Investigating the collision dynamics with heavy flavors

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in collaboration with K. WERNER, Iu. KARPENKO and T. PIEROG

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Outline

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Why event generators?

- Useful for experimentalists
  - For instance, background estimation
- Allow calculations which are not feasible by hand $\Rightarrow$ more realistic framework (but more model dependent)
- Can reproduce exclusive events :
  - Deeper tests of models/theories
  - More profound understanding of the collision dynamics compare to inclusive calculations

EPOS : a "real" event generator for pp, pA and AA collisions.

One of the main goal is the study of collective behavior (flow) in hadronic collisions

"Real" ⇒ 1 LHC event = 1 EPOS event

1. All kind of particles produced and registered in tables
2. We can (and have to) apply to these particles the same treatment as in experiments
   ⇒ anti-kt for jets, background subtraction ...

⇒ **Ideal for comparisons with experiments**

Why heavy flavors in EPOS?

- Today, lack of event generators with heavy flavor production in pp, pA and AA.
    - Rem : In EPOS, heavy flavor production in pA and AA is completely determined by HF production in pp
- Interest of heavy flavors :
    1. Produced perturbatively
    2. Can be used to test and constrain theories/models
        - pQCD, partonic cascades (more in the following)
    3. Can be used for the study of physical mechanism
        - Energy loss
        - Saturation
        - Flow (collective behavior) (more in the following)

Outline

Universal approach for pp, pA and AA collisions

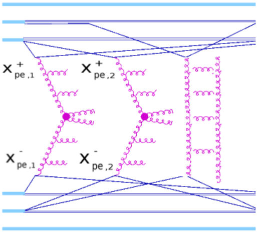
- Quantum mechanical multiple scattering approach based on pQCD and Gribov-Regge theory
- Saturation scale $Q_s \propto N_{part}\hat{s}^{\lambda}$ for non-linear effects
- Core-corona approach to separate fluid and jet hadrons
- 3+1 D viscous Hydrodynamical evolution done event by event

EPOS3 : arXiv:1312.1233, K. Werner, B. Guiot, Y. Karpenko, T. Pierog, M. Bleicher

Multiple scattering in EPOS

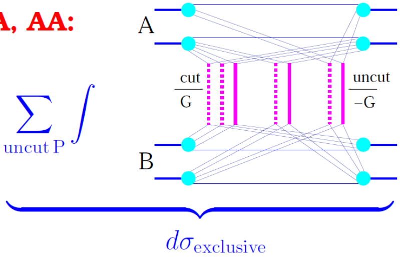
- Phenomenological treatment of multiple scattering based on the Gribov-Regge theory

- Multiple pomerons exchange :

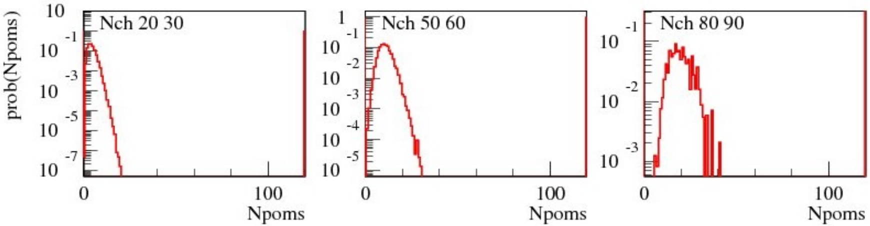


For pp, pA, AA:

$$\sigma^{tot} = \sum_{\text{cut P}} \int \sum_{\text{uncut P}} \int$$



Cut pomerons important for particle production...



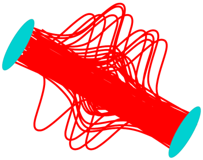
- More cut pomerons, more charged particles and heavy quarks

$\Rightarrow$ A linear rise of the number of heavy quarks with Nch is expected

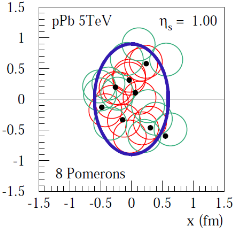
… and collective behavior

Cut pomerons provide initial conditions for hydro

- Cut pomeron ⇒ several color flux tubes
- Color flux tube : Mainly a longitudinal object

