Complementarity of the LHC and the EIC for heavy-ion studies with quarkonia

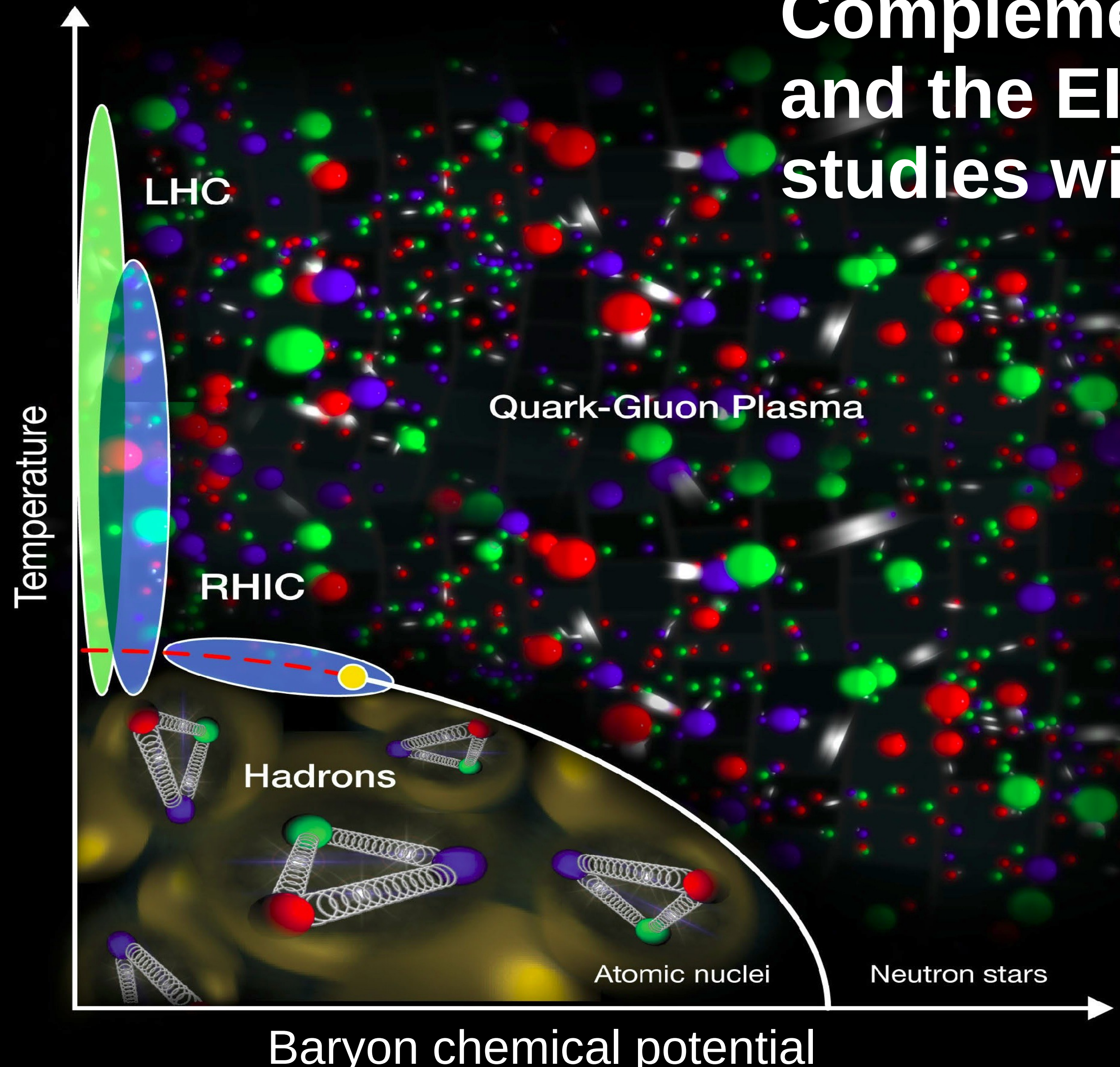
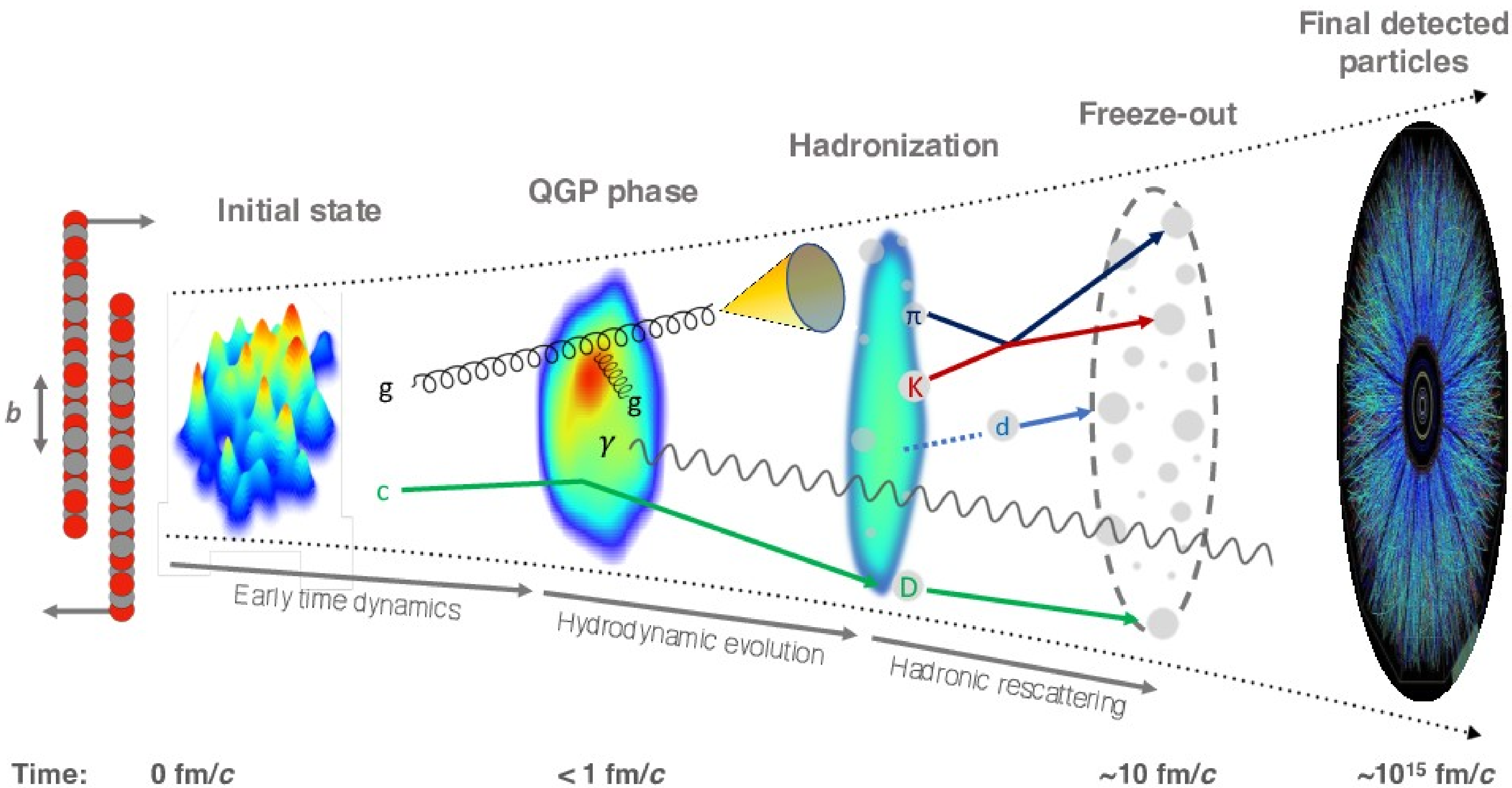


Fig. Courtesy Brookhaven National Laboratory

Daniel Kikoła

ETC* Trento, 12.07.2024

Heavy ion collisions and heavy quarks

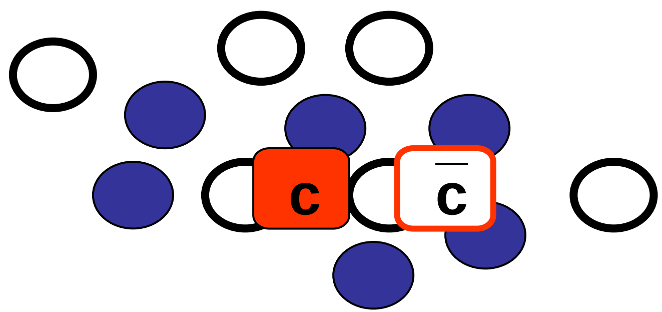


Hot QCD White Paper, arXiv:2303.17254

Matsui & Satz (1986):

Quark-gluon plasma (QGP)

= suppression of J/ψ production



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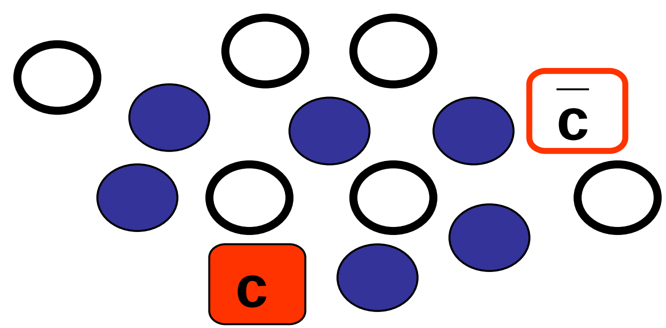
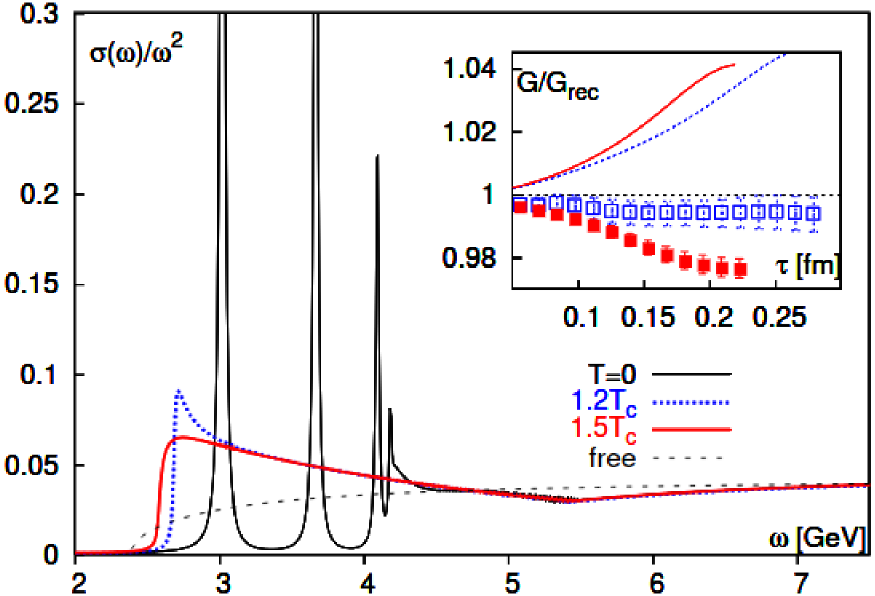
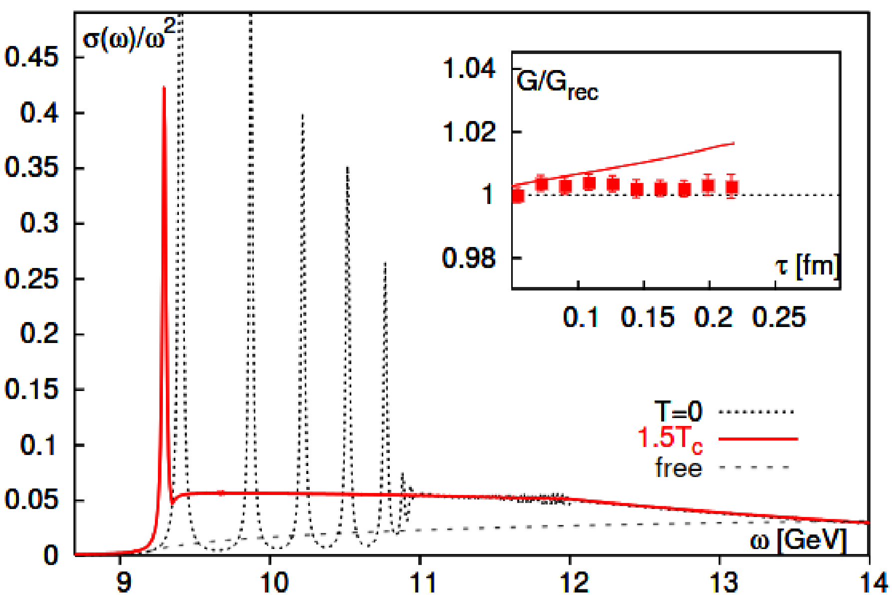




Suppression pattern

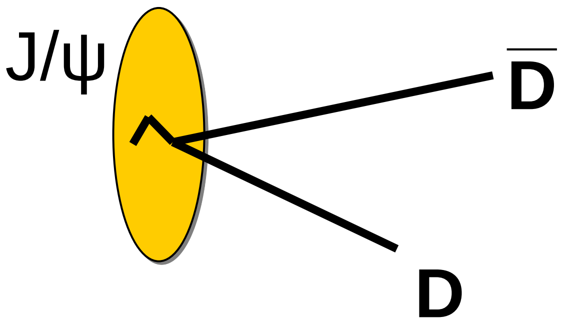
→ temperature of the QGP



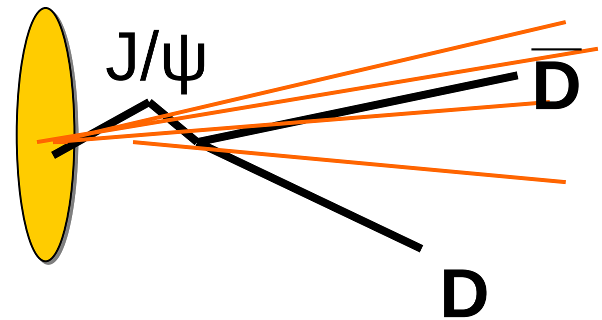
Charmonium (top) and bottomonium (bottom) spectral functions at different temperaturesa

A. Mocsy, P. Petreczky, Phys.Rev. D73 (2006) 074007

Break-up in nuclear matter



Break-up in a final state



Sensitive to the feed-down e.g.

