RHIC-BES online seminar, April 4th, 2023

Heavy ion collisions from 5 TeV down to 4 GeV in the EPOS4 framework

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The EPOS4 project

☐ **NOT provide “another model” to study flow**

☐ **BUT a “complet” event generator**

- ▷ **to do normal pp physics**
  (total cross section, light flavor spectra, jets, charm,...)
- ▷ **which in addition accounts for collective effects in small systems**
- ▷ **which in addition can handle nuclear scatterings from LHC to RHIC**

To check if we get a consistent overall picture

☐ **Oct. 2022 EPOS4.0.0 release** (no "official" EPOS3 release)
https://klaus.pages.in2p3.fr/epos4/
thanks **Laurent Aphecetche** for explaining gitlab pages, nextjs etc
thanks **Damien Vintache** for managing installation/technical issues

- ▷ **a full general purpose approach, public, and testable**
- ▷ **tested (by myself) for 4 GeV - 13000 GeV,**
  pp to PbPb, light / heavy flavor, collective / hard

☐ **Papers:**

- ▷ **https://arxiv.org/pdf/2301.12517.pdf**
  will be updated from v1 to v2 very soon
- ▷ **many more coming soon**
  checkout https://klaus.pages.in2p3.fr/epos4/physics/papers

☐ Work in progress:

- ▷ **EPOS4+HQ (heavy flavor)**
  with Jiaxing Zhao, Jorg Aichelin, Pol-Bernard Gossiaux
- ▷ **EPOS4+JETS**
  with Alexander Lind, Jorg Aichelin, Pol-Bernard Gossiaux, Iurii Karpenko, Damien Vintache
- ▷ **EPOS3+PHSD** (hydro versus transport)
  with Mahbobeh Jafarpour, Elena Bratkovskaya, Vadym Voronyuk

Outline

- ☐ **Parallel and sequential scattering**
  What kind of model do we need in the energy range from few GeV up to infinity?
- ☐ **Parallel scattering scenario in EPOS4**
- ☐ **The role of core, corona, and remnants for different energies**
  and how the physics changes
- ☐ **Results**
  Comparing with data. Successes and failures.

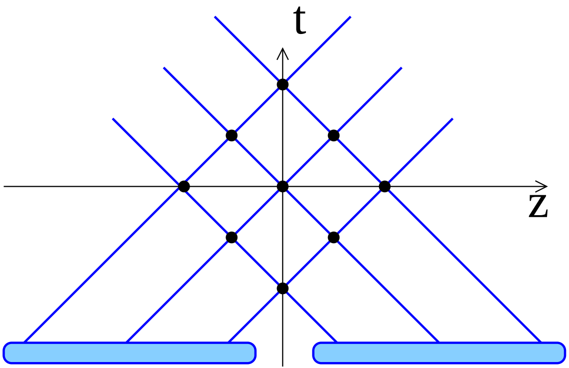
Parallel and sequential scattering in AA

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 hadron formation time after the interaction of two nucleons



A+A collision in space-time

Blue lines: nucleons

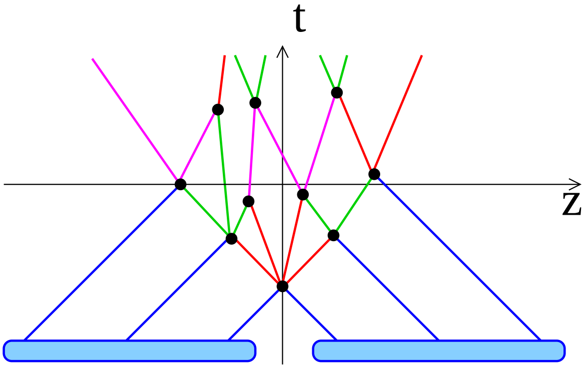
Points: possible interactions (assuming that the trajectories are close in transverse direction)

At “low” energy

Sequential collisions (cascade)

Condition:

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



A+A collision at low energy red/green/magenta lines: produced hadrons

τ_{form} is the particle formation time

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

At “high” energy ($\gg$1GeV):

Longitudinal size

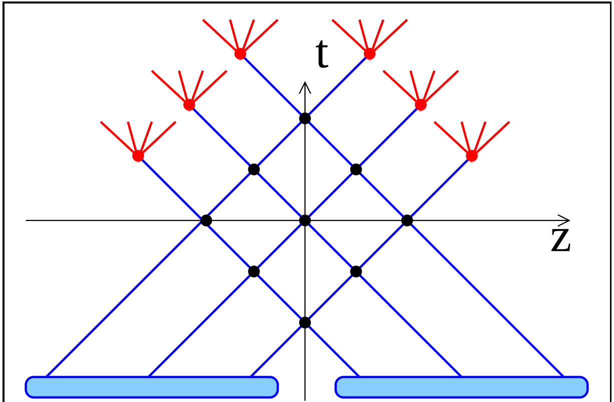
$$d = \frac{2R}{\gamma} \ll 1\,\mathrm{fm/c}$$

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

Hadron production later. Condition:

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

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



A+A collision at high energy

Collision zone pointlike

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

☐ **At high energies, one can completely separate**

- ▷ **primary interactions (at $t \approx 0$)**
- ▷ **and secondary interactions (hydro evolution etc)**

☐ **High energy approach = parallel primary interactions**

What means "high/low energy" ?

Define (E in the sense of $\sqrt{s_{NN}}$):

☐ **High energy thresholds E_{HE} by $\tau_{\mathrm{form}} = \tau_{\mathrm{collision}}$**

☐ **Low energy thresholds E_{LE} by $\tau_{\mathrm{form}} = \tau_{\mathrm{interaction}}$**

Numerical estimates (assuming $\tau_{\mathrm{form}} \approx 1\,\mathrm{fm/c}$):

High energy threshold ($\tau_{\mathrm{form}} = \tau_{\mathrm{collision}}$):

$$1\,\mathrm{fm/c} = \frac{2R}{\gamma v}$$

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

$$\gamma\frac{v}{c} = \frac{2R}{1\,\mathrm{fm}} = 13 \quad \rightarrow \quad E(\mathrm{nucleon}) \approx 12\,\mathrm{GeV}$$

$$\boxed{E_{\mathrm{HE}} = 24\,\mathrm{GeV}}$$

Low energy threshold ($\tau_{\text{form}} = \tau_{\text{interaction}}$):

