Forward Physics: An Experimental Perspective

Prof Paul Newman
(University of Birmingham)

H1, ATLAS, LHeC, ePIC experiments

(please call me Paul)
Email: p.r.newman@bham.ac.uk

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Lecture 1: Forward Physics and the Low x Frontier

Rough Synopsis

- An enormous topic!
- Overlaps with almost every other lecturer at this school

BUT

- I am an experimentalist (unlike most lecturers)
- This is a personal (and maybe complementary) view, guided by the data

Lecture 1: Forward Physics & the Low x Frontier

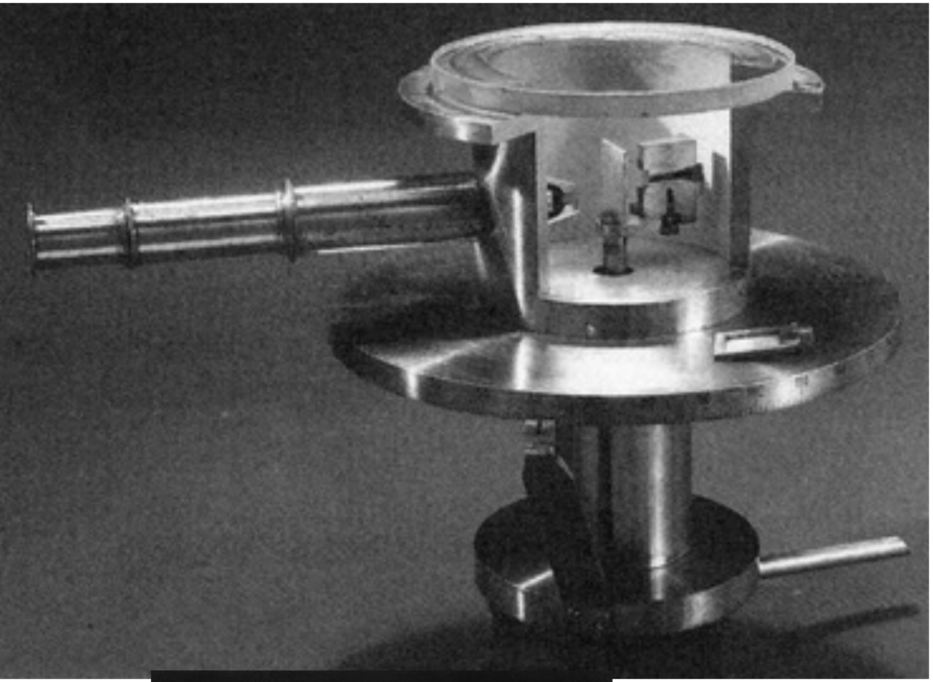
Lecture 2: Forward Physics & Diffraction in pp Collisions

Lecture 3: Diffractive DIS and Future Lepton-Hadron Prospects

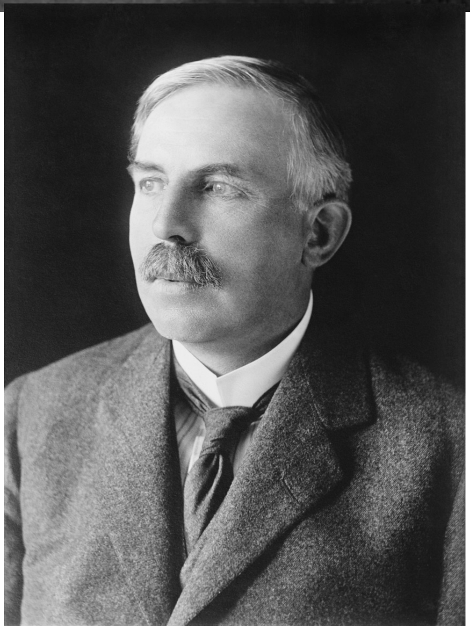
Lecture 1

- Scattering experiments
- Deep Inelastic Lepton-Hadron Scattering
- Forward Physics is Low-x Physics
- Situation from HERA
- ‘Mainstream’ LHC / pp observables

Rutherford (1927, as President of Royal Society)



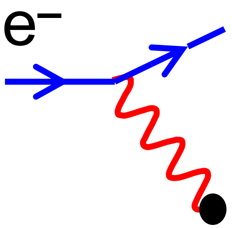
Following from the original scattering experiments (α particles on gold foil target) …



"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."

