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Heavy ion collisions from 200 GeV down to 4 GeV in the EPOS4 framework

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☐ **EPOS4 & some history of high energy collisions**

☐ **Parallel vs sequential scattering (high vs low en.)**

☐ **From Pomerons to hadrons (energy dependence)**

☐ **Detailed model/data comparisons (energy dependence)**

Some history

Before QCD

☐ **Gribov-Regge (GR) approach, for pp, pA, AA**
V. A. Abramovsky, V. N. Gribov, O. V. Kancheli, L. N. Lipatov **(1967-1973)**

☐ **S-matrix theory, parallel scattering scheme**

☐ **Exchanged “objects” are called Pomerons**

☐ **AGK theorem ($\sigma_{\mathrm{incl}}^{AB} = AB \times \sigma_{\mathrm{incl}}^{\mathrm{single\,Pom}}$)**

☐ **Infinite energy limit**
(problematic...)

Perturbative QCD for pp

- ☐ **Asymptotic freedom**
  D. Gross, F. Wilczek,H. Politzer **(1973)**
- ☐ **DGLAP (linear) evolution**
  V. N. Gribov, L. N. Lipatov **(1973)**
  G. Altarelli, G. Parisi **(1977)**, Y. L. Dokshitzer **(1977)**
- ☐ **Factorization** J. Collins, D. Soper, G. Sterman **(1989)**
- ☐ **Covers only a small fraction of observables** (inclusive, MB, hard)
  NOT covered: Triggering on high multiplicity or on centrality classes
  (in connection with soft or hard probes)

Saturation (CGC, low-x physics,...)

- ☐ **Nonlinear evolution**
  L. V. Gribov, E. M. Levin, and M. G. Ryskin **(1984)**
  L. D. McLerran and R. Venugopalan **(1994)**, Y. V. Kovchegov **(1996)**, ...

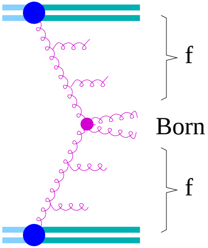
An attempt to couple GR and pQCD

- ☐ **NEXUS model, earlier EPOS versions**
  H.J. Drescher, M. Hladik, Sergey Ostapchenko, Tanguy Pierog, K. Werner (2001)
- ☐ **Using: Pomeron = pQCD parton ladder**
- ☐ **With energy sharing! (GR^{+}) ... crucial for MC applications**
  Keeping parallel scattering scheme!!!
- ☐ **Problem: violates AGK (and binary scaling and factorization)**

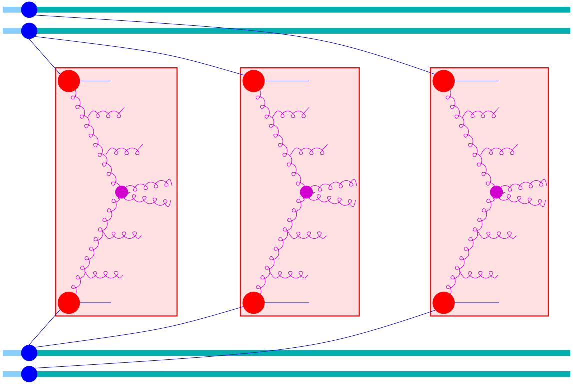
Solution: EPOS4 = GR^{+} & pQCD & saturation

- ☐ **Redefine connection Pomeron <-> pQCD parton ladder**
  by taking into account saturation in a very particular way
- ☐ **Fully recovers AGK (and geometric properties which follow)**
  Parallel scattering scheme, going beyond factorization,
  perfectly covering "observables per event class", soft physics
  but at the same time
  factorization works for inclusive xsections for hard processes

(A) Factorization picture
(inclusive cross sections, ond ONLY for these)



(B) Parallel scattering (considering real events)



EPOS4: fully selfconsistent picture (B) to be used for "event class issues", which breaks down to (A) for inclusive hard particle production, due to lots of cancellations

Problematic to get from (A) to (B), the multiple scattering information is lost!
(A) to (B) usually based on the eikonal model (from 1958)

EPOS4 documentation

- ☐ **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

- ☐ **Papers** (https://klaus.pages.in2p3.fr/epos4/physics/papers)

