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Hadronization in Vacuum and in the Medium

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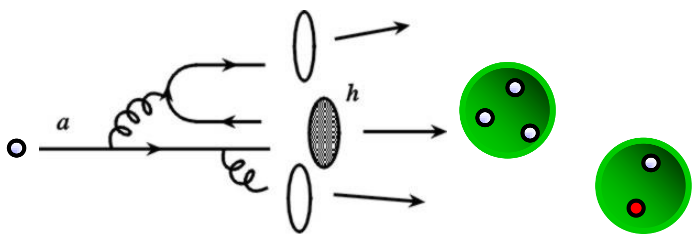
Overview

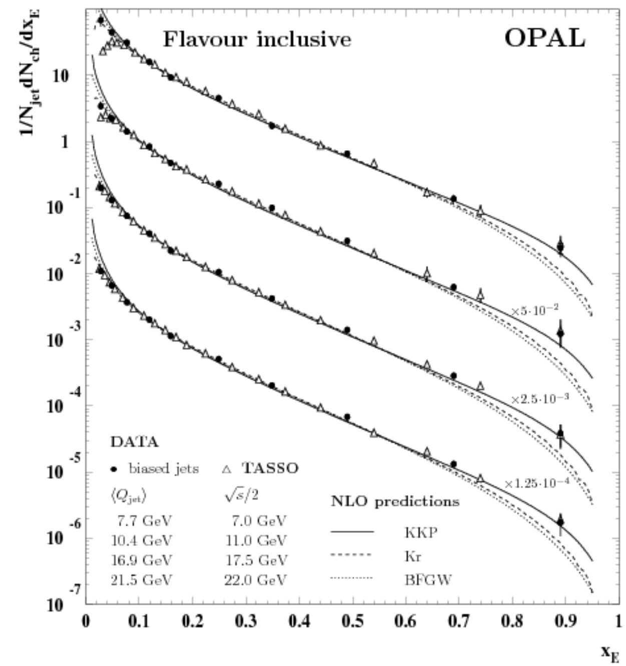
- Hadronization models.
- Instantaneous vs resonance recombination
- Applications to the HQ sector
- The JET recombination/fragmentation hybrid model
- Including a medium; JETSCAPE

Hadronization

- Fragmentation of a parton from a hard process well-defined and well measured

$$D_{\mathrm{u}\to\mathrm{h}} \sim \langle 0|u_\alpha|h\rangle\langle h|u_\beta|0\rangle$$





- Little theoretical and experimental guidance for jet hadronization: n quarks → m hadrons
  - Conservation laws and color
  - New generation of sub-jet observables?

Dirt Effects or Interesting Physics?

- In jet physics: 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 $\theta_{ij} \to 0$)

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

[Jesse Thaler slides]

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

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

- Hadronization is interesting because (generally)
  - it connects observables to deconfined partons
  - probe-parton interactions at T_c (hadronization) = lim($T \to T_c$) probe-parton interactions at $T > T_c$
- The problem: theoretical control over the process.
- But: systematic comparison of p+p, p+A and A+A possible.

Jet Hadronization: Initial State

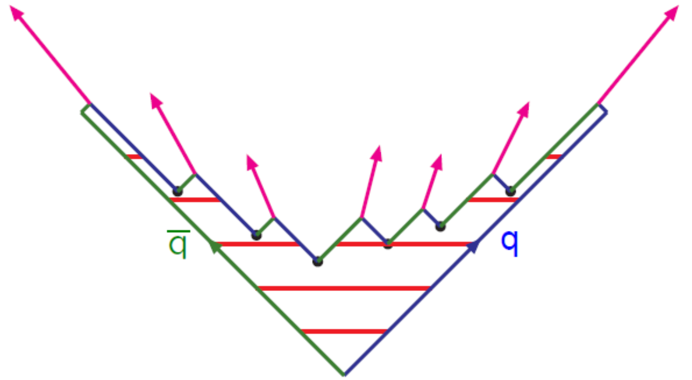
- Working definition: jet = (perturbative) parton shower + hadronization

- Traditional matching point:
  - Cutoff virtuality Q_0 for each parton
  - Results in complicated space-time picture

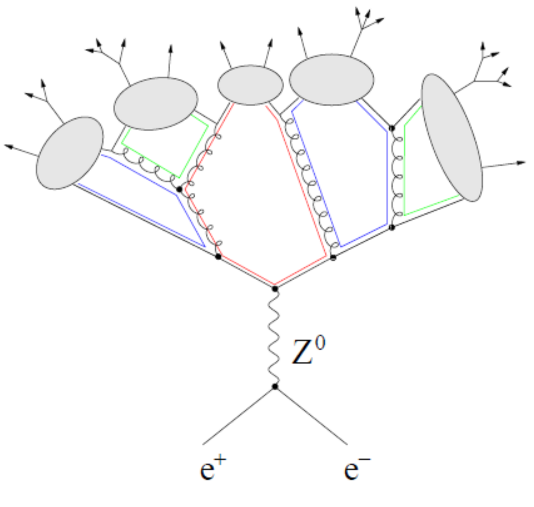
- With medium:
  - Well-defined space-time picture for the jet is important to utilize information from simulations of the medium (for in-medium evolution and hadronization!)
  - Parton virtuality and background temperature; might have to add phase space constraints.

Candidate Models

- String fragmentation: based on string pictures of hadrons emerging in the early 70s
  - Lund string model
  - JETSET (e+e-) → PYTHIA (e+e-, pp, …)



- Cluster hadronization
  - Force non-perturabative g->q qbar splitting
  - Local color neutrality: q-qbar form color-neutral clusters.
  - Clusters decay into hadrons which can decay further into stable hadrons.
  - Some similarities with recombination.

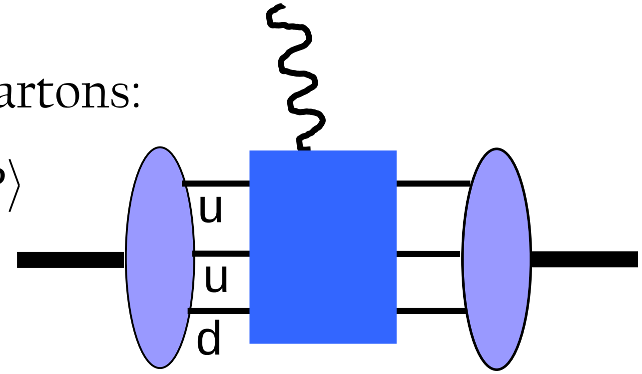


- Quark recombination
  - Based on parton-parton interactions

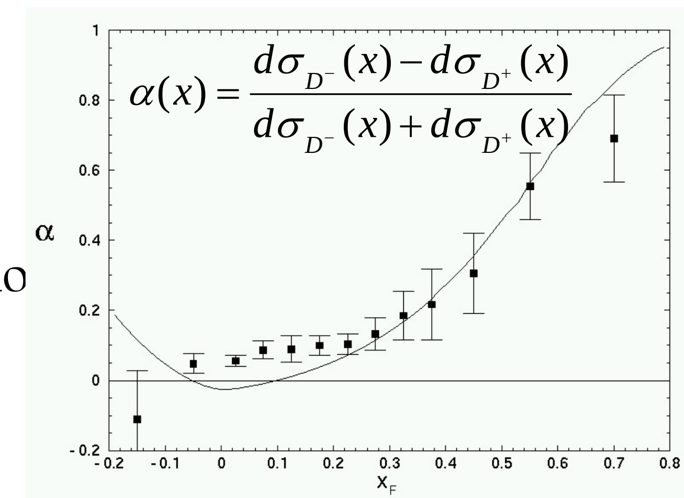
Quark Recombination

- 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

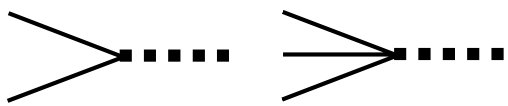


- Charm-strange correlations in heavy ion collisio[ns]: strangeness enhancement seen in D_s.
- Quark scaling law in HI collisions

Recombination Approaches

- Instantaneous recombination: project parton states onto hadron states:

$$N_h = \int \frac{d^3P}{(2\pi)^3} \langle h; \mathbf{P}| \, \rho \, |h; \mathbf{P}\rangle$$



- Probabilities or yields usually expressed through Wigner function overlap

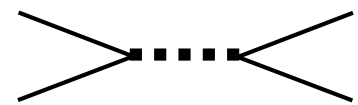
$$\frac{dN_M}{d^3\mathbf{p}_M} = g_M \int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 f_q(\mathbf{x}_1, \mathbf{p}_1) f_{\bar{q}}(\mathbf{x}_2, \mathbf{p}_2) \times W_M(\mathbf{y}_1, \mathbf{k}_1) \delta^{(3)}(\mathbf{P}_M - \mathbf{p}_1 - \mathbf{p}_2) \,, \quad (3)$$

- Suitable for fast processes like jet hadronization.

