Fixed target experiments at LHC - Strong2020 Workshop
22-24 June 2022, CERN

Cold Nuclear Matter effects at LHC fixed-target experiment energy:

How can heavy-ion physics profit from these measurements

Elena G. Ferreiro

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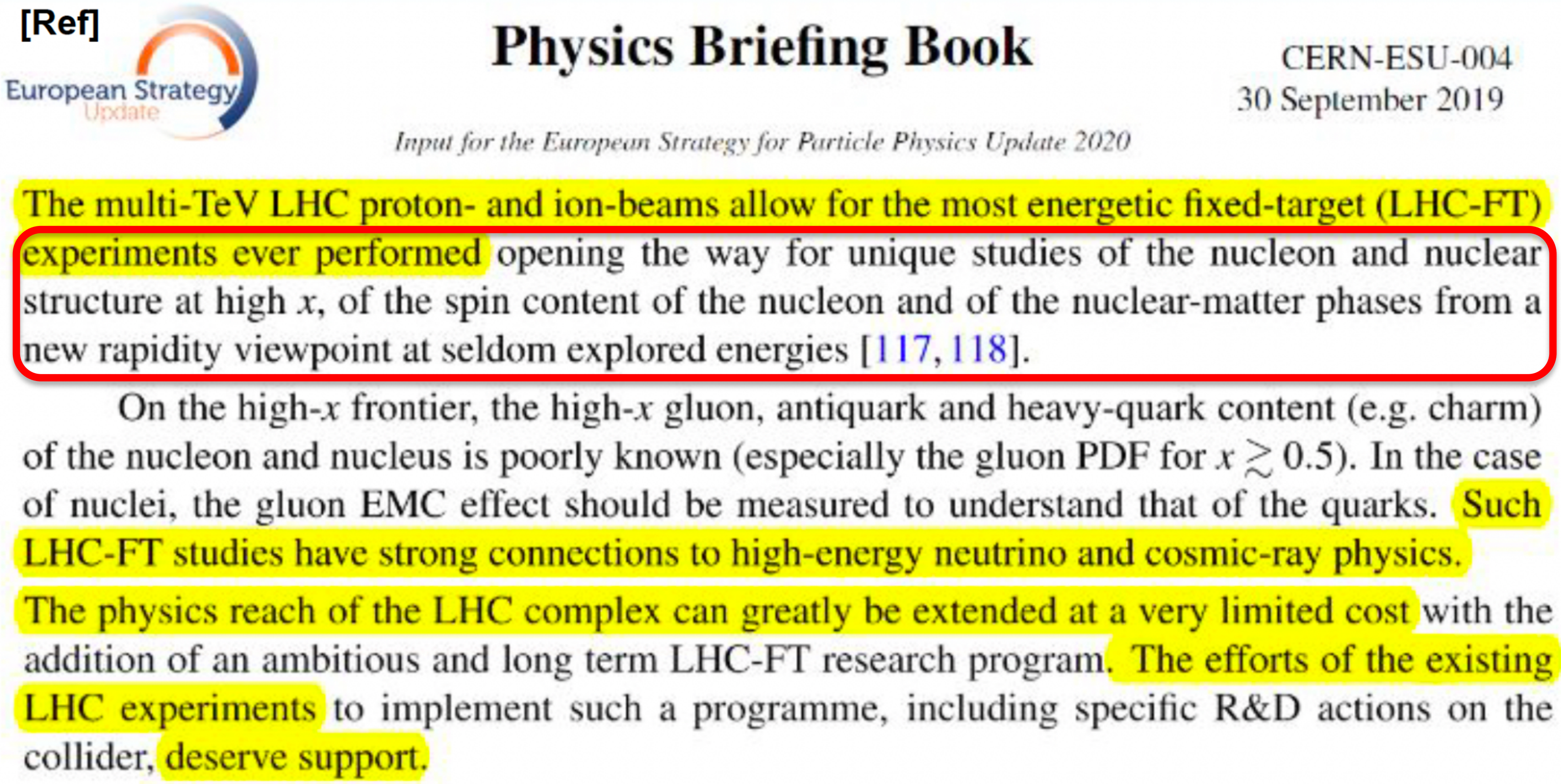
The context: LHC fixed-target experiments



[Ref]

Physics Briefing Book

CERN-ESU-004
30 September 2019

Input for the European Strategy for Particle Physics Update 2020

The multi-TeV LHC proton- and ion-beams allow for the most energetic fixed-target (LHC-FT) experiments ever performed opening the way for unique studies of the nucleon and nuclear structure at high x, of the spin content of the nucleon and of the nuclear-matter phases from a new rapidity viewpoint at seldom explored energies [117, 118].

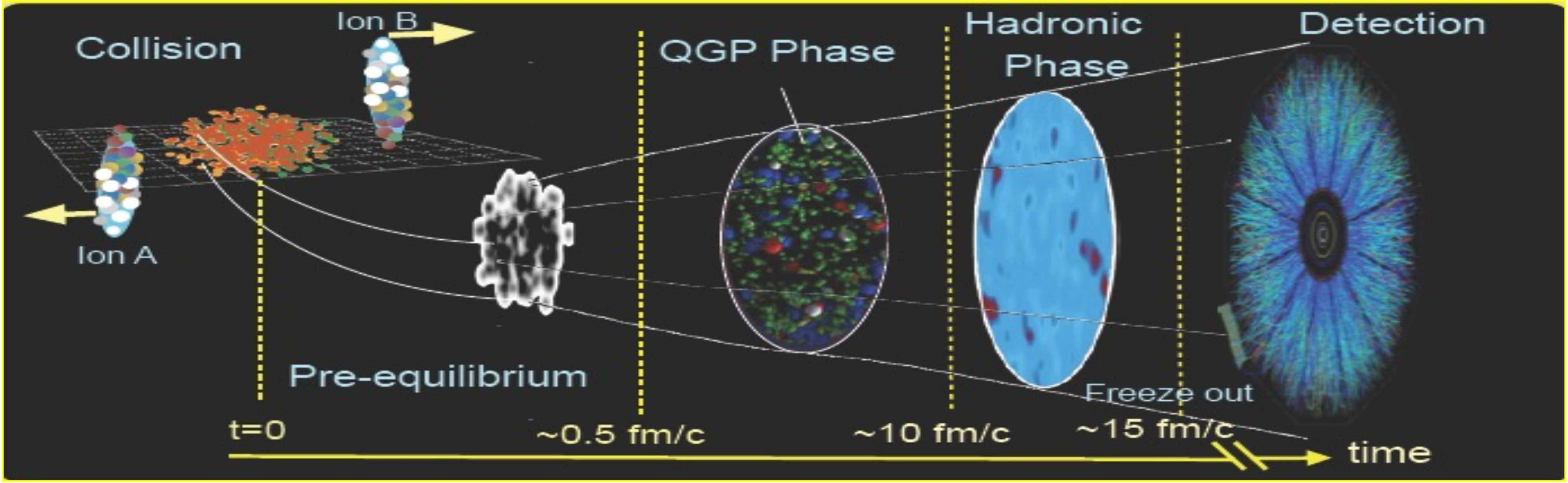
On the high-x frontier, the high-x gluon, antiquark and heavy-quark content (e.g. charm) of the nucleon and nucleus is poorly known (especially the gluon PDF for $x \gtrsim 0.5$). In the case of nuclei, the gluon EMC effect should be measured to understand that of the quarks. Such LHC-FT studies have strong connections to high-energy neutrino and cosmic-ray physics.

The physics reach of the LHC complex can greatly be extended at a very limited cost with the addition of an ambitious and long term LHC-FT research program. The efforts of the existing LHC experiments to implement such a programme, including specific R&D actions on the collider, deserve support.

$\sqrt{s} = 72 - 115$ GeV between SPS and RHIC
from mid to backward rapidities

How can heavy-ion physics profit from these measurements?

Goal of HIC experiments: Study hot and dense QCD matter



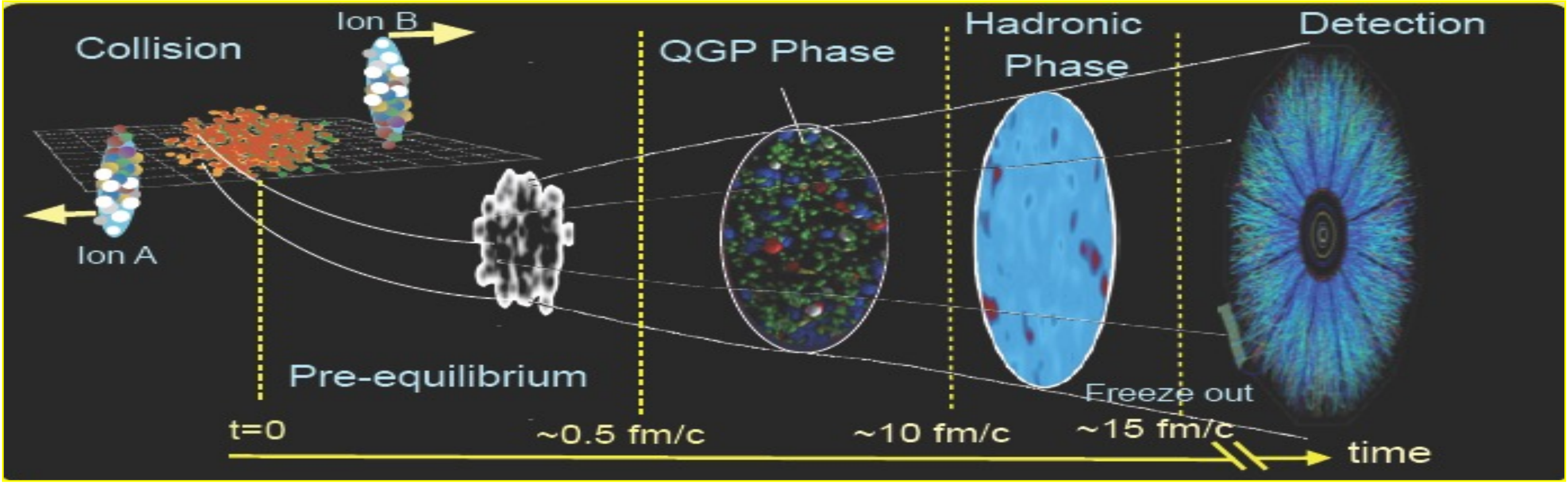
Bulk Observables: p~<pt>,T
~ 99% of detected particles

- Multiplicities
- Thermal dileptons & direct photons
- Asymmetries, correlations, fluctuations

