HEAVY-ION PHYSICS [LECTURE 2]

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OUTLINE [LECTURE 2]

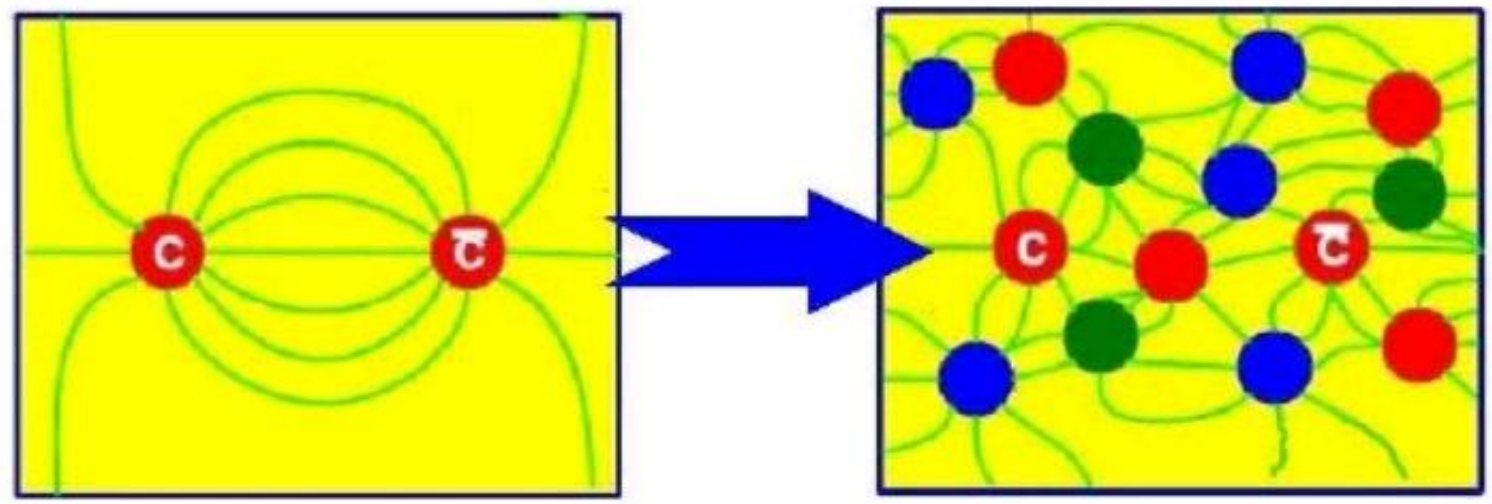
- ✓ hard probes
  - ✓ quarkonia suppression
  - ✓ high-pt hadrons and jets

- ✓ wrap-up

quarkonia

QUARKONIA MELTING

✓ colour screening in a deconfined plasma reduces binding of quarks



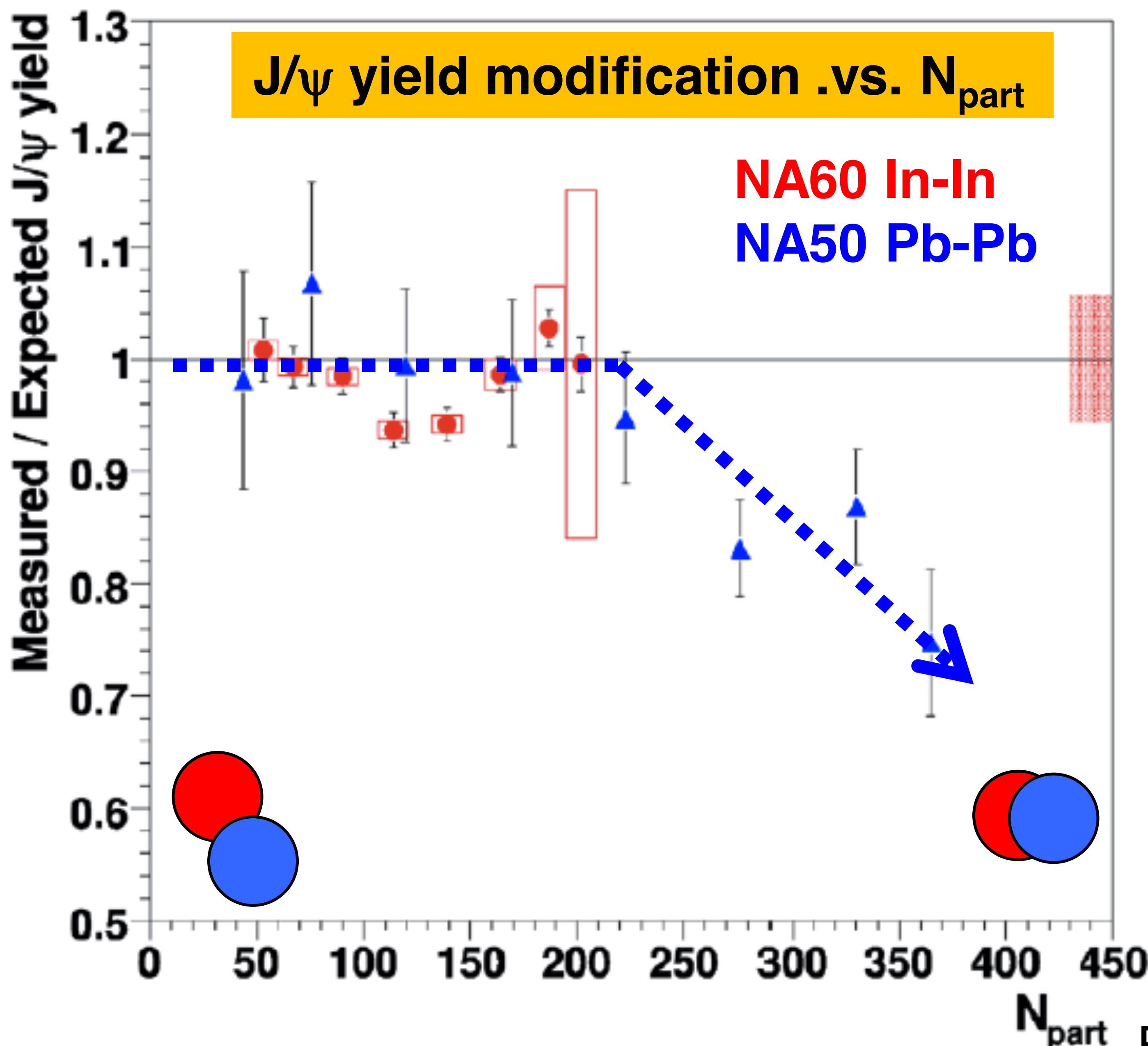
Cartoon: T. Tveter

- ✓ bound states of heavy quarks [c-cbar: J/ψ, ψ’][b-bbar: Υ, Υ’, Υ’’] have small binding energy and thus should be suppressed [melt] in QGP
- ✓ effect should increase with increasing QGP temperature

✓ a very simple, attractive and powerful idea [Matsui, Satz 1986]

J/Ψ SUPPRESSION

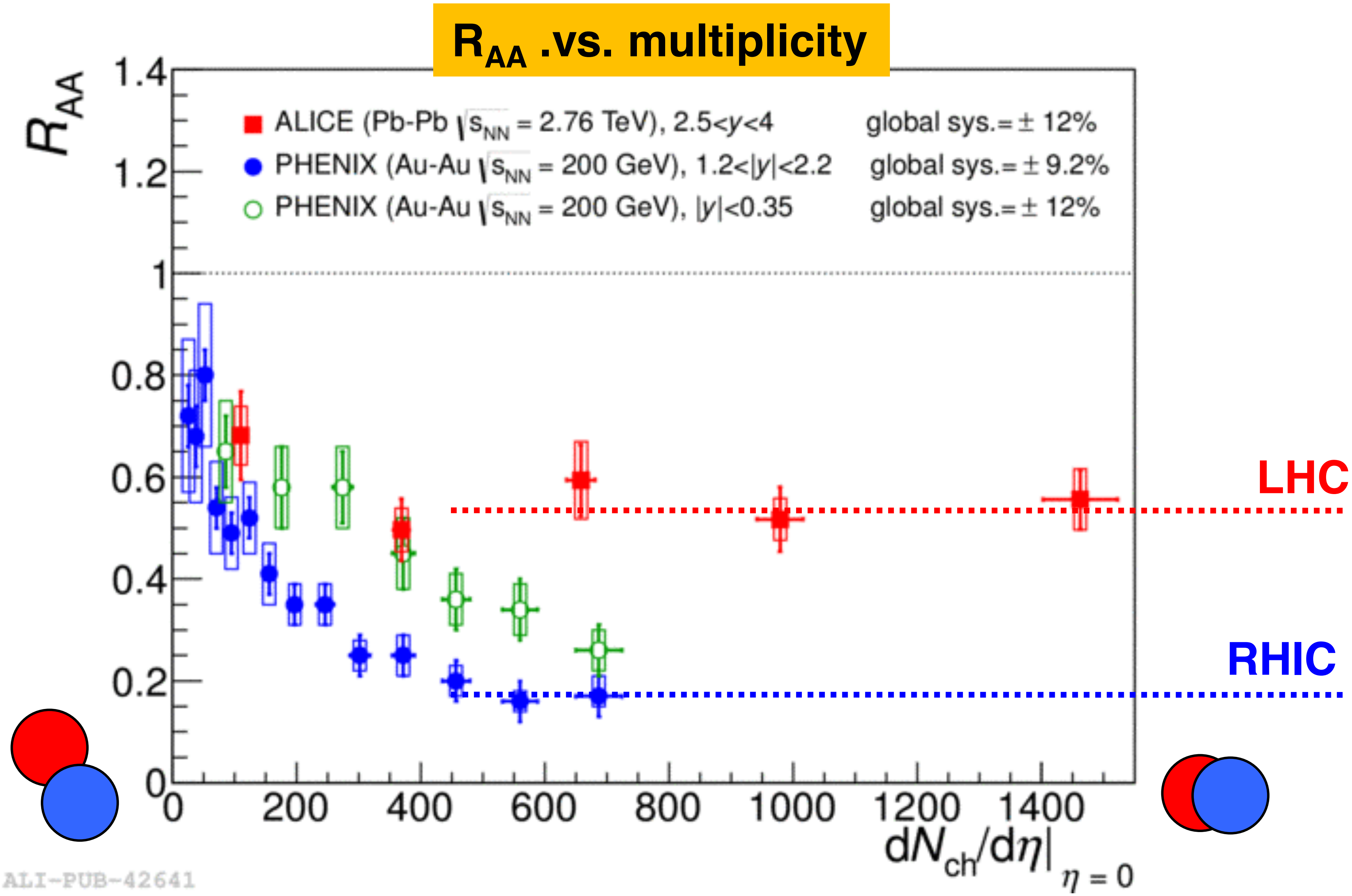
:: first measured at CERN SPS [√s=17 GeV]



In: A = 105
Pb: A = 208

EPJC (2011) 71:1534

RHIC vs LHC

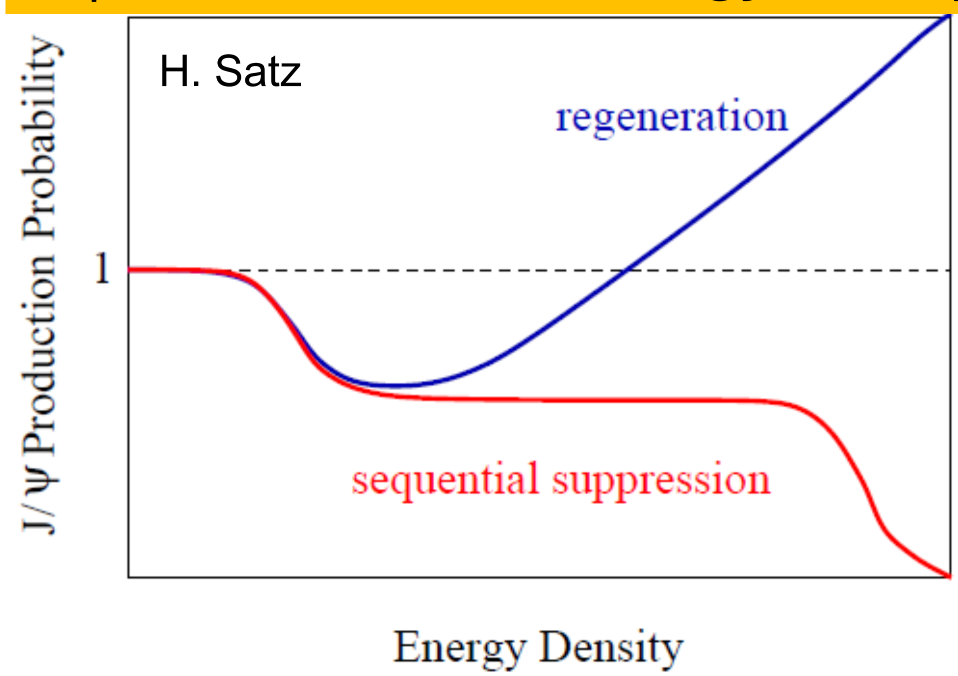


:: higher temperature at LHC, but more suppression at RHIC ?

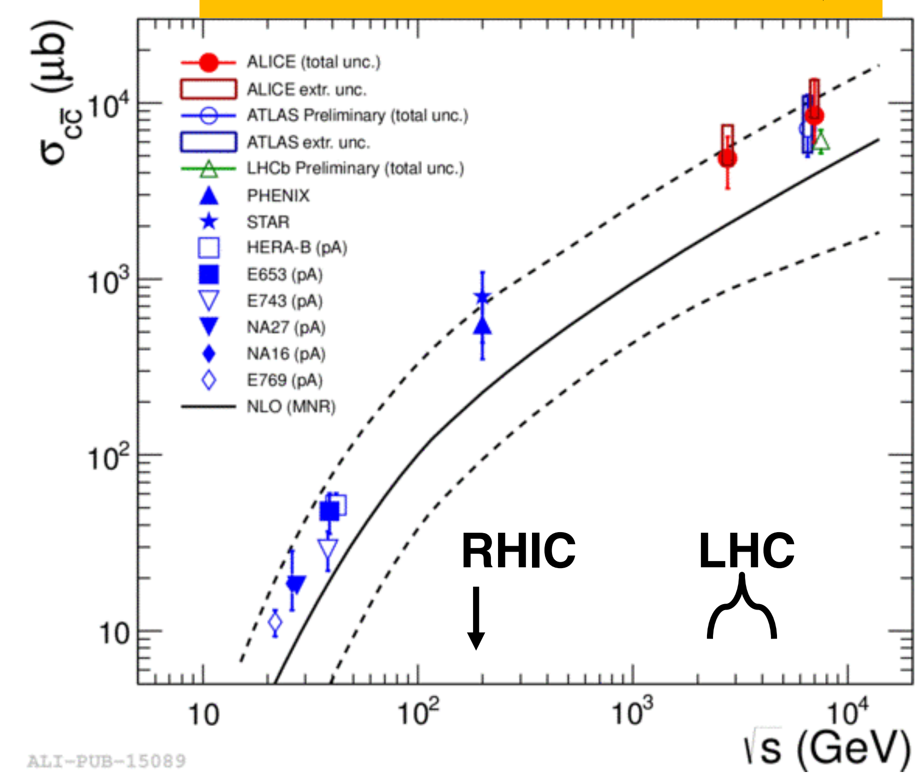
RECOMBINATION

- ✓ number of c-cbar pairs increases with collision energy
  - ✓ quarks from different pairs have increasing probability of binding together at hadronization [later] stage :: cf statistical hadronization models

J/ψ modification .vs. energy density



Charm cross-section .vs. √s



JHEP 1207 (2012) 191

:: the simple idea quickly becomes less simple…

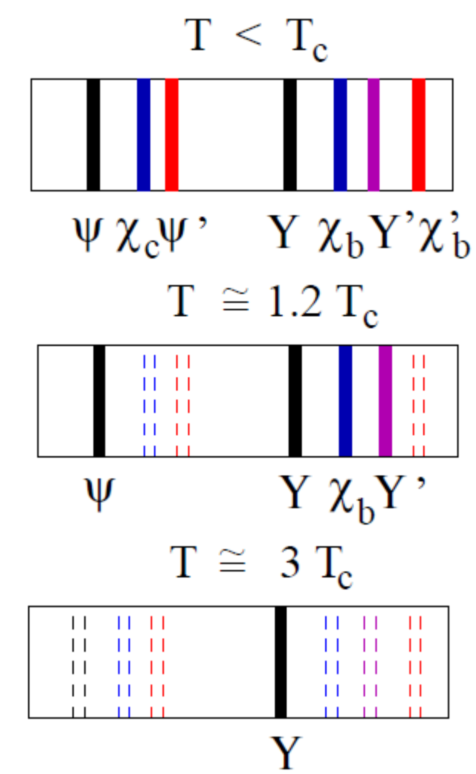
:: also, quarkonia production in vacuum [pp] not fully understood…

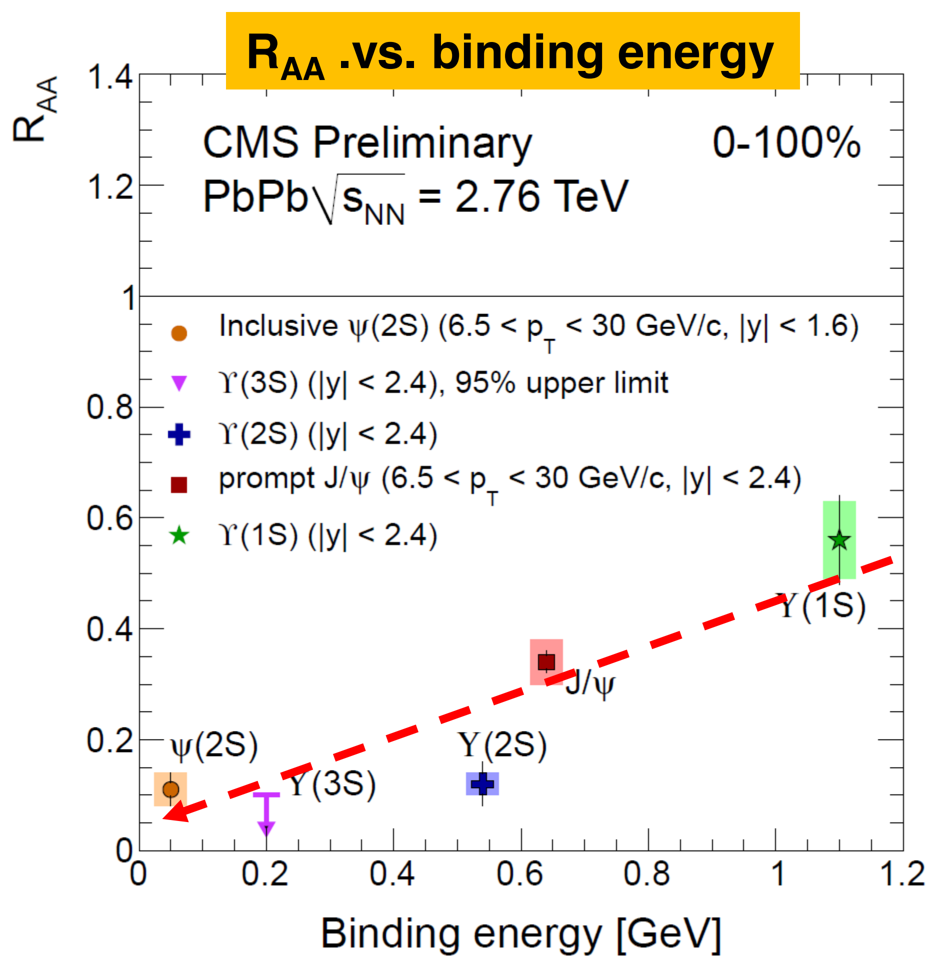
SEQUENTIAL SUPPRESSION

✓ different states should melt at different temperatures

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ'_b	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

dissociates first **dissociates last**

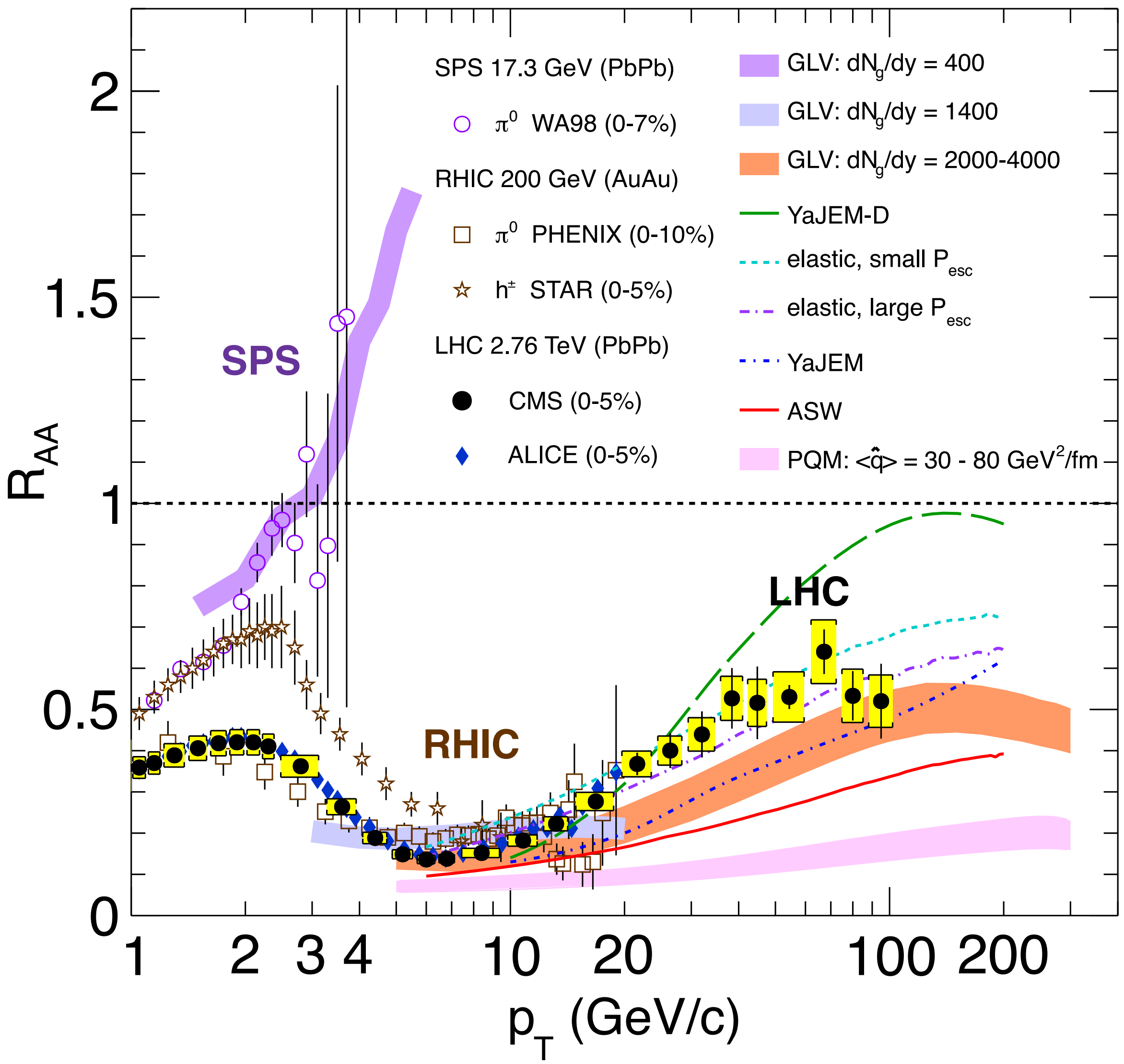


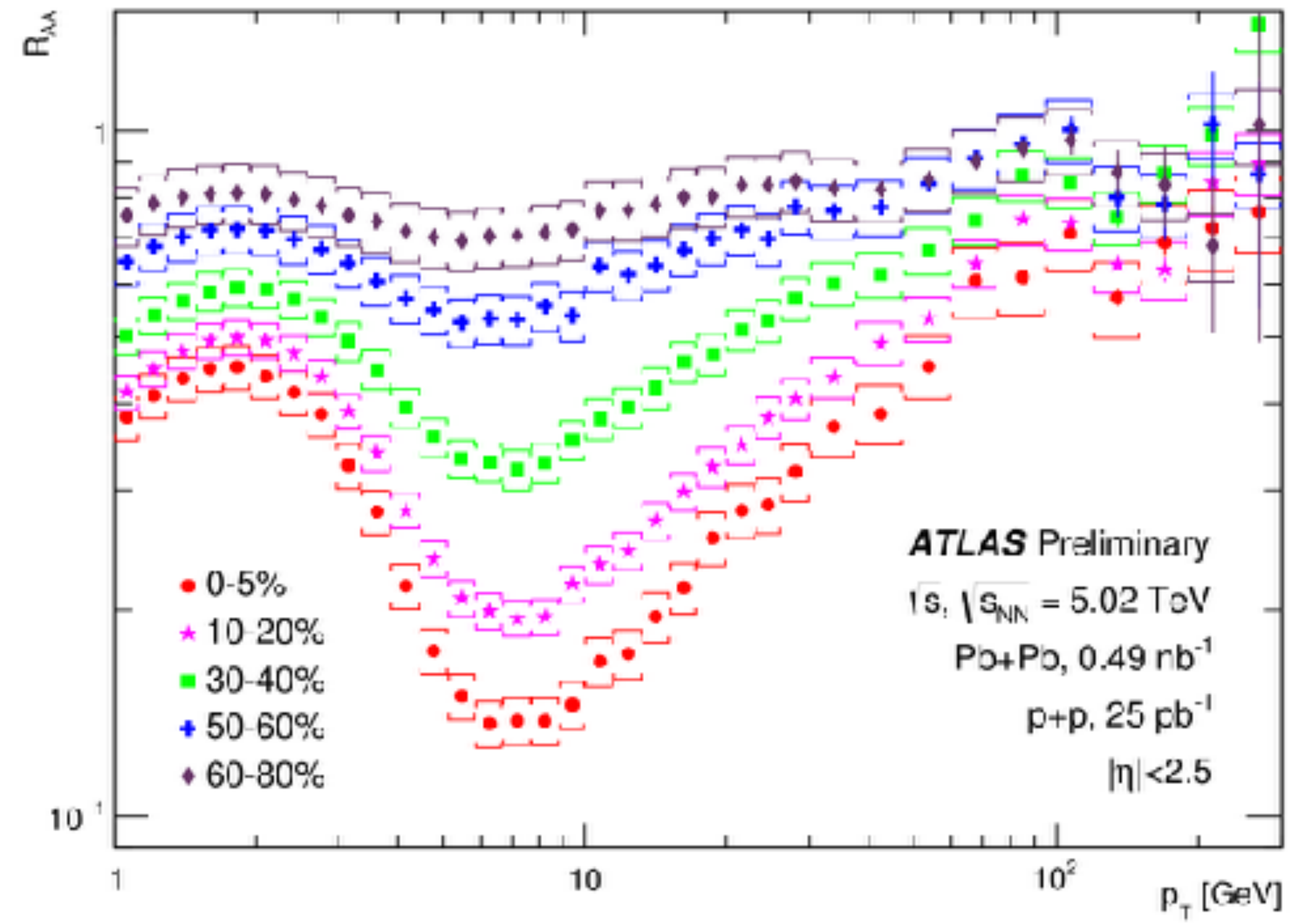


:: quarkonia is a QGP thermometer
[despite all the complications]