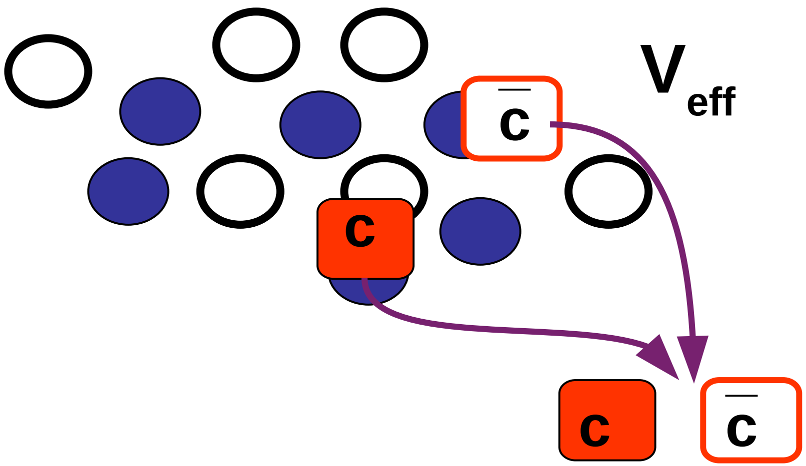
$\psi(2S) \rightarrow J/\psi$,

$\Upsilon(3S) \rightarrow \Upsilon(2S) \rightarrow \Upsilon(1S)$

$\chi_b\,(1P) \rightarrow \Upsilon(1S)$

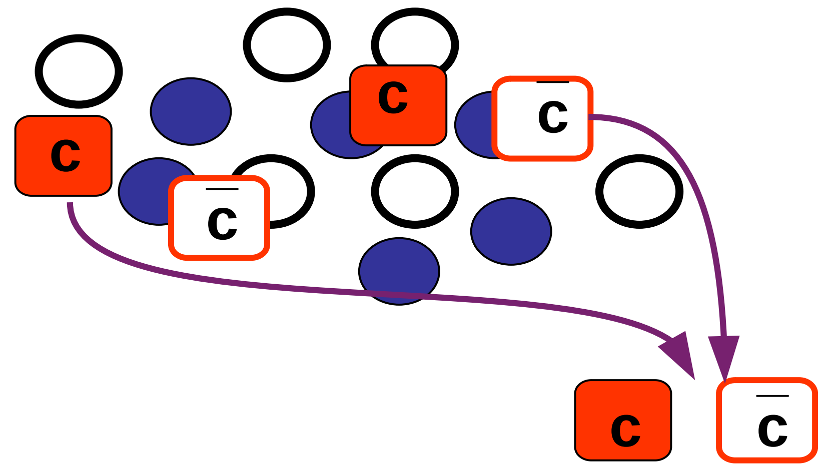
Secondary production in QGP

Regeneration



vs.

Coalescence



Recombination of c $\bar{c}$ quarks close in space

Coalescence over a large volume, c an $\bar{c}$ quarks could be uncorrelated originally

Secondary production may depend on charm cross section and details of the in-medium interactions

Production in a final state, e.g.:

$$\langle\sigma v\rangle(D\bar{D} \to J\Psi + \pi) = .03 \pm .01 \text{ mb}$$

$$\langle\sigma v\rangle(D^*\bar{D}^* \to J\Psi + \pi) = 1 \text{ mb}$$

$$\langle\sigma v\rangle(D^*\bar{D} \to J\Psi + \pi) = 3.75 \pm .25 \text{ mb}$$

$$\langle\sigma v\rangle(D\bar{D} \to J\Psi + \rho) = .065 \pm .01 \text{ mb}$$

$$\langle\sigma v\rangle(D^*\bar{D} \to J\Psi + \rho) = .15 \pm .05 \text{ mb}$$

$$\langle\sigma v\rangle(D^*\bar{D}^* \to J\Psi + \rho) = .95 \pm .05 \text{ mb}$$

$$\langle\sigma v\rangle(D_s\bar{D} \to J/\psi + K) = .25 \pm .05 \text{ mb}$$

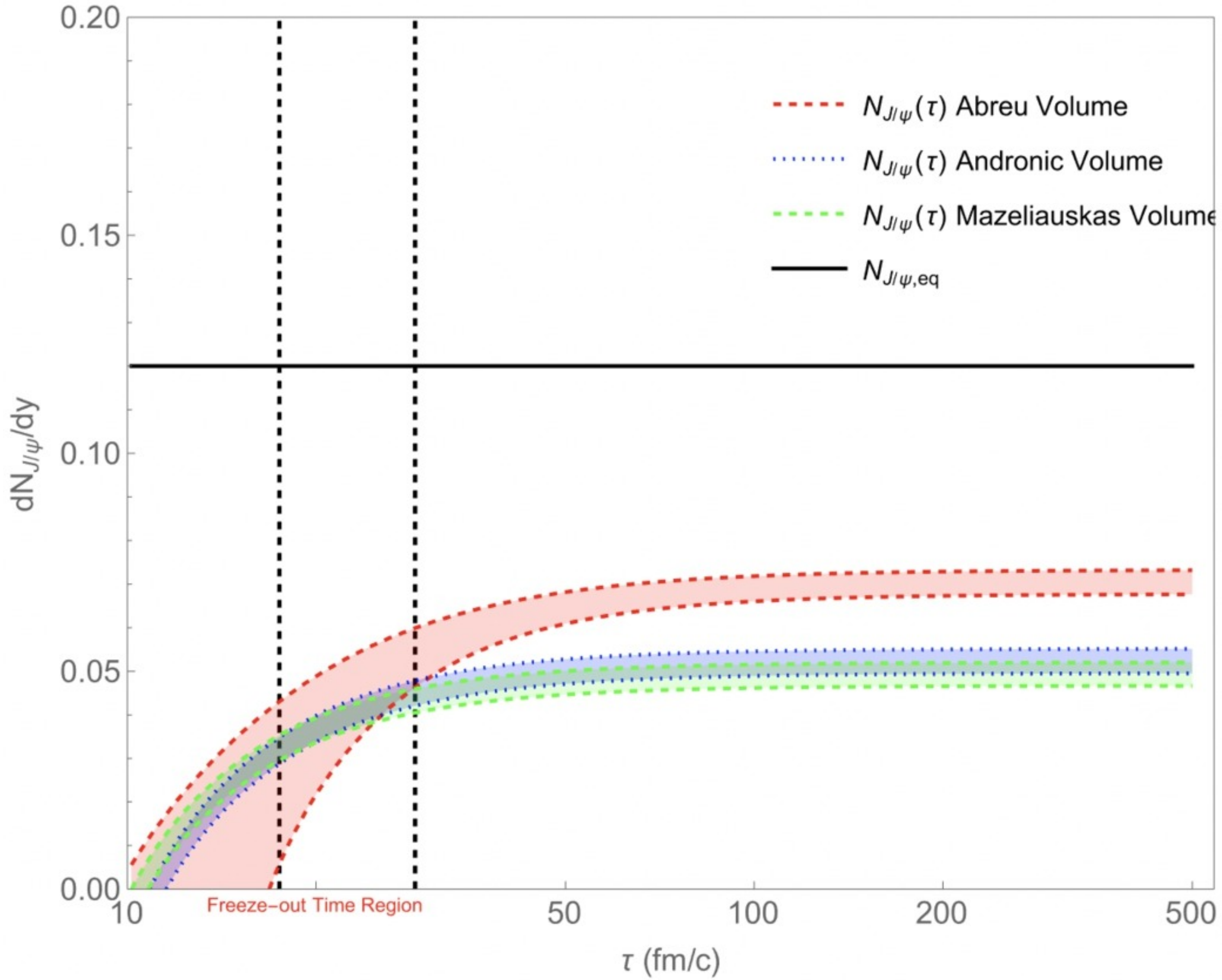
$$\langle\sigma v\rangle(D_s^*\bar{D} \to J/\psi + K) = 1.7 \text{ mb}$$

$$\langle\sigma v\rangle(D_s\bar{D}^* \to J/\psi + K) = 1.5 \text{ mb}$$

$$\langle\sigma v\rangle(D_s^*\bar{D}^* \to J/\psi + K) = .4 \text{ mb}$$

L. M. Abreu et al, Phys. Rev. C 97, 044902 (2018):
J. D. Lap, B. Mullr, Phys.Lett.B 846 (2023):

Time dependence of hadronic J/ψ production by D-mesons



J. D. Lap, B. Mullr, Phys.Lett. B 846 (2023)

Production in a final state

L. M. Abreu et al: Phys. Rev. C 97, 044902 (2018):

We conclude that the interactions between J/ψ and all the considered mesons reduce the original J/ψ abundance (determined at the end of the quark gluon plasma phase) by 20% and 24% in RHIC and LHC collisions respectively. Consequently, any really significant change in the J/ψ abundance comes from dissociation and regeneration processes in the QGP phase.

J. D. Lap, B. Muller, PLB 846 (2023):

Our calculation demonstrates that we cannot safely ignore the contribution from hadronic charmonium production processes to the J/ψ yield in heavy-ion collisions at LHC energies. As such, any calculation of thermal production of J/ψ must take regeneration by D-meson collisions into account.

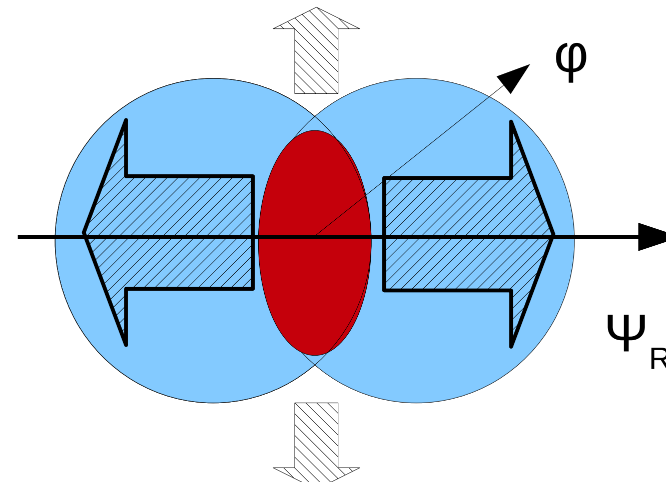
Observables

- Nuclear modification factor R_{pA}, R_{AA}

  $R_{AA} = 1$, $R_{pA} = 1$ if no modification in the medium

$$R_{AB} = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{d^2N^{AB}/dy\,dp_T}{d^2N^{pp}/dy\,dp_T}$$

- Azimuthal momentum anisotropy

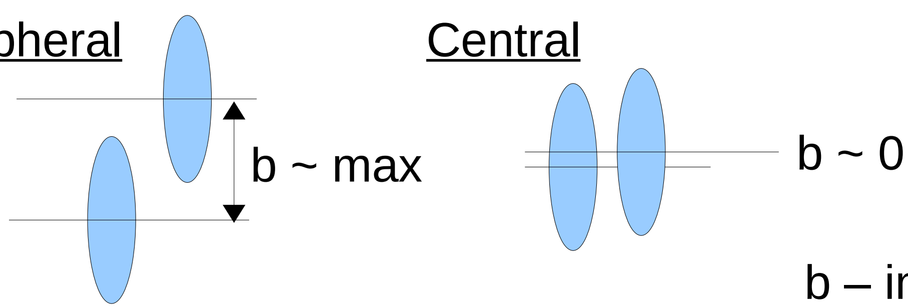


$$\frac{dN}{d(\varphi - \Psi_{RP})} \propto 1 + 2v_2 \cos 2(\varphi - \Psi_{RP})$$

