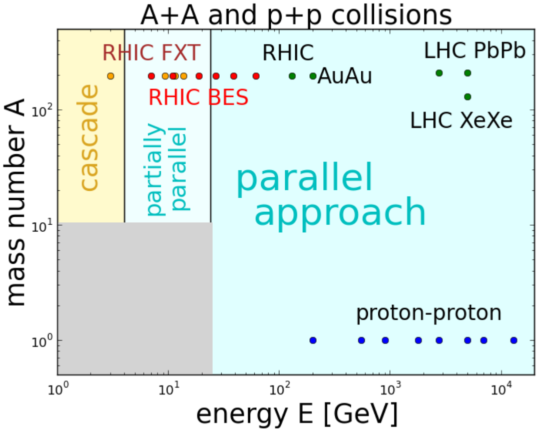
EPOS4: A MC tool for high-energy scatterings

- ☐ Released three weeks ago
  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 coming soon**

Parallel vs sequential scattering (primary interactions)



Points (besides FXT): Epos comparisons to data

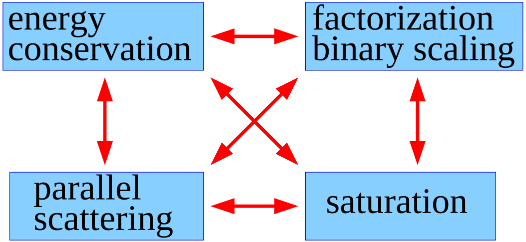
From very elementary time scale arguments: parallel scheme needed everywhere beyond 25 AGeV,
partly beyond 4AGeV

The EPOS4 concept

- ☐ **implement parallel scattering using appropriate theoretical tools (S-matrix theory)**

The S-matrix approach leaves some freedom,

but also provides severe constraints which allow to see a deep connection between four crucial concepts



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 $(T = T_{ii}$, elastic $^{*)})$ **:**

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

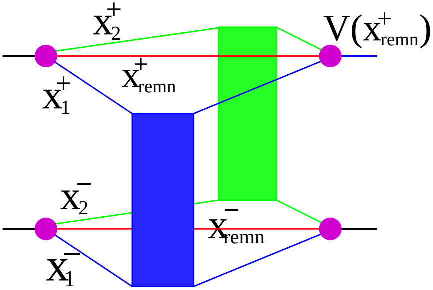
with V representing connection to projectile / target remnant

Energy-momentum conservation

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

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

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



$^{*)}$Relation S-matrix - T-matrix: $S_{fi} = \delta_{fi} + i(2\pi)^4 \delta(p_f - p_i) T_{fi})$; $T = T_{ii}$

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

Connection with inelastic scattering ("optical theorem")

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

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

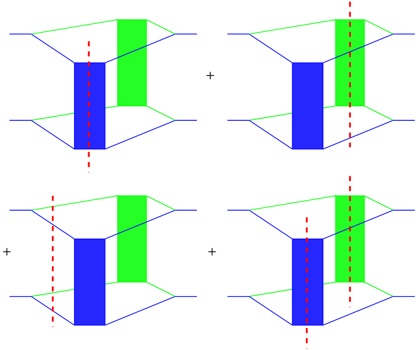
$$\frac{1}{\mathrm{i}}\mathrm{disc}\,\{V \times iT_{\mathrm{Pom}} \times \ldots \times iT_{\mathrm{Pom}} \times V\}$$

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

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

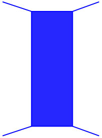
-> interference, cancellations!

Absolutely crucial!!!



Simple example

Uncut diagram:



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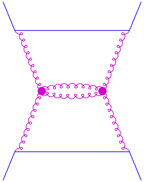
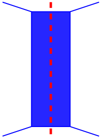


Cut diagram:



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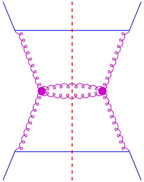
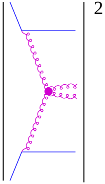
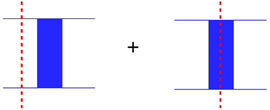
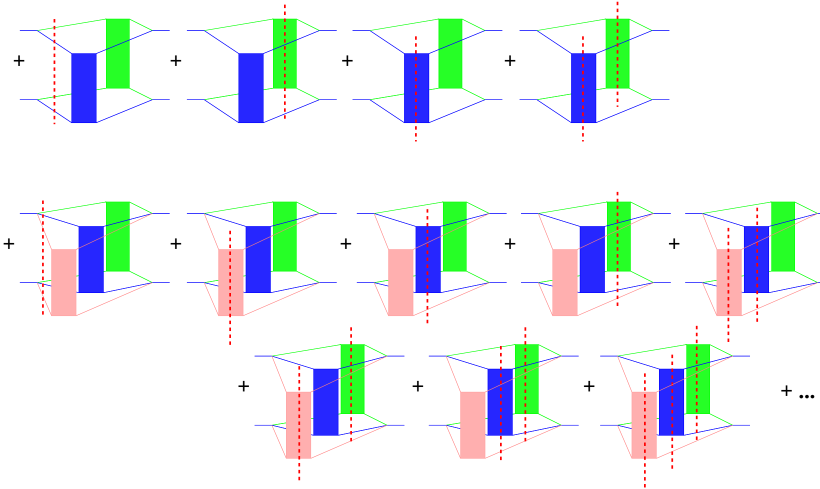


corresponds to:

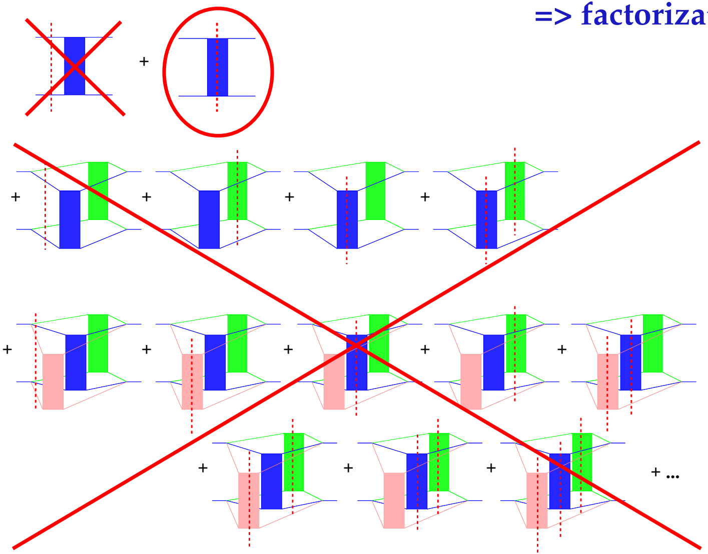


All the diagrams which contribute to pp





For inclusive cross sections, when <u>ignoring energy conservation</u>
everything cancels - up to one diagram
=> factorization



Ignoring energy conservation (remove vertices) one can prove (rigorously) for pp scattering for $x^{\pm}$ (and so for any inclusive variable)

$$\frac{d\sigma_{\mathrm{incl}}^{pp}}{dx^{+}dx^{-}} = \frac{d\sigma_{\mathrm{incl}}^{\mathrm{single\,Pom}}}{dx^{+}dx^{-}}$$

which means factorization (treating the cancellations is trivial)

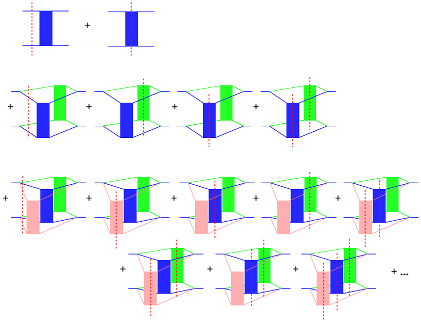
and for AB scattering:

$$\frac{d\sigma_{\mathrm{incl}}^{AB}}{dx^{+}dx^{-}} = AB\,\frac{d\sigma_{\mathrm{incl}}^{\mathrm{single\,Pom}}}{dx^{+}dx^{-}}$$

which means binary scaling

Great ... but getting factorization /binary scaling ALWAYS (large and small pt) is not so great ...

so we better keep energy conservation, but here the "cancellation issues" become 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)