Probing the Proton with Electrons

Simple uncertainty principle arguments:



Resolved dimension: $\Delta x \sim \frac{200}{E\ (\text{MeV})}$ MeV fm

… need a beam energy of ~200 MeV to see proton structure (~1 fm)

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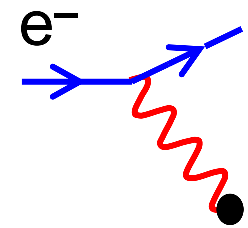

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1950s
Hoffstadter

First
observation
of **finite proton size**
using ~200 MeV e beam

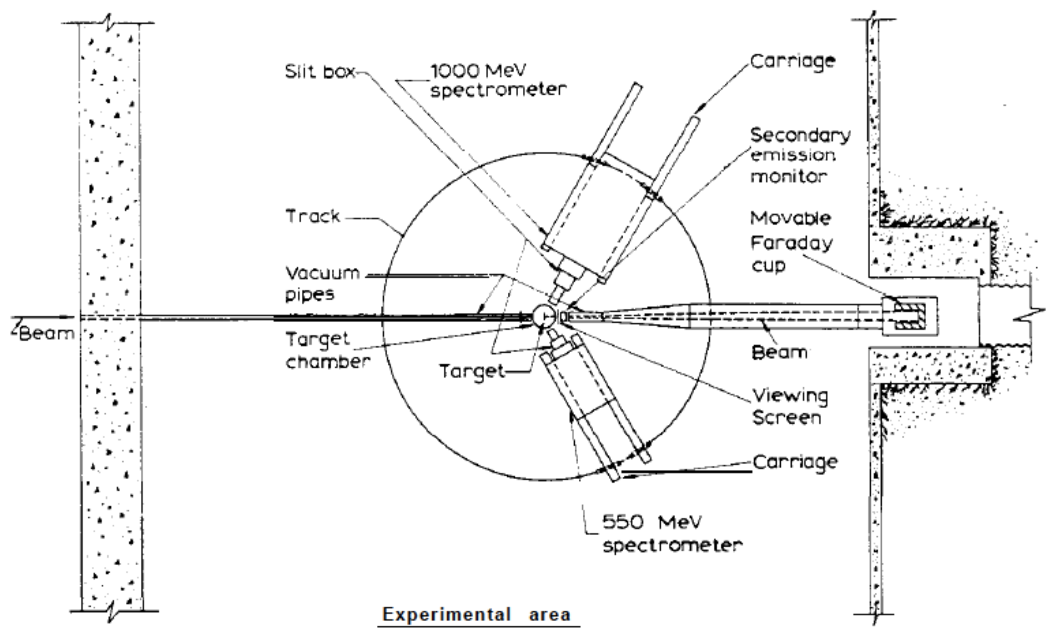


Fig. 2. This figure shows a schematic diagram of a modern electron-scattering experimental area. The track on which the spectrometers roll has an approximate radius of 13.5 feet.

