HARD PROBES 2018, AIX-LES-BAINS

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Hybrid Hadronization

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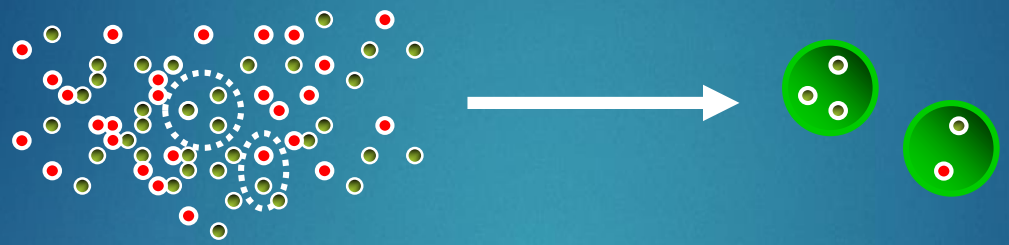
In collaboration with Michael Kordell

What is Hybrid Hadronization?

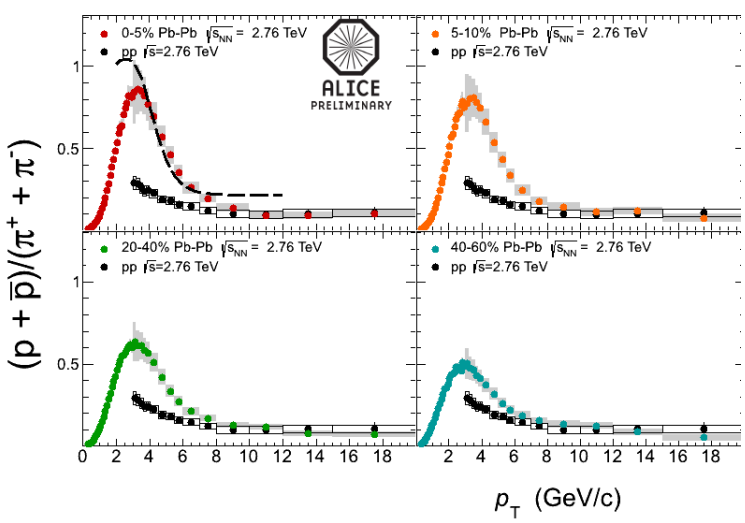
- Take two existing hadronization models and merge them to create something with a wider range of applicability.

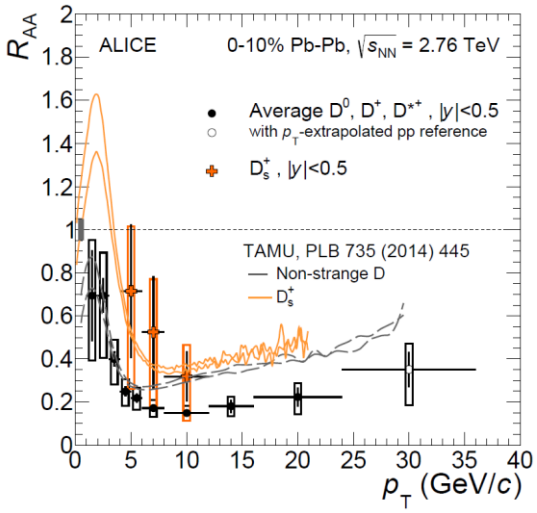
Quark Recombination

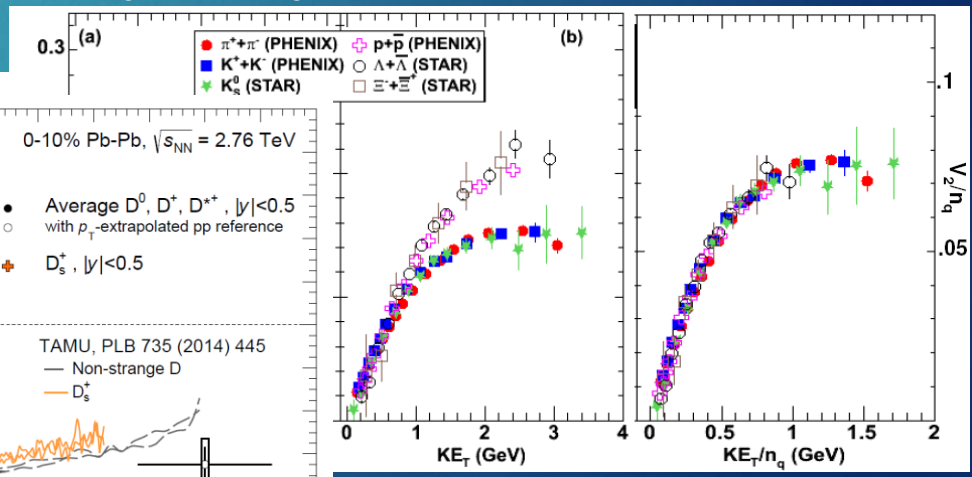
- Signature of quark recombination processes are seen in dense systems (nucleus-nucleus collisions, beam of fixed target experiments)



