HADRONIZATION

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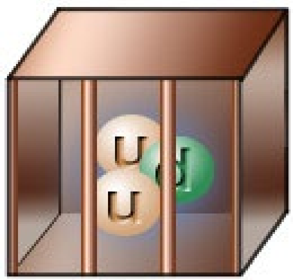
- Hadronization in QCD
- How to make hadrons in five different ways
- Hybrid Hadronization
- Hadronization in JETSCAPE and XSCAPE

PART I: HADRONIZATION IN QCD

WHAT'S THE DEAL WITH HADRONIZATION?

- The fundamental degrees of freedom in QCD (quarks and gluons) form bound states at low energies.
- This true also in QED, but there is an added complication in QCD: Confinement.



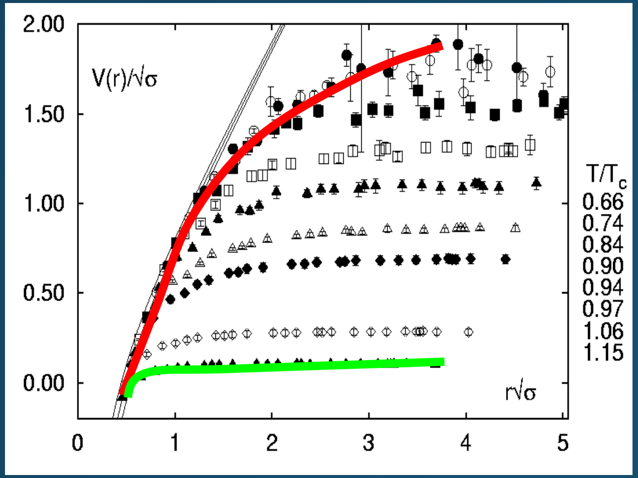
- Quarks and gluons *must* be in color singlet bound states, i.e. mesons or baryons.

⇒ Every simulation or event generator with parton physics must know how to get the partons from hadrons and how to turn partons back into hadrons (hadronization).

- Confinement is not understood from first principles.

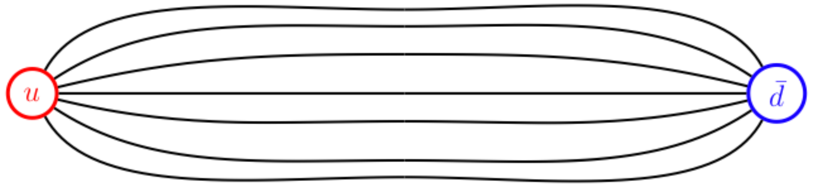
HADRONIZATION ⟷ QCD AT LARGE DISTANCES

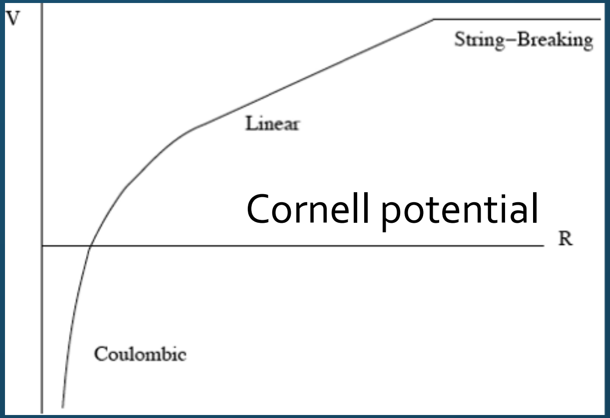
- Confinement can be seen on the lattice:



Static heavy quark potential at different temperatures (Karsch et al.)

- Phenomenology: Dual Meissner Effect in QCD vacuum leads to flux tubes ⇒ string picture!





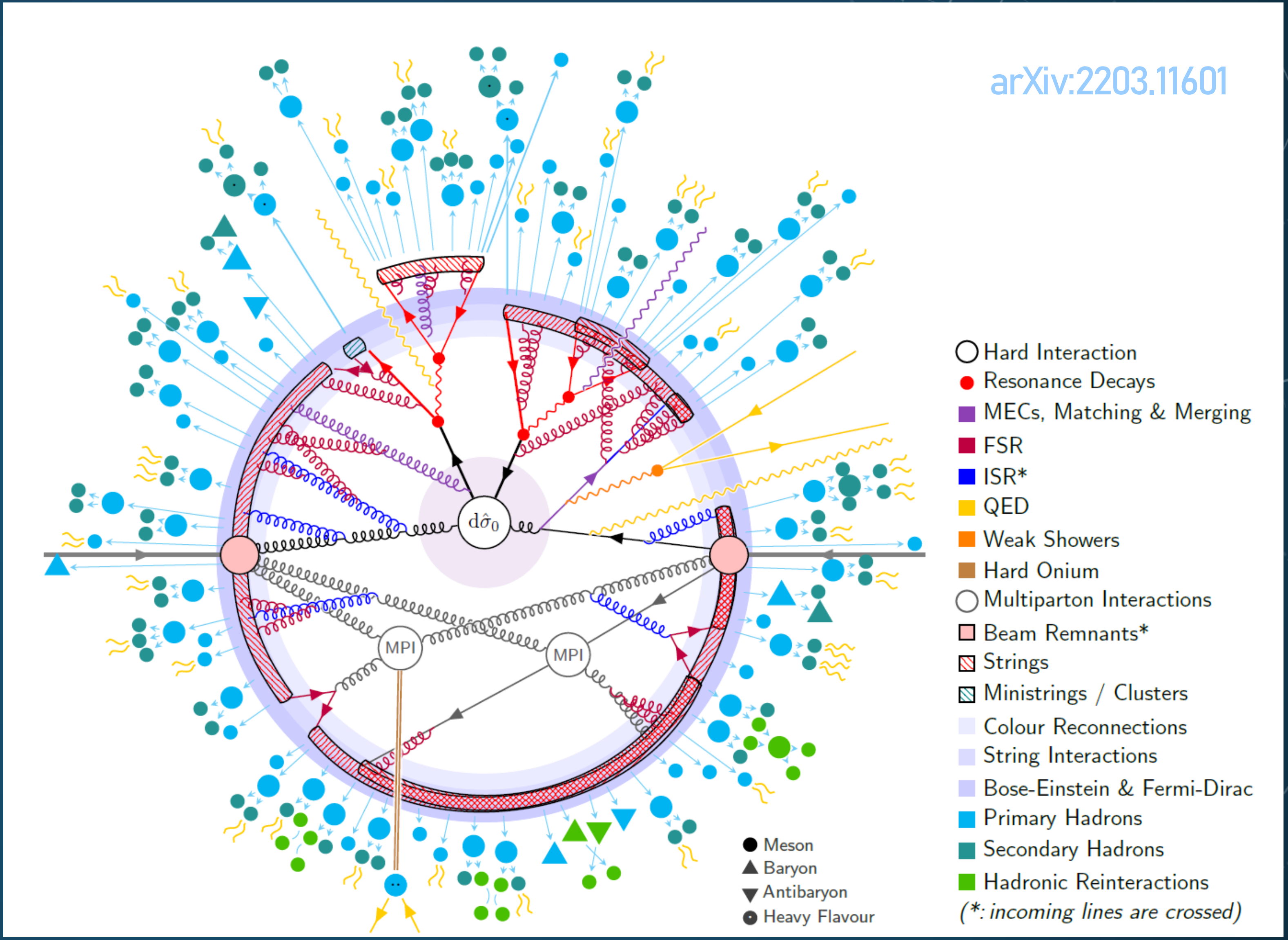
$$V(r) = -\frac{a}{r} + Kr$$

THE CHALLENGE

In the absence of first principle calculations we need to model hadronization.

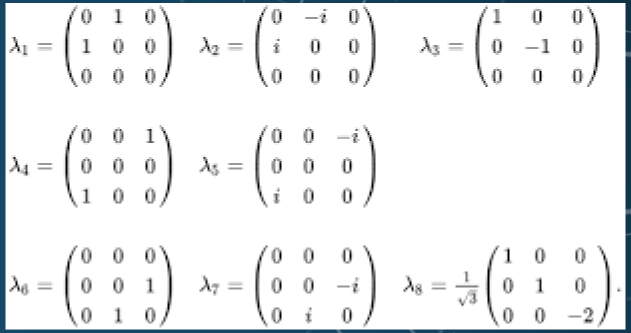
Models should:

- ○ Obey relevant observation laws and symmetries.
- ○ Enforce confinement.
- ○ Implement as many phenomenological properties of QCD as possible.



arXiv:2203.11601

THE ROLE OF COLOR



$$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

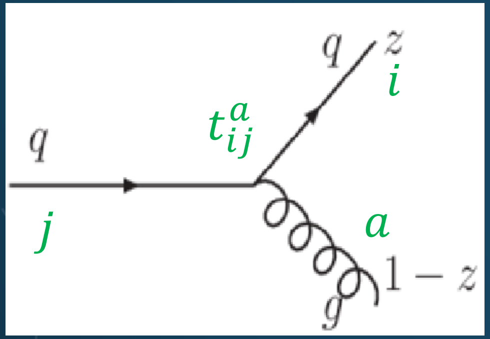
$$\lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}$$

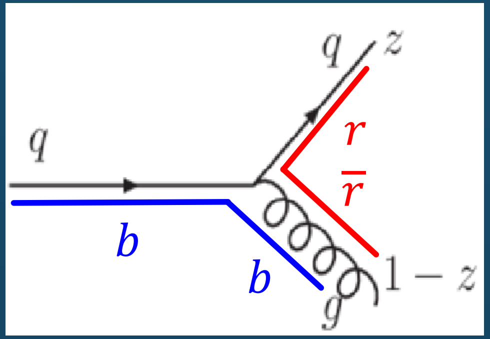
$$\lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad \lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \quad \lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}.$$

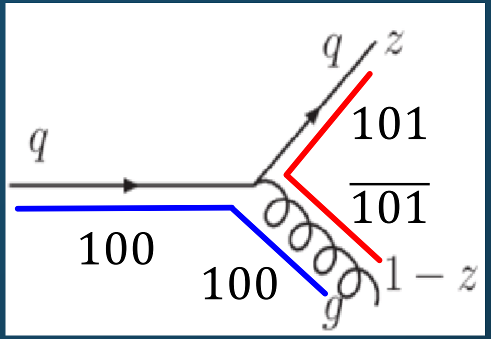
- QCD color is based on the group SU(3).
- We are not interested in color degrees of freedoms, our world is “white”. Calculations thus typically sum or average over color degrees of freedom ⟶ “color factors”.

- Parton based Monte Carlo’s typically employ the correct color factors for perturbative processes. In addition, there might be a need to track the “direction” of a parton is SU(3) as well: e.g. we might want to track which partons can form color singlets for hadronization.

- Instead of the full SU(3) information partons are assigned color tags in an $N \to \infty$ approximation.







