

HARD PROBES 2018, AIX-LES-BAINS

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Hybrid Hadronization

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In collaboration with Michael Kordell



What is Hybrid Hadronization?

2

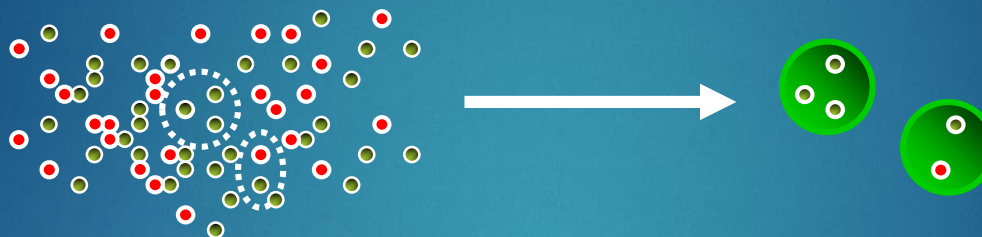
- Take two existing hadronization models and merge them to create something with a wider range of applicability.



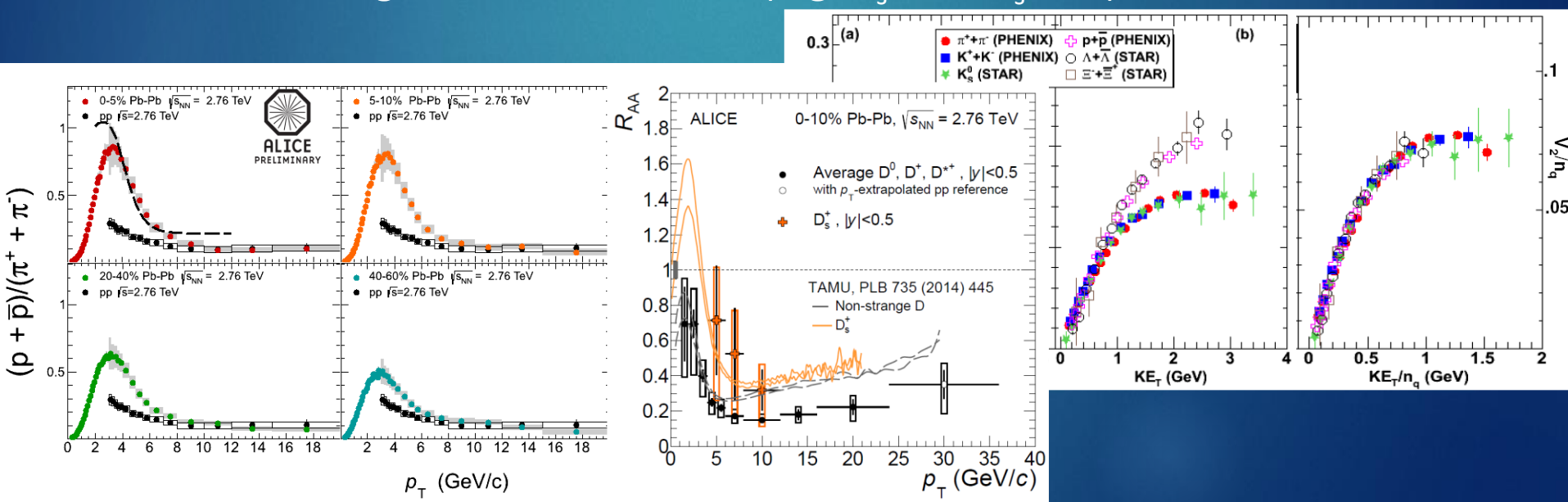
Quark Recombination

3

- Signature of quark recombination processes are seen in dense systems (nucleus-nucleus collisions, beam of fixed target experiments)



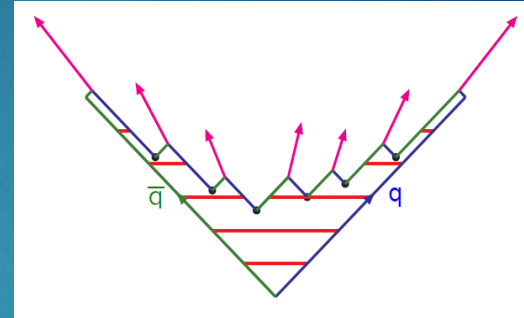
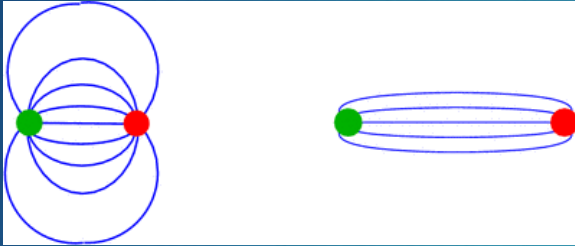
- Enhanced baryon/meson ratios, elliptic flow scaling with quark number, strangeness enhancement (e.g. D_s vs D , B_s vs B).



Compare To String Fragmentation

4

► Lund string fragmentation picture



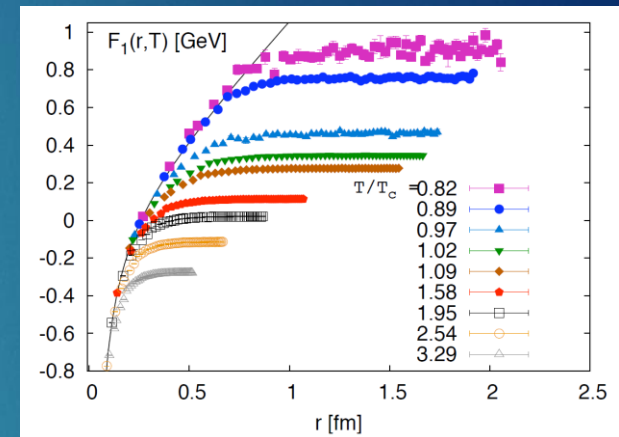
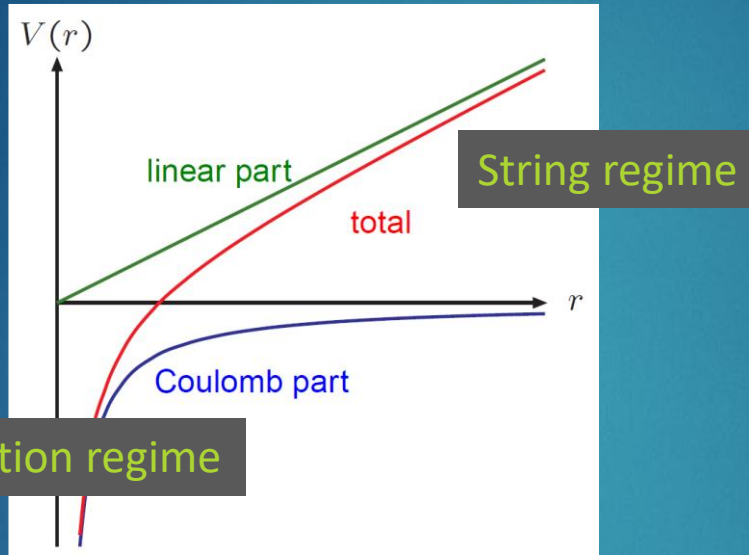
Andersson, Gustavson, Ingelman,
Sjostrand, Phys. Rep. 97, 33 (1983)