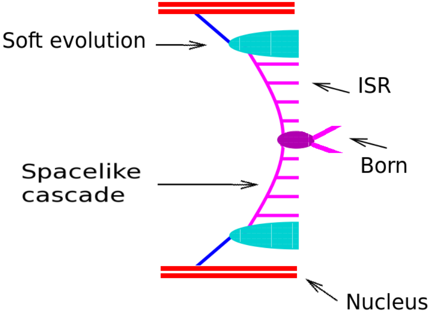


- High density of color flux tubes (in red) = **core** . Hydrodynamical evolution (hadronization : Cooper-Frye)
- Flux tubes in green = **corona** . Jet hadrons (hadronization : string fragmentation)



Outline

Particle production in cut pomerons



particles produced during :

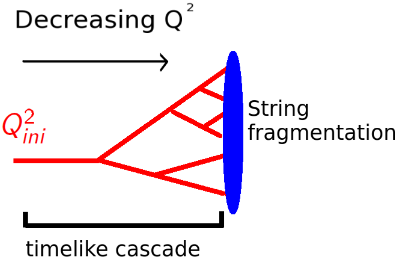
- Spacelike cascade, with splittings $g \to gg$, $g \to q\bar{q}$ and $q \to qg$. Obeys to the DGLAP equation
- Born process $= \sigma_{QCD}$ at L.O

saturation scale :
$Q_s \propto N_{part} \hat{s}^{\lambda}$

- Moreover, all emitted particles will initiate a timelike cascade

Timelike cascade ⊗ fragmentation

ISR and out born particles have $Q^2 \neq 0 \Rightarrow$ timelike cascade



splitting probability :

$dP(z, Q^2) \propto \frac{\alpha_s}{2\pi} \frac{p(z)}{Q^2} \Delta(Q_0^2, Q^2)$

z : energy fraction

Q^2 : virtuality

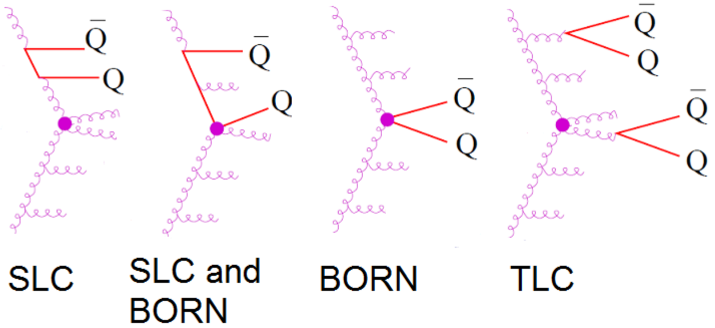
$p()$: splitting functions

$\Delta(Q_0^2, Q^2)$: Sudakov form factor = proba for no emission between Q_0^2 and Q^2

- **DGLAP + angular ordering**

No heavy flavor production in string fragmentation

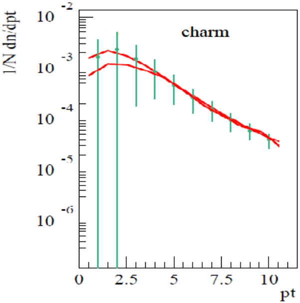
Complete picture for heavy quark production

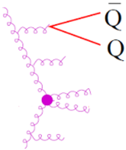


Details on the timelike cascade

- Standard choice : initial virtuality, $Q^2_{ini} = p_t^2$, for ISR and out-Born partons

Low pt heavy flavors : important contribution from gluon splitting in a timelike cascade initiated by a ISR





- But, lack of theoretical constraint on Q^2_{ini} (for ISR and out-Born partons)

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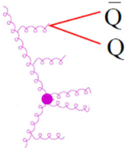

