HARD PROBES FROM RHIC TO LHC

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EÖTVÖS UNIVERSITY, BUDAPEST, HUNGARY

XXXVII Physics in Collision
PRAGUE, CZECH REPUBLIC
4-8 SEPTEMBER, 2017
CONTENT OF THIS TALK

• INTRODUCTION
  • Universe history, Big Bang and Little Bangs
  • Time evolution of heavy ion collisions
  • Phase map of QCD and the experimental control parameters
  • Accelerators, experiments

• HARD PROBES, BASIC OBSERVATIONS
  • Nuclear modification of high energy particles and jets
  • Nuclear modification of hadrons versus photons
  • Heavy flavors

• RECENT RESULTS
  • Jet and hadron suppression in asymmetric/small/low-energy systems
  • Heavy flavor suppression
  • Jet energy loss via fragmentation and jet correlations
3 INTRODUCTION

Universe history, Big Bang and Little Bangs

Time evolution of heavy ion collisions

Phase map of QCD and the experimental control parameters

Accelerators, experiments
BIG BANG IN THE LAB

- Ages of the Universe:
  - Stars & Galaxies
  - Atoms
  - Nuclei
  - Nucleosynthesis
  - Elementary particles
  - …?

- How to investigate?
  - Create little bangs
  - Collisions of heavy ions
  - Record outcoming particles
HOW TO INVESTIGATE THESE LITTLE BANGS?
TIMELINE OF A HEAVY ION COLLISION

- Pre-thermalization stage:
  \(~1 \text{ fm/cm}\)

- Quark-hadron transition:
  \(~7-10 \text{ fm/c}\)

- Chemical + kinetic freeze-out

MIT Heavy Ion Event Display: Au+Au 200 GeV

Heavy Ion Group @ MIT
Yen-Jie Lee, Andre S. Yoon and Wit Busza

Time = -10.0 fm/c
**TIME EVOLUTION OF A HEAVY ION COLLISION**

**Initial stage:**
- Hard scattering
- Jet formation

**Leptons, photons:**
- "shine through"

**Hadrons:**
- Dissociation and coalescence
- "Final" hadrons created at freeze-out
EXPLORING THE PHASE MAP OF QCD

- Phase map: temperature versus matter excess (baryochem. pot. \( \mu_B \))
- 1st order quark-hadron phase transition at high \( \mu_B \)
- Crossover at low \( \mu_B \) and \( T \approx 170 \text{ MeV} \)
- \( 170 \text{ MeV} \leftrightarrow \sim 10^{12} \text{ K} \)
- Control parameters:
  - Collision energy
  - Collision system
  - Collision geometry
- High \( \mu_B \): nuclear matter, neutron stars, color superconductors…
EXPERIMENTAL CONTROL PARAMETERS

- Collision energy: controls initial temperature, initial $\mu_B$
- Collision system & centrality: controls available volume
- Event geometry: reaction plane, event plane, fluctuations
- Important parameters: $N_{\text{part}}$ (system size), $N_{\text{coll}}$ (x-sect)

Central Au+Au
$N_{\text{part}} \sim 300$

Peripheral Au+Au
$N_{\text{part}} \sim 50$

d+Au

p+p

Reaction Plane

Reality

Multipole event planes
COLLISIONS OF DIFFERENT CENTRALITY

Peripheral  Central

Introduction  Hard Probes Basics  Recent Results
FACILITIES: RELATIVISTIC HEAVY ION COLLIDER

- At the Brookhaven National Laboratory, Long Island, New York, USA
- Collisions of: $\bar{p}$, d, $^3\text{He}$, Al, Cu, Au, U
- Collision energies: 7-200 GeV/nucleon, even 0.5 TeV for $\bar{p}$
- Experiments: PHENIX & STAR; future: sPHENIX; past: BRAHMS & PHOBOS
FACILITIES: LARGE HADRON COLLIDER

- Past high energy physics facilities: LEP, SPS (also currently in use)
- LHC collisions: p+p, p+Pb and Pb+Pb
- Energies: from 2.76 TeV/nucleon to 13 TeV (p+p only)
- Experiments: ALICE, ATLAS, CMS, LHCb, LHCf, MoEDAL, TOTEM
HARD PROBES, BASIC OBSERVATIONS

Nuclear modification: $R_{AA}$

Jet quenching

Hadrons, photons

Heavy flavors
Simply just more?
A+A = many p+p?

\[ R_{AA} = \frac{\text{High } p_T\text{ particle yield in } A+A}{\text{High } p_T\text{ particle yield in } p+p} \times \text{Number of } p+p\text{ collisions} \]
COLD VERSUS HOT NUCLEAR MATTER EFFECTS