high-pt hadrons and jets

HADRON SUPPRESSION

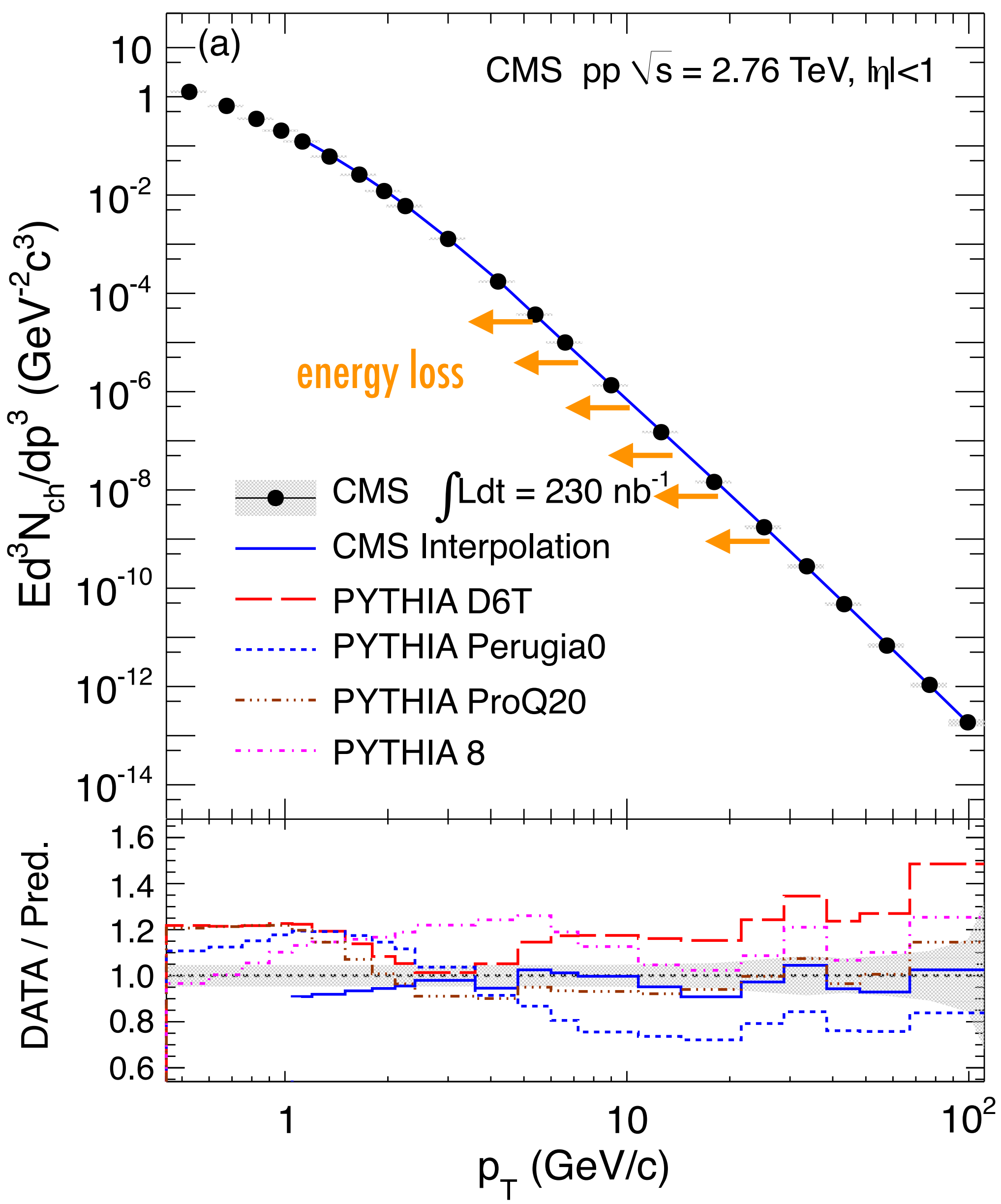


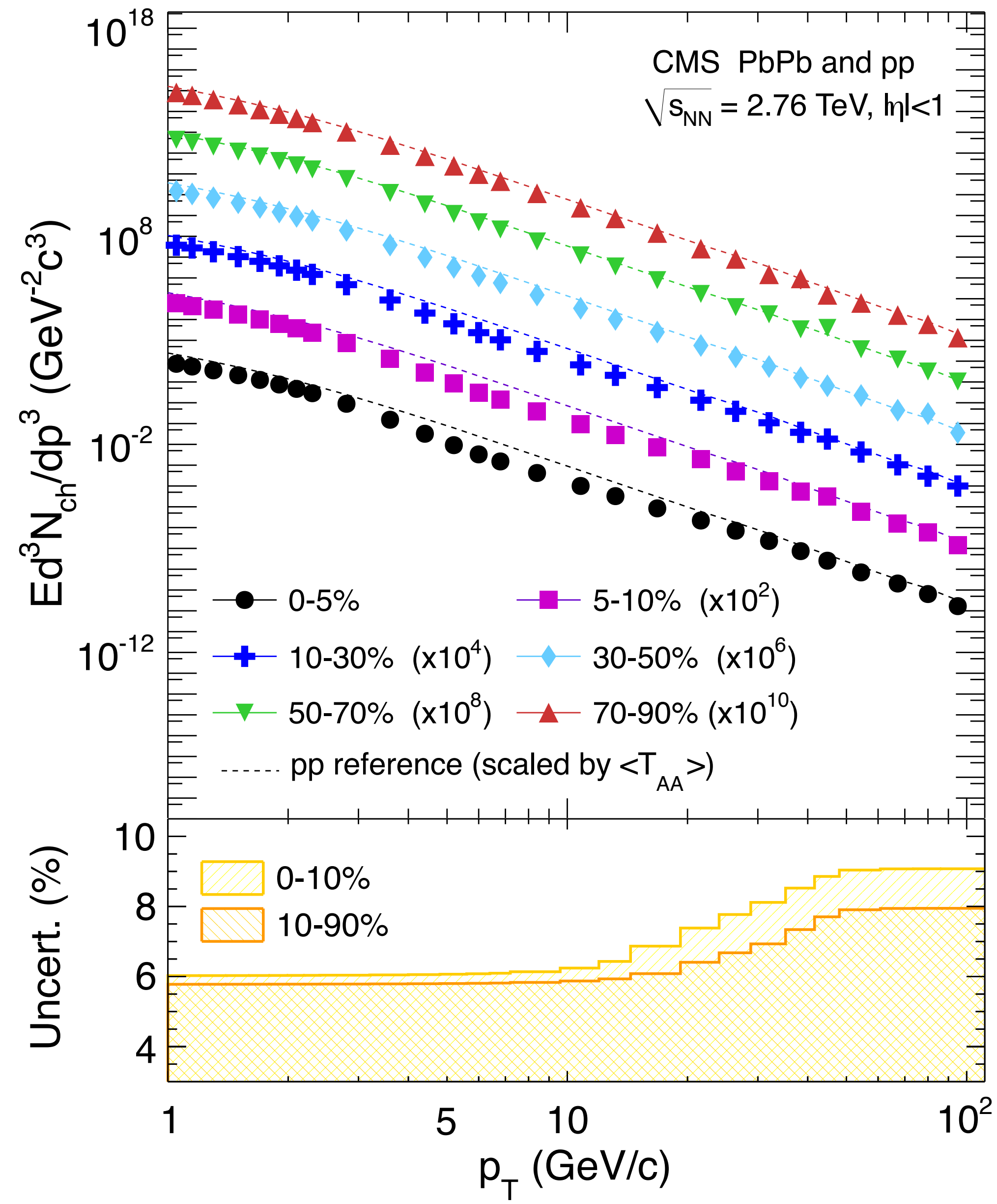


$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{\rm ch}^{AA}/d\eta dp_T}{\langle N_{\rm coll}\rangle\,(1/N_{evt}^{pp})\, d^2N_{\rm ch}^{pp}/d\eta dp_T}$$

- ✓ hadrons yields are strongly suppressed with respect to pp
  - ✓ effect increases with increasing centrality [larger and hotter QGP]

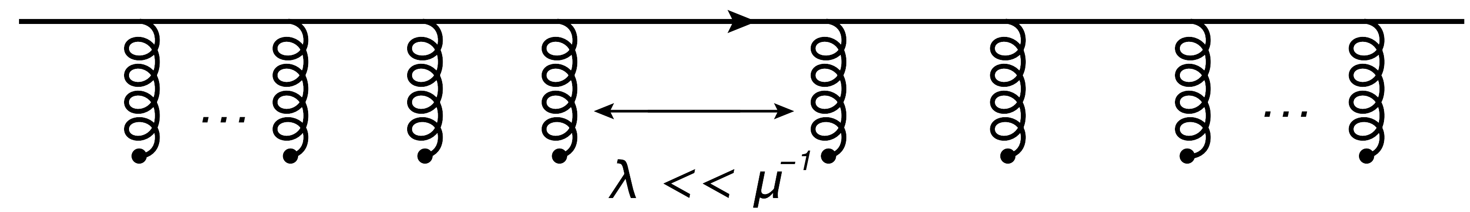
HADRON SUPPRESSION





- ✓ hadron spectrum is steeply falling
  - ✓ suppression implies energy loss of what became the hadron [parton]
  - ✓ this suppression was coined ‘jet quenching’ even before any jet was observed in heavy-ion collisions

PARTON ENERGY LOSS



- ✓ energetic hadrons come from hard partons
  - ✓ first step in understanding hadron suppression is to tackle parton energy loss
  - ✓ 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

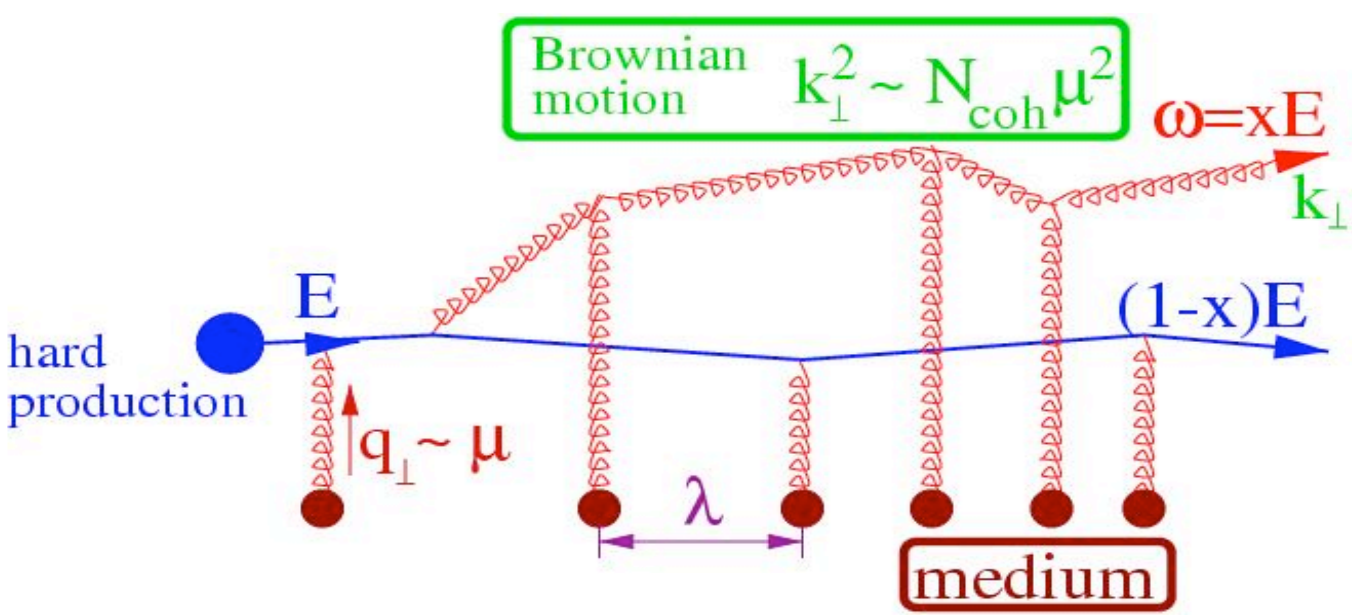
$$A^-_{\rm med}(q) = 2\pi\,\delta(q^+)\int_0^\infty dx^+\, e^{iq^-x^+}A^-_{\rm med}(\boldsymbol{q},x^+)$$

  - ✓ 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



historical figure [one of the ugliest I have ever seen]

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

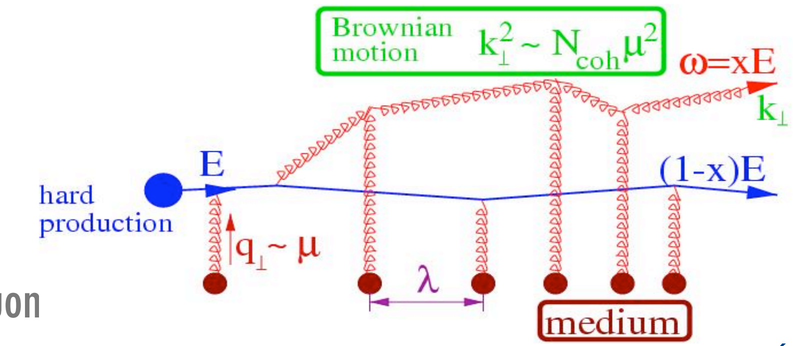
$$\hat{q} \simeq \frac{\mu^2}{\lambda}$$

transport coefficient
[average momentum square transfer per unit length]

SINGLE EMISSION [BDMPS-Z]

:: Brownian motion [accumulated transverse momentum]

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



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

:: 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

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

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

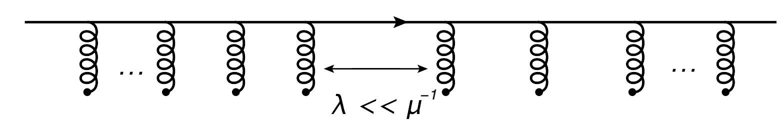
:: average energy loss

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

BEYOND BACK THE ENVELOPE [PATH-INTEGRAL]

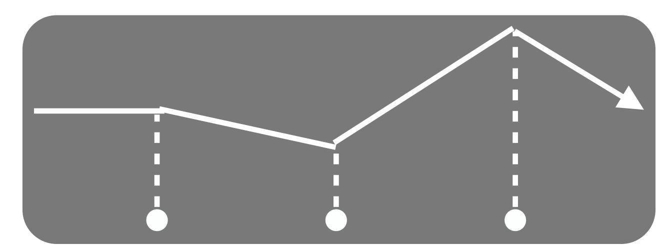
:: eikonal [straight line] parton trajectory resumming multiple exchanges

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

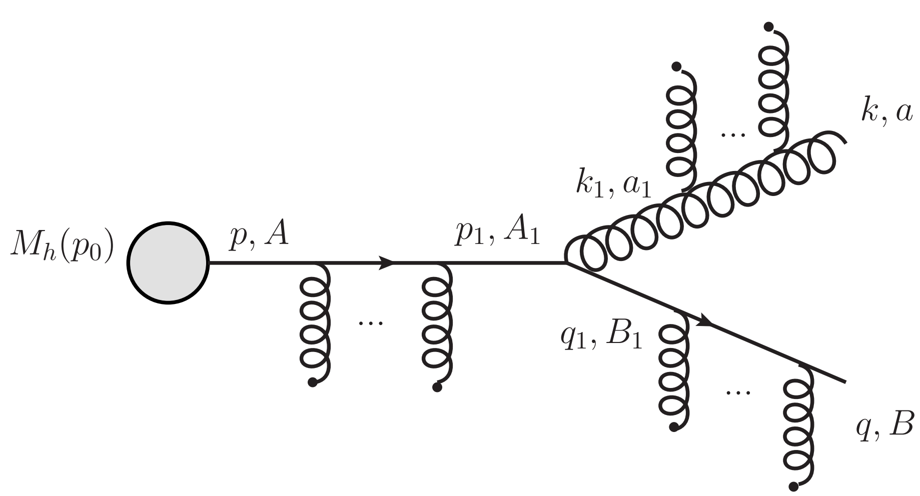


:: off-eikonal [transverse motion] parton trajectory resumming multiple exchanges

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



:: observables computed from medium averages of G correlators



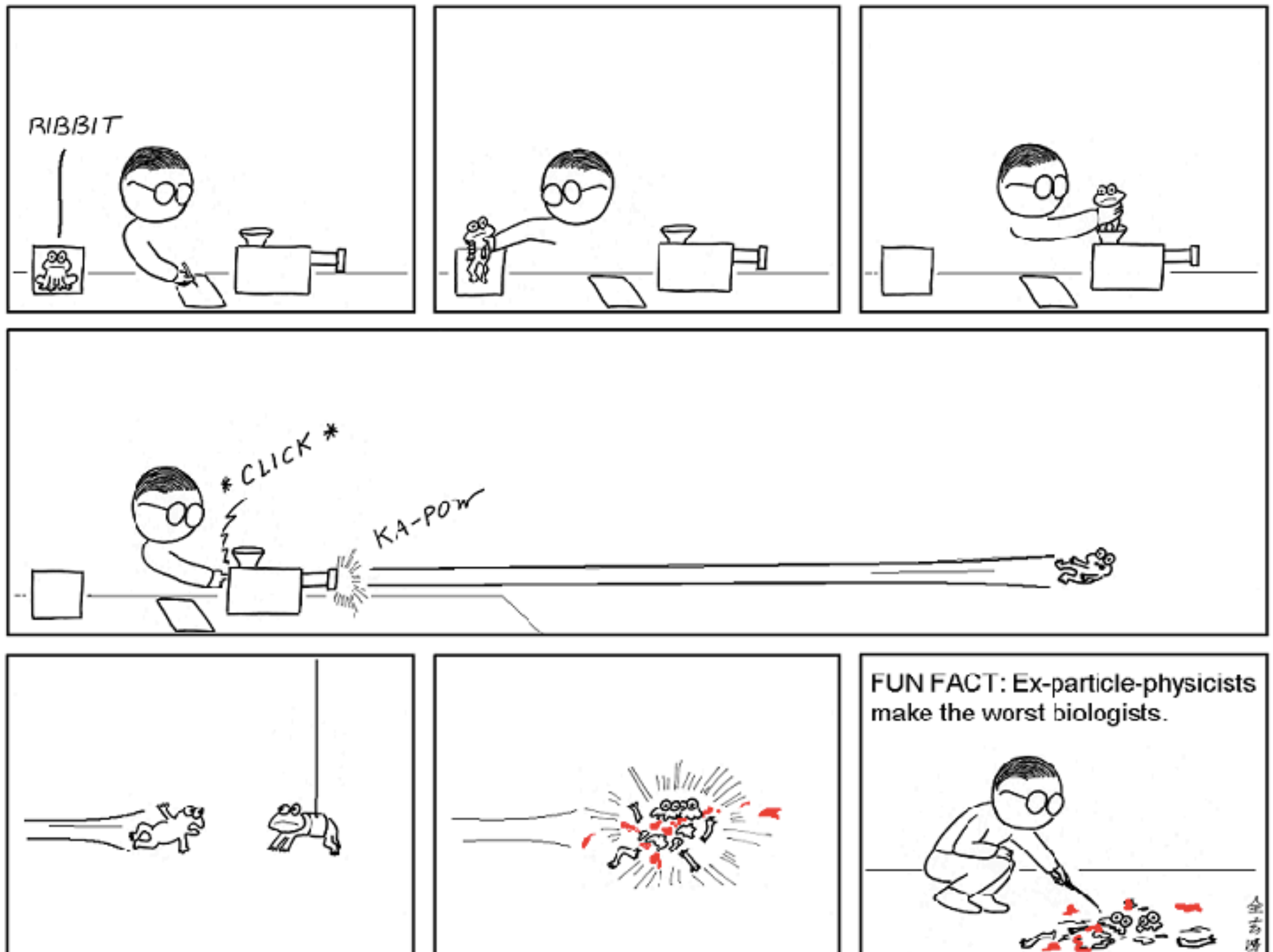
:: calculations become rather complicated very quickly

HOW TO PROBE ANYTHING

so far we haven't invoked the best way probing anything

HOW TO PROBE ANYTHING

scatter something off it



Abstruse Goose

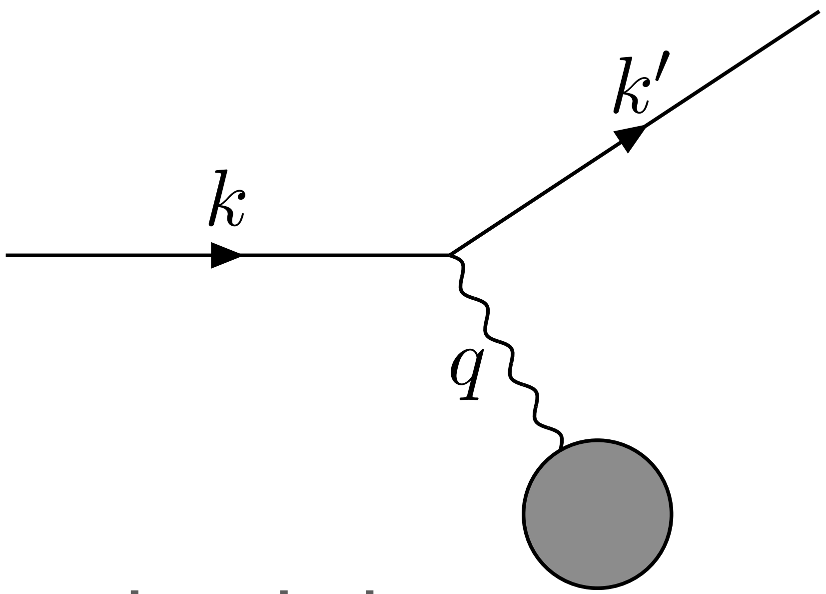
HOW TO PROBE ANYTHING

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

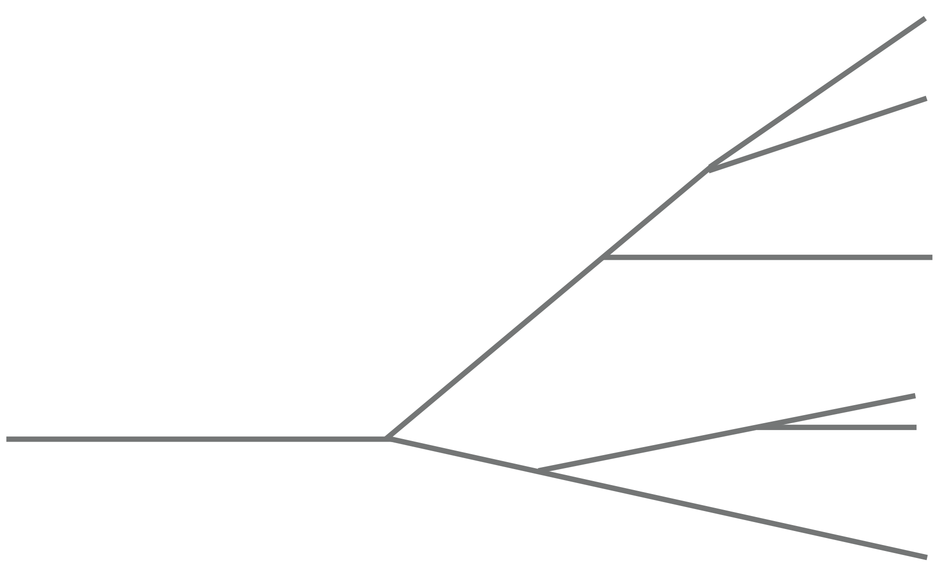
:: to mimic DIS paradigm need multi-scale probes produced in the same collision as the QGP

→ jets

WHAT IS A JET ?

jet is a **jet** is a jet is a jet

[theory view]
the offspring of the QCD
branching of a hard parton



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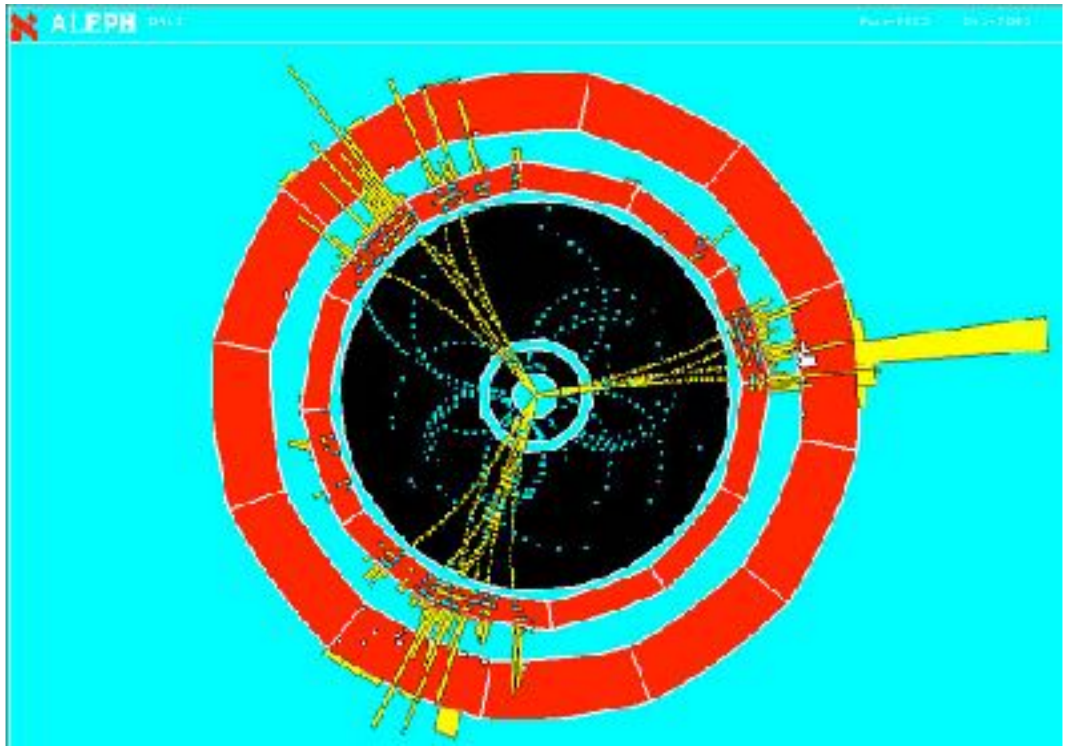

