STRONG-2020 ANNUAL MEETING (2022)

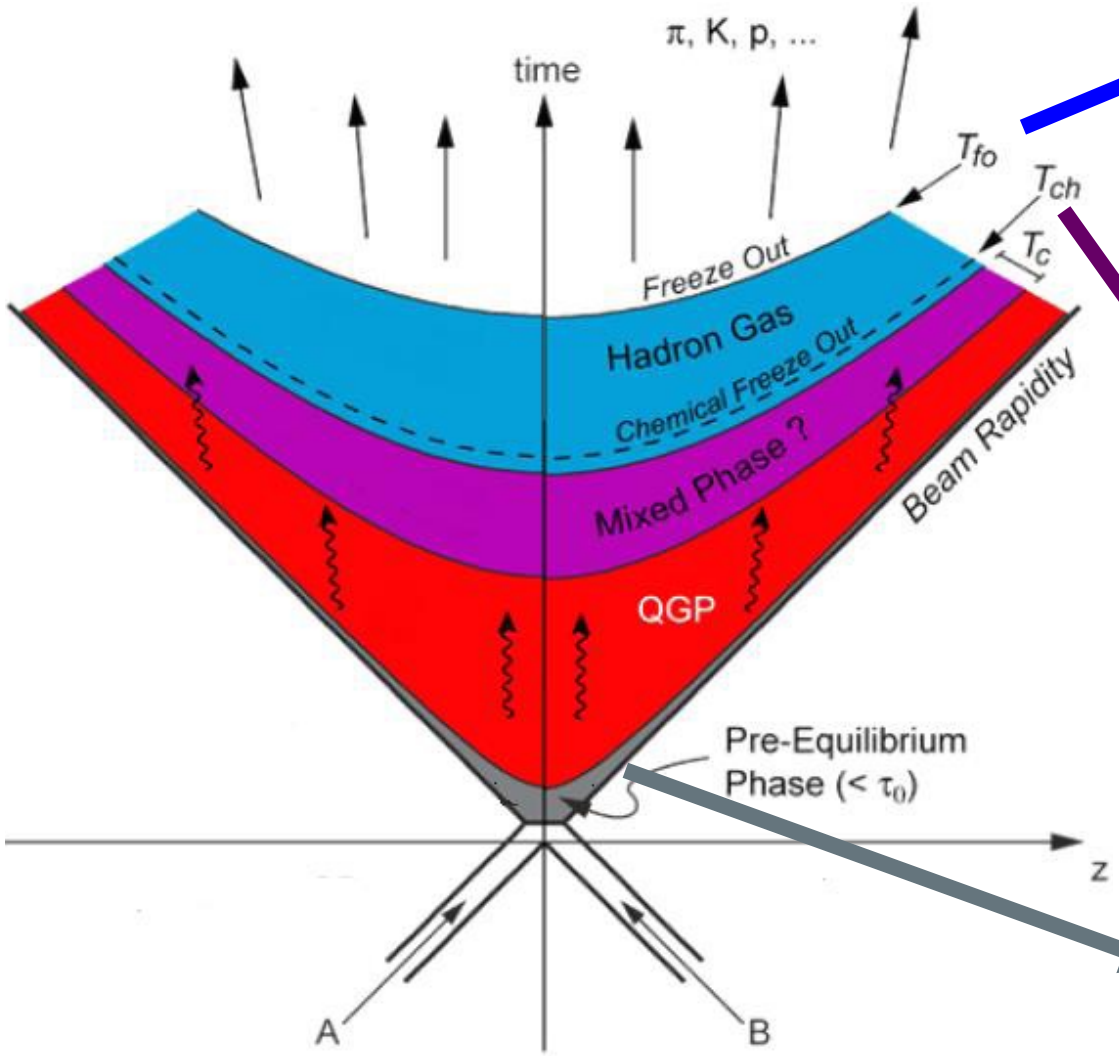
REPORT FROM NA7 - "QUARK-GLUON PLASMA CHARACTERISATION WITH HEAVY FLAVOUR PROBES"

WP18 – NA7

J. Aichelin and G.E. Bruno

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824093

SPACE TIME EVOLUTION OF A-A COLLISION



Thermal freeze-out

- Elastic interactions cease
- Particle dynamics ("momentum spectra") fixed
- T_{fo} ~ 110-120 MeV

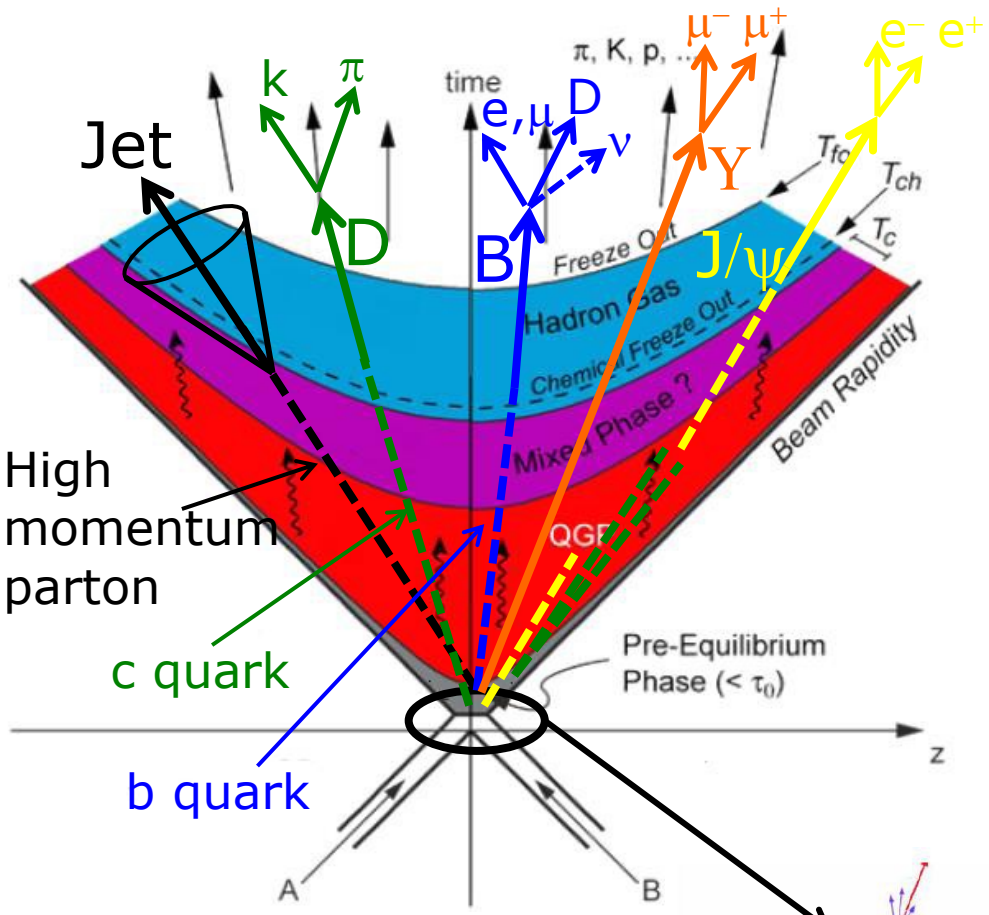
Chemical freeze-out

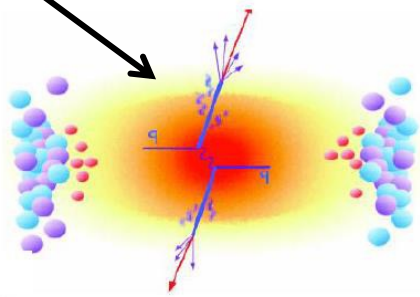
- Inelastic interactions cease
- Particle abundances ("chemical composition") are fixed
- T_{ch} ~ 155 MeV

Thermalization time

- System reaches local equilibrium
- τ_{eq} ~ 0.5 fm/c

HARD PROBES OF A-A COLLISION





$$\tau_f = \frac{\hbar}{m_T}$$

$m_T=\sqrt{(m^2+p_T^2)}$

Hard probes in nucleus-nucleus collisions:

- produced at the very early stage of the collisions in partonic processes with large Q^2
- pQCD can be used to calculate initial cross sections
- traverse the hot and dense medium
- can be used to probe the properties of the medium

HF quarks, due to their rest mass, are natural hard probes

PLAN OF PRESENTATION

1) Scientific results obtained since the last year. Focus on:
   - heavy flavour hadron production
   - azimuthal correlation of charm hadrons
   - quarkonia production
2) Modifications of the scientific Work Plan (as compared to the initial plan in the Grant Agreement)
3) Possibilities/needs of another request for the extension of the project (beyond 30 November 2023)

SCIENTIFIC RESULTS

Successful workshop held in November 2021 in Trento at ECT*, just after our last general meeting

One of the first workshop with the possibility of *in person* participation after the long lockdown of the Covid19 Pandemic

ORGANIZERS:

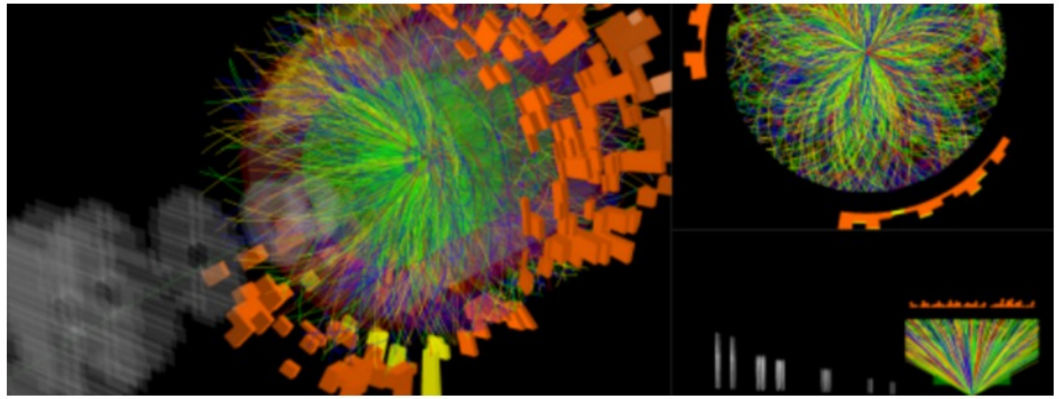
- ☐ Giuseppe Bruno (Politecnico & INFN Bari, Italy)
- ☐ Joerg Aichelin (SUBATECH, France)
- ☐ Ralf Averbeck (GSI & EMMI, Germany)
- ☐ Fabrizio Grosa (INFN Torino, Italy)

