Jet quenching in nuclear collisions: theory overview

Guilherme Milhano (LIP & IST & CERN-TH)

gmilhano@lip.pt

TÉCNICO LISBOA

INVESTIGADOR FCT

QM2018, Venezia, 18 May 2018

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]

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

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

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

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

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

p = 1 :: k_T algorithm

p = 0 :: Cambridge/Aachen algorithm

p = -1 :: anti-k_T algorithm

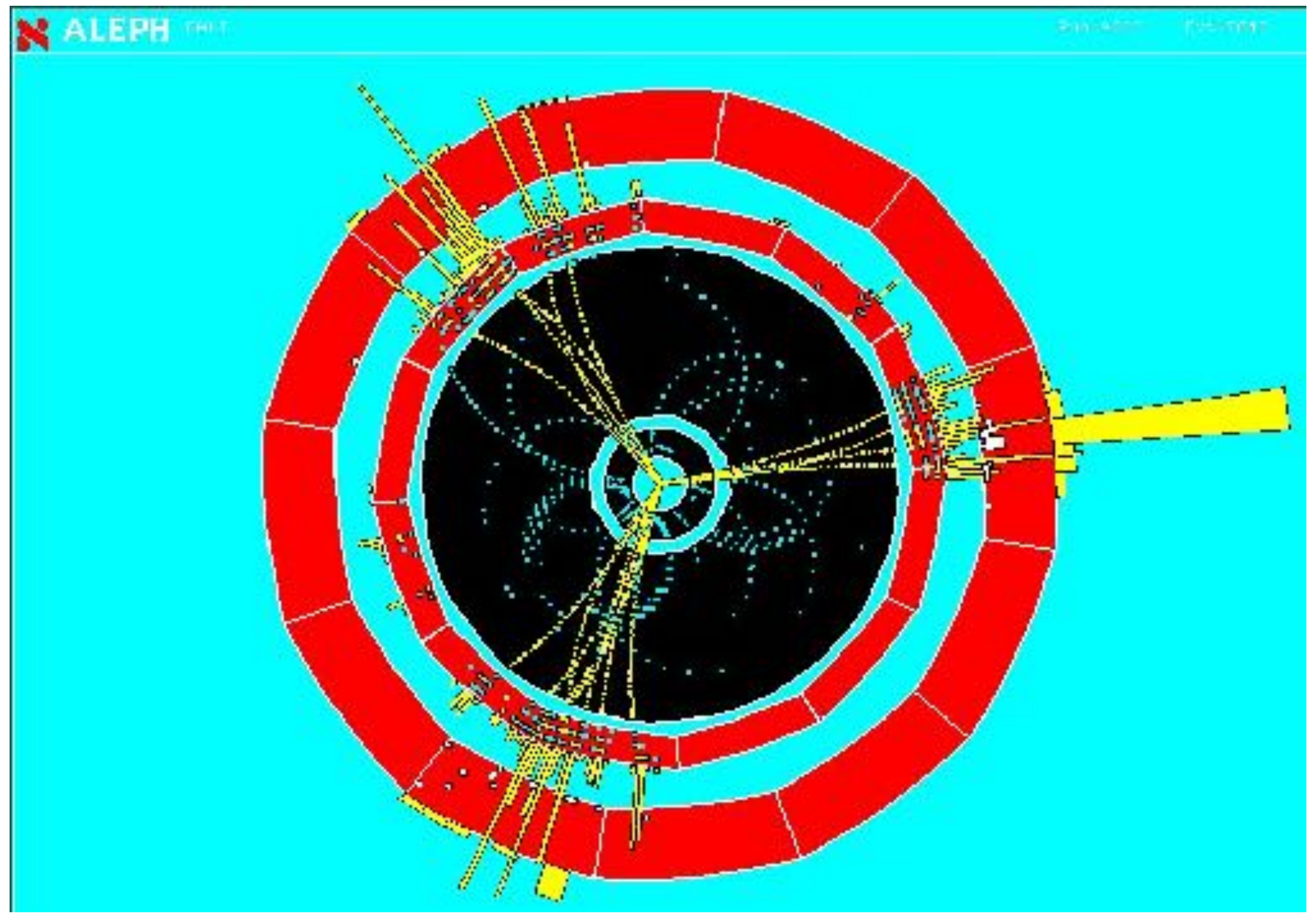
jet definition [in elementary collisions]

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

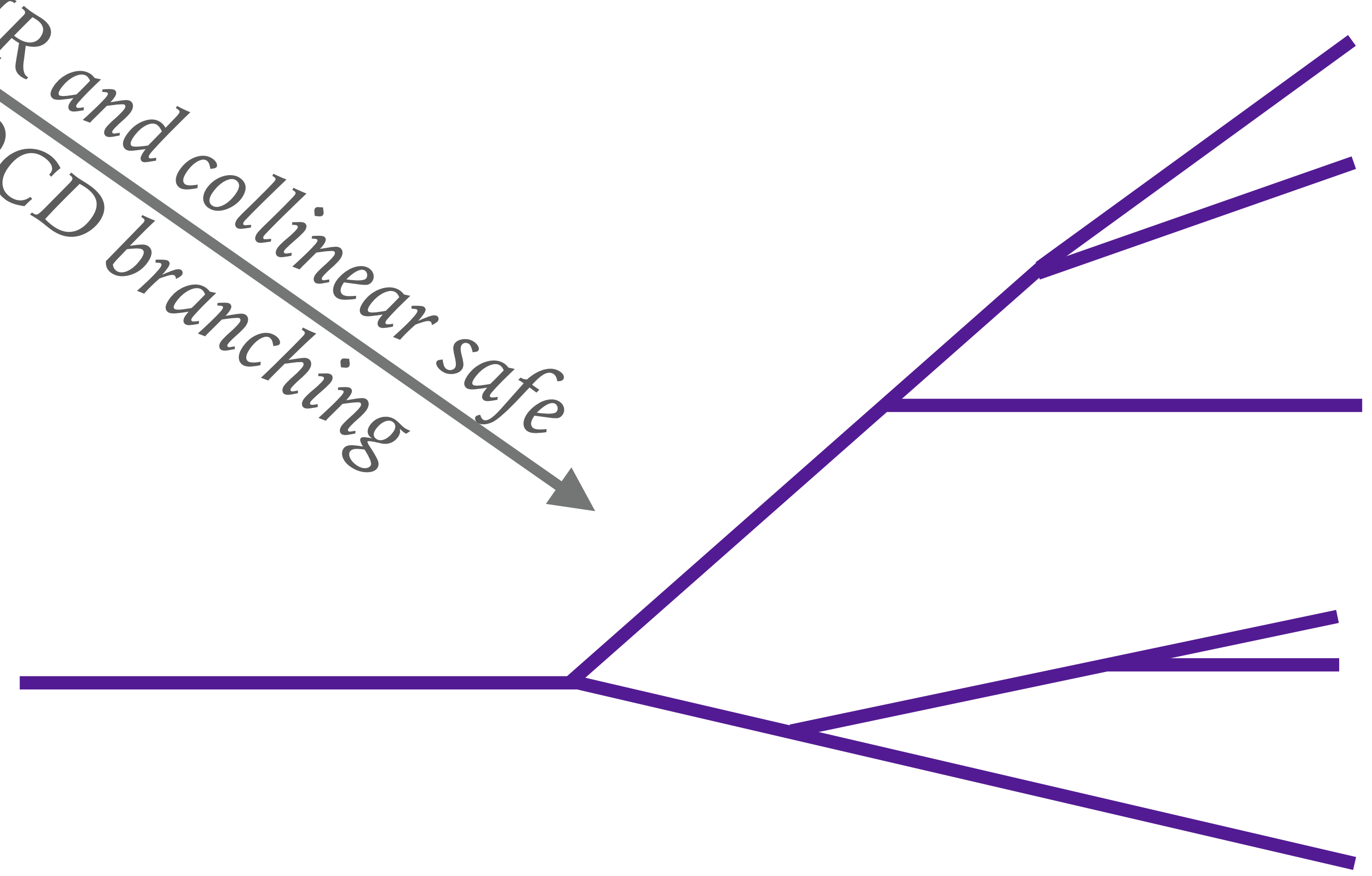
jet algorithm

robust and efficient
IR and collinear safe

IR and collinear safe
QCD branching



experimentally measurable
collimated spray of hadrons

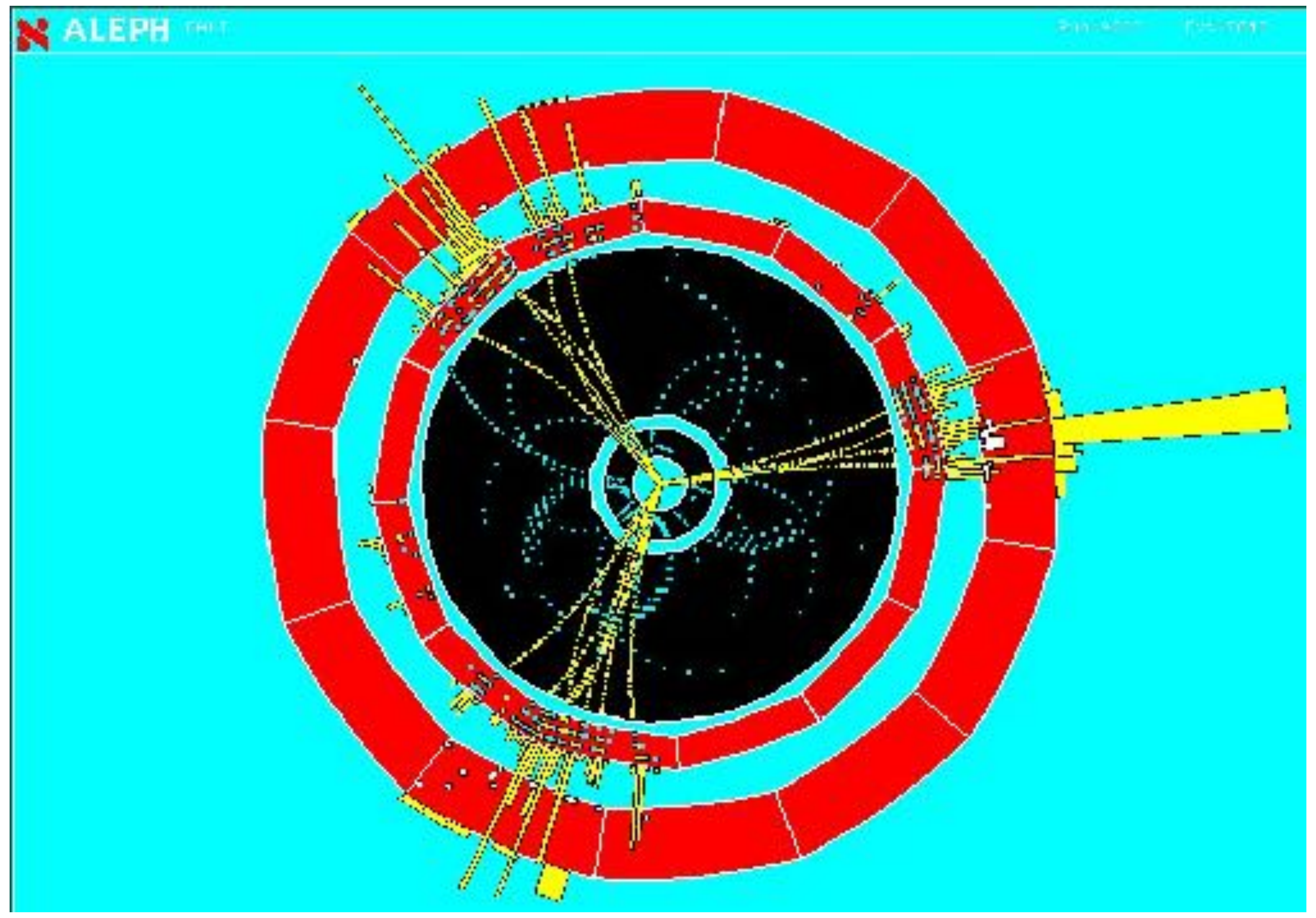


theoretically calculable
fragmentation of energetic parton

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



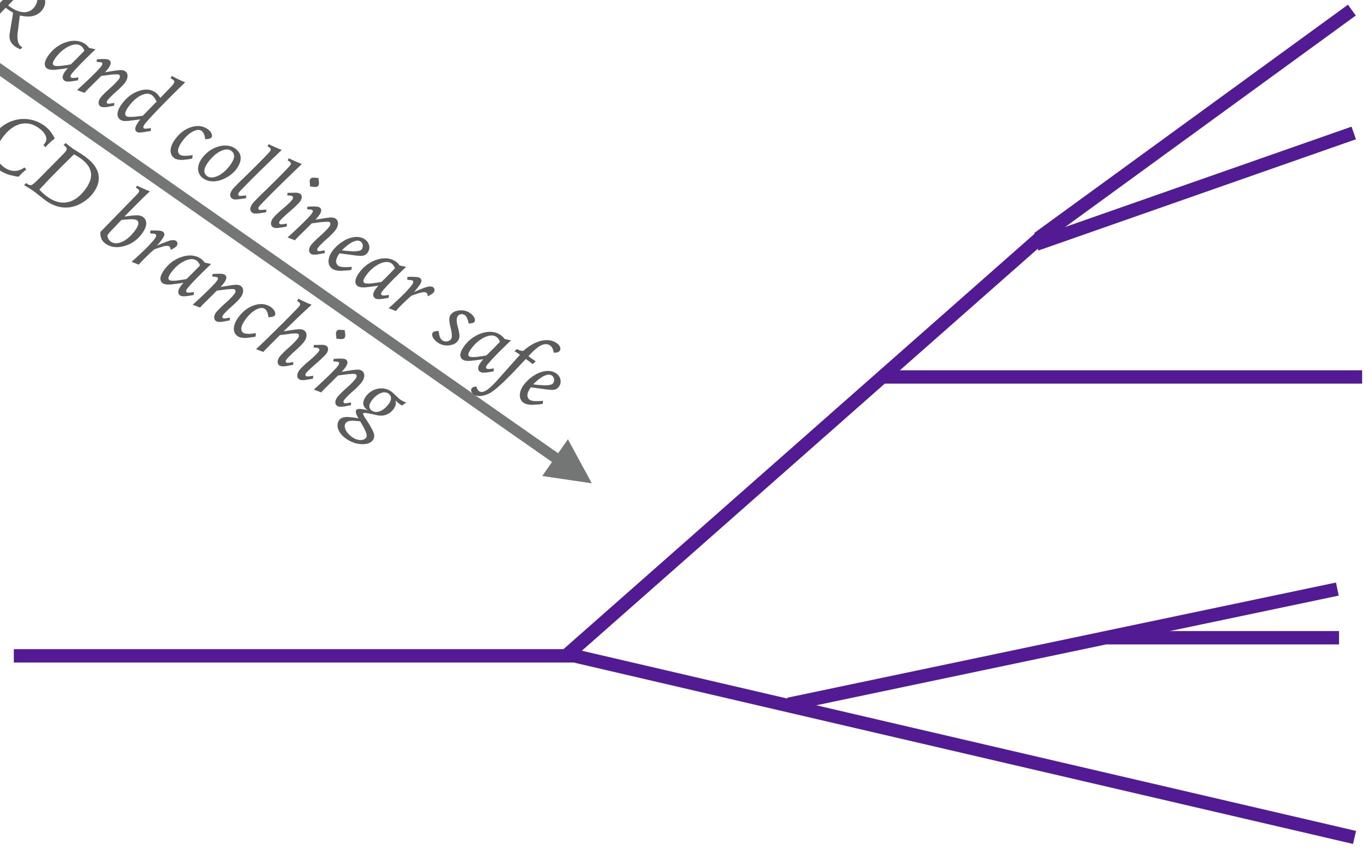
experimentally measurable
collimated spray of hadrons

