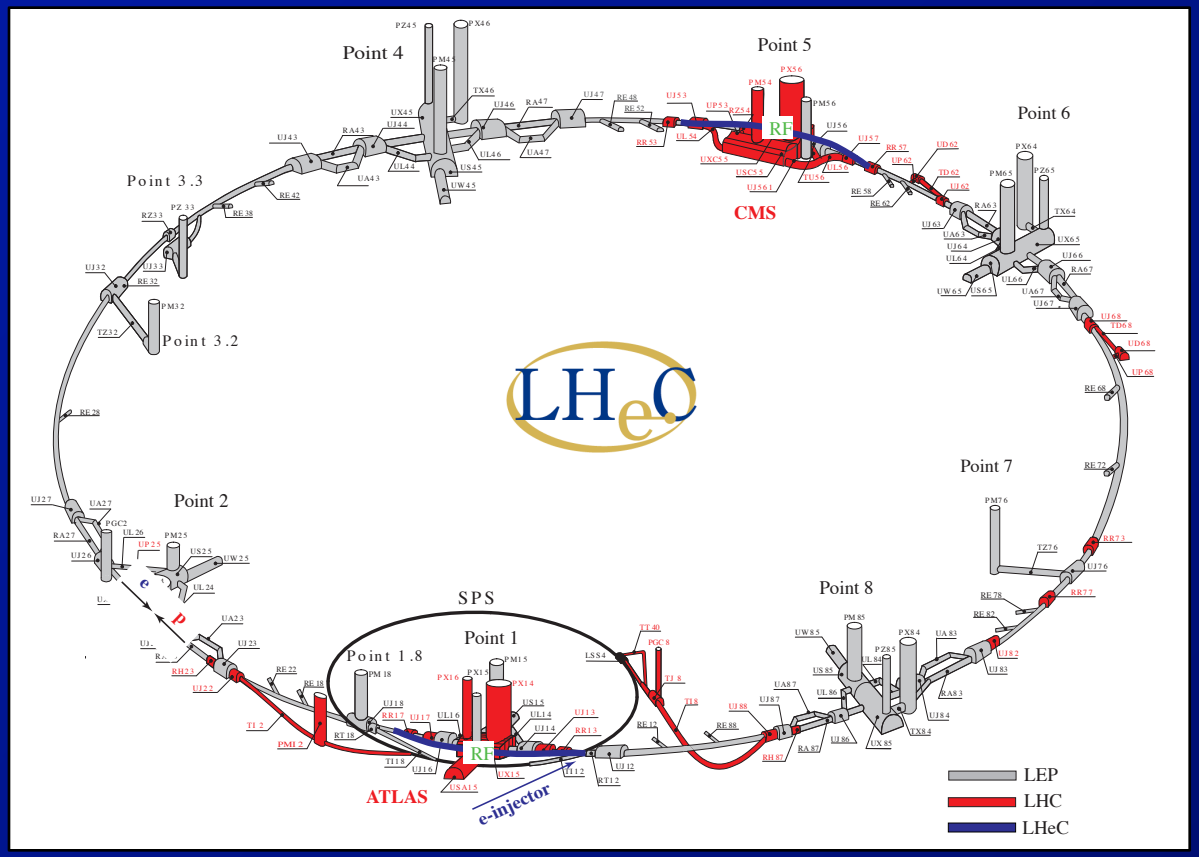
Small-x physics at the Large Hadron electron Collider

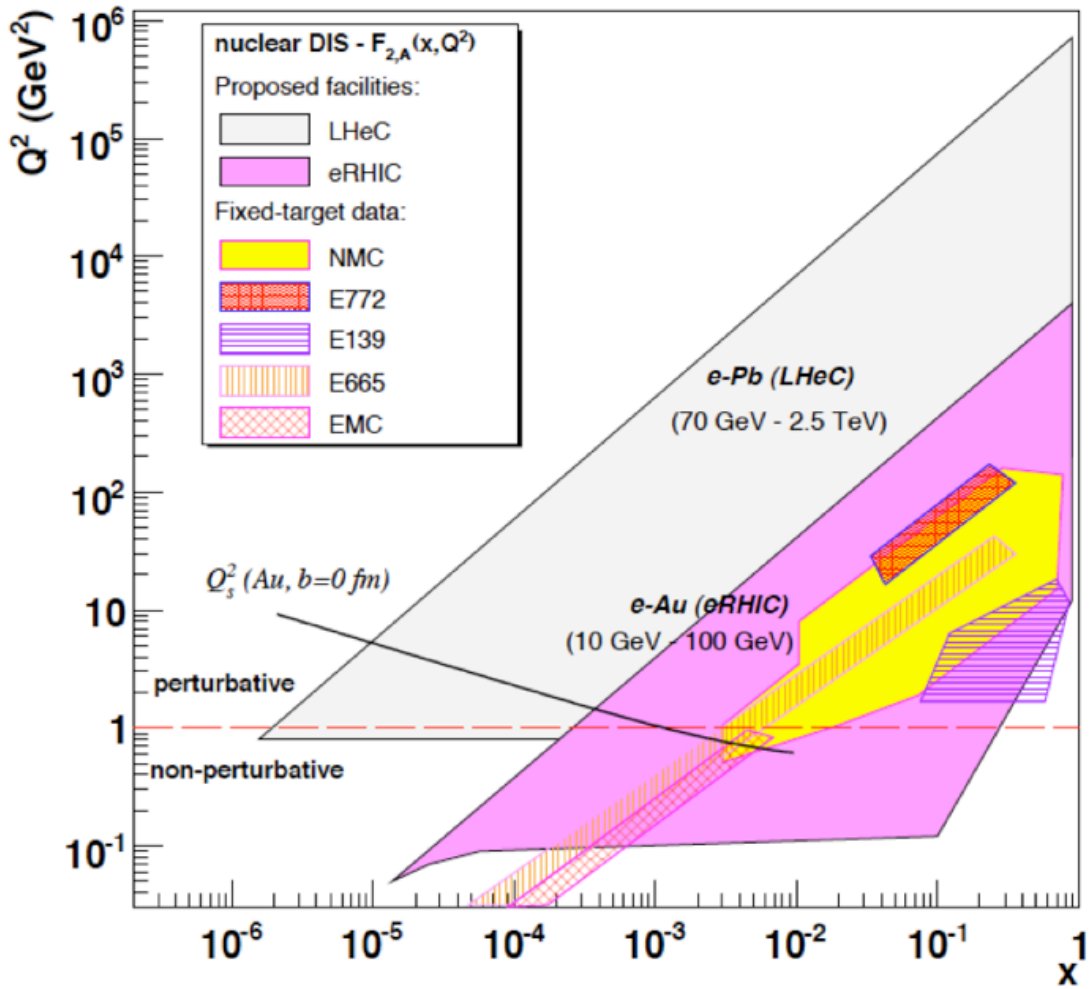


Nestor Armesto and Brian Cole

on behalf of LHeC working group and High Parton Density/low-x WG conveners:

N. Armesto, B. Cole,
P. Newman, A. Stasto

LHeC Scope



x: fractional parton momentum
Q^2: -four momentum transfer^2

electrons (and positions ?) with polarization:
- maximum energy 50-140 GeV

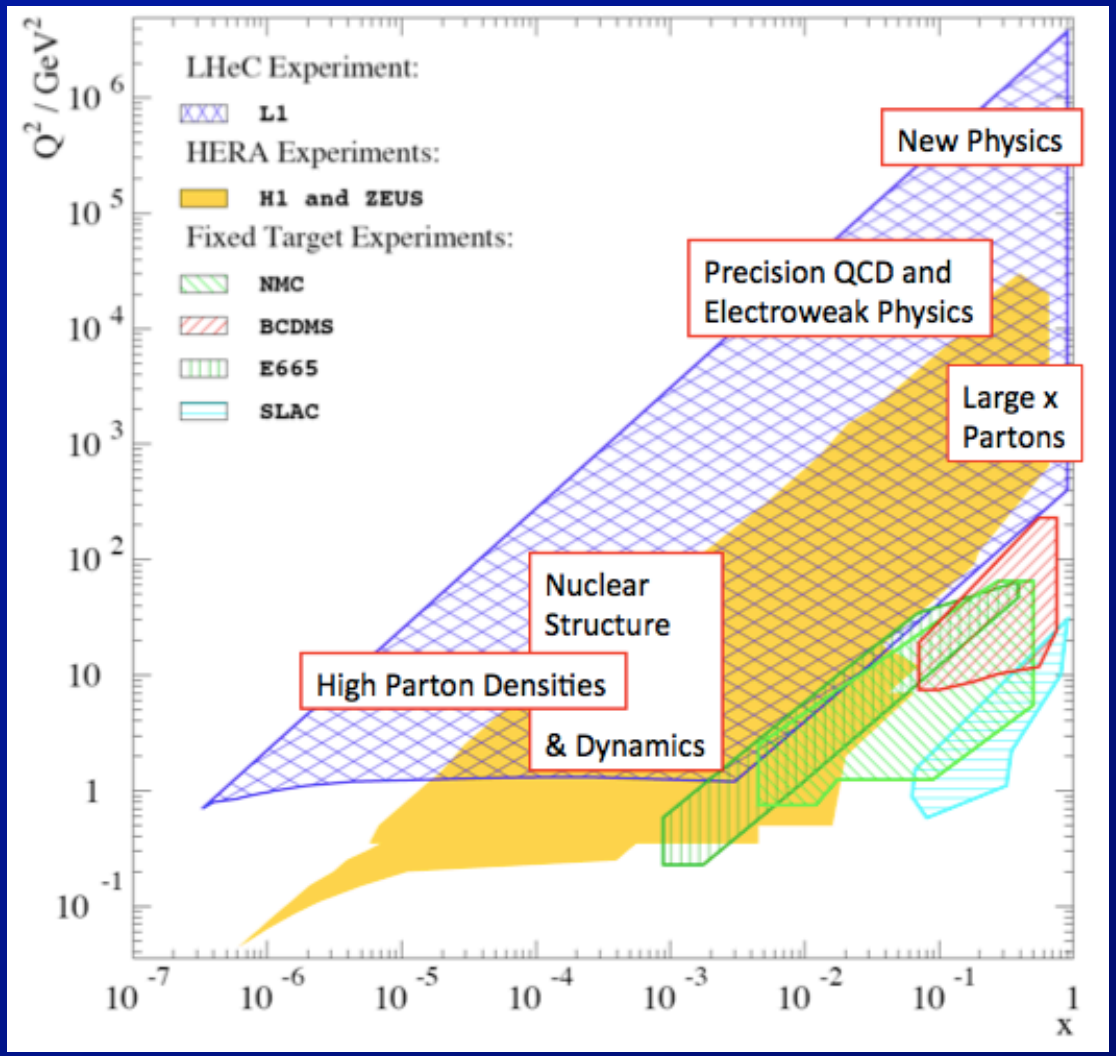
on protons:
- maximum energy 7 Tev

on nuclei:
- maximum energy 2.75 TeV / A for Pb

on deuterons:
- maximum energy 3.5 TeV / A

- See www.lhec.org.uk

LHeC physics program

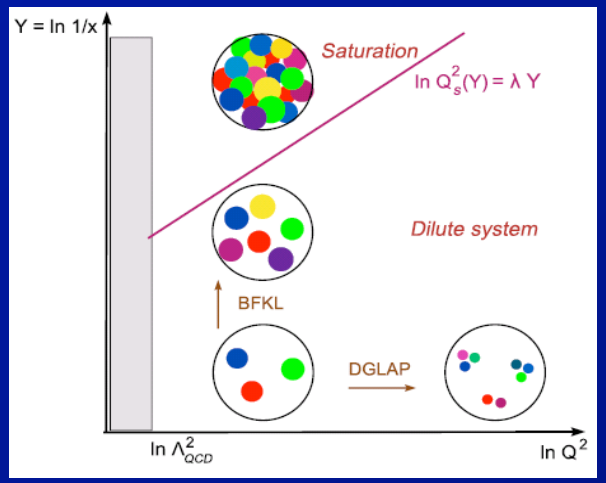


- Proton structure to a few 10^{-20} m:
  - ⇒Q2 lever arm.
- Precision QCD& EW
- High-mass frontier
  - ⇒leptoquarks, excited fermions contact interactions).
- Ultra-low x
  - ⇒access a novel regime of matter predicted by QCD.
- Precision studies of partons in nuclei
  - ⇒A+A initial state

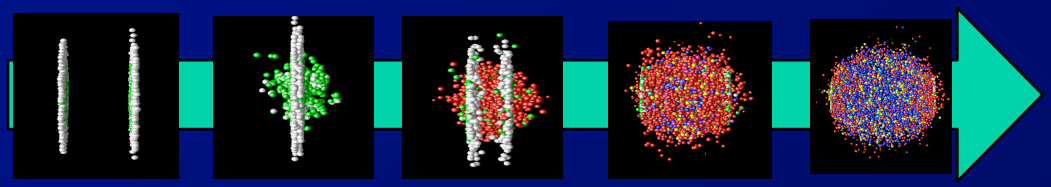
LHeC Physics Program

- **Precision standard model measurements**
  - Precision α_s, effective couplings, flavor dependence
  - Precision Higgs measurements
- **Beyond SM physics**
  - Lepto-quarks, contact interactions, excited fermions
  - R-parity violating SUSY
- **Precision measurements of proton structure**
  - HERA++ (esp. charged current measurements)
  - Neutron PDFs via deuteron w/ forward proton tagging
- **High Parton Density**
  - Evolution @ low x, non-linear evolution (saturation)
- **Nuclear PDFs and SIDIS**
  - Improved PDFs, $g^A(x, Q^2)$ via F_L and F_2^c
  - Evolution & fragmentation of quark in nucleus

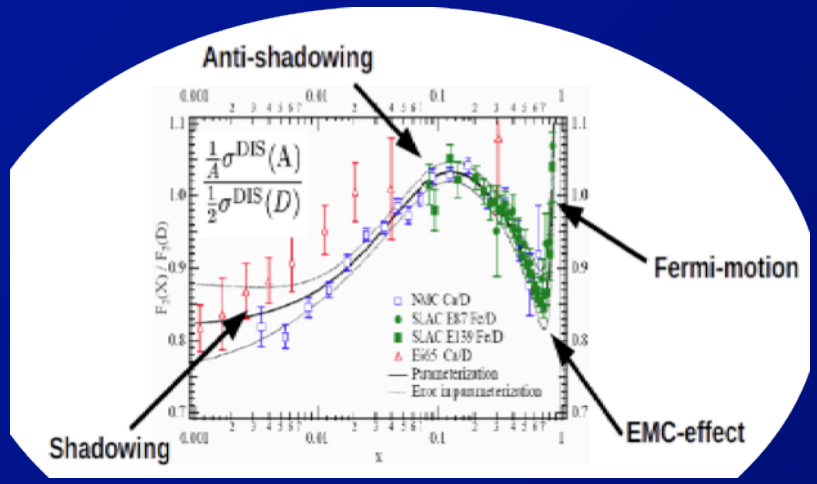
Nuclear Physics Program



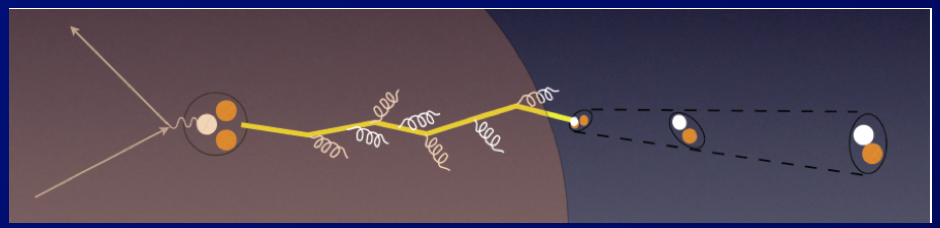
QCD @ high parton density (unitarity limit), parton saturation in nucleons and nuclei



Measure the initial state leading to (strong coupled) quark gluon plasma



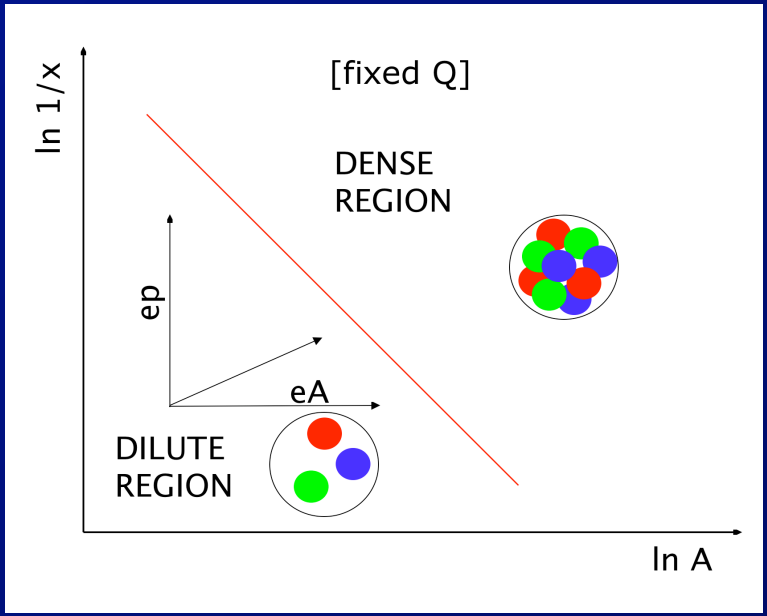
Study evolution of struck quark in nucleus over large range of ν, Q^2

