Opportunities and Challenges with Jets at LHC and beyond
IOPP/CCNU, Wuhan, June 11, 2018

Hadronization: From Dilute to Dense Systems

Rainer Fries
Texas A&M University

Work in collaboration with
Michael Kordell
Kyongchol Han
Che Ming Ko

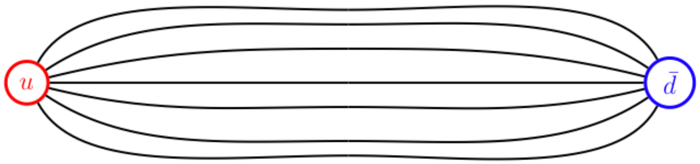
Overview

- Hadronization
- Hybrid Hadronization
- Adding a Medium
- JETSCAPE

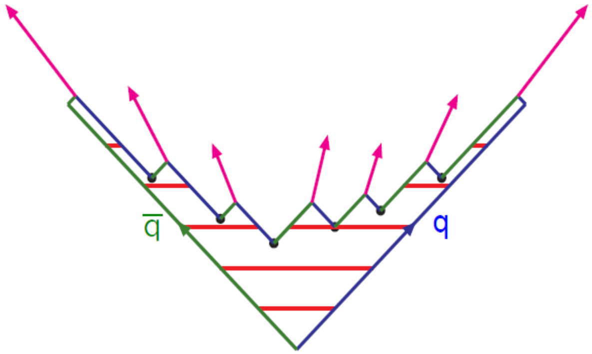
Hadronization

String Fragmentation

- Color flux expelled from the QCD vacuum → color flux tubes → string-like behavior.

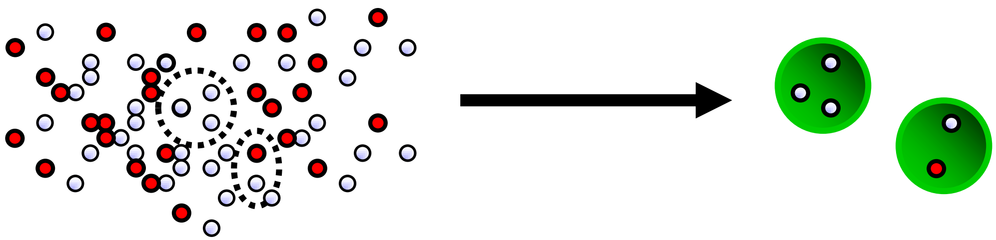


- Lund string fragmentation picture
- Successful phenomenology starting at PETRA, LEP, … → PYTHIA

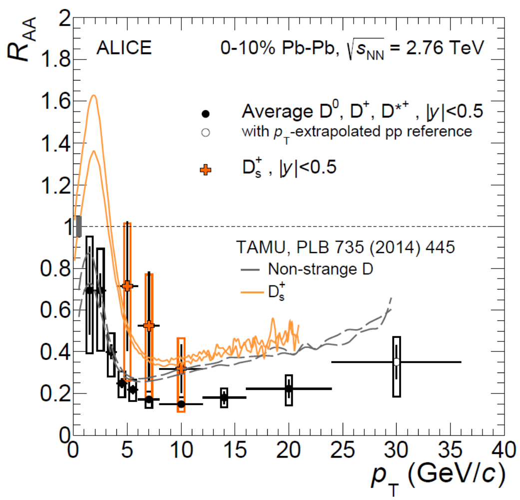


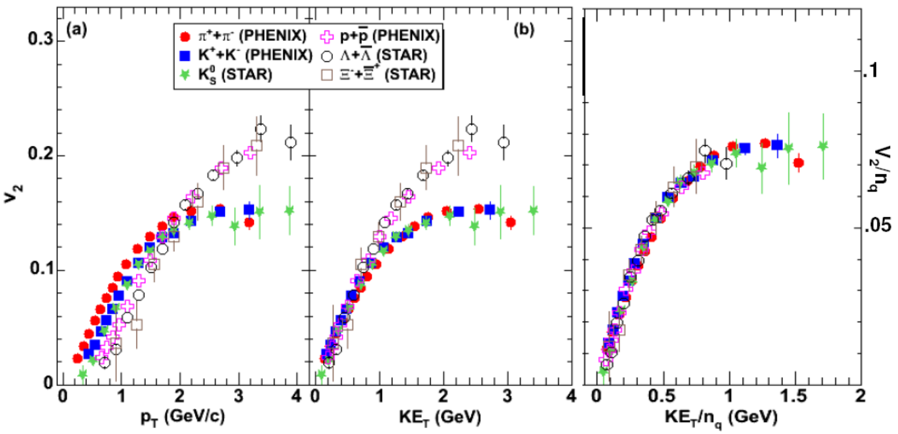
Quark Recombination

- Densely populated phase space: Recombination of quarks into mesons and baryons.



- Recombination models started around the same time as string models. Successes:
  - Exclusive processes, leading particle effect
  - Heavy ion physics: baryon/meson ratios, elliptic flow scaling, heavy quark sector (D_s)





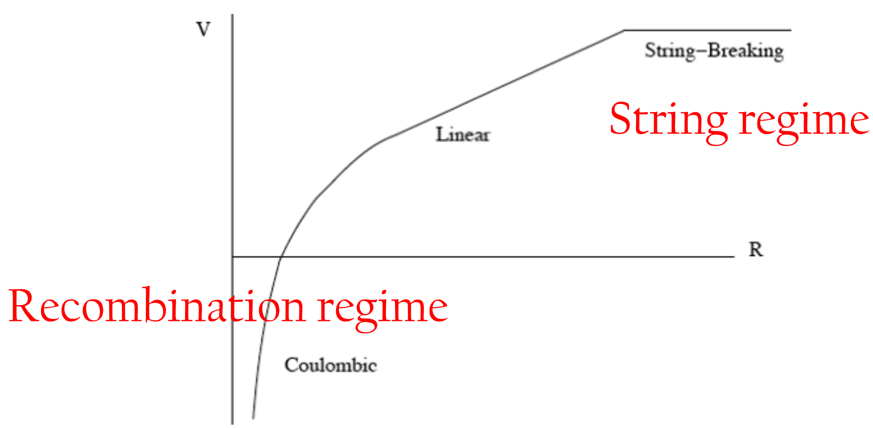
Hybrid Hadronization

- We propose a hybrid hadronization model with two well-defined limits:
  - Dilute systems → String fragmentation
  - Dense systems → Quark recombination
- Extrapolate smoothly between successful vacuum phenomenology of string fragmentation and quark recombination in a thermal environment.

- Original motivation: in-medium effects for jet hadronization in a medium.
  - Hadron chemistry
  - Momentum diffusion

- Surprise: jets can be "dense" systems of partons

- QQ-potential:



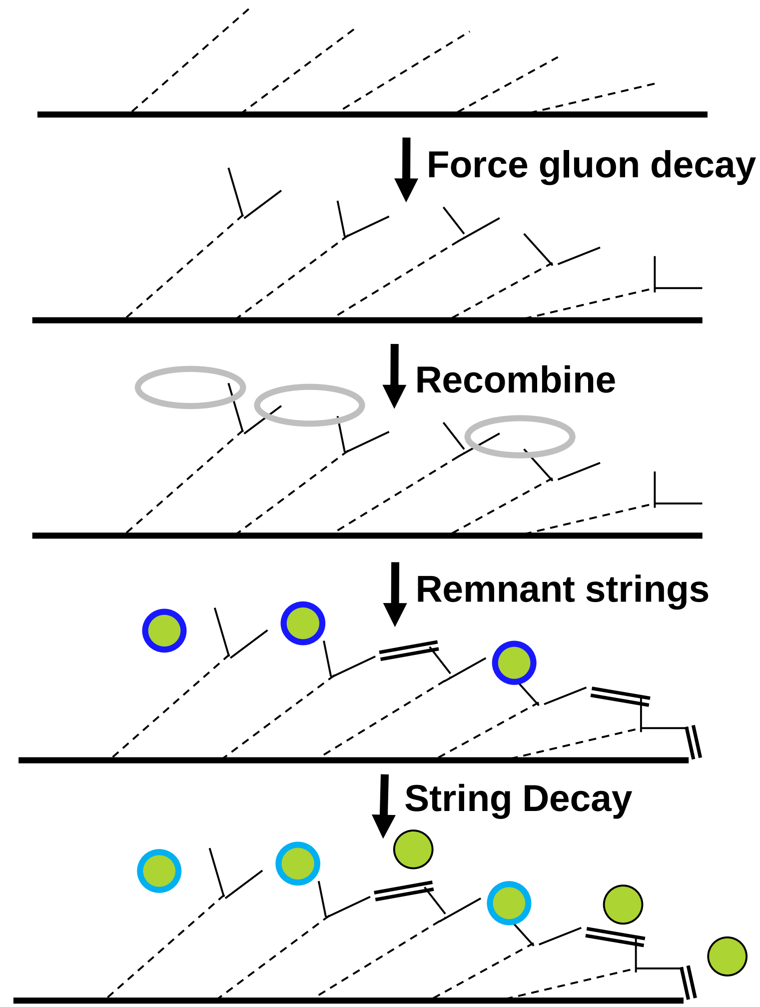
Hybrid Hadronization

Outline Of The Model

- Start with initial parton system "ready" to hadronize
- Partons can start to hadronize at different times *t*.

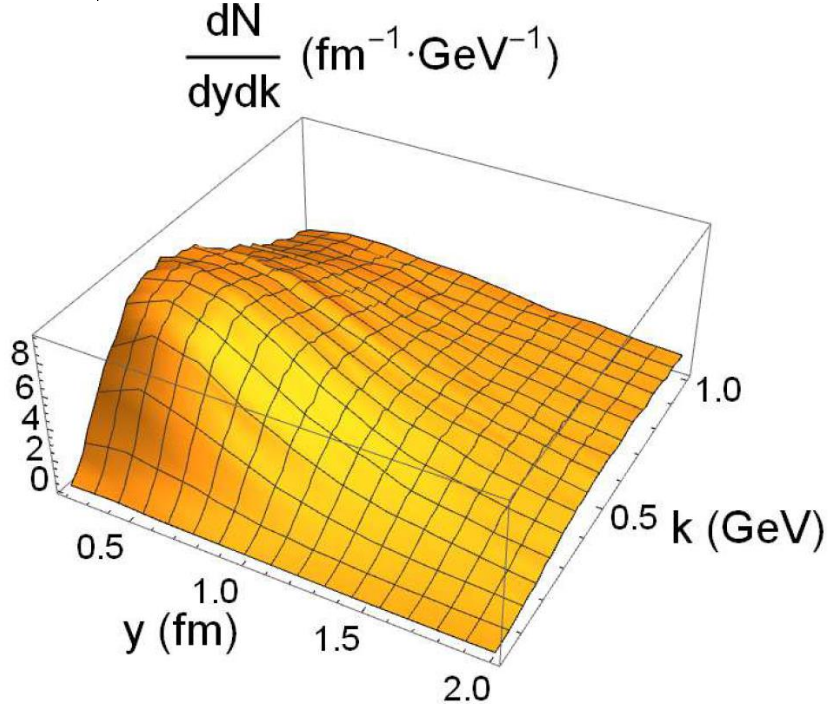
- This example: perturbative parton showers evolved to a scale Q_0.
- Decay gluons with remaining virtualities into quark-antiquark pairs.

