Experimental overview: Initial stages with heavy-flavour observables

Heavy Flavours from small to large systems
Institut Pascal
Michael Winn, 5.10.2022

Plan of presentation

1) Extended motivation for initial state physics at hadron colliders

2) Inclusive production measurements

3) Exclusive production measurements

4) Azimuthal-angle correlation measurements

By no means comprehensive, try to introduce some notions and caveats

Standard model of a heavy-ion collision

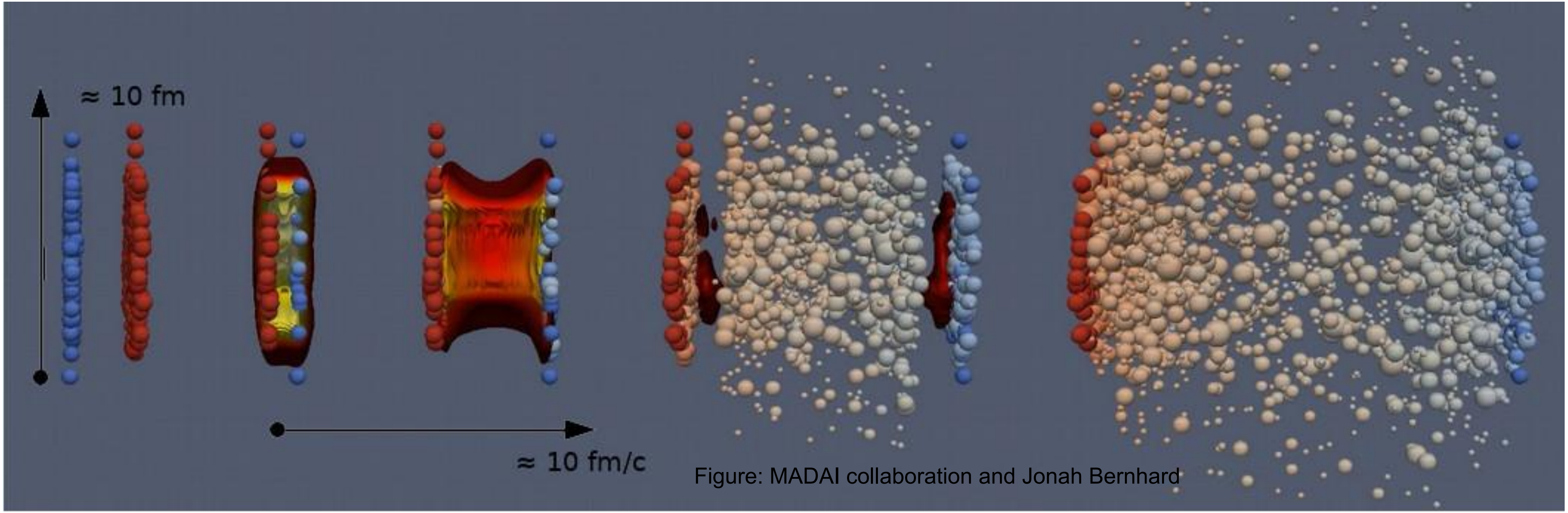
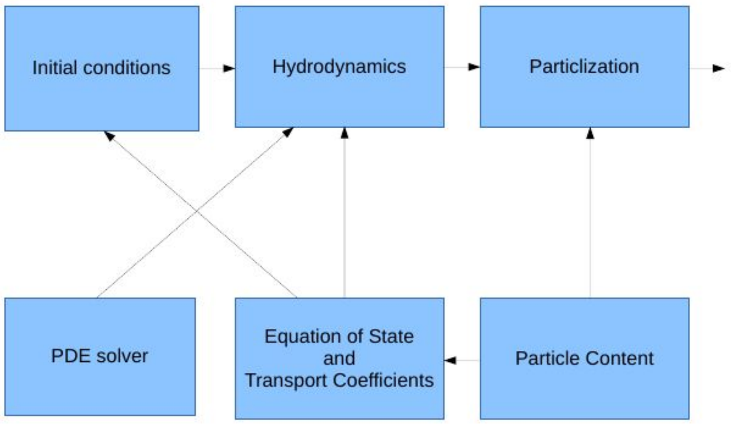


Figure: MADAI collaboration and Jonah Bernhard

- Traditional primary goals:
  - derive equilibrium properties of produced QCD matter: equation of state, transport coefficients
  - Characterise the transition to hadrons:
    deconfinement and chiral transition properties

´Global´ fit to heavy-ion data



Current attempts to retrieve matter properties

One example (also from other groups):
particle spectra and azimuthal anisotropy measurements:
Nijs, van der Schee, Gürsoy, Snellings, Phys. Rev. C 103, 054909

Treatment of initial state:
¨…The Trento model describes nuclei using a Woods-Saxon distribution….¨

- **very rough**

9 parameters for initial state vs. 9 for hydro and 1 for freeze-out , but:

´our model comfortably fits almost all data, thereby giving confidence that our (phenomenological) model scope is wide enough to capture most of the physics presented´

Why do we need to know better the initial stage than some Glauber model with free parameters for any heavy-ion physics?

One could say:

1) Soft particles with hydrodynamics

    sensitive to late stages & initial state azimuthal anisotropy in energy deposition

2) High-pt or large mass production

    collinear factorisation gives initial partons as in proton-proton collisions

    interesting QGP physics (energy loss etc.) time ordered afterwards

Some Glauber good enough, don´t need more:

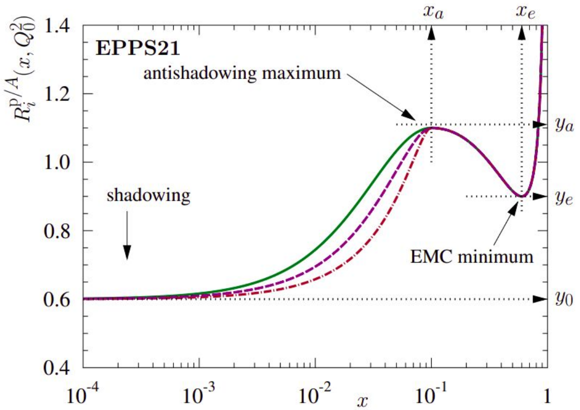
Let´s take nucleus-nucleus data only, measure QGP properties, no digression

Why do we need to know better the initial stage?

