QCD "froide": parton densities and correlations and other effects not related to deconfinement

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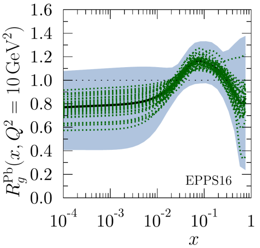
profitting from ongoing work in Yellow Report and Physics Beyond Colliders discussions

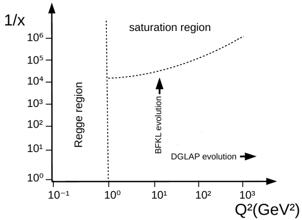
Outline

- Motivation
- Current knowledge from HERA, RHIC and LHC
- EIC
- HL-LHC
- Summary

Not comprehensive:
$\rightarrow$ focus on QGP-related topics and current perspective/interests
$\rightarrow$ often observables can be recasted also in different contexts as here

Motivation: partonic structure, initial stage & more of ion-ion



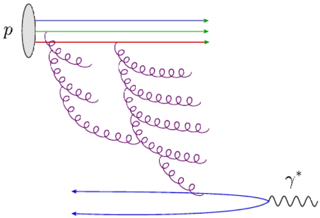


EPPS '16, QCD and collider physics(adapted)

- nuclear parton density and correlations poorly known
- low-x: probe non-linear regime of QCD, so far not ambiguously observed
  $\rightarrow$ Color Glass Condensate: eff. field theory in the weak coupling limit
  $\rightarrow$ non-trivial emergent phenomena
- other effects as coherent energy loss
- initial conditions for QGP physics: one of largest uncertainties
  $\rightarrow$ nuclear partons over full Q^2, x: densities, fluctuations and correlations
  $\rightarrow$ low-x: bulk particle and low p_T heavy-flavour production
- QGP & saturation physics: 'background' for each other

Introduction: the small-x problem

- Bremsstrahlung favors soft (low energy, or small $x \equiv \frac{k_z}{p_z} \ll 1$) gluons:

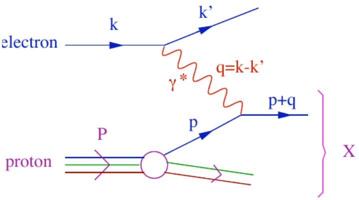


- gluon recombination

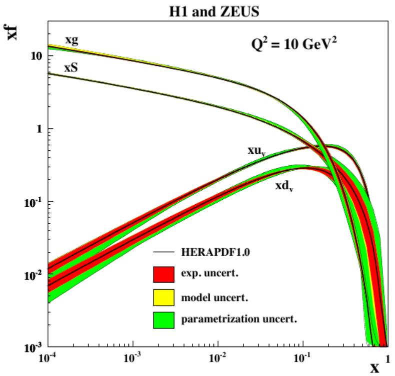
$$\frac{\sigma_{\text{dipole}}}{\pi R^2} \sim \alpha_s \frac{xG(x, Q^2)}{\pi R^2\, Q^2} \lesssim 1$$

- All-order resummations of gluon ladders (BFKL) lead to an explosive growth
- Cross-sections are proportional to parton distributions: unitarity violations
- The natural mechanism to stop this growth: gluon saturation
- The modern theory for gluon saturation: Color Glass Condensate
  - non-linear generalization of the BFKL dynamics
  - currently known to next-to-leading order in pQCD

Parton distributions from DIS



$$Q^2 = -q^\mu q_\mu > 0\,, \quad x = \frac{Q^2}{s}$$



- Gluon distribution $xG(x, Q^2) \equiv x\frac{\mathrm{d}N}{\mathrm{d}x}$: # of gluons with longitudinal momentum fraction x and transverse size $\Delta x_\perp \sim 1/Q$
- For $x \leq 0.01$ the proton wavefunction contains mostly gluons

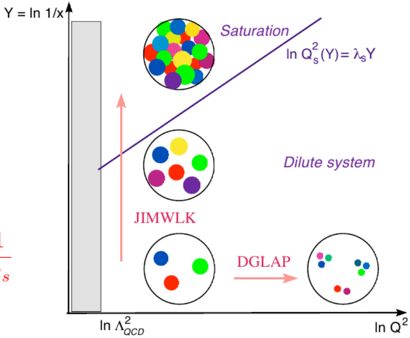
Gluon evolution at small x

- Gluon occupation number:

$$n(x, Q^2) \simeq \frac{xG(x, Q^2)}{\pi R^2\, Q^2}$$

- Non-linear evolution (BK-JIMWLK)

$$\frac{\partial n}{\partial Y} = \alpha_s n - \alpha_s^2 n^2 \sim 0 \quad \text{when } n \sim \frac{1}{\alpha_s}$$

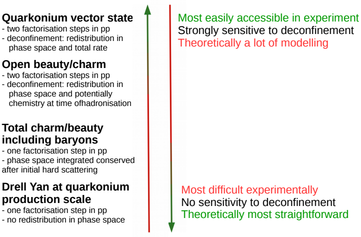


- Saturation momentum: $n(x, Q^2) \sim 1/\alpha_s$ when $Q^2 = Q_s^2(x)$

$$Q_s^2(x) \simeq \alpha_s \frac{xG(x, Q_s^2)}{\pi R^2} \sim \frac{1}{x^{\lambda_s}}$$