- Extremely successful phenomenology e^+e^- , $p+p$
- Shortcomings of individual models:
 - Long distance behavior not properly described in recombination models; confinement not enforced.
 - Color flow needed for string fragmentation not readily available in in-medium shower MC; no cross talk of shower and thermal partons

Two Sides Of The Same Coin?

5

► QQ potential:



Kaczmarek et al. (2007)

- Strong force \sim Coulomb at short distances, string behavior at large distances
- How to make this work for nuclear collisions? Put the Coulomb part back and add quark recombination to string fragmentation

Partons in Monte Carlos (e.g. JETSCAPE)

- How we describe a parton depends on its virtuality Q , the ambient medium, and its energy (with respect to a suitable reference)

| Ambient medium | Large virtuality Q (typically FS after hard process) | Large energy* | Hadronization ($T < T_c$; Q, E small) |
|--|---|---|---|
| $T < T_c$ or vacuum | Radiation → Shower (e.g. PYTHIA, MATTER) | * wrt next neighbors in phase space non-perturbative treatment → strings | String breaking |
| $T > T_c$ or sufficiently dense system | Radiation → In-medium Shower (e.g. MATTER) | * wrt surrounding medium in-medium scattering (e.g. LBT, MARTINI) | Recombination ($T = T_c$) |

- Virtuality usually drops faster → steps above are typically sequential.
- A single jet in A+A typically is a blend of several of these situations.

Hybrid Hadronization

- ▶ Hybrid hadronization has two well-defined limits:
 - ▶ Dilute systems \rightarrow String fragmentation
 - ▶ Dense systems \rightarrow Quark recombination
- ▶ Extrapolate smoothly in between, based on probabilities calculated with realistic potentials.
- ▶ Monte Carlo implementation suitable for event generators.
- ▶ Recombination Step: Developed for the JET Collaboration
 - K. Han, RJF., C. M. Ko, *Phys. Rev. C* 93, 045207 (2016)
- ▶ (Remnant) string formation
- ▶ String fragmentation: standard PYTHIA

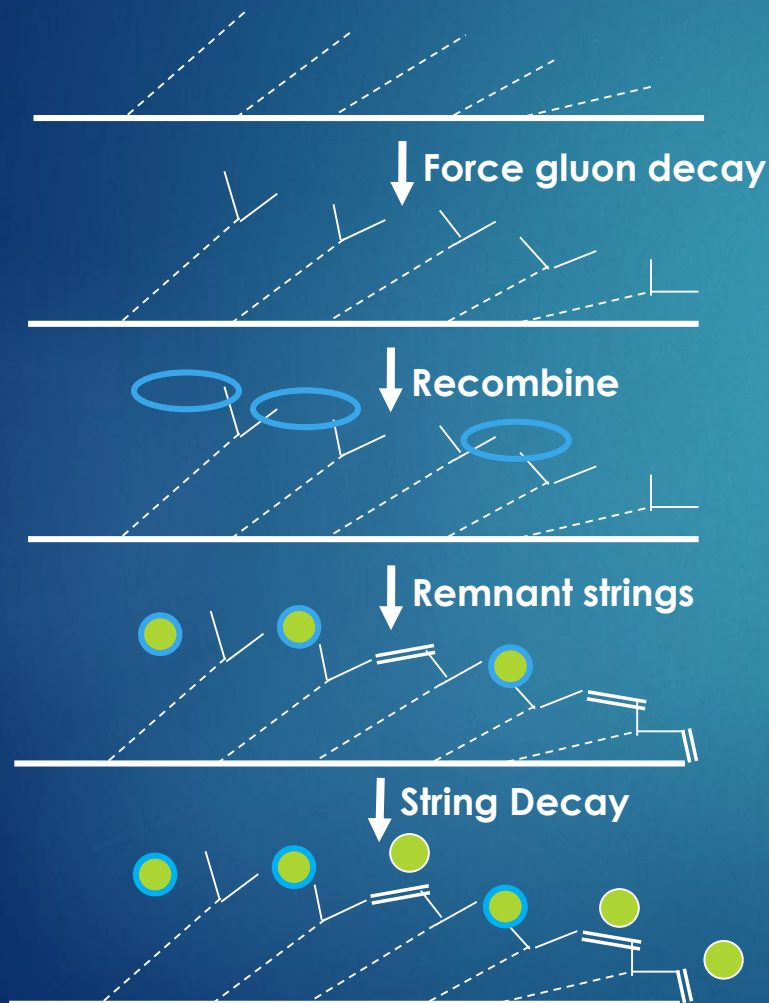


Steps in Monte Carlo Implementation

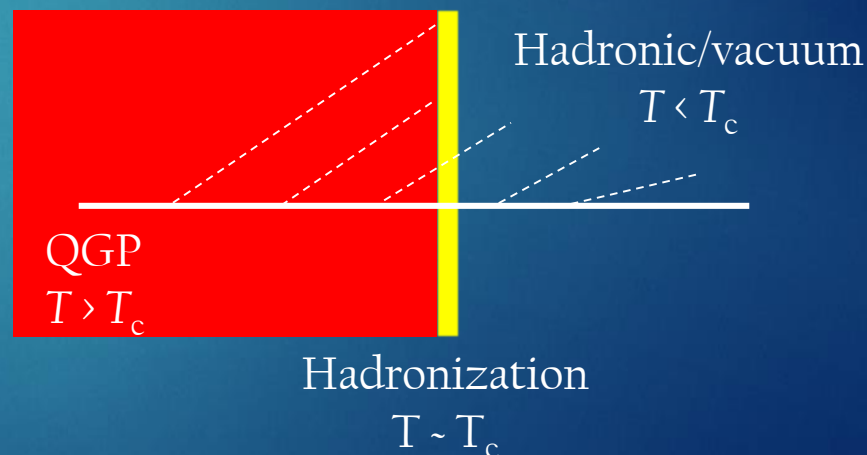
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► Implementation for jets in an event generator

