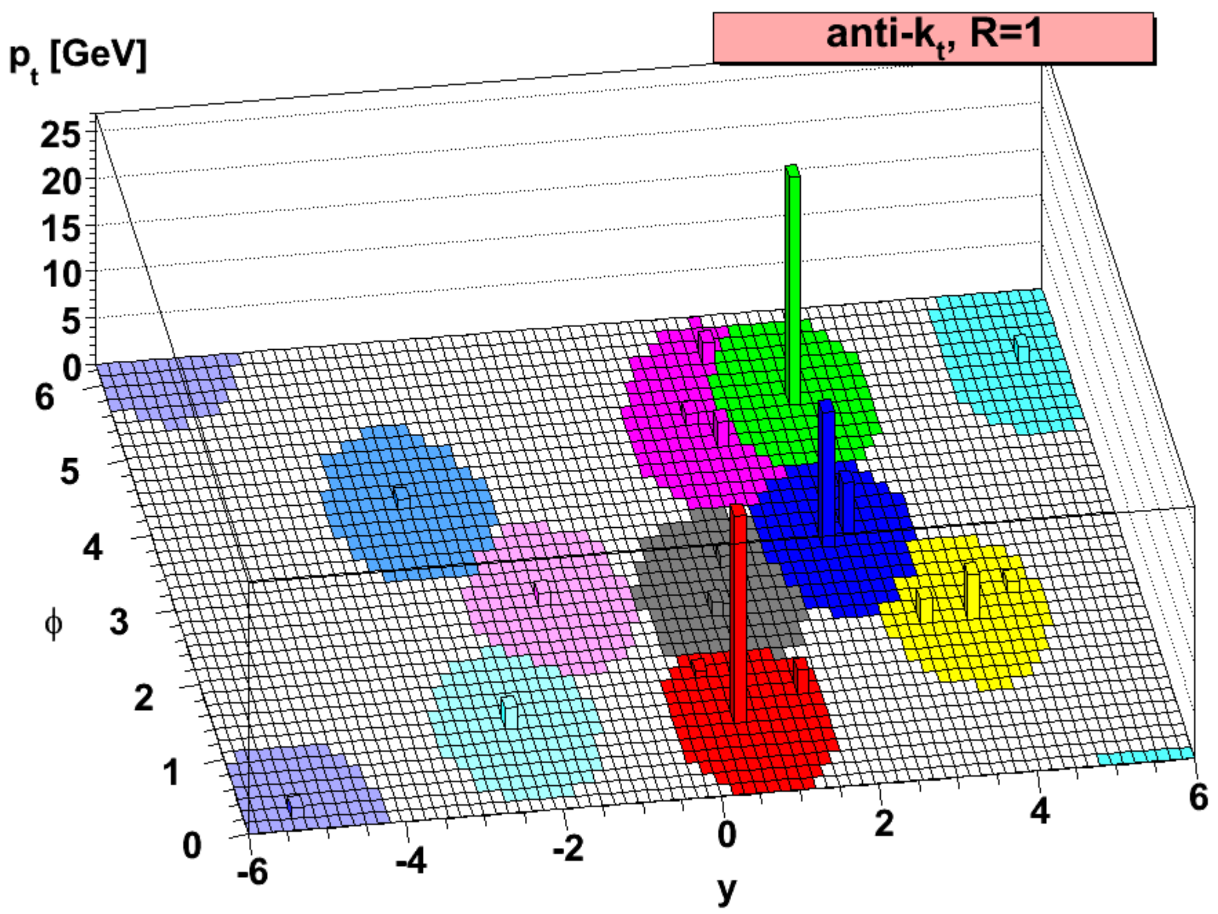
theoretically calculable
fragmentation of energetic parton

a jet is a jet is a jet is a jet

jet diversity

- k_T R=0.4 jets are **different** from anti-k_T R=0.4,



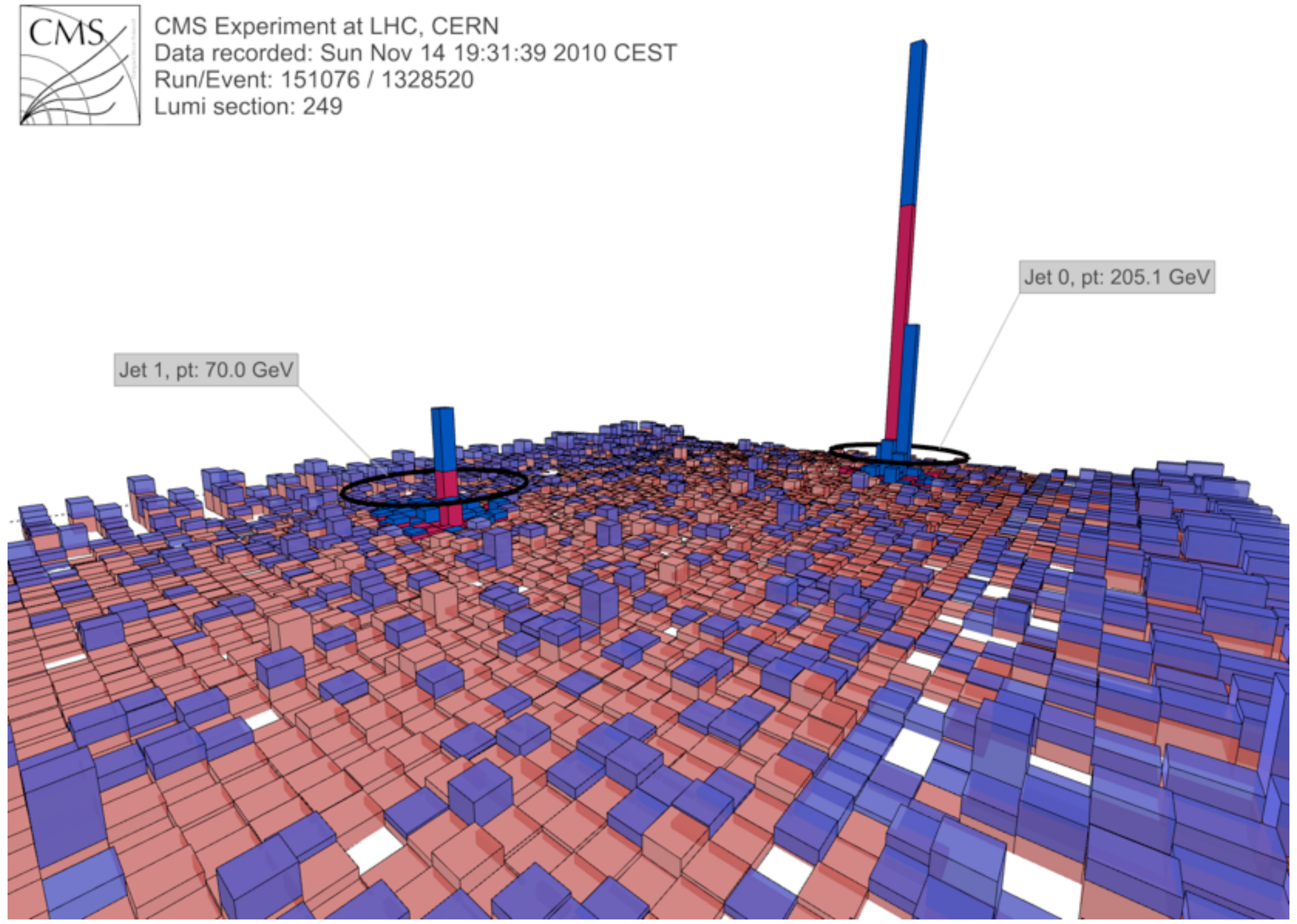


Cacciari, Salam, Soyez 0802.1189

- also, anti-k_T R=0.2 are **not** the inner R=0.2 core of anti-k_T R=0.4 jets, etc.
- jets reconstructed with a given algorithm [typically anti-k_T for experimental robustness] can be reinterpreted [**reclustered**] with a different algorithm to benefit simultaneously from experimental robustness and direct theoretical interpretation
  - however, C/A reclustering of anti-kt R=0.4 jet is not C/A R=0.4 jet
- **jet diversity is a tool** rather than a hindrance :: grooming/substructure methods

jets in heavy ion collisions

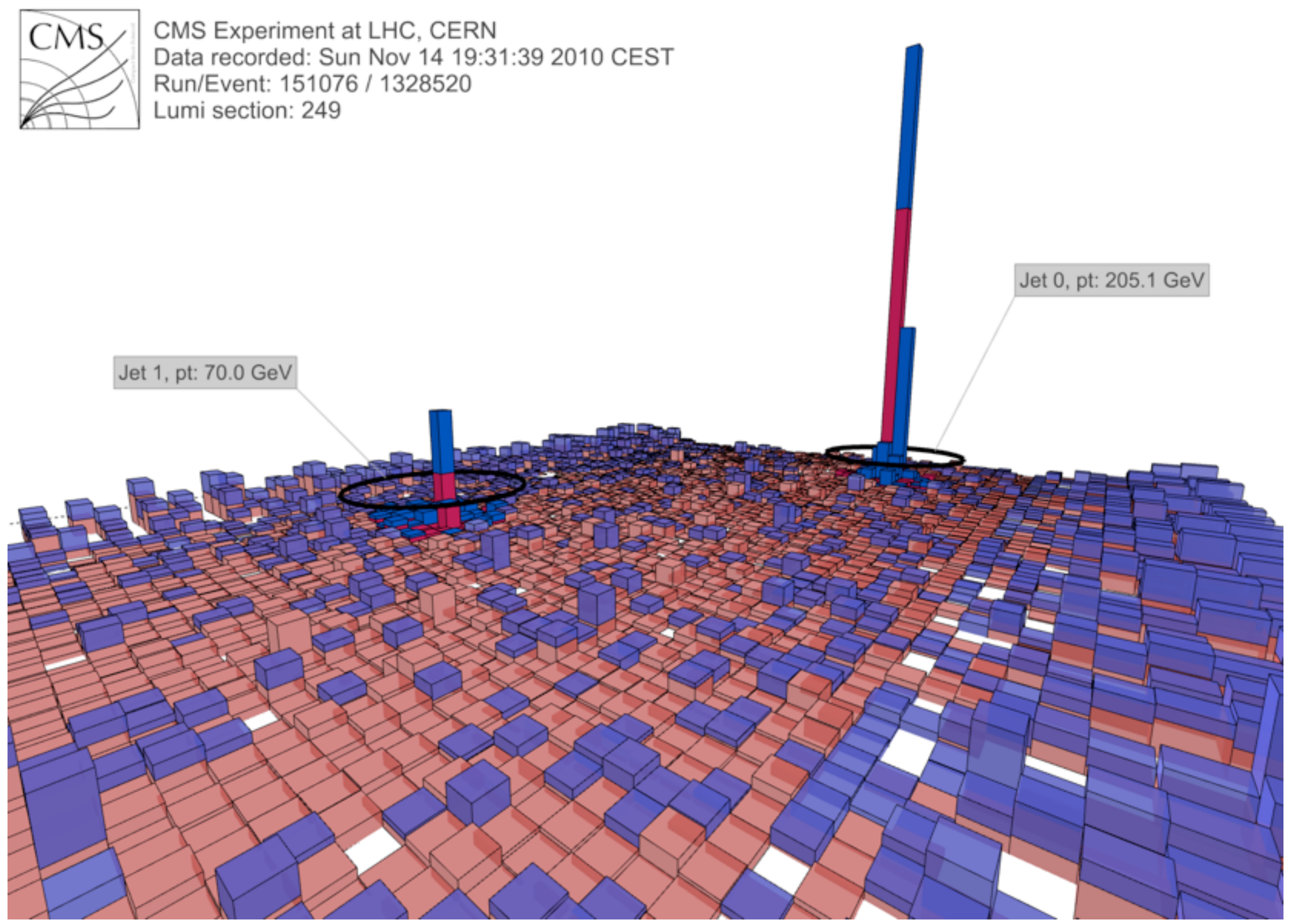
- defined by same jet algorithm[s] as in elementary collisions with essential background subtraction



jet algorithm
+
background subtraction

jets in heavy ion collisions

- defined by same jet algorithm[s] as in elementary collisions with essential background subtraction

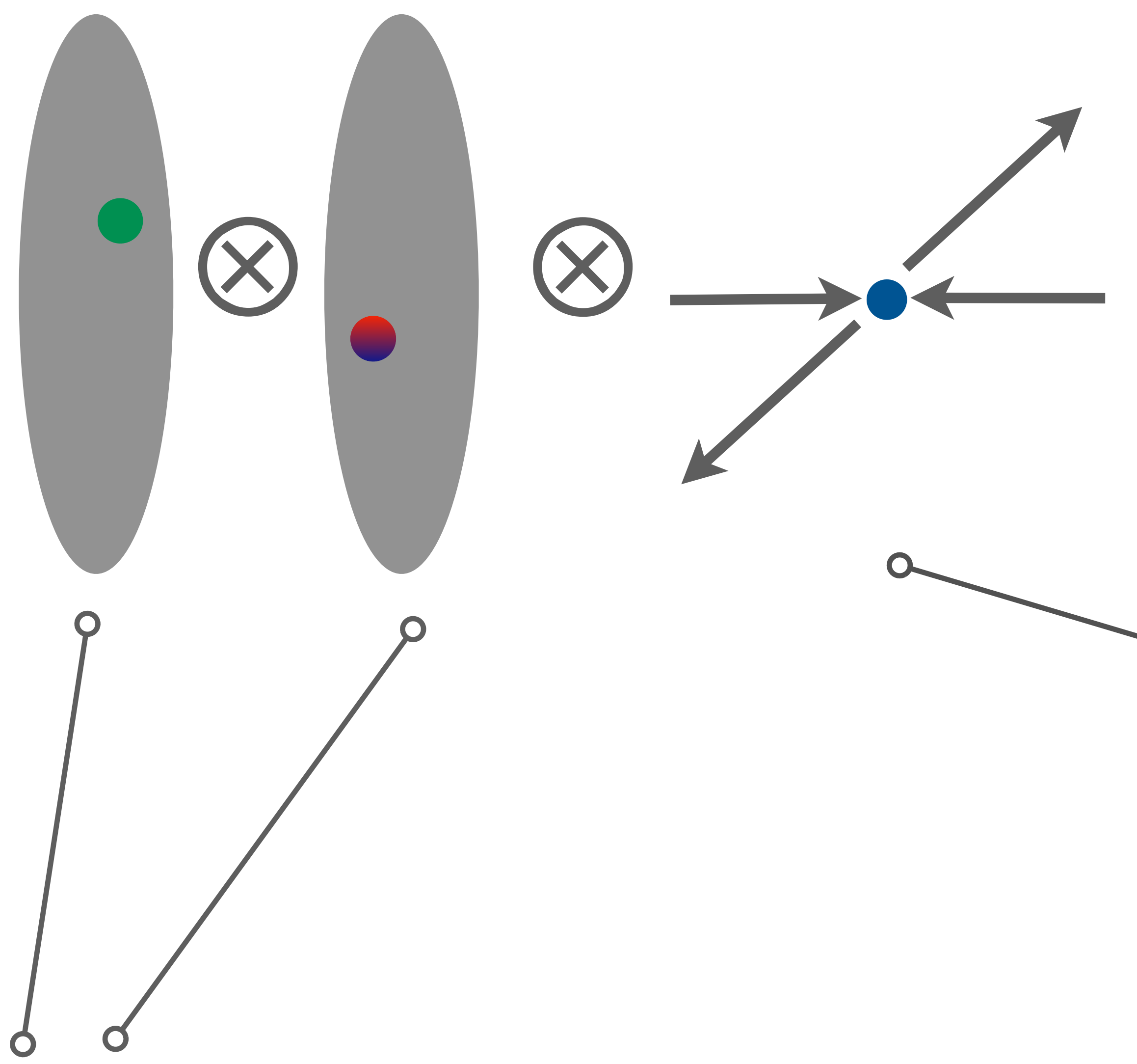


jet algorithm
+
background subtraction

what has to be calculated?

what is in a heavy ion jet?

A JET IN QGP :: HARD PRODUCTION



hard scattering localized on point like scale
oblivious to surrounding matter
[calculable to arbitrary pQCD order]

nuclear structure sufficiently
constrained in relevant
kinematical domain

all will be easy [denial]

A JET IN QGP :: PARTON SHOWER

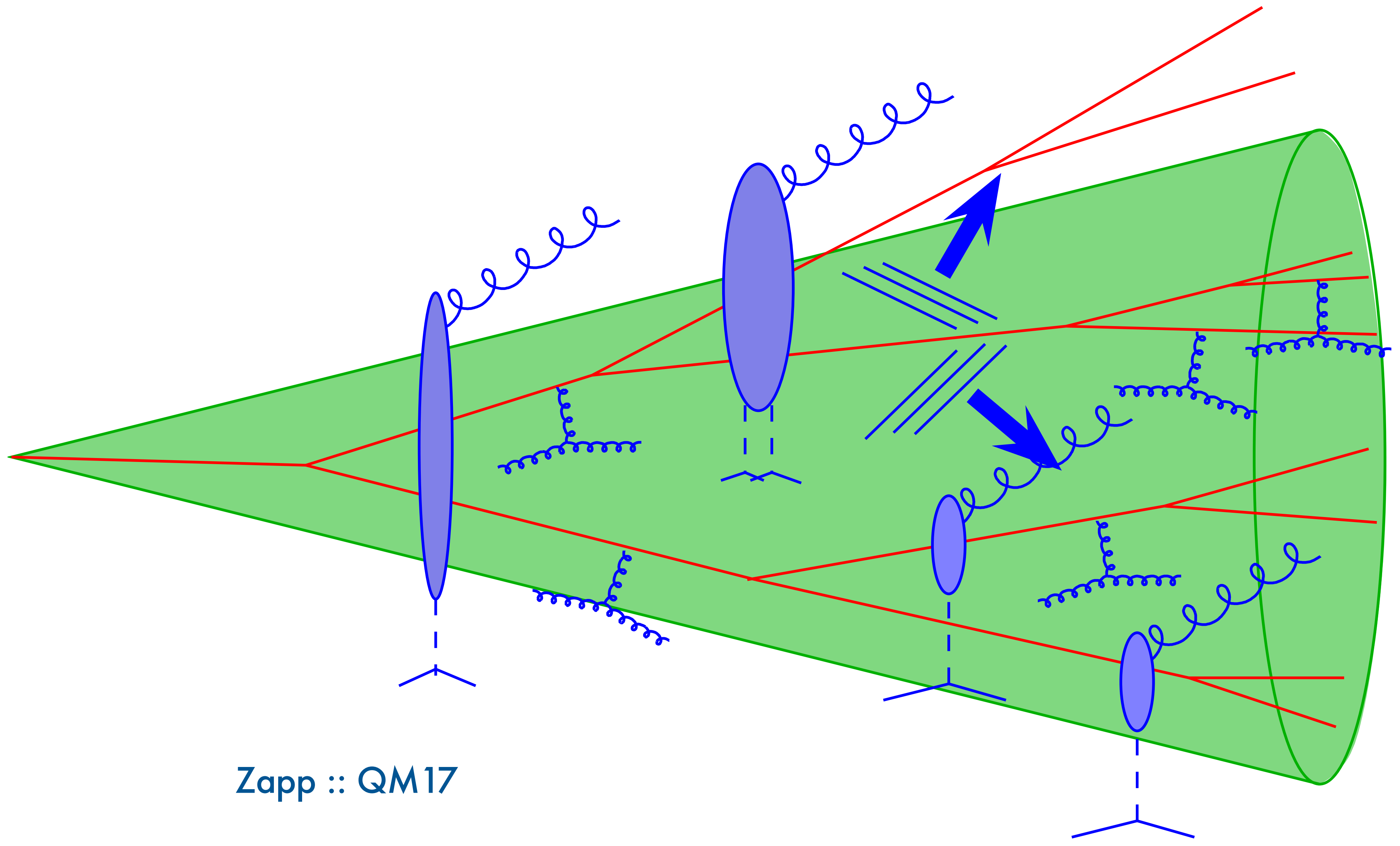
shower constituents exchange [soft] 4-momentum and colour with QGP :: shower modified into interleaved vacuum+induced shower :: modified coherence properties :: single parton intuition and results do not carry through trivially :: multi-scale problem :: some shower constituents de-correlate :: response of QGP to jet becomes correlated with jet direction

Mehtar-Tani, Milhano, Tywoniuk :: Int.J.Mod.Phys. A28 (2013)

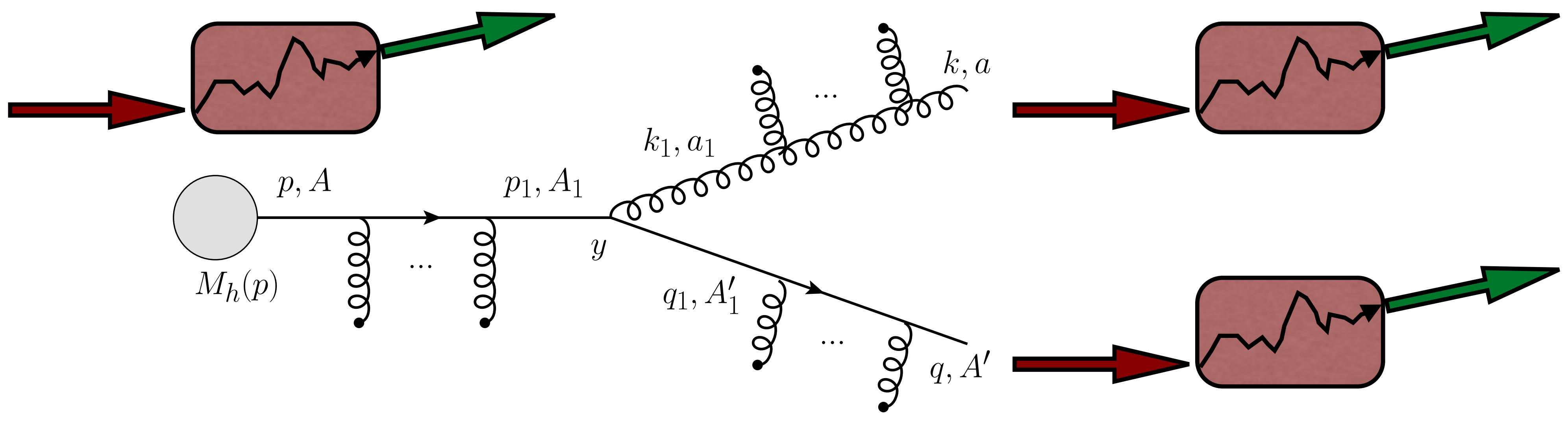
Mehtar-Tani, Tywoniuk, Salgado :: many

Blaizot, Dominguez, Iancu, Mehtar-Tani :: JHEP 1406 (2014)

Apolinário, Armesto, Milhano, Salgado :: JHEP 1502 (2015)



Zapp :: QM17

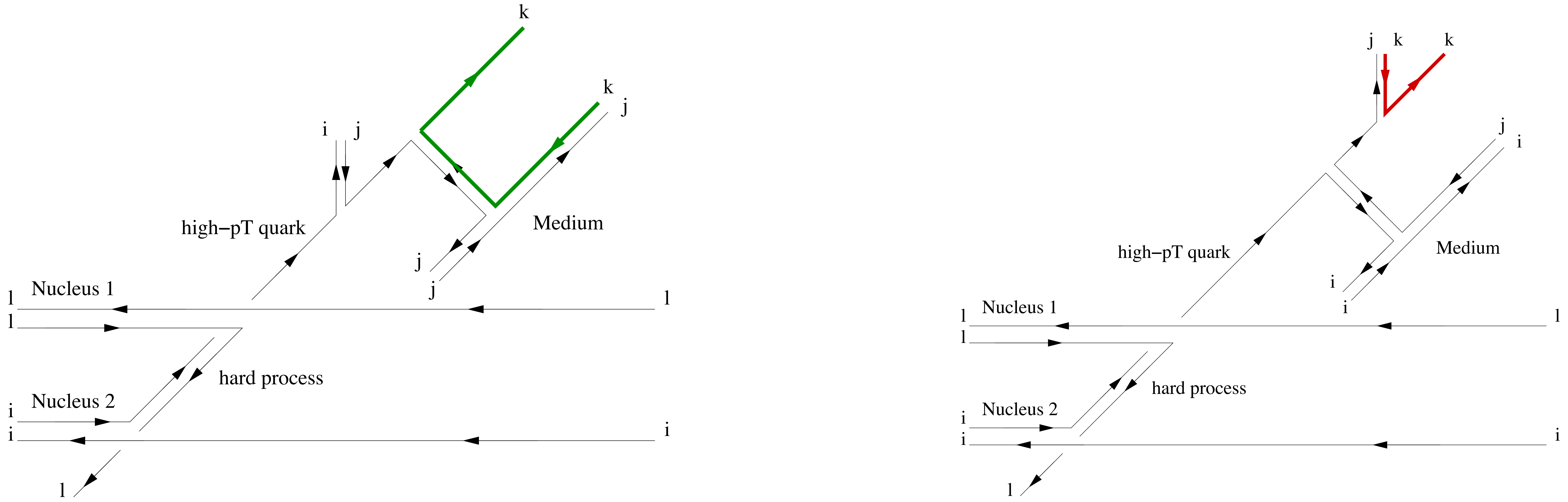


this is tough [anger]

A JET IN QGP :: HADRONIZATION

Beraudo, Milhano, Wiedemann :: JHEP 1207 (2012)

very little known about QGP induced modifications of already ill-understood hadronization in vacuum

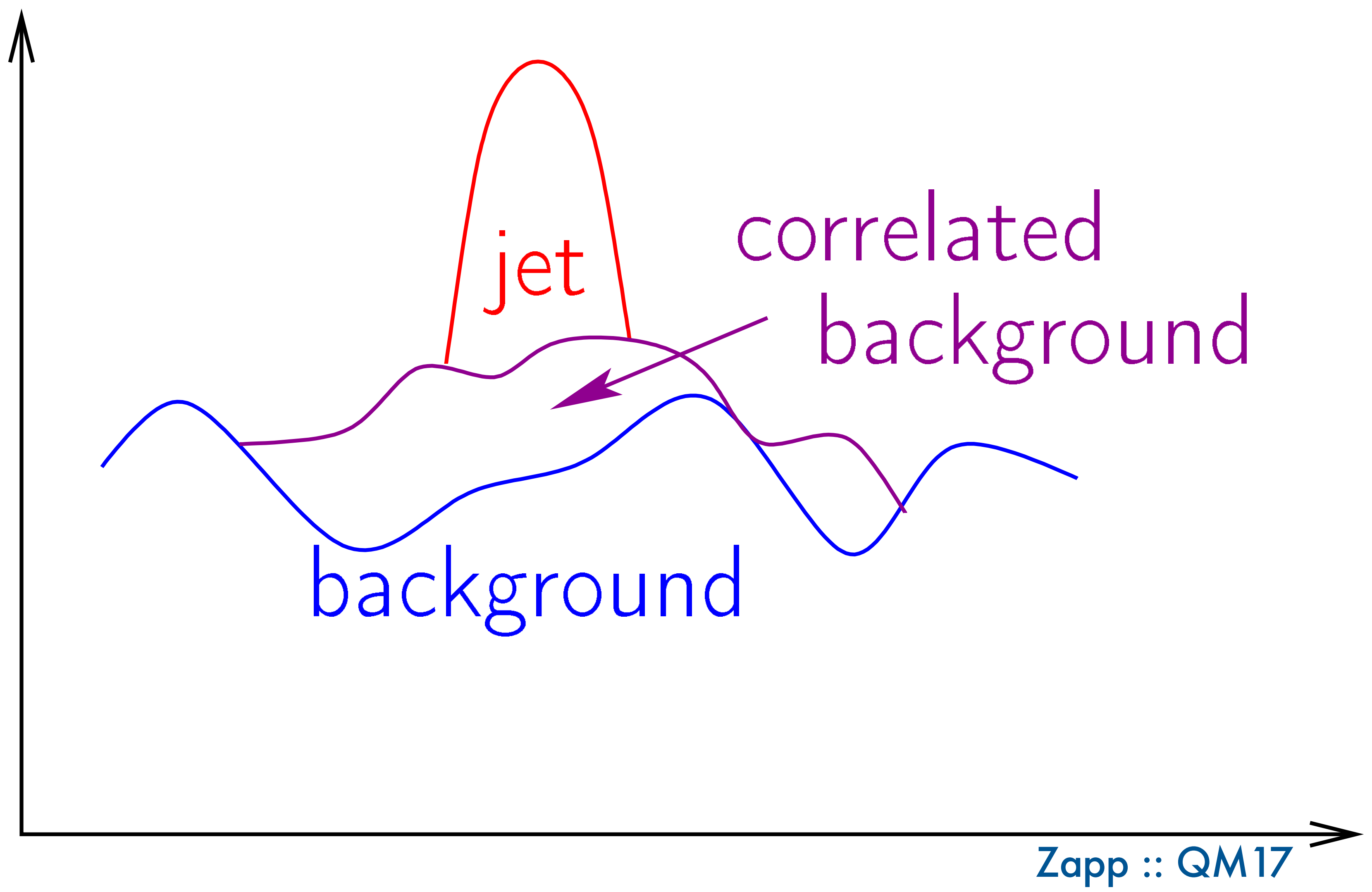


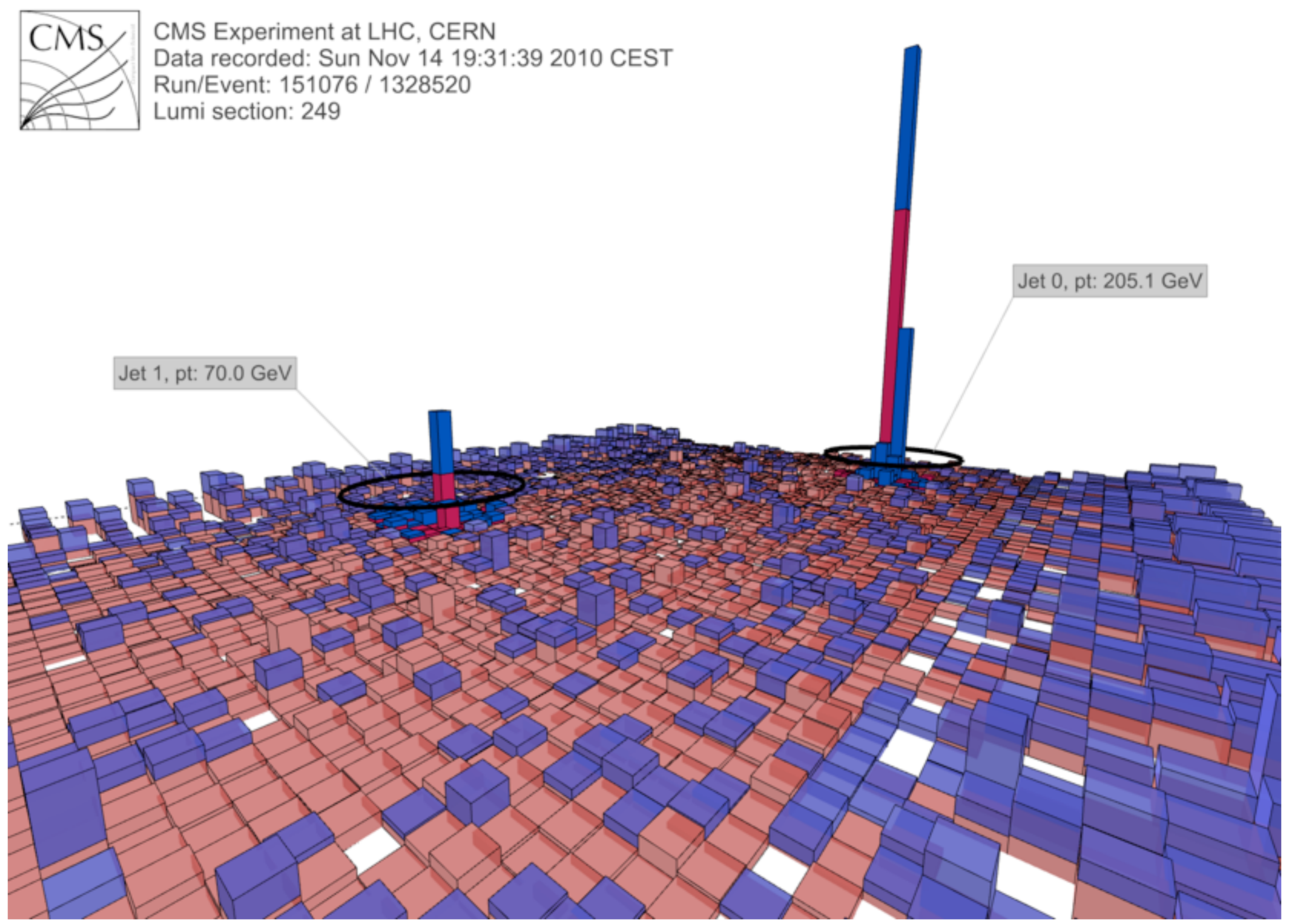
jet-QGP interaction modifies color connections in the jet and thus hadronization pattern
[in any reasonable effective model]
can learn about hadronization modifications at an EIC

if you let me do away with this, I will produce some results [bargaining]

