Describing ϕ meson production in small collision systems with nuclear modified parton distribution functions

Mitrankova M. M., Bannikov E.V., Berdnikov Ya.A., Berdnikov Ya.A., Kotov D.O., Mitrankov Iu.M., Larionova D.M.

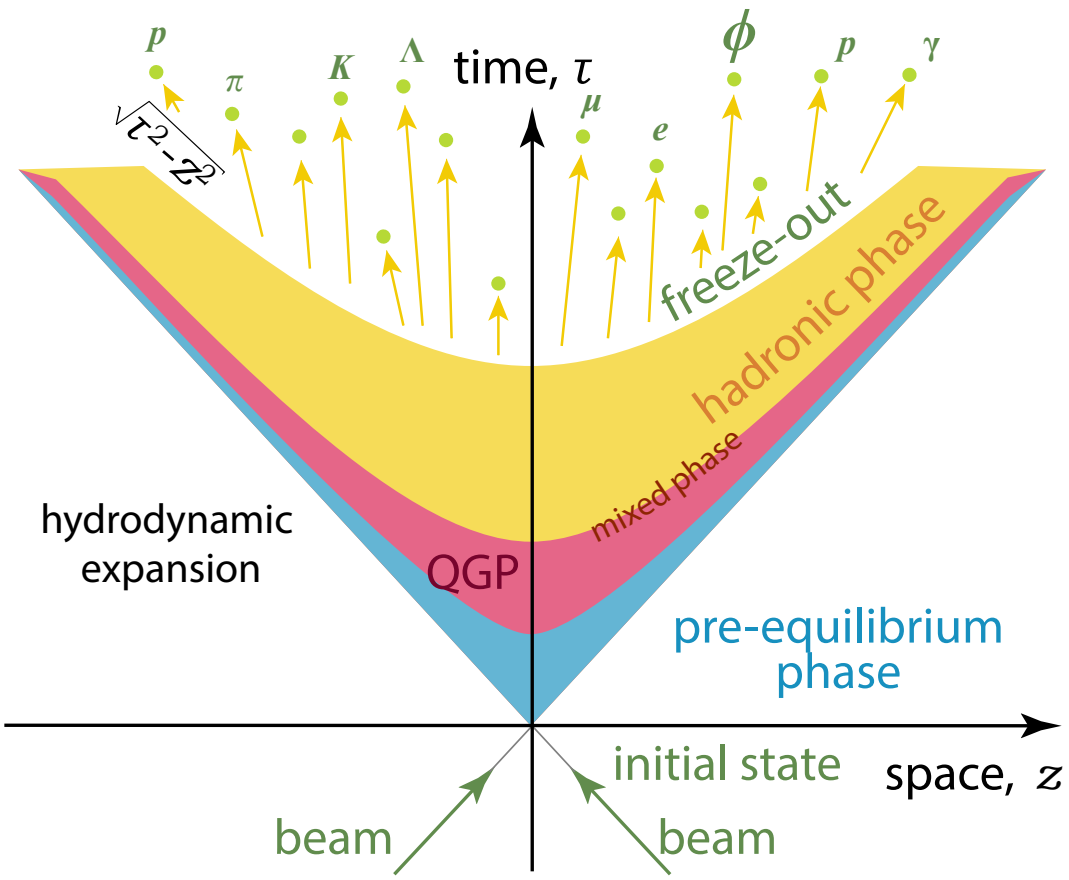
Peter the Great St.Petersburg Polytechnic University, Saint Petersburg, Russia

The 6th International Conference on Particle Physics and Astrophysics
November 29th – December 2nd, 2022

Minimal conditions for the QGP formation

RHIC collider and PHENIX experiment – QCD phase transition and QGP formation under extreme conditions