K. Han, RJF., C. M. Ko,
Phys. Rev. C 93,
045207 (2016)

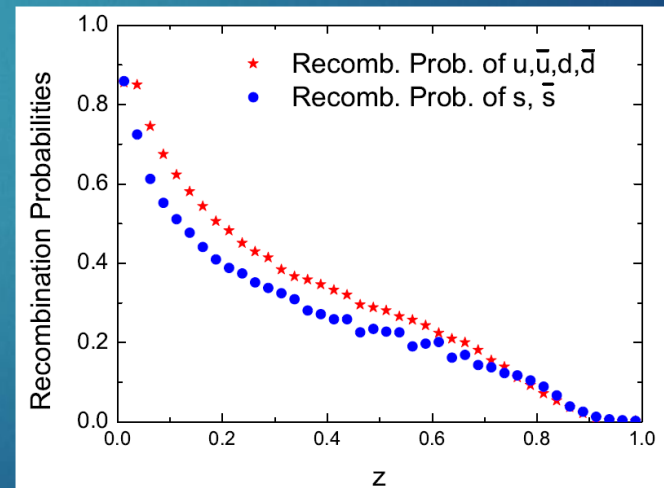
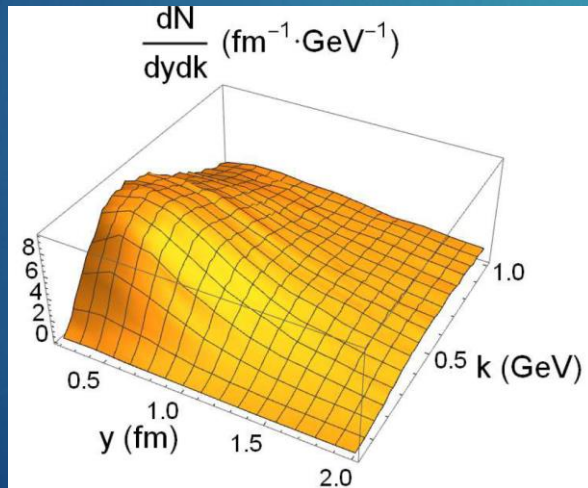


► Jets in QGP: add sampled thermal quarks on the $T=T_c$ hypersurface



Hybrid Hadronization

- ▶ Distance of quark-antiquark pairs in phase space (in their local rest frame) determines the recombination probability.
- ▶ Earlier studies with PYTHIA 6 showers: “dense” jet bulk with long tails (mostly large- z)



K. Han, RJF., C. M. Ko, Phys. Rev. C 93, 045207 (2016)

Recombination Probabilities

- Calculate probabilities for quark wave packets to form mesons or baryons. Wigner formalism to include space-time information:

$$\bar{W} = \int d^3x_1 d^3p_1 \int d^3x_2 d^3p_2 W_a(x_1, p_1) W_b(x_2, p_2) W_M(\Delta x, \Delta p)$$

- Bound state Wigner function from harmonic oscillator wave functions

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

$$u = \frac{\hbar\omega}{2} \left(\frac{x^2}{\sigma^2} + \sigma^2 k^2 \right)$$

- For the probabilities to be positive definite, need proper q , \bar{q} wave packets. Not provided by shower MCs.
- Assume Gaussian wave packets of certain width for simplicity. The probability densities for the n -th excited states (position y , momentum k) are

$$\bar{W}_{M,n}(\mathbf{y}, \mathbf{k}) = \frac{v^n}{n!} e^{-v}$$

$$v = \frac{1}{2} \left(\frac{\mathbf{y}^2}{\sigma_M^2} + \mathbf{k}^2 \sigma_M^2 \right)$$

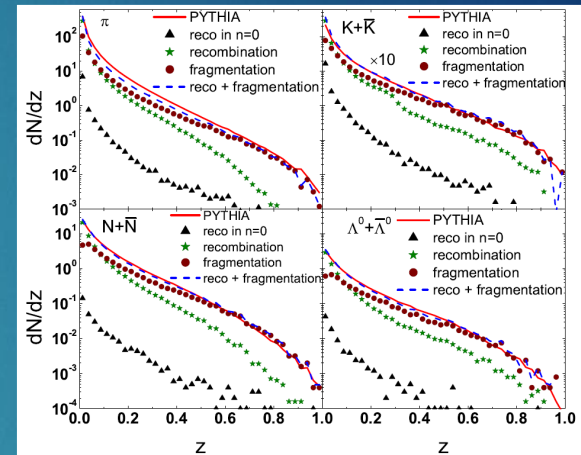
K. Han, RJF., C. M. Ko, Phys. Rev. C 93, 045207 (2016)

Monte Carlo Implementation

11

- ▶ Old JET collaboration code: could only handle limited string configurations.

- ▶ Reproduced PYTHIA 6 results in vacuum

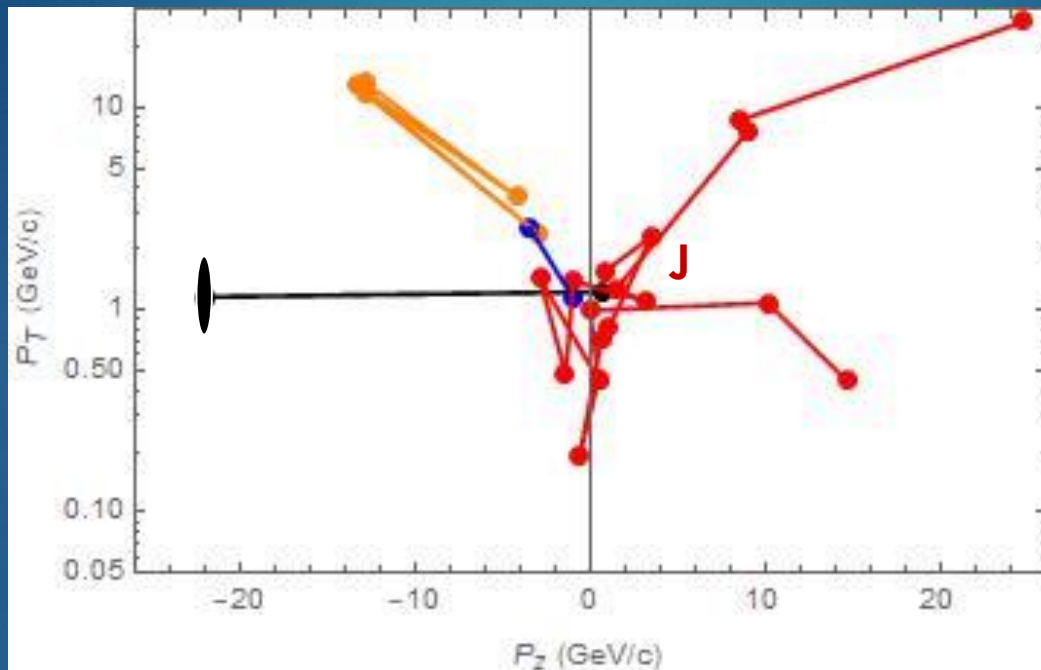


- ▶ 2018: complete rewrite of the code in C++ for JETSCAPE \rightarrow v3.0
- ▶ Can now handle complex string configurations (junctions and multi-junction systems, full p+p events with MPIs etc.)