Minimal consideration:

1) Deep inelastic cross section measurements in e-A are not equal to A * e-p: interpreted as need of nuclear PDFs
   - relevant at some point for anything using pQCD in nucleus-nucleus collisions

$$R_i^A(x,Q^2) = \frac{Z f_i^{p/A}(x,Q^2) + N f_i^{n/A}(x,Q^2)}{Z f_i^{p}(x,Q^2) + N f_i^{n}(x,Q^2)}$$



Parameterization of one popular global fitter group, EPPS21
https://arxiv.org/pdf/2112.12462.pdf
Now also traditional pp fitter groups fit nuclear PDFs
motivation heavy-ions or motivation to improve proton PDF

Jets: large jet quenching effects in nucleus-nucleus collisions, mild nPDF effects

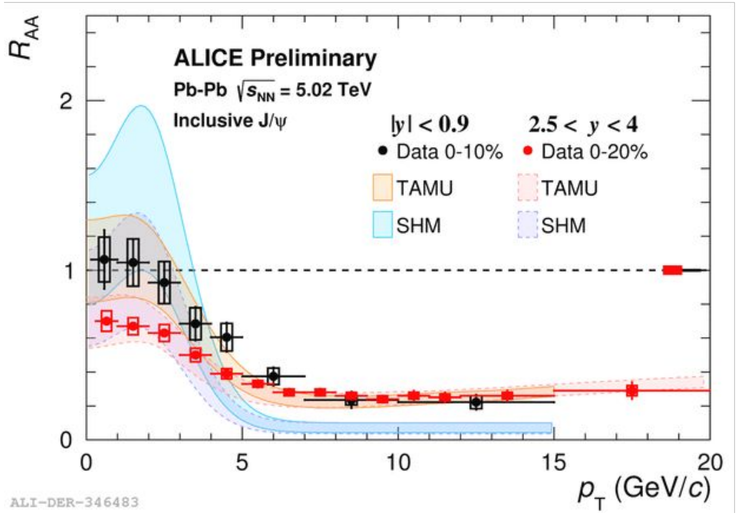
Why do we need to know the initial state better for heavy-flavour observables?

For charm and beauty very relevant:

- large effects (at least in most approaches), large uncertainties

Example J/ψ R_{AA}

error band: uncertainty on total $c\bar{c}$ yield



Modeling does not agree on:

- the central value: up to a factor 2
- a strategy to estimate the uncertainty

Limiting factor of any more precise interpretation of this hallmark result

$$R_{AA} = N^{jpsi} / N^{evt}_{AA} / (\langle T_{AA} \rangle \, \boldsymbol{\sigma}_{jpsi,pp})$$

Why do we need to know the initial state better for heavy-flavour observables?

You make the total charm/beauty sum in nucleus-nucleus collisions

- Don´t need any external knowledge via nPDFs or other collision system
- Main goal of ALICE in Run 3 in nucleus-nucleus collisions

This solves the problems, if you assume $c\bar{c}$/ $b\bar{b}$ production only in the initial state, charm conversation over time

- Is the mass large enough for this assumption to hold?
- Not the case for energy loss, see e.g. https://arxiv.org/abs/2209.13600, Jasmine yesterday

    - a separate measurement of total charm production in pp, pA, AA is interesting as a test of factorisation w.r.t. the initial state

Why do we need to know better the initial state?

2) Thermalization puzzle: Baier et al. (Bottom-up) Phys.Lett.B502:51-58,2001

¨The single most important question in the physics of heavy ion collisions is thermalization.¨

- Even more urgent question provided small system results

What does it mean, what is the attached physical picture, that we see long-range correlations reasonably well described by hydrodynamic modeling down to O(100) particles in the event?

- Knowing partonic densities in the beginning adds an additional constraint
    - given energy deposition can be understood in terms of pQCD
        - At the basis of MPI in Pythia as well as of CGC approaches to multiplicities

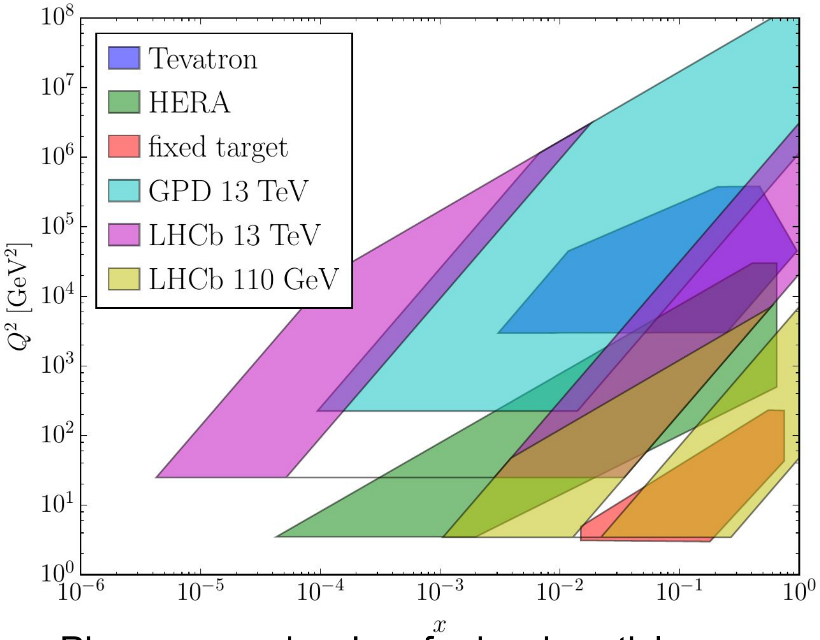
Why do we need to know better the initial state?