Condition, with n nucleons in a row:

$$1\,\text{fm/c} = \frac{2R/n}{\gamma v}$$

For $R = 6.5\,\text{fm}$ and $n = 7$, we get

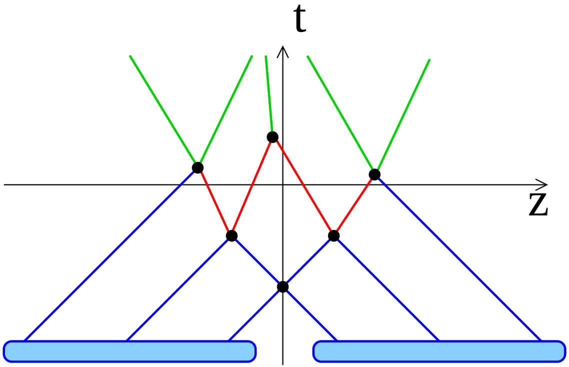
$$\gamma\frac{v}{c} = \frac{2R/n}{1\text{fm}} \approx \frac{13}{7} \quad \rightarrow \quad E(\text{nucleon}) \approx 2\,\text{GeV}$$

$$\boxed{E_{\text{LE}} = 4\,\text{GeV}}$$

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

One needs a “partially parallel approach”

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



A+A collision at intermediate energy

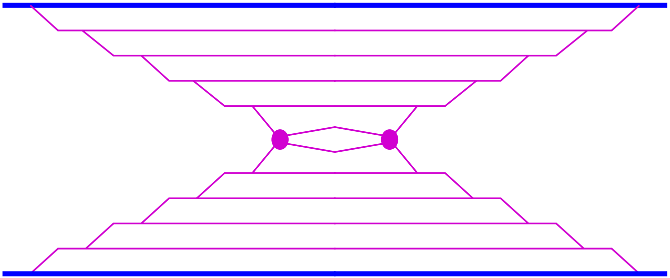
Red/green lines: produced hadrons

Parallel approach in pp

At LHC energy: Interaction: successive parton emissions

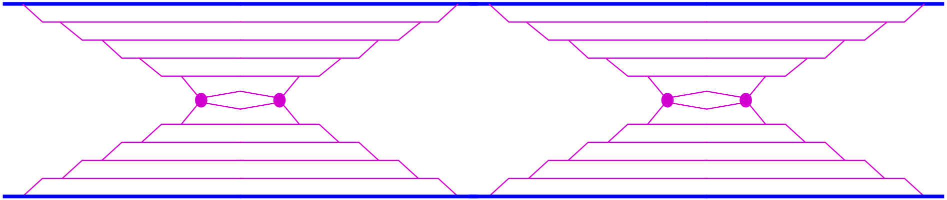
Large gamma factors, very long lived ptls

The complete process takes a very long time



pp collision
Exchange of parton ladder

Impossible to have several of these interactions in a row

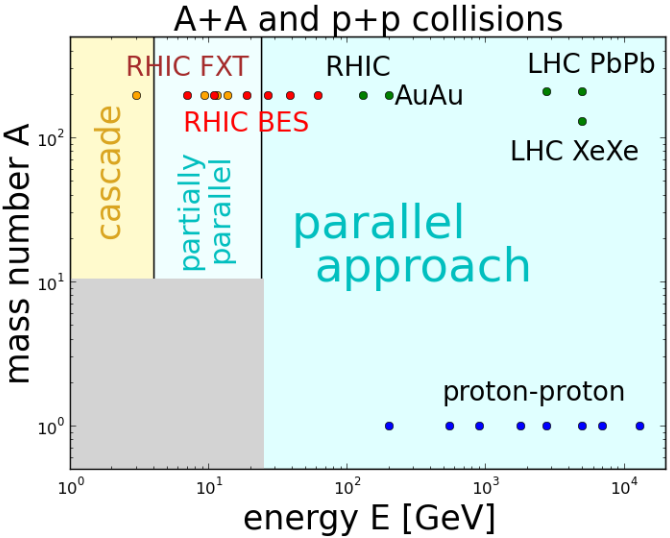


So also in pp:

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

And we know that multiple scattering is important!

Parallel approach needed almost everywhere



$$E_{\mathrm{LE}} = 4\,\mathrm{GeV}$$

$$E_{\mathrm{HE}} = 24\,\mathrm{GeV}$$

EPOS4 parallel scattering scenario

- ☐ **We will start with high energy and then move down**
  - ○ The high energy case contains in principle everything,
  - ○ we do not need to add "features" at low energies,
  - ○ simply certain phenomena "die out" when reducing the energy.

- ☐ **We start with pp**
  - ○ Impossible to construct AA approach without understanding parallel scattering in pp
  - ○ pp -> AA is trivial
- ☐ **High energy starts at few GeV !!**
  - ○ Useful to understand the HE tools

EPOS4 S-matrix approach **(for parallel scatterings!!!)**

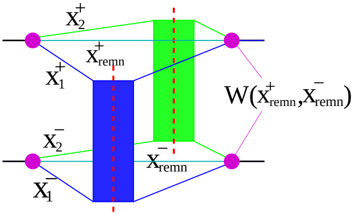
Very compact summary (details: https://arxiv.org/pdf/2301.12517.pdf)

☐ **Start: elastic scattering T-matrix *T* for pp scattering**

☐ **= product of “elementary” T-matrices** (parton-parton scatterings)
pp->AA trivial: product of T-matrices per NN pair

☐ **Connection to inelastic:**
optical theorem / cutting rules
cross section = sum of products of
“cut Pomerons”

☐ **cut Pomeron = squared**
inelastic amplitude
ends up as two
(or more) **kinky strings**



two cut Pomerons
(QCD inside)

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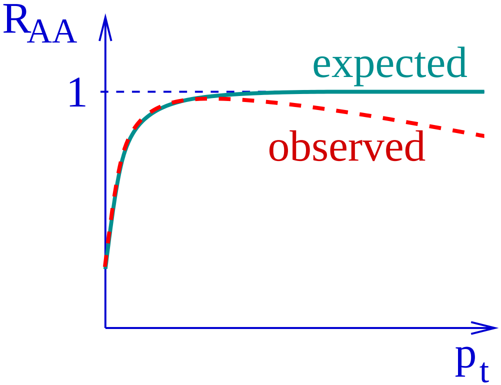
*) Relation S-matrix - T-matrix: $\mathbf{S}_{fi} = \delta_{fi} + i(2\pi)^4\delta(p_f - p_i)\mathbf{T}_{fi})$
$T = \mathcal{F}[\mathbf{T}_{ii}]/(2s)$ (Fourier transform w.r.t. to transv. momentum , depends on b)

A major problem

Popular observable:
nuclear modification factor
$R_{AA} = AA/(N_{coll} \times pp)$

- ☐ **should be unity for hard probes w/o final state interactions or in pA**
- ☐ **but without new (good) ideas this is not the case**
  (like in EPOS LHC)

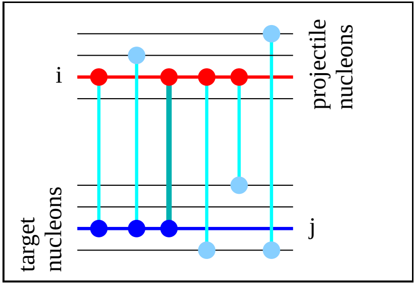


The problem is the energy sharing among Pomerons.