- $Q_s(x)$ rises with the energy (i.e. with decreasing x)

Initial state in view of QGP physics

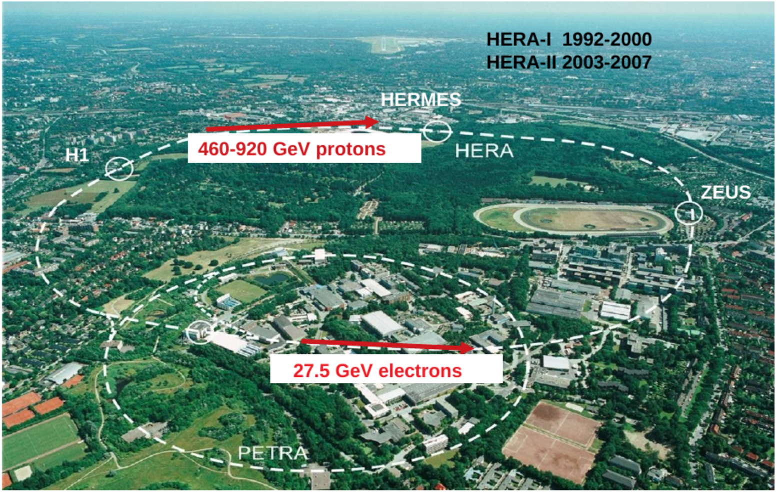


example for heavy-flavour arxiv:1609.01135

- QGP physics at the LHC & beyond: extract matter properties
- understanding of effects that are usually tried to be elimimated: **initial state one of limiting factors**
- chance at **high energy** in 'canonical' picture:
  1) **time scales**: crossing $\rightarrow$ shortest scale
  2) **eff. field theory** for initial state
  3) **lattice QCD**@$\mu_B = 0$: thermal properties
- precision required: large statistics prerequisite

Current knowledge from HERA, RHIC and LHC

HERA's Legacy



HERA: Hadron Elektron Ring Anlage

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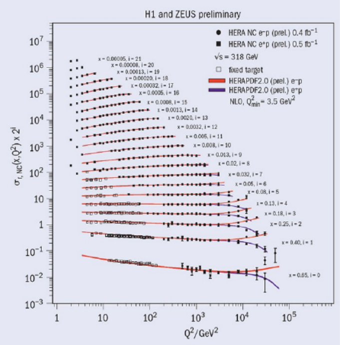
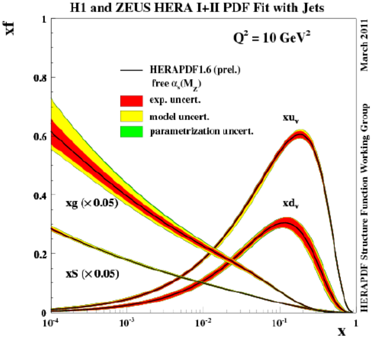
HERA's Legacy





Proton structure at high-energy is:

- Far from elementary
- Gluon-dominated for x < 0.1

- Gluon content increases with decreasing x
- Gluons pose a number of questions
- HERAPDF2.0: 15 parameters, ~1400 combined data points

PoS EPS-HEP2011 (2011) 320 arXiv:1112.2107 and http://cerncourier.com/cws/article/cern/60160

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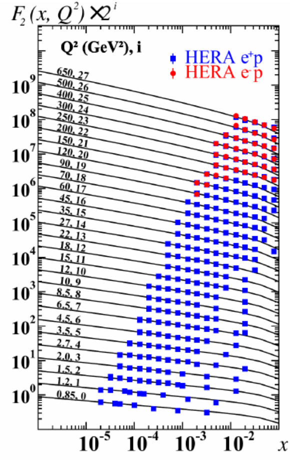
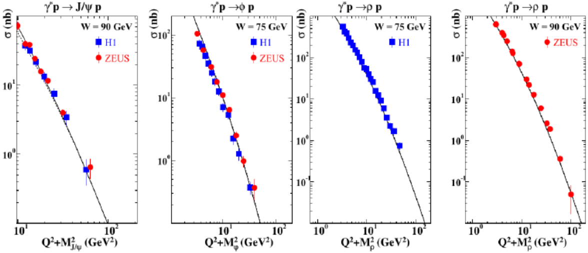
Saturation at HERA?



