First Results from Hybrid Hadronization in Small and Large Systems

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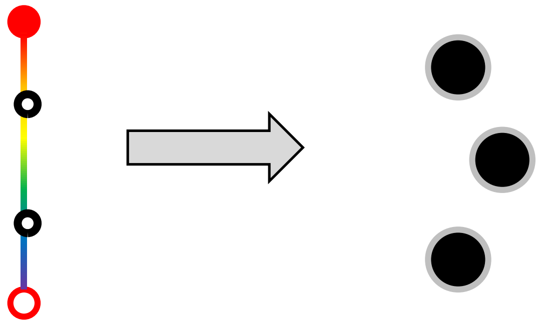
On behalf of the JETSCAPE Collaboration

Overview

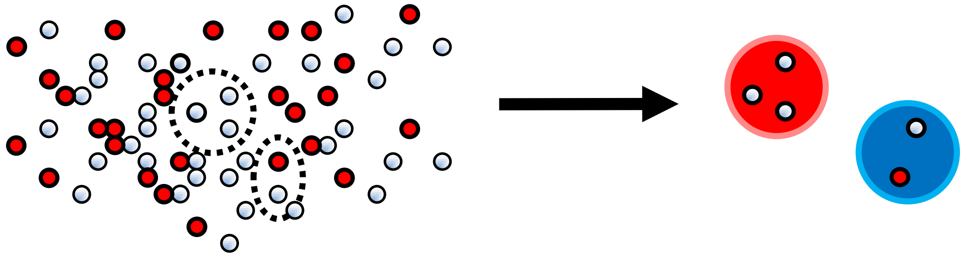
- Hadronization Models
- Hybrid Hadronization
- Hybrid Hadronization Implementation
- Space-time Structure
- Qualitative Study of Hybrid Hadronization
- Summary

Hadronization Models

- String fragmentation:
  - Color flux expelled from the QCD vacuum at large distances leads to color flux tubes; results in string-like behavior.
  - Implemented in PYTHIA
  - Quarks in the event are connected with strings, gluons are part of these strings – these strings are then broken to form hadrons.



- Recombination/Quark Coalescence:
  - In a densely populated parton system, quarks can directly recombine into hadrons
  - Successful phenomenology in heavy-ion collisions
    - Baryon/meson ratios
    - Elliptic flow scaling



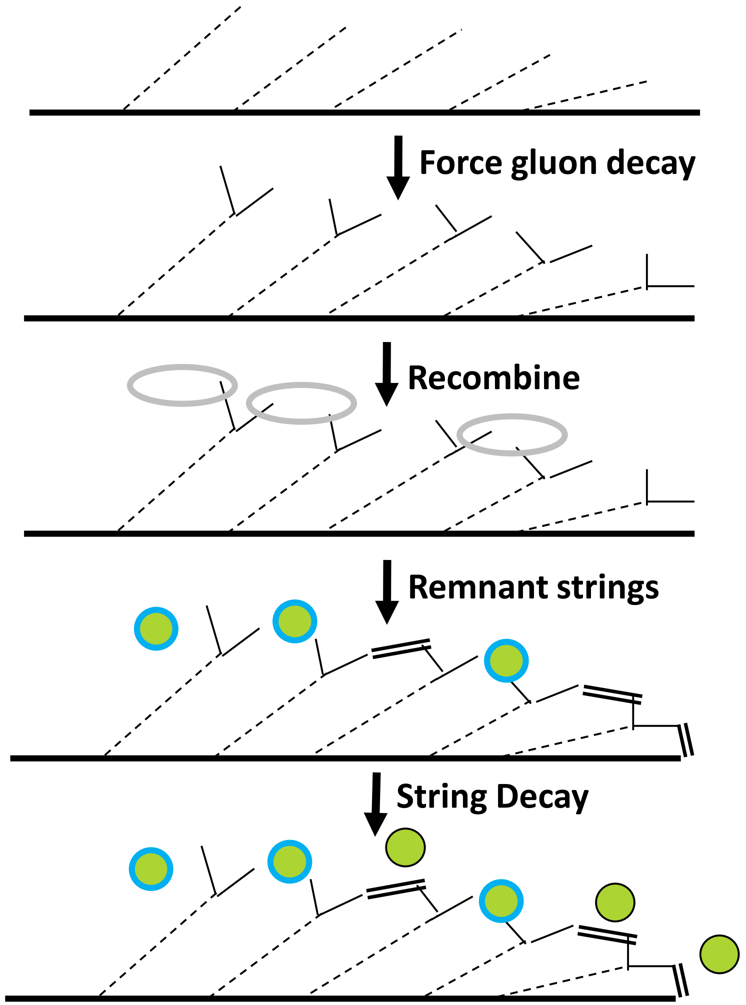
Hybrid Hadronization Model

- Hybrid Hadronization:
  - A hybrid of the existing models of string fragmentation and recombination.
  - Extrapolates smoothly between vacuum phenomenology of string fragmentation and recombination in a densely populated environment, with a focus on the hadronization of parton showers/jets.

- Motivation: in-medium effects for jet hadronization
  - Hadron chemistry
  - Momentum diffusion
  - Medium flow effects

Hybrid Hadronization – Vacuum

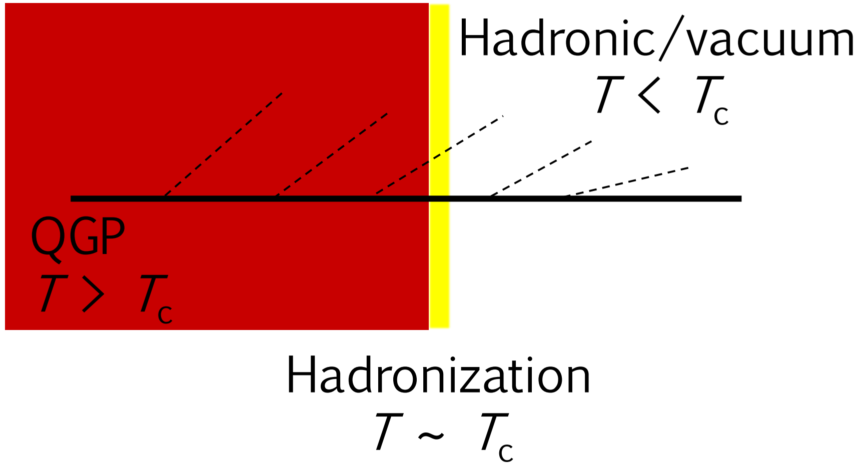
- Algorithm[1] developed and implemented as a part of the JET Collaboration.
- Input: partons from a shower Monte-Carlo.
- Gluons are split into $q\bar{q}$ pairs. Quarks that are close in coordinate and momentum space could recombine into hadrons.
  - Probability (meson): $\overline{W}_{M,n}(\mathbf{y},\mathbf{k}) = \frac{v^n}{n!}e^{-v}, \quad v = \frac{1}{2}\left(\frac{\mathbf{y}^2}{\sigma_M^2} + \mathbf{k}^2\sigma_M^2\right)$
- Gluons are allowed to reform if the decayed pair is still present.
- Holes in strings are naturally repaired using the color flow information.
- Remnant strings are fragmented into hadrons using PYTHIA 8.



[1]K. Han, R. J. Fries, C. M. Ko, Phys. Rev. C 93, 045207 (2016)

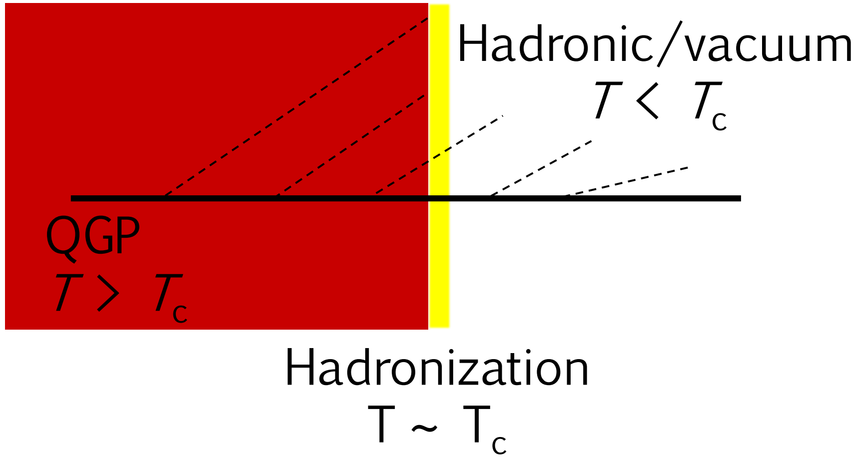
Hybrid Hadronization – Medium

- This procedure can be extended to include thermal parton recombination.



- All partons to be considered for hadronization must exist at or outside the surface of the QGP.
  - If there are shower partons inside the QGP, they must either be propagated by the shower MC to the hypersurface, or absorbed by the medium.

- Sampled thermal partons from the medium are added to the list of available partons.



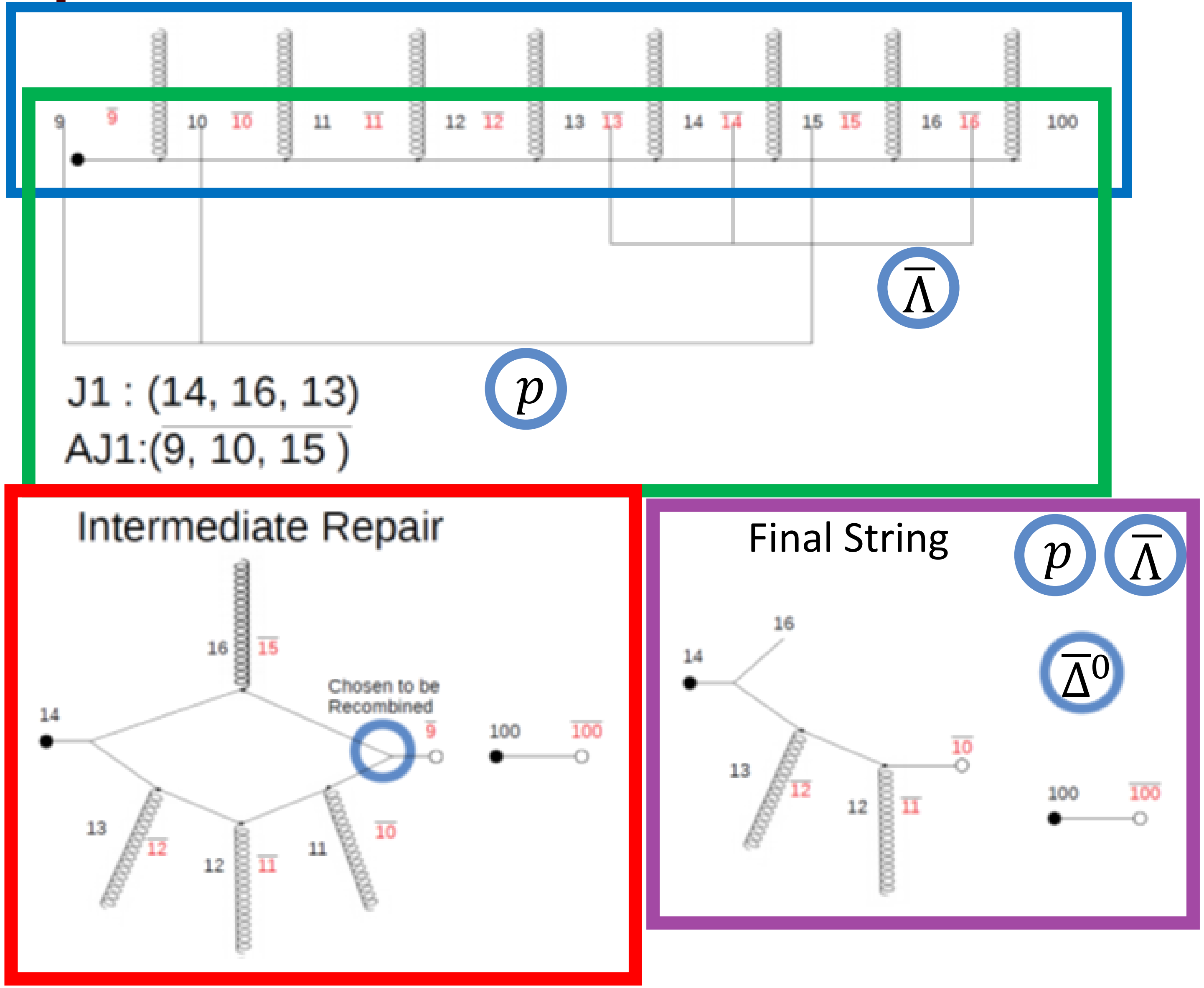
- Apply same recombination MC procedure
  - Allow shower-thermal (sh-th) hadrons
  - Purely thermal hadrons are not included.