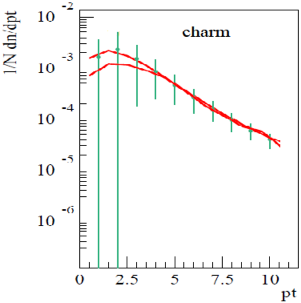

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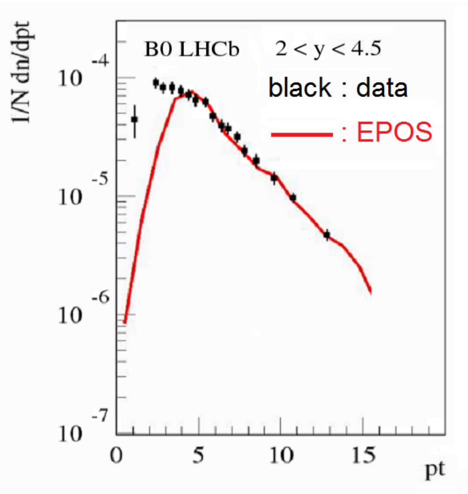
Outline

B mesons production, $Q^2_{ini} = p_t^2$ and $m_{bottom} = 4.6$ GeV



- Threshold for $g \rightarrow B\bar{B}$: $Q^2 > 4m_B^2$
- ISRs have generally a small pt $\Rightarrow Q^2_{ini} = p_t^2$ is below the threshold

Higher Q^2_{ini} will give more low pt B mesons

New choice for Q^2_{ini}

- For ISR : $Q^2_{ini} \sim 5p_t^2$
- For out Born partons, $Q^2_{ini} \sim p_t^2$ is sometimes in violation with 4-momentum conservation :

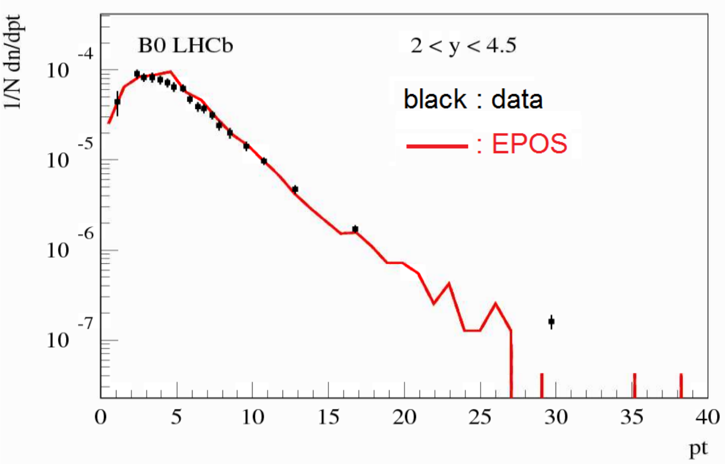
$$p_1 = (\sqrt{s}/2, \overrightarrow{p_t}, p_z)\ ,\ p_2 = (\sqrt{s}/2, -\overrightarrow{p_t}, -p_z) \Rightarrow (p_1 + p_2)^2 = s$$

$$p_1^2 = Q^2 = \frac{s}{4} - p_t^2 - p_z^2 \Rightarrow Q^2_{ini} < \frac{s}{4} - p_t^2$$

Or, in the Born process, $p^2_{t,min} < p_t^2 < s/4$. For $p_t^2 > s/8$, $Q^2_{ini} = p_t^2$ is in violation with 4-momentum conservation. New choice :

$$Q^2_{ini} = min(p_t^2, \frac{s}{4} - p_t^2)$$

Results for B mesons, $m_{bottom} = 4.6$ GeV



Data : arXiv 1306.3663

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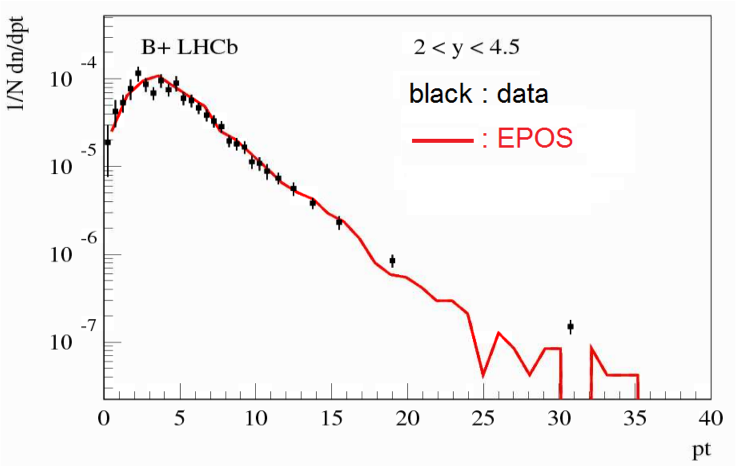

