MODELING OF HADRONIZATION OF JETS IN VACUUM AND IN MEDIUM

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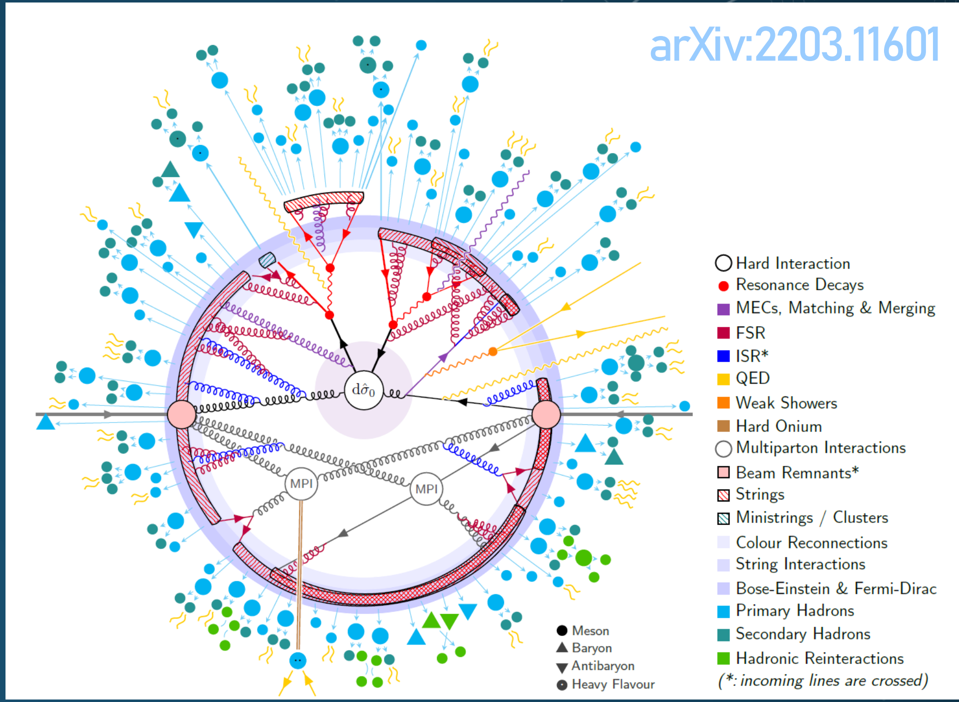
TEXAS A&M UNVERSITY

INT 21r-2b: Probing QCD at Hgh Temperature and Density with Jets

UW, Seattle, October 19 2023

THE HADRONIZATION PROBLEM

- No solutions based on first principles.
- For Monte Carlos: need models based on reasonable assumptions that can describe data.
- Long, successful history for 'vacuum' systems: Lund string fragmentation, cluster hadronization.
- Excellent results in e+e- and p+p systems.

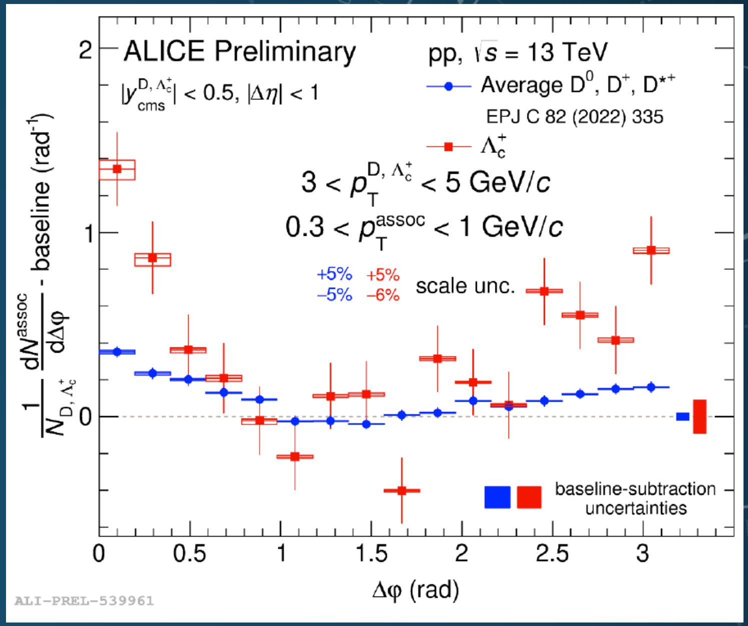


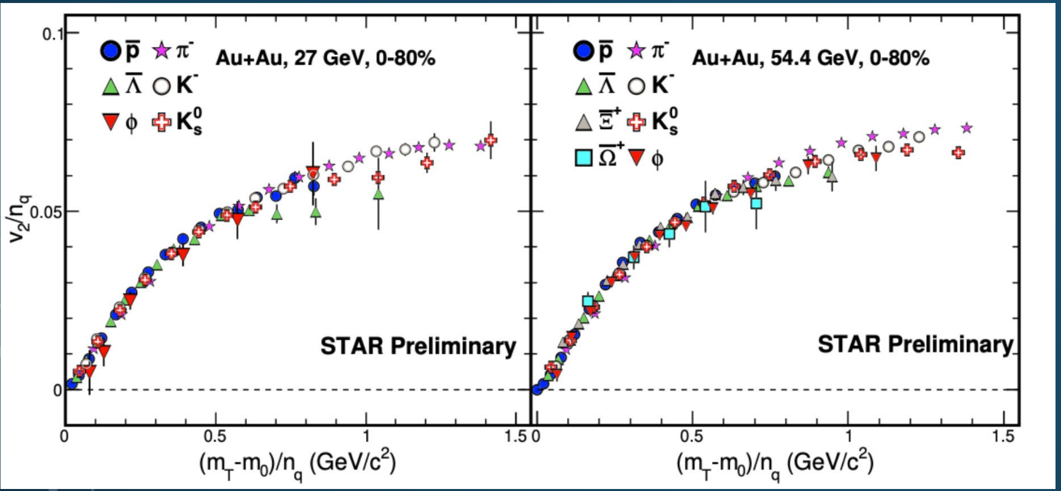
THE HADRONIZATION PROBLEM

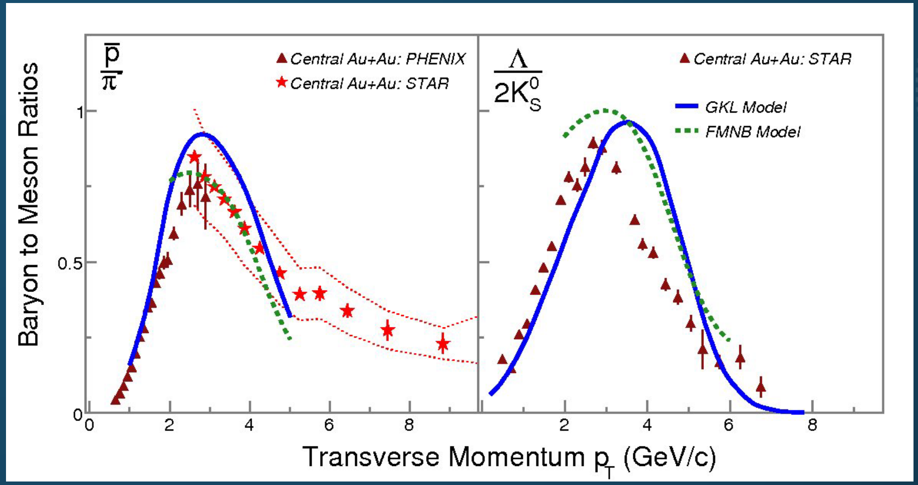
- Many features in heavy ion collisions not addressed by these models (baryon chemistry, quark number scaling): can be explained by quark recombination

- New data, even in p+p is challenging some models.

- We want to look for a comprehensive model that can be consistently applied to everything from e+e- to A+A collisions → Hybrid Hadronization

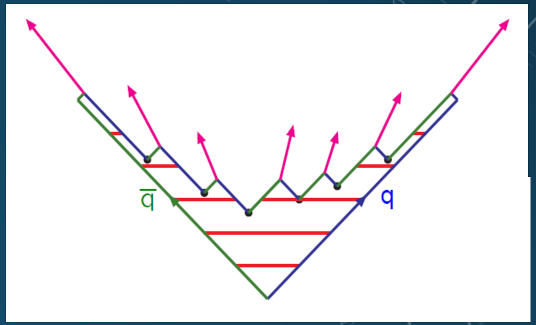






HYBRID HADRONIZATION

- A hybrid of string fragmentation and recombination.

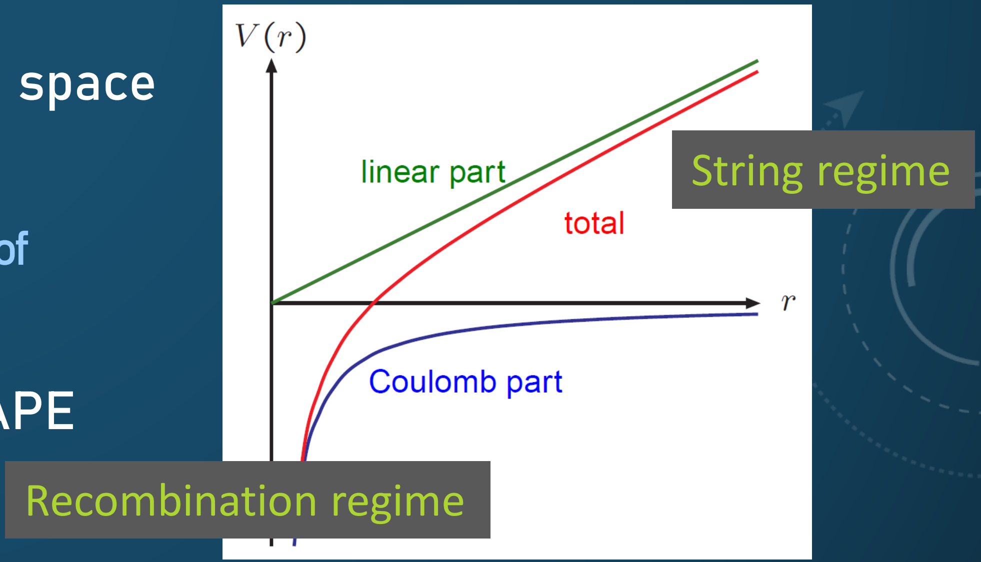


- Interpolates smoothly in between, two limits:
  - Dilute systems → Dominance of string fragmentation
  - Dense systems → Dominance of quark recombination

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

K. C. Han, R. J. Fries, C. M. Ko, Jet Fragmentation via Recombination of Parton Showers, Phys.Rev.C 93, 045207 (2016)

- Monte Carlo implementation available, e.g. JETSCAPE since v2.0.



