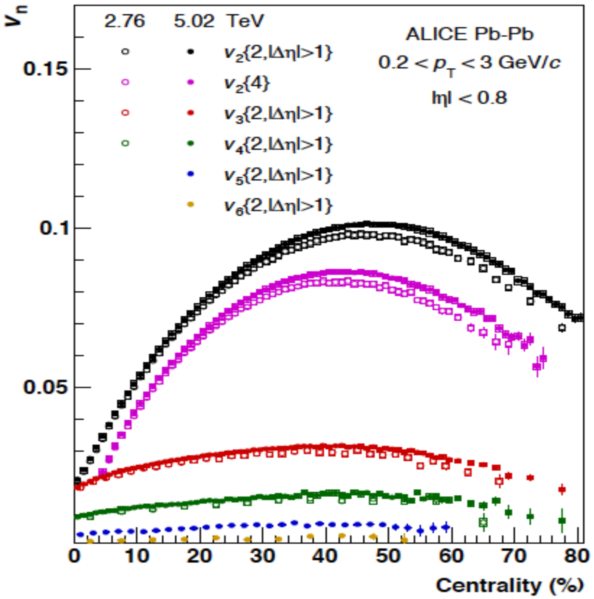
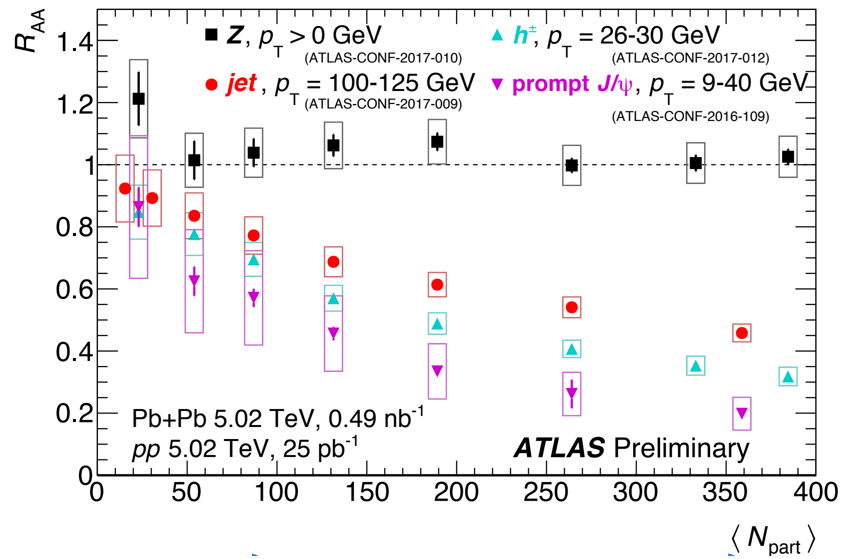
Nuclear matter effects in the Electron Ion Collider:
How can heavy-ion physics profit from eA measurements

Elena G. Ferreiro

IGFAE, Universidade de Santiago de Compostela, Spain

Status of Heavy Ions





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

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

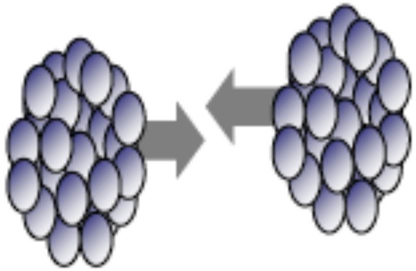
Current status: matter created in **AA** at RHIC and LHC, with energy densities larger than those expected in lattice QCD for deconfinement=>QGP

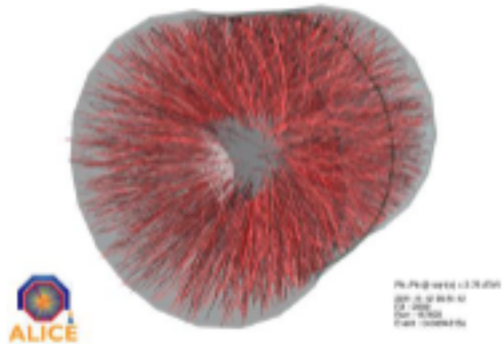
- collective features in the soft sector
- well described by relativistic hydrodynamics if applied very early ($\lesssim$ 1 fm/c) after the collision
- equilibration?

- 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)

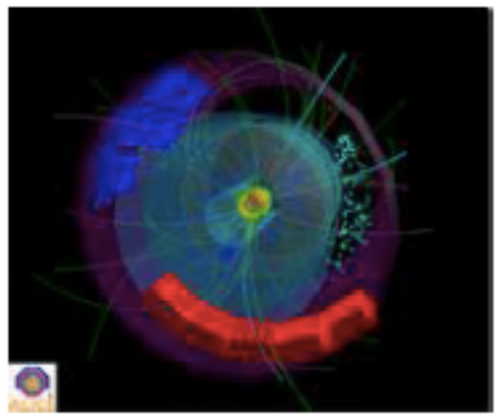
Pb-Pb





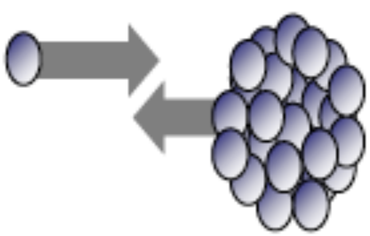
Hot QCD matter:
This is where we expect the QGP to be created in central collisions

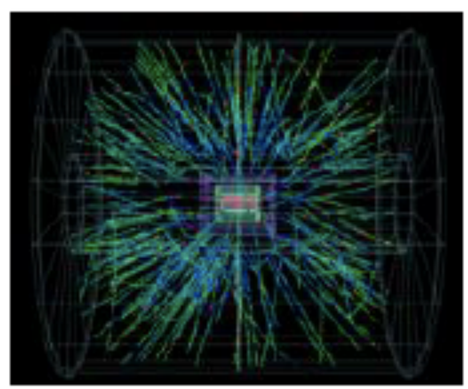
pp



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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Two serious contenders remain today:

- 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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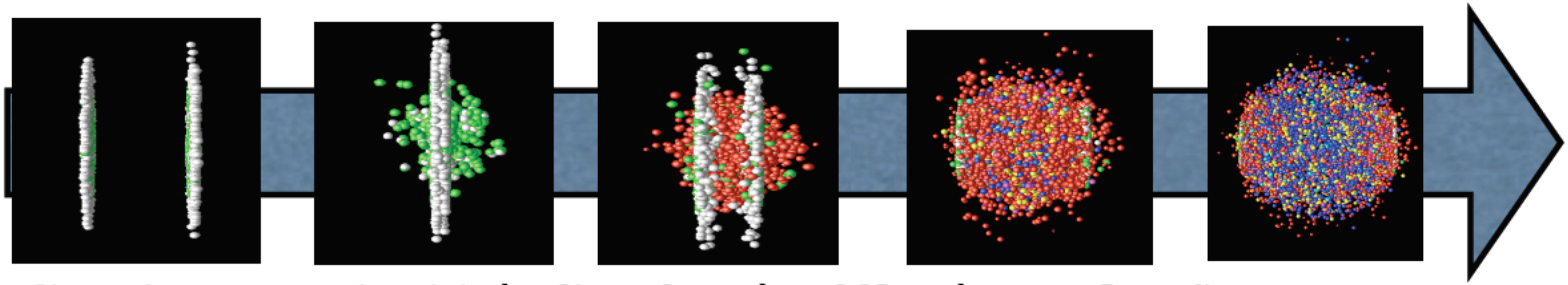

Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

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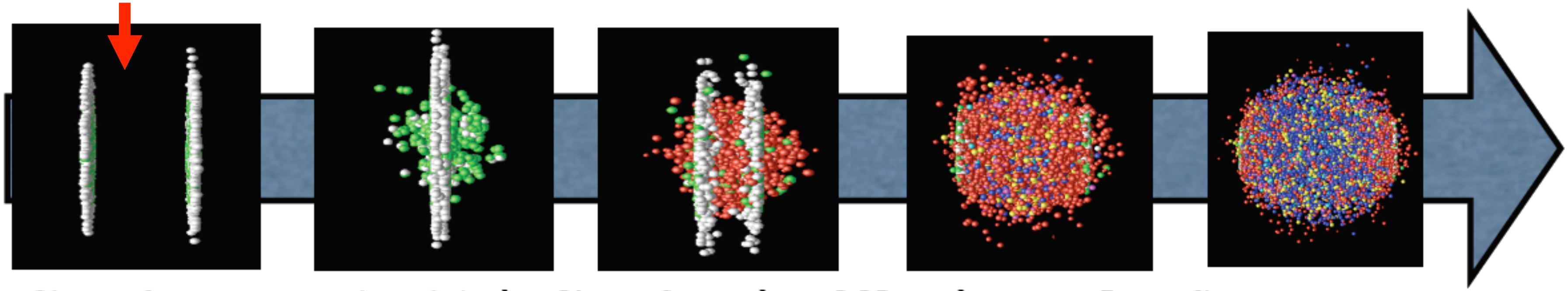

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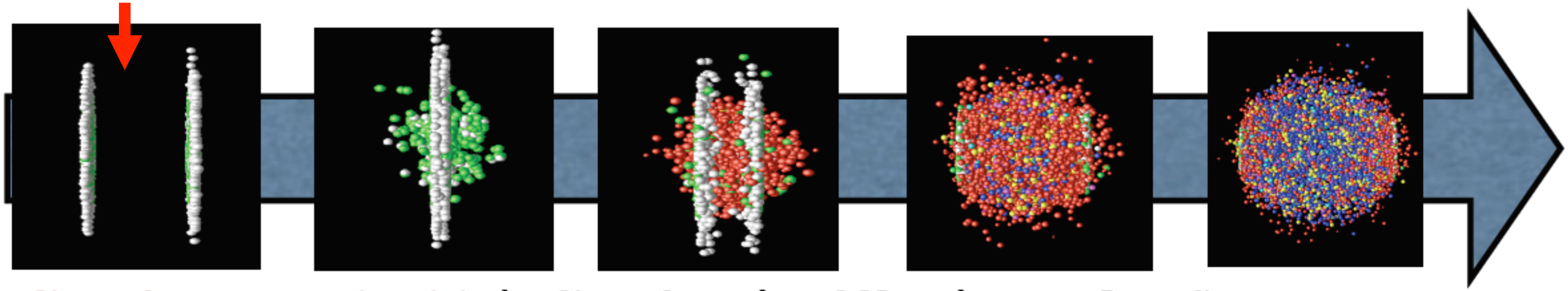

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- correlations
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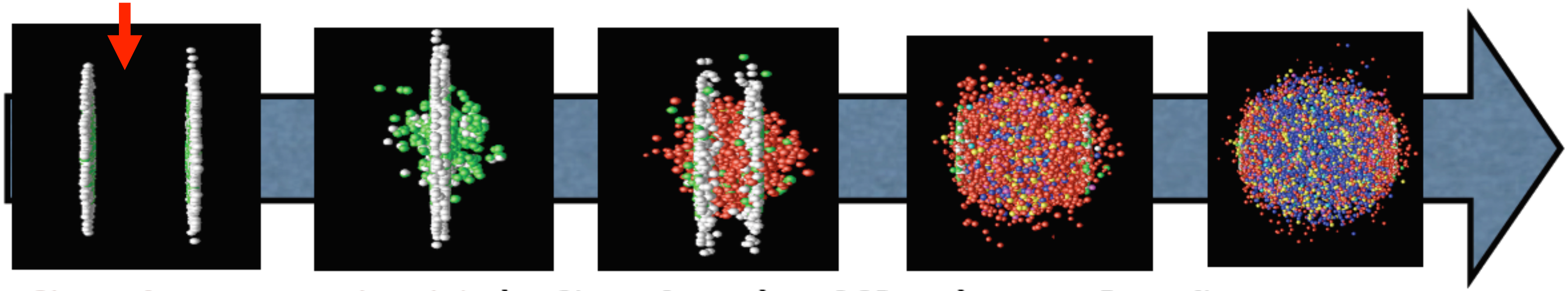

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- mechanism of particle production
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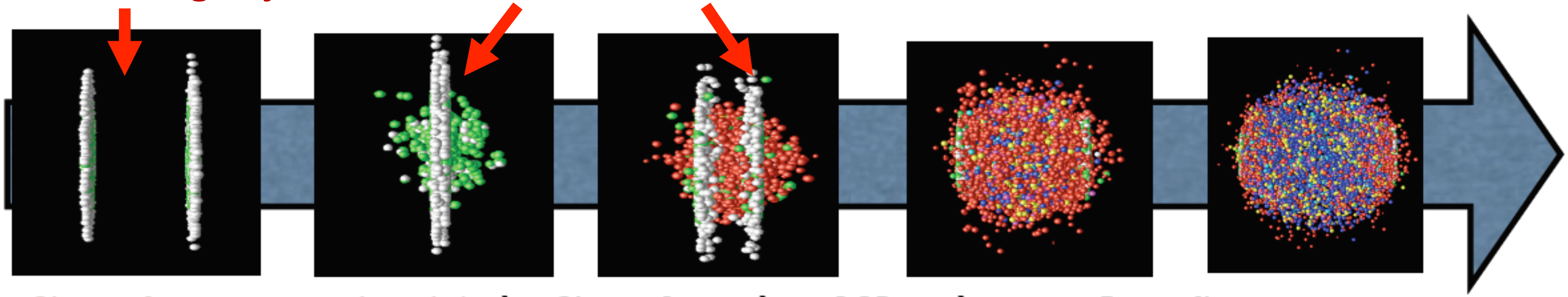

