Bayesian Methods for Finding Jets in Heavy Ion Collisions

Ron Soltz
Lawrence Livermore National Laboratory

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)

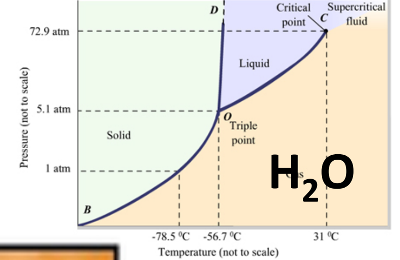
$$L_{QCD} = -\frac{1}{4} F^a_{\mu\nu}(x) F_a^{\mu\nu}(x) + \sum_{f=1}^{n_f} \overline{\psi}^{\alpha}_f(x) \left(\not{D}_{\alpha\beta} - m_f \delta_{\alpha\beta} \right) \psi^{\beta}_f(x)$$

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

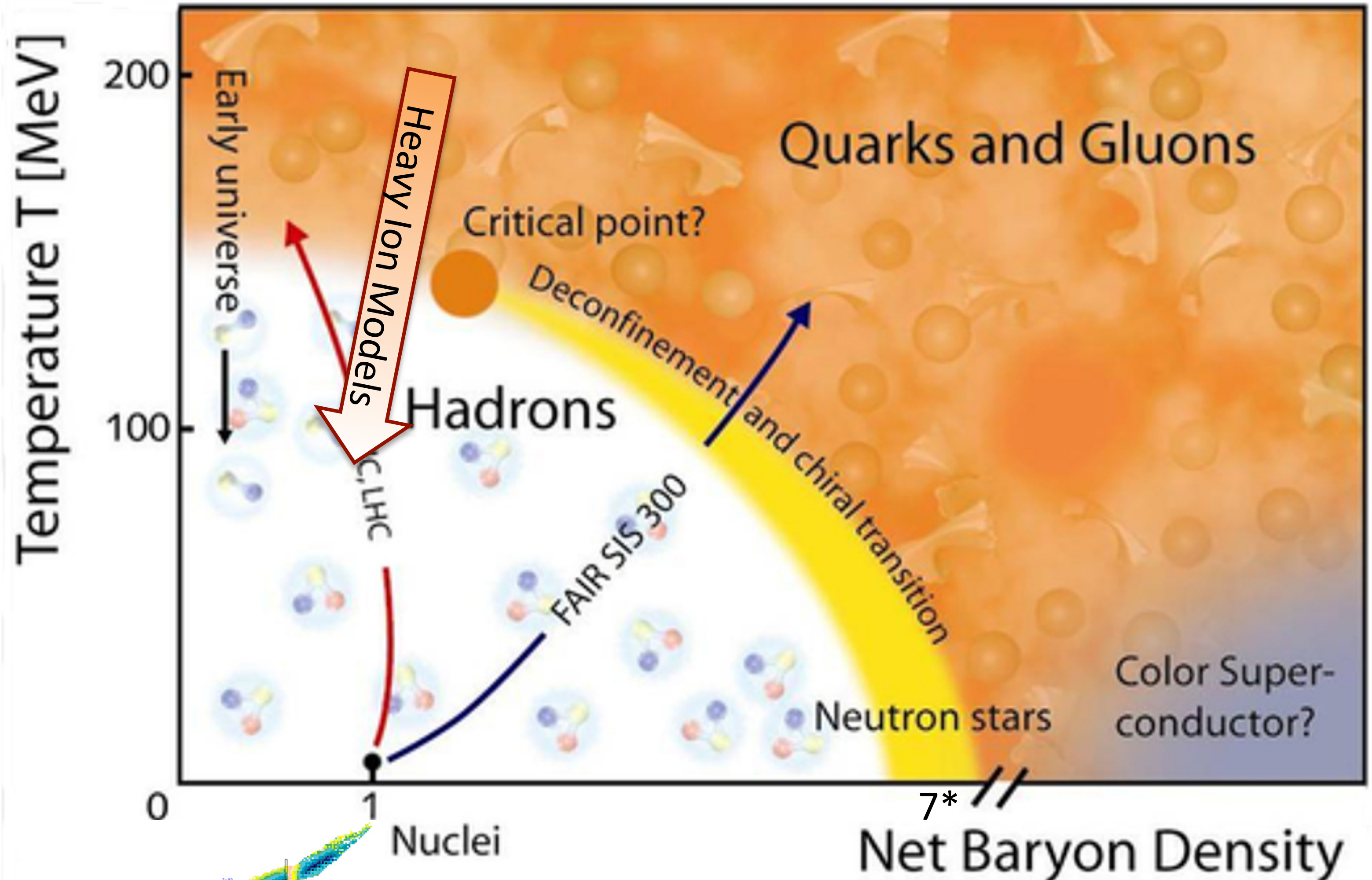
- Models and/or Numerical Techniques needed for
  - nuclear structure/reactions
  - nuclear astrophysics
  - finite temperature phenomena

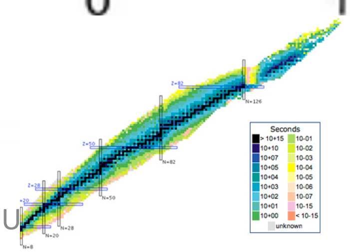
Bayesian Methods are good fit for (messy) Nuclear Physics

Quark Gluon Plasma (QGP) Phase Diagram



(10^{10} K)