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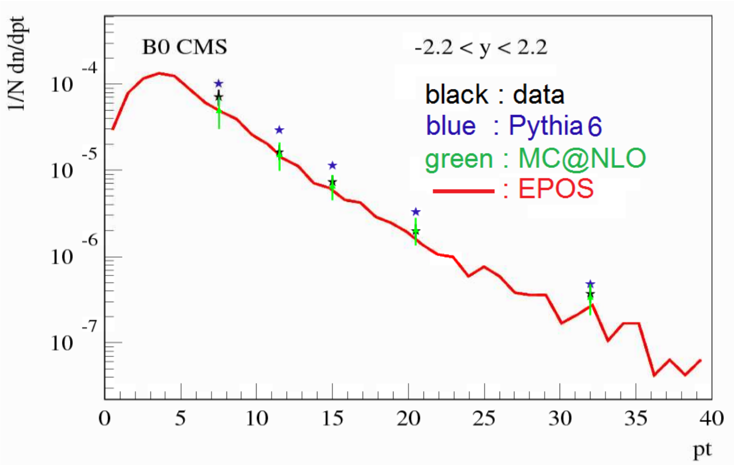

Data : PRL 106, 252001 (2011)

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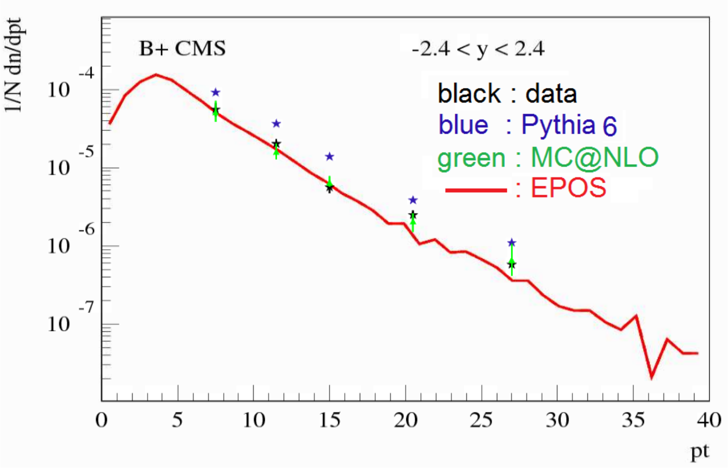

Data : PRL 106, 112001 (2011)

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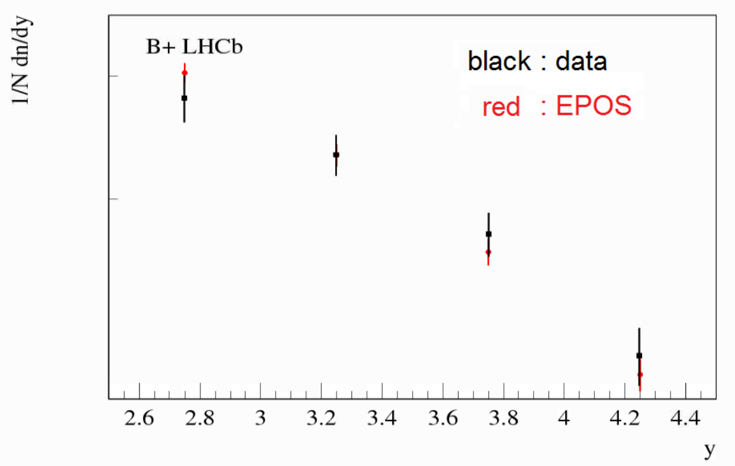