3) Back to global fit: as many parameters for initial state than for hydrodynamics

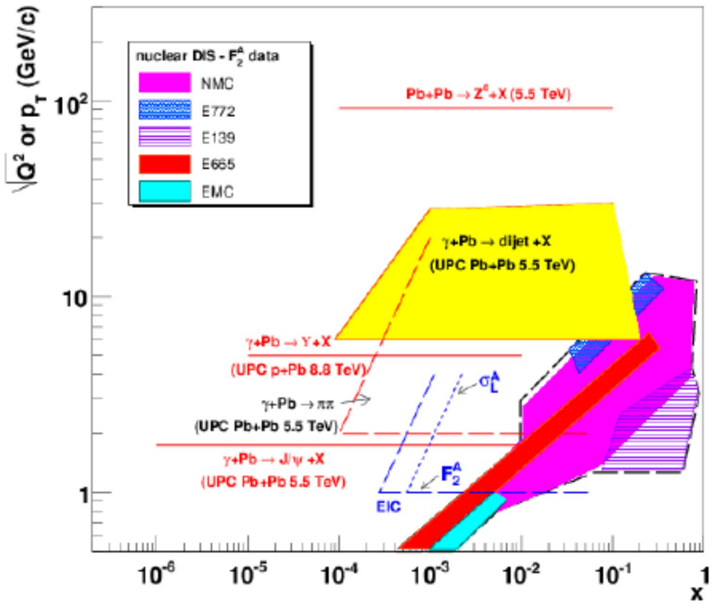
hadronisation fully encoded in a single parameter, the transition temperature…

External sources of information on transverse geometry would be improve hydro-fit information content

Initial stages from a hadron structure view



Phase space borders for hard-particle production courtesy by T. Boettcher



UPC kinematic plane overview compared to nuclear DIS facilities by N. Armesto, https://arxiv.org/abs/1812.06772

LHC with unique kinematic coverage down to low-x even compared to EIC in pA and UPC

Nucleus-nucleus collisions address the situation of collisions of two dense colour-charge fields

David Hilbert:

¨we must know,

we will know.¨

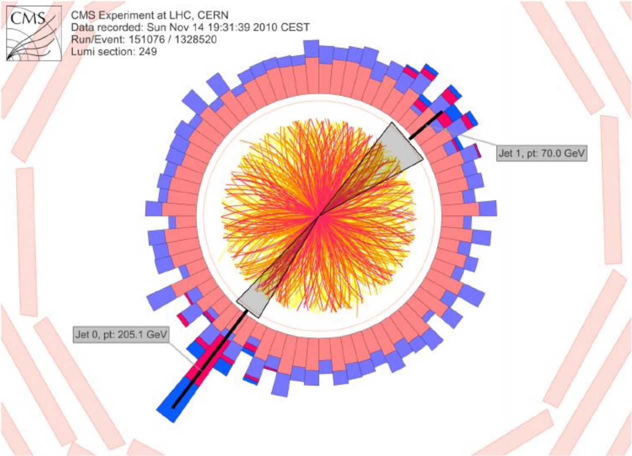
Let´s go into the trouble.

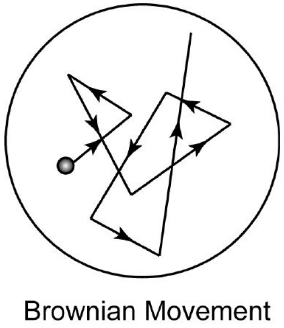
Focus on interest from heavy-ion community perspective

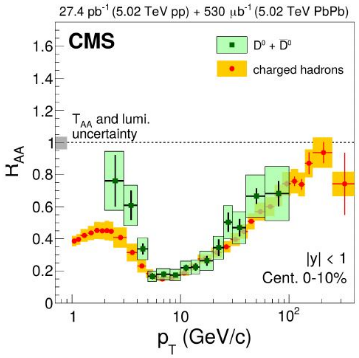
Focus on collinear perspective and not on signatures of saturation for sake of simplicity: Cyrille this afternoon more on saturation

Initial state of nucleus-nucleus collisions with collinear pQCD

since nucleus-nucleus environment modifies most pQCD-based observables:







right: PLB 782 (2018) 474

Only indirect constraints, need to rely on transfer from another collision system to nucleus-nucleus

Notable exception: massive weak gauge bosons in nucleus-nucleus collisions

colour neutral final state and sqrt(Q²)>>4th root of energy density at any time

Initial state of nucleus-nucleus collisions with collinear pQCD

1st option for partonic initial state:

Rely on ep/eA (HERA/nuclear DIS, in future: EIC)

- would be ideal, but not covering low enough x even in EIC for LHC heavy-ion programme

2nd best option:

Rely on pPb or gamma-Pb: get at low-x relevant for nucleus-nucleus at the LHC

- What we try to do despite of caveats

Initial state of nucleus-nucleus collisions with collinear pQCD based on hadron collider data

Inclusive hadroproduction:

1) Ratio between pPb (or d-Au) and pp measurements or double ratios (e.g. jets CMS) or forward-backward ratios
   - Rely on pQCD calculation applicability including factorisation with respect to initial state PDF and final state hadronisation in pPb

   Most often used: R_{pA} = sigma_pA / (A sigma_pp)

Photoproduction:

2) Ratio between photoproduction data and naive theory expectation, e.g. in Guzey et al.: https://arxiv.org/pdf/2008.10891.pdf

$$S_{Pb}(x) = \sqrt{\frac{\sigma_{\gamma A \to J/\psi A}(W_{\gamma p})}{\sigma^{\mathrm{IA}}_{\gamma A \to J/\psi A}(W_{\gamma p})}},$$

$$\sigma^{\mathrm{IA}}_{\gamma A \to J/\psi A}(W_{\gamma p}) = \frac{d\sigma_{\gamma p \to J/\psi p}(W_{\gamma p}, t=0)}{dt} \int_{|t_{\min}|}^{\infty} dt |F_A(t)|^2,$$

   - Rely on transition from exclusive reaction nonperturbative objects (GPDs) to inclusive production PDFs

Always: rely on applicability of pQCD in PbPb collisions for initial parton densities

- If Dense-dense color-glass-condensate theory valid: this type of knowledge transfer not working

Measurement types to constrain parton densities

Inclusive hadroproduction measurements: charm/beauty and jets used

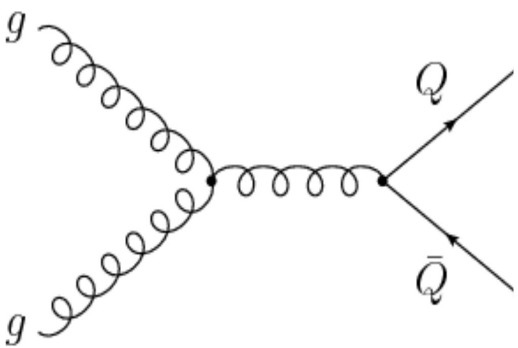
also inclusive hadrons, identified hadrons measurements available

- Focus on charm/beauty pPb measurements: only used constraint in global fits in lowest x regime

Exclusive vector-meson production measurements and inclusive dijet photo-production

- Focus on exclusive heavy-vector-meson production
    - Only observable potentially probing lowest x

