EPOS4

A full general purpose event generator to do multi-observable analysis

Aim of the EPOS4 project

- ☐ **NOT provide "another hydro model" to get v2 in pp**
- ☐ **BUT a full pp event generator to do normal pp physics** (total cross section, light flavor spectra, jets, charm,...)
- ☐ **which in addition accounts for collective effects in small systems**
- ☐ **and which in addition can handle nuclear scatterings**

To check if we get a consistent overall picture?

- 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:**

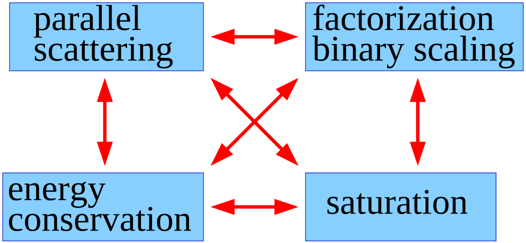
  – **https://arxiv.org/pdf/2301.12517.pdf NEW**

  – **more coming soon**

Primary pp and AA scattering

- **Much more complex than simple factorization formula**

Deep connection between four crucial concepts



missing out one spoils the whole picture

Factorization / binary scaling is not assumed,
it is a constraint, which affects saturation!

EPOS S-matrix approach (for parallel scatterings!!!)

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

$$iT = \int_{\text{momenta}} \sum_k \frac{1}{k!} V \times \{iT_{\text{Pom}} \times \ldots \times iT_{\text{Pom}}\} \times V$$

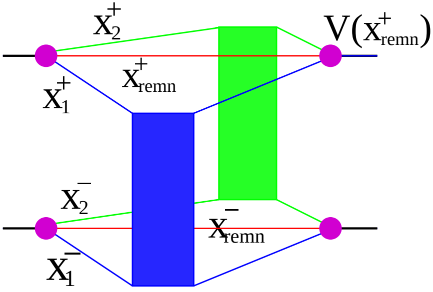
with V representing connection to projectile / target remnant

Energy-momentum conservation

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

$$x_{\text{remn}}^{\pm} = 1 - \sum x_i^{\pm}$$

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



$^{*)}$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:

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

which does NOT mean at all superposition of pp collisions!

Completely parallel!

No collision sequence!

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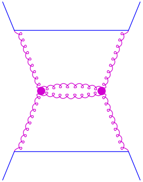
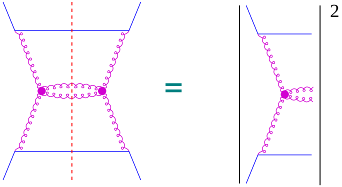
*) conceptually trivial ... but we have 10 000 000 dimensional non-separable integrals

Crucial : cut and uncut diagrams

Simple example of a uncut diagram
(a normal diagram)



Corresponding cut diagram



connects the elastic amplitude
to the squared inelastic amplitude

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:

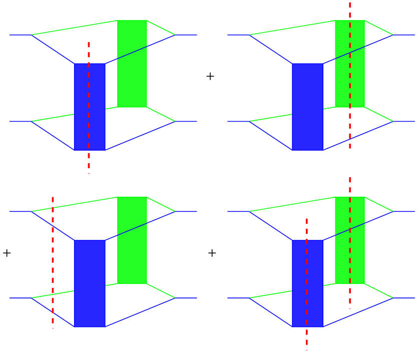
$$\mathbf{cut}\,\{V \times iT_{\mathbf{Pom}} \times ... \times iT_{\mathbf{Pom}} \times V\}$$

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!

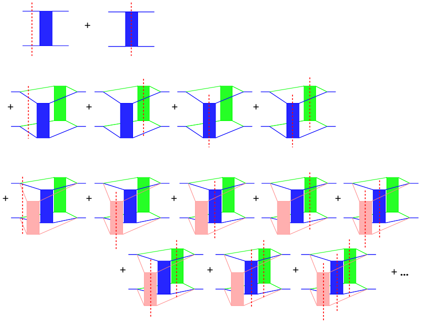
Absolutely crucial!!!



remnants not plotted

Many contributions!

