LHeC
Large Hadron electron Collider

Project for electron-proton and ion collisions at CERN

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http://www.cern.ch/lhec

Lawrence Berkeley National Laboratory, February 21,2012

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Around 540 pages, about 150 contributors

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DRAFT 1.0
Geneva, December 20, 2011
CERN report
ECFA report
NuPECC report
LHeC-Note-2011-001 GEN

A Large Hadron Electron Collider at CERN

Report on the Physics and Design Concepts for Machine and Detector

LHeC Study Group

THIS IS THE VERSION FOR REFEREEING, NOT FOR DISTRIBUTION

To be submitted for publication

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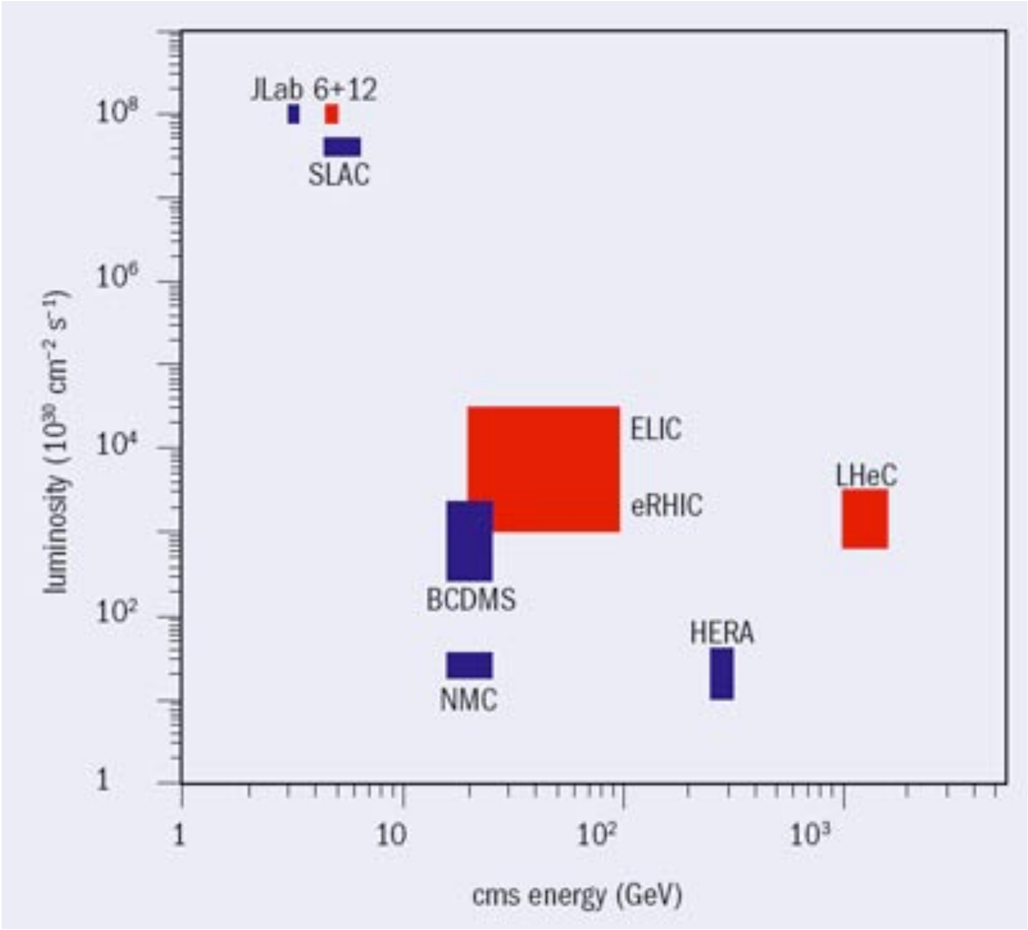
Tentative list of people who contributed (from Dec. 20, 2011, more to be included), from about 60 institutions.



LHeC is the latest & most promising idea to take ep physics to the TeV centre-of-mass scale …
… at high luminosity

Outline of the talk:

- Physics motivation
- Accelerator and detector design
- Physics possibilities
- Timeline and outlook

Scattering experiments

Rutherford-Geiger-Marsden 1909

Scattering of alpha particles off the gold foil. Atomic structure.

Hofstadter 1950-1957

Electron scattering off nuclei, charge and shape of nuclei, determining size of protons of about 1fm.

MIT - SLAC experiment 1967-1973

20 GeV electron scattering off protons, discovery of proton structure, spin 1/2 constituents.

First Observation Of Proton Structure

VOLUME 23, NUMBER 16 PHYSICAL REVIEW LETTERS 20 OCTOBER 1969

OBSERVED BEHAVIOR OF HIGHLY INELASTIC ELECTRON-PROTON SCATTERING

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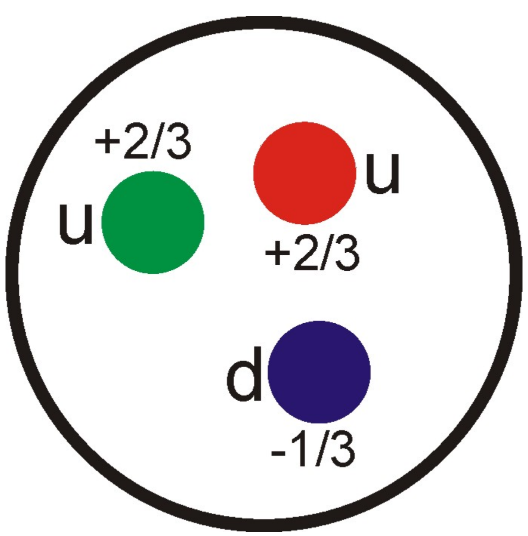
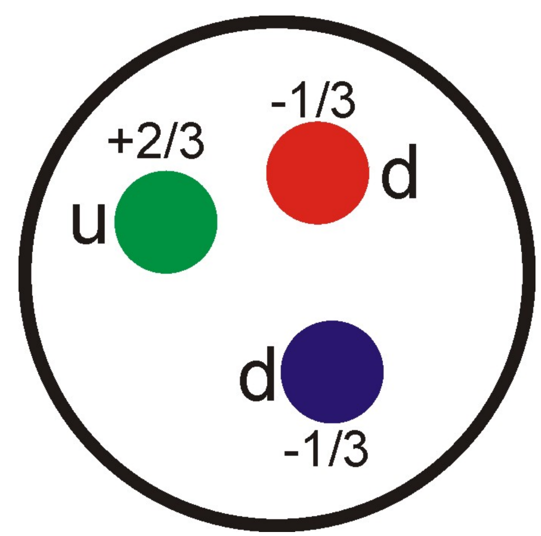


proton



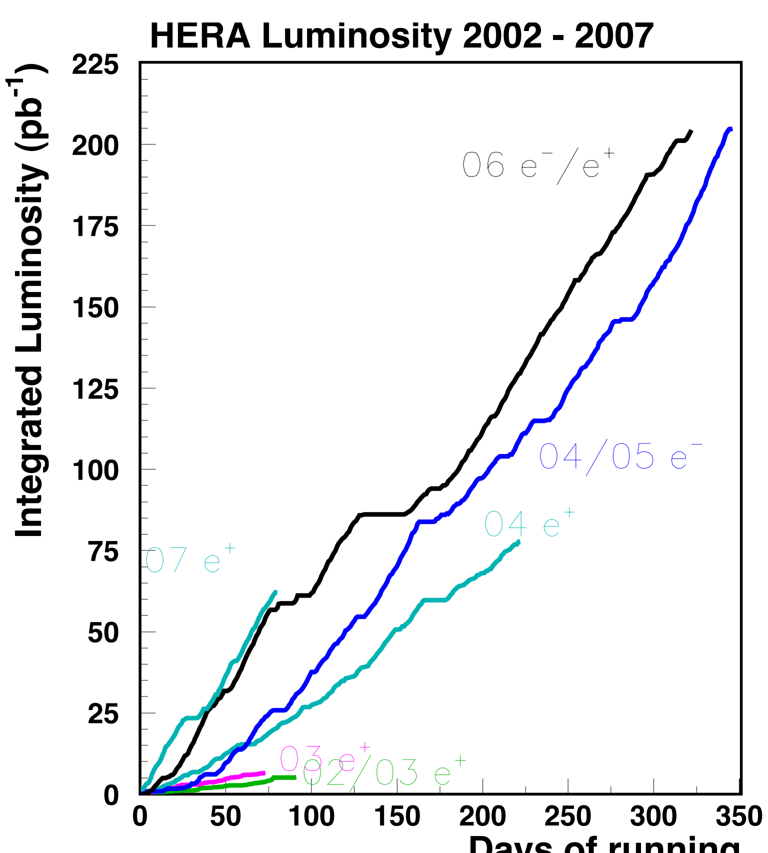
neutron

... and so on ...

Deep inelastic electron-proton collider

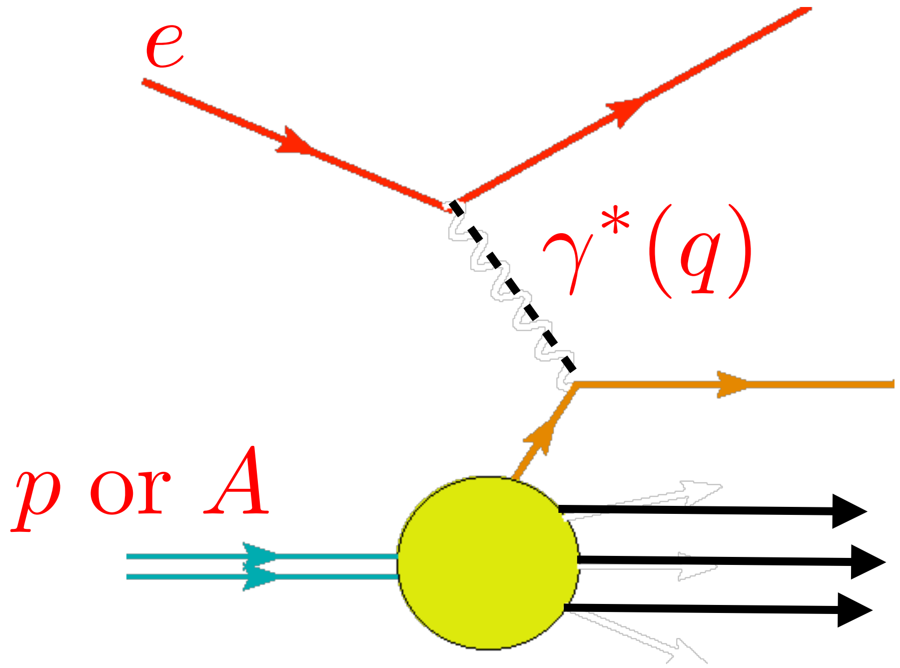
First (and up to now last) electron-proton collider

HERA Hamburg 1992-2007



Deep Inelastic Scattering

Scattering of electron off a hadron(proton):



Photon virtuality:

$$Q^2 = -q^2 > 0$$

Total energy of the photon-proton system

$$s = (p+q)^2$$

Bjorken x

$$x = \frac{Q^2}{s+Q^2} \simeq \frac{Q^2}{s}$$

cross section

parton density

$$\sigma^{\gamma^* p} \sim \frac{1}{Q^2} x f(x, Q^2)$$

$$0 \leq x \leq 1$$

x fraction of the longitudinal momentum of the proton carried by the quark

Electroweak:

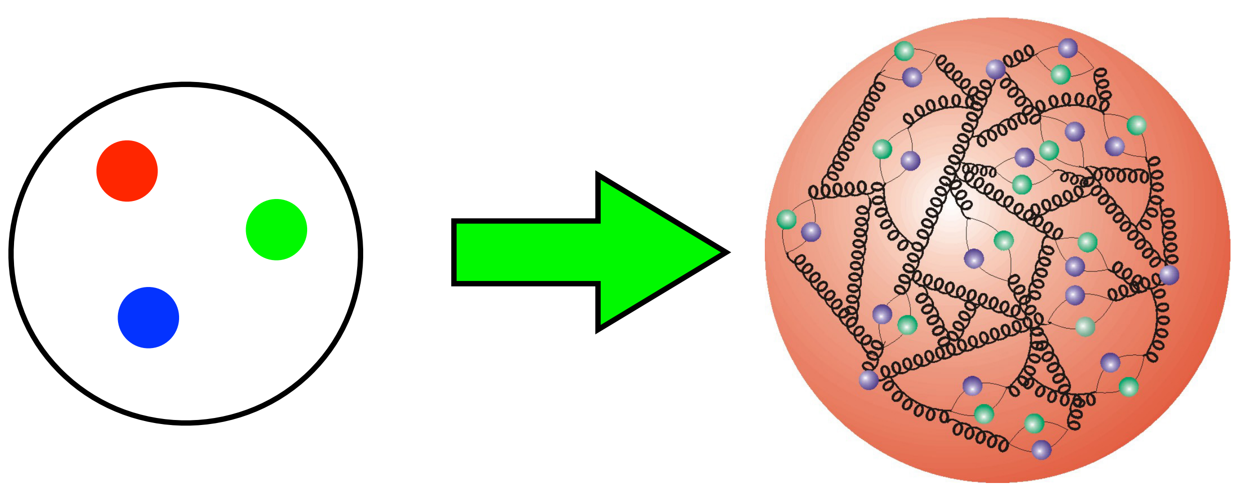
Neutral current

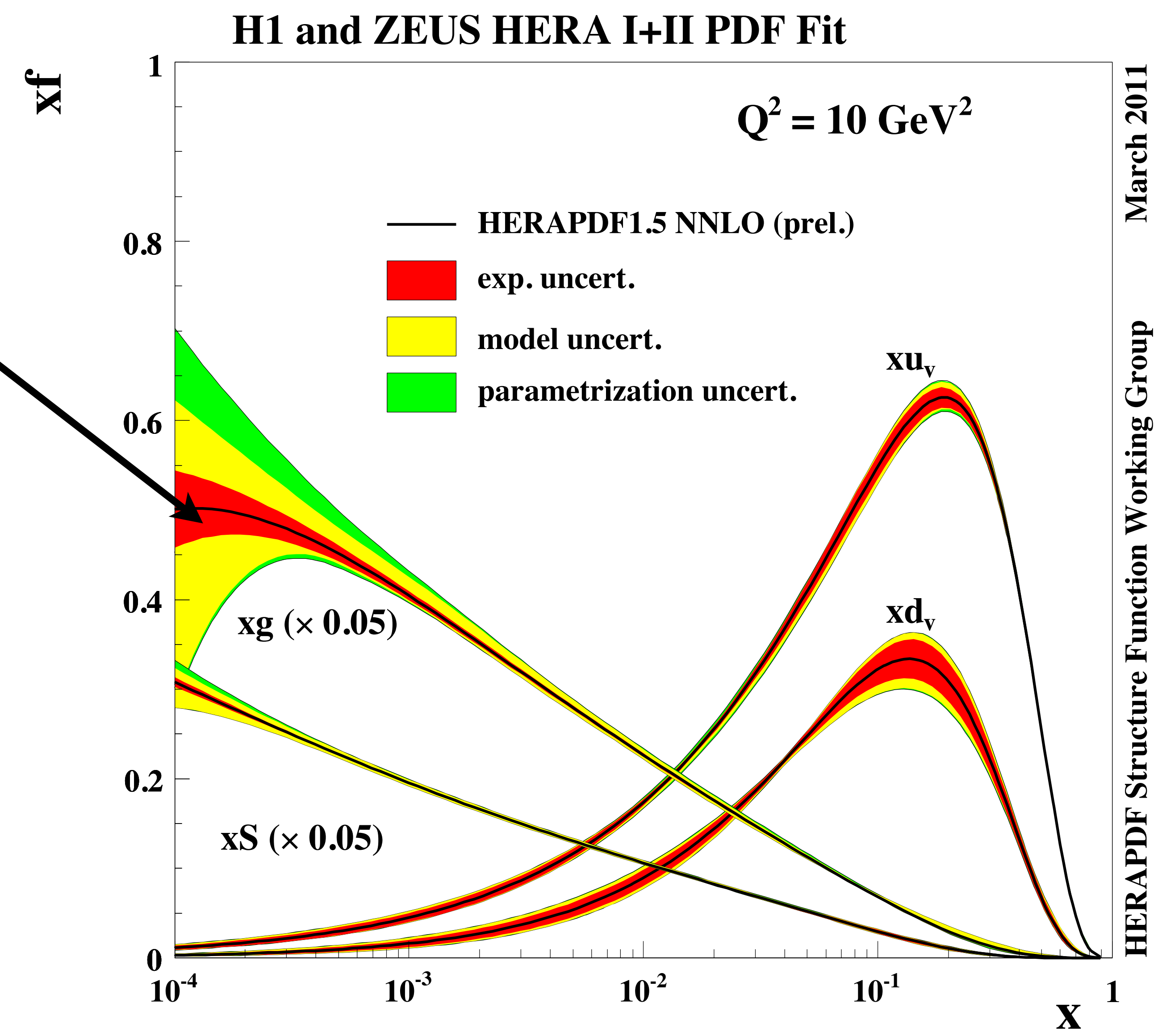
Charge current (neutrino in the final state)

Results from HERA

HERA established detailed proton structure: parton density functions.

Increasing role of gluons at small x. Proton structure is highly complex due to the QCD radiation (evolution).





Other results: measurement of coupling constant, jets, photon structure, diffractive processes, charm and bottom structure functions, limits for new physics (leptoquarks).

Limitations of HERA

HERA in one box
the first ep collider

$E_p * E_e =$
$920*27.6 GeV^2$
$\sqrt{s} = 2\sqrt{E_e E_p} = 320$ GeV

$L = 1..4\ 10^{31} cm^{-2} s^{-1}$
→ $\Sigma L = 0.5 fb^{-1}$
1992-2000 & 2003-2007

$Q^2 = [0.1 -- 3 * 10^4]\ GeV^2$
-4-momentum transfer^2

$x = Q^2/(sy) \cong 10^{-4}$ .. 0.7
Bjorken x

$y \cong 0.005$ .. 0.9
inelasticity

- Low luminosity for high precision(large x)
- No deutrons
- No heavy nuclei
- Low x saturation ?(too small s)
- Precision measurement of α_s (overall not precise enough)
- …

HEP needs a TeV energy scale machine with 100 times higher luminosity than HERA to develop DIS physics further and to complement the physics at the LHC. The Large Hadron Collider p and A beams offer a unique opportunity to build a second ep and first eA collider at the energy frontier.

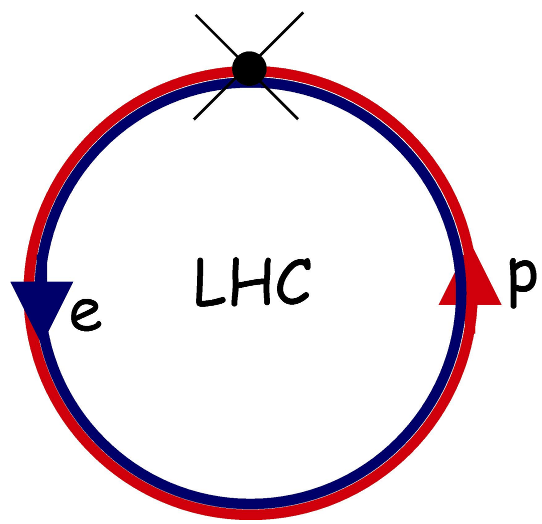
Physics motivation for ep/eA in TeV range

- Details of parton structure of the nucleon (from ep,ed/eA), full unfolding of PDFs. Measurement of GPDs and unintegrated PDFs.
- Mapping the gluon field down to very low x. Saturation physics.
- Heavy quarks, factorization, diffraction, electroweak processes.
- Properties of Higgs (if it exists). Very good sensitivity to: H to bbar, H to WW coupling in the 120-130 GeV mass range.
- Searches and understanding of new physics. Very precise measurement of the coupling constant. Leptoquarks, excited leptons...
- Deep inelastic scattering off nuclei. Nuclear parton distributions. Pinning down the initial state for heavy ion collisions.

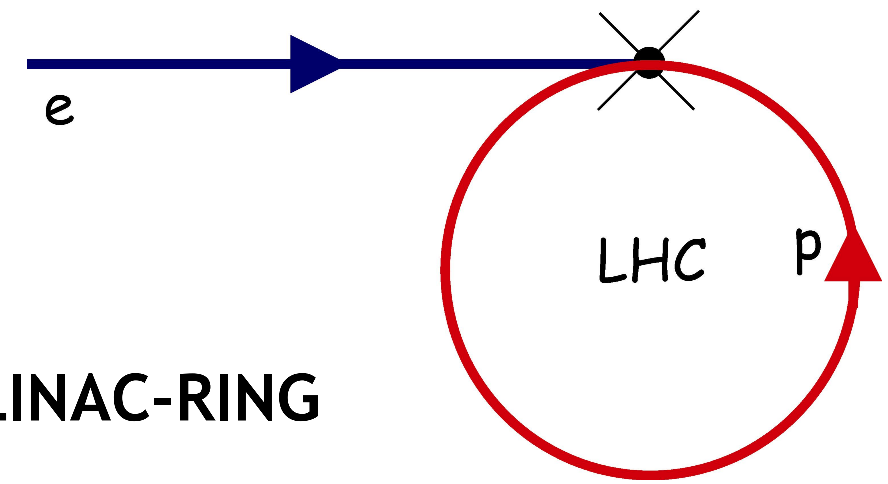
How Could ep be Done using LHC?

… whilst allowing simultaneous ep and pp running …

RING-RING



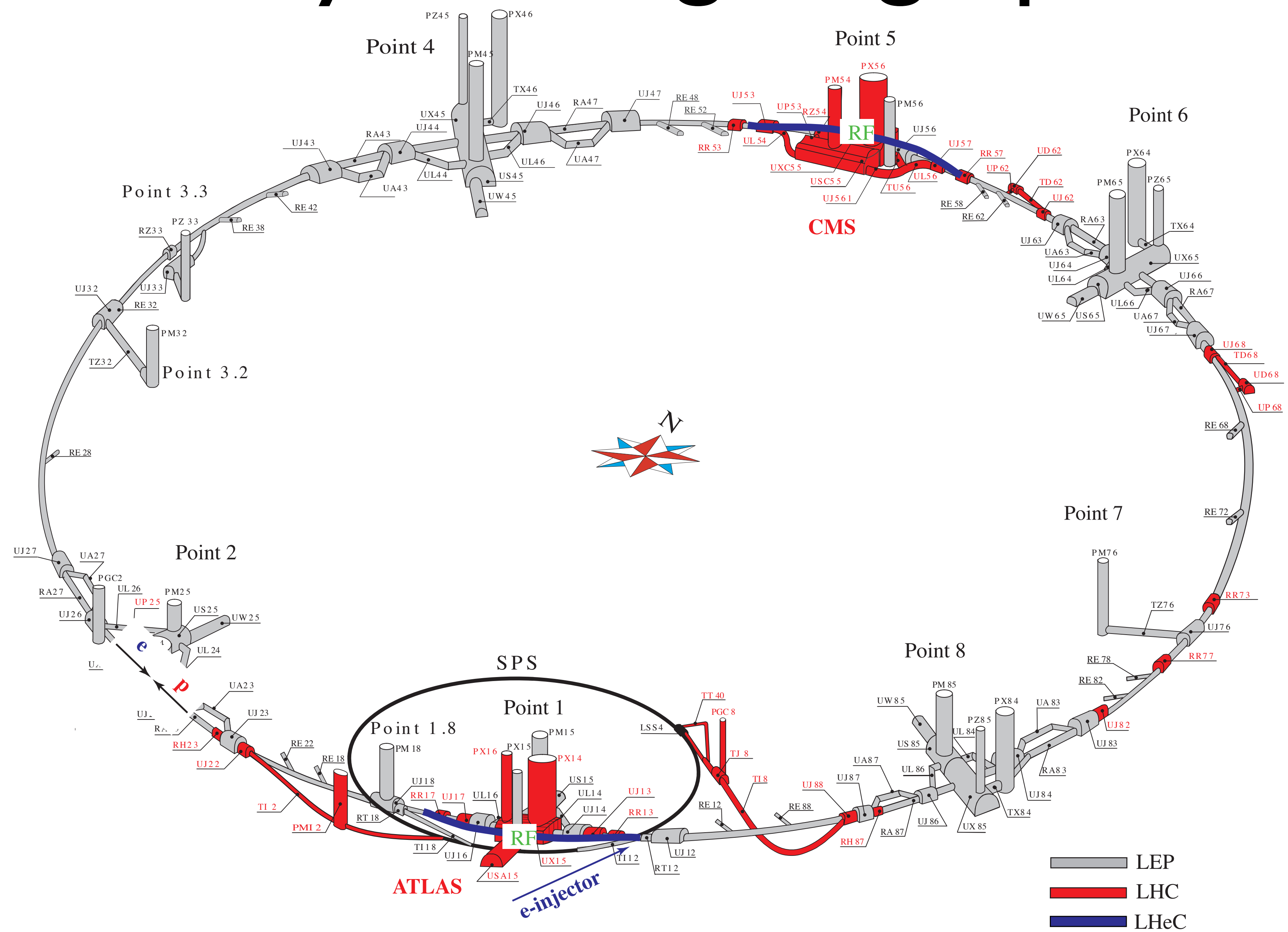
LINAC-RING

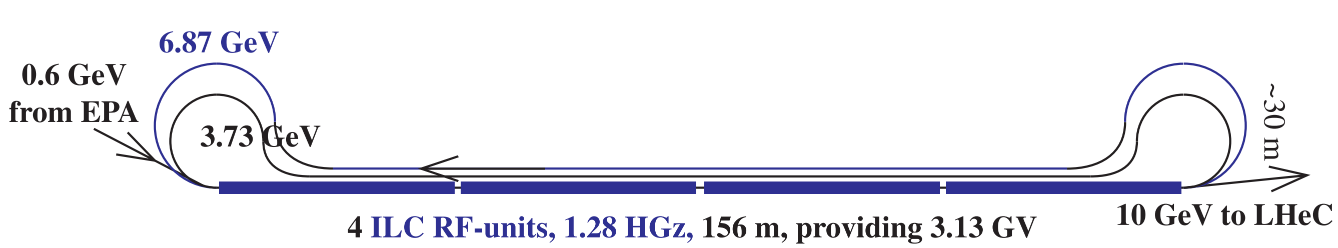


- First considered (as LEPxLHC) in 1984 ECFA workshop
- Main advantage: high peak lumi obtainable (~2.10^{33} cm^{-2} s^{-1})
- Main difficulties: building round existing LHC, e beam energy (60GeV?) and lifetime limited by synchrotron radiation

- Previously considered as `QCD explorer' (also THERA)
- Main advantages: low interference with LHC, high E_e (→ 150 GeV?) and lepton polarisation, LC relation
- Main difficulties: lower luminosity <10^{33} cm^{-2} s^{-1}? at reasonable power, no previous experience exists