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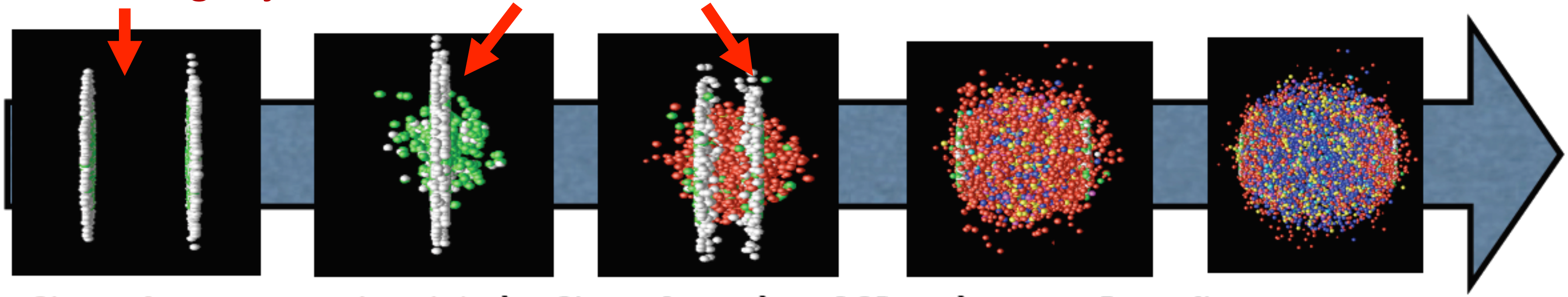

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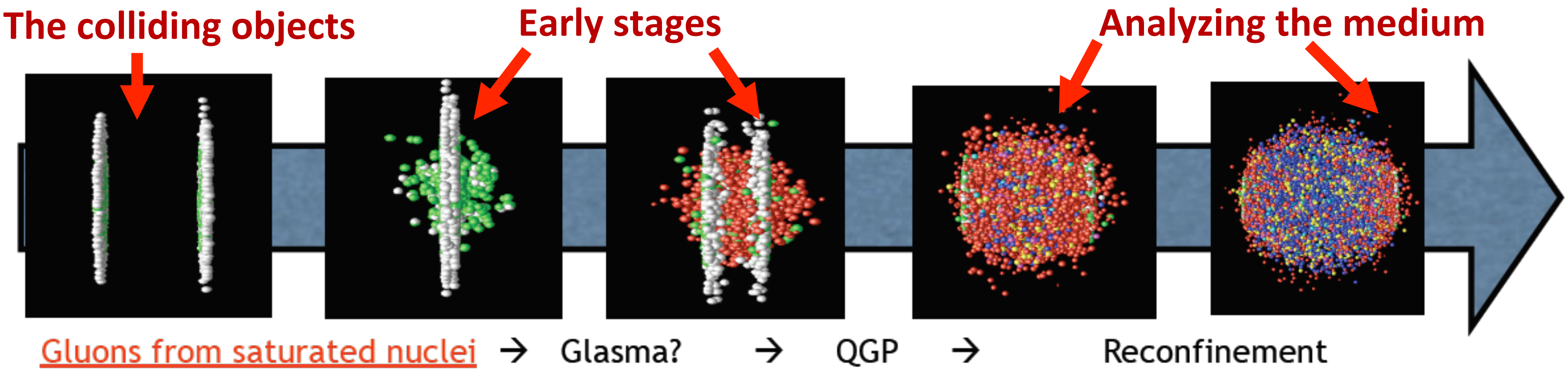

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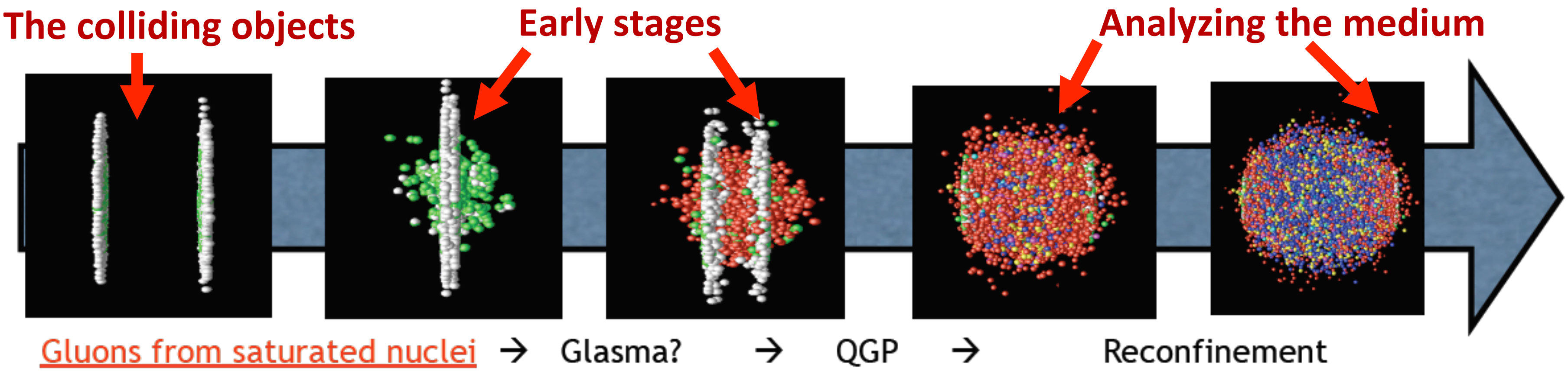

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- Dynamical mechanisms for opacity
- How to extract accurately medium parameters?

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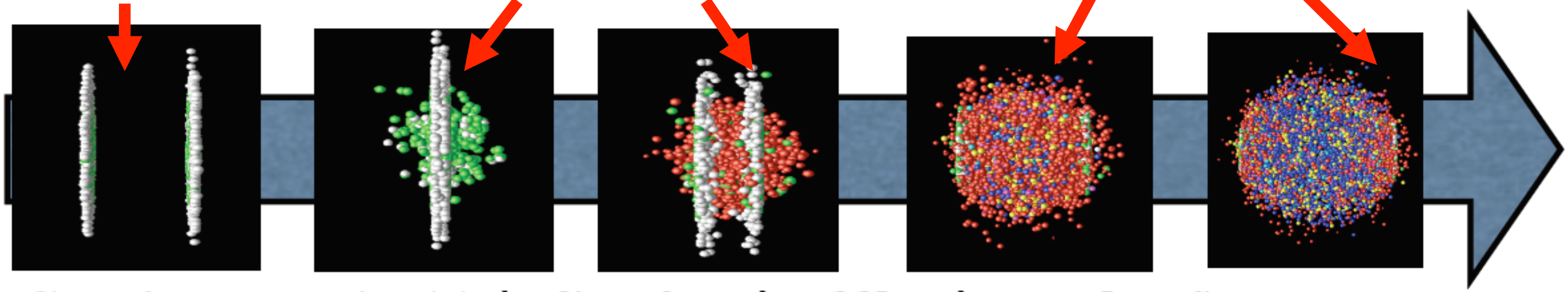

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ep and eA:
- modification of radiation and hadronization in the nuclear medium
- initial effects on hard probes

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

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

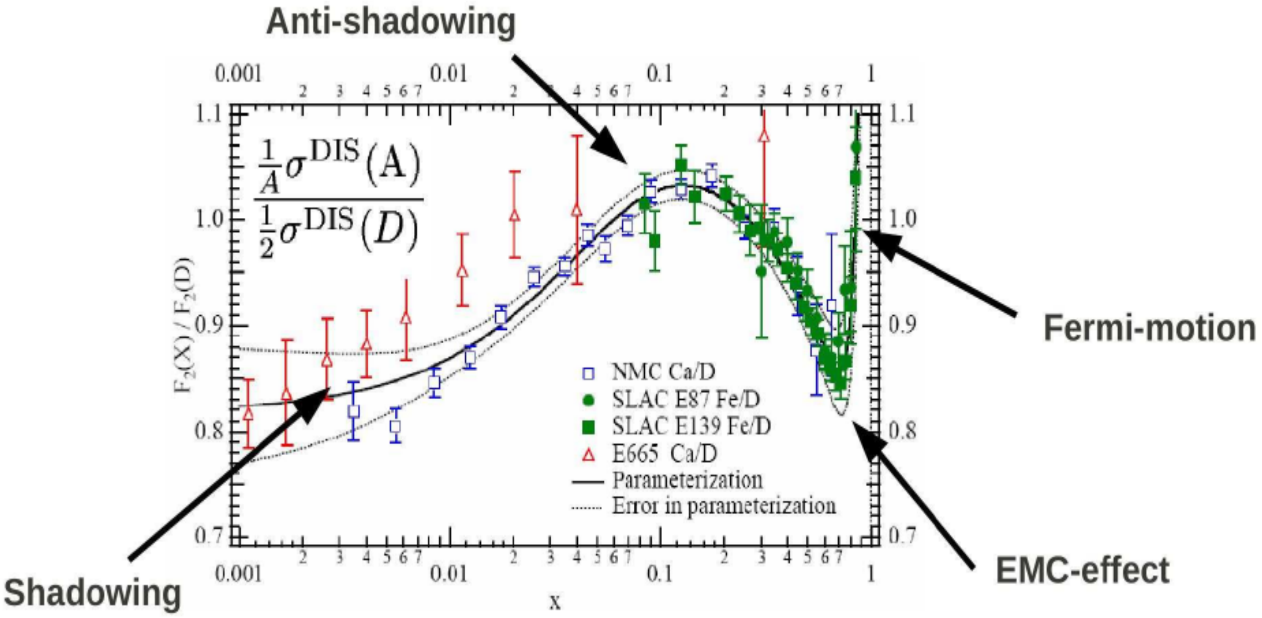
- If nuclear effects at play $R_i^A(x,Q^2) \neq 1$

$$\sigma_{\rm DIS}^{\ell+A\to\ell+X} = \sum_{i=q,\bar{q},g} f_i^A(\mu^2) \otimes \hat{\sigma}_{\rm DIS}^{\ell+i\to\ell+X}(\mu^2)$$

Nuclear PDFs, obeying the standard DGLAP

Usual perturbative coefficient functions

assuming collinear factorization



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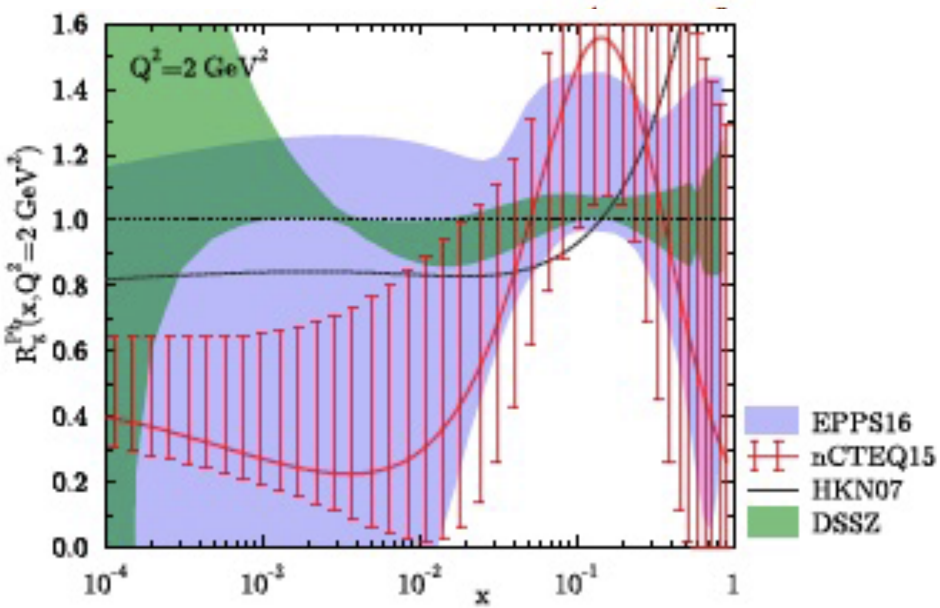

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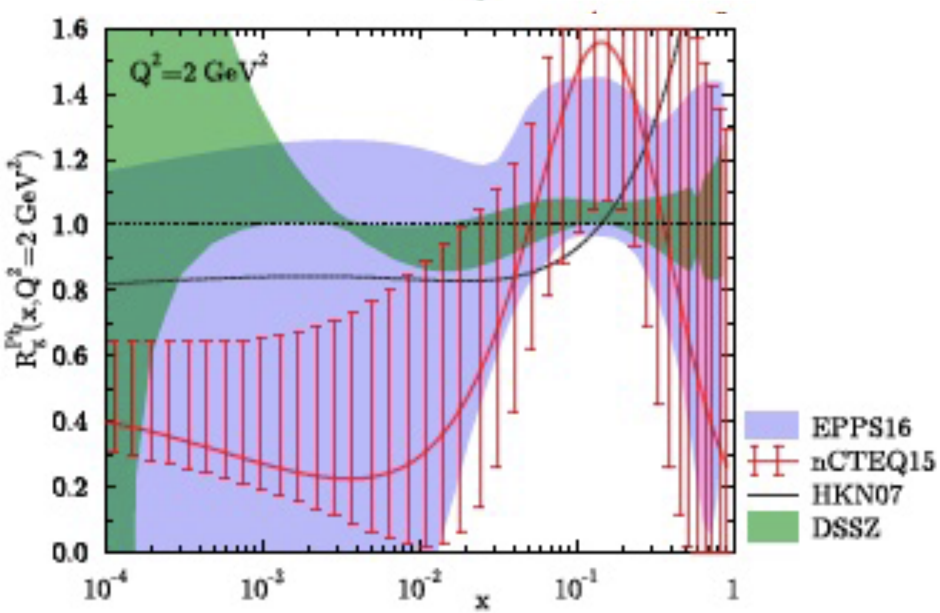