Factorization for σ_{incl} means:
Only one contribution.
Not correct for soft part



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)

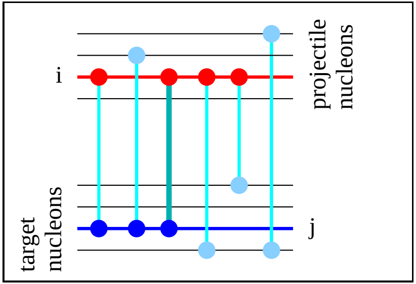
To achieve this

- □ **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



Crucial variable: the Pomeron's squared CMS energy fraction

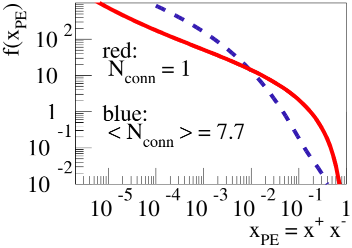
$$x_{\mathrm{PE}} = x^{+}x^{-} \approx s_{\mathrm{Pom}} / s_{\mathrm{tot}}$$

x_{PE}-distribution $f(x_{\mathrm{PE}})$ determines p_t distributions of partons

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

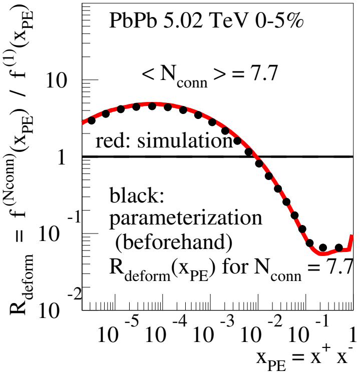
**Large N_{conn} => large x_{PE} suppressed
small x_{PE} enhanced**

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



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

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

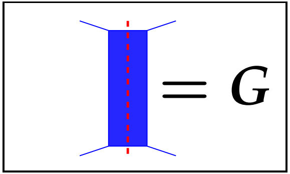


We are able to parameterize the "deformation" beforehand(!)
(iterative process, converges fast)
for all systems, all centrality classes

So R_{deform} can be considered to be known, it is tabulated.

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)



We compute and tabulate $G_{QCD}(Q^2, x^+, x^-, s, b)$, DGLAP parton ladder, with low virtuality cutoff Q^2 (=> G_{QCD} accessible via interpolation)

For each cut Pomeron, for given $x^\pm$, s, and b, we postulate:

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

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".

Multi-observable analysis

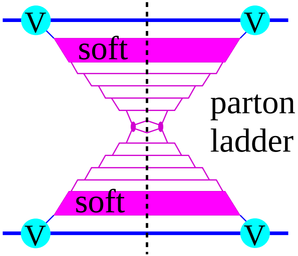
- **"Normal" pp physics**
- **High multiplicity phenomena**

Is the overall picture correct?

In our field there is not "the one key observable" for each physics phenomenon

EPOS4 factorization mode (1 Pom) and EPOS4 PDFs

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



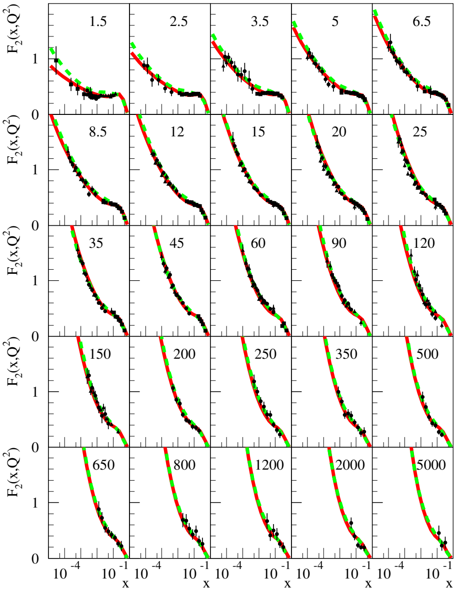
we may compute (and tabulate) PDFs, corresponding to half of the diagram
including Pomeron-nucleon coupling,
excuding the Born process

