

# A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector

Oliver Bruening, Max Klein, Paul Laycock, the LHeC Study Group

(Submitted on 13 Jun 2012)

## Physics at Larger $Q^2$

The physics programme of the Large Hadron Electron Collider (LHeC), in which the electron beam is collided with the intense hadron beams of the LHC. Compared to the LHC, the LHeC has a four-momentum squared,  $Q^2$ , and in the LHeC is projected to exceed the integrated HERA luminosity by two orders of magnitude. The physics programme is devoted to an exploration of the energy frontier, complementing the LHC and deep inelastic scattering measurements. These are electroweak interactions. The physics programme is extended by four orders of magnitude as compared to HERA and nuclear structure, the initial conditions of Quantum Chromodynamics (QCD). The LHeC may be realised either as a ring-ring or as a fixed-target version, along with technical design considerations. A design study for a high acceptance detector. Civil engineering and installation studies are presented for the accelerator and the detector. The LHeC can be built within a decade and represents a major opportunity for progress in particle physics.

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**Paul Laycock**

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From: Paul Laycock [[view email](#)]

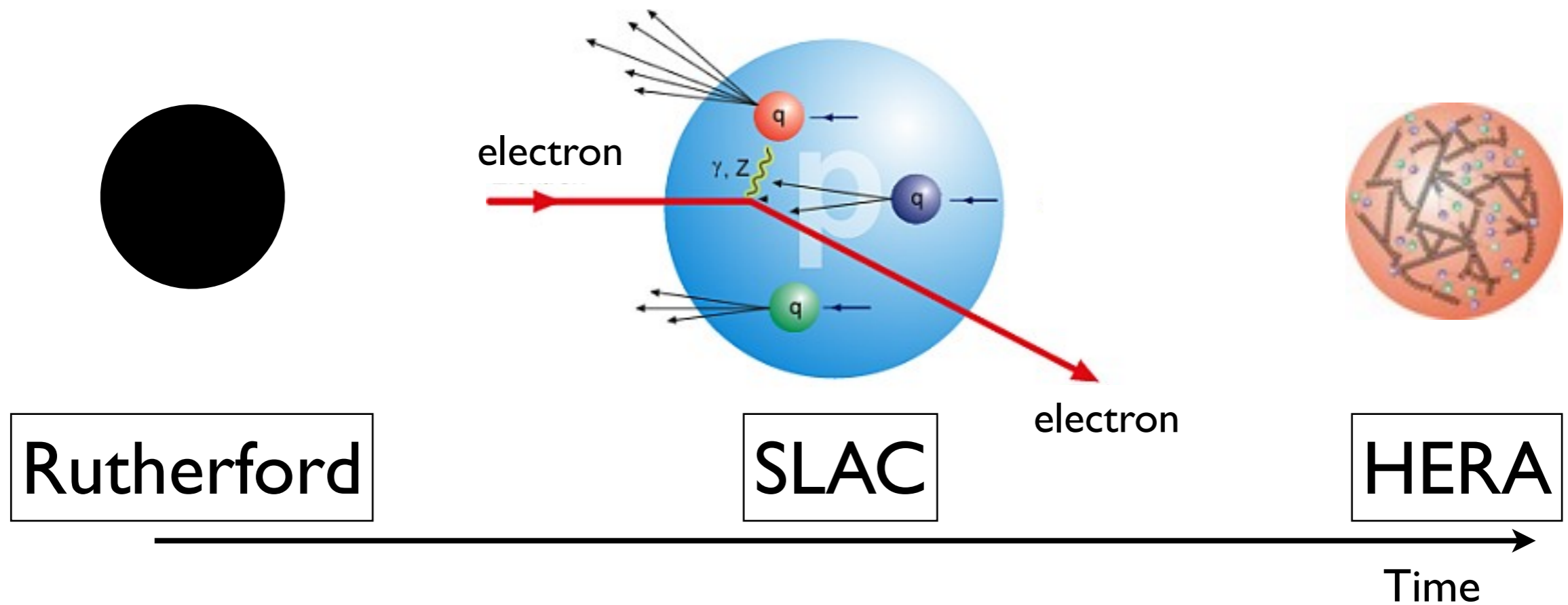
[v1] Wed, 13 Jun 2012 20:26:39 GMT (91155kb,D)



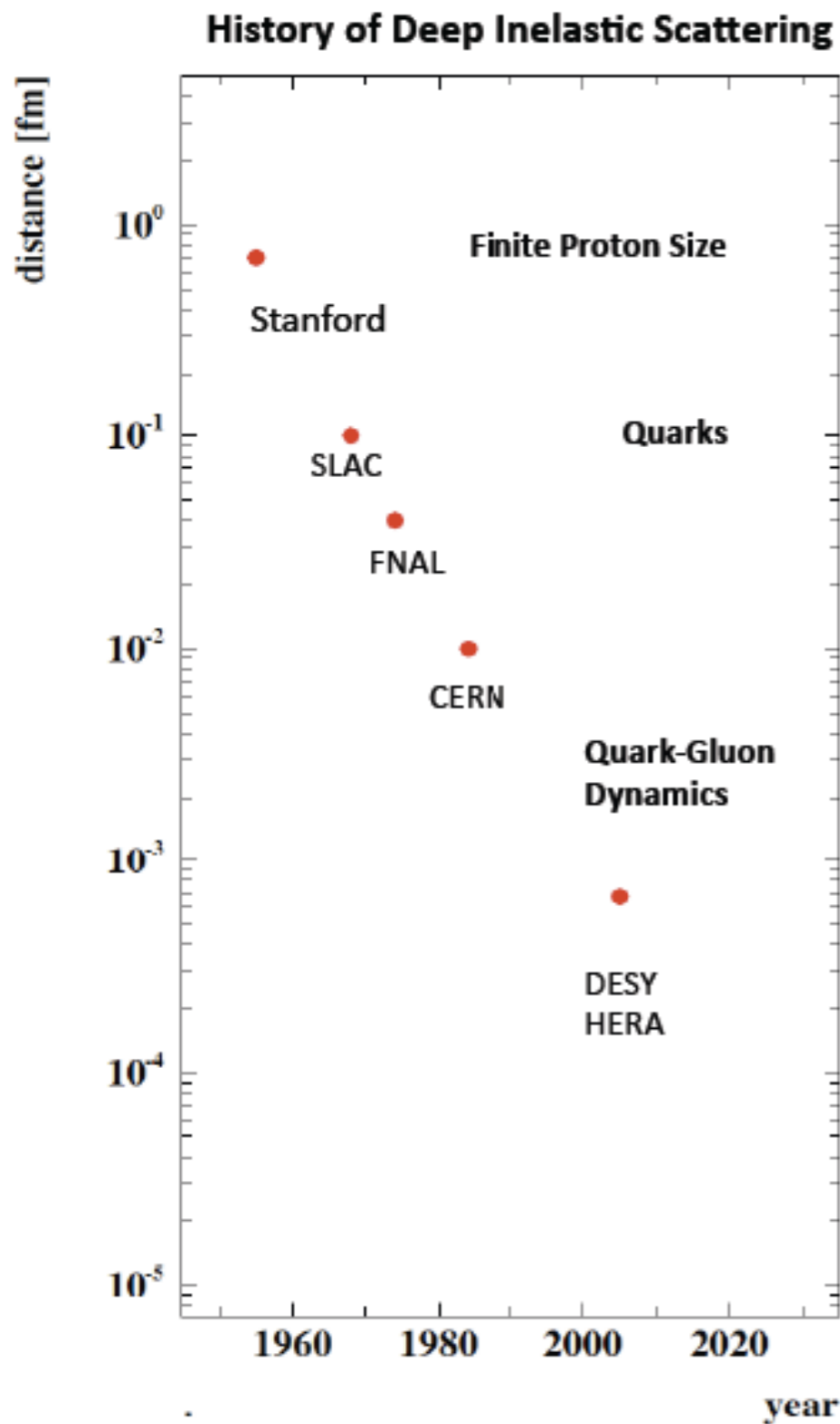
**14th June 2012**

**2012 CERN-ECFA-NuPECC Workshop on the LHeC**

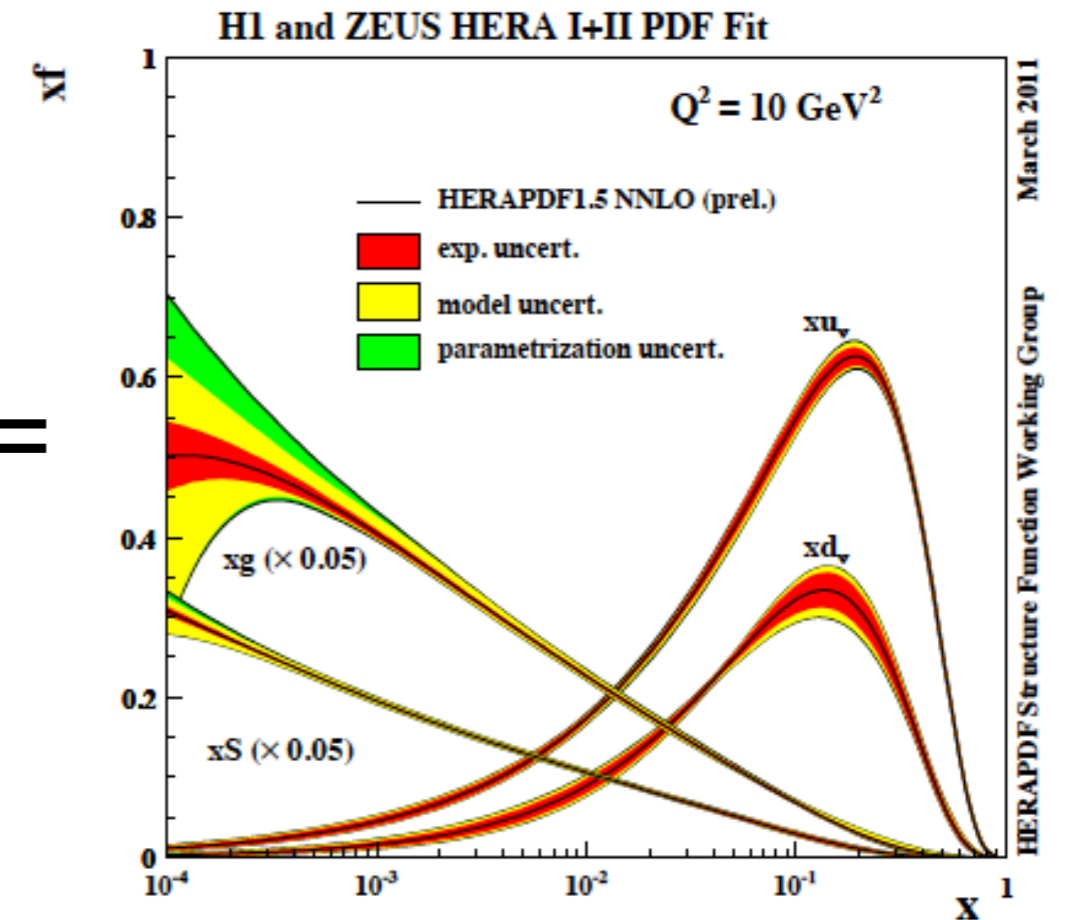
# What is the proton?



# An incomplete history of deep-inelastic scattering

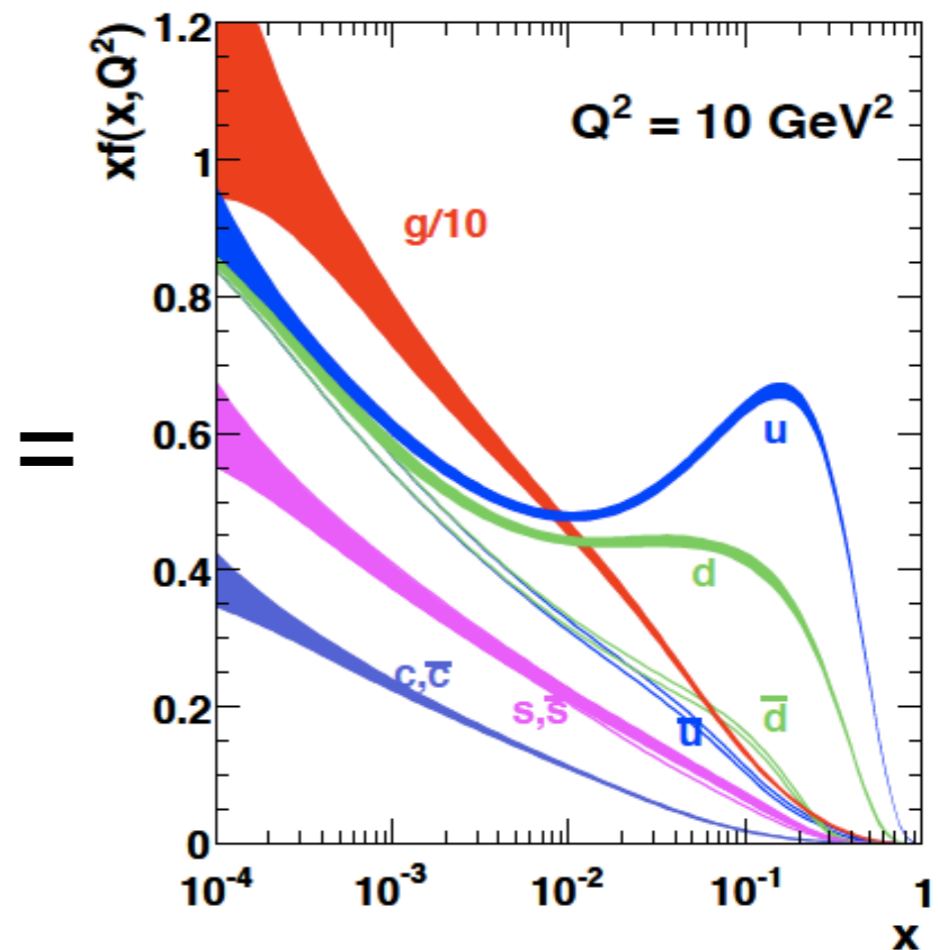
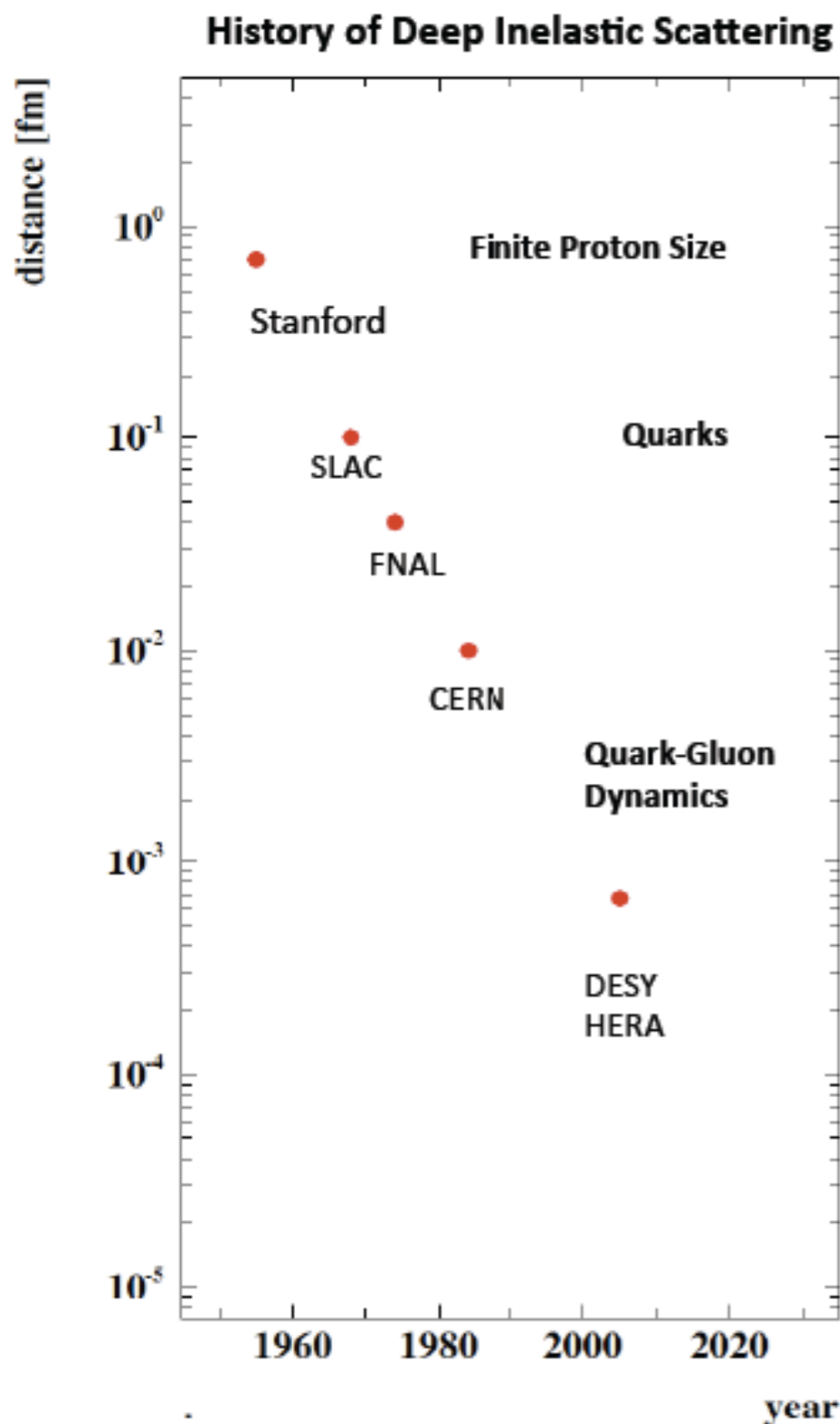


