Heavy quark production and the initial stages: progress and open questions

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Outline

- Importance of the initial stages for Quark-Gluon-Plasma physics
- Initial stages for & with heavy-quarks:
  successes, caveats & future developments at the LHC
- The preequilibrium and charm production
- Conclusions

Heavy-ion collisions: laboratory for strong interaction

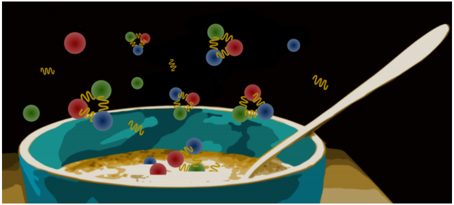


figure by A. Ershova, Harvard university.

- matter properties at high temperature
  transition from Quark-Gluon Plasma (QGP) to hadrons
  classical QGP physics

  Busza, Rajagopal, von der Schee, ARNPS 68 (´18)

- hadron factory different from e^+e^-, pp collisions & particle decays
  hadron spectroscopy & interactions

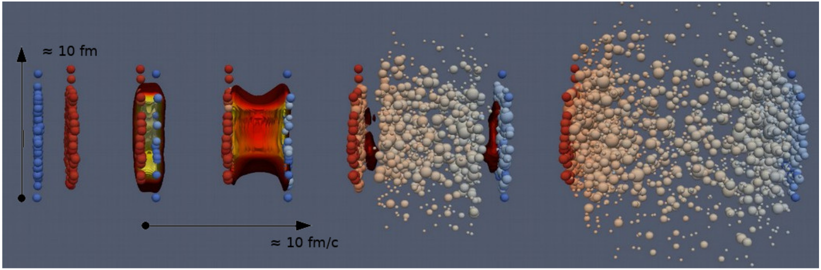
  Braun-Munzinger, Dönigus, NPA 987 (´19)

- initial state of nuclear collisions
  hadron and nuclear structure

  Ethier,Nocera, ARNPS 70 (´20), arXiv:2311.00450, Paukkunen, Klasen Gelis et al., ARNPS 60 (´10), thesis G. Giacalone

- thermalisation under extreme conditions
  far-from-equilibrium strong interaction Schlichting Teaney, ARNPS 69 (´19)

Heavy-ion collisions at colliders in a nut-shell

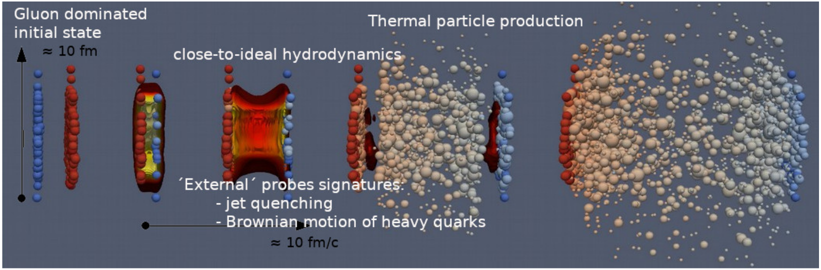


Visualisation of a hydrodynamic simulation of a nucleus-nucleus collision by Madai project web page.

Time ordered ´standard model´ at colliders

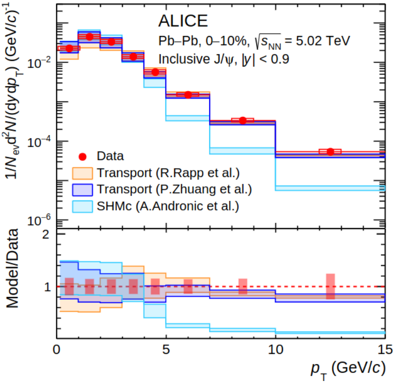
- **initial state**
- **preequilibrium phase** (≈ 0-1 fm/c)
- hydrodynamic phase (≈ 1-10 fm/c)
- hadronisation

Heavy-ion collisions at colliders: key observations



- ´ideal liquid´: nearly ideal hydrodynamics for energy-momentum flow
  review: Gale, Jeon, Schenke; Int.J.Mod.Phys.A 28 (2013), 1340011
- ´jet quenching´: energy loss of energetic partons in matter
  review: Apolinário, Lee, Winn; Prog.Part.Nucl.Phys. 127 (2022) 103990
- ´Brownian motion´ & tests of deconfinement with heavy quarks
  review: Apolinário, Lee, Winn; Prog.Part.Nucl.Phys. 127 (2022) 103990
- ´thermal matter´: chemical equilibrium at hadronisation
  review: Andronic, Braun-Munzinger, Redlich, Stachel; Nature 561 (2018) 7723, 321
- ´small systems´: continuities proton-proton/nucleus to nucleus-nucleus
  review: Nagle, Zajc; Ann.Rev.Nucl.Part.Sci. 68 (2018) 211

J/ψ production: signature of deconfinement

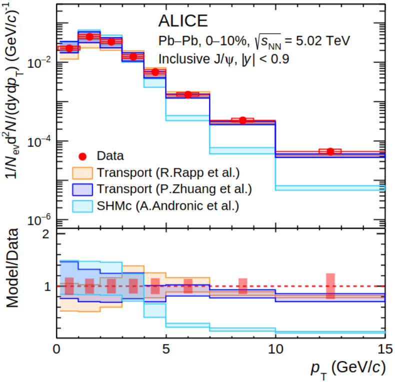


arXiv:2303.13361, accepted by PLB.