  - ▷ **arxiv:2301.12517 PRC 108, 064903** **EPOS4 Overview**
  - ▷ **arxiv:2306.02396 PRC 108, 034904** **pQCD in EPOS4** with B. Guiot
  - ▷ **arxiv:2310.09380 PRC 109, ...**
    Parallel scattering formalism, S-matrix theory & pQCD & saturation
    46 pages, systematic and complete presentation of the theoretical basis,
  - ▷ **arxiv:2306.10277 PRC 109, 014910**
    Microcanonical hadronization, core-corona in EPOS4
  - ▷ **arxiv:2401.11275** **EPOS4 results on RHIC**
    with J. Jahan, I. Karpenko, T. Pierog, M. Stefaniak, D. Vintache
  - ▷ **arxiv:2310.08684** **EPOS4HQ**: Heavy flavor collectivity in pp
  - ▷ **arxiv:2401.17096** **EPOS4HQ**: Heavy flavour in HI at RHIC and LHC
    EPOS4HQ: Jiaxing Zhao, Joerg Aichelin, Pol-Bernard Gossiaux, KW

EPOS4 general structure (Possible at “high energies”)

☐ **Primary scatterings (at t = 0)**
parallel scattering approach based on S-matrix theory
(Major changes)

☐ **Secondary scatterings (at t > 0)**
- core-corona procedure (New methods)
- hydro evolution [1]
- microcanonical decay (New)
- hadronic rescattering [2]

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[1]) I. Karpenko et al, Computer Physics Communications 185, 3016 (2014), K. Werner, B. Guiot, I. Karpenko, and T. Pierog, Phys. Rev. C 89, 064903 (2014), 1312.1233,

[2]) S. A. Bass et al., Prog. Part. Nucl. Phys. 41, 225 (1998), M. Bleicher et al., J. Phys. G25, 1859 (1999)

Parallel and sequential scattering in AA

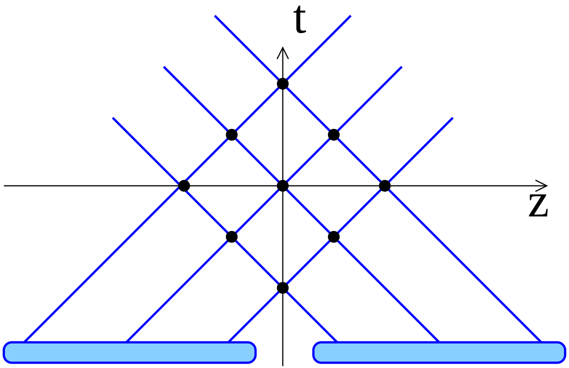
What kind of model do we need depending on the collision energy

Crucial time scales

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

$\tau_{\mathrm{interaction}}$ **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

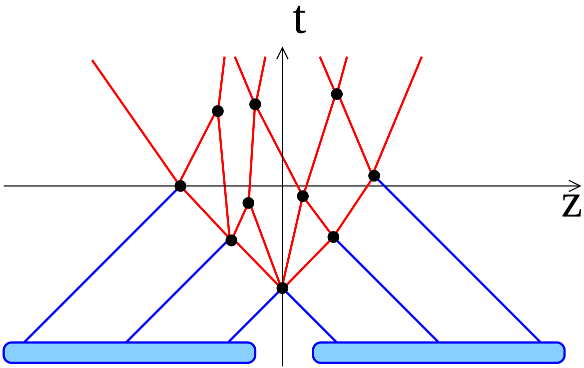
Sequential collisions (cascade)

Condition:

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

τ_{form} is the particle formation time

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



A+A collision at low energy

red lines: produced hadrons

At “high” energy

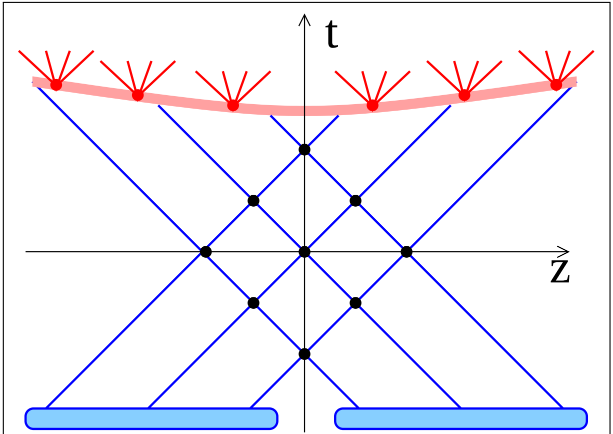
First all *NN* interactions occur, instantaneously, in parallel

