ISVHECRI 2024, Puerto Vallarta, Mexico, Jul 8 – 12, 2024
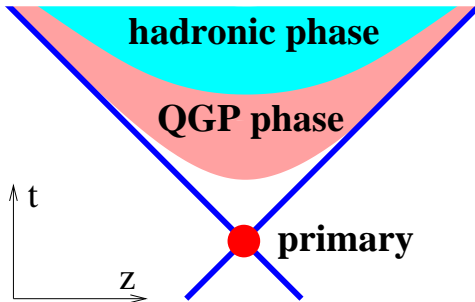
EPOS4
What are the new concepts?

Klaus Werner

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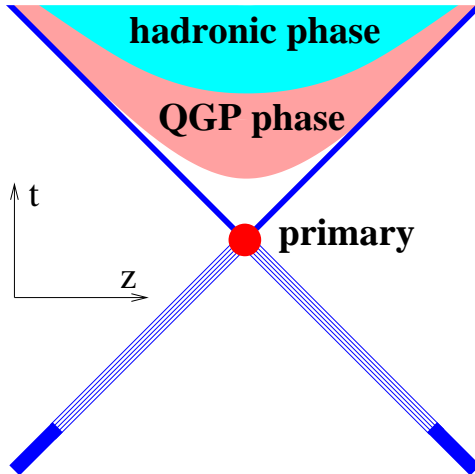
Space-time picture of pp, pA, AA at high energy

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
T(s, t)	**elastic scattering T-matrix; s, t Mandelstam variables**
$T(s, b)$	**Fourier transformation of T(s, t) with respect to the momentum transfer, divided by $2s$ (impact parameter representation)**
G	**2 ImT – 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 coordinates 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.
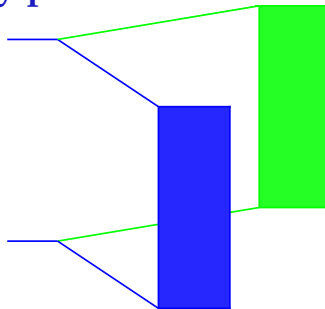
Warmup: Gribov-Regge (GR) approach

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

$$\tilde{\sigma}_{\text{in}}^{pp} = \sum_{m=1}^{\infty} \underbrace{\frac{1}{m!} G^m\, e^{-G}}_{P(m)}, \qquad \tilde{\sigma}_{\text{in}}^{AB} = \sum_{\{m_k\}} \underbrace{\prod_{k=1}^{AB} \frac{1}{m_k!} (G_k)^{m_k}\, e^{-G_k}}_{P(\{m_k\}) \text{ basis of MC}}$$
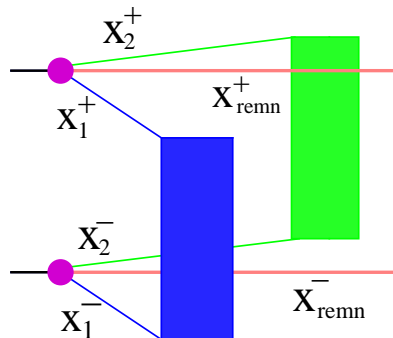
EPOS4 improvement, step 1:

☐ **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:

$$x_{\text{remn}}^{\pm} = 1 - \sum x_m^{\pm} \quad (pp)$$

X_2^+, X_1^+, X_{remn}^+, X_2^-, X_1^-, X_{remn}^-

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

Solid basis of Monte Carlo:

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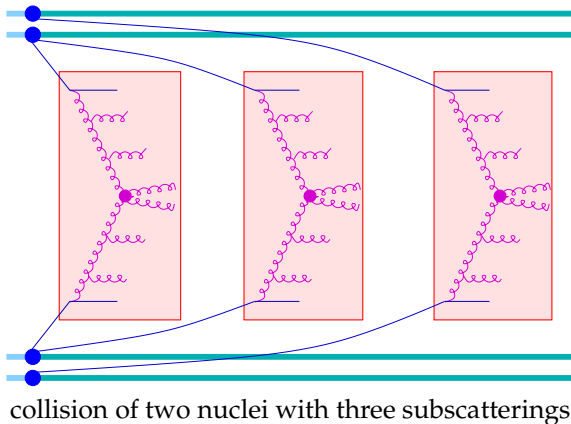☐ **instantaneously, no sequences, in parallel!! Here: MC = theory**