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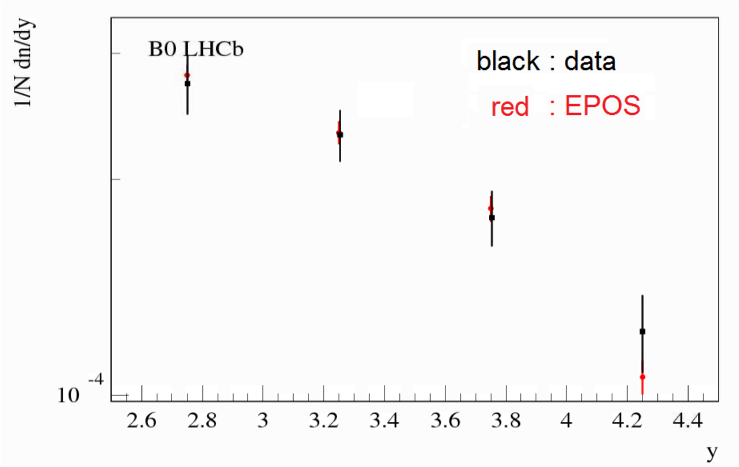
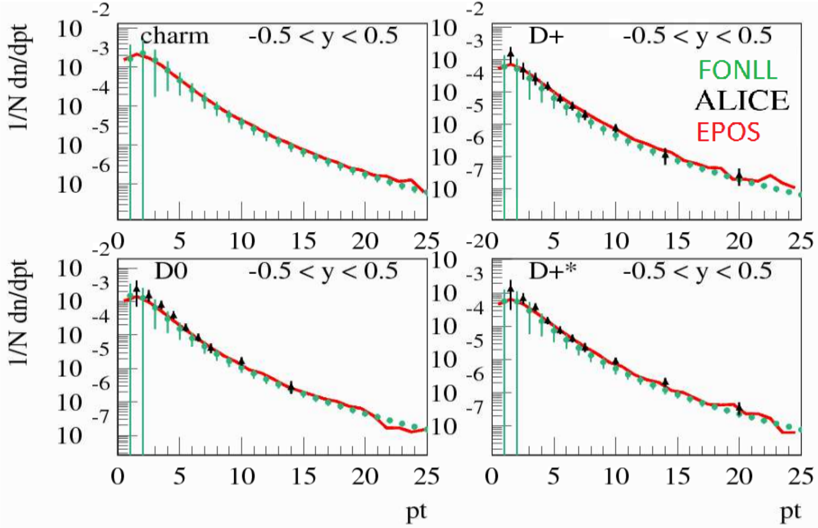