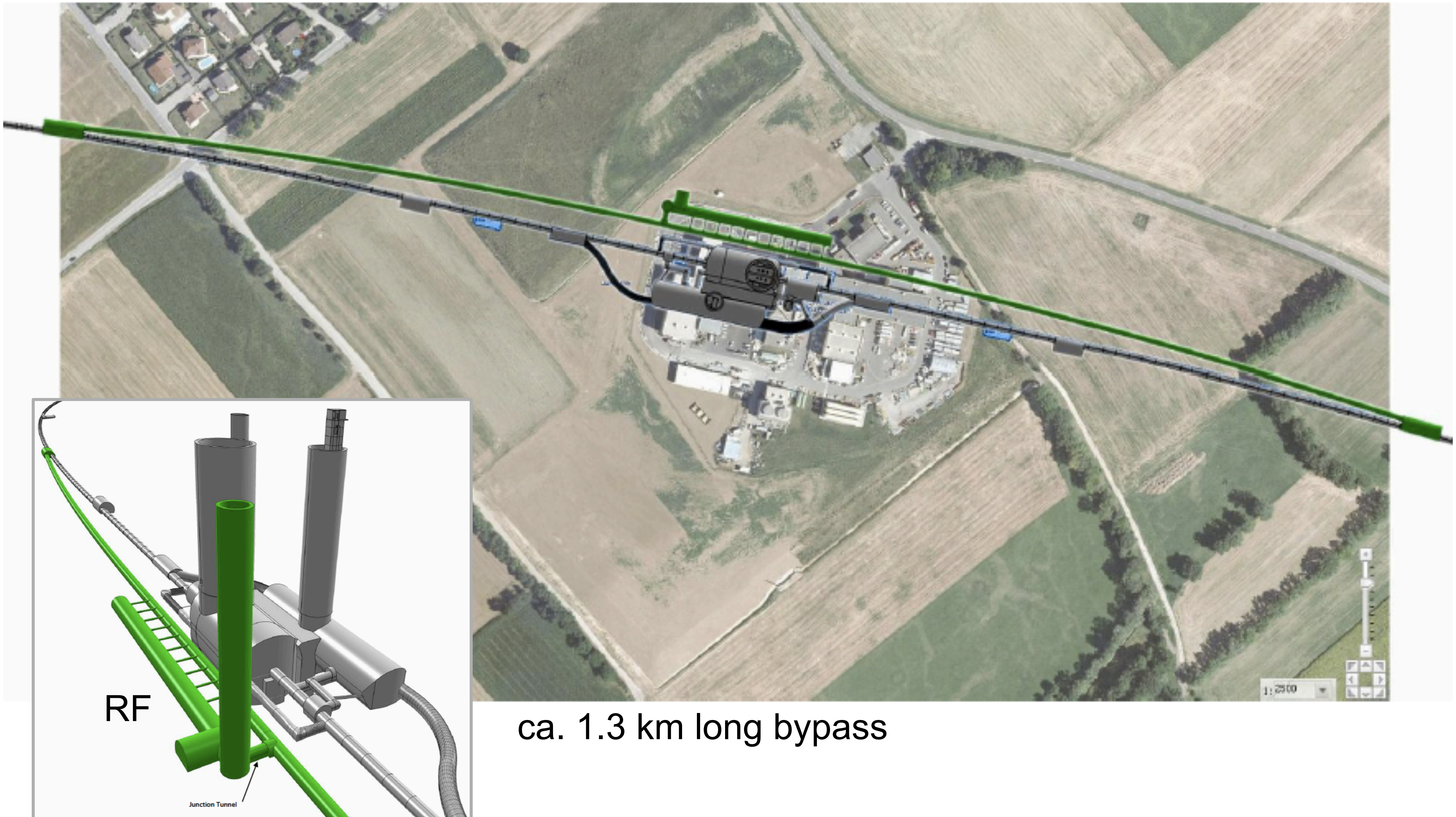
LHeC layout: ring-ring option





10 GeV injector

Bypassing CMS: 20m distance to Cavern

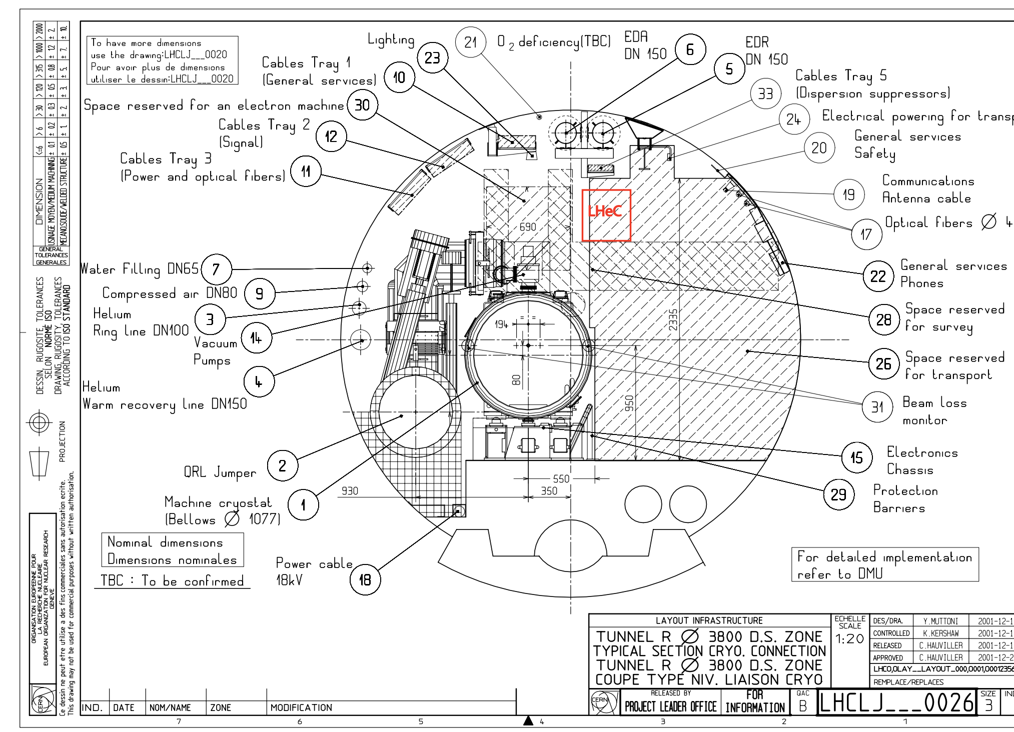


ca. 1.3 km long bypass

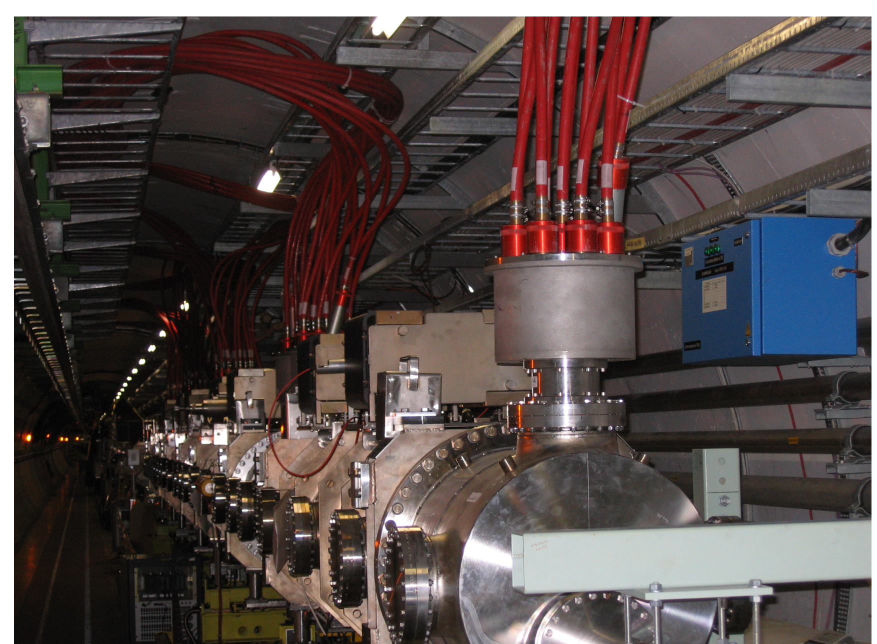
Accelerator design

Multi-lab involvement: CERN, BNL, Novosibirsk, Cockroft, Cornell, DESY, EPFL Lausanne, JLab, KEK , Liverpool, SLAC, TAC Turkey, NTFU Norway, INFN, ...

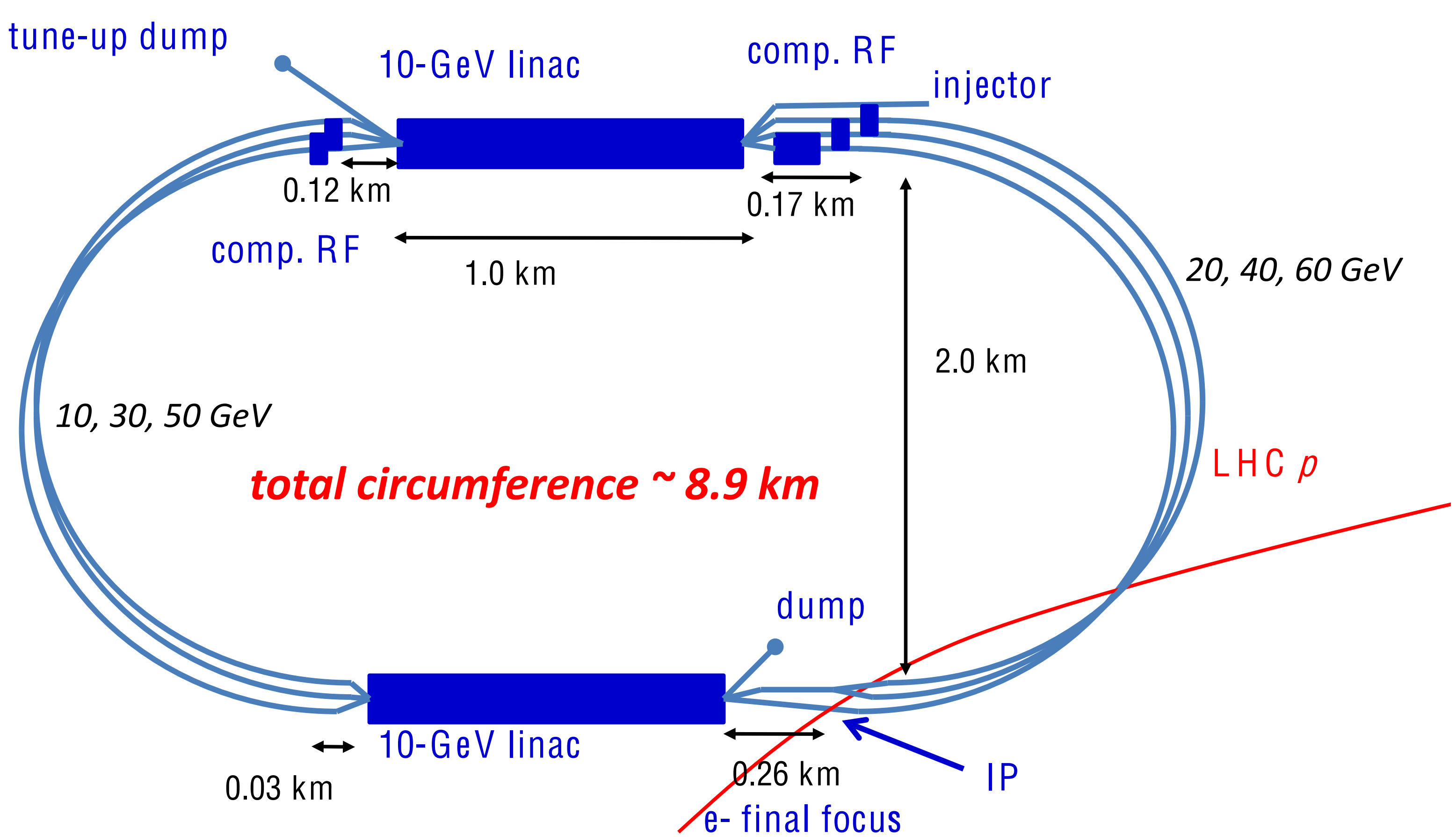
Design constraint: power consumption < 100 MW. Electron energy 60 GeV in ring-ring mode



Installation 1m above LHC and 60cm to the inside.
By-passes of existing experiments.
Challenging, but possible.



Accelerator design in linac-ring option



500 MeV injection
3 turns
2 linacs, 10 GeV
energy recovery
90% polarisation

$$L = 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

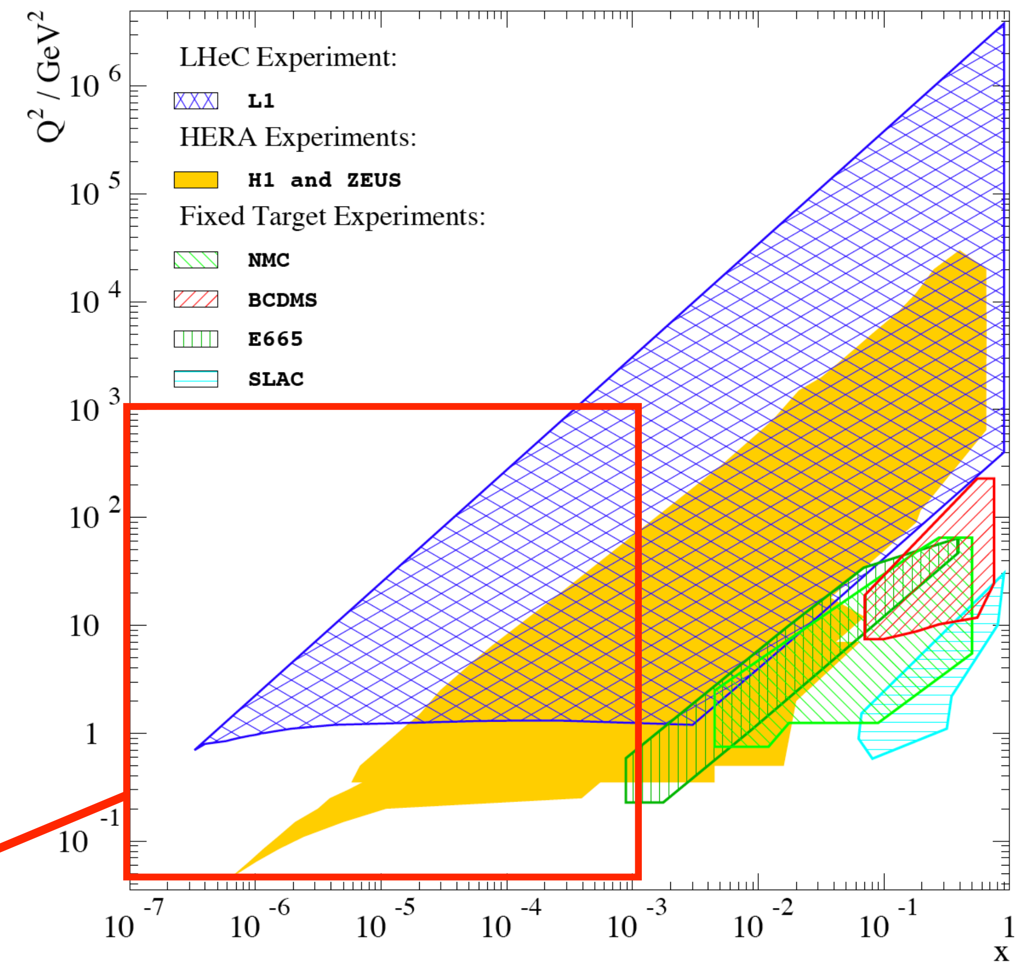
Higher energy:
140 GeV linac
ILC type
31.5 MV/m
without energy recovery
lower luminosity

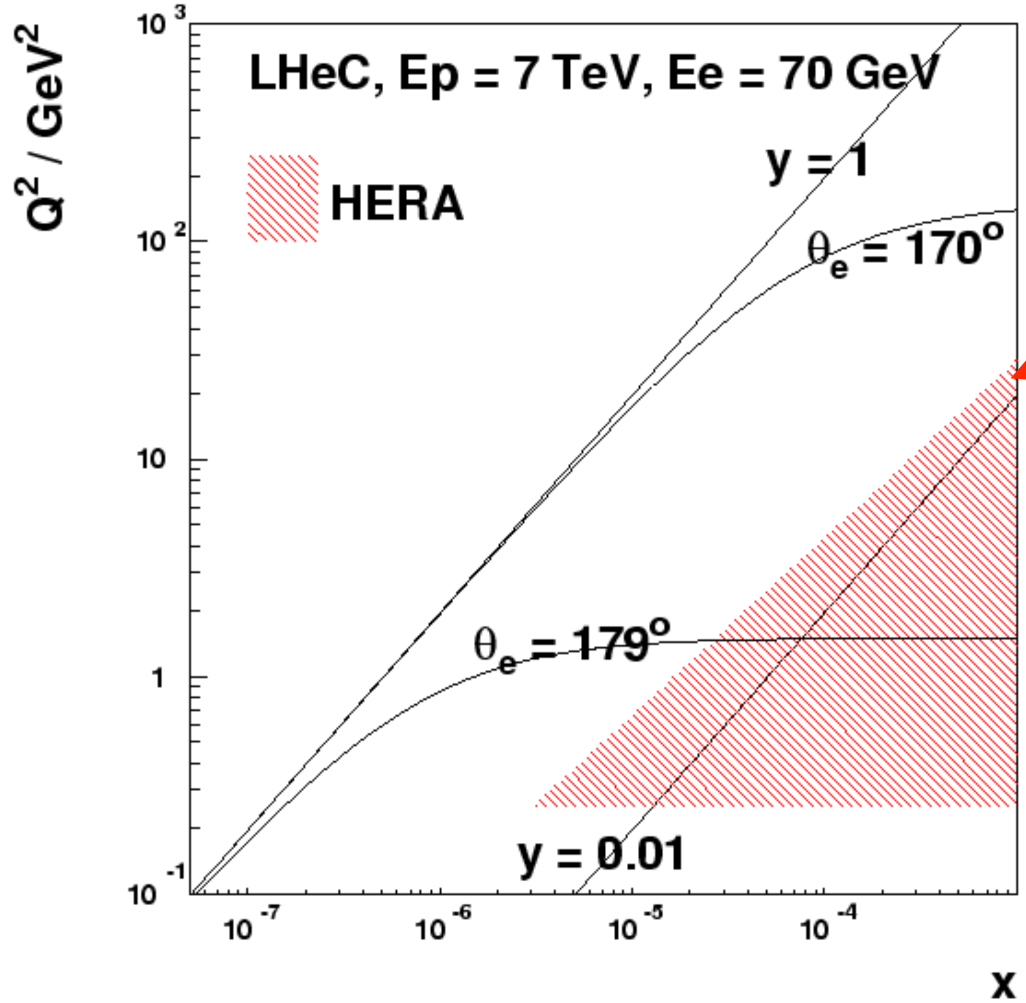
TUPC017

Civil Engineering Studies for Major Projects after LHC

Detector Acceptance Requirements

Access to Q^2=1 GeV^2 in ep mode for all x > 5 x 10^{-7} 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)

Experimental Precision Aims

Requirements to reach a per-mille α_s (c.f. 1-2% now) …

The new collider …

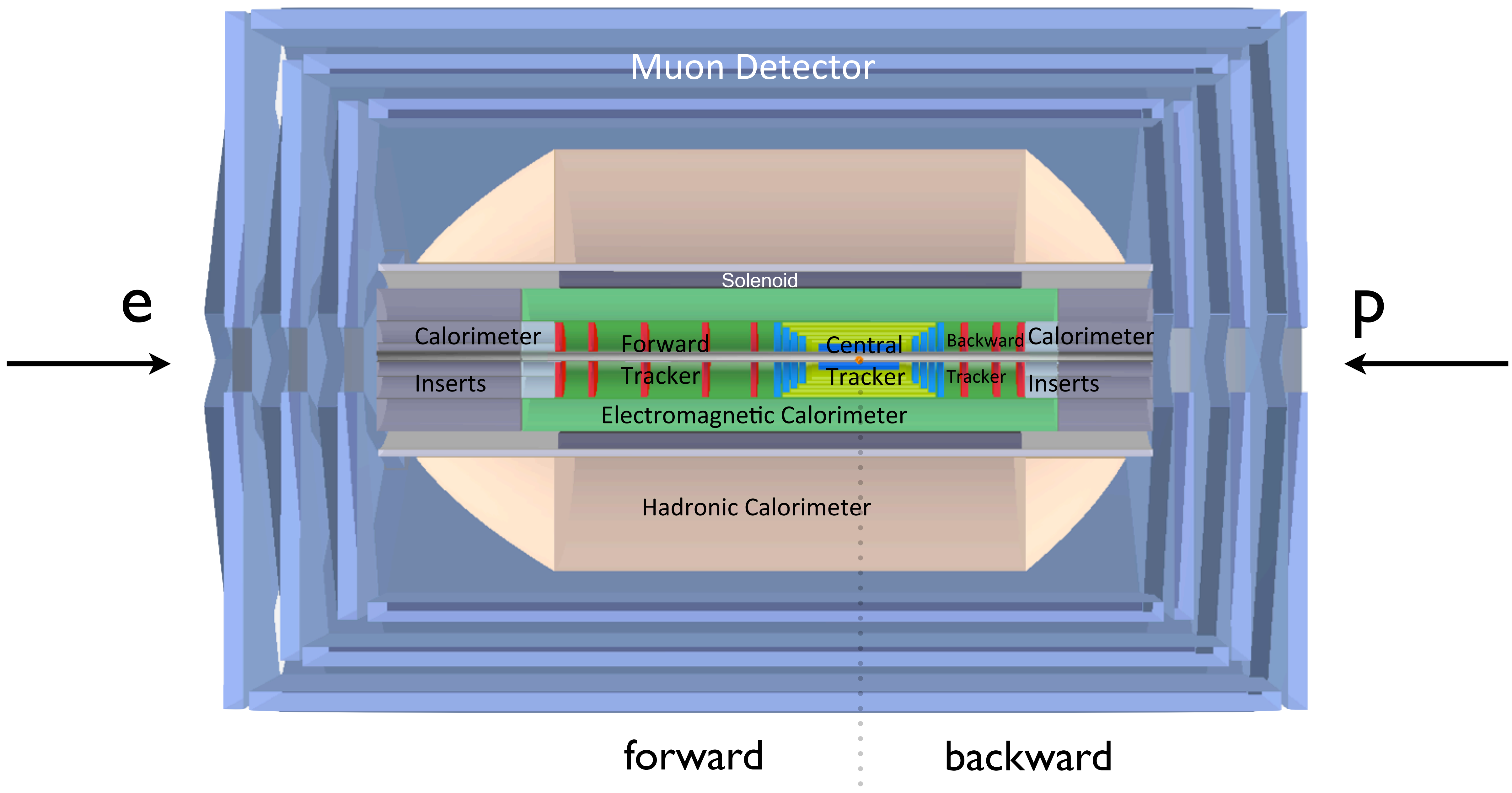
- should be ~100 times more luminous than HERA

The new detector

- should be at least 2 times better than H1 / ZEUS

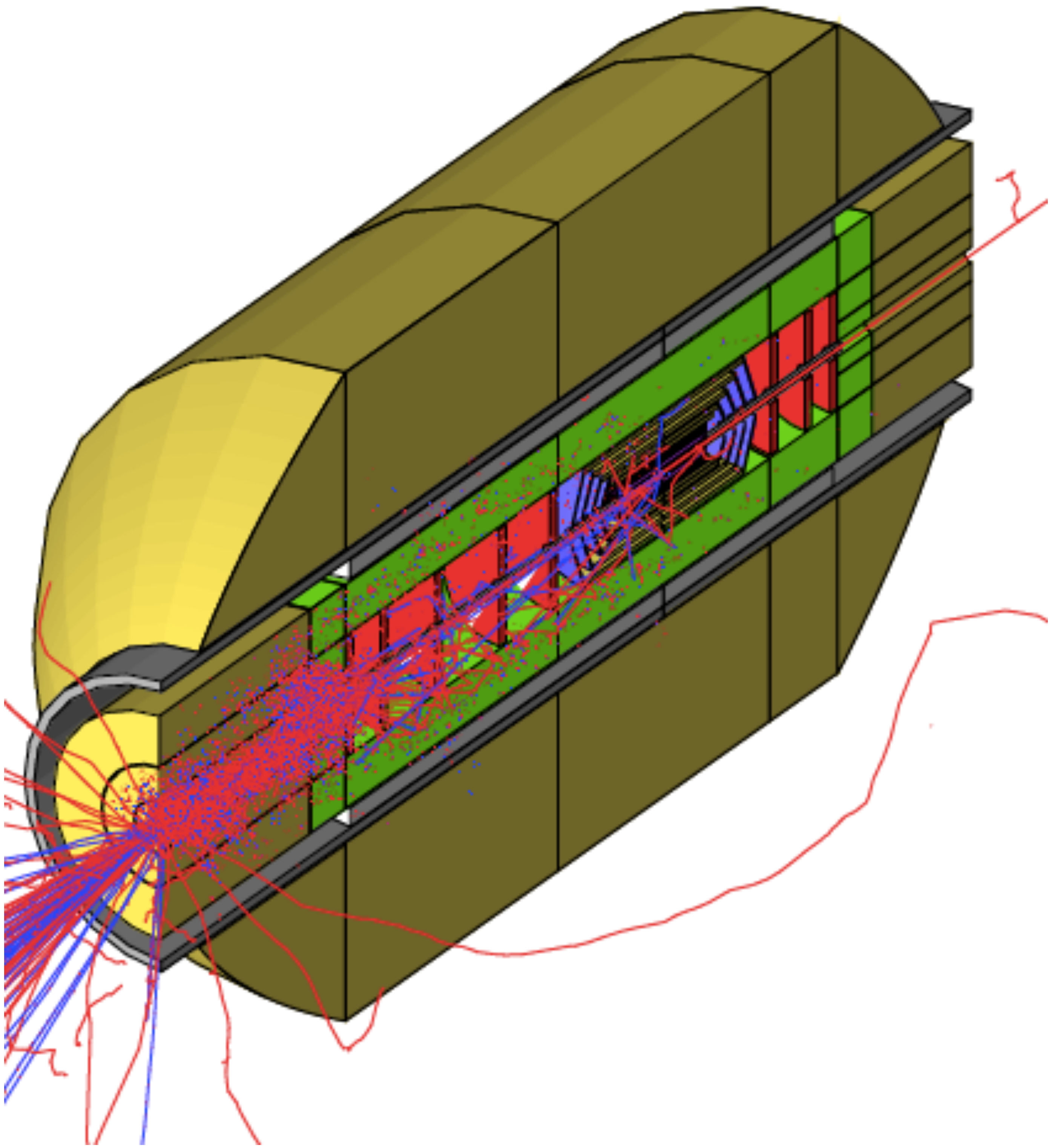
	LHeC	HERA
Lumi [$cm^{-2}s^{-1}$]	10^{33}	$1\text{-}5 \times 10^{31}$
Acceptance [°]	1-179	7-177
Tracking to	0.1 mrad	0.2-1 mrad
EM calorimetry to	0.1%	0.2-0.5%
Hadronic calorimetry	0.5%	1-2%
Luminosity	0.5%	1%

Detector design



Forward/backward asymmetry in energy deposited and thus in geometry and technology
Present dimensions: LxD =14x9m^2 [CMS 21 x 15m^2, ATLAS 45 x 25 m^2]
Taggers at -62m (e),100m (γ,LR), -22.4m (γ,RR), +100m (n), +420m (p)

A GEANT4 Simulated Low x Event



Physics possibilities

Beyond Standard Model

Leptoquarks
Contact Interactions
Excited Fermions
Higgs in MSSM
Heavy Leptons
4th generation quarks
Z'
SUSY
???

QCD and EW precision physics

Structure functions
Quark distributions from direct measurements
Strong coupling constant to high accuracy
Higgs in SM
Gluon distribution in extended x range to unprecedented accuracy
Single top and anti-top production
Electroweak couplings
Heavy quark fragmentation functions
Heavy flavor production with high accuracy
Jets and QCD in photoproduction
Partonic structure of the photon
...

Small x and high parton densities

New regime at low x
Saturation
Diffraction
Vector Mesons
Deeply Virtual Compoton Scattering
Forward jets and parton dynamics
DIS on nuclei
Generalized/unintegrated parton distribution functions

Searches for new physics

- In general LHC has a bigger potential for discovery of new physics than the LHeC due to its kinematic range (unless the electron energy is pushed to 500GeV).
- LHeC can be competitive with LHC in cases where initial lepton is an advantage.
- LHeC offers cleaner final states.
- Combining LHC/LHeC will help clarify the new physics.