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

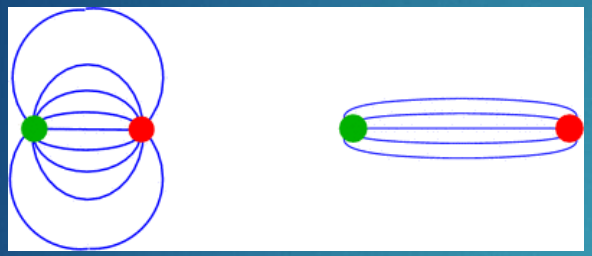


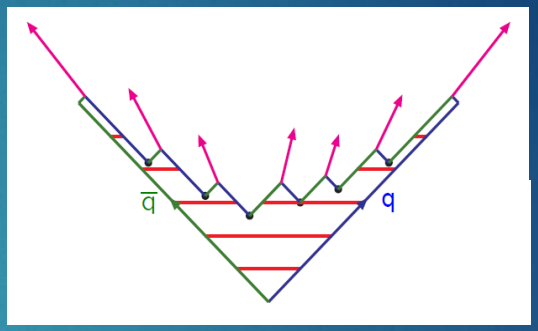




Compare To String Fragmentation

- Lund string fragmentation picture





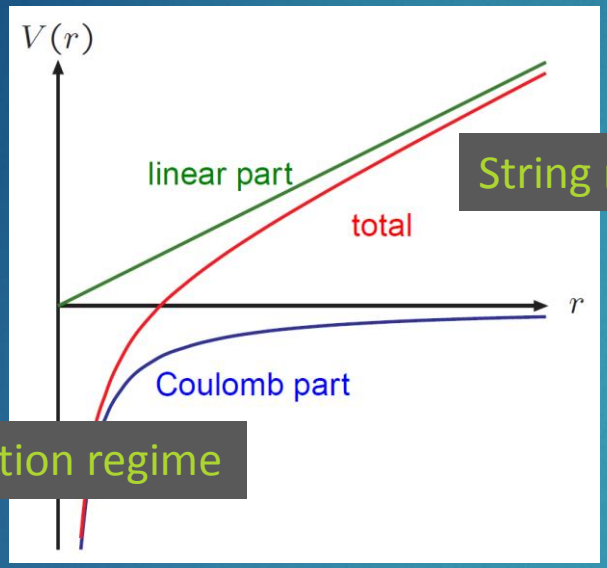
Andersson, Gustavson, Ingelman, Sjostrand, Phys. Rep. 97, 33 (1983)

  - Extremely successful phenomenology e^++e^-, p+p

- Short comings 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

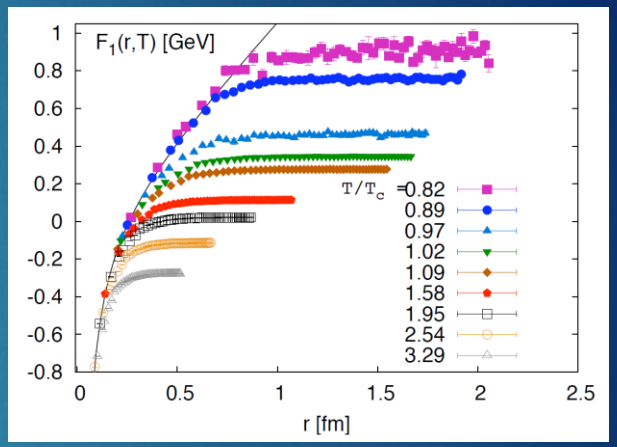
Two Sides Of The Same Coin?

