EPOS

Klaus Werner

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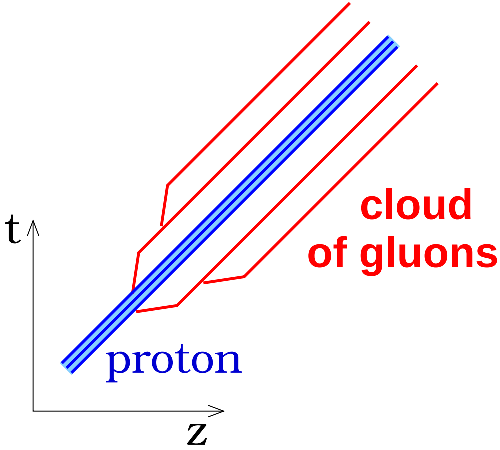
1 Parton evolution and Pomerons in EPOS

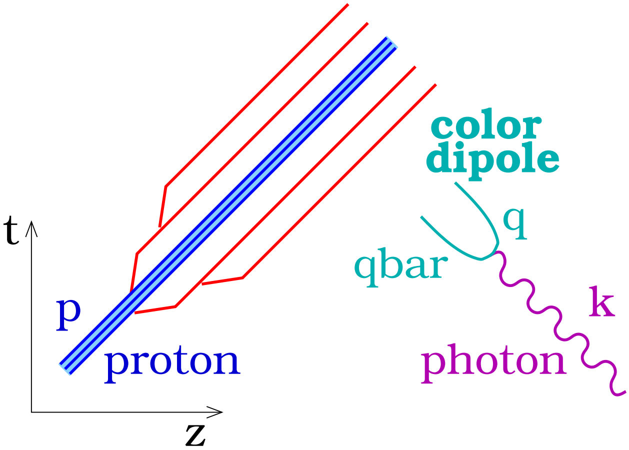
1.1 Parton evolution

A fast moving proton



emits successively partons (mainly gluons), quasi-real (large gamma factors)

... which can be probed by a virtual photon
(emitted from an electron)



photon splits into q-qbar

$\rightarrow$ Color dipole

p and k are proton and photon momentum

What precisely the photon "sees" depends on two kinematic variables,

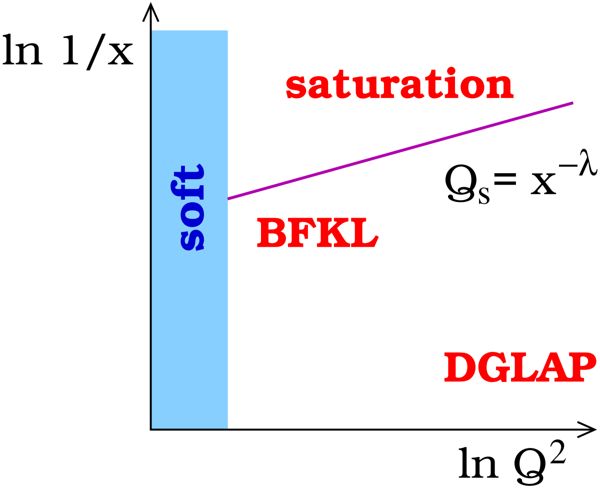
the **virtuality**

$$Q^2 = -k^2$$

and the **Bjorken variable**

$$x = \frac{Q^2}{2pk}$$

which probes partons with momentum fraction x.
It determines also the **approximation scheme** to compute the parton cloud.



DGLAP: summing to all orders of $\alpha_s \ln Q^2$

BFKL: summing to all orders of $\alpha_s \ln \frac{1}{x}$

Linear equations

BFKL (Balitsky, Fadin, Kuraev, and Lipatov):

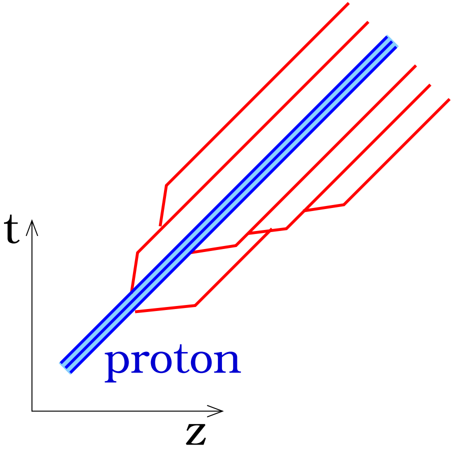
$$\frac{\partial \varphi(x,\boldsymbol{q})}{\partial \ln \frac{1}{x}} \; \frac{\alpha_s N_c}{\pi^2} \int d^2k \, K(\boldsymbol{q},\boldsymbol{k}) \varphi(x,\boldsymbol{k})$$

$$\text{with } xg(x,Q^2) = \int_0^{Q^2} \frac{d^2k}{k^2} \varphi(x,\boldsymbol{k}),$$

DGLAP (Dokshitzer, Gribov, Lipatov, Altarelli and Parisi):

$$\frac{\partial g(x,Q^2)}{\partial \ln q^2} = \int_x^1 \frac{dz}{z} \, \frac{\alpha_s}{2\pi} P(z) g(\frac{x}{z},Q^2)$$

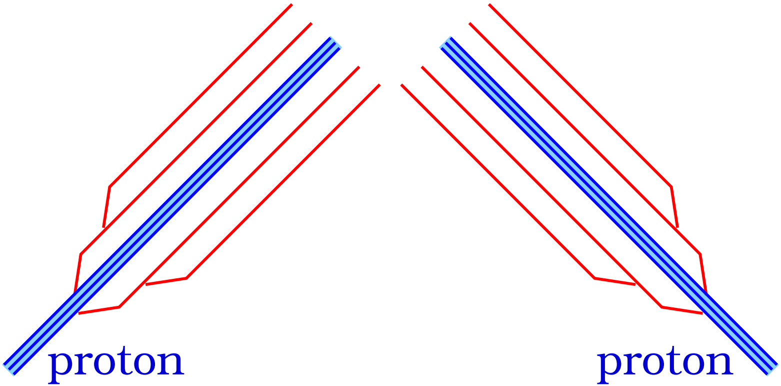
Very large $\ln 1/x$: Saturation domain



Non-linear effects

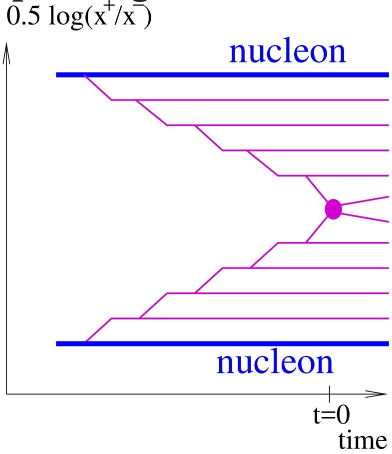
Gluon from one cascade is absorbed by another one

1.2 pp scattering (linear domain)



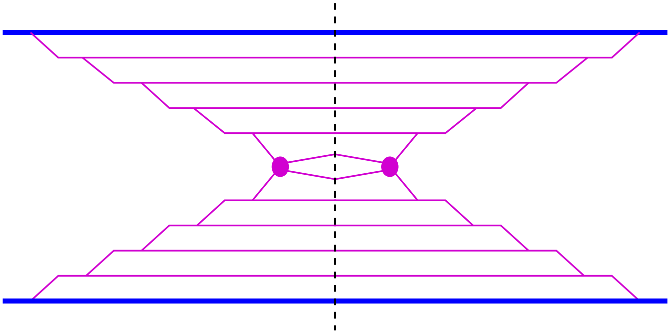
Same evolution as in proton-photon (causality)

Different way of plotting the same reaction



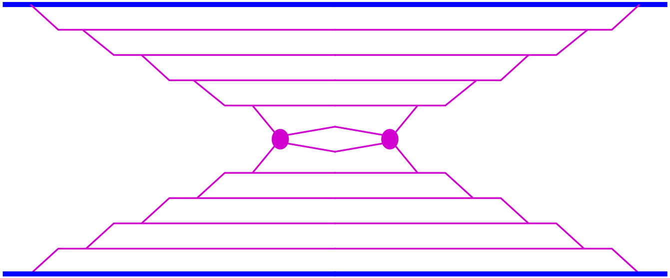
inelastic scattering diagram

Corresponding cut diagram



referred to as “cut parton ladder”
= amplitude squared of the inelastic diagram

Corresponding elastic diagram



referred to as “(uncut) parton ladder”

1.3 Soft domain

Very small $\ln Q^2$: No perturbative treatment!

