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EPOS4: a comprehensive MC for high-energy collisions from pp, pA to AA

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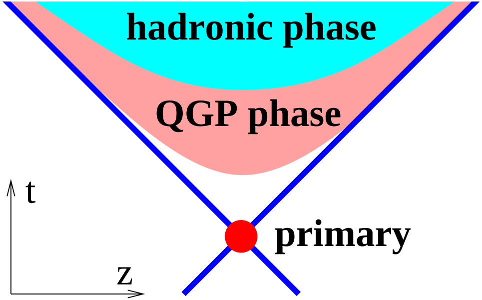
Space-time picture of pp, pA, AA at high energy

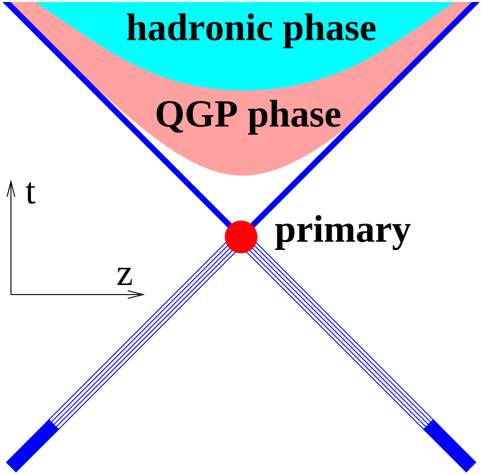


Primary interactions, pointlike overlap
(even in *pA*, *AA* scattering: large γ factors)

followed (later) by QGP formation

BUT the picture is not really correct...

More realistic space-time picture



splitting into multiple partons (parton evolution) long in advance, takes a long time (large γ factors)

but the interaction region (red point) is pointlike

multiple scatterings must happen in parallel

EPOS4 philosophy

concerning primary interactions

- □ **Avoid sequential scatterings,**
  - **concerning both parton-parton**
  - **and nucleon-nucleon interactions**
- □ **Do multiple scatterings rigorously in parallel**
- □ **Respect the rule “MC = theory”**

Some technical remarks:

Graphs are nice ... but it should be clear what is behind. We use

symbol	meaning
$\mathrm{T}(s,t)$	**elastic scattering T-matrix; s, t Mandelstam variables**
$T(s,b)$	**Fourier transformation of $\mathrm{T}(s,t)$ with respect to the momentum transfer, divided by $2s$ (impact parameter representation)**
G	**$2\,\mathrm{Im}T$ – representing inelastic scattering (cut diagram)**
$\tilde{\sigma}$	**pp cross sections: $\sigma^{pp} = \int d^2b\, \tilde{\sigma}^{pp}(s,b)$** **$A$+$B$ cross sections: $\sigma^{AB} = \int db_{AB}\, \tilde{\sigma}^{AB}(s,b,\{b_i^A\},\{b_i^B\})$**

$$\int db_{AB} = \int d^2b \int \prod_{i=1}^{A} d^2b_i^A\, T_A(b_i^A) \int \prod_{j=1}^{B} d^2b_j^B\, T_B(b_j^B),$$

with transv. nucleon coordiates b_i^A and b_j^B, with the nuclear thickness function

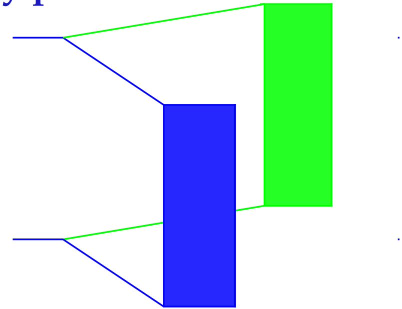
$$T_A(b) = \int dz\, \rho_A\left(\sqrt{b^2+z^2}\right)$$

where ρ_A is the (normalized) nuclear density for nucleus A.

Warmup: Gribov-Regge (GR) approach

V. A. Abramovsky, V. N. Gribov, O. V. Kancheli, L. N. Lipatov (1967-1973)

Multiple scattering in pp strictly parallel



Box: inelastic subscattering G, producing chain of particles
(precise structure: unknown)

No contradictions even when long "preparation"

Xsections expressed in terms of weights P depending on G

$$\tilde{\sigma}_{\mathrm{in}}^{pp} = \sum_{m=1}^{\infty} \underbrace{\frac{1}{m!} G^m \, e^{-G}}_{P(m)}, \qquad \tilde{\sigma}_{\mathrm{in}}^{AB} = \sum_{\{m_k\}} \underbrace{\prod_{k=1}^{AB} \frac{1}{\mathrm{m_k}!} (G_k)^{m_k} \, e^{-G_k}}_{P(\{m_k\}) \text{ basis of MC}}$$