A JET IN QGP :: JET RECONSTRUCTION

uncorrelated QGP background needs to be subtracted :: jet-correlated QGP response should not :: do experimental and phenomenological procedures do the same [and the right] thing? :: how can I know?





this is probably hopeless [depression]

A JET IN QGP :: OBSERVABLES

keeping in mind all the caveats compute something that has been/you want to be measured and understand what it might be sensitive to and how it can help removing the caveats

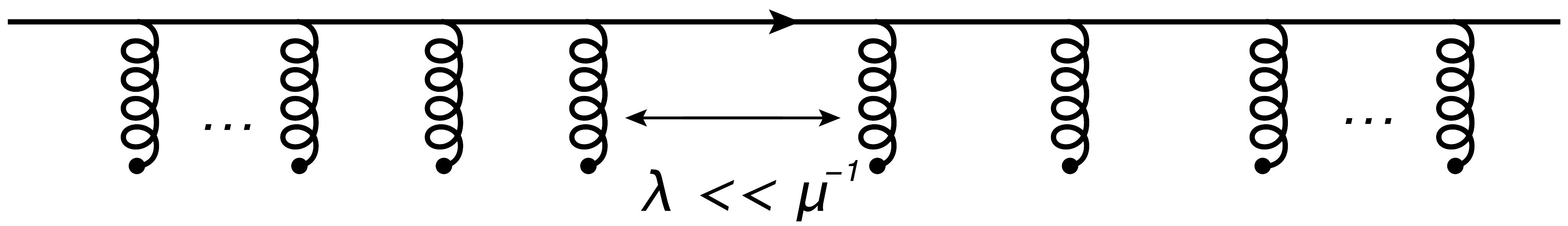
work with what you have to eventually have more [acceptance]

THE FIVE STAGES OF HEAVY ION JET PHENOMENOLOGY

denial :: anger :: bargaining :: depression :: acceptance

the theoretical, phenomenological, and experimental challenges posed by the complexity of jets in heavy ion collisions are the best shot we have at furthering our understanding of the QGP

PARTON ENERGY LOSS



- first step in understanding modifications of jets is to tackle energy loss of a single parton
- take a QGP as discrete set of non-interacting [screened] and recoilless scattering centres expanding or not [here not]
- interaction between parton and QGP on timescale much shorter than characteristic QGP time scales [compute for fixed configuration and average over ensemble later on]
- momentum exchange purely transverse — medium gauge field written as

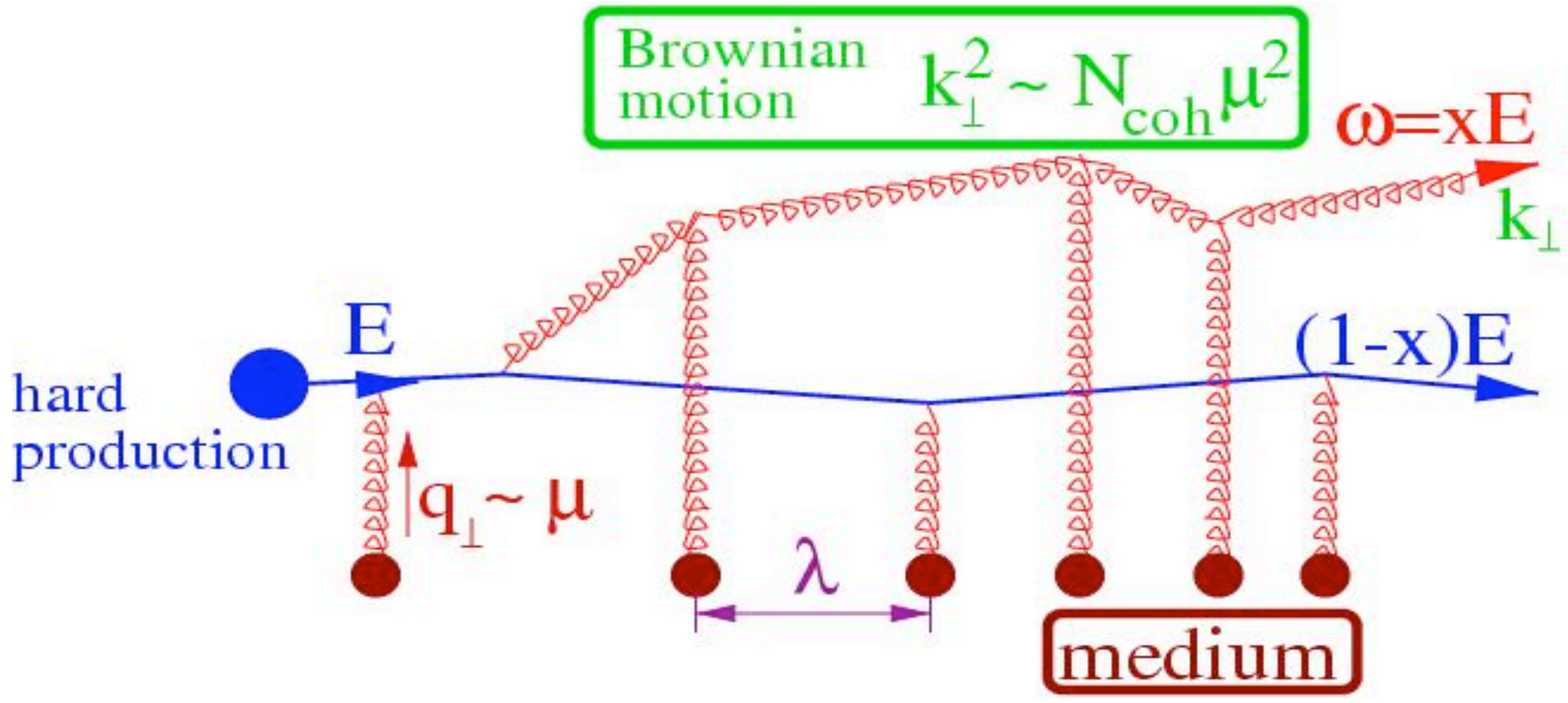
$$A^{-}_{\rm med}(q) = 2\pi\,\delta(q^{+})\int_0^{\infty} dx^{+}\, e^{iq^{-}x^{+}} A^{-}_{\rm med}(\boldsymbol{q}, x^{+})$$

- assuming gaussian distribution, medium properties enter via 2-point correlator

$$\langle A^{a,-}_{\rm med}(\boldsymbol{q},t) A^{*\,b,-}_{\rm med}(\boldsymbol{q}',t')\rangle = \delta^{ab}\, n(t)\, \delta(t-t')\, (2\pi)^2 \delta^{(2)}(\boldsymbol{q}-\boldsymbol{q}')\, \gamma(\boldsymbol{q}^2)$$

PARTON ENERGY LOSS

- parton can exchange 4-momentum with QGP
  - transfer to QGP results in [elastic] energy loss
  - transfer from QGP results in energy gain which can stimulate radiation :: medium induced radiation is the leading mechanism for parton energy loss

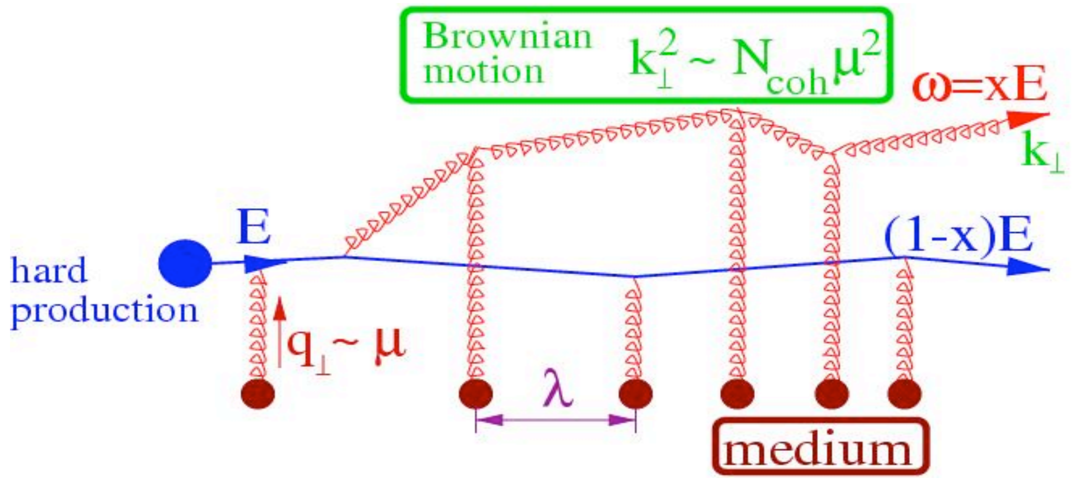


$$\hat{q}(t) \equiv \alpha_s n(t) \int_{|\boldsymbol{q}|<q^*} d\boldsymbol{q}^2\ \boldsymbol{q}^2 \gamma(\boldsymbol{q}^2)$$

$$\hat{q} \simeq \frac{\mu^2}{\lambda}$$

transport coefficient
[average momentum squared transfer per unit length]

SINGLE EMISSION [BDMPS-Z]



:: Brownian motion [accumulated transverse momentum]

$$\langle k_\perp^2 \rangle \sim \hat{q} L$$

:: accumulated phase

$$\left\langle \frac{k_\perp^2 L}{\omega} \right\rangle \sim \frac{\hat{q} L^2}{\omega} \sim \frac{\omega_c}{\omega}$$

characteristic [maximum] gluon energy

$$\hat{q} \simeq \frac{\mu^2}{\lambda}$$

:: coherence time [time it takes for a gluon decohere from its emitter]

$$t_{coh} \sim \frac{\omega}{k_\perp^2} \sim \sqrt{\frac{\omega}{\hat{q}}}$$

→ number of coherent scatterings

$$N_{coh} \sim \frac{t_{coh}}{\lambda}$$

$$k_\perp^2 \sim \hat{q}\, t_{coh}$$

:: radiated gluon energy distribution

$$\omega \frac{dI_{med}}{d\omega dz} \sim \frac{1}{N_{coh}} \omega \frac{dI_1}{d\omega dz} \sim \alpha_s \sqrt{\frac{\hat{q}}{\omega}}$$

non-abelian LPM

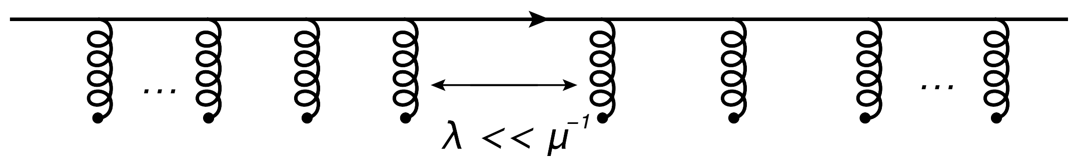
:: average energy loss

$$\Delta E = \int_0^L dz \int_0^{\omega_c} \omega d\omega \frac{dI_{med}}{d\omega dz} \sim \alpha_s \omega_c \sim \alpha_s \hat{q} L^2$$

BEYOND BACK THE ENVELOPE [PATH-INTEGRAL]

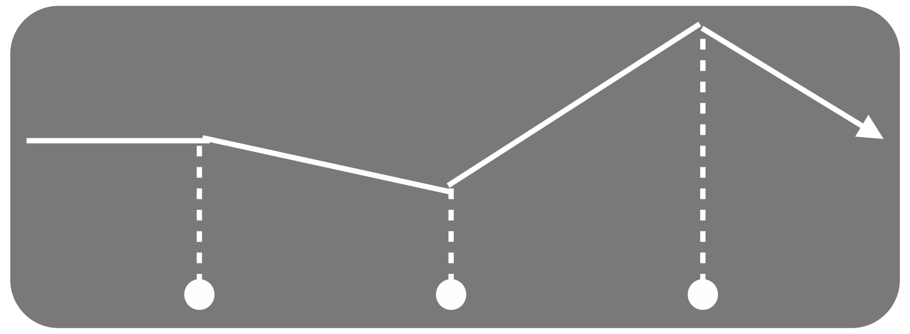
:: eikonal [straight line] parton trajectory resumming multiple exchanges

$$W_{\alpha_f \alpha_i}\big(x_{f+}, x_{i+}; \mathbf{r}(\xi)\big) = \mathcal{P} \exp \left\{ ig \int_{x_{i+}}^{x_{f+}} d\xi A_-\big(\xi, \mathbf{r}(\xi)\big) \right\}$$

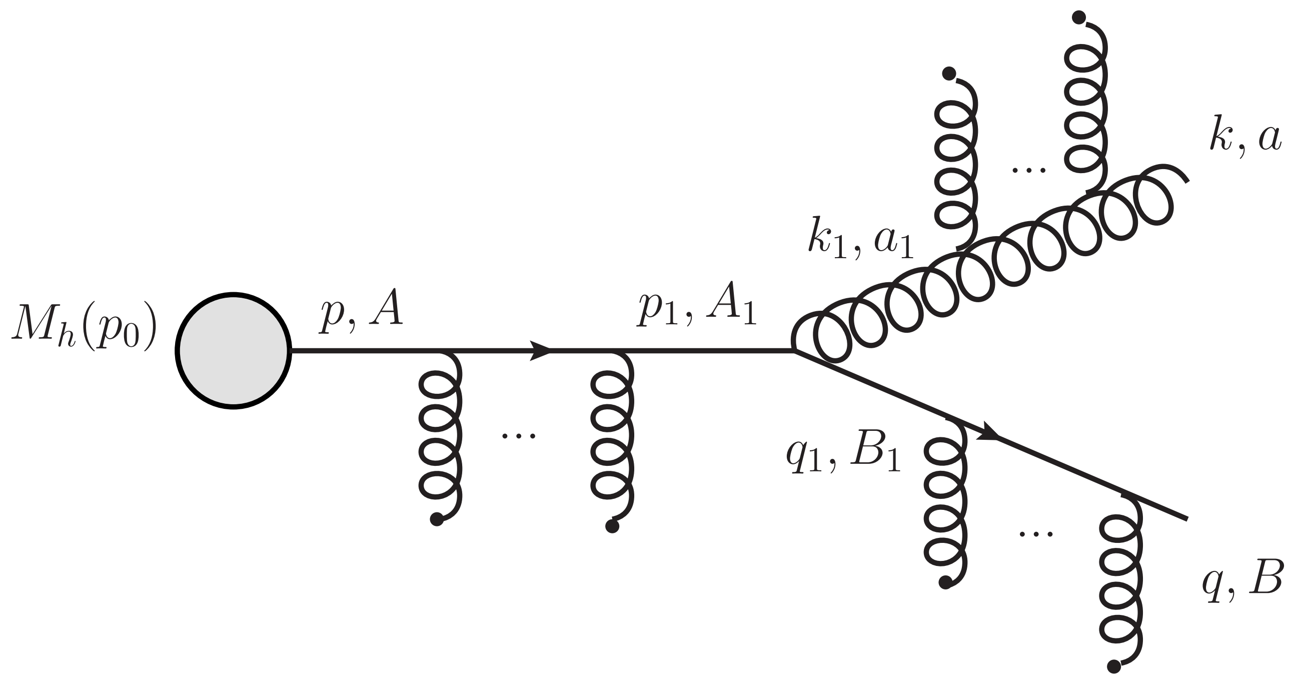


:: off-eikonal [transverse motion] parton trajectory resumming multiple exchanges

$$G_{\alpha_f \alpha_i}(x_{f+}, \mathbf{x}_f; x_{i+}, \mathbf{x}_i | p_+) = \int_{\mathbf{r}(x_{i+})=\mathbf{x}_i}^{\mathbf{r}(x_{f+})=\mathbf{x}_f} \mathcal{D}\mathbf{r}(\xi) \exp \left\{ \frac{ip_+}{2} \int_{x_{i+}}^{x_{f+}} d\xi \left(\frac{d\mathbf{r}}{d\xi} \right)^2 \right\} W_{\alpha_f \alpha_i}\big(x_{f+}, x_{i+}; \mathbf{r}(\xi)\big)$$



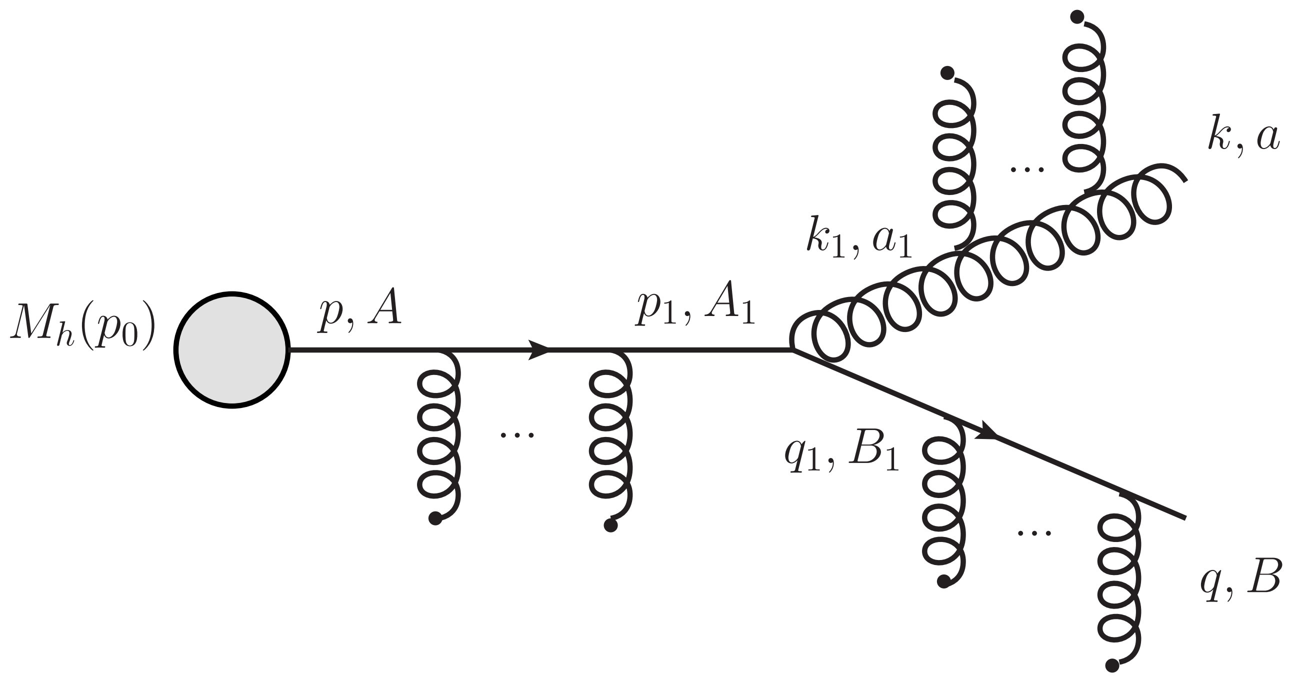
:: observables computed from medium averages of G correlators



GLUON RADIATION WITH FULL RESUMMATION OF MEDIUM INTERACTIONS

Andres, Apolinário, Dominguez :: 2002.01517 [hep-ph]
Andres, Dominguez, Martinez :: 2011.06522 [hep-ph]

$$\omega \frac{dI}{d\omega d^2\boldsymbol{k}} = \frac{2\alpha_s C_R}{(2\pi)^2\omega^2} \,\text{Re} \int_0^\infty dt' \int_0^{t'} dt \int_{\boldsymbol{pq}} \boldsymbol{p}\cdot\boldsymbol{q}\, \widetilde{\mathcal{K}}(t', \boldsymbol{q}; t, \boldsymbol{p}) \mathcal{P}(\infty, \boldsymbol{k}; t', \boldsymbol{q})$$



$$\mathcal{K}\,(t', \boldsymbol{z}; t, \boldsymbol{y}) \equiv \int_{\boldsymbol{pq}} e^{i(\boldsymbol{q}\cdot\boldsymbol{z} - \boldsymbol{p}\cdot\boldsymbol{y})}\, \widetilde{\mathcal{K}}\,(t', \boldsymbol{q}; t, \boldsymbol{p})$$

$$= \int_{\boldsymbol{r}(t)=\boldsymbol{y}}^{\boldsymbol{r}(t')=\boldsymbol{z}} \mathcal{D}\boldsymbol{r} \exp\left[\int_t^{t'} ds \left(\frac{i\omega}{2}\dot{\boldsymbol{r}}^2 - \frac{1}{2} n(s)\sigma(\boldsymbol{r})\right)\right]$$

Yukawa

$$V(\boldsymbol{q}) = \frac{8\pi\mu^2}{(\boldsymbol{q}^2 + \mu^2)^2}$$

$$\mathcal{P}(t'', \boldsymbol{k}; t', \boldsymbol{q}) \equiv \int d^2\boldsymbol{z}\, e^{-i(\boldsymbol{k}-\boldsymbol{q})\cdot\boldsymbol{z}} \exp\left\{-\frac{1}{2}\int_{t'}^{t''} ds\, n(s)\,\sigma(\boldsymbol{z})\right\}$$

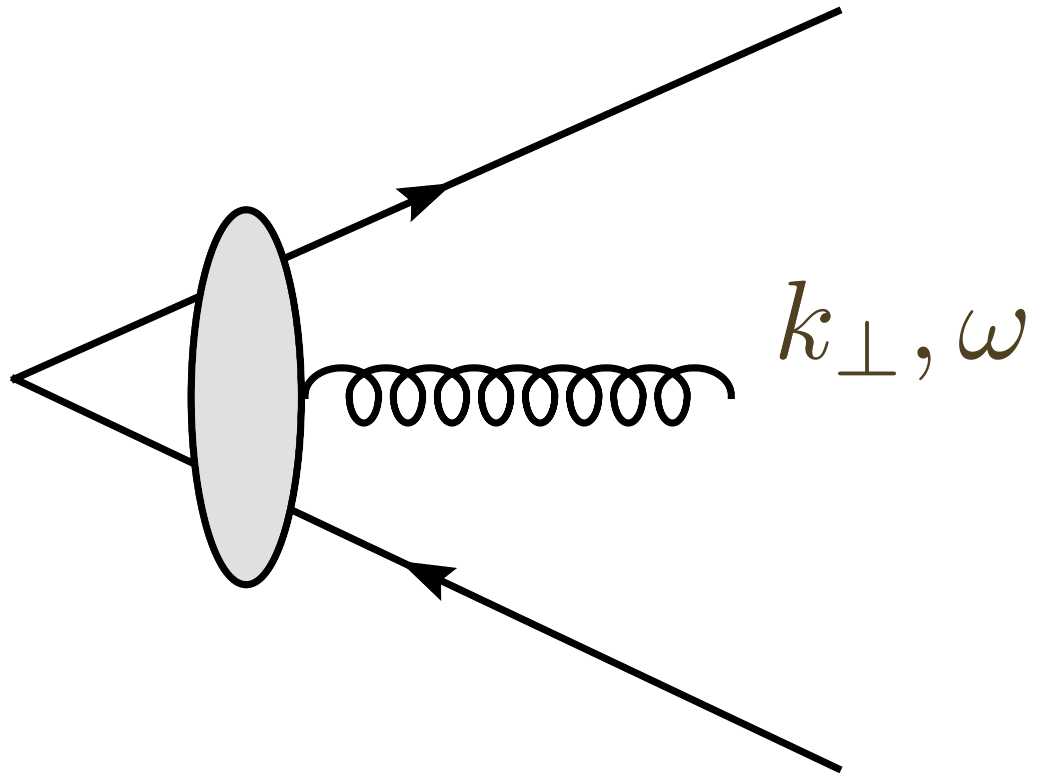
HTL

$$\frac{1}{2} n\, V(\boldsymbol{q}) = \frac{g_s^2 N_c m_D^2 T}{\boldsymbol{q}^2(\boldsymbol{q}^2 + m_D^2)}$$

$$\sigma(\boldsymbol{q}) = -V(\boldsymbol{q}) + (2\pi)^2 \delta^{(2)}(\boldsymbol{q}) \int_{\boldsymbol{l}} V(\boldsymbol{l})$$

THE NEXT STEP: COHERENT EMISSION

- 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

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

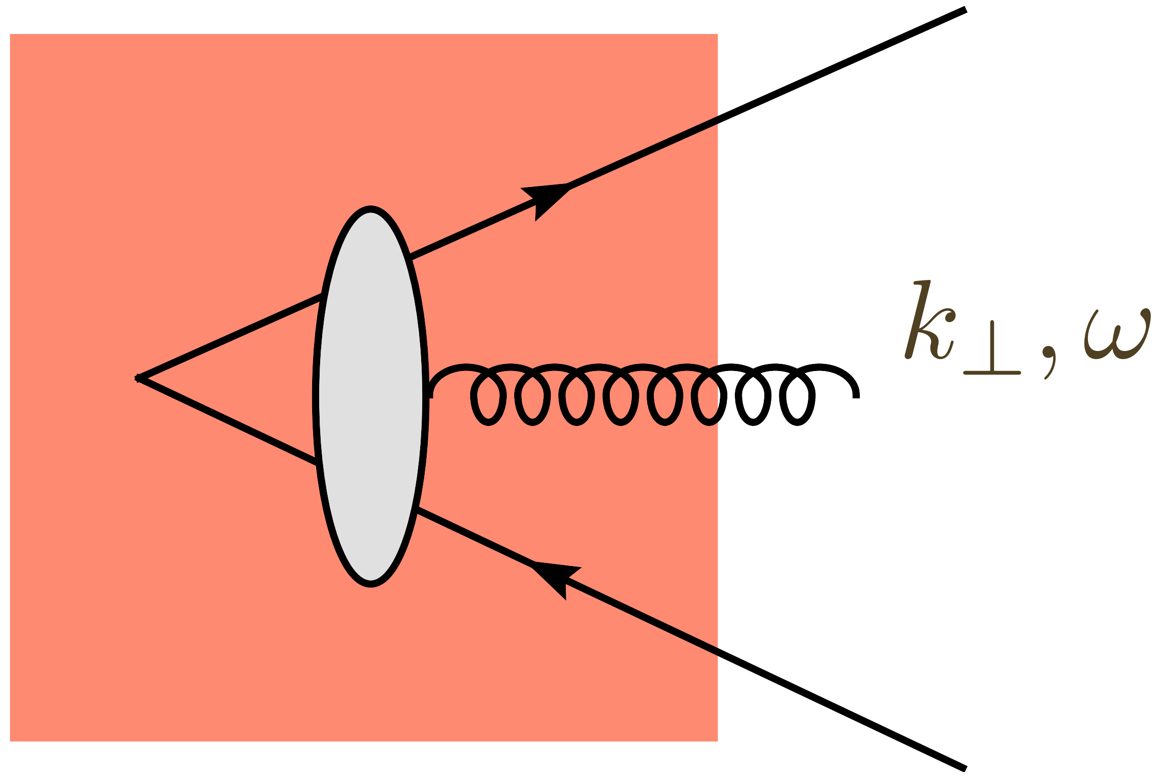
for $\lambda_\perp > r_\perp$ *emitted gluon cannot resolve emitters, thus emitted coherently from total colour charge*