- Other quantities that saturation models (here IP-Sat) reproduce: F_2 and F_L structure functions, exclusive vector meson (J/psi and phi) production cross sections, etc.



e-Print: arXiv:1212.2974

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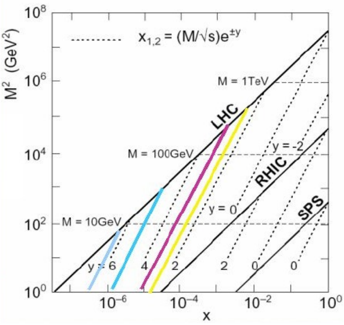
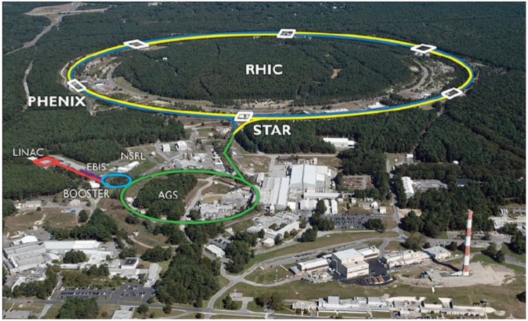
RHIC





Saturation physics at RHIC?

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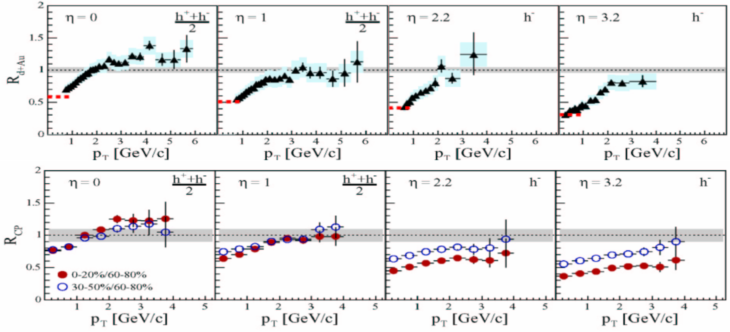
Forward particle production in d+Au collisions

BRAHMS, PRL 93, 242303



Sizable suppression in charged hadron production in d+Au collisions relative to p+p collisions at forward rapidity.
BRAHMS PHENIX and PHOBOS reported similar effects
However, at the LHC at midrapidity similar x-values probed and no strong suppression

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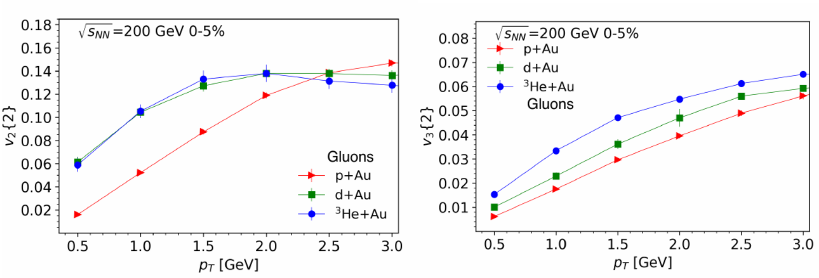
LHC in Run 1 and 2

LHC: correlations in pp, *p*A

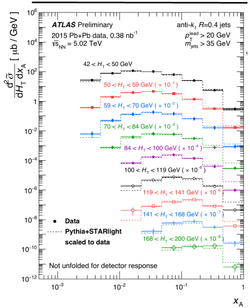
System size dependence at RHIC captured by CGC initial state gluon correlations

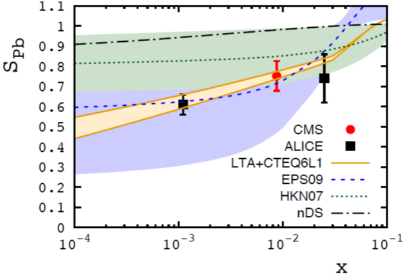


Mark Mace at QM '18

- *pp* ridge: first LHC-discovery, initially seen in view of saturation physics
- developments in recent years to interpret in hydro, initial state and one-touch approaches/transport
  $\rightarrow$ quest still open, see small systems talk
  $\rightarrow$ fundamental for basic understanding of heavy-ion physics
  $\rightarrow$ requires more studies: not necessarily lumi, but ideas and hence time

LHC as γ-hadron collider: QCD in Ultra-peripheral collisions

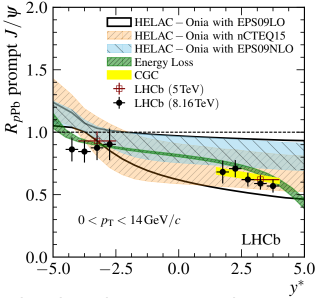


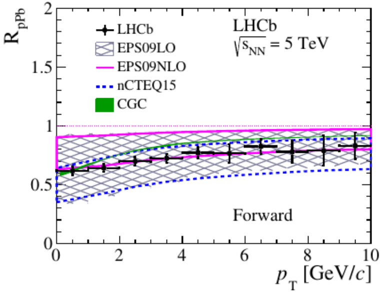


ATLAS-CONF-2017-011, right compilation provided by E. Kryshen.

