Heavy Ion Physics and the Large Hadron electron Collider

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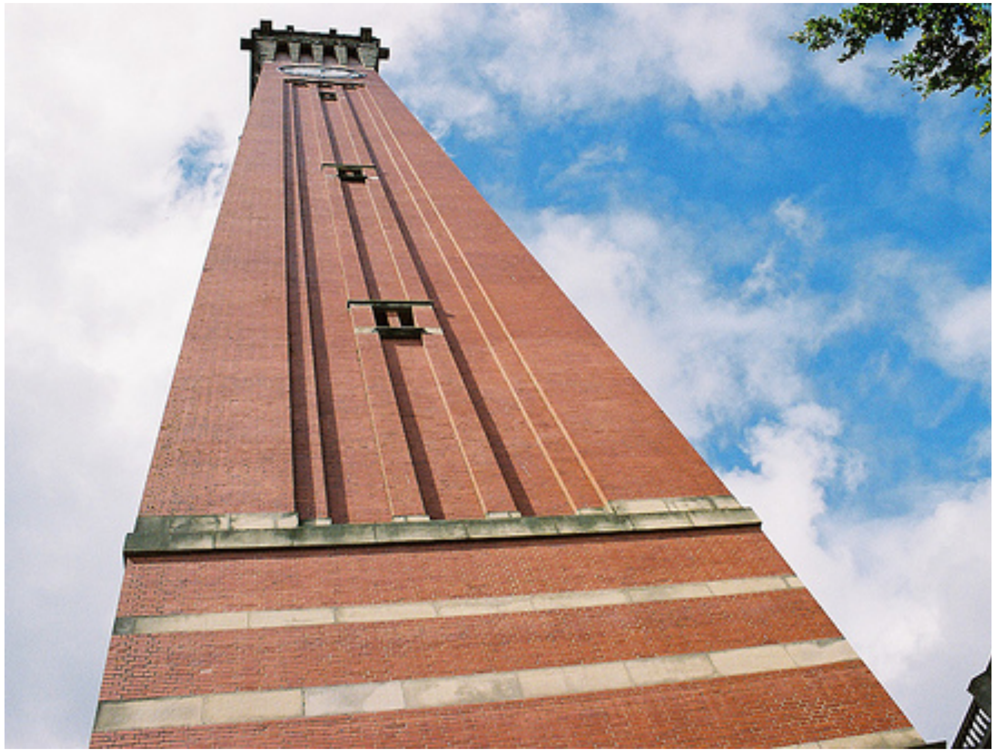


Can we add ep and eA collisions to the existing LHC pp, AA and pA programme?

… for the LHeC Study Group

… towards a full understanding of QCD at high temperatures, baryon and parton densities …

Strangeness in Quark Matter
Birmingham, Tues 23 July 2013

http://cern.ch/lhec

Conceptual Design Report (July 2012)

630 pages, summarising 5 year workshop commissioned by CERN, ECFA and NuPECC

~200 participants, 69 institutes

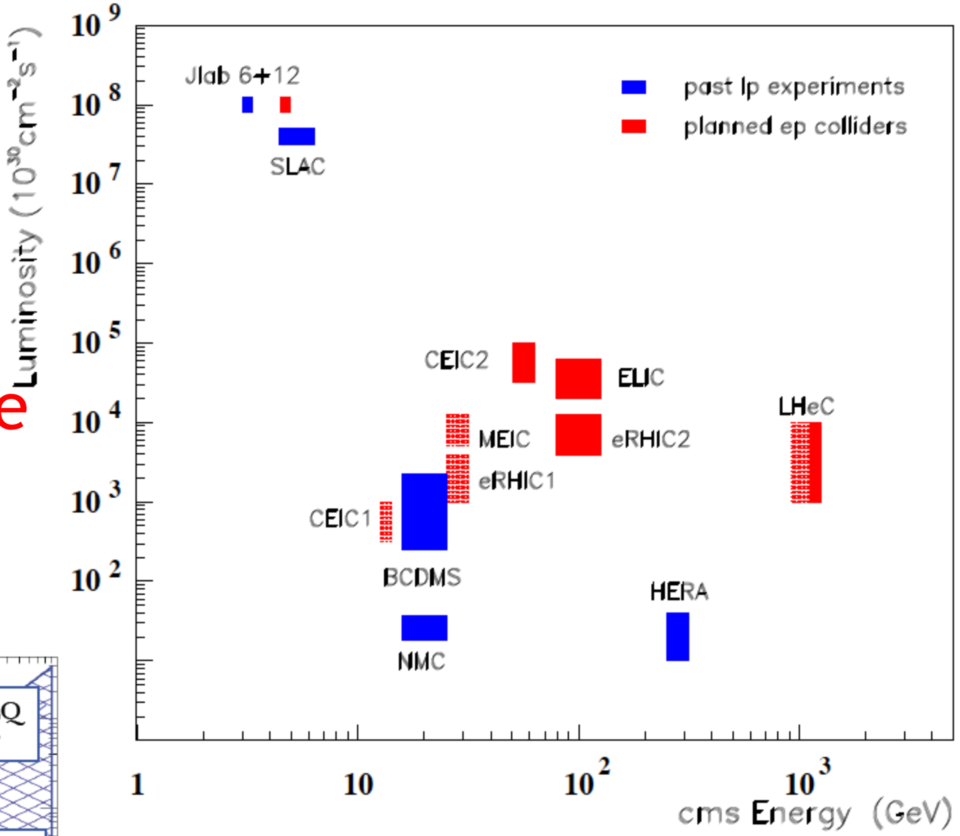
Additional material in subsequent updates:

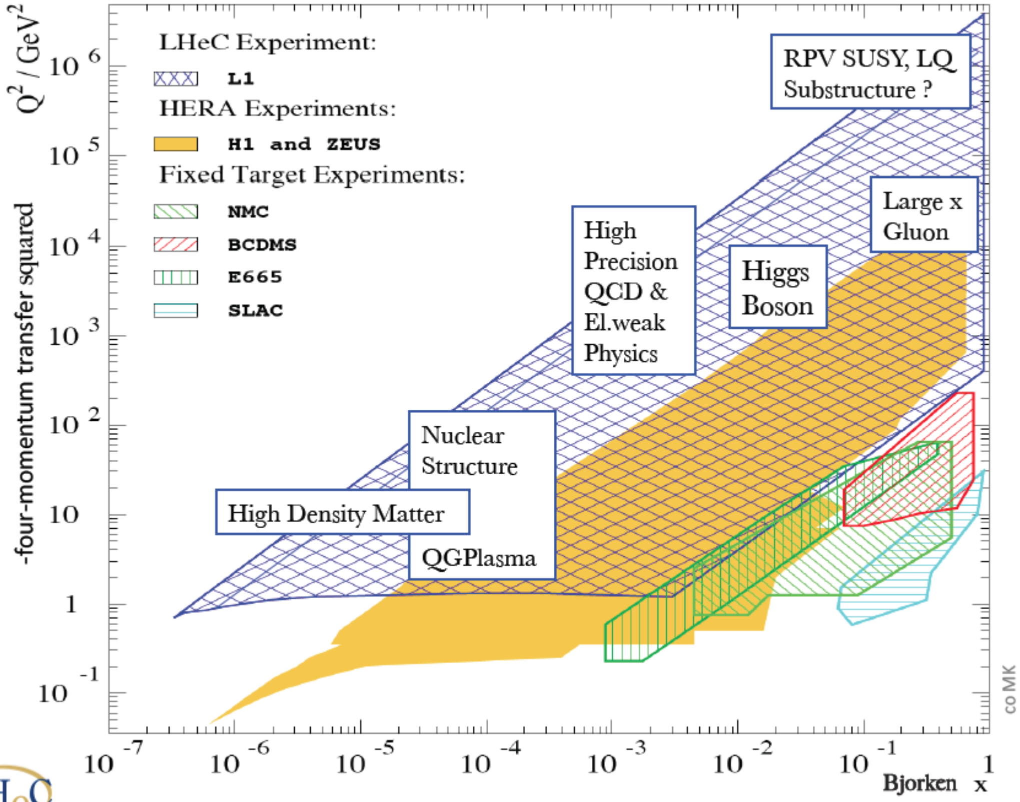
“A Large Hadron Electron Collider at CERN” [arXiv:1211.4831]

“On the Relation of the LHeC and the LHC” [arXiv:1211.5102]

LHeC Context

Latest & most promising idea to take lepton-hadron physics to the TeV centre-of-mass scale … at high luminosity





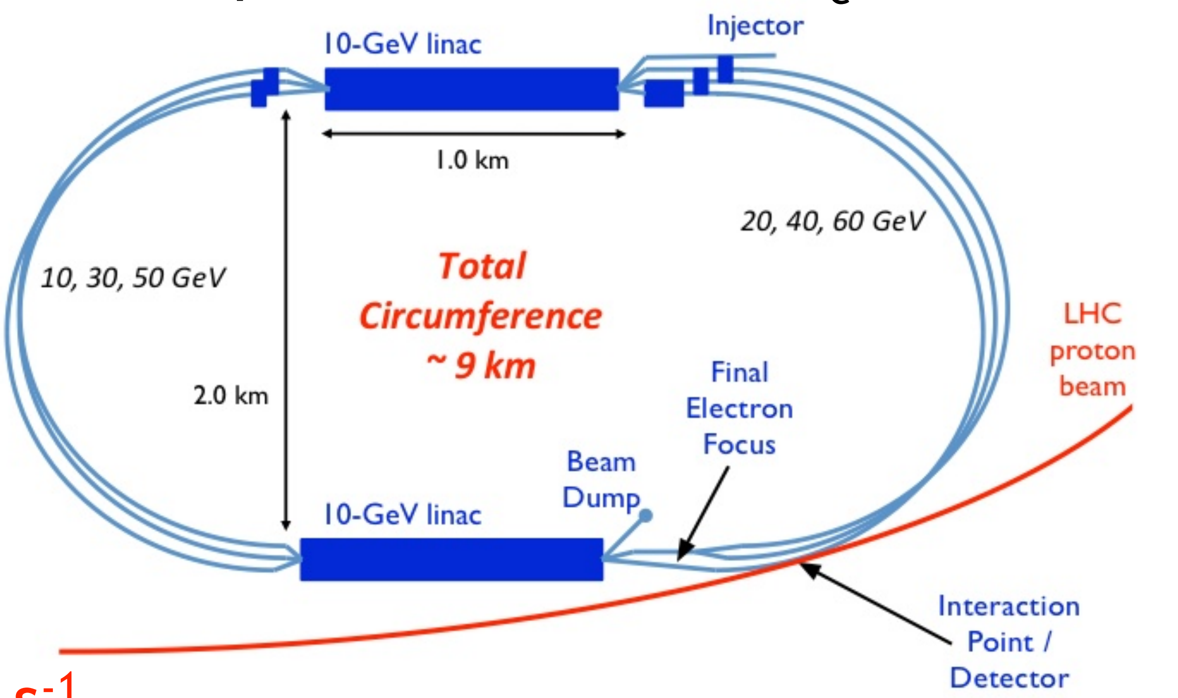
Designed to exploit intense hadron beams in high luminosity phase of LHC running from mid 2020s

