Space-time structure of hadron production in high-energy collisions

How closely are hadrons packed?

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Outline

- Motivation
- Timescale in physical processes
- Lund String Model
- Analysis and results
- Summary

Motivation

High-multiplicity pp collisions display a collective behaviour typical of heavy ion collisions: strangeness productions is enhanced.

Goal: Study hadron production density in different situations

Method: Space-time implementation in PYTHIA

[1] ALICE Collaboration (Adam, Jaroslav *et al.*) arXiv:1606.07424 [nucl-ex]

Timescale in physical processes

Hadronization typical scales of order of fermi

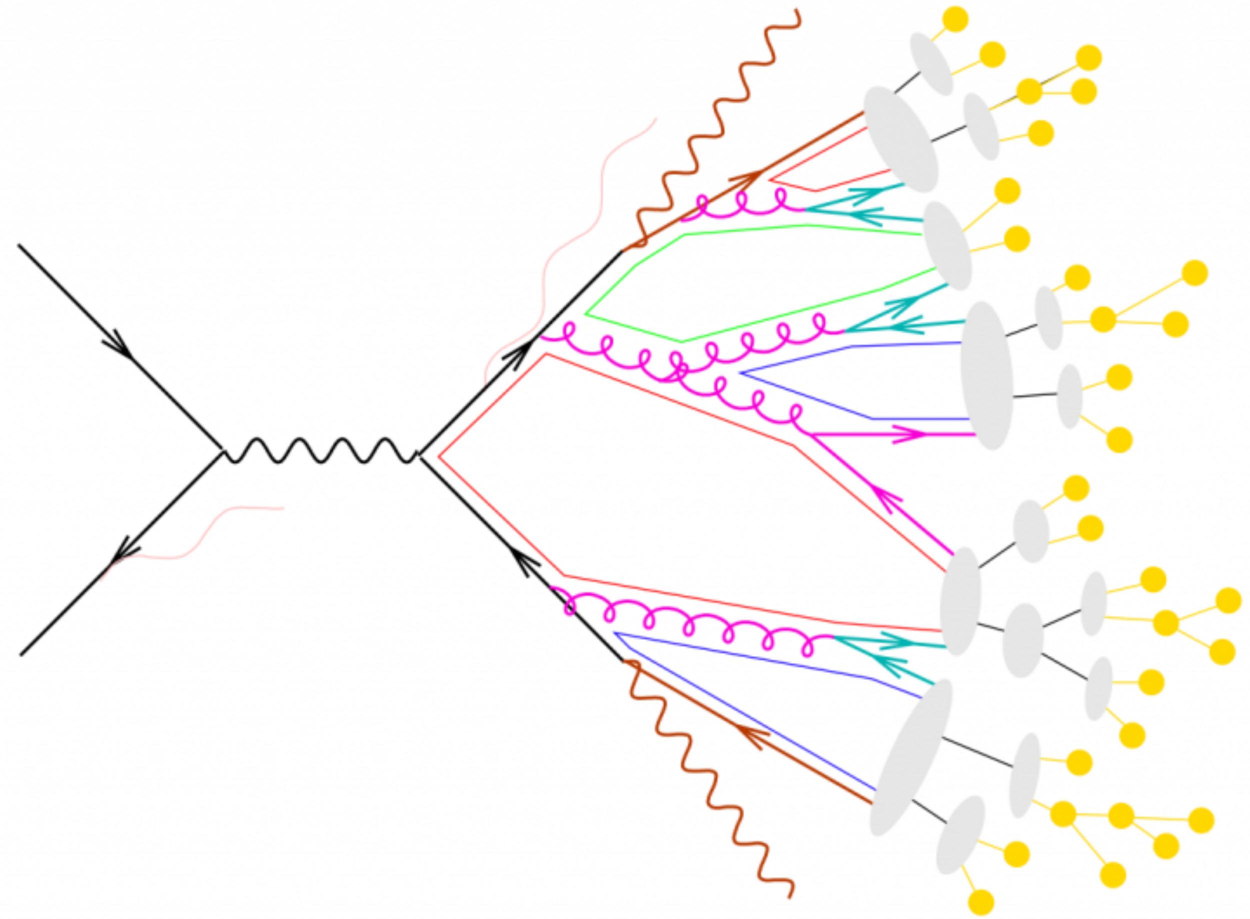


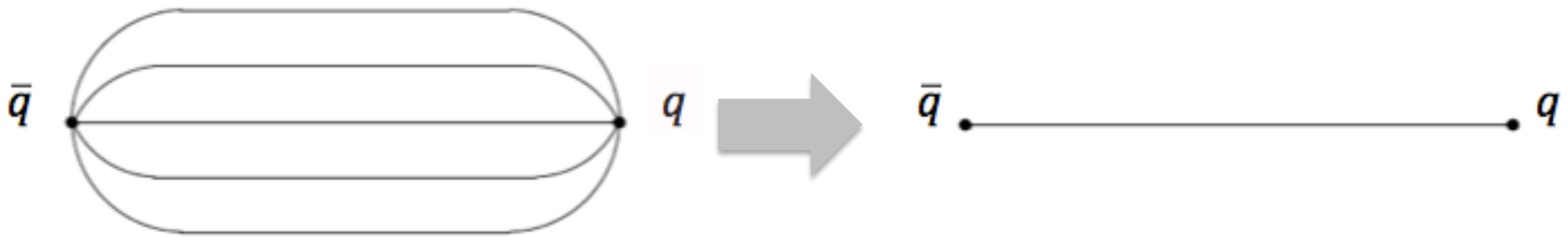
Figure from arXiv:1412.3649v1

Linear force field in QCD

Colour confinement → Non-existence of free quarks

$$V_{QCD}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \kappa r$$

For large separation between partons



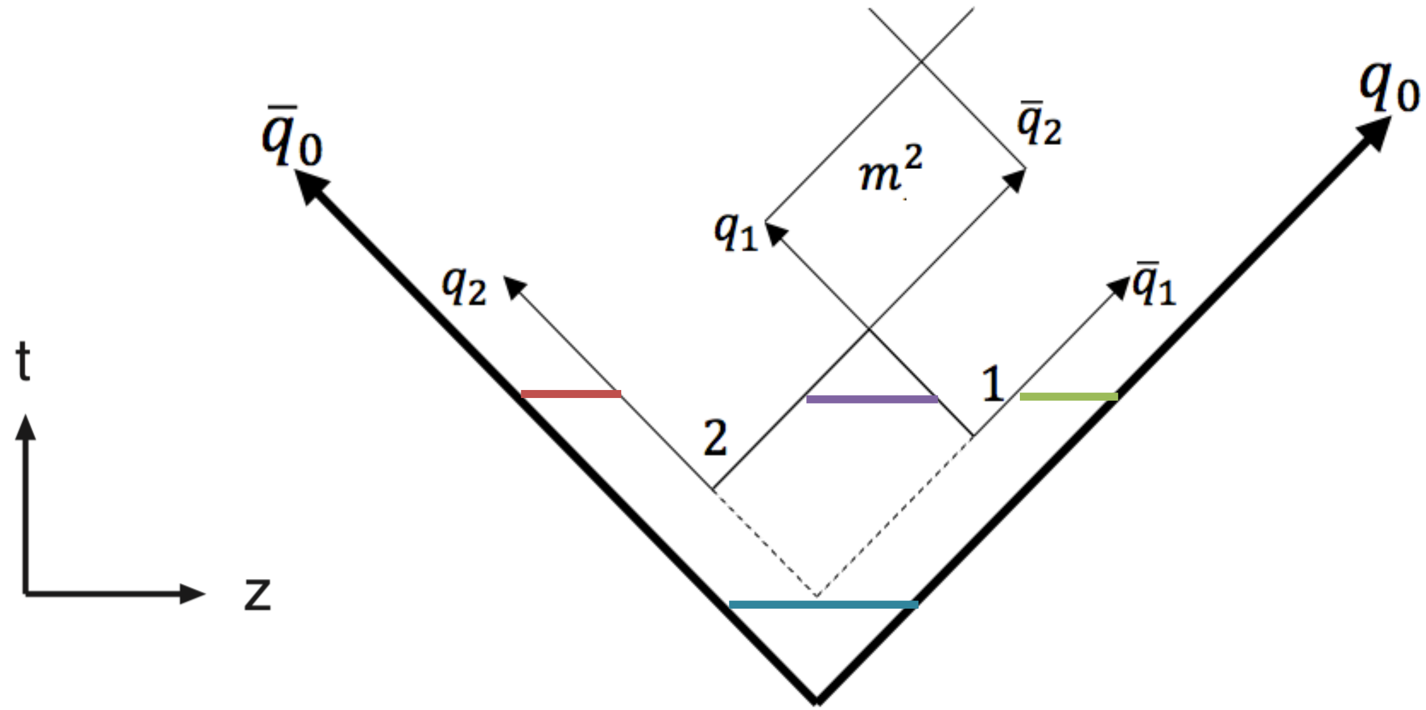
Approximation: linear potential expressed as string of zero width , whose string tension is

$$\kappa \approx 1\mathrm{GeV}/\mathrm{fm}$$

String breaking

Linearity between space-time and energy-momentum picture

$$\left|\frac{dp_z}{dt}\right| = \left|\frac{dp_z}{dz}\right| = \left|\frac{dE}{dt}\right| = \left|\frac{dE}{dz}\right| = \kappa$$



