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A Hybrid Hadronization Model

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JETSCAPE

NSF

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Overview

- Introduction and motivation
- The Hybrid Hadronization model
- Including a medium
- Matching to jet MCs and JETSCAPE

Hadronization Models

- We propose a new kind of hadronization model: a hybrid of existing models.
  - String fragmentation
  - Quark recombination

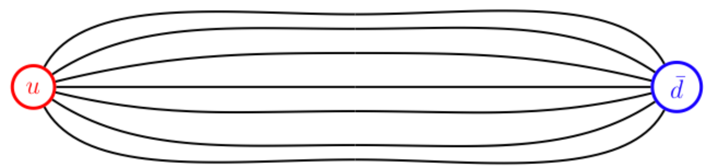
- Goal: extrapolate smoothly between successful vacuum phenomenology of string fragmentation and hadronization in a thermal environment. Focus on hadronization of parton showers/jets.

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

- More recently: modification of hadronization even in small systems?

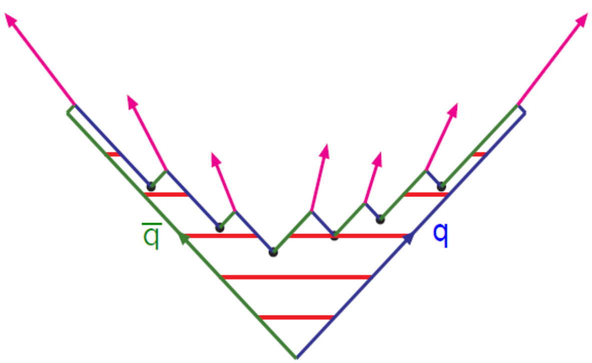
String Fragmentation

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



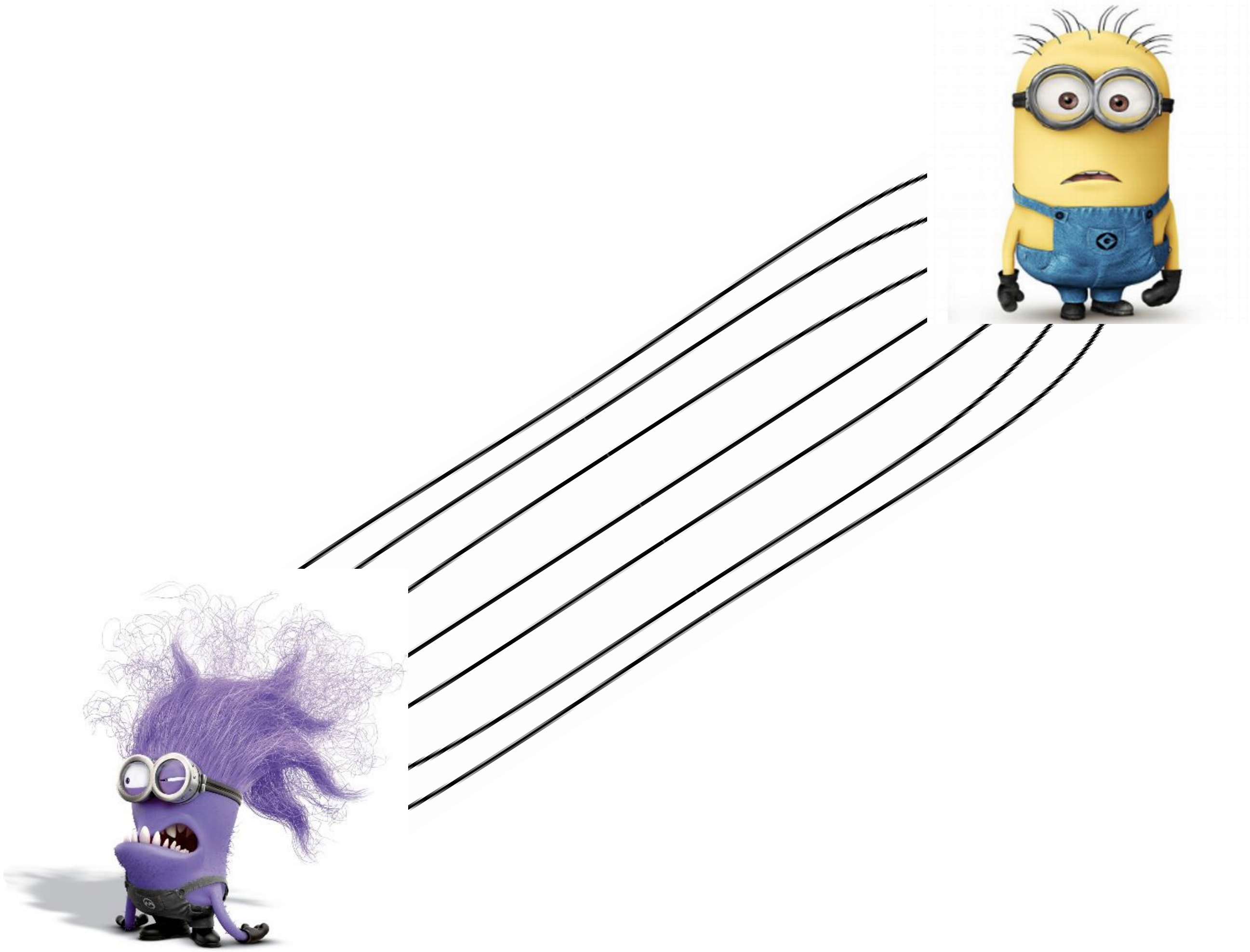
- Lund string fragmentation picture
- Successful phenomenology starting at PETRA, LEP, … → PYTHIA

- Here: we will use default PYTHIA string fragmentation.

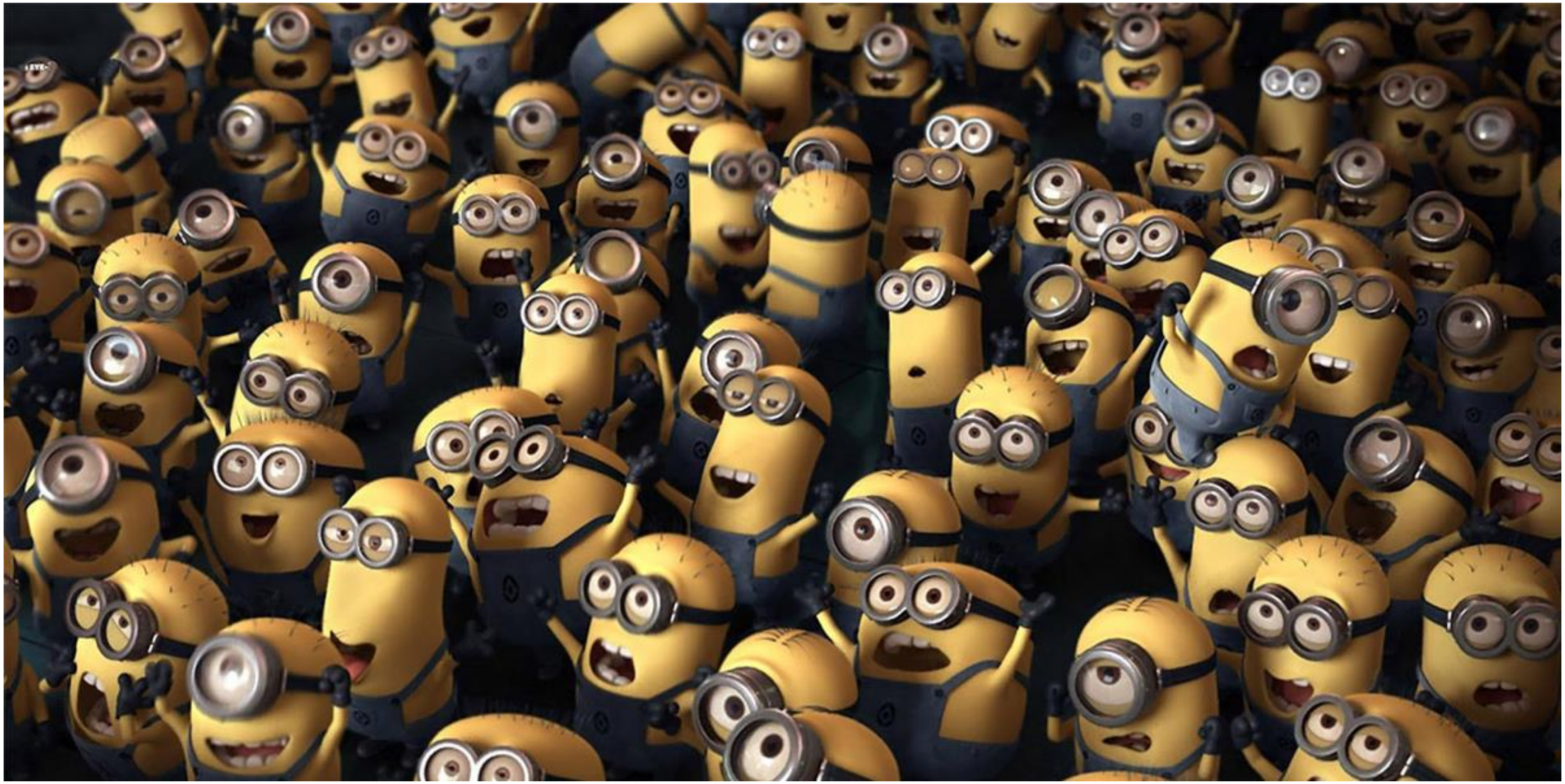


Hadronization!

Hadronization!