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

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

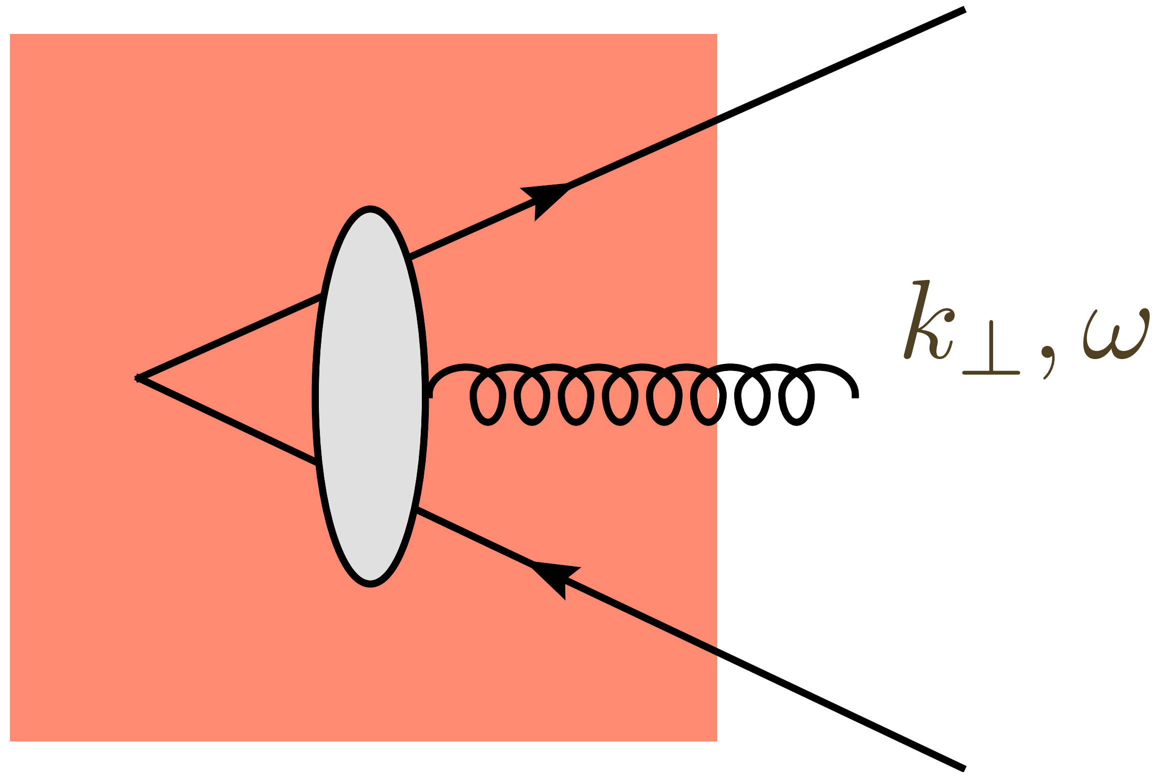
- such that decorrelation driven by timescale

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

[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 > τ_d

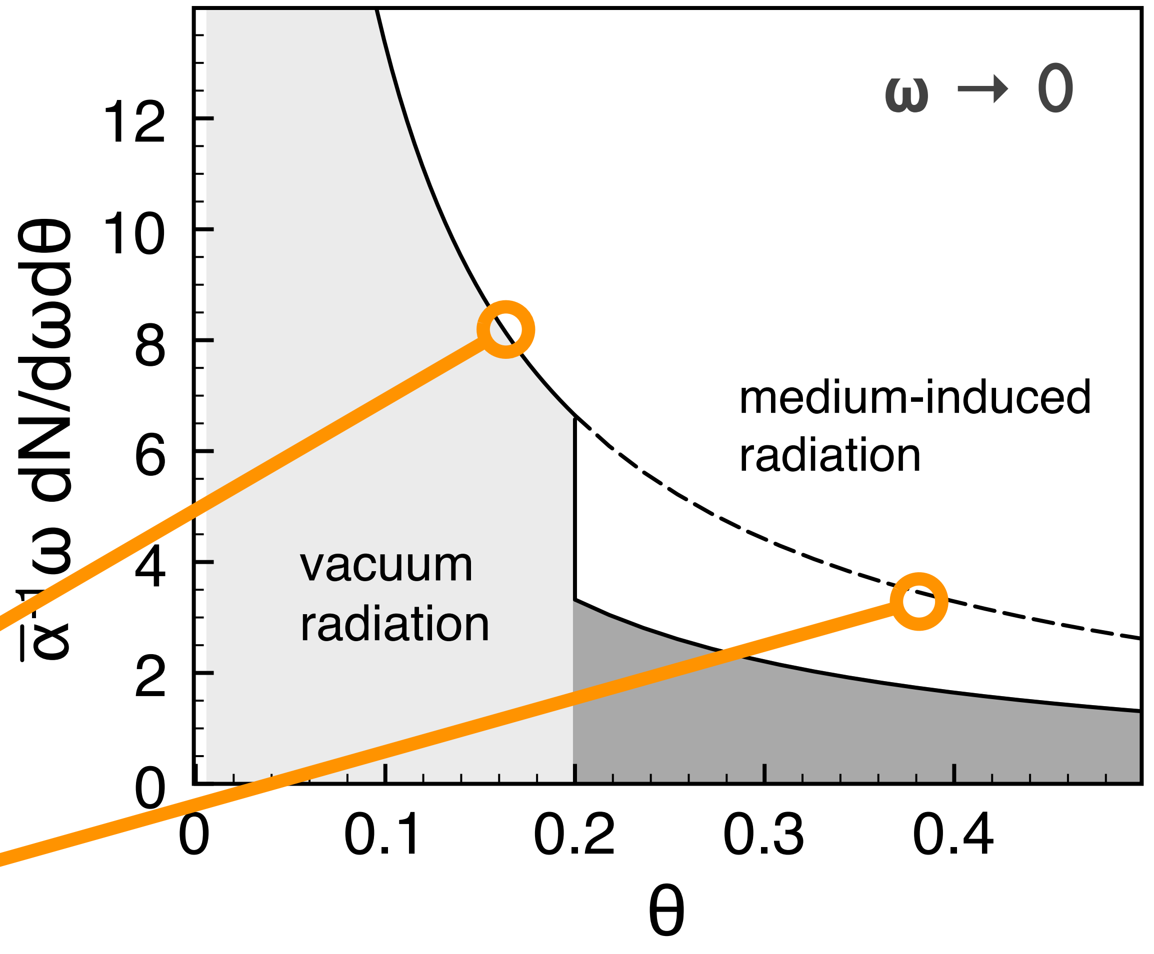
- colour decoherence opens up phase space for emission
  - large angle radiation [anti-angular ordering]

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

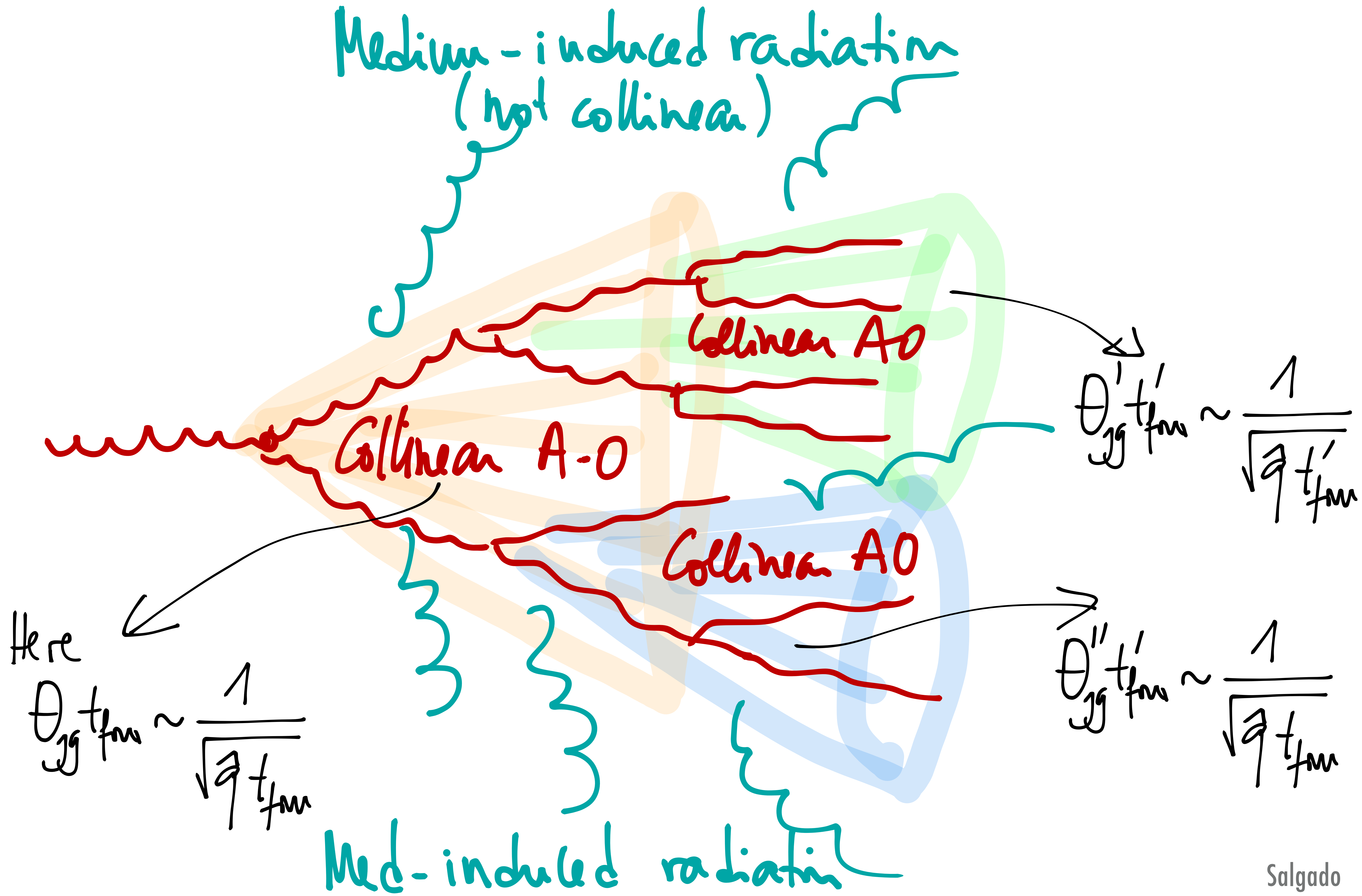
  - *geometrical separation [in soft limit]*

$\Delta_{med} \to 0$ coherence

$\Delta_{med} \to 1$ decoherence



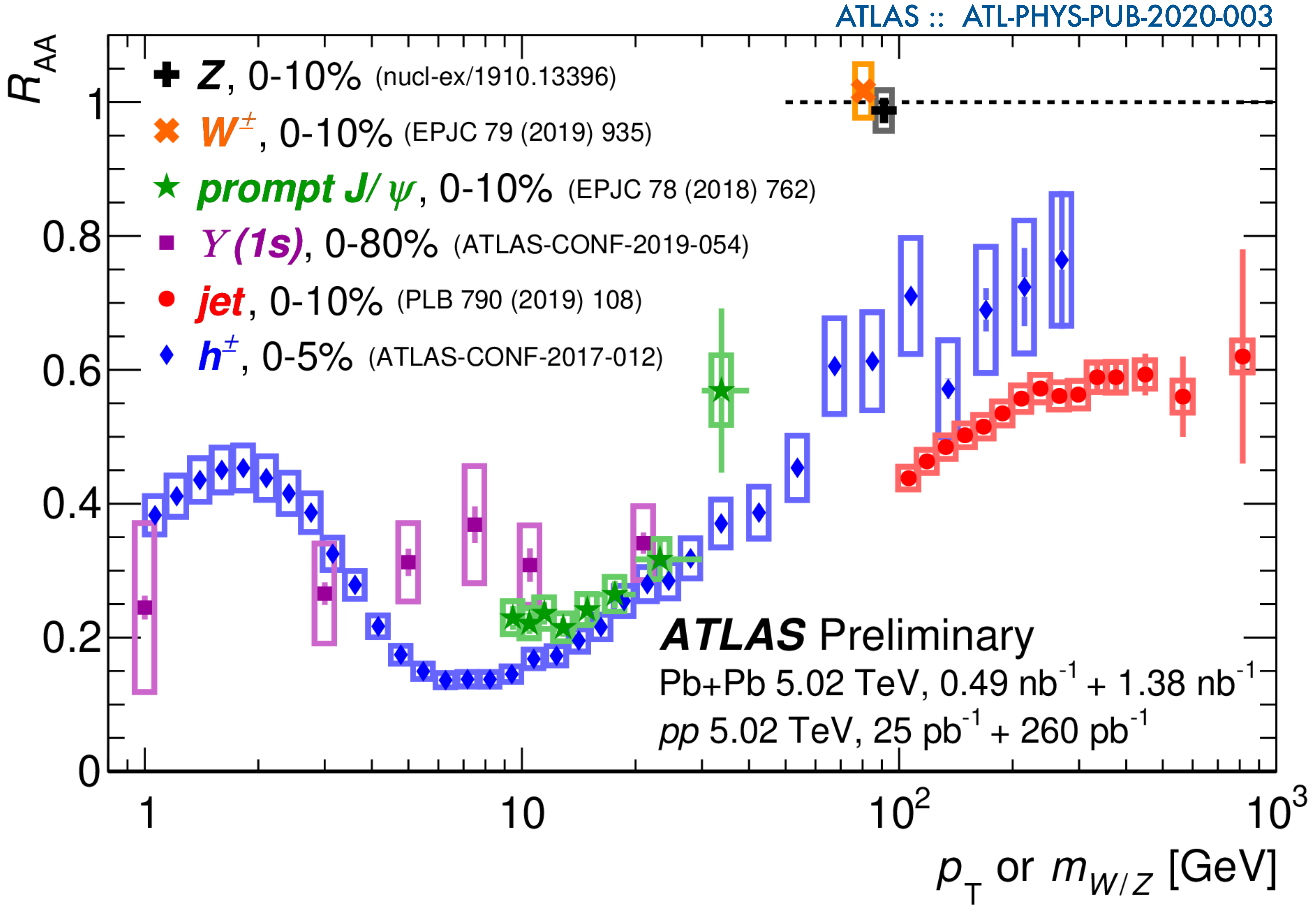
FROM ANTENNAS TO JETS



Salgado

lessons from observables

JETS AND HADRONS LOSE ENERGY WHEN TRAVERSING QGP



$$R_{AA} = \left.\frac{\sigma^{\rm eff}_{\rm AA}}{\sigma^{\rm eff}_{\rm pp}}\right|_{p_T}$$

$$\sigma^{\rm eff}_{\rm pp} = \sigma_{\rm pp}$$

$$\sigma^{\rm eff}_{\rm AA} = \sigma_{\rm AA}/\langle N_{\rm coll}\rangle$$

essentially measures fraction of jets that lost little or no energy

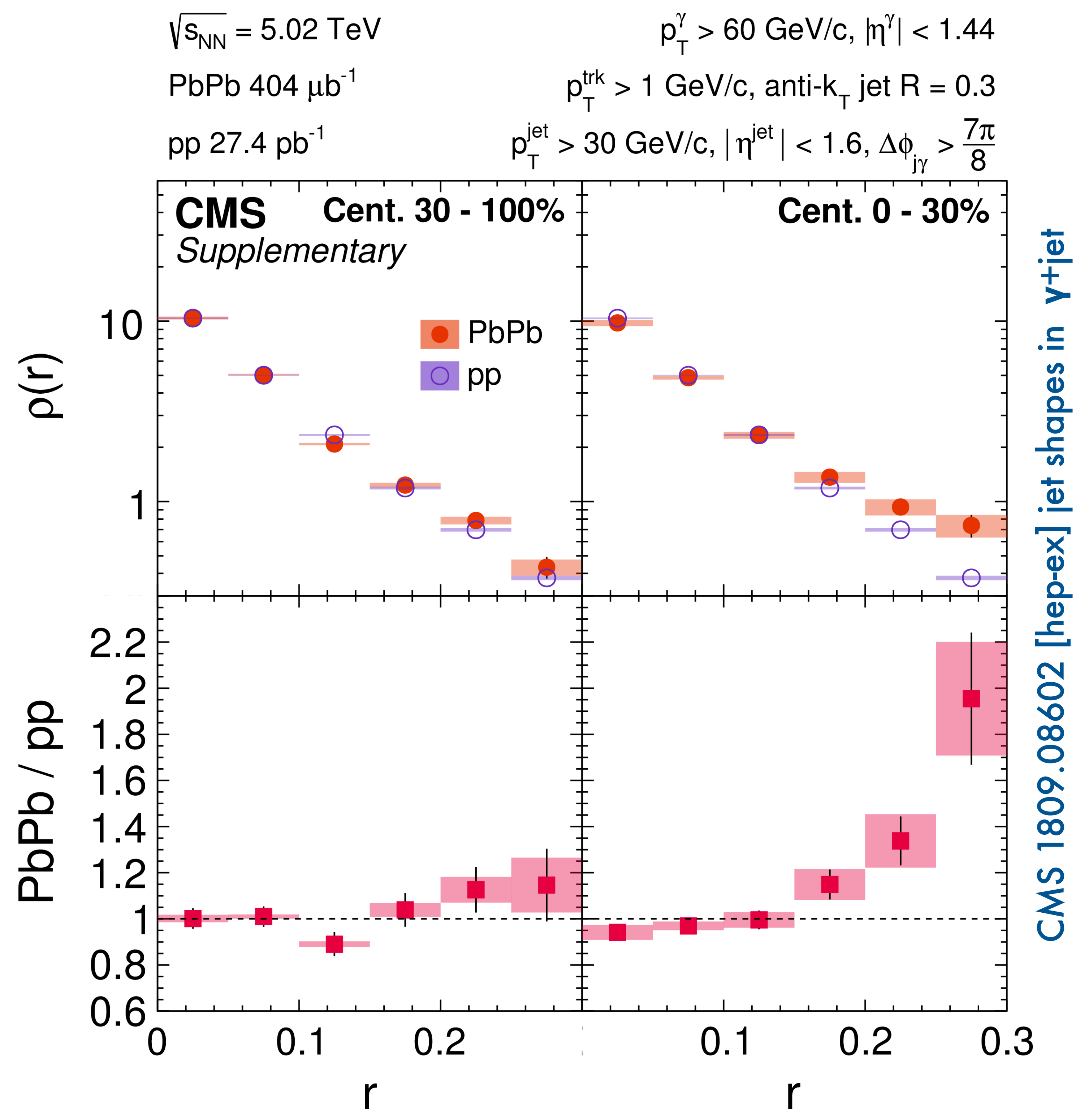
- in steeply falling spectrum large energy losses translate into very small effects
- R_{AA} provides quantitative handle on energy loss only within some model framework
- it compares jets [hadrons] that were detected with same p_T, not born alike

- R_{AA} only measures suppression :: it does not quantify energy loss in a model independent way
- both jets and hadrons (which belong to jets) are suppressed, but differently

SUPPRESSION IS NOT THE SAME AS ENERGY LOSS

- the standard approach to assess QGP effects on jets [quenching] compares a given observable in AA and pp collisions for jets with the same reconstructed p_t
    - e.g., a jet shape

$$\rho(r) = \frac{1}{\delta r} \frac{\sum_{\text{jets}} \sum_{r_a<r<r_b} (p_T^{\text{trk}}/p_T^{\text{jet}})}{\sum_{\text{jets}} \sum_{0<r<r_f} (p_T^{\text{trk}}/p_T^{\text{jet}})},$$



CMS 1809.08602 [hep-ex] jet shapes in γ+jet

comparison between AA and pp at same reconstructed jet p_t confounds QGP-induced shape modification with bin-migration [survivor bias] effects

- here the comparison is between jets that were born different
- again, some model framework that must be invoked for assessment of what was modified in a jet

BETTER CAN DE DONE

Phys. Rev. Lett. 122 (2019), no. 22 222301

- divide jet samples sorted in p_t [from highest] in quantiles of equal probability
- compare the p_t of jets in AA and pp in *the same quantile*

$$Q_{AA} = \left. \frac{p_T^{\mathrm{AA}}}{p_T^{\mathrm{pp}}} \right|_{\Sigma^{\mathrm{eff}}}$$

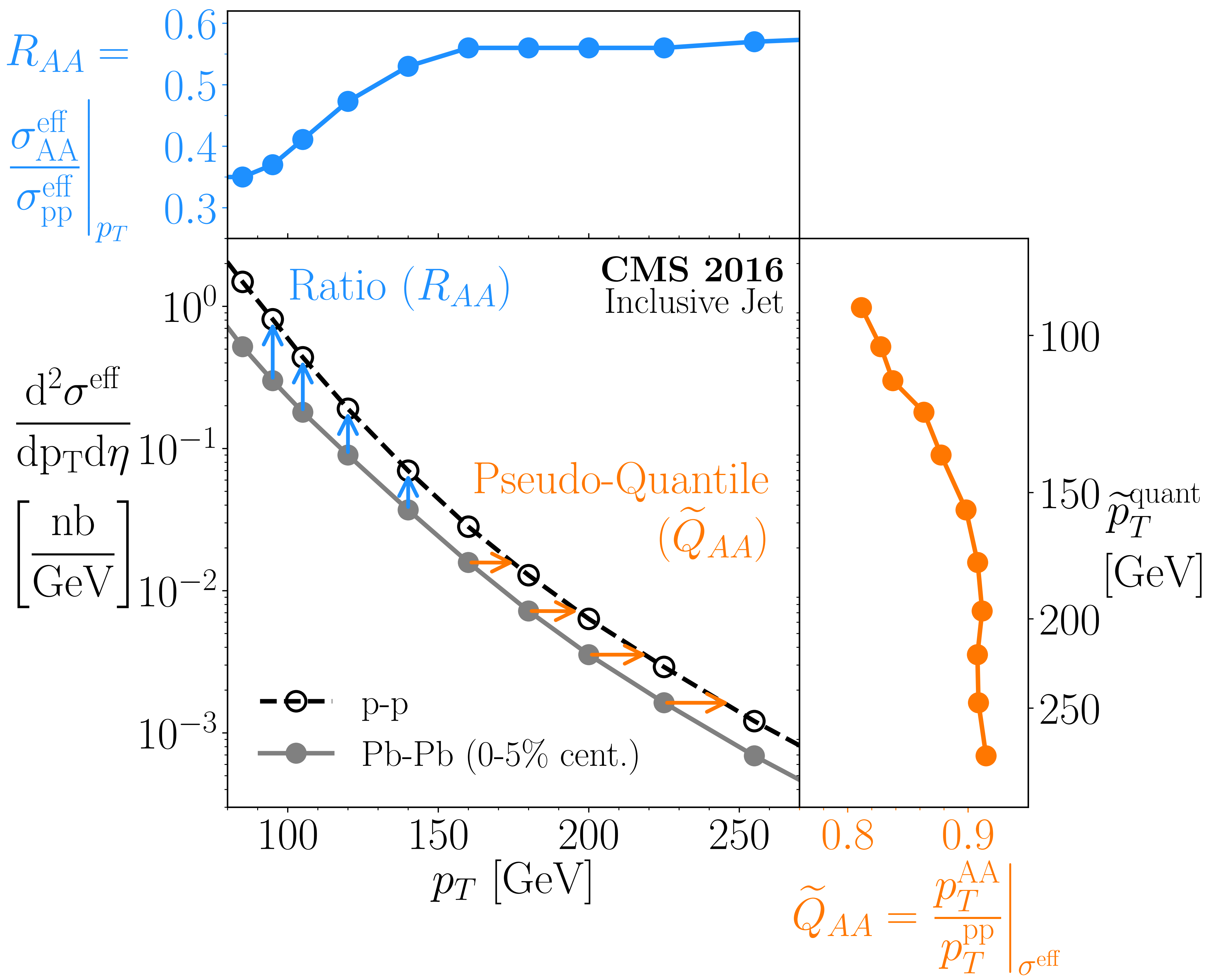
$$\Sigma^{\mathrm{eff}}(p_T^{\mathrm{min}}) = \int_{p_T^{\mathrm{min}}}^{\infty} \mathrm{d}p_T \, \frac{\mathrm{d}\sigma^{\mathrm{eff}}}{\mathrm{d}p_T}$$

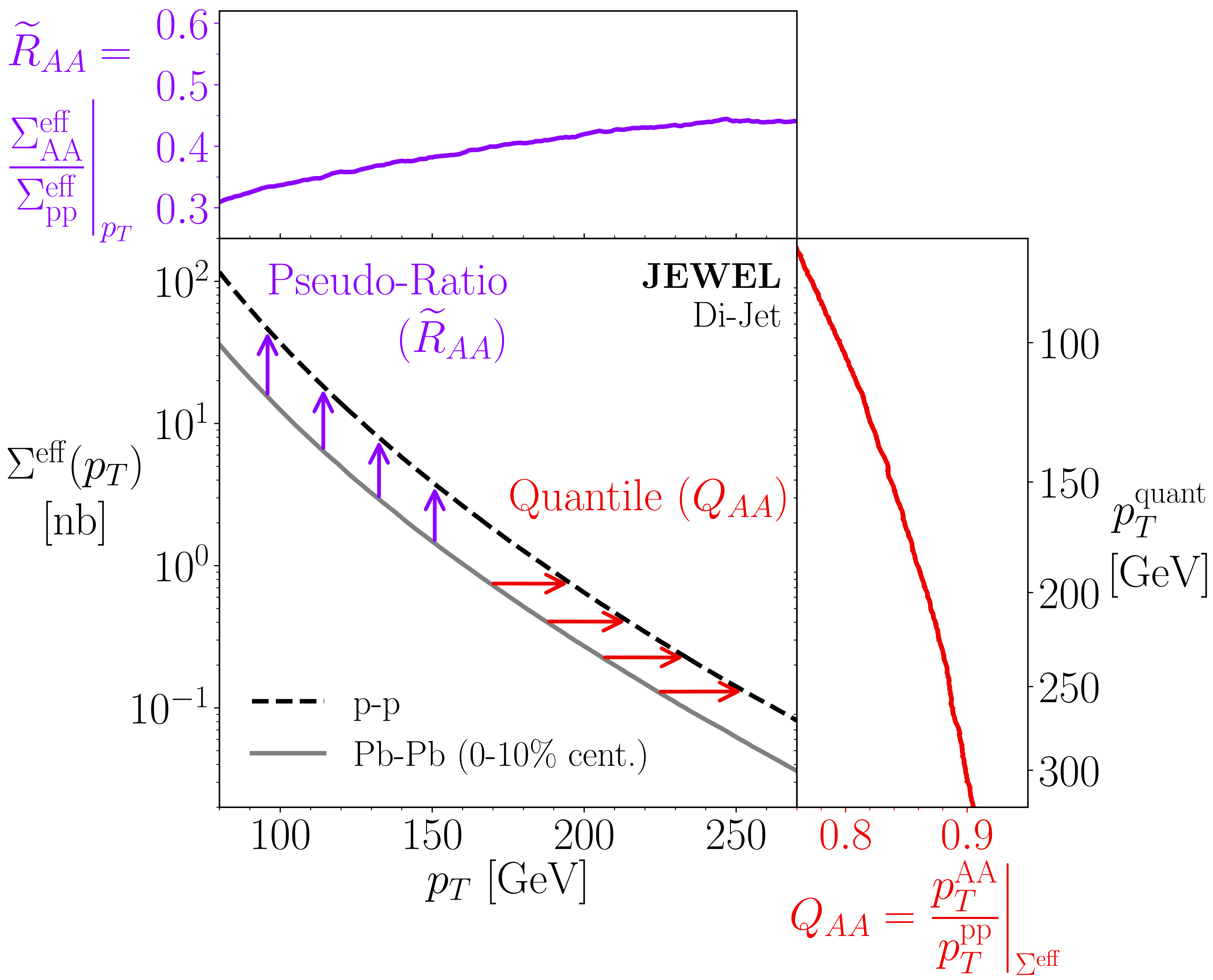
(1-QAA) is a proxy for the average energy loss :: would be exact if energy loss was strictly monotonic

QAA is also the (average) solution to the optimal transport problem, in the space of all allowed theories, of deforming pp spectrum into AA spectrum

QUANTILE PROCEDURE

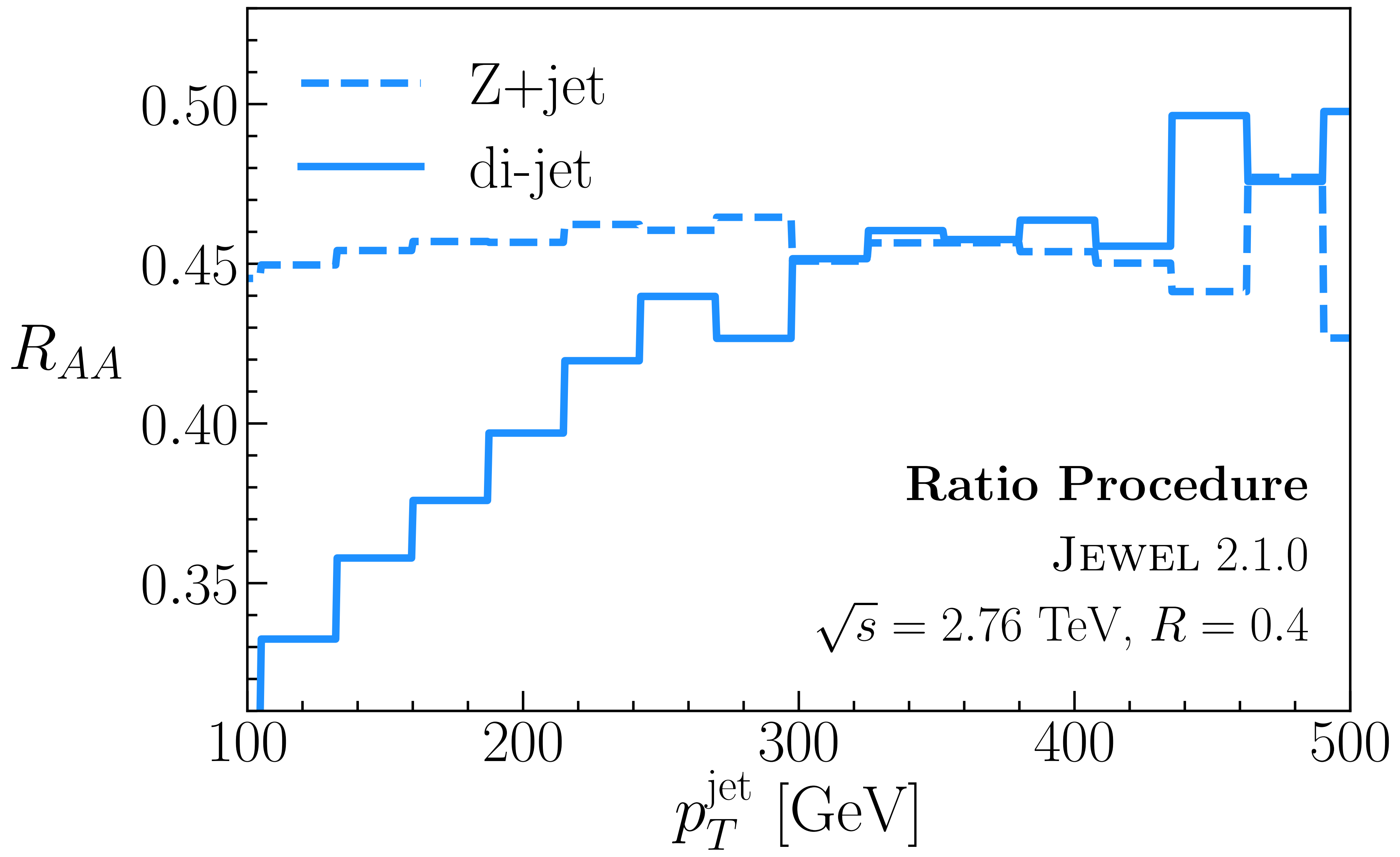
Phys. Rev. Lett. 122 (2019), no. 22 222301