• Modification of $R_{AA}$ may be due to hot or cold nuclear matter effects

• Hot matter: suppression/quenching of hard particles

• Cold matter: initial state effect
  • Nuclear modification of PDF's
  • Shadowing
  • Energy loss of partons in nucleus
  • $kT$ broadening

• Idea: hot nuclear matter not present in $d+Au$

• Cold nuclear matter: also in $d+Au$
SUPPRESSION AS A FUNCTION OF CENTRALITY

- No suppression in d+Au or peripheral Au+Au; strong suppression in central!

\[ R_{AA} \]

\[ \pi^0 \text{ 0-5\% Ce} \quad \bullet \text{d+Au} \]

PHENIX

SUPPRESSION OF THE AWAY SIDE JET

- Angular correlation of high energy hadrons
- Outgoing jet: similar in p+p, d+Au, Au+Au
- Inward going (away side) jet: missing in central Au+Au

INTRODUCTION  HARD PROBES BASICS  RECENT RESULTS
SUPPRESSION OF HIGH ENERGY PARTICLES

• Suppression in Au+Au collisions: 1st milestone
• Lack of suppression in d+Au: 2nd milestone
• Two PRL covers

Zajc, Riordan, Scientific American
A NEW TYPE OF MEDIUM FORMED

- More evidence from soft probes:
  - Flow: strong coupling, hydro behavior
  - Direct and thermal photons: large initial temp.

Zajc, Riordan, Scientific American

Low momentum direct photon enhancement
PRC 91,064904

\[
\frac{1}{2\pi p_T} \frac{d^2N}{d^3p_T} = C \left( \frac{p_T}{m} \right)^{\alpha - 2}
\]

\[\sqrt{s_{NN}} = 200\text{GeV}\]
HOW DO OTHER PARTICLES BEHAVE?

- All hadrons suppressed, direct photons „shine through”
- Suppression dependent of system size (controlled by centrality or $N_{\text{part}}$)

PHENIX Au+Au, $\sqrt{s_{NN}} = 200$ GeV, 0-10% most central

![Graph showing suppression of different particles in Au+Au collisions](image.png)

$R_{AA}(p_T > 6.0 \text{ GeV/c})$

- Photons
- $\pi^0$

PHENIX Au+Au $\sqrt{s_{NN}}=200$ GeV

JET RECONSTRUCTION

- Basic way to analyze suppression: yield of identified particles
- Advanced medium probe: reconstructed jets (and their correlations...)
- Jet measurement: algorithm required
  - Define jet/particle distance: 
    \[ d_{ij} = \frac{\min\left(k_{T,i}^{-2p}, k_{T,j}^{-2p}\right) \left(\Delta y_{ij}^2 + \Delta \phi_{ij}^2\right)}{R^2}, \]
  - Widely used: anti-\(k_T\), \(p = -1\)

\[ d_{i,\text{Beam}} = k_{T,i} \]
WHAT ABOUT HEAVY FLAVOR MESONS?

- Timeline: quarkonium ($q\bar{q}$) formation $\rightarrow$ QGP evolution $\rightarrow$ $q\bar{q}$ decay
- Quarkonia experience the whole QGP evolution, competing processes
- Suppression due to color-screening: temperature and size/mass dependence

Statistical regeneration in time:

Images from J Castillo, SQM17 and A Mócsy, HardProbes2009
SUPPRESSION OF HEAVY FLAVOR

- Electrons from HF decays are suppressed (collision or radiation, mass ordering)
- $J/\Psi$ are also suppressed
- Described by strong coupling, large transport coefficients

![Graph showing suppression of heavy flavor](image)


$|y|<0.35$ syst$_{\text{global}} = 12\%$

$|y|=[1.2, 2.2]$ syst$_{\text{global}} = \pm 7\%$
HADRON SUPPRESSION AT THE LHC

- Similar results at $\sqrt{s} = 2.76$ and 5.02 TeV
- Local maximum at $p_T \approx 2$ GeV
- Minimum at $p_T \approx 7$ GeV
- Less suppression at very high momenta!
- RHIC and LHC similar?
- Competing effects:
  - Spectra flattening with incr. $\sqrt{s}$
  - Energy loss increasing with $\sqrt{s}$
PHOTONS SHINE THROUGH AT THE LHC ALSO

- No photon suppression for any energy or any centrality
- Electroweak bosons also not suppressed
- Comparison to MC (JETPHOX) up to 200 GeV: similar conclusion

CMS talk at
Hard Probes 2013
Matthew Nguyen
SUMMARY OF THE STATUS QUO

• Jet suppression in A+A, lack of suppression in d+A: new, strongly interacting medium created at RHICD
• Confirmed by soft probes: elliptic flow and thermal photons
• Also heavy flavor hadrons suppressed
• Photons shine through
• Observations confirmed by the LHC
• Rising trend for very large momenta
• Jet reconstruction possible
RECENT RESULTS