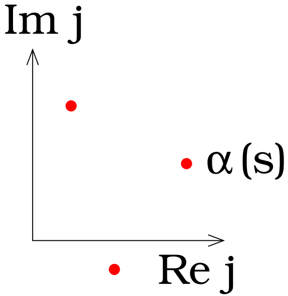
But one may use the hypothesis of **Lorentz invariance** and **analyticity** of the T-matrix. One starts with a partial wave expansion of the T-matrix (Watson-Sommerfeld transform) :

$$T(t,s) = \sum_{j=0}^{\infty} (2j+1)\mathcal{T}(j,s)P_j(z)$$

with $t \propto z-1$, $z = \cos\vartheta$, P_j: Legendre polynomials.

With $\alpha(s)$ being the right-most pole of $\mathcal{T}(j,s)$ one gets for $t \to \infty$:

$$T(t,s) \propto t^{\alpha(s)}$$



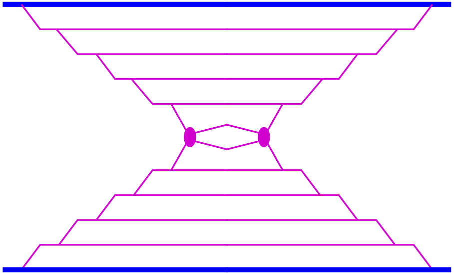
and assuming crossing symmetry one gets the famous asymptotic result

$$T(s,t) \propto s^{\alpha(t)}$$

with the “Regge pole”

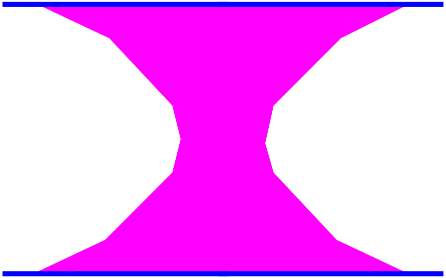
$$\alpha(t) = \alpha(0) + \alpha' t$$

Perturbative:
Parton ladder



T-matrix computed
(DGLAP)

Soft:
Soft Pomeron



gluon fields

T-matrix parametrized

Formulas (see Phys.Rept. 350 (2001) 93-289):

$$T_{\mathrm{soft}}(\hat{s},t) \;=\; 8\pi s_0\, i\, \gamma^2_{\mathrm{Pom-parton}} \left(\frac{\hat{s}}{s_0}\right)^{\alpha_{\mathrm{soft}}(0)}$$

$$\times \exp(\lambda_{\mathrm{soft}}\, t)$$

with

$$\lambda_{\mathrm{soft}} = 2R^2_{\mathrm{Pom-parton}} + \alpha'_{\mathrm{soft}} \ln \frac{\hat{s}}{s_0}.$$

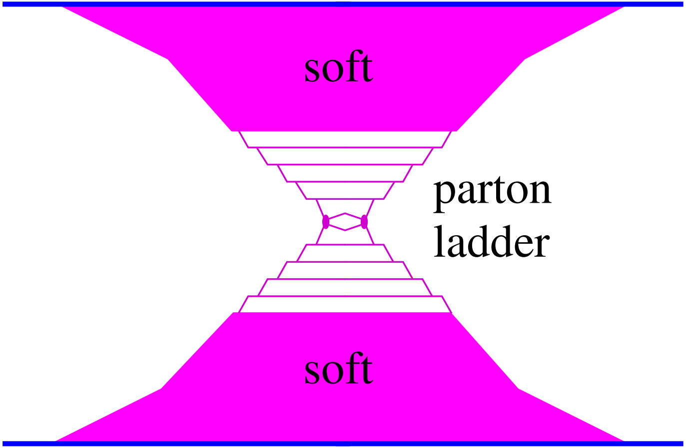
Interaction cross section,

$$\sigma_{\mathrm{soft}}(\hat{s}) = \frac{1}{2\hat{s}} 2\mathrm{Im}\, T_{\mathrm{soft}}(\hat{s},0)\,,$$

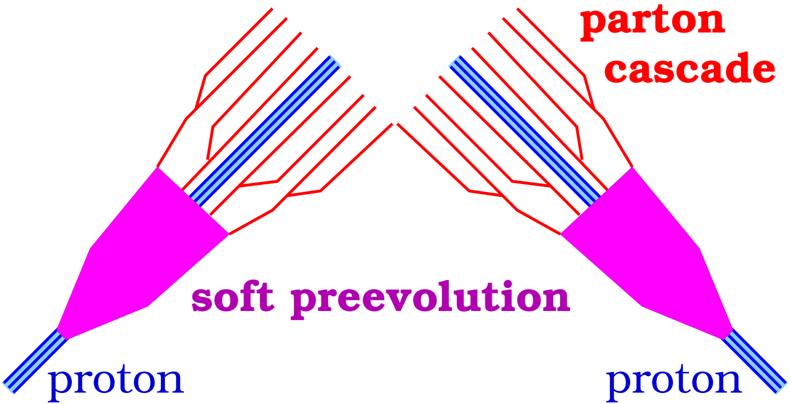
$$= 8\pi\gamma_{\mathrm{part}}^{2} \left(\frac{\hat{s}}{s_0}\right)^{\alpha_{\mathrm{soft}}(0)-1}$$

which grows too fast

1.4 Semihard Pomeron



Space-time picture of semihard Pomeron



Hard cross section and amplitude (see Phys.Rept. 350 (2001) 93-289):

$$\sigma_{\mathrm{hard}}^{jk}(\hat{s},Q_0^2) = \frac{1}{2\hat{s}} 2\mathrm{Im}\, T_{\mathrm{hard}}^{jk}(\hat{s},t=0)$$
$$= K \sum_{ml} \int dx_B^+ dx_B^- dp_\perp^2 \frac{d\sigma_{\mathrm{Born}}^{ml}}{dp_\perp^2}(x_B^+ x_B^- \hat{s}, p_\perp^2)$$
$$\times E_{\mathrm{QCD}}^{jm}(x_B^+, Q_0^2, M_F^2)\, E_{\mathrm{QCD}}^{kl}(x_B^-, Q_0^2, M_F^2)\theta\left(M_F^2 - Q_0^2\right),$$

One knows (Lipativ, 86): amplitude is imaginary, and nearly independent on t => (with $R_{\mathrm{hard}}^2 \simeq 0$) :

$$T_{\mathrm{hard}}^{jk}(\hat{s},t) = i\hat{s}\, \sigma_{\mathrm{hard}}^{jk}(\hat{s},Q_0^2)\ \exp\left(R_{\mathrm{hard}}^2\, t\right)$$

Semihard amplitude :

$$iT_{\text{semihard}}(\hat{s},t) = \sum_{jk} \int_0^1 \frac{dz^+}{z^+} \frac{dz^-}{z^-}$$

$$\times \mathrm{Im}\, T^{j}_{\text{soft}}\Big(\frac{s_0}{z^+},t\Big)\ \mathrm{Im}\, T^{k}_{\text{soft}}\Big(\frac{s_0}{z^-},t\Big)\ iT^{jk}_{\text{hard}}(z^+z^-\hat{s},t)$$

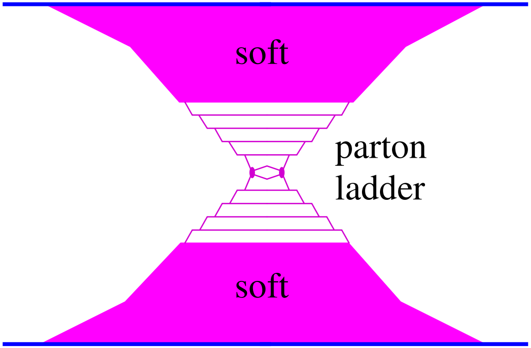
(valid for $s \to \infty$ and small parton virtualities except for the ones in the ladder)

2 Multiple scattering in EPOS

in collaboration with T. Pierog and B. Guiot

Parton based Gribov-Regge theory. By H.J. Drescher, M. Hladik, S. Ostapchenko, T. Pierog, K. Werner. hep-ph/0007198. Published in Phys.Rept. 350 (2001) 93-289.

