Charmonium production in nuclear collisions at the LHC

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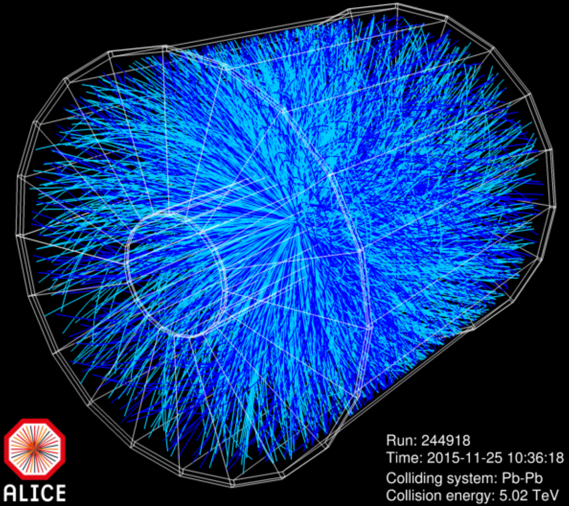
Outline

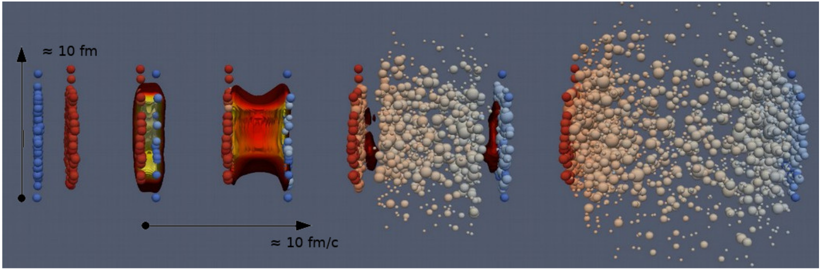
1. Introduction
2. Charmonium in nucleus-nucleus collisions at the LHC
3. Open questions and auxiliary measurements
4. Conclusion and outlook



Nucleus–nucleus collision in ALICE Time Projection Chamber

Average charged track multiplicity about 40 $\times$ average *pp* multiplicity
most central: about 2000 tracks per unit of rapidity   ALICE event displays

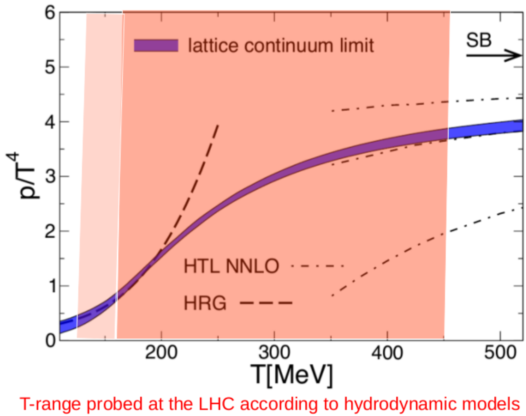
Heavy-ion collisions: creating strongly interacting matter



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

- Ultrarelativistic heavy-ion collisions at colliders: Hydrodynamic models describe bulk of deposited energy
- Experimental access to many-body physics governed by quantum chromodynamics (QCD)

Heavy-ion collisions: Quark-Gluon Plasma Physics



p/T^4: pressure over temperature^4

HRG: hadron resonance gas

HTL: hard thermal loop

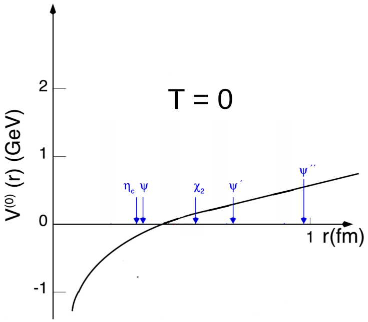
SB: non-interacting quarks and gluons

Figure taken from PLB 370 (2014), T-range from PRC 89, 044910 (2014)

- Lattice QCD: cross-over from Hadron Resonance Gas to Quark-Gluon Plasma at vanishing baryochemical potential
- Quark-Gluon Plasma tested by ultra-relativistic heavy-ion collisions
- Goal: characterize this matter

Quark-Gluon Plasma: heavy quarkonium as tool

- Key measurement:
  direct experimental signature for deconfinement
- **Heavy quarkonia:**
  bound states of $c\bar{c}/b\bar{b}$—quark pairs
  model systems for interaction of color charges at T=0 and finite T



Adapted from EPJC 71:1534 (2011).

