How could heavy-ion physics at the energy frontier profit from LHeC measurements

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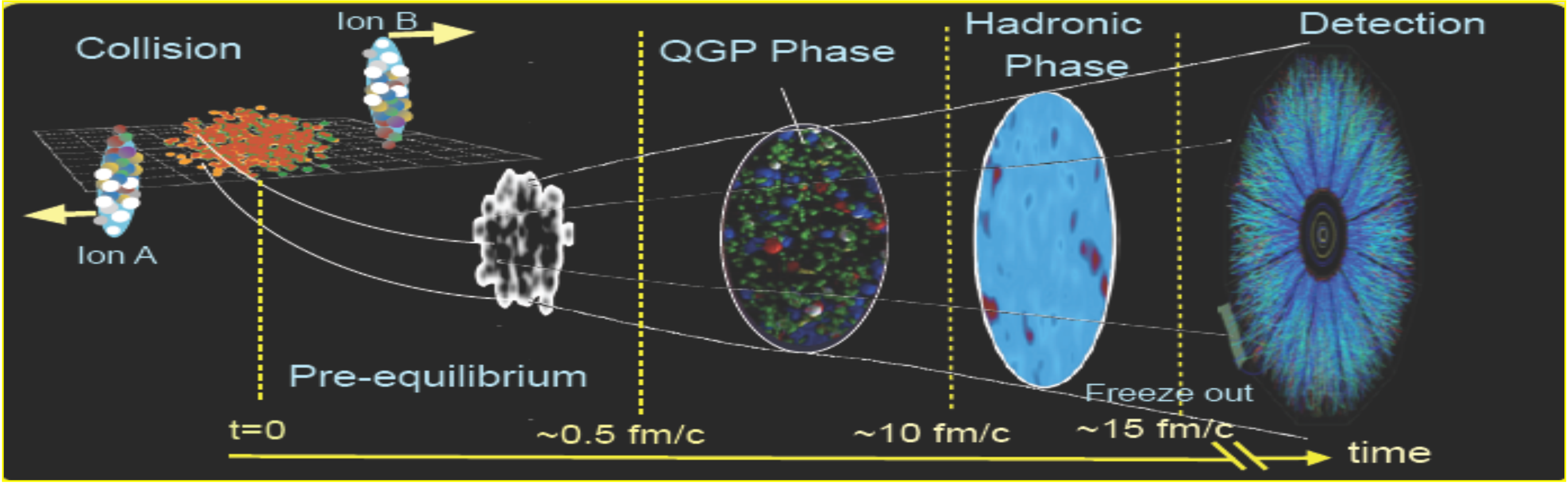
LLR, École polytechnique , France

Goal of HIC experiments: Study hot and dense QCD matter



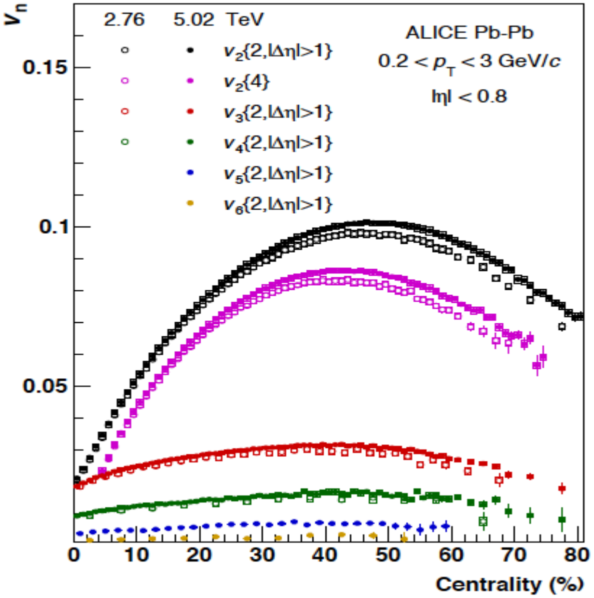
Bulk Observables: p~<pt>,T
~ 99% of detected particles
Multiplicities
Thermal dileptons & direct photons
Asymmetries, correlations, fluctuations

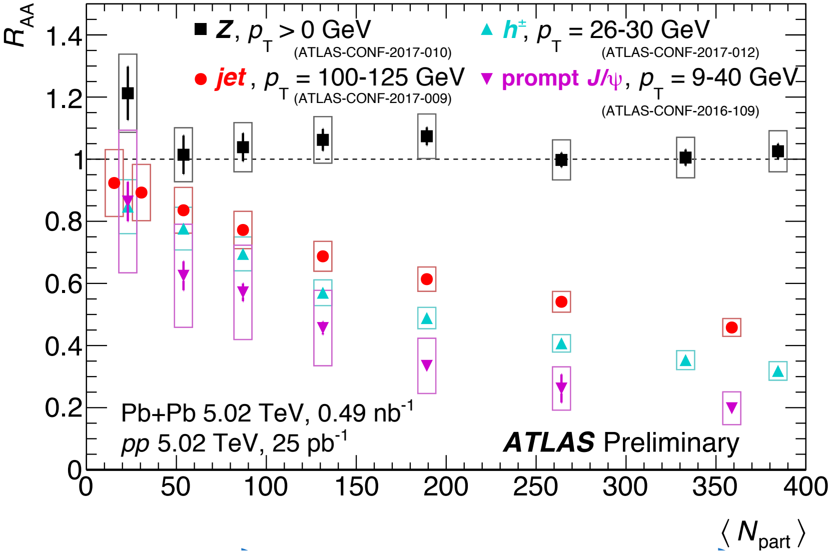
Collective behavior of the medium
Initial conditions: T, ε, μ
Thermalization and hydrodynamics

Hard Probes: p >> <pt>,T
~ 1% of detected particles
Fast quarks and gluons
Jet quenching
Quarkonia dissociation

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

Status of Heavy Ions





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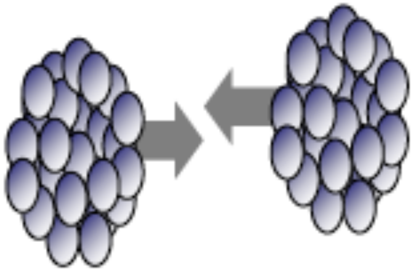
Current status: matter created in **AA** at RHIC and LHC, with energy densities larger than those expected in lattice QCD for deconfinement=>QGP

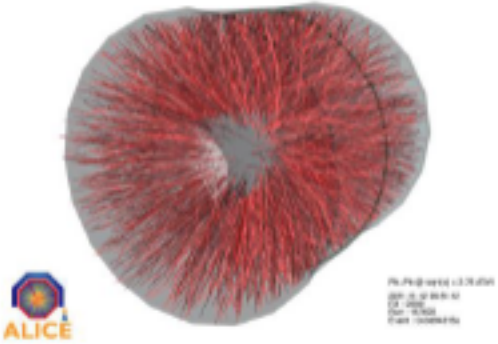
- collective features in the soft sector
- well described by relativistic hydrodynamics if applied very early ($\lesssim$ 1 fm/c) after the collision
- equilibration?

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

Old paradigm: the three systems (understanding before 2012)

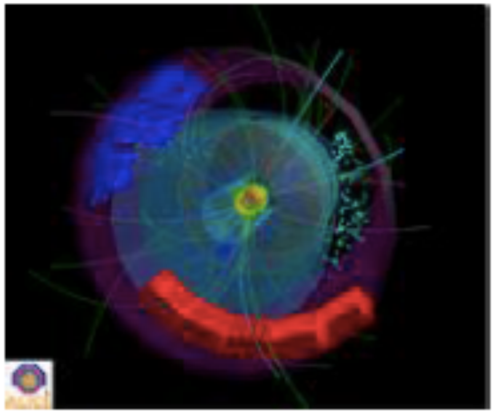
Pb-Pb





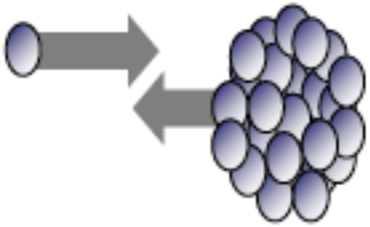
Hot QCD matter:
This is where we expect the QGP to be created in central collisions

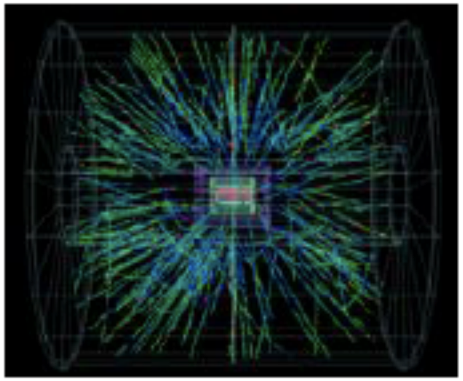
pp



QCD baseline:
This is the baseline for "standard" QCD phenomena

p-Pb





Cold QCD matter:
This is to isolate nuclear effects in absence of QGP, e.g. nuclear pdfs

New paradigm: small systems

Totally unexpected:

the discovery of correlations –ridge, flow- in small systems pA & pp

- Smooth continuation of heavy ion phenomena to small systems and low density
- Small systems as pA and pp show QGP-like features

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- initial state: quantum correlations as calculated by CGC
- final state: interactions leading to collective flow described with hydrodynamics => equilibration?

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- we study hot & dense matter properties in heavy ion AA collisions
- cold nuclear matter modifications in pA
- and we use pp primarily as comparison data   appears no longer sensible

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We should examine a new paradigm, where the physics underlying soft collective signals can be the same in all high energy reactions, from e^+e^- to central AA

It becomes fundamental to have access to ep & eA collisions

What we can learn in an ep/eA collider

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

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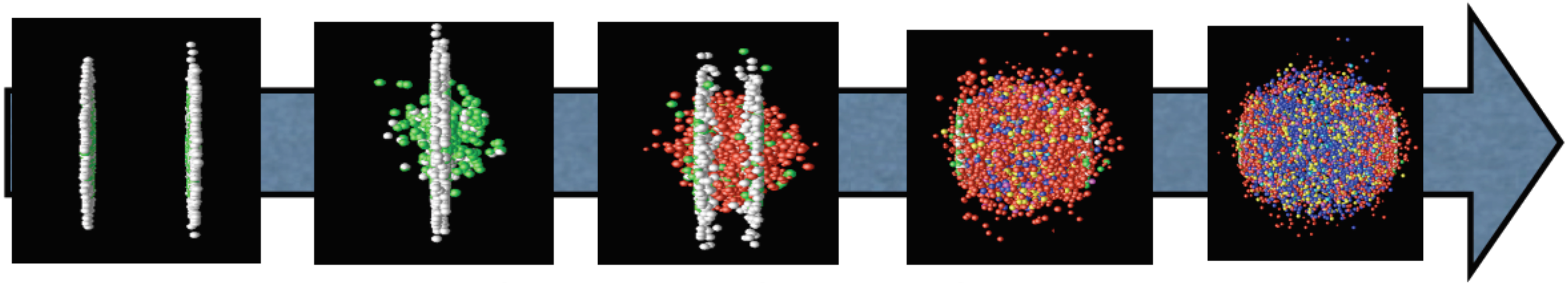

Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

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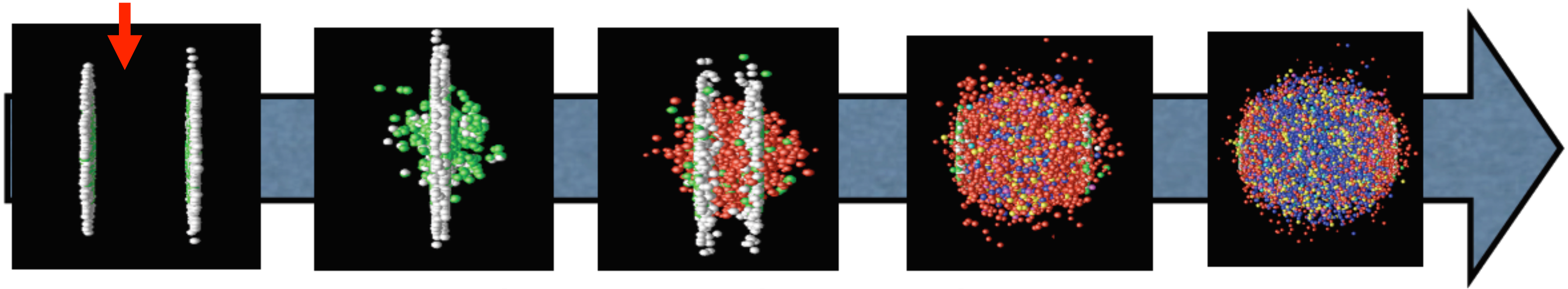
The colliding objects



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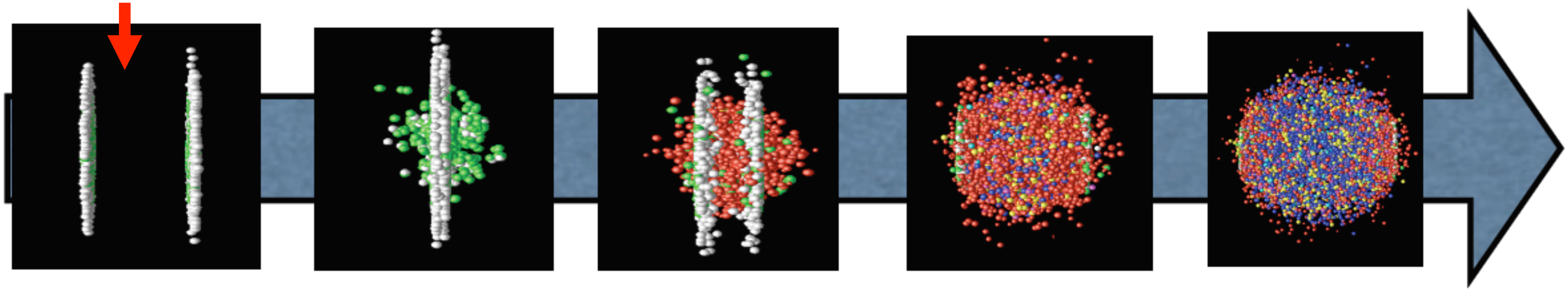

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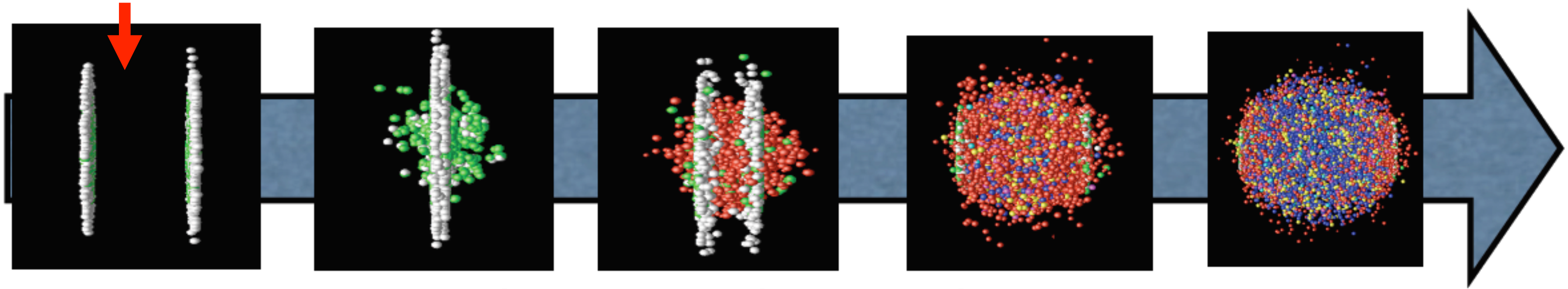

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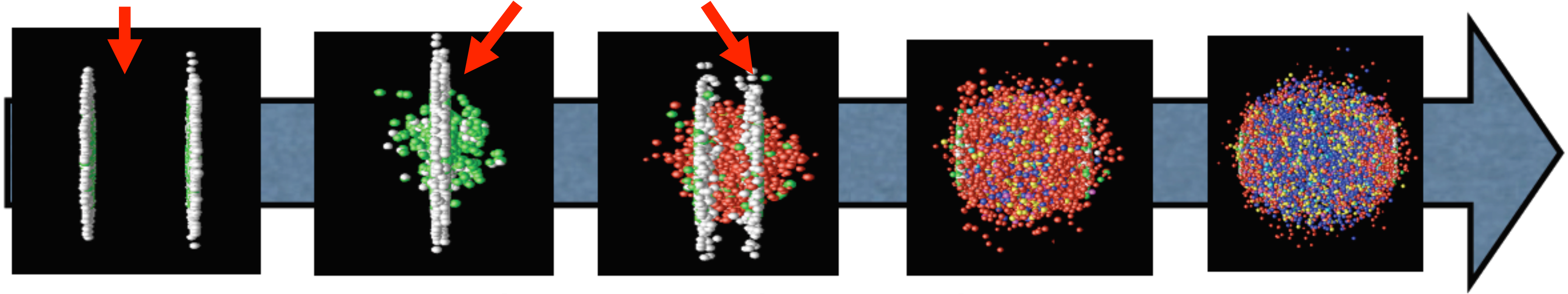

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- Which factorization?
- How can a system behave as isotropised so fast?

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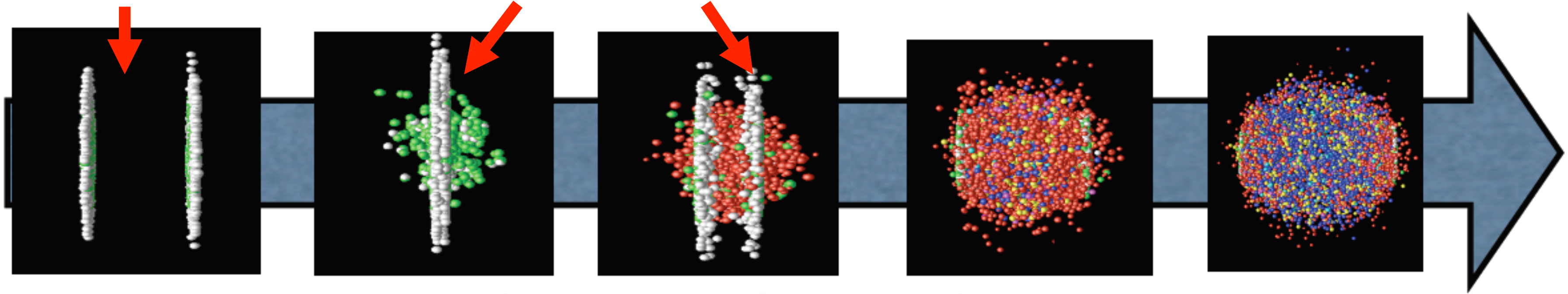

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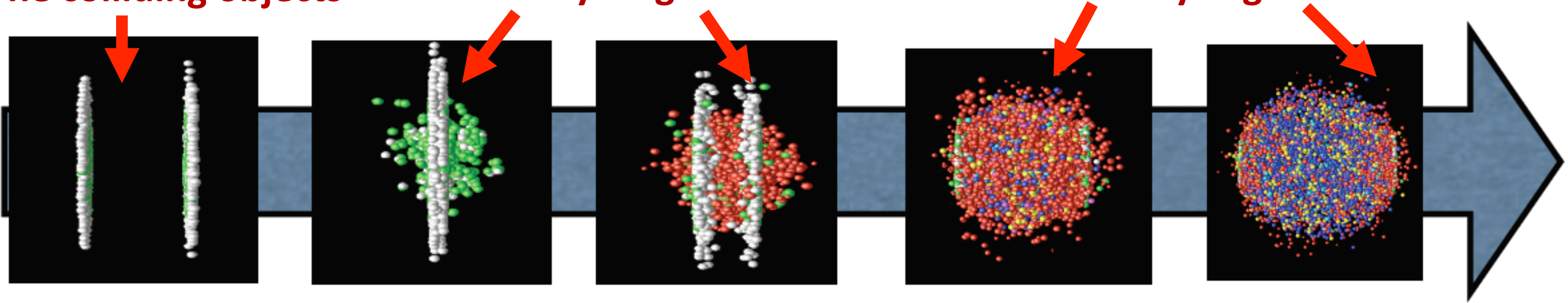

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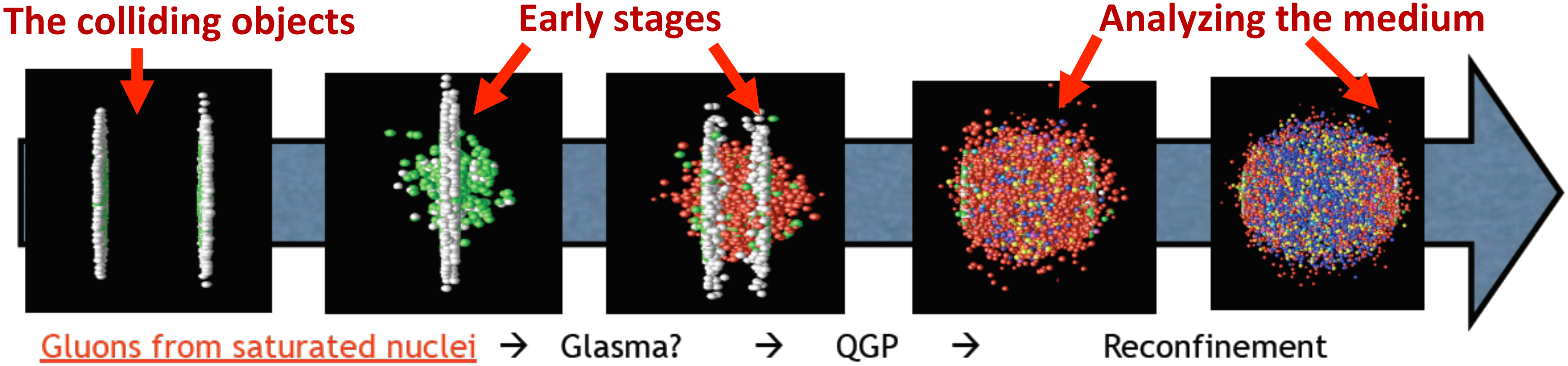

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- Dynamical mechanisms for opacity
- How to extract accurately medium parameters?