robust and efficient
IR and collinear safe

jet algorithm

IR and collinear safe
QCD branching

theory jet

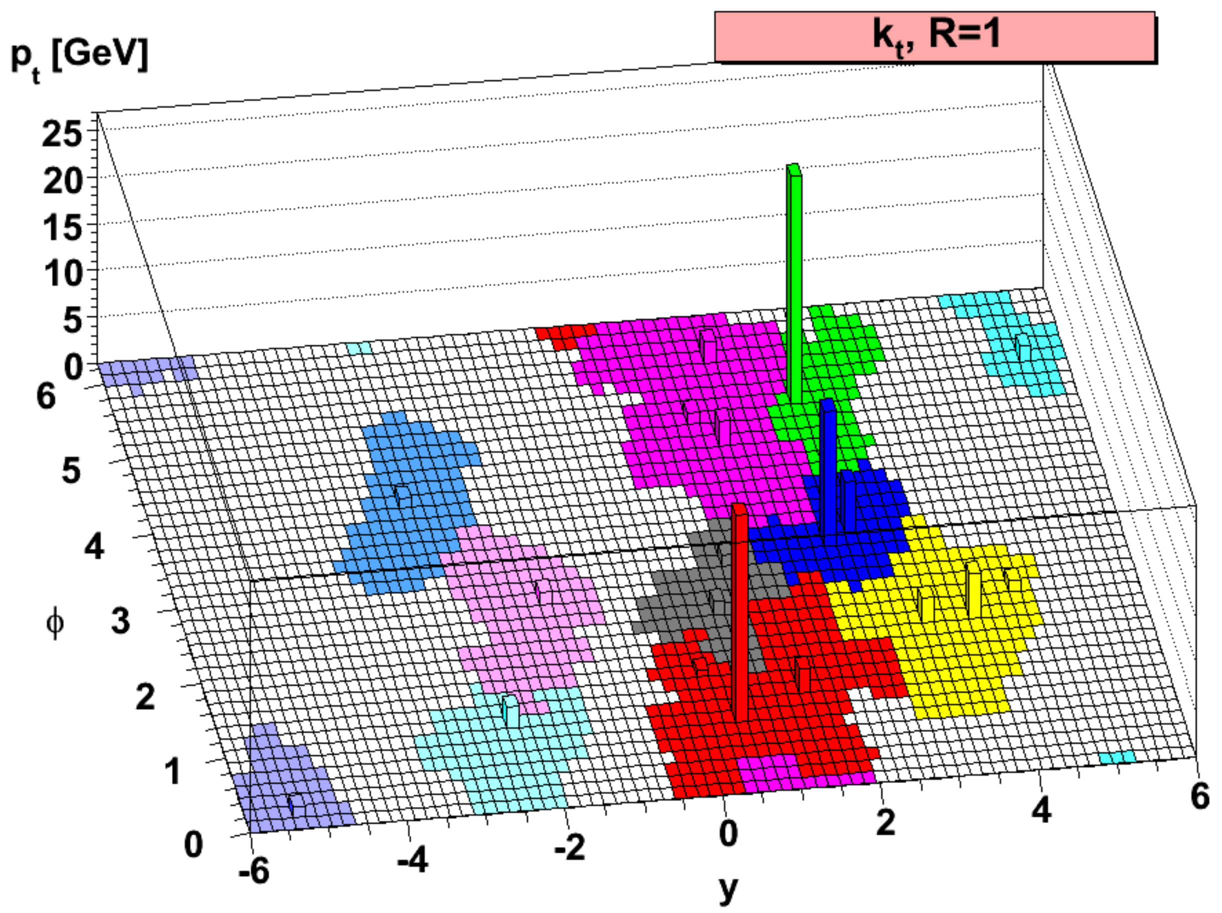


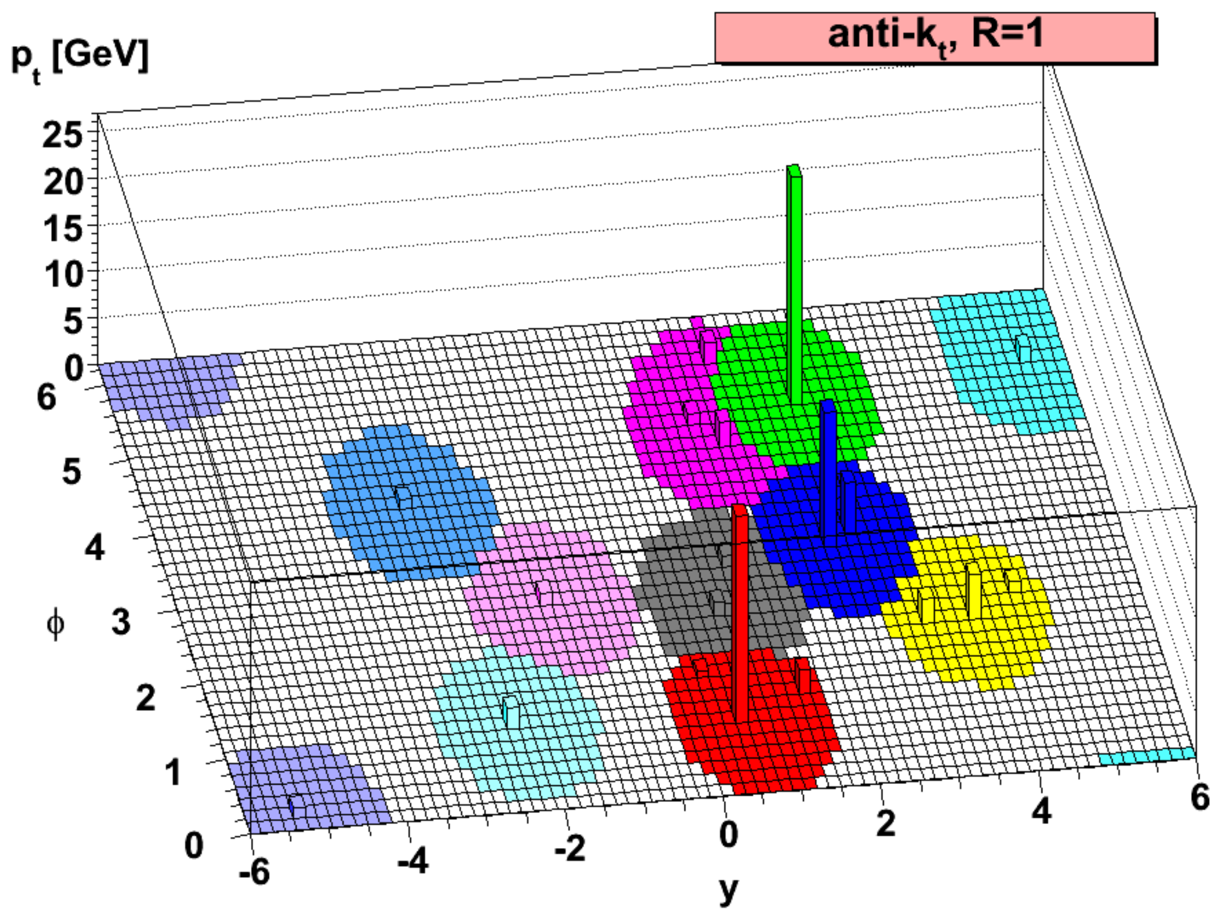
theoretically calculable
fragmentation of energetic parton

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,



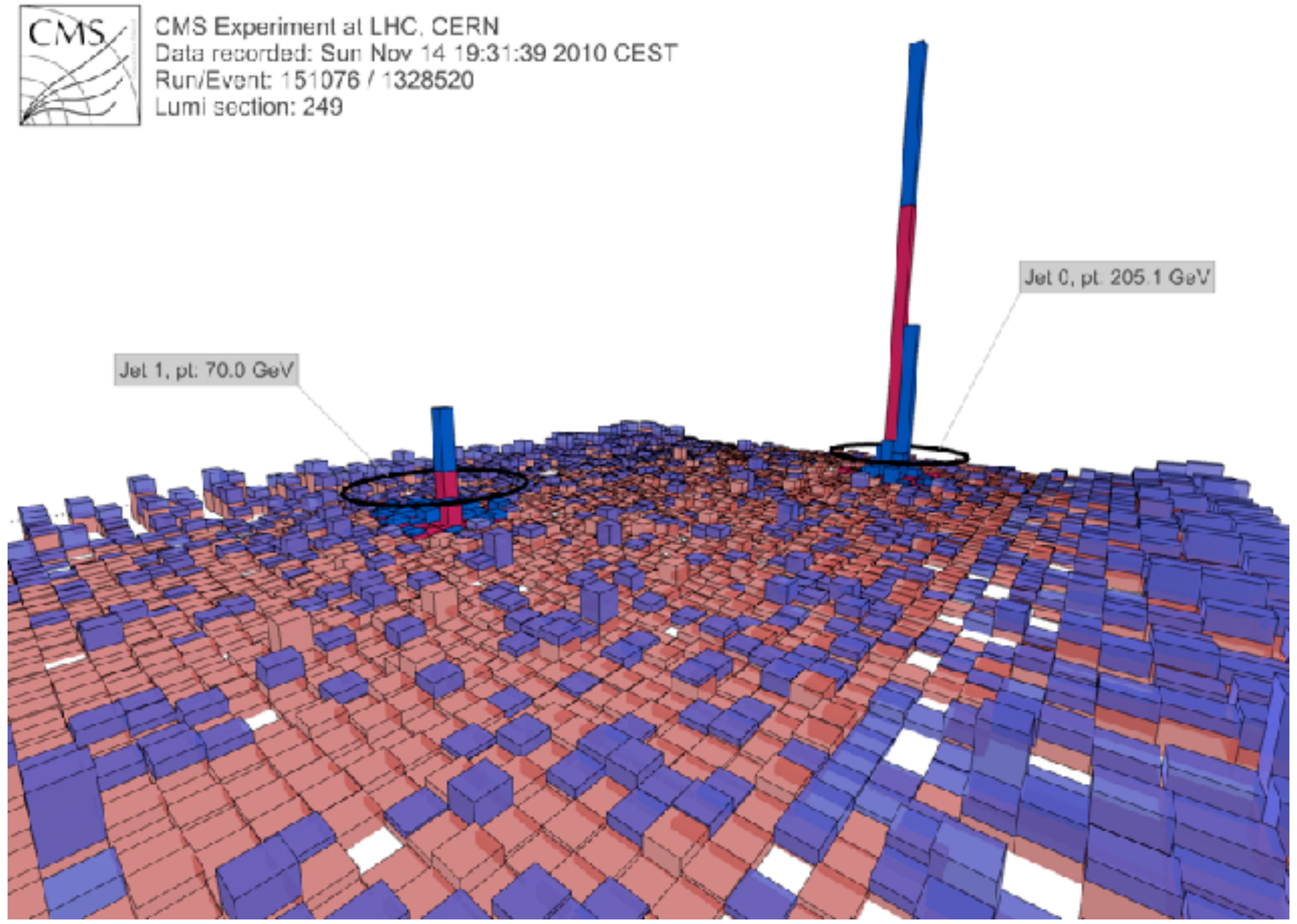


Cacciari, Salam, Soyez 0802.1189

- 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 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

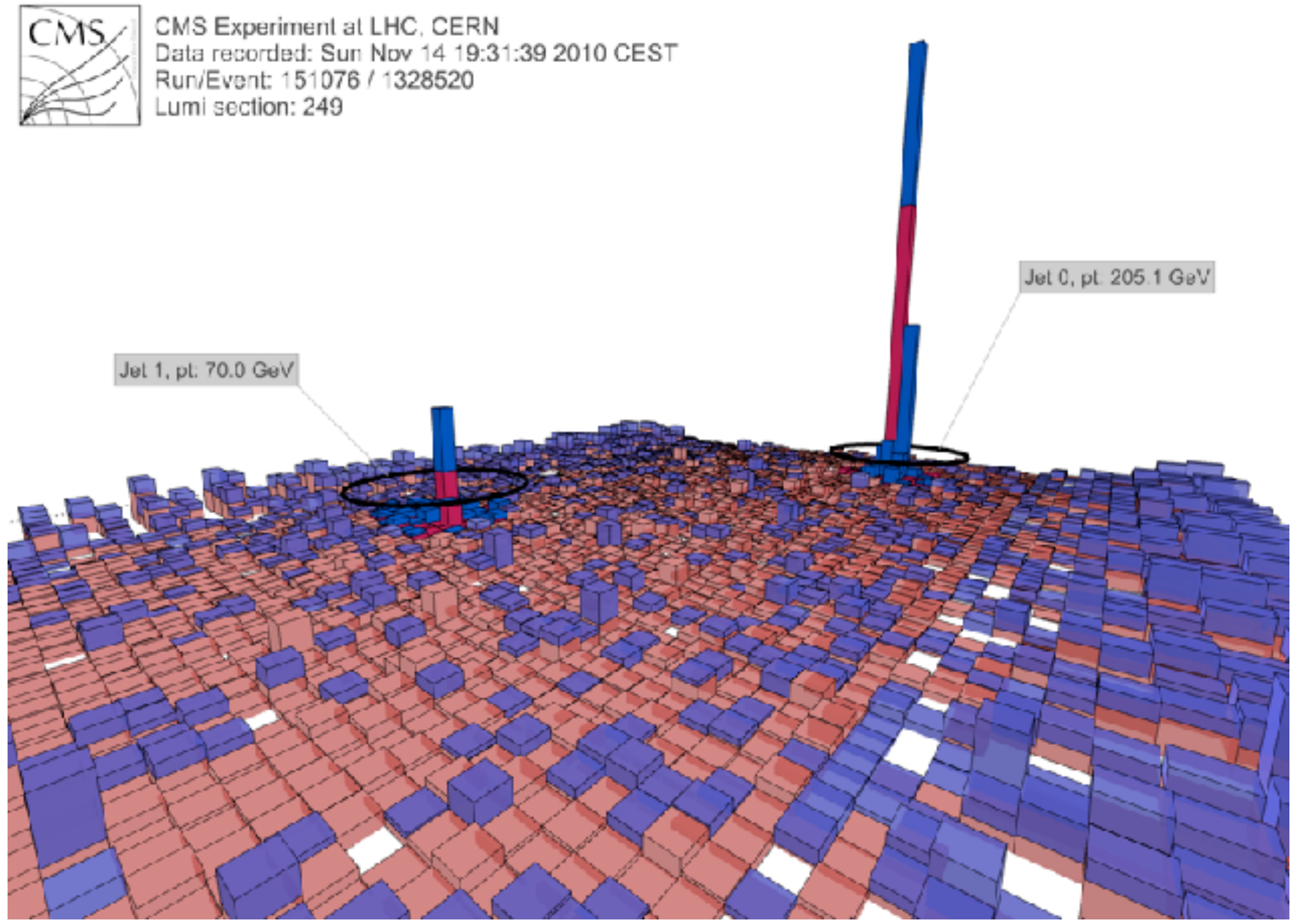
- defined by same jet algorithm[s] as in elementary collisions with essential background subtraction