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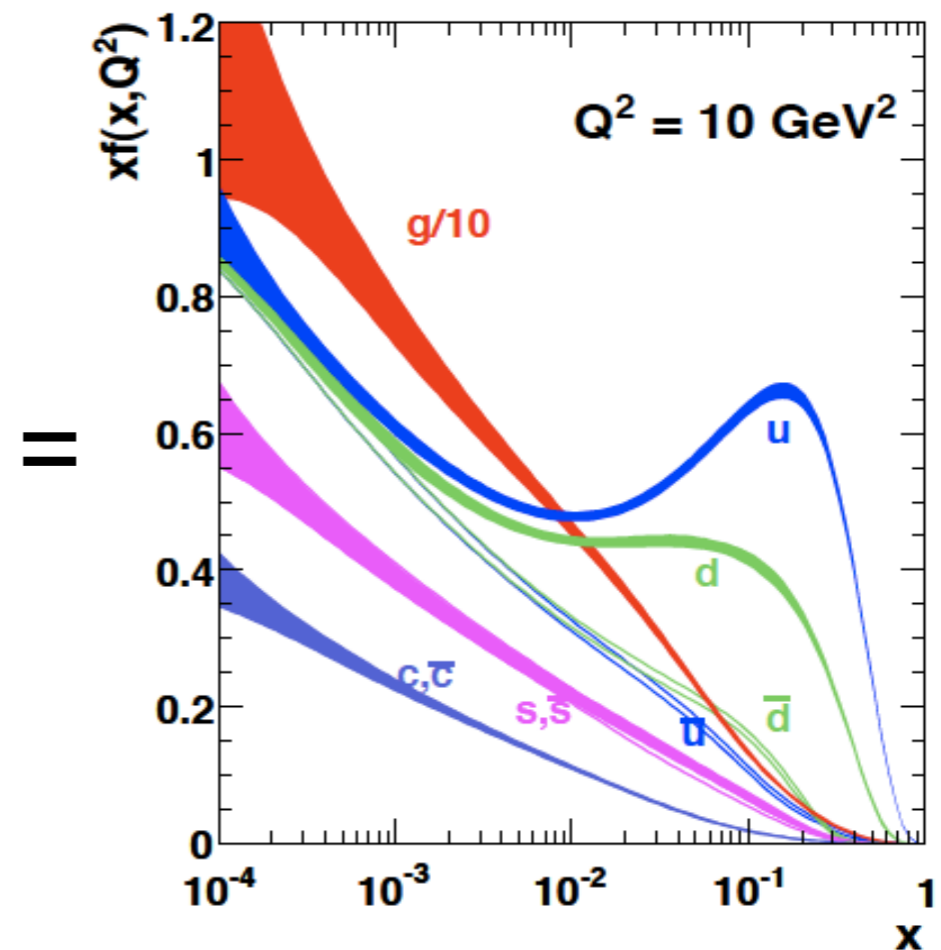
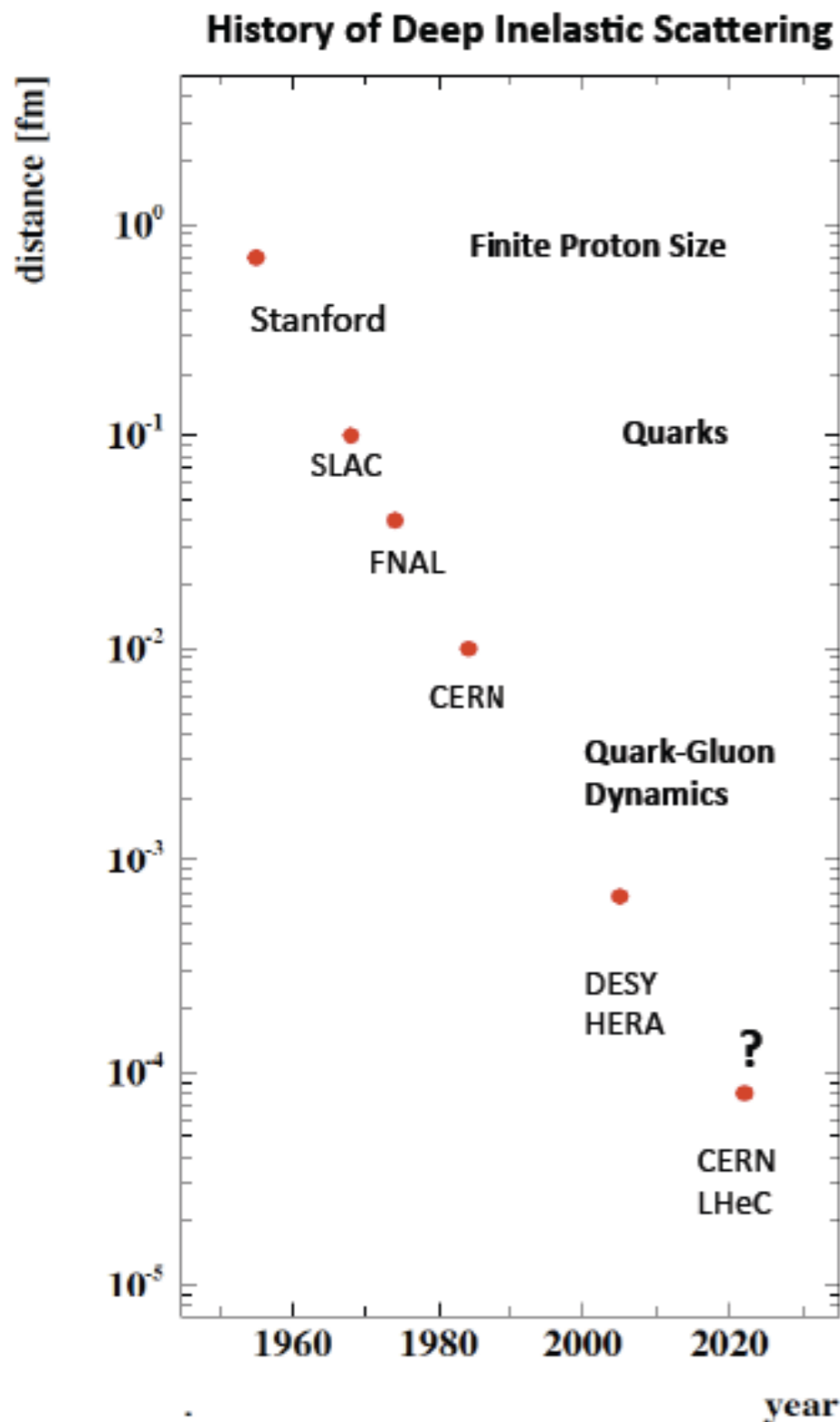
- A rich history of exploiting scattering experiments to study structure, culminating in the HERA electron-proton machine
- Confirmation of the QCD picture of the proton, structure mapped with high precision...

# An incomplete history of deep-inelastic scattering



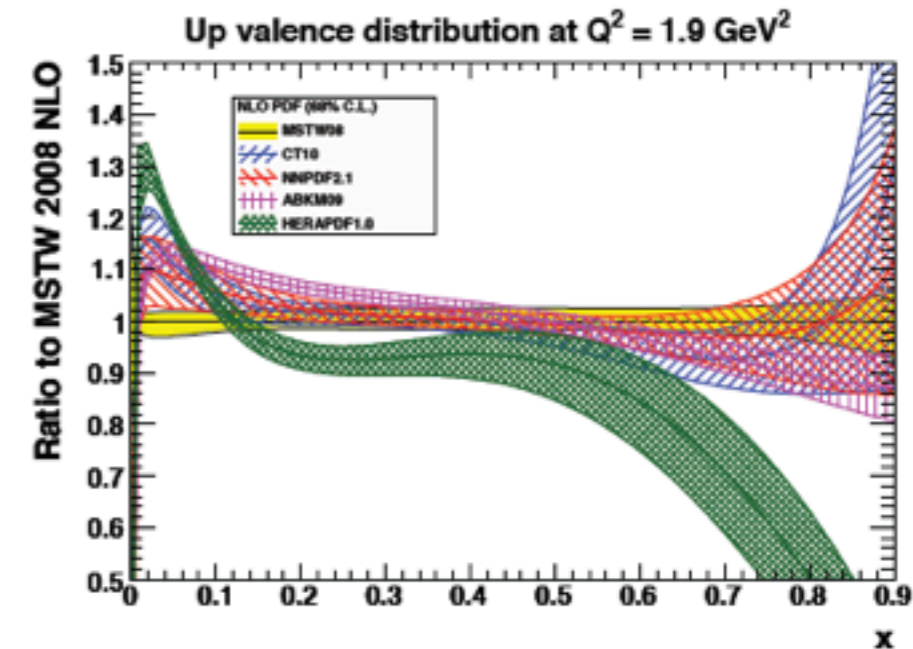
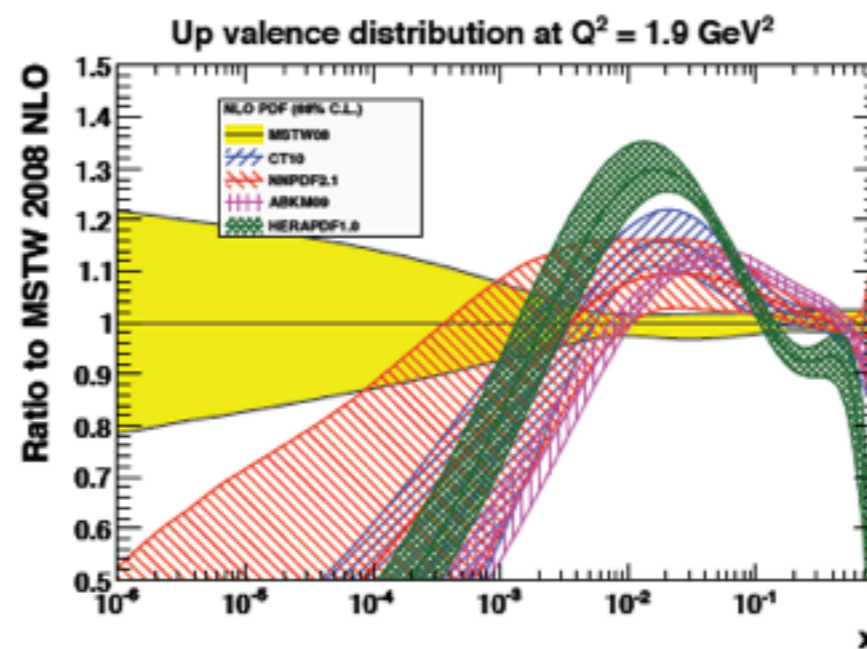
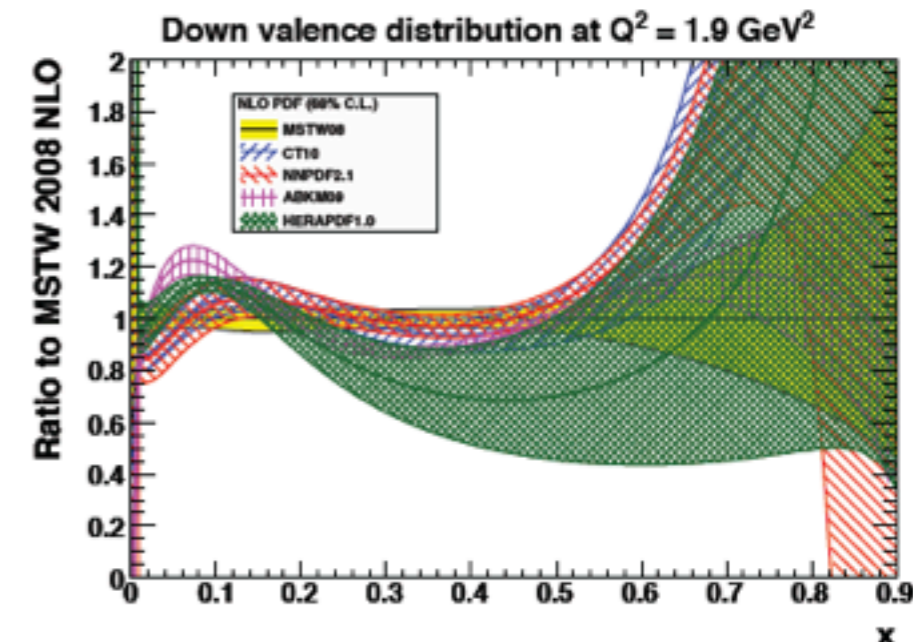
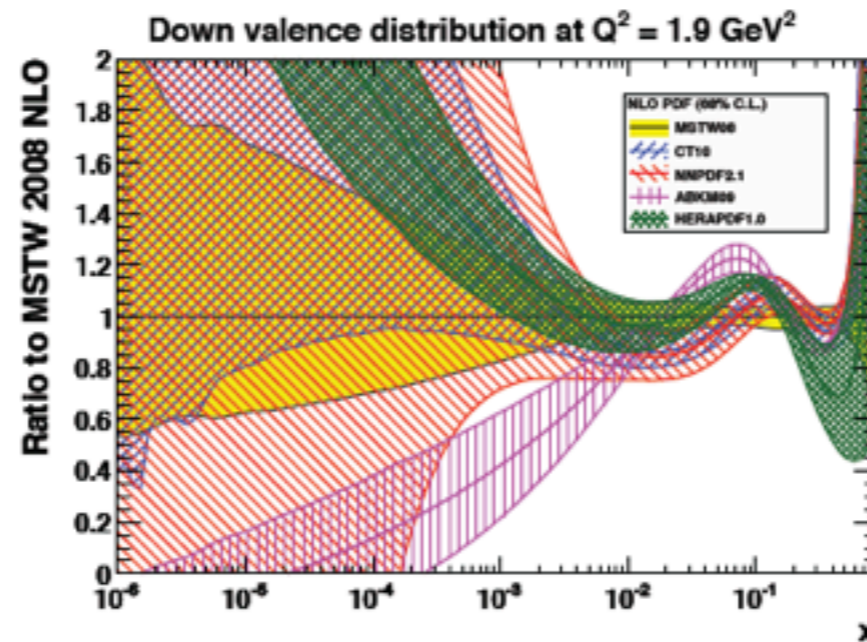
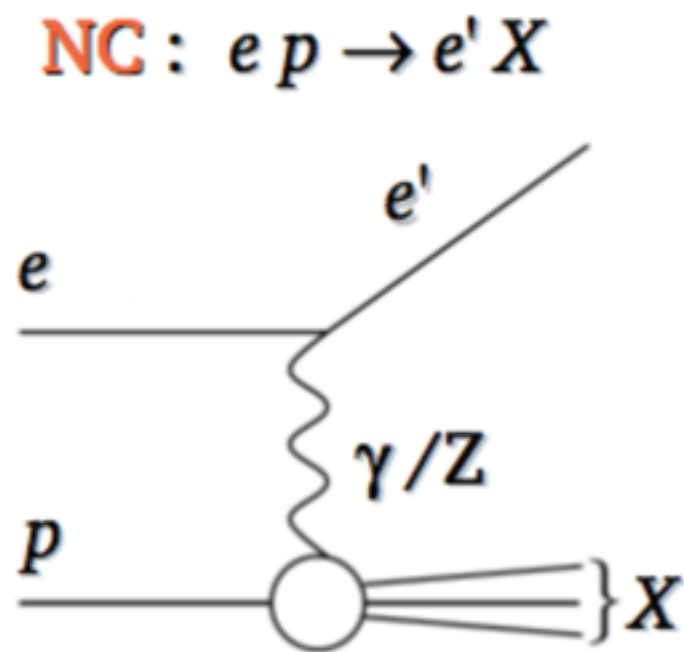
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# An incomplete history of deep-inelastic scattering



- A rich history of exploiting scattering experiments to study structure, culminating in the HERA electron-proton machine
- Confirmation of the QCD picture of the proton, structure mapped with high precision...
- But QCD is a very subtle theory and not easily mastered, it has not given up all of its secrets

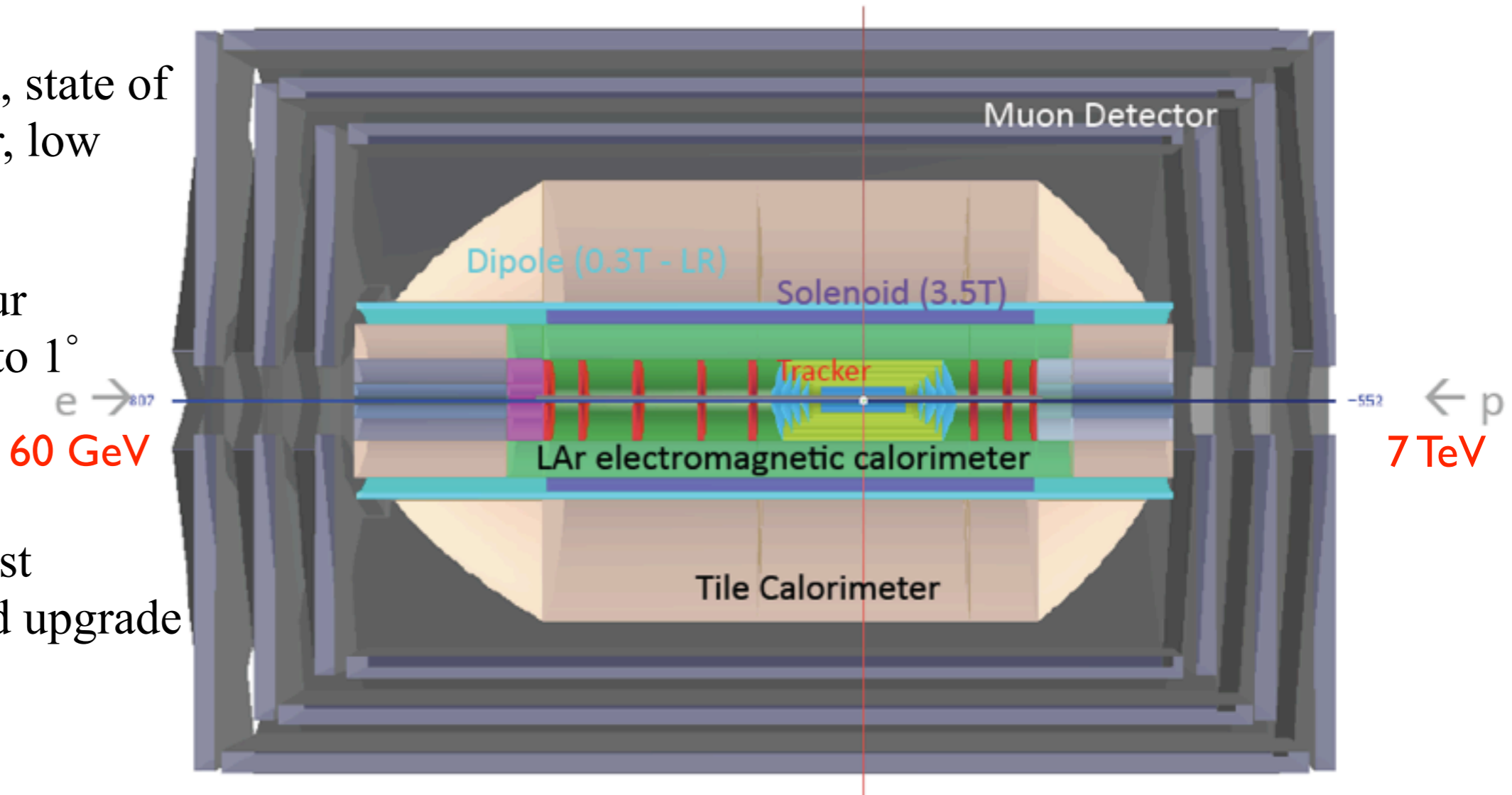
# Current knowledge of the valence quarks



- The valence structure of the proton may be known, the details are not
- The range of answers offered by the latest and greatest is surprisingly varied

# The LHeC Detector (see talks of Polini & Kostka)

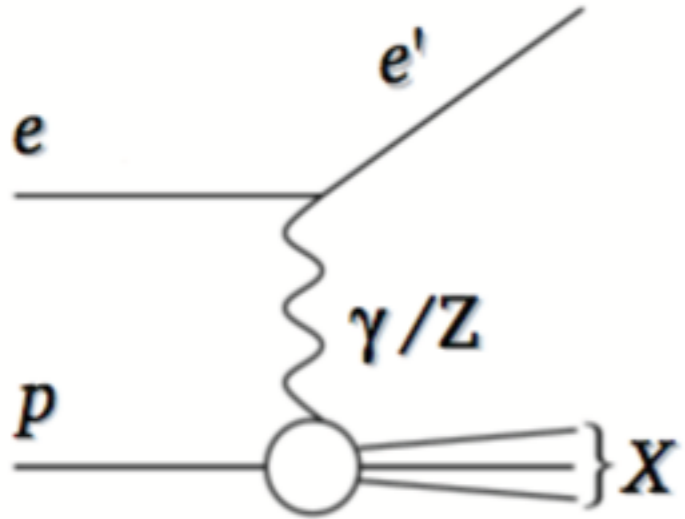
- High precision, state of the art detector, low noise
- efficient flavour tagging down to  $1^\circ$
- No R&D
- Modular for fast installation and upgrade
- Affordable



So what could we do with this?