Hybrid Hadronization Implementation

- Input
  - Shower & thermal partons – momentum, position, color information
- Recombination
  - Sample probabilities for random quark pairs and triplets to recombine into hadrons, using color flow information from a shower MC
- String Prep
  - Prepare remnant partons on a string-by-string basis for PYTHIA – constructing a fake history for junction containing strings
- PYTHIA invocation
  - Call PYTHIA to perform string fragmentation on remnant strings and handle hadron resonances
- Output
  - Recombined and fragmented hadrons, including space-time information
- Hybrid Hadronization is included in JETSCAPE since v2.0

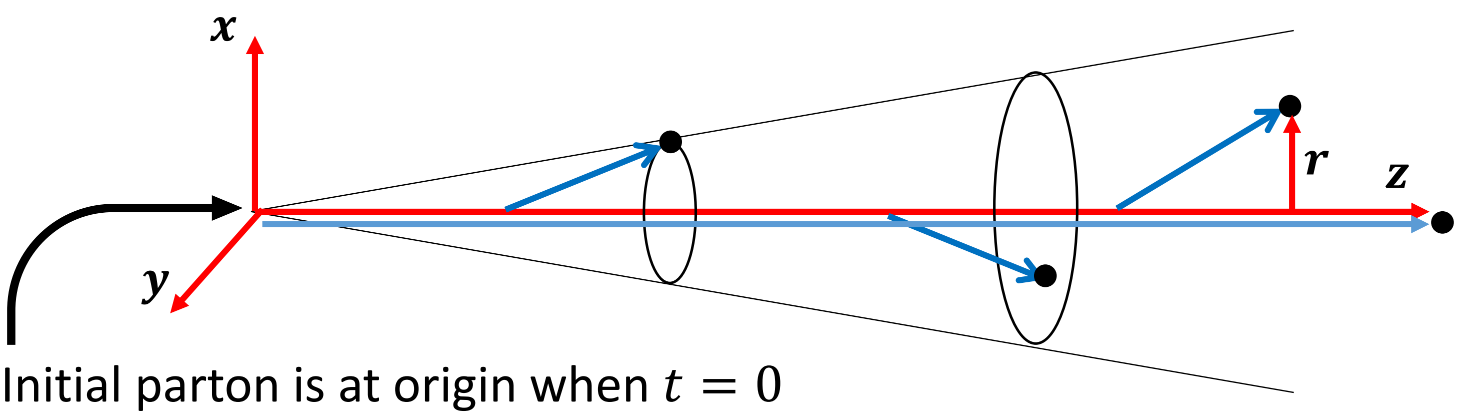
Example Event

- This is a MATTER jet with a trailing color tag (100).
- Two baryons were recombined.
    - Color flow handling gives unique structures
- This resulted in a junction-antijunction system.
    - Junctions will result in baryons after string fragmentation, resulting in baryon number conservation.
- Strings may need to be modified for PYTHIA
    - A parton was added to pair off the trailing color tag – enforcing color neutrality.
    - A junction was chosen to be recombined, cutting the string
        - Multi-junction systems often present difficulties for PYTHIA (including this one)



Space-time Structure

- Space-time information is important in heavy-ion collisions, including for hadronization!
- The parton shower typically extends further in space-time than the fireball size (>$100\ \mathrm{fm}/c$ for $500\ \mathrm{GeV}$ jets).
- The example that follows is for MATTER jets in a vacuum & MATTER+LBT jets in a 4 fm QGP brick.
  - Showing both the partonic and hadronic space-time structures.

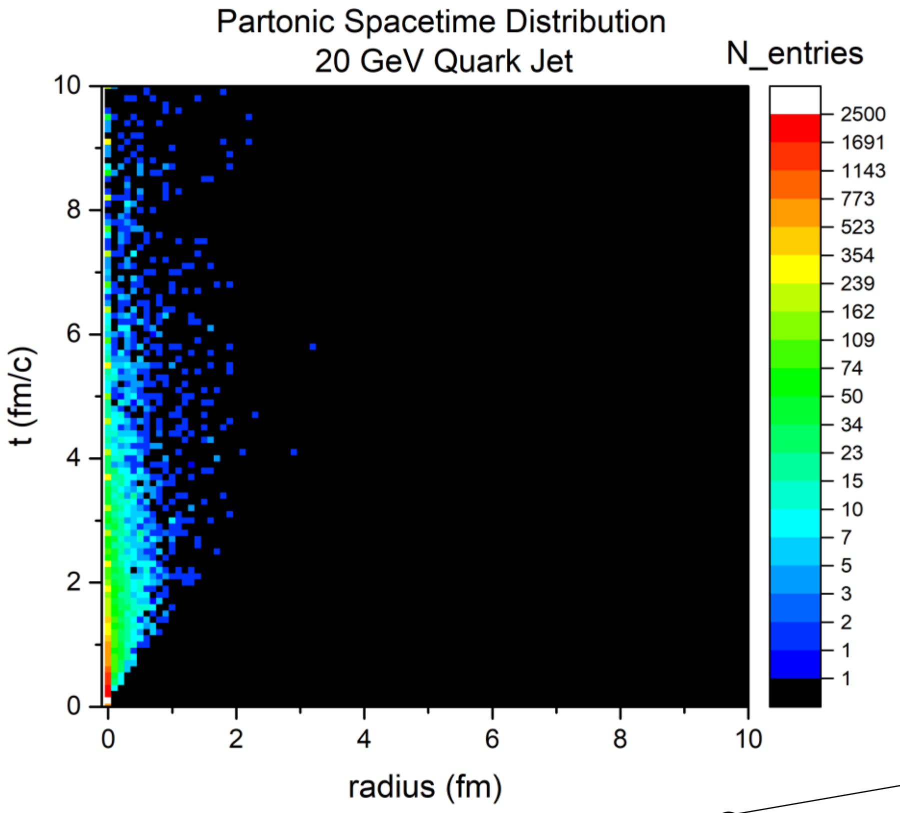


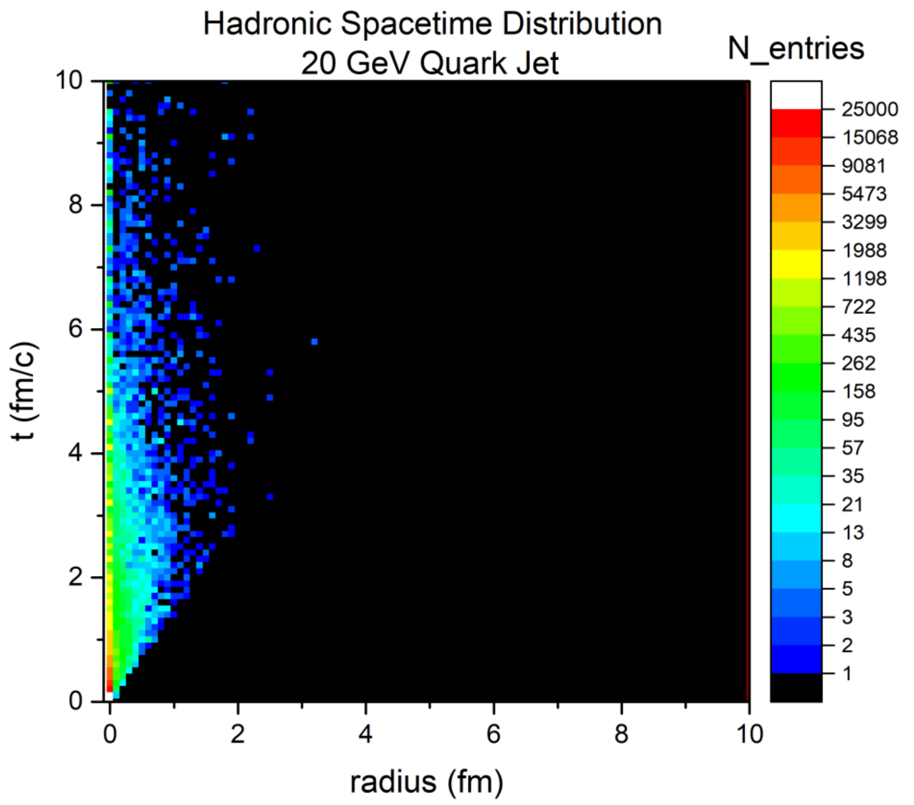
Initial parton is at origin when $t = 0$

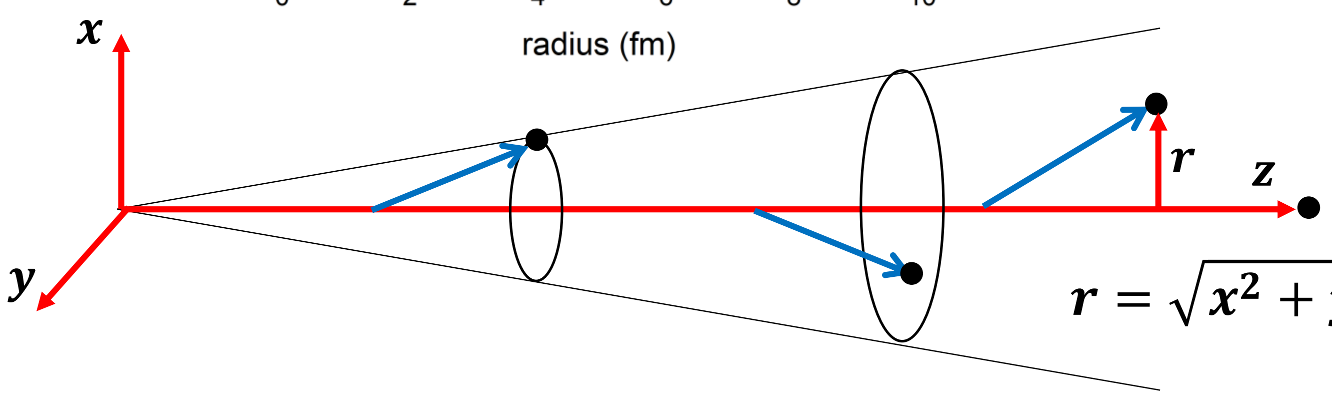
$$r = \sqrt{x^2 + y^2}$$

Partons propagate with $v \sim c$

Results – Vacuum Jets Space-time







$r = \sqrt{x^2 + y^2}$

Partons shown have virtuality $Q < Q_0 = 1$ GeV

Partons propagate with $v \sim c$

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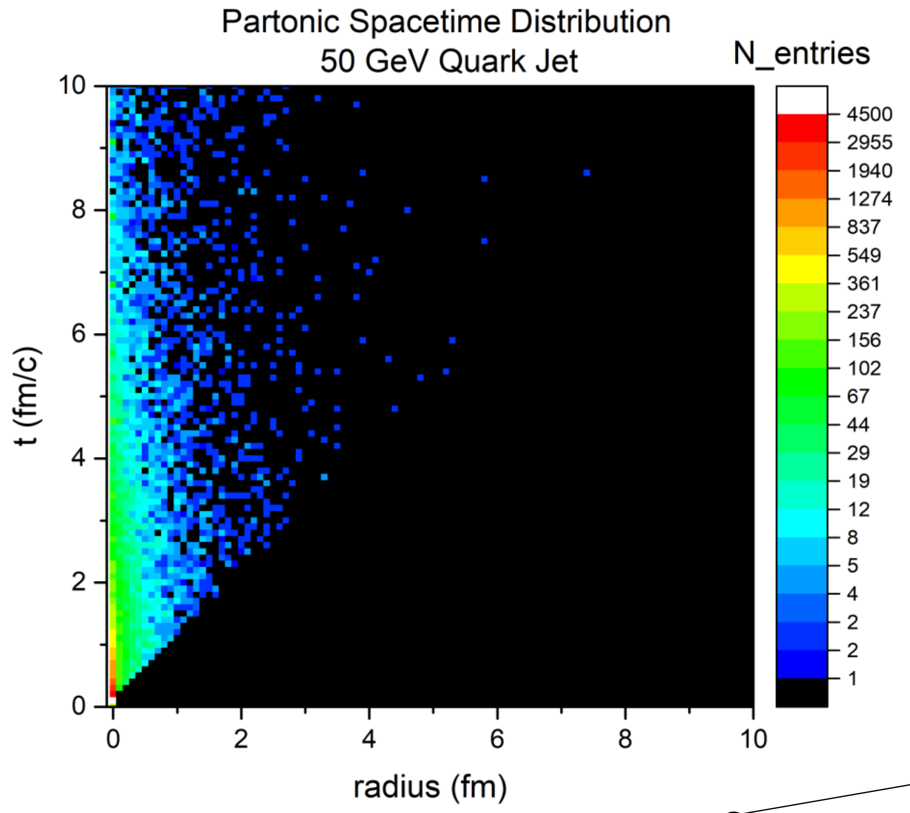