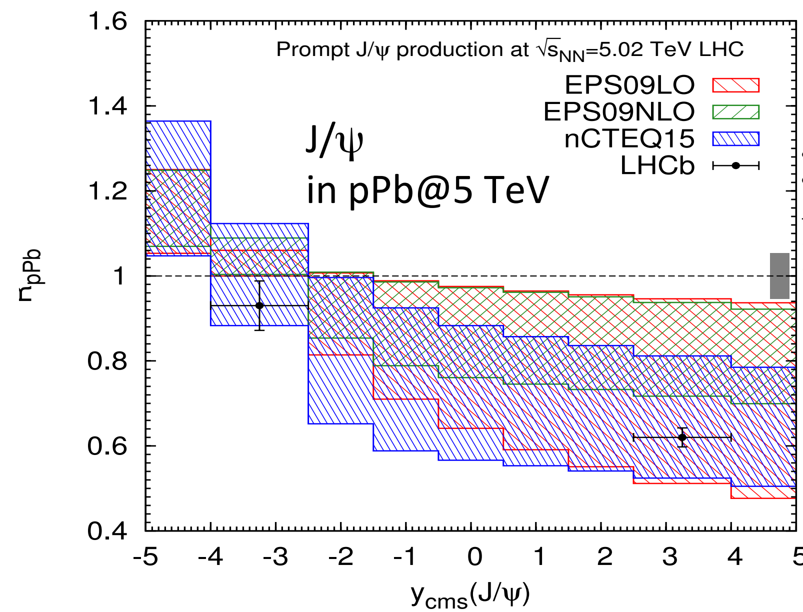

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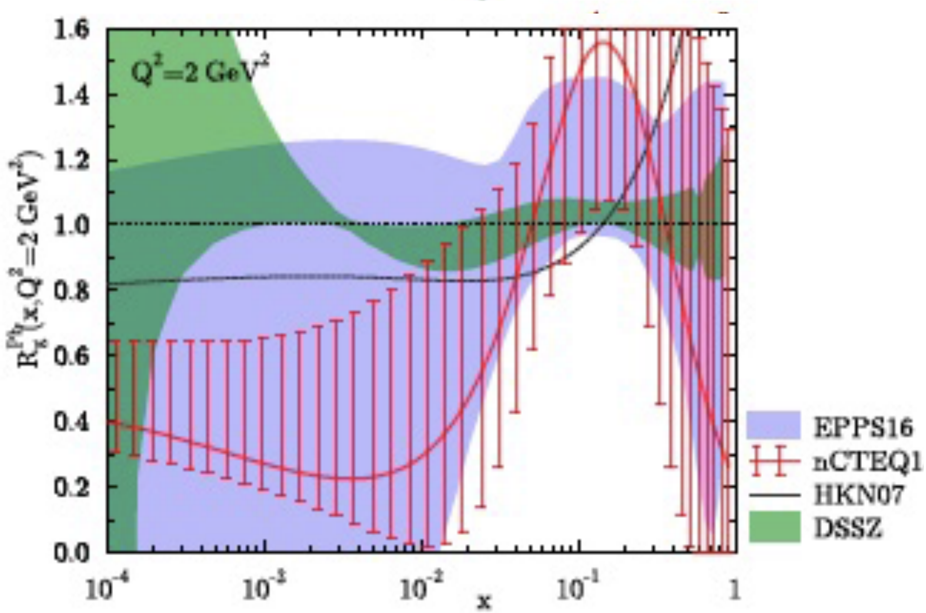

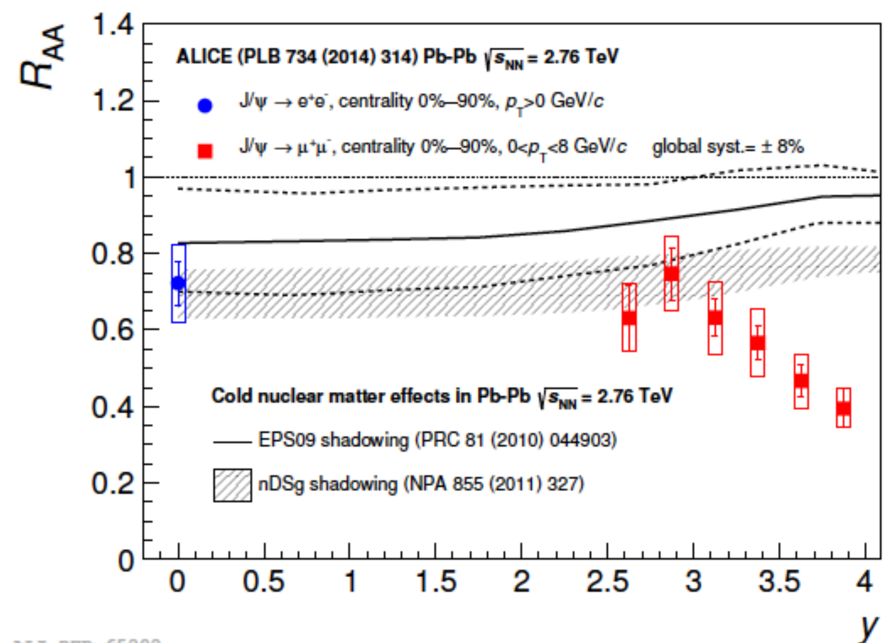

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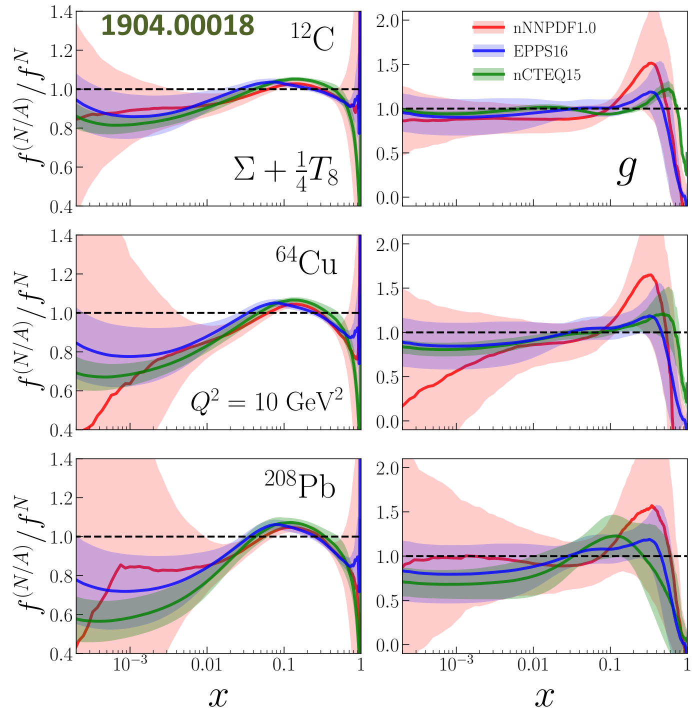
nPDFs status

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

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	✔	✔	✔	✔	✔	✘
	π⁰	✔	✔	✔	✘	✔	✘
	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 π⁰	$\Delta\chi^2$=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

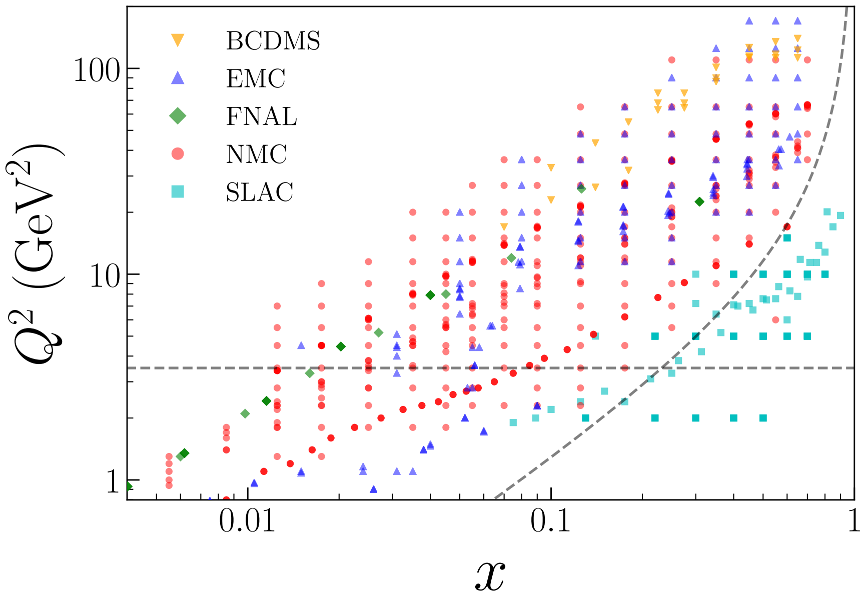


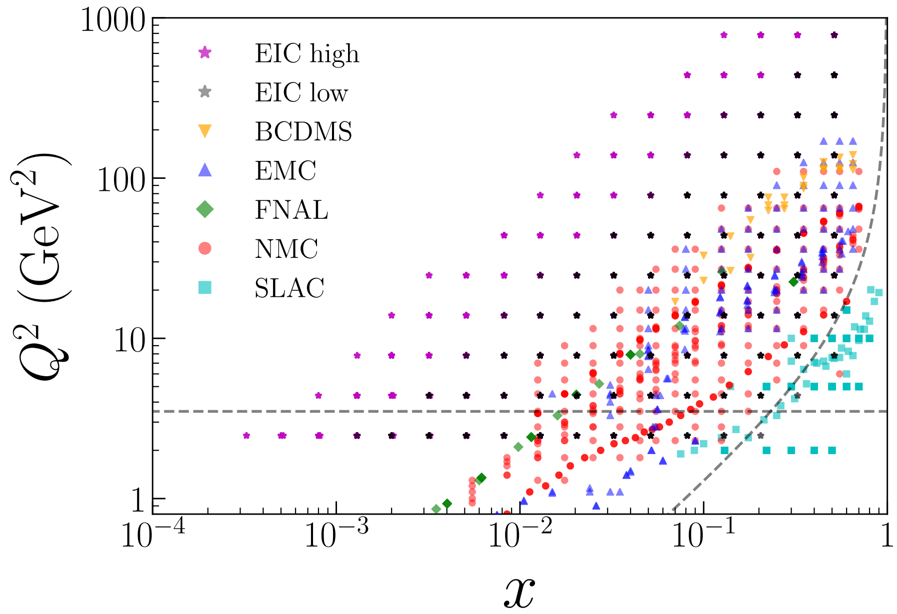
- Without additional experimental input, we are rather far from being able to probe in detail the nuclear modications of the quark and gluon PDFs
- Large uncertainties for x<0.01 and for large x glue
- Small impact of LHC data

nPDFs: 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





Impact of EIC pseudodata on nPDFs

The direct observable used for constraining the nPDF is the red. cross section σ_r expressed in terms of the structure function F_2 and F_L → gluons

- Old fixed-target DIS experiments: σ_r dominated by F_2
- EIC high luminosity and wide kinematic reach will enable the direct extraction of F_L => more information on the behaviour of the nuclear gluons
- EIC will offer possibilities to measure the charm (bottom) structure function => complementary information on the gluon distribution in nuclei

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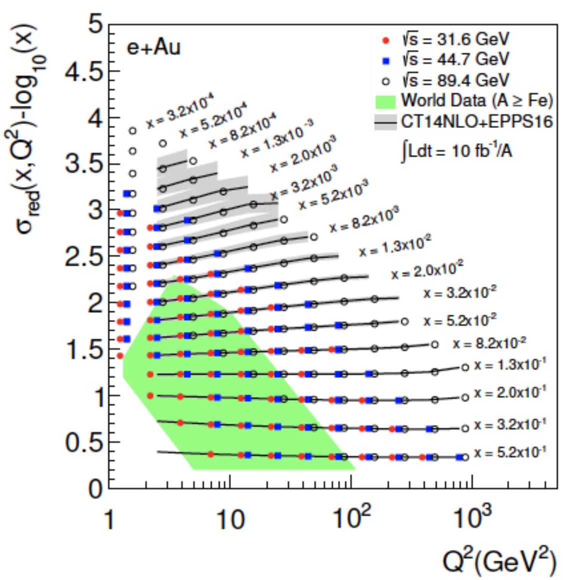