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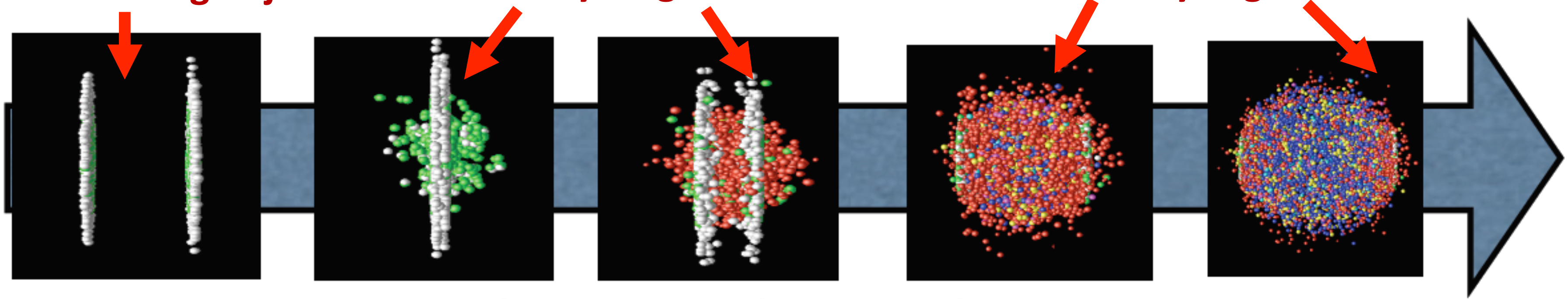

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- How to extract accurately medium parameters?

ep and eA:

- modification of radiation and hadronization in the nuclear medium
- initial effects on hard probes

The colliding objects: nuclear PDFs in heavy ions

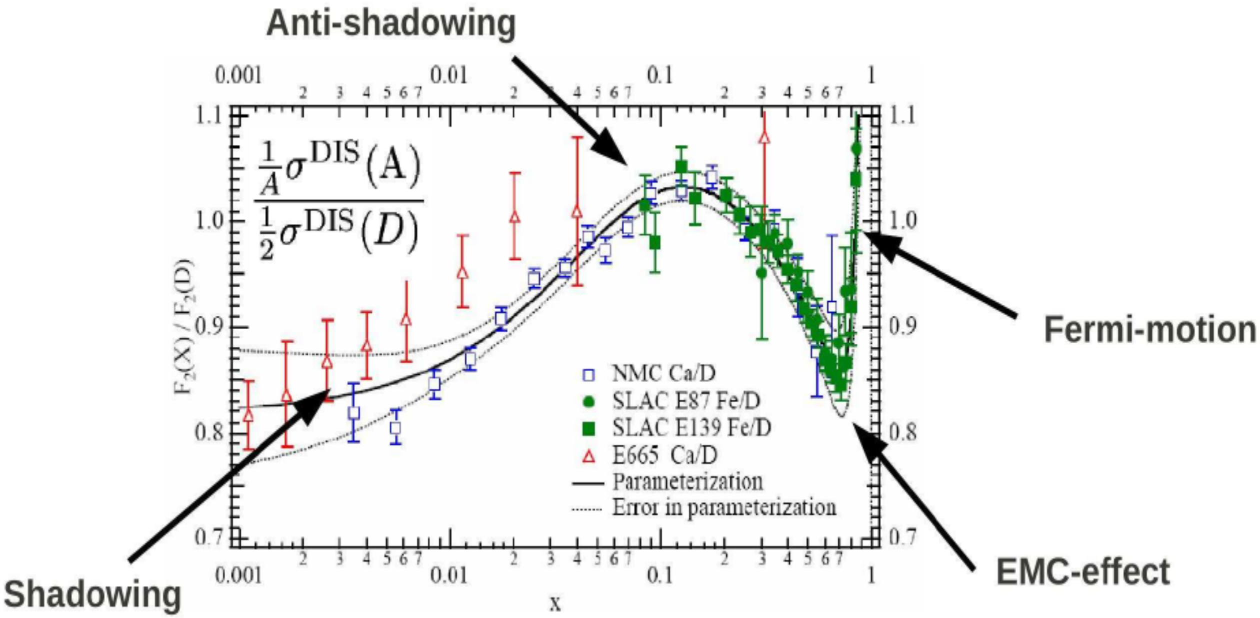
- Parton densities in nuclei are modified
  Bound nucleon ≠ free nucleon
- Nuclear PDF assumed to be factorizable in terms of the nucleon PDFs

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

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

assuming collinear factorization

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



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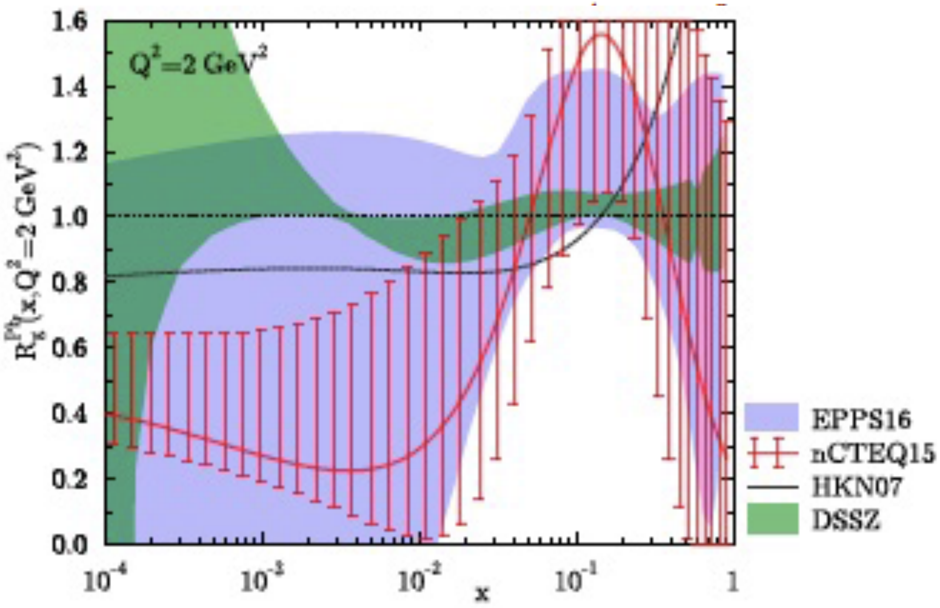

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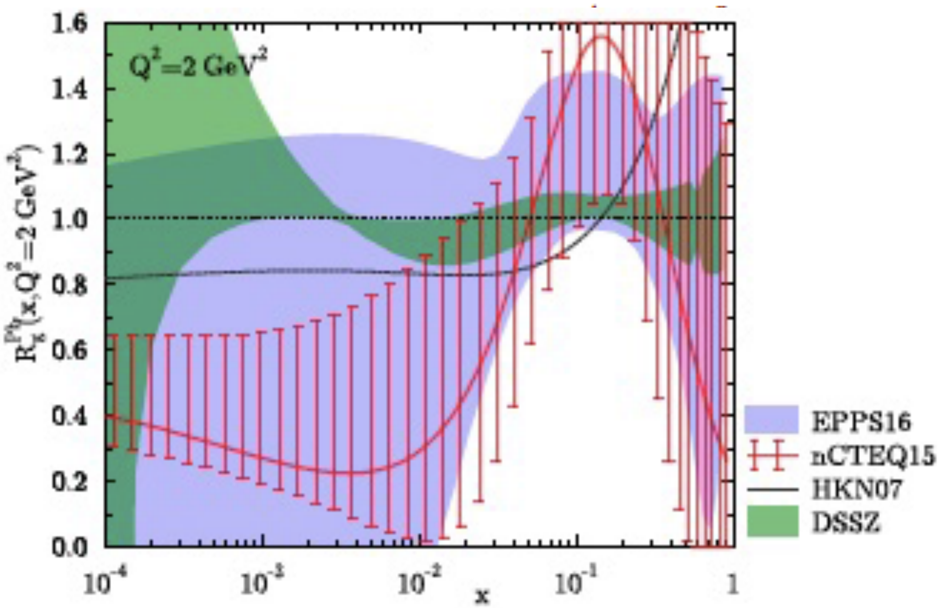

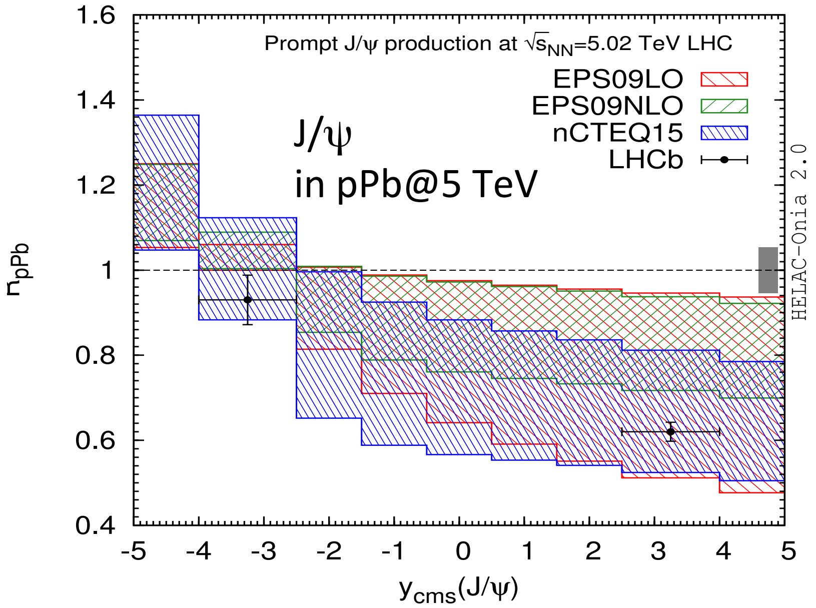

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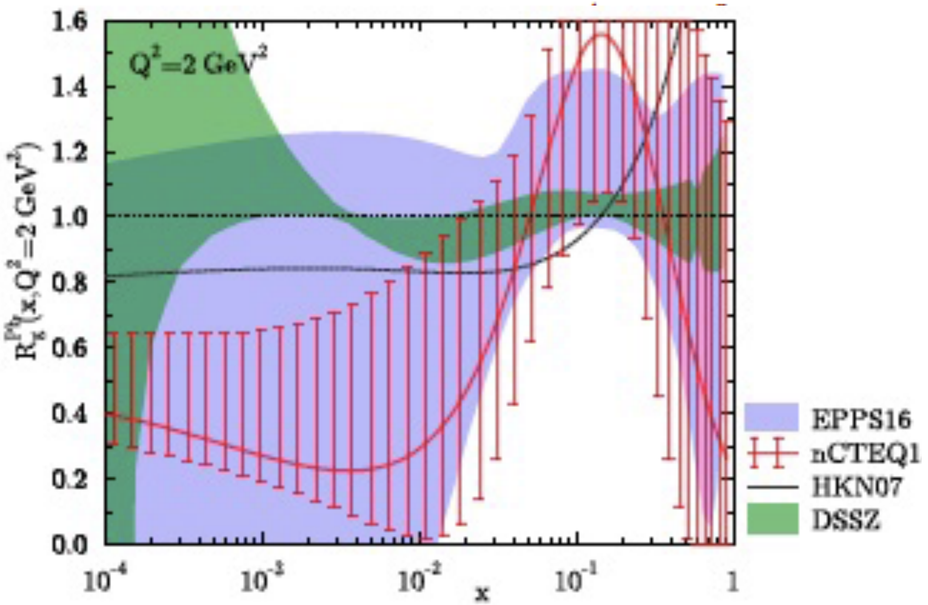