- Collision geometry

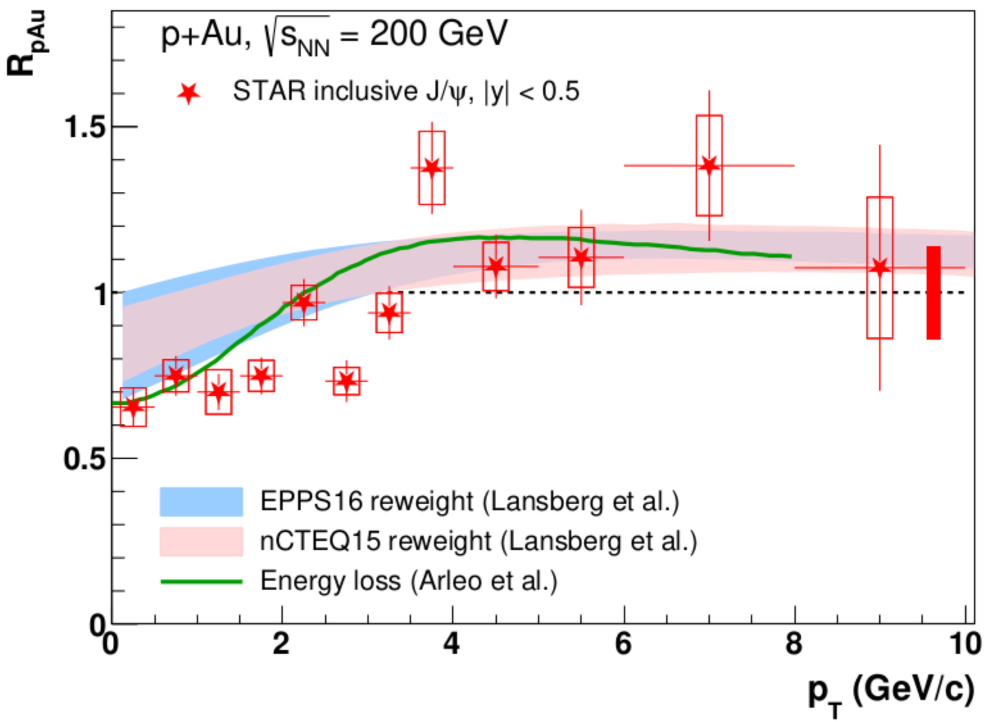
Peripheral

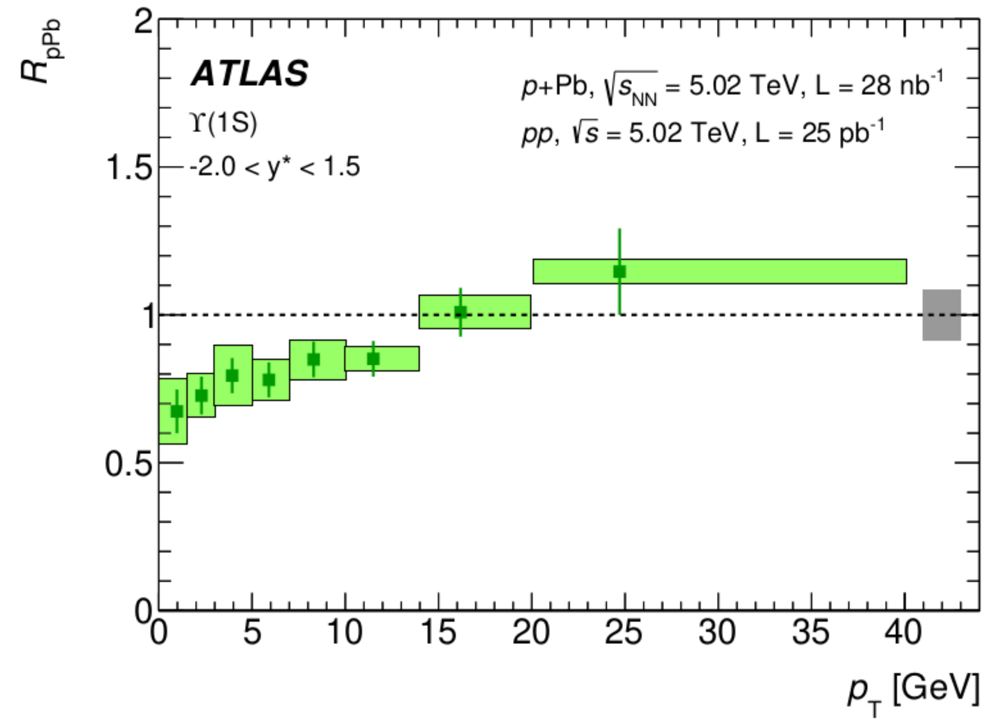
Central



b – impact parameter

Cold nucler matter effects

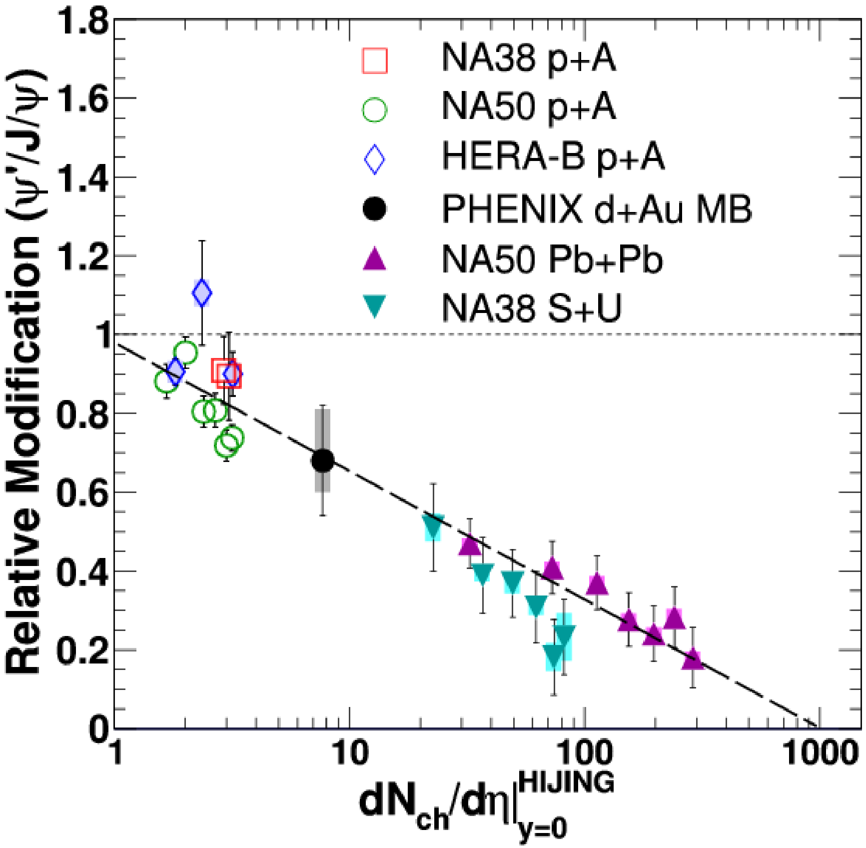


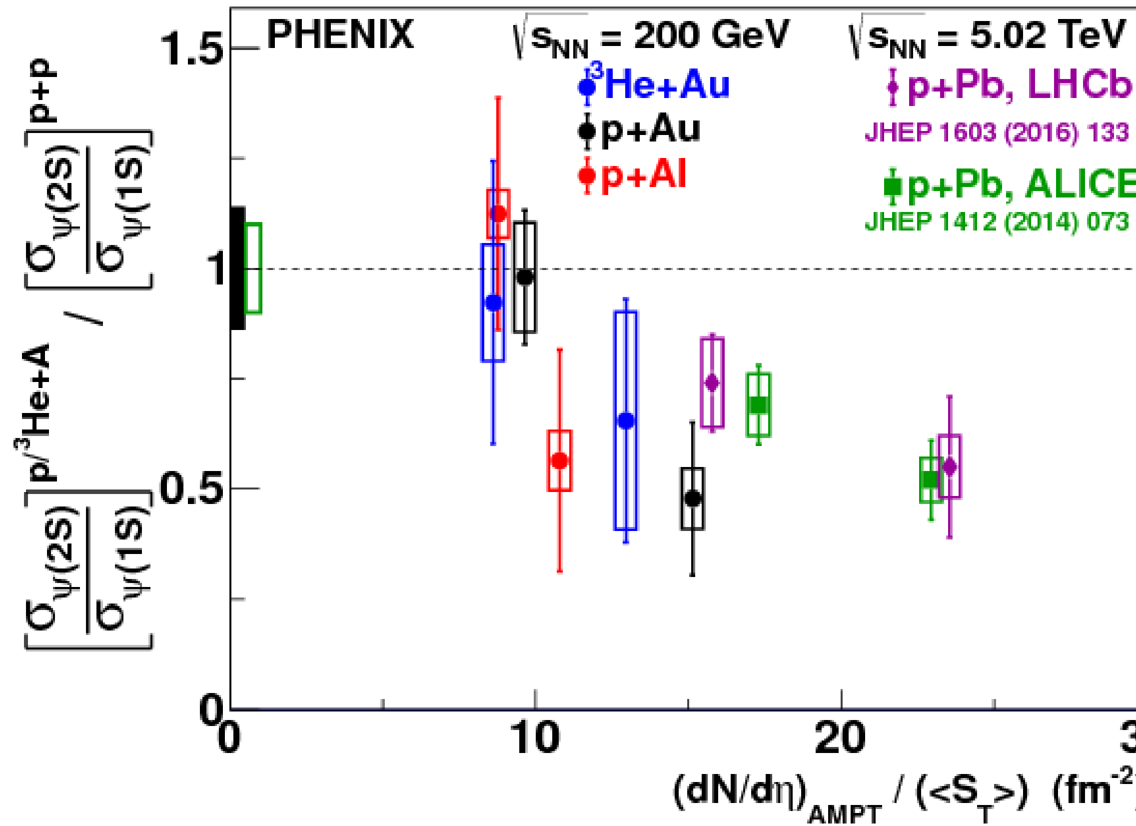


Sizable uncertainty on model calculations due to nPDF

Hot QCD White Paper, arXiv:2303.17254

Break-up in a final state?

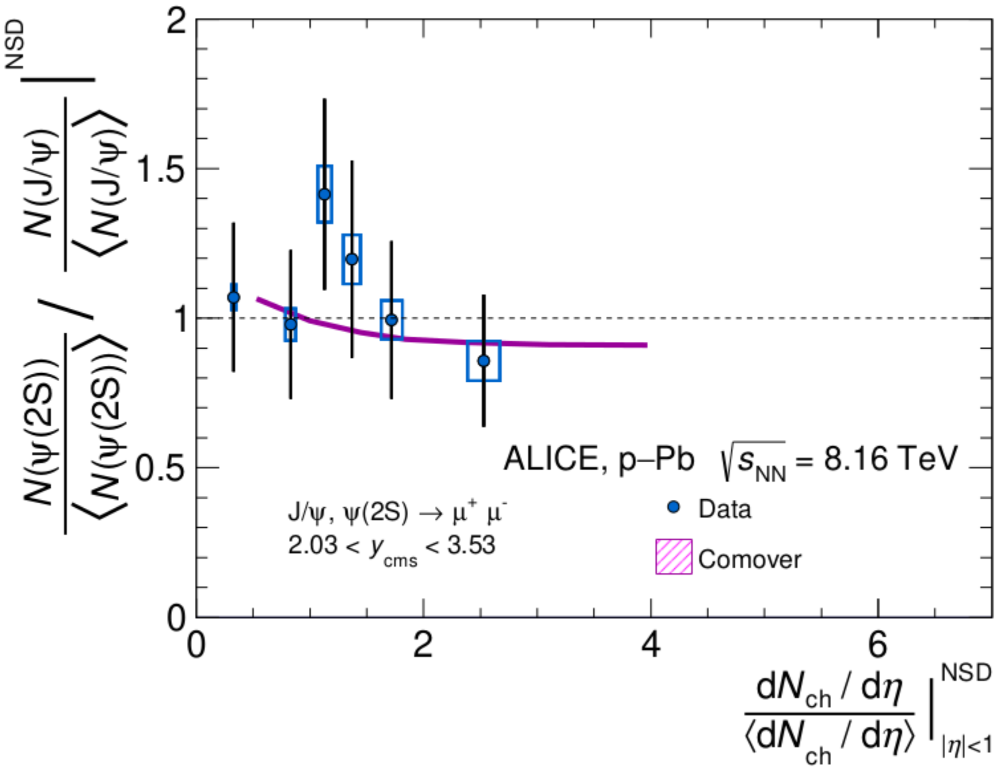


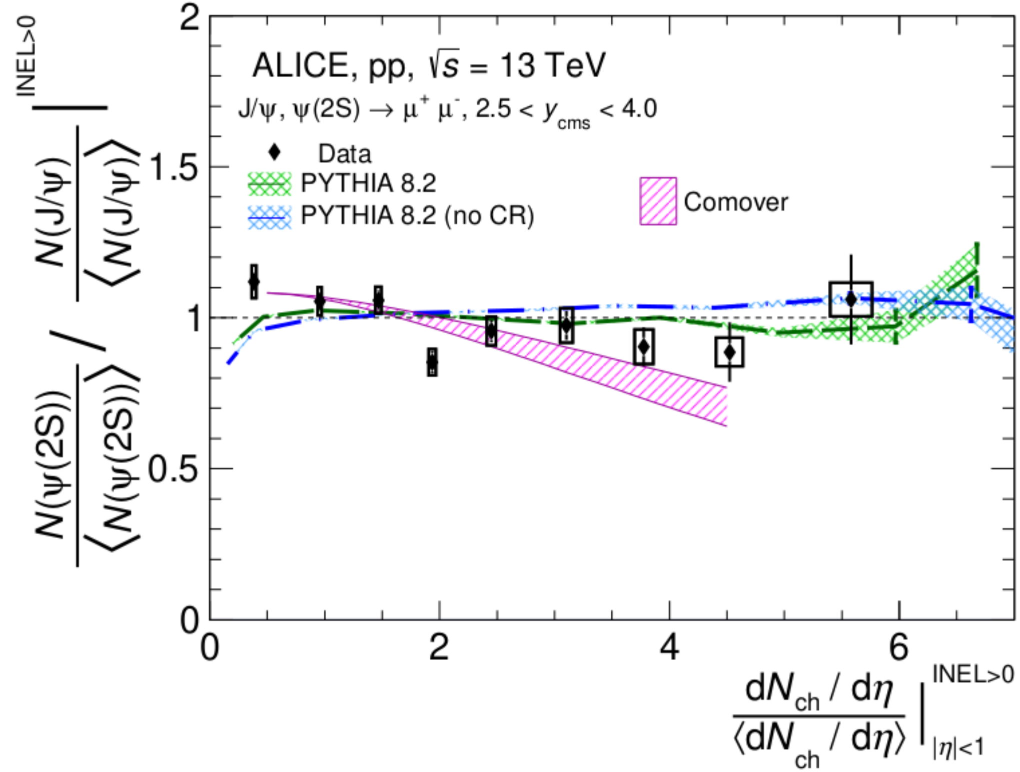


Phys. Rev. Lett. 111, 202301 (2013).

Phys.Rev. C 95 (2017) 3, 034904

Break-up in a final state?