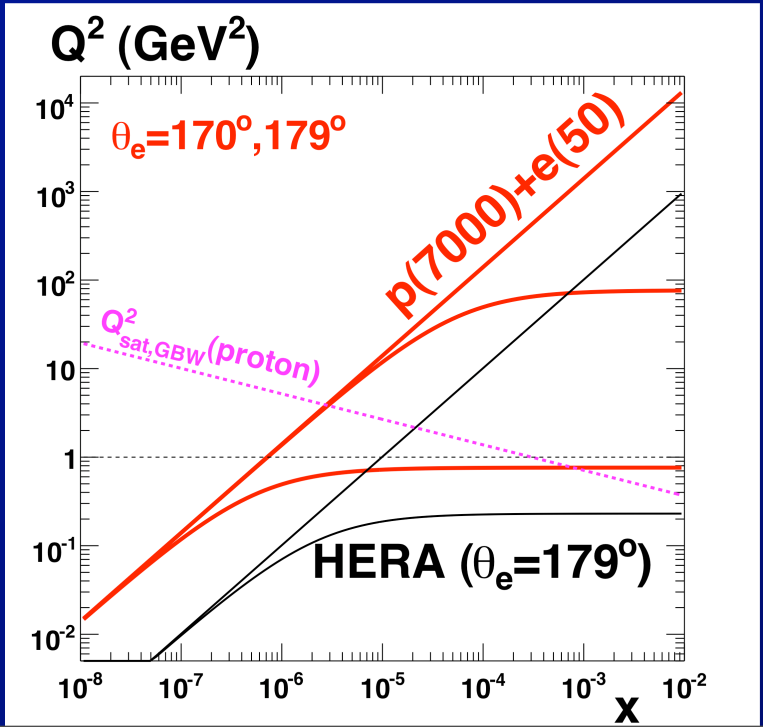


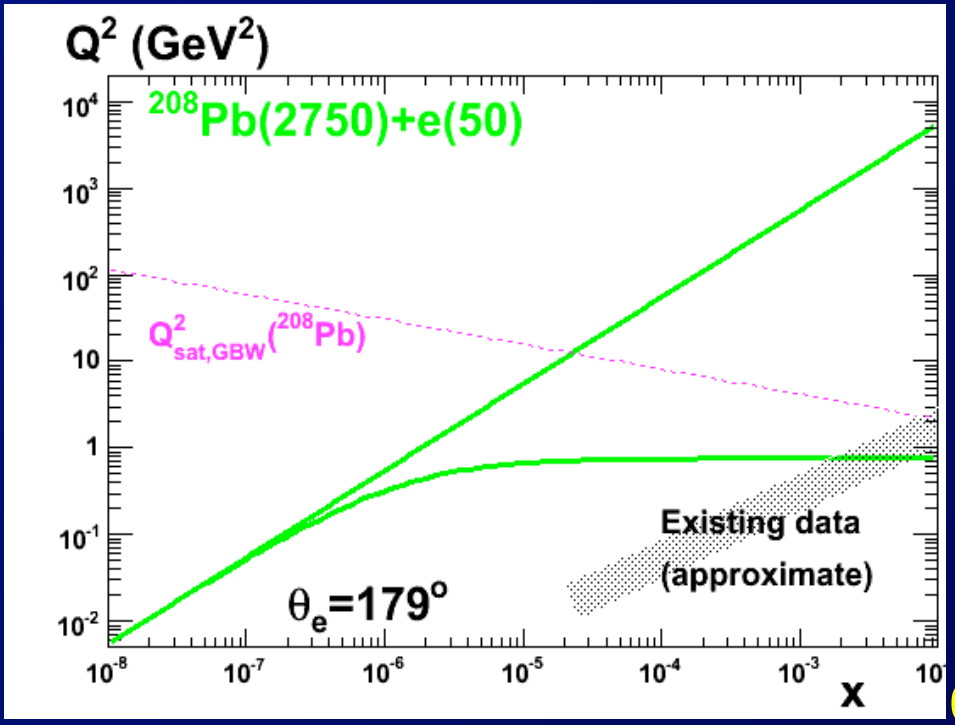
Precision nuclear and neutron parton distributions (especially gluons) over wide kinematic range

Making the target blacker

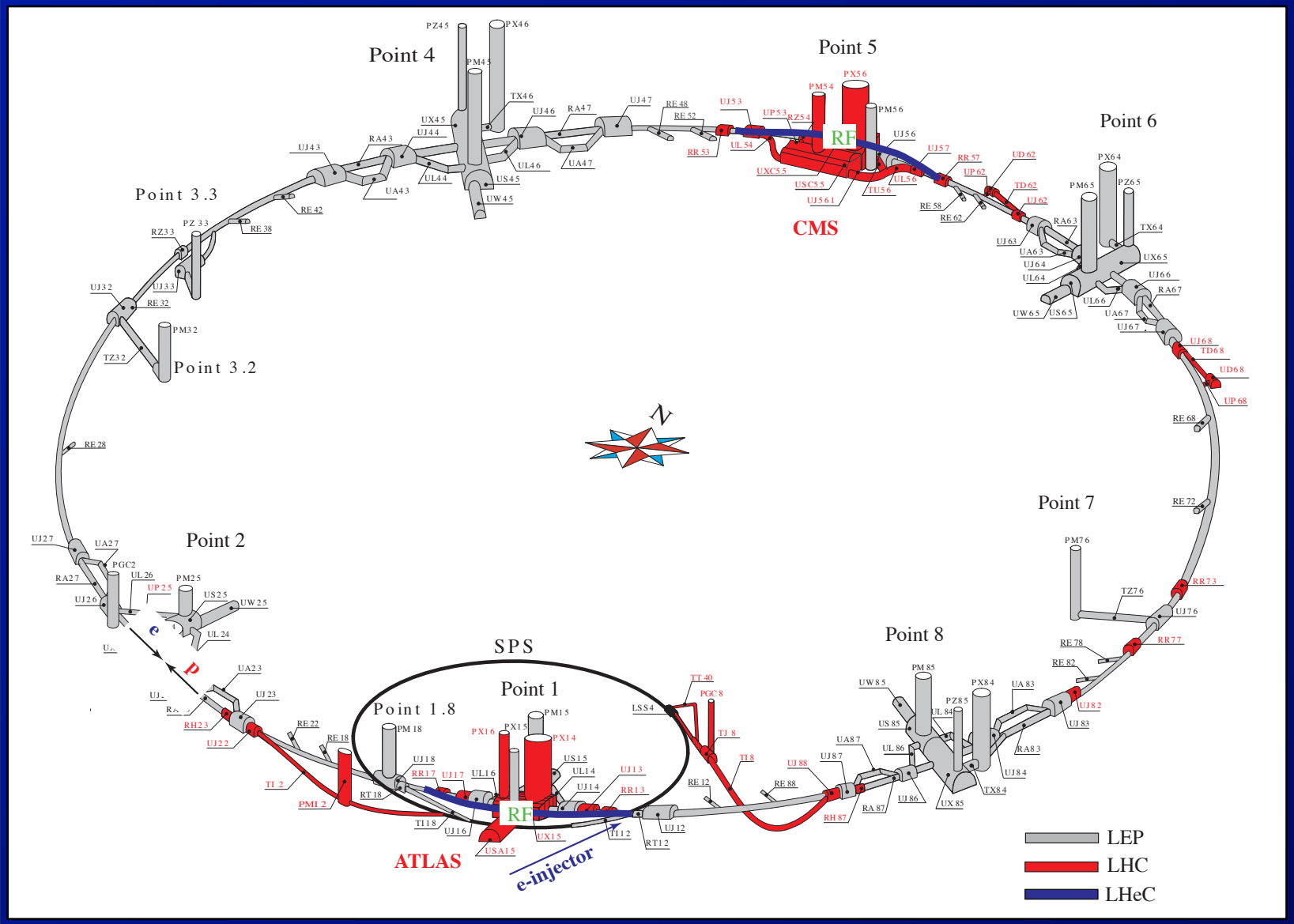
- 2-pronged approach:
  - Probing lower x at fixed Q^2 in e+p
    ⇒evolution of a single source
  - Increasing target density in e+A
    ⇒overlapping many sources at fixed kinematics … density
    ⇒ worth factor of 100 in x







LHeC: Ring-Ring Option



LHeC: Ring-Ring Option

Point 4

Point 5

Point 6

Point 3.3

Point 3.2

Point 2

Point 1

Point 1.8

Point 8

SPS

CMS

ATLAS

RF

e

p

e-injector

BYPASS

Bypass ATLAS

S.BP1

E.BP1

38 m

50 m

IP1

free sections

42 m

42 m

RF

RF

Injection

6.87 GeV

0.6 GeV from EPA

3.73 GeV

~30 m

4 ILC RF-units, 1.28 HGz, 156 m, providing 3.13 GV

10 GeV to LHeC

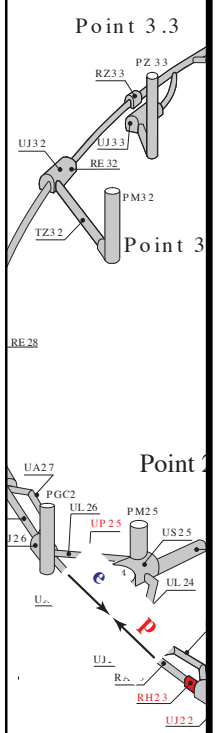
LHeC: Ring-Ring Option

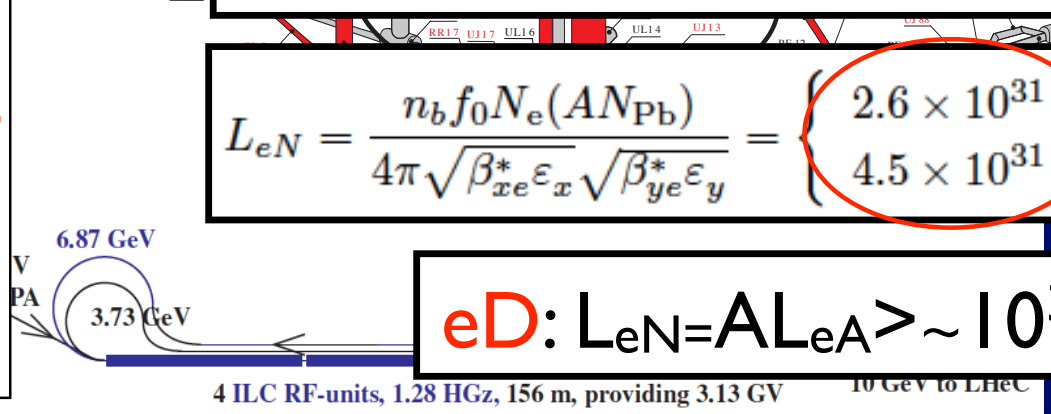
Preliminary; LHeC Design Study Report, CERN 2012

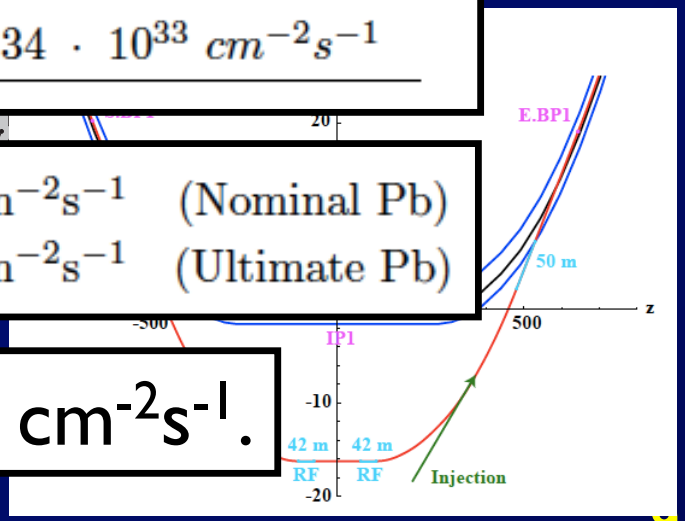
IR Option	1 degree		10 degree	
Beams	Electrons	Protons	Electrons	Protons
Energy	60 GeV	7 TeV	60 GeV	7 TeV
Intensity	$2 \cdot 10^{10}$	$1.7 \cdot 10^{11}$	$2 \cdot 10^{10}$	$1.7 \cdot 10^{11}$
β_x^*	0.4 m	4.05 m	0.18 m	1.8 m
β_y^*	0.2 m	0.97 m	0.1 m	0.5 m
ϵ_x	5 nm	0.5 nm	5 nm	0.5 nm
ϵ_y	2.5 nm	0.5 nm	2.5 nm	0.5 nm
σ_x	45μm		30μm	
σ_y	22μm		15.8μm	
Cross angle	1 mrad		1 mrad	
$\xi_{bb,x}$	0.086	0.0008	0.085	0.0008
$\xi_{bb,y}$	0.088	0.0004	0.090	0.0004
Luminosity	$7.33 \cdot 10^{32}\ cm^{-2}s^{-1}$		$1.34 \cdot 10^{33}\ cm^{-2}s^{-1}$	

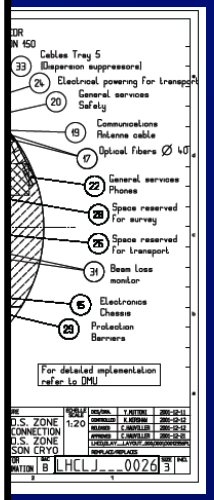
$$L_{eN} = \frac{n_b f_0 N_e (A N_{Pb})}{4\pi\sqrt{\beta_{xe}^*\varepsilon_x}\sqrt{\beta_{ye}^*\varepsilon_y}} = \begin{cases} 2.6 \times 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} & \text{(Nominal Pb)} \\ 4.5 \times 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} & \text{(Ultimate Pb)} \end{cases}$$

eD: $L_{eN}=AL_{eA}>\sim 10^{31}\ cm^{-2}s^{-1}$.