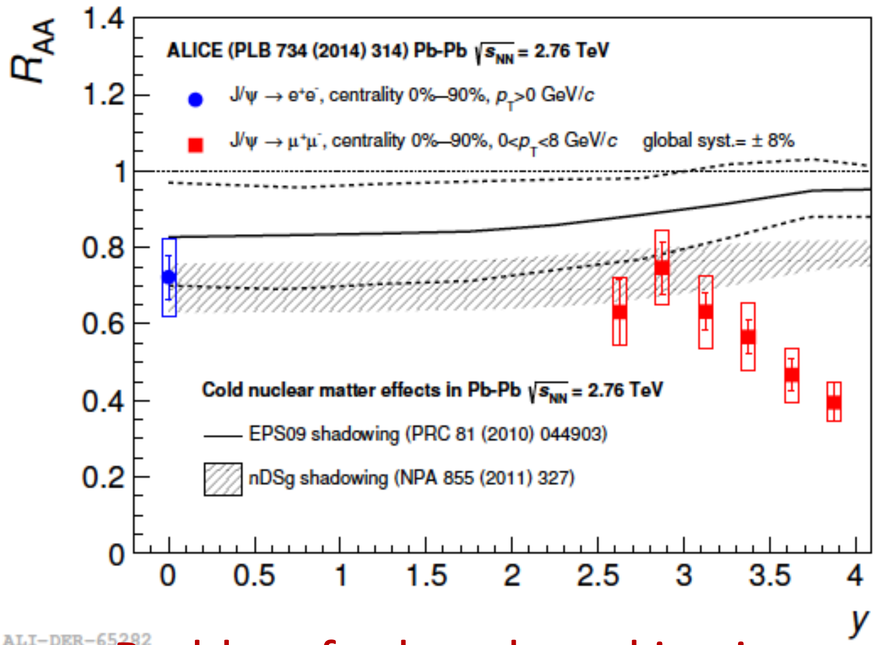

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nPDFs collection

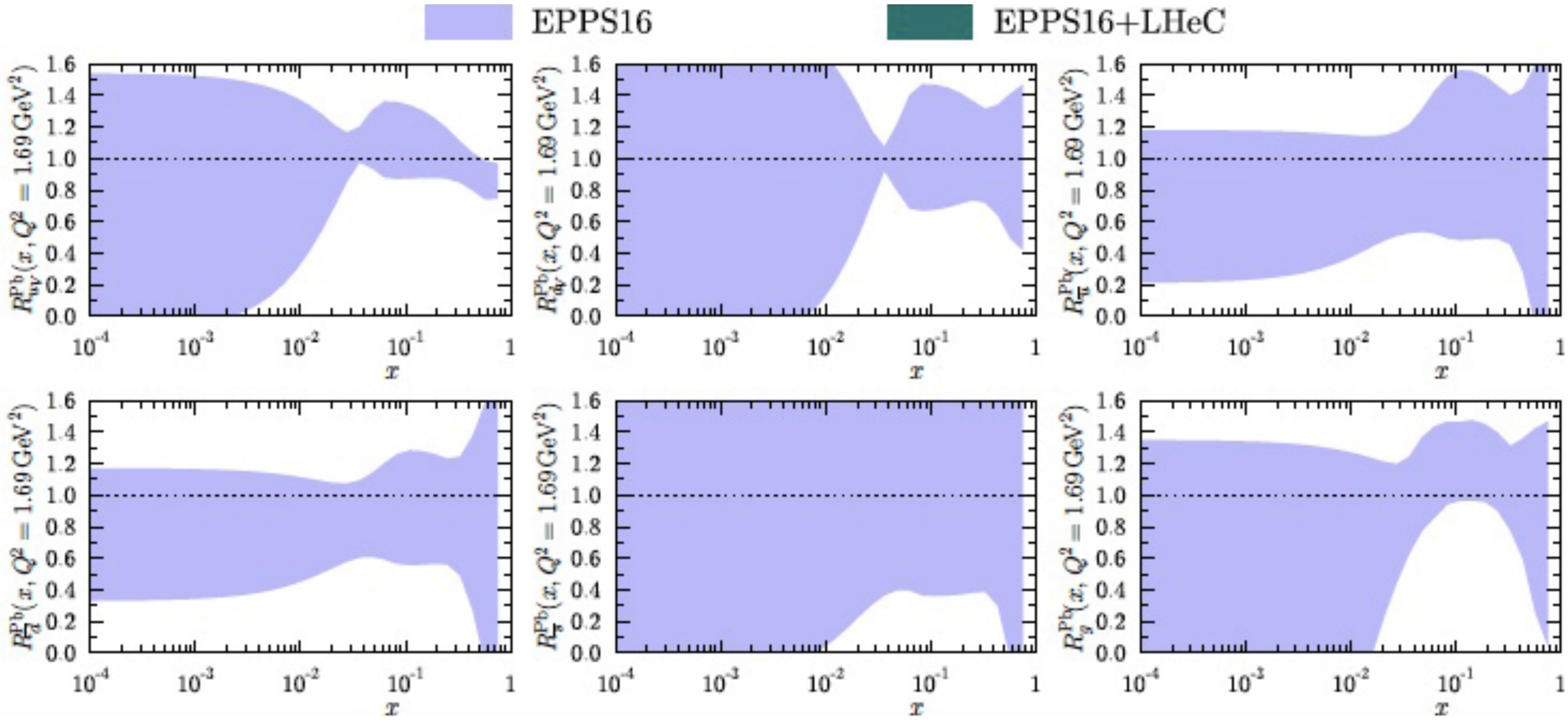
Several nPDF sets available (using various data, LO/NLO, etc)

Nestor Armesto

SET		**HKN07** PRC76 (2007) 065207	**EPS09** JHEP 0904 (2009) 065	**DSSZ** PRD85 (2012) 074028	**nCTEQ15** PRD93 (2016) 085037	**KA15** PRD93 (2016) 014036	**EPPS16** EPJC C77 (2017)163
data	eDIS	✔	✔	✔	✔	✔	✔
	DY	✔	✔	✔	✔	✔	✔
	π^0	✘	✔	✔	✔	✘	✔
	νDIS	✘	✘	✔	✘	✘	✔
	pPb	✘	✘	✘	✘	✘	✔
# data		1241	929	1579	740	1479	1811
order		NLO	NLO	NLO	NLO	NNLO	NLO
proton PDF		MRST98	CTEQ6.1	MSTW2008	~CTEQ6.1	JR09	CT14NLO
mass scheme		ZM-VFNS	ZM-VFNS	GM-VFNS	GM-VFNS	ZM-VFNS	GM-VFNS
comments		$\Delta\chi^2$=13.7, ratios, no EMC for gluons	$\Delta\chi^2$=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