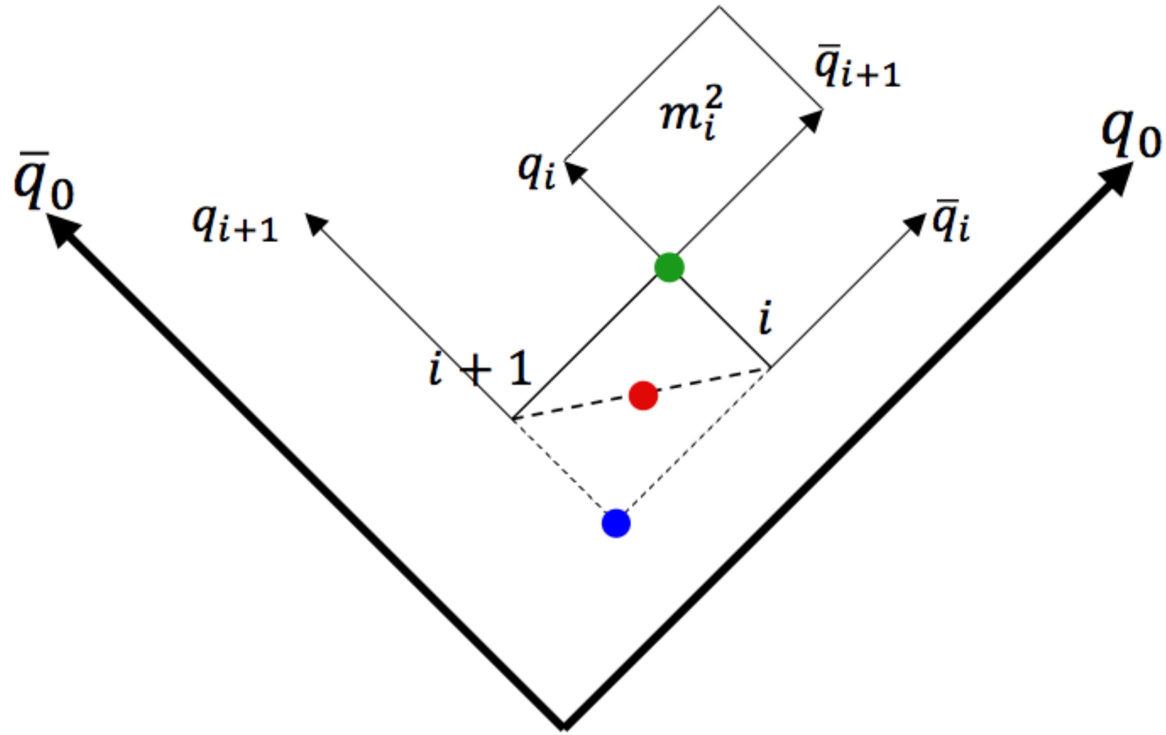
Hadron Production Points

The definition for hadron production point is not unique

$$v_i^h = \frac{v_i + v_{i+1}}{2} + \frac{p_h}{2\kappa}$$

$$v_i^h = \frac{v_i + v_{i+1}}{2}$$

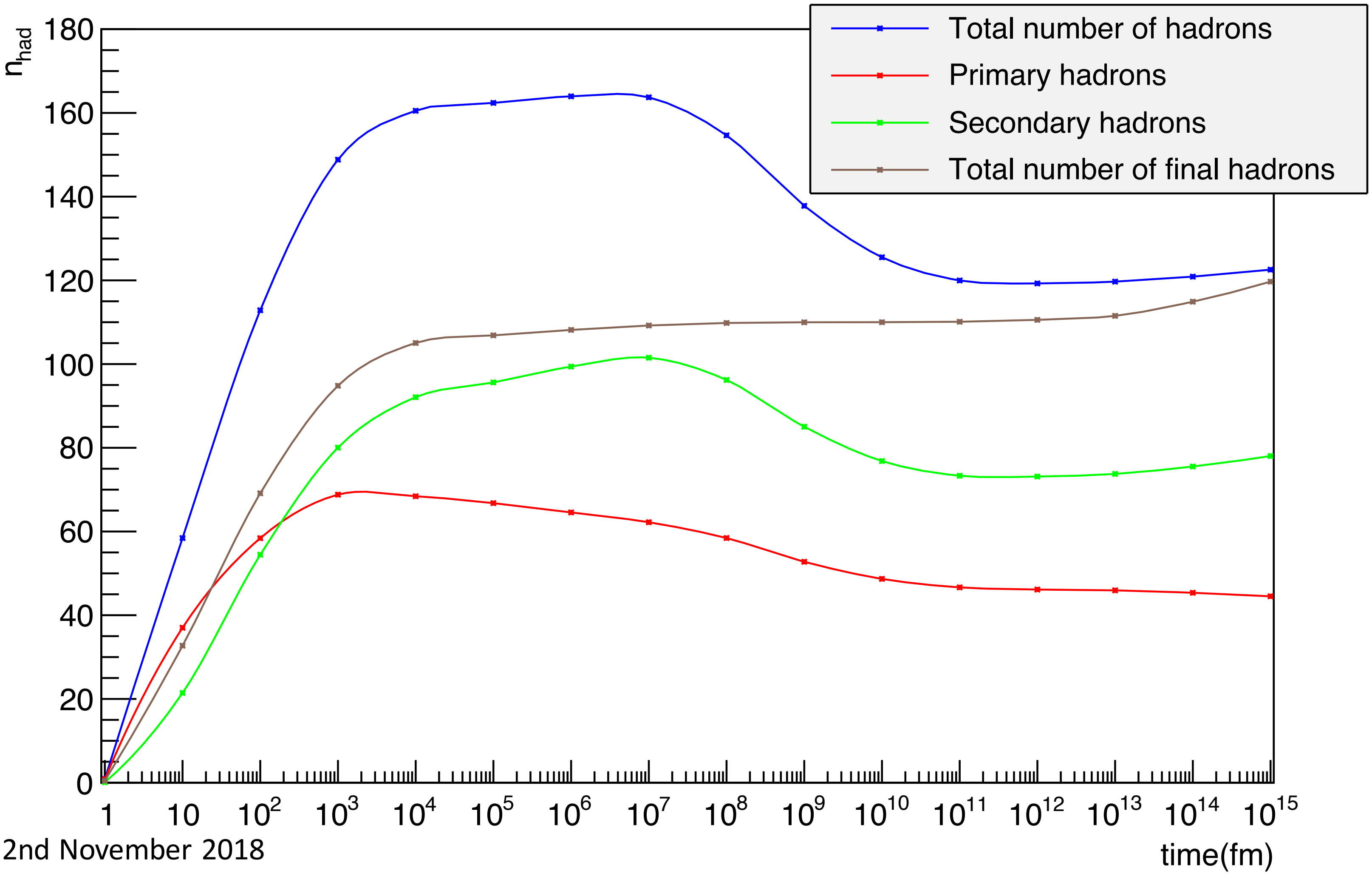
$$v_i^h = \frac{v_i + v_{i+1}}{2} - \frac{p_h}{2\kappa}$$