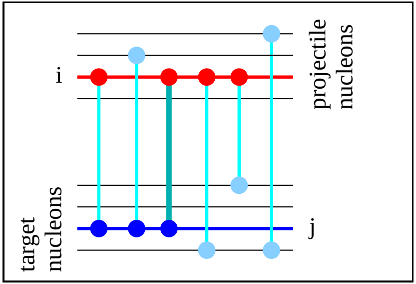
To achieve this

- ☐ **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:

$$N_{\mathrm{conn}} = \frac{N_P + N_T}{2}$$

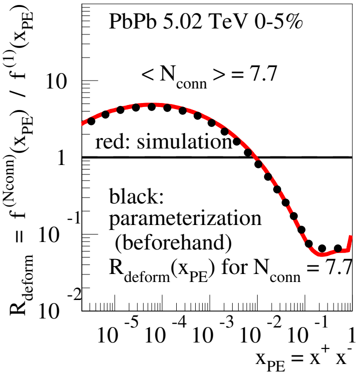
N_P = number of Pomerons connected to i
N_T = number of Pomerons connected to j



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

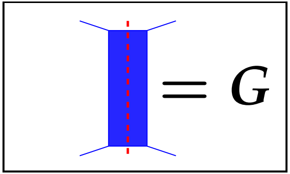
$$R_{\mathrm{deform}} = f^{(N_{\mathrm{conn}})} \,/\, f^{(1)} \neq 1$$

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

(DGLAP parton ladder, with Q^2 being the low virtuality cutoff)

we postulate:

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

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

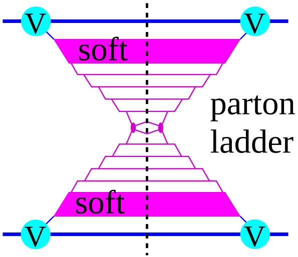
(f is a normalization depending linearly on N_{conn})

which assures factorization and binary scaling, always!

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

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,

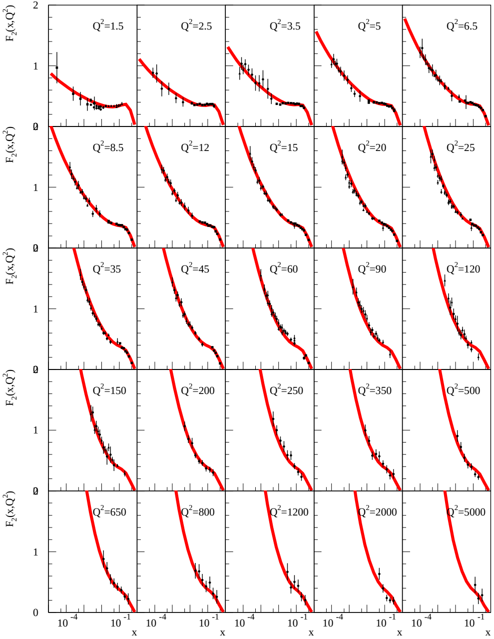
excuding the Born process

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

$$E_3 E_4 \frac{d^6\sigma_{\mathrm{dijet}}}{d^3p_3 d^3p_4} = \sum_{kl} \int\!\!\int dx_1 dx_2\, f^k_{\mathrm{PDF}}(x_1,\mu_{\mathrm{F}}^2)\, f^l_{\mathrm{PDF}}(x_2,\mu_{\mathrm{F}}^2)$$

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

Electron-proton scattering F_2 vs x



To check our f_{PDF}, we can compute

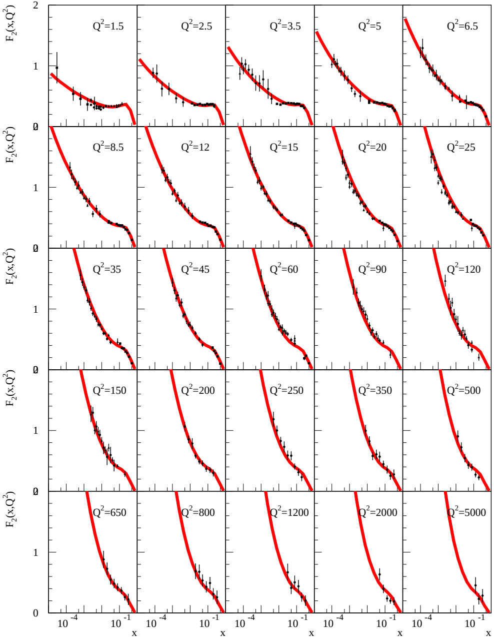
$$F_2 = \sum_k e_k^2 \, x \, f_{\mathrm{PDF}}^k(x, Q^2)$$