Hybrid Hadronization Example

12

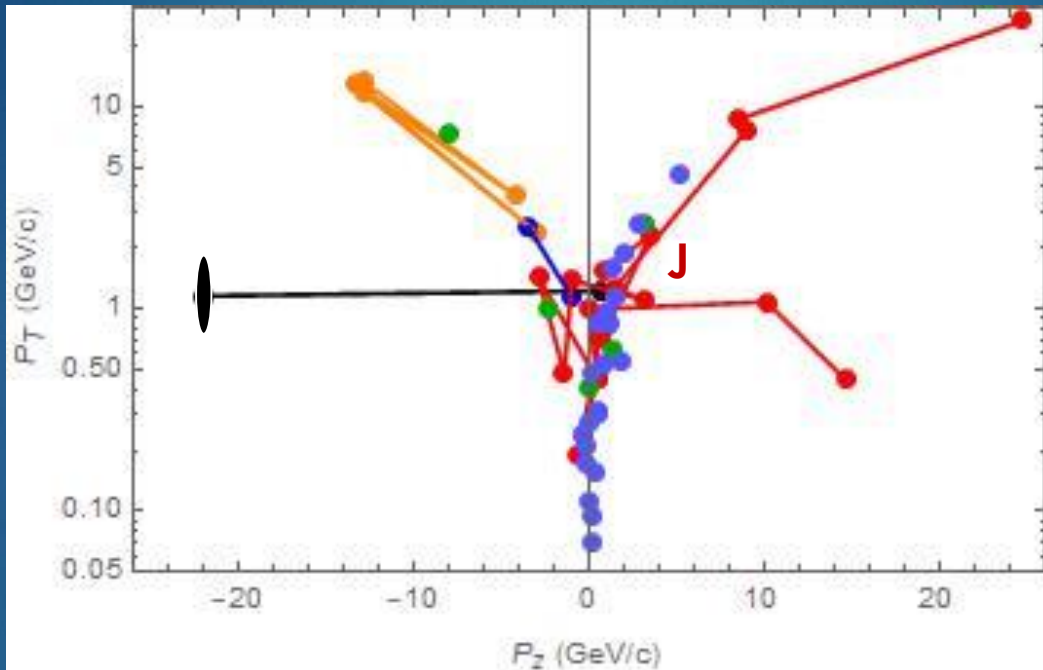
- ▶ Example: complete p+p 200 GeV event (generated by PYTHIA 6)
- ▶ Two “jets” plus underlying event and beam remnants



Hybrid Hadronization Example

13

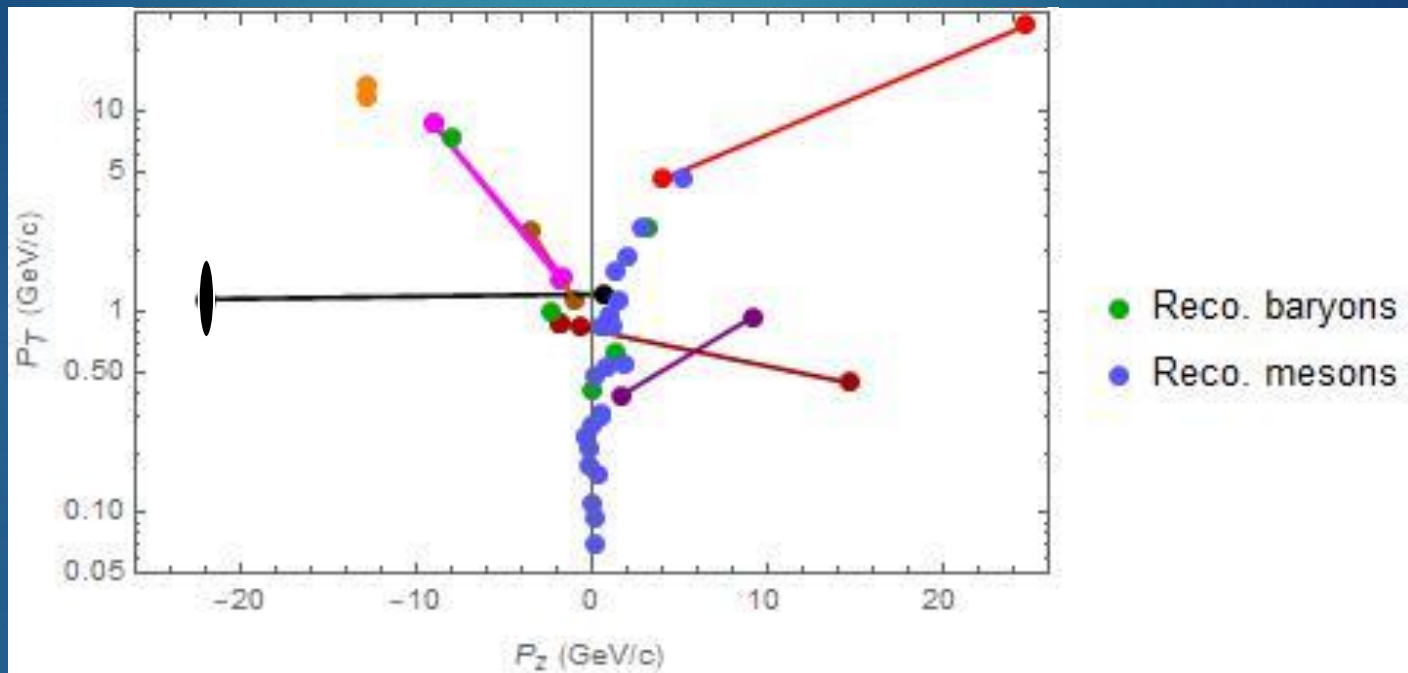
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Hybrid Hadronization Example

