RHIC/LHC
Complementarity

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Important experimental and theoretical developments

Experimental techniques developed

Increasing precision of key observable

2000
2002
2004
2006
2008
2010
2012
2014
2022

Full jet reconstruction measurements and comparison to theory over a wide range of collision and jet energies

Precision RHIC data are essential

Disclaimer:
This is not a real talk!
Hopefully starting point for further discussions!

CMS Preliminary $\langle \eta_{jet} \rangle = 140 \mu b$

2010, 0-30%, Leading jet
2011, 0-10%, Inclusive jet

RHIC BES-II and detector upgrades required to
- determine $\hat{q}(T)$ dependence
- characterize quasi particle nature over a wide range in jet energy
- constrain importance of collisional vs. radiative energy loss; QCD analog to QED energy loss

Momentum transport parameter $\hat{q}(T)$, $\hat{e}(T)$, ...

• reduce $\hat{q}$ uncertainties

RHIC White Paper: “Hot and Dense QCD Matter”
The QGP at the LHC:

- fireball hotter (~20%) and denser (~x2) and longer lifetime wrt RHIC

- bulk dynamics, $v_n(p_T)$, similar at RHIC and LHC, mainly driven by initial state “geometry”

Huge increase in yield of hard probes/jet production!
RHIC and LHC “Landscape”

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Mainly gluon jets ($p_T<200$ GeV) at the LHC. Quark jets at RHIC $p_T>40$ GeV.

Huge increase in yield of hard probes/jet production!
LHC and RHIC $R_{AA}$

$R_{AA}$ rising as function of $p_T$; constant for $p_T > 50$ GeV?
LHC and RHIC $R_{AA}$

**Diagram:**
- 0-5% Centrality
- $R_{AA}$ vs. $p_T$ (GeV/c)
- $p_T$ range: 4 to 20 GeV/c
- Data points:
  - PHENIX $\pi^0$ Au+Au 200 GeV
  - ALICE $h^{+/-}$ Pb+Pb 2.76 TeV
- Spectrum quantified the slow rise in $p_T$ rising as function of $p_T$.
- $R_{AA}$ rising as function of $p_T$; constant for $p_T > 50$ GeV?
- RHIC $R_{AA} \sim$ LHC $R_{AA}$ up to $p_T \sim 20$ GeV
- $\rightarrow$ larger energy loss at LHC (not a surprise)

Joern Putschke, RHIC Strategy Meeting @ WSU
The stopping power of the QGP: RHIC vs. LHC

PRC 87, 034911 (2013)

\[ \delta p_T(LHC) \approx 1.3 \times \delta p_T(RHIC) \quad \text{but} \quad dN/dy(LHC) \approx 2.2 \ dN/dy(RHIC) \]

→ Smaller coupling at the LHC?

**Is such a simplistic model sufficient?**

Hadron \( p_T \) ~ parton\( p_T \) okay at RHIC but not at LHC.

More realistic/MC models needed!
**Temperature dependence of energy loss**

\[ \eta / s = \text{const} \times T^3 / \hat{q} \]

for weak coupling (PRL 99, 192301, 2007)

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**Differential measurements of transport properties of the QGP:**

Temperature dependence of \( q \) (\( \hat{e}, \eta/s, .. \))

**Sensitivity of \( q \) to 1-2 \( T_c \) requires RHIC measurements for different colliding systems and smaller \( \sqrt{s} \) (LHC larger initial \( T \))
Jet $R_{AA}/R_{CP}$ at the LHC

$R=0.2$

$R=0.4$

$R_{CP}^{Jet} \sim R_{AA} \sim 0.5$ (>50 GeV)

No significant $p_T$ and $R$ dependence of $R_{CP}$ for $p_T>100$ GeV
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**RHIC:** Jet $R_{AA}$ less suppressed than hadrons!

**Caveat:** Large systematic uncertainties; needs sPhenix!
Di-jet asymmetry/imbalance as function of leading jet $p_T$

![Graph showing di-jet asymmetry ratio, $A_J$, in bins of leading jet transverse momentum from 120 < $p_{T,1}$ < 150 GeV/c to $p_{T,1}$ > 300 GeV/c for subleading jets of $p_{T,2}$ > 30 GeV/c and $\Delta \phi_{12} > \frac{2\pi}{3}$ between leading and subleading jets. Results for 0–20% central PbPb events are shown as points, while the histogram shows the results for PYTHIA dijets embedded into HYDJET PbPb simulated events. The error bars represent the statistical uncertainties.]
Di-jet asymmetry/imbalance as function of leading jet $p_T$

Di-Jet imbalance decreasing with increasing jet energy!