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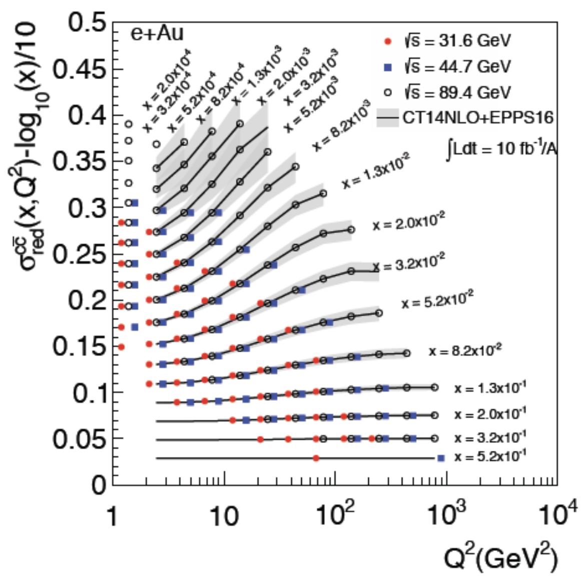
- Pseudodata generated with PYTHIA+EPS09
- Uncertainties as achieved at HERA
- Pseudodata included in EPPS16 global fits



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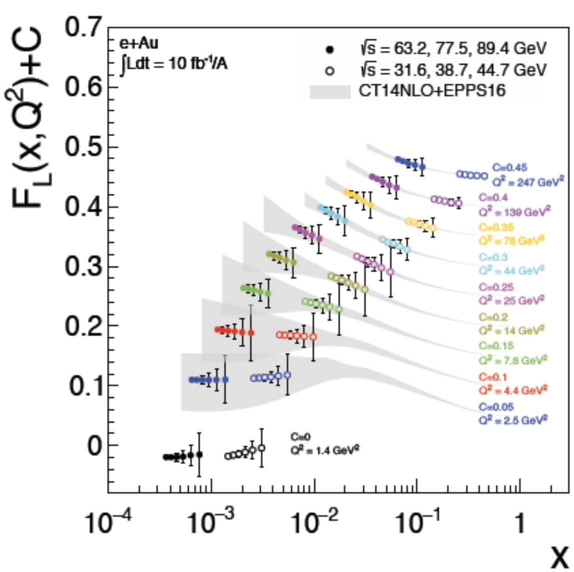

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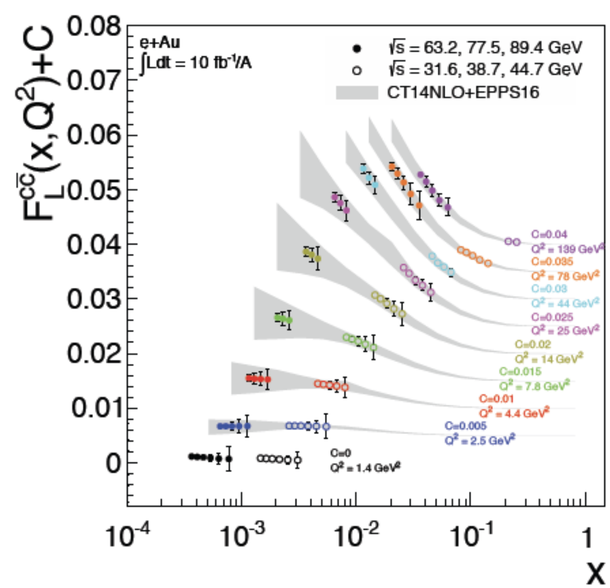
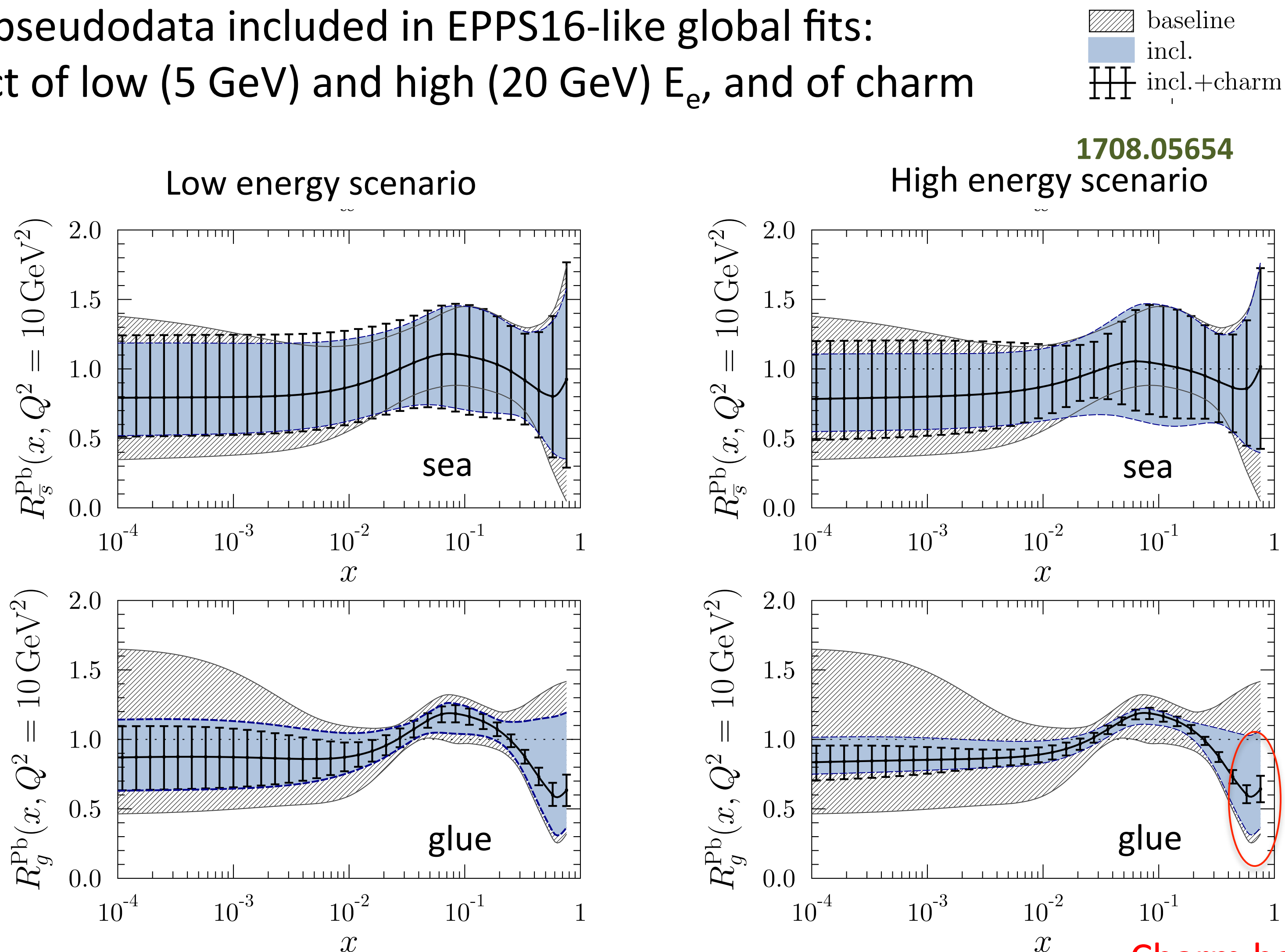


Impact of EIC pseudodata on nPDFs

EIC eAu pseudodata included in EPPS16-like global fits:

- Impact of low (5 GeV) and high (20 GeV) E_e, and of charm



Charm has a large impact for the large x glue

Impact of EIC pseudodata on nPDFs

EIC eC and eAu pseudodata included in nNNPDF-like global fits:

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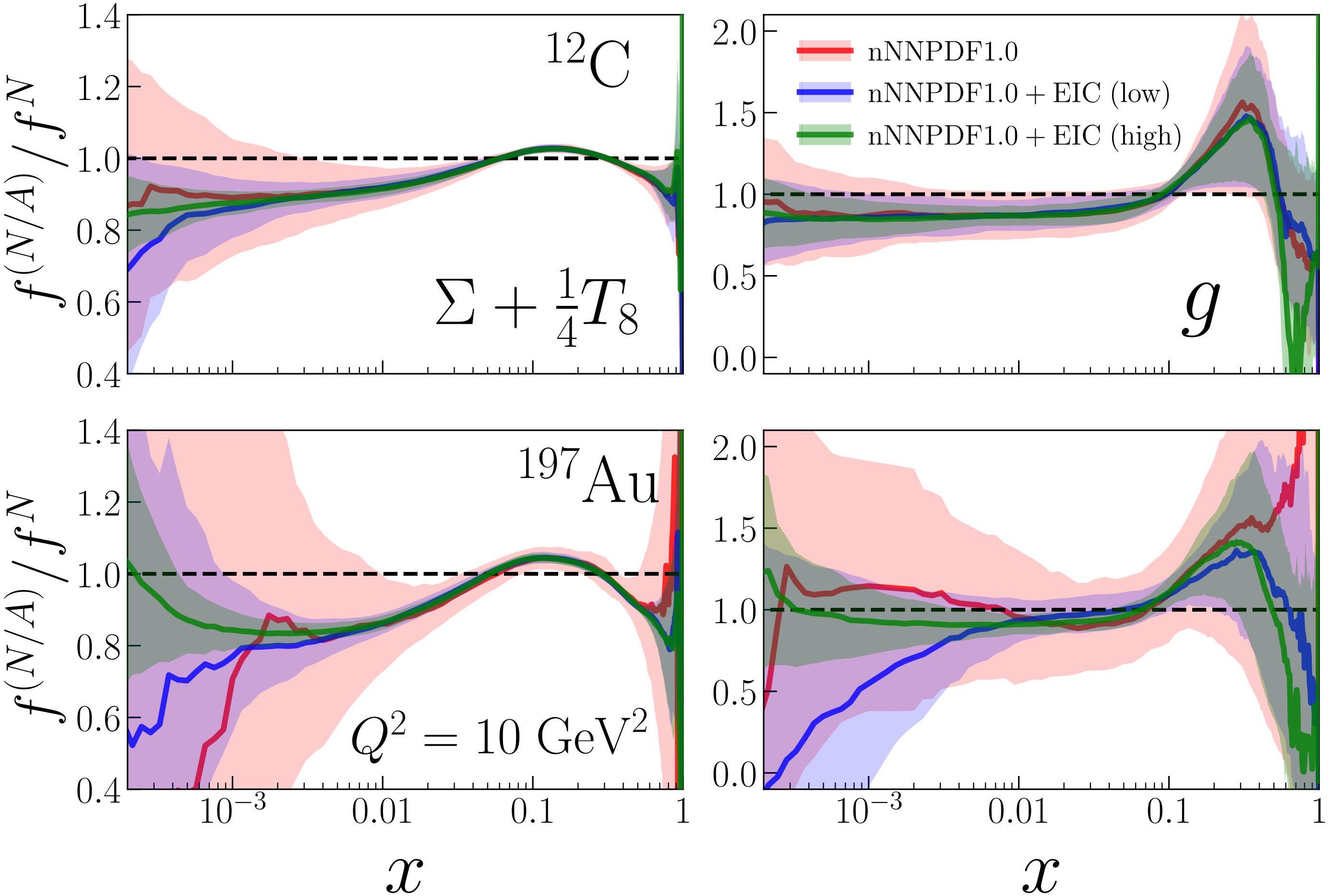
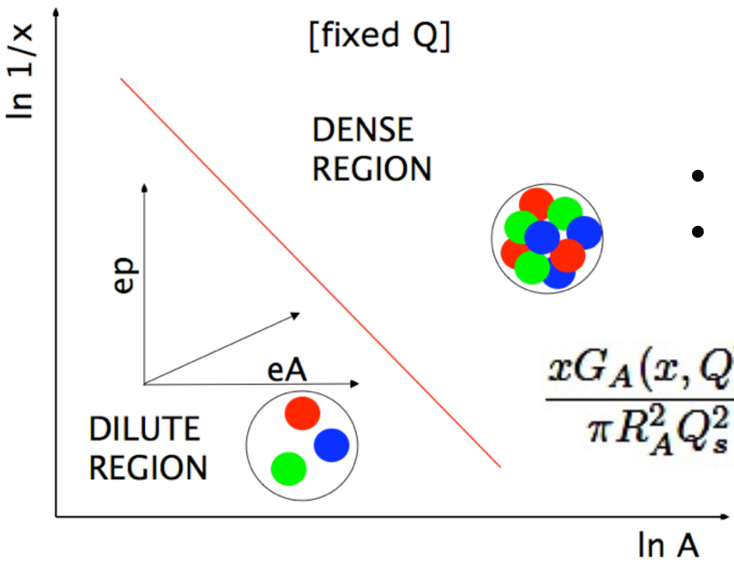


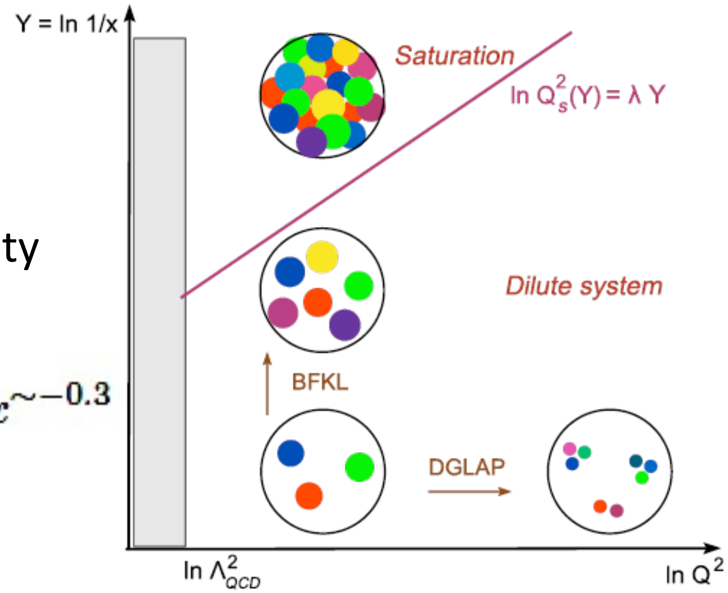
Small x and non-linear dynamics: saturation



