EPOS4 - An overview

A MC tool for high-energy scatterings (AA, pp, ...)

☐ Released very recently

https://klaus.pages.in2p3.fr/epos4/

thanks Laurent Aphecetche for explaining gitlab pages, nextjs etc
thanks Damien Vintache for managing installation/technical issues

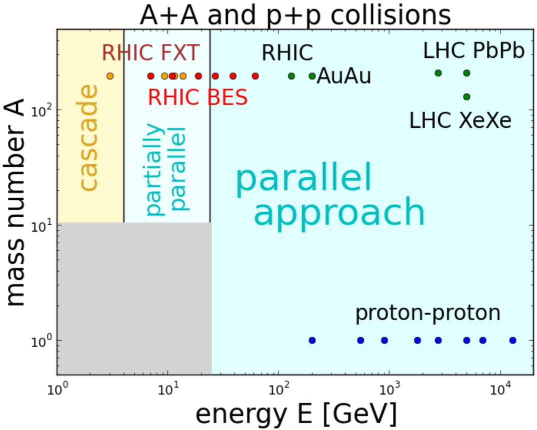
☐ **a full general purpose approach, public, and testable**

☐ **tested (by myself) for 4 GeV - 13000 GeV,**
pp to PbPb, light / heavy flavor, collective / hard

☐ **Papers:**

- **https://arxiv.org/pdf/2301.12517.pdf NEW**
- **more coming soon**

Parallel vs sequential scattering (primary interactions)



Points (besides FXT): Epos comparisons to data

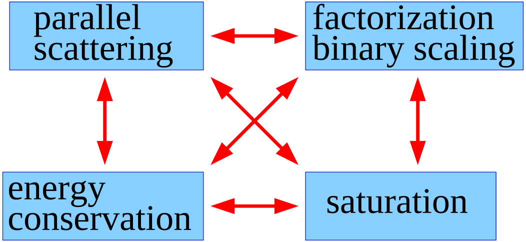
From very elementary time scale arguments: parallel scheme needed everywhere beyond 25 AGeV, partly beyond 4AGeV

New insight into pp and AA scattering

☐ **We MUST implement parallel scattering**

☐ **Appropriate tool: S-matrix theory**

We reveal a deep connection between four crucial concepts



missing out one spoils the whole picture

In EPOS<4, we could never accommodate all of them

Factorization / binary scaling is not “assumed”, it must come out!

EPOS S-matrix approach:

Parallel "Pomerons" structure of T for pp (T = elastic $^{*)}$) **:**

$$iT = \int_{\mathbf{momenta}} \sum_k \frac{1}{k!} V \times \{iT_{\mathrm{Pom}} \times ... \times iT_{\mathrm{Pom}}\} \times V$$

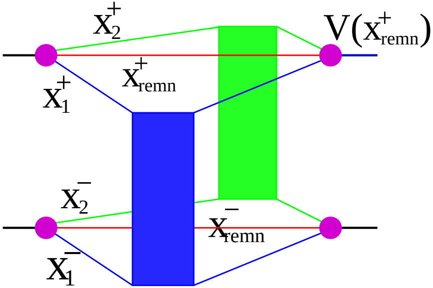
with V representing connection to projectile / target remnant

Energy-momentum conservation

$x_i^{\pm}$ light-cone momentum fractions

$$x^{\pm}_{\mathbf{remn}} = 1 - \sum x_i^{\pm}$$

the boxes contain ... whatever
in our case: parton ladders, i.e.
all the pQCD part



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

$^{*)}$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)

Generalisation for pA and AA: trivial *)

Just a product of pp expressions:

$$iT = \int_{\text{momenta}} \prod_{i=1}^{A} V \prod_{n=1}^{AB} \left\{ \sum_{k} \frac{1}{k!} \{ iT_{\text{Pom}} \times \ldots \times iT_{\text{Pom}} \} \right\} \prod_{j=1}^{B} V$$

which does NOT mean at all superposition of pp collisions!

Completely parallel!

No collision sequence!