- From wave functions of bound states calculate the probability that a given q-qbar pair (q-q-q triplet) forms a meson (baryon)
- Connect remaining remant partons with strings.



How Dense are Parton Showers?

- Distance of quark-antiquark pairs in phase space is the deciding factor for recombination into mesons.
- Distribution of pair distances in 100 GeV (PYTHIA 6) parton showers in phase space (in the pair center of mass frame)



- PYTHIA 6 jets: most of the jet is relatively dense in phase space.
  - Space-time structure reconstructed from formation times.
- Long tails exist (~ large z partons)
- Test for other jet Monte Carlos? Perturbative evolution should not lead to dilute showers, otherwise non-perturbative effects are already dominant.

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

Recombination Step

- Wigner function coalescence yield:

$$\frac{dN_M}{d^3\mathbf{p}_M} = g_M \int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 f_q(\mathbf{x}_1,\mathbf{p}_1) f_{\bar{q}}(\mathbf{x}_2,\mathbf{p}_2) \times W_M(\mathbf{y}_1,\mathbf{k}_1)\delta^{(3)}(\mathbf{P}_M - \mathbf{p}_1 - \mathbf{p}_2), \quad (3)$$

$$\frac{dN_B}{d^3\mathbf{p}_B} = g_B \int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 d^3\mathbf{x}_3 d^3\mathbf{p}_3 f_{q_1}(\mathbf{x}_1,\mathbf{p}_1) \times f_{q_2}(\mathbf{x}_2,\mathbf{p}_2) f_{q_3}(\mathbf{x}_3,\mathbf{p}_3) W_B(\mathbf{y}_1,\mathbf{k}_1;\mathbf{y}_2,\mathbf{k}_2) \times \delta^{(3)}(\mathbf{P}_B - \mathbf{p}_1 - \mathbf{p}_2 - \mathbf{p}_3), \quad (4)$$

[RJF, V. Greco, P. Sorensen, Ann. Rev. Nucl. Part. Sci. 58, 177 (2008)]

- Can be turned into a formula for recombination probability (here 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.
  - Throw dice to accept or reject a pair or triplet for recombination.

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

Recombination Step

- Bound state Wigner function derived from harmonic oscillator wave functions (L_n= Laguerre polynomials).

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

- For the probabilities to be positive definite, we need proper q, qbar Wigner functions: Introduce Husimi smearing by representing quarks by proper wave packets of width δ.
- For $\sigma^2 = 2\delta^2$ the result for the overlap of wave packets and Wigner function is extremely simple. The probability densities for the n-th excited states are

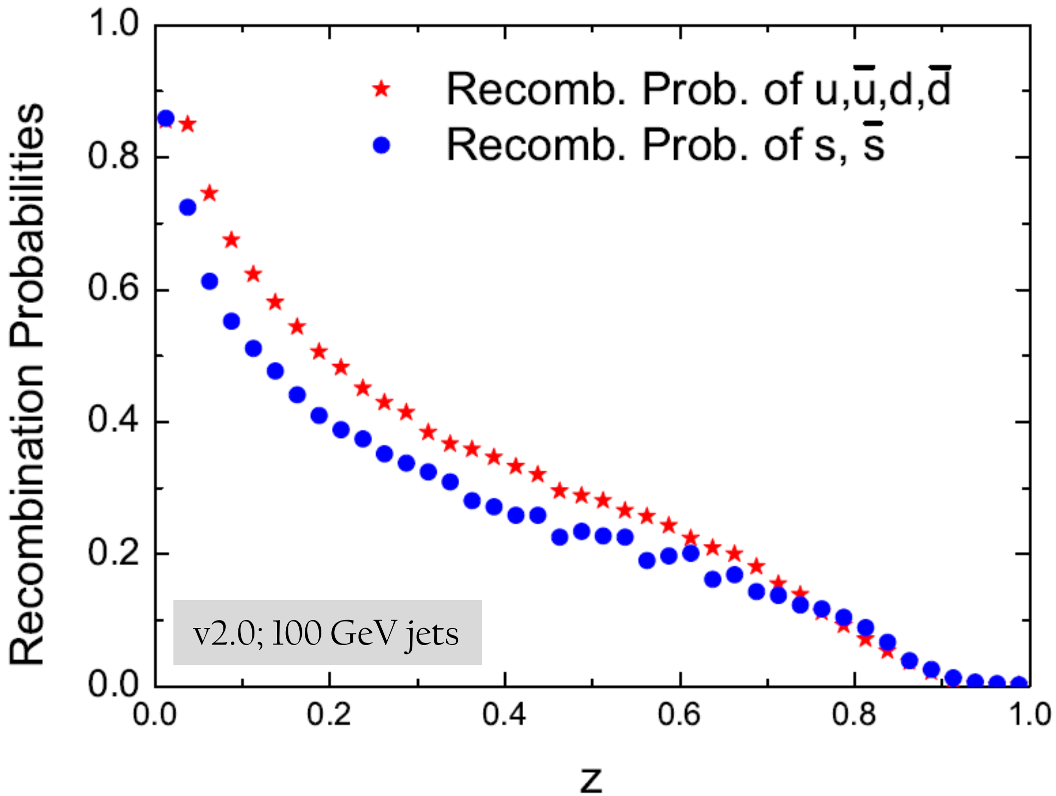
$$\overline{W}_{M,n}(\mathbf{y},\mathbf{k}) = \frac{v^n}{n!} e^{-v} \qquad v = \frac{1}{2}\left(\frac{\mathbf{y}^2}{\sigma_M^2} + \mathbf{k}^2 \sigma_M^2\right)$$

- The true shape and size of the input wave packets are not known.
- Hadron wave function widths fixed by measured charge radii.

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

Remnant Strings

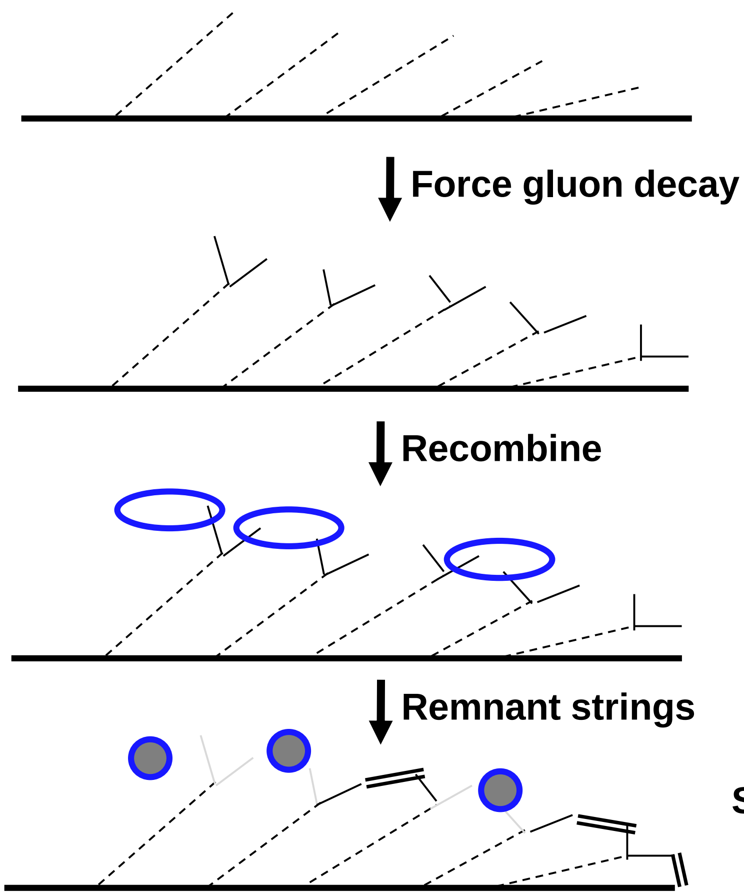
- Check on recombination probability (100 GeV PYTHIA 6 vacuum jets)



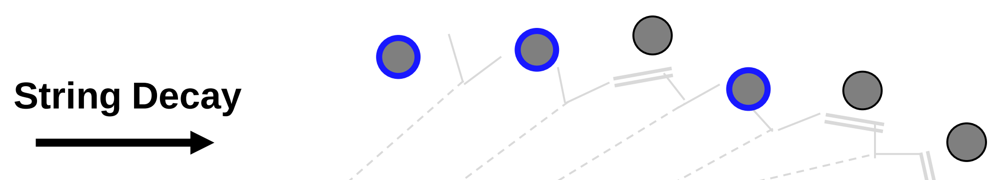
[K. Han, R.J.F., C. M. Ko, Phys. Rev. C 93, 045207 (2016)]

Remnant Strings

- Naturally there are remnant quarks and antiquarks which have not found a recombination partner.

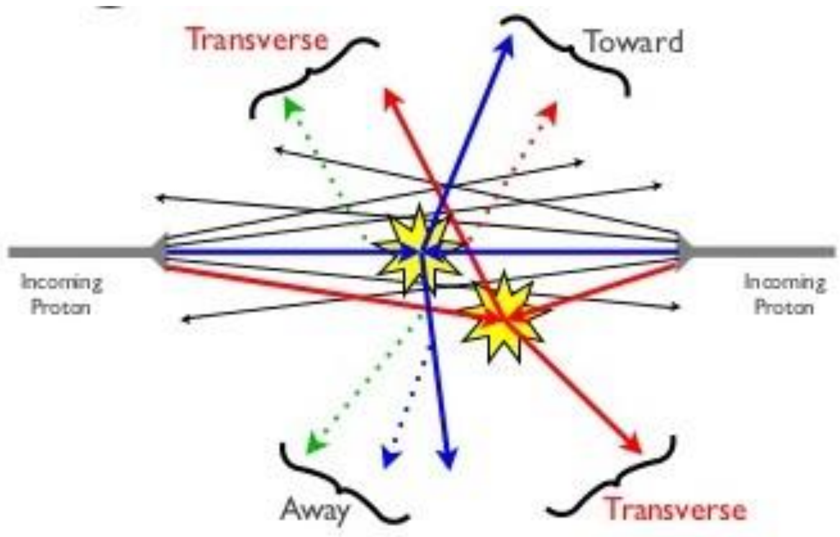


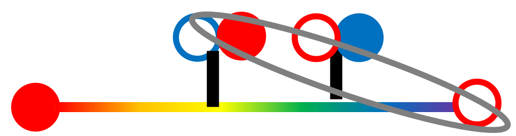
- Why? No confinement in parton shower, quarks can get far away.
- In reality: colored object needs to stay connected.
- Return these partons to PYTHIA to connect them with remnant strings.