jet algorithm
+
background subtraction

jets in heavy ion collisions

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

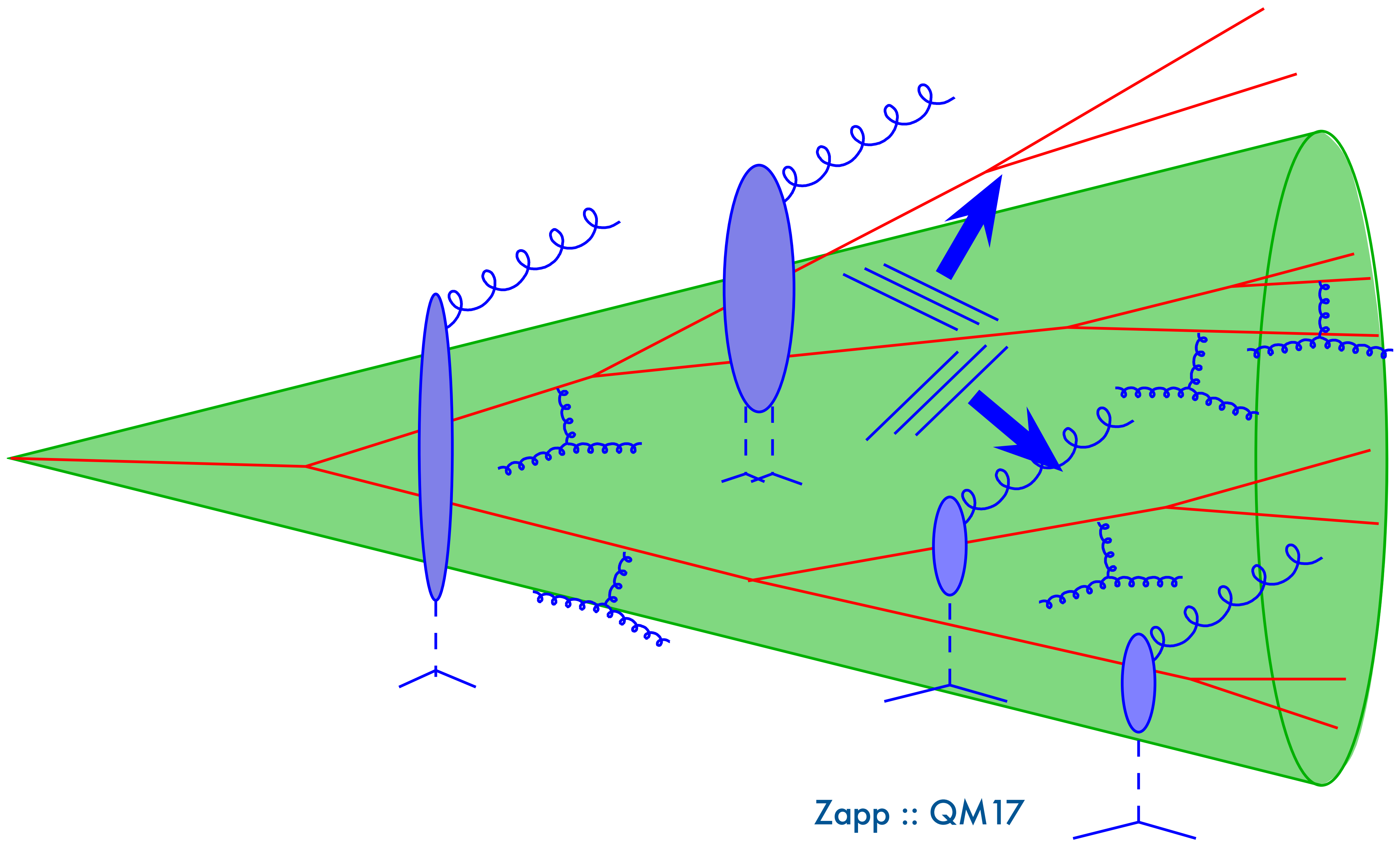


jet algorithm
+
background subtraction

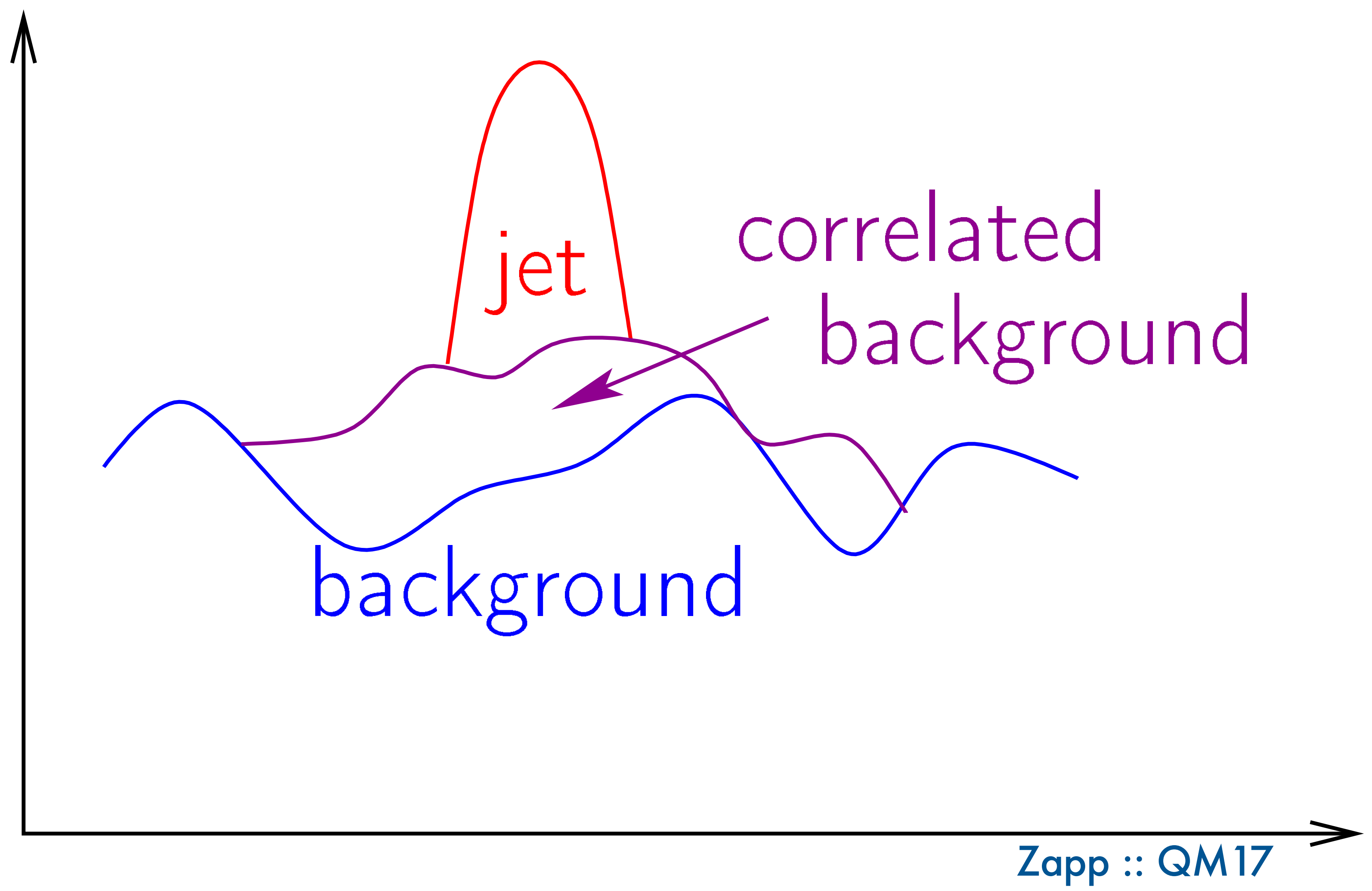
what has to be calculated?

what is in a heavy ion jet?

jets in heavy ion collisions

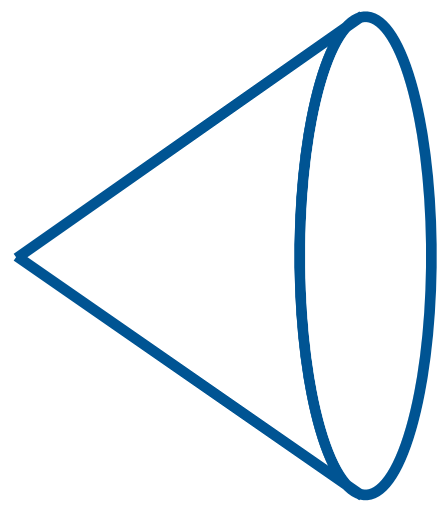


- shower constituents exchange [soft] 4-mom and colour with QGP
- interleaved [vacuum]+[medium induced] emission pattern
- some shower constituents decorrelate from jet :: are lost
- some QGP becomes correlated with jet [medium response] :: it is part of the jet

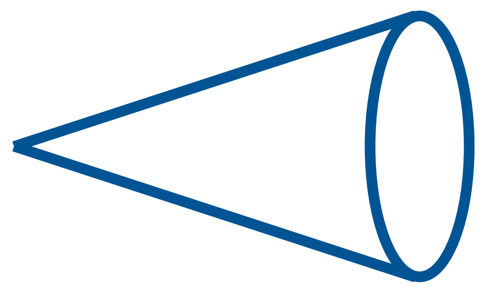


the importance of vacuum-like parton branching in QGP

- parton branching in vacuum driven by initial mass [p^2] and species [quark or gluon], and angular ordered
- scale of first splitting defines jet envelope



large m^2 :: wide jet :: more constituents

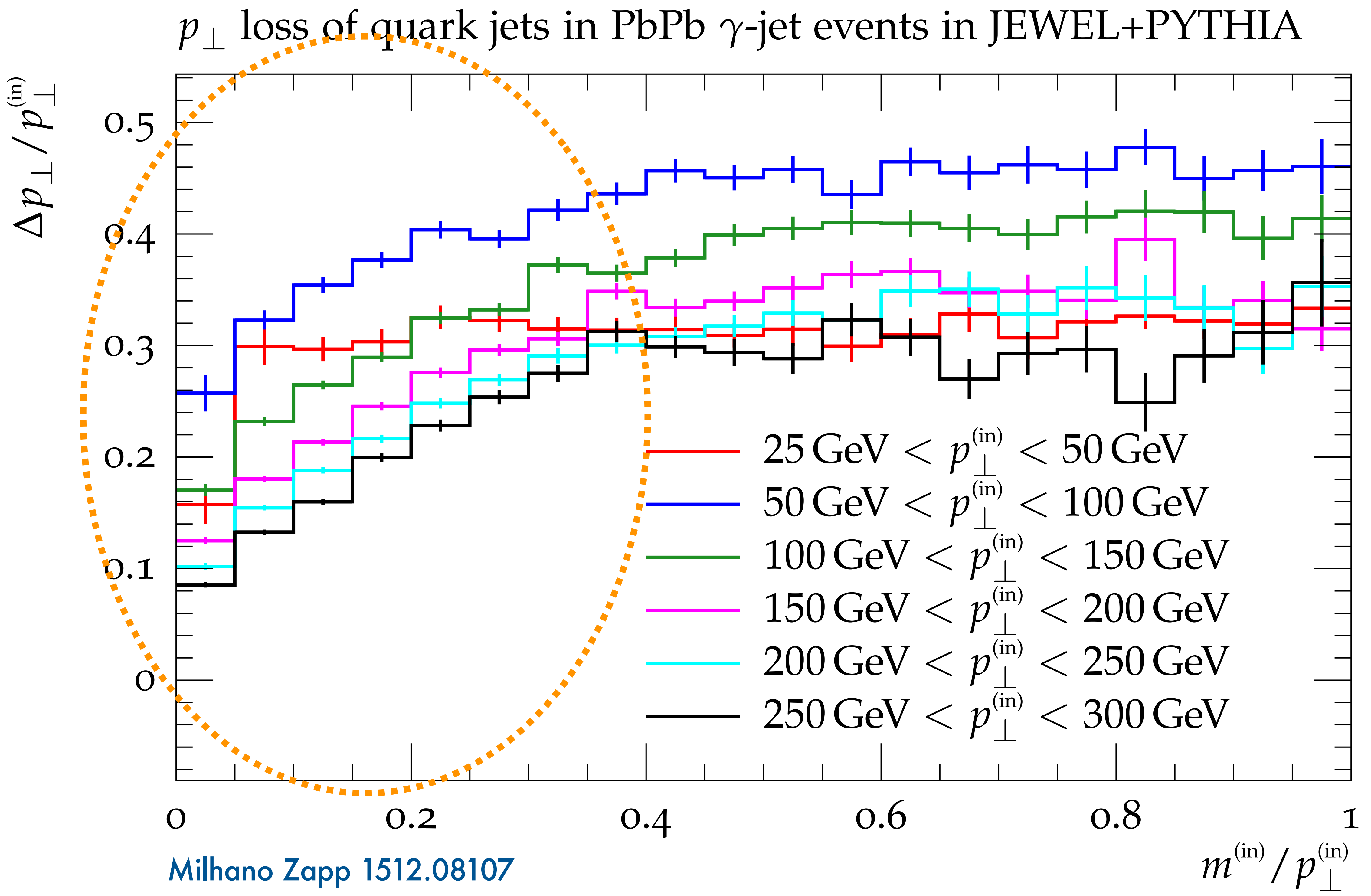


small m^2 :: narrow jet :: fewer constituents

- vacuum-like evolution at play, and dominant, within QGP :: jets are modified not re-invented
  - first splitting in QGP always vacuum-like [very short formation time]
  - number of constituents largely determined by vacuum-like physics

wide and narrow jets

- fixed p_T mother partons give rise to ensemble of varying envelope size jets [with varying number of constituents]
- with each constituent as an independent energy-loss source, wide jets must lose more energy than narrow jets :: this is what drives increase of dijet asymmetry



