Jet Modifications in the RHIC and LHC Era
Wayne State, August 19, 2014

Hadronization for Jet Showers MCs

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Outline

- In-medium hadronization
- String and Cluster Hadronization
- The JET Jet Recombination Formalism
- Outlook: application to in-medium shower MCs
- Summary

Hadronization of Jet Showers

- JET goal related to NSAC Performance Measures: *Complete realistic calculations of jet production in a high energy density medium for comparison with experiment.* (DM7)
  - This includes chemical composition
  - We will need jet-shower MC with in-medium hadronization

- Well-established hadronization models for vacuum shower Monte-Carlo's
  - Lund string fragmentation
  - Cluster hadronization
- How to generalize to jets in a medium?

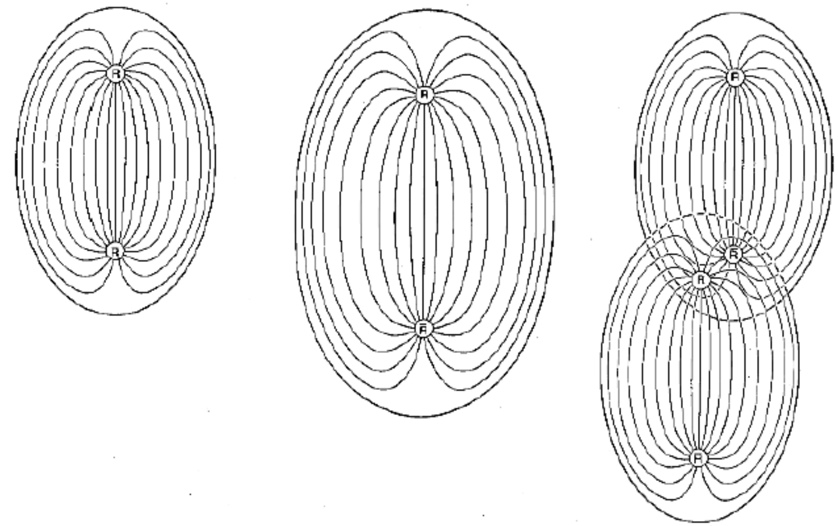
- New kid on the block: recombination
  - some early work on vacuum showers.

    [R. Migneron, M. E. Jones, K. E, Lassila, PLB 114, 189 (1983)]
    [R.C. Hwa and C.B. Yang, PRC 70, 024904 (2004); 024905 (2004)]

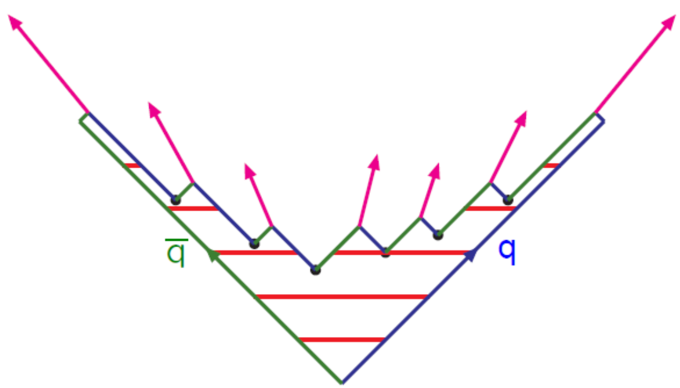
  - Challenge: get vacuum fragmentation right.
  - Medium effects in principle are straight forward to implement; does well with heavy ion single particle spectra.

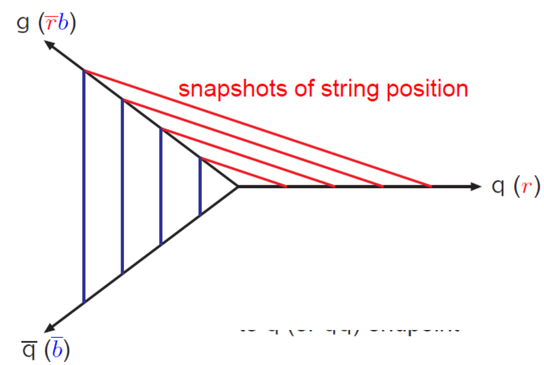
String Fragmentation

- String pictures of hadrons emerging in the early 70s



- Lund string model:
- Very successful in e+e-: JETSET → PYTHIA





- This is probably the most used hadronization model, also in HI jet MC.

String Fragmentation

- Very well tested ....

The Lund String

— a string that works —

[from a talk by T. Sjostrand]

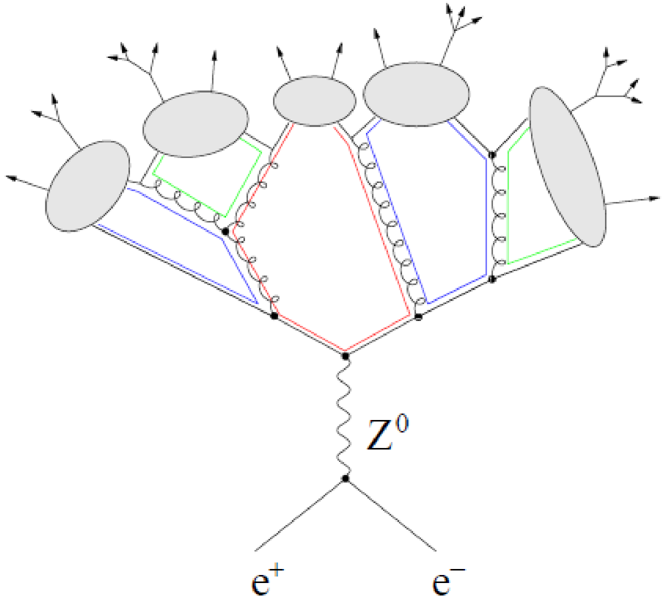
- ... to a point

Further numerous and detailed tests at LEP favour string picture . . .
. . . but much is still uncertain when moving to hadron colliders.

[from the same talk by T. Sjostrand]

Cluster Fragmentation (HERWIG)

- Force gluon decays into quarks and antiquarks.
- Local color neutrality: q-qbar form colorneutral clusters.
- Clusters decay isotropically into 2 hadrons which can decay further into stable hadrons.
- Quite a few similarities if compared to recombination.



