What we have learnt from jet quenching at the LHC

Guilherme Milhano [LIP & IST, Lisbon]
gmilhano@lip.pt

LIP TÉCNICO LISBOA FCT Fundação para a Ciência e a Tecnologia MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA erc European Research Council Established by the European Commission

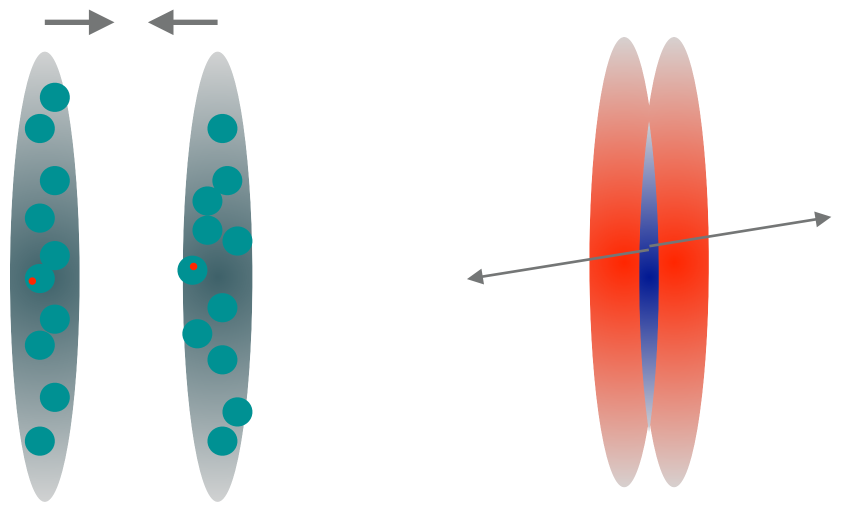
LIP seminar, 23 Jun 2022

I. what we want to understand

FROM NUCLEI TO QGP :: A HEAVY ION COLLISION

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

time



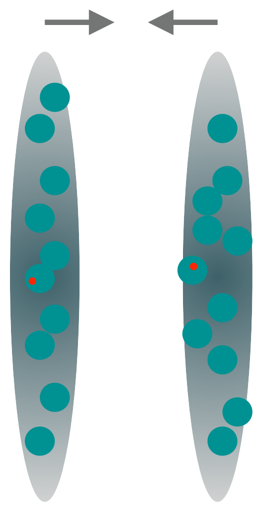
colliding nuclei

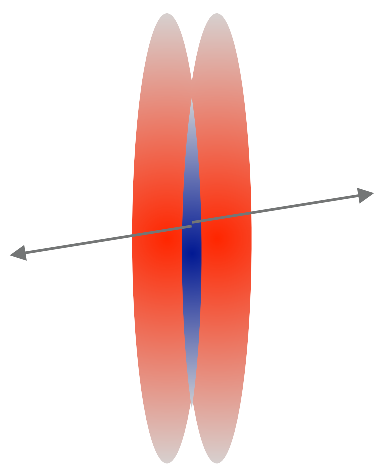
collision
[out-of-equilibrium process]

FROM NUCLEI TO QGP :: A HEAVY ION COLLISION

$\sim$ 0.1 fm/c
[$\sim 10^{-25}$ s]

time





colliding nuclei

collision
[out-of-equilibrium process]

many soft [small momentum exchange] collisions
- responsible for bulk low-momentum particle production
- will quickly hydrodynamize

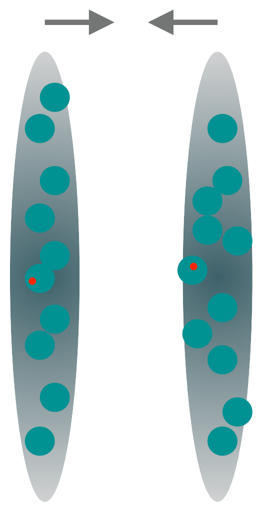
very few hard [large momentum exchange] collisions
- offspring will slowly relax towards hydrodynamization, yet remain out-of-equilibrium, while propagating through soft soup

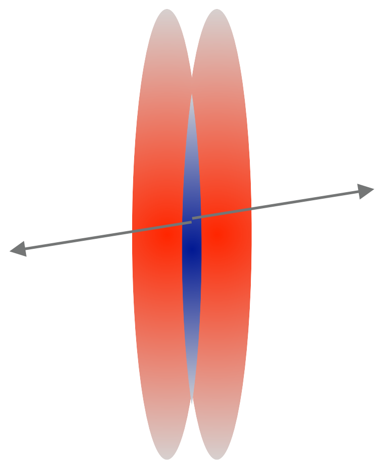
FROM NUCLEI TO QGP :: A HEAVY ION COLLISION

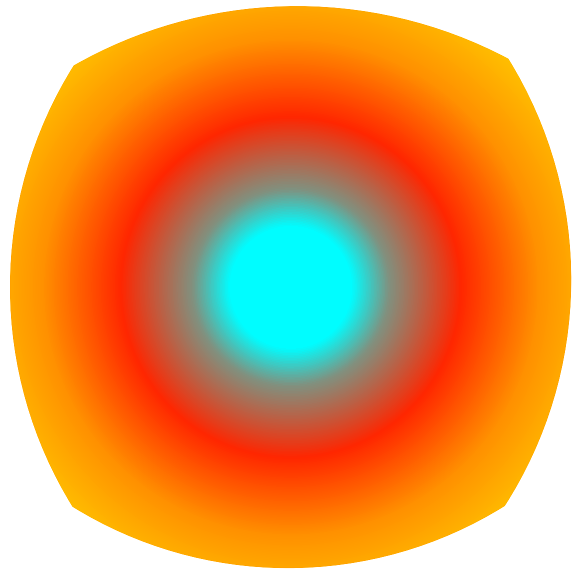
~ 0.1 fm/c
[~10^{-25} s]

~1 fm/c
[~10^{-24} s]

time



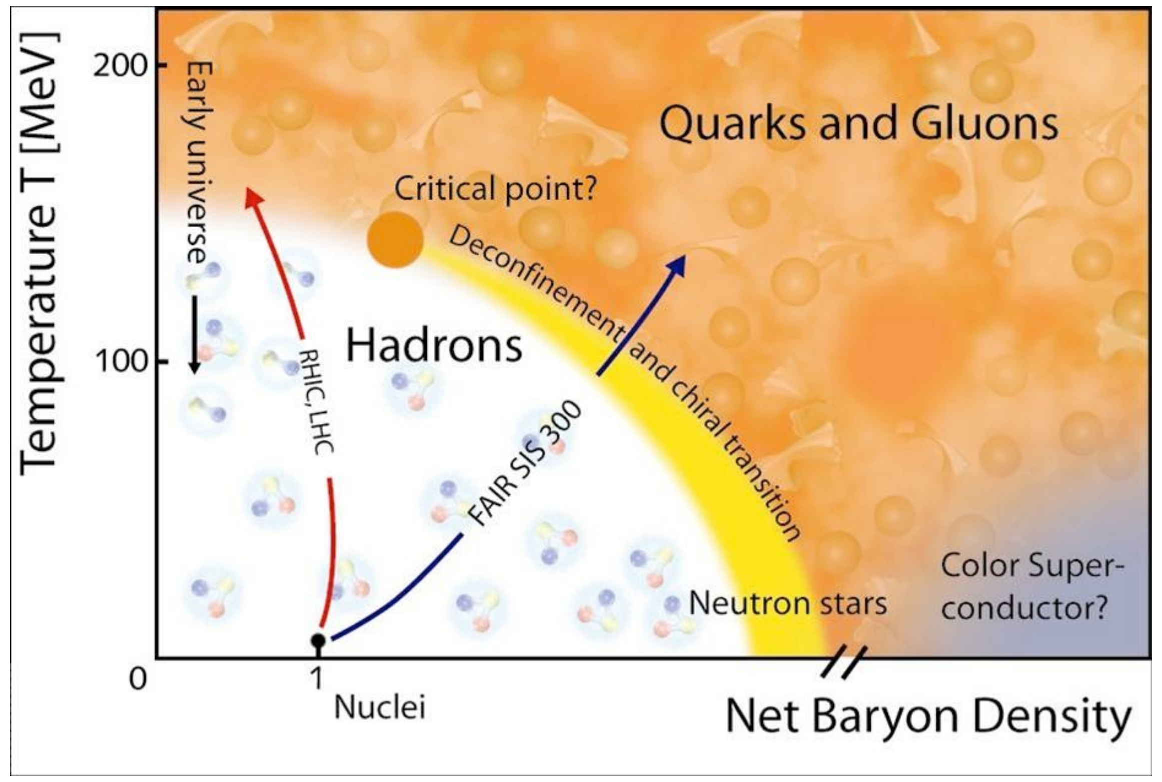




colliding nuclei
[nuclear structure encoded in nPDFs]

collision
[out-of-equilibrium process]

Quark Gluon Plasma
[hot, dense and coloured nuclear matter]
[quarks and gluons are the relevant dof]



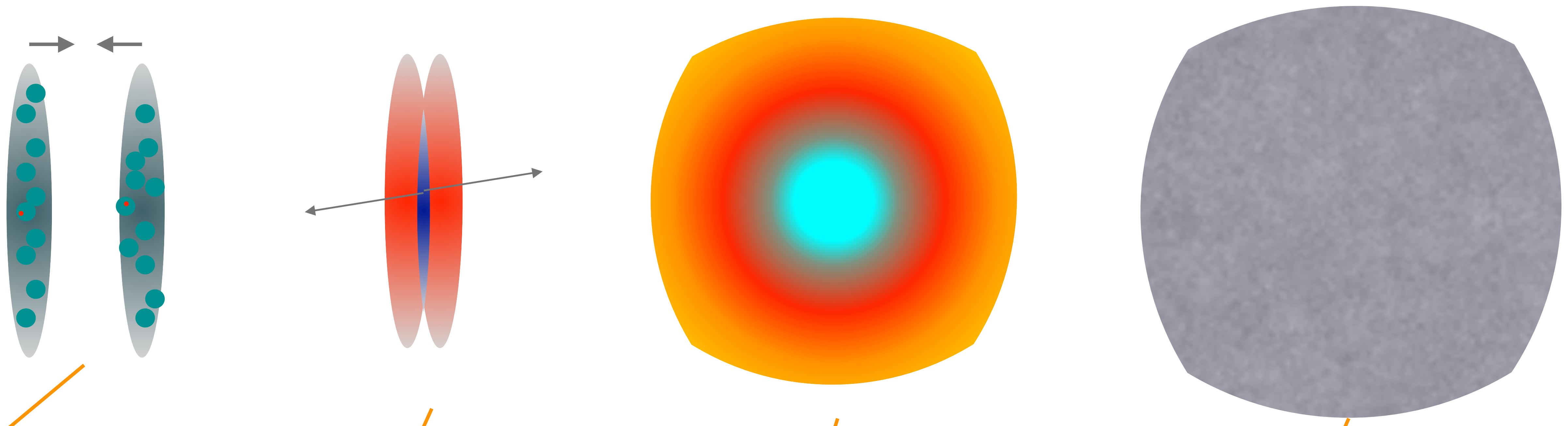
FROM NUCLEI TO QGP :: A HEAVY ION COLLISION

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

~1 fm/c [~10^{-24} s]

~ 10 fm/c

time

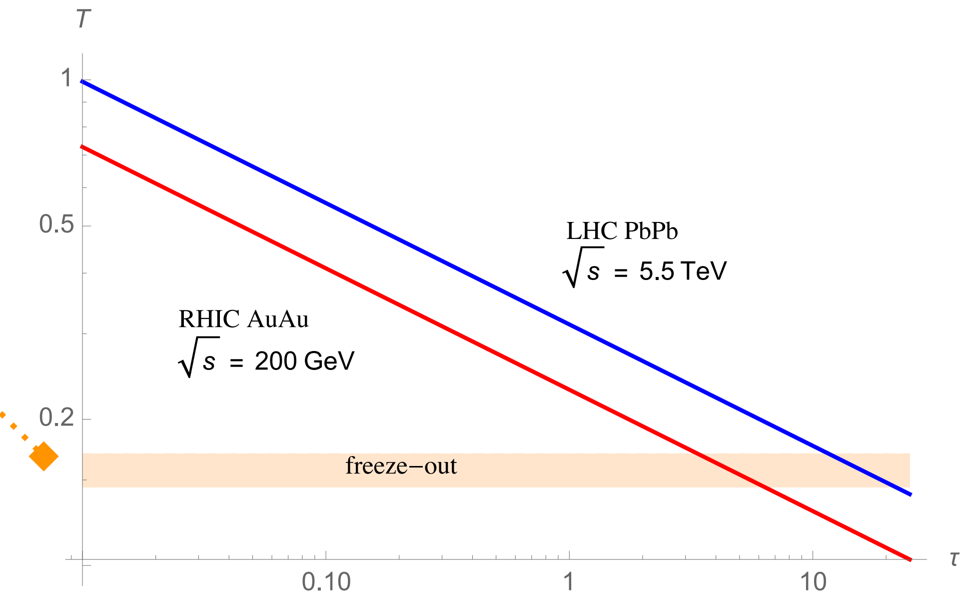


colliding nuclei
[nuclear structure encoded in nPDFs]

collision
[out-of-equilibrium process]

Quark Gluon Plasma
[hot, dense and coloured nuclear matter]
[quarks and gluons are the relevant dof]

hadronization
[the QGP expands and thus cools down]
[once T ~ 150 MeV back to hadronic matter]



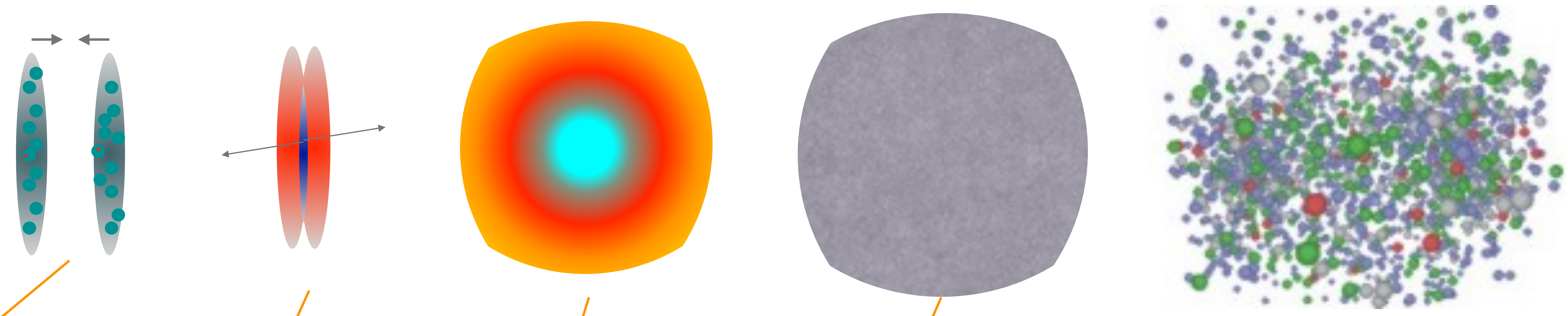
FROM NUCLEI TO QGP :: A HEAVY ION COLLISION

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

~1 fm/c
[~10^{-24} s]

~ 10 fm/c

time



colliding nuclei
[nuclear structure encoded in nPDFs]

collision
[out-of-equilibrium process]

Quark Gluon Plasma
[hot, dense and coloured nuclear matter]
[quarks and gluons are the relevant dof]

hadronization
[the QGP expands and thus cools down]
[once T ~ 150 MeV back to hadronic matter]

hadrons
[what is seen by experiments]

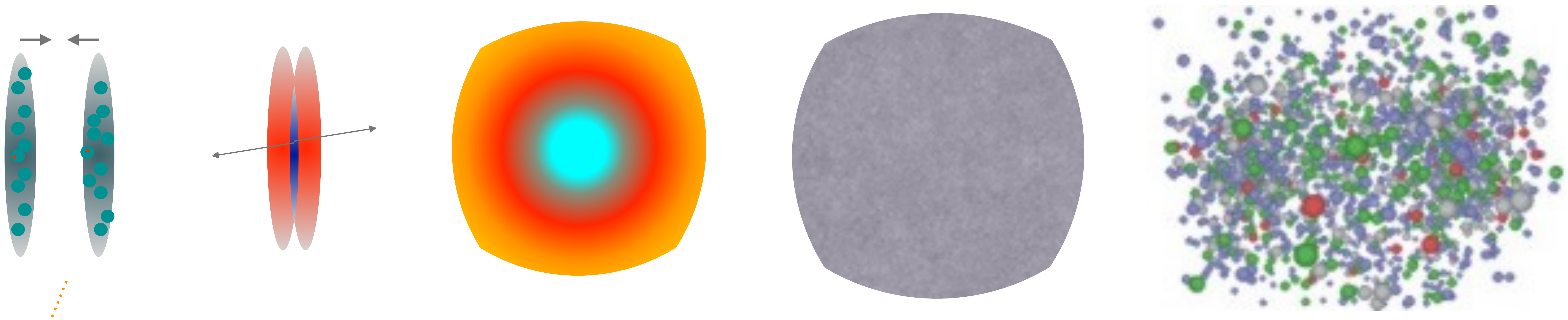
FROM NUCLEI TO QGP :: A HEAVY ION COLLISION

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

~1 fm/c [~10^{-24} s]

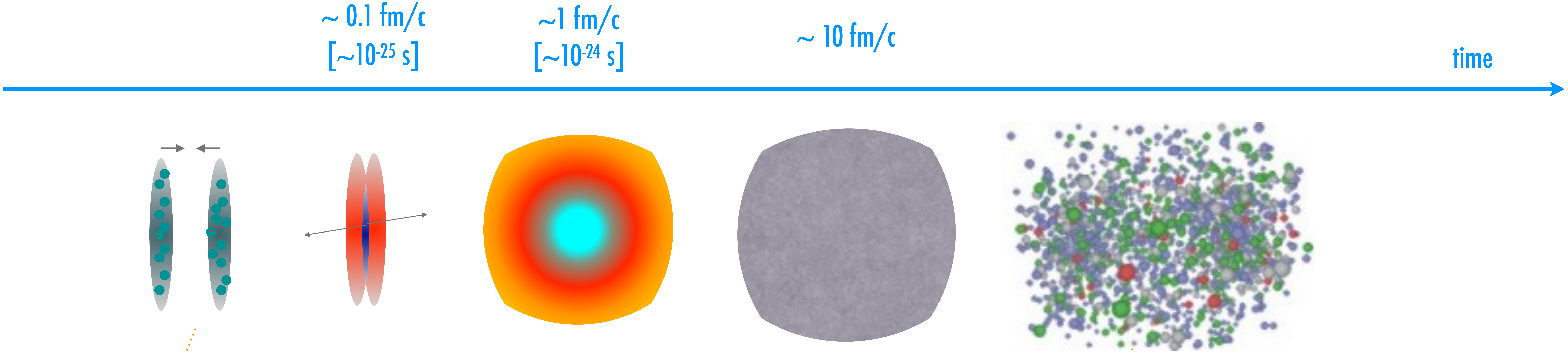
~ 10 fm/c

time



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

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

all we have

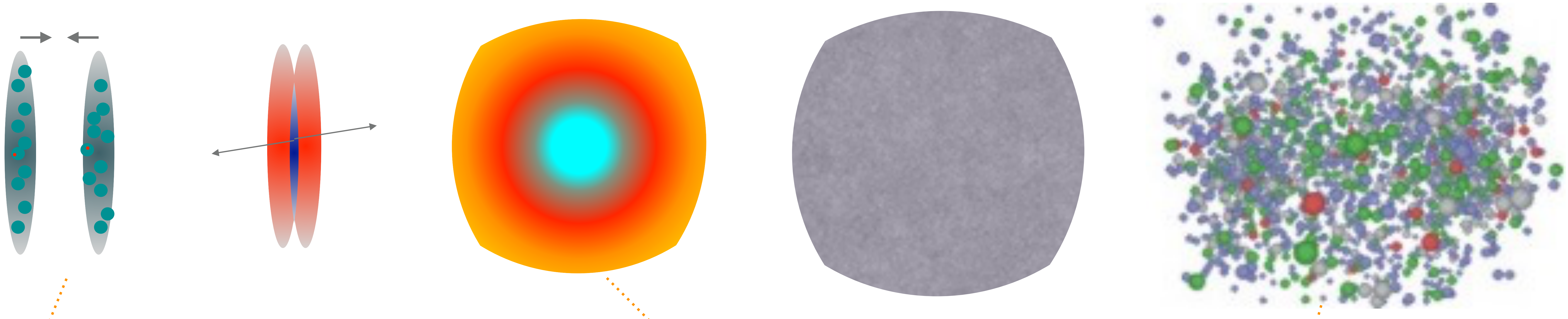
FROM NUCLEI TO QGP :: A HEAVY ION COLLISION

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

~1 fm/c [~10^{-24} s]

~ 10 fm/c

time



what we want to understand
- how we get here?
- what it is?
- how it stops being?

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

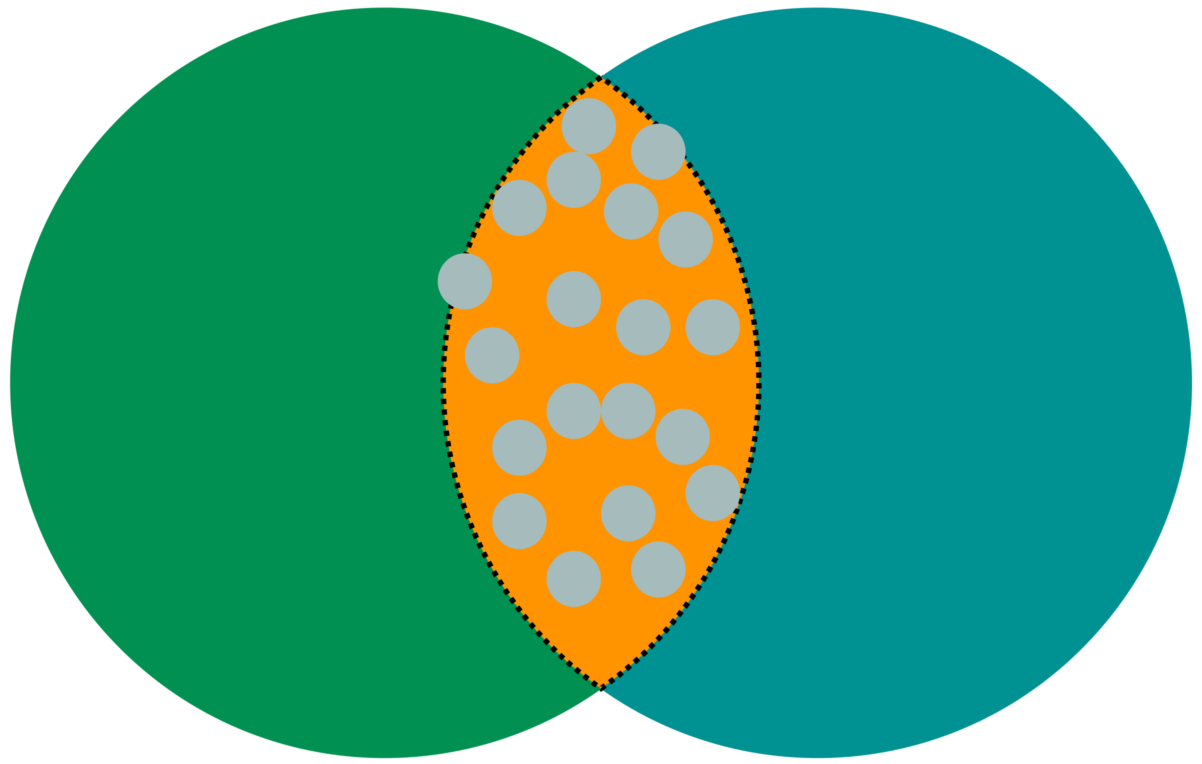
all we have

WHAT IS QGP?

a slight misnomer…

WHAT IS QGP?

a slight misnomer…

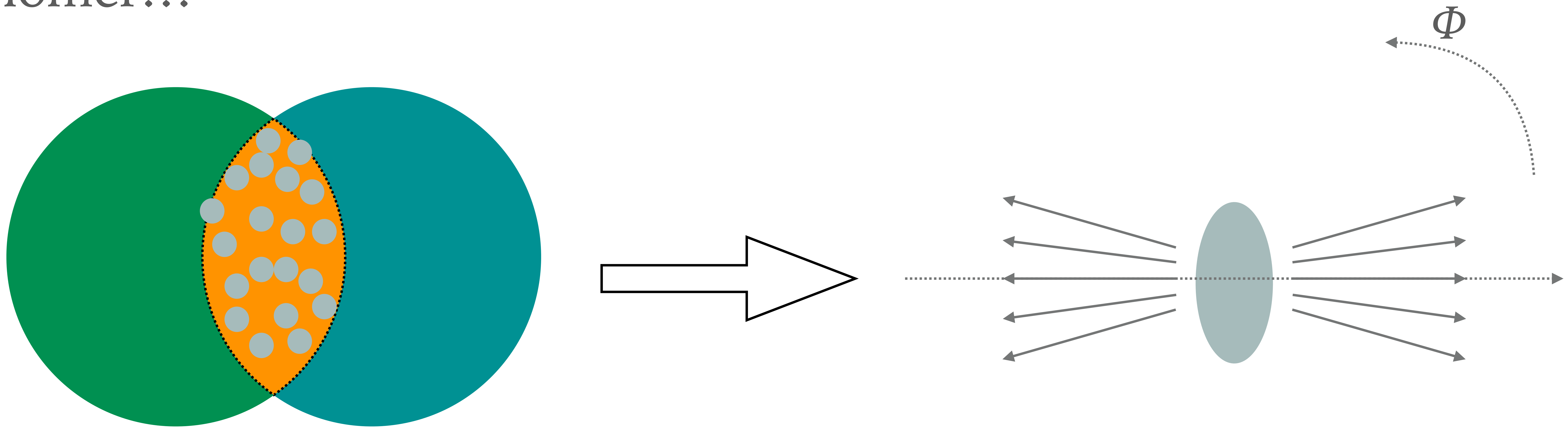


[beam axis view of collision]

initial *spatial* anisotropy
[pressure gradients]

WHAT IS QGP?

a slight misnomer…



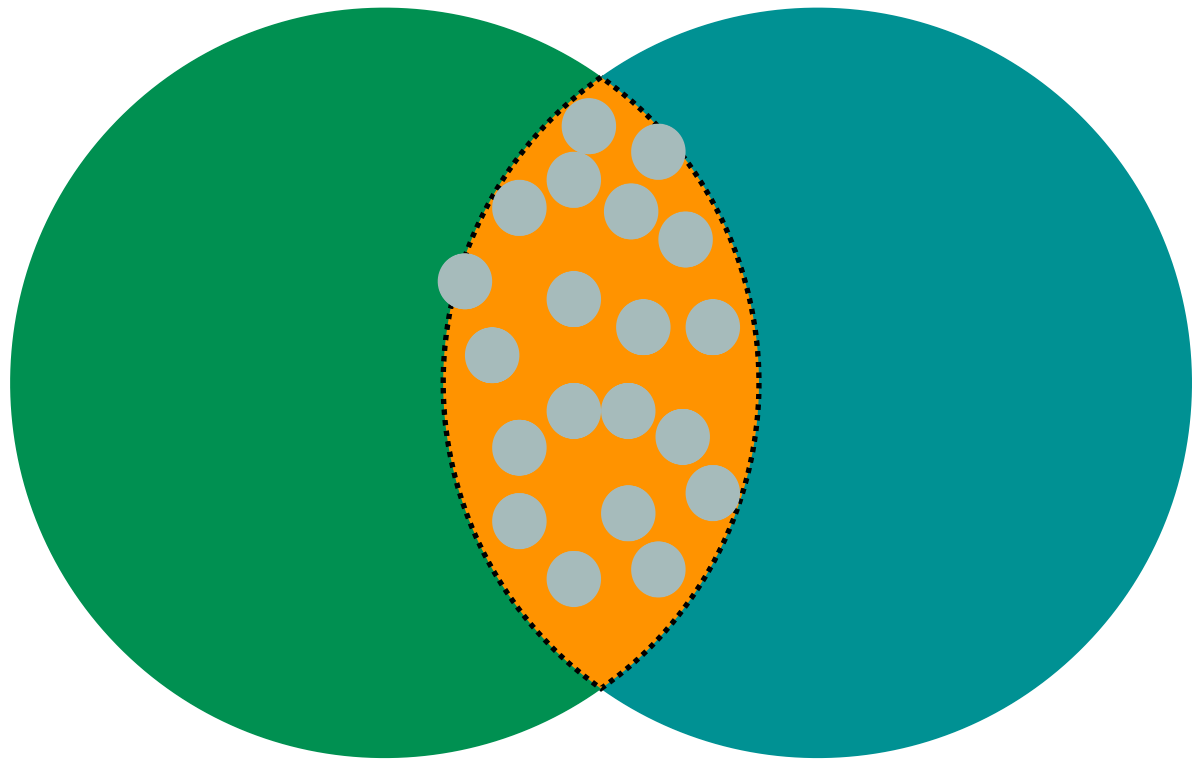
[beam axis view of collision]

final state soft particles preferably aligned the collision plane

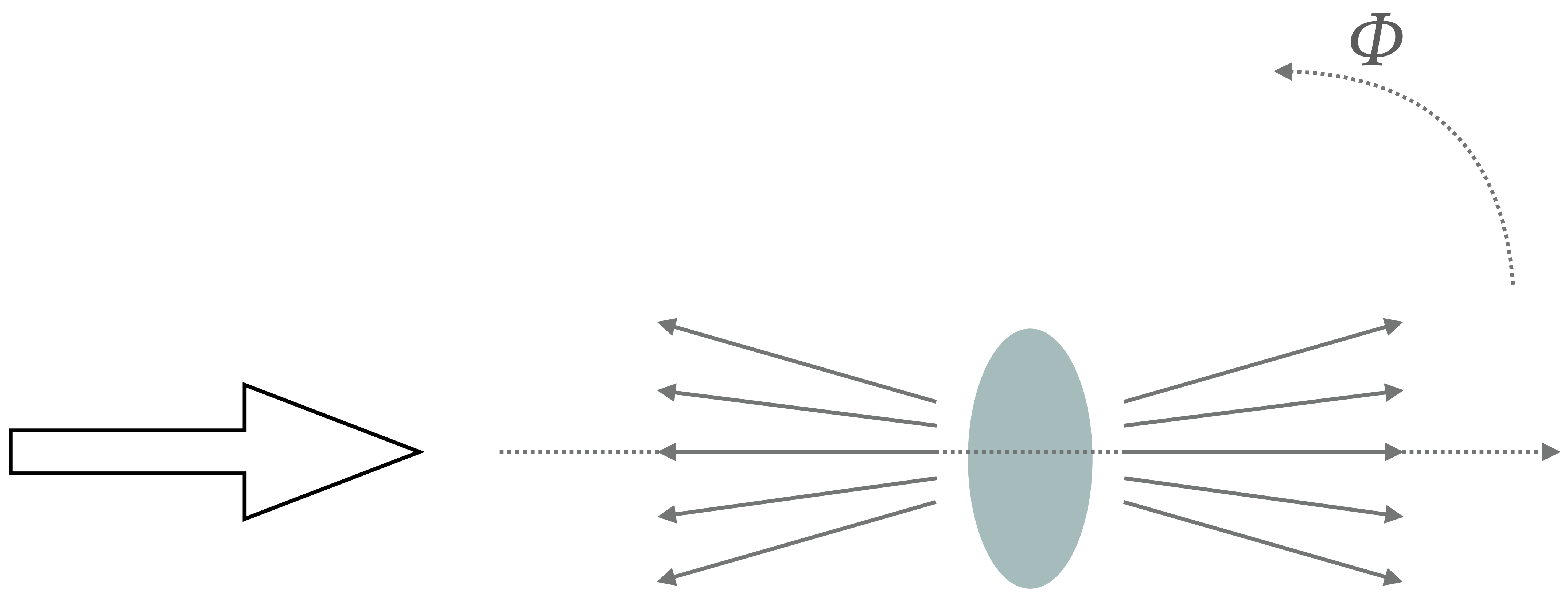
initial *spatial* anisotropy $\longrightarrow$ final state *momentum* anisotropy
[pressure gradients]

WHAT IS QGP?

a slight misnomer…



[beam axis view of collision]



final state soft particles preferably aligned the collision plane

initial *spatial* anisotropy → final state *momentum* anisotropy

[pressure gradients]

a natural consequence of hydrodynamics

QGP flows :: it is a [rather perfect] liquid

QUARK-GLUON PLASMA

QUARK–GLUON PLASMA

- an almost perfect liquid [the most perfect ever observed] of fundamental degrees of freedom [quarks and gluons] :: direct manifestation of collective behaviour in a fundamental non-abelian Quantum Field Theory [QCD]

QUARK–GLUON PLASMA

- an almost perfect liquid [the most perfect ever observed] of fundamental degrees of freedom [quarks and gluons] :: direct manifestation of collective behaviour in a fundamental non-abelian Quantum Field Theory [QCD]

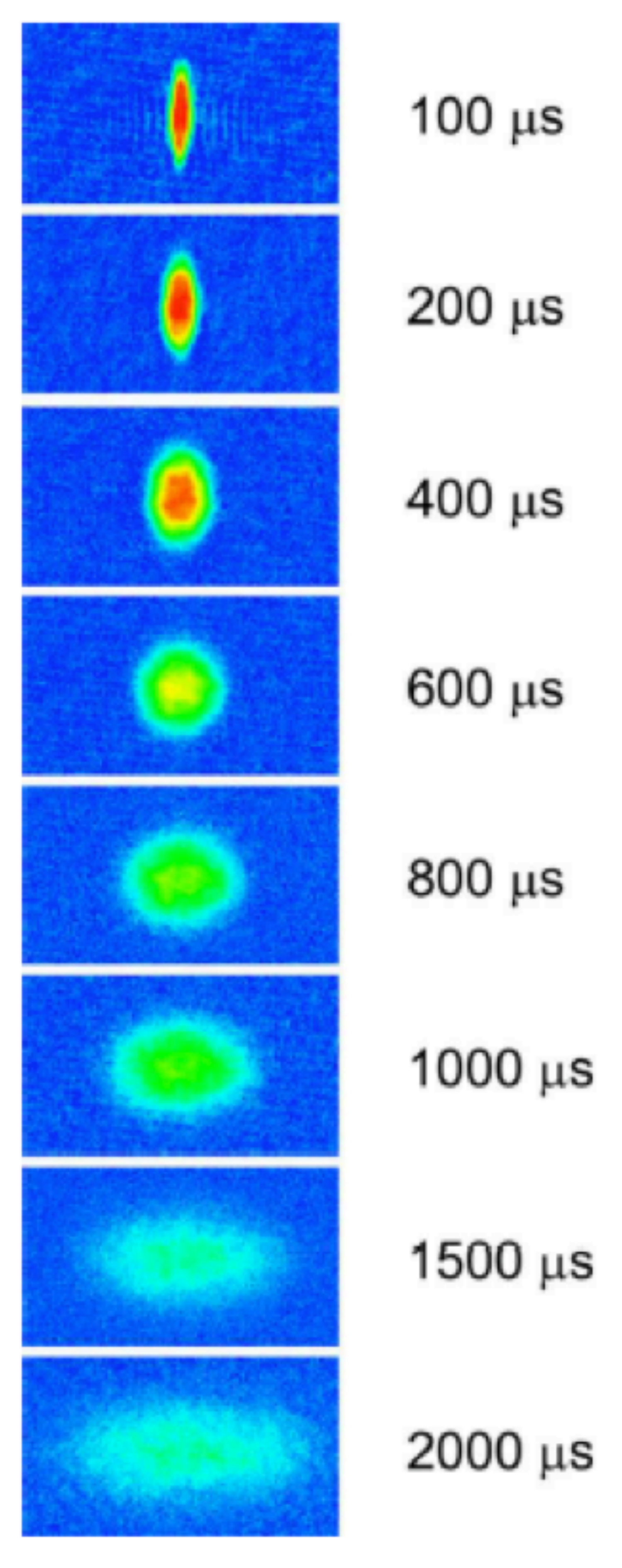
- a unique, experimentally accessible and theoretically tractable, opportunity to further the understanding of QCD in a novel regime [deconfined, yet strongly interacting, quarks and gluons] also of critical importance in the early history of the Universe

- current focus on understanding of dynamics and precise measurement of properties :: must rely on self-generated probes [short-lived QGP]

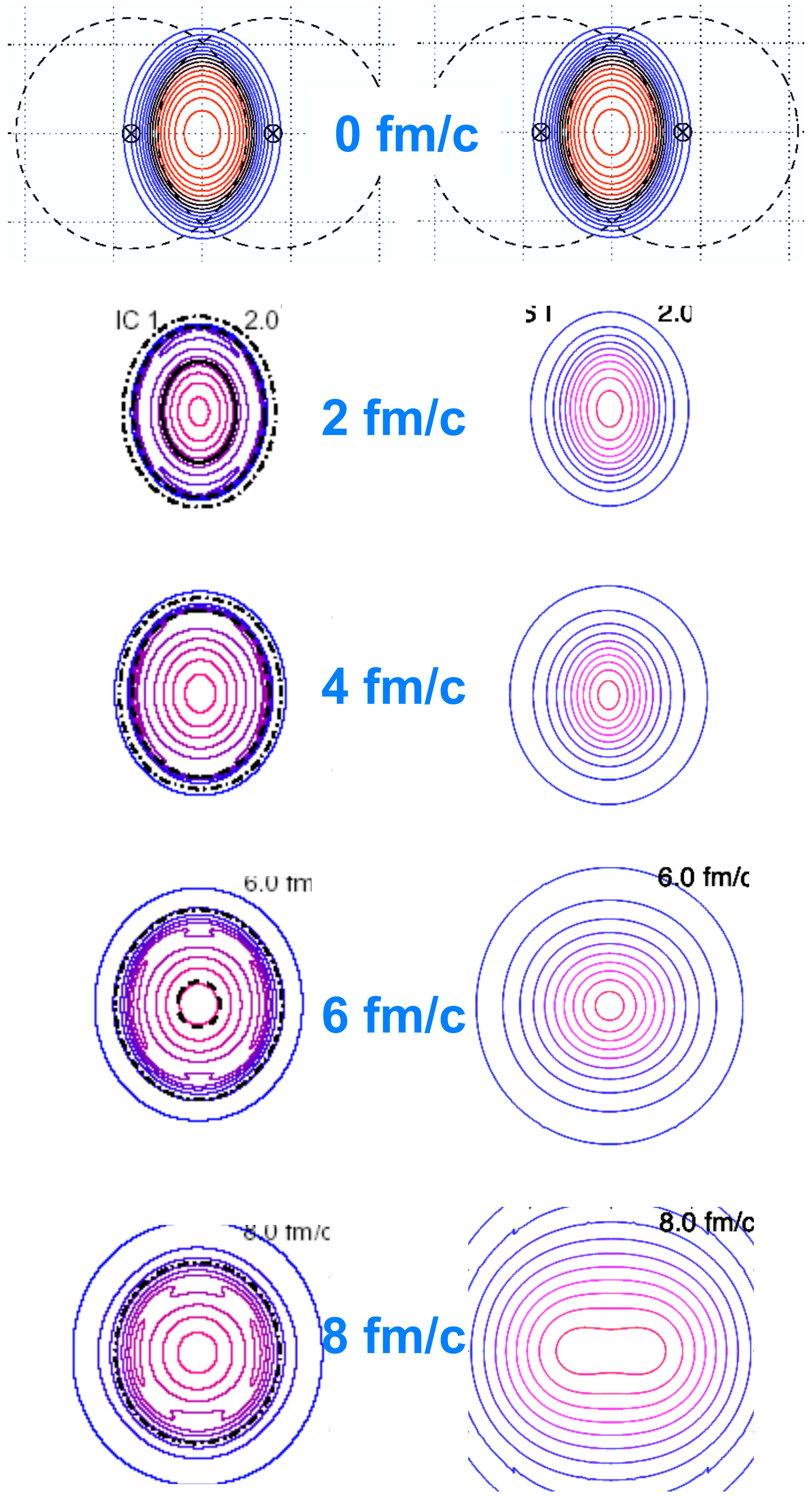
FLOW AND STRONG COUPLING

strong coupled systems flow

degenerate Fermi gas of ultracold Li atoms released from anisotropic trap



O'Hara et al. :: Science 298 (2002)



Kolb and Heinz :: QGP3 (2003)

Lisa et al. :: New J.Phys 13 (2011)

understanding QGP can be invaluable for understanding strongly coupled systems in general

[and vice-versa]

QGP is the strongly coupled system closest to Standard Model microscopic degrees of freedom