For a given Pomeron, connecting projectile nucleon *i* and target nucleon *j* define:

$$N_{\mathrm{conn}} = \frac{N_{\mathrm{P}} + N_{\mathrm{T}}}{2}$$

N_{P} = number of Pomerons connected to i
N_{T} = number of Pomerons connected to j



Crucial variable: the Pomeron's squared CMS energy fraction

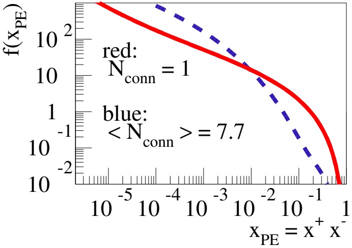
$$x_{\mathrm{PE}} = x^{+}x^{-} \approx s_{\mathrm{Pom}} \,/\, s_{\mathrm{tot}}$$

x_{PE}-distribution $f(x_{\mathrm{PE}})$ determines p_t distributions of partons

The x_{PE} distributions $f(x_{\mathrm{PE}})$ depend on N_{conn}

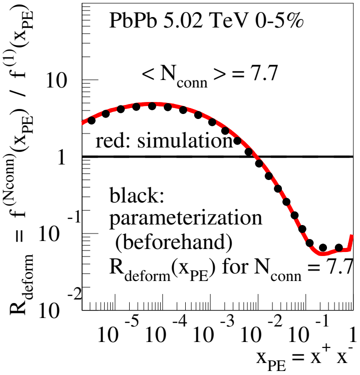
Large N_{conn} => large x_{PE} suppressed
small x_{PE} enhanced

We will use the notation $f^{(N_{\mathrm{conn}})}(x_{\mathrm{PE}})$



We define the "deformation" of $f^{(N_{\mathrm{conn}})}(x_{\mathrm{PE}})$ relative to the reference $f^{(1)}(x_{\mathrm{PE}})$

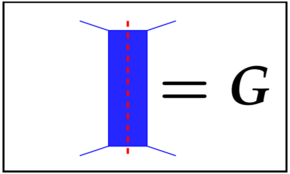
$$\boxed{R_{\mathrm{deform}} = \frac{f^{(N_{\mathrm{conn}})}(x_{\mathrm{PE}})}{f^{(1)}(x_{\mathrm{PE}})}}$$



We are able to parameterize
the "deformation" beforehand(!)
(iterative process, converges fast)
for all systems, all centrality classes

So R_{deform} can be considered to be known, it is tabulated.

We compute and tabulate $G_{\mathrm{QCD}}(Q^2, x^+, x^-, s, b)$, DGLAP parton ladder, with low virtuality cutoff Q^2 (=> G_{QCD} accessible via interpolation)



Now we can define the "box", called "cut Pomeron" and named $G(x^+, x^-, s, b)$

the crucial building block used in the multi-Pomeron expessions (pp,AA)

(and make the link with pQCD):

For each cut Pomeron, for given $x^\pm$, s, b, and N_conn, we postulate:

$$G(x^+, x^-, s, b) = \frac{1}{R_\mathrm{deform}^{(N_\mathrm{conn})}(x_\mathrm{PE})} \times n \times G_\mathrm{QCD}(Q^2_\mathrm{sat}, x^+, x^-, s, b)$$

G does not depend on N_conn, Q^2_sat depends on x^+, x^-, N_conn
(n is a normalization depending linearly on N_conn)

which perfectly solves the "R_{AA} problem", the model can be used to study hight p_t and low p_t phenomena

For large N_conn, low pt is suppressed, the Pomeron gets "hard".

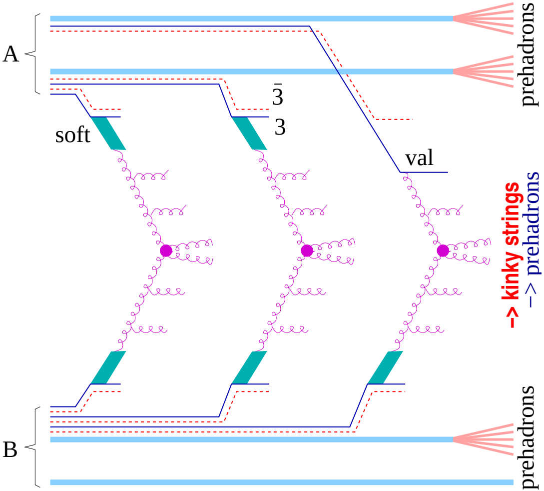
Role of core, corona, remnants for different energies

From diagrams
to "prehadrons"
High energy (several TeV)

A+B scattering
(three cut Pomerons)

Remnants always "white"
but excited (large masses)
-> prehadrons

"Pomeron ends" (3 — $\bar{3}$)
+ parton ladders
-> kinky strings constructed
following color flow
-> prehadrons



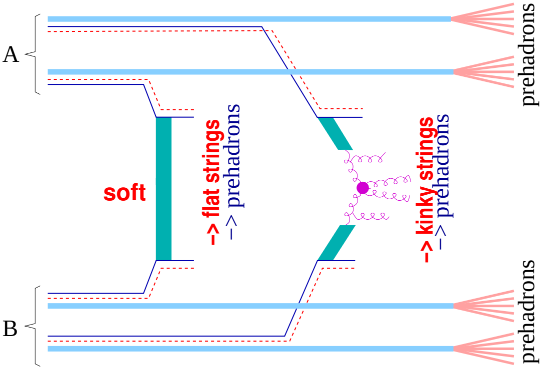
light blue: remnants

From diagrams to “prehadrons” Low energy (several GeV)

A+B scattering
(two cut Pomerons)
only one Pom. per NN !!