Baseline# Design (Electron "Linac")

Design constraint: power consumption < 100 MW → E_e = 60 GeV

- Two 10 GeV linacs,
- 3 returns, 20 MV/m
- Energy recovery in same structures

[CERN plans energy recovery prototype]



- ep Lumi 10^{33} – 10^{34} cm^{-2} s^{-1}

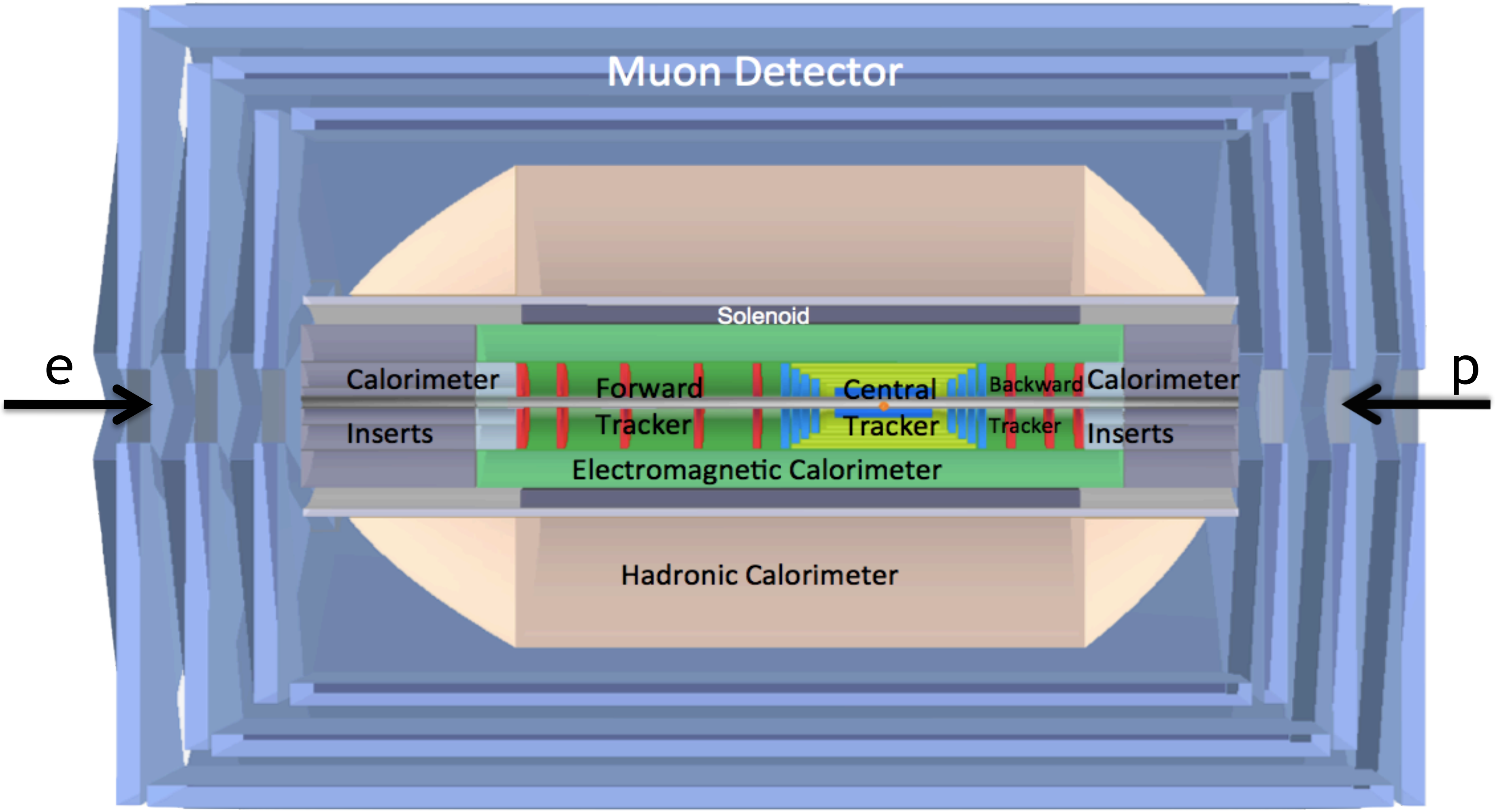
→ 10 - 100 fb^{-1} per year

→ 100 fb^{-1} – 1 ab^{-1} total

- **eD and eA collisions have always been integral to programme**
- **e-nucleon Lumi estimates ~ 10^{31} (10^{32}) cm^{-2} s^{-1} for eD (ePb)**

Alternative designs based on electron ring and on higher energy, lower luminosity, linac also exist

Detector Overview



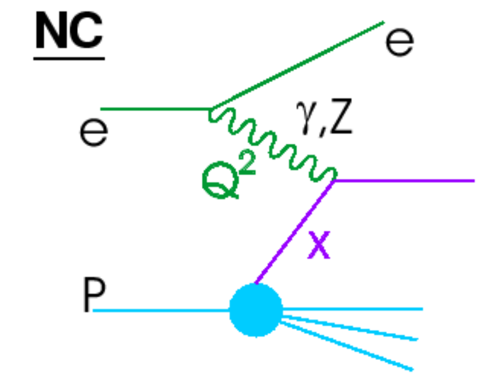
- Forward / backward asymmetry reflecting beam energies
- Present size 14m x 9m (c.f. CMS 21m x 15m, ATLAS 45m x 25m)
- **ZDC, proton spectrometer integral to design from outset**

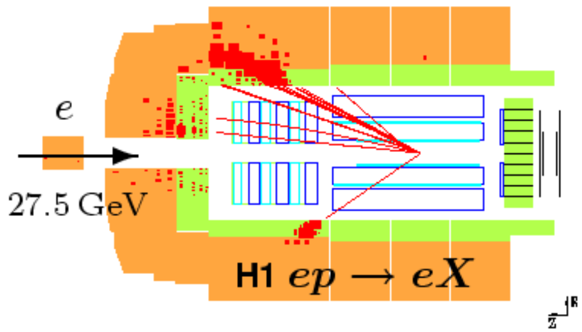
DIS: Parton Microscopy

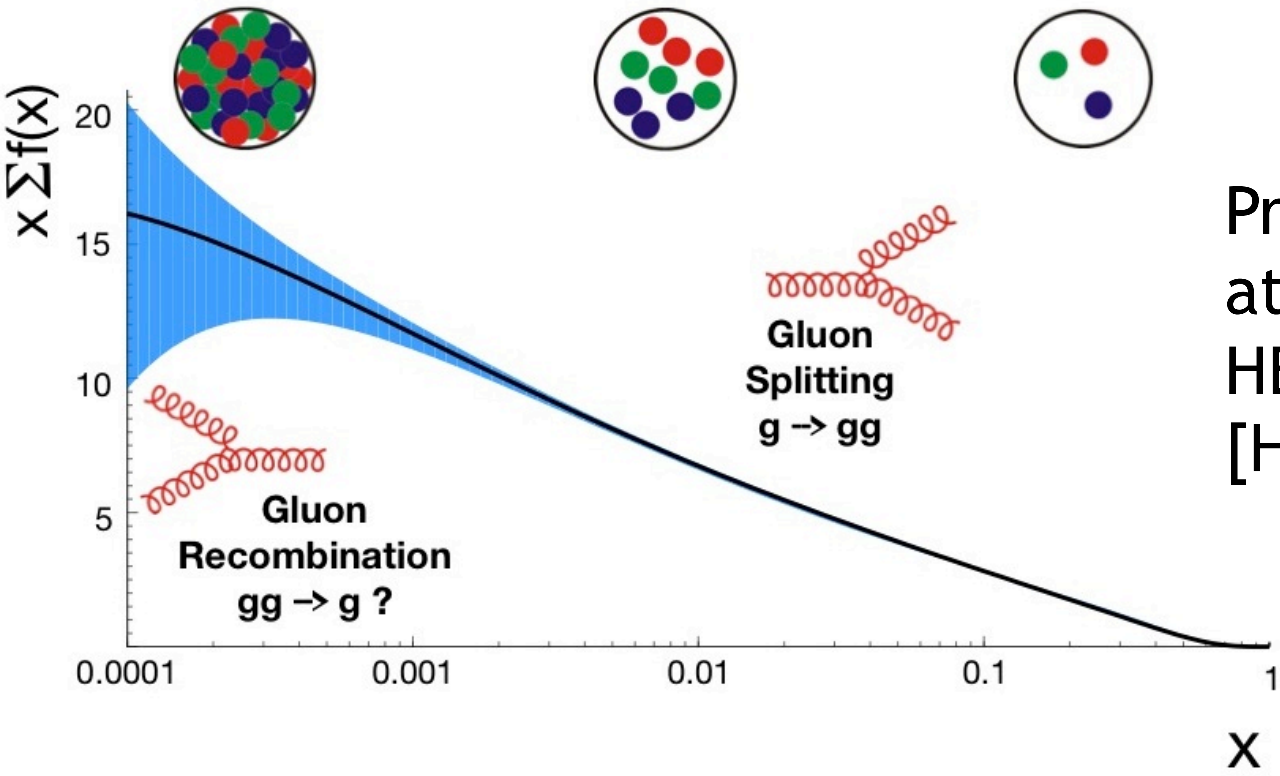
Q^2: exchanged boson resolving power

x: fractional momentum of struck quark

Only previously studied in collider mode and in ep at HERA (1992-2007)