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

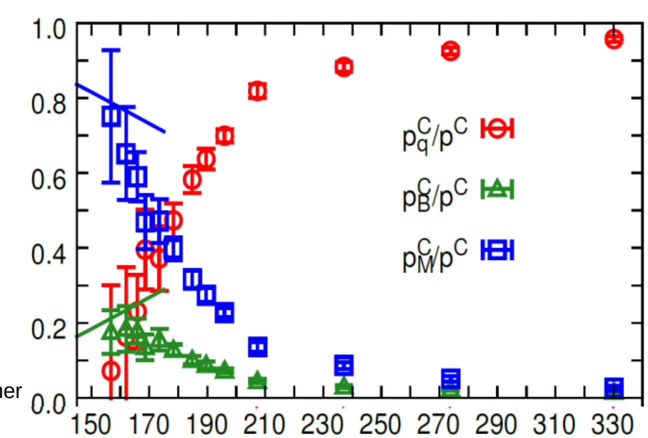
- Resonance recombination: formation of hadron states as resonances in parton scattering.

$$\frac{\partial}{\partial t} f_M(t,\vec{p}) = -\frac{\Gamma}{\gamma_p} f_M(t,\vec{p}) + g(\vec{p})$$



[Ravagli & Rapp, PLB 655 (2007)]
[Ravagli, van Hees & Rapp, PRC 79 (2009)]

- Consistent with hadronic survival results from lattice.



[S. Mukherjee et al., Phys. Rev. D 93, 014502 (2016)]

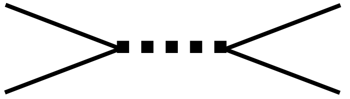
Resonance and Heavy Quark Hadronization

<u>In collaboration with</u>
Min He
Ralf Rapp

Resonance Recombination

- Mesons appear as resonances of quark-antiquark scattering
- Described by Boltzmann equation, start with ensemble of quarks/antiquarks
- Breit-Wigner resonance cross sections:

$$\frac{\partial}{\partial t} f_M(t,\vec{p}) = -\frac{\Gamma}{\gamma_p} f_M(t,\vec{p}) + g(\vec{p})$$



$$\sigma(s) = C_M \frac{4\pi}{k^2} \frac{(\Gamma m)^2}{(s-m^2)^2 + (\Gamma m)^2}$$

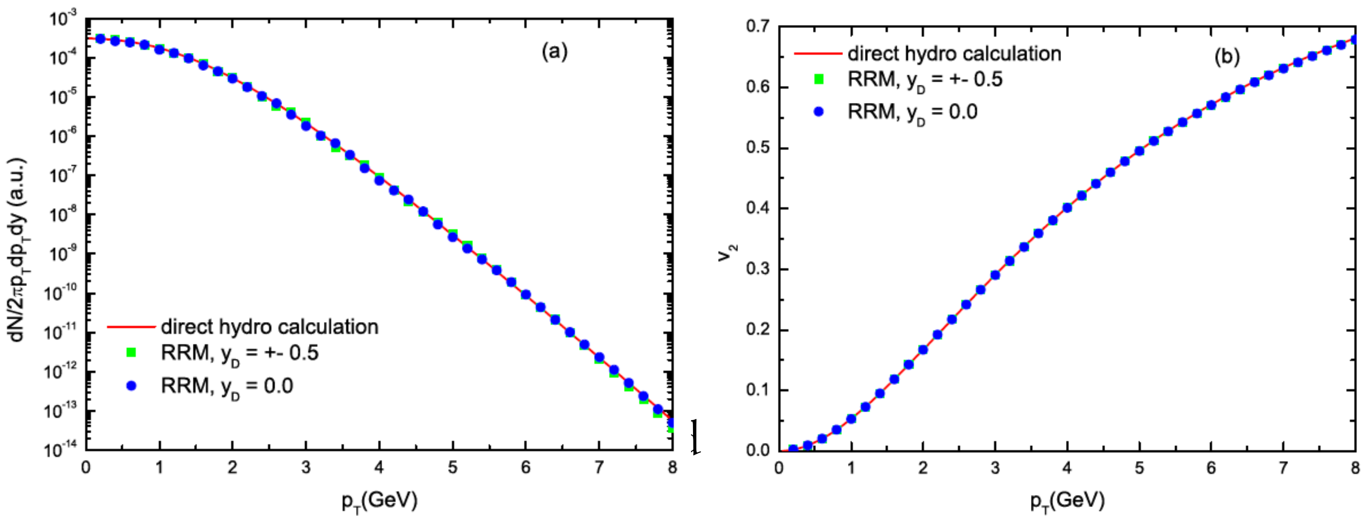
[Ravagli & Rapp PLB 655 (2007)]
[Ravagli, van Hees & Rapp, PRC 79 (2009)]

  - Long-time limit:

$$E\frac{dN_M}{d^3P} = \frac{E\gamma}{8(2\pi)^3\Gamma} \int \frac{d^3x d^3p_{rel}}{(2\pi)^3} f_a(x,p_1) f_a(x,p_2) \sigma(s) v_{rel}(P,p_{rel})$$

- Conserves energy <u>and</u> momentum, should be able to attain equilibrium.
- Compatible with the picture of a strongly interacting medium.

Test of Equilibrium Limit

- Energy conservation + detailed balance + equilibrated quark input → equilibrated hadrons.
- Can be applied to any hadronization hypersurface Σ.
- Numerical tests: compare blast wave hadrons at T_c-ε to hadrons coalesced from quarks of the same blast wave at T_c+ε: heavy-light system at AZHYDRO hypersurface
- 

[M. He, RJF and R. Rapp, PRC 82 (2010)]

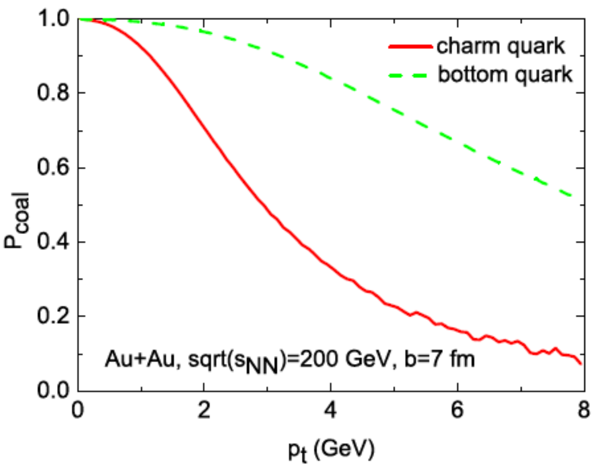
Implementation for Heavy Quarks

- Resonance recombination ideal for systems close to equilibrium.
- How to decide recombination vs fragmentation rate?

Q-q recombination rate ~ Q-q in medium scattering rate

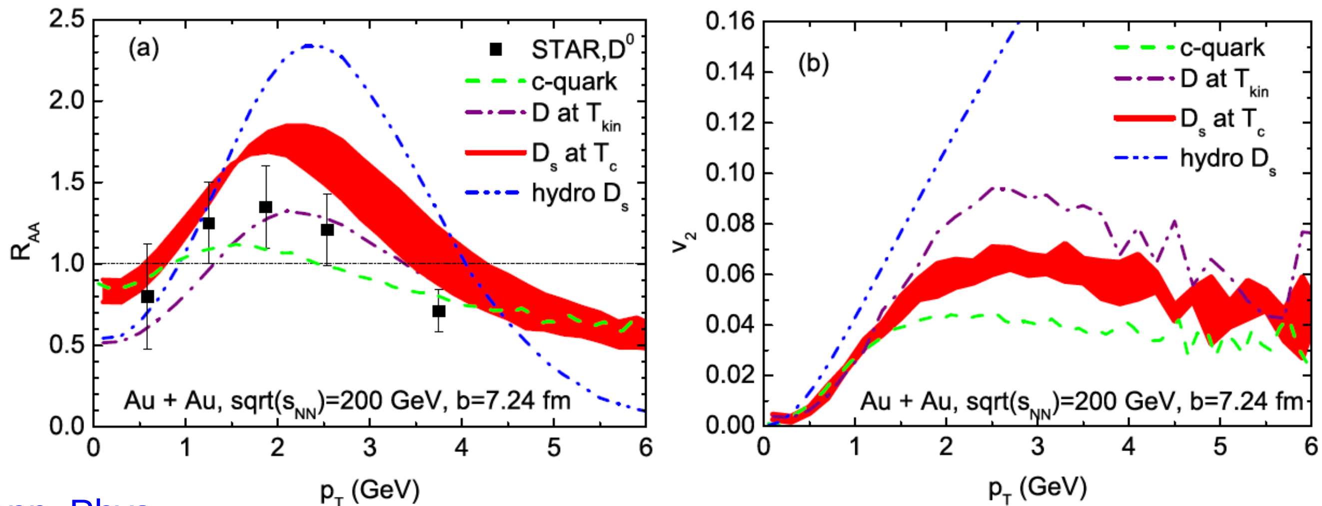
$$P_{\rm coal}(p) = \Delta\tau_{\rm res}\ \Gamma_Q^{\rm res}(p)$$