Hard Probes: p >> <pt>,T
~ 1% of detected particles

- Fast quarks and gluons
- Jet quenching
- Quarkonia dissociation

Goal of HIC experiments: Study hot and dense QCD matter



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- Collective behavior of the medium
- Initial conditions: T, ε, μ
- Thermalization and hydrodynamics

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- Medium tomography & diagnosis

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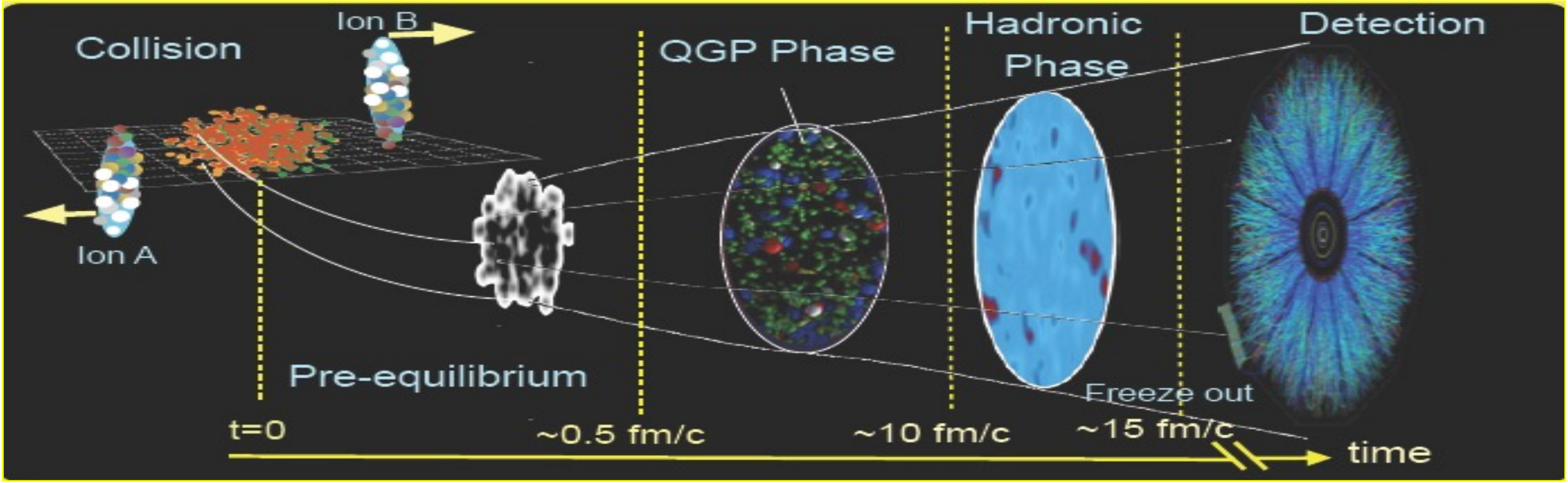

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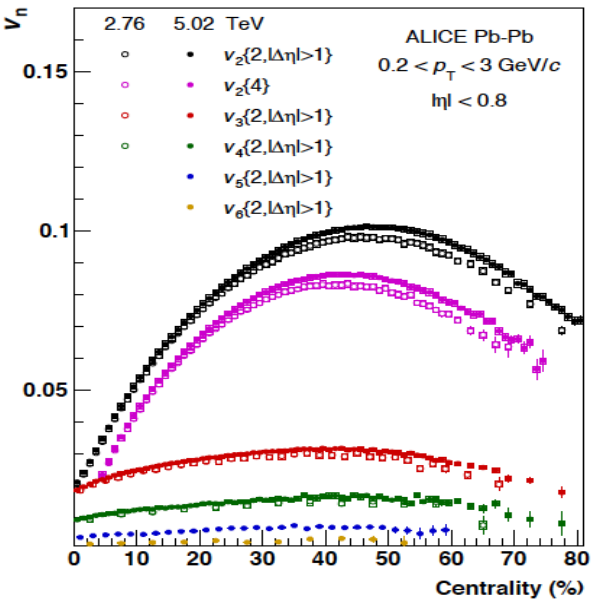
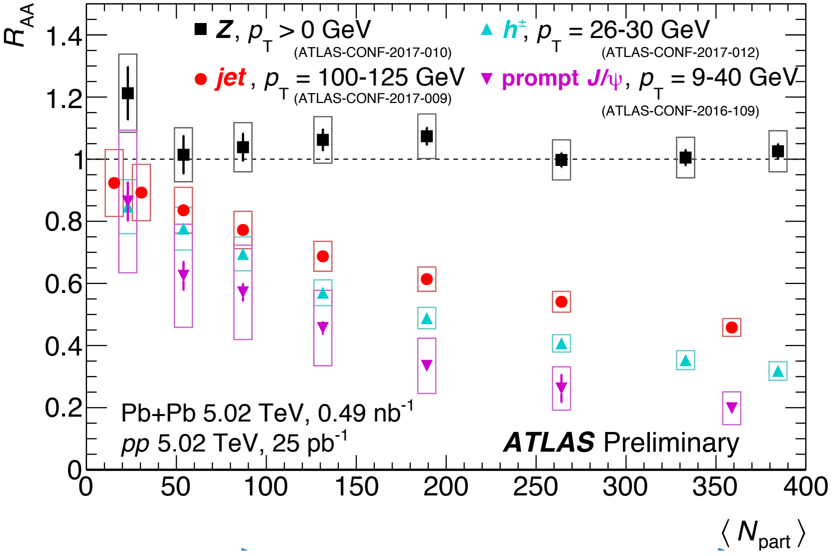
  Interpretation requires "vacuum" (p+p) and "cold nuclear" (p+Pb) data at the same energy

Status of Heavy Ions





Bulk Observables: p~<pt>,T
~ 99% of detected particles

Hard Probes: p >> <pt>,T
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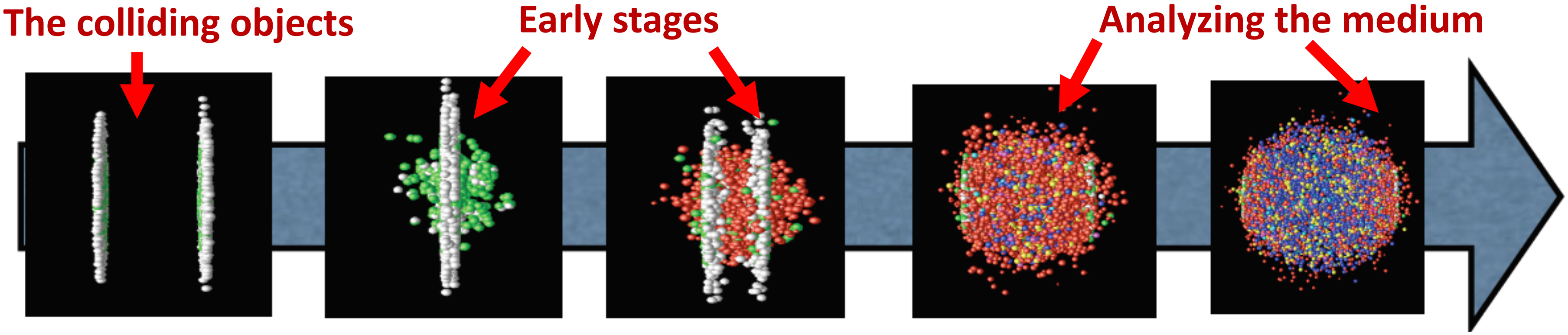
Current status: matter created in **AA** at RHIC and LHC, with energy densities larger than those expected in lattice QCD for deconfinement=>QGP

- collective features in the soft sector
- well described by relativistic hydrodynamics if applied very early (≲ 1 fm/c) after the collision
- equilibration?

- very opaque to energetic partons or particles traversing
- modification of the yield of hard probes like high-p_T particles, jets, quarkonia

What can we learn in a fixed-target LHC experiment?

We do not have a **QUANTITATIVE** understanding of the nuclear behaviour → required for A-A and QGP studies



Initial effects: lack of information about

- Small and large-x partons
- Which factorization?
- Transverse structure

Final effects: probing the medium

- With or without thermalization
- Onset of deconfining?
- Nuclear absorption
- Multiparticle interactions

The colliding objects: nuclear PDFs in heavy ions

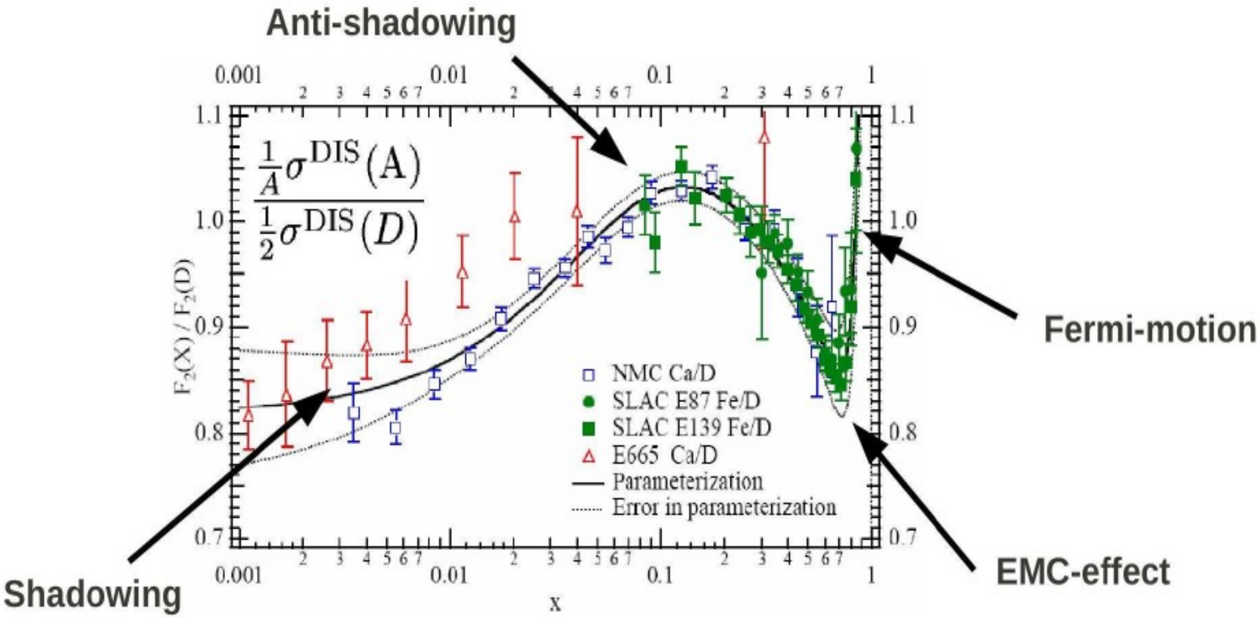
- Parton densities in nuclei are modified
  Bound nucleon ≠ free nucleon
- Nuclear PDF assumed to be factorizable in terms of the nucleon PDFs

$$f_i^A(x,Q^2) = R_i^A(x,Q^2)\, f_i(x,Q^2)$$

$$\sigma_{\rm DIS}^{\ell+A\to\ell+X} = \sum_{i=q,\bar{q},g} \underbrace{f_i^A(\mu^2)}_{\text{Nuclear PDFs, obeying the standard DGLAP}} \otimes \underbrace{\hat{\sigma}_{\rm DIS}^{\ell+i\to\ell+X}(\mu^2)}_{\text{Usual perturbative coefficient functions}}$$

assuming collinear factorization

- If nuclear effects at play $R_i^A(x,Q^2)$ ≠ 1



More than 30 years ago, the EMC collaboration discovered that nuclear structure functions in DIS are suppressed compared to the prediction from the naive combination of free proton and neutron structure functions in the high-x region

