Bayesian Methods for Finding Jets in Heavy Ion Collisions

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Outline

• Why are we here?
• Heavy Ion Collisions & Finite T QCD
• Jets in Heavy Ion Collisions
• Bayesian Methods for Finding Jets
• Other Applications
Why are we here (at the INT)?

- It’s the QCD Lagrangian (our most perfect theory)
  \[
  L_{QCD} = -\frac{1}{4} F_{\mu\nu}^a(x) F_{a\mu\nu}^a(x) + \sum_{f=1}^{n_f} \bar{\Psi}_f(x) \left( \mathcal{D}_{\alpha\beta} - m_f \delta_{\alpha\beta} \right) \psi_f^\beta(x)
  \]

- Analytic Solution Exists for one Problem
  - high energy scattering (jet production)

- Models and/or Numerical Techniques needed for
  - nuclear structure/reactions
  - nuclear astrophysics
  - finite temperature phenomena

Bayesian Methods are good fit for (messy) Nuclear Physics
Quark Gluon Plasma (QGP) Phase Diagram

*from Kyle’s talk, $1.4 \frac{m_{sol}}{(4/3 \pi (12\text{km})^3} = 7$
How we now know that there is no true phase transition separating quark-gluon plasma from nucleons.

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Prior

Pratt (15), Moreland (16), W-B and HotQCD (14)

Posterior

HQ
WB
S95
Bayesian
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Relativistic Heavy Ion Collision History

• First theory: Chapline et al. (73), Bjorken (83)
• Experimental Program
  – LBL-Bevalac 1980s
  – BNL-AGS/CERN-SPS 80s and 90s
  – BNL-RHIC 2000 – 2025
  – CERN-LHC 2009 – 20??

First attempt at Bayesian Methods began in 2009.

1st Compelling Results
Flow and Jet Quenching

Flow

Both initial results are measurements of asymmetry

Jets
p+p vs. Au+Au
The Heavy Ion Model

- Bulk properties \((T,V,\rho,\eta/s,\xi)\) now constrained \(\rightarrow\)
  - previous talks by Scott, Steffen/Jonah
- Remaining questions require jets (& heavy quarks)
  - What are the (strongly interacting) constituents ?
  - How does the QGP form (thermalize) ?

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Jet Production in p+p collisions

- Jets = highly collimated streams of produced by hard scattering of quarks/gluons
  - jet production calculated precisely in perturbation theory
  - fragmentation into particles (hadrons) modeled with PYTHIA Monte Carlo model of Lund String Fragmentation
  - For our purpose, p+p jet models have *no tunable parameters*
Analyzing Jets in p+p collisions

- Experimentalists rely on jet-finding algorithms to identify and study jets
  - particles are combined in pair-wise fashion for small values of \((\Delta R_{ij})^2/R^2 = [(y_i-y_j)^2+(\phi_i-\phi_j)^2]/R^2\), R=jet-cone radius
  - jet-finding proceeds until all particles above specified momentum \(p_T\) within radius \(R\) are combined
  - this works well for p+p and e+e- collisions
Jets fragmentation in vacuum and QGP

use photon-quark jet as example

- photon escapes unscathed, with unmodified jet energy
- quark jet modified by plasma
- jet-finder to contend with reduced energy jet within high multiplicity backgrounds

jet processes in p+p
- quark (parton) distribution function – measured with DIS
- QCD scattering cross-sections – calculated perturbatively
- string fragmentation – modeled, parameters tuned with data

jet processes in QGP
- first two process same as p+p
- full jet evolution model under construction → JETSCAPE

Present theory depends on
Jets in Heavy Ion Collisions

- Jets scatter, radiate, loss energy as they traverse QGP
- This process is governed by parameters
  - diffusion: \( \hat{q} = <p_T>^2 \), drag: \( \hat{e} = <p_z>/L \)
  - and higher moments of \( <p_T^4>, <p_z^2> \), etc.
- Energy loss + backgrounds will challenge jet finding algorithms

LHC Data

R=0.4 RHIC Simulation

slowjet in pythia with treno background
treno multiplicity = 661
My goals for this workshop (and beyond)

• Understanding jets in heavy ion physics depends on our ability to find them using algorithms developed for simpler environments (p+p and e+e-)

• The most interesting jets are the hardest to find
  – the ones that couple most strongly to the medium

• Can we develop simple model to apply jet-modification to Pythia outputs, add heavy ion backgrounds, and compare directly to particle distributions?

Bayesian approach to extract jet quench parameters from data
Develop simple model to test idea

• Use 3 Component Model
  1. Generate photon-quark jets with Pythia
  2. Modify jet-outputs with q, e parameters
    • loop over particle list
      – rescale momenta || to jet axis (drag)
      – add to momenta ⊥ to jet axis (diffusion)
  3. Generate heavy ion background particles
    1. Multiplicity = number of particles
    2. Geometry = generate L for transport
    3. Particle Flow = determined by geometry

Have all we need for heavy ion backgrounds in initial state
Heavy Ion Backgrounds with $T_R$ ENTO

• $T_R$ ENTO = Thickness$_{\text{Reduced}}$ Event Nuclear Topology
• Monte Carlo samples reduced nuclear thickness
  – Settings: input nuclei, energy dependent n-n cross-section
  – Parameters: $p=0$ (weights), $k=1.4$ (binomial factor)
  – constrained independently
• Outputs: entropy=multiplicity, $\varepsilon_2$, $\varepsilon_3$, $\varepsilon_4$, $\varepsilon_5$

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TRENTO Multiplicity Study

PHENIX data / TRENTO comparison

Joseph Simpson, USNA

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$T_R$ ENTO with Flow and Jet-Finder

slowJet w/ trento background

anti-$k_T$
with $R=0.7$
Bayesian Formulation

• Model θ = Pythia + Re-Scaling + T_R ENTO
• Model Parameters to Constrain: q, e
• Other Parameters: mult, L, ε_2, p_{CM}, R
  – mult can be measured, and L inferred
  – R = cone-like radius opposite photon-jet
• Measurements: p_{jet} (photon), p_i for particles/cells
• Bayesian formulation
  – P[θ(e,q, ε_2);mult,p_{jet}, p_i] ≈ \exp -\Sigma[y_i^{model}(x) - y_i^{exp}(x)]/(2\sigma_i^2)
  – errors are from summing particle/cells (Poisson)
Figure for discussion

slowJet in pythia with trento background
trento multiplicity = 523

sum over cells and compare to model for same $p_{jet}$ and mult
Another figure for discussion

slowJet in pythia with trento background

trento multiplicity = 661
Questions

• Is this approach sensible?
• Which assumptions are suspect?
• What have I missed?
• Has this approach already been attempted?
  – see DataScience@LHC2015 talk by SLAC scientists
• Where do I get started: MADAI, mtd@github?

• How does this relate to nuclear detection/attribution?
• Jetscape plans develop new event generator to model full physics of jets in QGP, constrain with data
• Data comparison may benefit from this work