  - Apply fragmentation with probability 1-$P_{coal}(p)$.
- Hence consistent with in-medium dynamics.
  - Low momenta = recombination dominated (co-moving thermal partons)
  - High momenta = fragmentation dominated (no co-moving thermal partons)
- Usually two extreme assumptions about $\Delta\tau$:
  - Corresponding to P_{coal} =1 or 1-e^{-1} at p=0.
- Total recombination probability averaged over fluid cells in lab frame:



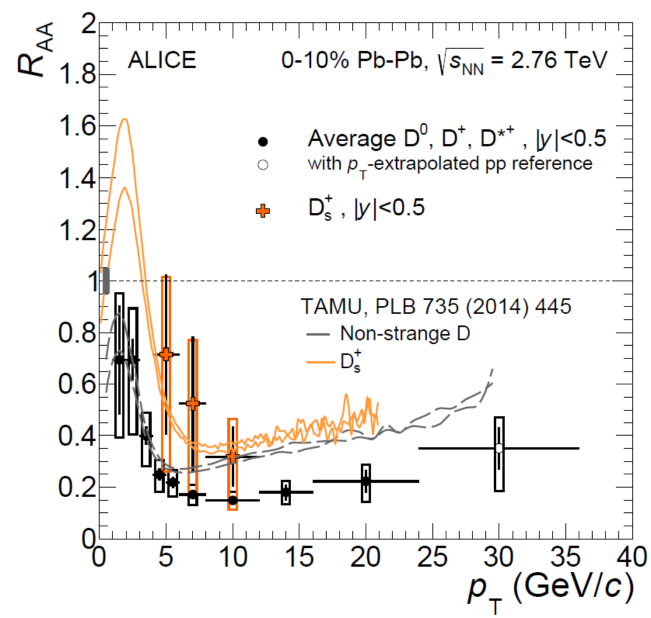
The D_s as a Signature

- RHIC:



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

- LHC:



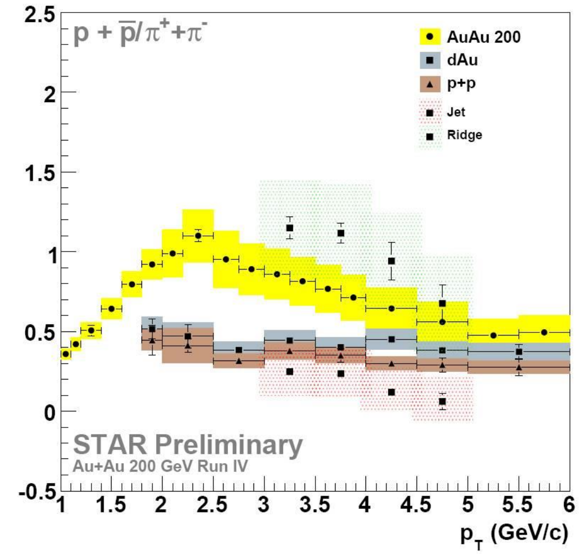
- D_s enhancement seen but not yet statistically significant

JET Jet Hadronization

The JET Effort on Jet Hadronization

- JET collaboration goal: "*... realistic calculations of jet production in a high energy density medium...*"
  → Comprehensive modeling of jet showers, including hadron chemistry.

- Find a unified approach to modelling hadronization of jets that includes vacuum and in-medium cases



→ Hybrid model including quark recombination and string fragmentation.

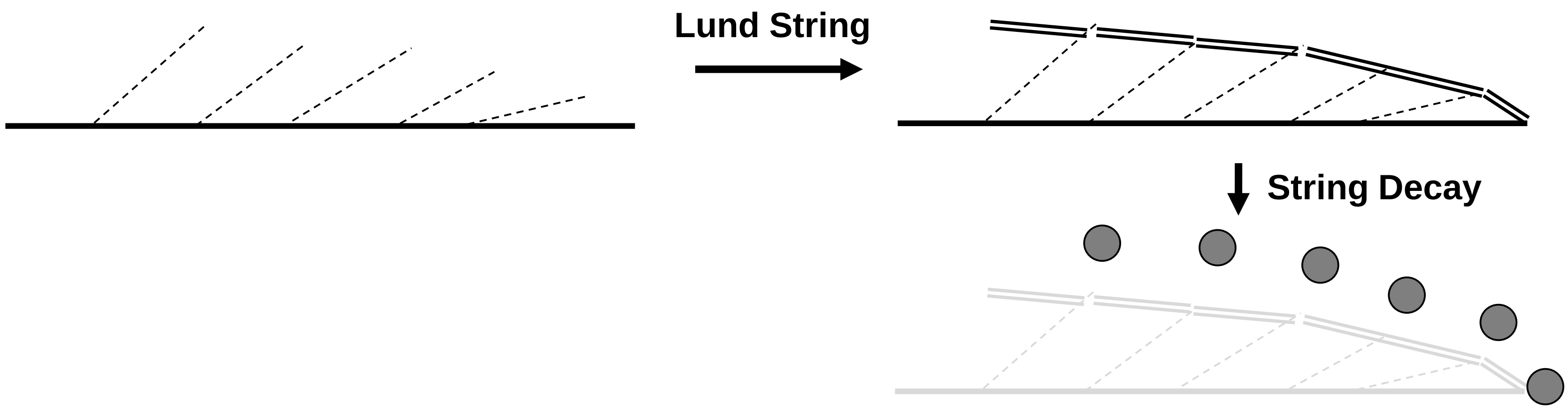
→ Instantanteous recombination of constituent quark degrees of freedom.

→ Include space-time information

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

Vacuum Baseline

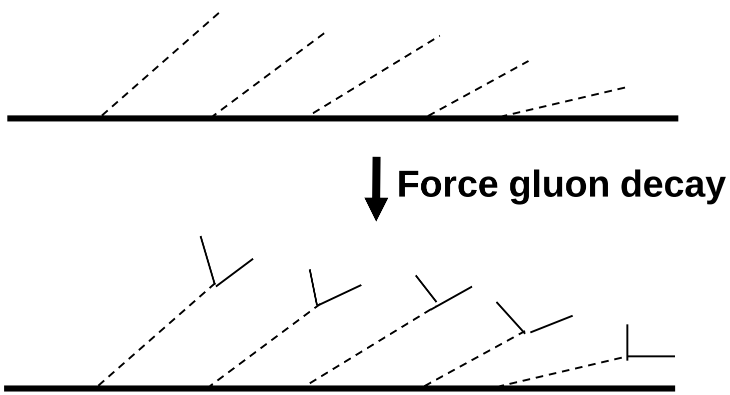
- Parton shower ceases at some virtuality Q_0.
- Keep string fragmentation for the large-*z* part of a jet.



- Replace string fragmentation by recombination in the “dense” part of a parton shower.

Prepping Parton Showers

- Perturbative parton showers evolved to a scale Q_0.