PART II: HOW TO MAKE HADRONS IN FIVE DIFFERENT WAYS

THE HYDRO ANGLE

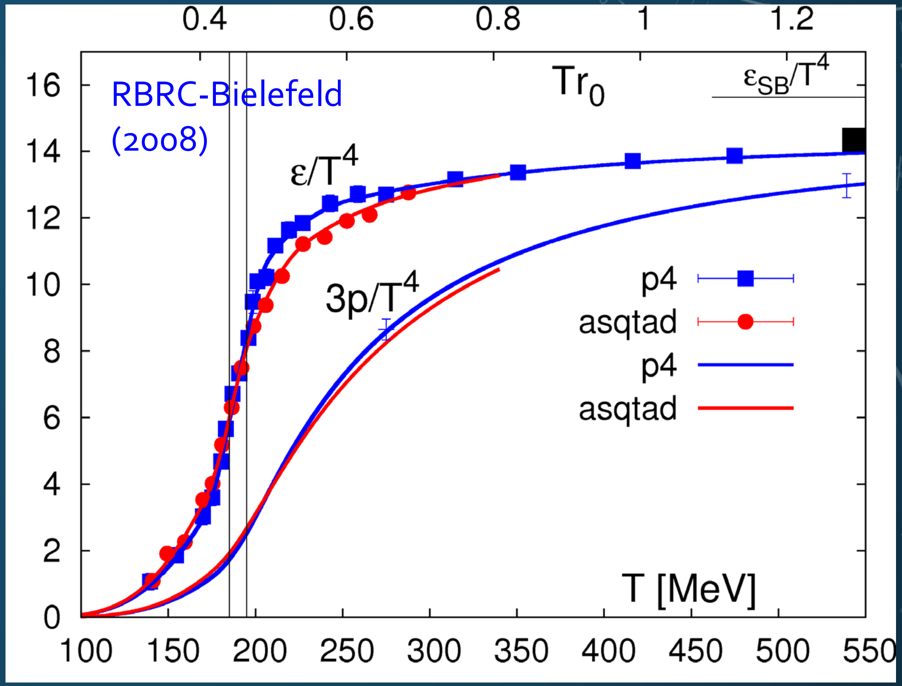
- In the long wave-length, large time, large volume limit of QCD we do not care about individual partons and hadrons. We only want to know average, thermodynamic quantities.

- Applies for fluid dynamic simulations for the bulk of heavy ion collisions!

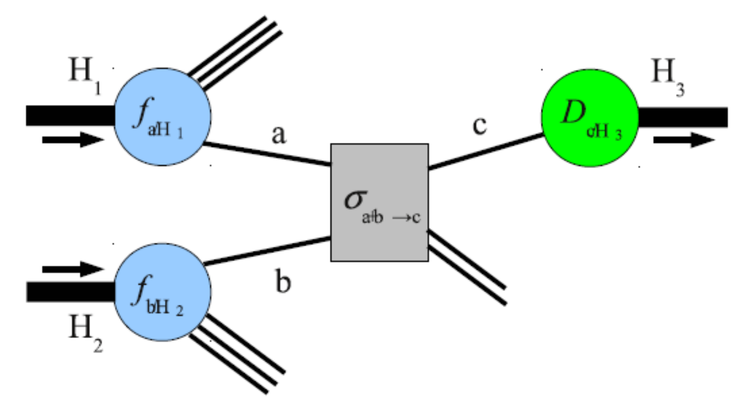
- It is sufficient to know the equation of state (+ any necessary transport coefficients) around T_c from lattice QCD or experiment.

- For an event-by-event description a hypersurface at a lower temperature can be sampled to create hadrons.

- This avoids the much more challenging particle-by-particle modelling required in parton transport models!



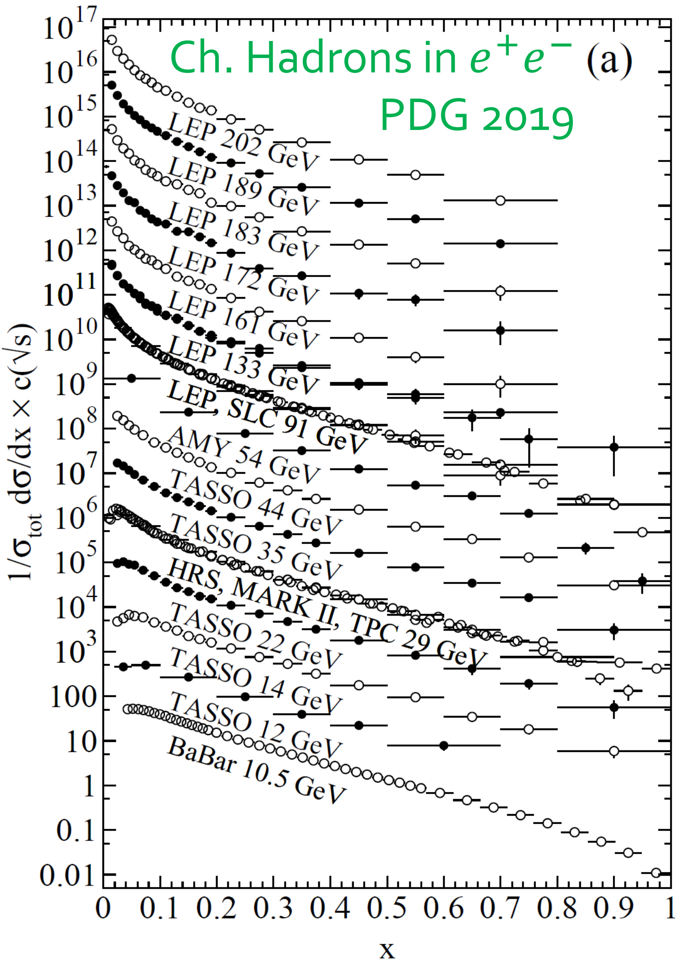
INDEPENDENT FRAGMENTATION



- A first-principle approximation based on QCD factorization, but the necessary fragmentation functions are not calculable (even lattice is hard).
- Proper operator definition. E.g. quark fragmenting into a hadron H:
- $$D_{q/H}(z) = z\int \frac{dy^-}{4\pi} e^{-iP^+y^-/z} \left\langle 0 \middle| q(0)a_H^{+}(P^+)a_H(P^+)\bar{q}(x^-) \middle| 0 \right\rangle$$

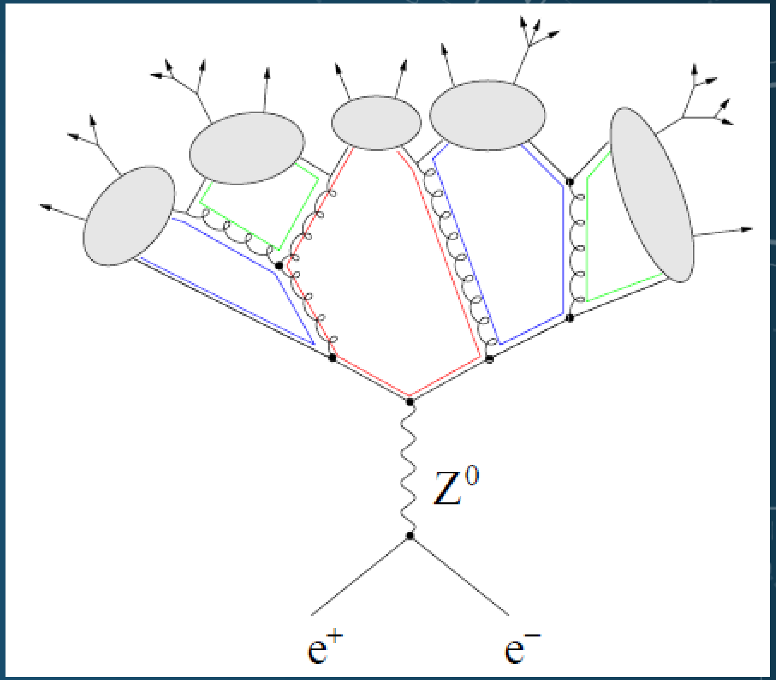
J. C. Collins and D. E. Soper, *Nucl.Phys.* 194, 445 (1982)

- Perfect for semi-inclusive pQCD but could be more widely applied as a model.
- The input are partons from a hard process without final state radiation!
- Fragmentation functions ~ final state radiation + hadronization



CLUSTER HADRONIZATION

- Primarily for jet Monte Carlos: take fully developed parton showers.
- Force non-perturbative $g \rightarrow q\bar{q}$ splitting
- Local color neutrality: $q\bar{q}$ form color-neutral clusters.
- Clusters typically have masses of several GeV; decay into hadrons which can decay further into stable hadrons.
- Some similarities with recombination!

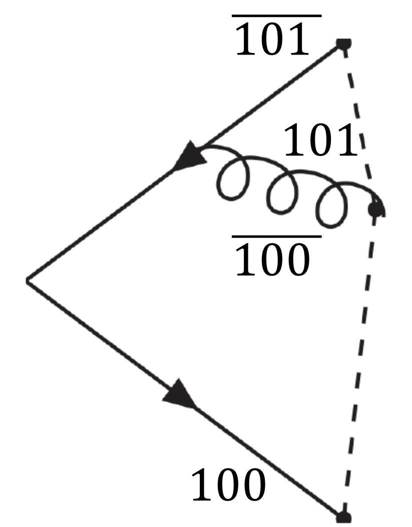


Implemented in HERWIG.

G. Marchesini, B.R. Webber et al.

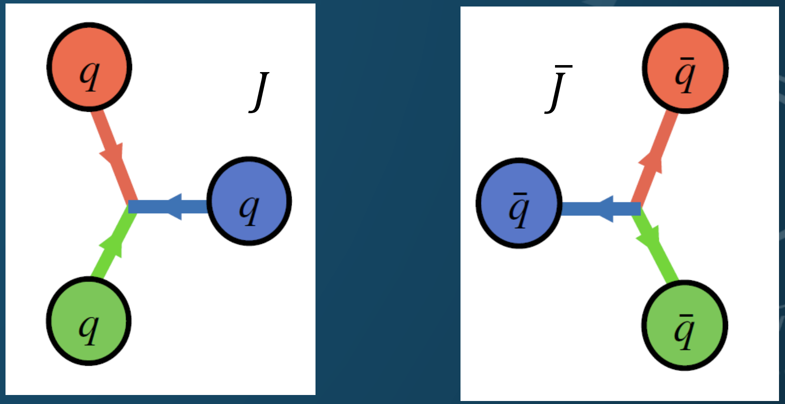
STRING FRAGMENTATION

- Again primarily applied in jet Monte Carlos, most notably PYTHIA and JETSET.
- Keep track of color singlet configurations via color tags.
- In a color singlet string configuration each color tag (except those in junctions) has a matching anti-color tag and vice versa and they are connected by the string.
- Strings terminate in (anti)quarks, (anti)diquarks or can connect to a (anti)junction.



