Future High Energy Electron Proton Scattering: The LHeC Project

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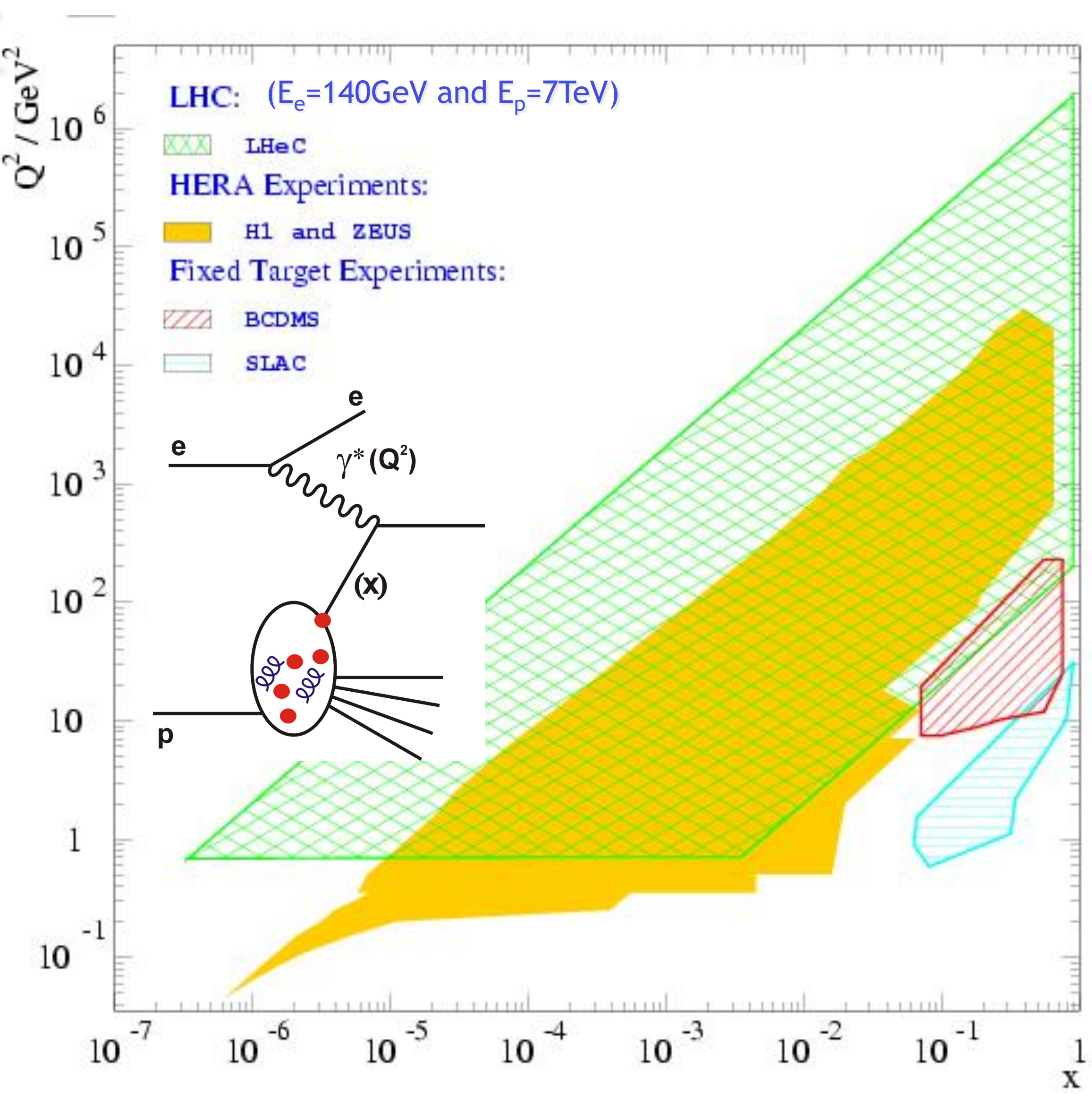
(for LHeC study group)



Cambridge Seminar
30 October 2012

A second generation lepton-hadron collider in the 2020s, based on the high luminosity phase of the LHC

http://cern.ch/lhec

Material from recently published Conceptual Design Report

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

~200 participants
from 69 institutes

arXiv:1206.2913 [physics.acc-ph]

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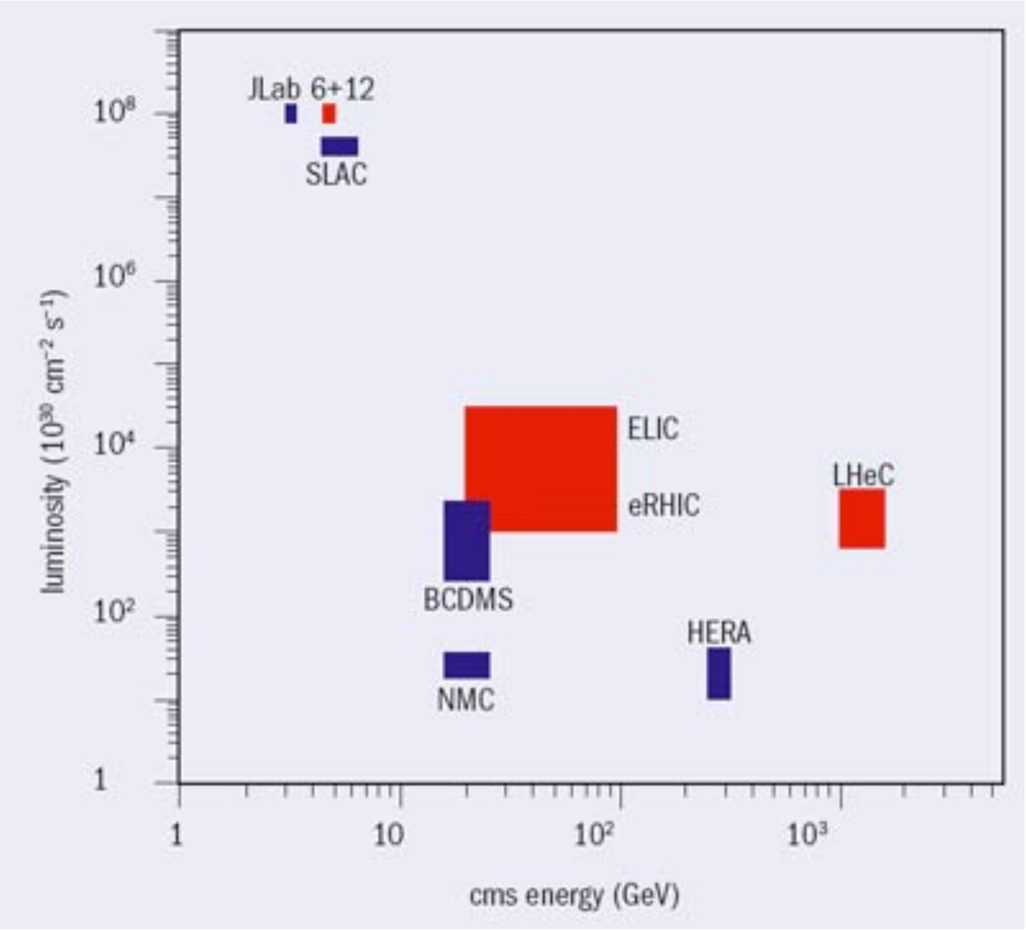
A Large Hadron Electron Collider at CERN
Report on the Physics and Design Concepts for Machine and Detector
LHeC Study Group

iopscience.org/jphysg

IOP Publishing

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



Contents

- A brief history of ep Physics
- How to build an ep Collider based on the LHC
- Detector considerations
- Physics motivation
  - Proton structure / Impact on the LHC
  - QCD at high parton densities
  - Electron – ion collisions
  - BSM physics
- Timeline and outlook

Electron Scattering Experiments

"It would be of great scientific interest if it were possible to have a supply of electrons … of which the individual energy of motion is greater even than that of the alpha particle."
[Ernest Rutherford, Royal Society, London, (as PRS) 30 Nov 1927]

1950s
Hoffstadter

First observation of **finite proton size** using 2 MeV e beam

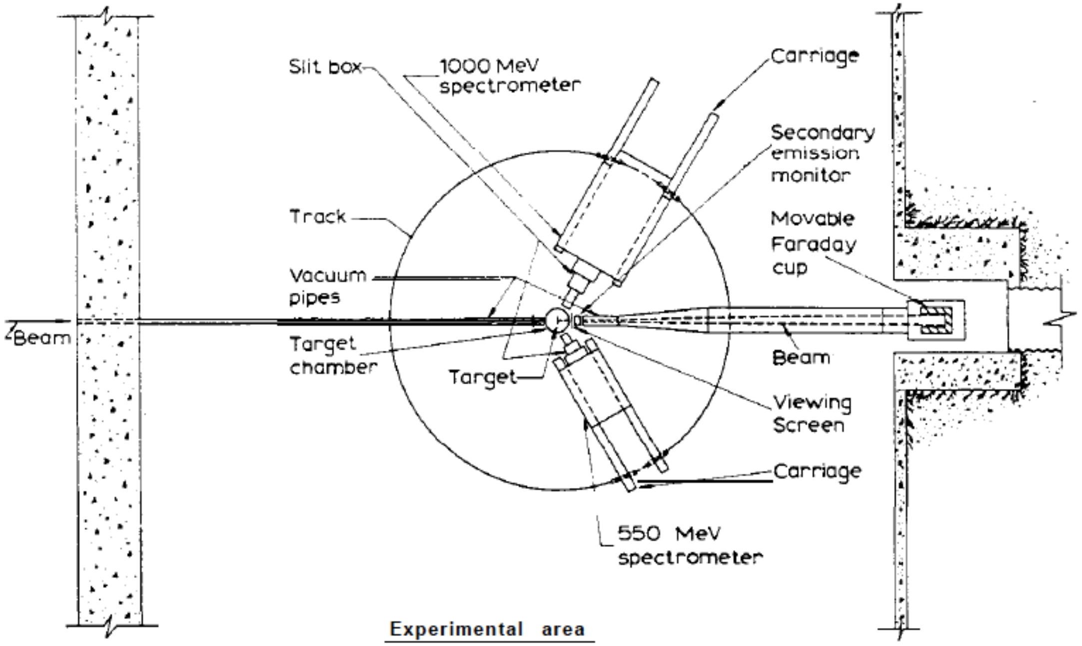
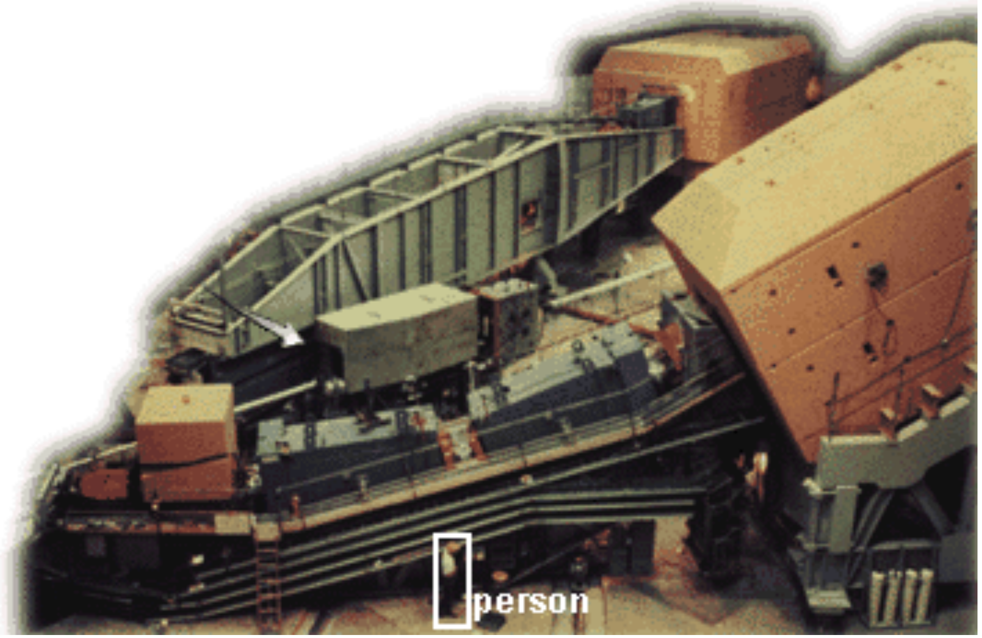


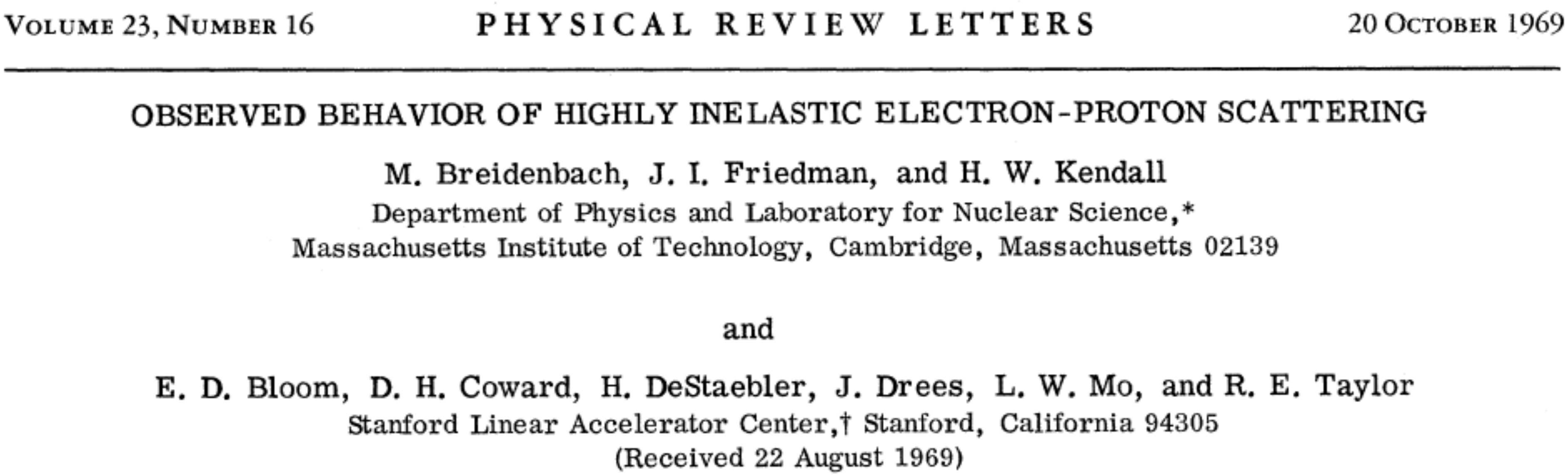
Fig. 2. This figure shows a schematic diagram of a modern electron-scattering experimental area. The track on which the spectrometers roll has an approximate radius of 13.5 feet.

SLAC 1969: Electron Energies 20 GeV



Proposal:
“A general survey of the basic cross sections which will be useful for future proposals”

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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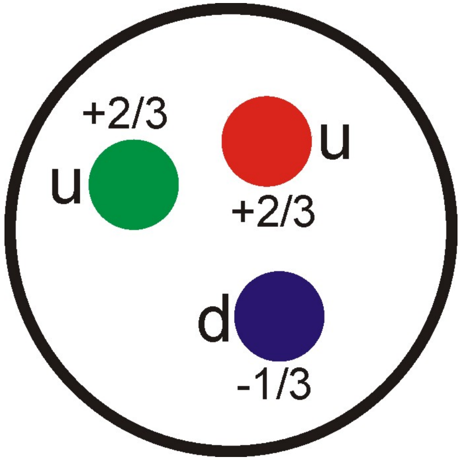
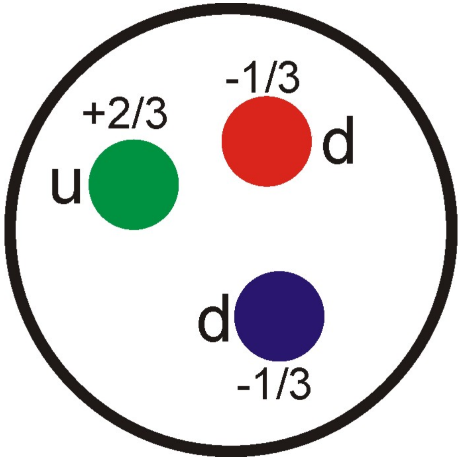
(Received 22 August 1969)



proton

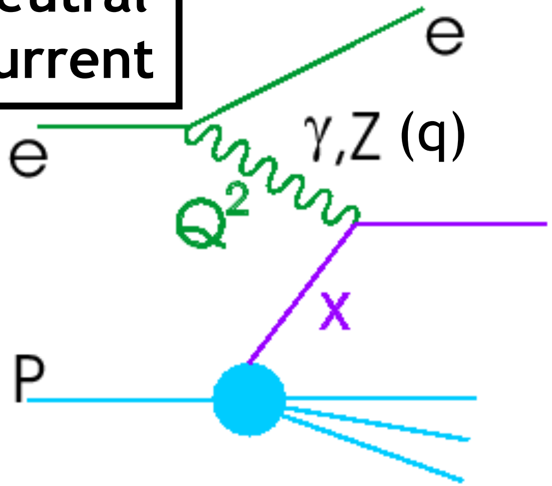


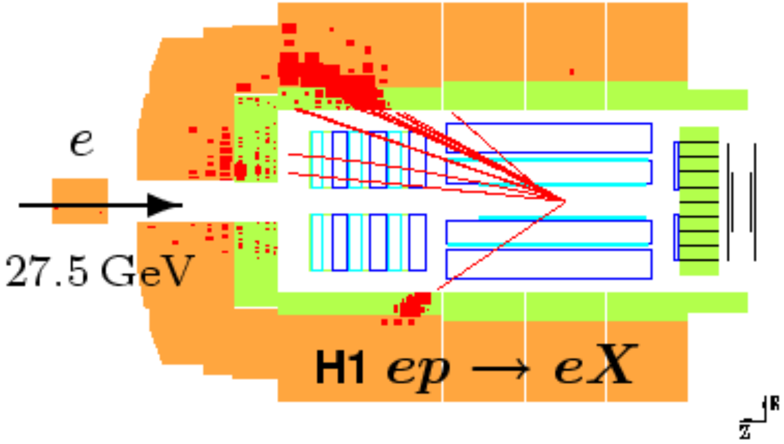
neutron

… and so on …

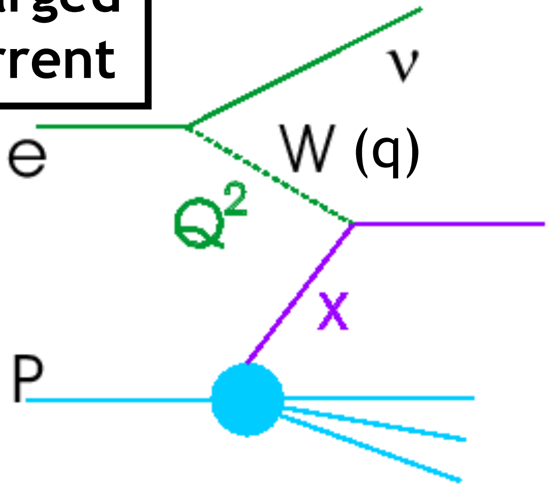
Basic Deep Inelastic Scattering Processes