- late-stage bound state production: deconfinement signature
- two conceptually different scenarios describe the data: statistical hadronisation & transport models

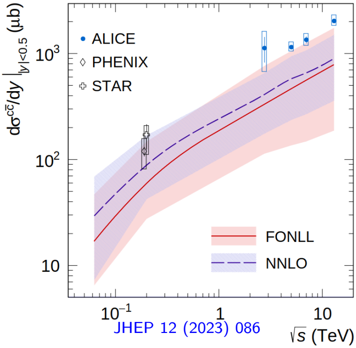
statistical hadronisation (SHM): PLB797 (2019) 134836, transport (Rapp) NPA 943, (2015). transport (Zhuang): PRC89, 5(2014)

J/ψ production: deconfinement & the initial state



- common uncertainty: total charm production in nucleus-nucleus collisions
  $\rightarrow$ different value required to describe data
  in transport a factor 2 larger than in statistical hadronisation
  $\rightarrow$ however, total charm is an actual observable

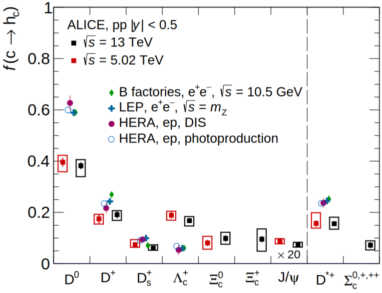
Total charm production in PbPb collisions: theory uncertainties



JHEP 12 (2023) 086

- collinear pQCD calculations describe hadroproduction in proton-proton collisions
- But: uncertainties very large
  → charm mass small: large scale uncertainties
- rely on measurement:
  → feasible: dominating open charm hadrons decay weakly
  → decay vertex displacement

Total charm production in PbPb collisions: experiment



JHEP 12 (2023) 086

- charm fragmentation fraction not universal between proton-proton compared to ee
  $\rightarrow$ experimental challenge to make the sum: proton-proton aroun 12% uncertainty achieved
  $\rightarrow$ not yet achieved in PbPb, extrapolations from PbPb data model-dependent
  $\rightarrow$ goal of future measurements at the LHC
- what can we do in the mean-while for total charm produced in PbPb?

Total charm production in PbPb: extrapolate from pp

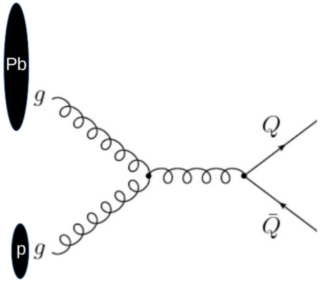
Assume:

1. charm production only from initial hard scatterings
2. charm predominantly gluon produced at the LHC
3. consider only gluon density modification in nucleus compared to nucleon

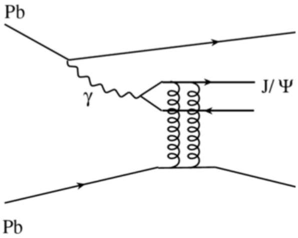
Total charm production in PbPb: extrapolate from pp

- start from pp measurements including all baryons:
  available in pp at midrapidity (ALICE), to be done forward (LHCb)
- take ratios of pPb to pp inelastic particle production and γPb to γp exclusive production
  $\rightarrow$ theory ratio uncertainties dominated by parton density uncertainties, not by pQCD
  $\rightarrow$ hence: gluon density modification in the nucleus compared to the proton
- need processes amenable to pQCD probing at scales (Q^2,x) of charm

Total charm production in PbPb: extrapolation processes

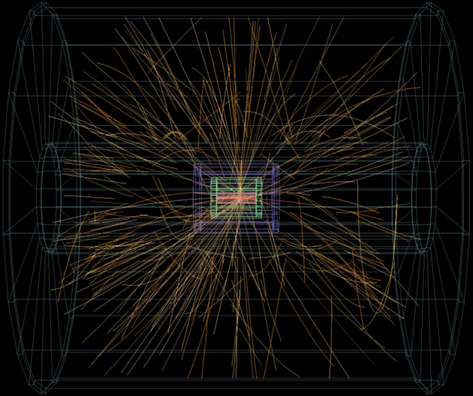


Inclusive heavy-flavour hadron production in proton-nucleus collisions



Exclusive photo-production in ultra-peripheral nucleus-nucleus collisions

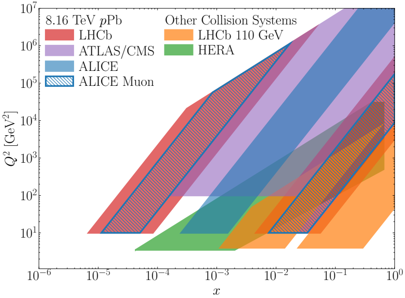
Inelastic Proton–nucleus collisions: constrain nuclear gluon density

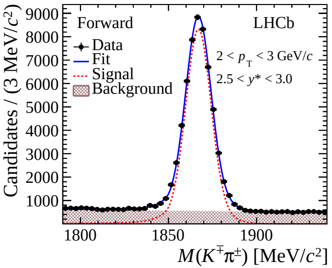


p–lead (pPb) event display
with ALICE Time Projection Chamber

Average charged track multiplicity about 3 $\times$ average pp multiplicity

Why using charm and beauty in pPb collisions?