[experimental view]
collimated bunch of particles

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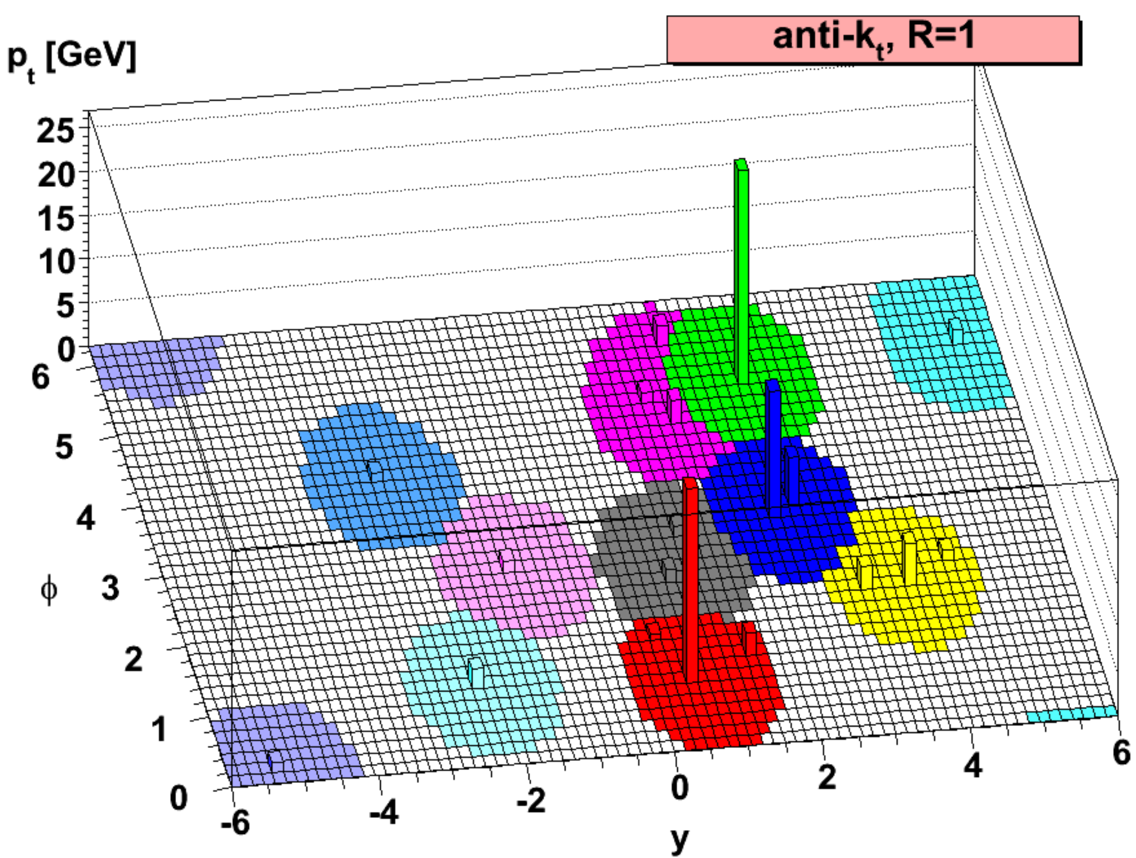


[experimental view]
collimated bunch of particles

[strictly]
defined by a jet algorithm

WHAT IS A JET ?

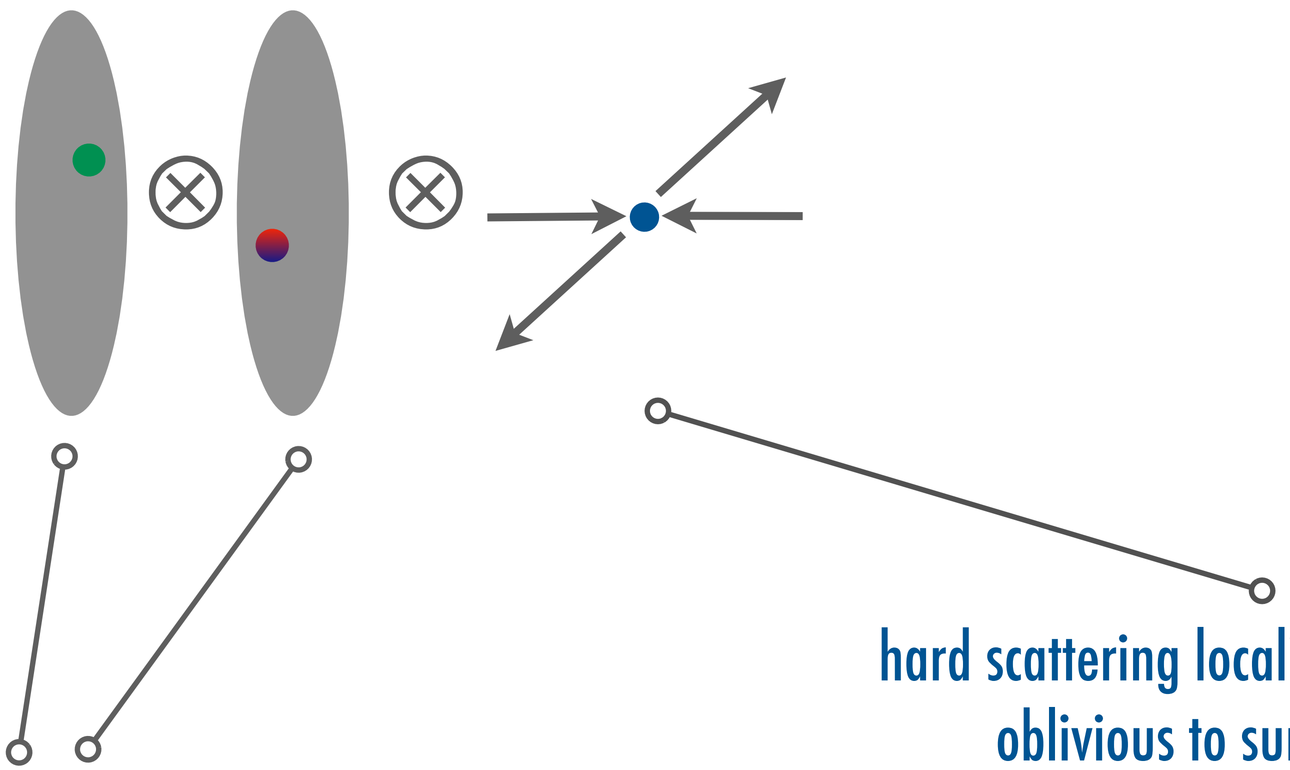
jet is a jet is a jet is a jet

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

A JET IN QGP :: HARD PRODUCTION

robust arguments for non-modification wrt vacuum :: familiar physics



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

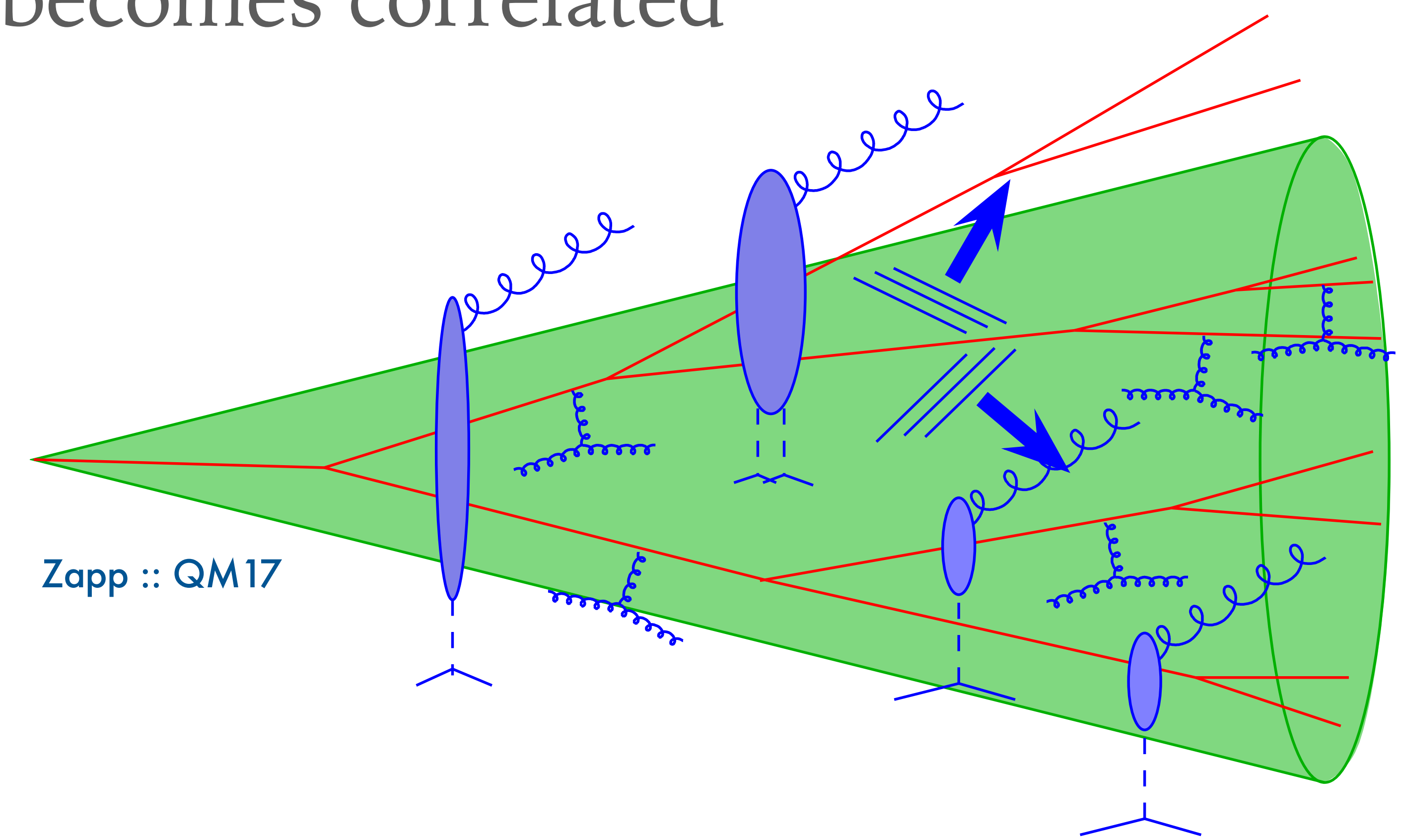
shower constituents exchange [soft] 4-momentum and colour with QGP :: shower modified into interleaved vacuum+induced shower :: modified coherence properties :: single parton intuition and results do not carry through trivially :: multi-scale problem :: some shower constituents de-correlate :: some QGP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

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

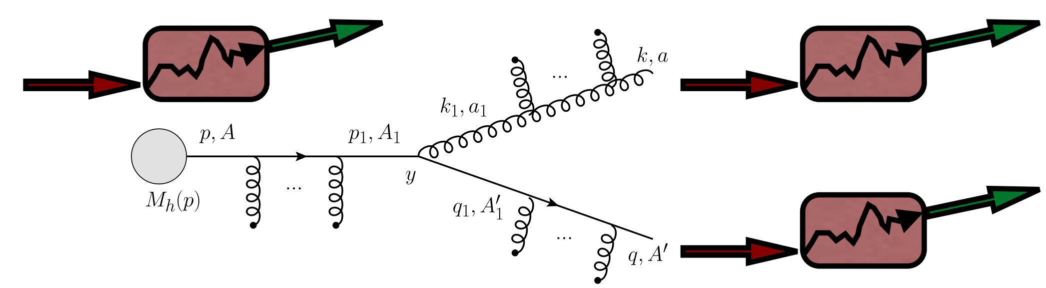
Mehtar-Tani, Tywoniuk, Salgado :: many

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

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



Zapp :: QM17

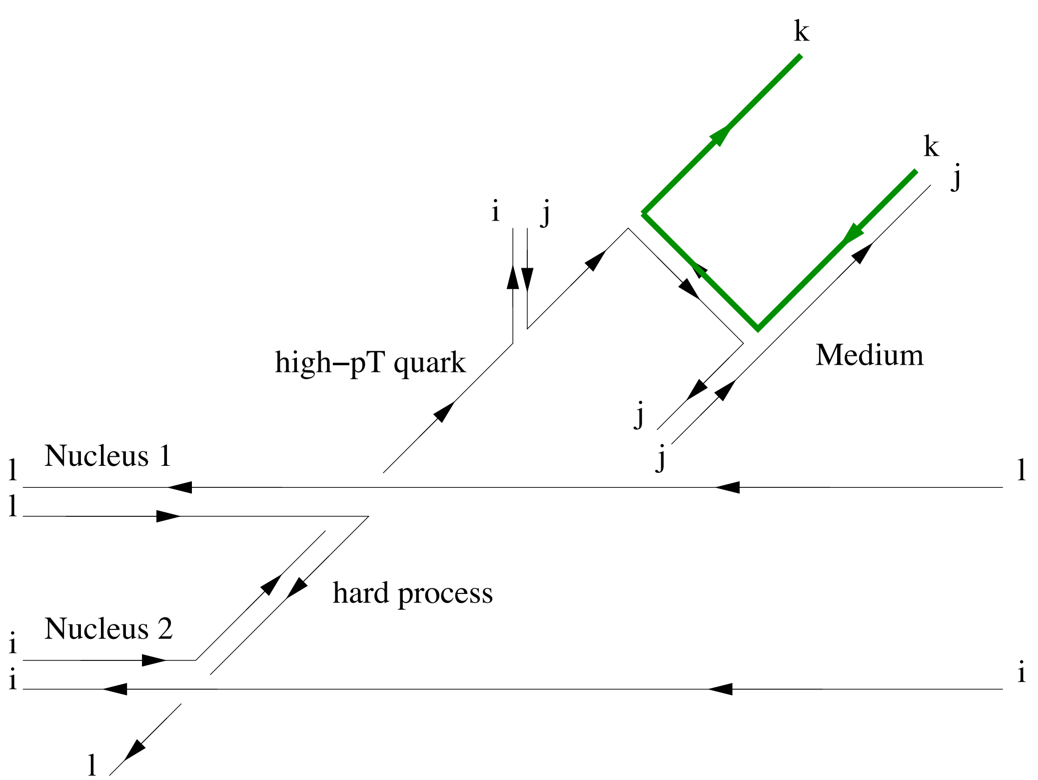


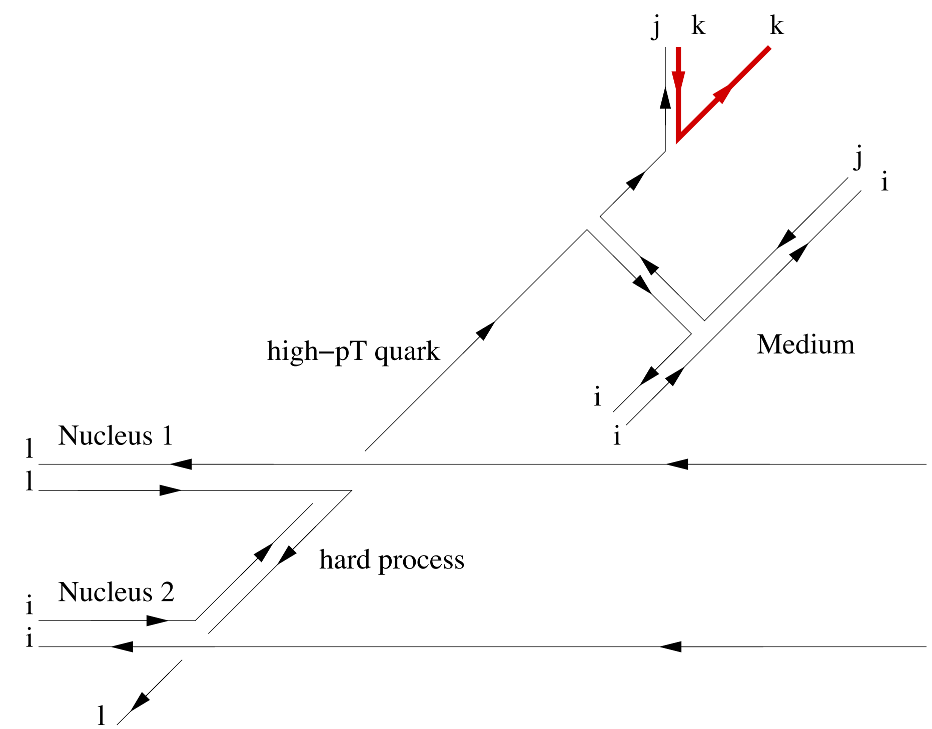
this is tough [anger]

A JET IN QGP :: HADRONIZATION

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

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



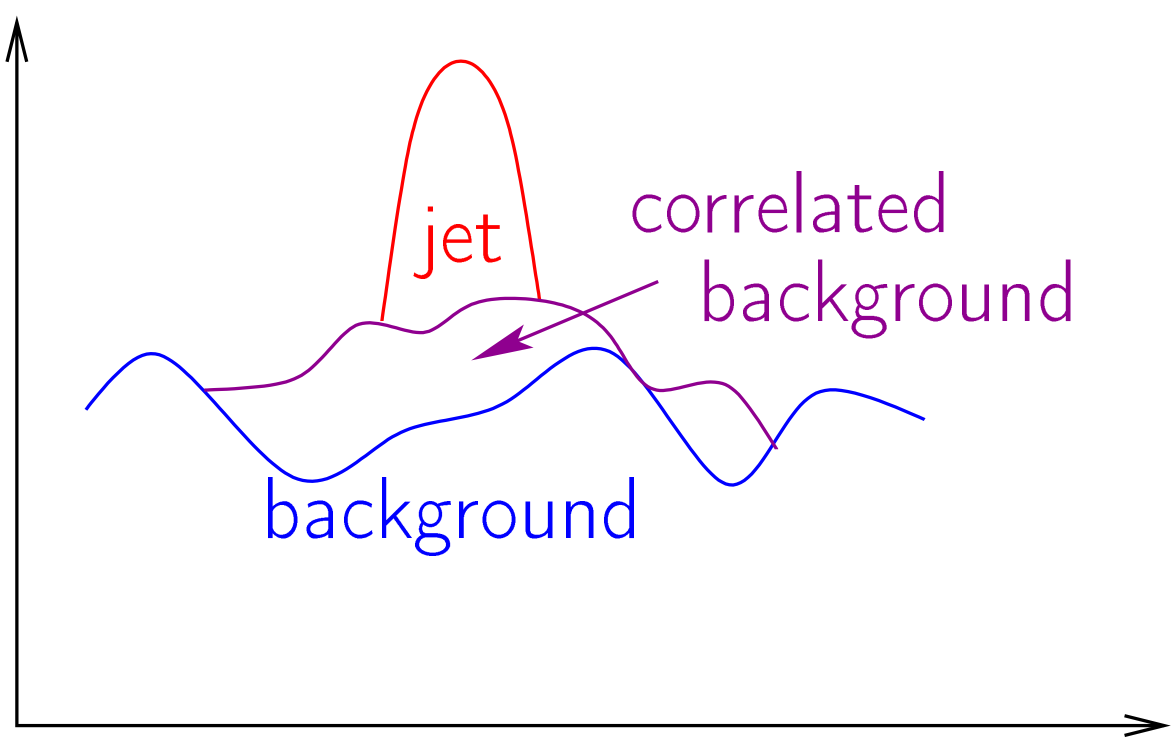


jet-QGP interaction modifies color connections in the jet and thus hadronization pattern
[in any reasonable effective model]
can learn about hadronization modifications at an EIC

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?



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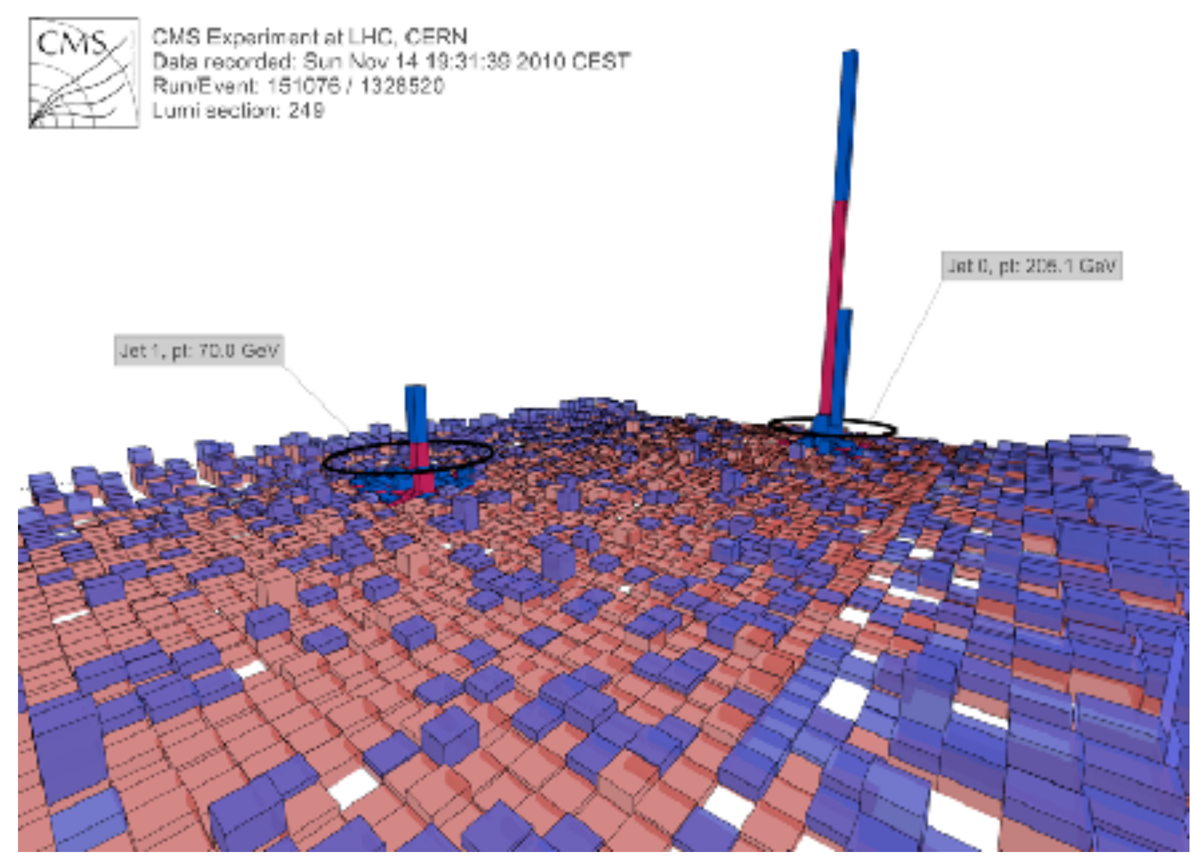


this is probably hopeless [depression]

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

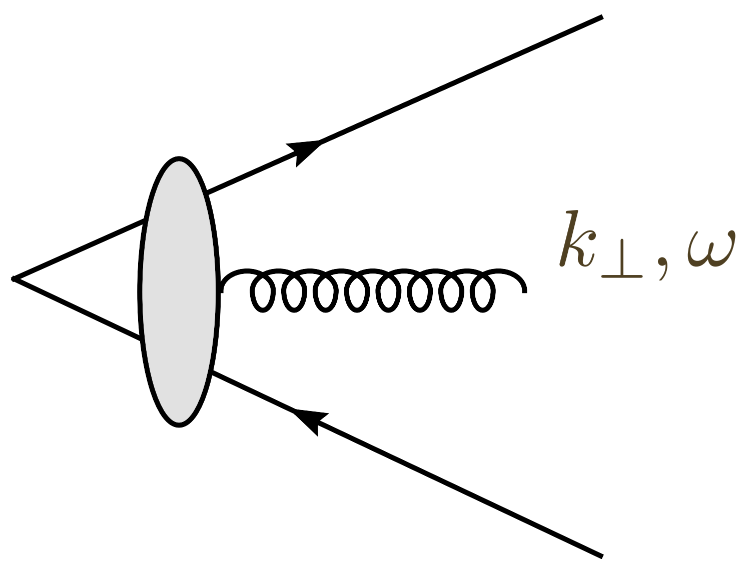
denial :: anger :: bargaining :: depression :: acceptance

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

from partons [hadrons] to jets

MULTIPLE EMISSIONS :: VACUUM ANTENNAS

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



::vacuum::

- transverse separation at formation time

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

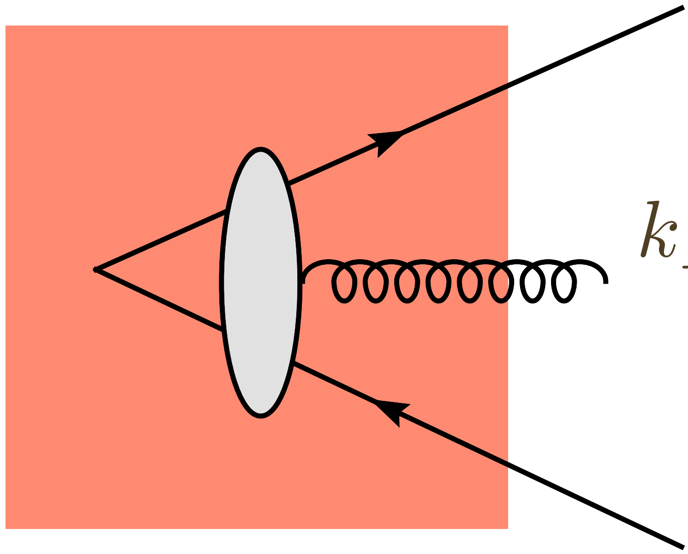
- wavelength of emitted gluon

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

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



MAJOR EFFORT
Mehtar-Tani, Salgado, Tywoniuk
Casalderrey-Solana & Iancu
Blaizot, Dominguez, Iancu, Mehtar-Tani
Mehtar-Tani, Milhano, Tywoniuk [review]