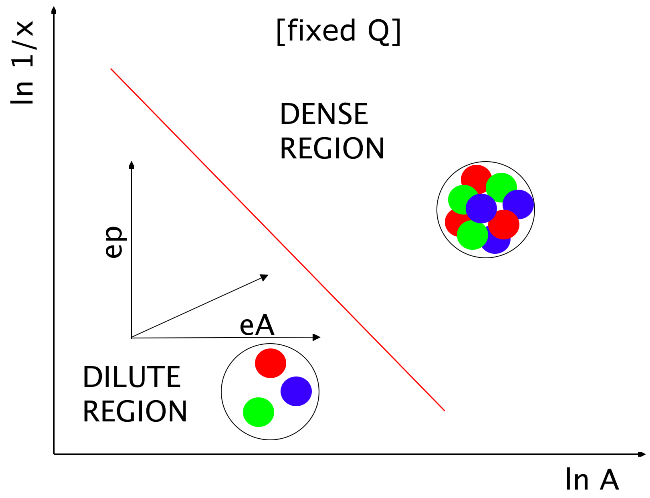




Proton parton density at Q^2 = 10 GeV^2 from HERA data alone [HERAPDF1.5 NNLO]

... Low x saturation?

LHeC Strategy for making the target blacker

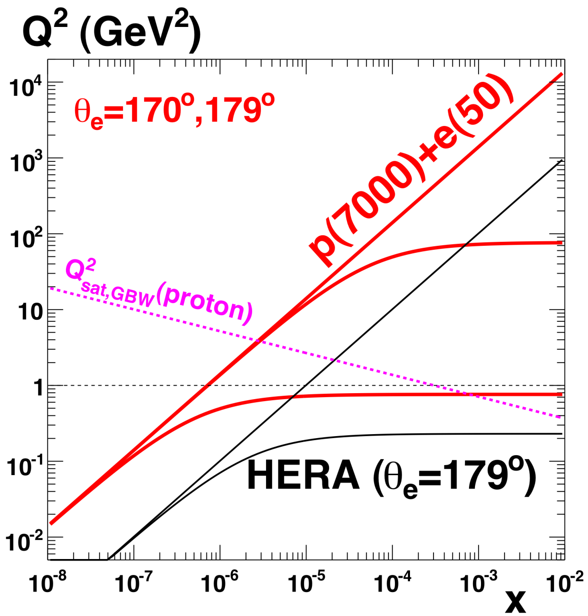


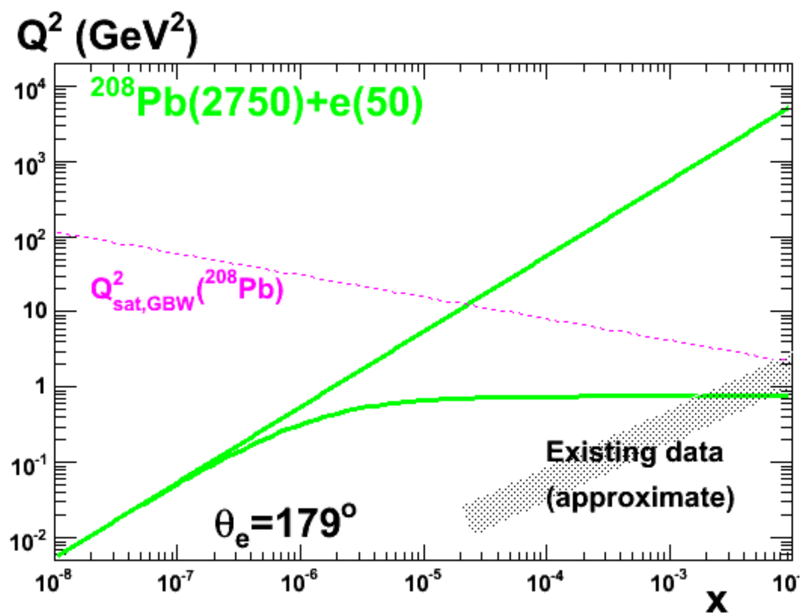
LHeC delivers a 2-pronged approach:

Enhance target `blackness' by:

1) Probing lower x at fixed Q^2 in ep
   [evolution of a single source]

2) Increasing target matter in eA
   [overlapping many sources at fixed kinematics … density ~ $A^{1/3}$ ~ 6 for Pb … worth 2 orders of magnitude in x]

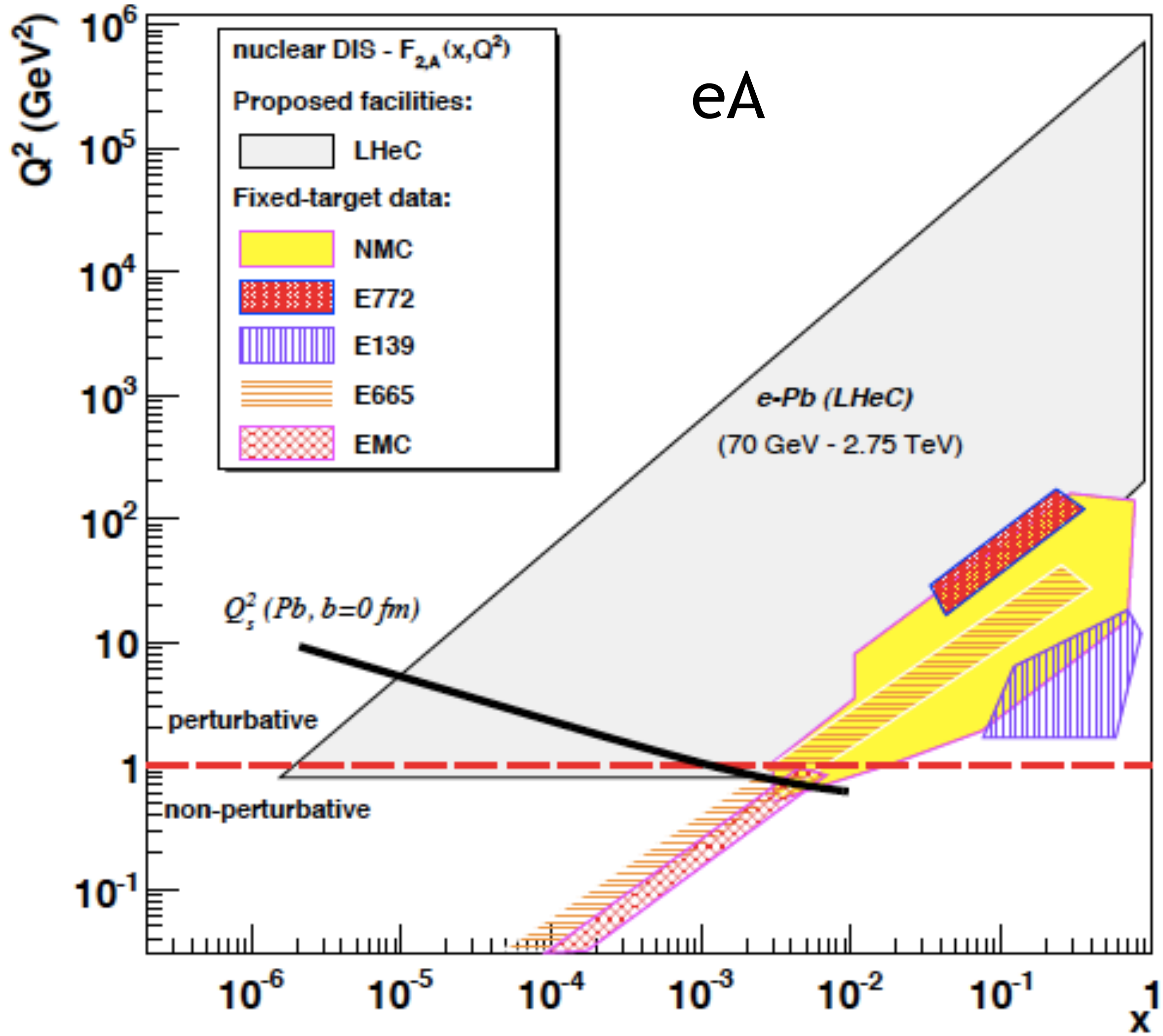




… Reaching saturated region in both ep & eA according to current models

LHeC as an Electron-ion Collider

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

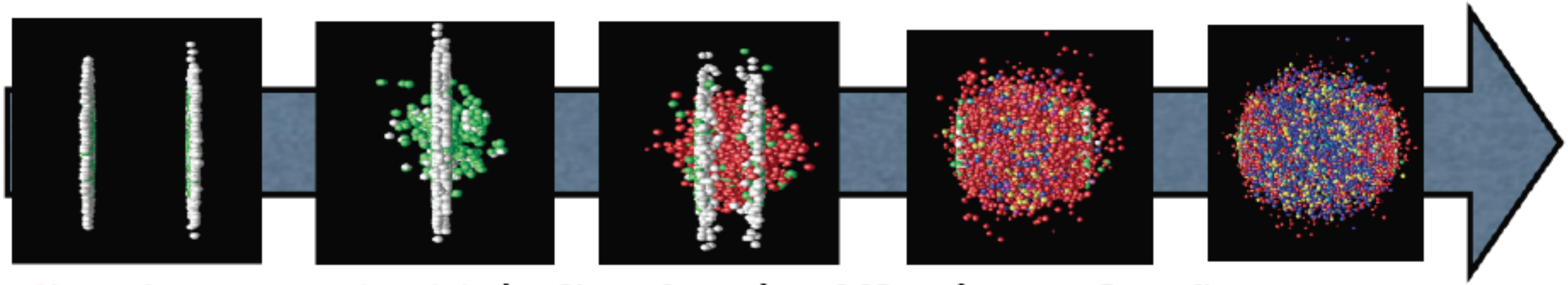


→Revolutionise our view of the partonic structure of nuclear matter.