14

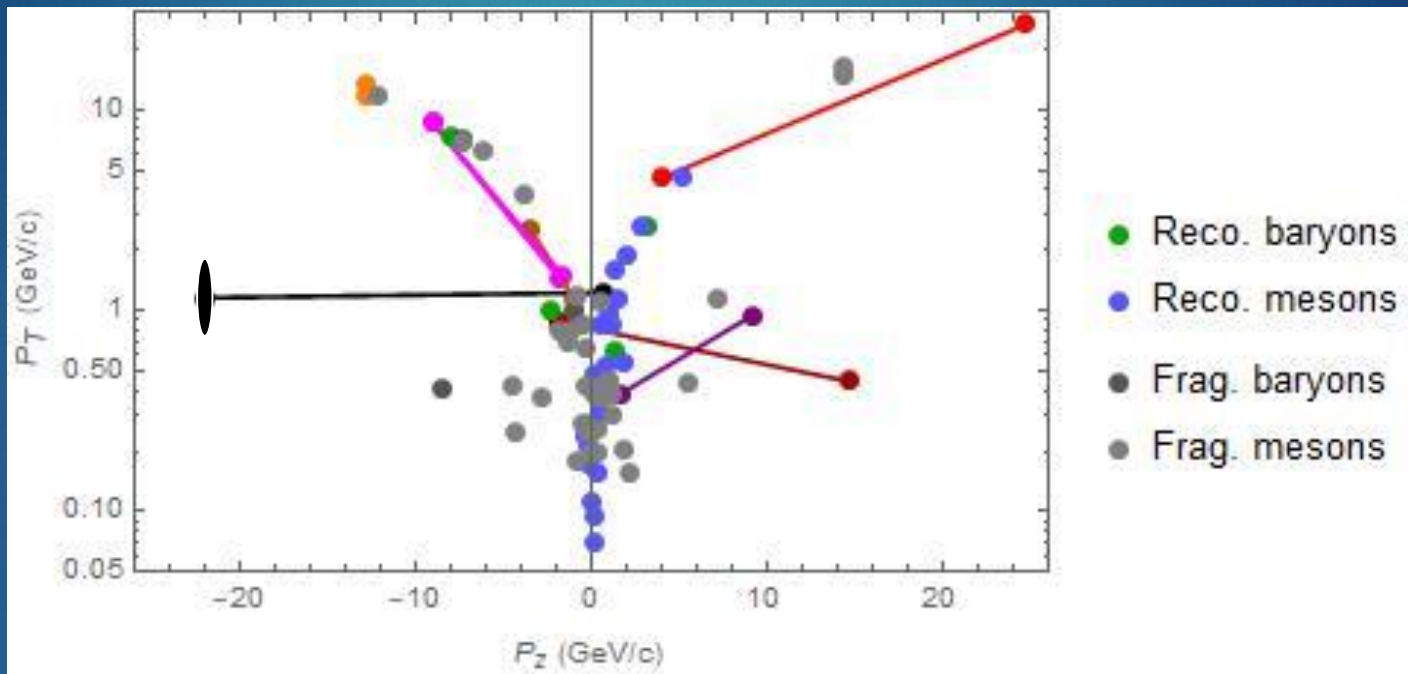
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Hybrid Hadronization Example

15

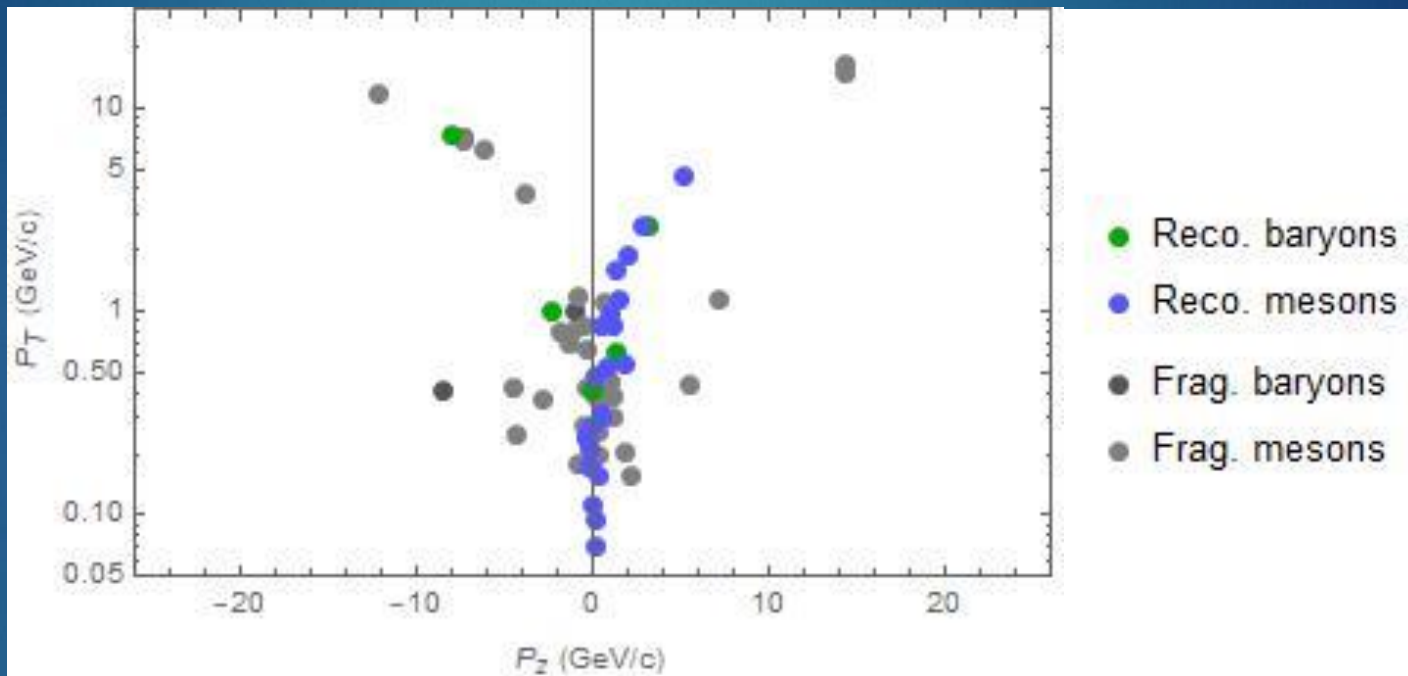
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Hybrid Hadronization Example