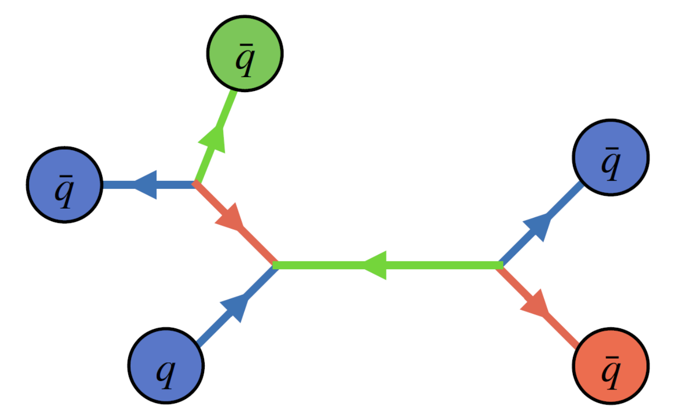
S. Prestel (Lund)

- Gluons are “kinks” in strings.
- (Anti)junctions are objects with three (anti)color tags in a singlet configuration that carry baryon number ± 1.
- Simple examples (they could have many gluons or connect to other junctions):



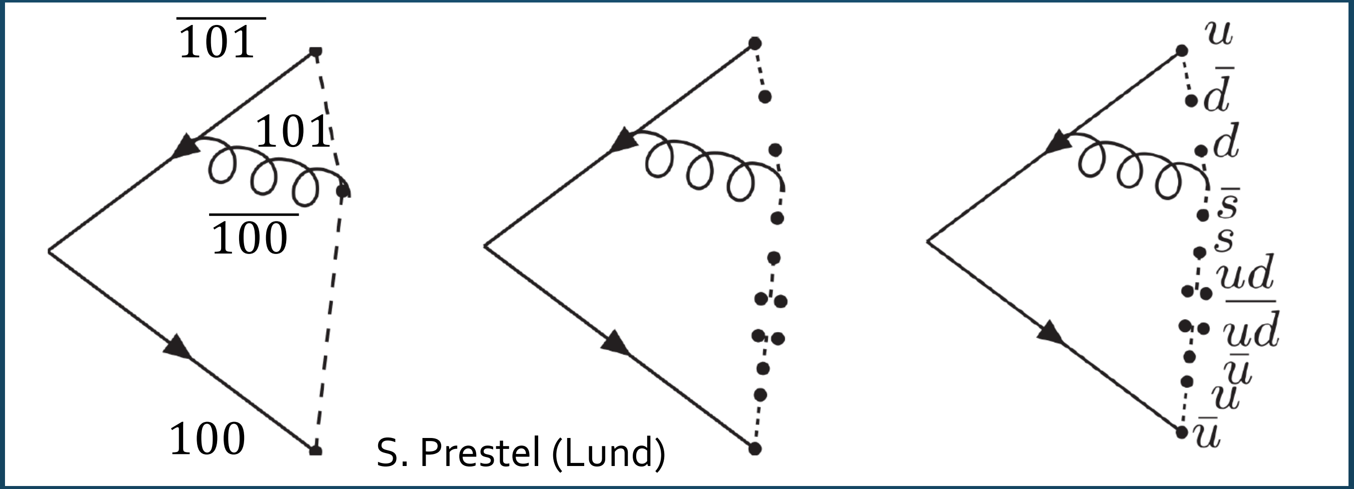
J. Altmann (Monash)

STRING FRAGMENTATION



J. Altmann (Monash)

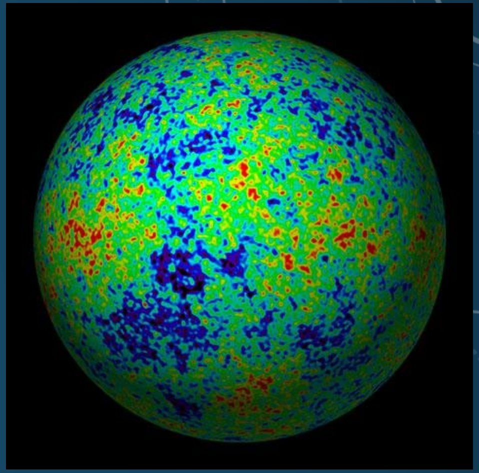
- The formalism allows for very complicated string topologies.
- Anything beyond di-junctions can usually not be handled by PYTHIA 8.
- Break strings by pair creation of quarks or diquarks.
- Let the emerging color singlet systems collapse into hadrons.



S. Prestel (Lund)

QUARK RECOMBINATION

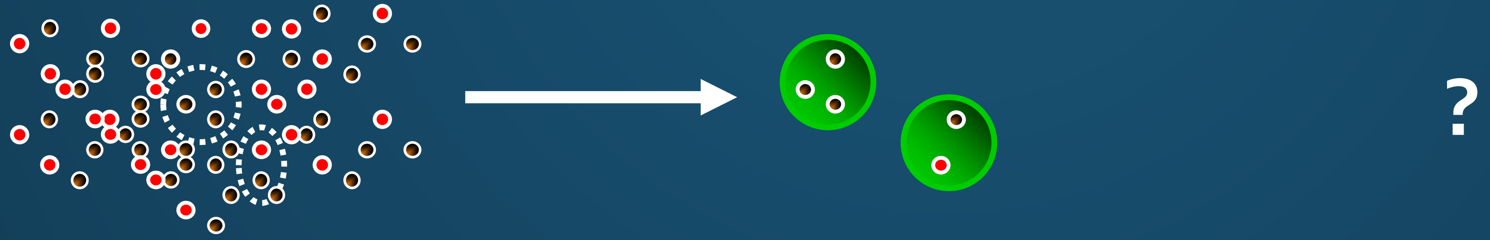
- Atomic physics: recombination of protons and electrons into hydrogen + photons



WMAP

  - Photons from the recombination event 300,000 years after the Big Bang.

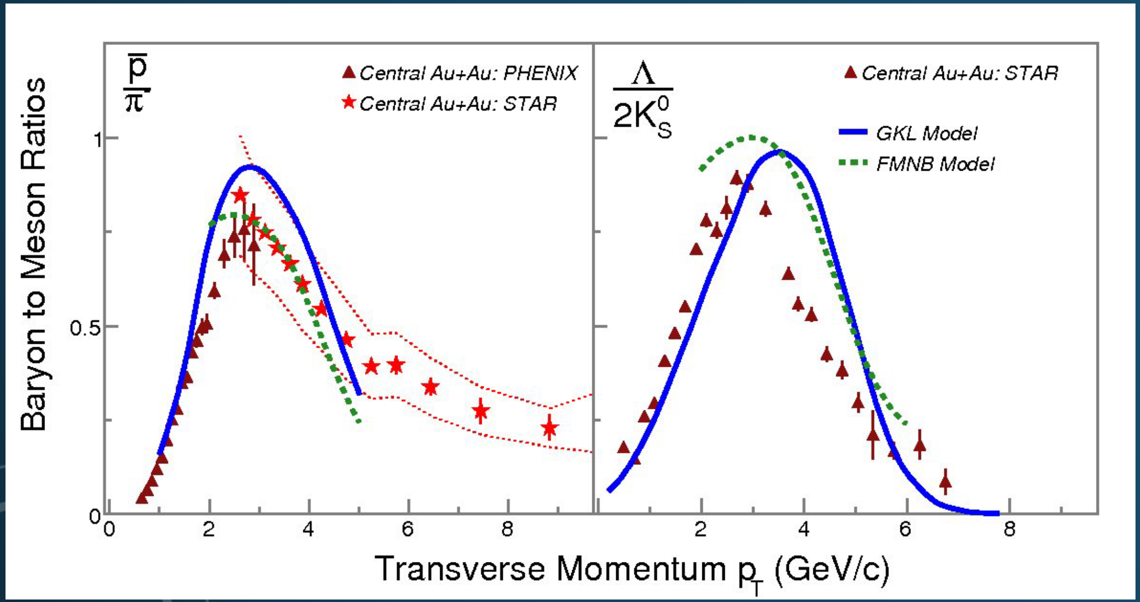
- Nuclear/particle physics: recombination of quarks into mesons and baryons?

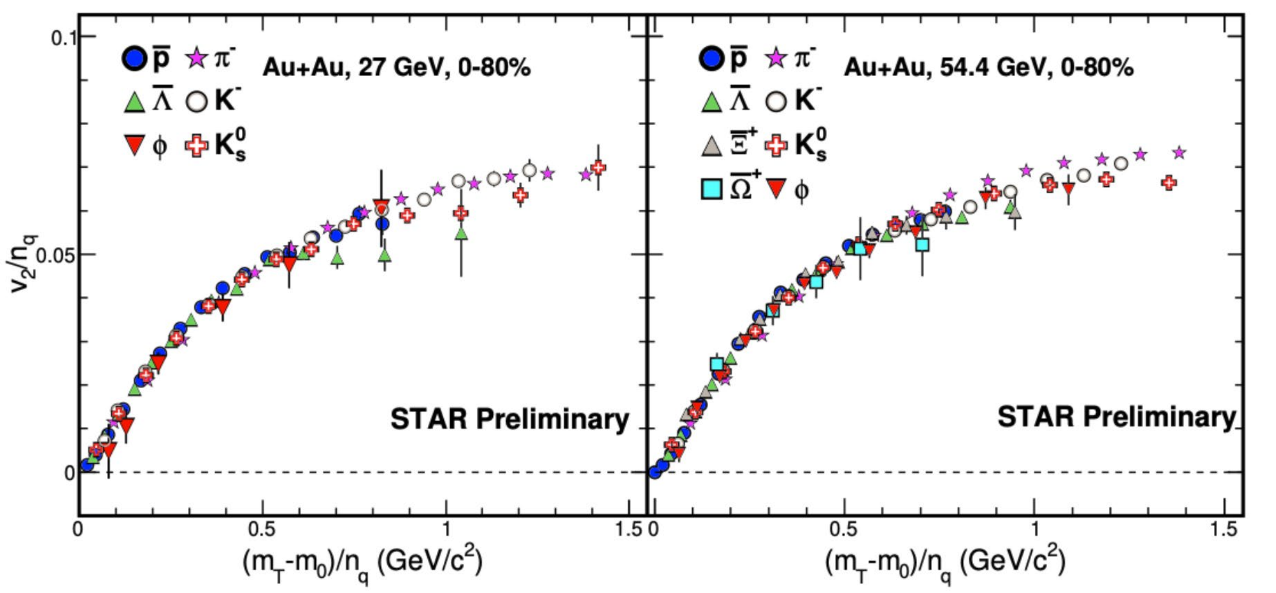


  - Complications: gluons, confinement, relativistic dynamics, chiral symmetry breaking,…