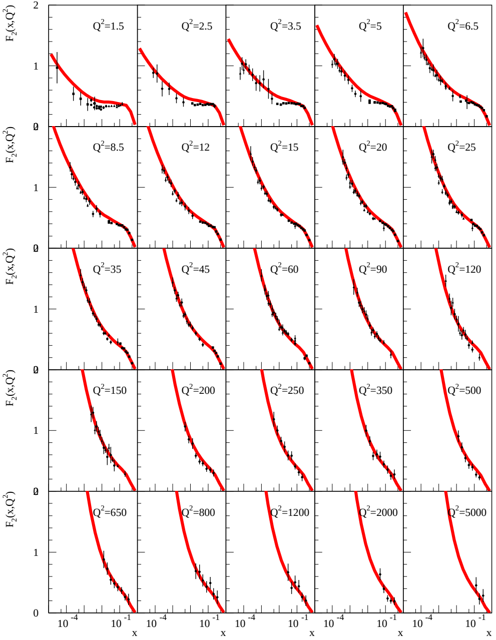
with

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

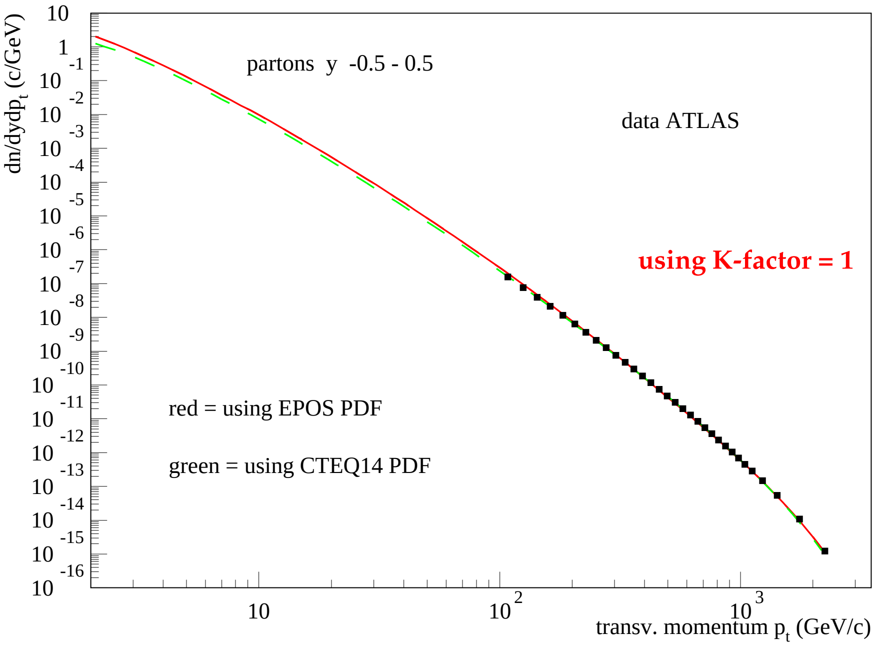
in the EPOS framework, and compare with data from ZEUS, H1

F_2 with EPOS PDF (left) and CTEQ14(5f) PDF (right)