- QQ potential:



String regime

Recombination regime



Kaczmarek et al. (2007)

- Strong force ~ 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 → String fragmentation
  - Dense systems → 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)

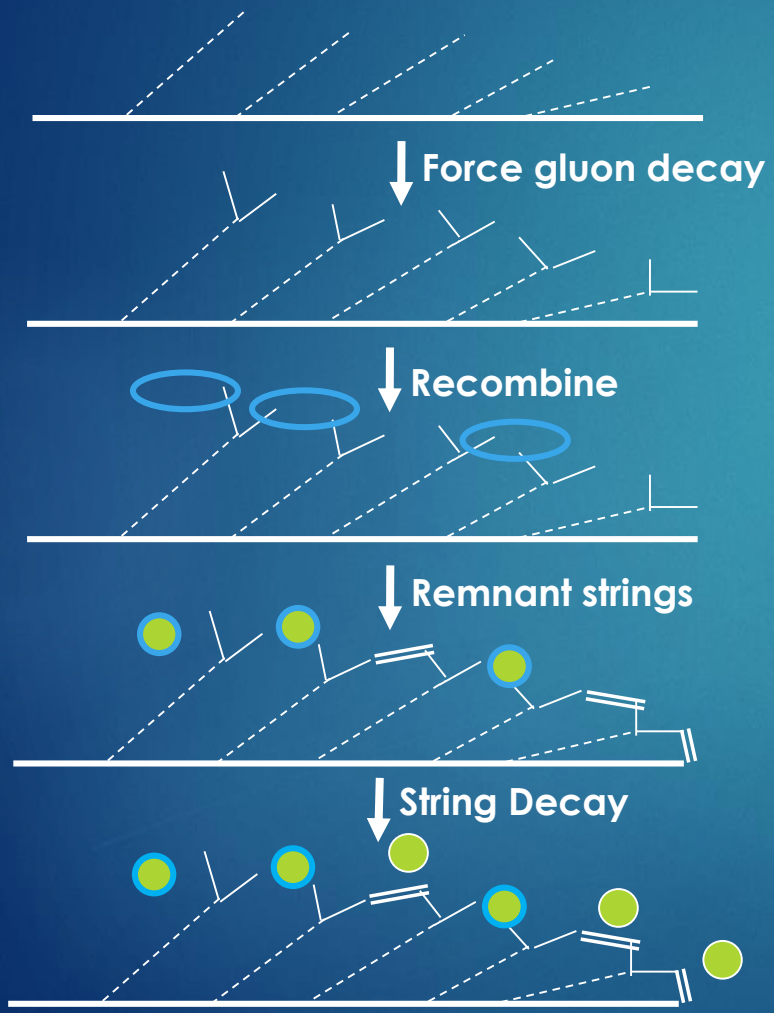
- (Remnant) string formation

- String fragmentation: standard PYTHIA

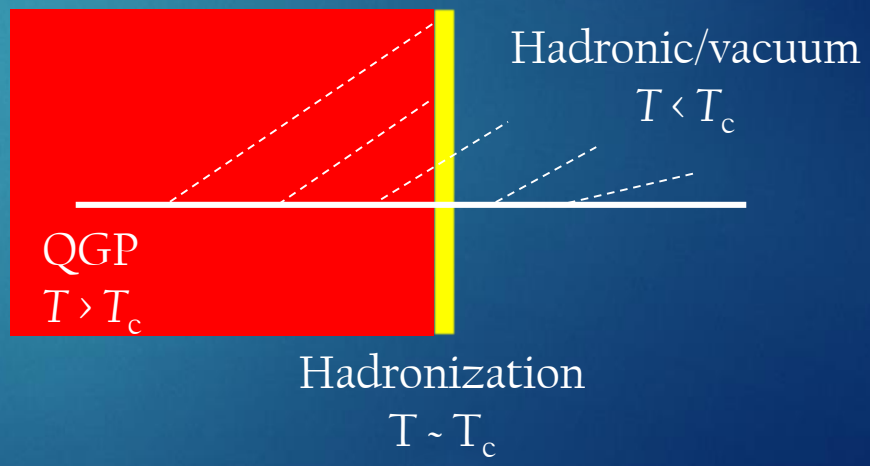
Steps in Monte Carlo Implementation

- Implementation for jets in an event generator

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



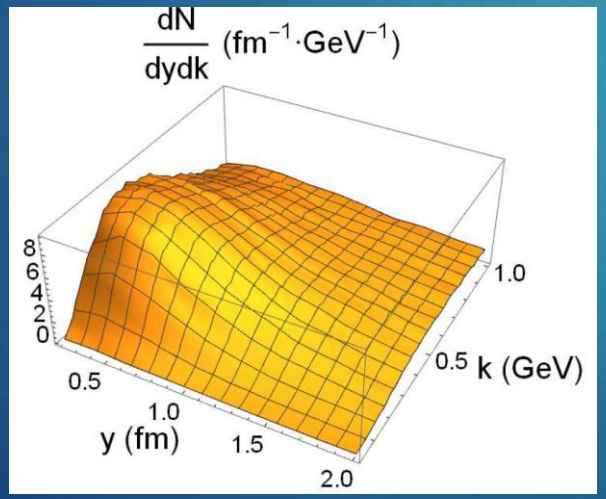
- Jets in QGP: add sampled thermal quarks on the $T=T_c$ hypersurface

