HEAVY-ION PHYSICS [LECTURE 2]

Guilherme Milhano

LIP Lisbon & CERN TH
guilherme.milhano@cern.ch
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

✓ bound states of heavy quarks [c-cbar: J/ψ, ψ’][b-bbar: Y, Y’, Y’’] 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]
RHIC vs LHC

$R_{AA}$ vs. multiplicity

- ALICE (Pb-Pb $s_{NN} = 2.76$ TeV), $2.5 < \gamma < 4$
- PHENIX (Au-Au $s_{NN} = 200$ GeV), $1.2 < |\gamma| < 2.2$
- PHENIX (Au-Au $s_{NN} = 200$ GeV), $|\gamma| < 0.35$

Global sys. = ± 12%

Higher temperature at LHC, but more suppression at RHIC?
✓ 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

:: 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

<table>
<thead>
<tr>
<th>state</th>
<th>$J/\psi$</th>
<th>$\chi_c$</th>
<th>$\psi'$</th>
<th>$\Upsilon$</th>
<th>$\chi_b$</th>
<th>$\Upsilon'$</th>
<th>$\chi_b'$</th>
<th>$\Upsilon''$</th>
</tr>
</thead>
<tbody>
<tr>
<td>radius [fm]</td>
<td>0.25</td>
<td>0.36</td>
<td>0.45</td>
<td>0.14</td>
<td>0.22</td>
<td>0.28</td>
<td>0.34</td>
<td>0.39</td>
</tr>
</tbody>
</table>

dissociates first

dissociates last

:: quarkonia is a QGP thermometer [despite all the complications]
high-pt hadrons and jets
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

\[ A_{\text{med}}^{-}(q) = 2\pi \delta(q^+) \int_0^\infty dx^+ e^{iq^-x^+} A_{\text{med}}^{-}(q, x^+) \]

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

\[ \langle A_{\text{med}}^{a,-}(q, t) A_{\text{med}}^{b,-}(q', t') \rangle = \delta^{ab} n(t) \delta(t - t') (2\pi)^2 \delta^{(2)}(q - q') \gamma(q^2) \]
PARTON ENERGY LOSS

✓ parton can exchange 4-momentum with QGP

✓ transfer to QGP results in [elastic] energy loss

✓ transfer from QGP results in energy gain which can stimulate radiation :: medium induced radiation is the leading mechanism for parton energy loss

\[
\hat{q}(t) \equiv \alpha_s n(t) \int_{|q|<q^*} dq^2 \, q^2 \gamma(q^2) \]

\[
\hat{q} \sim \frac{\mu^2}{\lambda}
\]

transport coefficient [average momentum square transfer per unit length]
SINGLE EMISSION [BDMPS-Z]

:: Brownian motion [accumulated transverse momentum]
\[ \langle k_\perp^2 \rangle \sim \hat{q} L \]

:: accumulated phase
\[ \langle \frac{k_\perp^2 L}{\omega} \rangle \sim \frac{\hat{q} L^2}{\omega} \sim \frac{\omega_c}{\omega} \]

:: coherence time [time it takes for a gluon decohere from its emitter]
\[ t_{coh} \sim \frac{\omega}{k_\perp^2} \sim \sqrt{\frac{\omega}{\hat{q}}} \rightarrow \text{number of coherent scatterings} \quad N_{coh} \sim \frac{t_{coh}}{\lambda} \]

:: radiated gluon energy distribution
\[ \frac{\omega}{N_{coh}} \frac{dI_{med}}{d\omega dz} \sim \frac{1}{\omega} \frac{dI_1}{d\omega dz} \sim \alpha_s \sqrt{\frac{\hat{q}}{\omega}} \]

:: average energy loss
\[ \Delta E = \int_0^L dz \int_0^{\omega_c} \omega d\omega \frac{dI_{med}}{d\omega dz} \sim \alpha_s \omega_c \sim \alpha_s \hat{q} L^2 \]
:: eikonal [straight line] parton trajectory resumming multiple exchanges

\[
W_{\alpha_f \alpha_i}(x_f^+; x_i^+; r(\xi)) = \mathcal{P} \exp \left\{ ig \int_{x_i^+}^{x_f^+} d\xi A^- (\xi, r(\xi)) \right\}
\]