→ Study interactions of densely packed, but weakly coupled, partons

→Ultra-clean probe of passage of `struck' partons through cold nuclear matter

Relation to the Heavy Ion Programme



Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

- Nuclear wave function at small x: nuclear structure functions.

- Particle production at the very beginning: which factorisation in eA?

- How does the system behave as ~ isotropised so fast?: initial conditions for plasma formation to be studied in eA.

- Probing the medium through energetic particles (jet quenching etc.): modification of QCD radiation and hadronization in the nuclear medium.

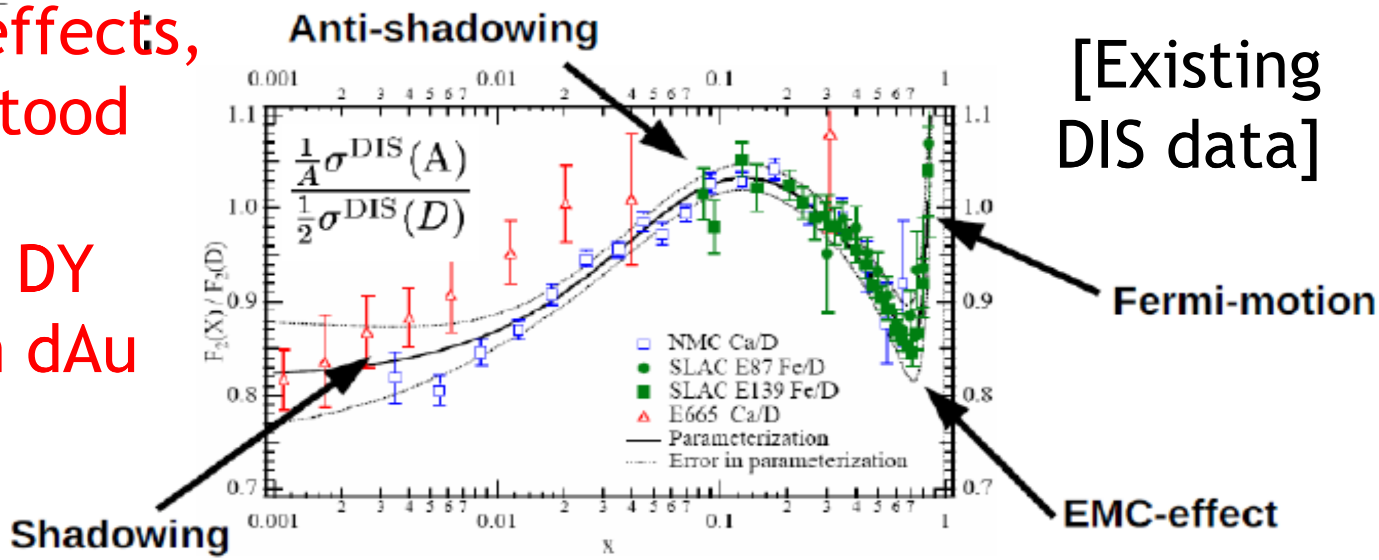
Current Status of Nuclear Parton Densities

- Complex nuclear effects, not yet fully understood

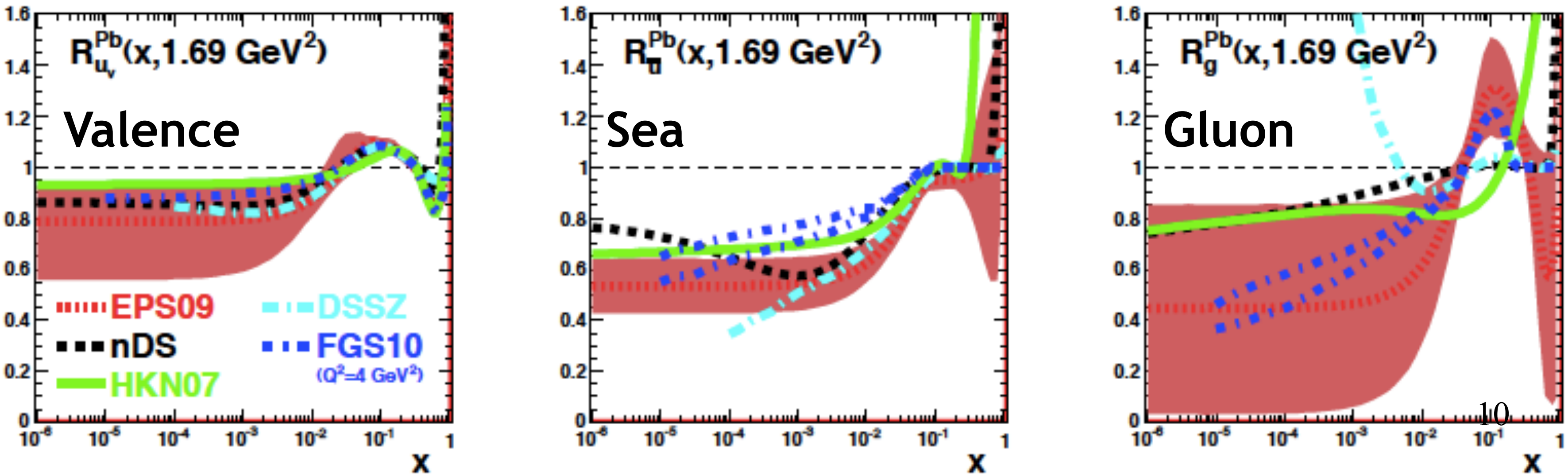
- Quarks from DIS & DY
- Gluon mainly from dAu single π^0 rates

- All partons poorly constrained for $x < 10^{-2}$

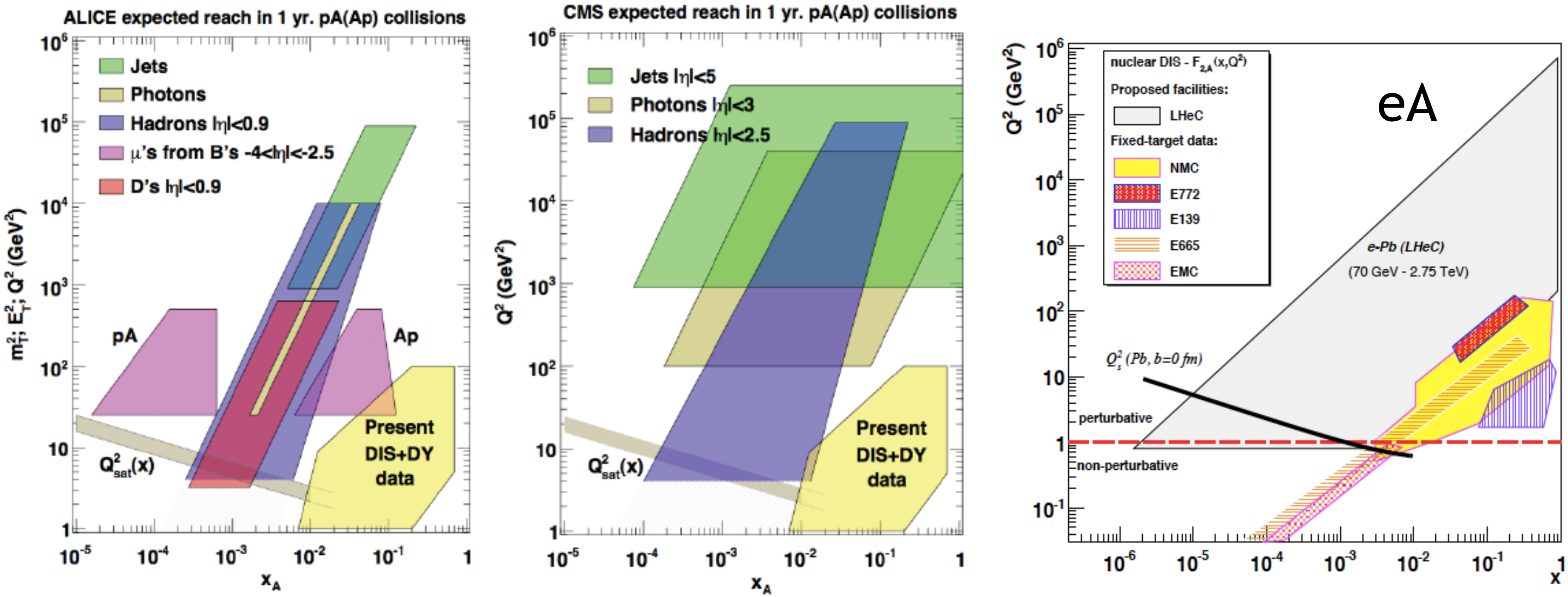
[Existing DIS data]



R_i = Nuclear PDF i / (A * proton PDF i)