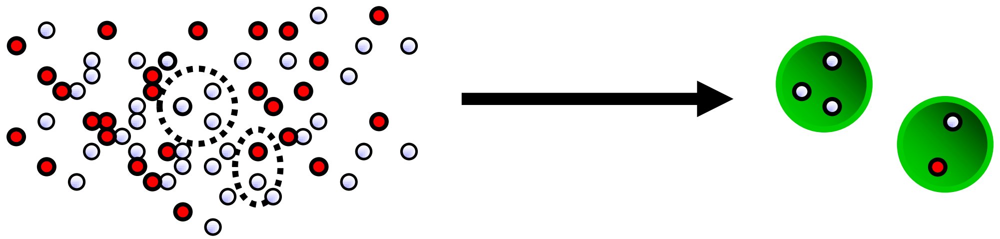


Hadronization?



Quark Recombination

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

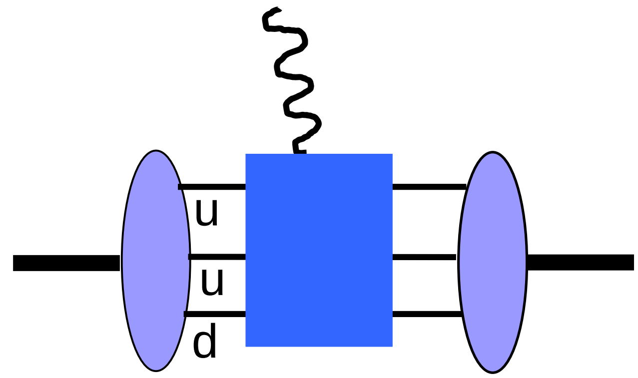


- Qualitatively similar to recombination in atomic physics.
- Here: instantaneous recombination of constituent quark-like partons to stable hadrons and resonances.
- Recombination models started in the 70s, were only successful in niches:
  - Exclusive processes
  - Leading particle effect
  - Since 2000: heavy ion physics

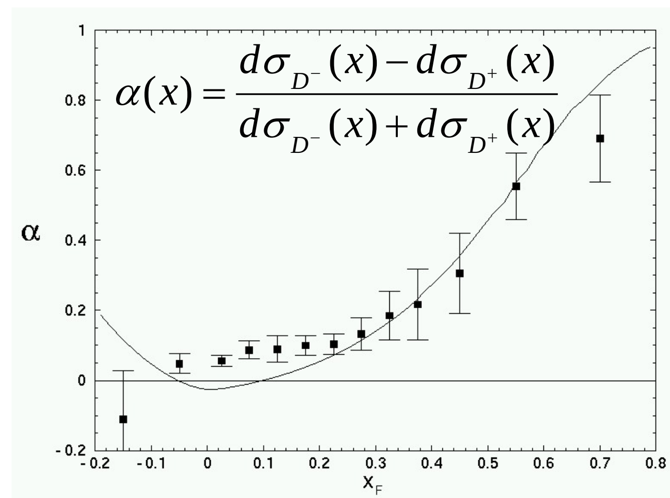
Quark Recombination

- Exclusive processes: recombination of all beam partons:

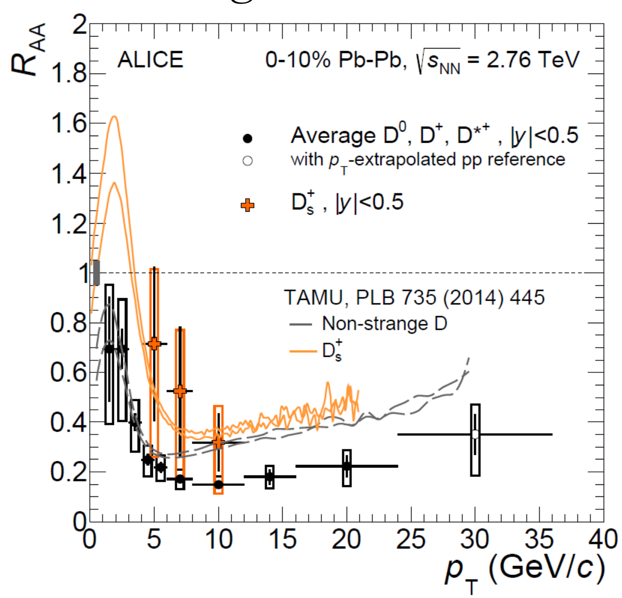
$$\psi \sim \langle 0 | u_\alpha u_\beta d_\gamma | P \rangle$$



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

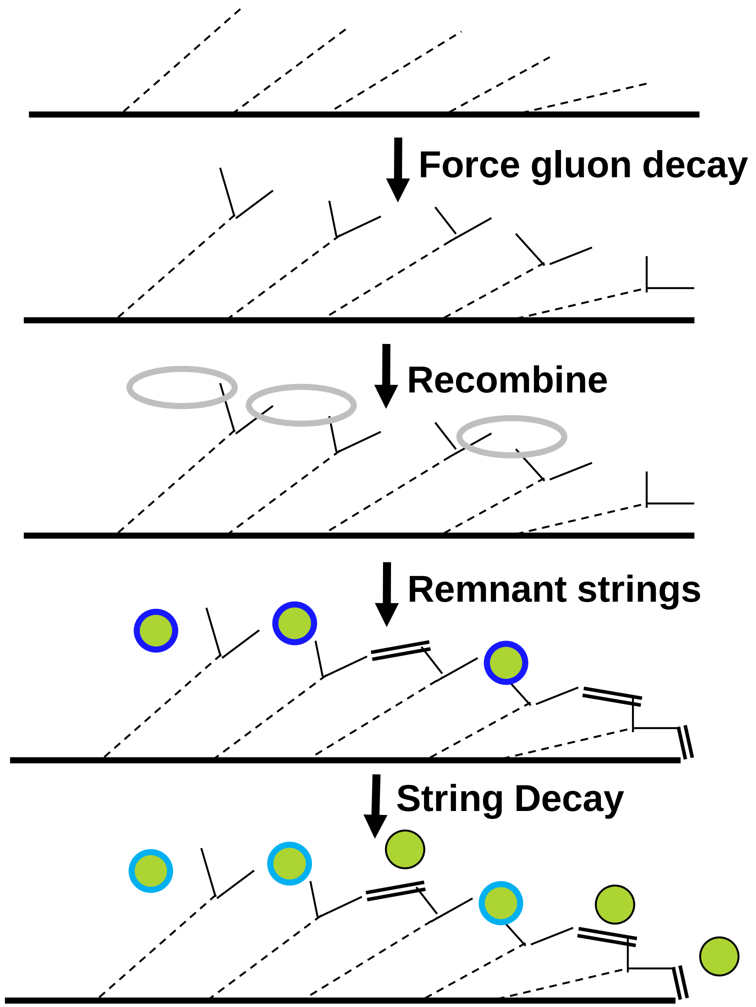


- Charm-strange correlations in heavy ion collisions: strangeness enhancement seen in D_s.



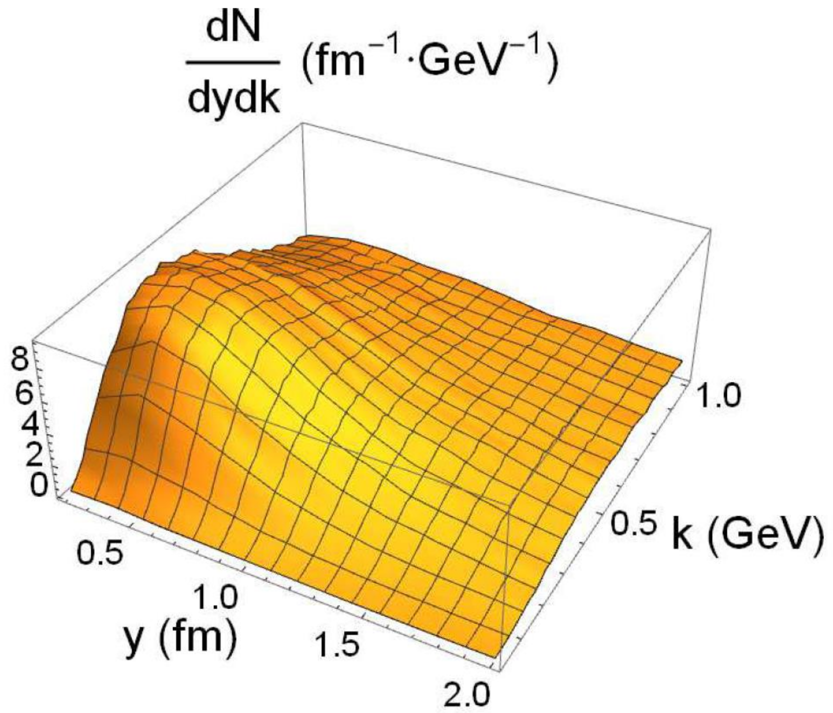
Input: Parton Shower

- For illustration: single jet.
- Perturbative parton showers evolved to a scale Q_0.
- Decay gluons with remaining virtualities into quark-antiquark pairs.



How Dense are Parton Showers?