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

\[
G_{\alpha_f \alpha_i}(x_f^+, \mathbf{x}_f; x_i^+, \mathbf{x}_i|p_+ \rangle = \int_{r(x_i^+)=\mathbf{x}_i}^{r(x_f^+)=\mathbf{x}_f} \mathcal{D}r(\xi) \exp \left\{ \frac{ip_+}{2} \int_{x_i^+}^{x_f^+} d\xi \left( \frac{dr}{d\xi} \right)^2 \right\} W_{\alpha_f \alpha_i}(x_f^+, x_i^+; r(\xi))
\]

:: 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

FUN FACT: Ex-particle-physicists make the worst biologists.
scatter something off it

HOW TO PROBE ANYTHING

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

Abstruse Goose
HOW TO PROBE ANYTHING

scatter something you understand off it

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

\[ \text{dial } Q^2 = -q^2 = -(k' - k)^2 \text{ to probe distances } \lambda = \hbar/Q \]

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
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
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

[experimental view]
collimated bunch of particles
WHAT IS A JET?

Jet is a...

Jet is a...

Jet is a...

Jet is a...

[theory view] the offspring of the QCD branching of a hard parton
[experimental view] collimated bunch of particles

Figure 1: A sample parton-level event (generated with Herwig[8]) together with random "ghosts", clustered with four different jets algorithms, illustrating the "active" catchment areas of the resulting hard jets. For k_t and Cam/Aachen the detailed shapes are in part determined by the specific set of ghosts used, and change when the ghosts are modified.

The above properties of the anti-k_t algorithm translate into concrete results for various quantitative properties of jets, as we outline below.

2.2 Area-related properties

The most concrete context in which to quantitatively discuss the properties of jet boundaries for different algorithms is in the calculation of jet areas. Two definitions were given for jet areas in [4]: the passive area (\(a\)) which measures a jet's susceptibility to point-like radiation, and the active area (\(A\)) which measures its susceptibility to diffuse radiation. The simplest place to observe the impact of resilience is in the passive area for a jet consisting of a hard particle \(p_1\) and a soft one \(p_2\), separated by a \(\Delta \phi\) distance \(\Delta 12\). In usual IRC safe jet algorithms (JA), the passive area \(a_{JA}\), \(R(\Delta 12)\) is \(\pi R^2\) when \(\Delta 12 = 0\), but changes when \(\Delta 12\) is increased. In contrast, since the boundaries of anti-k_t jets are unaffected by soft radiation,
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
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]
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

A JET IN QGP :: PARTON SHOWER

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]
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

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
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

\[ \begin{align*}
\lambda_\perp \sim & \frac{1}{k_\perp} \sim \frac{1}{\omega \theta} \\
\end{align*} \]

\[ \begin{align*}
r_\perp \sim & \theta_{q\bar{q}} \tau_f \sim \frac{\theta_{q\bar{q}}}{\theta^2 \omega} \\
\end{align*} \]

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

large angle radiation suppressed :: angular ordering
\[ \Lambda_{med} \sim \frac{1}{k_{\perp}} \sim \frac{1}{\sqrt{\hat{q}L}} \]

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

- new medium induced colour decorrelation scale

- such that decorrelation driven by timescale
**[DE]COHERENCE OF MULTIPLE EMISSIONS**

- qqbar colour coherence survival probability
  \[ \Delta_{med} = 1 - \exp \left\{ -\frac{1}{12} \frac{\hat{q}^2}{\hat{q}_{qq}^2} t^3 \right\} = 1 - \exp \left\{ -\frac{1}{12} \frac{r^2}{\Lambda^2_{med}} \right\} \]

- time scale for decoherence
  \[ \tau_d \sim \left( \frac{1}{\hat{q}^2_{qq}} \right)^{1/3} \]

- total decoherence when \( L > \tau_d \)