2.1 Single scattering (single Pomeron)



somewhat simplified

2.2 Multiple scattering

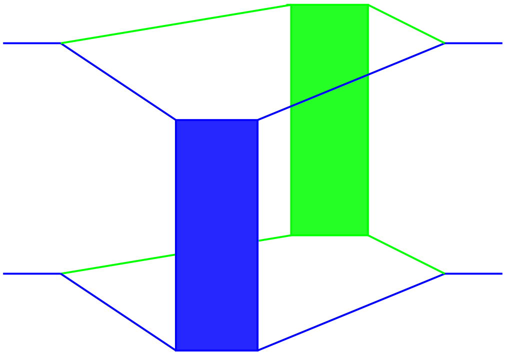
Be T the elastic (pp,pA,AA) scattering T-matrix =>

$$2s\,\sigma_{\mathrm{tot}} = \frac{1}{\mathrm{i}}\mathrm{disc}\,T$$

Basic assumption : Multiple "Pomerons"

$$iT = \sum_k \frac{1}{k!}\left\{iT_{\mathrm{Pom}} \times ... \times iT_{\mathrm{Pom}}\right\}$$

Example: 2 “Pomerons”



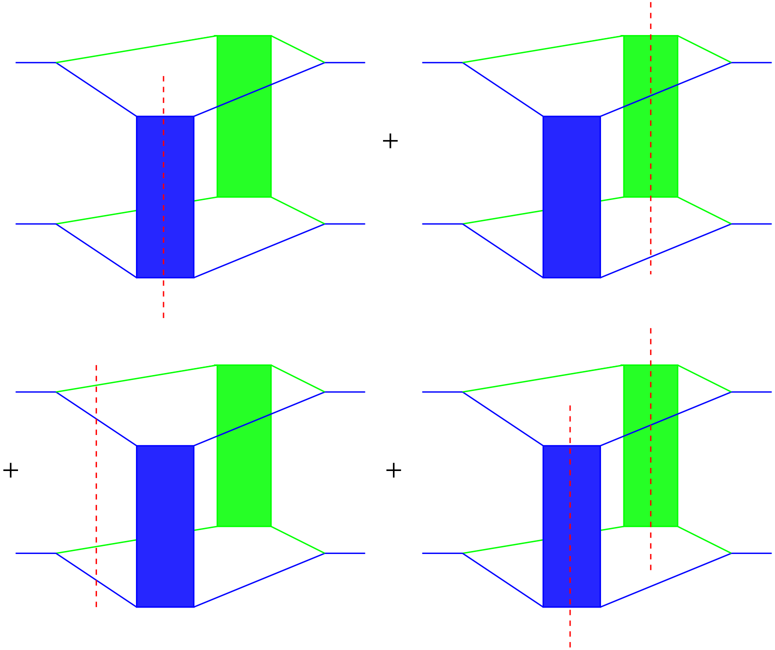
Evaluate

$$\frac{1}{\mathrm{i}}\mathrm{disc}\left\{iT_{\mathrm{Pom}} \times \ldots \times iT_{\mathrm{Pom}}\right\}$$

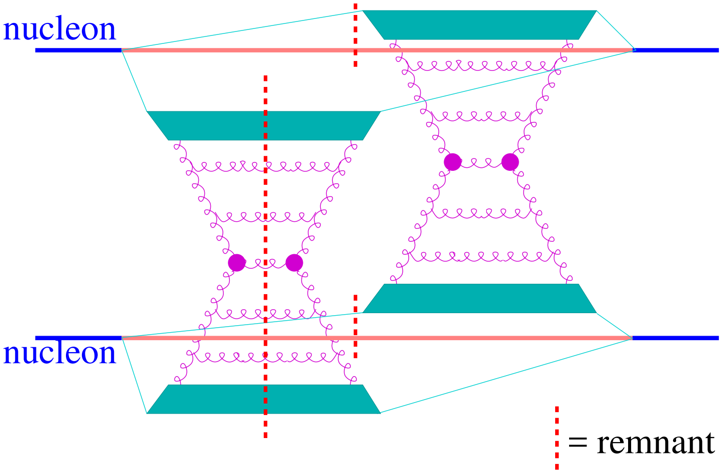
using “cutting rules” :

A “cut” multi-Pomeron diagram amounts to the sum of all possible cuts

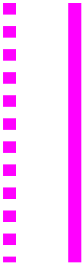
Example of two Pomerons



Using “Pomeron = parton ladder + soft”, we have (first diagram)



Using a simplified notation
for “cut” and “uncut” Pomeron



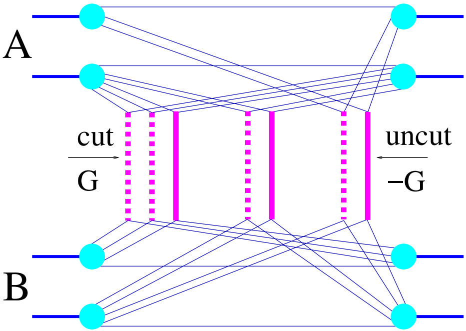
one gets ...

2.3 Complete result (strict energy conservation)

(Drescher, Hladik, Ostapchenko, Pierog, and Werner, Phys. Rept. 350, 2001)

For pp, pA, AA:

$$\sigma_{\mathrm{tot}} = \sum_{\mathrm{cut\,P}} \int \sum_{\mathrm{uncut\,P}} \int$$



partial cross section σ_K

Dotted lines : Cut Pomerons (parton ladders)

$$
\begin{aligned}
\sigma^{\mathrm{tot}} = \int d^2b \int \prod_{i=1}^{A} d^2b_i^A\, dz_i^A\, \rho_A\Big(\sqrt{(b_i^A)^2 + (z_i^A)^2}\Big) \\
\prod_{j=1}^{B} d^2b_j^B\, dz_j^B\, \rho_B\Big(\sqrt{(b_j^B)^2 + (z_j^B)^2}\Big) \\
\sum_{m_1 l_1} \ldots \sum_{m_{AB} l_{AB}} (1 - \delta_{0\Sigma m_k}) \int \prod_{k=1}^{AB} \left(\prod_{\mu=1}^{m_k} dx_{k,\mu}^{+} dx_{k,\mu}^{-} \prod_{\lambda=1}^{l_k} d\tilde{x}_{k,\lambda}^{+} d\tilde{x}_{k,\lambda}^{-} \right) \Bigg\{ \\
\prod_{k=1}^{AB} \left(\frac{1}{m_k!} \frac{1}{l_k!} \prod_{\mu=1}^{m_k} G(x_{k,\mu}^{+}, x_{k,\mu}^{-}, s, |\vec{b} + \vec{b}_{\pi(k)}^{A} - \vec{b}_{\tau(k)}^{B}|) \right. \\
\left. \prod_{\lambda=1}^{l_k} -G(\tilde{x}_{k,\lambda}^{+}, \tilde{x}_{k,\lambda}^{-}, s, |\vec{b} + \vec{b}_{\pi(k)}^{A} - \vec{b}_{\tau(k)}^{B}|) \right) \\
\prod_{i=1}^{A} \left(1 - \sum_{\pi(k)=i} x_{k,\mu,}^{+} - \sum_{\pi(k)=i} \tilde{x}_{k,\lambda}^{+} \right)^{\alpha} \prod_{j=1}^{B} \left(1 - \sum_{\tau(k)=j} x_{k,\mu}^{-} - \sum_{\tau(k)=j} \tilde{x}_{k,\lambda}^{-} \right)^{\alpha} \Bigg\}
\end{aligned}
$$