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

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

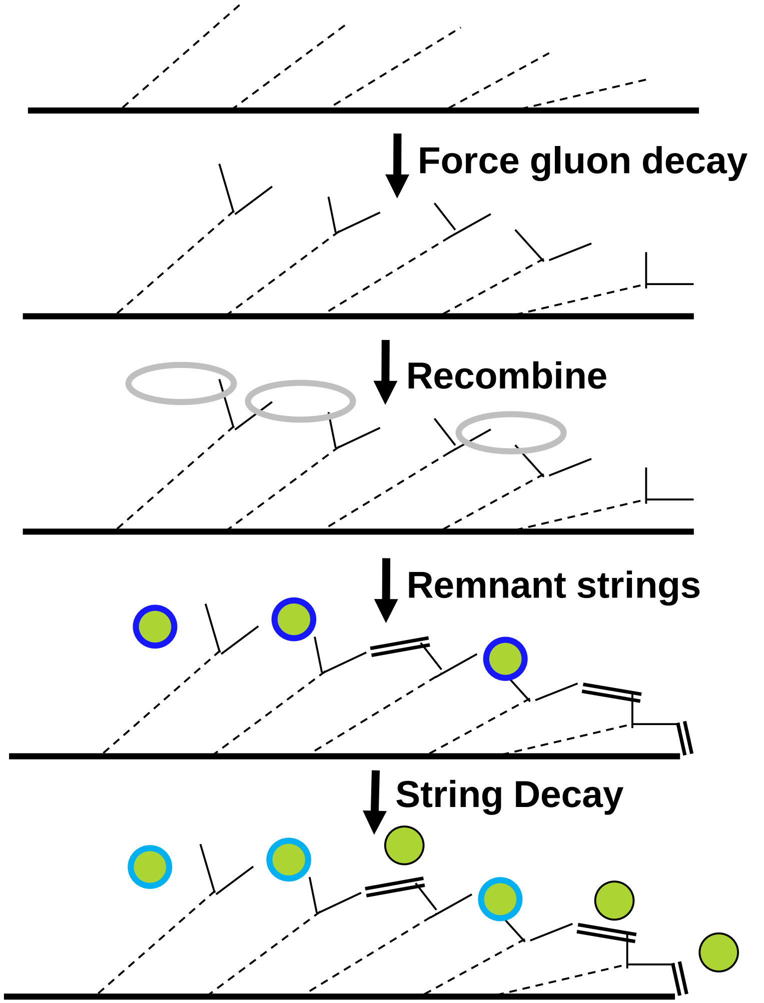
$$\overline{W}_{M,n}(\mathbf{y},\mathbf{k}) = \frac{v^n}{n!} e^{-v} \qquad v = \frac{1}{2}\left(\frac{\mathbf{y}^2}{\sigma_M^2} + \mathbf{k}^2 \sigma_M^2\right)$$

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

Recombination Step

- Monte Carlo implementation:
- Evaluate recombination probability for q-qbar pairs and q (qbar) triplets.
- Roll dice to decide if recombination happens.

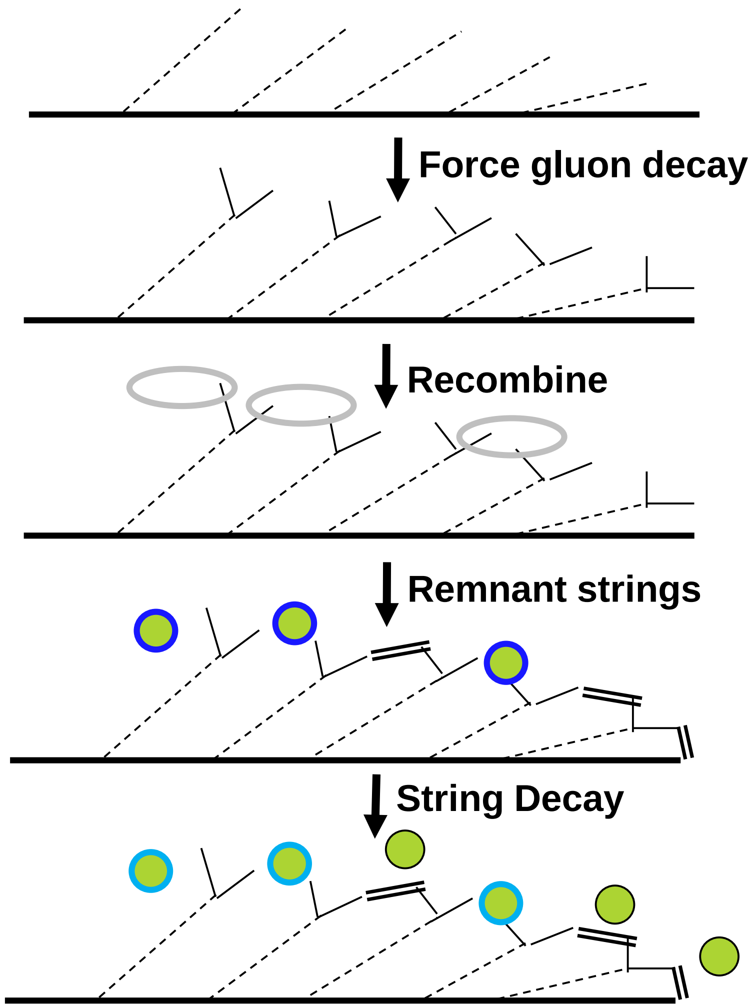
- Recombine into stable hadrons and resonances, let resonances decay



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

Remnant Strings

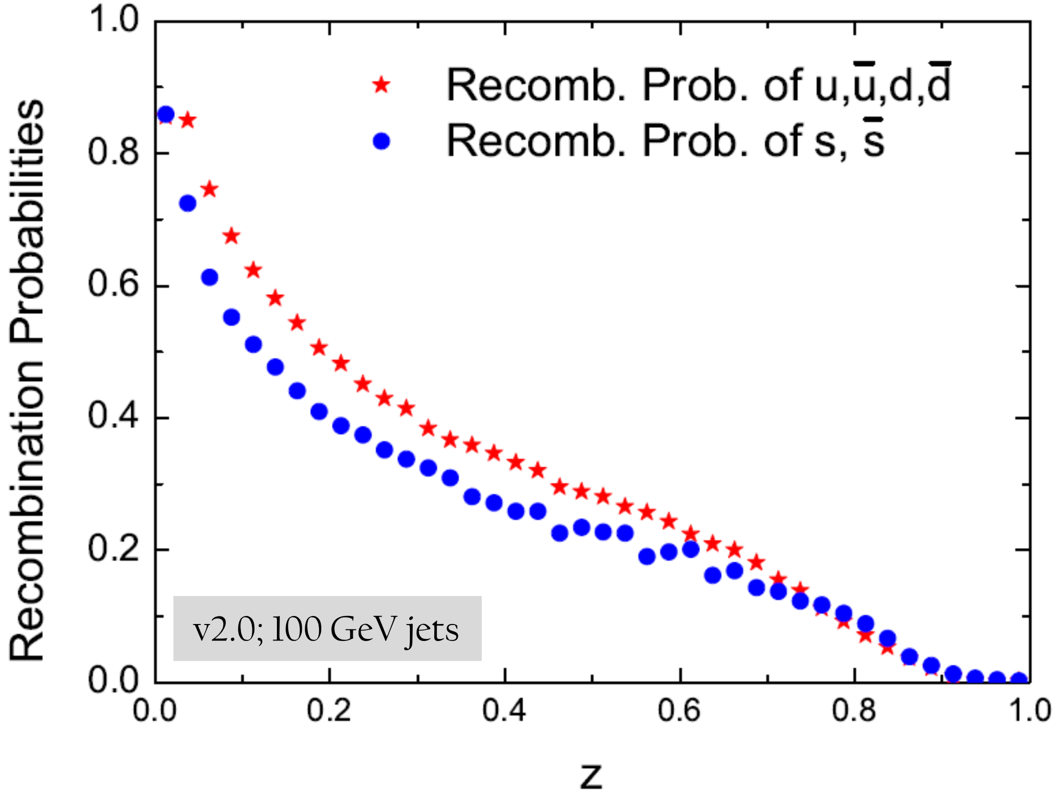
- Naturally there are remnant quarks and antiquarks which have not found a recombination partner.
- Why? No confinement in parton shower, quarks can get far away.
- In reality: colored object needs to stay connected.
- Connect partons with strings, return to PYTHIA for string fragmentation.



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

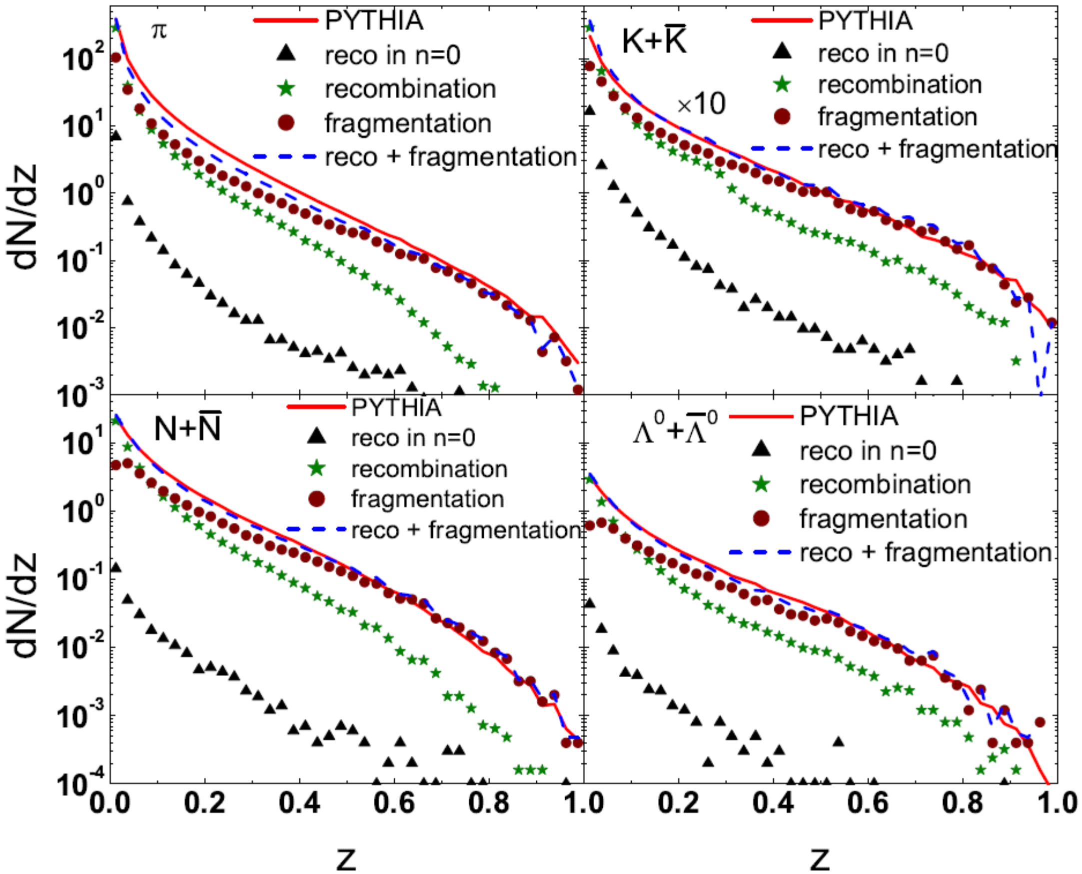
Remnant Strings

- Check on recombination probability (100 GeV PYTHIA e+e- jets)