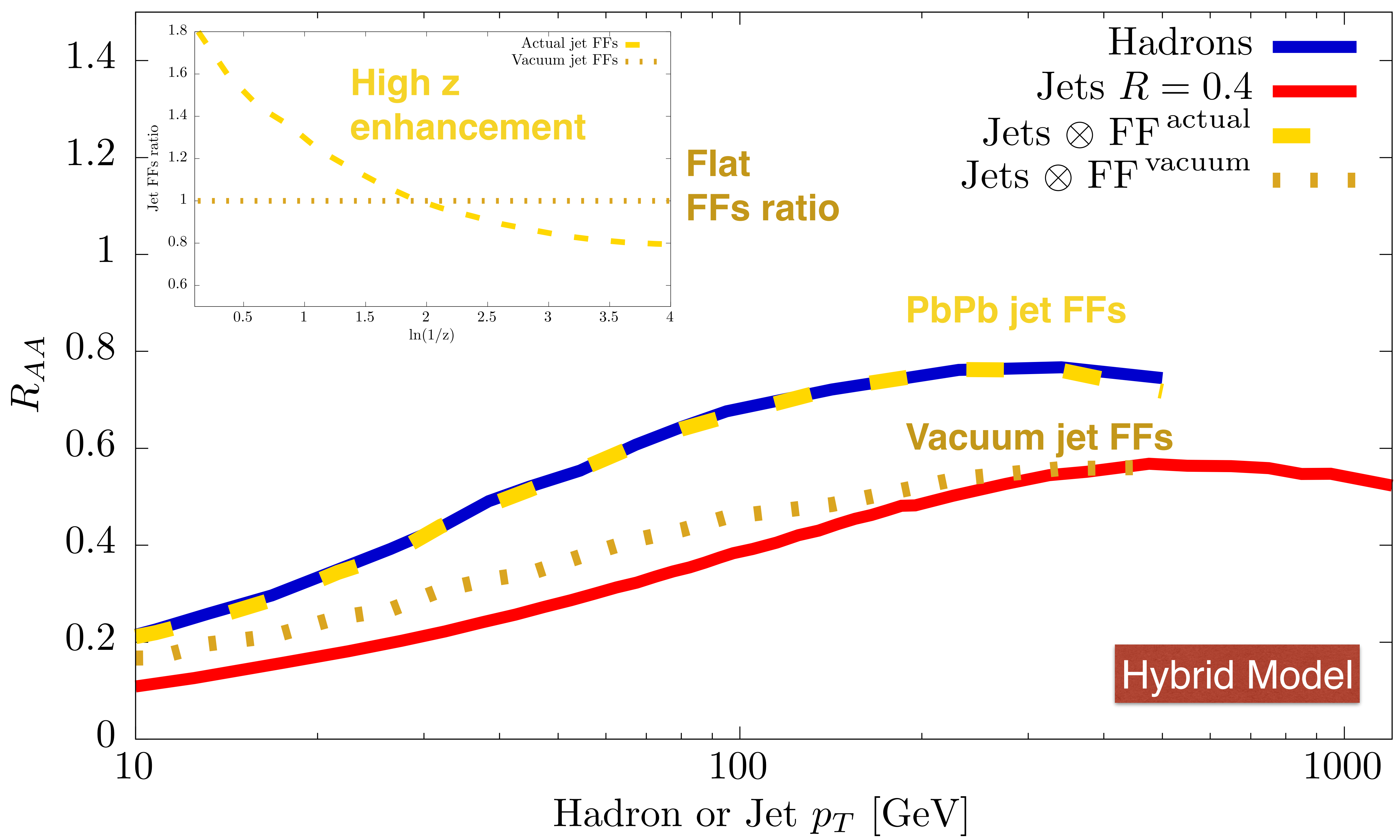
Milhano Zapp 1512.08107

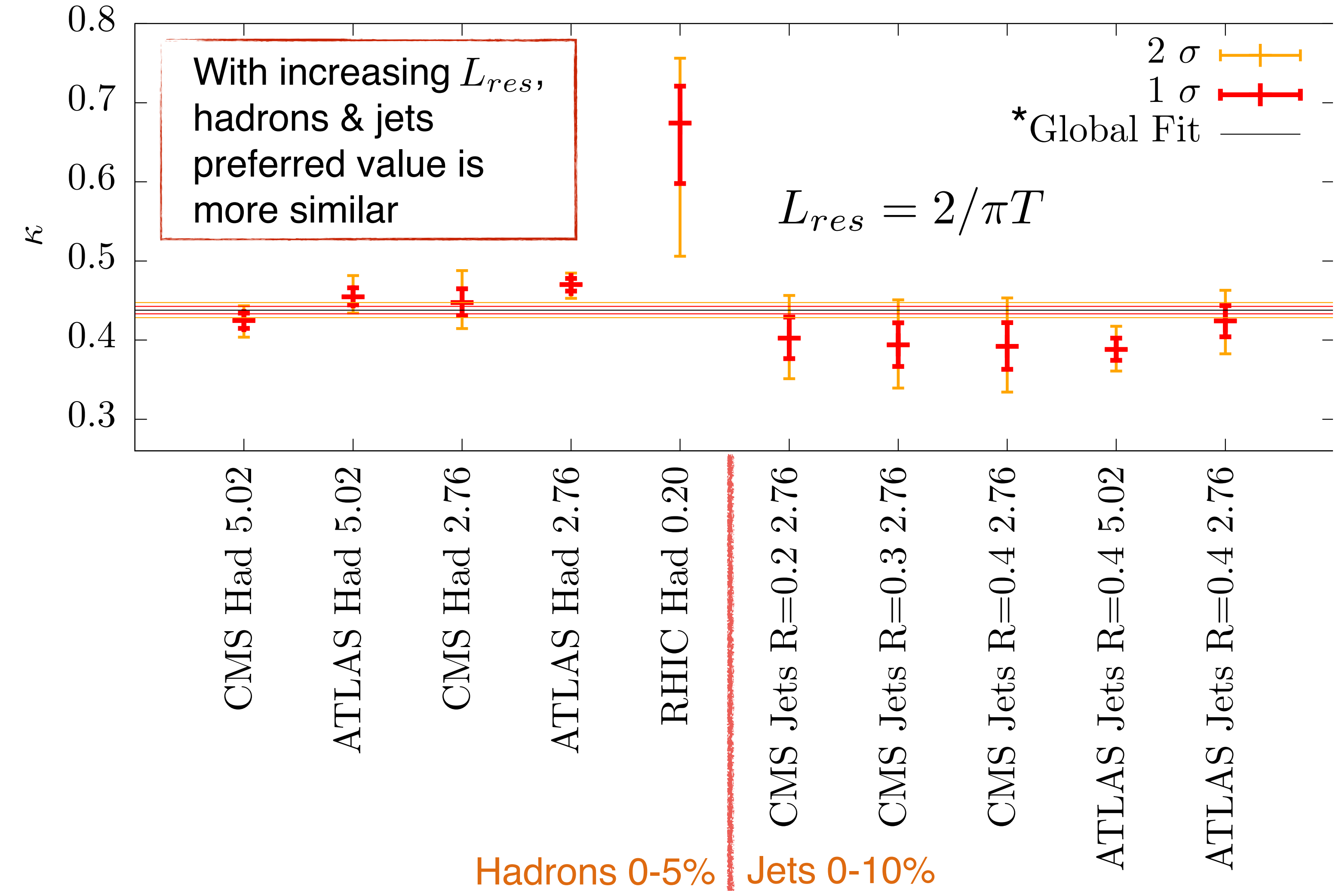
• same conclusion for holographic 'jets' •

Chesler, Rajagopal 1511.07567
Rajagopal, Sadofyev, van der Schee 1602.04187
Brewer, Rajagopal, van der Schee 1710.03237

wide and narrow jets :: jet and hadron R_{AA}

Pablos QM18



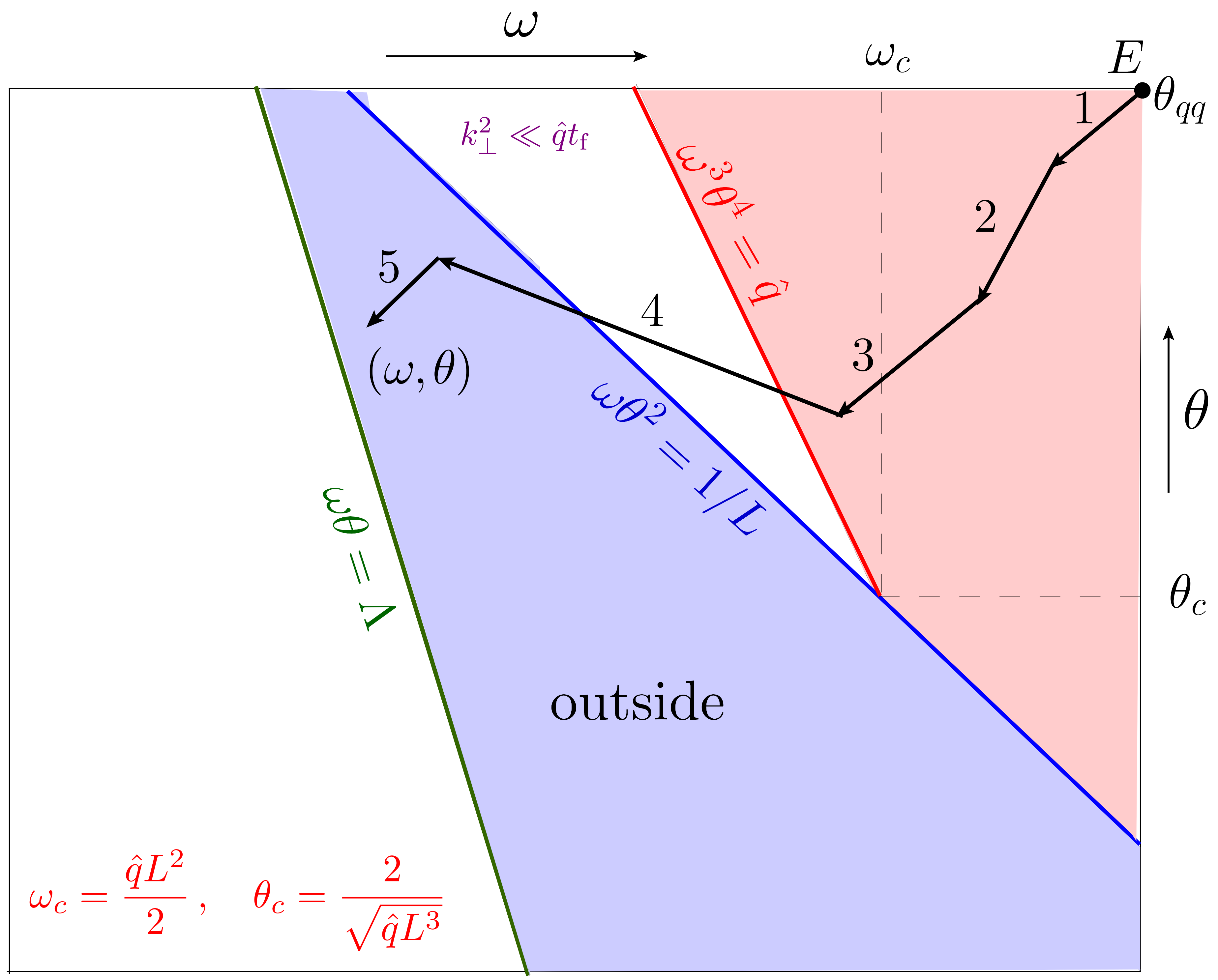


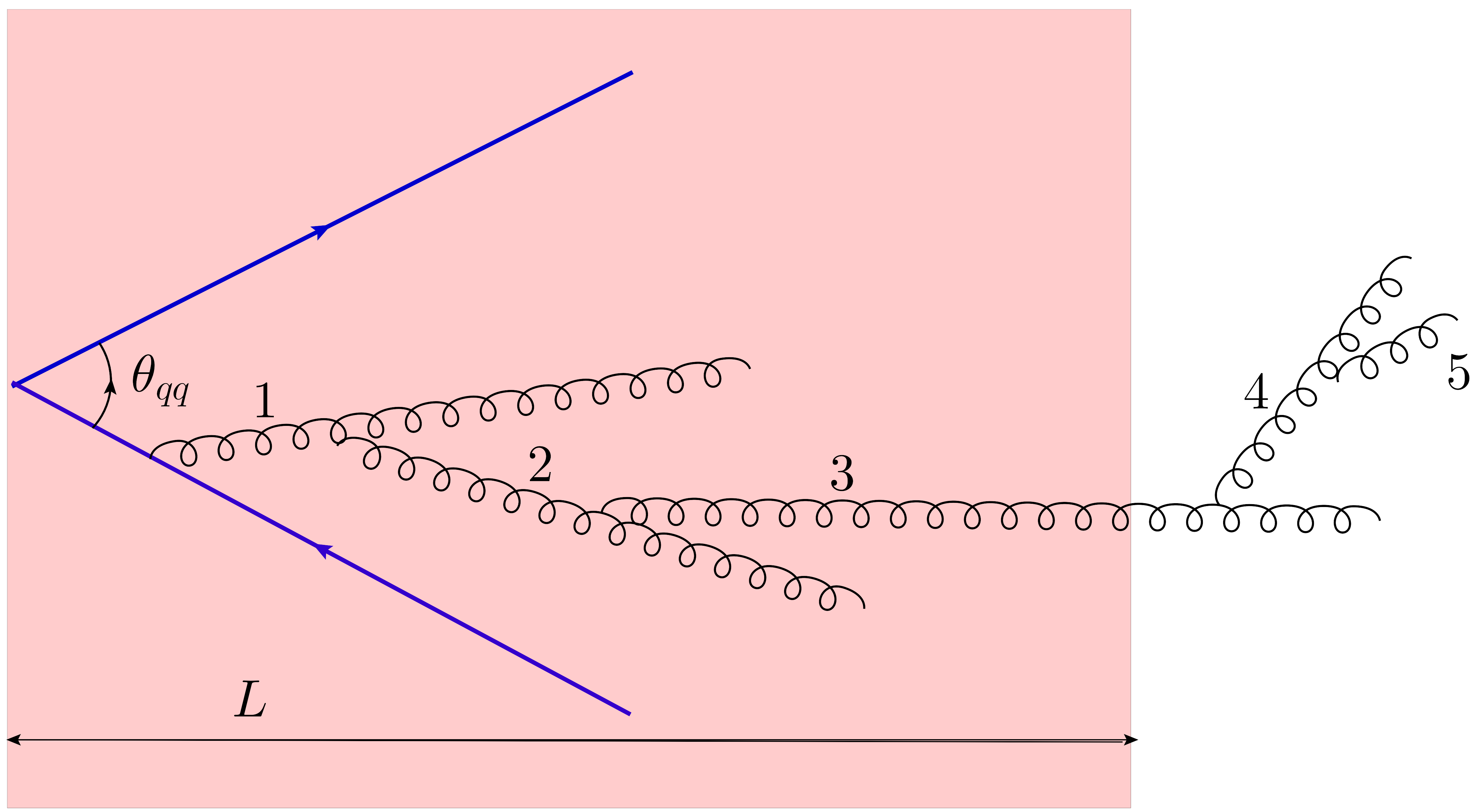
- high p_T hadrons originate from narrow jets which are less suppressed than inclusive jets
- simultaneous description of jet and hadron R_{AA} natural feature of any approach that treats jets as such
- modification of FF is essential
- LHC/RHIC tension substantially less in Hybrid than with quenching weights. why?