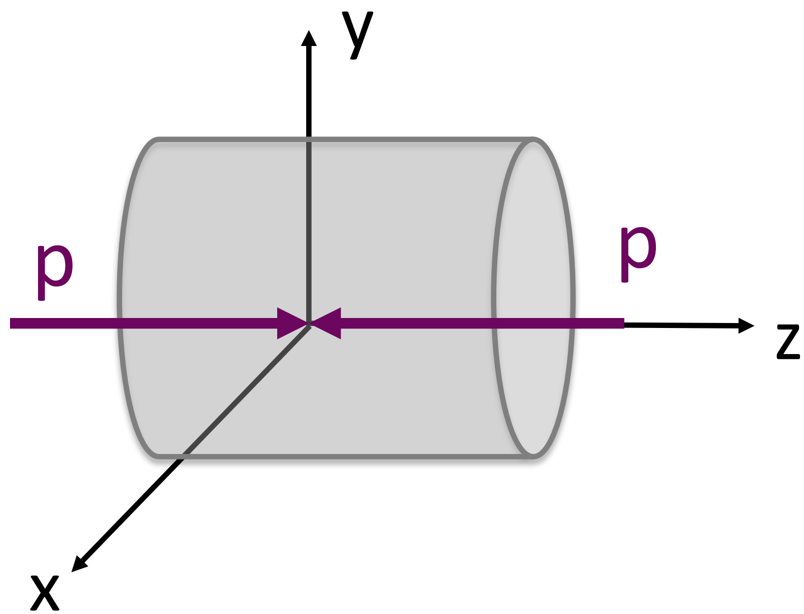
Temporal evolution of hadron production

$p,\ \bar{p}$ → Truly stable

$\pi^{\pm},\ K^{\pm},\ K_L$ and n → Regarded as stable



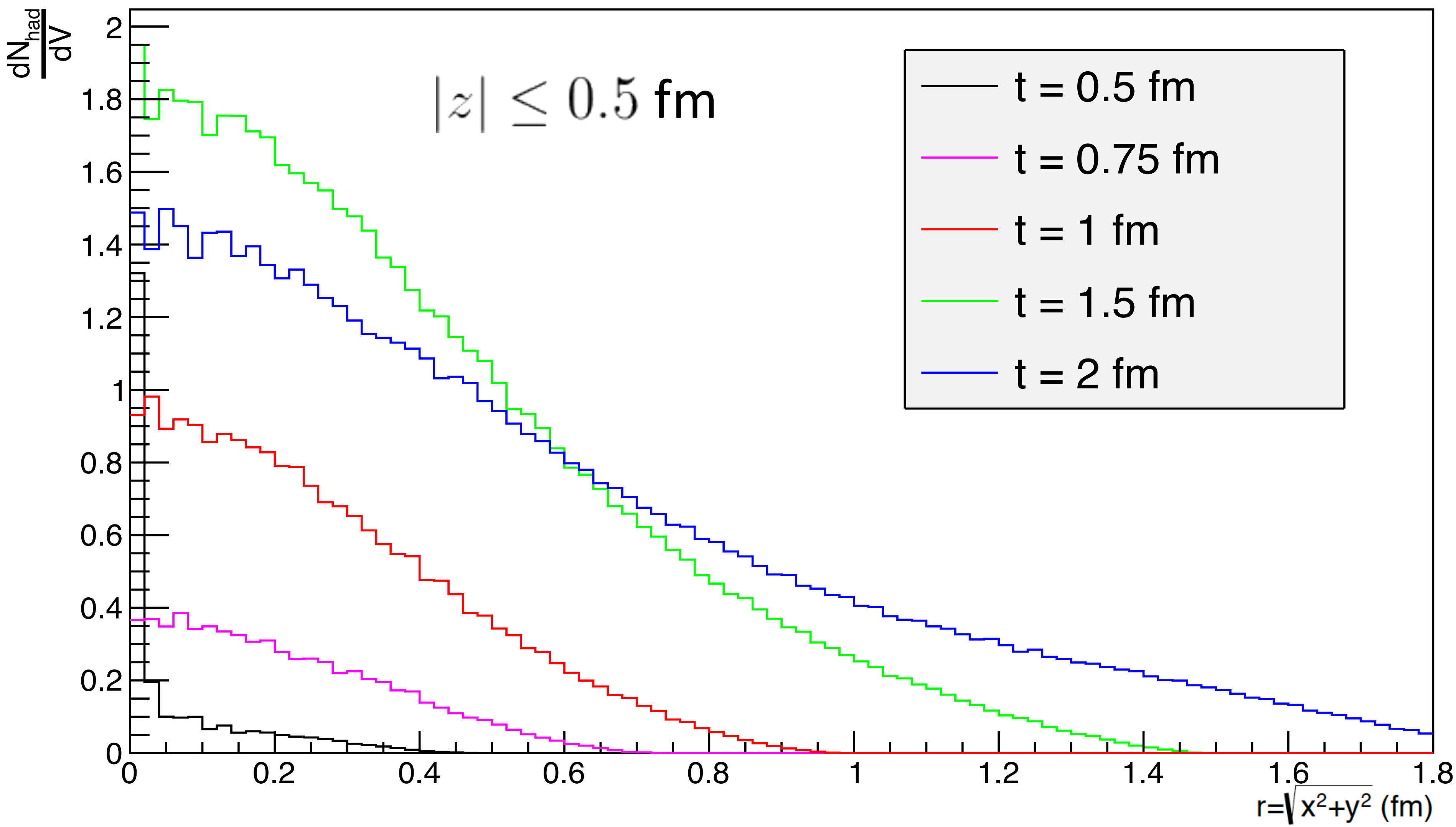
Hadron density in central region



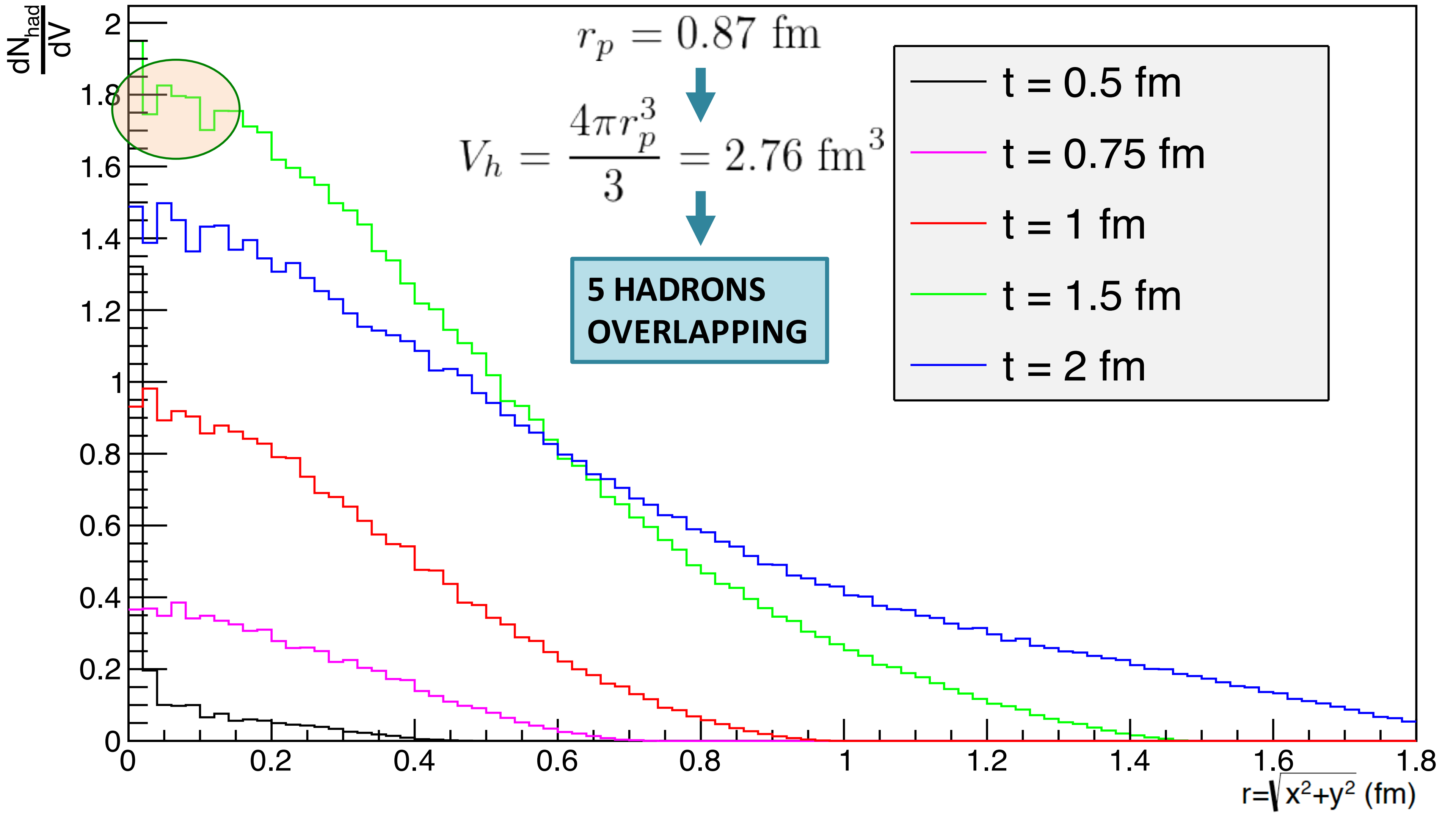
Hadron density in the longitudinal central region $|z| \leq 0.5$ fm

$$\left.\frac{dN}{dV}\right|_{|z|\leq 0.5} = \left.\frac{dN}{dxdydz}\right|_{|z|\leq 0.5} = \frac{dN}{dxdy} = \frac{dN}{2\pi r dr}$$