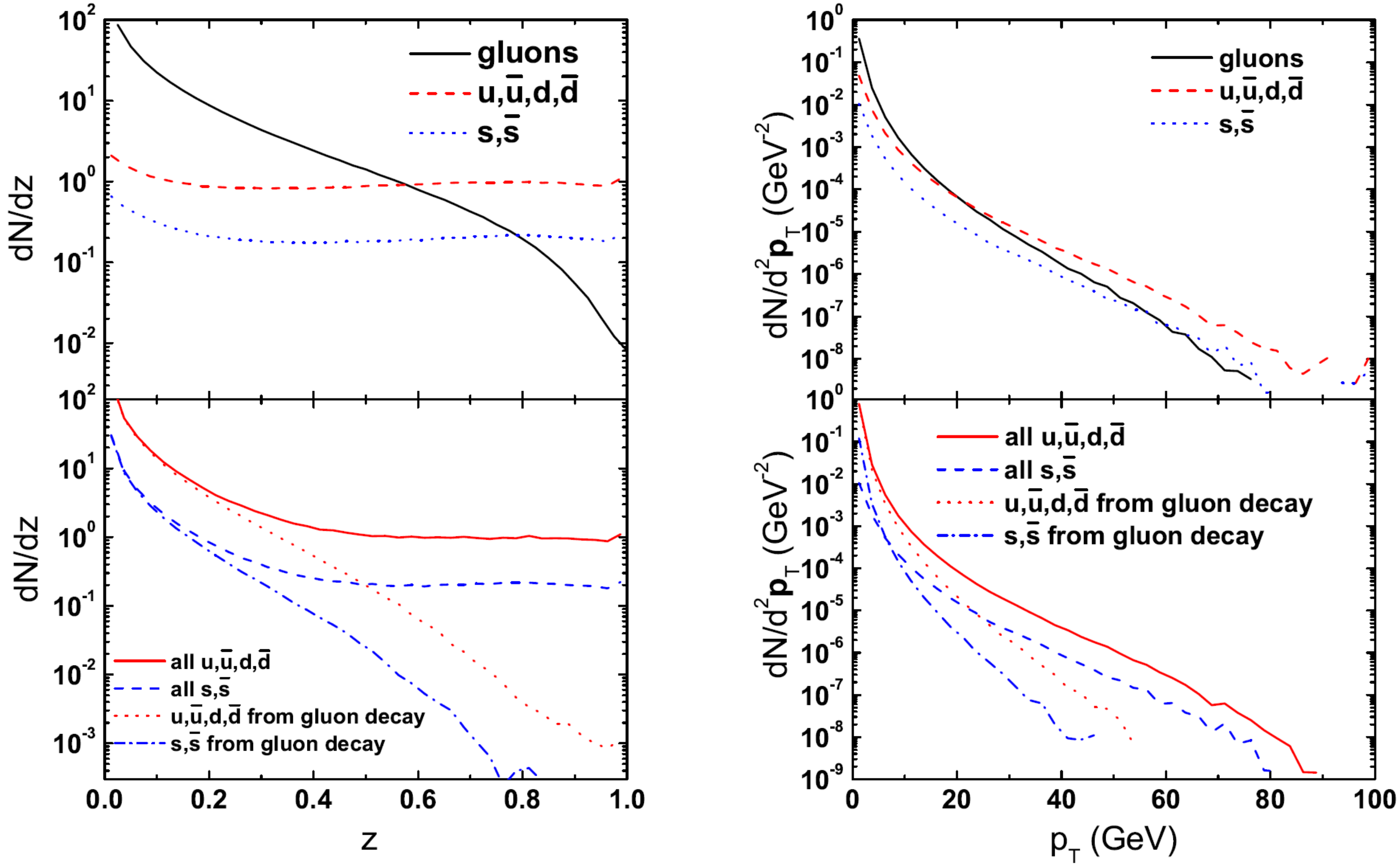
Examples here are PYTHIA showers supplemented by a space-time picture from tracking virtuality of partons which defines an average lifetime until splitting. Here: 100 GeV quark jets.

- Decay gluons with remaining virtualities into quark-antiquark pairs.
- Light and strange quarks, chemistry from phase space

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

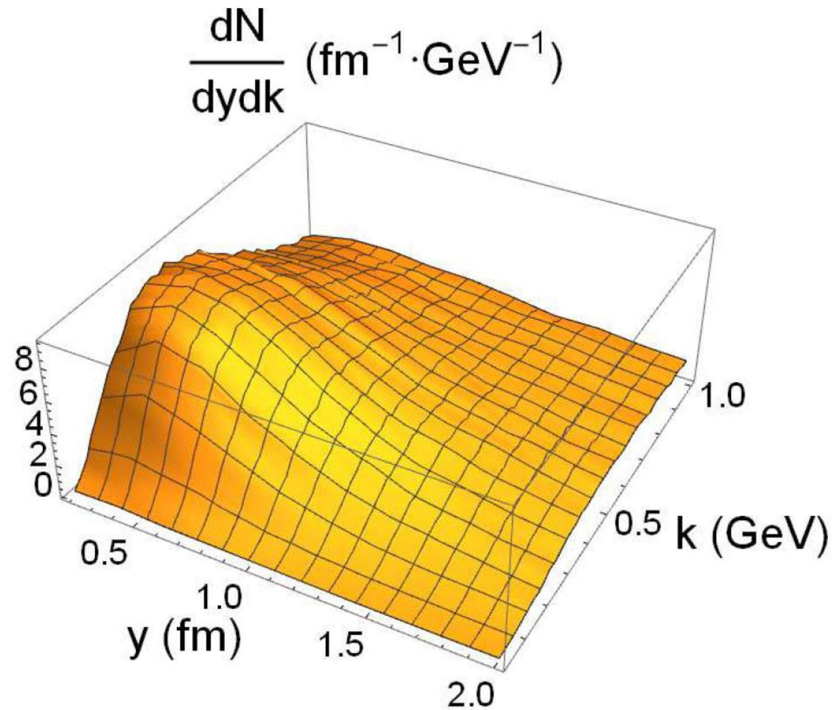
Prepping Parton Showers

- 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



Prepping 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 (PYTHIA) parton showers in phase space (in their center of mass frame)



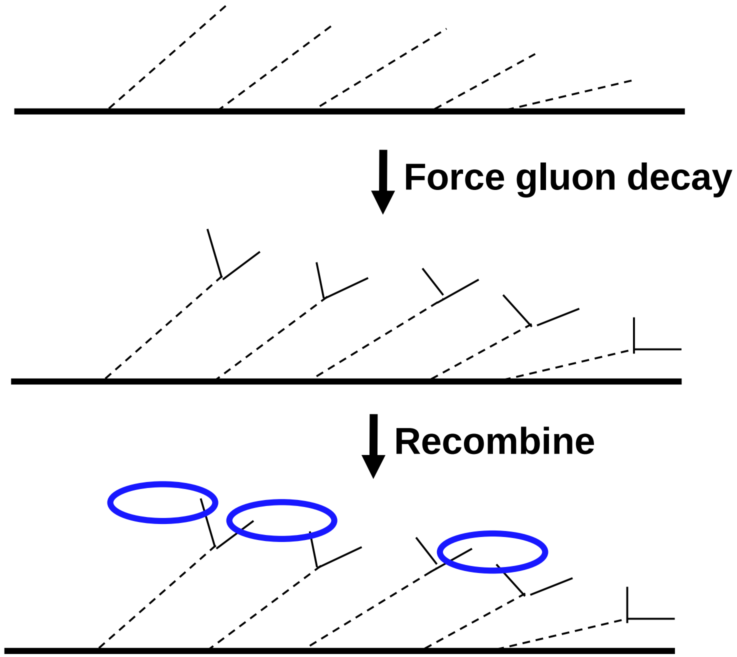
- "Our" PYTHIA jets: most of the jet is relatively "dense" in phase space.
- Long tails exist (~ large z partons)

- Fundamental test for other jet Monte Carlos: perturbative evolution should not lead to dilute showers, otherwise non-perturbative effects are already dominant.

Recombination Step

- Monte Carlo version of the instantaneous recombination model by Greco, Ko and Levai based on Wigner function formulation

[Greco, Ko & Levai, PRL 90, 202302 (2003)]



- Evaluate recombination probability for q-qbar paris and q (qbar) triplets.
- Roll dice to decide if recombination happens.
- Recombine into stable hadrons and resonances, let resonances decay (connections to cluster hadronization).
- Color treated statistically.

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

Recombination Step

- Well-known Wigner function coalescence formulas:

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

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

[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).