The physics mechanism behind this EMC effect is still not understood

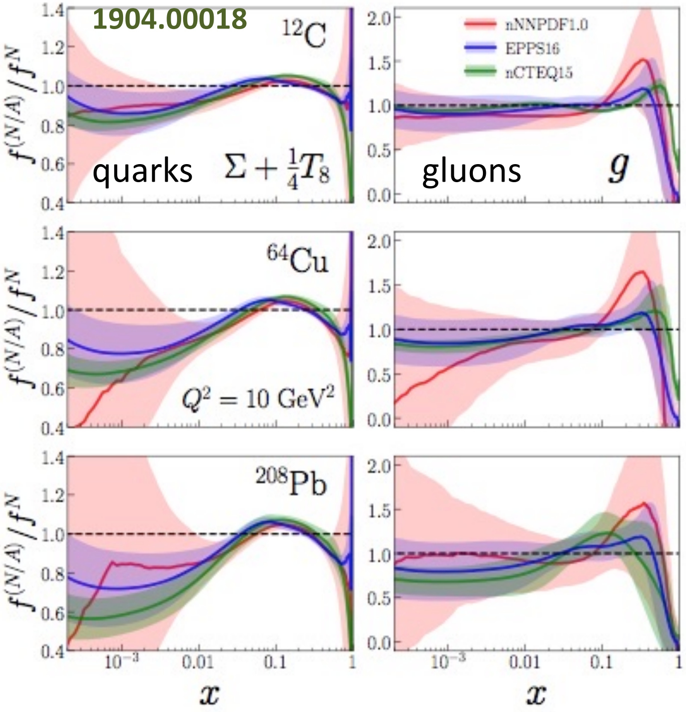
Initial effects: nPDFs status

Several nPDF sets available (using various data, different orders, etc)

Nuclear PDFs are determined in global analyses of DIS and DY data

Nestor Armesto

SET		**EPS09** JHEP 0904 (2009) 065	**DSSZ** PRD85 (2012) 074028	**nCTEQ15** PRD93 (2016) 085037	**KA15** PRD93 (2016) 014036	**EPPS16** EPJC C77 (2017)163	**nNNPDF1.0** 1904.00018
data	eDIS	✔	✔	✔	✔	✔	✔
	DY	✔	✔	✔	✔	✔	✘
	π^0	✔	✔	✔	✘	✔	✘
	νDIS	✘	✔	✘	✘	✔	✘
	pPb	✘	✘	✘	✘	✔	✘
# data		929	1579	740	1479	1811	451
order		NLO	NLO	NLO	NNLO	NLO	NNLO
proton PDF		CTEQ6.1	MSTW2008	~CTEQ6.1	JR09	CT14NLO	NNPDF3.1
mass scheme		ZM-VFNS	GM-VFNS	GM-VFNS	ZM-VFNS	GM-VFNS	FONLL-B
comments		$\Delta\chi^2$=50, ratios, huge shadowing-antishadowing	$\Delta\chi^2$=30, ratios, medium-modified FFs for π^0	$\Delta\chi^2$=35, PDFs, valence flavour sep., not enough sensitivity	PDFs, deuteron data included	$\Delta\chi^2$=52, flavour sep., ratios, LHC pPb data	NNPDF methodology, isoscalarity assumed

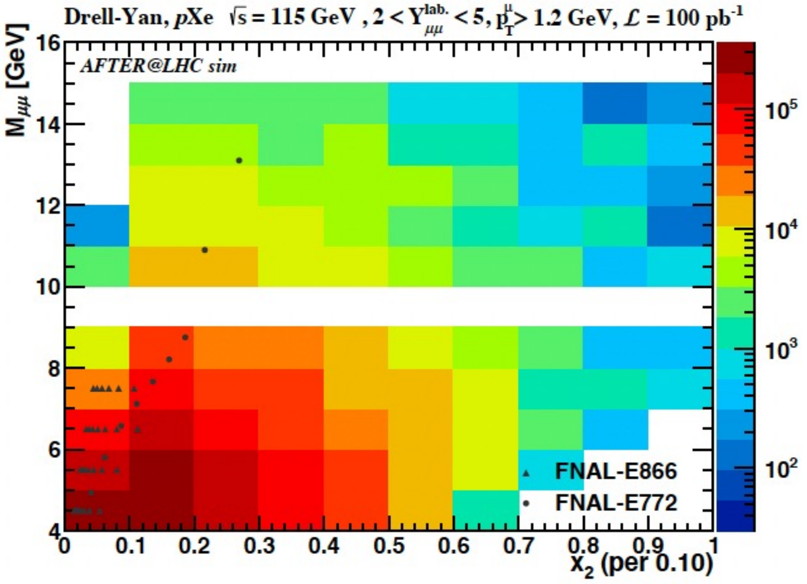


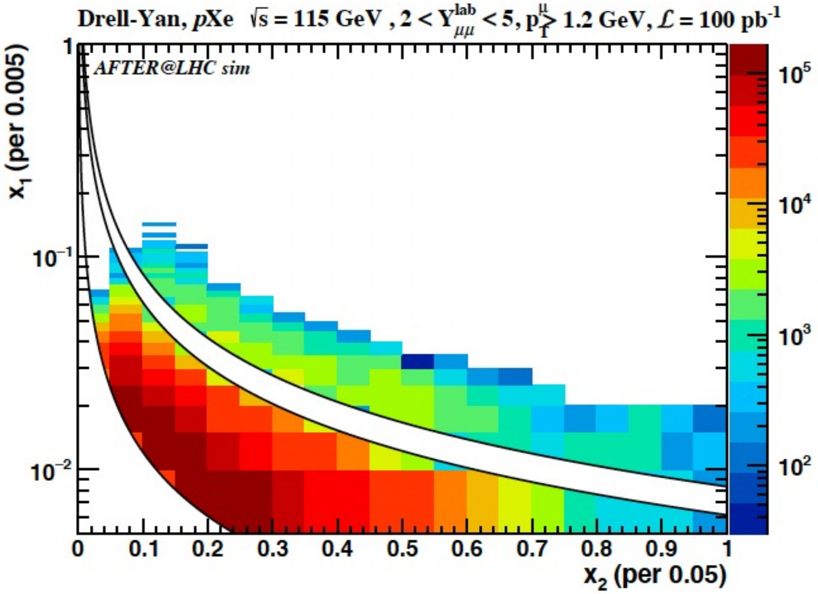
- Without additional experimental input, we are rather far from being able to probe in detail the nuclear modications of the quark and gluon PDFs
- Large uncertainties for x<0.01 and for large-x glue
- Small impact of LHC collider-mode data

nPDFs: what can we learn from fixed-target experiments

Compared to the proton PDFs, the nPDF determinations are clearly lagging behind due to the much smaller number of experimental constraints

- Currently, the analyses are statistically dominated by DIS data with few data points from the DY process entering the fits.





Access to DY data with a wide kinematic coverage will provide a unique opportunity for:

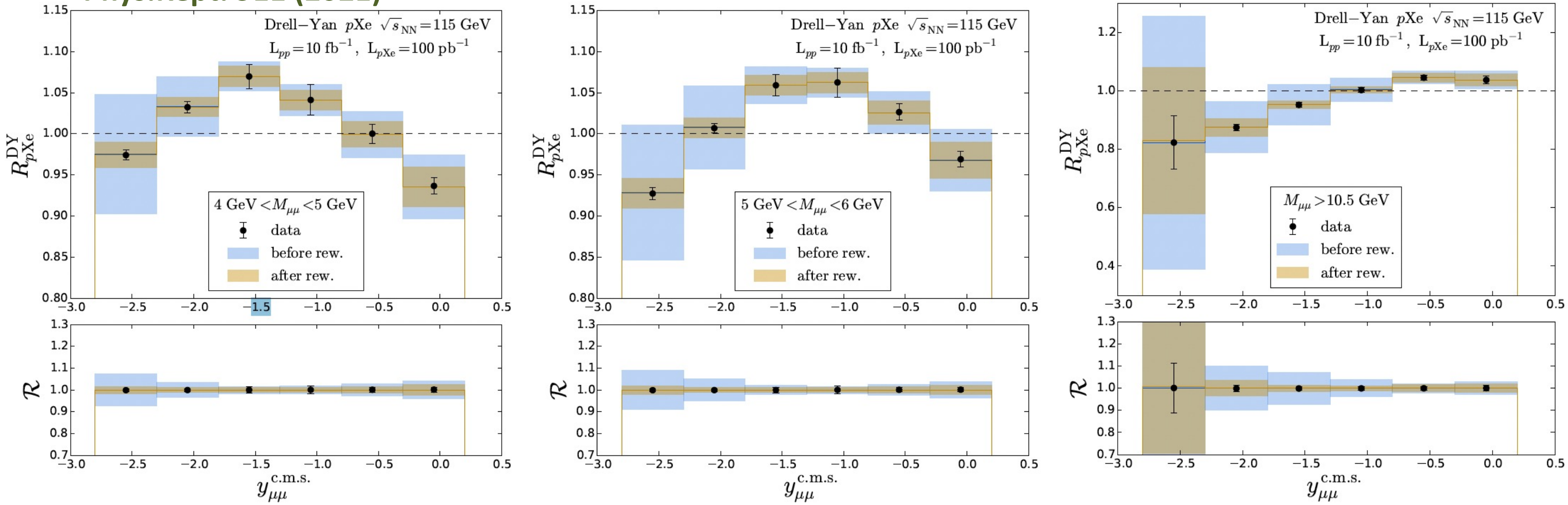
- more precise PDF determinations
- to test their universality which is a fundamental property of QCD and the basis for all high energy hadron scattering computations

nPDFs: what can we learn from fixed-target experiments

The kinematic reach of AFTER@LHC allow to probe
much higher x than the currently available data for a variety of targets