Hoffstadter's Results

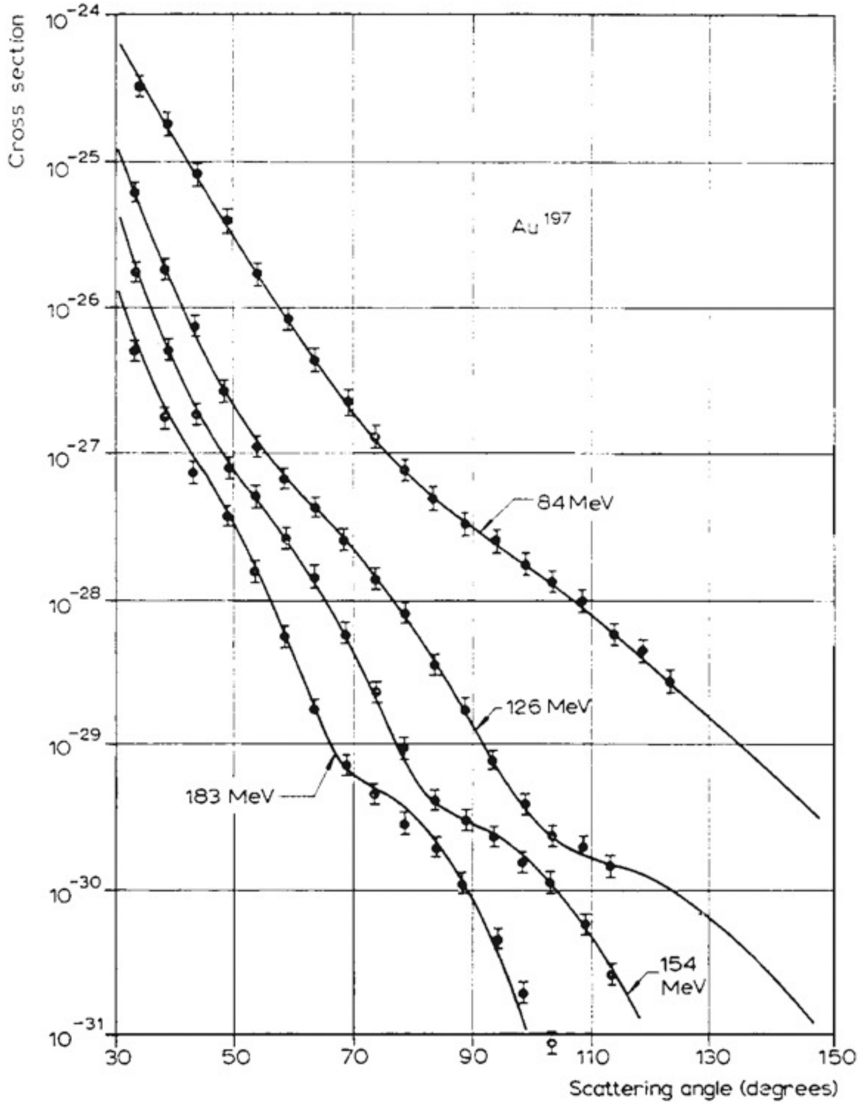
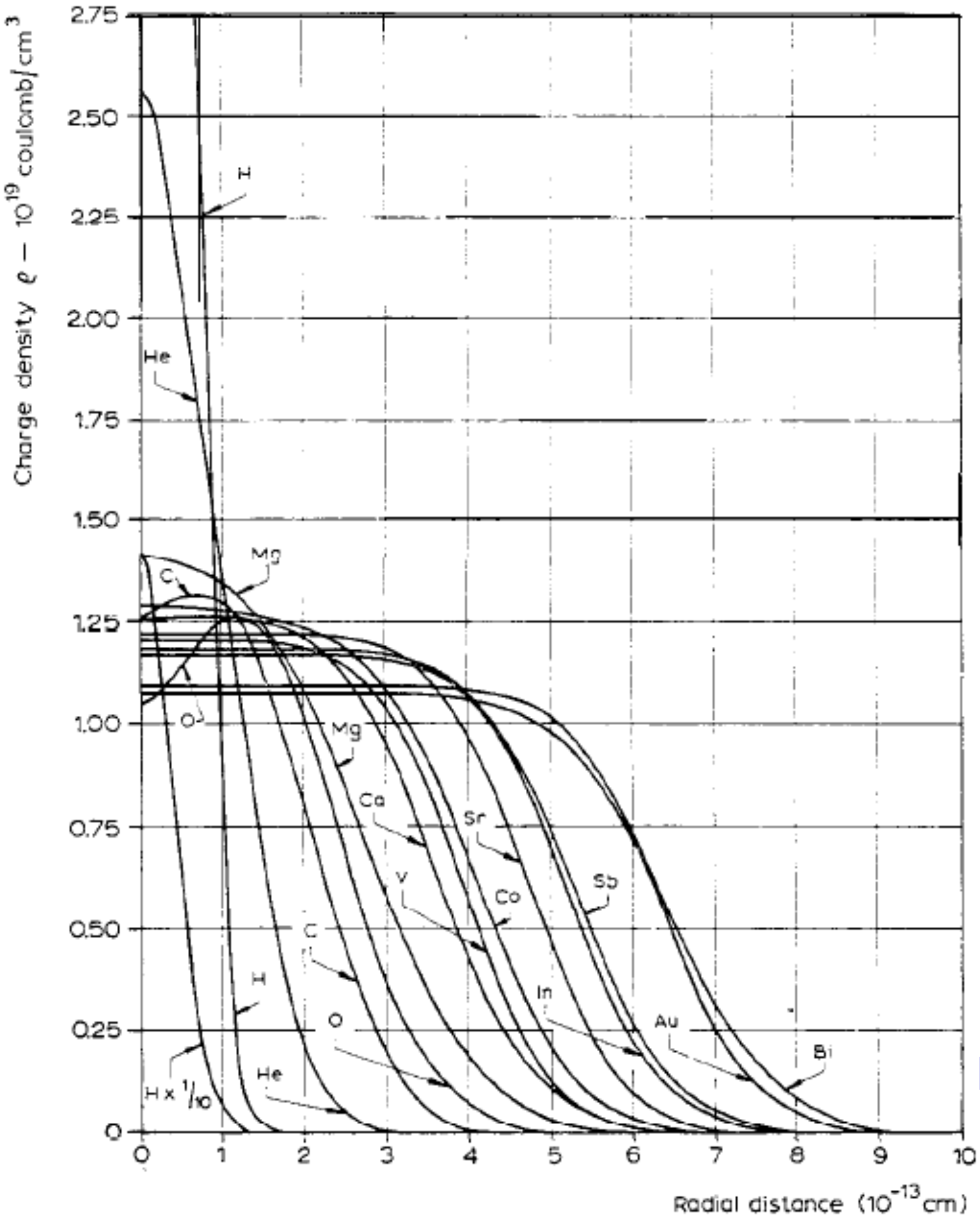