"Can be explained in terms of essentially known physics, i.e. the increased collimation of jets due to kinematics and a transition to a less gluon- dominated regime." : T.Renk, arXiv:1204.5572
Direct Photon-Jet Measurements

3 Results

not constitute the full picture. There are genuine photon+jet events which do not contribute to the distribution because the associated jet falls below the threshold. To quantify this effect, Fig. 4(b) shows $R_{gJ}$, the fraction of isolated photons that have an associated jet passing the analysis selection. The value of $R_{gJ}$ is found to decrease, from $R_{gJ} = 0.685 \pm 0.008 \text{(stat.)} - 0.698 \pm 0.006 \text{(stat.)}$ for the \textsc{pythia}+\textsc{hydjet} reference, as well as pp and peripheral PbPb data, to the significantly lower $R_{gJ} = 0.49 \pm 0.03 \text{(stat.)} \pm 0.02 \text{(syst.)} - 0.54 \pm 0.05 \text{(stat.)} \pm 0.02 \text{(syst.)}$ for the three PbPb bins above 50% centrality.

An analysis with a lower $p_T$ cutoff on the associated jet energy would result in values of $R_{gJ}$ closer to unity. This would shift the cutoff at low $x_{gJ}$ in Fig. 3 closer to zero. It is likely, although not certain, that these additional events would result in a larger deviation in $x_{gJ}$ between the PbPb data and the reference shown in Fig. 4(a).

3.4 Systematic uncertainties

Photon purity, reconstruction efficiency, and isolation, as well as the contamination from $e^\pm$ and fake jets contribute to the systematic uncertainties of the photon+jet azimuthal correlation and the observables related to momentum asymmetry, $h_x$ and $R_{gJ}$. Additionally, the momentum asymmetry observables are also influenced by the relative photon and jet energy calibrations.

For the measurement of $s(D_f)$, the uncertainty due to the photon angular resolution is negligible, less than 10$^{-5}$.

Large quenching effects seen in direct photon measurements (Consistent with jets measurements? Quark vs. gluon energy loss?)

No angular de-correlation (also seen in di-jets @RHIC)

Comparable measurements only possible with sPhenix!
Jet Shape Observables

Jet broadening at the LHC:
Seen in differential jet shape and R dependence of jet $R_{CP}$
(especially at lower jet $p_T$)
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**RHIC: Stronger broadening observed (?)**

Reminder: These measurements look at the jet shape in a cone of $R=0.2-0.5$!

Joern Putschke, RHIC Strategy Meeting @ WSU
The momentum difference in the di-jet is balanced by low $p_T$ particles at large angles relative to the away side jet axis.
Enhancement at low $z$
Suppression at high $z$
Broadening at low $z$
Trigger Jet: R=0.4, $p_{T,cut}=2$ GeV/c and EMCal Tower>6 GeV

Energy difference: AuAu-pp

Hint of Jet Broadening at low $p_T$ (large uncertainties due to potential jet $v_2/v_3$)

Quenched energy at high $p_T$ balanced by low $p_T$ enhancement

Consistent picture between $\gamma^{direct}$/jet-hadron correlations @ RHIC!
RHIC: Jet-Hadron Correlations

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$p_T$ scale of low $p_T$ enhancement: ~2 GeV RHIC, 3-4 GeV LHC

Caveat: RHIC measurement: Statistical. Need per jet quantities ($A_j$, FF) to allow one-to-one comparison to LHC.
Consistency or a way too simplistic explanation?

Integrated energy loss (in a brick)

LHC larger energy loss at early times → diffusion in medium → larger angles

RHIC smaller energy loss at early times → less diffusion in the medium → closer to jet axis → can qualitatively explain the differences RHIC/LHC (!?)

⇒ Easier to study details of soft gluon radiation at RHIC!? Can be further studied via correlations at RHIC with available data-sets! Would provide additional strong argument for future precision RHIC JET measurements!
Enhancement at low z
Suppression at intermediate z
No suppression at high z
Enhancement at low $z$

Suppression at intermediate $z$

No suppression at high $z$

**RHIC:** Suppression at high di-hadron $z_T$

*Caveat:* Not apple to apple comparison $\rightarrow$ sPhenix
Fragmentation Functions cont.

**FF ratio @ high z → 1**

**Trivial or something new?**

“Trivial” (T. Renk):
Jet flavor bias in PbPb due to jetfinding with small R towards quark jets.
pp reference contains more gluons.

In FF measurements:
E_{Jet}(pp) = E_{Jet}(AA)

(only small enhancement of jet energy at low-z, few %)

But what about the virtuality of the (leading) parton after energy loss in the medium?

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Joern Putschke, RHIC Strategy Meeting © WSU
Disclaimer: The jet mass definition in experiments is crucial dependent on the jet algorithm, but so are all jet measurements.

\[ E_{\text{Jet/LP}}(\text{AA}) = E_{\text{Jet}}(\text{pp}) \] but \[ \text{Virtuality/M}_{\text{LP,Jet}}(\text{AA}) < M_{\text{Jet}}(\text{pp}) \]

Caveat: So far not really apples to apples comparison. Just on a conceptual level.
Disclaimer: The jet mass definition in experiments is crucial dependent on the jet algorithm, but so are all jet measurements.