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

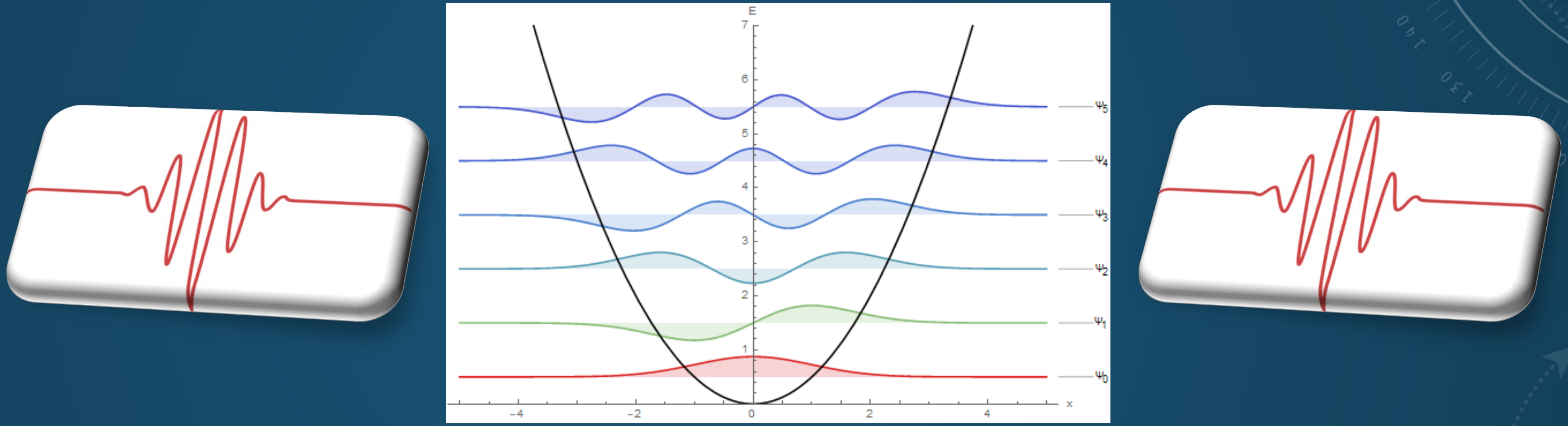
Intermediate Step:
Recombined hadrons and remnant partons in a string system (only color singlets were removed).

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.
- Total probability for coalescence $P_{tot} = P_{phase-space} \times P_{spin} \times P_{color}$

ANGULAR MOMENTUM EIGENSTATES IN PHASE SPACE

- Wigner distribution in phase space for given wave functions ψ_1, ψ_2:

$$W_{\psi_2,\psi_1}(\mathbf{r},\mathbf{q}) = \int \frac{d^3\mathbf{r}'}{(2\pi\hbar)^3} e^{\frac{i}{\hbar}\mathbf{r}'\cdot\mathbf{q}} \psi_2^*\left(\mathbf{r}+\frac{1}{2}\mathbf{r}'\right)\psi_1\left(\mathbf{r}-\frac{1}{2}\mathbf{r}'\right)$$

- (Diagonal) results known for angular momentum eigenstates: S. Shlomo, M. Prakash, *Phase space distribution of an N –dimensional harmonic oscillator*, Nucl. Phys. A 357,157 (1981).
- In 2-D closed-form, elegant result from the quantum optics community: R. Simon, G. S. Agarwal, *Wigner representation of Laguerre-Gaussian beams*, Opt. Lett. 25, 1313 (2000);
- Recalculate Wigner distributions using an expansion of angular momentum eigenstates in products of 1D-states.

  M. Kordell, R. J. Fries, C. M. Ko, Annals Phys. 443, 168960 (2022)
- Here summed over magnetic quantum number m (no polarization).

3D-HARMONIC OSCILLATOR IN PHASE SPACE

- Use the well-studied 1D-phase space distributions to build the 3D ones

$$W_{kl}(\mathbf{r},\mathbf{q}) = \sum_{\substack{n_1,n_2,n_3 \\ n_1',n_2',n_3'}} D_{kl}\binom{n_1,n_2,n_3}{n_1',n_2',n_3'} W_{n_1'n_1}(r_1,q_1) W_{n_2'n_2}(r_2,q_2) W_{n_3'n_3}(r_3,q_3)$$

Radial quantum number k, angular momentum quantum number l

Three off-diagonal 1-D Wigner distributions

$$D_{kl}\binom{n_1,n_2,n_3}{n_1',n_2',n_3'} = \frac{1}{2l+1} \sum_m C^*_{klm,n_1'n_2'n_3'} C_{klm,n_1n_2n_3}$$

Averaging magnetic quantum numbers m, since not interested in polarization.

Expansion coefficients for angular momentum eigenstates in terms of products of 1-D states

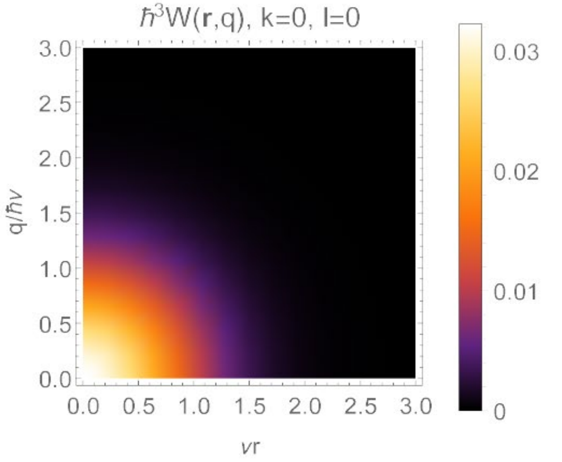
- The off-diagonal 1-D Wigner distributions are known [T. Curtright, T. Uematsu, C. K. Zachos, J. Math. Phys. 42 (2001)]

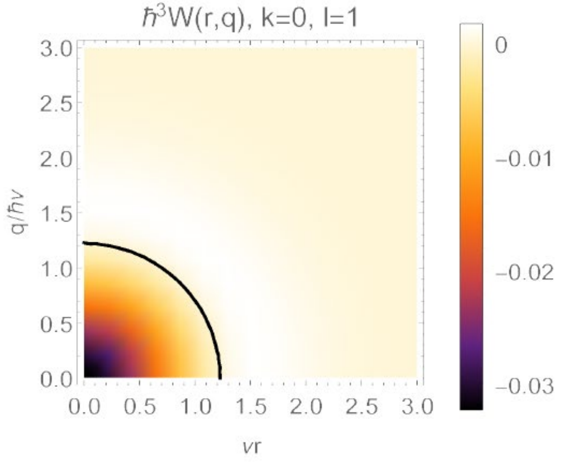
$$W_{n'n}(x,q) = \frac{(-1)^{n'}}{\pi\hbar} \sqrt{\frac{n'}{n}} u^{\frac{n-n'}{2}} e^{-u/2} e^{-i(n-n')\zeta} L_{n'}^{(n-n')}(u)$$

$$u = 2\left(q^2/(\hbar^2\nu^2) + \nu^2 x^2\right) \qquad \tan\zeta = q/(\hbar\nu^2 x)$$

WIGNER DISTRIBUTIONS

- Recall that Wigner distributions can be negative.
- When summed over m, they only depend on magnitudes of position r and momentum q, and the relative angle θ between.
- Examples of a few lowest states

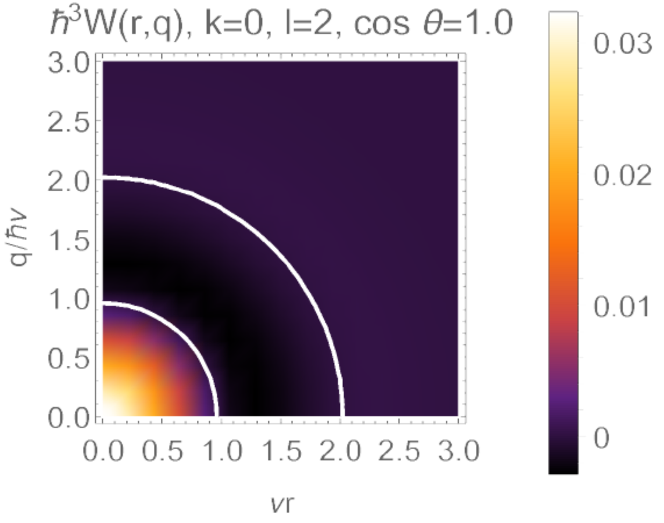


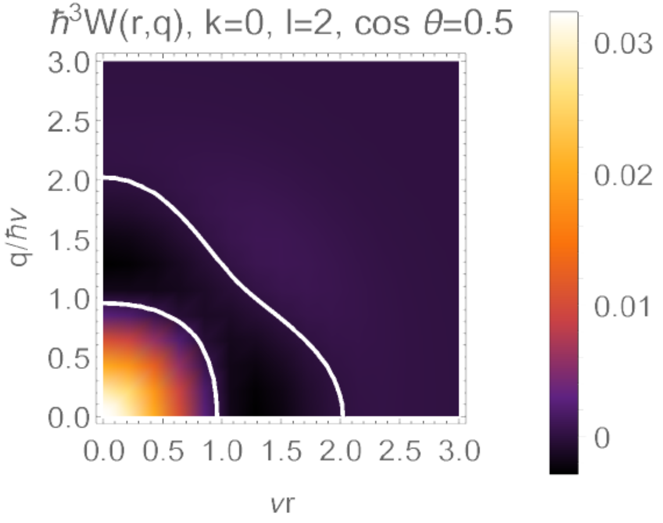


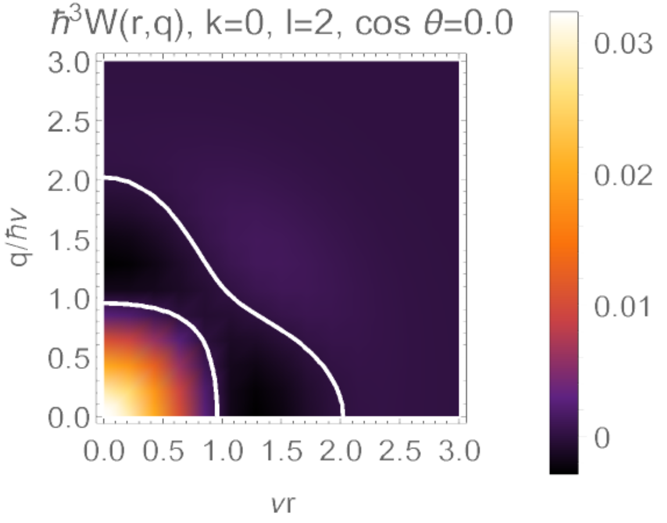
$$W_{00} = \frac{1}{\pi^3 \hbar^3} e^{-\frac{q^2}{\hbar^2 \nu^2} - \nu^2 r^2},$$

$$W_{01} = W_{00}\left(-1 + \frac{2}{3}\nu^2 r^2 + \frac{2}{3}\frac{q^2}{\hbar^2 \nu^2}\right),$$

$$W_{02} = W_{00}\left(1 + \frac{4}{15}\nu^4 r^4 - \frac{4}{3}\nu^2 r^2 + \frac{16}{15}\frac{r^2 q^2}{\hbar^2} - \frac{8}{15}\frac{(\mathbf{r}\cdot\mathbf{q})^2}{\hbar^2} - \frac{4}{3}\frac{q^2}{\hbar^2\nu^2} + \frac{4}{15}\frac{q^4}{\hbar^4\nu^4}\right)$$







COALESCENCE

- Probability for coalescence of Gaussian wave packets using the Wigner distributions.

$$\tilde{\mathcal{P}}_{klm,\mathbf{P}_f} = (2\pi\hbar)^6 \int d^3\mathbf{x}_1 d^3\mathbf{x}_2 d^3\mathbf{k}_1 d^3\mathbf{k}_2 \tilde{W}_{\mathbf{P}_f}(\mathbf{K})\, W_{klm}\left(\Delta\mathbf{x}, \Delta\mathbf{k}\right) W_1(\mathbf{x}_1, \mathbf{k}_1) W_2(\mathbf{x}_2, \mathbf{k}_2)$$

$$\mathcal{P}_{kl} = \sum_m \int d^3\mathbf{P}_f \tilde{\mathcal{P}}_{klm,\mathbf{P}_f}$$

Wigner for center of mass motion.