Inclusive production of heavy quarks in hadronic collisions to constrain the initial state



Inclusive production of heavy quarks and jets in hadronic collisions to constrain the initial state

Kinematic estimate: $$x_2 = \frac{m_T}{\sqrt{s_{\mathrm{NN}}}} \cdot e^{-y}$$

Forward rapidity and low-mass scales for heavy-flavour production allows to test very low values of x

See for an introduction to the topic and a experimentalist´s discussion of successes and caveats in:

Heavy quarks and jets as probes of the QGP
(Apolinario, Lee, Winn) , published in PPNP 103990 (2022), https://arxiv.org/abs/2203.16352

Heavy-flavour production in pPb collisions

Large body of experimental data by LHCb and ALICE

- Charmonium, Bottomonium (including some excited states), open charm and open beauty
- Measurements at sqrt(s_{NN})= 5 TeV and sqrt(s_{NN})= 8.16 TeV

You can find all relevant publications here:

- https://alice-publications.web.cern.ch/publications
- https://lhcbproject.web.cern.ch/Publications/LHCbProjectPublic/Summary_IFT.html

First used in PDF sensitivity reweight studies by Kusina et al. (CTEQ group):
Phys.Rev.Lett. 121 (2018) 5, 052004

N.B.: also precise inclusive charged particle spectra and pi^0 available over a broad range in pt at midrapidity (ALICE) and at forward rapidity (LHCb)

One example used in nPDF fits: D-mesons by LHCb at 5 TeV

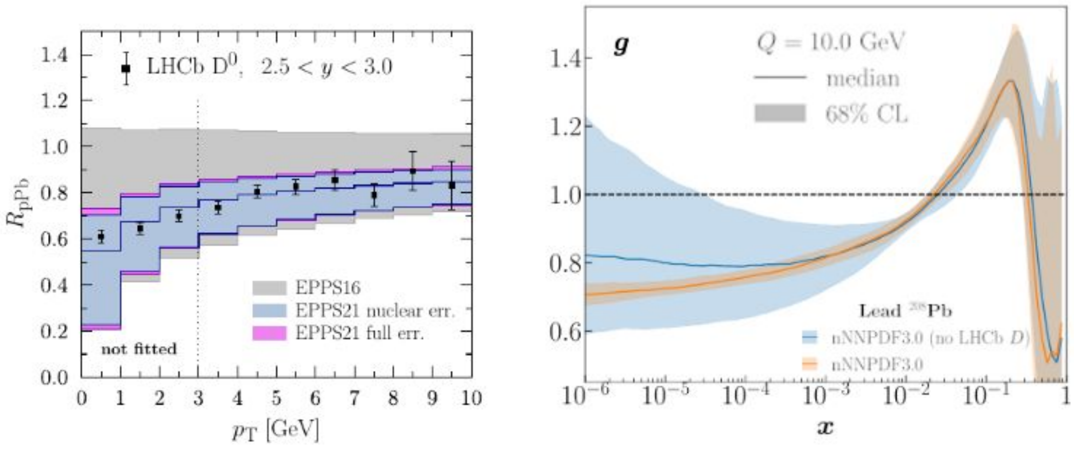


Figure 6: Left: Comparison of nuclear modification factor with EPPS16 (gray) and EPPS21 (blue) with 90 % confidence level uncertainties, adapted from [40]. Right: The ratio of the lead gluon PDF divided by the proton gluon PDF for nNNPDF3.0 without D-mesons constraint (blue) and nNNPDF3.0 with D-mesons constraint as a function of Bjorken-x, adapted from [41].

EPPS21 and NNNPDF3.0
Excerpt from
https://arxiv.org/abs/2203.16352

Strong power, also more measurements, including 8.16 TeV measurement available
Suppression also described by CGC-type calculations (x down to 10^{-5} in Pb nucleus)

- However, a list of caveats

Caveats of inclusive heavy-flavour particle production

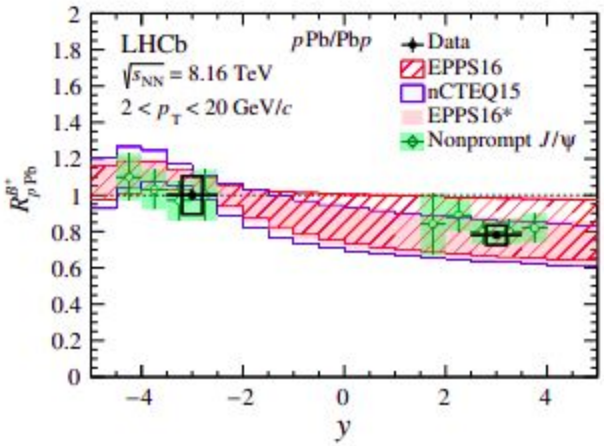
Does standard pQCD collinear theory work for such low-scale physics?
See Maxim´s talk for a theory list of issues within collinear factorization

List of an experimentalist´s fears of caveats:

- Already in saturation regime, where collinear factorization breaks down at low-pT?
- Coherent energy loss effect dominant effect producing suppression at forward rapidity?
  - Higher scale dijets at least consistent, see Francois Arleo
- Hadronization modification between pp and pPb: does it sufficiently cancel in the ratio?
  - see talk by Andrea
- Kinematics modification between pp and pPb due to ¨radial flow¨: does it sufficiently cancel in the employed ratio?
- Late-stage rescattering influencing production yields? Only relevant for ´fragile´ excited quarkonium?
  - See talk by Jana and Elena
- Scale variation uncertainties on absolute quantities huge, smaller on ratio, but still very large
  - See talk by Maxim

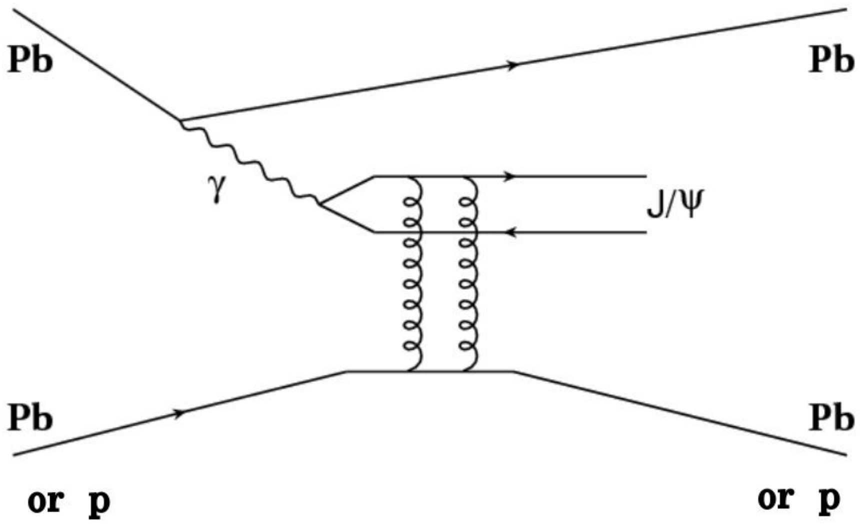
Caveats of inclusive heavy-flavour particle production