Hadron production comes later

Condition:

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

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



A+A collision at very 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 of thresholds

$\tau_{\mathrm{form}} = \tau^0_{\mathrm{form}}\gamma_{\mathrm{hadr}}$, with $\tau^0_{\mathrm{form}} = 1\,\mathrm{fm/c}$,
and $\gamma_{\mathrm{hadr}} = 1$ (→ upper limits for energy thresholds)

High energy threshold ($\tau_{\mathrm{form}} = \tau_{\mathrm{collision}} = \frac{2R}{\gamma v}$)
Using $R = 6.5\,\mathrm{fm}$:

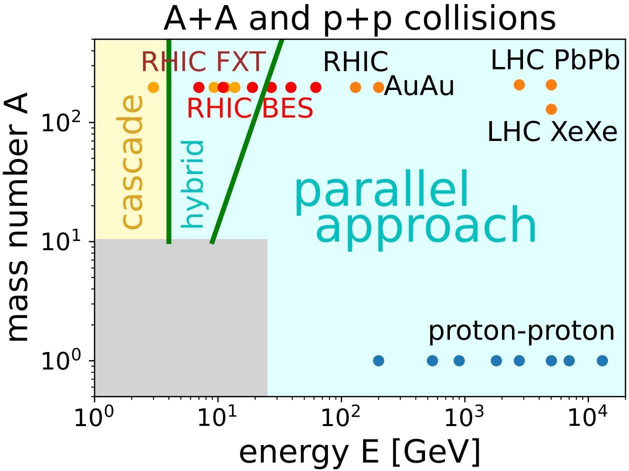
$$\boxed{E_{\mathrm{HE}} = 24\,\mathrm{GeV} \qquad (\sqrt{s_{NN}})}$$

Low energy threshold ($\tau_{\mathrm{form}} = \tau_{\mathrm{interaction}} = \frac{2R/n}{\gamma v}$)
Using $R = 6.5\,\mathrm{fm}$, $n = 7$ (n = nr of nucleons in a row) **:**

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

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

Which approach at what energy?



green lines:

Threshholds E_{LE} and E_{HE}

for $A = 200$:

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

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

Parallel : EPOS4 = GR$^+$ & pQCD & saturation

From Pomerons to hadrons (details: arXiv:2306.02396)

From multiple Pomeron configurations, after making the link with pQCD, we get partonic configurations

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Color flow => parton chains =>kinky strings => string segments = prehadrons

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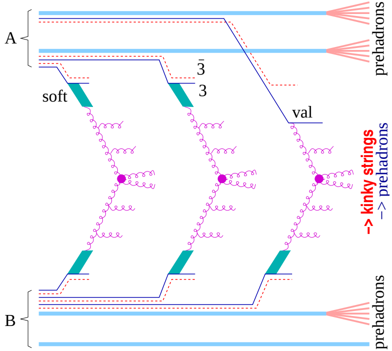
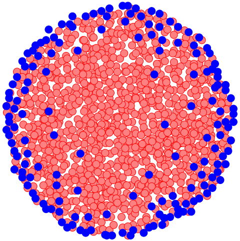
Remnants => prehadrons



At lower energies: Pomerons less energetic, softer, fewer, remnants important

Core-corona separation among prehadrons
(at some τ_0)

- ☐ **corona prehadrons become hadrons**
- ☐ **core prehadrons constitute "the core" = hydro initial condition**



Energy density ε of core
at τ_0 (hydro start time)