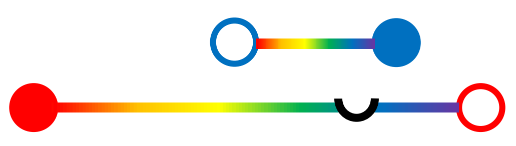


Underlying Events: p+p

- Original model: e+e- jets, simple strings!
- Full p+p event: many strings, junctions, diquarks, …
  - New in v2.2
- Complexity requires instant "repair" of string objects that have lost partons to other hadronization channels.
- Many possible channels to consider:
- Start with well-defined string structure (e.g. PYTHIA), end with well-defined strings + hadrons: Strings → Strings' + hadrons

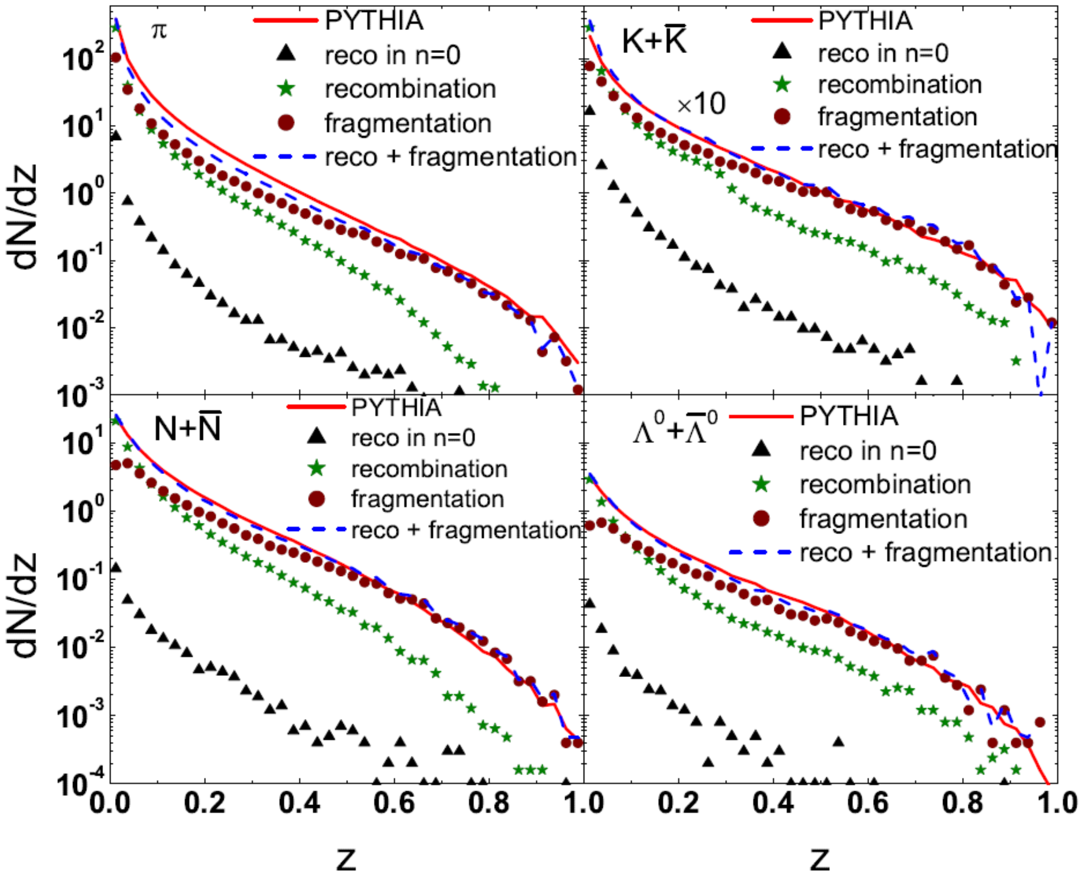






Results for Single Jet Showers

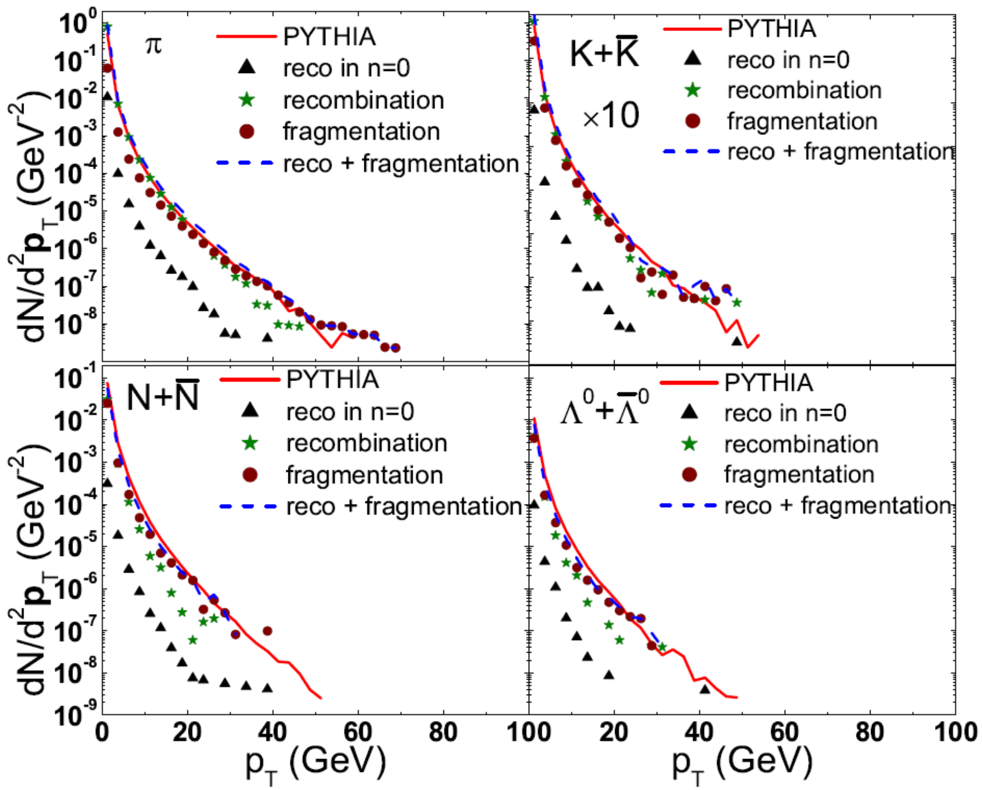
- Longitudinal structure: *dN/dz* of stable particles compared to PYTHIA string fragmentation (e+e-).



v2.0; 100 GeV jets

Results (Vacuum)

- Transverse structure: dN/d^2P_T of stable particles compared to PYTHIA string fragmentation (e+e-).

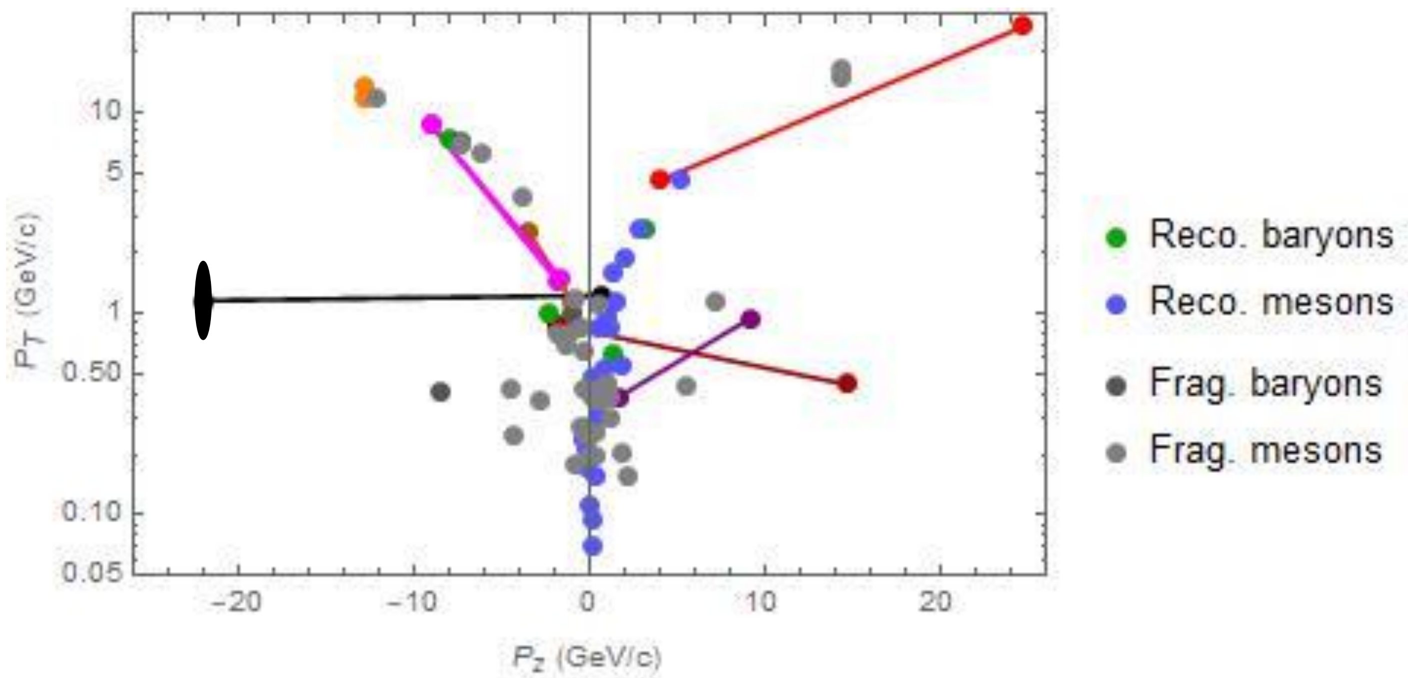


- Generally good agreement with pure string fragmentation.
- No precision tuning to data.