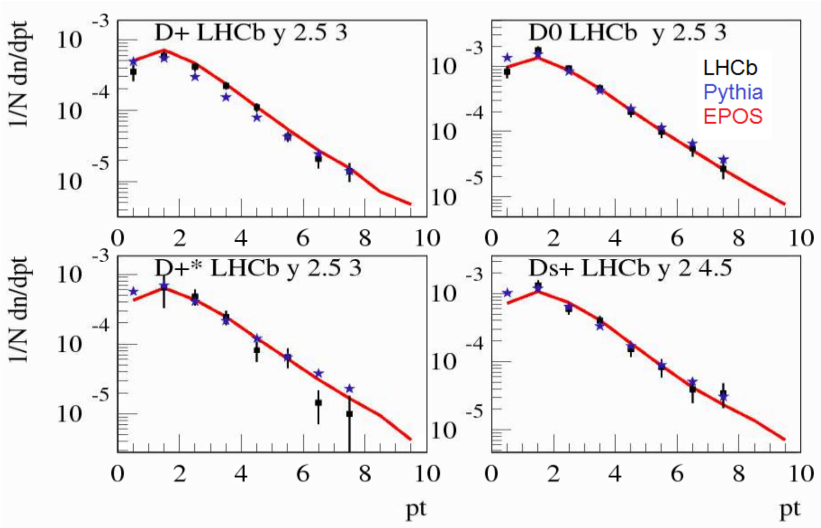
Data : arXiv 1306.3663

Results for charms with the same parametrization and $m_c = 1.2$ GeV

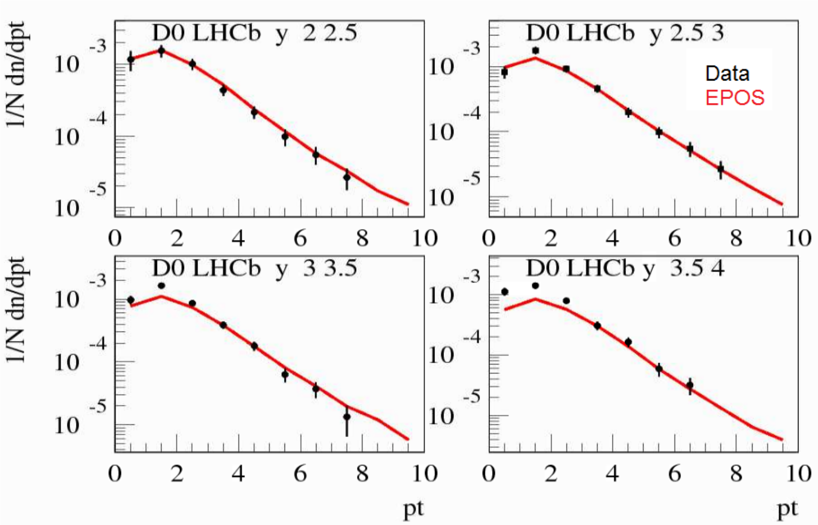
pt distribution of D mesons, ALICE collaboration



pt distribution of D mesons, LHCb collaboration



y dependence of D meson, LHCb collaboration

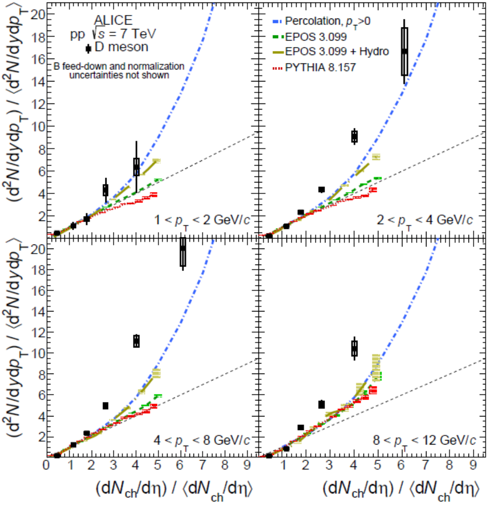


Remarks on D meson production

- Use M. Cacciari's numbers for decays $D^{+*} \to D^{+}$ and $D^{+*} \to D0$
- Lack of D mesons at high y (and small pt) : $Q_{ini}^2 = 5p_t^2 + f(y)$ for ISR?
    - Remark : with $Q_{ini}^2 \propto p_t^2$, a high energy, but small pt, ISR will never split into a $Q\bar{Q}$ pair. Realistic?

Globally in good agreement with different experiments, for pt and y distributions

Collective behavior in high multiplicity pp events



Without hydro, a linear rise is expected.

In EPOS, hydro plays a role in high multiplicity pp events. Reduces multiplicity of charged particles

Better description of data with hydro

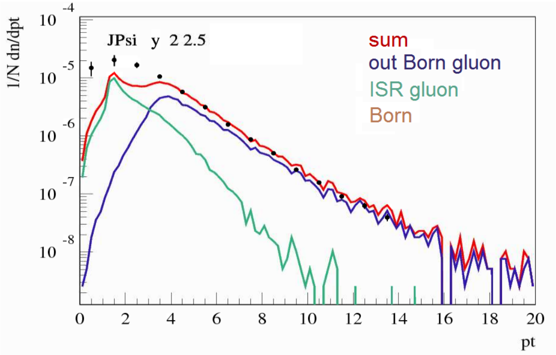
Plot : ALICE collaboration, JHEP 09 (2015) 148
Percolation : E. Ferreiro and C. Pajares, arXiv:1501.03381

J/ψ production with the color evaporation model (CEM)