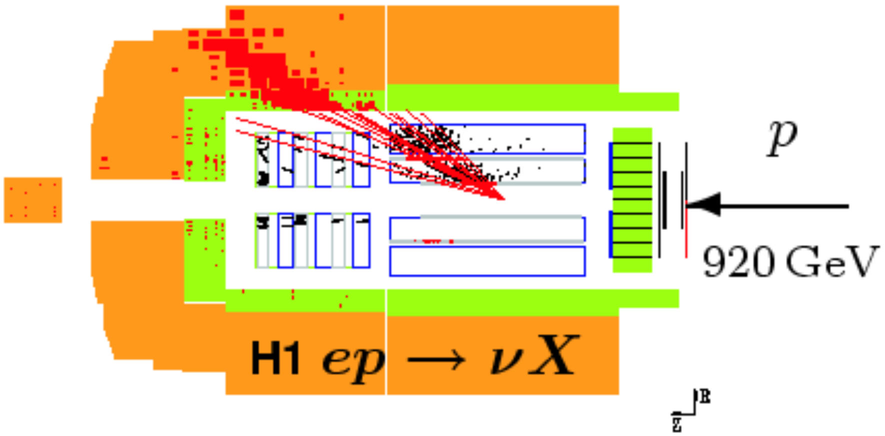
Neutral Current





Charged Current





$Q^2 = -q^2$:resolving power of interaction

$x = Q^2 / 2q.p$: fraction of struck quark / proton momentum

DESY, Hamburg

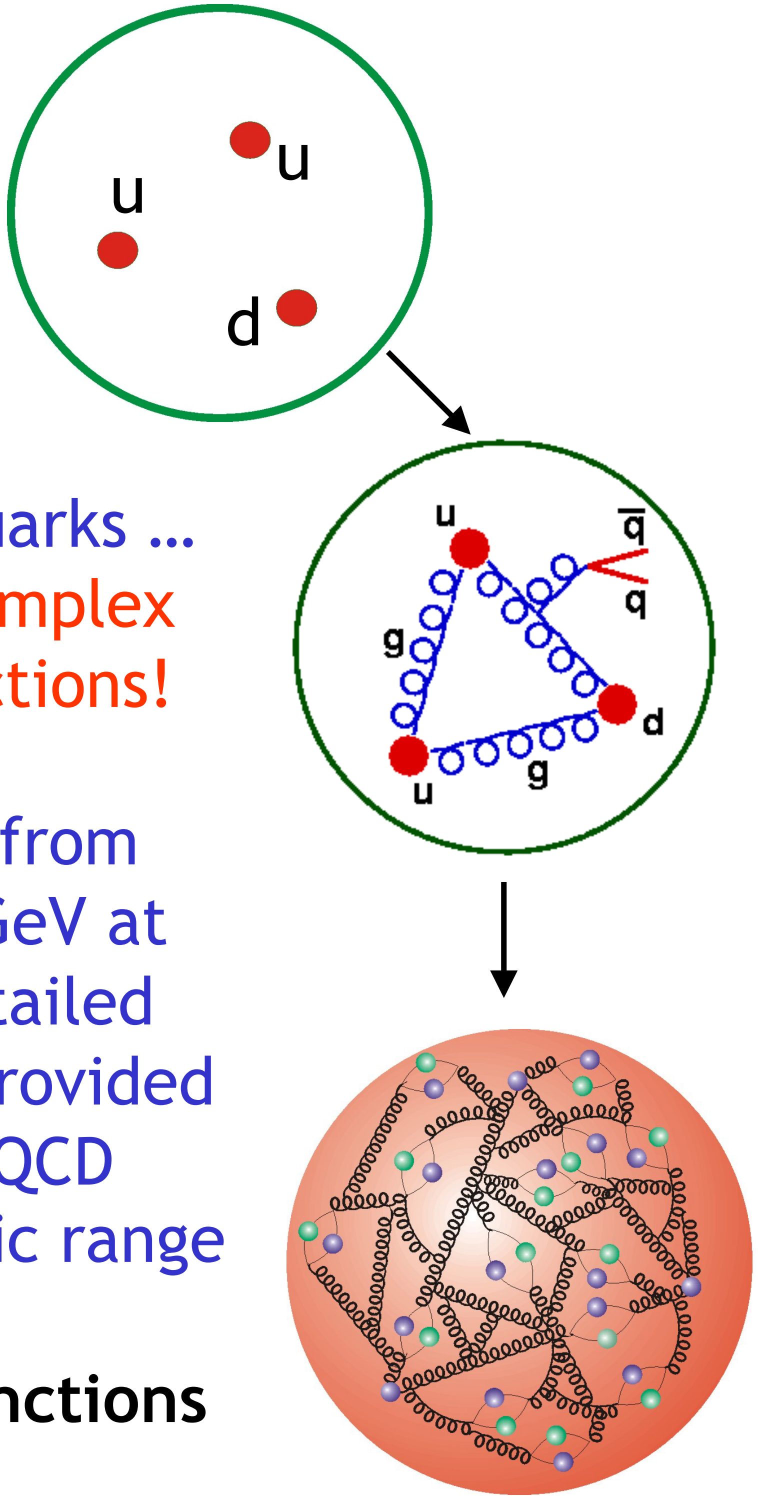
HERA (1992-2007)

… the only ever collider of electron beams with proton beams

Equivalent to a 50 TeV beam on a fixed target proton
~2500 times more than SLAC!

Around 500 pb^{-1} per experiment

Proton “Structure”?



Proton constituents …

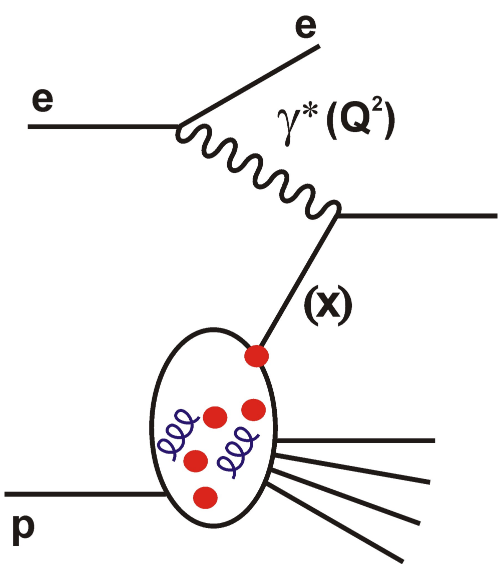
2 up and 1 down **valence quarks**

… and some **gluons**

… and some **sea quarks**

… and lots more gluons and sea quarks …

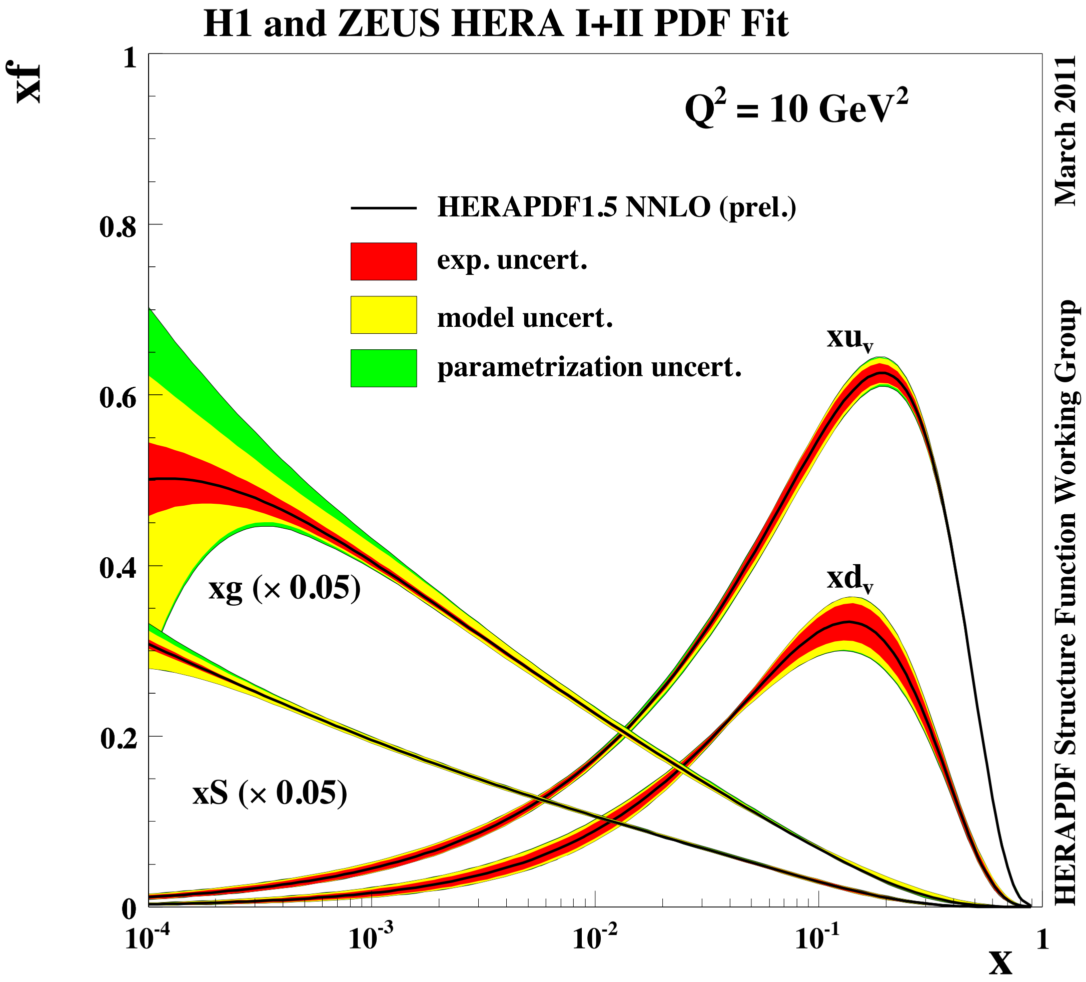
→ strong interactions induce rich and complex `structure’ of high energy proton interactions!



Scattering electrons from protons at √s > 300GeV at HERA established detailed proton structure & provided a testing ground for QCD over a huge kinematic range

… **parton density functions**

HERA's greatest legacy



Proton parton densities in x range well matched to LHC rapidity plateau

Some limitations:

- Insufficient lumi for high x precision

- Lack of Q^2 lever-arm for low x gluon

- Assumptions on quark flavour decomposition

- No deuterons … u and d not separated

- No heavy ions

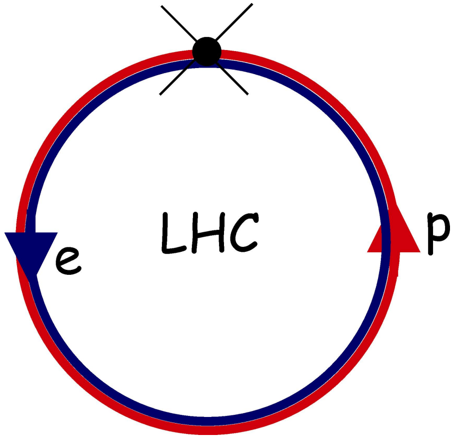
- H1/ZEUS publications still coming
- Further progress requires higher energy and luminosity …

Currently Approved Future of High Energy DIS

How Could ep be Done using LHC?

… whilst allowing simultaneous ep and pp running …

RING-RING

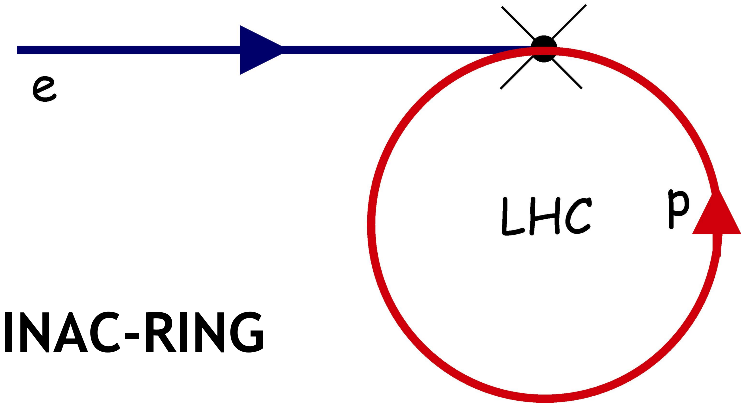


- First considered (as LEPxLHC) in 1984 ECFA workshop

- Main advantages: high peak lumi, tunnelling (mostly) exists

- Main difficulties: building round existing LHC, e beam energy and lifetime limited by synchrotron radiation

LINAC-RING



- Previously considered as `QCD explorer’ (also THERA)

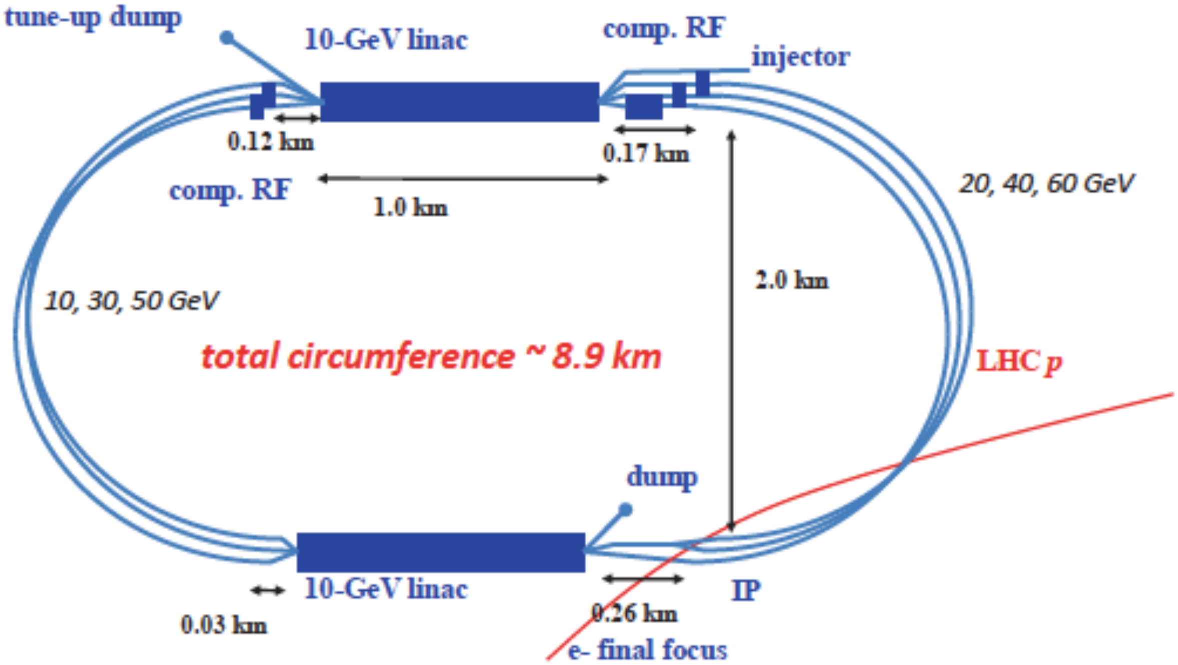
- Main advantages: low interference with LHC, high and stageable E_e, high lepton polarisation, LC relation?

- Main difficulties: obtaining high positron intensities, no previous experience exists

Baseline# Design (Electron "Linac")

Design constraint: power < 100 MW → E_e = 60 GeV @ 10^{33} cm^{-2} s^{-1}

- Two 10 GeV linacs,
- 3 returns, 20 MV/m
- Energy recovery in same structures [CERN plans energy recovery prototype]



- ep Lumi ~ 10^{33} cm^{-2} s^{-1} corresponds to ~10 fb^{-1} per year (~ 100 fb^{-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

Schematic layouts for several potential future projects are shown on this Google Earth view of the Geneva region around CERN :

- LIC (Compact Linear Collider) at collision energies of 500GeV and 3 TeV.
- LC (International Linear Collider) at 500GeV energy
- The Linac-Ring Solution of LHeC (A new electron beam supplied via a 60 GeV

TUPC017

Civil Engineering Studies for Major Projects after LHC

Design Parameter Summary

RR= Ring - Ring
LR =Linac -Ring

electron beam	RR	LR	LR
e- energy at IP[GeV]	60	60	140
luminosity [10^{32} cm^{-2}s^{-1}]	17	10	0.44
polarization [%]	40	90	90
bunch population [10^9]	26	2.0	1.6
e- bunch length [mm]	10	0.3	0.3
bunch interval [ns]	25	50	50
transv. emit. $\gamma\varepsilon_{x,y}$ [mm]	0.58, 0.29	0.05	0.1
rms IP beam size $\sigma_{x,y}$ [μm]	30, 16	7	7
e- IP beta funct. $\beta^*_{x,y}$ [m]	0.18, 0.10	0.12	0.14
full crossing angle [mrad]	0.93	0	0
geometric reduction H_{hg}	0.77	0.91	0.94
repetition rate [Hz]	N/A	N/A	10
beam pulse length [ms]	N/A	N/A	5
ER efficiency	N/A	94%	N/A
average current [mA]	131	6.6	5.4
tot. wall plug power[MW]	100	100	100

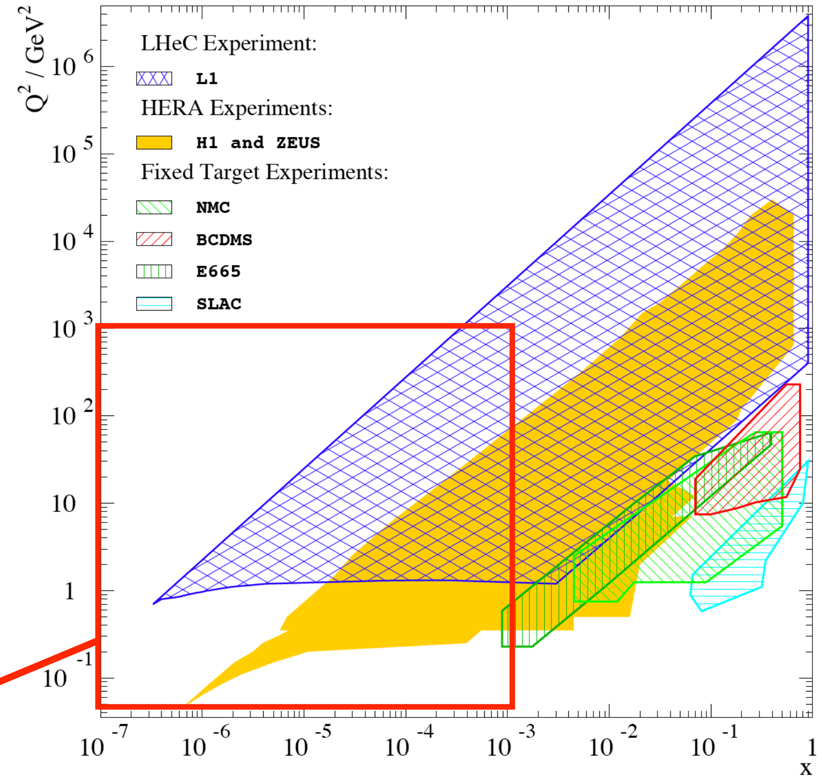
proton beam	RR	LR
bunch pop. [10^{11}]	1.7	1.7
tr.emit.$\gamma\varepsilon_{x,y}$ [μm]	3.75	3.75
spot size $\sigma_{x,y}$ [μm]	30, 16	7
$\beta^*_{x,y}$ [m]	1.8,0.5	0.1
bunch spacing [ns]	25	25

Include deuterons (new) and lead (exists)