EPOS4 improvement, step 1:

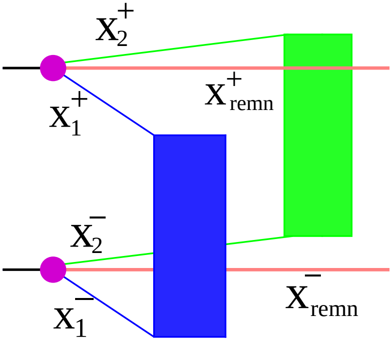
- **Implement energy-momentum conservation, referred to as GR^+**
- **For certain observables not so important**
  (total cross sections)
- **For others absolutely crucial**
  (particle production)
- **Necessary as solid basis for MC**
  (otherwise contradictions, but GR still widely used)

Energy-momentum sharing (GR$^+$) in EPOS

In *pp* or for each *NN* scattering in *A*+*B*

New variables: lightcone momentum fractions x_m^+ and x_m^- of subscatterings, being conserved:

$$x^{\pm}_{\mathrm{remn}} = 1 - \sum x^{\pm}_m \quad (pp)$$



Xsections still expressed in terms of weights P of configurations $K = \{\{m_k\}, \{x^{\pm}_{k\mu}\}\}$ (m_k subscatterings per pair k, with $x^{\pm}_{k\mu}$)

Solid basis of Monte Carlo:

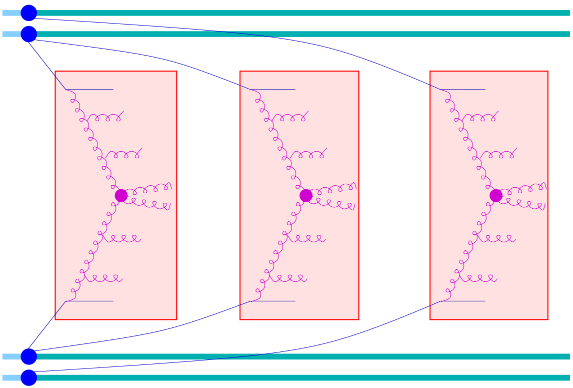
- ☐ one determines K according to $P(K)$,
- ☐ instantaneously, no sequences, in parallel!! Here: MC = theory

EPOS4 improvement, step 2:

- **So far: general framework, based on "some G"**
- **G represents a subscattering**
- **Now: make link with QCD: $G = G_{\mathrm{QCD}}$**
- **G_{QCD} represents parton-parton scattering, based on pQCD, including DGLAP evolution**

  See: K. Werner and B. Guiot, PRC 108, 034904 (2306.02396)
  Early work (no HF): H.J. Drescher, M. Hladik, S. Ostapchenko, T. Pierog, K. Werner, Phys.Rept. 350 (2001) 93-289 (hep-ph/0007198)

Replace boxes by QCD



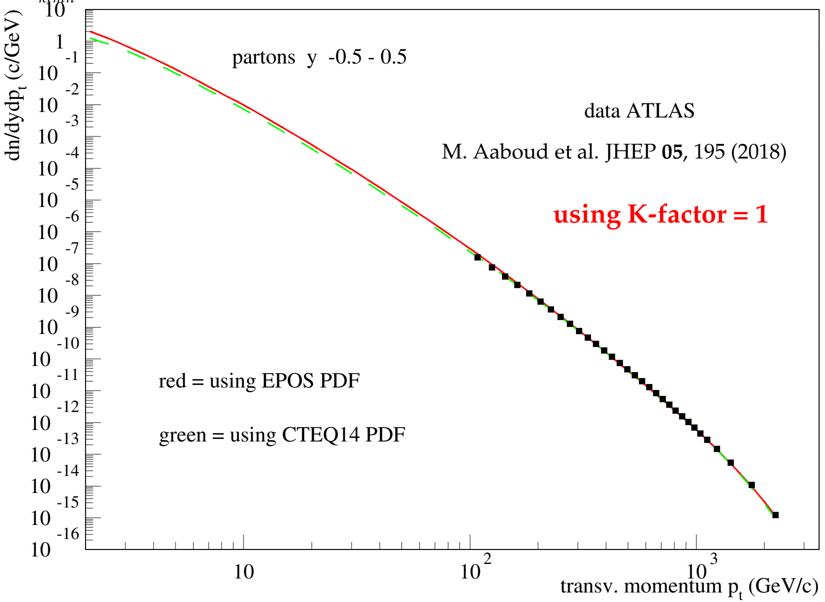
collision of two nuclei with three subscatterings