Complementarity of pA and eA



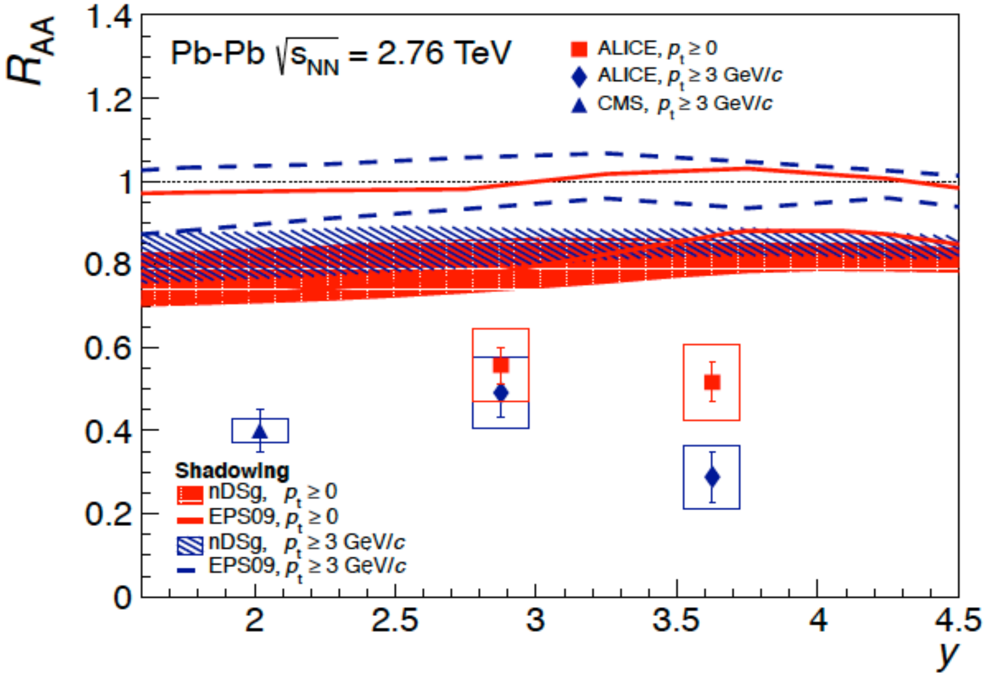
• **New effects likely to be revealed in tensions between eA and pA, AA, ep (breakdown of factorisation)**

• **Detailed precision understanding likely to come from eA**

- LHeC offers access to lower x than is realistically achievable in pA at the LHC
- Clean final states / theoretical control to (N)NLO in QCD

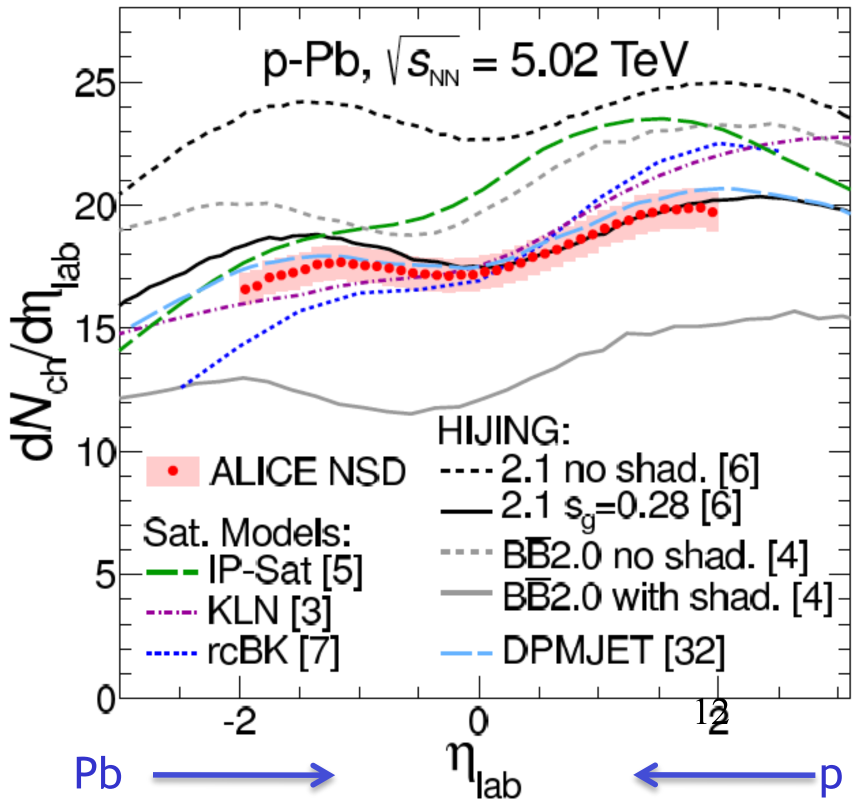
Current Low x Understanding in LHC Ion Data

Inclusive J/Ψ AA data



Uncertainties in low-x nuclear PDFs preclude precision statements on medium produced in AA (e.g. extent of screening of c-cbar potential)

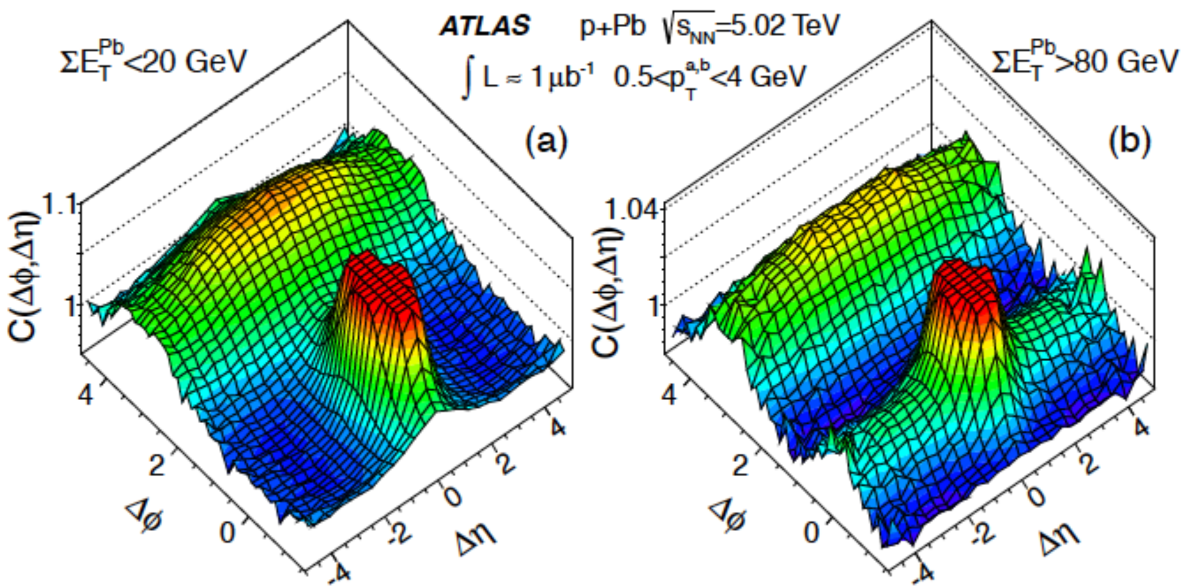
Minimum Bias pA data

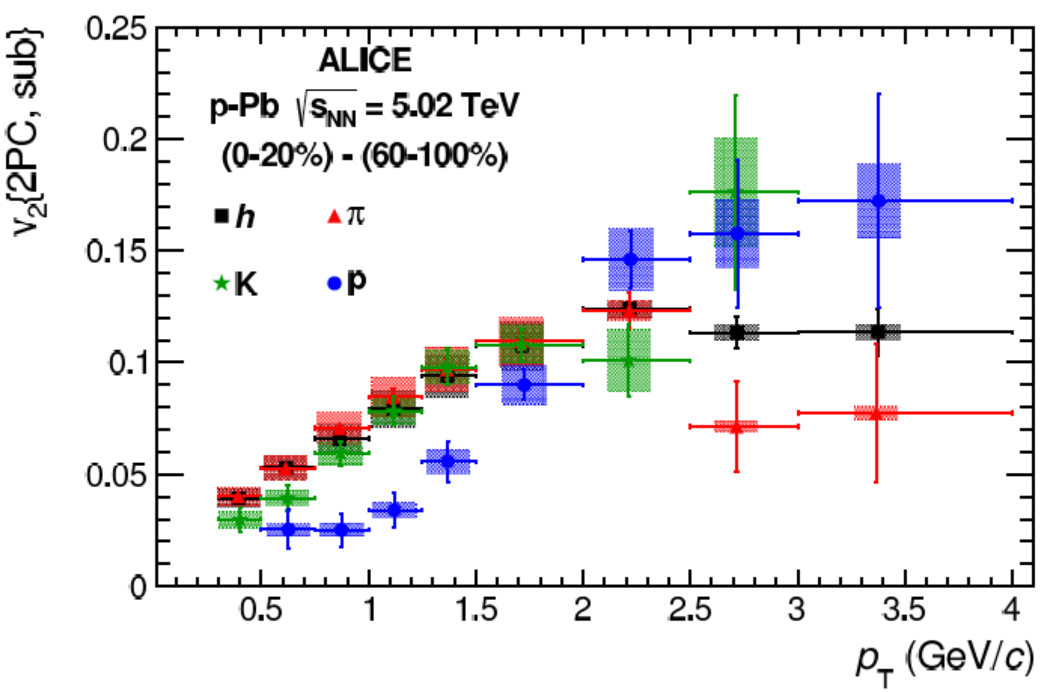


η dependence of pPb charged particle spectra best described by shadowing-only models (saturation models too steep?)