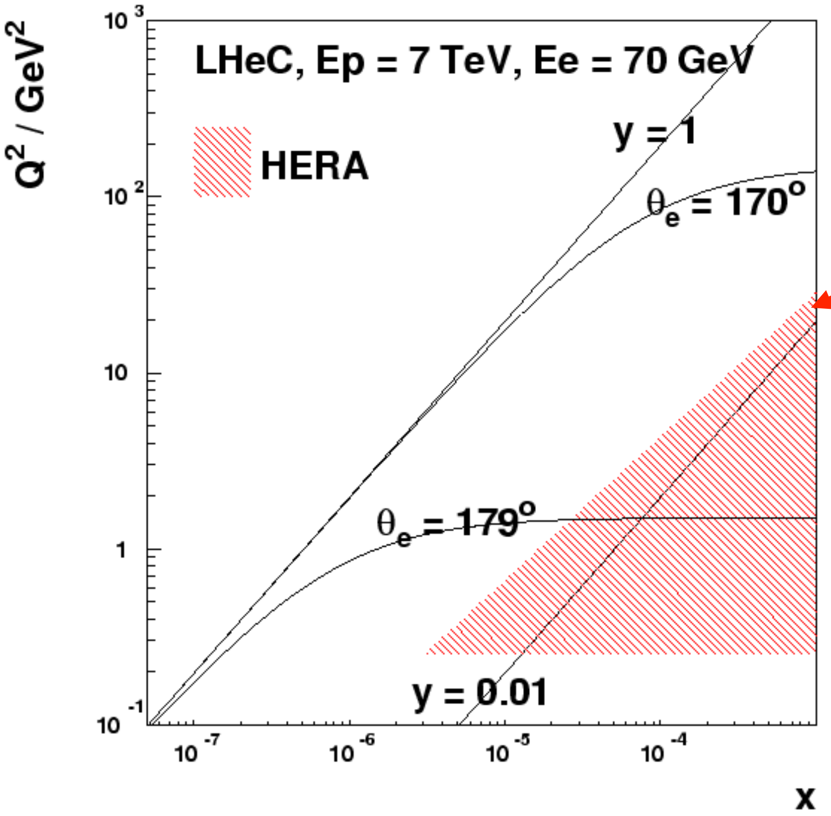
10 fb^{-1} per year looks possible

… ~ 100 fb^{-1} total

Detector Acceptance Requirements

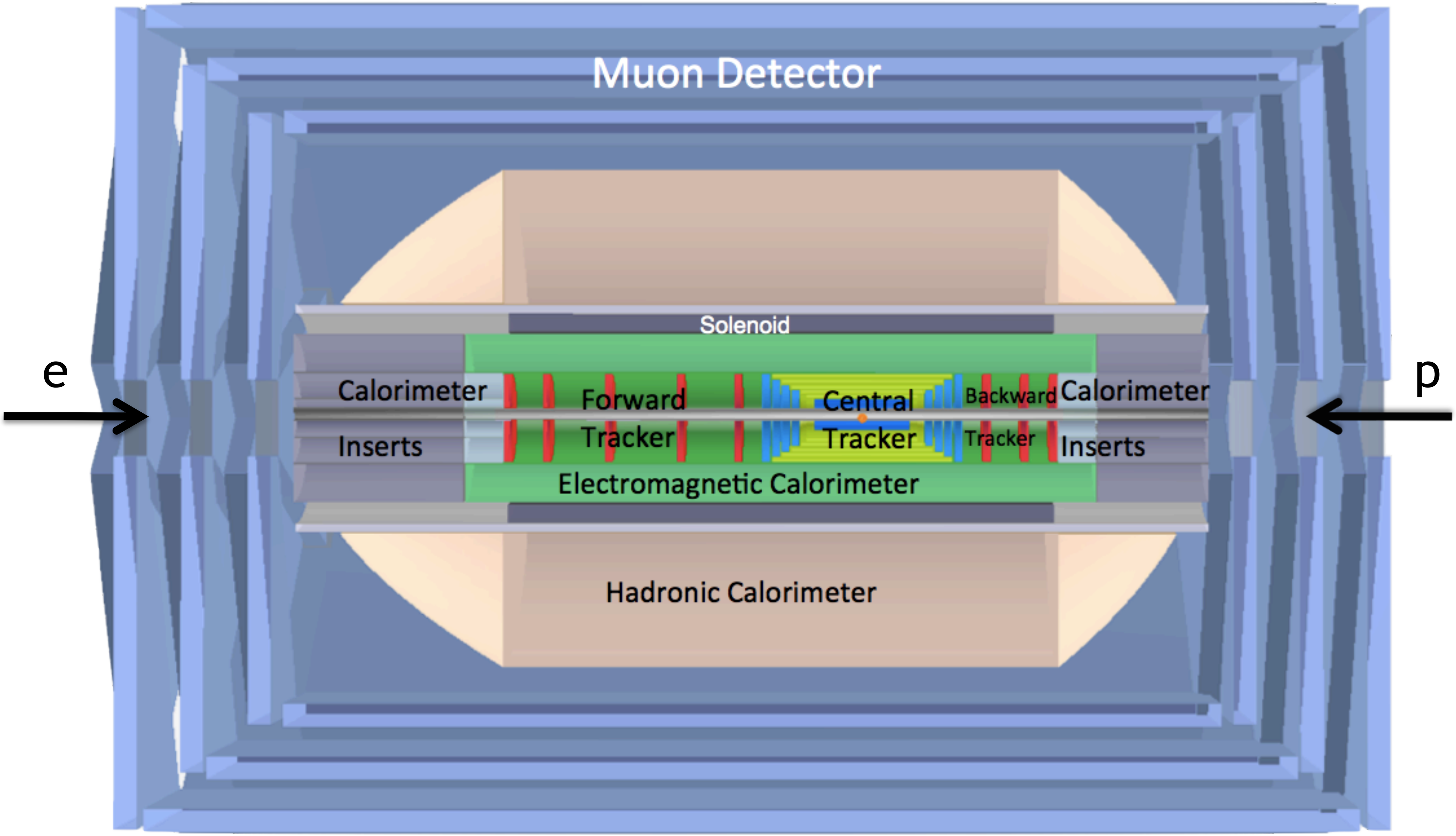


Access to Q^2=1 GeV^2 in ep mode for all x > 5 x 10^{-7} requires scattered electron acceptance to 179^o



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

Detector Overview: LR full acceptance version



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)

Transverse momentum $\Delta p_t/p^2_t$ → $6\ 10^{-4}$ GeV^{-1}
transverse
impact parameter
→ 10μm

Tracking Region

[encased in
3.5T solenoid
field]

Central Pixel Tracker

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

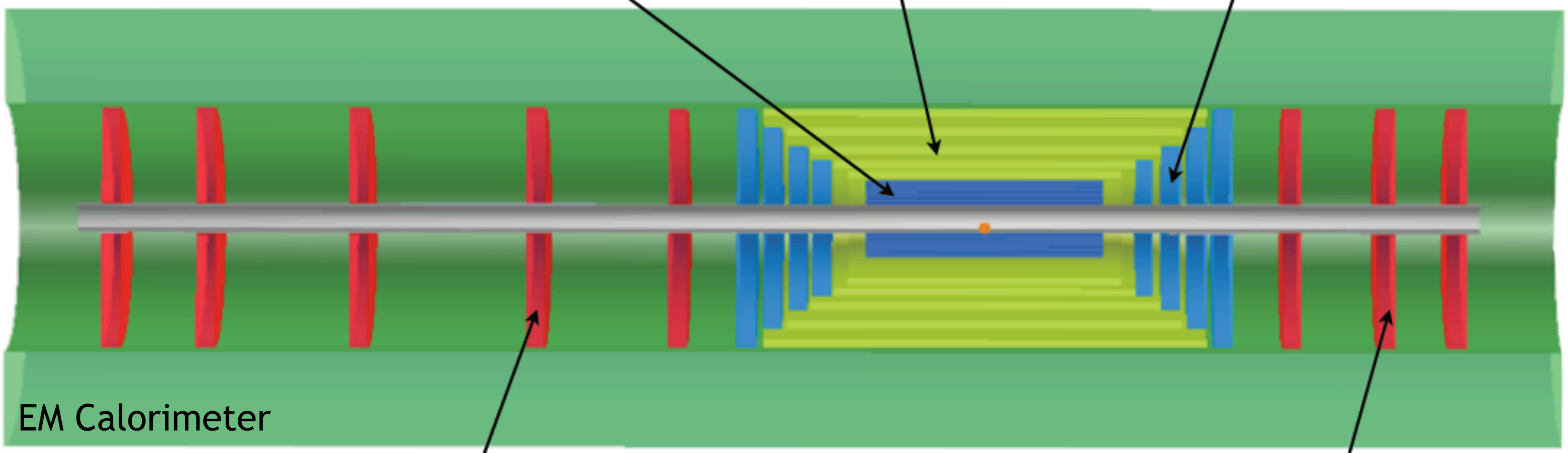
ΔR = 15. cm

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

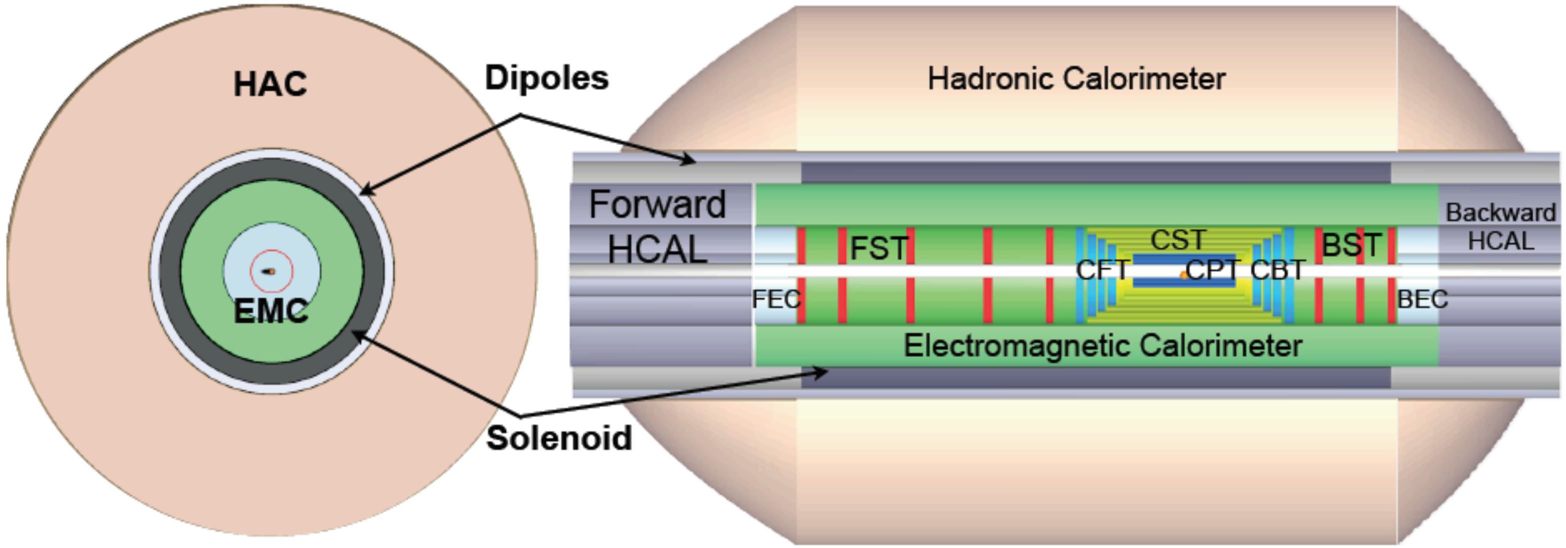
FST - ΔZ= 8. cm
min-inner-R = 3.1 cm; max-inner-R= 10.9 cm
outer R = 46.2 cm
Planes 1-5:
$z_{5\text{-}1}$ = 370. / 330. / 265. / 190. / 130. cm

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:
$z_{1\text{-}3}$ = -130. / -170. / -200. cm

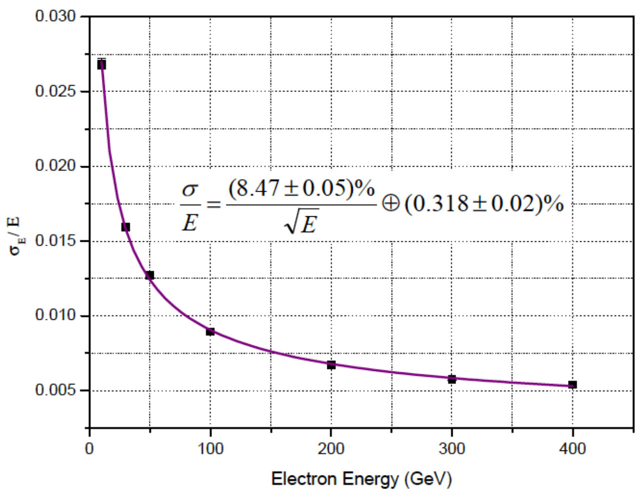
- Full angular coverage, long tracking region → 1° acceptance
- Several technologies under discussion

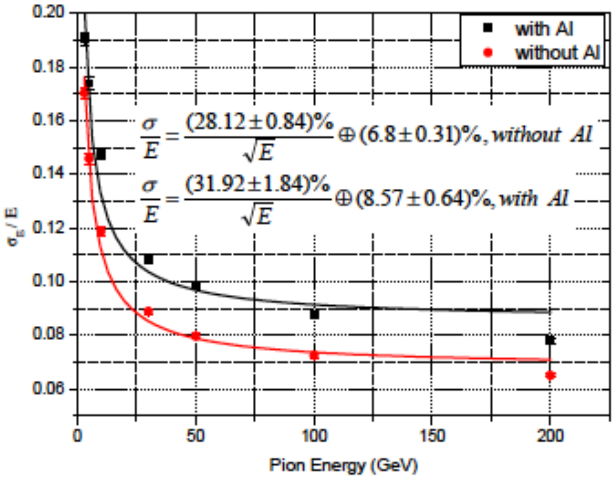
Calorimeters



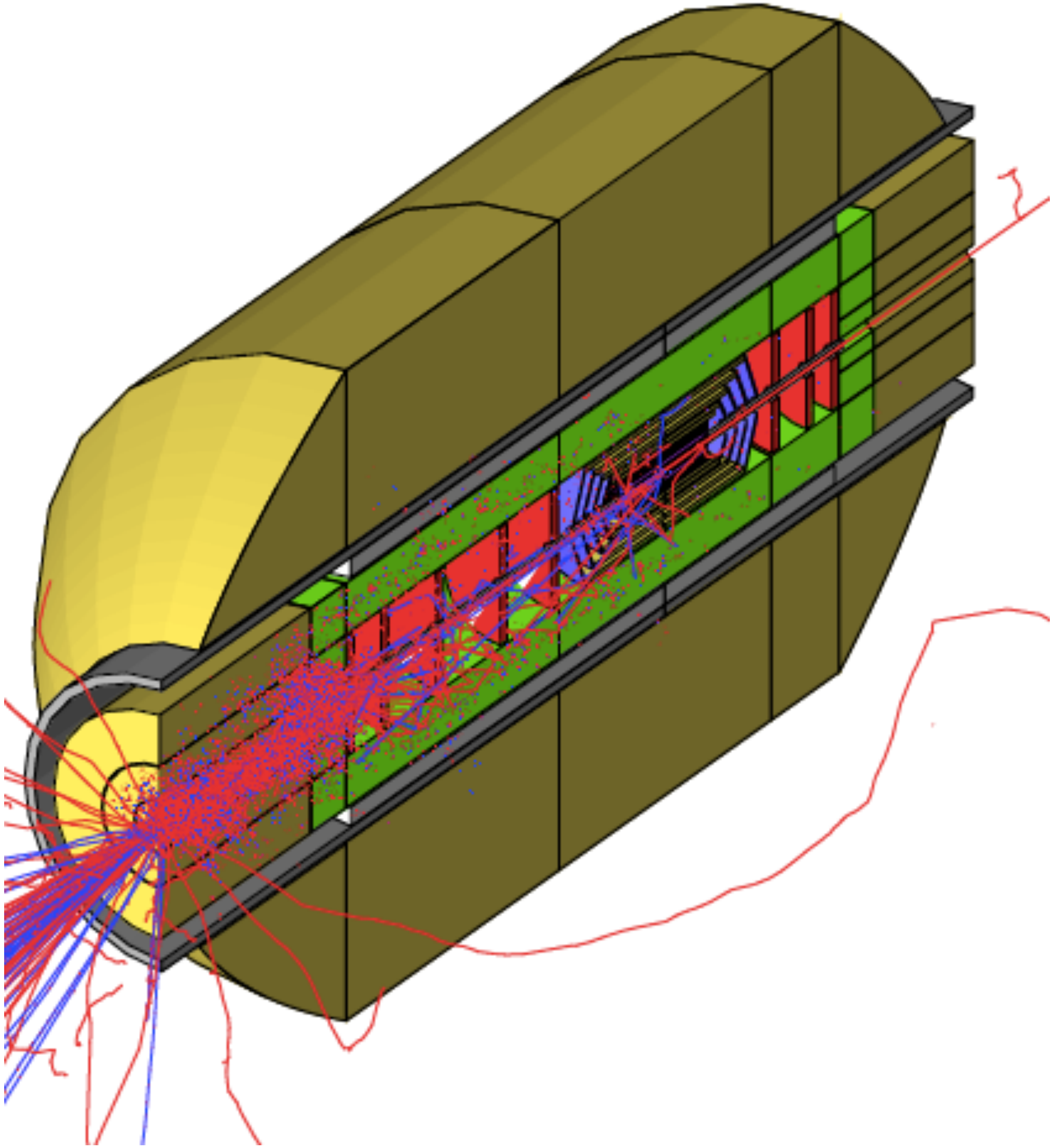
Liquid Argon EM Calorimeter [accordion geometry, inside coil]
Barrel: Pb, 20 X_0 , 11m^3 FEC: Si -W, 30 X_0 BEC: Si -Pb, 25 X

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



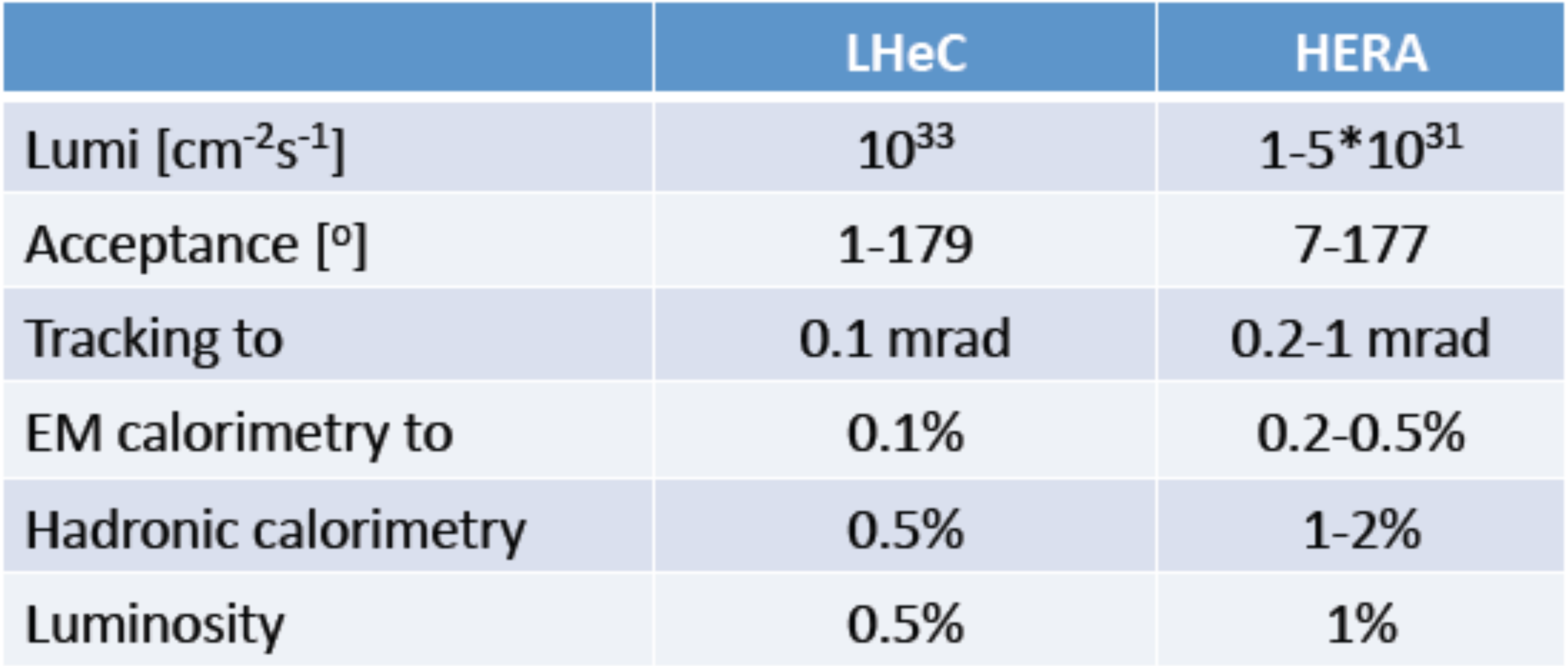


A GEANT4 Simulated High x Event



Assumed Systematic Precision

In the absence of a detailed simulation set-up, simulated `pseudo-data’ produced with reasonable assumptions on systematics (typically 2x better than H1 and ZEUS at HERA).