Bound state Wigner distribution; only depends on relative phase space corrdinates

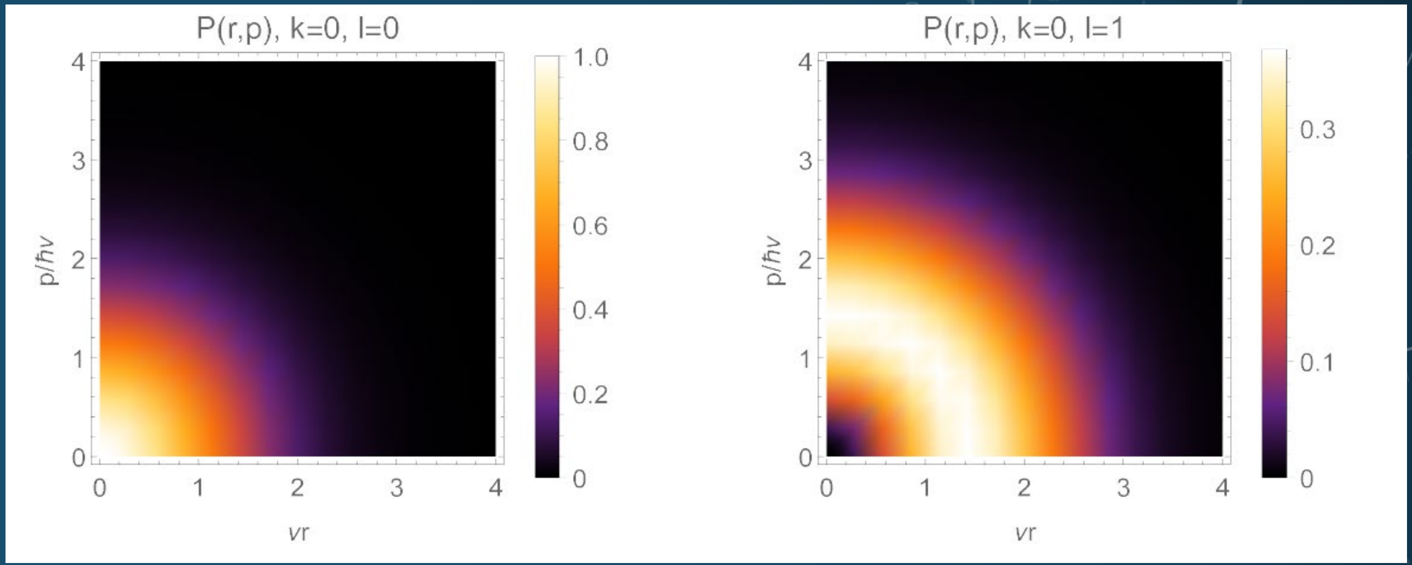
Wigner distributions of two Gaussian wave packets.

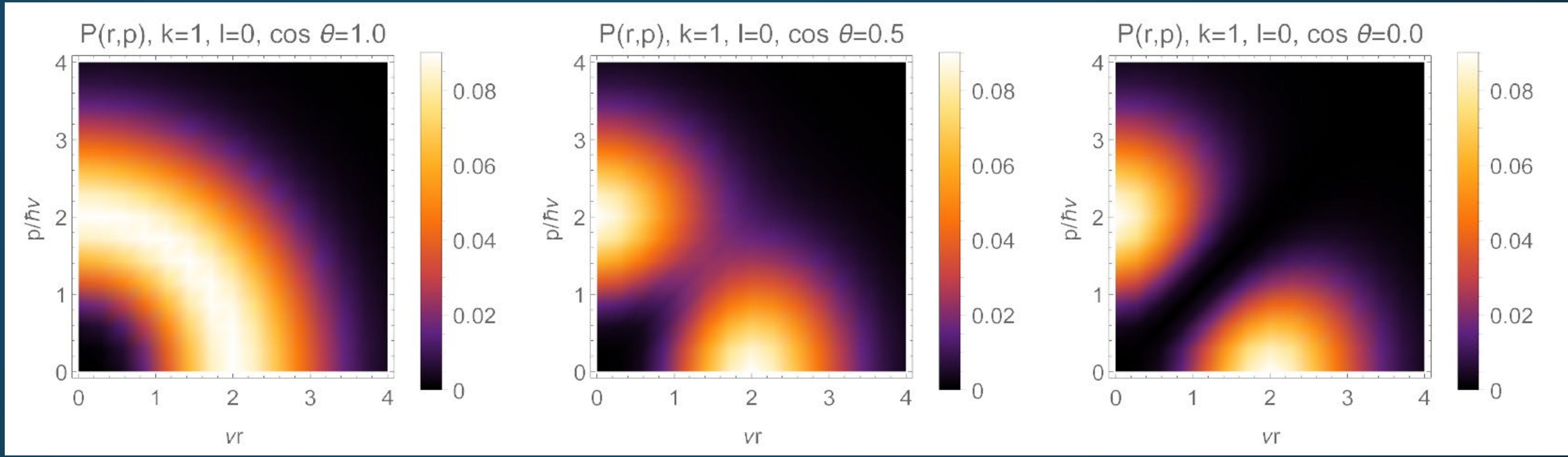
- Again sum over m, since we are not interested in polarization here (see remark later).

- Results discussed here for $1/\nu = 2\delta$ (relation between quark wave packet width δ and harmonic oscillator length scale $1/\nu$).

COALESCENCE PROBABILITIES

- Probabilities depend on the relative coordinates of the wave packet centroids, called r and p here.
- θ = angle between r and p.





COALESCENCE PROBABILITIES

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

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

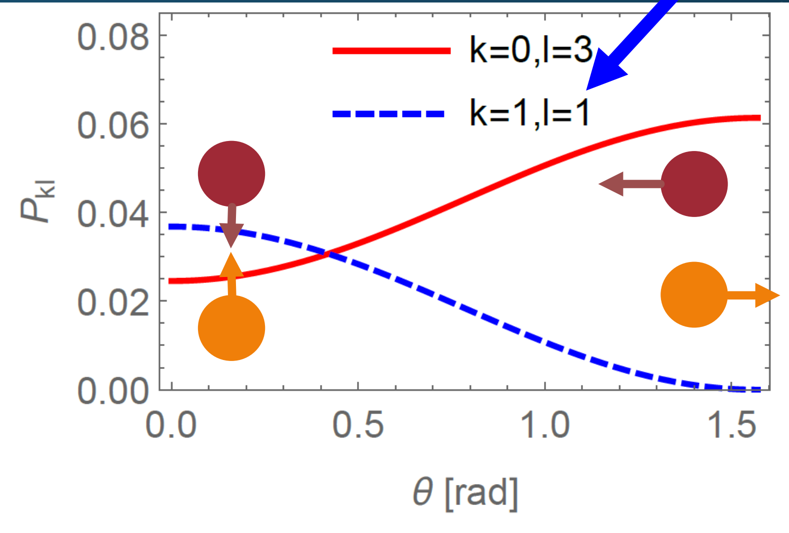
$$\mathcal{P}_{00} = e^{-v},$$
$$\mathcal{P}_{01} = e^{-v} v,$$
$$\mathcal{P}_{02} = \frac{1}{2}e^{-v}\left(\frac{2}{3}v^2 + \frac{1}{3}t\right)$$
$$\mathcal{P}_{10} = \frac{1}{2}e^{-v}\left(\frac{1}{3}v^2 - \frac{1}{3}t\right)$$

- If summed over states with the same energy, the probabilities are simply Poissonian given by phase space distance

$$\sum_{2k+l=N} \mathcal{P}_{kl} = e^{-v}\frac{v^N}{N!}$$

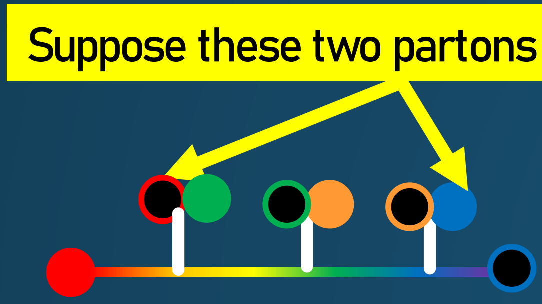
- Energy degeneracy broken by orbital angular momentum of the quarks. t makes an intuitive connection between the relative angular momentum of the incoming quarks and the quantum number l of their bound state.

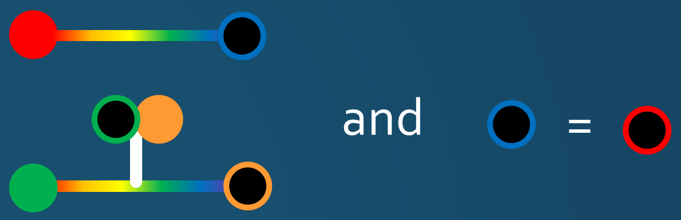
Both are states with N=3



REMNANT PARTONS: STRING REPAIR

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





- 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 thermal partons, beam partons, or extra partons with zero momentum).