Hadron density in central region



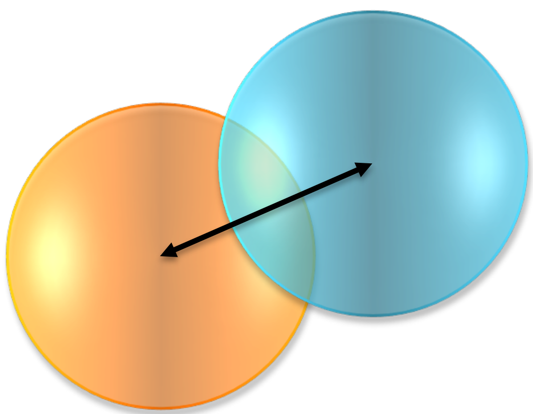
Hadron density in central region



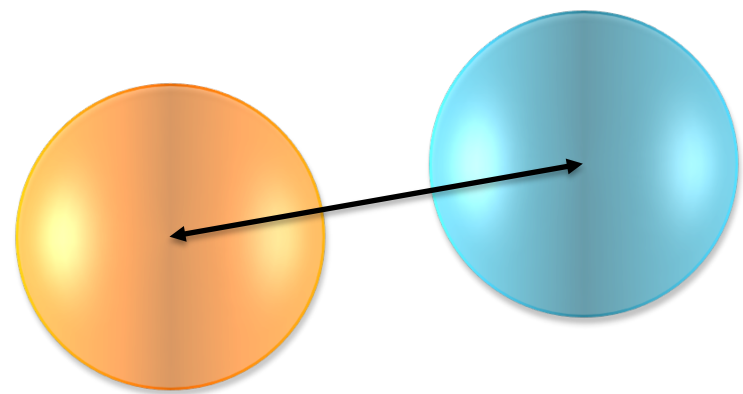
Close-packing in hadron rest frame

Number of overlapping hadrons in **hadron rest frame**

Hadrons are spheres with $r_p = 0.87 \text{ fm}$



$r < 2r_p$

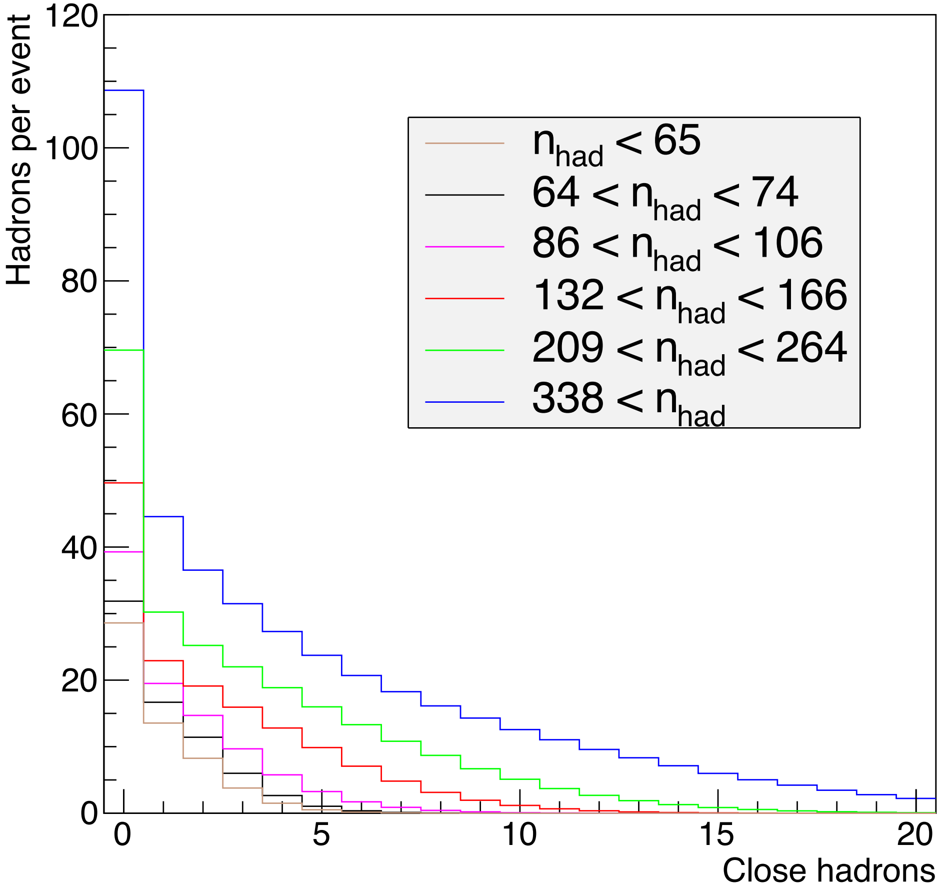


$r > 2r_p$

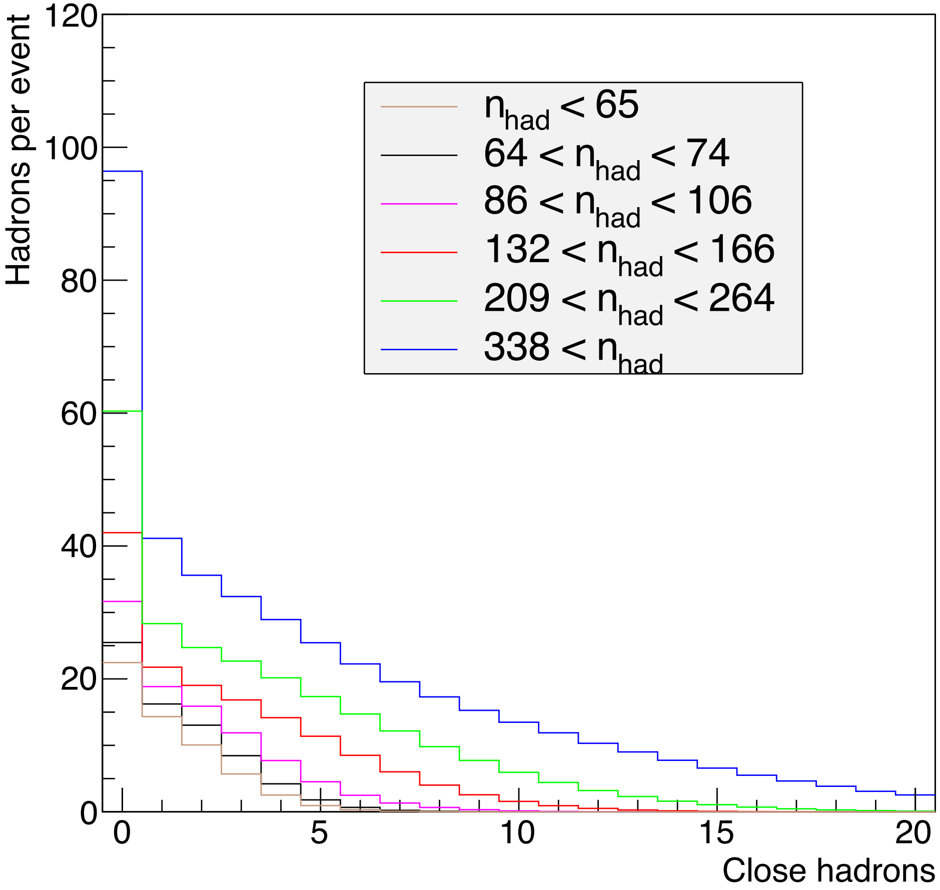
Adjacent hadrons $\longrightarrow$ Closest hadron on each side in the same string