QUARK RECOMBINATION

- Quark recombination is as ancient as QCD, but has been in the shadows of string and cluster hadronization (because data was mostly from e^+e^-, ep and pp machines!)
- Enter high energy heavy ion data ~ 2000.
- Quark recombination could explain anomalous large baryon numbers (“baryon puzzle”)
- It could also explain the elliptic flow scaling with valence quark number (“universal quark flow is translated to hadrons via recombination”)



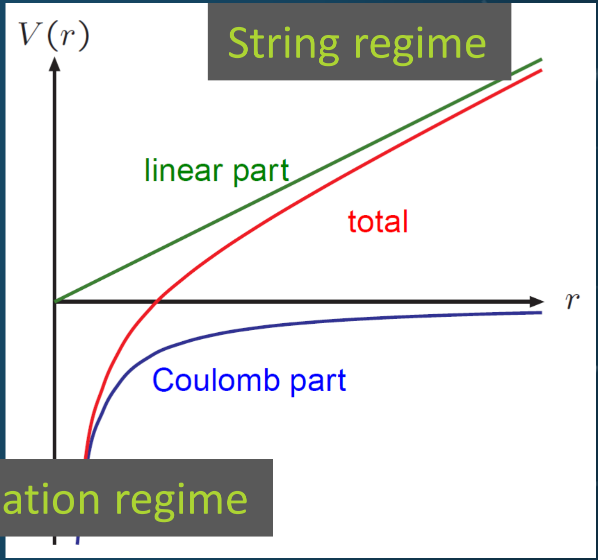


PART III: HYBRID HADRONIZATION

THE NEED FOR A COMPREHENSIVE MODEL

- We need a model that can work for systems from $e^+ + e^-$ to $A + A$.
- Excluding soft bulk hadronization in $A + A$ for now (hydro does an excellent job)
- Strings work very well for jet-like systems (partons at large distances in phase space)
- Quark recombination works well if thermal/background partons are involved in large numbers.
- Enter Hybrid Hadronization, a hybrid of string fragmentation and recombination.

  K. C. Han, R. J. Fries, C. M. Ko, Jet Fragmentation via Recombination of Parton Showers, Phys.Rev.C 93, 045207 (2016)
- Interpolates smoothly in between, two limits:
  - Dilute systems → Dominance of string fragmentation
  - Dense systems → Dominance of quark recombination



String regime

Recombination regime

- Use a physics criterion to separate the domains: recombination probabilities vanish for large phase space distances

HYBRID HADRONIZATION WORK FLOW

Input:
Provide partons with virtualities below some cutoff, with space-time information and color tags

Recombination Step:
Provisionally decay gluons into $q\bar{q}$. Go through the system sampling the recombination probabilities for all possible q-qbar and q-q-q bound states.

Intermediate Step:
Recombined hadrons and remnant partons in a string system (only color singlets were removed).

Fragmentation Step:
Remnant partons tend to be farther apart in phase space. Fragement using PYTHIA 8.

HYBRID HADRONIZATION WORK FLOW IN A MEDIUM

Input:
Provide partons with virtualities below some cutoff, with space-time information and color tags

Bath of thermal partons

Recombination Step:
Provisionally decay gluons into $q\bar{q}$. Go through the system sampling the recombination probabilities for all possible q-qbar and q-q-q bound states.

Recombination with thermal partons

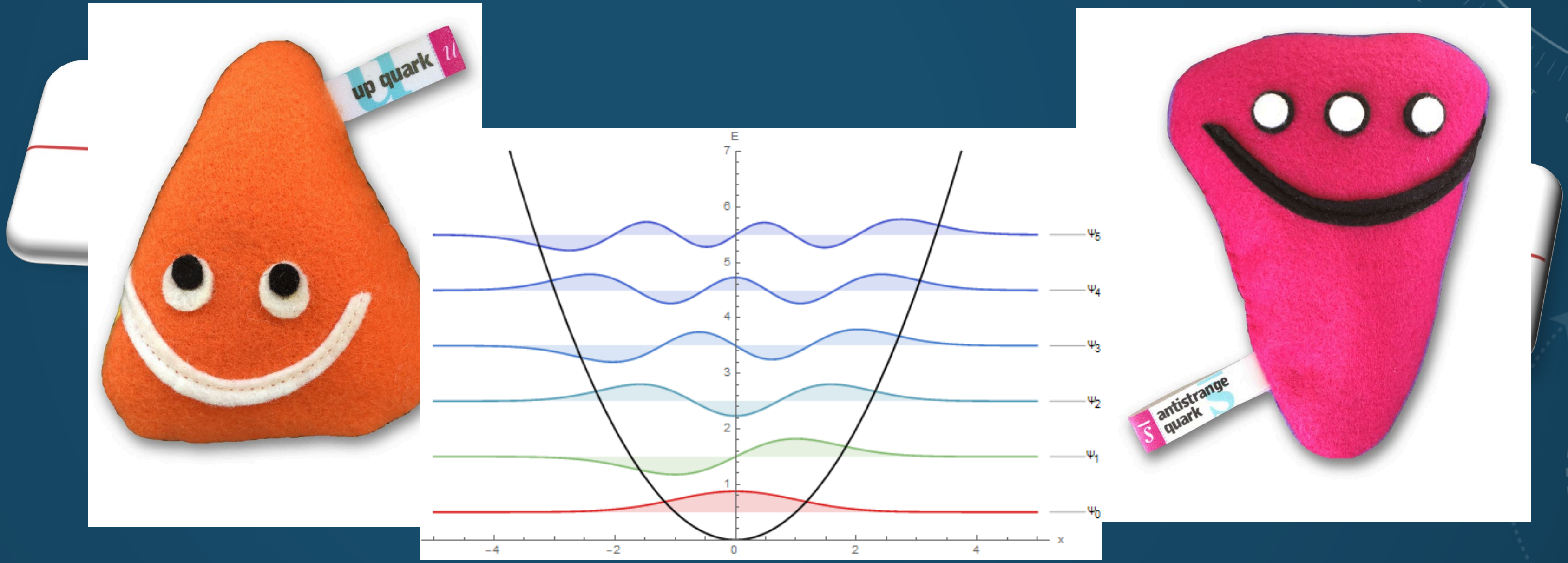
Intermediate Step:
Recombined hadrons and remnant partons in a string system (only color singlets were removed).

Remnant strings with thermal partons

Fragmentation Step:
Remnant partons tend to be farther apart in phase space. Fragement using PYTHIA 8.

SETTING UP THE RECOMBINATION PROBLEM

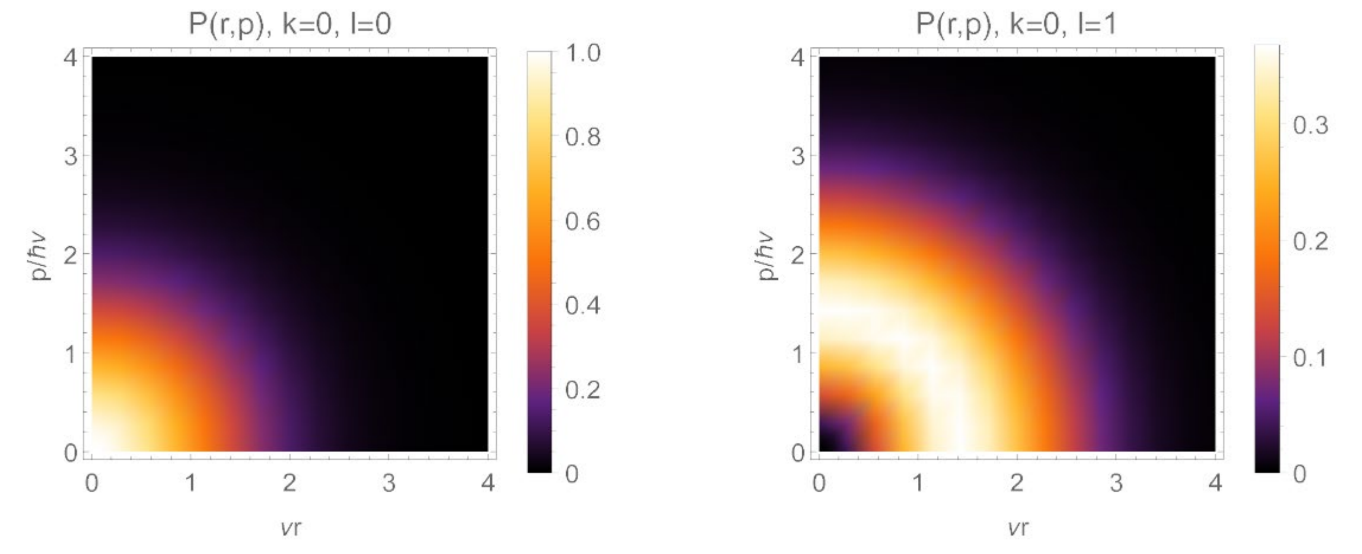
- Quarks/antiquarks = wave packets in phase space
- For simplicity: Gaussian wave packets around centroid phase space coordinates $(\vec{r}_i, \vec{p}_i)$, of given width δ. Color and spin information might be available (otherwise treated statistically).

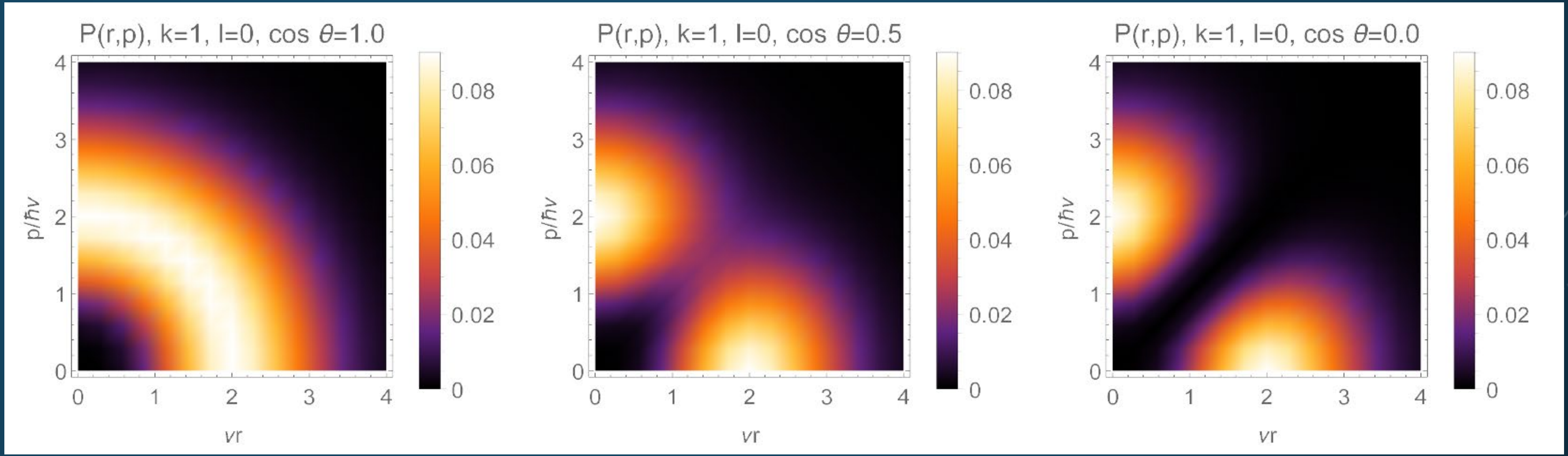


- Short range interaction modeled by isotropic harmonic oscillator potential of width $1/\nu$.
- Use the Wigner formalism in phase space. We need angular momentum eigenstates.