We compute and tabulate "moduls" (QCD evolution, Born cross sections, vertices) which then allow to evaluate the diagram

Different ways to rearrange the modules...

one may define (and tabulate) a PDF, allowing to compute the jet cross section vs pt for pp at 13 TeV

$$E_3E_4\frac{d^6\sigma}{d^3p_3d^3p_4}=\sum_{klmn}\int\!\!\int d\xi_1 d\xi_2\, f^k_{\mathrm{PDF}}(\xi_1,\mu_\mathrm{F}^2)f^l_{\mathrm{PDF}}(\xi_2,\mu_\mathrm{F}^2)\,\frac{1}{32s\pi^2}\bar{\sum}|\mathcal{M}^{kl\to mn}|^2\delta^4(p_1+p_2-p_3-p_4)\,\frac{1}{1+\delta_{mn}}$$



Looks good, but

- ☐ **Here we considered just one single subscattering**
- ☐ **In GR, the full multiple scattering scenario is equal to the single one for inclusive cross sections (AGK theorem)**

$$\frac{d\sigma_{\mathrm{incl}}^{AB}}{dp_t} = AB \times \frac{d\sigma_{\mathrm{incl}}^{\mathrm{single\ scattering}}}{dp_t}$$

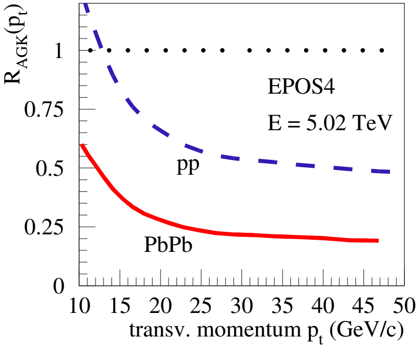
- ☐ **Does AGK hold in our case (GR^{+}) ?**
- ☐ **And does AGK hold for nuclear scattering (which would amount to binary scaling)?**

Validity of AGK Check p_t of partons for minimum bias PbPb and pp scatterings at 5.02 TeV.

Ratio

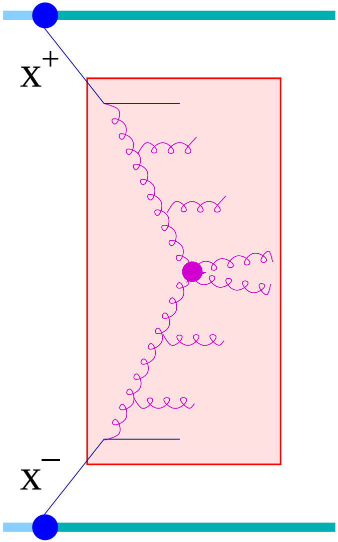
$$R_{\mathrm{AGK}}(p_t) = \frac{d\sigma_{\mathrm{incl}}^{AB}}{dp_t} \Big/ \left\{ AB \times \frac{d\sigma_{\mathrm{incl}}^{\mathrm{single\,scattering}}}{dp_t} \right\}$$

should be unity



AGK badly violated!!!

The problem is the energy sharing among subscatterings



Inclusive particle spectra (like p_t) are determined by the distribution of the LC momenta x^+ and x^- of the subscatterings.

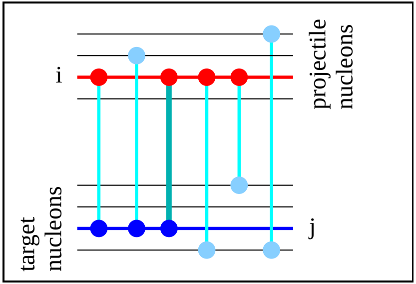
Crucial variable: the squared CMS energy fraction

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

For a given scattering, involving
projectile nucleon *i* and
target nucleon *j*
define:

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

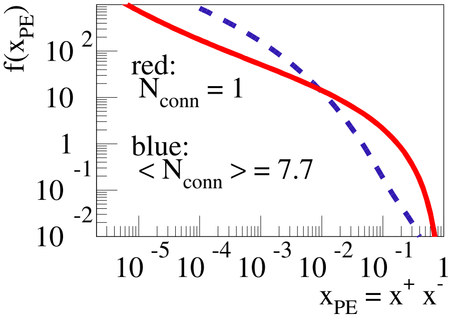
N_{P} **= number of scatterings involving *i***
N_{T} **= number of scatterings involving *j***