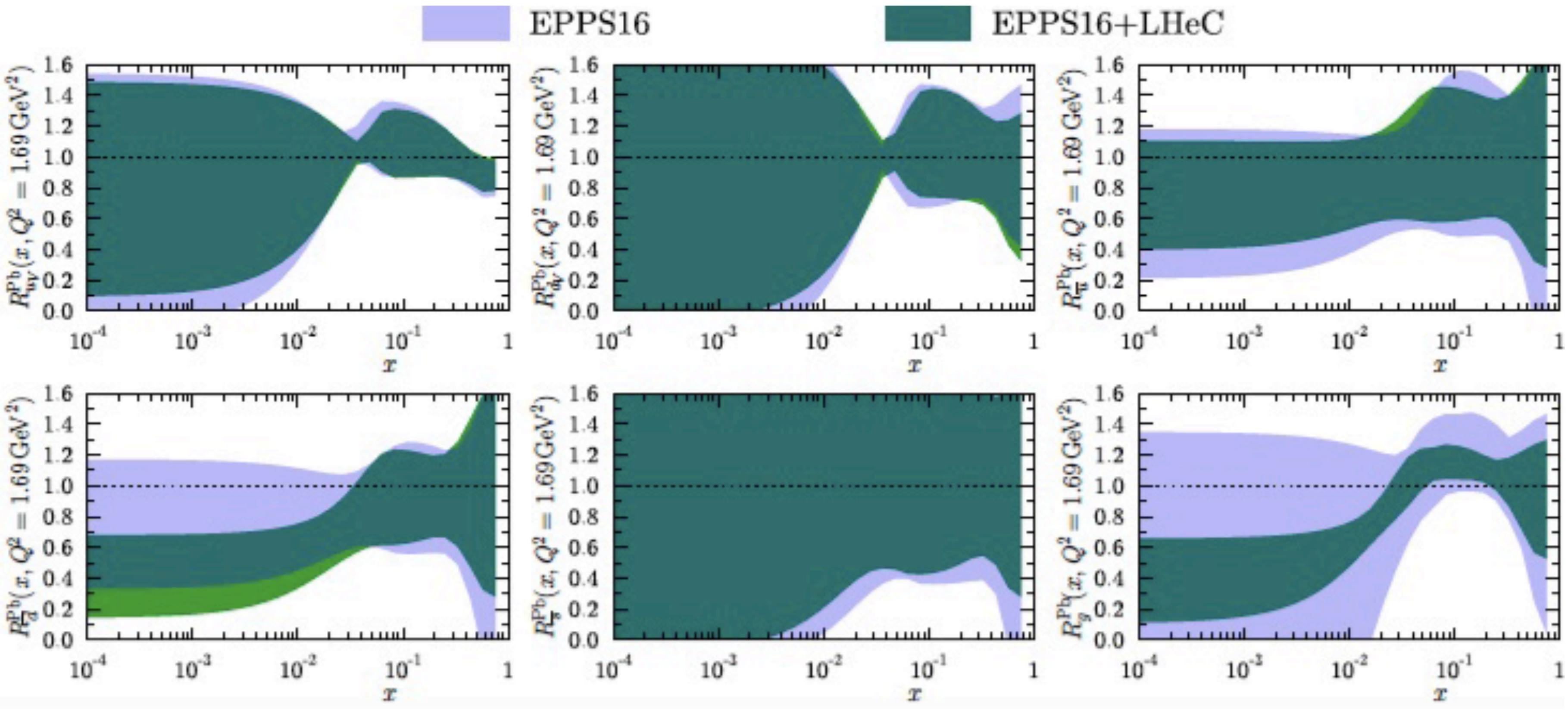
Nuclear PDFs at present

The EPPS16 errorbands at $Q^2 = 1.69$ GeV^2



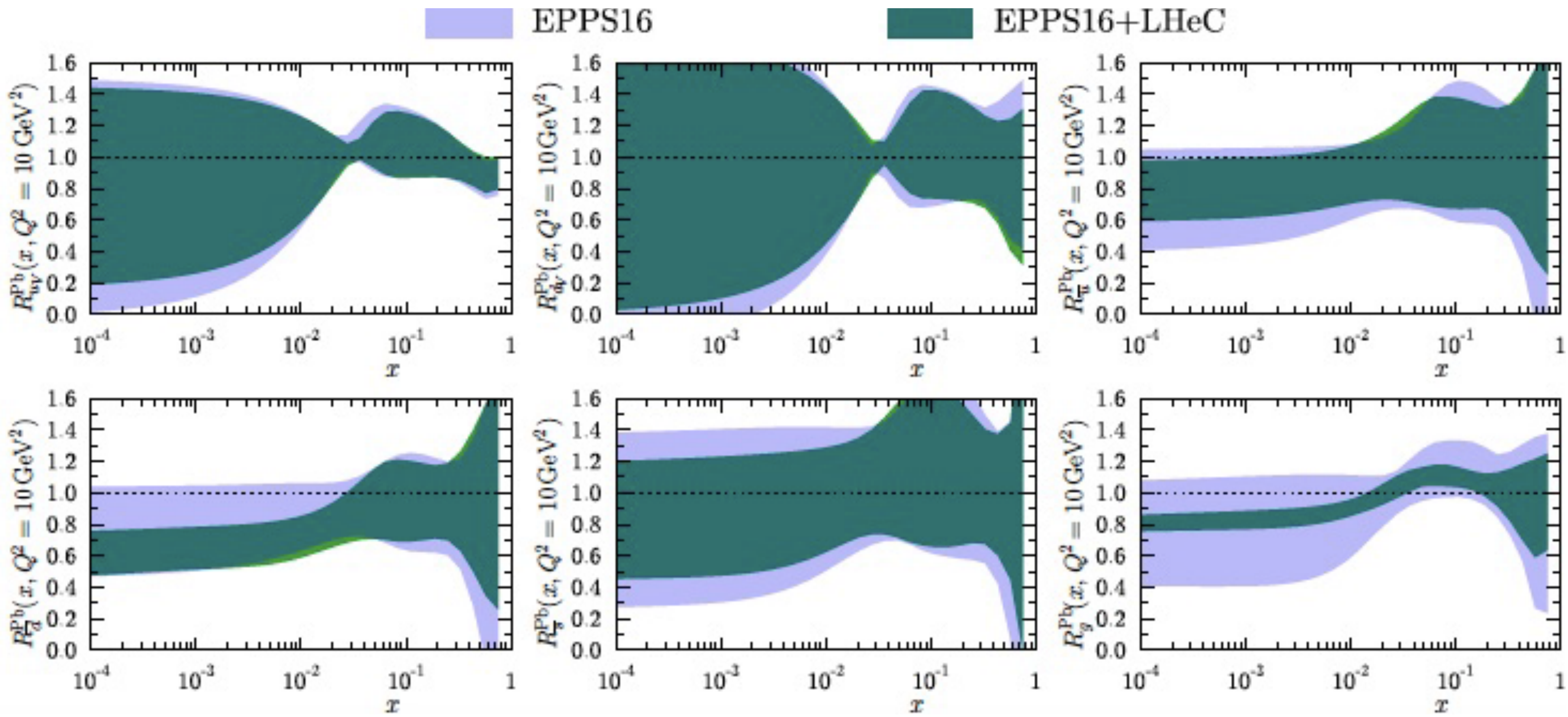
Nuclear PDFs with LHeC pseudodata

The improvement after adding the LHeC pseudodata at Q^2 = 1.69 GeV^2



Nuclear PDFs with LHeC pseudodata

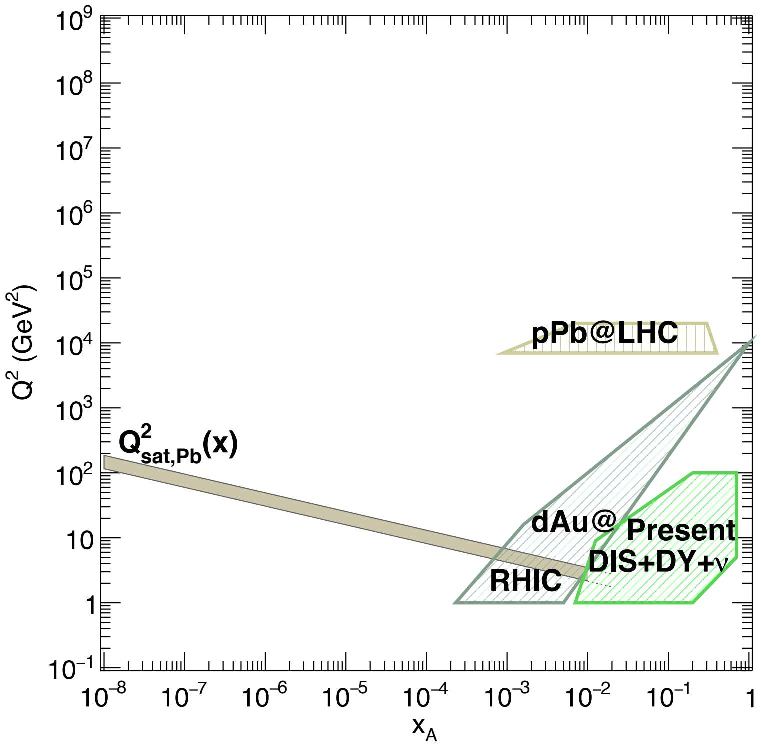
The improvement after adding the LHeC pseudodata at Q^2 = 10 GeV^2



Nuclear PDFs: what we can learn in an ep/eA collider

At an ep/eA collider:

- DIS theoretically much cleaner
- PDF of a single nucleus possible, no need of ratios as for pA
- Same method of extraction in both ep and eA



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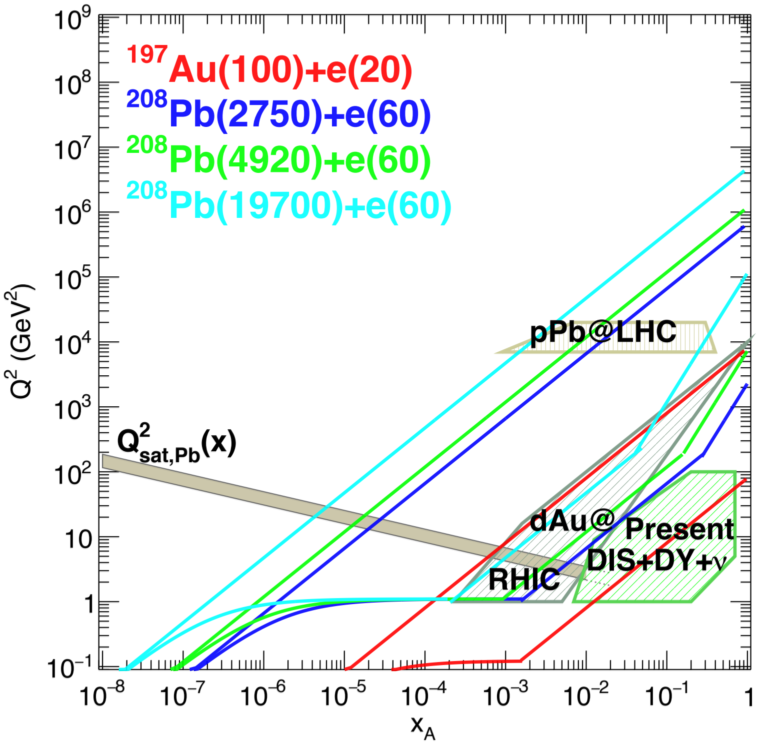
- Four orders of magnitude increase in kinematic range over previous DIS experiments

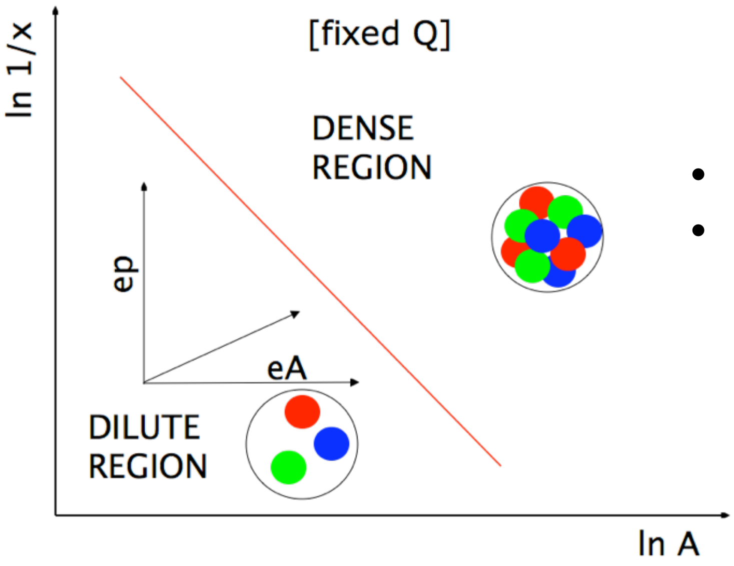
⇒ can change QCD view of the structure of nuclear matter

⇒ physics beyond standard collinear factorization can be studied in a single setup

  - size effects disentangled from energy effects

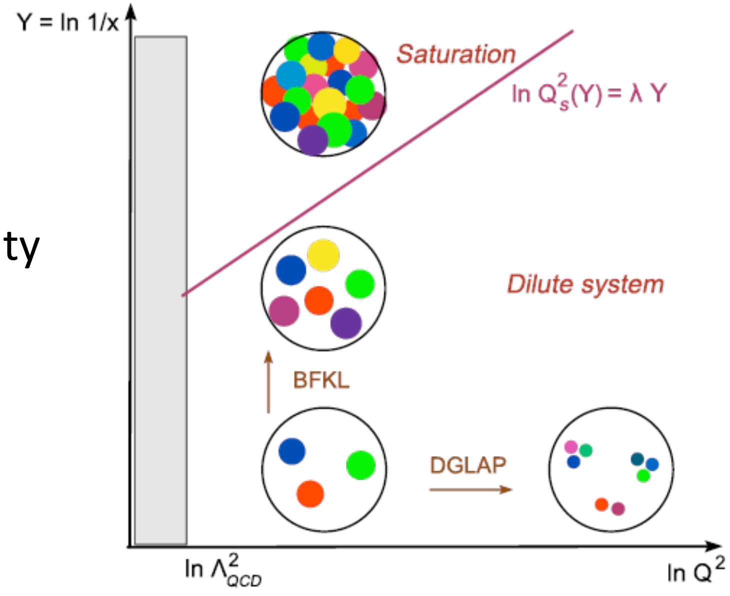


Small x and non-linear dynamics: saturation



Saturation is a density effect:

- small x (high energy)
- increase A or centrality



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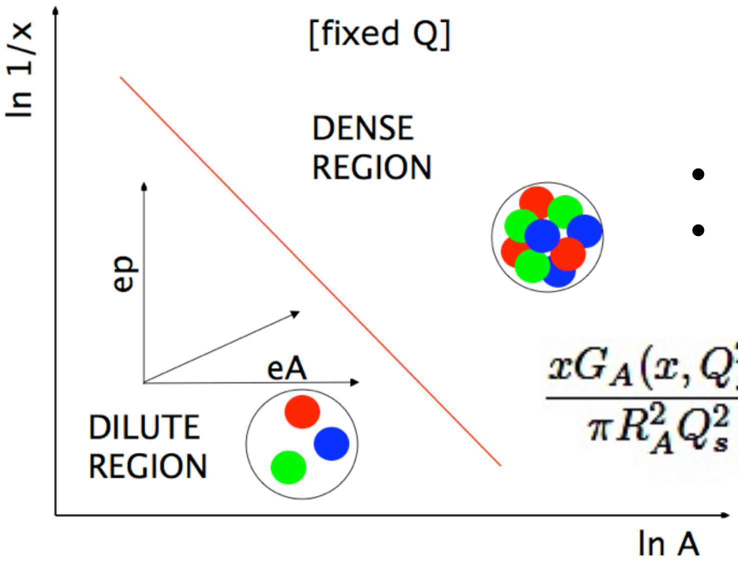

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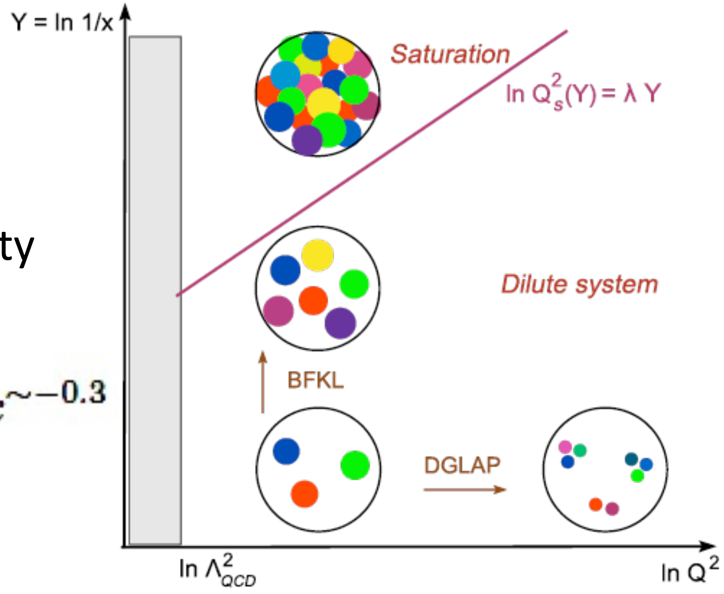
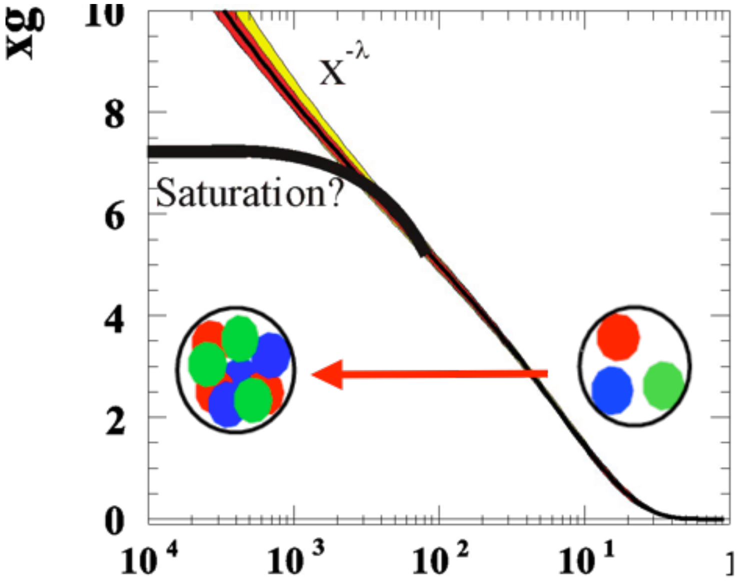