REMNANT STRINGS: FRAGMENTATION

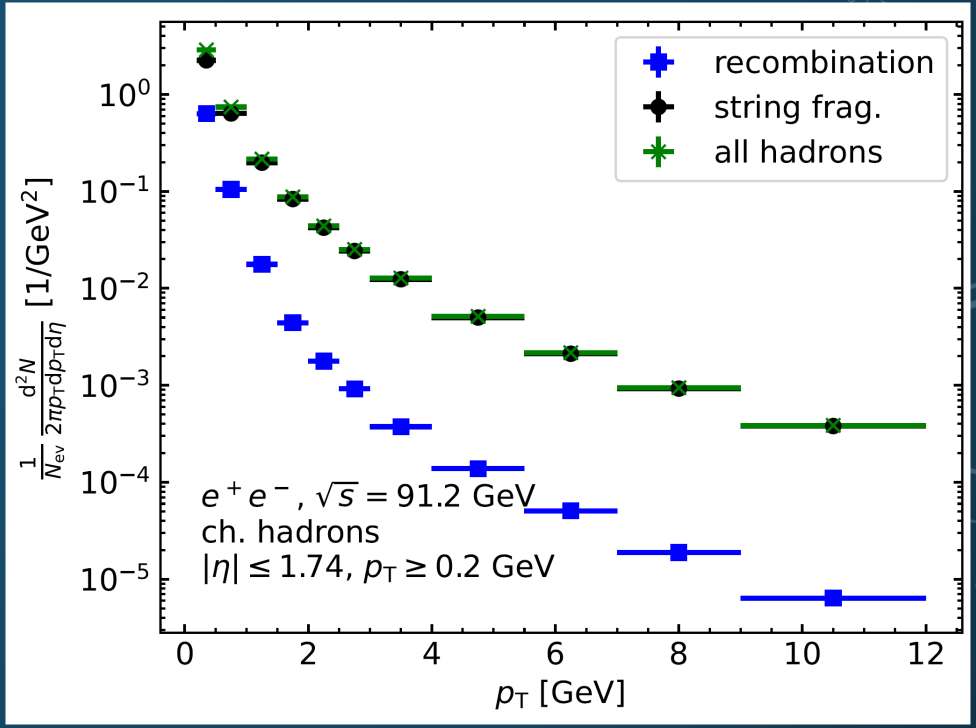
- Strings are handed to PYTHIA 8 for fragmentation.

- Decays of excited states can happen in PYTHIA or by invoking the hadronic transport model SMASH.

- In a vacuum system all partons hadronize.

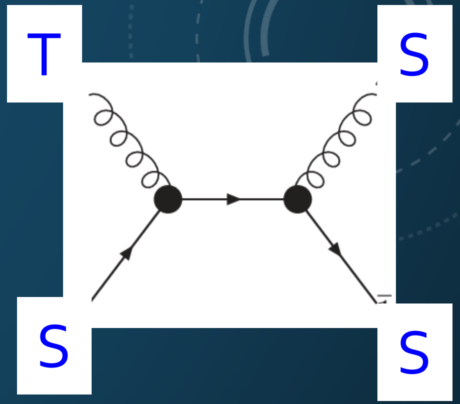
- Check on the cutoff between recombination and fragmentation with e^+e^- example:

- As intended fragmentation dominates this dilute system, in particular for high energy hadrons.



ADDING A MEDIUM

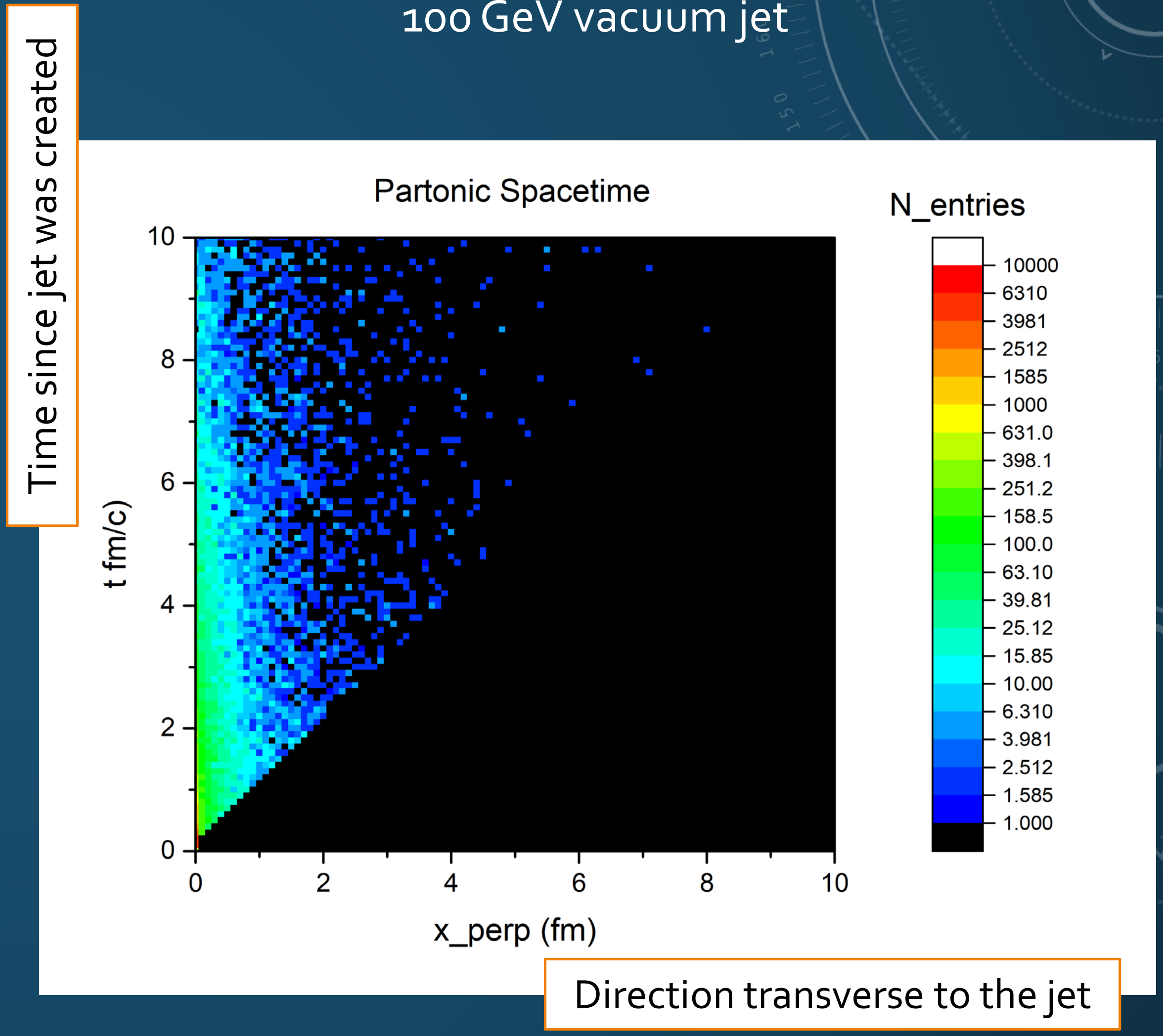
- The formalism stays the same, just take care of these additional points
- Some shower partons (e.g. LBT) arrive with randomized color (color tag 0)
- Thermal partons can be sampled from a specified $T = T_c$ hypersurface, or a brick.
- Recombination from only thermal partons, or strings with only thermal partons are disabled. Shower partons are always hadronized.
- HH can process "negative partons" separately, if needed for background subtraction. Depending on the shower MC they can be used to track "holes" left in the medium through processes like q (shower) + g (medium) -> q (shower) + g (shower).



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

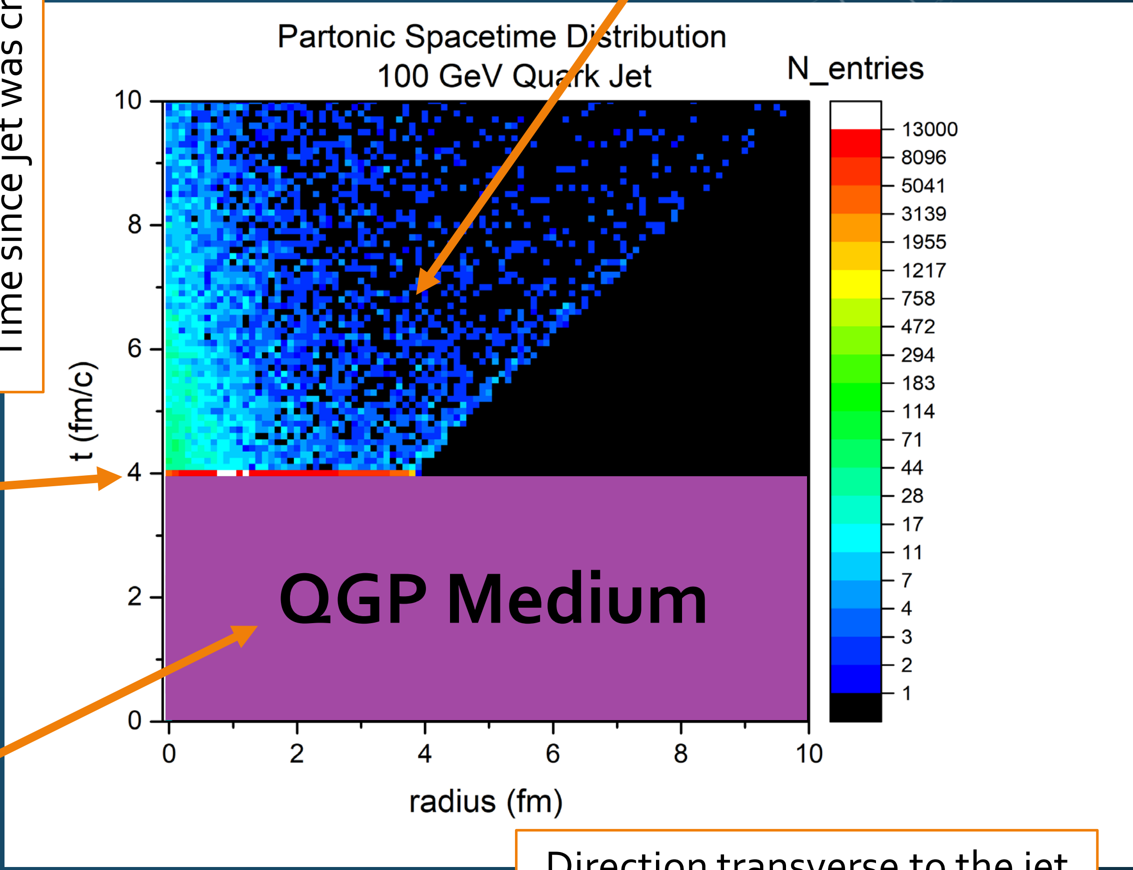


IN-MEDIUM JETS: SPACE-TIME CONSIDERATIONS

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

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

Time since jet was created



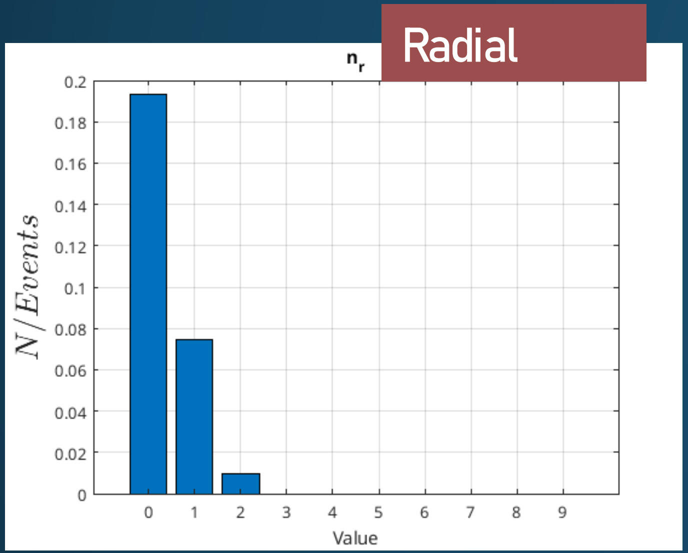
Shower partons inside QGP are absorbed by the medium or accumulate on the hypersurface; color is randomized