… progress with pPb, but uncertainties still large, detailed situation far from clear

Further Puzzles from pA Data





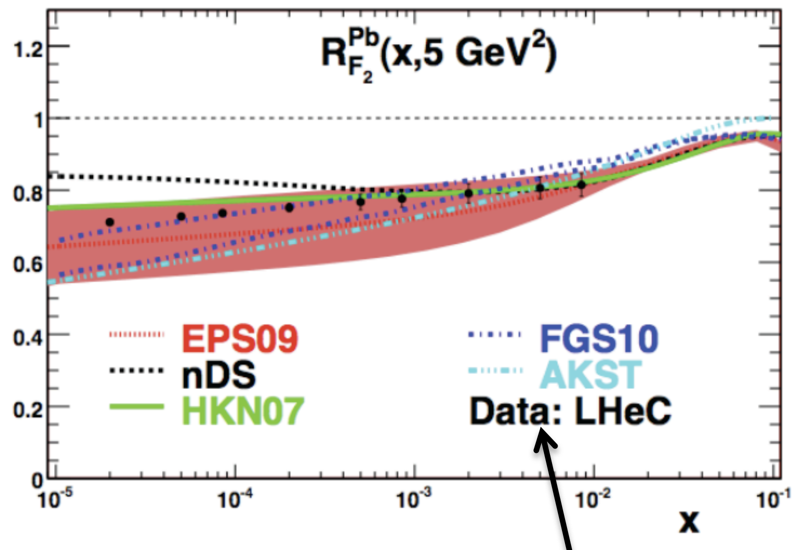
- Surprising ridge structures observed in high multiplicity pPb events have been attributed to saturation effects (CGC …)

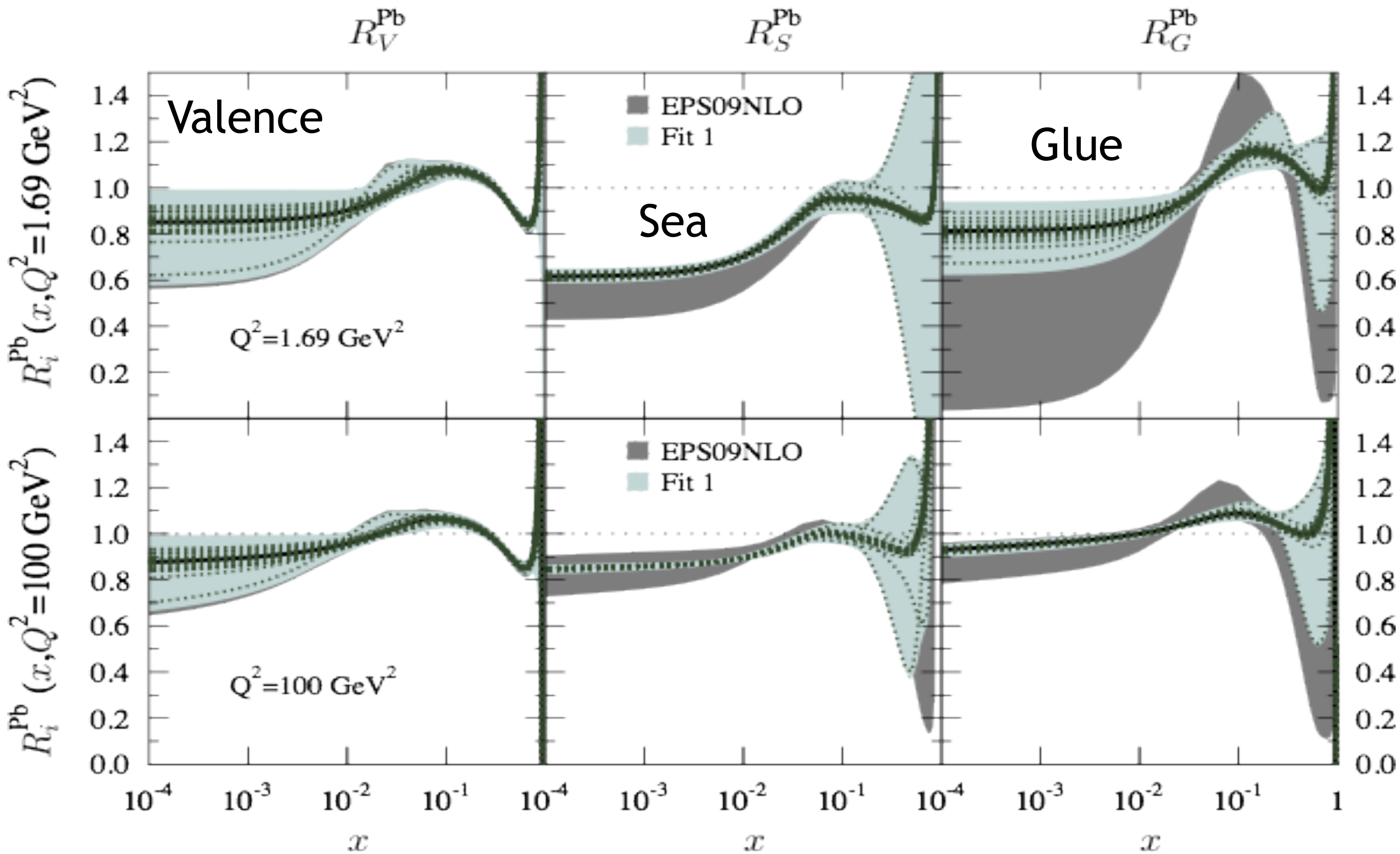
- Flow characteristics in pPb (mass ordering at low p_T) resembles that in PbPb … ascribed to hydrodynamics.

"A lot more needs to be understood about our pA baseline"

Impact of eA F_2 LHeC data

- Simulated LHeC ePb F_2 measurement has huge impact on uncertainties
- Most striking effect for sea & gluons
- High x gluon uncertainty still large



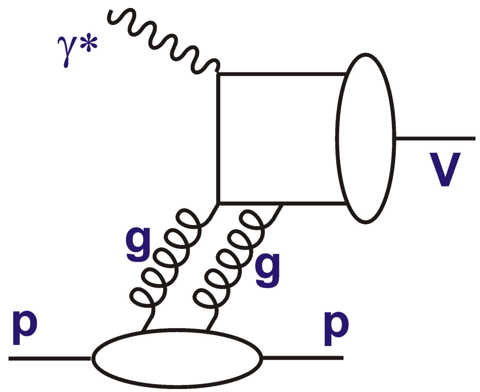


[Example pseudo-data from single Q^2 Value]

[Effects on EPS09 nPDF fit]

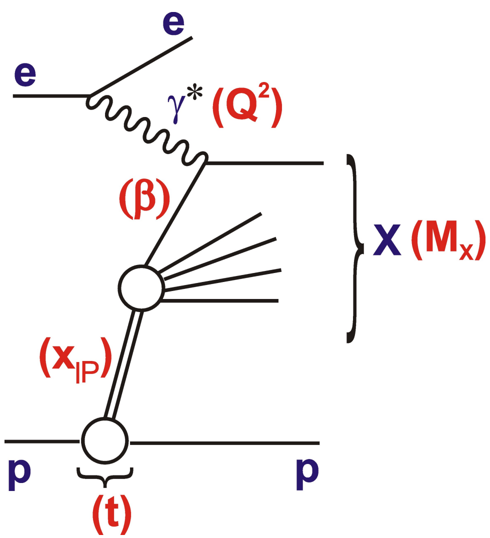
Exclusive / Diffractive Channels and Saturation

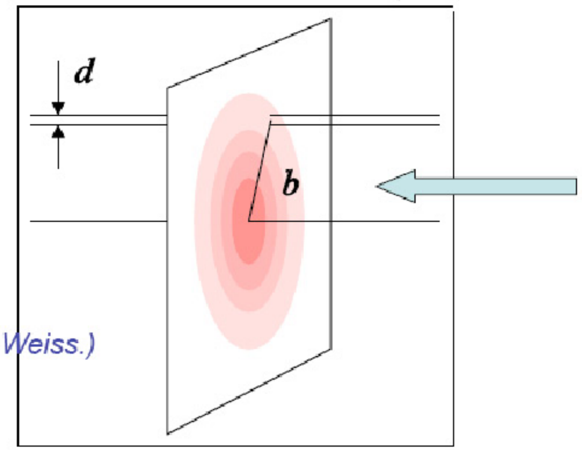
1) [Low-Nussinov] interpretation as 2 gluon exchange enhances sensitivity to low x gluon



2) Additional variable t gives access to impact parameter (b) dependent amplitudes

→ Large t (small b) probes densest packed part of proton?



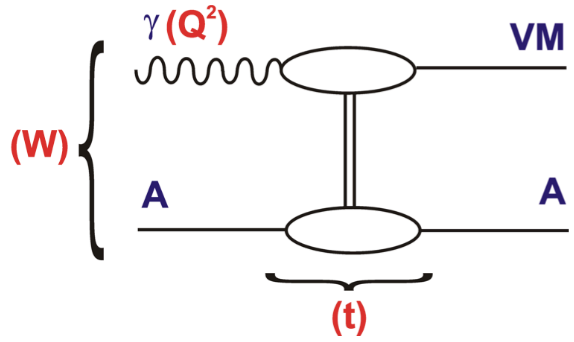


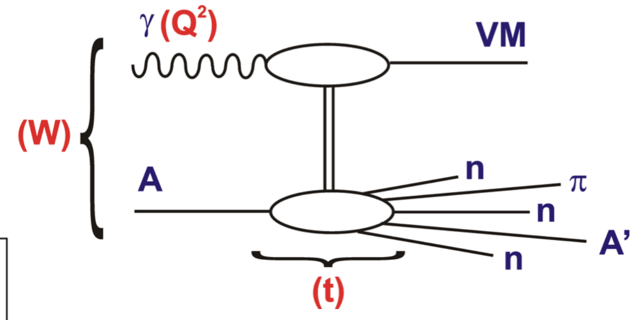
(figure from C. Weiss.)

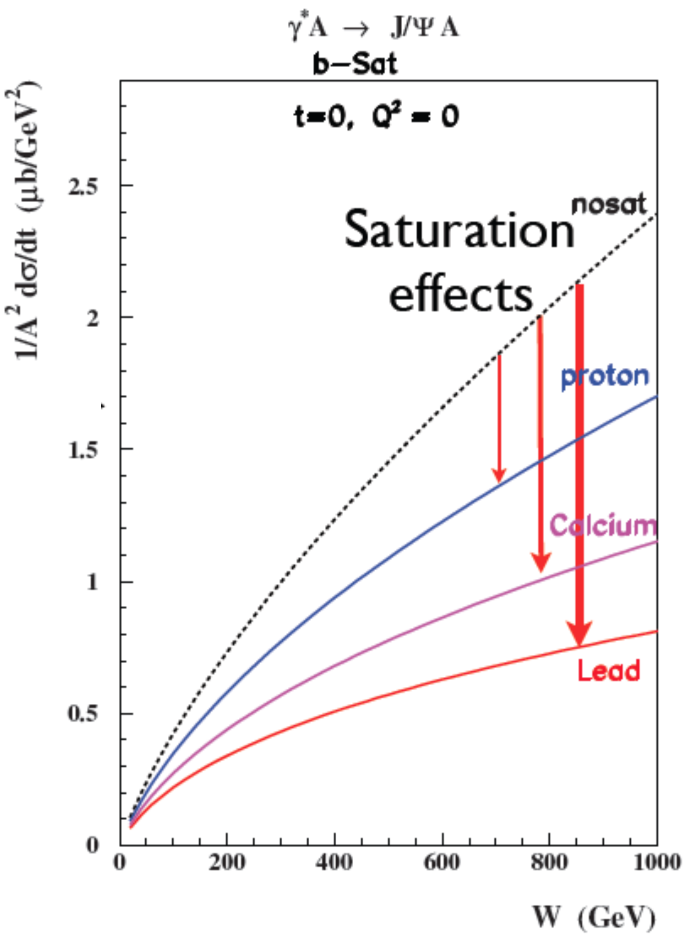
Central black region growing with decrease of x.