Andrés, Armesto, Luzum, Salgado, Zurita 1606.04837

modification of vacuum-like dynamics by QGP

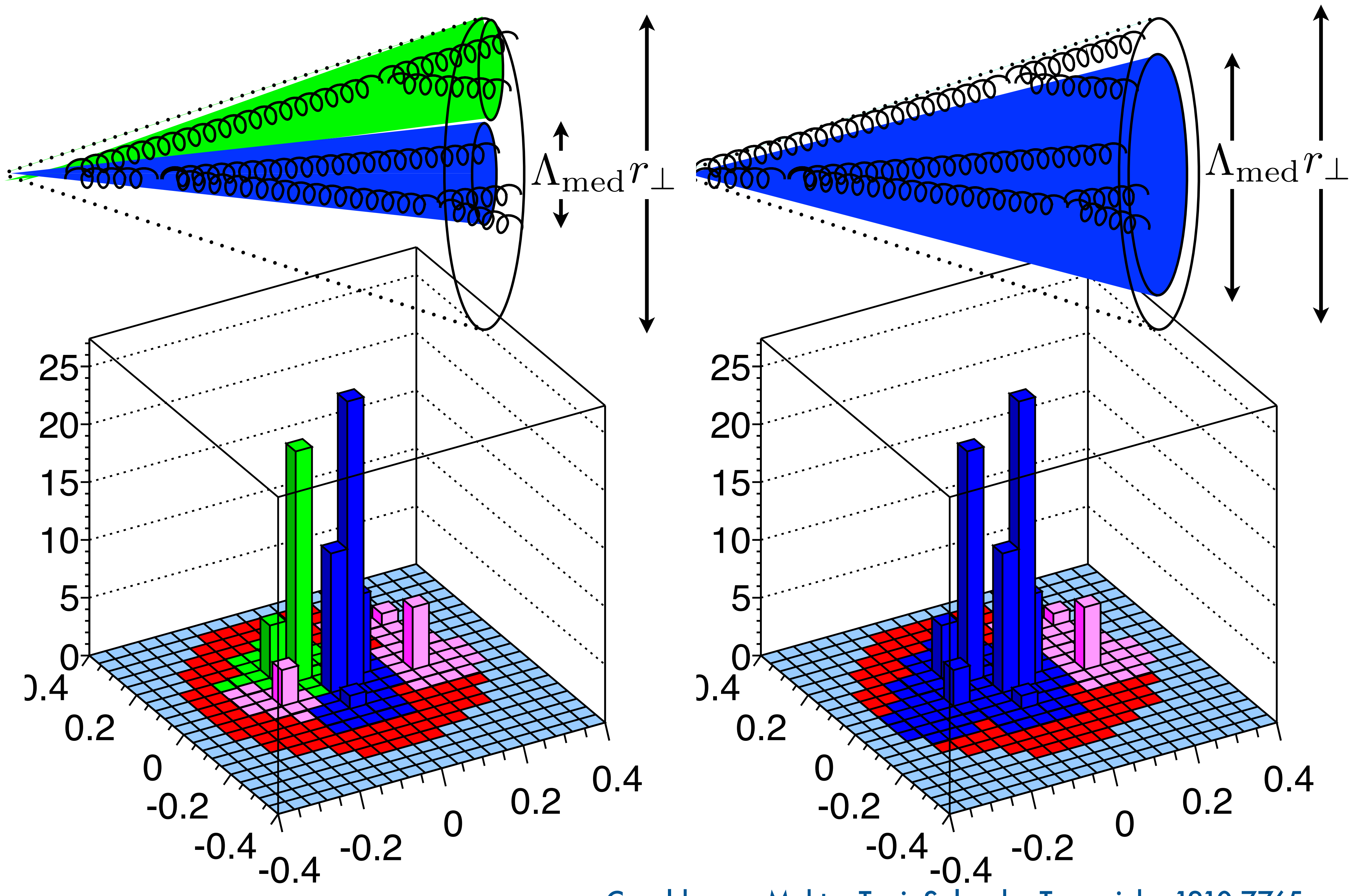
Caucal, Iancu, Mueller, Soyez 1801.09703





- in-medium DLA cascade as in vacuum but with phase space veto
- first splitting outside NOT angular ordered, subsequent evolution is
- effects beyond DLA will fill the vetoed region
- full description of in-medium cascade requires simultaneous resummation of dynamical processes that are ordered differently [medium-induced radiation ordered in distance travelled] :: a BIG challenge

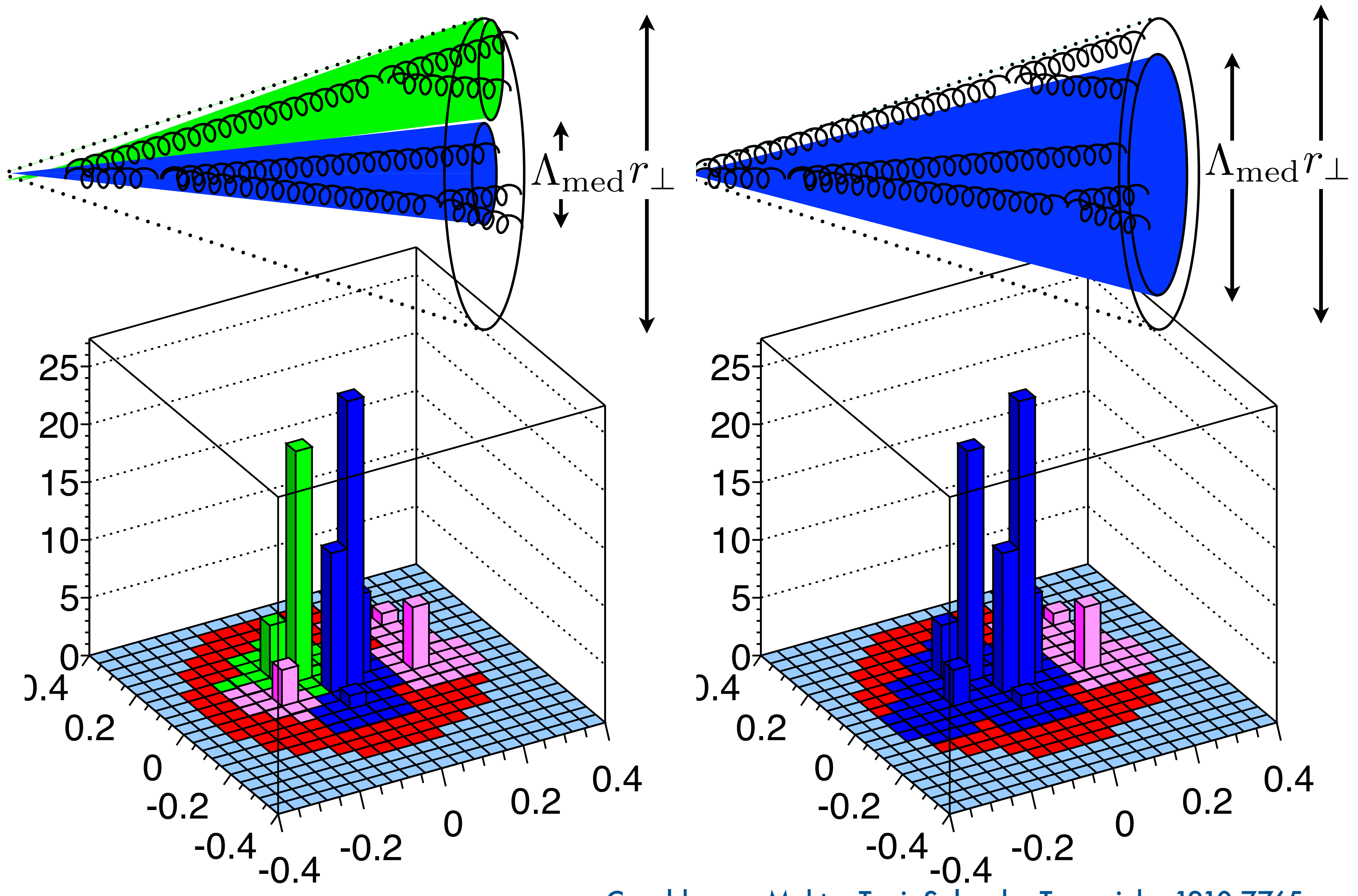
what in a jet interacts with QGP



Casalderrey, Mehtar-Tani, Salgado, Tywoniuk 1210.7765

- only structures that are resolvable by the QGP can interact with it independently
- for interaction with QGP, a developing jet is a set of resolved structures
- a delicate interplay between an evolving QGP scale and distances within jet

what in a jet interacts with QGP



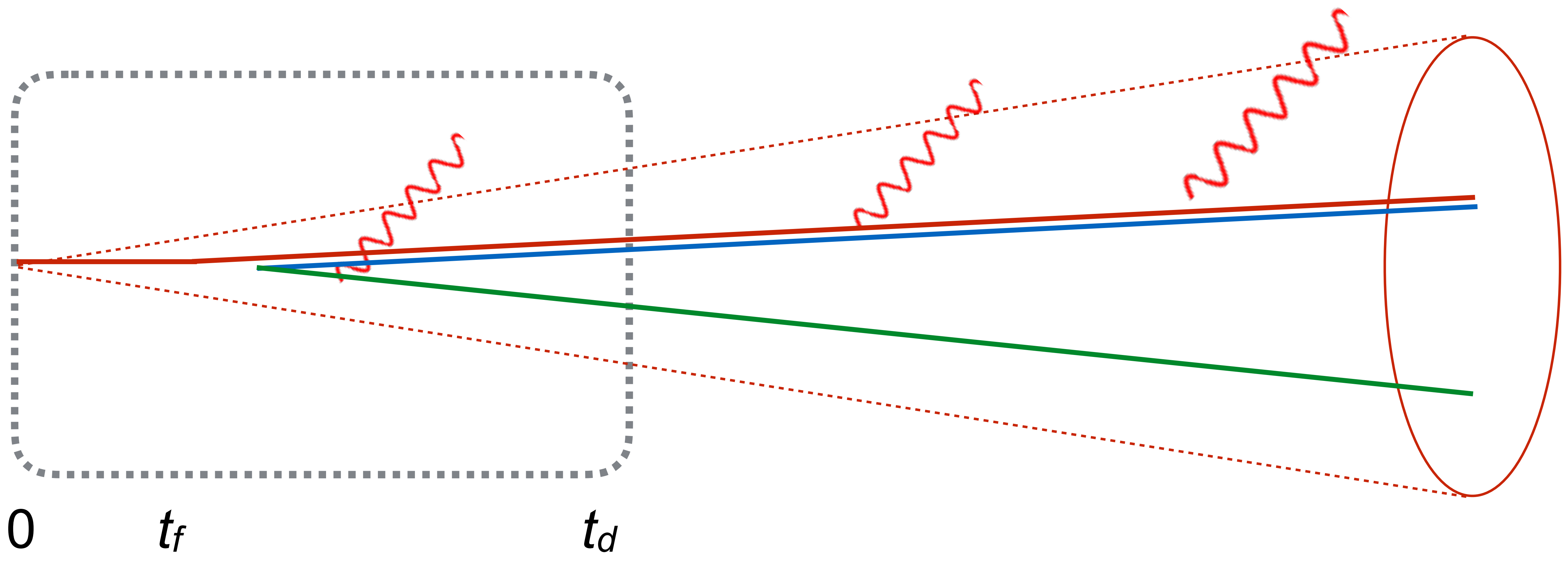
Casalderrey, Mehtar-Tani, Salgado, Tywoniuk 1210.7765

- only structures that are resolvable by the QGP can interact with it independently
- for interaction with QGP, a developing jet is a set of resolved structures
- a delicate interplay between an evolving QGP scale and distances within jet

at present, only MC implementation is that of Hybrid

energy loss of a 2-prong object :: building up a jet

Mehtar-Tani, Tywoniuk 1706.06047



$t_{\mathrm{d}} \sim (\hat{q}\theta_{12})^{-1/3}$

$$\mathcal{P}_{qg} = \mathcal{P}_q \otimes \mathcal{P}_{\mathrm{sing}}$$

- energy loss probability [quenching weight] for 2-prong object is convolution of energy loss of total charge with resolved colour singlet dipole

scale summary

[$p^2=m^2$] the mother parton 'virtuality'

:: determines vacuum-like branching dynamics and, to a large extent the multiplicity of candidate resolvable structures

[Λ_{med}] the evolving QGP scale

:: determines what within the jet can be resolved, and thus interacted with independently

[r_t] evolving distances between jet constituents

:: to be compared locally with medium scale

medium response

... is an unavoidable component of a jet

- implemented very differently in different approaches where it is essential for description of some observables [FF, jet shapes, z_J, ...]