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

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

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

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

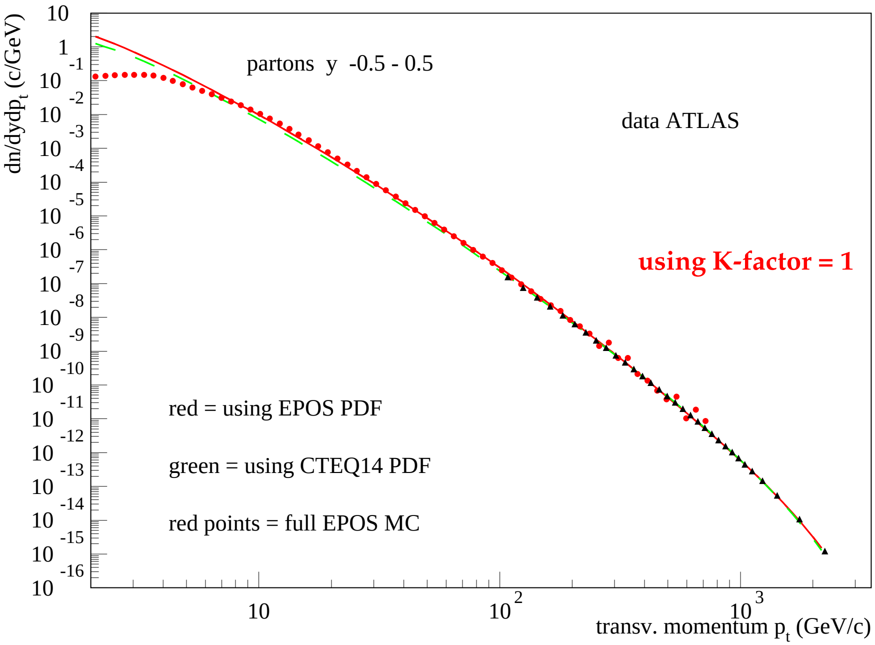
$$x = x_B = \frac{Q^2}{2pq}$$

in the EPOS framework,

and compare with data from ZEUS, H1

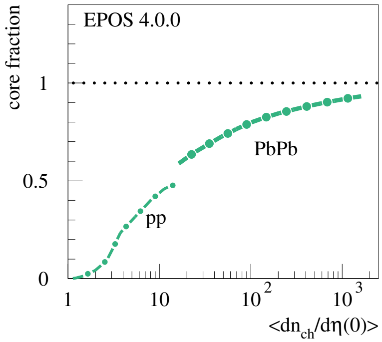
and with calculations based on CTEQ14(5f)

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

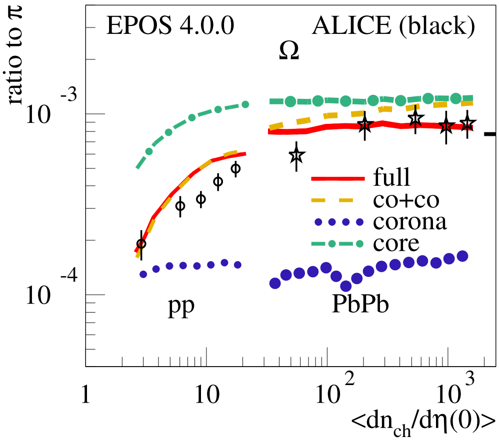
Microcanonical core alone does not work!