- colour decoherence opens up phase space for emission
  - large angle radiation [anti-angular ordering]
    - geometrical separation [in soft limit]

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

- \( \Delta_{med} \to 0 \) coherence
- \( \Delta_{med} \to 1 \) decoherence
From Antennas to Jets

- $r_t < \Lambda_{\text{med}}$ :: antenna unresolved by medium :: vacuum like
- $r_t > \Lambda_{\text{med}}$ :: 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]

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

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

✓ Aj 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

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

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

paradigm change triggering experimental analyses and theoretical developments

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

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

✓ 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\textsubscript{J} CAN BE GENERATED FOR EQUAL PATH LENGTHS

\[ A\textsubscript{J} = \frac{p_{\perp,1} - p_{\perp,2}}{p_{\perp,1} + p_{\perp,2}} \]

\begin{itemize}
  \item di-jet event sample with no difference in path-length have A\textsubscript{J} distribution compatible with realistic [full-geometry] sample
  \item ‘typical’ event has rather similar path-lengths
  \item difference in path-length DOES NOT play a significant role in the observed modification of A\textsubscript{J} distribution
\end{itemize}
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

Mass distribution of partons in the initial configuration in $p+p$
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 \( p_t \) 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

➤ 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

\[ z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} \quad z_g > 0.1 \]

➤ in vacuum this measures the fundamental [Altarelli-Parisi] QCD splitting probabilities
**GROOMED SHARED MOMENTUM FRACTION**

**modified Mass Drop Tagger / Soft Drop [$\beta=0$]**

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 \(z_g > z_{\text{cut}}\) stop,
   else discard softer prong and go back to 3

\[
\begin{align*}
\frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}}
\end{align*}
\]

\(p(\tau_g) = \frac{P(z_g) + P(1 - z_g)}{\int_{z_{\text{cut}}}^{0.5} dz (P(z) + P(1 - z))} \Theta(z_g - z_{\text{cut}})\)

- **in vacuum, the procedure measures the LO Altarelli-Parisi splitting function**
substantial modification observed in PbPb collisions

- proceed as with di-jets to isolate physical origin
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

\[
g = \sum_i \frac{p_{\perp, i} \Delta R_{ij}}{p_{\perp}^J} \quad \text{:: first radial moment of the intra-jet } p_{\perp} \text{ distribution}
\]

- 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?

Is it a gas of quarks and gluons (close to $T_c$)?

What is the correct picture of the QGP?

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

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

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 $0.32 < \kappa_{sc} < 0.41$

$O(1)$ as expected.

$x_{stop}^{QCD} \sim (2 - 3)x_{stop}^{N=4}$
HYBRID STRONG/WEAK COUPLING MODEL :: PREDICTIONS

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

- 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

CMS Preliminary

$\sqrt{s_{NN}} = 5.02$ TeV

anti-$k_T$, Jet $R = 0.3$, $p_T^{\text{jet}} > 30$ GeV/c, $|\eta^{\text{jet}}| < 1.6$, $\Delta\phi_{J\gamma} > \frac{7\pi}{8}$

PbPb $404 \mu$b$^{-1}$, pp $25.8$ pb$^{-1}$

50 - 100%

$50 - 100\%$

$10 - 30\%$

$0 - 10\%$

$P_T > 60$ GeV/c

$P_T > 60$ GeV/c

$P_T > 60$ GeV/c

$P_T > 60$ GeV/c

$\frac{1}{N_{J\gamma}} \frac{dN_{J\gamma}}{dx_{J\gamma}}$

$\frac{dN}{dx_{J\gamma}}$

$p_T^{\text{jet}}$/$p_T^{\gamma}$

$p_T^{\text{jet}}$/$p_T^{\gamma}$

$p_T^{\text{jet}}$/$p_T^{\gamma}$

$p_T^{\text{jet}}$/$p_T^{\gamma}$

JEWEL + PYTHIA

HYDJET + PYTHIA

Hybrid Model

PAS-HIN-16-002
Theory Comparison: Distribution of $x_{J\gamma}$ vs. $p_T\gamma$

- Overlaid PYTHIA, JEWEL, LBT and Hybrid Model
Theory Comparison: $R_{J\gamma}$ in PbPb