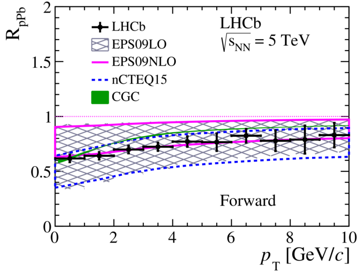


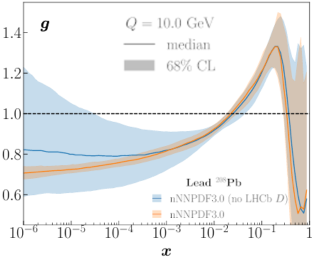


$Q^2 - x$ plane by T. Boettcher (MIT), LHCb JHEP 10 (2017).

- (semi)-hard scale, mostly gluon initiated production
- high production rate, good signal over background
- large phase space coverage with adequate instrumentation
  $\rightarrow$ cover Bjorken-x for heavy-flavour production in nucleus-nucleus
  & (nearly) any other processes amenable to pQCD

Charm and beauty results in pPb: strong suppression





charm included in global fits: LHCb JHEP 10 (2017), $R_{pPb} = \sigma_{pA}/(A_{Pb} \cdot \sigma_{pp})$ nPDF with charm example: nNNPDF3.0 EPJC 82 (2022) 6.

- interpreted as strong depletion of gluons at low Bjorken-x in global fits

  EPPS21 EPJC 82 (2022) 5, nNNPDF3.0 EPJC 82 (2022) 6, global nCTEQ fit under preparation,

  sensitivity for heavy-flavour studied input paper

- charm production also described within Color Glass condensate

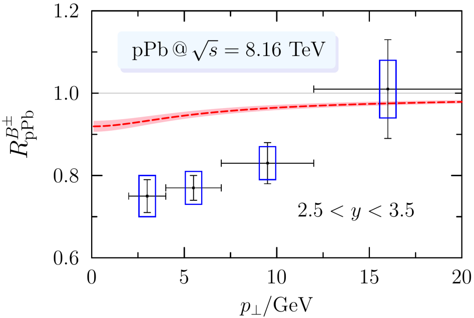
  low-x effective field theory, Ducloué et al. PRD 91, 114005 (2015)

- depletion confirmed with recent measurements

  beauty: Phys.Rev.D 99 (2019) 5, charm PRL 131 (2023) 10, 102301 charged particles PRL 128 (2022) 14

  and neutral pions PRL131 (2023) 4, 042302

Charm & beauty in pPb collisions: possible caveats



beauty LHCb JHEP 01 (2022) 164

- energy loss: as important as parton depletion? JHEP 01 (2022) 164
- midrapidity tend to weaker suppression
  to be investigated with more precision JHEP 12 (2019) 092
- hadronisation from proton-proton to proton-nucleus
  small variations for baryons e.g. ALICE in PRL 127 (2021)
- kinematics partially driven by effects beyond perturbative calculations?
  e.g. ALICE in PLB 780 (2018) 7-20, PLB 791 (2019) 172

Outlook for inclusive pPb measurements for parton densities

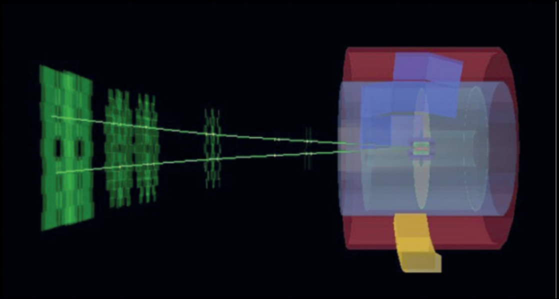
- address role of energy loss by Drell-Yan measurements in LHCb, predicted to be not affected:
  program starting in Saclay in 2024 with existing data

- measure photon production in pPb in 20ies with LHCb and ALICE
  Forward calorimeter under construction

- measure total charm and beauty ratios between pp and pPb:
  remove or strongly reduce uncertainties related to hadronisation

- global comparison of collinear and saturation-based models:
  to be redone after these ´cleaner´ measurements & improved calculations

Photoproduction to constrain gluon densities & hadron geometry

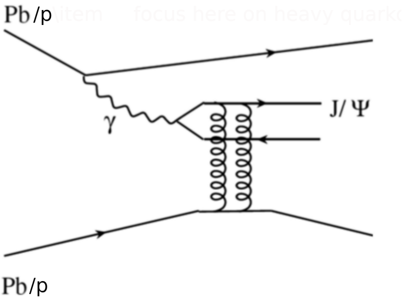


Ultra-peripheral collisions: J/ψ candidate in muon arm of ALICE with otherwise empty detector