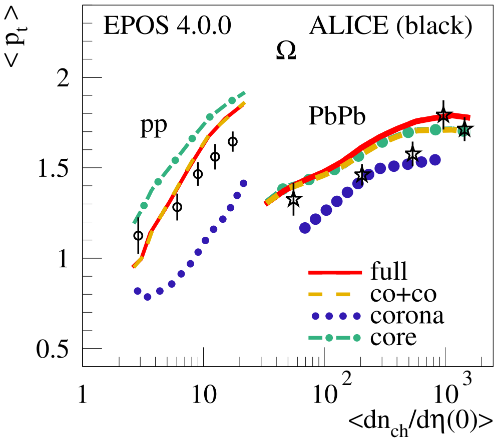
Check in the following

- ☐ hadron to pion ratios
- ☐ mean pt

versus multiplicity in core-corona approach

continuous curve **jump**





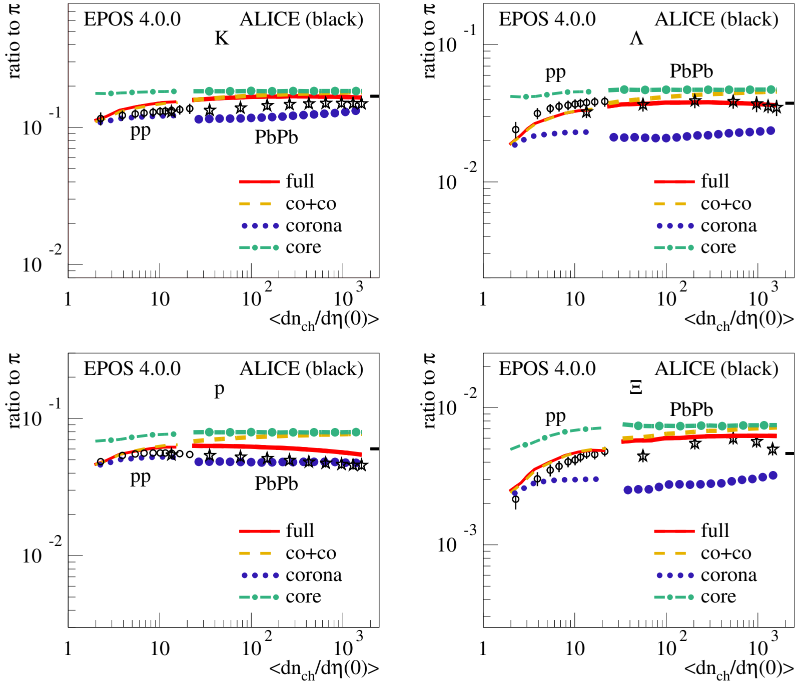
core-corona effect

+ 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
<dn_ch/dη(0)>
Λ
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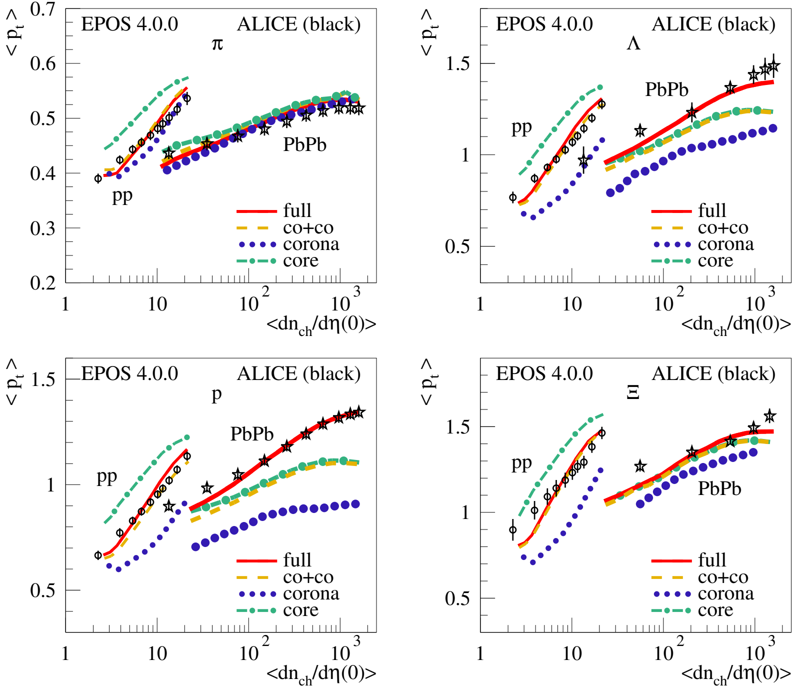
EPOS 4.0.0
ALICE (black)
π
pp
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Multiplicity dependence of charm production

