Importance of parallel scatterings

Based on the lecture “Monte Carlo Event Generators” by Klaus WERNER, given at the summer school “Heavy Ion Collisions in the QCD phase diagram” , June 27 - July 08, 2022, Nantes, France.

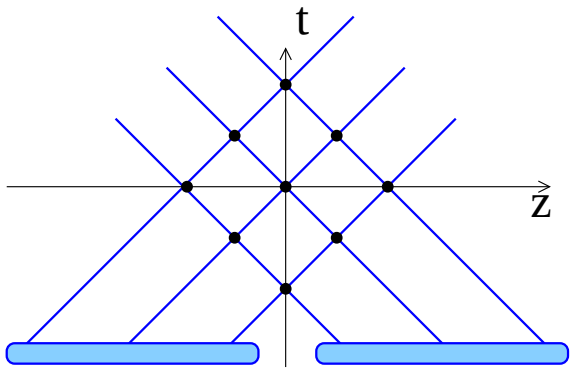
Parallel and sequential scattering in AA

Crucial time scales

$\tau_{\text{collision}}$ is the duration of the AA collision

$\tau_{\text{interaction}}$ is the time between two NN interactions

τ_{form} is the particle formation time



A+A collision in space-time
Blue lines: nucleons

At "low" energy

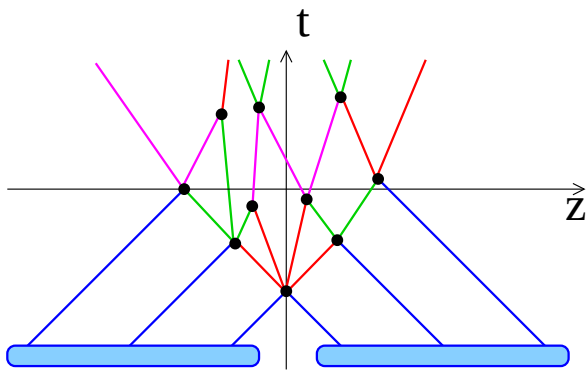
Sequential collisions (cascade)

Crucial:

$$\tau_{\text{form}} < \tau_{\text{interaction}}$$

τ_{form} is the particle formation time

$\tau_{\text{interaction}}$ is the time between two NN interactions



A+A collision at low energy

red/green/magenta lines: produced hadrons

At "high" energy ($\gg$1GeV):

Longitudinal size

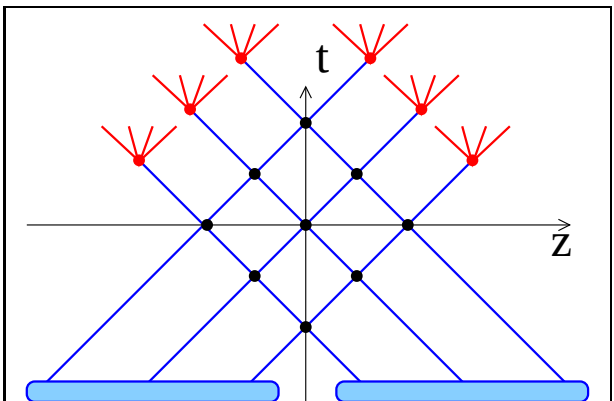
$$d = \frac{2R}{\gamma} \ll 1\,\text{fm/c}$$

All interactions simultaneously at $t = 0$ (in parallel)

Particle production later. Condition:

$$\tau_{\text{form}} \gg \tau_{\text{collision}}$$

$\tau_{\text{collision}}$ is the duration of the AA collision



A+A collision at high energy

Collision zone pointlike

Low energy and high energy nuclear scattering are completely different, and completely different theoretical methods are needed

- **High energy approach = parallel interactions (as done in EPOS)**

  (and this is why we need these Markov chain techniques...)

- **At LHC energies, one can completely separate**
  - **primary interactions (within < 0.01 fm/c)**
  - **and secondary interactions (hydro evolution etc)**

What is the range of validity of the "parallel approach" ?

The condition is

$$\tau_{\text{collision}} = \frac{2R}{\gamma c} < \tau_{\text{form}} \approx 1\,\text{fm/c}$$

For $R = 6.5\,\text{fm}$, we get

$$\gamma > \frac{2R}{c\tau_{\text{form}}} \approx \frac{13}{1}$$

so the critical energy per nucleon is $E \approx 13\, m_p c^2 \approx 12\,\text{GeV}$

The "parallel approach" is valid (and required) for $\sqrt{s_{NN}} \gtrsim 24\,\text{GeV}$ (upper BES energies, LHC)

What is the range of validity of the "cascade approach" ?