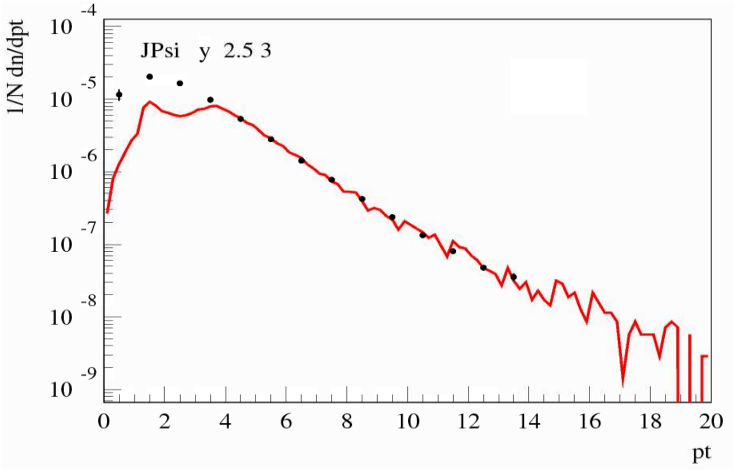
- Interest of J/ψ : no light flavor.
- $\sigma_{J/\psi} = a_{J/\psi} \int_{2m_c}^{2m_D} dm \frac{d\sigma_{c\bar{c}}}{dm}$, m invariant mass of the $c\bar{c}$ pair
- $a_{J/\psi}$: constant parameter. Fraction of $c\bar{c}$ pairs which hadronize in J/ψ (model dependent)
- The implementation in pp could be used later for the study of :
    - # J/ψ v.s N_{ch} in pp collisions (ALICE collaboration)
    - J/ψ production in pA and AA : Study of saturation, flow
- Also useful for experimentalists

J/ψ production in EPOS

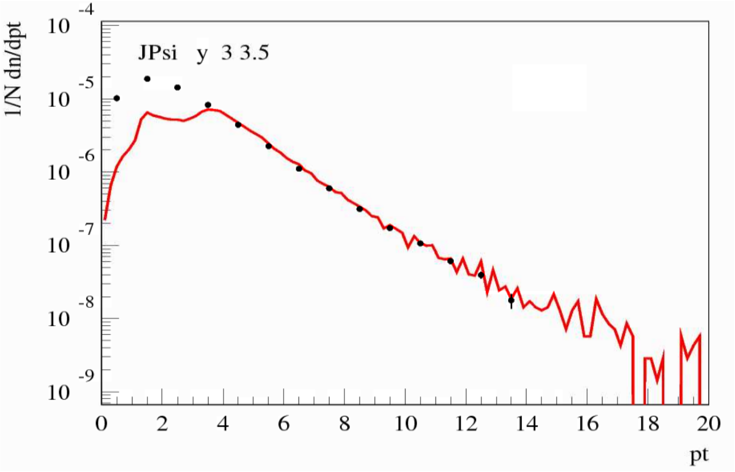
- Missing Born contribution due to the cut-off $s_{min} \sim 40\text{GeV}^2 > 4m_D^2$ for cut pomerons. Expected to contribute at small pt
- Due to technical issue, not easy to lower the value of s_{min}