Using LHC beams as source of quasi-real photons and collide with hadrons:

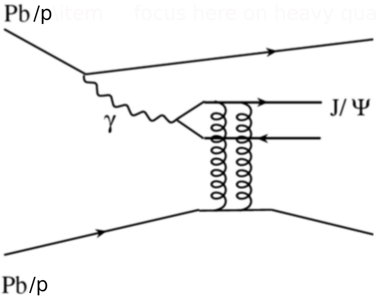
avoiding complications from hadronisation and rescattering

Exclusive vector meson production in ultra-peripheral collisions



- exclusive vector meson production via γ-pomeron scattering
- sensitive to generalised gluon distributions for Bjorken-$x \in 10^{-2} - 10^{-5}$
- for small $q\bar{q}$ at leading twist, $t \to 0$: $\sigma \propto$ (gluon PDF)^2
  (Brodsky et al. Phys.Rev.D50:3134-3144,1994)

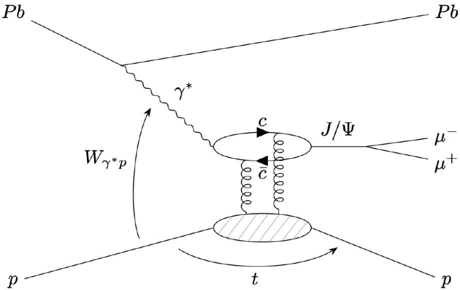
Motivation: coherent quarkonium production in UPC



- ultra-peripheral collisions:
  instrumentation and rate limitations, restriction to photo-production

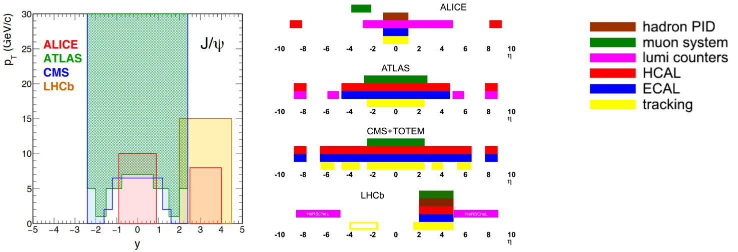
- quarkonium coherent photoproduction:
  most prominent accessible observables with hard scale provided by heavy quark mass
  $\rightarrow$ amenable to perturbative QCD calculations
  $\rightarrow$ matches naturally kinematics for deconfinement studies

From UPC to γ-hadron cross section



- incoming hadron energy known, hadron-hadron luminosity measured
- photon fluxes: QED calculation & nuclear form factors
- quantify γ-hadron process: determine W and Mandelstam-t
  $\rightarrow$ first t-dependent γPb J/ψ measurements by ALICE
  $\rightarrow W^2 = 2 \cdot E_p M_{jpsi} exp^{\pm y_{jpsi}}$, $t \approx -p^2_{T,J/\psi}$, for $t \rightarrow 0$: $1/x = W^2/M^2_{jpsi}$
- a priori unknown photon emitter: two contributions $\pm y$

Experimental set-ups



Acceptance of *pp* inclusive charmonium measurements by T. Dahms link.

- bulk of coherent/incoherent J/ψ photoproduction: $p_{T,jpsi} << m_{jpsi}$
  $\rightarrow$ complementary acceptance of LHC experiments
- different forward instrumentation, luminosities, triggers and resolution
- ALICE, CMS and LHCb:
  $\rightarrow$ important contributions to quarkonium measurements in UPC
  $\rightarrow$ partial redundancy to check for consistency

γ-proton collisions

reference measurement for the nucleus

γ-proton collisions: extract W-dependence using *pp* & HERA

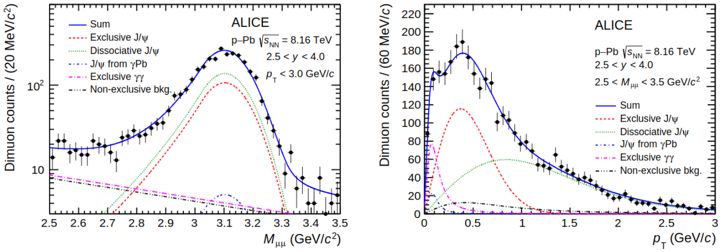
- measure at midrapidity, where it does not matter (not done)
  $\rightarrow$ limited to 1 W-point per centre-of-mass energy

- LHCb: deconvolute assuming power-law dependence for low-W component based on HERA measurements: $\sigma_{\gamma p \rightarrow \psi p} = a(W/90\text{GeV})^{\delta}$
  $\rightarrow$ LHCb dimuon forward rapidity in pp at $\sqrt{s_{pp}} = 7, 13$ TeV
  $\rightarrow$ profit from large luminosity at still relatively low pile-up μ about 1
  W-range for J/ψ up to almost 2 TeV

$$\sigma_{pp \rightarrow p\psi p} = r(W^{+})k_{+}\frac{dn}{dk_{+}}\sigma_{\gamma p \rightarrow \psi p}(W_{+}) + r(W^{-})k_{-}\frac{dn}{dk_{-}}\sigma_{\gamma p \rightarrow \psi p}(W_{-})$$