Leptoquarks

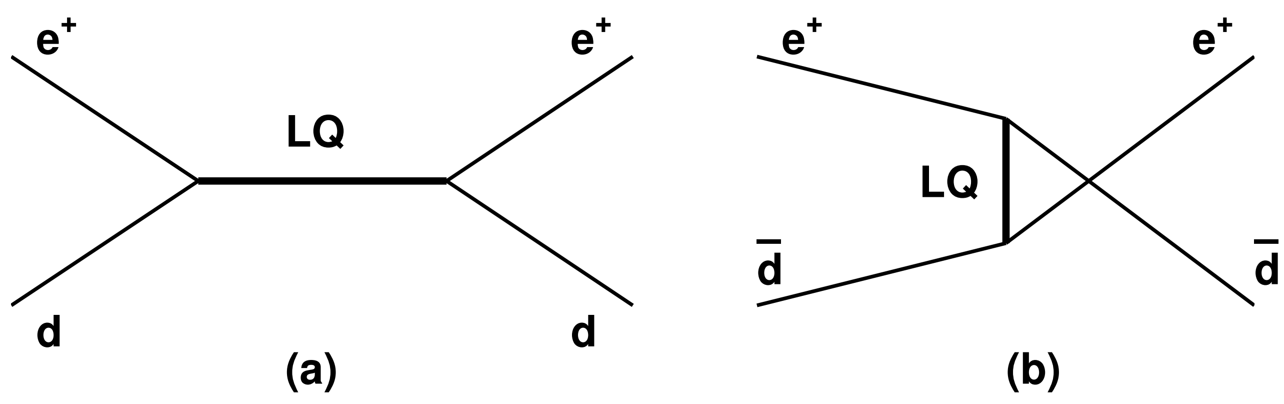
Leptoquarks appear in many extensions of the SM.

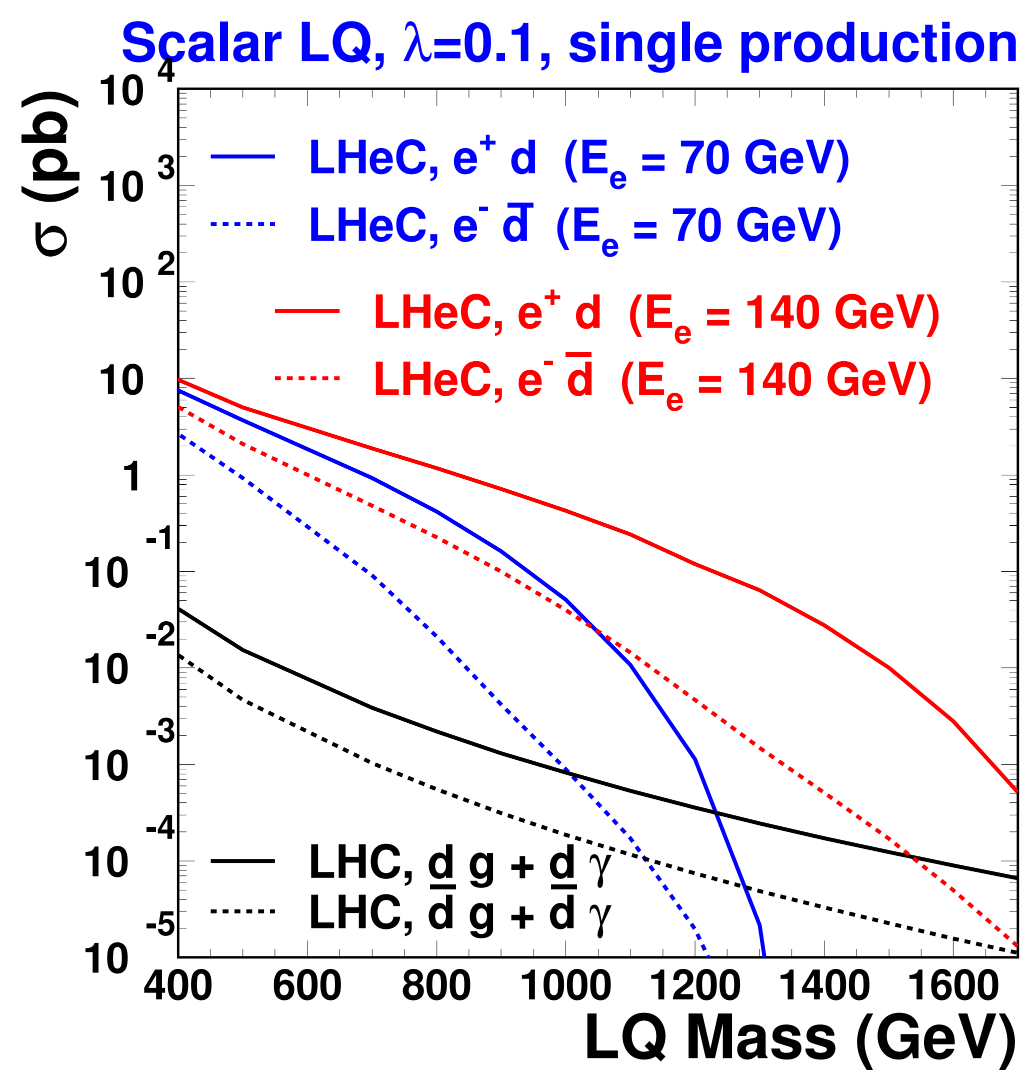
May help explain remarkable symmetry between lepton and quark sectors.

Produced via fusion of electron with the quark (antiquark) from the proton.

In pp leptoquarks mainly produced in pairs. Single production in ep. Better suited for studies of properties (quantum numbers etc.)

Mass sensitivity to 1.0-1.5 TeV. Comparable with LHC, much cleaner!

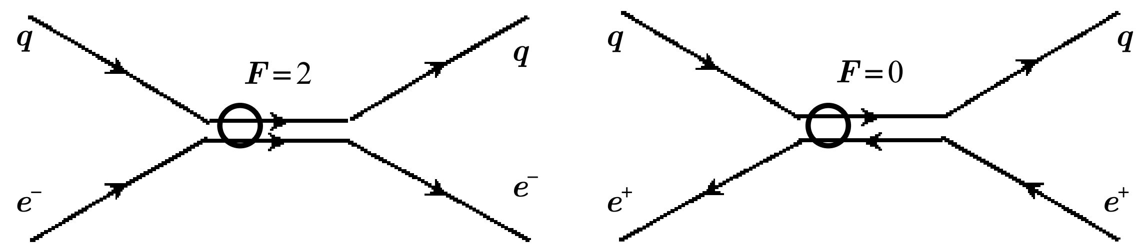


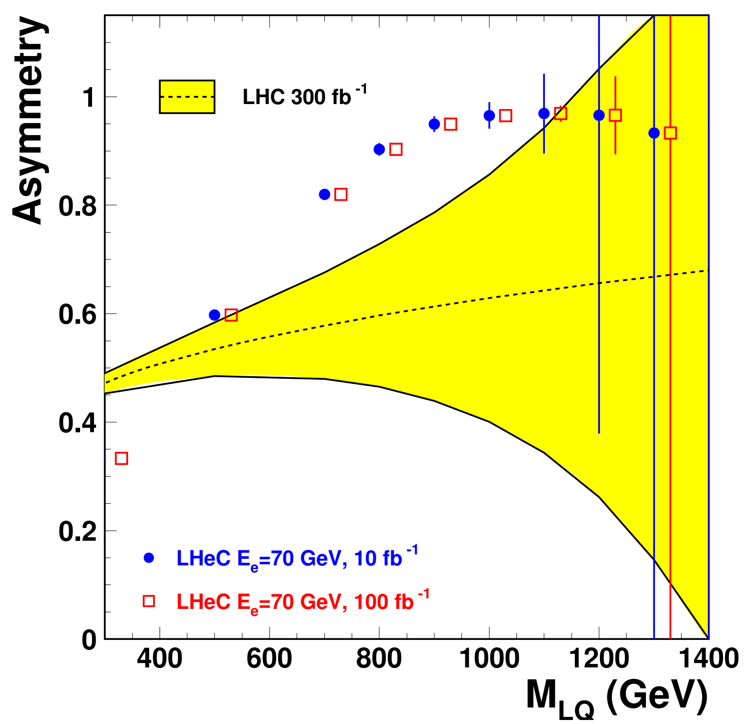


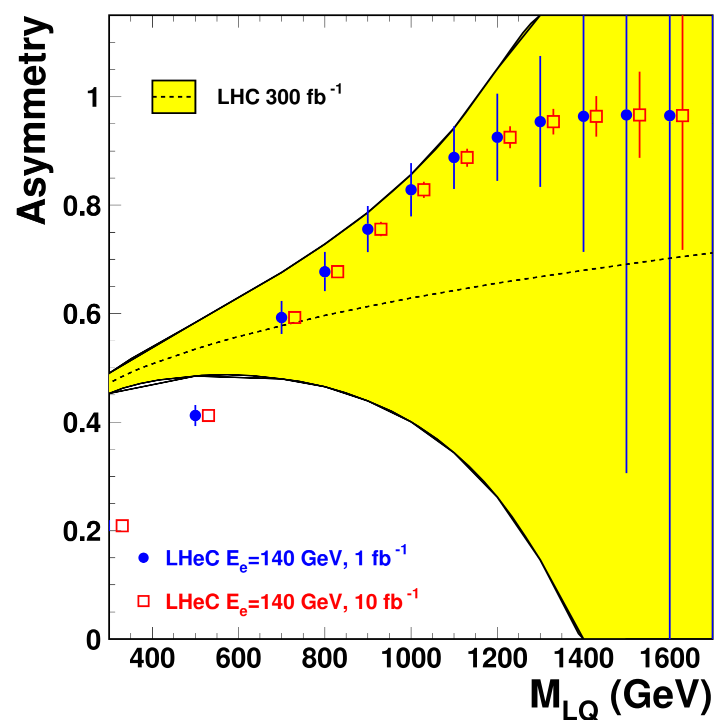
Leptoquark properties

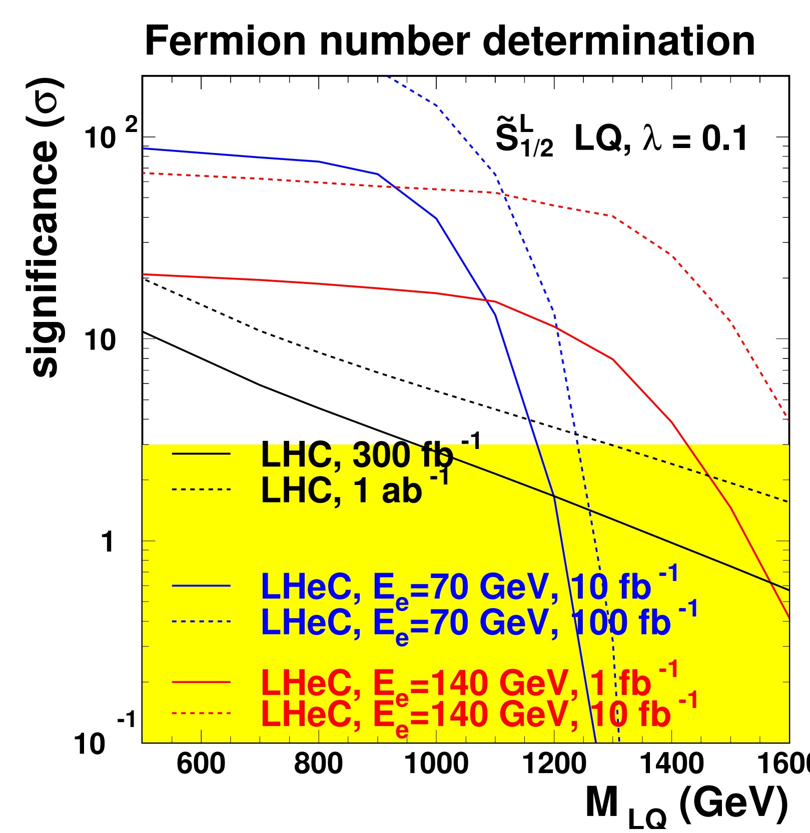
- Quantum numbers and couplings:
  - **F: fermion number can be obtained from asymmetry in single LQ production, since q have higher x than $\overline{q}$**

$$A = \frac{\sigma_{e^-} - \sigma_{e^+}}{\sigma_{e^-} + \sigma_{e^+}} \begin{cases} > 0 \text{ for F=2} \\ < 0 \text{ for F=0} \end{cases}$$



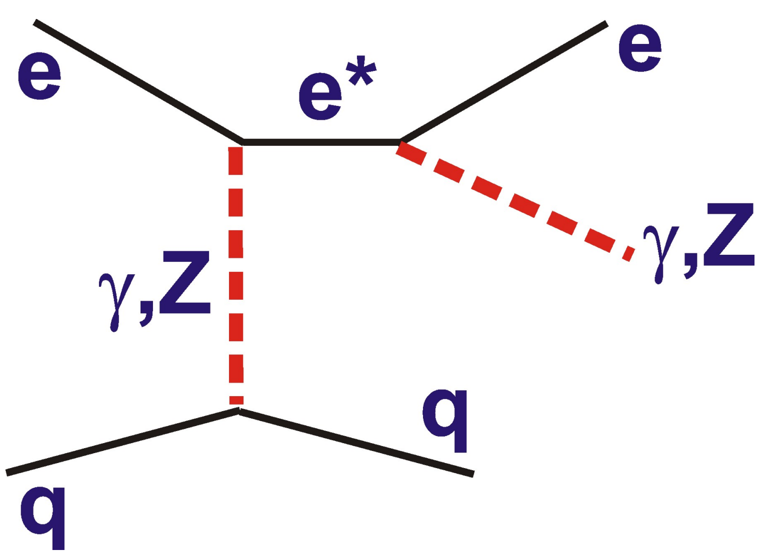


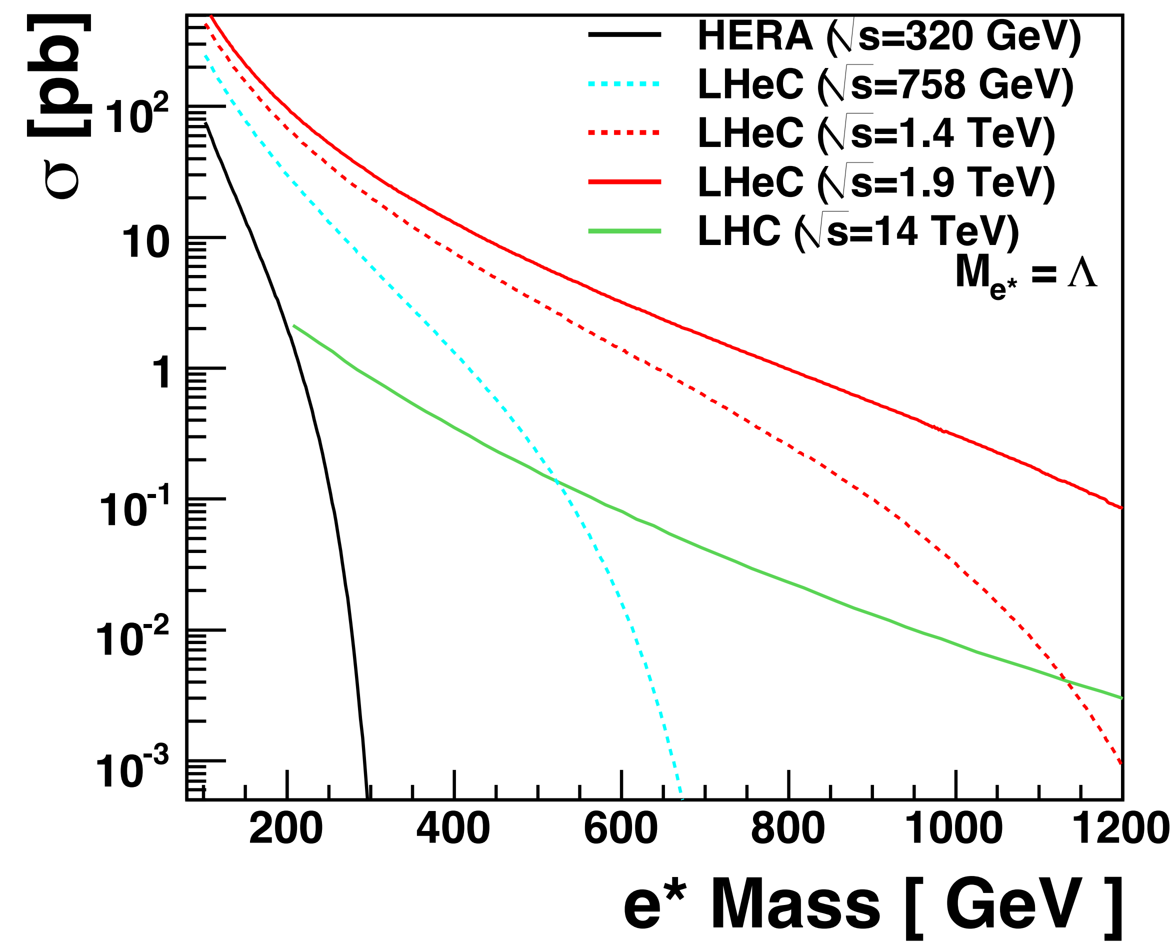


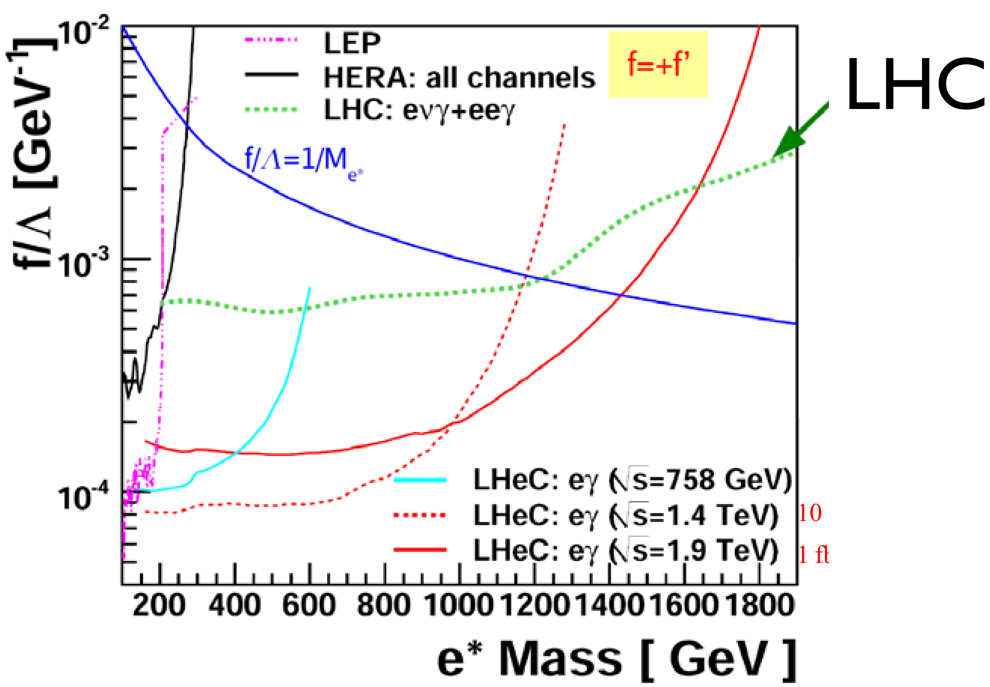


Excited leptons

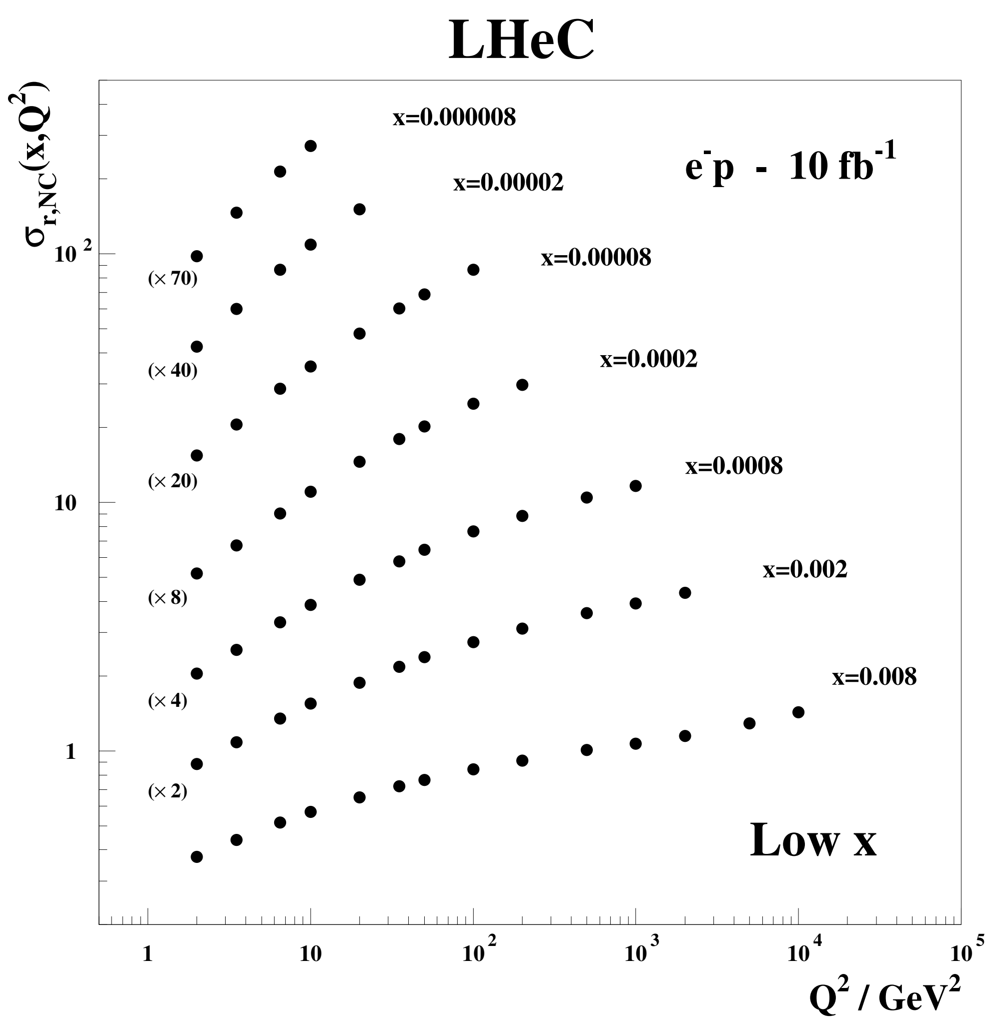
Why 3 families ? Could be a sign of composite structure. Excited leptons could appear as sign of compositeness. Heavier leptons (4th family). Appear in GUTs and technicolor models.

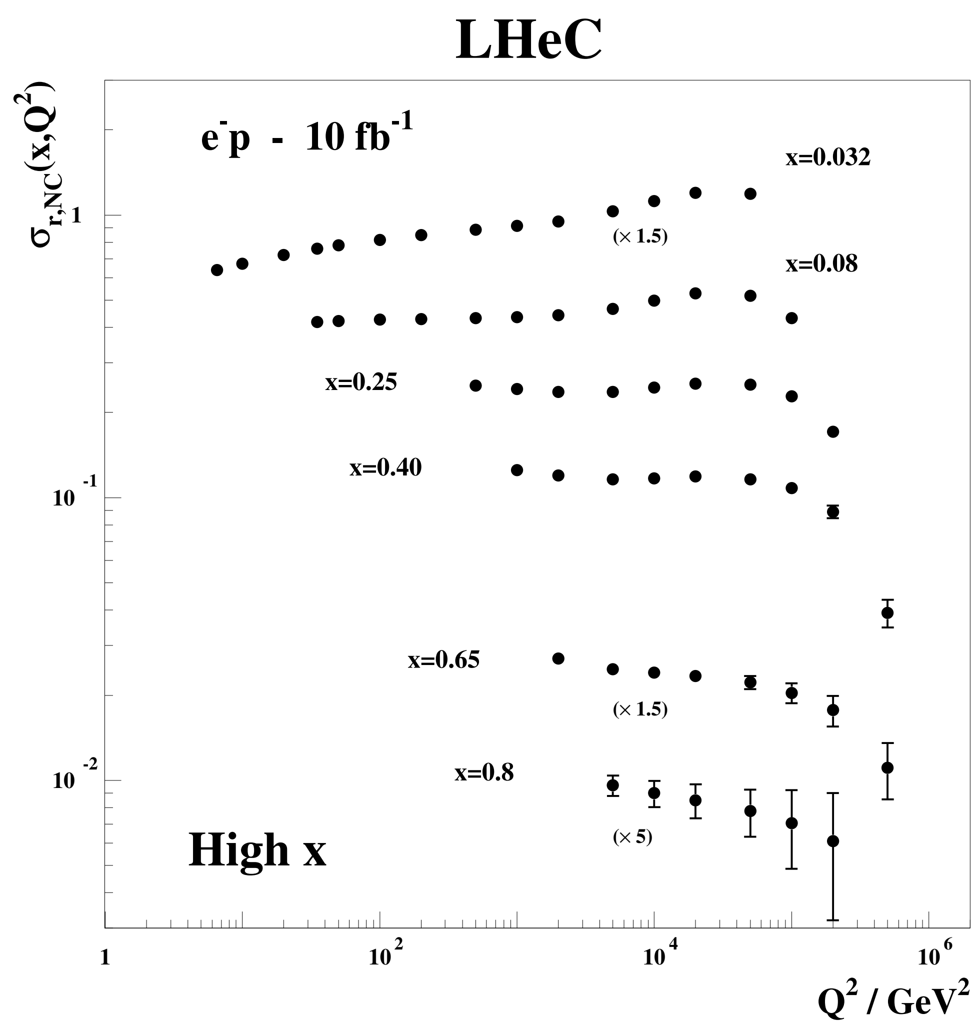




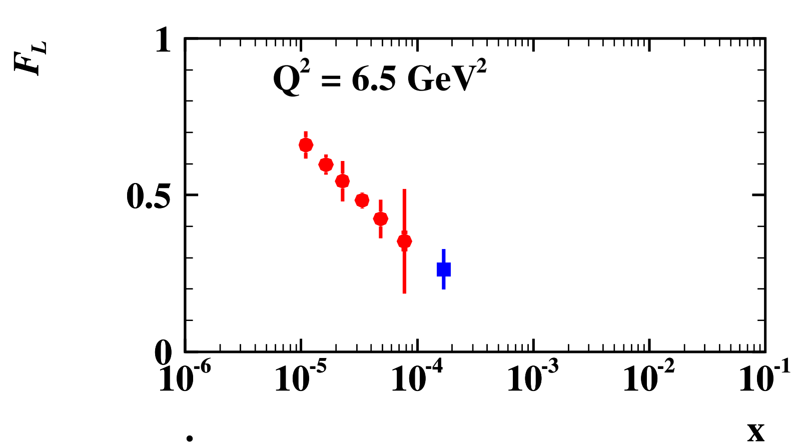


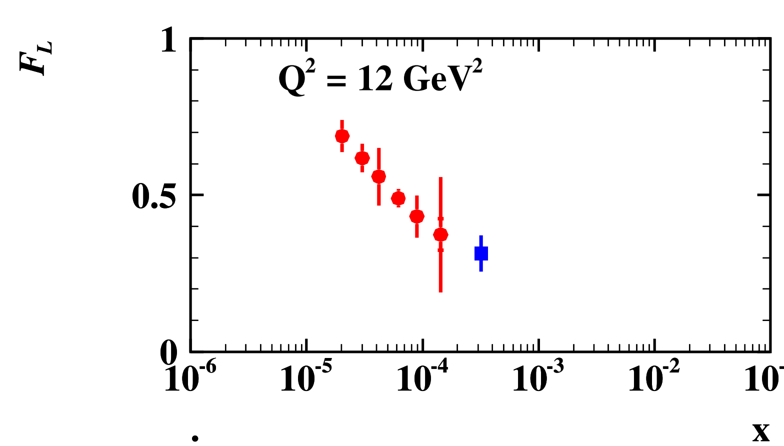
F_2, F_L structure functions





Reduced cross section: huge kinematic range and excellent accuracy

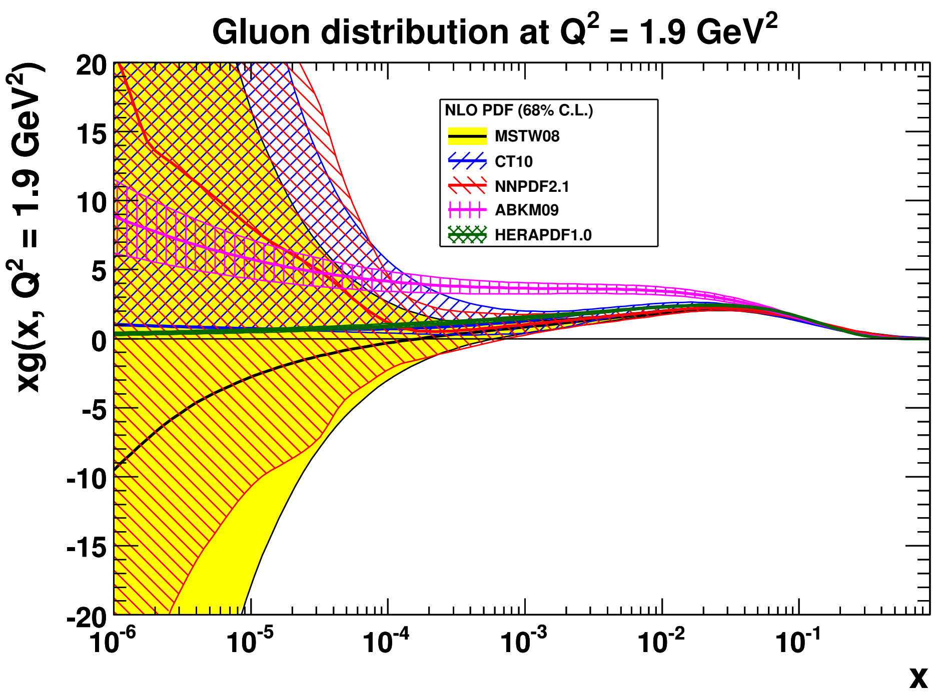




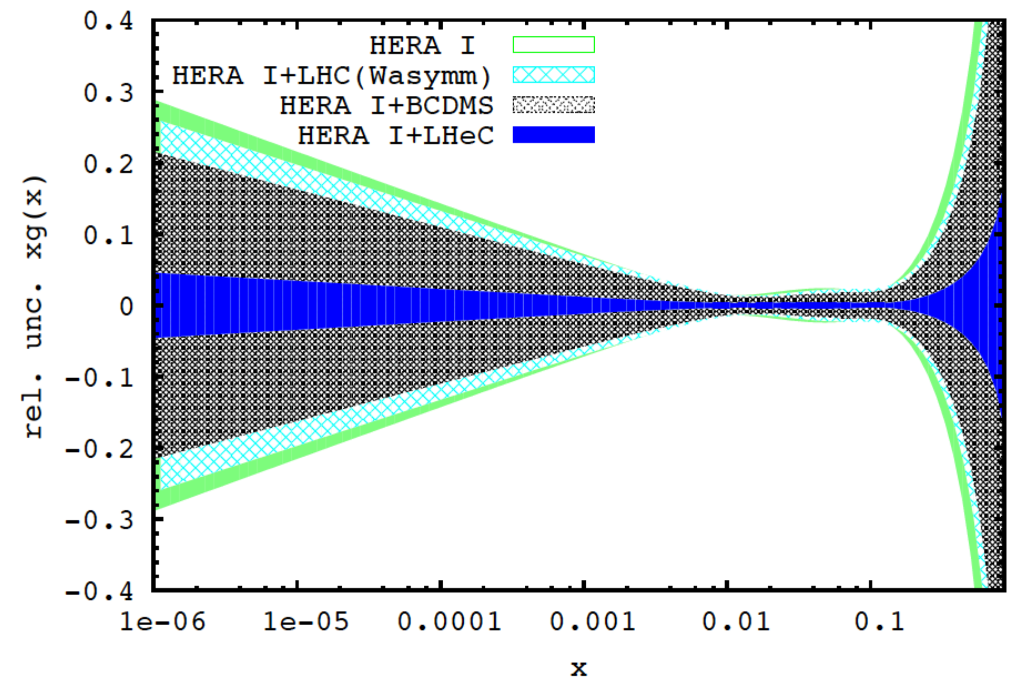
Longitudinal structure function: lowering electron energy