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*) conceptually trivial ... but we have 10 000 000 dimensional non-separable integrals

For inelastic scattering (“optical theorem” in b-representation**)**

$$\sigma_{\mathbf{tot}} = \int d^2b\, \mathbf{cut}\, T \quad (\mathbf{cut}\, T = \frac{\mathbf{1}}{\mathbf{i}}\mathbf{disc}\, T = \text{"cut diagram"})$$

so we need to compute the “cut” of the complete diagram, i.e. for pp:

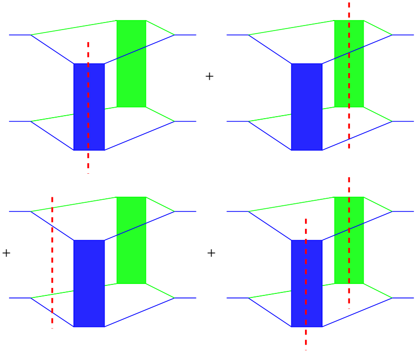
$$\mathbf{cut}\,\{V \times iT_{\mathbf{Pom}} \times ... \times iT_{\mathbf{Pom}} \times V\}$$

and a “cut” multi-Pomeron diagram = sum of all possible cuts

gives a sum of positive and negative terms (which we sum up)

-> interference, cancellations!

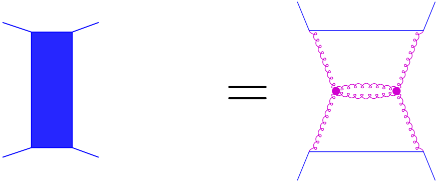
Absolutely crucial!!!



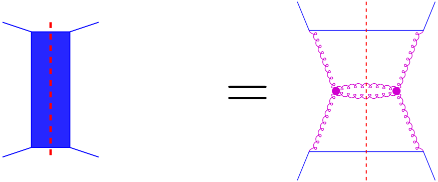
remnants not plotted

Simple example

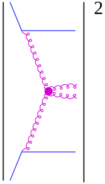
Uncut diagram:



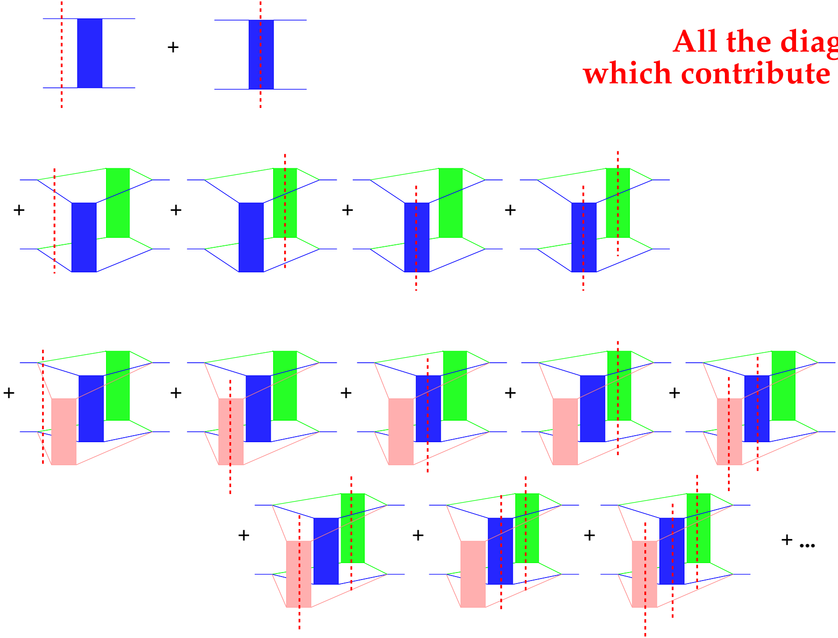
Cut diagram:



corresponds to:

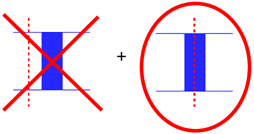


All the diagrams which contribute to pp



Ignoring energy sharing:

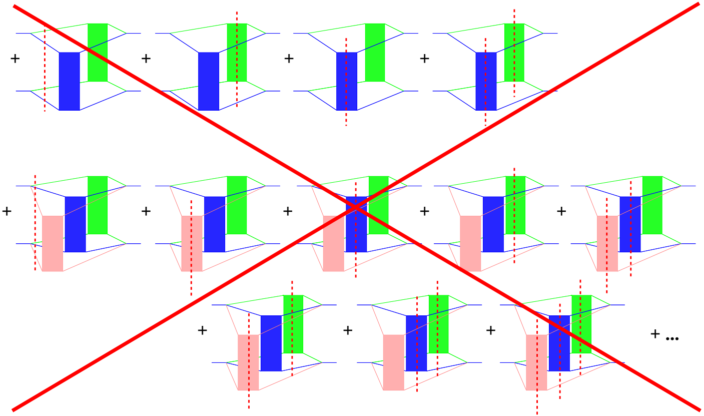
For inclusive cross sections everything cancels - up to one diagram



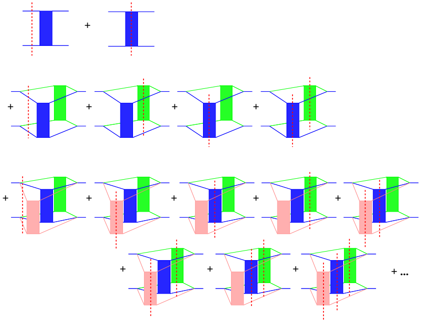
=> factorization ... ALWAYS, soft & hard

WRONG ... better keep energy sharing

which makes things complicated!!



The difficulty is



- ☐ **to keep all diagrams**
- ☐ **make sure that they cancel where they should do so:** for inclusive cross sections, for "hard probes"
- ☐ **make sure that energy conservation does not spoil factorization in that case** (like in EPOS LHC)

To achieve this

- ☐ **precision concerning the pQCD calculations**
- ☐ **good strategy to implement saturation** to cure the factorization issues spoiled by energy conservation

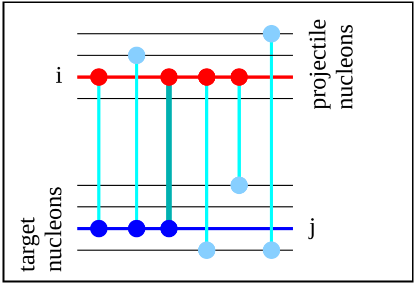
For a given Pomeron, connecting projectile nucleon i and target nucleon j

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



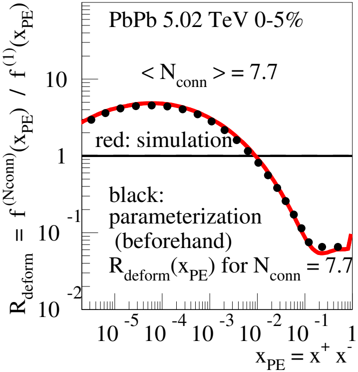
The x_{PE} (Pomeron energy squared) **distribution for $N_{\mathrm{conn}} > 1$ will be "deformed" wrt the case $N_{\mathrm{conn}} = 1$**

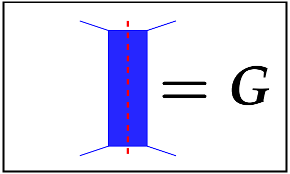
$$R_{\mathrm{deform}} = f^{(N_{\mathrm{conn}})} \;/\; f^{(1)} \quad \neq \quad 1$$

But we are able to parameterize the "deformation" beforehand(!)

(iterative process, converges fast)

for all systems, all centrality classes





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)

For each cut Pomeron, for given $x^\pm$, s, and b, and for a given functional dependence $G_{\mathrm{QCD}}(Q^2, x^+, x^-, s, b)$

with G_{QCD} = DGLAP parton ladder, with Q^2 being the low virtuality cutoff

we postulate:

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

with Q^2_{sat} depending on x^+, x^- and N_{conn}

(f is a normalization depending linearly on N_{conn})

which assures factorization and binary scaling, for hard processes!

For large N_{conn}, low pt is suppressed, the Pomeron gets "hard".