Saturation is a density effect:

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

$$\frac{xG_A(x,Q_s^2)}{\pi R_A^2 Q_s^2} \sim 1 \Longrightarrow Q_s^2 \propto A^{1/3} x^{\sim -0.3}$$



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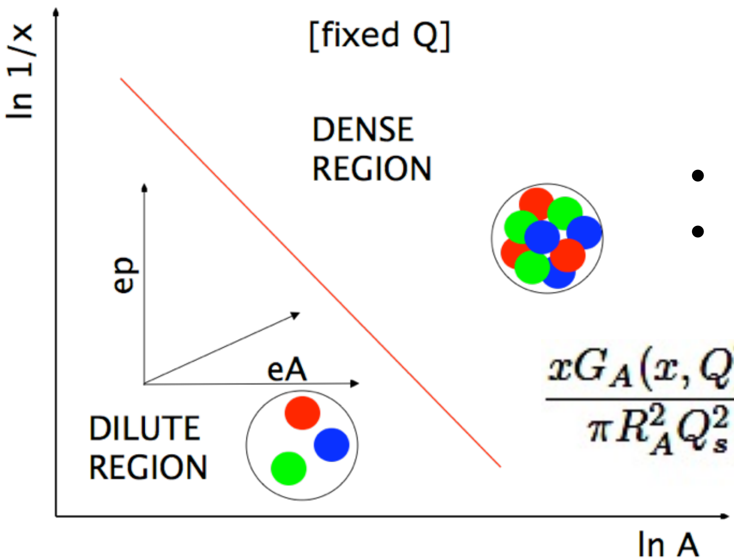

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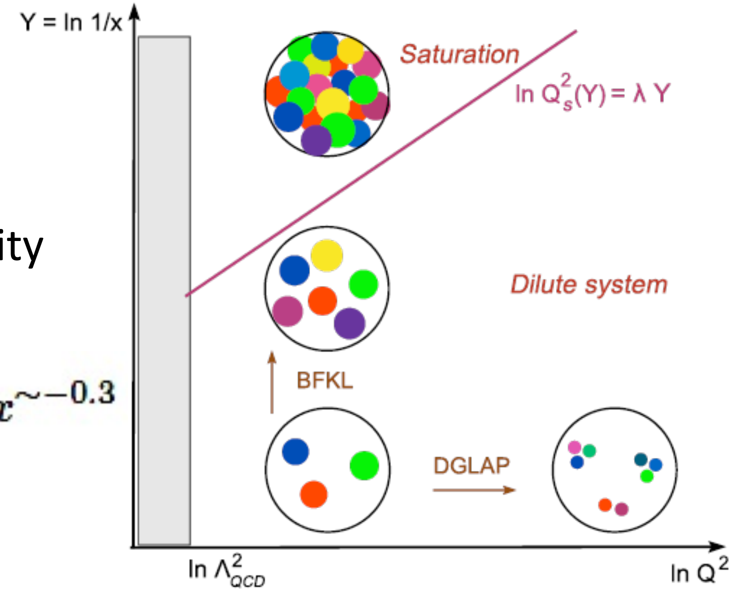
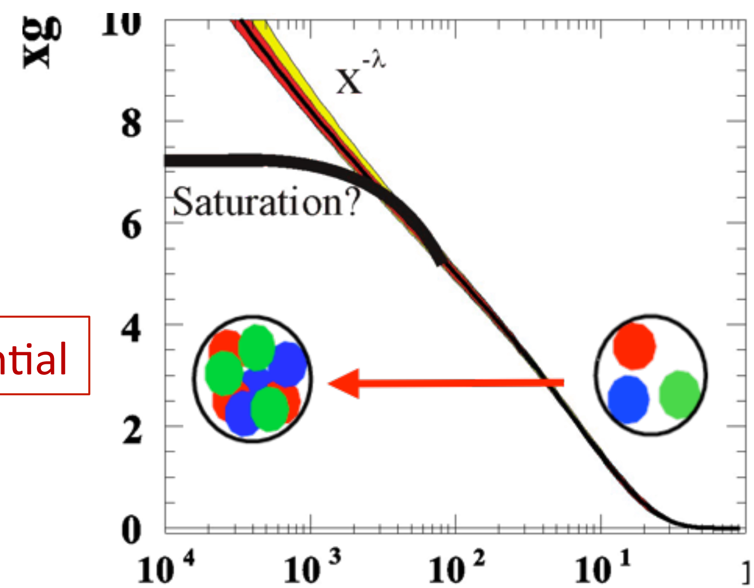


- Radiation as x decreases → large number of gluons
- At small x, alternatives to collinear approaches exist, breaking collinear factorisation including non-linear dynamics
- Determining the dynamics at small x has been a major subject at HERA, and RHIC and the LHC both in pp, pA and AA

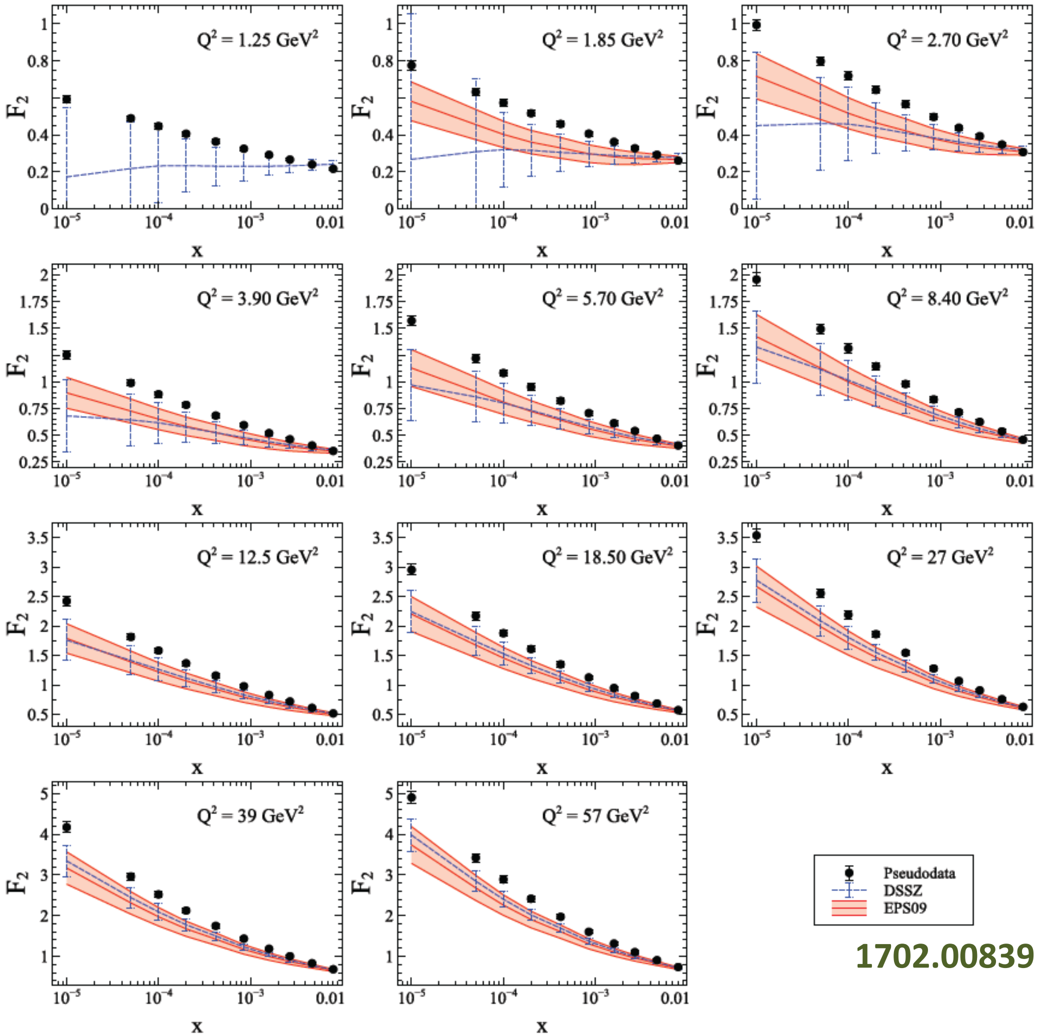
ep and eA essential

- Non-linear resummation techniques (weak coupling but nonperturbative CGC) better for dilute-dense systems: pA, eA



Trying to discriminate: non-linear effects vs linear DGLAP evolution

EIC F^{Au}_2 and F^{Au}_L pseudodata with saturation effects based on rcBK evolution:



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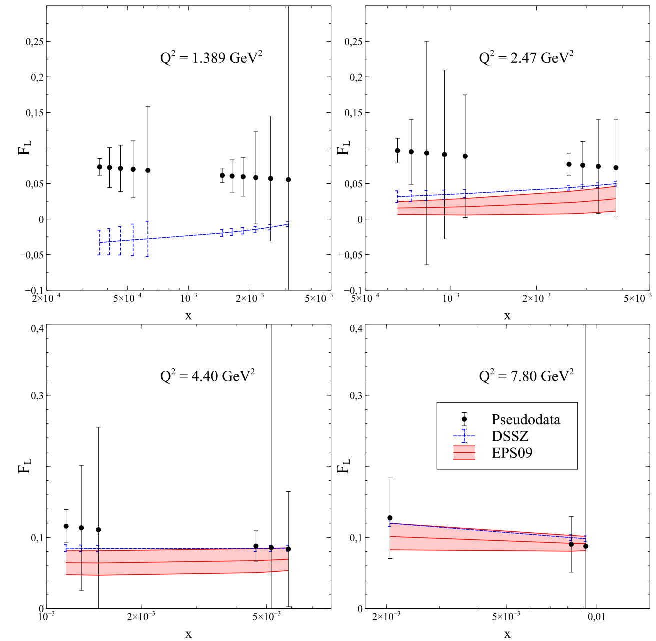
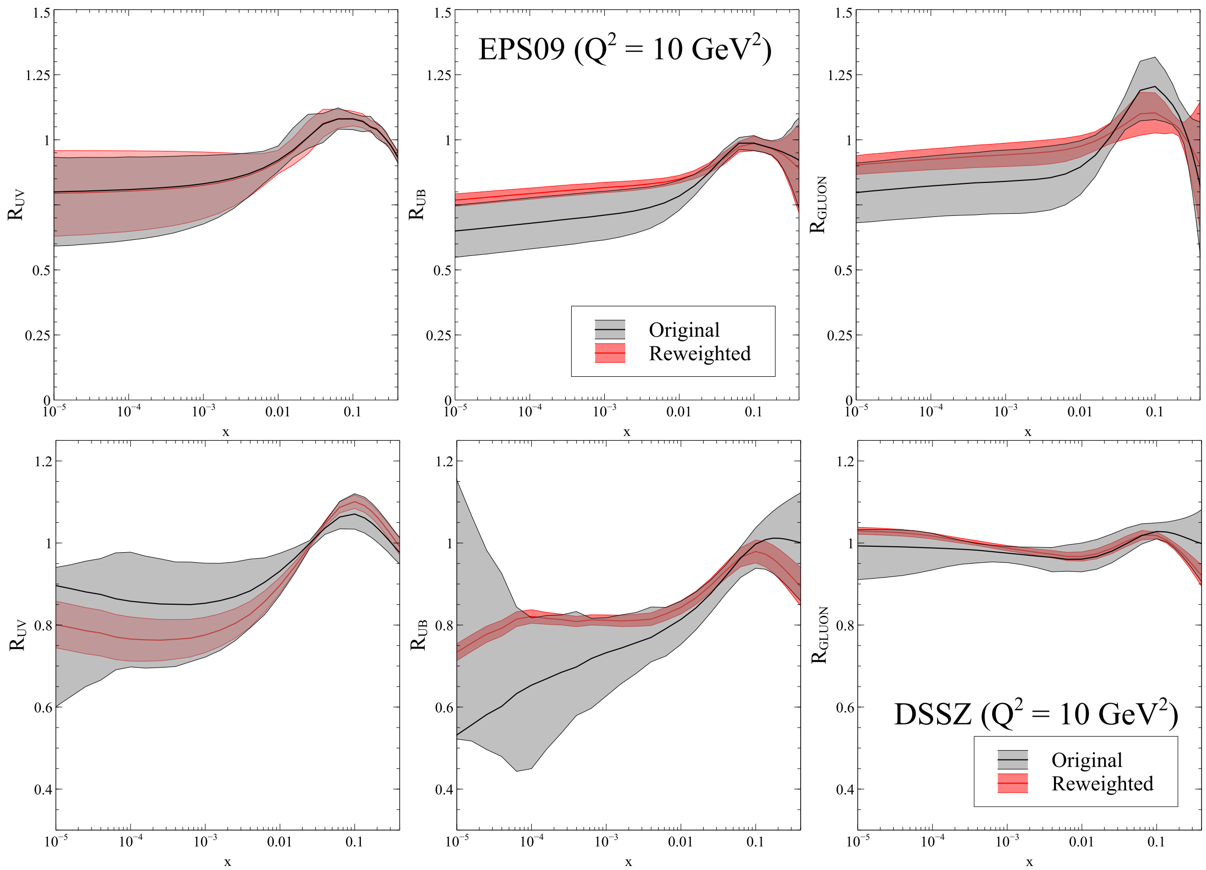