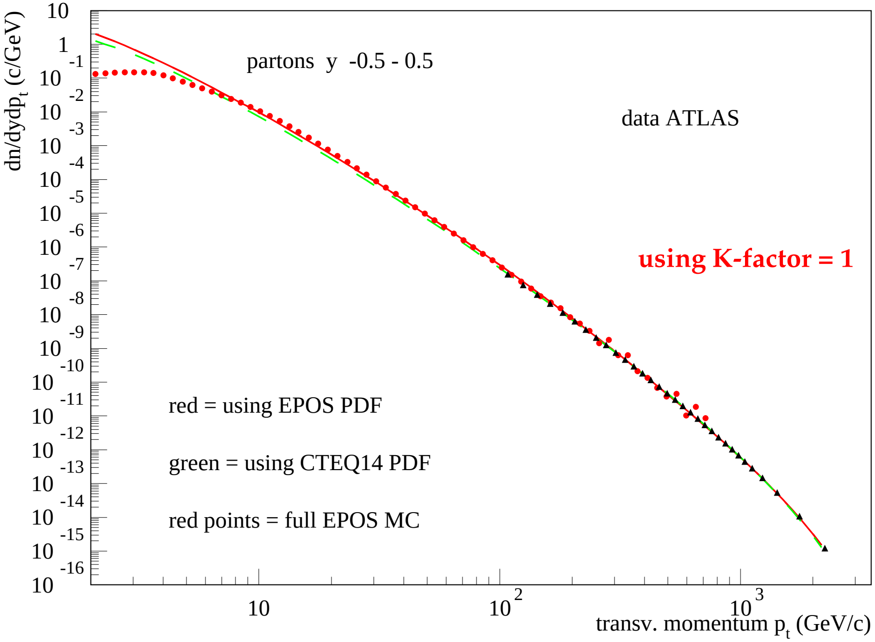




Jet cross section vs pt for pp at 13 TeV

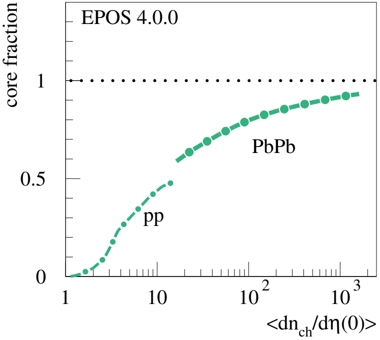


Jet cross section vs pt for pp at 13 TeV



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

Core fraction



Core: microcanonical

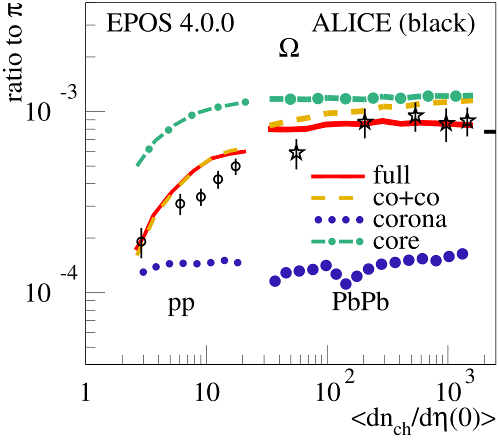
NEW FO concept
NEW numerical methods
used for pp and AA

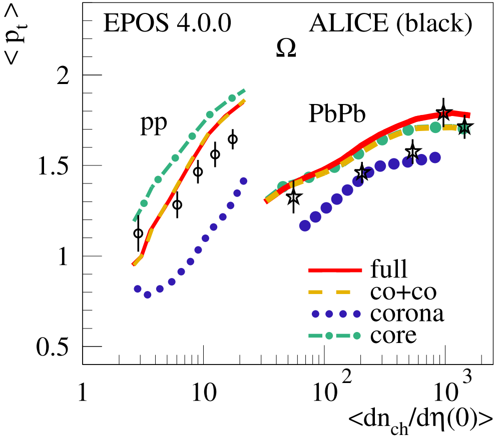
Microcanonical core alone does not work!
Check
in the following