saturation and flow effect

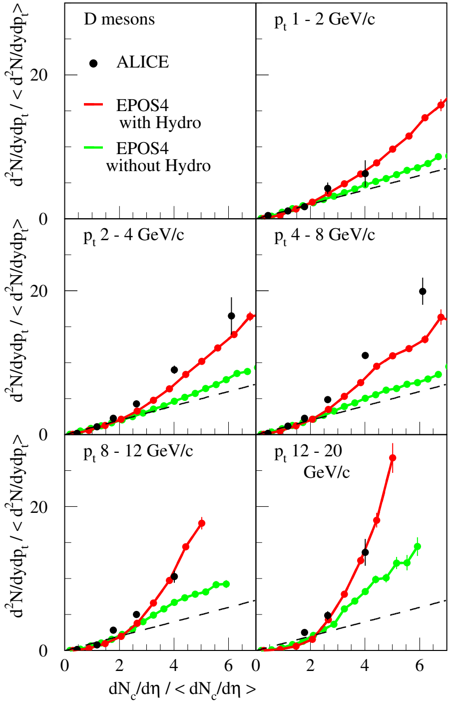
pp 7TeV

Self-normalized *D* meson multiplicity

for different transverse momentum ranges

versus self-normalized charged particle multiplity,

compared to ALICE data

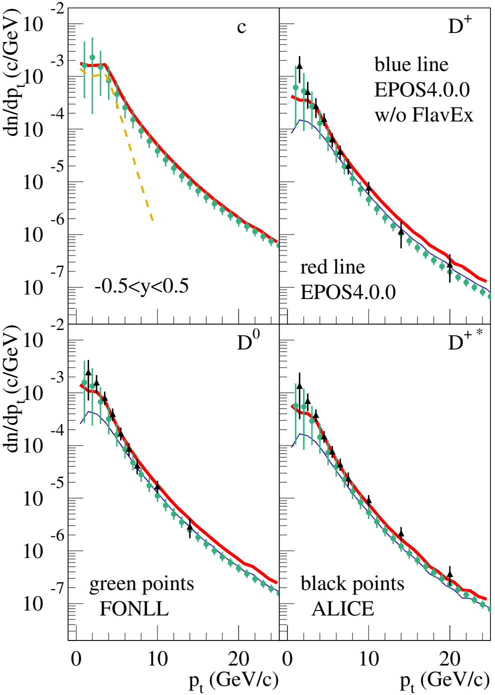


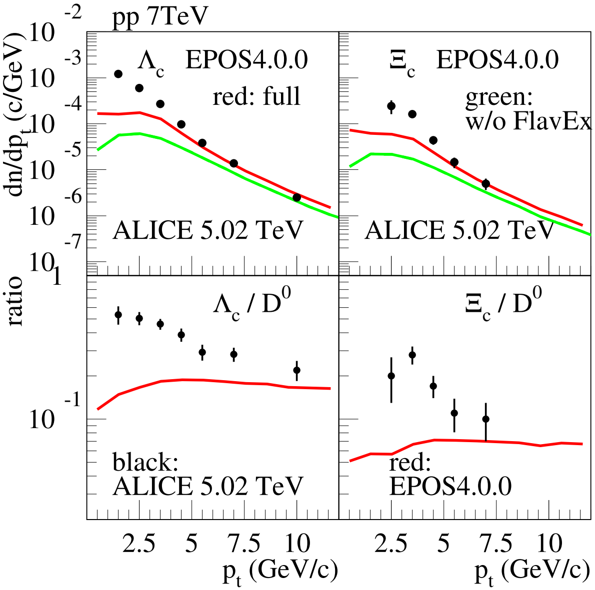
Charmed hadrons

pp 7TeV
charmed final partons and mesons

EPOS4 simulations w/o hydro,

compared to ALICE data and FONLL





pp 7TeV

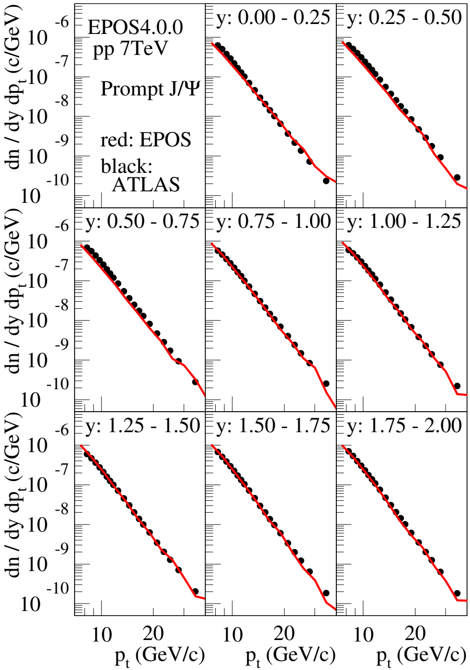
charmed baryons

Λ_c and Ξ_c

EPOS4 simulations w/o hydro,

compared to ALICE data (at 5.02 TeV).