Lattice QCD: $\varepsilon_c \sim 1GeV/fm^3, T_c \sim 170MeV$



Large system collisions
Au+Au, Cu+Cu, Cu+Au, U+U at $\sqrt{s_{NN}} = 200$ GeV

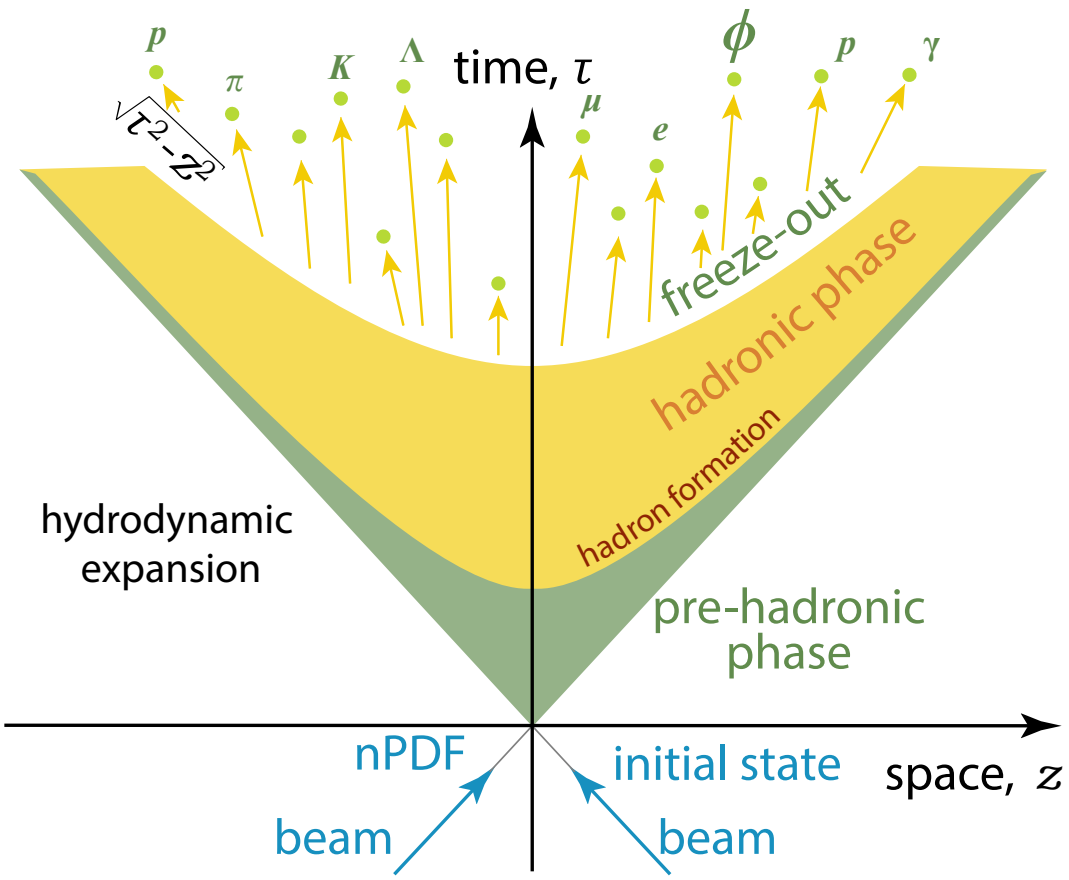
QGP signatures are observed:

- Strangeness enhancement
- Jet quenching
- Baryon to meson ration enhancement

Minimal conditions for the QGP formation

RHIC collider and PHENIX experiment – QCD phase transition and QGP formation under extreme conditions

Lattice QCD: $\varepsilon_c \sim 1GeV/fm^3, T_c \sim 170MeV$



Small system collisions

p+p, p+Al, p+Au, d+Au, ^{3}He+Au at $\sqrt{s_{NN}} = 200$ GeV

CNM effects play the predominant role:

- nPDFs
- Parton interactions

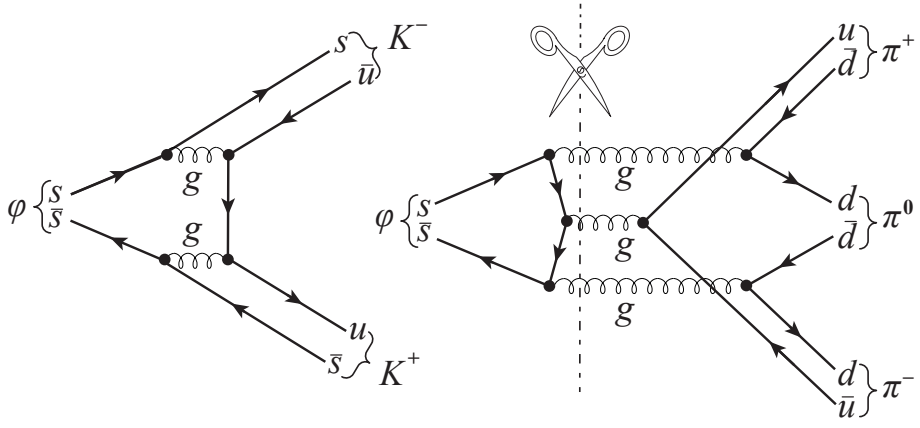
ϕ meson production

$\tau_{QGP} < \tau_{\phi}$
Small interaction cross-section with nonstrange hadrons