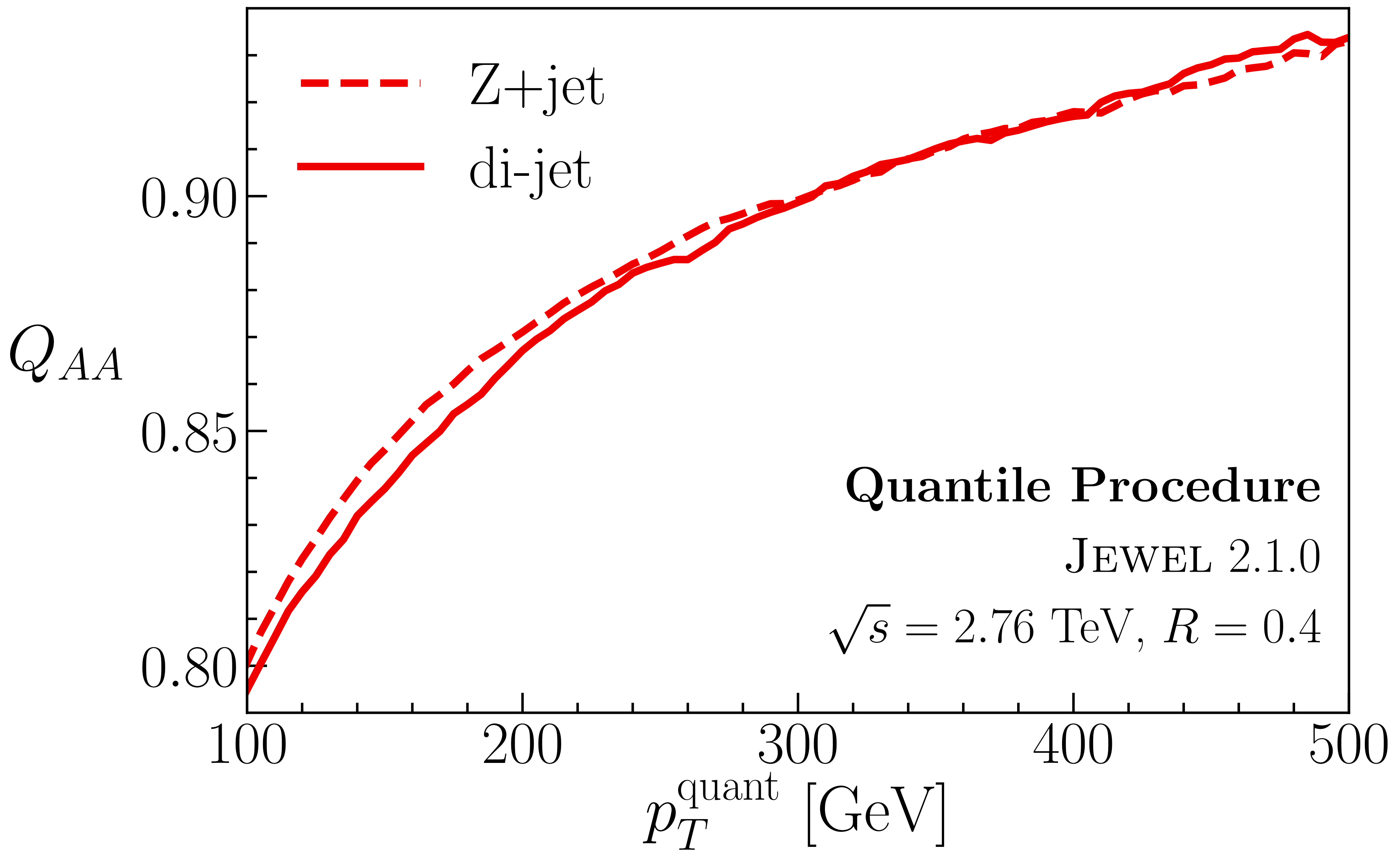




COMPLEMENTARY INFORMATION

Phys. Rev. Lett. 122 (2019), no. 22 222301

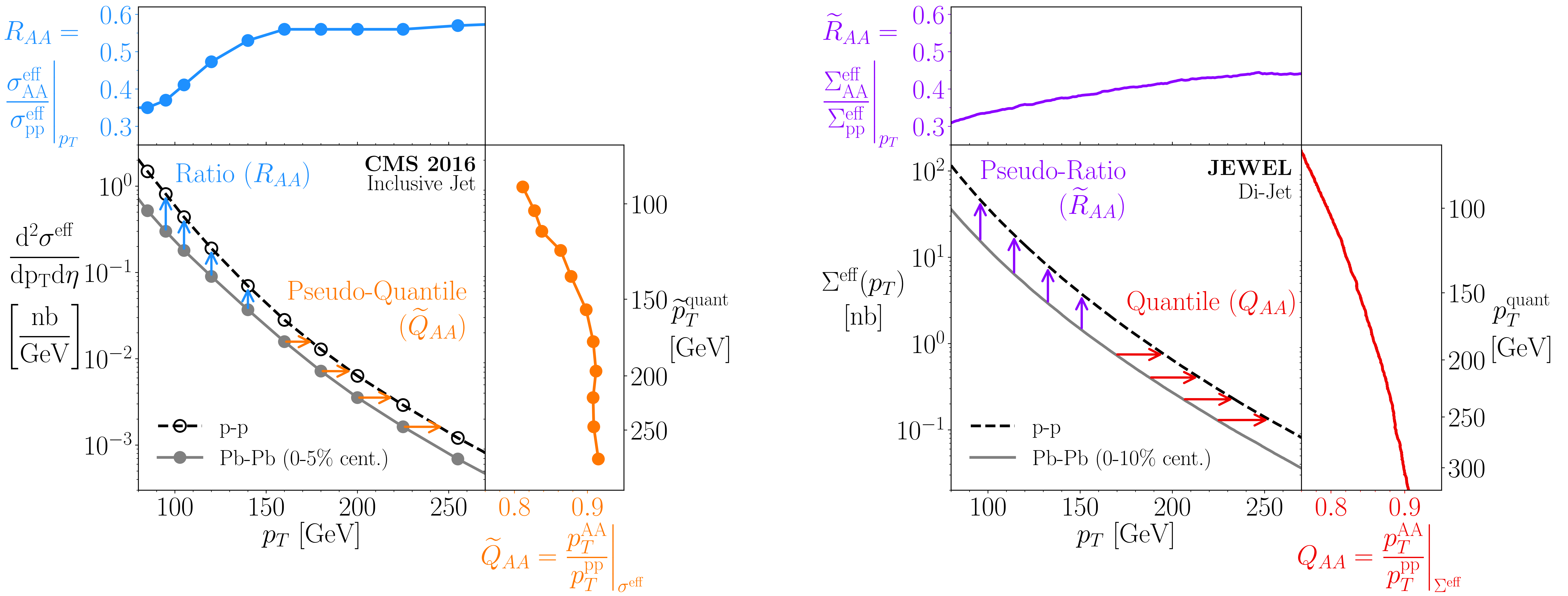




- Q_{AA} and R_{AA} provide very different information
  - R_{AA} depends on different spectral shape for quark and gluon initiated jets :: Q_{AA} does not

QUANTILE PROCEDURE AS PROXY FOR INITIAL ENERGY

Phys. Rev. Lett. 122 (2019), no. 22 222301

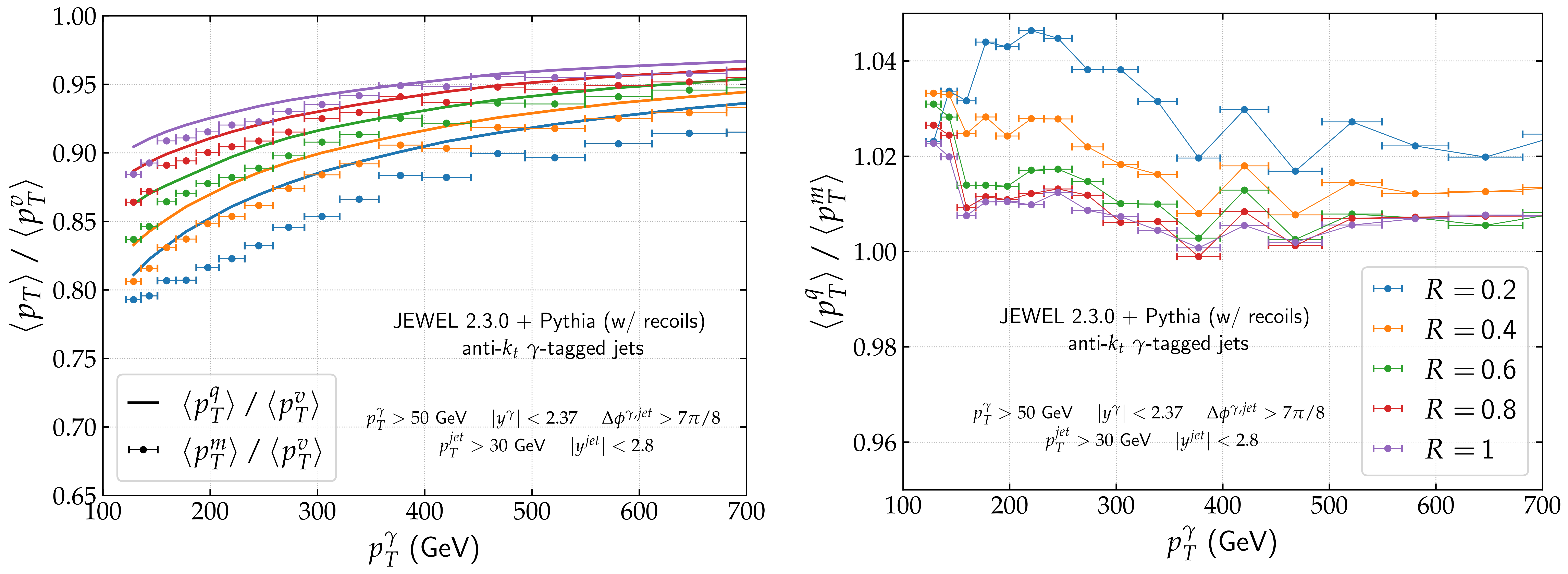


- provides a proxy for the initial p_t of a quenched [prior to QGP-induced energy loss]

$$\Sigma^{eff}_{pp}(p_T^{quant}) \equiv \Sigma^{eff}_{AA}(p_T^{AA})$$

VALIDATION

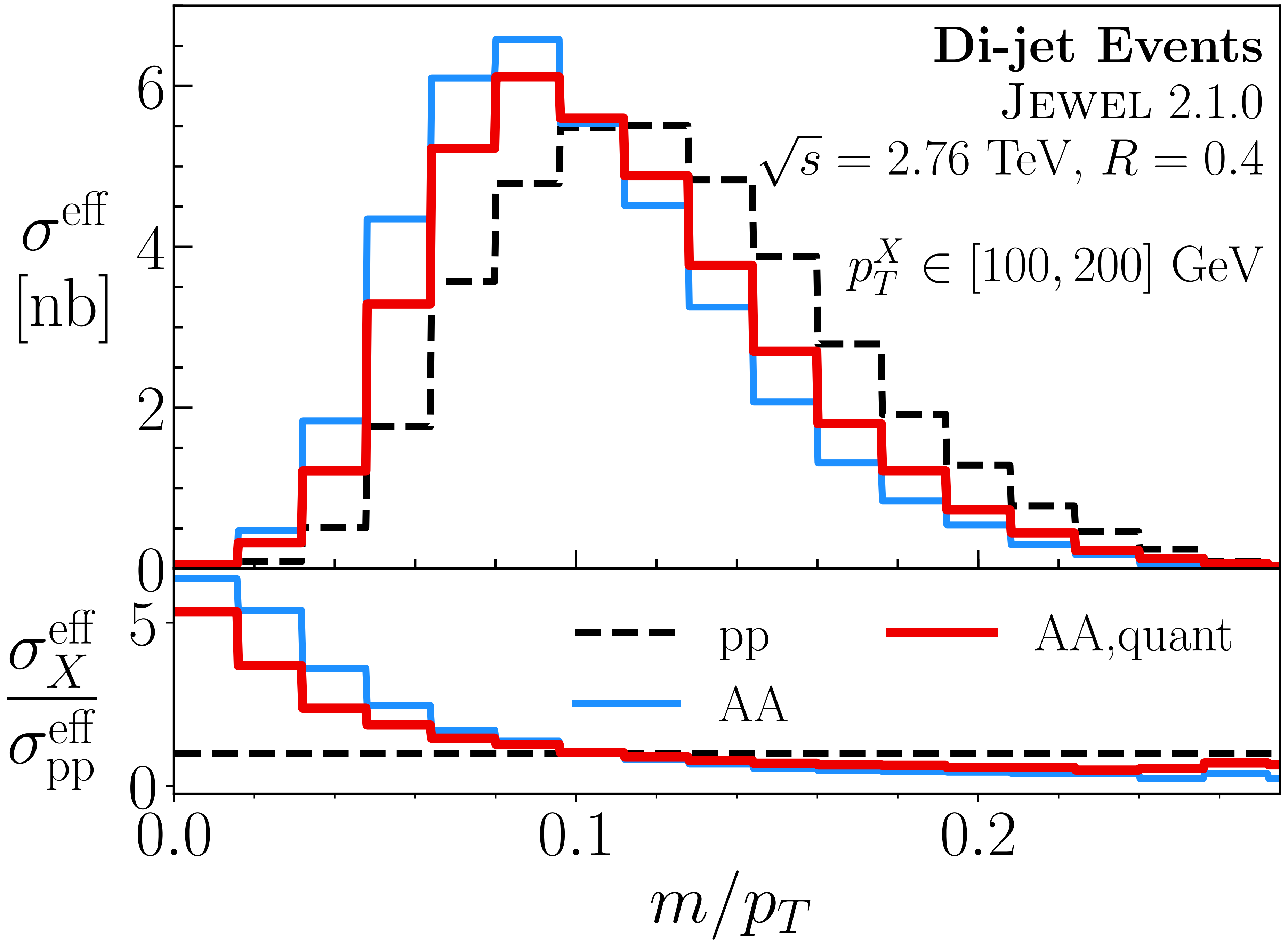
2409.12238 [hep-ph]



- quantile procedure closely reconstructs unquenched [initial] p_t :: in this case measurable

MITIGATION OF MIGRATION EFFECTS :: AN EXAMPLE

Phys. Rev. Lett. 122 (2019), no. 22 222301



$p_T^{\rm AA} \in [80, 173]$ GeV

$p_T^{\rm quant} \in [100, 200]$ GeV

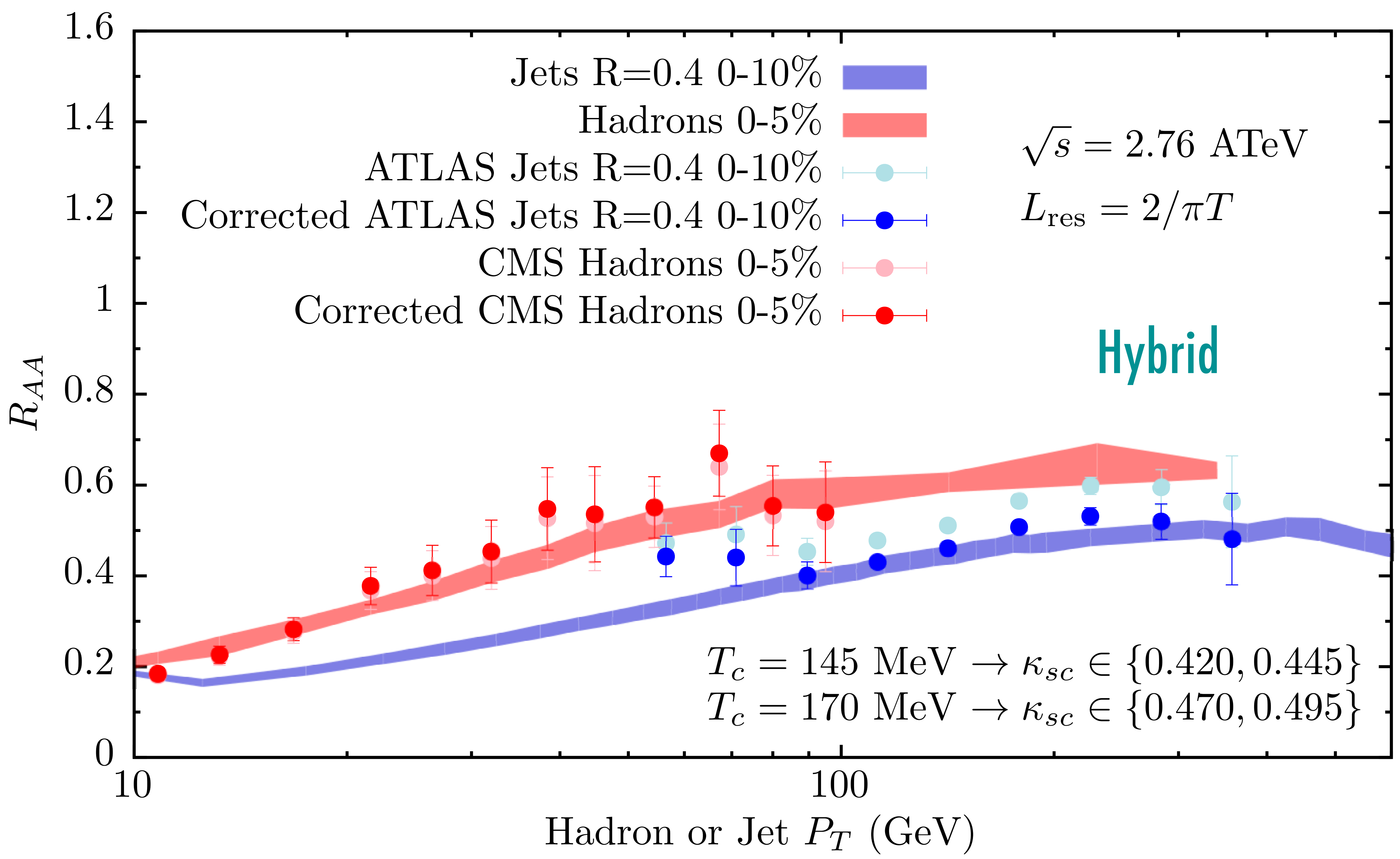
- part of observable modification due to bin migration [comparison of jets with different initial energy]
- quantile procedure isolates ‘true’ modification

survivor bias can be a very sizeable effect and obscure true QGP induced modifications of jet properties

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}

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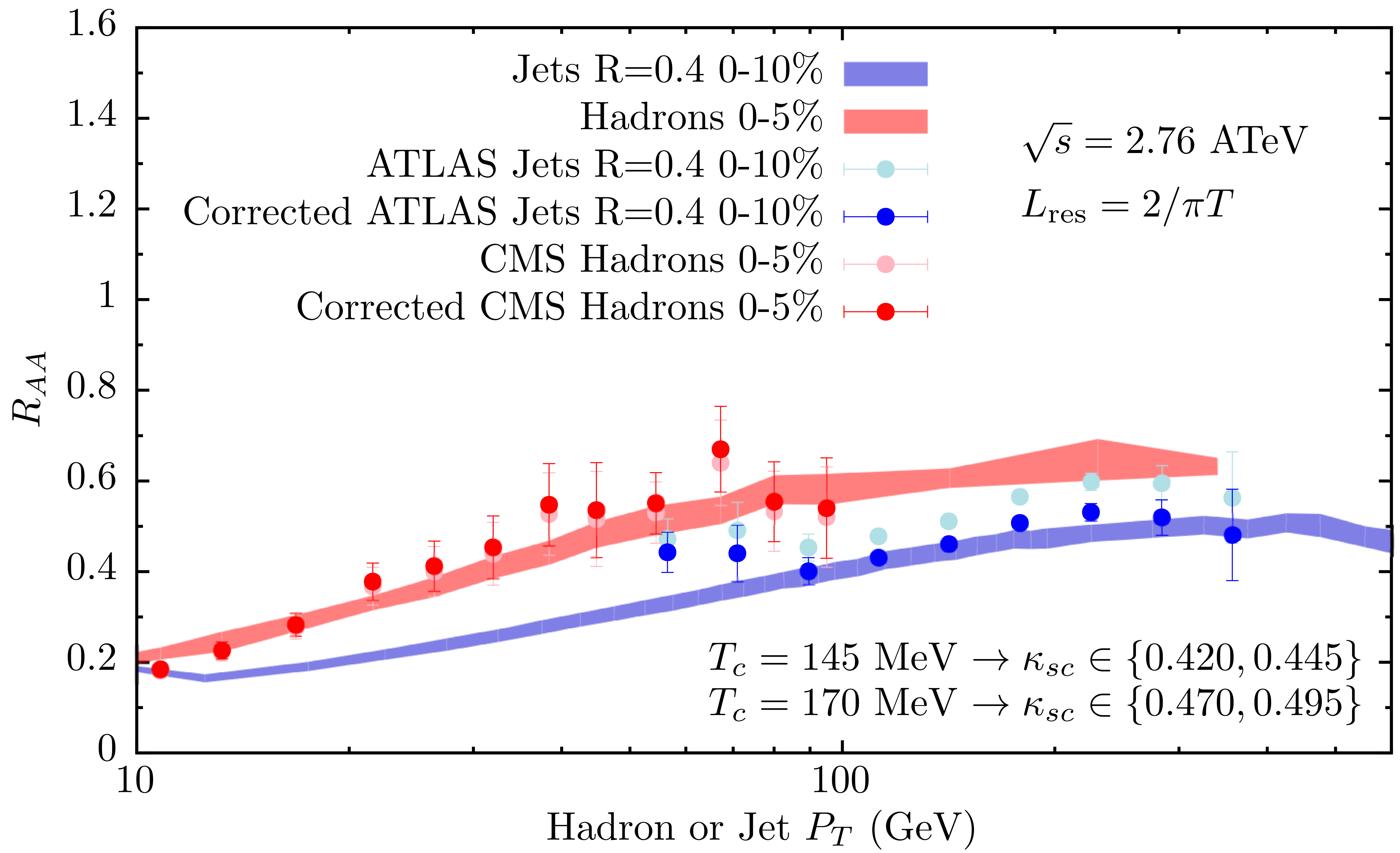
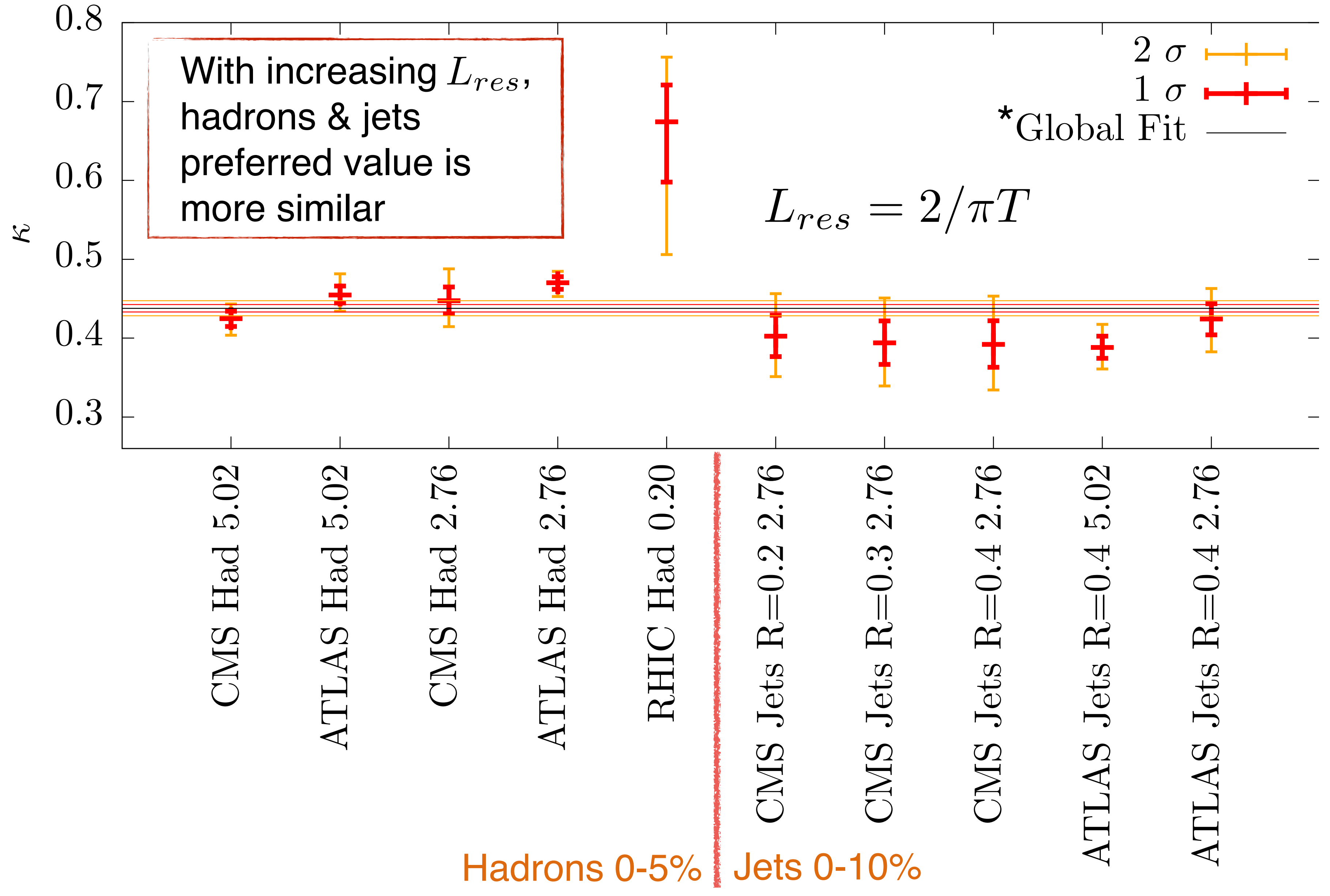




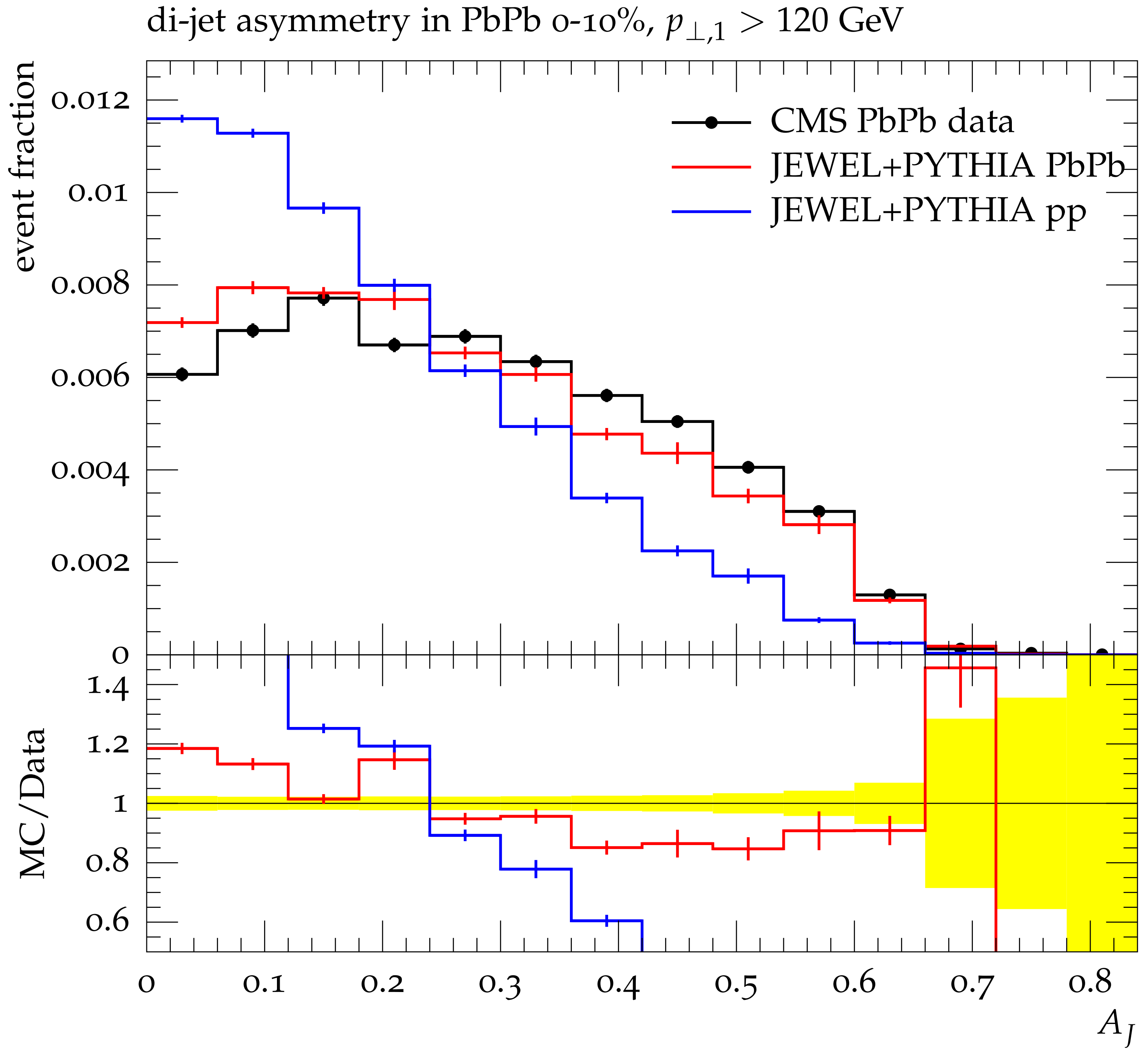
- excellent global fit for LHC data :: some tension with RHIC data
- high p_T hadrons originate from narrow jets [fragmented less] which are less suppressed than inclusive jets
- simultaneous description of jet and hadron R_{AA} natural feature of any approach that treats jets as such [ie, objects resulting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