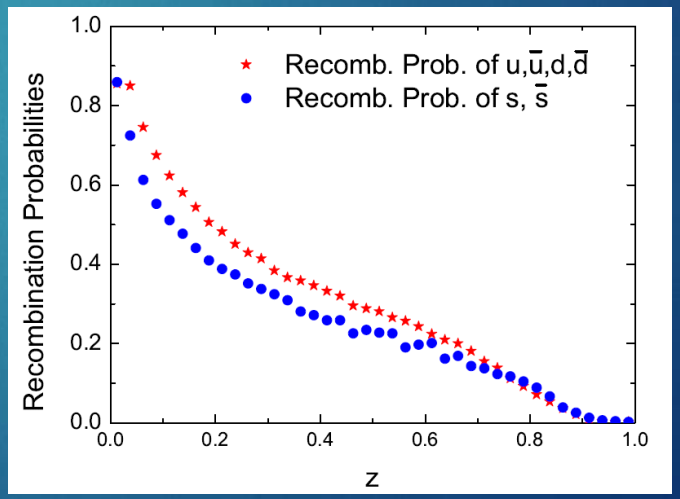


Hybrid Hadronization

- 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:

$$\overline{W} = \int d^3x_1 d^3p_1 \int d^3x_2 d^3p_3\, W_a(x_1,p_1) W_b(x_2,p_2) W_M(\Delta x, \Delta p)$$

- 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, qbar 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

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

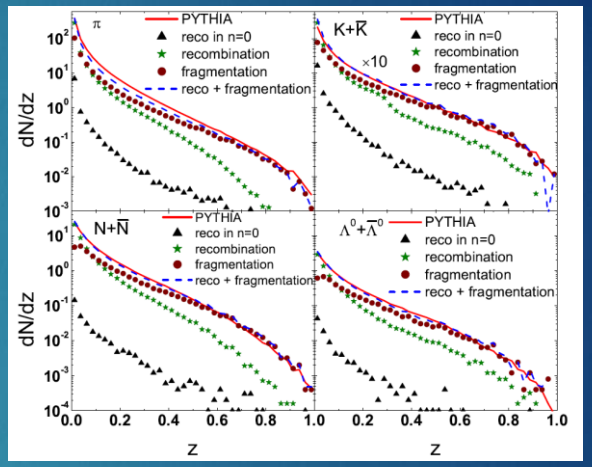
$$v = \frac{1}{2}\left(\frac{\mathbf{y}^2}{\sigma_M^2} + \mathbf{k}^2\sigma_M^2\right)$$