Results: Single Vacuum Jets

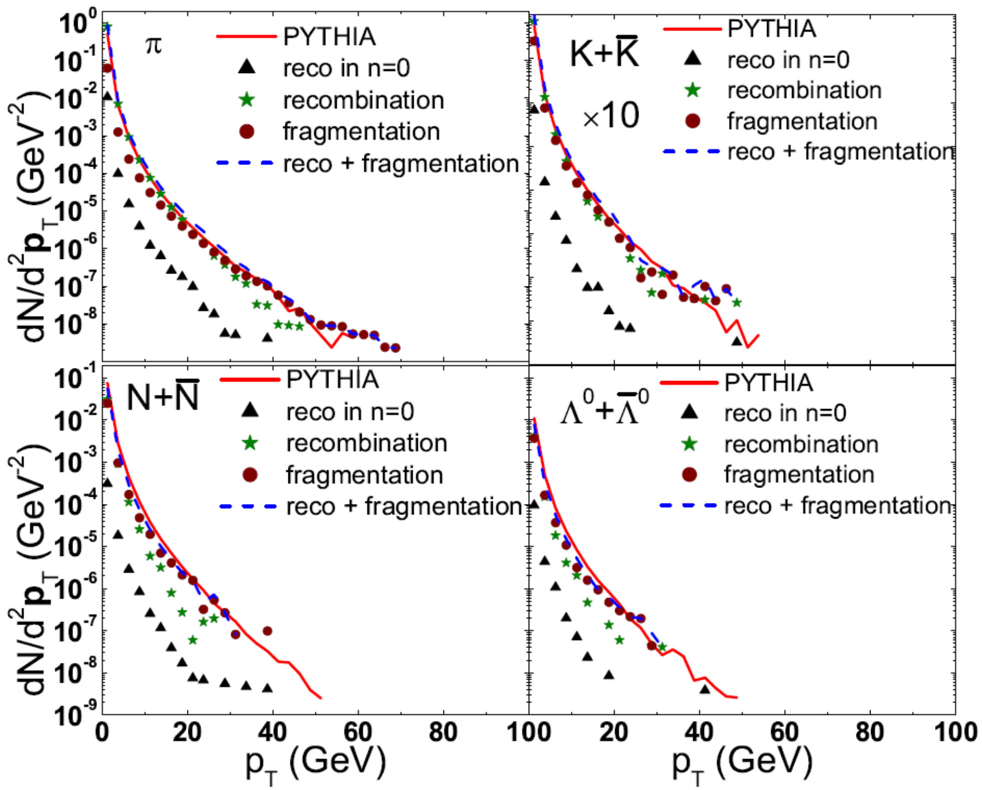
- Longitudinal structure: *dN/dz* of stable particles compared to PYTHIA 6 string fragmentation (e+e-).



v2.0; 100 GeV jets

Results: Single Vacuum Jets

- Transverse structure: dN/d^2P_T of stable particles compared to PYTHIA 6 string fragmentation (e+e-).



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

v2.0; 100 GeV jets

Adding a Medium

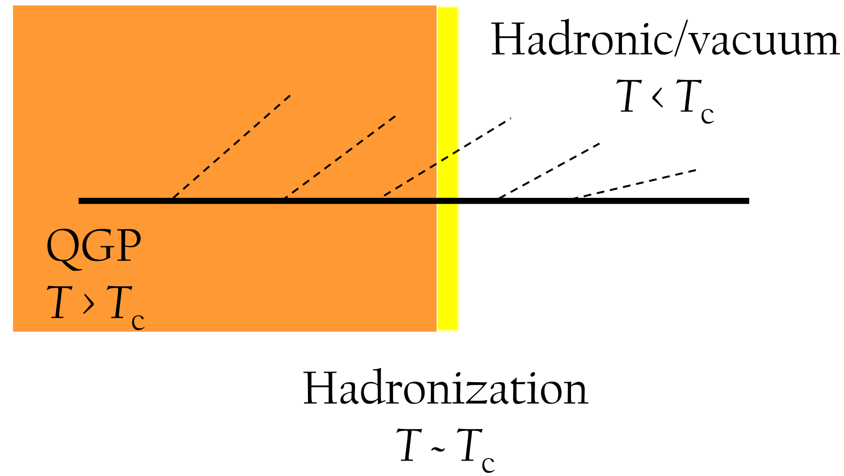
- Sample thermal partons.
- Add thermal partons to the list of shower partons.

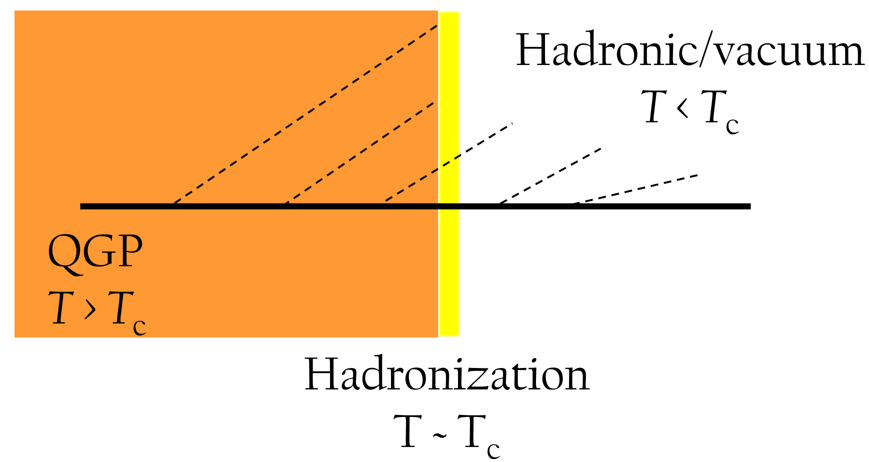
- Apply same recombination MC procedure
  - Allow shower-thermal (S-T) mesons, S-T-T + S-S-T baryons.
  - Vetoing pure thermal hadrons for now.

- Keep track of energy, momentum, quantum numbers removed from the thermal medium.

Adding a Medium

- Jets in a medium: space-time picture is important.
- 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.