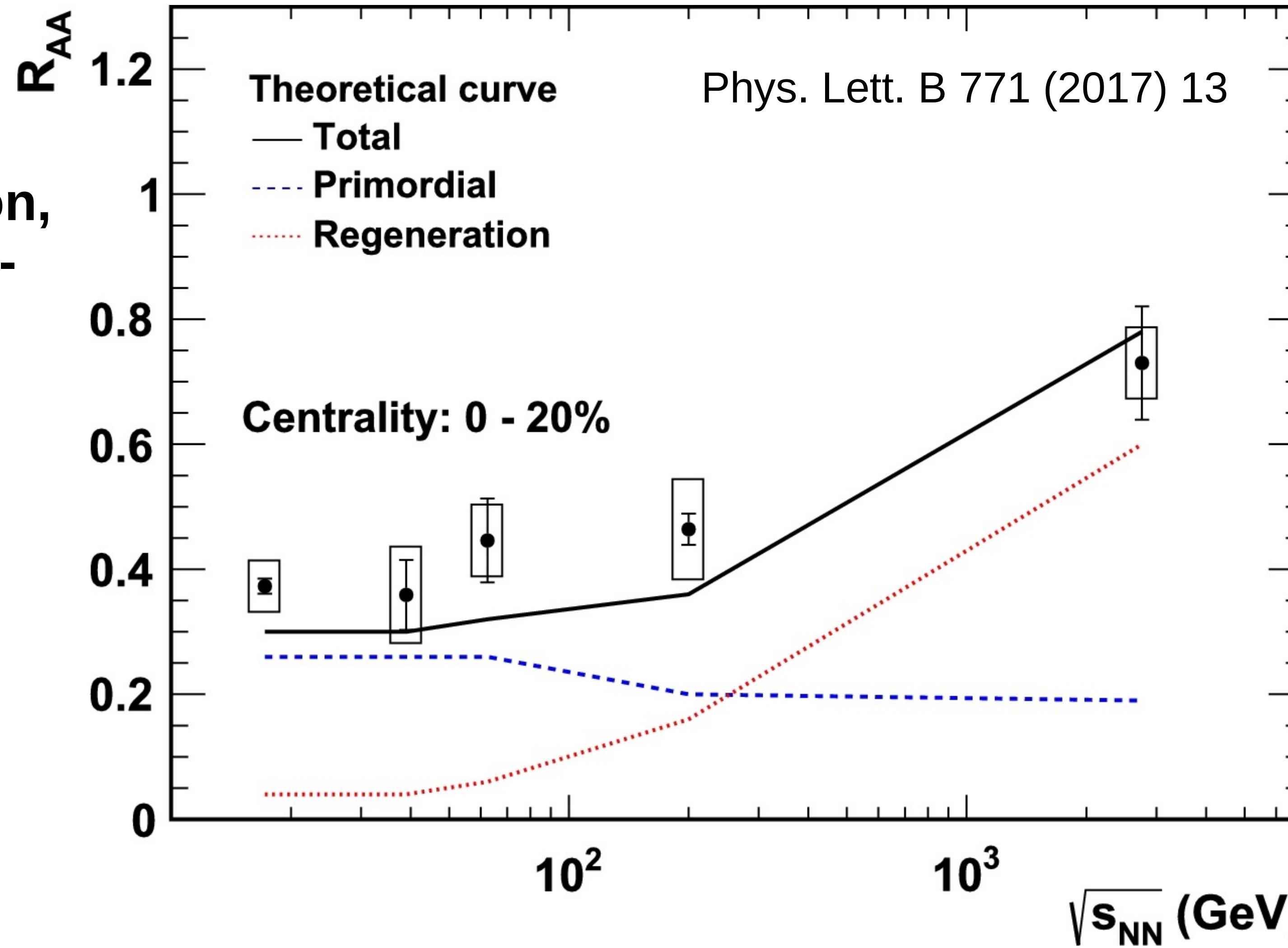


The ratio of ψ (2S) over J/ψ yield does not show a significant multiplicity dependence in pp nor pPb at forward radipidty

JHEP 06 (2023) 147

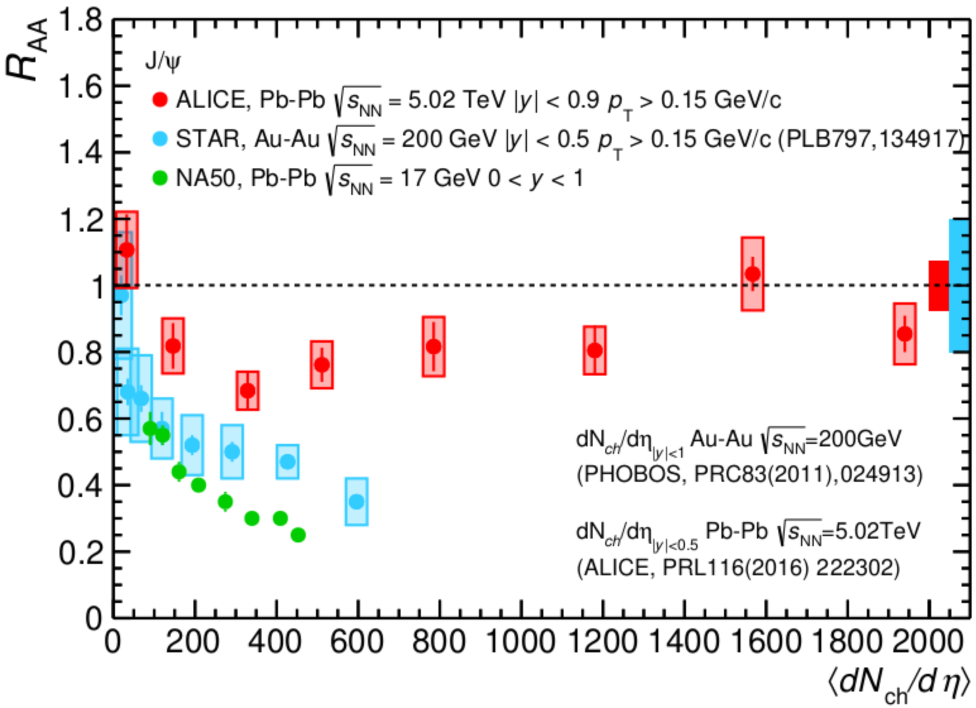
J/ψ R_{AA} vs collision energy

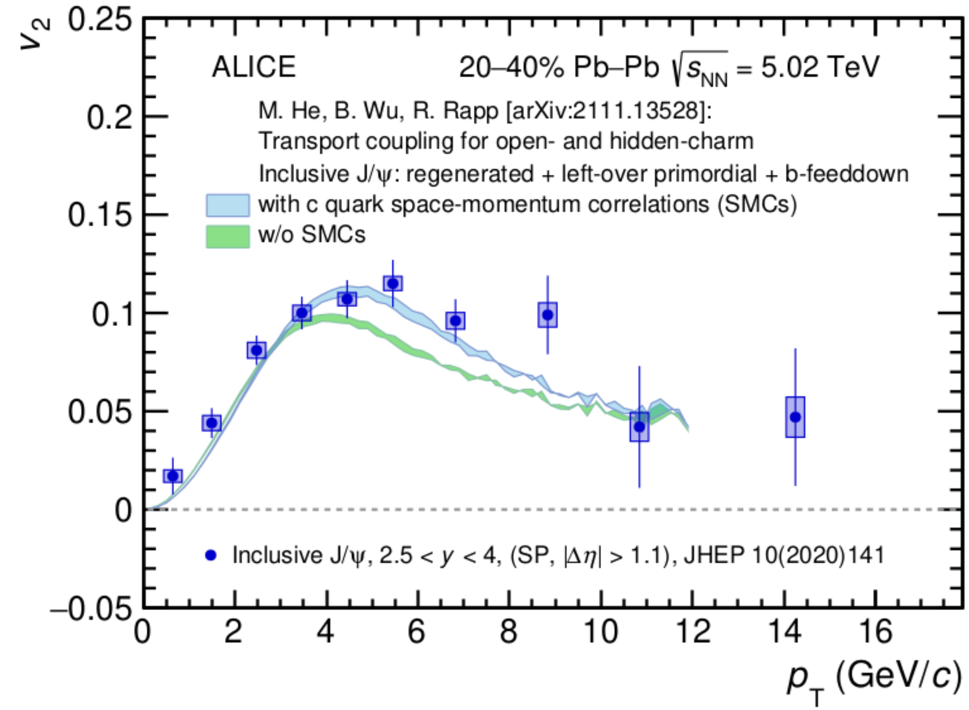
Primordial suppression, regeneration and cold-nuclear matter effect depend on collision energy



Model: X. Zhao, R. Rapp,
PRC, 82 (2010), 064905

J/ψ R_{AA} and elliptic flow

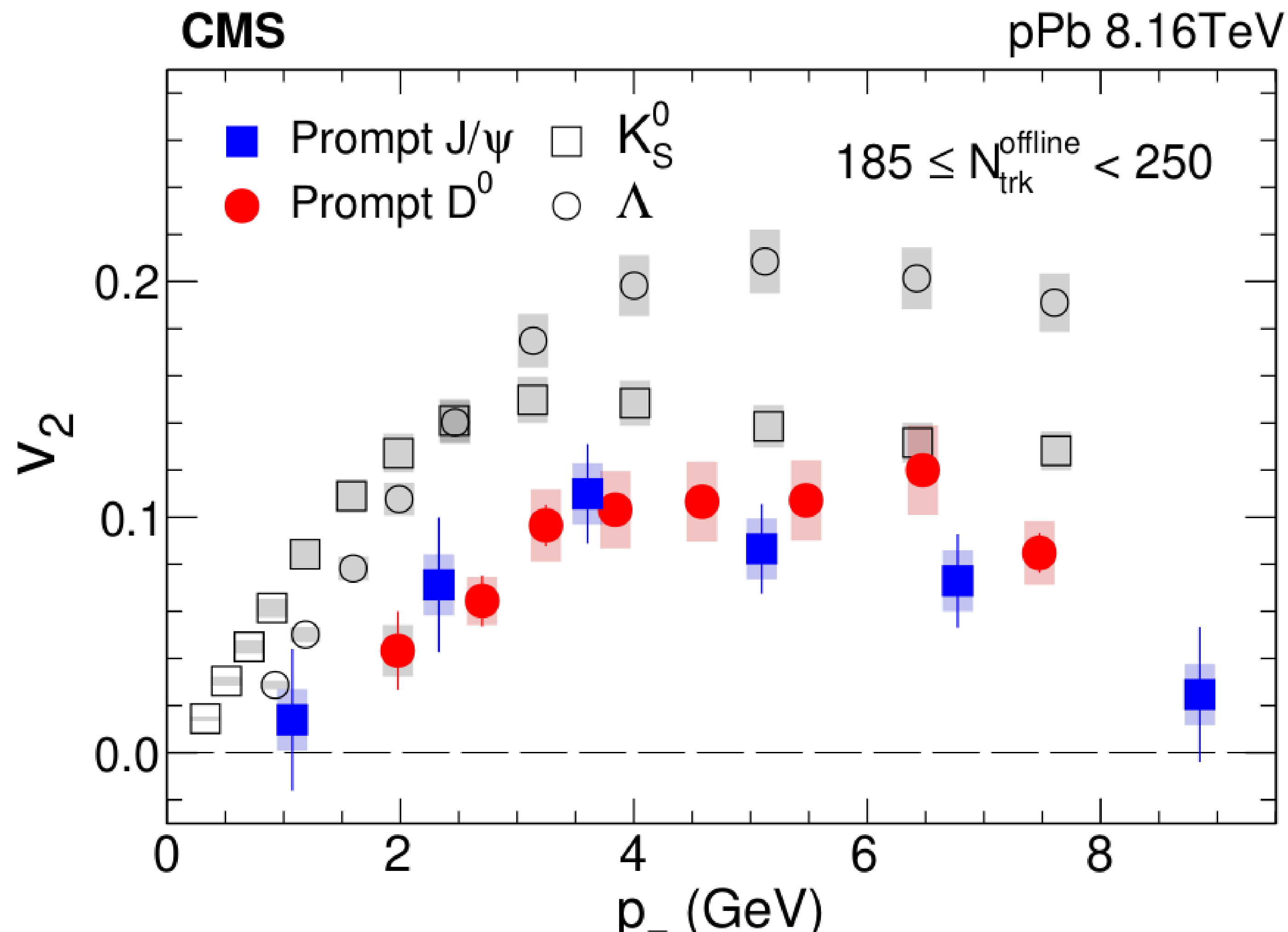




Elliptic flow measurement to constrain $c+\bar{c} \rightarrow J/\psi$ recombination (?)