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

Monte Carlo Implementation

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

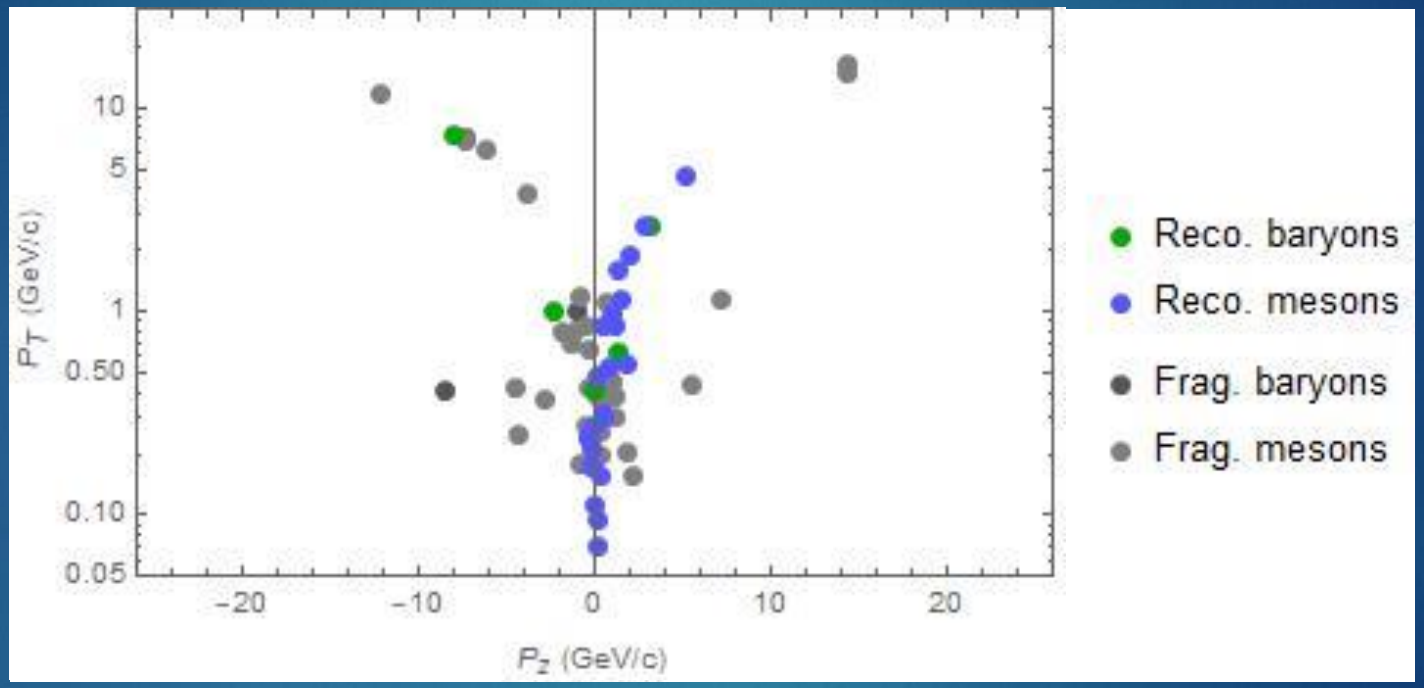
- Reproduced PYTHIA 6 results in vacuum



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

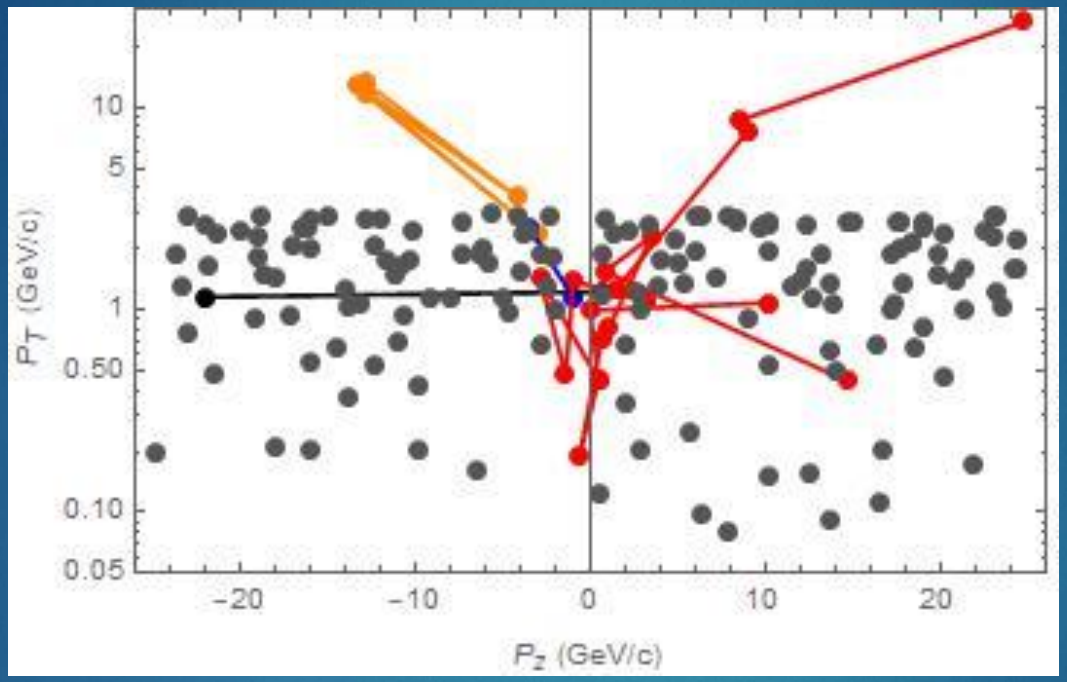
Hybrid Hadronization Example

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



Hybrid Hadronization Example

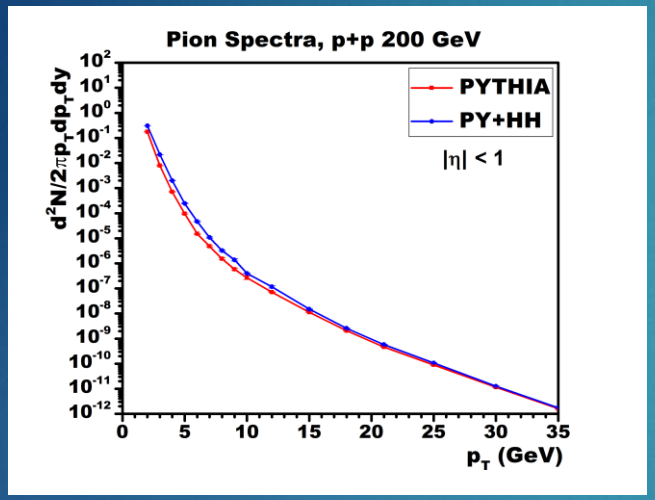