16

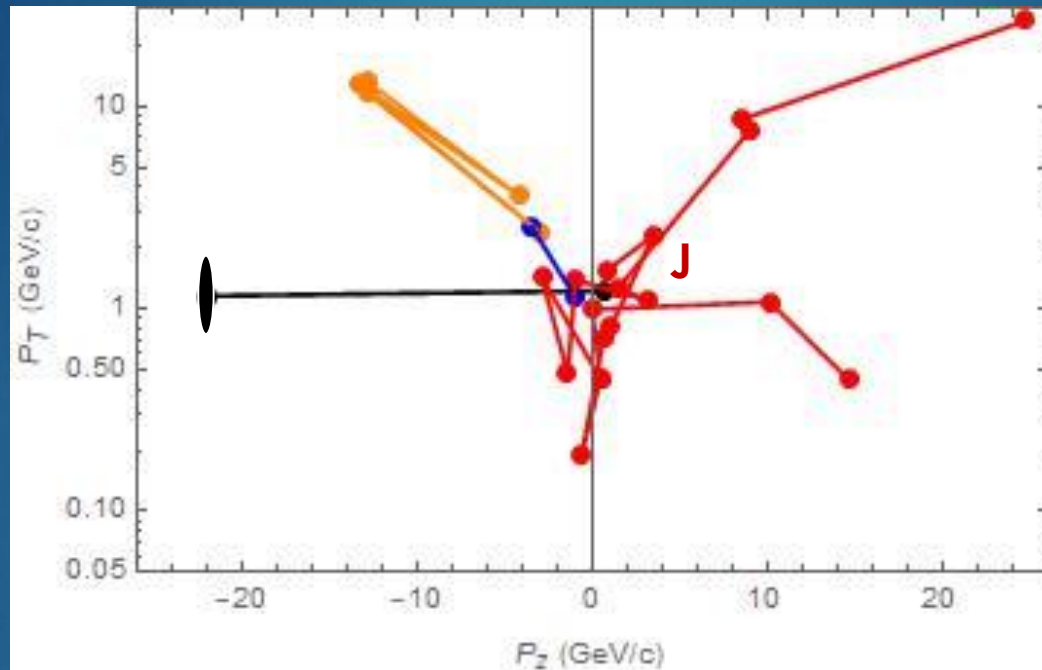
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Hybrid Hadronization Example

17

- Cartoon: Same event with added thermal partons

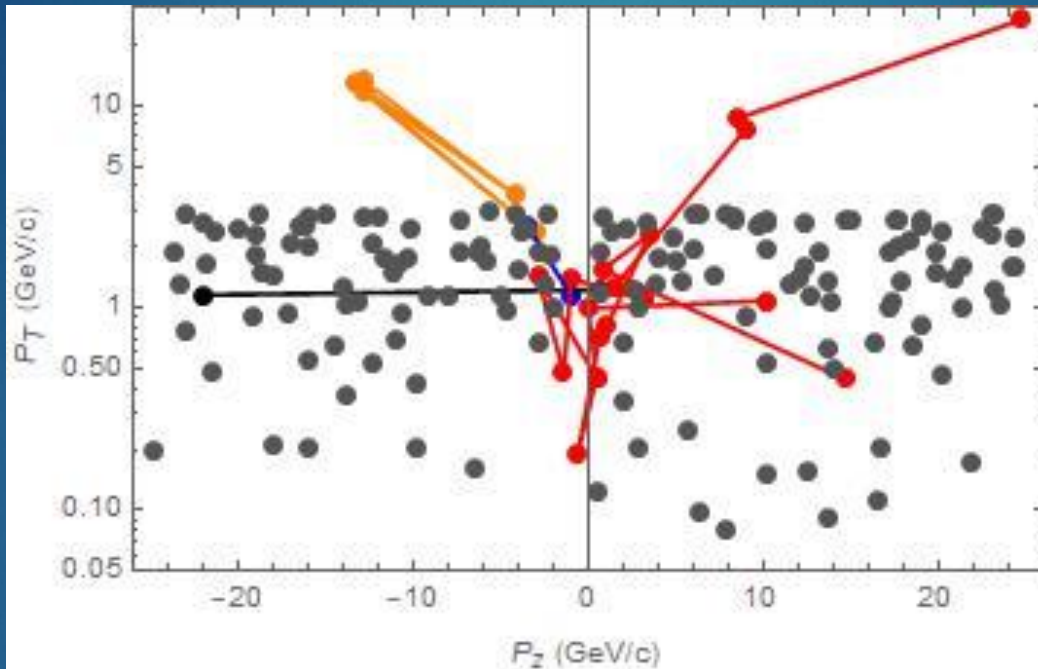


- Sample thermal partons from a hydro code at $T=T_c$.
 - In JETSCAPE: MUSIC hydro

Hybrid Hadronization Example

18

- Cartoon: Same event with added thermal partons

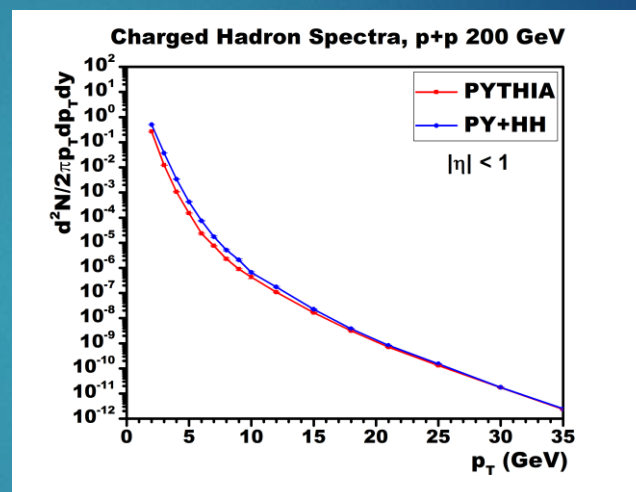
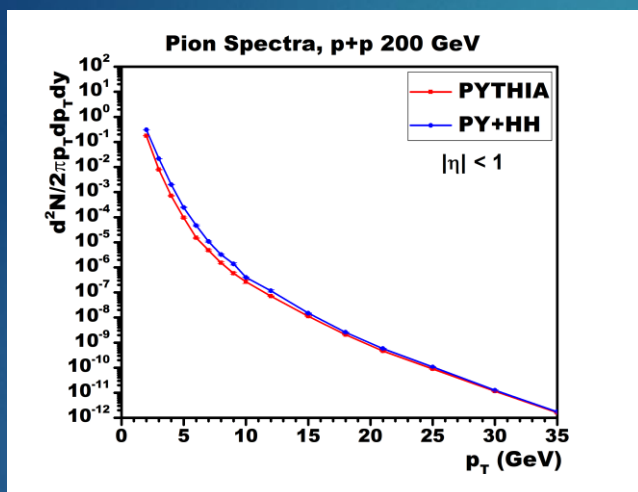


- Sample thermal partons from a hydro code at $T=T_c$.
 - In JETSCAPE: MUSIC hydro

Some Results: p+p

19

- p+p: preliminary results from v3.0 applied to PYTHIA 8 showers compared to PYTHIA 8 with string fragmentation only.