QGP sees jet substructure

sensitivity to QGP of different scales present in jets can be used to study QGP

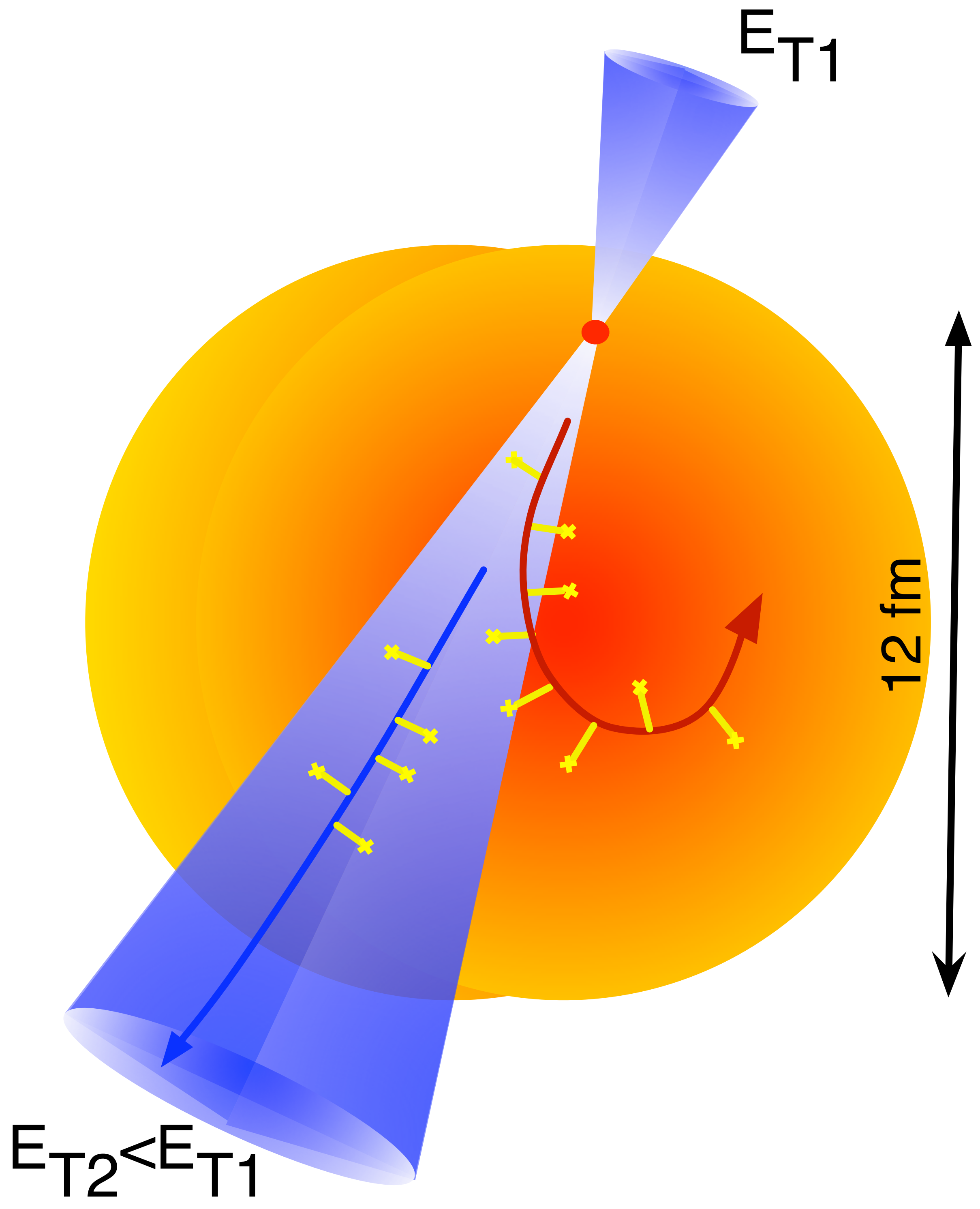
dijet asymmetry

Eur.Phys.J. C76 (2016))



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

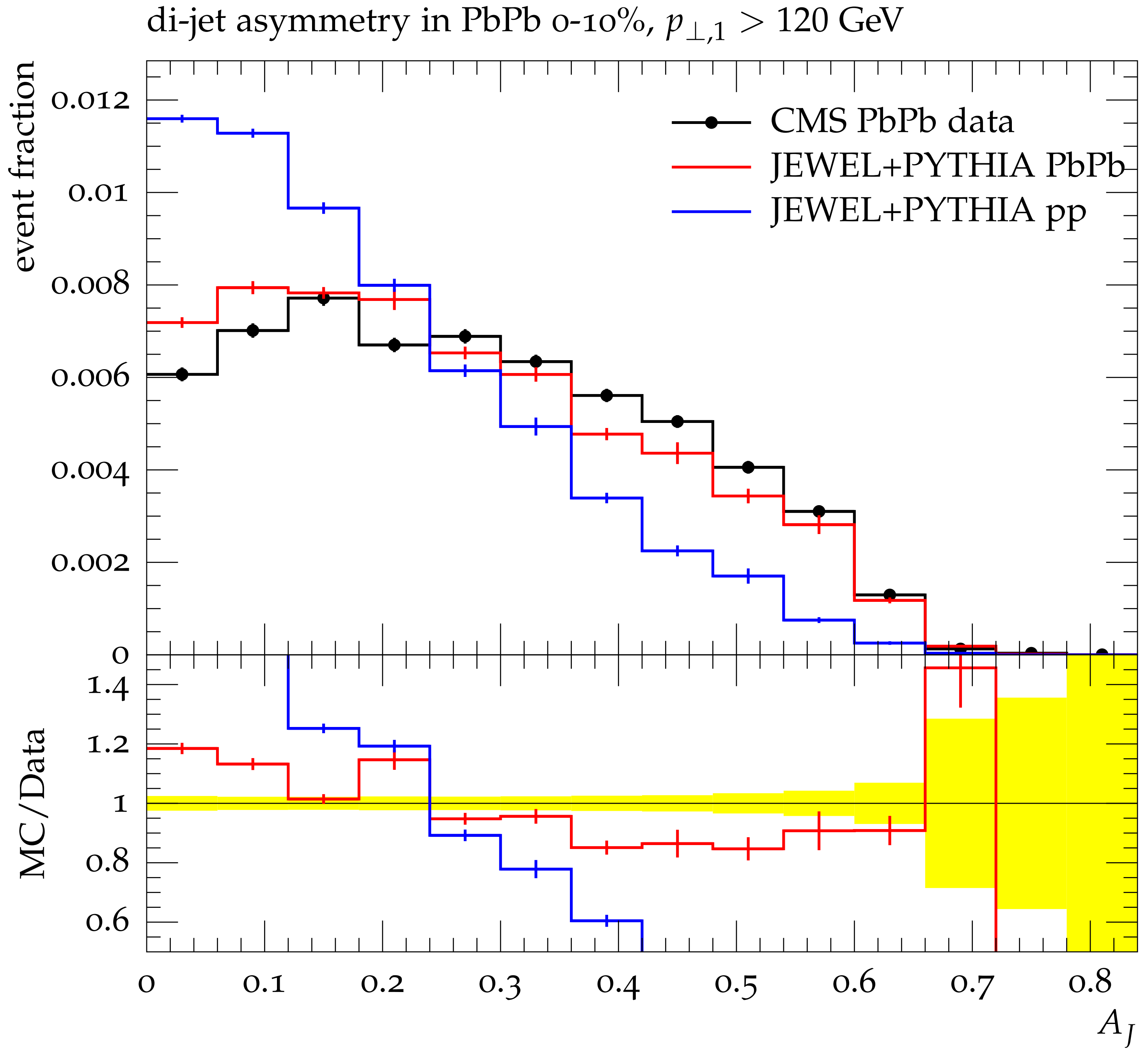
$$A_J = \frac{p_{\perp,1} - p_{\perp,2}}{p_{\perp,1} + p_{\perp,2}}$$



- 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

Eur.Phys.J. C76 (2016))



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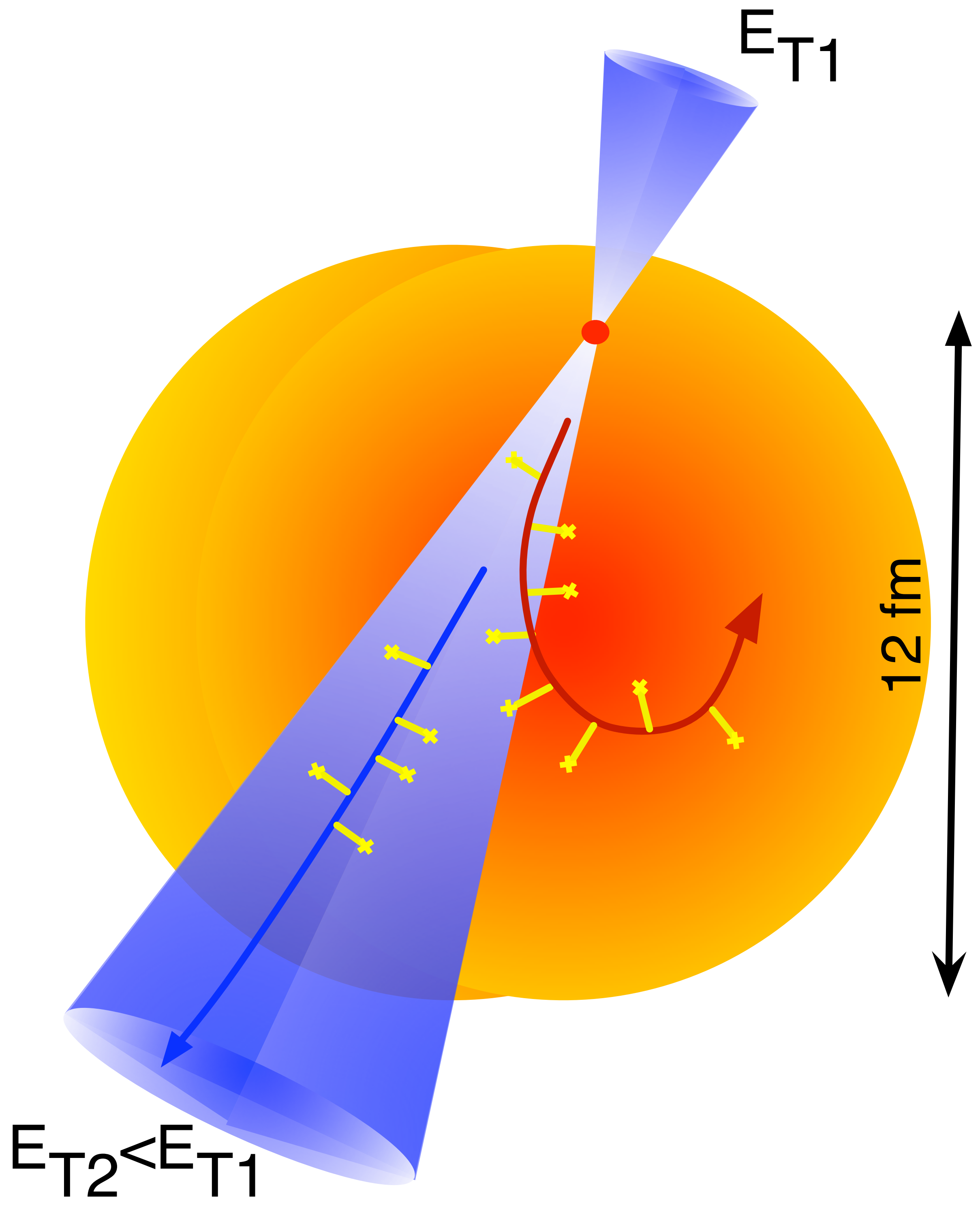
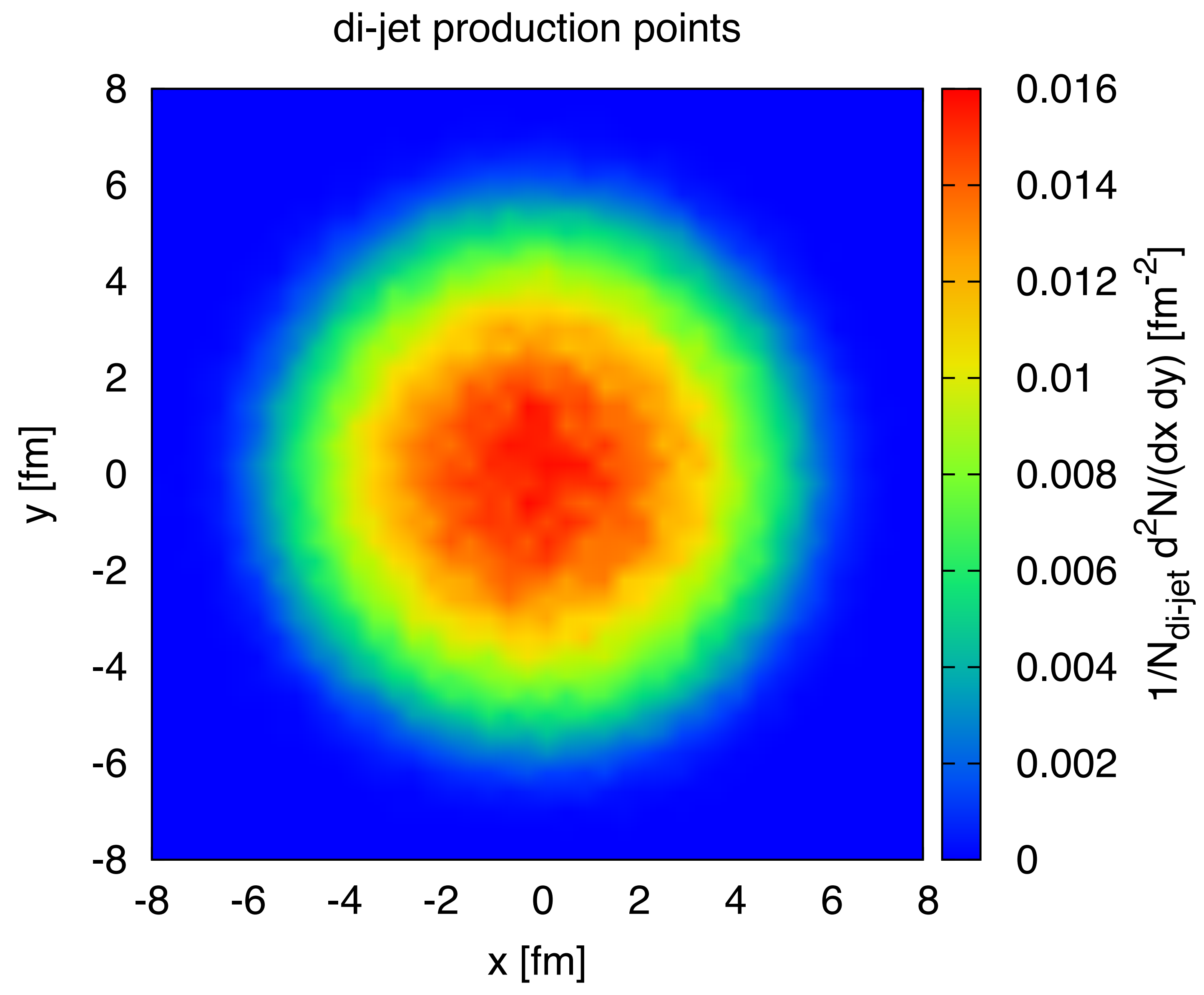


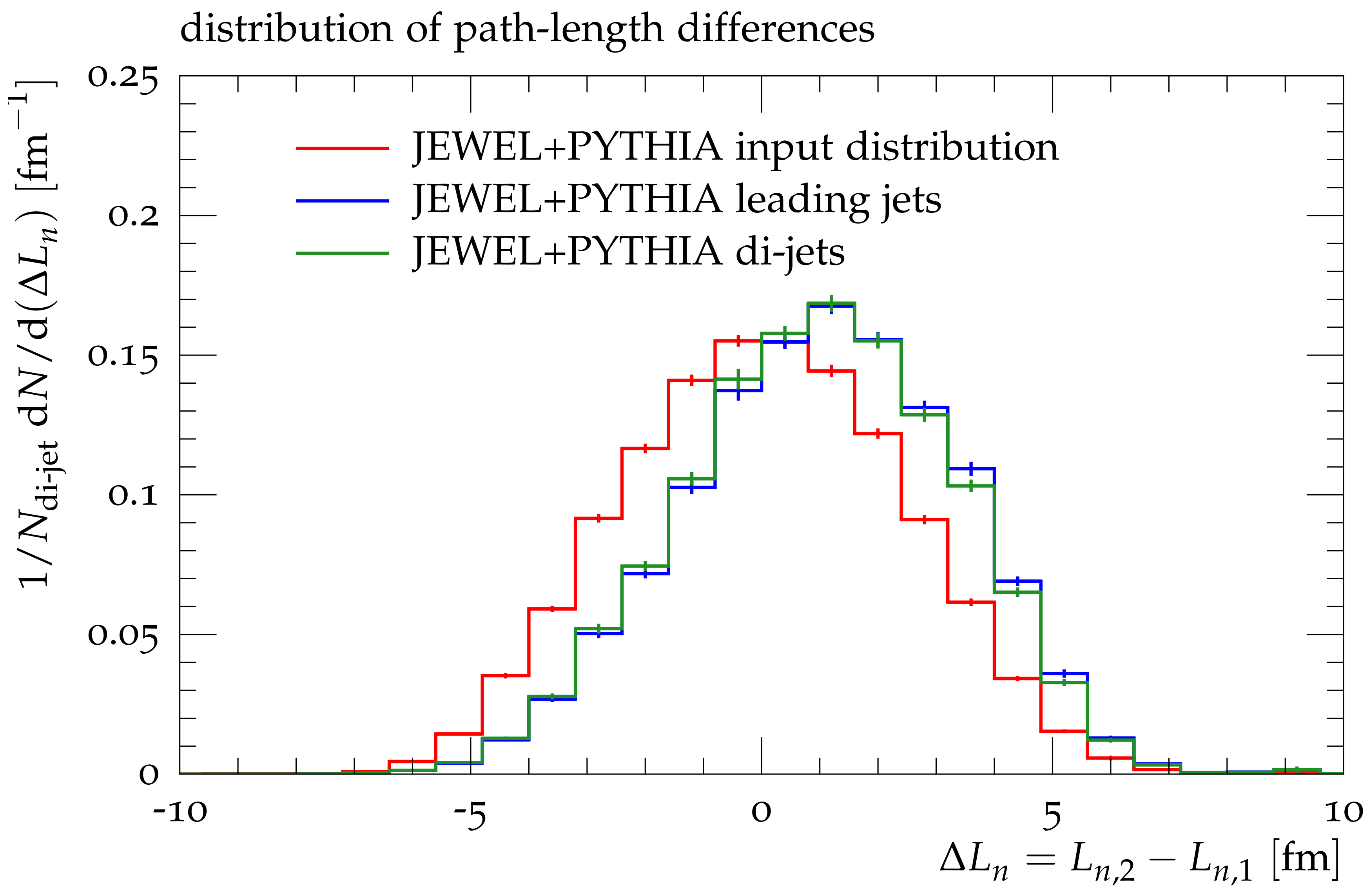
- JEWEL provides good data description
- very tempting naive geometrical interpretation
  - one jet loses more energy than the other DUE TO different traversed amount of QGP matter

really not the case ...

dijet asymmetry

Eur.Phys.J. C76 (2016))





density weighted path-length

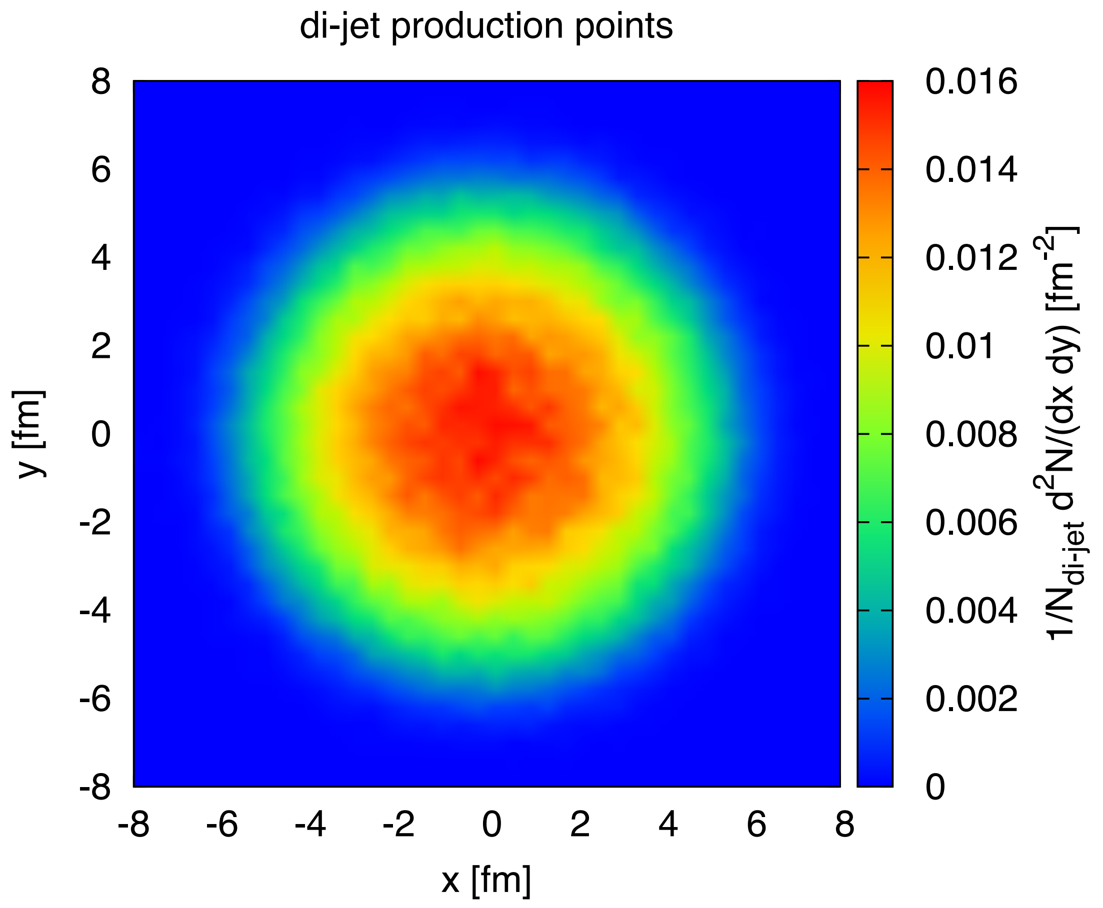
[accounts for medium expansion, rapidity independent for boost invariant medium]

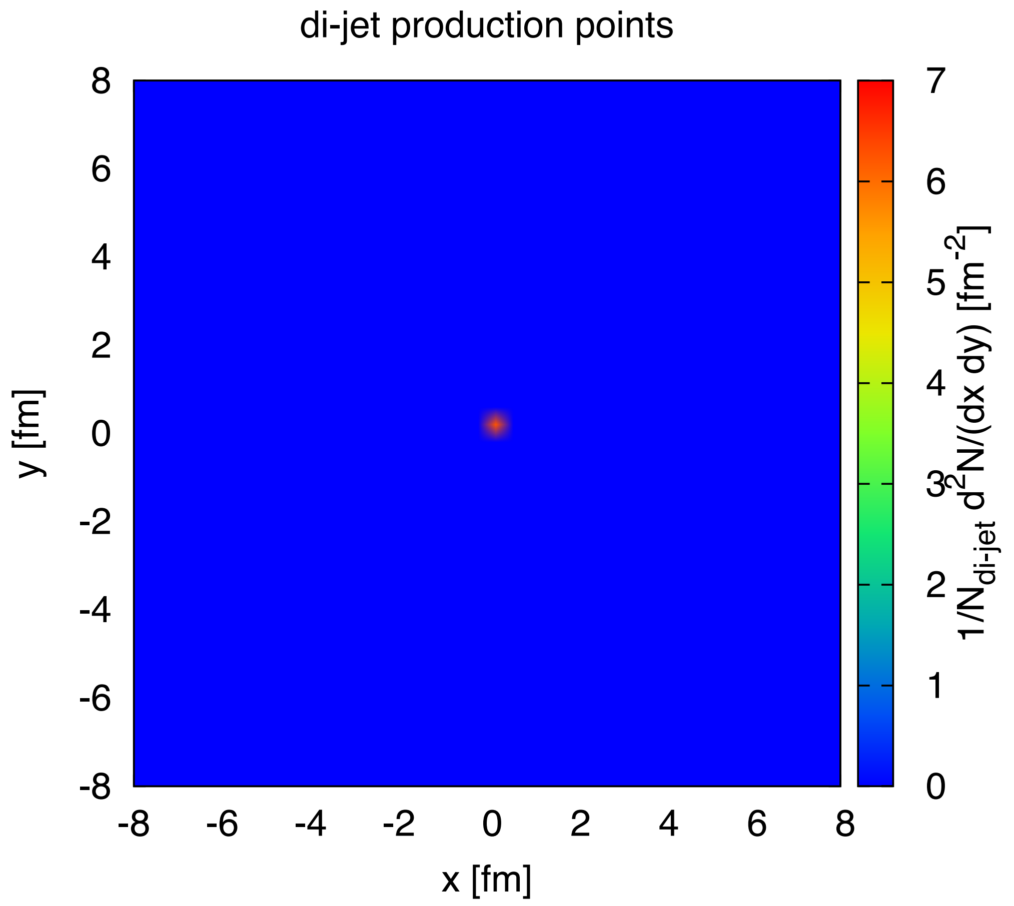
$$L_n = 2\frac{\int d\tau\, \tau n(\mathbf{r}(\tau), \tau)}{\int d\tau\, n(\mathbf{r}(\tau), \tau)}$$

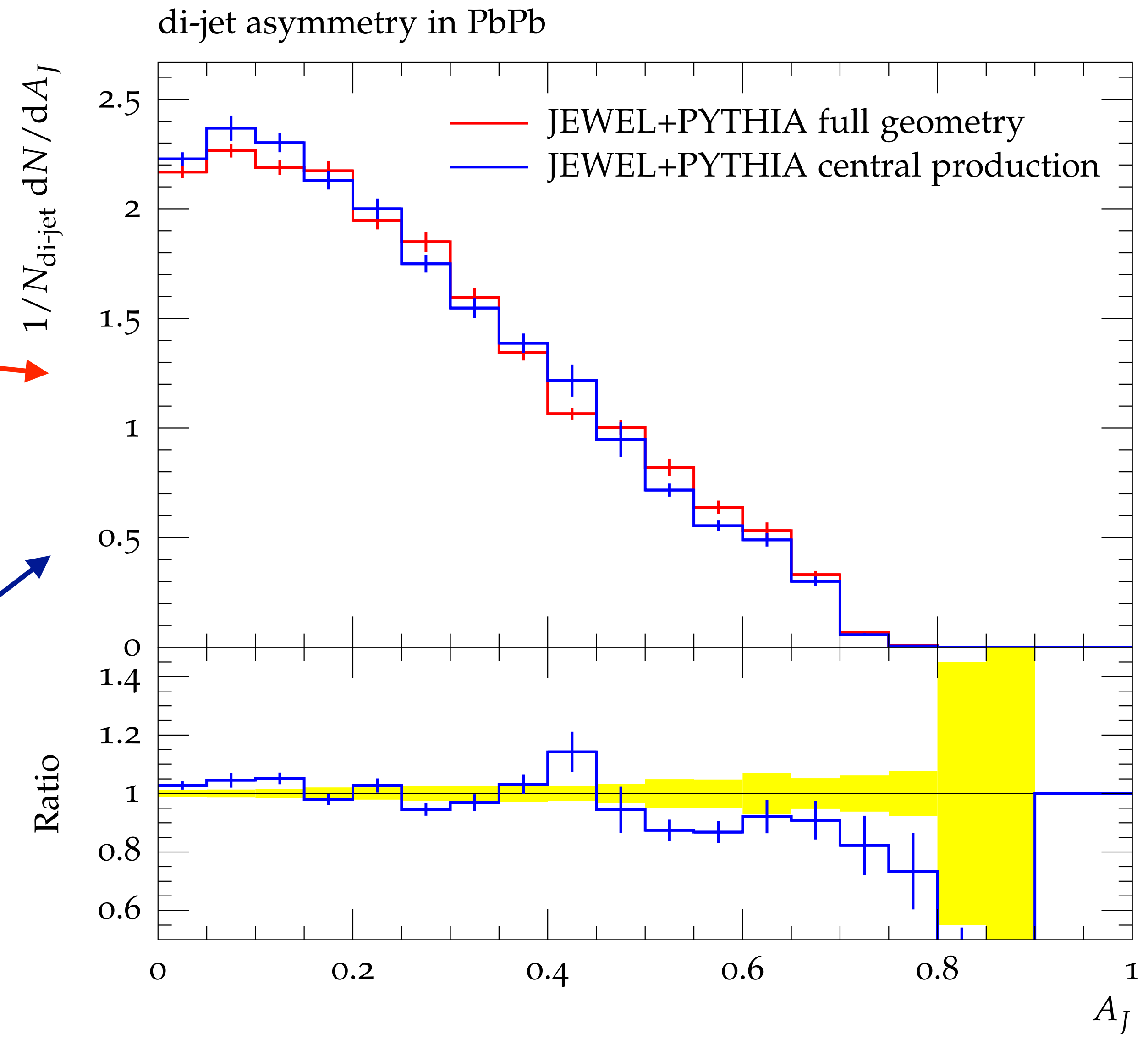
- small bias towards smaller path-length for leading jets
  - however, significant fraction [34%] of events have longer path-length for leading jet
  - consequence of fast medium expansion

dijet asymmetry

Eur.Phys.J. C76 (2016))