Suppression in asymmetric/small/low-energy systems

Heavy flavors: charm and beauty

Jets and jet correlations
SUPPRESSION IN THE BEAM ENERGY SCAN

- $R_{CP}$ analyzed here instead of $R_{AA}$, transition above one with collision energy
- Hadron enhancement: Cronin-effect, radial flow, coalescence domination
- Identified particles: less suppression for kaons, enhancement for protons

STAR collaboration, arXiv:1707.01988
SUPPRESSION IN HIGHLY ASYMMETRIC SYSTEMS

- $p+Au$, $d+Au$, $^3He+Au$ compared
- Centralities determined as for large systems
- New $p+Au$ results show large centrality dependence
- System sizes agree at high $p_T$
- At moderate $p_T$, ordering seen
- Model comparison:
  - Vitev, HIJING++ investigated
  - No full match of ordering, peak location, etc
SUPPRESSION IN HIGHLY ASYMMETRIC SYSTEMS

- Jet energy dependence observed at LHC
- Suppression/enhancement in central/peripheral pPb
- Parton energy fraction dependent mechanism?

**ATLAS** Preliminary

\[
\int L \, dt = 27.8 \text{ nb}^{-1}
\]

**p+Pb** \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)

anti-\(k_t\), \(R=0.4\)
SUPPRESSION IN CU+AU, AU+AU, CU+CU

- Comparing different systems of the same size: Cu+Cu, Cu+Au, Au+Au
- Different centrality but same number of nucleon participants ($N_{\text{part}}$)
- Clear $N_{\text{part}}$ dependence („participant scaling”)

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**Figure:**

- **Left panel:**
  - 20-40% ($N_{\text{part}} = 80.37$) Cu+Au, $|s_{\text{NN}}| = 200$ GeV
  - 40-50% ($N_{\text{part}} = 74.4$) Au+Au, $|s_{\text{NN}}| = 200$ GeV
  - 0-10% ($N_{\text{part}} = 88.2$) Cu+Cu, $|s_{\text{NN}}| = 200$ GeV

- **Right panel:**
  - 0-10% ($N_{\text{part}} = 177.2$) Cu+Au, $|s_{\text{NN}}| = 200$ GeV
  - 20-30% ($N_{\text{part}} = 166.6$) Au+Au, $|s_{\text{NN}}| = 200$ GeV

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**References:**

- S Zharko, Hard Probes 2016
- Phys. Rev. Lett. 101, 232301
- Phys. Rev. Lett. 101, 162301

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**Citation:**

J/ψ AND D SUPPRESSION AT RHIC & LHC

- Recall: heavy flavor probes medium beyond light quark mesons
- Low $p_T$ J/ψ more suppressed at RHIC, smaller regeneration cross-section
- High $p_T$ J/ψ more suppressed at LHC: more dissociation due to higher temp.
- Strong D (open charm) suppression at LHC, comparable to light hadrons
QUARKONIUM SUPPRESSION AT RHIC & LHC

• Upsilon \((Y(1-2-3S), b\bar{b})\): more suppression in central collisions

• Sequential melting: \(Y(1S)\) less suppressed than \(Y(2S+3S)\)

Zaochen Ye and Alexander Schmah, Quark Matter 2017
COLD NUCLEAR EFFECTS VIA J/Ψ IN P+PB

- Suppressed Ψ(2S) compared to J/Ψ: final state effect beyond cold nucl. matt.?
- Prompt J/Ψ enhanced at Pb-going rapidity and at midrapidity
- Suppression at the most forward rapidity
- Shadowing calculations describe suppression
BEAUTY VERSUS CHARM SUPPRESSION AT RHIC

- Nuclear modification factor for $c \rightarrow e$, $b \rightarrow e$, using unfolding results
- Beauty is less suppressed than charm for 3-5 GeV/c
- Charm in 0-10% is more suppressed than in Minimum Bias
- Reasonable agreement with theory, strong coupling, very small diffusion coeff

K. Nagashima (PHENIX), Quark Matter 2017
B MESON SUPPRESSION AT RHIC

- Three ways of measuring B (q+b): J/Ψ, D⁰, e
- Suppression observed for all channels
- Less suppression of B (qb) than D (qc)?