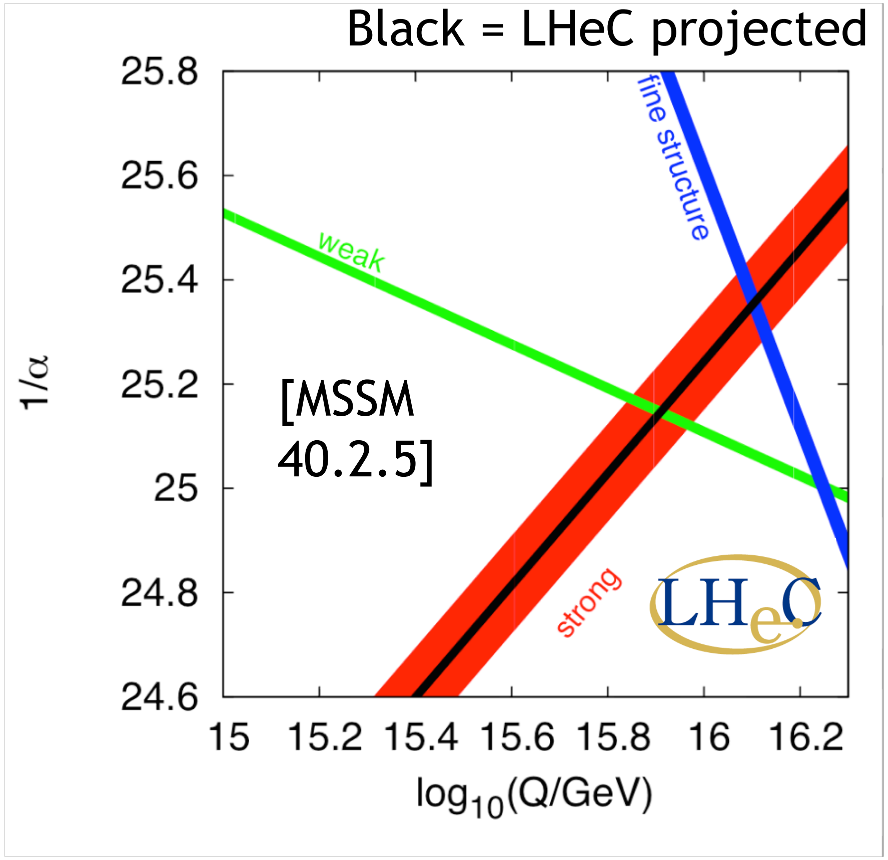


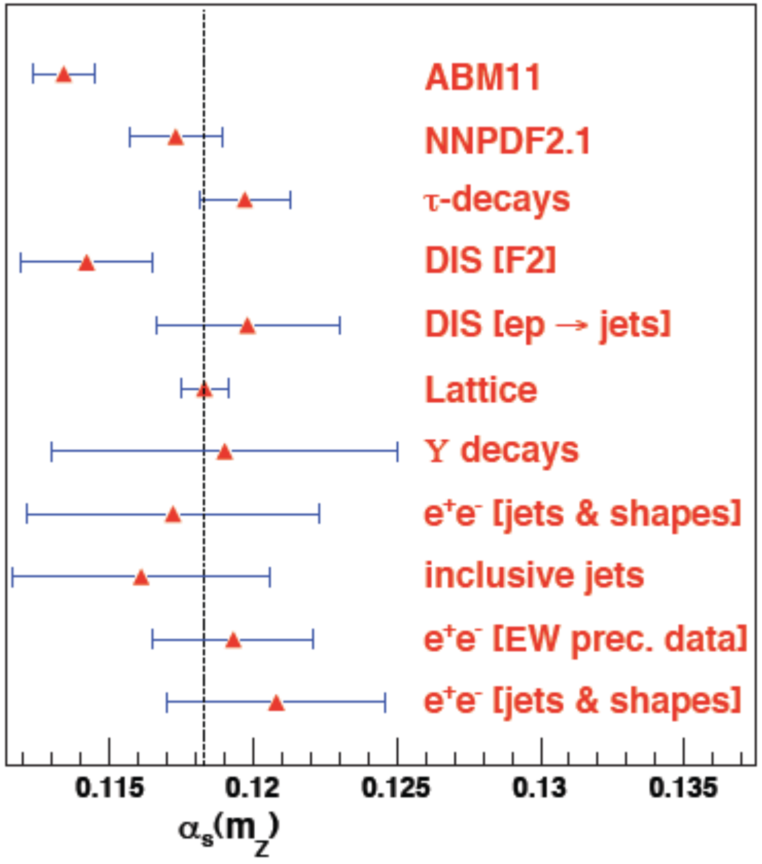
	LHeC	HERA
Lumi [cm^{-2}s^{-1}]	10^{33}	$1\text{-}5 * 10^{31}$
Acceptance [°]	1-179	7-177
Tracking to	0.1 mrad	0.2-1 mrad
EM calorimetry to	0.1%	0.2-0.5%
Hadronic calorimetry	0.5%	1-2%
Luminosity	0.5%	1%

Measuring α_s

- Least constrained fundamental coupling by far (known to ~1%)
- Do coupling constants unify (with a little help from SUSY)?
- (Why) is DIS result historically low?

Red = current world average
Black = LHeC projected



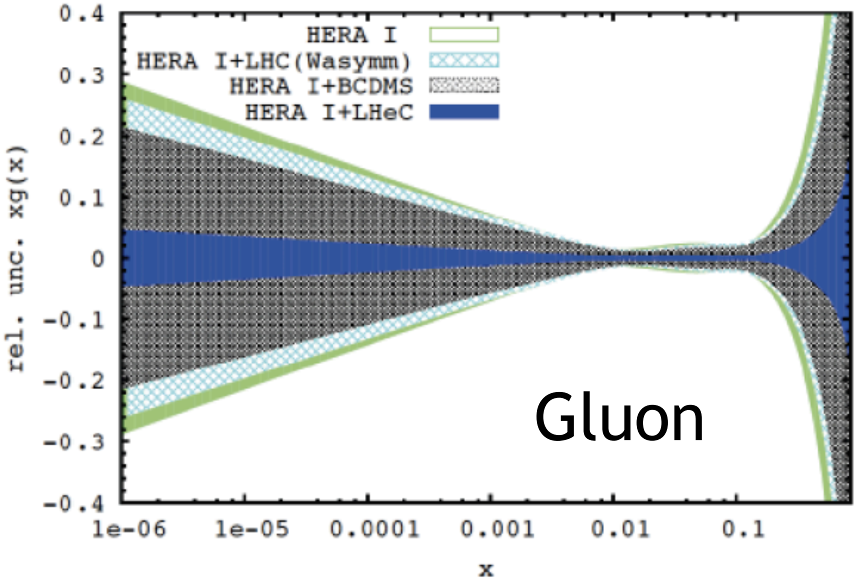


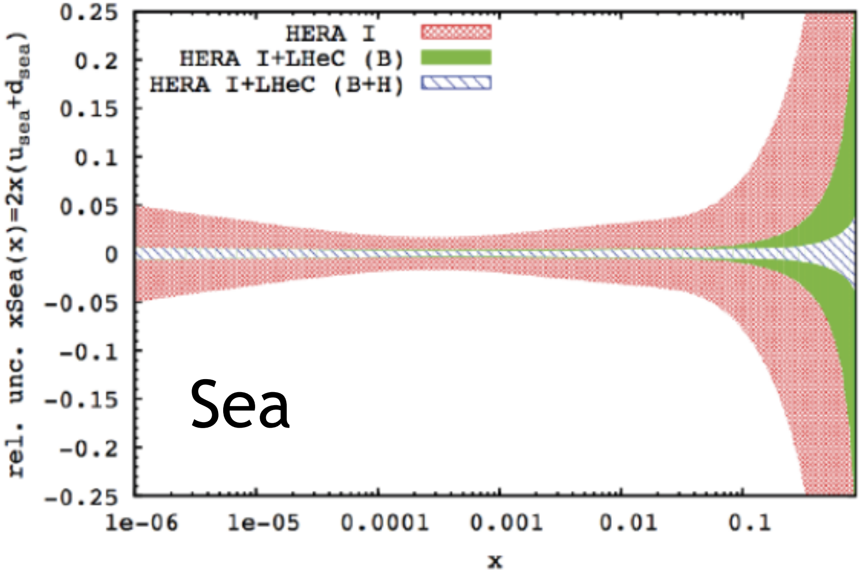
- Simulated LHeC precision from fitting inclusive data

→ per-mille (experimental)
→ also requires improved theory

PDF Constraints at LHeC

Full simulation of inclusive NC and CC DIS data, including systematics → NLO DGLAP fit using HERA technology…

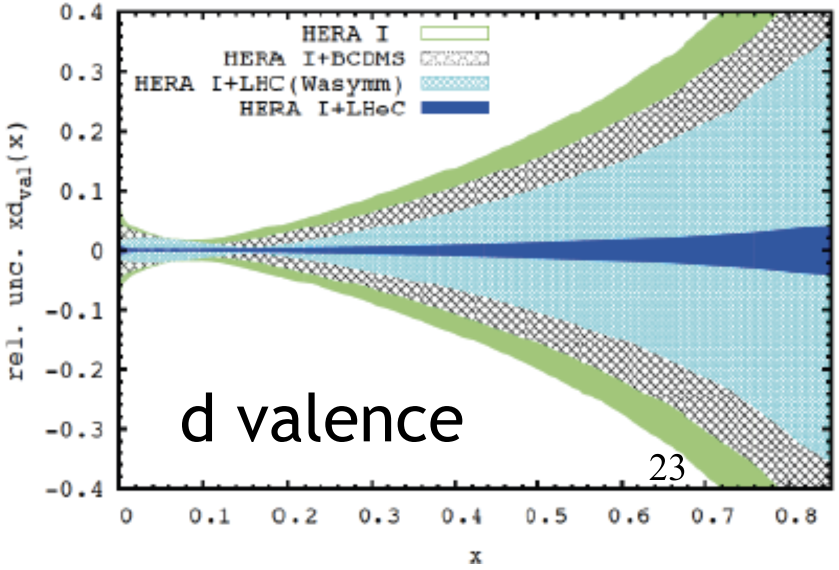




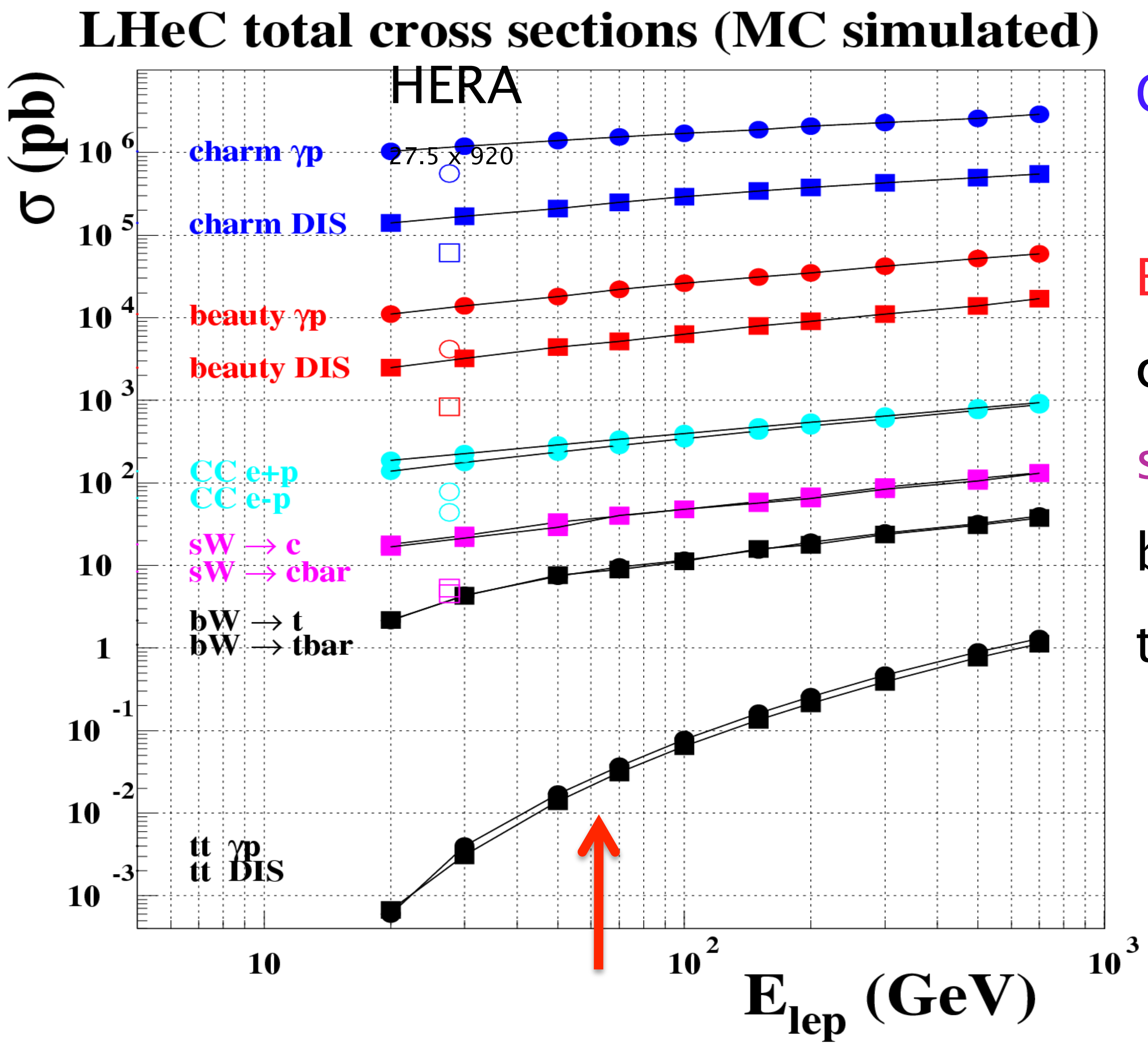
… impact at low x (kinematic range) and high x (luminosity)

… precise light quark vector, axial couplings, weak mixing angle

… full flavour decomposition



Cross Sections and Rates for Heavy Flavours



Charm $[10^{10}$ / 10 $fb^{-1}]$

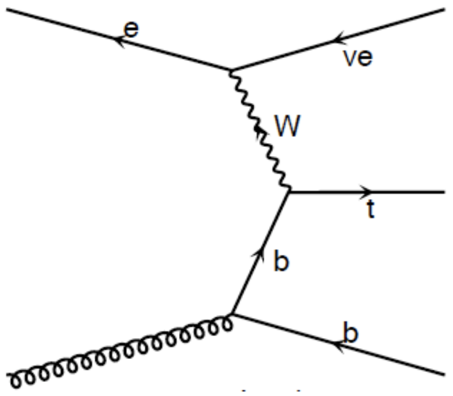
Beauty $[10^8$ / 10 $fb^{-1}]$

cc

sW → c $[4.10^5$ / 10 $fb^{-1}]$

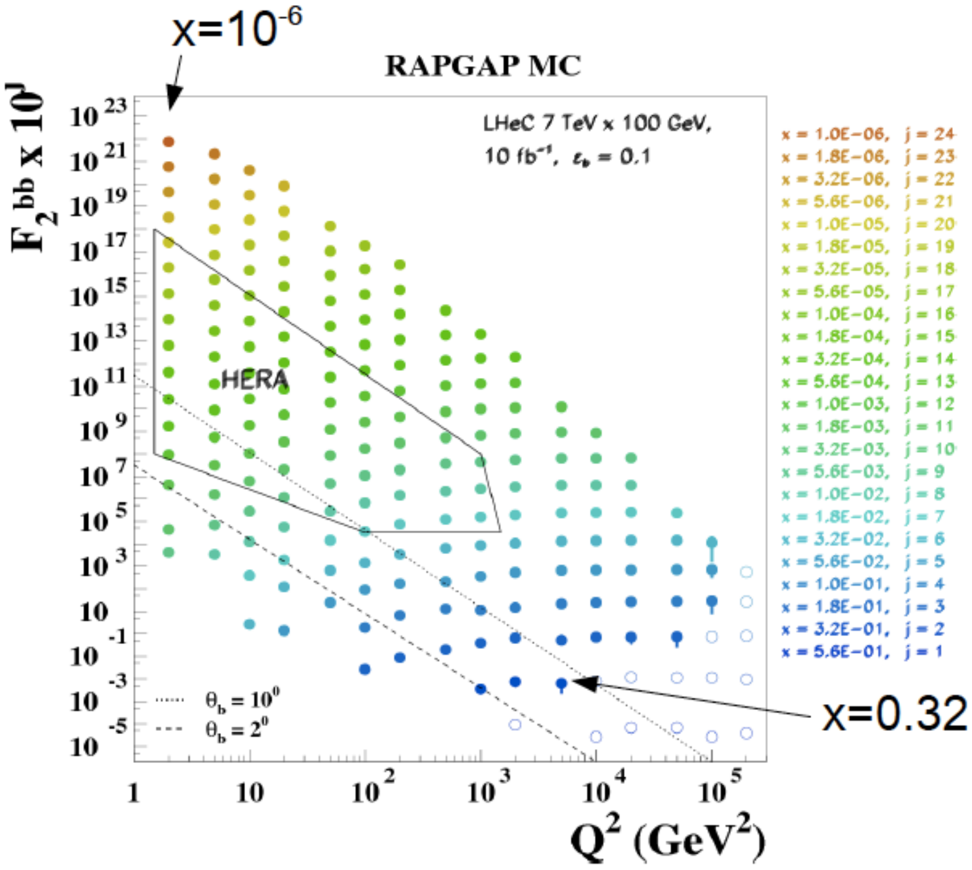
bW → t $[10^5$ / 10 $fb^{-1}]$

ttbar $[10^3$ / 10 $fb^{-1}]$



c.f. luminosity of ~10 fb^{-1} per year …

Flavour Decomposition

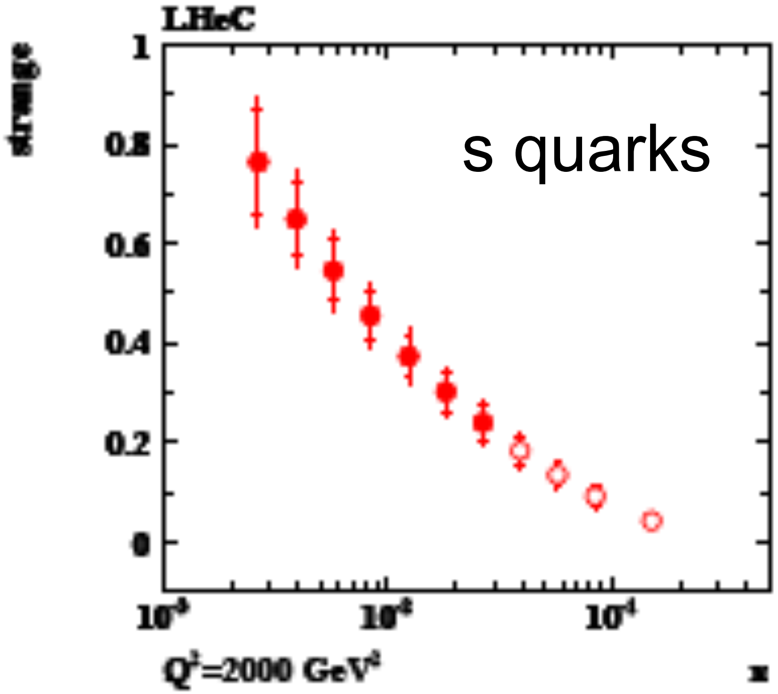


Precision c, b measurements (modern Si trackers, beam spot 15 * 35 μm^2 , increased HF rates at higher scales).