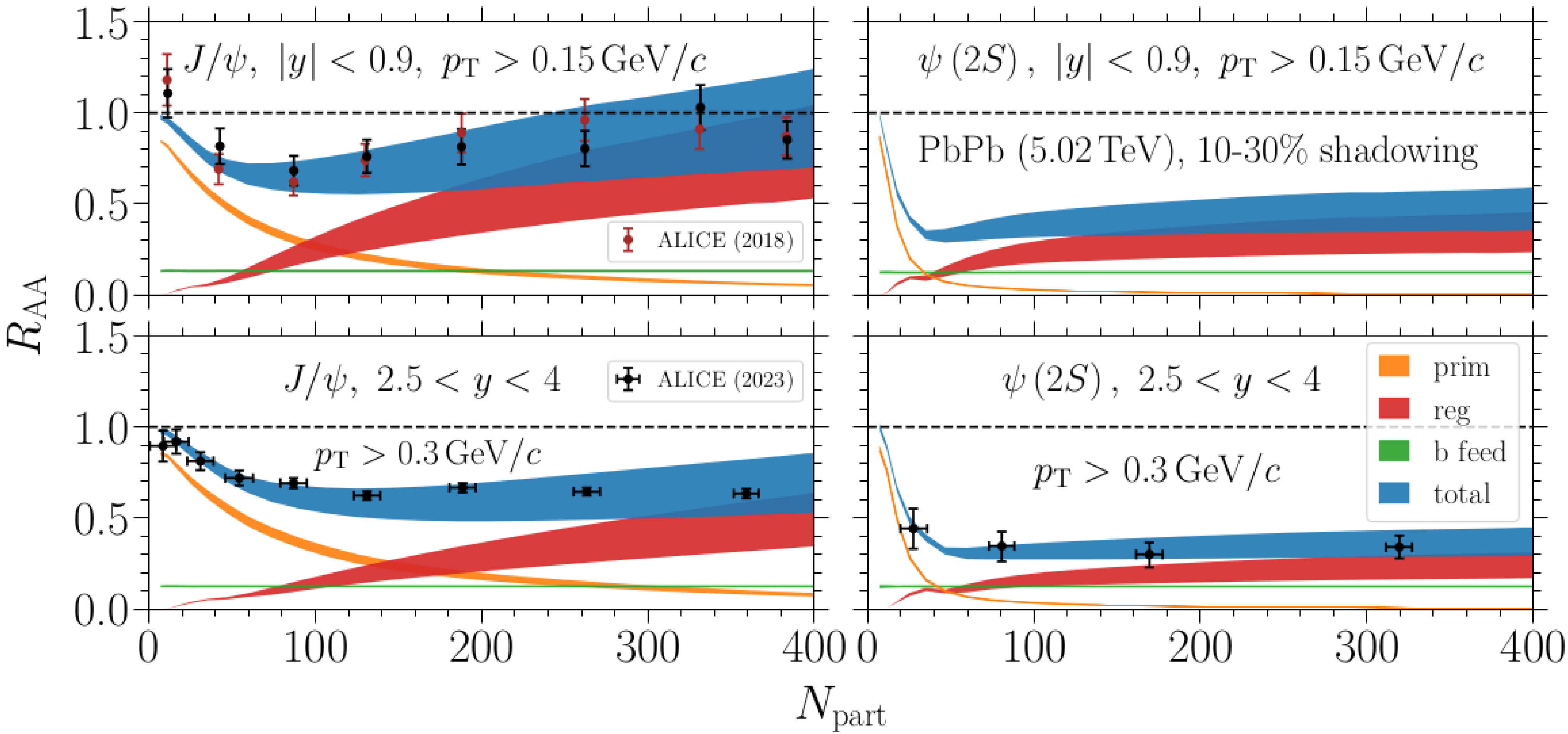
Hot QCD White Paper, arXiv:2303.17254

Complications: non-trivial effects in inp+p and p+Pb at the LHC



Phys. Lett. B 791 (2019) 172

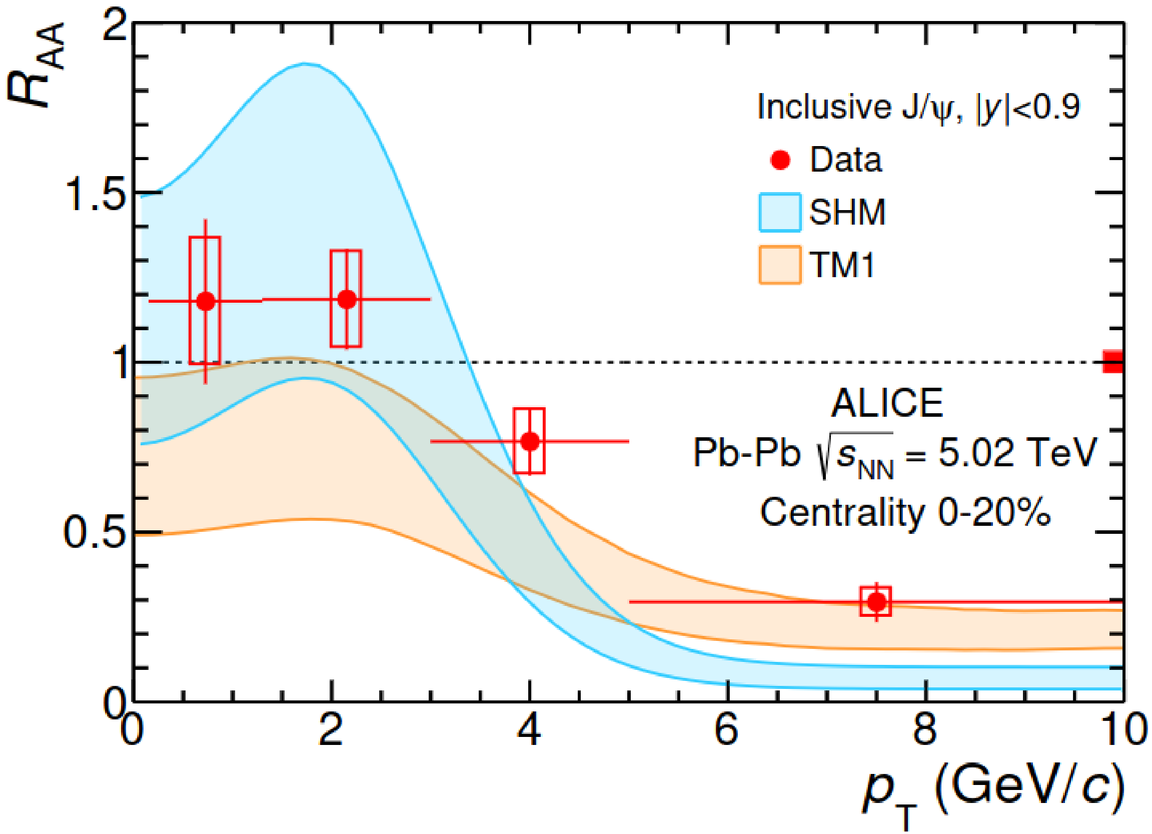
Example: theoretical uncertities



B. Wu ,R. Rapp, Universe 2024, 10, 244

Uncertiaties due to: charm cross section, feed-down, shadowing parametrization

Example: theoretical uncertities



SHM: Statistical Hadronization Model (PLB 797 (2019) 134836)

TM1: Transport model (PLB 664 (2008) 253–257)

PLB 805 (2020) 135434

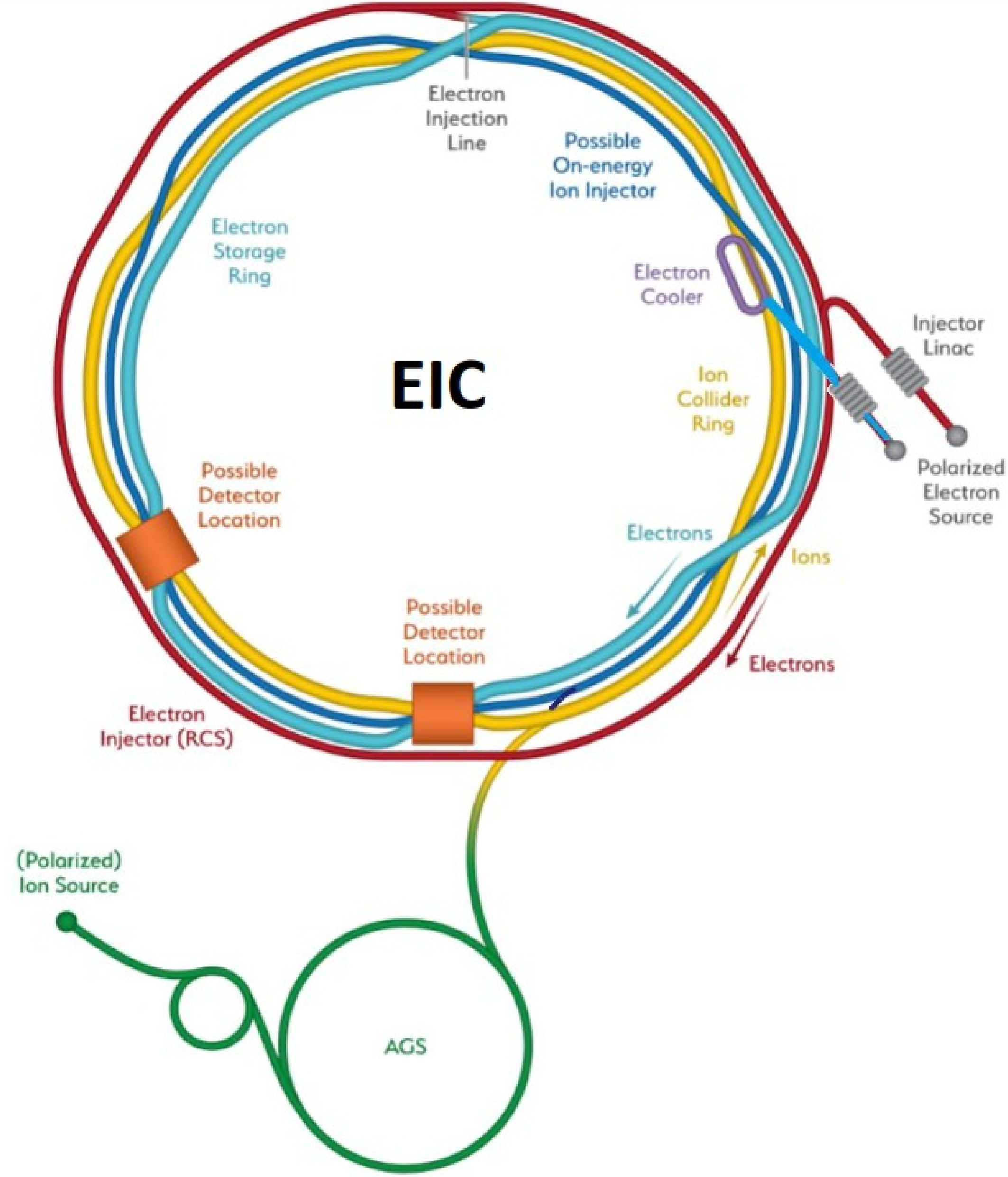
Uncertiaties due to: charm cross section, feed-down, shadowing parametrization

Opportunities at the EIC and fixed-target collisions at the LHC:

Callibration of quarkonium as a probe of the QGP

Electron-Ion Collider

Energy: √s = 20 – 140 GeV



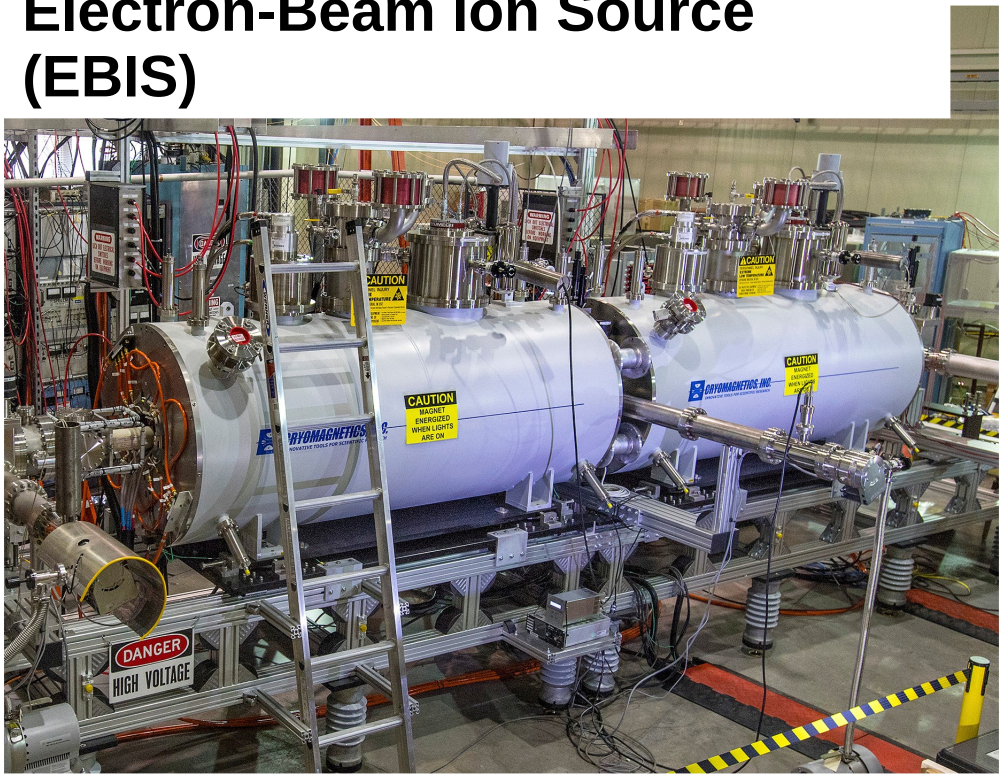
https://indico.cern.ch/event/949203/contributions/3988180/attachments/2117011/3564269/EIC-Acc-Overview-Oct-7-2020-Seryi-r3.pdf

Electron-Ion Collider

Energy: $\sqrt{s}$ = 20 – 140 GeV

Ion species: from p to U

Electron-Beam Ion Source (EBIS)



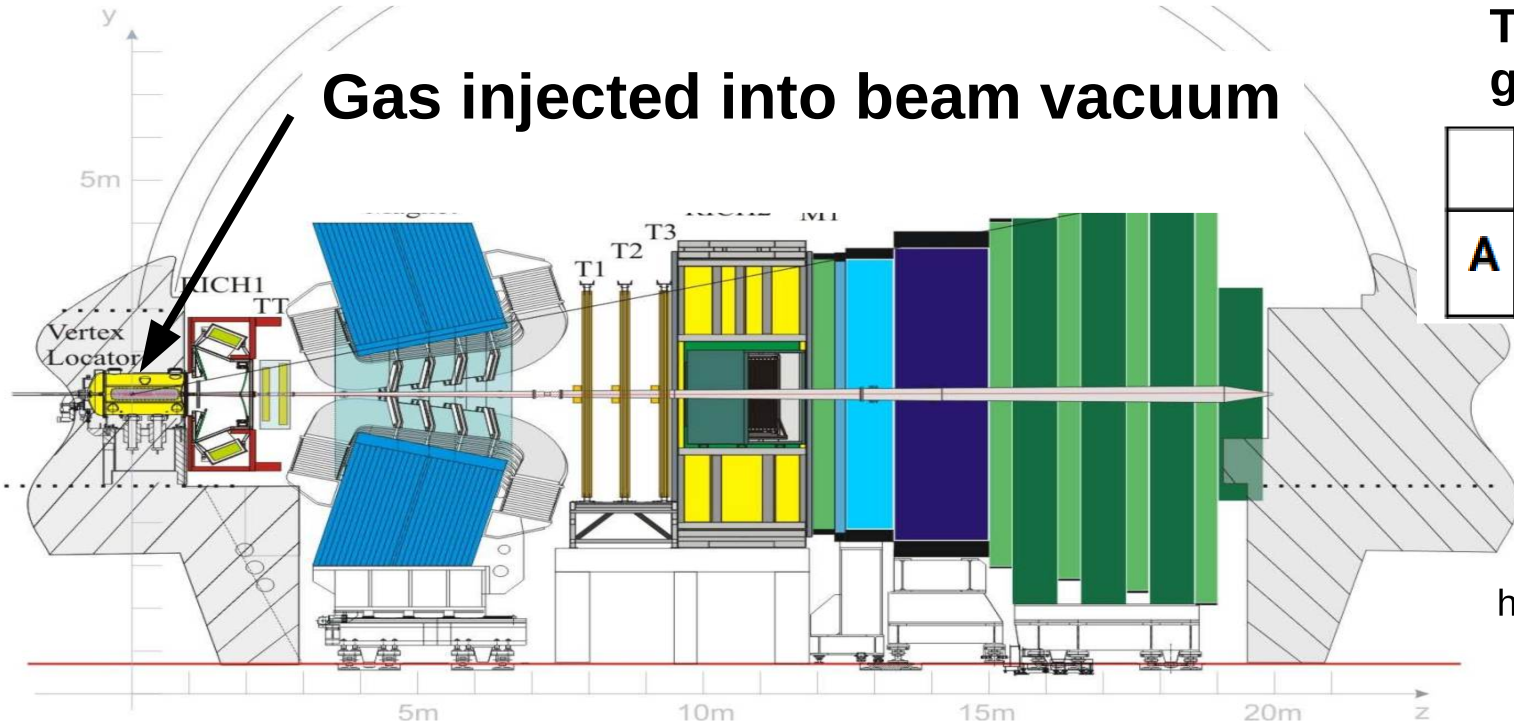
Ion Pairs in the RHIC Complex

Zr-Zr, Ru-Ru	(2018)
Au-Au	(2016)
d-Au	(2016)
p-Al	(2015)
h-Au	(2015)
p-Au	(2015)
Cu-Au	(2012)
U-U	(2012)
Cu-Cu	(2012)
D-Au	(2008)
Cu-Cu	(2005)

https://indico.cern.ch/event/949203/contributions/3988180/attachments/2117011/3564269/EIC-Acc-Overview-Oct-7-2020-Seryi-r3.pdf