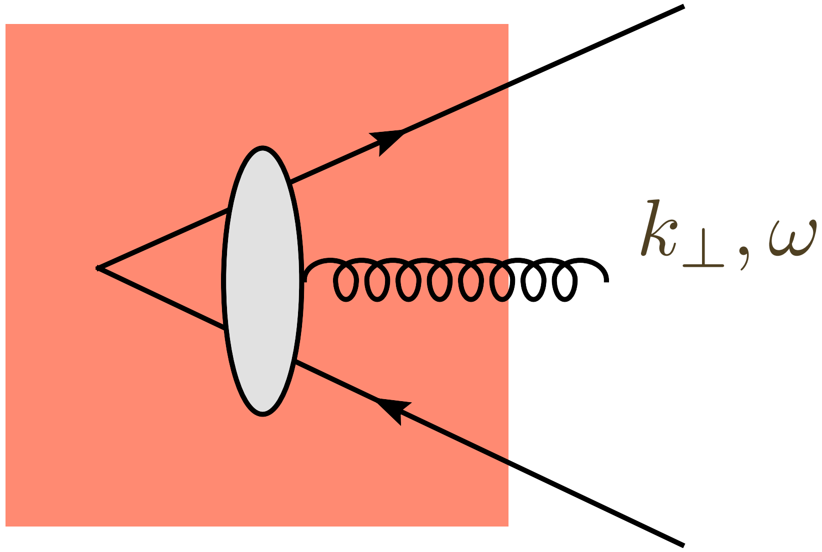
$$\Lambda_{med} \sim \frac{1}{k_\perp} \sim \frac{1}{\sqrt{\hat{q}L}}$$

- new medium induced colour decorrelation scale

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

- such that decorrelation driven by timescale

[DE]COHERENCE OF MULTIPLE EMISSIONS



- 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

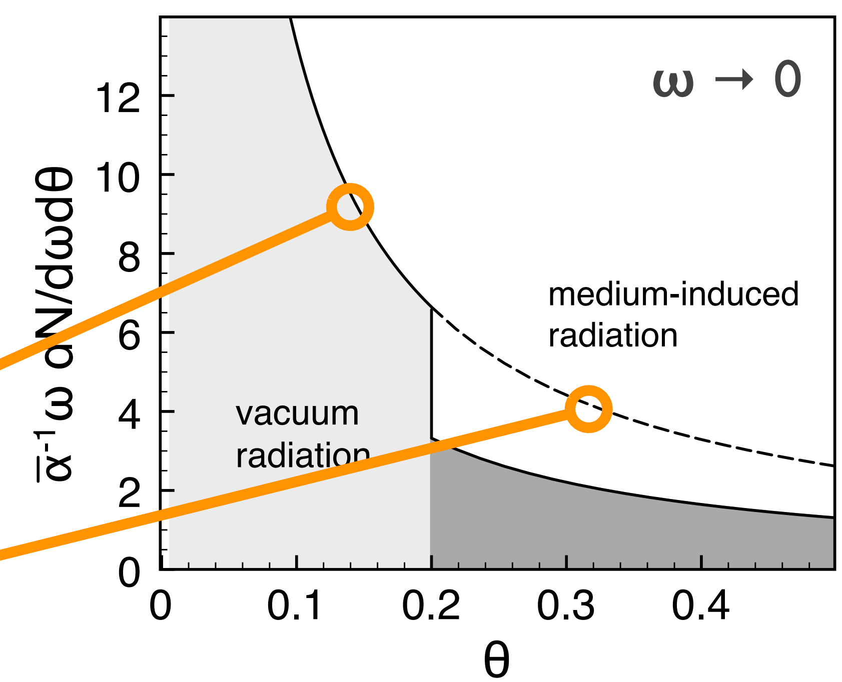
 ➤ large angle radiation [anti-angular ordering]

  ➤ *geometrical separation [in soft limit]*

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

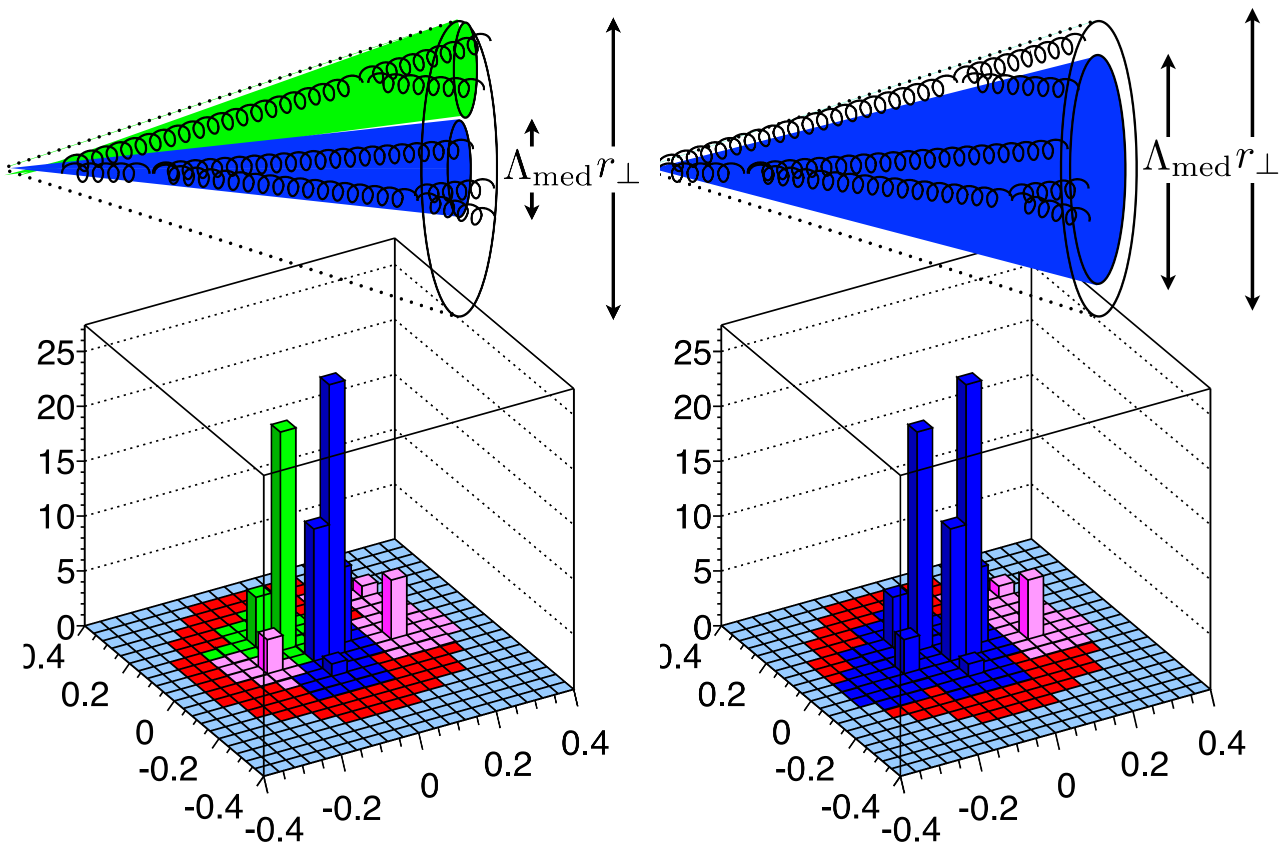
$\Delta_{\text{med}} \to 0$ coherence

$\Delta_{\text{med}} \to 1$ decoherence



FROM ANTENNAS TO JETS

Casalderrey, Mehtar-Tani, Salgado, Tywoniuk [1210.7765]

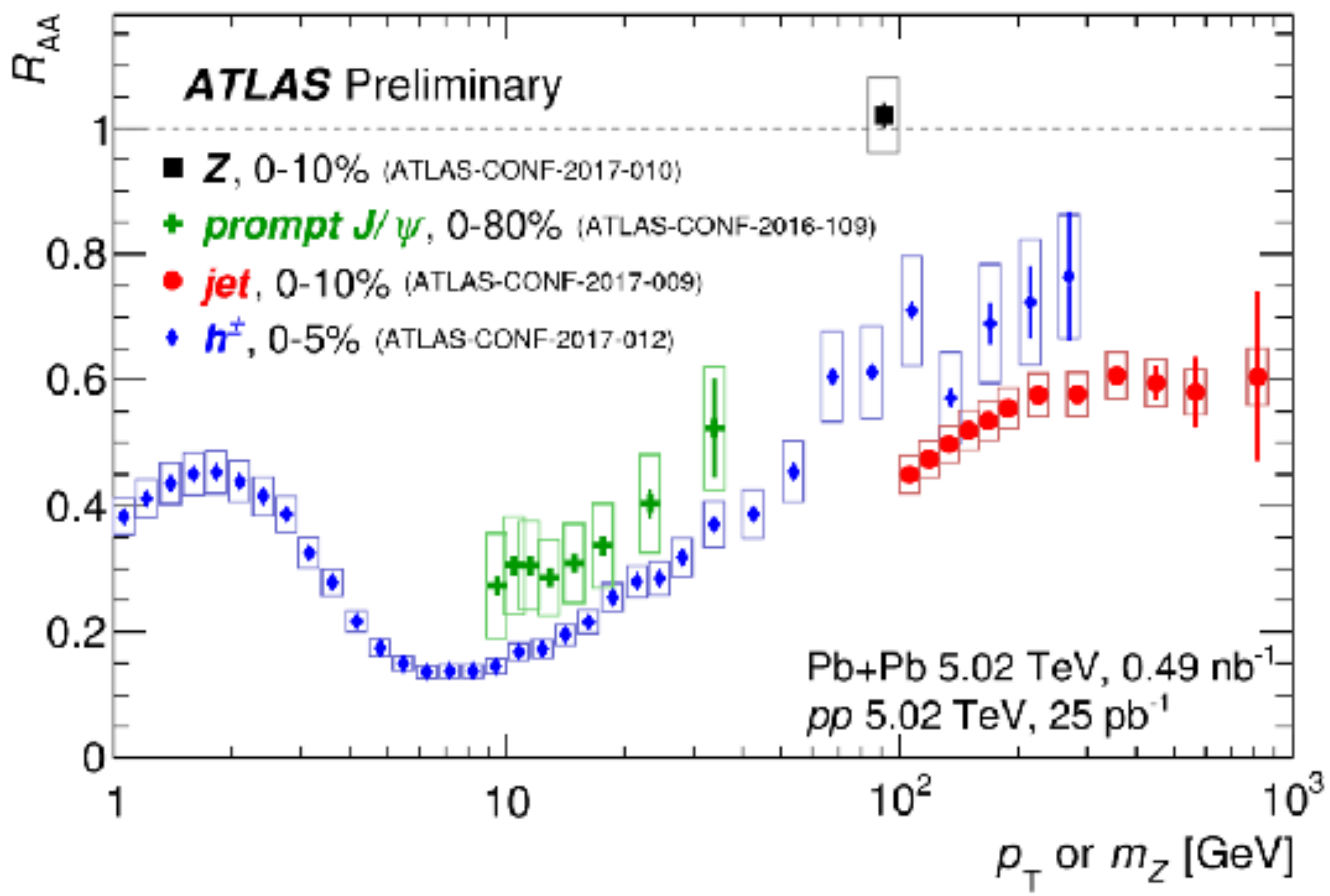


✓ $r_t < \Lambda_{med}$ :: antenna unresolved by medium :: vacuum like

✓ $r_t > \Lambda_{med}$ :: medium probes antenna :: strong suppression of interference :: independent radiation from each constituent

✓ in-medium jet dynamics driven by number of resolved charges

HADRON AND JETS



✓ hadrons belong to jets

✓ jets more suppressed than hadrons…

- ✓ the QGP resolves the jets [‘sees’ its components] what can jets do for you?

better, what can you do with jets?

significant progress requires detailed understanding
of the sensitivity of each observable

A TOOL :: MONTE-CARLO EVENT GENERATORS

- ✓ MCs implement most known jet quenching physics
  - ✓ many MCs in the market [Q-PYTHIA, PYQUEN, MATTER, MARTINI, Hybrid,…] implementing various ‘alternatives’
- ✓ MCs allow for fair comparison with data
- ✓ MC status not the same as in pp :: we don’t know all the physics yet !
- ✓ MCs that have been validated for a wide set of observables can be used as an exploration tool

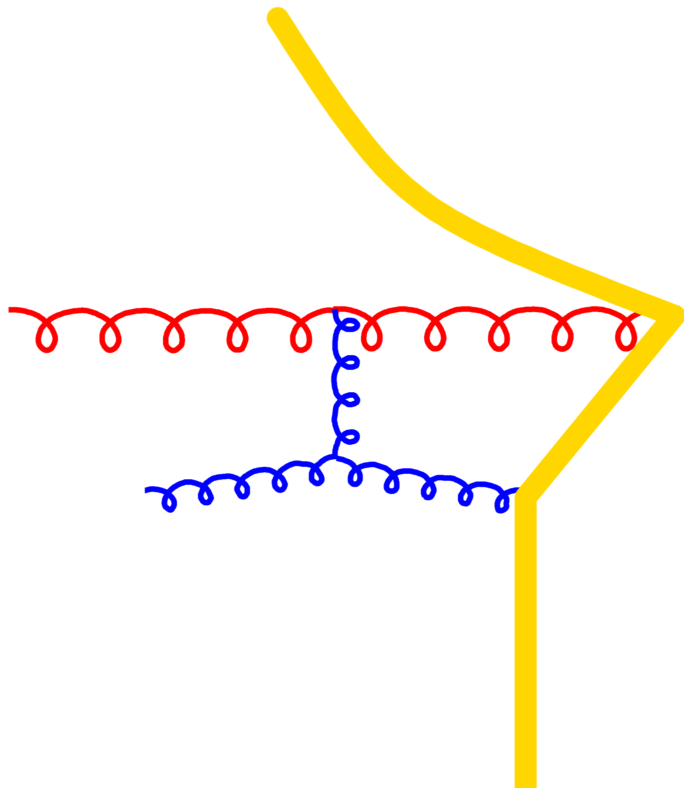
JEWEL [AN MC I LIKE]

Zapp, Krauss & Wiedemann, JHEP 1303 (2013) 080

- jet evolution and interaction with medium described within single formalism
  - jet evolution well understood in pp :: use standard tools from pp description
  - dynamical model of jet evolution anchored in analytical understanding of pQCD
- key assumptions
  - medium seen by jet as collection of quasi-free partons
  - use infra-red continued perturbation theory to describe all jet-medium interactions
  - formation times govern the interplay of different sources of radiation [vacuum-like and medium induced]
  - LPM effect encoded through eikonal limit analytical results

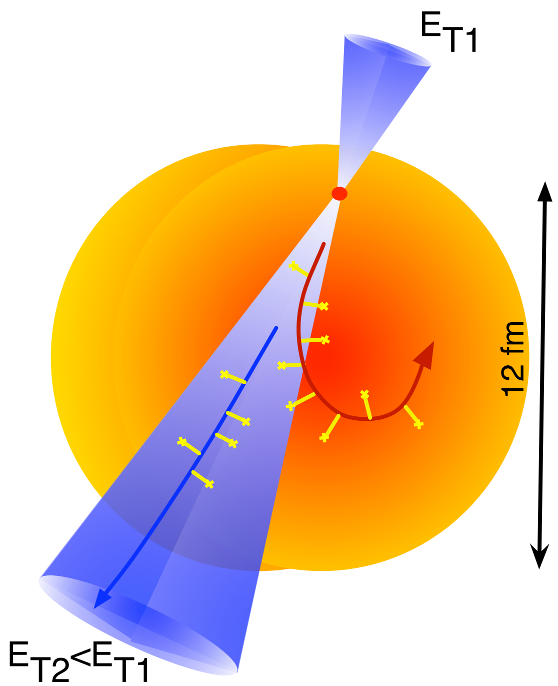
JEWEL: MEDIUM RESPONSE

Zapp and Kunnawalkam Elayavalli



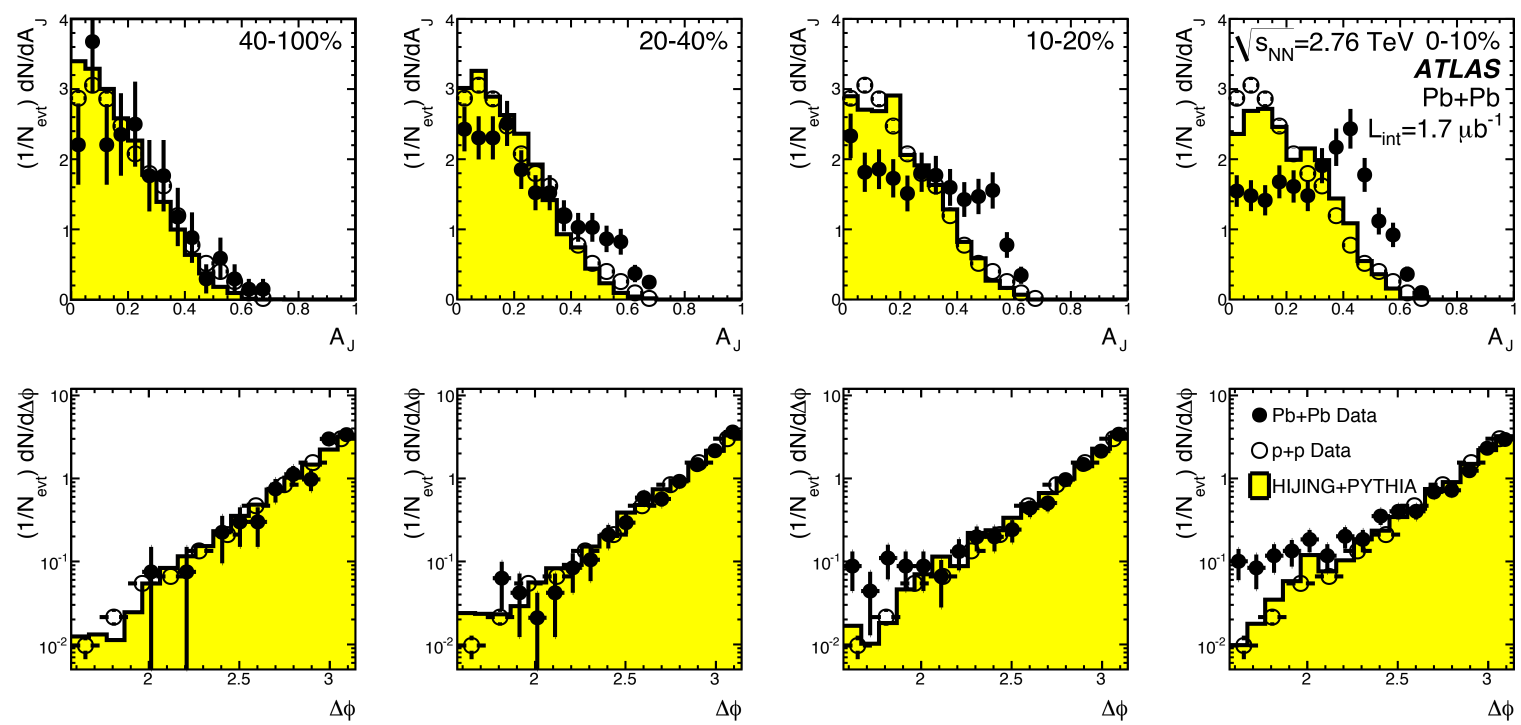
- two possible operating modes in JEWEL
  - medium partons **not included** in event record :: no tracking of medium response
  - medium partons that interact with jet **included** in event record
    - part of the medium becomes correlated with jet and thus part of jet
    - requires subsequent background subtraction :: only 4-momentum acquired by medium partons should survive not that in thermal distribution
    - no further re-scattering of medium partons :: jet-correlated medium arguably too hard

[MANY] LESSONS FROM THE FIRST JET MEASUREMENT



di-jet asymmetry
:: energy imbalance of back-to-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

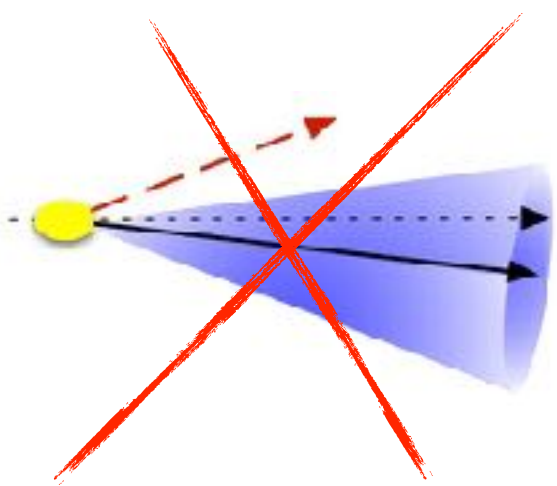
[MANY] LESSONS FROM THE FIRST JET MEASUREMENT

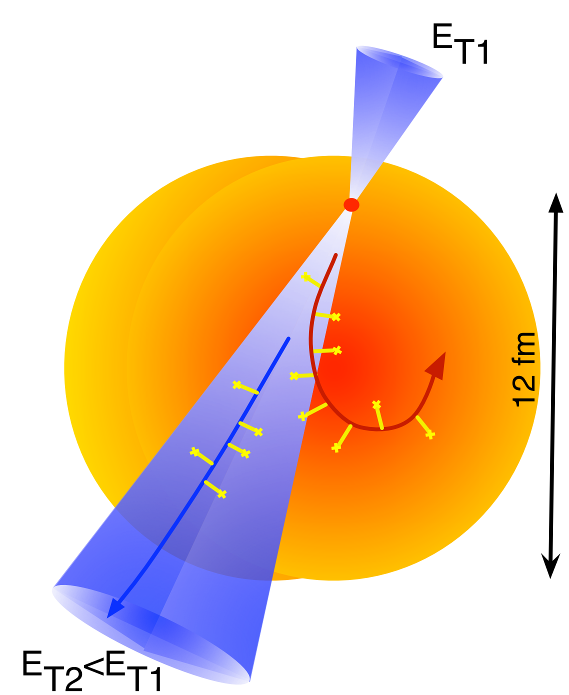
measurement of increase of di-jet asymmetry without disturbance of acoplanarity distribution

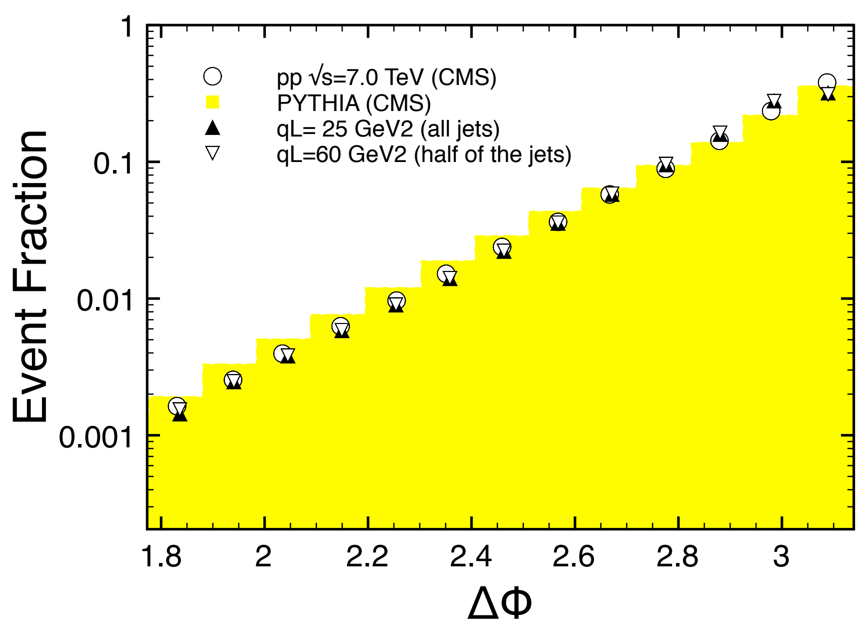
paradigm change triggering experimental analyses and theoretical developments

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

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

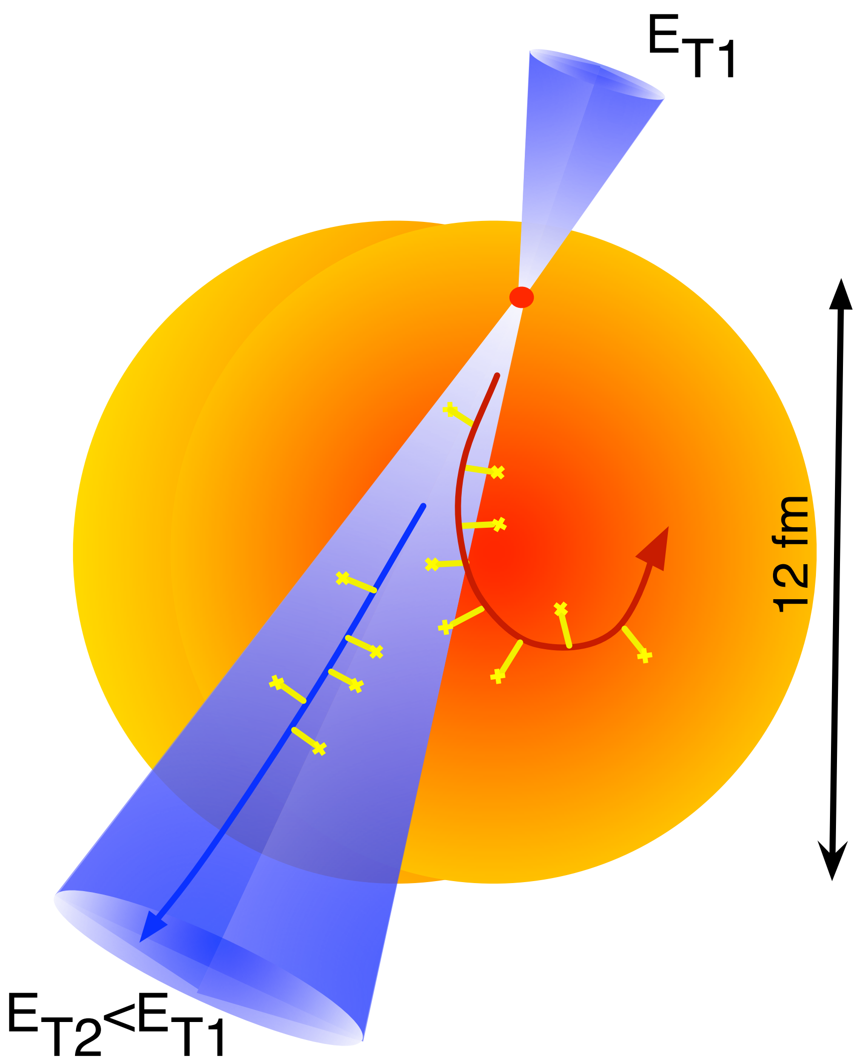






Casalderrey-Solana, Milhano, Wiedemann :: J. Phys. G38 (2011)