[Webber, Marchesini]

Comparison

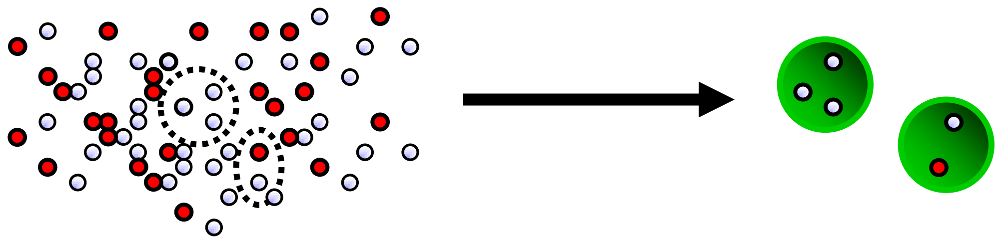
program	PYTHIA	HERWIG
model	string	cluster
energy–momentum picture	powerful	simple
	predictive	unpredictive
parameters	few	many
flavour composition	messy	simple
	unpredictive	in-between
parameters	many	few

"There ain't no such thing as a parameter-free *good* description"

[T. Sjostrand]

Recombination in Jets

- Bulk hadronization: recombination is successful b/c of large phase space occupation.



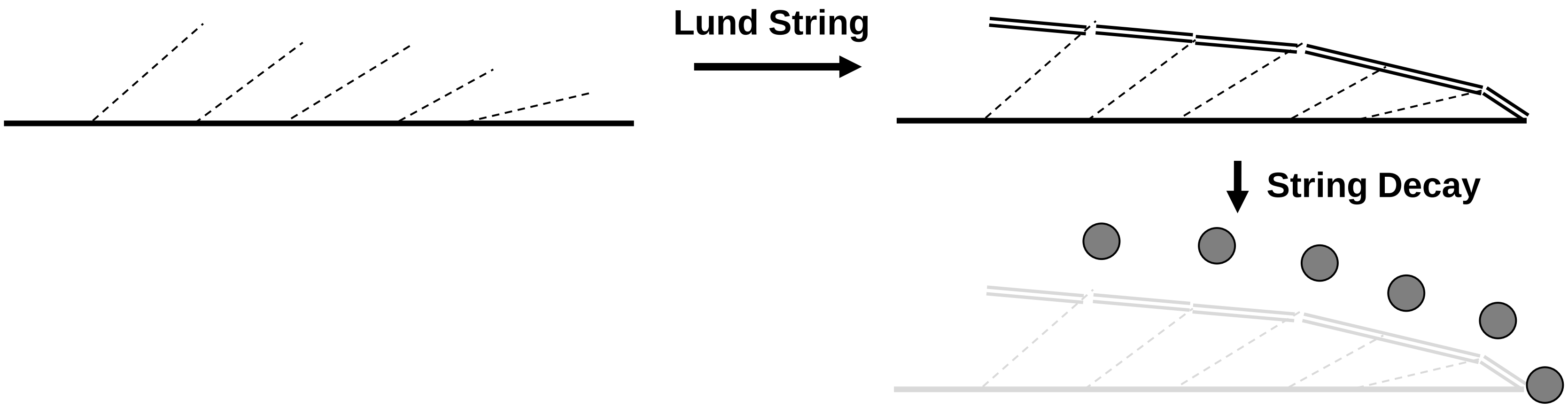
- Jets: ~10^1 quarks+antiquarks in a narrow phase space volume; quarks in the "jet bulk" (small *z*) might be packed close enough to recombine.
- This situation will improve dramatically if the jet is in a medium.

- Traditional: direct production of hadrons.
- Include resonances with decays: picture becomes similar to cluster fragmentation.

- Isolated quarks (not in the "jet bulk"): need for strings

Baseline: String Fragmentation (PYTHIA)

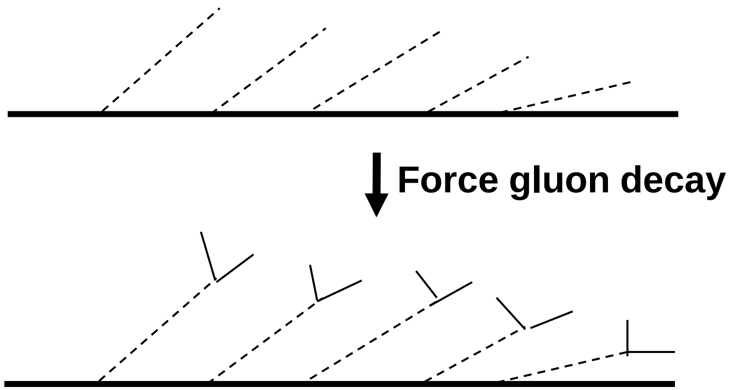
- Perturbative PYTHIA parton showers evolved to a scale Q_0.
- Standard PYTHIA Lund string fragmentation:



- Phenomenologically successful.
- Goal: reproduce main aspects of PYTHIA (string) hadron production with the recombination model.

Formalism (I): Prepare Shower

- Perturbative PYTHIA parton showers evolved to a scale Q_0.



- Decay gluons with remaining non-perturbative virtualities into quark-antiquark pairs.
- Isotropic decay in the gluon restframe.
- Decay chemistry (only up, down, strange quarks)