II. how we can probe (to try to understand) QGP

PROBES OF QGP I WILL NOT TALK ABOUT

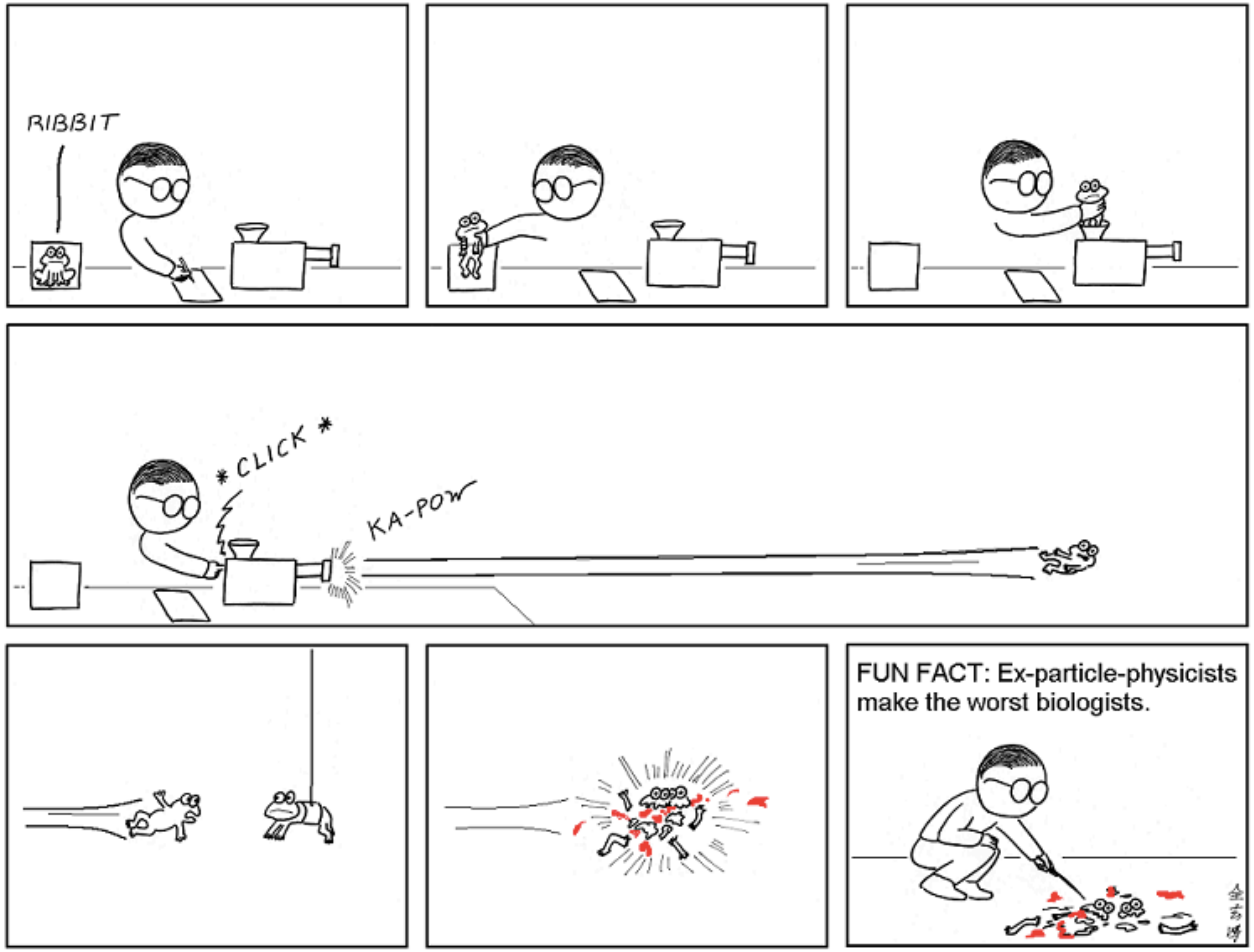
- **soft particle correlations :: flows, …**
  - sensitive to global QGP properties
  - analogous behaviour in high multiplicity pA and pp confounds straightforward interpretation [very personal opinion]
- **electroweak bosons**
  - oblivious to QGP [benchmark]
- **quarkonia/heavy flavour**
  - sensitive to temperature
  - underconstrained vacuum benchmark

HOW TO PROBE ANYTHING

scatter something off it

HOW TO PROBE ANYTHING

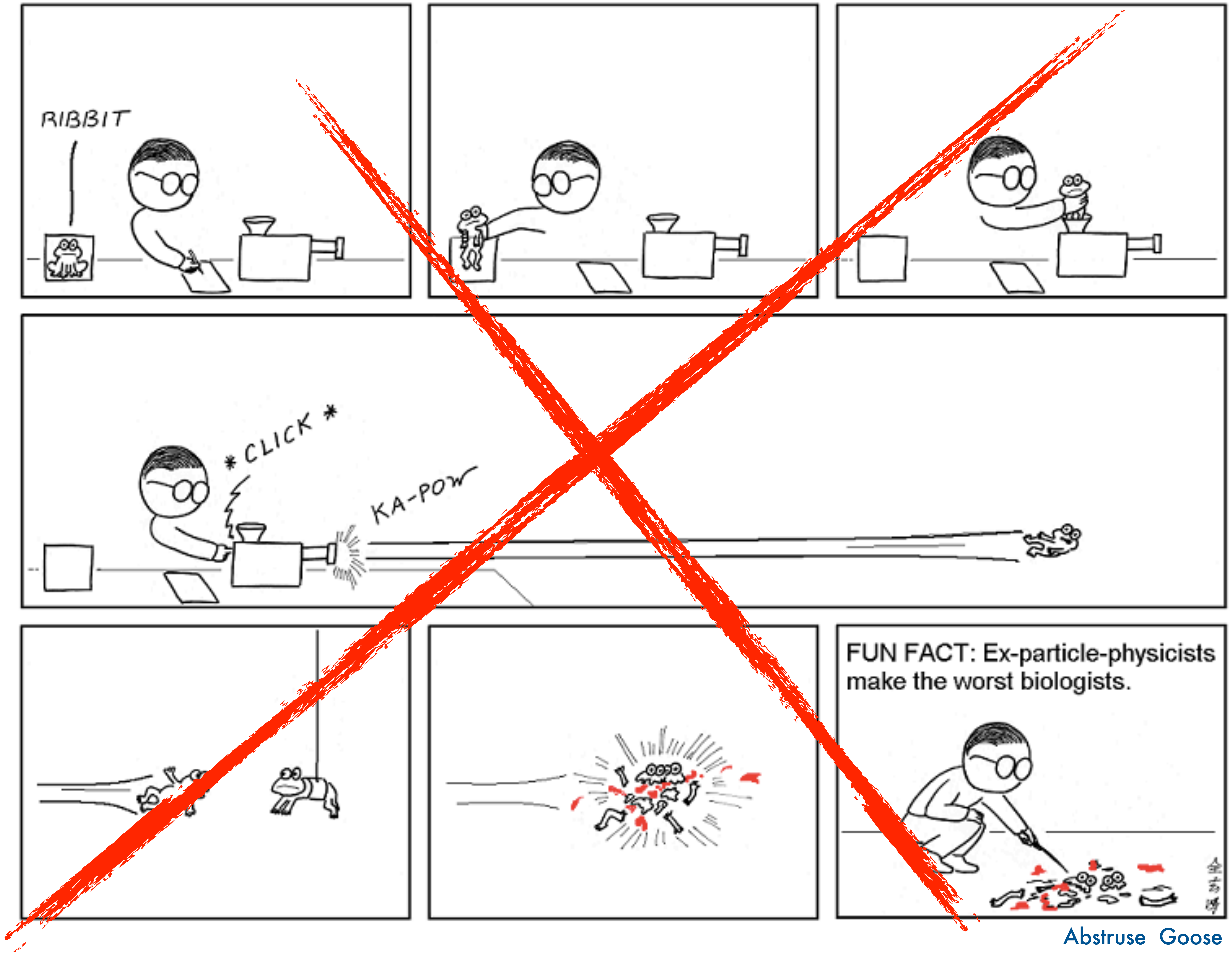
scatter something off it



Abstruse Goose

HOW TO PROBE ANYTHING

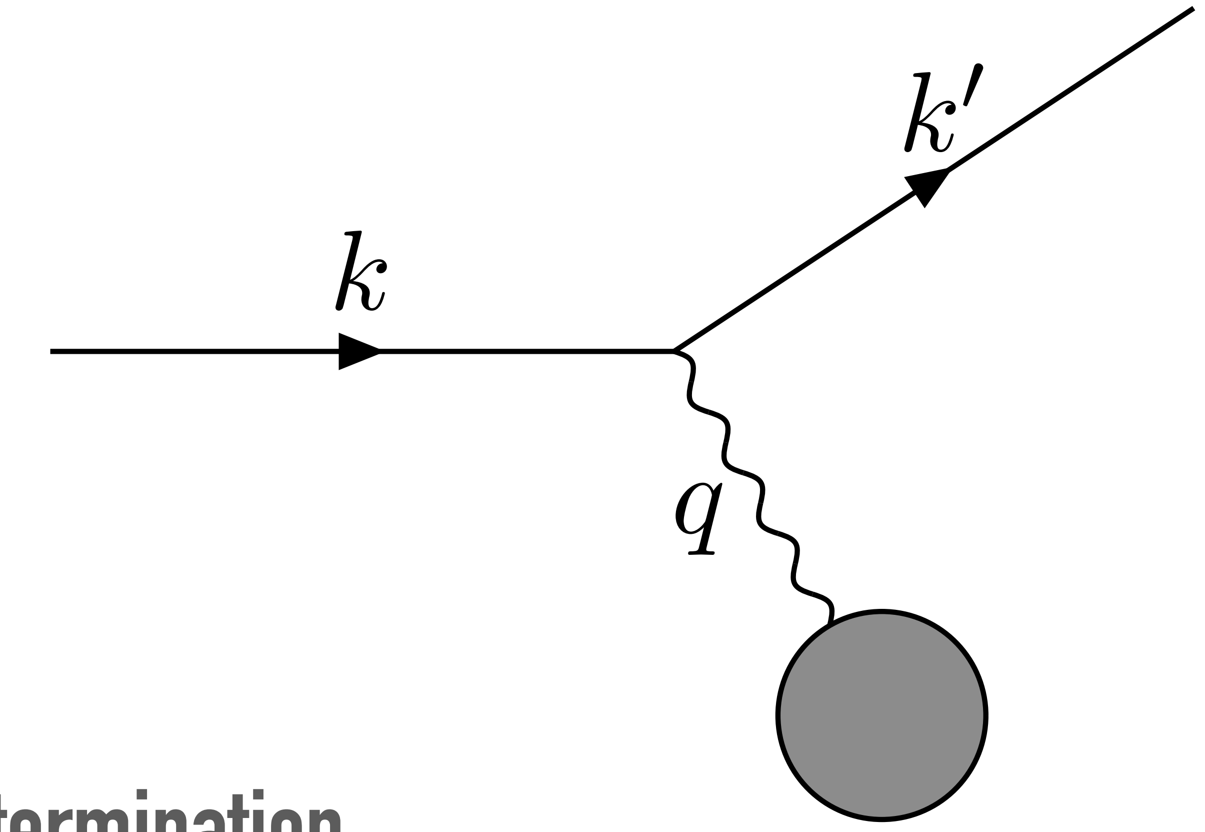
scatter something off it



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

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

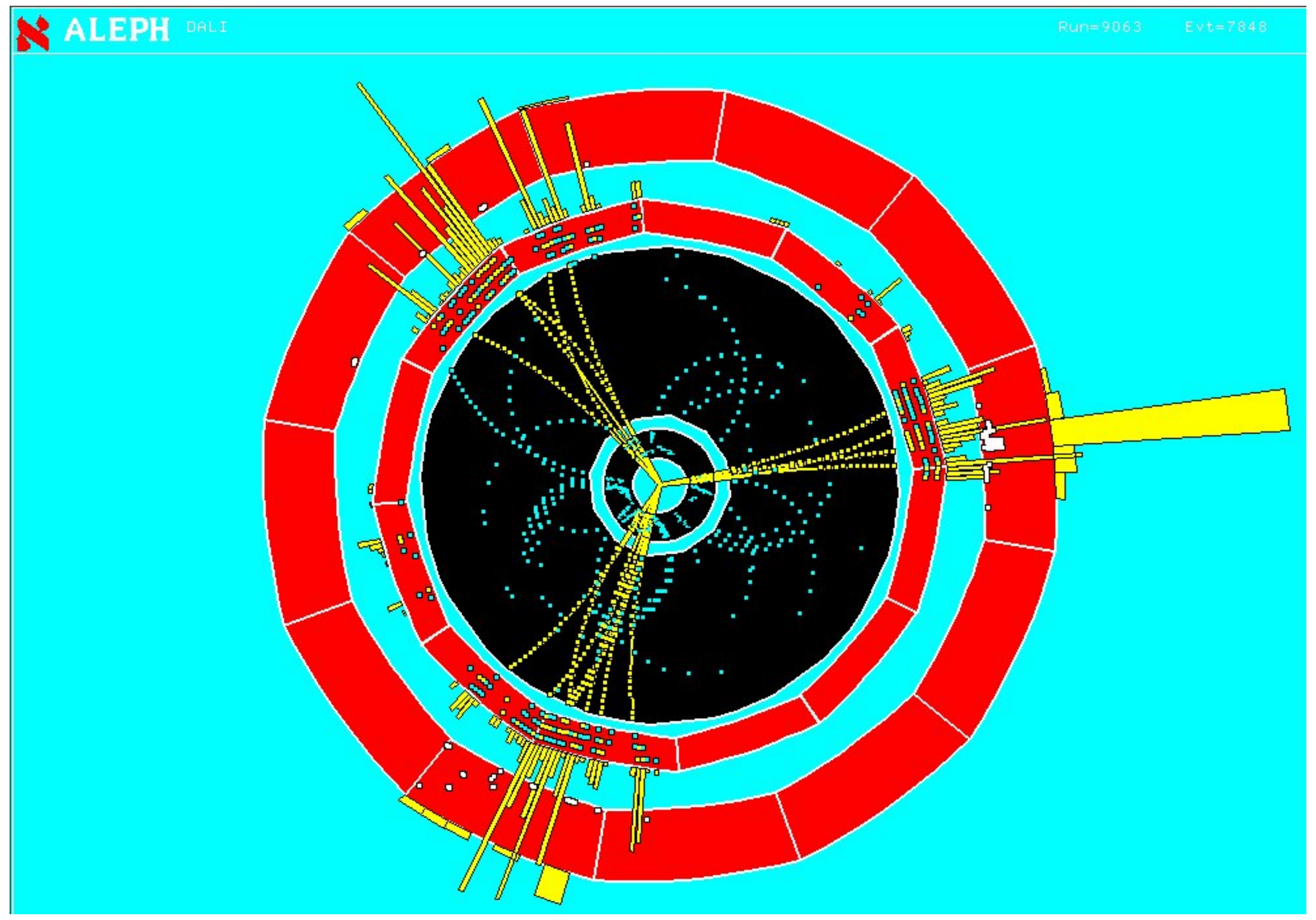
jet definition [in elementary collisions]

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

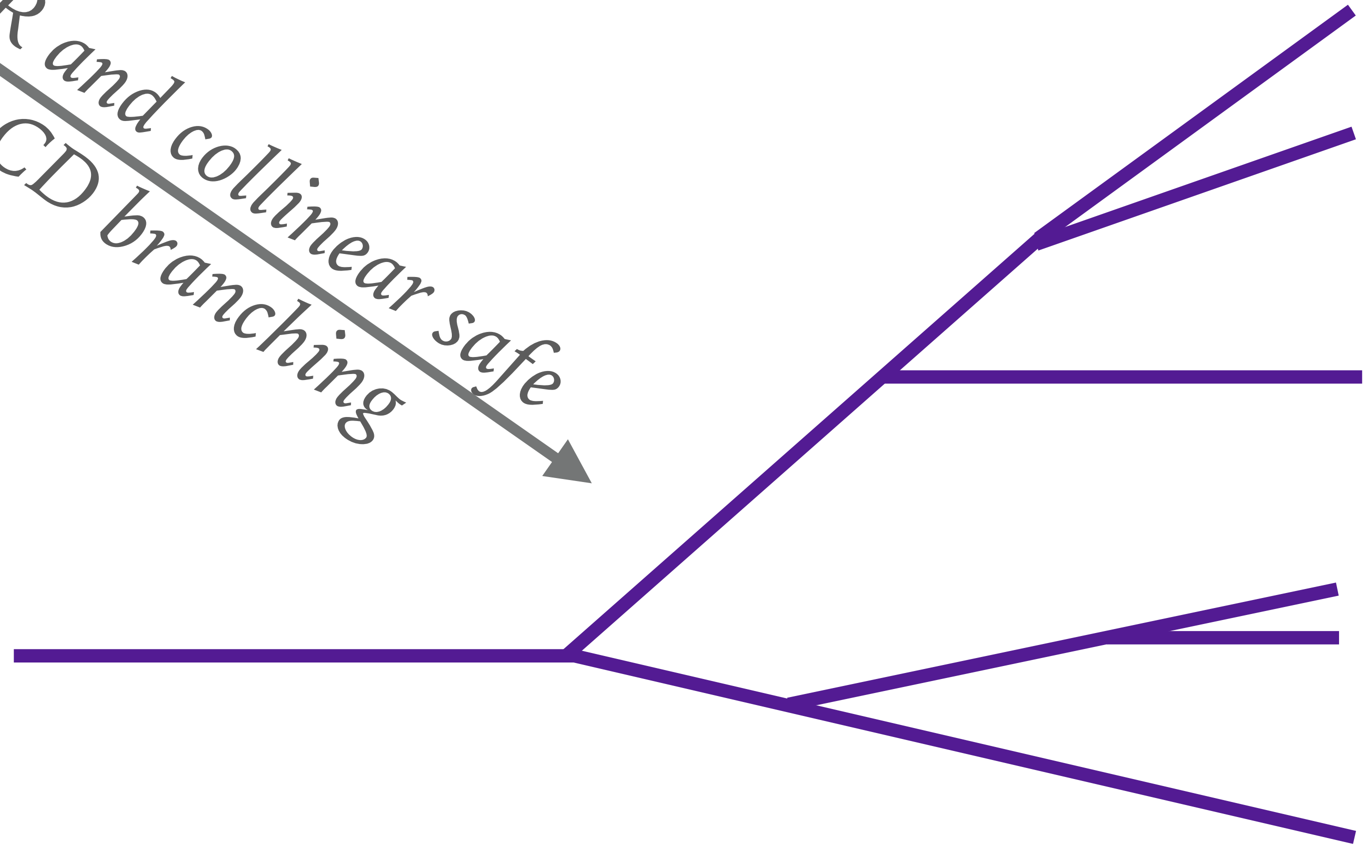
jet algorithm

robust and efficient
IR and collinear safe

IR and collinear safe
QCD branching



experimentally measurable
collimated spray of hadrons

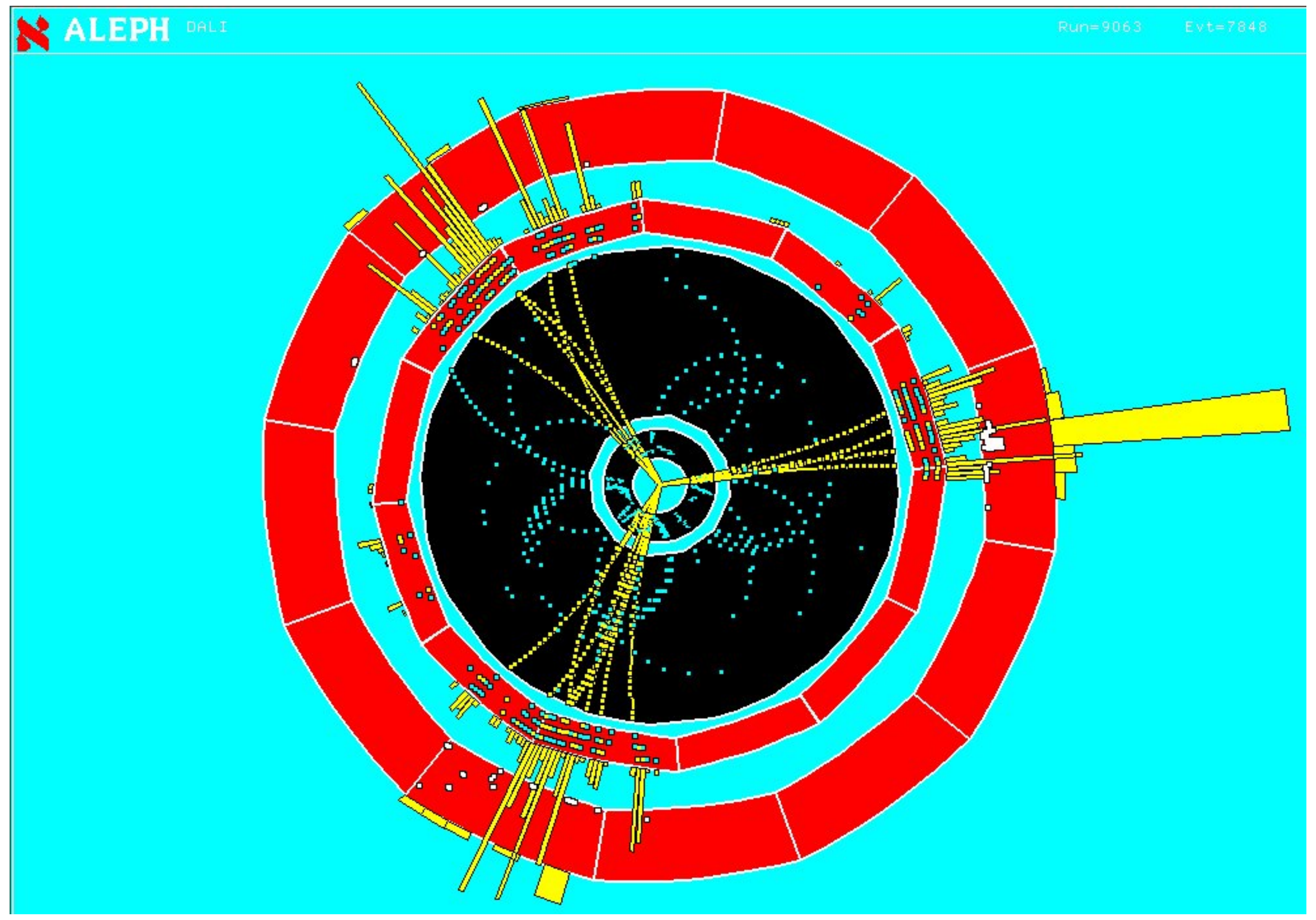


theoretically calculable
fragmentation of energetic parton

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



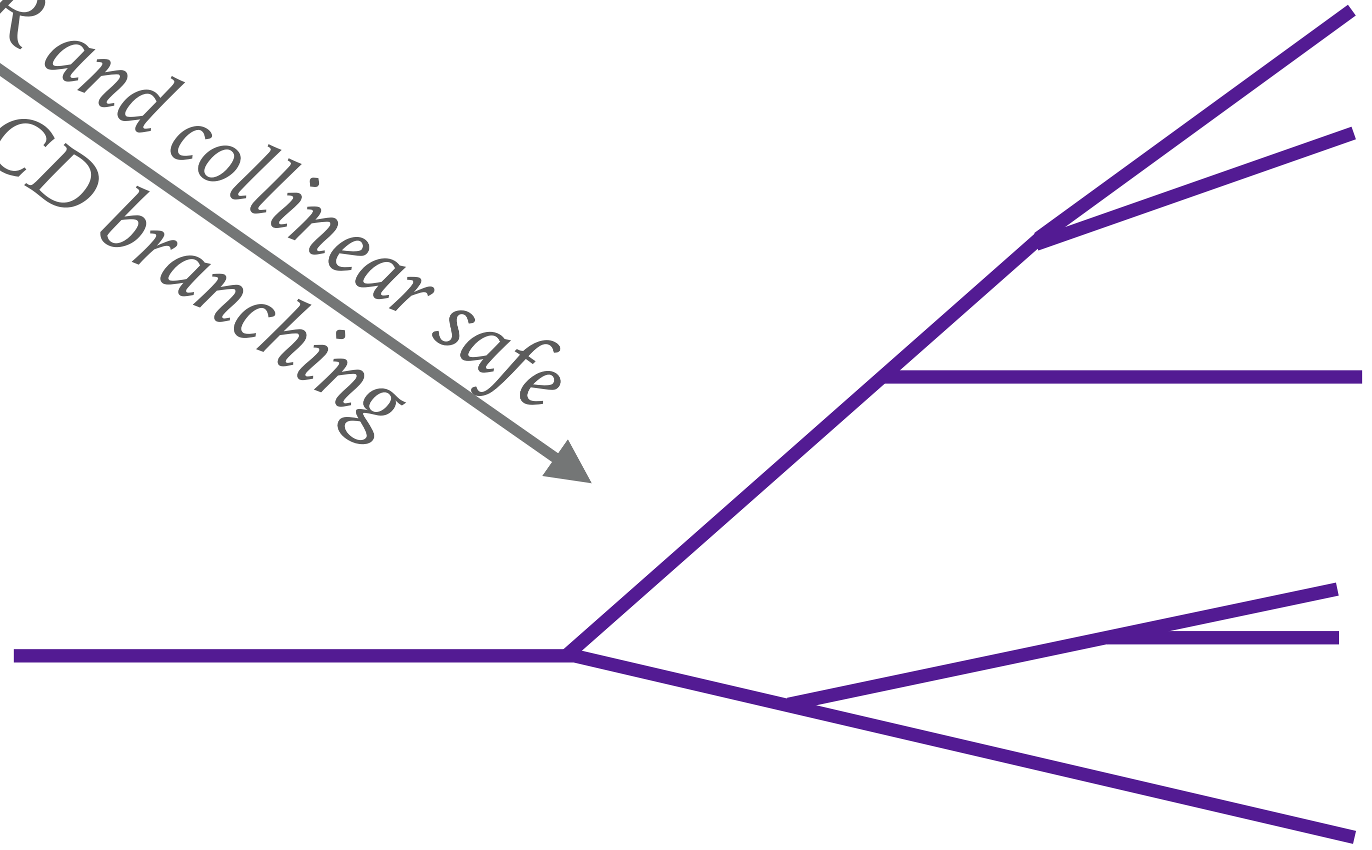
experimentally measurable
collimated spray of hadrons

robust and efficient
IR and collinear safe

jet algorithm

IR and collinear safe
QCD branching

theory jet

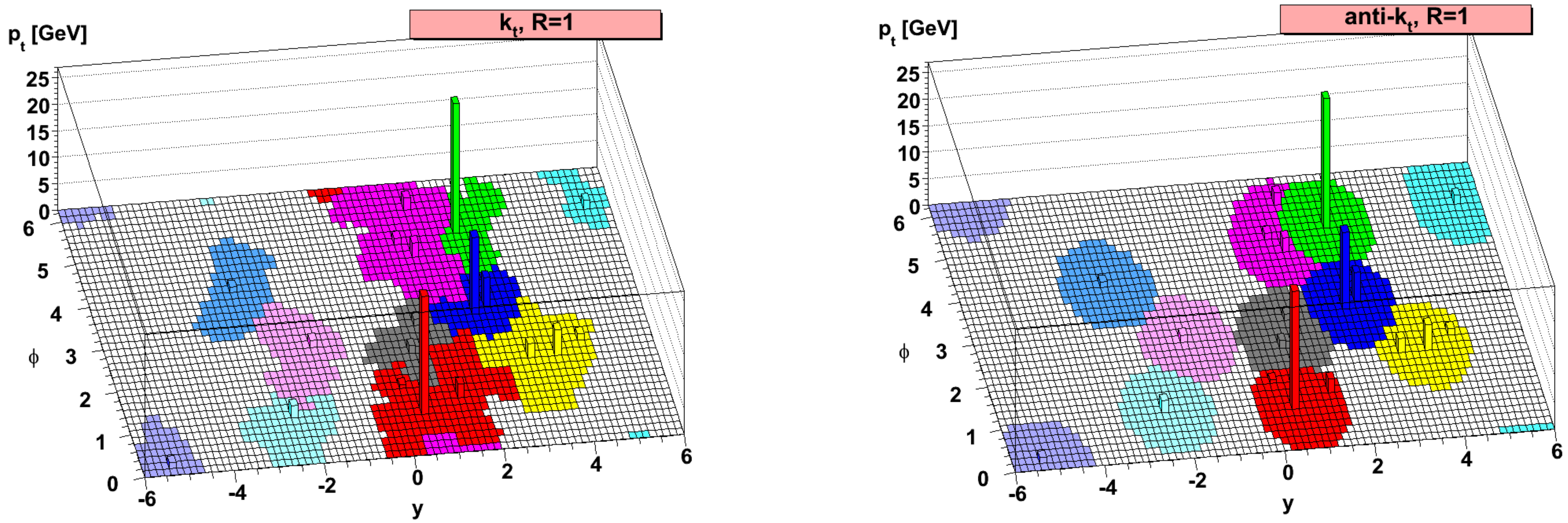


theoretically calculable
fragmentation of energetic parton

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,

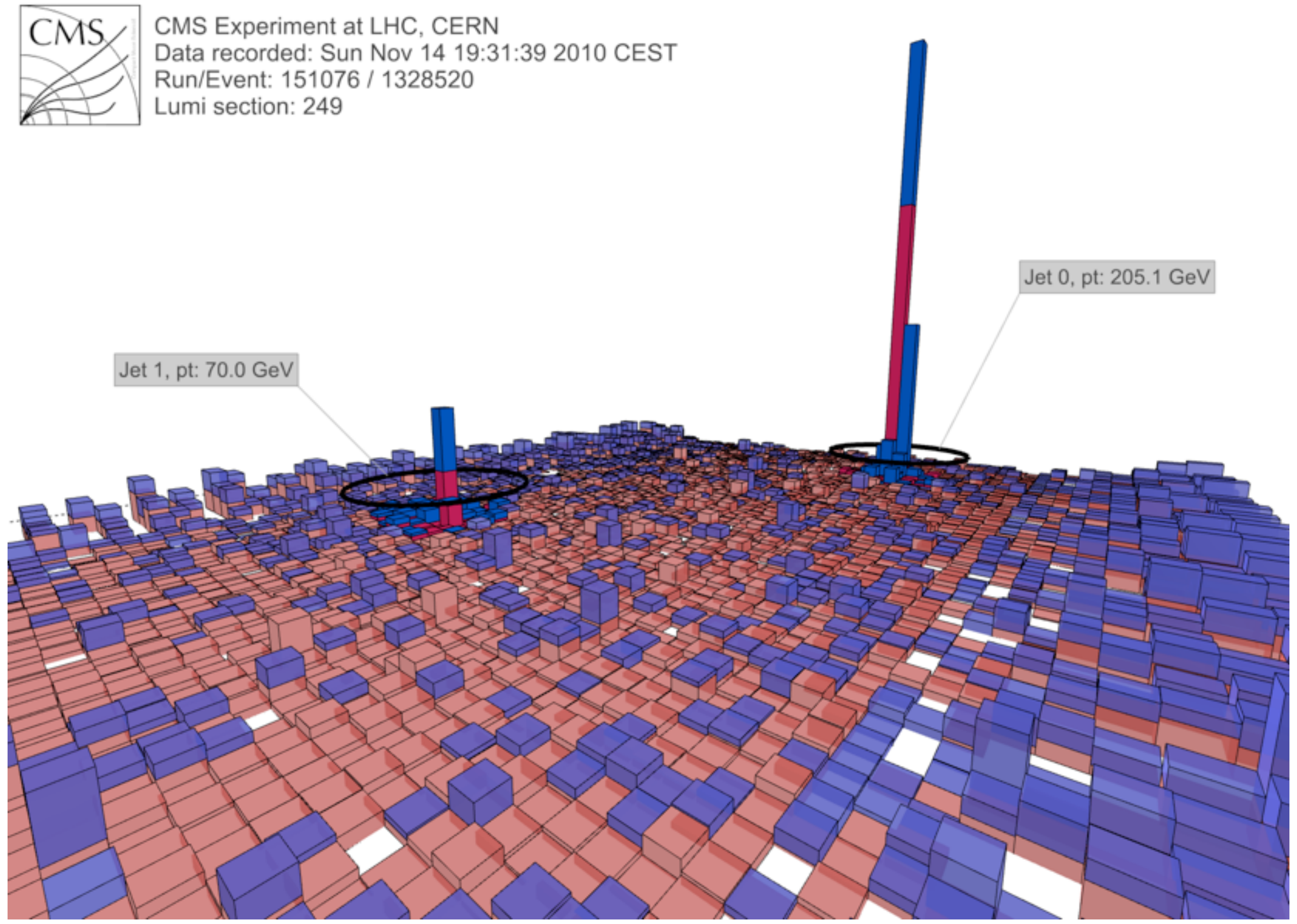


Cacciari, Salam, Soyez 0802.1189

- 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

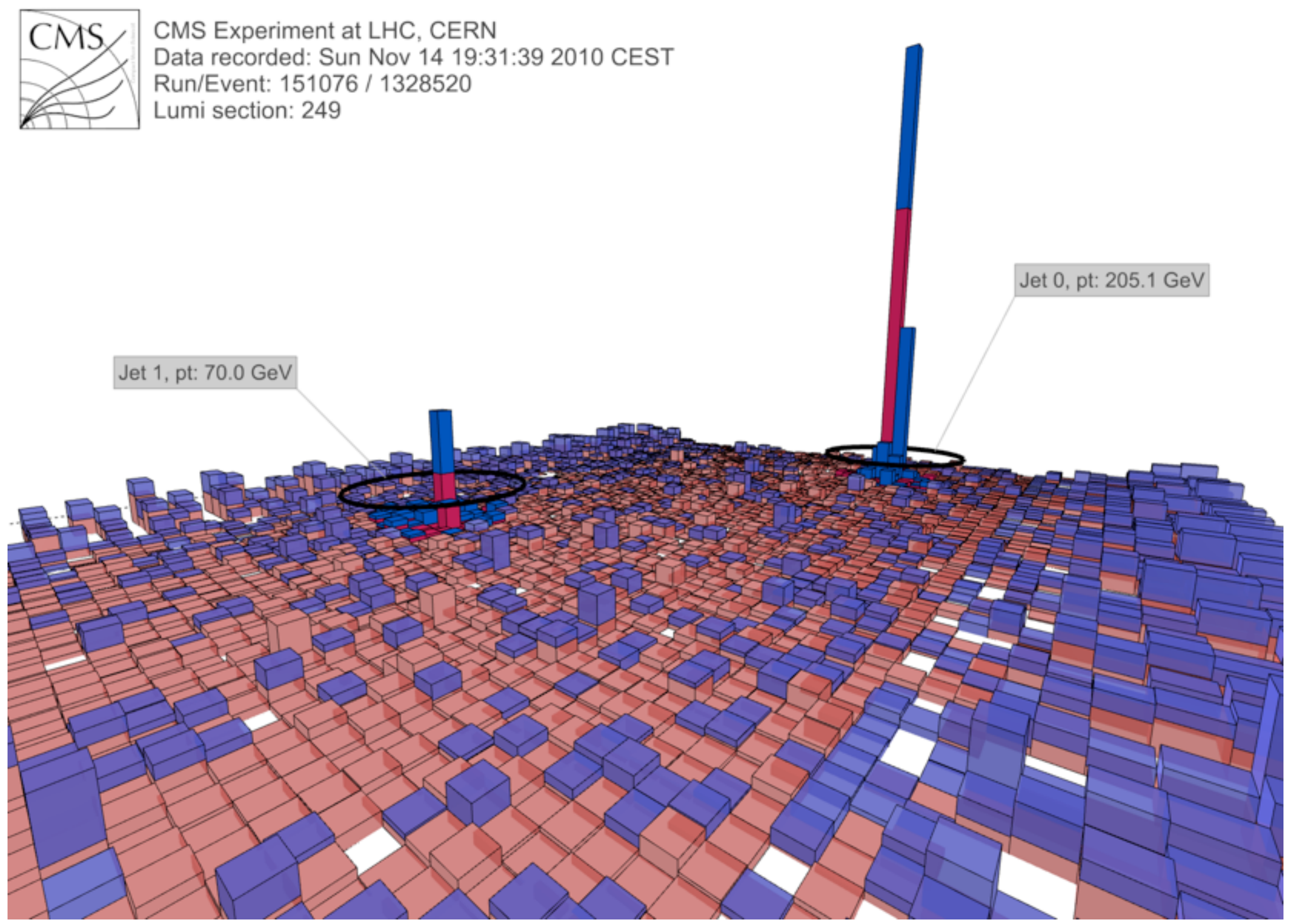
- defined by same jet algorithm[s] as in elementary collisions with essential background subtraction



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

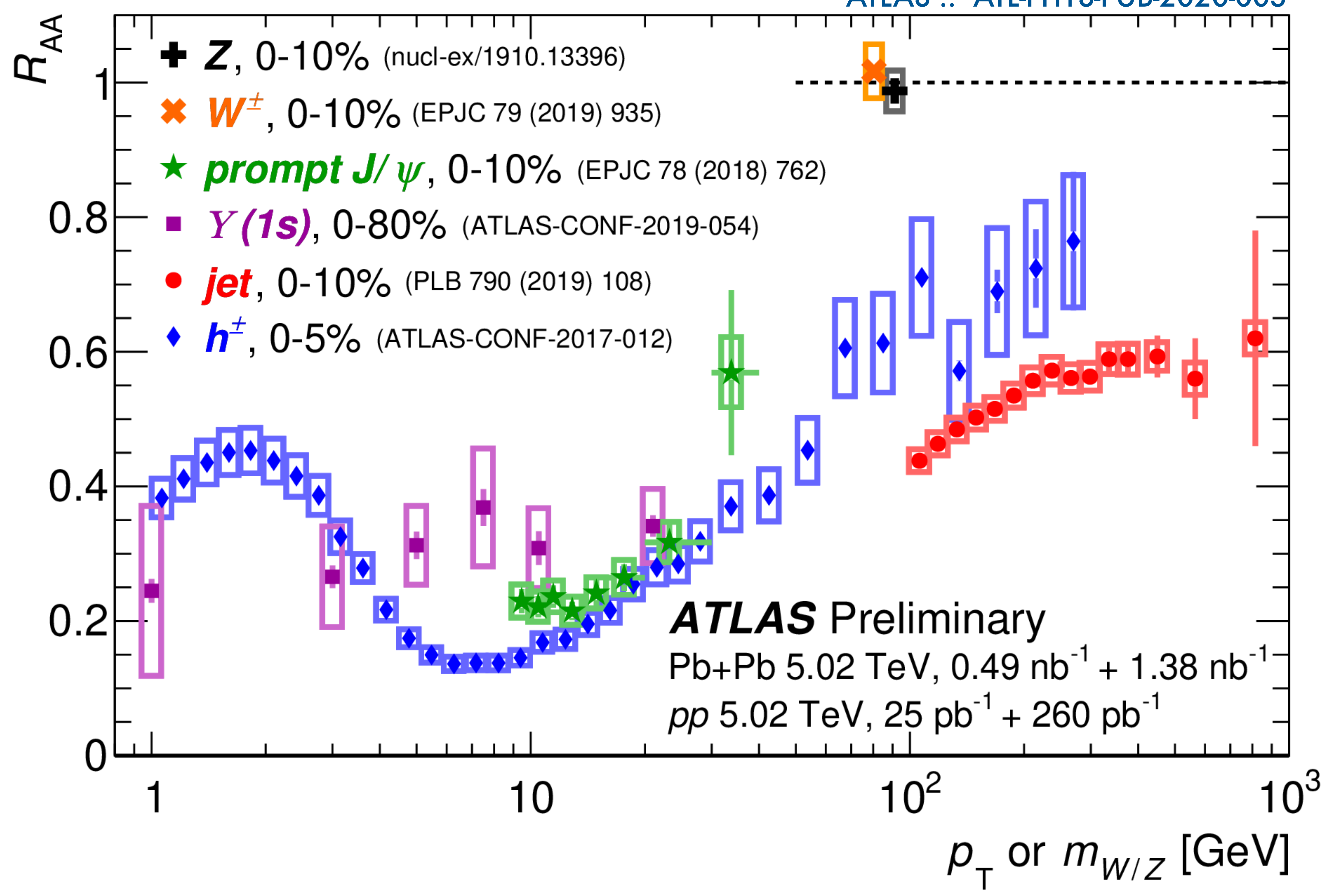
what has to be calculated?

what is in a heavy ion jet?