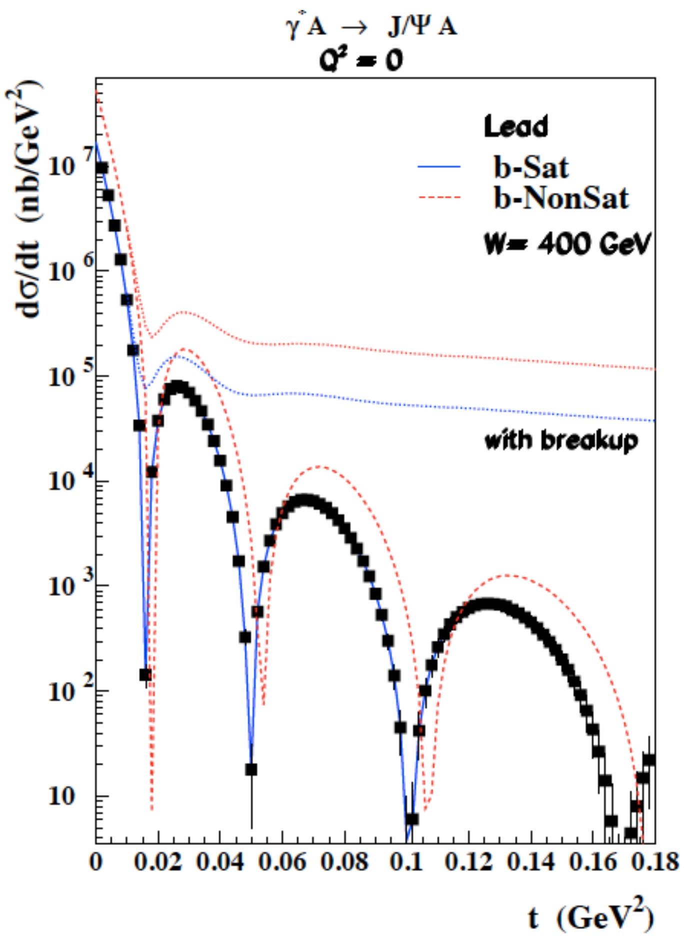
Exclusive Diffraction in eA

Experimentally clear signatures and theoretically cleanly calculable saturation effects in coherent diffraction case (eA → eVA)







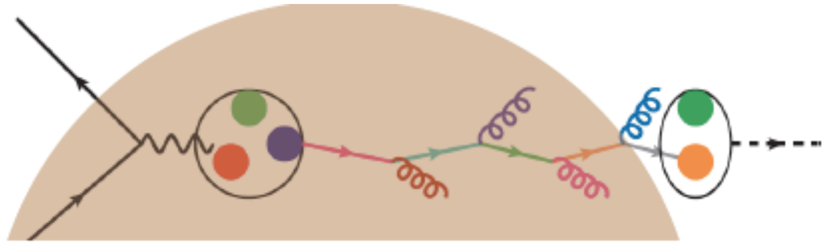


Experimental separation of incoherent diffraction based mainly on ZDC

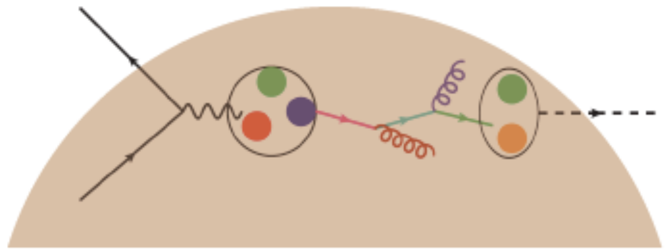
… potential saturation smoking gun?

In-medium radiation and hadronisation effects

How do virtual parton probes lose Virtuality and colour to hadronise?

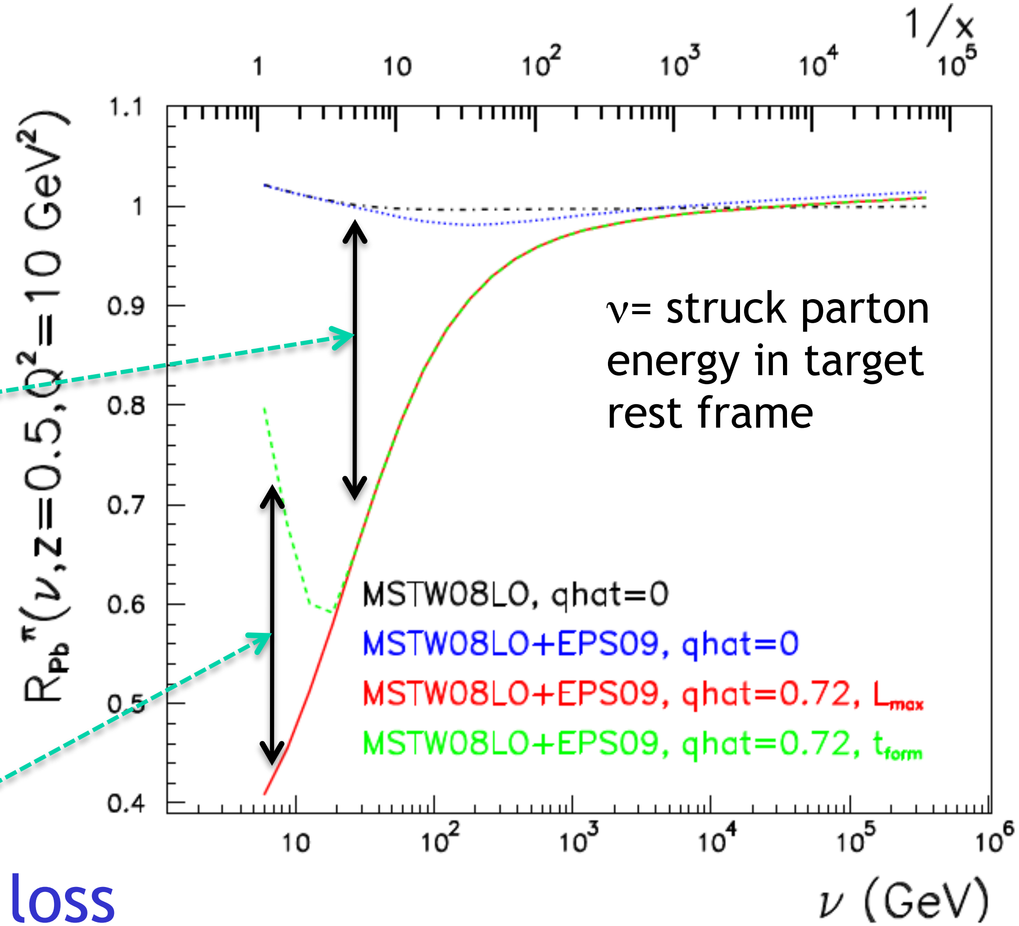


Large ν: Hadronisation beyond medium. Partonic energy loss



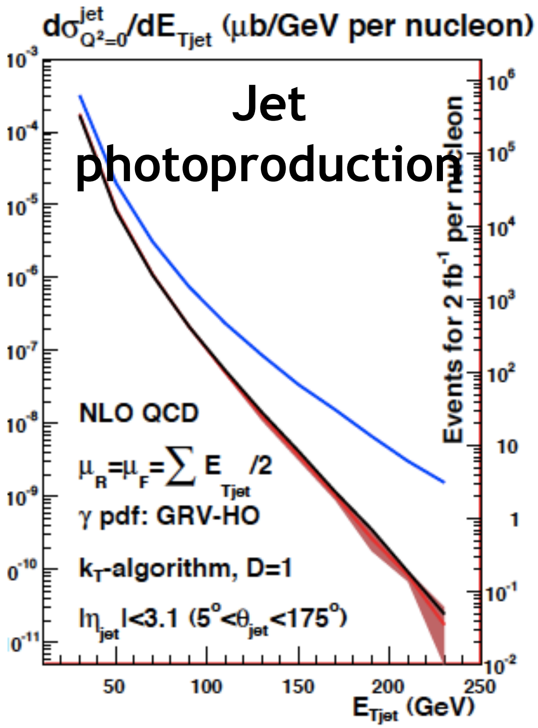
Small ν: Hadron formation may be inside. Hadronic energy loss

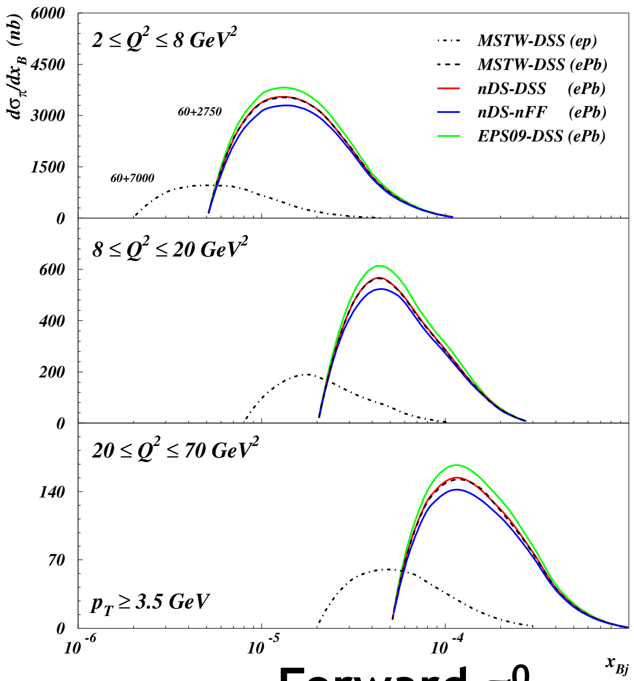
Ratio of π^0 frag^n functions Pb / p (Armesto et al.)