ϕ $(s\bar{s})$
Measurable up to high-p_T
Mass: $1,019 \pm 0.020$ MeV$/c^2$

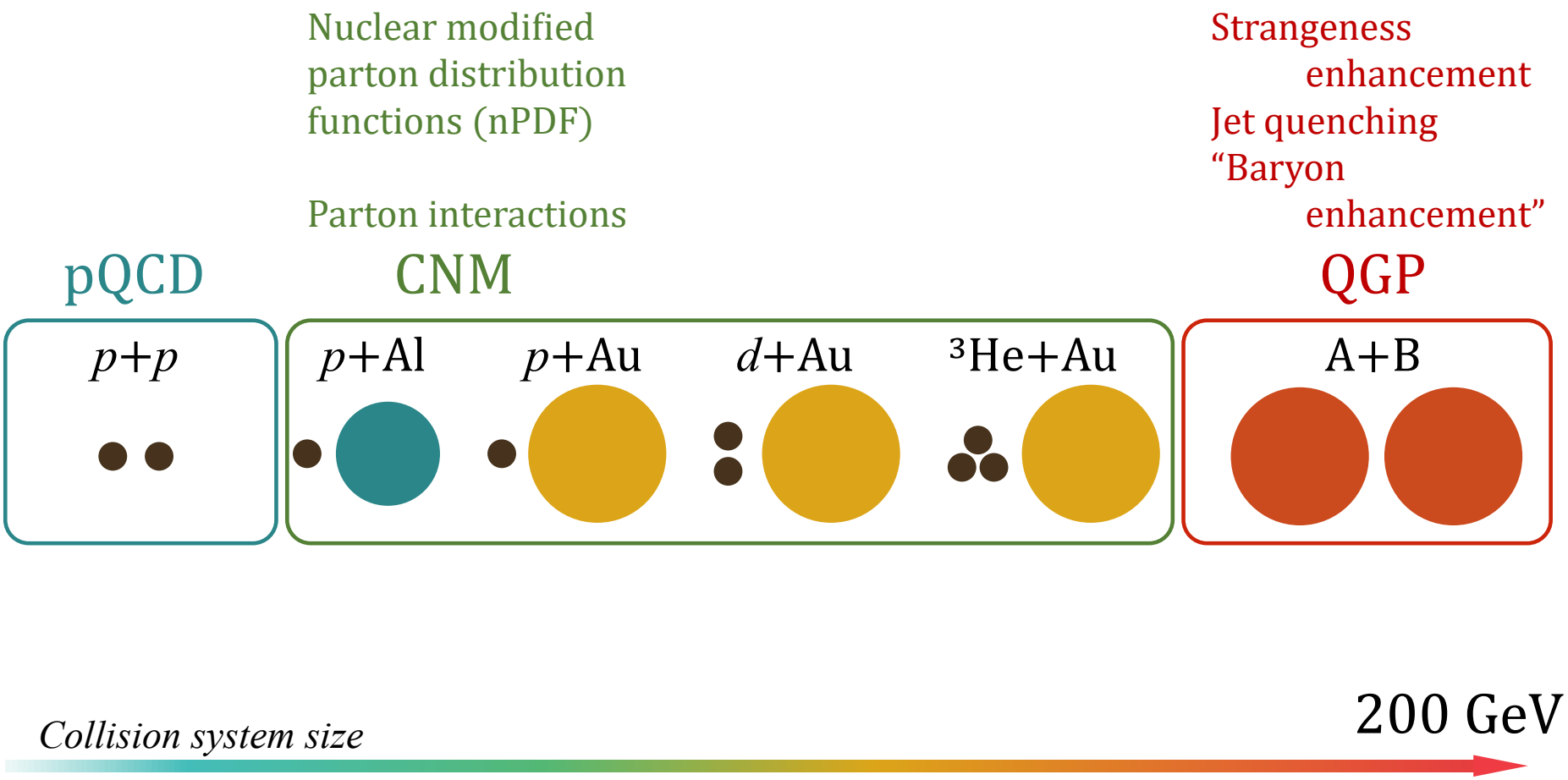
Clean probe to investigate the properties of QGP

Signatures of QGP:
Strangeness enhancement
Jet quenching
Comparable to the masses of the lightest baryons



OZI rule – S. Okubo, G. Zweig, J. Iizuka

Minimal conditions for the QGP formation



Minimal conditions for the QGP formation

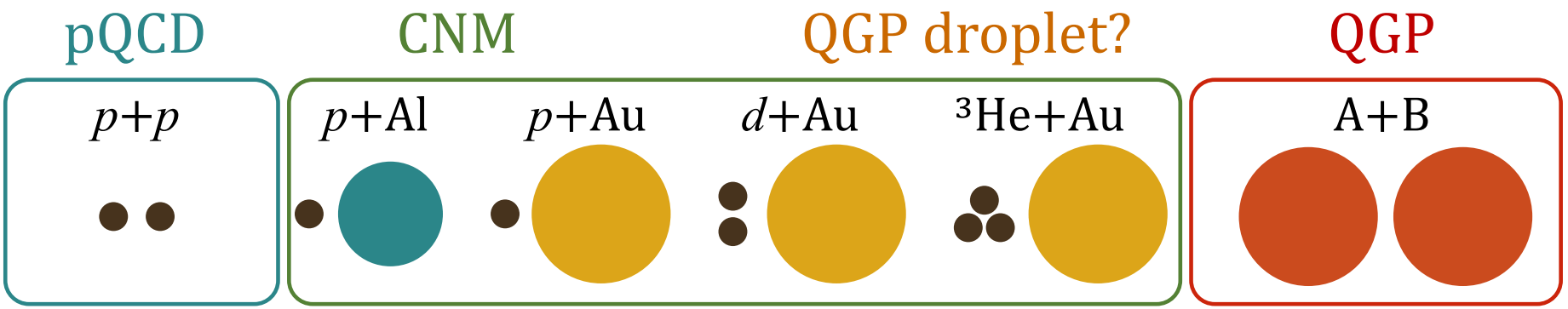
Nuclear modified parton distribution functions (nPDF)