Experimental escapes mitigating/weakening issues:
Higher mass: bottom, see e.g. **Phys. Rev. D99 052011 (2019)** , statistically limited, higher x



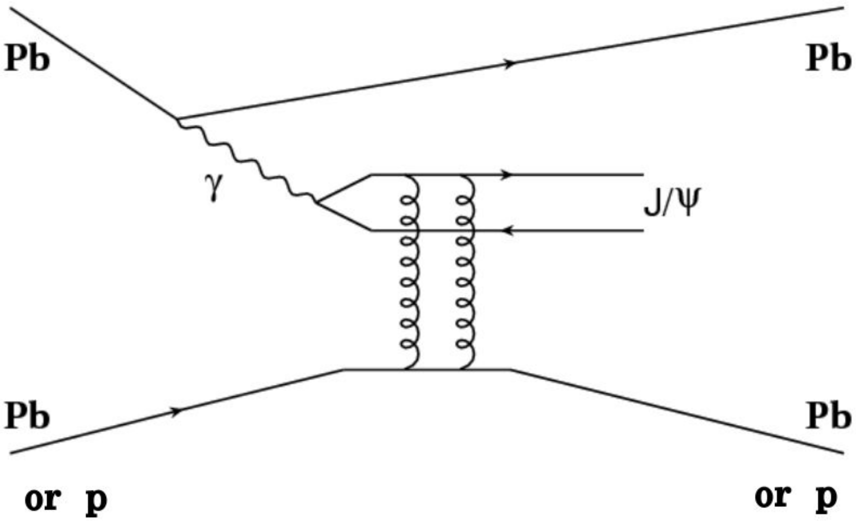
- Measure in future Drell-Yan (LHCb: https://cds.cern.ch/record/2648625) and photons (ALICE Focal, LHCb) instead (less sensitive to gluons a priori)

Exclusive hard particle production to constrain the initial state



At least:
no issue with variation of hadronisation as function of environment and no issue with final state interactions

Photoproduction at high-energy hadron colliders



Heavy-ion collision:

large flux of quasi-real photons

Enables photoproduction studies

in analogy to deep-inelastic scattering facilities including nuclei as target

Focus on J/ψ production:

Hard scale amenable to perturbative QCD, high precision data

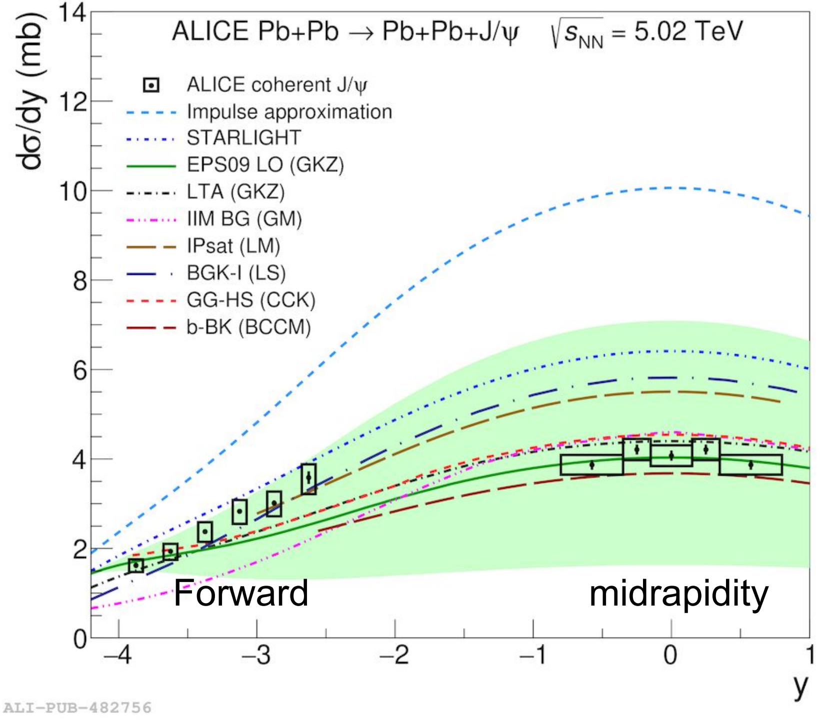
- Some results also on Upsilon (LHCb, pp, and CMS, pA)

For small $q\bar{q}$ at leading twist, leading alpha(s), $t \to 0$: $\sigma \propto (\text{gluon PDF})^2$

Brodsky et al.: PRD50 (1994) 3134-3144

See also: t-dependence of J/ψ production in PbPb collisions by ALICE Phys. Lett. B 817 (2021) 136280
approaching the black disk limit with ρ - meson in XeXe collisions by ALICE Phys. Lett. B 820 (2021) 136481

Photoproduction at the LHC: nucleus gluon density



Ultra-peripheral collisions: no hadronic interaction

- Photon direction ambiguity forward:
  sensitive to high- and low-x combination

- Measurement at midrapidity:
  sensitive to $x \approx 6\times10^{-4}$
  Consistent with moderate
  gluon shadowing of 0.65

$$S_{Pb}(x) = \sqrt{\frac{\sigma_{\gamma A\to J/\psi A}(W_{\gamma p})}{\sigma^{\mathrm{IA}}_{\gamma A\to J/\psi A}(W_{\gamma p})}},$$

Midrapidity: Eur. Phys. J. C 81 (2021) 712
Forward rapidity: Phys.Lett. B798 (2019) 134926