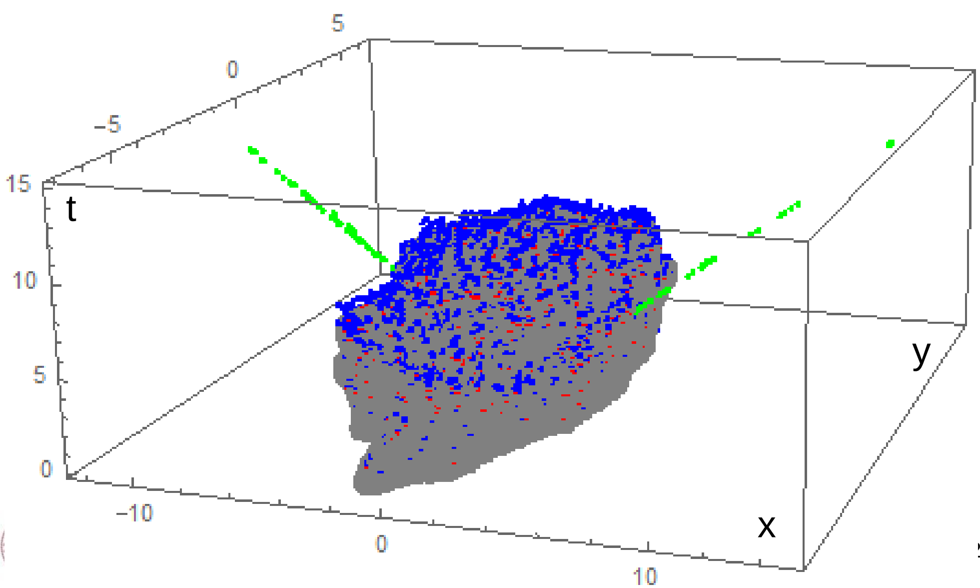


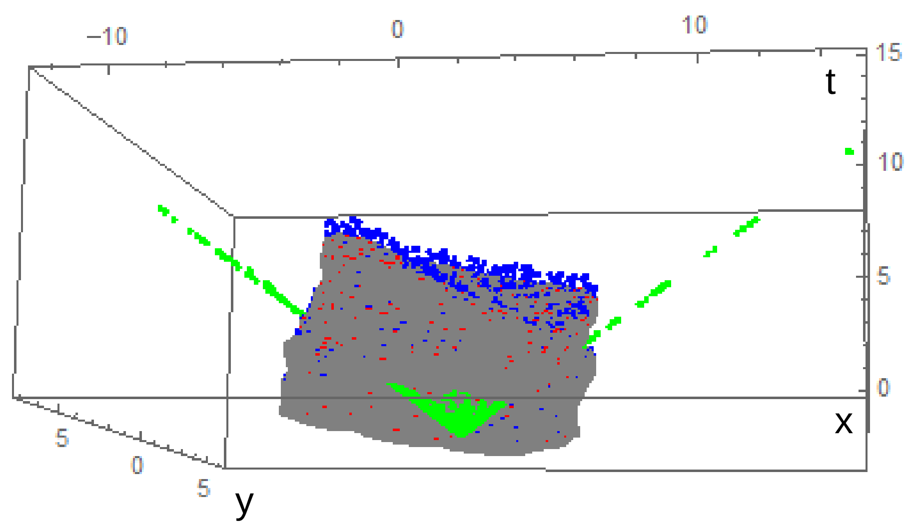


Jet + Medium

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

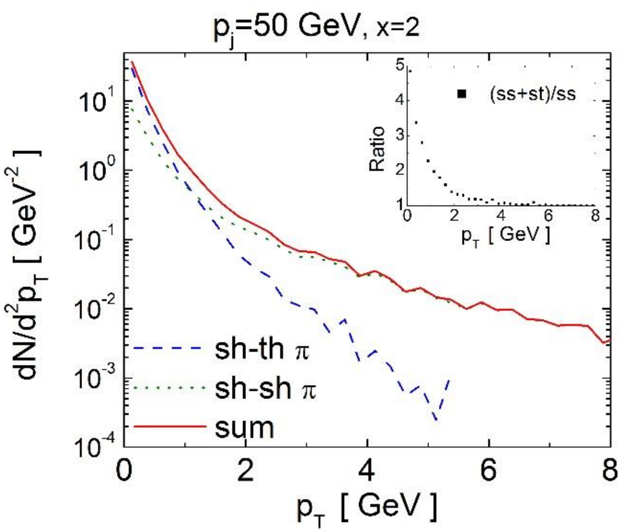
- Plots: 500 PYTHIA (vacuum) showers emerging from the center embedded into an iEBE event
  - blue = sampled thermal partons; green = shower; grey = hypersurface

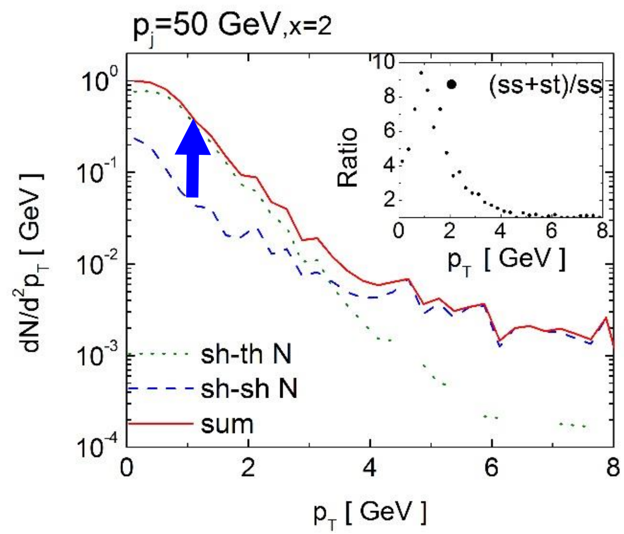




In-Medium Effects

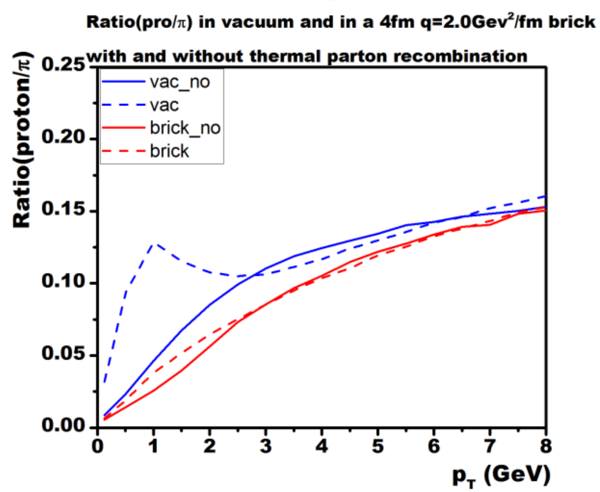
- Demonstration of baryon enhancement (iEbE + PYTHIA)





v2.1

- MATTER + brick (no flow)

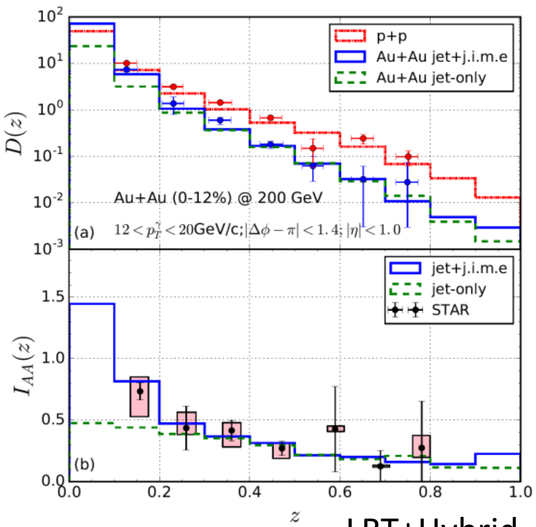


Code Details

v2.1: single jets, basic in-medium functionality: JET Collaboration

v2.2: current beta version

v3.0: JETSCAPE version (C++) under development



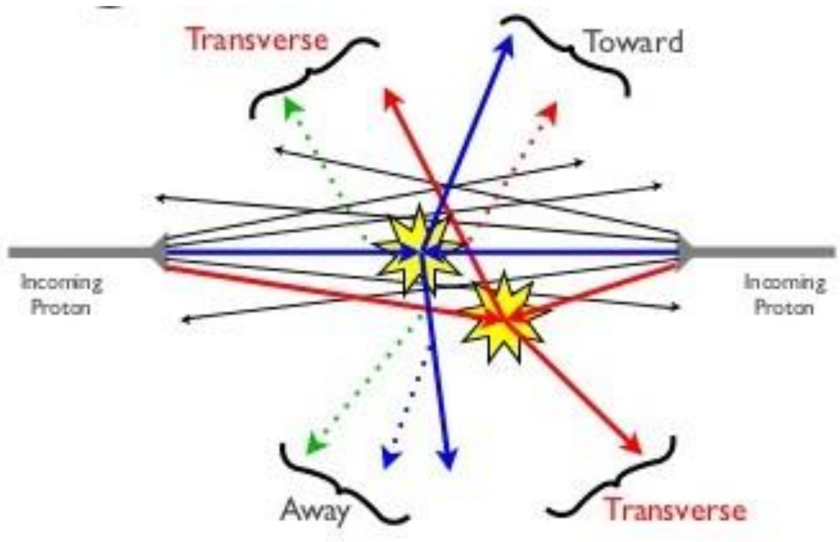
LBT+Hybrid

- Input:
  - Parton showers with color/string information.
  - Sampled thermal partons (JETSCAPE functionality)
  - Additional shower partons on the hypersurface.
- Hadronization trigger: $Q < Q_0$, $T < T_c$
- Abilities:

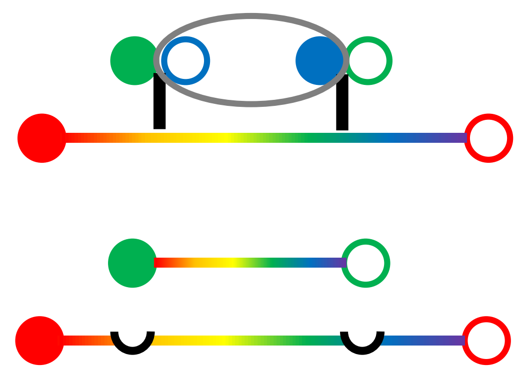
Hadronize	p+p	A+A
Parton showers	YES	YES
Parton-medium interaction	YES	YES
Medium/ underlying event	YES	?