v2.0; 100 GeV jets

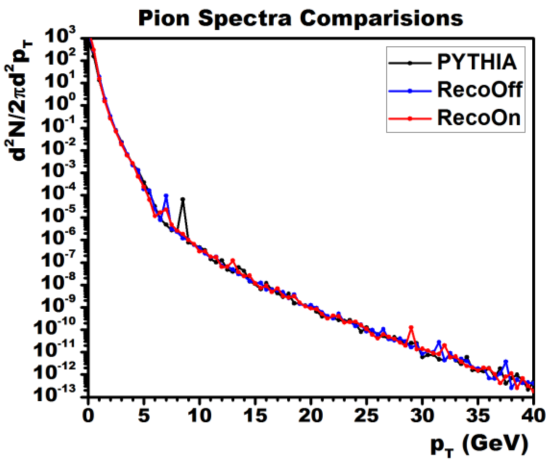
String-Recombination Interplay

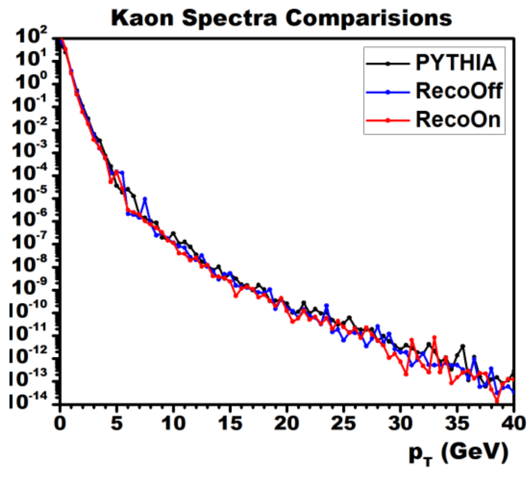
- 200 GeV p+p event from PYTHIA, ~50 GeV momentum transfer.

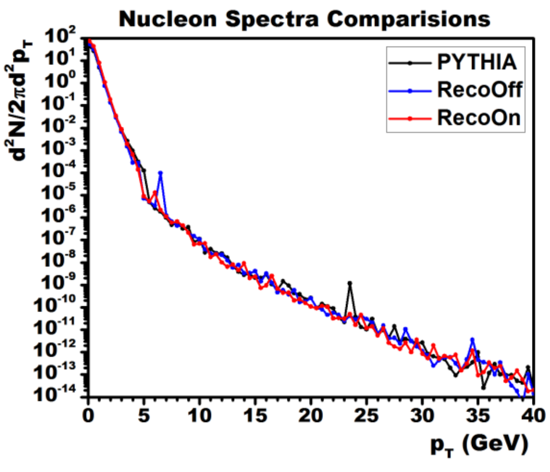


v2.2 Full p+p Events

- 3-way test:
  - PYTHIA
  - Hybrid hadronization reco=off
  - Hybrid hadronization full
- PYTHIA ~ benchmark.





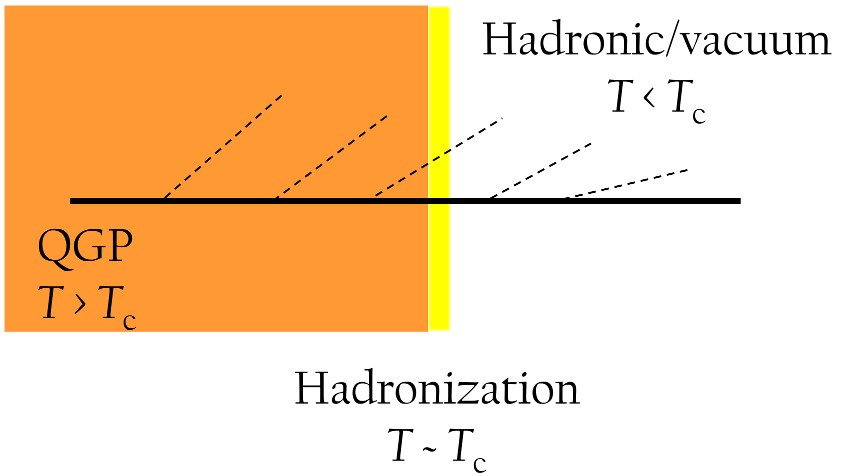


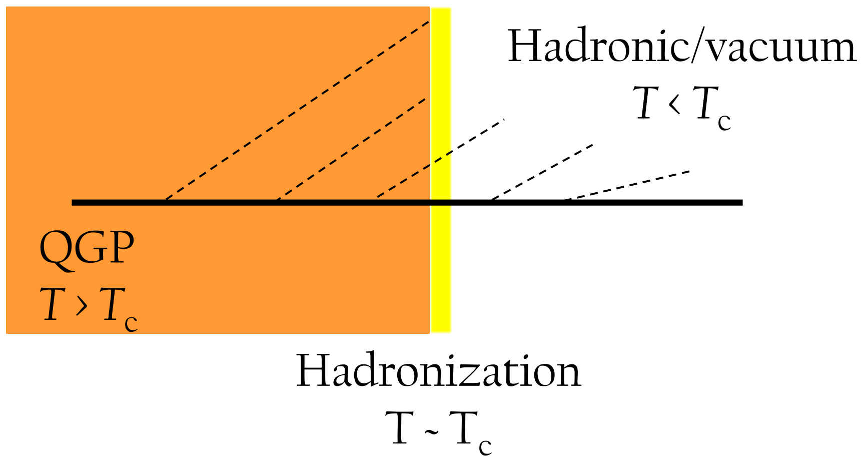
- No tuning. Need more testing: jet observables, etc …

Adding Thermal Partons

Adding a Medium

- The space-time picture is complicated and it matters.
- All relevant partons have to be on the surface of the QGP or outside the QGP to hadronize.
- Propagate all shower partons to the hadronization hypersurface, or make them part of the medium.

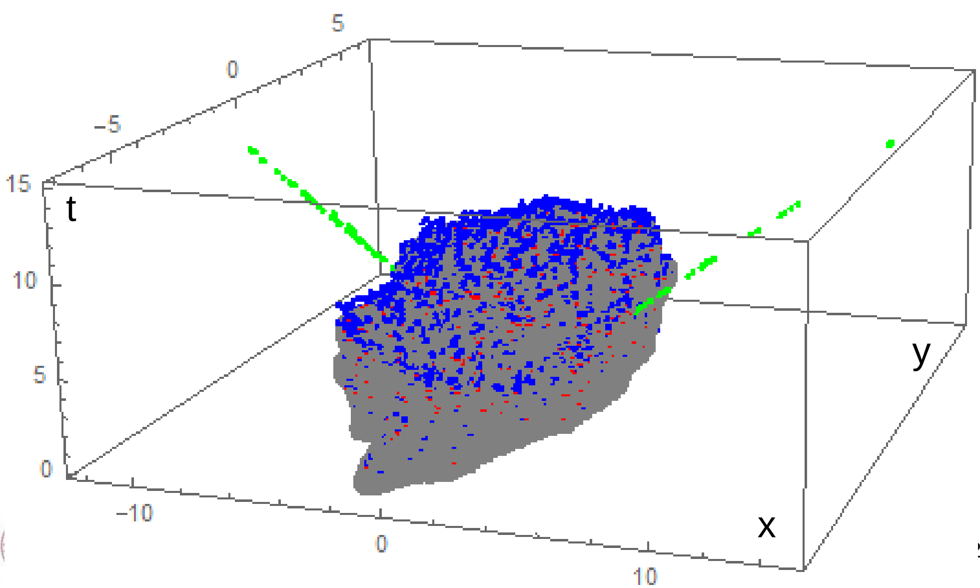


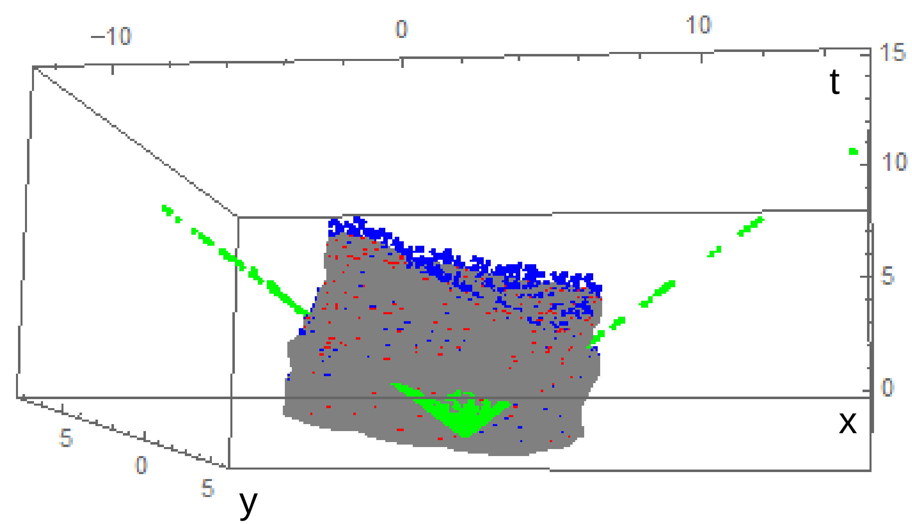


Adding a Medium

- iEBE (Ohio State) event-by-event hydro with sampled thermal partons on the T=T_c hypersurface.