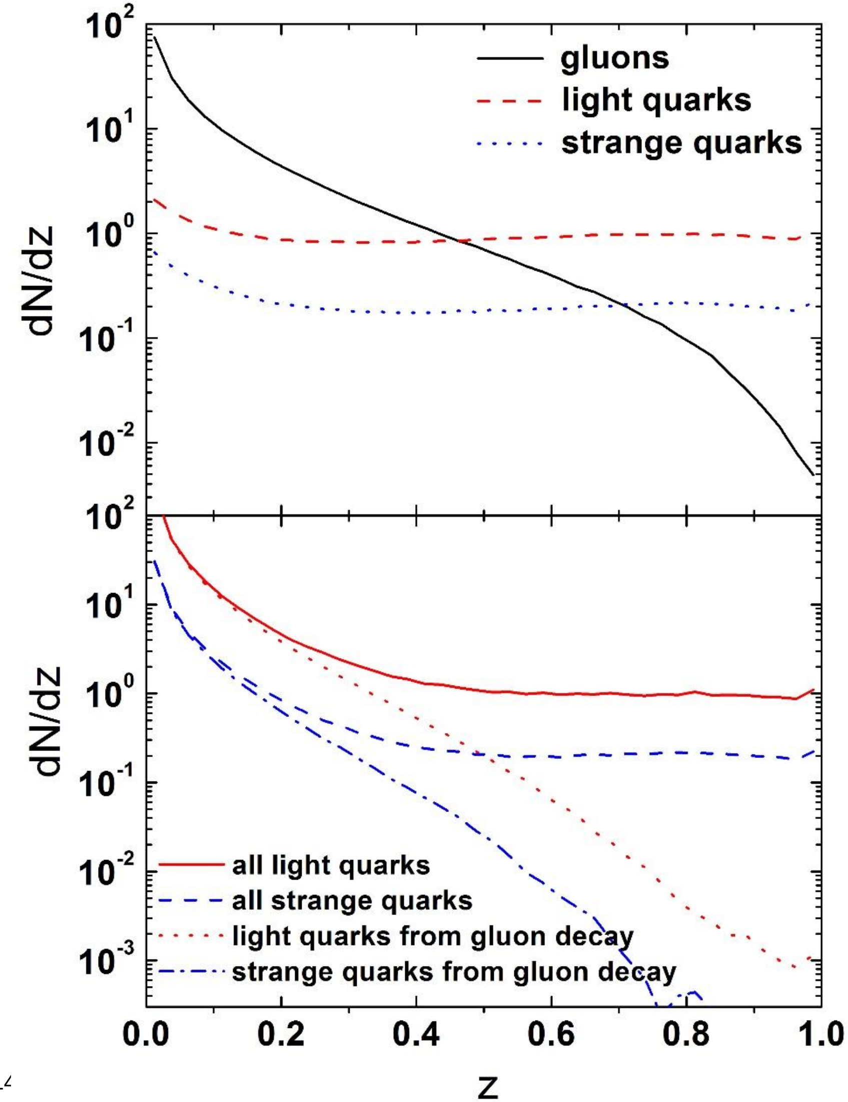
$$\frac{\Gamma(g^* \to u\bar{u}, d\bar{d})}{\Gamma(g^* \to s\bar{s})} = 2\frac{m^2 + 2m_{u,d}^2}{m^2 + 2m_s^2}\sqrt{\frac{m^2 - 4m_{u,d}^2}{m^2 - 4m_s^2}}$$

Formalism (I): Prepare Showers

- Example: Sample of 10^6 PYTHIA parton showers with E_{jet} = 100 GeV.

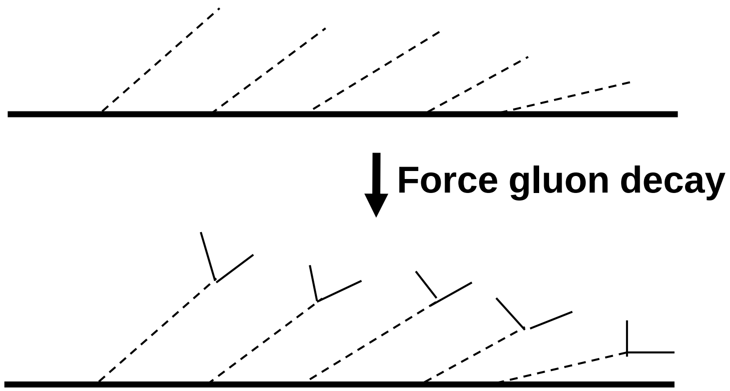
- *dN/dz* before vs after gluon decay

$$z = \frac{\mathbf{p} \cdot \mathbf{P}_{\rm jet}}{|\mathbf{P}_{\rm jet}|^2}$$



Formalism (II): Space-Time Evolution

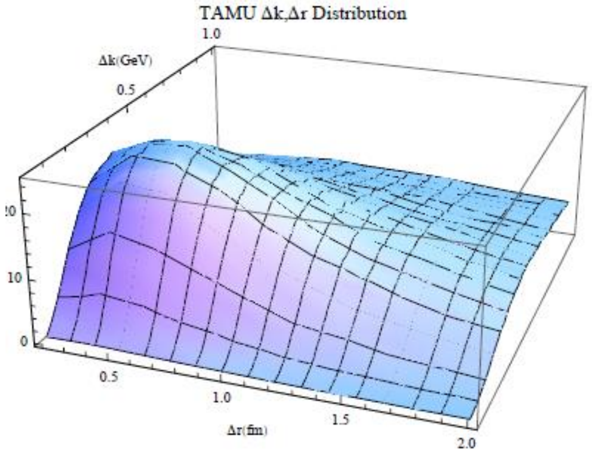
- Perturbative PYTHIA parton showers evolved to a scale Q_0.



- Track shower partons
- Assign average life time $\tau = 1/Q$ to partons with virtuality Q in their own restframe.
- Boost to lab frame to get average space-time points of birth of partons

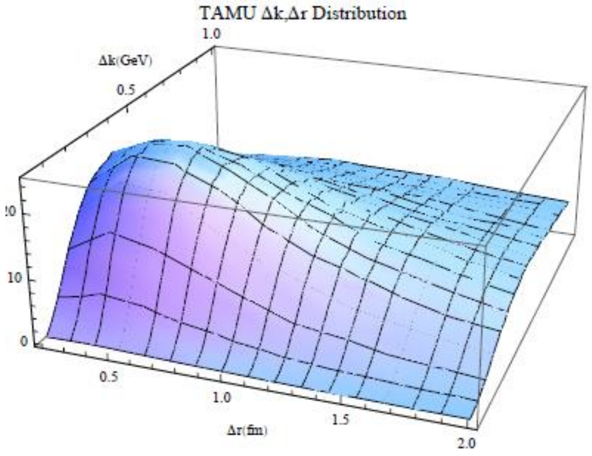
Phase Space Picture of Parton Showers

- Distance of quarks in phase space is the deciding factor for the success of recombination.
- Berkeley, WS and TAMU vacuum showers agree qualitatively!
- Thus: hadronization module should be able to work universally with minor tweaks.
- Plots: distribution of quark-antiquark distance in space (Δr) and momentum space (Δk) in the local rest frame of the pair.