Parton interactions

Strangeness enhancement

Jet quenching

"Baryon enhancement"



Nature Phys. 15 (2019) 3, 214-220
Phys. Rev. C 102, 014902 (2020)
Phys. Rev. Lett. 121, 222301 (2018)
Phys. Rev. C 101, 034910 (2020)
Phys. Rev. C 92, 044909 (2015)

Collision system size → 200 GeV

Minimal conditions for the QGP formation

Nuclear modified parton distribution functions (nPDF)

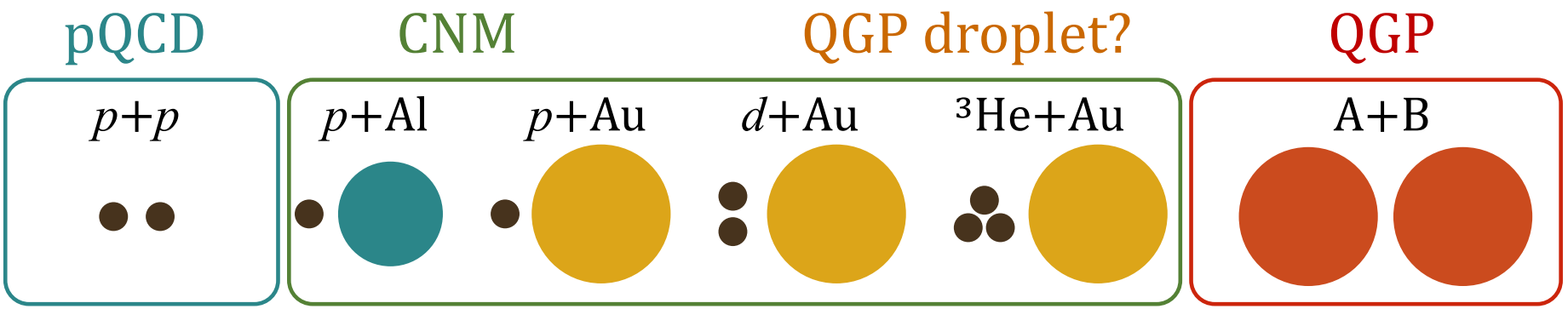
Parton interactions

Need to distinguish effects

Strangeness enhancement

Jet quenching

"Baryon enhancement"



Nature Phys. 15 (2019) 3, 214-220
Phys. Rev. C 102, 014902 (2020)
Phys. Rev. Lett. 121, 222301 (2018)
Phys. Rev. C 101, 034910 (2020)
Phys. Rev. C 92, 044909 (2015)

Collision system size → 200 GeV

Theoretical baseline

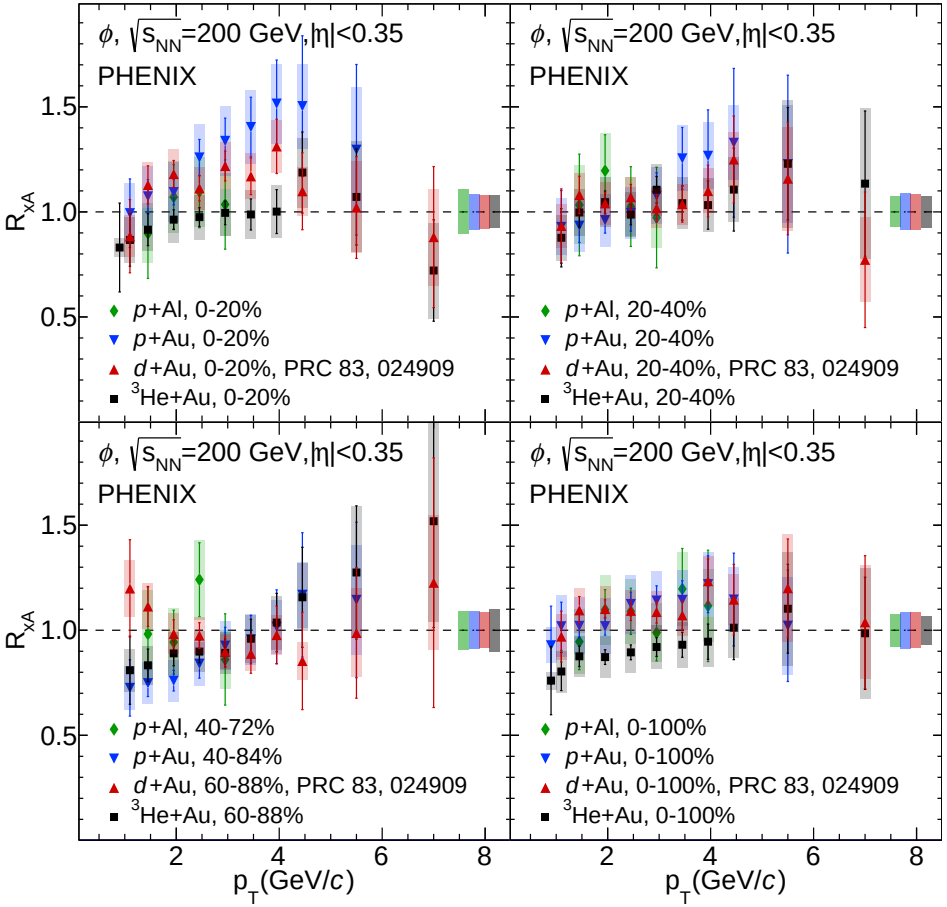
NonQGP baseline:

- PYTHIA+EPPS16
- PYTHIA+nCTEQ15
- PYTHIA/Angantyr
- AMPT "default" version

QGP formation:

- AMPT "string melting" version

PDF play a key role in event generators – input data for modeling hard processes, parton showers, and multiple parton interactions



Distinguishing CNM effects from QGP effects
Interpretation of experimental results in small and large system collisions
Minimal conditions sufficient for the QGP formation from the experiment

Parton distribution functions

Considered as an underlying physics mechanism of CNM effects

$$\sigma(a+b \to X) = \int dx_a dx_b f_i(x_a, Q^2) f_j(x_b, Q^2) \hat{\sigma}_{ij}(x_a, x_b, Q^2)$$

$f(x, Q^2)$ – PDF – probability of a parton to have a certain fraction of the nucleon momentum x at any scale of the square of the momentum transfer Q^2 in the interaction
Deep inelastic scattering: nuclear modification –

$$R_i = \frac{f_i^A}{f_i}$$

f_i^A – PDF in a nucleus A – nPDF
f_i – PDF in a free nuclon

Parton distribution functions

nPDF sets were implemented with PYTHIA 8

EPPS16	EPPS16nlo_CT14nlo_Al27 EPPS16nlo_CT14nlo_Au197	Eur.Phys.J. C77 (2017) no.3, 163
nCTEQ15	nCTEQ15_27_13 nCTEQ15_197_79	Phys. Rev. D 93 085037

- p – cteq6l
- d – NNPDFv1.0
- ^{3}He – nCTEQ15_3_2

EPPS16 and nCTEQ15 are widely used nPDFs sets in previous analyzes

[PRC105(2022)064902, PRC102(2020)014902, PRC101(2020)034910, PRC105(2022)064912]

PYTHIA parameters

Parameter	Value	Description
SoftQCD:	inelastic=on	All soft QCD processes, except for elastic
PDF:pSet	=8	cteq6l1 parton-distribution function
MultipartonInteractions:	Kfactor=0.5	Multiplication factor for multiparton interaction

Nuclear modification factors

The observable used to quantitatively describe the features of particle production in x+A collisions

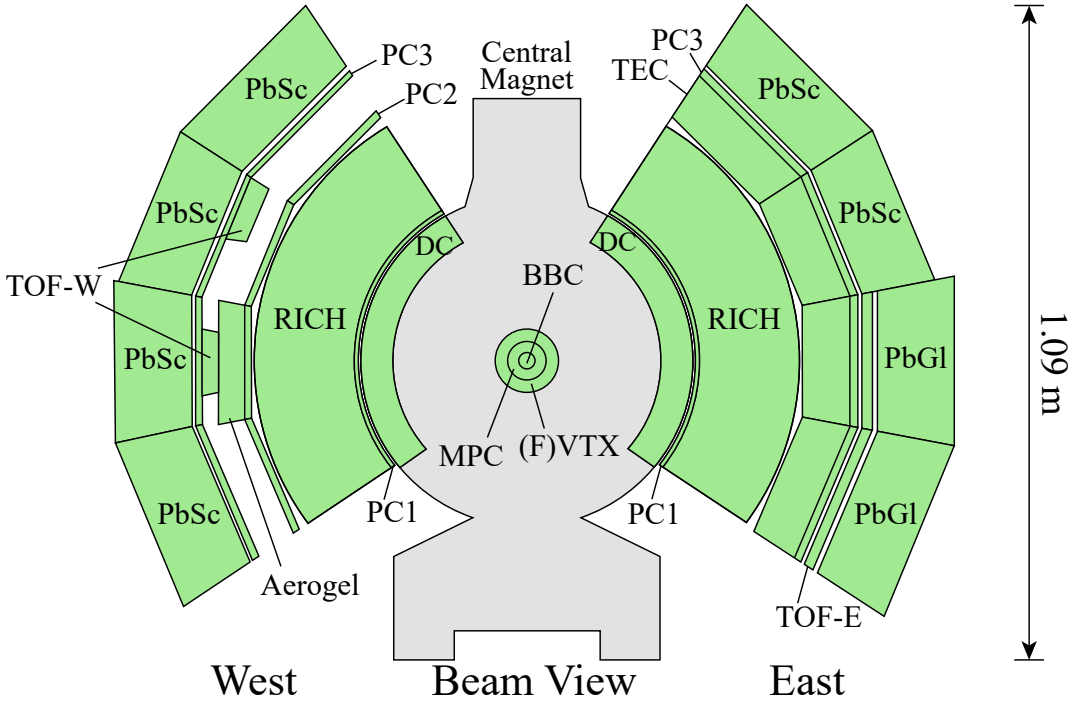
$$R_{xA} = \frac{1}{\langle N_{coll} \rangle} \cdot \frac{d^2 N_{xA}/dydp_T}{d^2 N_{pp}/dydp_T}$$