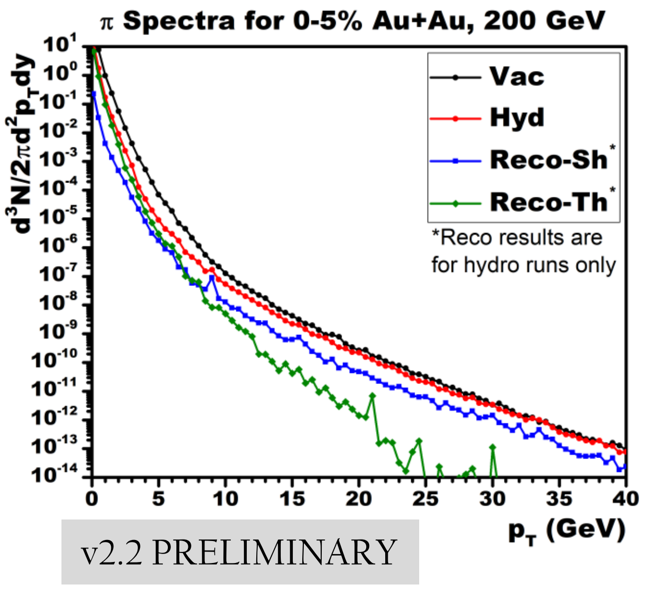
- Plots: 500 PYTHIA 6 (vacuum!) showers emerging from the center embedded into an iEBE event
  - blue = sampled thermal partons; green = shower; grey = hypersurface

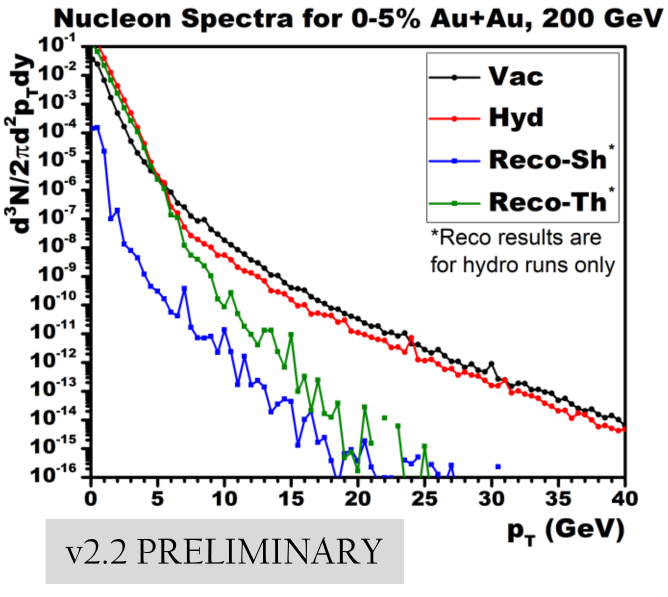




NEW: v2.2 Results With Medium

- v2.2: in-medium MATTER showers in hydro background; partons propagated to the $T=T_c$ hypersurface if Q_0 is reached inside QGP.
- Central Au+Au collisions at RHIC energy. No tuning to data.

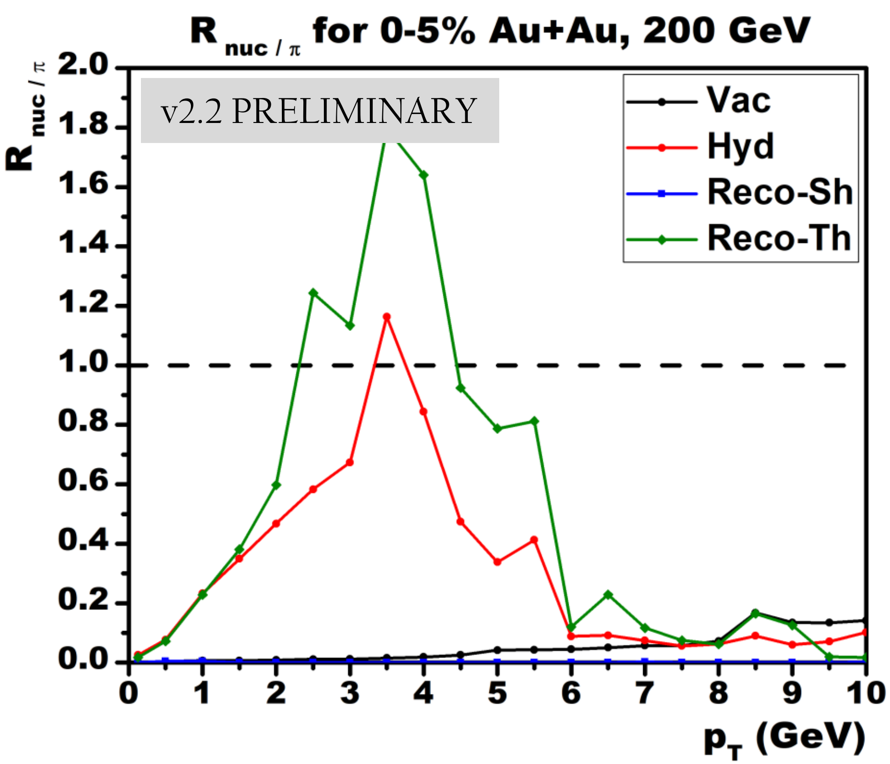




- Basic phenomenology: internal shower recombination is largely replaced by shower-thermal recombination at low to intermediate p_T.
- Shower-thermal recombination much more important for baryons!

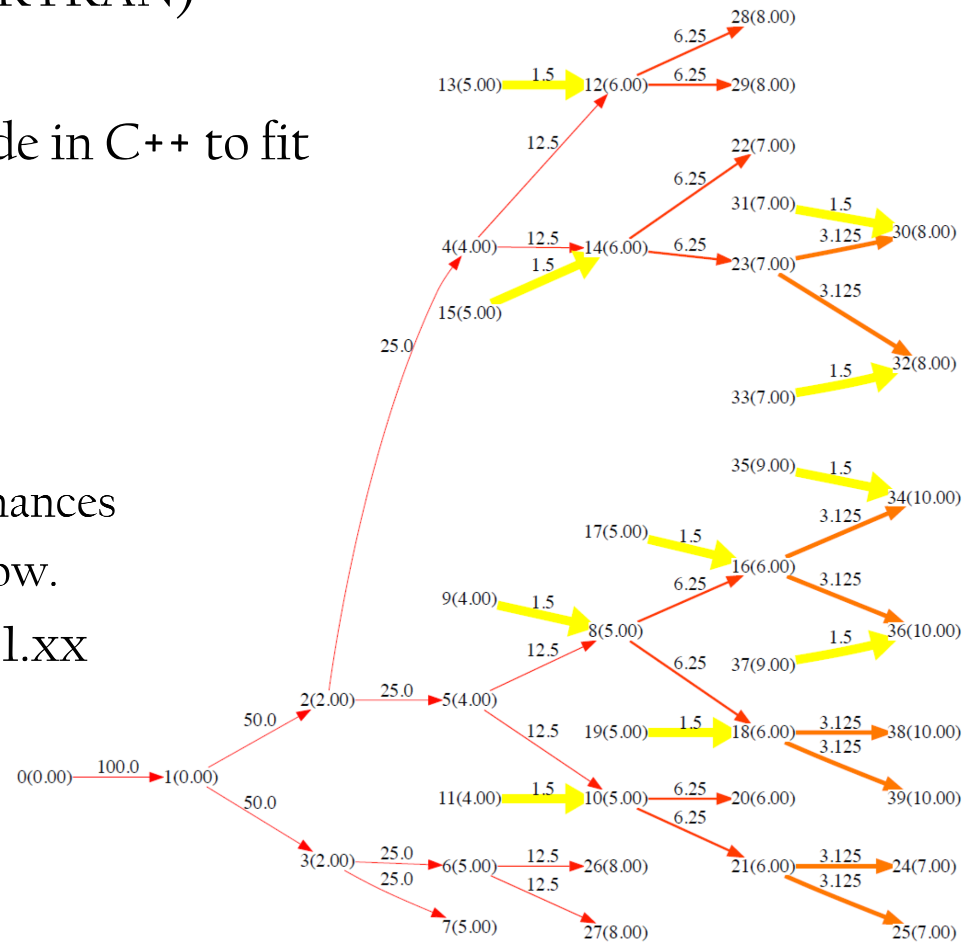
NEW: v2.2 Results With Medium

- Enhanced baryon/meson ratio as expected from quark recombintion.
- No thermal partons here!
- No tuning to data but very promising



Outlook

- Latest official version: v2.2 (FORTRAN)
- Coming soon: v3.0: Rewrote code in C++ to fit into JETSCAPE framework
- Work with PYTHIA 8
- Add physics along the way
  - Correct treatment of isospin
  - Better implementation of resonances
  - Infrastructure to track color flow.
- Will be included in JETSCAPE 1.xx



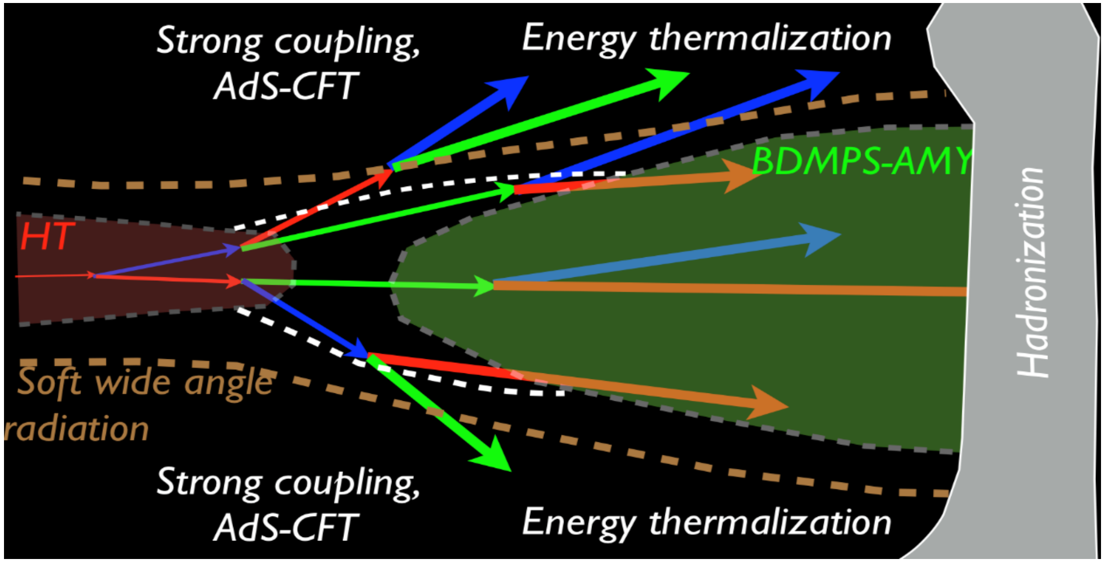
An (unphysical) example shower; credit: J. Putschke