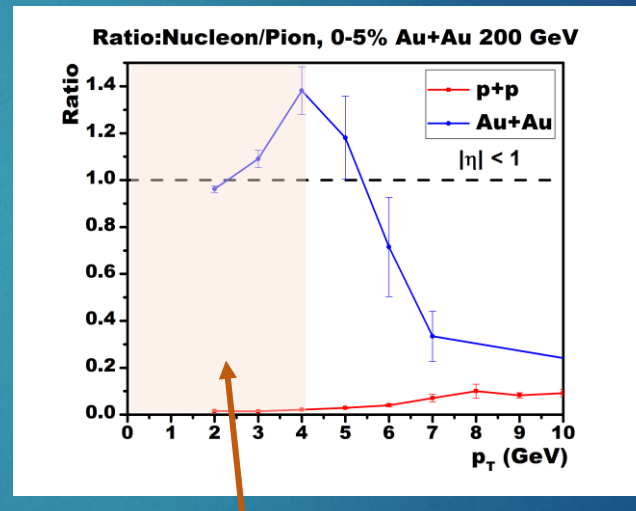
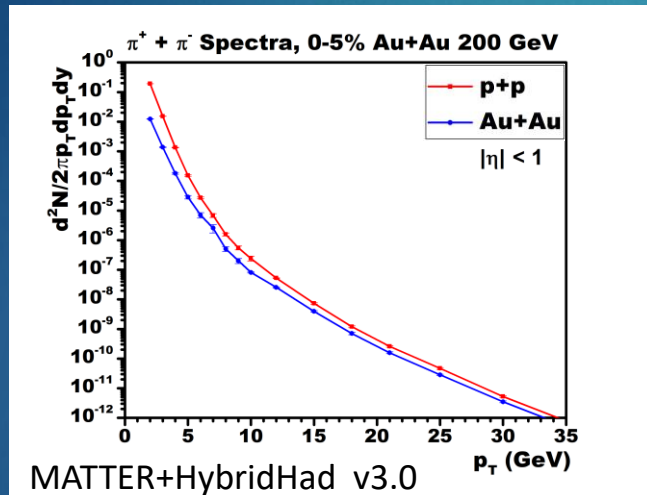


- No space-time information used in PYTHIA 8 → likely overestimate recombination contribution at intermediate momenta.
- No tuning yet.

Some Results: A+A

20

- ▶ MATTER showers with v3.0 ($\hat{q} = 1 \text{ GeV}^2/\text{fm}$)
 - ▶ MUSIC hydro event
 - ▶ Not tuned to data



No bulk hadrons in this calculation

- ▶ Shower-thermal recombination increases nucleon production at intermediate momenta as expected.
- ▶ Caveat: thermal bulk not added!

Hadronization: Conclusion and Outlook

21

- ▶ Hybrid Hadronization: Combine aspects of string fragmentation and quark recombination.
- ▶ MC implementation: Use recombination as a first stage before PYTHIA string fragmentation
- ▶ Challenge: Incomplete information. Ideally we need color flow and space-time information.
- ▶ Future developments:
 - ▶ JETSCAPE 2.0; code will become publicly available
 - ▶ Tune vacuum part to data (using MATTER?)

Announcement

22

2nd JETSCAPE Winter School and Workshop

January 9-13, 2019

Texas A&M University

Backup

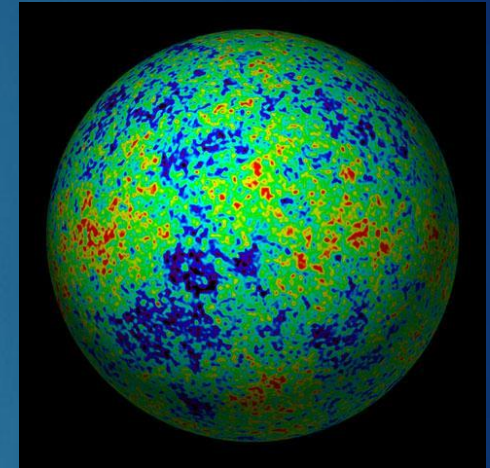
Recombination Processes

24

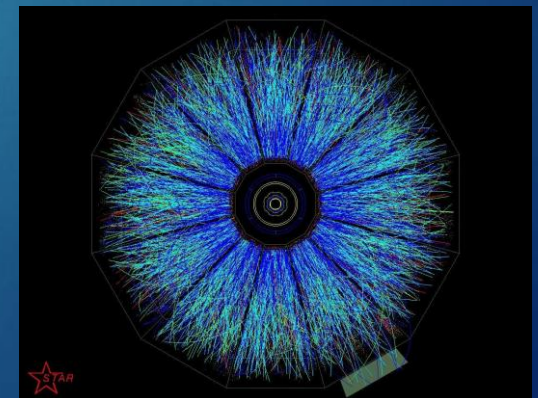
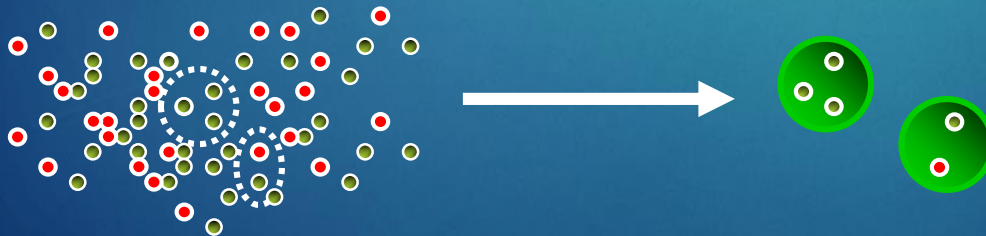
- Atomic physics: recombination of protons and electrons into hydrogen + photons



WMAP: Afterglow of photons from the recombination event 300,000 years after the Big Bang (CMB).