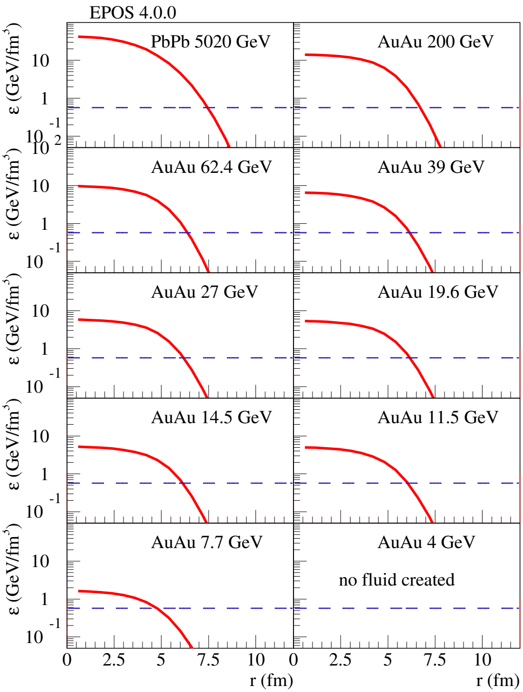
Compute $T^{\mu\nu}$ from prehadrons, boost to comoving frame, extract ε and flow vector

Dashed line: FO en. density

From high to low energy:

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

Then: Hydro evolution, microcanonical “decay” of the fluid, hadronic cascade (UrQMD)



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
AuAu at 200 GeV

π, K, p, Λ
(top to bottom)

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

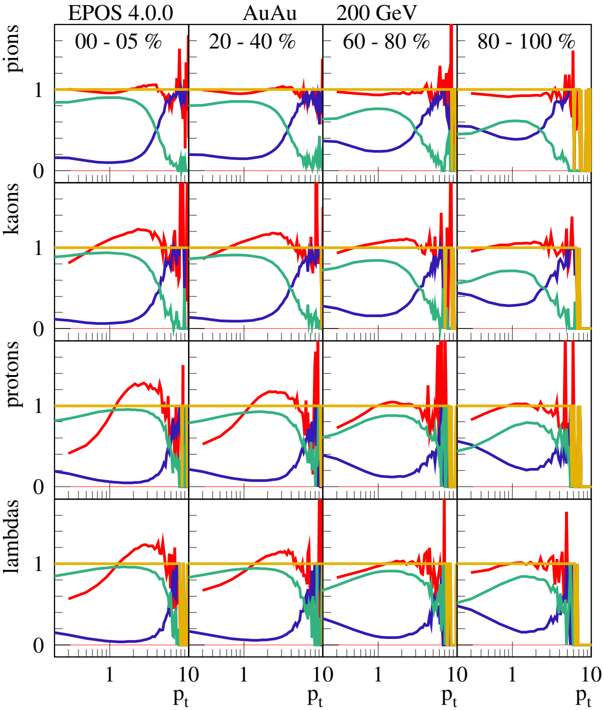
Blue: $\frac{\text{corona}}{\text{core}+\text{corona}}$

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

crossing between 2 and 6 GeV/c (larger for baryons)

core drops for low pt

Big rescattering effects



Core, corona, full
AuAu at 39 GeV

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

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

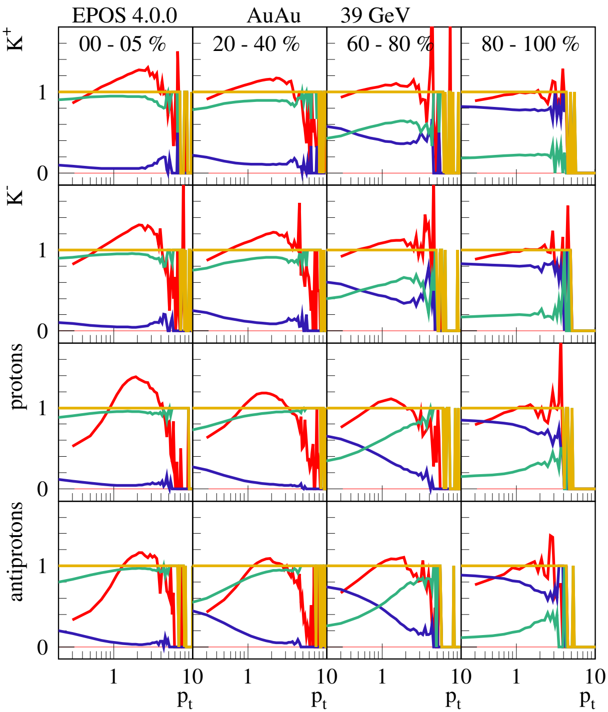
Blue: $\dfrac{\text{corona}}{\text{core+corona}}$