EPOS4 improvement, step 2:

☐ **So far: general framework, based on "some G"**

☐ **G represents a subscattering**

☐ **Now: make link with QCD: $G = G_{QCD}$**

☐ **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,
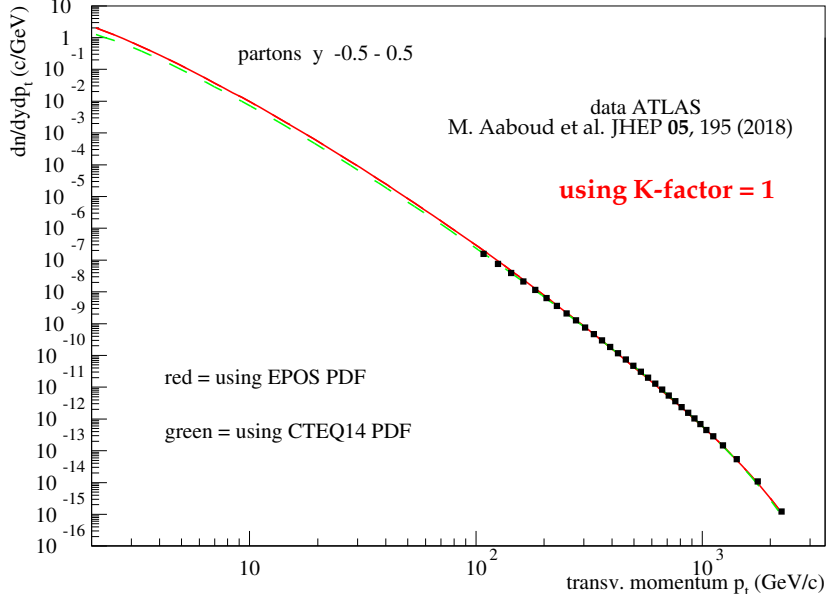   K. Werner, Phys.Rept. 350 (2001) 93-289 (hep-ph/0007198)

collision of two nuclei with three subscatterings

Replace boxes by QCD

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

$$E_3 E_4 \frac{d^6\sigma}{d^3 p_3 d^3 p_4} = \sum_{klmn} \int\int d\xi_1 d\xi_2 \, f^k_{\text{PDF}}(\xi_1, \mu_F^2) f^l_{\text{PDF}}(\xi_2, \mu_F^2) \frac{1}{32 s \pi^2} \sum |\mathcal{M}^{kl \to mn}|^2 \delta^4(p_1 + p_2 - p_3 - p_4) \frac{1}{1+\delta_{mn}}$$

partons y -0.5 - 0.5

data ATLAS
M. Aaboud et al. JHEP **05**, 195 (2018)

using K-factor = 1

red = using EPOS PDF

green = using CTEQ14 PDF

dn/dydp$_t$ (c/GeV)

transv. momentum p$_t$ (GeV/c)

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)**

$$\frac{d\sigma_{\text{incl}}^{AB}}{dp_t} = AB \times \frac{d\sigma_{\text{incl}}^{\text{single scattering}}}{dp_t}$$
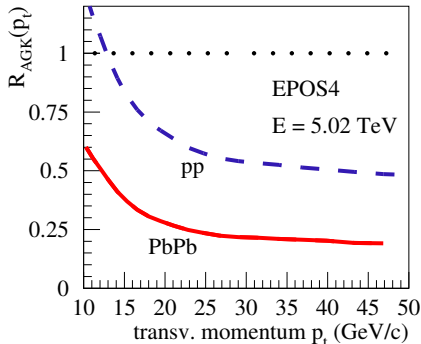
☐ **Does AGK hold in our case (GR+) ?**

☐ **And does AGK hold for nuclear scattering (which would amount to binary scaling)?**

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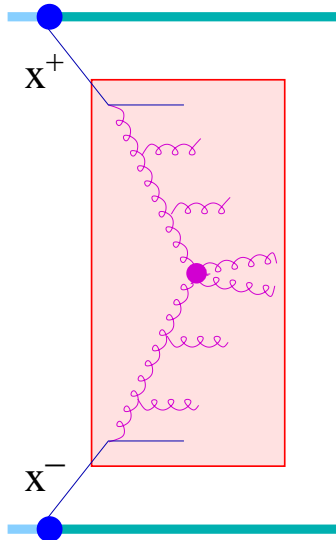for minimum bias PbPb and pp scatterings at 5.02 TeV.