# Studying proton structure

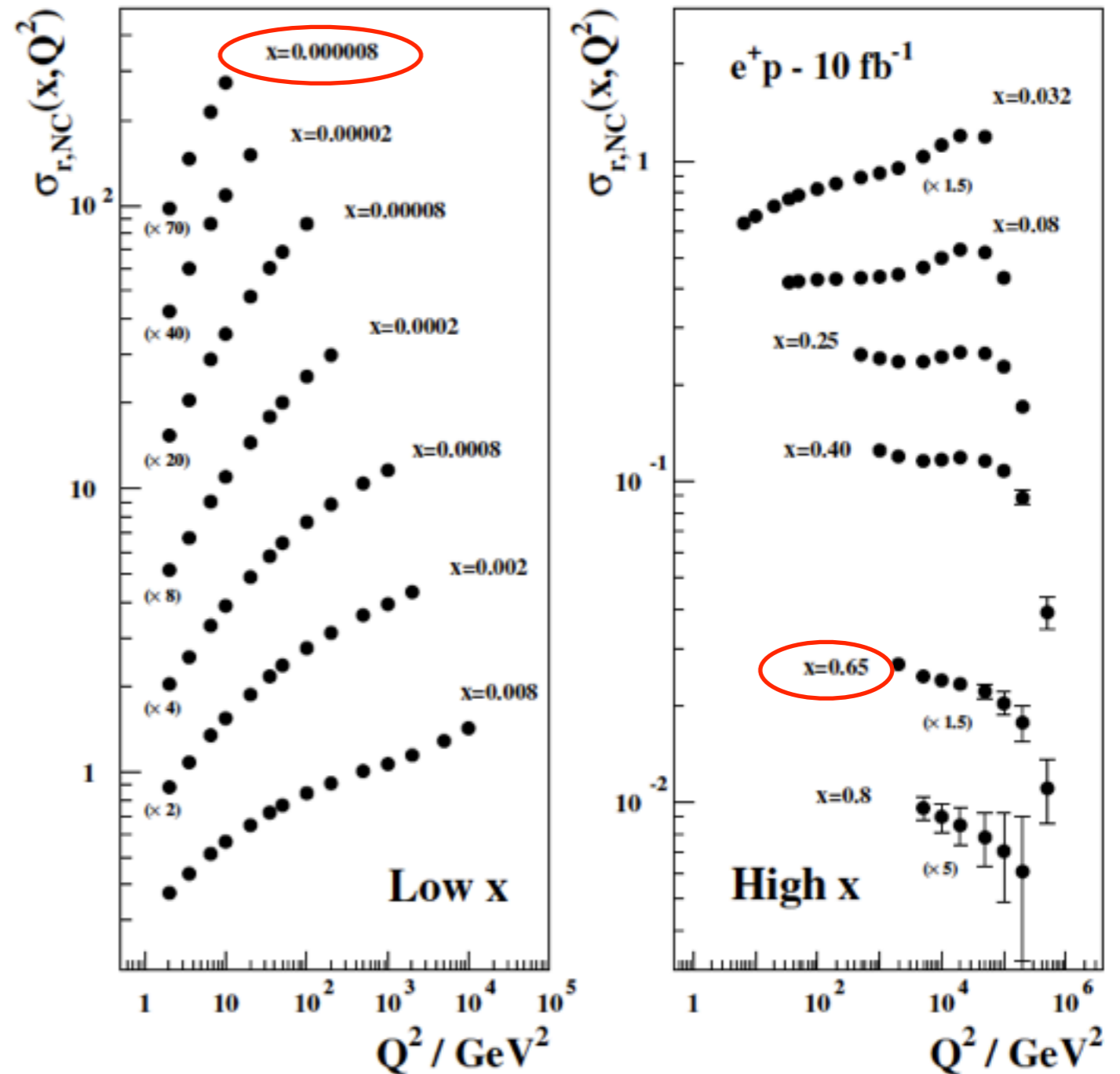
**NC :  $e p \rightarrow e' X$**



$$\frac{d^2\sigma_{NC}}{dx dQ^2} = \frac{2\pi\alpha^2 Y_+}{Q^4 x} \cdot \sigma_{r,NC}$$

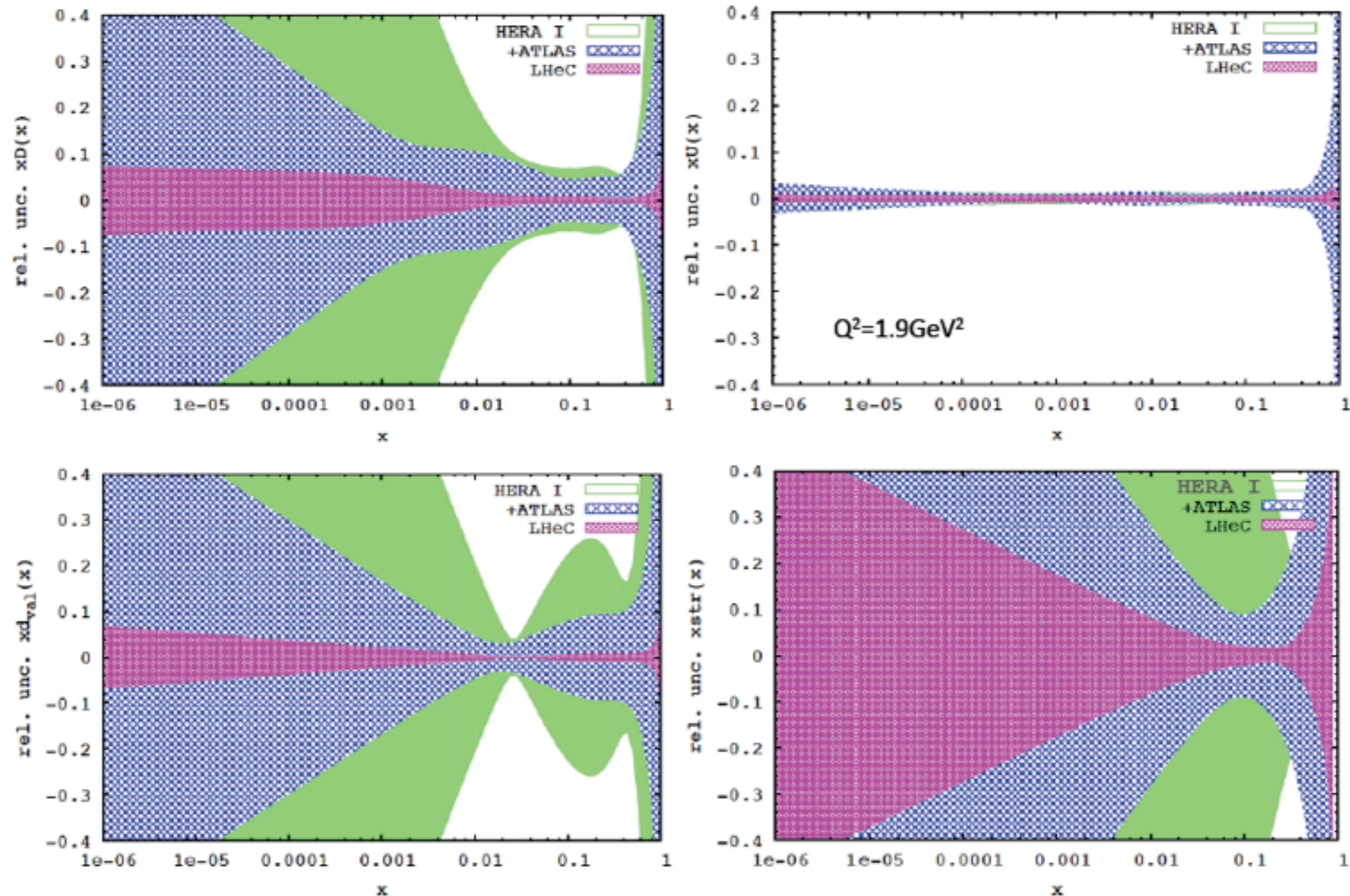
$$\sigma_{r,NC} = F_2 + \frac{Y_-}{Y_+} x F_3 - \frac{y^2}{Y_+} F_L,$$

**LHeC**



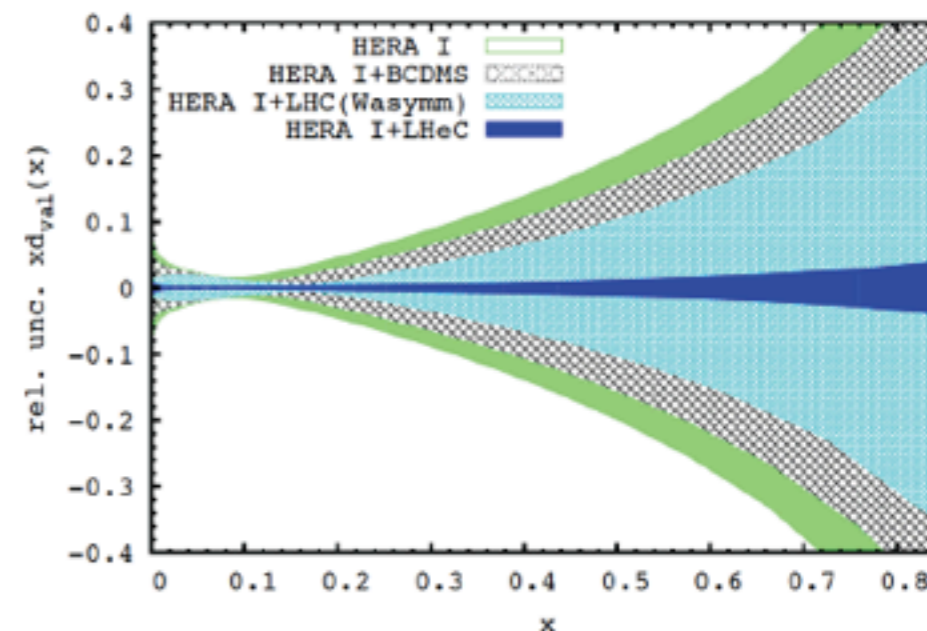
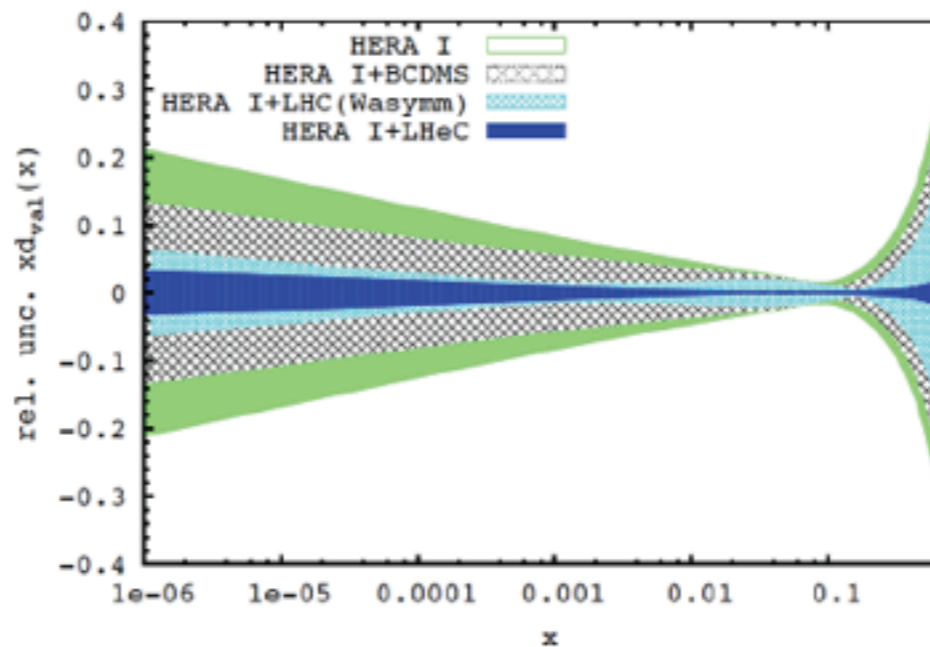
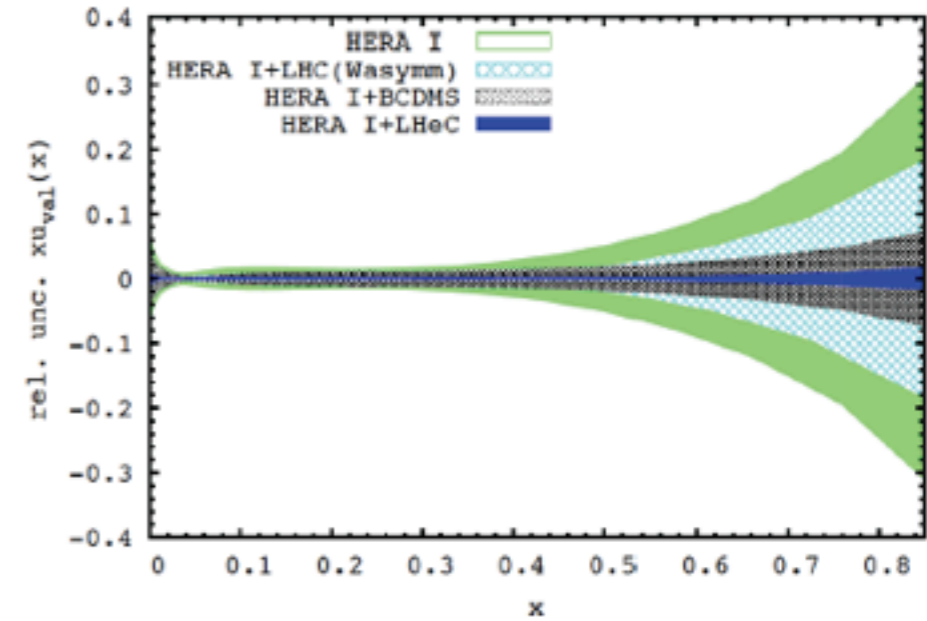
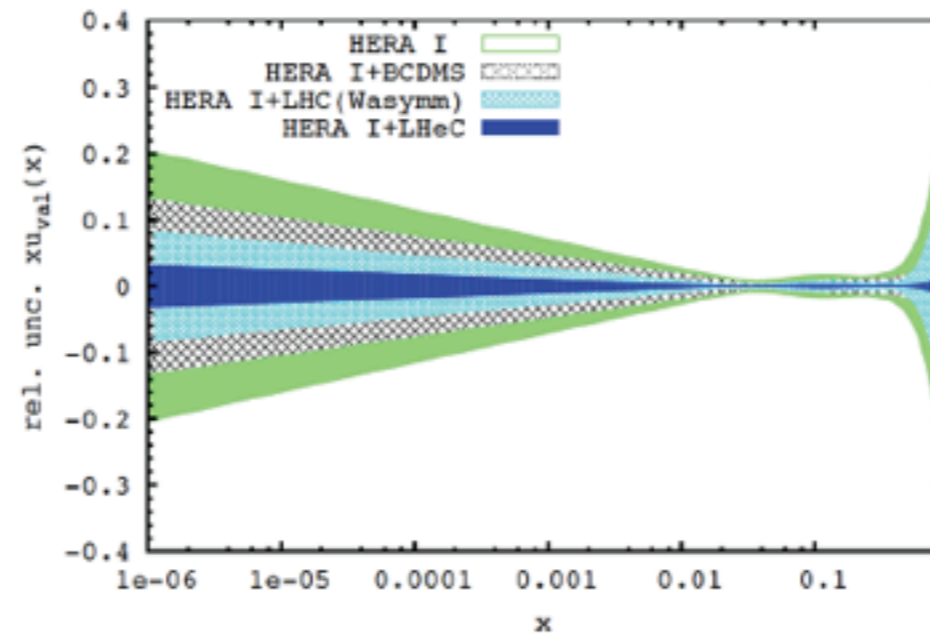
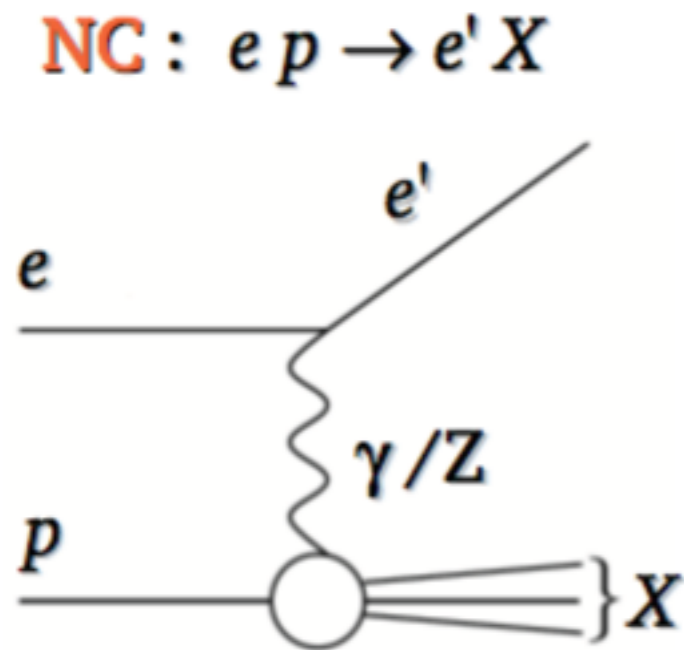
- The optics of the LHeC means no pile-up, a clean unfolding of the proton structure with 100 times the HERA luminosity over a huge kinematic range
- Thanks to the large acceptance, precision data at even the lowest and highest  $x$