COALESCENCE PROBABILITIES

- Example: Mesons
- We sum over magnetic quantum number m. (we do not track the spin polarization of hadrons)
- Probabilities depend on the relative coordinates of the wave packet centroids, called r and q here.
- θ = angle between r and q.





COALESCENCE PROBABILITIES

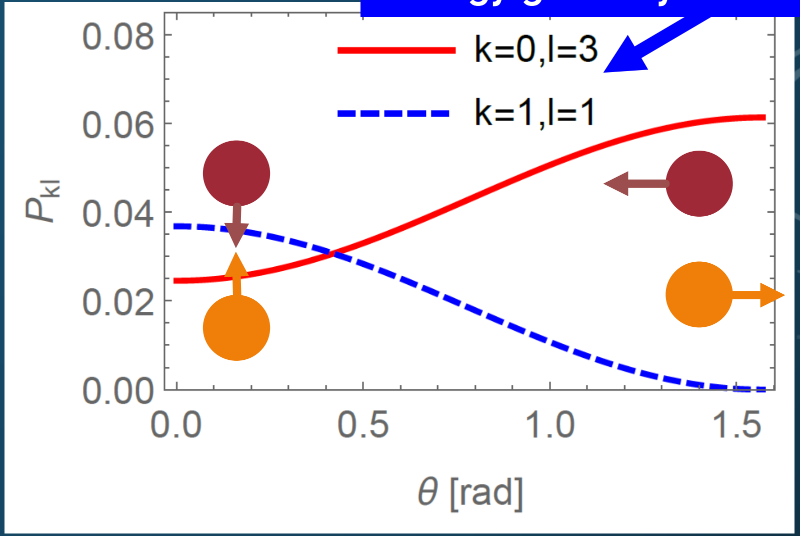
- Probabilities can be written in terms of just two variables: total phase space distance squared v and total angular momentum squared t.

$$v = \frac{\nu^2 r^2}{2} + \frac{p^2}{2\hbar^2\nu^2},$$
$$t = \frac{1}{\hbar^2}\left[p^2 r^2 - (\mathbf{p}\cdot\mathbf{r})^2\right] = \frac{1}{\hbar^2}L^2$$

$$\mathcal{P}_{00} = e^{-v},$$
$$\mathcal{P}_{01} = e^{-v}v,$$
$$\mathcal{P}_{02} = \frac{1}{2}e^{-v}\left(\frac{2}{3}v^2 + \frac{1}{3}t\right)$$
$$\mathcal{P}_{10} = \frac{1}{2}e^{-v}\left(\frac{1}{3}v^2 - \frac{1}{3}t\right)$$

- t makes an intuitive connection between the relative angular momentum of the incoming quarks and the quantum number l of their bound state.

- The total recombination probability also takes into account quark spins (always statistically) and quark color.
- Color factors are determined by color tags. Thermal partons and shower partons with random color are initialized with color tag 0.

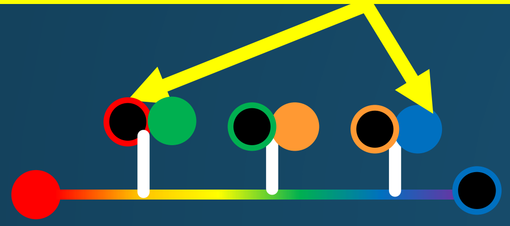


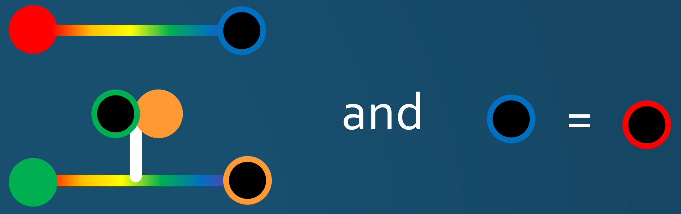
Both are states with the same energy given by N=2k+l=3

REMNANT PARTONS: STRING REPAIR

- Recombination only removes color singlets. Remaining strings “snap together” the right way automatically.

Suppose these two partons recombine.





- Remnant partons with color tag 0 (e.g. from LBT) must be introduced into strings; unused gluons are restored.
- If the initial system was not a color singlet extra partons must be introduced to balance color (this could be beam partons, thermal partons, or fake partons with zero momentum).

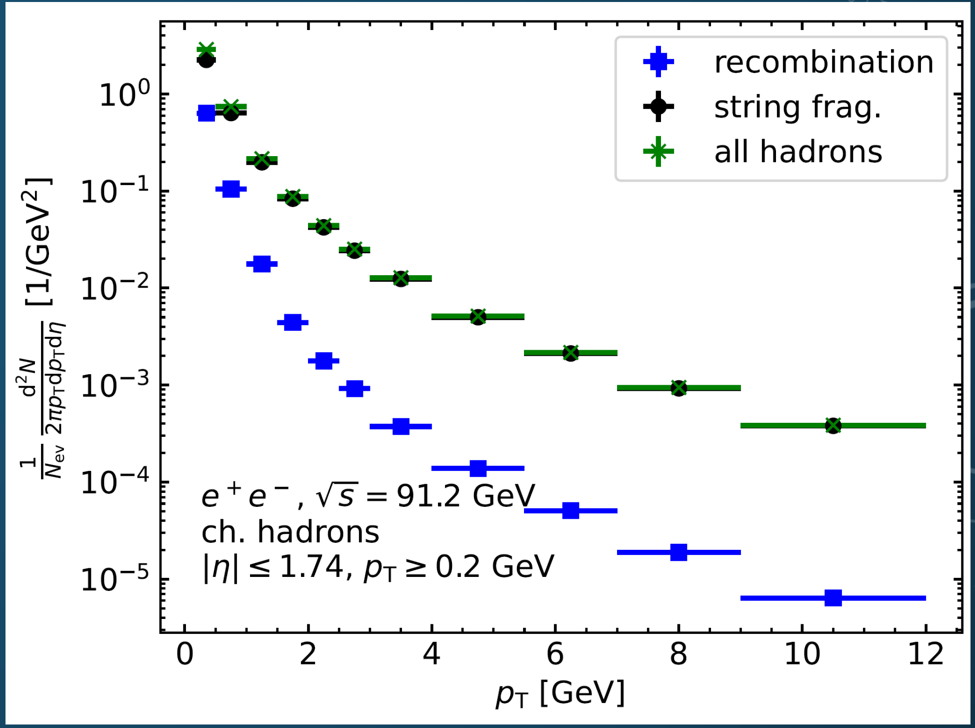
REMNANT STRINGS: FRAGMENTATION

- Hand remaining string systems to PYTHIA 8 for fragmentation.

- Hadronic resonances are presumably important channels in hadronization (both through string fragmentation and recombination). In JETSCAPE decays of excited states can happen in PYTHIA or by invoking SMASH.

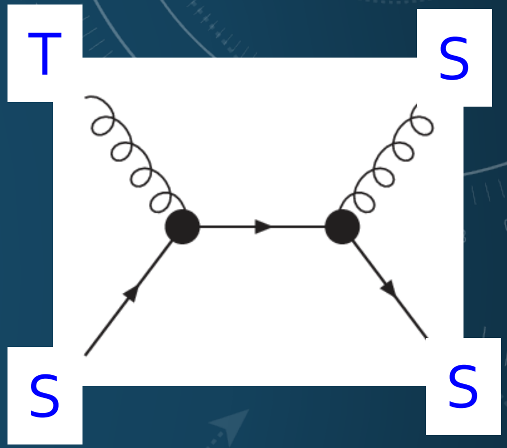
- Remnant partons tend to be farther removed from each other in phase space.
- e^+e^- example:

- As intentioned fragmentation dominates this diluate system, in particular for the jet core.



ADDING A MEDIUM

- The formalism stays the same, just include the additional partons!
- Some shower partons (e.g. LBT) arrive with randomized color (color tag 0)
- HH can process “negative partons” separately. They are the “holes” left in the medium through processes like q (shower) + g (medium) -> q (shower) + g (shower). Important for background subtraction.



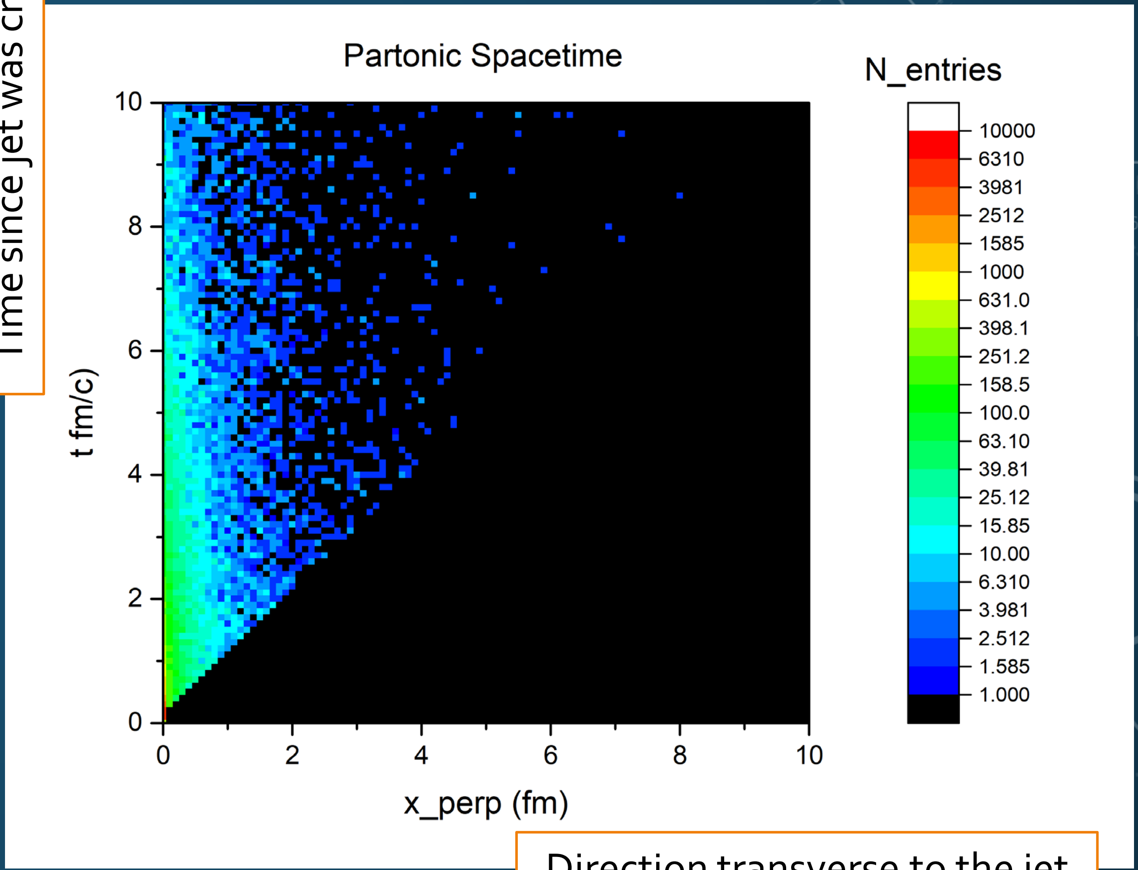
- Thermal partons can be added, or will be sampled from a $T = T_c$ hypersurface or a brick.
- Recombination from only thermal partons, or strings with only thermal partons are currently disabled. On the flip side, all shower partons are always hadronized.