$k_{\pm} = M_{\psi}/2e^{\pm y}$ r: survial factor (taken from calculation), $\frac{dn}{dk}$: photon flux, see JHEP 10 (2018) 167 J/ψ 13 TeV: LHCb-PAPER-2018-011, JHEP 10 (2018) 167; Υ 7,8 TeV: JHEP 1509 (2015) 084, LHCb-PAPER-2015-011; J/ψ/ψ(2S) 7 TeV: J. Phys. G41 (2014) 055002, LHCb-PAPER-2013-059; J/ψ/ψ(2S) 7 TeV: J. Phys. G40 (2013) 045001, LHCb-PAPER-2012-044

γ-proton collisions: extract W-dependence using pPb

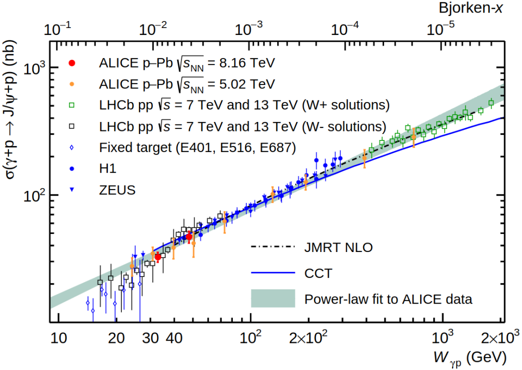


PRD 108, 112004 (2023)

- pPb collider: Pb in 95% of the cases photon emitter
- typical t of γ-p and γ-Pb very different due to different digluon p_T
  $\rightarrow$ ´subtract´ γ-Pb
  $\rightarrow$ ALICE measurements for J/ψ at $\sqrt{s_{NN}} = 5, 8.16$ TeV
  $\rightarrow$ cover broad W-range from 20 up to 700 GeV

J/ψ 8.16 TeV (fwd rapidity): arXiv:2304.12403(accepted by PRD), J/ψ 5 TeV with both tracks barrel and barrel muon+ forward muon pair: EPJC (2019) 79: 402 J/ψ 5 TeV (fwd rapidity): PRL 113 (2014) 232504, CMS Υ at 5 TeV: EPJC 79 (2019) 277; Erratum: EPJC 82 (2022) 343

Results on exclusive production



compilation from arXiv:2304.12403, accepted by PRD put ref

- good agreement between experiments within uncertainties
- need precise high-W from pPb: confirm LHCb high-energy solution
- strong sensitivity to constrain gluons at low-x $\rightarrow$ steps towards PDF-fit

  e.g. sensitivity proton Flett et al.PRD 102 (2020) 114021, NLO calc. for Pb Eskola et al. PRC 106 (2022)
- however exclusive: generalized parton distributions, not PDFs
  $\rightarrow$ develop more rigorous theory uncertainty for ´PDF´-extraction

Dutrieux, Winn, Bertone. PRD 107 (2023)

Motivation for dissociative production: measure fluctuations

incoming ($|i\rangle$) and outgoing state ($|f\rangle$) different

$$use: \sum_{f\neq i} |\langle f|A|i\rangle|^2 = \sum_f \langle i|A^*|f\rangle\langle f|A|i\rangle - \langle i|A|i\rangle\langle i|A^*|i\rangle$$
$$= \langle i|A^*A|i\rangle - |\langle i|A|i\rangle|^2$$

average over i :

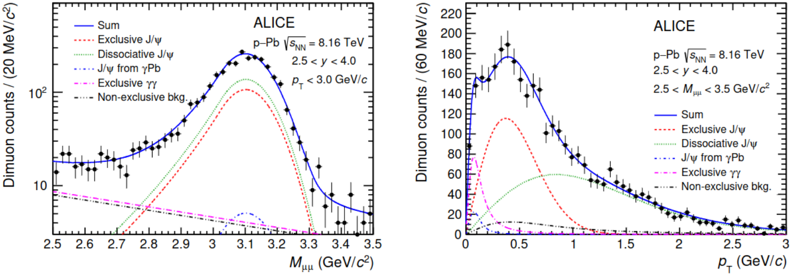
$$\frac{d\sigma^{\gamma^* p\to p^*\ J/\psi}}{dt} = \frac{1}{16\pi}\left(\langle|\mathcal{A}^{\gamma^* p\to pJ/\psi}|^2\rangle - |\langle\mathcal{A}^{\gamma^* p\to pJ/\psi}\rangle|^2\right)$$

p: proton (also valid for nuclei), p^* proton excited, J/ψ could be any vector, recent review in H. Mäntisaary Rep. Prog. Phys. 83 (2020), ´Good-Walker´ formalism, also in Frankfurt, Strikman, Treleani, WeissPRL 101 (2008) 202003.