NUMBER OF PARTICIPANTS:

60 (about 20 in persons and 40 from remote). The workshop took place as a hybrid meeting.

https://www.ectstar.eu/workshops/quark-gluon-plasma-characterisation-with-heavy-flavour-probes/

QUARK-GLUON PLASMA CHARACTERISATION WITH HEAVY FLAVOUR PROBES



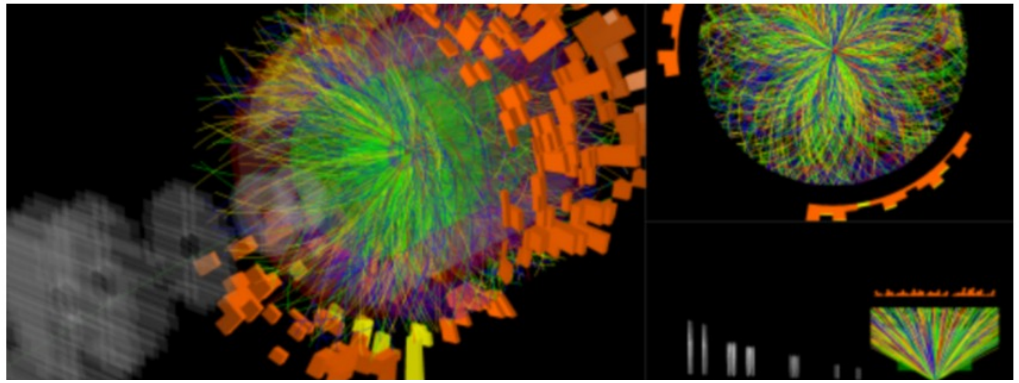
15 November 2021 — 19 November 2021 **Hybrid/Mixed**

Heavy flavor (HF) quarks are excellent probes for the properties of the QGP created in ultra-relativistic heavy-ion collisions. Open HF hadron production allows one to determine the transport coefficients of the QGP. At high transverse momentum, they serve to study parton energy-loss mechanisms in the QGP. Present models, however, differ in many details. In the quarkonia sector, open questions include: up to which temperature can the different quarkonium states survive in a QGP and how do these objects interact with the QGP? How can the recombination of HF quarks/antiquarks from independent hard parton-parton interactions be described in an expanding medium? How constraining is the knowledge of the total HF production crosssection? How do quarkonia interact with the expanding gas of hadrons? Experimentalists and theorists will gather to contribute to answering these questions.

The workshop will take place as a hybrid meeting, with limited on-site participation, provided that the pandemic situation permits this

SCIENTIFIC RESULTS

QUARK-GLUON PLASMA CHARACTERISATION WITH HEAVY FLAVOUR PROBES



RESULT AND HIGHLIGHTS

assessment of the whole field of heavy hadron production in ultra-relativistic collisions: key people from all experiments at LHC and RHIC as well as European and non-European theorists of the concerned fields have joined and fruitfully participated to the workshop. The following goals have been reached:

- identification of the key issues which have to be addressed on the theory side (initial condition, hadronization, validity of the transport approaches);
- identification of the key observables which may validate the different approaches in the theoretical description, posed in respect to the achievable experimental uncertainties (present, midterm, and long-term future upgrades and/or new experiments);
- steering of common efforts (supported by the STRONG-2020 NA7 network) to address the open questions.

A dedicated session was devoted to a detailed comparisons of the recombination and hadronisation schemes implemented in the different transport models, by also performing simulations on reference processes. A road-map of actions to be taken over the first half of 2022 was agreed among the major theory groups.

The workshop has also served to start a discussion for the preparation of a Review Paper, a main deliverable expected from NA7, with recommendations for the dedicated heavy-ion periods at the LHC, with a focus on the runs after the 3rd Long Shutdown (run4, run5 and beyond), for the different LHC experiments.

SCIENTIFIC RESULTS

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At the ECT* NA7 workshop in Trento:

- influence on v_2 (elliptic flow)

- influence on R_{AA} (ratio between AA and pp transverse momentum spectrum)

Assigned "homework for hadronization" on the basis of a **common** (and simplistic) hydrodynamics of the fireball *at given hadronization temperature, in connection with a common charm-quark phase space*

Workshop last week (10-14.10) in Orsay

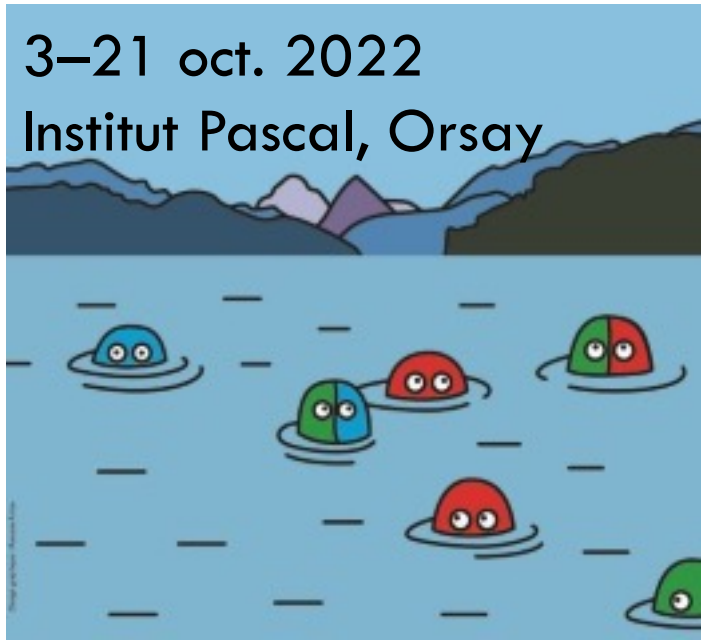
Presentations of the homework results obtained so far

Definition of additional tasks for the different codes

Preparation of a dedicated publication on the role of hadronization in open heavy flavour production in high energy nuclear collisions

SCIENTIFIC RESULTS

HF2022: Heavy Flavours from small to large systems



https://indico.ijclab.in2p3.fr/event/7656

Organisers:

Zaïda Conesa del Valle

Jean-Philippe Lansberg

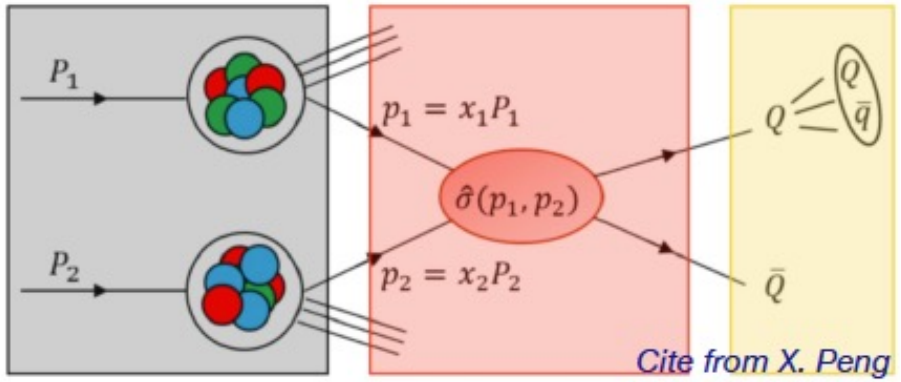
Laure Massacrier

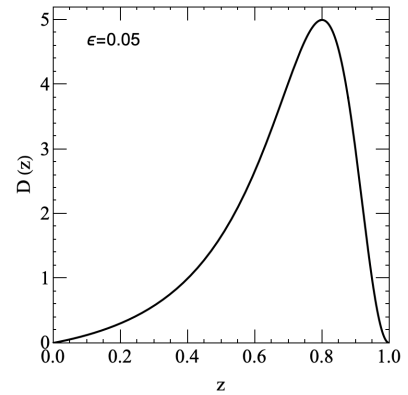
Jiaxing Zhao, post-doc hired by STRONG-2020, within NA7

Hadronization mechanism in vacuum

$$\frac{d\sigma^{H_c}}{dp_T}(\mu_F,\mu_R) = \mathrm{PDF}(x_1,\mu_F)\cdot\mathrm{PDF}(x_2,\mu_F) \otimes \frac{d\sigma^{c}}{dp_T^{c}}(x_1,x_2,\mu_F,\mu_R) \otimes D_{c\to H_c}(z=p_{H_c}/p_c,\mu_F)$$

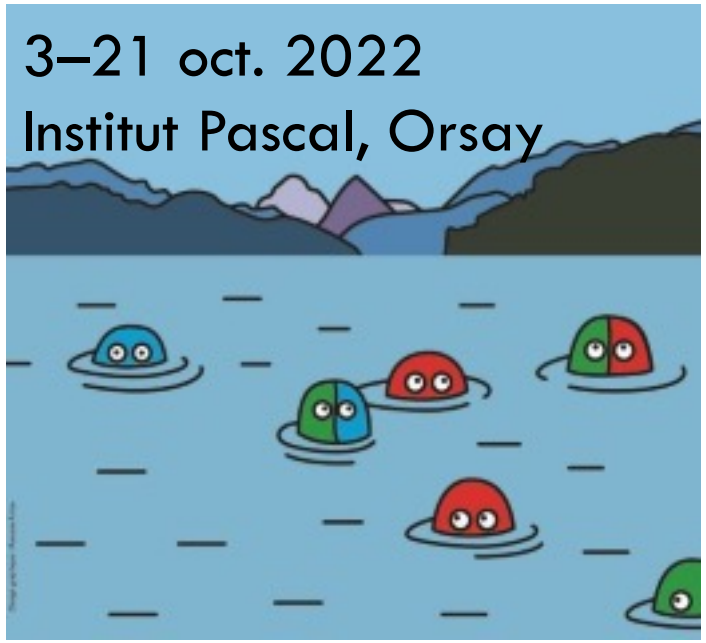
Parton distribution functions (PDFs) | Hard scattering cross section (pQCD) | Fragmentation function (hadronisation)