AFTER@LHC could shed new light on the origin of the EMC effect
by verifying its presence/absence in DY lepton-pair production

Phys.Rept. 911 (2021)

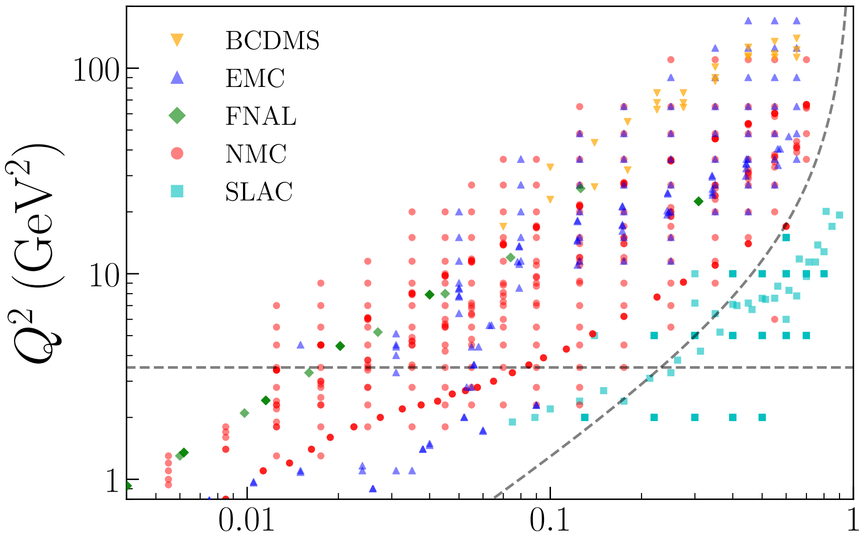


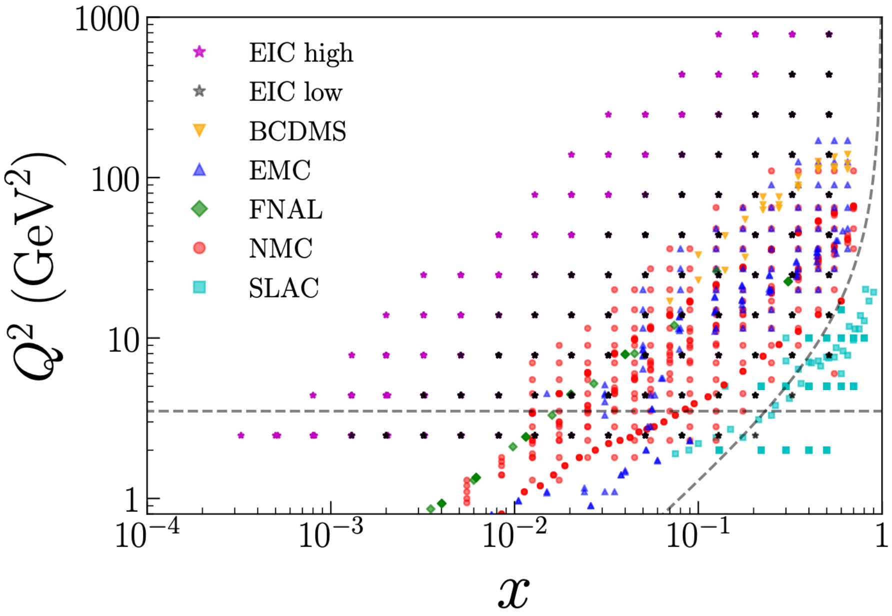
(a) 4 GeV $< M_{\mu\mu} <$ 5 GeV (b) 5 GeV $< M_{\mu\mu} <$ 6 GeV (c) $M_{\mu\mu} >$ 10.5 GeV

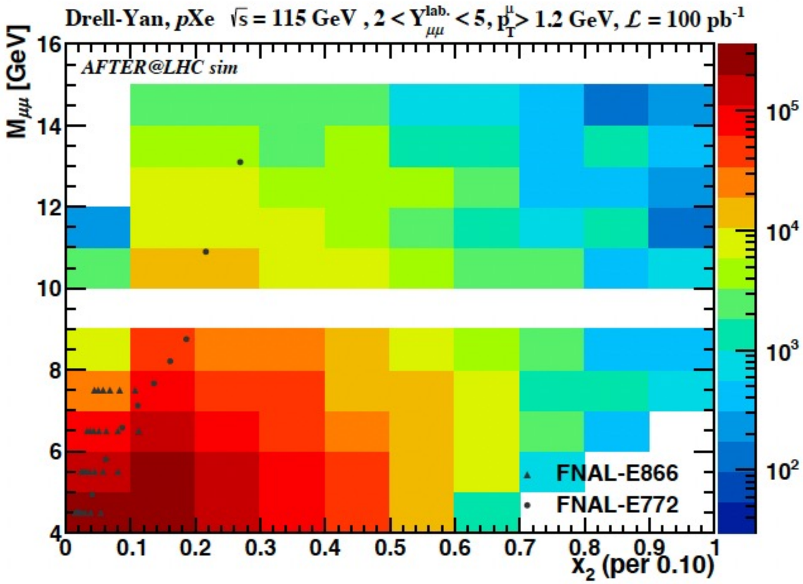
Reweighting analysis showing the potential impact of the
DY lepton-pair production data from AFTER@LHC in pXe collisions on the nCTEQ15 nPDFs

We can see a significant decrease of the errors for up and down quark distributions showing the potential of the AFTER@LHC to constrain nPDFs.

nPDFs: what can we learn from fixed-target experiments





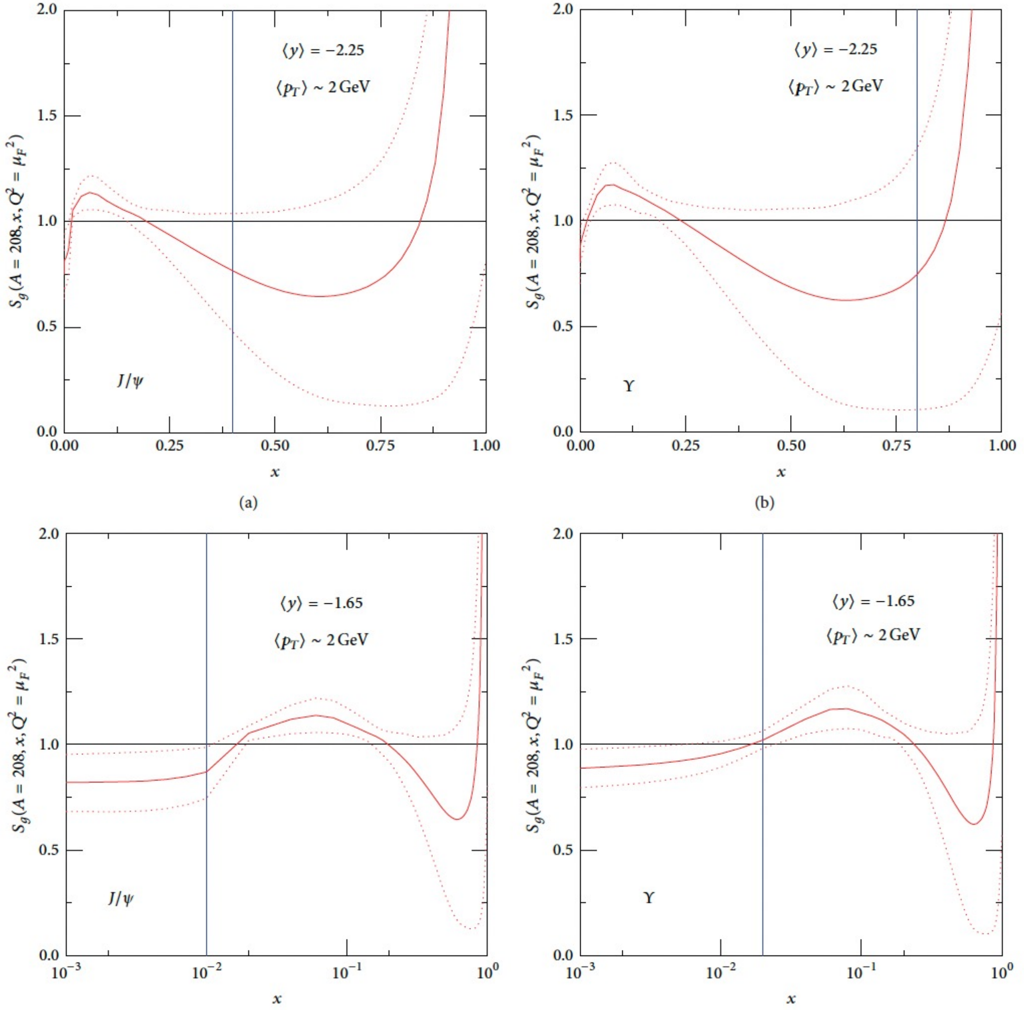


a modern precision measurement of DY lepton-pair production covering a wide range in invariant masses of the lepton pairs and extending to higher x would lead to significant improvements over the current state of the art and would be complementary to results from a future Electron-Ion-Collider

nPDFs: what can we learn from fixed-target experiments

- Fixed-target experiments @LHC will be also able to constrain the high-x nuclear gluon distribution, which is the least known nPDF