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

Difficult to access high pt, no crossing

core drops for low pt

Big rescattering effects



Results (focus on RHIC)

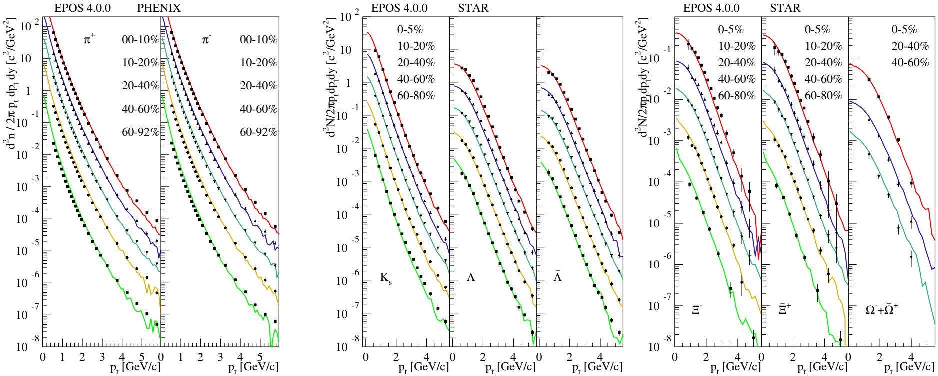
- ☐ **Systematic check 200 GeV** arxiv:2310.09380 PRC
  and 39 GeV down to 7.7 GeV arxiv:2401.11275
  with J. Jahan, I. Karpenko, T. Pierog, M. Stefaniak, D. Vintache

- ☐ **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)

- ☐ **Log plots for spectra, but such that 10-20% deviation is visible**

- ☐ **Always: Colored Lines = EPOS4.0.0, black dots = data**

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



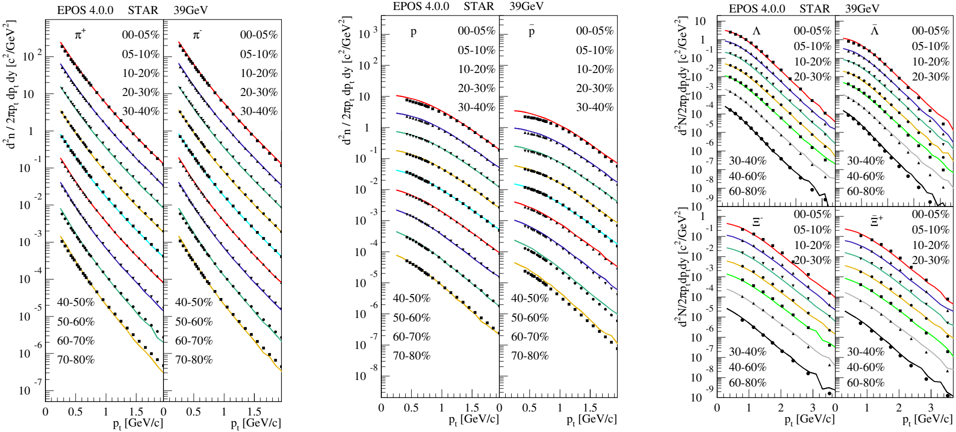
PHENIX, Phys.Rev.C 88 (2013), pp. 024906.
STAR Phys.Rev.Lett. 108 (2012), pp. 072301; Phys.Rev.Lett. 98 (2007), pp. 062301.

Contribution from both core (intermediate p_t, central)
and corona (low/high p_t, peripheral)

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, $\bar{\Xi}$



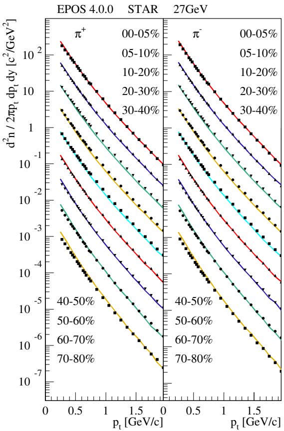
STAR Phys.Rev.C 96 (2017), pp. 044904., Phys.Rev.C 102 (2020), pp. 034909.