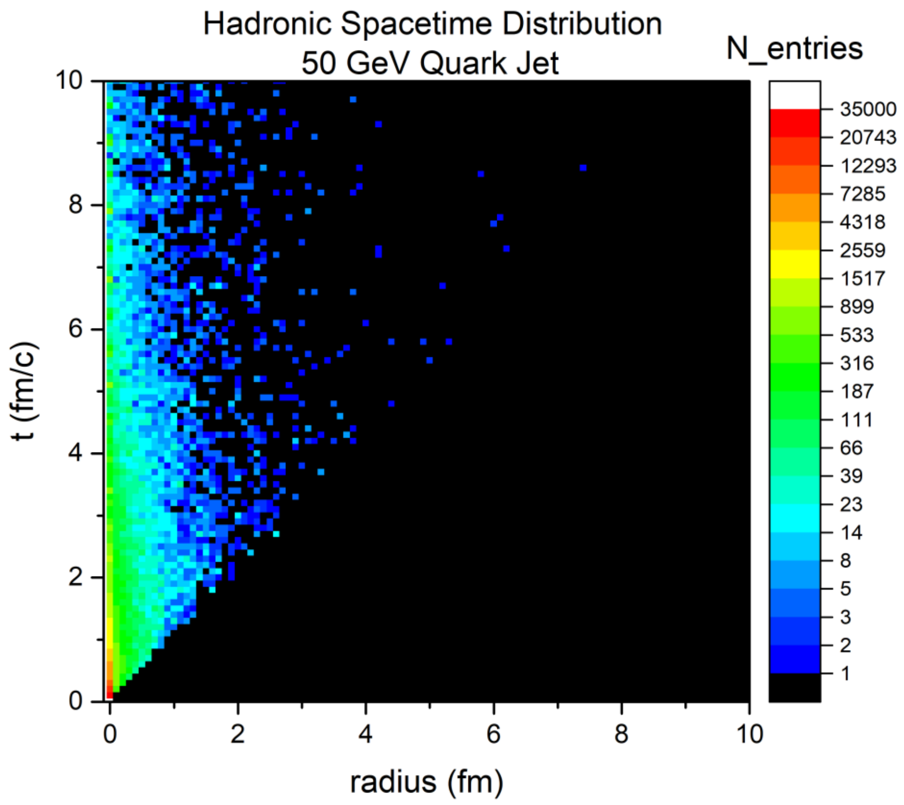

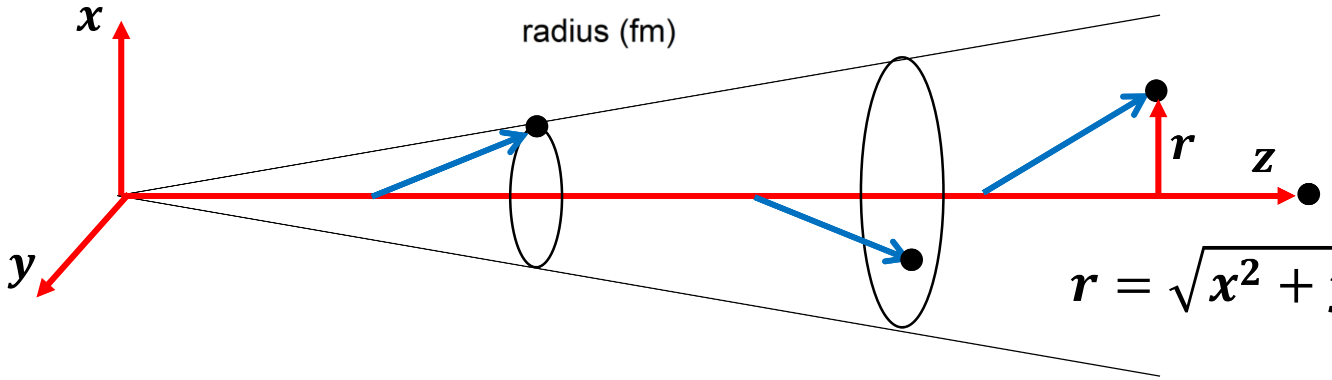

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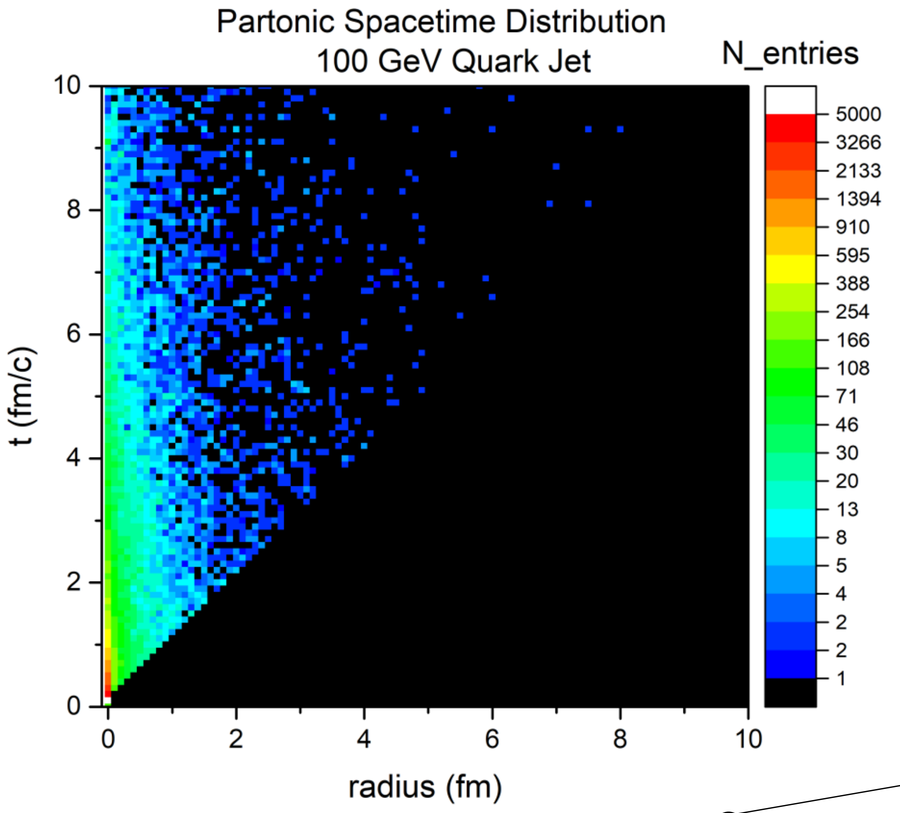