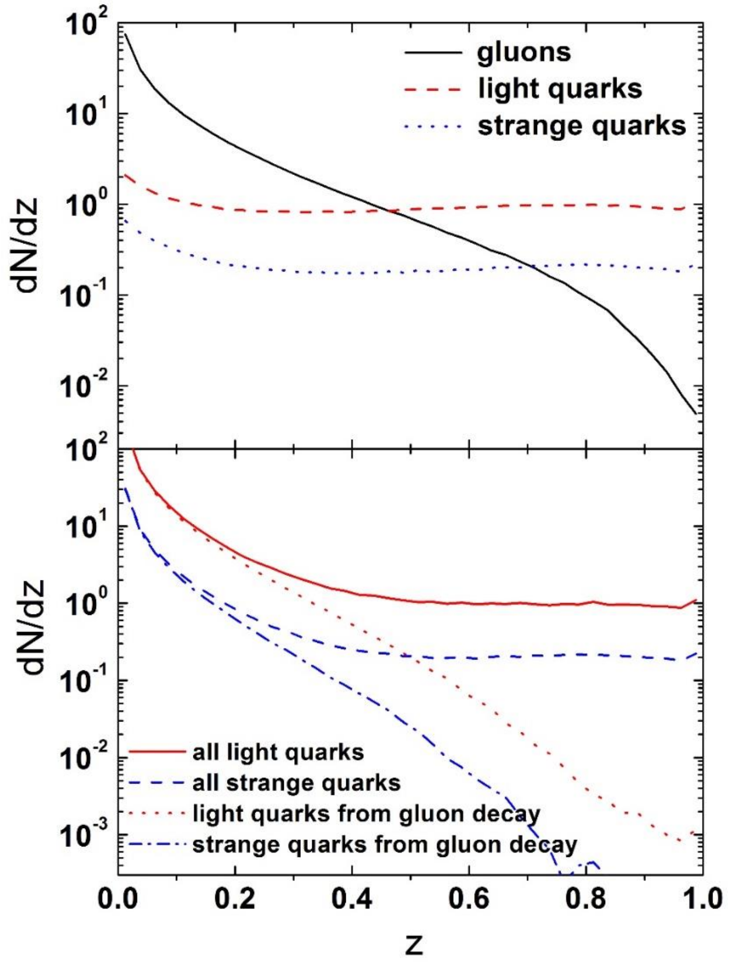
Phase Space Picture of Parton Showers

- Cuts in Δr-Δk space (light quark mesons):
- Δr ‹ σ: recombination; Δr › σ: strings
- For recombination (Δr ‹ σ):
  - Δk ‹ 1/ σ recombination into hadronic ground states
  - Δk › 1/ σ recombination into resonances and decay
  - M ~ Δk, (high mass resonances similar to clusters)