Complicated due to strict energy conservation

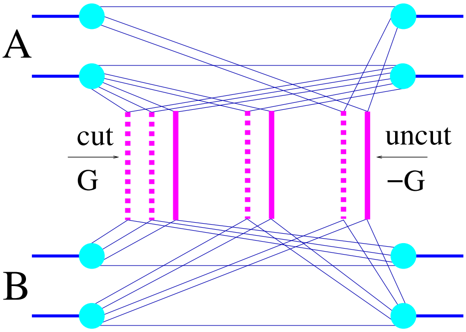
=> 10,000,000-dimensional intergrals, not separable

but doable:

- ☐ **Parameterizations for $G(x^+, x^-, s, b)$**
- ☐ **Analytical integrations**
- ☐ **Employing Markov chain techniques to generate configurations K according to multidimensional probalility distributions f(K)= $\sigma_K/\sigma_{\text{tot}}$**

σ_K :

$$\sum_{\text{uncut P}} \int$$



Dotted lines : Cut Pomerons
Full lines : Uncut Pomerons

2.4 Configurations via Markov chains

the heart of EPOS, see Phys. Rept. 350, 2001
or https://ejc2018.sciencesconf.org/data/pages/joliot.20.pdf

We construct sequences of random configurations

$$K_1\,,\; K_2\,,\;\; K_3, ...K_t\,, ...$$

such that $f_t(K_t)$ **converges towards** $f(K)$ **for** $t \to \infty$

like a physical process reaching eqilibrium

The law changes step by step ($f_t \to f_{t+1}$) :

$$f_{t+1}(K) = \sum_{K'} f_t(K')\, p(K' \to K)\,.$$

The transition probability p has to be chosen properly to assure convergence towards f

Sufficient condition: detailed balance

$$f(K')\, p(K' \to K) = f(K)\, p(K \to K')\,,$$

Metropolis:

One can prove that a $p(K \to K')$ of the form

$$w(K \to K') \times \min\left(1, \frac{f(K')}{f(K)}\frac{w(K' \to K)}{w(K \to K')}\right)$$

with any choice of w fulfills detailed balance!!

But still w needs to be chosen in an intelligent way ... even then long iterations,

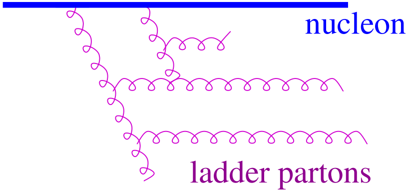
but the method allows to generate very complex configurations according to very complex laws

2.5 Parton saturation

Computing the expressions G for single Pomerons:
A cutoff Q_0 is needed (for the DGLAP integrals).

Taking Q_0 constant leads to a power law increase of cross sections vs energy (=> wrong)

because non-linear effects like gluon fusion are not taken into account



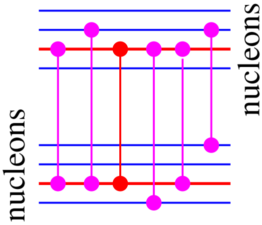
Solution: Instead of a constant Q_0, use a dynamical saturation scale for each Pomeron:

$$Q_s = Q_s(N_{\mathbb{P}}, s_{\mathbb{P}})$$

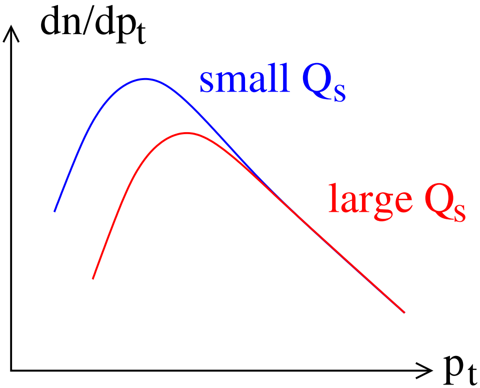
with

$N_{\mathbb{P}}$ = number of Pomerons connected to a given Pomeron (whose probability distribution depends on Q_s)

$s_{\mathbb{P}}$ = energy of considered Pomeron



Parton distributions

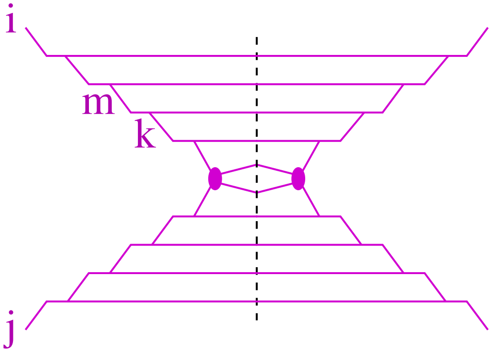


=> Increase of $\langle p_t \rangle$ with multiplicity

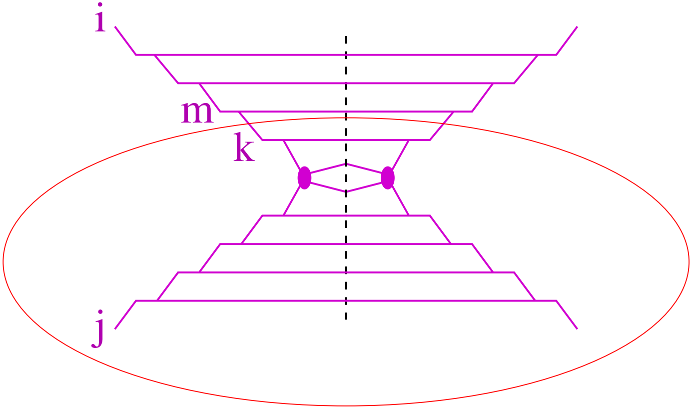
2.6 "Outside to inside" parton production

How to reconstruct the Pomerons?
(knowing the properties of the Pomeron ends)

Having the end partons i, j, how to get the intermediate ones (like m, k etc)? We iterate from outside to inside!



Actually the diagram k to j correponds to $\sigma_{\mathrm{hard}}^{kj}(\hat{s}, Q_1^2, Q_2^2)$,
already used to generate multiple scattering configurations



Probability of single emission $m \to k$:

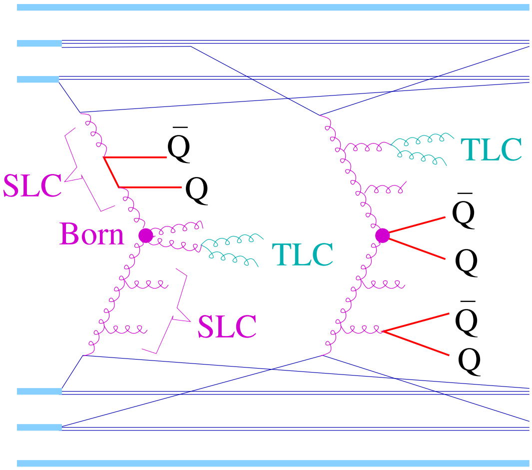
$$prob(\xi, Q^2) = d\xi \frac{dQ^2}{Q^2}\, \Delta^m(Q_1^2, Q^2)\, \frac{\alpha_s}{2\pi}\, P_m^k(\xi)\, \sigma_{\text{hard}}^{kj}(\xi\hat{s}, Q^2, Q_2^2)$$

with a given parton j on the other end.

Attention: emission on one side depends on existing parton the the other end!

=> precalculation of cross sections,
tabulations, interpolation ....