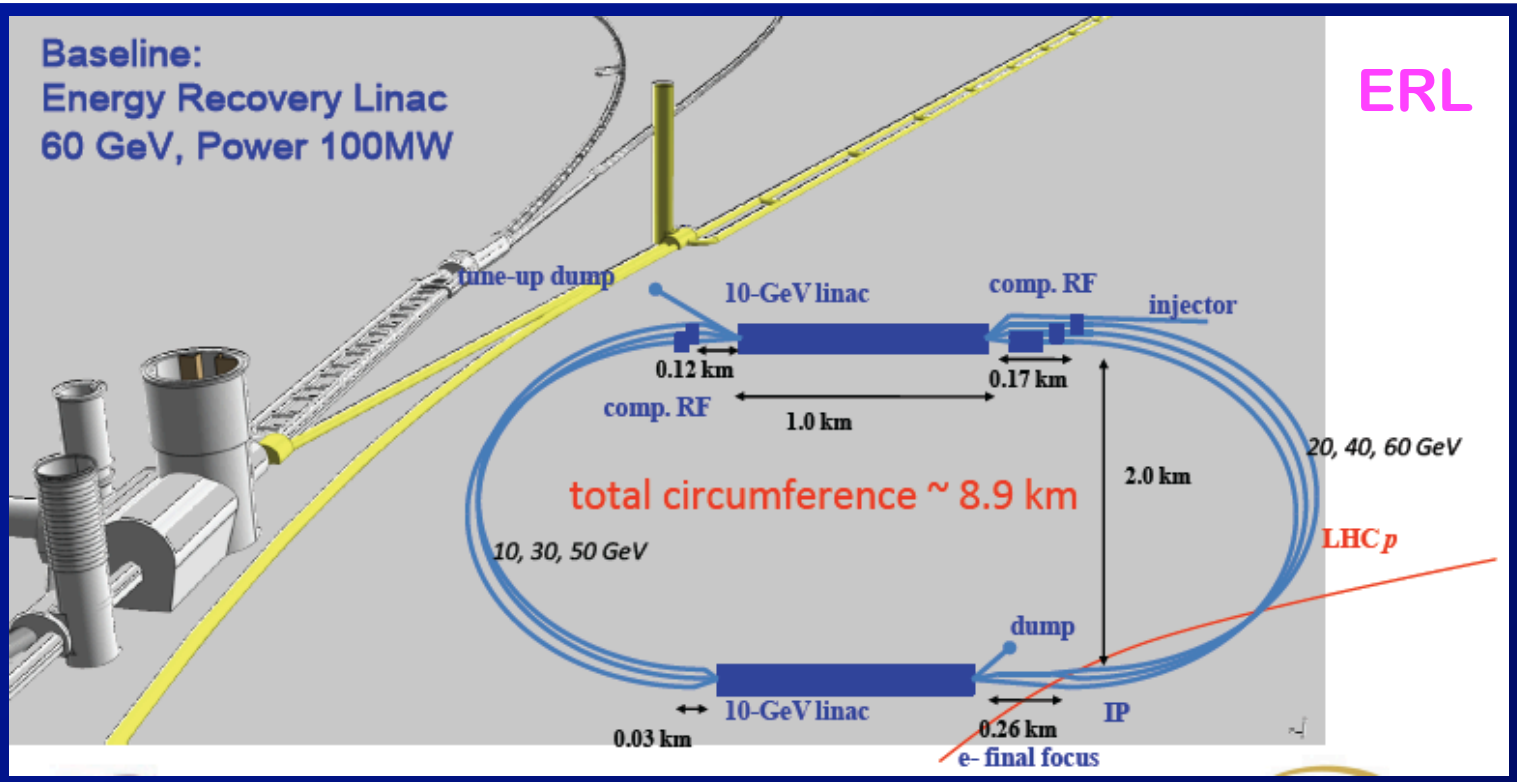


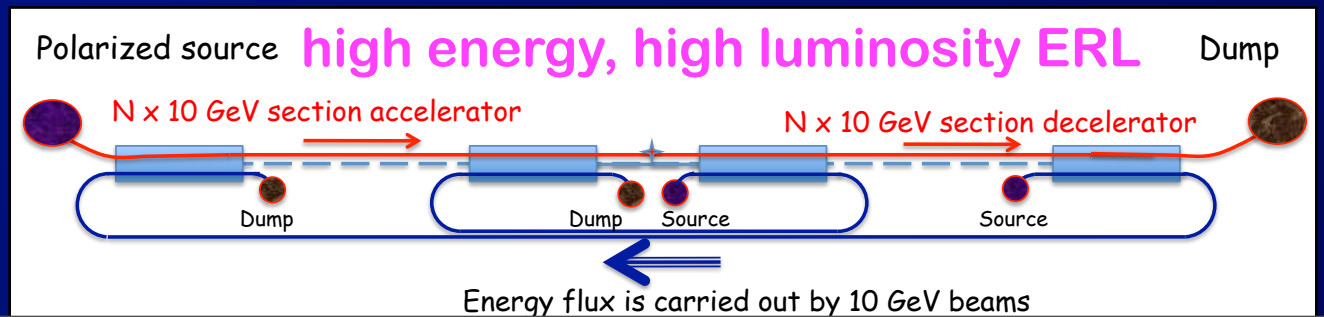






Linac-ring options

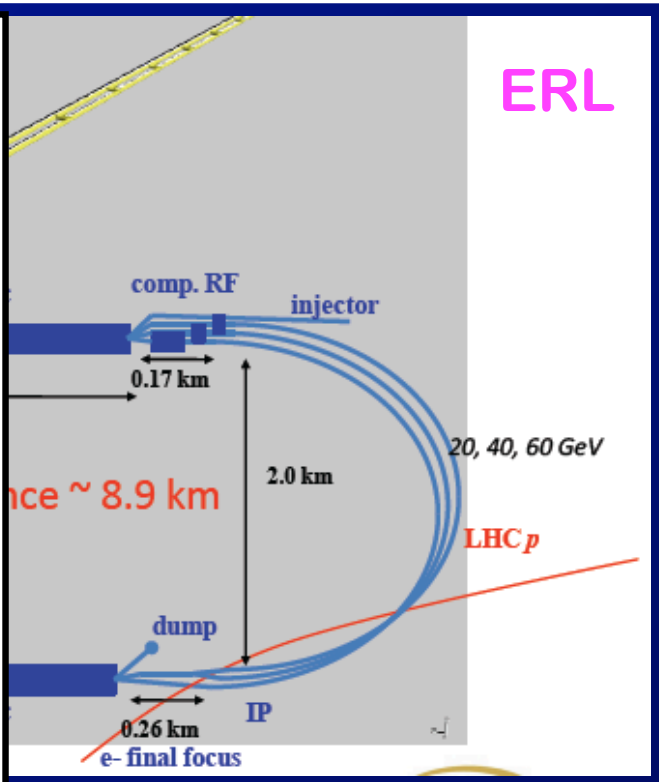


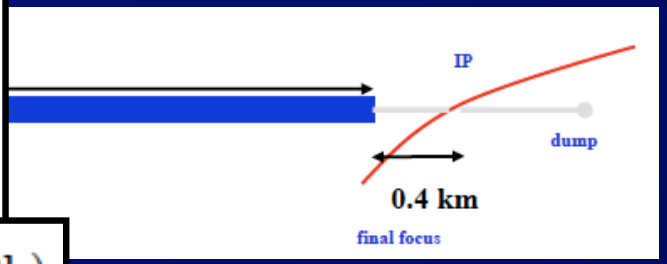


Linac-ring options

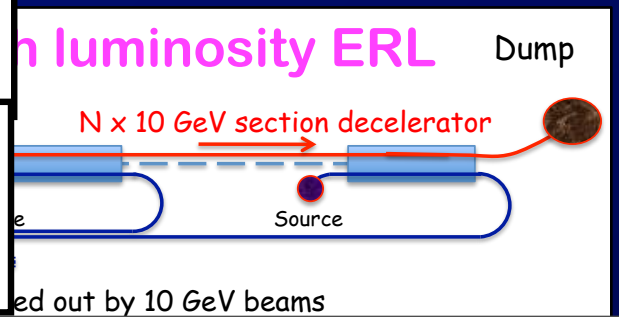
Preliminary; Bogacz@DIS11; LHeC Design Study Report, CERN 2012

electron beam	LR ERL	LR
e- energy at IP[GeV]	60	140
luminosity [10^{32} cm^{-2}s^{-1}]	10	0.44
polarization [%]	90	90
bunch population [10^9]	2.0	1.6
e- bunch length [mm]	0.3	0.3
bunch interval [ns]	50	50
transv. emit. $\gamma\varepsilon_{x,y}$ [mm]	0.05	0.1
rms IP beam size $\sigma_{x,y}$ [μm]	7	7
e- IP beta funct. $\beta^*_{x,y}$ [m]	0.12	0.14
full crossing angle [mrad]	0	0
geometric reduction H_{hg}	0.91	0.94
repetition rate [Hz]	N/A	10
beam pulse length [ms]	N/A	5
ER efficiency	94%	N/A
average current [mA]	6.6	5.4
tot. wall plug power[MW]	100	100





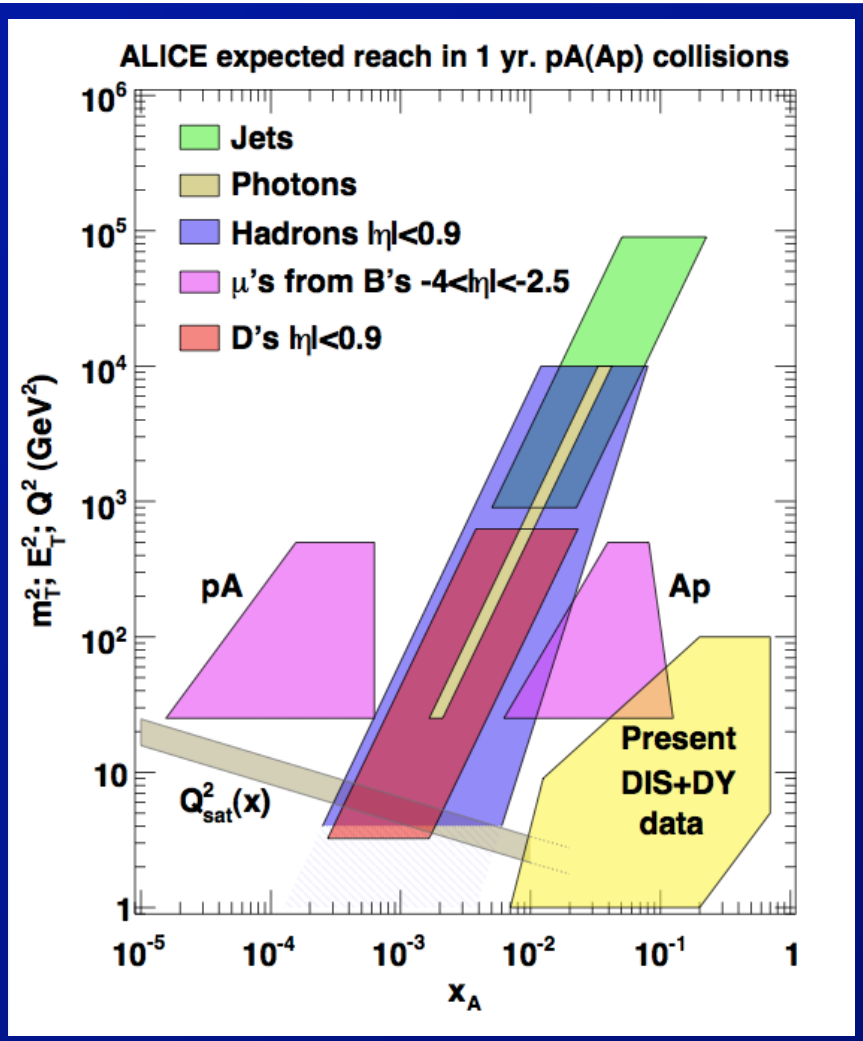
$$L_{eN} = \begin{cases} 9 \times 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} & \text{(Nominal Pb)} \\ 1.6 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} & \text{(Ultimate Pb)} \end{cases}$$

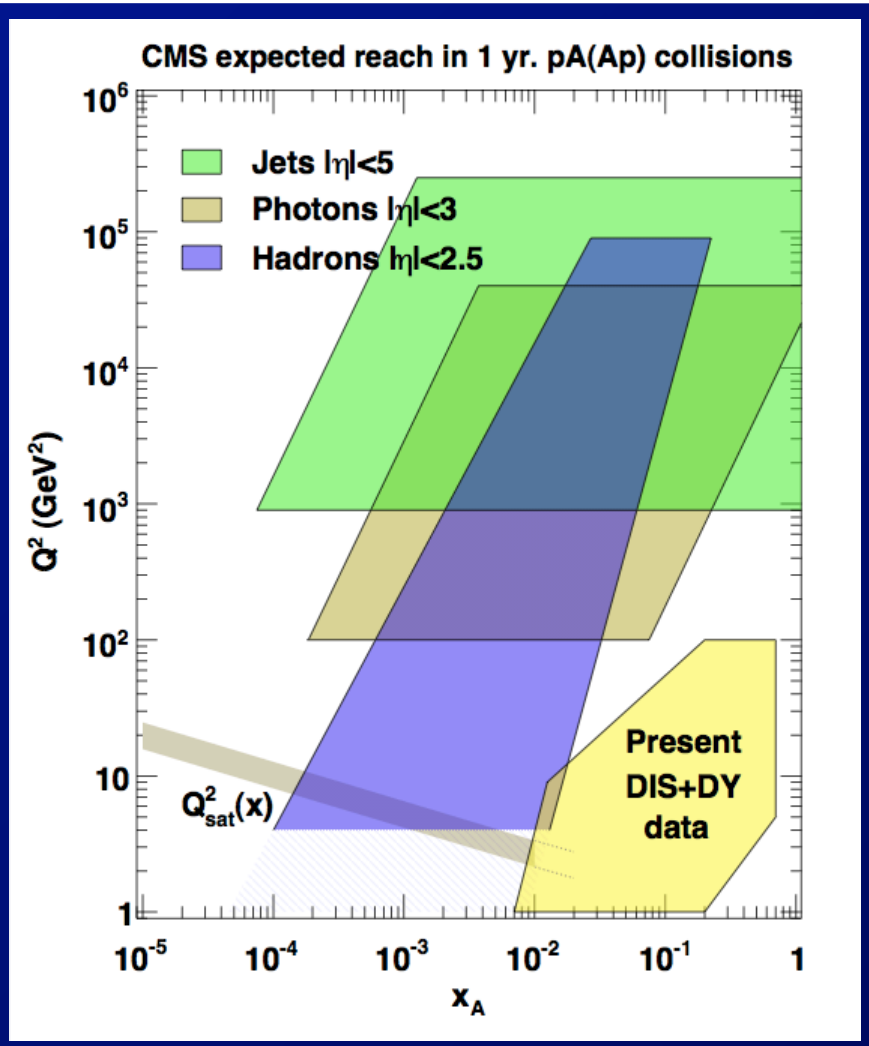


eD: $L_{eN}=AL_{eA}>\sim 3\times 10^{31}$ cm^{-2}s^{-1}.

Large L for e$^+$ challenging.

Reaching low x in nuclei

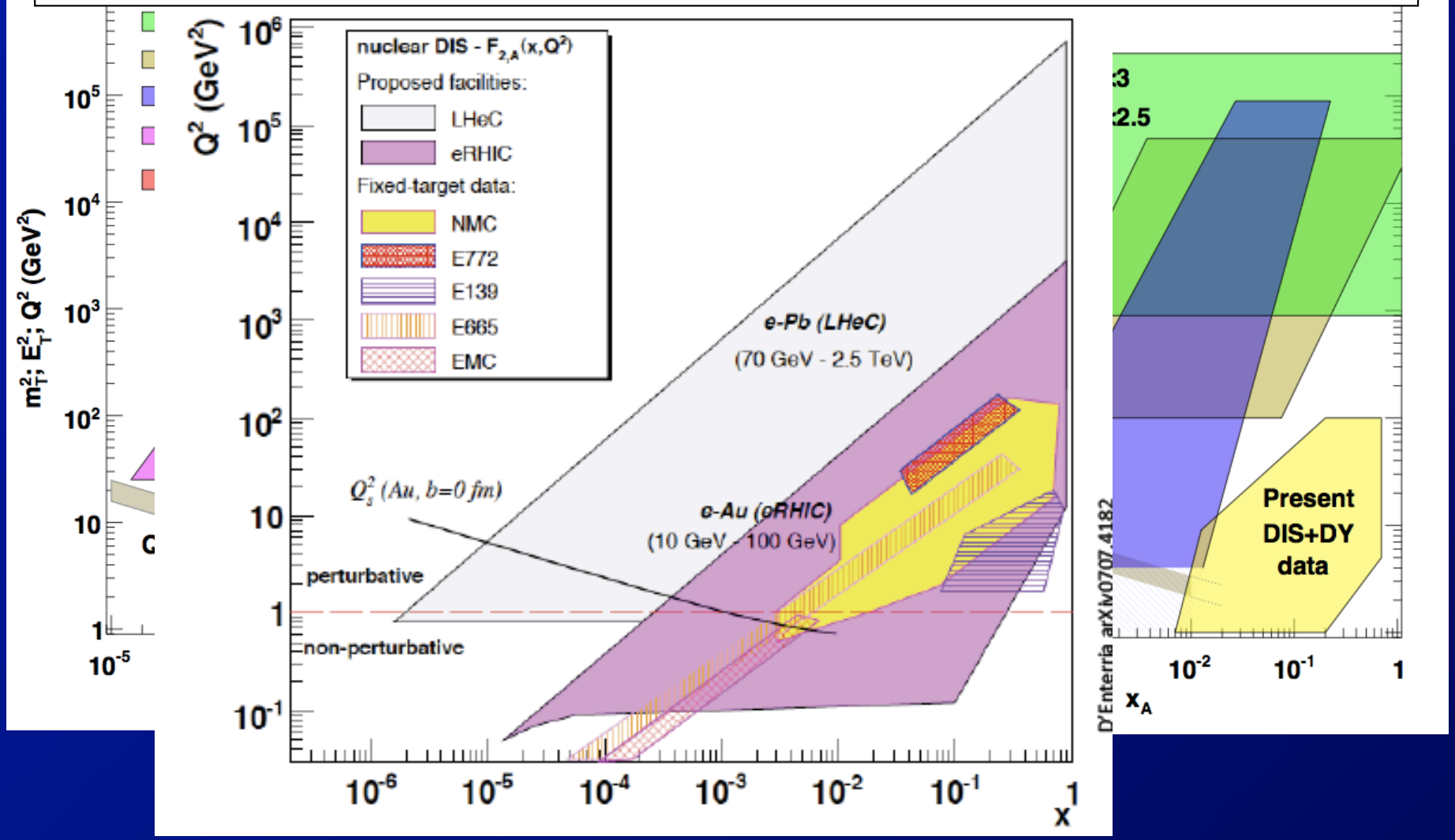




- LHC p-A reach (e.g. ALICE, CMS ~ ATLAS)