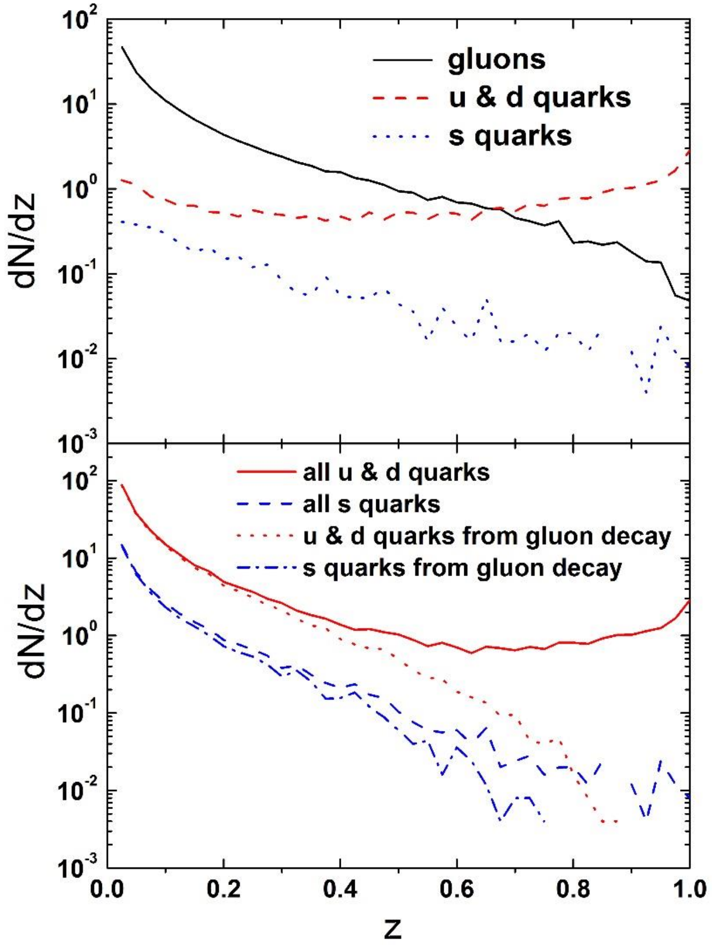


Global Picture of Parton Showers

TAMU PYTHIA

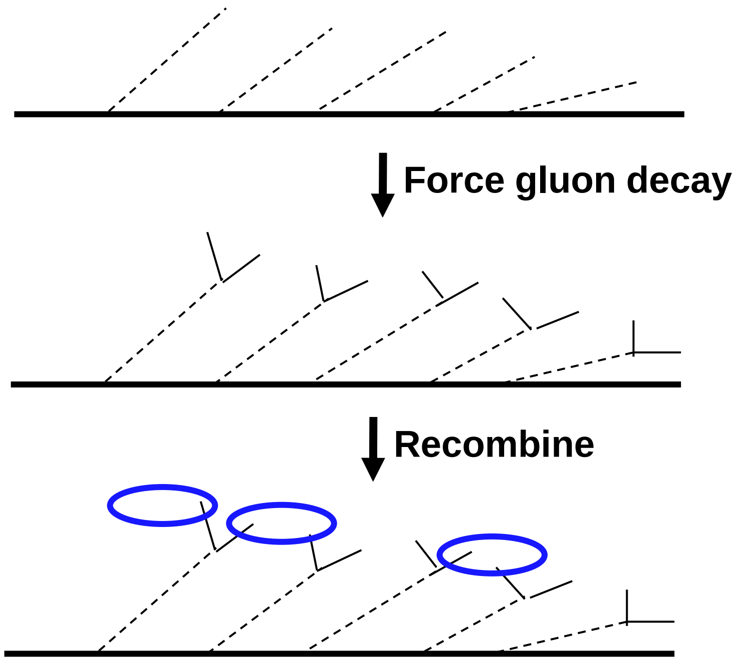


Majumder

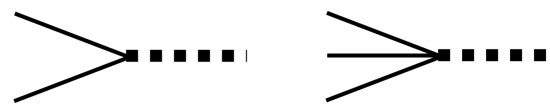


Formalism (III): Recombination

- Use a Monte Carlo version of the instantaneous recombination model by Greco, Ko and Levai.



- Projection of partons onto meson and baryon states, and resonances.
- Equivalent to $2 \rightarrow 1$, $3 \rightarrow 1$ processes



- But many of the recombined particles will be resonances $\rightarrow$ energy conserved.
- Process can be written in terms of Wigner functions.

Formalism (III): Recombination

- Meson (q-qbar) and baryon (3q, 3qbar) yields (and their resonances):

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

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

- Hadron & resonance Wigner functions: Inspired from harmonic oscillator potentials.
  - Gaussian WF available but here simple step functions: $\frac{9\pi}{2} d \frac{n+1}{2n^2} \theta(\sigma - y)\theta\left(\frac{n}{\sigma} - k\right)$
  - Evaluated at equal time in the pair or triplet rest frame.

- Relative coordinates

$$\mathbf{y}_1 = \frac{\mathbf{x}'_1 - \mathbf{x}'_2}{\sqrt{2}}, \qquad \mathbf{y}_2 = \frac{\mathbf{x}'_1 + \mathbf{x}'_2 - 2\mathbf{x}'_3}{\sqrt{6}},$$

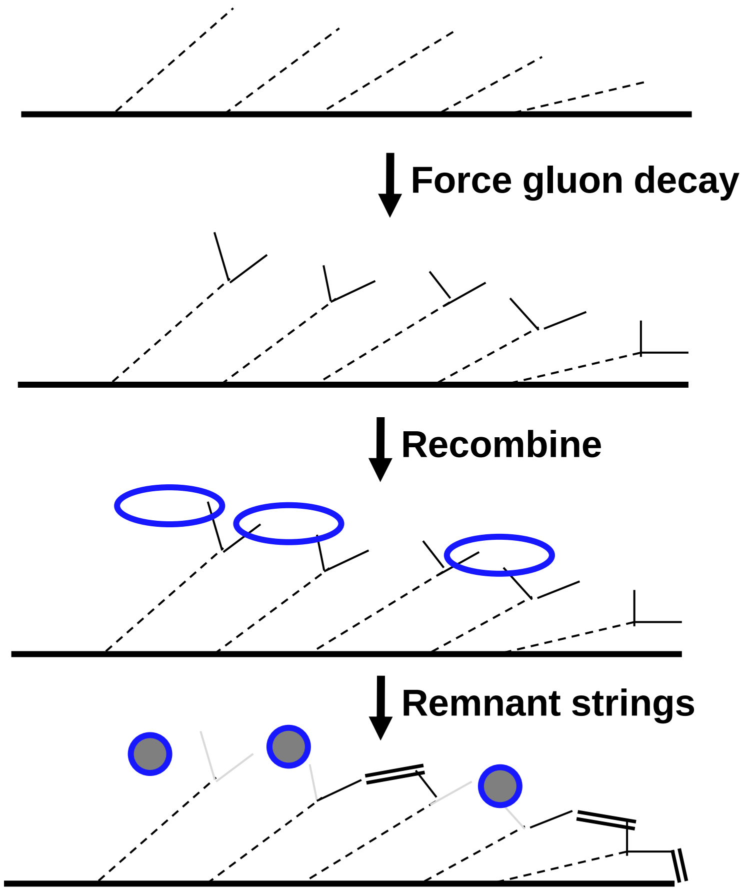
$$\mathbf{k}_1 = \frac{\mathbf{p}'_1 - \mathbf{p}'_2}{\sqrt{2}}, \qquad \mathbf{k}_2 = \frac{\mathbf{p}'_1 + \mathbf{p}'_2 - 2\mathbf{p}'_3}{\sqrt{6}},$$

Formalism (III): Recombination

- Quantum numbers treated statistically via statistical factors.
  - E.g. color factor $d = 1/9$ for q-qbar.
  - This underestimates probabilities to form color singlets for small systems (room for improvement).
- WF parameters physically motivated (but they can be tuned within limitations).
  - Current results done with $\sigma = 1$ fm
- Resonances and their decays are important (~ clusters)
- Recombination probabilities evaluated in the hadron rest frame.
- Throw dice to determine whether recombination happens.