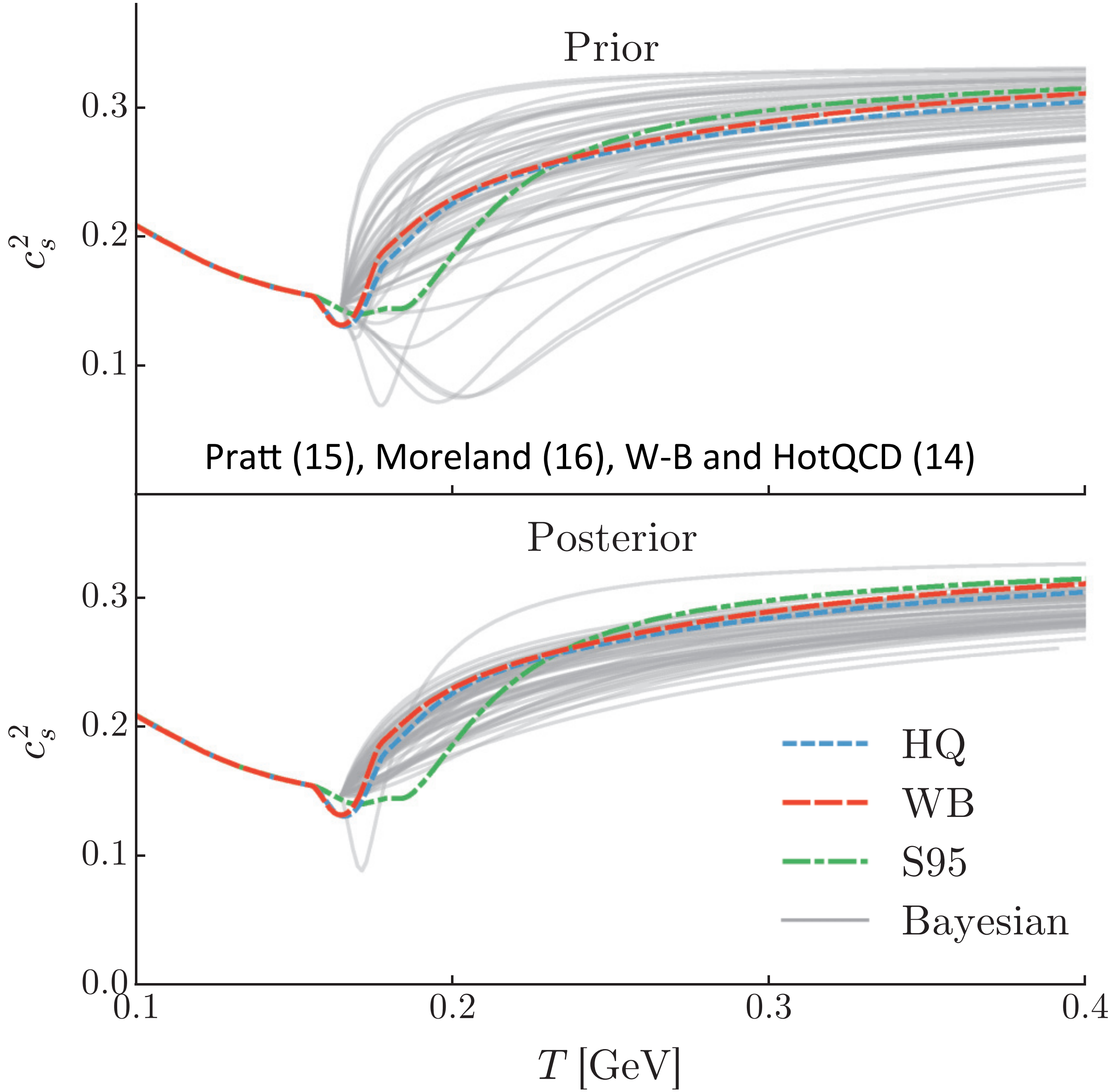




*from Kyle's talk, 1.4 $m_{sol}/(4/3\ \pi\ (12km)^3 = 7$

Digression

How we now know that there is no true phase transition separating quark-gluon plasma from nucleons



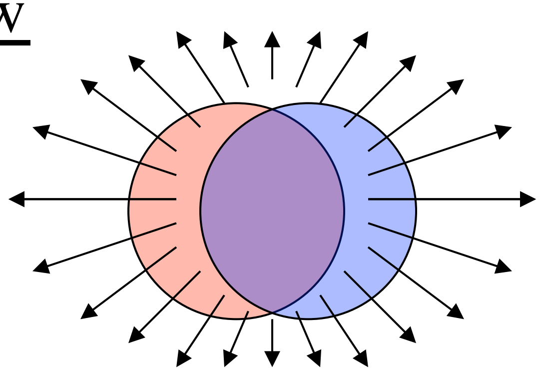
Relativistic Heavy Ion Collision History

- 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??

} 1st Compelling Results — Flow and Jet Quenching

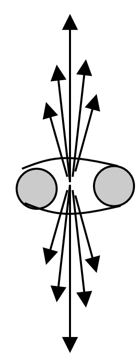
First attempt at Bayesian Methods began in 2009.