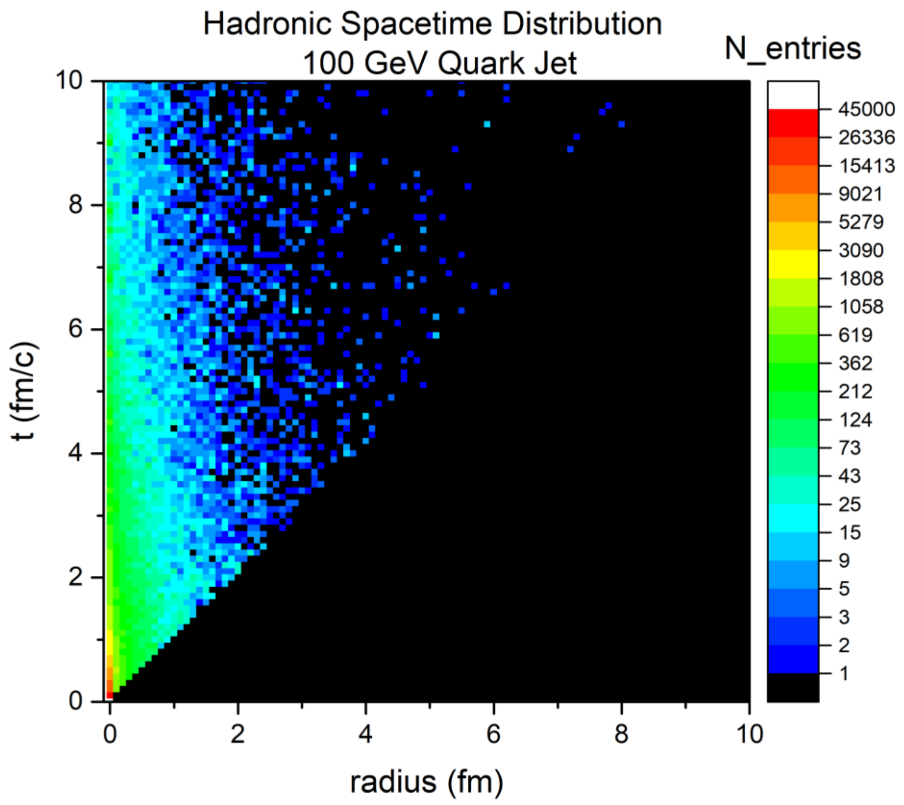

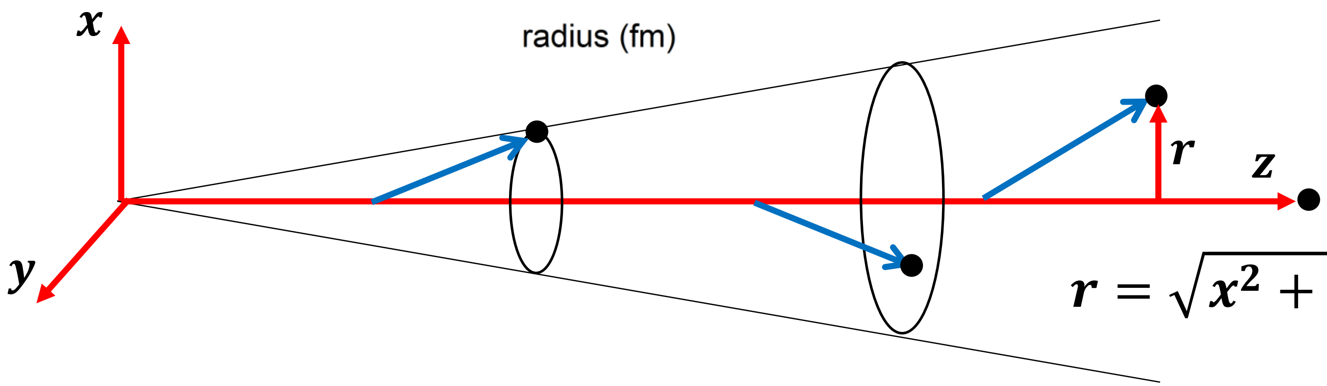

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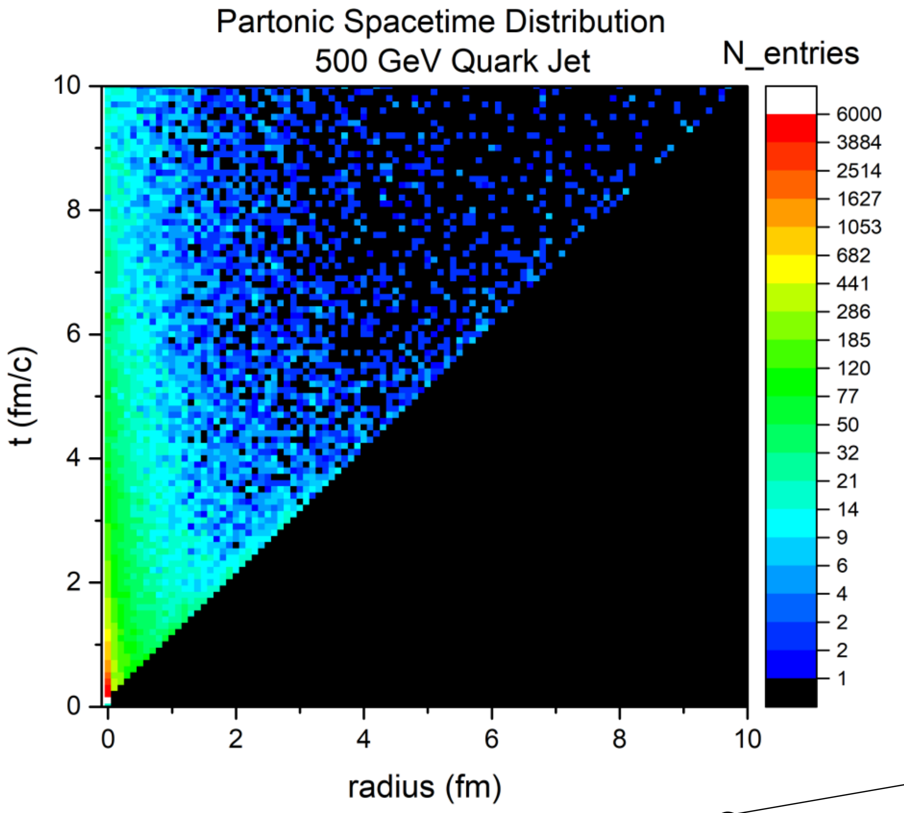
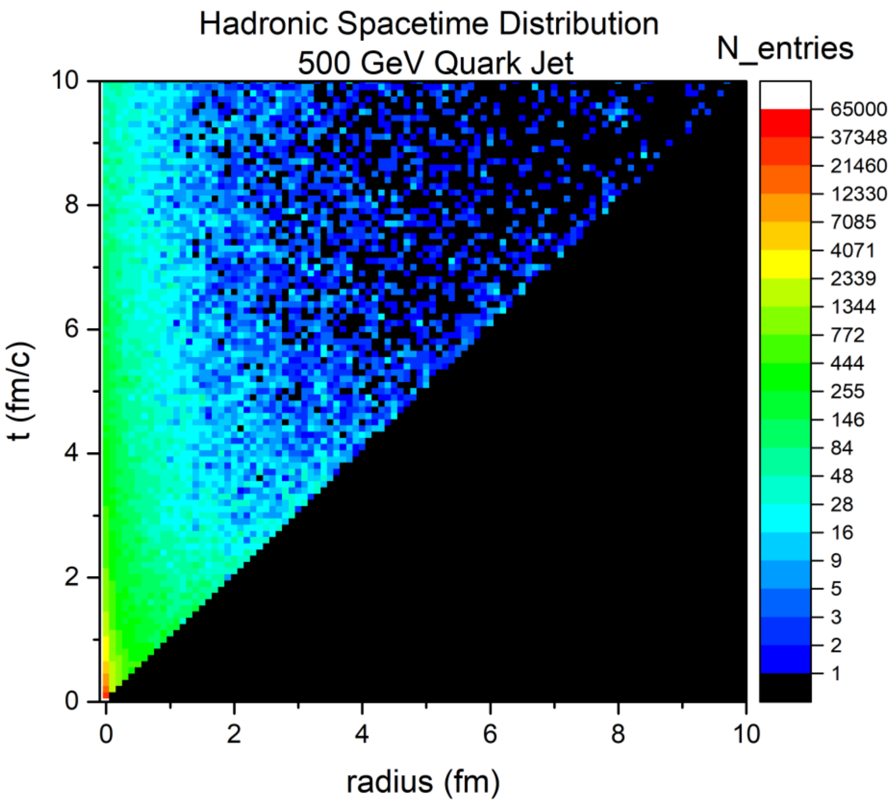
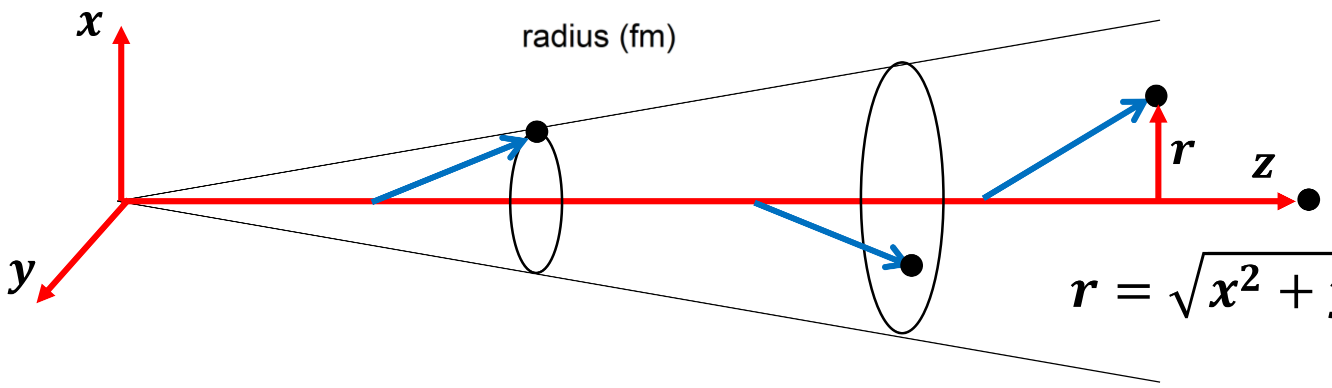


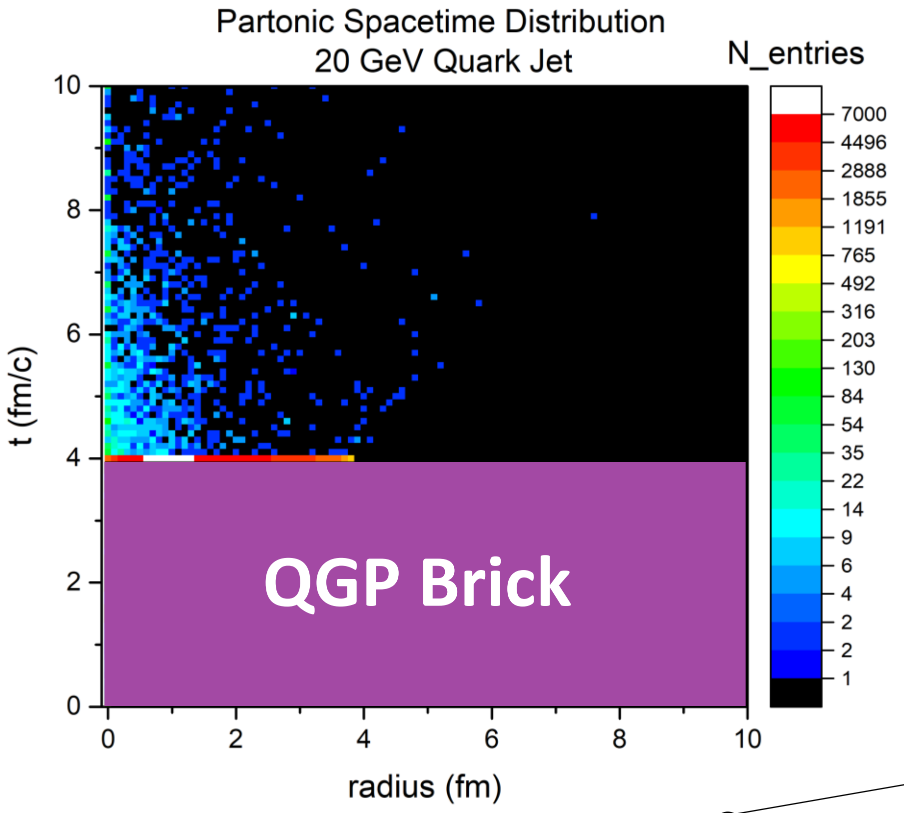


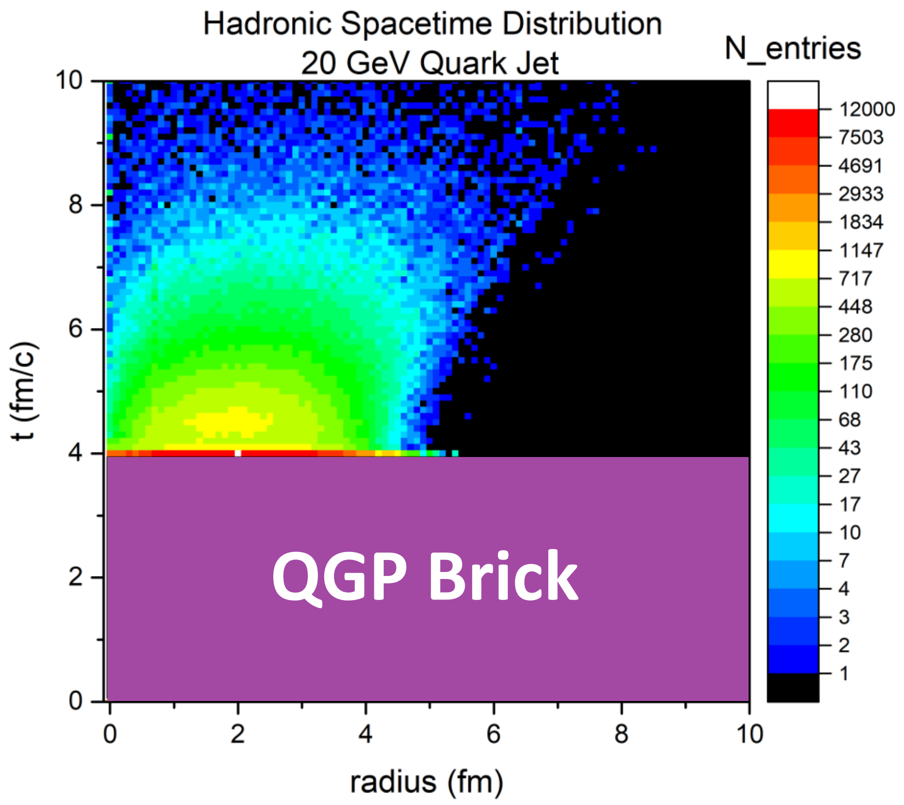


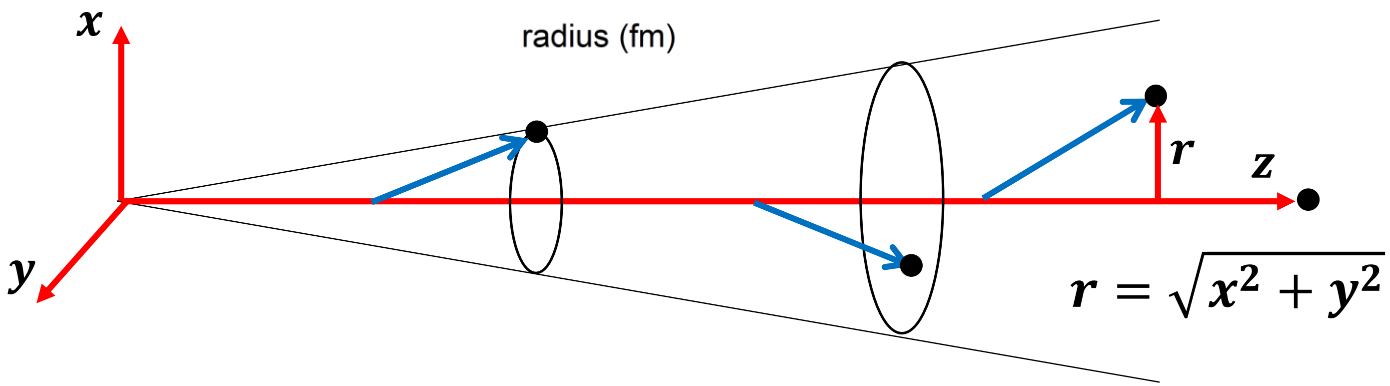
$$r = \sqrt{x^2 + y^2}$$

Partons shown have virtuality $Q < Q_0 = 1$ GeV
Partons propagate with $v \sim c$