Ratio
$$R_{\text{AGK}}(p_t) = \frac{d\sigma_{\text{incl}}^{AB}}{dp_t} \bigg/ \left\{ AB \times \frac{d\sigma_{\text{incl}}^{\text{single scattering}}}{dp_t} \right\}$$
should be unity

AGK badly violated!!!

The problem is
the energy sharing
among subscatterings

x^+

x^-

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

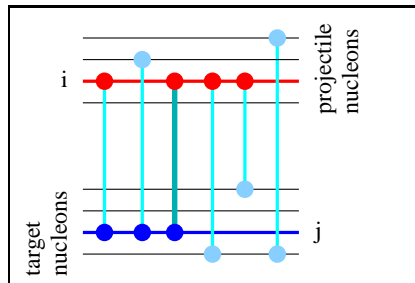$$x_{\mathrm{PE}} = x^+ x^- \approx s / s_{\mathrm{tot}}$$

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

define:
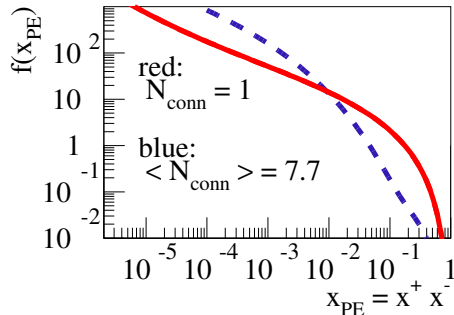$$N_{\text{conn}} = \frac{N_P + N_T}{2}$$

N_P = **number of scatterings involving i**
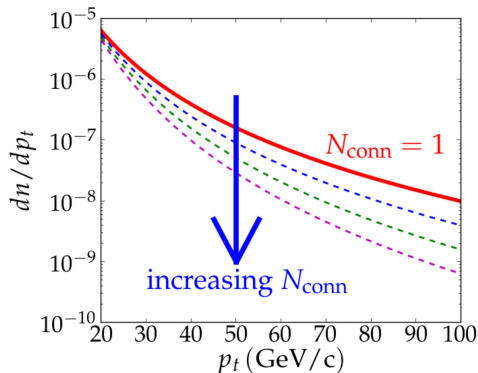N_T = **number of scatterings involving j**

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

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

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

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 $f^{(N_{\text{conn}})}(x_{\text{PE}})$ relative to the reference $f^{(1)}(x_{\text{PE}})$

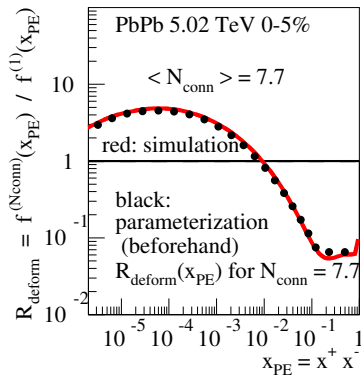$$R_{\text{deform}} = \frac{f^{(N_{\text{conn}})}(x_{\text{PE}})}{f^{(1)}(x_{\text{PE}})}$$

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

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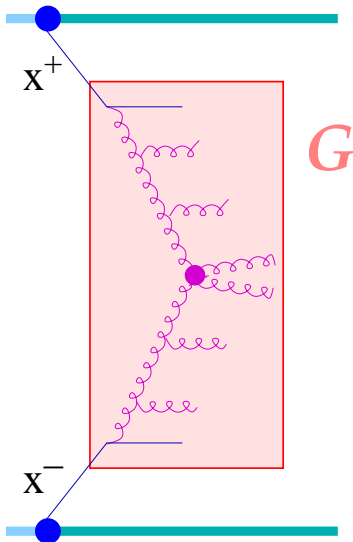
So

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

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

PbPb 5.02 TeV 0-5%

$< N_{\text{conn}} > = 7.7$

red: simulation

black: parameterization (beforehand) $R_{\text{deform}}(x_{\text{PE}})$ for $N_{\text{conn}} = 7.7$