- coherent vector mesons: more and more results, start to exploit γA over γp to cancel part of non-perturbative uncertainties on theory side
- first inclusive dijets just becoming available: to be seen how far systematics can be pushed

LHC: Heavy-flavour production



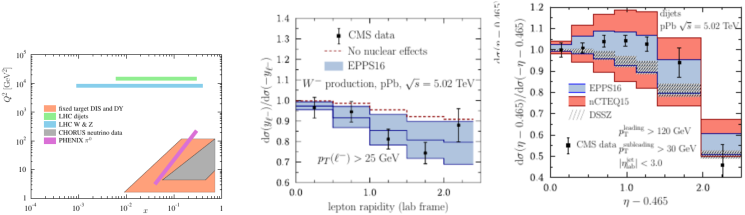


- hard scale via mass, large potential for constraints down to low-x: 10^{-5}, but energy loss could be main effect
- universal factorisation broken in quarkonia & universal fragmentation broken in heavy-flavour (latter however in pPb $\approx$ pp)

  $\rightarrow$ to be understood both for low-x and QGP physics
- updates with higher statistics still to come: beauty data down to low-p_T and with better baryon results
- excited states and beauty will eventually remain limited in discriminative power with available data

Involvement of multiple French groups: interface with heavy-flavour/quarkonia

LHC: W, Z, Dijets as nPDF constraints



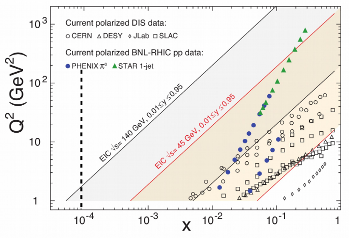
from EPPS paper

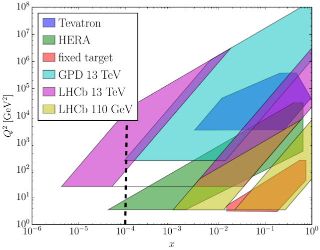
- clean probes at high Q^2 with Run 1 data, will be updated with larger Run 2 data
- limited in kinematic reach down to low-x, need high-precision

Involvement of CMS heavy-ions: interface with high-p_T

Future opportunities

Hadron and lepton-hadron colliders



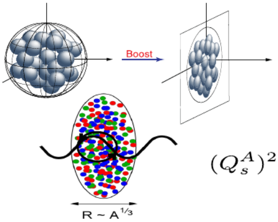


- Hadron machines, see summary by Yen-Jie Lee at HL-LHC workshop:
  → "HL"-LHC: Run 3 & Run 4, till ≈ 2030
  approved dedicated PbPb, pPb and pp programme in the 20ies
  → HL-LHC beyond Run 4 after 2030: ions runs to be seen
  lighter ions attractive mainly to go to higher luminosities: factor 20-100
- Lepton-hadron machines:
  → Electron-ion collider, possible physics start ≈ 2030:
  priority project of the nuclear US community: spin, TMD, GPD & low-x
  LHeC: desirable for low-x, usually considering ALICEs IP2

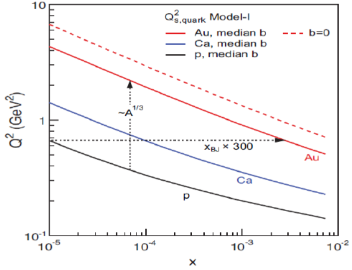
How to explore/study the saturation regime of QCD?

(multi-TeV) e-p collider (LHeC) OR **a (multi-10s GeV) e-A collider**

Advantage of nucleus



$$(Q_s^A)^2 \approx c Q_0^2 \left[\frac{A}{x}\right]^{1/3}$$



$L \sim (2 m_N x)^{-1} > 2\, R_A \sim A^{1/3}$

Enhancement of Q_s with A:

Saturation regime reached at significantly lower energy (read: "cost") in nuclei. Also: saturation a priori claimed to be observed in pA collisions (RHIC, LHC), but eA is cleaner since one of the probe is leptonic and the kinematics is under better control.

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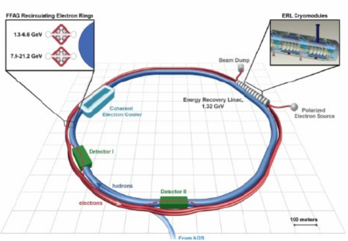
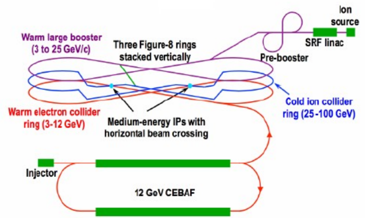


eRHIC at BNL (New York)



JLEIC at JLab (Virginia)

EIC

-There are two proposals for building the machine.

-As of today it is not yet decided where it will be built.

eRHIC:
- Upgrade of RHIC hadron beam facility
- Addition of a recirculating electron ring
- electron-proton: 5-18 GeV on up to 275 GeV
- electron-ion: 5-18 GeV on 100 GeV (Pb)

JLEIC:
- Upgrade of CEBAF 12 GeV electron beam facility
- Addition of a new hadron injector
- electron-proton: 3-12 GeV on 40 GeV
- 100-400 GeV with new to be proven magnet technology (up to 12 T)
- electron-ion: 3-12 GeV on 40 GeV (Pb)

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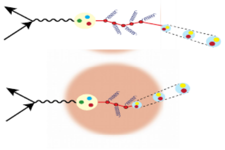
Emergence of Hadrons from Partons

Nucleus as a Femtometer sized analyzer

ν: the virtual photon energy range

$$\nu = \frac{Q^2}{2mx}$$

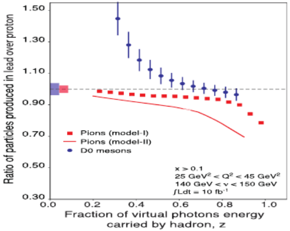


Control of ν by selecting kinematics;

The nuclear size is also under control

Colored quark emerges as color neutral hadron What is the impact of colored media on confinement?