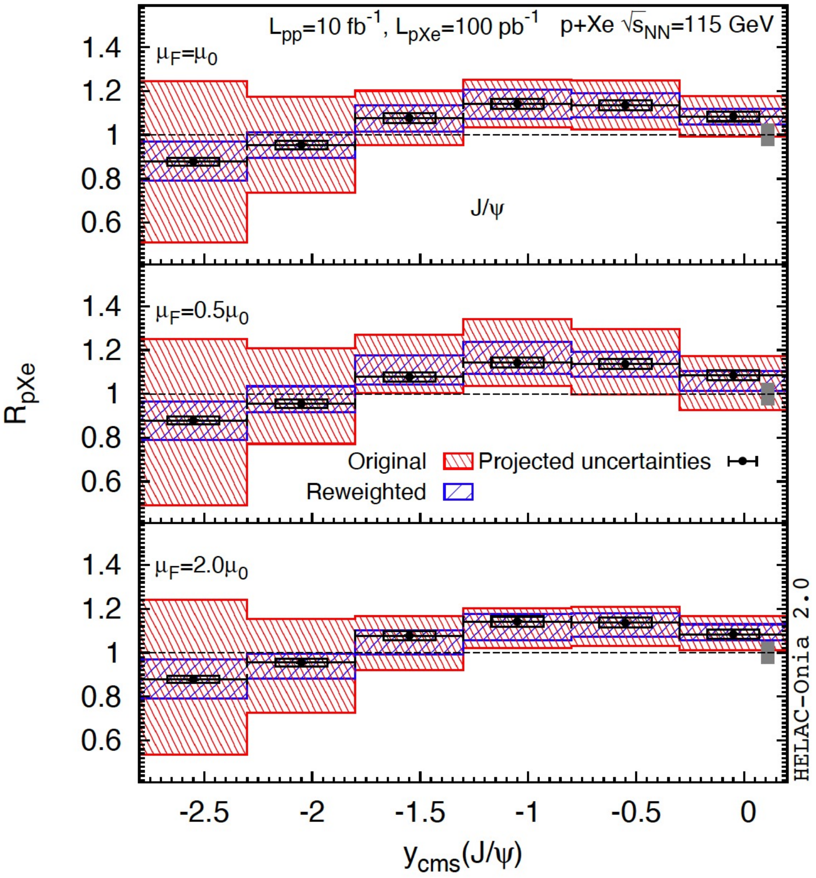
nPDF effect on J/Ψ and Υ production at fixed-target LHC energies

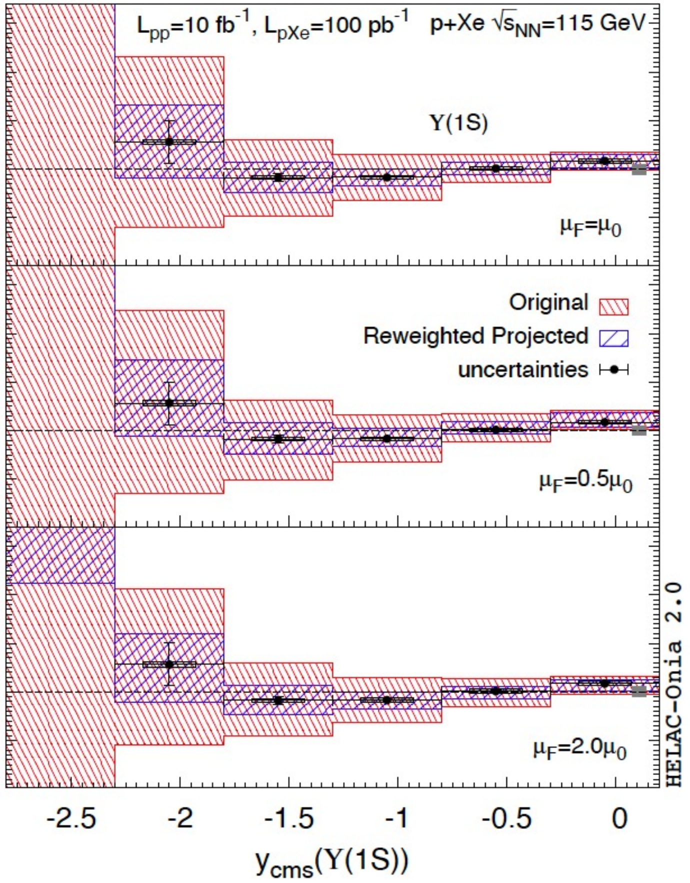


Ramona Vogt
EPS09 NLO

nPDFs: what we can learn from fixed-target experiments

Potential of hidden heavy flavour mesons production in pXe collision 115 GeV to pin down the high-x gluon density in nPDF by performing a Bayesian-reweighting analysis





Effect on nCTEQ-15, Phys.Rept. 911 (2021)

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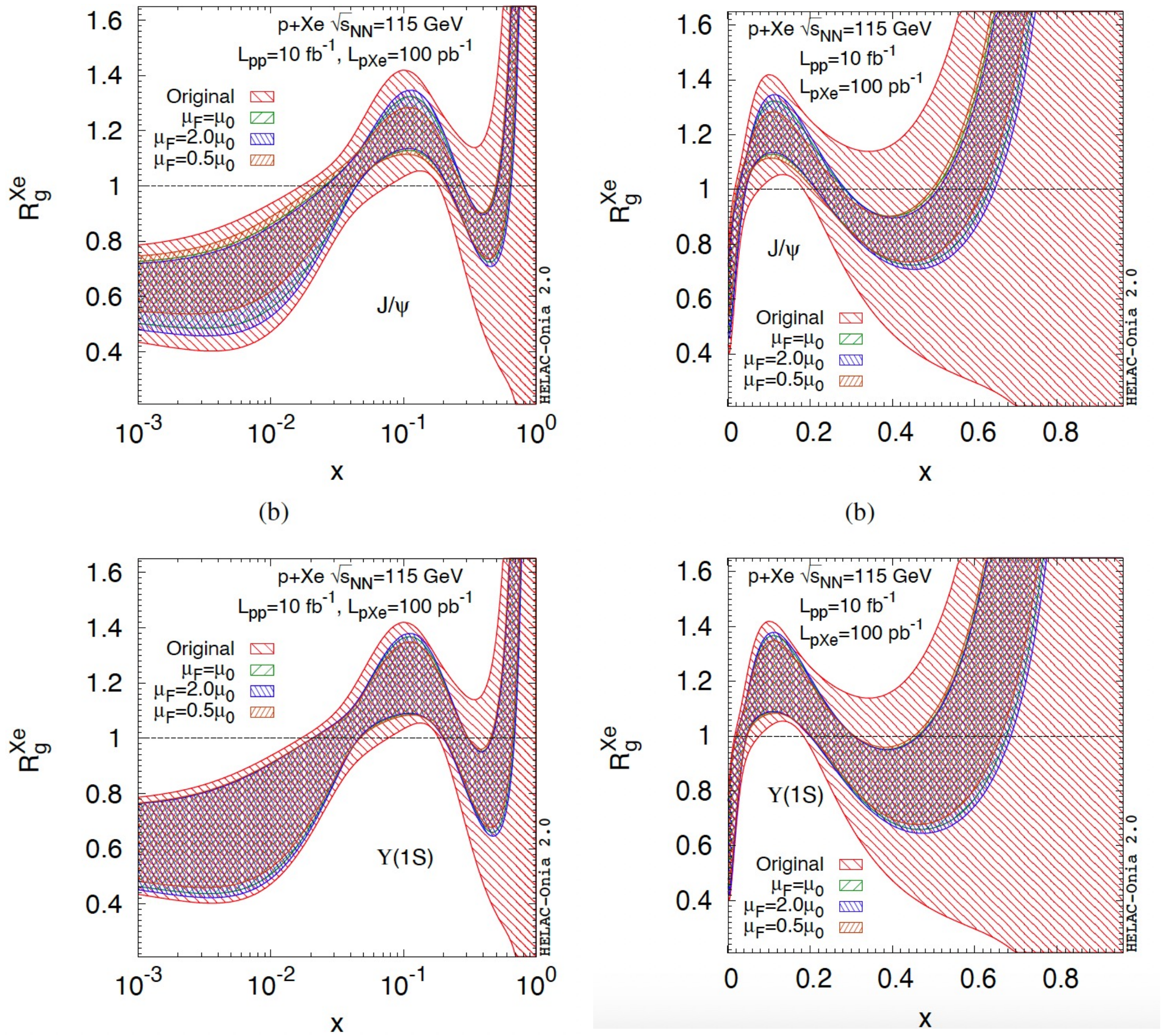

(b)

(b)

Effect on nCTEQ-15, Phys.Rept. 911 (2021)

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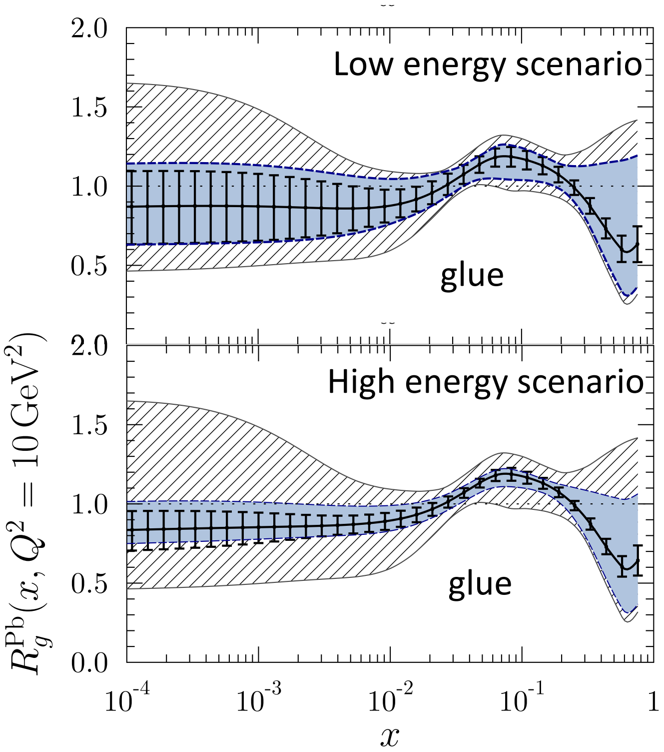
Complementary to EIC:
eAu pseudodata included in EPPS16-like global fits
Impact of low (5 GeV) and high (20 GeV) E_e