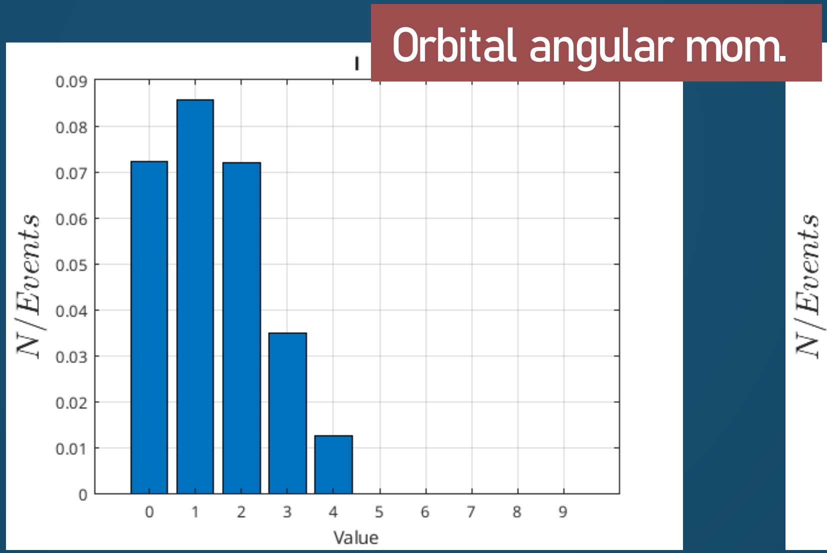
The jet starts in QGP; the temperature is set to drop below T_c after 4 fm/c

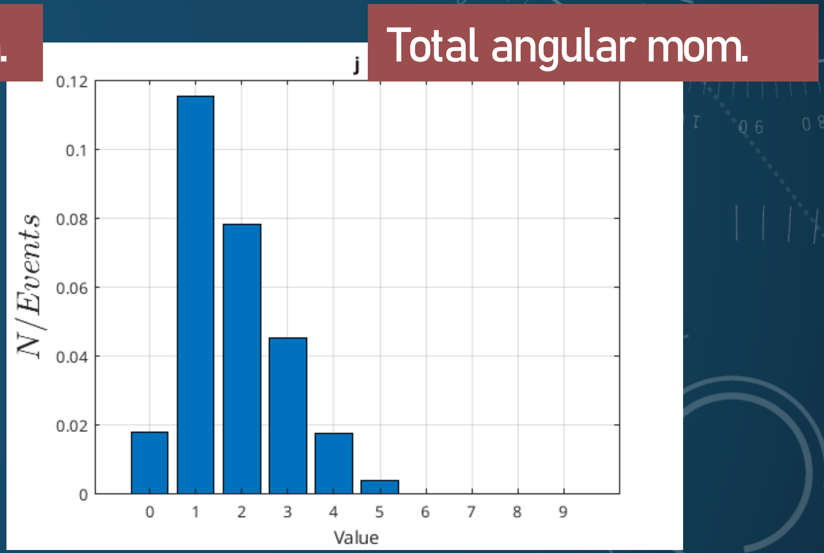
Direction transverse to the jet

EXCITED HADRON STATES ARE IMPORTANT

- In the recombination channel, occupation numbers of excited hadron states are determined by their respective probabilities.
- Here: meson states up to $N = 2k + l = 4$. Parton input from PYTHIA 8 e+e- at 91 GeV
- No decays. Spin treated statistically, color flow from PYTHIA.







(Hadrons from recombination only)

TUNING TO VACUUM SYSTEMS

- The features of HH introduced here are available in v3.6 of JETSCAPE (and will be in v1.1 of XSCAPE)
- Credit: Hendrik Roch, Michael Kordell, Cameron Parker

- Next step: parameter tuning

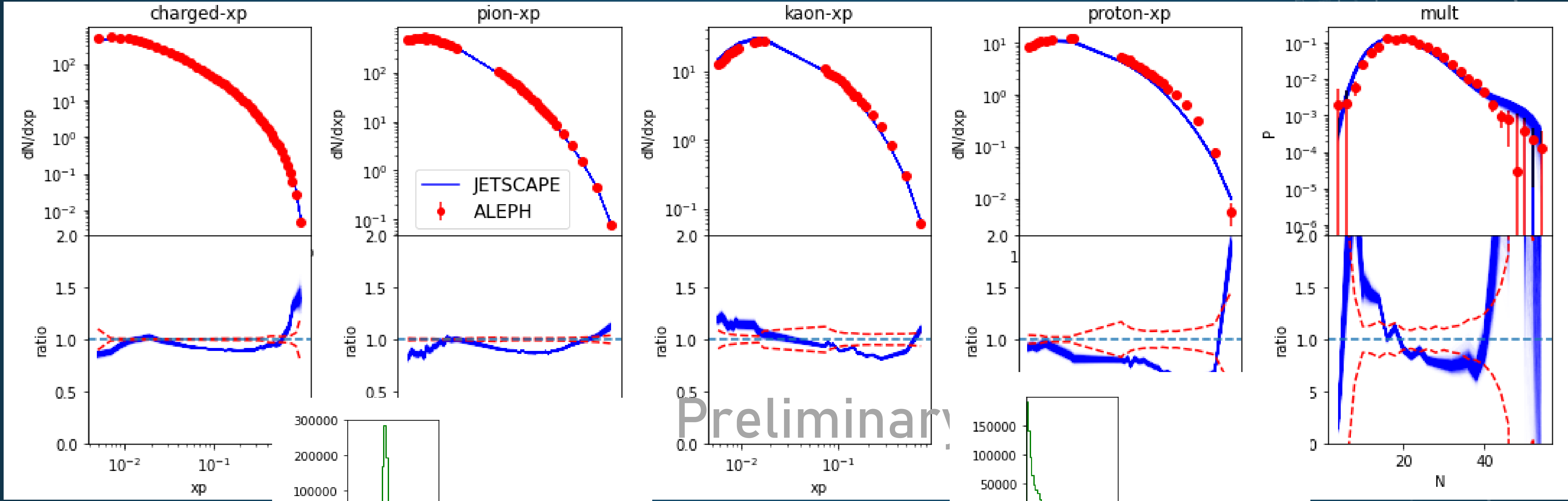
- Hadronization can not be tuned by itself, only in conjunction with the codes that create the parton input
- Ongoing effort to create a new vacuum tune for JETSCAPE 3.6:PYTHIAgun+MATTER+HH

- Mix of parameters from MATTER, HH and PYTHIA 8 fragmentation
- Bayes inference to determine optimal parameters

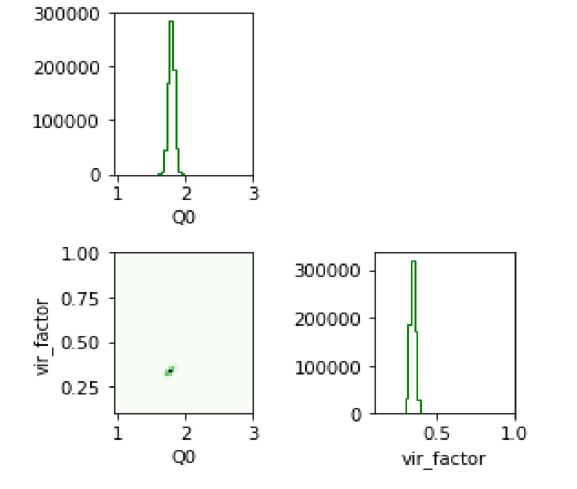
VACUUM SYSTEMS: E^+E^- WITH JETSCAPE 3.6

- ALEPH data for 91.2 GeV and posteriors

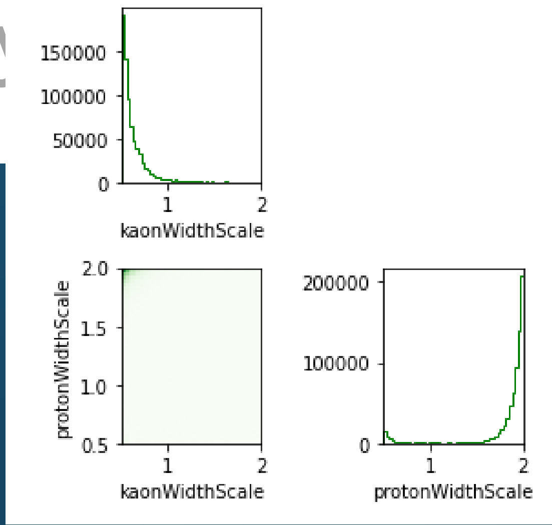
ALEPH: https://doi.org/10.17182/hepdata.47582