Close-packing in hadron rest frame

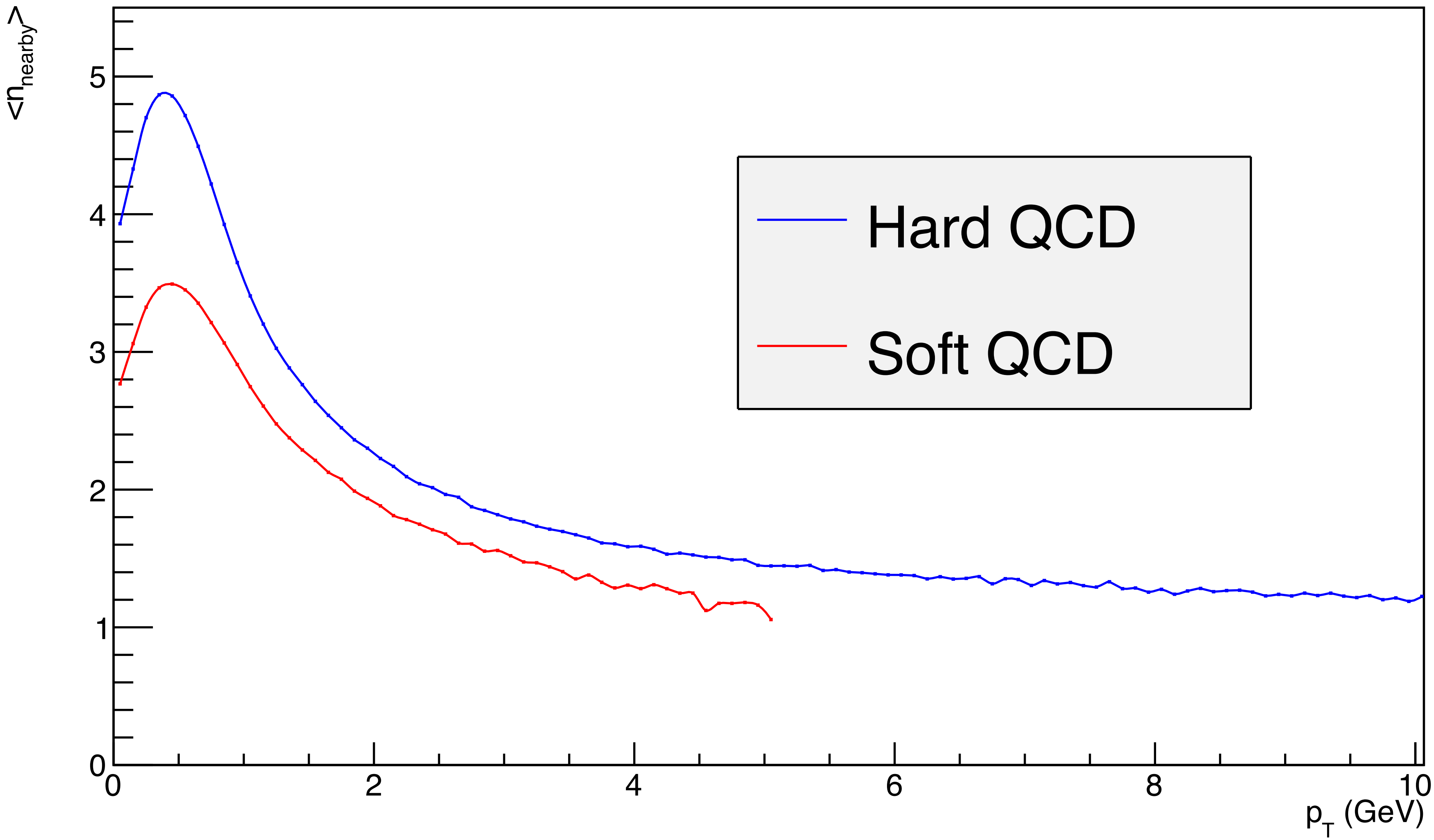
Excluding adjacent hadrons



Including adjacent hadrons



Close-packing in hadron rest frame



Summary

- Close—packing is important in the central region and seems to affect mainly low transverse momentum hadrons.
- Hadronic overlap specially important in high—multiplicity pp collisions.

In the future:

- Include hadron scattering in PYTHIA.
- Analyze further hadronic close—packing and its effects.

References

- B. Andersson *et al.* ***Parton fragmentation and string dynamic***, Phys. Rept. 97, Nos 2&3 (1983).

- T. Sjöstrand, ***Jet fragmentation of multiparton configurations in a string framework,*** Nuc. Phys. B248 (1984).

Two parton system

Linearity between space-time and energy-momentum picture

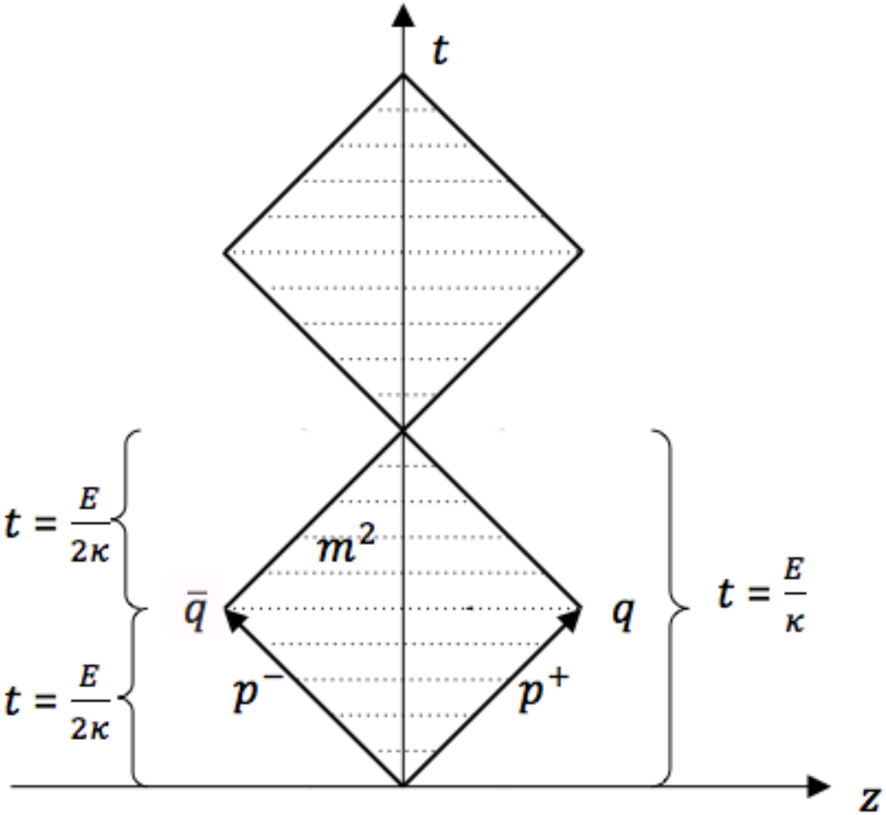
$$\left|\frac{dp_z}{dt}\right| = \left|\frac{dp_z}{dz}\right| = \left|\frac{dE}{dt}\right| = \left|\frac{dE}{dz}\right| = \kappa$$

Initial motion of a system with energy E:

- Quark moving in +z direction
- Antiquark moving in –z direction

$$p^+ = p_q = E_q(\,1,\ 0,\ 0,\ 1)$$
$$p^- = p_{\bar{q}} = E_{\bar{q}}(\,1,\ 0,\ 0,-1)$$