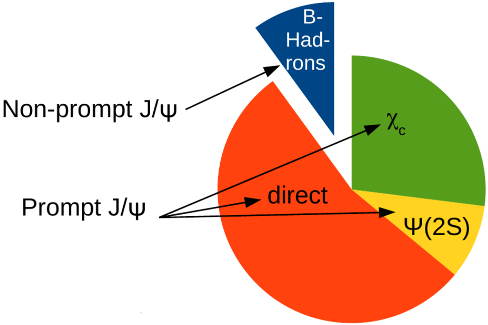
- Color screening and medium-induced dissociation influencing bound states
  first discussed as sign of deconfinement in heavy-ion collisions by Matsui & Satz PLB 178 (1986)
- Theory effort towards quantitative understanding
  detailed review about heavy quarkonium in extreme conditions by A. Rothkopf Phys.Rept. 858 (2020)

Heavy-ion collisions and charmonium detection

- Charmonium ($c\bar{c}$) bound vector states **J/ψ and ψ(2S)**
  BR(J/$\psi \rightarrow e^+e^-/\mu^+\mu^-$) $\approx$ 6 %
  BR(ψ(2S)$\rightarrow e^+e^-/\mu^+\mu^-$) $\approx$ 0.8 %
  $\rightarrow$ **accessible in nucleus-nucleus collisions**

  in pp/p-nucleus collisions more state accessible

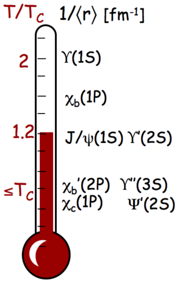
- **Inclusive** J/ψ production in hadronic collisions:



Approx. production fractions integrated over p_T in pp collisions at TeV-scale collision energies.

Charmonium in heavy-ion collisions: ´melting´ as initial idea

- **Suppression of J/ψ production** via color screening as a probe of deconfinement in heavy-ion collisions since 1986
  Matsui & Satz PLB 178 (1986)
- **Sequential Suppression** of quarkonia as a function of temperature:
  $\rightarrow$ quarkonia as thermometer
  F. Karsch, H. Satz F.Karsch, H. Satz, Z.Phys. C51 (1991)



adapted from A. Mócsy EPJC 61, 705 (2009), T_c: pseudocritial temperature separating hadrons from QGP.

- Underlying picture:
  charmonia produced before QGP formation
  $\rightarrow$ subsequent ´melting´ in fireball

Charmonium in heavy-ion collisions at the LHC: new effects

- Large initial charm quark densities & charm conserved:
  new mechanism beyond ´melting´
  $\rightarrow$ **late stage production:**
  sign of deconfinement

Charmonium in heavy-ion collisions at the LHC: scenarios

Statistical Hadronization

$$N_{c\bar{c}} = \frac{1}{2} g_c V \left(\sum_i n^{\mathrm{th}}_{D_i} + n^{\mathrm{th}}_{\Lambda_i} + \cdots \right) + g_c^2 V \left(\sum_i n^{\mathrm{th}}_{\psi_i} + n^{\mathrm{th}}_{\chi_i} + \cdots \right) + \cdots$$

Input production of charm, Volume V, thermal densities n: fixes fugacity g_c

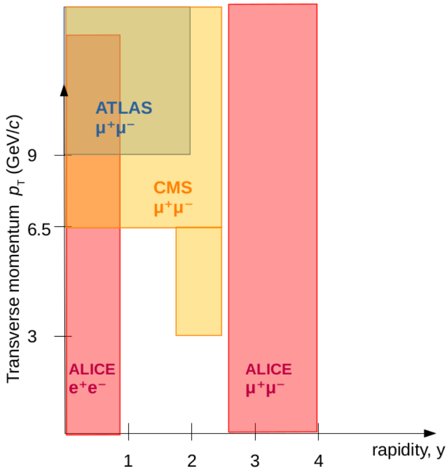
Transport model

$$\frac{\mathrm{d}N_\Psi(\tau)}{\mathrm{d}\tau} = -\Gamma_\Psi(T(\tau)) \left[N_\Psi(\tau) - N_\Psi^{\mathrm{eq}}(T(\tau)) \right]$$

Dynamic modelling as function of time τ with reaction rate Γ_ψ

- 2 **late stage production - non-primordial - production scenarios**
- **The statistical hadronization model**
  charmonium production exclusively at phase boundary
  P. Braun-Munzinger and J. Stachel PLB, 490 (2000)
- **Transport models**
  J/ψ production and destruction during lifetime of deconfined phase from initially uncorrelated and from same hard scattering $c\bar{c}$ pairs
  R. L. Thews, M. Schroeder, J. Rafelski PRC, 63 (2001)