# Before and after LHeC



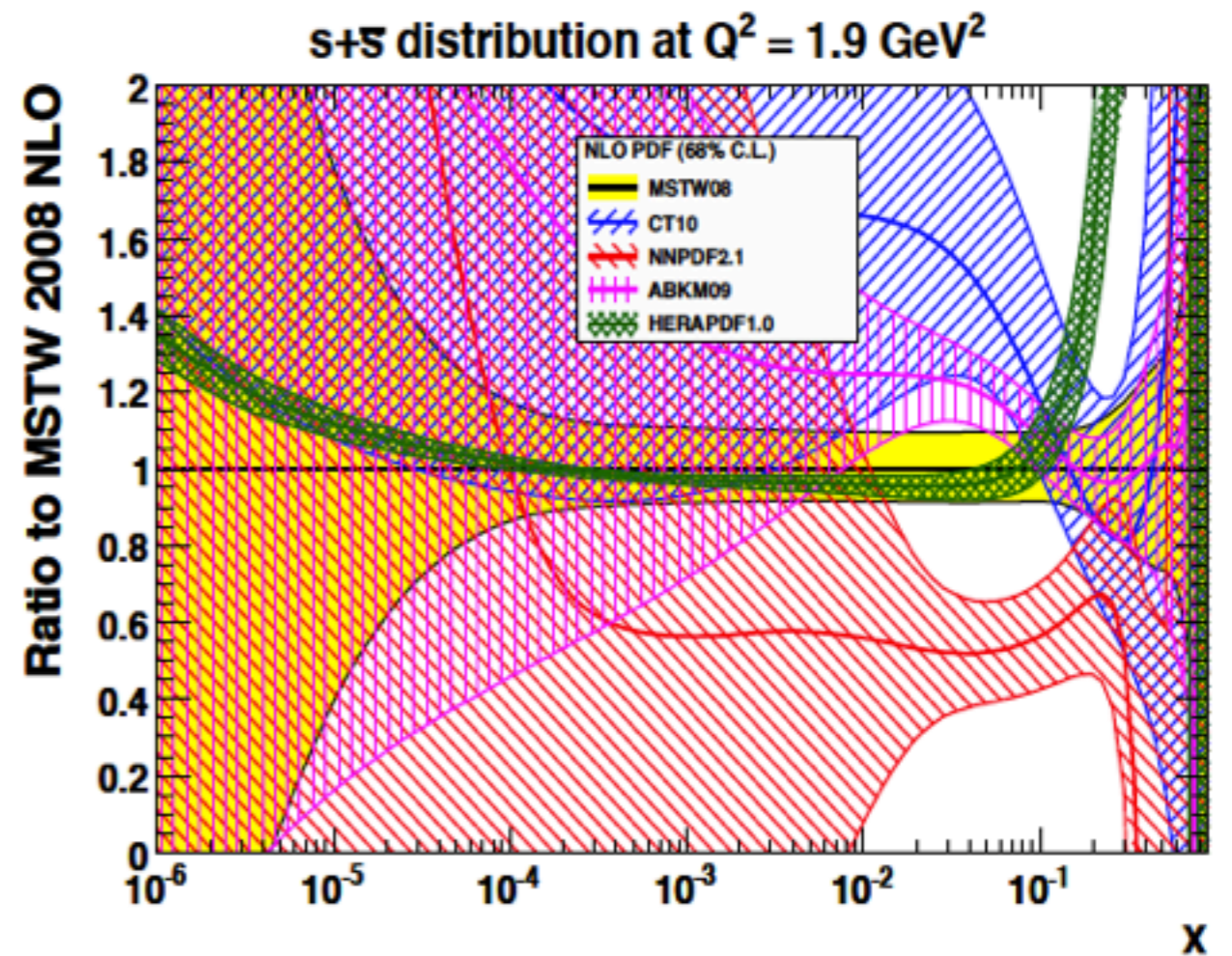
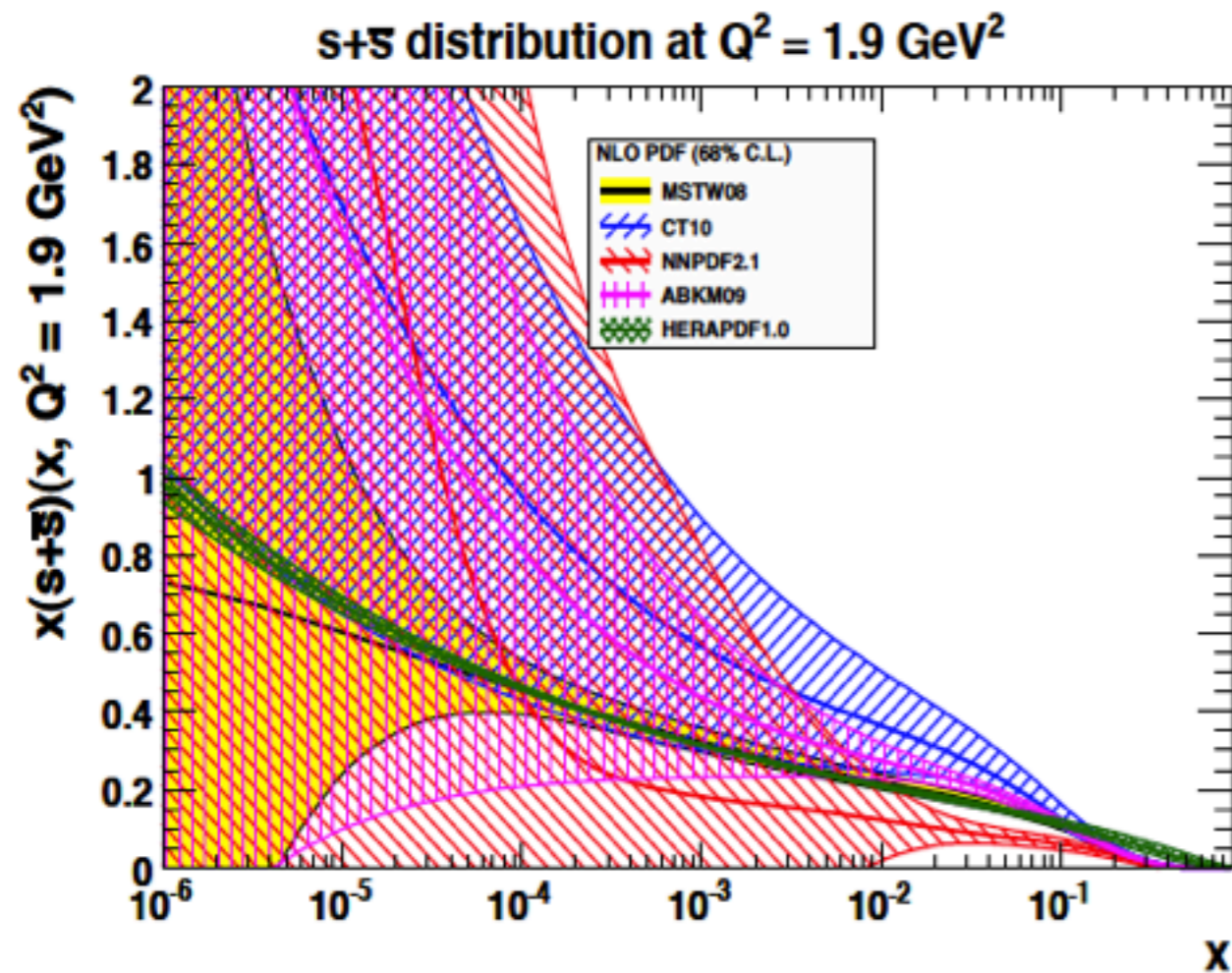
- QCD fits usually employ assumptions out of necessity, we don't have all needed data
- Relaxing those assumptions reveals our ignorance, adding LHC data helps
- *With the LHeC, we can replace assumptions with data* (see talk by Voica)

# The proton has its ups and downs



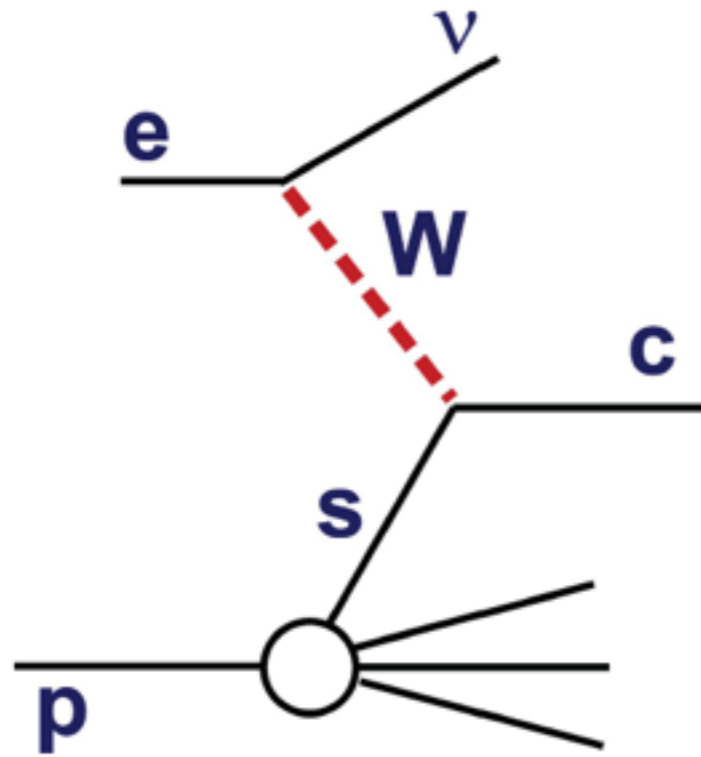
- The LHeC would be able to constrain the valence quarks across the whole kinematic range to better than  $\sim 2\%$  precision
- c.f. LHC searches continue to push towards higher masses, i.e. higher  $x$

# How strange is the proton?

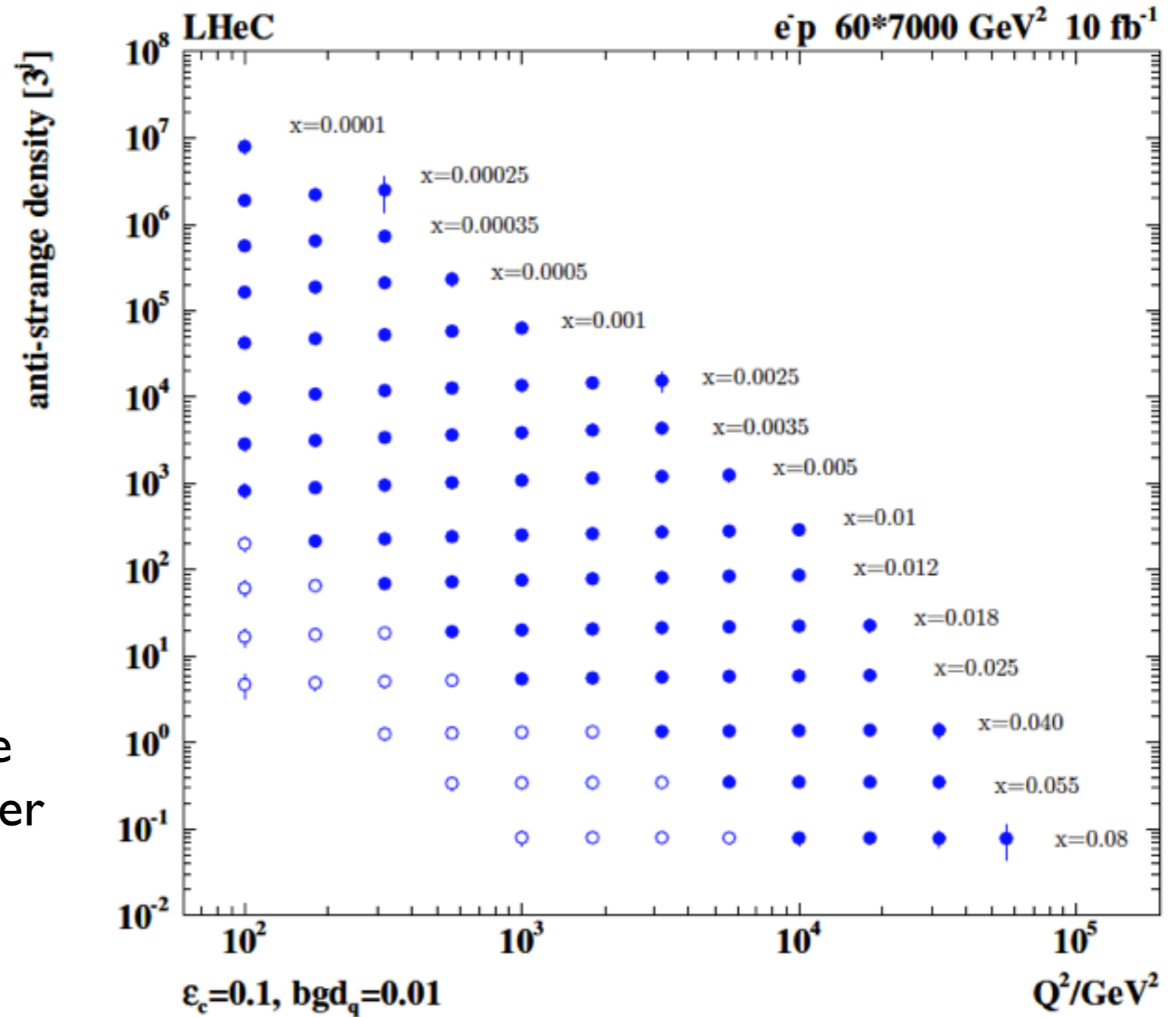


- Very strange? The spread of distributions looks appropriately strange
- But not really strange, the current constraints from data are very poor and consequently the strange content of the proton is very poorly known

# How strange is the proton?

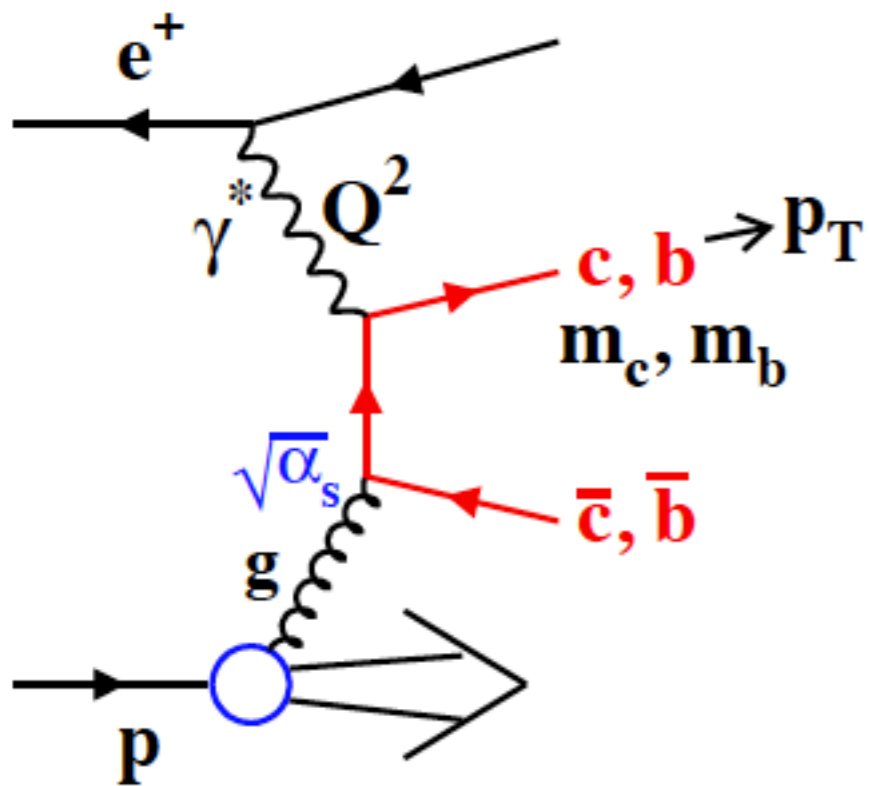


Charm tagging employing the high acceptance silicon tracker

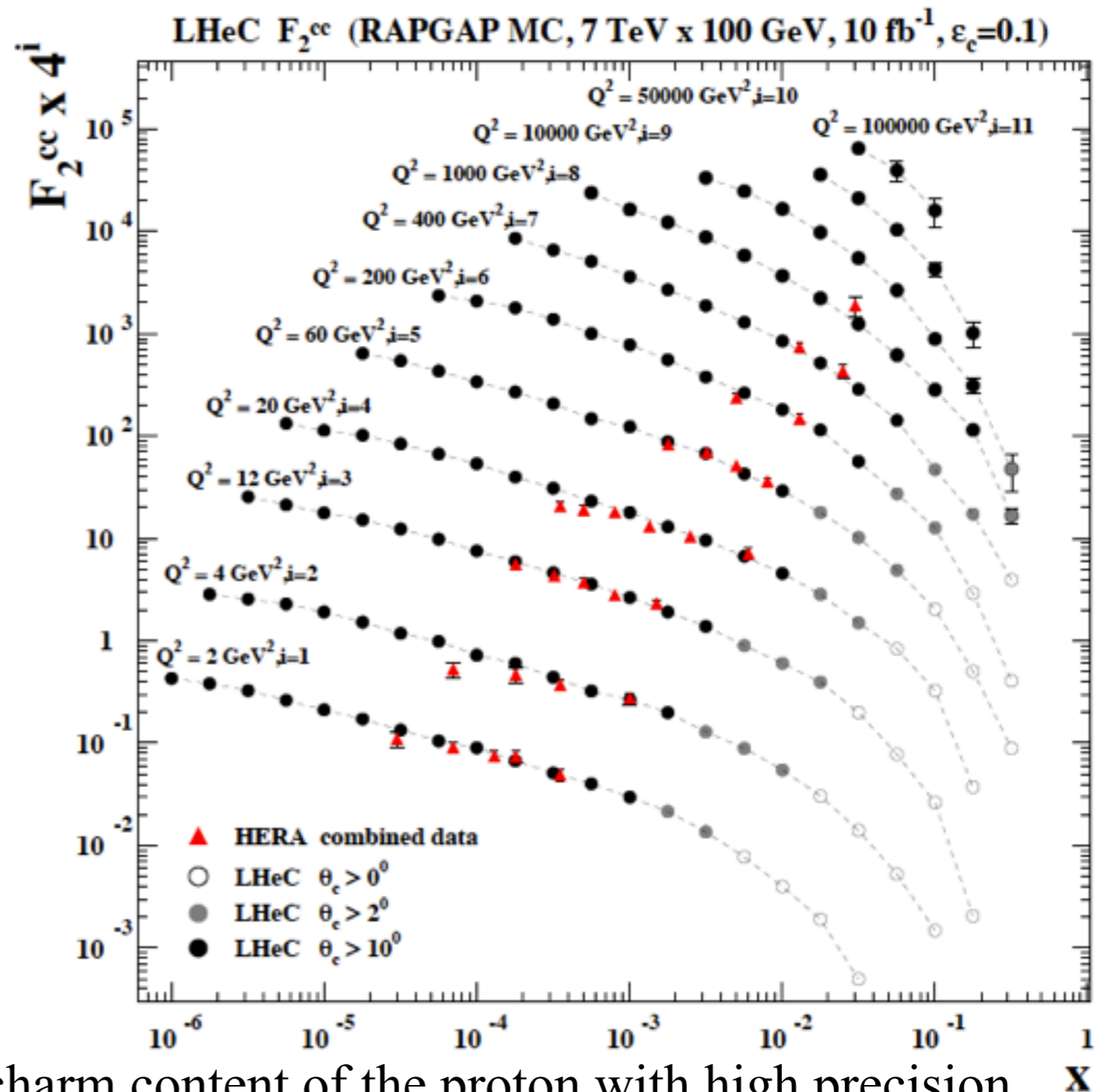


- The LHeC would measure the strangeness of the proton with very high precision
- Positrons and electrons would disentangle strange from anti-strange