$R_{\text{deform}} = f^{(N_{\text{conn}})}(x_{\text{PE}}) / f^{(1)}(x_{\text{PE}})$
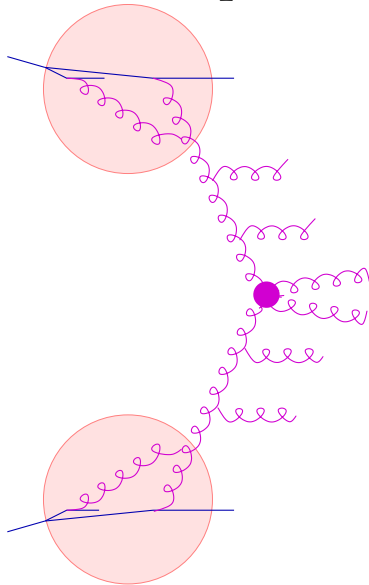
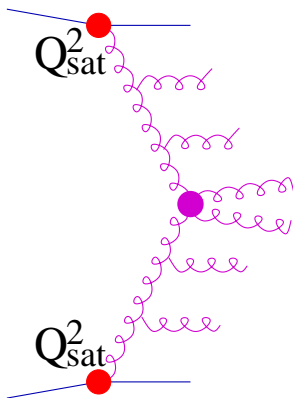$x_{\text{PE}} = x^{+} x^{-}$

There are actually two problems

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

☐ **The assumption $G = G_{QCD}$ 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_{sat}^2 as the lower limits Q_0^2 of the virtualities for DGLAP evolutions

We compute and tabulate $G_{\text{QCD}}(Q_0^2, x^+, x^-, s, b)$ 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}:

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

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)
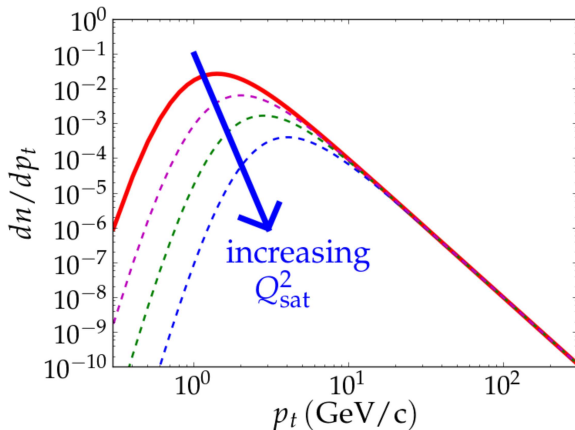T. Pierog and K. Werner, Acta Phys. Polon. Supp. 8, 1031 (2015)

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

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

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

   □ **is equal to the single scattering case,**

   □ **but with Q_{sat}^2 corresponding to N_{conn}**

Same relation for p_t distributions (deduced from x⁺x⁻)

one expects with in-creasing N_{conn}

☐ **an increasing Q_{sat}^2**

☐ **and a reduction at $p_t^2 < Q_{sat}^2$ compared to $N_{conn} = 1$ (red)**

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

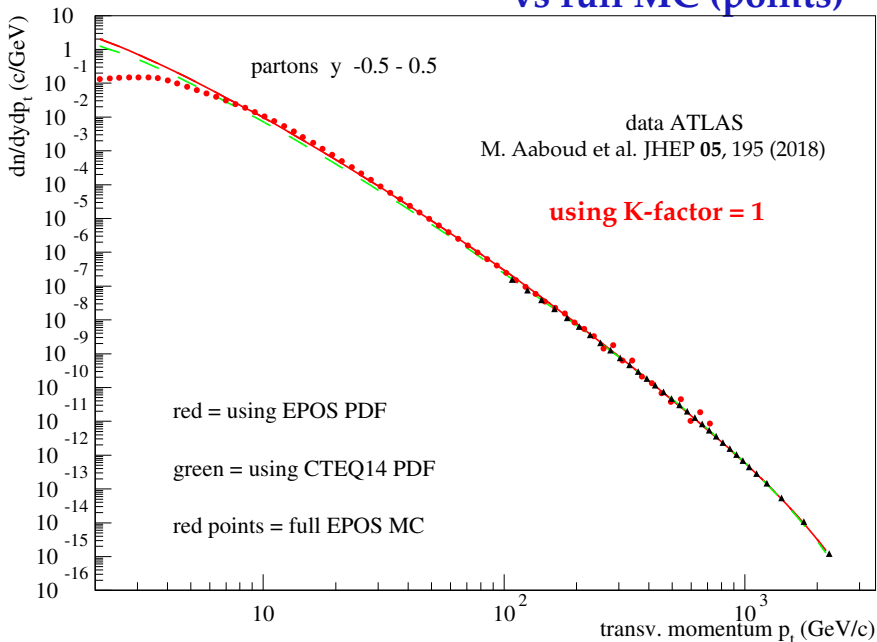One replaces Q_{sat}^2 by some constant $Q_0^2 = \max\{Q_{sat}^2\}$