Recent: Heavy quark (Q) production in EPOS framework



as light quark production

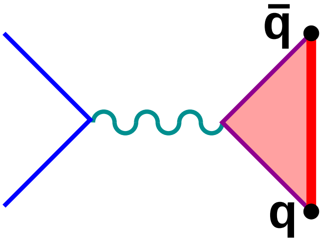
In any of the ladders

- ☐ **during SLC** (space-like cascade)
- ☐ **during TLC** (time-like cascade)
- ☐ **in Born**

but m_Q non-zero (1.3, 4.2) matrix elements, kinematics

2.7 From partons to strings

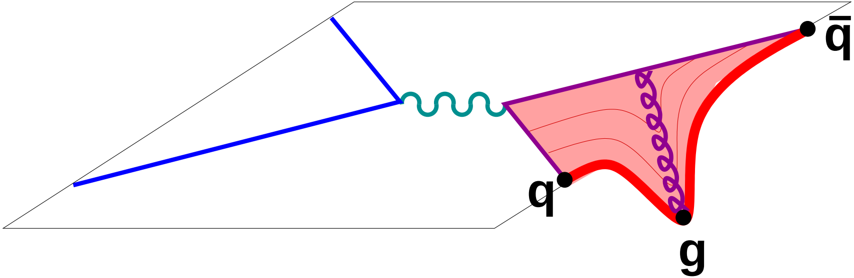
Electron-positron annihilation



Color field between two color charges
=> relativistic string

B. Andersson, G. Gustafson, G. Ingelman, and T. Sjostrand, Phys. Rep. 97 (83) 31
X. Artru, Phys. Rep. 97 (83) 147

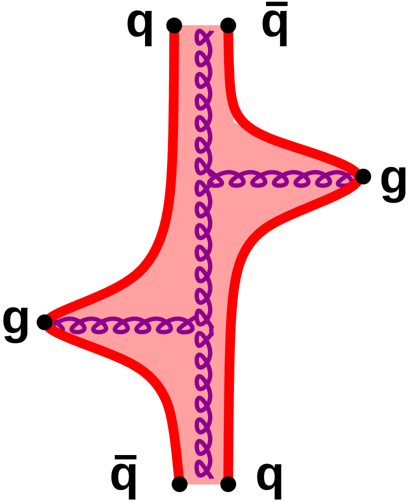
High pt gluon emission in e^+e^-



Kinky relativistic string

Cut Pomerons

(cut parton ladders)



Two kinky relativistic strings (at least)

Theoretical framework: **Classical string theory**

Nambu, Scherk, Rebbi ... 1969-1975

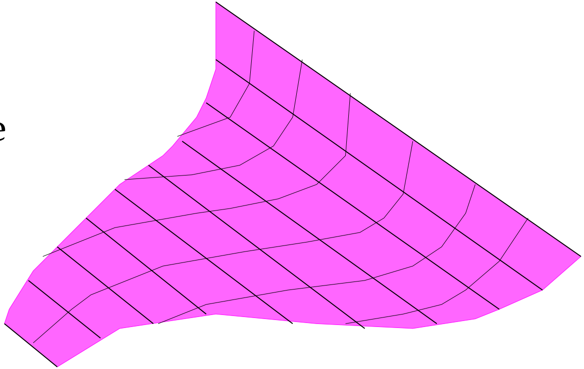
reviewed in PR 232, pp 87-299, 1993, PR 350, pp 93-289, 2001

String:

two-dimensional surface

$$x(\sigma, \tau)$$

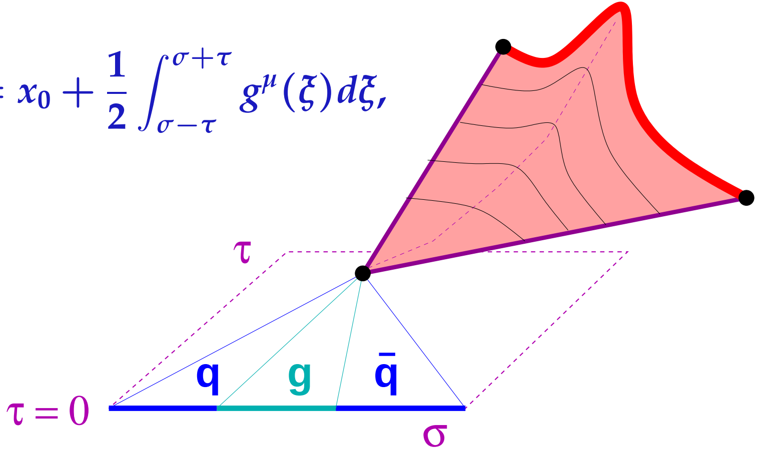
in Minkowski space



Action $S = \int L d\tau d\sigma, \quad L \propto \sqrt{|\det g|}$

String evolution

$$x^\mu(\sigma,\tau) = x_0 + \frac{1}{2}\int_{\sigma-\tau}^{\sigma+\tau} g^\mu(\xi)\,d\xi,$$

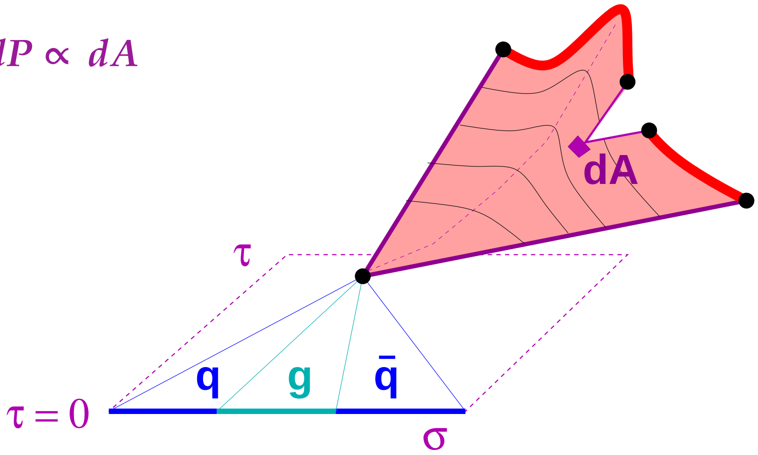


Mapping partons => string initial conditions

String decay within dA

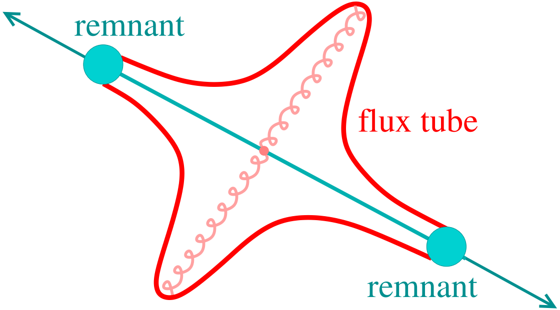
$$dP \propto dA$$

(area law)



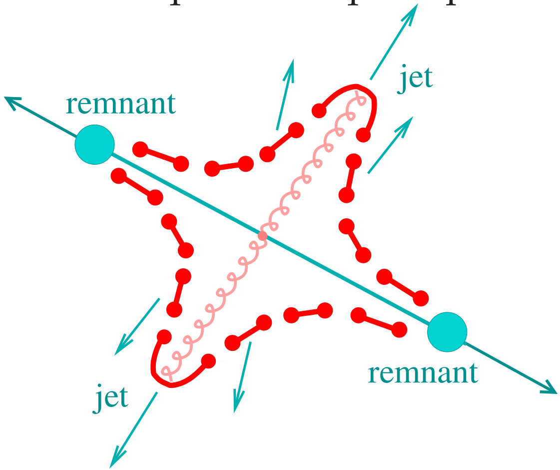
pp:

Parton ladder = color flux tubes = **2 kinky strings**



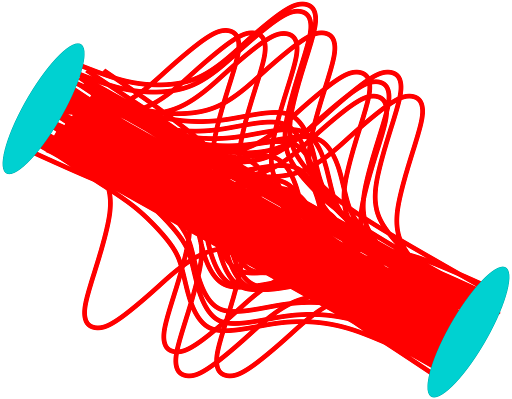
(here no IS radiation, only hard process producing two gluons)

which expand and break
via the production of quark-antiquark pairs



String segment = hadron. Close to “kink”: jets

Unless we have many color flux tubes



=> core + corona

3 Collectivity in EPOS

- □ Core-corona separation (pp,pA,AA)
- □ EPOS 3:
  - Hydrodynamic expansion of core
  - Statistical decay of fluid (Grand canonical, big systems)
- □ EPOS LHC:
  - Effective flow, droplet decay (like resonance decay, small systems)
- □ "Unification": Microcanonical decay (small and big)

3.1 Microcanonical hadronization of plasma droplets

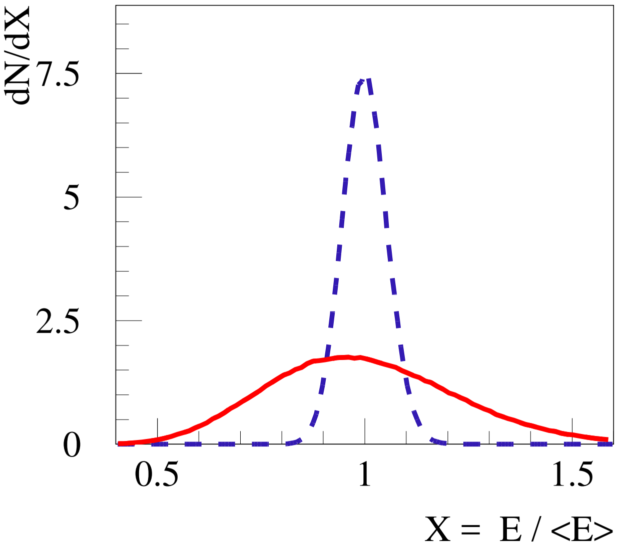
- □ **No need to match dynamical part of hydro evolution**

- □ **Energy and flavor conservation for small systems**

- □ **Needed to "unify" EPOSLHC and EPOS3**

Grand canonical decay, T = 130 MeV

V=50 fm^3; V=1000 fm^3



Microcanonic decay

of given volume in its CMS into n hadrons

$$dP = C_{\mathrm{vol}}\, C_{\mathrm{deg}}\, C_{\mathrm{ident}} \times \delta(E - \Sigma E_i)\, \delta(\Sigma \vec{p}_i) \prod_A \delta_{Q_A, \Sigma q_{A\,i}} \prod_{i=1}^{n} d^3 p_i$$

$$C_{\mathrm{vol}} = \frac{V^n}{(2\pi\hbar)^{3n}}, \quad C_{\mathrm{deg}} = \prod_{i=1}^{n} g_i, \quad C_{\mathrm{ident}} = \prod_{\alpha \in \mathcal{S}} \frac{1}{n_\alpha!}$$

(n_α is the number of particles of species α, $\mathcal{S}$ is the set of particle species)

Different from decay rate of a massive particle (using LIPS), where asymptotic states are defined over an infinitely large volume

(see Becattini et al, EPJC35:243-258,2004). **But $E_i = \sqrt{p_i^2 + m_i^2}$**

Microcanonical decay

$$dP \propto d\Phi_{\mathrm{NRPS}} = \delta(M - \Sigma E_i)\,\delta(\Sigma \vec{p}_i)\,\prod_{i=1}^{n} d^3p_i$$

- □ Hagedorn 1958 methods to compute Φ_{NRPS}
- □ Lorentz invariant phase space (LIPS) (James 1968)
- □ Hagedorn methods used for decaying QGP droplets (Werner, Aichelin, 1994, Becattini 2003)
- □ 2012 (Bignamini,Becattini,Piccinini) compute Φ_{NRPS} via the Lorentz invariant phase space (LIPS)

- **Hagedorn integral method can be made very efficient at large n (new),** but it is VERY time consuming at small n

- **LIPS method very fast for small n,** gets time consuming at large n

- **around $n \approx 30 - 40$ both methods work (=> checks)**

Hagedorn integral method

The phase-space integral:

$$\phi_{\mathrm{NRPS}}(M, m_1, \ldots, m_n)$$
$$= (4\pi)^n \int \prod_{i=1}^{n} p_i^2 \, \delta(E - \sum_{i=1}^{n} E_i) \, W(p_1, \ldots, p_n) \prod_{i=1}^{n} dp_i,$$

with the “random walk function” W (angular integral)

$$W(p_1, \ldots, p_n) := \frac{1}{(4\pi)^n} \int \delta(\sum_{i=1}^{n} p_i \times \vec{u}_i) \prod_{i=1}^{n} d\Omega_i$$

We obtain (Werner, Aichelin 94)

$$\phi(M, m_1, \ldots, m_n) = \int_0^1 dr_1 \ldots \int_0^1 dr_{n-1} \psi(r_1, ..., r_{n-1})$$

$$\psi = \frac{(4\pi)^n \, T^{n-1}}{(n-1)!} \prod_{i=1}^{n} p_i \, E_i \, W(p_1, \ldots, p_n),$$

with $z_i = r_i^{1/i}$, $x_i = z_i x_{i+1}$, $s_i = x_i T$, $t_i = s_i - s_{i-1}$,
$E_i = t_i + m_i$, $T = M - \sum_{i=1}^{n} m_i$

Suitable for MC provided *W* is known

The random walk function may be written as

$$W(p_1,\ldots,p_n)=\frac{1}{(4\pi)^n}\frac{1}{(2\pi)^3}\int\int e^{-i\vec{\lambda}\Sigma p_j\hat{p}_j}\prod_{j=1}^{n}d\Omega_j\,d^3\lambda,$$

which gives $W=\int_0^\infty F(\lambda)\,d\lambda$ with

$$F(\lambda)=\frac{1}{2\pi^2}\lambda^2\prod_{j=1}^{n}\frac{\sin p_j\lambda}{p_j\lambda}.$$

New: using the fact that for large *n*

$$\prod_{j=1}^{n}\frac{\sin p_j\lambda}{p_j\lambda}\approx\exp\left(-P^2\lambda^2\right),\quad P=\sqrt{\frac{1}{6}\sum_{j=1}^{n}p_j^2}$$

With $F_0(\lambda) = F(\lambda) \times \exp\left(P^2\lambda^2\right)$:

$$W = \int_0^\infty F(\lambda)\, d\lambda = \frac{1}{P} \int_0^\infty F_0\left(\frac{x}{P}\right) \times \exp\left(-x^2\right)\, dx$$

with F_0 being a slowly varying function of x,
which allows to use the Gauss-Hermite formula

$$W \approx \frac{1}{P} \sum_{k=1}^{K} w_j^{GH} F_0\left(\frac{x_j^{GH}}{P}\right),$$

with nodes and weights x_j^{GH} and w_j^{GH} found in text books.

With only six nodes we get excellent results.