# How charming is the proton?

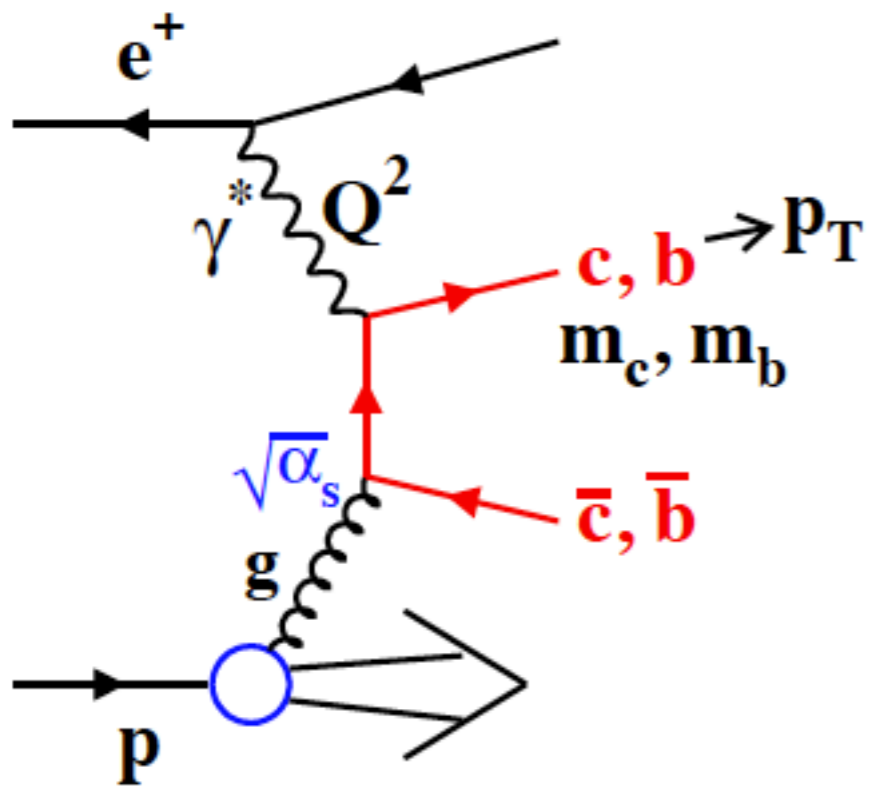


Charm tagging employing the high acceptance silicon tracker

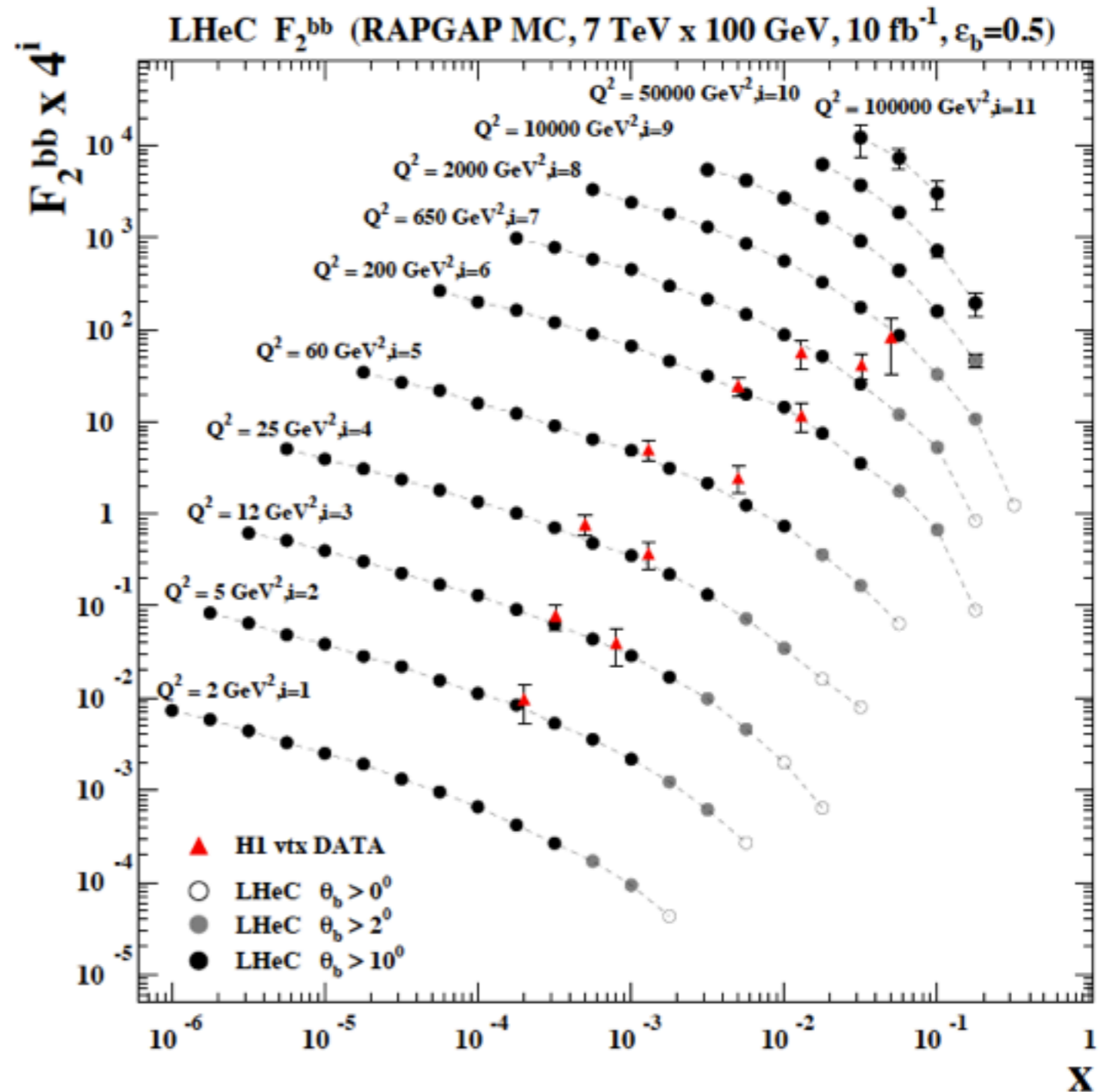


- The LHeC would measure the charm content of the proton with high precision across more than 5 decades in  $x$  and  $Q^2$
- These data could determine the charm mass to  $\sim 3 \text{ MeV}$
- It will finally measure the charm content at high  $x$  - is there intrinsic charm?

# How beautiful is the proton?

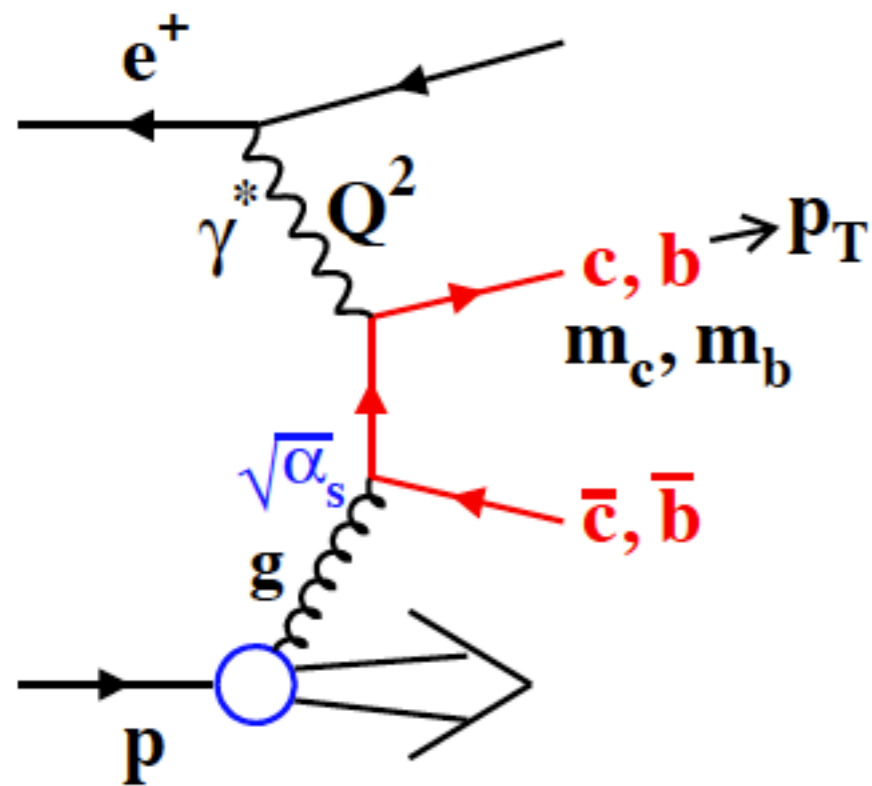


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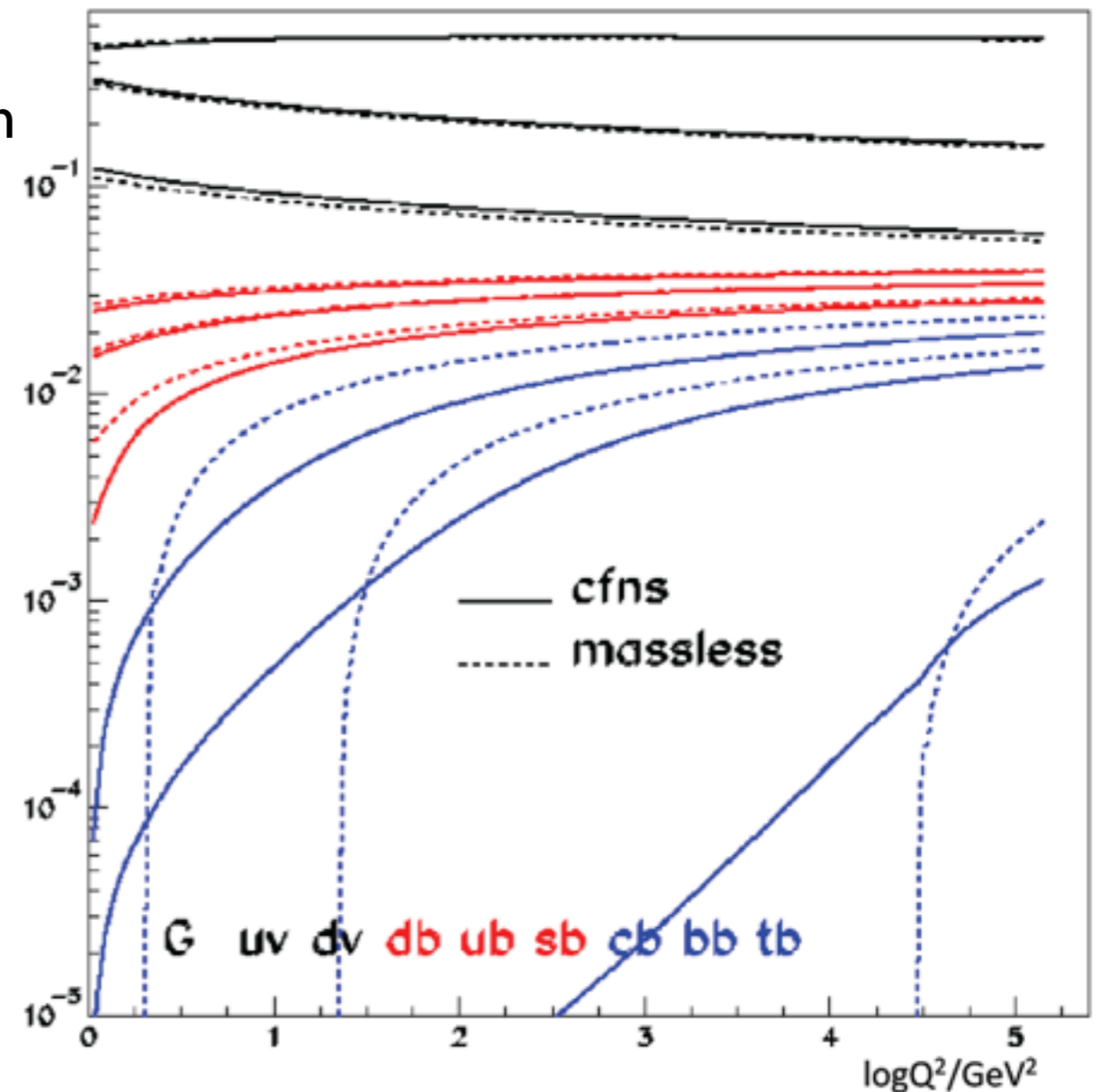


- Thanks to the vastly superior tracking detector, the beauty of the proton will be fully appreciated, finally measuring this precisely across the complete kinematic range
- Of extreme importance for very many searches at the LHC (see talk of Behnke)

# How to treat heavy flavours?

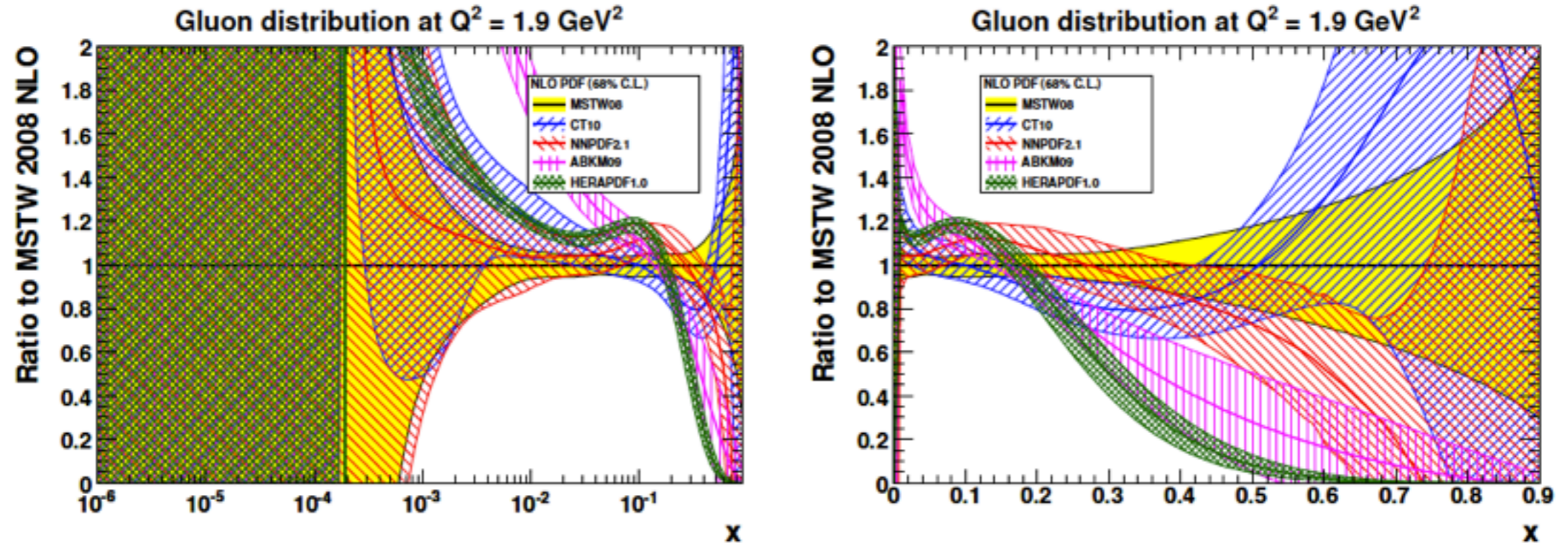


parton  
momentum  
fraction



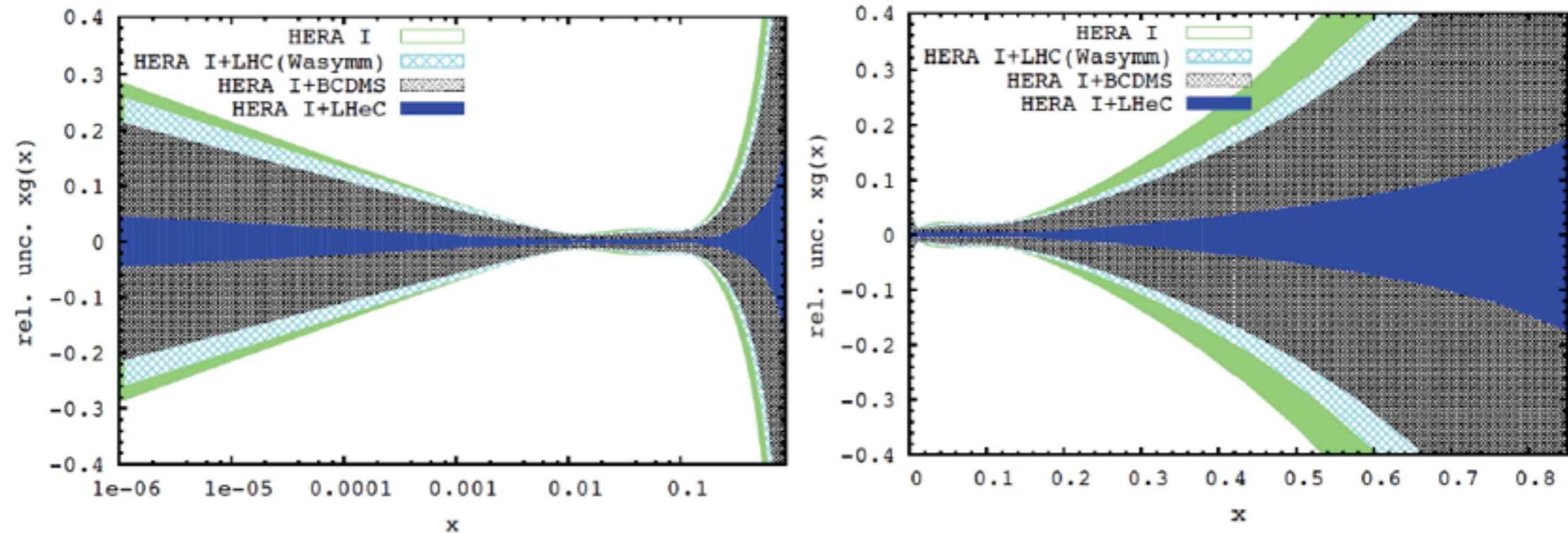
- We expect to see many top quarks (100,000 events) at the LHeC, opening up the field of top PDFs
- Need to have 6 flavour-number scheme (see talk of Pascaud)
- The LHeC would map the transition between the massive and massless approaches, precision heavy flavour data invaluable for theory

# The gluon - a big unknown



- The gluon dominates production mechanisms at the LHC
- At low x it becomes extremely large, and yet it is not well known
- It's all but unknown at high x - are there even “cold spots”, e.g. at the scaling point around  $x=0.2$ , with  $g=0$ ?