Energy loss by light vs. heavy quarks:



Identify light vs. charm hadrons in e-A: Understand energy loss of light vs. heavy quarks in cold nuclear matter.

Provides insight into energy loss in the Quark-Gluon Plasma

DIS at collider energies enables control of parton/event kinematics

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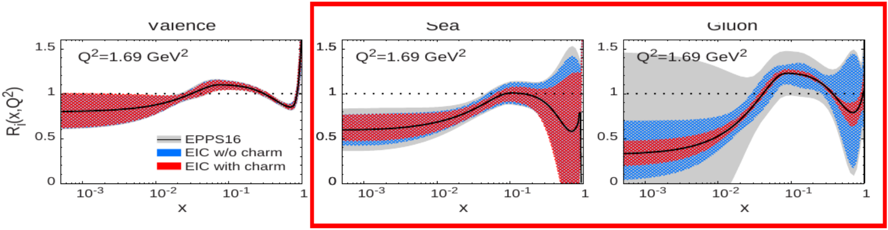
EIC: impact on the knowledge of 1D Nuclear PDFs



Ratio of Parton Distribution Functions of Pb over Proton:

- -Grey: Without EIC, large uncertainties in nuclear sea quarks and gluons
- *-Colored: With EIC significantly reduced uncertainties*
- Complementary to RHIC and LHC pA data.
- Provides information on initial state for heavy ion collisions.
- Does the nucleus behave like a proton at low-x? (question for EIC)

• Users within Europe

map based on mailing list: open for all interested people

French groups: Saclay (CEA), Orsay (CNRS) and IGDORE-RONIN (Astrid)

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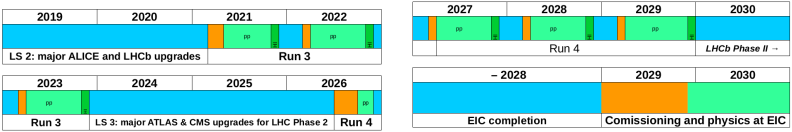
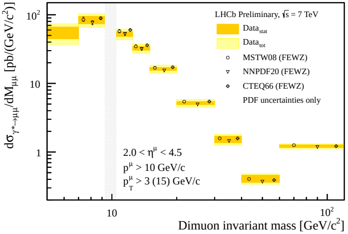
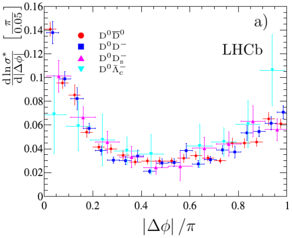
HL-LHC: schedule, luminosities, overview



- Run 3/4: luminosities in pPb 0.5-2 pb^{-1} for ATLAS/CMS/ALICE, LHCb factor 3-10 less
  5-10 more w.r.t. Run 2 at 8.8 TeV: **significant improvements, to be quantified**
- beyond Run 4 for ion-running: lighter ions for higher nucleon-nucleon luminosities $\approx$ 10-100 (see J. Jowett QM)
  $\rightarrow$ measurements as in pPb now, larger kinematic range, smaller A
  $\rightarrow$ smaller A: A-dependence of nuclear modification ad-hoc in parameterisation, important for impact parameter dep.
  $\rightarrow$ thinking about new instrumentation:
  lower-p_T, larger rapidity coverage, forward instrumentation
- "energy scan": not very appealing in this context $\rightarrow$ rather low lumi per step unless a lot time invested
- focus on current statistically demanding measurements in the following

HL-LHC: low-x in pA in Run3/4

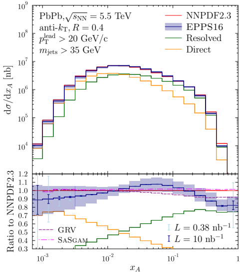


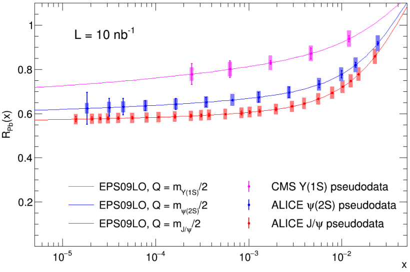


Run 1 pp results.