One gets finally

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

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,
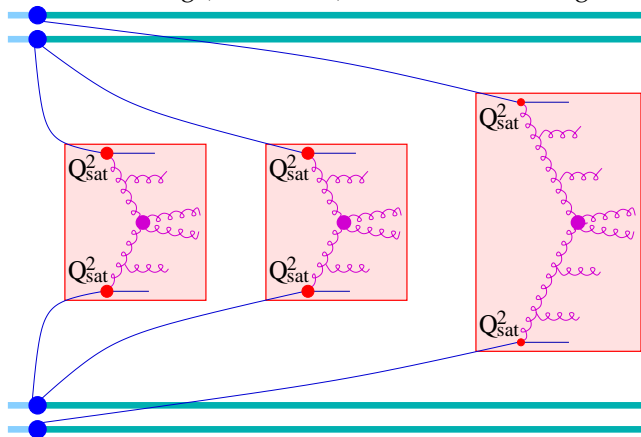(C) MC = theory,   (D) factorization

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

partons y -0.5 - 0.5

data ATLAS
M. Aaboud et al. JHEP **05**, 195 (2018)

using K-factor = 1

red = using EPOS PDF

green = using CTEQ14 PDF

red points = full EPOS MC

How to understand N_{conn}-dependent saturation scales

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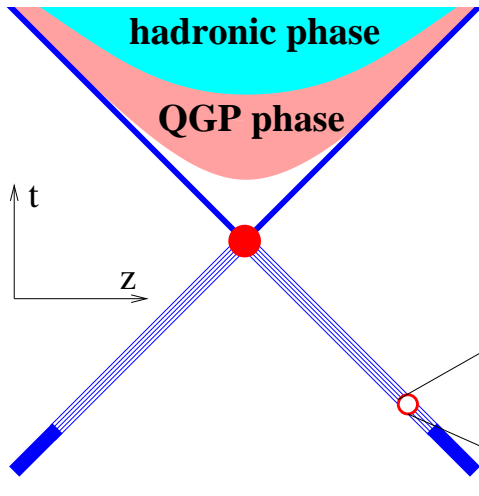

Two left scatterings compared to right one:

☐ N_{conn} **bigger**

☐ **energy ($\sqrt{s}$) smaller**

☐ Q^2_{sat} **bigger** (bigger dots)

☐ **evolution shorter**

☐ **central part identical**

☐ **particle production harder**

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

Implementing both energy-mom conservation and saturation is needed, the one compensates the other, such that the central part remains unchanged
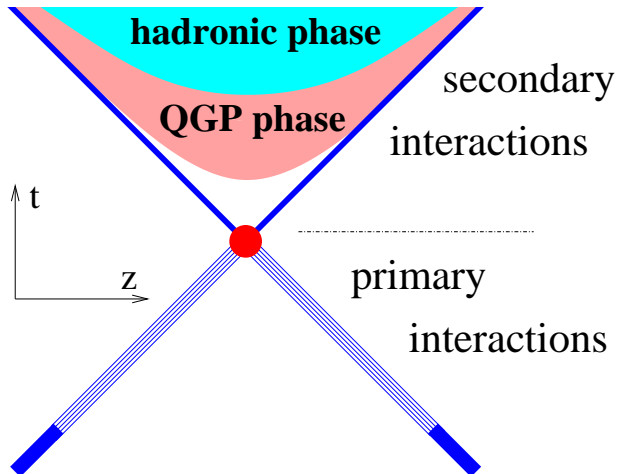
**Nonlinear effects
happen very early**

hadronic phase

QGP phase

t

z

**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

hadronic phase

QGP phase

t

z

secondary

interactions

primary

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)