III. a few of the things we have learnt about jets in QGP

JETS AND HADRONS LOSE ENERGY WHEN TRAVERSING QGP

ATLAS :: ATL-PHYS-PUB-2020-003



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

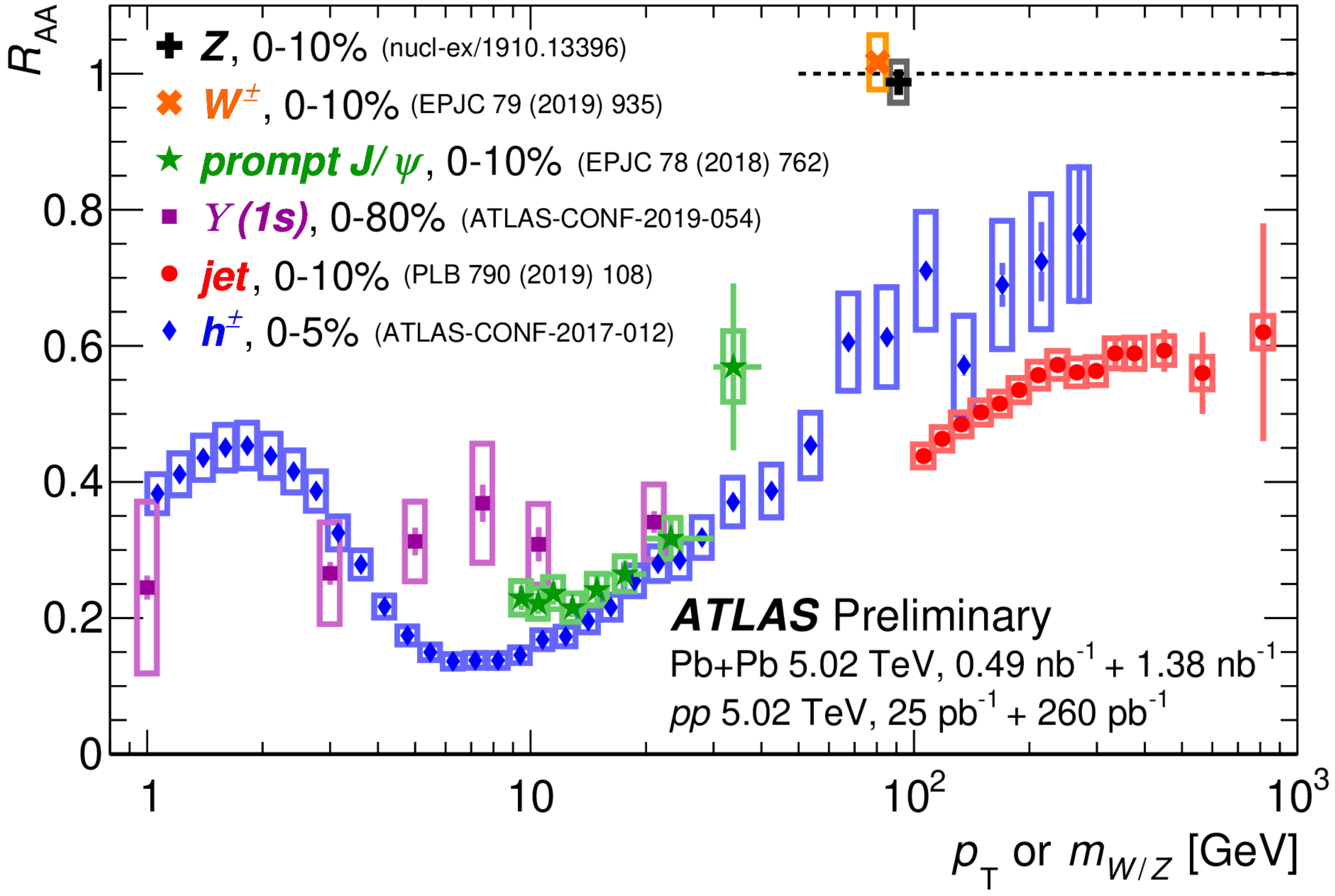
$$\sigma^{\text{eff}}_{\text{pp}} = \sigma_{\text{pp}}$$

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

- 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

JETS AND HADRONS LOSE ENERGY WHEN TRAVERSING QGP

ATLAS :: ATL-PHYS-PUB-2020-003



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

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

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

essentially measures fraction of jets that lost little or no energy

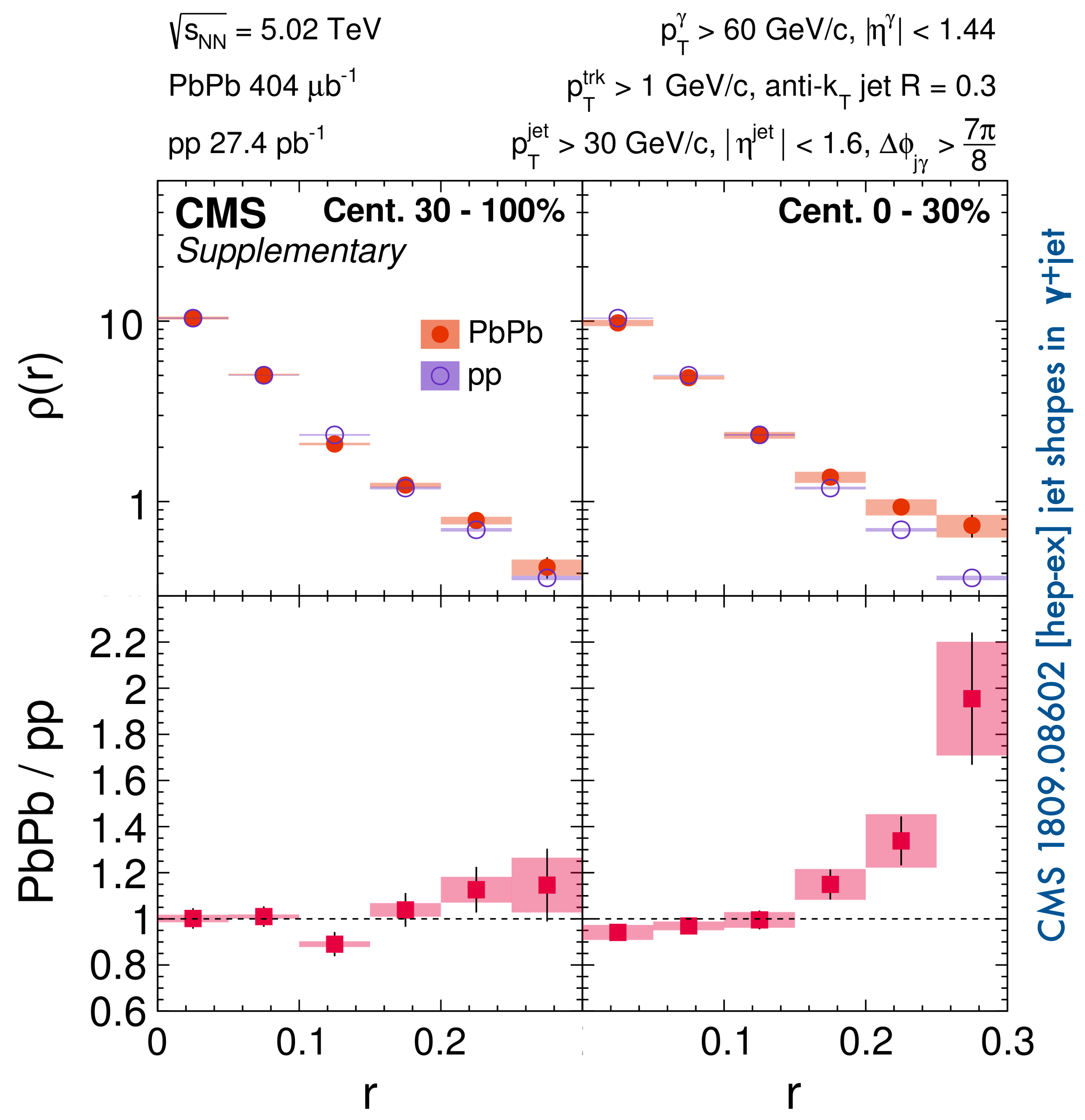
- in steeply falling spectrum large energy losses translate into very small effects
- R_{AA} provides quantitative handle on energy loss only within some model framework
- it compares jets [hadrons] that were detected with same p_T, not born alike

- 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

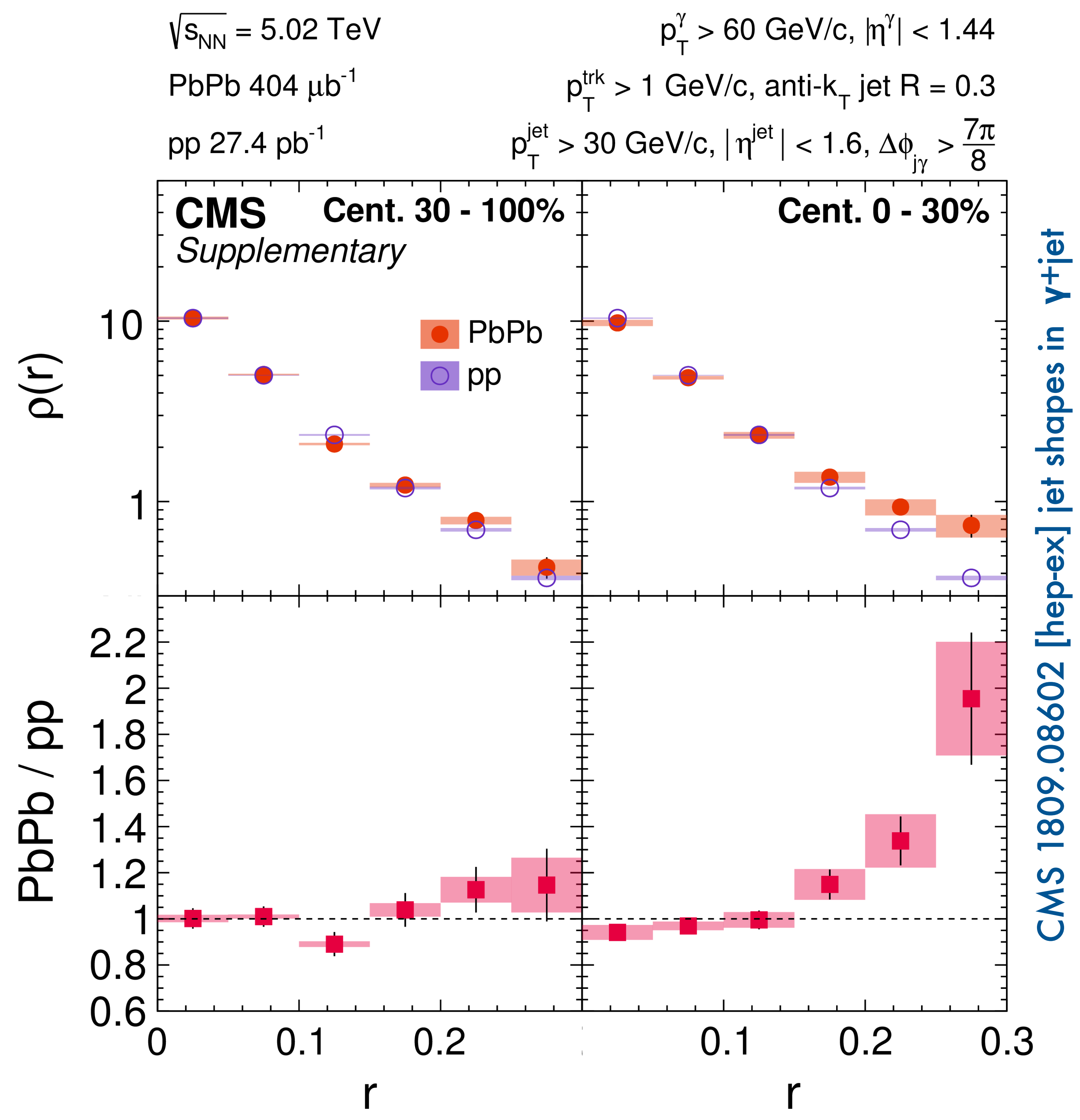
$$\rho(r) = \frac{1}{\delta r} \frac{\sum_{\text{jets}} \sum_{r_a < r < r_b} (p_T^{\text{trk}} / p_T^{\text{jet}})}{\sum_{\text{jets}} \sum_{0 < r < r_f} (p_T^{\text{trk}} / p_T^{\text{jet}})},$$



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

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



comparison between AA and pp at same reconstructed jet p_t confounds QGP-induced shape modification with bin-migration 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

Brewer, Milhano, Thaler :: 1812.05111 [hep-ph]

- 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*

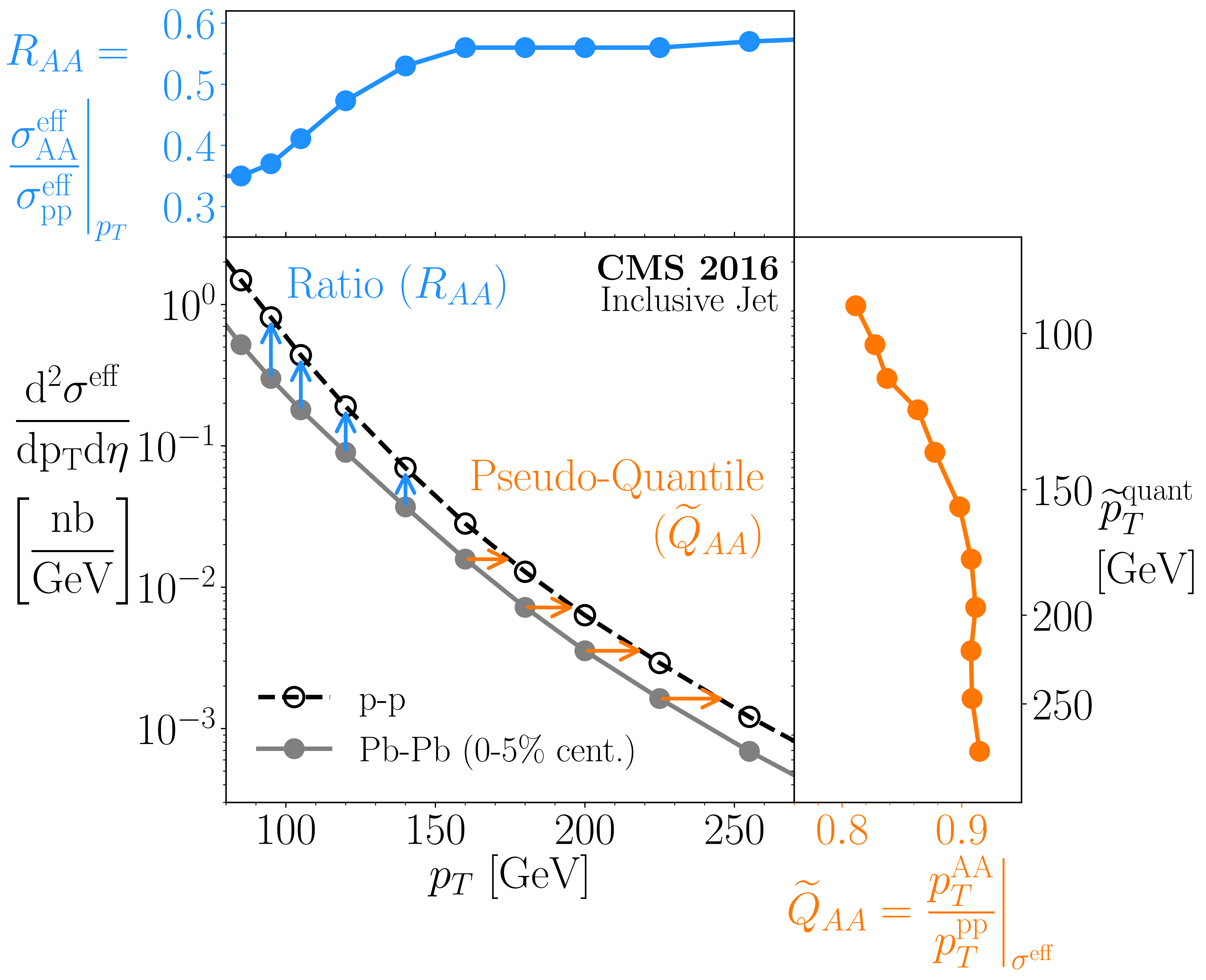
$$Q_{AA} = \left. \frac{p_T^{\mathrm{AA}}}{p_T^{\mathrm{pp}}} \right|_{\Sigma^{\mathrm{eff}}}$$

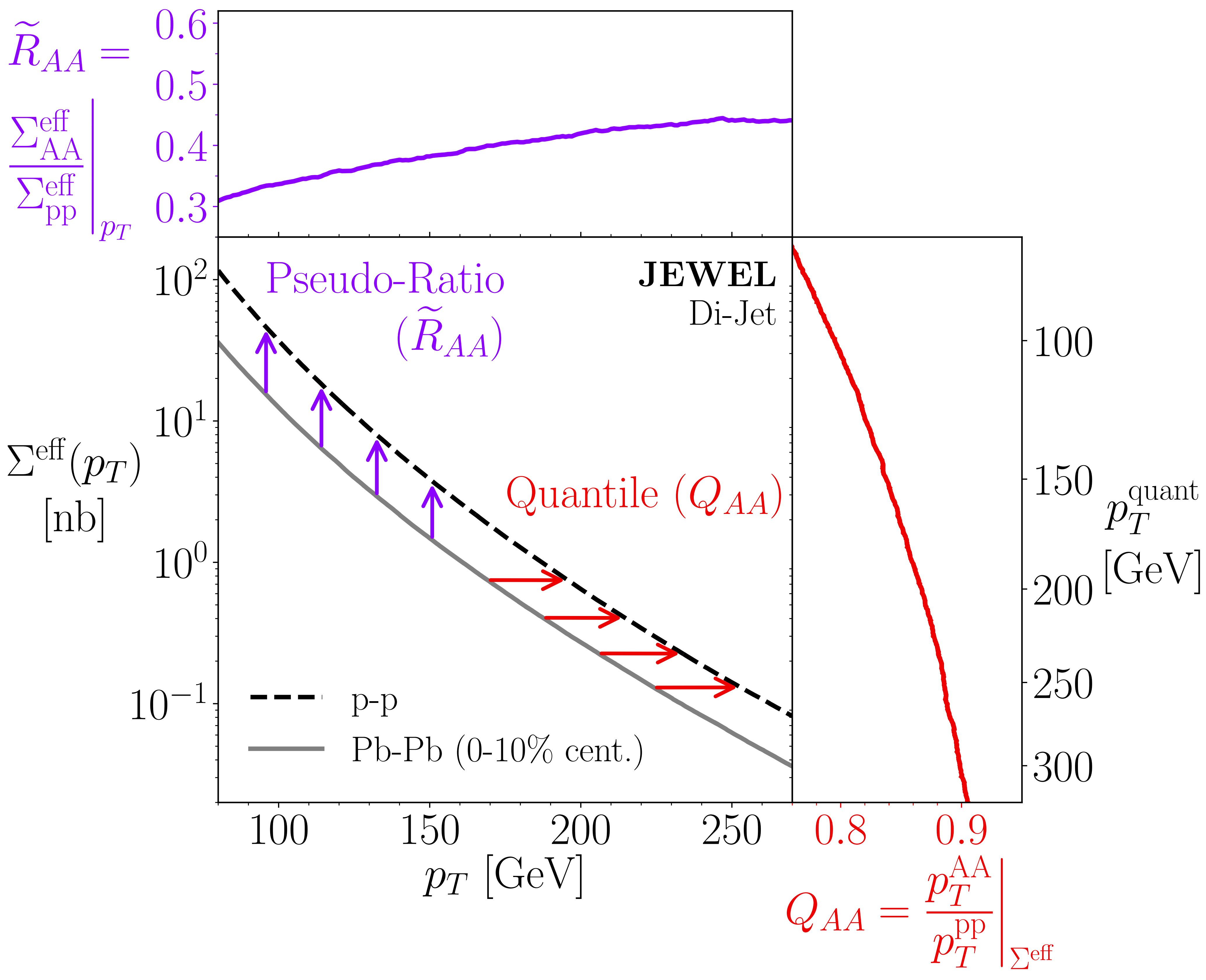
$$\Sigma^{\mathrm{eff}}(p_T^{\mathrm{min}}) = \int_{p_T^{\mathrm{min}}}^{\infty} \mathrm{d}p_T \, \frac{\mathrm{d}\sigma^{\mathrm{eff}}}{\mathrm{d}p_T}$$

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

QUANTILE PROCEDURE

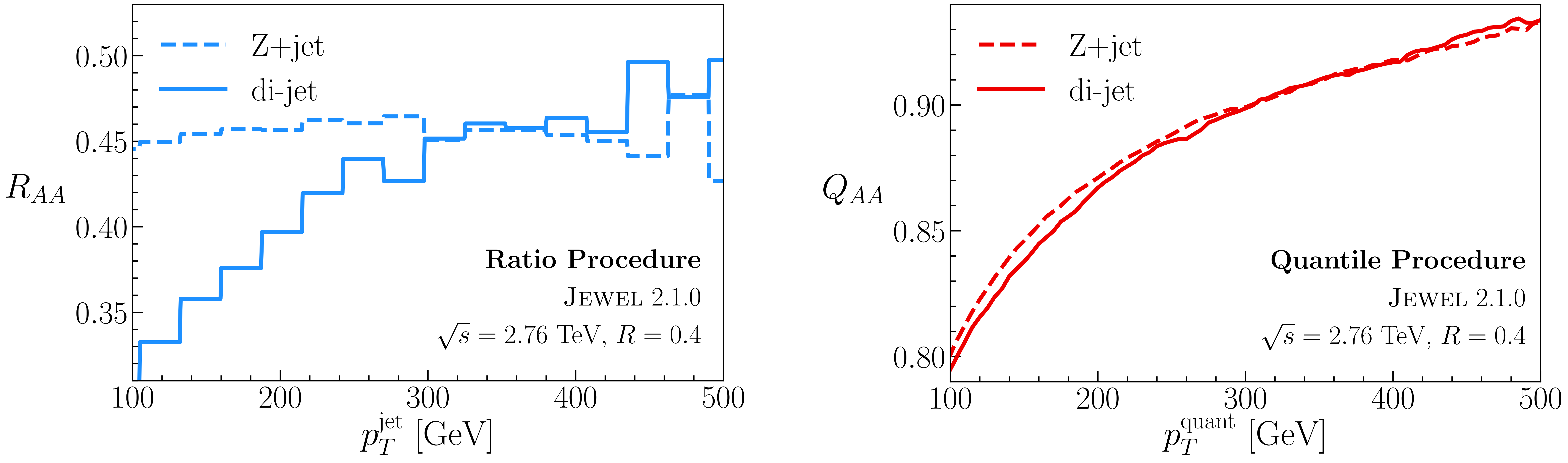
Brewer, Milhano, Thaler :: 1812.05111 [hep-ph]





COMPLEMENTARY INFORMATION

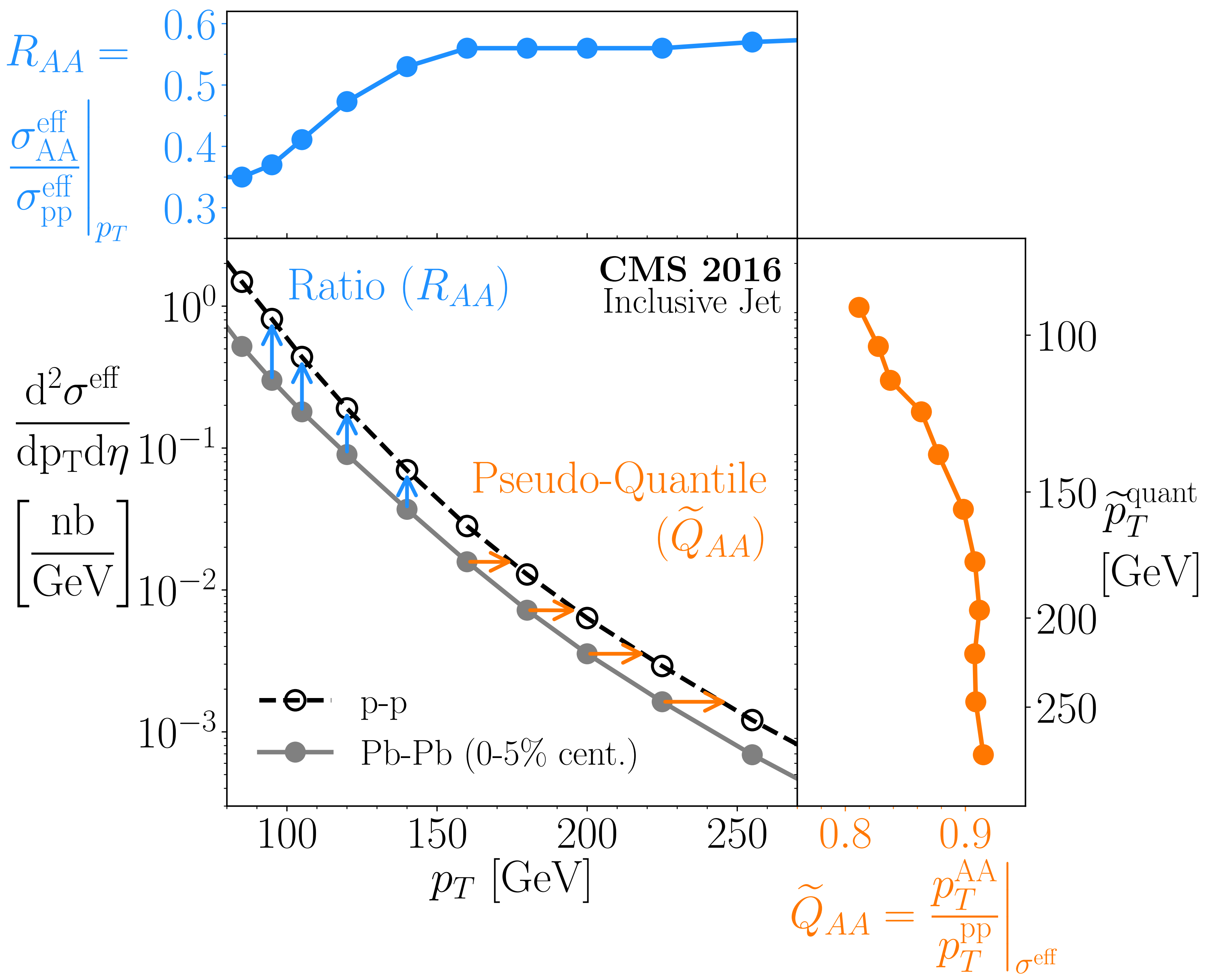
Brewer, Milhano, Thaler :: 1812.05111 [hep-ph]

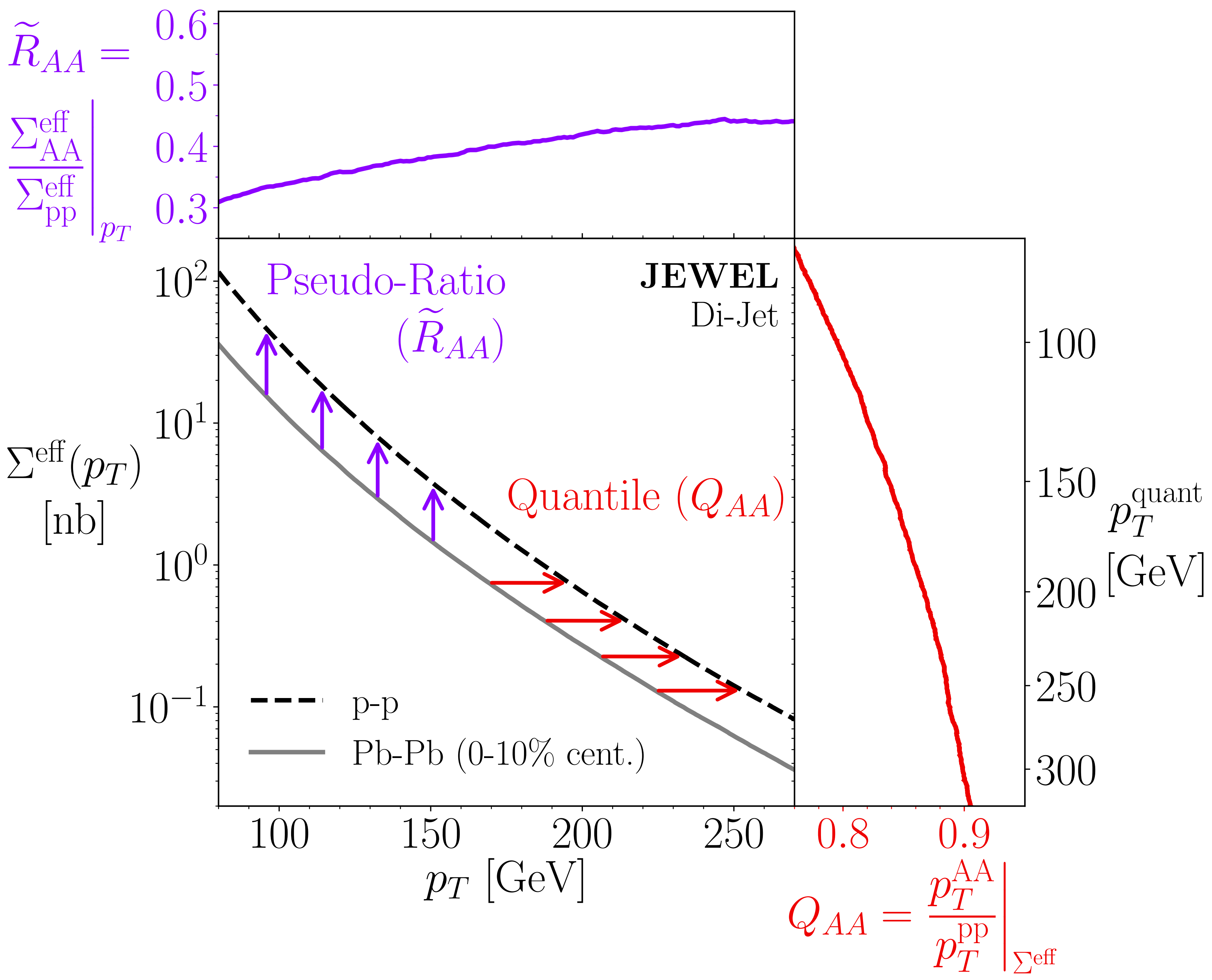


- Q_{AA} and R_{AA} provide very different information
  - R_{AA} depends on different spectral shape for quark and gluon initiated jets :: Q_{AA} does not

QUANTILE PROCEDURE AS PROXY FOR INITIAL ENERGY

Brewer, Milhano, Thaler :: 1812.05111 [hep-ph]



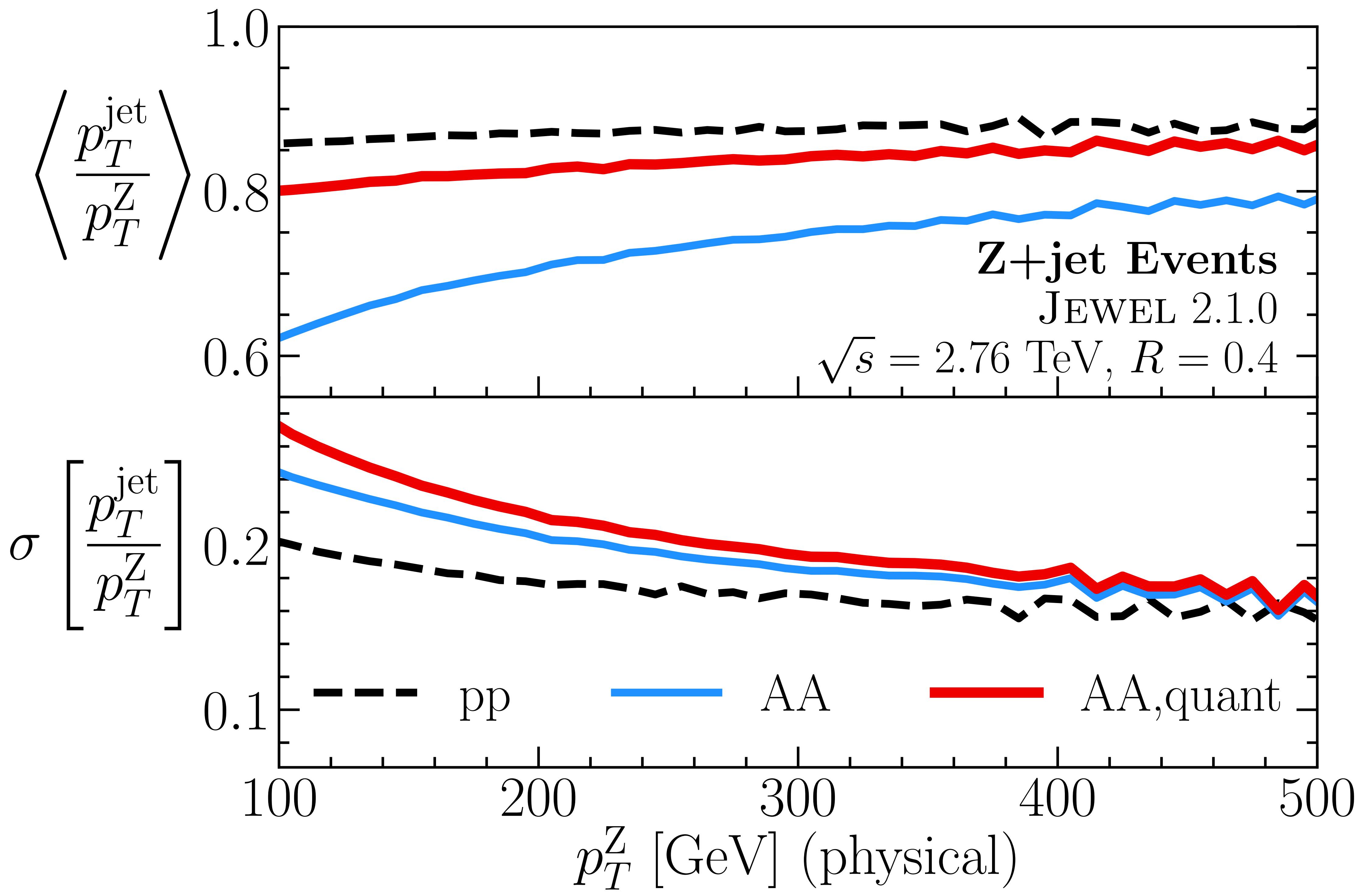


- provides a proxy for the initial p_t of a quenched [prior to QGP-induced energy loss]

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

VALIDATION IN Z+JET

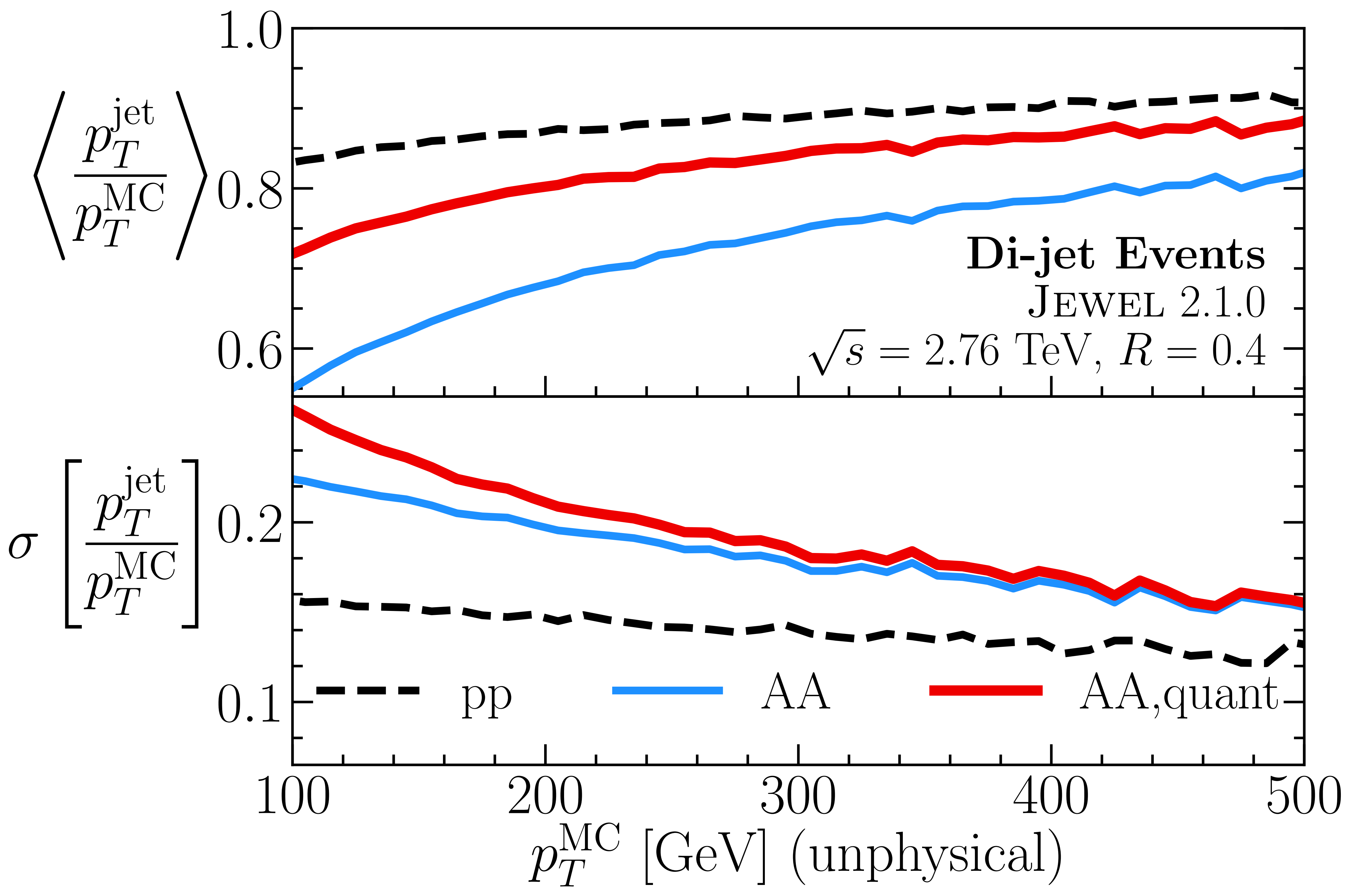
Brewer, Milhano, Thaler :: 1812.05111 [hep-ph]



- quantile procedure closely reconstructs unquenched [initial] p_t :: in this case measurable
- quantile procedure cannot [yet] undo fluctuations

PERFORMANCE IN DI-JET EVENTS

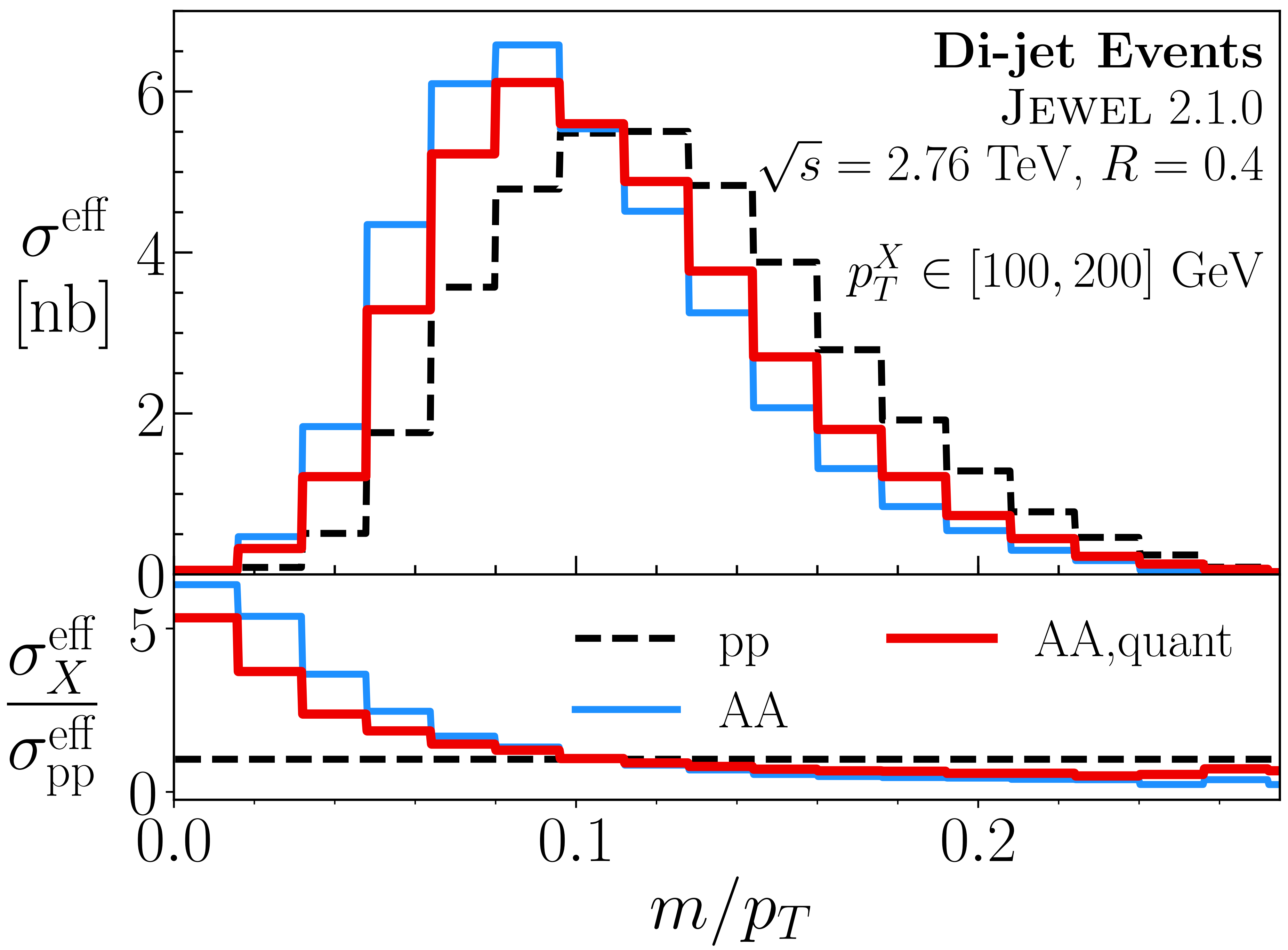
Brewer, Milhano, Thaler :: 1812.05111 [hep-ph]



- similar performance to Z+jet
- access to unmeasurable quantity :: allows for comparison of large statistics samples of jets that were born fairly equal

MITIGATION OF MIGRATION EFFECTS :: AN EXAMPLE

Brewer, Milhano, Thaler :: 1812.05111 [hep-ph]

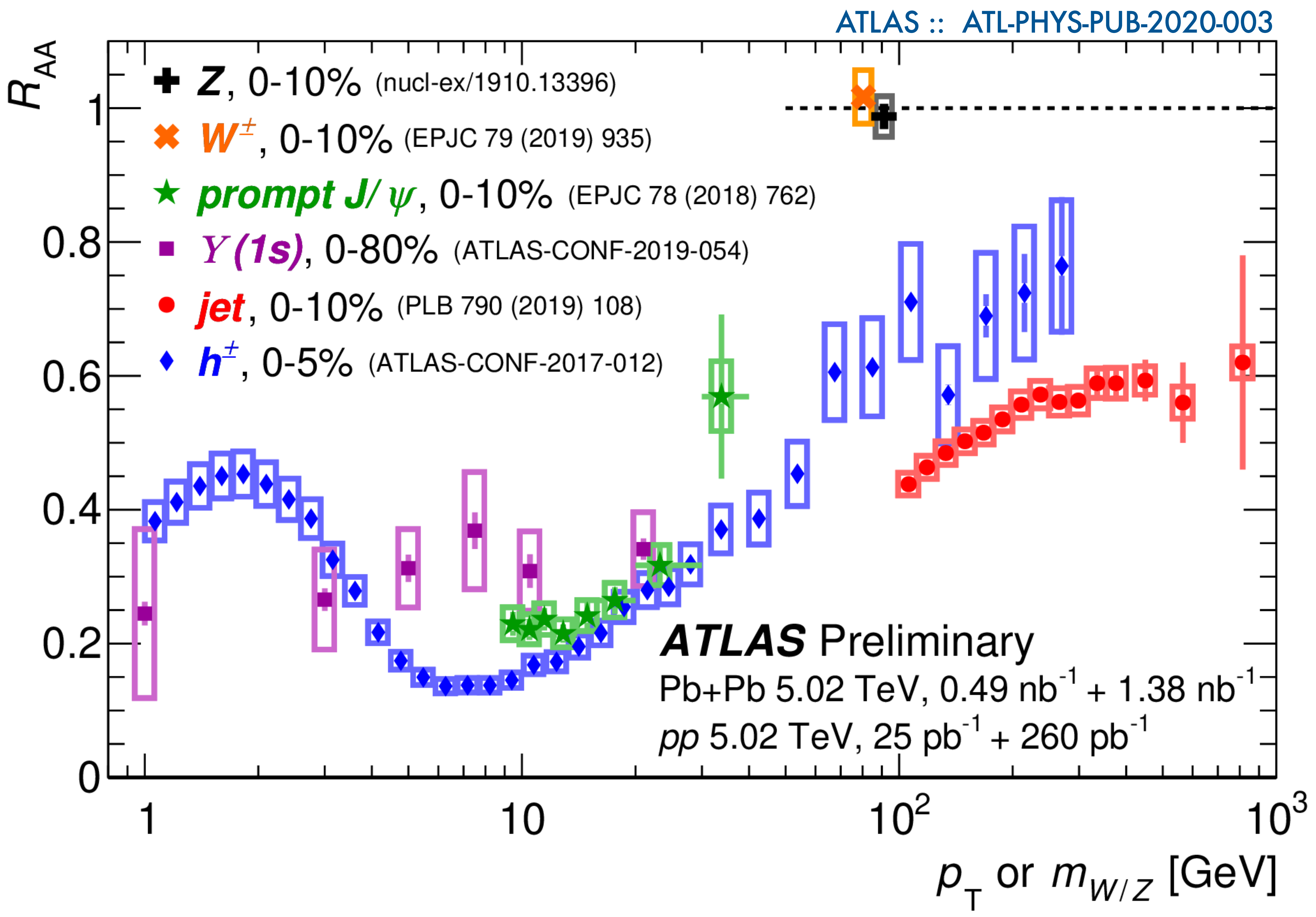


$p_T^{\mathrm{AA}} \in [80, 173]$ GeV

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

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

JETS AND HADRONS LOSE ENERGY WHEN TRAVERSING QGP



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

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

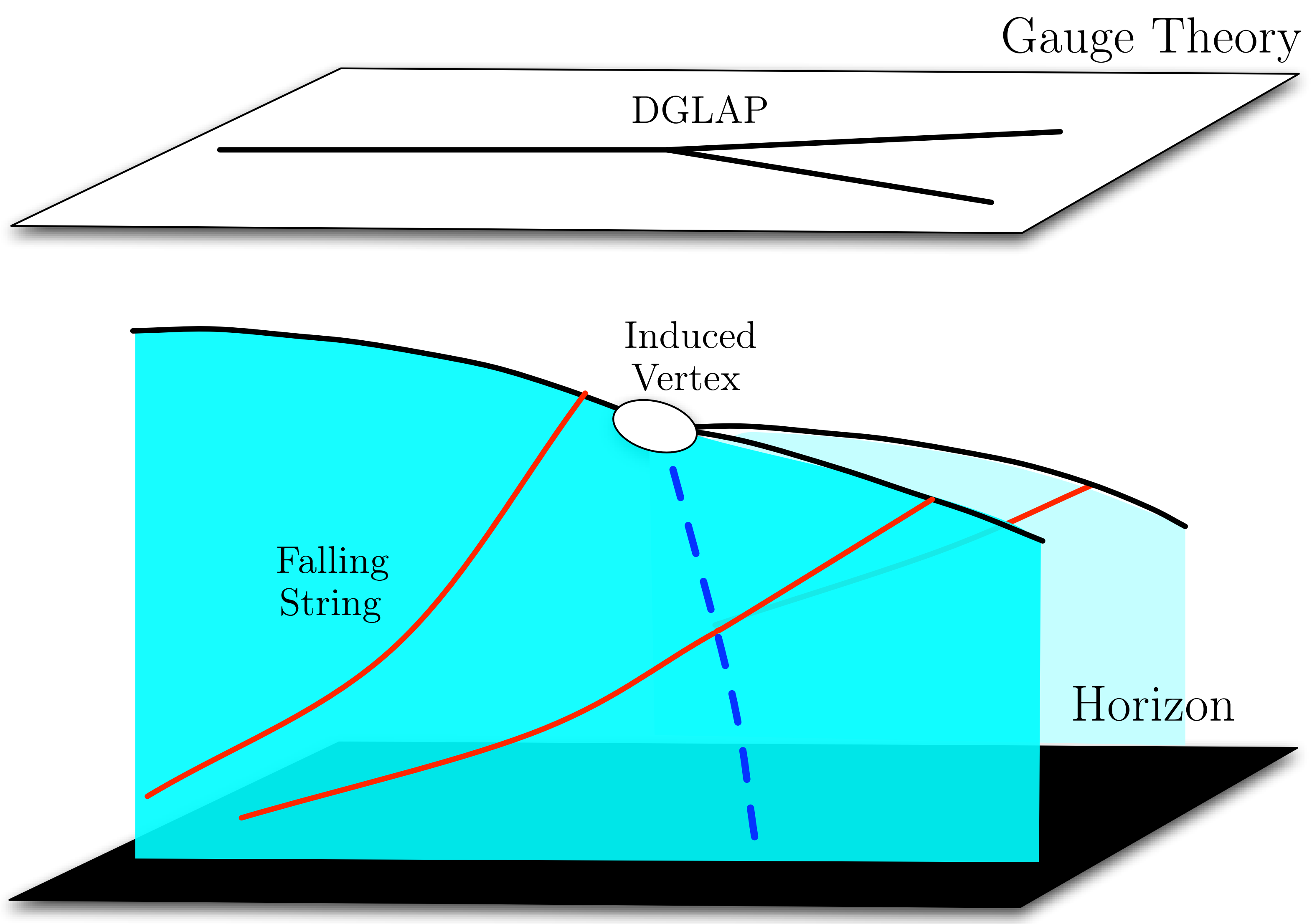
$$\sigma^{\rm eff}_{\rm AA} = \sigma_{\rm AA}/\langle N_{\rm coll}\rangle$$

- both jets and hadrons (which belong to jets) are suppressed, but differently
  - can the difference be understood? is it important?