- not yet fully exploited in pPb due to stat. limitations, to start with Run 2
- Drell-Yan at forward rapidity & midrapidity at low-masses + photons in pp vs. pA
- dileptons including low-mass Drell-Yan and W: very precise based on data driven calibrations
  $\rightarrow$ even after Run 3 and Run 4: further uncertainty reductions
- $b\bar{b}$ and $c\bar{c}$ correlations in pp vs. pA: Transverse Momentum Dependent pdfs meets CGC
- non-statistical dominated observable classes can profit from theory progress: observable redefinitions of correlation measures

HL-LHC: low-x in UPC

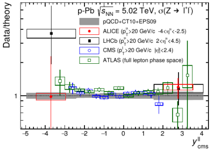


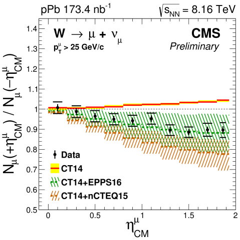


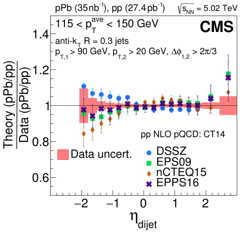
taken from Ilkka Helenius for UPC dijets, and Evgeny Kryshen for ALICE/CMS

- inclusive UPC-studies with dijets, including flavour tagged to increase kinematic range down to lower p_T
- large UPC vector mesons samples both in pA and AA for suppression factor
  measurements also with different mass scales: Υ first time at QM
  incoherent production a lot of potential and stat. hungry, to be seen what is feasible at hadron collider

HL-LHC: nPDFs with high-Q^2 in Run 3/4



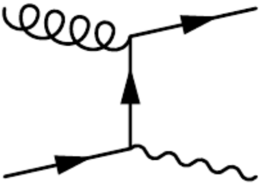


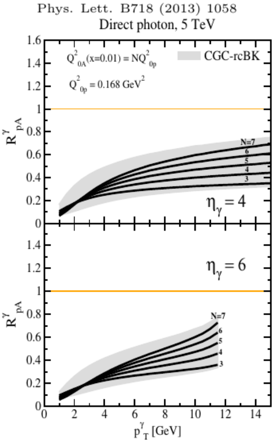


final result on Z from Run 1 (in contrast to Run 2, ALICE got more lumi in Run 1 than LHCb), Run 2 first prelim. for W, Run1 Dijets.

- unique kinematic range at perturbative scales at the LHC
- statistics increase: shrink syst. uncertainties in normalised distributions or asymmetries
- enlarge kinematic coverage towards forward, backward rapidity and in p_T → more statistics, but also larger tracker coverage at forward rapidity in ATLAS/CMS from Run4 on
- top as add. check for DGLAP consistency

HL-LHC: ALICE Focal in Run 4





- plan for a ultra-granular calorimeter at forward rapidity as an option for ALICE
- measure photons in *p*Pb at forward rapidity
- competition: current LHCb and future LHCb tracker/calo-upgrades

Beyond Run 4: HL-LHC in view of nPDF & low-x

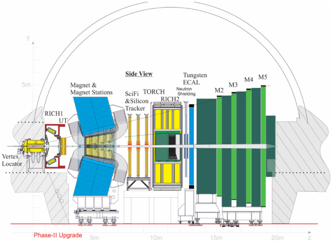
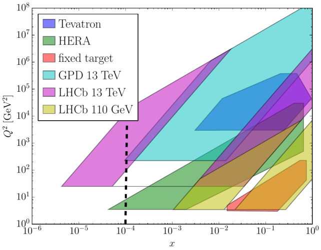


Figure 4.1: Schematic side view of the Phase-II detector.

- ATLAS/CMS with HL-LHC detectors: fully profit from higher lumi for hard nPDF probes
- LHCb upgrade II: similar pile-up as ATLAS/CMS now → precision measurements at high luminosities in pp and pA at forward acceptance → in design phase
- ALICE to be seen, for ideas: p. 23
  → instrumentation ideas not focused on low-x aspect

Fixed-target options at the LHC



- fixed-target: potential of high-luminosity compared to collider
  → "high-x frontier" → nPDF constraints in x-range as high Q^2-collider
  and energy loss studies with charm, beauty, Drell-Yan, photon
  → interesting (very) backward: EMC and even Fermi-motion with relatively low-Q^2
- LHCb internal gas target upgrade in next shutdown: 10-100 higher instant. lumi's than now (current about 1-100 /nb in one special run)
- ideas for ALICE (also with TPC) and LHCb for solid state and polarised targets being considered

Opportunities at the LHC and instrumentation

- for hard probes at high Q^2: CMS and ATLAS most interesting, lumi-hungry:
  pp measurements can be used to see where ultimate limits
- for low-x clean reach in pPb: LHCb most interesting, clean DY as well as photons, lumi-hungry
  pp measurements to be done to know how far precision can be pushed
- UPC-dijets: ATLAS/CMS: just started
  a lot of potential also extending to heavy-flavour as well as not only inclusive dijets
- UPC-vector mesons: LHCb, ALICE:
  so far focus on coherent production, extensions possible
- better forward instrumentation could be beneficial for exclusive studies to improve and enlarge UPC program