Reaching low x in nuclei

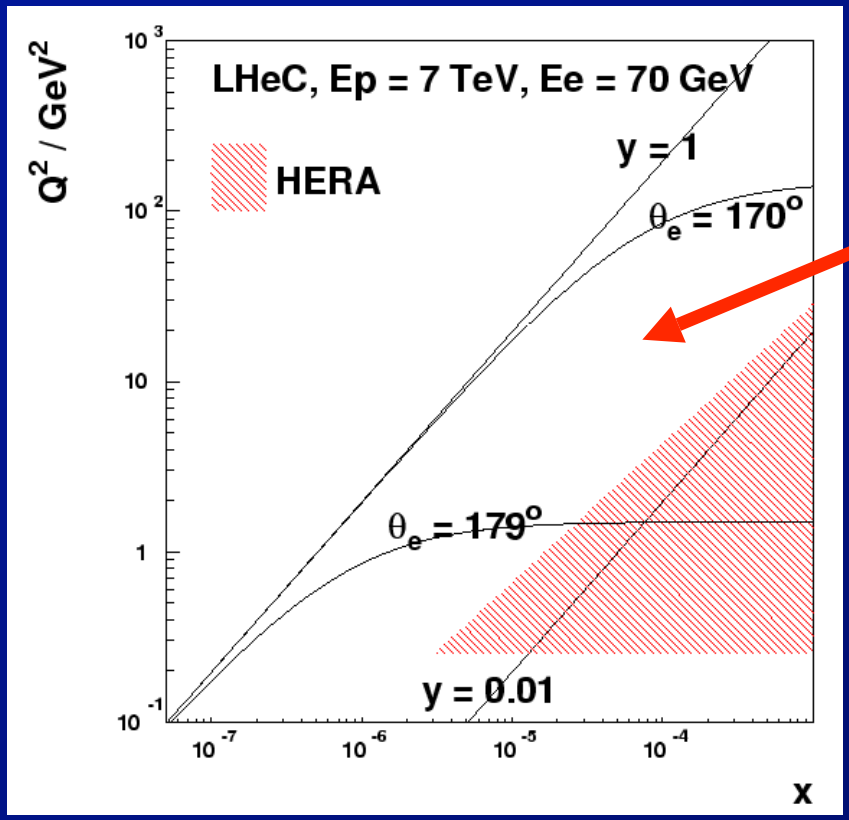
Preliminary; LHeC Design Study Report, CERN 2012

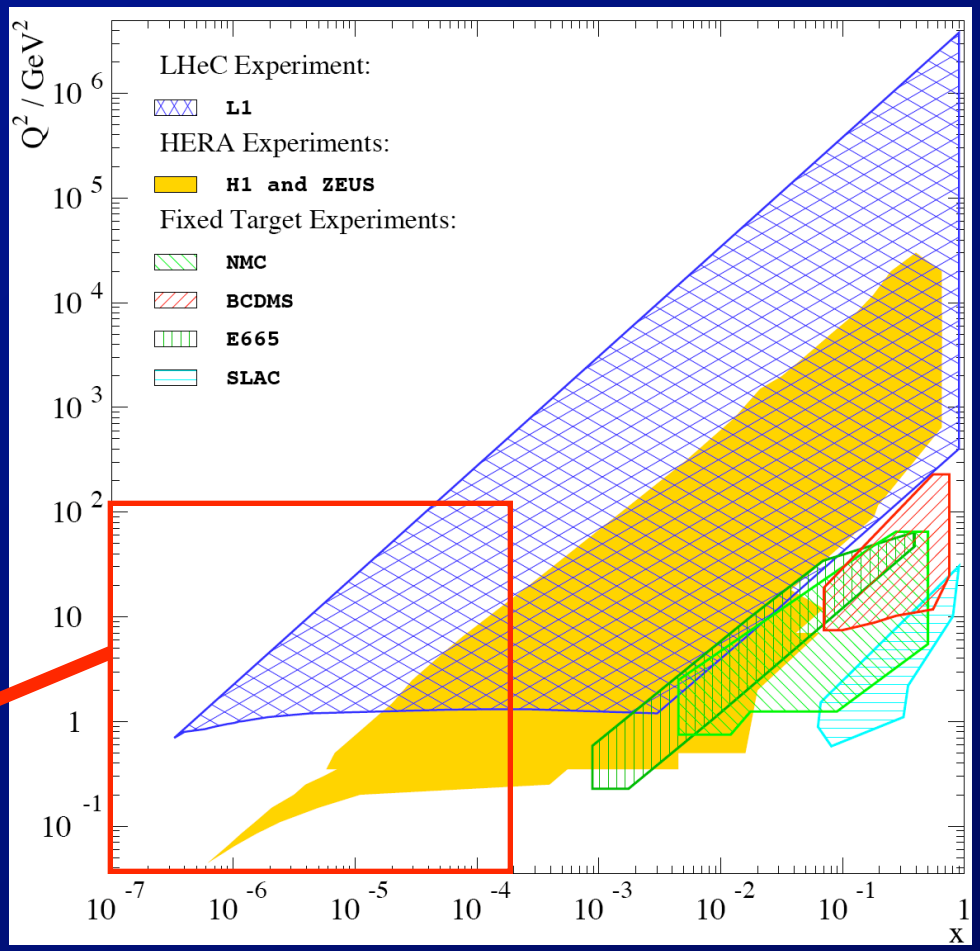


- LHeC will probe > 10 smaller x than p-A @ LHC
- More important: test factorization with e/p-A

Low x detector requirements

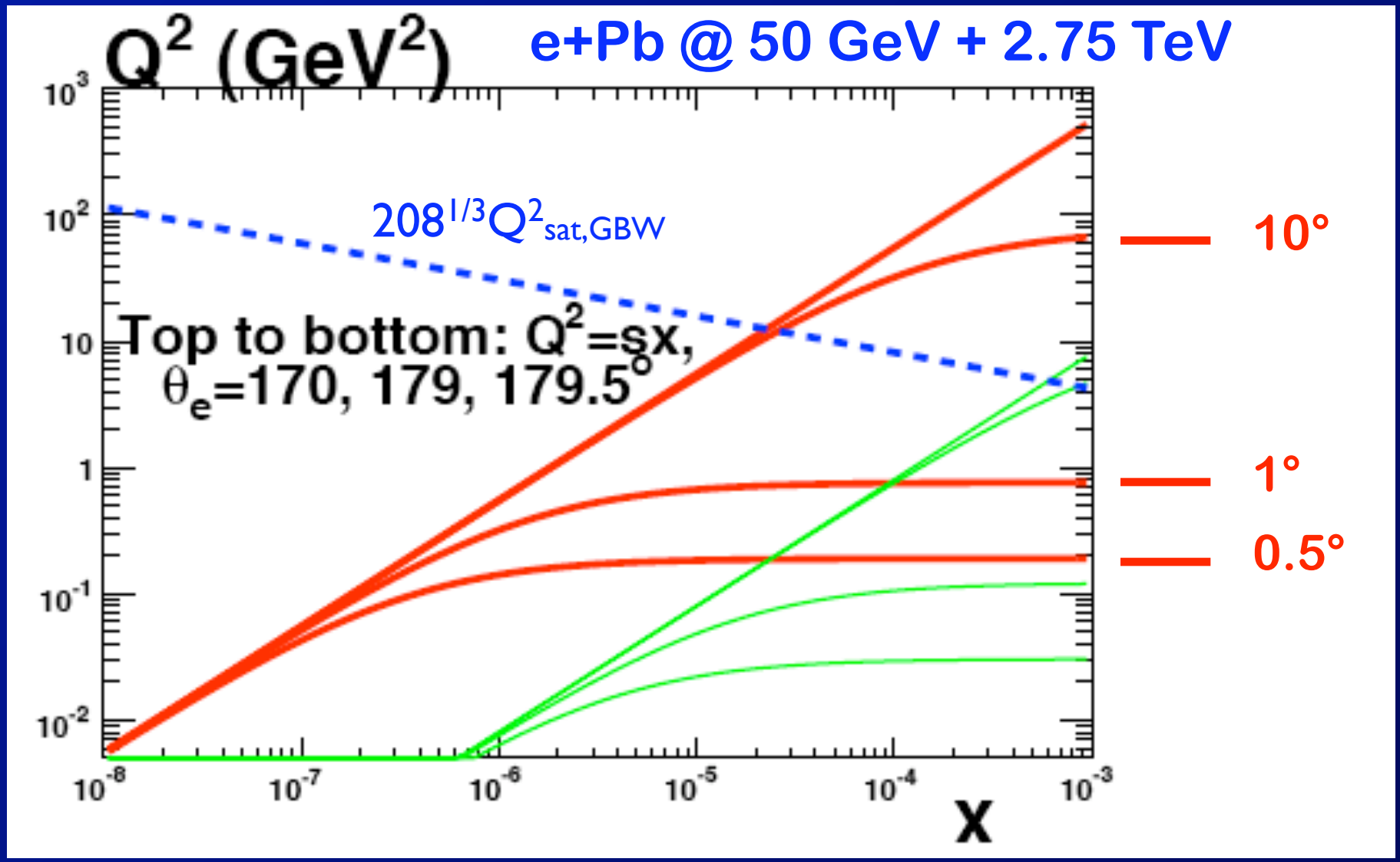
Access to $Q^2 = 1\ GeV^2$ @ low x requires scattered electron acceptance to 179°





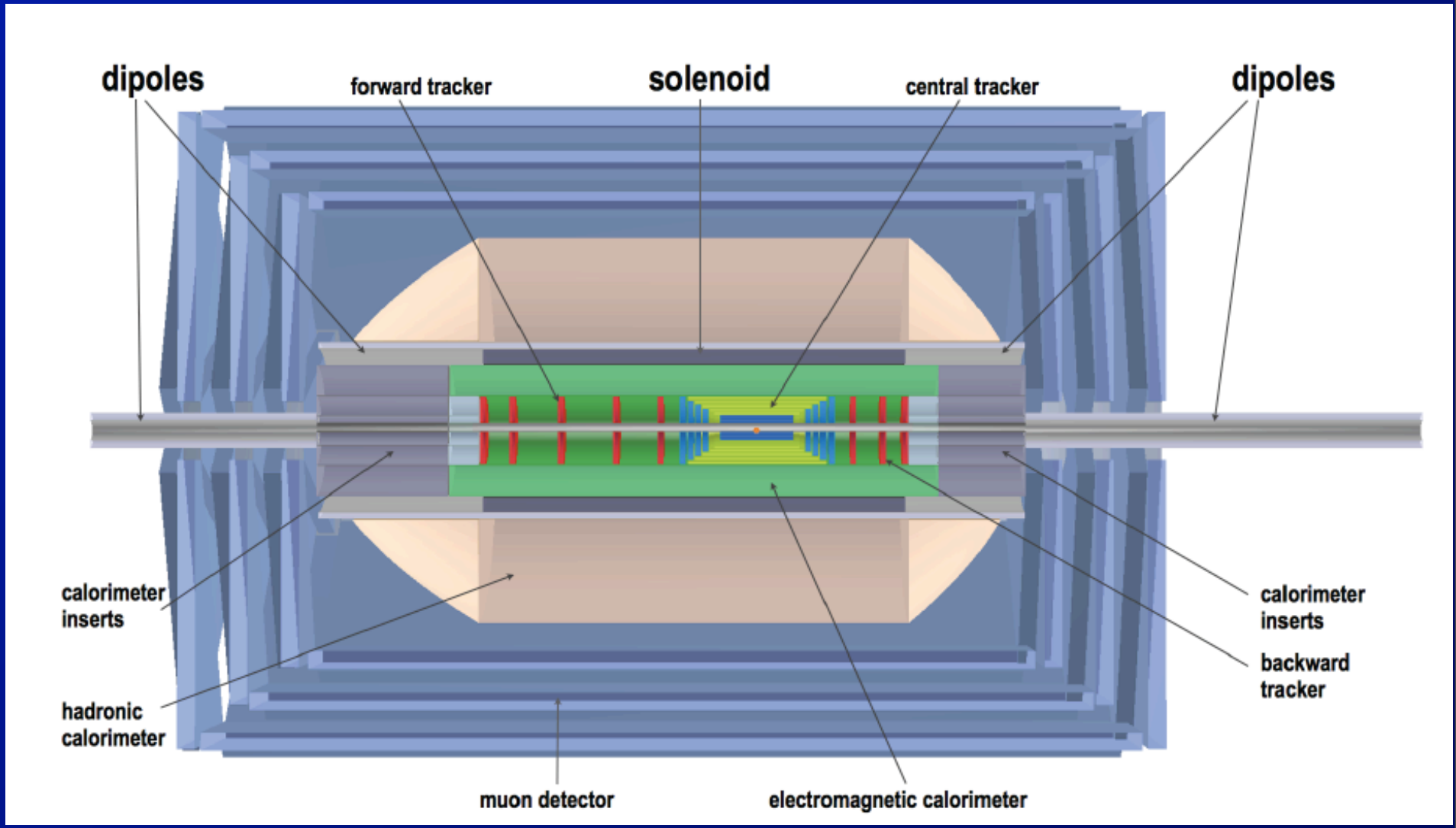
Similarly, need 1° acceptance in outgoing proton direction to contain hadrons at high x (essential for good kinematic reconstruction)

e+A kinematics



- LHeC will be able to access x-Q^2 values deep into the saturation regime.

LHeC - Detector, low-Q^2 setup



- Plus luminosity detector, electron tagging, polarimeter, ZDC and leading proton detector.

Detector: tracking

Transverse momentum $\Delta p_t/p^2_t \rightarrow 6\times10^{-4}$ GeV^{-1}

transverse impact parameter→ 10 μm

All in 3.5T solenoid

Central Pixel Tracker

4 layer **CPT**:
min-inner-R = 3.1 cm
max-inner-R = 10.9 cm

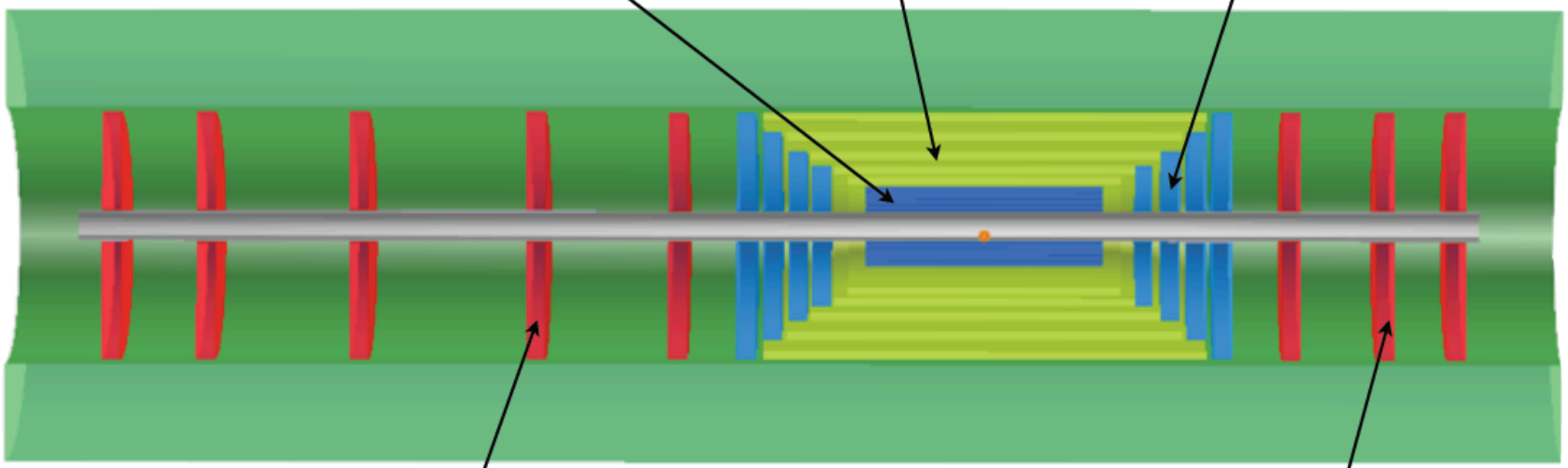
ΔR = 15. cm

Central Si Tracker

CST - ΔR 3.5cm each
1. layer: inner R = 21.2 cm
2. layer: = 25.6 cm
3. layer: = 31.2 cm
4. layer: = 36.7 cm
5. layer: = 42.7 cm