Fig. 6. The *points* represent experimental data observed by scattering electrons of the appropriate incident energies from gold nuclei[9]. The *solid lines* are calculated angular distributions for a model of the gold nucleus similar to that shown in Fig. 8.

… essentially taking
a Fourier transform
of the pattern of emerging
scattered electrons
to determine spatial
distribution of the
target charge distribution

[cf Rutherford scattering]

Hoffstadter's Results



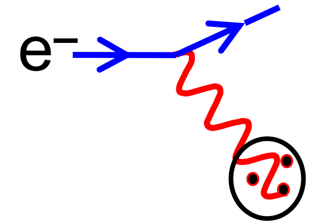
… essentially taking a Fourier transform of the pattern of emerging scattered electrons to determine spatial distribution of the target charge distribution

[cf Rutherford scattering]

Although suggestive, finite spatial size does not necessarily imply proton has identifiable constituents!

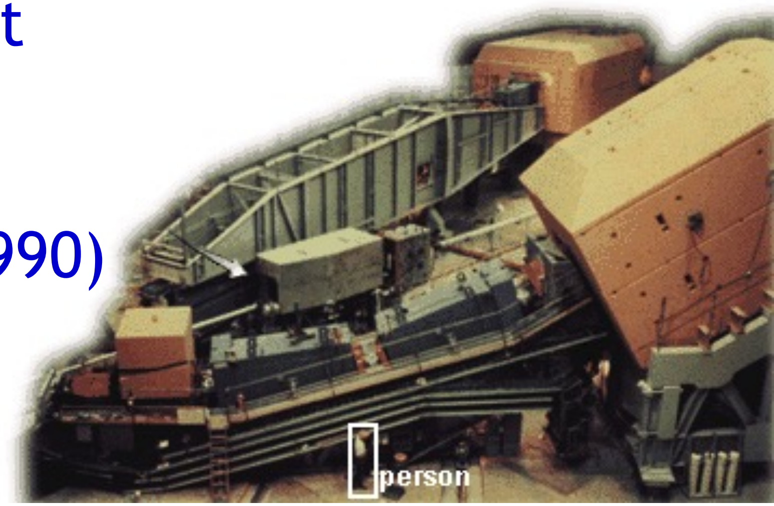
Probing the Proton with Higher Energy Electrons

… 1-2 more orders of magnitude → 0.1-0.01 fm



ESA experiment
At SLAC (1969)

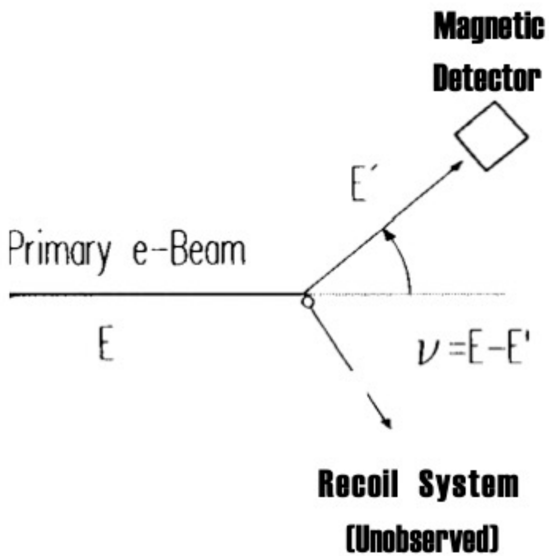
Nobel prize (1990)