- F_2: Pseudodata for $x<10^{-3}$ lies in the upper limit of the nPDFs
- F_L: Big differences, gluon density not well determined

Saturation modifies evolution: tension between the description in DGLAP analyses if enough lever arm in Q^2 at small x available

Trying to discriminate: non-linear effects vs linear DGLAP evolution

Reweighting nPDFS with EIC rcBK F^{Au}_2 and F^{Au}_L pseudodata:

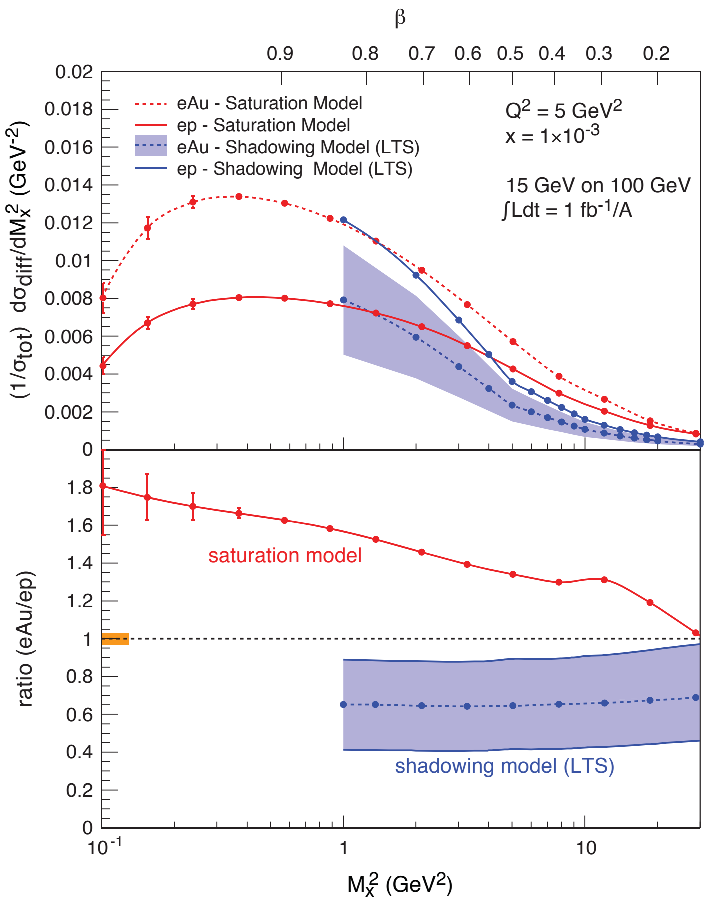


1702.00839

- The results look quite different from the original distributions
- If EIC provide data compatible with the expected theoretical description from the saturation model, a successful refitting of the nPDFs may not be achievable, unambiguously signal the presence of non-linear effects

Trying to discriminate: non-linear effects vs linear DGLAP evolution

Diffractive physics will be a major component of the e+A program at an EIC



- HERA observed: ~14% of all events are diffractive
- Saturation models predict up to $\sigma_{diff}/\sigma_{tot}$ ~ 25% in eA
- Ratio enhanced for small M_X and suppressed for large M_X
- Standard QCD predicts no M_X dependence and a moderate suppression due to shadowing.

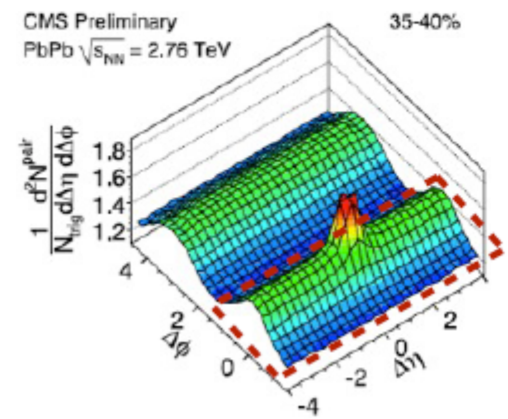
Diffraction can be a most precise probe of non-linear dynamics in QCD

- High sensitivity to gluon density: σ~$[g(x,Q^2)]^2$ due to color-neutral exchange

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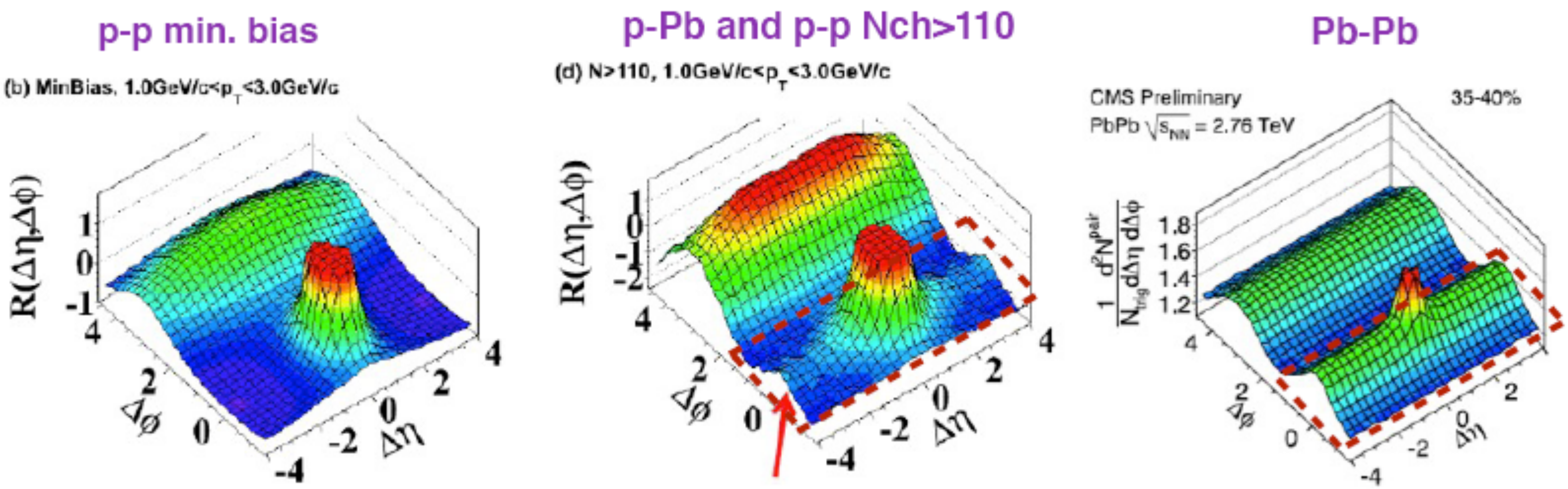
Also observed in high mult. p+Pb & p+p @LHC



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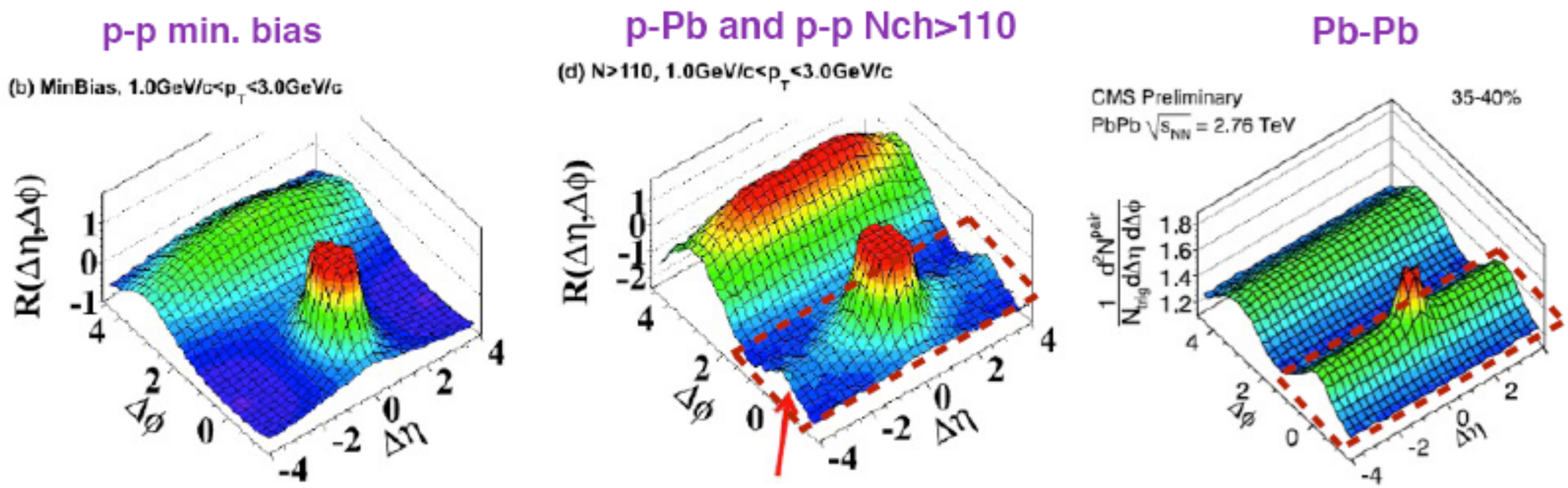

Different theoretical models of the ridge: hydrodynamic flows, local hot spots, initial-state fluctuations, parton cascades, glasma flux tubes, glasma turbulence fields, the momentum kick model, pQCD modeling, etc.

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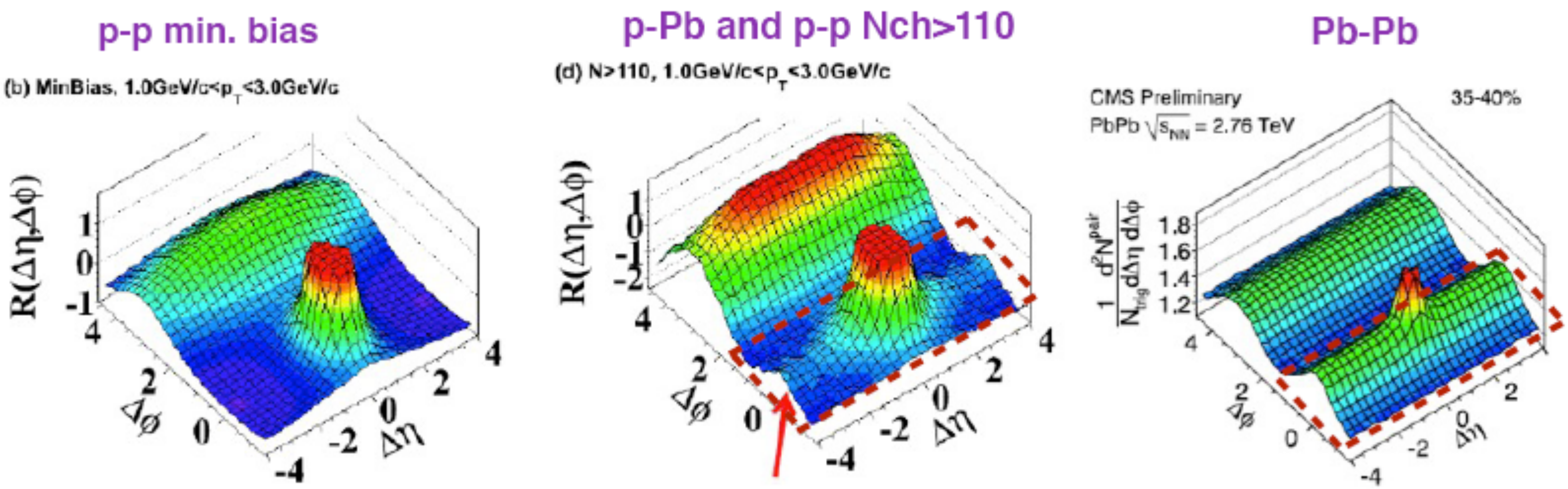


Different theoretical models of the ridge: hydrodynamic flows, local hot spots, initial-state fluctuations, parton cascades, glasma flux tubes, glasma turbulence fields, the momentum kick model, pQCD modeling, etc.