JETSCAPE

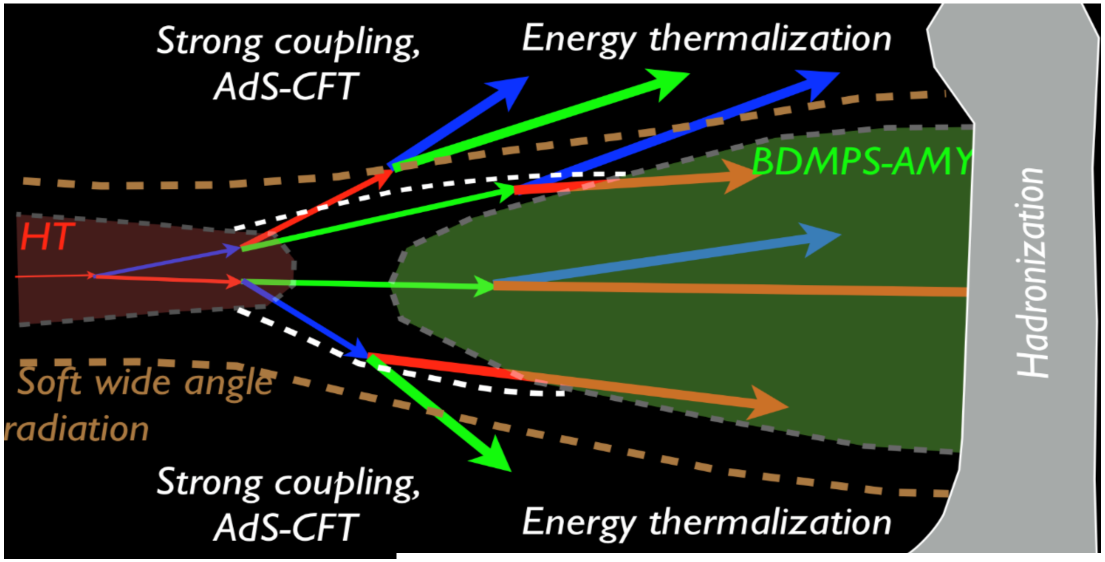
[Credit for slides: Kolja Kauder, Jorn Putschke]

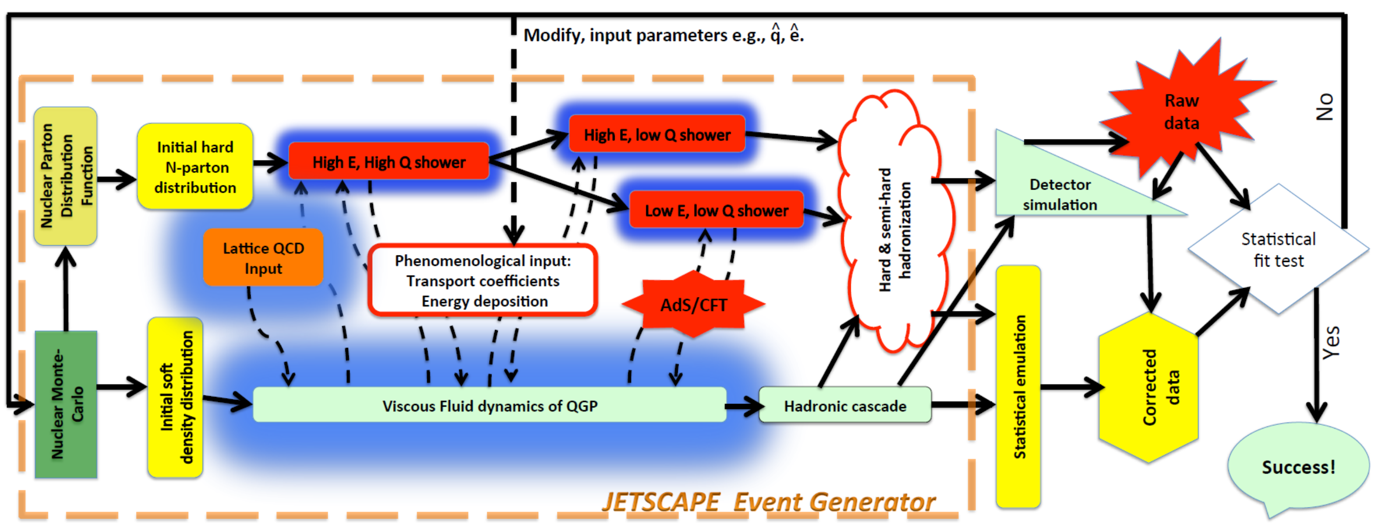
JETSCAPE

- JETSCAPE = The next generation event generator framework for high energy nuclear physics, NSF funded since 2016.
  - Theorist, experimentalist, statisticians, computer scientists
- Key issue: different Monte Carlo codes exist for different aspects of nuclear collisions. Make them work smoothly together in one framework
  - Modular, flexible, extensible
  - Use out of the box or add/replace code.
  - Also provide a default setup with the best science we can currently provide.



JETSCAPE Framework





JETSCAPE v1.0

- The first version of the code is now available for testing and community feedback.
- www.github.com/JETSCAPE/JETSCAPE

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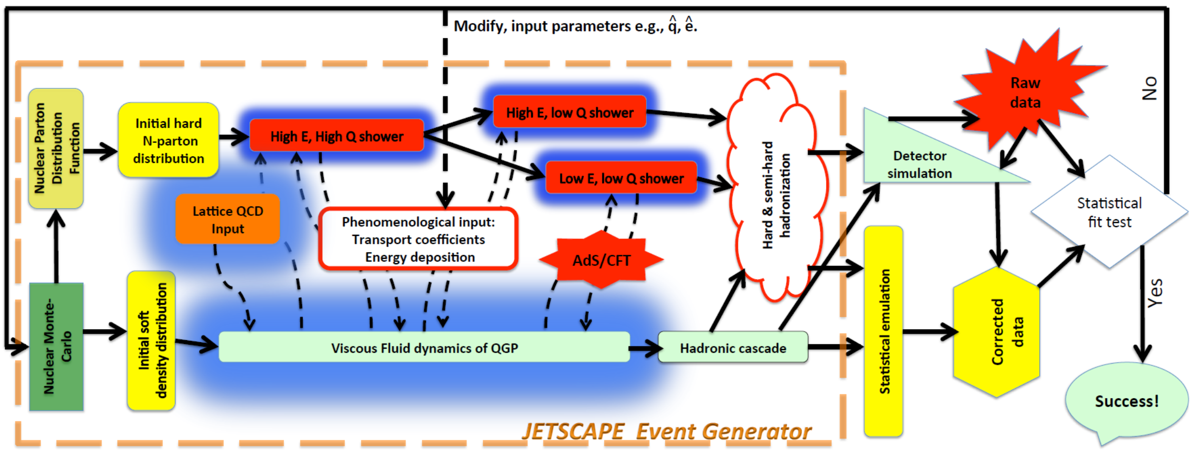
JETSCAPE v1.0

- Modules included in this release (optional modules)



- ✓ Trento (2+1)
- ✓ Free Streaming
- ✓ MUSIC (2+1, 3+1), external reader, brick, Gubser,
- ✓ Pythia8, parton gun
- ✓ MATTER, Martini, AdS/CFT, LBT
- ✓ Cooper Frye
- ✓ Pythia8 string fragmentation
- ✓ Custom and HepMC output

JETSCAPE Beyond v1.0

- Statistical analysis tools
- Hybrid hadronization
- SMASH
- Jet feedback into the medium (concurrent running?)
- Speed up through GPU support
- [Your enery loss model here]

First Science Results

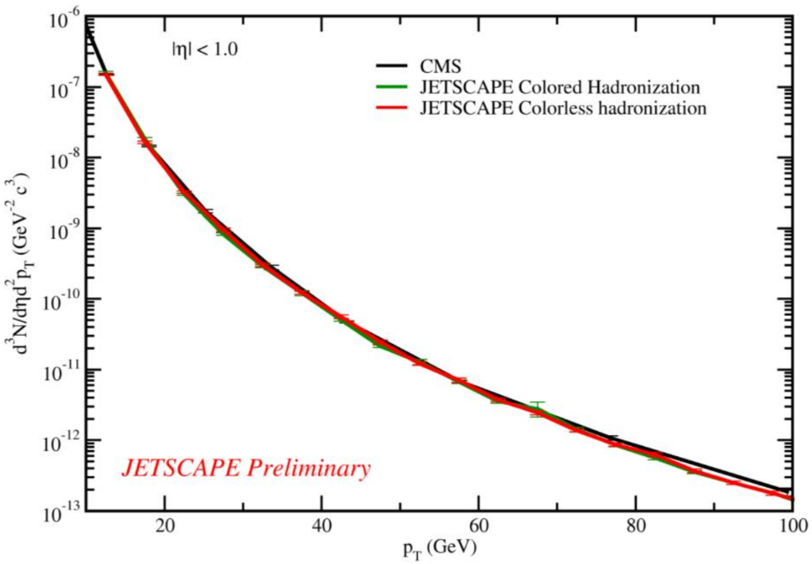
- p+p jet and high p_T results for tuning and validation
- Baseline for A+A!

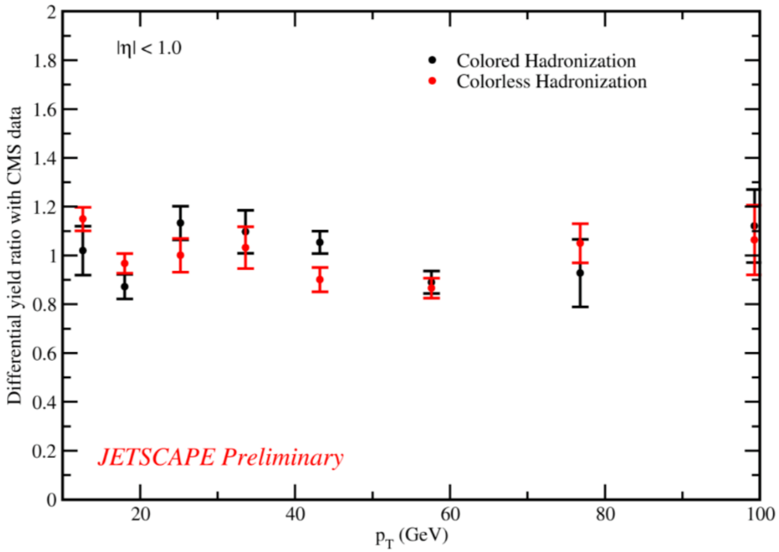
- p+p tests
  - PYTHIA 8 hard QCD process (+ISR +MPI)
  - MATTER final state shower
  - String fragmentation (again PYTHIA 8)

- Charged hadrons, 2.76 TeV compared to LHC results

First Science Results

- Charged hadrons, 2.76 TeV compared to CMS results



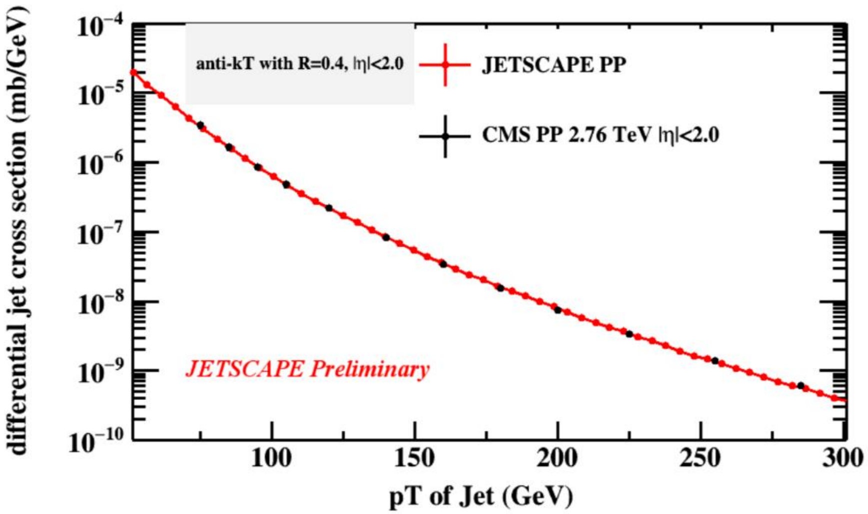


- Good agreement with data.