IN-MEDIUM JETS: SPACE-TIME CONSIDERATIONS

- Sampled spatial positions of shower partons after shower evolution for 100 GeV jets (arb. normalization)
- Here: JETSCAPE:pGun+MATTER

100 GeV vacuum jet

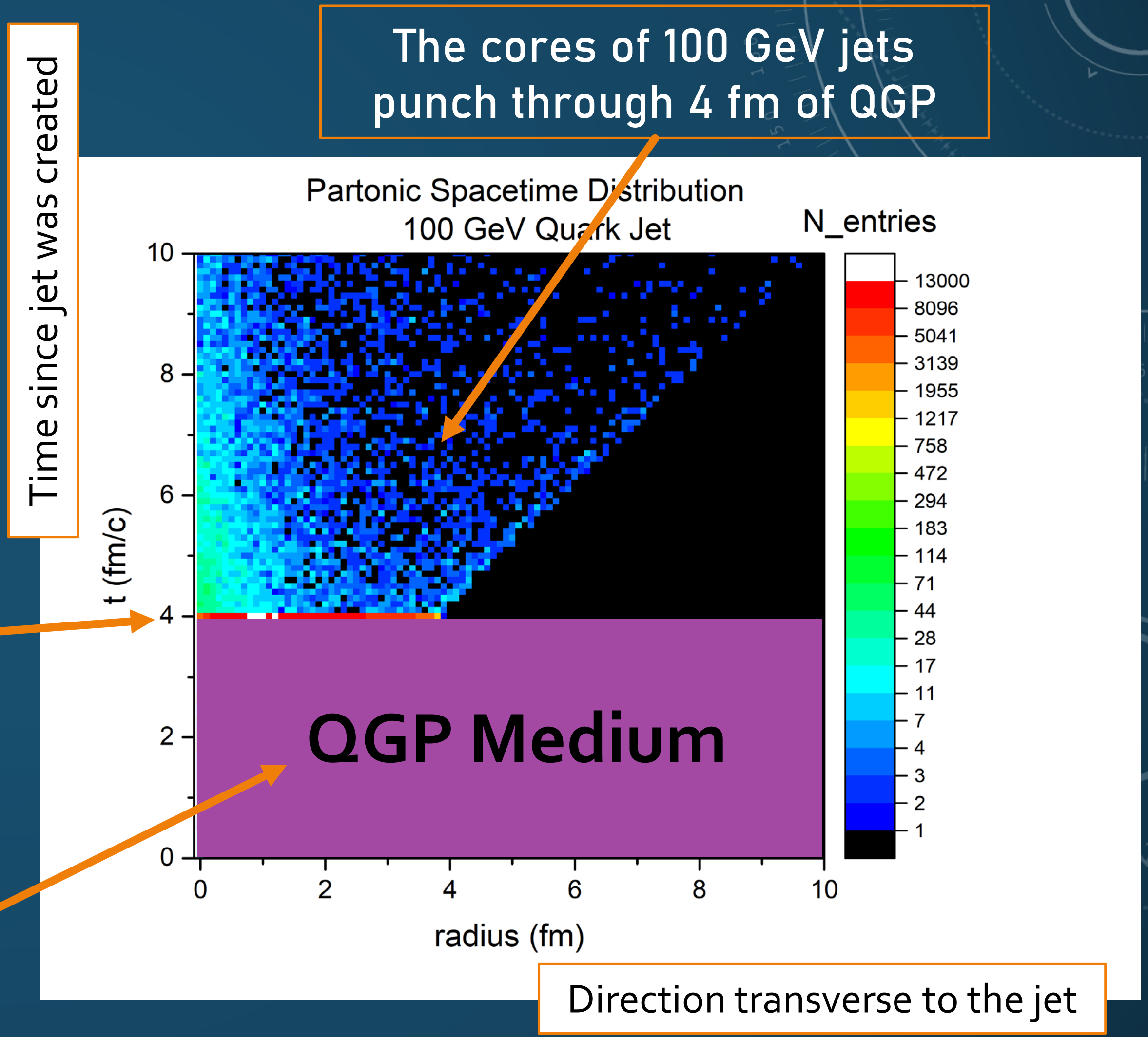
Time since jet was created



Direction transverse to the jet

IN-MEDIUM JETS: SPACE-TIME CONSIDERATIONS

- Sampled spatial positions of shower partons after shower evolution for 100 GeV jets (arb. normalization)
- Here: JETSCAPE:pGun+MATTER+LBT+Brick



Time since jet was created

The cores of 100 GeV jets punch through 4 fm of QGP

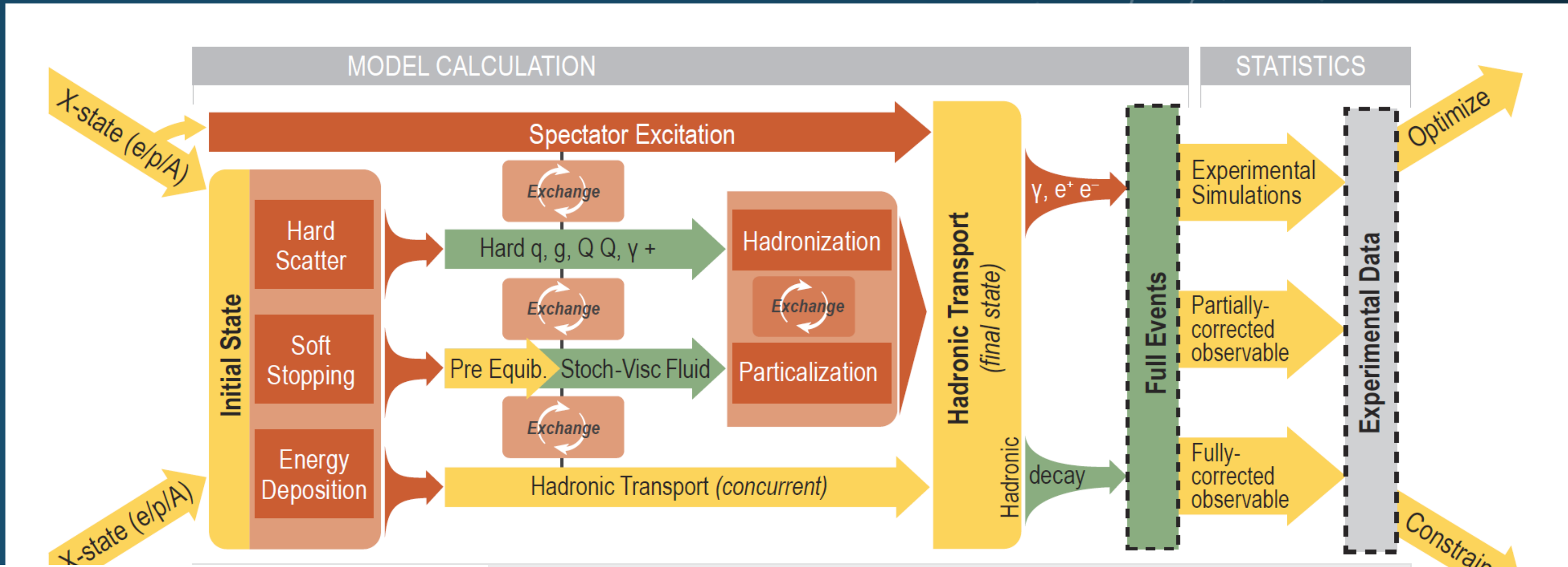
Shower partons inside QGP are absorbed by the medium or accumulate on the hypersurface; color is randomized

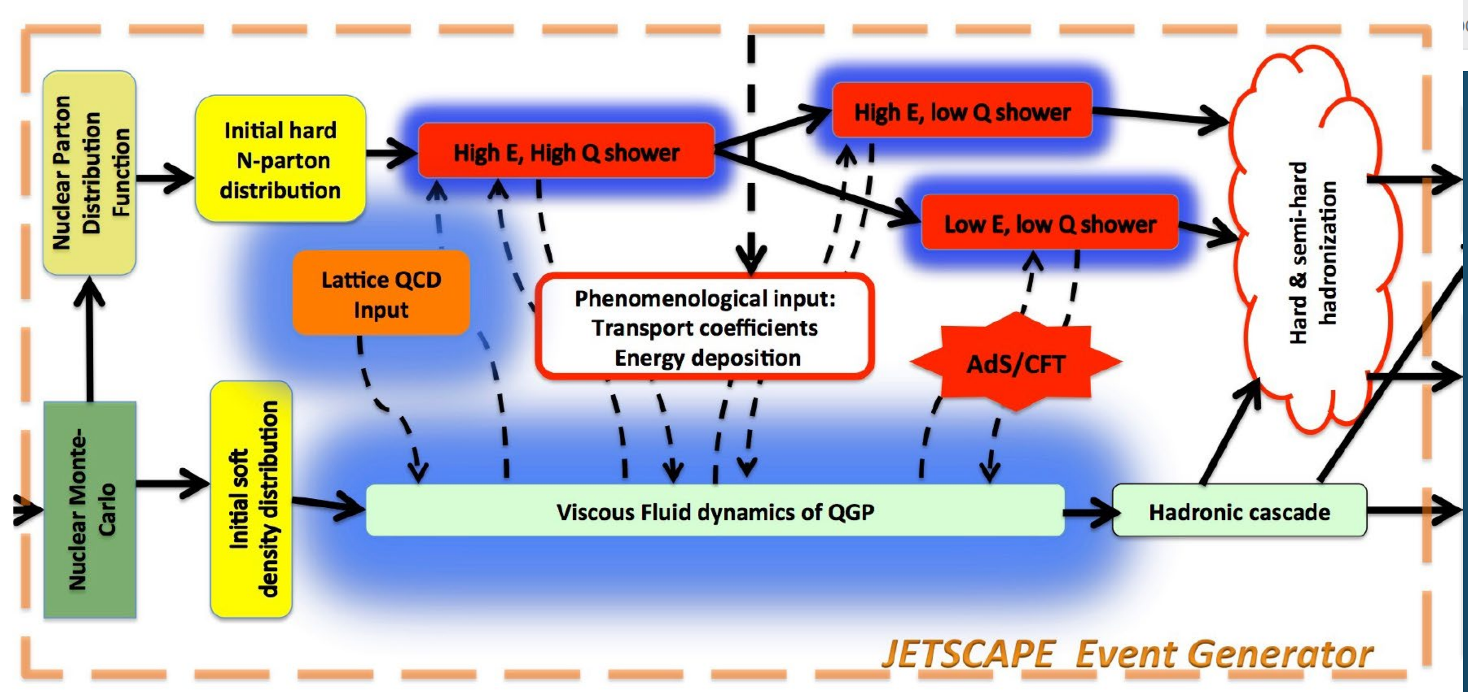
The jet starts in QGP; the temperature is set to drop below T_c after 4 fm/c