Results – Brick Jets Space-time



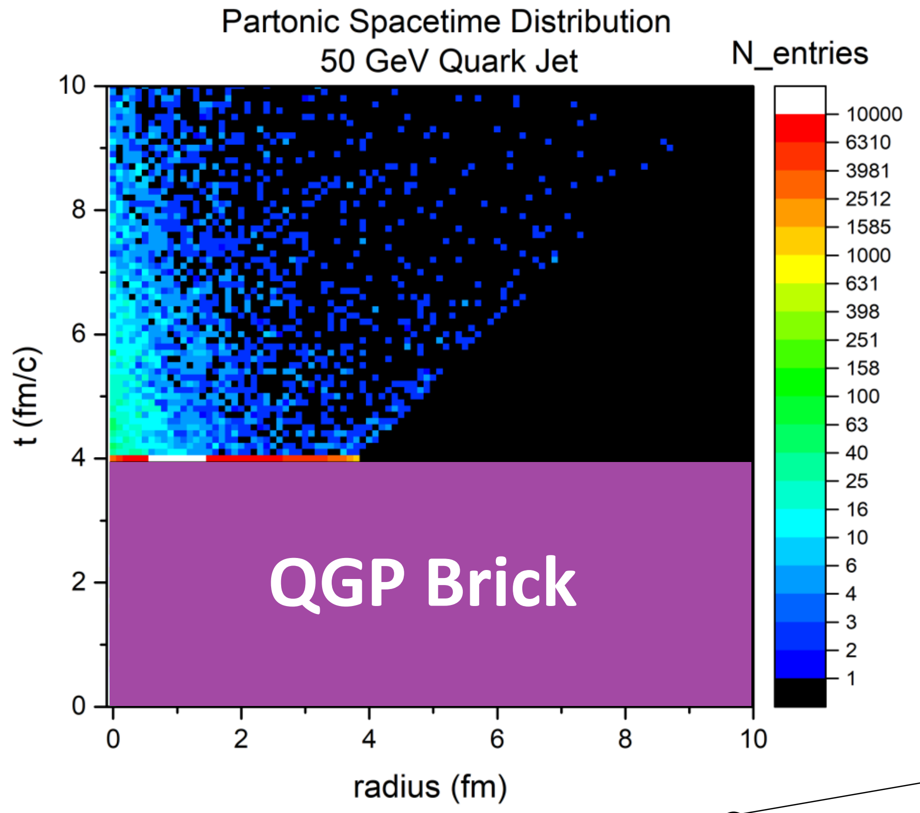


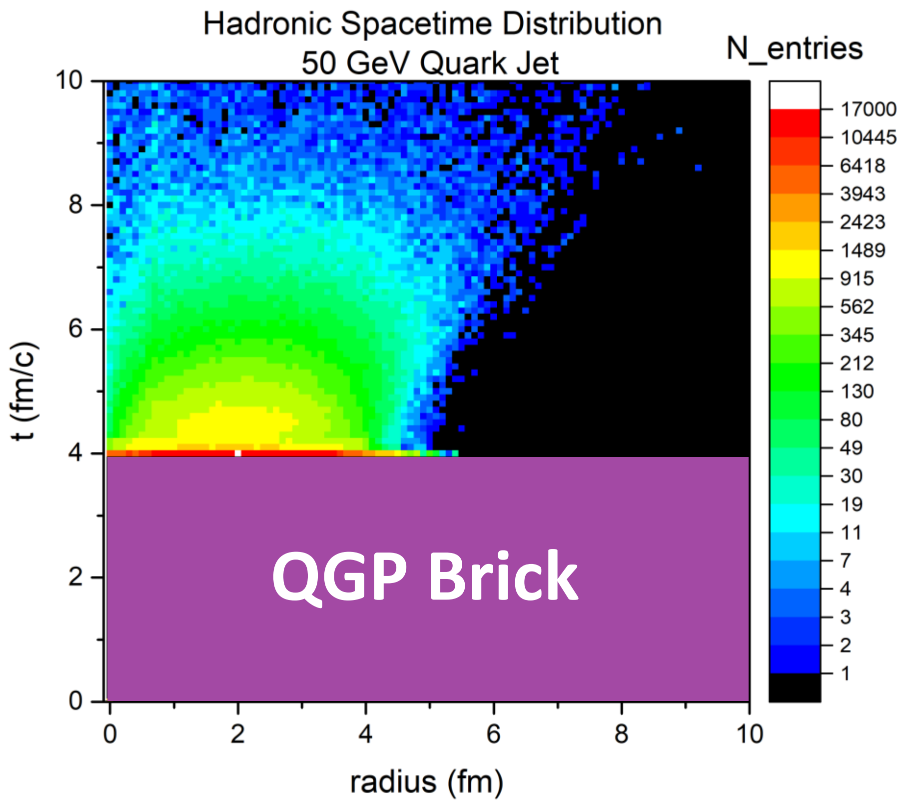


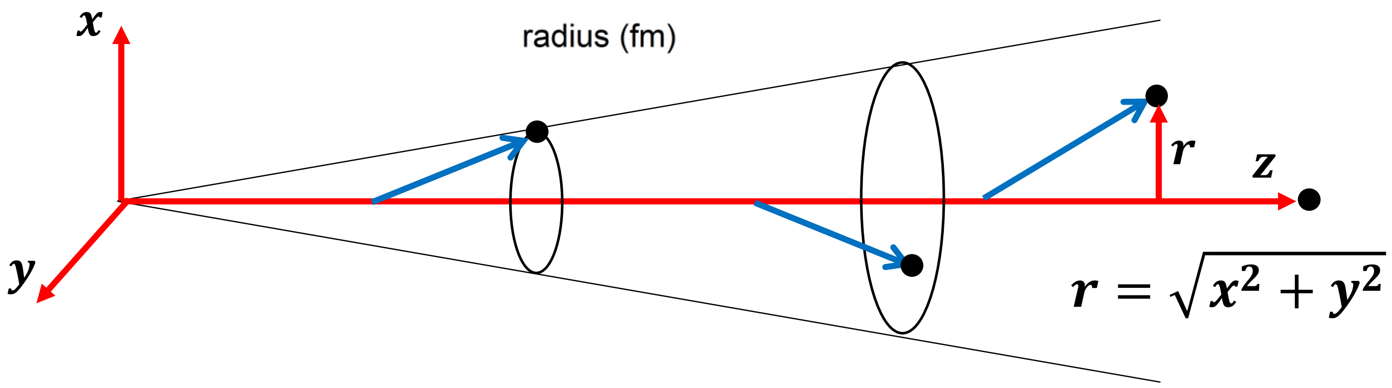
Partons with virtuality $Q < Q_0 = 1$ GeV shown where the temperature $T < T_C$