$\rightarrow$ dissociative (´incoherent´): variance $< x^2 > - < x >^2$, not average $< x >^2$

- γp: dissociative production $\rightarrow$ fluctuations of the proton
- unique high-energy reach at the LHC

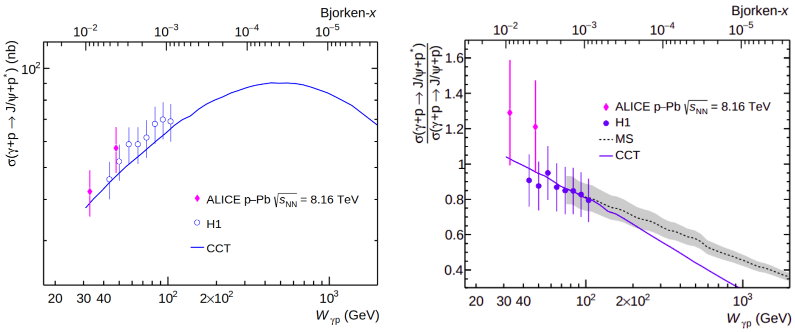
Analysis key aspect: signal extraction



- Exclusive: shape fixed with pure exclusive sample
- Dissociative J/ψ parameterisation following HERA measurement
- γ-Pb production fixed from PbPb measurement

details in thesis by Aude Glaenzer conducted at CEA-Saclay link, also at UPC2023 slides

Results on dissociative production



PRD 108, 112004 (2023)

- measurement compatible with H1 results, similar precision for absolute cross section
- larger uncertainty on ratio
  anticorrelation of statistical and signal extraction uncertainties
  $\rightarrow$ **proof-of-principle**
- in future: cover full available kinematics at the LHC up to $W = 1\,TeV$

γ-lead collisions

constrain nuclear gluon densities

γ-lead:
extract W-dependence directly

Direct approaches:

- measure at midrapidity, where W the same for both emitters
  $\rightarrow$ ALICE measurements at 2.76 TeV and 5 TeV
- measure in pPb collisions, where only one lead
  $\rightarrow$ need to isolate w.r.t. dominating γ-p, not done so far

γ-lead: W-dependence via impact-parameter dependent photon fluxes

$$\frac{d\sigma_{PbPb}}{dy} = n_\gamma(y,\{b\})\sigma_{\gamma Pb}(y) + n_\gamma(-y,\{b\})\sigma_{\gamma Pb}(-y)$$

If:

- several independent measurements with different sampled impact parameters b
- capacity to calculate $n_\gamma(y,\{b\})$ precisely

$\rightarrow$ system of equations to extract $\sigma_{\gamma Pb}$ from $d\sigma/dy$

γ-lead: W-dependence via impact-parameter dependent photon fluxes

Two approaches realised:

- measure in neutron emission classes via zero degree calorimeters
  $\rightarrow$ proposed by Baltz et al. PRL 89 (2002) 012301 and by Guzey et al. EPJC 74 (2014) 2942
- measure in peripheral and ultraperipheral collisions
  $\rightarrow$ proposed by J. G. Contreras PRC 96 (2017) 015203

1st method:
modeling of photon fluxes associated to neutron emission
$\rightarrow$ done with $n_0^0 n$ model in ALICE, CMS with Starlight

see discussion and reference in ALICE publication for differences JHEP 10 (2023) 119, relevant difference for most forward bins

2nd method:
neglect difference (or model difference in future) in peripheral collisions
take impact parameter from centrality determination in hadronic collisions

γ-lead: W-dependence results compilation

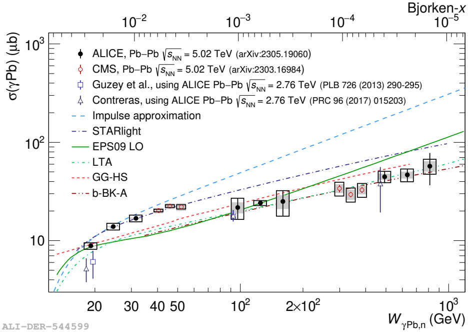


Figure from ALICE JHEP 10 (2023) 119 including CMS data PRL131 (2023) 262301

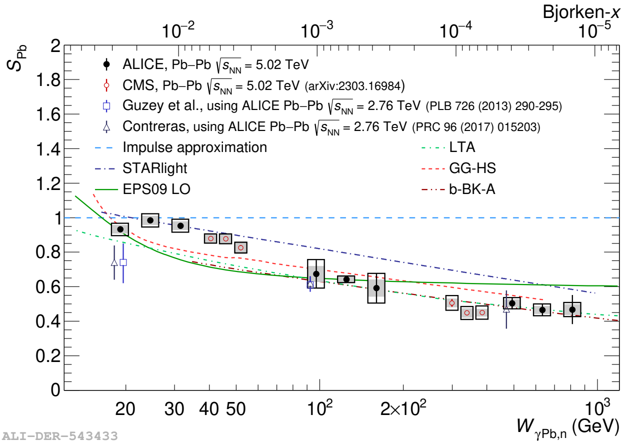
- both methods agree, compatibility between experiments
- strong nuclear suppression based on impulse approximation (IA) comparison
  $\rightarrow$ consistent with findings based on inclusive heavy-quark *pPb* data
- model spread much larger than experimental uncertainties
  no model curve describes all measurement points