SCIENTIFIC RESULTS

HF2022: Heavy Flavours from small to large systems



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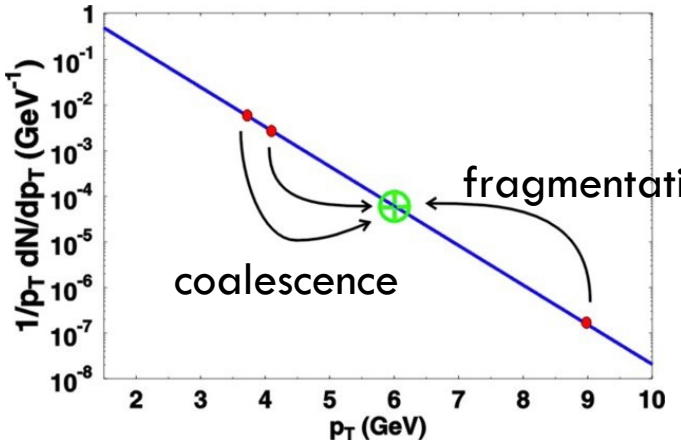
Hadronization mechanism in hot medium

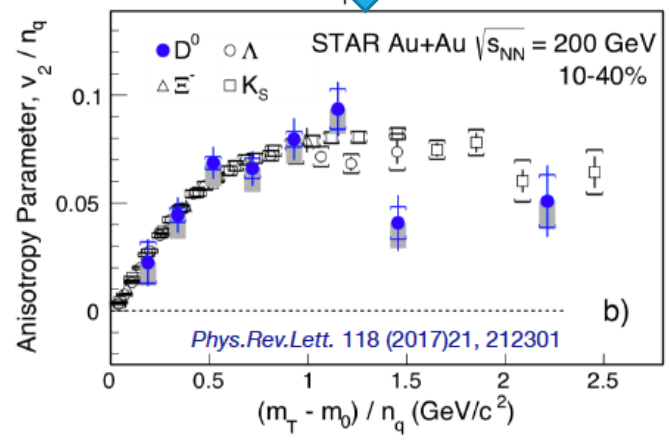


$$N_M = \sum_{ab} \int \frac{d^3P}{(2\pi)^3} \langle M;\mathbf{P}| \hat{\rho}_{ab} |M;\mathbf{P}\rangle$$

R. Fries, B. Muller, C. Nonaka and S. Bass. Phys. Rev. C68, 044902(2004).

For mesons

$$\frac{dN}{d^2P_T d\eta} = C \int \frac{P^\mu d\sigma_\mu}{(2\pi)^3} \int \frac{d^4r d^4q}{(2\pi)^3} F(x_1,p_1,x_2,p_2) W(r,q)$$



- *Quark distribution functions:*

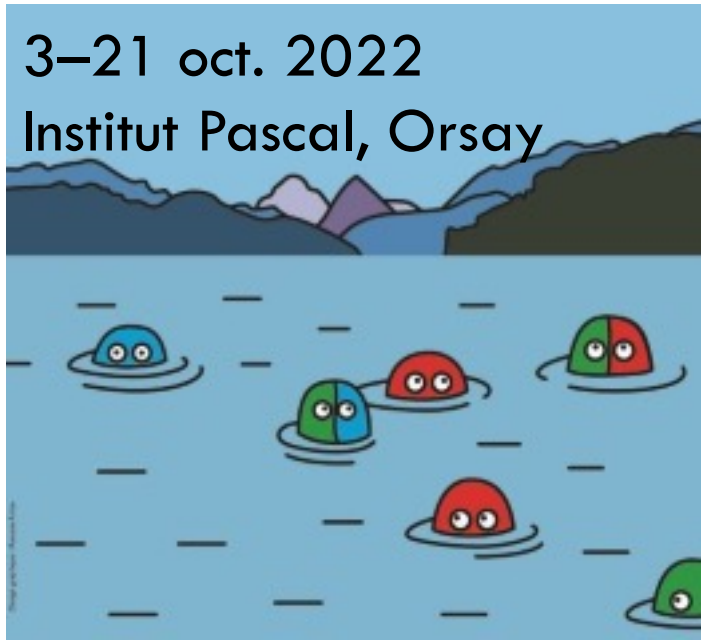
$$F(x_1,p_1,x_2,p_2) = f_c(x_1,p_1) f_q(x_2,p_2)$$

- *The Wigner function can self-consistently be determined by the wavefunction. (advantage of heavy flavor).*

$$W(r,p) = \int d^4y e^{-ipy} \psi(r+\frac{y}{2}) \psi(r-\frac{y}{2})$$

SCIENTIFIC RESULTS

HF2022: Heavy Flavours from small to large systems



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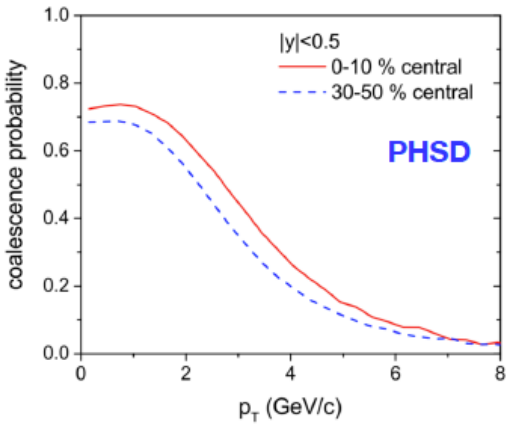
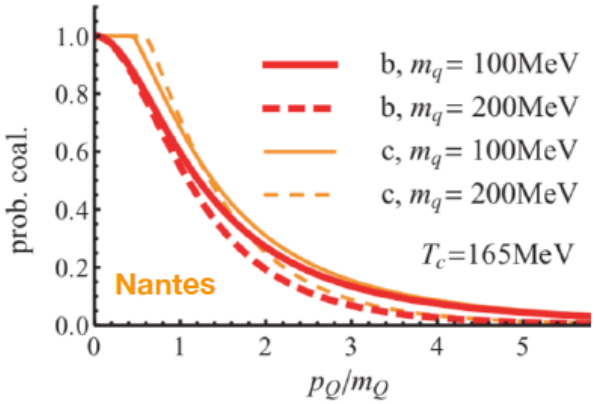
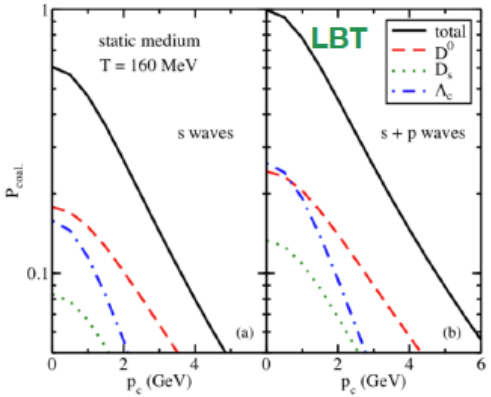
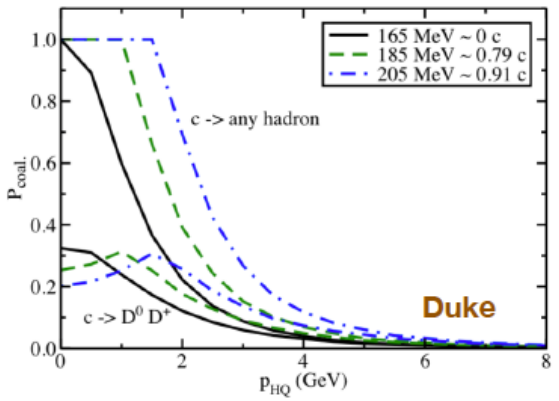
Hadronization mechanism in hot medium

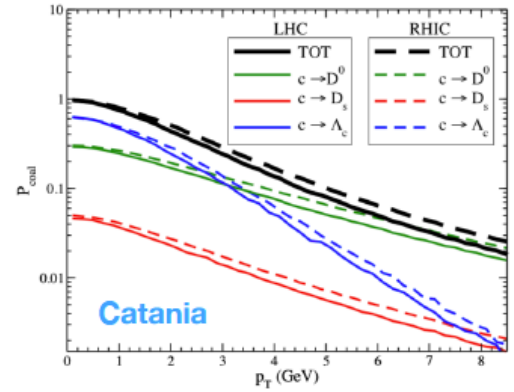
- *Recombination + Fragmentation*:







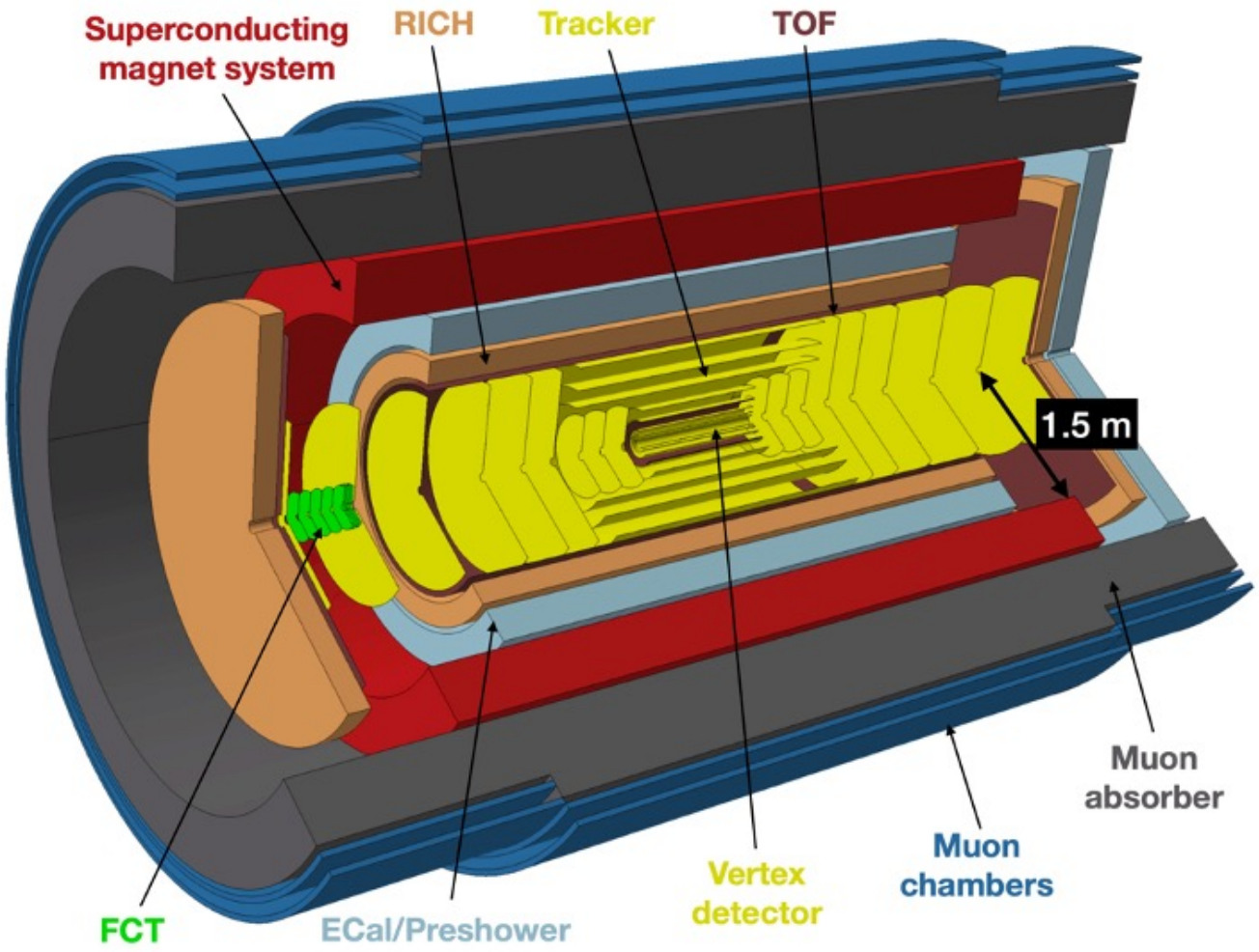




$$P_{frag.}(p_T) = 1 - P_{coal.}(p_T)$$

PERFORMANCE STUDIES FOR DDBAR CORRELATIONS WITH ALICE 3

ALICE 3: the *next-generation* heavy-ion *experiment at the LHC*



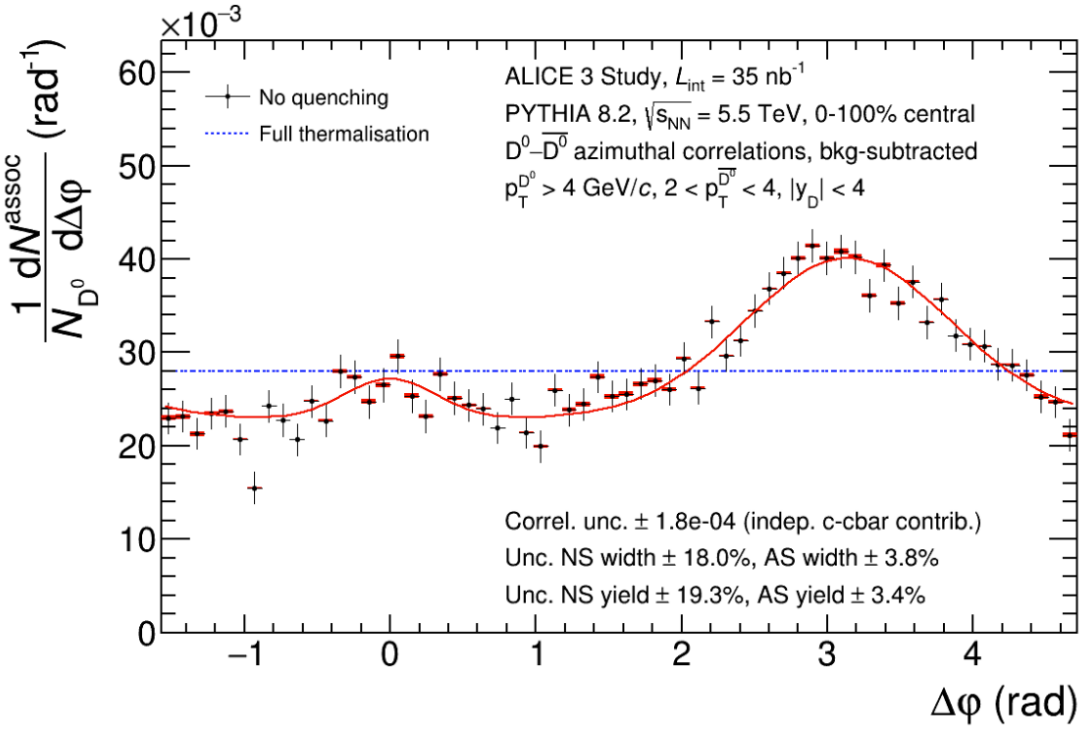
- Compact all-silicon tracker with high-resolution vertex detector
- Superconducting magnet system
- Particle Identification over large acceptance
- Fast read-out and online processing

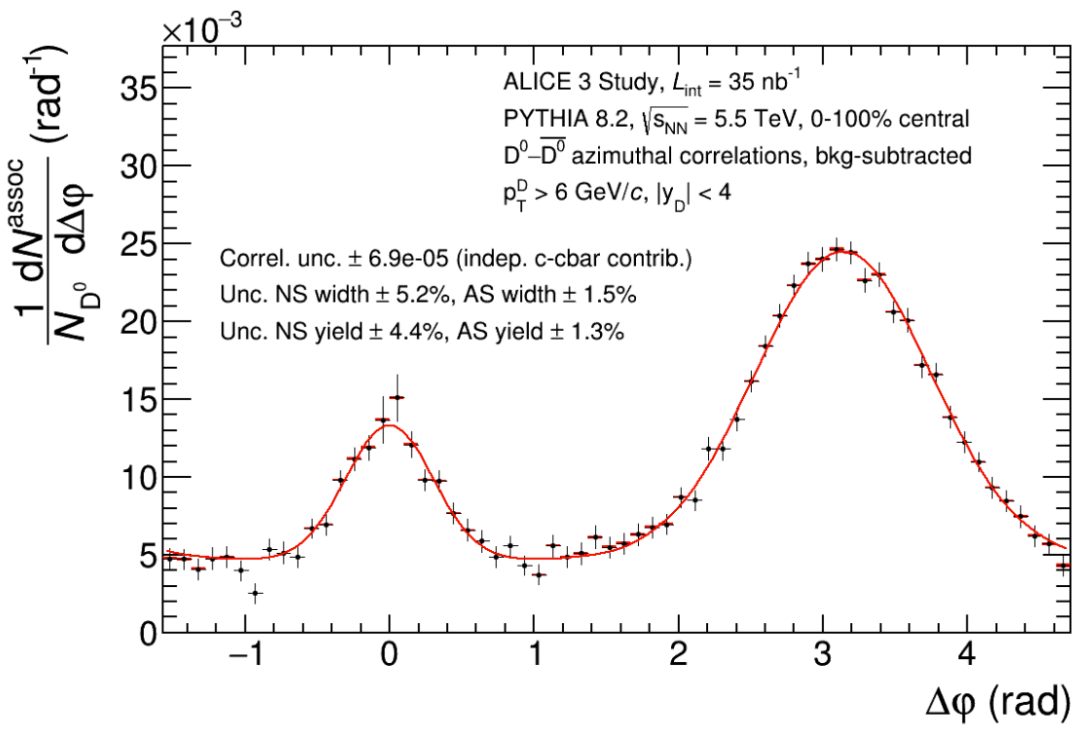
To be installed for LHC run 5 (2032)

PERFORMANCE STUDIES FOR DDBAR CORRELATIONS WITH ALICE3

- Estimated the feasibility and performance of the correlation analysis of D0 and D0bar mesons in MB Pb-Pb collisions with the ALICE 3 detector

F. Colamaria



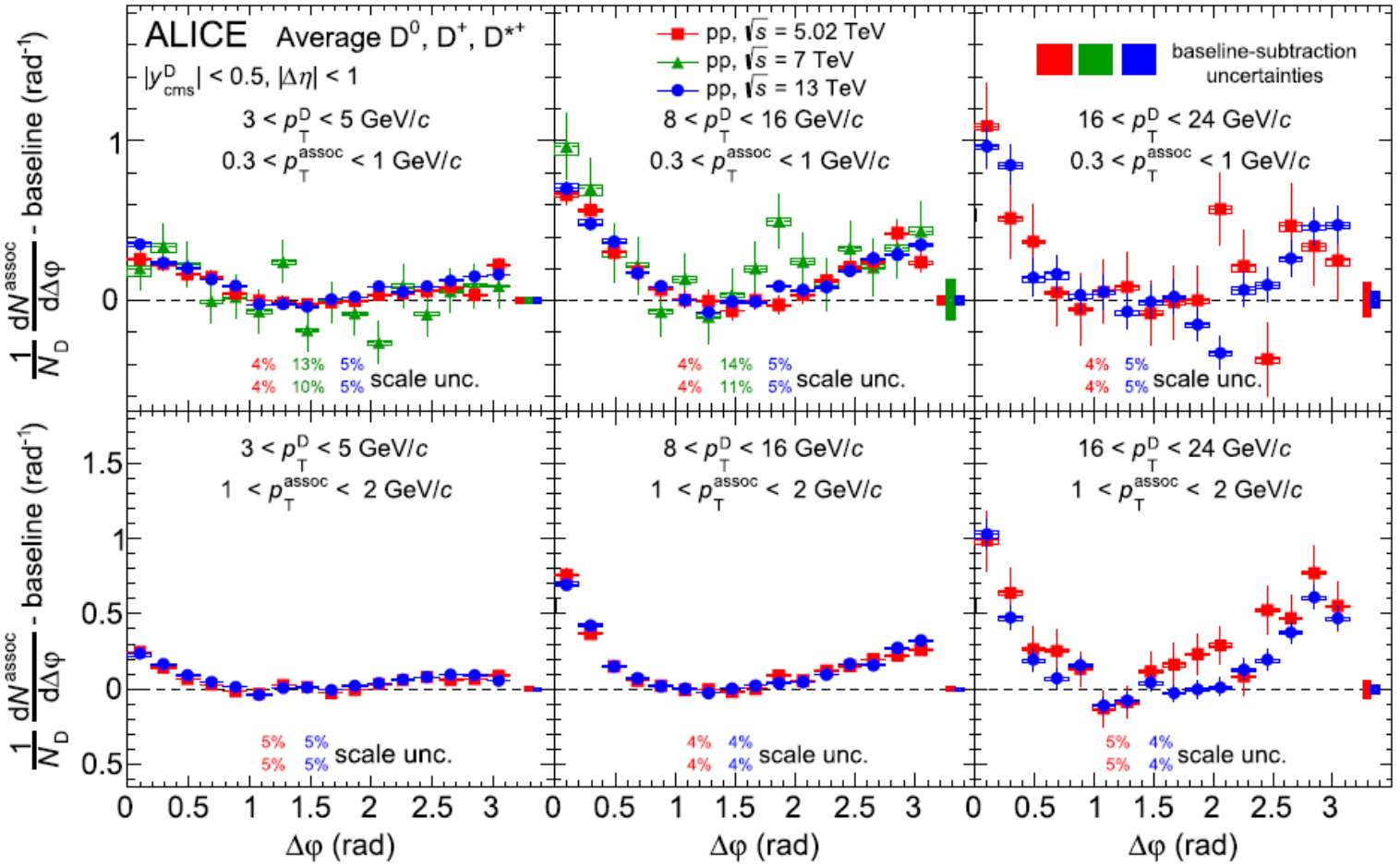


- DDbar correlations can probe degree of thermalization of charm quarks in QGP medium by probing the isotropization of the distribution. Also sensitive to the different energy loss regime (collisional vs radiative)
  - Excellent precision for near-and away-side widths → parameters of merit for the above goals
  - Results available in the ALICE3 LoI: https://cds.cern.ch/record/2803563/files/LHCC-I-038.pdf