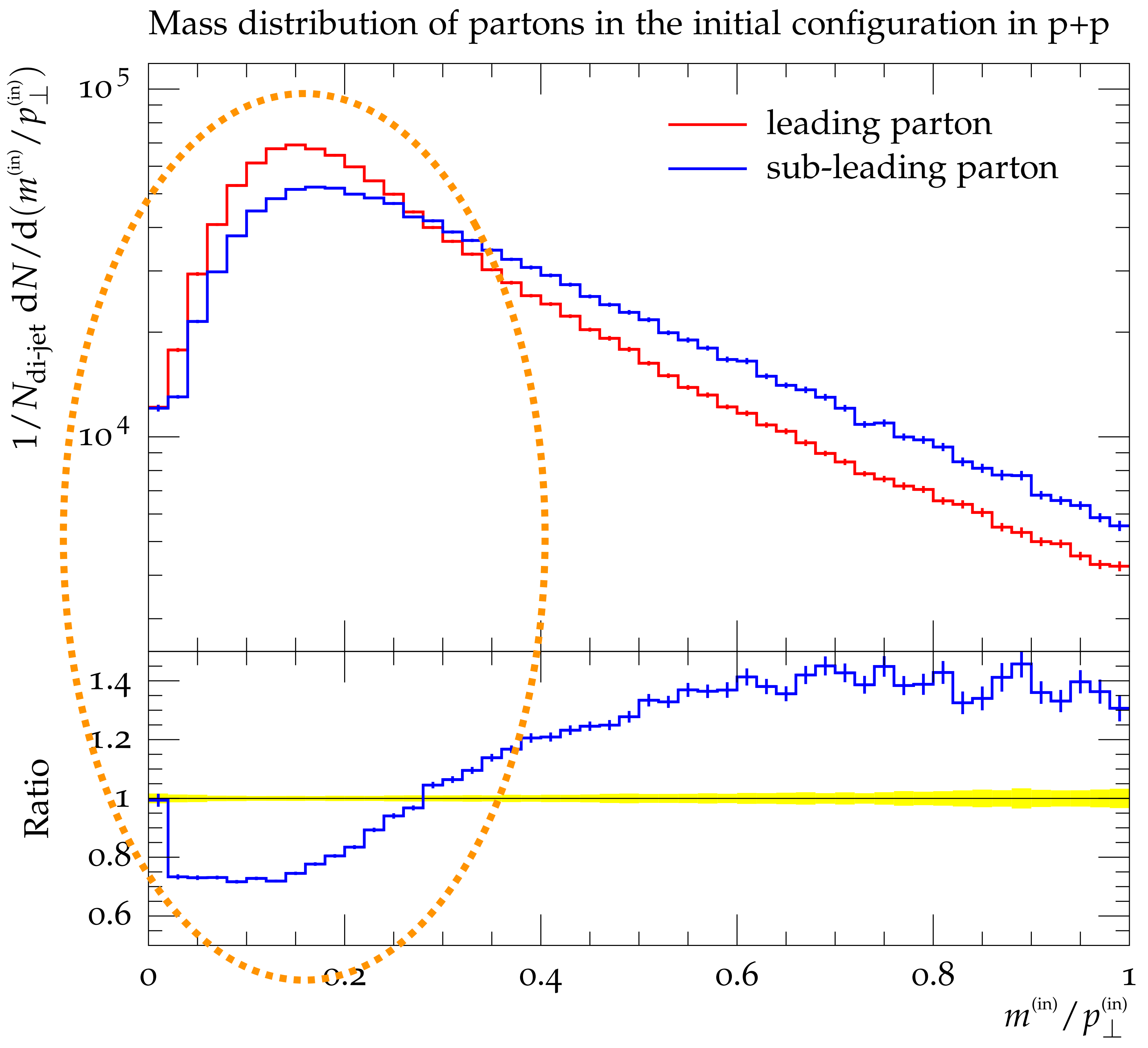


$$A_J = \frac{p_{\perp,1} - p_{\perp,2}}{p_{\perp,1} + p_{\perp,2}}$$

- di-jet event sample with no difference in path-length has 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

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

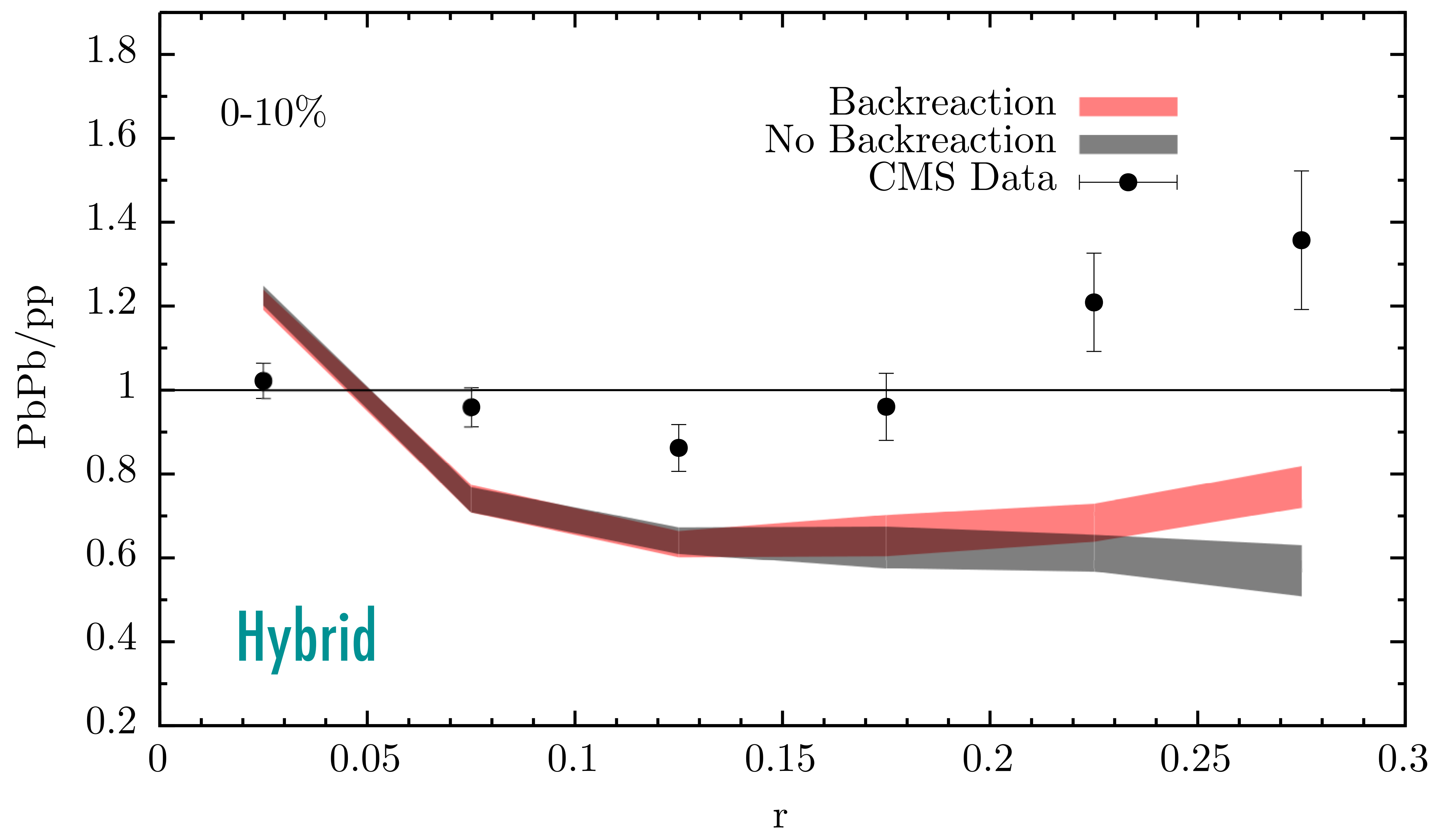
Escobedo, Iancu 1609.06104 [hep-ph]

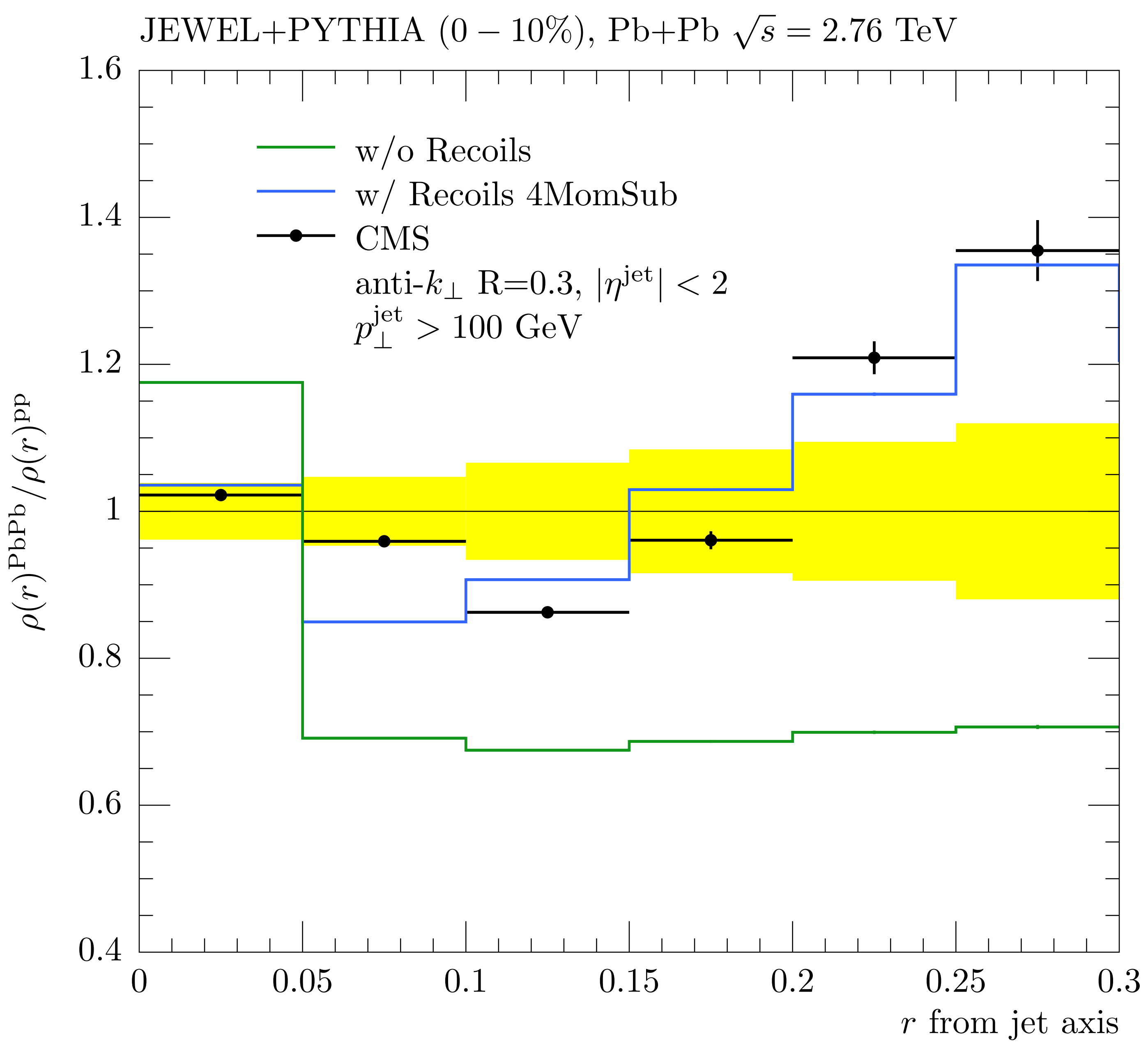
QGP sees inside jets

and total energy loss is indeed dominated by number of constituents

need to be careful not to fall for simplistic intuition

‘discovery’ of medium response



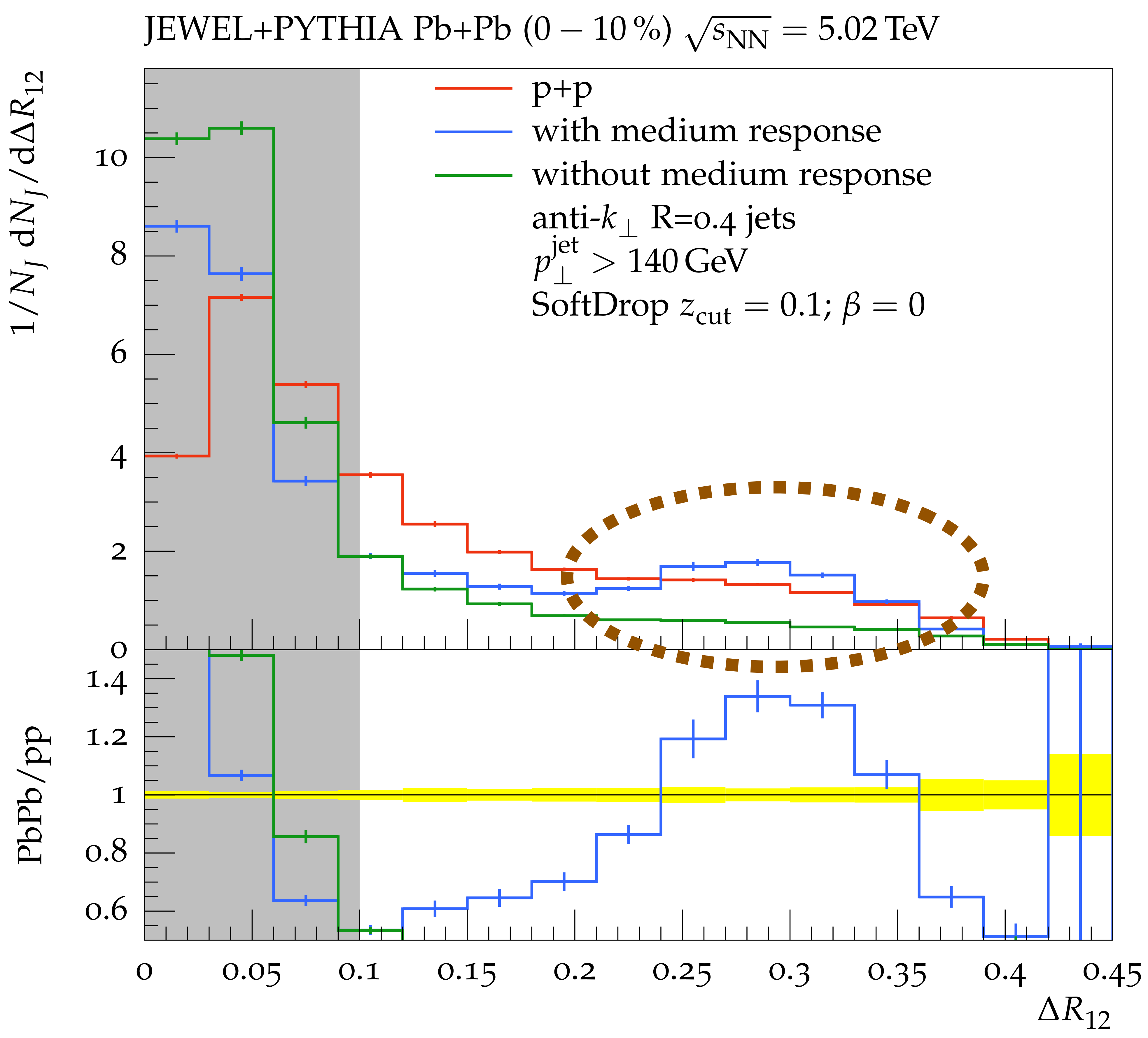


- propagating particles [what will be a jet] modify the QGP they traverse and modification of QGP reconstructed as part of jet
  - inclusion of QGP response in MC improves agreement with data
  - first evidence for importance of QGP response was seen in MC
  - QGP response of full shower remains untractable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

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

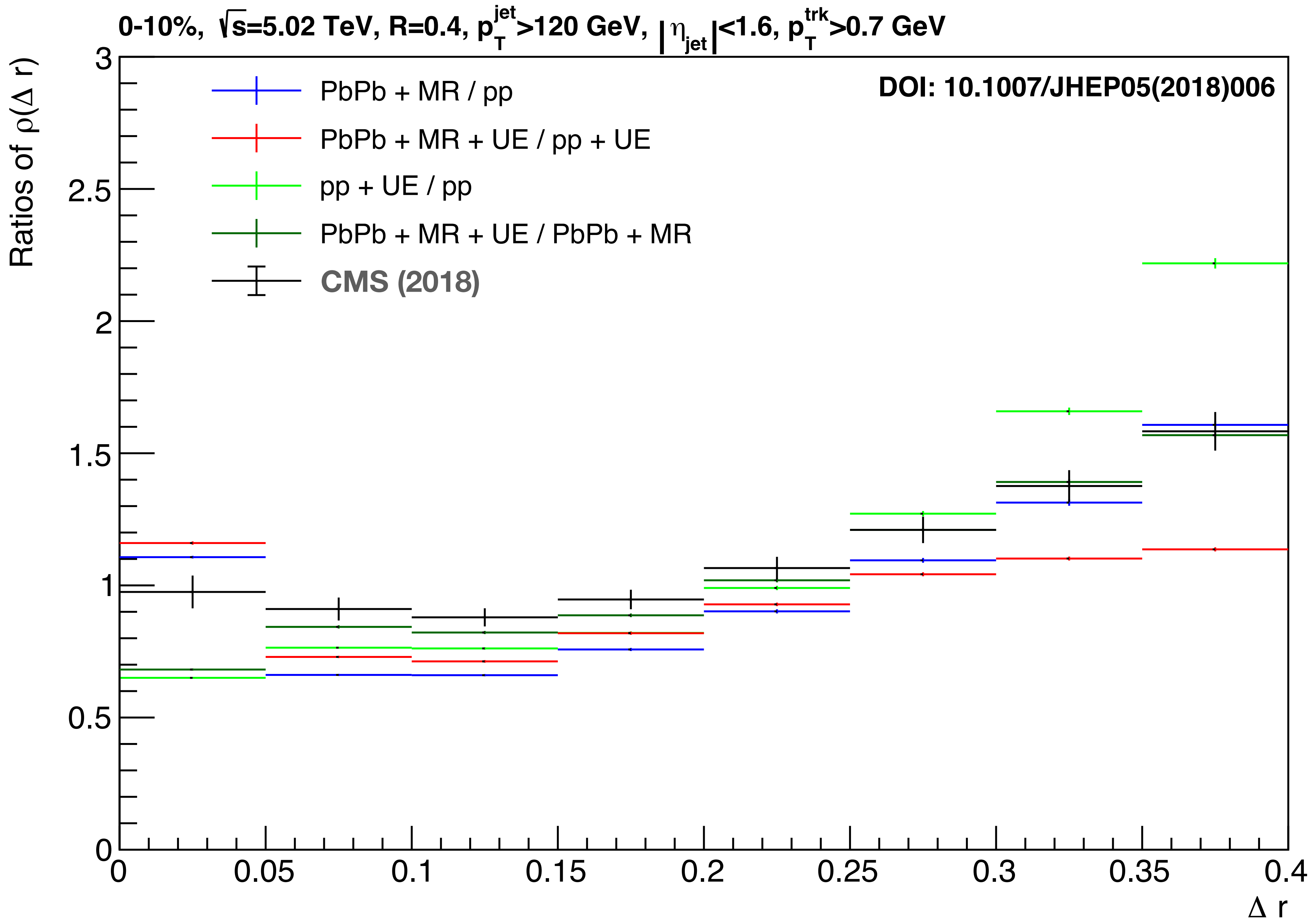
QGP response in jet substructure

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



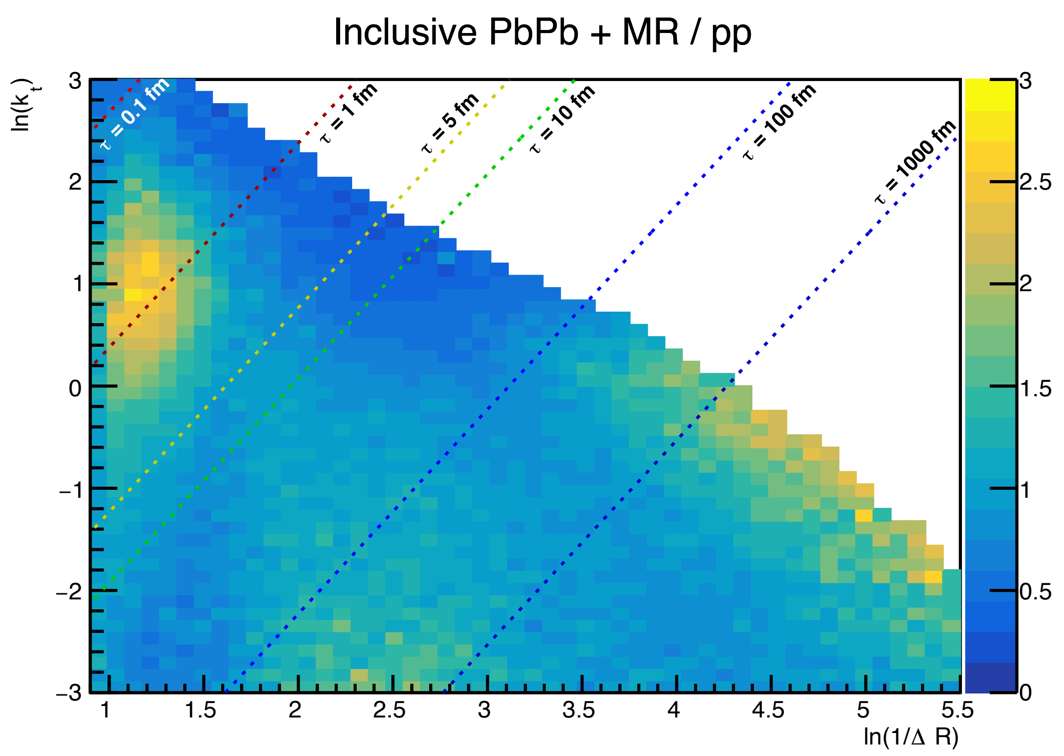
- distance between main prongs of jet declustered with SoftDrop [largest hard splitting angle]
  - clear QGP response signal
  - HOWEVER: effect also present for unmodified jet [no interaction with QGP] embedded in HI event and background subtracted
  - QGP response signal overlaps with contamination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

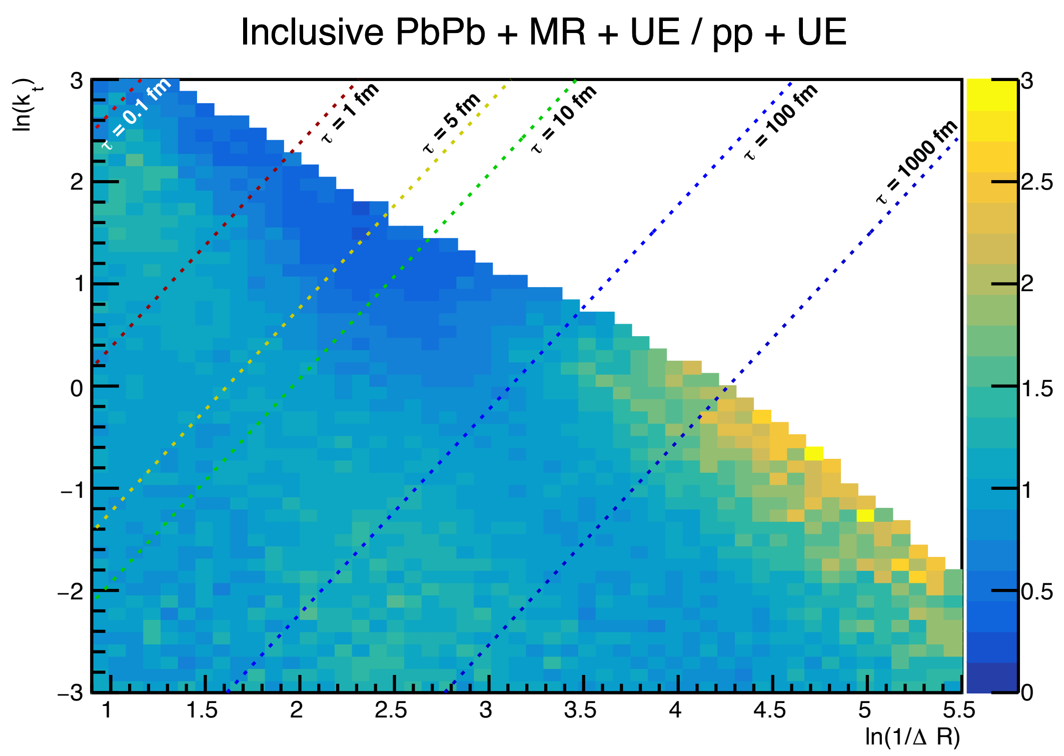
not all observed modifications are due to quenching



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

- apparent agreement with data due to MR not robust once UE contamination accounted for

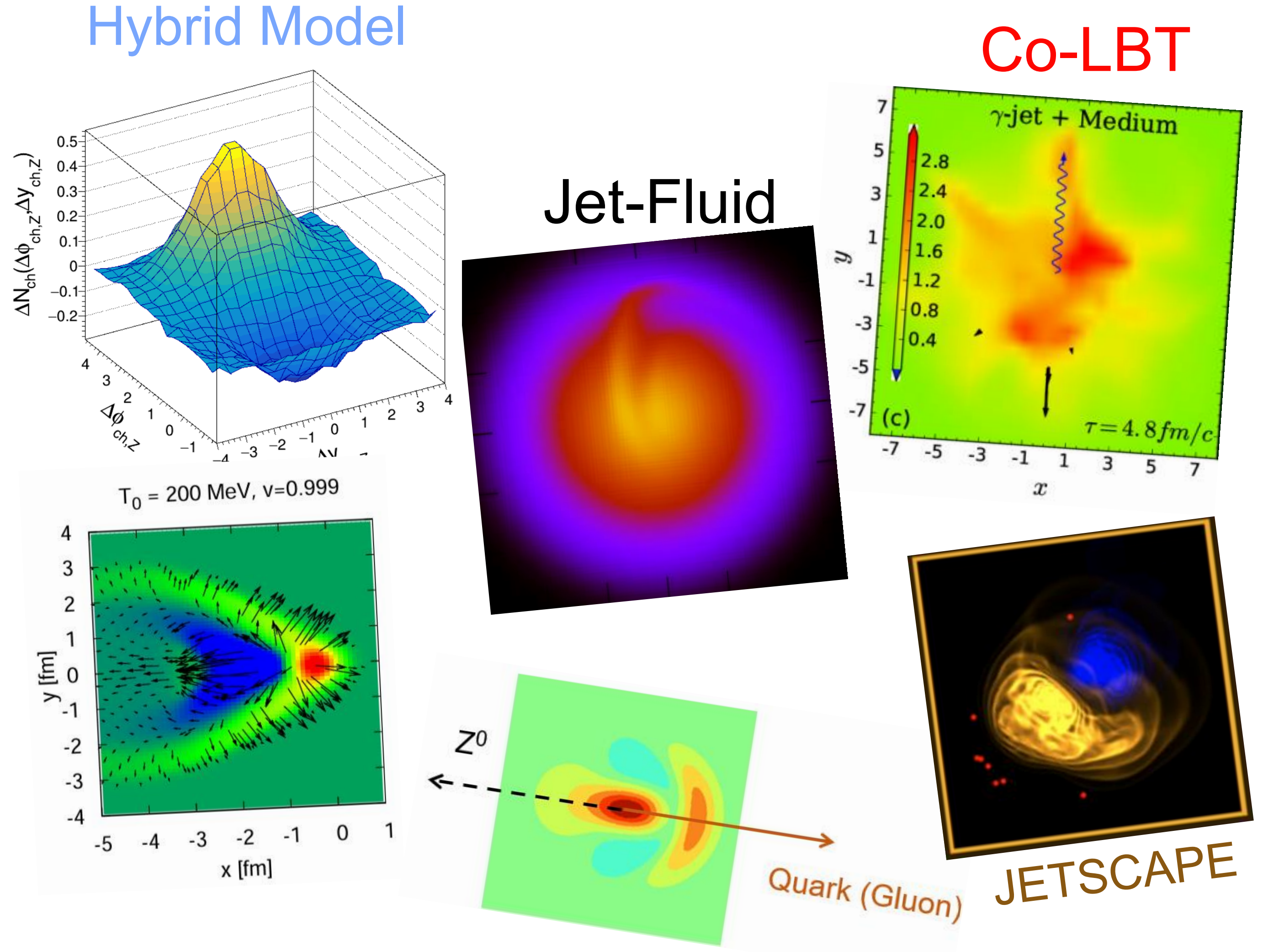


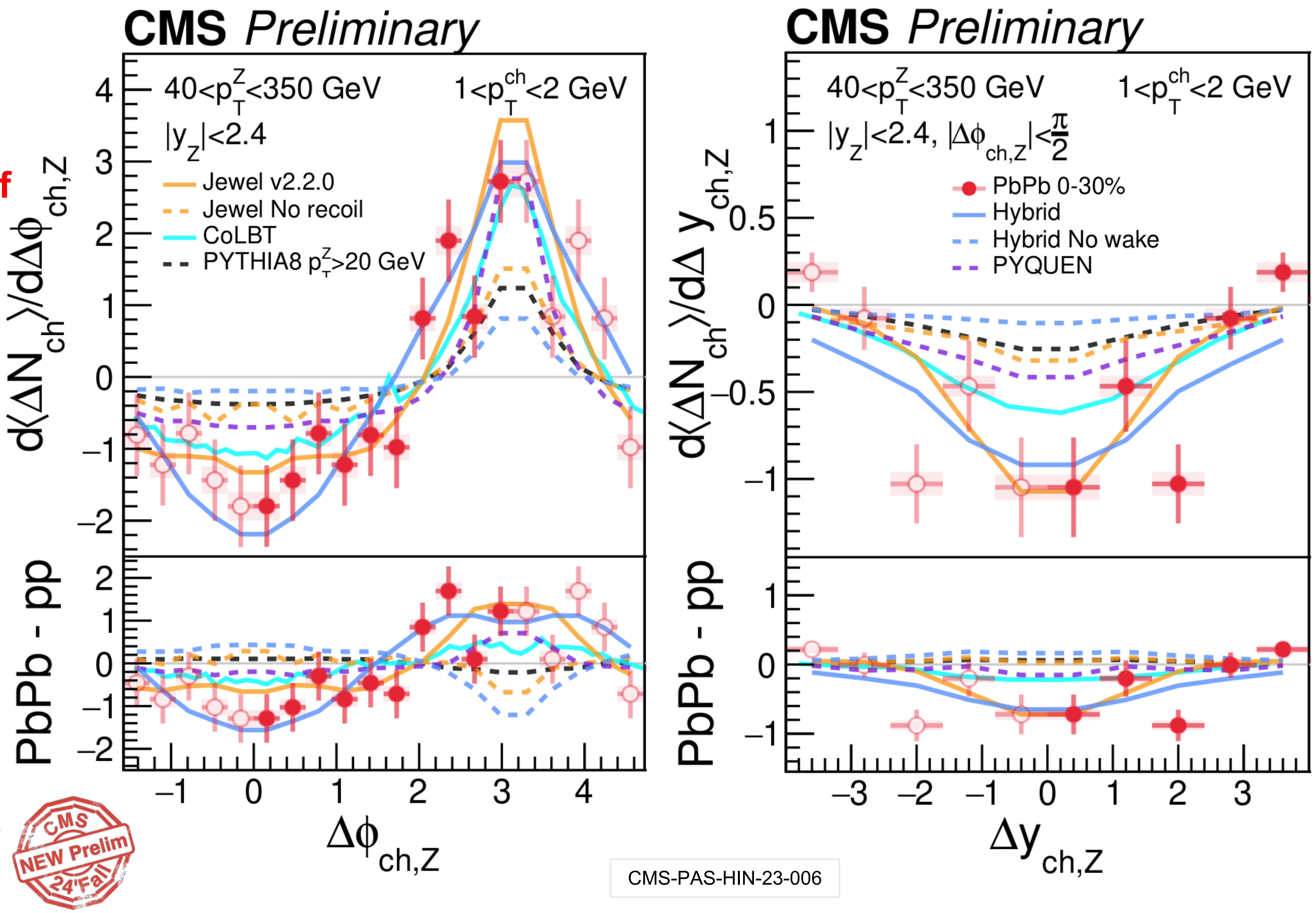


observation of medium response

Summary and Outlook

- First p_T^{ch} differential measurement of Z^0-hadron correlation in azimuthal angle and rapidity
- We report the **first direct evidence of medium response in QGP**
- High statistics analysis with Run3+4 data in the near future