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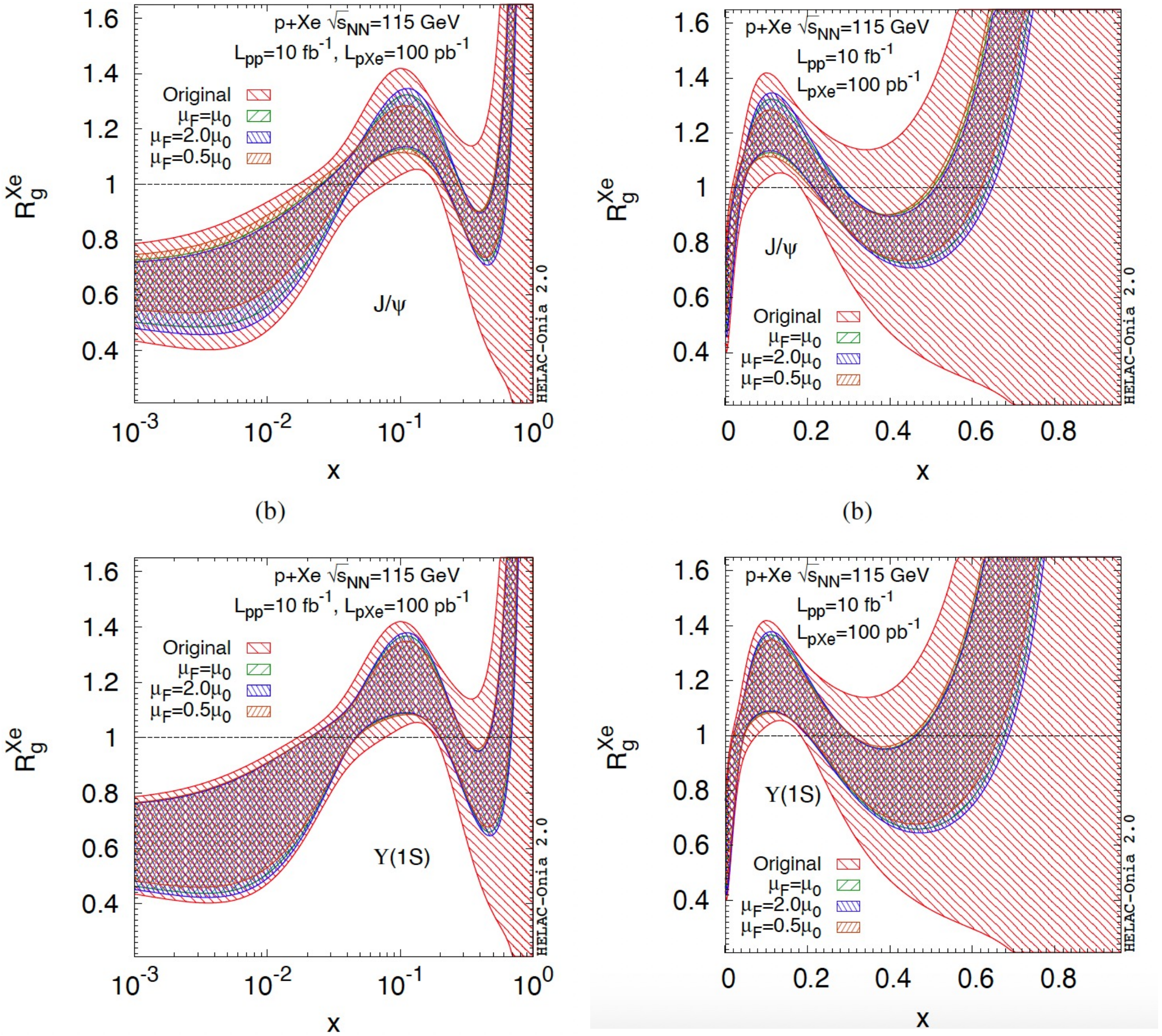


Effect on nCTEQ-15, Phys.Rept. 911 (2021)

Advantage: absence of saturation effects at fixed-target energies

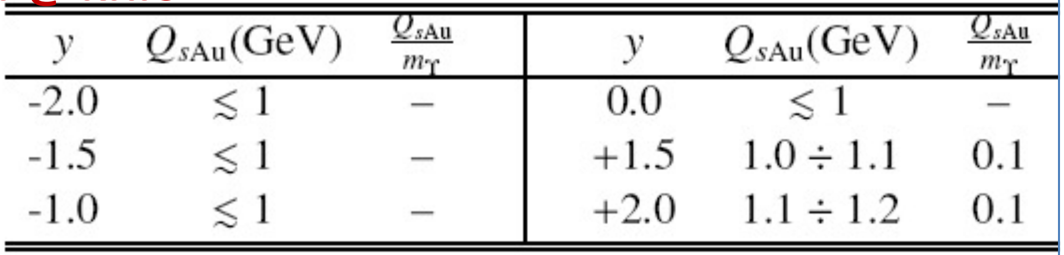
Saturation scale

$$Q_{sA}^2 = A^{\frac{1}{3}} \times 0.2 \times \left(\frac{x_0}{x}\right)^{\lambda} (\text{in unit of GeV}^2),$$

sets the minimum momentum fraction below which one expects non-linear effects to be significant in the evolution of the parton distribution

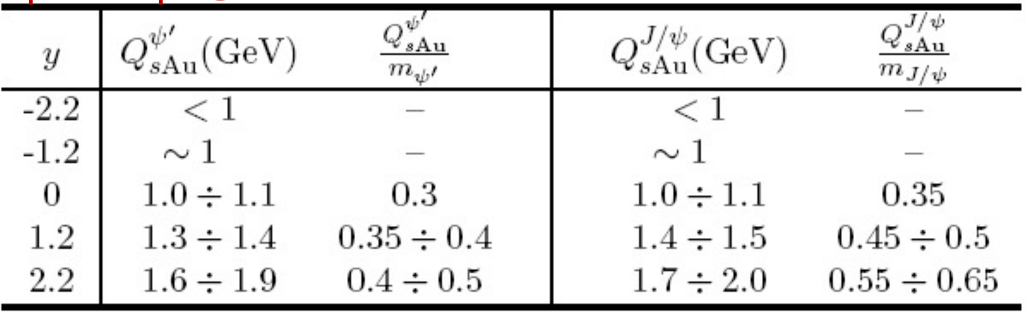
with $\lambda \sim 0.2 \div 0.3$ and with $x_0 = 0.01$

ϒ @ RHIC



y	$Q_{s\mathrm{Au}}(\mathrm{GeV})$	$\frac{Q_{s\mathrm{Au}}}{m_\Upsilon}$	y	$Q_{s\mathrm{Au}}(\mathrm{GeV})$	$\frac{Q_{s\mathrm{Au}}}{m_\Upsilon}$
-2.0	$\lesssim 1$	–	0.0	$\lesssim 1$	–
-1.5	$\lesssim 1$	–	+1.5	$1.0 \div 1.1$	0.1
-1.0	$\lesssim 1$	–	+2.0	$1.1 \div 1.2$	0.1

J/ψ and ψ' @ RHIC



y	$Q^{\psi'}_{s\mathrm{Au}}(\mathrm{GeV})$	$\frac{Q^{\psi'}_{s\mathrm{Au}}}{m_{\psi'}}$	$Q^{J/\psi}_{s\mathrm{Au}}(\mathrm{GeV})$	$\frac{Q^{J/\psi}_{s\mathrm{Au}}}{m_{J/\psi}}$
-2.2	< 1	–	< 1	–
-1.2	~ 1	–	~ 1	–
0	$1.0 \div 1.1$	0.3	$1.0 \div 1.1$	0.35
1.2	$1.3 \div 1.4$	$0.35 \div 0.4$	$1.4 \div 1.5$	$0.45 \div 0.5$
2.2	$1.6 \div 1.9$	$0.4 \div 0.5$	$1.7 \div 2.0$	$0.55 \div 0.65$

Saturation scale always well below the typical energy scale of the process *m*

=> one does not expect any specific saturation effect on ϒ or J/ψ production in collisions @ AFTER

=> shadowing of gluons as encoded in the nPDF fits based on the collinear factorisation should give a reliable account of the possible physics

J/ψ, ψ' and ϒ @ AFTER:
Qs<1 for all rapidities

This effect is not relevant at fixed-target LHC energies

Caveat: Other effects

- Important to note: the above projections for the constraints on the gluon nPDF were obtained assuming only the modification of nPDFs and the absence of other cold nuclear matter effects, or that such other effects can be subtracted

- At LHC collider energies, this kind of leading-twist-factorisation approach was applied with success to a large class of existing data

- At lower energies, especially in the backward region, quarkonium break up will likely play a role and should be separated out

- For that matter, the extensive access of AFTER@LHC to quarkonium excited-state studies will be crucial

- Another example of an effect that can matter when gluons are involved is the coherent energy loss

Final effects: Nuclear absorption through break-up cross section

The bound states may be destroyed by inelastic scatterings with nucleons if they are formed in the nuclear medium. One expect

$$\sigma_{\mathrm{break-up}} \propto r^2_{\mathrm{meson}}$$

- In order to interact with nuclear matter => $\boxed{t_f \leq R}$

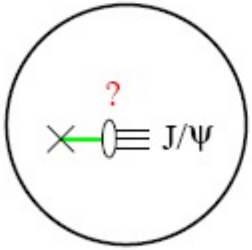
$$S_{abs} = \exp(-\rho\sigma_{\text{break-up}} L)$$

- In the meson rest frame: $\tau_f = \dfrac{2M_{c\bar{c}}}{(M^2_{2S} - M^2_{1S})} \approx$ 0.3÷0.4 fm for quarkonium

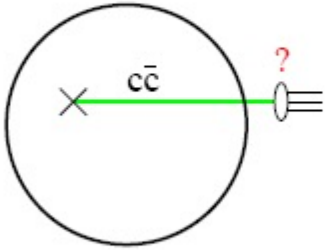
- t_f has to be considered in the rest frame of the target nucleus => $\boxed{t_f = \gamma\, \tau_f}$

Low energy: $t_f = \gamma(x_2)\,\tau_f \ll R$

High energy: $t_f = \gamma(x_2)\,\tau_f \gg R$



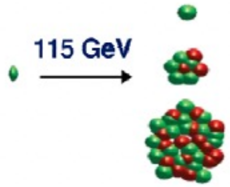
Formation time depends on the boost



Final effects: Nuclear absorption through break-up cross section

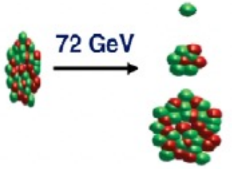
7 TeV proton beam on a fixed target

c.m.s. energy: $\sqrt{s}=\sqrt{2m_N E_p}\approx 115\,\text{GeV}$	**Rapidity shift:** $y_{c.m.s.}=0\rightarrow y_{lab}=4.8$
Boost: $\gamma=\sqrt{s}/(2m_N)\approx 60$	



2.76 TeV Pb beam on a fixed target

c.m.s. energy: $\sqrt{s_{NN}}=\sqrt{2m_N E_{\text{Pb}}}\approx 72\,\text{GeV}$	**Rapidity shift:** $y_{c.m.s.}=0\rightarrow y_{lab}=4.3$
Boost: $\gamma\approx 40$	



γ = cosh(y-y^{A}_{beam})

115 GeV			72 GeV		
y	$\gamma(y)$	$t_f(y)$	y	$\gamma(y)$	$t_f(y)$
-3.0	3	1 fm	-3.0	2	0.7 fm
-2.0	8	3 fm	-2.0	5	2 fm
0.0	60	20 fm	0.0	37	13 fm