Partons propagate with $v \sim c$

Results – Brick Jets Space-time



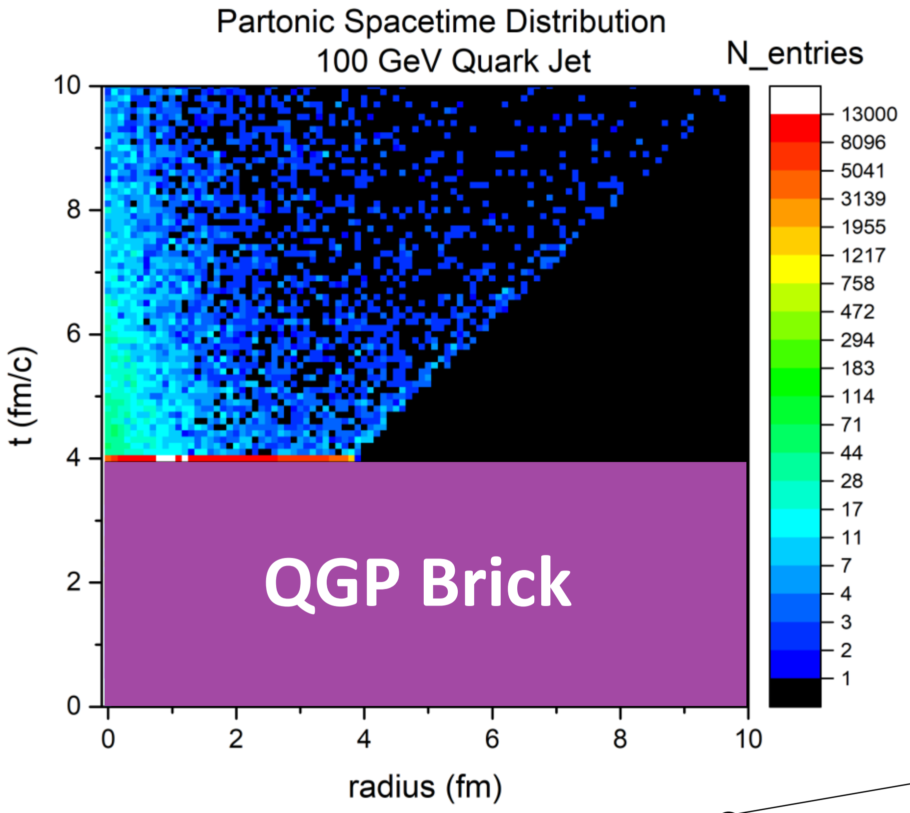


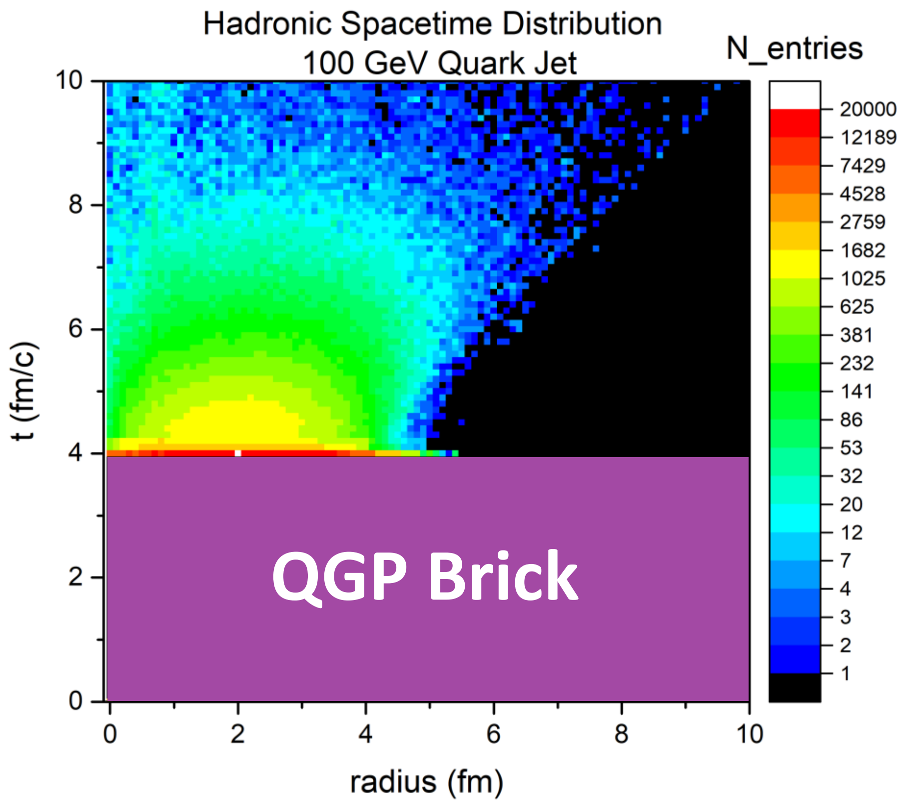


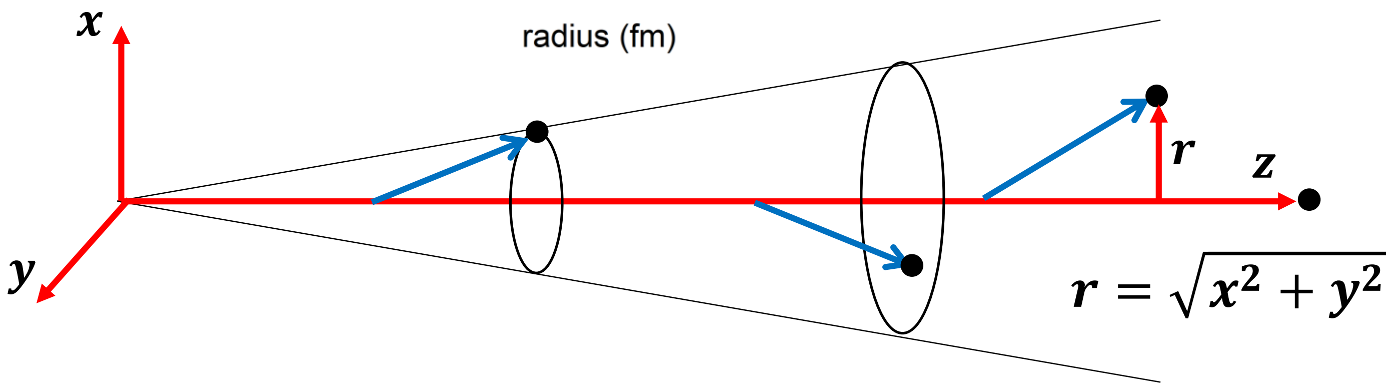
Partons with virtuality $Q < Q_0 = 1$ GeV shown where the temperature $T < T_C$

Partons propagate with $v \sim c$

Results – Brick Jets Space-time





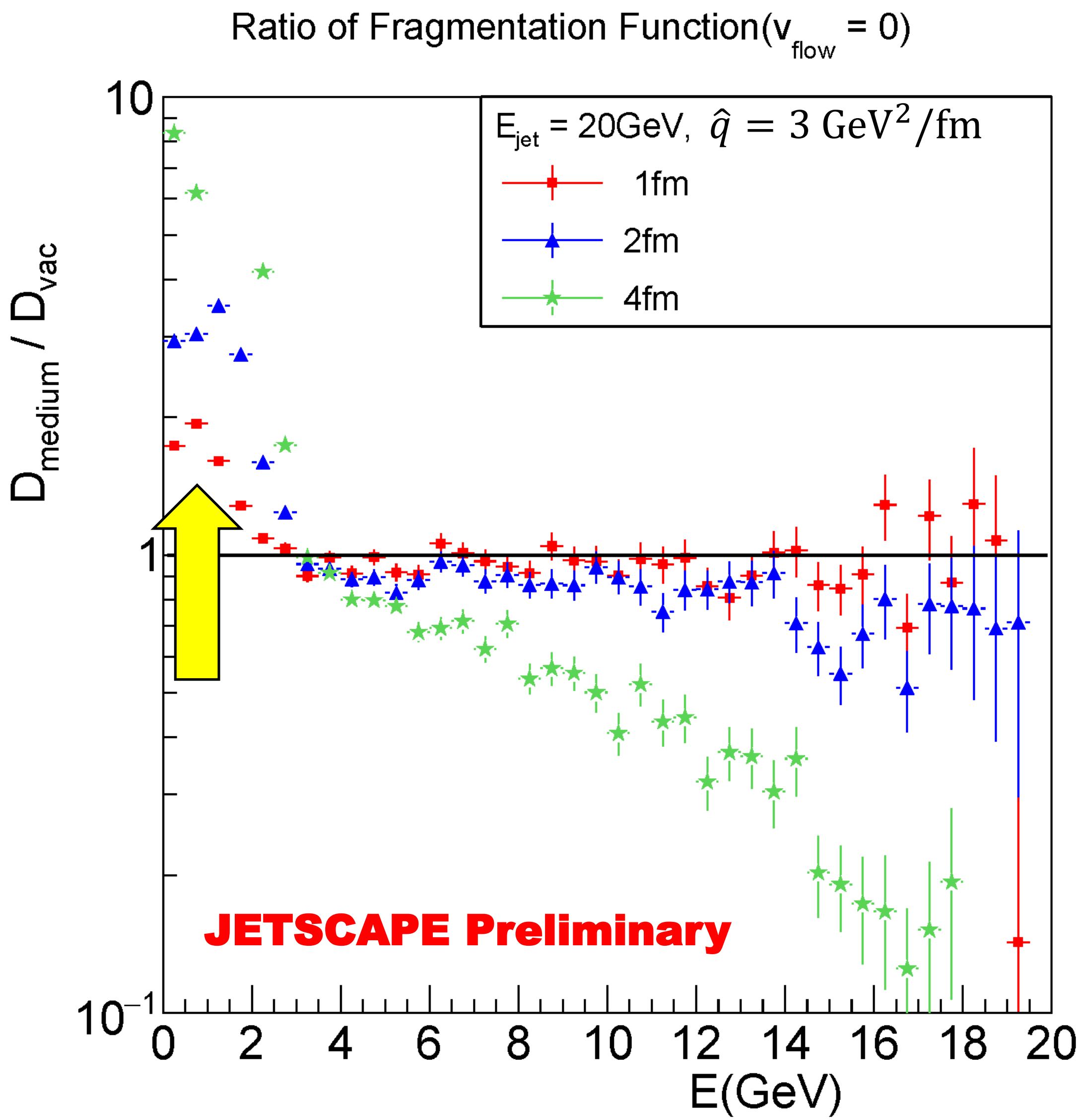


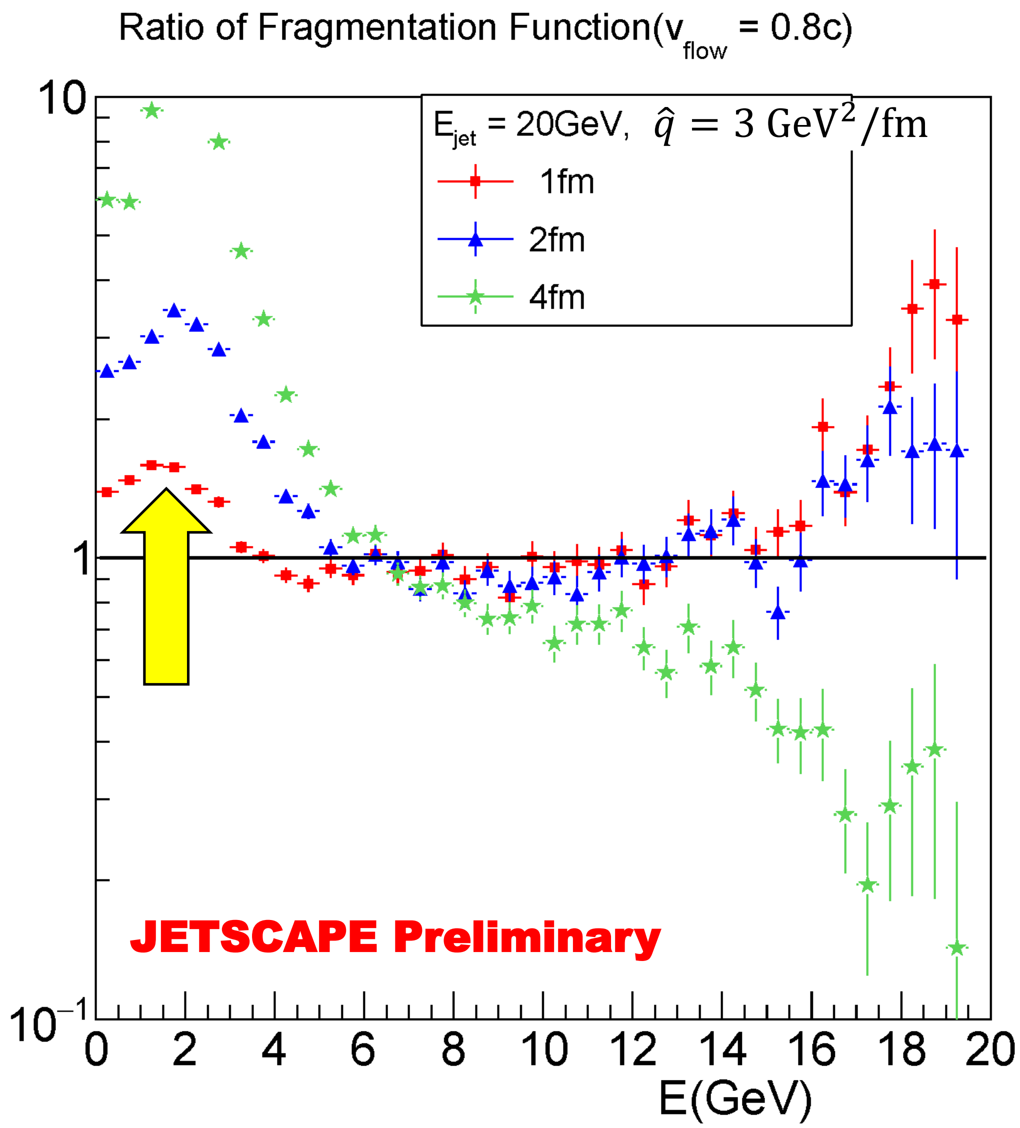
Partons with virtuality $Q < Q_0 = 1$ GeV shown where the temperature $T < T_C$
Partons propagate with $v \sim c$

JETSCAPE Hybrid Hadronization Study

- We consider a QGP brick with a space-like hypersurface with varying sizes.
- The flow velocity of the thermal partons is varied.
- The jet initiating parton is a fixed energy quark, showered with MATTER and LBT, then hadronized with Hybrid Hadronization.
- We look for traditional recombination signals – an enhanced baryon meson ratio & flow.
- Caveat – there are no purely thermal hadrons in the following. Here we wish to study the systematics of Hybrid Hadronization; a comparison to experimental data will follow later.