Direction transverse to the jet

PART IV: HADRONIZATION IN JETSCAPE

THE PLACE OF HADRONIZATION IN JETSCAPE/XSCAPE





JETSCAPE/XSCAPE OPTIONS

- There are three options for hadronization: colored, colorless, and hybrid hadronization.
- Colored and colorless hadronization are both pure PYTHIA 8 string fragmentation but with different implementations (honoring or discarding color tags). They can not add medium partons.

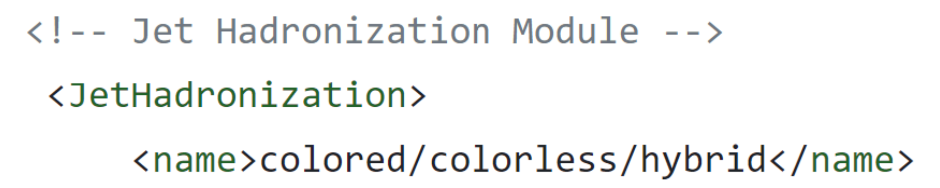
- In a nutshell:

	Uses color tags	Can deal with missing color tags	Can use or generate thermal partons	Can handle junctions/baryon
Colored	YES	NO	NO	NO
Colorless	NO	YES	NO	NO
Hybrid	YES	YES	YES	YES

- Colored hadronization is only recommended for vacuum systems, like p+p.

JETSCAPE/XSCAPE OPTIONS

- Set the module you want in <JetHadronization> in the XML-file together with any parameters you want to customize.



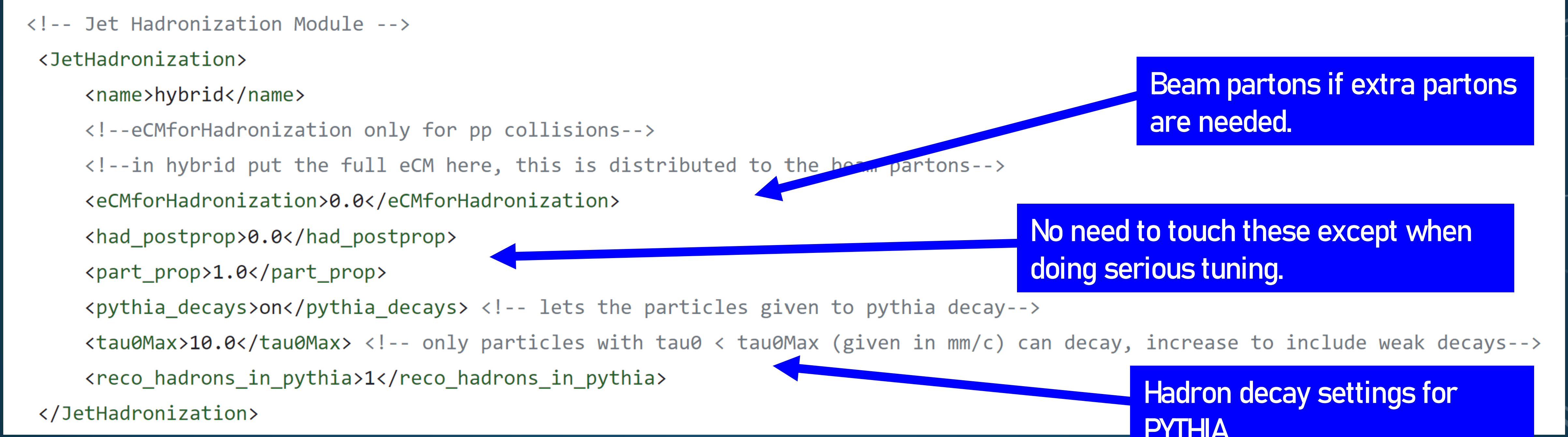
```
<!-- Jet Hadronization Module -->
 <JetHadronization>
     <name>colored/colorless/hybrid</name>
```

- You will play mostly with Hybrid Hadronization and a little bit with Colorless Hadronization later.

- Caution, the version of HH used at the school is not yet official, it will be in the JETSCAPE 3.6 release

HYBRID HADRONIZATION OPTIONS

- A few options for HH:

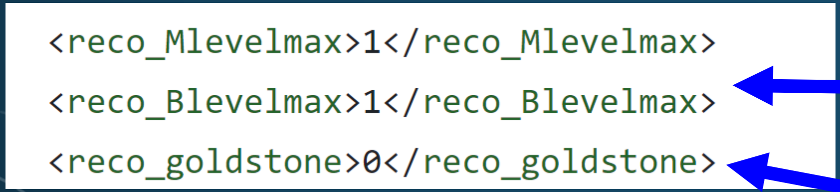


```
<!-- Jet Hadronization Module -->
 <JetHadronization>
     <name>hybrid</name>
     <!--eCMforHadronization only for pp collisions-->
     <!--in hybrid put the full eCM here, this is distributed to the beam partons-->
     <eCMforHadronization>0.0</eCMforHadronization>
     <had_postprop>0.0</had_postprop>
     <part_prop>1.0</part_prop>
     <pythia_decays>on</pythia_decays> <!-- lets the particles given to pythia decay-->
     <tau0Max>10.0</tau0Max> <!-- only particles with tau0 < tau0Max (given in mm/c) can decay, increase to include weak decays-->
     <reco_hadrons_in_pythia>1</reco_hadrons_in_pythia>
 </JetHadronization>
```

Beam partons if extra partons are needed.

No need to touch these except when doing serious tuning.

Hadron decay settings for PYTHIA



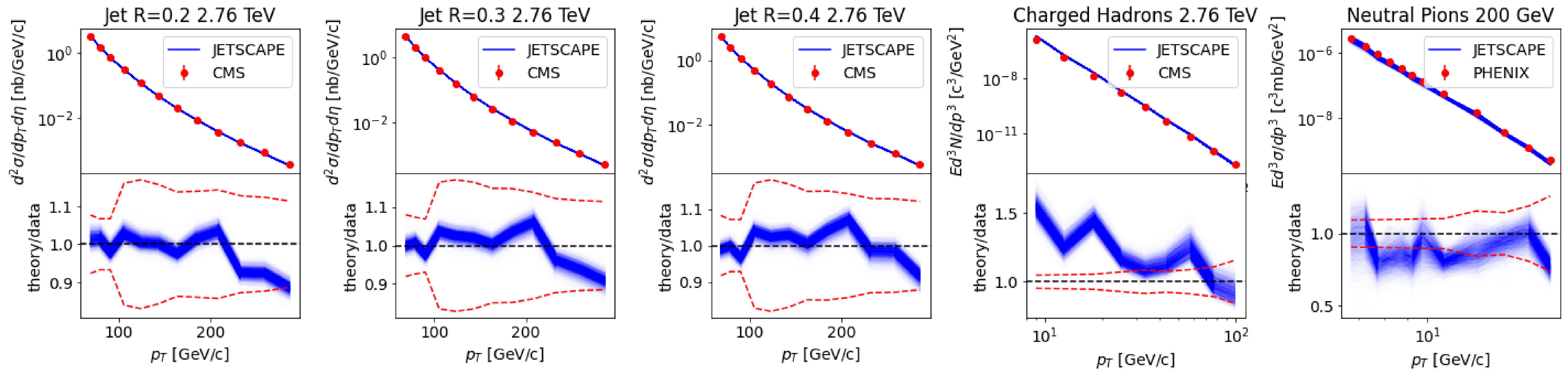
```
<reco_Mlevelmax>1</reco_Mlevelmax>
<reco_Blevelmax>1</reco_Blevelmax>
<reco_goldstone>0</reco_goldstone>
```

Highest excited energy level for mesons and baryons in recombination. (0=ground state; 1=p-wave allowed)

Pions and kaons have anomalously small masses and don't fit well into the recombination scheme.