Systematics at 10% level

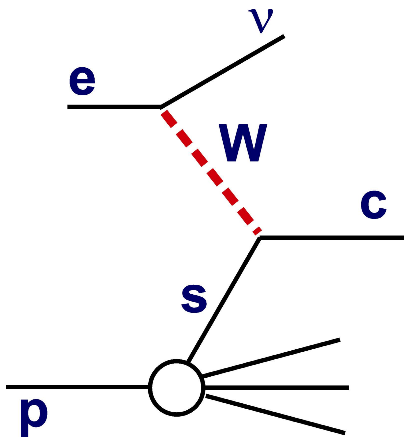
→beauty is a low x observable!

→s, sbar from charged current



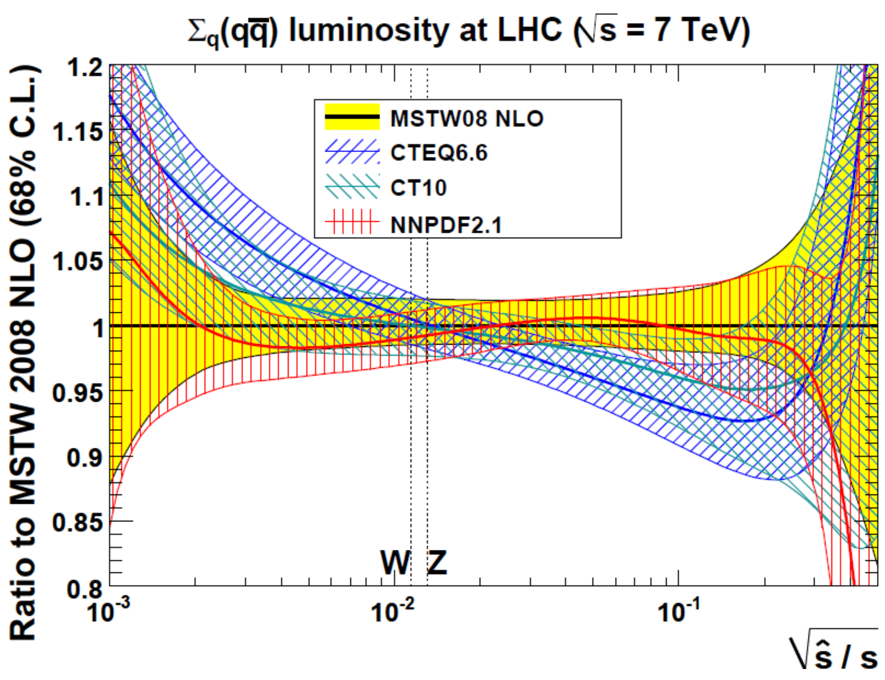
● LHeC 10^o acceptance

○ LHEC 1^o acceptance



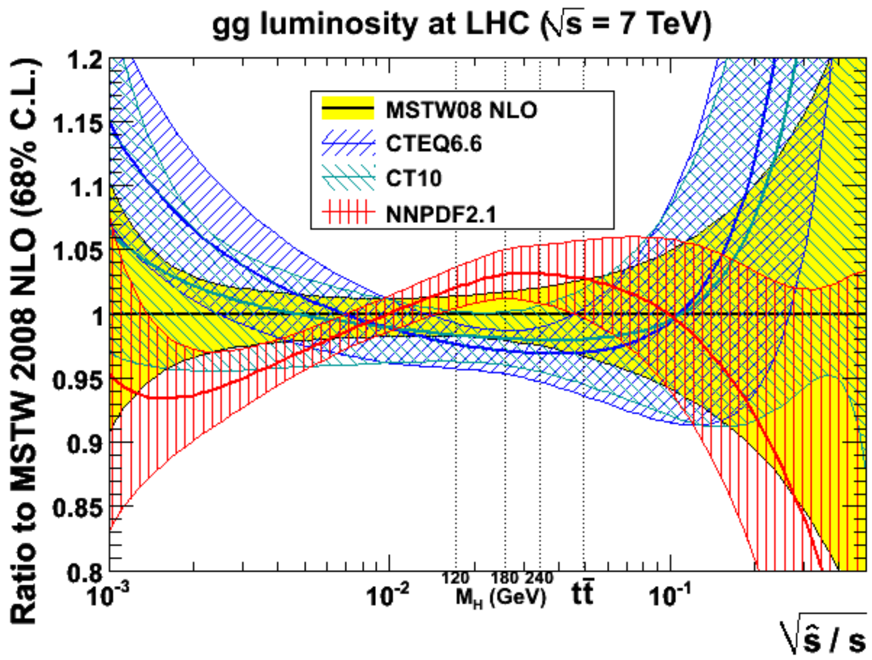
(Assumes 1 fb^{-1} and
- 50% beauty, 10% charm efficiency
- 1% uds → c mistag probability.
- 10% c → b mistag)

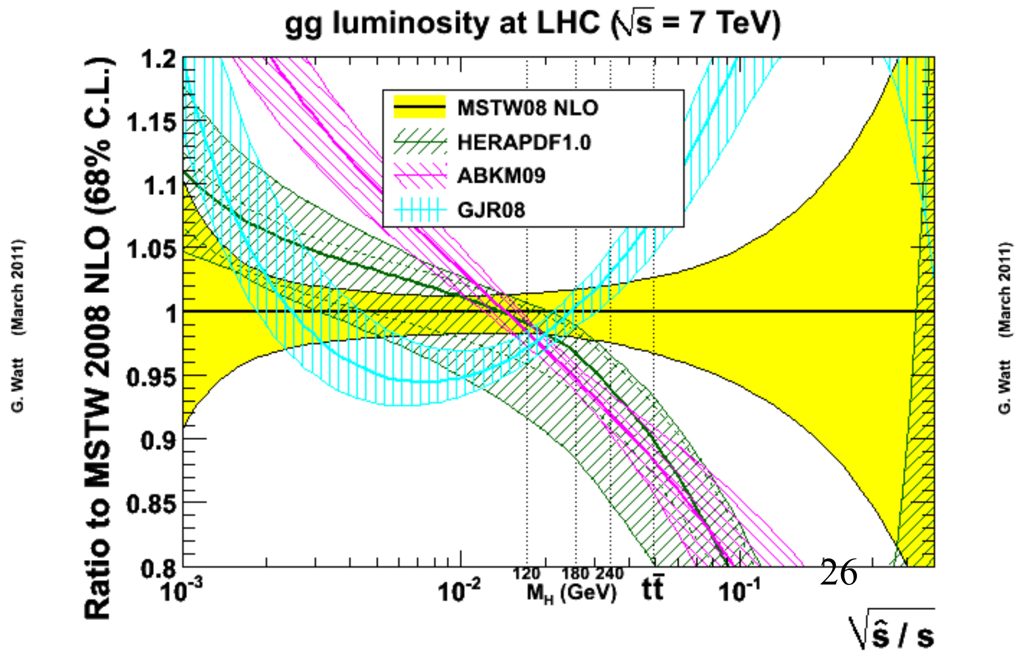
PDFs and LHC



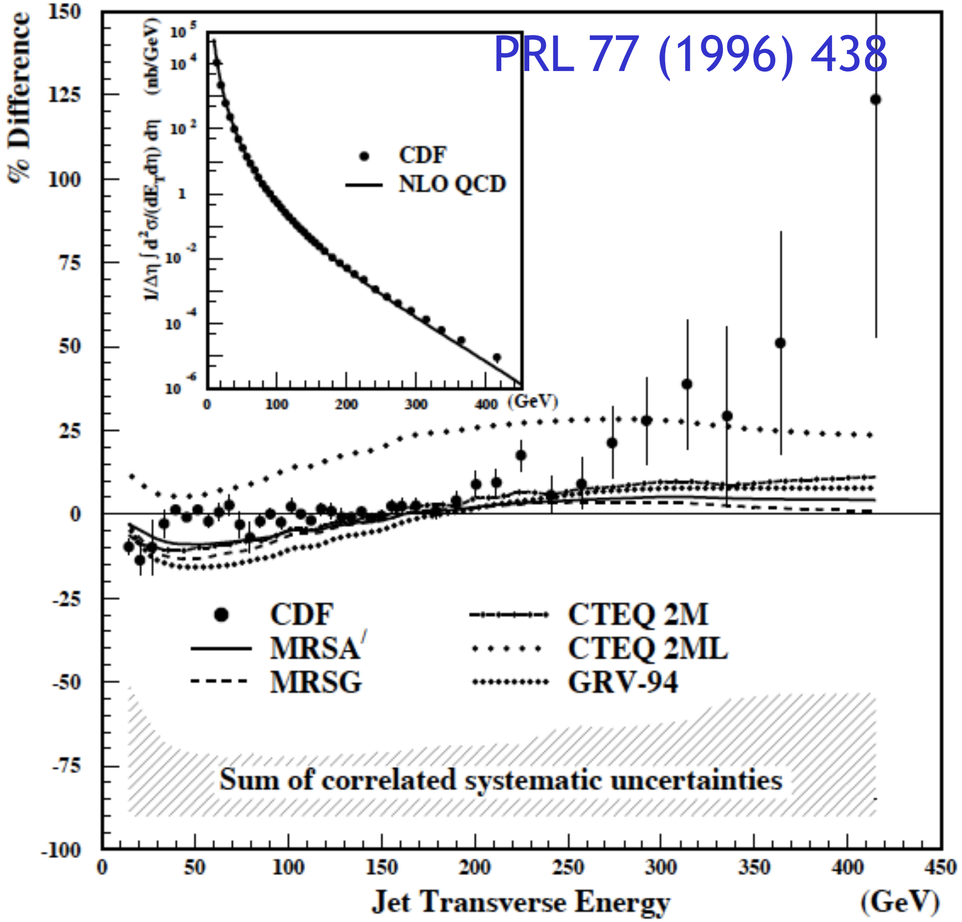
Current uncertainties due to PDFs for particles on LHC rapidity plateau (NLO):

- Most precise for quark initiated processes around EW scale
- Gluon initiated processes less well known
- All uncertainties explode for largest masses





Do we need to Care?



PRL 77 (1996) 438

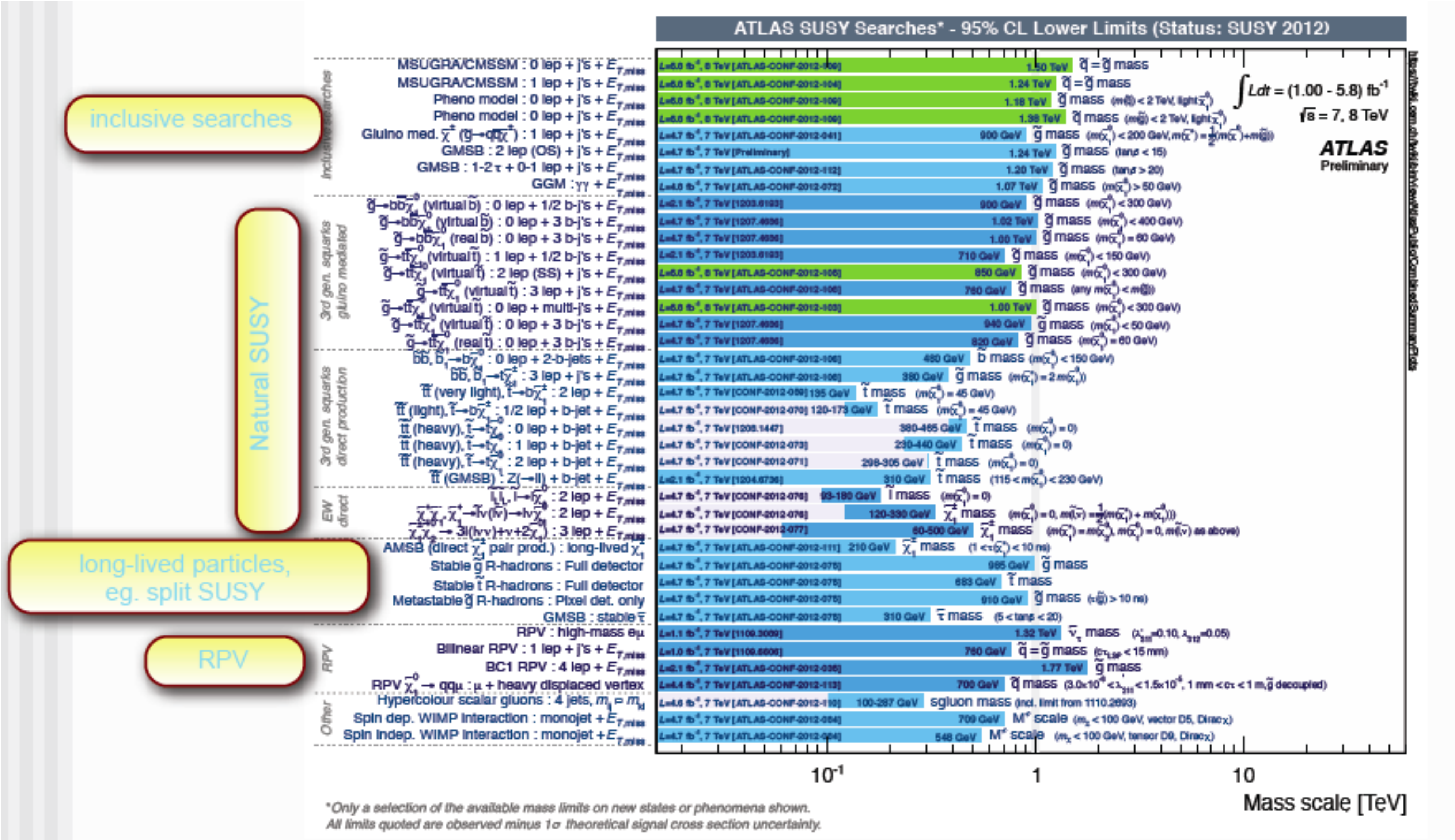
Ancient history (HERA, Tevatron)

- Apparent excess in large E_T jets at Tevatron turned out to be explained by too low high x gluon density in PDF sets

- Confirmation of (non-resonant) new physics near LHC kinematic limit relies on breakdown of factorisation between ep and pp

Searches near LHC kinematic boundary may ultimately be limited by knowledge of PDFs (especially gluon as x → 1)

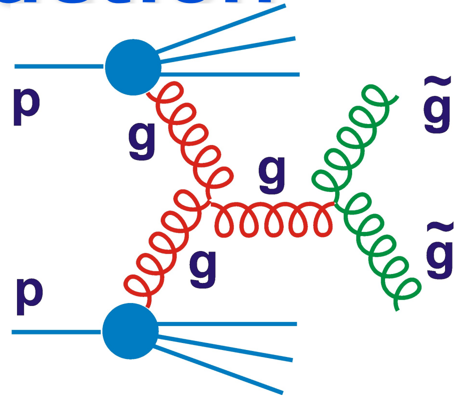
Current Status of LHC SUSY Searches



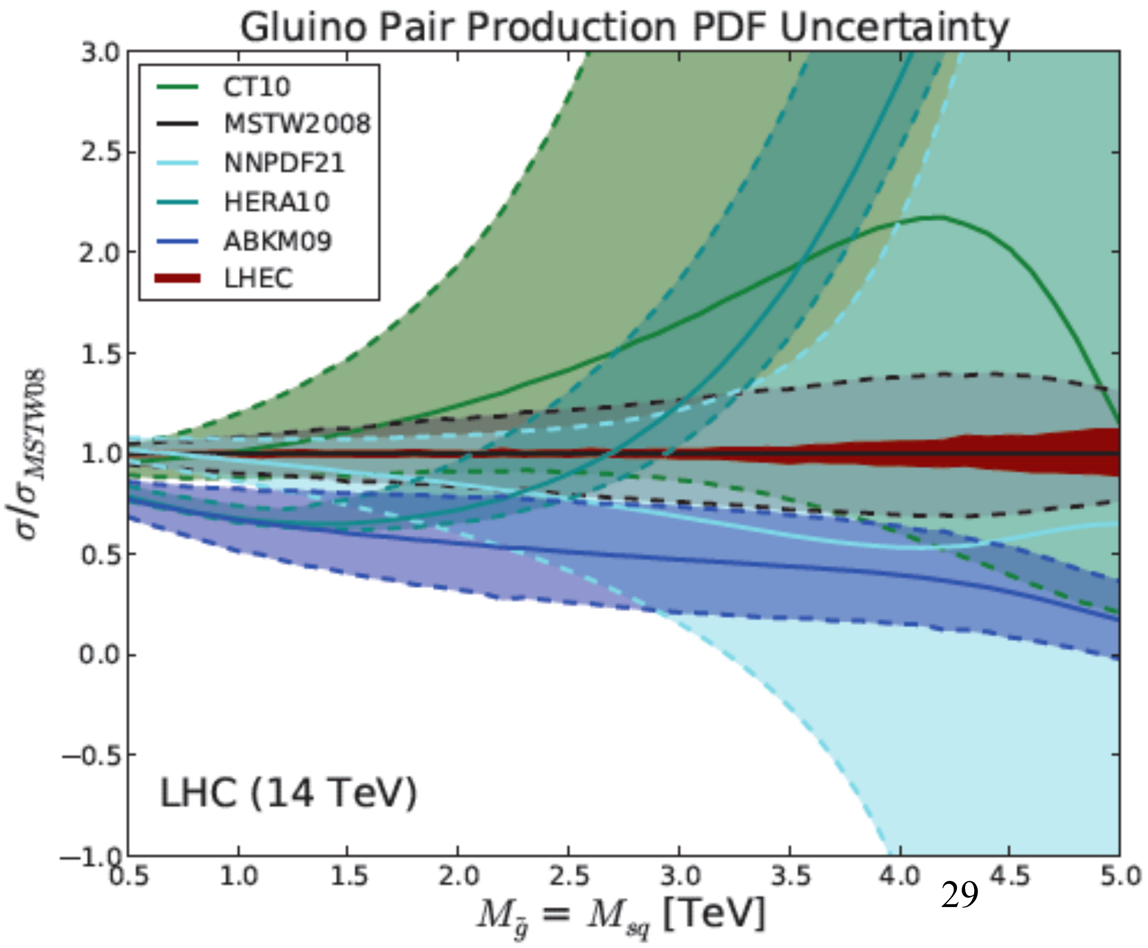
*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Executive summary: nothing on scale of 1 TeV … need to push sensitivity to higher masses (also non-SUSY searches)

e.g. High Mass Gluino Production



- Signature is excess @ large invariant mass
- Expected SM background (e.g. gg → gg) poorly known for s-hat > 1 TeV.