D-H CORRELATION MEASUREMENT IN PP COLLISIONS AT 13 TEV

- Completed the analysis of azimuthal correlations of D^0, D^+, D^{*+} mesons and charged particles in pp with ALICE
  - published in Eur. Phys. J. C (2022) 82, 335

F. Colamaria

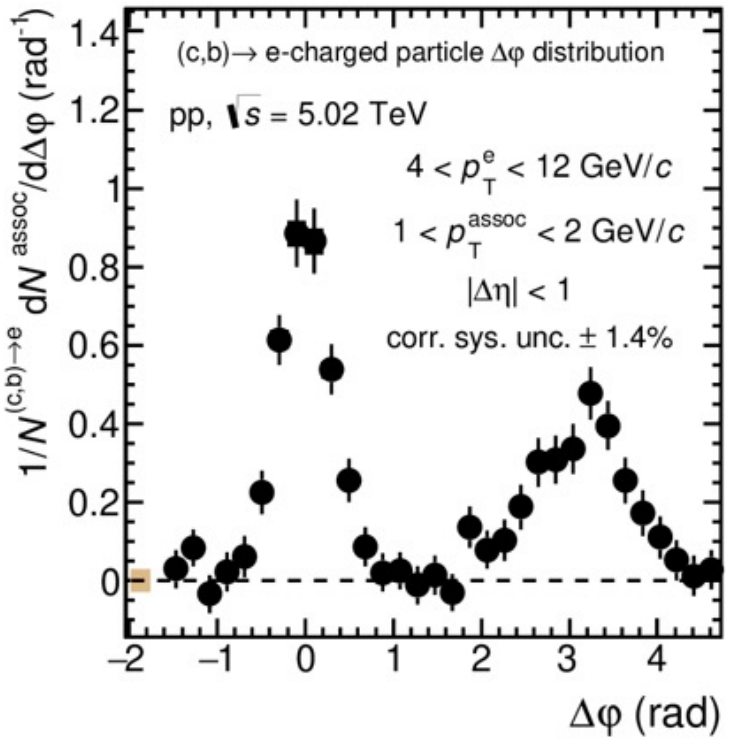


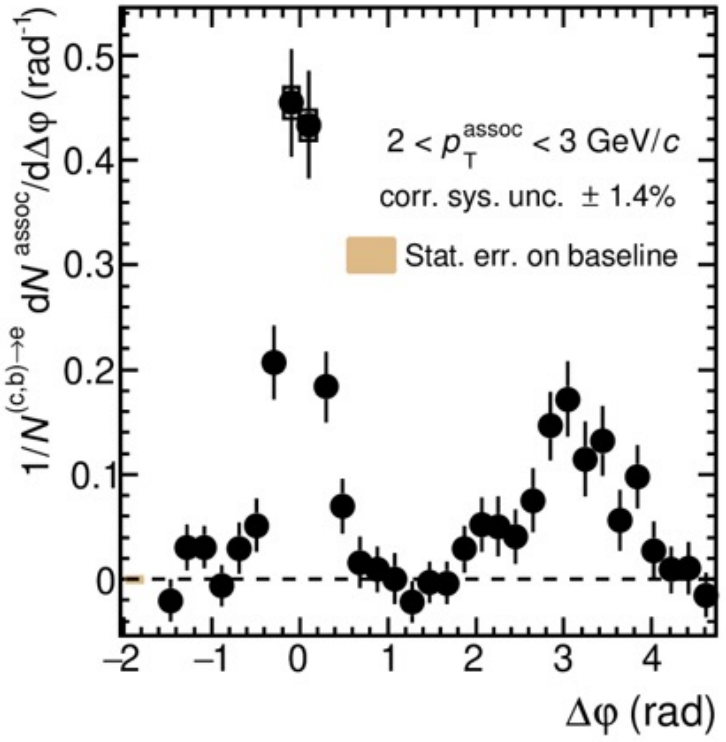
- Much better precision and extended p_T reach compared to previous studies at 5.02 and 7 TeV
- The results provide important insight into the fragmentation of charm quark and the structure of c-jets
- Set constraints on the event generators capable of describing c production and fragmentation with different ingredients/modelisation
  - PYTHIA8 and POWHEG+PYTHIA8 found to provide the closest predictions w.r.t. data results

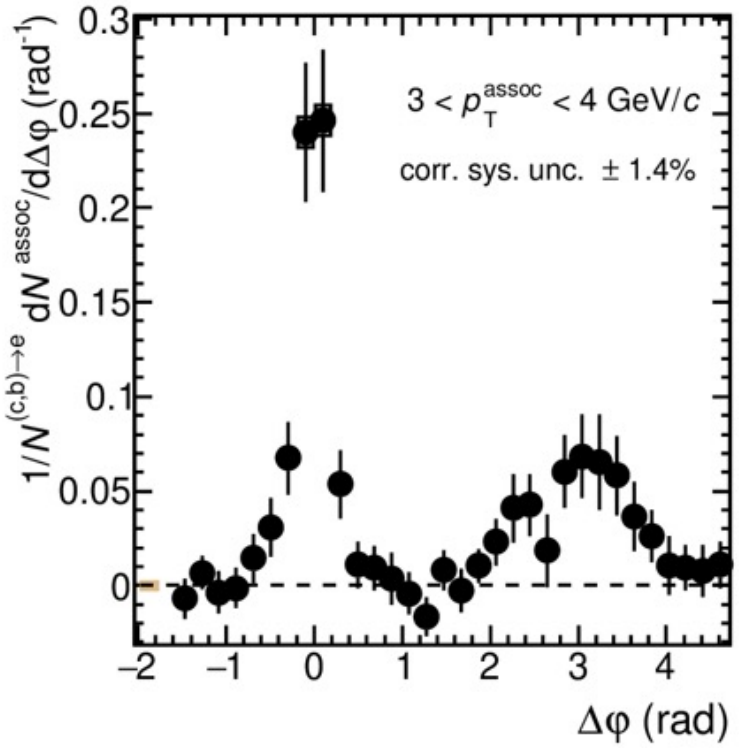
HFE-H CORRELATION MEASUREMENT IN PP AND P-PB COLLISIONS

- Working on the analysis of correlations between electrons from HF hadron decays and charged particles, in pp and p-Pb collisions at 5.02 TeV
  - Allow to extend the maximum pT reach to larger due to larger sample of correlation pairs
  - Access to beauty fragmentation, in particular for pT(e) > 5-6 GeV/c
  - Drawback: looser access to quark kinematics compared to D-h measurements

F. Colamaria







- Preliminary results shown here, a publication is currently being prepared with updated results

QUARKONIUM PRODUCTION IN PP AND PB-PB COLLISIONS

J.A., P.B. Gossiaux, D.Y. Arrebato Villar, Jiaxing Zhao

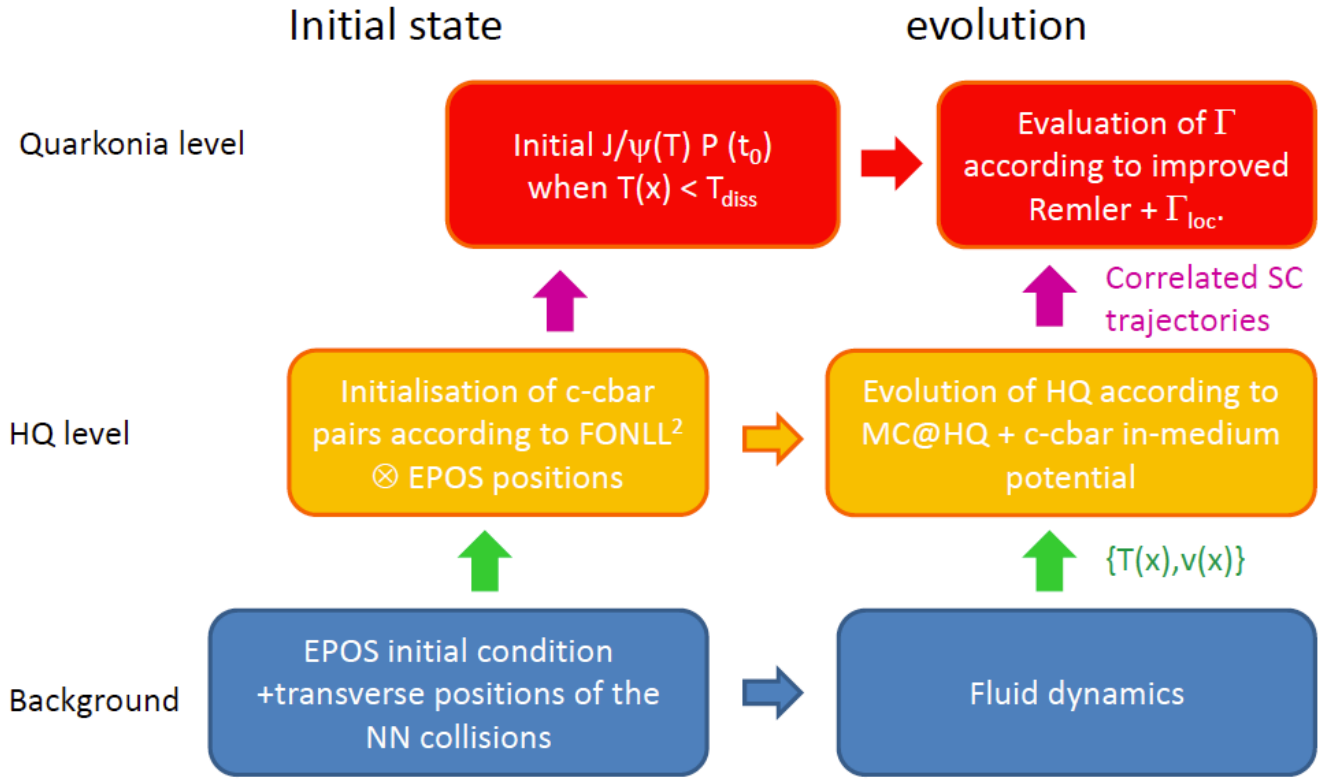
Development of this new approach fully boosted by NA7