- radiation as x decreases → large number of gluons
- breaks down at high densities → non-linear effects



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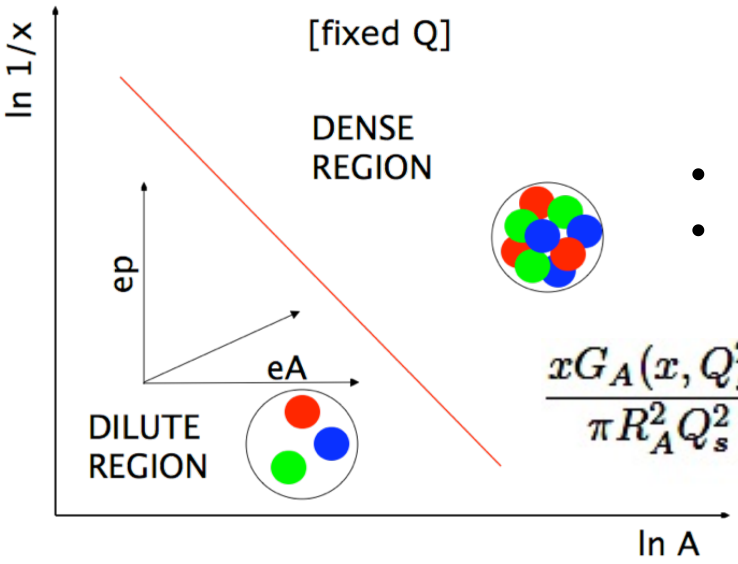

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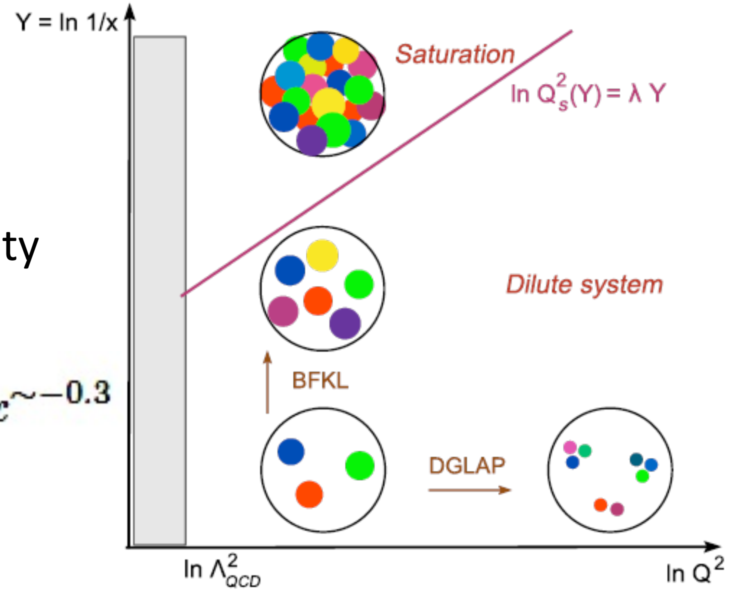

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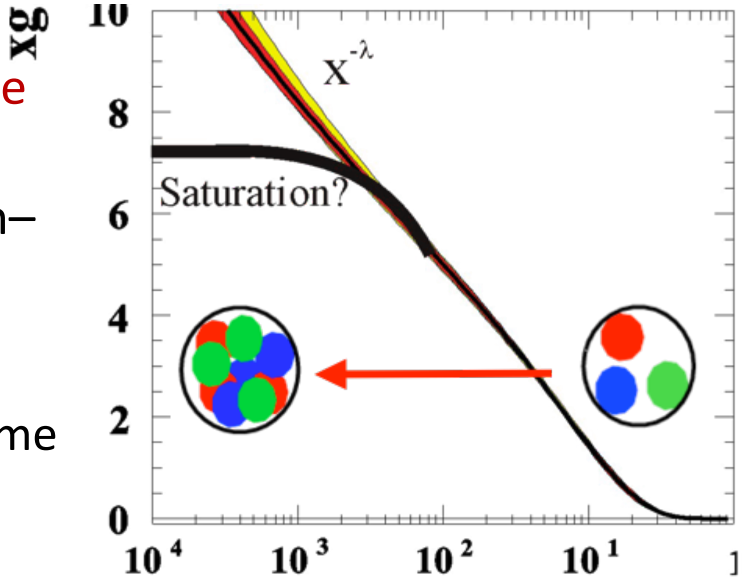
Nuclear matter in this regime: Color Glass Condensate

The CGC -the weak coupling realisation of saturation– provides a framework to compute:

- the hadron/nucleus wave function
- the process of particle production at the collision time
- initial conditions for subsequent evolution



Saturation: what we can learn in an ep/eA collider

- At small x, alternatives to collinear approaches exist, some of them breaking collinear factorisation or including non-linear dynamics
- Determining the dynamics at small x has been a major subject at HERA, and RHIC and the LHC both in pp, pA and AA
- Non-linear resummation techniques (weak coupling but nonperturbative CGC) better for dilute-dense systems: pA, eA

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- One would expect naively that suppression effects are larger when going from p to A in saturation than in collinear approaches

- Not necessarily: nuclear unitarization effect can be smaller for an already unitarized proton input
  => saturation due to the increase of density when going from p to A could be smaller for an already saturated proton input

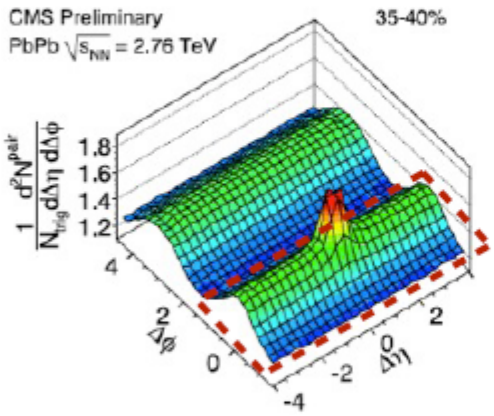
ep and eA essential

Early stages: Collectivity in small systems? The ridge

The ridge: 2-particle long range correlation elongated in η and collimated in azimuth

In AA attributed to final state interactions described by hydro: signal of equilibration

Pb-Pb



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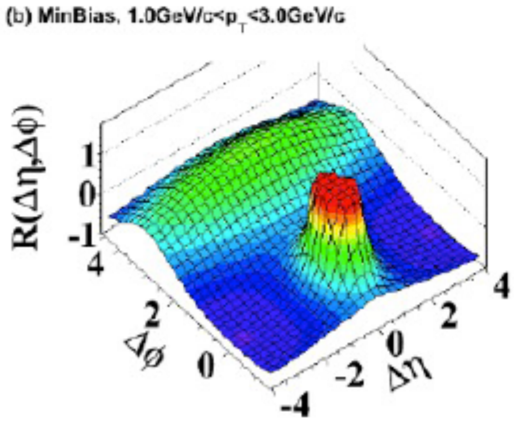
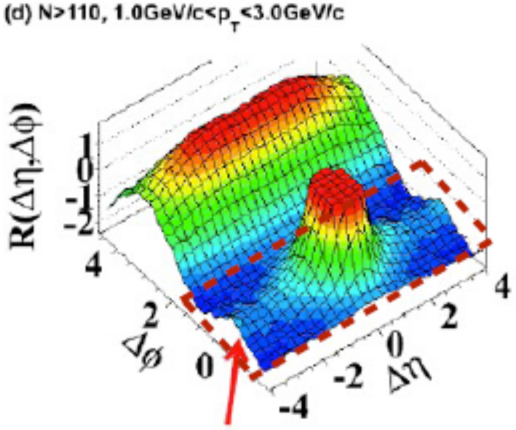
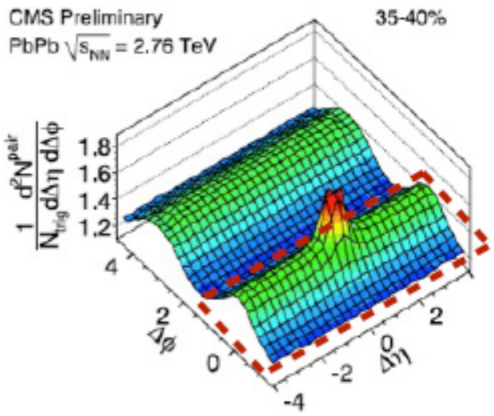
Also observed in high mult. p+Pb & p+p @LHC


p-p min. bias


p-Pb and p-p Nch>110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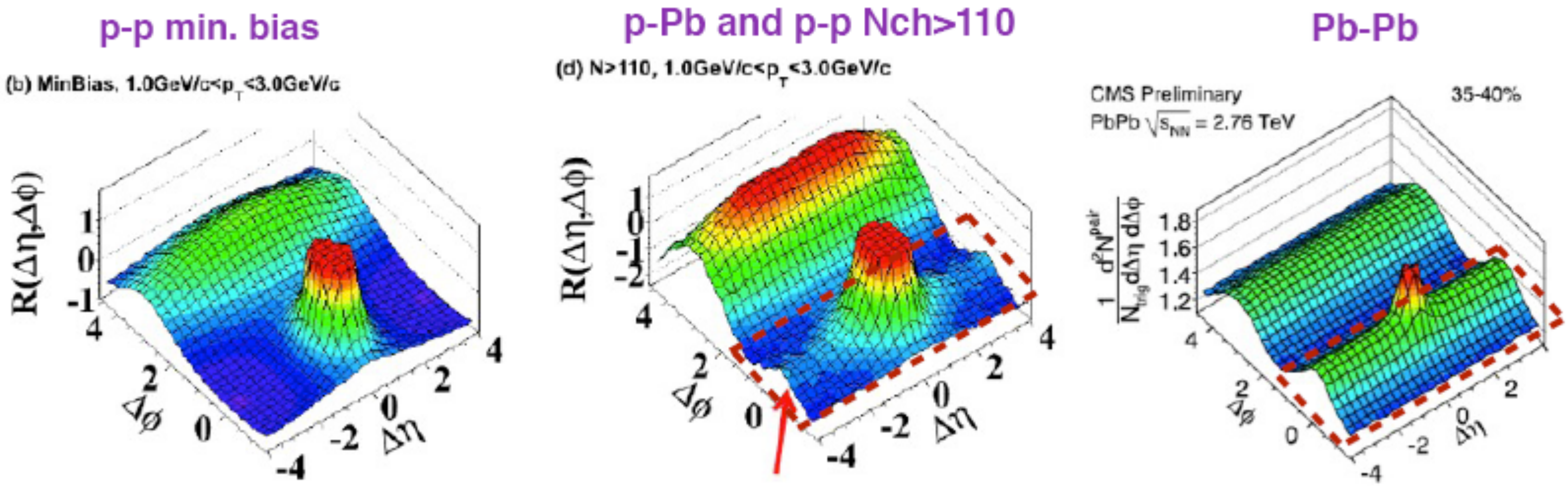

Different theoretical models of the ridge: hydrodynamic flows, local hot spots, initial-state fluctuations, parton cascades, glasma flux tubes, glasma turbulence fields, the momentum kick model, pQCD modeling, etc.