- Both signal & background uncertainties driven by error on gluon density … Essentially unknown for masses much beyond 2 TeV

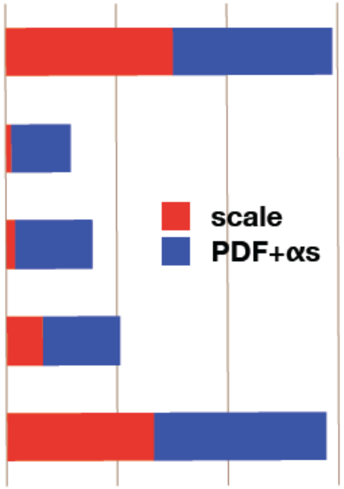
- Similar conclusions for other non-resonant LHC signals involving high x partons (e.g. contact interactions signal in Drell-Yan)

PDF Uncertainties for Higgs Physics

Theory Cross Section Uncertainties

(125 GeV Higgs
J Campbell, ICHEP'12)

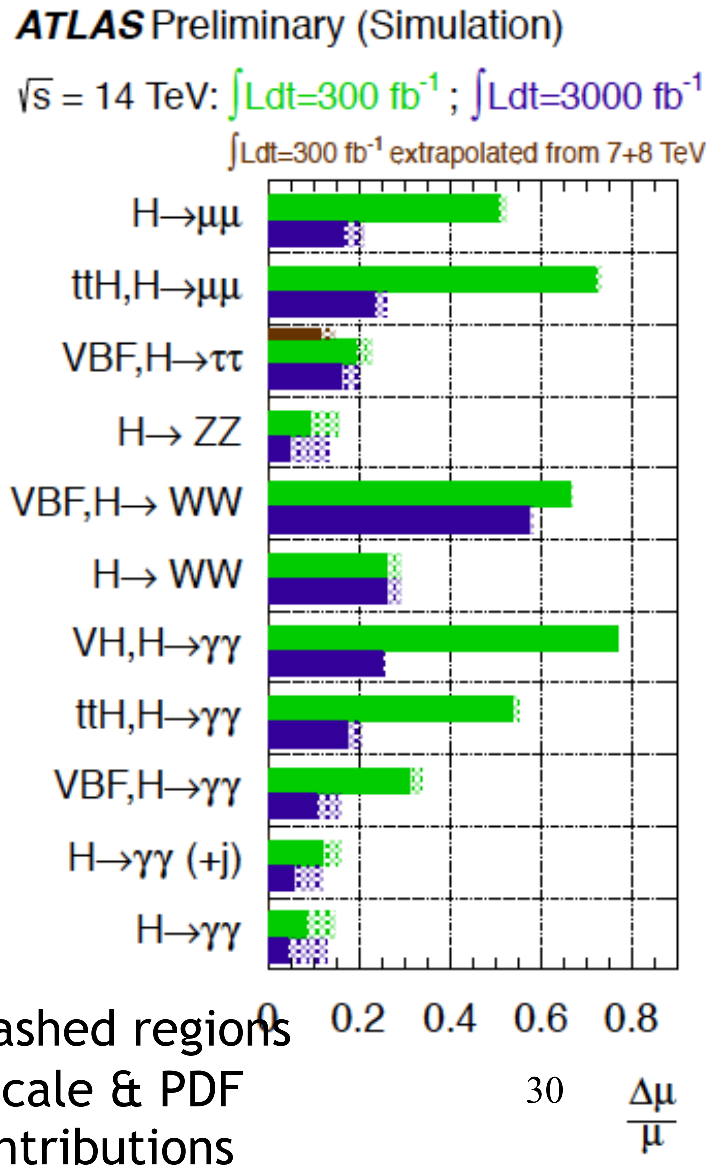
		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
NNLO QCD +NLO EW	VBF	1.56 pb	2.9%
	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%



Similarly fermionic modes (bbbar, ccbar)

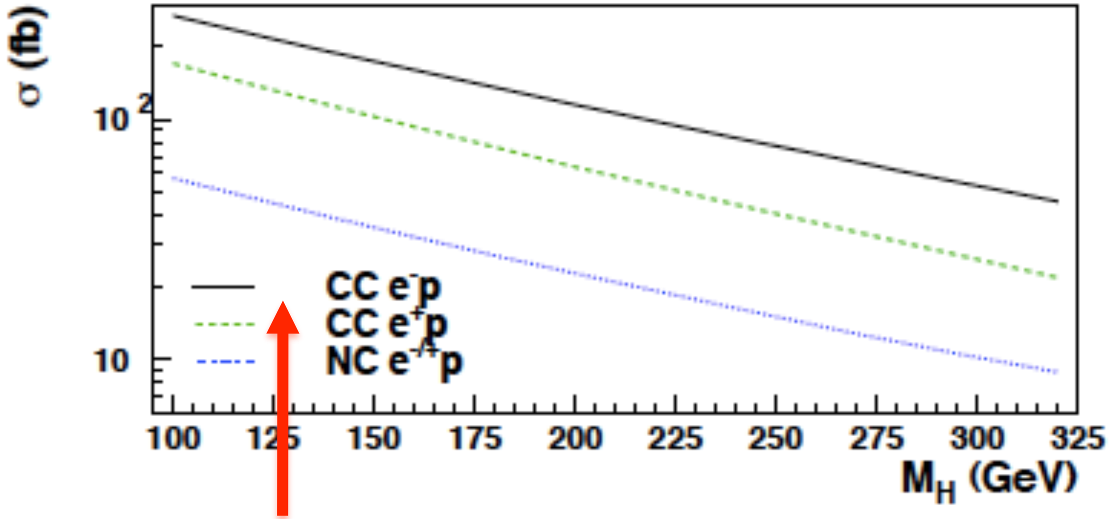
... tests of Standard Model in Higgs sector may become limited by knowledge of PDFs in HL-LHC era

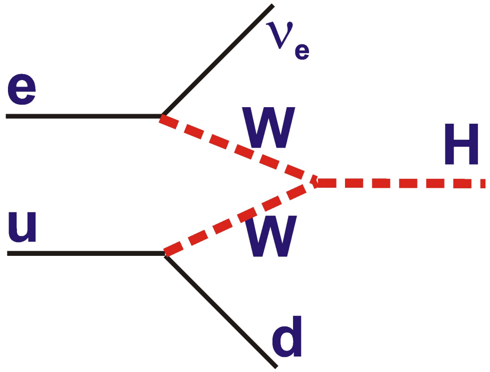
Projected Experimental Uncertainties



[Dashed regions = scale & PDF contributions]

ep Higgs Production at LHeC





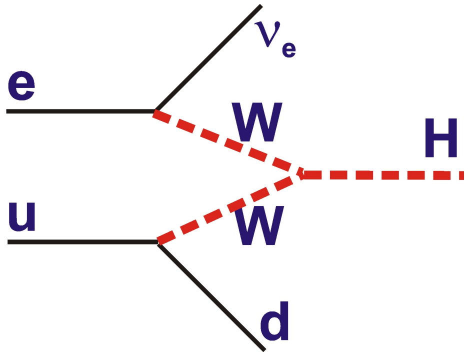
Clean signature:
H (→bbbar) + j + p_t^{miss}

Dominant charged current process probes product of WW → H and H → bbbar couplings

Clean separation from (smaller cross section) neutral current process ZZ → H

Sensitive to anomalous couplings and (via azimuthal degree of freedom) anomalous CP structure

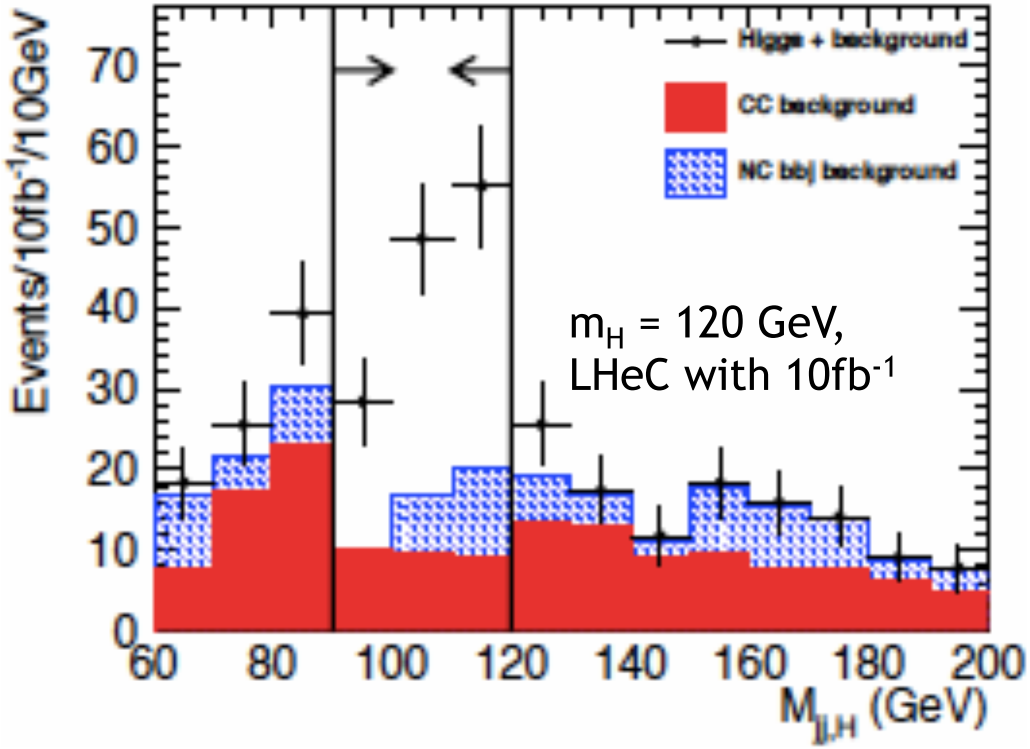
A First Higgs Study



2 b-tags in a simulated `generic LHC detector'

Backgrounds (b & light jets in NC, CC, Z→ bbbar single top) suppressed with cuts on jet multiplicity, b-tags, event kinematics, missing p_t

	E_e = 150 GeV ($10\ fb^{-1}$)	E_e = 60 GeV ($100\ fb^{-1}$)
H → bb signal	84.6	248
S/N	1.79	1.05
S/√N	12.3	16.1



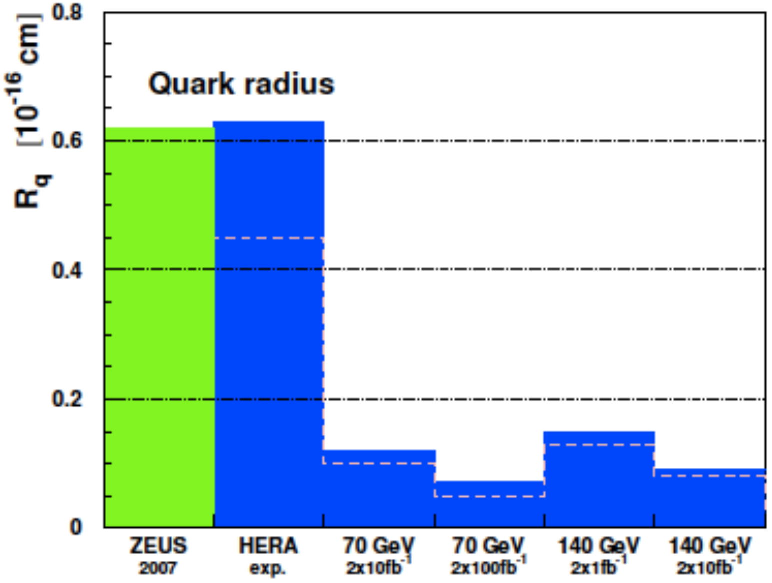
m_H = 120 GeV,
LHeC with $10fb^{-1}$

90% lepton polarisation enhances signal by factor 1.9

→ ~500 events … H→bbbar coupling to a few %.

Direct Sensitivity to New Physics

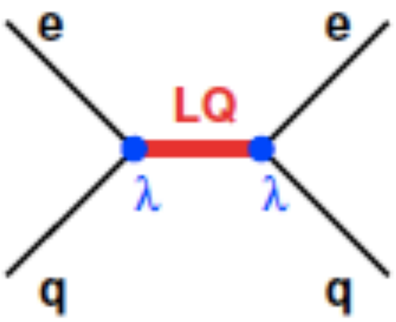
- The (pp) LHC has much better discovery potential than LHeC (unless E_e increases to ~500 GeV and Lumi to 10^{34} cm^{-2} s^{-1})

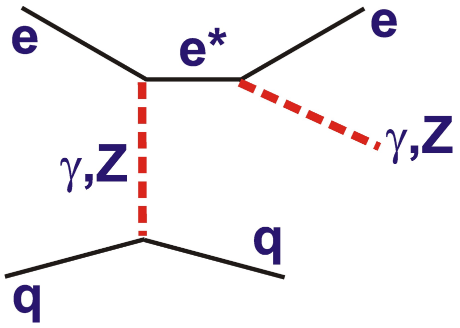


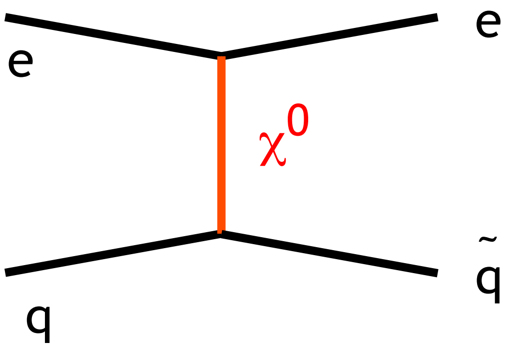
e.g. Expected quark compositeness limits below 10^{-19} m at LHeC

… big improvement on HERA, but already beaten by LHC

- LHeC *is* competitive with LHC in cases where initial state lepton is an advantage and offers cleaner final states





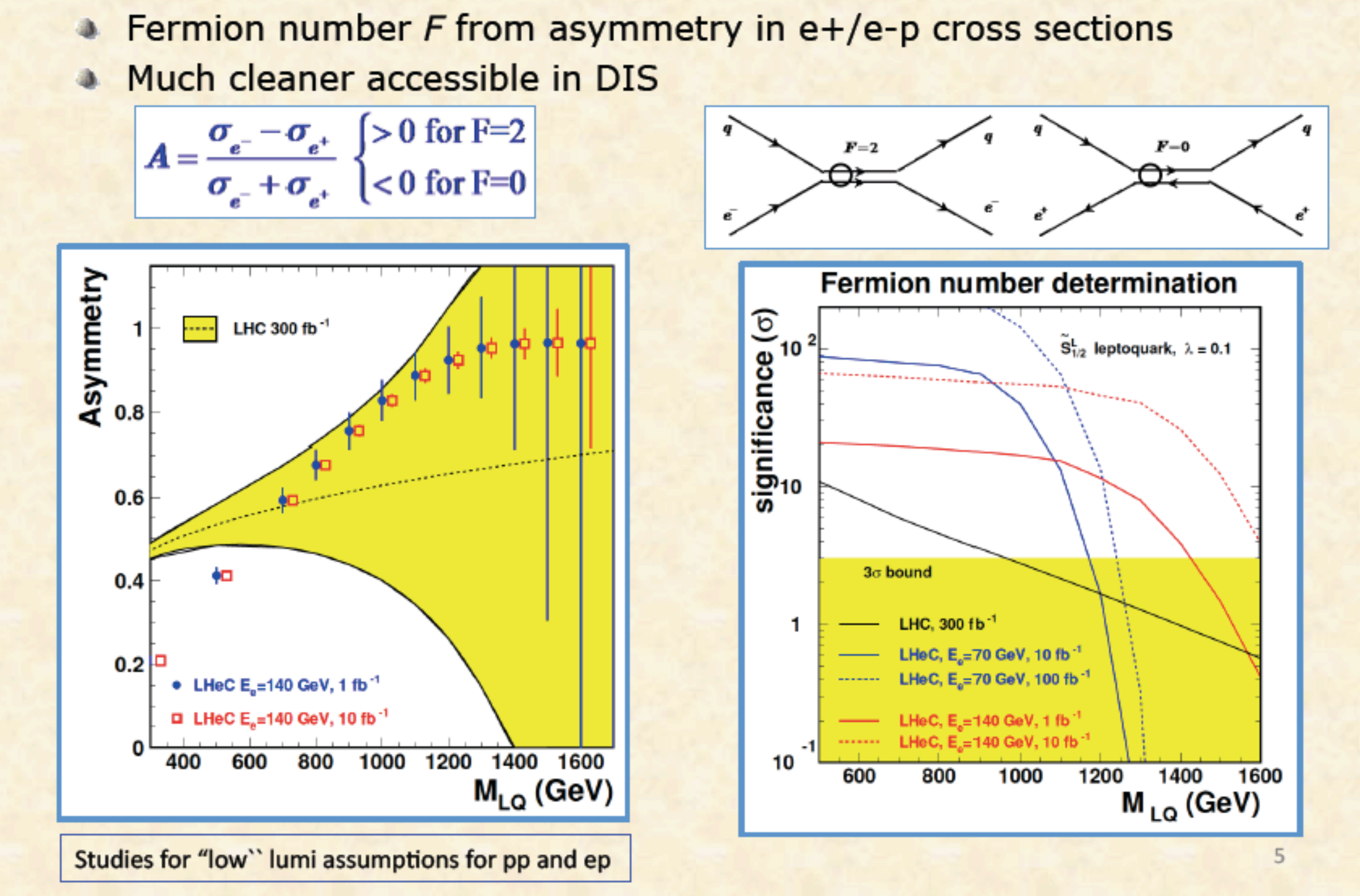


Determining Leptoquark Quantum Numbers

Mass range of LQ sensitivity to ~ 2 TeV … similar to LHC

Single production gives access to LQ quantum numbers:

- fermion number (below)   - spin (decay angular distributions)
- chiral couplings (beam lepton polarisation asymmetry)

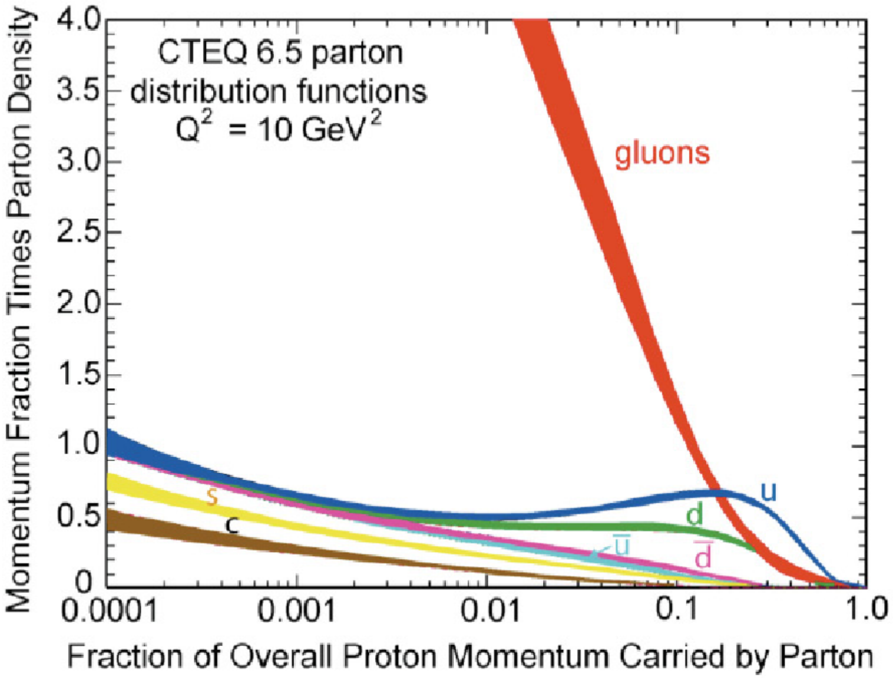


- Fermion number *F* from asymmetry in e+/e-p cross sections
- Much cleaner accessible in DIS