Constraining the pdfs

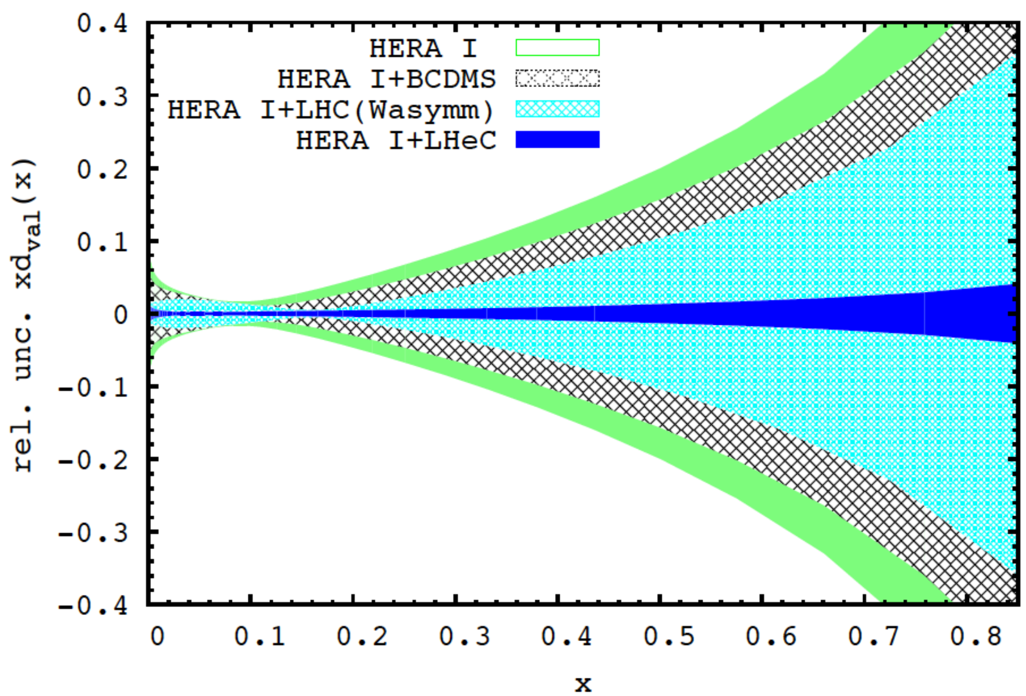
Gluon at small x: large uncertainties



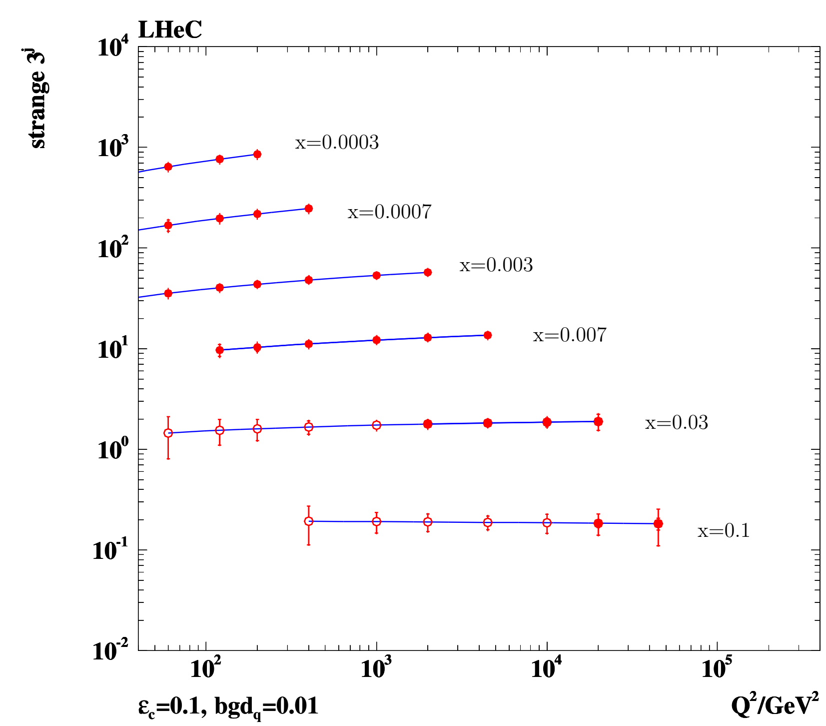
Constraints by including LHeC simulated data



Constraints on valence at large x

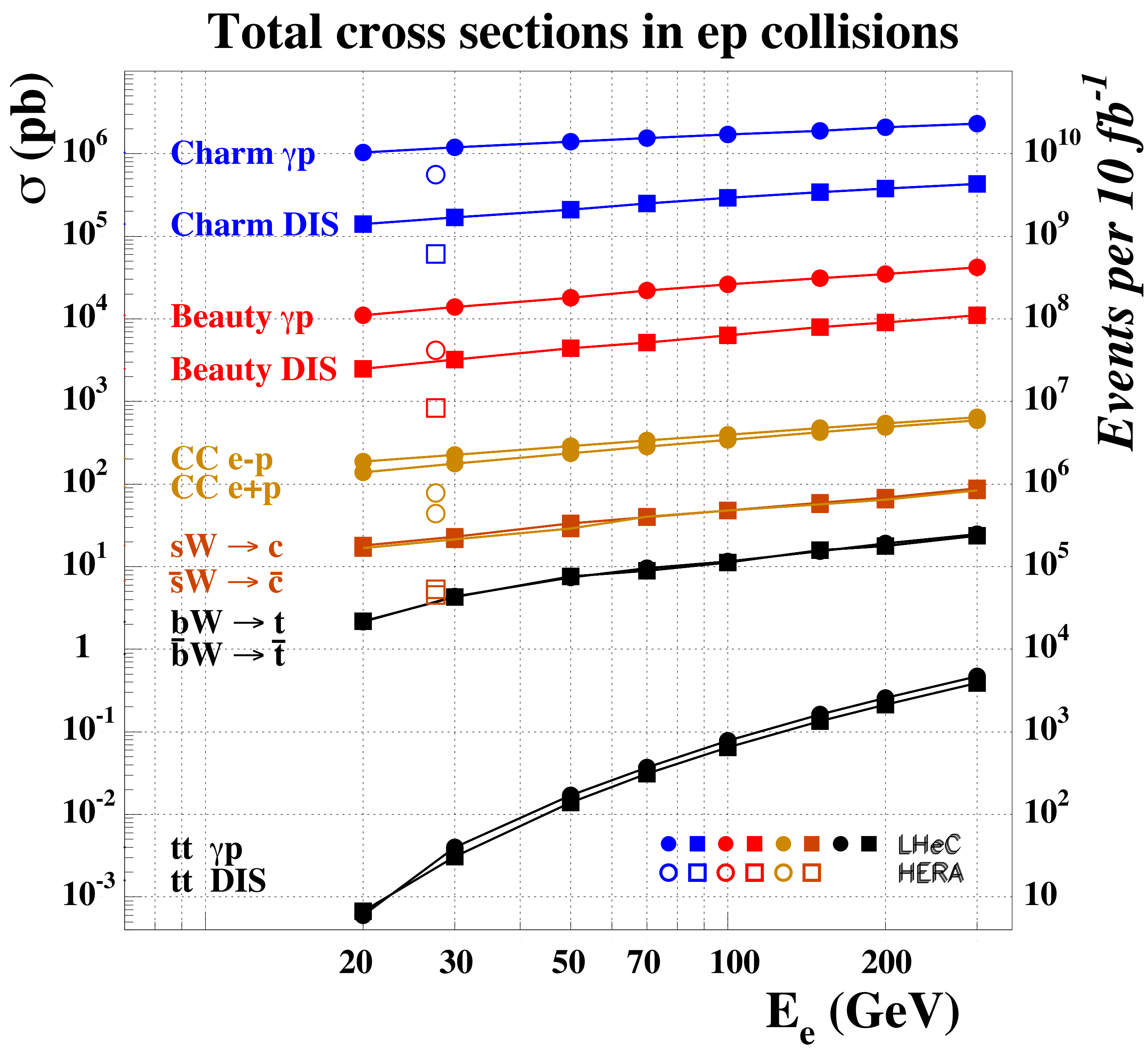


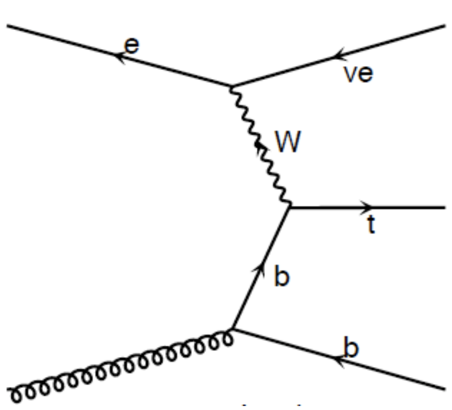
Constraints of strange quark density through charm tagging



Physics with heavy flavors

Luminosity
$10\ fb^{-1}$

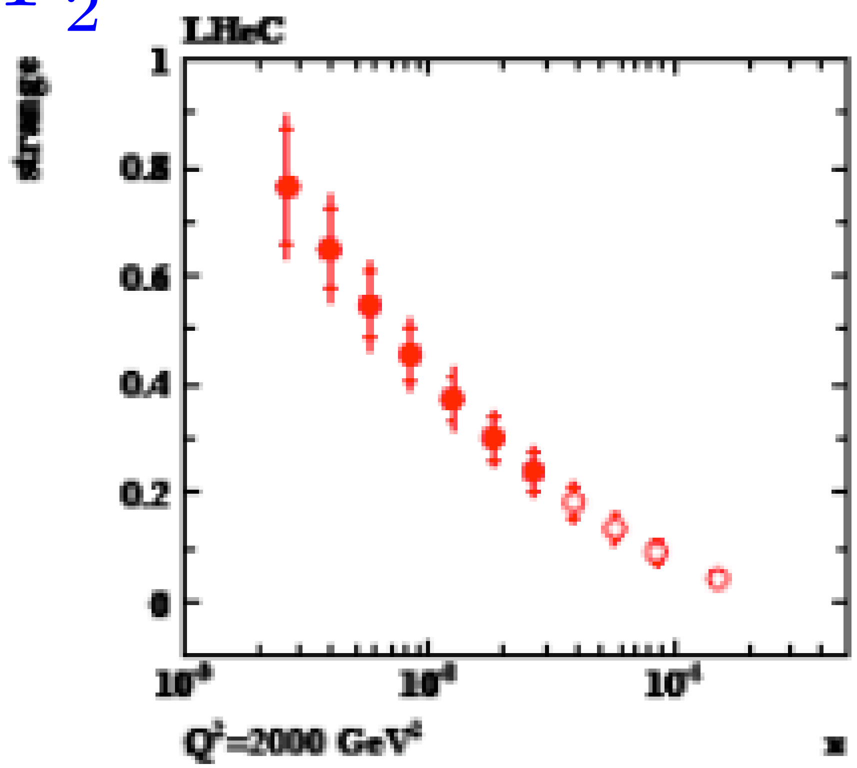


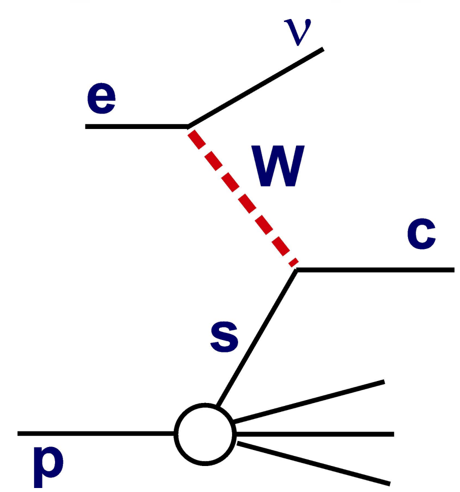


LHeC is a flavor factory!

Flavor decomposition

F_2^{strange}

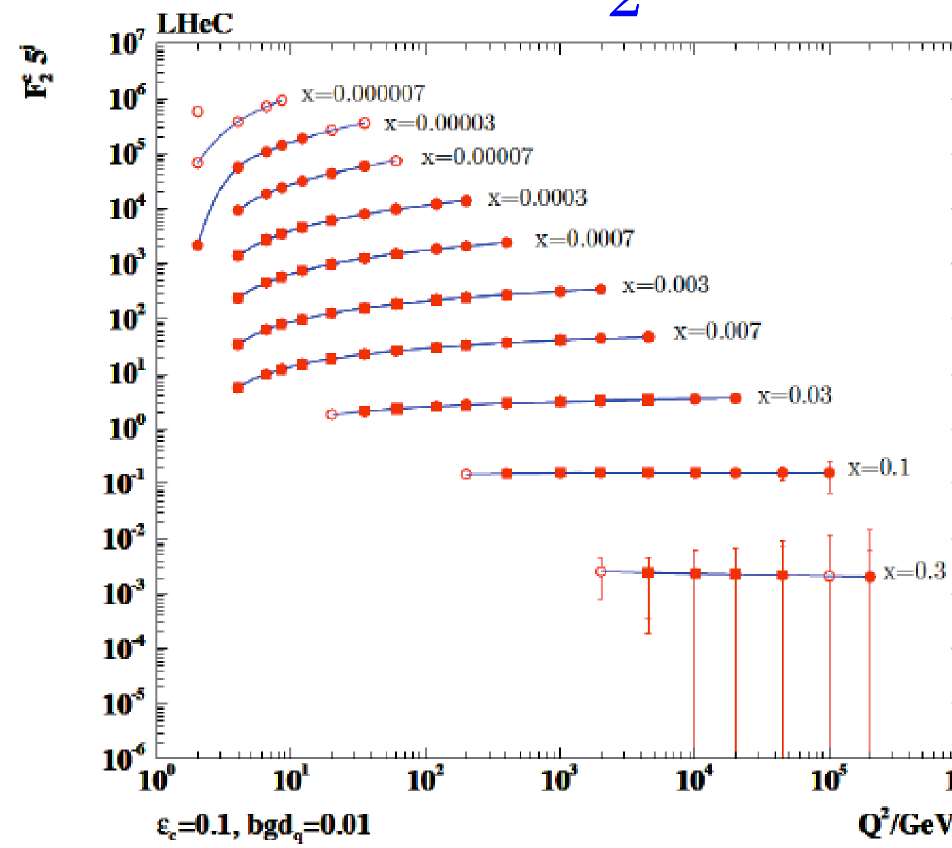




● LHeC 10° acceptance

○ LHEC 1° acceptance

F_2^{charm}



Systematic error dominates (so far 3%)

Precise measurement near threshold and up to 10^5 GeV²

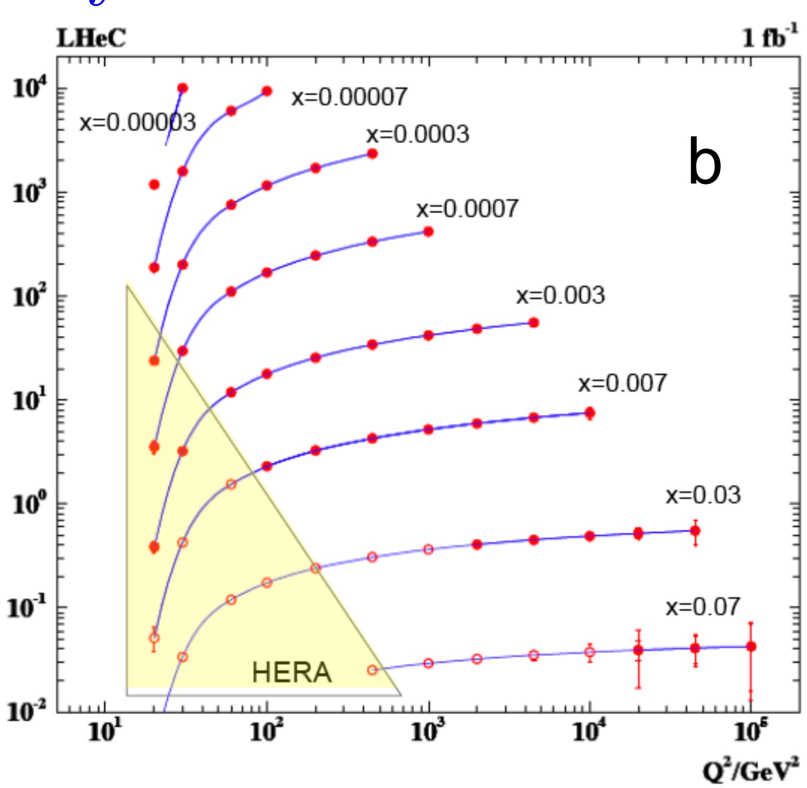
F_2^{cc} will become precision testing ground for QCD and proton structure

open: 1°

closed: 10°

box: 1 TeV

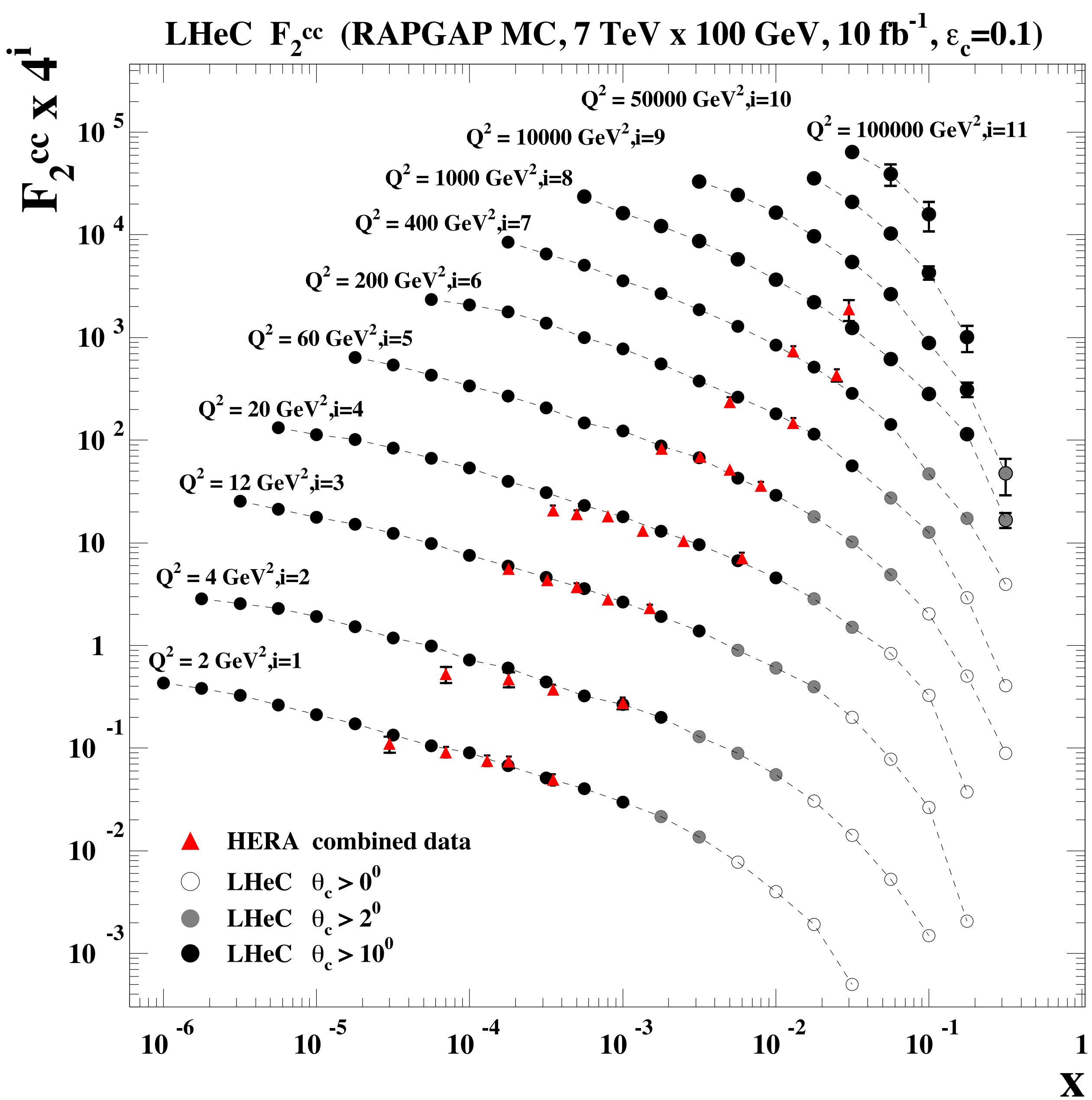
F_2^{beauty}



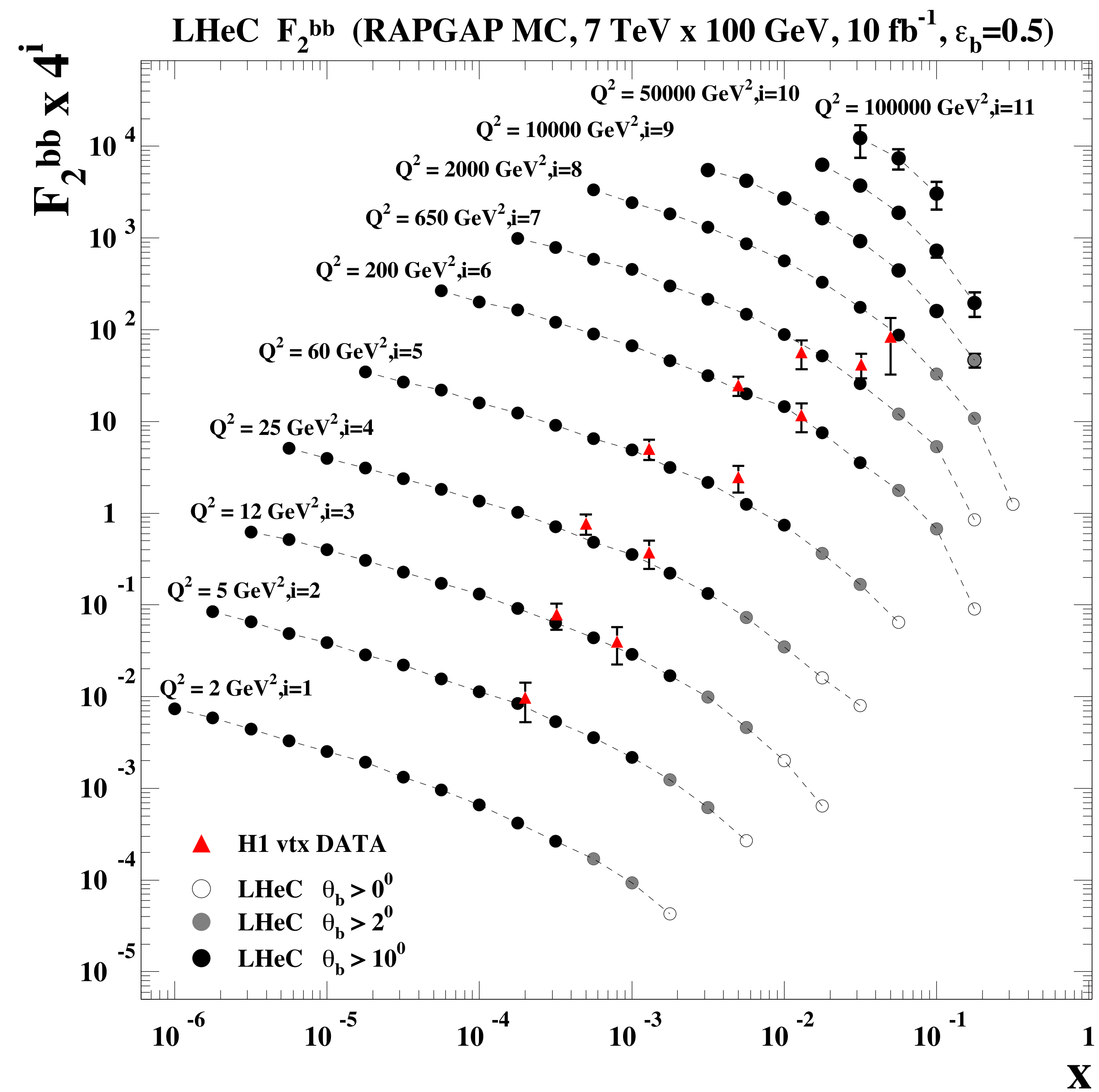
- High precision c,b measurements
- Possible s (and sbar) from charged current
- b is a small x observable
- Also possible $Wb \rightarrow t$