J/ψ measurements in nucleus-nucleus collisions at the LHC

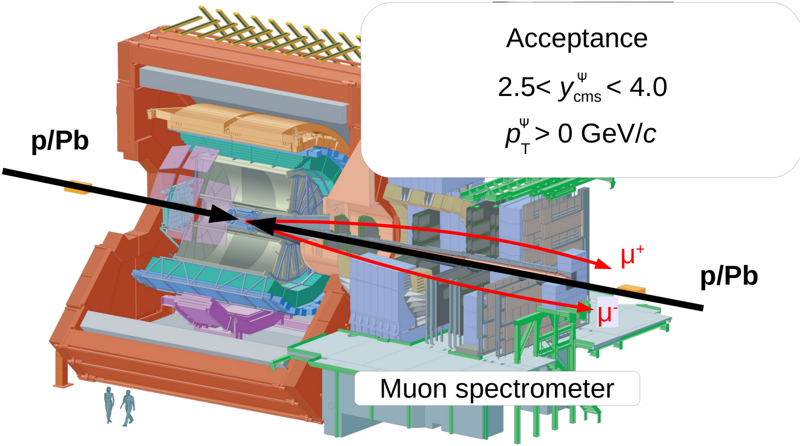


- ATLAS/CMS low p_T reach: instrumentation/background
- LHCb in Run 1/2: not granular enough for central PbPb collisions
- Only ALICE down to $p_T = 0$ GeV/c in PbPb collisions $\rightarrow$ most crucial for late stage production and charm thermalization
- High p_T: statistics limited
  CMS up to 50 GeV/c, ATLAS up to 40 GeV/c

  ALICE statistics limited to 15-20 GeV/c

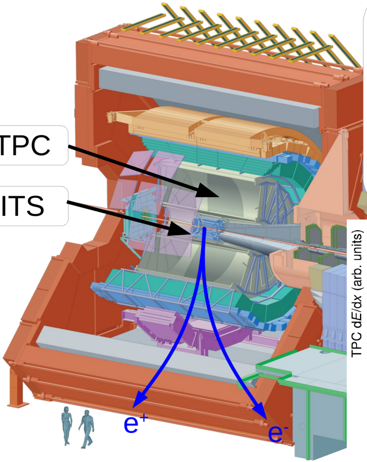
Acceptances from most recent published results at $\sqrt{s_{NN}} = 5.02$ TeV ATLAS, CMS, ALICE forward, ALICE midrapidity

Charmonium measurements at the LHC



Inclusive J/ψ and ψ(2S) down to $p_T = 0$ GeV/c at forward rapidity

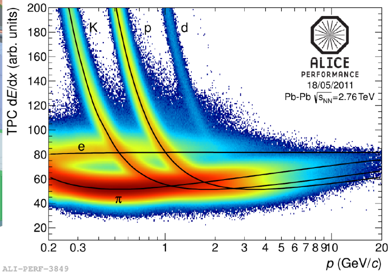
Charmonium with ALICE at the LHC



Acceptance

$|y^{\psi}_{cms}| < 0.9$

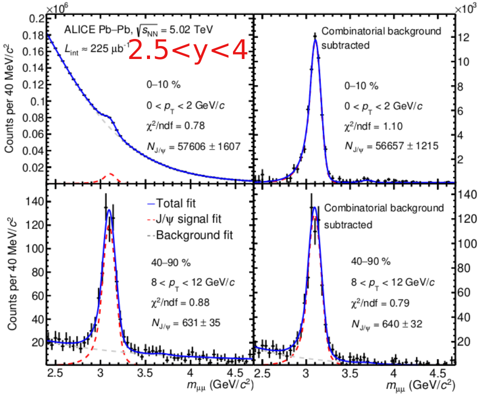
$p^{\psi}_{T} > 0$ GeV/c



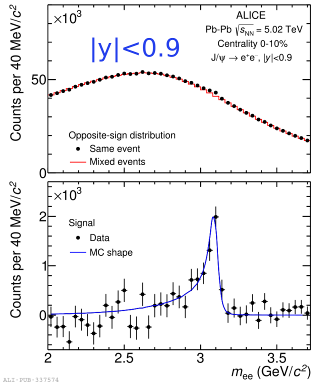
Inclusive J/ψ down to $p_T = 0$ GeV/c at midrapidity

Separation of prompt and non-prompt J/ψ down to low p_T

J/ψ analyses in Pb-Pb collisions



Taken from JHEP 2002 (2020) 041



Taken from PLB 805 (2020) 135434

- Low S/B due to combinatorial background at low transverse momentum
  $\rightarrow$ relying on data-driven mixed-event technique, for $\mu^+\mu^-$ also direct fit

Nuclear modification factor observables

$$R_{AA} = \frac{N_{J/\psi \text{ in AA}}}{\langle T_{AA} \rangle \cdot \sigma_{J/\psi \text{ in pp}}}$$