Central Forward/Backward Tracker

4 **CFT/CBT**
min-inner-R = 3.1 cm, max-inner-R = 10.9 cm



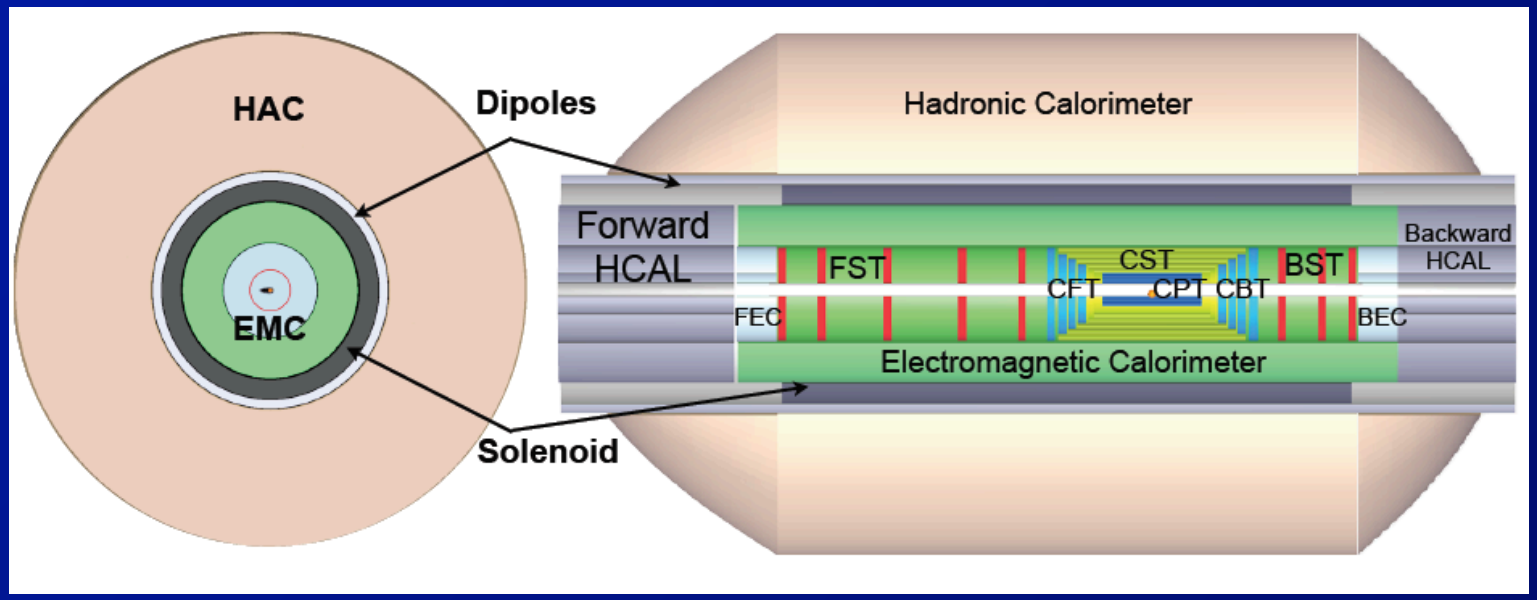
Forward Si Tracker

FST - ΔZ= 8. cm
min-inner-R = 3.1 cm; max-inner-R= 10.9 cm
outer R = 46.2 cm
Planes 1-5:
z_{5-1} = 370. / 330. / 265. / 190. / 130. cm

Backward Si Tracker

BST - ΔZ= 8. cm
min-inner-R = 3.1 cm; max-inner-R= 10.9 cm
outer R = 46.2 cm
Planes 1-3:
z_{1-3} = -130. / -170. / -200. cm

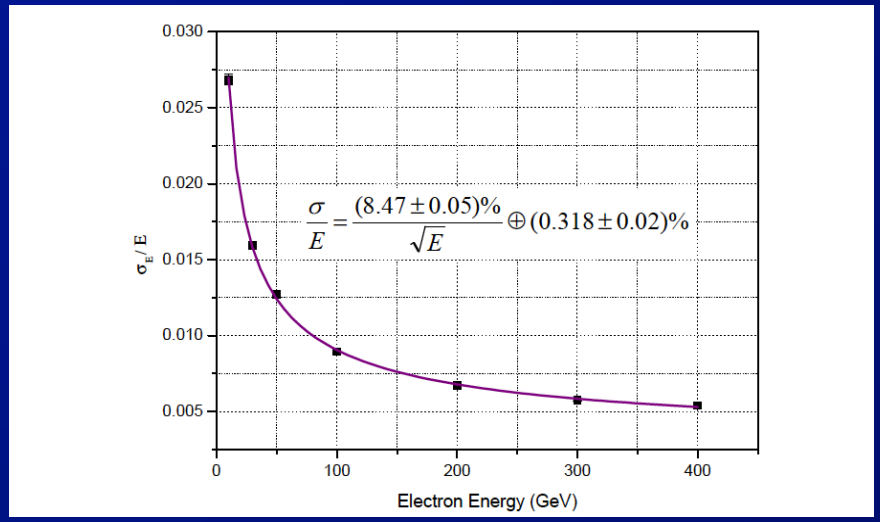
Detector: calorimetry

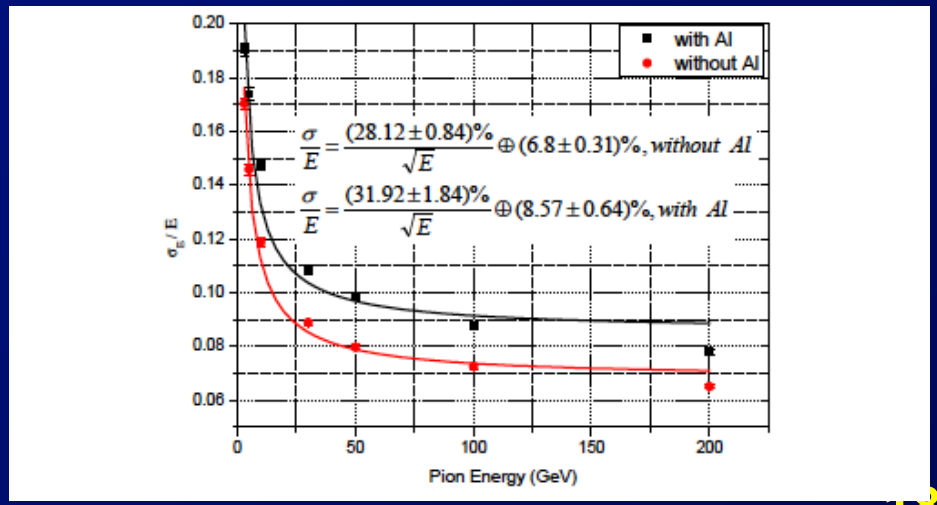


Liquid Argon EM Calorimeter [accordion geometry, inside coil]

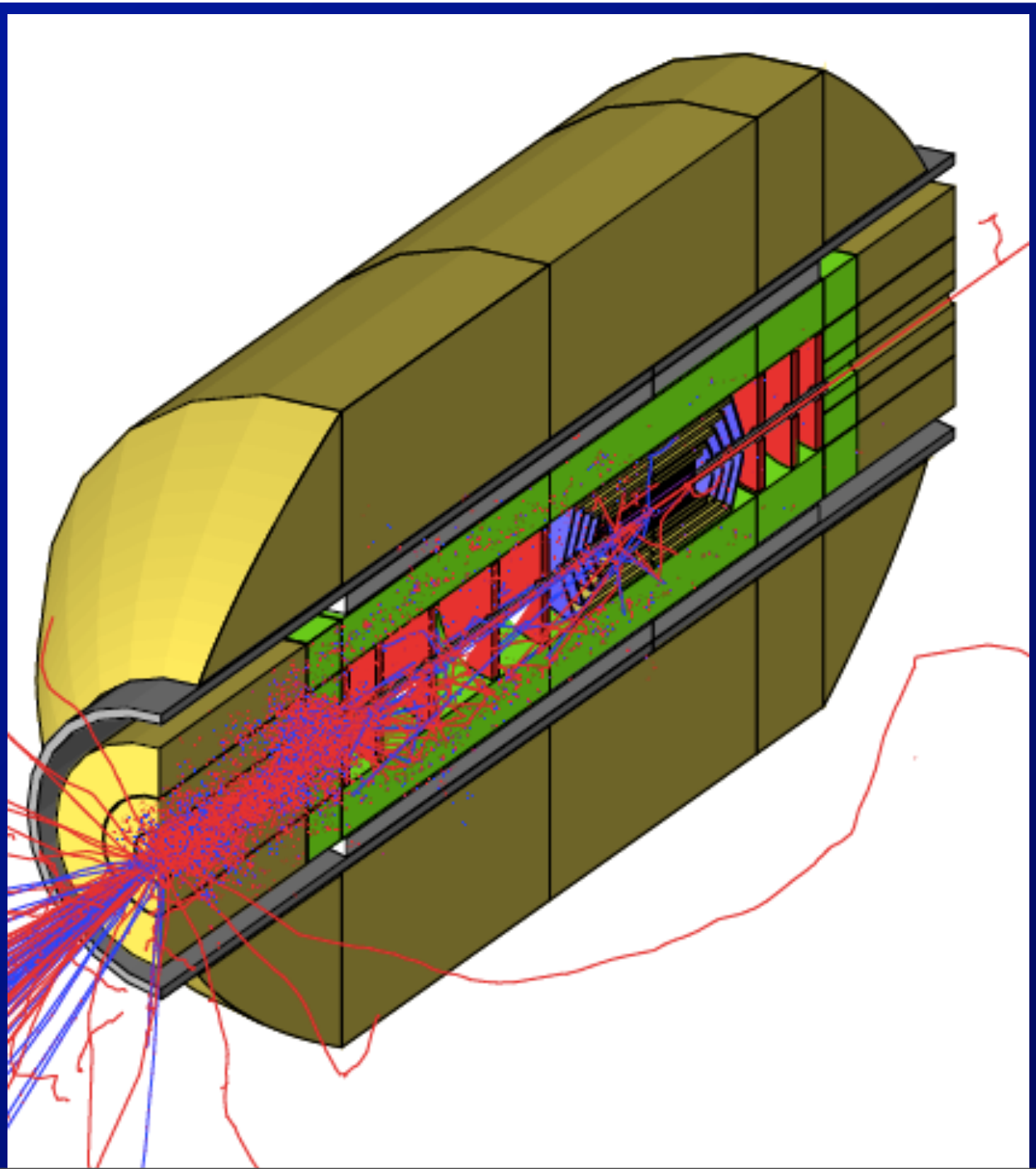
Barrel: Pb, 20 X_0 , 11m^3 FEC: Si -W, 30 X_0 BEC: Si -Pb, 25 X

Hadronic Tile Calorimeter [modular, outside coil: flux return]





GEANT4 simulated event

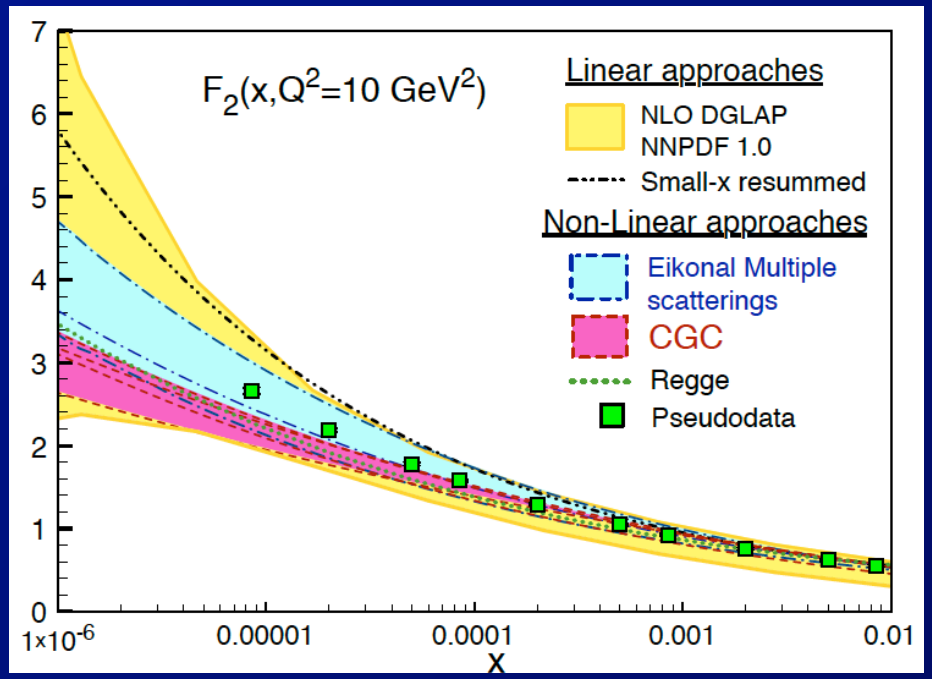


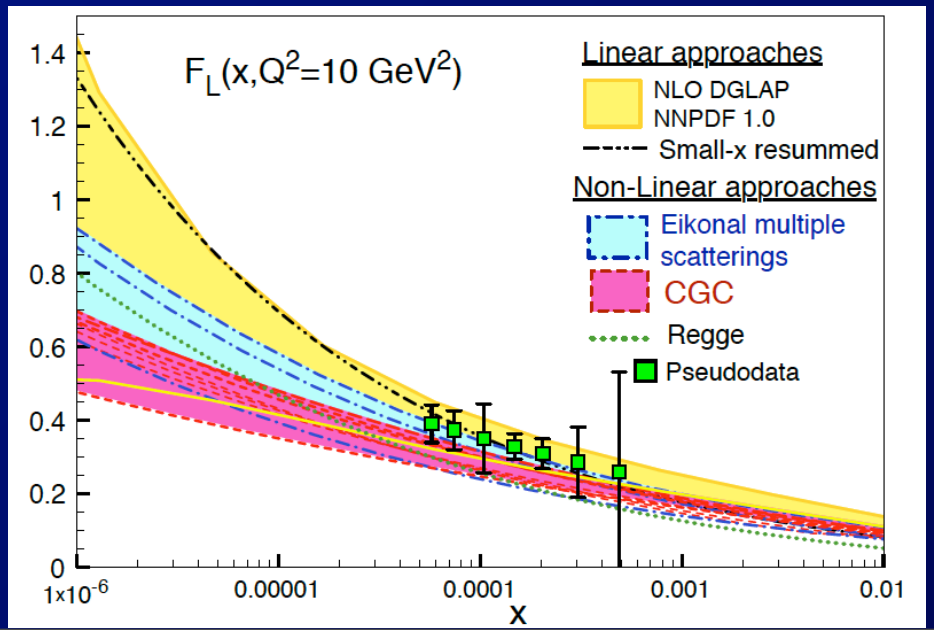
Proton DIS @ LHeC

- Extensive studies of discriminating power of LHeC DIS data

  ⇒Measurements capable of discriminating between different descriptions of F_2, F_L

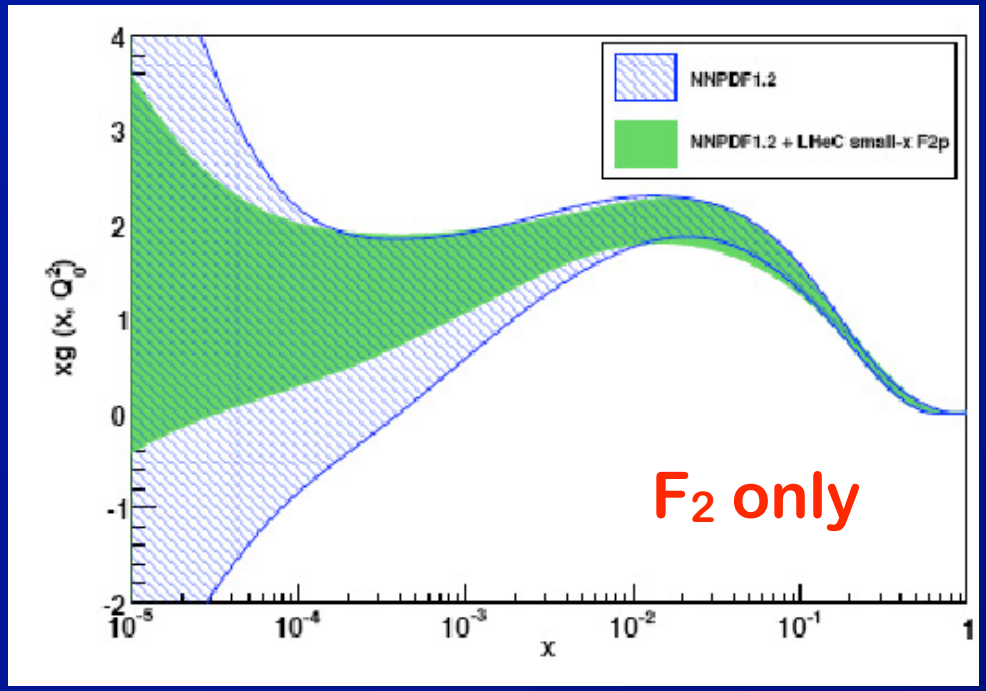
  – Caveat: effects of radiative corrections still being evaluated