How the different "concepts" affect factorization – in terms of R_{AA} – in our "parallel scattering scenario"

energy conservation	dynamical saturation	resulting R_{AA} vs pt
No	No	1 everywhere ☹
Yes	No	< 1 everywhere ☹
Yes	Yes	< 1 at small pt 1 at large pt ☺

The approximate so-called N_{part} scaling at low pt in AA scattering,

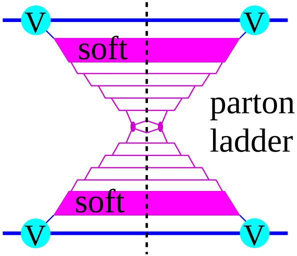
$$\text{Multiplicity} \propto N_{\text{part}}$$

is in reality simply screening (saturation) of binary scatterings

$$\text{Multiplicity} \propto N_{\text{coll}} \times f_{\text{screen}}(N_{\text{coll}})$$

EPOS4 factorization mode (1 Pom) and EPOS4 PDFs

Based on cut single Pomeron diagrams (composed of soft parts + parton ladder),



we may compute (and tabulate) PDFs, corresponding to half of the diagram

including Pomeron-nucleon coupling,

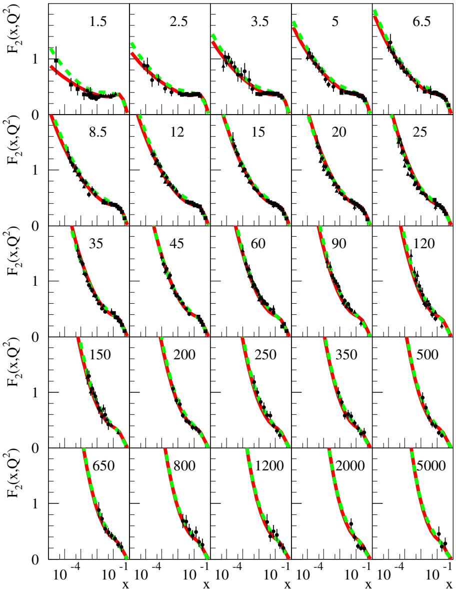
excuding the Born process

and then express the di-jet cross sections in terms of the PDFs

$$E_3E_4\frac{d^6\sigma_{\mathrm{dijet}}}{d^3p_3d^3p_4} = \sum_{kl}\int\!\!\int dx_1dx_2\, f^k_{\mathrm{PDF}}(x_1,\mu_{\mathrm{F}}^2)\, f^l_{\mathrm{PDF}}(x_2,\mu_{\mathrm{F}}^2)$$

$$\frac{1}{32s\pi^2}\bar{\sum}|\mathcal{M}^{kl\to mn}|^2\delta^4(p_1+p_2-p_3-p_4)$$