Formalism (III): Remnant Strings

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



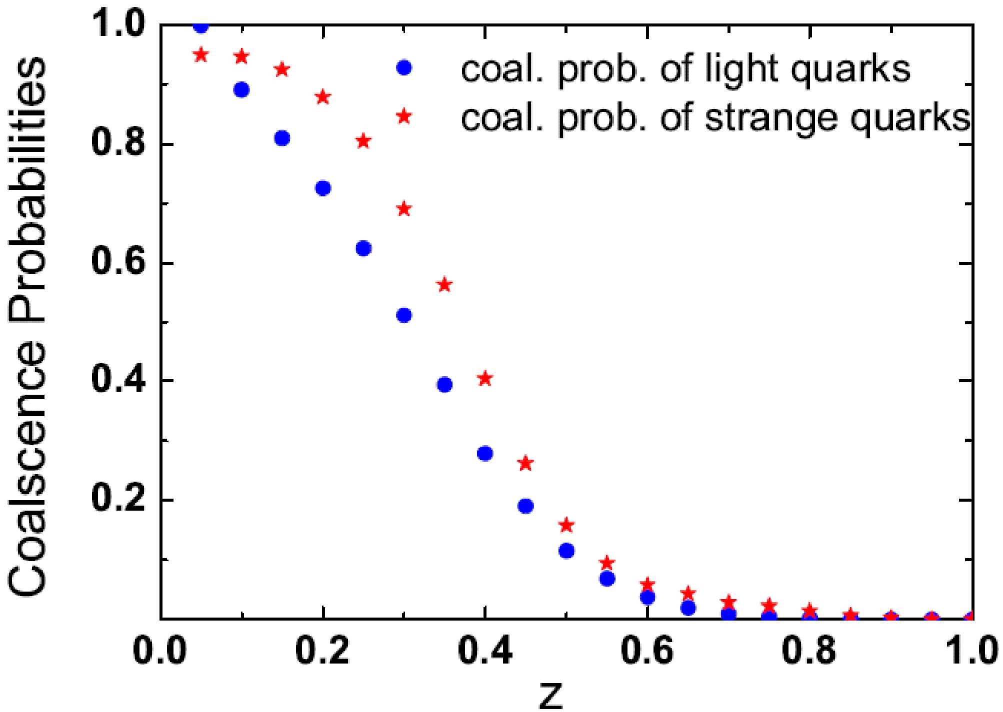
- Why? No confinement in parton shower, quarks can get far away.
- In reality: colored object needs to stay connected.
- Return these partons to PYTHIA to connect them with remnant strings.

Formalism (III): Remnant Strings

- "Bulk" low-*z* quarks like to recombine.

- Lonely high-*z* quarks like to fragment.

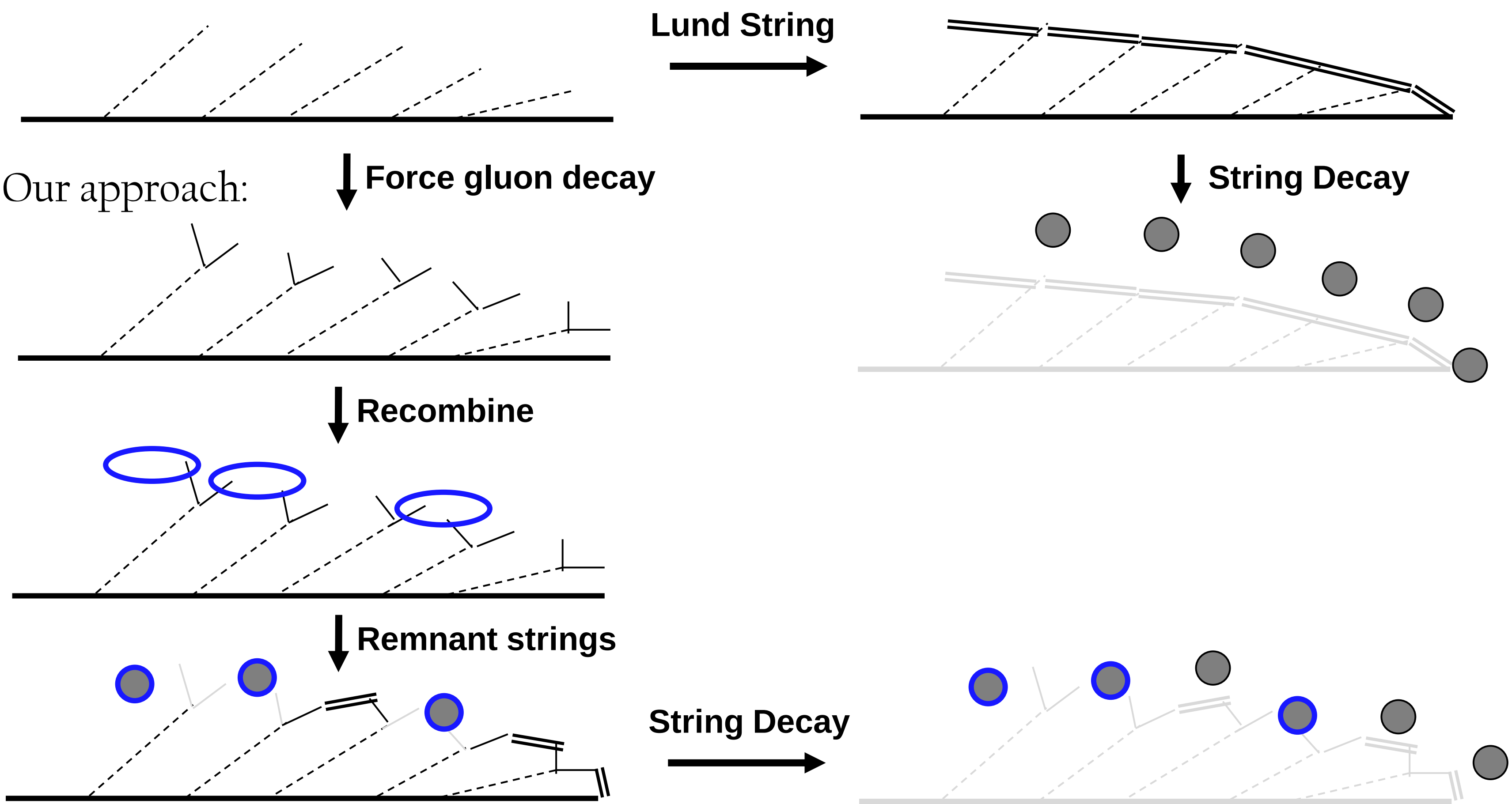
→ High–*z* part of the jet guaranteed to hadronize as in the vacuum.