UNDERSTANDING DIFFERENT SUPPRESSION OF JETS AND HADRONS

- essential to describe both within same theoretical framework
    - here in the strong/weak coupling hybrid model [conclusions are general]

[Can Gulan, Hulcher, Yao], Casalderrey, Milhano, Pablos, Rajagopal :: since 2014



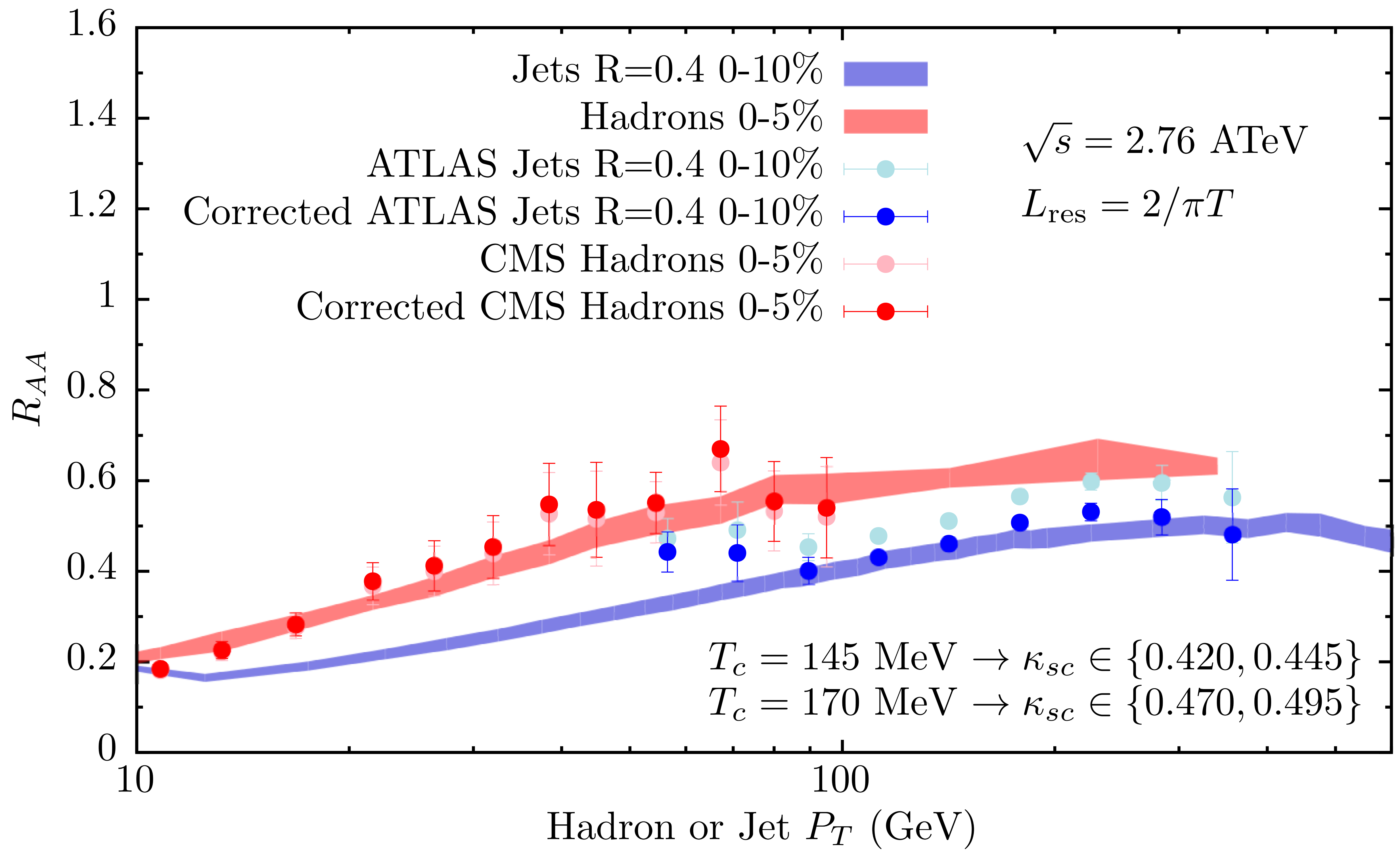
- physics at different scales merit different treatments
    - vacuum jets where each parton loses energy non-perturbatively [as given by a holographic AdS-CFT calculation]
- lost energy becomes a wake [QGP response], part of which will belong to the jet

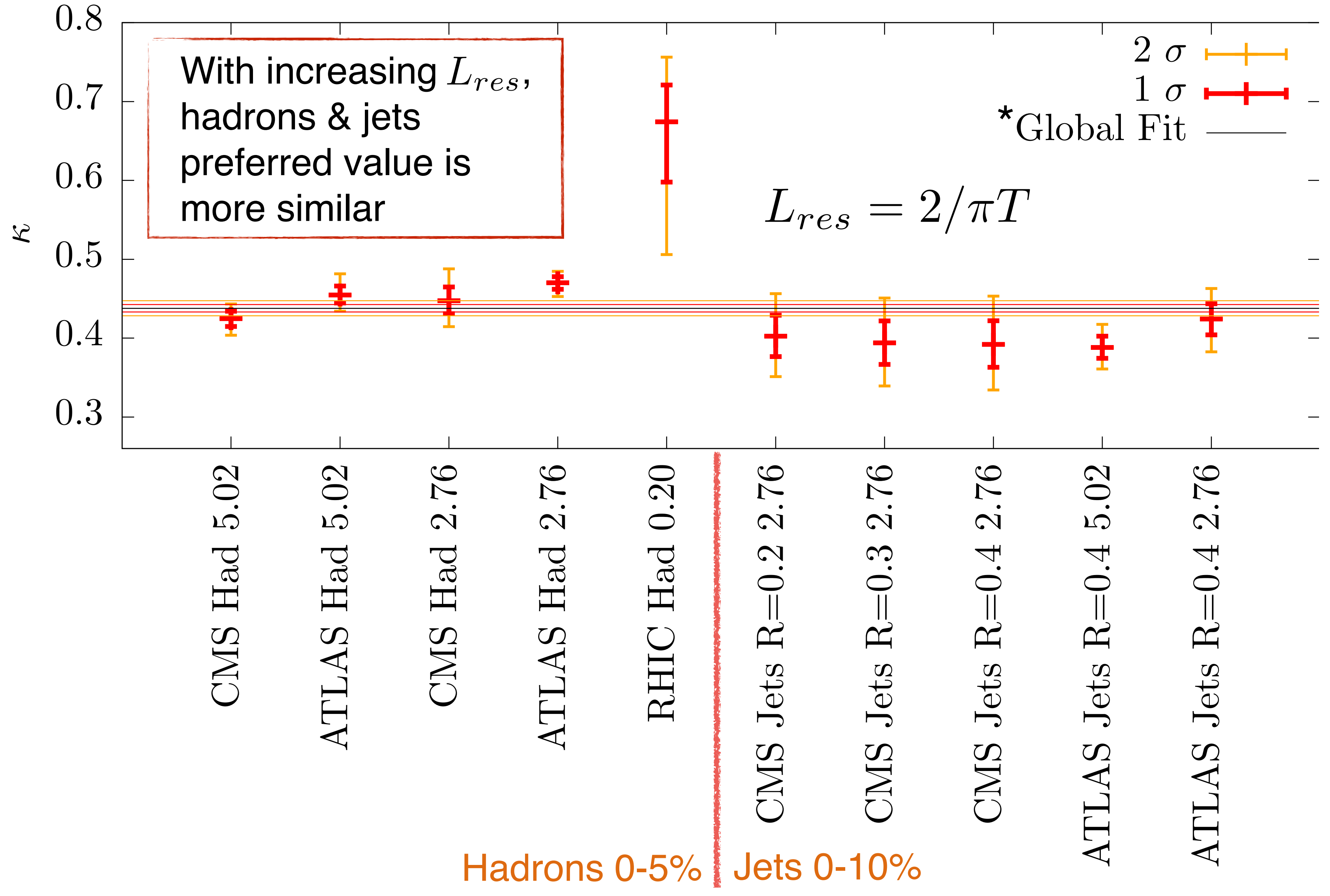
$$\left.\frac{dE}{dx}\right|_{\text{strongly coupled}} = -\frac{4}{\pi} E_{\text{in}} \frac{x^2}{x^2_{\text{stop}}} \frac{1}{\sqrt{x^2_{\text{stop}} - x^2}}\,, \qquad x_{\text{stop}} = \frac{1}{2\kappa_{\text{sc}}} \frac{E_{\text{in}}^{1/3}}{T^{4/3}}$$

single free parameter
[accounts for QCD/N=4 SYM differences]

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

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

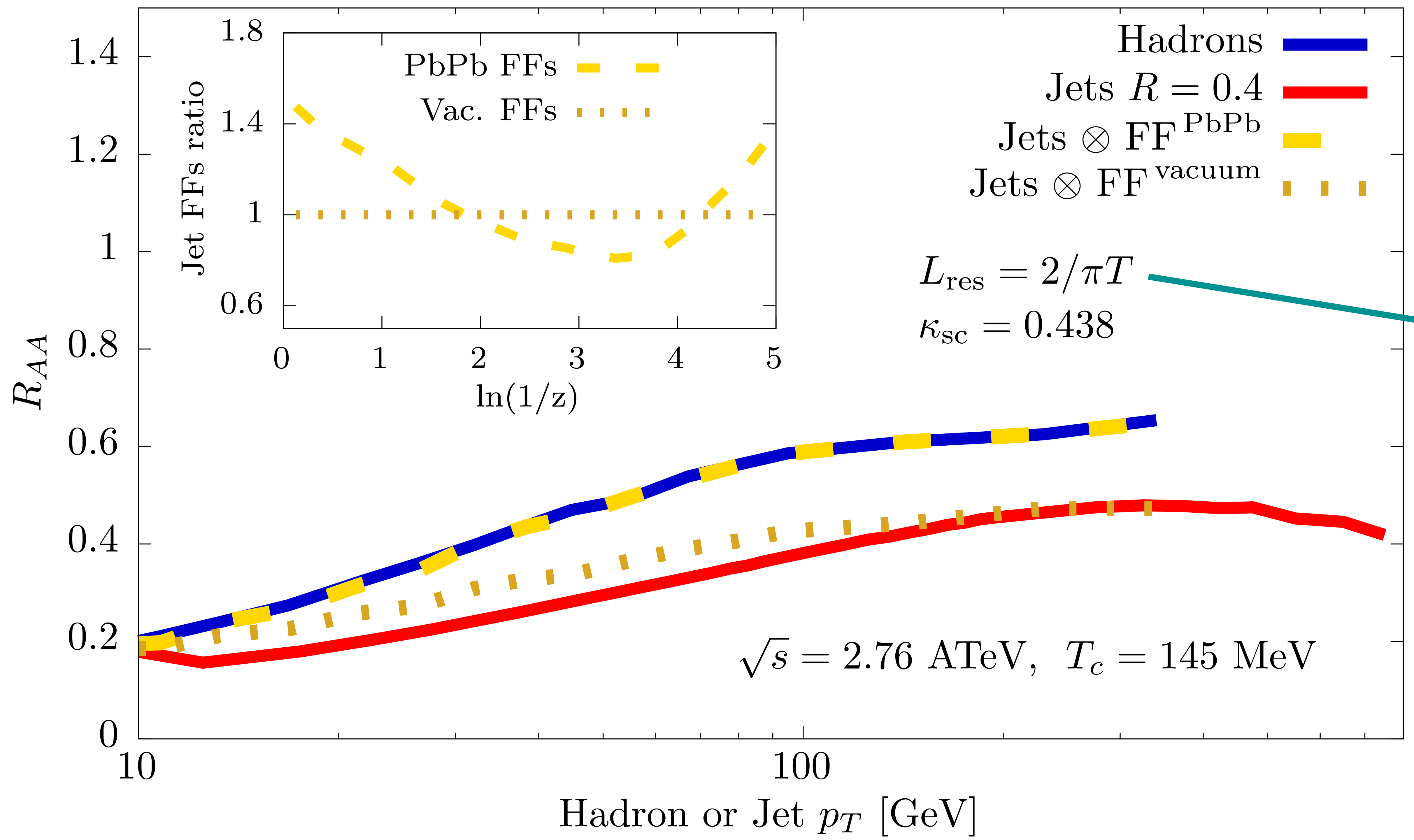




- excellent global fit for LHC data :: tension with RHIC data
- high p_T hadrons originate from narrow jets [fragmented less] which are less suppressed than inclusive jets
- simultaneous description of jet and hadron R_{AA} natural feature of any approach that treats jets as such [ie, objects with internal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

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

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



the QGP resolution power

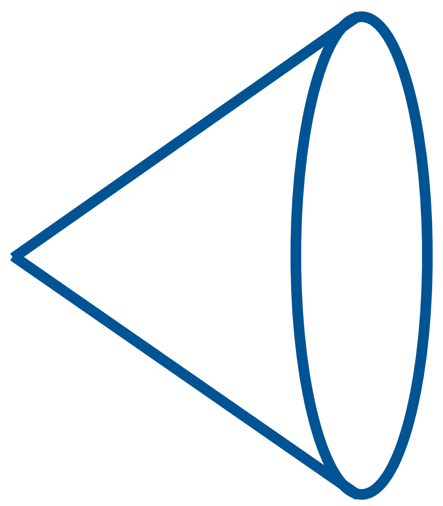
- modification of FF is essential for joint description :: jets change
- QGP resolves the internal partonic structure of a jet

VERY IMPORTANT LESSONS

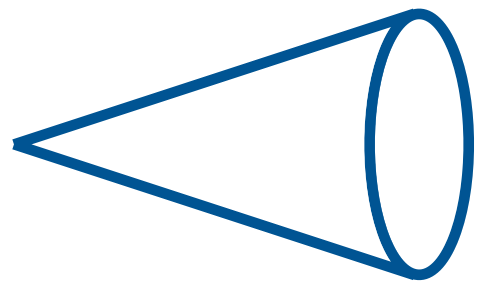
- the QGP resolves the partonic structure of an evolving branching sequence
  - this is a highly non-trivial statement
    - quark and gluons [partons] are NOT asymptotic states [an infinite resolution spacetime detector/tracker CANNOT see partons] :: the QGP allows us to 'see' them
    - evolving branching sequence resolves the QGP
      - explore sub-structure to see spatio-temporal dynamics of QGP [a lot of ongoing work]
- jet quenching depends strongly on branching 'width'
  - branching 'width' is dictated [because QCD is angular ordered] by first branching step
  - first branching step occurs before QGP forms :: it is vacuum physics
  - vacuum physics drives jet quenching

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



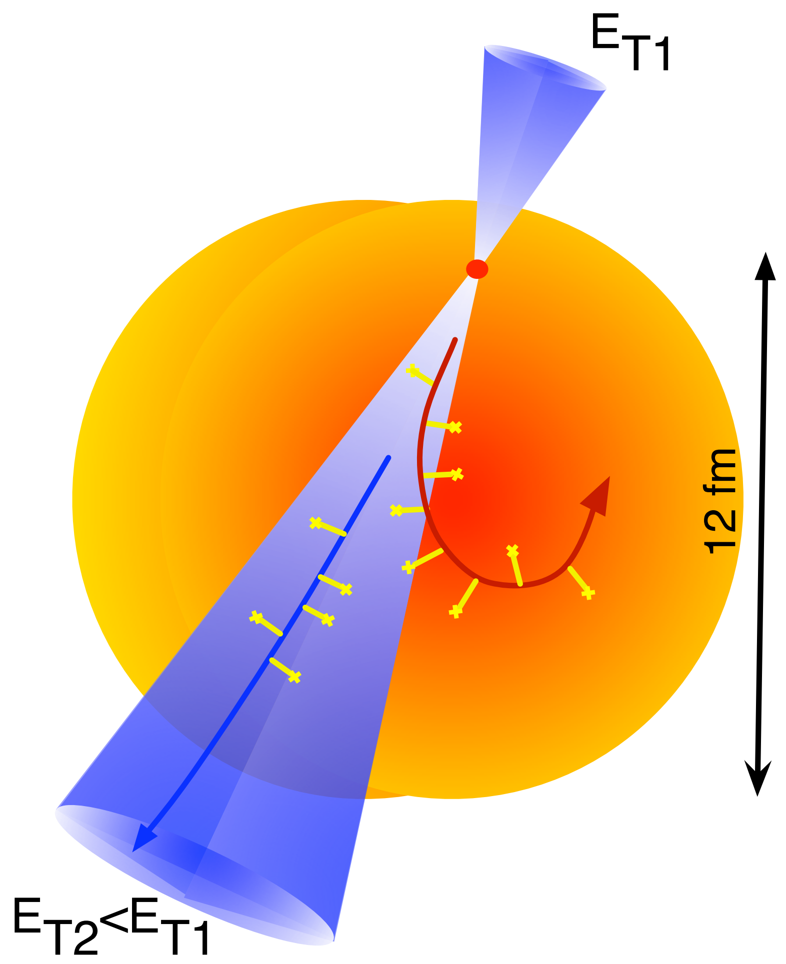
large m^2 :: wide jet :: more constituents



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

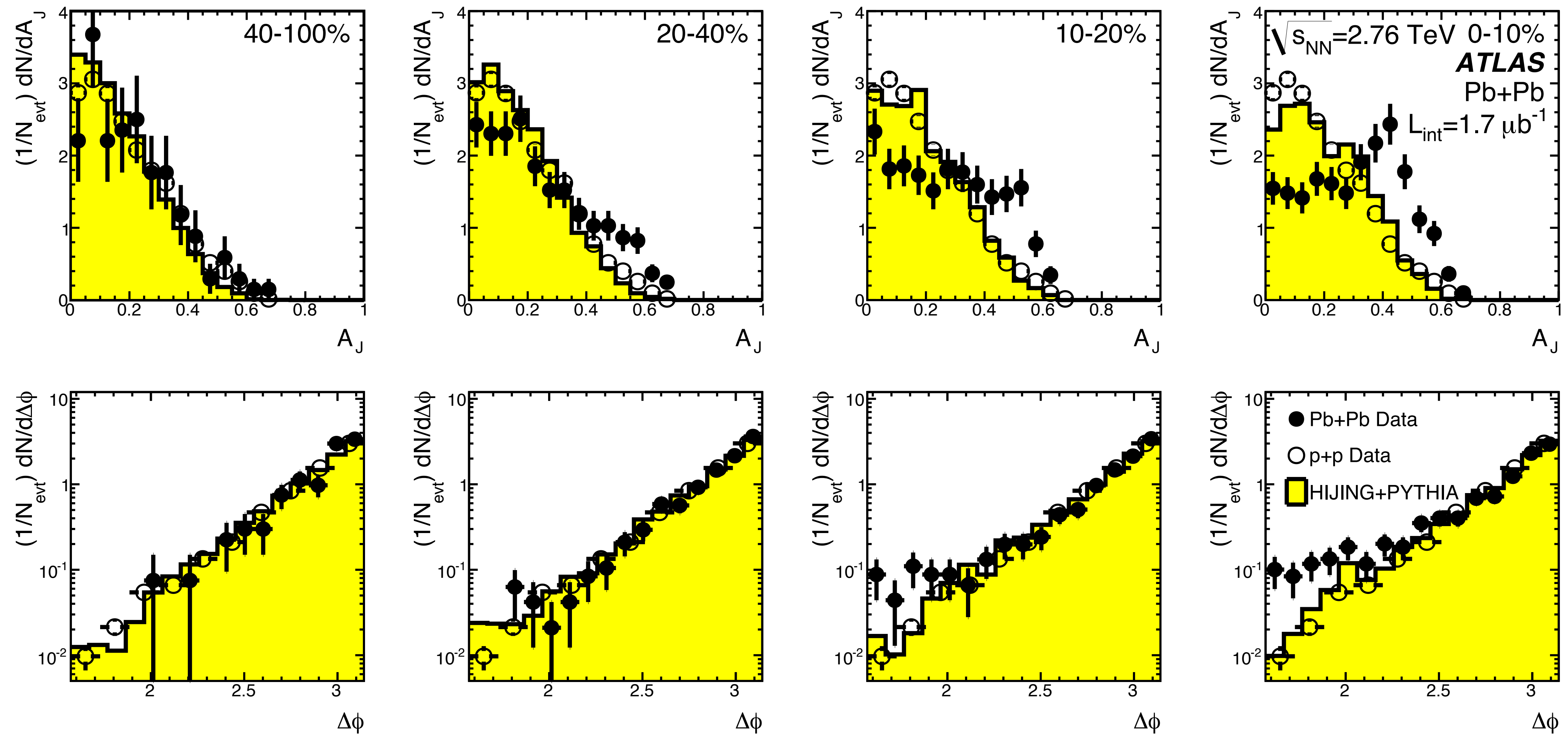
[MANY] LESSONS FROM THE FIRST JET MEASUREMENT AND ITS REMEASURENTS



di-jet asymmetry

:: energy imbalance of back-back jets

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



ATLAS :: PRL 105 (2010)

- A_J distribution shifted to larger asymmetries
- no modification of acoplanarity distribution

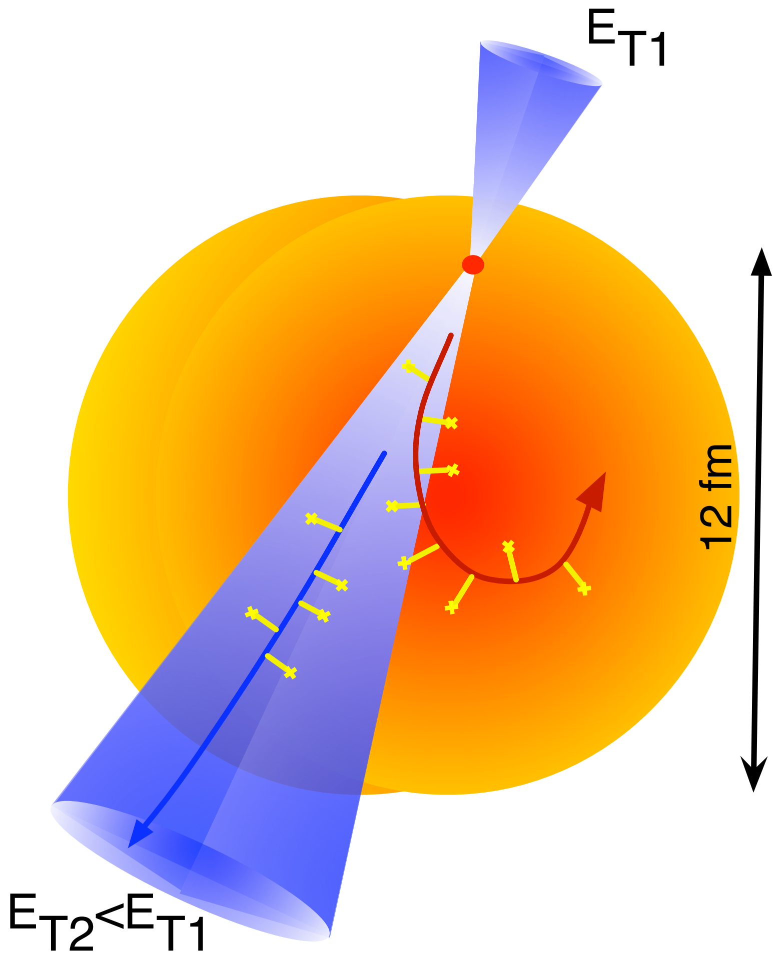
[MANY] LESSONS FROM THE FIRST JET MEASUREMENT

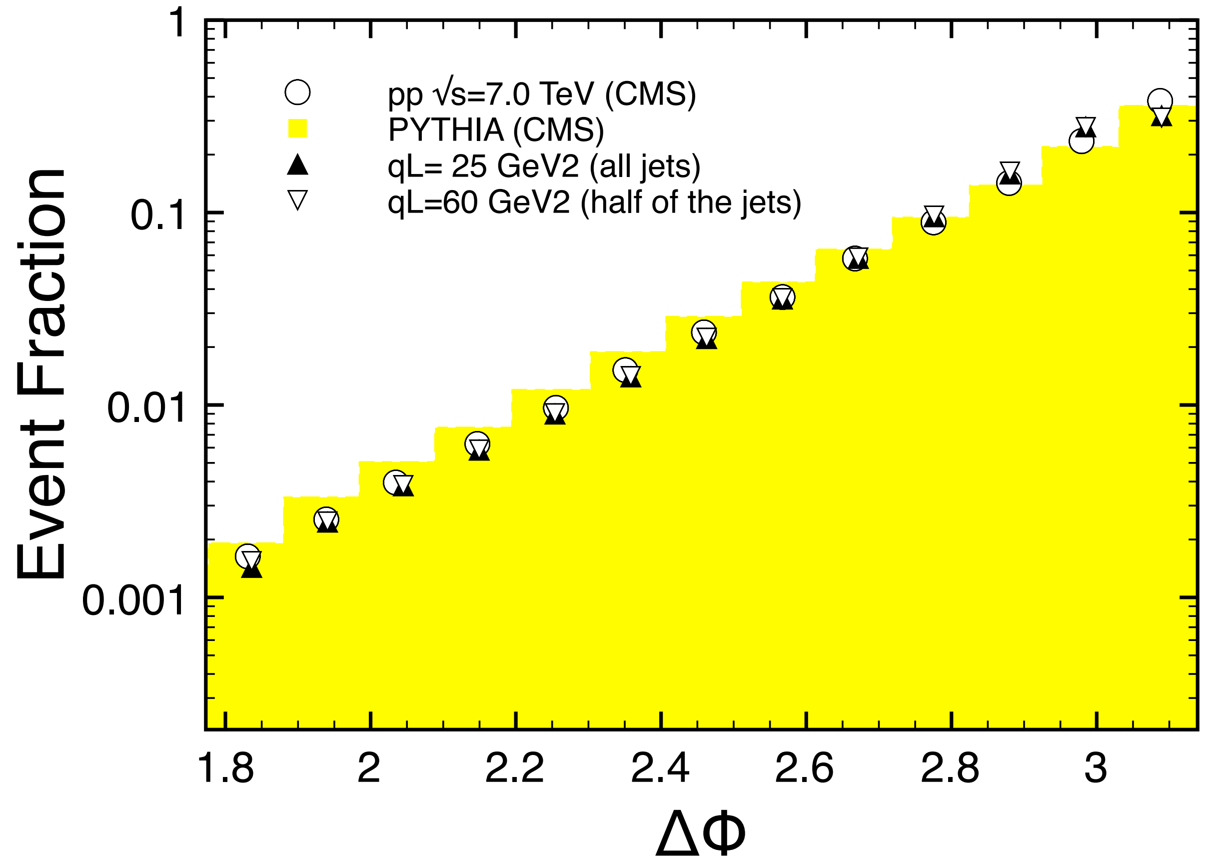
measurement of increase of di-jet asymmetry without disturbance of acoplanarity distribution

[MANY] LESSONS FROM THE FIRST JET MEASUREMENT

measurement of increase of di-jet asymmetry without disturbance of acoplanarity distribution

peeling-off of soft gluons is driving mechanism of jet energy loss



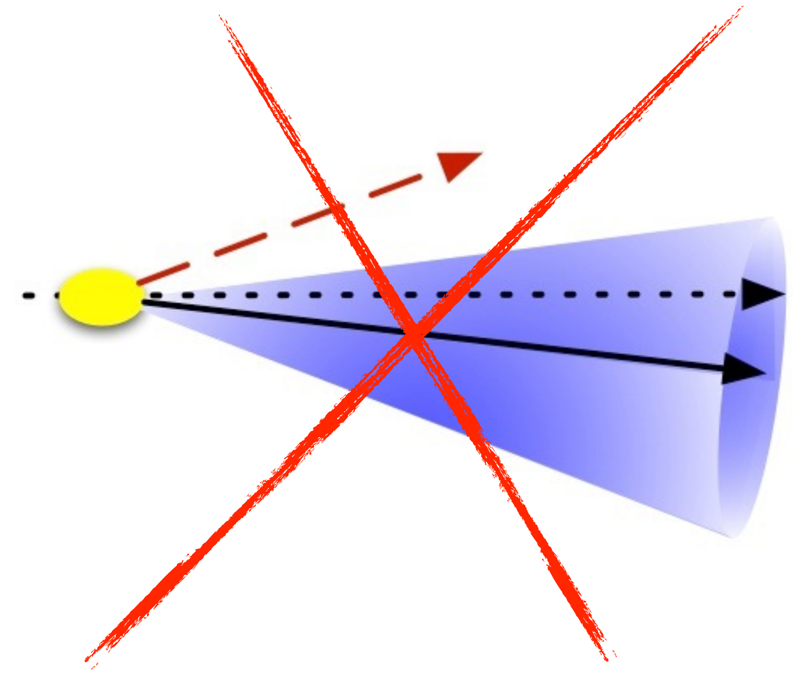


Casalderrey-Solana, Milhano, Wiedemann :: J. Phys. G38 (2011)

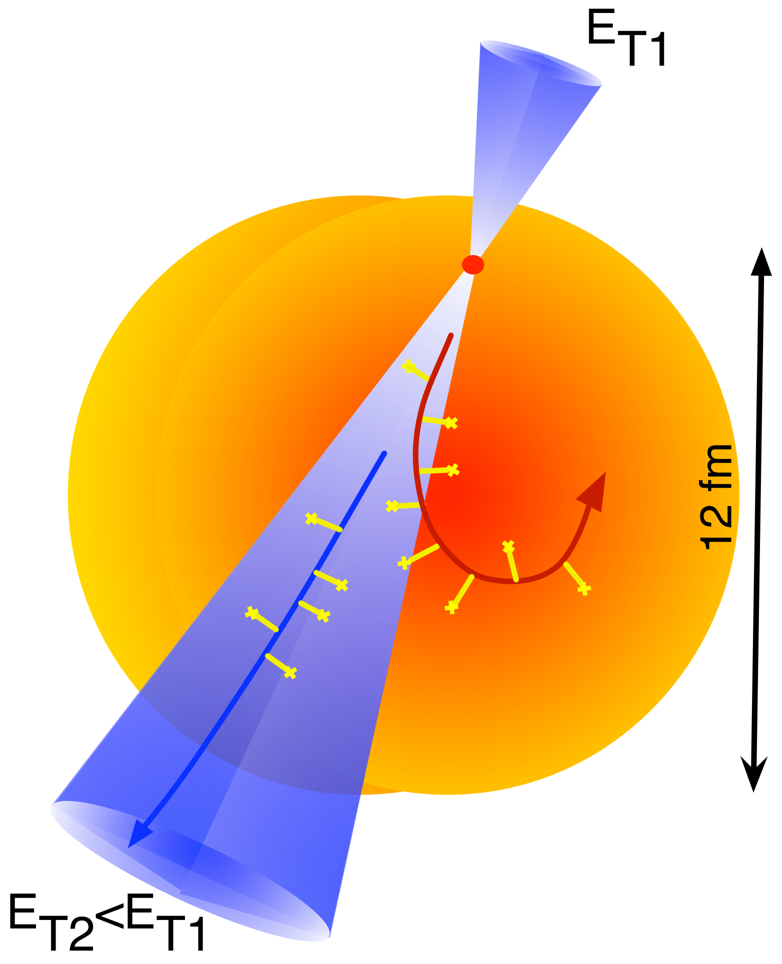
[MANY] LESSONS FROM THE FIRST JET MEASUREMENT

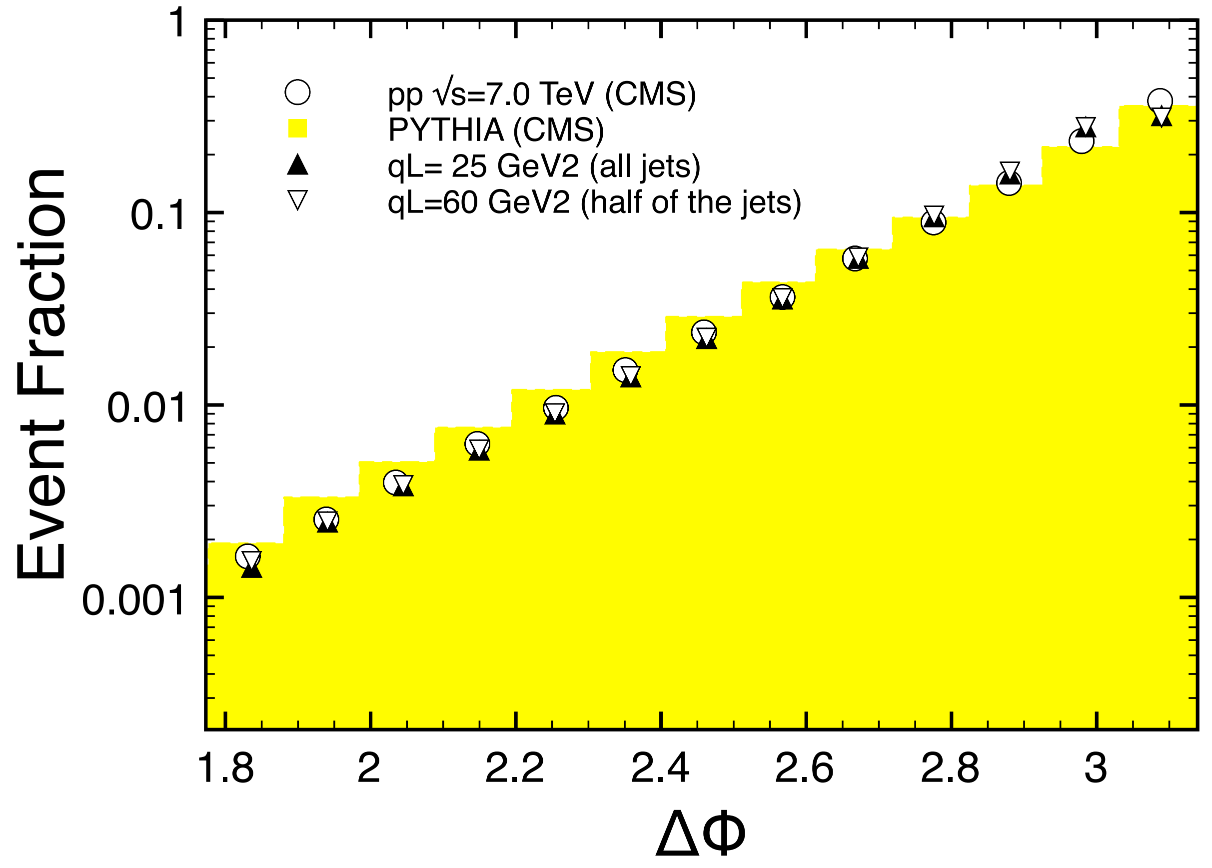
measurement of increase of di-jet asymmetry without disturbance of acoplanarity distribution

NOT out of cone semi-hard rare emissions as previously thought



peeling-off of soft gluons is driving mechanism of jet energy loss





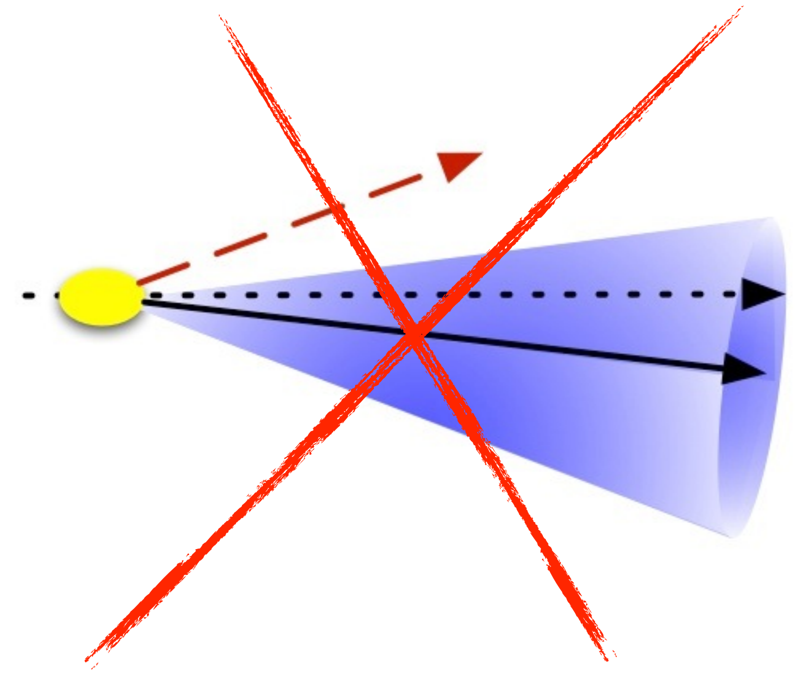
Casalderrey-Solana, Milhano, Wiedemann :: J. Phys. G38 (2011)