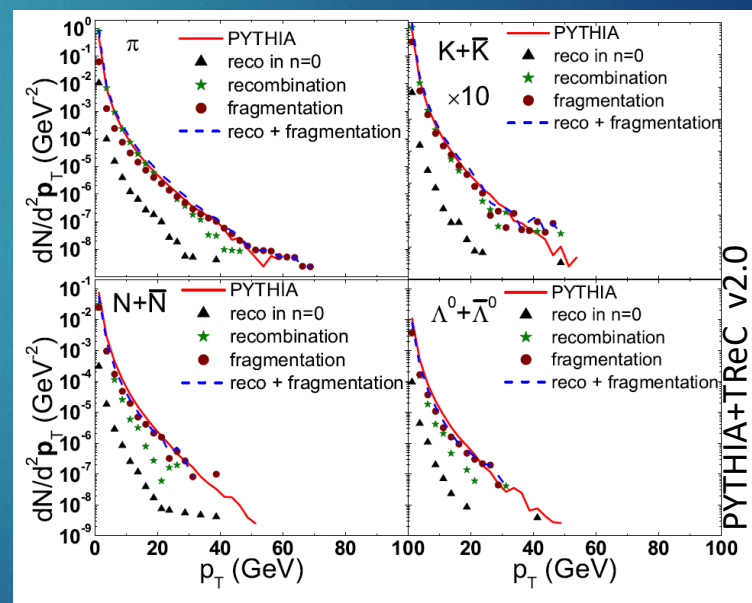
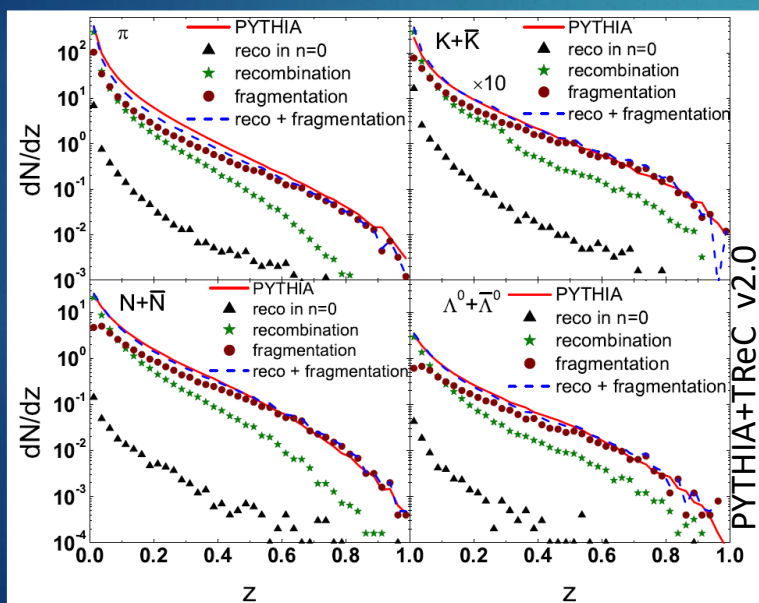


- Nuclear/particle physics: recombination of quarks into mesons and baryons?



Old Results

25

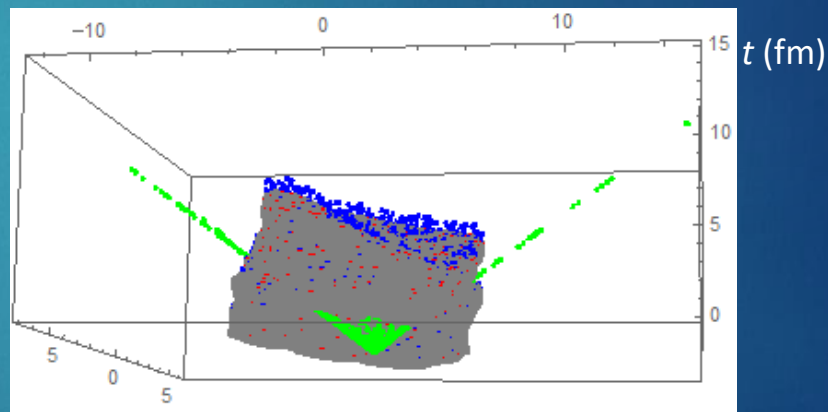
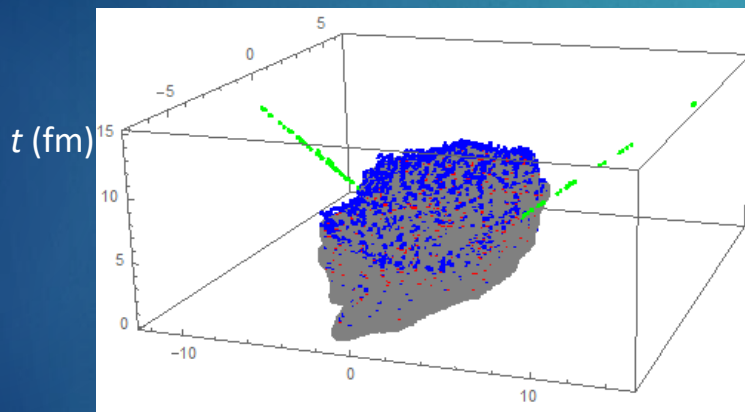


[K. Han, RJF., C. M. Ko, Phys. Rev. C 93, 045207 (2016)]

Hard and Semi-Hard Hadronization

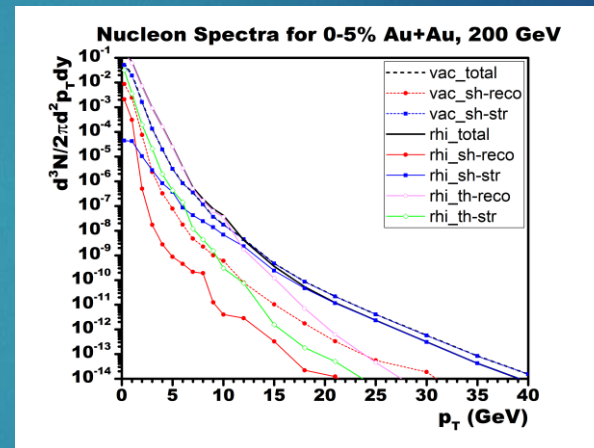
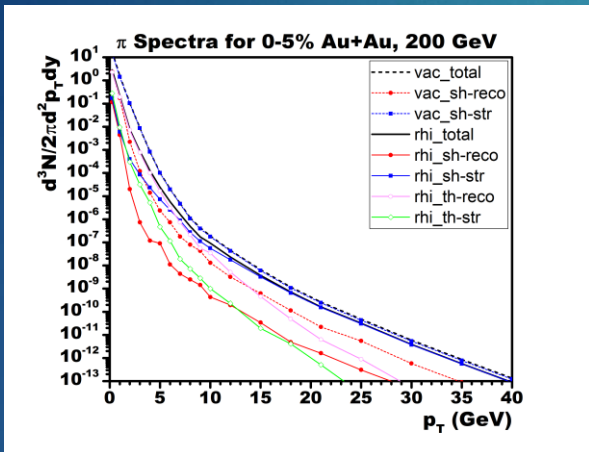
26

- Vacuum jets embedded in a background computed with fluid dynamics



Some Results: A+A

27



MATTER+HybridHad v3.0