TREC v0.1
100 GeV jets

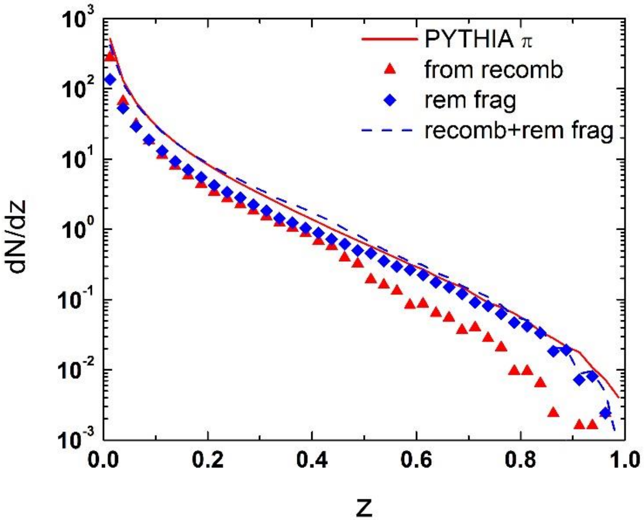
Model Summary

- We replaced string fragmentation in the jet "bulk" by recombination.
- Standard PYTHIA Lund string fragmentation:
- Our approach:

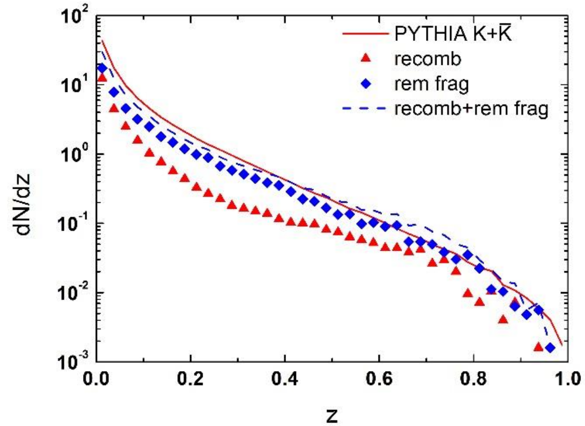


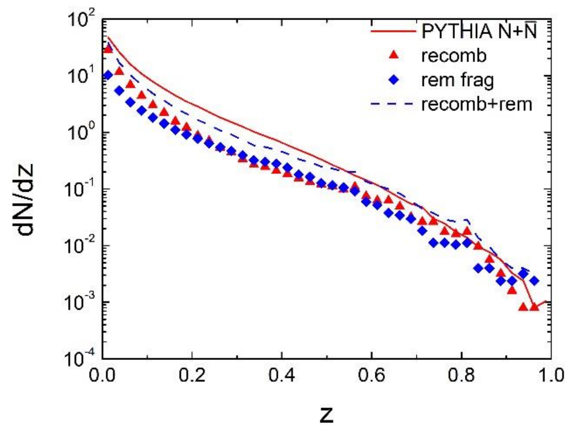
Results and Comparison: Longitudinal

- Longitudinal structure: *dN*/*dz* of stable particles compared to PYTHIA string frag



- Good results for pions
- Ok for K, N, but need more resonance decays (e.g. ϕ-like→KK)





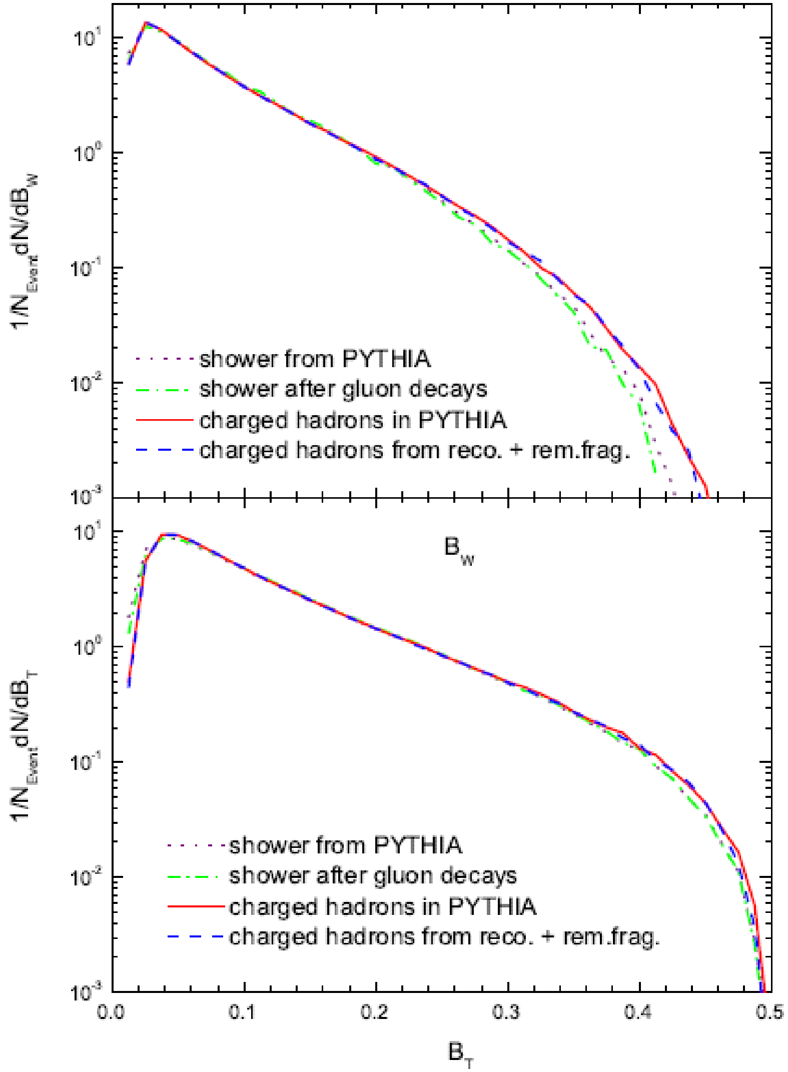
TREC v0.2
100 GeV jets

Results and Comparison: Transverse

- Transverse structure: Jet Broadening

$$B_k = \frac{\sum_{i \in H_k} |\boldsymbol{p}_i \times \boldsymbol{n}_\mathrm{T}|}{2 \sum_i |\boldsymbol{p}_i|} \ .$$