[MANY] LESSONS FROM THE FIRST JET MEASUREMENT

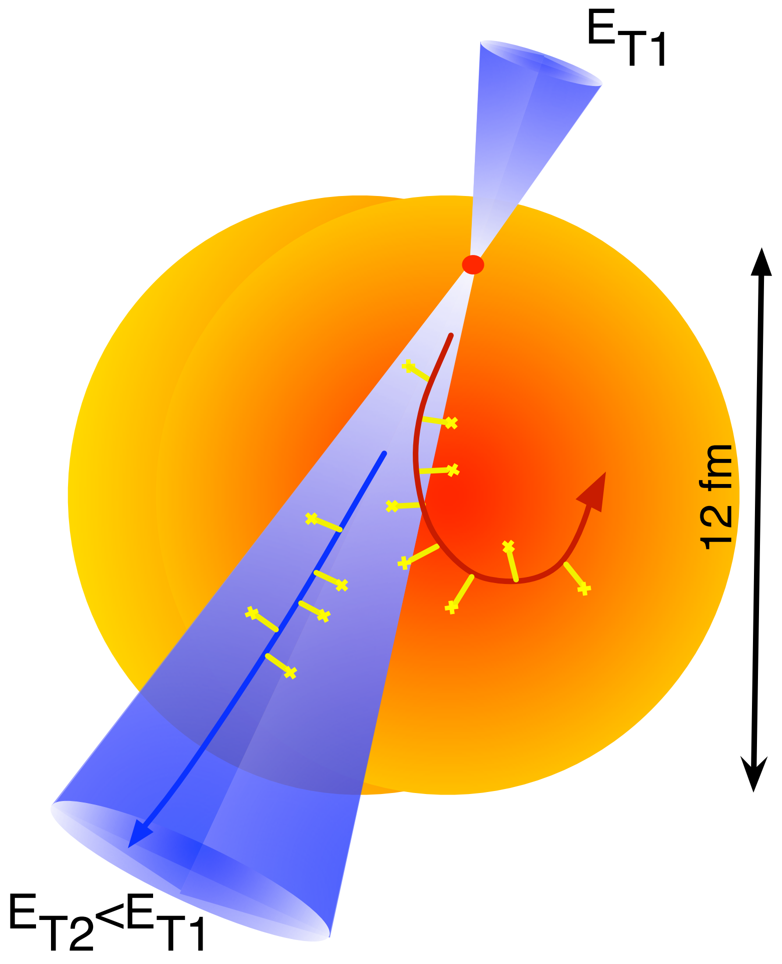
measurement of increase of di-jet asymmetry without disturbance of acoplanarity distribution

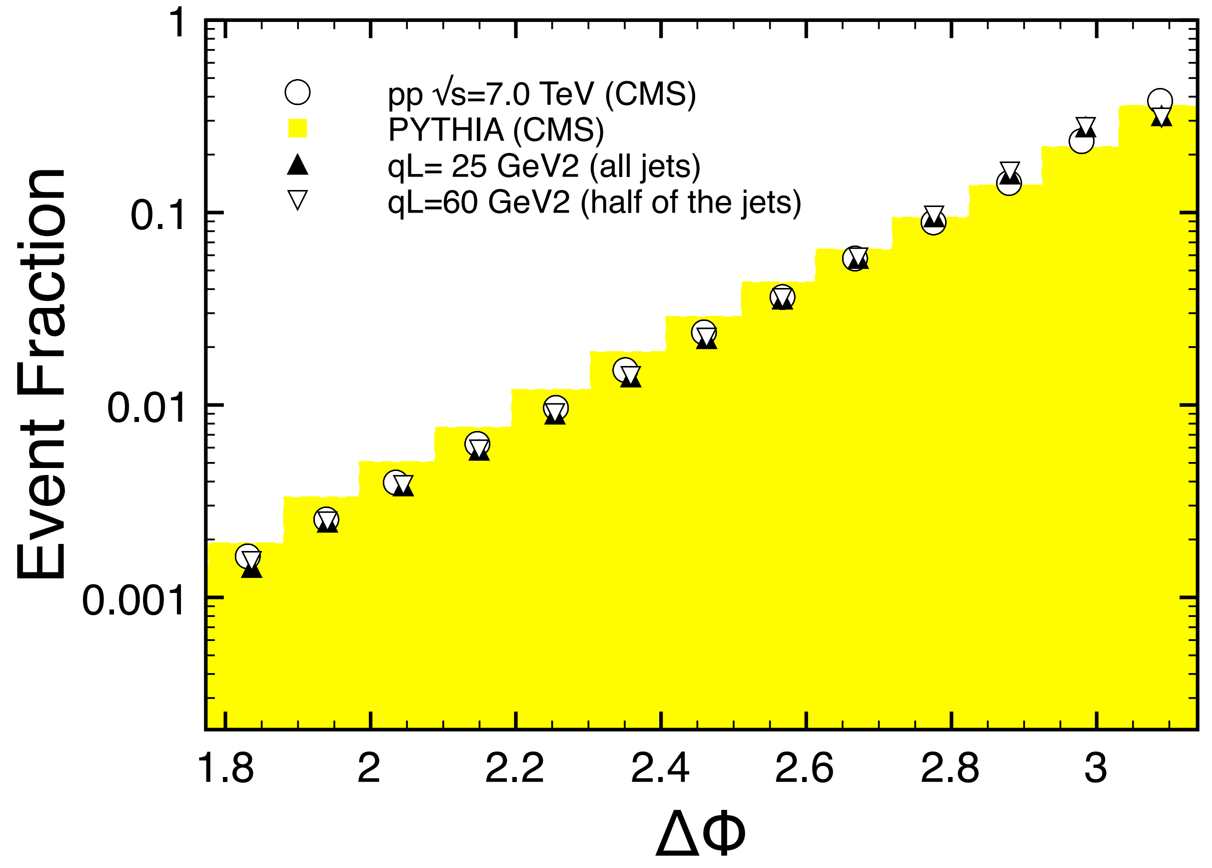
paradigm change triggering experimental analyses and theoretical developments

NOT out of cone semi-hard rare emissions as previously thought



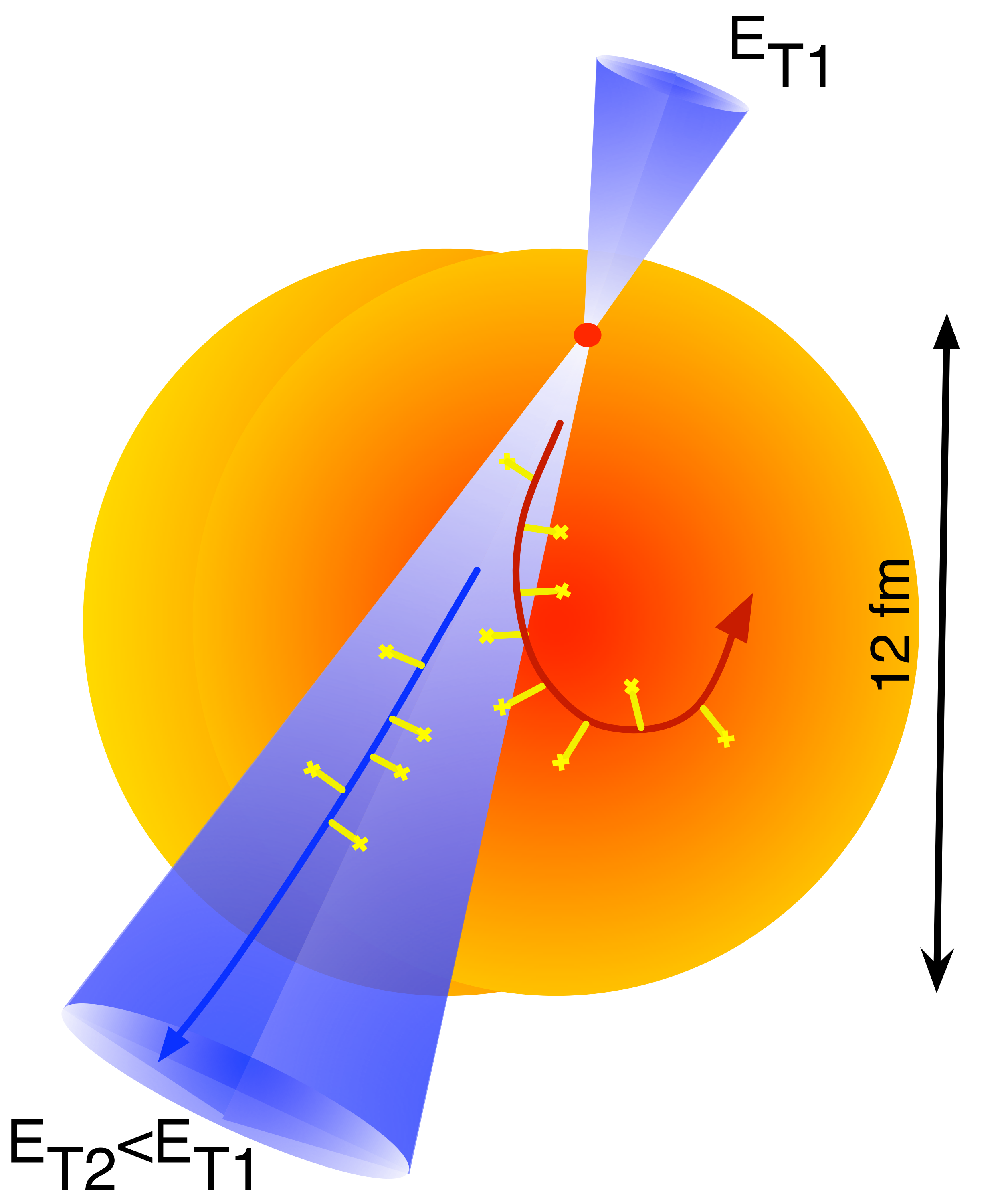
peeling-off of soft gluons is driving mechanism of jet energy loss



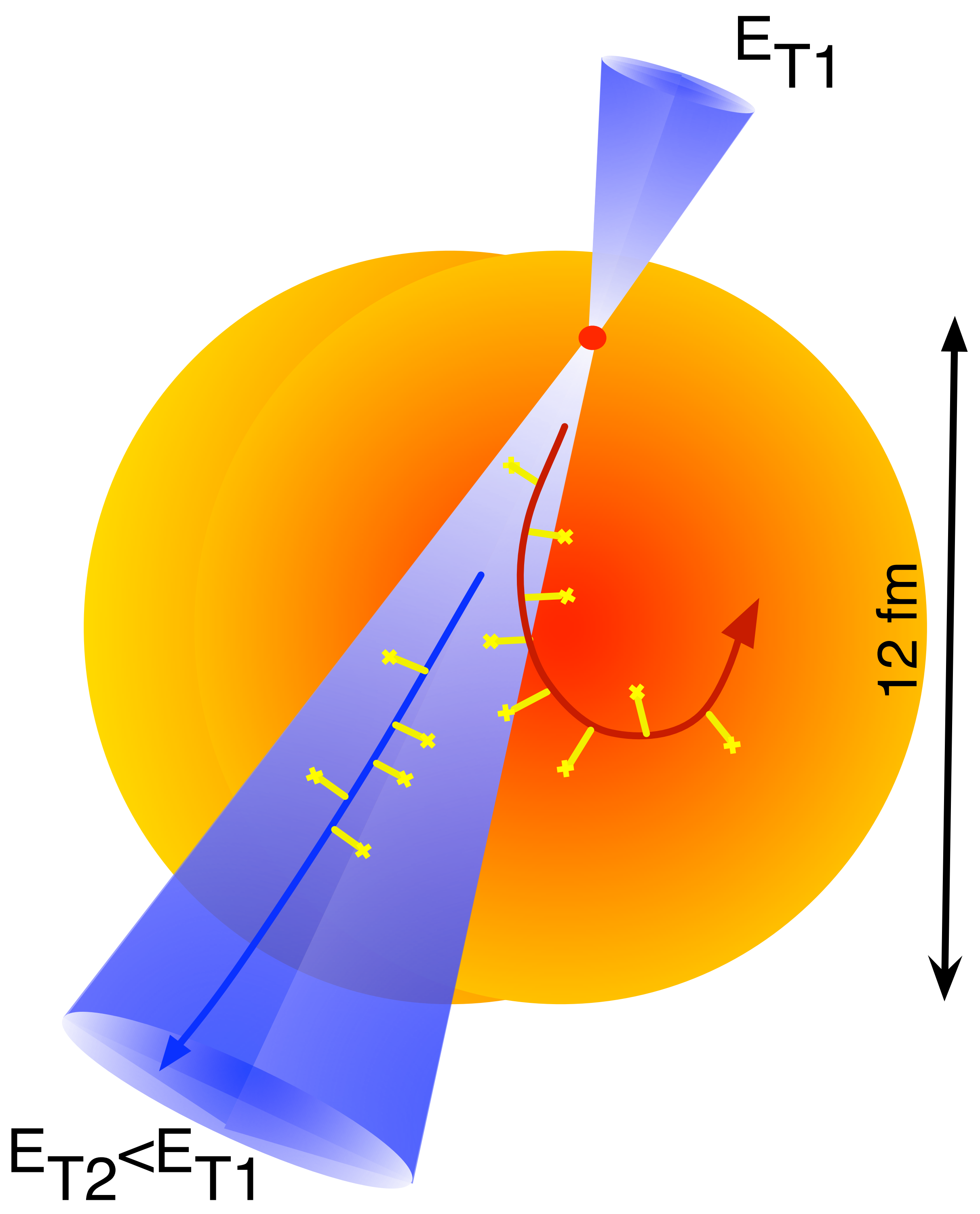


Casalderrey-Solana, Milhano, Wiedemann :: J. Phys. G38 (2011)

[MANY] LESSONS FROM THE FIRST JET MEASUREMENT

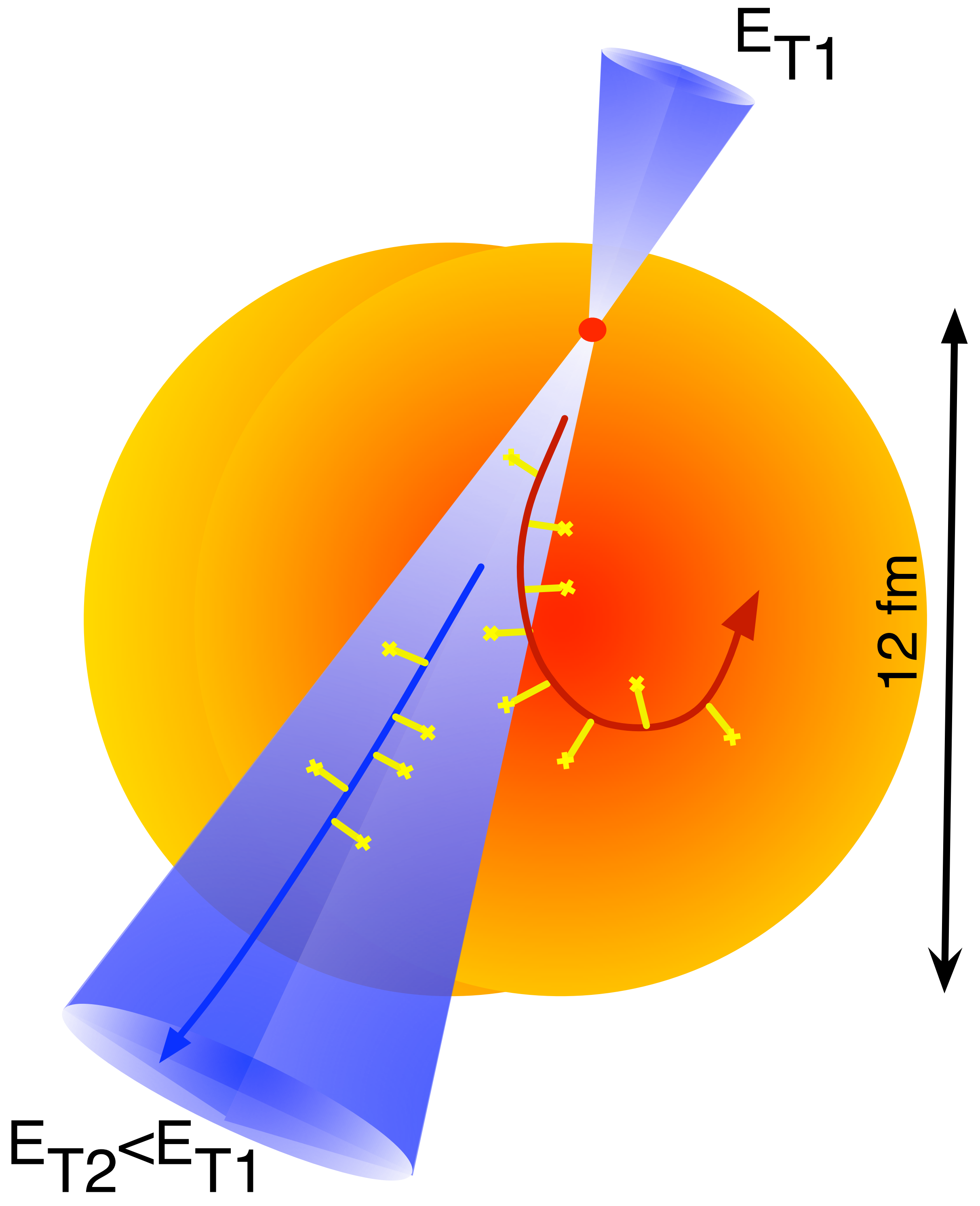


[MANY] LESSONS FROM THE FIRST JET MEASUREMENT



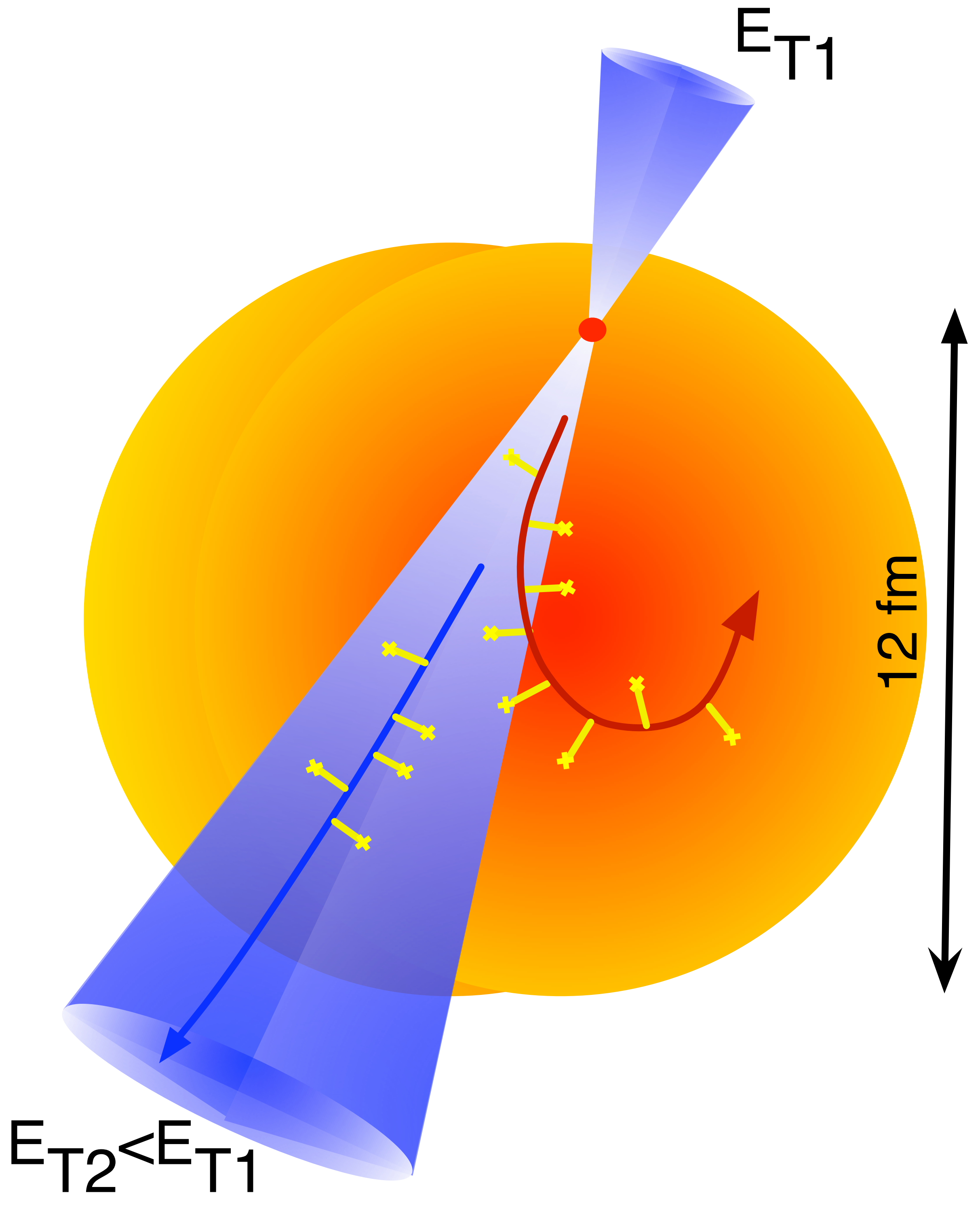
- cartoon implicitly suggests importance of path-length difference in di-jet asymmetry

[MANY] LESSONS FROM THE FIRST JET MEASUREMENT



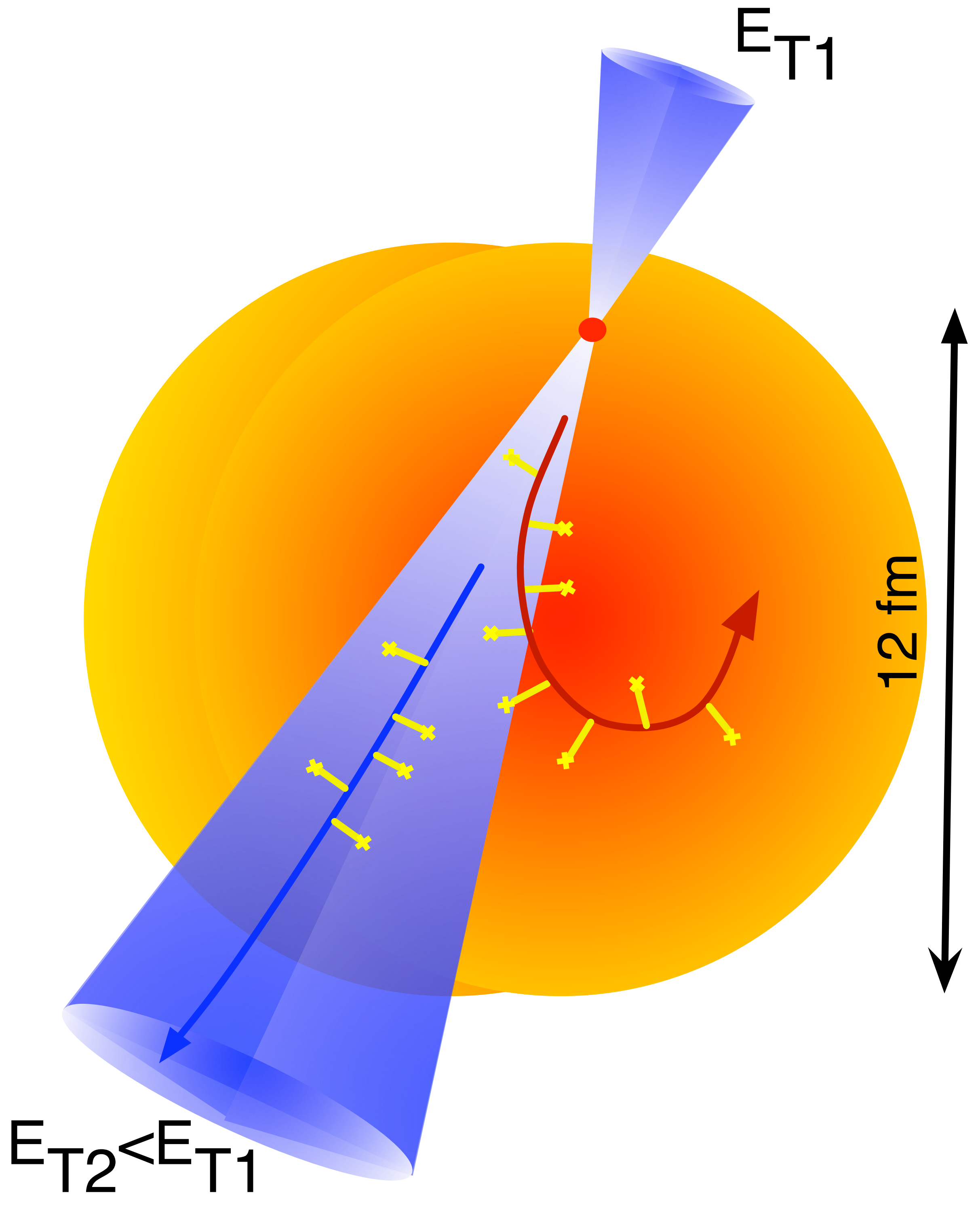
- cartoon implicitly suggests importance of path-length difference in di-jet asymmetry
- follows naive intuition and introduces cognitive bias that can compromise your conclusions

[MANY] LESSONS FROM THE FIRST JET MEASUREMENT



- cartoon implicitly suggests importance of path-length difference in di-jet asymmetry
- follows naive intuition and introduces cognitive bias that can compromise your conclusions
    - it should not have in this case as peeling-off of soft jet components is the key mechanism for jet energy loss [in whatever language you choose to address it]

[MANY] LESSONS FROM THE FIRST JET MEASUREMENT



- cartoon implicitly suggests importance of path-length difference in di-jet asymmetry
- follows naive intuition and introduces cognitive bias that can compromise your conclusions
  - it should not have in this case as peeling-off of soft jet components is the key mechanism for jet energy loss [in whatever language you choose to address it]
- however there is much more to it

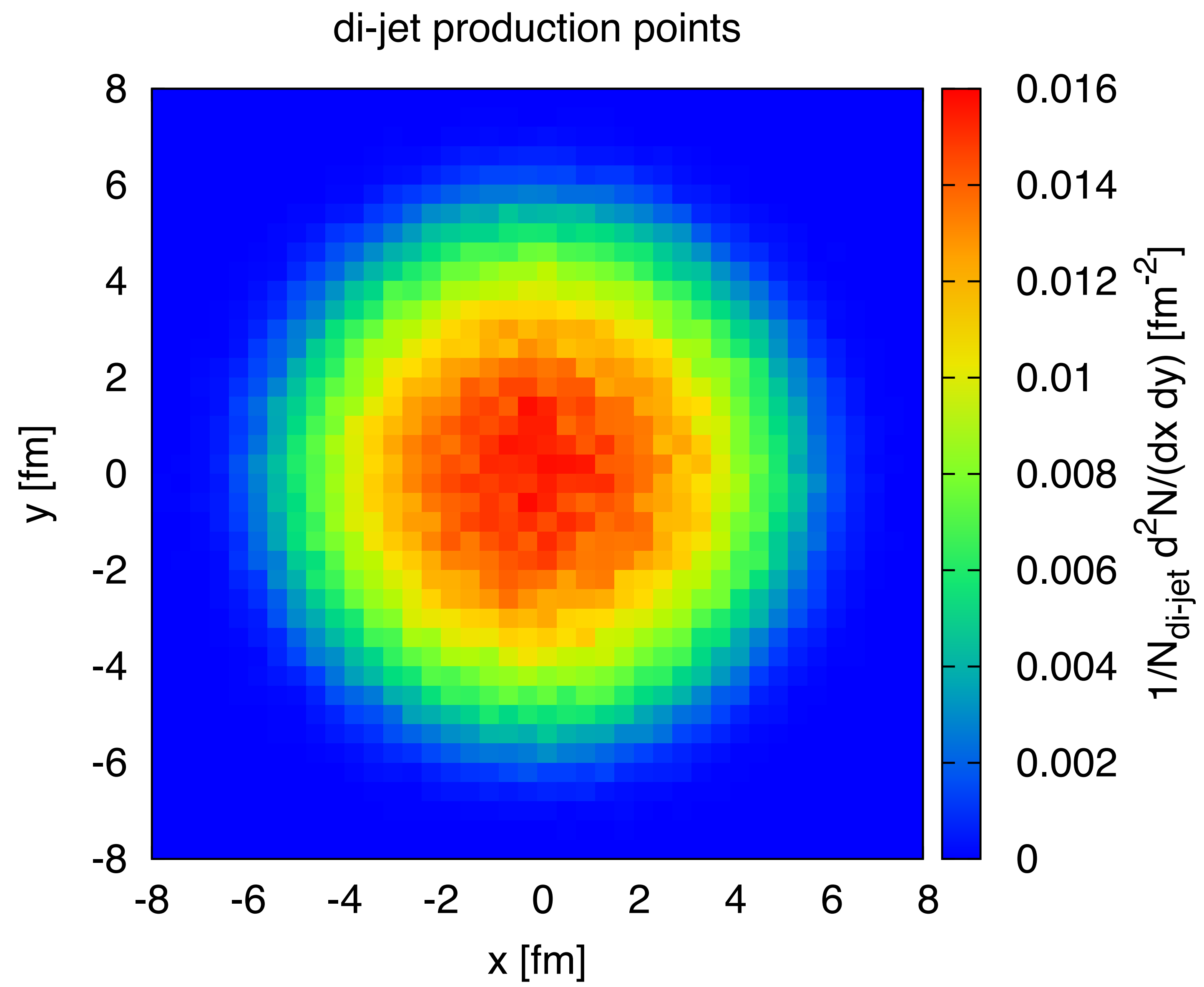
A TOOL :: MONTE-CARLO EVENT GENERATOR

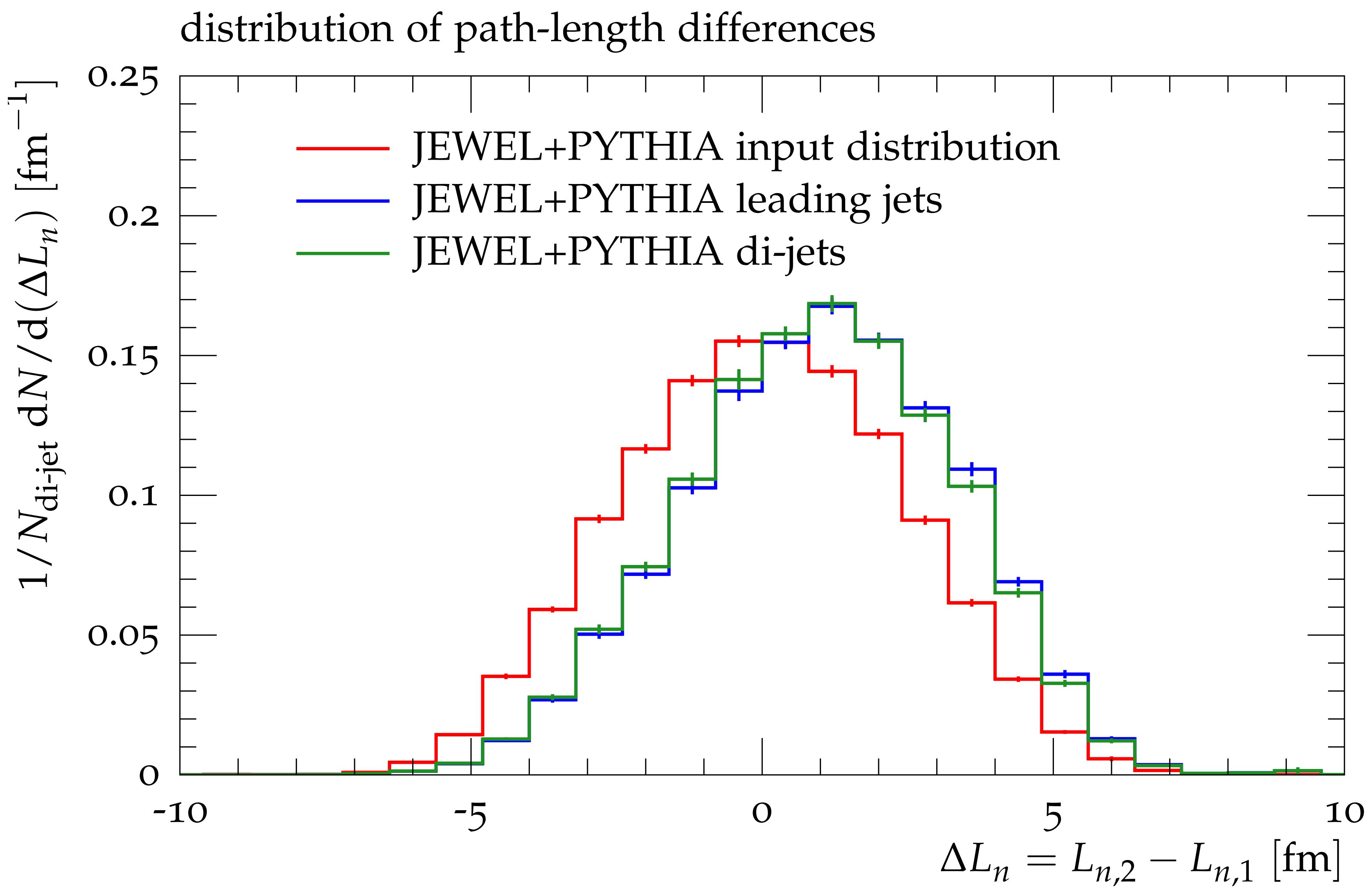
Zapp, Krauss, Wiedemann :: JHEP 1303 (2013)

- JEWEL implements most known jet quenching physics as modification of parton shower from scattering of constituents with QGP partons
- JEWEL tackles jet evolution and jet-QGP interaction within a common framework solidly based on perturbative QCD
- JEWEL has been validated for a wide set of observables
- JEWEL can be used as an exploration tool

KEY LESSON :: ALWAYS CHECK

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





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

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

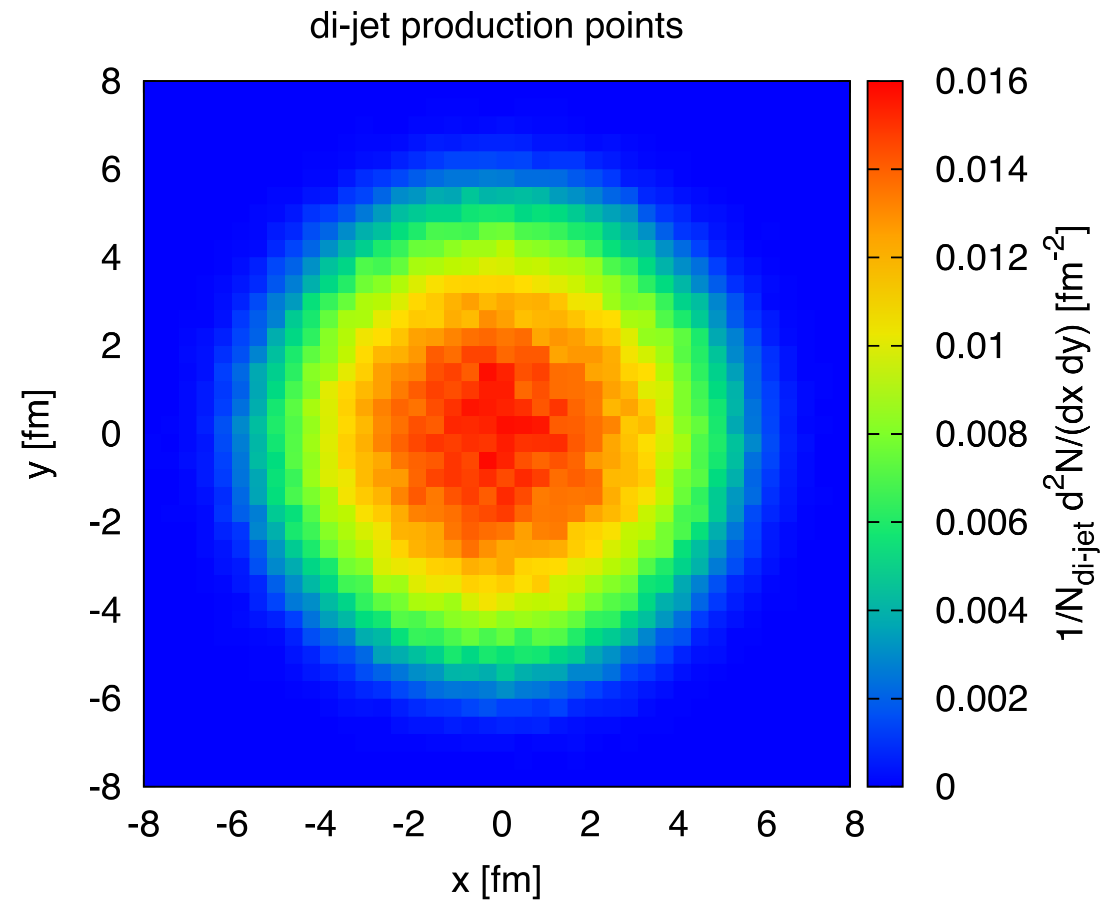
- small bias towards smaller path-length for leading jets
  - however, significant fraction [34%] of events have longer path-length for leading jet
  - consequence of fast medium expansion

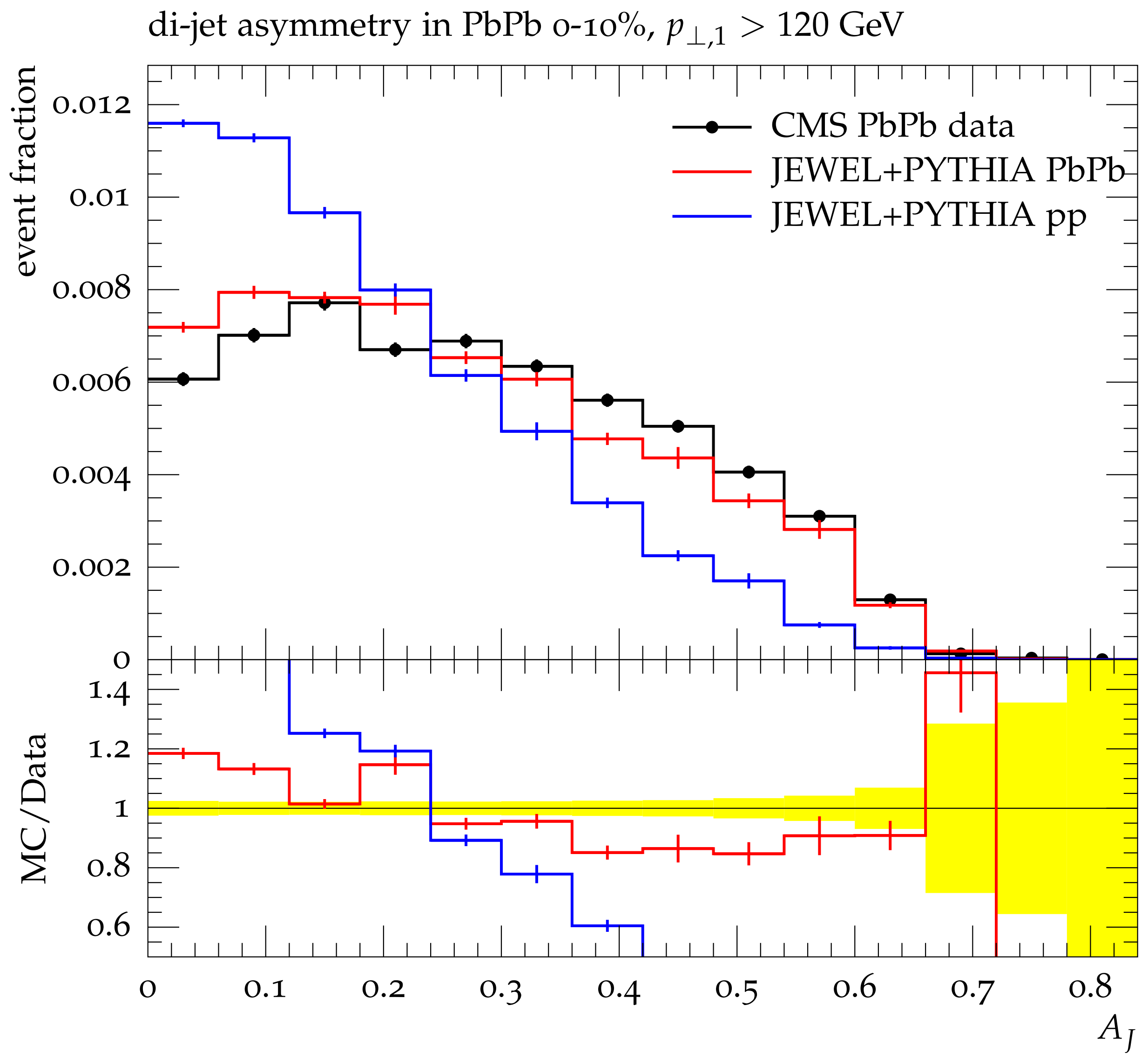
A_J CAN BE GENERATED FOR EQUAL PATH LENGTHS