- $d^2 N_{xA}/dydp_T$ – calculated with nPDFs
- $d^2 N_{pp}/dydp_T$ – calculated with proton PDFs
- $\langle N_{coll} \rangle = 1$ – for PDF calculations

Experimental data

Collected by PHENIX at $\sqrt{s_{NN}} = 200$ GeV at midrapidity ($|\eta| < 0.35$)

- p+Al $\sim 2,0 \cdot 10^9$ events, 2015
- p+Au $\sim 3,8 \cdot 10^9$ events, 2015
- d+Au $\sim 1,8 \cdot 10^9$ events, 2008
- ^{3}He+Au $\sim 2,8 \cdot 10^9$ events, 2014



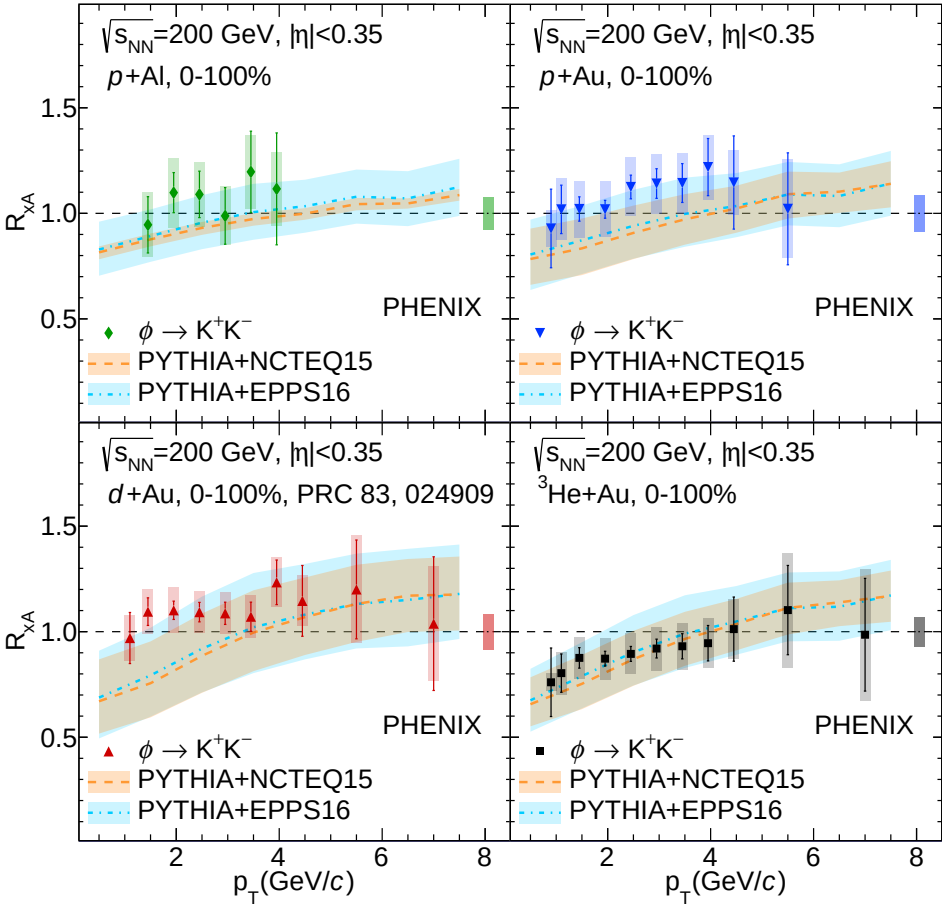
$$\phi \to K^+K^-$$

Detectors, used in the analyzes – BBC, DC-PC1, ToF-E

PYTHIA+nPDFs

ϕ meson R_{xA} calculated with PYTHIA+nPDFs and the ones, measured by PHENIX are in agreement within uncertainties

- PHENIX – $R_{HeAu} < R_{dAu} < R_{pAu}$
- PYTHIA+nPDFs – do not predict the R_{xA} ordering