Photoproduction at the LHC: gluon densities

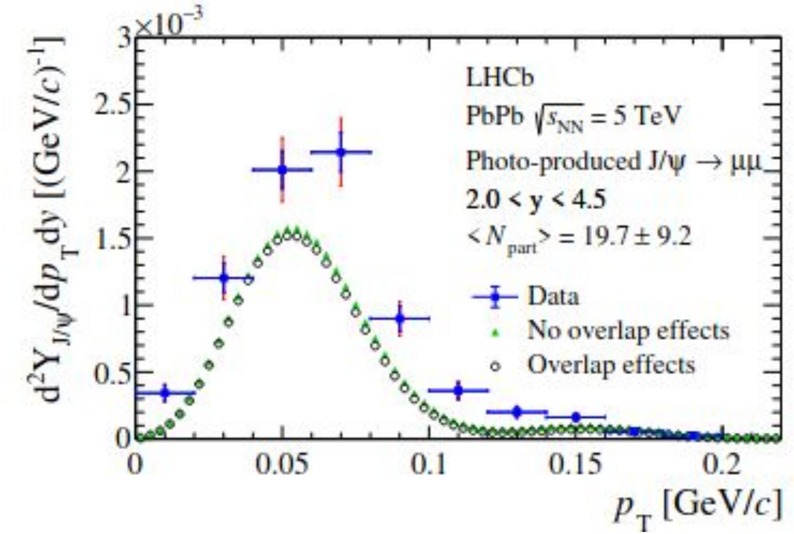
Potential constraints on gluon PDF of proton, since kinematic reach of forward LHCb acceptance beyond HERA at top energy, could also use ALICE pPb data

- a number of publications, see e.g Flett et al.: PhysRevD.102.114021(2020)
  - Strong power of data, no sign of saturation at low-x seen,
    - No ´saturation´ already from untamed power-law dependence on photon-proton energy of cross section

A list of caveats

- connection between GPDs and PDFs relies on approximations
- Scale variation show large variations at NLO for J/psi: Eskola, Flett et al. PhysRevC.106.035202, 2022), at NLO also quarks come into play
  - Resembling issues in inclusive production
- Dependence on wave function assumptions for quarkonium

Coherent Photoproduction in hadronic collisions



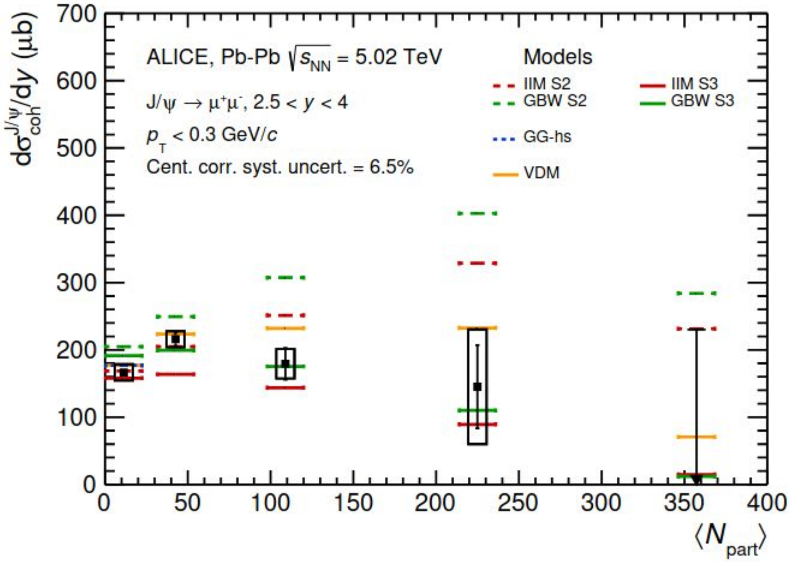
Measurement of low-p_T excess at above hadronic production in peripheral collisions

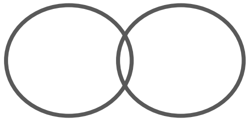
LHCb transverse momentum distribution

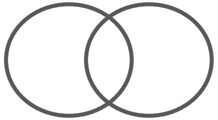
- Actually ´coherent´ production

Phys.Rev.C 105 (2022) 3, L032201

Photoproduction at the LHC: nucleus gluon density







https://arxiv.org/abs/2204.10684, accepted by PLB

Hadronic collisions

Measurement of low-p_T excess at forward rapidity above hadronic production in peripheral collisions

- Extended up to semicentral collisions
- Input to understand coherence condition
- Peripheral collisions:

  resolve photon direction ambiguity in conjunction with ultra-peripheral collisions

J. G. Contreras: Phys. Rev. C 96, 015203 (2017)

Can be also done with neutron emission classes, see https://arxiv.org/abs/1812.06772 and ref. therein

Measurement types to constrain initial geometry

Material taken from Mäntisaary review: [Rept.Prog.Phys. 83 (2020) 8, 082201]()

Exclusive production measurements: measure average amplitude

$$\frac{\mathrm{d}\sigma^{\gamma^* A \to V A}}{\mathrm{d}t} = \frac{1}{16\pi} \left| \left\langle \mathcal{A}^{\gamma^* A \to V A} \right\rangle \right|^2$$

Mandelstam t conjugate to impact parameter:

- quarkonium point-like:

  t-slope measures transverse size of target (proton/nucleus)

Dissociative production: measures fluctuations around average

$$\frac{\mathrm{d}\sigma^{\gamma^* A \to V A^*}}{\mathrm{d}t} = \frac{1}{16\pi} \left(\left\langle \left| \mathcal{A}^{\gamma^* A \to V A} \right|^2 \right\rangle - \left| \left\langle \mathcal{A}^{\gamma^* A \to V A} \right\rangle \right|^2 \right)$$

Measurement types to constrain initial geometry

Average by Star via

ρ production

[Phys.Rev.C 96 (2017) 5]

Can in principle get a ´form factor´-type

measurement with exclusive production

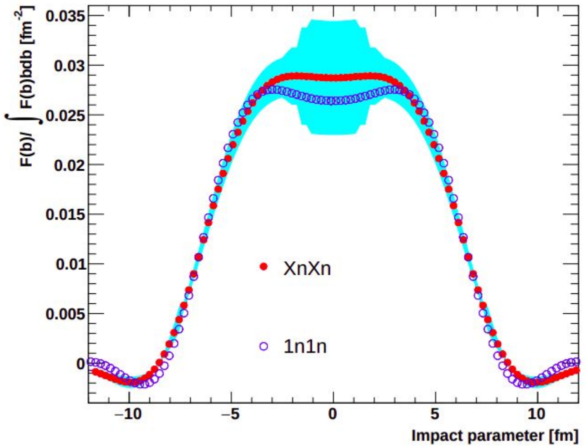


Figure 9: The target distribution in the transverse plane, the result of a two-dimensional Fourier transform (Hankel transform) of the XnXn and 1n1n diffraction patterns shown in Fig. 8. The integration is limited to the region $|t| < 0.06\ (GeV/c)^2$. The uncertainty is estimated by changing the maximum $-t$ to 0.05, 0.07 and 0.09 $(GeV/c)^2$. The cyan band shows the region encompassed by these $-t$ values. In order to highlight the similarity of both results at their falling edges, the resulting histograms are scaled by their integrals from -12 to 12 fm. The FWHM of both transforms is $2 \times (6.17 \pm 0.12)$ fm, consistent with the coherent diffraction of ρ^0 mesons off an object as big as the Au nuclei.