Parton ladders disappear
soft Pomerons take over
-> flat strings constructed
following color flow
-> prehadrons

Excited remnants
-> prehadrons
Relative importance increases
Production at mid-rapidity



light blue: remnants

Core-corona procedure
(Big and small systems)

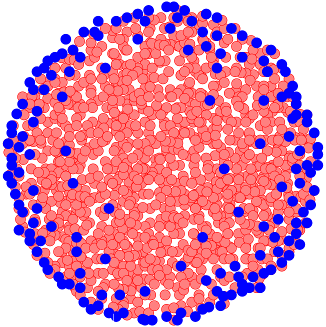
Consider all prehadrons

Each prehadron: estimate energy loss ΔE on its way out of this system
(keeping the positons of the others)

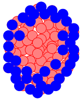
If $\Delta E > E$ -> core prehadron
If $\Delta E < E$ -> corona prehadron

Corona hadrons -> hadrons
Core hadrons -> "the core"
(matter)

Big system



Small system



corona = blue **core = red**

Core-corona procedure
for minimum bias proton-proton

Prehadron yield vs space-time rapidity $\eta_s = \frac{1}{2}\ln\frac{t+z}{t-z}$

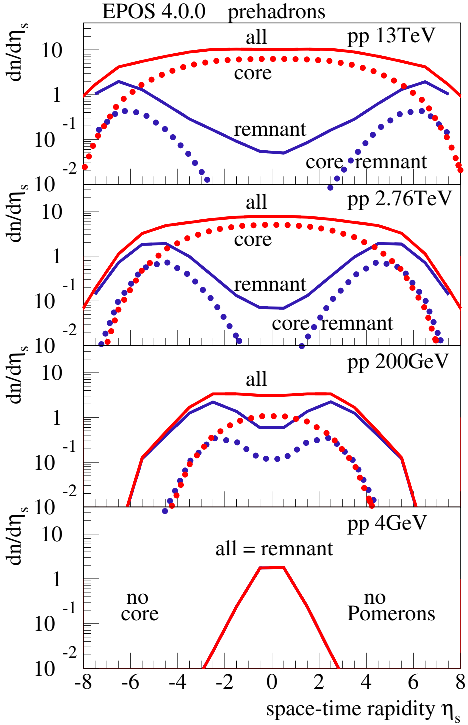
Note: $\eta_s \approx y$ (rapidity)

HE: big core contribution even for min bias!

From high to low energy:

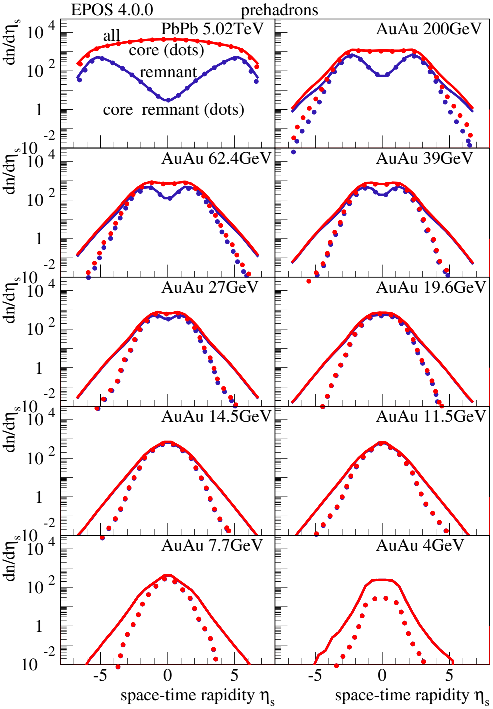
- ☐ **core contribution smaller**
- ☐ **remnants more important**
- ☐ **contribute at mid-rapidity**

4 GeV : No Pomerons, no core



Core-corona procedure
for central nucleus-nucleus

Prehadron yield vs η_s



**PbPb: core almost 100%
even for remnants**

From high to low energy:

☐ **core drops at large η_s**

☐ **remnants more important contribute at mid-rapidity**

☐ **core remains close to 100% at mid-rapidity**

☐ **27 to 7GeV: little change**

4 GeV : core drops

Core-corona procedure
for central nucleus-nucleus

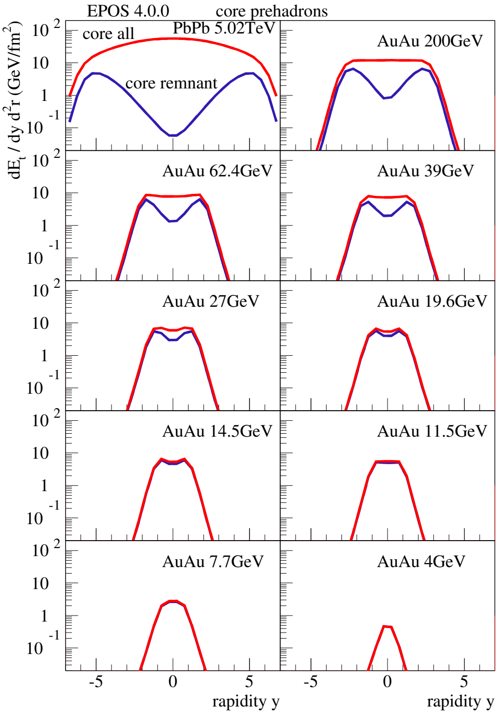
Estimate energy density ε
(at proper time τ, **only core**)

$$\frac{dE_t}{dy\, d^2r} \approx \varepsilon \times c\tau$$

y = rapidity; r=radial distance

From high to low energy (use $c\tau = 1\,\text{fm}$):

- ☐ **remnants more important**
- ☐ **ε first drops slowly**
- ☐ **drops quickly below 11.5 GeV to finally reach a value around of 0.5 GeV/fm^3 at 4 GeV.**



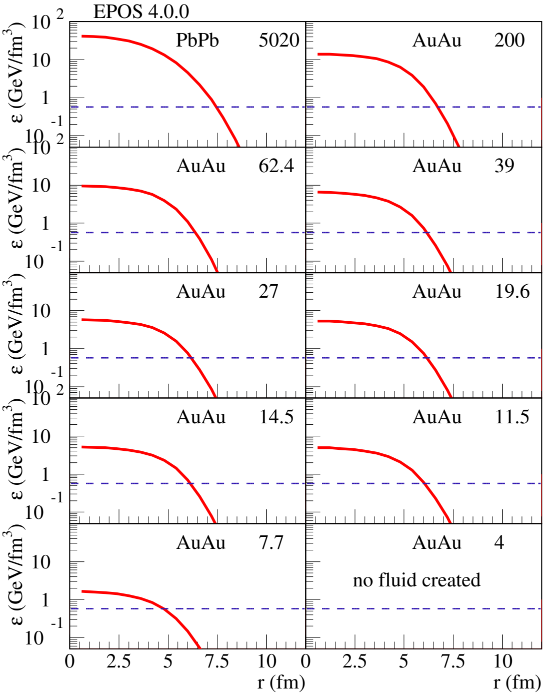
Energy density ε
Calculation at hydro start time τ_0