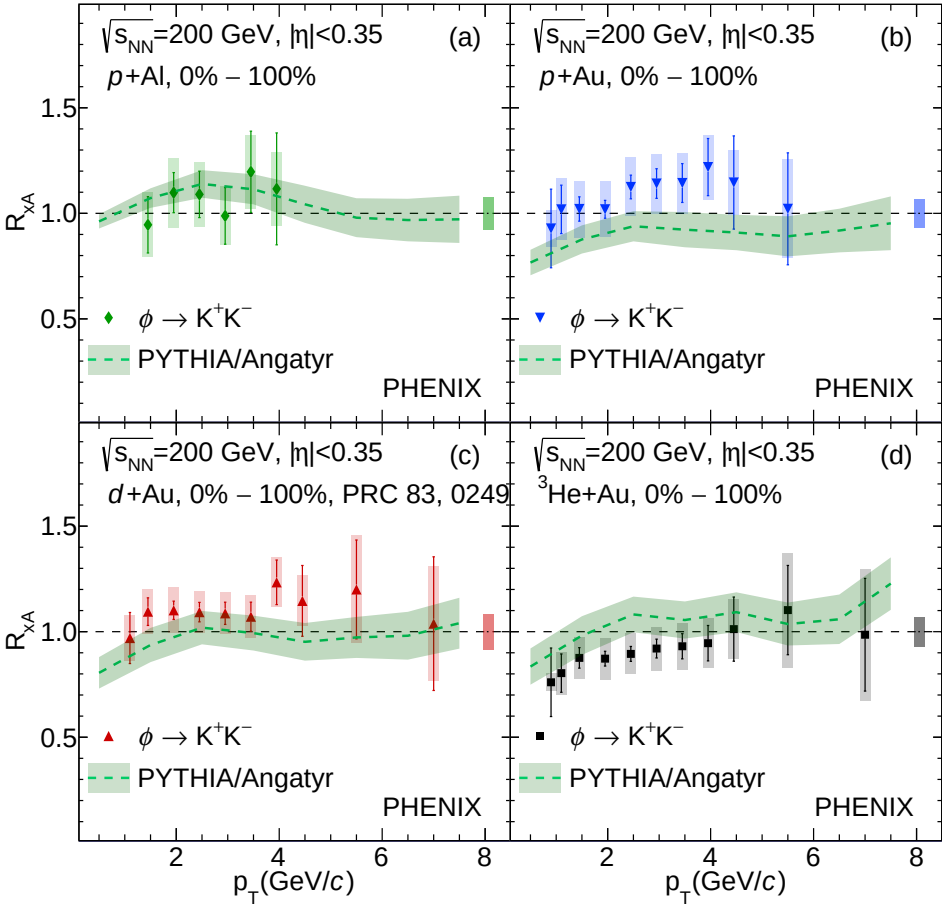


PYTHIA/Angantyr

NNPDF is the default Angantyr nPDF set

ϕ meson R_{xA} calculated with PYTHIA/Angantyr and the ones, measured by PHENIX are in agreement within uncertainties

- PHENIX – $R_{HeAu} < R_{dAu} < R_{pAu}$
- PYTHIA/Angantyr – predicts the reverse R_{xA} ordering