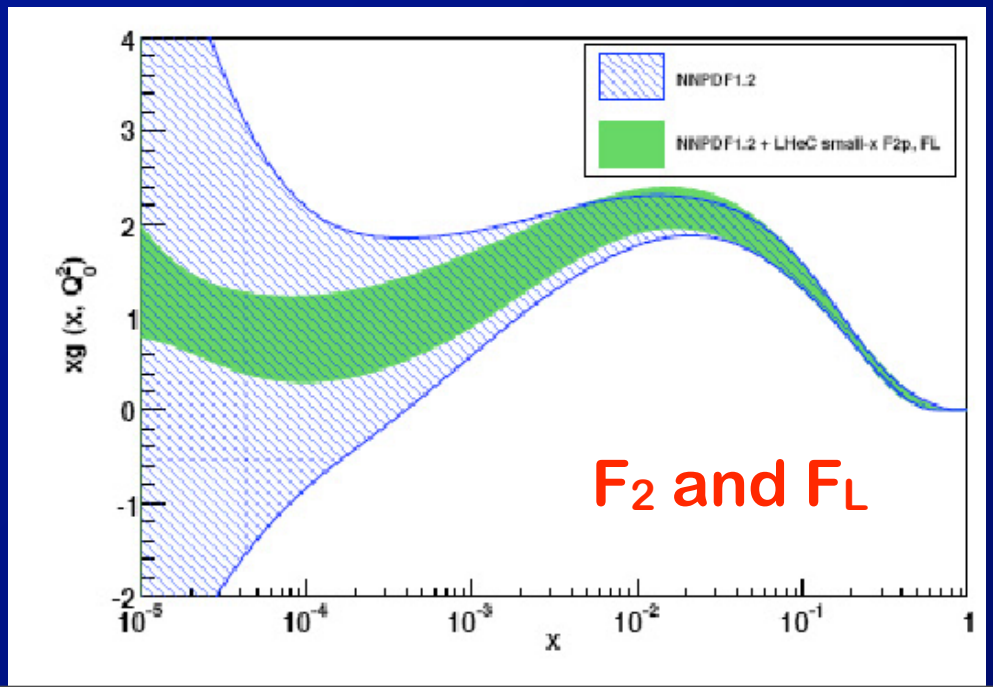




Preliminary; LHeC Design Study Report, CERN 2012

LHeC: proton F_2 and F_L impact



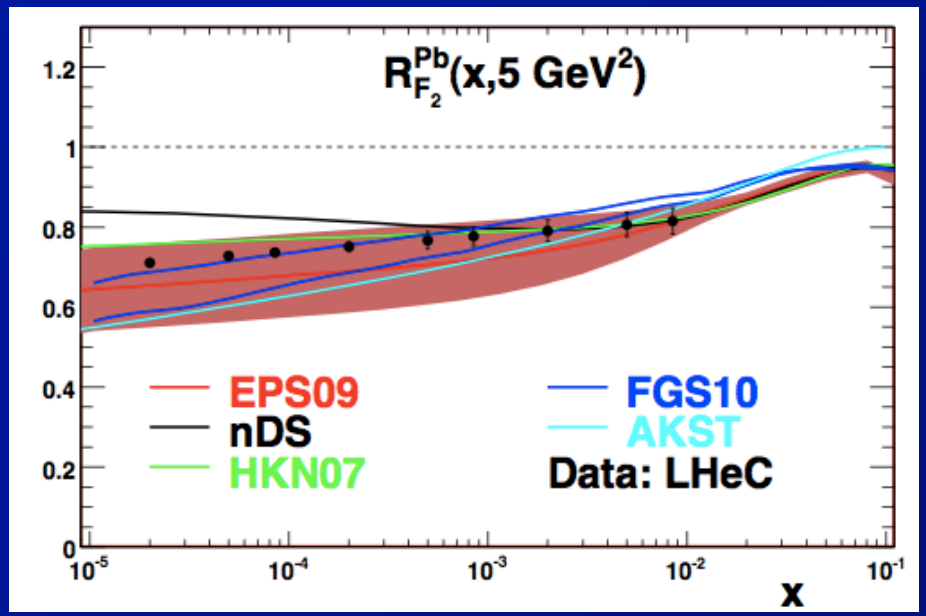


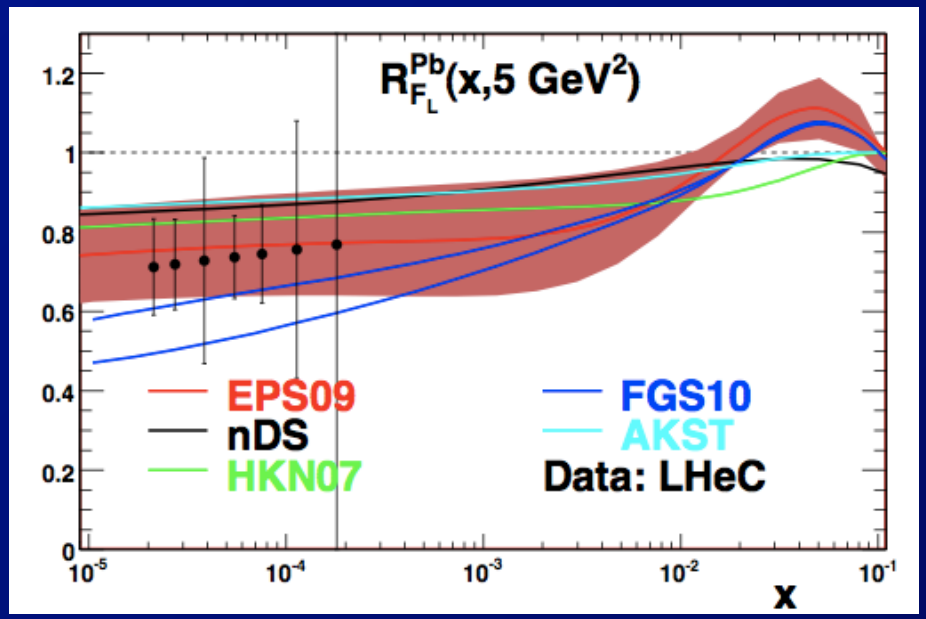
- Using measured F_2 and F_L in e-p can significantly improve knowledge of gluon distribution

Preliminary; LHeC Design Study Report, CERN 2012

LHeC: nuclear DIS impact

Preliminary; LHeC Design Study Report, CERN 2012





- **LHeC measurements will provide precise F_2 measurements @low x**

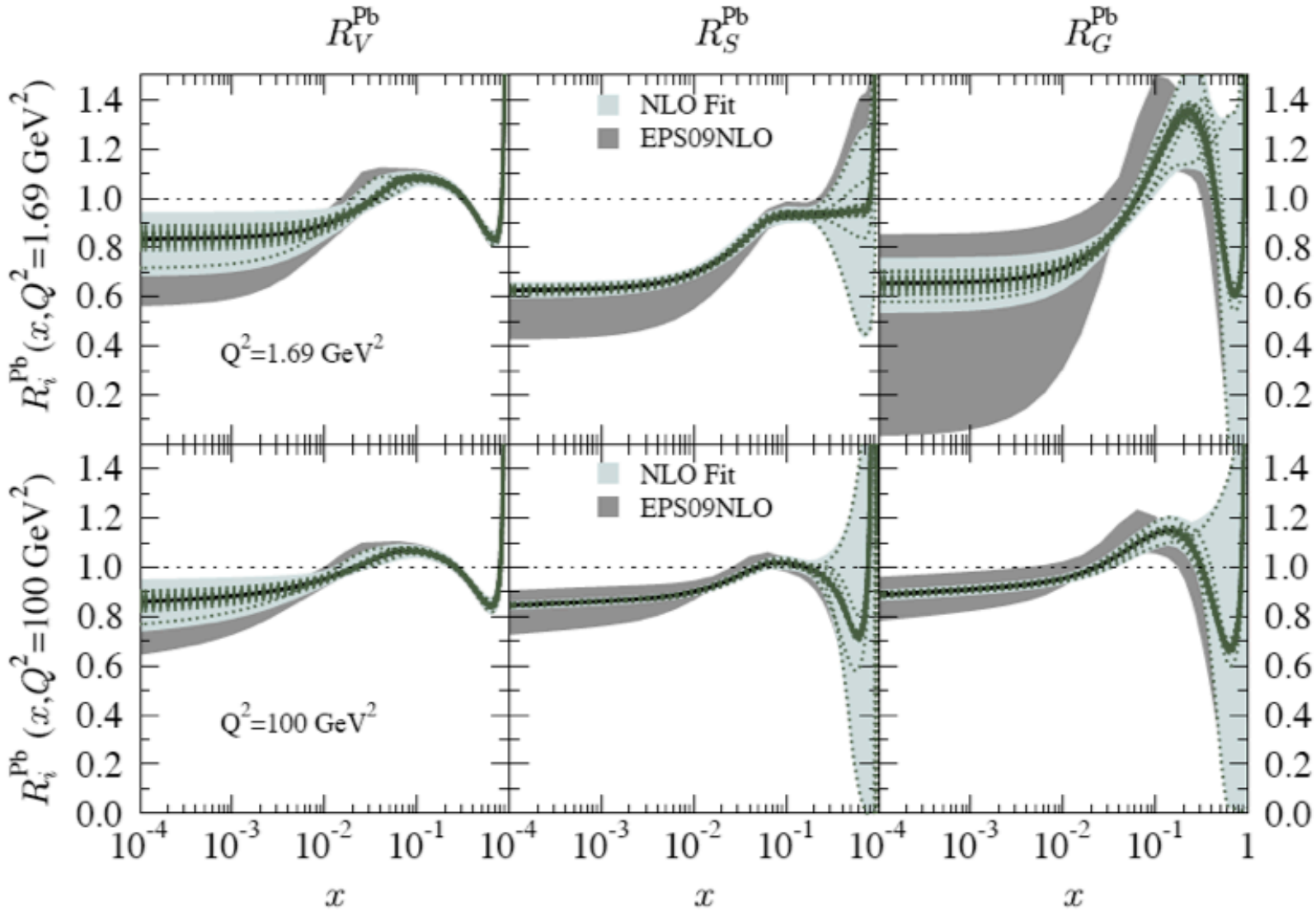
  ⇒dramatically reduce nuclear PDF uncertainties (next)

  – And new measurements of F_L, F_2^c, F_2^b

  – And charged-current events (flavor decomposition)

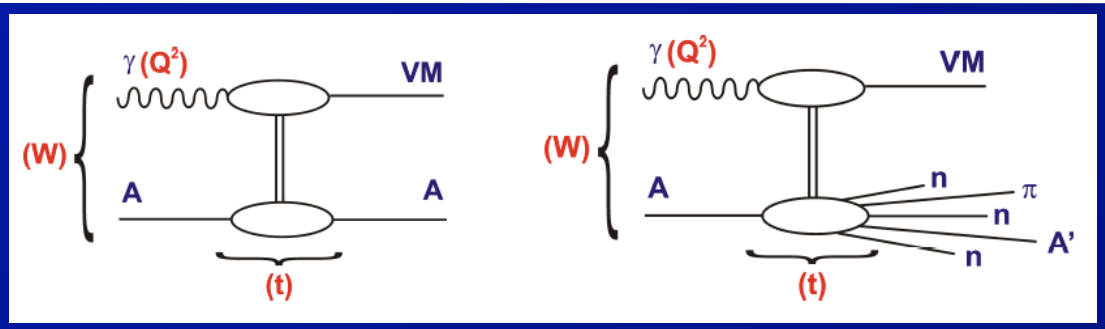
LHeC nuclear DIS impact

Preliminary; LHeC Design Study Report, CERN 2012



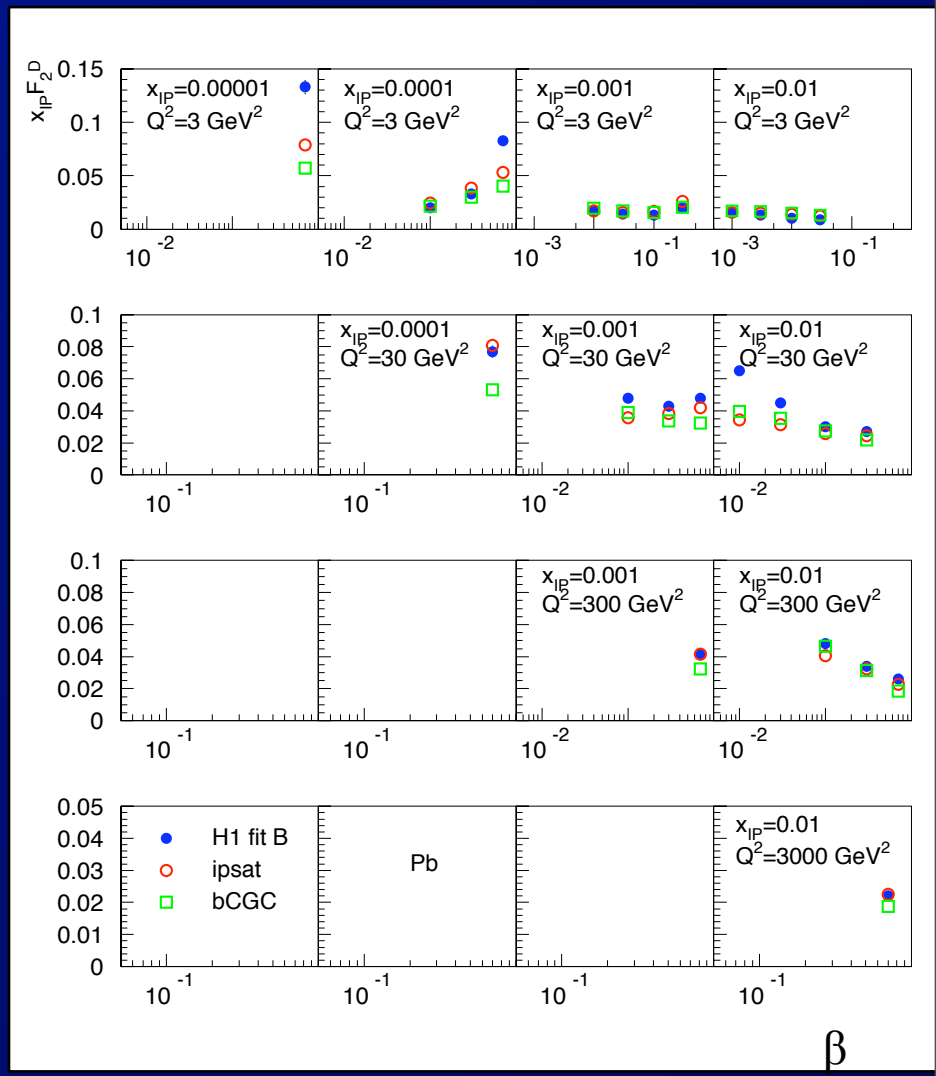
- LHeC measurements will dramatically reduce uncertainties on nuclear PDFs

Diffractive DIS on nuclear targets



Preliminary; LHeC Design Study Report, CERN 2012

- **Challenging experimental problem**
  - Requires Monte Carlo simulation with detailed understanding of the nuclear break-up.
  - For the coherent case, predictions available.



A+A initial conditions

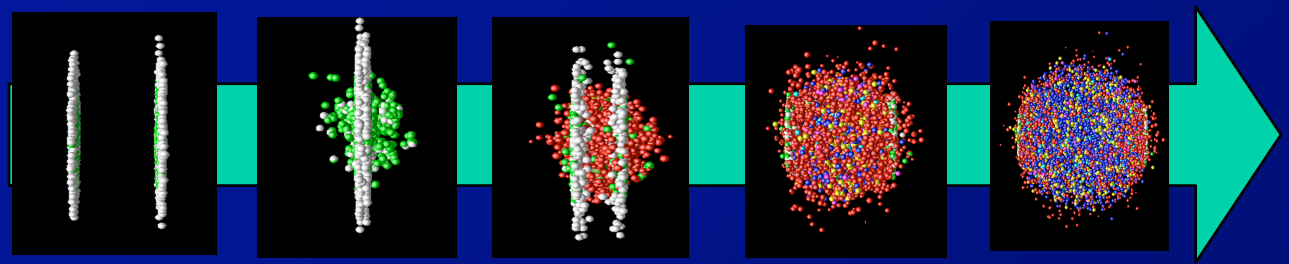
Gluon emission from (saturated?) nuclei

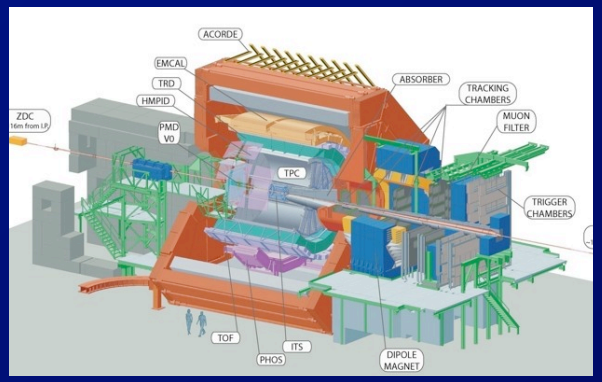
(Glasma?)