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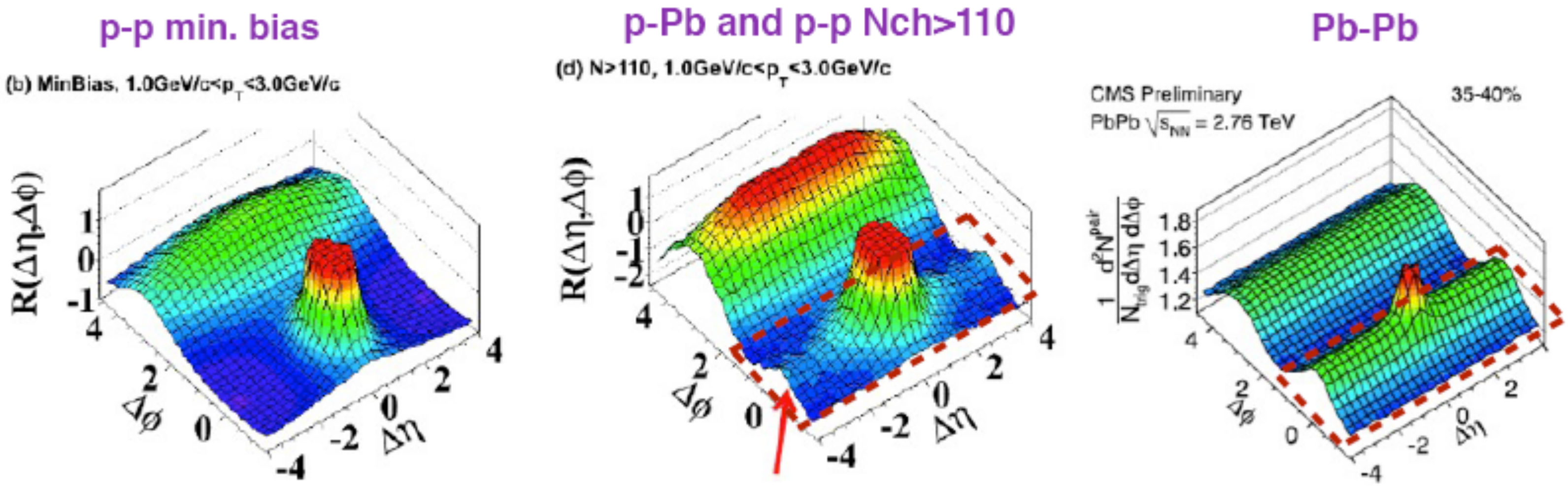
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Two lines of explanations:

Initial state effect

➜ CGC: assuming that the final state carry the imprint of initial-state correlations

Medium effect

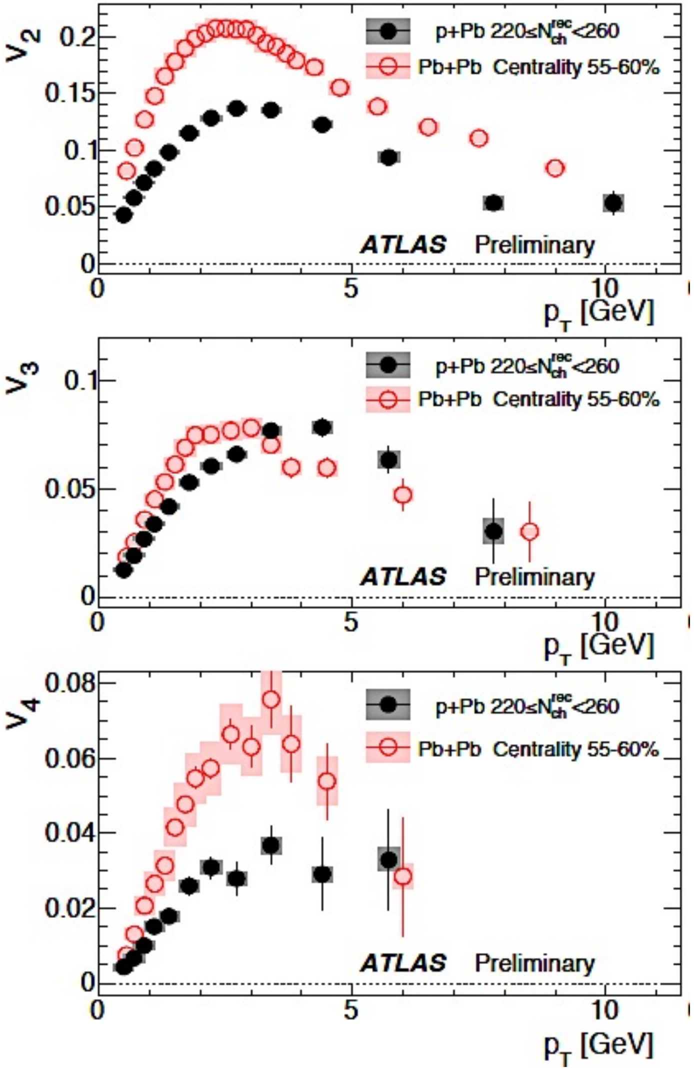
➜ Coupling to a flowing medium: hydrodynamics at work already on pPb@LHC

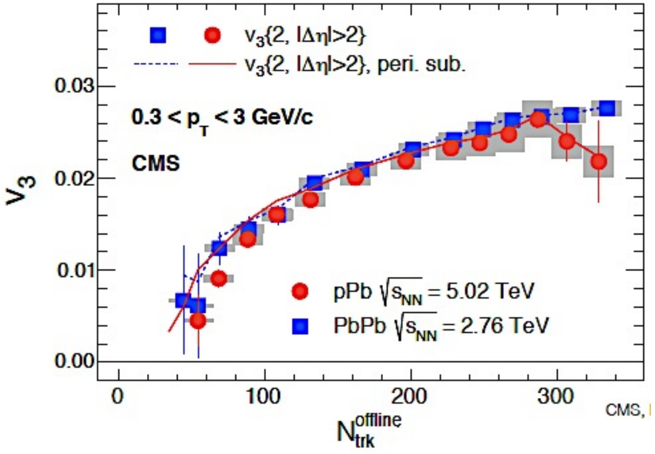
What about IC?

Early stages: Collectivity in small systems? The flow

The experimental data was surprising:

- Similarity of experimental data in pA and AA collisions





Hydro works well in AA

Hydro also works well in pA

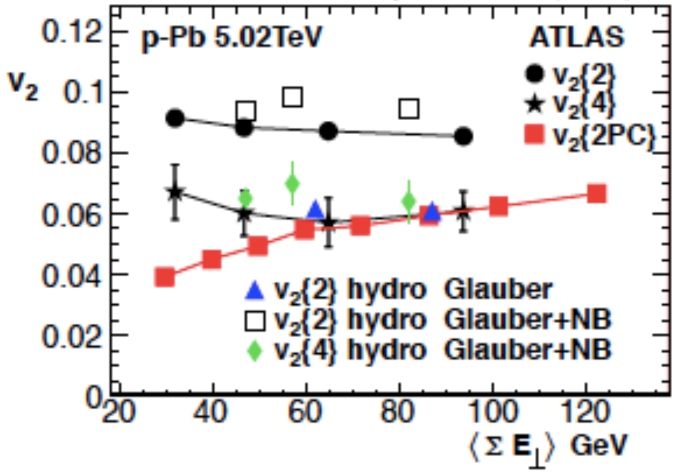
Some issues:

- Very sensitive to the initial state
- Applicability of hydrodynamics is questionable

Early stages: Collectivity in small systems?

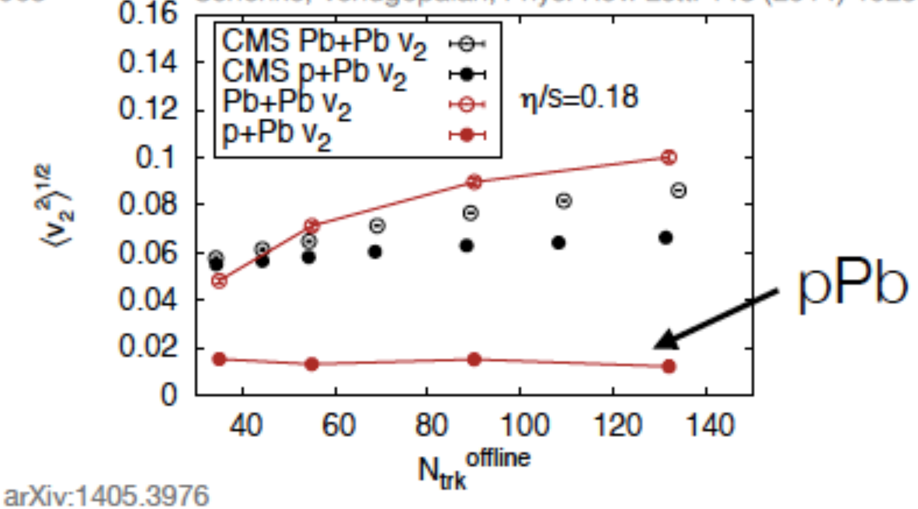
Different initial states: very different results

Bozek, Broniowski, Phys.Rev. C88 (2013) 014903

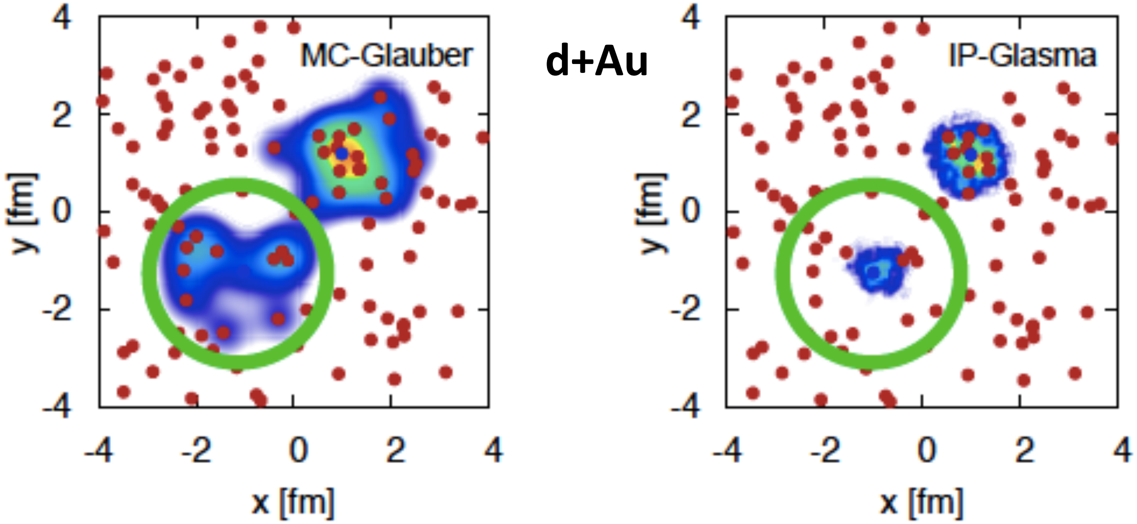


see also: Kozlov, Luzum, Denicol, Jeon, Gale, arXiv:1405.3976

Schenke, Venugopalan, Phys. Rev. Lett. 113 (2014) 10230



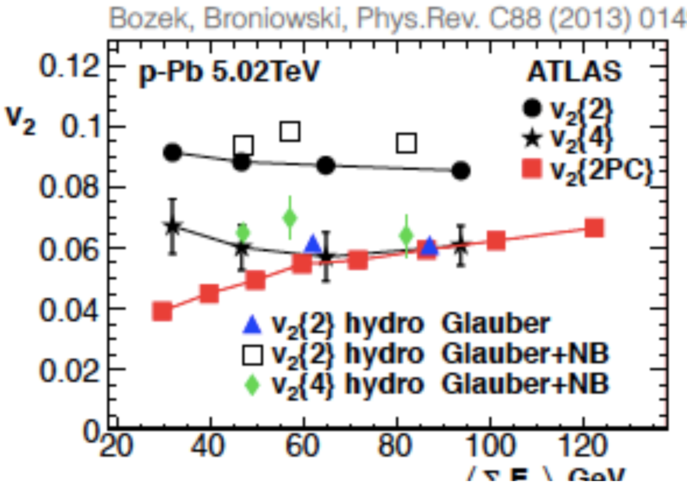
MC-Glauber does not constrain energy density dististribution



IP-Glasma constrains energy density deposition. However, it does not describe v_n in p+Pb