The condition is (with n nucleons in a row)

$$\tau_{\text{interaction}} = \frac{2R}{n\gamma\beta c} > \tau_{\text{form}} \approx 1\,\text{fm/c}$$

For $R = 6.5\,\text{fm}$ and $n = 6$, we get

$$\gamma\beta < \frac{2R}{nc\tau_{\text{form}}} \approx \frac{13}{6}$$

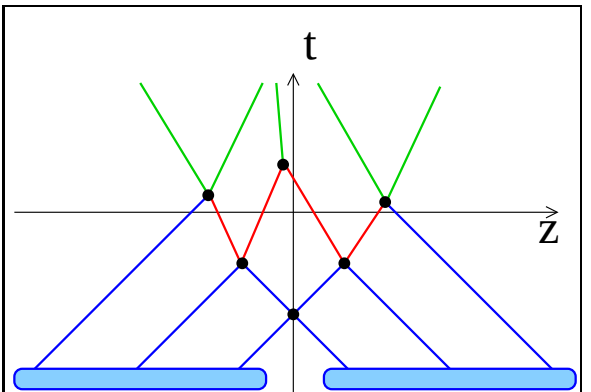
so the critical energy per nucleon is $E \approx \gamma\, m_p c^2 \approx 2.2\,\text{GeV}$

The "cascade approach" is valid for $\sqrt{s_{NN}} \lesssim 4\,\text{GeV}$

The intermediate range $4 < \sqrt{s_{NN}} < 24$ GeV

On needs a "partially parallel approach"

Several (but not all) NN scatterings are realized, before particle production starts



A+A collision at intermediate energy

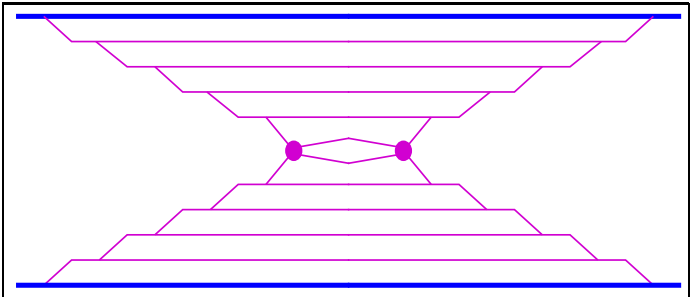
Red/green lines: produced hadrons

Parallel approach in pp

At LHC energy: Interaction: successive parton emissions

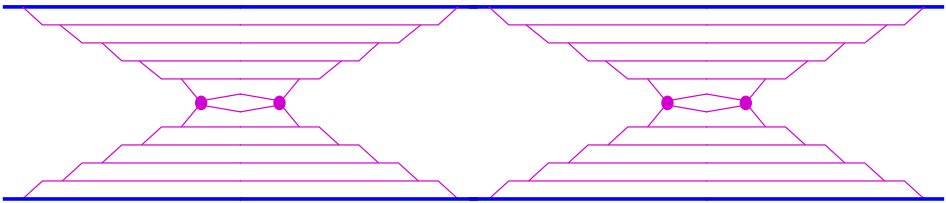
Large gamma factors, very long lived ptls

The complete process takes a very long time



pp collision
Exchange of parton ladder

Impossible to have several of these interactions in a row



So also in pp:

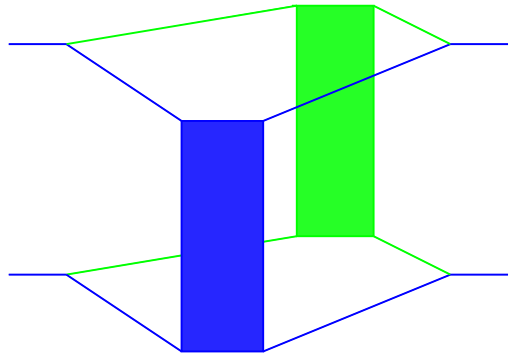
- High energy approach = parallel interactions
  (as done in EPOS)

And we know that multiple scattering is important!

So double scattering in pp should look like this:

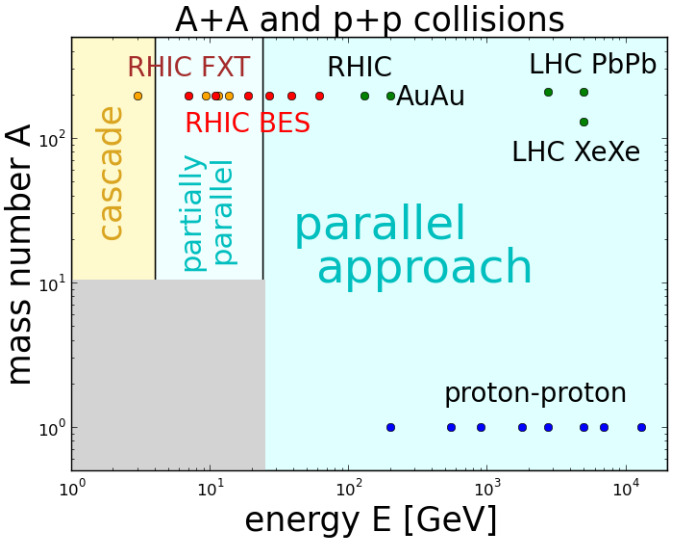
Here two parallel scatterings

No contradictions with respect to timescales



So it seems mandatory to use a parallel scattering scheme, for pp and AA, known since a long time ... but somewhat forgotten nowadays ...

Parallel approach needed almost everywhere



Points (besides FXT):
Epos comparisons to data