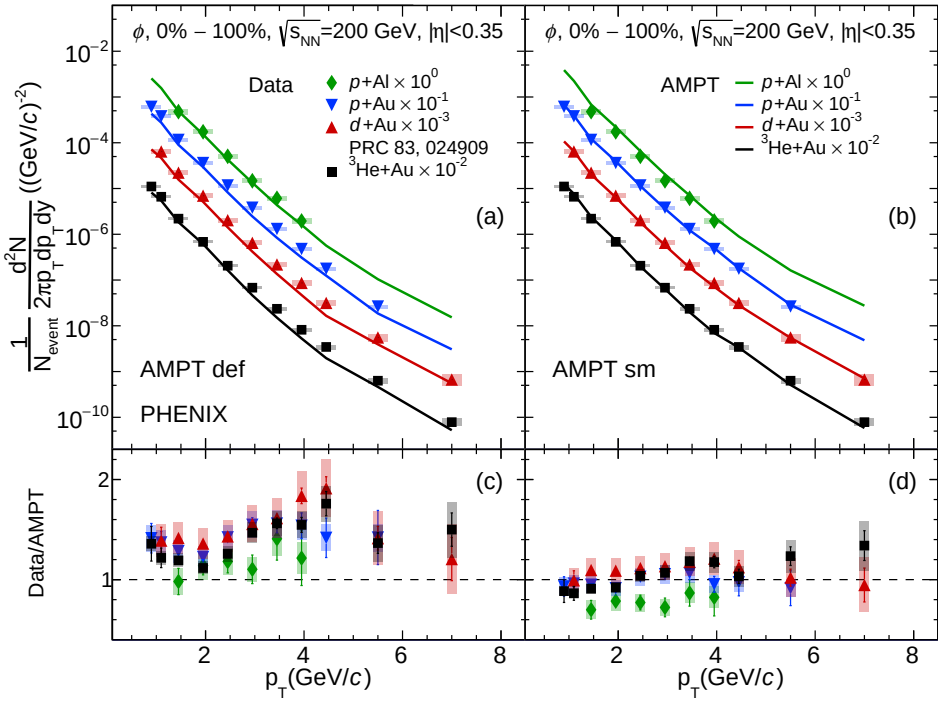


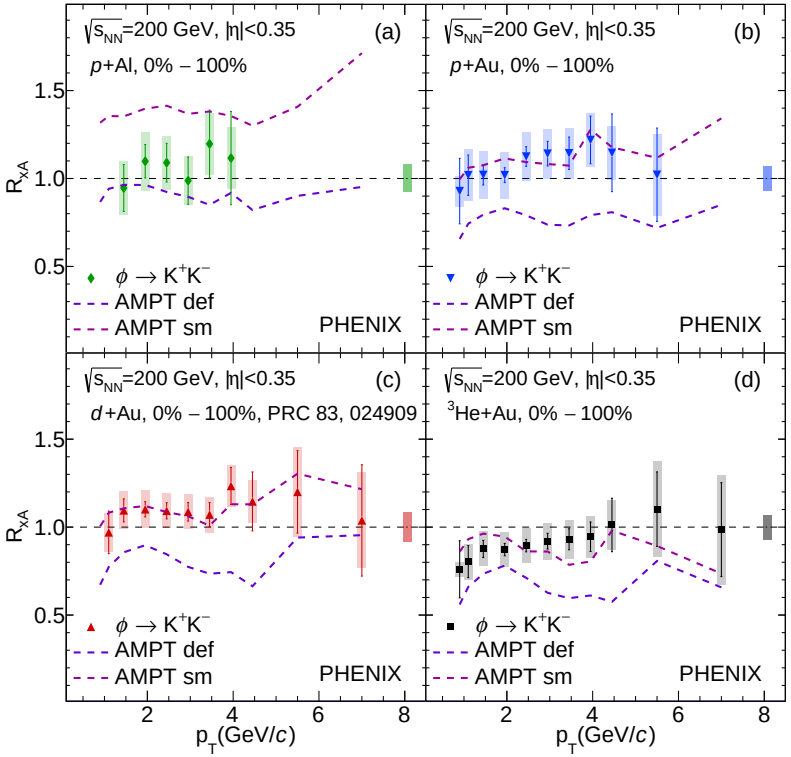
AMPT "default" vs "string melting" versions

Duke-Owens PDF set 1 [Phys. Rev. D 30, 49]

ϕ meson production at $\sqrt{s_{NN}} = 200$ GeV

- p+Al – default version
- $p/d/^3$He+Au – string melting version





Summary

- R_{xA} calculated with PYTHIA+nPDFs (EPPS16 and nCTEQ15) and the ones, measured by PHENIX are consisted with each other within uncertainties
- Model calculations do not predict the ordering, observed in the experiment:$R_{HeAu} < R_{dAu} < R_{pAu}$
- ϕ meson production in $p/d/^3He + Au$ collisions at $\sqrt{s_{_{NN}}} = 200$ GeV might be driven by mechanisms additional to nPDF (Possible formation of QGP droplet?)

Thank you for attention!

System	p-value	
	PYTHIA + nCTEQ15	PYTHIA+EPPS16
p+Al	9.86$\times$ 10^{-1}	9.95$\times$ 10^{-1}
p+Au	1.34$\times$ 10^{-1}	3.88$\times$ 10^{-1}
d+Au	3.79$\times$ 10^{-4}	6.43$\times$ 10^{-3}
^{3}He+Au	9.79$\times$ 10^{-1}	9.97$\times$ 10^{-1}

System	p-value
	PYTHIA/Angantyr
p+Al	9.99$\times$ 10^{-1}
p+Au	2.66$\times$ 10^{-1}
d+Au	5.44$\times$ 10^{-1}
^{3}He+Au	2.54 $\times$ 10^{-1}

System	p-value	
	AMPT def	AMPT sm
p+Al	7.19 $\times$ 10^{-1}	2.57 $\times$ 10^{-2}
p+Au	3.60 $\times$ 10^{-4}	9.99 $\times$ 10^{-1}
d+Au	2.65 $\times$ 10^{-6}	9.99 $\times$ 10^{-1}
^{3}He+Au	2.27 $\times$ 10^{-4}	8.26 $\times$ 10^{-1}

$\langle N_{coll} \rangle$ values

	p+Al	p+Au	d+Au	^{3}He+Au
PYTHIA	2.1	4.2	6.2	7.9
AMPT	2.1	4.4	7.2	9.8
Experiment	2.1±0.1	4.7±0.3	7.6±0.4	10.4±0.7

$dN_{ch}/d\eta$ values

	p+Al	p+Au	d+Au	^{3}He+Au
PYTHIA	4.2	6.7	10.8	14.3
AMPT def	3.74	6.61	10.40	13.57
AMPT sm	3.70	6.50	10.22	13.43
Experiment	3.96±0.54	6.66±0.94	9.5±1.0	12.24±1.35

PYTHIA/Angantyr parameters

Parametr	Value	Description
SoftQCD:	all=on	All soft QCD processes
PDF:pSet	=8	cteq6l1 parton-distribution function
MultipartonInteractions:	Kfactor=0.5	Multiplication factor for multiparton interaction

AMPT parameters

- Parton scattering cross section - 3.0 mbn
- Nuclear shadowing