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

Studies for "low`` lumi assumptions for pp and ep

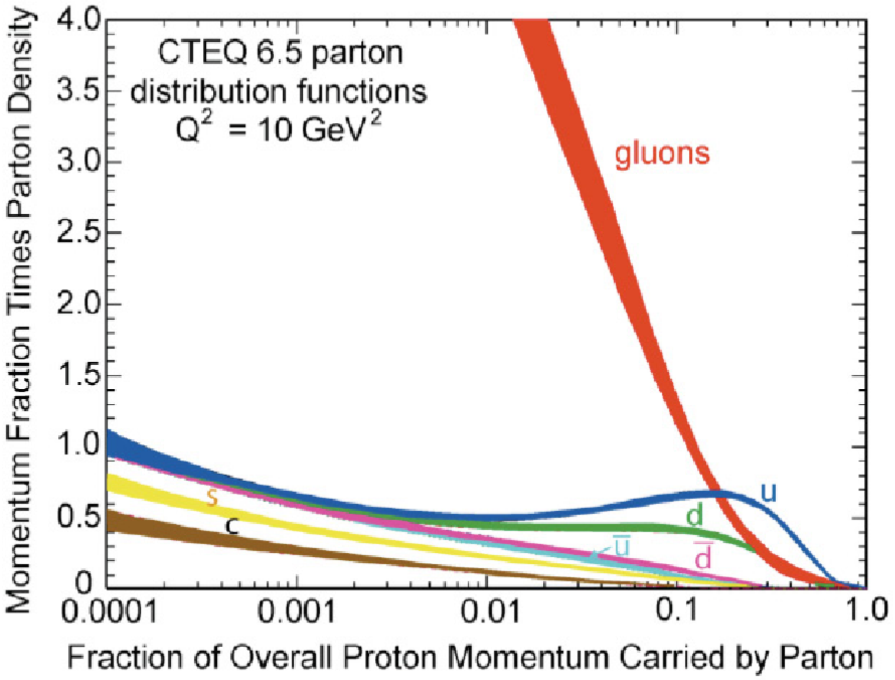
Low-x Physics and Parton Saturation

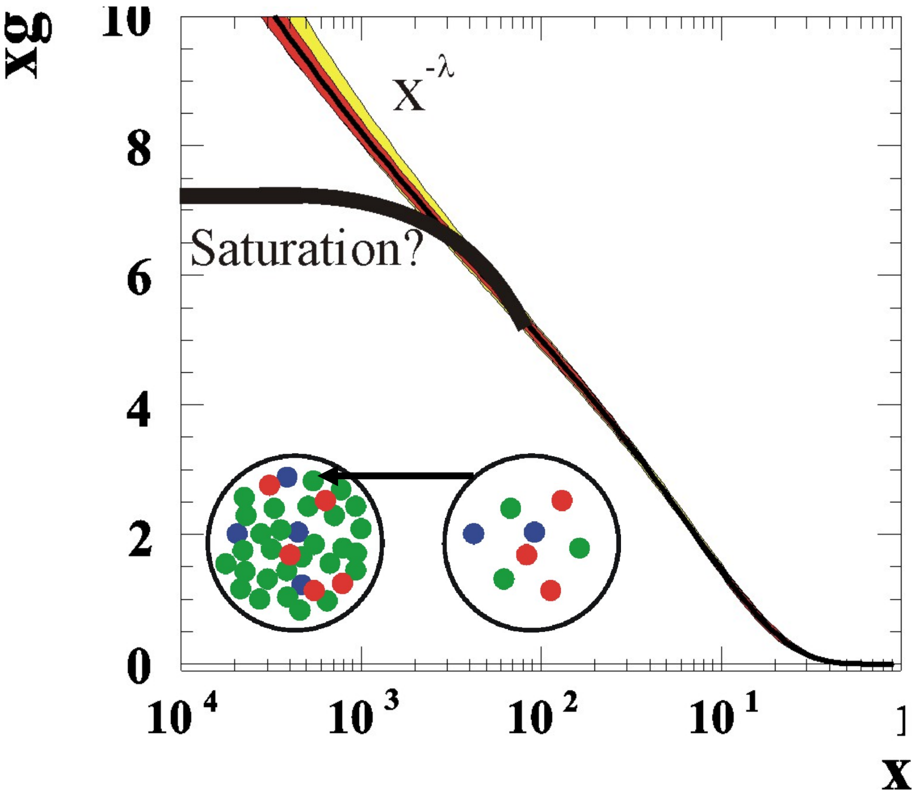


A fundamental QCD problem is looming … rise of low x parton densities cannot continue

… High energy unitarity issues reminiscent of longitudinal WW scattering in electroweak physics:

Low-x Physics and Parton Saturation



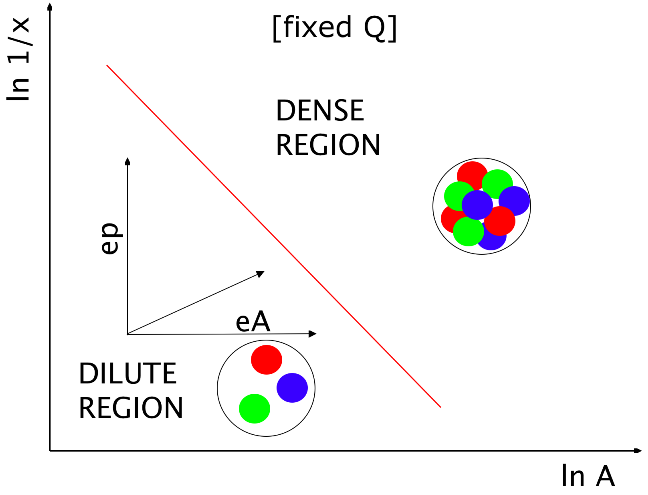


- Somewhere & somehow, the low x growth of cross sections must be tamed to satisfy unitarity … non-linear effects
- Parton level language → **recombination gg → g?**

… new high density, small coupling parton regime of non-linear parton evolution dynamics (e.g. Colour Glass Condensate)? …
… gluon dynamics → confinement and hadronic mass generation

Strategy for making the target blacker

LHeC delivers a 2-pronged approach:



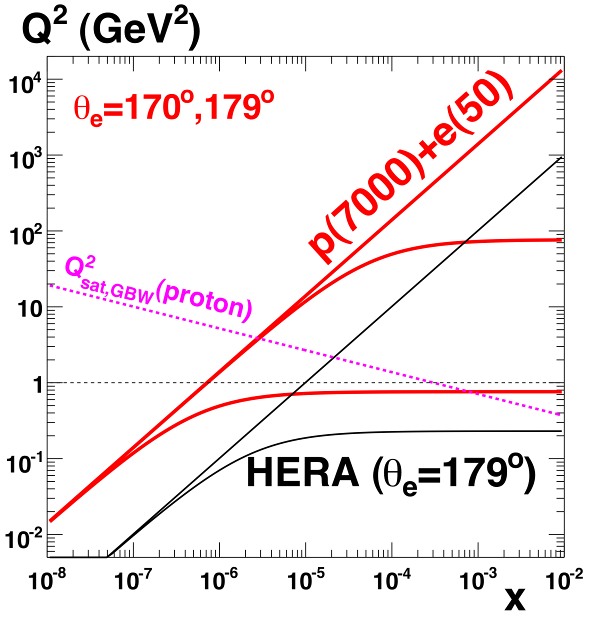
Enhance target `blackness' by:

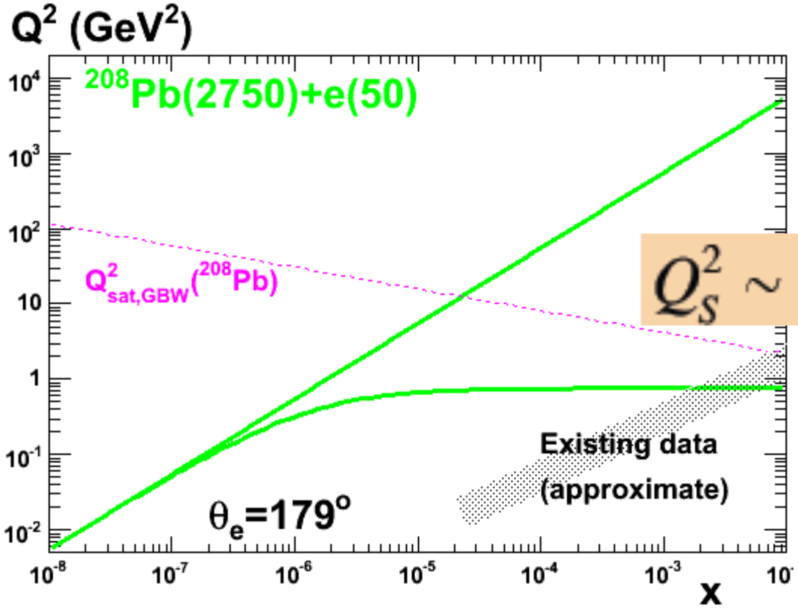
1) Probing lower x at fixed Q^2 in ep

[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]



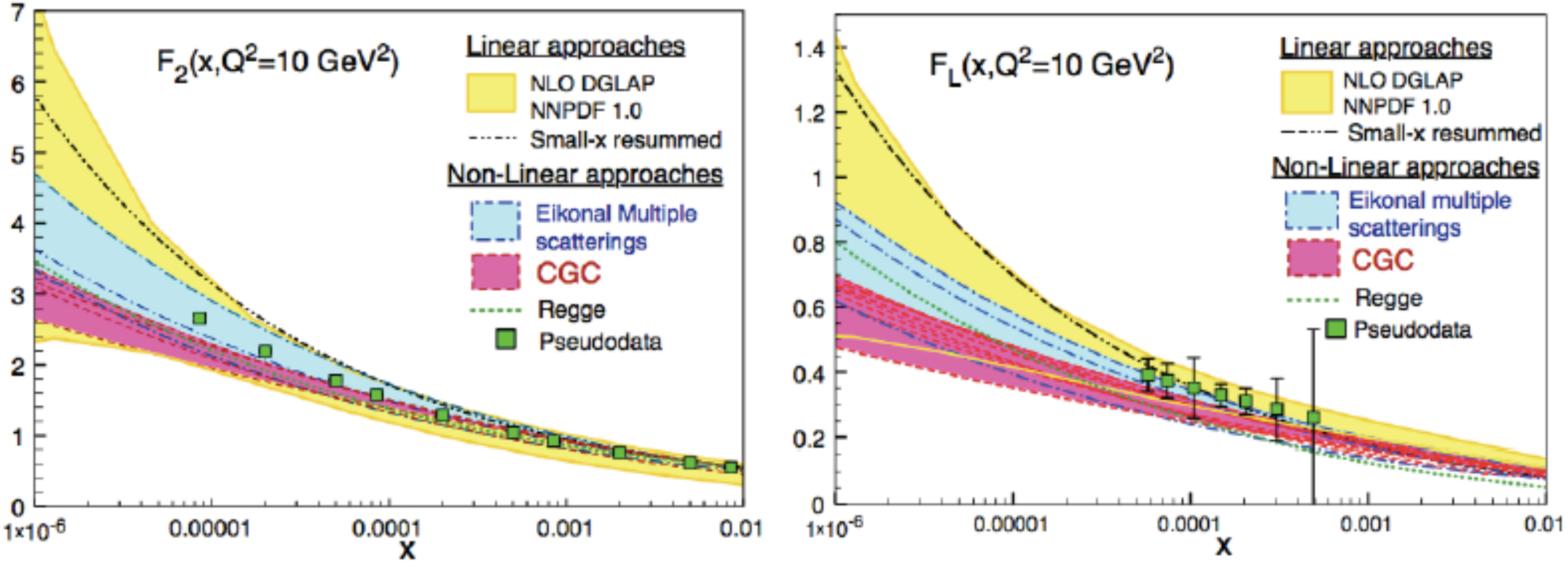


$$Q_S^2 \sim xg(x)\alpha_S \sim cx^{-\lambda}A^{1/3}$$

Establishing and Characterising Saturation

With 1 fb^{-1} (1 month at 10^{33} cm^{-2} s^{-1}), F_2 stat. < 0.1%, syst, 1-3%

F_L measurement to 8% with 1 year of varying E_e or E_p



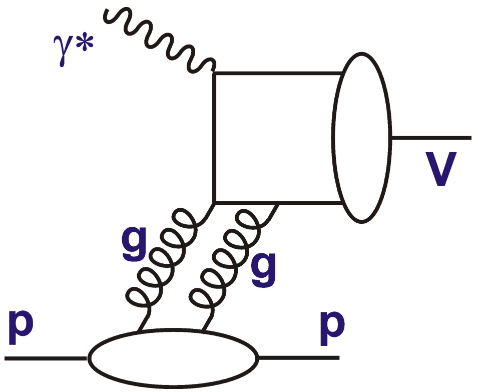
- LHeC can distinguish between different QCD-based models for the onset of non-linear dynamics
- Unambiguous observation of saturation will be based on tension between different observables e.g. F_2 v F_L in ep or F_2 in ep v eA

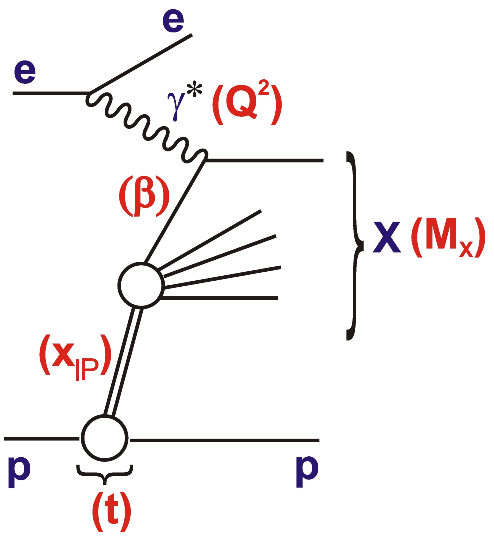
Exclusive / Diffractive Channels and Saturation

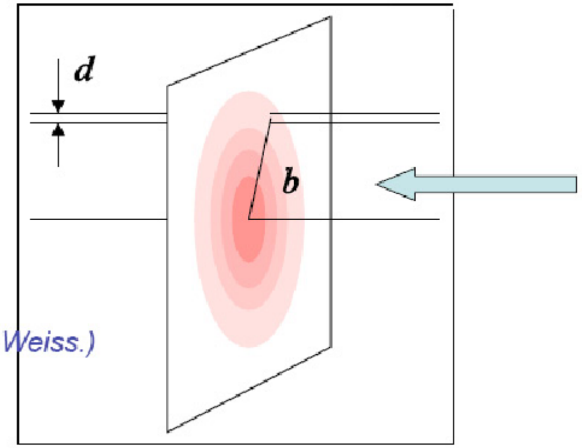
1) [Low-Nussinov] interpretation as 2 gluon exchange enhances sensitivity to low x gluon

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

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





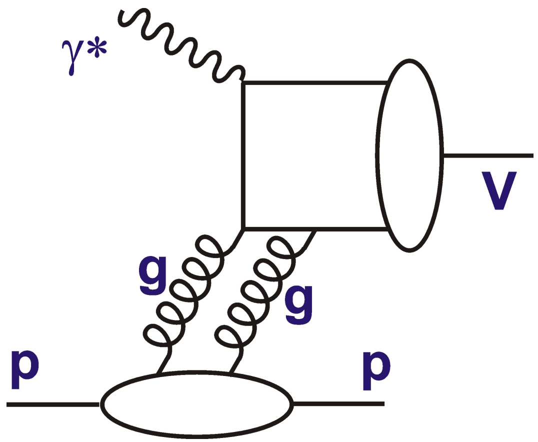


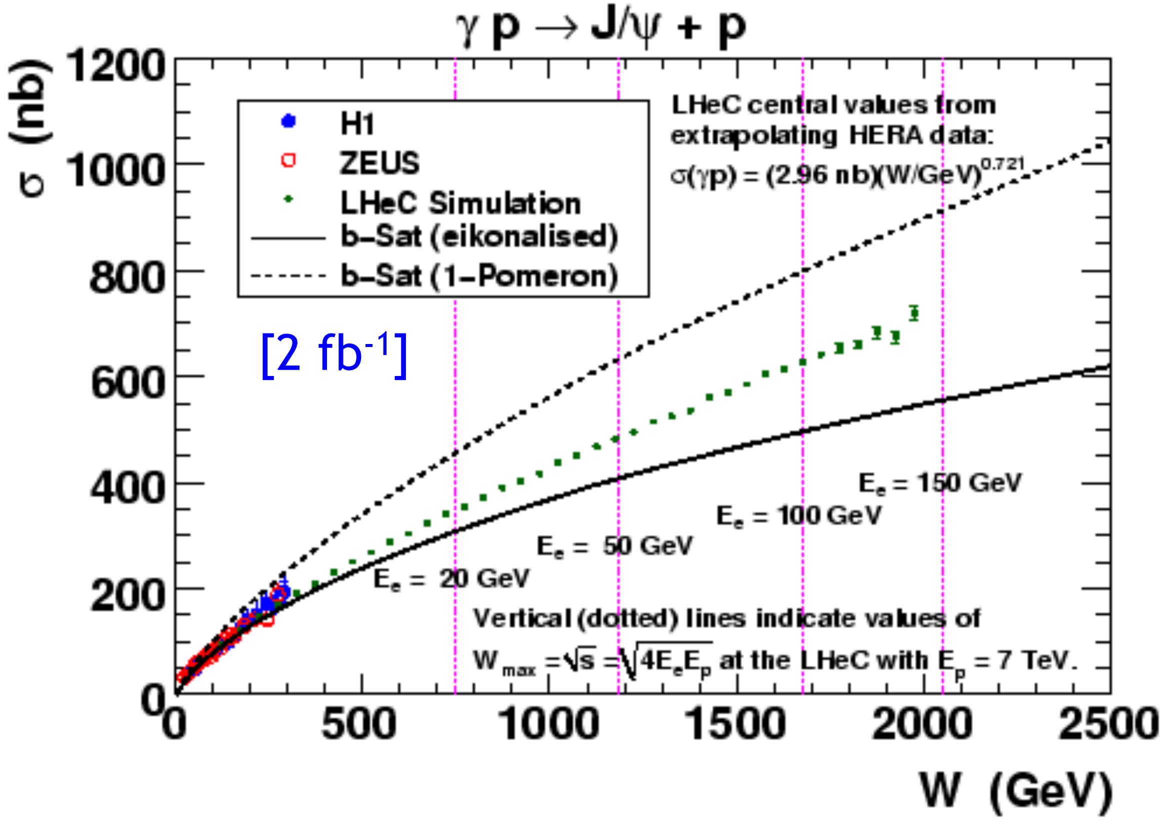
(figure from C. Weiss.)

Central black region growing with decrease of x.

Simulation of J/ψ Photoproduction

e.g. "b-Sat" Dipole model
- "eikonalised": with impact-parameter dependent saturation
- "1 Pomeron": non-saturating

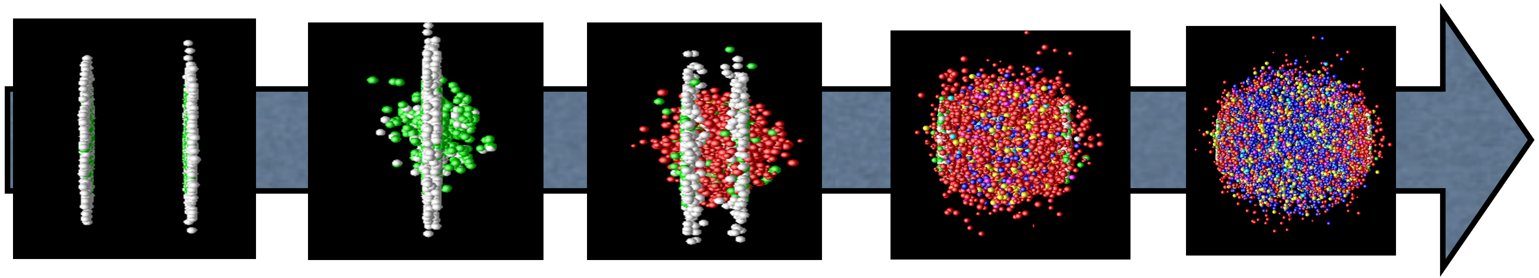




- Significant non-linear effects expected in LHeC kinematic range.
- Data shown are extrapolations of HERA power law fit for E_e = 150 GeV…

→ Sat^n smoking gun?

What is Initial State of LHC AA Collisions?