Example of two parameters that are well constrained …



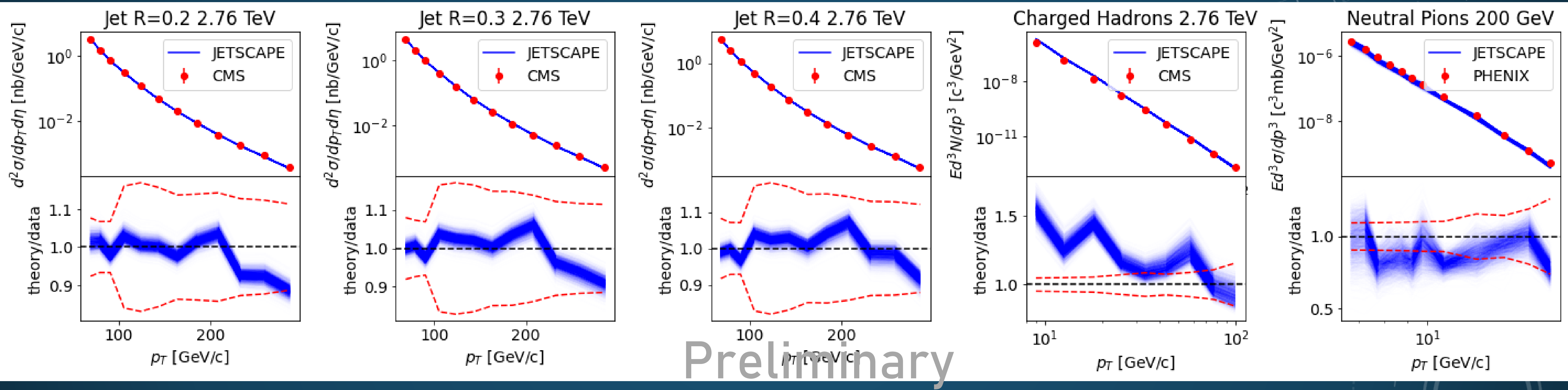
… and two parameters that aren't



Work in progress

VACUUM SYSTEMS: P+P

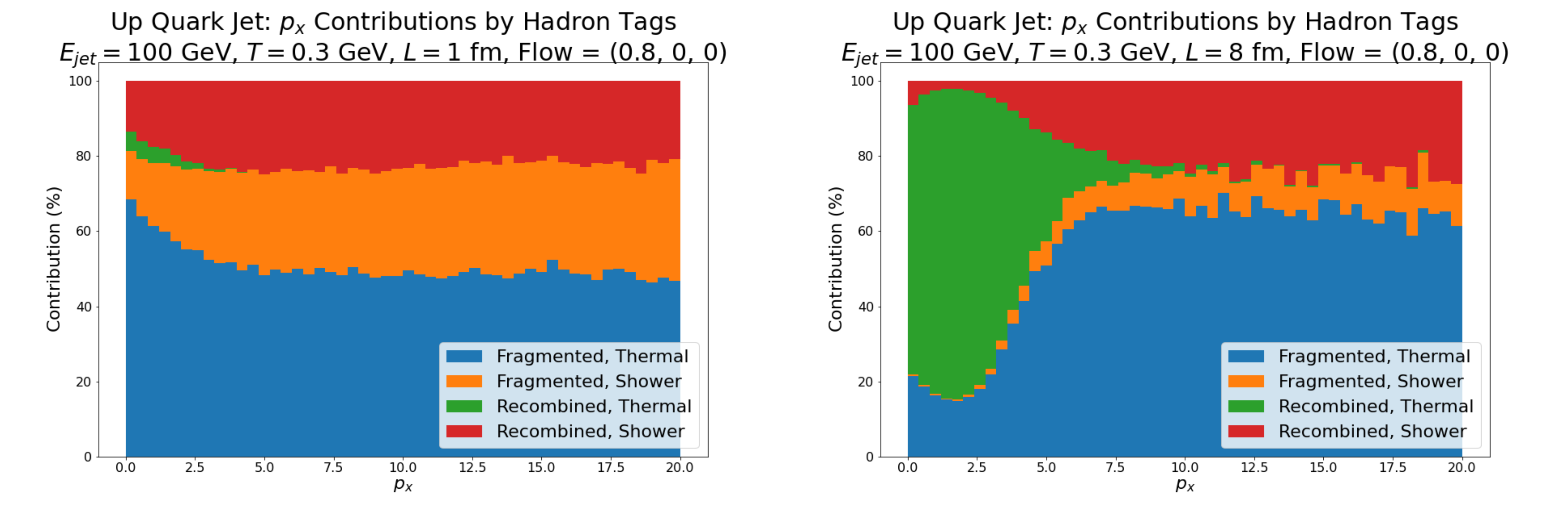
- Some Jet and High-PT observables with JETSCAPE 3.5 (new analysis coming)



CMS: https://doi.org/10.17182/hepdata.77601
PHENIX: https://doi.org/10.48550/arXiv.0704.3599

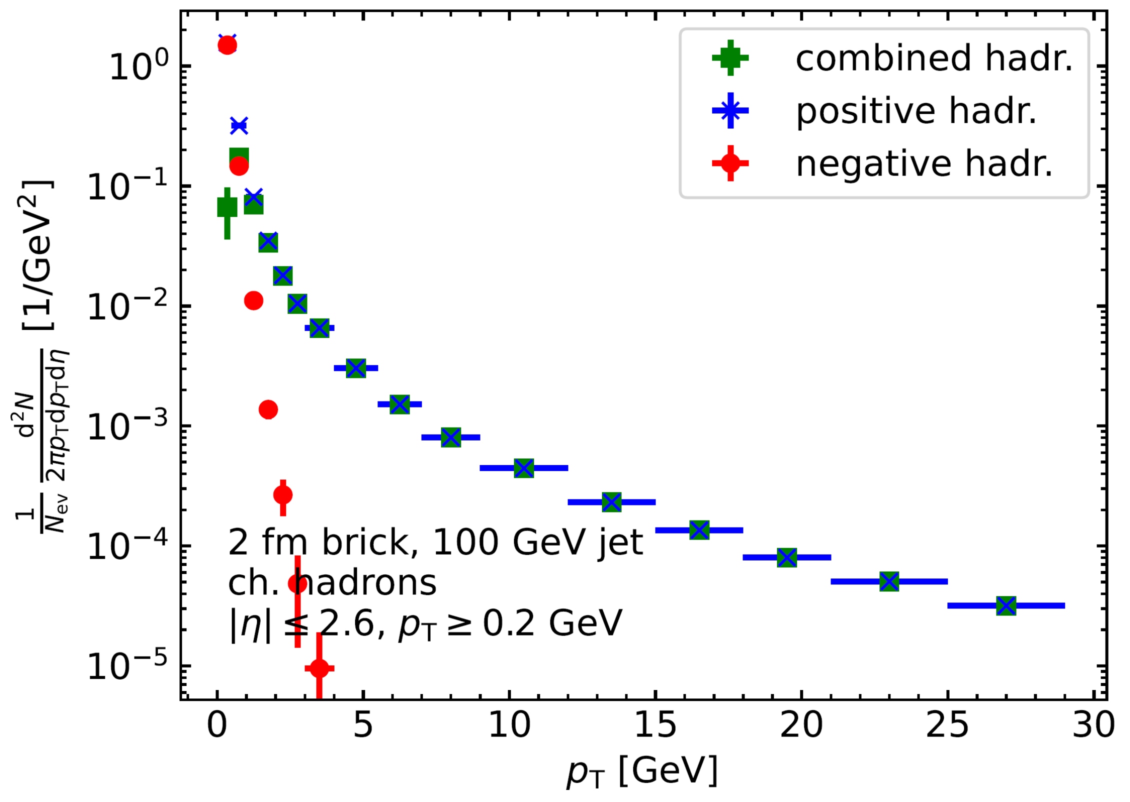
IN-MEDIUM JETS: ROLE OF THERMAL PARTONS

- The following study with a QGP brick was done with JETSCAPE 3.0
- Check hadron origin: Thermal parton contribution grows with medium size.



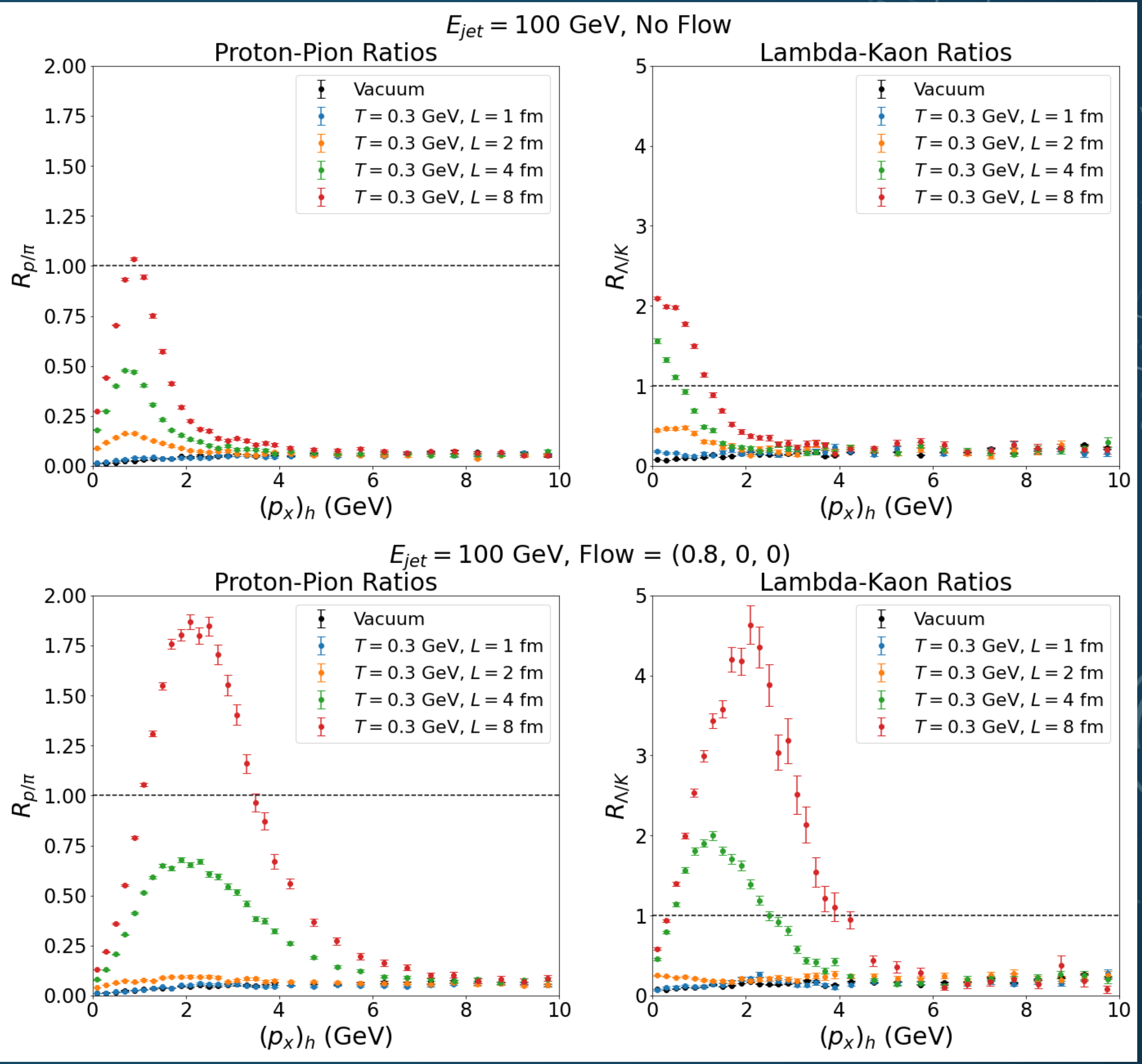
BACKGROUND SUBTRACTION EXAMPLE

- Example for subtraction of “negative” particles for jet in a 2 fm brick.