Sampling hadron configurations $K = \{h_1, \ldots, h_n; \vec{p}_1, ...\vec{p}_n\}$ via Markov chains

We construct sequences of random configurations

$$K_1\,,\; K_2\,,\; K_3, ...K_t\,, ...$$

such that $f_t(K_t)$ converges towards $f(K)$ for $t \to \infty$

with f = microcanonical probability distribution

The law changes step by step ($f_t \to f_{t+1}$) :

$$f_{t+1}(K) = \sum_{K'} f_t(K')\, p(K' \to K)\,.$$

with $p(K \to K')$ of the form

$$\boxed{w(K \to K') \times \min\left(1,\, \frac{f(K')}{f(K)}\, \frac{w(K' \to K)}{w(K \to K')}\right)}$$

3.2 Grand canonical limit

For very large M we should recover the "grand canonical limit" for single particle spectra:

$$f_k = \frac{g_k V}{(2\pi\hbar)^3} \exp\left(-\frac{E_k}{T}\right),$$

The average energy is

$$\bar{E} = \frac{g_k V}{(2\pi\hbar)^3} \sum_k \int_0^\infty E_k \exp\left(-\frac{E_k}{T}\right) 4\pi p^2 dp$$

Changing variables via $E_k dE_k = p dp$, and using $K_1(z) = z \int_1^\infty \exp(-zx)\sqrt{x^2-1}dx$, and $3\,K_2(z) = z^2 \int_1^\infty \exp(-zx)\sqrt{x^2-1}^3 dx$,

=>

$$\bar{E} = \frac{4\pi g_k V}{(2\pi\hbar)^3} m^2 T \left(3TK_2(\frac{m}{T}) + mK_1(\frac{m}{T}) \right).$$

The microcanonical decay of an object of mass M and volume V should converge (for $M \to \infty$) to the GC single particle spectra

with T obtained from $M = \bar{E}$.

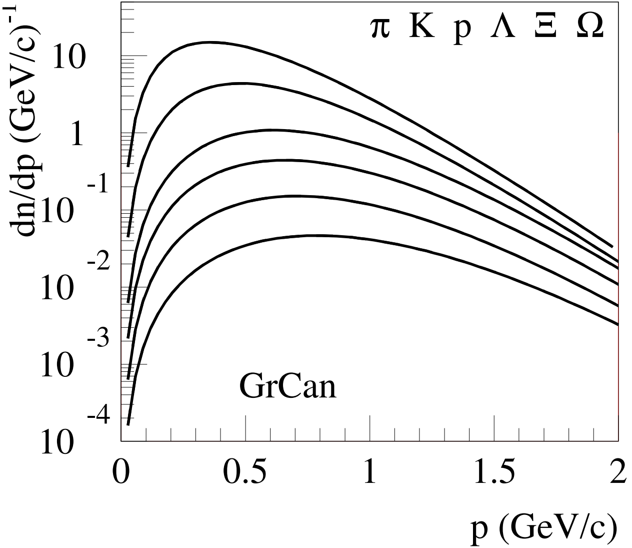
3.3 Comparing GC et MiC decay

We consider a complete (?) set of hadrons ($\approx$ 400, PDG list)

We check the effect of

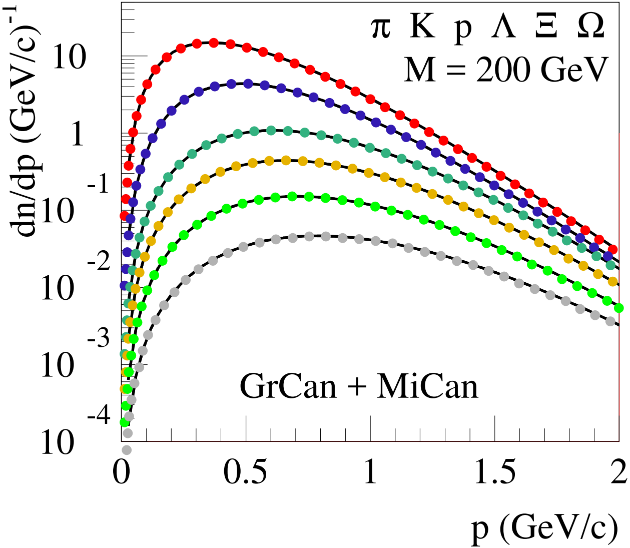
- **energy conservation**
- **flavor conservation**

GC decay, E/V= 0.333 GeV/fm^3 T=164 MeV



V=150 fm^3

GC+MiC decay, E/V= 0.333 GeV/fm^3 M=200 GeV

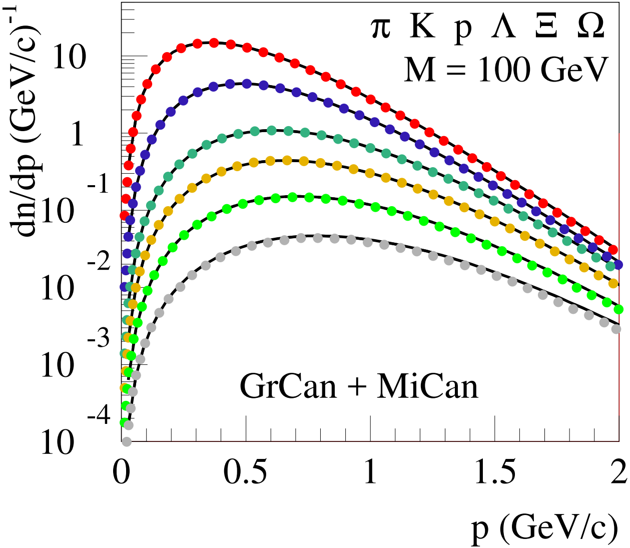


V=600 fm^3

$\times \frac{1}{4}$

good test for
Metropolis proposal

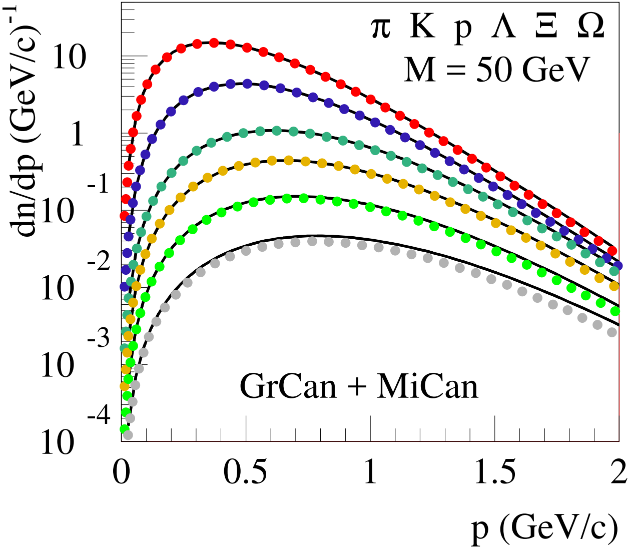
GC+MiC decay, E/V= 0.333 GeV/fm^3 M=100 GeV



V=300 fm^3

$\times \frac{1}{2}$

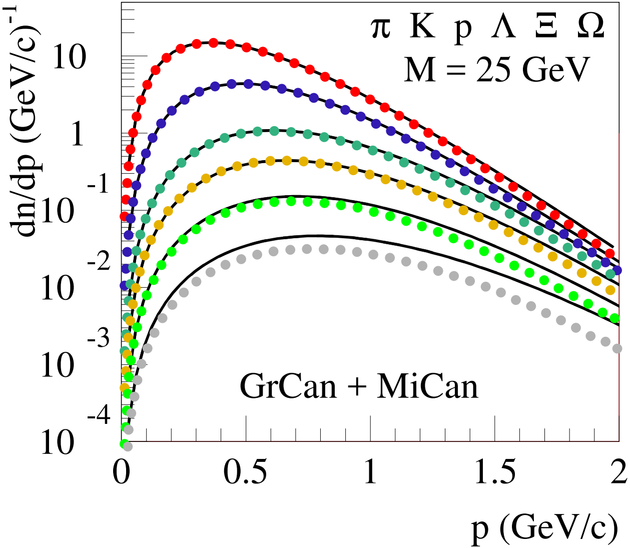
GC+MiC decay, E/V= 0.333 GeV/fm^3 M=50 GeV