Kunsu Oh and Alexander Schmah, Quark Matter 2017
MEDIUM EFFECTS WITH HEAVY FLAVOR AT CMS

- Similar prompt $J/\Psi$ and $D^0$: charmonium suppression through energy loss?
- High $p_T$: flavor-independent energy loss; low $p_T$: smaller b energy loss
HEAVY FLAVOR AND B-TAGGED JETS AT LHC

- B-tag: secondary vtx, displaced tracks
- Similar suppr. for light and heavy jets
- No flavor/mass dependence?
- How about low $p_T$?
JET SUPPRESSION AT VERY HIGH PT

- Recall jet reconstruction
- ALICE, ATLAS, CMS: compatible
- Jets more suppressed than $h^{\pm}$
- Note fwd suppression at high $p_T$!
CENTRALITY DEPENDENT JET $R_{AA}$ AT LHC

- Fully reconstructed anti-$k_T$ jets analyzed with various jet cone parameters
- No dependence on jet cone radius (for these small values)
- Clear centrality dependence
DIJET IMBALANCE AT RHIC

- Dijet imbalance: \( A_J = \frac{p_{T,\text{lead}} - p_{T,\text{sublead}}}{p_{T,\text{lead}} - p_{T,\text{sublead}}} \)
- \( p_T > 2 \text{ GeV} \) jets in Au+Au significantly more imbalanced than p+p di-jets
- \( p_T > 0.2 \text{ GeV} \): energy balance can be restored to p+p level
- Smaller jet cone: not even jets with softer constituents compatible
- Jet energy loss re-emerges via soft jet constituents, small broadening in Au+Au

![Graphs showing dijet imbalance in Au+Au and p+p collisions](image)
DIJET ASYMMETRY AT THE LHC

- Modified asymmetry compared to MC and pp, signature of jet-quenching
- Consistent with medium-induced jet energy loss (quenching)

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

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**CMS**

\( \sqrt{s_{NN}} = 2.76 \) TeV

\( \int L d\tau = 150 \mu b^{-1} \)

\textit{PLB 712 (2012) 176}

**ATLAS**

2011 Pb+Pb data, 0.14 nb\(^{-1}\)

2013 pp data, 4.0 pb\(^{-1}\)

anti-\(\kappa\), \(R = 0.4\) jets

\textit{arXiv:1706.09363}
Jet fragmentation: \[ D(p_T) = N_{\text{jet}}^{-1} dN_{\text{ch}} / dp_T, \text{ ratio: } R = D(p_T)_{AA} / D(p_T)_{pp} \]

- Clear enhancement/reduction pattern in Pb+Pb, no modification in p+Pb
- Soft enhancement: jet energy loss transferred to soft particles
- Large \( p_T \) enhancement unexpected, detailed quenching calculations required
DIRECT PHOTON – HADRON CORRELATIONS

- Photon as a trigger particle for the jet: unmodified momentum, no surface bias
- Introduce $z_T = p_T^h/p_T^\gamma$, define $\xi = \ln(1/z_T)$
- Measure for fragmentation, broadening: $I_{AA} = \text{Yield}_{AA}/\text{Yield}_{pp}$
- Energy redistribution leads to: small $p_T$ and large angle hadron production
- Compare $I_{AA}$ for different away side ranges
- Transition from suppression to enhancement at $\xi \approx 1$

![Graph showing the comparison of $I_{AA}$ for different away side ranges](image-url)
JET ASYMMETRIES IN JET-BOSON

- Modification of momentum balance compared to pp at CMS and ATLAS
- Constrains parton energy loss

\( x_{j\gamma} = \frac{p_T^{\text{jet}}}{p_T^{\gamma}} \)

\( \frac{1}{N_Z} \frac{dN}{dx} \)
SUMMARY

• Little Bangs @ RHIC & LHC, probed w/ high energy particles and jets
• Energy loss of very high momentum probes on very short distances
• Photons & E-W bosons do not lose energy
• Strongly interacting medium formed, non-hadronic medium
• Medium properties explored in detail:
  • Cold nuclear matter effects under control with systems of different sizes, energies
  • Full jet reconstruction now possible
  • Photon-jet correlations and jet fragmentation show details of jet quenching
  • Heavy flavor probes: hadron creation and melting, temperature
• Ongoing efforts for new, sophisticated results
THANK YOU FOR YOUR ATTENTION

If you are interested in these subjects, come to our
Zimányi School 2017
December 4-8., Budapest, Hungary

http://zimanyischool.kfki.hu/17
BACKUP
NEUTRAL PION – HADRON CORRELATIONS

- Neutral pion as a trigger particle for the jet: unmodified momentum
- $p_{out}$: non-perturbative momentum width
- Increase in acoplanarity compared to pp
- Decrease for $p+Al$ versus $p+Au$
JET SUPPRESSION IN CU+AU

- Similar behavior to usual Au+Au observations
QUARK PARTICIPANT SCALING

- fds

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**Suppression**
• independent on jet cone radius
HEAVY FLAVOR SUPPRESSION IN Cu+Au

- Charmonia, bound c\bar{c} (prompt J/\Psi): suppressed due to breaking/melting
- Open beauty (via non-prompt J/\Psi): unsuppressed
- Consistent with expectations (EPS09)
- Slight backward enhancement?