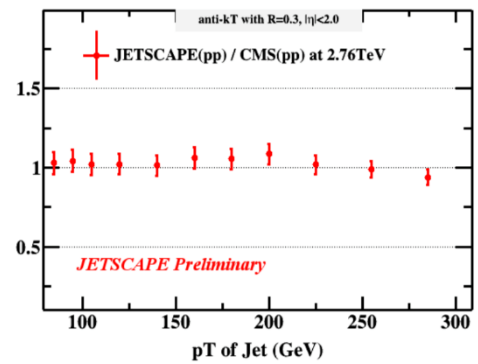
First Science Results

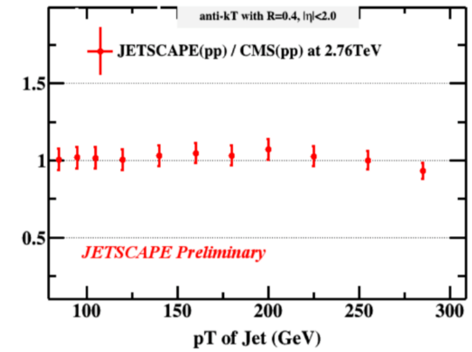
- Jets, 2.76 TeV compared to CMS results

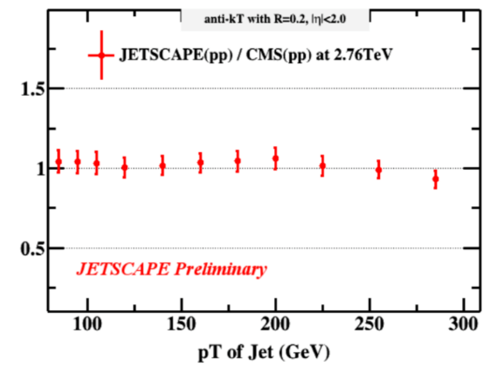
R=0.4



R=0.3





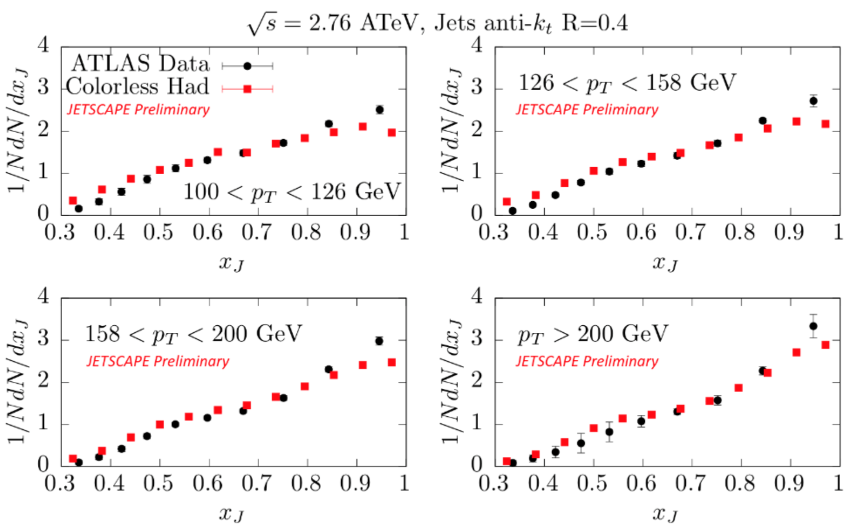


R=0.2

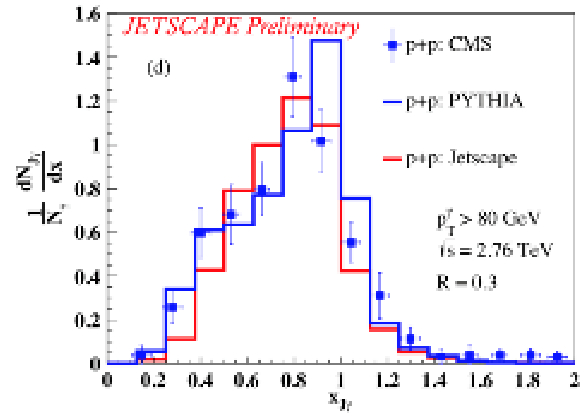
- Again good agreement with data.

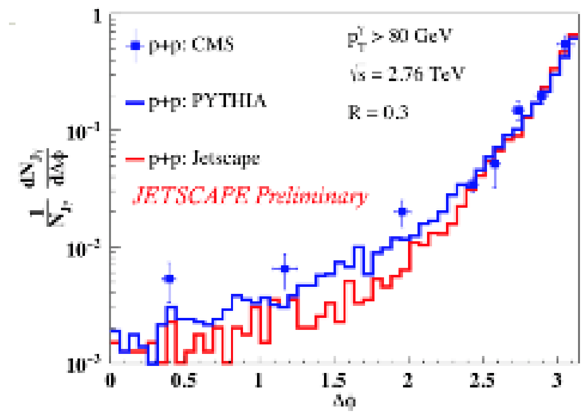
First Science Results

- x_j-distribution, 2.76 TeV, in dijets and photon-jet systems, compared to ATLAS and CMS results



Anti-k_T,
R=0.4
|η|<2.1

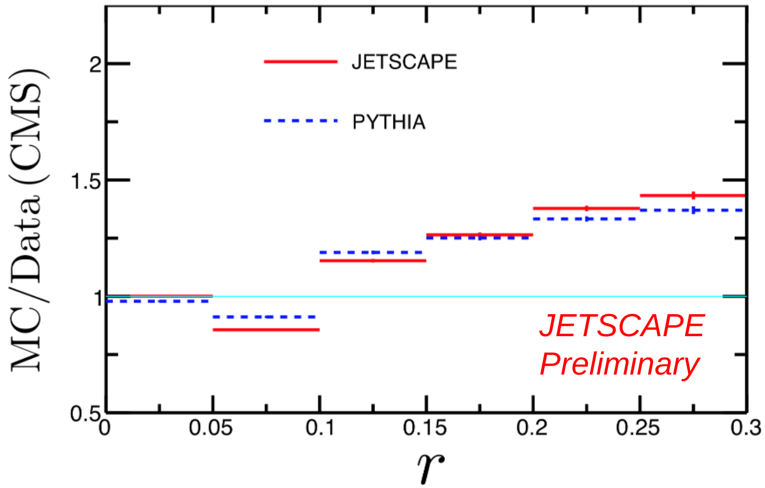


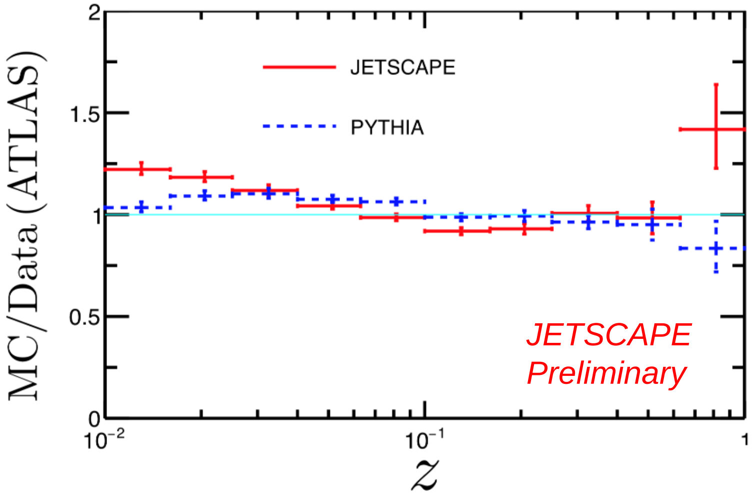


- Good agreement with data.

First Science Results

- Jet shape and jet fragmentation function, 2.76 TeV, systems, compared to



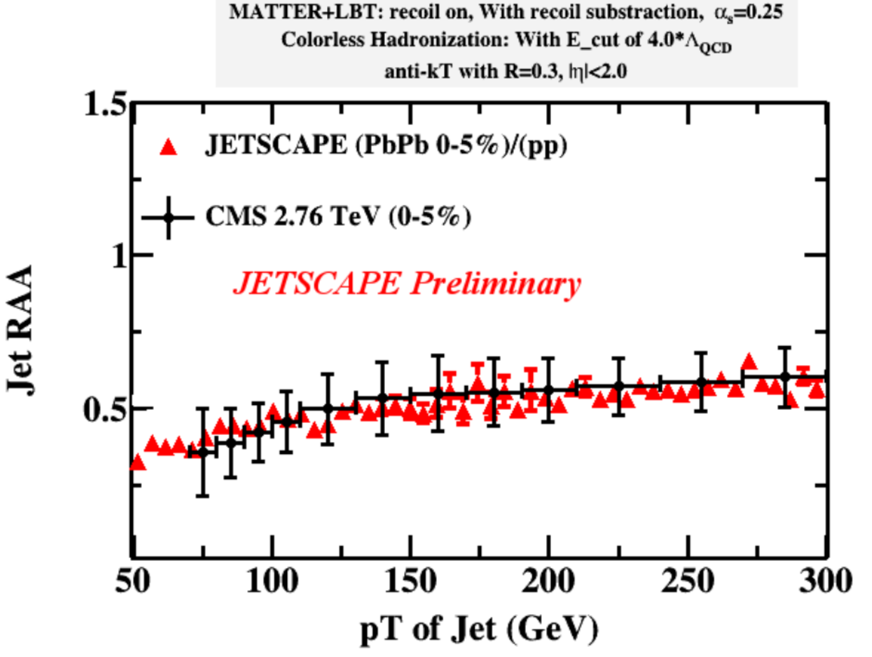


- Competitive with PYTHIA.

First Science Results

- Just a small selection of p+p results. Systematic study on the way, stay tuned.