Quark gluon plasma

"re-confinement"

Detection





The physics here

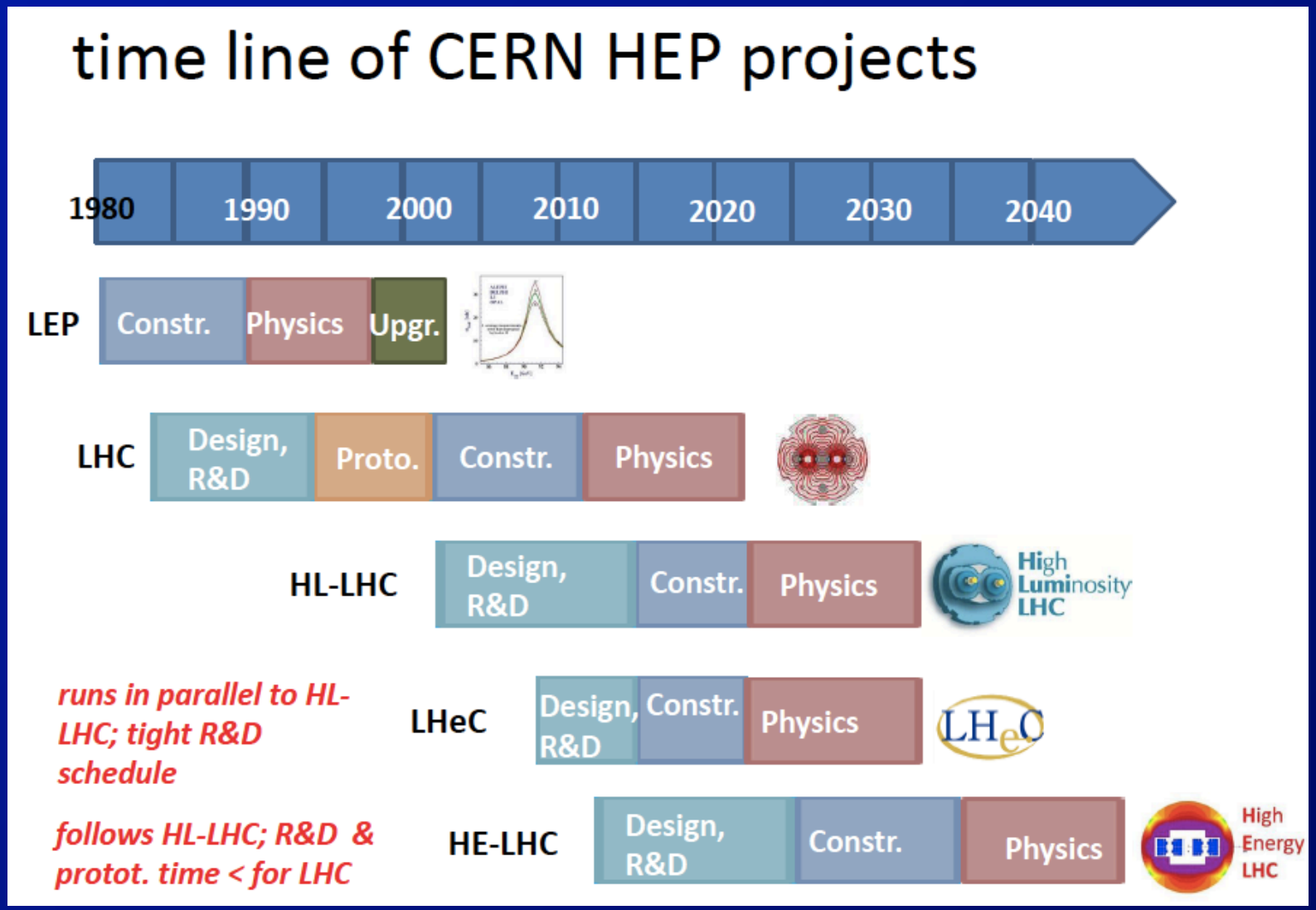
Influences the physics here

Determines the conditions here

And influences how we interpret data from here

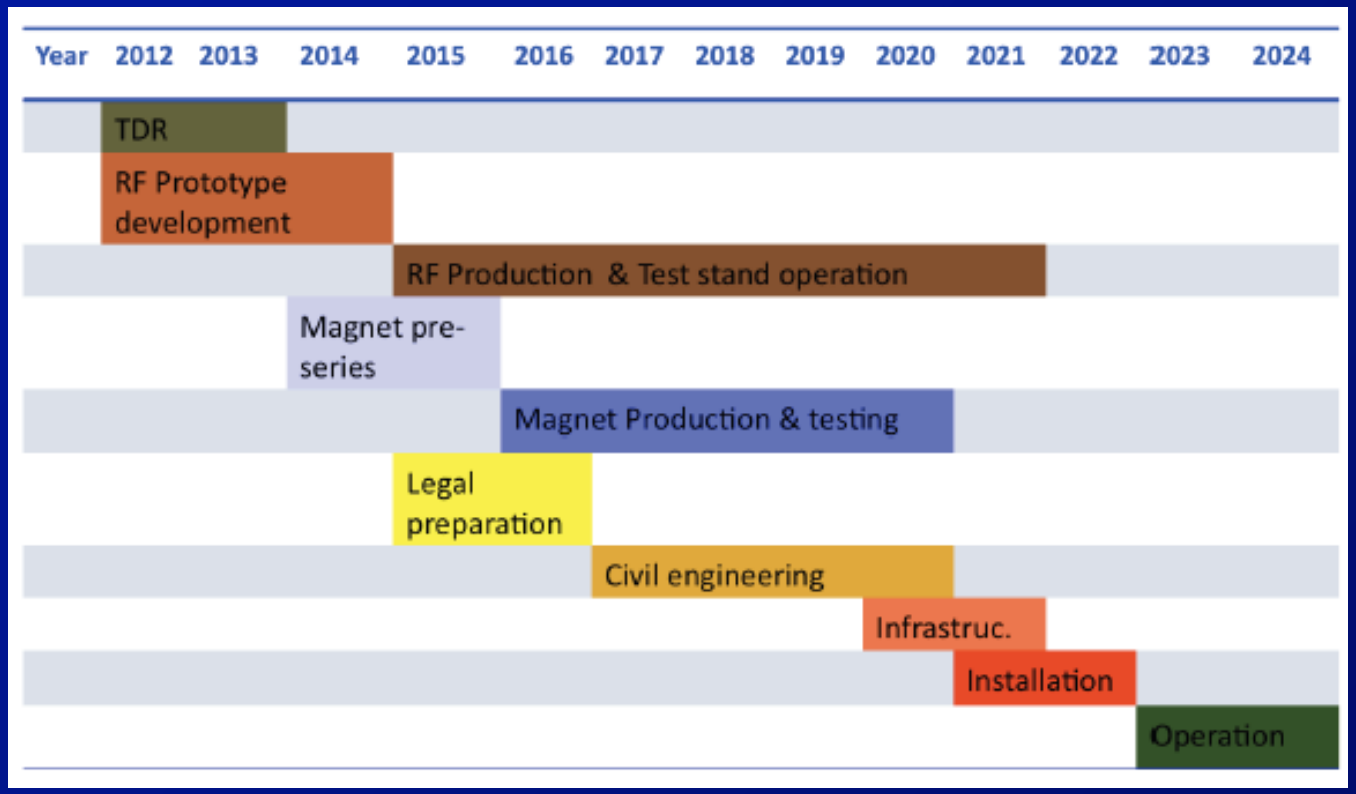
LHeC will probe the physics of the "initial state" of heavy ion collisions down to $x < 10^{-6}$ with $Q^2 > \sim 1\ \mathrm{GeV}^2$

LHeC timeline (2)



- **From 2012 Chamonix LHC Performance workshop summary (Rossi)**
  - See also NuPeCC long range plan

LHeC timeline

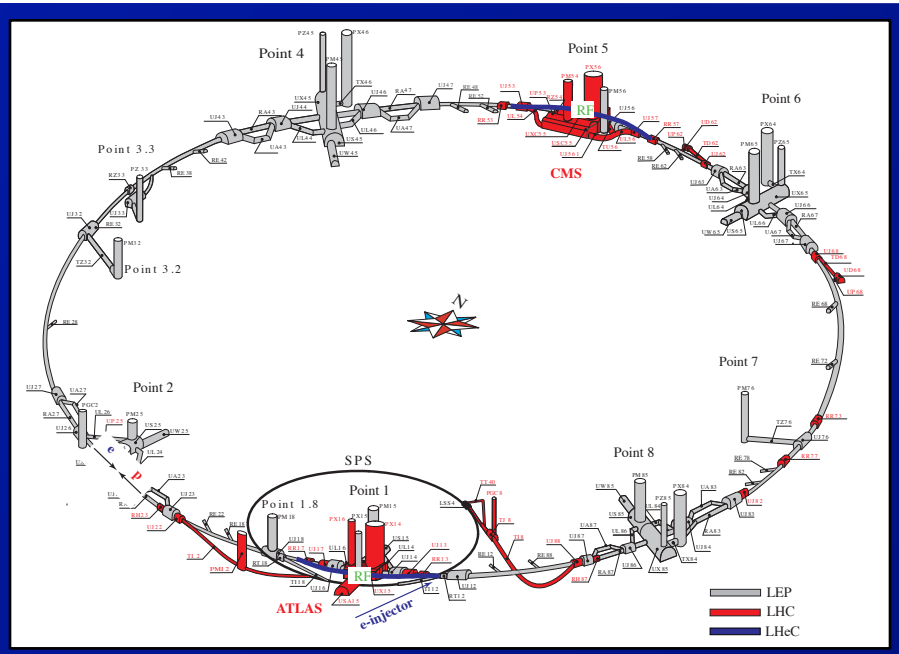


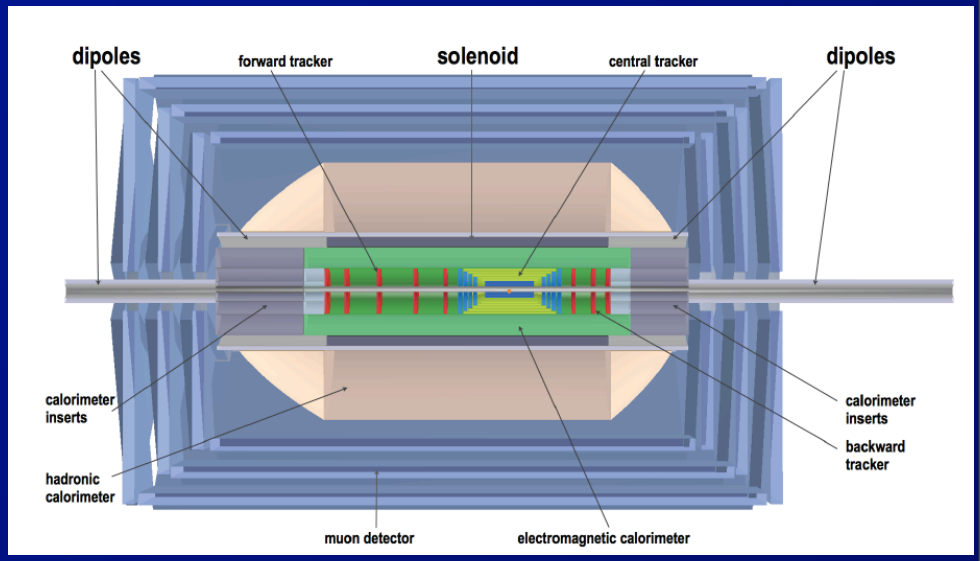
- **Goal: start operation by 2023 [LHC high lumi]**
  - ⇒ The major accelerator and detector technologies exist
  - ⇒ Cost is modest in major HEP project terms
- **Steps:**
  - Conceptual Design Report, 2012
  - Evaluation within CERN / European PP/NP strategy
  - If positive, move towards a TDR 2013/14

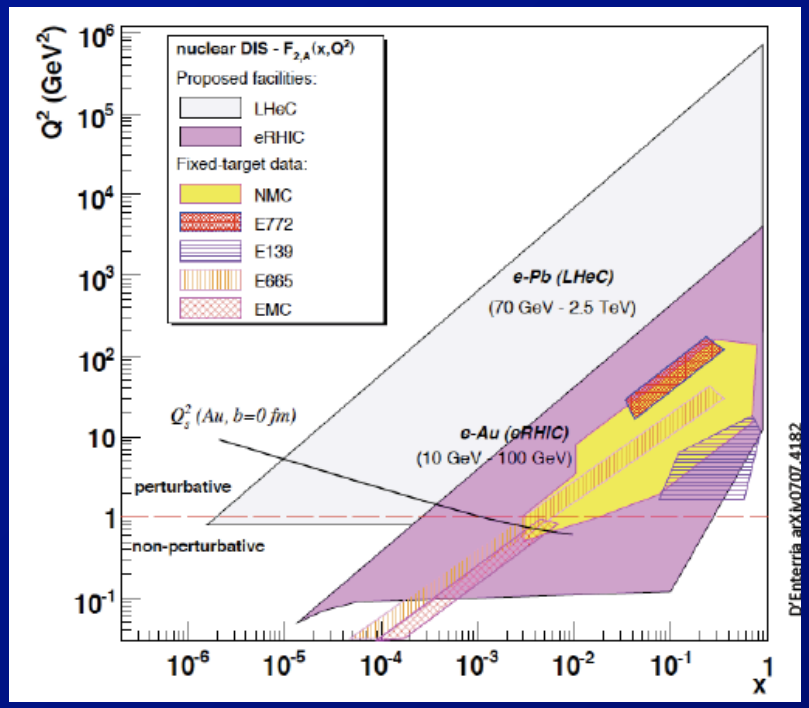
Summary

- Many issues remain open about precision perturbative QCD in nuclei and at small-x.
  - ⇒Lack of understanding limits our physics program
- e+p/A collider offers huge possibilities for QCD:
  - ⇒Improved proton and nucleus PDFs
  - ⇒Hadron/nuclear structure.
  - ⇒Factorization checks.
  - ⇒New (non-linear) regime at high energy/small x.
  - ⇒Questions we don't yet know (how) to ask
- e+A: amplifier of density effects,
  - – implications for A+A initial state & evolution to sQGP
  - – complementary to p+A@LHC.
- LHeC@CERN:
  - ⇒new facility for e+p/e+A at Ecm~1-2 TeV under design.

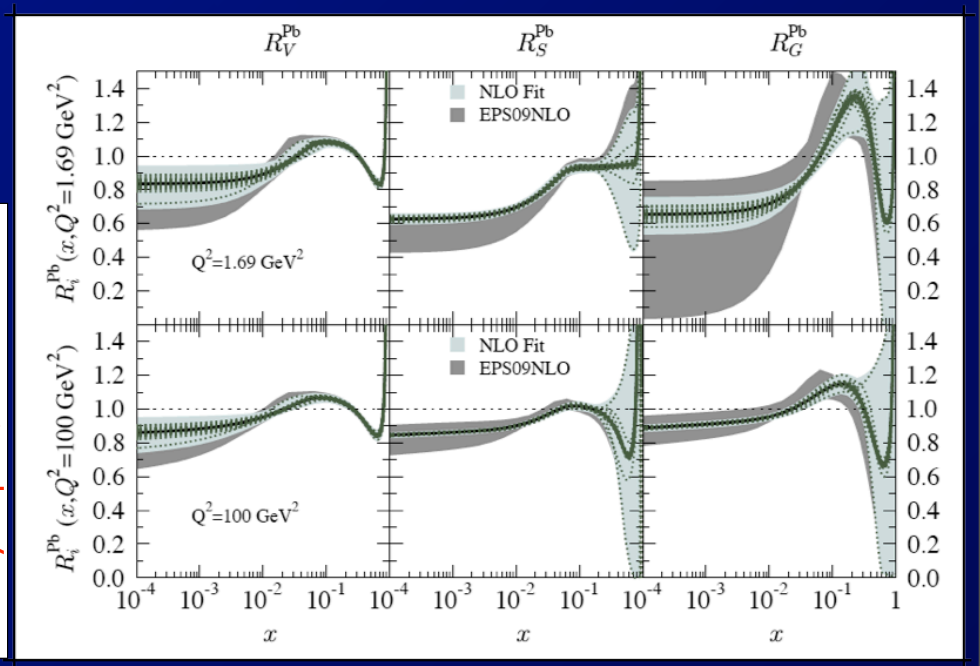
Summary (2)





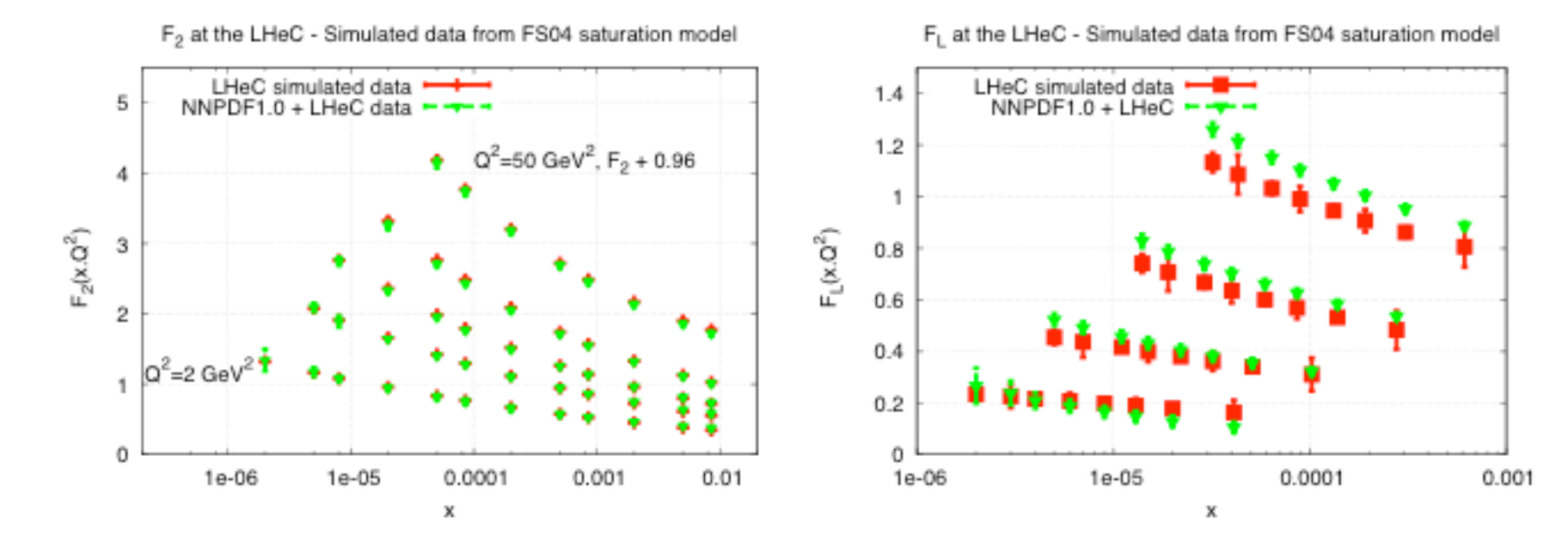


Preliminary; LHeC Design Study Report, CERN 2012



LHeC Data and PDFs, non-linearities?