CMS Preliminary

$\sqrt{s_{NN}} = 5.02$ TeV

$\Delta\phi_{J\gamma} > \frac{7\pi}{8}$

PbPb $404 \mu$b$^{-1}$, pp $25.8$ pb$^{-1}$

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

$PAS$-HIN-16-002
Theory Comparison: $x_{J\gamma}$ in PbPb

CMS Preliminary

$\sqrt{s_{NN}} = 5.02$ TeV

$\Delta\phi_{J\gamma} > \frac{7\pi}{8}$

PbPb 404 $\mu$b$^{-1}$, pp 25.8 pb$^{-1}$

0 - 30%

anti-$k_T$ Jet R = 0.3

$p_T^{\text{Jet}} > 30$ GeV/c

$|y^{\text{Jet}}| < 1.6$

$\langle x_{\gamma} \rangle$

$p_T^{\gamma}$ (GeV/c)

30 - 100%

CMS

PAS-HIN-16-002

PbPb

PYTHIA + HYDJET

JEWEL + PYTHIA

LBT (CCNU-LBNL)

Hybrid Model

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

CMS Preliminary

$\sqrt{s_{NN}} = 5.02$ TeV

$\Delta \phi_{J\gamma} > \frac{7\pi}{8}$

PbPb $404 \mu b^{-1}$, pp $25.8$ pb$^{-1}$

$P_T^\gamma > 60$ GeV/c

anti-$k_T$ Jet R = 0.3

$P_T^{Jet} > 30$ GeV/c

$|\eta^{Jet}| < 1.6$

NN$-1$, pp $25.8$ pb$^{-1}$

$\gamma \pi_7 > 40$

$\gamma \phi_\delta$

$\Delta \phi_{J\gamma}$

PAS-HIN-16-002

Hybrid Model

LBT (CCNU-LBNL)

JEWEL + PYTHIA

PYTHIA + HYDJET

PbPb

$N_{coll}$-weighted $<N_{part}>$

$N_{coll}$-weighted $<N_{part}>$

$<x_{J\gamma}>$

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

- Overlaid PYTHIA+HYDJET, JEWEL, LBT and Hybrid Model
HYBRID STRONG/WEAK COUPLING MODEL :: PREDICTIONS

- \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)
- CMS Preliminary
- PbPb + PYTHIA
- LBT (CCNU-LBNL)
- Hybrid Model
- pQCD jet E-loss

**PbPb 404 \( \mu b^{-1} \), pp 25.8 \( \text{pb}^{-1} \)**

- Jet I
- 0 - 30%
- 30 - 100%
- 40 < \( p_T \) < 50 GeV/c
- 50 < \( p_T \) < 60 GeV/c
- 60 < \( p_T \) < 80 GeV/c
- 80 < \( p_T \) < 100 GeV/c
- \( \eta > 30 \text{ GeV/c} \), \( |\eta| < 1.6 \)

**Jet R = 0.3, \( p_T^{\text{jet}} > 30 \text{ GeV/c} \)**

**\( p_T \) (GeV/c)**

0 50 100 150 200 250 300
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

➤ 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

➤ 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

![Diagram](image-url)

**Timescale Sensitivity vs Energy Configuration**

- **Unquenched**
- **Quenched**
- **Brick** $\tau = 1.0$ fm
- **Brick** $\tau = 3.0$ fm
- **Brick** $\tau = 5.0$ fm

**Energy (TeV)**
- 5
- 6
- 7
- 8
- 9
- 10
- 20
- 30
- 40

**Luminosity (nb⁻¹)**
- $10^{-1}$
- 1
- 10
- $10^2$
- $10^3$

**Time (fm/c)**
- 0.8
- 1
- 1.2
- 1.4
- 1.6
- 1.8
- 2
- 2.2
- 2.4
- 2.6

**Min Reco Top pt (GeV)**
- 60
- 65
- 70
- 75
- 80
- 85
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
✓ #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