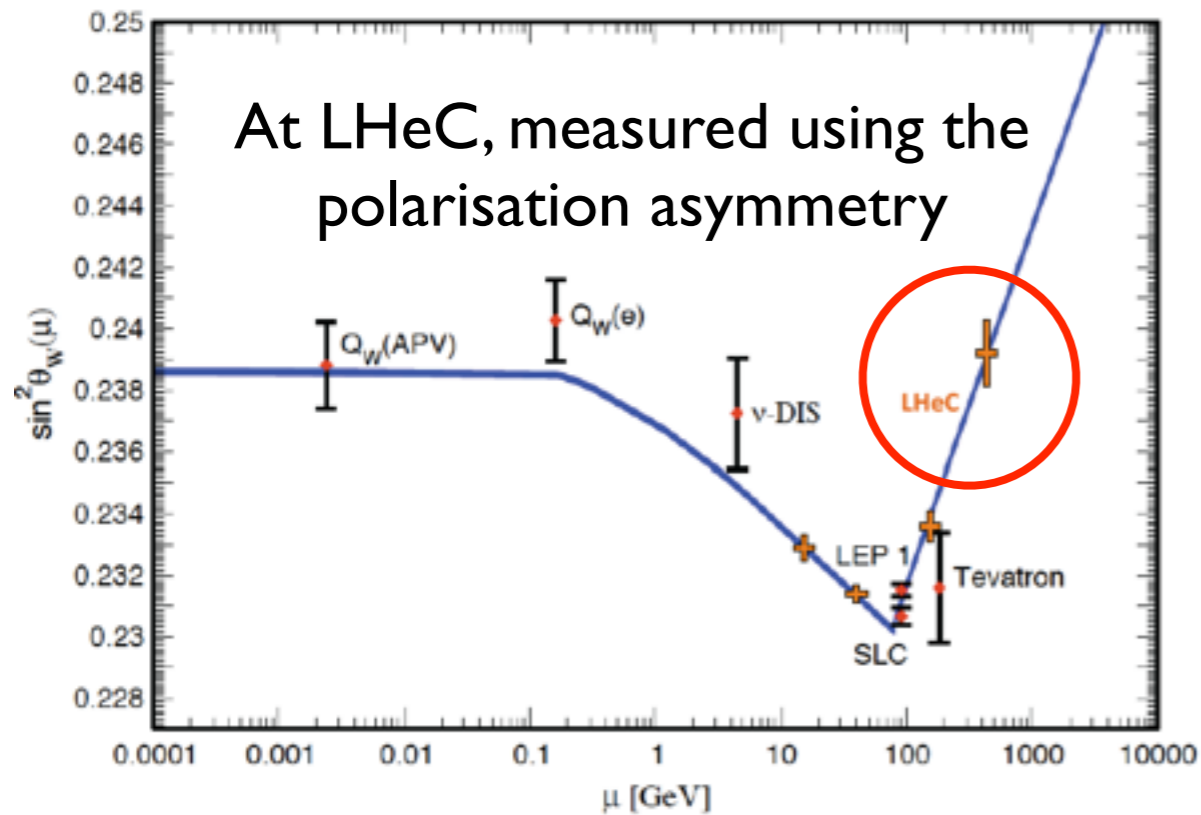
# The new age in PDFs



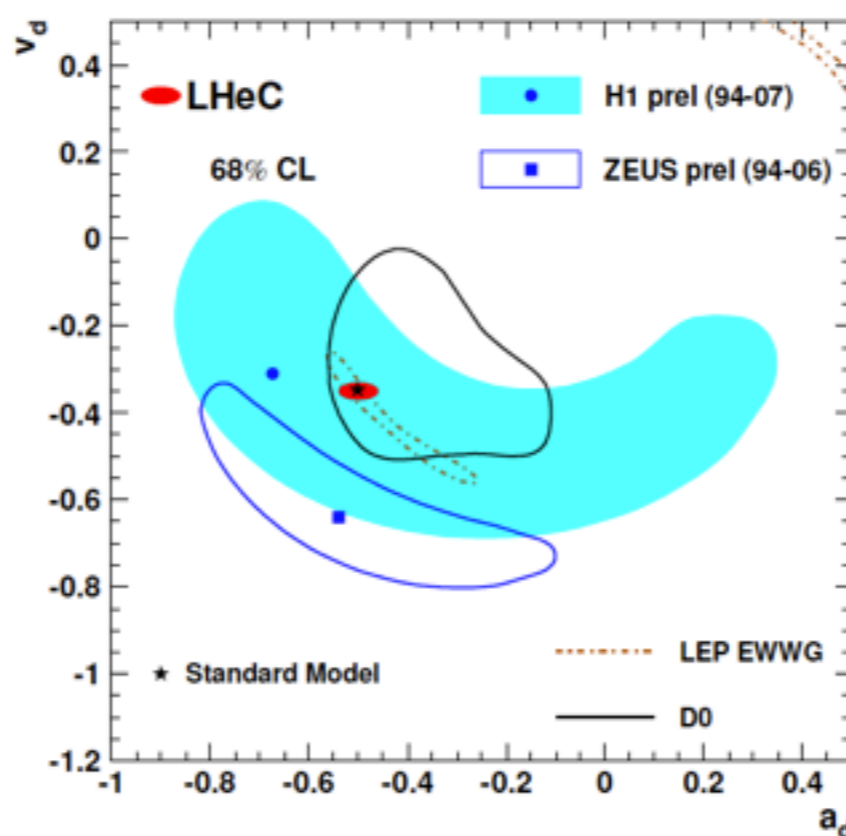
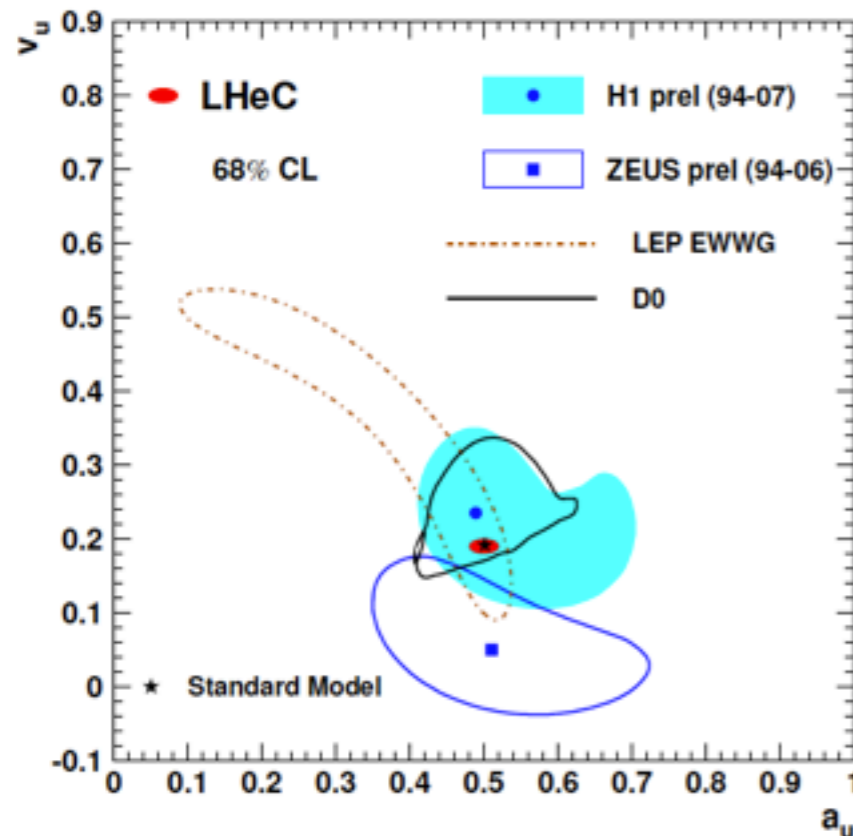
- The LHeC completely unfolds the gluon field in the proton
- Not to mention the expected improvements from adding deuteron data
  - Test whether the neutron  $d$  is equivalent to the proton  $u$
  - Have another handle on singlet / non-singlet evolution
- Taken together, this data will give the QCD physics community, not least our theory friends, a lot of data and a lot less freedom!
- What happens at low  $x$ ? Next talk by Armesto...

# Precision electroweak measurements

$$\sin^2\theta_W$$



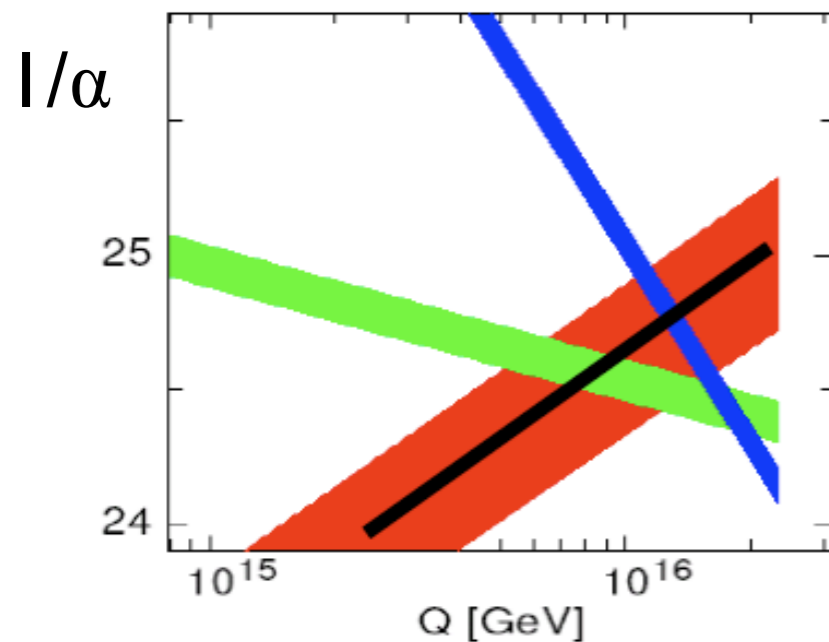
- An interesting proposal to measure the electroweak mixing angle using polarisation asymmetry measurements
- Good precision and the scale dependence measured in one experiment
- To be pursued further



The vector and axial-vector weak NC couplings to the u and d quarks would be measured to very high precision (look closely!)

# Precision $\alpha_s$ measurement - Grand Unification?

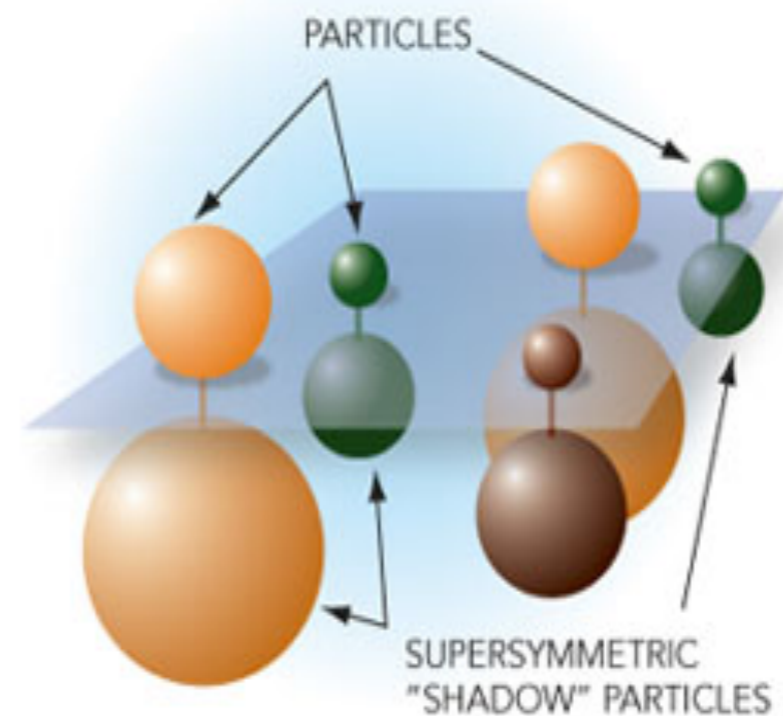
## $\alpha_s$ scenarios



case	cut [ $Q^2$ in $\text{GeV}^2$ ]	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	1.94
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LHeC only (14p)	$Q^2 > 3.5$	0.15
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LHeC only (14p)	$Q^2 > 20.$	0.25
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LHeC+HERA (10p)	$Q^2 > 10.$	0.26

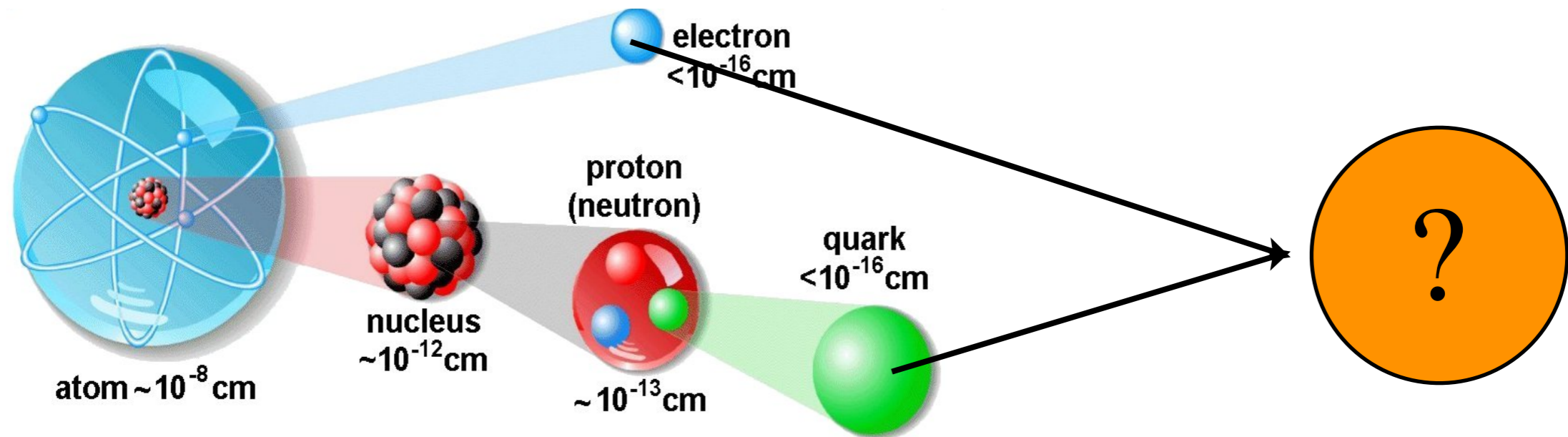
- It may be that the forces unify, i.e. have the same strength, at high energy
- Verifying that demands improvements in our knowledge of  $\alpha_s$  which is by far the least well known
- Presently known to  $\sim 1\%$  precision, it would be determined at the per mille level..
- ..and at a couple per mille for  $Q^2 > 20 \text{ GeV}^2$ , i.e. no non-perturbative effects (see talk by Bluemlein)

# What lies beyond?



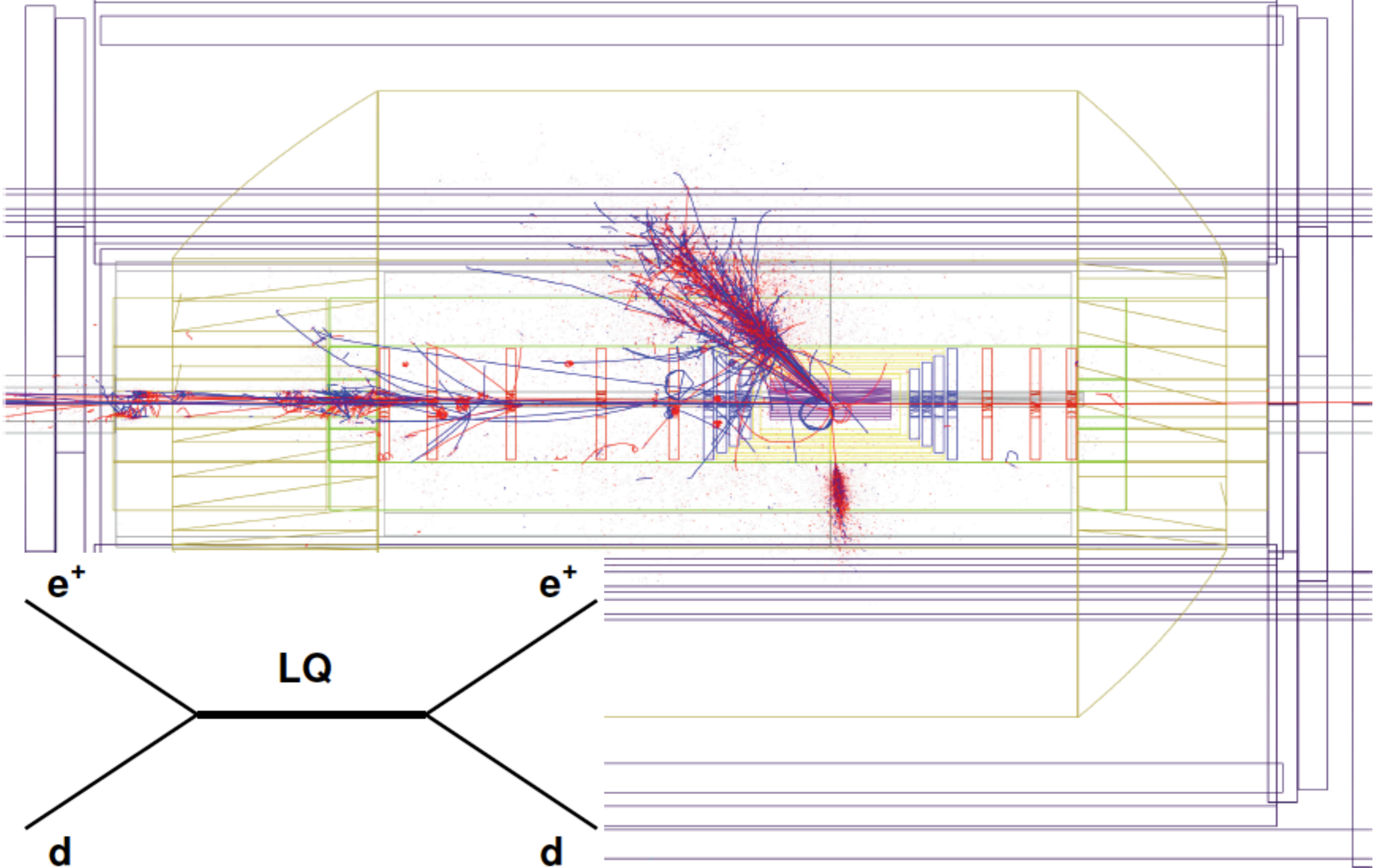
- Is nature supersymmetric?
- Normally consider pair-production of SUSY particles at the LHC which decay into the lightest SUSY particle, they can't decay if R-parity is conserved
  - Striking missing energy signatures in the detector as the LSP escapes
- But if R-parity isn't conserved?
- More on SUSY and LHeC in Monica's talk tomorrow