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

versus multiplicity
in core-corona approach

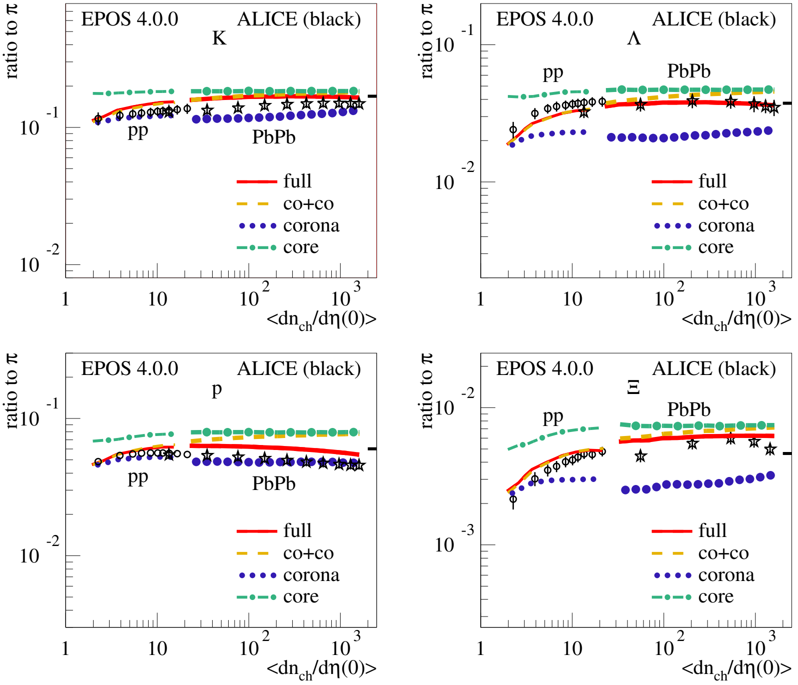
continuous curve **jump**





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)>
EPOS 4.0.0
ALICE (black)
Λ
pp
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EPOS 4.0.0
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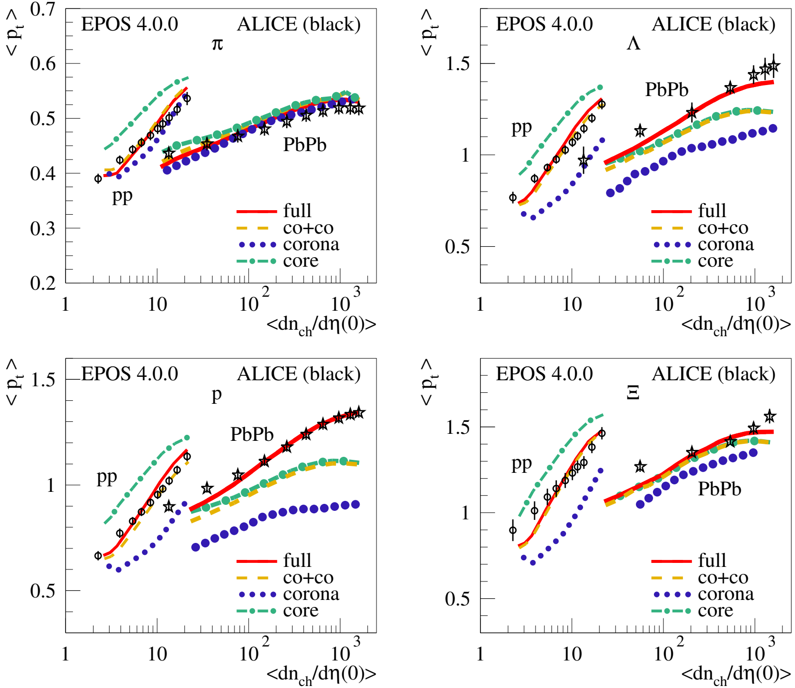
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Crucial in all cases

- ☐ **core-corona**
- ☐ **saturation**
- ☐ **flow**
- ☐ **mirocanonical**

all of them !!!