  JEWEL :: recoil partons free-stream :: hadronized jointly with jet

  LBT/MARTINI :: recoil partons transported :: hadronized separately

  CoLBT :: sources further hydro evolution :: hadronized separately

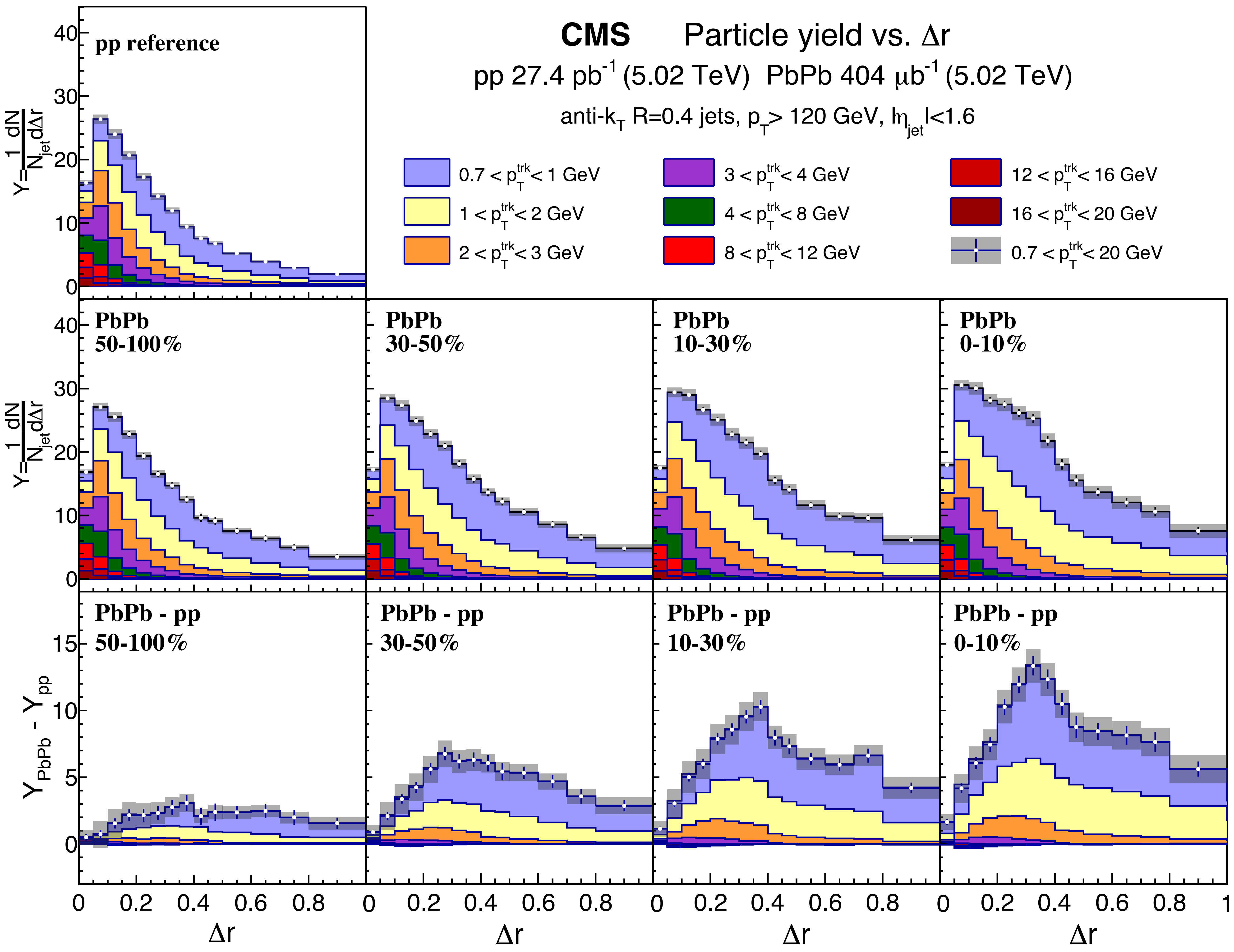
  Hybrid :: fully thermalized wake :: hadronized separately

- links jet quenching to physics of thermalization :: how a QGP converts external perturbations into more QGP

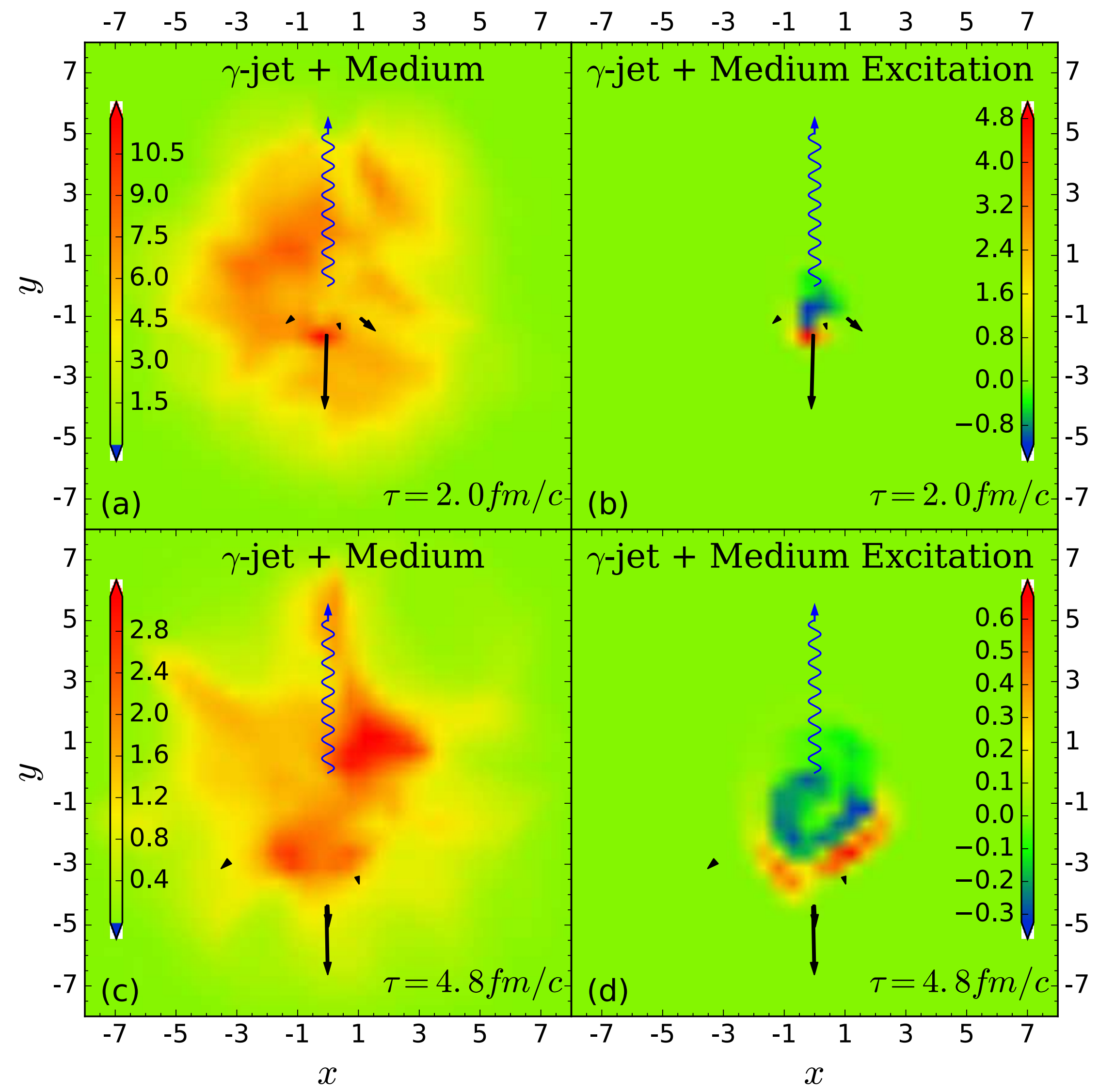
... relative importance is observable dependent

medium response

plenty of data available



1803.00042



Chen, Cao, Luo, Pang,Wang 1704.03648

how important is contamination from uncorrelated background?

what does jet interact with?

hydro paradigm → QGP is a strongly coupled fluid → no quasiparticles

jet-fluid interaction

- full holographic 'jets'
- strong/weak coupling hybrid

what does jet interact with?

hydro paradigm → QGP is a strongly coupled fluid → no quasiparticles

however,

jet–[quasi]particle interaction

- underlies pQCD based calculations
  - ✳ BDMPS-Z, [D]GLV, AMY, HT, SCET_G
- and their MC implementations, regardless of sophistication of simulated QGP
  - ✳ HIJING, Q-PYTHIA, PYQUEN, CUJET, JEWEL, MARTINI, LBT, CoLBT, JETSCAPE

jet-fluid interaction

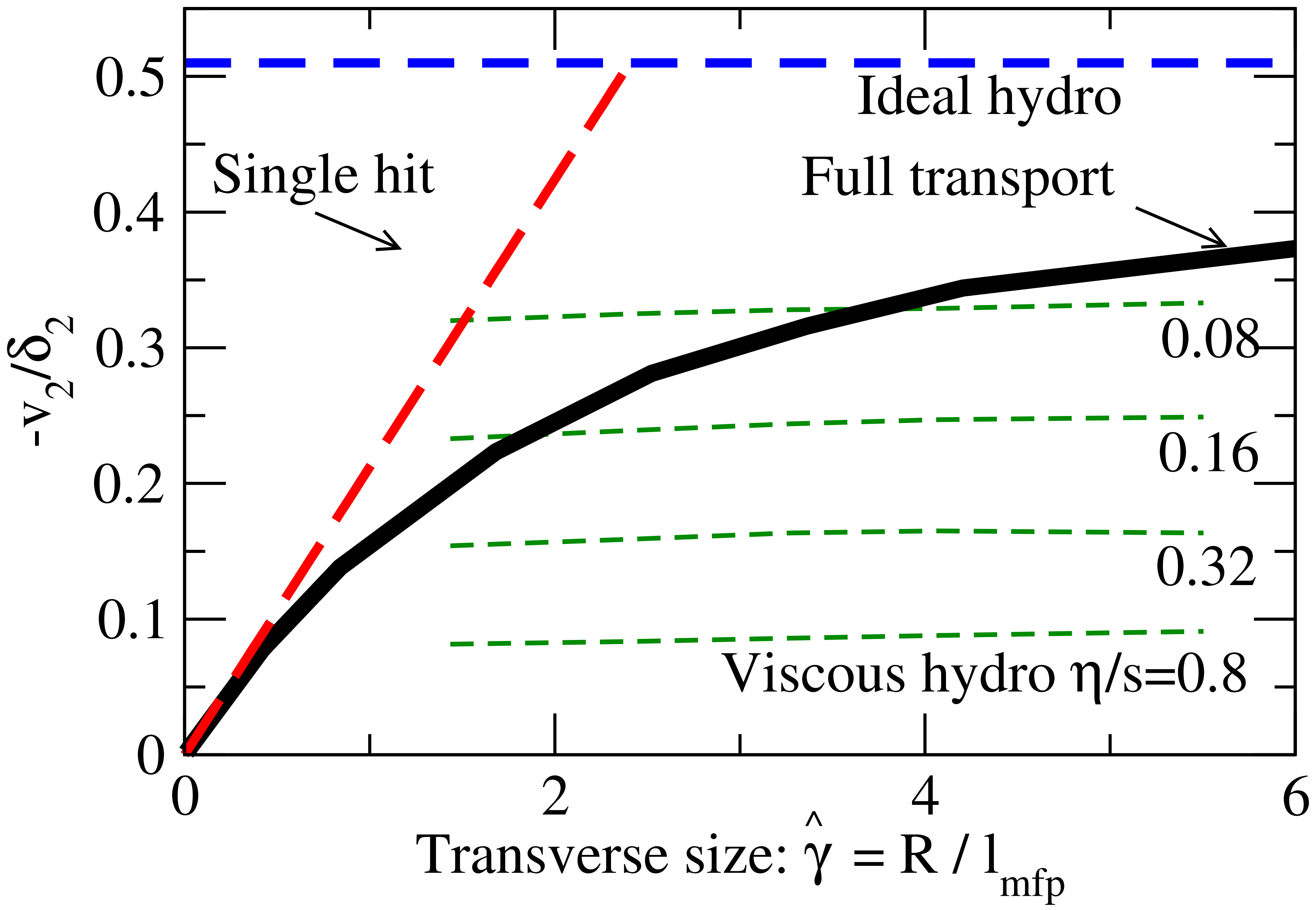
- full holographic ‘jets’
- strong/weak coupling hybrid

phenomenological success claimed in both cases

what does jet interact with?

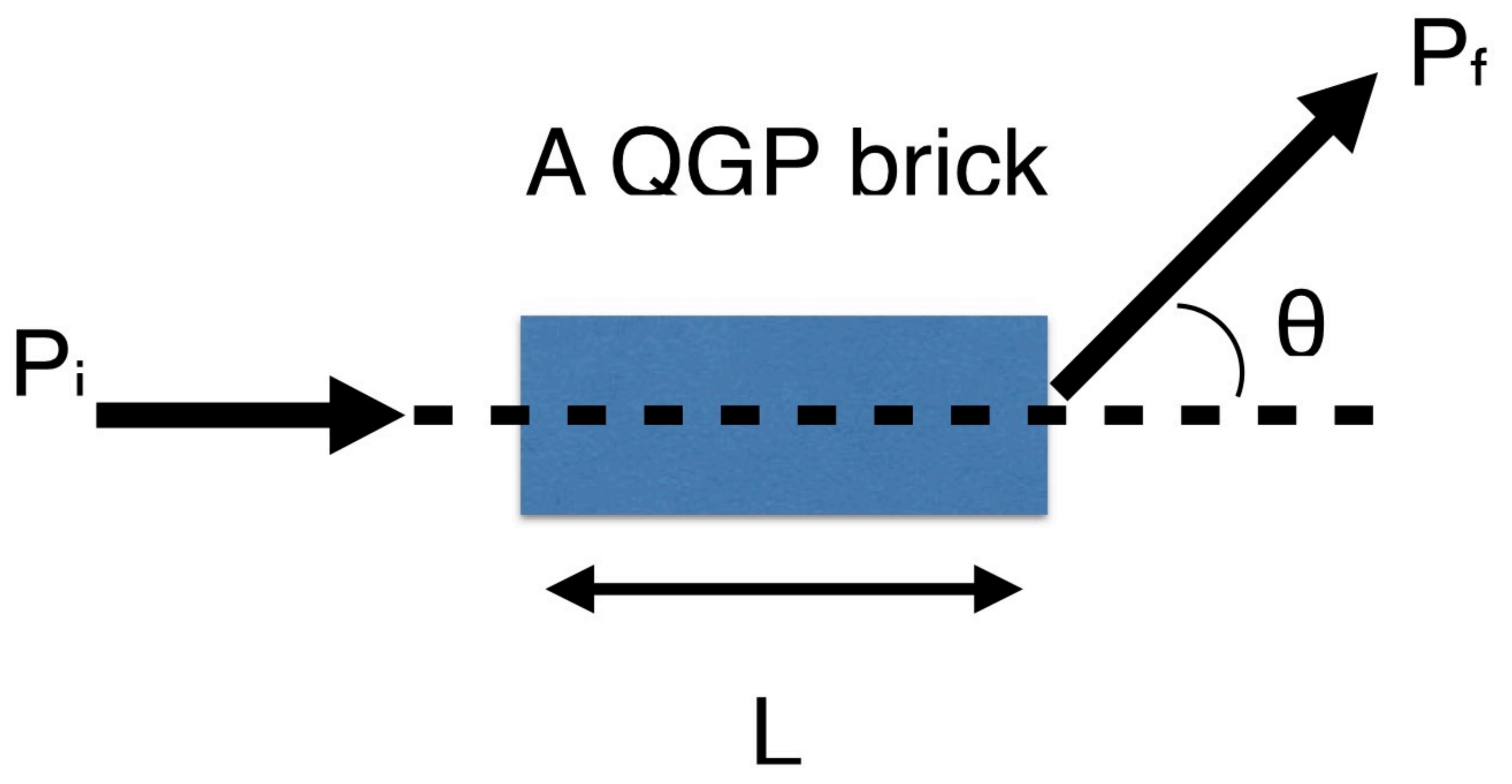
- success of approaches reliant on interaction with QGP quasiparticles is conceptually challenging
  - account of v_n coefficients in kinetic theory [which implies a larger η/s than that extracted from hydro] may provide a solid theoretical underpinning to quasiparticle structure of QGP