Different behavior at RHIC? Smaller effect? Or “just” jet flavor bias. Should be able to test this at RHIC via jet energy dep. > 20 GeV.
“Direct” Comparison of RHIC and LHC energy loss

γ_{direct}-jet at the LHC (quark jet) compared to di-jets at RHIC (quark jets) @ 40-50 GeV

To remove/reduce geometric biases one needs an unbiased/less biased jet/direct photon measurement at RHIC → sPhenix
Biases are not always bad - actually a strength of RHIC

Due to the steeply falling spectrum at RHIC, even with imposing biases ($p_{T \text{cut}}$, ...), a good correlation to the initial parton energy is preserved.
Due to the steeply falling spectrum at RHIC, even with imposing biases ($p_T^{cut}$, ...), a good correlation to the initial parton energy is preserved.

Biases ($p_T^{cut}$, ...) can be used to change systematically the pathlength of the recoil jet.

Biases ($p_T^{cut}$, ...) can be further utilized to favor gluon recoil jets.

Caveat: Can only compare to MC models!
Lots of discussions during the Jet Workshop
→ Consensus: Not easy experimentally

Energy loss at fixed $p_T \sim 2$-$3$ GeV
→ Opportunity at RHIC signal to background better $> 1$ GeV !?
Testing the quasi-particle nature of the QGP

Jet Virtuality: Controls the Physics of Radiative Energy Loss

\[ Q^2(L) \approx \max \left( \hat{q} L, \frac{E}{L} \right) \]

RHIC: 20 GeV parton, \( L = 3 \) fm

\[ \hat{q} L \approx 1.5 \text{GeV}^2 \approx \frac{E}{L} \approx 1.5 \text{GeV}^2 \]

Virtuality of primary parton is medium influenced and small enough to “experience” the strongly coupled medium

LHC: 200 GeV parton, \( L = 3 \) fm

\[ \hat{q} L \approx 3.5 \text{GeV}^2 < \frac{E}{L} \approx 13 \text{GeV}^2 \]

Virtuality of primary parton is vacuum dominated and only its gluon cloud “experiences” the strongly coupled medium

RHIC can explore the region between the weak and strong coupling limits!
Passage of particles through matter

Ionization energy loss by heavy particles

Moderately relativistic charged particles other than electrons lose energy in matter primarily by ionization. The mean rate of energy loss (or stopping power) is given by the Bethe-Bloch equation,

\[ \frac{-dE}{dx} = K z^2 Z A \beta^2 \left[ \ln \left( \frac{m_e c^2}{\beta^2 - \delta^2} \right) \right]. \]

Here \( T_{\text{max}} \) is the maximum kinetic energy which can be imparted to a free electron in a single collision, and the other variables are defined in Table 23.1. The units are chosen so that \( dx \) is measured in mass per unit area, e.g.,\( \text{ing} \cdot \text{c} \cdot \text{m}^{-2} \).

In this form, the Bethe-Bloch equation describes the energy loss of pions in a material such as copper to about 1% accuracy for energies between about 6 MeV and 6 GeV (momenta between about 40 MeV/c and 6 GeV/c). At lower energies "C/Z" corrections

At the LHC/at large jet energies, jet modification dominated by radiative energy loss

At lower jet energies balance/interplay between radiative energy and collisional energy loss

RHIC and LHC combined will map out the stopping power \(-dE/dx\) of hot and dense QGP for colored patrons
RHIC is always good for surprises: d+Au $R_{AA}$

Enhancement of Jet $R_{AA}$ in peripheral d+Au collision?
Ridge/flow also in d+Au?
Ridge/flow in d+Au: Different systems already included in the next runs!

Event-by-Event energy loss: Change initial fluctuations via system size and select jets via jet mass?

Changing system size dial in pre-equilibrium vs. hydro? Or is centrality dep. sufficient?

RHIC is the only place to study system size!
Near Future: RJE(T)T → Summarize RHIC quenching status

RJE(T)T=RHIC Jet Experiments (& Theory) Task-force

Can something like this be realized at RHIC? Would in my opinion strengthen the need for a future dedicated RHIC jet detector!
RJE(T)T: Opportunity at RHIC in the next 2-3 years

What is “not” possible with the current exp. & data?

• Inclusive jet x-section
• direct photon-jet correlations
• heavy-flavor jets

What could be possible with the current exp. & data?

• Jet-Hadron and direct photon hadron correlations
  (try to compare them more quantitatively PHENIX/STAR)

• Utilize biased jet/jet-correlations ($p_T^{\text{cut}}$ & R dep.)
  → is the lost energy more “collimated” than at the LHC?

• Biased jet $v_n$ measurements (needed for correlation bkg)

(Potential) Advantage of a task-force: one can utilize the individual strength of both experiments and in addition reduce systematic uncertainties (!?)
In many respects RHIC and LHC are complementary and an active jet program at RHIC is essential to further and quantify our understanding of partonic energy loss in the future!