Measurement types to constrain initial geometry

Dissociative production:

measures fluctuations around average

H1 data explained by Hot-spot model

Used for proton eccentricity in hydrodynamic

modeling in pA to get large enough v2

See for a review in H. Mäntisaary [Rept.Prog.Phys. 83 (2020) 8, 082201]

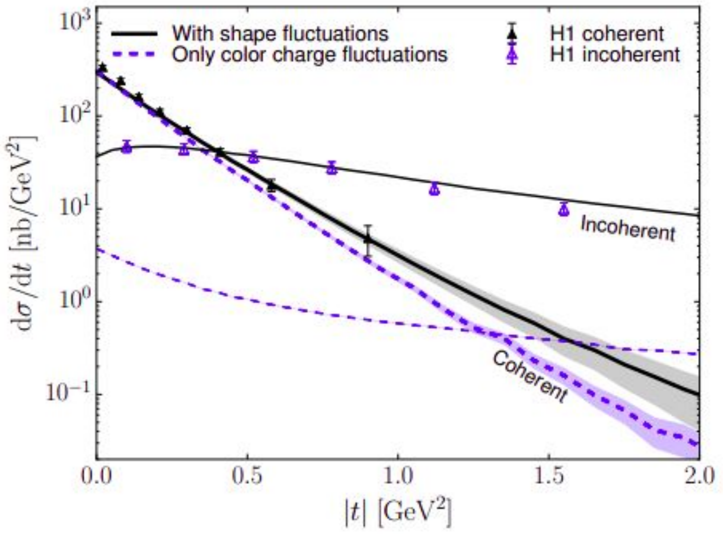


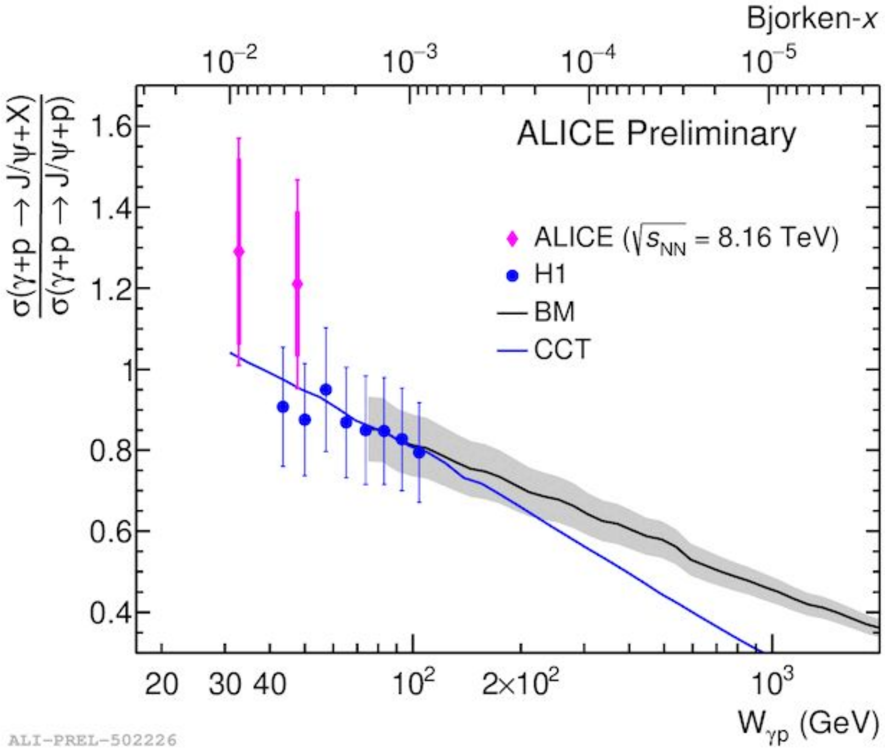
FIG. 3: Coherent and incoherent J/ψ photoproduction spectra at $W = 75$ GeV compared with the H1 data [58]. In the dashed lines only the color charge fluctuations contribute to the fluctuations, and in solid lines additional geometry and density fluctuations are included with the parameters constrained by this data. Figure based on [72].

First measurement at the LHC of dissociative production

Dissociative production:

First measurement at the LHC in ALICE

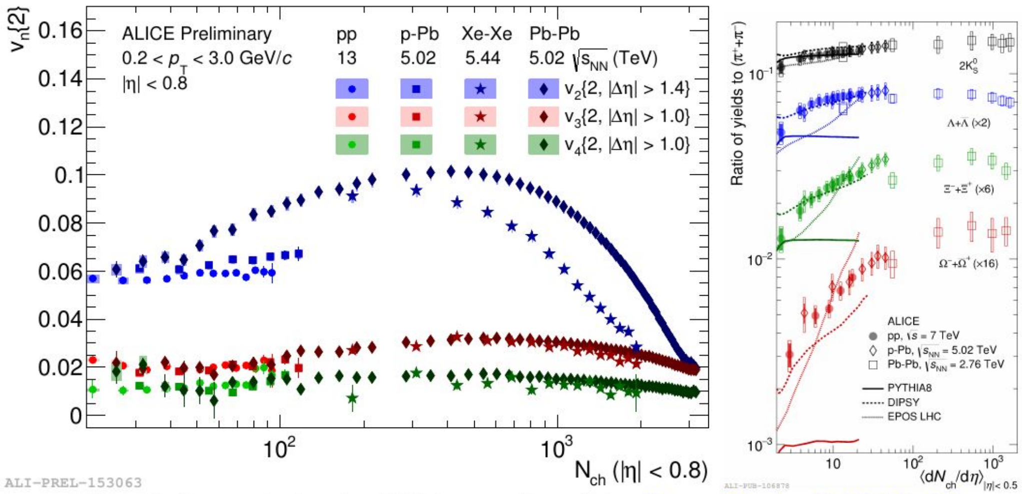
- At the LHC higher energy available as at HERA



Correlation measurements

Azimuthal anisotropies interpreted as signature of initial state eccentricities hard to switch off is (even in UPC inclusive, see ATLAS): what is the basic interpretation?