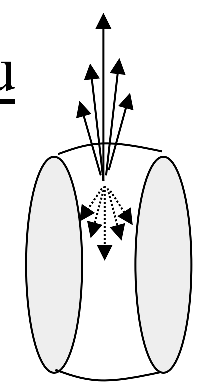
Flow



Jets

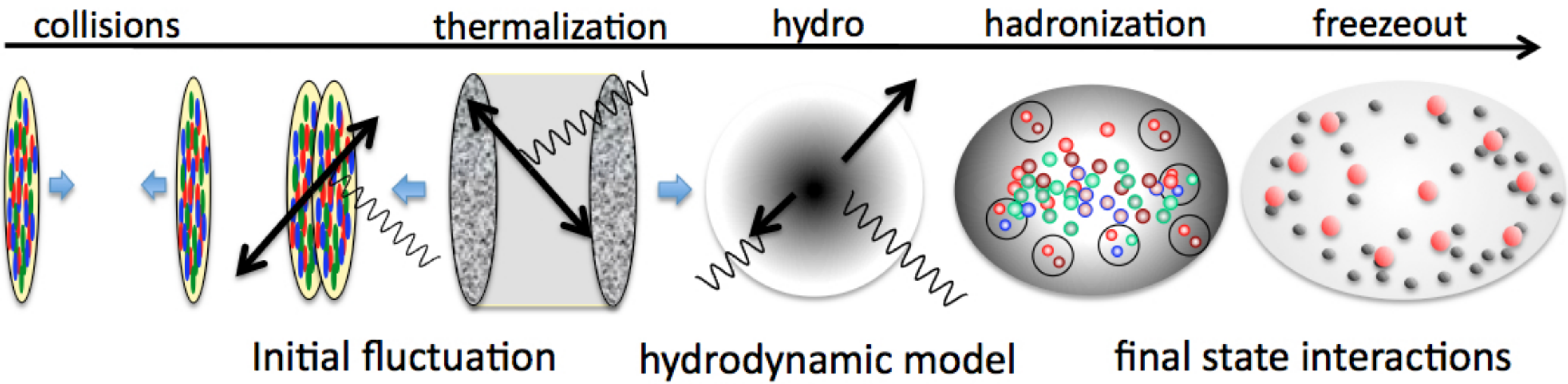
p+p *vs.* Au+Au

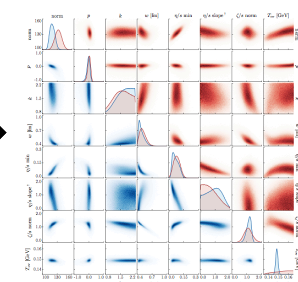




Both initial results are measurements of asymmetry

The Heavy Ion Model

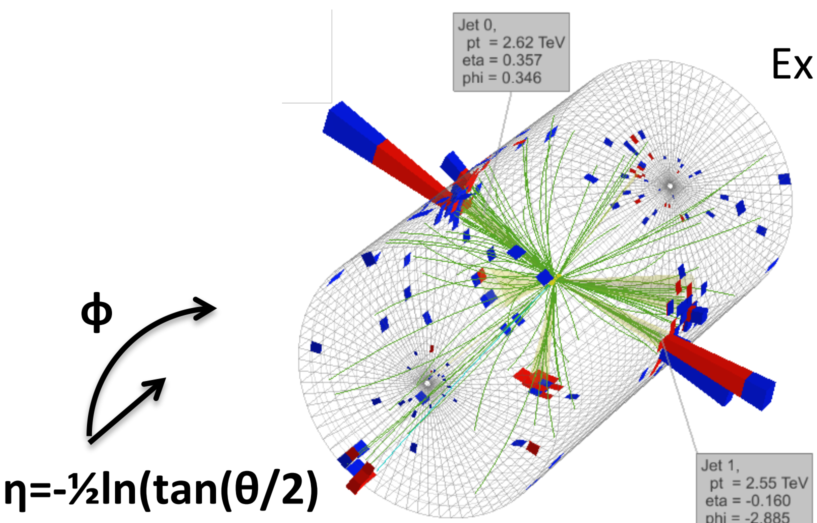


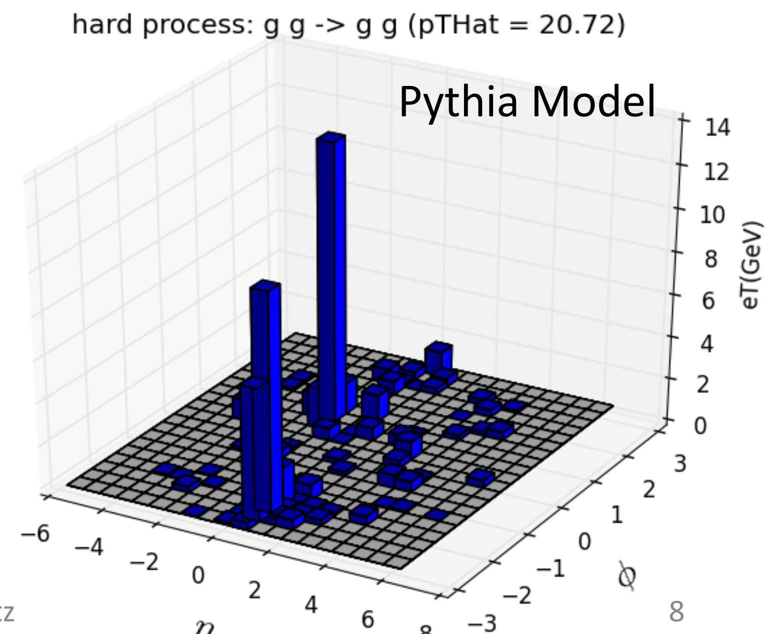


- Bulk properties (T,V,ρ,η/s,ξ) now constrained →
  - previous talks by Scott, Steffen/Jonah
- Remaining questions require jets (& heavy quarks)
  - What are the (strongly interacting) constituents ?
  - How does the QGP form (thermalize) ?

