RECENT OPEN HEAVY FLAVOR RESULTS

M. Csanád (Eötvös U) for ALICE, ATLAS, CMS, LHCb
HEAVY FLAVOR PROBES TIME EVOLUTION

- Special role of heavy flavor: negligible thermal production (mass > temperature), Brownian motion
- From production at less than 0.1 fm/c until QGP lifetime: experience whole evolution
- Initial production:
  - pQCD, shadowing, pre-equilibrium effects, glasma, electromagnetic field, vorticity
- Dynamics in QGP
  - Heavy quark interaction, transport, thermalization
- Hadronization
  - Coalescence, fragmentation, rescattering
- Main heavy flavor observables:
  - Baryon/meson ratios: hadronization
  - $R_{AA}$: interaction, energy loss
  - $v_2$: coupling, thermalization

from Santosh Kumar Das, HP 2023
**PROMPT $Λ_C^+ / D^0$ RATIO AT 5.02 TEV**

- First measurement of prompt $Λ_C^+ / D^0$ at forward rapidities in PbPb [LHCb, arXiv:2210.06939]
  - Enhancement at intermediate $p_T$, PYTHIA8+CR compatible, Statistical hadronization (RQM+Frag) above data

  - Possibly due to interplay of coalescence and radial flow, or hadronic rescattering for PbPb

- $(Λ_C^+ + Λ_C^-) / (D^0 + D^0)$ consistent in pp and PbPb [CMS-PAS-HIN-21-004]
  - No significant contribution from coalescence?
Non-prompt $D_s$ and $D^0$ production measured in PbPb by ALICE

Compared to prompt results and model calculations

Larger non-prompt $R_{AA}$ than prompt $R_{AA}$
  - For both non-prompt $D_s$ and $D^0$
  - Larger impact of dead-cone effect for beauty

Hints of larger $D_s/D^0$ yields in AA than in pp
  - Coalescence production in a strangeness-rich environment

ALICE paper: arXiv:2204.10386

Further results in recent ALICE publications
  - JHEP 12 (2022) 126, JHEP 01 (2022) 174, etc.
CHARM QUARK HADRONIZATION IN PPB AT 8.16 TEV

- First conclusive measurement of $\Lambda_c/D^0$ vs multiplicity in pPb (note similar ALICE preliminary for QM22)
  - Different trend compared to strange sector: smaller dependence

- Extending the system, $p_T$, and centrality dependence
  - $\Lambda_c/D^0$ in pPb and MB PbPb consistent at intermediate momenta
  - High momenta: MB and central PbPb approach the ratio from $e^+e^-$: no coalescence
**PROMPT D^0 PRODUCTION IN PPB AT 8.16 TEV**

- Forward: suppression consistent with 5.02 TeV result, with nPDF and CGC
- Backward: data partly below nPDF at high $p_T$
- Room for additional effects at backward rapidity

LHCb paper: arXiv:2205.03936
**D⁰-TAGGED JET R⁰AA IN PbPb**

- Nuclear modification of D⁰-tagged jets in PbPb measured by ALICE
- Compared with single-particle D⁰ and inclusive-jets
- Larger R⁰AA for D⁰-jets than single-particle D⁰
  - in common p_T range
  - hadron-to-parton and jet-to-parton p_T scales differ
- Larger R⁰AA for D⁰-jets than inclusive jets
  - Here quark/gluon jet ratio and parton fragmentation differ

**Results:**
ALI-PREL-506534

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![Graph showing nuclear modification of D⁰-tagged jets](https://alice-figure.web.cern.ch/node/22030)
B-JETS IN PBPB COLLISIONS

- B-jets: different from inclusive jets due to quark mass
  - Medium-induced gluon radiation suppressed; lose smaller amount energy than gluon jets due to color factor

- B-jet ID: jets with muonic b-decays; template fit of muon momentum relative to jet axis
  - $R_{AA}$ decreased for more central events; larger for b-jets than for light-jets
  - Reason: different gluon fraction – b-mass subdominant at high $p_T$

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**ATLAS**

- Pb+Pb 2018, 1.4(1.7) nb$^{-1}$
- pp 2017, 260 pb$^{-1}$
- $\sqrt{s_{NN}} = 5.02$ TeV, Centrality 0-20%

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**ATLAS**

- Pb+Pb 2018, 1.4(1.7) nb$^{-1}$
- pp 2017, 260 pb$^{-1}$
- $\sqrt{s_{NN}} = 5.02$ TeV, Centrality 50-80%

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May 23, 2023

M. CSANÁD @ LHCP
Jet shape: Measure of charged particle $p_T$ distribution w.r.t. jet axis:

\[ P(\Delta r) = \frac{1}{\Delta r_b - \Delta r_a} \frac{1}{N_{\text{jet}}} \sum_{\text{jets}} \sum_{\text{trk} \in (\Delta r_a, \Delta r_b)} p_T^{\text{trk}} \]

\[ \rho(\Delta r) = \frac{P(\Delta r)}{\sum_{\text{jets}} \sum_{\text{trk} \in (\Delta r<1)} p_T^{\text{trk}}} \]

- Depletion of $p_T$ at small $\Delta r$ from jet axis
  - Already present in pp, consistent with a dead-cone
  - Quantitative measurement of dead-cone effect for b-jets?

- QGP modifies energy flow around b-jets
  - Transfer of $p_T$ from small to large radial distances?