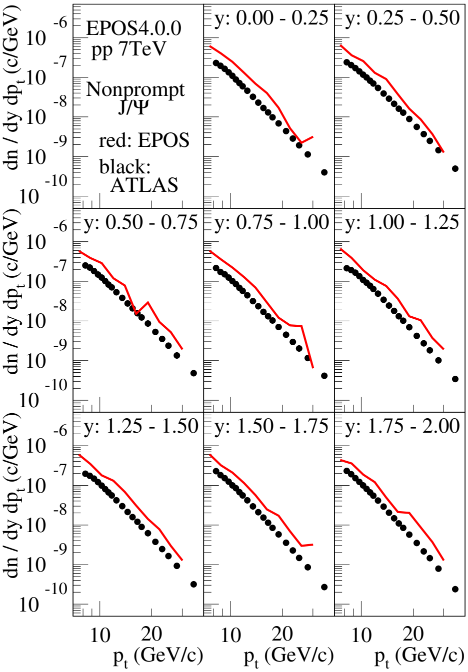
Deficit at low pt ... thermal?



pp 7TeV
Prompt J/Ψ

compared to ATLAS

EPOS J/Ψ production: Color Evaporation Model

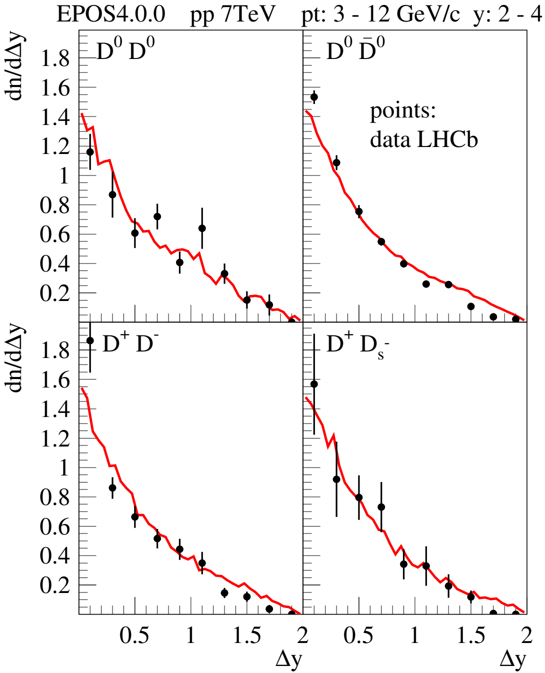


pp 7TeV

Nonprompt J/Ψ

compared to ATLAS

strange: *B* spectra are very good



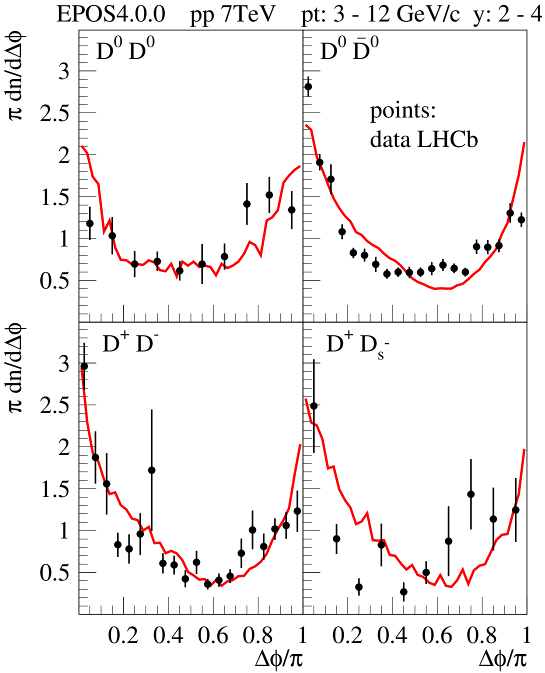
pp 7TeV

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 “multi-observable analysis” concerning**

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