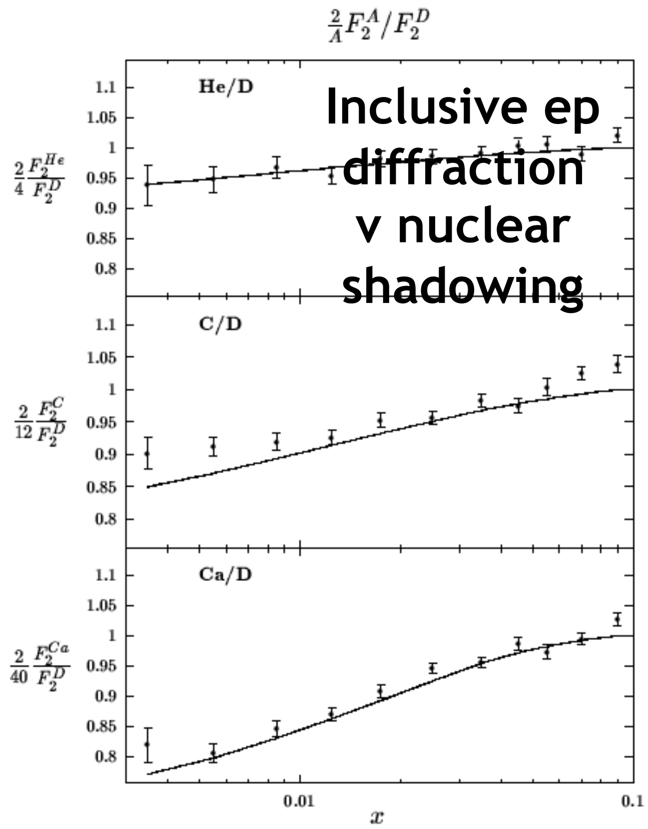
LHeC most sensitive to partonic loss. → Baseline `cold matter' input to use energy loss mechanisms to characterise QGP

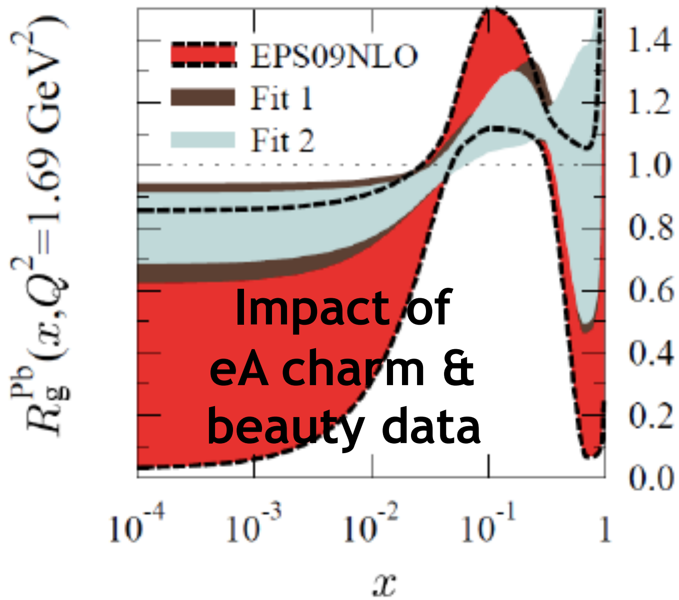
Some other LHeC eA Studies …





Forward π^0 production & fragmentation





Many more processes and observables still to be investigated

Summary / Outlook [More at http://cern.ch/lhec]

- LHC is a new world for heavy ions even more than for protons

- LHeC adds ep and eA to existing pp, pA and AA programme
  - 3-4 orders of magnitude in nPDF kinematic range
  - New non-linear QCD dynamics of low x parton saturation?
  - Baseline for establishing QGP effects

- Conceptual Design Report available.

- Ongoing work …
  - Further physics motivation
  - Detector / simulation,
  - Superconducting RF, ERL, machine

- Timeline?... Optimal impact by running in High Lumi LHC Phase

… with thanks to Nestor Armesto, Max Klein, Anna Stasto and many experimentalist, theorist & accelerator scientist colleagues …

LHeC study group …

J.L.Abelleira Fernandez[16,23], C.Adolphsen[57], P.Adzic[74], A.N.Akay[03], H.Aksakal[39], J.L.Albacete[52], B.Allanach[73], S.Alekhin[17,54], P.Allport[24], V.Andreev[34], R.B.Appleby[14,30], E.Arikan[39], N.Armesto[53,a], G.Azuelos[33,64], M.Bai[37], D.Barber[14,17,24], J.Bartels[18], O.Behnke[17], J.Behr[17], A.S.Belyaev[15,56], I.Ben-Zvi[37], N.Bernard[25], S.Bertolucci[16], S.Bettoni[16], S.Biswal[41], J.Blümlein[17], H.Böttcher[17], A.Bogacz[36], C.Bracco[16], J.Bracinik[06], G.Brandt[44], H.Braun[65], S.Brodsky[57,b], O.Brüning[16], E.Bulyak[12], A.Buniatyan[17], H.Burkhardt[16], I.T.Cakir[02], O.Cakir[01], R.Calaga[16], A.Caldwell[70], V.Cetinkaya[01], V.Chekelian[70], E.Ciapala[16], R.Ciftci[01], A.K.Ciftci[01], B.A.Cole[38], J.C.Collins[48], O.Dadoun[42], J.Dainton[24], A.De.Roeck[16], D.d'Enterria[16], P.DiNezza[72], M.D'Onofrio[24], A.Dudarev[16], A.Eide[60], R.Enberg[63], E.Eroglu[62], K.J.Eskola[21], L.Favart[08], M.Fitterer[16], S.Forte[32], A.Gaddi[16], P.Gambino[59], H.García Morales[16], T.Gehrmann[69], P.Gladkikh[12], C.Glasman[28], A.Glazov[17], R.Godbole[35], B.Goddard[16], T.Greenshaw[24], A.Guffanti[13], V.Guzey[19,36], C.Gwenlan[44], T.Han[50], Y.Hao[37], F.Haug[16], W.Herr[16], A.Hervé[27], B.J.Holzer[16], M.Ishitsuka[58], M.Jacquet[42], B.Jeanneret[16], E.Jensen[16], J.M.Jimenez[16], J.M.Jowett[16], H.Jung[17], H.Karadeniz[02], D.Kayran[37], A.Kilic[62], K.Kimura[58], R.Klees[75], M.Klein[24], U.Klein[24], T.Kluge[24], F.Kocak[62], M.Korostelev[24], A.Kosmicki[16], P.Kostka[17], H.Kowalski[17], M.Kraemer[75], G.Kramer[18], D.Kuchler[16], M.Kuze[58], T.Lappi[21,c], P.Laycock[24], E.Levichev[40], S.Levonian[17], V.N.Litvinenko[37], A.Lombardi[16], J.Maeda[58], C.Marquet[16], B.Mellado[27], K.H.Mess[16], A.Milanese[16], J.G.Milhano[76], S.Moch[17], I.I.Morozov[40], Y.Muttoni[16], S.Myers[16], S.Nandi[55], Z.Nergiz[39], P.R.Newman[06], T.Omori[61], J.Osborne[16], E.Paoloni[49], Y.Papaphilippou[16], C.Pascaud[42], H.Paukkunen[53], E.Perez[16], T.Pieloni[23], E.Pilicer[62], B.Pire[45], R.Placakyte[17], A.Polini[07], V.Ptitsyn[37], Y.Pupkov[40], V.Radescu[17], S.Raychaudhuri[35], L.Rinolfi[16], E.Rizvi[71], R.Rohini[35], J.Rojo[16,31], S.Russenschuck[16], M.Sahin[03], C.A.Salgado[53,a], K.Sampei[58], R.Sassot[09], E.Sauvan[04], M.Schaefer[75], U.Schneekloth[17], T.Schörner-Sadenius[17], D.Schulte[16], A.Senol[22], A.Seryi[44], P.Sievers[16], A.N.Skrinsky[40], W.Smith[27], D.South[17], H.Spiesberger[29], A.M.Stasto[48,d], M.Strikman[48], M.Sullivan[57], S.Sultansoy[03,e], Y.P.Sun[57], B.Surrow[11], L.Szymanowski[66,f], P.Taels[05], I.Tapan[62], T.Tasci[22], E.Tassi[10], H.Ten.Kate[16], J.Terron[28], H.Thiesen[16], L.Thompson[14,30], P.Thompson[06], K.Tokushuku[61], R.Tomás García[16], D.Tommasini[16], D.Trbojevic[37], N.Tsoupas[37], J.Tuckmantel[16], S.Turkoz[01], T.N.Trinh[47], K.Tywoniuk[26], G.Unel[20], T.Ullrich[37], J.Urakawa[61], P.VanMechelen[05], A.Variola[52], R.Veness[16], A.Vivoli[16], P.Vobly[40], J.Wagner[66], R.Wallny[68], S.Wallon[43,46,f], G.Watt[69], C.Weiss[36], U.A.Wiedemann[16], U.Wienands[57], F.Willeke[37], B.-W.Xiao[48], V.Yakimenko[37], A.F.Zarnecki[67], Z.Zhang[42], F.Zimmermann[16], R.Zlebcik[51], F.Zomer[42]