Flavor decomposition

Charm

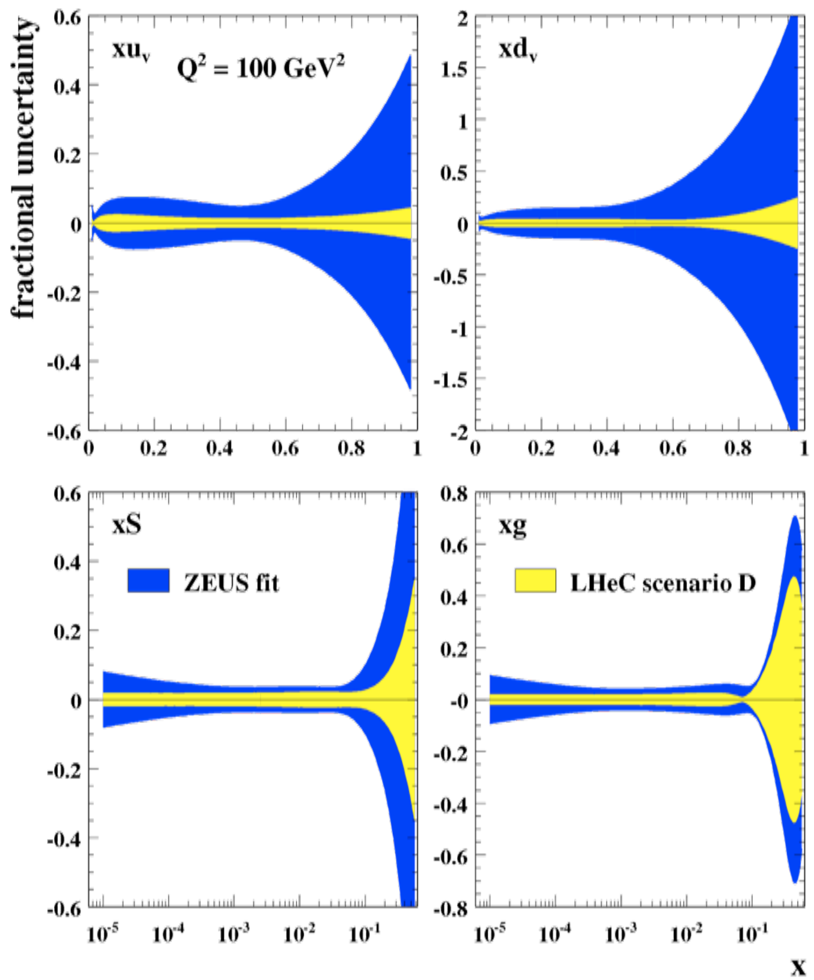


Beauty

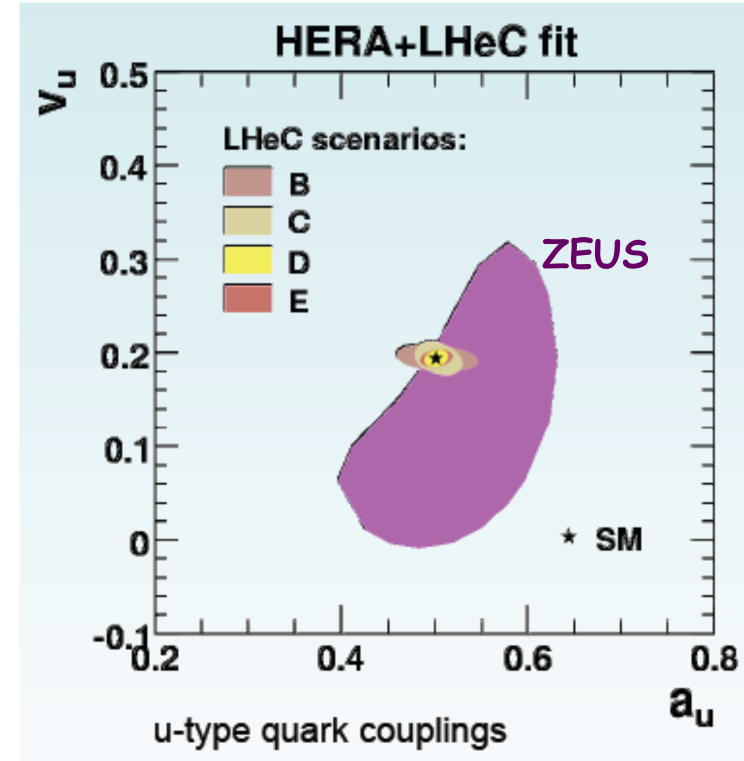


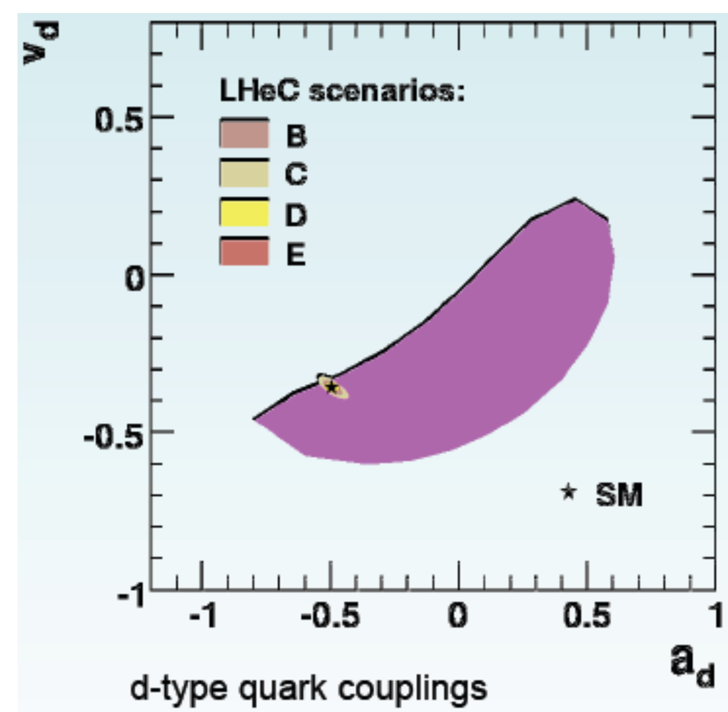
Electroweak precision

PDFs & EW Couplings



[Gwenlan]





Using ZEUS fitting code, HERA + LHeC data … EW couplings free

E_e = 100 GeV, L = 10+5 fb^{-1}, P = +/- 0.9

Also measurement of weak mixing angle below and above Mz (scale variation)

Higgs at LHeC

Production of Higgs at LHeC

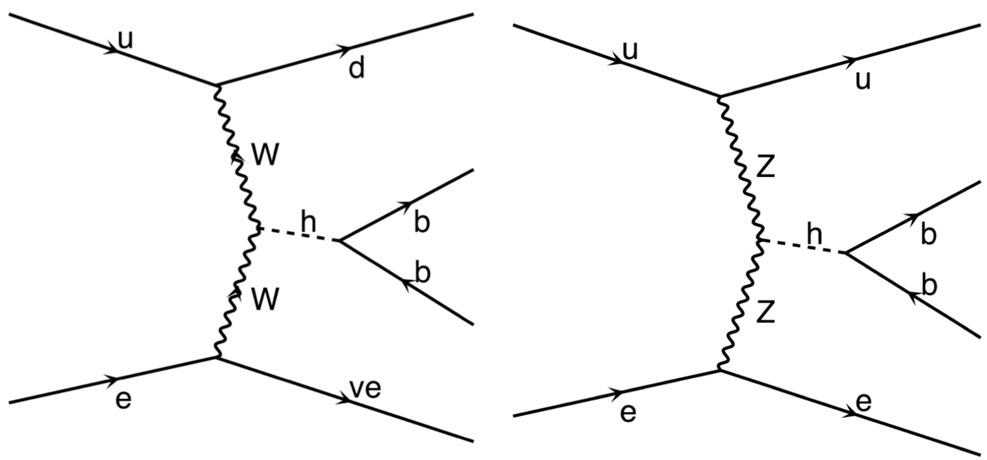
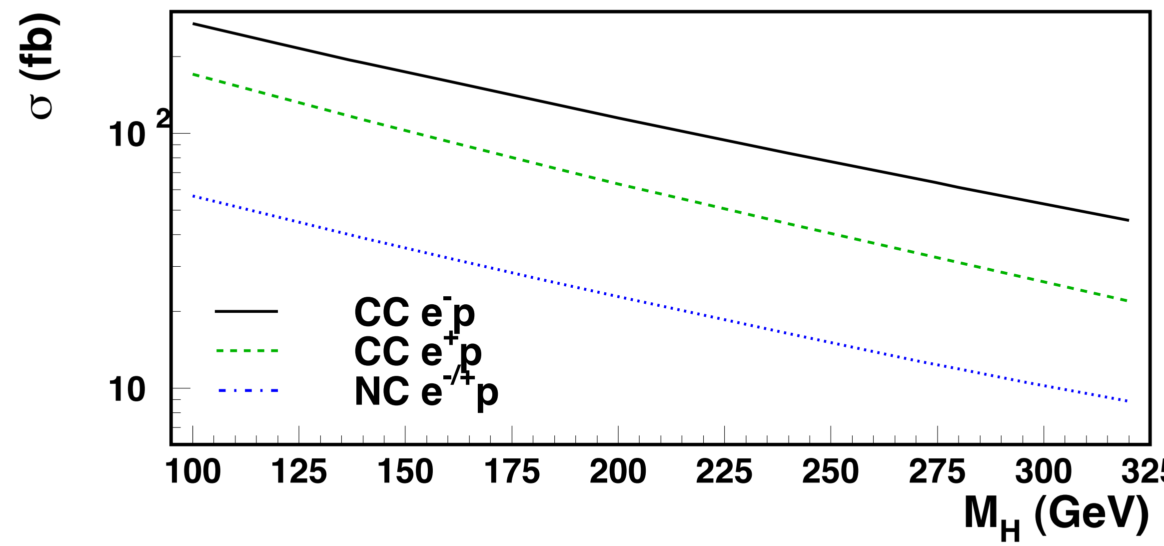


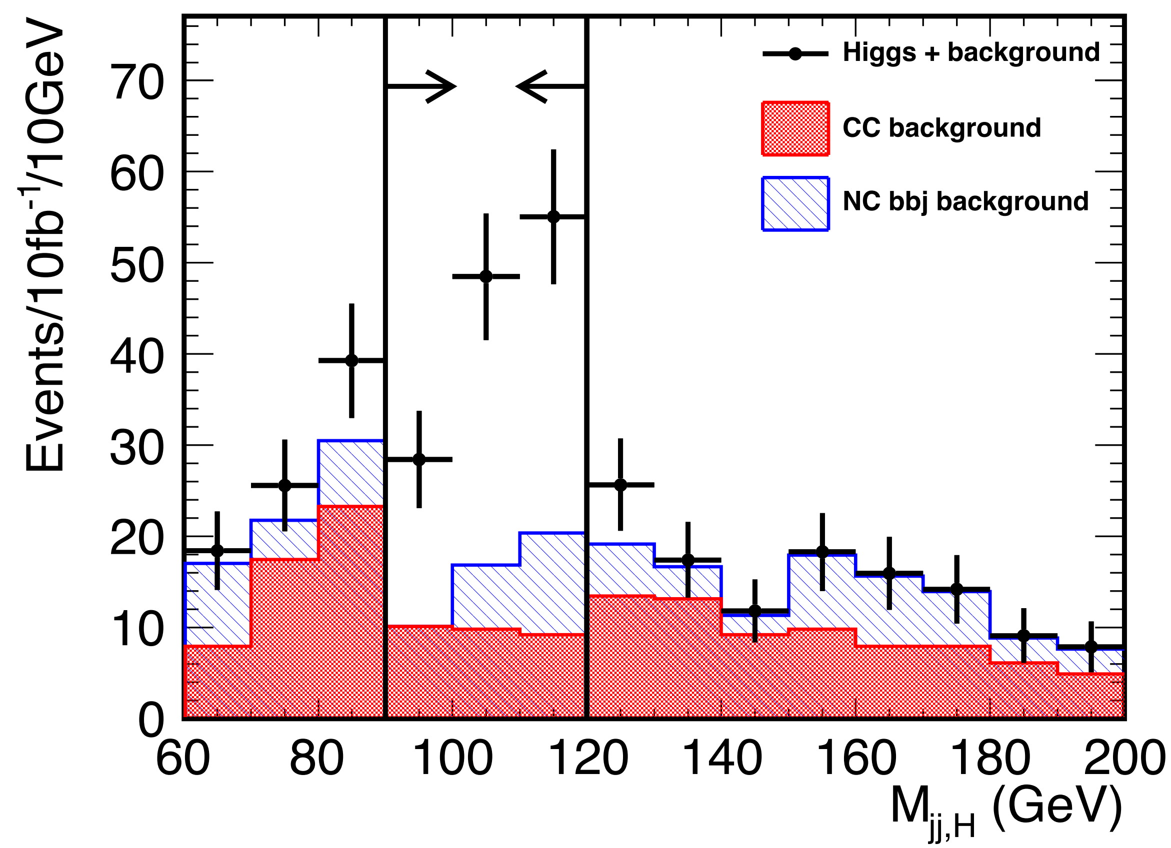
Figure 5.24: Feynman diagrams for CC(left) and NC(right) Higgs production at the LHeC.

$$ep \to H + X \to b\bar{b} + X$$

$Hb\bar{b}$ coupling could be measured at LHeC (easier than at LHC)

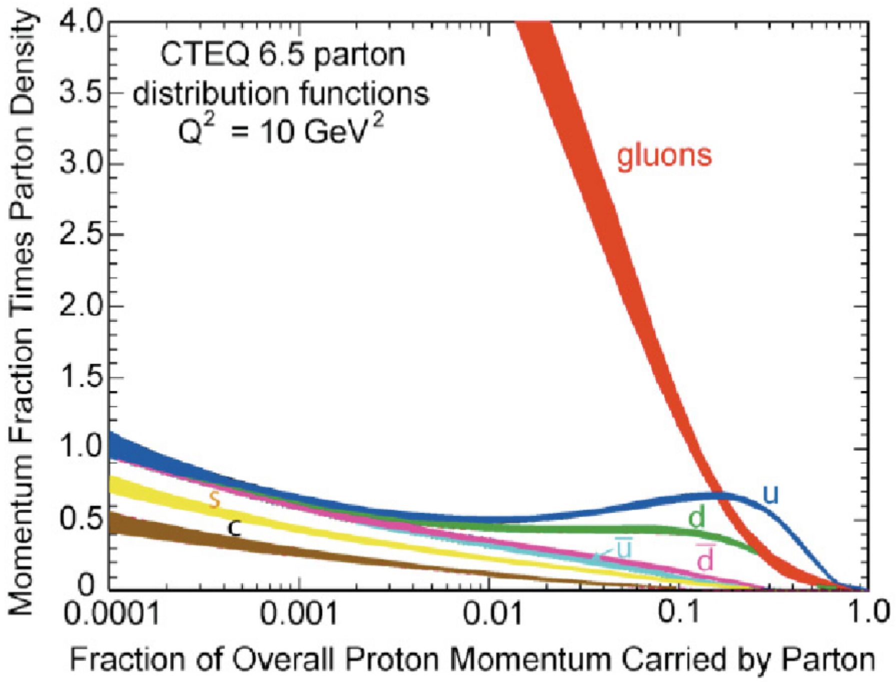
100 H-bbar events after cuts





Also: excellent sensitivity to (anomalous) HWW coupling.

Low x and saturation

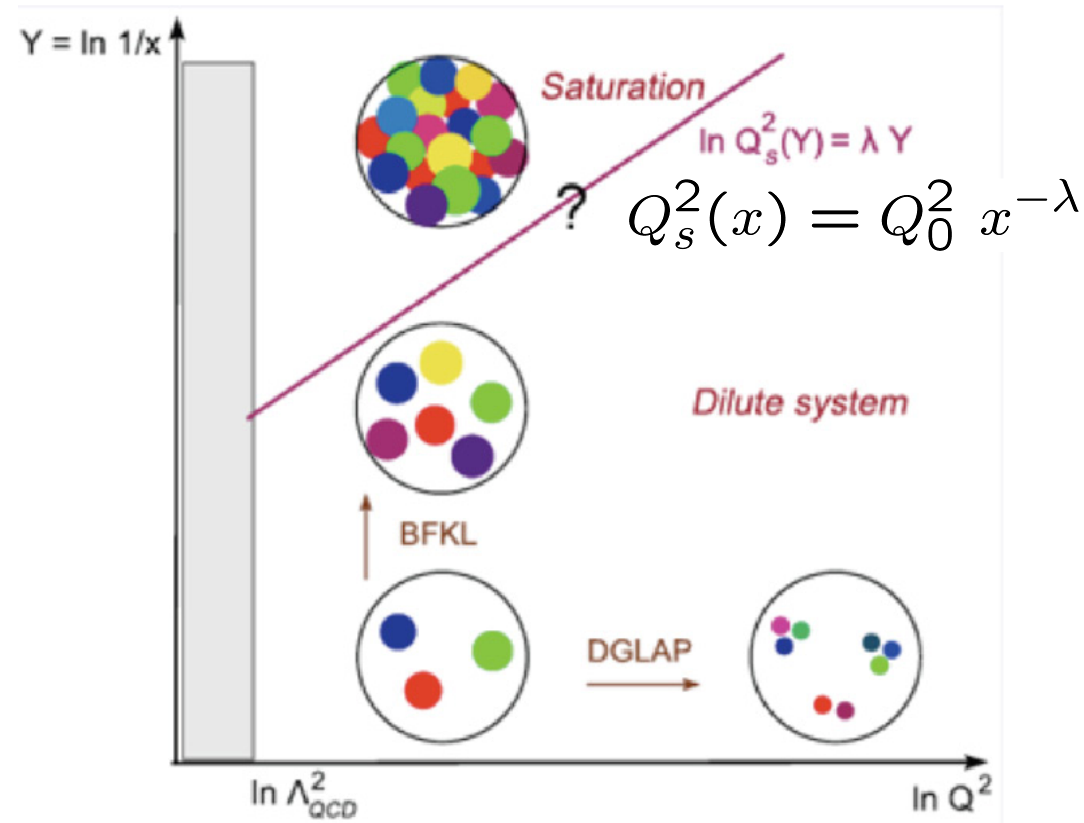


HERA established strong growth of the gluon density towards small x

Unitarity must be preserved, but how it is realized in microscopic terms?

Parton saturation: recombination of gluons at sufficiently high densities leading to nonlinear modification of the evolution equations.

Emergence of a dynamical scale: saturation scale dependent on energy.



What we learned from HERA about saturation?

Linear DGLAP evolution works well at HERA.

Hints of saturation at low Q and low x: deterioration of the global fit in that region.

Large diffractive component.

Success of the dipole models in the description of the data.

The models point at the low value of the saturation scale

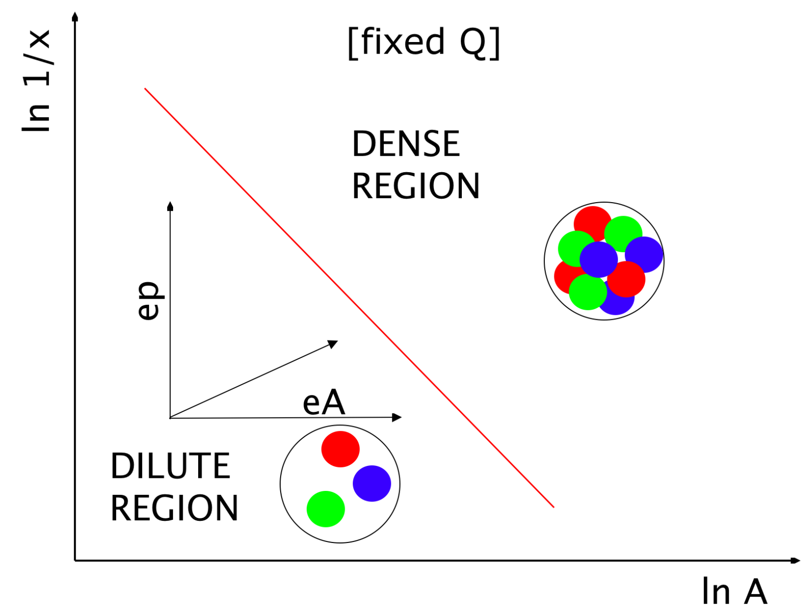
LHeC would provide an access to a kinematic regime where the saturation scale is perturbative

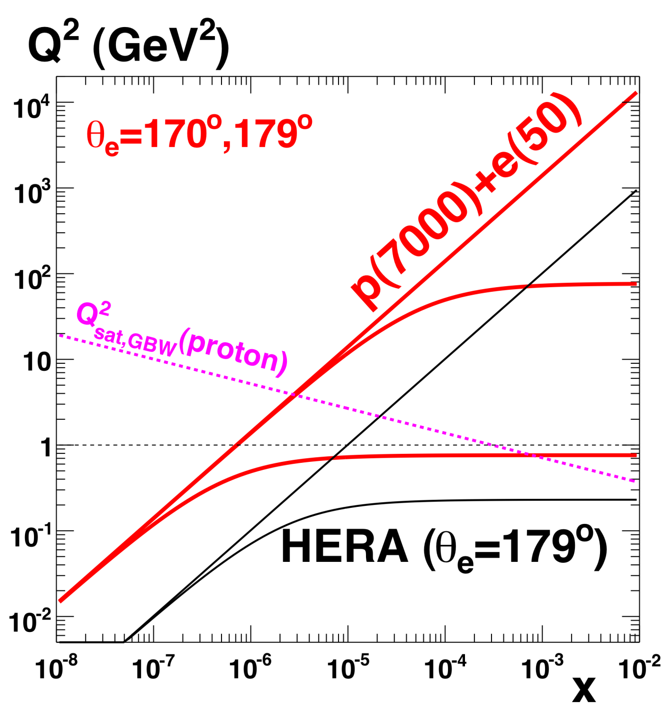
Strategy for making target more 'black'

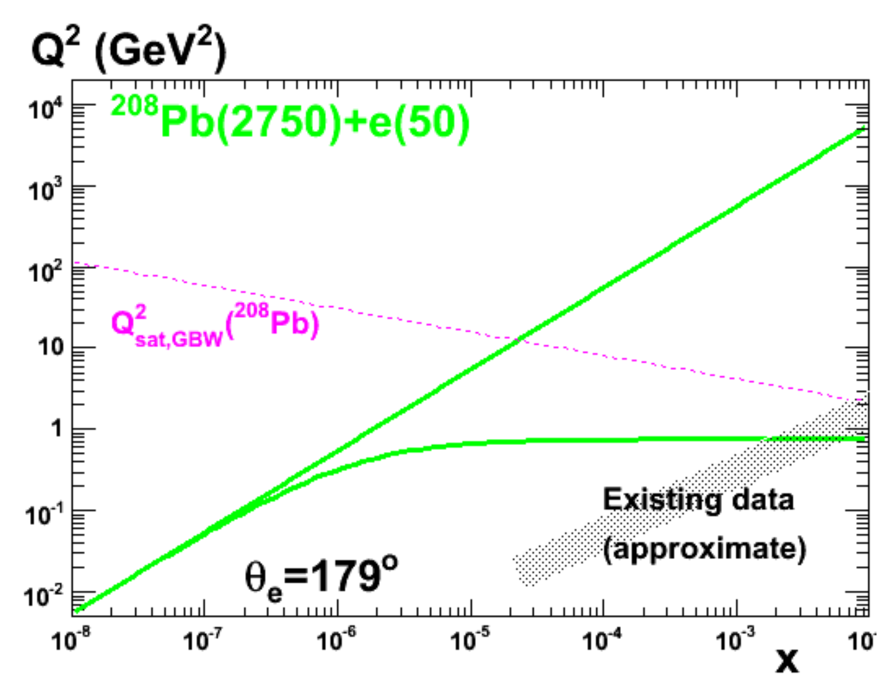
LHeC would deliver a two-pronged approach:

Probing lower x in ep. Evolution of a single source

More nucleons: eA scattering. Many sources overlapping in impact parameter .

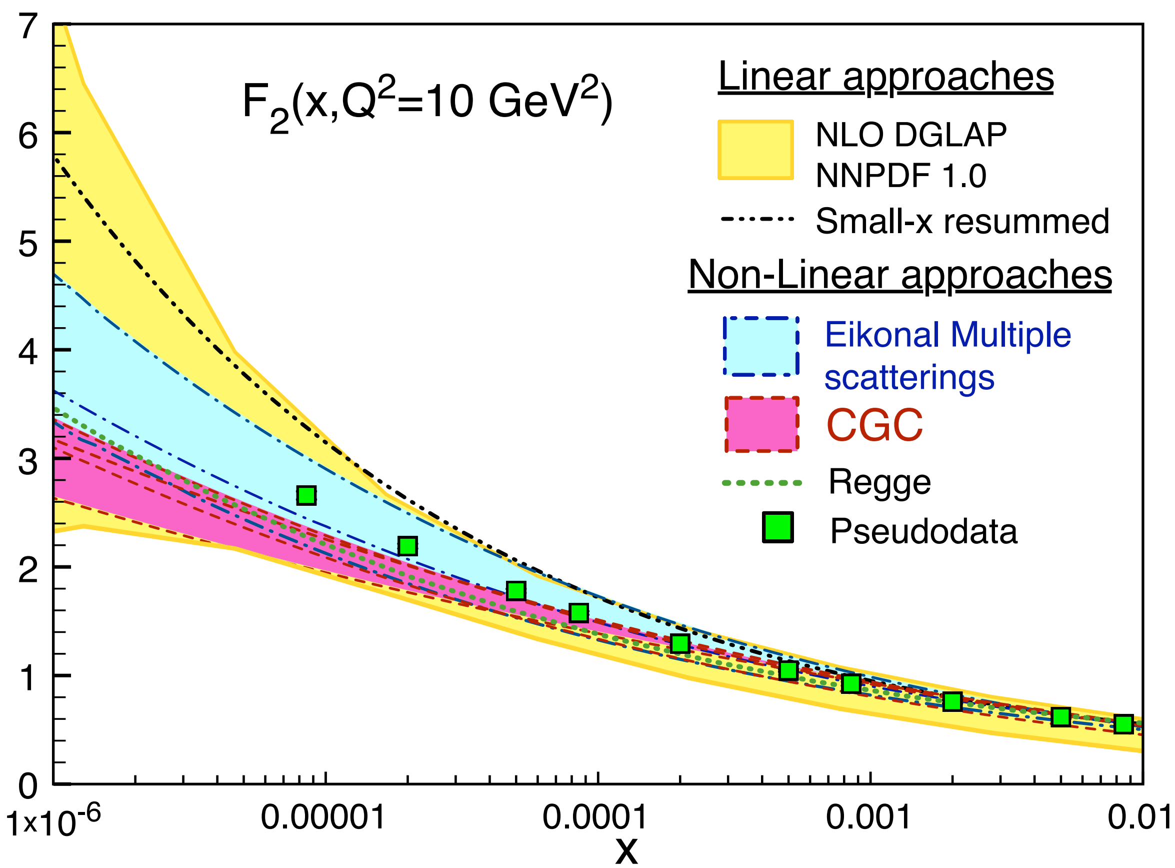


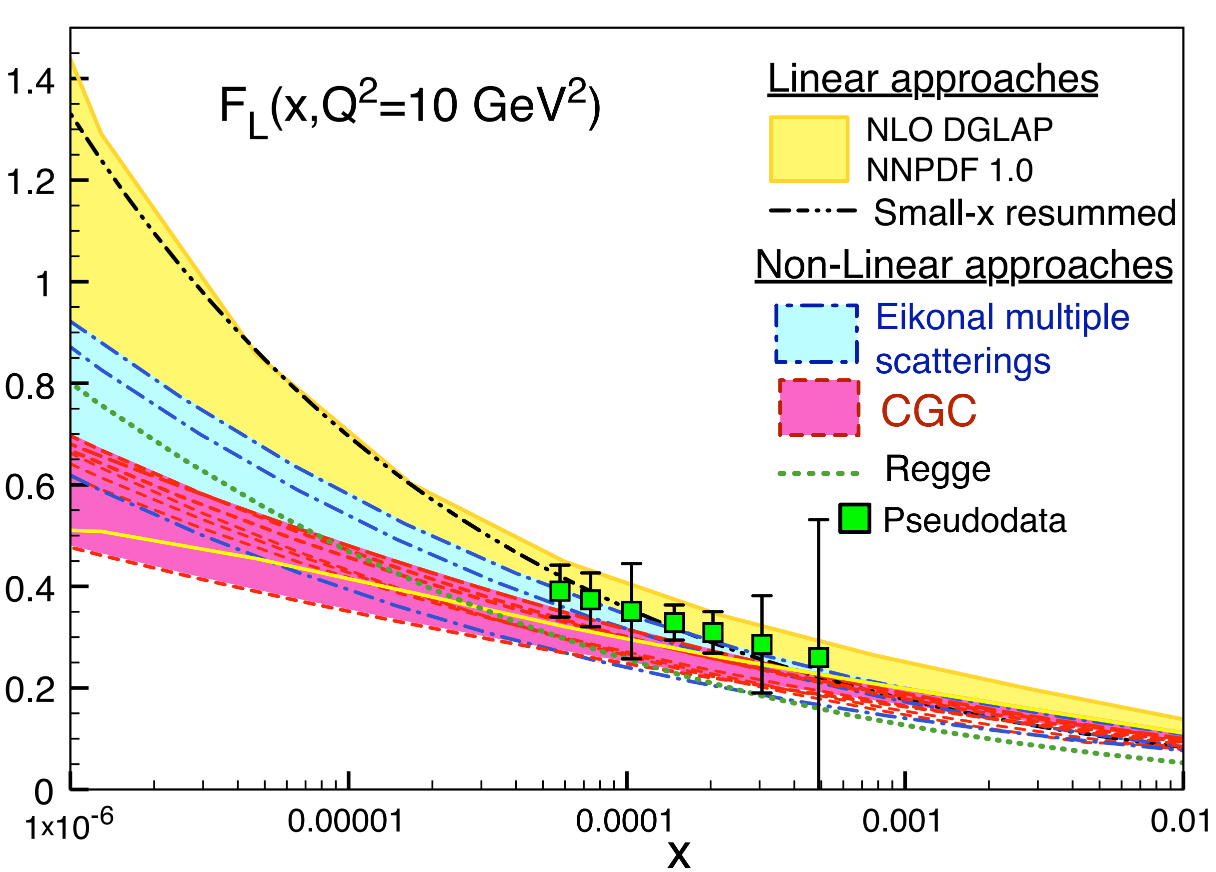




F_2,F_L structure functions at low x

Precision measurements of structure functions at very low x: test DGLAP, small x, saturation inspired approaches.