- first time of a transport approach which follows the production of the individual c quarks until the J/ψ seen in the experiments

- contains potential interactions between c and cbar quarks

- contains collisions of the c and cbar with partons of the QGP

- phenomenological approach with the same structure as the Lindblad eq.
  (correct qm non equilibrium approach which is up to now only formal)



Expected result: enhanced production of low p_T J/ψ due to the potential interaction between c and cbar (taken from lattice QCD results)

J/Ψ CREATION IN HEAVY ION COLLISIONS

Starting point: von Neumann equation for the density matrix of all particles

$$\partial\rho_N/\partial t = -i[H,\rho_N] \quad \text{with} \quad H = \Sigma_i K_i + \Sigma_{i>j} V_{ij}$$

gives the probability that at time t the state Φ is produced:

$$P^\Phi(t) = \mathrm{Tr}[\rho^\Phi \rho_N(t)] \qquad \rho^\Phi = |\Psi^\Phi >< \Psi_\Phi|$$

This is the solution if we could calculate the quantal $\rho^N(t)$

In our semiclassical approach (correlations are lost) preferable to calculate the rate

$$\Gamma^\Phi(t) = \frac{dP^\Phi}{dt} = \frac{d}{dt}\mathrm{Tr}[\rho^\Phi \rho_N(t)] \qquad P^\Phi(T) = \int_0^T \Gamma^\Phi(t)dt$$

For time independent : ρ^Φ

$$\Gamma^\Phi = Tr(\rho^\Phi d\rho^N(t)/dt) = -iTr(\rho^\Phi[H,\rho^N(t)]) = -iTr(\rho^\Phi[U_{12},\rho^N])$$
$$U_{12} = \sum_{j\leq 3}(V_{1j}+V_{2j})$$

J.A., P.B. Gossiaux, D.Y. Arrebato Villar, Jiaxing Zhao

J/Ψ CREATION IN HEAVY ION COLLISIONS

Heavy ion studies (BUU,QMD,PHSD) have shown that we obtain very satisfying results if we assume

$$W = \langle W^{classic} \rangle$$

We assume in addition that heavy quarks and QGP partons interact by collisions only

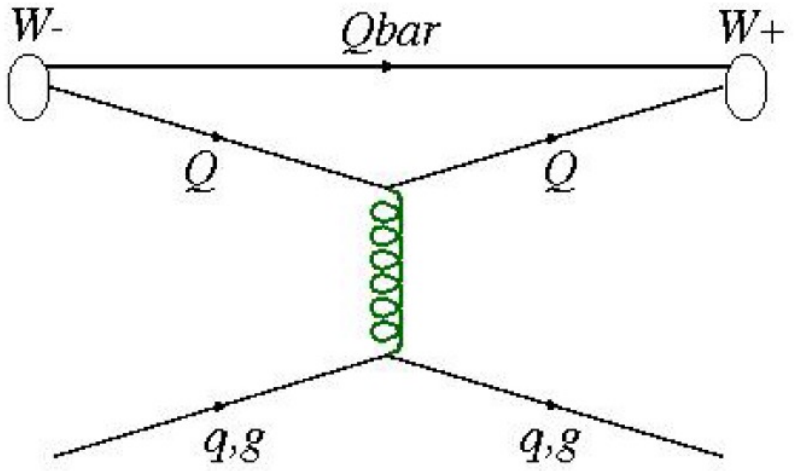
$$\frac{dP^{\Phi}(t)}{dt} = \prod_j^N \int d^3\mathbf{r}_j d^3\mathbf{p}_j \; W^{\Phi} \frac{d}{dt} W_N^c(t)$$

with

$$\begin{aligned} \frac{\partial}{\partial t} W_N^c(t) &= \Sigma_i v_i \cdot \partial_{r_i} W_N^c(\{\mathbf{r}\},\{\mathbf{p}\},t) \\ &+ \Sigma_{j\geq i} \Sigma_n \delta(t - t_{ij}(n)) \\ &\cdot (W_N^c(\{\mathbf{r}\},\{\mathbf{p}\},t+\epsilon) - W_N^c(\{\mathbf{r}\},\{\mathbf{p}\},t-\epsilon)). \end{aligned} \tag{19}$$

If the collisions are point like in time and if $W^{\Phi}(\mathbf{r}_1,\mathbf{r}_2,\mathbf{p}_1,\mathbf{p}_2)$ is time independent

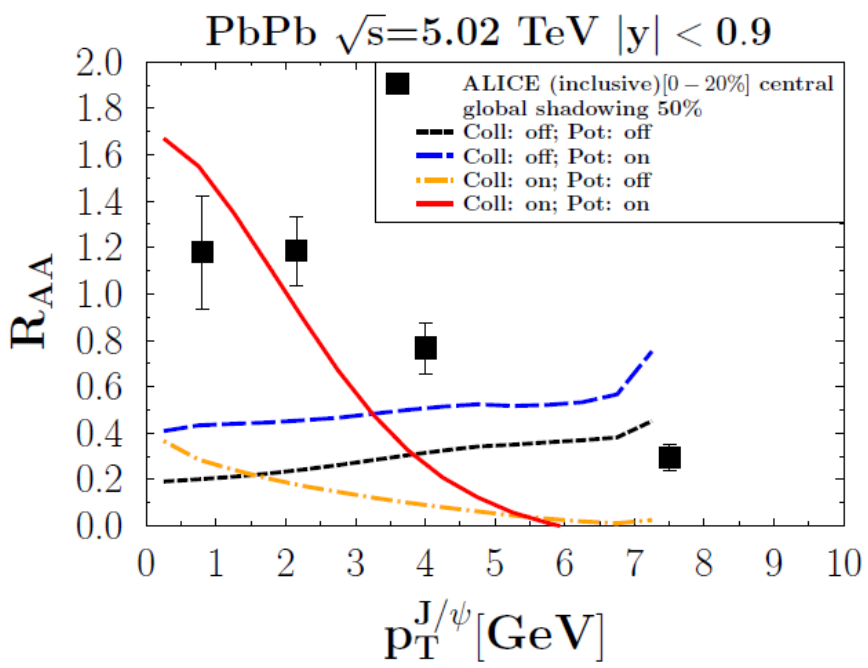
$$\begin{aligned} \Gamma^{\Phi}(t) &= \sum_{i=1,2} \sum_{j\geq 3} \delta(t - t_{ij}(n)) \prod_{k=1}^{N} \int d^3\mathbf{r}_i d^3\mathbf{p}_i \\ &\cdot W^{\Phi}(\mathbf{r}_1,\mathbf{r}_2,\mathbf{p}_1,\mathbf{p}_2) \\ &\cdot [W_N(\{\mathbf{r},\mathbf{p}\};t+\epsilon) - W_N(\{\mathbf{r},\mathbf{p}\};t-\epsilon \end{aligned}$$



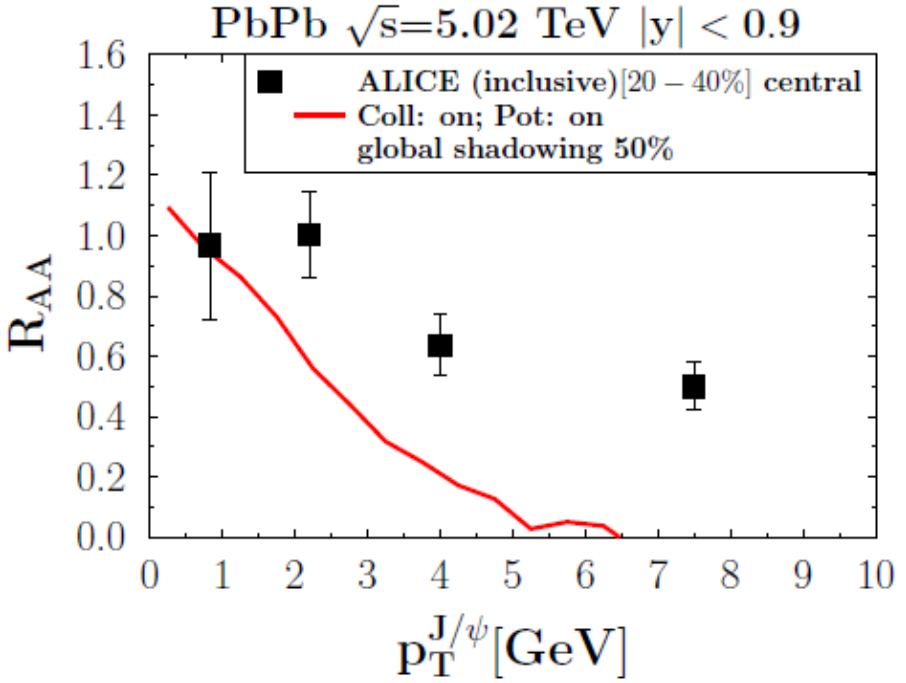
J.A., P.B. Gossiaux, D.Y. Arrebato Villar, Jiaxing Zhao

COMPARISON WITH ALICE DATA

[0-20%]



[20-40%]

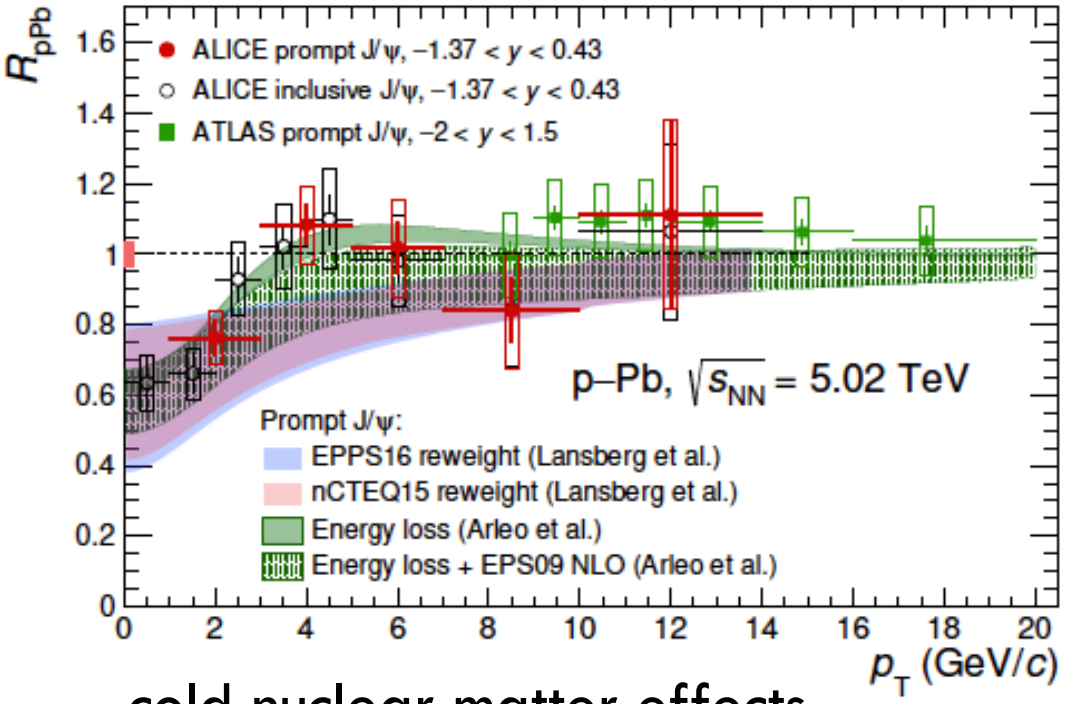


Caution: we compare inclusive ALICE data with calculation of direct prod.