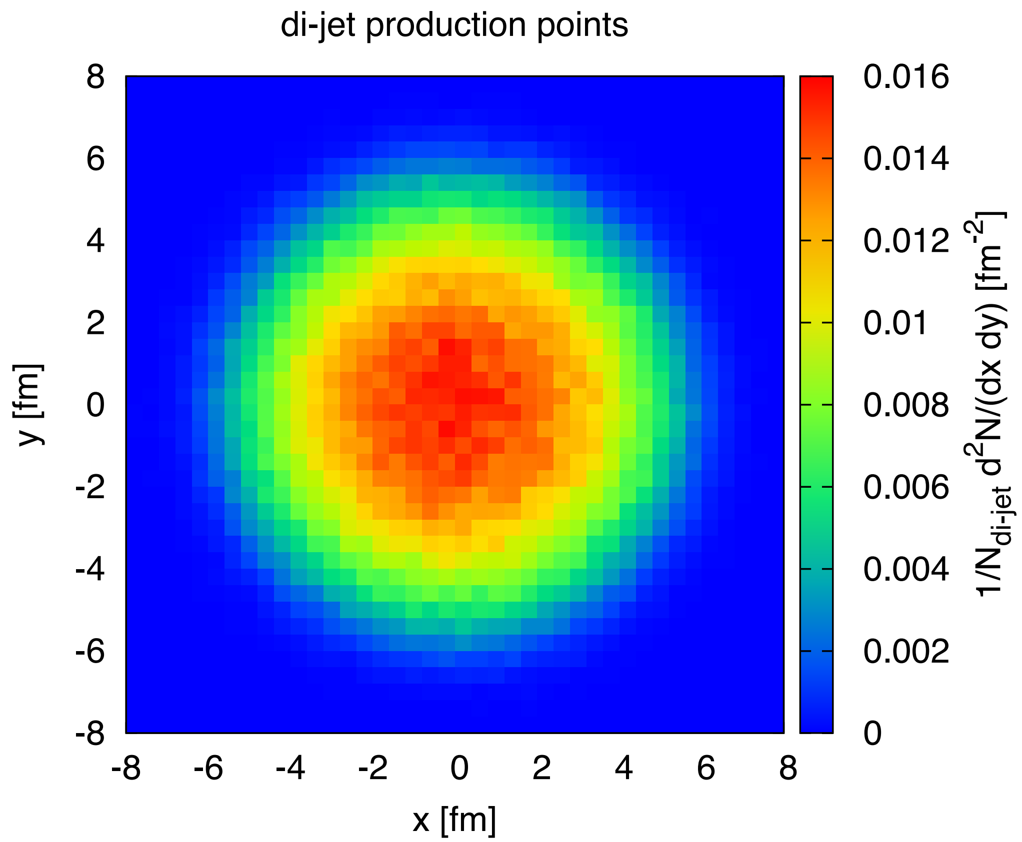
[MANY] LESSONS FROM THE FIRST JET MEASUREMENT

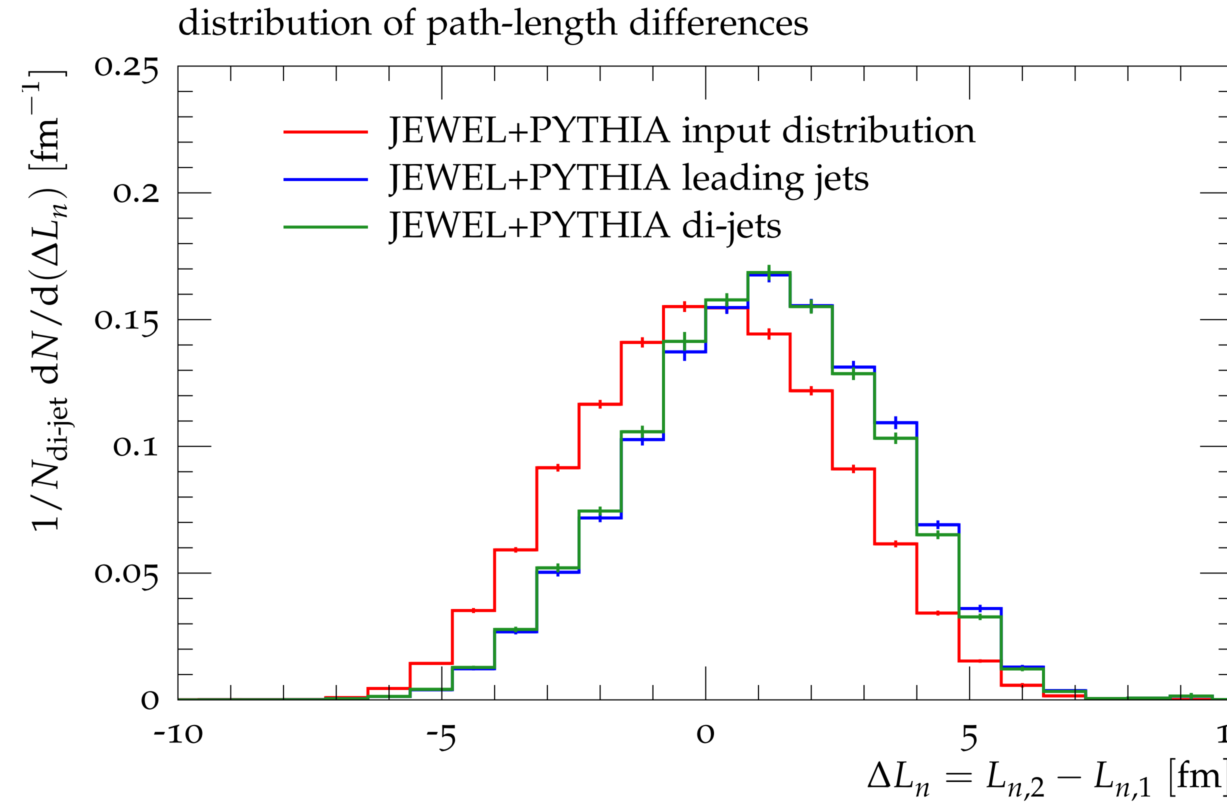


- cartoon implicitly suggests importance of path-length difference in di-jet asymmetry
- follows naive intuition and introduces cognitive bias that can compromise your conclusions
    - it should not have in this case as peeling-off of soft jet components is the key mechanism for jet energy loss [in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

KEY LESSON :: ALWAYS CHECK

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





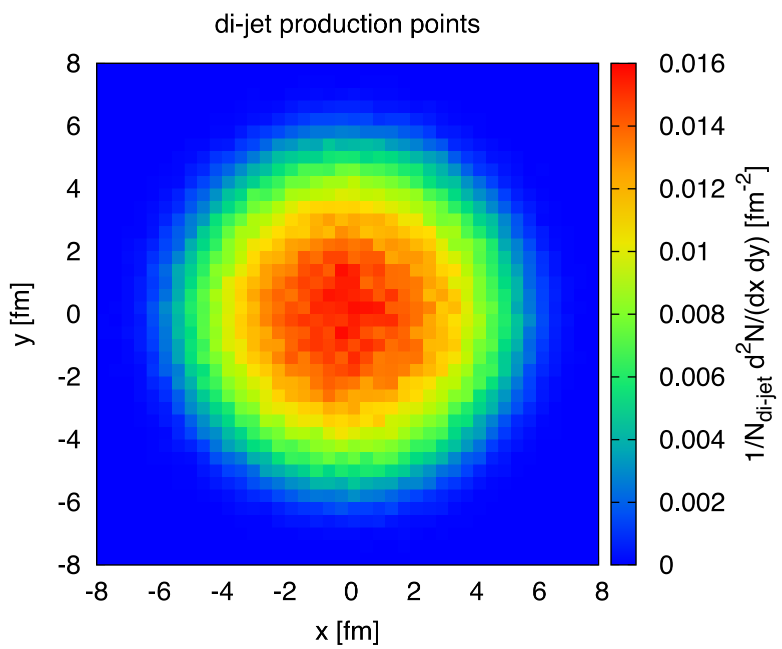
density weighted path-length
[accounts for medium expansion, rapidity independent for boost invariant medium]

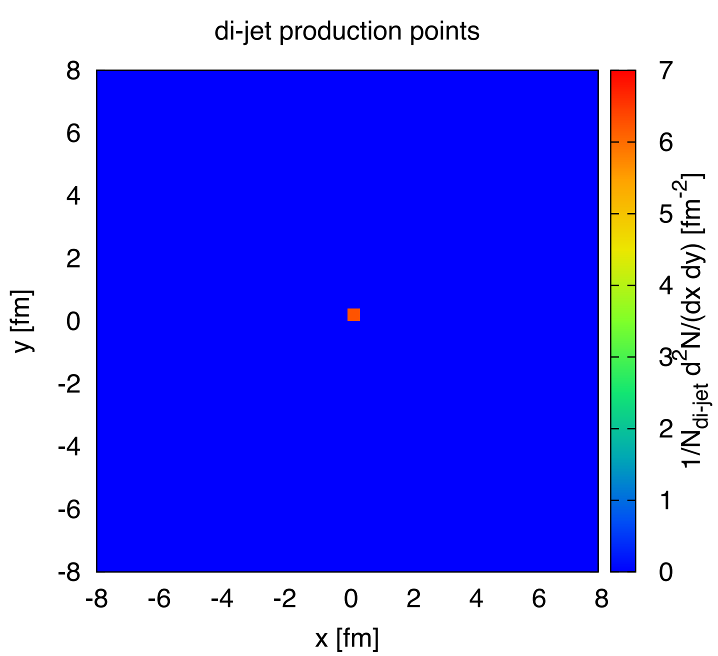
$$L_n = 2\frac{\int d\tau\, \tau n(\mathbf{r}(\tau),\tau)}{\int d\tau\, n(\mathbf{r}(\tau),\tau)}$$

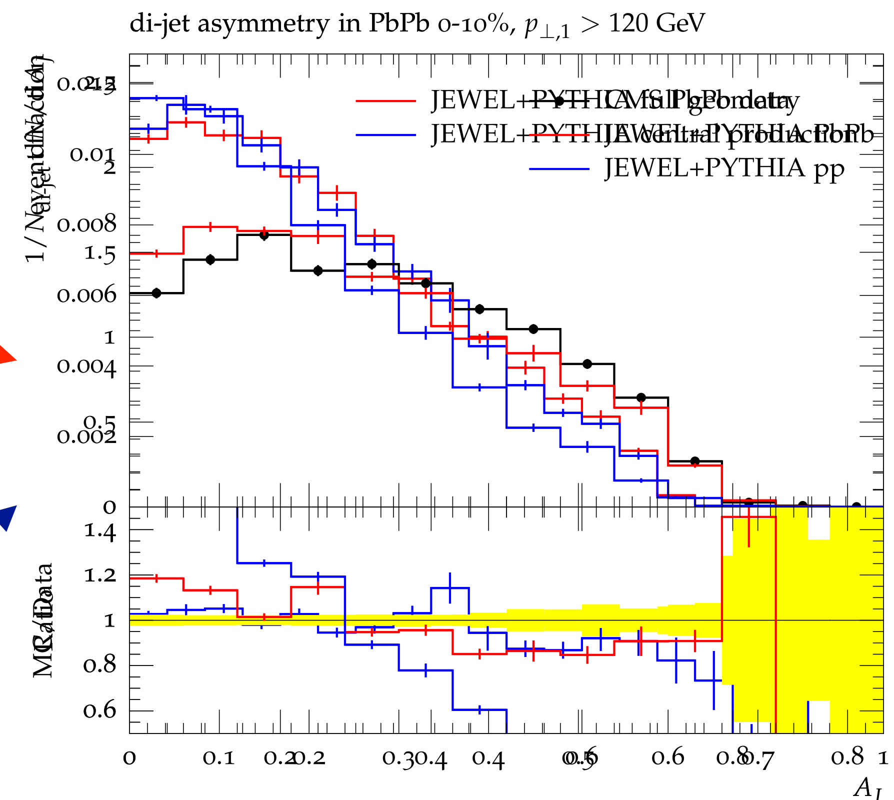
- ✓ small bias towards smaller path-length for leading jets
  - ✓ however, significant fraction [34%] of events have longer path-length for leading jet
  - ✓ consequence of fast medium expansion

A_J CAN BE GENERATED FOR EQUAL PATH LENGTHS

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





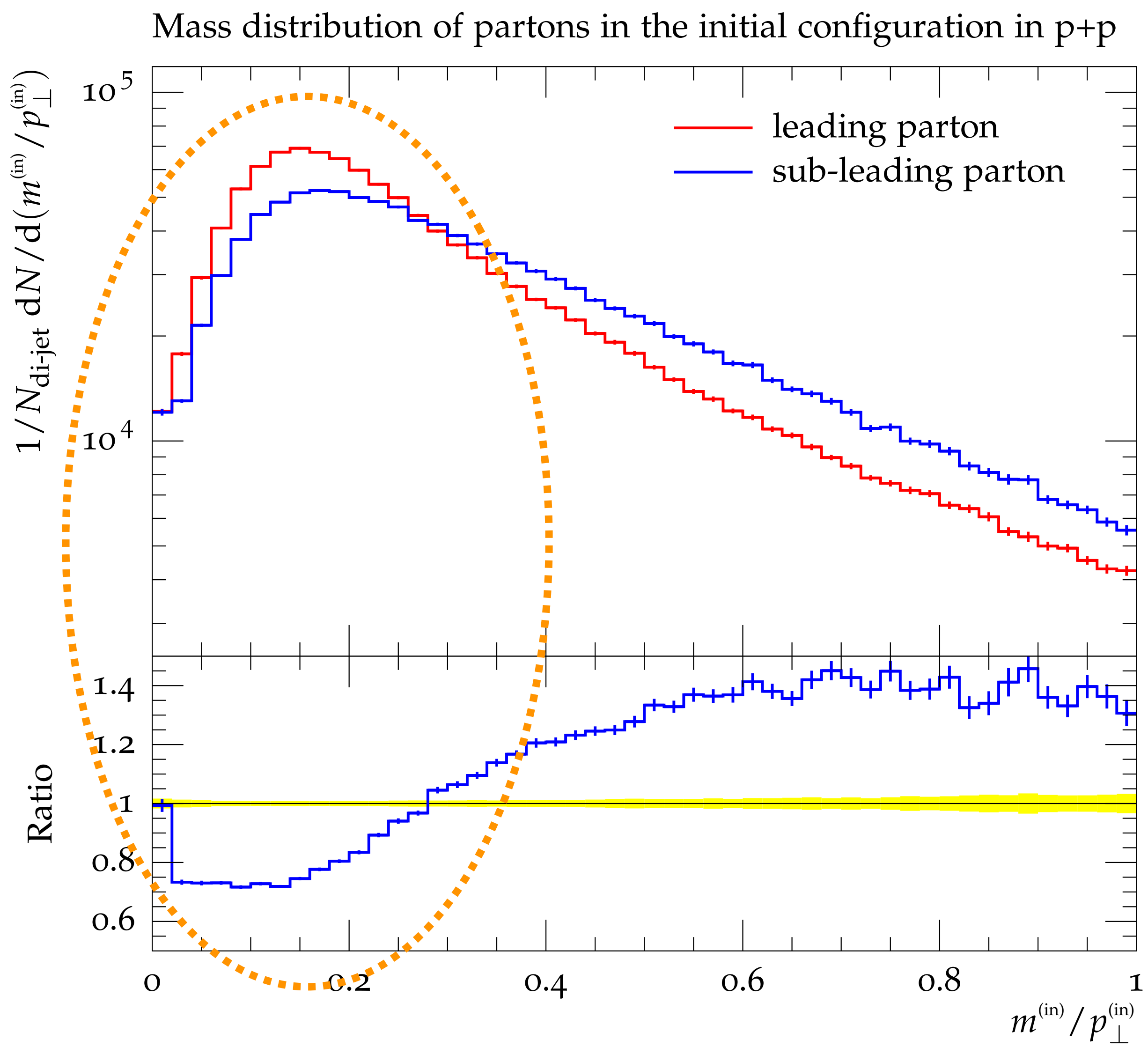


$$A_J = \frac{p_{\perp,1} - p_{\perp,2}}{p_{\perp,1} + p_{\perp,2}}$$

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

JET ENERGY LOSS DOMINATED BY FLUCTUATIONS

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

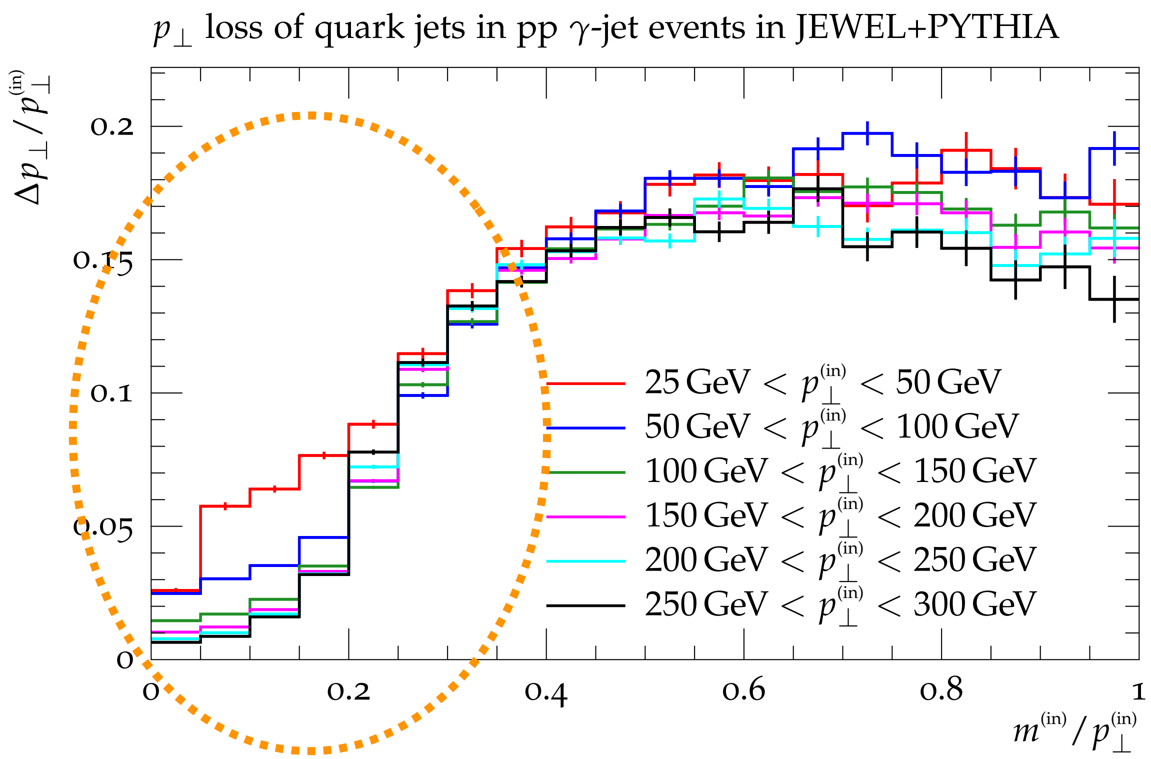


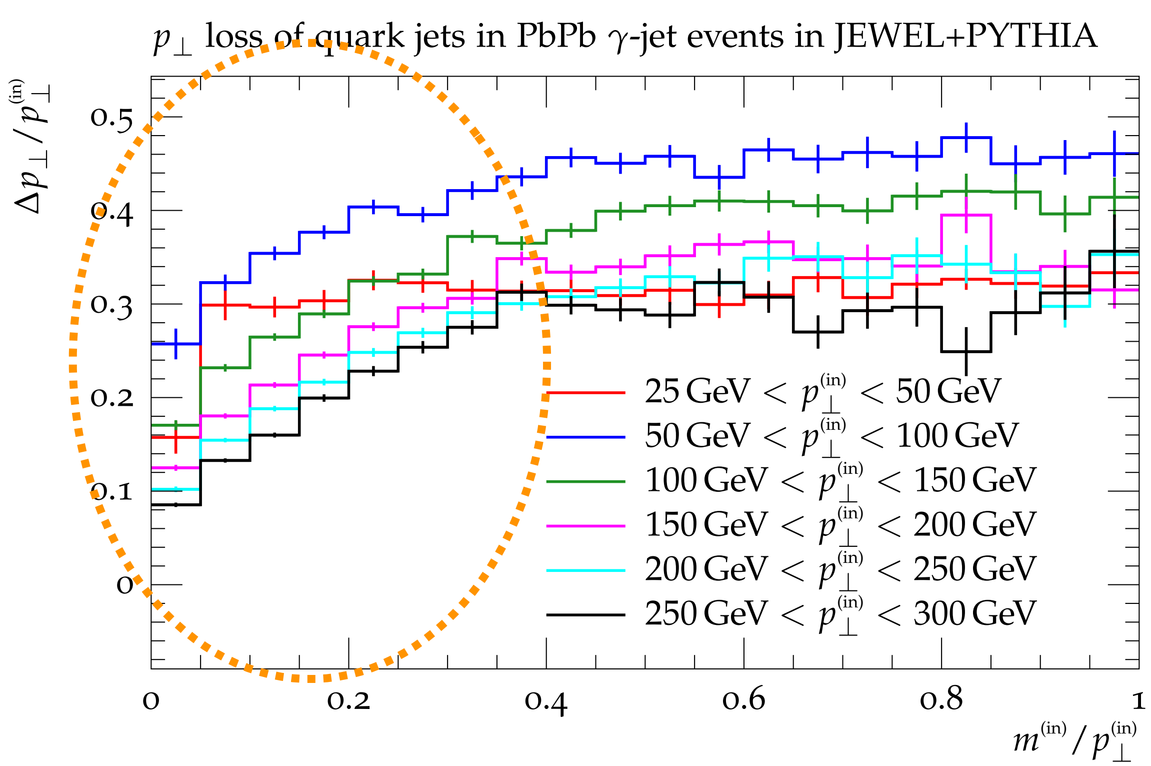
- not all same-energy jets are equal
  - number of constituents driven by initial mass-to-p_t ratio
  - more populated jets have larger number of energy loss candidates

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

understanding of sensitivity of an observable paves the way for physical understanding of QGP properties

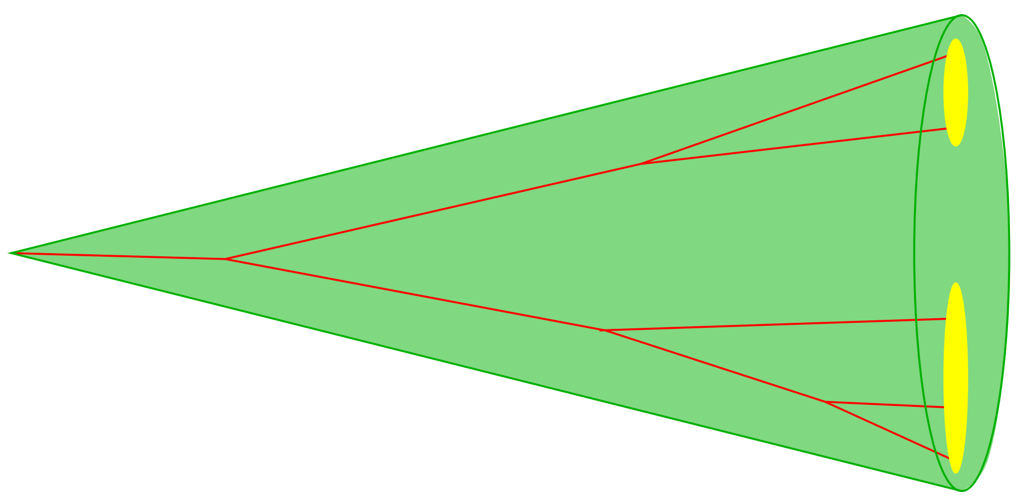
experimental measurement of di-jet imbalance allows for identification of leading mechanism of jet energy loss and isolates the importance of all same energy jets not all losing the same energy

DIGGING DEEPER :: A NEW GENERATION OF JET OBSERVABLES

Milhano, Wiedemann, Zapp :: 1702.xxxxx

- instead of looking at back-to-back jets, focus on what happens inside each jet
  - look at the widest angular separated hard prongs in a jet

SoftDrop procedure:: Larkoski, Marzani, Soyez, Thaler :: JHEP 1405 (2014)