Electron-proton scattering F_2 vs x



To check our f_{PDF}, we can compute

$$F_2 = \sum_k e_k^2 \, x \, f_{\mathrm{PDF}}^k(x, Q^2)$$

with

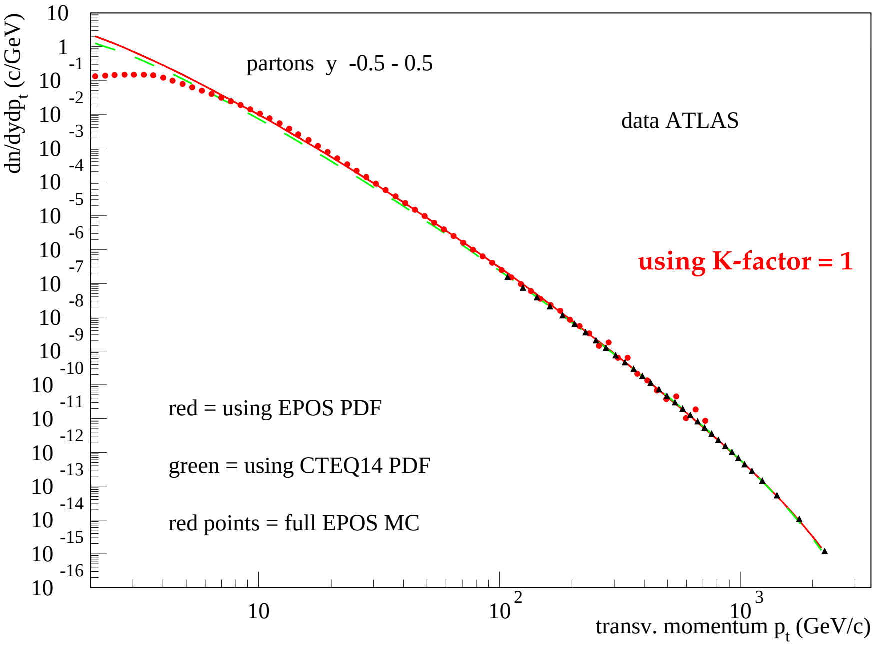
$$x = x_B = \frac{Q^2}{2pq}$$

in the EPOS framework,

and compare with data from ZEUS, H1

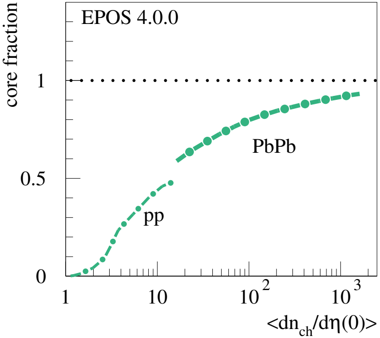
and with calculations based on CTEQ14(5f)

Jet cross section vs pt for pp at 13 TeV



Full EPOS4, core + corona, hydro, microcanonical decay: checking multiplicity dependencies

Core fraction



Core: microcanonical

NEW FO concept
NEW numerical methods
used for pp and AA

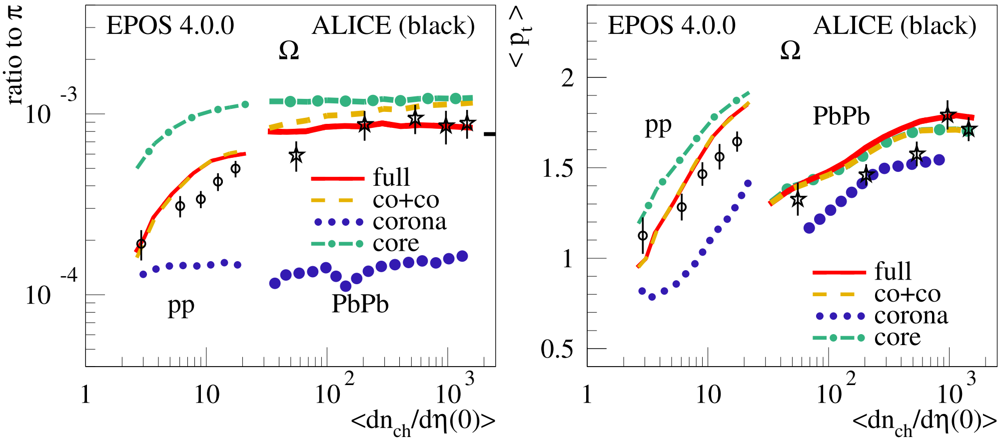
Microcanonical core alone does not work!