Multiplicity dependence of charm production

saturation and flow effect

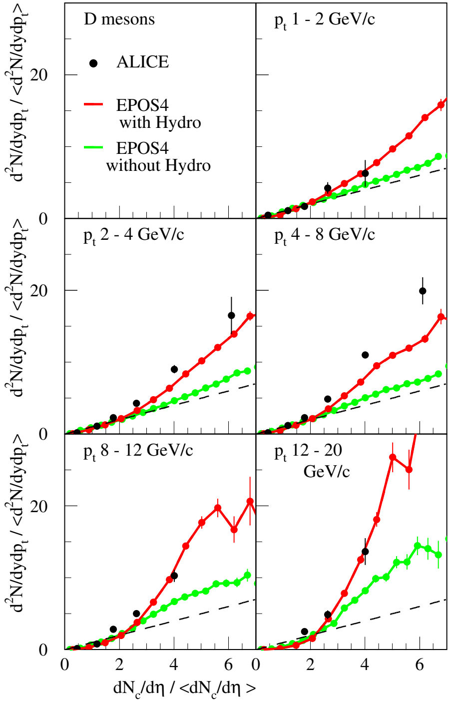
pp 7TeV

Self-normalized *D* meson multiplicity

for different transverse momentum ranges

versus self-normalized charged particle multiplity,

compared to ALICE data

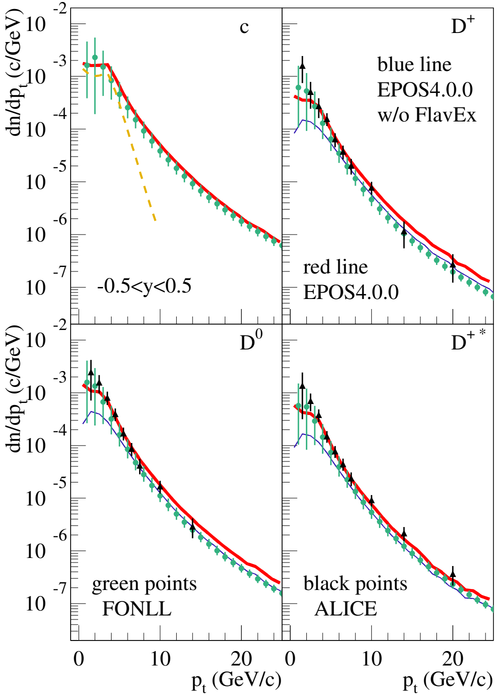


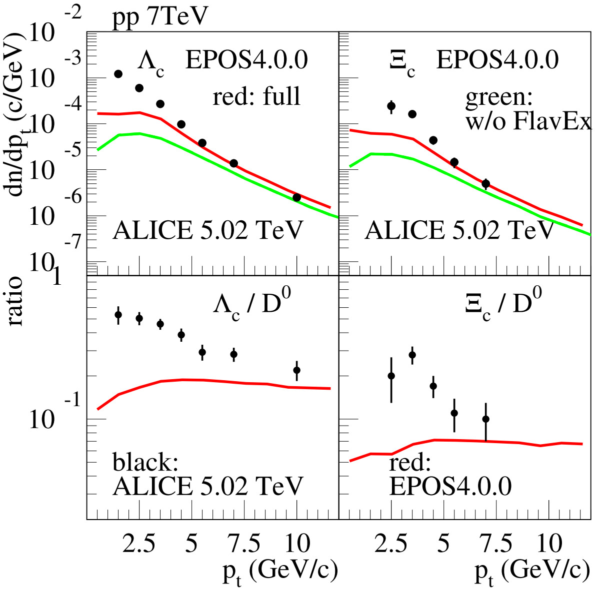
Charmed hadrons

pp 7TeV
charmed final partons and mesons

EPOS4 simulations w/o hydro,

compared to ALICE data and FONLL



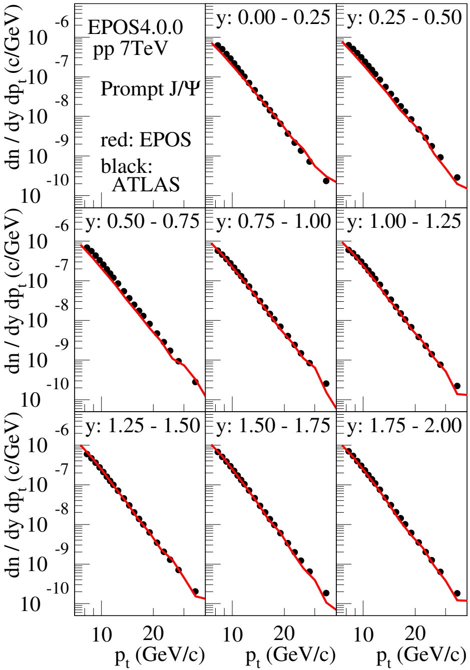


pp 7TeV
charmed baryons
Λ_c and Ξ_c

EPOS4 simulations
w/o hydro,

compared to ALICE data
(at 5.02 TeV).