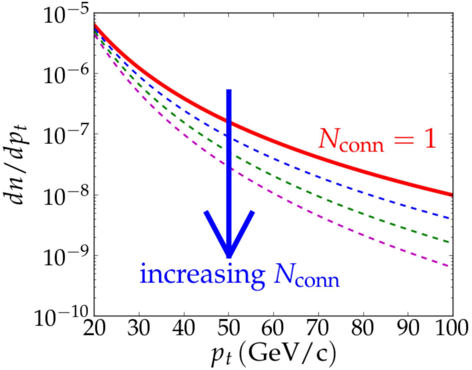
The x_{PE} distributions $f(x_{\mathrm{PE}})$ depend on N_{conn}

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

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



Large N_{conn} => large x_{PE} suppressed => large p_t suppressed



Min, bias pp or AA = superposition of different N_{conn} contributions

Cannot be equal to the single-scattering case ($N_{\text{conn}} = 1$)
=> violation of AGK

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

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

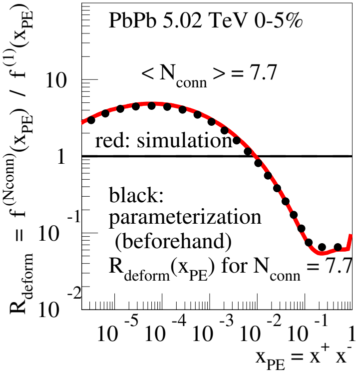
$R_{\mathrm{deform}} \neq 1$ creates the problem

But we are able to parameterize R_{deform} and tabulate it, for all systems, all centrality classes

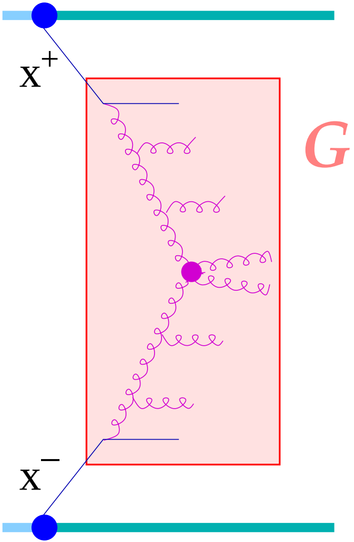
So

$$R_{\mathrm{deform}} = R_{\mathrm{deform}}(N_{\mathrm{conn}}, x_{\mathrm{PE}})$$

can be considered to be known, it is tabulated and available via interpolation (to be used later).



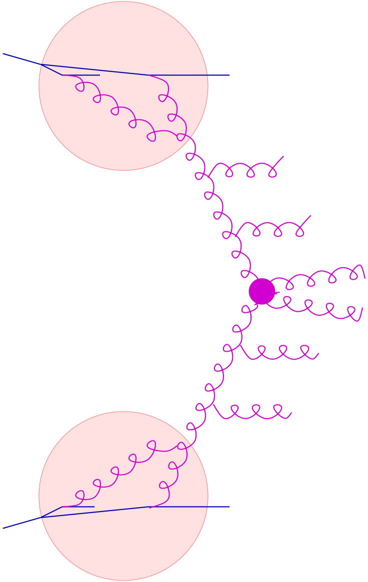
There are actually two problems



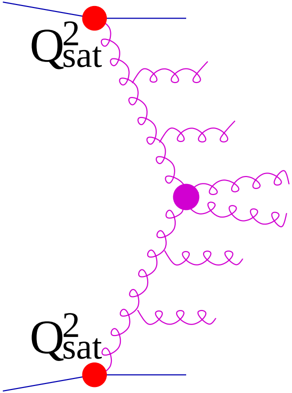
concerning the single scattering expression G, the fundamental building block of the multiple scattering formalism

- The assumption $G = G_{\rm QCD}$ seems to be wrong (AGK problem)
- Nonlinear effects are completely missing

EPOS4 improvement, step 3: Add saturation



Saturation phenomena
(nonlinear effects, inside circles)
may be "summarized"
by saturation scales



Saturation phenomena
(nonlinear effects, inside circles)
may be "summarized"
by saturation scales

suggesting to treat nonlinear effects
by introducing saturation scales Q^2_{sat}
as the lower limits Q_0^2 of the virtualities
for DGLAP evolutions

We compute and tabulate $G_{QCD}(Q_0^2, x^+, x^-, s, b)$ for a large range of Q_0^2 values
see K. Werner and B. Guiot, PRC 108, 034904 (2306.02396)

For the connection between the basic multiple scattering building block G and the QCD expression G_{QCD} one postulates:

For each subscattering, for given $x^{\pm}$, s, b, and N_{conn}:

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

such that G does not depend on N_{conn},
whereas Q^{2}_{sat} does depend on x^{+}, x^{-}, N_{conn}

n is a normalization constant

Early attemps in this direction:

K. Werner, F.-M. Liu, and T. Pierog, Phys. Rev. C 74, 044902 (2006), hep-ph/0506232
K. Werner, B. Guiot, I. Karpenko, and T. Pierog, J. Phys. Conf. Ser. 458, 012020 (2013)
T. Pierog and K. Werner, Acta Phys. Polon. Supp. 8, 1031 (2015)

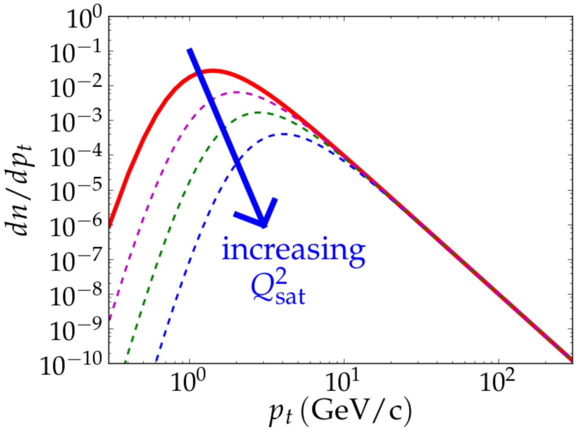
On can show see K. Werner, PRC 109, 034918 (2310.09380)

$$\frac{d^2\sigma_{\mathrm{incl}}^{AB\,(N_{\mathrm{conn}})}}{dx^+dx^-} \propto \frac{d\sigma_{\mathrm{incl}}^{\mathrm{single\,scattering}}}{dx^+dx^-}\left[Q_{\mathrm{sat}}^2(N_{\mathrm{conn}},x^+,x^-)\right]$$

i.e., the A+B cross section (given N_{conn})

- **is equal to the single scattering case,**
- **but with Q^2_{sat} corresponding to N_{conn}**

Same relation for p_t distributions (deduced from x^+x^-)



one expects with increasing $N_{\rm conn}$

- ☐ **an increasing $Q^2_{\rm sat}$**
- ☐ **and a reduction at $p_t^2 < Q^2_{\rm sat}$ compared to $N_{\rm conn} = 1$ (red)**

But no change for large p_t. If interested in large p_t:

One replaces $Q^2_{\rm sat}$ by some constant $Q_0^2 = \max\{Q^2_{\rm sat}\}$

One gets finally

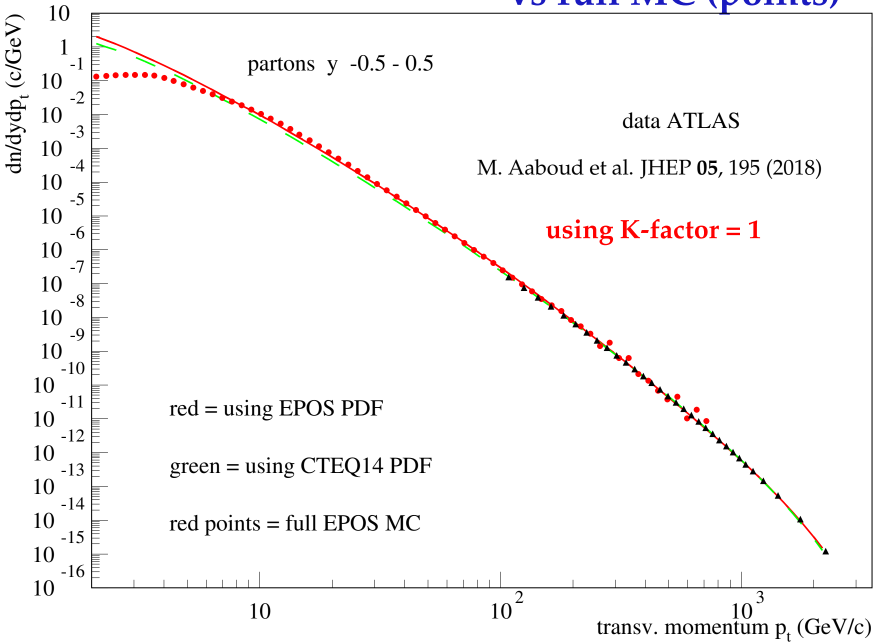
$$\frac{d\sigma_{\mathrm{incl}}^{AB\,(mb)}}{dp_t} = AB\,\frac{d\sigma_{\mathrm{incl}}^{\mathrm{single\,scattering}}}{dp_t}\left[Q_0^2\right]$$

but only for p_t^2 bigger than the relevant Q_{sat}^2 values (gAGK theorem)

Extremely important: One gets factorization (in *pp* and *A*+*B*) for inclusive cross sections at high pt in a fully self-consistent (*) multiple (parallel) scattering scheme.