Check in the following

- ☐ **hadron to pion ratios**
- ☐ **mean pt**

versus multiplicity
in core-corona approach

continuous curve **jump**



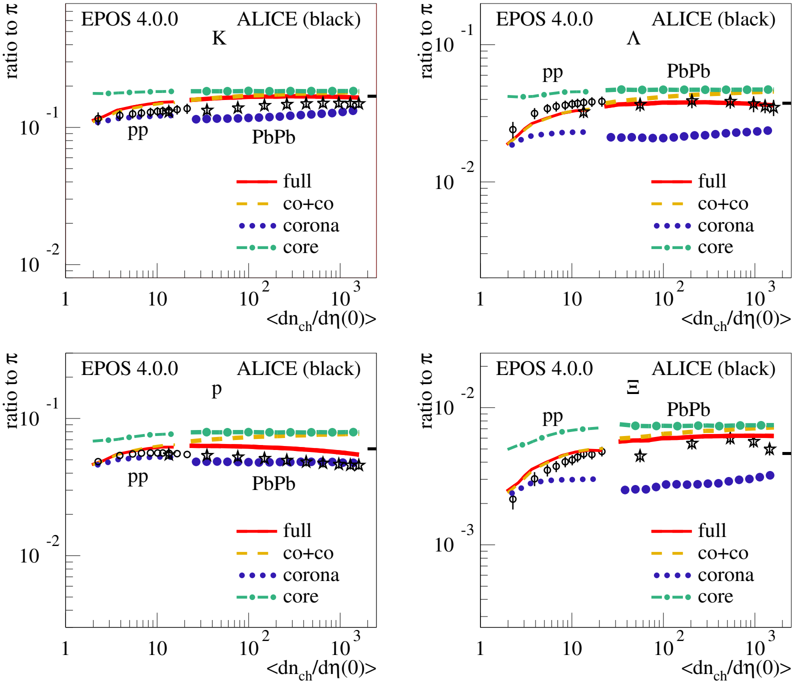
core-corona effect

+ microcanonical effect

core-corona effect

saturation effect

+ flow effect


EPOS 4.0.0
ALICE (black)
K
pp
PbPb
full
co+co
corona
core
ratio to π
10^{-1}
10^{-2}
1
10
10^2
10^3
$<dn_{ch}/d\eta(0)>$
EPOS 4.0.0
ALICE (black)
Λ
pp
PbPb
full
co+co
corona
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ratio to π
10^{-1}
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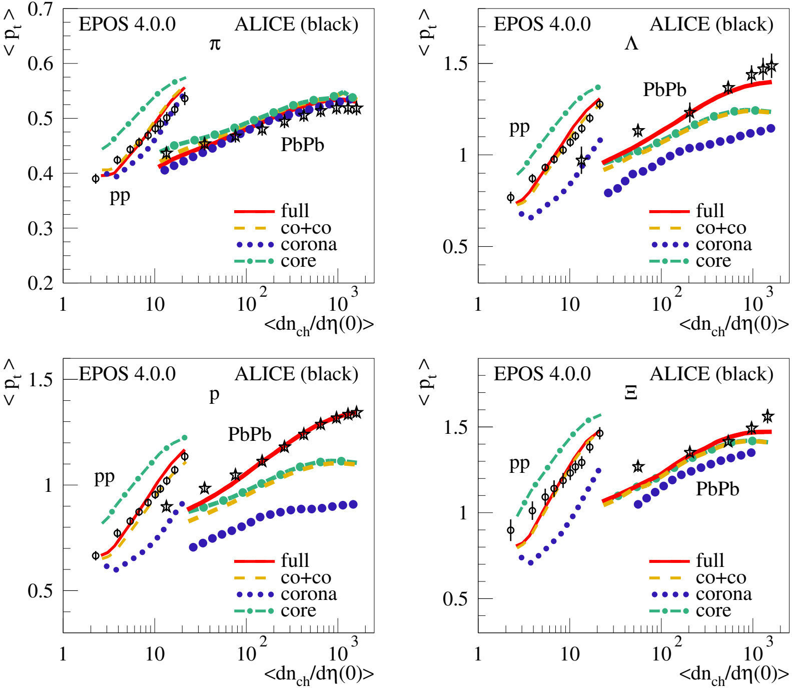
EPOS 4.0.0
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0.6
0.7
0.5
1
1.5
1
10
10^2
10^3