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

- in vacuum this measures the fundamental [Altarelli-Parisi] QCD splitting probabilities

z_g : GROOMED SHARED MOMENTUM FRACTION

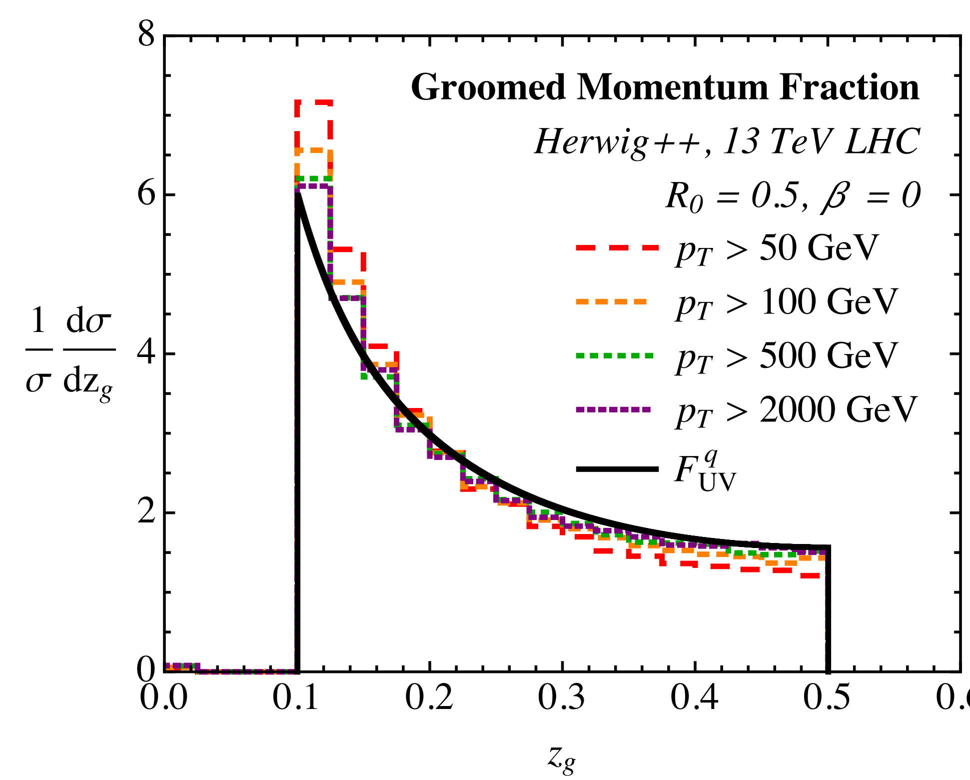
modified Mass Drop Tagger / Soft Drop [β=0]

1. cluster jets with anti-k_t
2. re-cluster with Cambridge/Aachen [from closest to furthest in angle]
3. undo last clustering [jet as 2-prong object] step and compute z_g
4. if $z_g > z_{cut}$ stop,
   else discard softer prong and go back to 3

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

at LO

$$p(z_g) = \frac{P(z_g) + P(1-z_g)}{\int_{z_{cut}}^{0.5} dz\,\left(P(z) + P(1-z)\right)}\,\Theta(z_g - z_{cut})$$

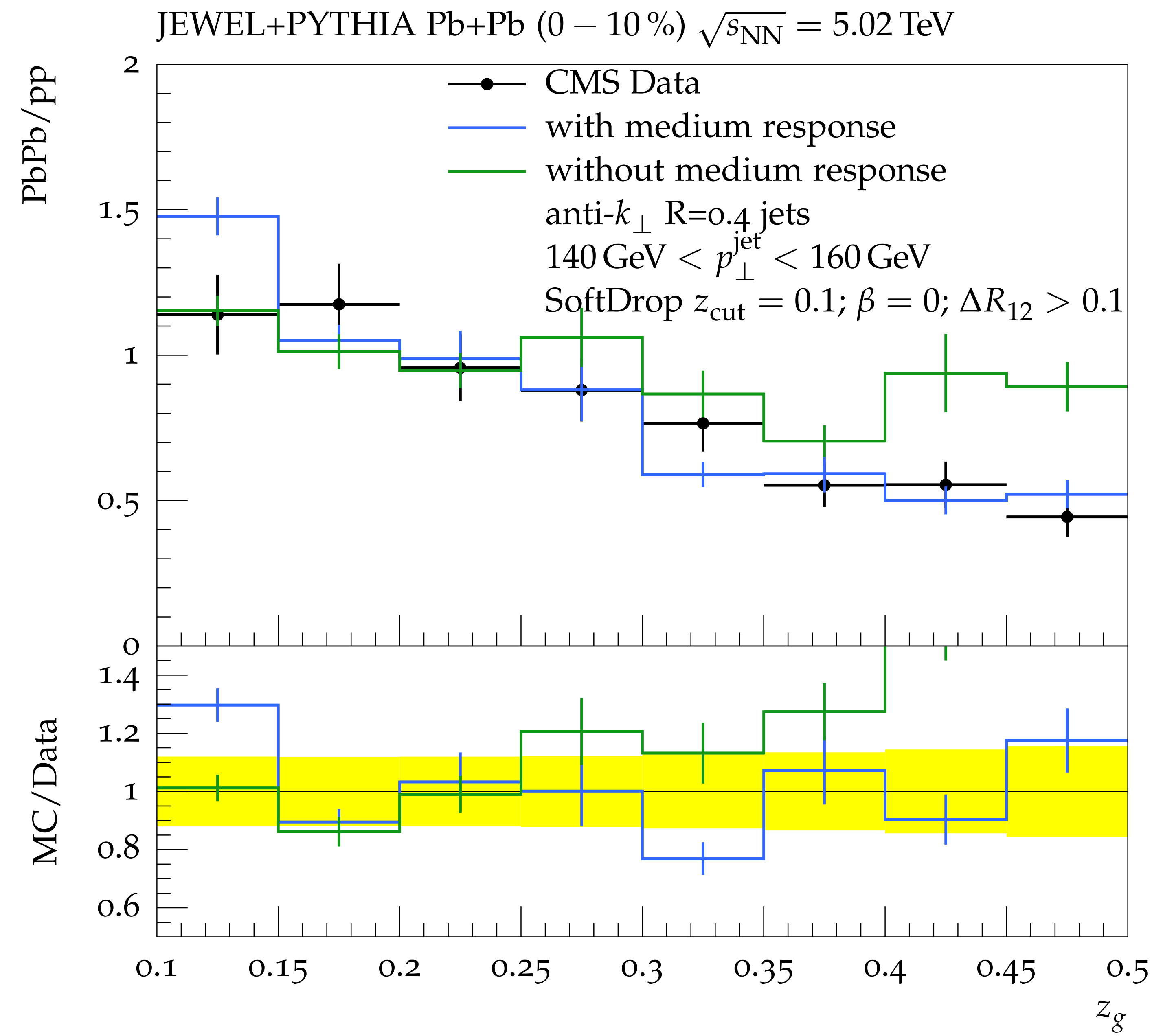


➤ **in vacuum, the procedure measures the LO Altarelli-Parisi splitting function**

DIGGING DEEPER :: A NEW GENERATION OF JET OBSERVABLES

Milhano, Wiedemann, Zapp :: 1707.04142

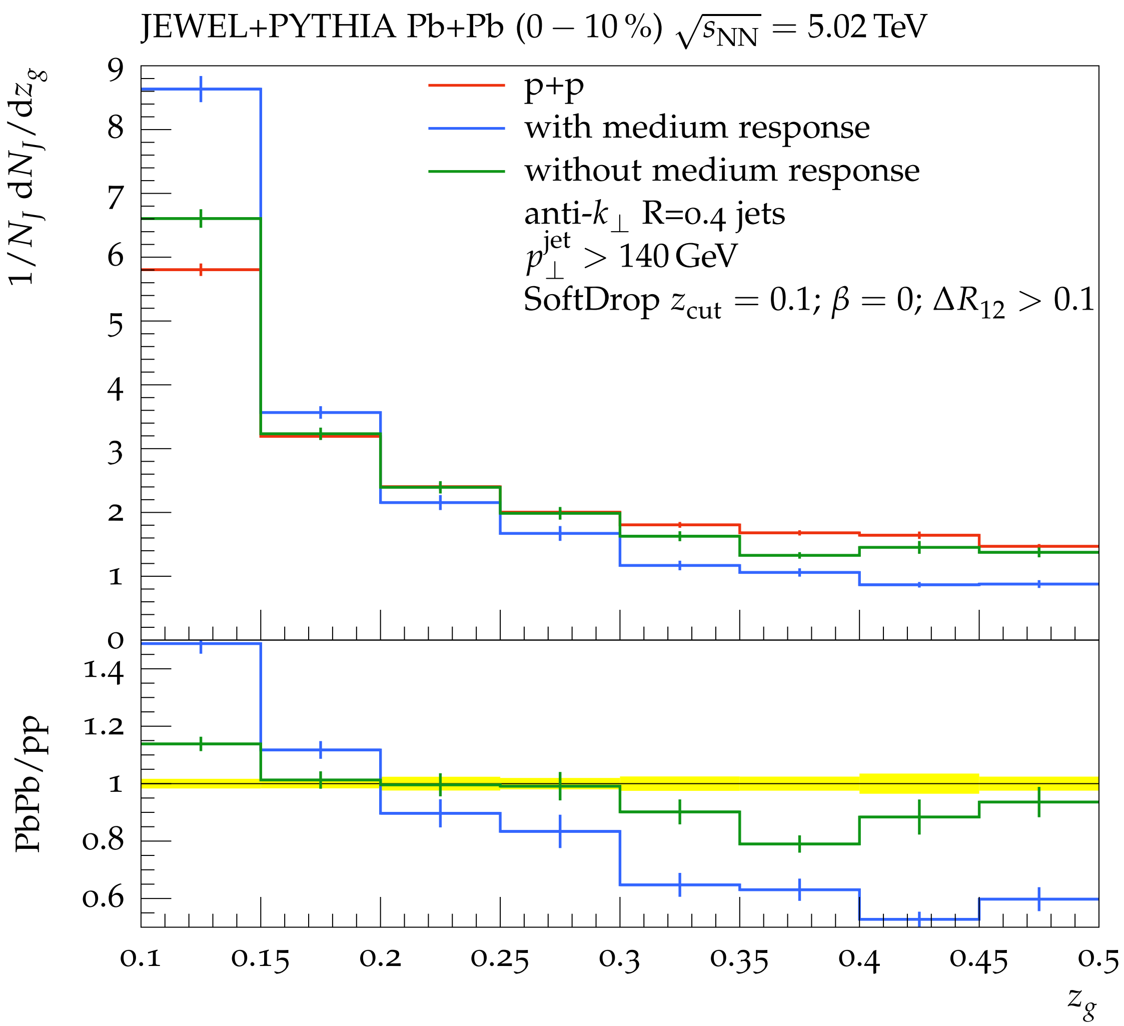
- substancial modification observed in PbPb collisions

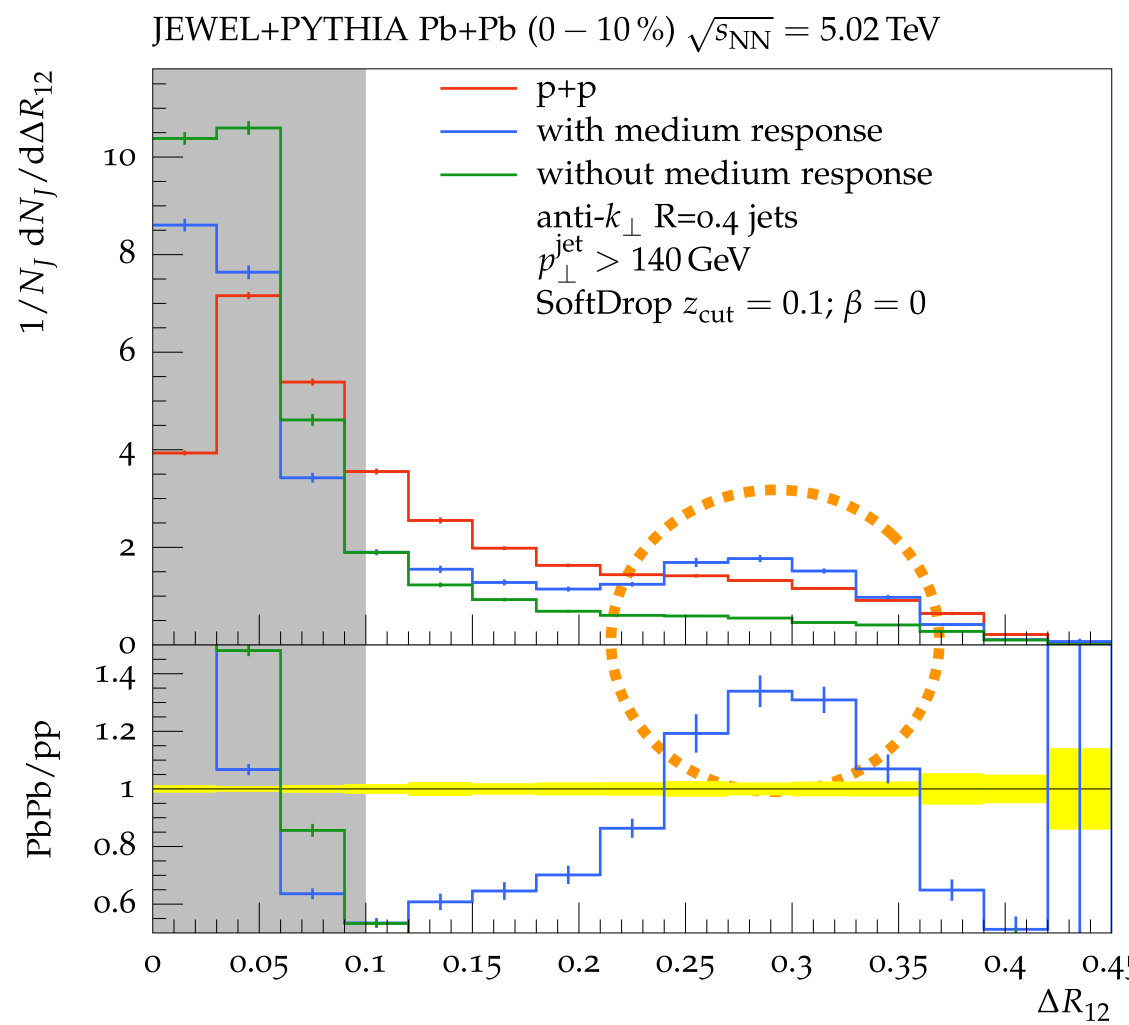


- proceed as with di-jets to isolate physical origin

DIGGING DEEPER :: A NEW GENERATION OF JET OBSERVABLES

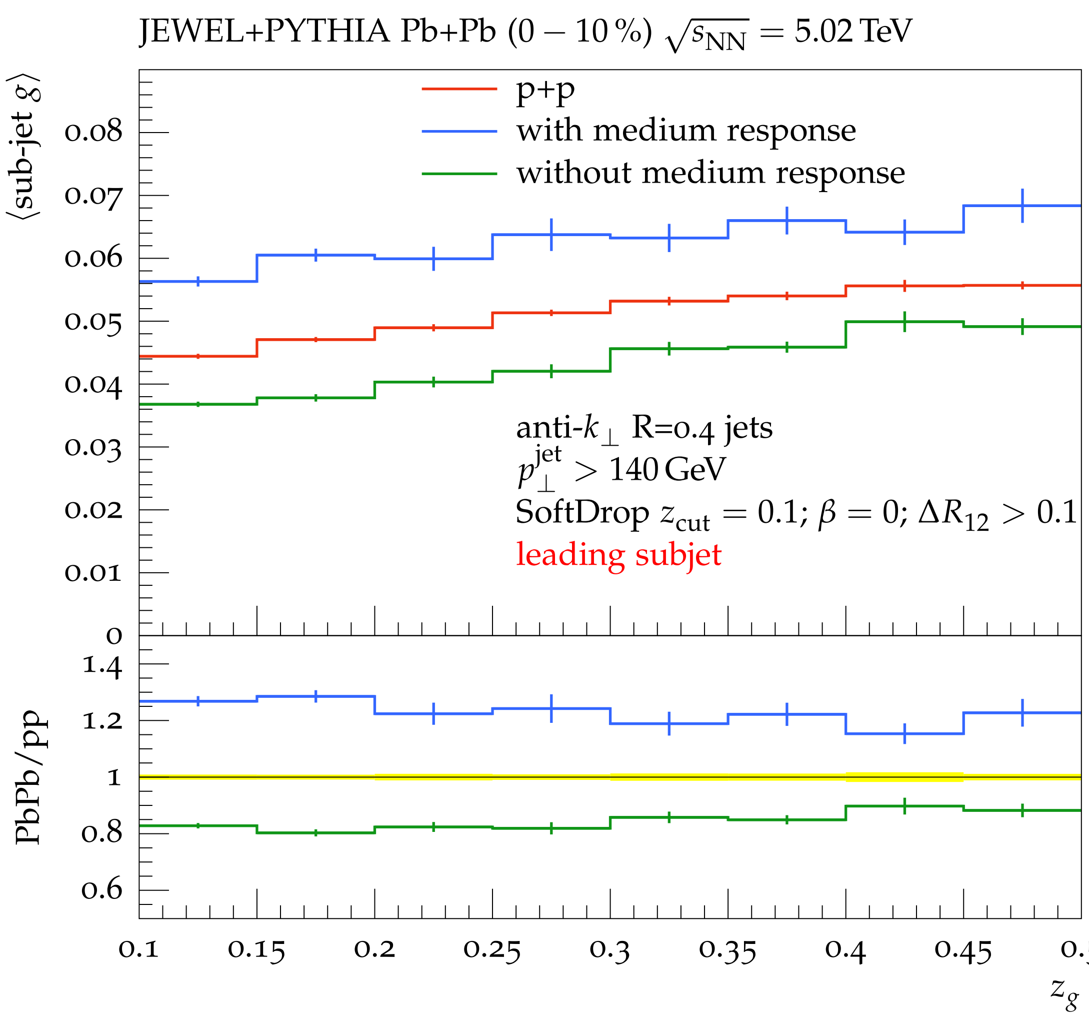
Milhano, Wiedemann, Zapp :: 1702.xxxxx

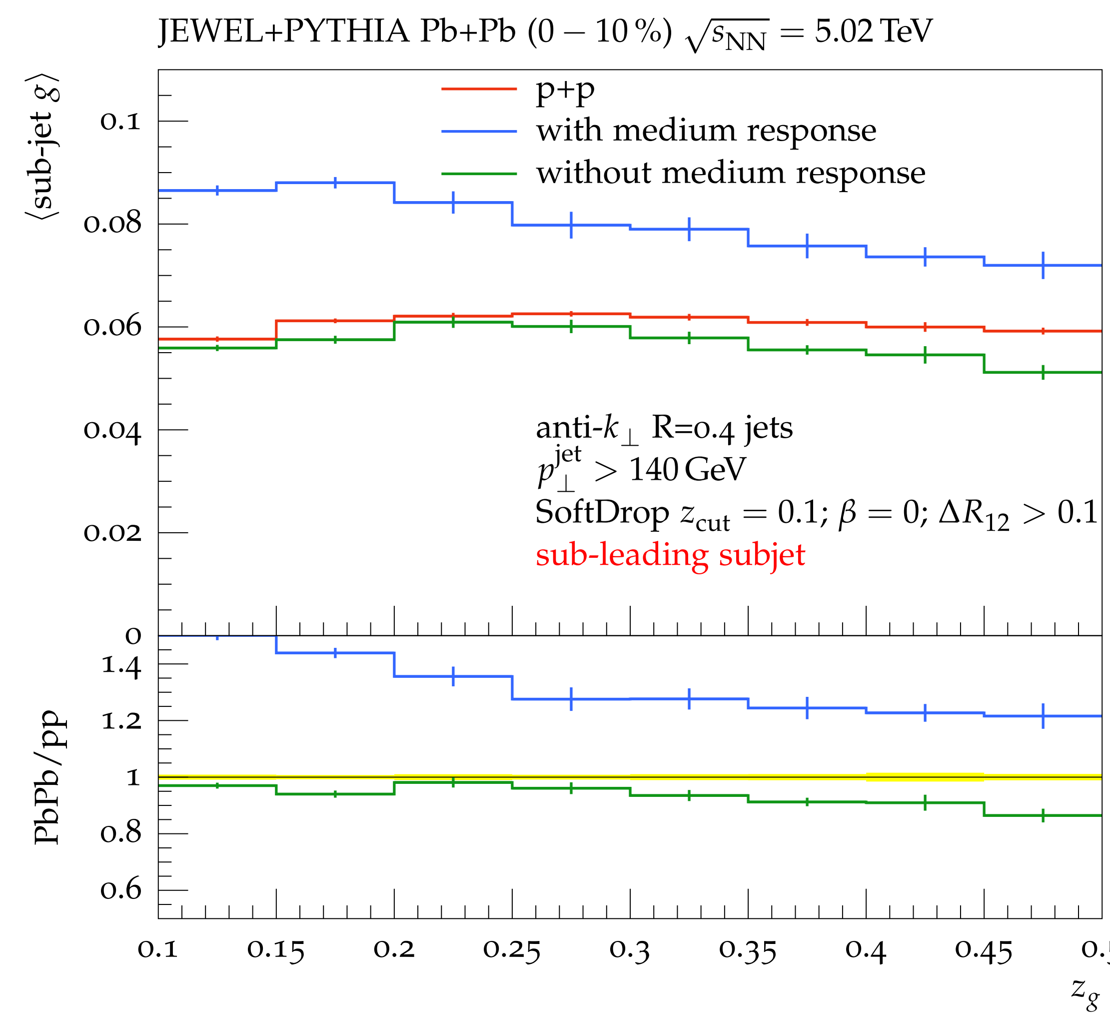




- requires account of QGP response
  - *predicted* additional *measurable* component at large angular separation
- **effect conceivably arising from promotion of configuration where sub-leading prong became hard enough due to contribution from QGP response to pass hardness cut :: seeing QGP response**

THE GIRTH OF PRONGS :: MEASURABLE CROSS CHECK





$$g = \sum_i \frac{p_{\perp,i}\, \Delta R_{ij}}{p_\perp^J}$$

:: first radial moment of the intra-jet $p_\perp$ distribution

- modification of girth distribution of sub-leading prong should be unique to jet-correlated medium mechanism increasingly engineered jet observables can provide direct access to QGP response to jets

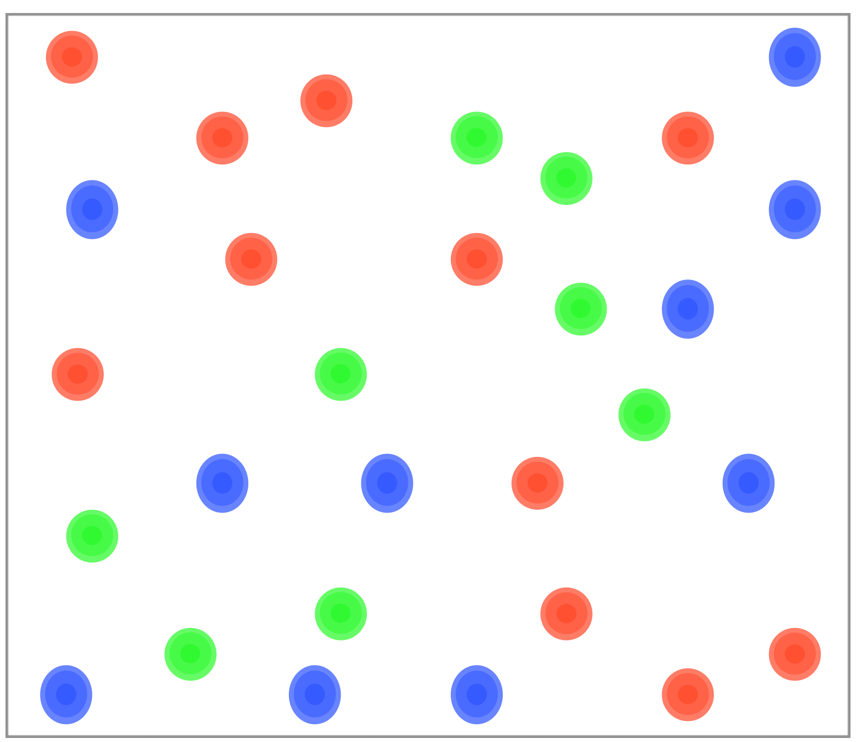
or better, how the energy lost by jets couples QGP with the jet

trade-off between observable complexity and improved potential for insight worth it

what is hot nuclear matter?

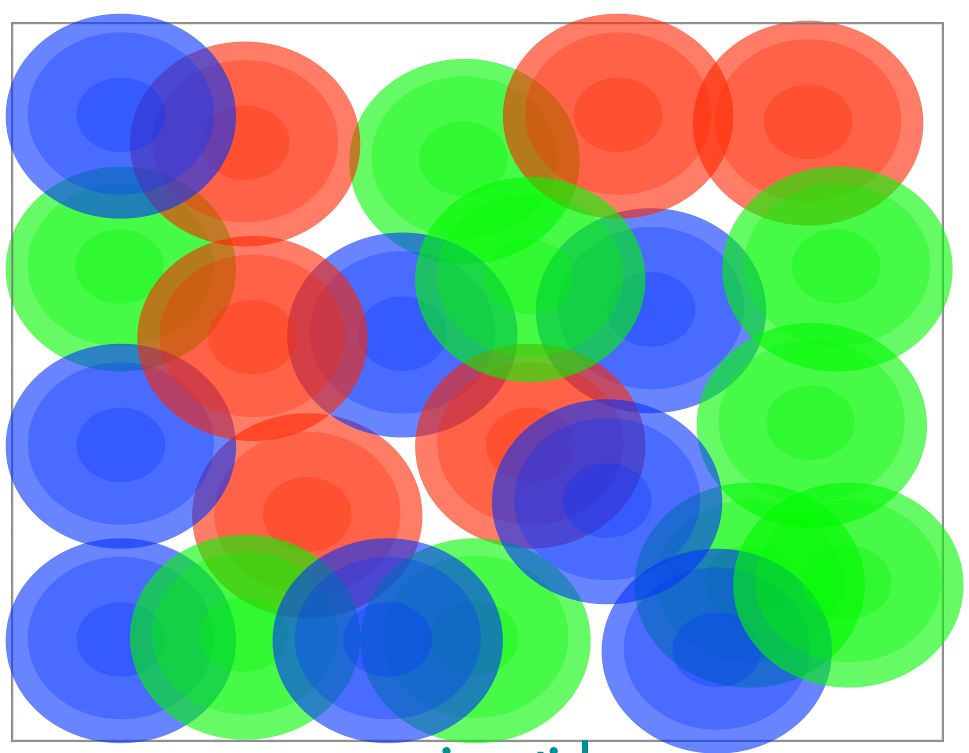
what do jets interact with?