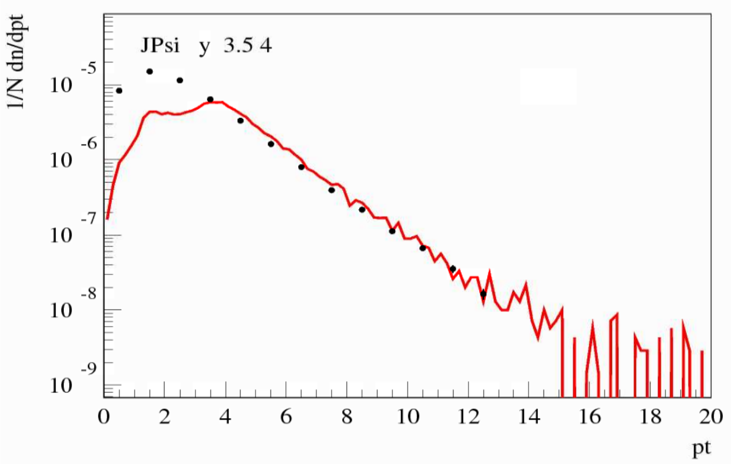
J/ψ production, $2.5 < y < 3$



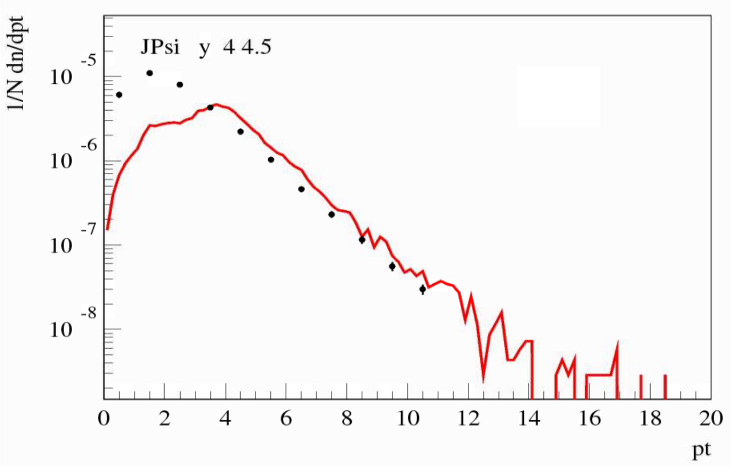
J/ψ production, $3 < y < 3.5$



J/ψ production, $3.5 < y < 4$



J/ψ production, $4 < y < 4.5$



Summary

- The low pt distribution and y distribution of heavy flavors constrain the timelike cascade and the choice for Q^2_{ini} (low and high pt light particles also sensitive to the timelike cascade)
- J/ψ production with the CEM (one constant parameter) works well for $p_t \gtrsim 4$ GeV. Below, lack of J/ψ due to technical issues (no $gg \to Q\bar{Q}$, $q\bar{q} \to Q\bar{Q}$ contributions)
- In high multiplicity pp collisions, appearance of collective behavior in EPOS $\Rightarrow$ helps to describe ALICE data

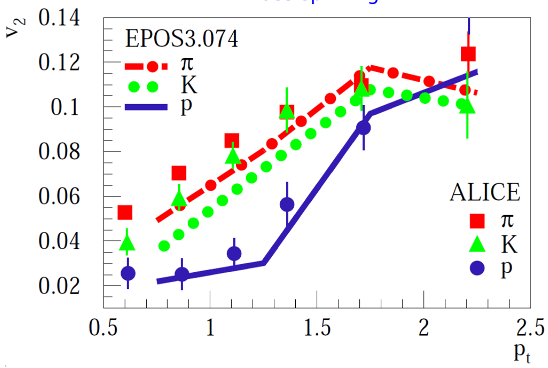
acknowledgment : projet together, Region des pays de la Loire ; CCTVAL project

Back-up slides

Collective behavior in pA

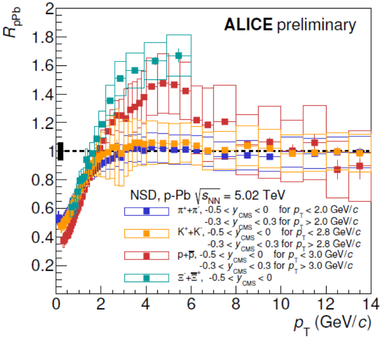
- Hydro ⇒ particles move with the same velocity v. Or $p = m\gamma v$
  ⇒ mass splitting, seen in data and reproduced by EPOS

v2 mass splitting



Mass splitting and Cronin peak

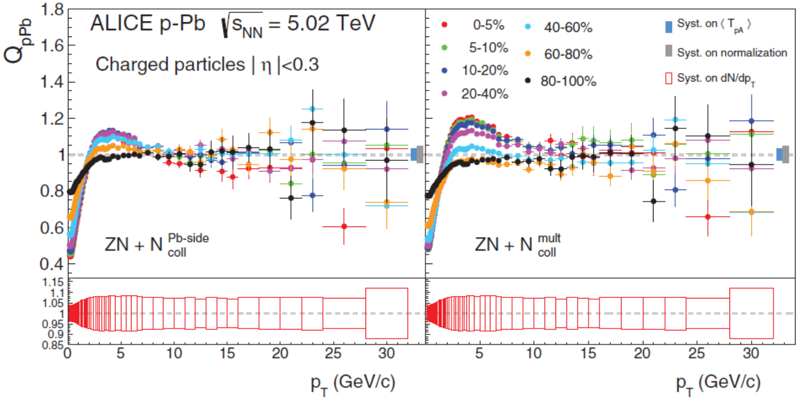
- ALICE collaboration arXiv:1408.0216v1 (2014)



- If the mass hierarchy is due to flow, we expect the same hierarchy in multiplicity

Cronin peak and multiplicity

- ALICE collaboration, Phys. Rev. C 91, 064905 (2015)



- **Higher multiplicity (more flow), bigger Cronin peak**