Interestingly, rather small band of uncertainties for models based on saturation as compared with the calculations based on the linear evolution. Possible cause: the nonlinear evolution washes out any uncertainties due to the initial conditions, or too constrained parametrization used within the similar framework.

approx. 2% error on the F2 pseudodata, and 8% on the FL pseudodata ,should be able to distinguish between some of the scenarios.

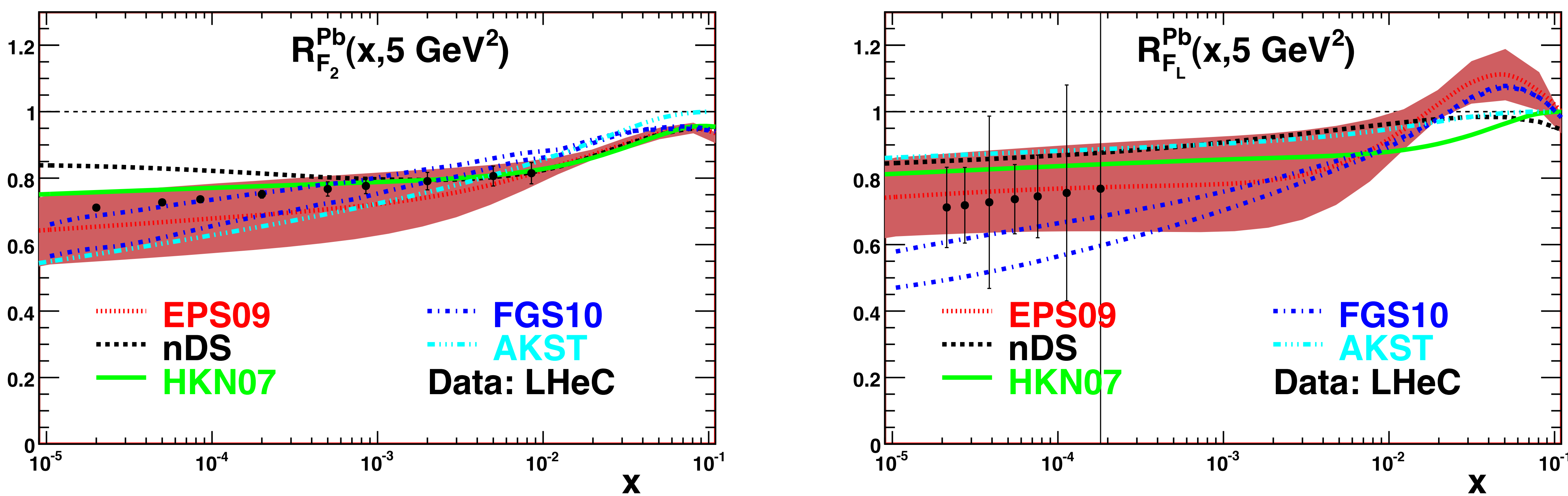
Nuclear structure functions at LHeC

Nuclear ratio for structure function or a parton density:

$$R_f^A(x,Q^2) = \frac{f^A(x,Q^2)}{A \times f^N(x,Q^2)}$$

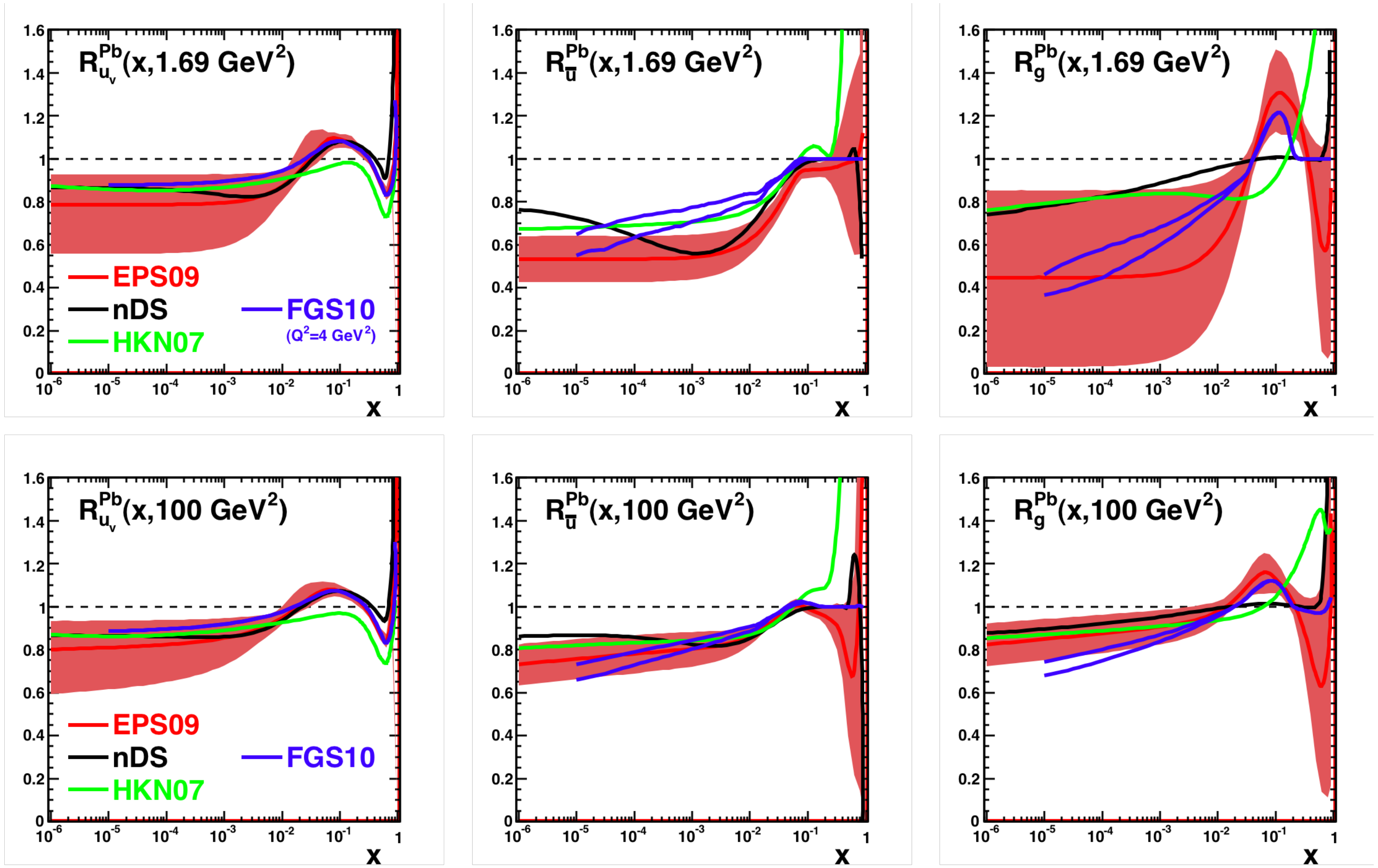
Nuclear effects $R^A \neq 1$

LHeC potential: precisely measure partonic structure of the nuclei at small x.



Nuclear structure functions measured with very high accuracy.

Nuclear parton distributions

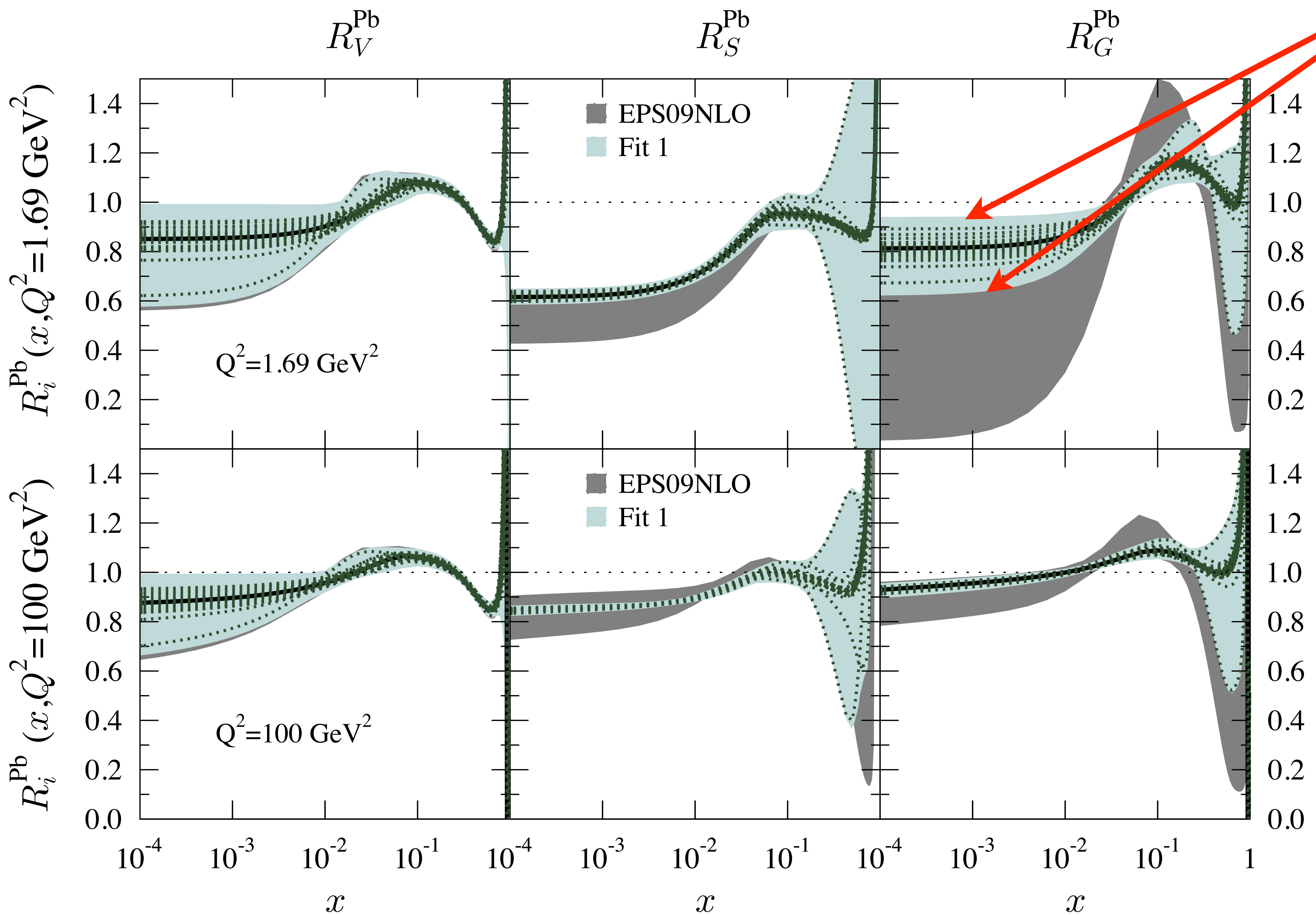


R_i = Nuclear PDF i / (A * proton PDF i)

Current status: nuclear parton distribution functions are poorly known at small x. Especially gluon density, below x=0.01 can be anything between 0 and 1....

Nuclear parton distributions at LHeC

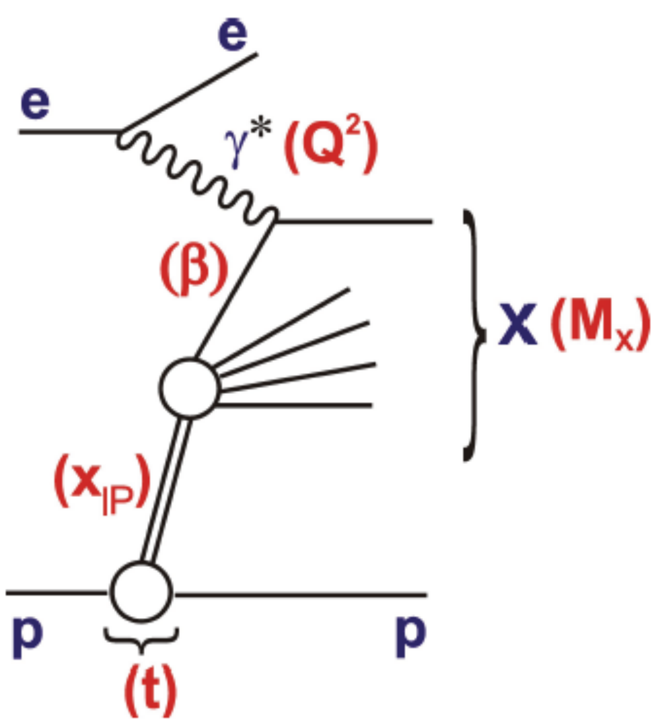
Global NLO fit with the LHeC pseudodata included



Much smaller uncertainties.

Very large constraint on the low x gluons and sea quarks with the LHeC pseudodata .

Diffraction



$$x_{IP} = \frac{Q^2 + M_X^2 - t}{Q^2 + W^2}$$

momentum fraction of the Pomeron w.r.t hadron

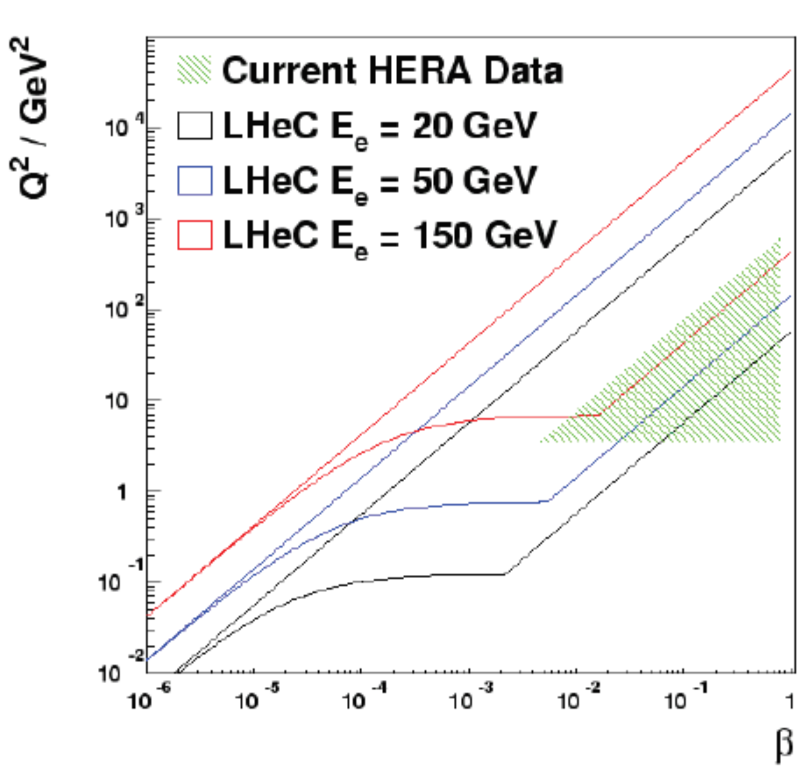
$$\beta = \frac{Q^2}{Q^2 + M_X^2 - t}$$

momentum fraction of parton w.r.t Pomeron

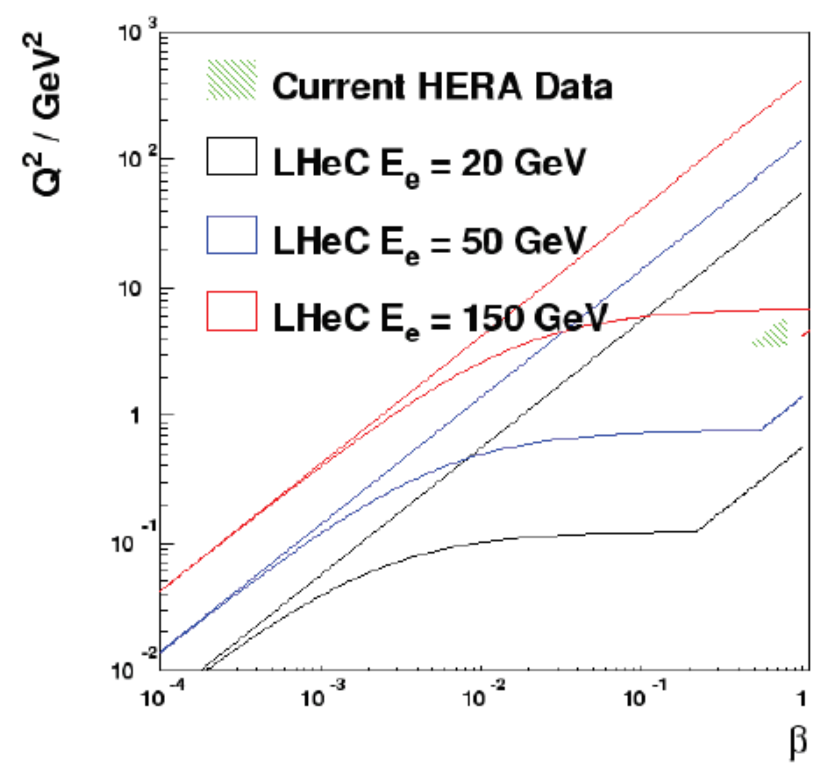
$$x_{Bj} = x_{IP}\beta$$

Methods: Leading proton tagging, large rapidity gap selection

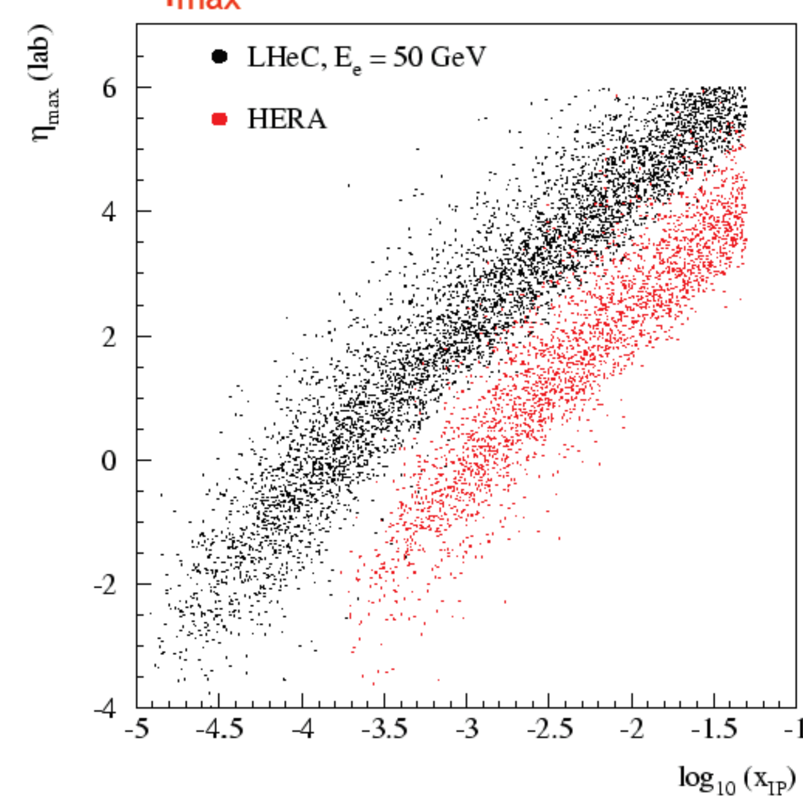
Diffractive Kinematics at x_{IP}=0.01



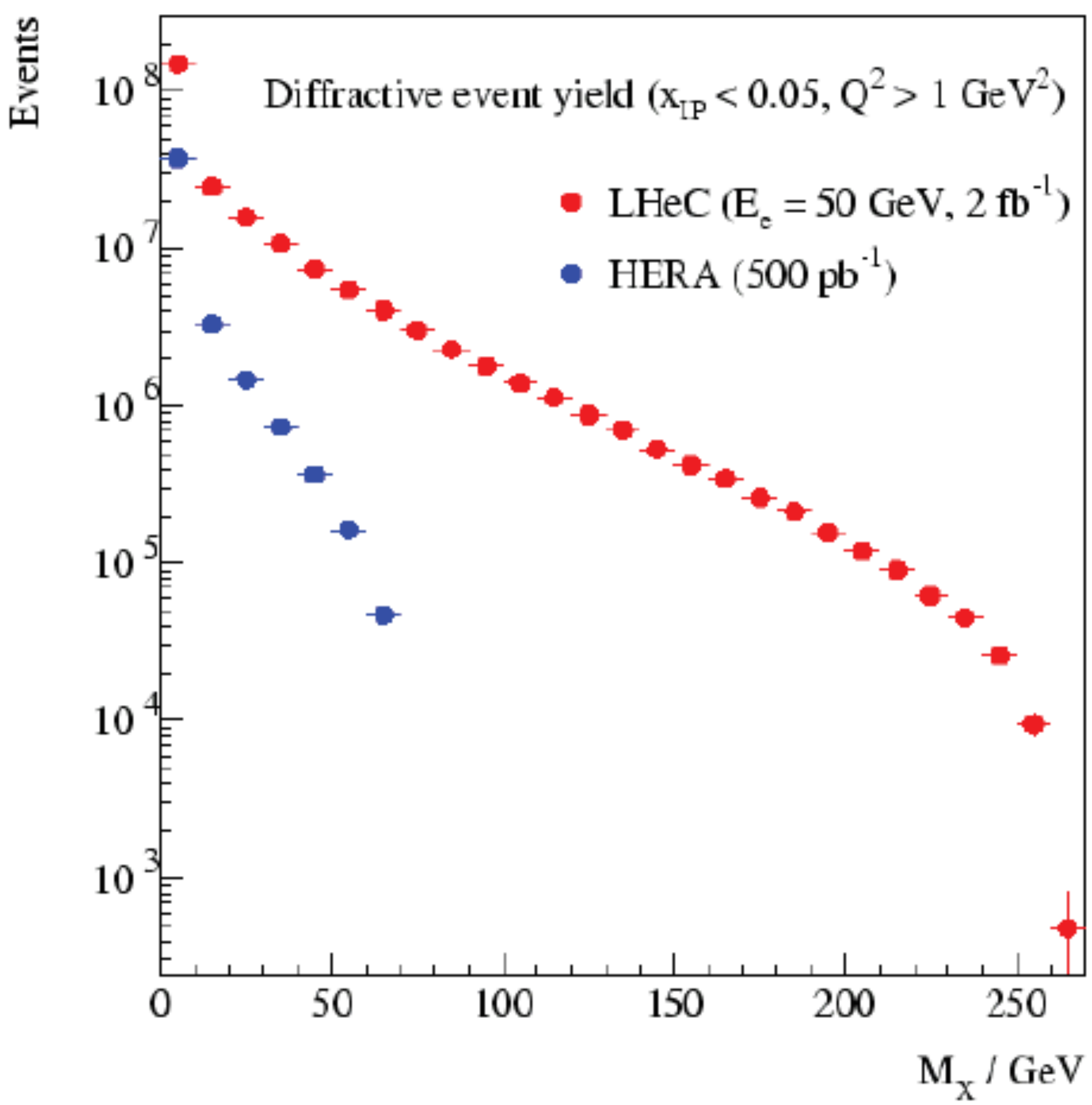
Diffractive Kinematics at x_{IP}=0.0001

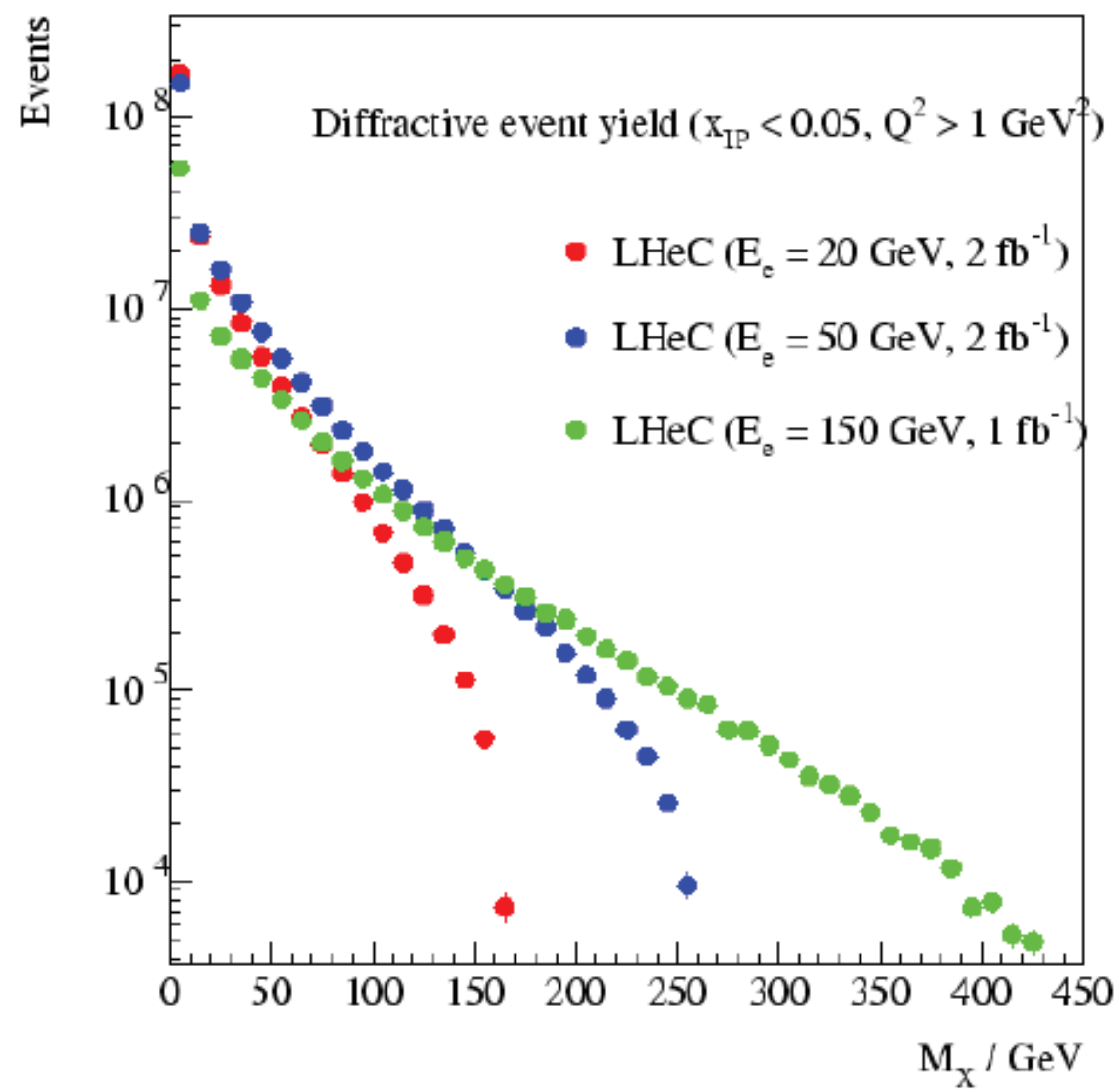


η_{max} from LRG selection ...