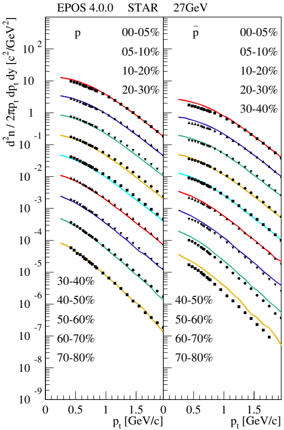
Contribution from both core (intermediate p_t, central)
and corona (low p_t, peripheral, with increasing weight)

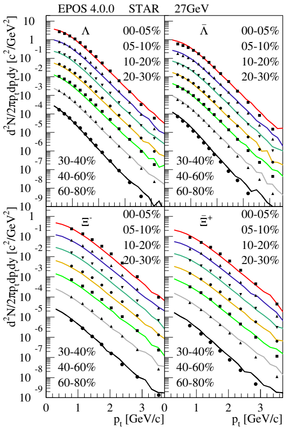
Also important rescattering effect

Overall: AuAu 39 GeV looks OK

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







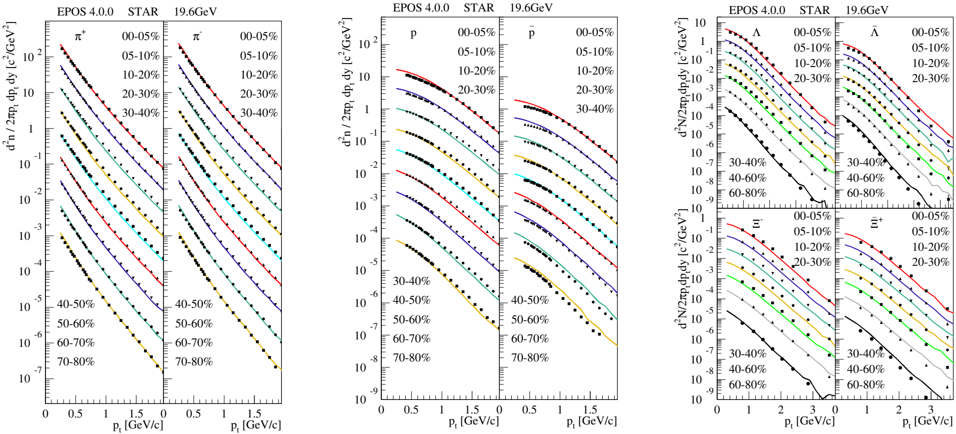
STAR Phys.Rev.C 96 (2017), pp. 044904., Phys.Rev.C 102 (2020), pp. 034909.

Almost like 39 GeV, maybe slight antiproton problem

(but $\bar{\Lambda}$, $\bar{\Xi}$ look OK) ... anyway:

Including additional checks: AuAu 27 GeV looks OK

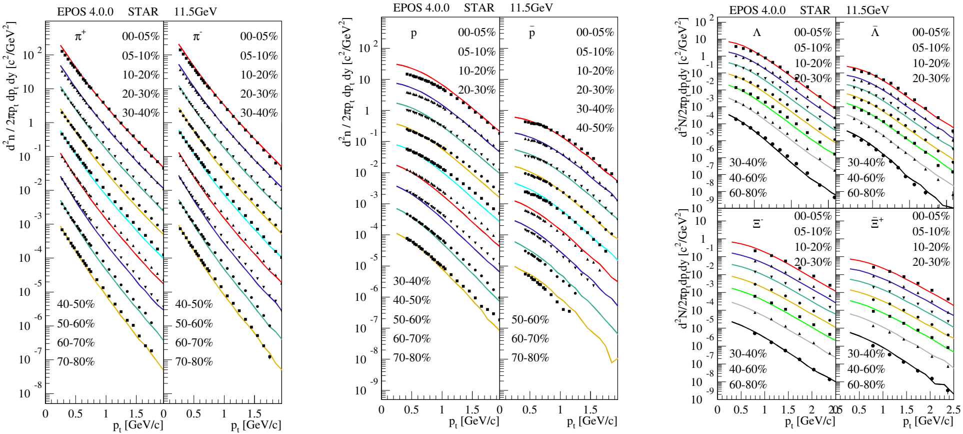
AuAu 19.6 GeV: pt spectra π^+,π^-, p, $\bar{p}$, Λ, $\bar{\Lambda}$, Ξ, $\bar{\Xi}$