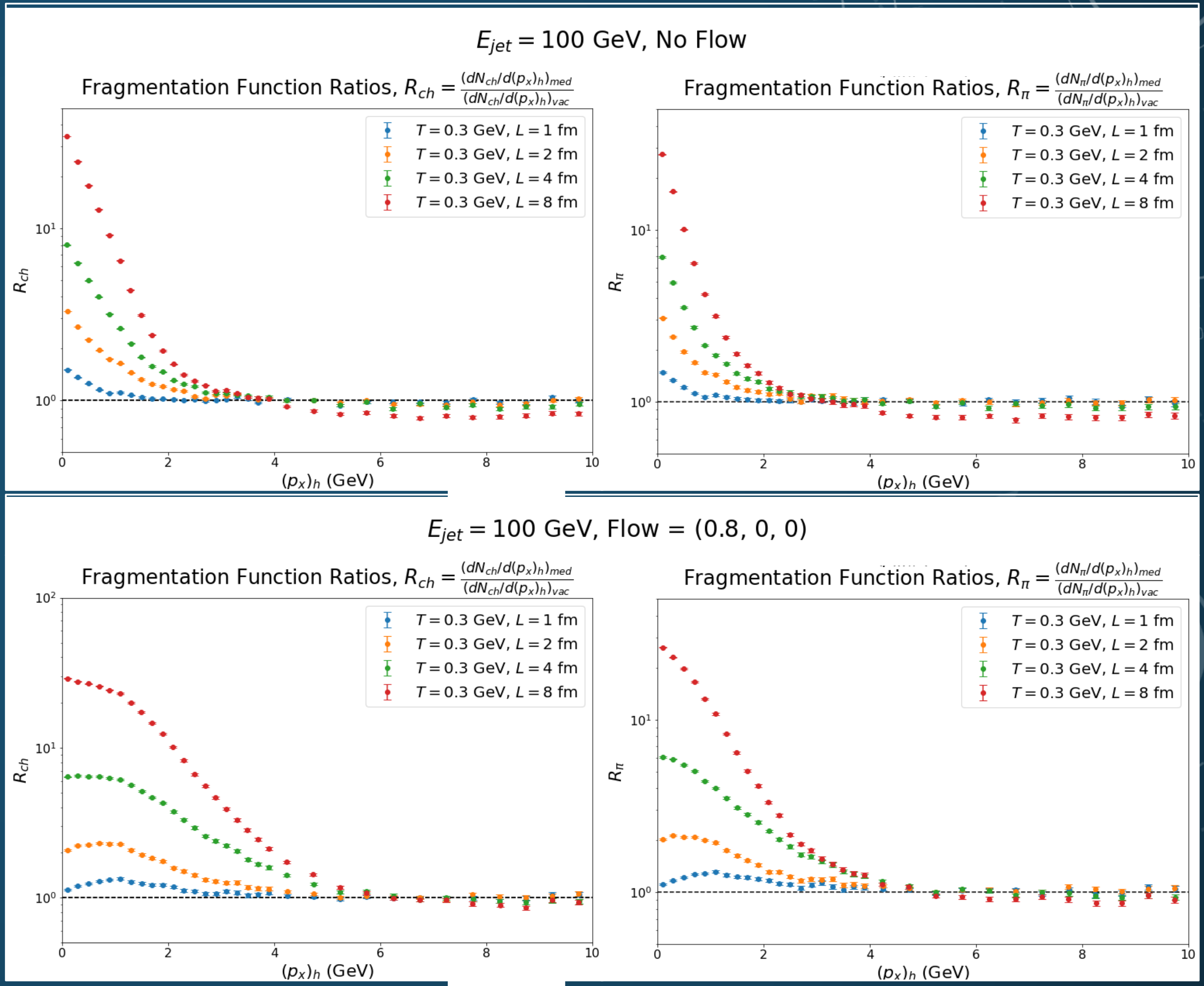
IN-MEDIUM JETS: BARYON ENHANCEMENT

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



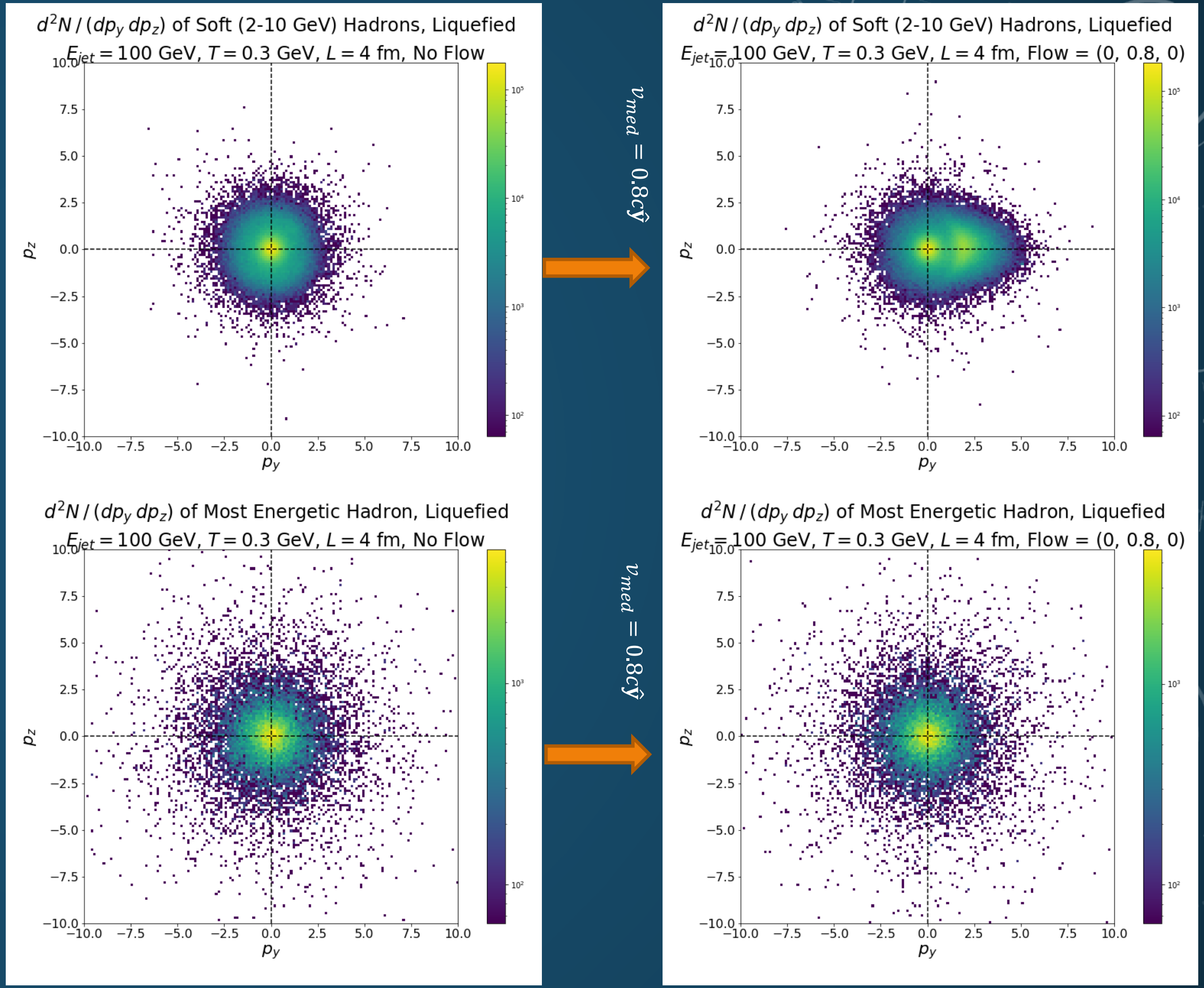
IN-MEDIUM JETS: FLOW SIGNALS

- Correlation of soft partons with the jet increases with medium size.
- Hadronization is sensitive to medium flow.



IN-MEDIUM JETS: FLOW TRANSVERSE TO THE JET

- Medium flow transverse to the jets can be picked up by hadrons associated with the jet.
- Only releveant for low and intermediate momenta.



PREVIEW: POLARIZATION

- If we don't sum recombination probabilities over magnetic quantum numbers they are sensitive to the angular momentum component L_z of the quarks.
- If the collective motion of the quarks carries net orbital angular momentum, hadronization can give you correspondingly polarized p- and d-wave mesons.

$$P_{011} = e^{-v}\left(\frac{1}{2}v_T + \frac{L_z}{2\hbar}\right)$$

$$P_{011} = e^{-v}v_L$$

$$P_{01\,-1} = e^{-v}\left(\frac{1}{2}v_T - \frac{L_z}{2\hbar}\right)$$

L_z selects a preferred polarization of the meson

v_T, v_L: squared phase space distance perpendicular and parallel to the quantization axis.

PREVIEW: HADRONIC PHASE FOR HARD PROBES

- HH in JETSCAPE has not the capability to send hadrons from hard processes to an hadronic afterburner, in addition to the soft hadrons.
- Ongoing work: Follow up the pion jet + hadron gas study by Dorau et al. Phys.Rev.C 101, 035208 (2020) using SMASH.

J. Weil et al., Phys. Rev. C 94, 054905 (2016)

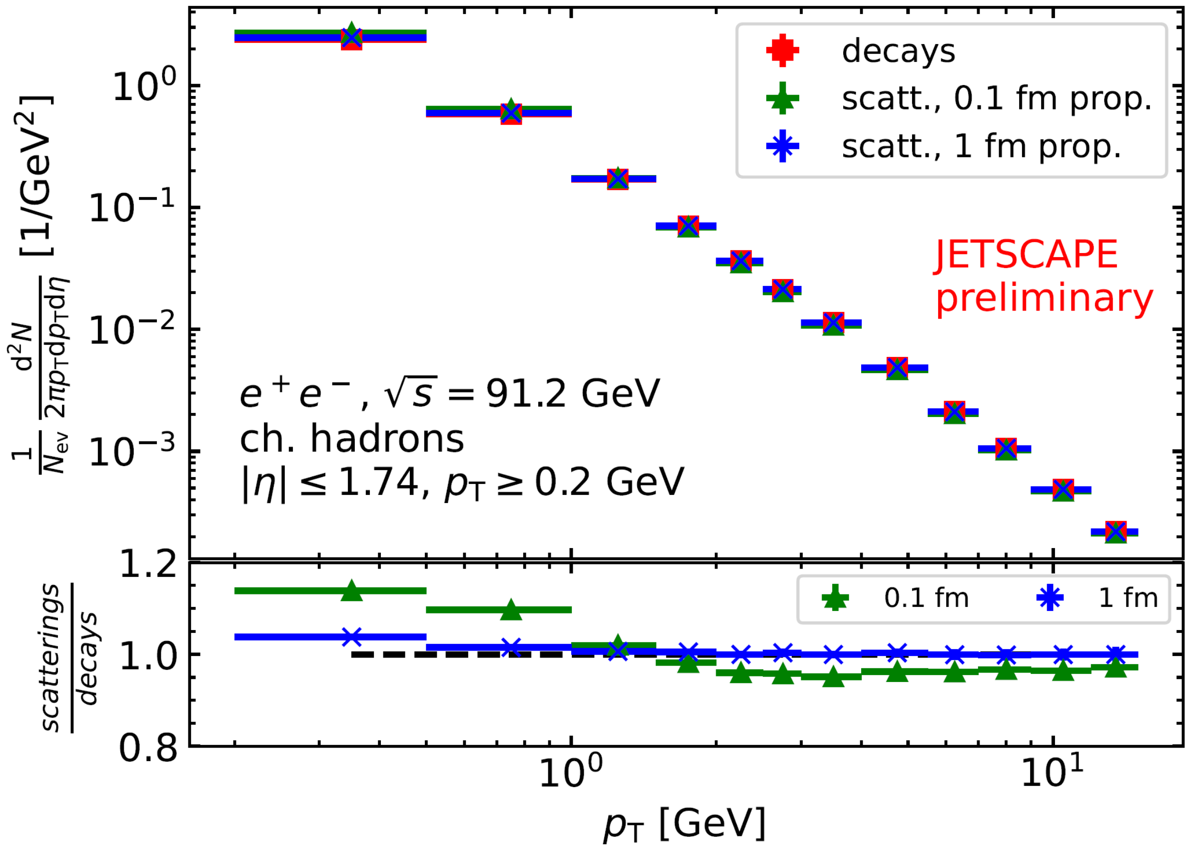
Simulating
Multiple
Accelerated
Strongly-interacting
Hadrons