SMOG-LHCb: the demonstrator of a gas target

System for Measuring Overlap with Gas



Target gas: only noble gases

	He	Ne	Ar	Kr	Xe
A	4	20	40	84	131

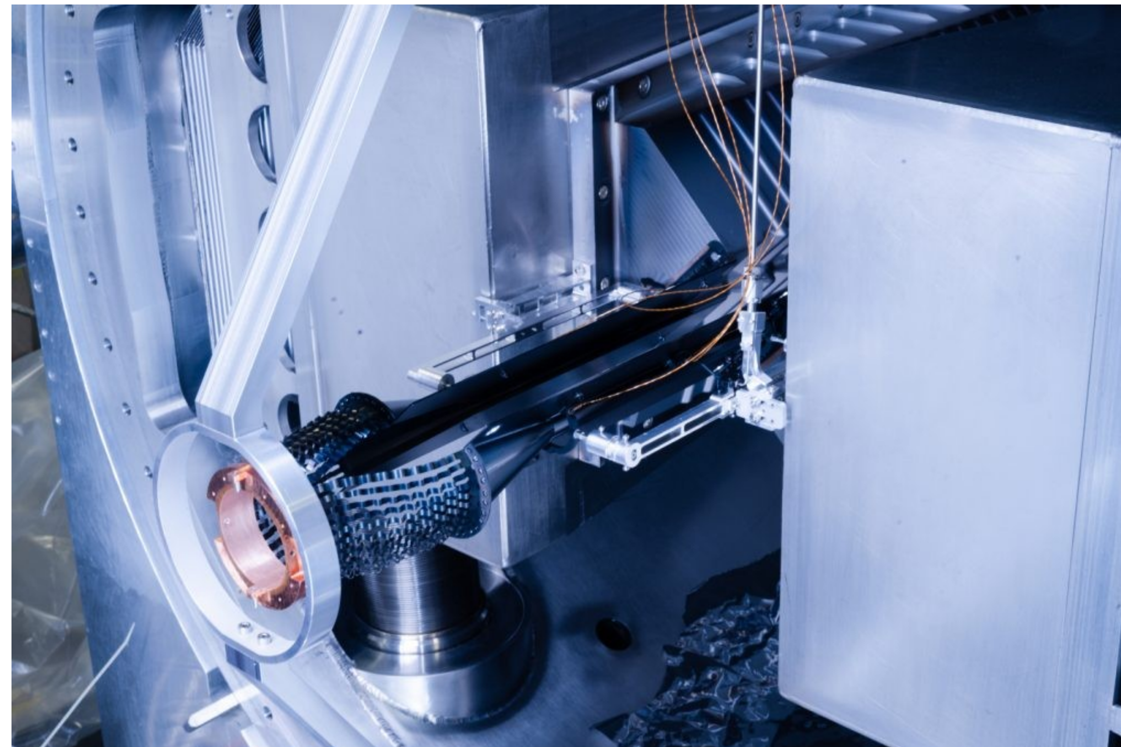
https://lhcb.web.cern.ch/lhcb

Successful p+Ne, p+Ar, p+He, Pb+Ar, Pb+Ne data taking

Energy range: $\sqrt{s_{pA}} \approx 68 - 115$ GeV, $\sqrt{s_{PbA}} = 72$ GeV

LHCb SMOG 2

Possibility of heavier and different noble gases (Kr, Xe, H_2, D_2, O_2, N_2) with a pressure two orders of magnitude higher than SMOG



SMOG2 gas confinement cell installed in the LHCb detector, https://lhcb-outreach.web.cern.ch/detector/smog/

LHCb SMOG 2

- Expected large quarkonium and open-charm meson yields

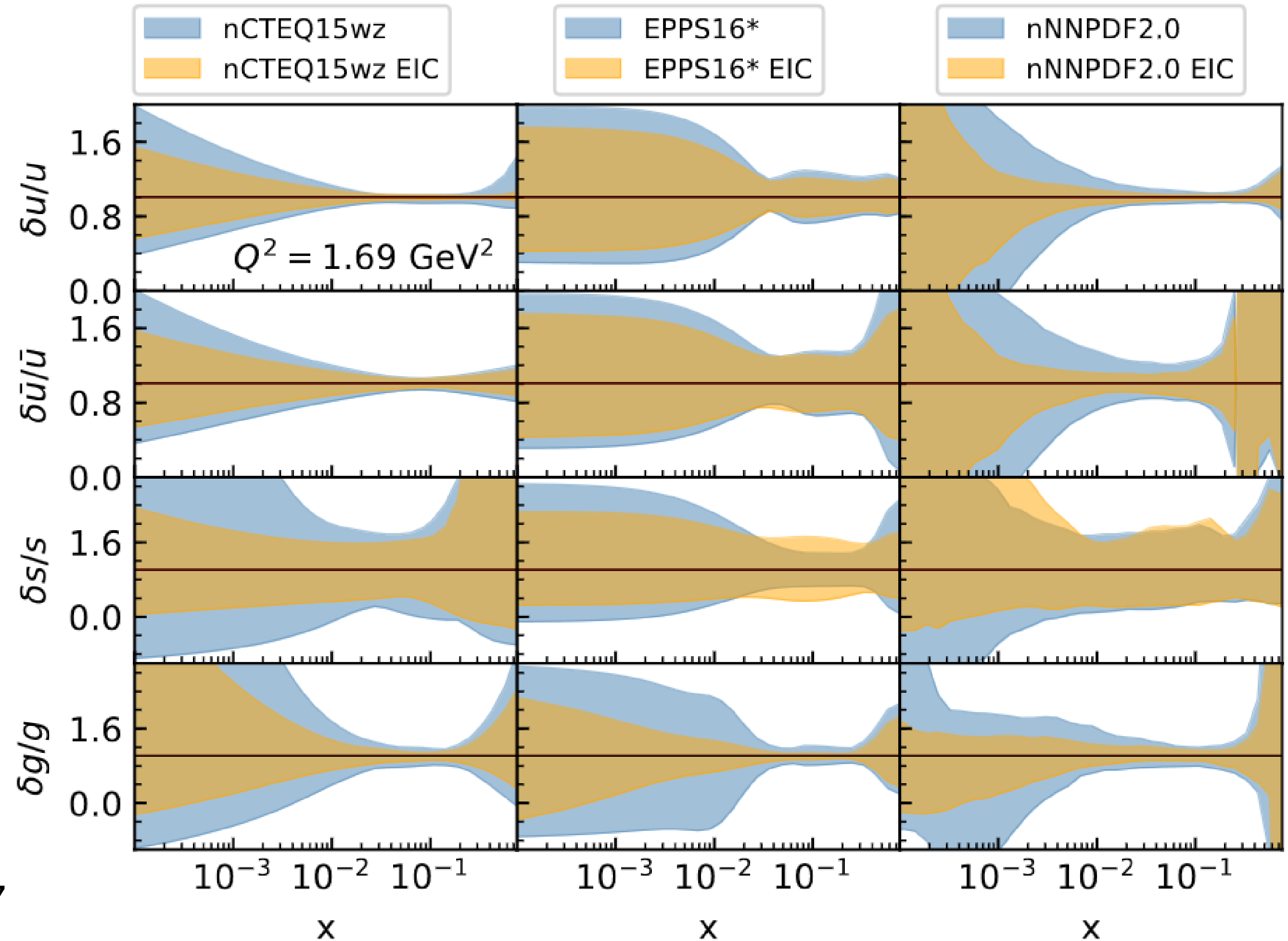
	SMOG pNe ($\sqrt{s}$ = 68 GeV)	SMOG2 pAr ($\sqrt{s}$ = 115 GeV)
Integrated luminosity	$\sim 100\ nb^{-1}$	$\sim 100\ pb^{-1}$
syst. error on J/Ψ x-sec.	6-7%	2-3%
J/Ψ yield	15k	35M
D^0	100k	350M
Λ_c yield	1k	3.5M
$\Psi(2S)$ yield	150	400k
$\Upsilon(1S)$	4	15k
Low-mass ($5<M_{\mu\mu}<9$ GeV/c^2) Drell-Yan yield	5	20k

https://cds.cern.ch/record/2825146?ln=en

Effects / factors to constrain

Effects / factors to constrain

- Charm production in A+A (nPDFs)

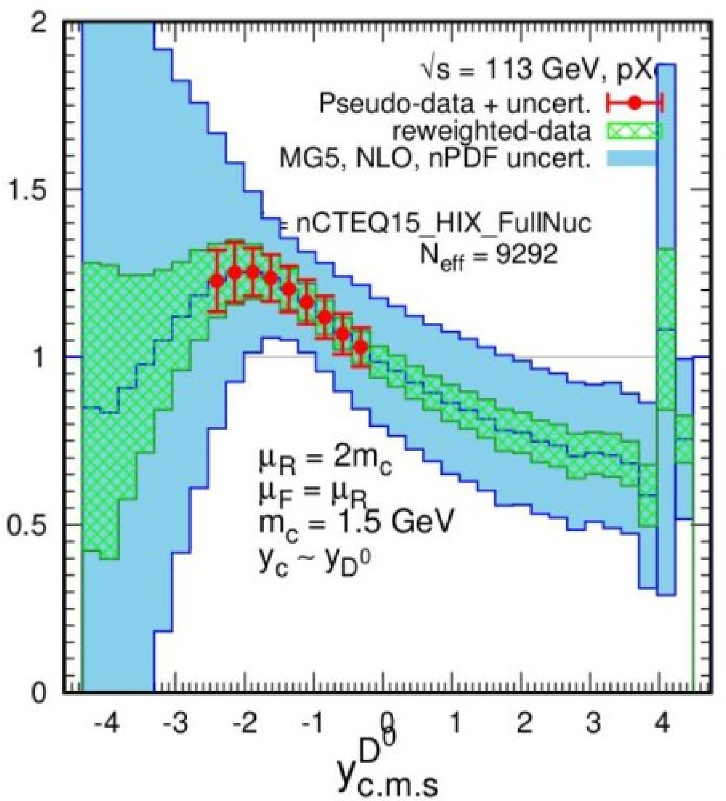


Nucl. Phys. A 1026 (2022) 122447

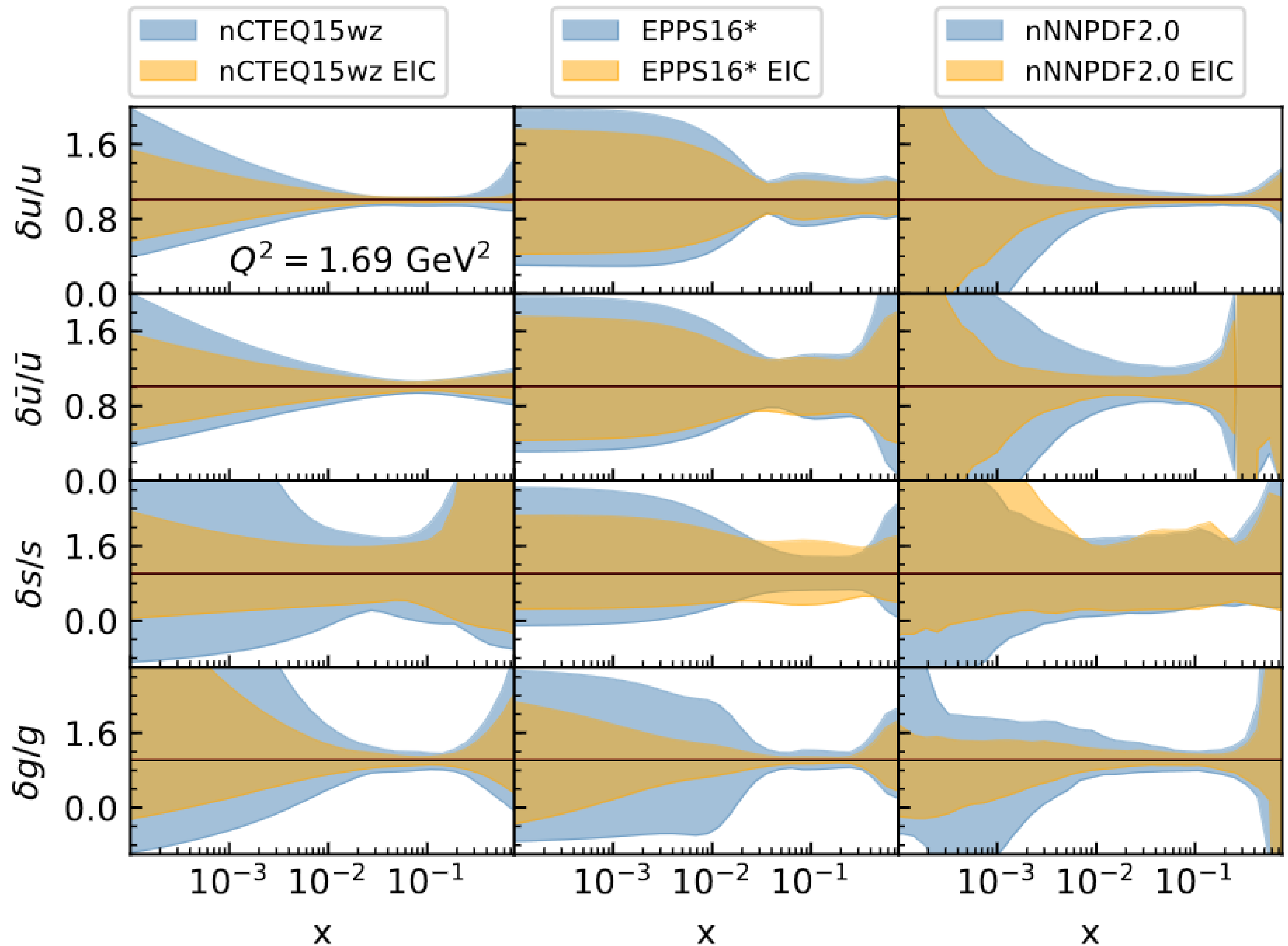
Effects / factors to constrain

- Charm production in A+A (nPDFs)