Jet Production in p+p collisions

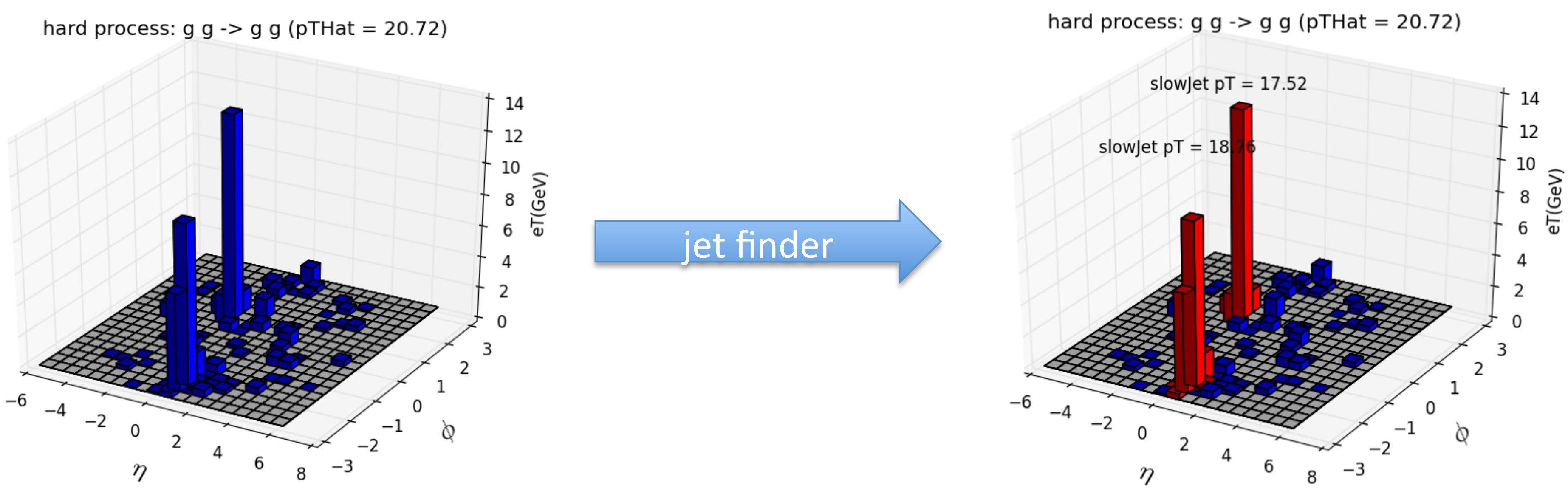
- Jets = highly collimated streams of produced by hard scattering of quarks/gluons
  - jet production calculated precisely in perturbation theory
  - fragmentation into particles (hadrons) modeled with PYTHIA Monte Carlo model of Lund String Fragementation
  - For our purpose, p+p jet models have *no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





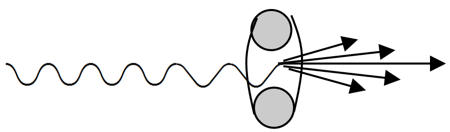
Analyzing Jets in p+p collisions

- Experimentalists rely on jet-finding algorithms to identify and study jets
  - particles are combined in pair-wise fashion for small values of $(\Delta R_{ij})^2/R^2 = [(y_i-y_j)^2+(\varphi_i-\varphi_j)^2]/R^2$, 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

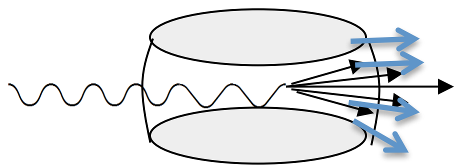


Jets fragmentation in vacuum and QGP

p+p



Au+Au



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

} Pythia

jet processes in QGP

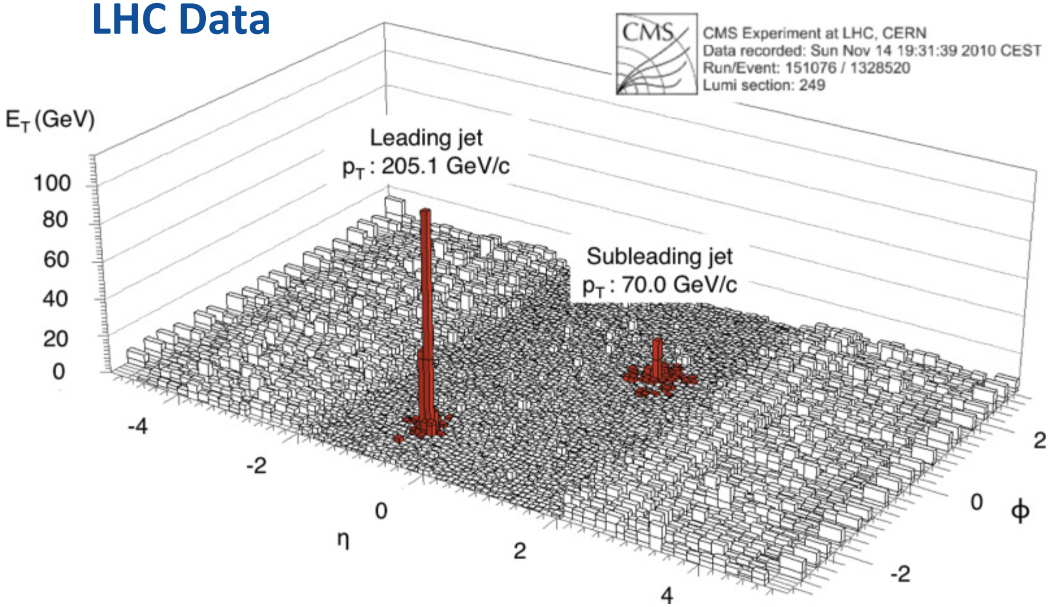
- first two process same as p+p
- full jet evolution model under construction → JETSCAPE