Pb-Pb collisions

$$\langle T_{AA} \rangle = \langle N_{\text{coll AA}} \rangle / \sigma_{NN}$$

$$R_{pA} = \frac{N_{J/\psi \text{ in pA}}}{\langle T_{pA} \rangle \cdot \sigma_{J/\psi \text{ in pp}}}$$

p-Pb collisions

$$\langle T_{pA} \rangle = \langle N_{\text{coll pA}} \rangle / \sigma_{NN}$$

$N_{J/\psi \text{ in AA(pA)}}$: measured yield in A-A/p-A

- PbPb collisions:
  dialing in ¨centrality¨
  $\rightarrow$ most central collisions: largest
  # participating nucleons N_{part} &
  colliding nucleons N_{coll}
- In absence of nuclear effects:
- $R_{AA} = 1$ $R_{pA} = 1$ for high-Q^2 processes

Nuclear modification factor observables

$$R_{AA} = \frac{N_{J/\psi \text{ in } AA}}{\langle T_{AA} \rangle \cdot \sigma_{J/\psi \text{ in } pp}}$$

Pb-Pb collisions

$$R_{pA} = \frac{N_{J/\psi \text{ in } pA}}{\langle T_{pA} \rangle \cdot \sigma_{J/\psi \text{ in } pp}}$$

p-Pb collisions

$$\langle T_{AA} \rangle = \langle N_{\text{coll } AA} \rangle / \sigma_{NN}$$

$$\langle T_{pA} \rangle = \langle N_{\text{coll } pA} \rangle / \sigma_{NN}$$

$N_{J/\psi \text{ in } AA(pA)}$: measured yield in A-A/p-A

- PbPb collisions: dialing in ¨centrality¨ $\rightarrow$ most central collisions: largest # participating nucleons N_{part} & colliding nucleons N_{coll}
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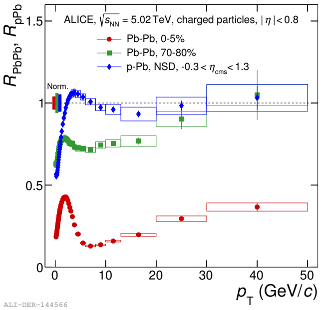
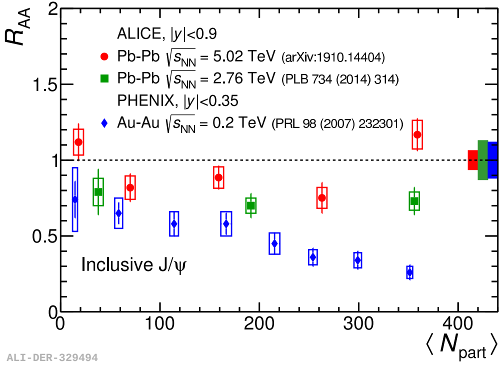
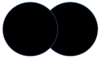


JHEP11(2018)013.

Results: centrality dependence at different collision energies



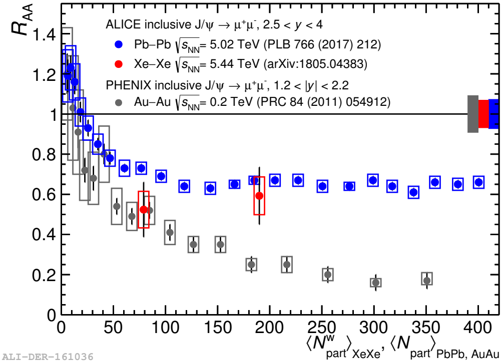


PLB 805 (2020) 135434.

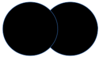
- $\sqrt{s_{NN}}$ =5.02 TeV: $|y| < 0.9$
- $\sqrt{s_{NN}}$ =2.76 TeV: $|y| < 0.9$
- $\sqrt{s_{NN}}$ =0.2 TeV: $|y| < 0.35$

- Qualitatively different behavior at the LHC compared to RHIC
- **Predicted by models including non-primordial J/ψ production**

Results: centrality dependence at different collision energies

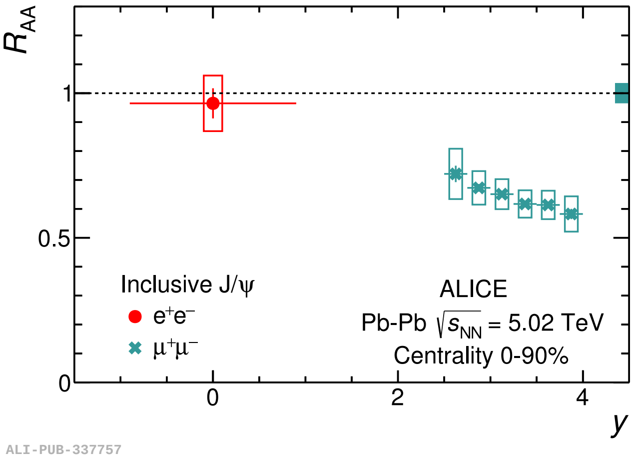


- $\sqrt{s_{NN}}$ =5.44 TeV: $2.5 < y < 4$
- $\sqrt{s_{NN}}$ =5.02 TeV: $2.5 < y < 4$
- $\sqrt{s_{NN}}$ =0.2 TeV: $1.2 < |y| < 2.2$