It takes $t_f \approx$ few fm/c at fixed-target energies for a quarkonium to form and to become distinguishable from its excited states

$t_f \leq R$

Nuclear absorption, negligeable at LHC collider energies, can be relevant at fixed-target energies

- Quarkonium excited-state studies will be crucial

Final effects: Comover interaction model

- In a comover model: suppression from scatterings of the nascent ψ with comoving medium of partonic/hadronic origin **Gavin, Vogt, Capella, Armesto, Ferreiro … (1997)**

- Stronger comover suppression where the comover densities are larger. For asymmetric collisions as proton-nucleus, stronger in the nucleus-going direction

- Rate equation governing the charmonium density:

$$\tau \frac{d\rho^{\psi}}{d\tau}(b,s,y) = -\sigma^{co-\psi}\,\rho^{co}(b,s,y)\,\rho^{\psi}(b,s,y)$$

$$\sigma^{co-\mathcal{Q}}(E^{co}) = \sigma^{\mathcal{Q}}_{geo}\times\left(1-\frac{E^{\mathcal{Q}}_{thr}}{E^{co}}\right)^{n}$$

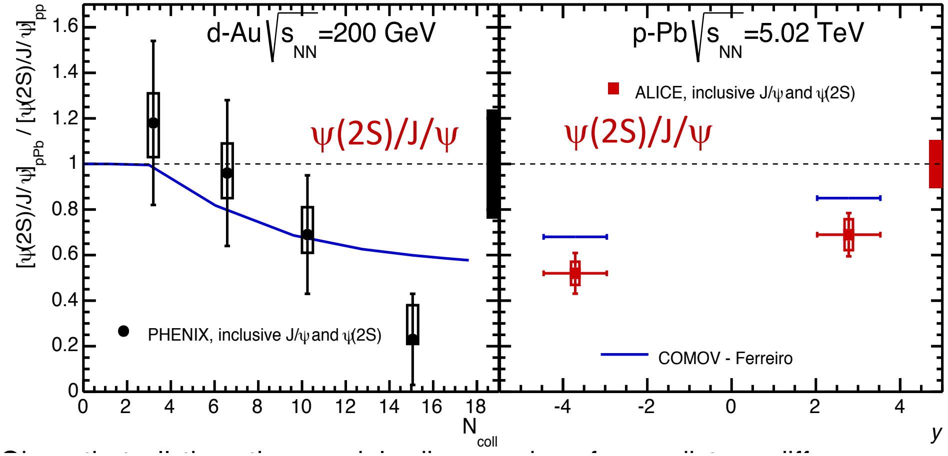
$\sigma^{\mathcal{Q}}_{geo}\simeq\pi r^2_{\mathcal{Q}}$, where $r_{\mathcal{Q}}$ is the quarkonium Bohr radius

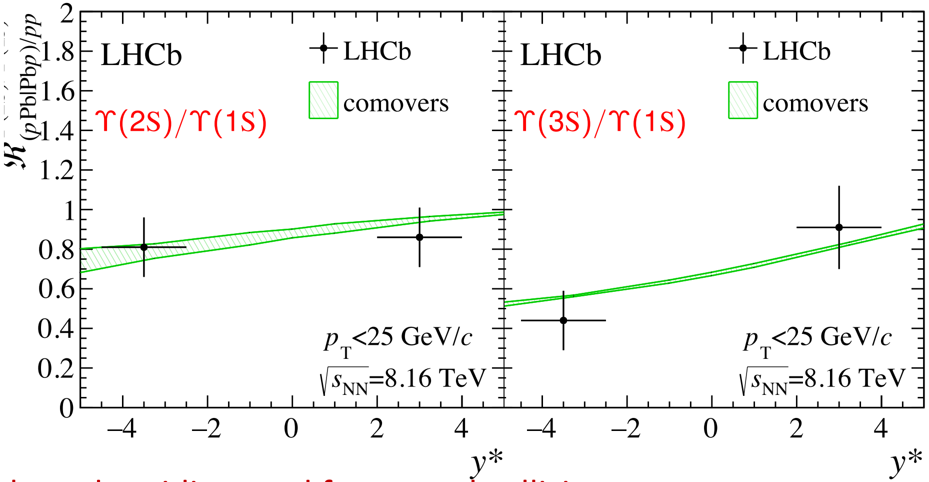
$$\langle\sigma^{co-\mathcal{Q}}\rangle(T_{eff},n) = \frac{\int_0^\infty dE^{co}\,\mathcal{P}(E^{co};T_{eff})\,\sigma^{co-\mathcal{Q}}(E^{co})}{\int_0^\infty dE^{co}\,\mathcal{P}(E^{co};T_{eff})}$$

$E^{\mathcal{Q}}_{thr} = 2M_B - M_{\mathcal{Q}_{b\bar b}}$, *i.e.* the threshold energy

$E^{co} = \sqrt{p^2+m^2_{co}}$ energy of the comovers

$$\mathcal{P}(E^{co};T_{eff}) \propto \frac{1}{e^{E^{co}/T_{eff}}-1}$$



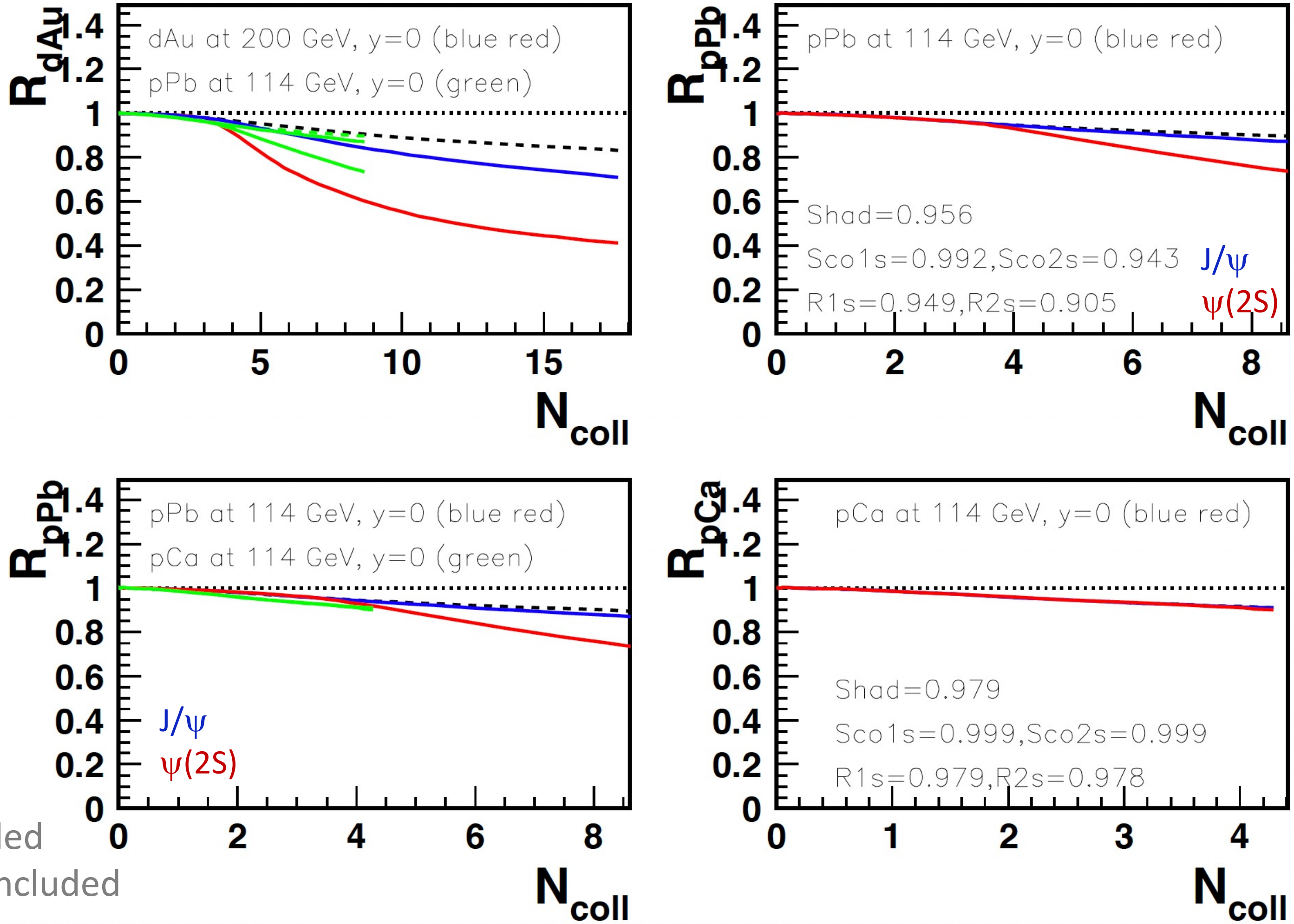


Stronger suppression in the nucleus-going direction –backward rapidity- and for central collisions

Final effects: Comover interaction model

Results from the CIM at fixed-target LHC energies

- At mid rapidities, the effect on charmonium excited vs ground state can be measurable for p-Pb collisions