Present theory depends on

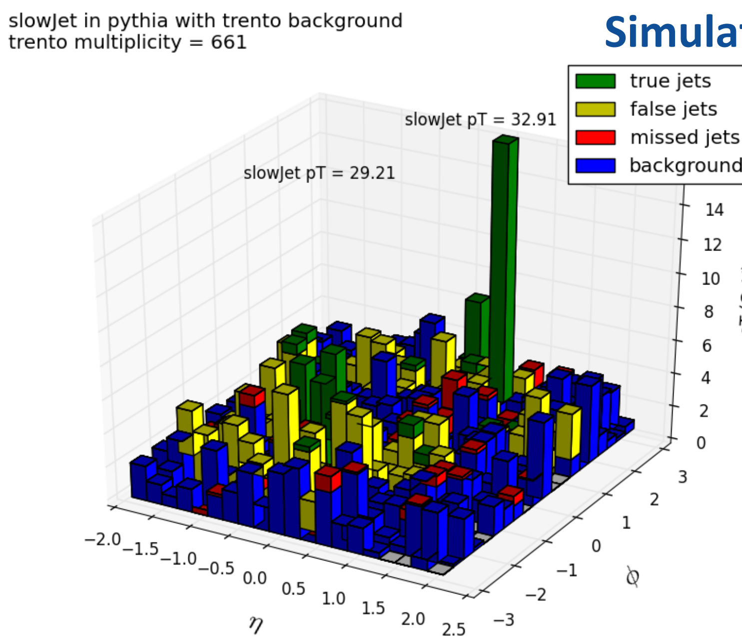
Jets in Heavy Ion Collisions

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

LHC Data



R=0.4 RHIC Simulation



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

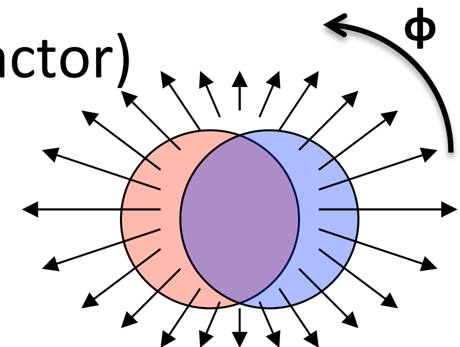
Develop simple model to test idea

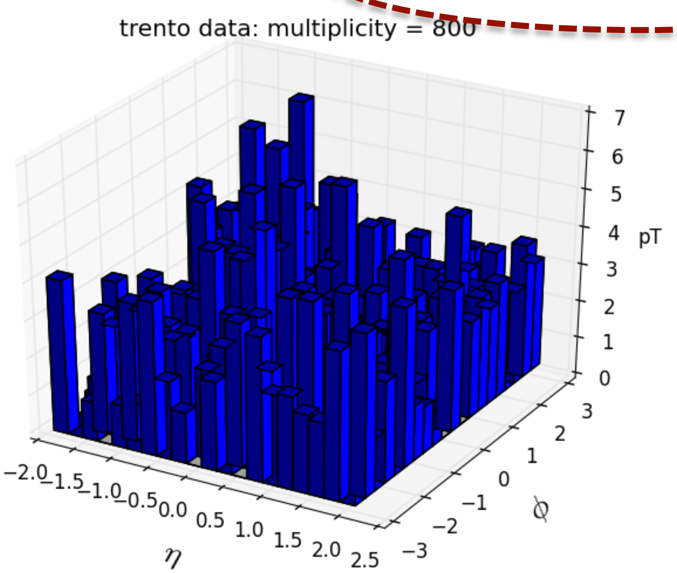
- Use 3 Component Model
  1. Generate photon-quark jets with Pythia
  2. Modify jet-outputs with q, e parameters
     - loop over particle list
       - rescale momenta || to jet axis (drag)
       - add to momenta $\perp$ to jet axis (diffusion)
  3. Generate heavy ion background particles
     1. Multiplicity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

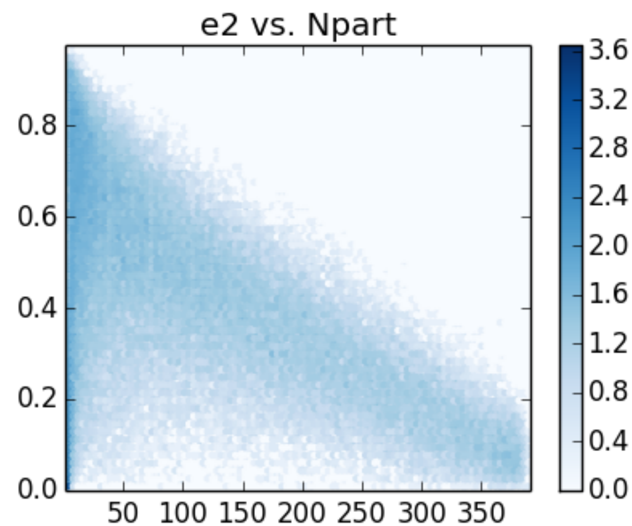
Have all we need for heavy ion backgrounds in initial state

Heavy Ion Backgrounds with T_RENTO

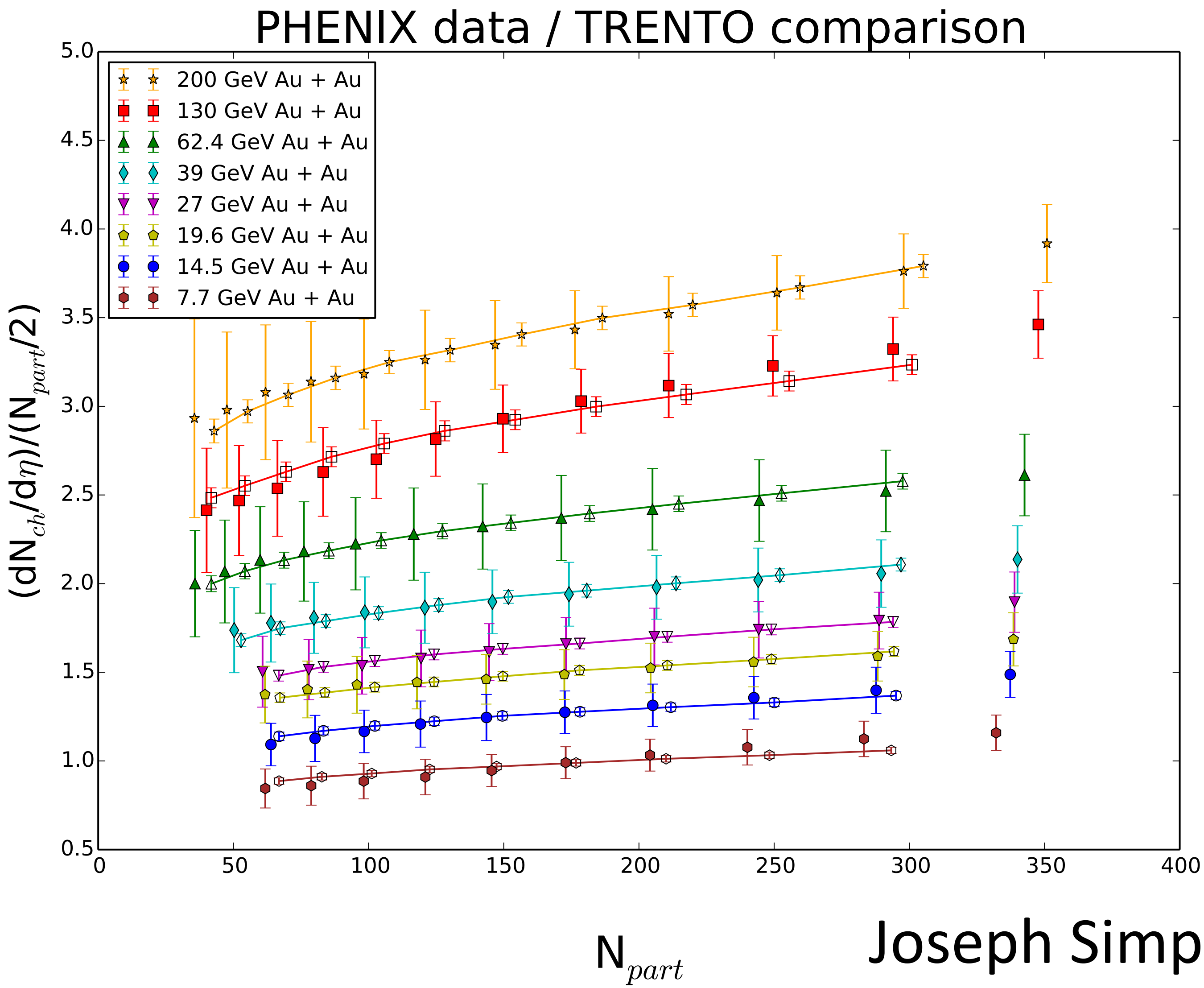
- T_RENTO = $\text{Thickness}_{\text{Reduced}}$ Event Nuclear Topology
- Monte Carlo samples reduced nuclear thickness
  - Settings : input nuclei, energy dependent n-n cross-section
  - Parameters : p=0 (weights), k=1.4 (binomial factor)
    - constrained independently
  - Outputs : entropy=multiplicity, ε_2, ε_3, ε_4, ε_5