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

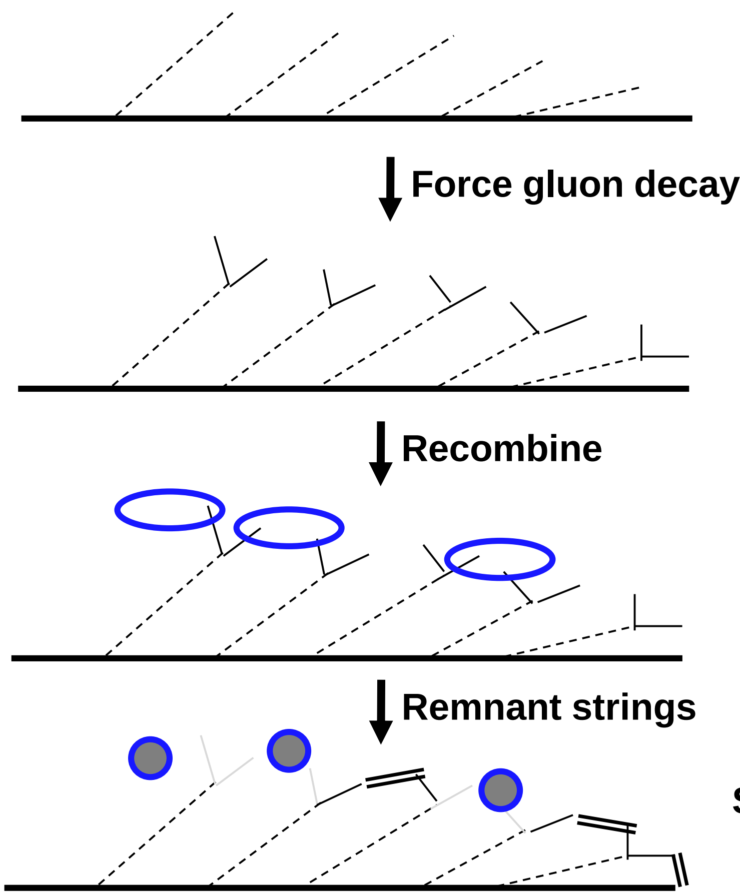
- For the probabilities to be positive definite, need proper q, qbar Wigner functions: Introduce Husimi smearing by representing quarks by proper wave packets of width δ.
- For $\sigma^2 = 2\delta^2$ the result for the overlap of wave packets and Wigner function is extremely simple. The probability densities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

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

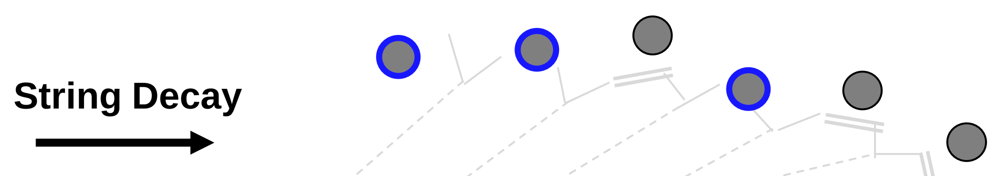
- The true shape and size of the input wave packets are not known.
- Hadron wave function widths fixed by measured charge radii.

Remnant Strings

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

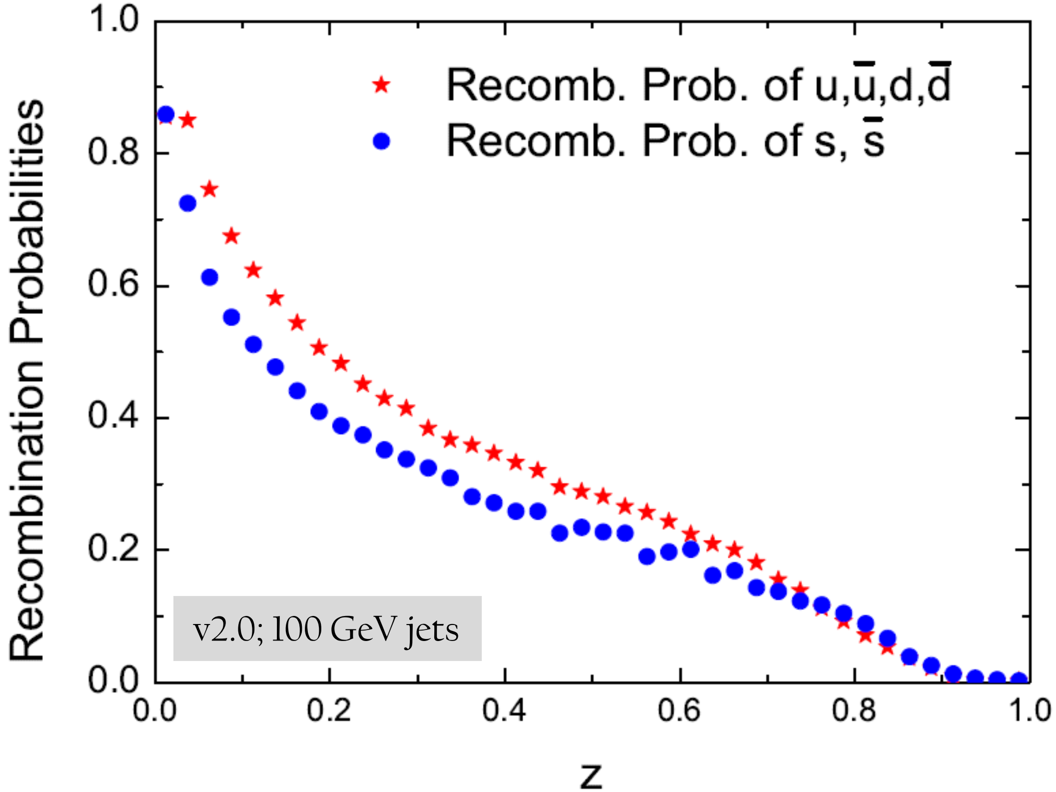


- Why? No confinement in parton shower, quarks can get far away.
- In reality: colored object needs to stay connected.
- Return these partons to PYTHIA to connect them with remnant strings.



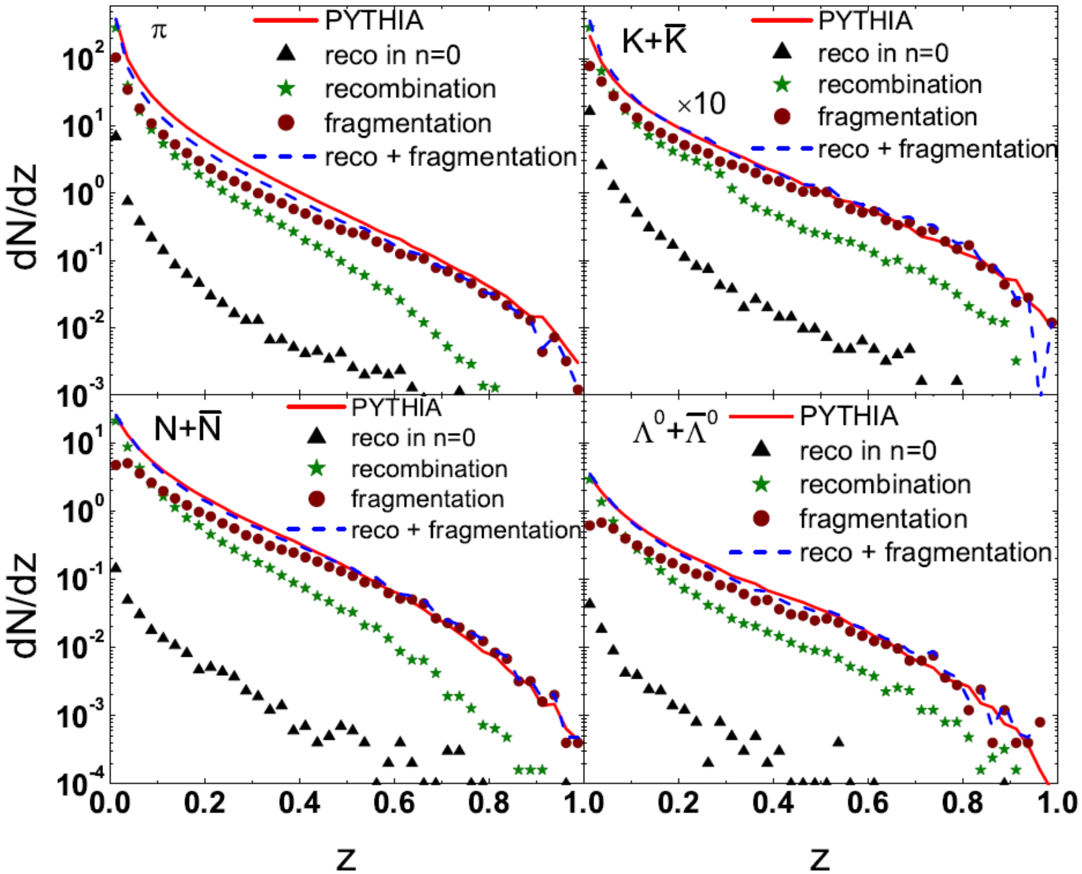
Remnant Strings

- Check on recombination probability (100 GeV PYTHIA vaccum jets)



Results (Vacuum)