Deficit at low pt ...
thermal?

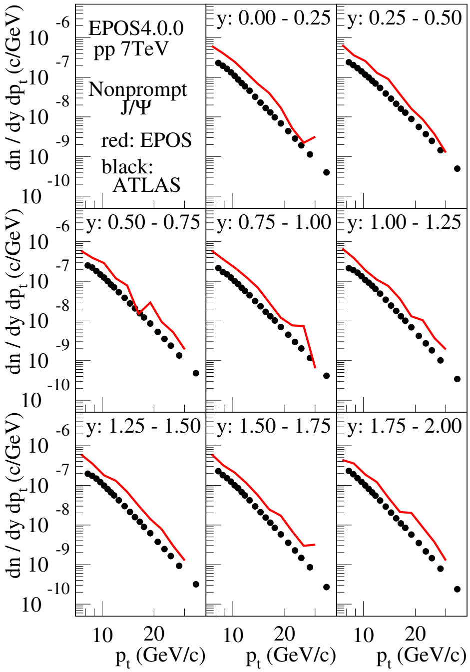


pp 7TeV

Prompt J/Ψ

compared to ATLAS

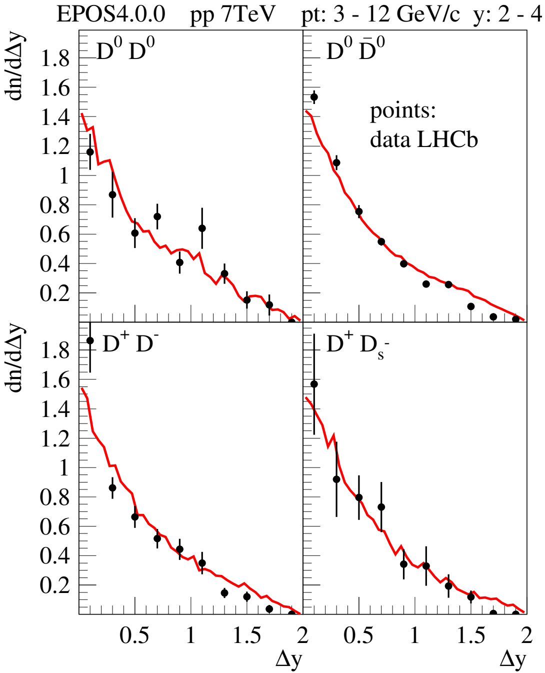
EPOS J/Ψ production: Color Evaporation Model



pp 7TeV
Nonprompt J/Ψ

compared to ATLAS

strange: *B* spectra are very good



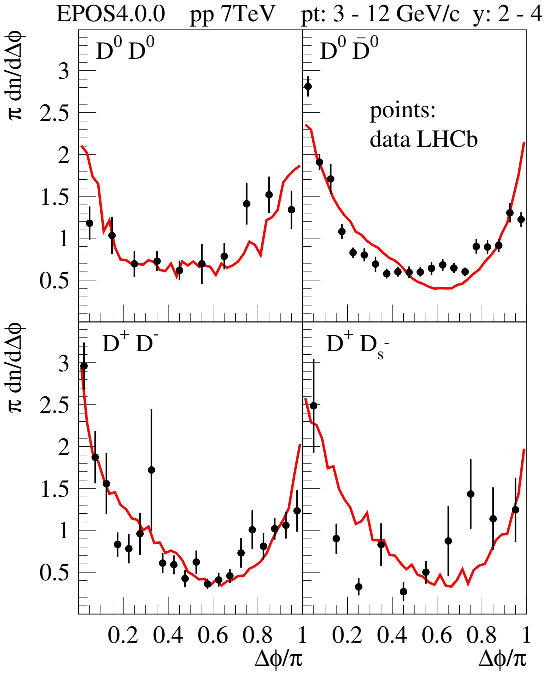
pp 7TeV

Two hadron correlations

D^0D^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

Summarizing the EPOS4 project

accomodate simultaneously

Energy conservation + Parallel scattering + factOrization + Saturation

representing 4 crucial concepts of HE scattering

note: S-matrix theory is a useful tool!