?



gas of quarks and gluons
[weakly coupled]

?



no quasi-particles
[strongly coupled]

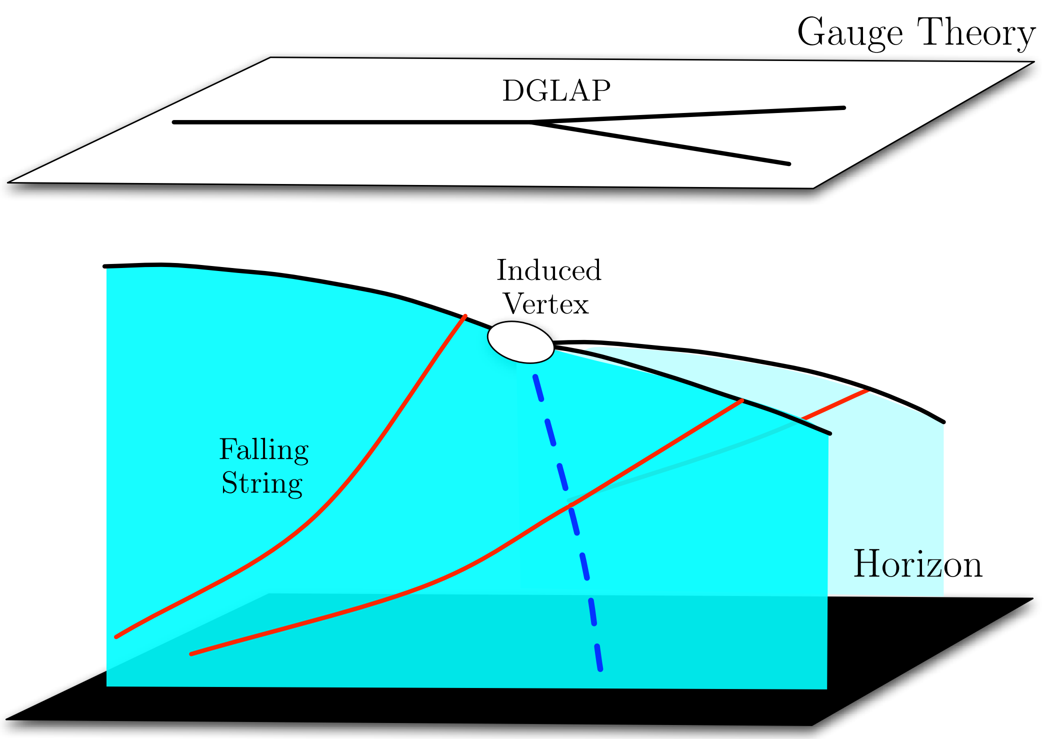
what is hot nuclear matter?

what do jets interact with?

can jet-QGP interaction be consistently described for a strongly coupled QGP?

HYBRID STRONG/WEAK COUPLING MODEL

Can Gulan, Casalderrey, Milhano, Pablos, Rajagopal :: JHEP 1410 (2014) 019
JHEP 1603 (2016) 053
1609.05842

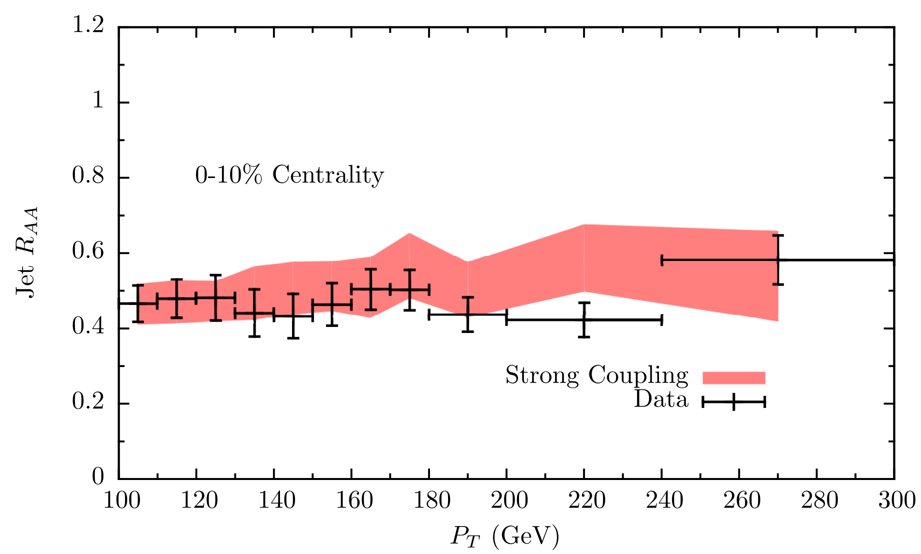


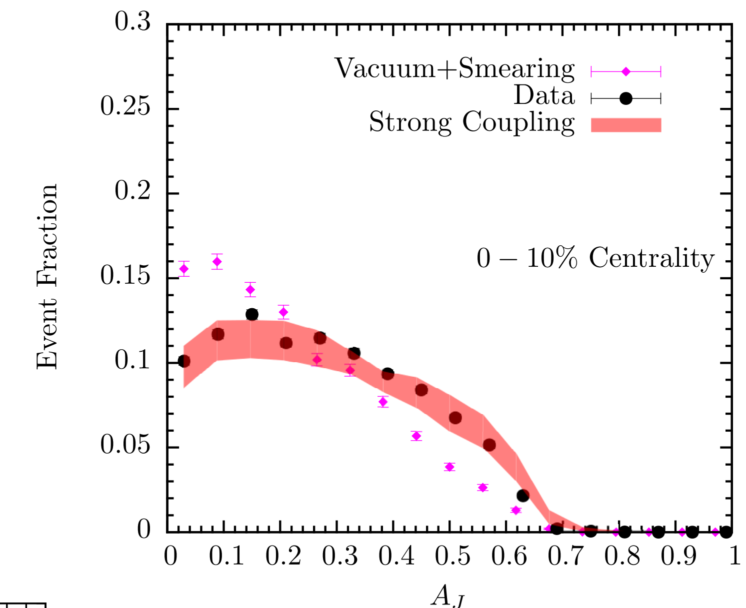
- physics at different scales merit different treatments
  - vacuum jets where each parton loses energy non-perturbatively [as given by a holographic AdS-CFT calculation]
- lost energy becomes a wake [QGP response], part of which will belong to the jet

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

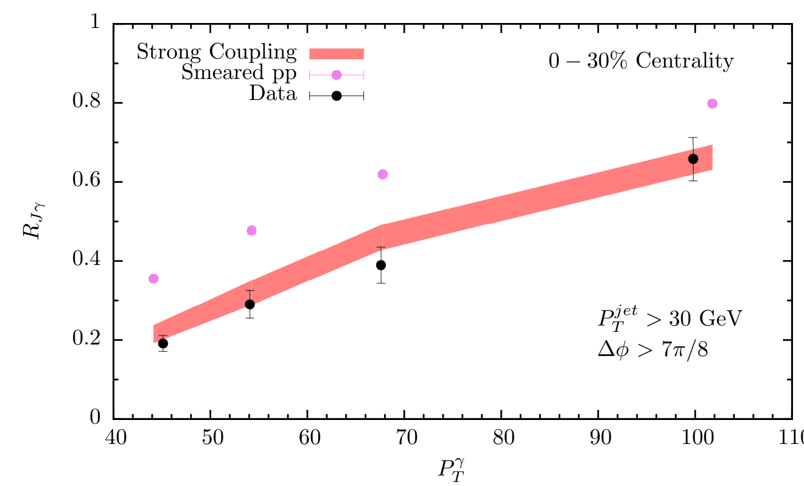
single free parameter
[accounts for QCD/N=4 SYM differences]

HYBRID STRONG/WEAK COUPLING MODEL :: POSTDICTIONS





5 observables
and centrality dependence
all described with
single parameter

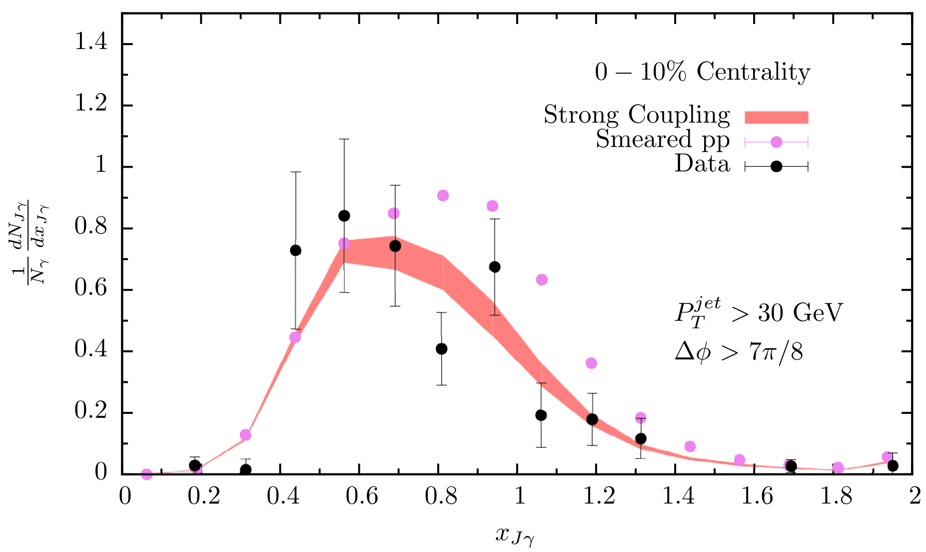


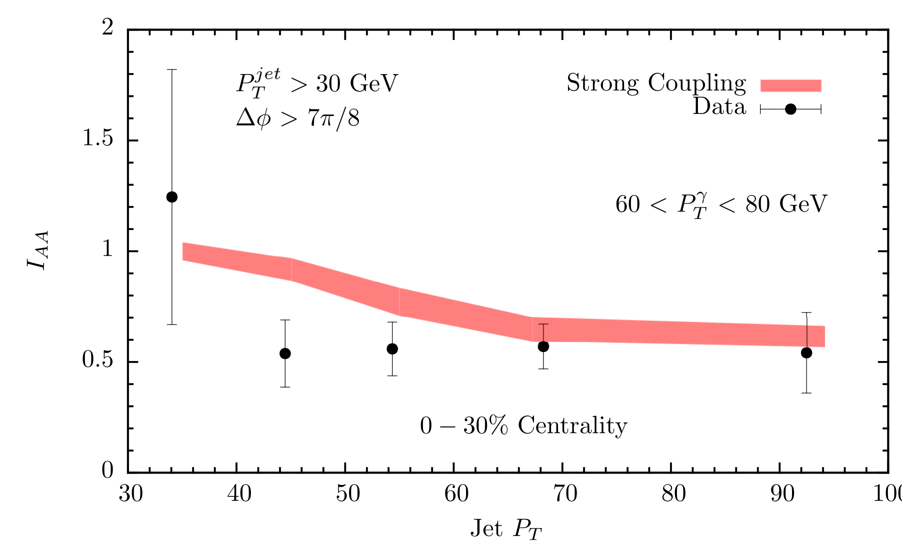
Bands in all plots correspond to

$$0.32 < \kappa_{sc} < 0.41$$

$\mathcal{O}(1)$ as expected.

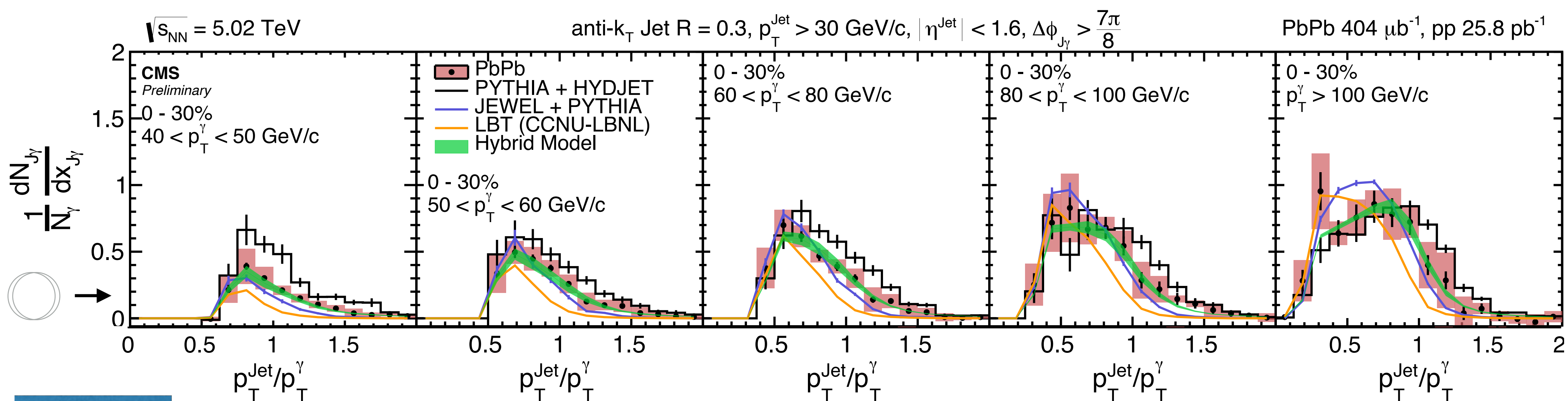
$$x_{stop}^{QCD} \sim (2 - 3) x_{stop}^{\mathcal{N}=4}$$





HYBRID STRONG/WEAK COUPLING MODEL :: PREDICTIONS

Theory Comparison: Central PbPb $x_{J\gamma}$

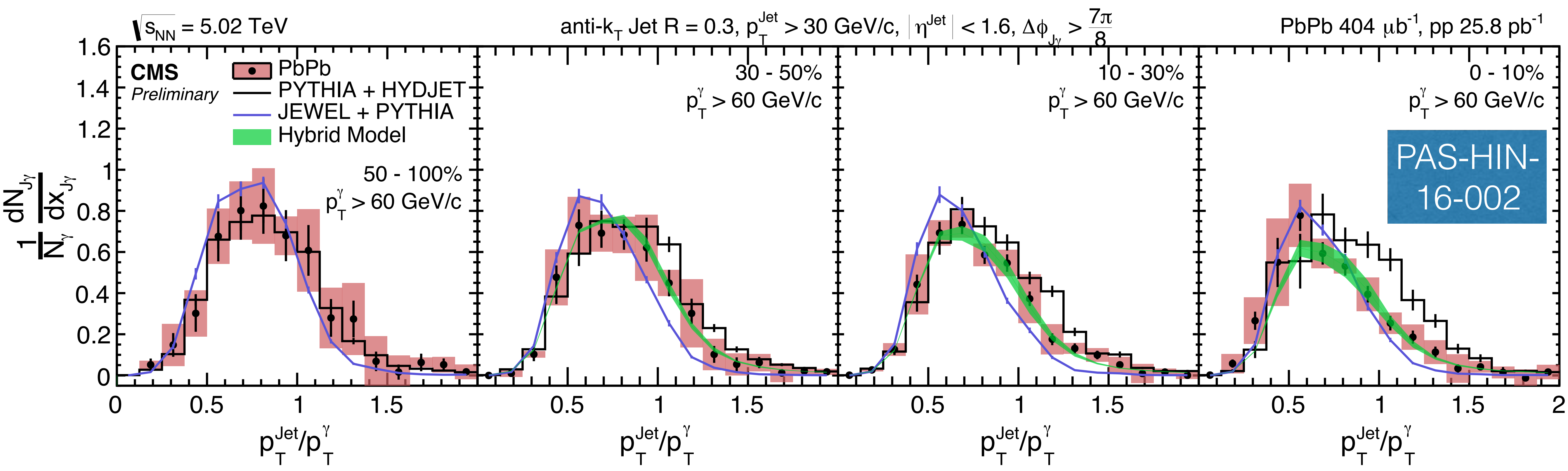


PAS-HIN-16-002

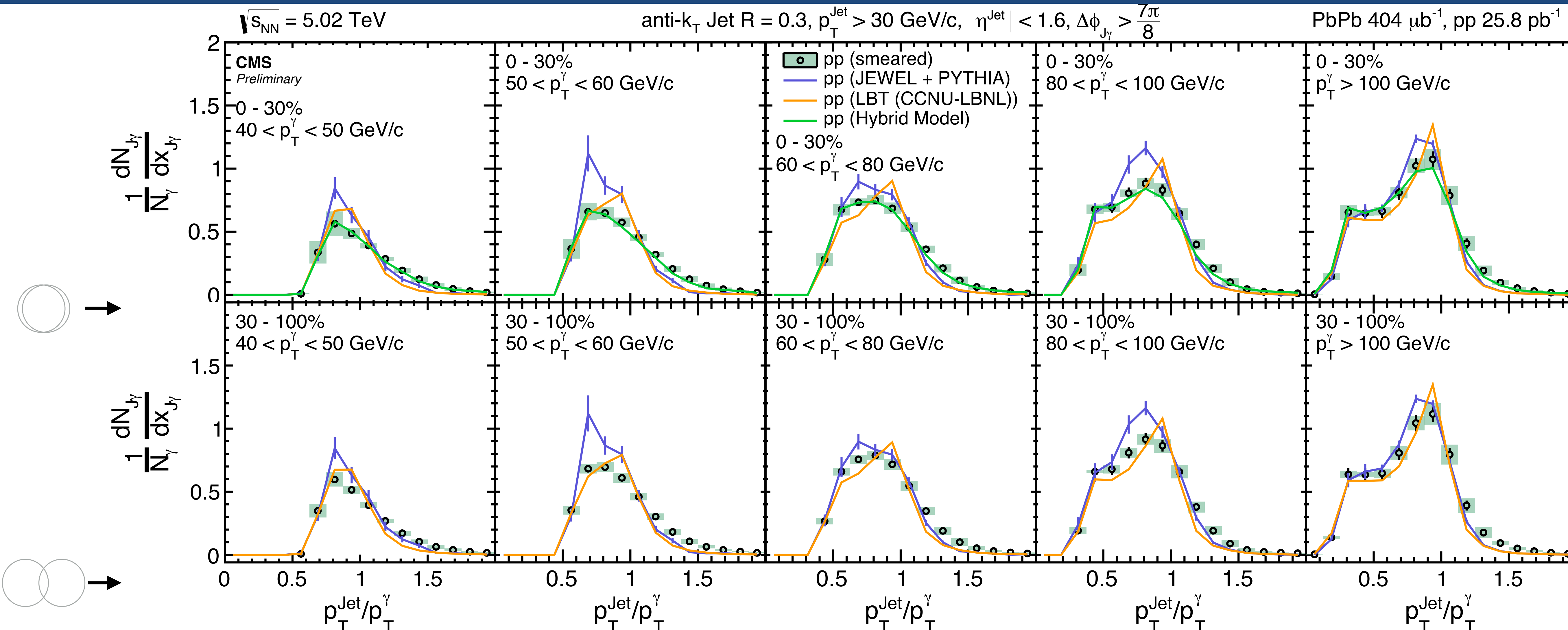
40 < p_T^γ < 50 **50 < p_T^γ < 60** **60 < p_T^γ < 80** **80 < p_T^γ < 100** **p_T^γ > 100**

- In general, models appear to describe $x_{J\gamma}$
  - LBT has normalization issue relative to other curves
    - To be fixed in conjunction with analyzers
  - JEWEL and HYBRID comparable through all bins

Theory Comparison: $x_{J\gamma}$ in PbPb



Theory Comparison: Distribution of $x_{J\gamma}$ vs. γ p_T

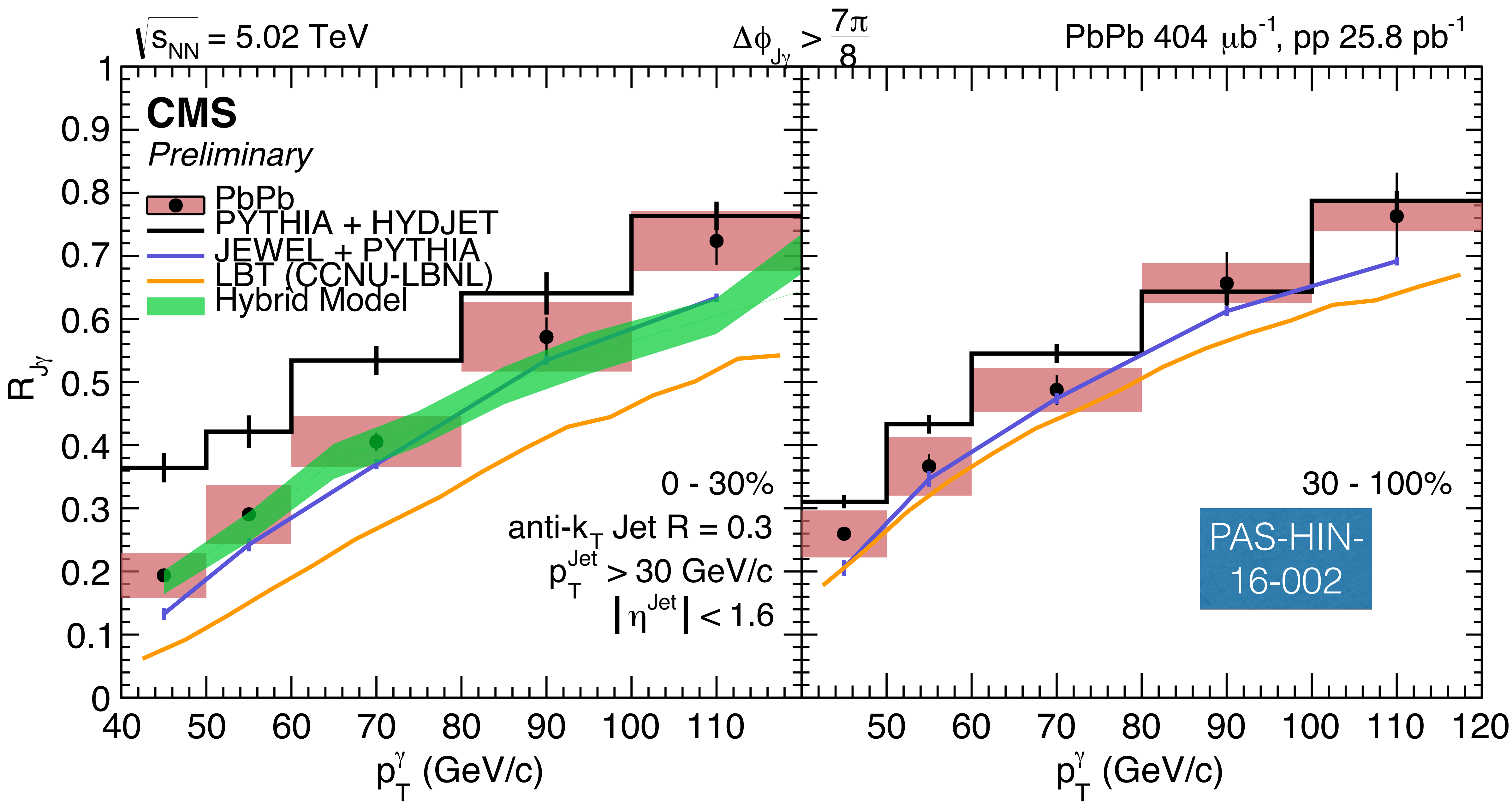


PAS-HIN-16-002

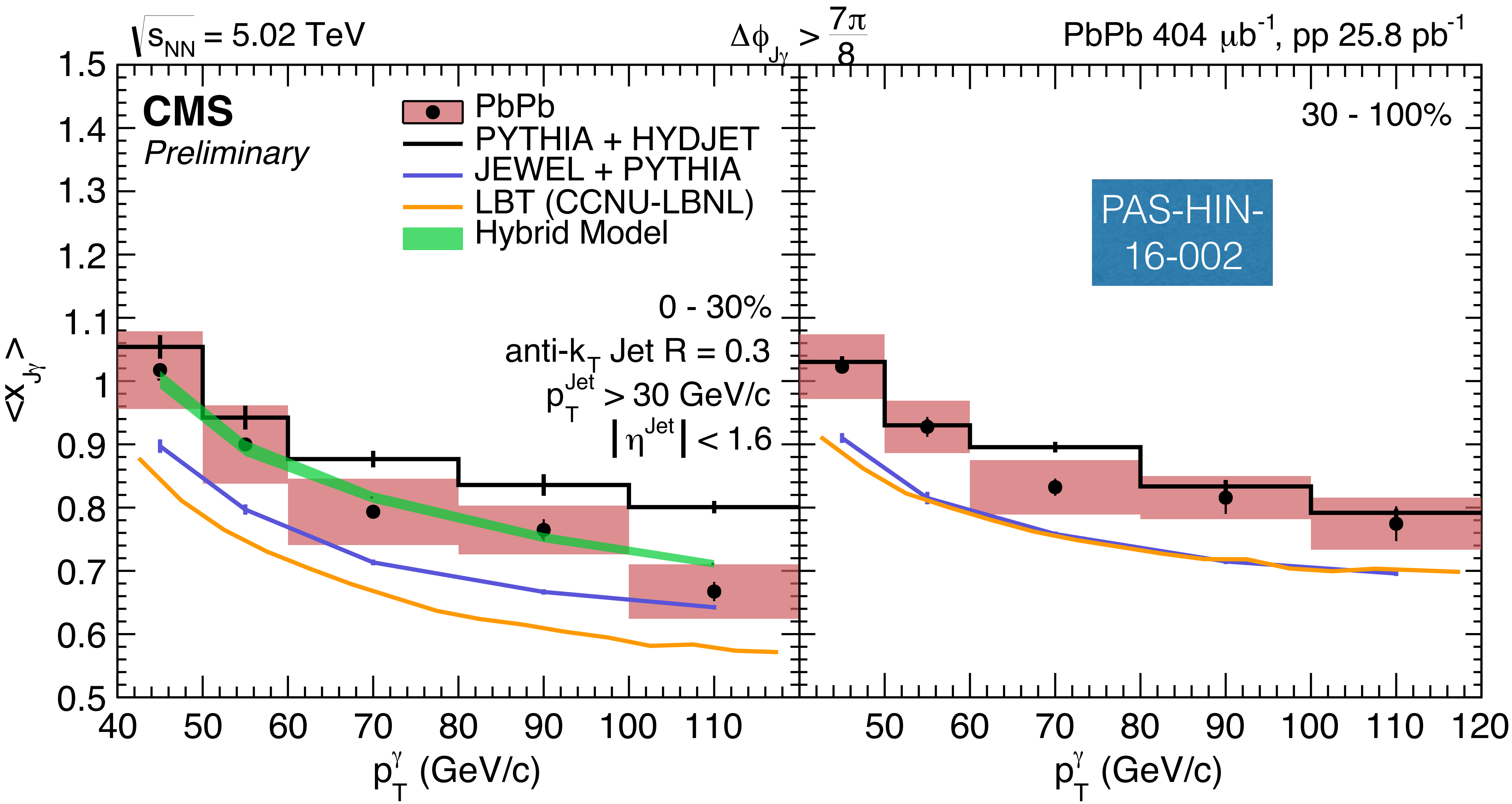
40 < p_T^γ < 50 **50 < p_T^γ < 60** **60 < p_T^γ < 80** **80 < p_T^γ < 100** **p_T^γ > 100**