Kurkela, Wiedemann, Wu 1803.02072
1805.04081



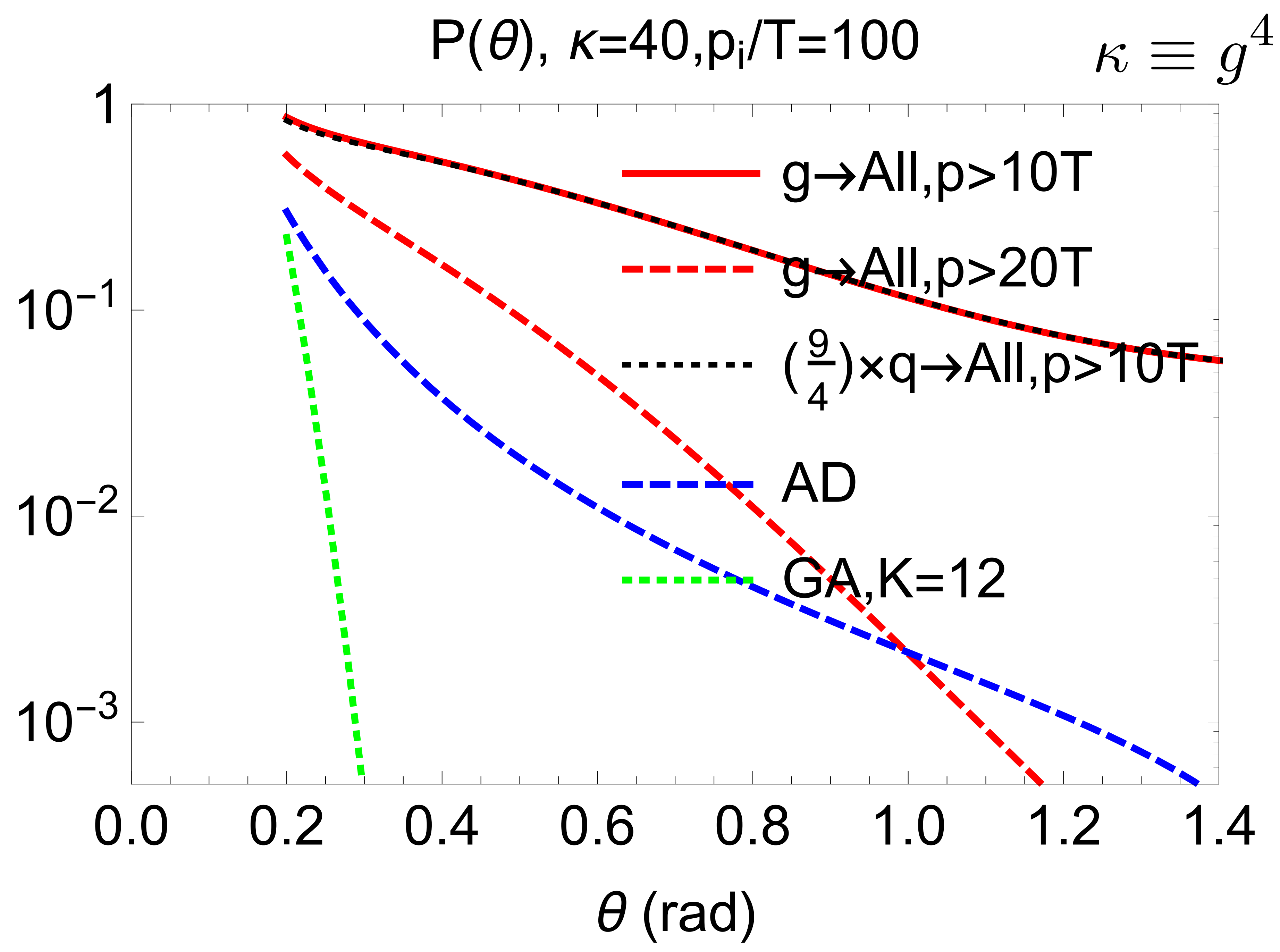
  - ... and incidentally challenge the hydro paradigm...

finding quasi-particles in QGP



D'Eramo, Lekaveckas, Liu, Rajagopal 1211.1922
D'Eramo, Rajagopal, Yi 18xx.xxxx

$\kappa \equiv g^4 \mathcal{T} T$



- compare Gaussian distribution of kicks [no quasiparticles] with perturbative tail [quasiparticles]
  - large kicks [Molière scattering] are rare but not exponentially so
- where to look?
  - energy distribution within and around jet [medium response depends on nature of QGP]
- change of acoplanarity distribution [in di-jet, γ/Z-jet, hadron-jet] Gyulassy QM18
  - multiple effects may make it very hard to see [a lesson from the Hybrid model] Casalderrey, Gulhan, Milhano, Pablos, Rajagopal 1609.05842

modelling

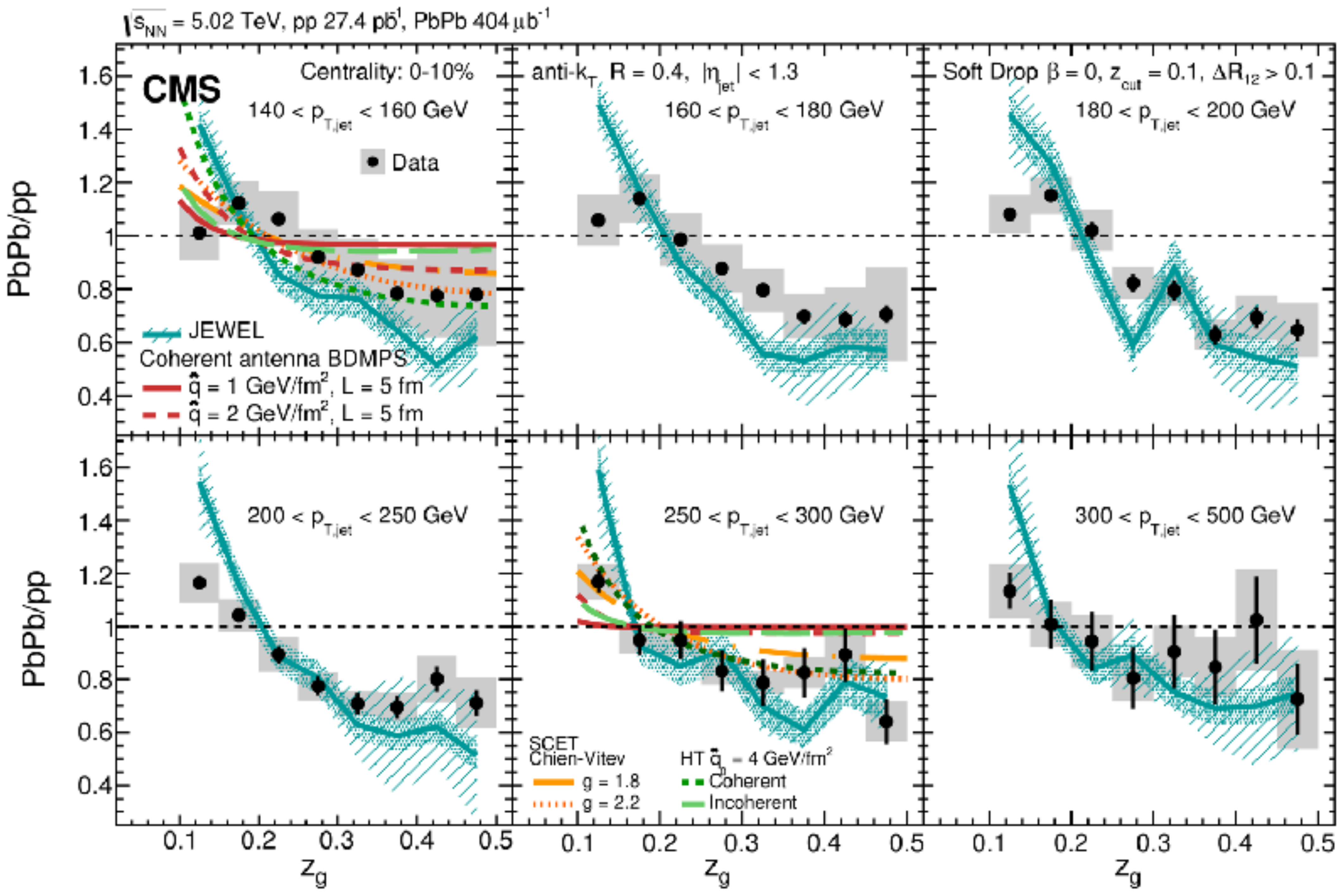
prosecco bitter soda ice garnish approaches

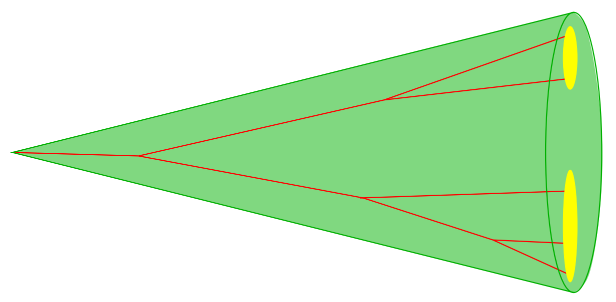
- sequential deployment of included mechanisms [shower then transport, etc.]
- requires *matching scales [added uncertainty?]*
  - ✳ MARTINI, LBT, CoLBT, JETSCAPE [in principle allows for concurrency]
- can it be justified? do different mechanism factorize?

spritz approaches

- all included mechanisms are concurrent
- dynamical decision on what happens when
  - ✳ Q-PYTHIA, JEWEL, Hybrid, and [by construction] analytical calculations

robust conclusions from agreement with data





$$z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} \qquad z_g > 0.1$$

modified splitting kernel [SCET$_G$]

Chien, Vitev 1608.07283

coherent+decoherent induced-radiation [BDMPS]

Mehtar-Tani, Tywoniuk 1610.08930

coherent+decoherent induced-radiation [HT]

Chang, Cao, Qin 1707.03767

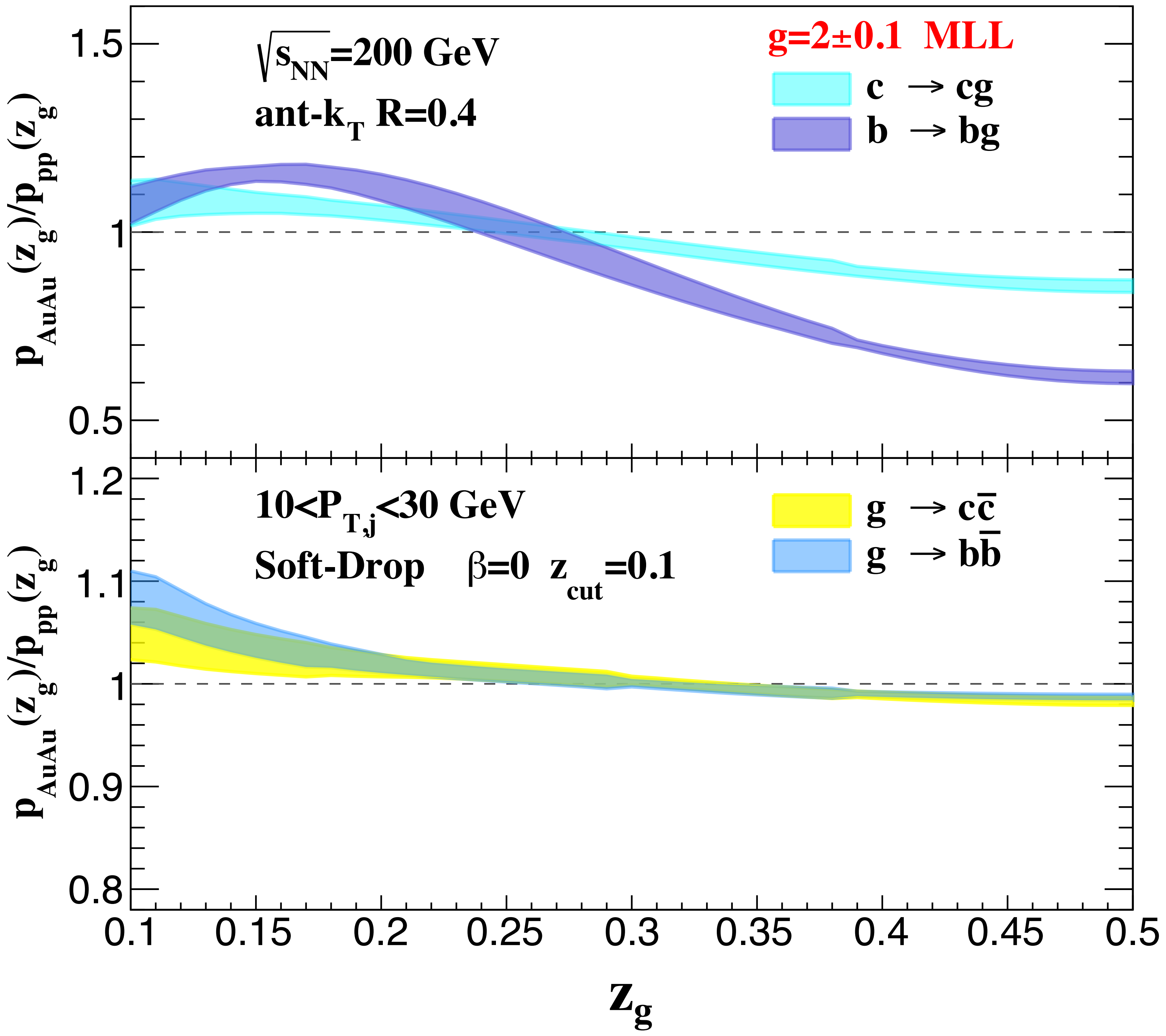
inelastic and elastic eloss + medium response