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

A_J CAN BE GENERATED FOR EQUAL PATH LENGTHS

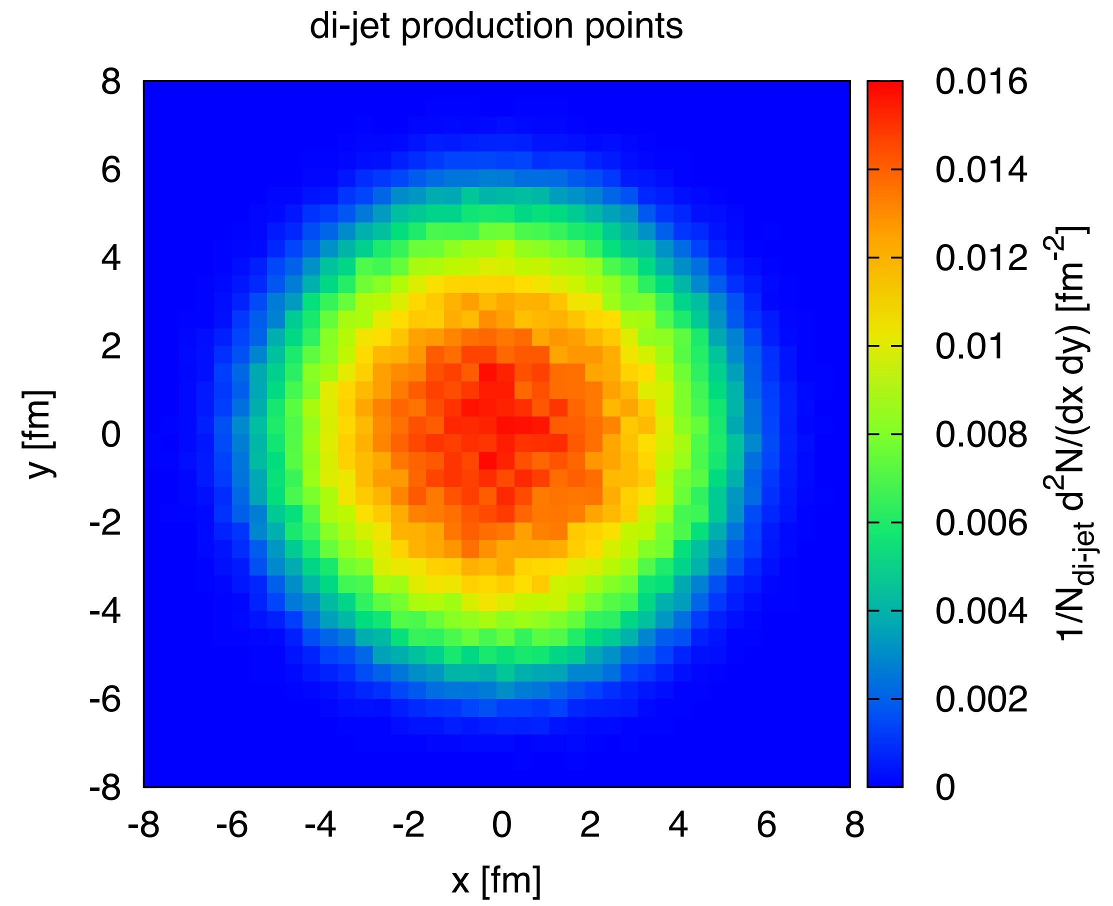
Milhano and Zapp :: Eur.Phys.J. C76 (2016))

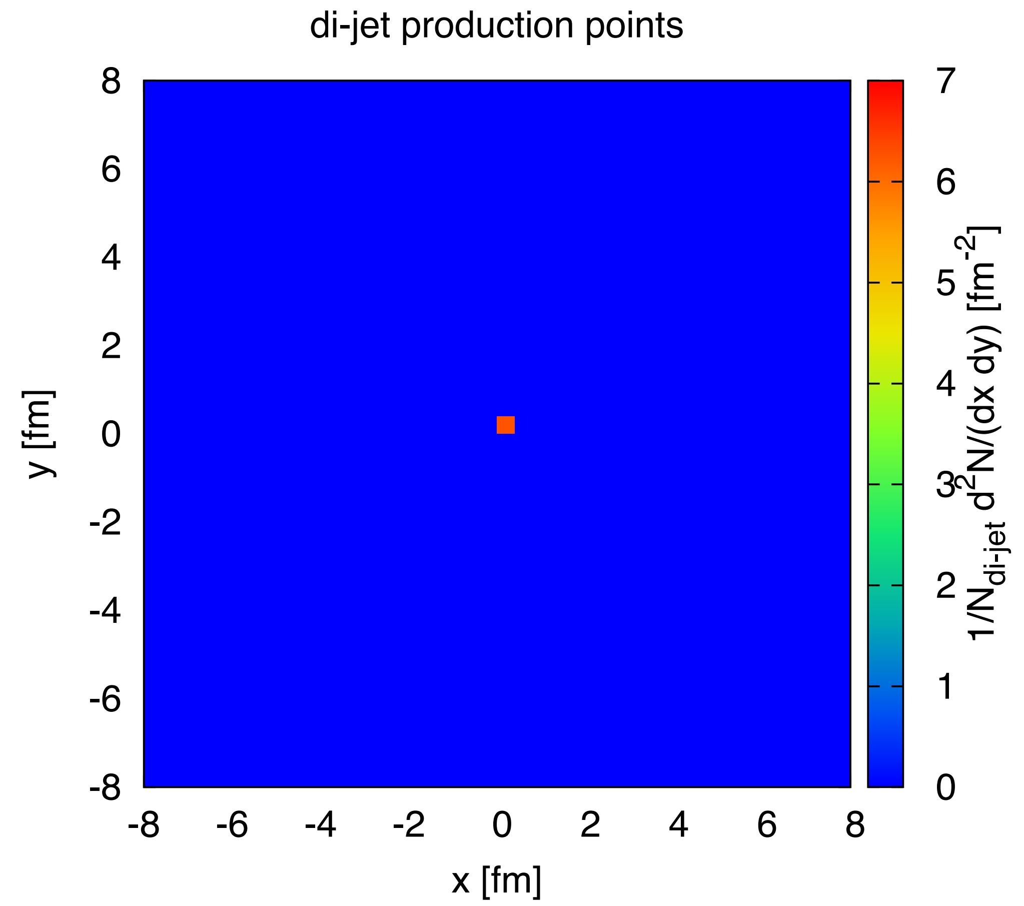


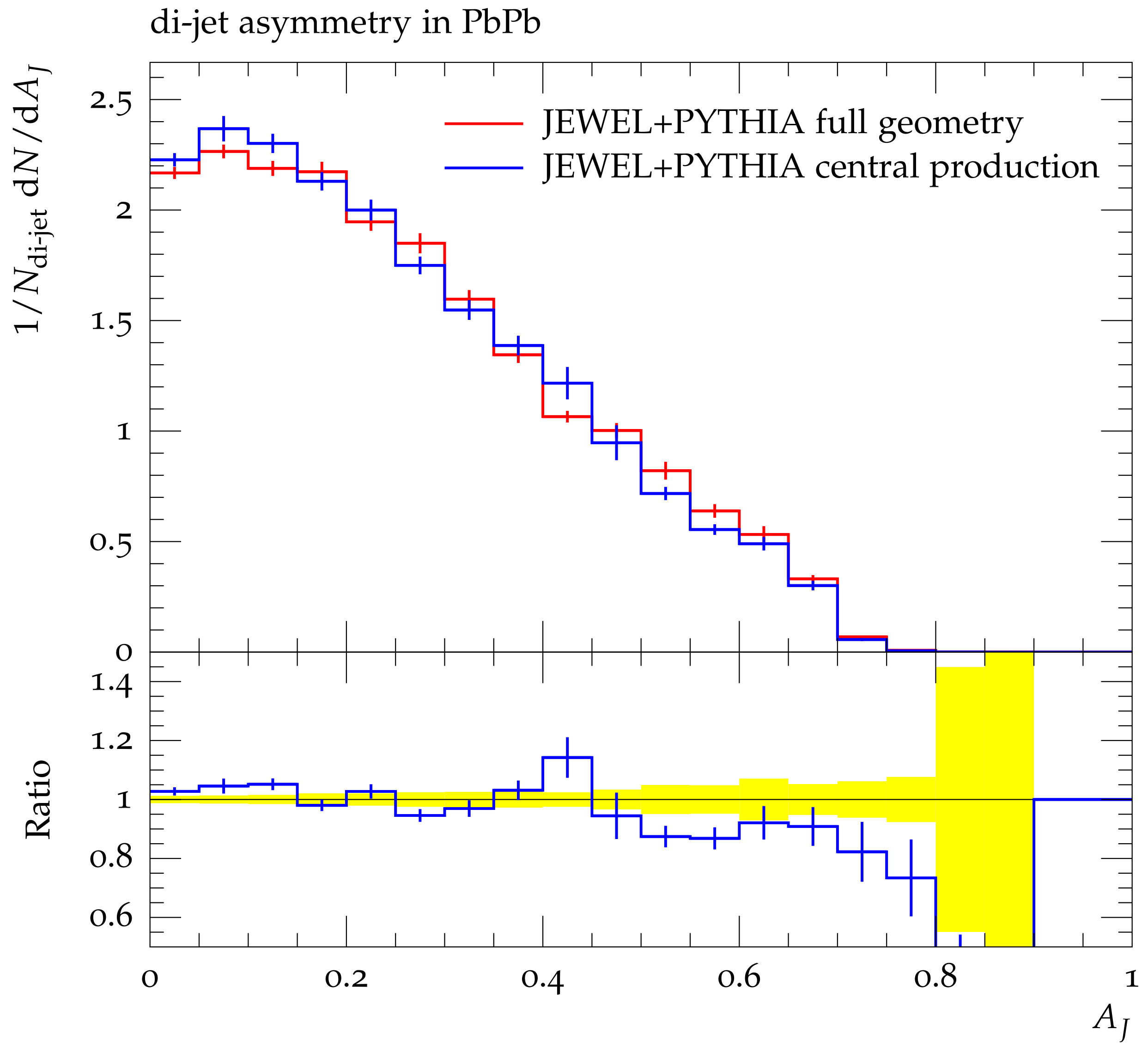


AJ CAN BE GENERATED FOR EQUAL PATH LENGTHS

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



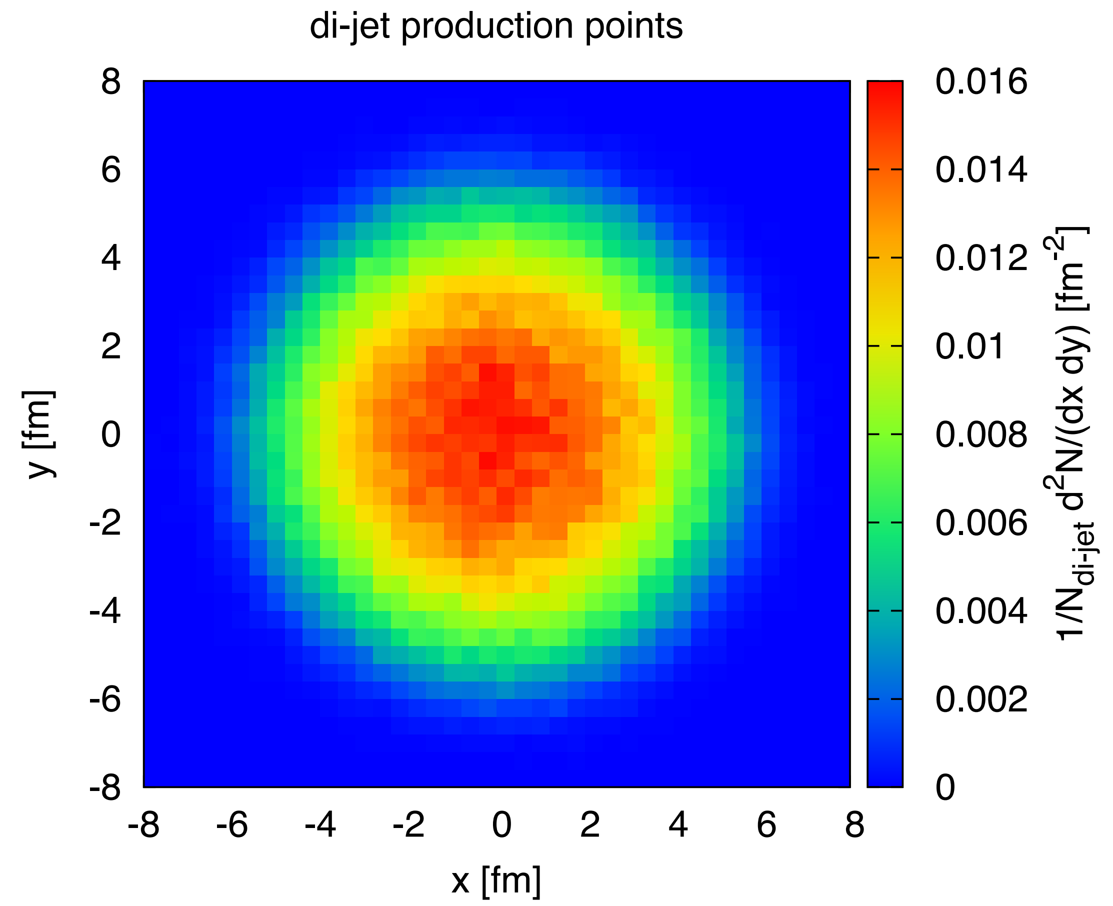


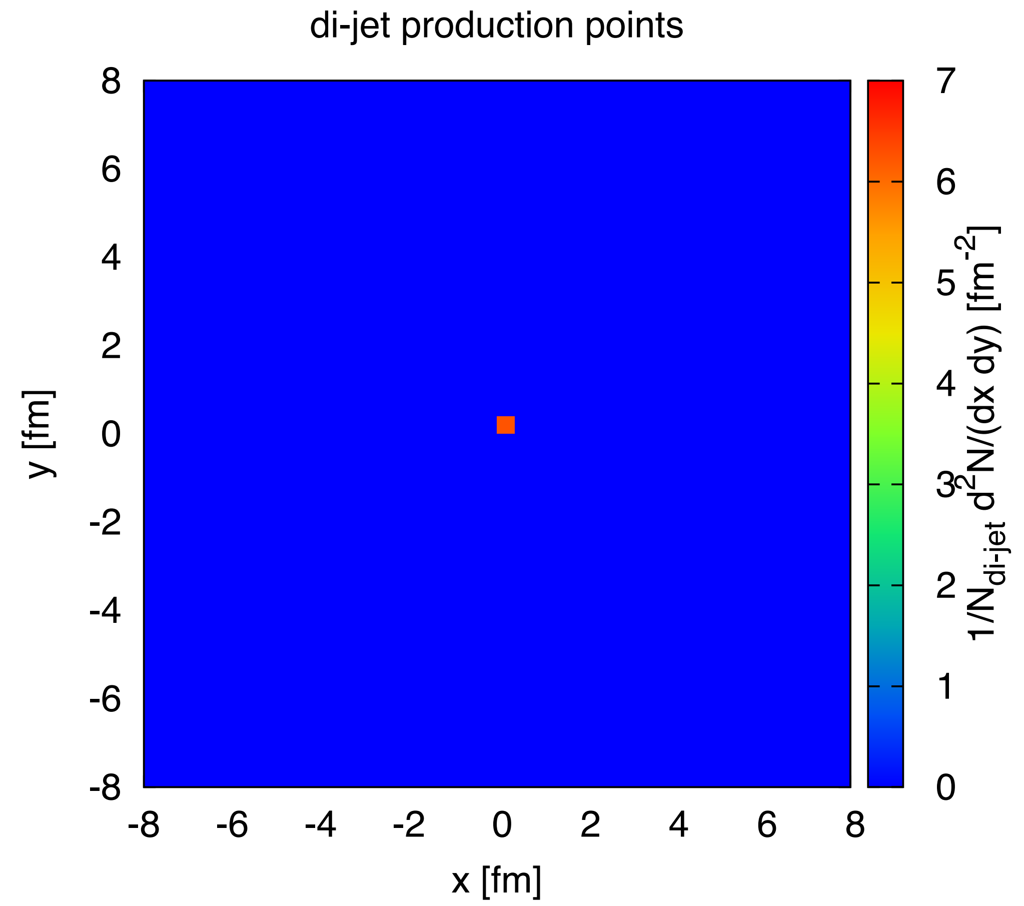


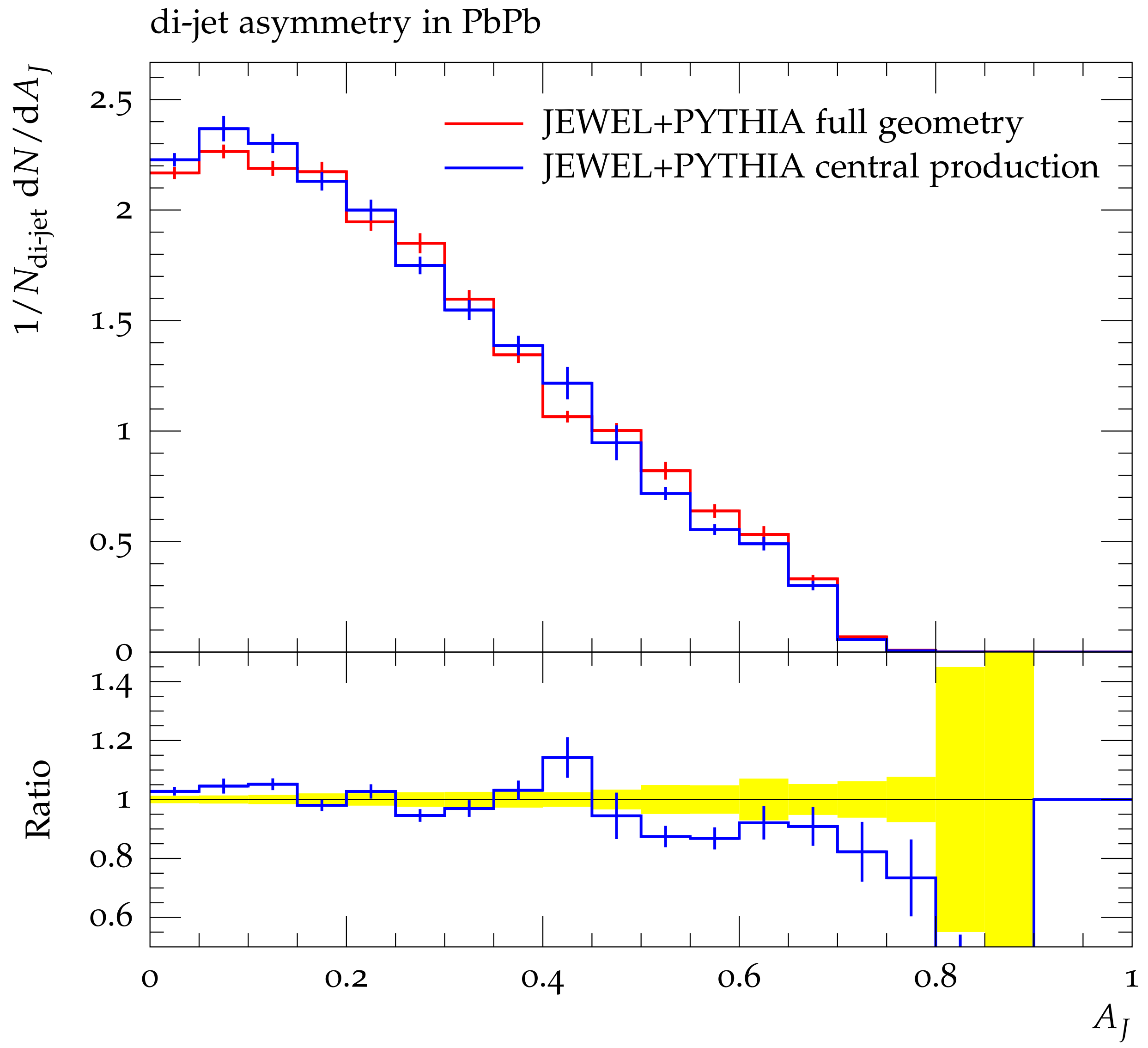
$$A_J = \frac{p_{\perp,1} - p_{\perp,2}}{p_{\perp,1} + p_{\perp,2}}$$

AJ CAN BE GENERATED FOR EQUAL PATH LENGTHS

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





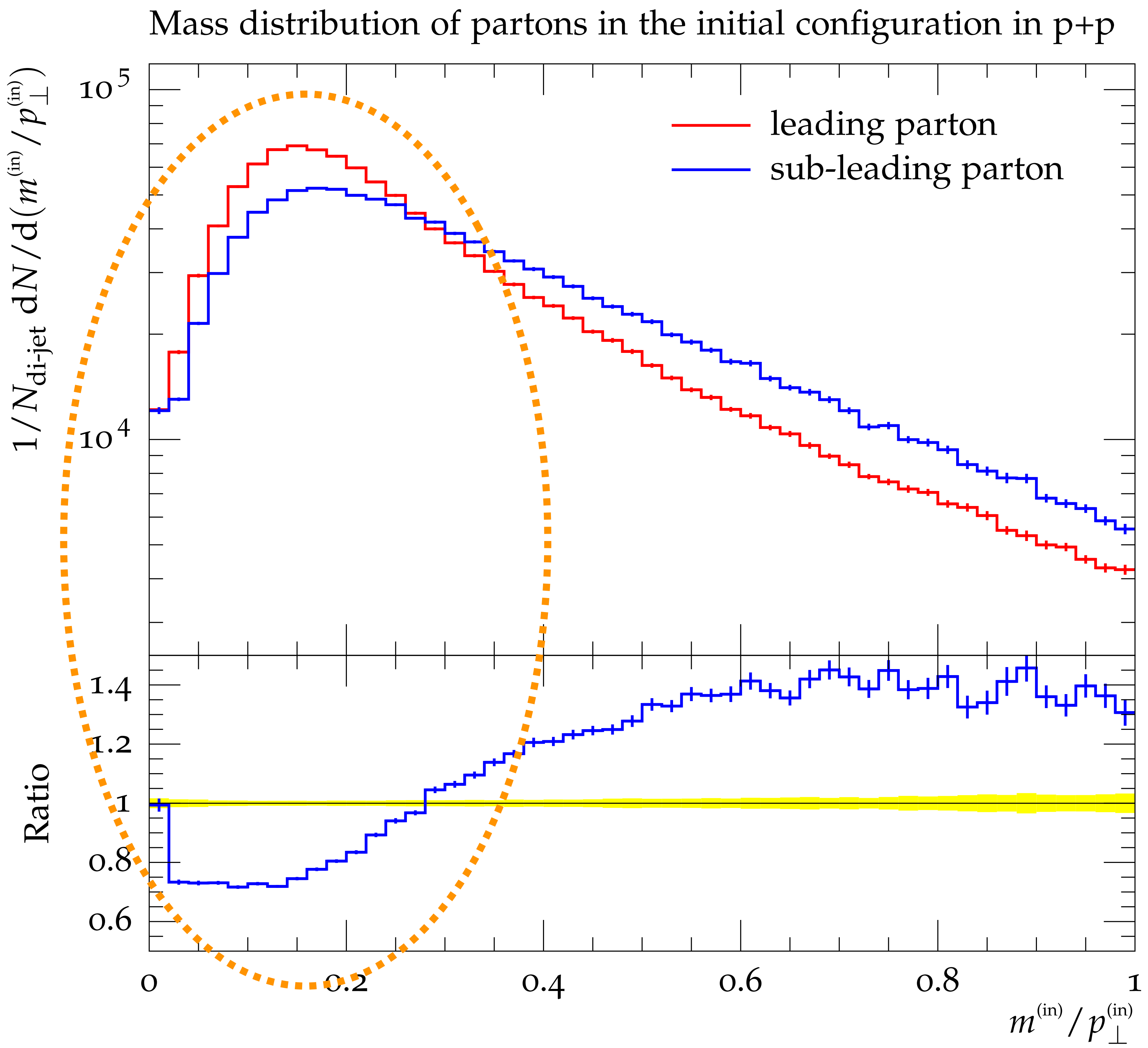


$$A_J = \frac{p_{\perp,1} - p_{\perp,2}}{p_{\perp,1} + p_{\perp,2}}$$

- di-jet event sample with no difference in path-length have AJ 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 AJ distribution

JET ENERGY LOSS DOMINATED BY FLUCTUATIONS

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

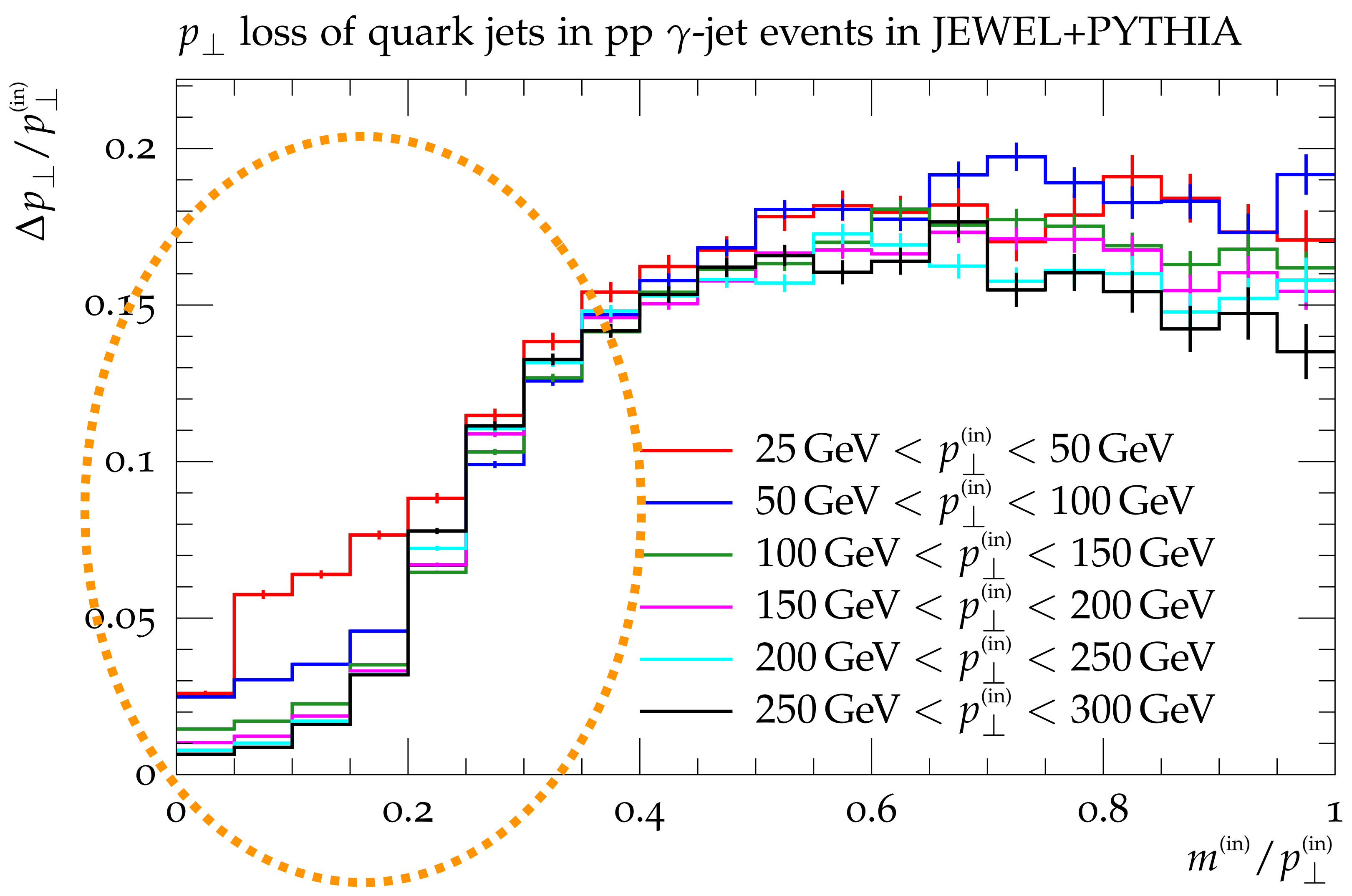


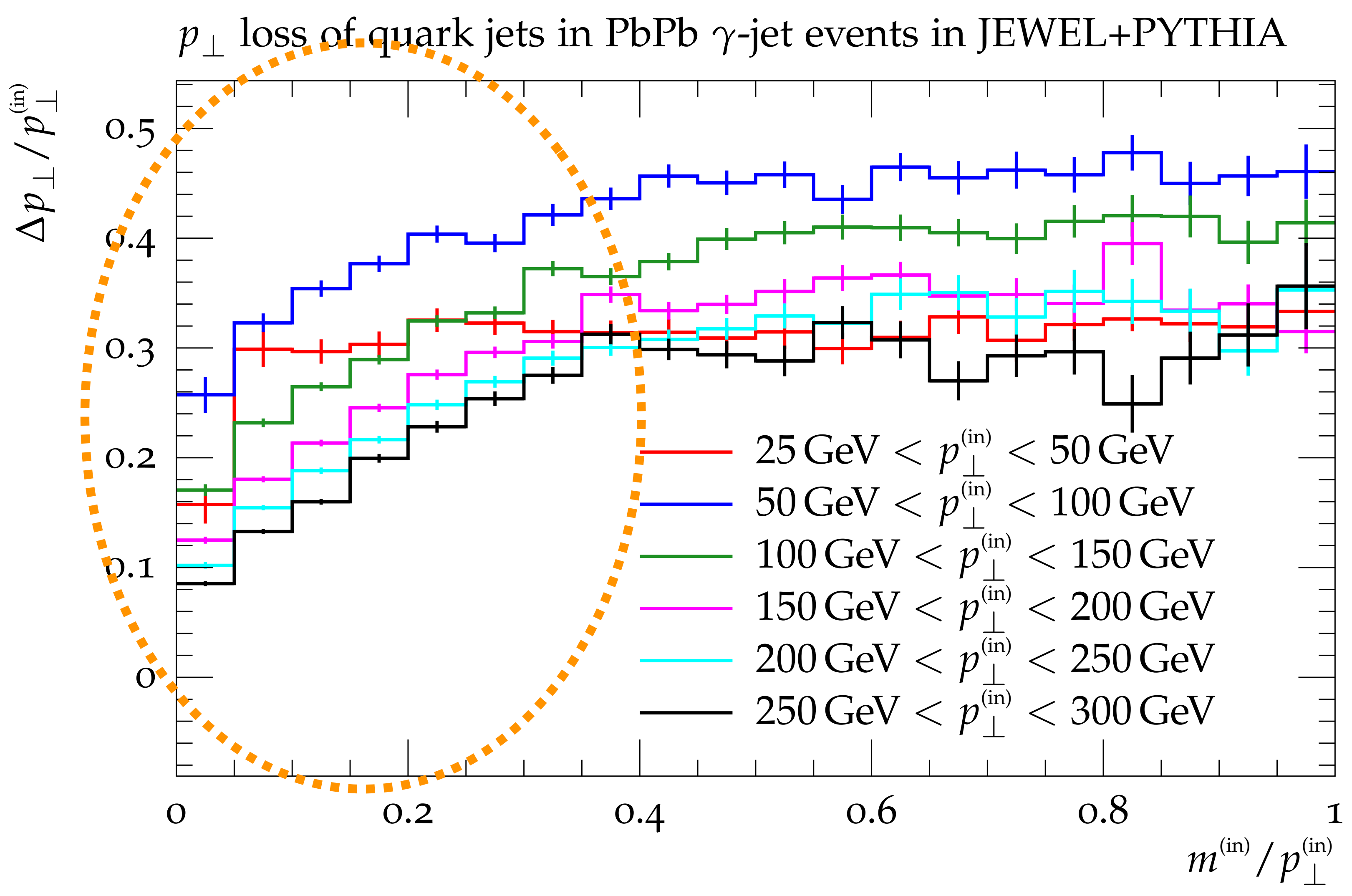
- not all same-energy jets are equal
  - number of constituents driven by initial mass-to-p$_t$ ratio
  - more populated jets have larger number of energy loss candidates

Escobedo, Iancu 1609.06104 [hep-ph] for related work

JET ENERGY LOSS DOMINATED BY FLUCTUATIONS

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





- transverse momentum loss largely determined by mass-to-p_t ratio of initial configuration in both pp and AA
  - strong dependence for bulk of distribution
  - saturation at high ratio result from reconstruction cone radius [large angle structure beyond R] :: will shift to higher values for higher R
  - effect of medium induced fluctuations seen in flattening for low pt jets

• same conclusion for holographic ‘jets’ •

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

A VERY IMPORTANT LESSON AND REASONABLE QUESTION

- quenched jets share most of their features with vacuum jets
    - vacuum parton branching is a drastic process through which highly virtual partons quickly relax their virtuality down to the hadronic scale
    - QGP induced modifications are comparatively small effects
        - however, modifications have been clearly measured and mostly theoretically described

- can quenched and unquenched [vacuum or those that escaped QGP without significant modification] be distinguished on a jet-by-jet basis ?
    - can a machine learn to tell them apart with minimal theoretical input?

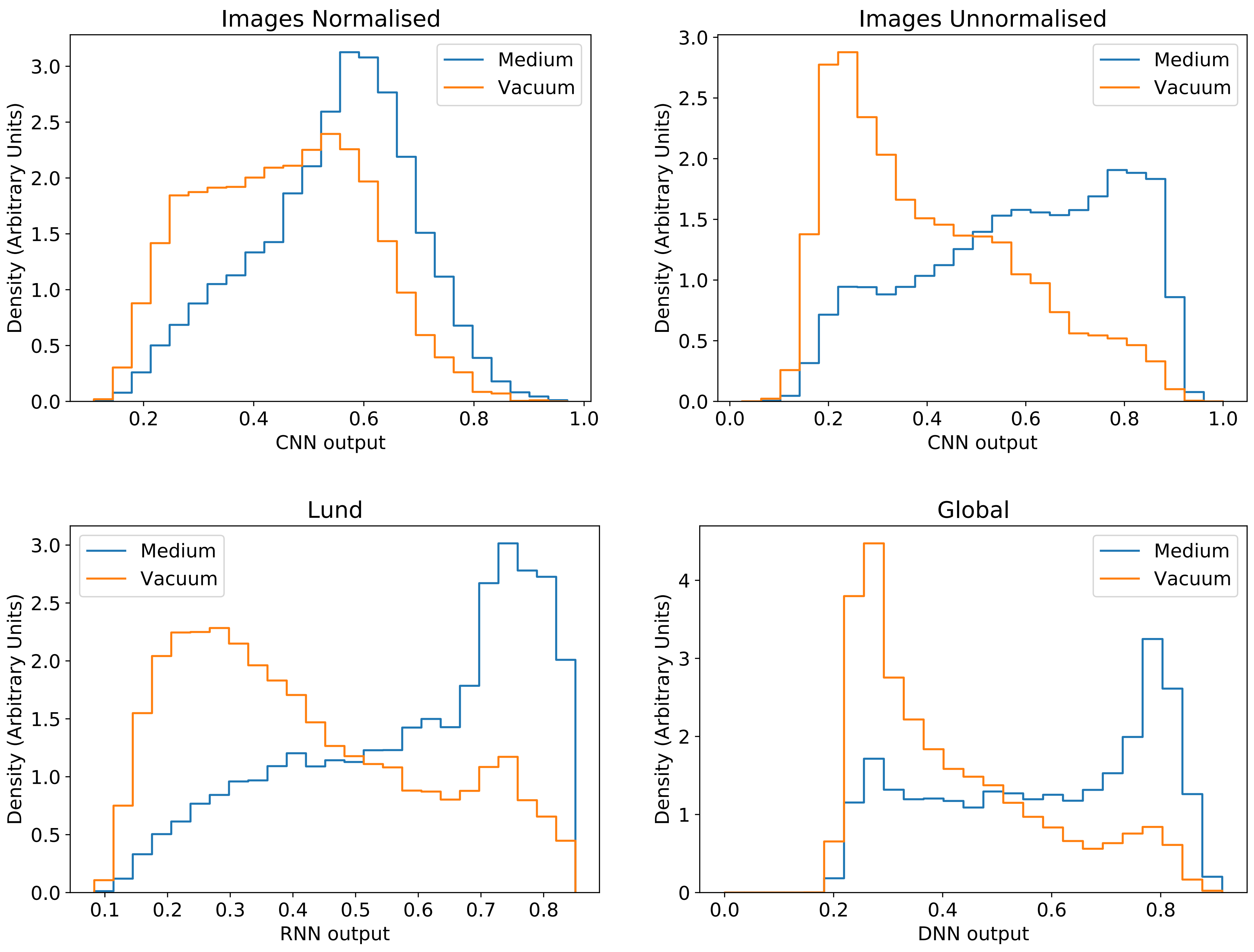
CLASSIFICATION OF QUENCHED JETS

Apolinário, Castro, Crispim Romão, Milhano, Pedro, Peres, :: *JHEP* 11 (2021) 219

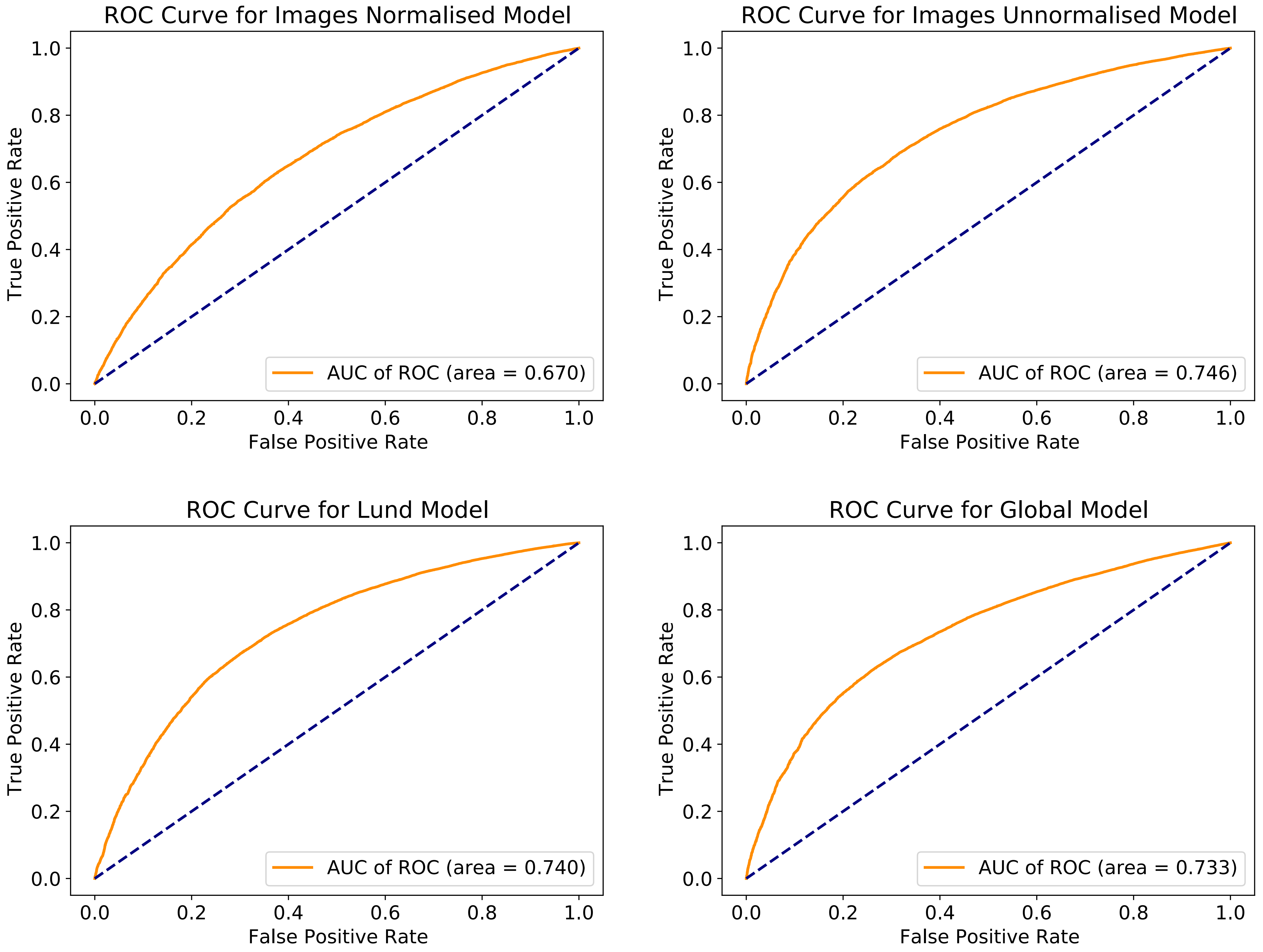
- jet representations with varying theoretical input for different ML/DL architectures
  - jet images :: 2-channel [p_T and multiplicity] calorimetric images in a grid centred on jet axis :: Convolutional Neural Network (CNN) :: channels both normalized and unnormalized
  - Lund plance coordinates :: (kT, ΔR) for primary branch of C/A [angular ordered] declustering of jet :: Recurrent Neural Network (RNN)
  - Tabular data :: global (pT and multiplicity) for each jet :: Dense Neural Network (DNN)
    - benchmark case with minimal information

CLASSIFICATION OF QUENCHED JETS

Apolinário, Castro, Crispim Romão, Milhano, Pedro, Peres, :: *JHEP* 11 (2021) 219



network outputs [discriminant]