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

Still reasonable

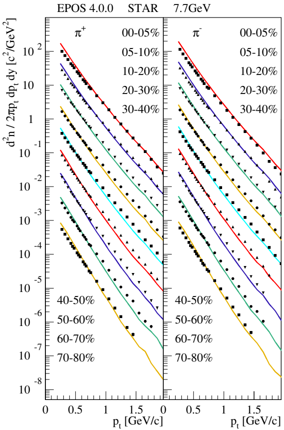
AuAu 11.5 GeV: pt spectra π^+,π^-, p, $\bar{p}$, Λ, $\bar{\Lambda}$, Ξ, $\bar{\Xi}$

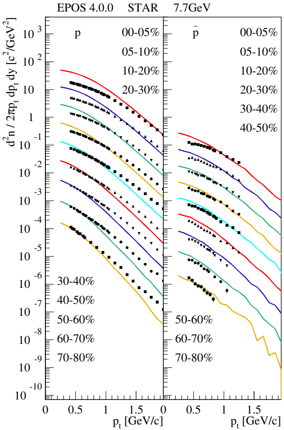


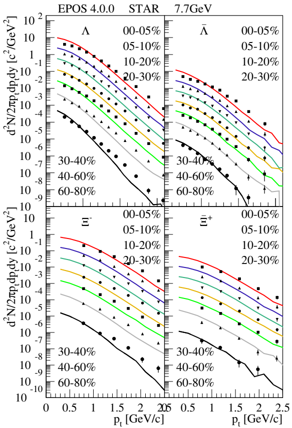
STAR Phys.Rev.C 96 (2017), pp. 044904., Phys.Rev.C 102 (2020), pp. 034909.

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, $\bar{\Xi}$





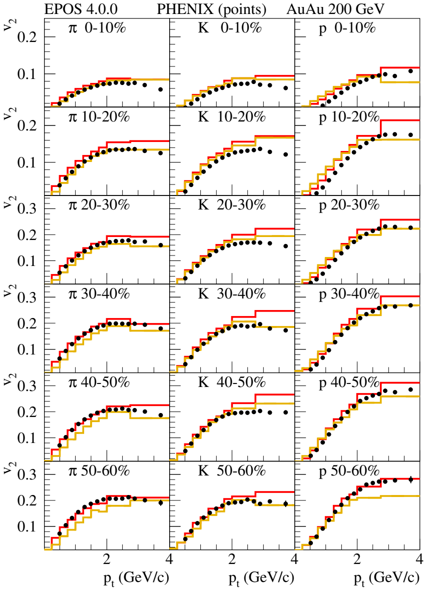


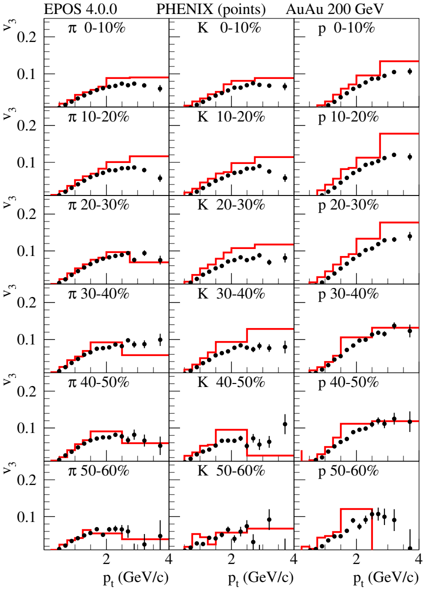
STAR Phys.Rev.C 96 (2017), pp. 044904., Phys.Rev.C 102 (2020), pp. 034909.