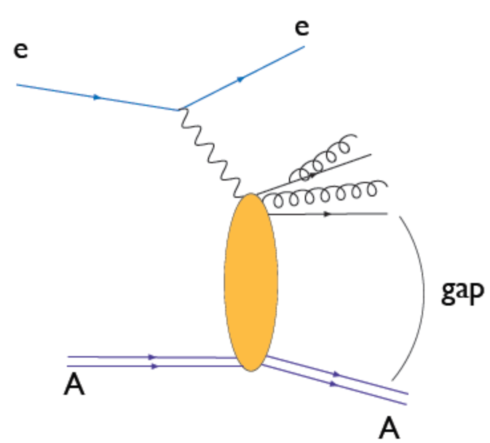
Diffractive mass distribution



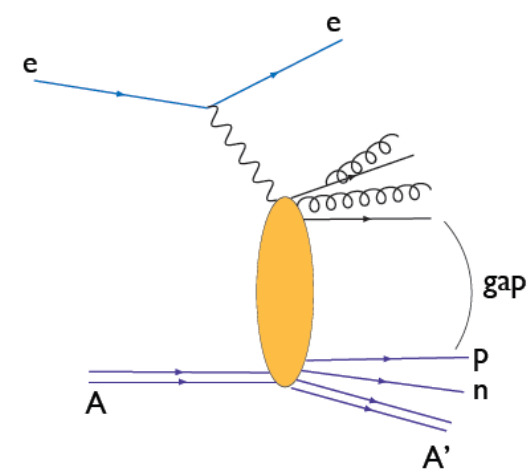


New domain of diffractive masses.
M_X can include W/Z/beauty

Inclusive diffraction in eA

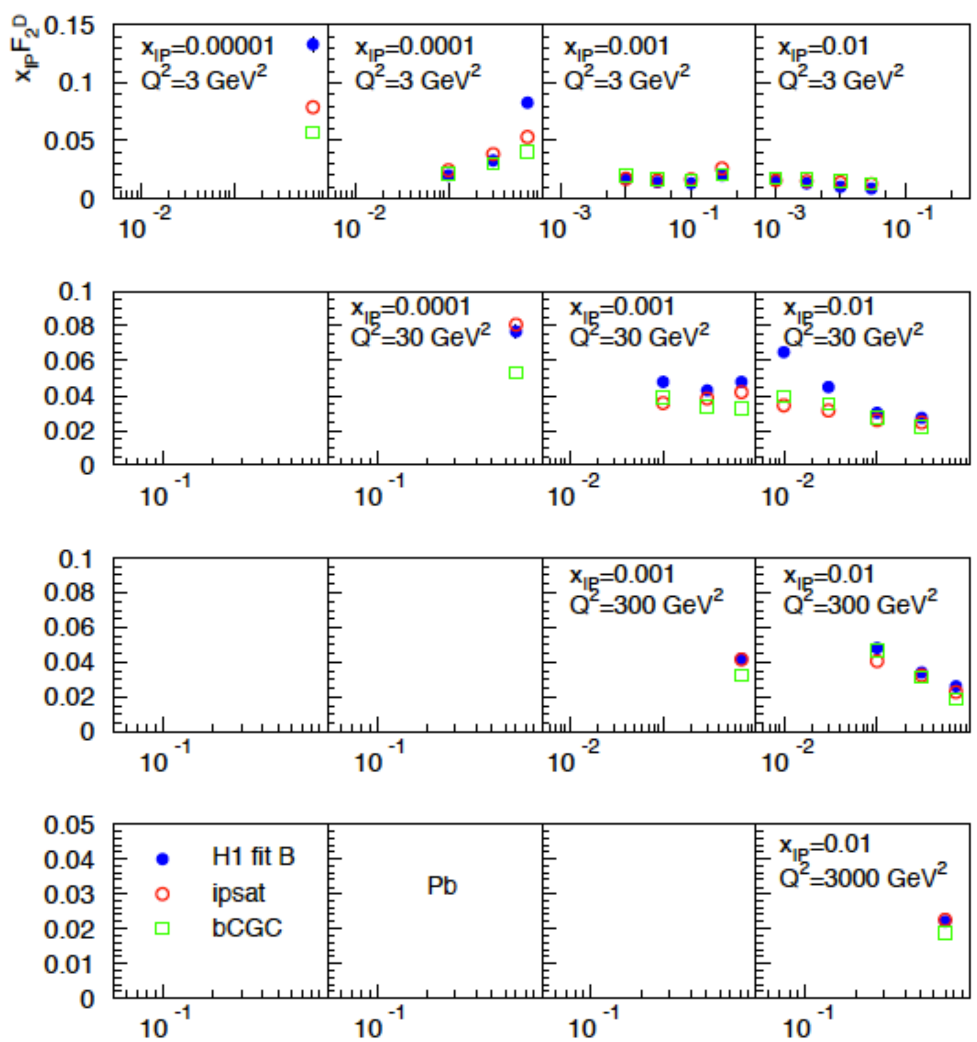


coherent

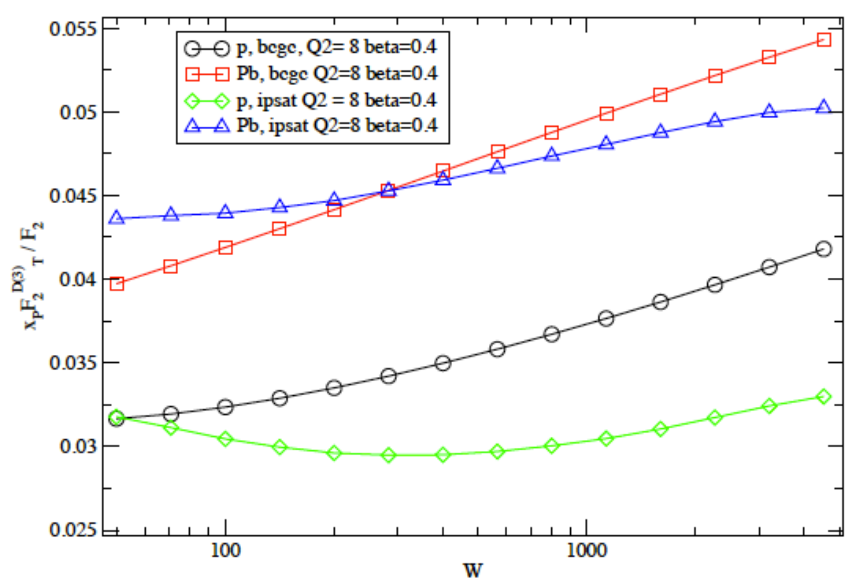


incoherent

Diffractive structure function for Pb



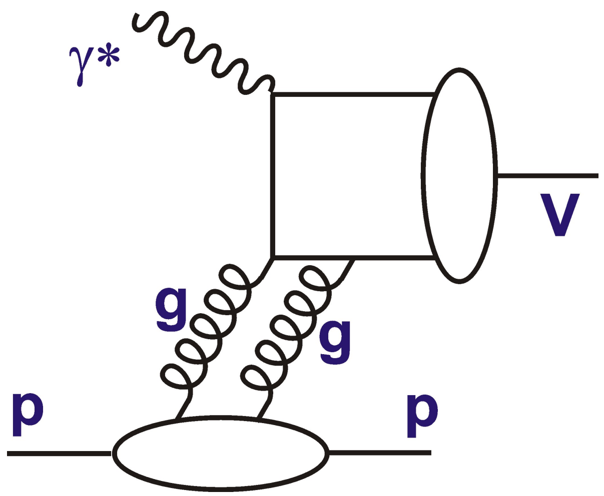
Diffractive to inclusive ratio for protons and Pb



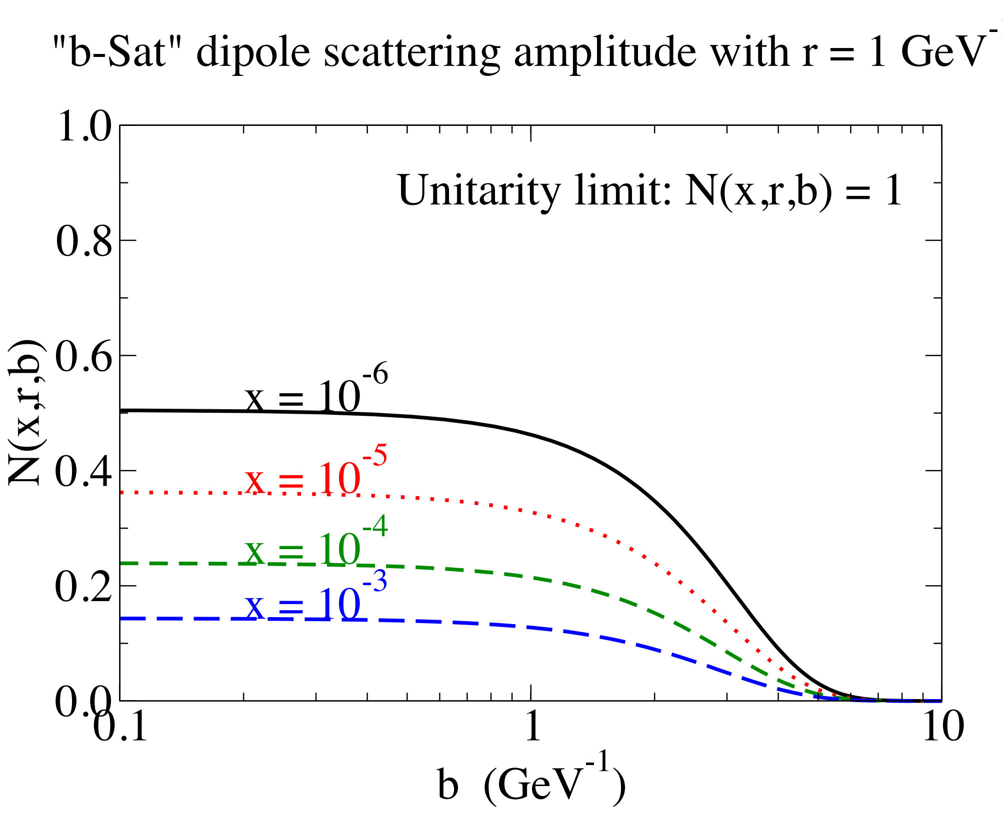
Enhanced diffraction in the nuclear case

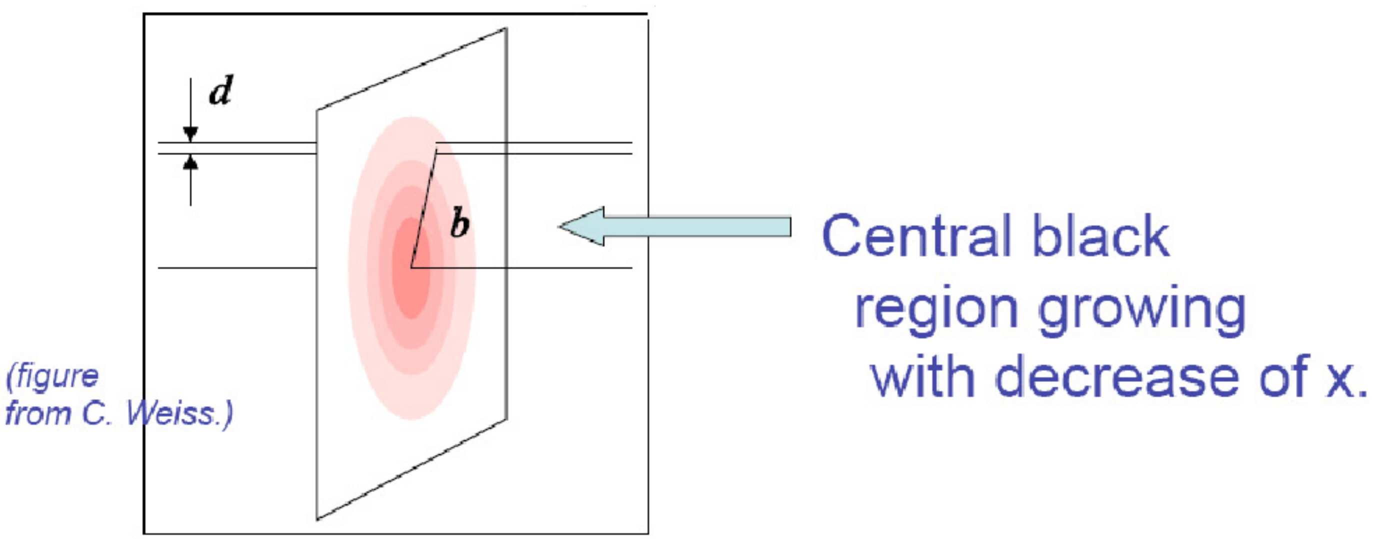
Study of diffractive dijets, heavy quarks for the factorization tests

Exclusive diffraction



- Exclusive diffractive production of VM is an excellent process for extracting the dipole amplitude
- Suitable process for estimating the 'blackness' of the interaction.
- t-dependence provides an information about the impact parameter profile of the amplitude.



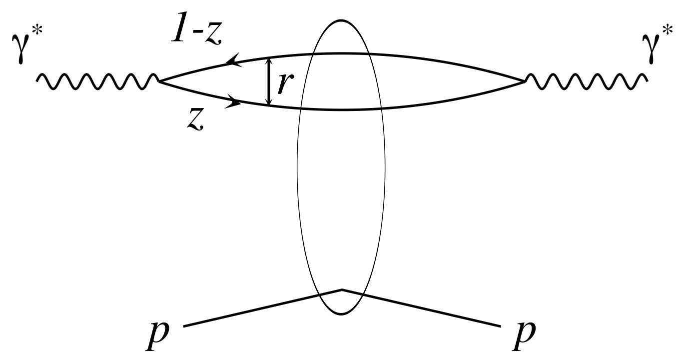


Large momentum transfer t probes small impact parameter where the density of interaction region is most dense.

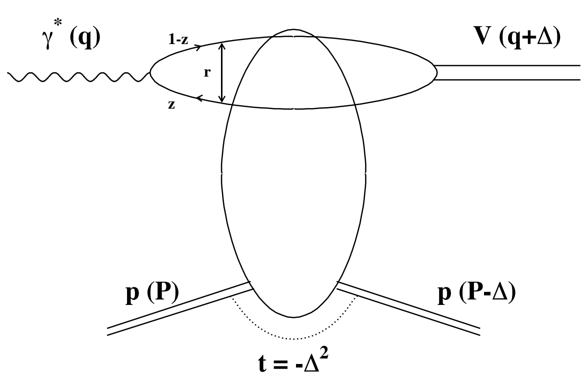
Diffraction and saturation

Dipole model at high energy: photon fluctuates into qqbar pair and undergoes an interaction with the target

$$\sigma_{T,L}(x,Q^2) = \int d^2\mathbf{r} \int_0^1 dz \sum_f |\Psi^f_{T,L}(\mathbf{r},z,Q^2)|^2 \, \hat{\sigma}(x,\mathbf{r}) \, .$$

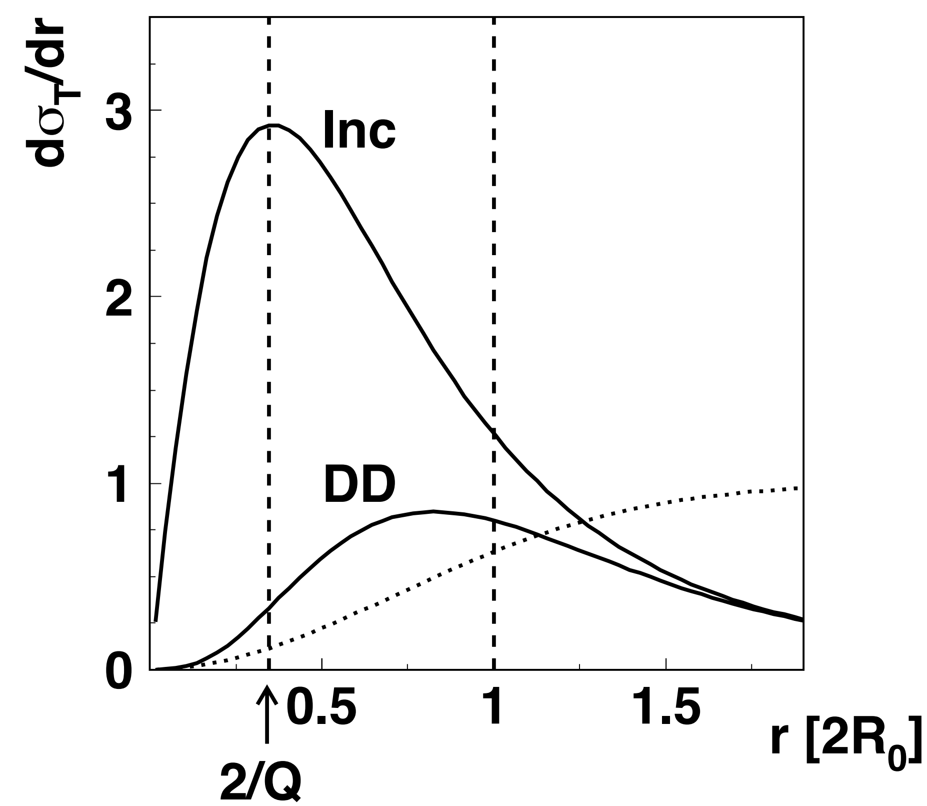


Inclusive: dominated by relatively hard component



Diffractive: dominated by the semi-hard momenta

overlap function in the dipole model
typical dipole sizes involved in the process

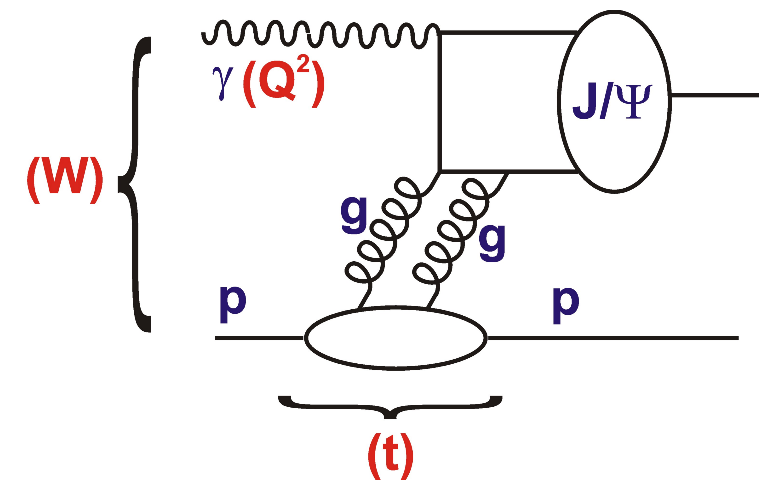


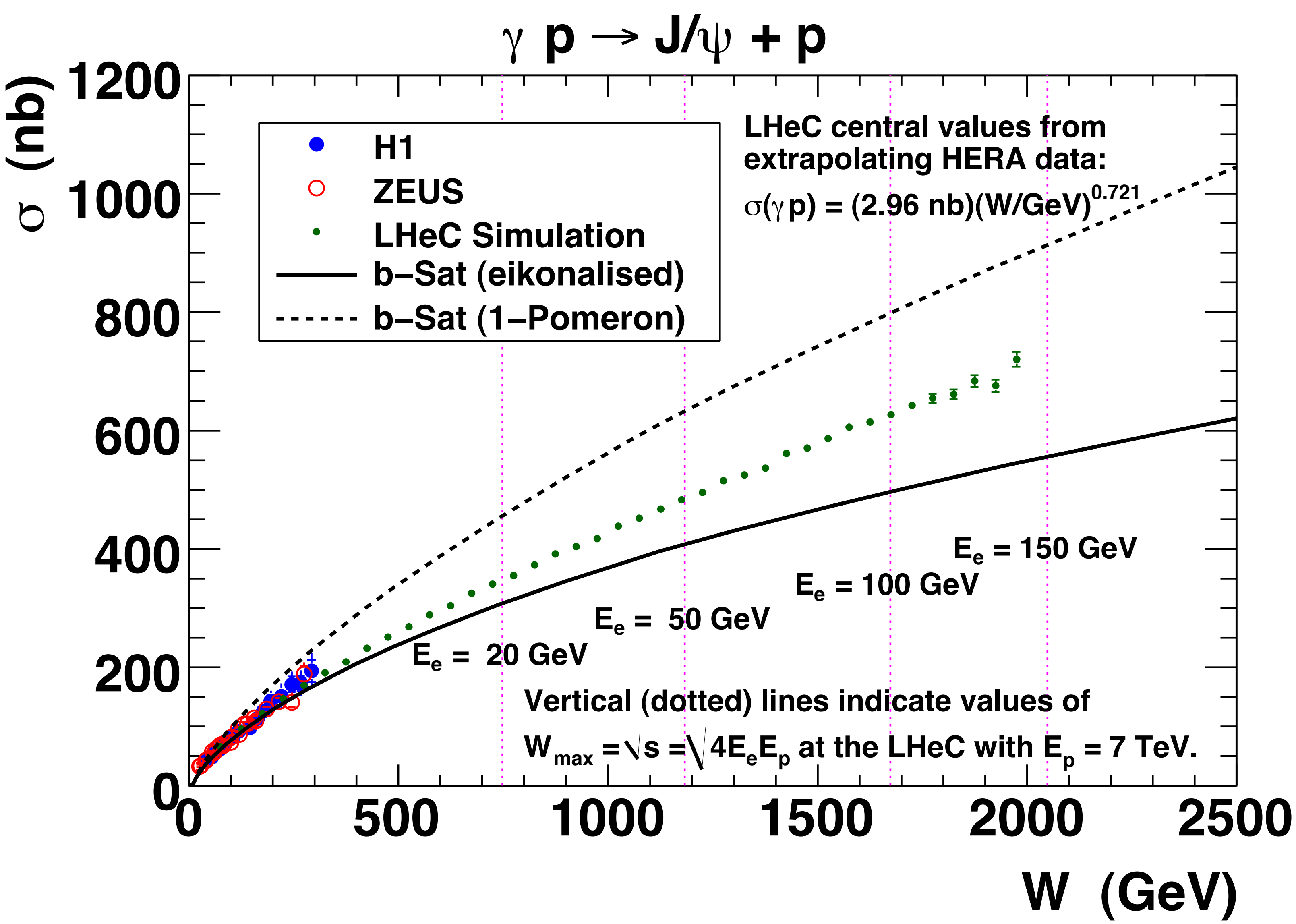
Diffraction is a collective phenomenon.
Explore relation with saturation.

Exclusive diffraction: predictions

$$\sigma^{\gamma p \to J/\Psi + p}(W)$$

- b-Sat dipole model (Golec-Biernat, Wuesthoff, Bartels, Motyka, Kowalski, Watt)
- eikonalised: with saturation
- 1-Pomeron: no saturation





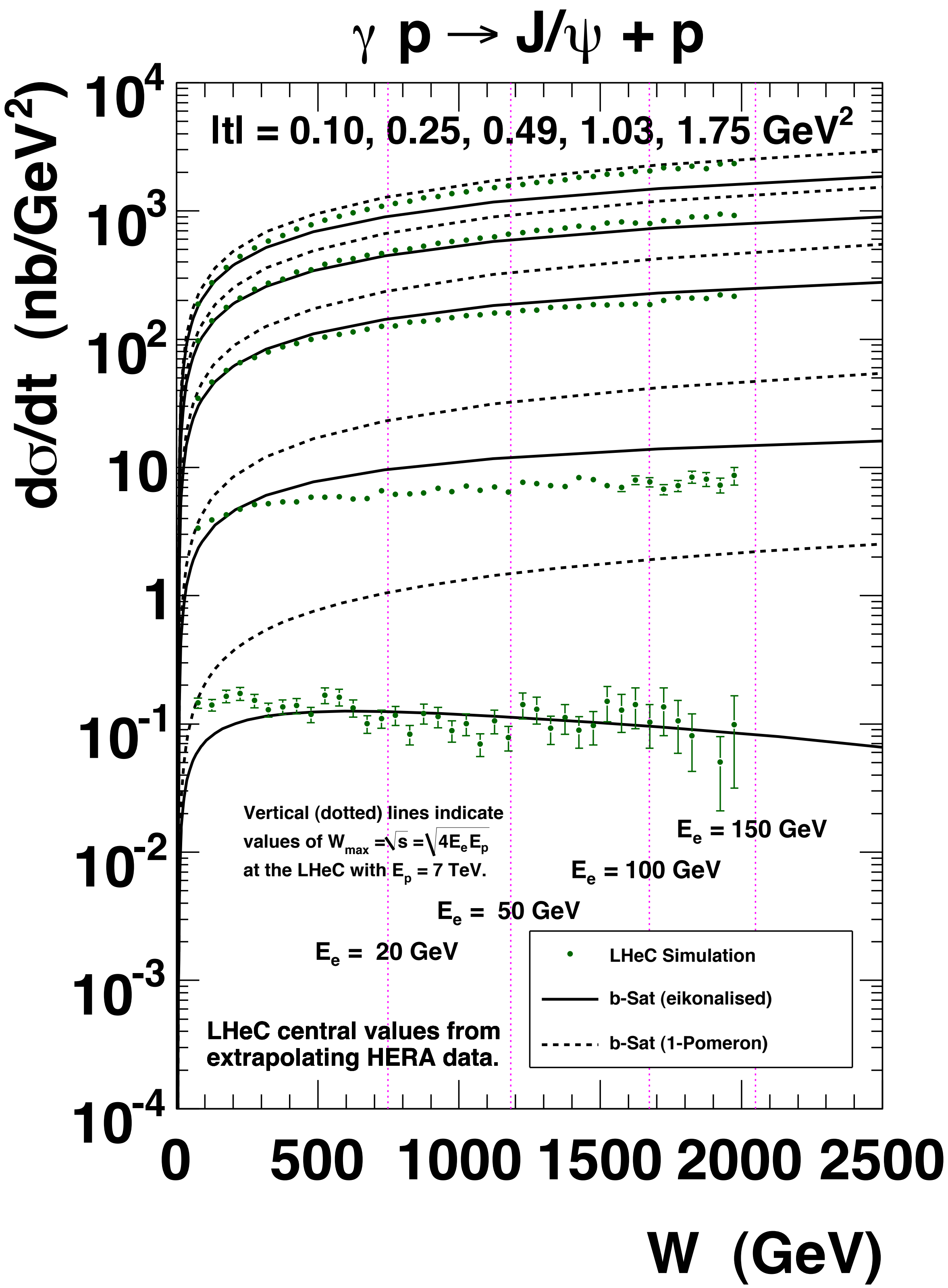
Large effects even for the t-integrated observable.