Compute $T^{\mu\nu}$ from prehadrons, boost to comoving frame, extract ε and flow vector

Dashed line: FO en. density

From high to low energy:

- ☐ **τ_0 goes from 1 $\frac{\text{fm}}{\text{c}}$ to 2 $\frac{\text{fm}}{\text{c}}$**
- ☐ **drastic change from 11.5 to 7 TeV**
- ☐ **at 4 GeV no fluid**



Next steps

☐ **Hydrodynamic evolution**
(code from Iu. Karpenko(1,2))

☐ **Sudden freeze-out (microcanonical) at $\varepsilon_{\mathrm{FO}} = 0.57\,\frac{\mathrm{GeV}}{\mathrm{fm}^3}$**
(many new features, important for small fluids, in pp and AA)

☐ **Hadronic cascade** (UrQMD(3,4))

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(1) Werner, K. and Guiot, B. and Karpenko, Iu. and Pierog, T., Phys. Rev. C 89, 6 (2014), pp. 064903

(2) Iu. Karpenko and P. Huovinen and M. Bleicher, Computer Physics Communications 185, 11 (2014), pp. 3016--3027

(3) S. A. Bass and others, Prog. Part. Nucl. Phys. 41 (1998), pp. 225-370.

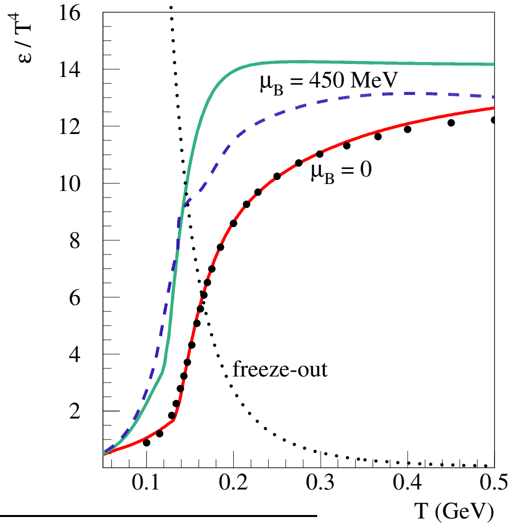
(4) M. Bleicher and others, J. Phys. G25 (1999), pp. 1859-1896.

Equation of state

Red: EPOS EoS (1,2)
($\mu_B = 0$, to fit lattice, points)

Green: EPOS EoS (1,2)
($\mu_B = 450\,\text{MeV}$)

Blue: BEST EoS (3,4,5)
($\mu_B = 450\,\text{MeV}$)



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(1) K. Werner, Iu Karpenko et al , Phys. Rev. C 89, 6 (2014), pp. 064903

(2) **used as default EPOS4**

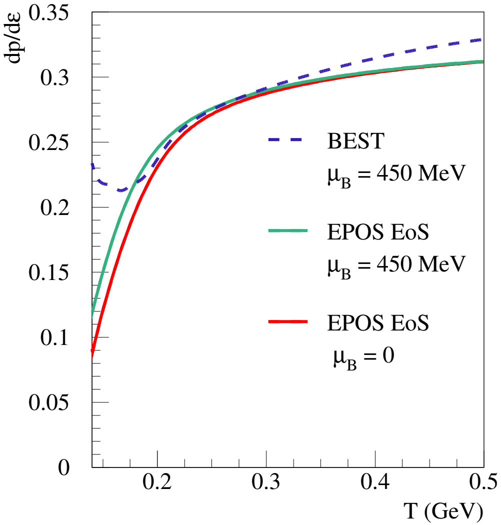
(3) Paolo Parotto et al., Phys. Rev. C 101, 034901 (2020)

(4) Parameters: $Mode\_T_C\_\mu_{BC}\_\alpha_1\_\alpha_2\_\omega T_C\_\rho\omega T_C$ = PAR_143_350_3_93_143_286

(5) Implemented in EPOS by **Maria Stefaniak** (PhD thesis)

Equation of state
$dp/d\varepsilon$

BEST EoS and EPOS EoS curves quite different at low *T*



But particle spectra (based on EPOS3) very similar[(1)]

will be redone with EPOS4

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(1) thesis **Maria Stefaniak**

Plot core and corona contributions to hadrons production

Distinguish:

(A) The "**core+corona**" contribution: primary + core-corona separation + hydrodynamic evolution + microcanonical hadronization, but **without hadronic rescattering**.

(B) The "**core**" contribution: as (A), but considering only core particles.

(C) The "**corona**" contribution: as (A), but considering only corona particles.

(D) The "**full**" EPOS4 scheme: as (A), but in addition hadronic rescattering.

Note: Rescattering concerns core and corona particles

Core, corona, full
PbPb at 5.02 TeV
(AuAu at 200GeV similar)

pions, kaons, protons, lambdas (top to bottom)

Green: $\frac{\text{core}}{\text{core+corona}}$

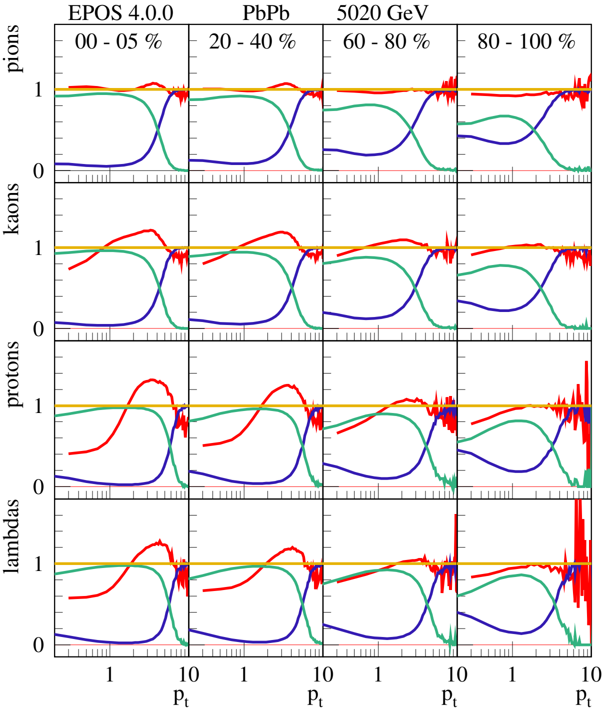
Blue: $\frac{\text{corona}}{\text{core+corona}}$