Underlying Events: p+p

- Full p+p event: many strings, junctions, diquarks, …



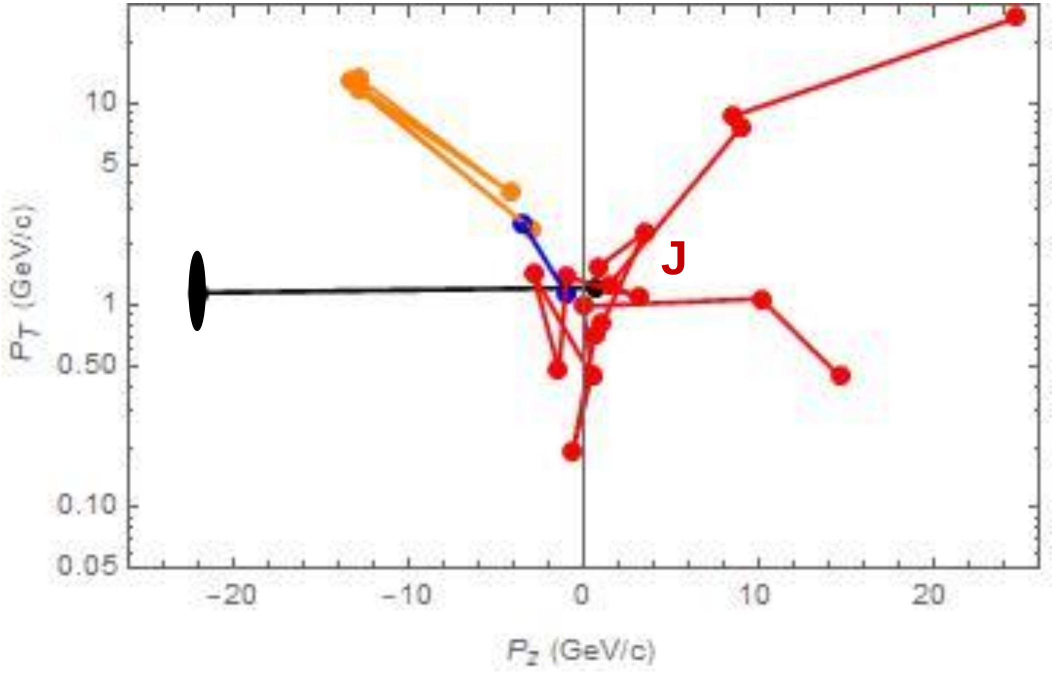
- Complexity requires instant "repair" of string objects that have lost partons to other hadronization channels.
- Many possible channels to consider:



- Start with well-defined string structure (e.g. PYTHIA), end with well-defined strings + hadrons: Strings → Strings' + hadrons

String-Recombination Interplay

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



String-Recombination Interplay

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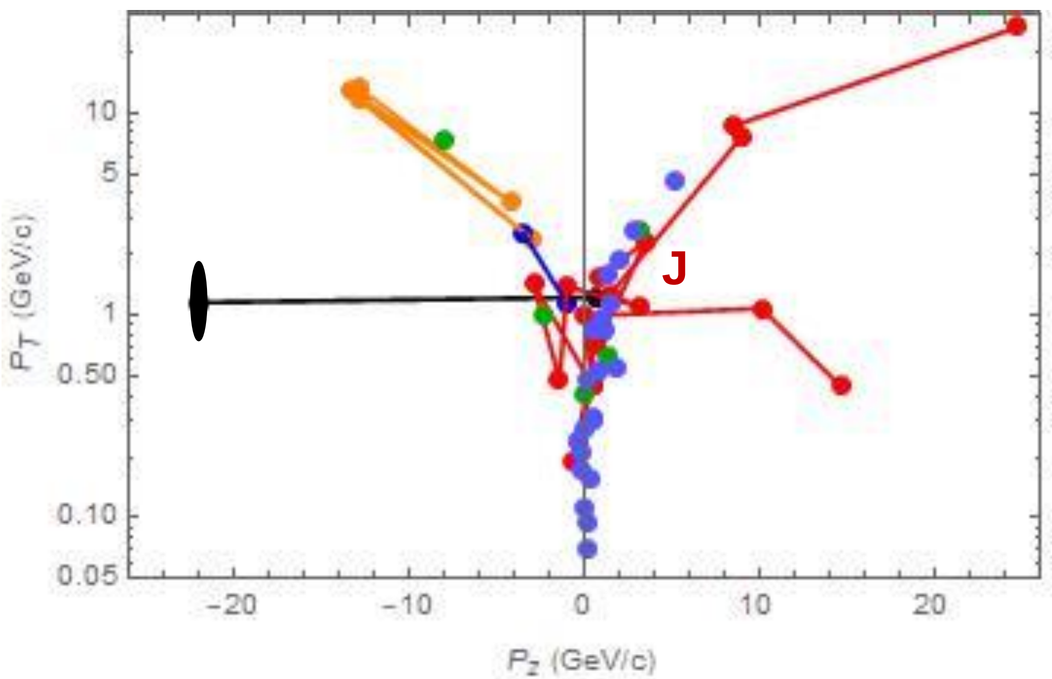

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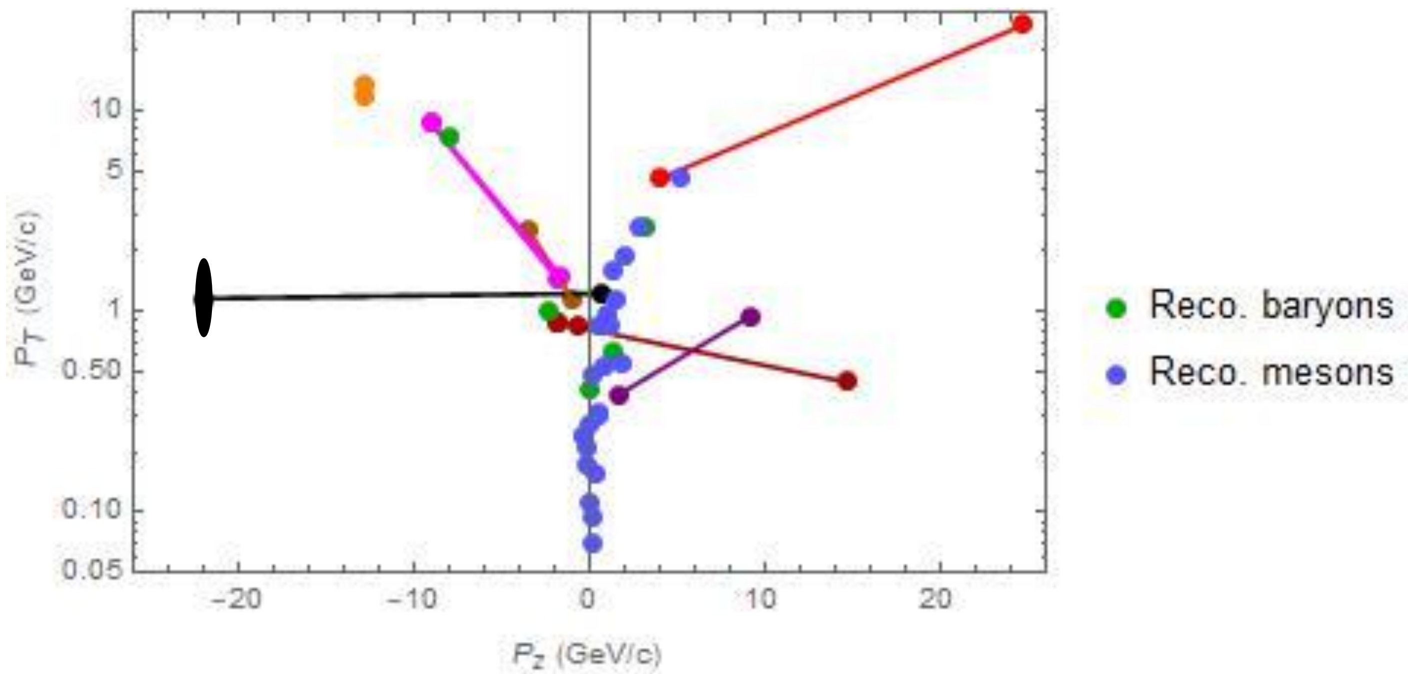