Different W behavior depending whether saturation is included or not.

Simulated data are from extrapolated fit to HERA data

LHeC can distinguish between the different scenarios.

Exclusive diffraction: t-dependence

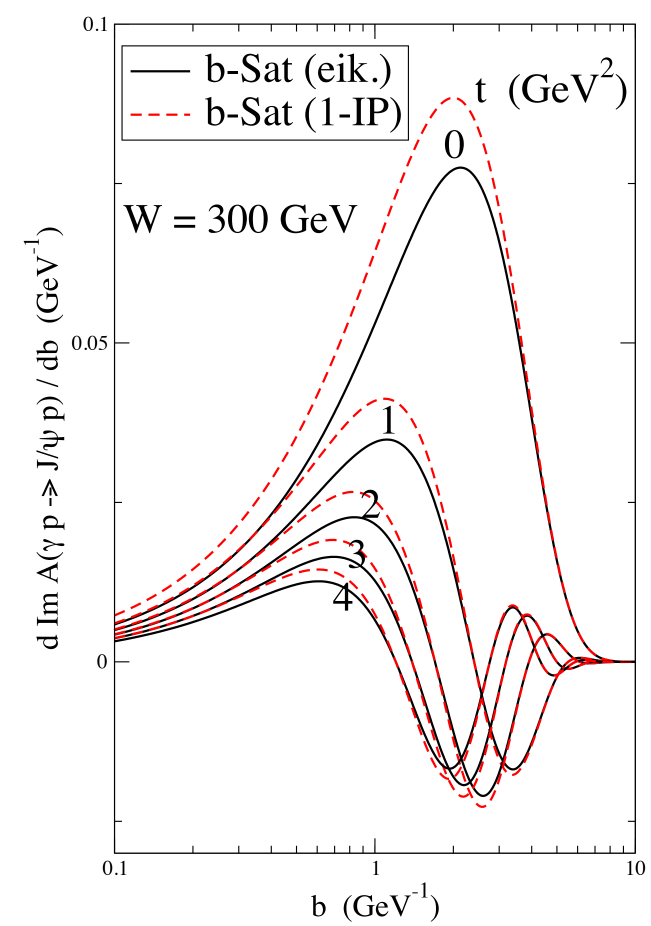


Photoproduction in bins of W and t.

Already for small values of t and smallest energies large discrepancies between the models. LHeC can discriminate.

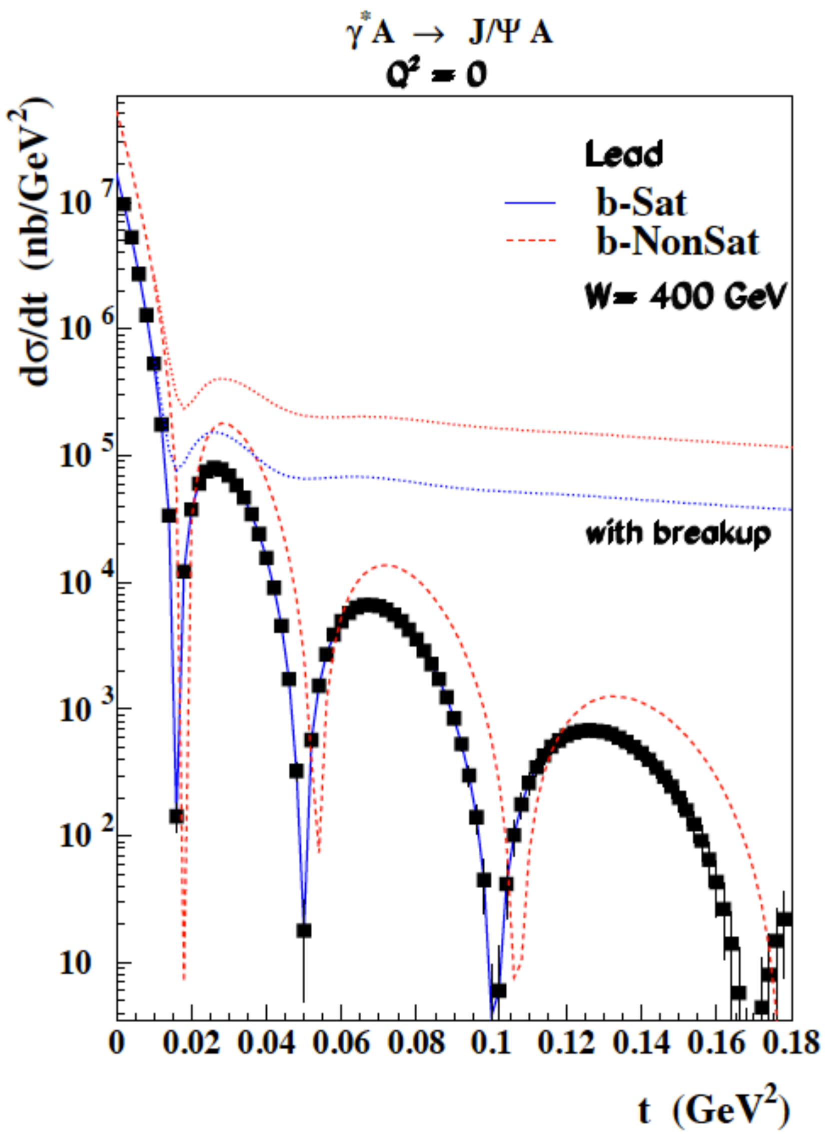
Large values of t : increased sensitivity to small impact parameters.

Amplitude as a function of the impact parameter.

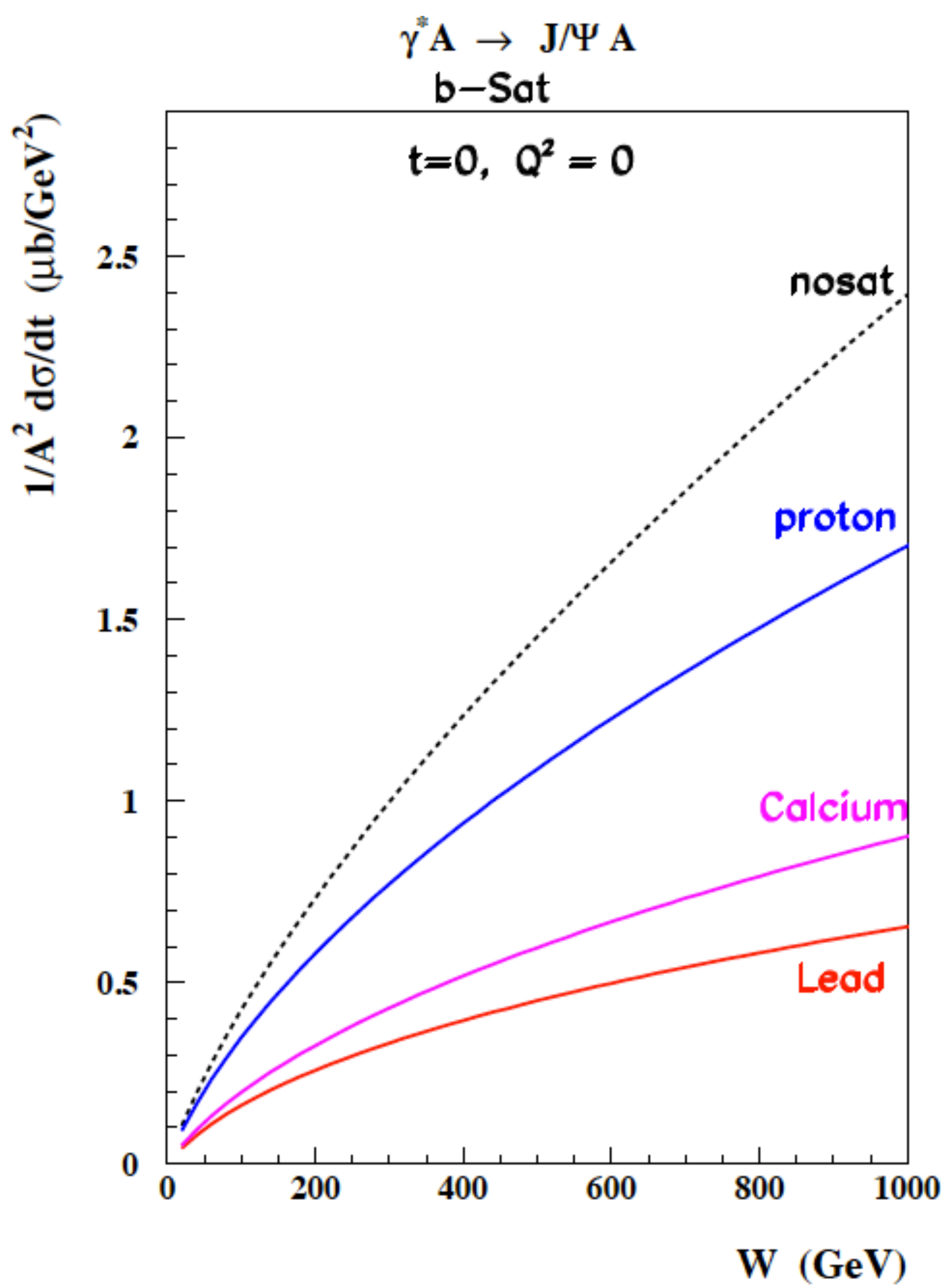


Exclusive diffraction on nuclei

Possibility of using the same principle to learn about the gluon distribution in the nucleus.
Possible nuclear resonances at small t?



Energy dependence for different targets.



t-dependence: characteristic dips.
Challenges: need to distinguish between coherent and incoherent diffraction. Need dedicated instrumentation, zero degree calorimeter.

Photoproduction cross section

Explore dual nature of the photon: pointlike interactions or hadronic behavior.

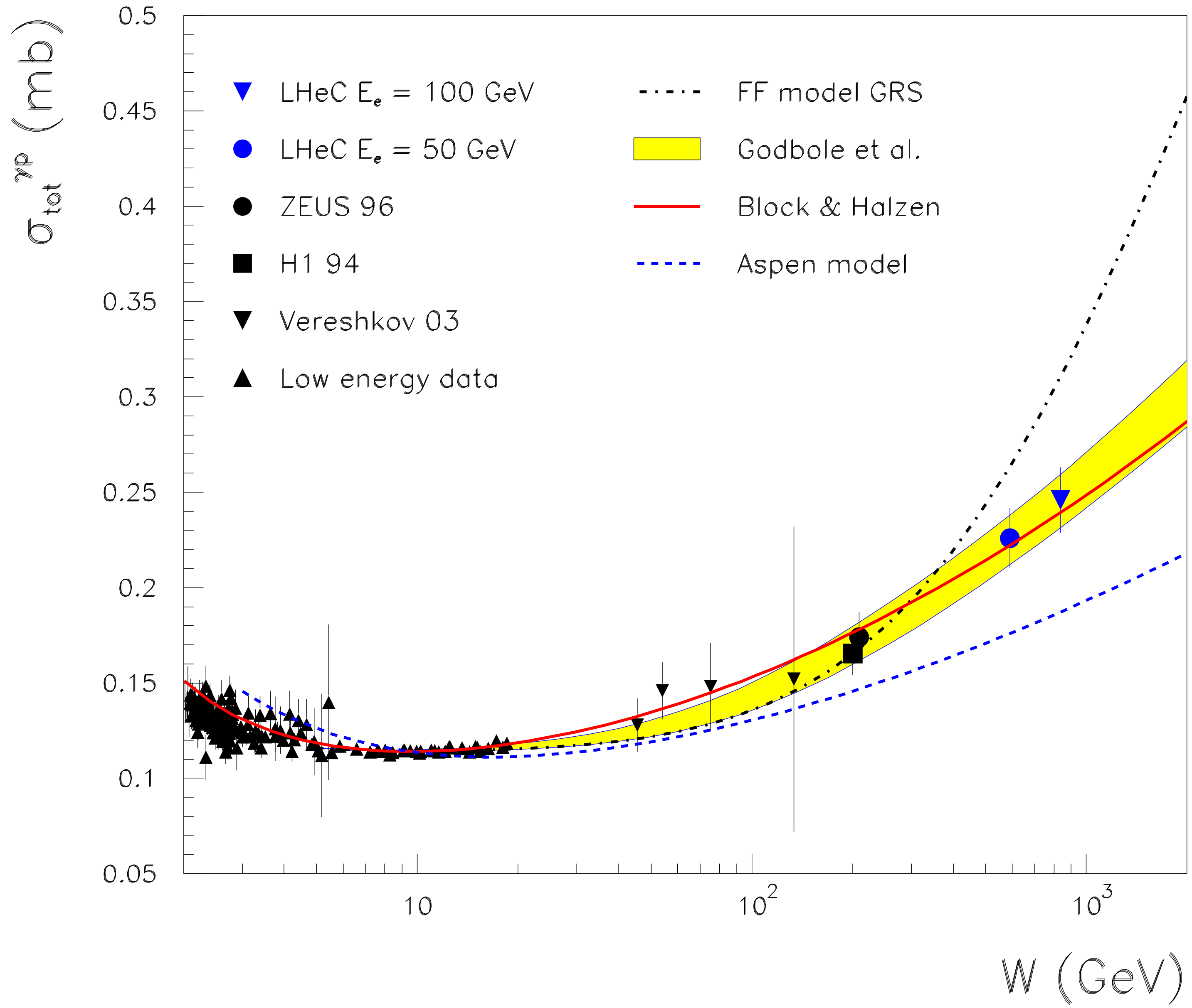
Tests of universality of hadronic cross sections, unitarity, transition between perturbative and nonperturbative regimes.

Dedicated detectors for small angle scattered electrons at 62m from the interaction point.

Kinematics of events:

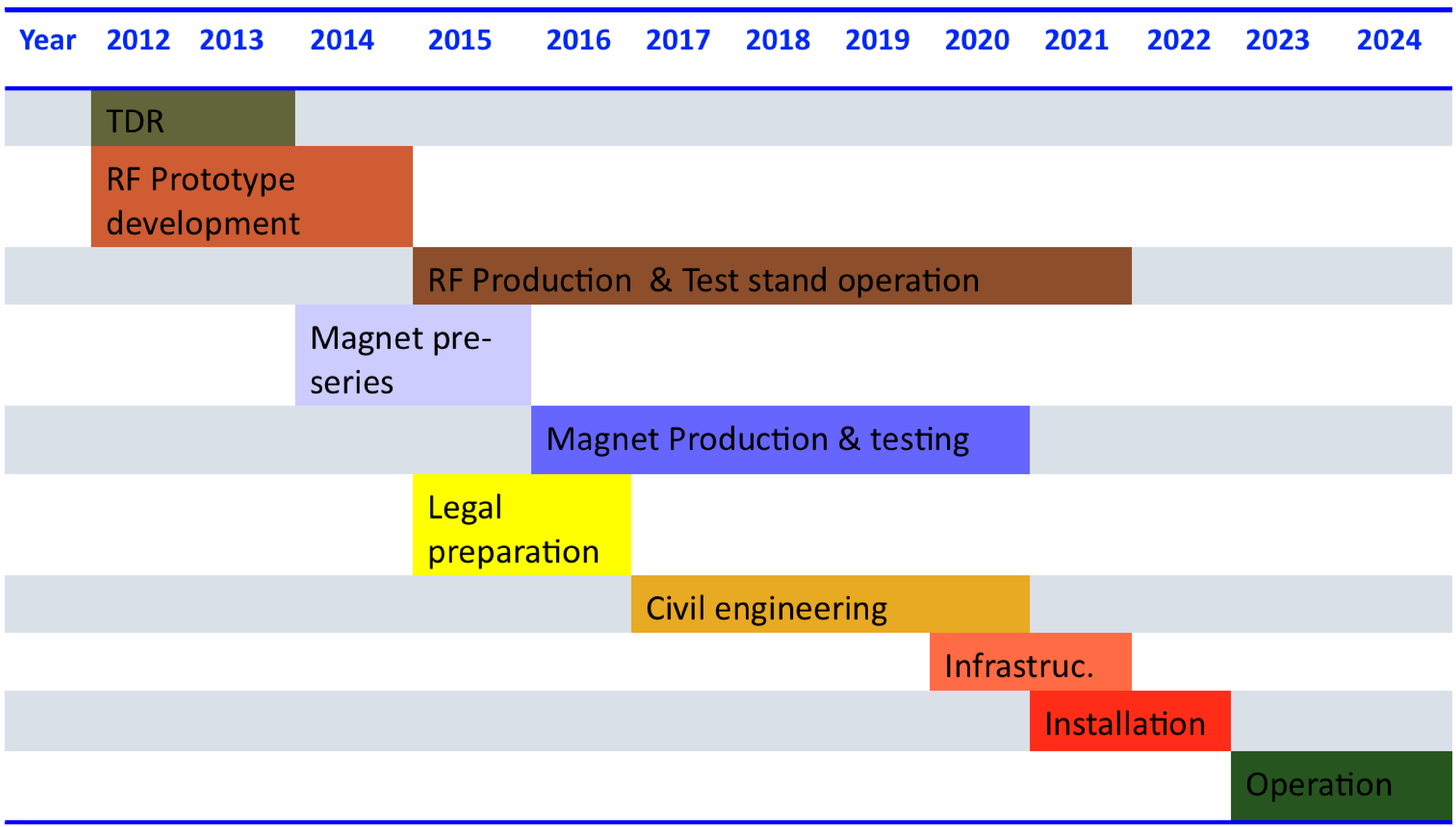
$$Q^2 \sim 0.01$$

$$y \sim 0.3$$

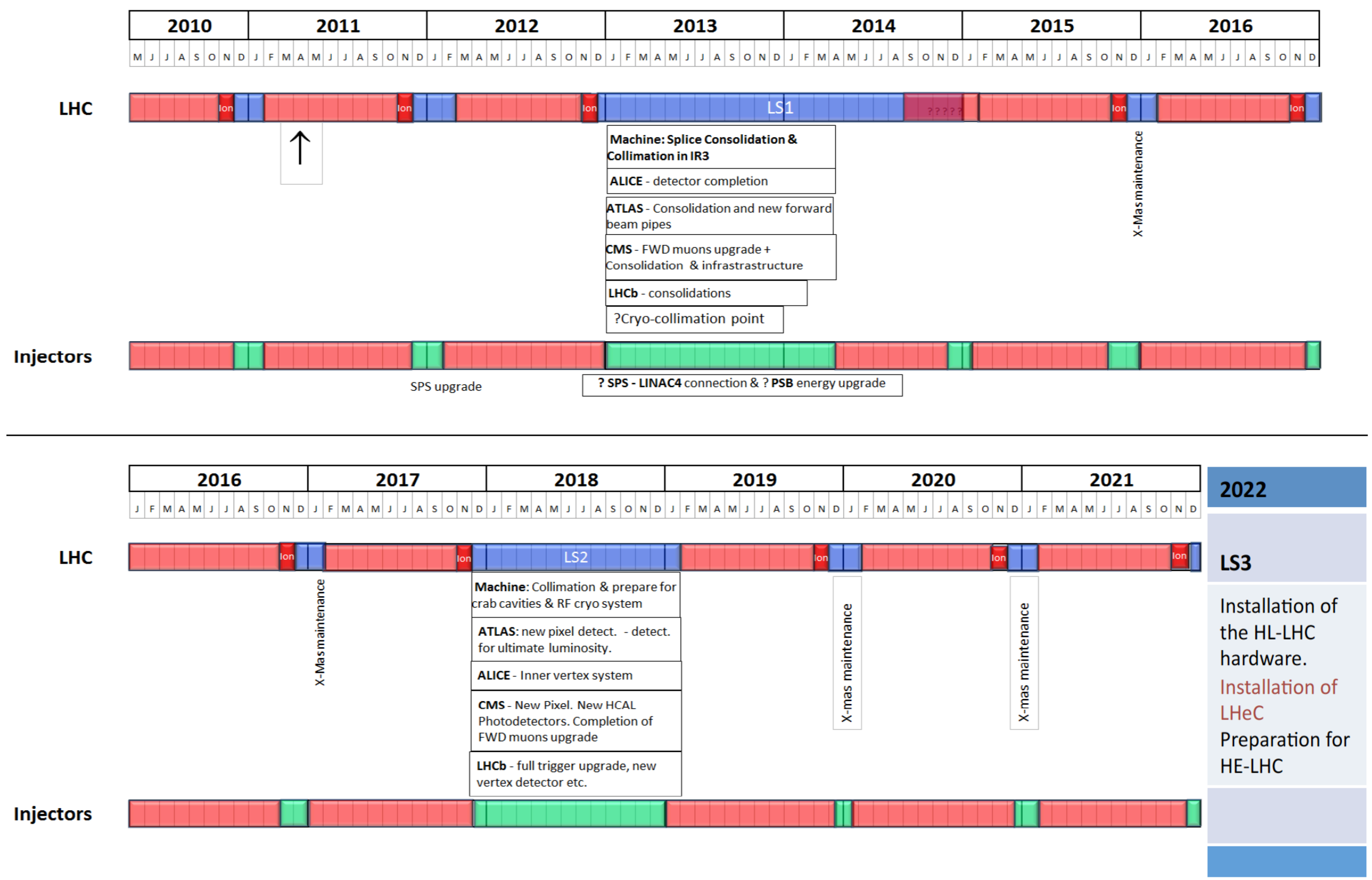


Systematics is the limiting factor here. Assumed 7% for the simulated data as in H1 and ZEUS.

Timeline


Year
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
TDR
RF Prototype development
RF Production & Test stand operation
Magnet pre-series
Magnet Production & testing
Legal preparation
Civil engineering
Infrastruc.
Installation
Operation

CERN Medium Term Plan (draft as of July 2011)



Summary

LHeC is a proposal to study deep inelastic scattering in a new domain of high energy and luminosity using the existing LHC proton and ion beams.

Ongoing CERN/ECFA/NuPECC workshop has gathered many experimentalists and theorists.

Conceptual Design Report will be released very soon.

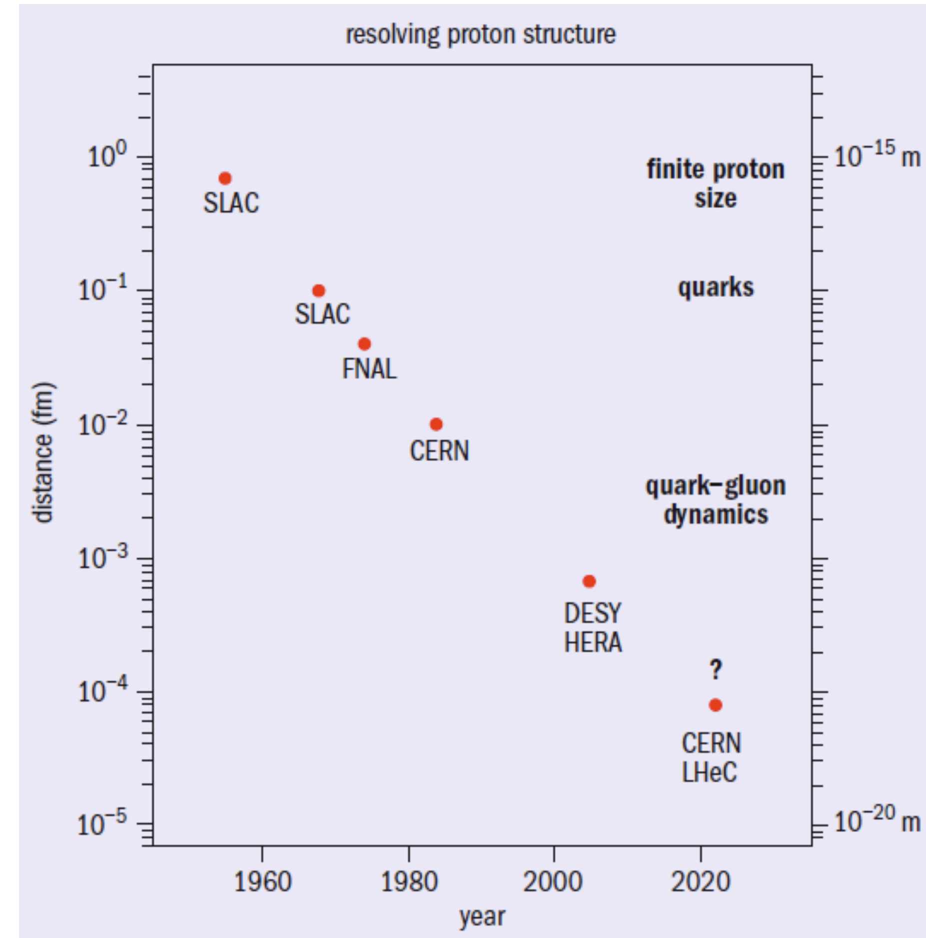


Fig. 1. Distance scales resolved in successive lepton–hadron scattering experiments since the 1950s, and some of the new physics revealed.

more info http://www.cern.ch/lhec

Summary

LHeC is a proposal to study deep inelastic scattering in a new domain of high energy and luminosity using the existing LHC proton and ion beams.

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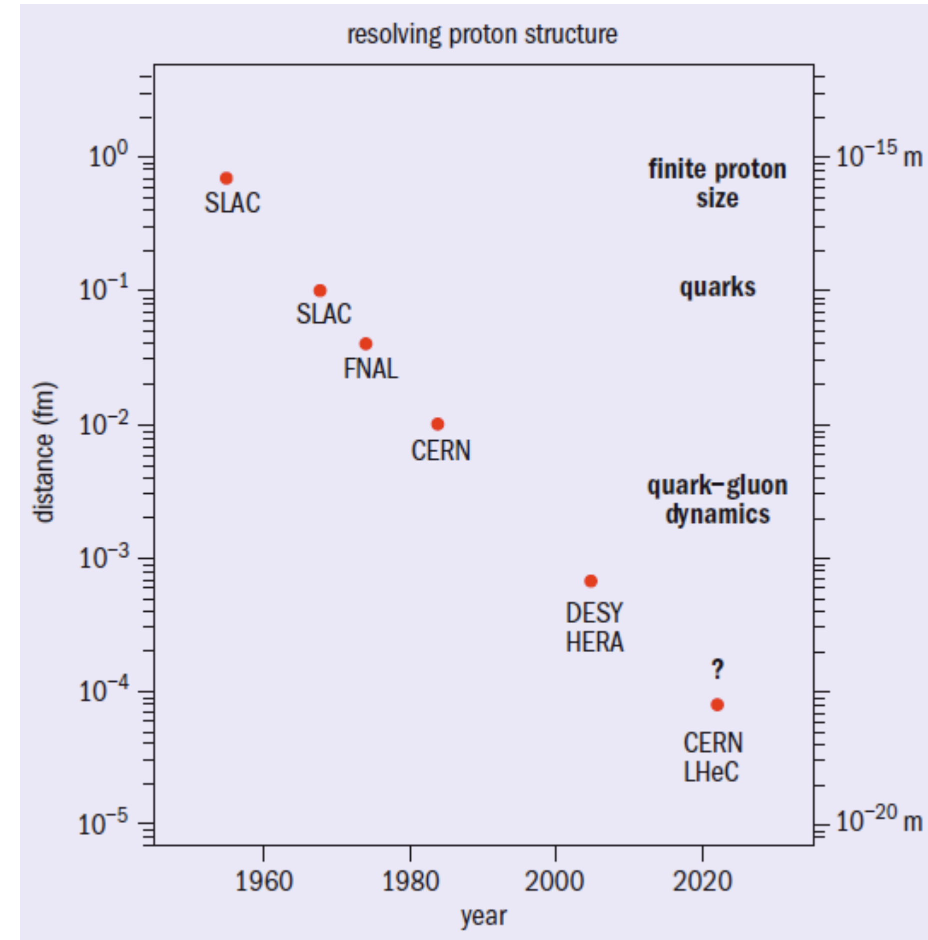

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It would be a waste not to exploit the 7 TeV beams for eP and eA physics at some stage during the LHC time

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Divonne 08