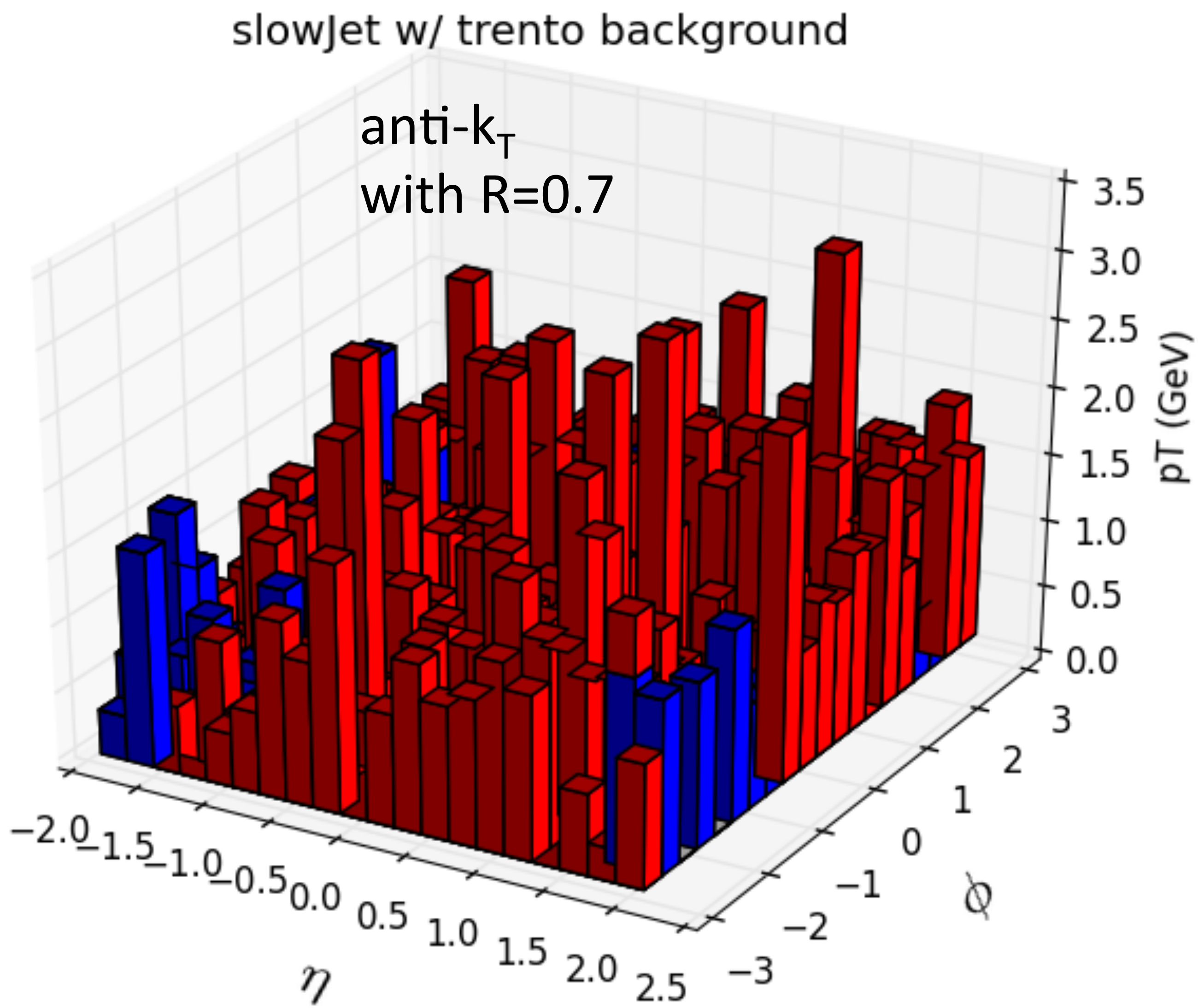


T_R ENTO Multiplicity Study



Joseph Simpson, USNA

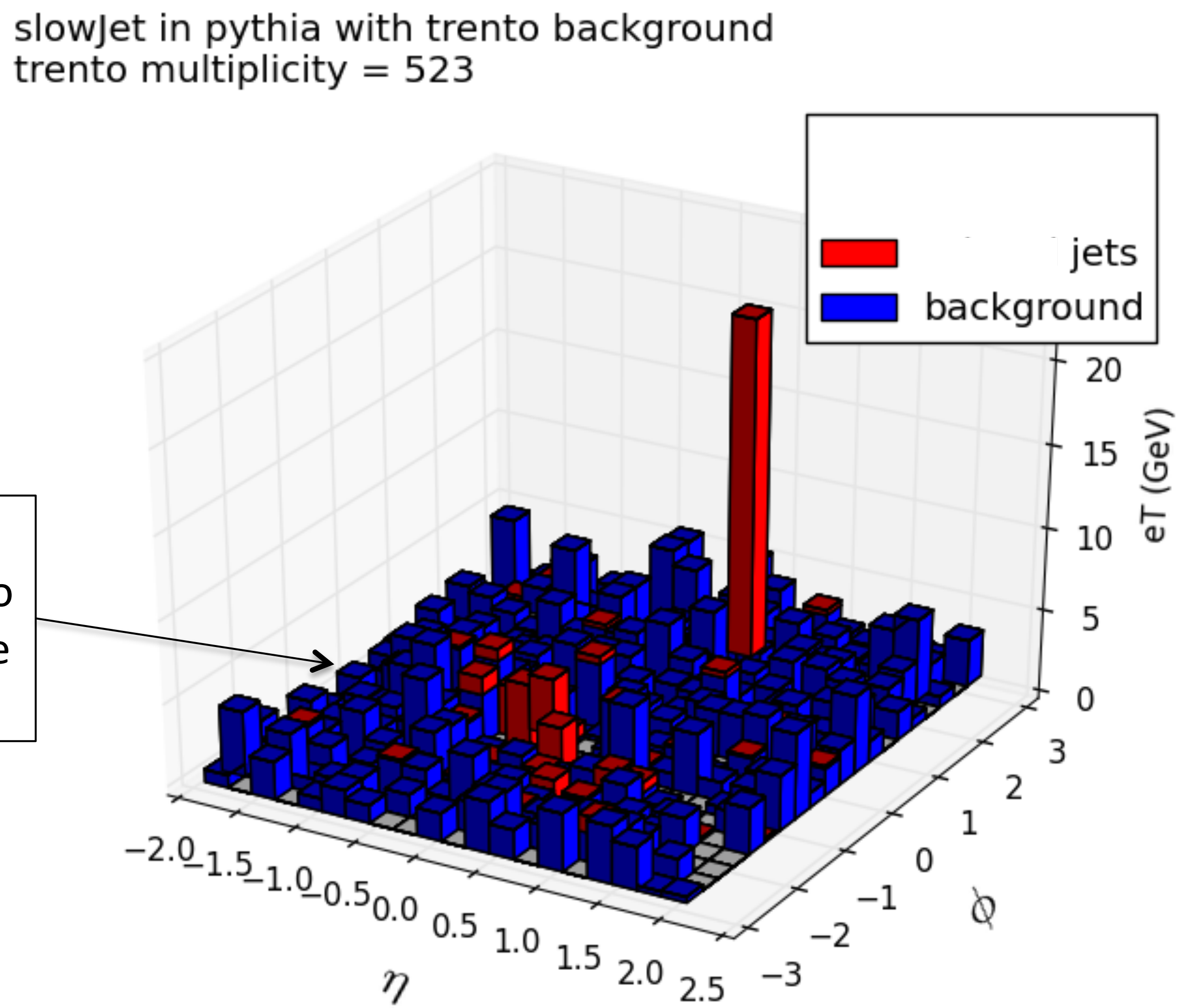
T_RENTO with Flow and Jet-Finder



Bayesian Formulation

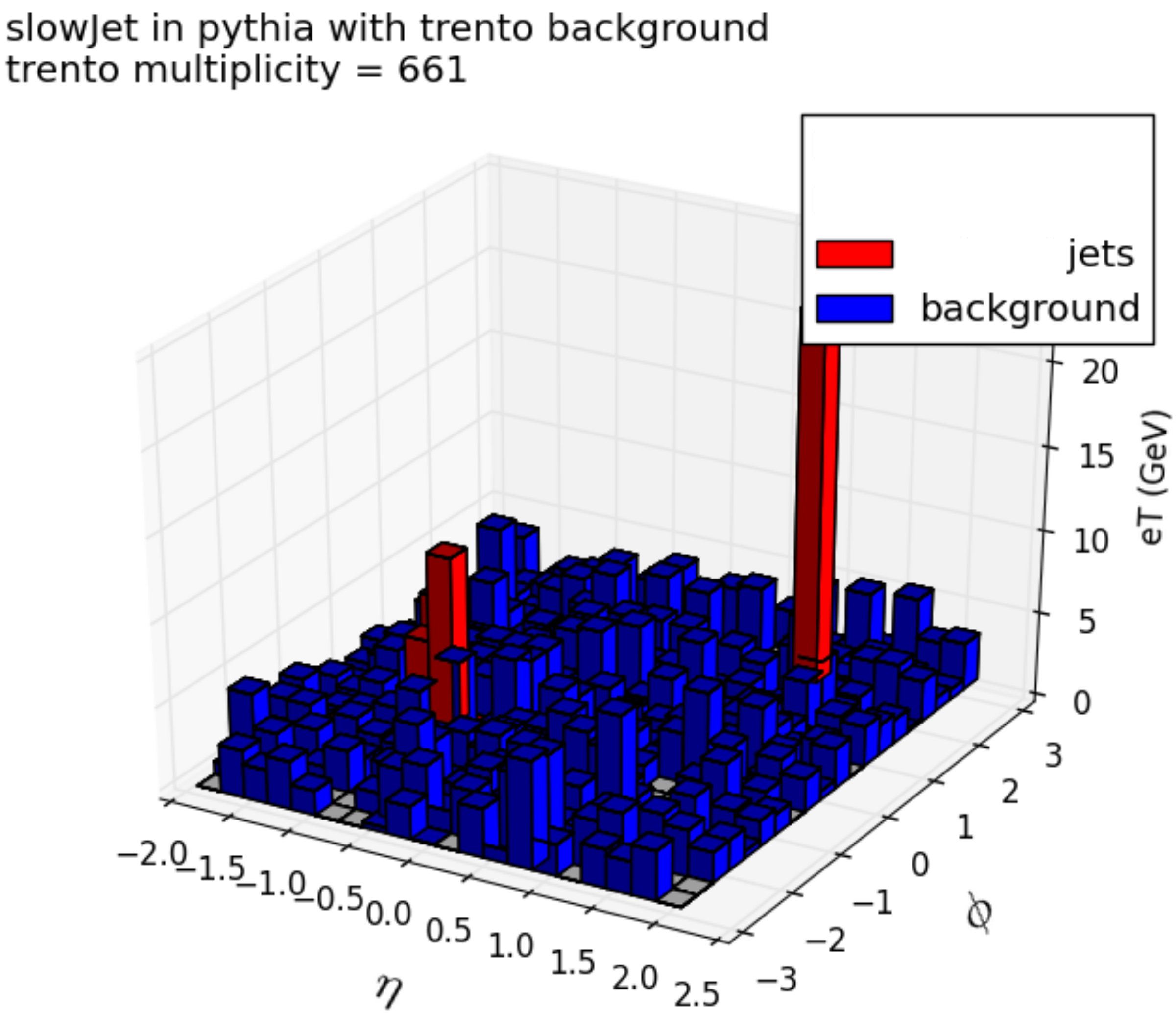
- Model θ = Pythia + Re-Scaling + T_RENTO
- Model Parameters to Constrain: q, e
- Other Parameters: mult, L, ε_2, p_{CM},R