# What lies beyond?

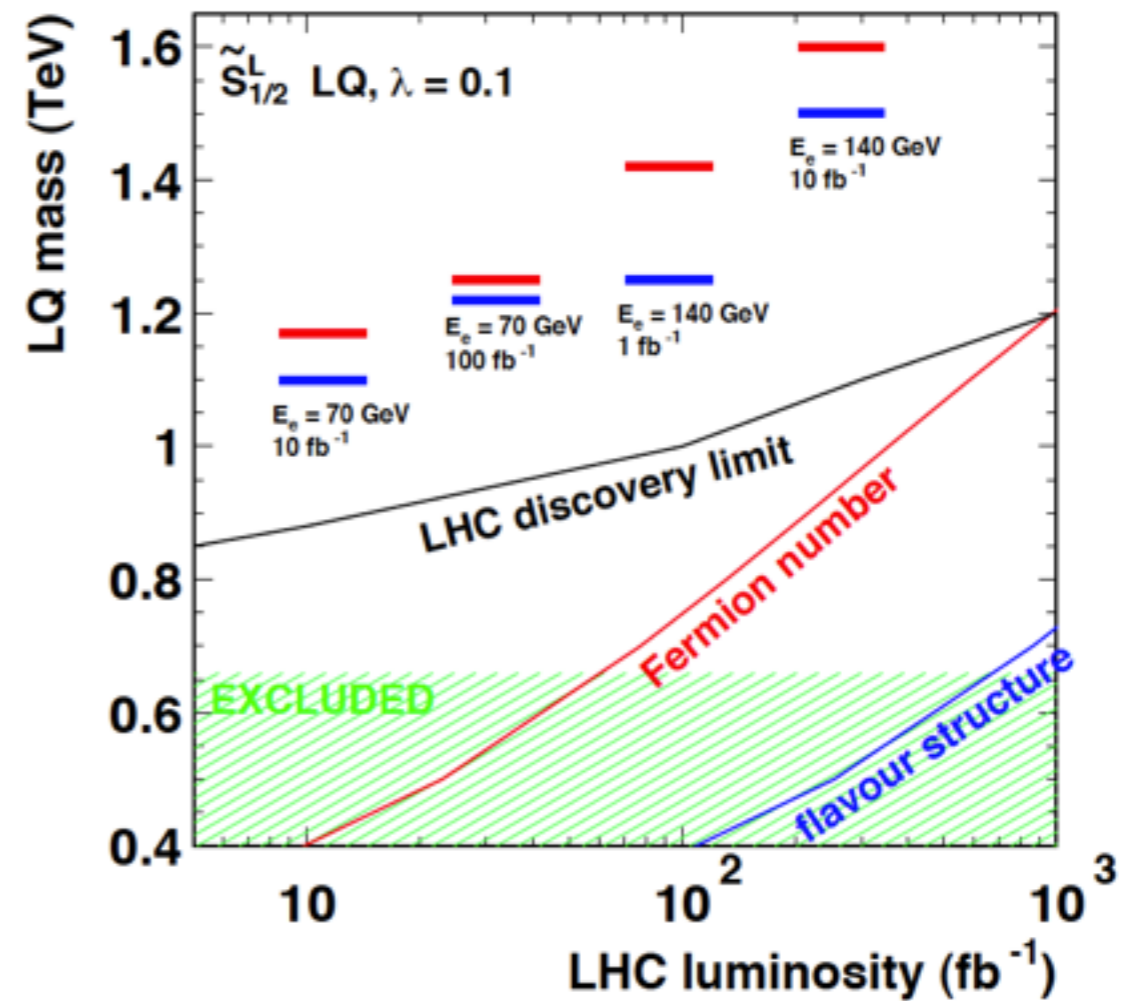
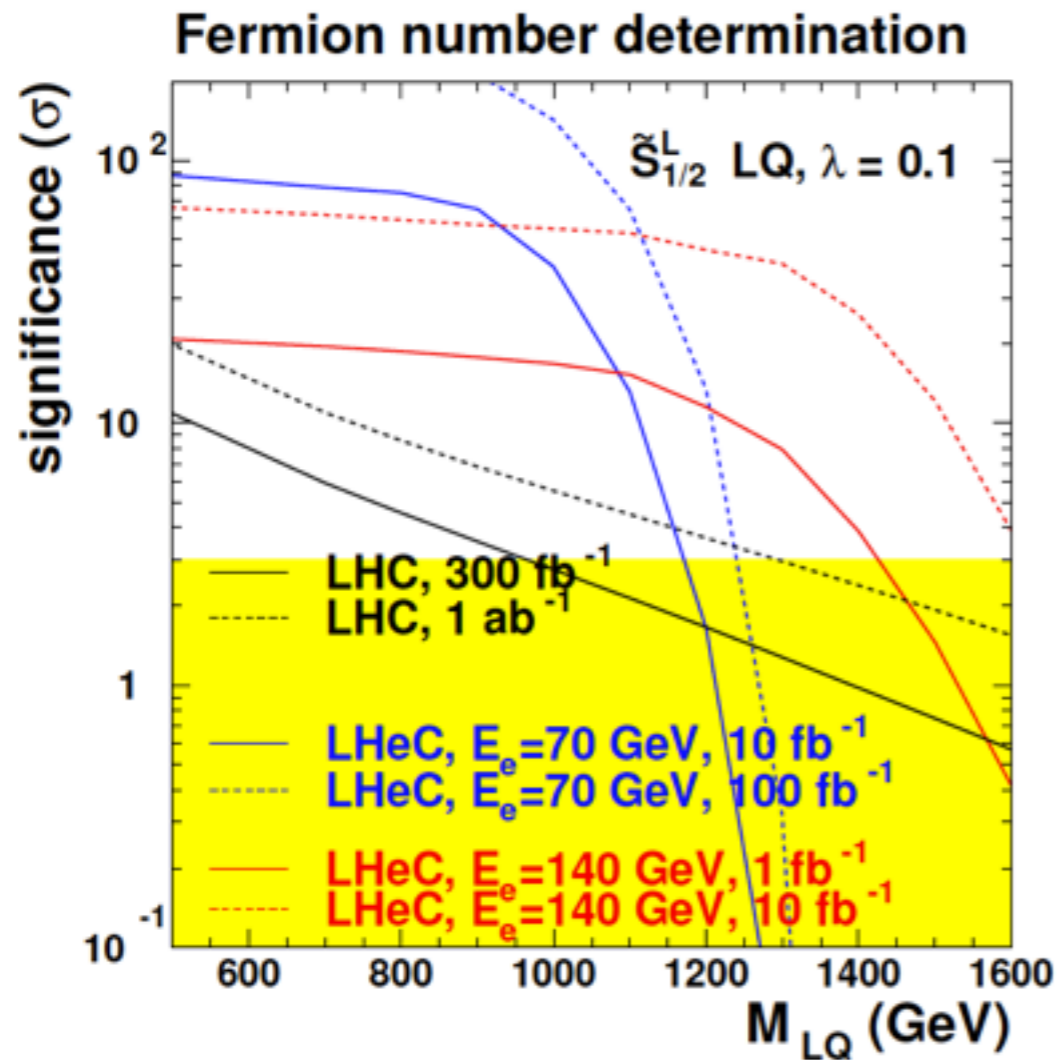


- Why are there quarks and leptons?
- They both experience the electromagnetic and weak forces, but only quarks feel the strong force, why??
- Perhaps quarks and leptons are composites of more fundamental particles, many theories, predict leptoquarks (may also be squarks in RPV SUSY)
- The LHeC provides lepton and baryon number in the initial state, a good leptoquark factory if such things exist

# Clean signatures of new physics - leptoquarks

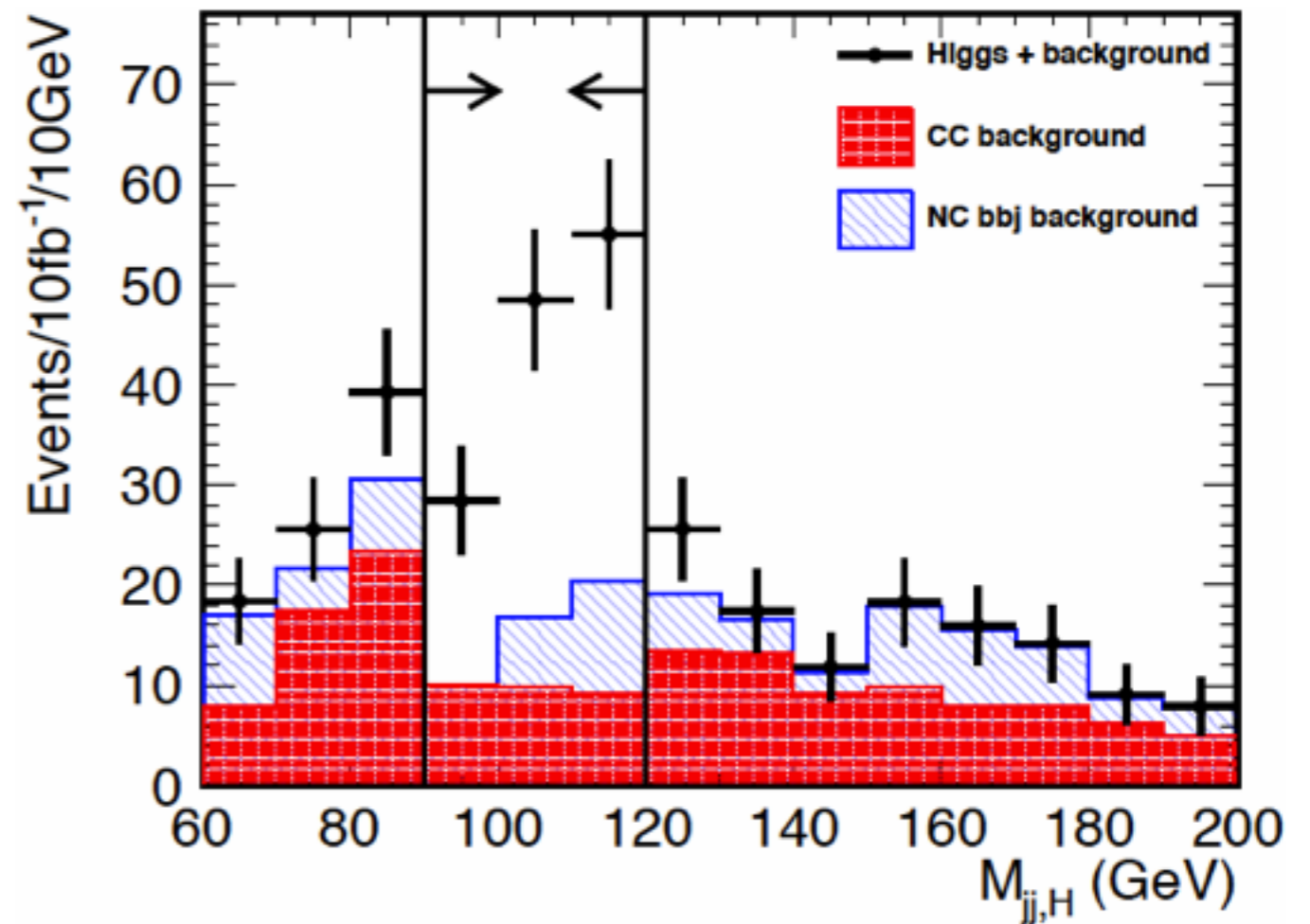
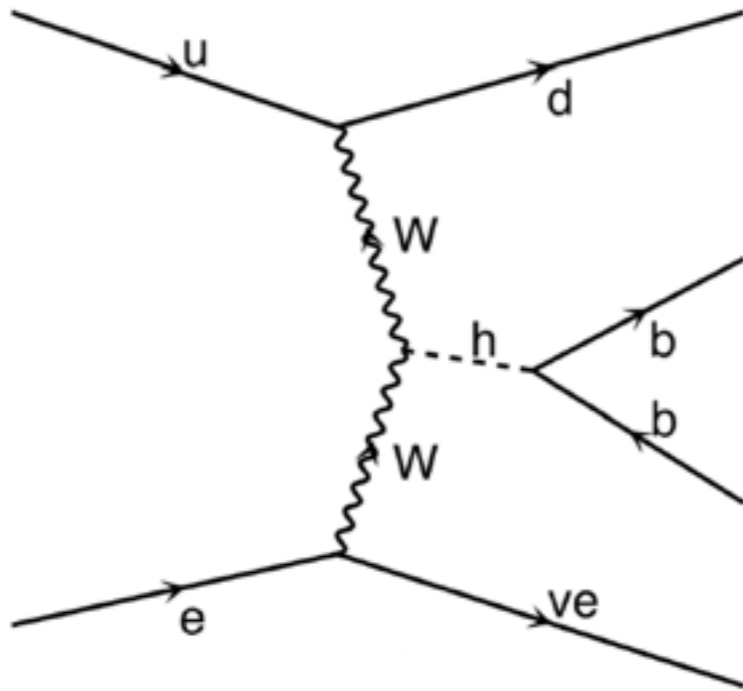


# Leptoquarks



- Similar or better sensitivity than LHC
- The key difference is that, if they exist, the LHeC can characterise them, measuring their quantum numbers
- Similar story for other new physics, e.g. excited electrons (see talk by Azuelos)

# Higgs



- Higgs cleanly produced in CC reactions, ~hundred events
- Particularly interesting if the hints for Higgs at 125 GeV endure
- Studied with the Higgs decaying to  $bb$ , possible due to LHeC tracking detector
- Signal significance of  $\sim 16$  found, clearly worthy of further study!
- See talk of Ishitsuka for more details

# Summary

- QCD will be placed under the electron microscope as never before, completely unfolding the proton
- It is all but impossible to quantify the effect that it will have on our understanding of the proton and QCD - it will change the way we do that physics
- Assumptions will be replaced by measurements of unprecedented precision
- In searches, the LHeC will be a complement to the LHC in a similar way as HERA was to the Tevatron
- The clean experimental environment and final state give the LHeC some advantages, especially regarding measurements of the quantum numbers of new particles

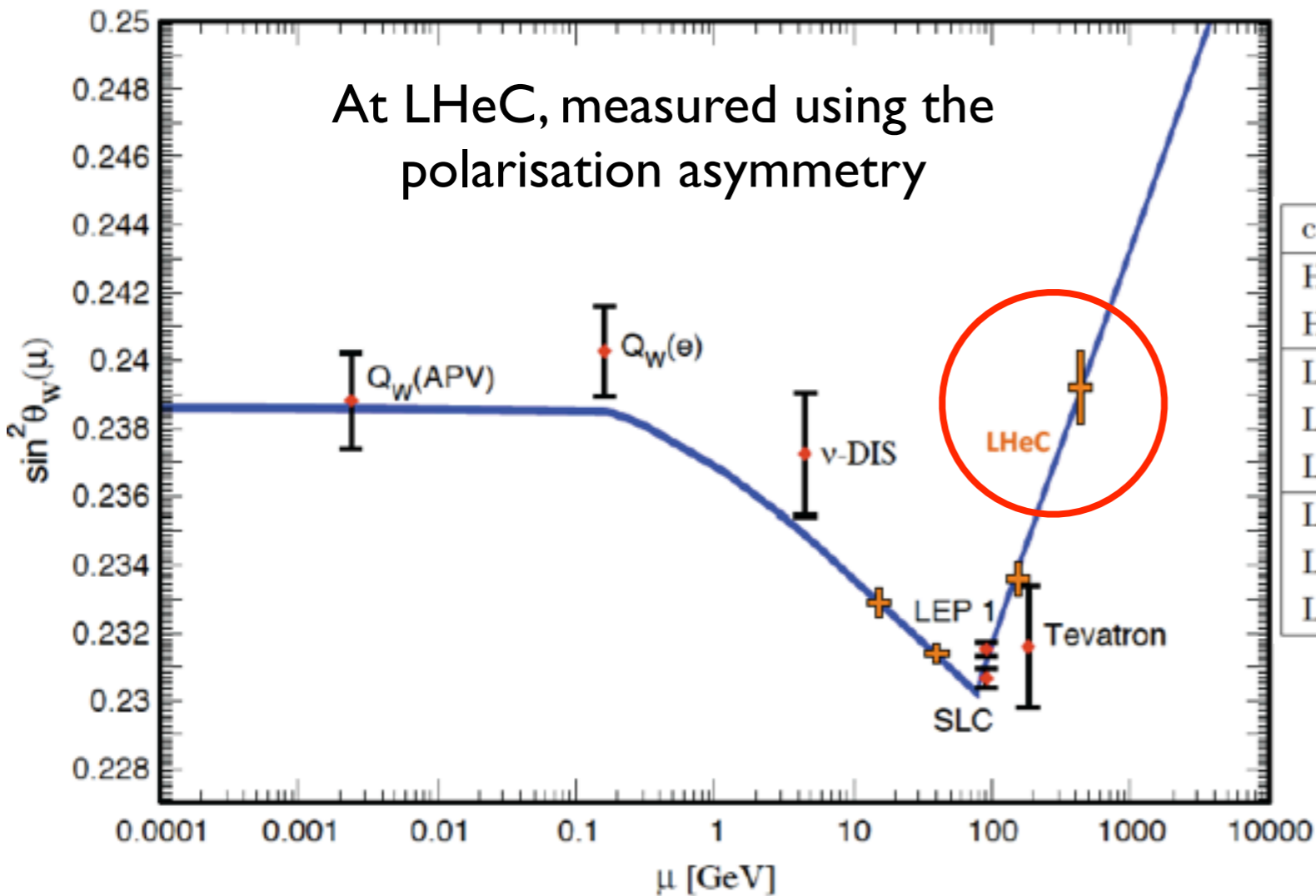
The LHeC will maximise the physics potential of the LHC

“Exploring a new territory with a precision instrument is the key to discovery” - Professor Ting, Erice 2011