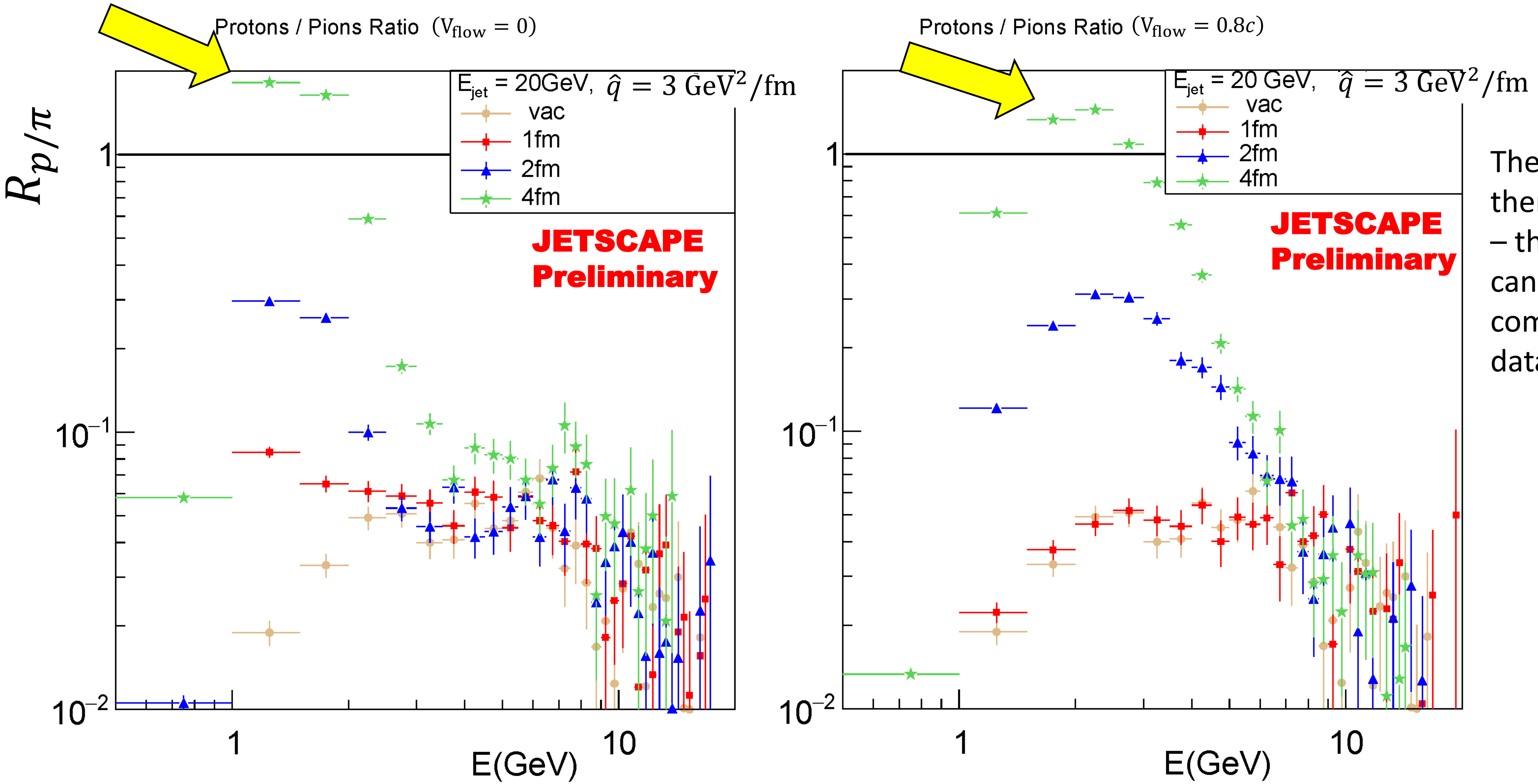
Ratio – Fragmentation Functions





There are no thermal hadrons – the soft sector cannot be directly compared to data!

Baryon/Meson Ratio $R_{p/\pi}$



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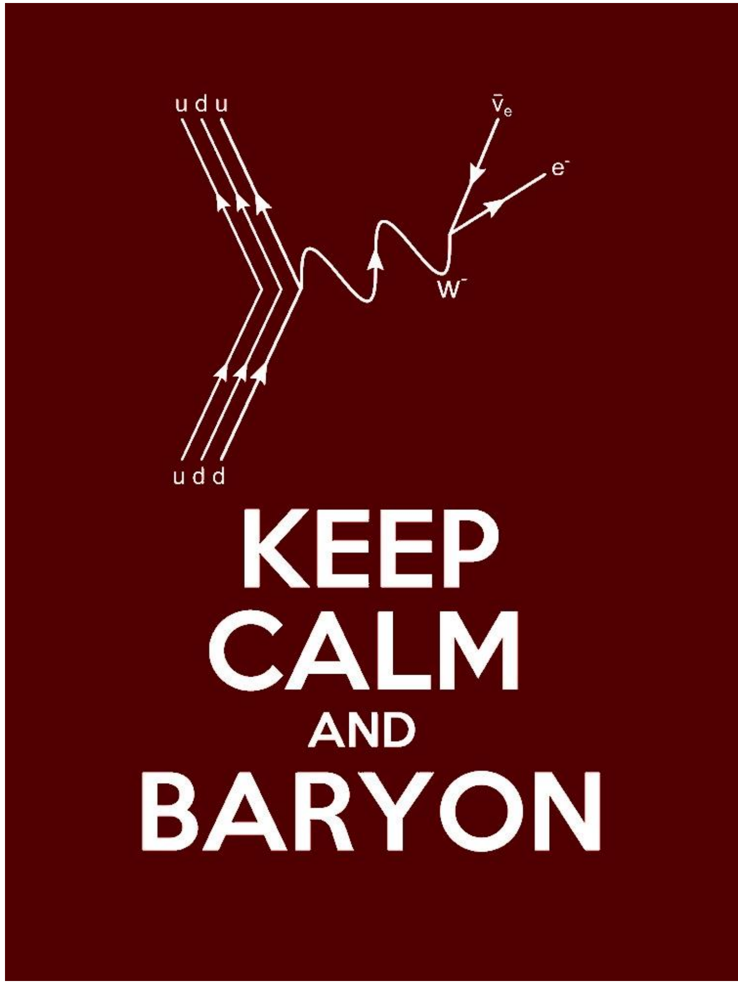
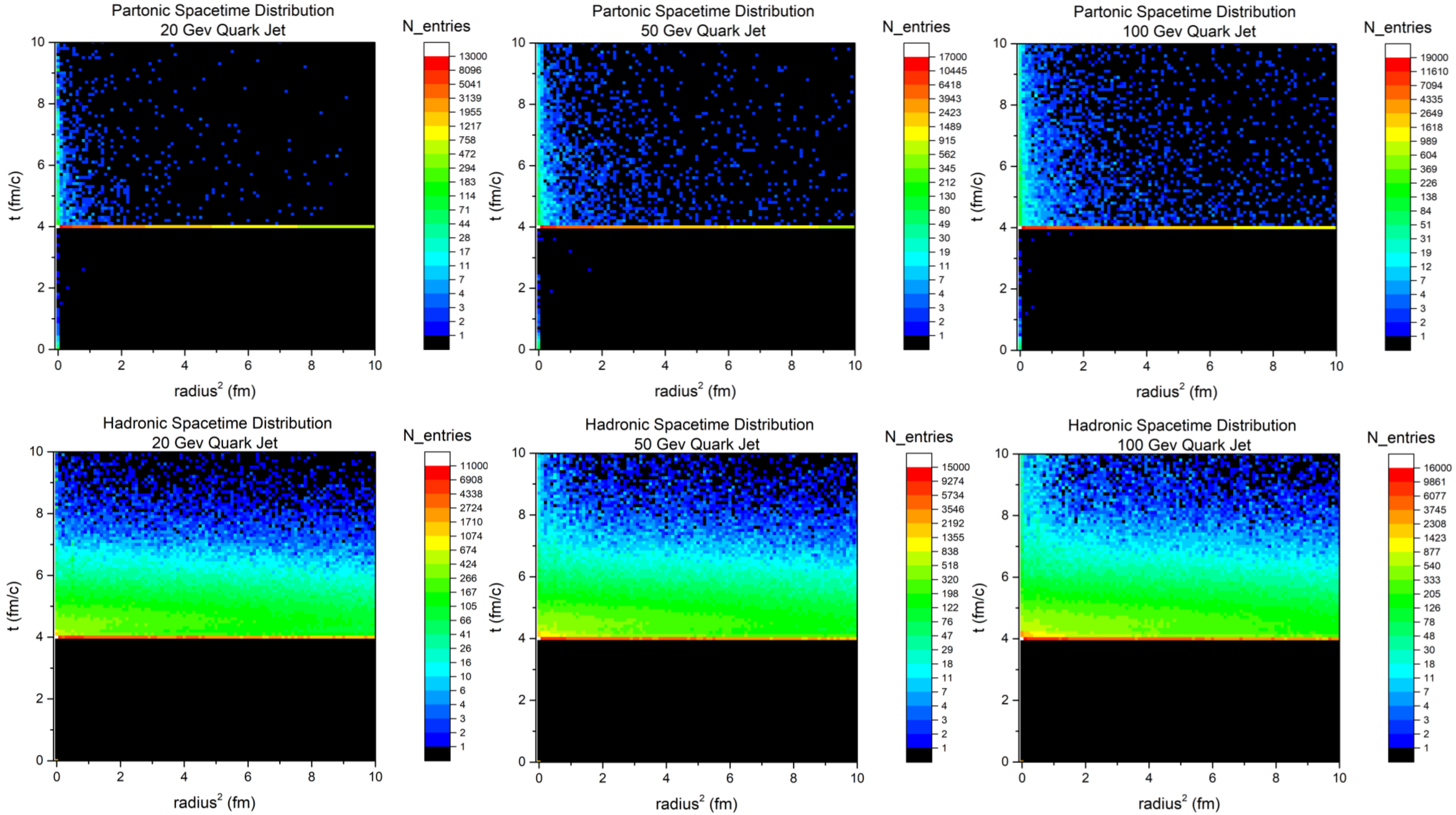
Summary

- Hybrid Hadronization is available in JETSCAPE v2.0 and later.
- Some features shown here are not yet in the public release.
- Study of the space-time structure of jets is important for hadronization.
- There is a strong scaling of medium signatures with the size of the medium.
- There are clear signals for thermal partons imparting flow and increasing baryon production below $10\ \mathrm{GeV}/c$
  - While we did not directly compare to experimental data, they share qualitatively similar trends with the results from this study.
- A tuning of MATTER + HH in vacuum (e^{+}+e^{-} and p+p) is underway.