Is it always the same?

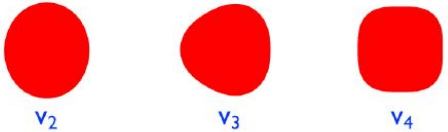


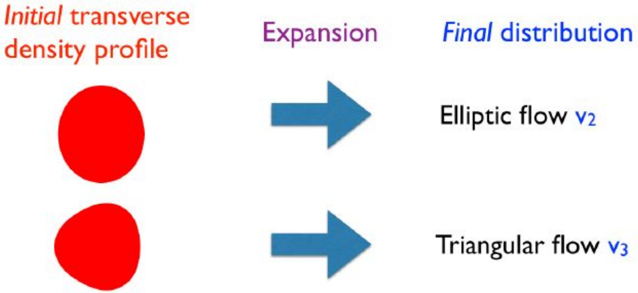
left: preliminary submitted to PRL in next days; right: Nature Physics 13 (2017) 535

- $v_n\{2\} = \sqrt{< e^{in(\Delta\phi} >_{pairs,events}}$ with $\Delta\phi$ between two tracks
- control variable N_{ch}: produced tracks $\propto$ 'freeze-out' volume

Correlation measurements in hydrodynamic picture

- The single-particle distribution is essentially independent of rapidity η but depends on azimuthal angle, φ in each event
- Fourier decomposition : $f(\varphi)=\sum_n V_n\, e^{-in\varphi}$
- $v_n \equiv |V_n|$=anisotropic flow fluctuates event to event





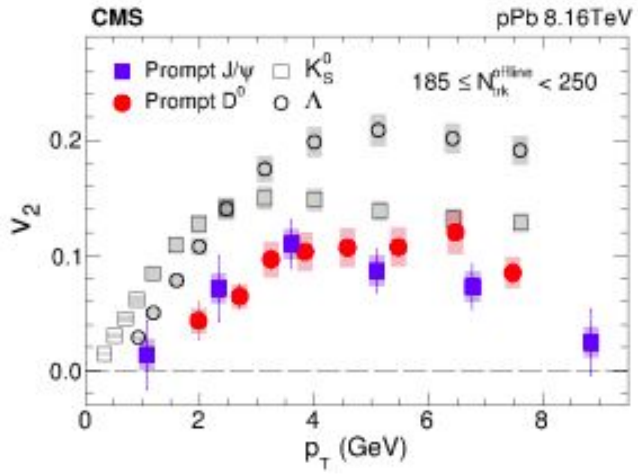
In hydrodynamics, anisotropic flow is a response to the anisotropy of the initial density profile.

taken from from J.-Y. Olltrault's talk at Epiphany conference '19

- transverse collision-zone **geometry in coordinate space** inducing azimuthal particle **correlations in final state in momentum space**

After RHIC and LHC results: predominant interpretation for small system flow today (pp, pA, AA and similar systems at RHIC), however recent caveats due to non-flow, see review by J. Nagle and W. Zaic: Ann.Rev.Nucl.Part.Sci. 68 (2018) 211-235

Charm & charmonium flow in pPb collisions



Phys.Lett.B 791 (2019) 172-194 (CMS Jpsi, pPb)

Phys.Rev.Lett. 121 (2018) 8, 082301 (CMS D-mesons, pPb)

PLB 780, 2018, 7-2 (ALICE jpsi, pPb)

ALICE preliminary in pp: no signal, but large uncertainties

However, quantitatively, charmonium and open charm flow quite large relative to model predictions bt Rapp et al.: to be revisited with latest update: relaxation of charm kinematics to equilibrium in nucleus-nucleus collisions of same order as time duration until uncoupling, small collision systems lifetime shorter, see e.g. some illustration plots in Heinz MIAPP 2018

Saturation-based model predicting large signal, but difference in observable definition w.r.t. experiment Cheng and Marquet et al. Phys. Rev. Lett. 122 (2019), see Cyrille´ contribution at INT 2019

- good to clarify, if either experiment could get a measurement closer to initial state observable or theory closer to measurement

My understanding based on discussions with Cyrille: For CGC-type, it would be more natural to look at dihardon or DDbar away-side peak broadening in pA vs. pp (PTpair<<Ptsingle) rather than flow moments, see e.g. in Giacalone et al. Phys.Rev.D 99 (2019) 1, 014002

Conclusions

A lot of experimental data available and also used to infer information on the initial state of HICs based on charm and beauty observables

- Gluon density via charm production
- Transverse geometry via HERA exclusive production

The interpretation as initial state quantification relies on:

- Transfer from collision-type to another or on assumptions on hydrodynamic response
- The subleadingness of ´secondary´ effects: factorisation, hadronization, energy loss, rescattering, pQCD uncertainties

Overall, the information remains quite qualitative given all the caveats, but:

- the experimental precision: new level in the last 10 years (LHC instrumentation and rates vs. RHIC), will continue to improve.
- data is very powerful, if one closes eyes on caveats for a moment. Encouraging to continue to clarify issues.

Outlook

Inclusive total charm cross section are major goal of ALICE upgrade:

avoiding final state factorisation issues?

Experimentally more challenging, but theoretically cleaner measurements are under preparation:

- Drell-Yan at low scales, photons at relatively low pt with LHCb and ALICE
- Photoproduction measurements sensitive to the fluctuations of the hadrons and separation of photon-flux sources to test low-x
- Beauty with larger luminosities

Cheng and Marquet et al. Phys. Rev. Lett. 122 (2019),

the final state. Similar to the measurements carried out at the LHC, we compute $v_2 \equiv \langle \cos 2\Delta\phi \rangle$ based on the production of a J/ψ meson in the CEM accompanied by another reference quark, which eventually fragments into a charged hadron; i.e., we disregard the $q \to qg \to qJ/\psi$ jetlike contributions.

ALICE

Energy dependence of J/psi photoproduction off the proton