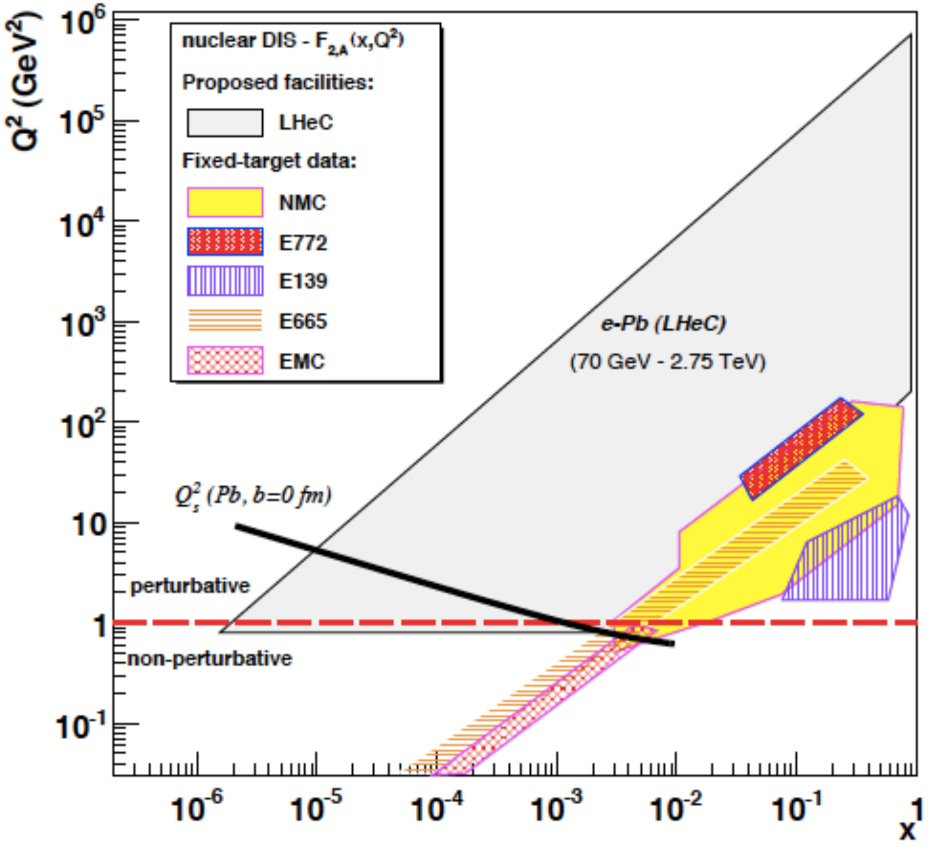


Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

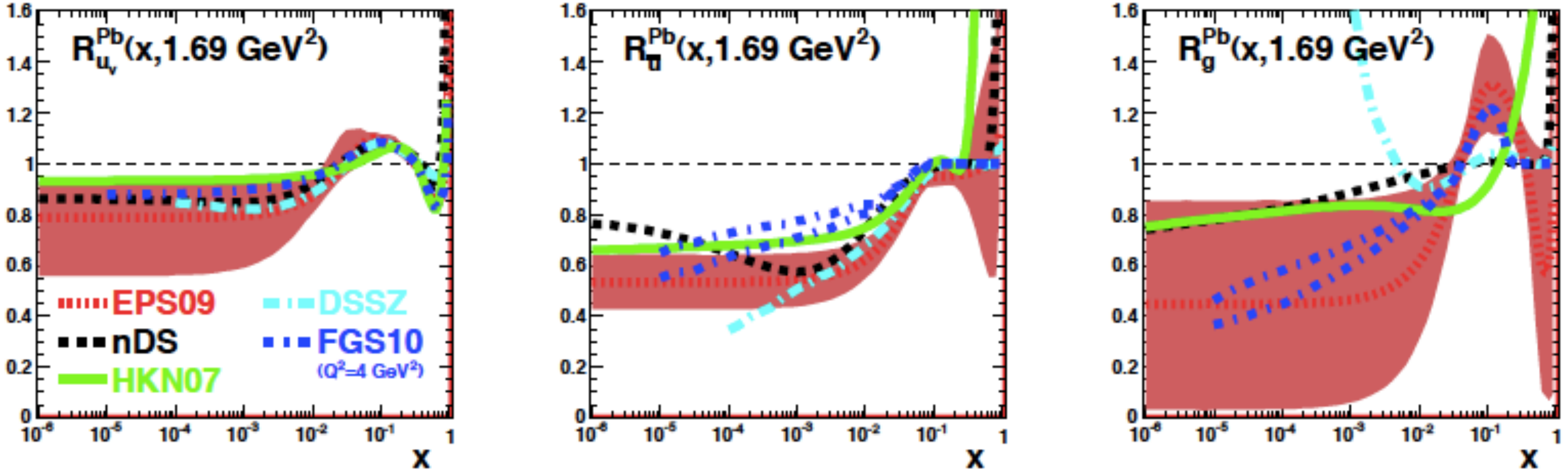
- Very limited x, Q^2 and A range for F_2^A so far (fixed target experiments covered x >~ 10^{-2})

- LHeC extends kinematic range by 3-4 orders of magnitude with very large A

[and eA potentially provides control for AA QGP signatures]



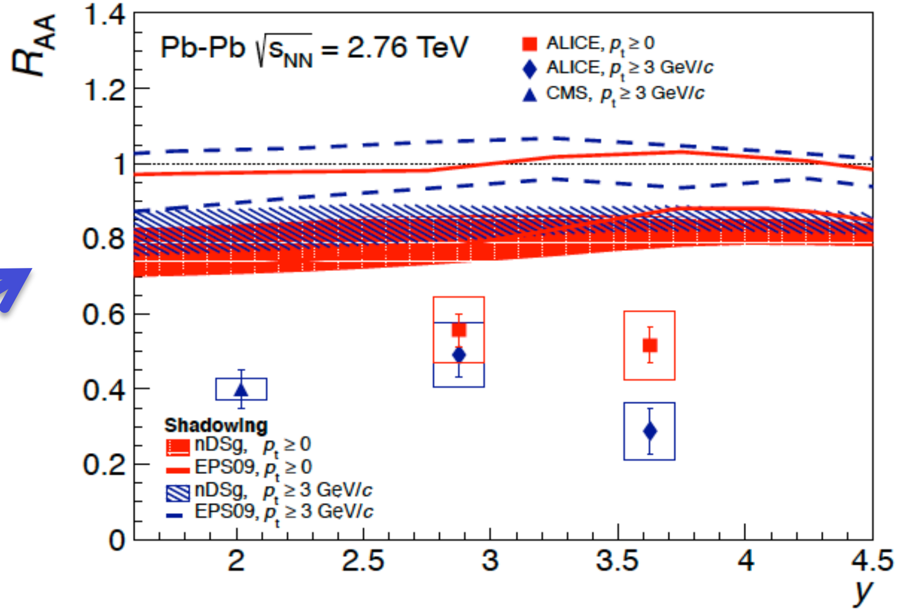
Current Knowledge: Nuclear Parton Densities



Nuclear parton densities don't scale with A (Fermi motion, shadowing corrections …

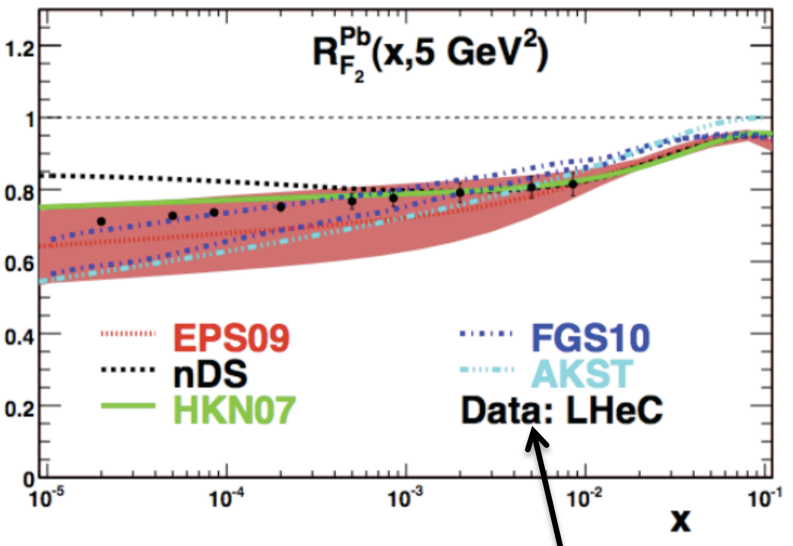
R_i = Nuclear PDF i / (A*proton PDF i)

Early LHC data (e.g. inclusive J/Ψ) suggest low x assumptions inadequate

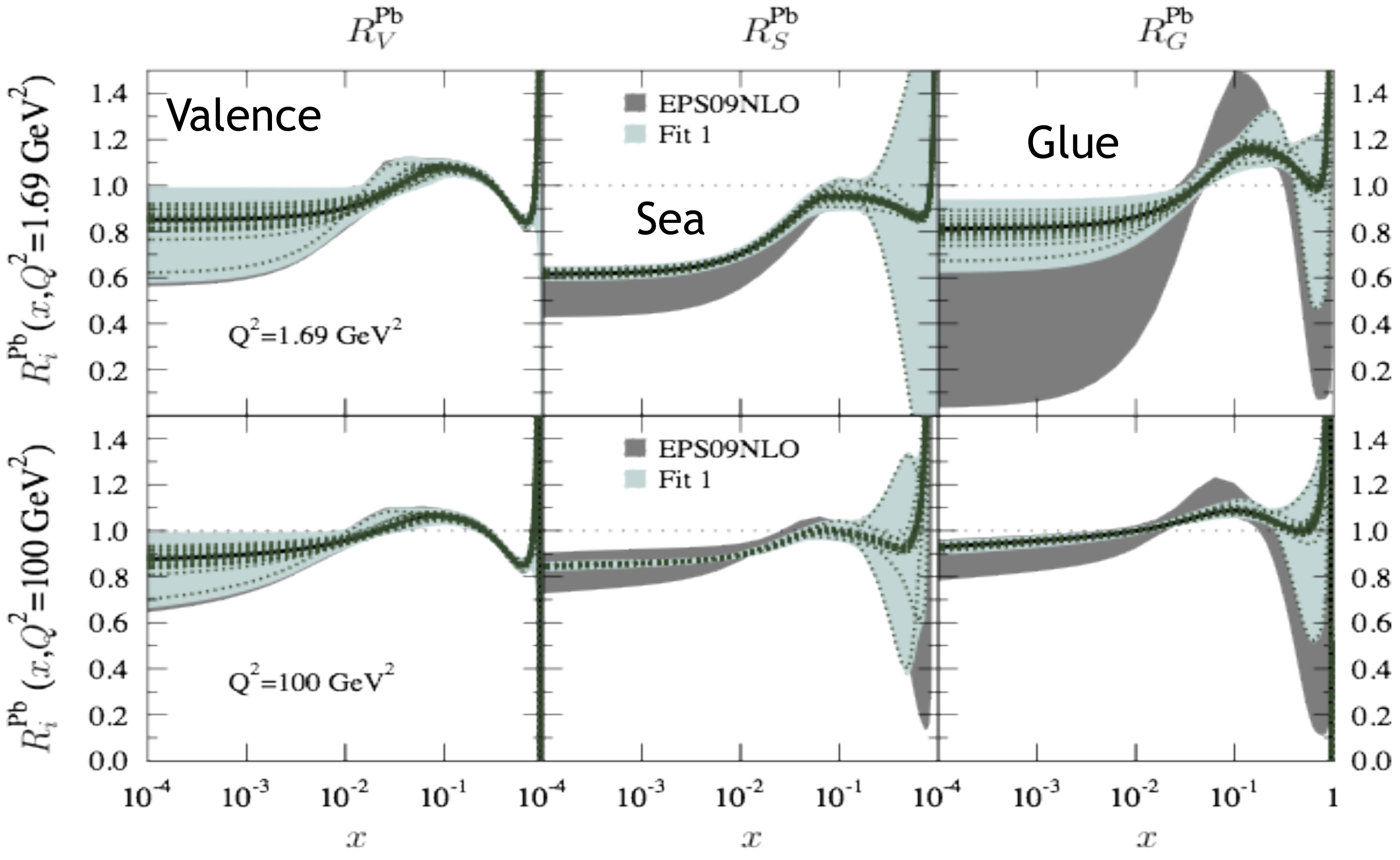


Impact of eA F_2 LHeC data

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

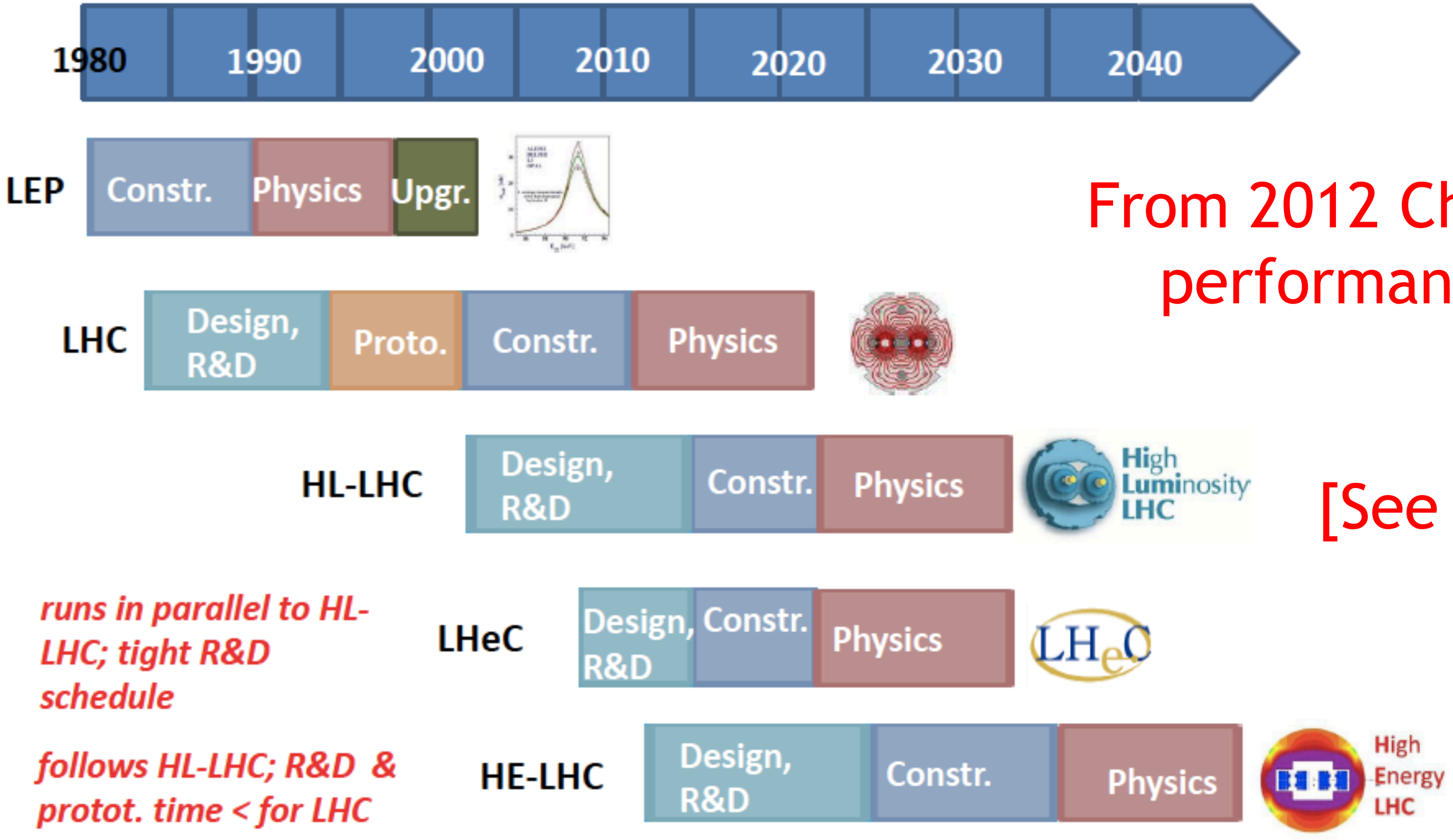


[Example pseudo-data from single Q^2 Value]



[Effects on EPS09 nPDF fit]

How and When might LHeC Fit?



1980 1990 2000 2010 2020 2030 2040

LEP Constr. Physics Upgr.

LHC Design, R&D Proto. Constr. Physics

HL-LHC Design, R&D Constr. Physics

runs in parallel to HL-LHC; tight R&D schedule

LHeC Design, R&D Constr. Physics

follows HL-LHC; R&D & protot. time < for LHC

HE-LHC Design, R&D Constr. Physics

From 2012 Chamonix LHC performance workshop summary

[See also NuPeCC long range plan]

Current mandate from CERN is to aim for TDR by ~ 2015.
… requires detailed further study and prototyping of accelerator components (including CERN ERL LHeC test facility), but also an experimental collaboration to develop the detector concept

Summary

- LHC is a totally new world of energy and luminosity, already making discoveries. LHeC proposal aims to exploit it for lepton-hadron scattering … ep complementing LHC and next generation ee facility for full Terascale exploration

- ECFA/CERN/NuPECC workshop gathered many accelerator, theory & experimental colleagues

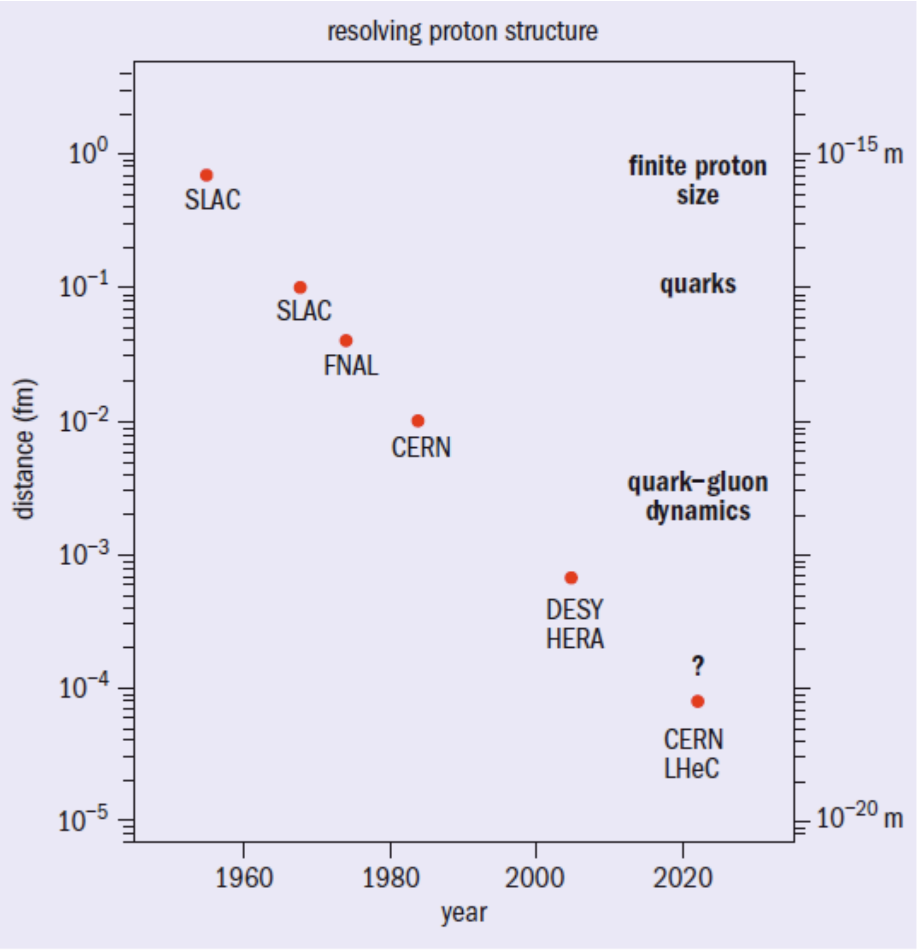


Fig. 1. Distance scales resolved in successive lepton–hadron scattering experiments since the 1950s, and some of the new physics revealed.

→ Conceptual Design Report published. Moving to TDR phase
→ Awaiting outcome of European strategy exercise
→ Build collaboration for detector development

[More at **http://cern.ch/lhec**]

… with thanks to many colleagues working on LHeC …

http://cern.ch/lhec

LHeC Study Group

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