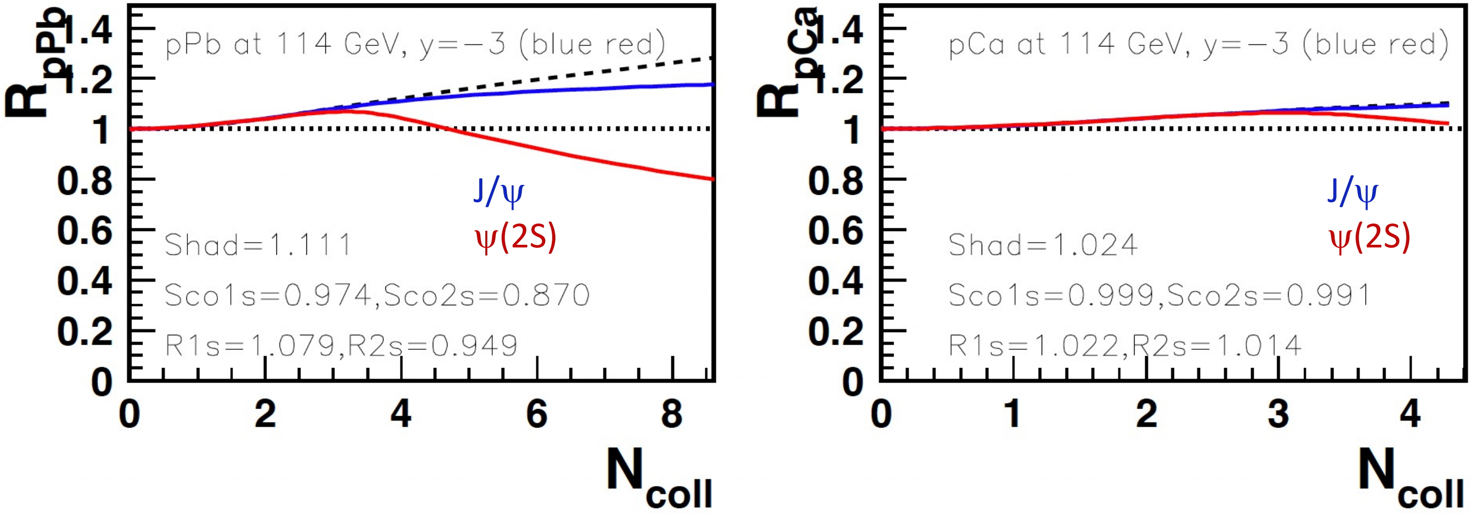


nPDF modification included
Nuclear absorption not included

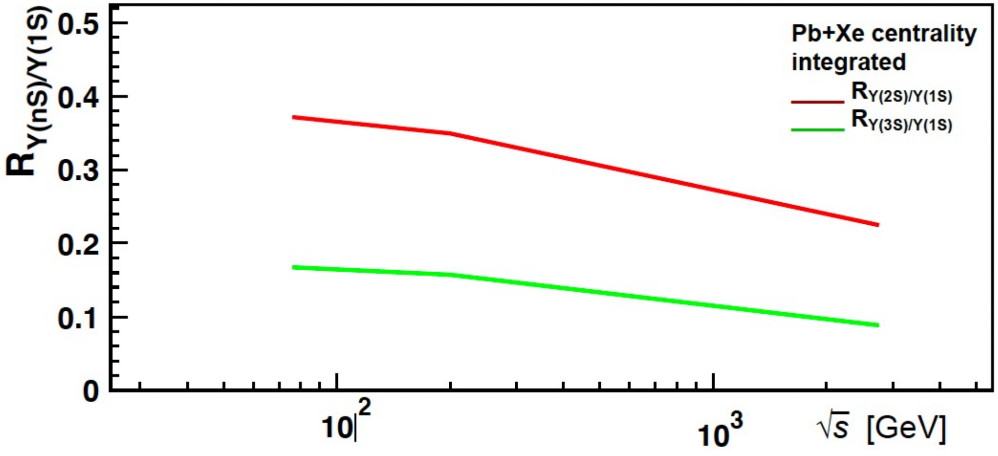
Final effects: Comover interaction model

Results from the CIM at fixed-target LHC energies

- At backward rapidities, the effect on charmonium excited vs ground state will be stronger and might be measurable for lighter nuclei



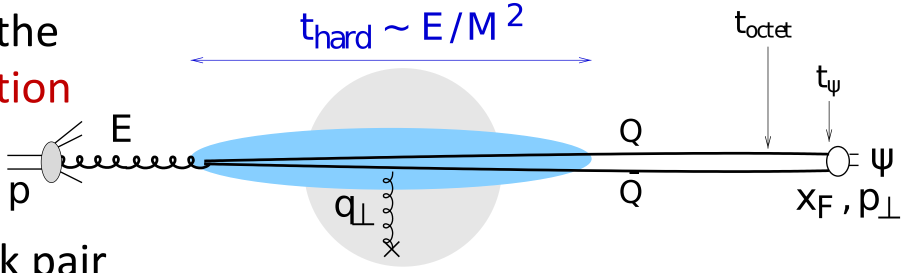
- It can be particularly relevant for upsilon production



nPDF modification included
Nuclear absorption not included

Other effects: Coherent energy loss

Nuclear transverse momentum broadening of the heavy quark pair induces coherent gluon radiation arising from the interference between emission amplitudes off the initial projectile parton and the final color octet quark pair

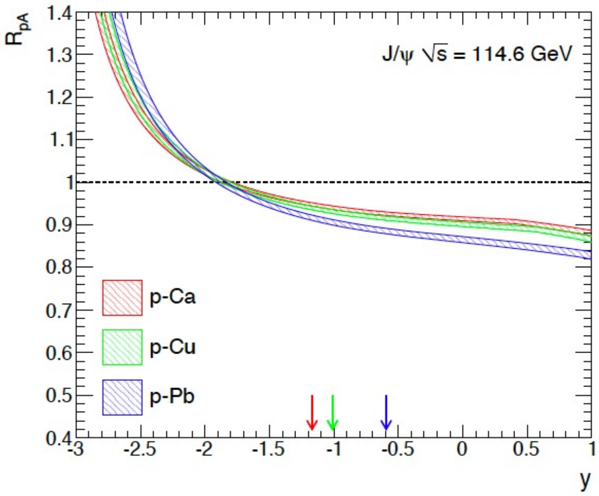


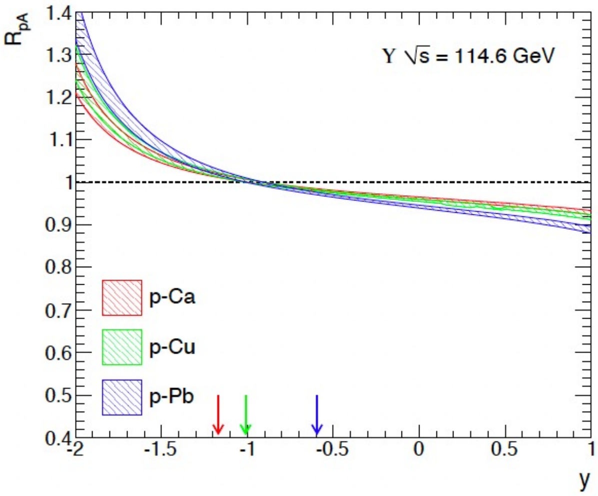
Arleo, Peigné, Rustamova (2015)

- Leads to a behaviour $\Delta E \;\alpha\; E$ $\sqrt{\Delta q_\perp^2}$ related to the transport coeficient

$$\Delta E = \int d\omega\, \omega\, \frac{dI}{d\omega}\bigg|_{\mathrm{ind}} = N_c \alpha_s \frac{\sqrt{\Delta q_\perp^2}}{m_T} E$$

$$\hat{q}(x) \simeq \hat{q}_0 \left(\frac{10^{-2}}{x}\right)^{0.3}$$





Same effect for ground and excited states

nPDF modification not included
Nuclear absorption not included

Summary of CNM effects relevants @ FT-LHC energies

Such effects, a priori measurable in proton-nucleus collisions, must include:

- the modification of the nuclear parton densities nPDF, commonly known as shadowing and anti-shadowing, with a particular view on the EMC effect
- the multiple scattering of partons or of the heavy-quark pair in the nucleus before or after the hard scattering, which leads to an energy loss or the break-up of the formed quarkonium state
- the interaction with other particles produced in the collision – comovers

One of the biggest challenge in HI collision is to find a good baseline to properly use heavy quarkonia to diagnose the QGP

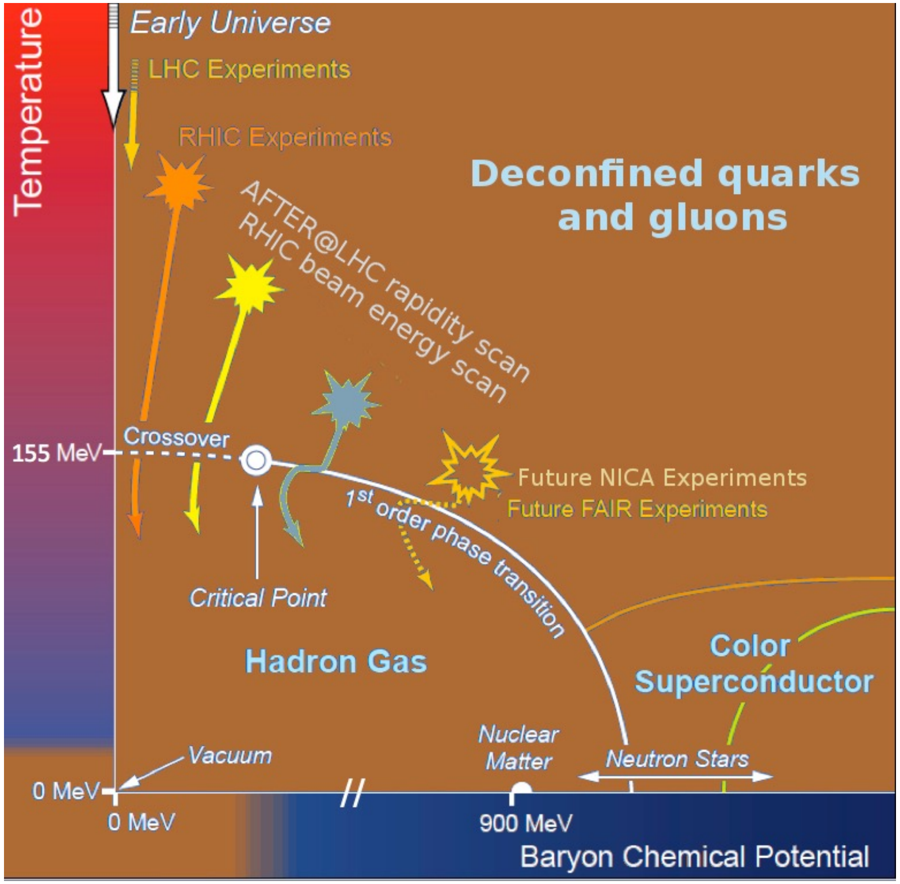
Ideally, this baseline should allow us to correct the yields for the effects characteristic of heavy-quarkonium production and evolution in hadronic matter when QGP is absent

New opportunities and conclusions

- Measuring together ground and excited quarkonium states -J/Ψ and Ψ' or $\Upsilon(nS)$, but also more states as $\chi_{c,b}$ or open charm and beauty- in p+A collisions with several targets can give a thorough control of Cold Nuclear Matter effects needed for a reliable baseline

- Energy domain: between SPS and RHIC Measuring together J/Ψ, Ψ' and χ_c in A+A collisions at these energies in a new rapidity domain can test sequential suppression scenario and the critical point for deconfining

- new energy, new rapidity domain and new probes



Moreover, the CNM effects (ex IC) can be fundamental to calculate nuclear cross section, identify atmospheric background and correctly identify astroparticle neutrinos or antiproton sources