A. Safronov



Nucl. Phys. A 1026 (2022) 122447



Effects / factors to constrain

- Charm production in A+A (nPDFs)
- Quarkonium and D-$\bar{D}$ interactions in the final state (absorption/production cross section)
  - femtoscopic correlations

Femtoscopic correlations:

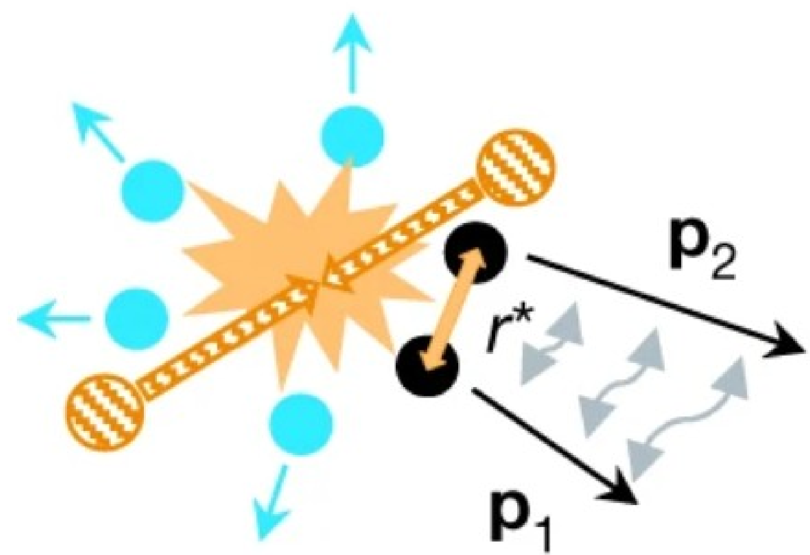
J/ψ – hadron correlations → co-mover breakup cross-section

D - $\bar{\text{D}}$ correlations → J/ψ regeneration cross section in hadronic phase

final state interactions +
emission volume

$$C(k^*) = \int \mathrm{d}^3 r^* S(\boldsymbol{r}^*) |\psi(\boldsymbol{r}^*, \boldsymbol{k}^*)|^2,$$

$$C(k^*) = \frac{P(\vec{p}_a \vec{p}_b)}{P(\vec{p}_a) P(\vec{p}_b)}$$



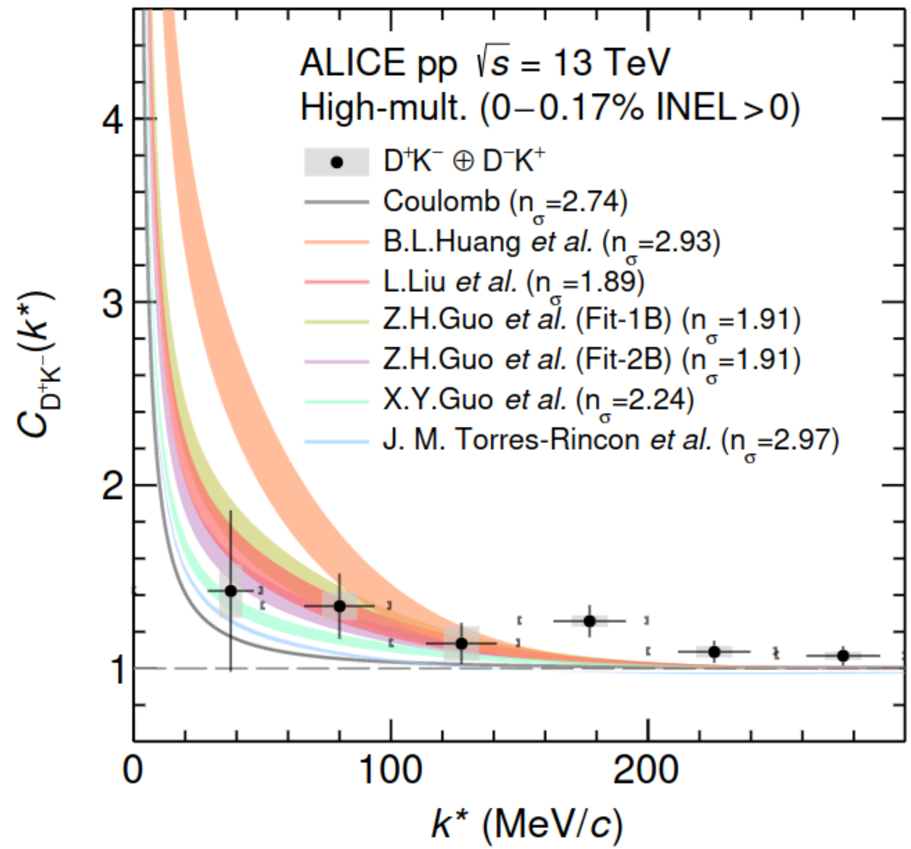
Nature volume 588, pages 232–238 (2020)

Femtoscopic correlations:

J/ψ – hadron correlations → **co-mover breakup cross-section**

D - $\overline{D}$ correlations → **J/ψ regeneration cross section in hadronic phase**

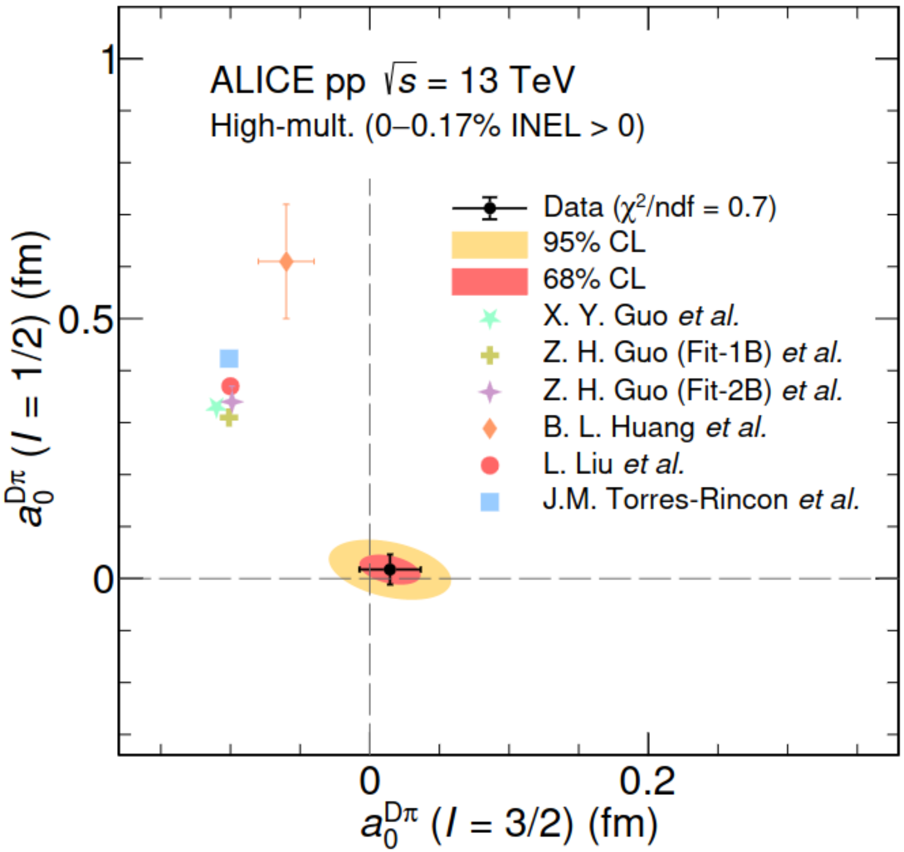
final state interactions +
emission volume



Femtoscopic correlations:

J/psi – hadron correlations → co-mover breakup cross-section

D - $\overline{\text{D}}$ → J/psi regeneration cross section



final state interactions +
emission volume

$$C(k^*) = \int \mathrm{d}^3 r^* S(\boldsymbol{r}^*) |\psi(\boldsymbol{r}^*, \boldsymbol{k}^*)|^2,$$

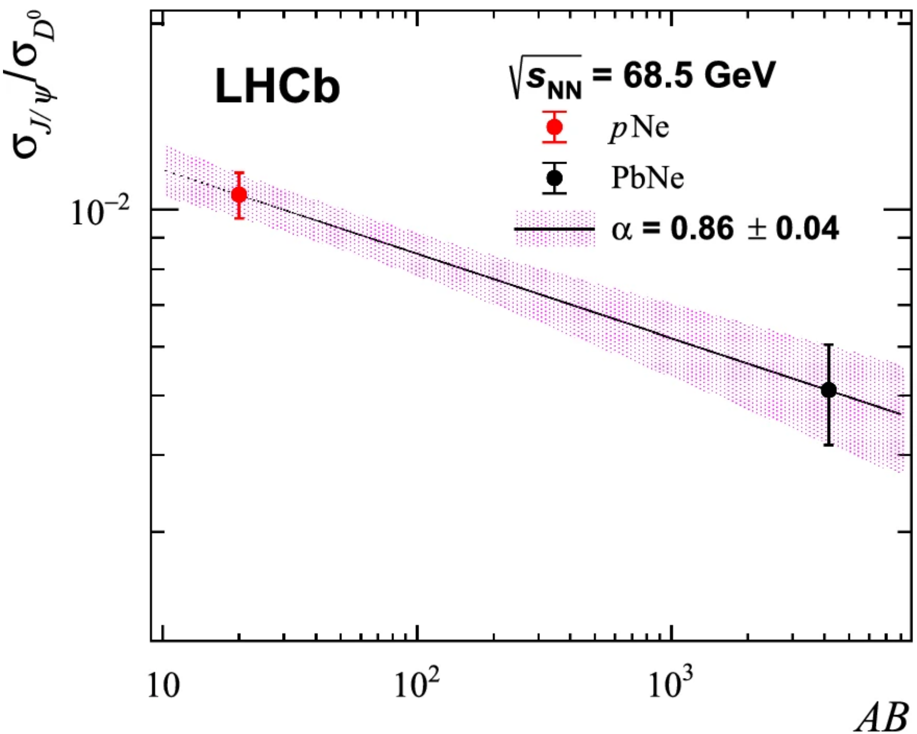
Scattering length of the Dπ interaction for two isospin channels

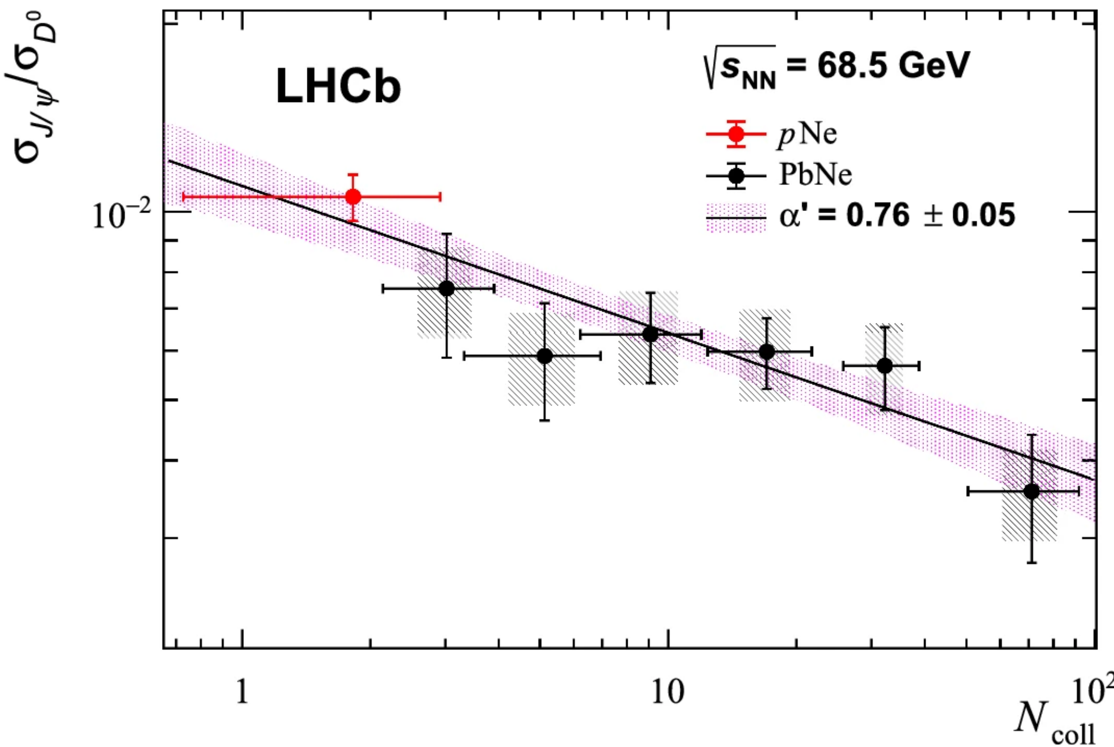
arXiv: 2401.13541

Effects / factors to constrain at the EIC and the LHC

- Charm production in A+A (nPDFs)
- Quarkonium interactions in the final state (absorption/production cross section)
- System-size and energy dependence of absorption in so-called nuclear matter and hadronic phase

Example: J/psi and charm at FT program at LHCb





Eur. Phys. J. C83 (2023) 658

Effects / factors to constrain at the EIC and the LHC

- Charm production in A+A (nPDFs)
- Quarkonium interactions in the final state (absorption/production cross section)
- System-size and energy dependence of absorption in so-called nuclear matter and hadronic phase
- Feed-down