Red: $\frac{\text{full}}{\text{core+corona}}$

Core reaches to higher pt for baryons

Core has maximum at intermediate pt (flow)

Rescattering important



Core, corona, full
AuAu at 39 GeV

$K^+, K^-, p, \bar{p}$
(top to bottom)

Green: $\frac{\textbf{core}}{\textbf{core+corona}}$

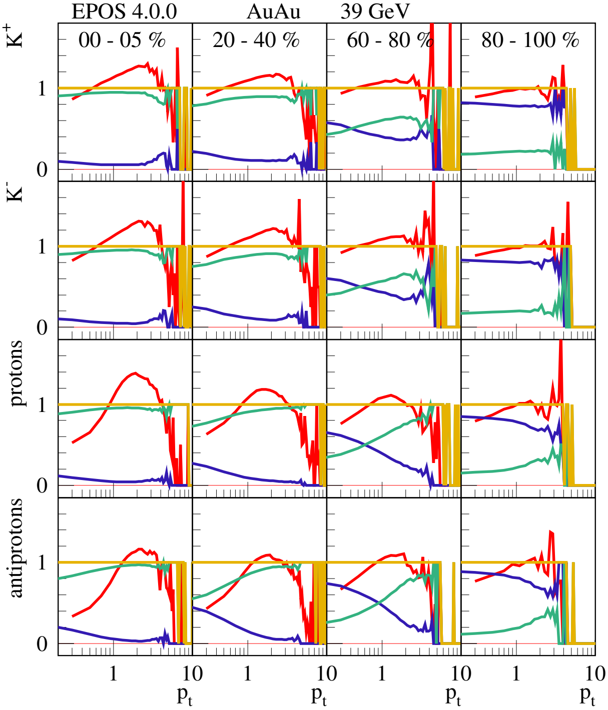
Blue: $\frac{\textbf{corona}}{\textbf{core+corona}}$

Red: $\frac{\textbf{full}}{\textbf{core+corona}}$

Difficult to access high pt

0-5% similar to 5 TeV result, core drops for semi-peripheral for low pt

Big rescattering (annihilation) effect for $\bar{p}$



Core, corona, full
AuAu at 11.5 GeV

K^+, K^-, p, $\bar{p}$
(top to bottom)

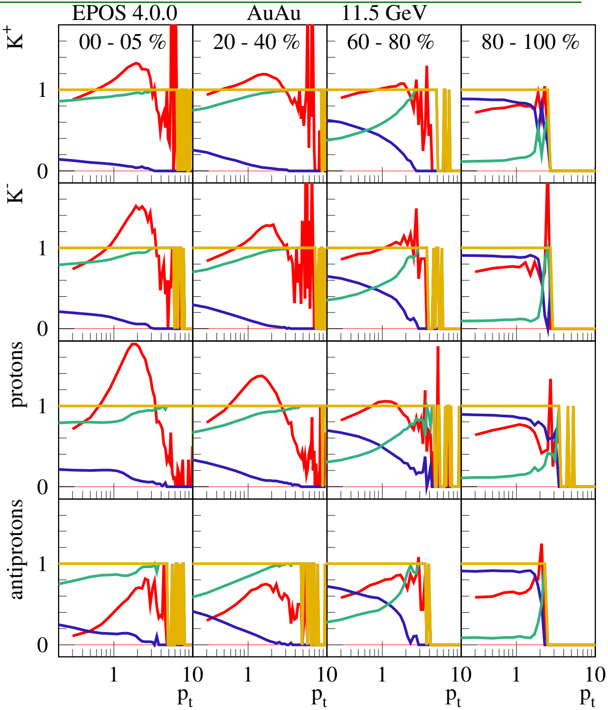
Green: $\dfrac{\textbf{core}}{\textbf{core+corona}}$

Blue: $\dfrac{\textbf{corona}}{\textbf{core+corona}}$

Red: $\dfrac{\textbf{full}}{\textbf{core+corona}}$

Core-corona similar to 39 GeV, core maximum at intermediate pt (flow)

Huge rescattering effect, big difference between p and $\bar{p}$



So what did we learn?

☐ **The core-corona picture (using the same prescription) does not change much from 5TeV down to 11.5 GeV**

☐ **Core dominates at intermediate pt, sign of strong radial flow (at all energies $\geq$ 11.5 GeV)**

☐ **Hadronic cascade increasingly important towards lower energies**

☐ **Below 11.5 GeV, the core disappears quickly**

Results

Aim:

- ☐ **Systematic check from 5.02 GeV down to 7.7 MeV**⁽¹⁾
- ☐ **Check if the concepts discussed in the previous chapters give a coherent picture (and reproduce the data) or not**
  (the aim is NOT to discuss each single curve)
- ☐ **Shown here: pt spectra (small selection**⁽²⁾**)**
  (Checked but not shown: flow harmonics)
- ☐ **Log plots, but such that 10-20% deviation is visible**
- ☐ **Always: Colored Lines = EPOS4.0.0, black dots = data**

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(1) BES: analysis of simulation + data collection by **Johannes Jahan**

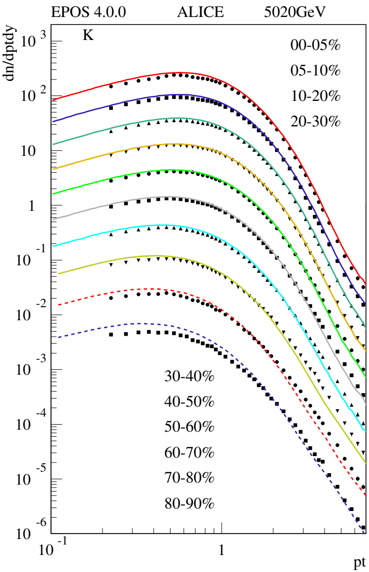
(2) paper with more complete selection will appear soon

PbPb 5.02 TeV

Spectra and flow harmonics for identified particles work “reasonably well” over wide pt range