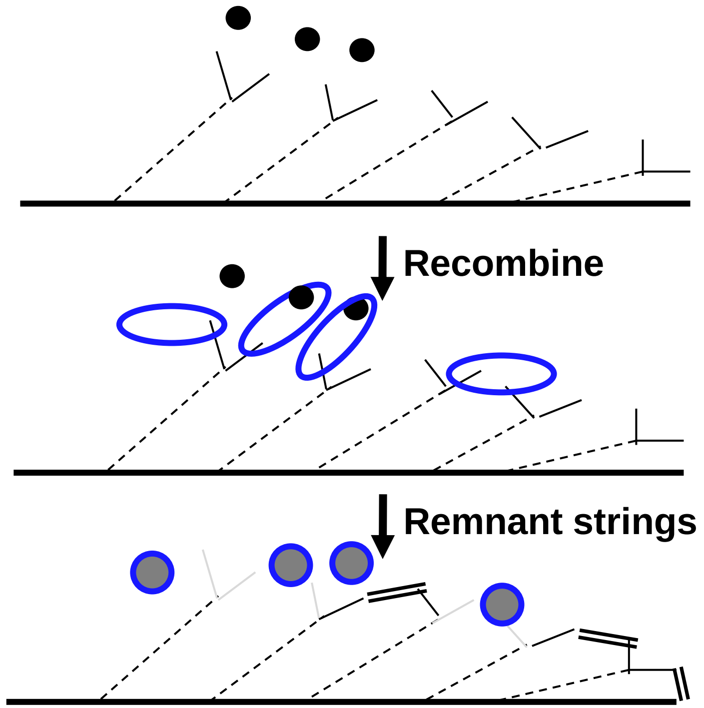
- Little difference between PYTHIA parton and hadron (string fragmentation) showers.
- Our shower recombination reproduces PYTHIA results.



TREC v0.1; 100 GeV light quark jets in $e^+ + e^-$

Adding Medium Partons

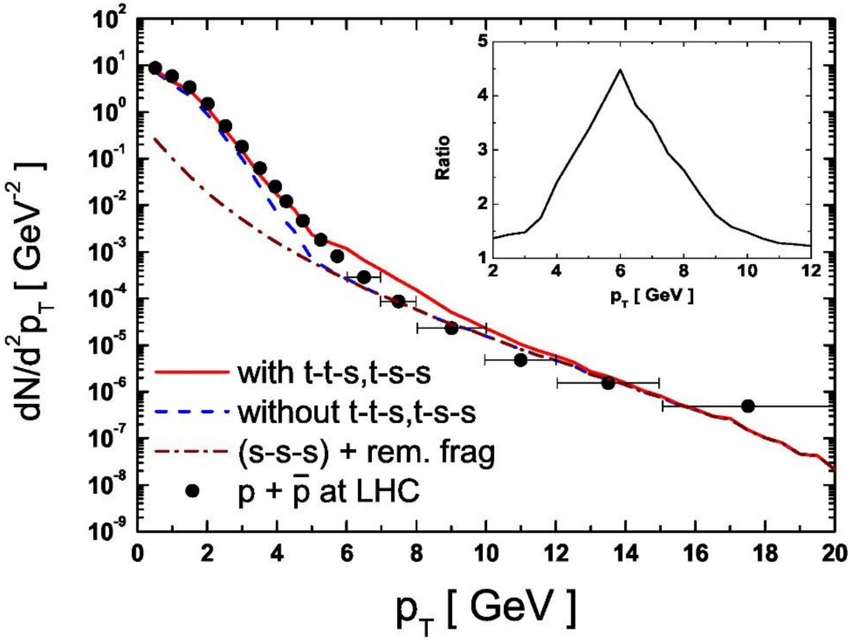
- Sampling thermal partons from a blastwave models or hydro.
- Allow recombination of shower partons with thermal partons.

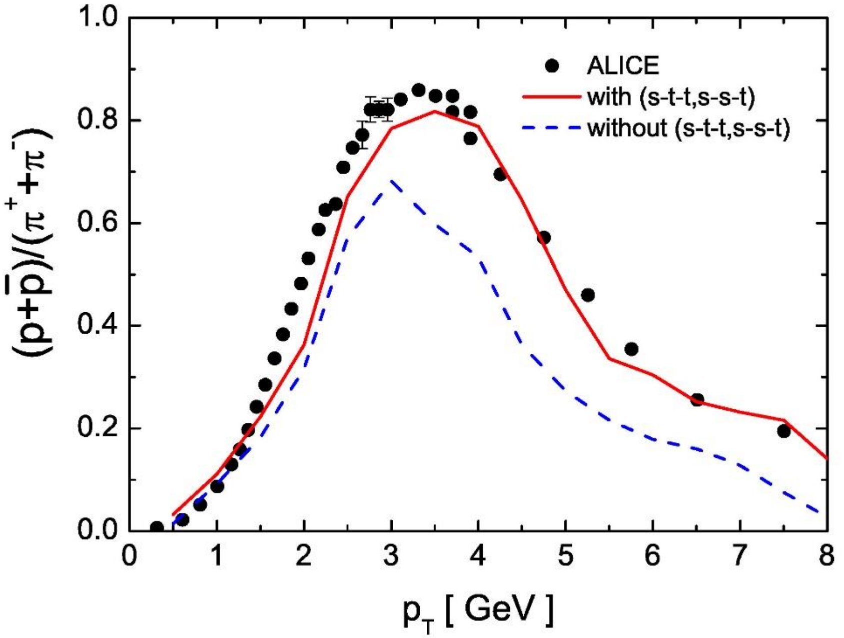


Shower-Thermal Recombination

- Study with blast wave model to study the role of shower-thermal recombination.
- Here: Protons at LHC.

TREC v0.1





- Baryon production enhanced.

Summary

- Jet recombination model is up and running.

- Inspiration from both string and cluster fragmentation
- High-*z* part explicitly uses string fragmentation.

- Knobs for fine tuning:
  - strange/light quark ratio at gluon splitting
  - Confinement size σ (separation of recombination/string domain)
  - Resonance decay channels

- Working currently with LBNL and WS shower MC to get good vacuum results.

Summary

- How to test? Any comparison to experiment is also (or mainly?) a test of the underlying shower MC.
- Even vacuum shower MC agree only qualitatively, not quantitatively.
- Question: are there good observables we should look at?

	String	Cluster	Recombination
Gluons	Kinks	Forced decay	Forced decay
Large separation quarks	String breaking	Clusters	String Breaking
Small separation quarks, low mass	Indirectly from string breaking	Clusters	Direct recombination
Small separation quarks, high mass	Indirectly from string breaking	High mass cluster	Resonance