(*) Mandatory: (A) energy-mom. conservation, (B) parallel scattering, (C) MC = theory, (D) factorization

Jet cross section vs pt for pp at 13 TeV, factorization result vs full MC (points)

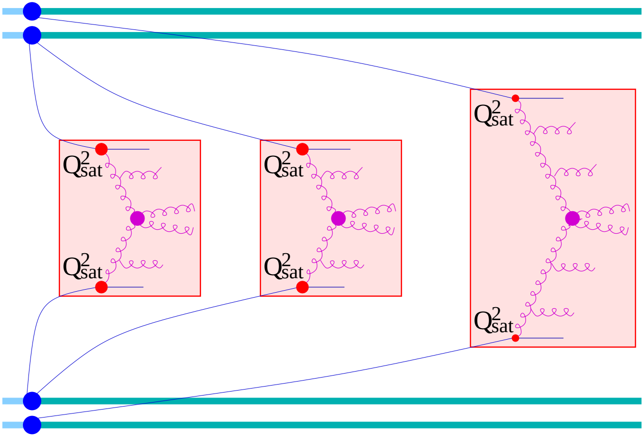


Why is this test so important?

- Does EPOS4 perform better for inclusive min. bias pp cross sections at high p_t? No
- But EPOS4 is designed to work for situations where multiple scattering is important (high mult. *pp*, *p*+A, A+B)
- And inclusive min. bias pp at high p_t is (although rare) a very important "special case", and we must show that this "test case" works as well

How to understand N_{conn}-dependent saturation scales

$A + B$ scattering ($A = B = 2$) with 3 subscatterings



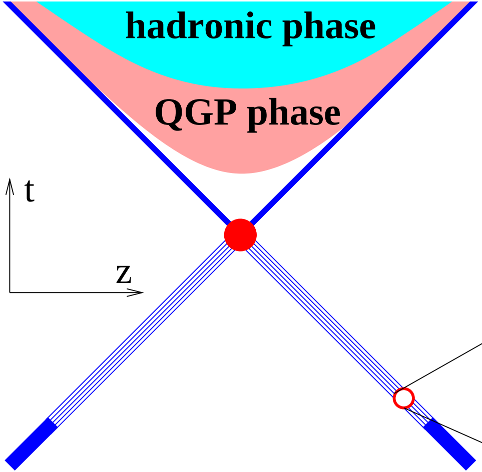
formulas: K. Werner, B. Guiot, PRC 108, 034904 (2306.02396)

Two left scatterings compared to right one:

- ☐ N_{conn} bigger
- ☐ energy ($\sqrt{s}$) smaller
- ☐ Q^2_{sat} bigger (bigger dots)
- ☐ evolution shorter
- ☐ central part identical
- ☐ particle production harder

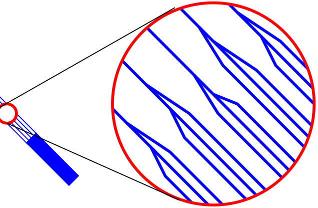
Implementing both energy-mom conservation and saturation is needed, the one compensates the other, such that the central part remains unchanged

Nonlinear effects happen very early

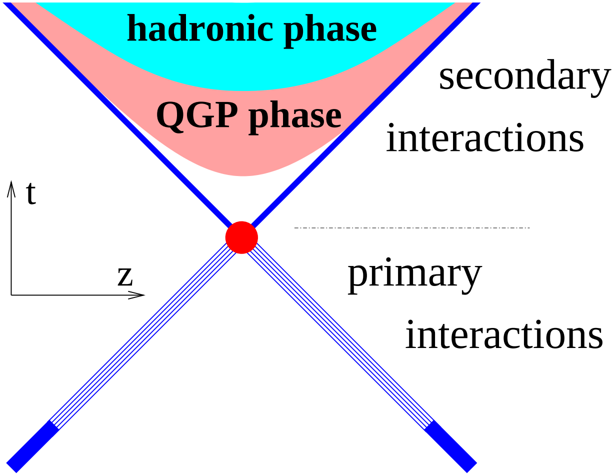


dynamical process happening long before the actual projectile-target overlap (red point)

initial state phenomenon, contrary to final state "string manipulations" (like color reconnections)



Secondary interactions



EPOS4 :
Solid basis for the primary interactions, setting the stage for what follows

Secondary interactions:

core-corona separation[1]
core hydro evolution[2]
microcanonical decay[1]
hadronic cascade[3]