Crucial in all cases

☐ **core-corona**

☐ **saturation**

☐ **flow**

☐ **(mirocanonical)**

Multiplicity dependence of charm production

saturation and flow effect

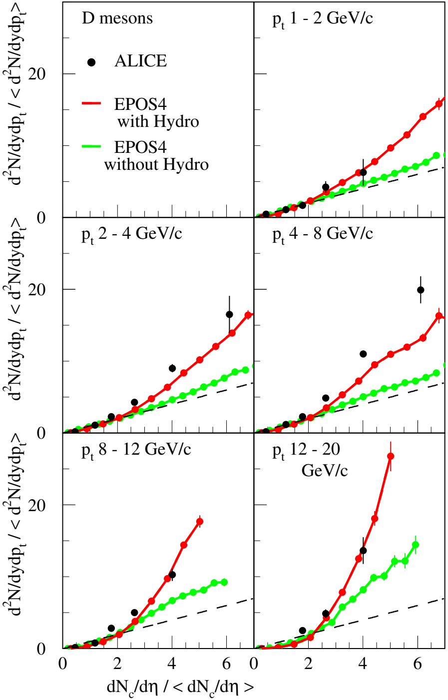
pp 7TeV

Self-normalized *D* meson multiplicity

for different transverse momentum ranges

versus self-normalized charged particle multiplity,

compared to ALICE data

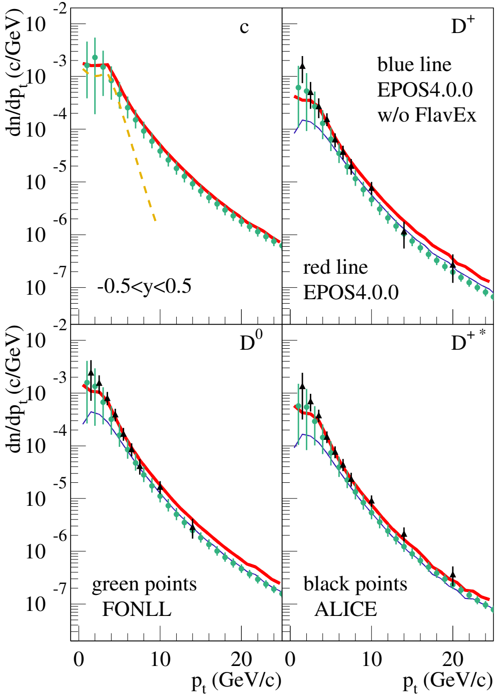


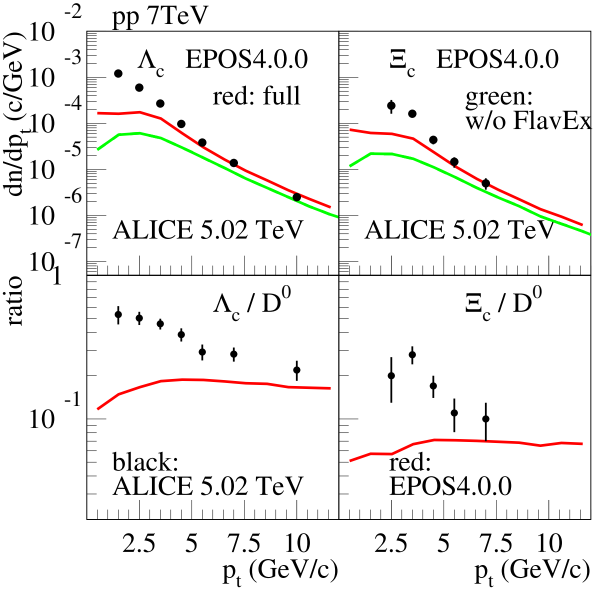
Charmed hadrons

pp 7TeV
charmed final partons
and mesons

EPOS4 simulations
w/o hydro,

compared to ALICE data
and FONLL





pp 7TeV

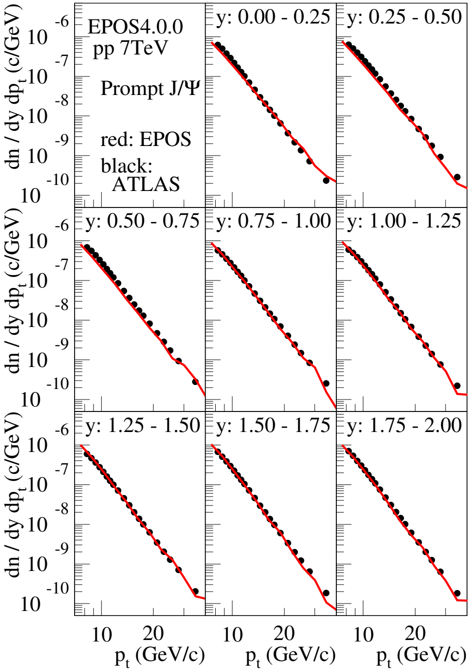
charmed baryons

Λ_c and Ξ_c

EPOS4 simulations w/o hydro,

compared to ALICE data (at 5.02 TeV).

Deficit at low pt ... thermal?