- Qualitatively different behavior at the LHC compared to RHIC
- **Predicted by models including non-primordial J/ψ production**

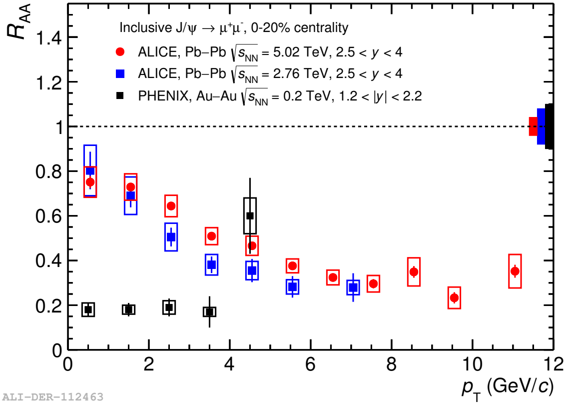
Results: rapidity dependence



PLB 805 (2020) 135434.

- Clear rapidity dependence visible
  $\rightarrow$ in constrast to expectation in sequential ´melting´ scenario
  $\rightarrow$ in accordance with expectation from non-primordial production

Results: p_T dependence



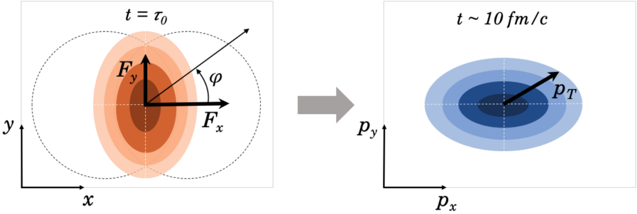
- $\sqrt{s_{NN}}$ =5.02 TeV: $2.5 < y < 4$
- $\sqrt{s_{NN}}$ =2.76 TeV: $2.5 < y < 4$
- $\sqrt{s_{NN}}$ =0.2 TeV: $1.2 < |y| < 2.2$

PLB 766, (2017), 212, PRC 84 (2011), 054912.

- Strong p_T dependence of suppression in contrast to RHIC observation
- Observed pattern in accordance with increased non-primordial production
  → **support for late stage ´combination´ pictures at low p_T**

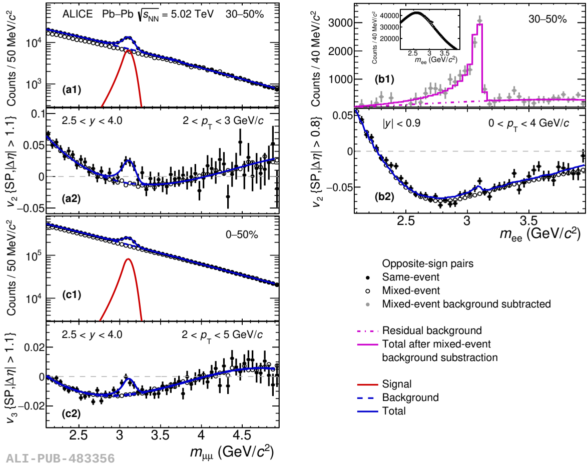
Elliptic flow and J/ψ at the LHC

- large average initial space asymmetry in non-central collisions
- *cos*(2ϕ)-modulation of soft particle emission w.r.t. symmetry plane: Fourier coefficient v_2
- **initial coordinate space asymmetry** $\rightarrow$ **momentum space asymmetry in final state**
- transmutation also for higher coefficients as v_3
- finite elliptic flow for charmonium: pointing to participation in collective motion $\rightarrow$ (partial) **thermalization**



Adapted from R. Caron PhD thesis.

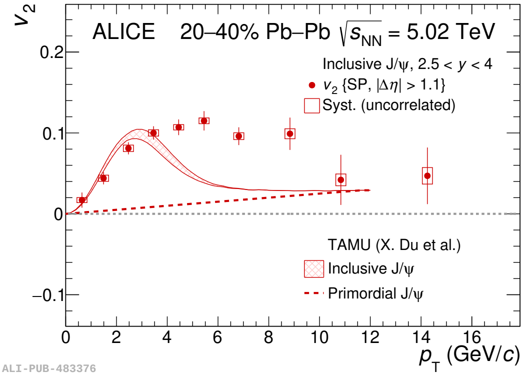
J/ψ Elliptic flow extraction



JHEP 10 (2020) 141

- signal is extracted in sequential fits of invariant mass and v_2
- the background v_2 under the peak estimated by an event-mixing technique