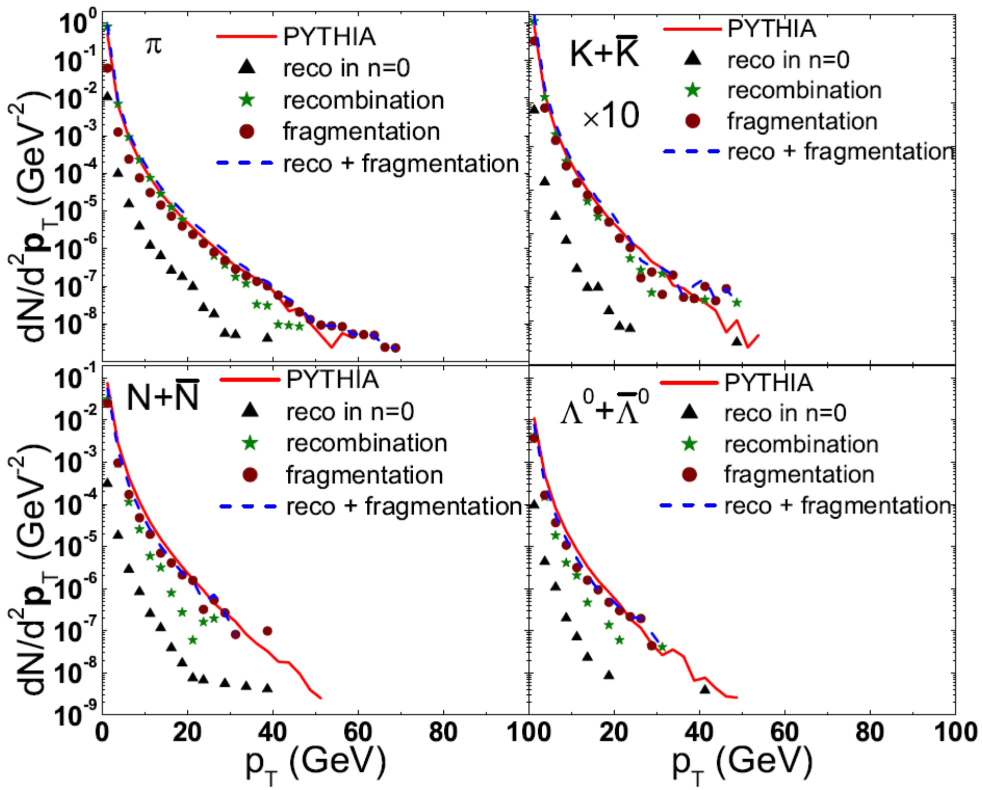
- Longitudinal structure: *dN/dz* of stable particles compared to PYTHIA string fragmentation (e+e-).



v2.0; 100 GeV jets

Results (Vacuum)

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

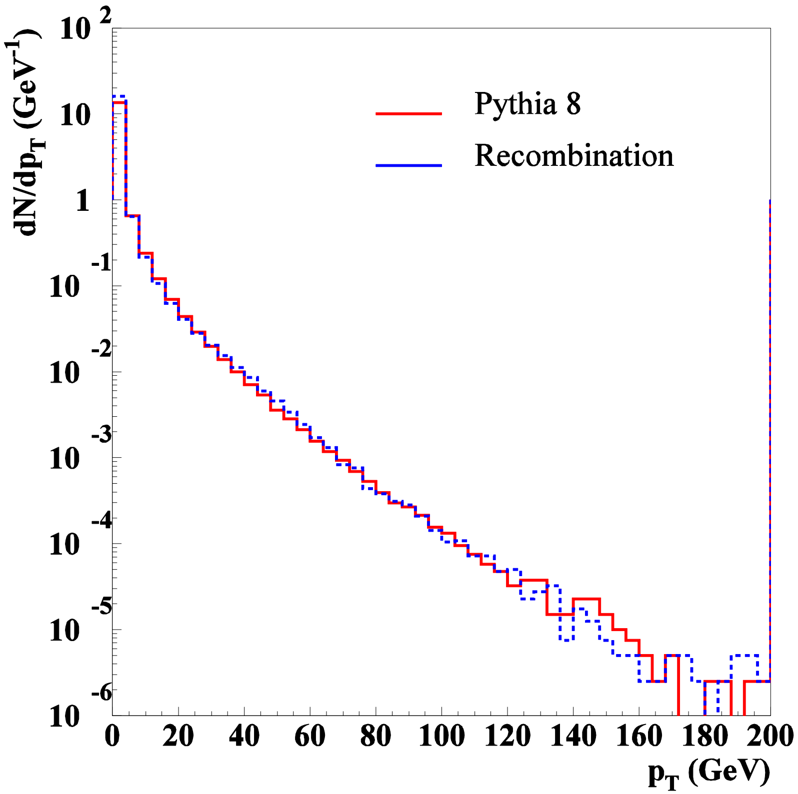


- Generally good agreement with pure string fragmentation.
- No precision tuning to data.

v2.0; 100 GeV jets

Results (Vacuum)

- More complicated systems: dN/dP_T of hadrons in p+p.



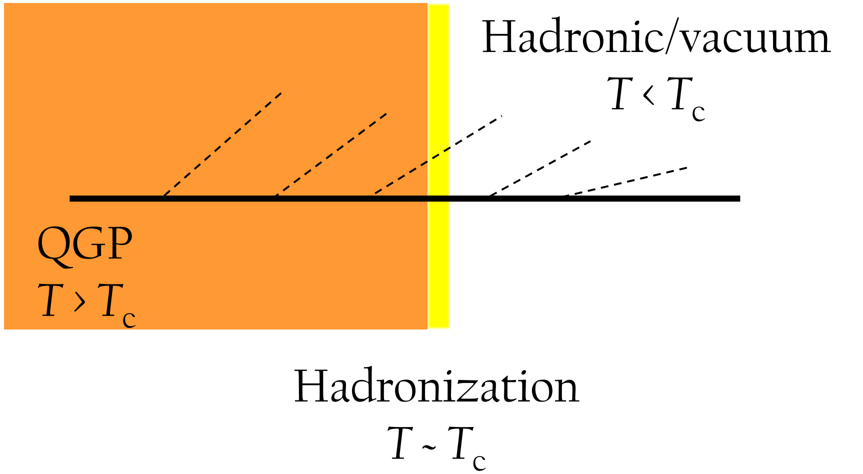
v1.0

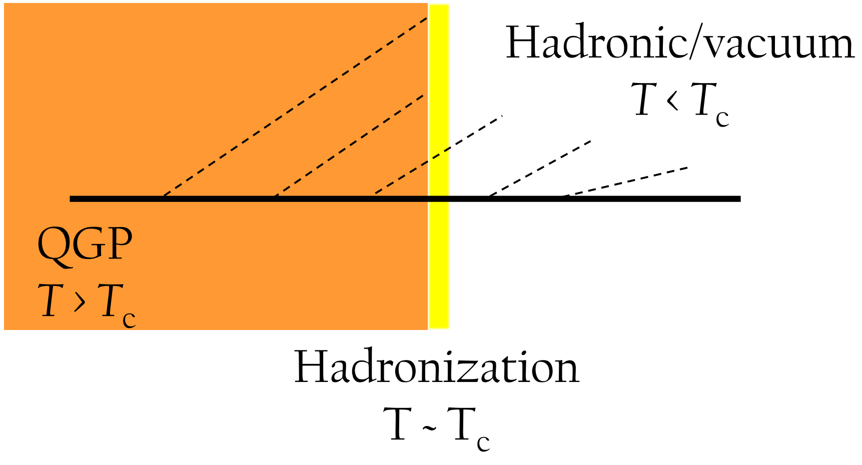
Credit: Tan Luo

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.