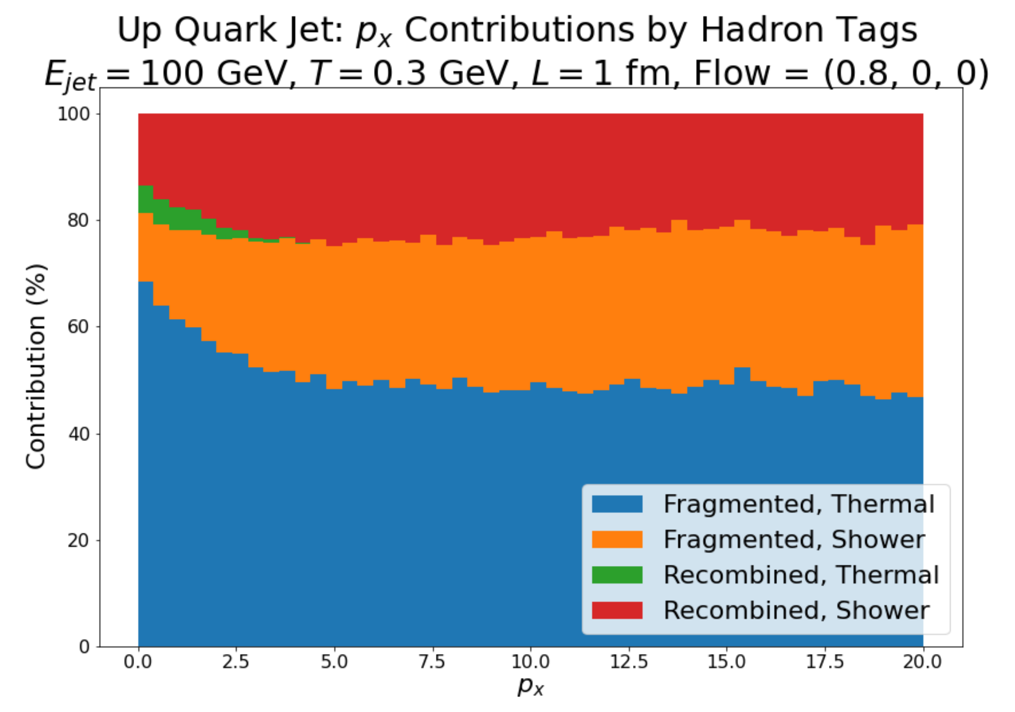
A FEW RESULTS

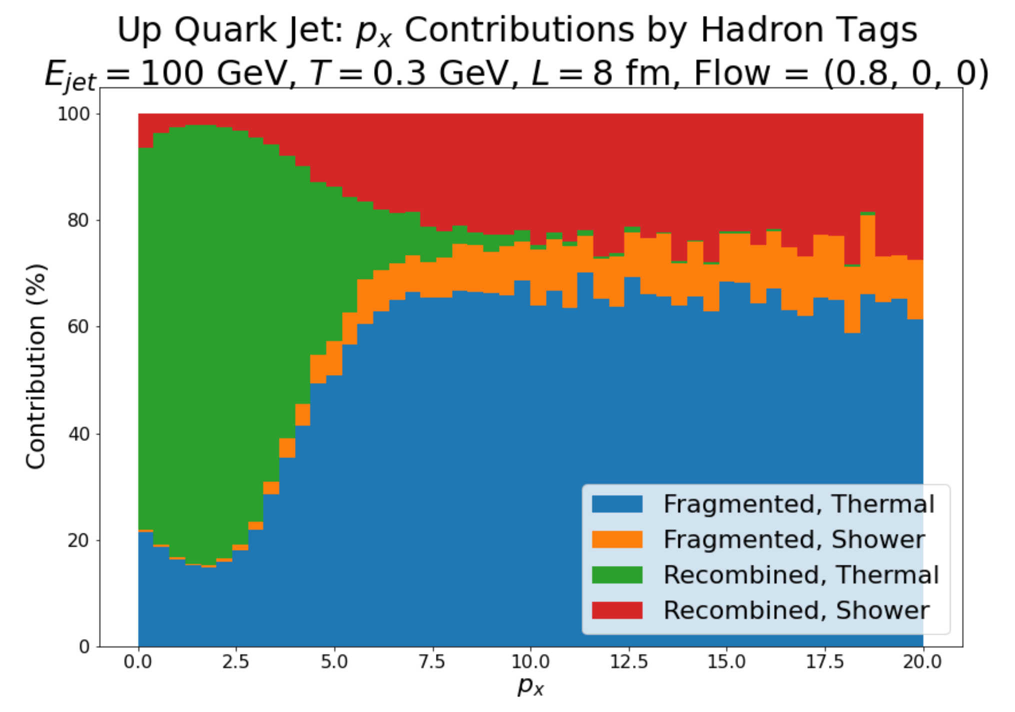
- Most of these are obtained with the older, official version of Hybrid Hadronization.
- For vacuum systems, HH is designed to work as well as string fragmentation, with little changes through the addition of recombination. This mostly works out.



A FEW RESULTS

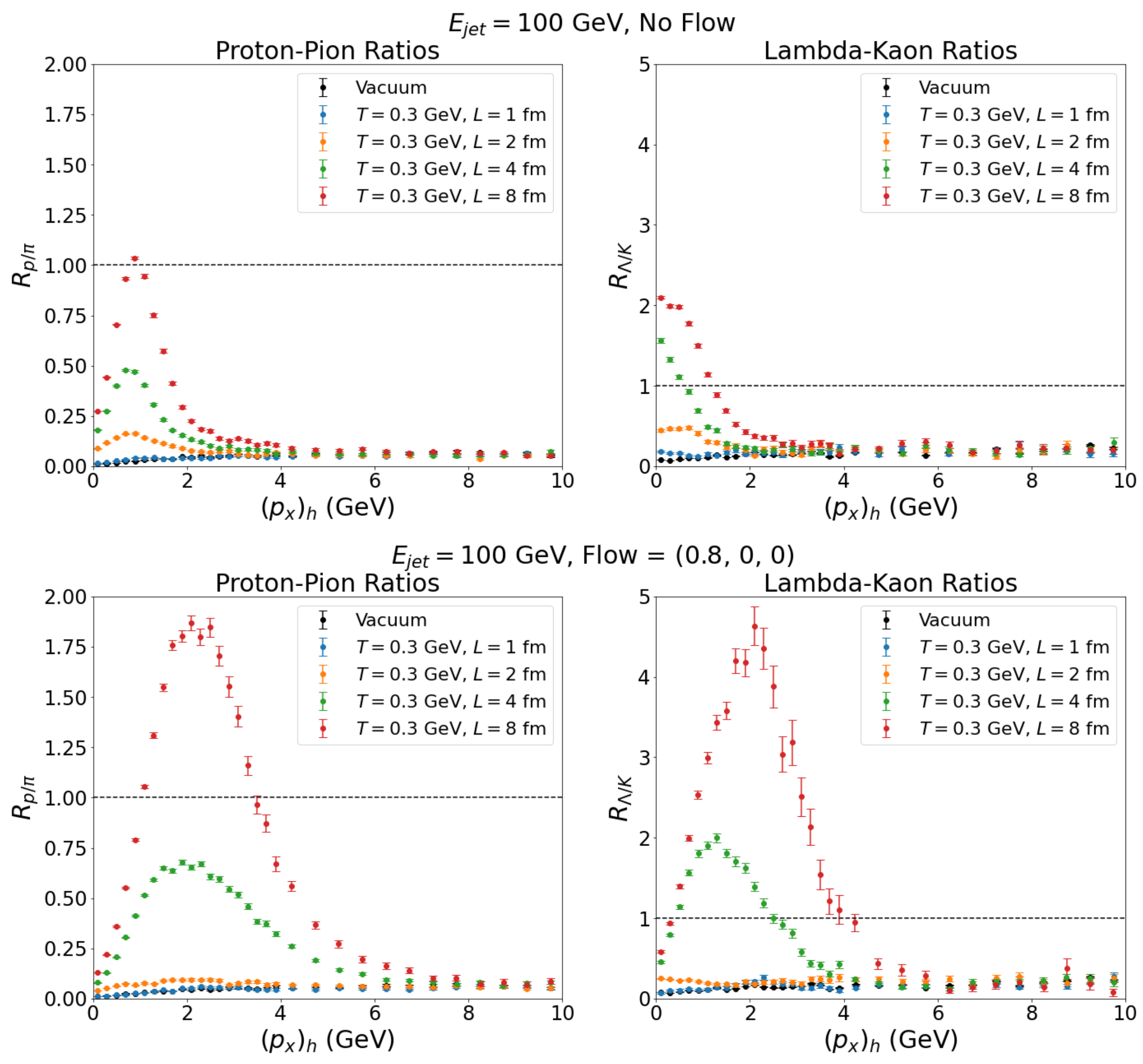
- In systems with a medium recombination, with medium partons becomes a strong contribution at low to intermediate momentum, growing with medium size.





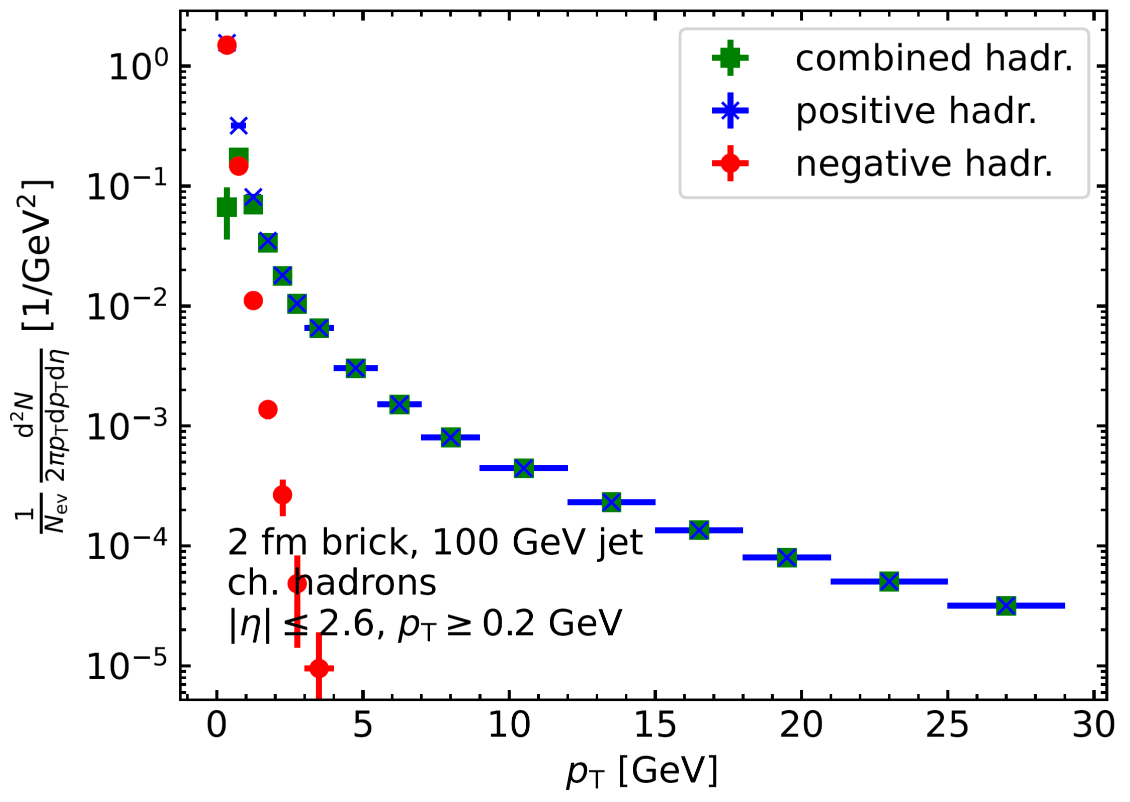
A FEW RESULTS

- We recover a key signature of quark recombination: baryon/meson enhancement in a medium
- Hadronization is sensitive to medium flow.



A FEW RESULTS

- This is a result with the new version: the background of negative hadrons can be successfully subtracted.



ON TO THE HANDS-ON SESSION

- A few exercises running different models for e^+e^- and a jet in a brick.