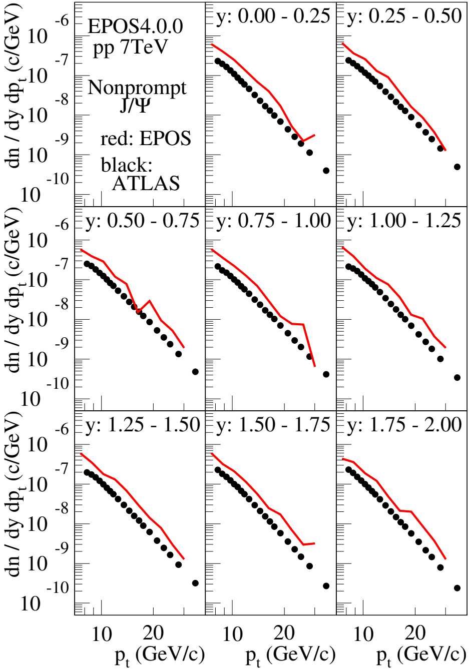


pp 7TeV

Prompt J/Ψ

compared to ATLAS

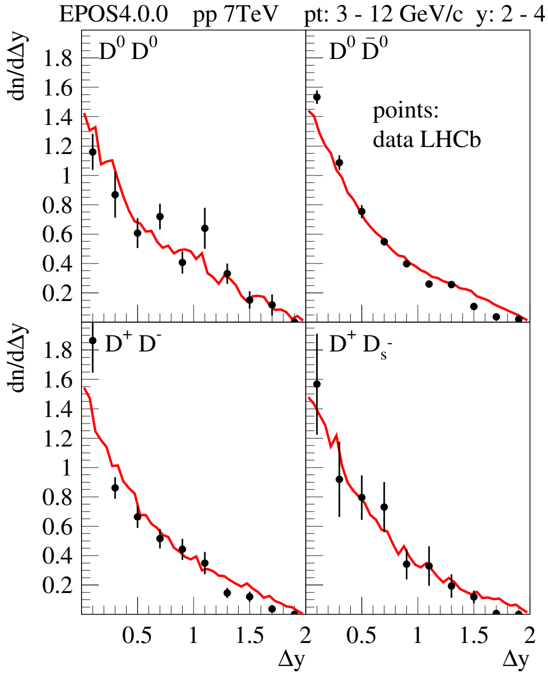
EPOS J/Ψ production:
Color Evaporation Model



pp 7TeV
Nonprompt J/Ψ

compared to ATLAS

strange: *B* spectra are very good



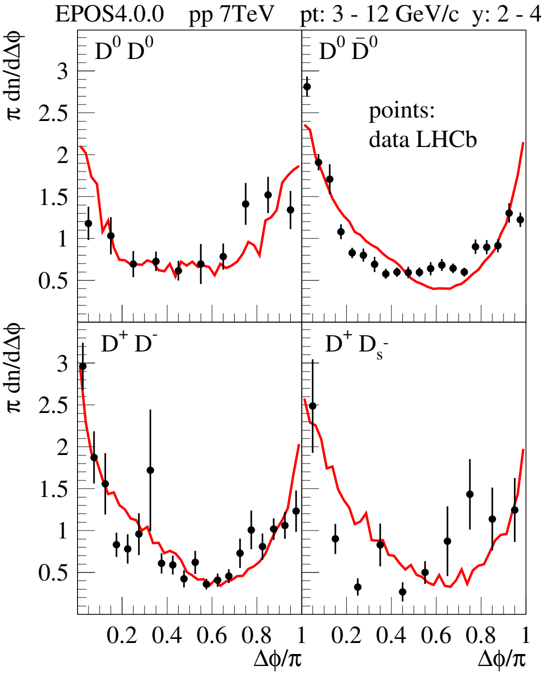
pp 7TeV

Two hadron correlations

$D^0 D^0$
$D^0 \bar{D}^0$
$D^+ D^-$
$D^+ D_s^-$

as a function of Δy

compared to LHCb



pp 7TeV

Two hadron correlations

$D^0 D^0$
$D^0 \bar{D}^0$
$D^+ D^-$
$D^+ D_s^-$

as a function of $\Delta\phi$

compared to LHCb

To summarize: The EPOS4 project

allows (for the first time!) to accommodate simultaneously

Energy conservation + Parallel scattering + factOrization + Saturation

Now we can do in one single (“general purpose”**) approach**

- ☐ **“normal” pp physics (high pt jets etc)**
  (where factorization comes into play)
- ☐ **high multiplicity pp events**
  (where saturation plays a crucial role)