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1) K. Werner, PRC 109, 014910 (2024), arXiv:2306.10277
2) I. Karpenko et al, Computer Physics Communications 185, 3016 (2014),
K. Werner, B. Guiot, I. Karpenko, and T. Pierog, PRC 89, 064903 (2014), 1312.1233
3) S. A. Bass et al., Prog. Part. Nucl. Phys. 41, 225 (1998),
M. Bleicher et al., J. Phys. G25, 1859 (1999)

For the following plots, 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 pp at 7 TeV

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

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

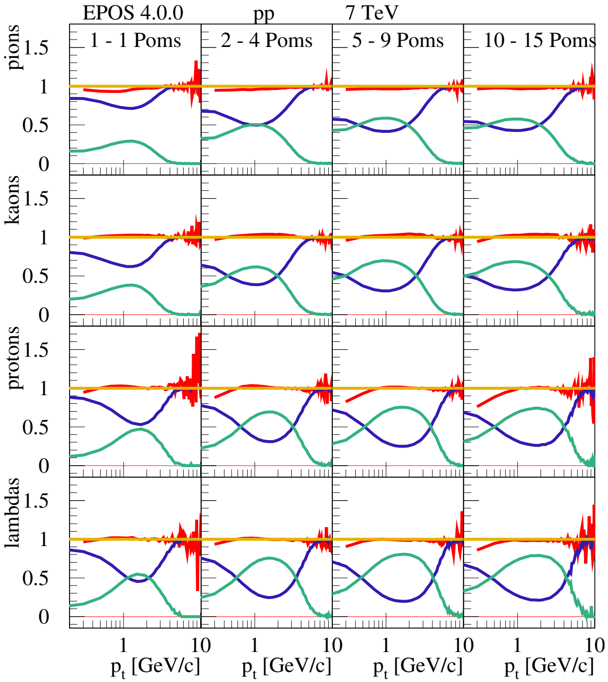
Blue: $\frac{\text{corona}}{\text{core+corona}}$

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

Core reaches to higher pt for baryons

Core has maximum at intermediate pt (flow)

Rescattering not very important



Core, corona, full PbPb at 5.02 TeV

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

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

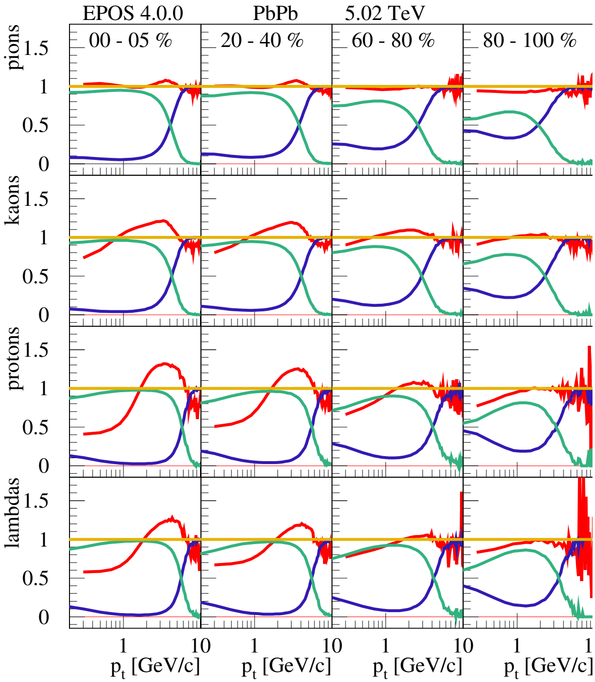
Blue: $\frac{\text{corona}}{\text{core+corona}}$

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

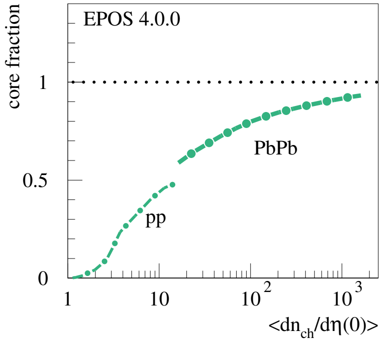
Core reaches to higher pt for baryons

Core has maximum at intermediate pt (flow)

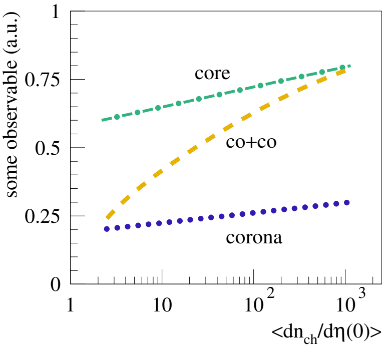
Rescattering important



Core fraction



Core + corona (co+co) results (sketch)



Almost continuous!