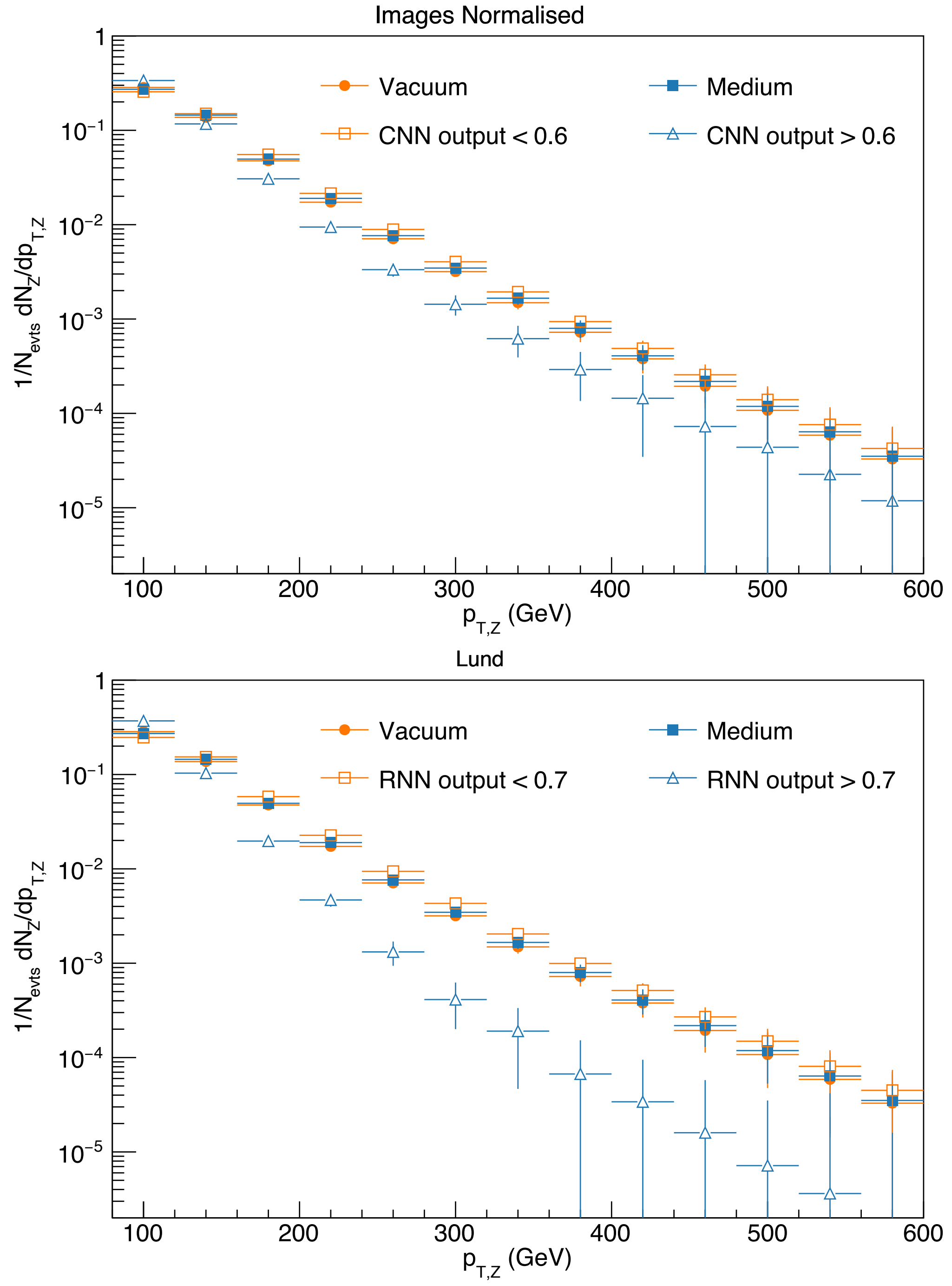


Model	$p_{T,jet}$ >30 GeV	$p_{T,jet}$ >125 GeV
Normalised jet images CNN	0.67	0.65
Unnormalised jet images CNN	0.75	0.68
Lund sequences RNN	0.74	0.69
Global DNN	0.73	0.64

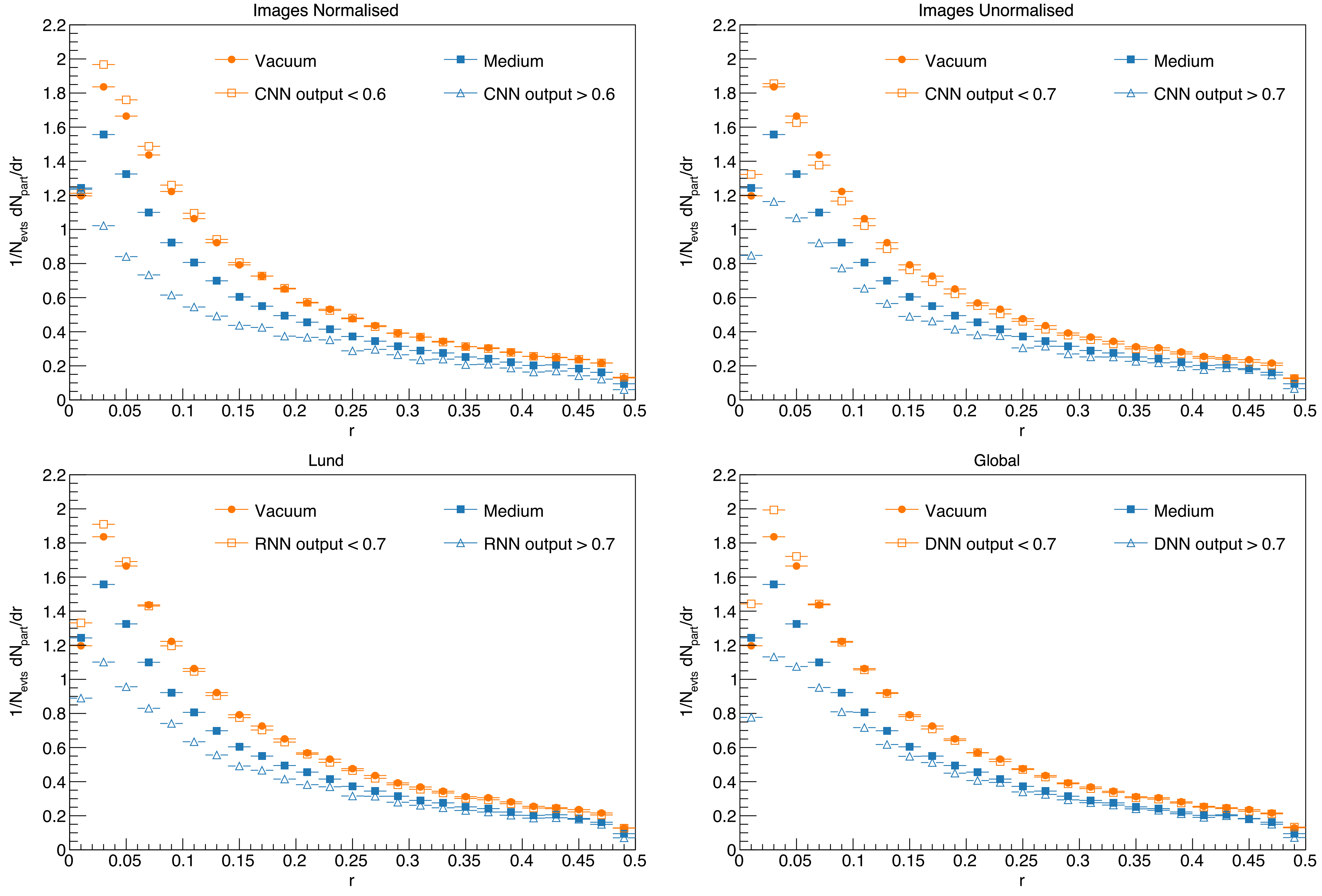
performance

CLASSIFICATION OF QUENCHED JETS :: RECONSTRUCTED

Apolinário, Castro, Crispim Romão, Milhano, Pedro, Peres, :: *JHEP* 11 (2021) 219



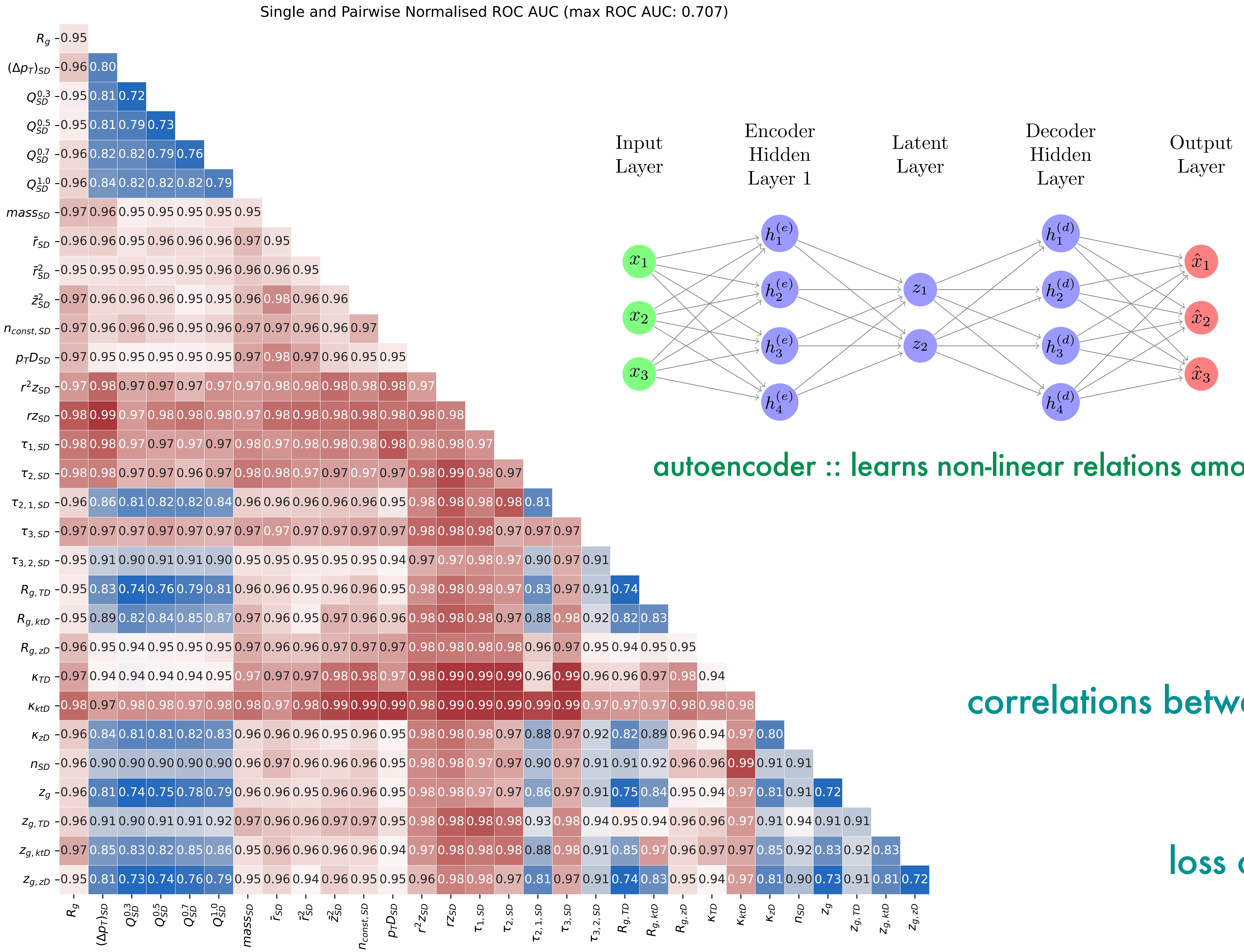
transverse momentum spectrum



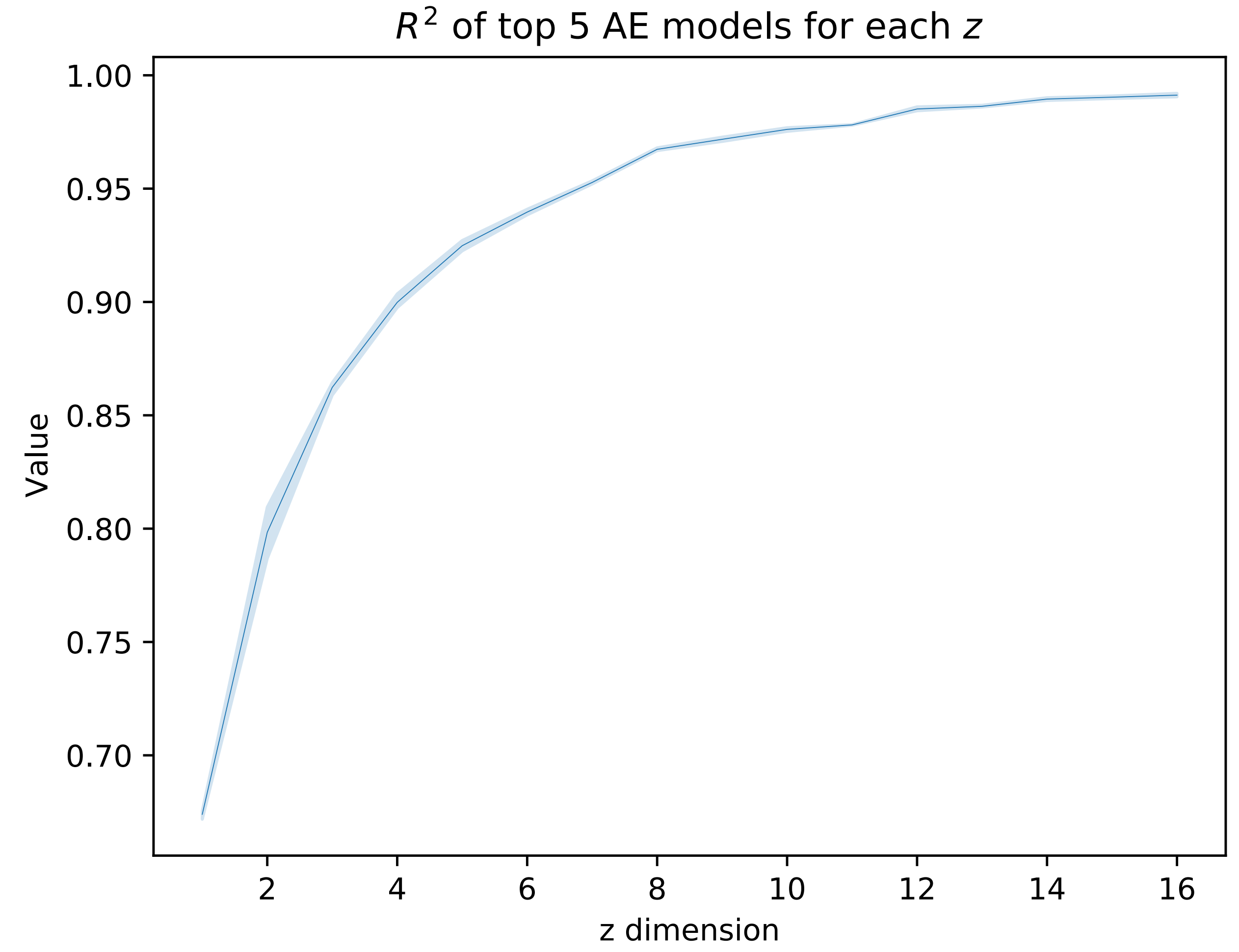
jet profile

HOW MANY OBSERVABLES IS ENOUGH?

Crispim Romão, Milhano, van Leeuwen, :: *in preparation*



autoencoder :: learns non-linear relations amongst inputs



correlations between observables encode a wealth of information

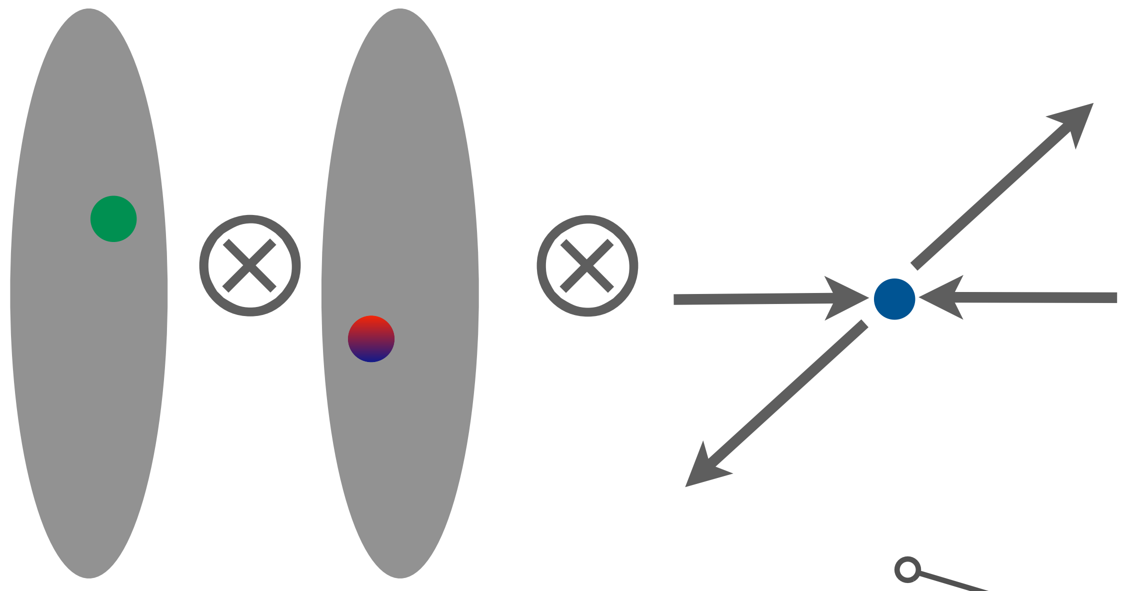
loss of predictive power signals sensitivity to QGP effects

FUTURE DIRECTIONS

- importance QGP response
  - see equilibration with QGP at work [same physics as emergence of QGP]
  - intrinsic property of quenched jets :: unfortunately shares many features with uncorrelated background

- jet sub-structure as probing tool of QGP dynamics
  - time structure of jet as clock for direct measurement of time evolution of QGP

A JET IN QGP :: HARD PRODUCTION



nuclear structure sufficiently
constrained in relevant
kinematical domain

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

all will be easy [denial]

A JET IN QGP :: PARTON SHOWER

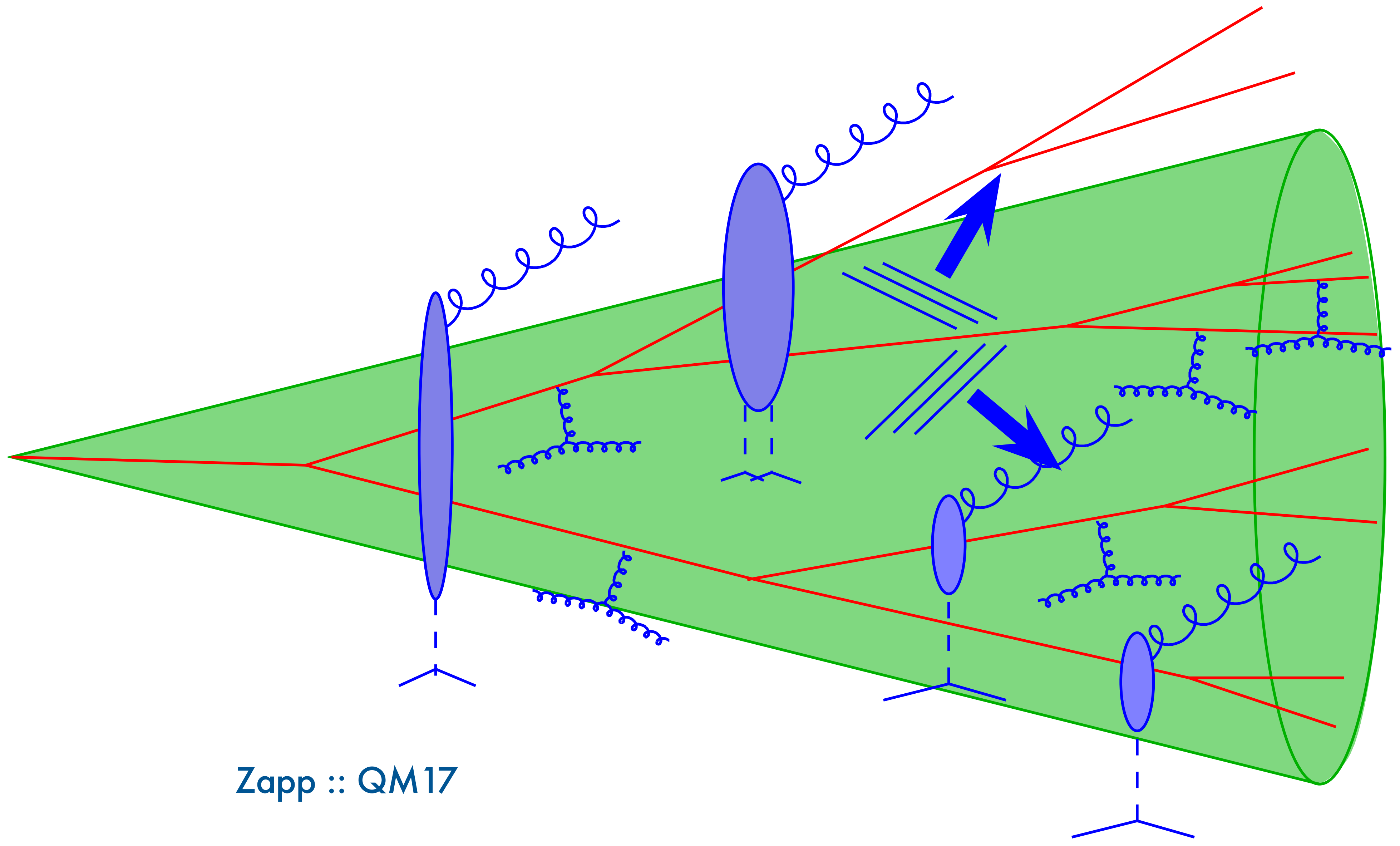
shower constituents exchange [soft] 4-momentum and colour with QGP :: shower modified into interleaved vacuum+induced shower :: modified coherence properties :: single parton intuition and results do not carry through trivially :: multi-scale problem :: some shower constituents de-correlate :: some QGP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

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

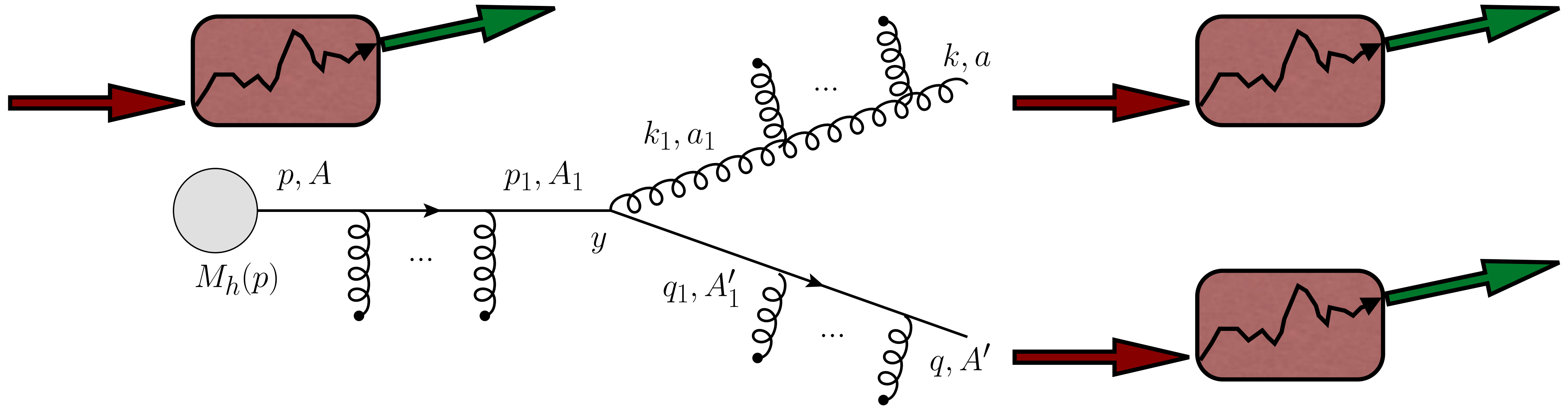
Mehtar-Tani, Tywoniuk, Salgado :: many

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

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



Zapp :: QM17

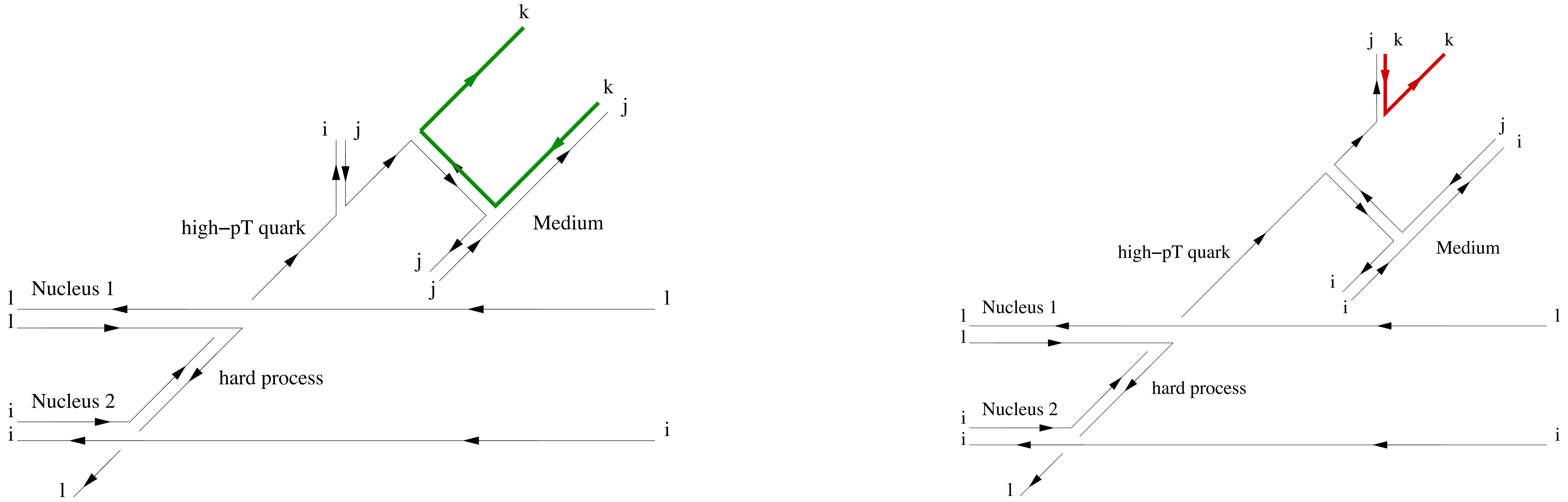


this is tough [anger]

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

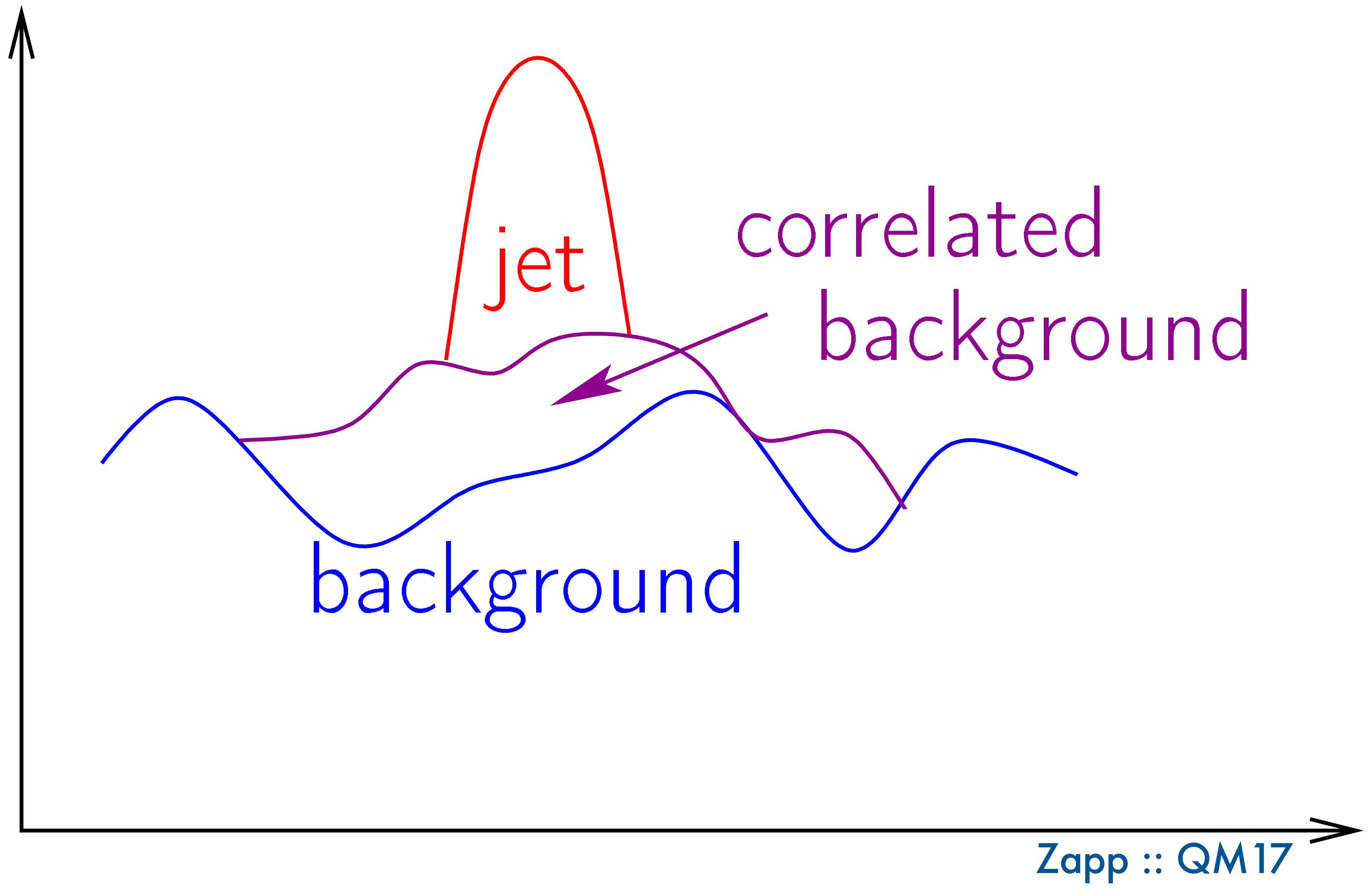


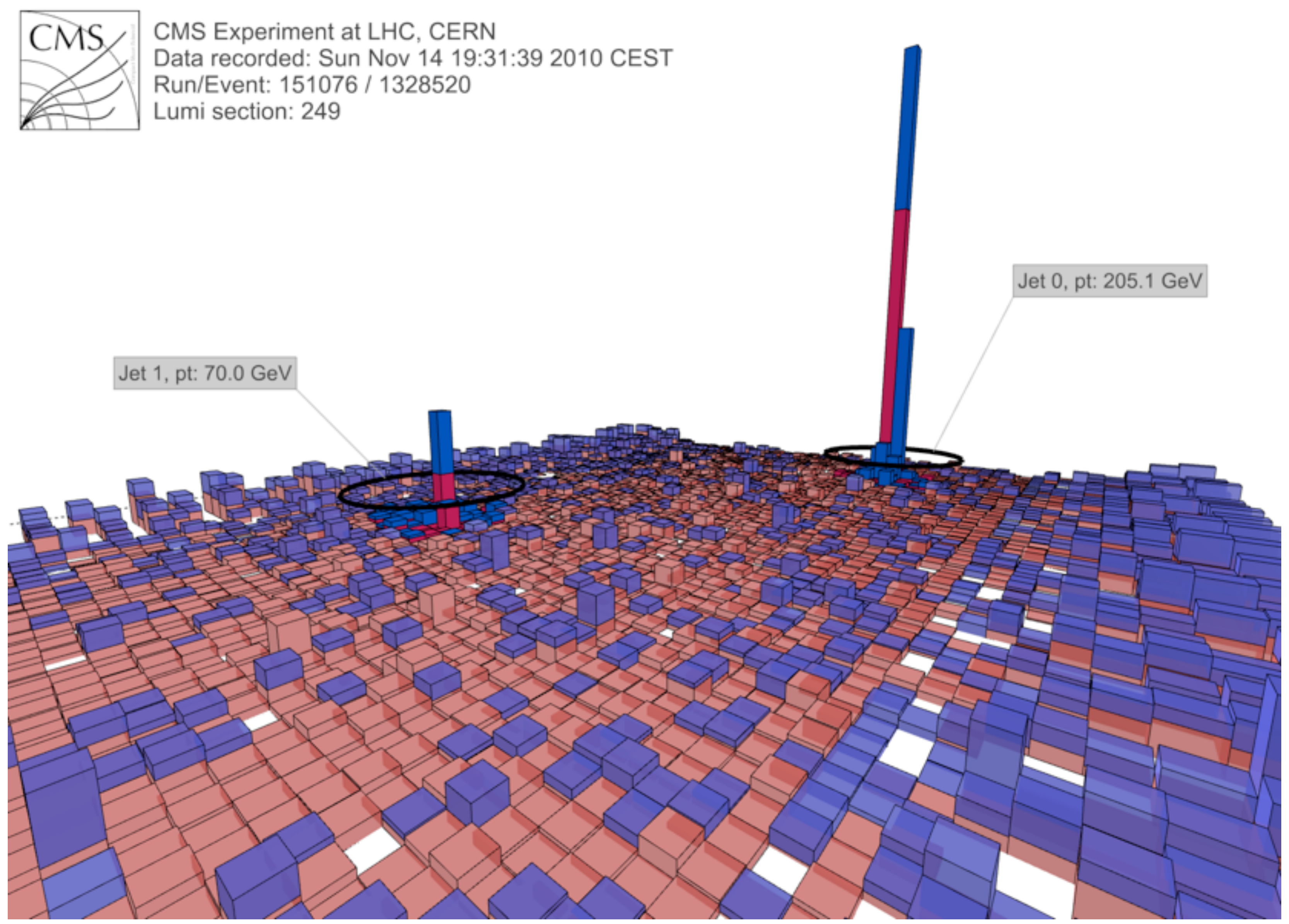
jet-QGP interaction modifies color connections in the jet and thus hadronization pattern
[in any reasonable effective model]
can learn about hadronization modifications at an EIC

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 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

THE FIVE STAGES OF HEAVY ION JET PHENOMENOLOGY

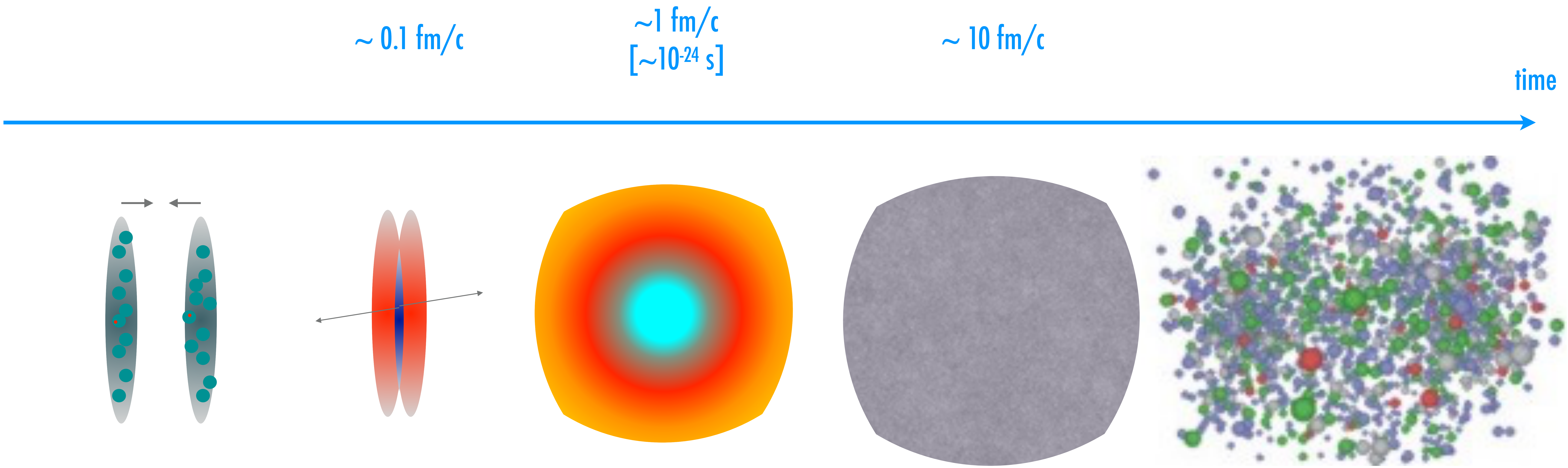
denial :: anger :: bargaining :: depression :: acceptance

Backups

probing QGP time evolution

Apolinário, Milhano, Salam, Salgado :: 1711.03150 [hep-ph]

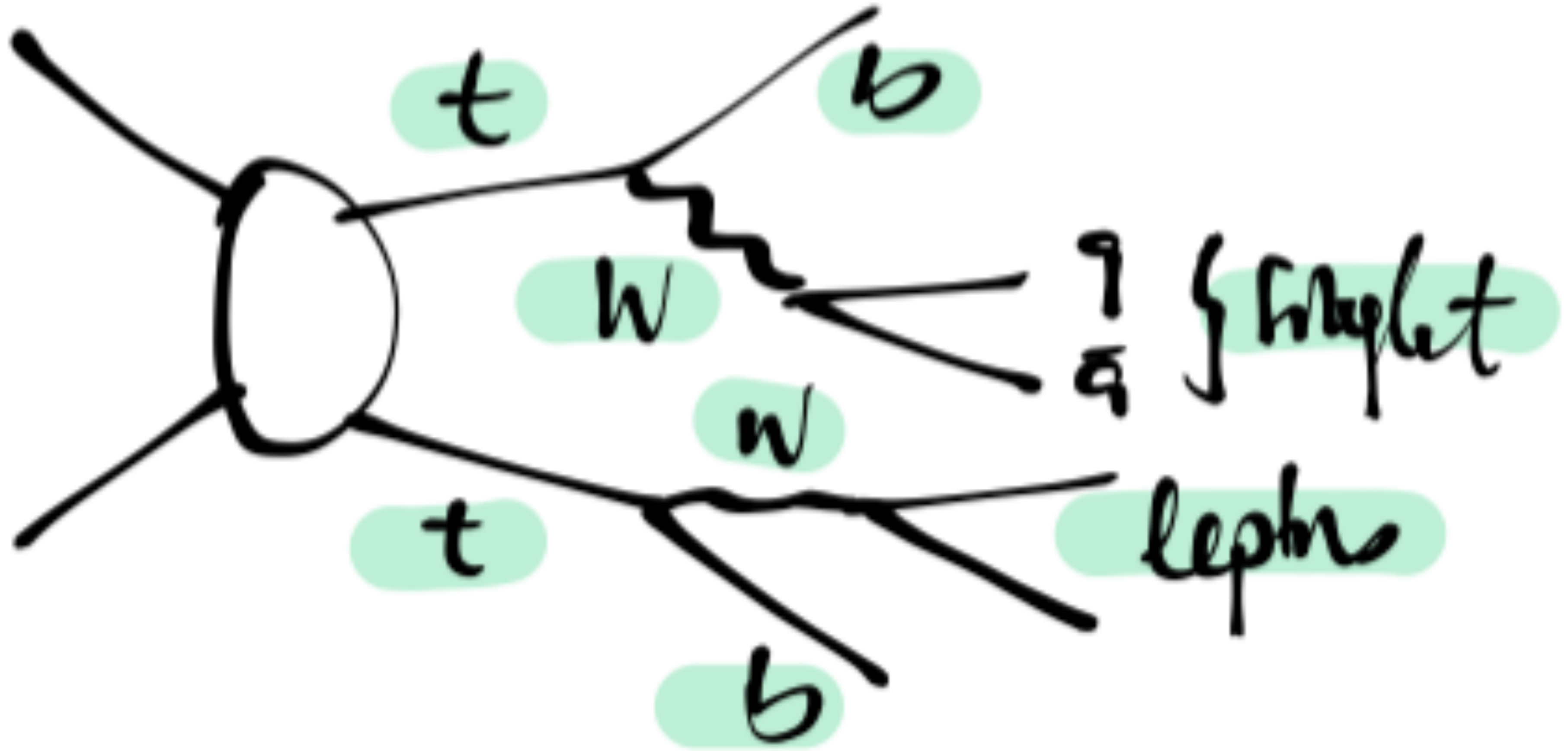
PROBING QGP



- 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 $\tau_{top} \simeq 0.15\,\mathrm{fm/c}$ and $\tau_W \simeq 0.09\,\mathrm{fm/c}$
- 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]