Current status and open questions

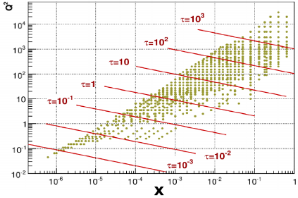
- exploring non-linear regime of QCD at low-x and other QCD effects in collisions involving nuclei:
  $\rightarrow$ low-x: strong theory interest in France, strong intrinsic motivation asking for asymptotic high energies
  $\rightarrow$ exp. community mainly interest driven by initial state ion-ion
- many open questions to be answered:
  saturation unambiguously seen? low-x gluon/quarks in general? How strong EMC for gluons? role of factorisation breaking, e-loss, fragmentation non-universality?
  $\rightarrow$ all inputs for QGP physics, required for precision
- Run 1 with pioneering measurements, only Run 2 exploitation will make contours fully visible

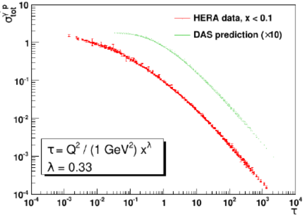
Perspectives

20/30ies projects with interest in experimental French QGP community:

- approved ions@HL-LHC in 20ies:
  enlarge kinematic reach/precision at high Q^2
  cleaner observables at low Q^2 with pA and AA (UPC)
- ions@HL-LHC in the 30ies:
  lighter ions for factor 10-100 increase in equivalent lumi
  $\rightarrow$ clean low and high-Q^2 observale profitting a lot: pp experience
- EIC, physics starting time $\approx$ 2030:
  control of kinematics and clean, very precise
  less reach in kinematics than LHC
- lepton-ion programme:
  profitting from "application" with contemporary ion-ion collisions as motivation

Saturation at HERA?





- No recent evidence so far from DGLAP fits in sub-ranges[1]

On the other hand it was observed that HERA data exhibits geometrical scaling[2] with respect to:

$$\tau = \frac{Q^2}{Q^2_{s|x|}} = \frac{Q^2 x^\lambda}{Q_0^2 x_0}, for\ x < 0.01$$

this has not been seen in prior fixed-target experiments and can be interpreted as an indirect consequence of the saturation regime

- 15% of events are diffractive. This is interesting as a sizable fraction of events are diffractive in most (all?) saturation models.

[1] arXiv:1007.5405 and [2] https://arxiv.org/pdf/hep-ph/0303204.pdf

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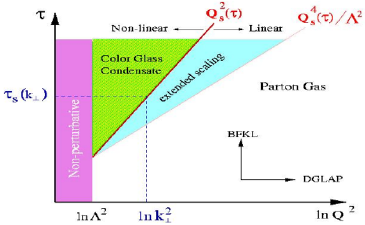
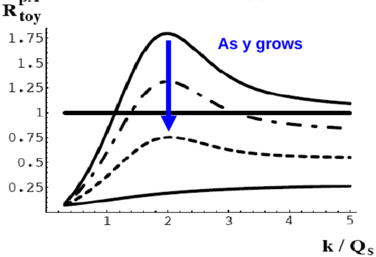
Expectations for a color glass condensate

$\tau = \ln\left(1\ x\right)$ τ related to rapidity of produced hadrons.



Iancu and Venugopalan, hep-ph/0303204

D. Kharzeev, hep-ph/0307037



Are the RHIC data evidence for **gluon saturation at RHIC energies**?

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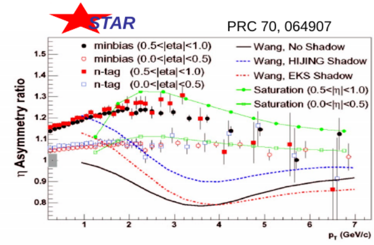
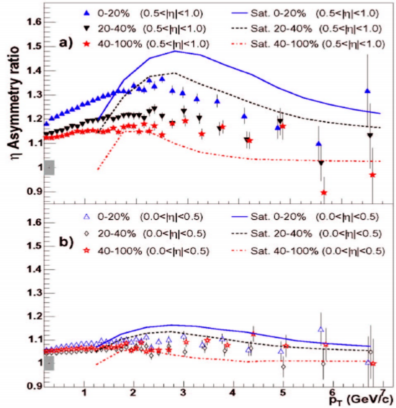
Pseudo-rapidity yield asymmetry vs p_T

Au direction / d direction



Back/front asymmetry in 200 GeV dAu consistent with general expectations of saturation or coalescence;

→ Doesn't match pQCD prediction.