V=150 fm^3

$\times 1$

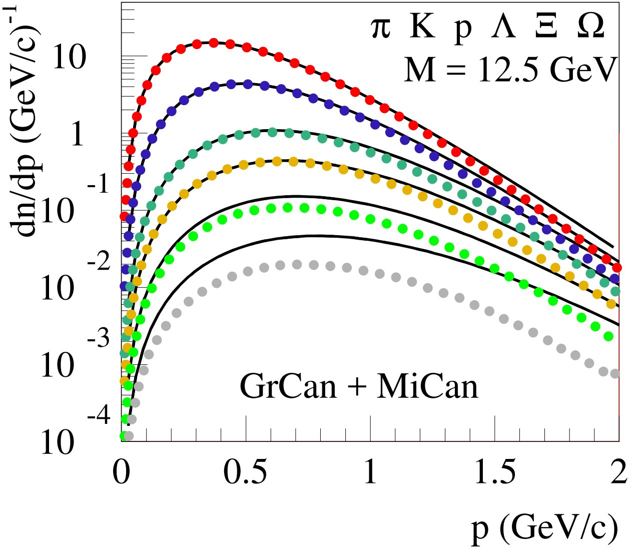
GC+MiC decay, E/V= 0.333 GeV/fm^3 M=25 GeV



V=75 fm^3

$\times 2$

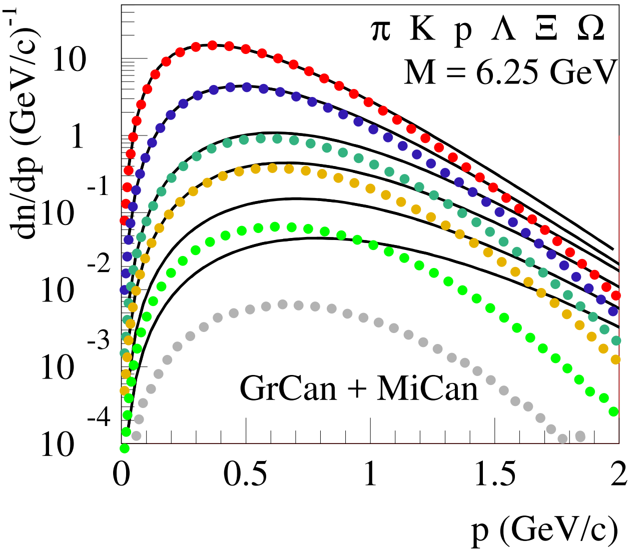
GC+MiC decay, E/V= 0.333 GeV/fm^3 M=12.5 GeV



V=37.5 fm^3

$\times 4$

GC+MiC decay, E/V= 0.333 GeV/fm^3 M=6.25 GeV

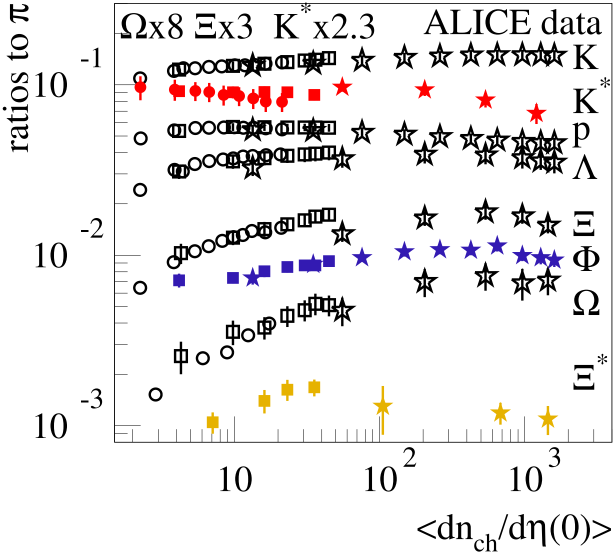


V=18.75 fm^3

×8

3.4 Particle ratios to pions

vs $\left\langle \frac{dn_{ch}}{d\eta}(0) \right\rangle$



circles = pp (7TeV)

squares = pPb (5TeV)

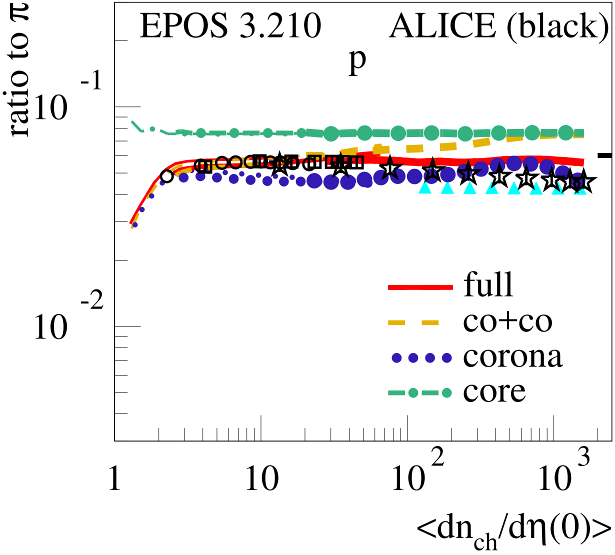
stars = PbPb (2.76TeV)

Data partly collected by A. G. Knospe

Refs:

<dNch/deta> in Pb+Pb: Phys. Rev. Lett. 106 032301 (2011)
pi+-, K+-, and (anti)protons in Pb+Pb: Phys. Rev. C 88 044910 (2013)
Lambda in Pb+Pb: Phys. Rev. Lett. 111 222301 (2013)
Xi- and Omega in p+Pb: Phys. Lett. B 758 389-401 (2016)
pi+-, K+-, (anti)protons, and Lambda in p+Pb: Phys. Lett. B 728 25-38 (2014)
<dNch/deta> in p+Pb: Eur. Phys. J. C 76 245 (2016)
Xi- and Omega in p+Pb: Phys. Lett. B 758 389-401 (2016)
<dNch/deta> in p+p 7 TeV: Eur. Phys. J. C 68 345-354 (2010)
pi+-, K+-, and (anti)protons in p+p 7 TeV: Eur. Phys. J. C 75 226 (2015)
Xi- and Omega in p+p 7 TeV: Phys. Lett. B 712 309 (2012)
and data points from Rafael Derradi de Souza, SQM2016

Proton to pion ratio (sofar GC)

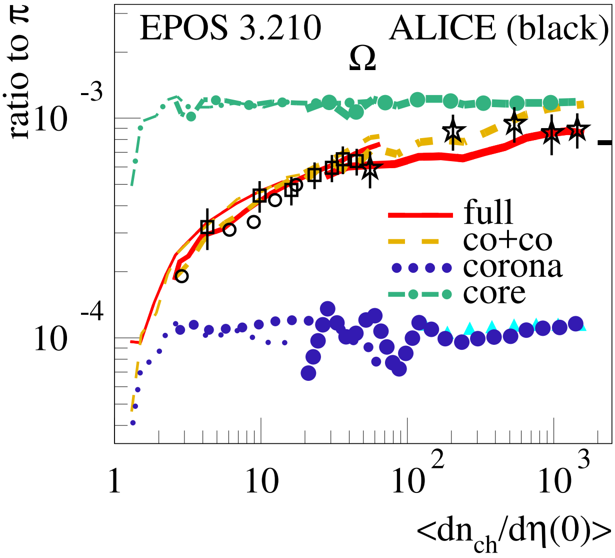


core hadronization:
$T = 164\,\mathrm{MeV},\ \mu_B = 0$

statistical model fit
(horizontal black line)
A. Andronic et al.,
arXiv:1611.01347
$T = 156.5\,\mathrm{MeV}, \mu_B = 0.7\,\mathrm{MeV}$

thick lines = pp (7TeV)
thin lines = pPb (5TeV)
circles = pp (7TeV)
squares = pPb (5TeV)
stars = PbPb (2.76TeV)

Omega to pion ratio (GC)



thick lines = pp (7TeV)
thin lines = pPb (5TeV)

circles = pp (7TeV)
squares = pPb (5TeV)
stars = PbPb (2.76TeV)

4 EPOS Summary

- ☐ Based on “semihard Pomerons” (parton ladders)
- ☐ Multiple scattering via Gribov-Regge approach, employing cutting rules
- ☐ Realizing configurations via Markov chains
- ☐ Consistent “outside to inside” parton production
- ☐ “Natural” parton-string mapping
- ☐ Core-corona separation, hydrodynamic expansion of core (=> flow)
- ☐ Statistical hadronization (new: microcanonical)