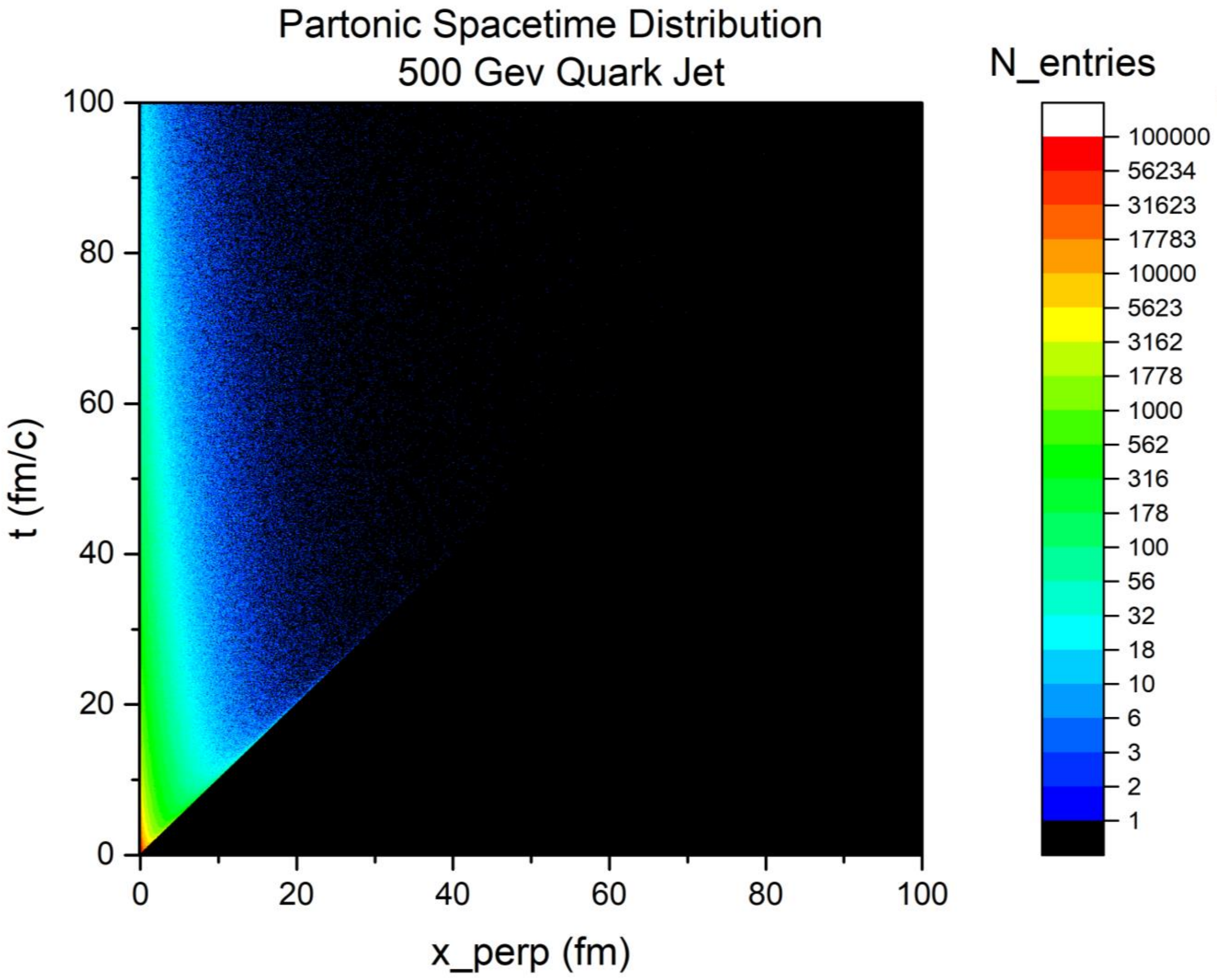


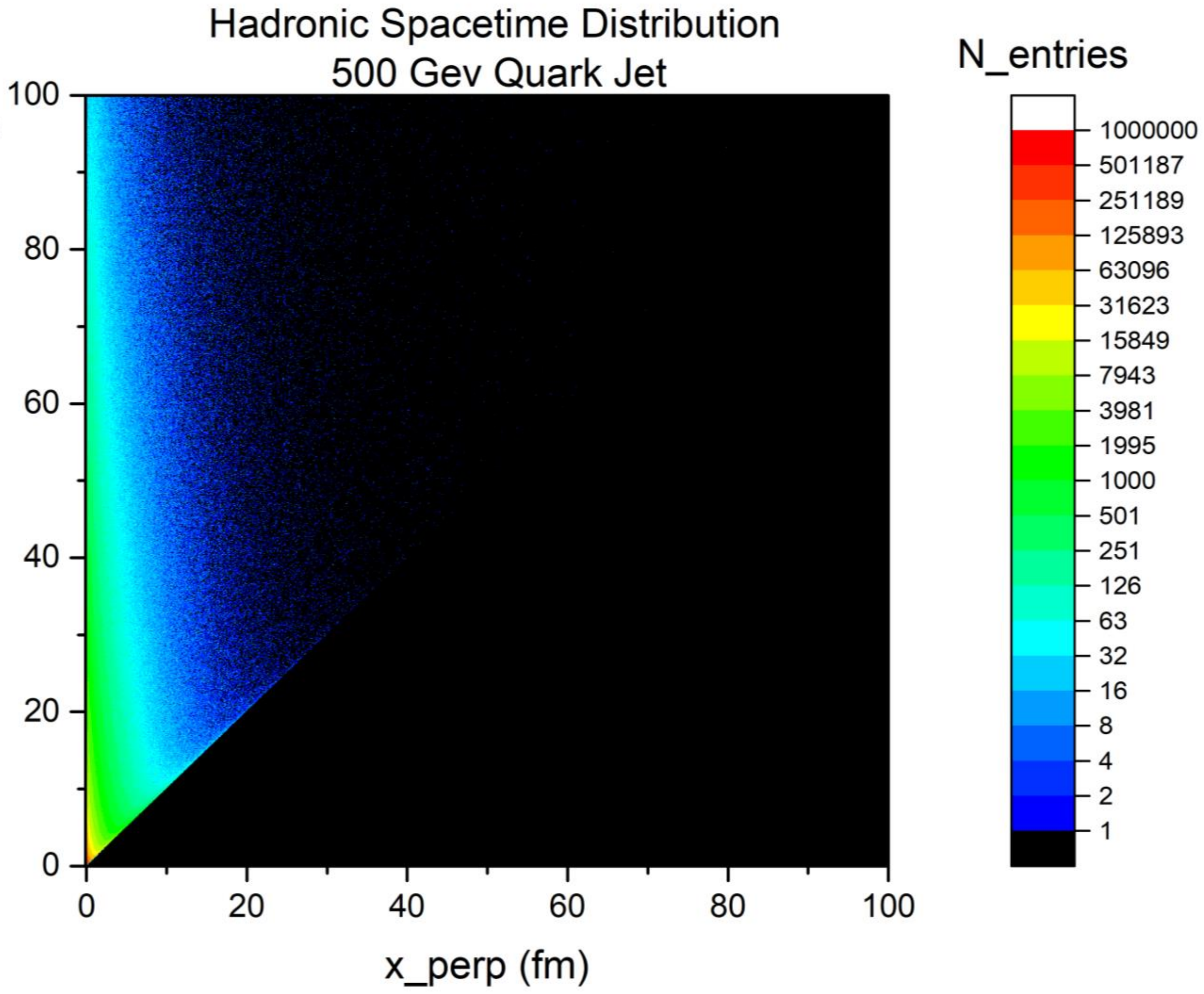
Backup Slides

Results – Brick Jets Spacetime II



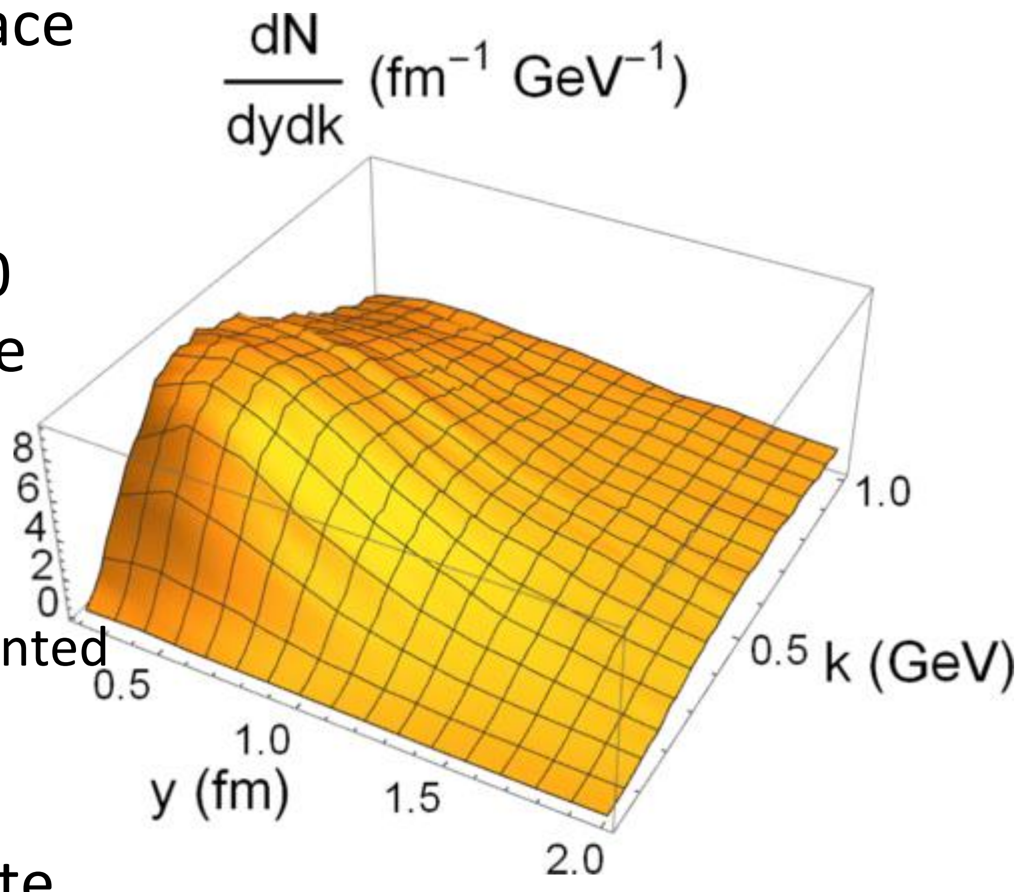
Results – Vacuum Jets Spacetime II





Jet Parton Density

- Distance of quark-antiquark pairs in phase space is the deciding factor for recombination into mesons.
- Example[1]: Distribution of pair distances in 100 GeV (PYTHIA 6) parton showers in phase space (center of mass frame of the pair):
    - Most of the jet is relatively dense in phase space.
    - Space-time structure for shower partons implemented with formation times E/Q^2.
    - There are long tails (~high z partons)
- Perturbative evolution should not lead to dilute showers, otherwise non-perturbative effects are already dominant.



[1]K. Han, R.J.F., C. M. Ko, Phys. Rev. C 93, 045207 (2016)

Recombination Formalism

- The formula for the recombination probability, as derived from the Wigner function coalescence yield (meson):

$$\overline{W}_M(\mathbf{y},\mathbf{k}) = \int d^3\mathbf{x}_1' d^3\mathbf{k}_1' d^3\mathbf{x}_2' d^3\mathbf{k}_2' \times W_q(\mathbf{x}_1',\mathbf{k}_1') W_{\bar{q}}(\mathbf{x}_2',\mathbf{k}_2') W_M(\mathbf{y}',\mathbf{k}').$$

  - Evaluated at equal time in the pair or triplet rest frame.
- Bound state Wigner function derived from harmonic oscillator wave functions (Laguerre polynomials L_n).

$$W_n(u) = 2(-1)^n L_n\left(\frac{4u}{\hbar\omega}\right) e^{-2u/\hbar\omega} \qquad u = \frac{\hbar\omega}{2}\left(\frac{x^2}{\sigma^2} + \sigma^2 k^2\right)$$

- For proper q, qbar Wigner functions, need to start from quark wave packets - for which the true shape is not known.
- With Gaussian wave packets, the overlap of wave packets and Wigner function is mathematically straightforward. The probability densities for the n-th excited states are:

$$\overline{W}_{M,n}(\mathbf{y},\mathbf{k}) = \frac{v^n}{n!} e^{-v} \qquad v = \frac{1}{2}\left(\frac{\mathbf{y}^2}{\sigma_M^2} + \mathbf{k}^2\sigma_M^2\right)$$

- Hadron wave function widths fixed by measured and predicted charge radii.

K. Han, R.J.F., C. M. Ko, Phys. Rev. C 93, 045207 (2016)

Recombination Code Flow

- Colored partons that recombination cannot handle (eg, diquarks, color octet hadrons) are passed through as parts of remnant strings.
- Gluons are decayed into q-qbar pairs.
- Quarks are randomly sampled to evaluate recombination probabilities, then this probability is sampled to determine if a hadron is formed.
- If a hadron is formed:
  - An immediate **string repair** is performed.
  - Hadron id is chosen based on quark composition.
- Repeat sampling procedure for all quark pairs/triplets.
- Reform unused q-qbar pairs back into original gluons.

Color Structure

- Partons are taken from a shower Monte-Carlo, these must include a valid color structure for reasonable results
  - Partons that have interacted with the medium at low virtuality scales (LBT, MARTINI) and thermal partons are assigned a random color
- A color correlation matrix is constructed, denoting the probability that a color/anticolor can form a color singlet
  - The colors of a single gluon will have a recombination probability of 0
  - A color with itself will have a recombination probability of 1
  - Uncorrelated colors will have a recombination probability of 1/9
- If a meson recombination occurs, this means that the chosen color tags *must* be equal
  - All remaining instances of one of those color tags is replaced with the other (arbitrary)
  - The color correlation matrix is updated to reflect this change
- For a baryon recombination, the color structure will result in the creation or annihilation of a junction
  - This preserves baryon number!

Color Structure

- Partons are taken from a shower Monte-Carlo, these must include a valid color structure for reasonable results
  - Color tags > 0 for partons in vacuum-type strings
  - Color tags = 0 for partons that have interacted with the medium at low virtuality scales (LBT, MARTINI) or for thermal partons
- A color correlation matrix is constructed, denoting the probability that a color/anticolor can form a color singlet
  - The color tags of a single gluon will have a probability of 0
  - A color tag with itself (except 0) will have a probability of 1
  - Uncorrelated color tags will have a probability of 1/9
- If a meson recombination occurs, this means that the chosen color tags *must* be equal
  - All remaining instances of one of those color tags is replaced with the other (arbitrary)
  - The color correlation matrix is updated to reflect this change
- For a baryon recombination, the color tags used will create (or annihilate) a junction
  - This preserves baryon number!
- Recombinations involving a 0 color tag may need a partner, another color tag 0 parton, that will be assigned a color tag.