- Cartoon: Same event with added thermal partons

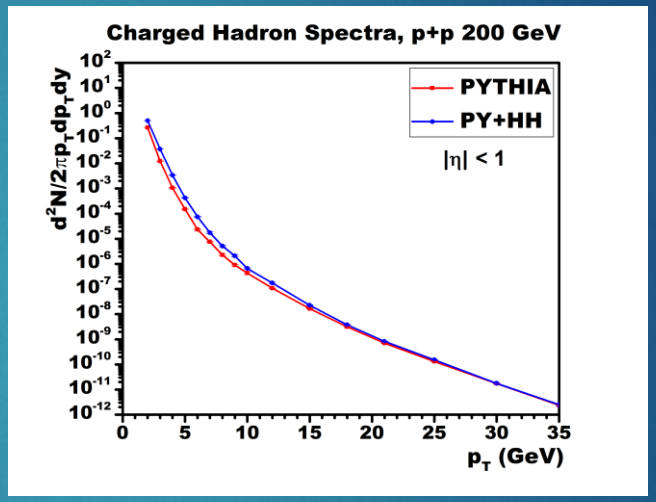


- Sample thermal partons from a hydro code at $T=T_c$.
  - In JETSCAPE: MUSIC hydro

Some Results: p+p

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

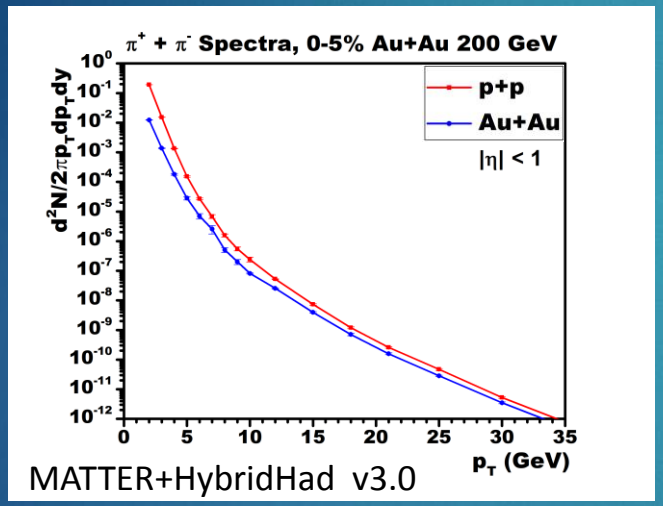


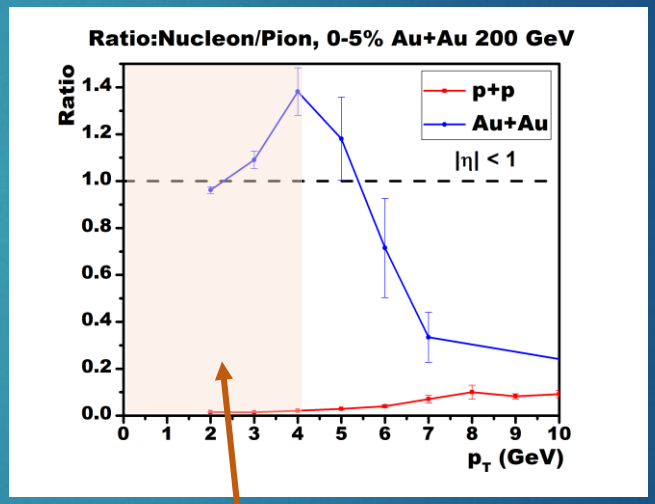


- No space-time information used in PYTHIA 8 → likely overestimate recombination contribution at intermediate momenta.
- No tuning yet.