- Overlaid PYTHIA, JEWEL, LBT and Hybrid Model

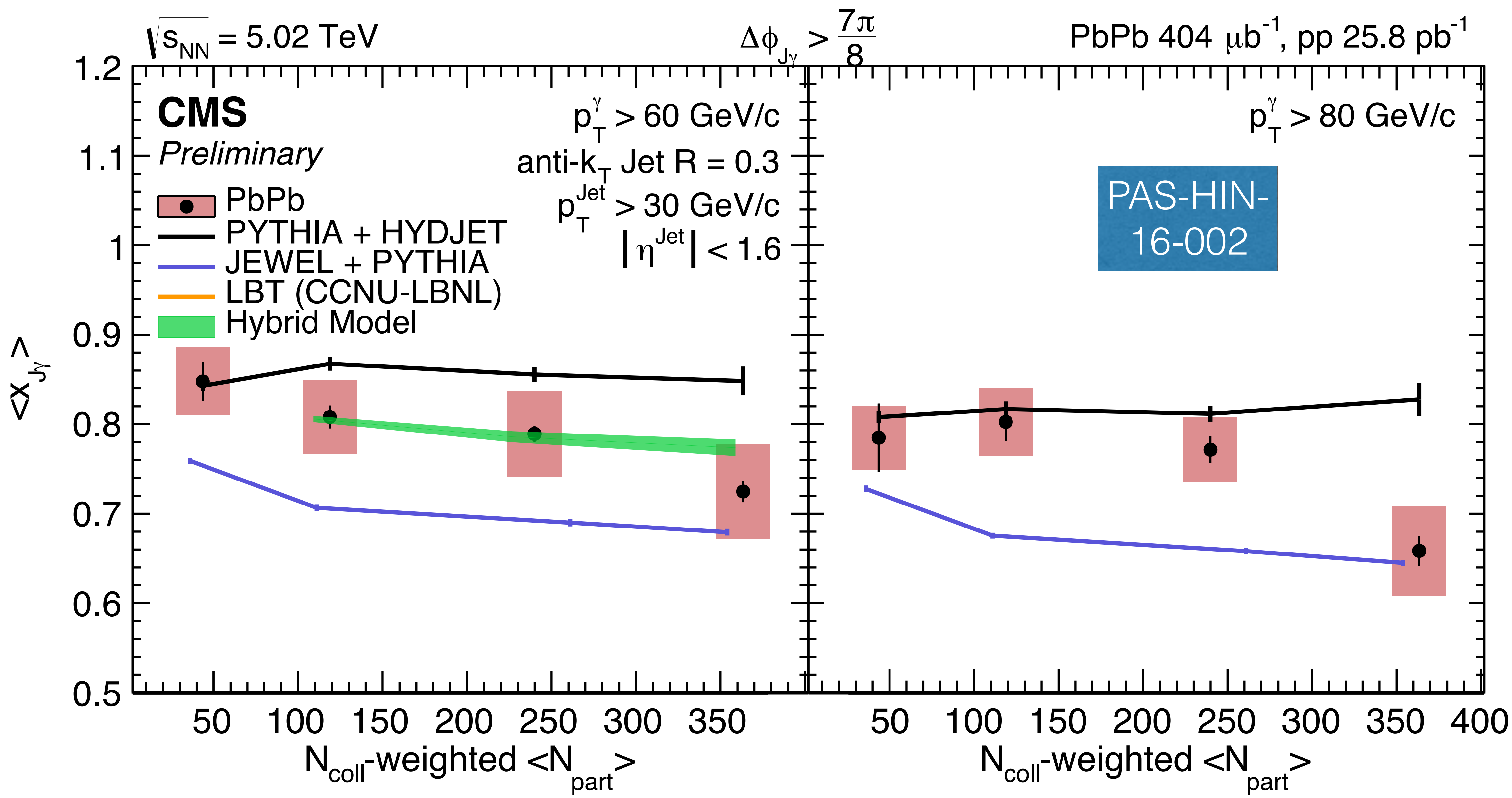
Theory Comparison: $R_{J\gamma}$ in PbPb



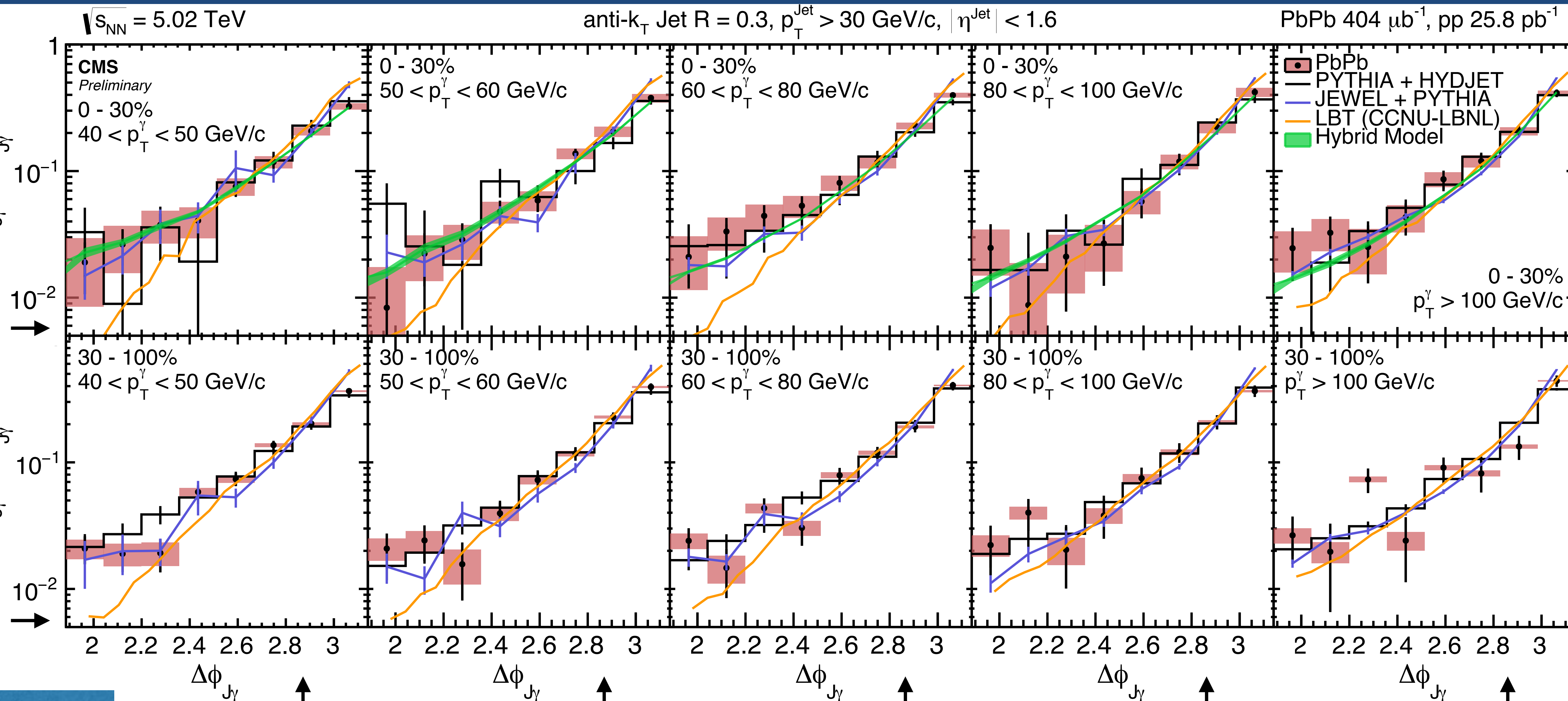
Theory Comparison: $x_{J\gamma}$ in PbPb



Theory Comparison: $x_{J\gamma}$ in PbPb



Theory Comparison: $\Delta\phi_{J\gamma}$ in PbPb

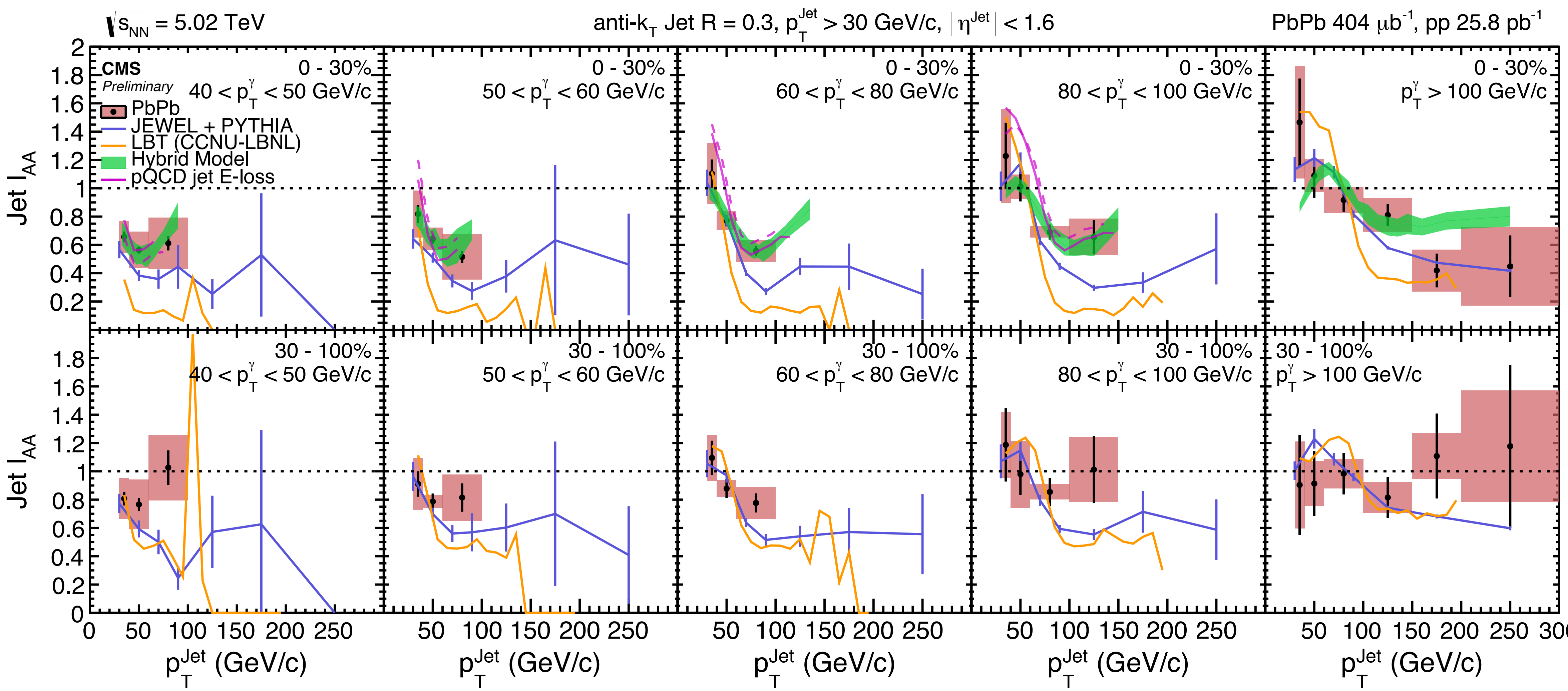


PAS-HIN-16-002

40 < p_T^γ < 50 **50 < p_T^γ < 60** **60 < p_T^γ < 80** **80 < p_T^γ < 100** **p_T^γ > 100**

- Overlaid PYTHIA+HYDJET, JEWEL, LBT and Hybrid Model

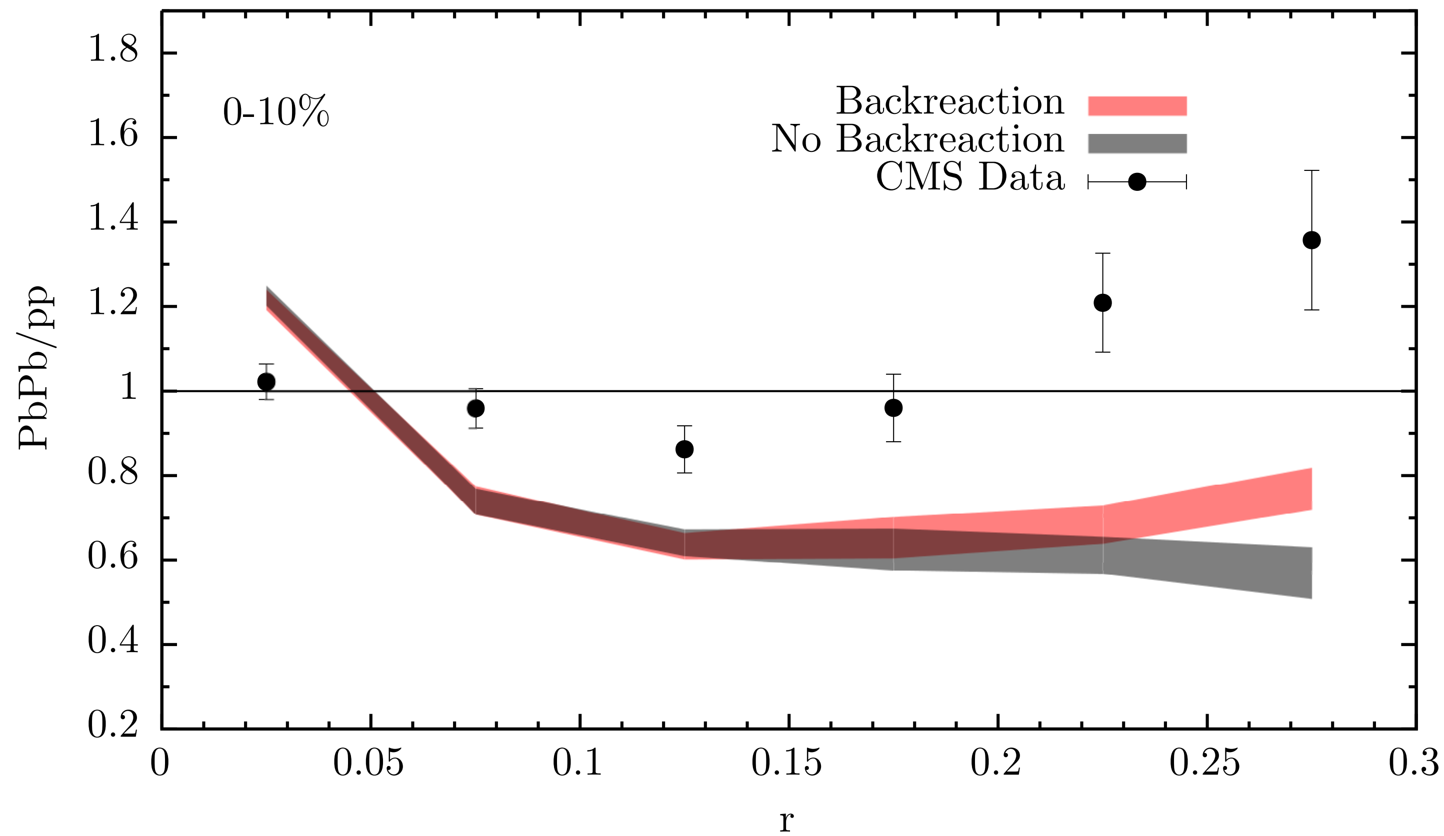
HYBRID STRONG/WEAK COUPLING MODEL :: PREDICTIONS



jet-QGP interaction can be described in strong coupling

however, effective models are most informative when and where they fail

THE FAILURES OF THE HYBRID STRONG/WEAK COUPLING MODEL



ratio of jet transverse density profiles

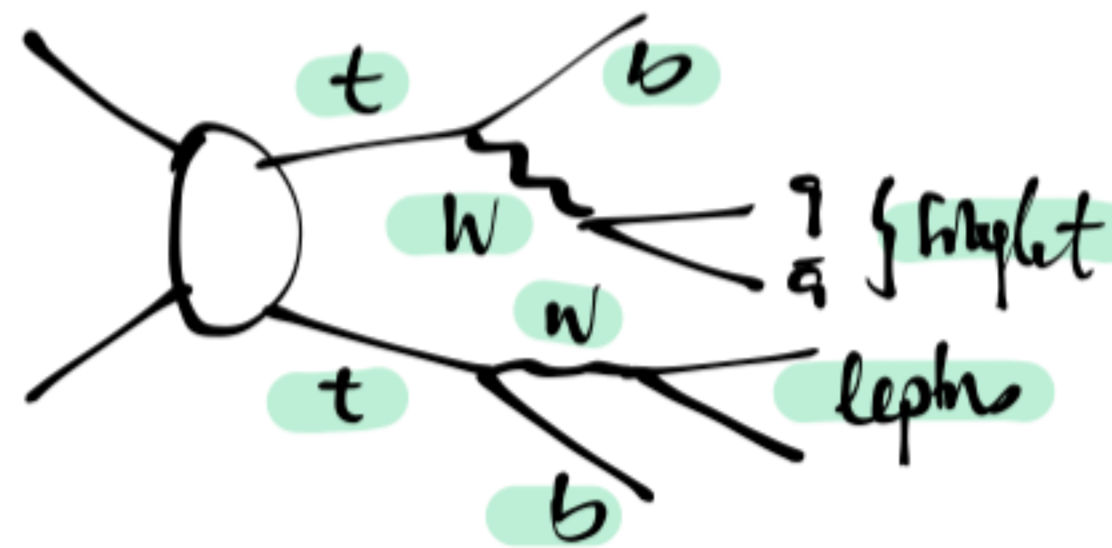
- an example of generic failure to describe edge structure of jets
- what Physics is missing?
  - possibly not all lost energy hydrodynamizes…
  - need improved treatment for conclusive check
  - fate of lost energy best handle on thermalization [how QGP came into being]

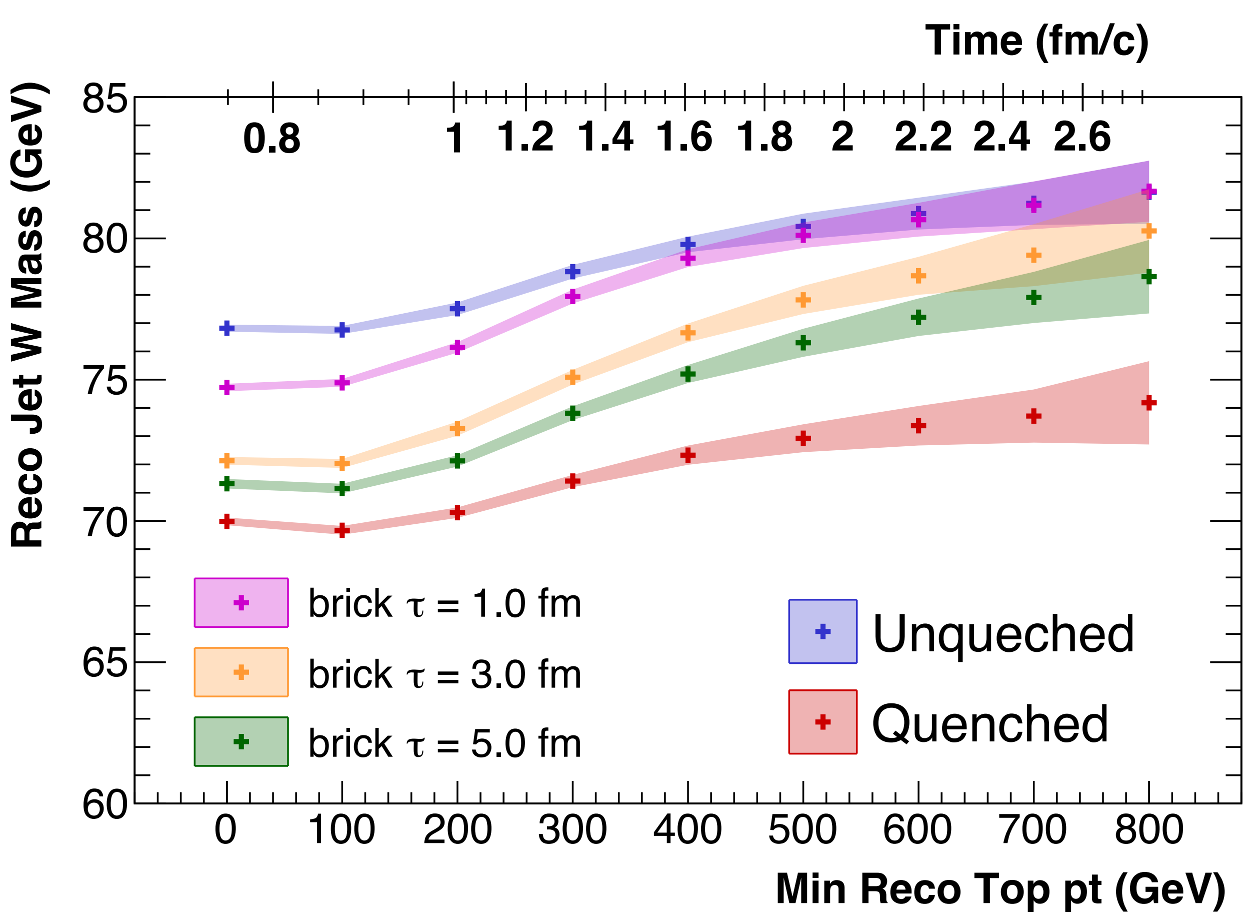
a look into the future

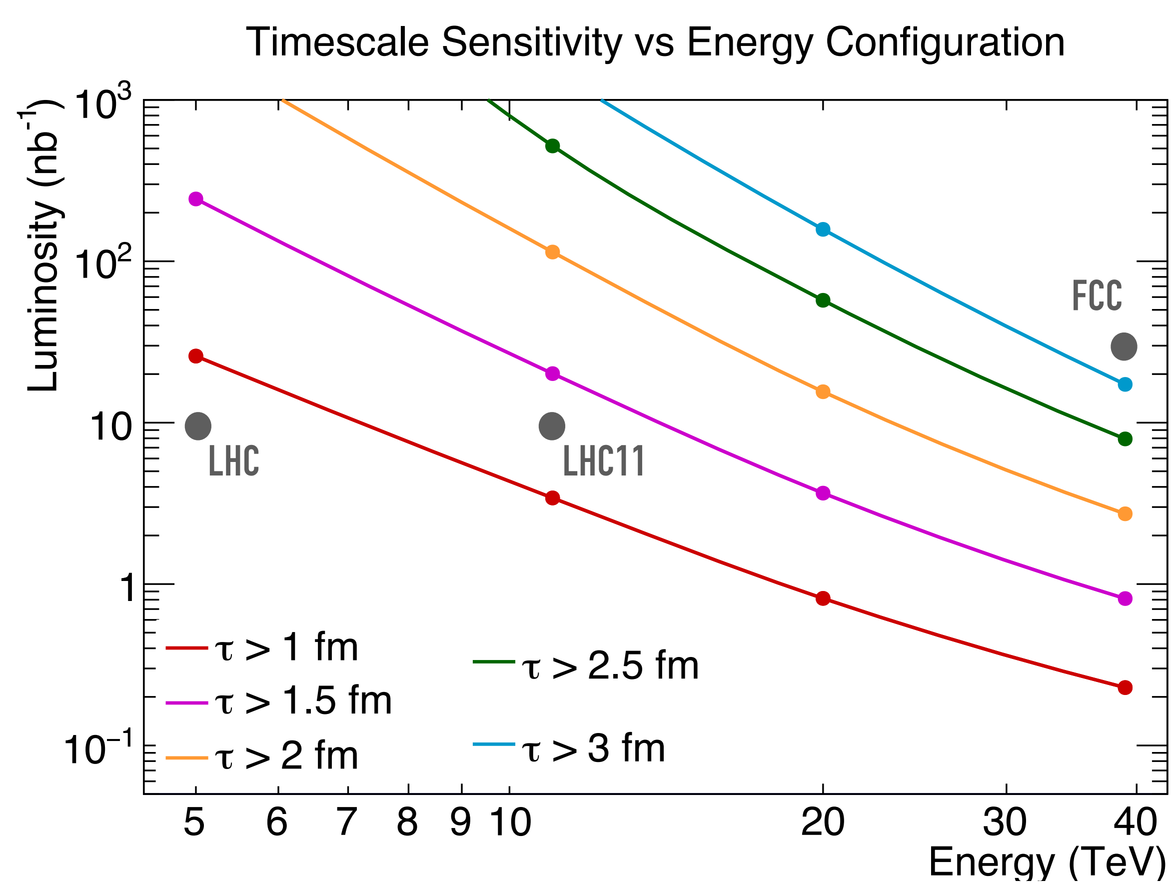
PROBING QGP TIME EVOLUTION

Apolinário, Milhano, Salam, Salgado :: FCC Yellow Report 1605.01389

- all current observables are sensitive to the integrated effect of the entire QGP lifetime
- use boosted objects to switch off jet-QGP interaction for some time







but that is not all !

oh no.

that is not all . . .

MANY THINGS I DID NOT TALK ABOUT [AND MAYBE SHOULD HAVE]

- ✓ all I had to skip [hopefully not too much]
- ✓ physics of initial condition: small Bjorken-x/saturation/non-linear parton evolution/CGC
- ✓ physics of initial stages: Glasma, …
- ✓ heavy flavour [beyond quarkonia]
- ✓ hadrochemistry: statistical hadronization models, …
- ✓ strangeness
- ✓ femtoscopy
- ✓ all I forgot

WRAP-UP [IN LINES OF LESS THAN 140 CHAR EACH]

- ✓ #HI physics is broad spectrum in #theory and #experiment @RHIC @LHC
- ✓ #HI is #NewPhysics
- ✓ #QGP is collective, an almost perfect liquid of #SM fundamental particles
- ✓ #HI physics at play in #pp and #pA
- ✓ #jets can image #QGP and help to understand #BirthOfQGP