Elliptic flow in semi-central collisions



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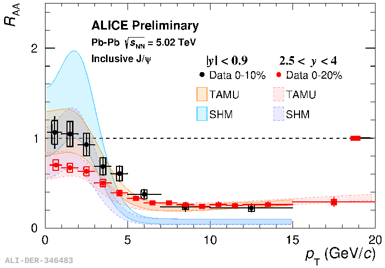
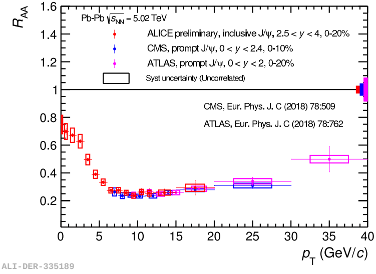
- large v_2 observed from low transverse momentum
  $\rightarrow$ generically expected from late stage combination picture
- Transport model can describe data at low transverse momentum
  intermediate mass range not fully accounted for
- high-p_T associated with path-length dependent suppression

Current limitations





Left: ALICE Preliminaries, publication under preparation. Right: forward ALICE with ATLAS EPJC (2018) 78:762 and CMS EPJC (2018) 78:509.

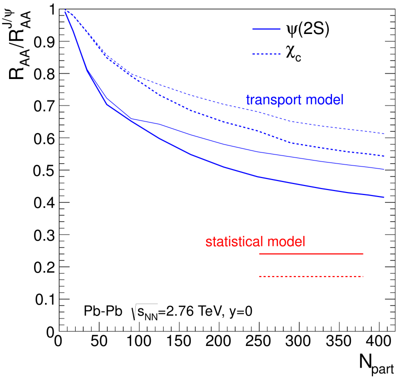
- Experimental precision already very good and still improving
- Statistical hadronization (SHM) and transport models (TM) describe data

  SHM: PLB797 (2019) 134836, TM NPA 943, (2015), 147(shown), additional TM: PRC89, 5(2014) 054911, comover model with regeneration: PLB731 (2014) 57
- Common uncertainty: total charm production in nucleus-nucleus collisions
  $\rightarrow$ very different value required to describe data
  TM-$\sigma_{c\bar{c}}$ a factor 2 larger than SHM-$\sigma_{c\bar{c}}$ for y around 0

Current limitations and possible improvements

$$N_{c\bar{c}} = \frac{1}{2} g_c V \left(\sum_i n^{\mathrm{th}}_{D_i} + n^{\mathrm{th}}_{\Lambda_i} + \cdots \right) + g_c^2 V \left(\sum_i n^{\mathrm{th}}_{\psi_i} + n^{\mathrm{th}}_{\chi_i} + \cdots \right) + \cdots$$

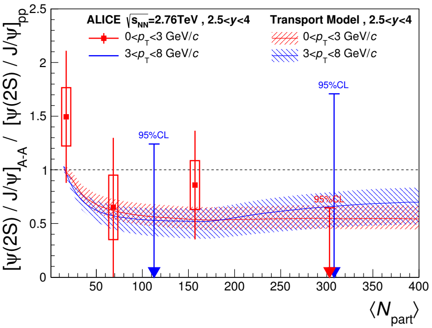
Statistical Hadronization Model:
total charm: fix fugacity g_c
Charmonium production quadratic in g_c
Most direct test: measure total charm

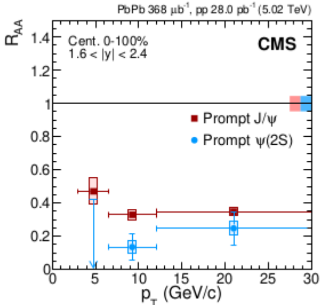


Right J. Phys. G 41 (2014) 087001

- Measure total charm production in rapidity window to fix parameter
- Excited state:
  ψ(2S) as potential discriminator between scenarios

ψ(2S) results in nucleus-nucleus collisions

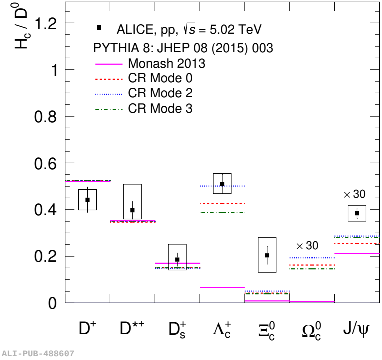




JHEP 05 (2016) 179, EPJC (2018) 78:509.