  - mult can be measured, and L inferred
  - R = cone-like radius opposite photon-jet
- Measurements: p_{jet} (photon), p_i for particles/cells
- Bayesian formulation
  - $P[\theta(e,q, \varepsilon_2);mult,p_{jet}, p_i] \approx \exp -\Sigma[y_i^{model}(x)-y_i^{exp}(x)]/(2\sigma_i^2)$
  - errors are from summing particle/cells (Poisson)

Figure for discussion



sum over cells and compare to model for same p_{jet} and mult

Another figure for discussion

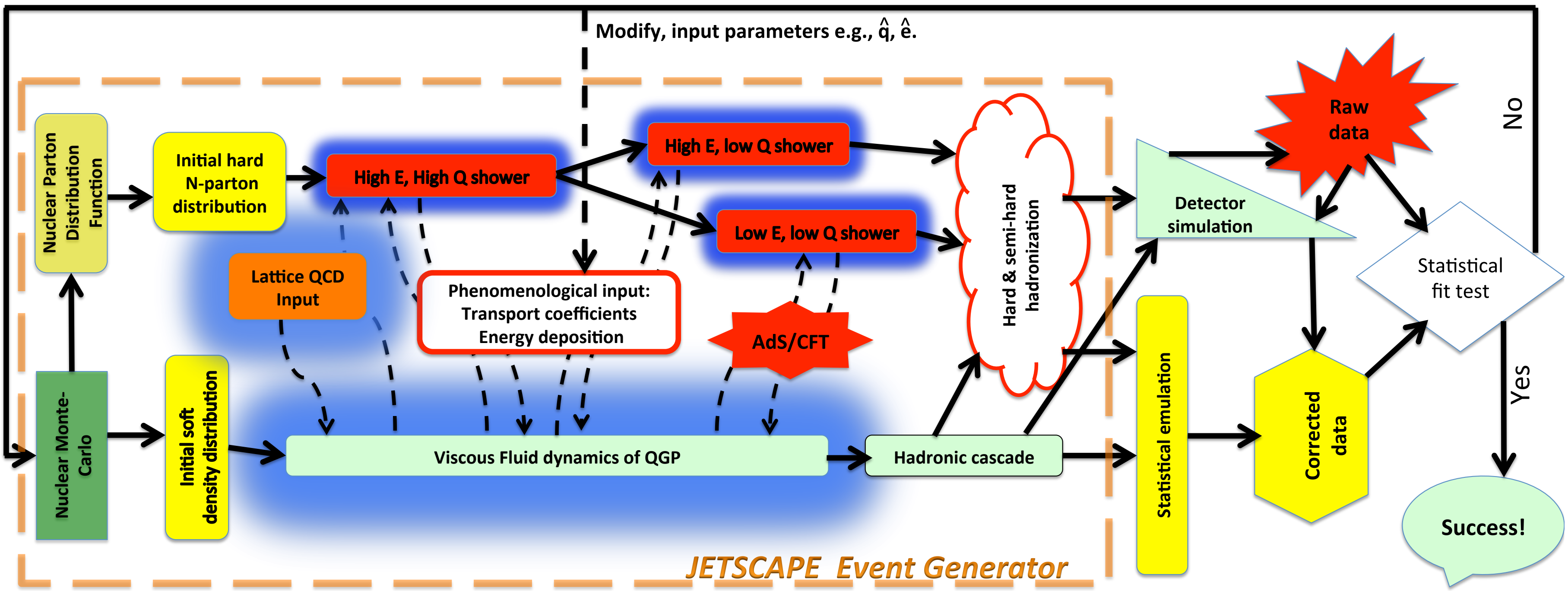


Questions

- 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 Collaboration (2016-2020)



- Jetscape plans develop new event generator to model full physics of jets in QGP, constrain with data
- Data comparison may benefit from this work