Some Results: A+A

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





No bulk hadrons in this calculation

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

Hadronization: Conclusion and Outlook

- 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

2nd JETSCAPE Winter School and Workshop

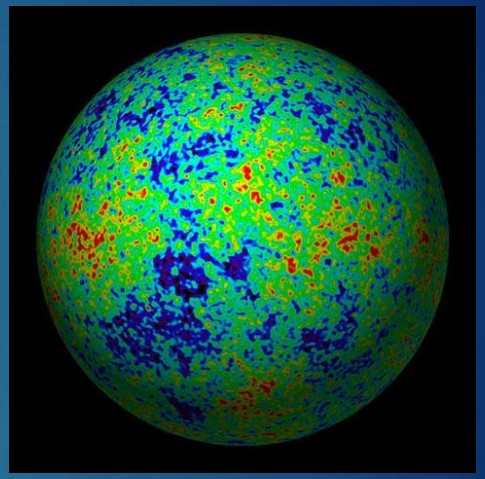
January 9-13, 2019

Texas A&M University

Backup

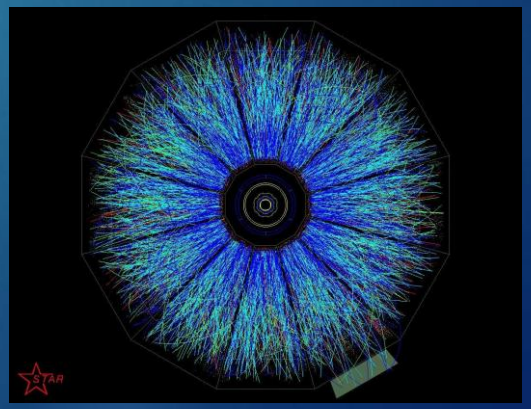
Recombination Processes

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

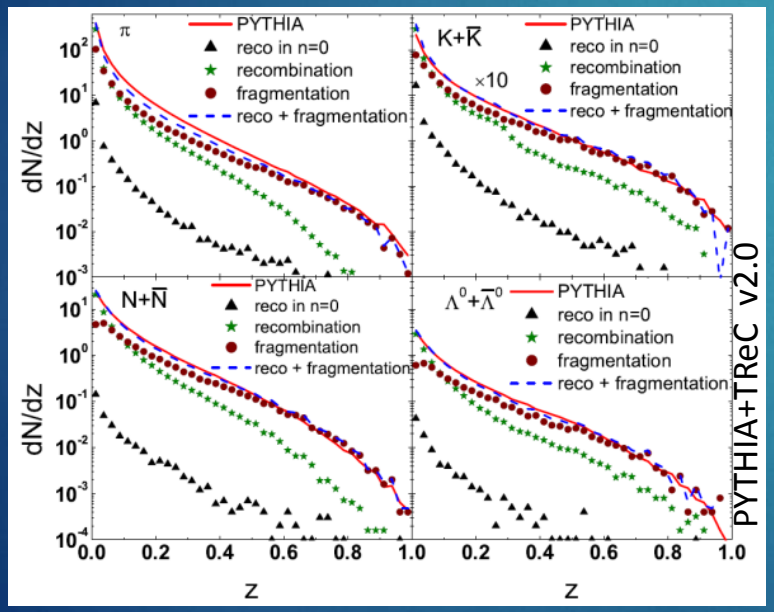


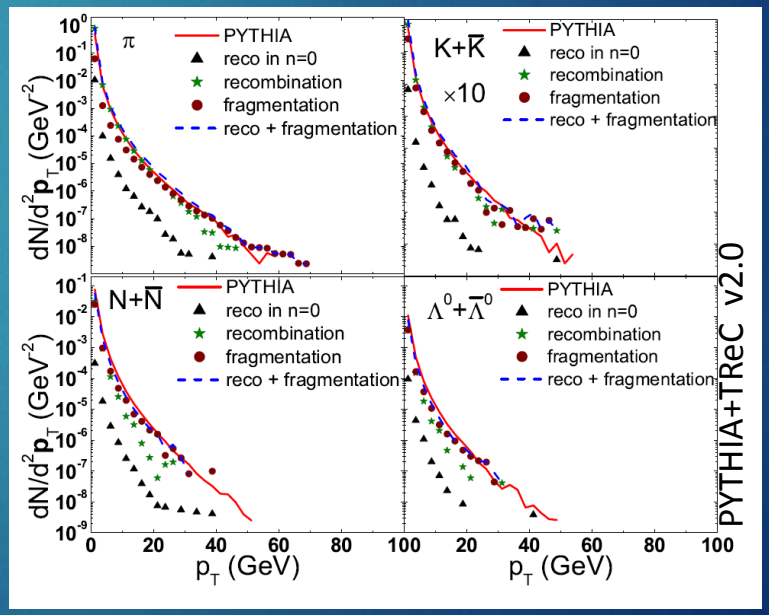
WMAP: Afterglow of photons from the recombination event 300,000 years after the Big Bang (CMB).