J.A., P.B. Gossiaux, D.Y. Arrebato Villar, Jiaxing Zhao

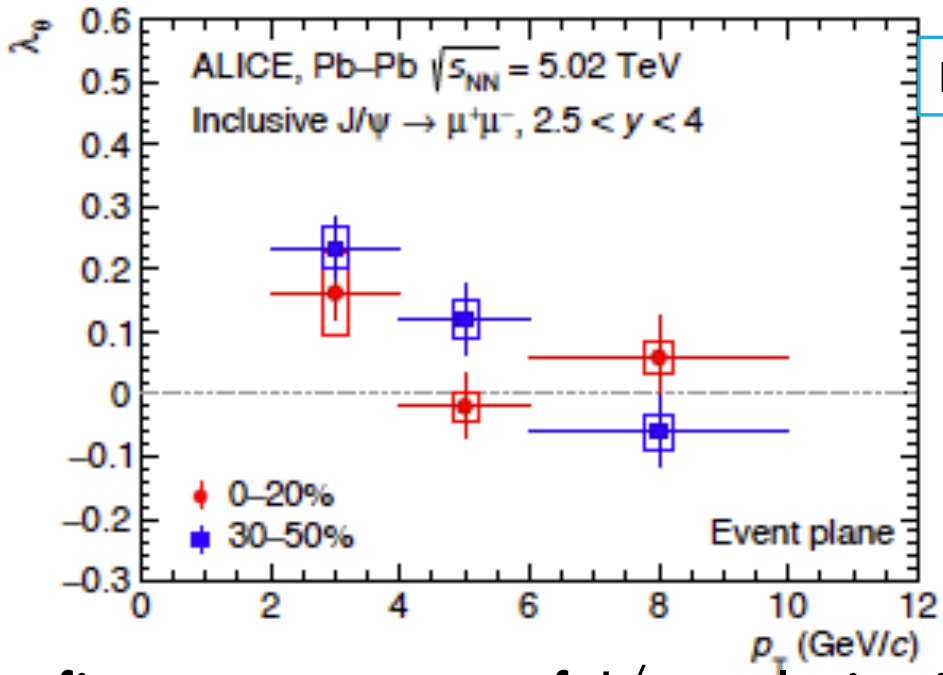
QUARKONIUM PRODUCTION: EXPERIMENTAL WORKS DONE THANKS TO SUPPORT OF STRONG-2020

JHEP06(2022)011



cold nuclear matter effects

arXiv:2204.10171, submitted to PRL



L. Micheletti

first measurement of J/ψ polarisation in HI

- Papers of experimental collaborations, so far with generic mention: "Individual groups and members have received support from the Horizon 2020 programme, European Union."
- Very recently also agreed (in ALICE) to mention the grant number (already in use in CMS)

MODIFICATIONS OF THE SCIENTIFIC WORK PLAN (AS COMPARED TO THE PLAN IN THE ORIGINAL AND AMENDED GRANT AGREEMENT)

- Being the networking activity mostly based on meetings, workshops, mutual visits, etc. the Covid pandemic had of course an impact w.r.t. the original work plan
  - e.g. the schedule of the three foreseen theory workshops was adjusted, postponing the first workshop to October 2021 (held regularly).

Actions were taken to face this unexpected situation:

- in the past amendment, we proposed a few modifications (all accepted) which facilitate us in reaching and fulfilling milestones and deliverables
- for a main deliverable of ours, we have used opportunistically an already existing framework (RIVET), putting a minor effort as originally foreseen, and thus concentrating the forces on other tasks

→ **all milestones and deliverables fulfilled or on reach at the due time of the amended grant agreement,** but eventually the last deliverable (and for a different reason)

POSSIBILITIES/NEEDS OF ANOTHER REQUEST FOR THE EXTENSION OF THE PROJECT

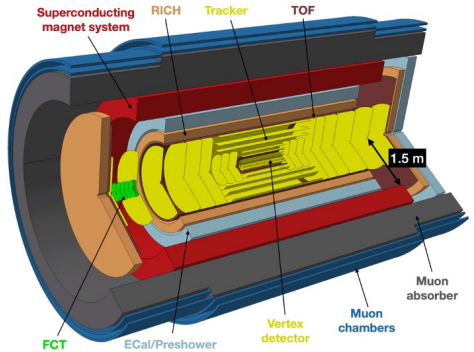
- All deliverables and milestones already passed or on the reach by the end of the project

- **Last deliverable** (D18.1) expected from our WP was a "Report with recommendation for the dedicated heavy-ion periods of LHC after Long Shutdown 2", **expected at M52**
  - LHC run3 and run4 time-shares and detector configurations quite well defined, and we have almost no influence on those anymore
  - heavy ion physics program at the LHC after LS4 (run5 and beyond) still to be shaped and supported

→efforts of the Networking Activity NA7 on this front

→contribution to the preparation of the Letter of Intent for "A next generation heavy-ion experiment at the LHC" https://cds.cern.ch/record/2803563 by post-docs (and staff) personnel employed (paid) with STRONG-2020 budget assigned to NA7

Further extension by few months might be useful to formally fulfil also D18.1, but not really determinant



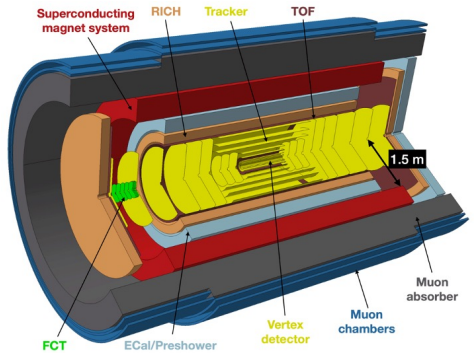
POSSIBILITIES/NEEDS OF ANOTHER REQUEST FOR THE EXTENSION OF THE PROJECT

- Further extension by few months might be useful to formally fulfil also D18.1

- <u>But more importantly</u>:
  a large fraction of the budget assigned to NA7 still to be spent

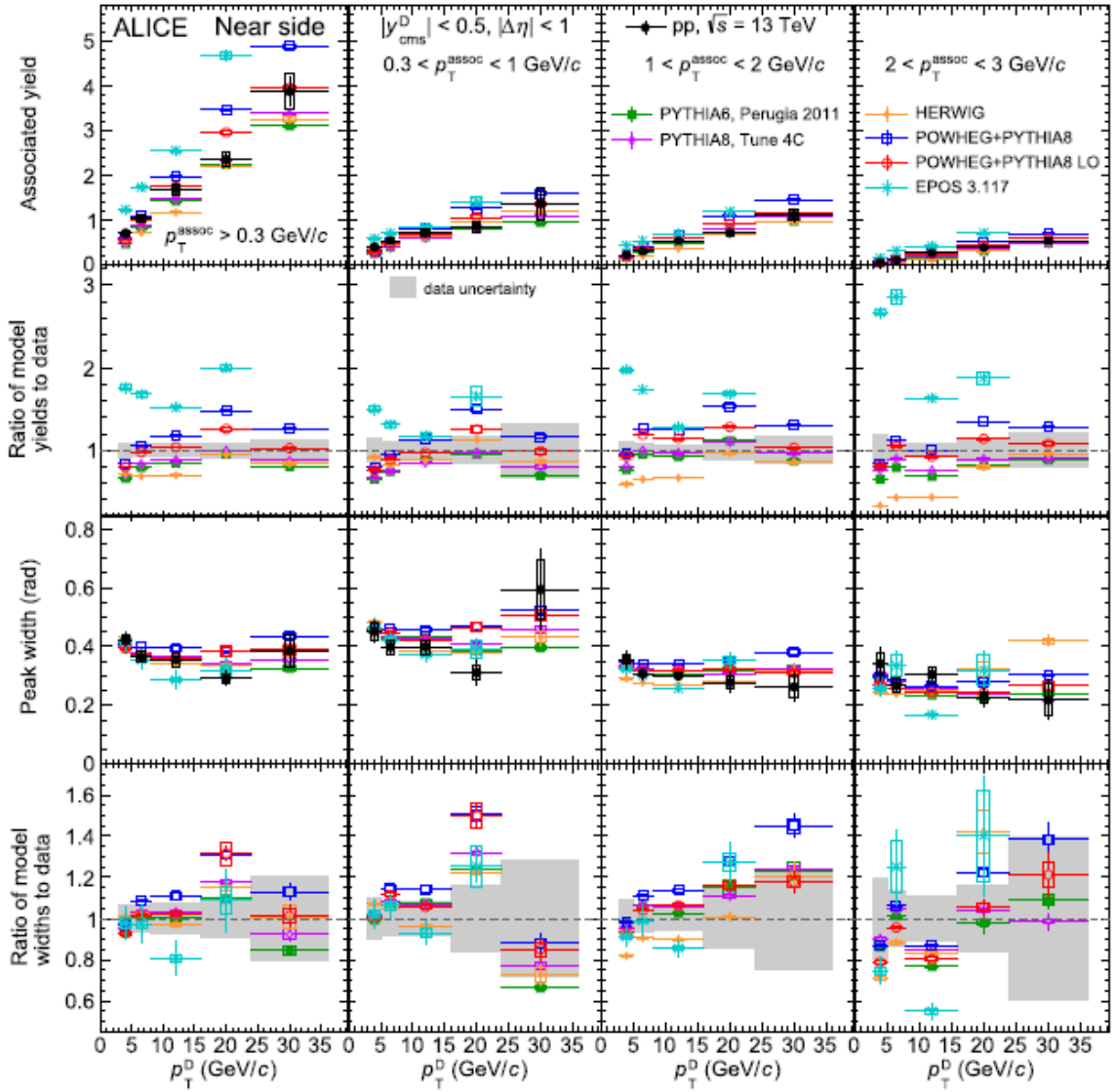
  - ~50% of budget for meeting/travel not yet used (due to Covid-19 pandemic)
  - budget for the cost of personnel (~125k€):
    - infn: no need of extension (budget fully allocated/accounted already)
    - cnrs: post-doc hired recently (Jiaxing Zhao) → extension of few months important for complete account of its cost