J. Rojo, from CERN HPD workshop

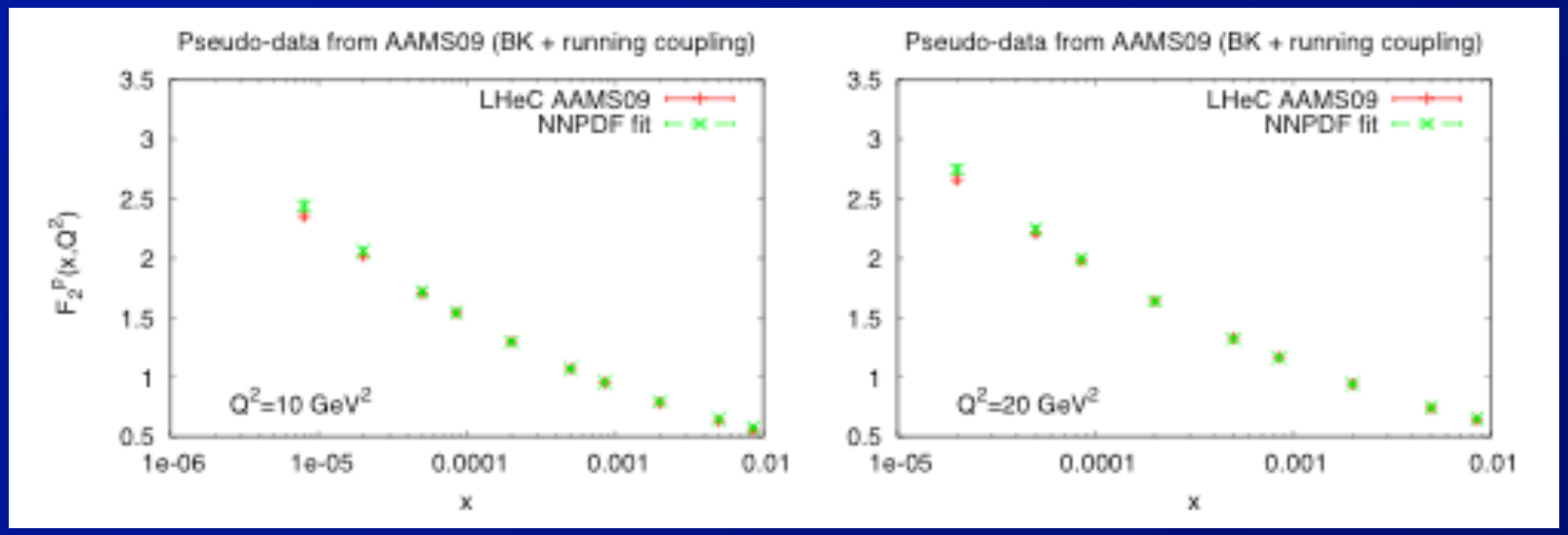


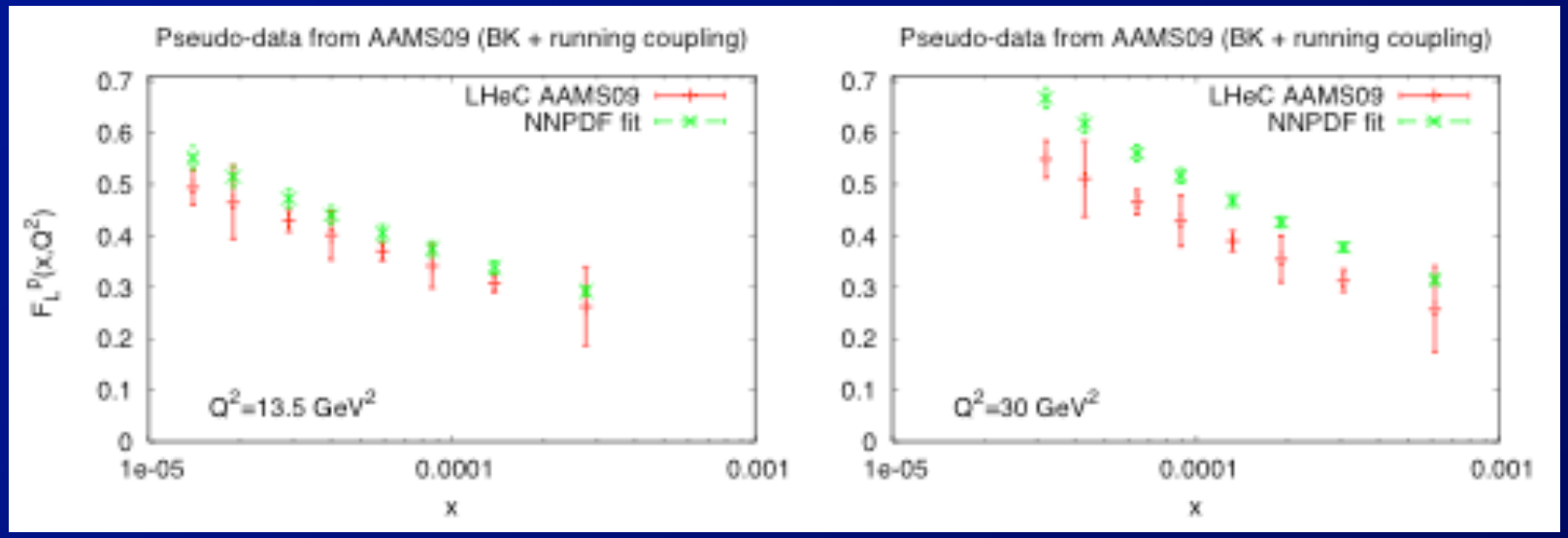
- **Can we see failure of linear evolution (including low-x resummation) with e-p data from LHeC?**
  - NNPDF fits to pseudo-data w/ saturation (here FS04)
  - Compare extracted PDFs, deviations indicate failure of linear evolution

⇒Need F_L to see significant

LHeC Data and PDFs, non-linearities?

J. Rojo, from CERN HPD workshop

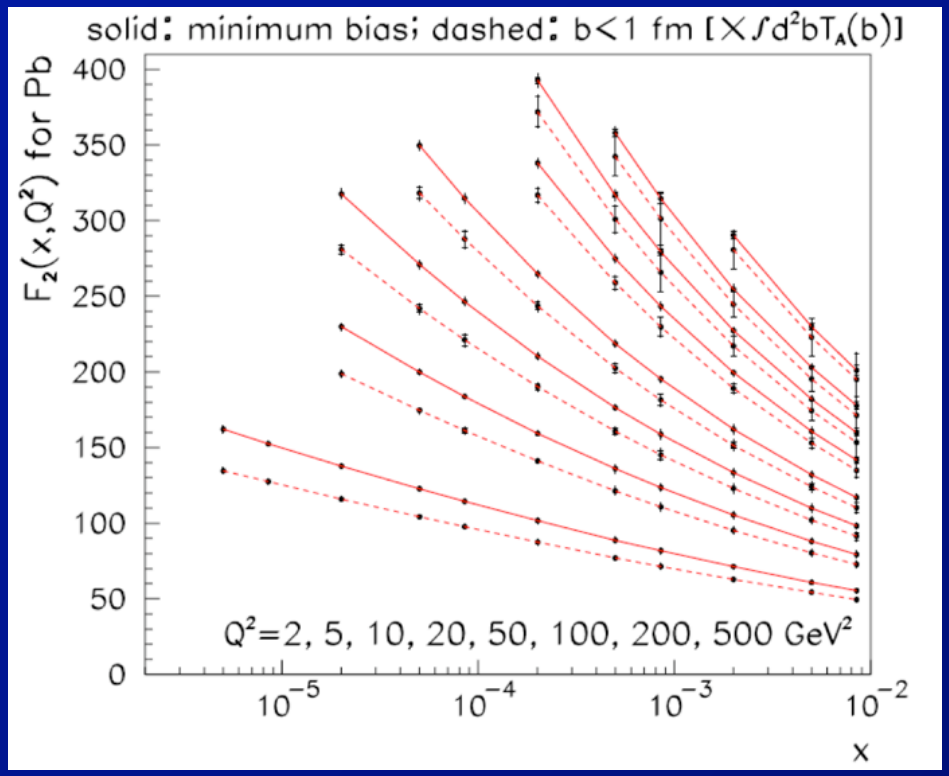


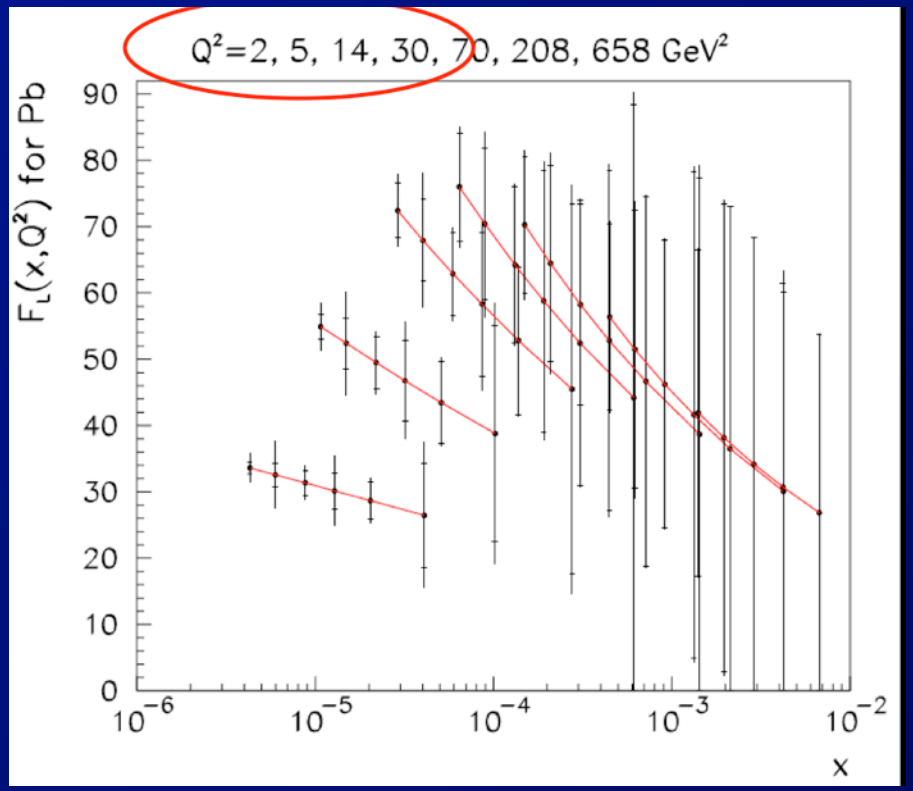


- **Similar conclusions w/ more modern saturation**

Nuclear PDF, LHeC

N. Armesto, CERN HPD workshop

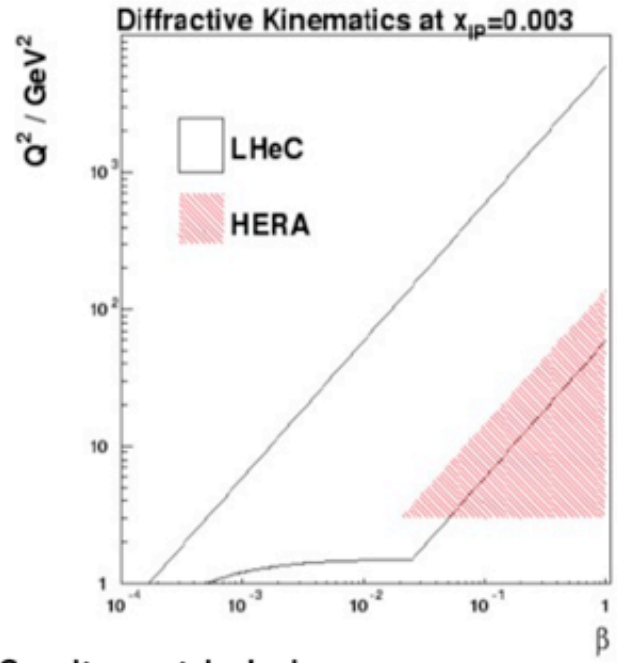




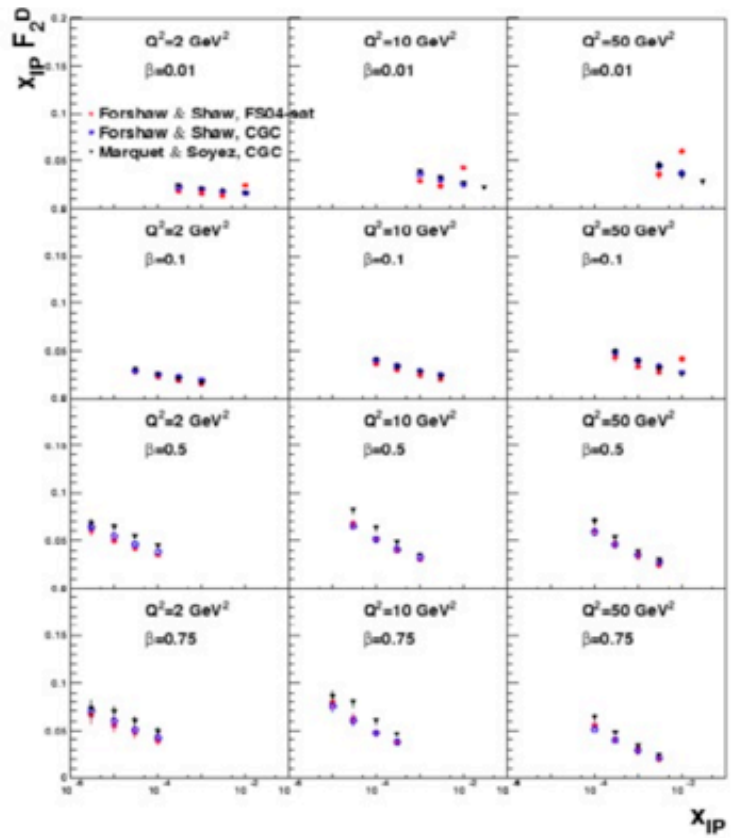
- **Nuclear pseudo-data for a given set of assumptions re: nuclear running**
  - Excellent statistics for F_2, not so good for F_L
  - ⇒But, sensitive to assumptions re: nuclear operation
  - F_L still as necessary with nuclei?

Inclusive Diffraction @ LHeC

Diffraction at LHeC: new possibilities



- Studies with 1 degree acceptance,
- Diffractive-PDFs
- Factorization in much bigger range
- Diffractive masses $M_X \sim 100\mathrm{GeV}$ with $x_{I\!P} = 0.01$
- X can include W,Z,b



Forshaw, Marquet, Newman

Simulated diffractive data available

- **From talk by P. Newman Divonne 2008**