- CMS paper: arXiv:2210.08547
**BOTTOM QUARK $R_{AA}$ IN PBPB**

- Electrons from b-decays measured by ALICE [arXiv:2211.13985]
- Consistent with models of b-quark energy loss
- Similar $R_{AA}$ of electrons from bottom and charm
  - C.f.: mass ordering or differences seen previously by PHENIX [2203.17058], STAR [2111.14615] and ATLAS [2109.00411]

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**Graphs**

- **Left Graph**: ALICE, $R_{AA}$ of electrons from b-decays in 0-10% Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.
- **Right Graph**: ALICE, $R_{AA}$ of electrons from b-decays in 0-10% Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

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May 23, 2023

M. CSANÁD @ LHCP

arXiv:2211.13985
EXPLORE ENERGY LOSS AND QGP EXPANSION: $R_{AA}$ AND $v_2$

- Constraining spatial diffusion coefficient
  - Different transport models for E-loss & hadronization
  - Simultaneous description: $1.5 < 2\pi D_s T_c < 4.5$
  - HF probes becoming powerful tomography tools

- Measurement of $R_{AA}$ and $v_2$ for c and b
  - Mass splitting of $v_2$ at low $p_T$, convergence at high $p_T$
  - Charm $D_s$: 2.23 (bottom: 2.79); in line with ALICE

ALICE

ALI-DER-499016
NON-PROMPT D⁰ ELLIPTIC FLOW IN PbPb

- Non-prompt D⁰ ν₂ measured in 30-50% PbPb by ALICE, compared with prompt D⁰
- Non-zero non-prompt flow observed, although smaller than prompt and larger uncertainties
- LIDO model compatible with current and earlier data on b(→ c) → e

https://alice-figure.web.cern.ch/node/21498

Baryon-meson ratios
Nuclear modification
Flow
PROMPT AND NON-PROMPT HEAVY FLAVOR $V_2$ AND $V_3$

- Prompt and non-prompt $D^0$: DCA separation
- Charm $v_2$ and $v_3$: affected by flow and energy loss characteristics
- Bottom: less flow, more resistant to collective effects, but still path-length dependent energy loss

![Graph showing $v_2$ and $v_3$ for different centrality classes]
HEAVY FLAVOR FLOW HIERARCHY

- Bridging heavy flavor flow measurements in small and large systems
- Clear mass hierarchy: heavier particles exhibit less flow in PbPb and in high-multiplicity pPb as well
  - $h^\pm$, $D^0$, $J/\psi$, $b \to D^0$, $b \to J/\psi$, $Y(1S)$
- Question: open/closed b flow as well?

https://boundino.github.io/hinHFplot/
SUMMARY

- Many HF observables measured at LHC
  - Baryon/meson ratios ($\Lambda_c/D^0$)
    - Role of coalescence
  - Suppression ($R_{AA}$)
    - D- and b-tagged jets measured
    - Understanding energy loss and fragmentation
  - Azimuthal anisotropy
    - Non-prompt $D^0$ $v_2$ observed
    - Heavy flavor $v_2$ and $v_3$: even for bottom
    - Clear heavy flavor flow hierarchy established

THANK YOU FOR YOUR ATTENTION!
PROMPT $\Lambda_C^+/D^0$ RATIO AT 5.02 TEV WITH LHCB

- First measurement of prompt $\Lambda_C^+/D^0$ at forward rapidities in PbPb [arXiv:2210.06939]
  - Flat ratio versus multiplicity and rapidity, enhancement at intermediate $p_T$
- Pythia8 + color reconnection: compatible with the data within $3\sigma$
- Statistical Hadronization Model (RQM+Frag): above the data
- Need better understanding of charm hadronization
**Λ⁺/D⁰** RATIO MEASURED BY ALICE

- **Λ⁺/D⁰** ratio (and individual yields) measured in PbPb [ALICE, arXiv:2112.08156]
  - Enhanced ratio in PbPb compared to pp at intermediate $p_T$
    - Although integrated ratios compatible in PbPb and pp
    - Possibly due to interplay of coalescence and radial flow, or hadronic rescattering for PbPb

- Models capture the trend of the data
  - Statistical hadronization models extended to charm hadron production
  - Models including hadronization via coalescence

![Graphs showing ALICE data for Λ⁺/D⁰ ratio in Pb-Pb collisions compared to pp collisions.](image-url)
CHARM QUARK HADRONIZATION IN PP AND AA WITH CMS

- PYTHIA+CR describes \( \frac{\Lambda_c^+ + \Lambda_c^-}{D^0 + \overline{D^0}} \) at \( p_T < 10 \) GeV in pp, similar to models
  - Containing decays of excited charm baryons; involving coalescence and fragmentation

- New results extend the \( p_T \) and centrality reach in PbPb
  - Ratio in pp and PbPb consistent: no significant contribution from coalescence
HEAVY FLAVOR HADRONIZATION IN PP WITH ALICE

- Charm baryon/meson ratios partially explained by models with modified hadronization mechanism

- $\Lambda_C^+/D^0$: Pythia Monash underestimates results, models with baryon enhancement work qualitatively
  - Ingredients: color reconnection, feed-down from unobserved charm baryons or coalescence (recombination)

- $D^0$ non-prompt fraction $f_{\text{non-prompt}}$: slight increase with $p_T$, no multiplicity dependence
  - Important test for hadronization models in HF sectors

**Figure:**

- $\Lambda_C^+/D^0$ vs. $p_T$ for ALICE pp, $\sqrt{s} = 5.02$ TeV, $|y| < 0.5$
- $D^0$ meson $|\eta| < 0.5$
- $D^+\text{ meson }|\eta| < 0.5$
CHARM ELLIPTIC FLOW IN AA WITH CUMULANTS

- Prompt $D^0$ elliptic flow measured with 2- and 4-particle cumulants: $v_2\{2\}$ and $v_2\{4\}$
  - Two-step fit process: mass spectrum and cumulant fit in $p_T$ intervals and centrality ranges

- Similar cumulant ratio as charged particles, pointing to similar origin: event-by-event fluctuations