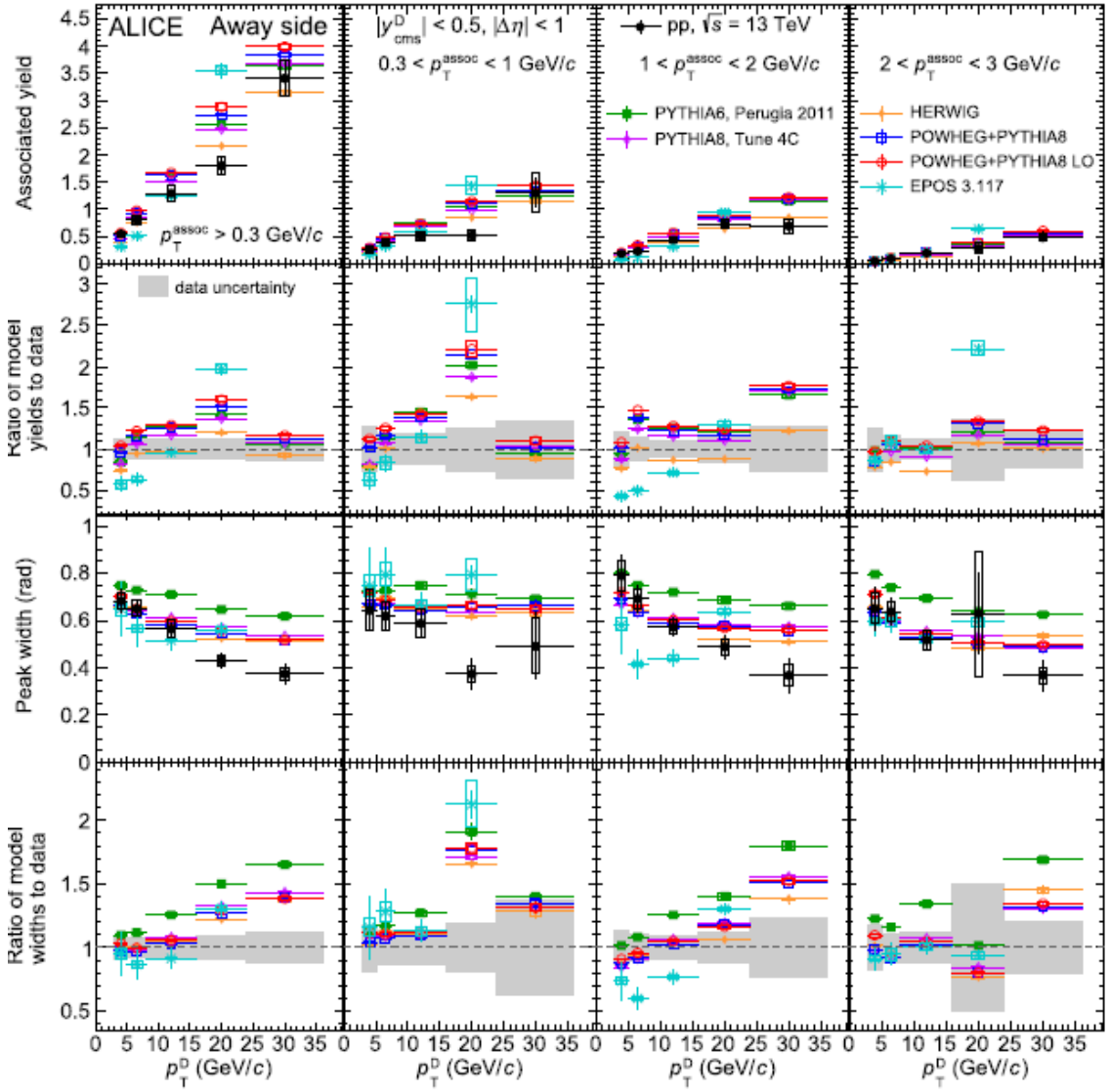
→ NA7 support the request of a further extension by few months



EXTRA SLIDES

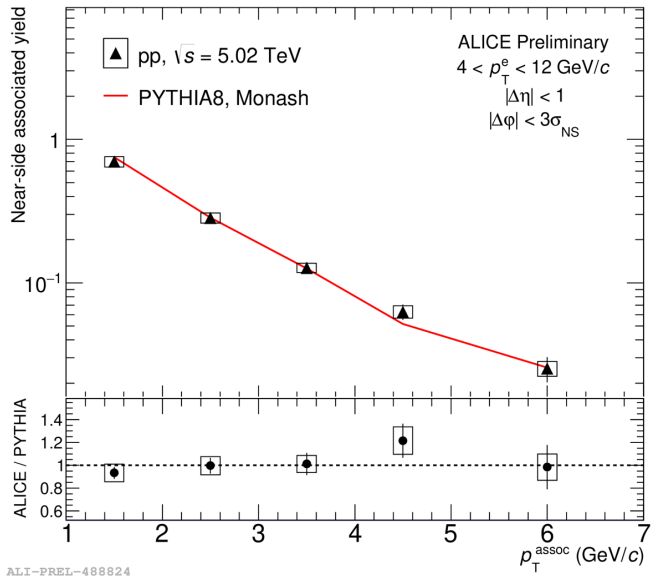
D-H CORRELATION MEASUREMENT IN PP COLLISIONS AT 13 TEV

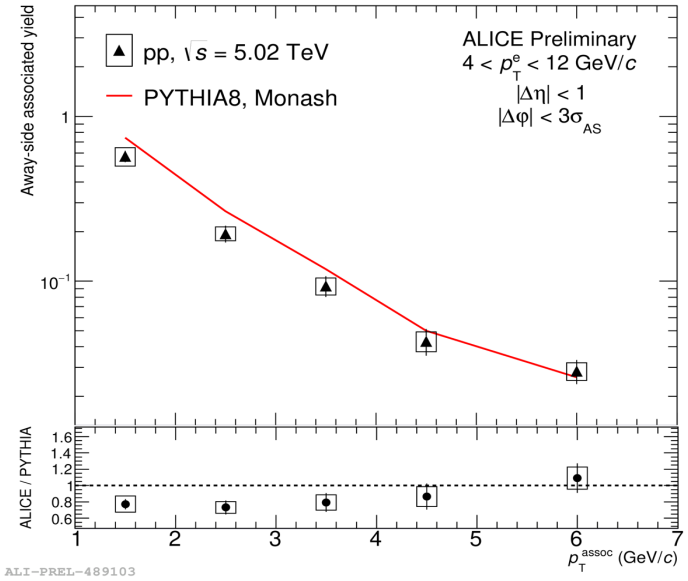


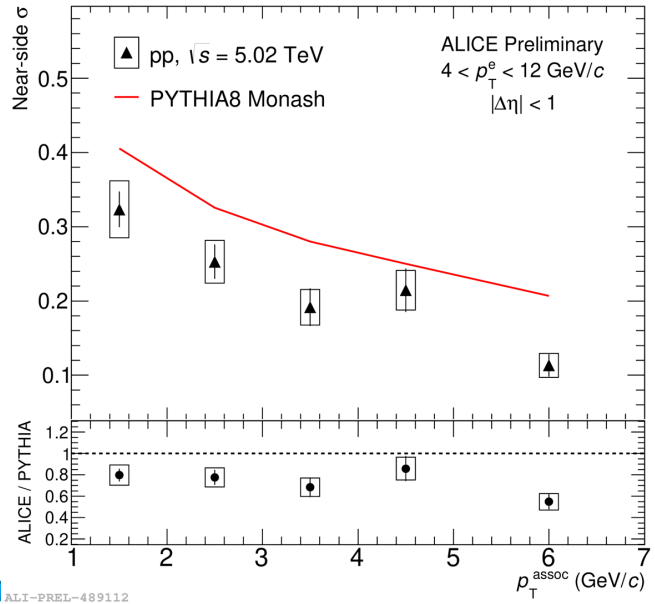


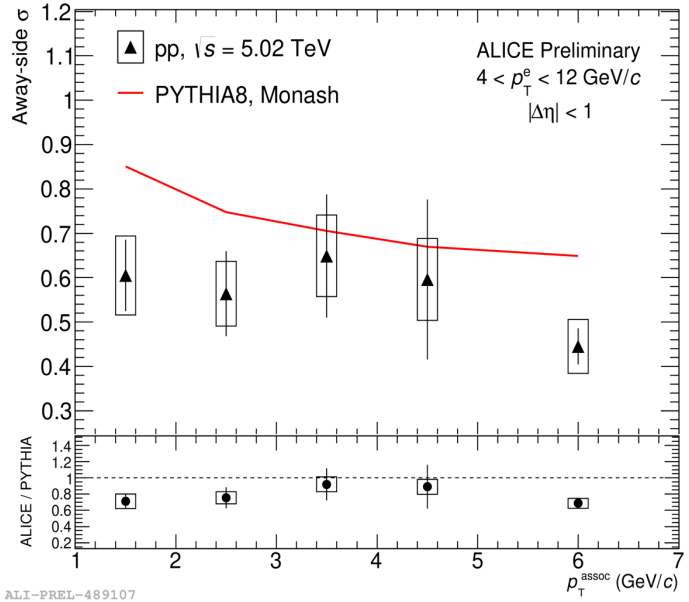
- Detailed characterization of near-and away-side correlation peaks over different kinematic ranges of D and particles

HFE-H CORRELATION MEASUREMENT IN PP AND P-PB COLLISIONS









- p_T evolution of near- and away-side peak yields and widths and comparison with PYTHIA8
- Further models/generators are being added for the publication