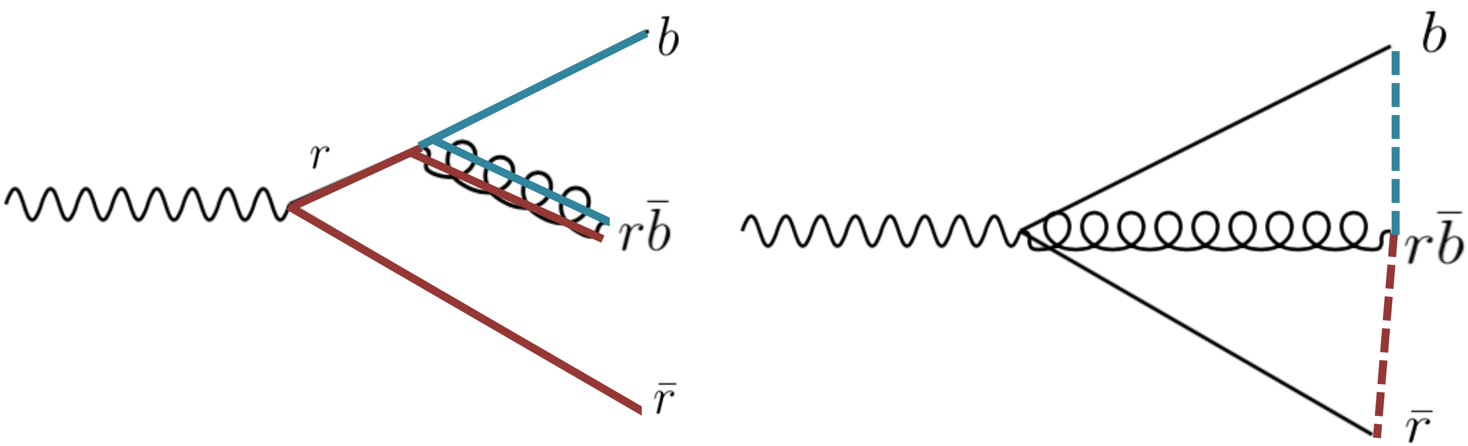
$$m^2 = (p_+ + p_-)^2 = 2p^+p^-$$



Colour flow

$$Z^0 \longrightarrow q\bar{q} \longrightarrow qg\bar{q}$$

Gluon = colour + anticolour



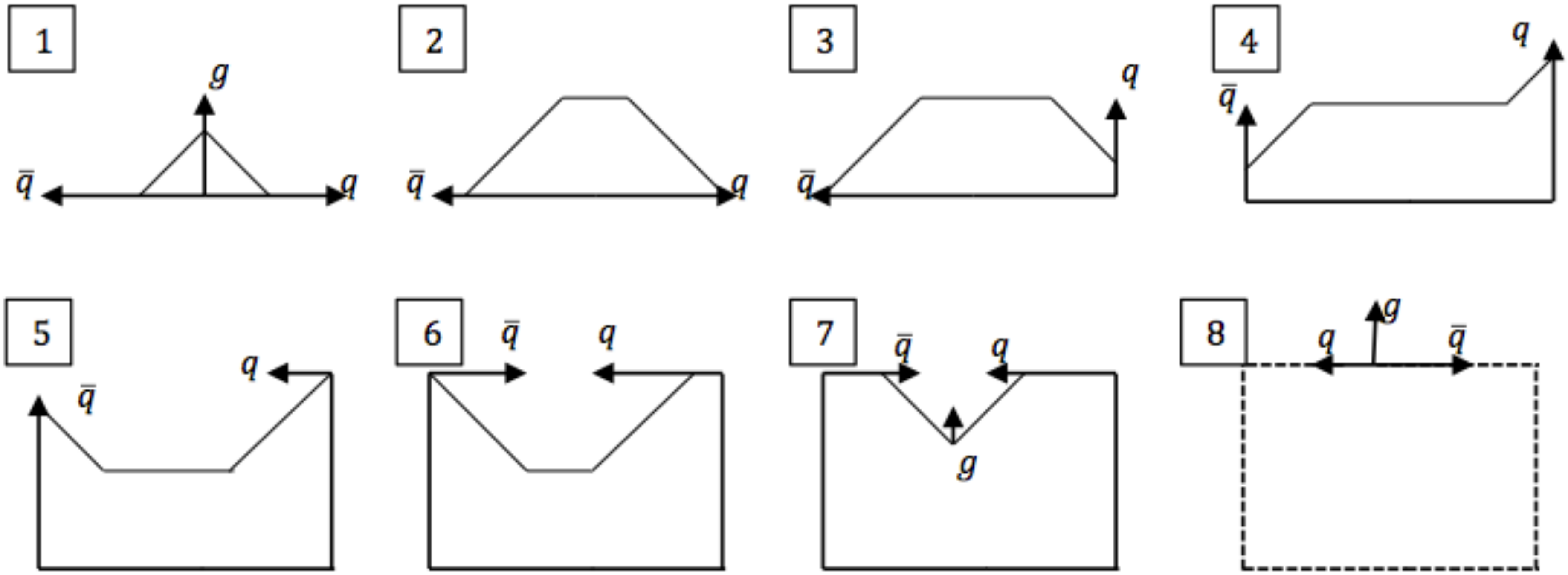
Diagonal gluons: $\left(r\bar{r} + g\bar{g} - 2b\bar{b}\right) / \sqrt{6}$

Diagonal gluons negligible when considering $N_c \longrightarrow \infty$

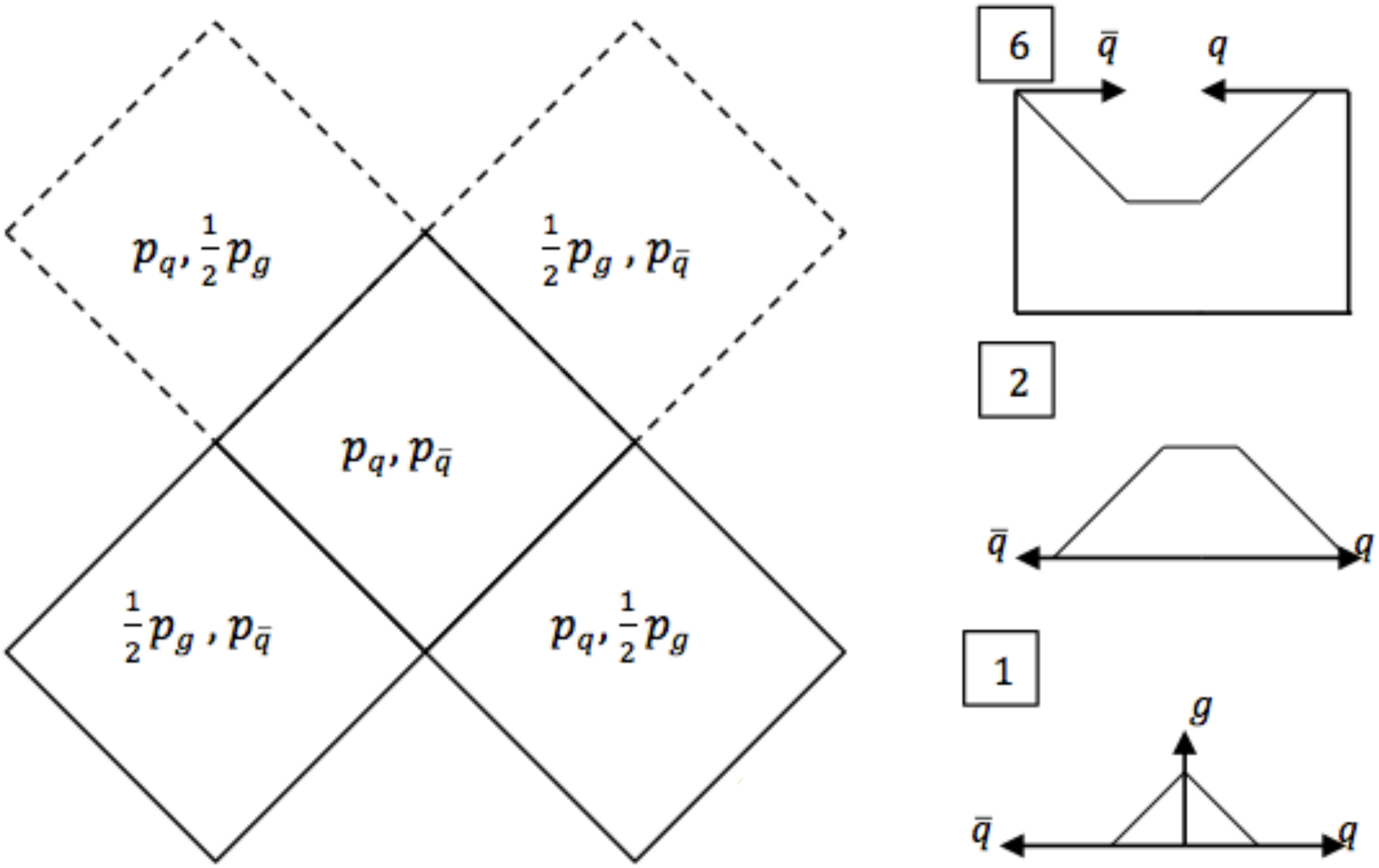
Multiparton system

Time evolution of system initially composed of:

- Quark moving in +z direction.
- Gluon moving in +x direction.
- Antiquark moving in –z direction.