String-Recombination Interplay

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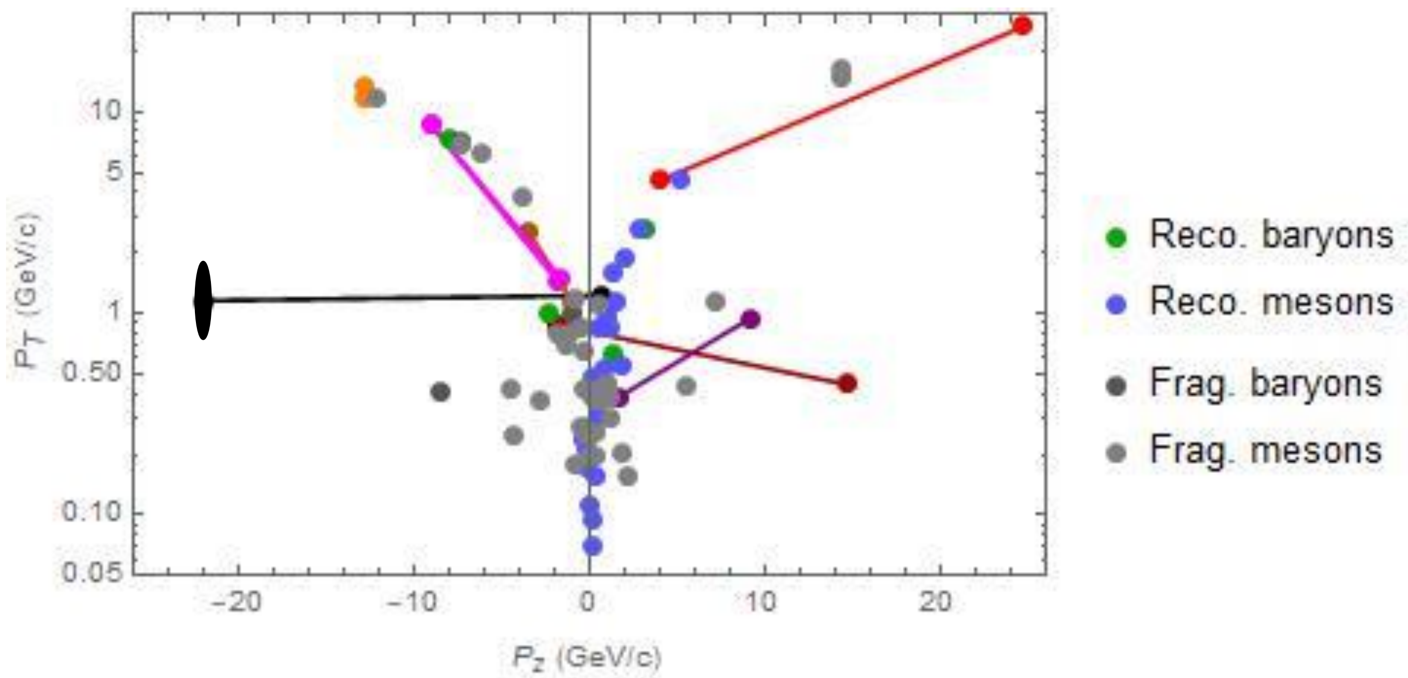
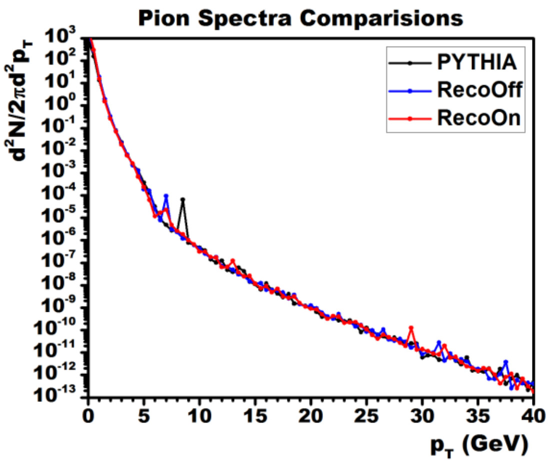
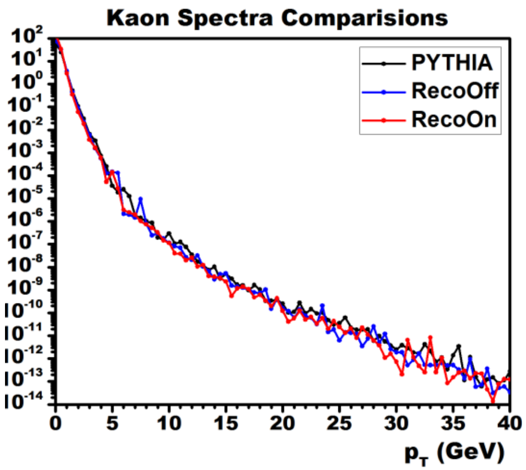
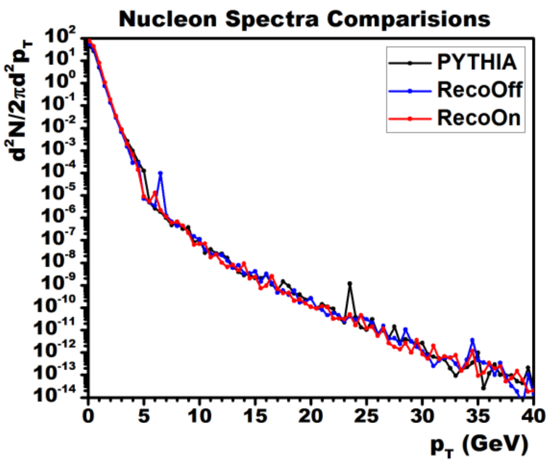


v2.2 Full p+p Events

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



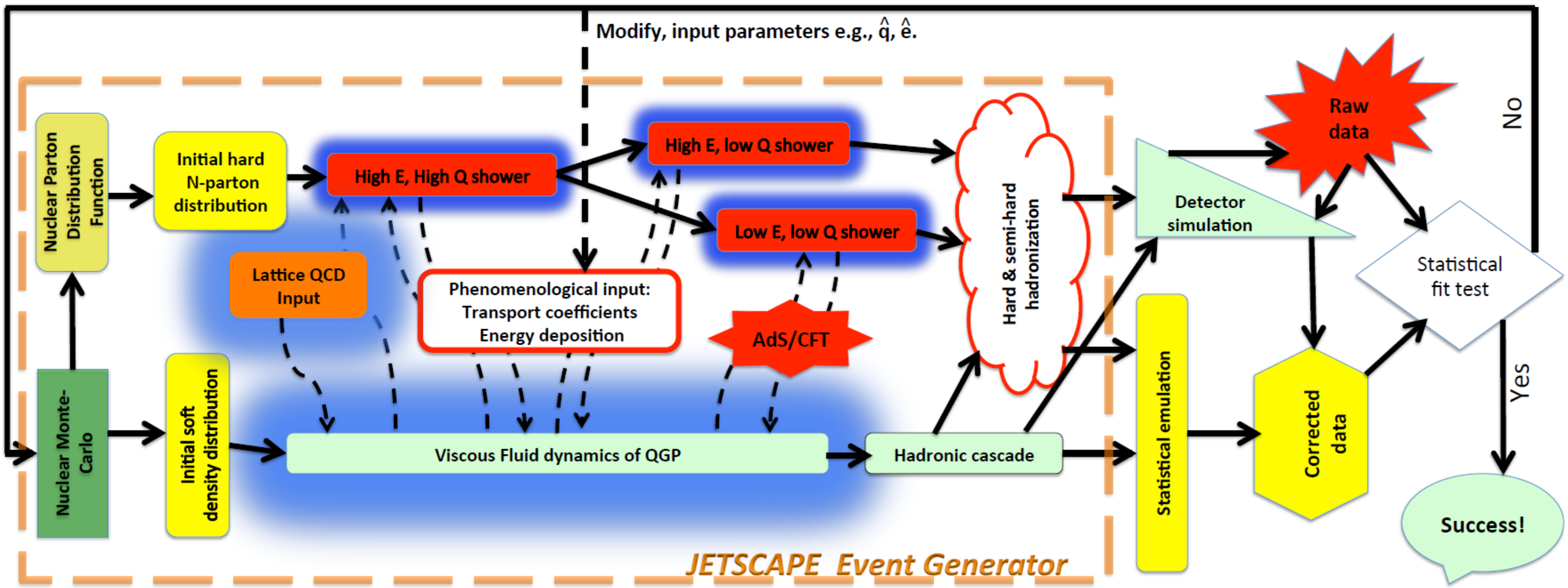




- More tests on the way.

Hybrid Hadronization in JETSCAPE

- v3.0: Existing functionalities + many physics improvements:



credit: J. Putschke

Summary

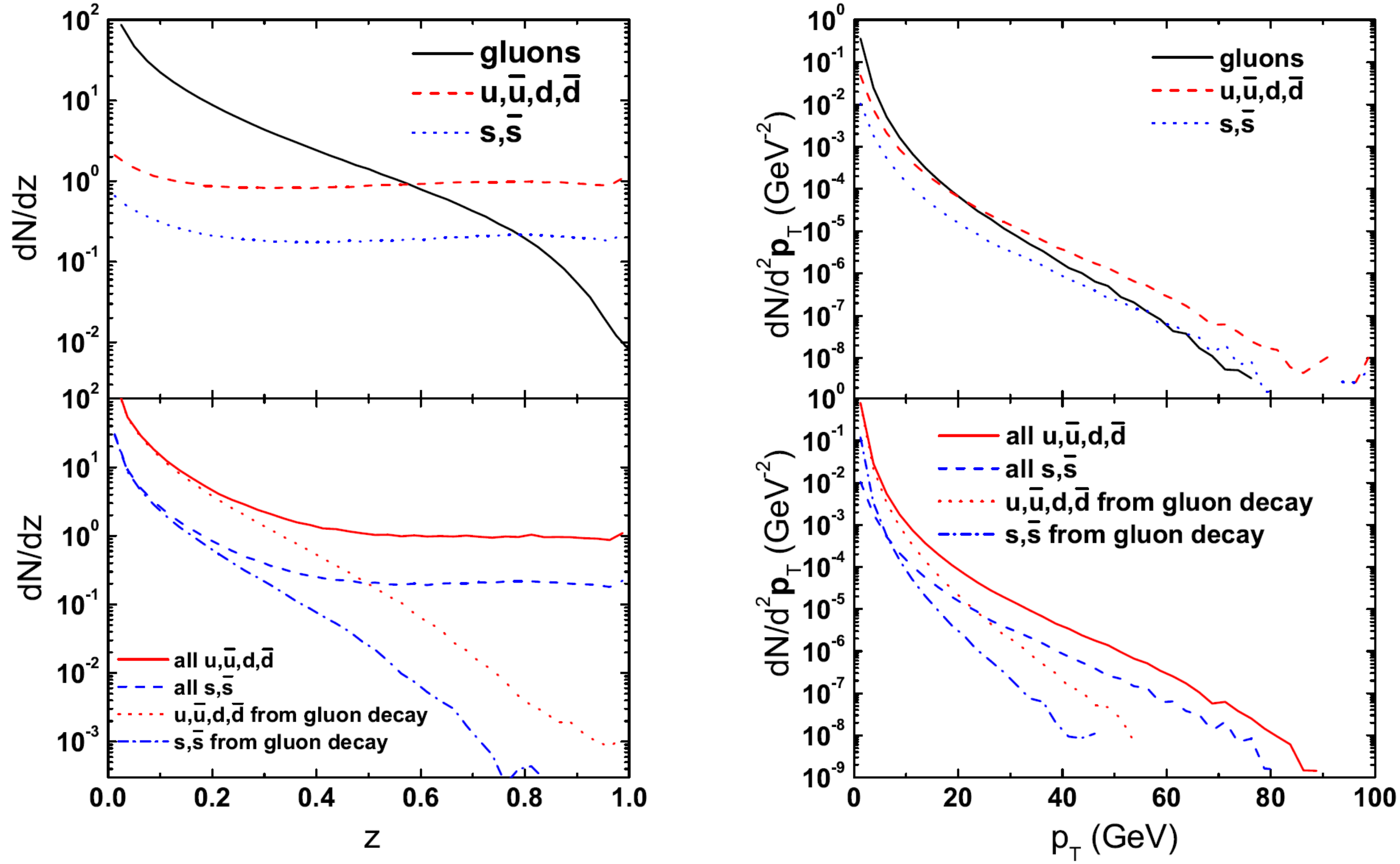
- We have developed an event-by-event hybrid hadronization module for jet Monte Carlos.
- Quark recombination + string fragmentation.
- Medium effects by sampling thermal partons on a hypersurface.