# Backup

# Measuring fundamentals

$$\sin^2\theta_W$$



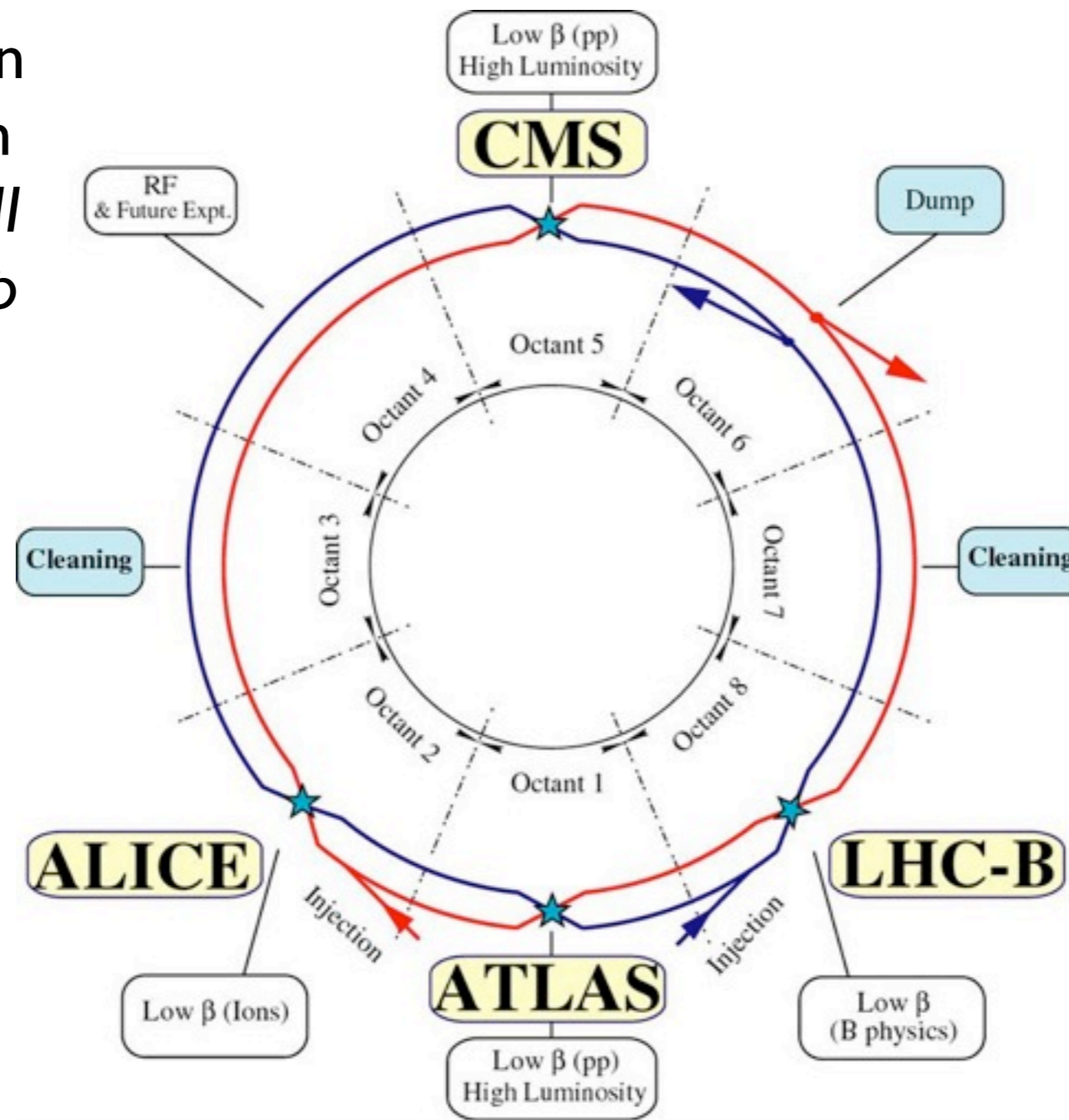
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- The LHeC would be able to measure the value of  $\sin^2\theta_W$  at different  $\mu(Q^2)$
- The strong coupling constant, presently known to  $\sim 1\%$  precision, would be determined at the per mille level
- At a couple per mille for  $Q^2 > 20 \text{ GeV}^2$ , i.e. no non-perturbative effects

# The LHeC Concept

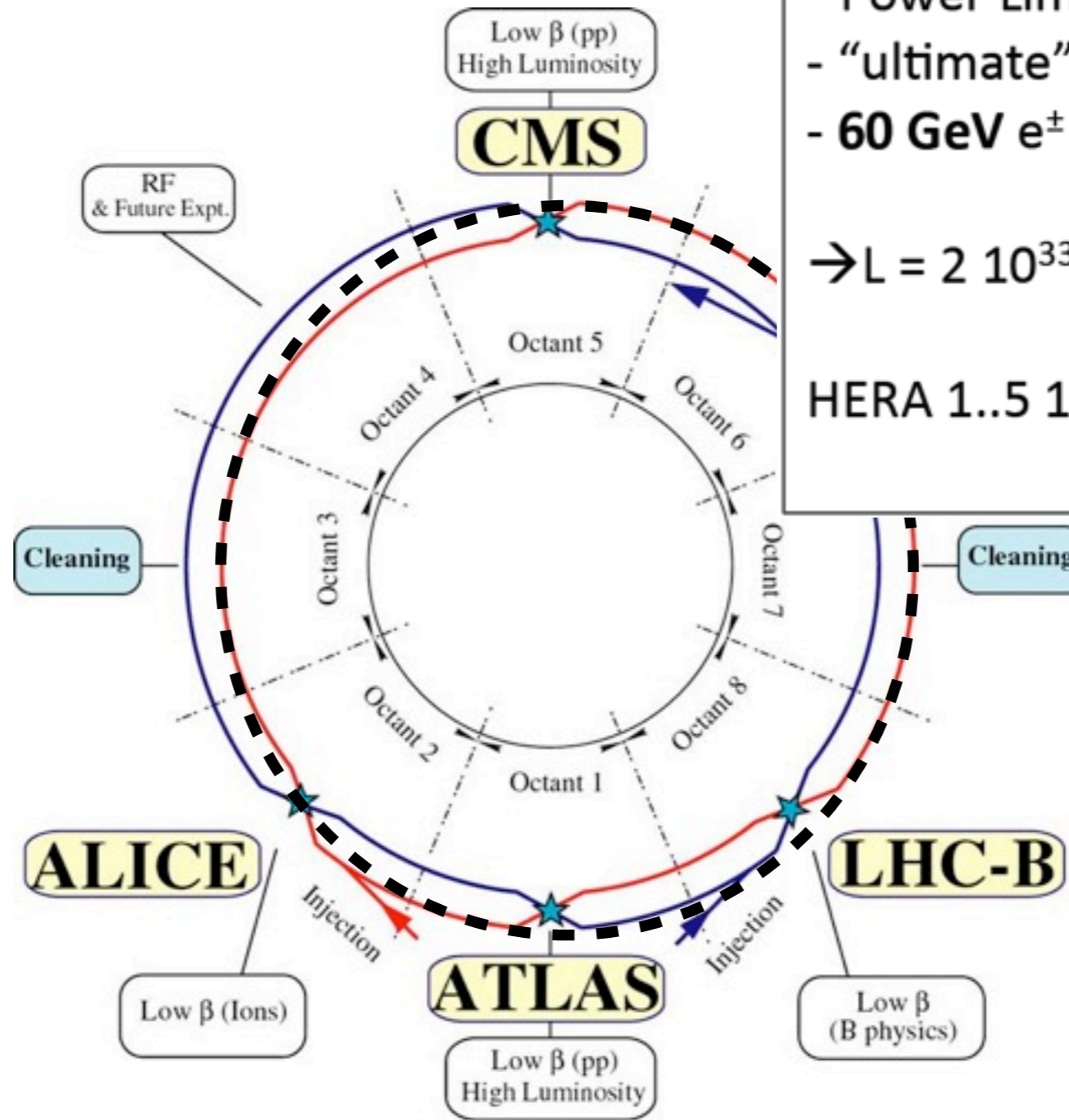
The LHeC  $ep$  program would run *simultaneously* with the LHC  $pp$  and  $HI$  programs (small  $ep$  tuneshifts)



- Collide a new polarised electron beam  $E \sim 60$  GeV with a proton/HI beam of the LHC

# The LHeC - Ring-Ring

To develop the concept, an IP is needed and Alice has been used



- Power Limit of **100 MW wall plug**
- "ultimate" LHC proton beam
- **60 GeV  $e^\pm$  beam**

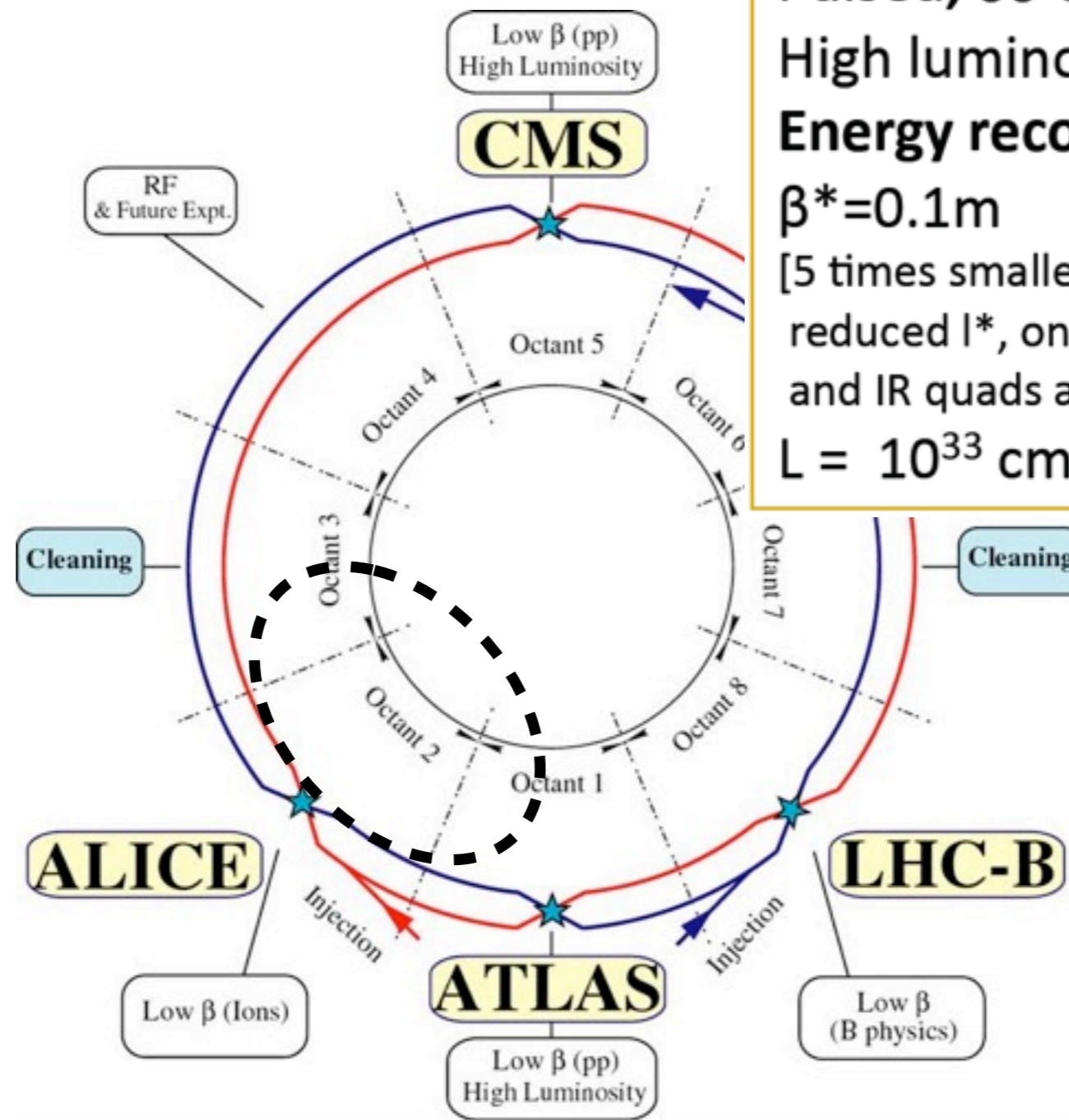
$$\rightarrow L = 2 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1} \rightarrow O(100) \text{ fb}^{-1}$$

$$\text{HERA } 1.5 \cdot 10^{31} \rightarrow 1 \text{ fb}^{-1} (\text{H1+ZEUS})$$

- Either by installing a new electron storage ring in the LHC tunnel (Pol~40%)

# The LHeC - Linac-Ring

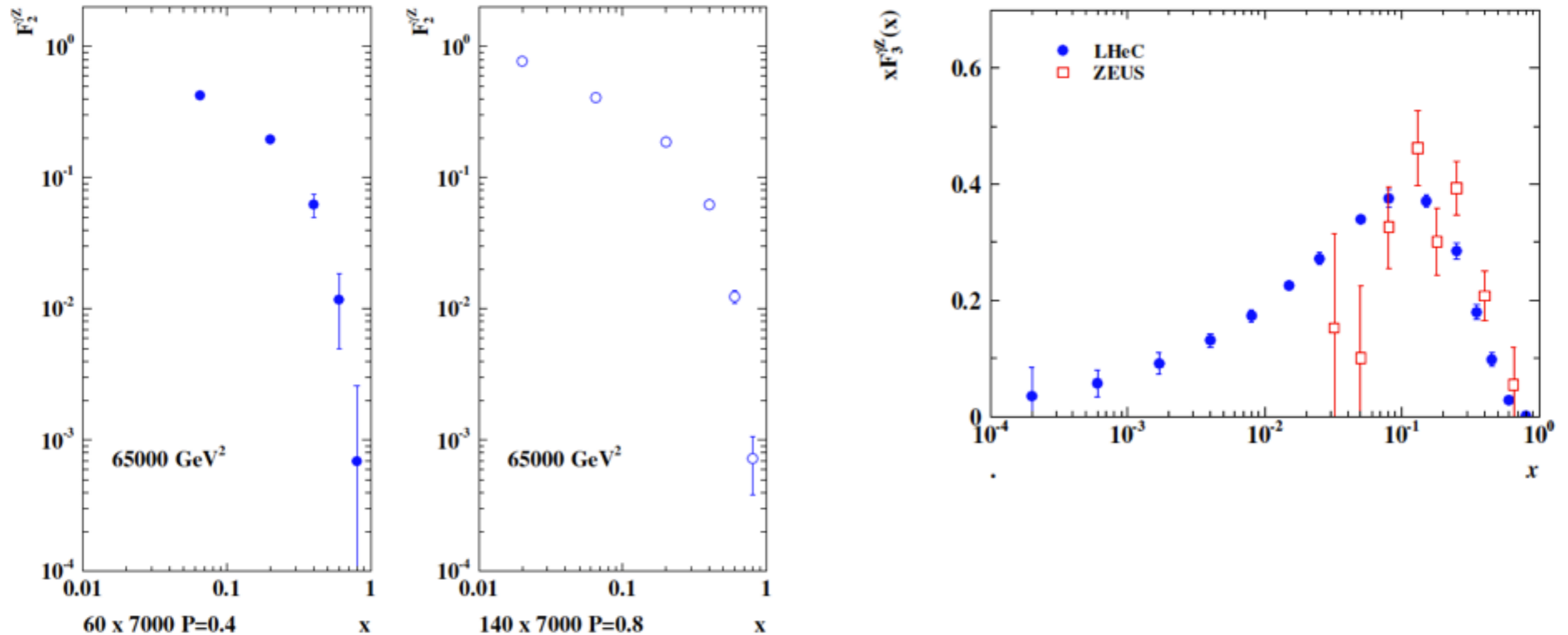
To develop the concept, an IP is needed and Alice has been used



Pulsed, 60 GeV:  $\sim 10^{32} \text{cm}^{-2} \text{s}^{-1}$   
 High luminosity:  
**Energy recovery:**  $P = P_0 / (1 - \eta)$   
 $\beta^* = 0.1 \text{m}$   
 [5 times smaller than LHC by  
 reduced  $I^*$ , only one p squeezed  
 and IR quads as for HL-LHC]  
 $L = 10^{33} \text{cm}^{-2} \text{s}^{-1} \rightarrow O(100) \text{fb}^{-1}$

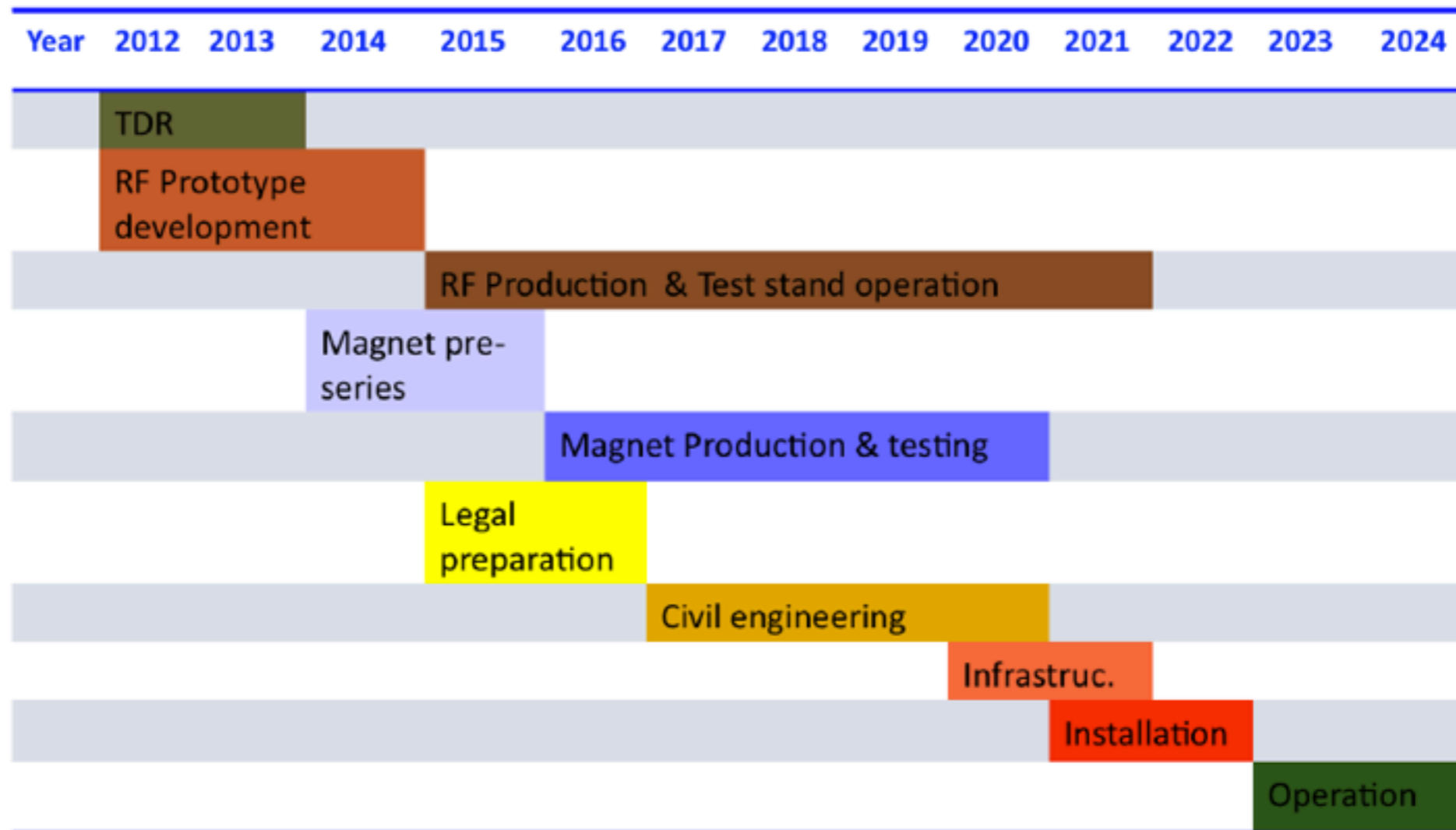
- Or by building a new super-conducting RF electron linac (Pol~90%)

# Neutral Current Boson Interference



- Limited measurements of the interference terms contributing to proton structure
- LHeC measures  $F_2^{YZ}$  for the first time - probing parity violation at small distances
- Also measures  $xF_3^{YZ}$  with good precision - probing the valence at  $x < 10^{-3}$

# Timeline



- The actual timeline will of course be constrained by the LHC, with the installation taking place during the pre-SLHC shutdown around 2021
- The CDR is being finalised now, for referees this month, then finalise and hand CDR to ECFA/ NuPECC/CERN
- Workshop to decide on Ring vs Linac in Fall 2011
- Participate in 2011/2012 European Strategy Process, starting at EPS 2011
- Predicting the future is difficult, but the LHeC realises DIS at the TeV scale