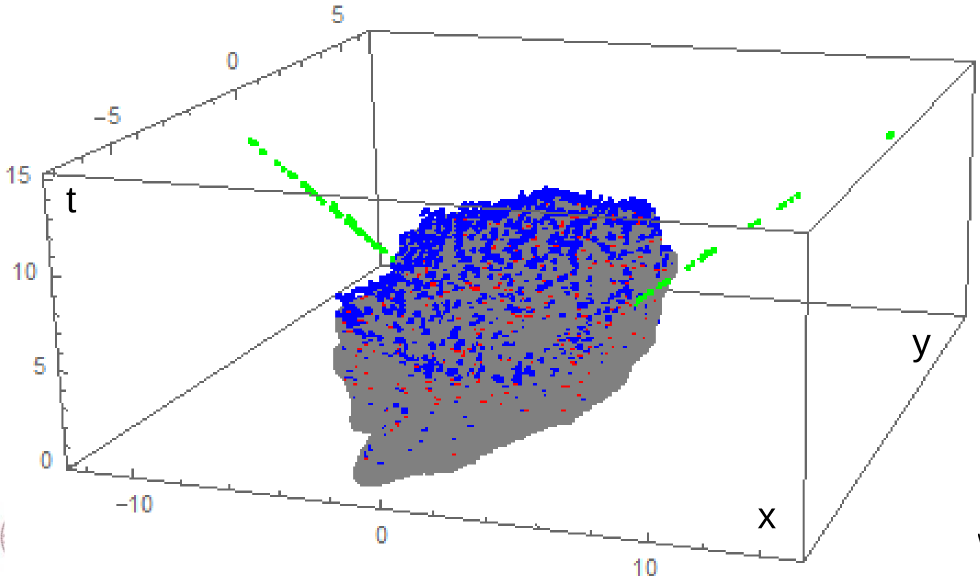


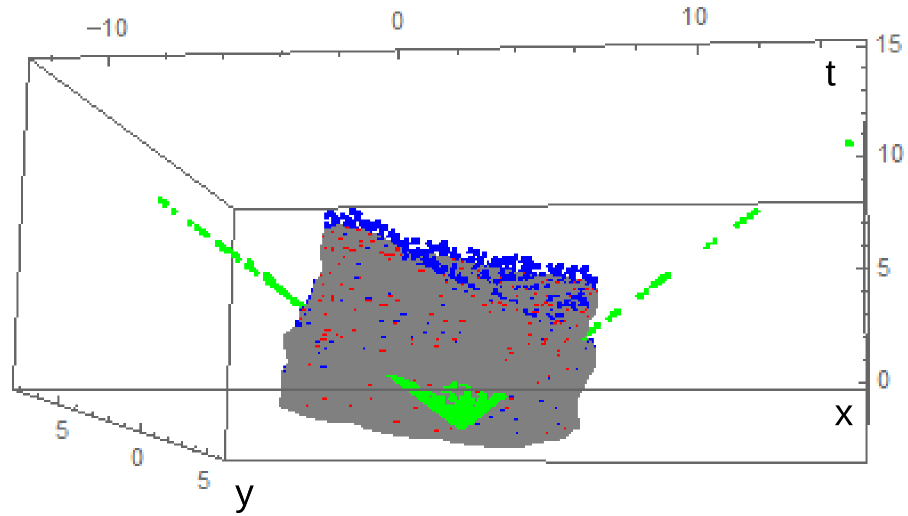


Adding a Medium

- iEBE (Ohio State) event-by-event hydro with sampled thermal partons on the T=T_c hypersurface.
- As input for recombination we need to sample $f(x,p)$, not $f(x,p)p\cdot\sigma/E$

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

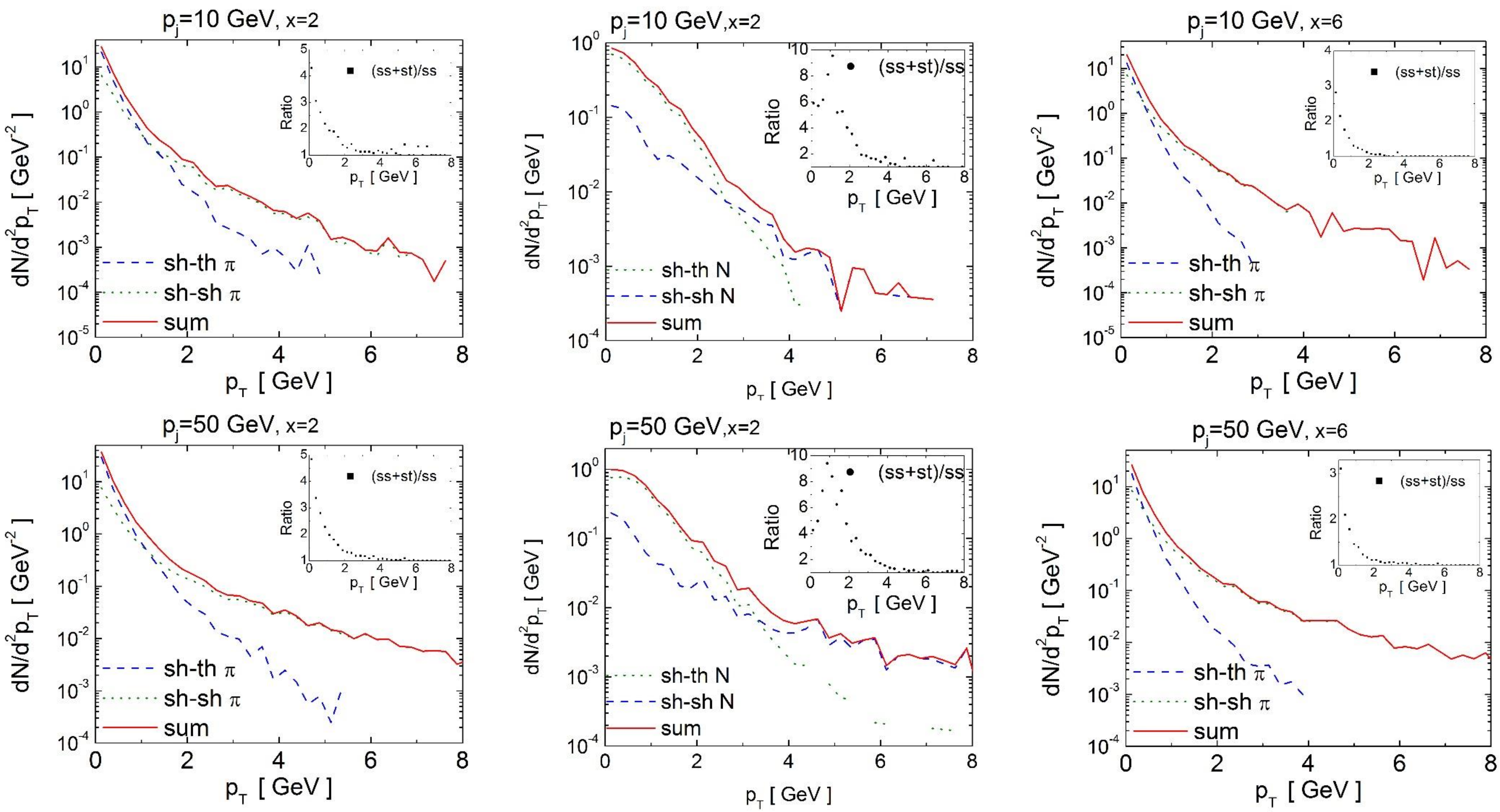




Early Results With Medium

- PYTHIA showers propagated to the $T=T_c$ hypersurface (E ‹ 600 MeV quarks assumed lost); sh-sh includes remnant fragmentation.