- Currently available measurements:
  no conclusion possible
- New measurements under way with full 2015+2018 data

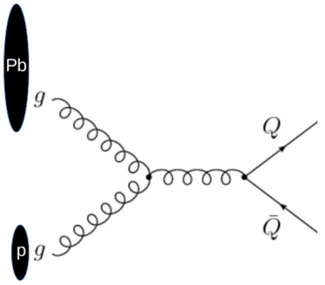
Directly contraining charm production in PbPb collisions



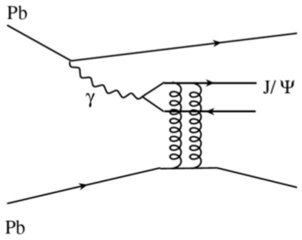
arxiv:2105.06335

- proton-proton: larger baryon fraction than expected from e^+e^-
  $\rightarrow$ first charm cross section taking this fully into account arXiv:2105.06335
  $\rightarrow$ major progress already: not yet full propagated to nucleus-nucleus collisions
- short lifetime baryons difficult in nucleus-nucleus collisions at low p_T
  $\rightarrow$ one of main goals of ALICE upgrades

Indirectly contraining charm production in PbPb collisions

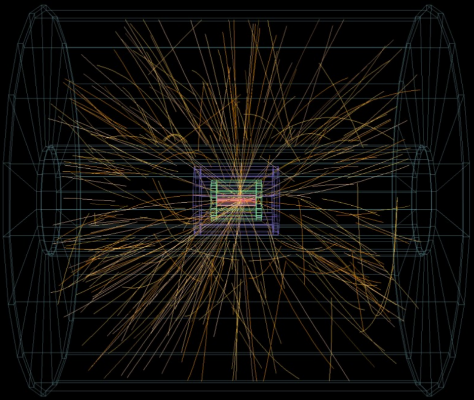


Inclusive heavy-flavour hadron production in proton-nucleus collisions



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

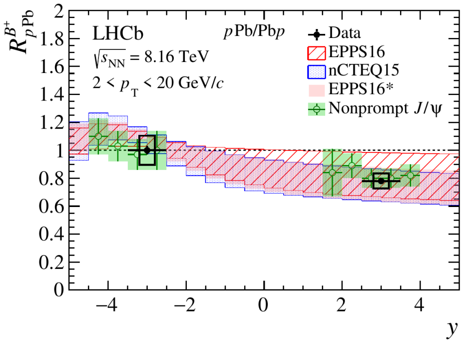
- extrapolation from proton-proton to nucleus-nucleus collisions
  $\rightarrow$ nuclear modification of gluon distributions at low x

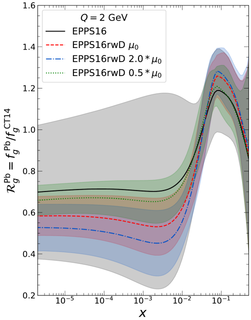


p–nucleus (pPb) event display with ALICE Time Projection Chamber

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

Charm and beauty measurements in pPb collisions





Example for beauty: Phys.Rev.D 99 (2019) 5; nPDF reweight from charm: PRD 104, 014010 (2021).

- consistent nuclear suppression of charm and beauty at forward rapidity with charm and beauty mesons and quarkonia

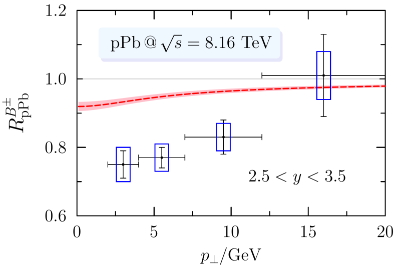
  see in PRD 104, 014010 (2021)

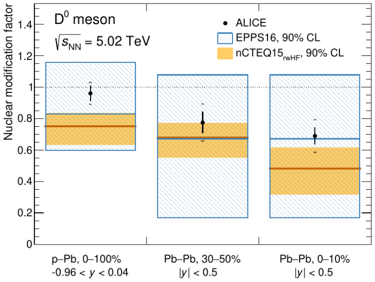
- interpreted as strong depletion of parton densities

  see most recently JHEP05(2020)037, PRD 104, 014010 (2021)

- charm production also described within Color Glass condensate calculations in the low-x regime of QCD

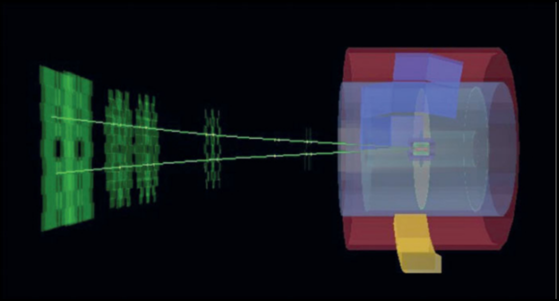
Charm and beauty measurements in pPb collisions: possible caveats