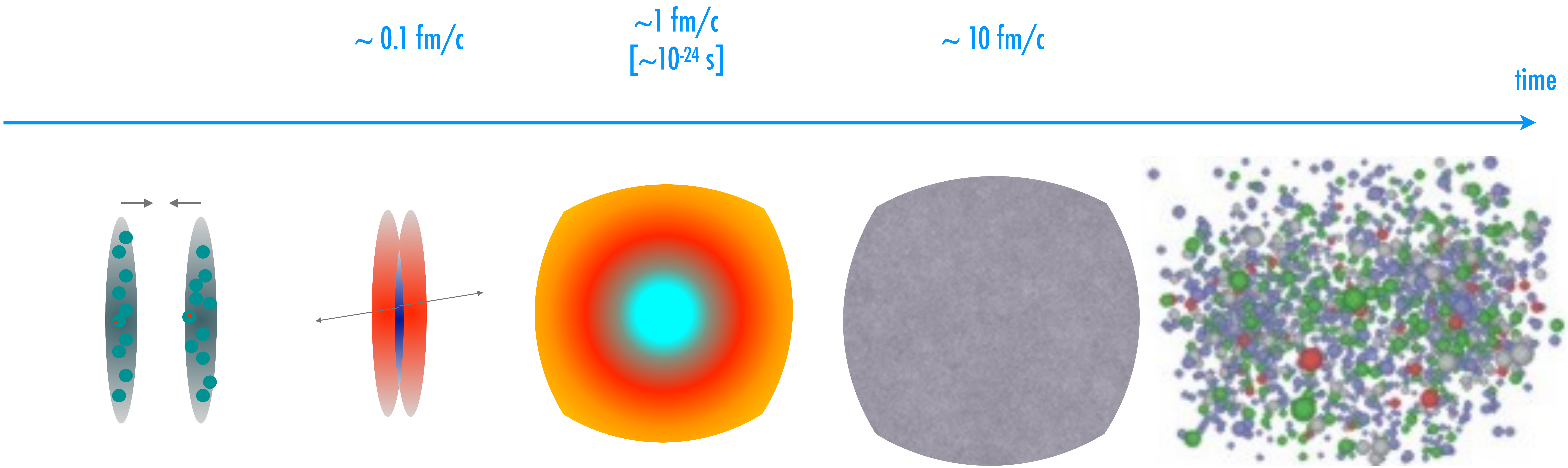
CMS-PAS-HIN-23-006

medium response is an intrinsic part of jets in HI

if medium response can be isolated, a wealth of information can be extracted

[it is the response of we want to understand to an excitation we control]

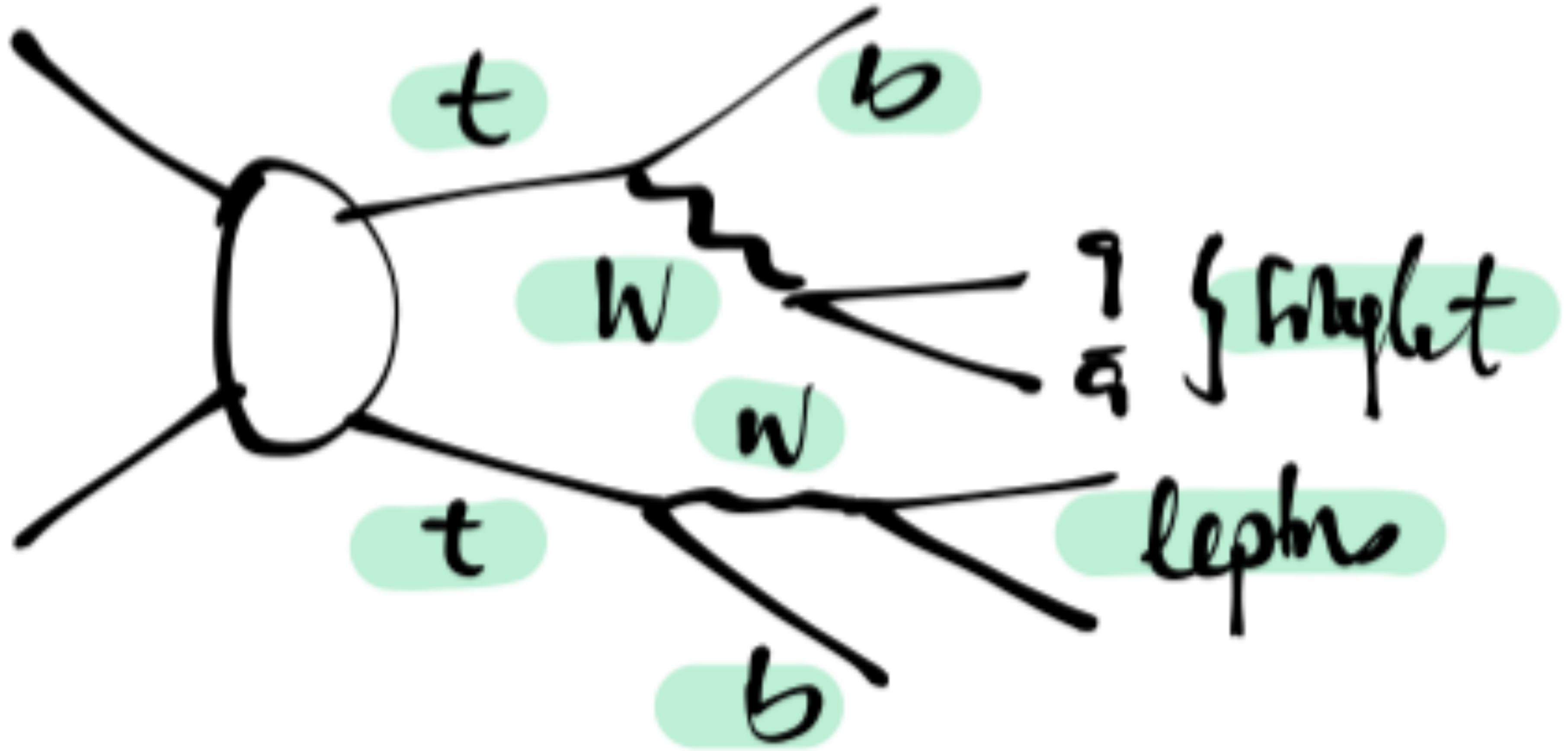
PROBING QGP



- all QGP probing so far is only sensitive to its integrated time evolution [flows and correlations, jets, ...]
- no time-differential information of a system whose properties are strongly time-dependent

PROBING QGP TIME EVOLUTION

- need probes produced later than at collision time
- need time delay to be inferable from final state
- need process that produces time-delayed probes to be accessible [cross-section   luminosity] and findable in HI



in semi-leptonic top-antitop production the jets from W-decay start interacting with QGP only after a series of time delays which is strongly correlated with the p_t of the top

TIME DELAYS

- at rest $\tau_{top} \simeq 0.15$ fm/c and $\tau_W \simeq 0.09$ fm/c
- the hadronic decays of the W will not interact with QGP until they are resolved [sufficiently far apart to be 'seen' by QGP]
- decoherence delay

$$\tau_d = \left(\frac{12}{\hat{q}\theta^2_{q\bar{q}}} \right)^{1/3}$$

Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk
:: 1210.7765 [hep-ph] PLB725, 357 (2013)

- the average delay time [correlated with top p_t]

$$\langle \tau_{tot} \rangle = \gamma_{t,top}\tau_{top} + \gamma_{t,W}\tau_W + \tau_d$$

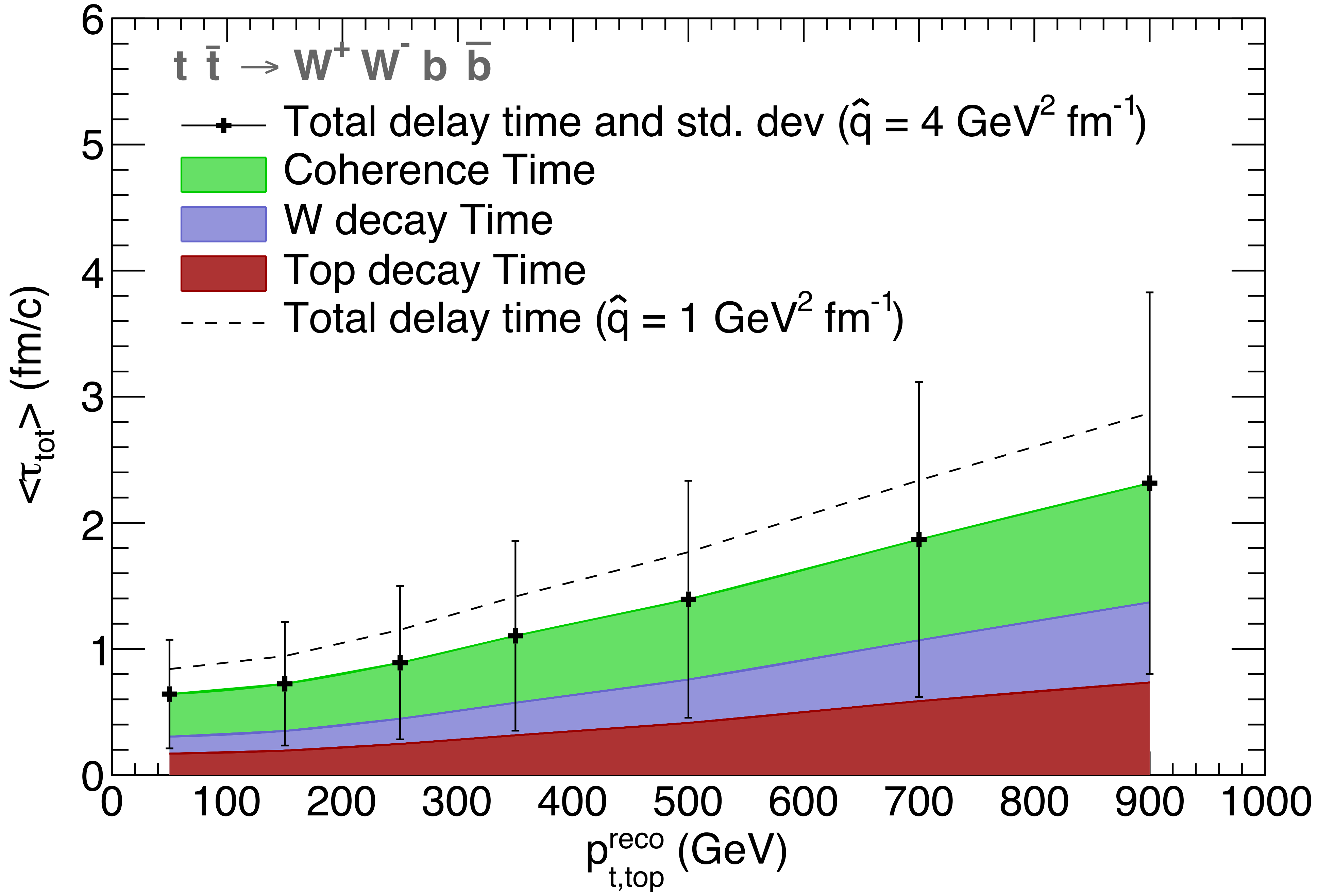
transverse boost

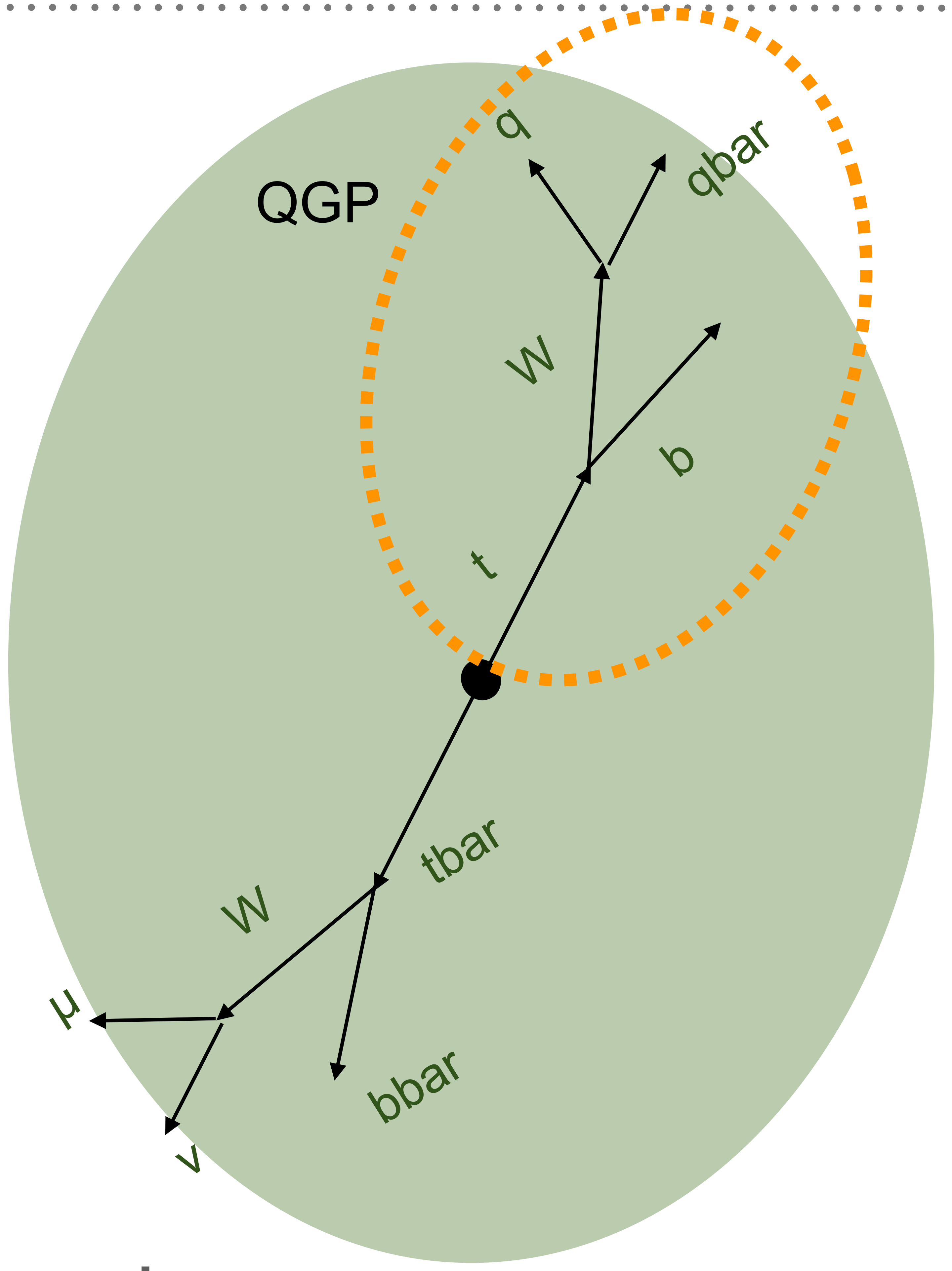
$$\gamma_{t,X} = (p^2_{t,X}/m^2_X + 1)^{\frac{1}{2}}$$

jets from hadronically decaying W only see QGP that remains after τ_{tot}

TIME DELAYS

$$\langle \tau_{tot} \rangle = \gamma_{t,top}\tau_{top} + \gamma_{t,W}\tau_W + \tau_d$$

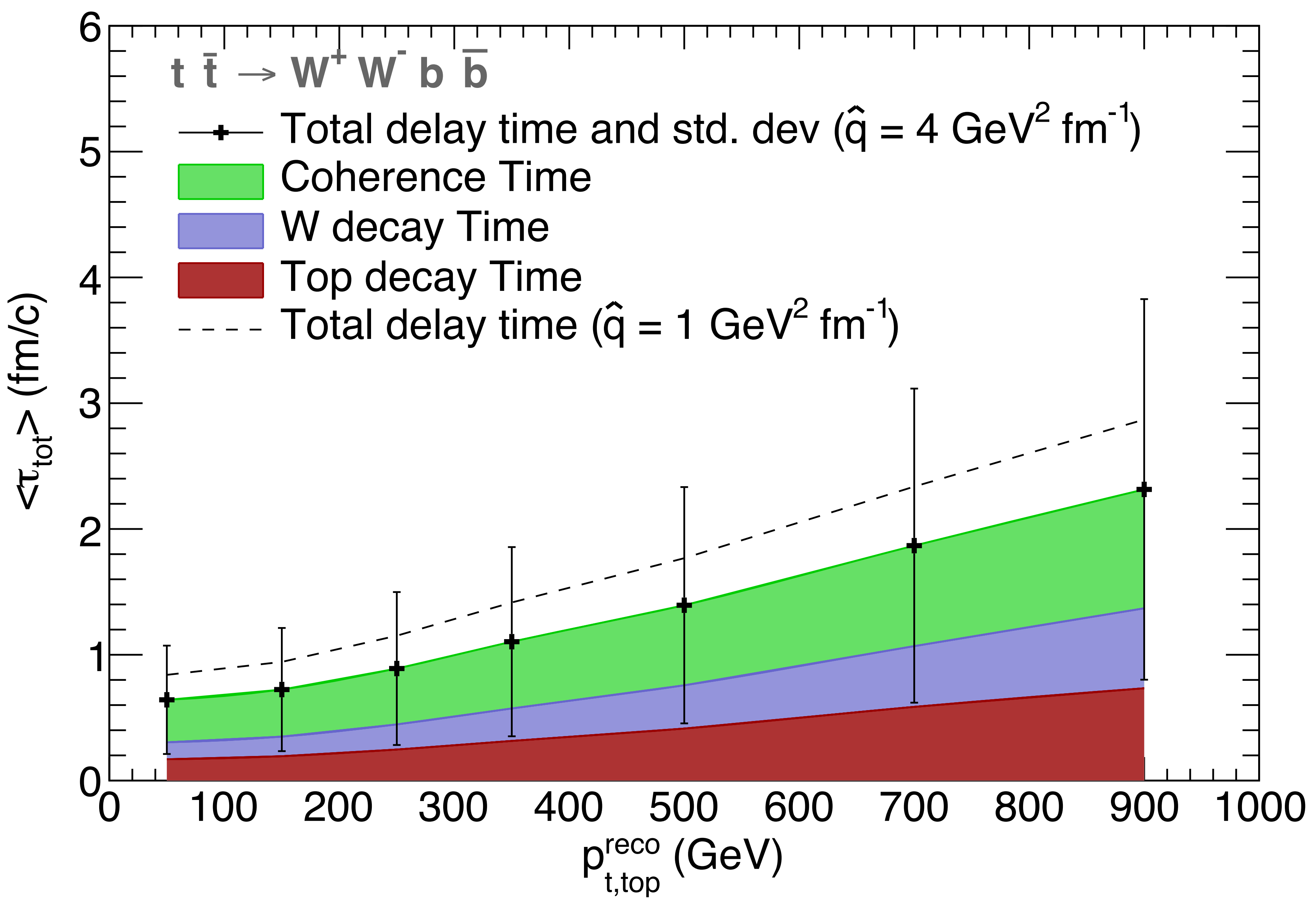


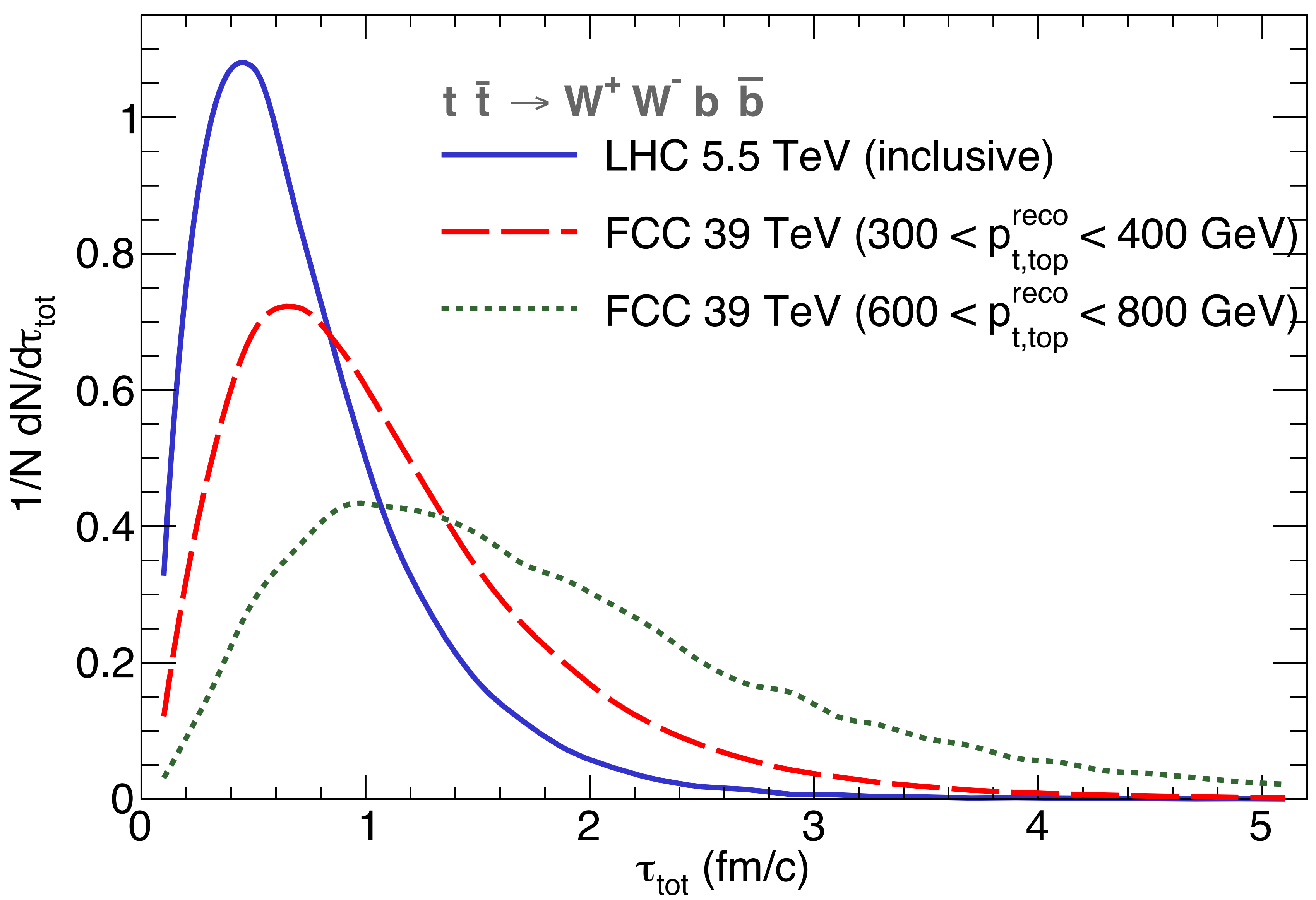


- τ_{tot} correlated with top p_t
- dispersion from considering random exponential distribution for each component
- weak dependence on $\hat{q}$

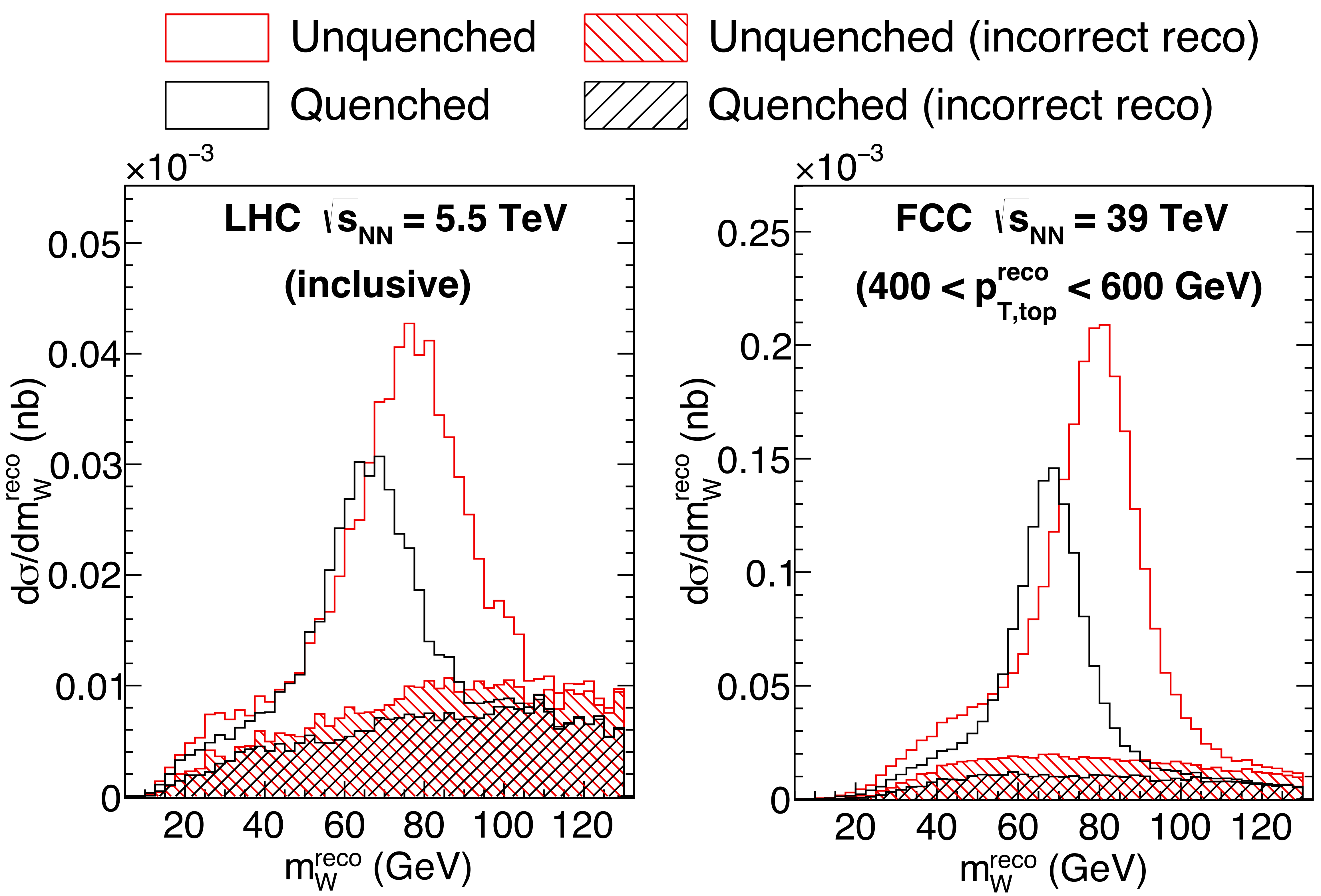
PROBING QGP TIME EVOLUTION

- measure jet quenching as modification of the reconstructed invariant mass m_{jj}
  - in pp closely related to W mass
- average time delay [thus time spent interacting with QGP] from reconstructed top p_t
- long tails in delay time distribution add sensitivity to times significantly larger than average