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Electron Ion Collider Initiatives

	PAST	FUTURE				
	HERA at DESY	LHeC at CERN	HIAF at CAS	ENC at GSI	MEIC/ELIC at Jlab	eRHIC at BNL
$\sqrt{s}$[GeV]	320	800-1300	12-65	14	20-140	78-148
Proton x_{min}	1×10^{-5}	5×10^{-7}	7×10^{-3}-3×10^{-4}	5×10^{-3}	1×10^{-4}	5×10^{-5}
Ion	p	p to Pb	p to U	p to ^{40}Ca	p to Pb	p to U
polarization	-	-	p, d, ^{3}He	p, d	p, d, ^{3}He(^{6}Li)	p, ^{3}He
L[$cm^{2}s^{-1}$]	2×10^{31}	10^{34}	10^{32}-10^{35}	10^{32}	10^{33}	10^{33}
Interaction points	2	1	1	1	2	2
Year	**1992-2007**	**post ALICE**	**2019-2030**	**FAIR upgrade**	**Post 12 GeV**	**2025**

STRATEGY:
-Use existing investments
-Pursue luminosity 10x - 100x that of HERA.
-Enable nuclei targets and polarization (eRHIC,MEIC).
-Enable nuclei and high energy (LHeC).
-Optimize the instrumentation.

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Project and Status

JELIC at JLab (Virginia)

eRHIC at BNL (New York)

	JELIC at JLab (Virginia)	eRHIC at BNL (New York)
e-Proton energy	3-12 GeV on 20 (65 ~140*) GeV	20 GeV on 275 GeV
Luminosity	**7.9 $10^{33} cm^{-2} s^{-1}$**	**2.7 10^{34} $cm^{-2} s^{-1}$**
e-Ion energy	3-12 GeV on 40 GeV (Pb)	20 GeV on 100 GeV (Au)
Luminosity	4.4 $10^{33} cm^{-2} s^{-1}$	1.6 10^{34} $cm^{-2} s^{-1}$

Polarization electron, proton(deuterium) 80%, 70%

What is needed to get there:
? WIP

1.Coherent electron cooling (CeC)

2. Proto-type of super-ferric magnets
(to get to higher energies of p/d)

3.Proof of principle ion beam formation (short bunches)

4.Demonstrate the feasibility of producing high figure 8 beam polarization

*depending on the magnets R&D

What is needed to get there:
~ $2 Billion

1.Coherent electron cooling (CeC)
To achieve high lumi without large beam power loss. Will need to be tested.

2.Energy recovery Linac
(electron accelerator) R&D ongoing

3.Demonstrate the feasibility of producing a 50mA polarized e-beam

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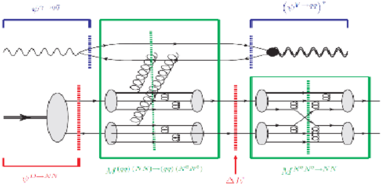
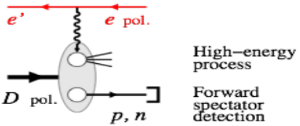
Short range correlations & physics with light nuclei

Exciting area of interest:

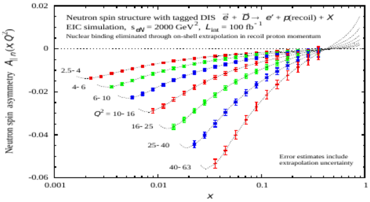
$e + D \rightarrow e' + p + n + J/\psi$

Exclusive measurements of tagged (polarized) protons and neutrons in coincidence with vector mesons probe the short-range quark-gluon nature of nuclear forces





Tag the recoil proton.
Study the neutron's spin structure function.
Other possibilities: Polarized EMC effect with polarized light nuclei



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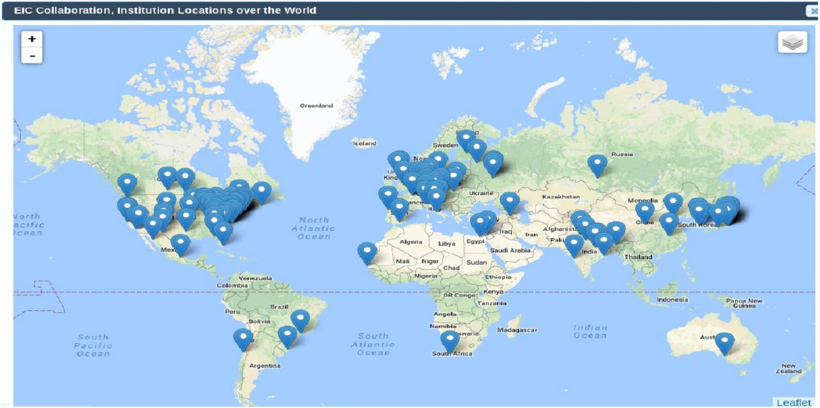
- # Electron Ion Collider Users



map based on mailing list: open for all interested people

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French participation to the EIC

CEA/Saclay:
Detector R&D funded through Temple University (Berndt Surrow's NSF, BNL R&D grant)
LDRD (Laboratory Directed R&D) from BNL with SBU and Saclay on zig-zag patterns for micropatterns detectors (GEM/Micromegas) for the EIC.
Strong-2020 proposal on detector R&D for EIC: ultra-low ion backflow Micromegas for TPC, inside next-DIS work package

CNRS/Orsay: Calorimetry R&D funded through NSF, BNL LDRD grant

IGDORE-RONIN:

- H2020: Detector R&D and saturation physics consolidator ERC submitted by Astrid

- NSF & DOE: R&D and saturation physics proposals will be also submitted in fall by Astrid.