Milhano, Wiedemann, Zapp 1707.04142

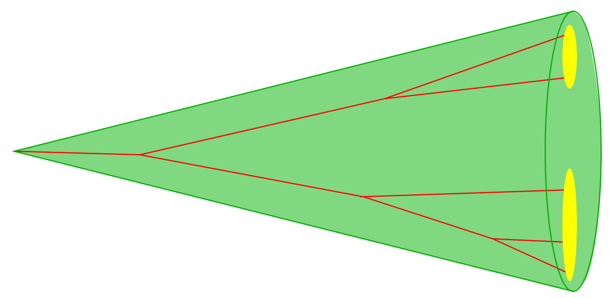
- no presently available model or calculation includes all known and potentially relevant mechanism underlying in-QGP jet modification
- successful data description leads to diverse conclusions in different models
- need to justify observable lack of sensitivity to missing ingredients for robust conclusion

better observables

extracting QGP properties with jets is all about understanding the specific sensitivity of observables



Li, Vitev 1801.00008



$$z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} \qquad z_g > 0.1$$

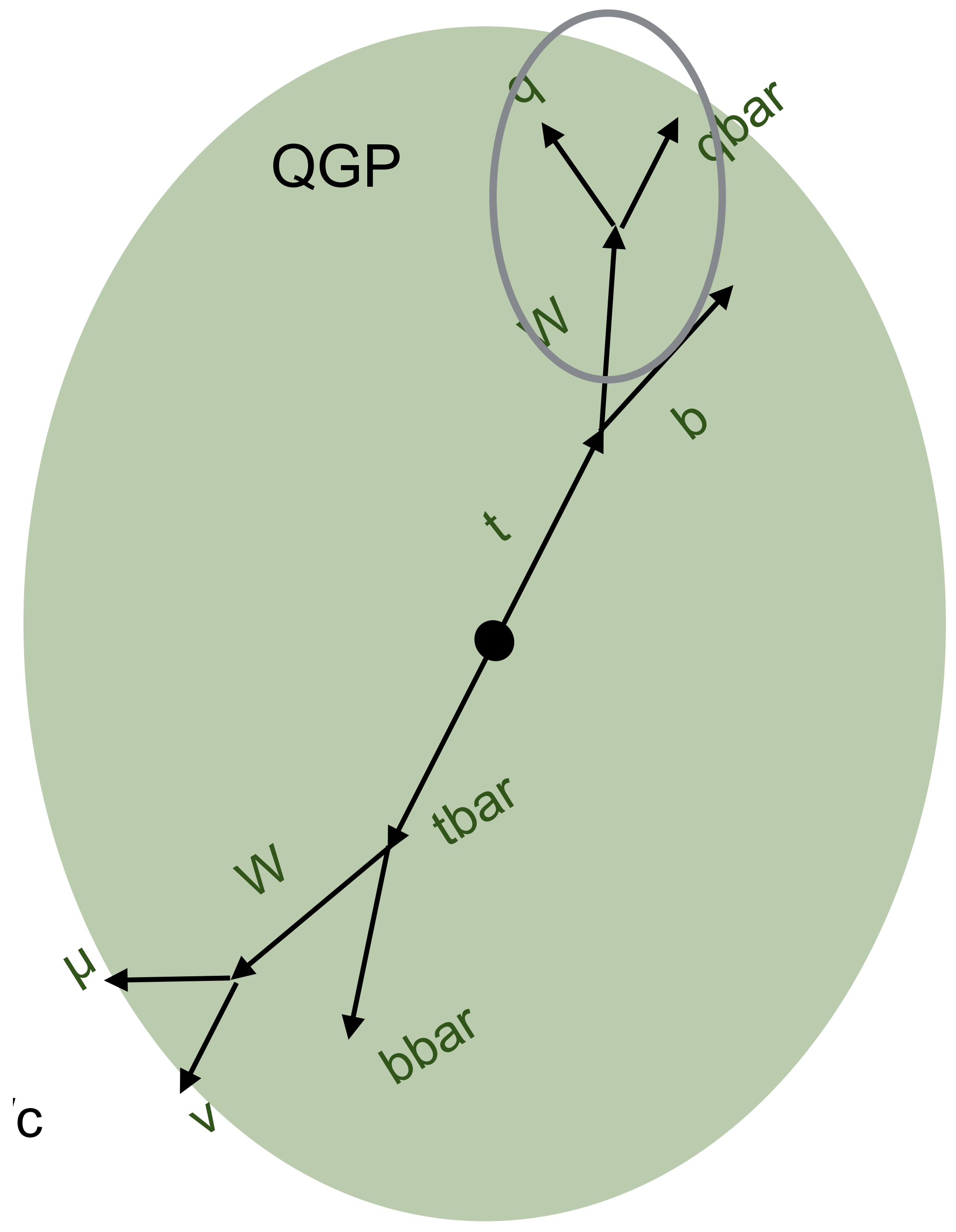
- observe different modification of light and heavy-quark jets via substructure of heavy-quark tagged jets

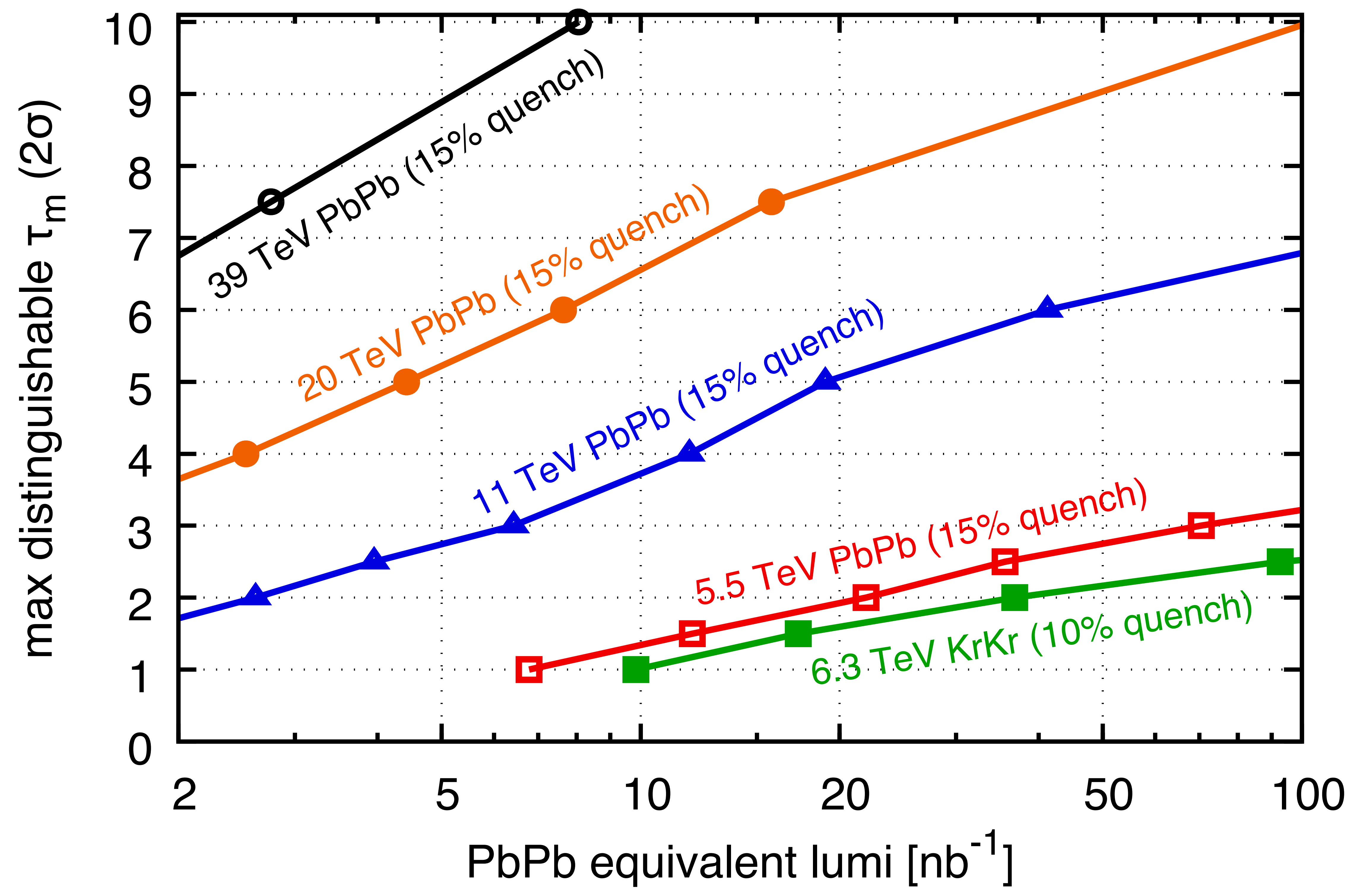
a very interesting idea…

another interesting idea

probe time-dependence of QGP properties

Apolinário, Milhano, Salam, Salgado 1711.03105



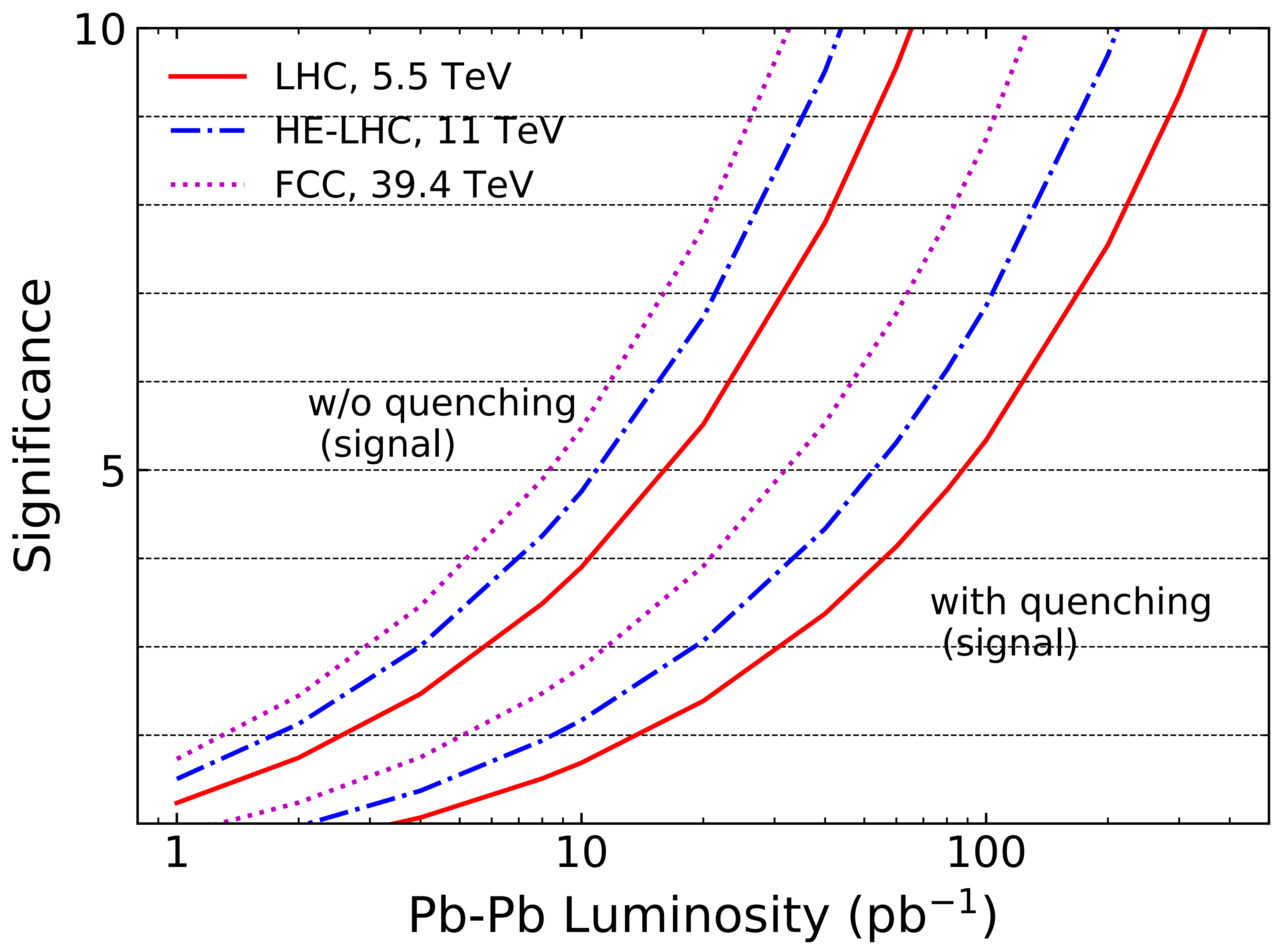


- inject time delayed [top decay + W decay + qqbar coherence] probes in QGP
  - reconstructed W mass will be quenched but less so the longer the delay
- requires large luminosity, but **within reach at LHC with lighter ion runs**

and one more

jet quenching as fake suppressant to study H→b bbar

Berger, Gao, Jueid, Zhang 1804.06858



$$\mathrm{PbPb} \to ZH \to \ell^+\ell^- bb$$

- b-jets from Higgs decay not quenched [$\tau_{\mathrm{Higgs}} \sim 47$ fm/c] but other b-jets are
  - signal cleaner than in pp
- requires huge luminosity
- conceptually open a path for jet quenching as a tool for [B]SM processes [searches]

outlook

- jet modification is the QGP hallmark that has not been observed in smaller systems
  - no QGP in small systems?
  - very small effect :: need dedicated observables

- analytical understanding and MC implementation of in-QGP jet dynamics advanced significantly over the last few years
  - increased meaningfulness of theory/data comparisons
  - however, 'all-dynamics' approach still not available

- access to rare processes [eg, top quark production] and configurations [eg, very asymmetric dijets], and increased precision in key observables [eg, Z-jet] within reach via lighter ion runs