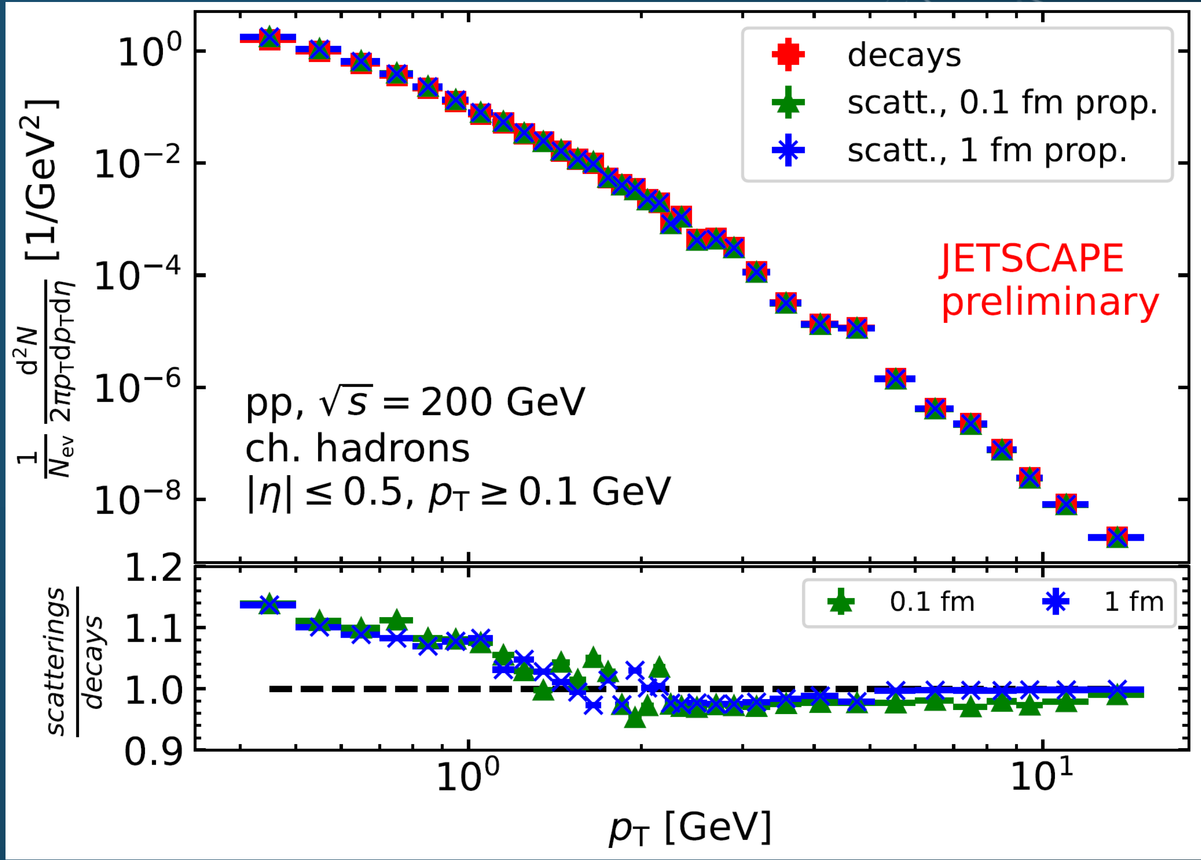
- Monte-Carlo solver of relativistic Boltzmann equations
  BUU type approach, testparticles ansatz: $N \to N \cdot N_{test}$, $\sigma \to \sigma / N_{test}$
- Degrees of freedom
  - most of established hadrons from PDG up to mass 2.3 GeV
  - strings: do not propagate, only form and decay to hadrons
- Propagate from action to action (timesteps only for potentials)
  action $\equiv$ collision, decay, wall crossing
- Geometrical collision criterion: $d_{ij} \leq \sqrt{\sigma / \pi}$
- Interactions: $2 \leftrightarrow 2$ and $2 \to 1$ collisions, decays, potentials, string formation (soft - SMASH, hard - Pythia 8) and fragmentation via Pythia 8

Slide by D. Oliinychenko

PRELIMINARY RESULTS OF HADRONIC RESCATTERING

- $e^+ + e^-$ charged hadrons at 91.2 GeV and p+p at 200 GeV: Hybrid Hadronization + SMASH
- Runs: SMASH decays only, SMASH rescattering with two assumptions about the duration of the hadronization process
- 5-15% effets observed depending on system density (explored by the time parameters)





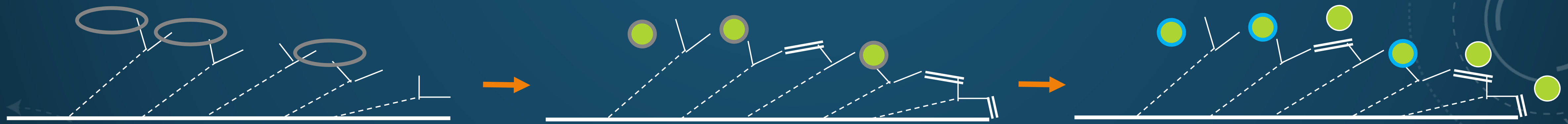
SUMMARY

- Hybrid Hadronization is an attempt to model hadronization consistently from very small to very large systems
- Recombination in Wigner formalism + string fragmentation
- Vacuum systems (e+e-, pp) computed with HH in JETSCAPE: tuning ongoing
- Clear medium effects: baryon enhancement and manifestation of flow
- Hadronic rescattering study for hard probes
- Novel polarization effects from orbital angular motion of quarks?

BACKUP

JETS IN HYBRID HADRONIZATION

- Decay gluons provisionally into qqbar pairs (gluons whose quarks don't recombine are later reformed)
- Go through all possible quark pairs/triplets, compute the recombination probability and sample it. Recombine the pair/triplet if successful.
- Rejected partons again form acceptable string systems (only color singlets removed!)
- Remnant strings are fragmented by PYTHIA 8.



Remnant strings from color flow

String Fragmentation

EXCITED MESONS AND THEIR DECAYS

- We include excited mesons up to $N = k + 2l = 4$.
- Hybrid Hadronization uses PYTHIA 8 for decays: available excited states are limited, but the user can easily add more.
- Many more resonances in the PDG -> add
- Add as of yet unconfirmed bound states: extrapolate unknown properties.

Light/Strange n = 1 (k = 0)

		L=0		L=1		L=2		L=3		L=4	
L=J S=0	$I=1$	xx1 1^1S_0 0^{-+}	π	10xx3 1^1P_1 1^{+-}	$b_1(1235)$	10xx5 1^1D_2 2^{-+}	$\pi_2(1670)$	10xx7 1^1F_3 3^{+-}	$b_3(2013)^\dagger$	10xx9 1^1G_4 4^{-+}	$\pi_4(2306)^\dagger$
	$I=\frac{1}{2}$		K		K_{1B}		$K_2(1770)$		$K_{3B}(2157)^\dagger$		$K_{4B}(2485)^\dagger$
	$I=0$		η		$h_1(1415)$		$\eta_2(1870)$		$h_3(2234)^\dagger$		$\eta_4(2547)^\dagger$
	$I=0$		$\eta'(958)$		$h_1(1170)$		$\eta_2(1645)$		$h_3'(2011)^\dagger$		$\eta_4'(2320)^\dagger$
J=L+1 S=1	$I=1$	xx3 1^3S_1 1^{--}	$\rho(770)$	xx5 1^3P_2 2^{++}	$a_2(1320)$	xx7 1^3D_3 3^{--}	$\rho_3(1690)$	xx9 1^3F_4 4^{++}	$a_4(1970)$	xx8‡ 1^3G_5 5^{--}	$\rho_5(2350)$
	$I=\frac{1}{2}$		$K^*(892)$		$K_2^*(1430)$		$K_3^*(1780)$		$K_4^*(2045)$		$K_5^*(2380)$
	$I=0$		$\phi(1020)$		$f_2'(1525)$		$\phi_3(1850)$		$f_4(2300)$		$\phi_5(2584)^\dagger$
	$I=0$		$\omega(782)$		$f_2(1270)$		$\omega_3(1670)$		$f_4(2050)$		$\omega_5(2323)^\dagger$
J=L S=1	$I=1$			20xx3 1^3P_1 1^{++}	$a_1(1260)$	20xx5 1^3D_2 2^{--}	$\rho_2(1715)^\dagger$	20xx7 1^3F_3 3^{++}	$a_3(2072)^\dagger$	20xx9 1^3G_4 4^{--}	$\rho_4(2376)^\dagger$
	$I=\frac{1}{2}$				K_{1A}		$K_2(1820)$		$K_{3A}(2160)^\dagger$		$K_{4A}(2453)^\dagger$
	$I=0$				$f_1(1420)$		$\phi_2(1835)^\dagger$		$f_3(2173)^\dagger$		$\phi_4(2464)^\dagger$
	$I=0$				$f_1(1285)$		$\omega_2(1733)^\dagger$		$f_3'(2087)^\dagger$		$\omega_4(2389)^\dagger$
J=L-1 S=1	$I=1$			10xx1 1^3P_0 0^{++}	$a_0(1450)$	30xx3 1^3D_1 1^{--}	$\rho(1700)$	30xx5 1^3F_2 2^{++}	$a_2(1918)^\dagger$	30xx7 1^3G_3 3^{--}	$\rho_3(2113)^\dagger$
	$I=\frac{1}{2}$				$K_0^*(1430)$		$K^*(1680)$		$K_2^*(1897)^\dagger$		$K_3^*(2092)^\dagger$
	$I=0$				$f_0(1710)$		$\phi_1(1931)^\dagger$		$f_2(2129)^\dagger$		$\phi_3(2310)^\dagger$
	$I=0$				$f_0(1370)$		$\omega(1650)$		$f_2'(1889)^\dagger$		$\omega_3(2101)^\dagger$

PDG states

Unconfirmed states