- A+A hors'd oevre:



- Much more to come!

Summary

- We have developed an event-by-event hybrid hadronization module for jet Monte Carlos.
- Quark recombination including resonances, supplemented by string fragmentation.
- Medium effects by sampling hydro event-by-event.

- Current v2.2: hadronize full events in p+p; add thermal medium
- New v3.0 under development for the JETSCAPE framework.

- JETSCAPE 1.0 is available.

Backup

Recombination Step

- Parameters (harmonic oscillator WF case)

TABLE I. Table of measured charge radii R (from Ref. [21]), widths σ_M (and σ_B), and statistical factor g for all hadrons used in this calculation.

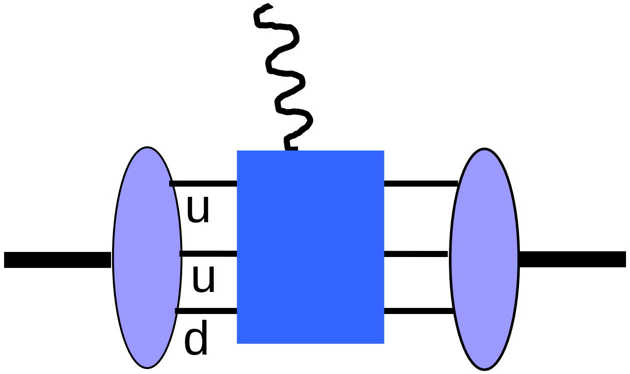
Hadron	R [fm]	σ_M (and σ_B) [fm]
π	0.67	1.09
ρ	–	1.09
K	0.56	1.10
K^*	–	1.10
N	0.88	1.24
Δ	–	1.24
Λ	–	1.15

Quark Recombination

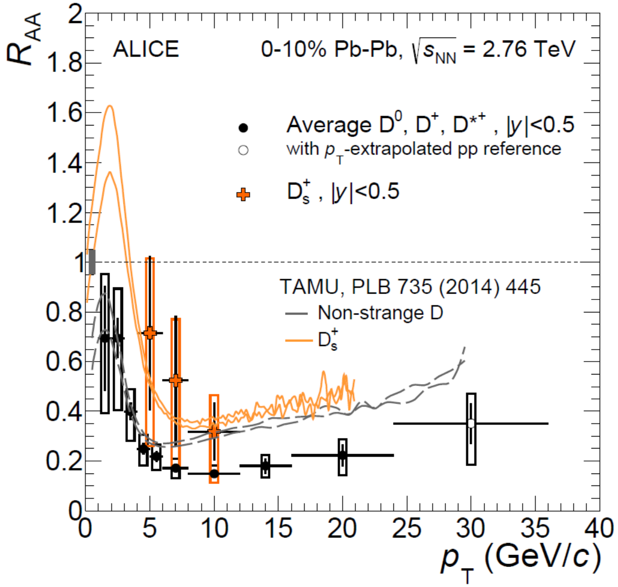
- Exclusive processes: recombination of all beam partons:

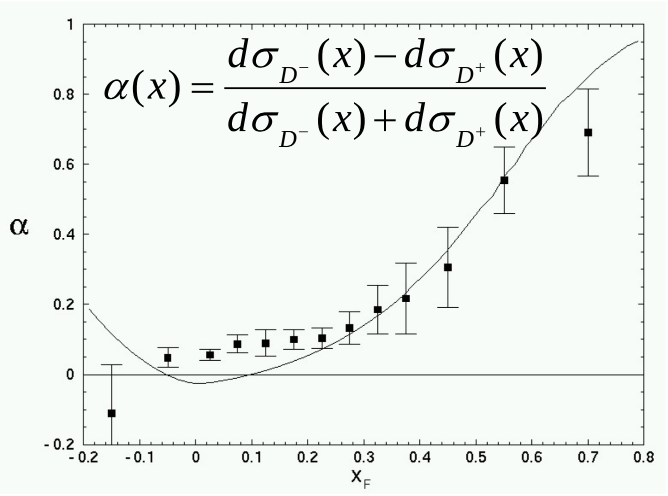
$$\psi \sim \langle 0 | u_\alpha u_\beta d_\gamma | P \rangle$$

- Leading particle effect: recombination of produced partons with beam partons



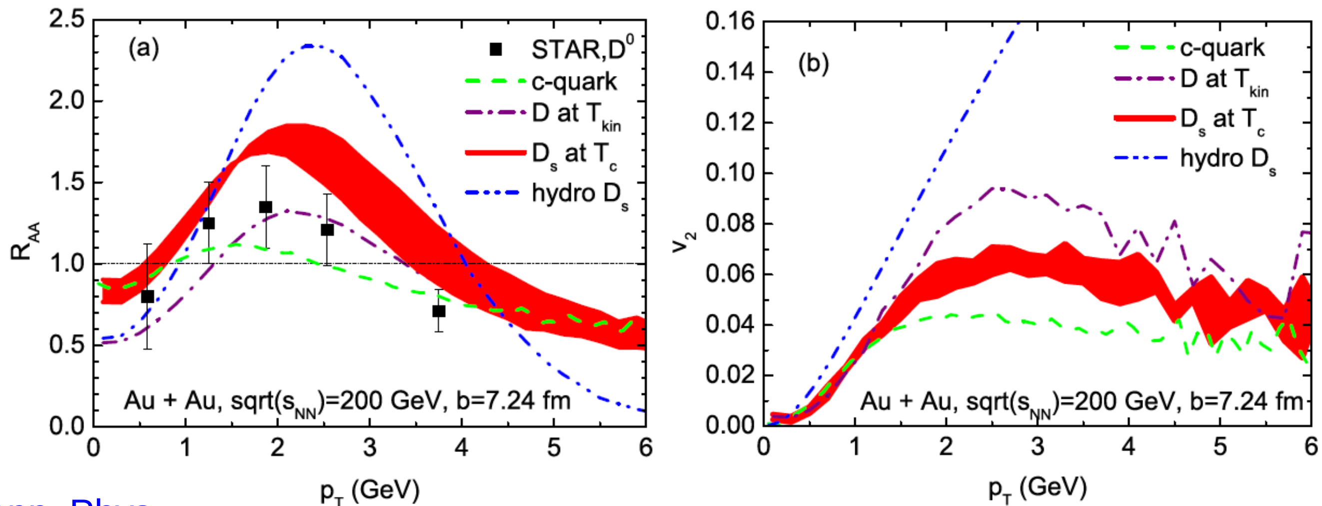
- Charm-strange correlations in heavy ion collisions: strangeness enhancement seen in D_s.





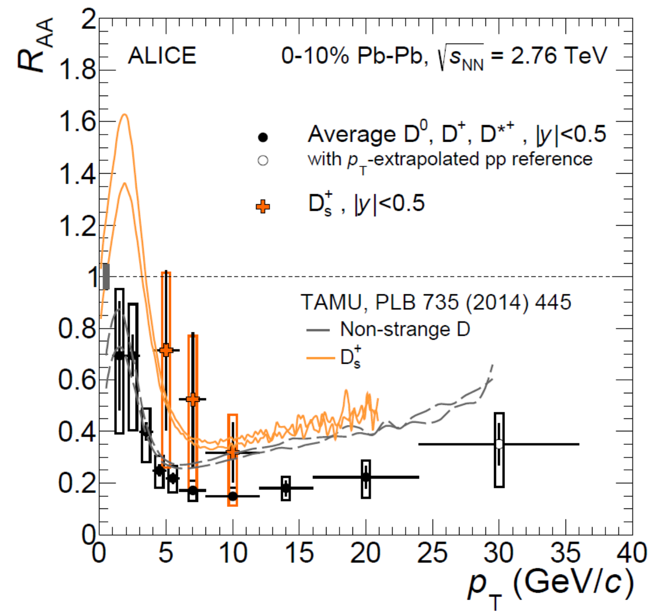
The D_s as a Signature

- RHIC:



[M. He, RJF and R. Rapp, Phys. Rev. Lett 110, 112301 (2013)]

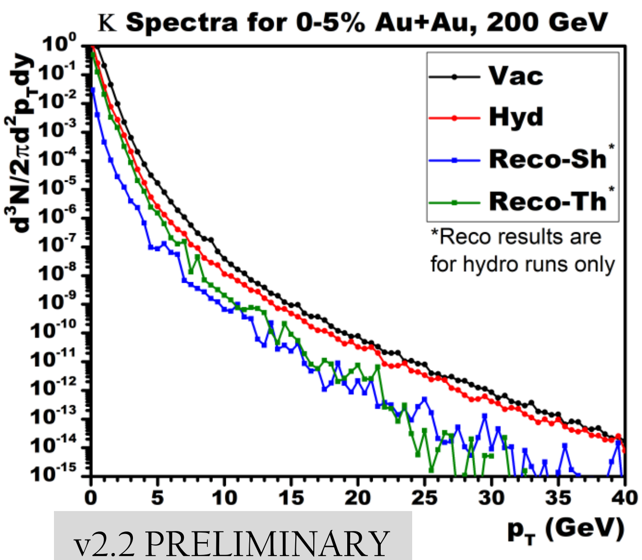
- LHC:



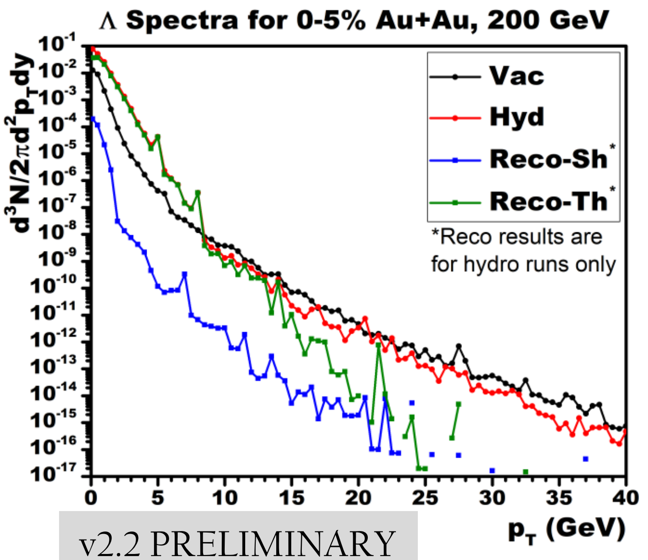
- D_s enhancement seen but not yet statistically significant

NEW: v2.2 Results With Medium

- v2.2: in-medium MATTER showers in hydro background; partons propagated to the $T=T_c$ hypersurface if Q0 is reached inside QGP.



v2.2 PRELIMINARY



v2.2 PRELIMINARY