v2.1

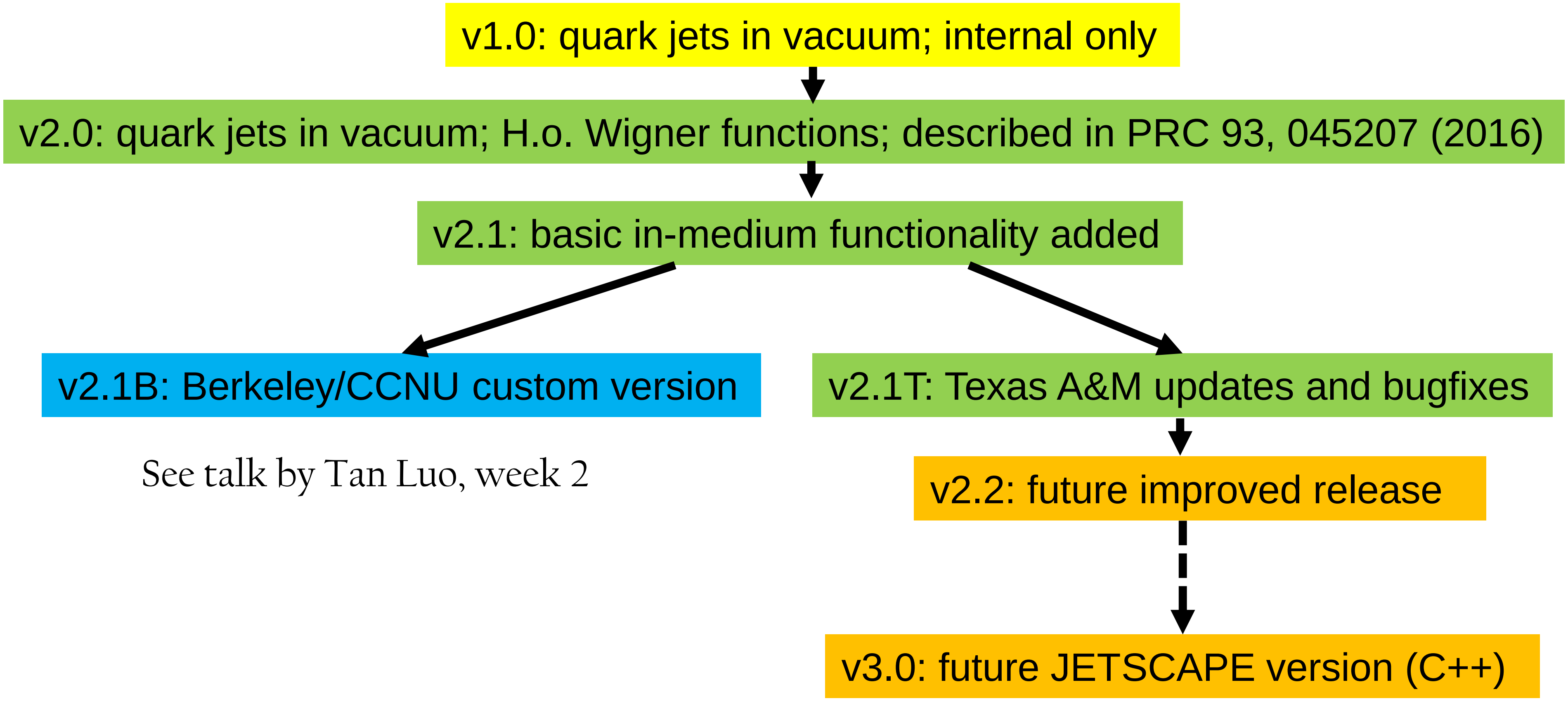


Some Results With Medium

- Medium effects can be seen for small momenta < 10 GeV.
- Shower-thermal recombination takes over from pure shower-shower recombination; remnant strings are still important.
- Importance of shower-thermal vs shower-shower: $N > K > \pi$. Large for nucleons.
- Caveat: these are not proper in-medium showers.

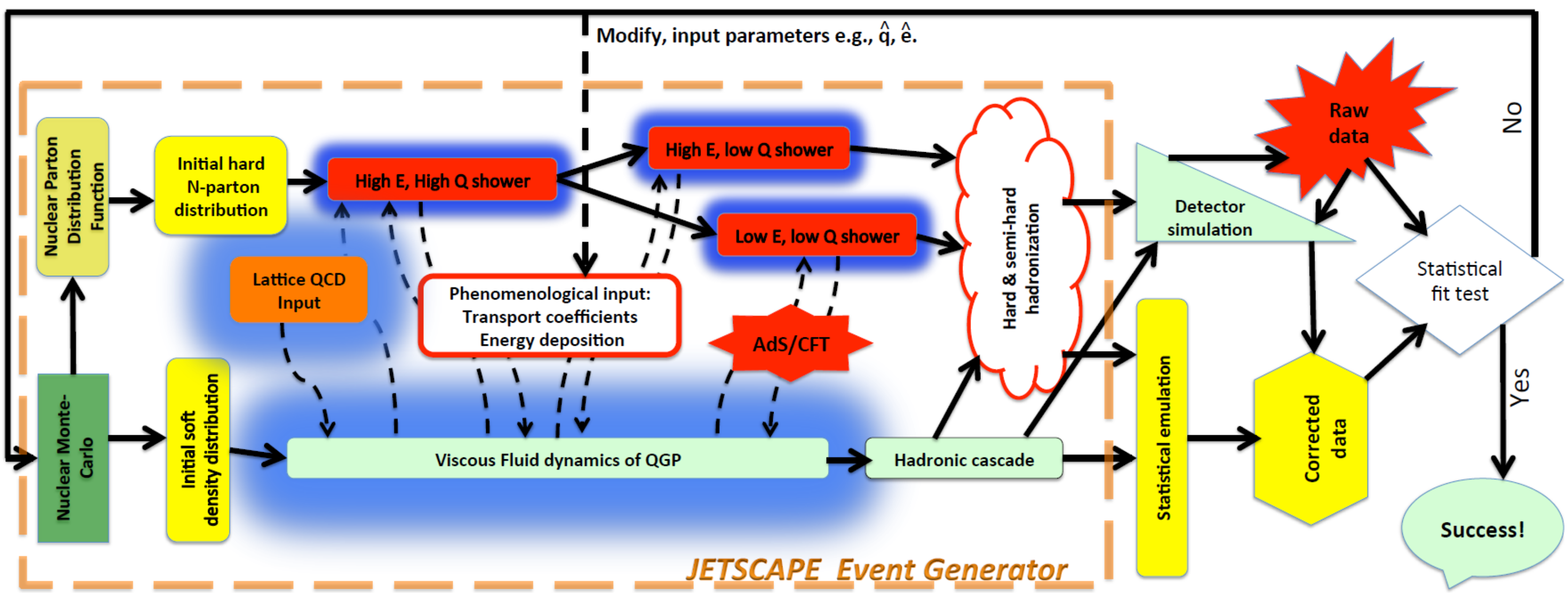
Current Work

- TReC Code versions



Current Work

- The JETSCAPE framework



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.

- v2.2 will be available soon.
- Systematic studies of jet medium effects with in-medium jet MCs are ongoing.

Backup

Recombination Step

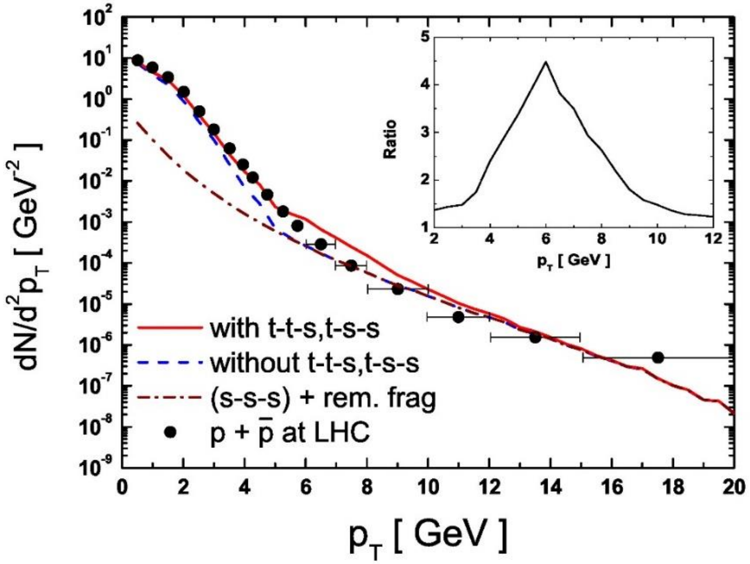
- Parameters (harmonic oscillator WF case)

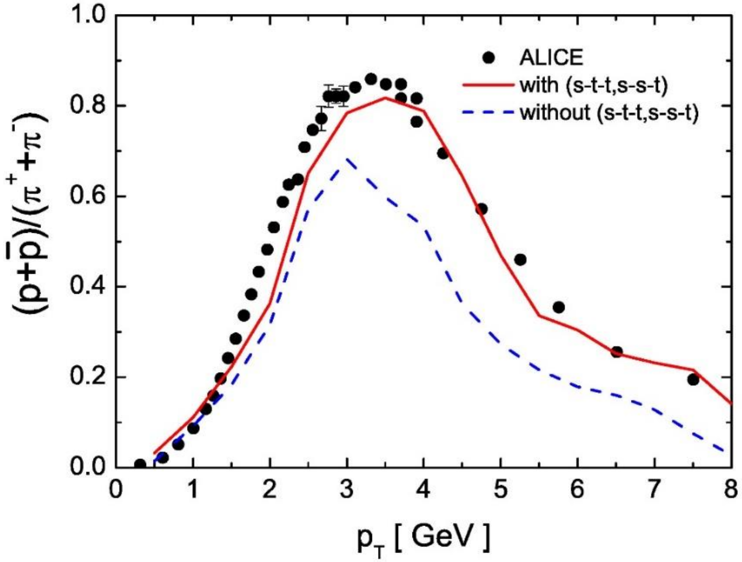
TABLE I. Table of measured charge radii R (from Ref. [21]), widths σ_M (and σ_B), and statistical factor g for all hadrons used in this calculation.

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

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)





The D_s as a Signature

- D_s = charm-strange bound state.
- Signature 1: D_s vs D R_{AA} is a measure for strength of recombination vs fragmentation.
  - Charm in D_s and D suffer from same drag and diffusion up to T_c.
  - If charm fragments: D_s/D as in p+p.
  - If charm recombines: D_s picks up enhanced strangeness $\rightarrow D_s$ enhanced.
  - Numerical check: hadronic phase does not destroy this signal.
- Signature 2: D_s vs D v_2 can measure the relative strength of D_s vs D interactions in the hadronic phase.
  - D_s is an analogue to multi-strange hadrons in the light sector.
  - If there is early freeze-out it can be read of from the D_s vs D v_2.

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