- Upcoming version: hadronization with underlying events.
- New v3.0 for the JETSCAPE framework: stay tuned.
- Systematic studies of jet medium effects with in-medium jets ongoing.

Backup

Prepping Parton Showers

- Example: Sample of 10^6 PYTHIA parton showers with E_{jet} = 100 GeV.
- dN/dz and dN/d^2P_T before vs after gluon decay



Recombination Step

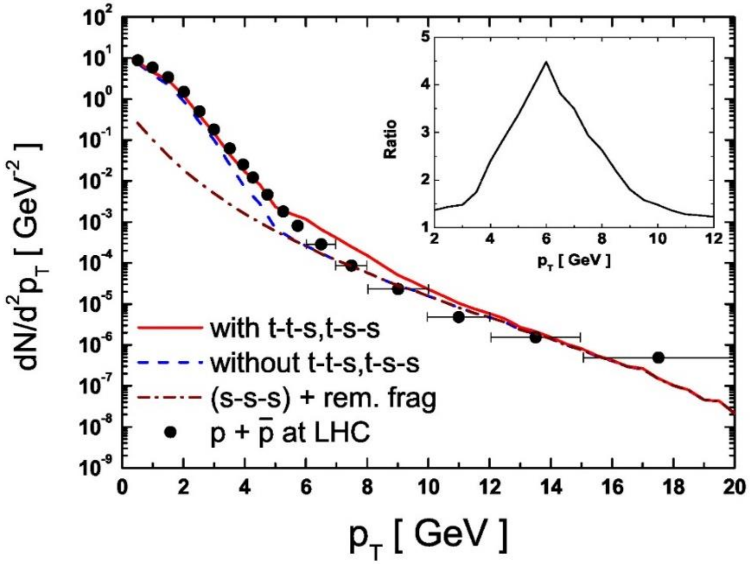
- Parameters (harmonic oscillator WF case)

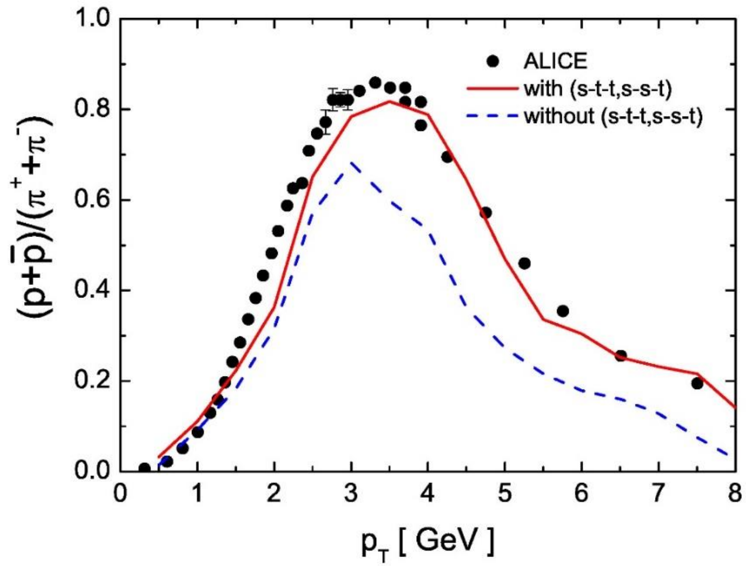
TABLE I. Table of measured charge radii R (from Ref. [21]), widths σ_M (and σ_B), and statistical factor g for all hadrons used in this calculation.

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

Towards a Full Picture

- Some older results calculated using v1.0 and a blast wave medium reproduces experimental p/π ratio (jet, jet-medium and thermal medium itself included)





[K. Han, C.M. Ko]

Dirt Effects or Interesting Physics?

- Hadronization is interesting in HI physics because
  - it connects observables to deconfined partons
  - probe-parton interactions at T_c (hadronization) = lim($T \rightarrow T_c$) probe-parton interactions at $T > T_c$
- Theoretical control over the process?
- But: wealth of new data, e.g.
  - comparison of p+p, p+A and A+A
  - new observables for jet substructure

$$F_N(\{p_i\}) = \sum_{i_1} \sum_{i_2} \cdots \sum_{i_N} E_{i_1} E_{i_2} \ldots E_{i_N} \, f_N(\hat{p}_{i_1}, \hat{p}_{i_2}, \ldots, \hat{p}_{i_N})$$

All N-tuples — N Energies — Angular Weighting (symmetric, vanishes for θij → 0)

$${}_v e_n^{(\beta)} = \sum_{\text{all } n\text{-tuples}} (n \text{ energies}) \, (v \text{ smallest angles})^{\beta}$$

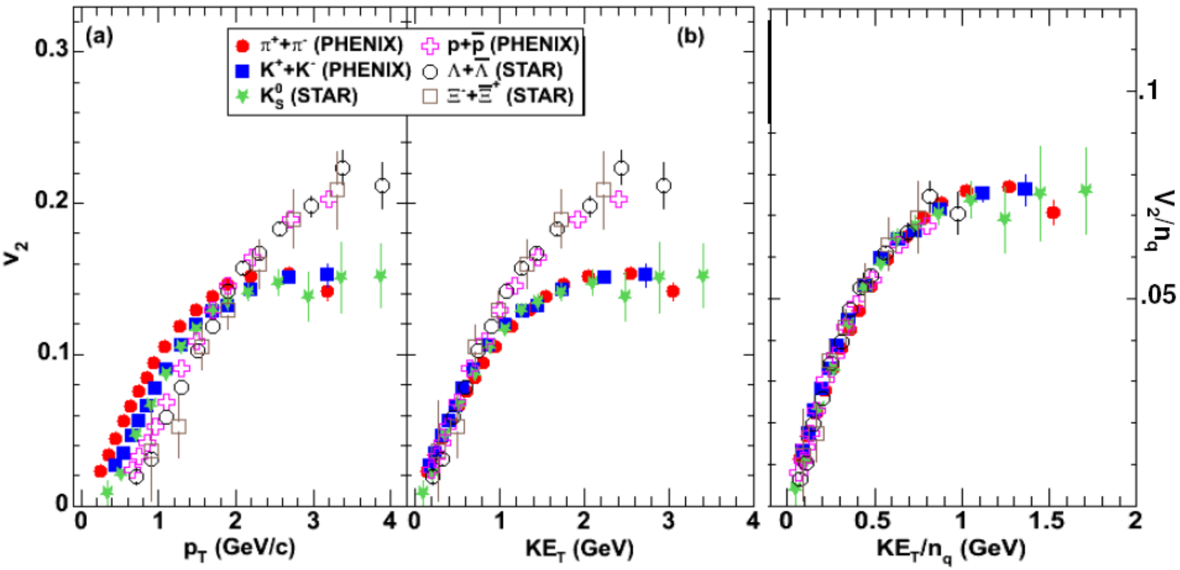
[Jesse Thaler]

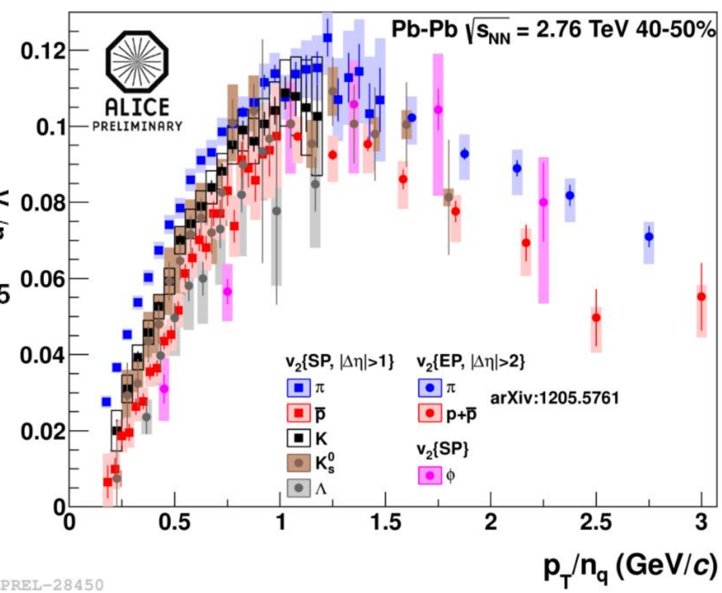
.... with varying degree of sensitivity to hadronization.

[A.J. Larkoski, S. Marzani, G. Soyez, J. Thaler: arxiv:1402.2657]

Elliptic Flow Scaling

- At low and intermediate P_T: scaling with kinetic energy KE_T and valence quark number n_q.
- Very good at RHIC, still good at LHC. Up to KE_T/n ~ 1.0…1.5 GeV.





- Quark coalescence predicts n_q-scaling under certain assumptions:

$$v_2^M(p_t) = 2v_2^p\left(\frac{p_t}{2}\right) \quad \text{and} \quad v_2^B(p_t) = 3v_2^p\left(\frac{p_t}{3}\right)$$

A signature for deconfined quarks?