Parameter plane



Lund String Model implementation

Quark flavour chosen randomly: $u\overline{u} : d\overline{d} : s\overline{s} \approx 1 : 1 : \frac{1}{3}$

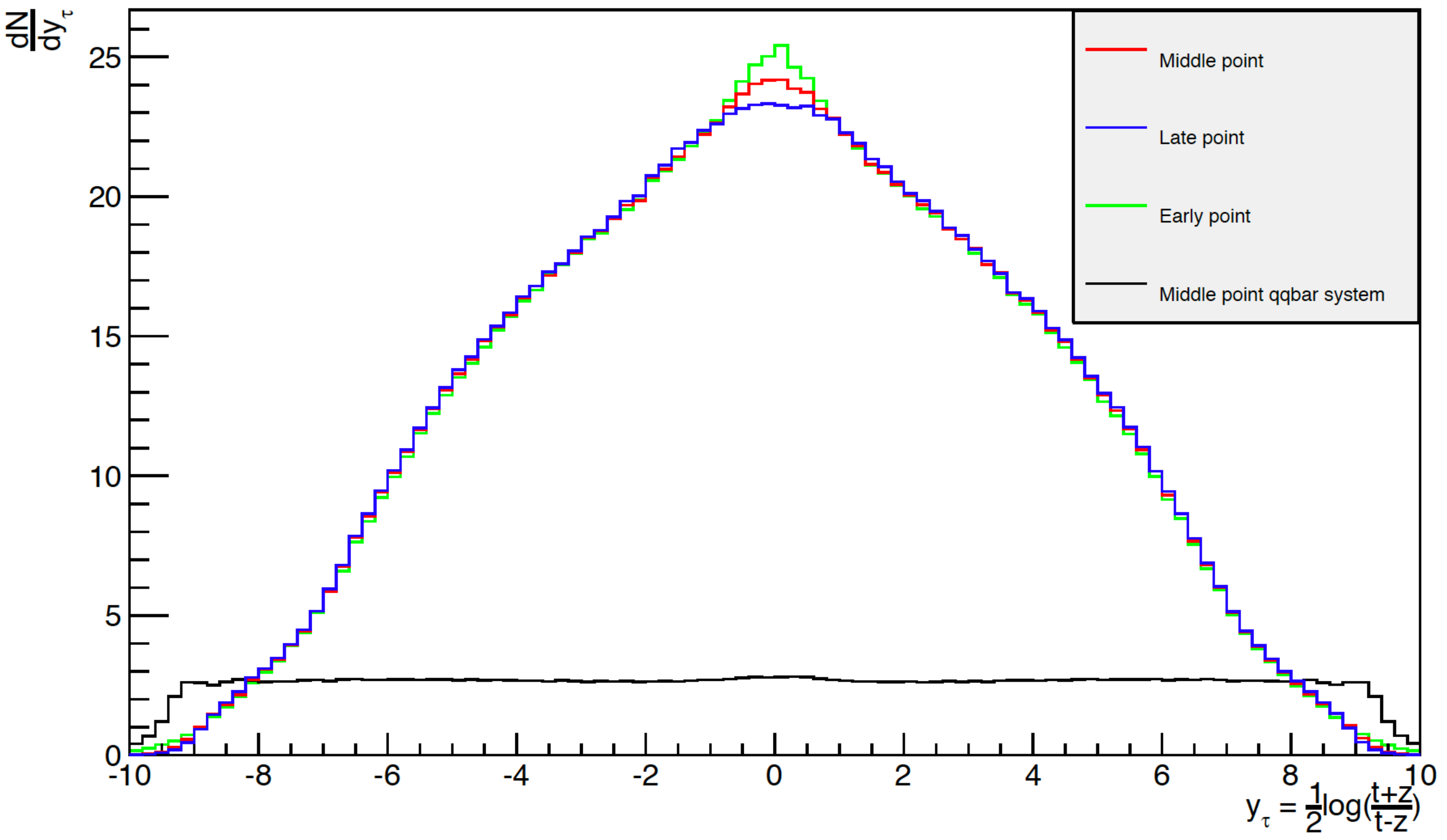
Hadron kind from quark content ➡ Two adjacent quark-antiquark

Mass effect vs Spin effect

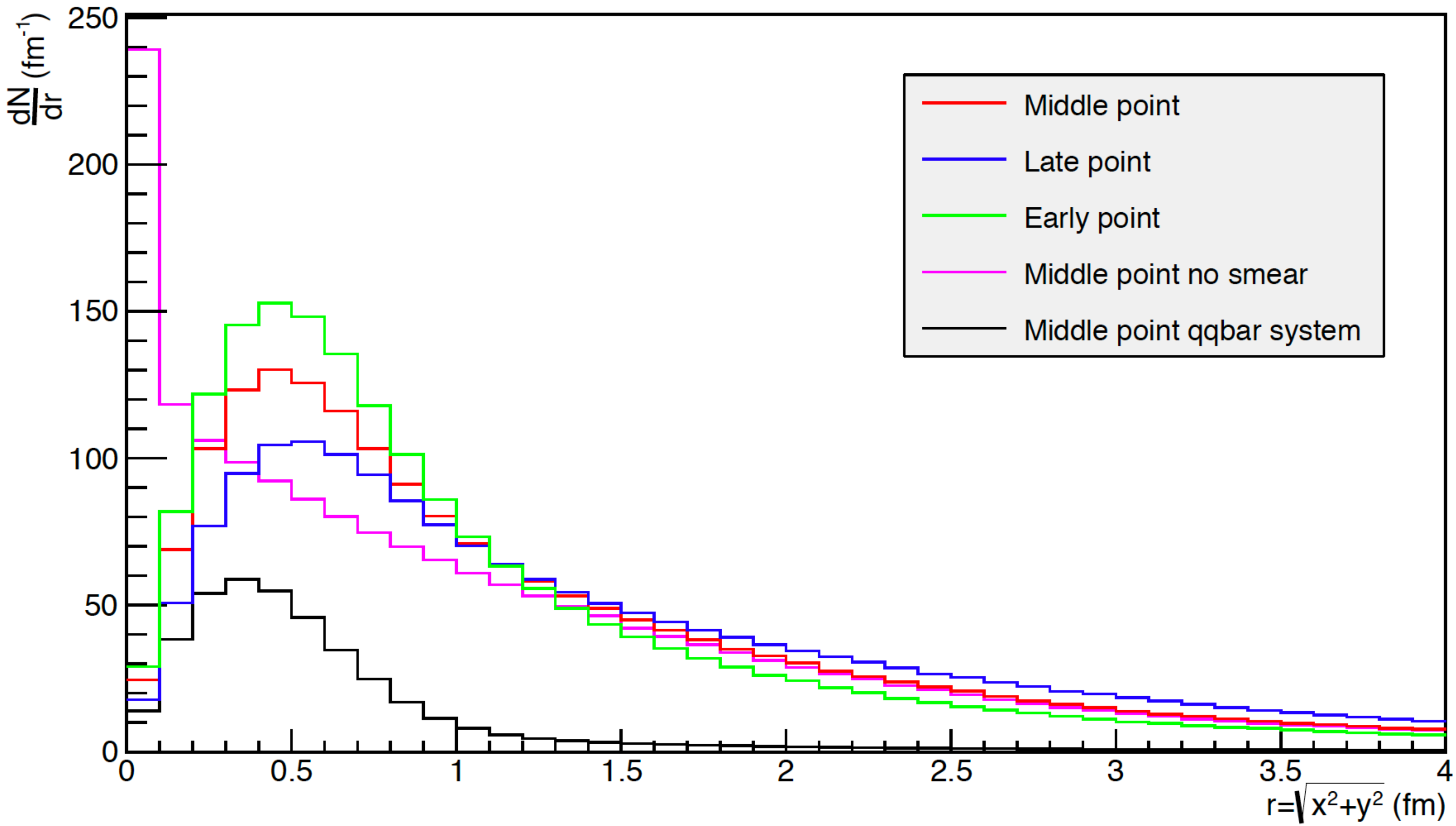
Transverse momentum of hadron from quark-antiquark (randomly)

Longitudinal momentum from $$f(z) = \frac{(1-z)^a}{z} \exp\left(-b\frac{m_h^2}{z}\right)$$