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

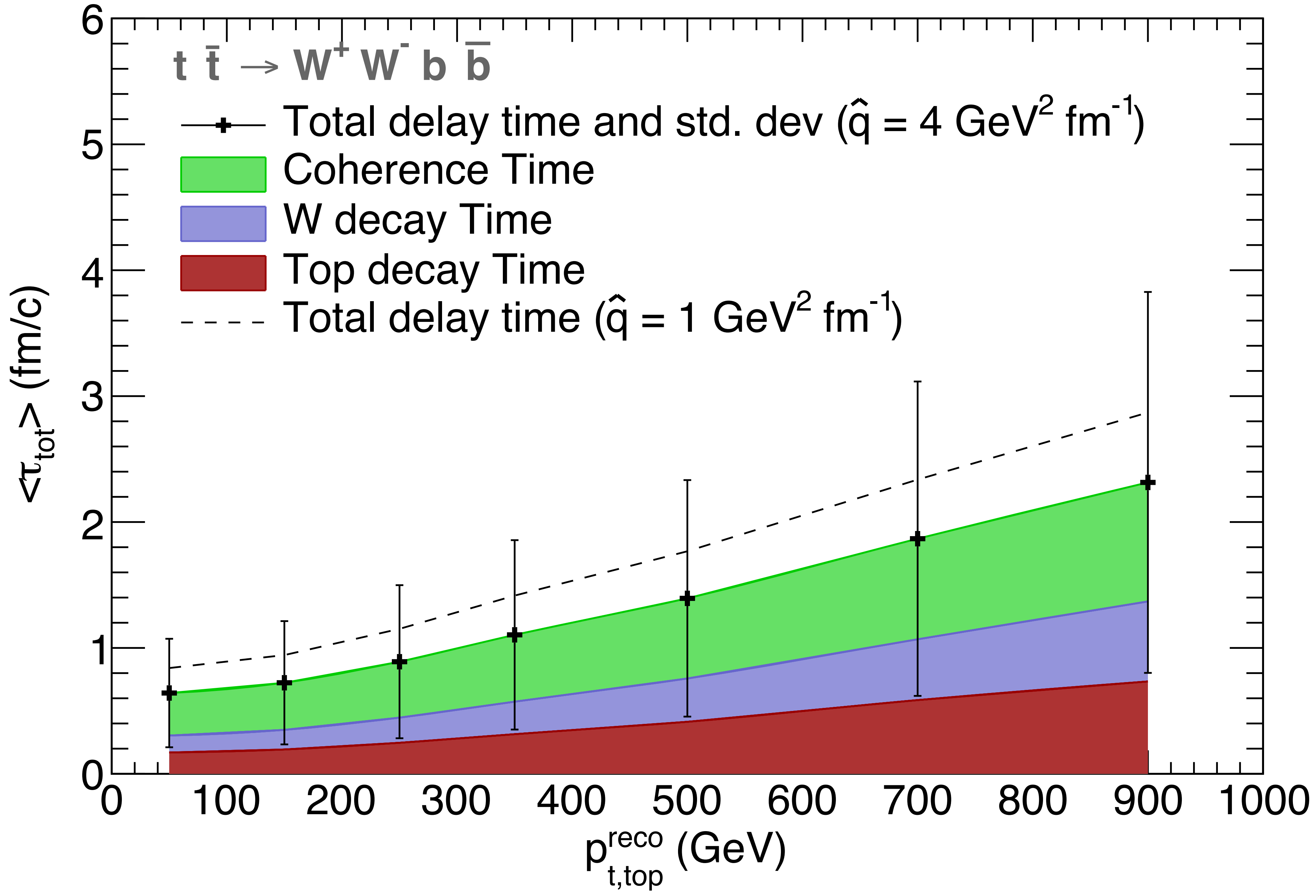
transverse boost

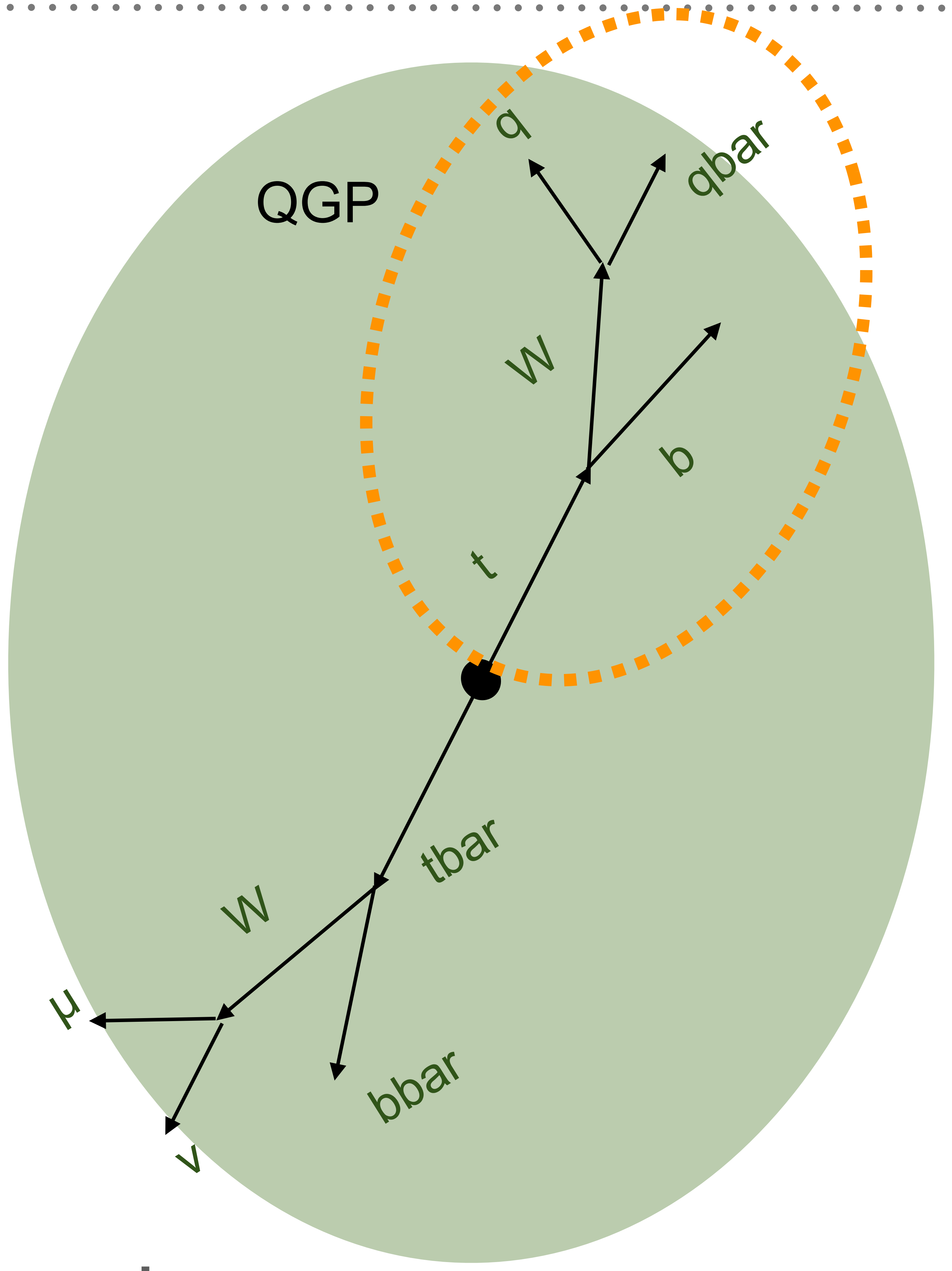
$$\gamma_{t,X} = (p^2_{t,X}/m^2_X + 1)^{\frac{1}{2}}$$

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

TIME DELAYS

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

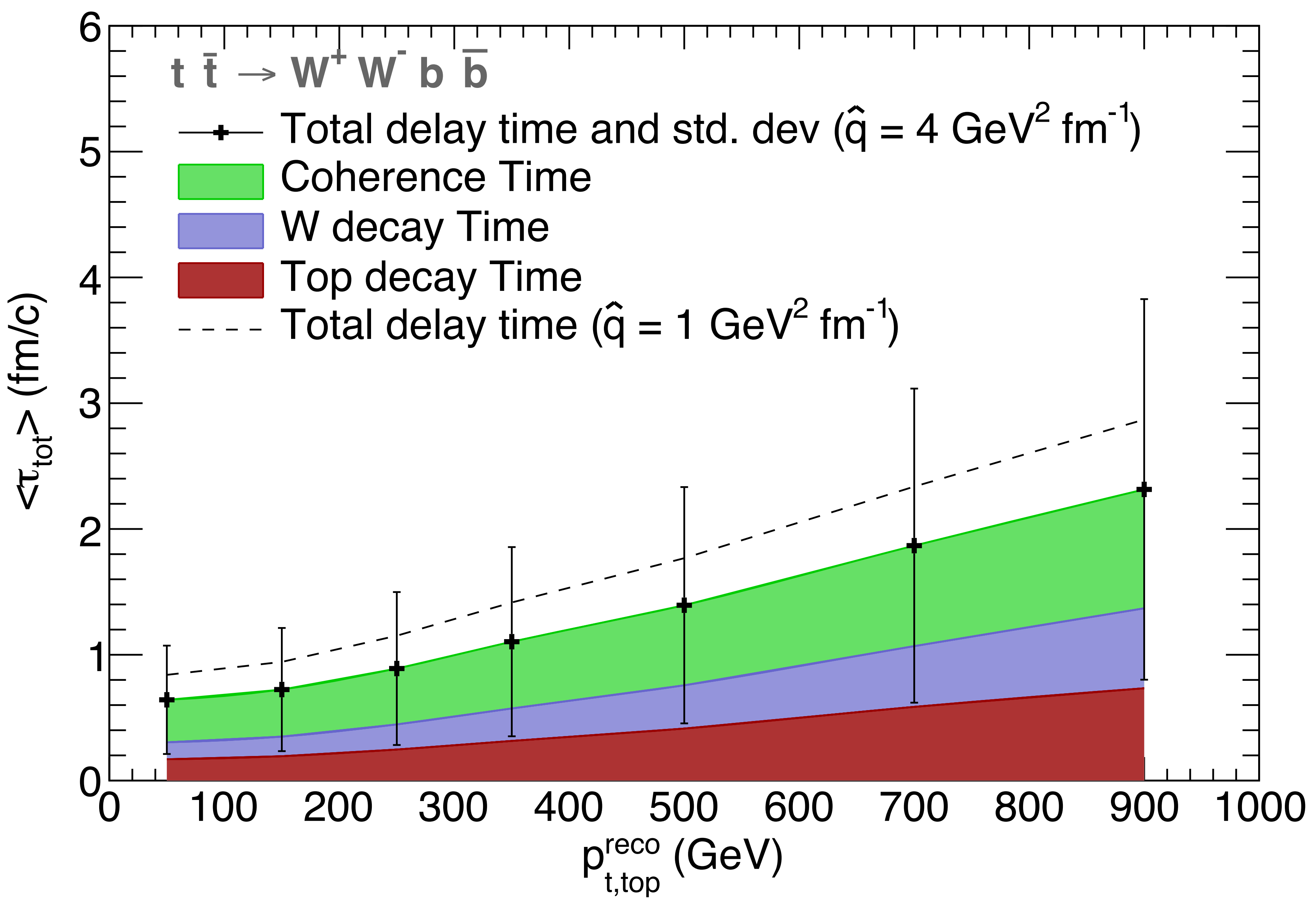


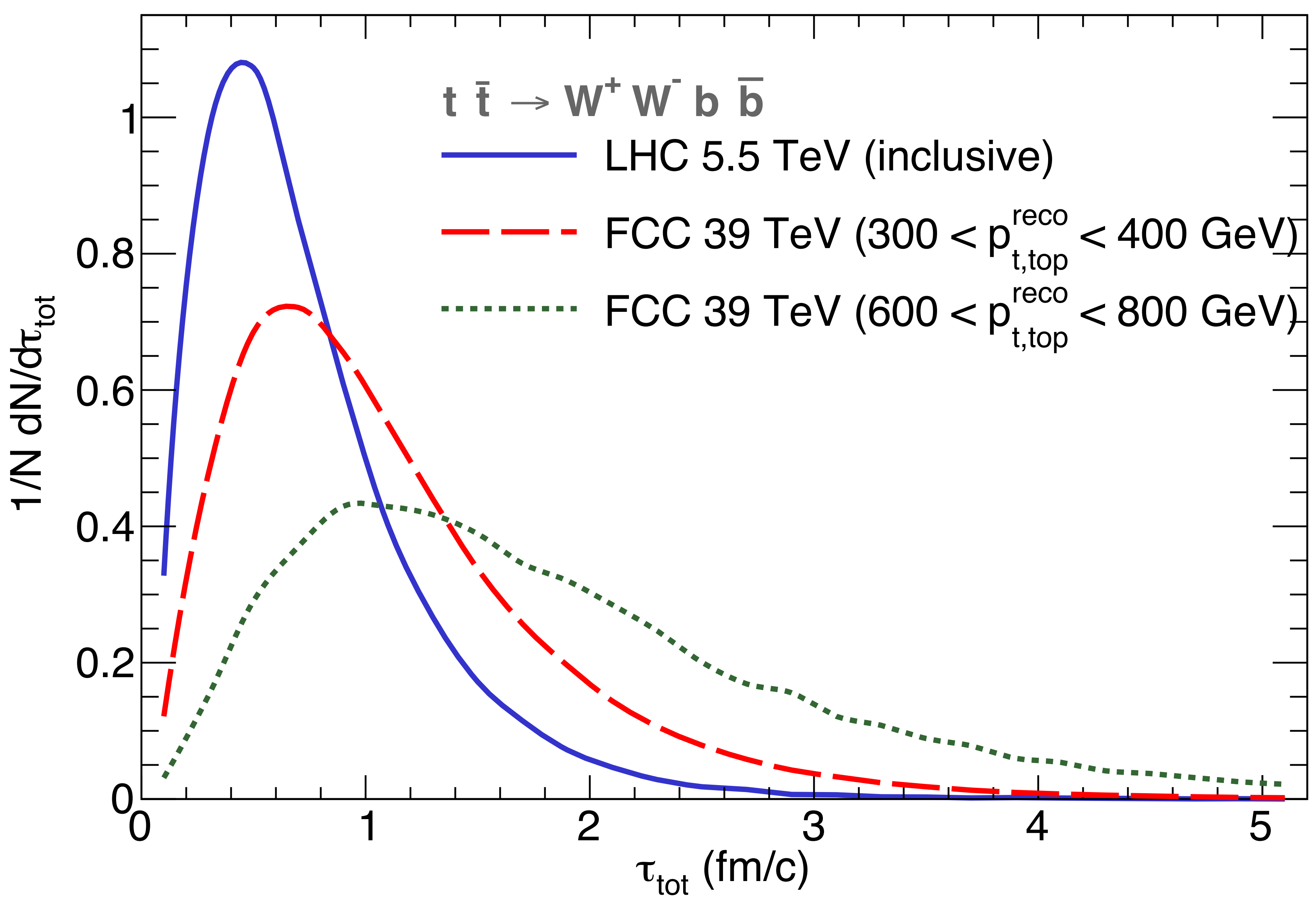


- τ_{tot} correlated with top p_t
- dispersion from considering random exponential distribution for each component
- weak dependence on $\hat{q}$

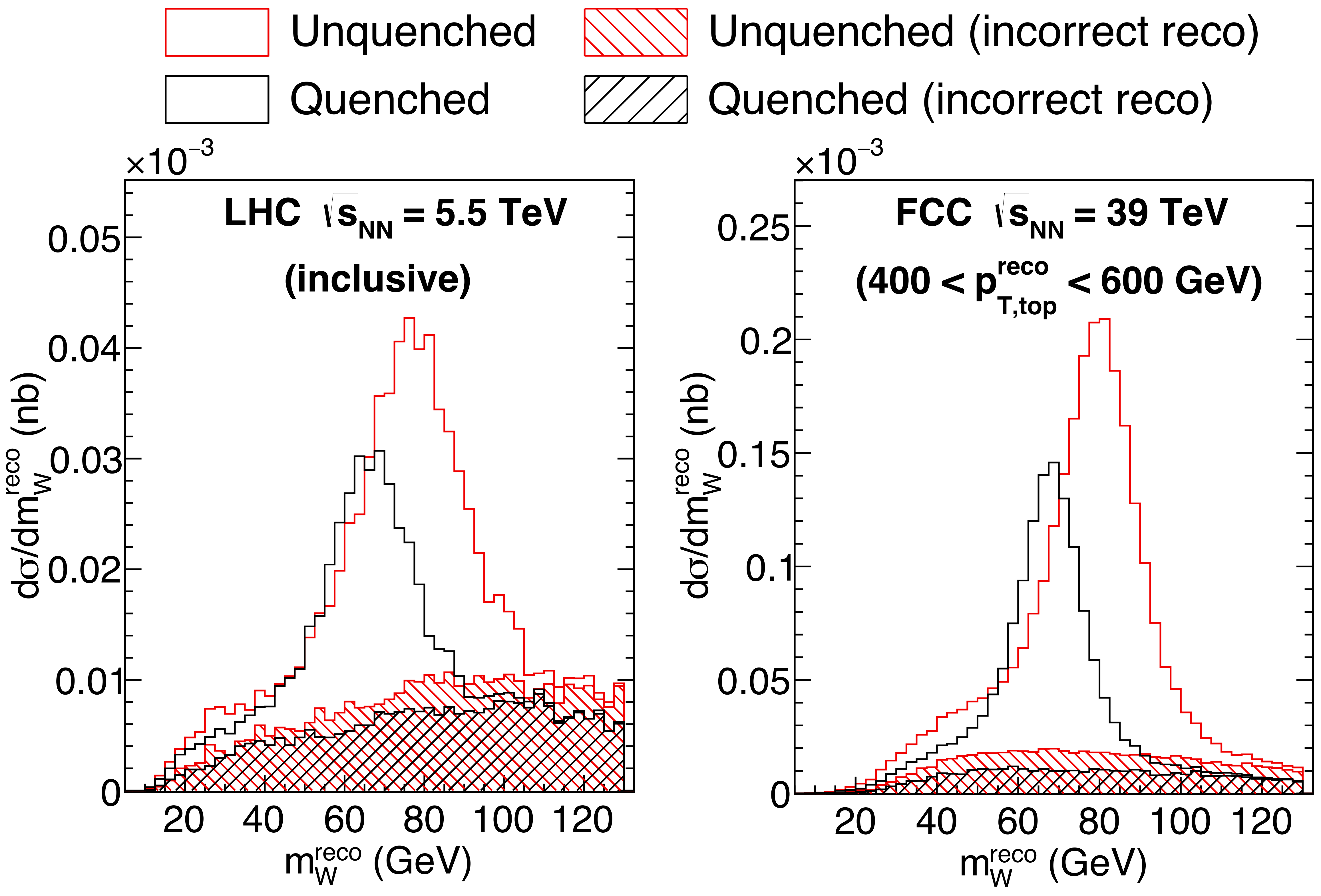
PROBING QGP TIME EVOLUTION

- 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

ANALYSIS

- semi-muonic t-tbar only [NLO+showering]
- hadron-level, no underlying event
- expected number of events in HI

$$n(f) \simeq \mathscr{L}_{AA}\, \sigma_{pp}^{t\bar{t}} A^2 c(f) \qquad\qquad c(0-10\%) \simeq 0.42$$

- not embedded in QGP :: introduce momentum re-scaling factor to mimic all sources of fluctuations particle-by-particle
  - [embedding + background subtraction + detector resolution + quenching dynamics]

$$\left(1 + r\sigma_{p_t}/\sqrt{p_{t,i} + 1\,\mathrm{GeV}}\right)$$

r is particle-by-particle Gaussian distributed random

Analysis

- baselines
  - pp :: no quenching
  - AA full quenching :: rescale all particle momenta by

$$\mathcal{Q}_0 = 0.85$$

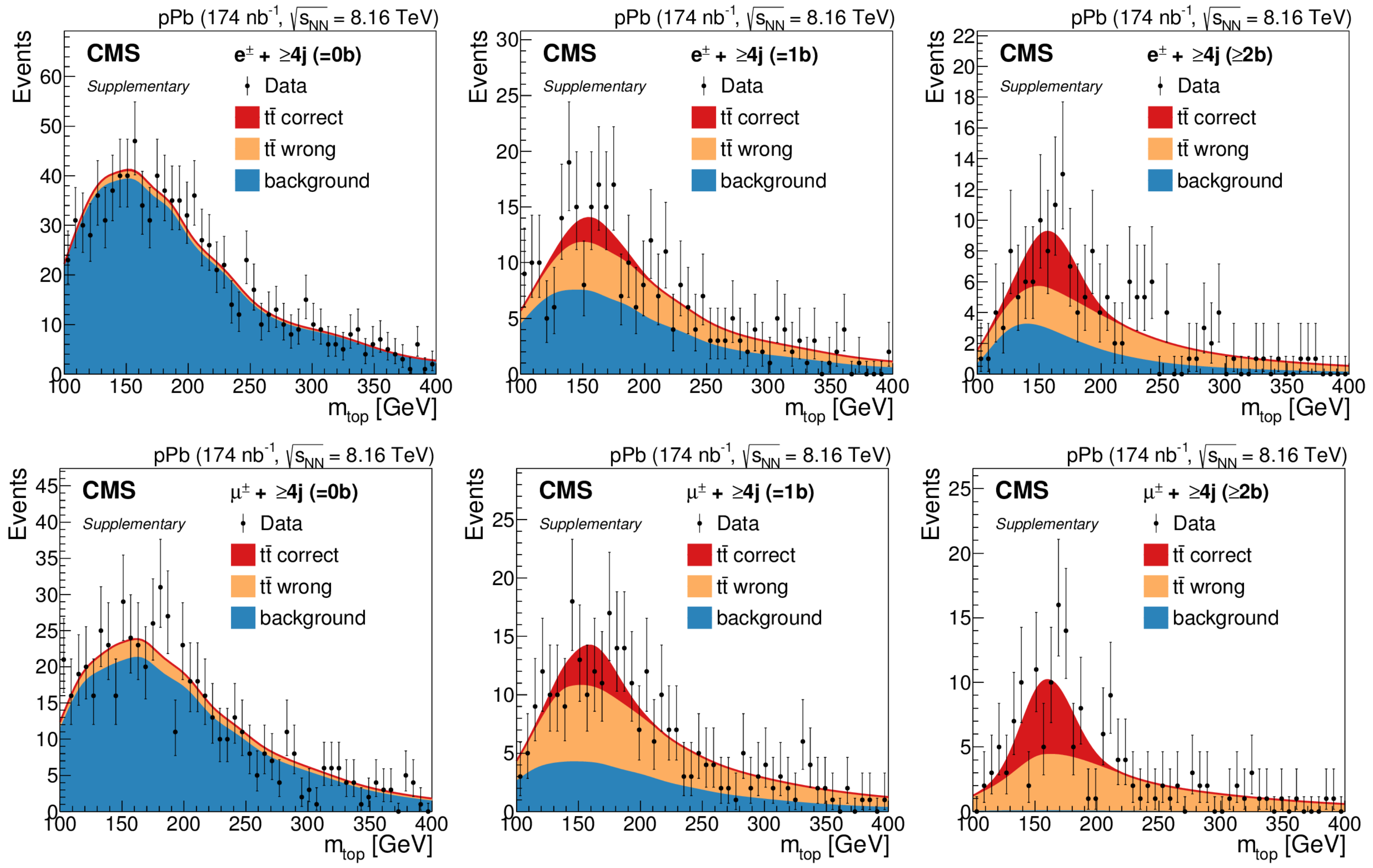
- particles from W hadronic decay scaled by

$$\mathcal{Q}(\tau_{tot}) = 1 \; + \; (\mathcal{Q}_0 - 1)\frac{\tau_m - \tau_{tot}}{\tau_m}\,\Theta(\tau_m - \tau_{tot})$$

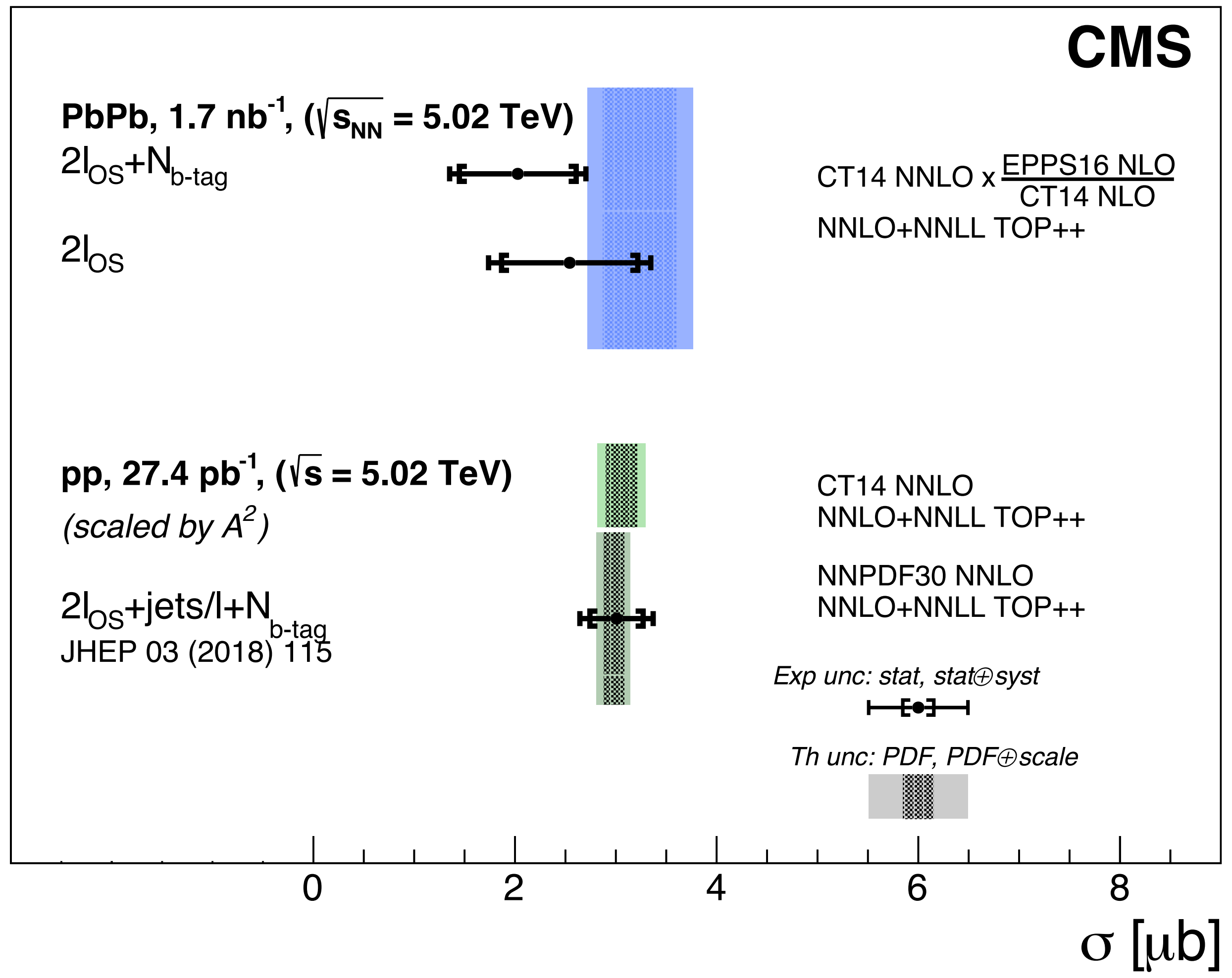
- event tagging requires
  - muon + two b-tagged jets + at least two non b-tagged jets [details provided on request]

FEASIBILITY

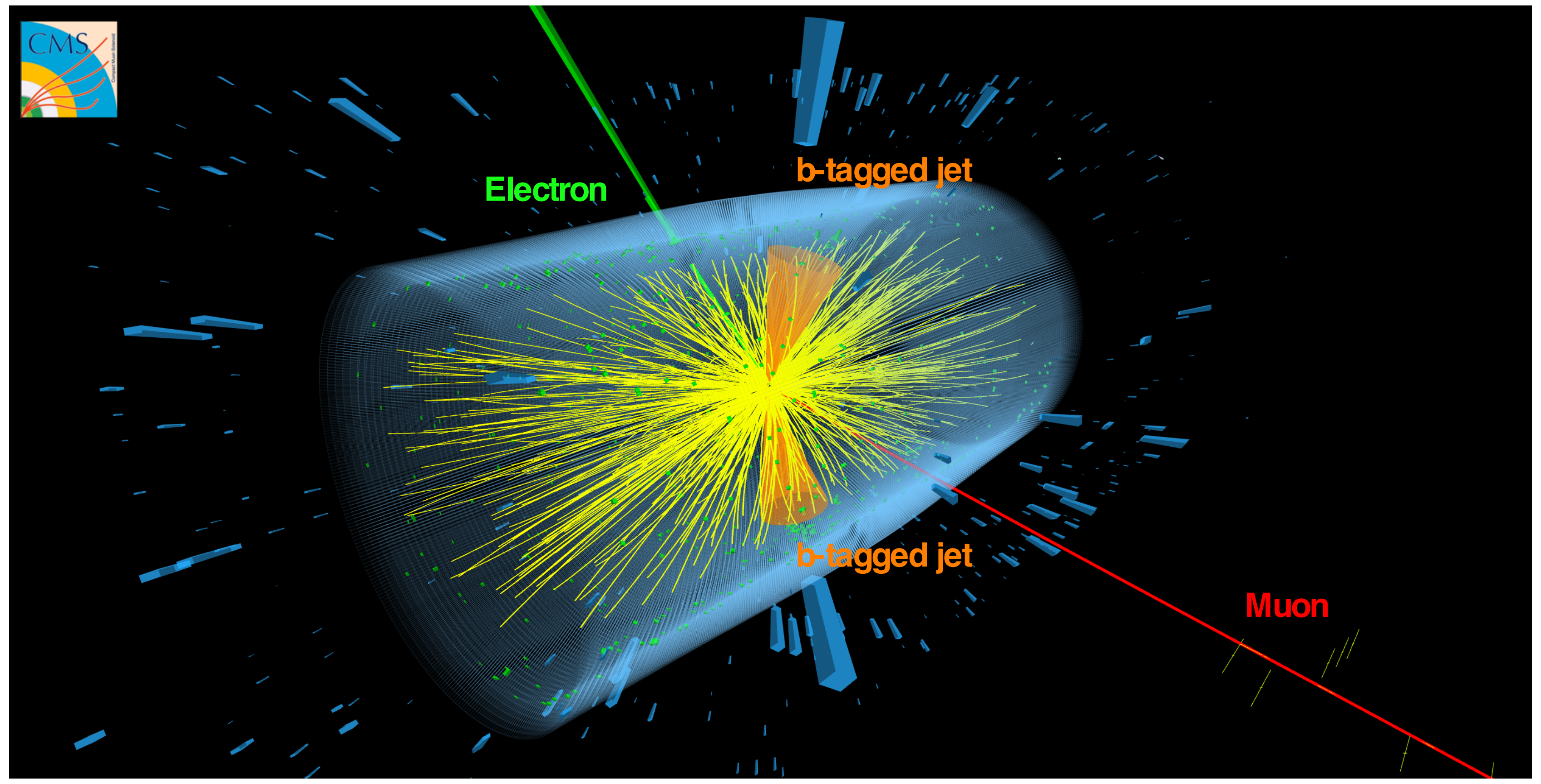
semi-leptonic channel measured in pA and leptonic in AA



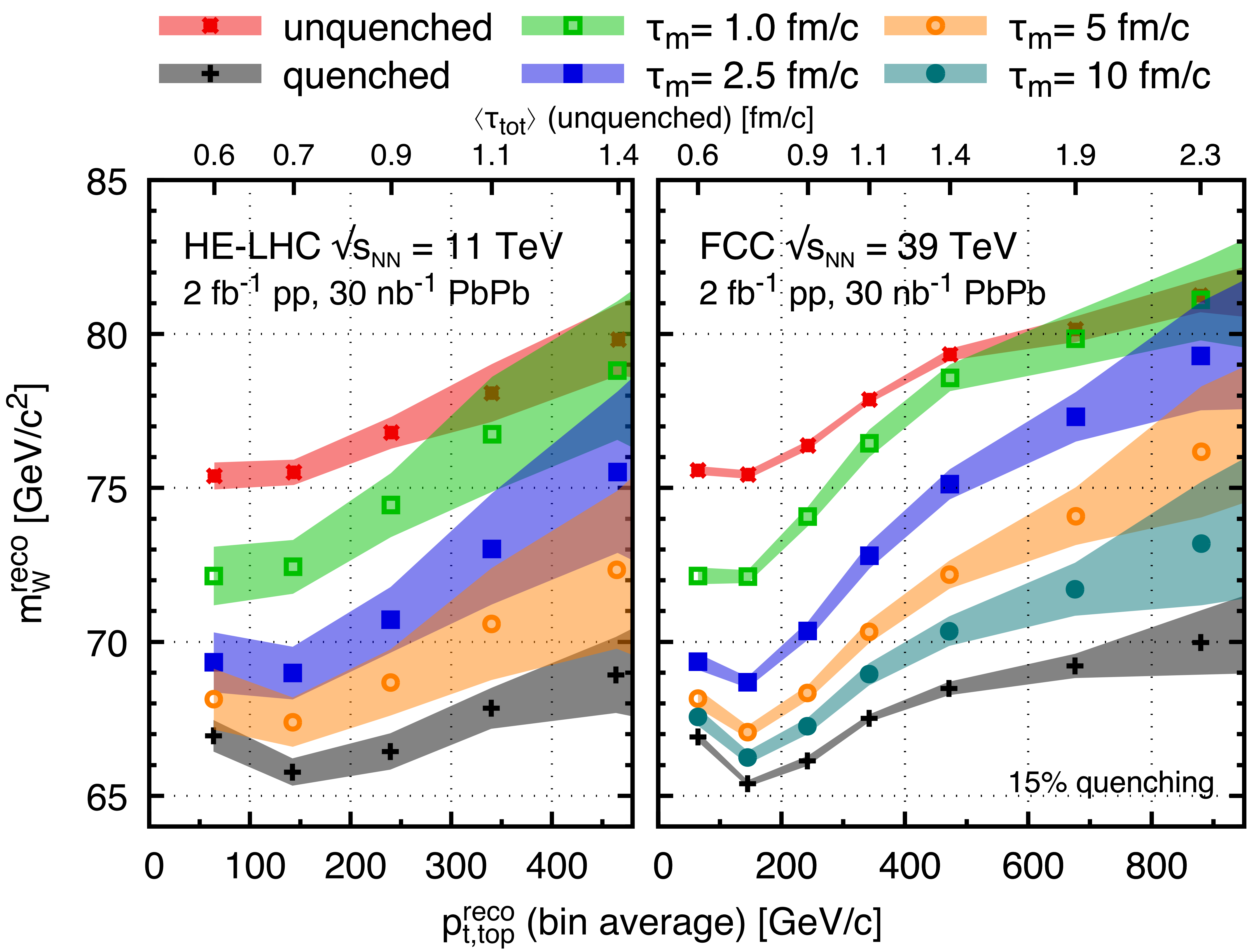
CMS :: 1709.07411[hep-ex] PRL119 (2017) 242001



CMS :: 2006.11110 [hep-ex]



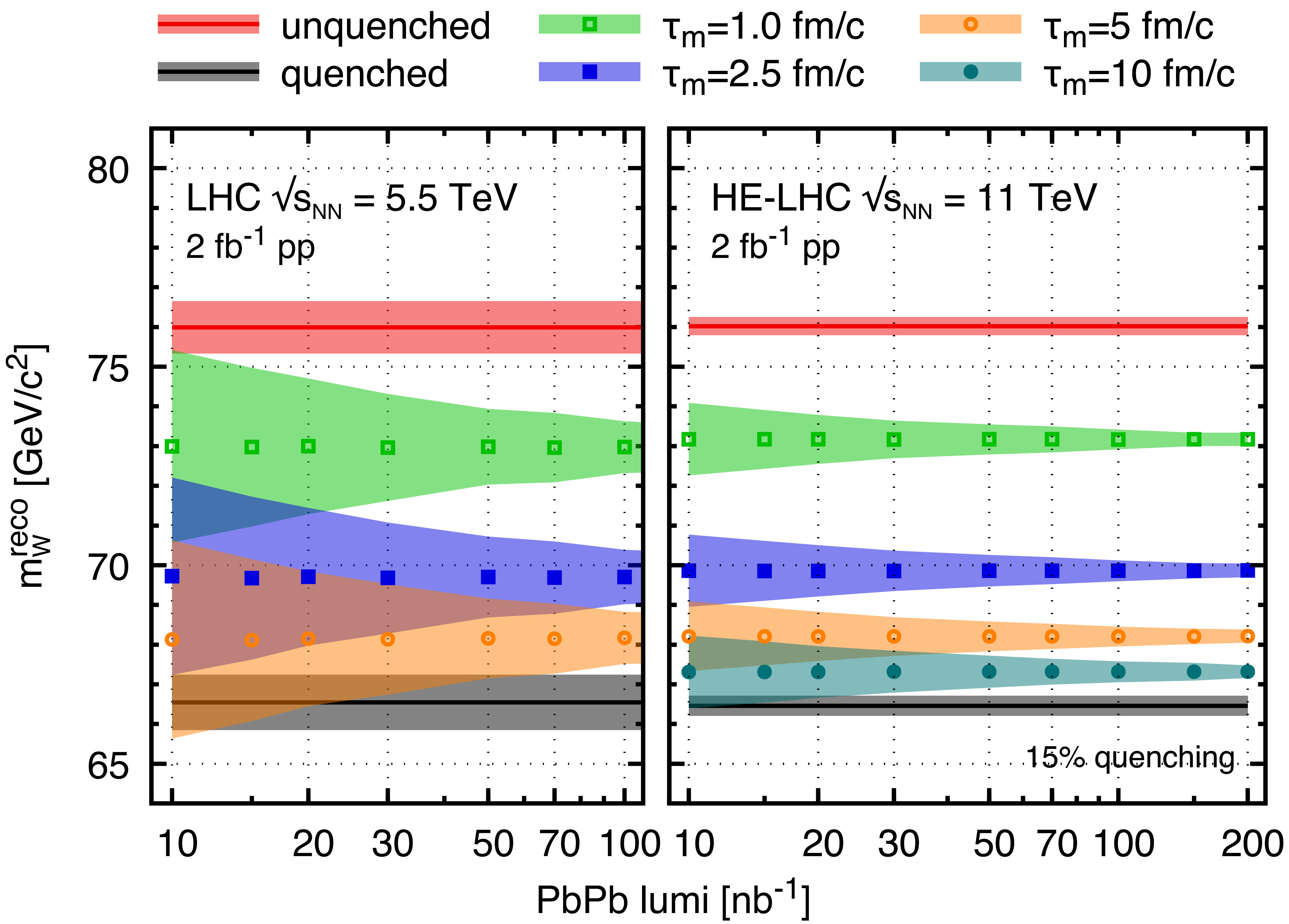
SENSITIVITY TO QGP SIZE AND DELAY TIME



- 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

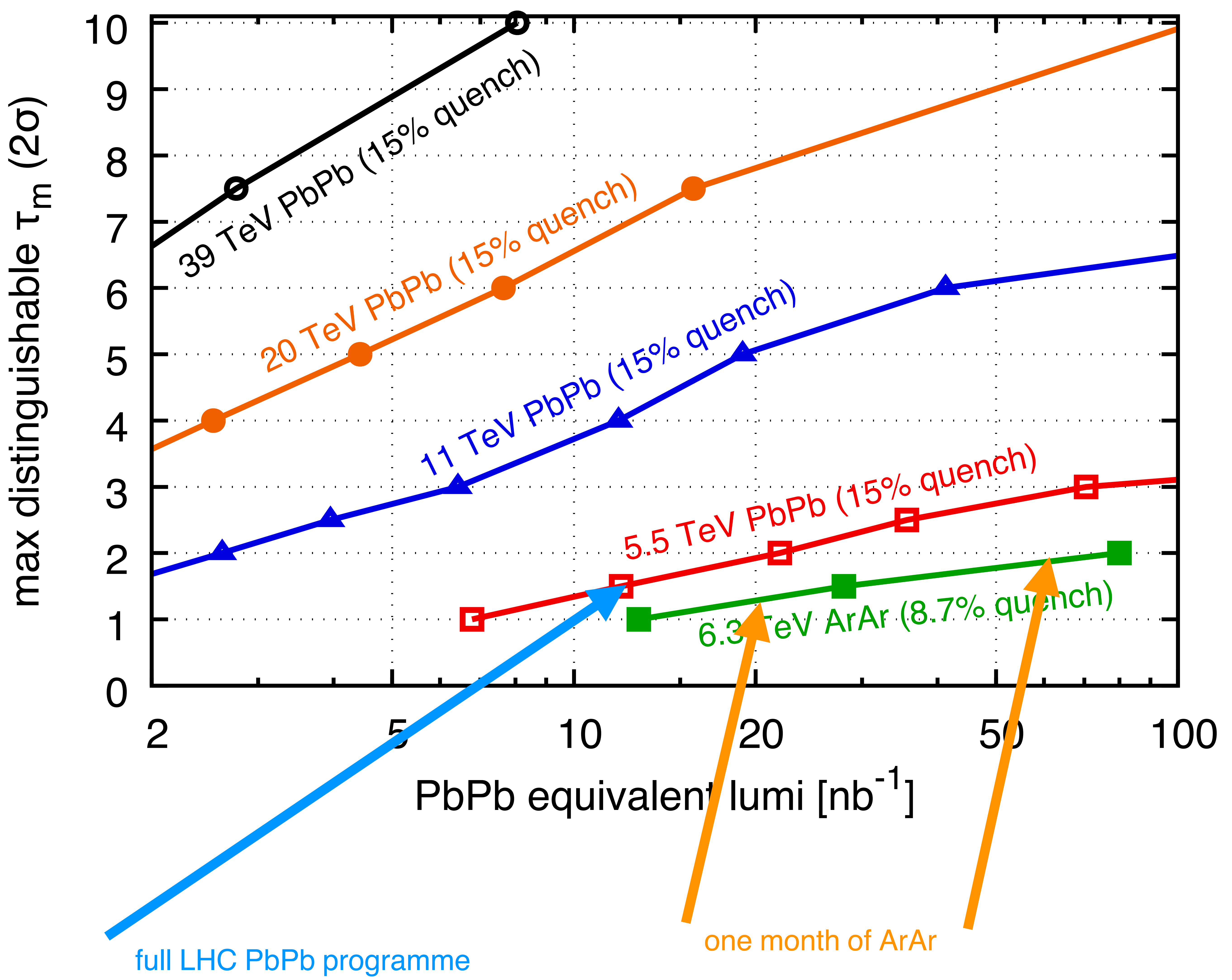
SENSITIVITY TO QGP SIZE [INCLUSIVE]

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 τ_m (2σ)
PbPb equivalent lumi [nb^{-1}]
10
9
8
7
6
5
4
3
2
1
0
2
5
10
20
50
100
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