W MASS RECONSTRUCTION

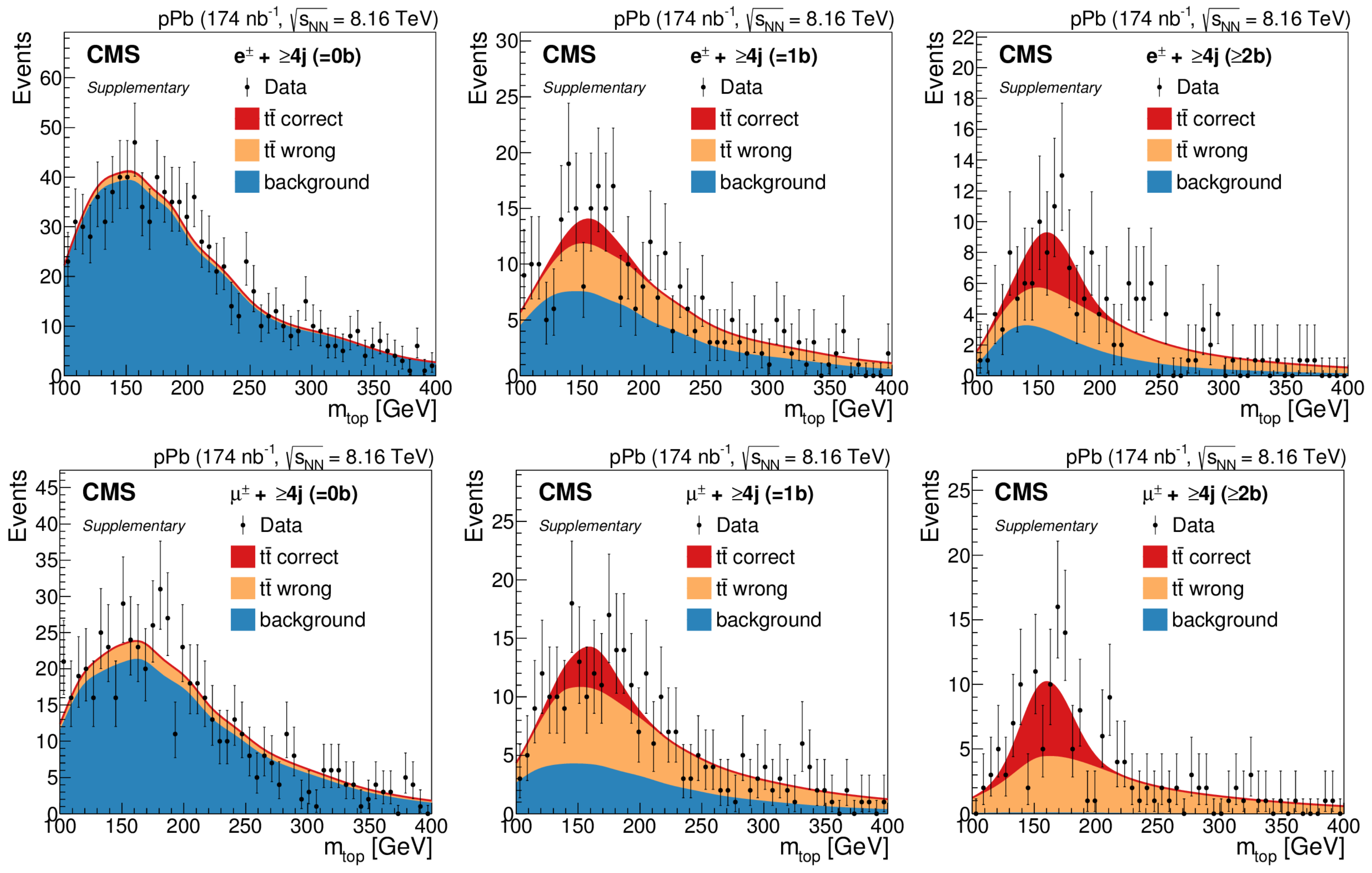


$$N(m) = a \exp\left[-\frac{(m - m_W^{fit})^2}{2\sigma^2}\right] + b + c\,m$$

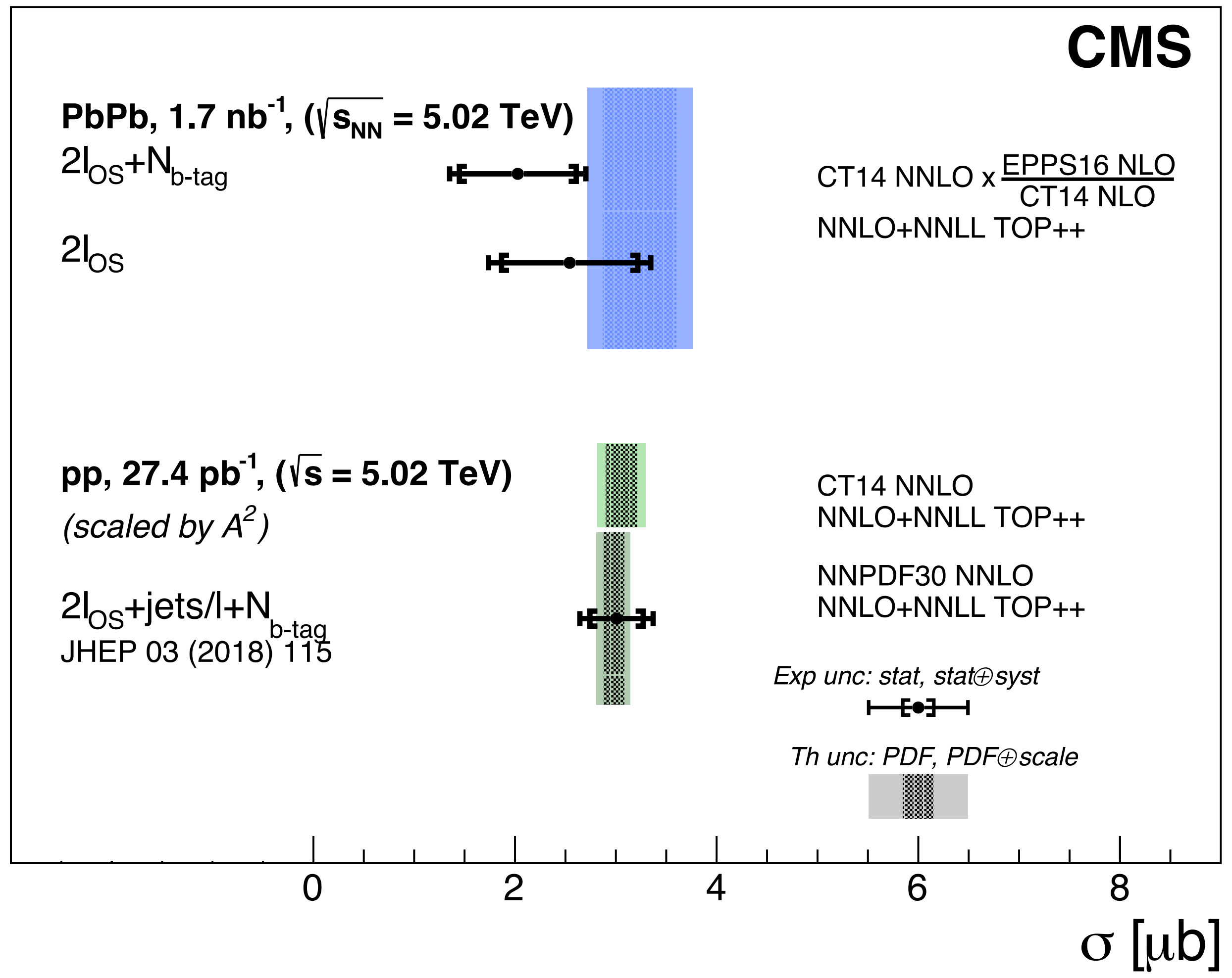
- quenching shifts mass peak and reduces number of events that satisfy cuts
- continuum [mis-reconstruction] reduced with increasing p_t

FEASIBILITY

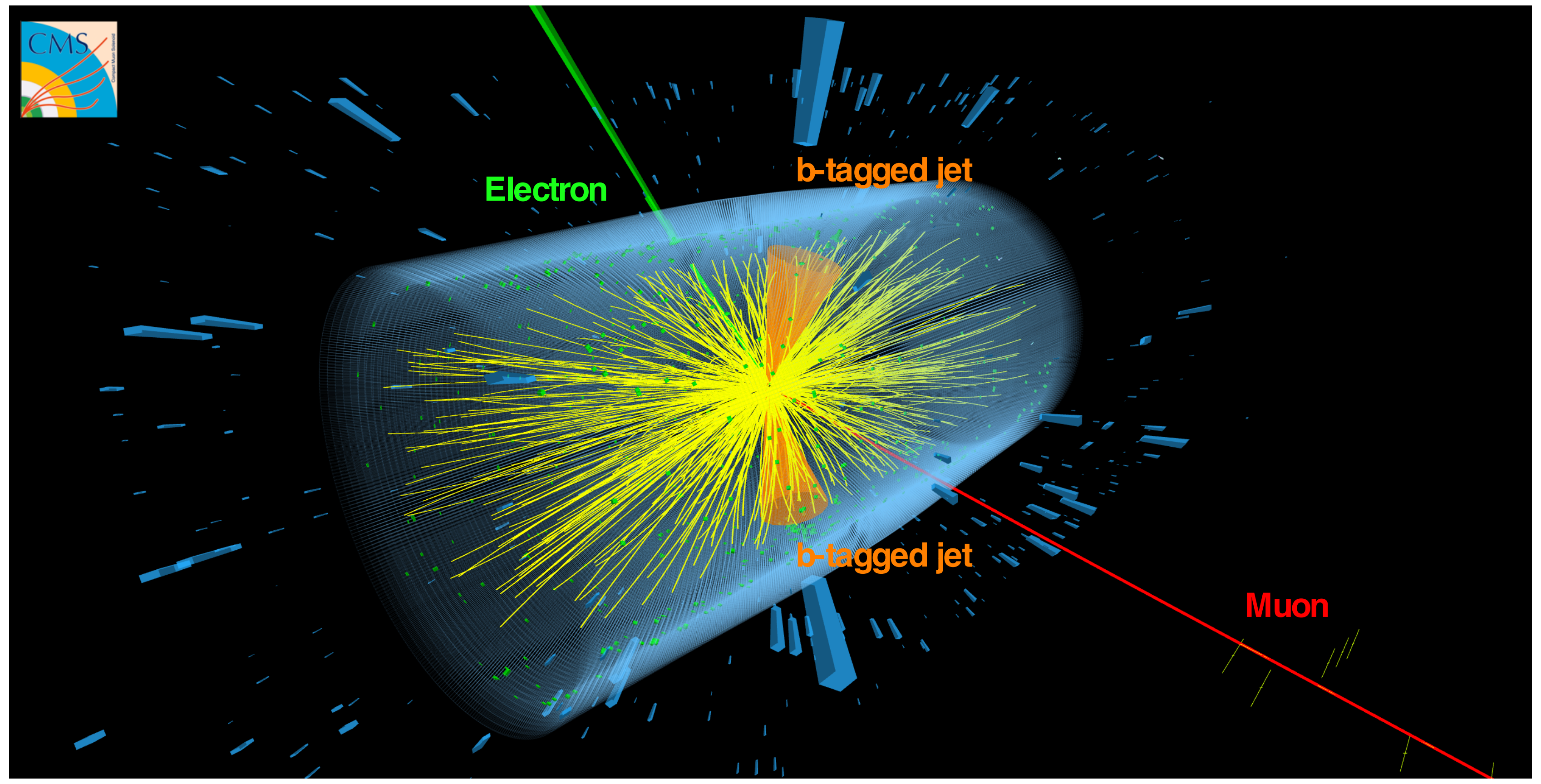
semi-leptonic channel measured in pA and leptonic in AA



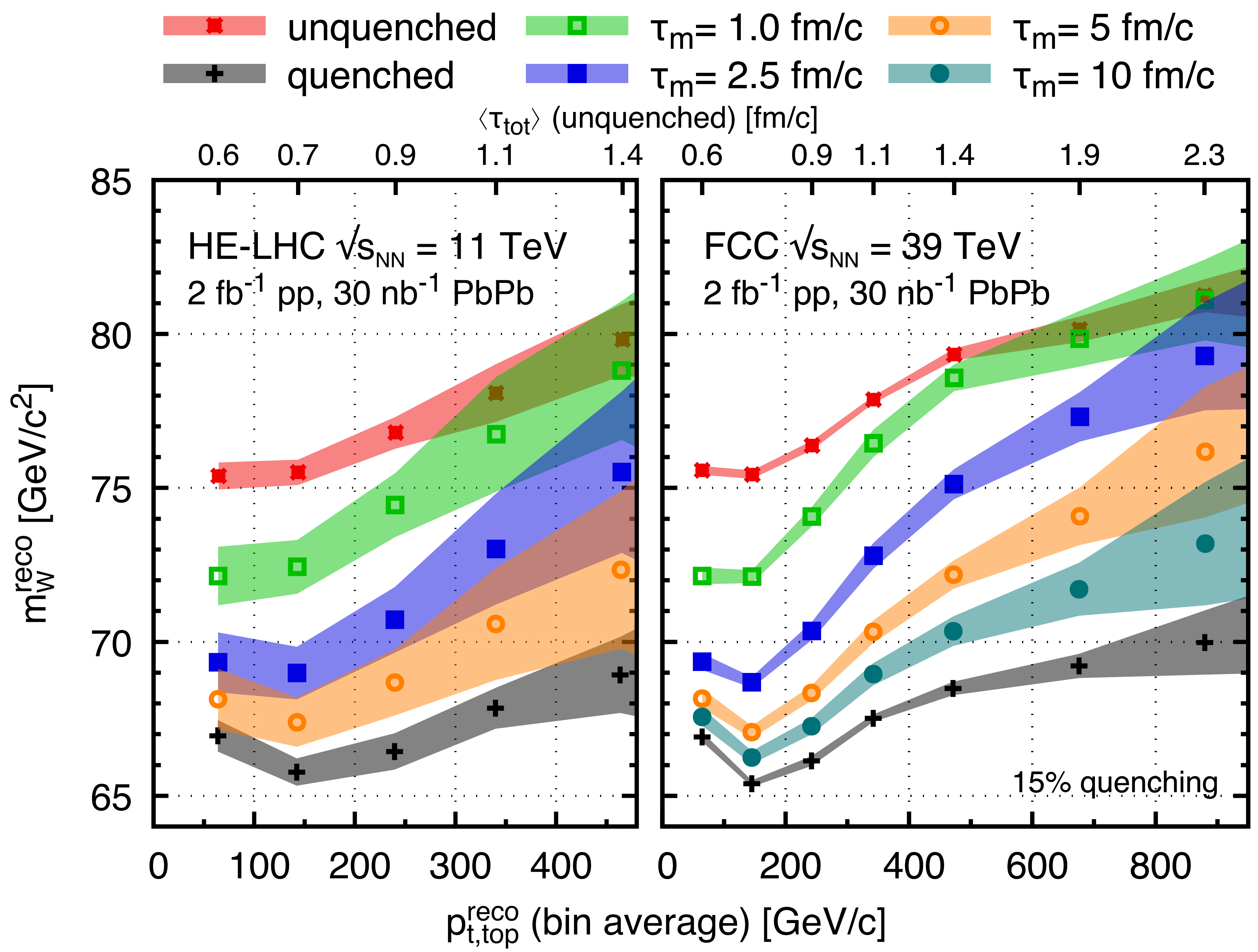
CMS :: 1709.07411[hep-ex] PRL119 (2017) 242001



CMS :: 2006.11110 [hep-ex]



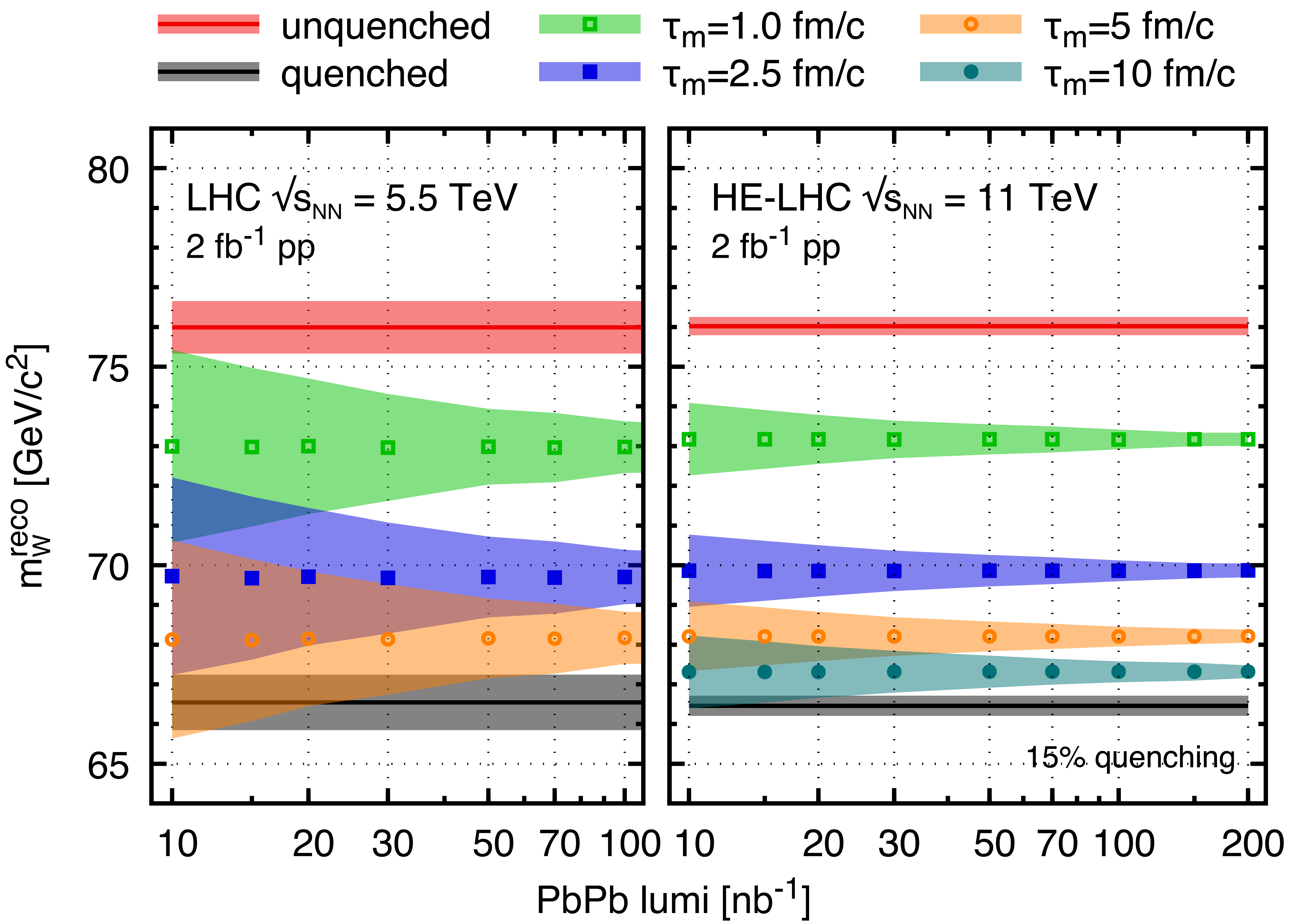
SENSITIVITY TO QGP SIZE AND DELAY TIME



- width of bands obtained from dispersion of results in large number of real size pseudo-experiments
- distance between bands measures diference in quenching for each QGP size and delay time

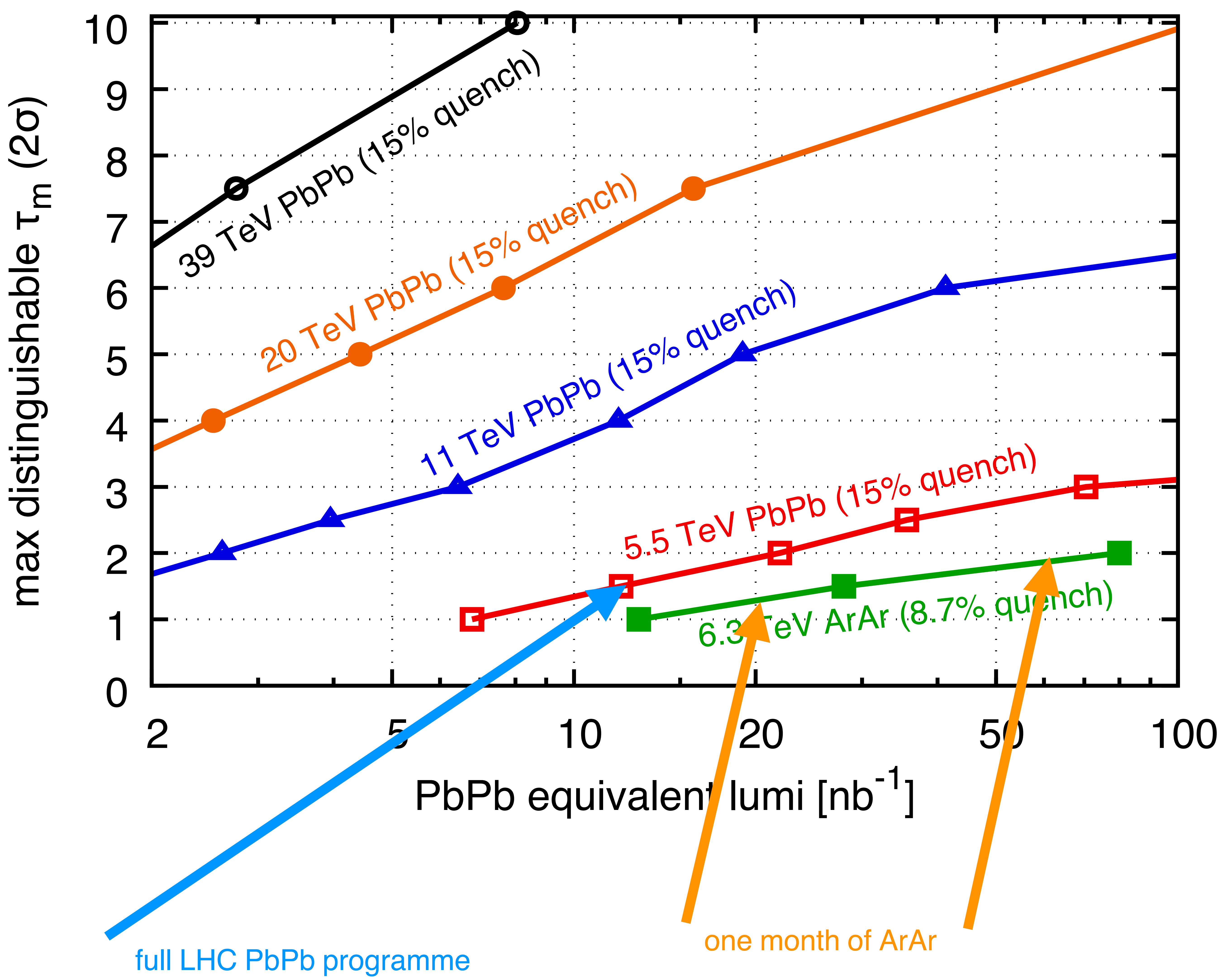
SENSITIVITY TO QGP SIZE [INCLUSIVE]

cases deemed distinguishable if separated by at least 2σ



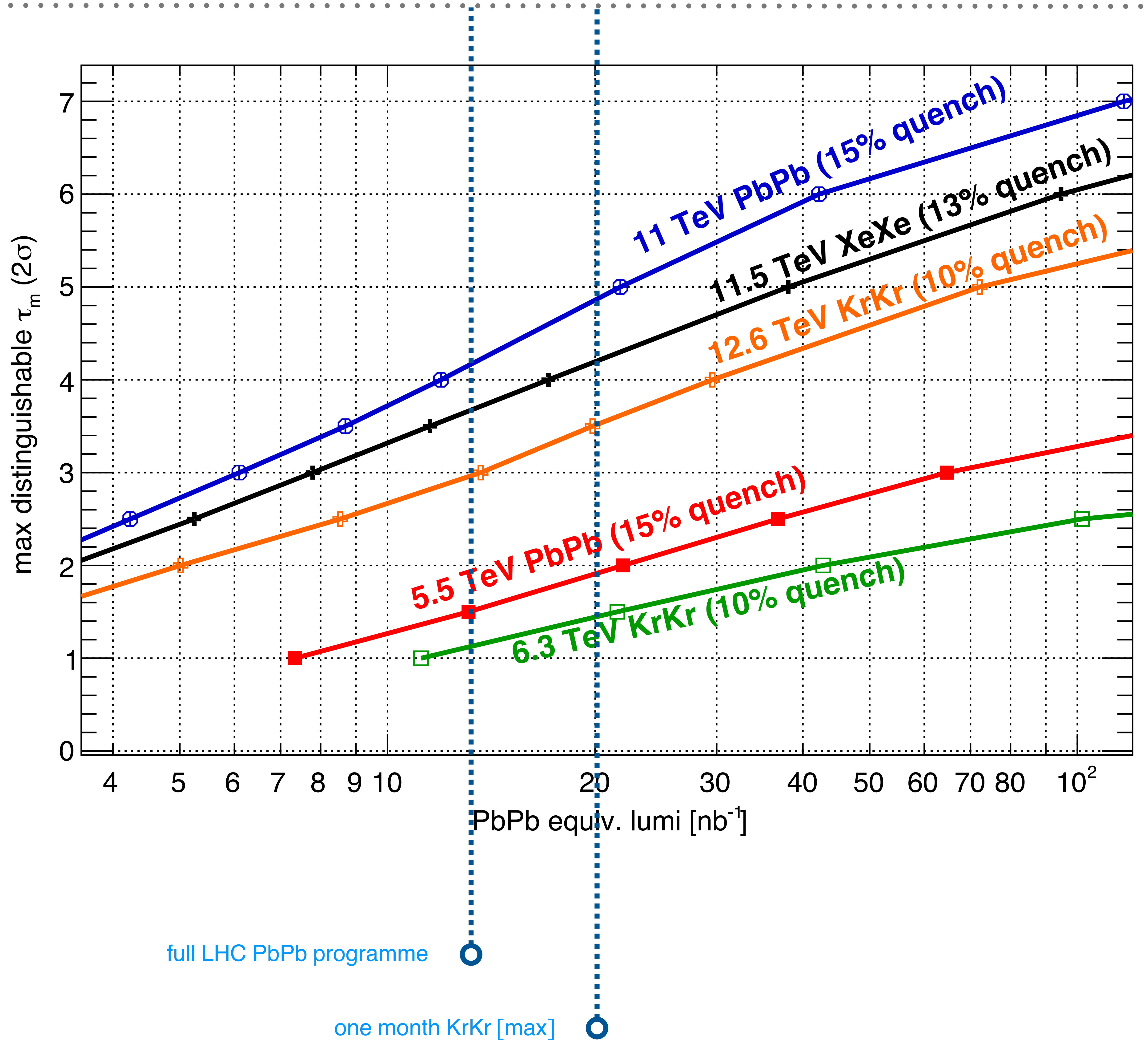
- at LHC [5.5 TeV, L=10 nb^{-1}] only a QGP of size τ_m = 1 fm/c can be distinguished from a full quenching scenario :: no sensitivity to QGP time evolution beyond 1 fm/c
- very significant improvements with increases in either or both $\sqrt{s}$ and luminosity

SCENARIOS



max distinguishable τm (2σ)
PbPb equivalent lumi [nb-1]
39 TeV PbPb (15% quench)
20 TeV PbPb (15% quench)
11 TeV PbPb (15% quench)
5.5 TeV PbPb (15% quench)
6.3 TeV ArAr (8.7% quench)
full LHC PbPb programme
one month of ArAr

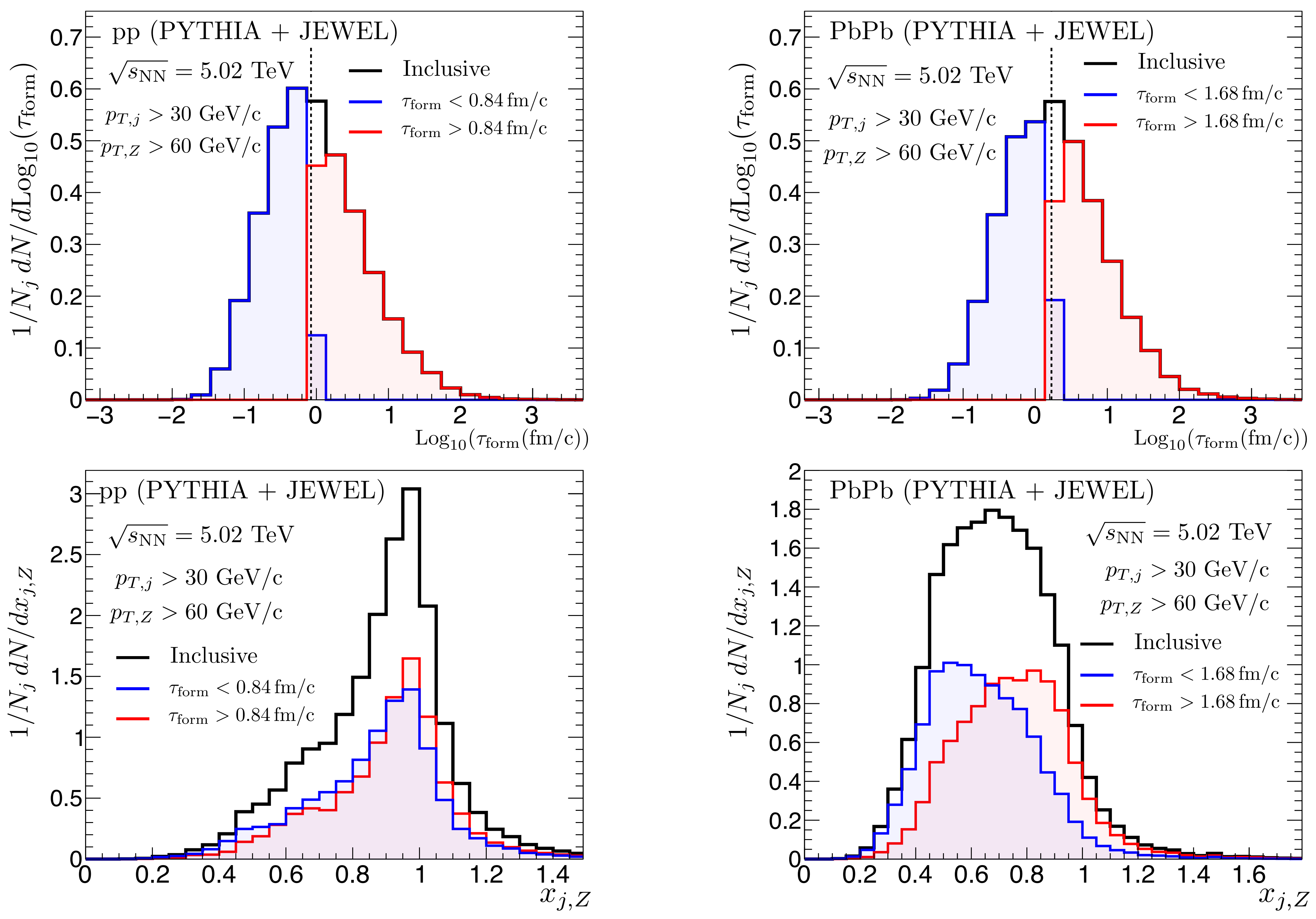
SCENARIOS :: LIGHT IONS



ACCESSING TIMES

Eur.Phys.J.C 84 (2024) 7, 672

- jet reclustering [infer a splitting history by regrouping jet constituents according to a specific ordering variable] allows us to have a space-time picture of parton branching
- for example, can determine the time the first splitting occurred and look at jet properties as function of that time



the earlier a jet starts splitting [the more it splits], the more energy it loses

jets can be used to probe QGP in a time differential way