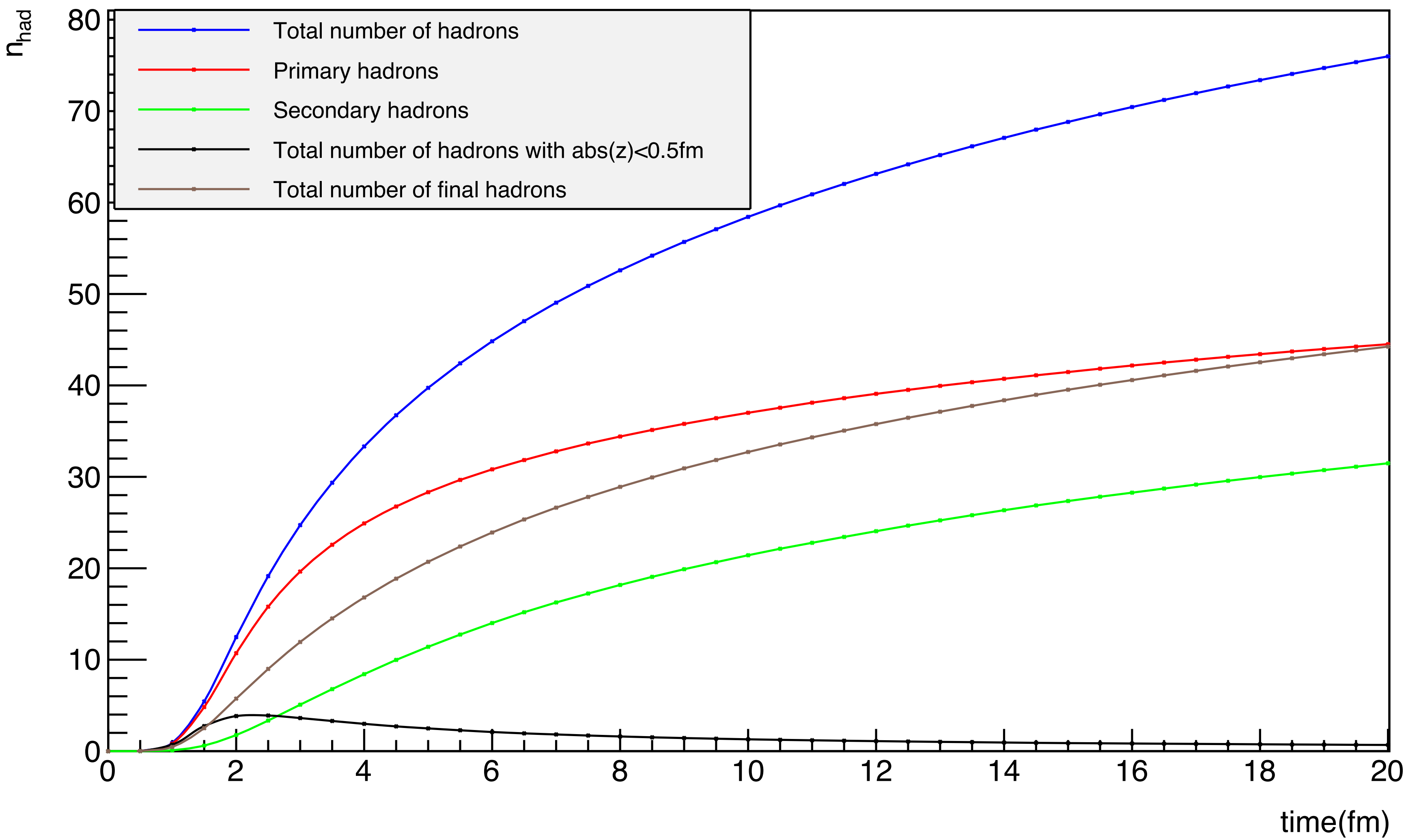
Longitudinal spectrum



Transverse spectrum



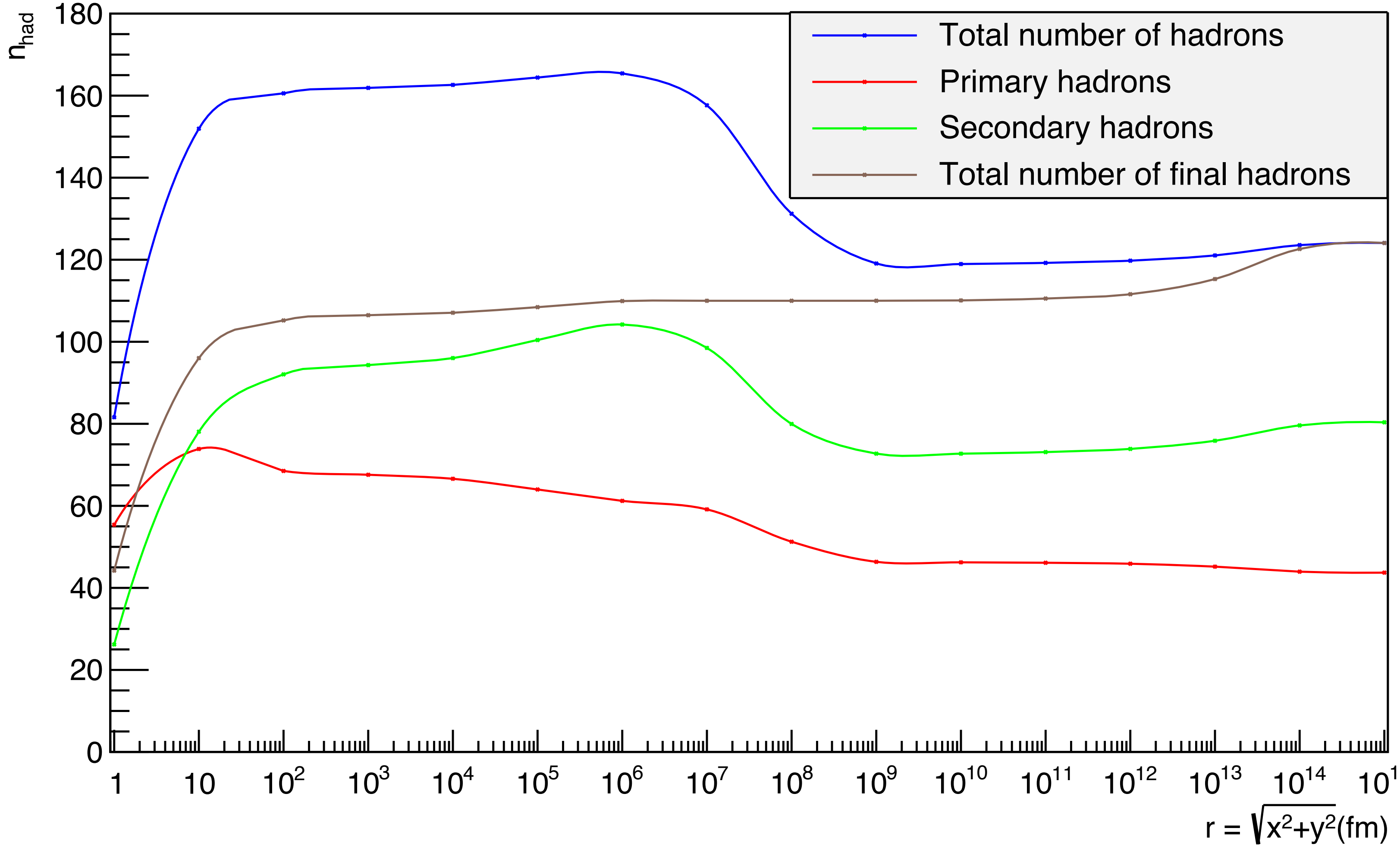
Temporal evolution of hadron production



Radial evolution of hadron production

$e^{\pm}$, p, $\bar{p}$, γ and ν → Truly stable

$\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, K_L and n → Regarded as stable



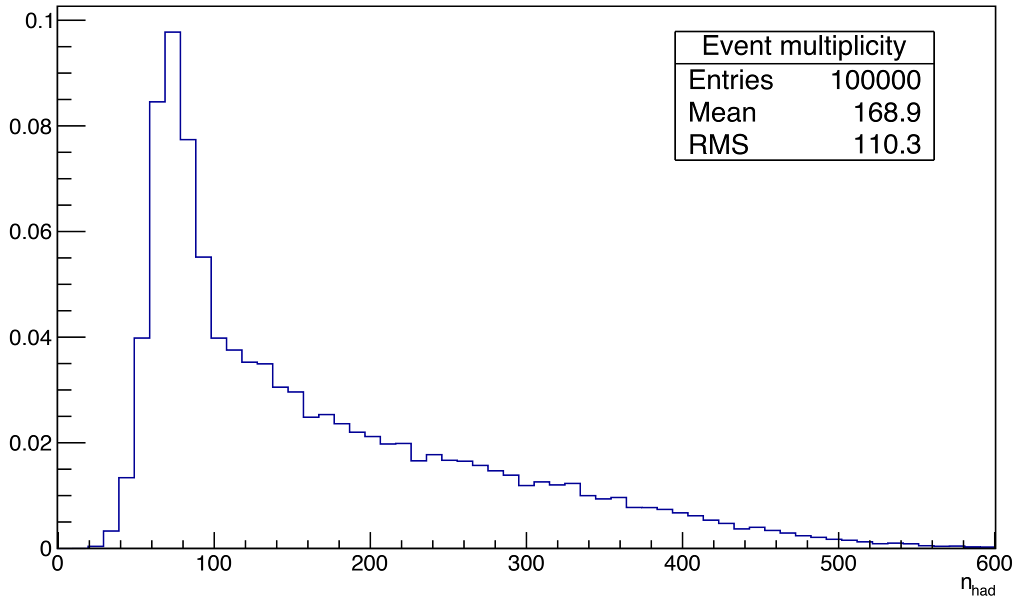
Hadron production for different multiplicities

Hadronic multiplicity constraints:

- Hadrons with lifetimes $\tau \geq \tau_{\pi^0}$ are stable.
- No decays taking place at $r > 10\ \mathrm{fm}$.

Only strong decays

- Secondary vertices enter with a weight one less than the number of hadron created in the decay.



10 hadronic multiplicity ranges

↓

Approximately same number of events