Two lines of explanations:

Initial state effect

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

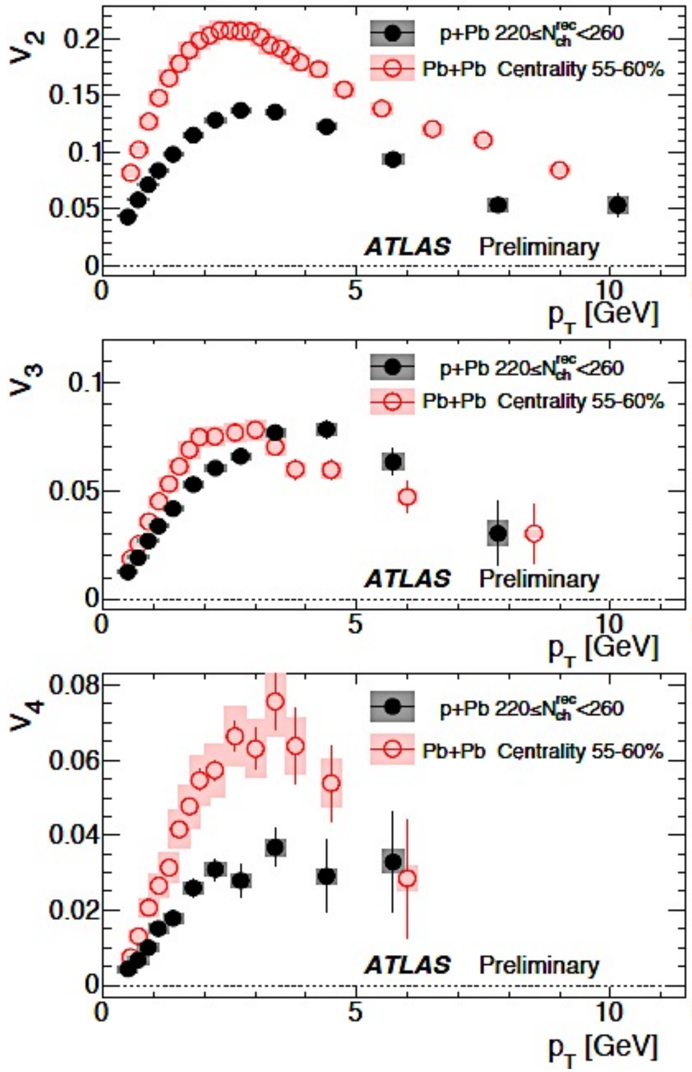
Medium effect

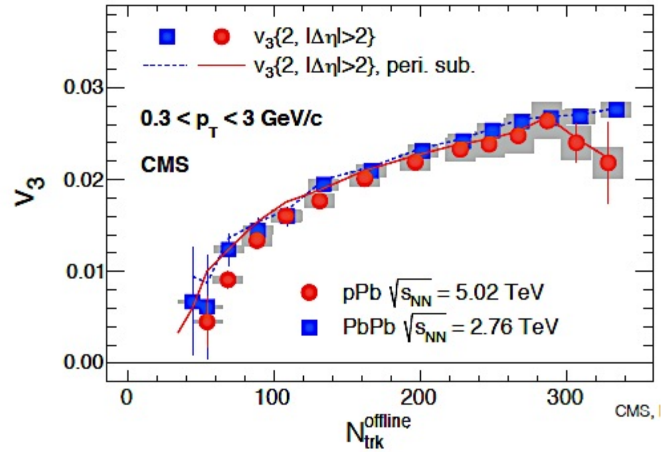
➜ Coupling to a flowing medium: hydrodynamics at work already on pPb@LHC

What about IC?

The experimental data was surprising:

- Similarity of experimental data in pA and AA collisions





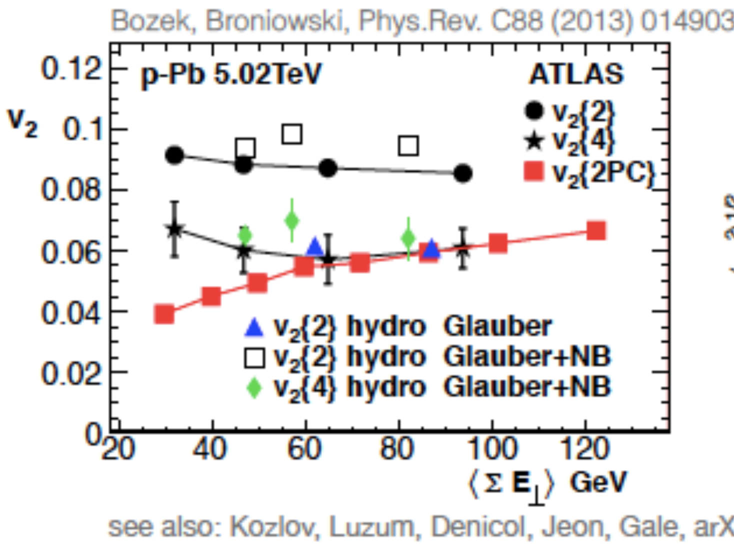
Hydro works well in AA

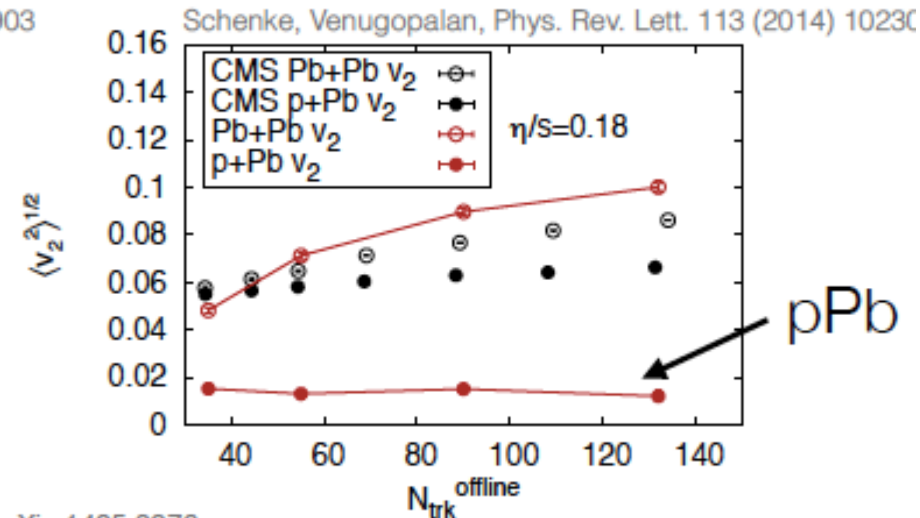
Hydro also works well in pA

Some issues:

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

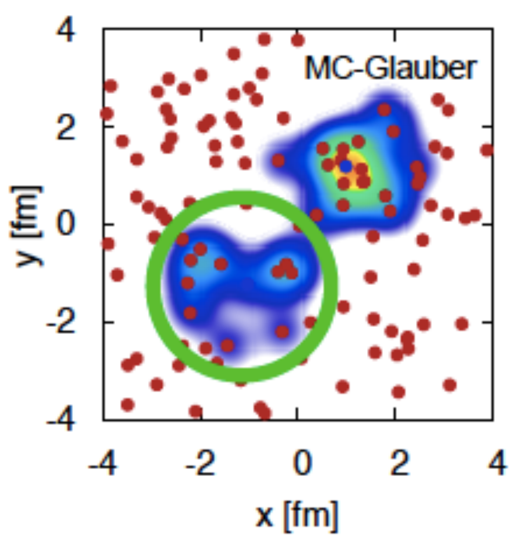
Different initial states: very different results



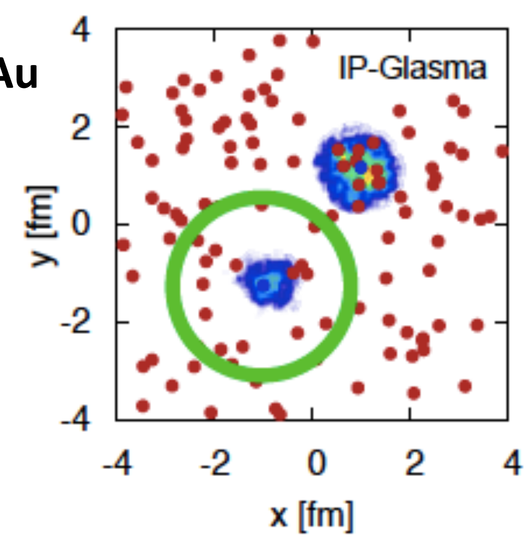


see also: Kozlov, Luzum, Denicol, Jeon, Gale, arXiv:1405.3976

MC-Glauber does not constrain energy density dististribution

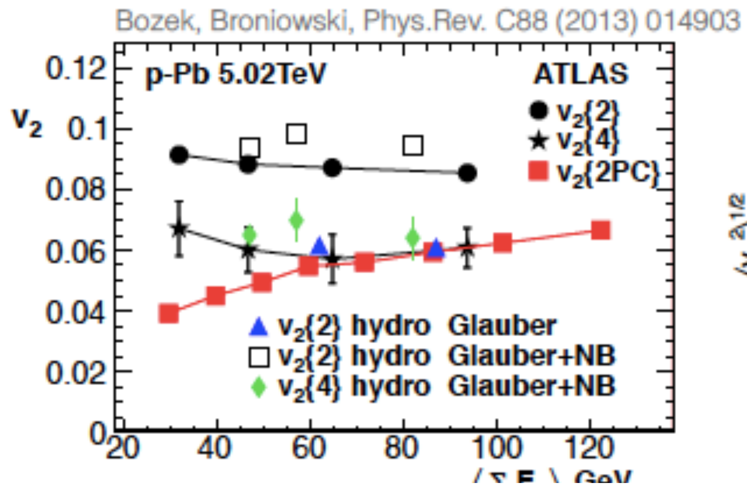


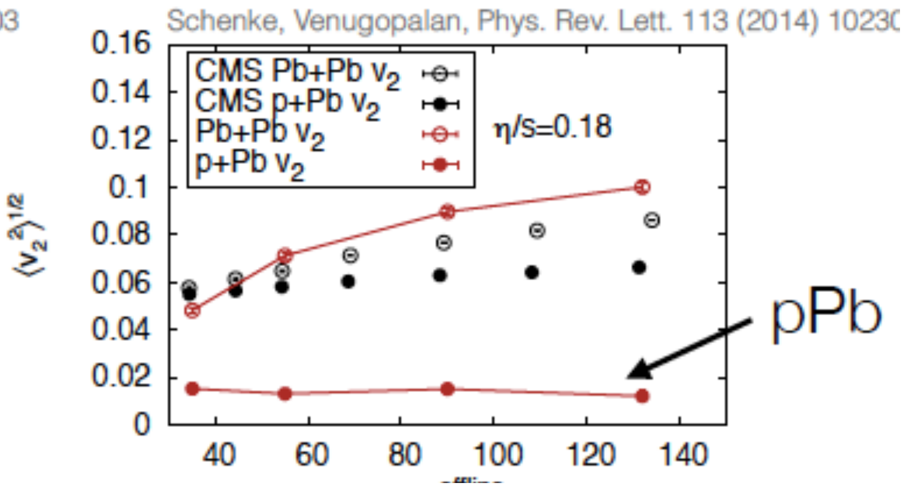
d+Au



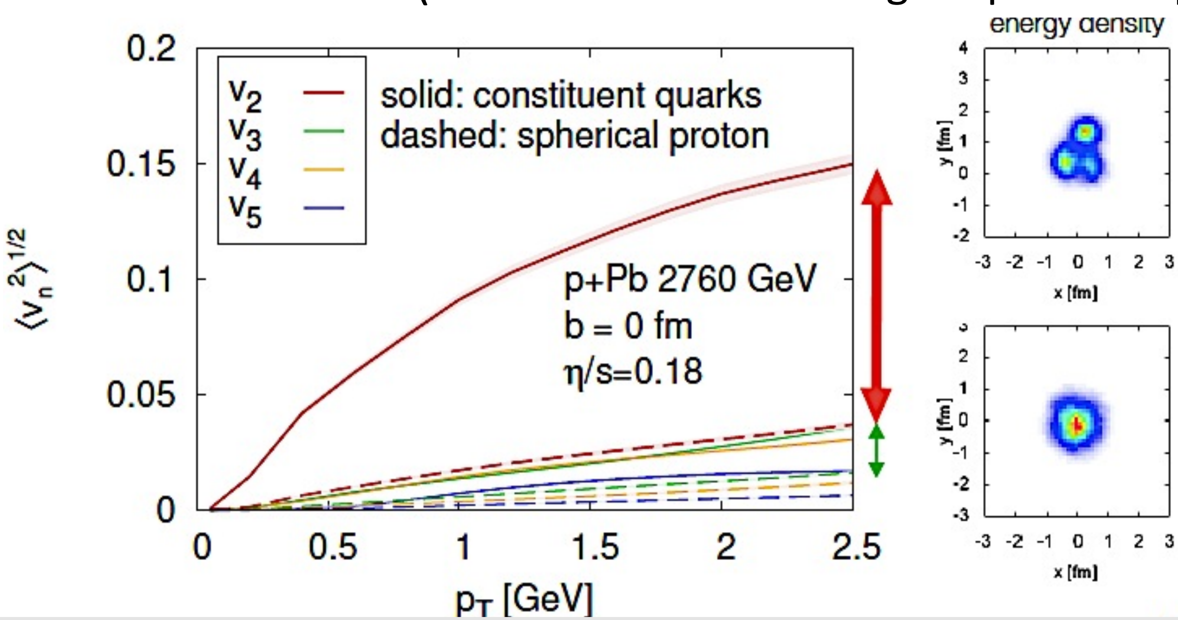
IP-Glasma constrains energy density deposition. However, it does not describe v_n in p+Pb

Different initial states: very different results





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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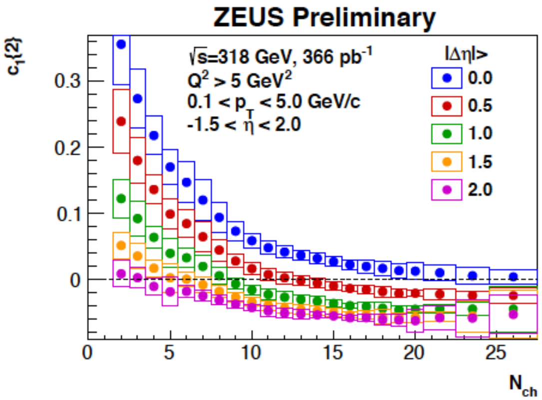
- pushing this idea even further would imply that any lump of sufficiently high energy density could expand according to the laws of hydrodynamics
  => natural consequence: presence of azimuthal correlations in e^+e^- collisions?