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

v_2 and v_3 AuAu 200 GeV EPOS full (red) EPOS no cascade (yellow)

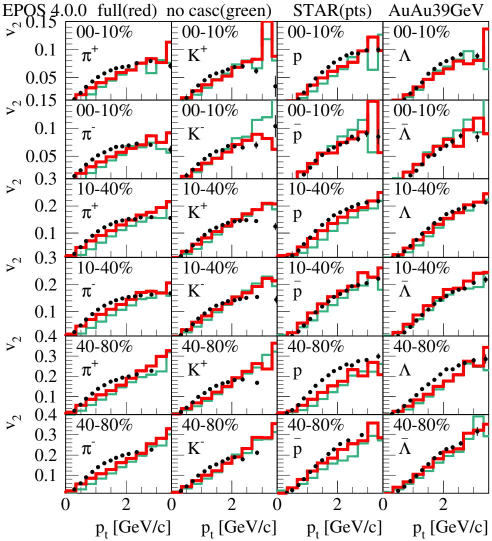
data PHENIX (black dots) Phys. Rev. C 93, 051902 (2016)

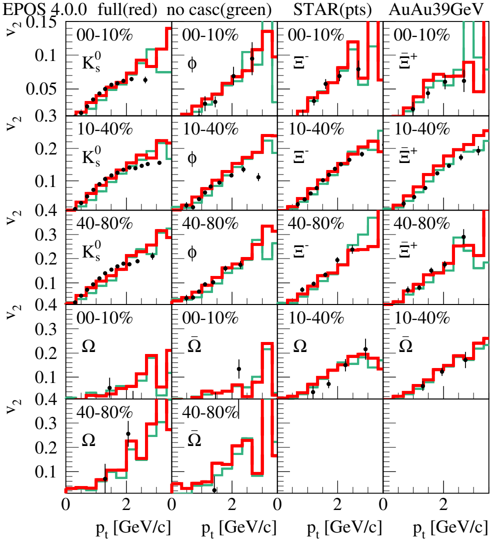




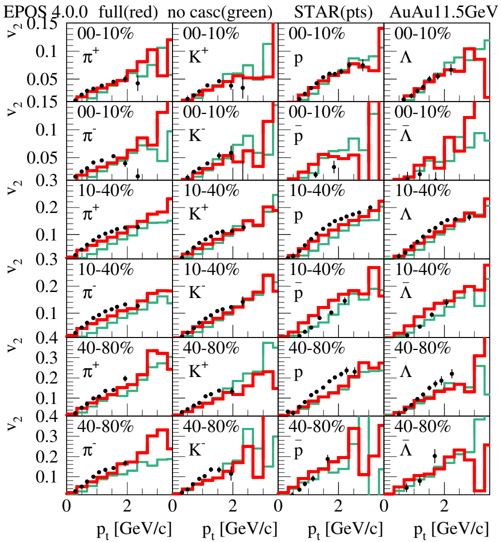
v_2 AuAu 39 GeV **EPOS full (red)** **EPOS no cascade (green)**

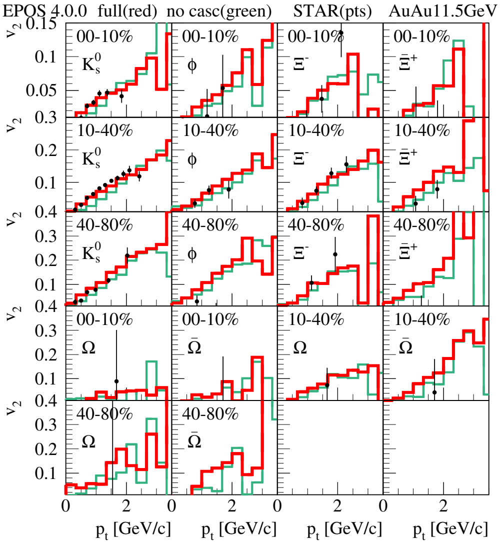
data STAR (black dots) Phys. Rev. C 93, 014907 (2016)





v_2 AuAu 11.5 GeV EPOS full (red) EPOS no cascade (green) STAR (black dots)





Summary

☐ **EPOS4 combines** (finally free of contradictions) **S-matrix parallel scattering approach with energy sharing (GR$^+$) and pQCD by introducing saturation**
Recovering factorization, but allows to go beyond
High energy approach! Can be used naturally at lower energies

☐ **Model works reasonably well down to 19.6 GeV**
the picture changes (amazingly) little from 39 to 19.6

☐ **and fails increasingly below**
and completely at 7.7 GeV, spectra too soft, baryon-antibaryon excess
... although v_2 is not too bad

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

< 24 GeV “partial parallel scenario” needed
→ primary collisions A, B
secondary scattering D