Early stages: Collectivity in small systems? The flow

Different initial states: very different results



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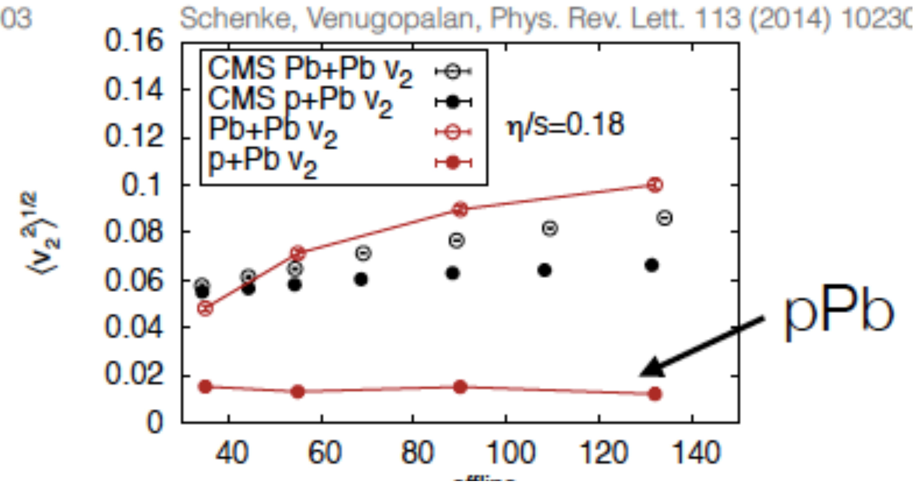
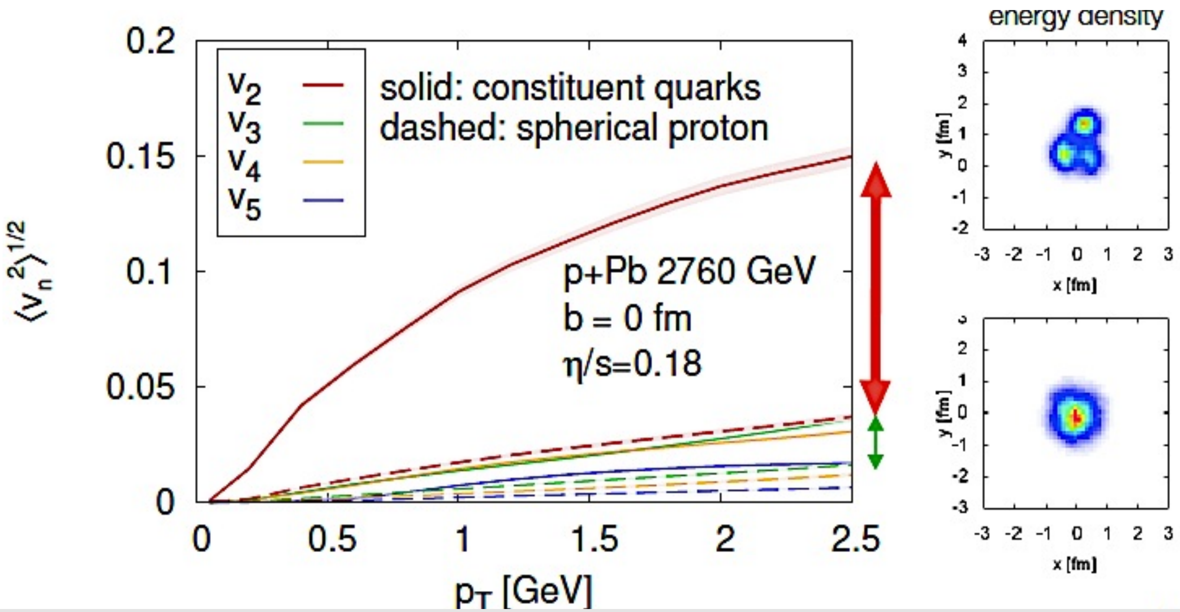


Schenke, Venugopalan, Phys. Rev. Lett. 113 (2014) 10230

Proton substructure can matter (effects of the fluctuating shape of the proton)



Early stages: what we can learn in an ep/eA collider

The success of hydro for small systems:

- Signal of equilibration or non-equilibrium evolution of a partonic system in QCD?

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- this naturally explain why pp data on azimuthal correlations appears to be so similar to data obtained in nucleus-nucleus collisions
- hydrodynamics will generically convert initial state geometry and fluctuations into correlations, thus making large and small systems look alike
- pushing this idea even further would imply that any lump of sufficiently high energy density could expand according to the laws of hydrodynamics
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The ideal place to further investigate this:
smaller systems ep and eA, that are in any case required for the initial conditions

Partonic evolution and hadronization

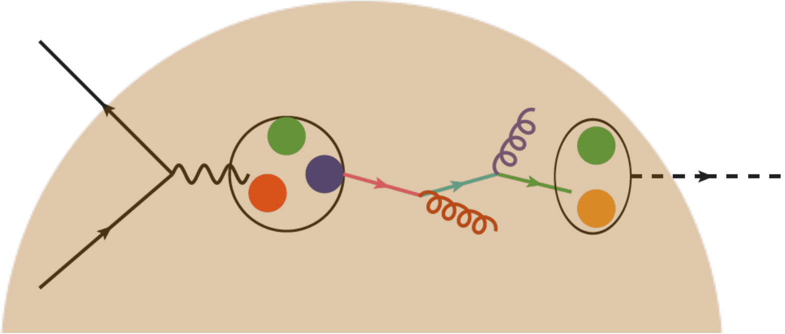
Relevant for particle production and QGP analysis in HIC:

jets plentiful in eA
benchmark for jet quenching studies in AA

Low energy:

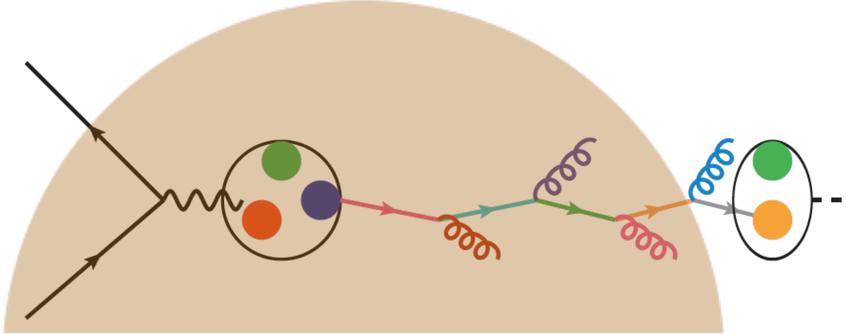
hadronization in matter

- (pre)hadronic absorption
- formation time

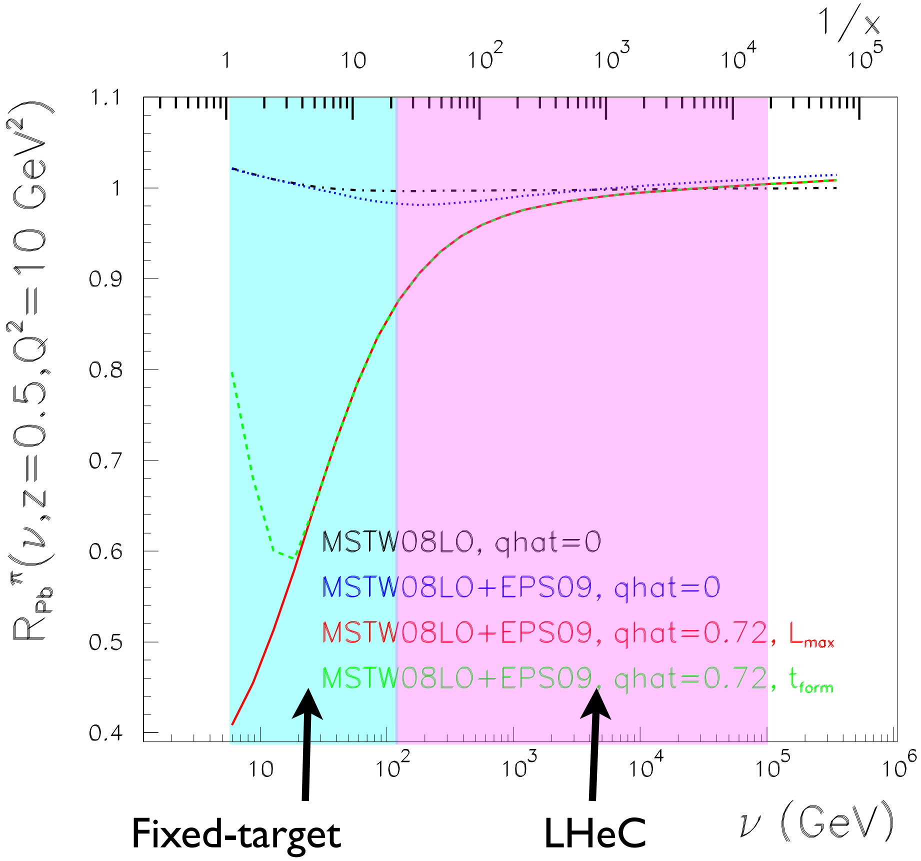


High energy:

- modification of partonic evolution



Ratio of fragmentation functions Pb/p



Fixed-target

LHeC

Other possible studies: quarkonium production

Production mechanism and polarization:

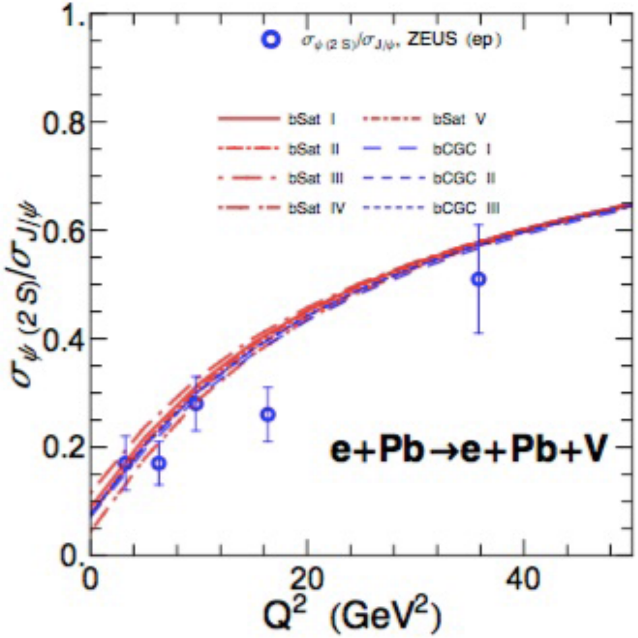
polarized J/ψ photoproduction can be studied more precisely and up to much larger values of p_T in ep @ LHeC

⇒ test NRQCD factorization in charmonium physics

Butenschoen Kniehl

Charmonium WF in diffractive DIS within the dipole formalism

Cheng et al.



Spatial and Momentum Tomography of Hadrons and Nuclei

Gluon TMDs could be directly probed by looking at p_T distributions and azimuthal asymmetries in $e\,p \rightarrow e\,Q\,\bar{Q}\,X$

Boer, Lansberg, Pisano

Gluon GPDs

Y production at an EIC to determine the gluon density transverse spatial profiles in a wide range of x and consequently provide a path to determine the gluonic radius of the nucleon and the contribution of the total angular momentum of gluons to the nucleon spin

Joosten and Meziani

Conclusions

ep & eA collisions at high energy offer huge possibilities:

To provide information about QCD first principles:

- Partonic structure
- New regimes of QCD
- 3D structure of hadrons and nuclei
- The role of gluons in structure and dynamics
- Dynamics of QCD radiation and hadronization
- Confinement: understand the emergence of hadrons from color charge

To clarify aspects of pp, pA and AA collisions at high energy:

- Initial conditions for macroscopic descriptions
- Nature of collectivity
- Thermalization
- Extraction of parameters of the medium
- Distinguish "genuine" QGP effects
- …