γ-lead: nuclear suppression factor

$$S = \sqrt{\frac{\sigma_{\gamma Pb}}{\sigma^{IA}_{\gamma Pb}}}$$

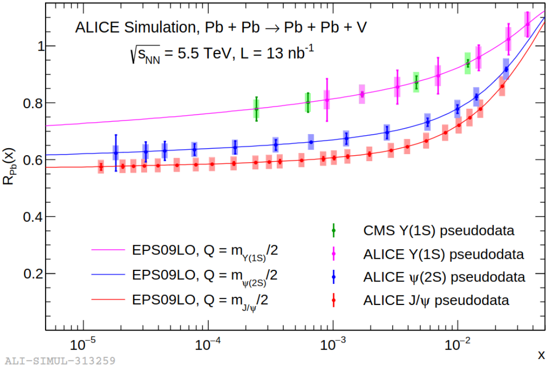
- observable to quantify nuclear effects introduced by Guzey et al.
  EPJC 74 (2014) 2942
- ALICE and CMS use calculation from Guzey et al.
  5% uncertainty assumed by authors based on parameterisation/experimental inputs of
  $\sigma^{IA}_{\gamma Pb} = \frac{d\sigma}{dy}_{\gamma p \rightarrow J/\psi p}(t=0) \cdot \int_{|t_{min}|}^{\infty} dt |F_A(t)|^2$
- assuming: gluon dominance, cross section proportional to gluon-PDF^2
  $\rightarrow$ measure of gluon PDF suppression in nucleus
- analogue to inclusive observables $R_{pPb} = \sigma_{pPb}/(208 \cdot \sigma_{pp})$
- in future:
  better to take experimental γ-p and not its parameterisation
  $\rightarrow$ better separation of theory & experiment when going to fit things

γ-lead: W-dependence of nuclear suppression factor



- **strong nuclear suppression**
- no discrimination: saturation vs. collinear factorisation-based

Outlook for photoproduction



HL-LHC Yellow Report WG5, arXiv:1812.06772

- proven that this type of measurement used for projection of 2020ies data sets already feasible with 2015/18 data
- and that we can do more difficult measurements

Nuclear suppression of gluons at low-x: UPC quarkonia data & inclusive heavy-quark pPb

- Charm/beauty inclusive pPb data already included in nuclear PDF fits since directly sensitive to PDFs
- constraining power of LHCb forward results
  see e.g. in EPP21 EPJC 82 (2022) 5, 413 and nNNPDF3.0 EPJC 82 (2022) 6, 507
  $\rightarrow$ uncertainties related to hadronisation difference pp vs. pPb & possible presence of coherent energy loss
- UPC coherent quarkonium production data:
  $\rightarrow$ uncertainties related to transfer from GPD to PDF, see Vadim Guzey´s talk at HP23 for references link
- however, emergence of a coherent picture
  $\rightarrow$ **strong nuclear suppression of gluons**
- should be fully taken into account for PbPb QGP model building
- collinear factorisation & saturation-based calculations compatible both with both type of data

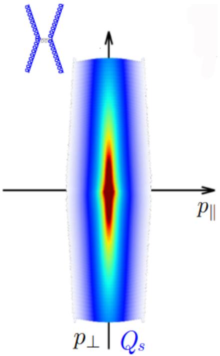
Is charm actually exclusively produced by initial hard scatterings?

Or is there a production from later stages?

´Thermal charm´ production in past calculations

- kinetic theory calculations Uphoff et al. (BAMPS) PRC82:044906 (2010),Zhang et al., PRC77:024901 (2008), Zhou et al. PLB758 (2016)
- indicating all non-negligible effect at the LHC
- All calculations ´start´ when matter is already thermal:
  $\rightarrow$ however, energy densities higher prior to thermalisation
  $\rightarrow$ What happens in the preequilibrium?
  $\rightarrow$ Is it relevant for total charm?
  $\rightarrow$ Why is this interesting?

Why trying to access the preequilibrium?

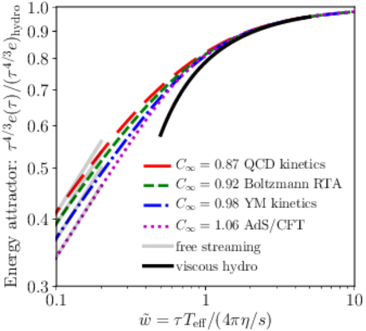


Adapted from "The first fm/c of Heavy-ion Collisions"

Schlichting, Teaney ARNPS 69 (2019)

- initially **far from equilibrium**
  $\rightarrow$ kinetically:
  rapid longitudinal expansion
  $\rightarrow$ chemically: very few quarks initially
- time scale not known, very different model assumptions
- hydrodynamics start not clear

Theory of preequilibrium: progress



Giacalone, Mazeliauskas, Schlichting PRL, 123(26) (2019),

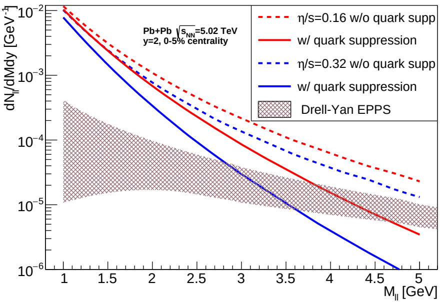
A. Mazeliauskas as Emmi Noether group leader &

G. Giacalone in Heidelberg (before Saclay) as

postdoc.