Core, corona, full
pp at 7 TeV

pions, kaons, protons, lambdas (top to bottom)
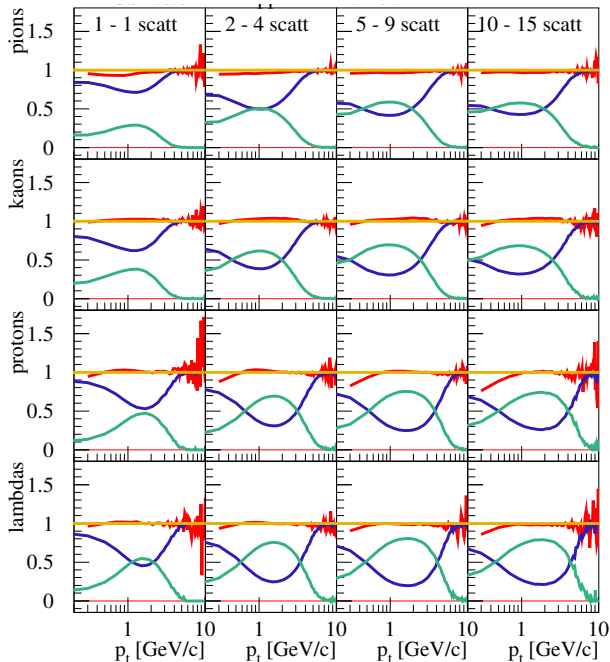
Green: $\dfrac{\text{core}}{\text{core}+\text{corona}}$

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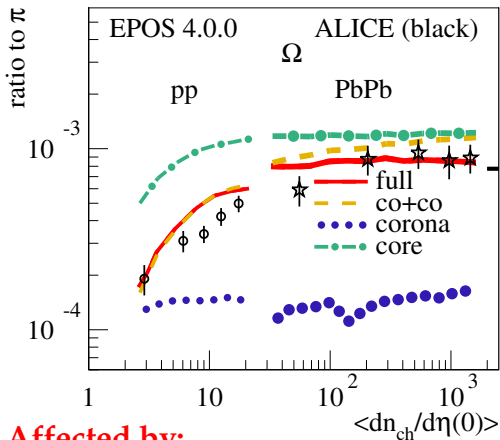
Red: $\dfrac{\text{full}}{\text{core}+\text{corona}}$

Core reaches to higher pt for baryons

Core has maximum at intermediate pt (flow)
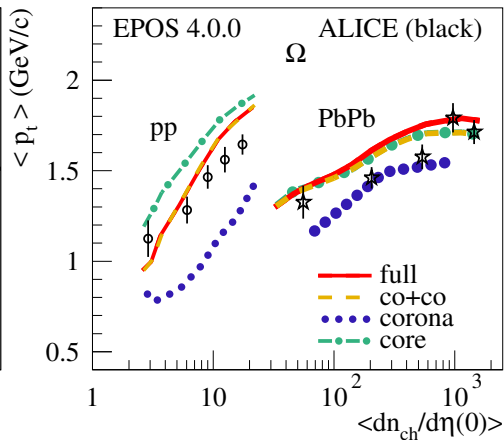
Rescattering not very important

continuous curve   **jump**

Affected by:

    core-corona

    microcanonical   **saturation**

    hadronic cascade (UrQMD)   **flow**

                                 core-corona

EPOS4 documentation

☐ **EPOS4 web page (since 10/2022) 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)

- **K. Werner, PRC 108, 064903 (2301.12517) EPOS4 Overview**

- **K. Werner and B. Guiot, PRC 108, 034904 (2306.02396) EPOS4 pQCD**

- **K. Werner, PRC 109, 034918 (2310.09380) Parallel scattering formalism**

- **K. Werner, PRC 109, 014910 (2306.10277) Microcanonical, core-corona**

- **J. Zhao, J. Aichelin, P.B. Gossiaux, and K. Werner, PRD 109, 054011 (2310.08684) EPOS4HQ**: Heavy flavor collectivity in pp

- **J. Zhao, J. Aichelin, P.B. Gossiaux, K. Werner, 2401.17096   EPOS4HQ**: Heavy flavour in HI at RHIC and LHC

- **K. Werner, J. Jahan, I. Karpenko, T. Pierog, M. Stefaniak, D. Vintache, 2401.11275   EPOS4 results at RHIC**

Summary (concerning primary scattering 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**