- Linear electron accelerator (~20 GeV)
- Fixed proton target
- Measure cross section v scattered electron energy and angle
- Some very wide-angle scattering confirmed proton contains point-like scattering centres (now called quarks)

SLAC: Electron Energies ~20 GeV on protons

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



[Magnetic field allows scattered electron energy measurement as well as angle]

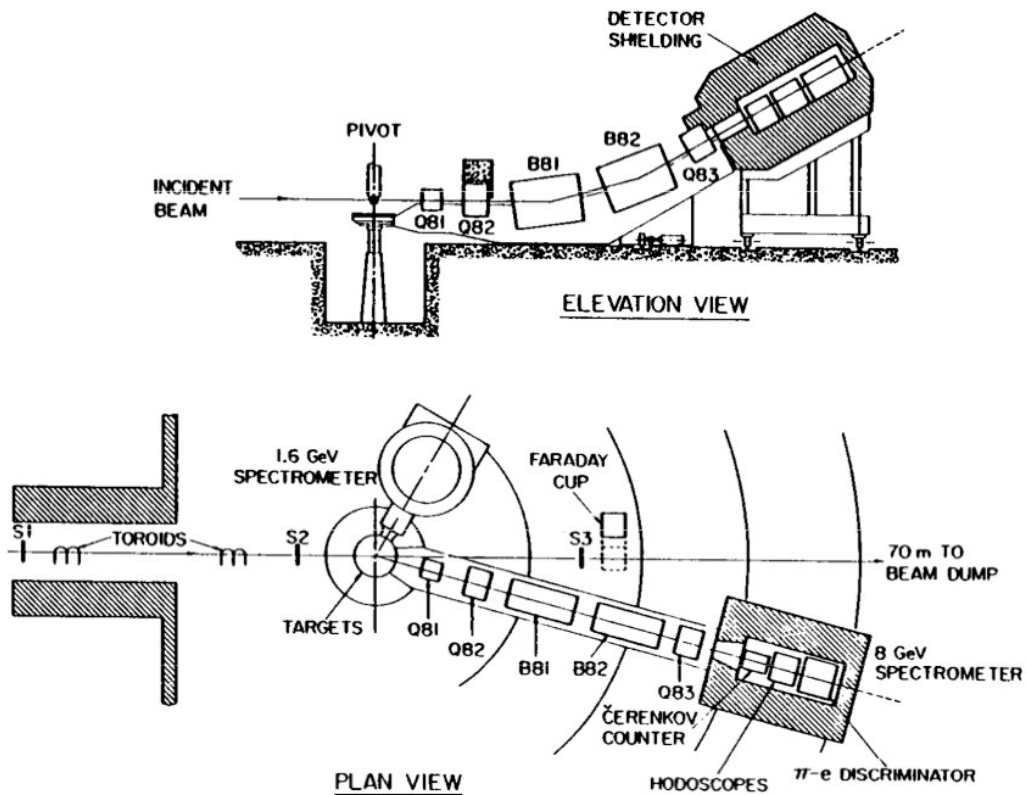


Fig. 2. (a) Plan view of End Station A and the two principal magnetic spectrometers employed for analysis of scattered electrons. (b) Configuration of the 8 GeV spectrometer, employed at scattering angles greater than 12°.

SLAC: Electron Energies ~20 GeV on protons

Q^2 = squared 4-momentum transfer

Absence of dependence of the (suitably expressed) cross section on the momentum transferred (correspondingly the 'resolution' of the probe) implies scattering from point-like 'parton' objects … i.e. QUARKS