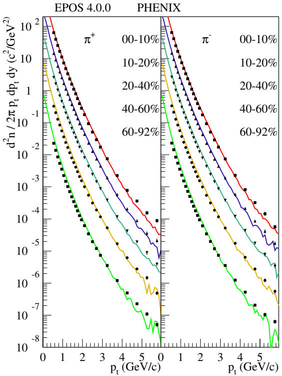
Example:
pt spectra of charged kaons at different centralities

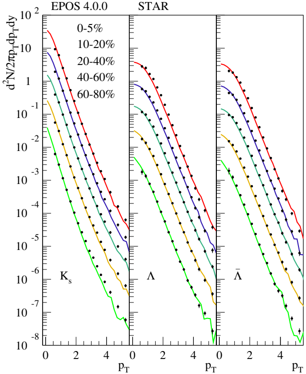
From core-corona plots: beyond p_t =4GeV/c corona takes over

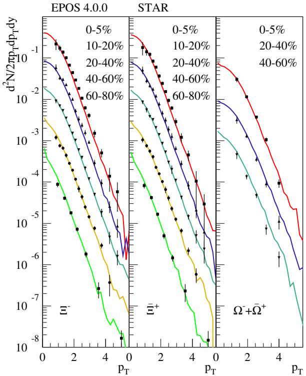


Lines: EPOS4.0.0
Black symbols: data ALICE
(Phys. Rev. C 101 (2020), pp. 044907)

AuAu 200 GeV: pt spectra π^+,π^-, K_s, Λ, $\bar{\Lambda}$, Ξ, $\bar{\Xi}$, Ω



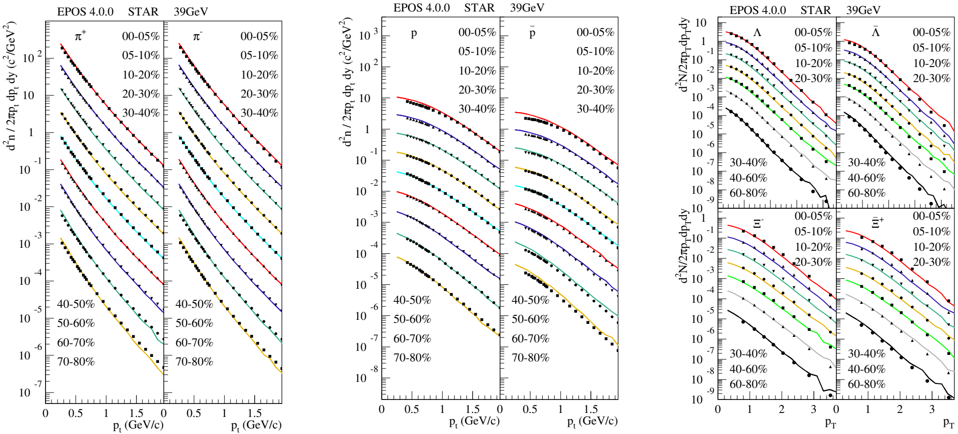




PHENIX, Phys.Rev.C 88 (2013), pp. 024906.
STAR Phys.Rev.Lett. 108 (2012), pp. 072301; Phys.Rev.Lett. 98 (2007), pp. 062301.

Pions: corona dominates at high pt (> 2-3GeV/c)
Baryons: core dominated at all centralities
flow+statistical hadronization crucial (hyperons)
but also important rescattering effect
Including many additional checks: AuAu 200 GeV looks OK

AuAu 39 GeV: pt spectra π^+,π^-, p, $\bar{p}$, Λ, $\bar{\Lambda}$, Ξ, $\bar{\Xi}$



STAR Phys.Rev.C 96 (2017), pp. 044904., Phys.Rev.C 102 (2020), pp. 034909.

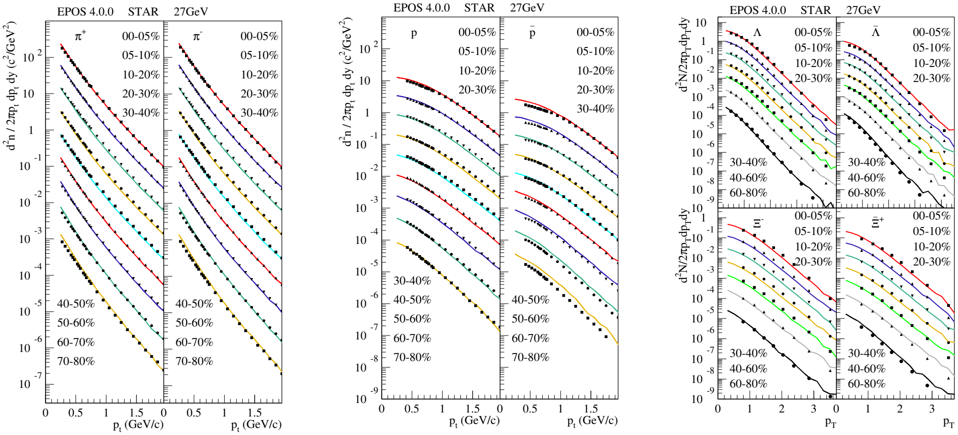
Everything core dominated up to 50% centrality

flow+statistical hadronization crucial (hyperons)

but also important rescattering effect ($B\bar{B}$ annihilation)

Including additional checks: AuAu 39 GeV looks OK

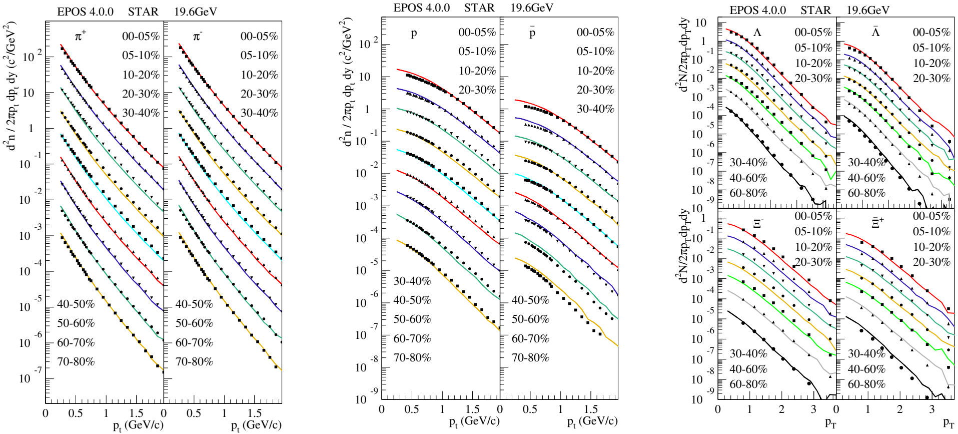
AuAu 27 GeV: pt spectra $\pi^+,\pi^-, p, \bar{p}, \Lambda, \bar{\Lambda}, \Xi, \bar{\Xi}$



STAR Phys.Rev.C 96 (2017), pp. 044904., Phys.Rev.C 102 (2020), pp. 034909.