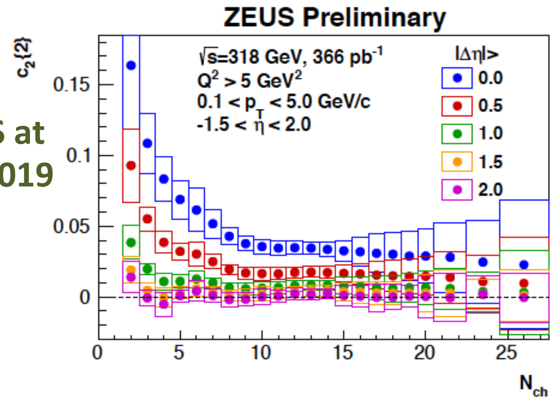
Early stages: what we can learn in an ep/eA collider

Preliminary analysis by ZEUS and ALEPH put strong limits on azimuthal 2-particle correlations in ep at HERA and e^+e^- at LEP

Multiplicity-dependent $c_1\{2\}$ and $c_2\{2\}$ with increasing η-separation



ZEUS at DIS2019

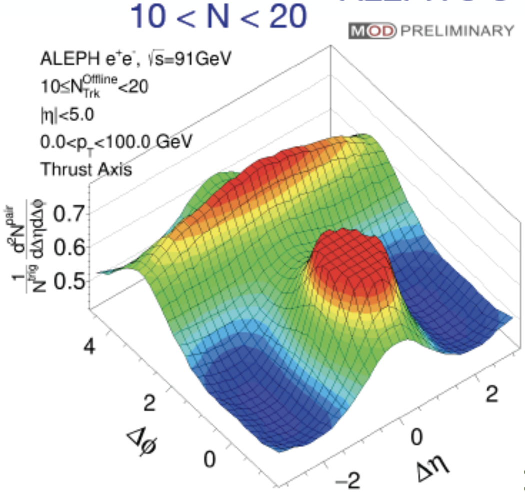


$|\Delta\eta| > 2.0$: $c_1\{2\}$ changes sign $\rightarrow$ consistent with momentum conservation.

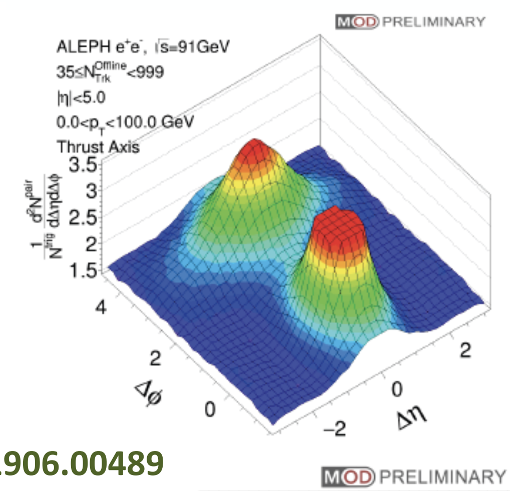
$|\Delta\eta| > 2.0$: $c_2\{2\}$ consistent with zero.

ALEPH e^+e^- thrust axis

10 < N < 20



N ≥ 35



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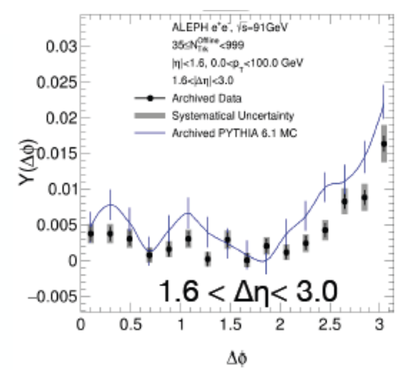
Switching off the flow: e^+e^-

No evidence of long-range correlations beyond Pythia expectation



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- long range rapidity correlations from initial state correlations

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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

Conclusions

ep & eA collisions at high energy offer huge possibilities:

To provide information about QCD first principles:

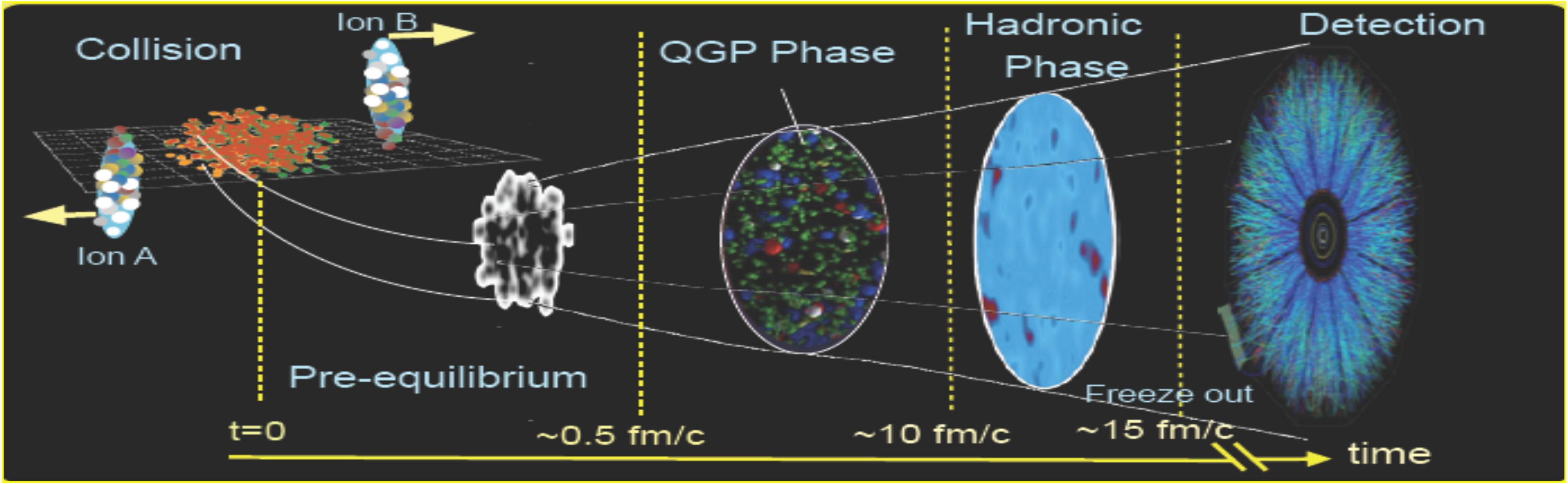
- Partonic structure
- New regimes of QCD
- 3D structure of hadrons and nuclei
- The role of gluons in structure and dynamics
- Dynamics of QCD radiation and hadronization
- Confinement: understand the emergence of hadrons from color charge

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
- …

Backup

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

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
- 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

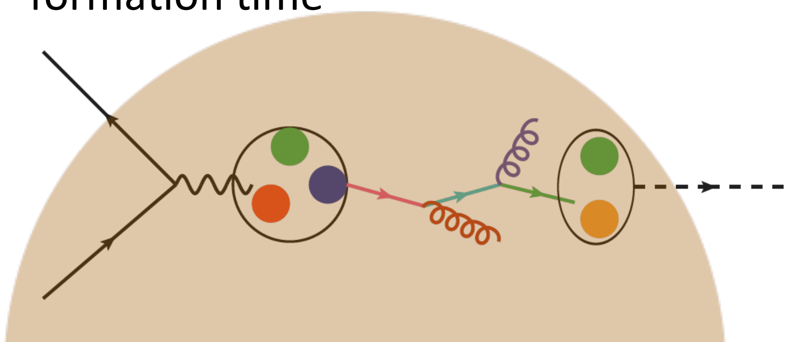
Partonic evolution and hadronization

Relevant for particle production and QGP analysis in HIC:

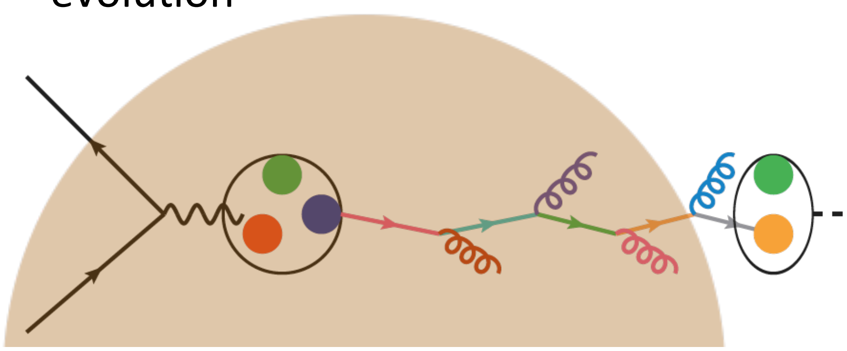
jets plentiful in eA
benchmark for jet quenching studies in AA

Low energy:

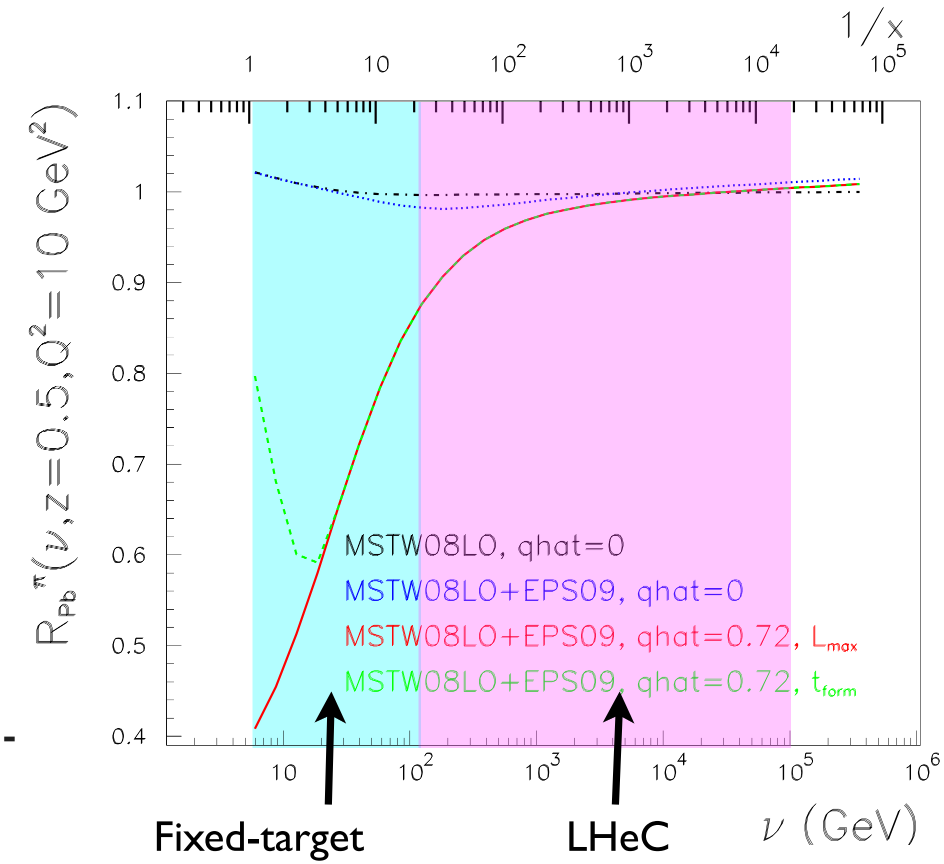
hadronization in matter
- (pre)hadronic absorption
- formation time



High energy:
- modification of partonic evolution



Ratio of fragmentation functions Pb/p



Other possible studies: quarkonium production

Production mechanism and polarization:

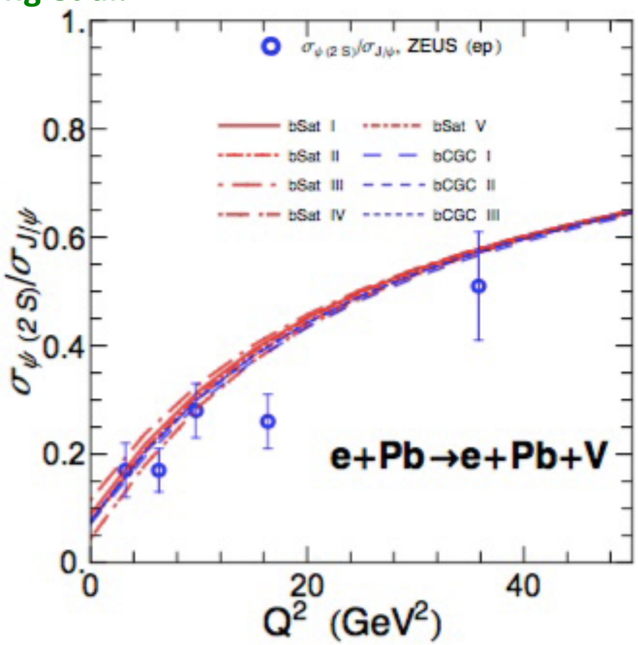
polarized J/ψ photoproduction can be studied more precisely and up to much larger values of p_T in ep @ LHeC

⇒ 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 $e\ p \to e\ Q\ \bar{Q}\ X$

Boer, Lansberg, Pisano

Gluon GPDs

Υ 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