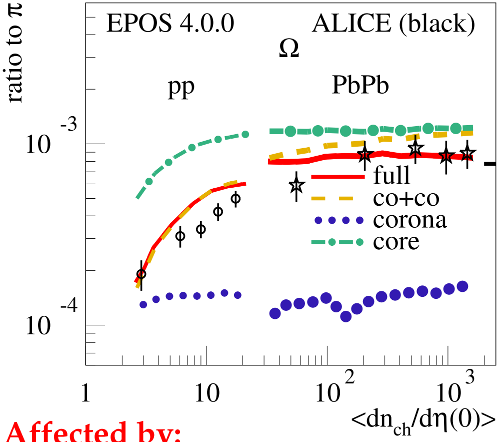
see DCCI2, Y. Kanakubo et al Phys. Rev. C 105 (2022) 2, 024905

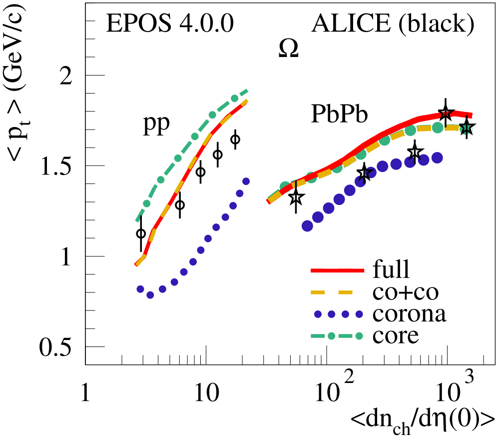
Transition from corona core

Attention ! Core and corona curve continuous ... or not (depends on variable)

On top: effects from hadronic cascade (UrQMD, S. A. Bass et al., Prog. Part. Nucl. Phys. 41, 225 (1998), M. Bleicher et al., J. Phys. G25, 1859 (1999))

continuous curve **jump**





Affected by:

core-corona

microcanonical

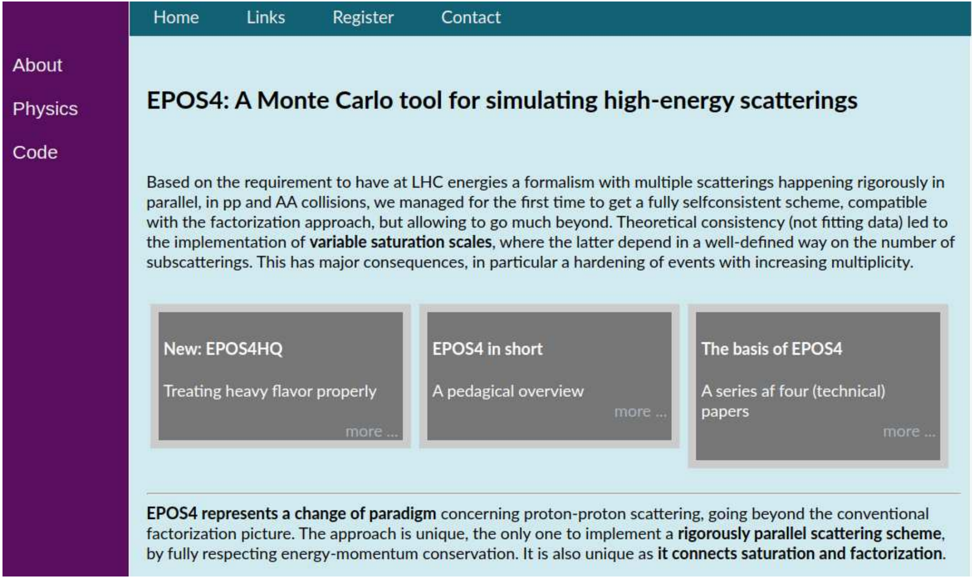
hadronic cascade (UrQMD)

saturation

flow

core-corona

EPOS4 web page: **https://klaus.pages.in2p3.fr/epos4**



thanks Damien Vintache for managing installation/technical issues

Summary (concerning primary scatterings in EPOS4)

- There are ad hoc assumptions, details may be questioned, but the overall multiple-scattering picture seems mandatory, since based on very fundamental principles:

  * parallel scattering formalism
  * energy-momentum sharing (EMS)
  * implementing saturation

    Seems mandatory to implement "environment dependent" factorization scales, which compensate exacly the effect of the EMS

  * validity of factorization at high pt
  * MC = theory

- Solid basis for further activities:
  EPOS4 systematic improvements
  EPOS4HQ, including quarkonia and HF collectivity,
  EPOS4JET ...

- AND (with Tanguy Pierog) create a fast version to be used for air shower simulations