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



Old Results

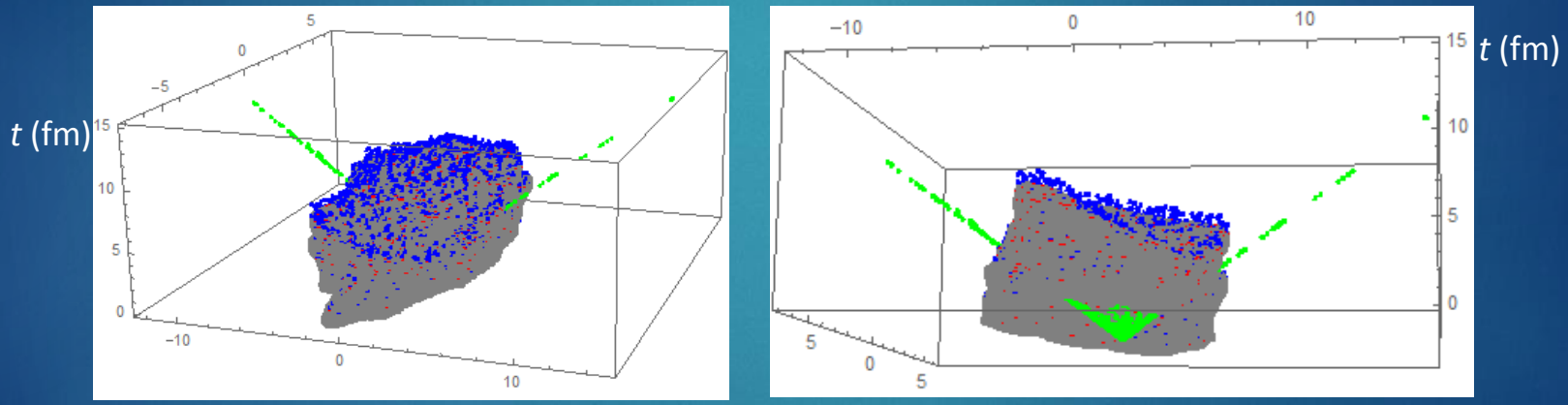




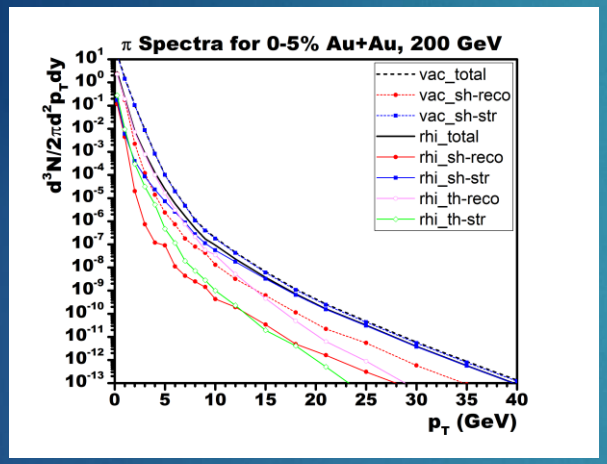
[K. Han, RJF., C. M. Ko, Phys. Rev. C 93, 045207 (2016)]

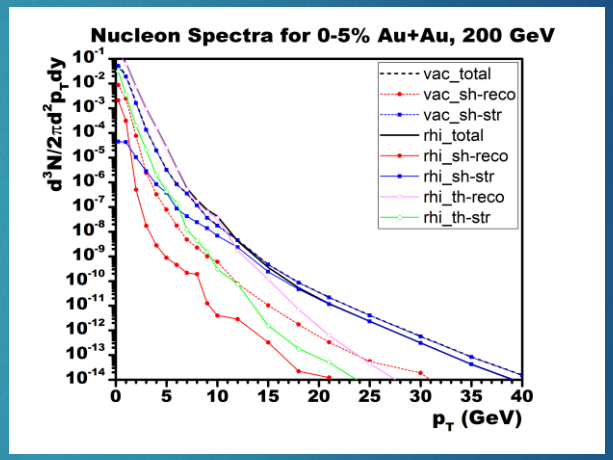
Hard and Semi-Hard Hadronization

- Vacuum jets embedded in a background computed with fluid dynamics



Some Results: A+A





MATTER+HybridHad v3.0