→ LHC and High-luminosity LHC

Summary

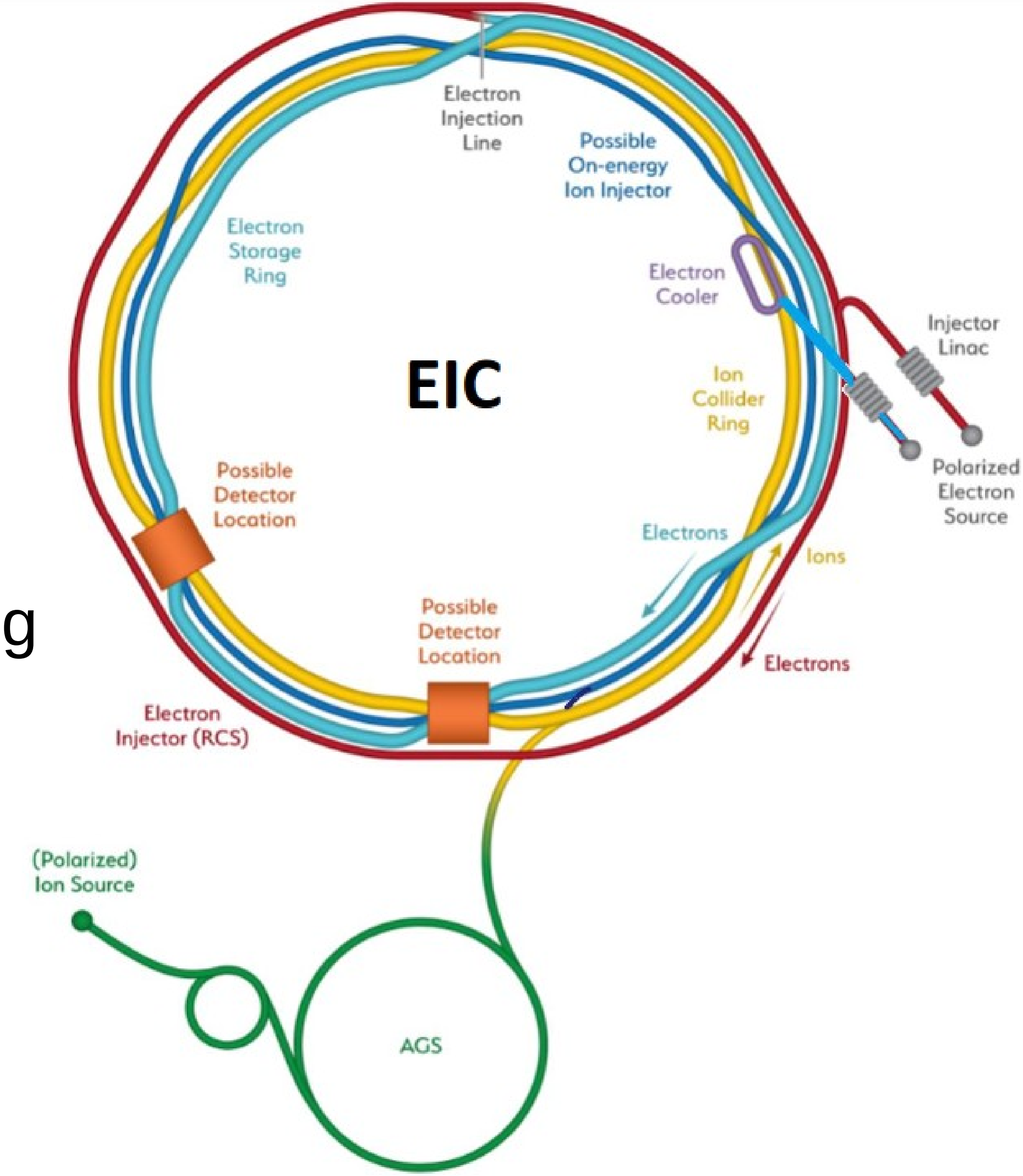
- **Quarkonium – an useful probe of the QGP**
- **Easy to measure, difficult to extract the QGP properties**
- **The EIC and the fixed-target program at the LHCb have potential to constrain and improve our understanding of non-QGP effects**

Backup

Electron-Ion Collider

Energy: $\sqrt{s}$ = 20 – 140 GeV

(Small) caveat:
EIC covers x-range overlapping with RHIC and fixed-target program at the LHC, but not very low-x at the LHC



https://indico.cern.ch/event/949203/contributions/3988180/attachments/2117011/3564269/EIC-Acc-Overview-Oct-7-2020-Seryi-r3.pdf

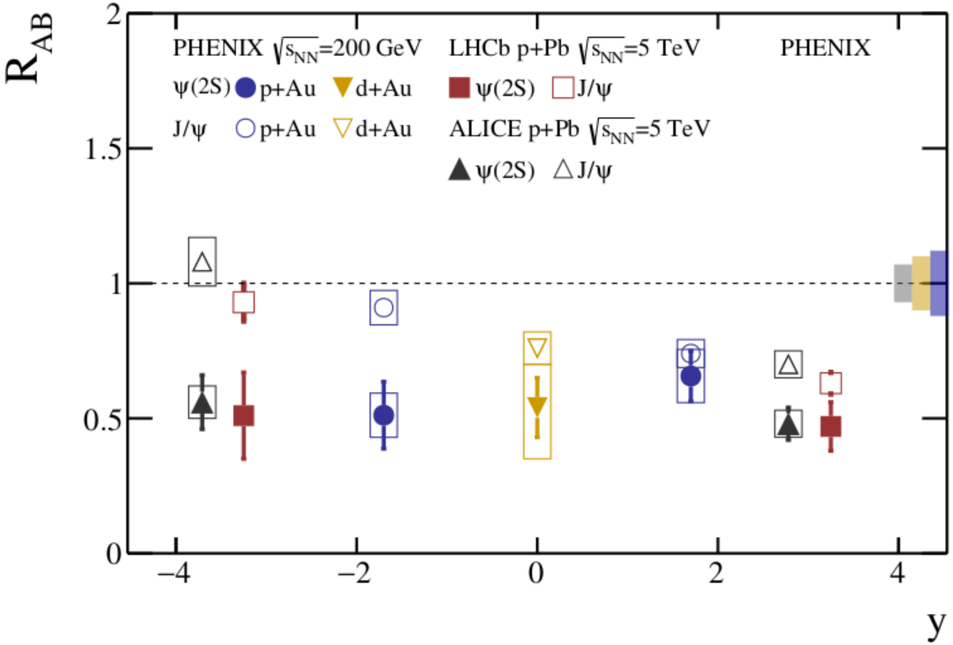
LHCb SMOG 2

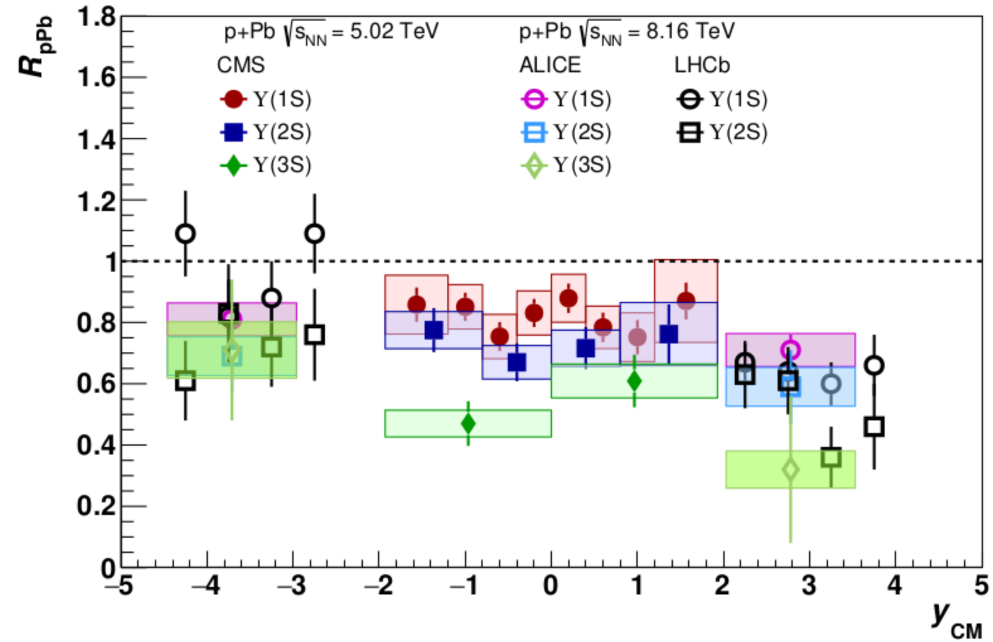
Possibility of heavier and different noble gases (Kr, Xe, H_2, D_2, O_2, N_2) with a pressure two orders of magnitude higher than SMOG

System	$\sqrt{s_{NN}}$ (GeV)	< pressure> (10^{-5} mbar)	ρ_S (cm^{-2})	$\mathcal{L}$ ($cm^{-2}s^{-1}$)	Rate (MHz)	Time (s)	$\int \mathcal{L}$ (pb^{-1})
pH$_2$	115	4.0	2.0×10^{13}	6×10^{31}	4.6	2.5×10^6	150
pD$_2$	115	2.0	1.0×10^{13}	3×10^{31}	4.3	0.3×10^6	9
pAr	115	1.2	0.6×10^{13}	1.8×10^{31}	11	2.5×10^6	45
pKr	115	0.8	0.4×10^{13}	1.2×10^{31}	12	2.5×10^6	30
pXe	115	0.6	0.3×10^{13}	0.9×10^{31}	12	2.5×10^6	22
pHe	115	2.0	1.0×10^{13}	3×10^{31}	3.5	3.3×10^3	0.1
pNe	115	2.0	1.0×10^{13}	3×10^{31}	12	3.3×10^3	0.1
pN$_2$	115	1.0	0.5×10^{13}	1.5×10^{31}	9.0	3.3×10^3	0.1
pO$_2$	115	1.0	0.5×10^{13}	1.5×10^{31}	10	3.3×10^3	0.1
PbAr	72	8.0	4.0×10^{13}	1×10^{29}	0.3	6×10^5	0.060
PbH$_2$	72	8.0	4.0×10^{13}	1×10^{29}	0.2	1×10^5	0.010
pAr	72	1.2	0.6×10^{13}	1.8×10^{31}	11	3×10^5	5

CERN-LHCb-PUB-2018-015

Cold nucler matter effects





arXiv:2303.17254

Lednicky and Lyuboshitz model of femtoscopic correlations

$$C(Q)=1+\sum_s \rho_s\left[\frac{1}{2}\frac{|f(k)|^2}{r_0^2}\left(1-\frac{1}{2\sqrt{\pi}}\frac{d_0}{r_0}\right)+\frac{\Re f(k)}{\sqrt{\pi}\, r_0}F_1(Qr_0)-\frac{\Im f(k)}{2r_0}F_2(Qr_0)\right]$$

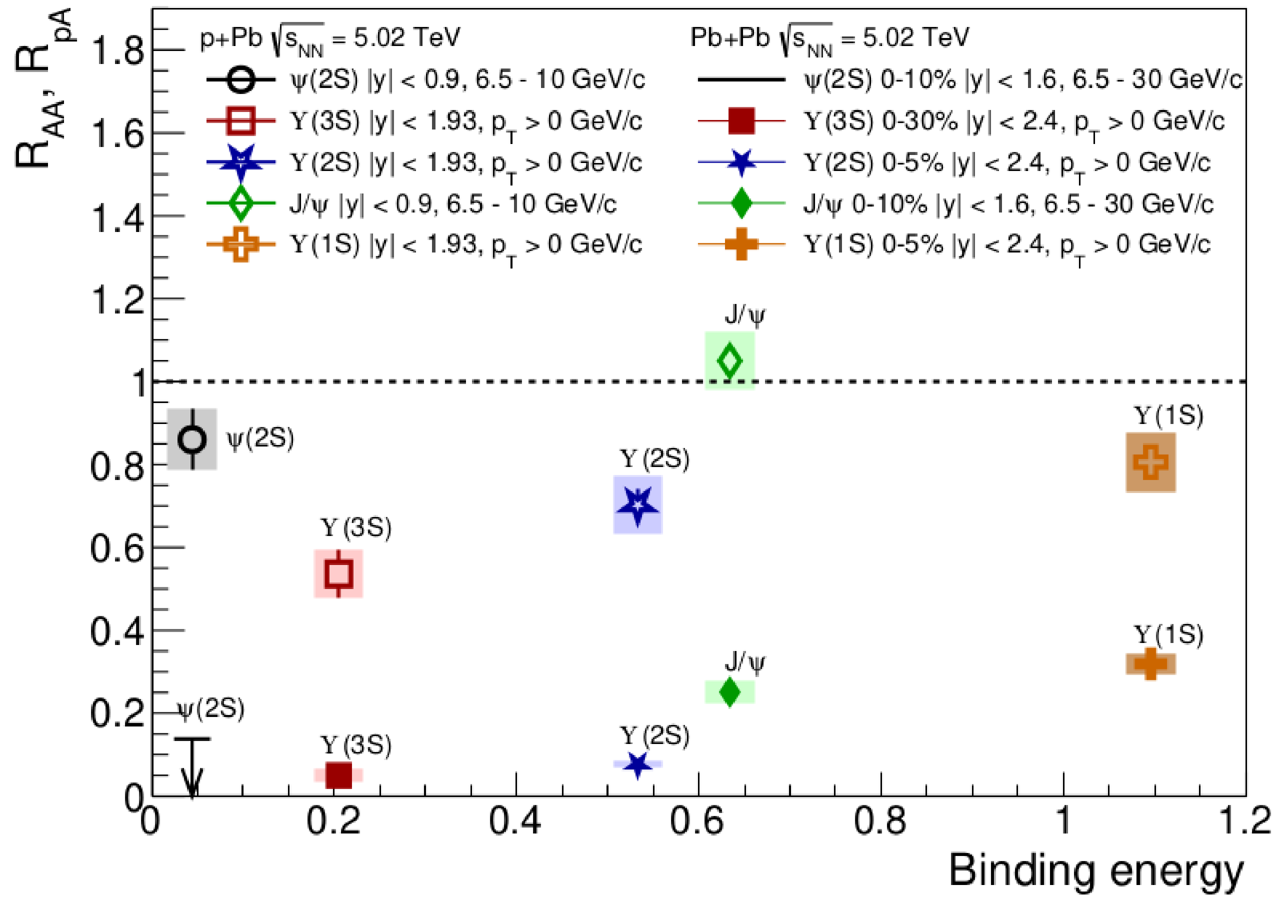
$$F_1(z)=\int_0^1 e^{x^2-z^2}/z\,dx \qquad F_2(z)=\left(1-e^{-z^2}\right)/z$$

k = Q/2

The s-wave scattering amplitude f(k) $$f(k)=\left(\frac{1}{f_0}+\frac{1}{2}d_0 k^2-ik\right)^{-1}$$

f_0 - the scattering length, d_0 - the effective range. r_0, f_0 and d_0 can be extracted from a fit of the LL formula to the experimental femtoscopic correlation function.

Quarkonium R_{AA}



arXiv:2303.17254