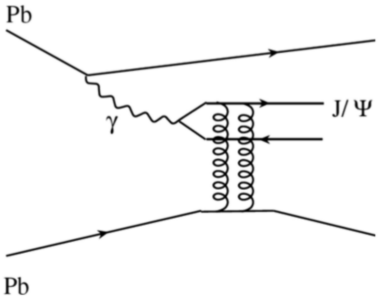
arXiv:2107.05871, arXiv:2110.09420

- cold nuclear energy loss could be as important than parton depletion arXiv:2107.05871
- midrapidity results tending to show weaker suppression: to be confirmed with more precision JHEP 12 (2019) 092
- hadronization from proton-proton to proton-nucleus: only small variations, e.g. in arXiv:2011.06078



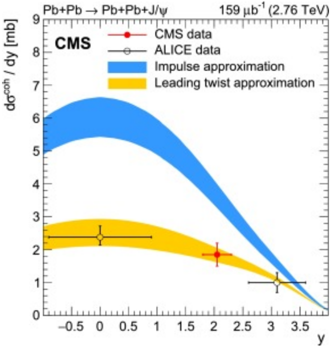
Ultra-peripheral collisions: J/ψ candidate in muon arm of ALICE with otherwise empty detector

Ultra-peripheral collisions: γ probe of the nucleus



- 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, leading $\ln(1/x)$, $t \to 0$: $\sigma \propto$ (gluon PDF)^2 (Phys.Rev.D50:3134-3144,1994)

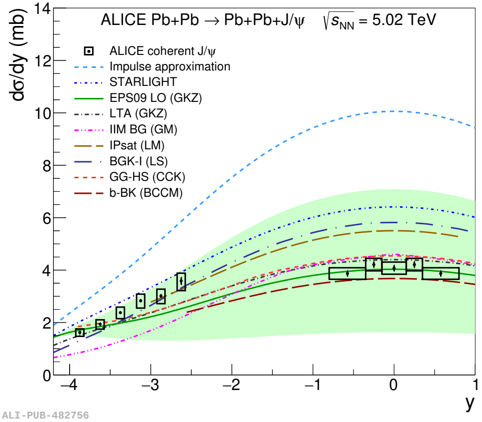
Charmonium production in UPC: results



- ALICE forward rapidity PLB 718 (2013) 1273
- ALICE midrapidity PJC 73 (2013) 2617
- CMS PLB772 (2017), 489
- Impuls approximation: neglecting any nuclear effects
- leading twist approximation: including nuclear suppression

- Run 1 results at $\sqrt{s_{NN}} = 2.76$ TeV: indication of clear nuclear modification measured by ALICE and CMS
- midrapidity sensitive to Bjorken-$x \approx 10^{-3}$
- forward rapidity: photon direction ambiguity sensitive to lower and larger x, larger x dominating

Charmonium production in UPC: Run 2 results



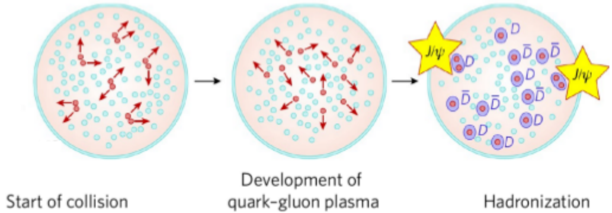
- forward rapidity ALICE PLB798 (2019) 134926
- midrapidity ALICE arXiv:2101.04577
- also first LHCb results on PbPb UPC available arXiv:2107.03223

- midrapidity measurement consistent with gluon suppression factor of 0.65
- caveats:
  → large scale uncertainties in collinear perturbative calculations at NLO
  → connection between generalized parton distribution function and PDF valid in the limit of low-x and t
  → first steps undertaking in proton-PDF case
  see e.g. in C. Flett et al.: PRD 101, 094011 (2020)

Conclusions

Charmonia at the LHC: a direct observable for deconfinement

- Predictions of transport and statistical hadronization model confirmed based on RHIC experience
- Qualitative picture from production confirmed by strong elliptic flow **non-primordial J/ψ production at the LHC**
- Discrimination between transport and statistical hadronization feasible experimentally:
- ψ(2S) and total charm as discriminators
  $\rightarrow$ not yet conclusive with available knowledge



P. Braun-Munzinger and J.Stachel, Nature 448 (2007)

Outlook

- within next year: new results on $\psi(2S)$ and more direct constraints on charm in nucleus-nucleus collisions
- Run 3 and 4 starting next year:
  jump in statistics by factor 10-100 for LHC heavy-ion programme
  $\rightarrow$ major ALICE upgrade, LHCb upgrade for Run 3 *pp* beneficial
  $\rightarrow$ Phase 2 ATLAS/CMS upgrade for mid-twenties

  CERN Yellow Report HE/HL-LHC

  - measure total charm production in PbPb directly
  - measure parton distribution sensitive observables with cleaner observables (electromagnetic, higher scales)
  - high-luminosity LHCb fixed-target programme
  - study non-primordial production with B_c in nucleus-nucleus: charm+beauty bound state

    see first CMS measurement CMS-PAS-HIN-20-004