Almost like 39 GeV, maybe slight antiproton problem
(but $\bar{\Lambda}$, $\bar{\Xi}$ look OK) ... anyway:
Including additional checks: AuAu 27 GeV looks OK

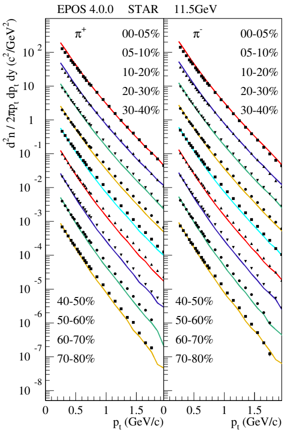
AuAu 19.6 GeV: pt spectra π^+,π^-, p, $\bar{p}$, Λ, $\bar{\Lambda}$, Ξ, $\bar{\Xi}$

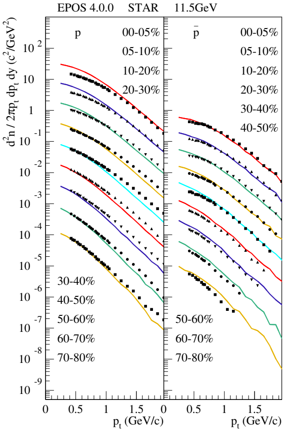


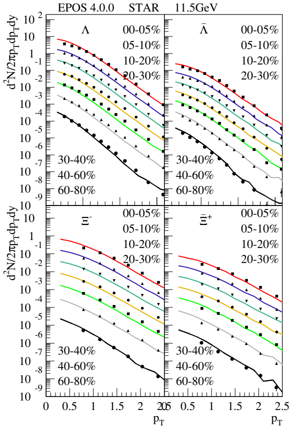
STAR Phys.Rev.C 96 (2017), pp. 044904., Phys.Rev.C 102 (2020), pp. 034909.

Still reasonable

AuAu 11.5 GeV: pt spectra π^+, π^-, p, $\bar{p}$, Λ, $\bar{\Lambda}$, Ξ, $\bar{\Xi}$



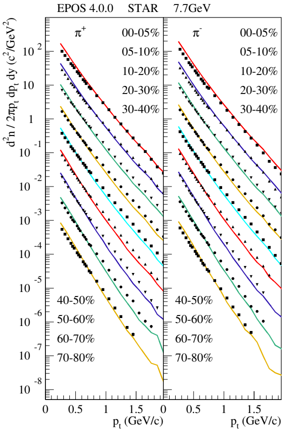


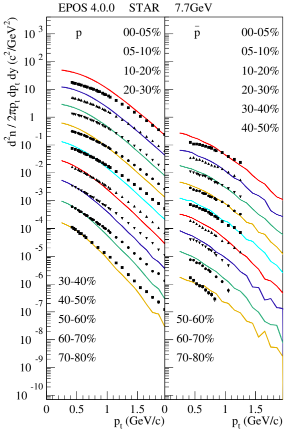


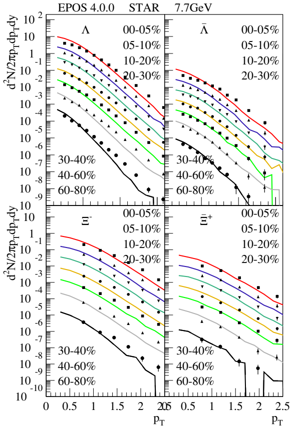
STAR Phys.Rev.C 96 (2017), pp. 044904., Phys.Rev.C 102 (2020), pp. 034909.

Spectra become too soft, in particular for protons nevertheles pions and hyperons not too bad

AuAu 7.7 GeV: pt spectra π^+,π^-, p, $\bar{p}$, Λ, $\bar{\Lambda}$, Ξ, $\bar{\Xi}$







STAR Phys.Rev.C 96 (2017), pp. 044904., Phys.Rev.C 102 (2020), pp. 034909.

All spectra too soft, baryon-antibaryon excess => model fails

What do we learn

The model works reasonably well down to 19.6 GeV

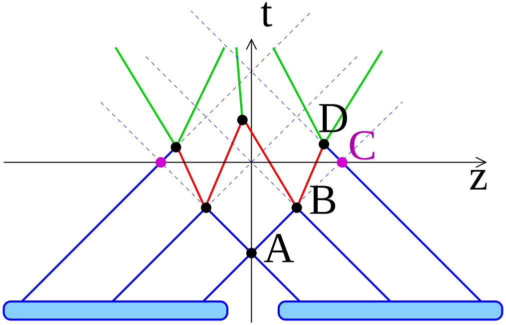
the picture changes (amazingly) little, core dominance, see hyperon production

and fails increasingly below

and completely at 7.7 GeV, spectra too soft, baryon-antibaryon excess

We use
“full parallel secenario”
→ primary collisions A, B, C
(with important remnant excitations)

We need below 24 GeV:
“partial parallel secenario”
→ primary collisions A, B
secondary scattering D



To summarize:

- ☐ **S-matrix approach looks like the natural tool to implement rigorously parallel scattering (as done in EPOS4); should be used beyond $\sqrt{s_{NN}} = 24$ GeV.**
- ☐ **Longstanding problems(1) (energy sharing which ruins factorization) could be fixed in EPOS4 → low and high pt phenomena equally accessible**
- ☐ **Smooth transition from high to low energy collions,**
  physics changes little down to 20 GeV, EPOS4 works "reasonably well".
- ☐ **Below 20 GeV "parallel scattering" fails, "partially parallel scattering" should be implemented (in principle straight-forward), definitely needed at 7.7 GeV**
- ☐ **Below 4 GeV no point to use EPOS4, even an "improved" version**
  (anyway, at least from our analysis it looks as if the core disappears quickly below 10 GeV, to be confirmed with a better low energy treatment)

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(1) **No "real" EPOS paper since 2013, no official releases**