- very different scenarios possible
- universal scaling observed as function of $\tilde{w} \propto 1/(\textit{equilibration time})$
- equilibration time itself within modeling
  $\rightarrow$ kinetic equilibration
  $\rightarrow$ chemical equilibration
- no experimental access so far
- crucial for limits of hydrodynamics in proton-proton/proton-nucleus

Dileptons: sensitivity to preequilibrium



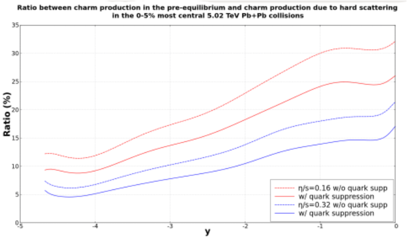
Coquet et al. Phys.Lett.B 821 (2021) 136626, m_T-scaling NPA 1030 (2023) 122579, polarisation arXiv:2309.00555 (Maurice Coquet, PhD student at Saclay)

Sensitive to:

- immediate equilibration & quark suppression from state-of-the-art model
- equilibration time scale $\propto \eta/s$
  $\rightarrow$ **one order of magnitude variation at high mass**

Crossing of preequilibrium and initial hard scattering above $2 \cdot m_c$!
What does the same model tell about charm production at leading order?

First results on charm: sensitivity to preequilibrium

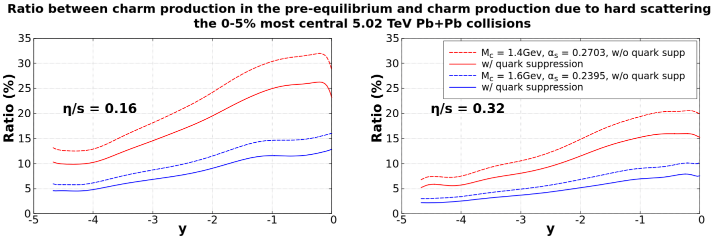


initial hard scattering shape from FONLL, scale from pp ALICE measurement and midrapidity

- calculation shows strong sensitivity to preequilibirum characteristics $\rightarrow$ **preequilibrium contribution between 17% and 33% of initial hard scattering**
- to be confirmed by full kinetic theory calculation

Work in progress by Thomas Faure, ongoing 6-month internship student at Saclay, and Mika Spier (PhD cotutelle Saclay-Bielefeld)

First results: sensitivity to other parameters

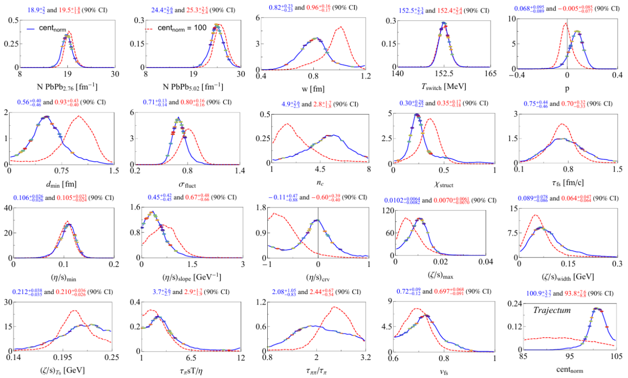


- estimated uncertainty on $m_c = 1.5 \pm 0.1$ GeV
- α_s derived from $\alpha_s(m_\tau)$ (PDG2023) and leading order running
  $\rightarrow$ **Ratio varies between 7% and 33% at midrapidity**
- further caveats:
  $\rightarrow$ production earlier than dileptons:
  charm production duration not small compared to ϵ decay time
  charm quarks not immediately onshell as assumed in transport
  $\rightarrow$ Leading order calculation
- access to initial stages properties and important input for charm in QGP:
  motivation for precise total charm in pp,pPb and PbPb & precise theory

Conclusions and outlook

- initial parton densities, initial energy density & thermalisation speed not well constrained
  $\rightarrow$ understand why hydrodynamics actually works
  $\rightarrow$ very important also for charm-in-QGP physics
- **gluon densities start to be constrained with pPb & γPb heavy-quark measurements**
  $\rightarrow$ experiment & theory progress with clear trajectories
- initial state fluctuations accessible in photoproduction:
  $\rightarrow$ experimental information on the proton geometry, otherwise not accessible
- **saturation: to be or not to be? A question for the LHC**
  $\rightarrow$ old, but open: LHC (about 10$\times$ higher energy) complementary to electron-ion collider
- **constraining thermalisation in nucleus-nucleus directly**:
  experimentally with dileptons & total charm:
  LHCb U1/U2 & ALICE2/ALICE3

Back-up: Matter properties estimation & the initial state



Nijs, van der Schee, Gürsoy, Snellings PRC 103, (2021); Nijs, van der Schee, PRC 106 (2022)

- Trajectum: 20-parameter fit
- 9 transport coefficient, 1 parameter for hadronisation
  10 parameters for initial stages!
- **no ´direct´ initial stages constraint within fitted data**
- Why is this important for physics of heavy quarks in the QGP?