We will see this scaling in its full glory in a moment

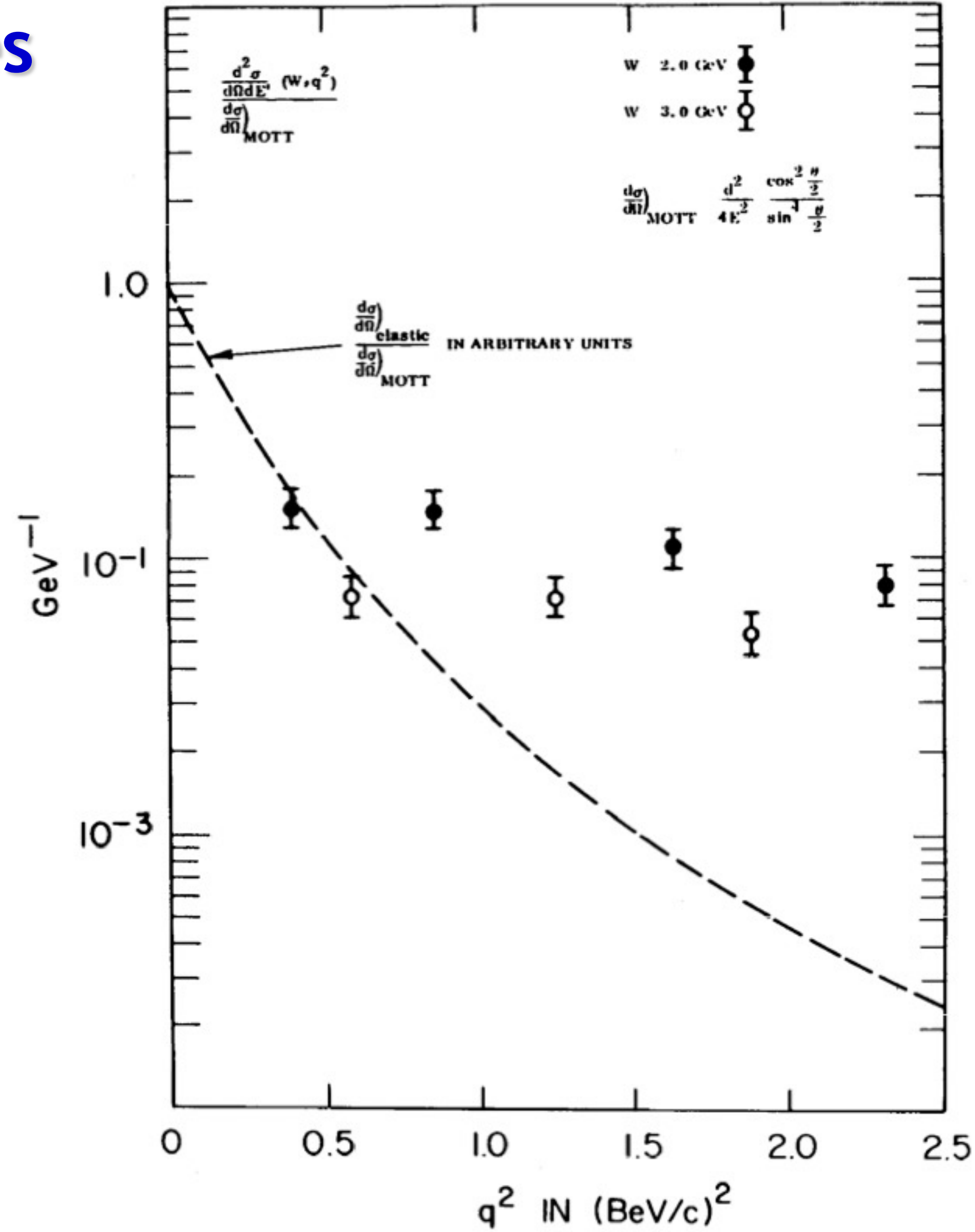


Fig. 11. Inelastic data for $W = 2$ and 3 GeV as a function of q^2. This was one of the earliest examples of the relatively large cross sections and weak q^2 dependence that were later found to characterize the deep inelastic scattering and which suggested point-like nucleon constituents. The q^2 dependence of elastic scattering is shown also; these cross sections have been divided by σ_M

- The only ever collider of electron with proton beams:

$\sqrt{s_{ep}}$ ~ 300 GeV

- Equivalent to **50 TeV** electrons on fixed target

… Resolved dimension

~ 10^{-20} m

… at such scales, proton structure is resolved in exquisite detail

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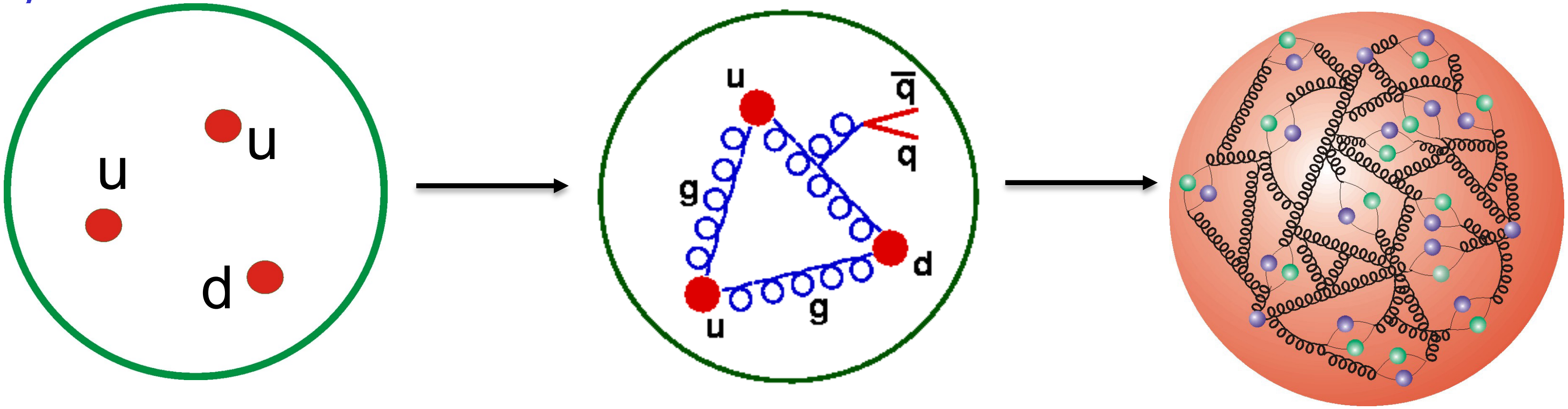
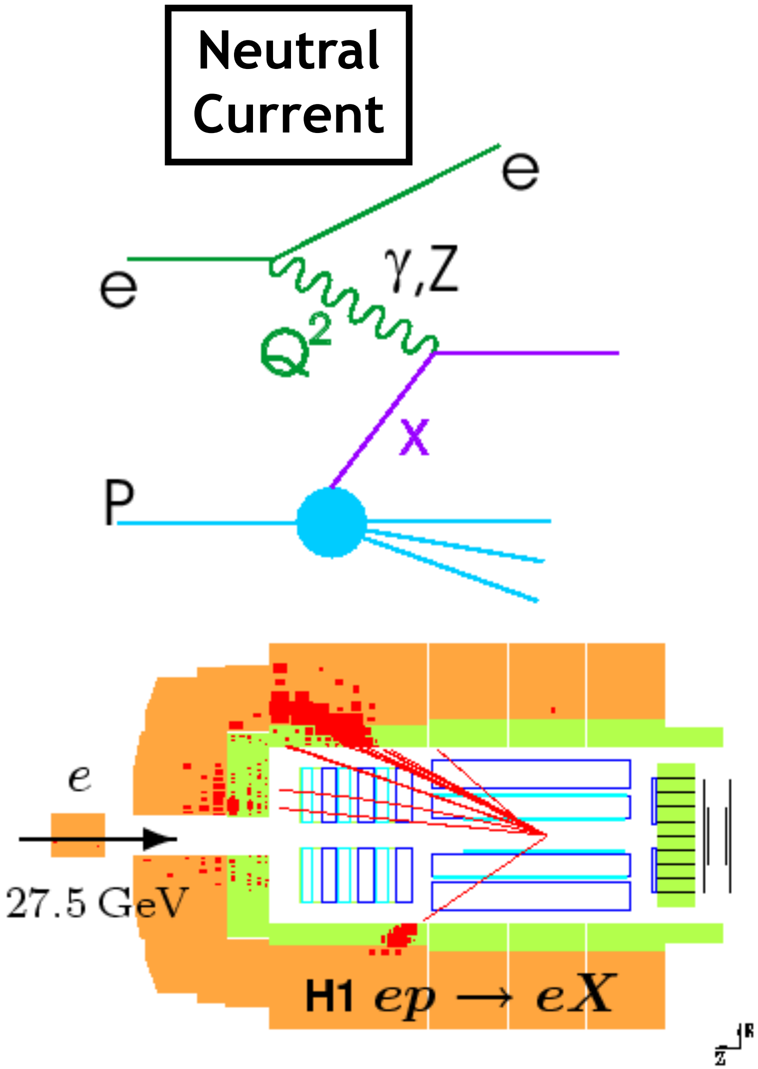
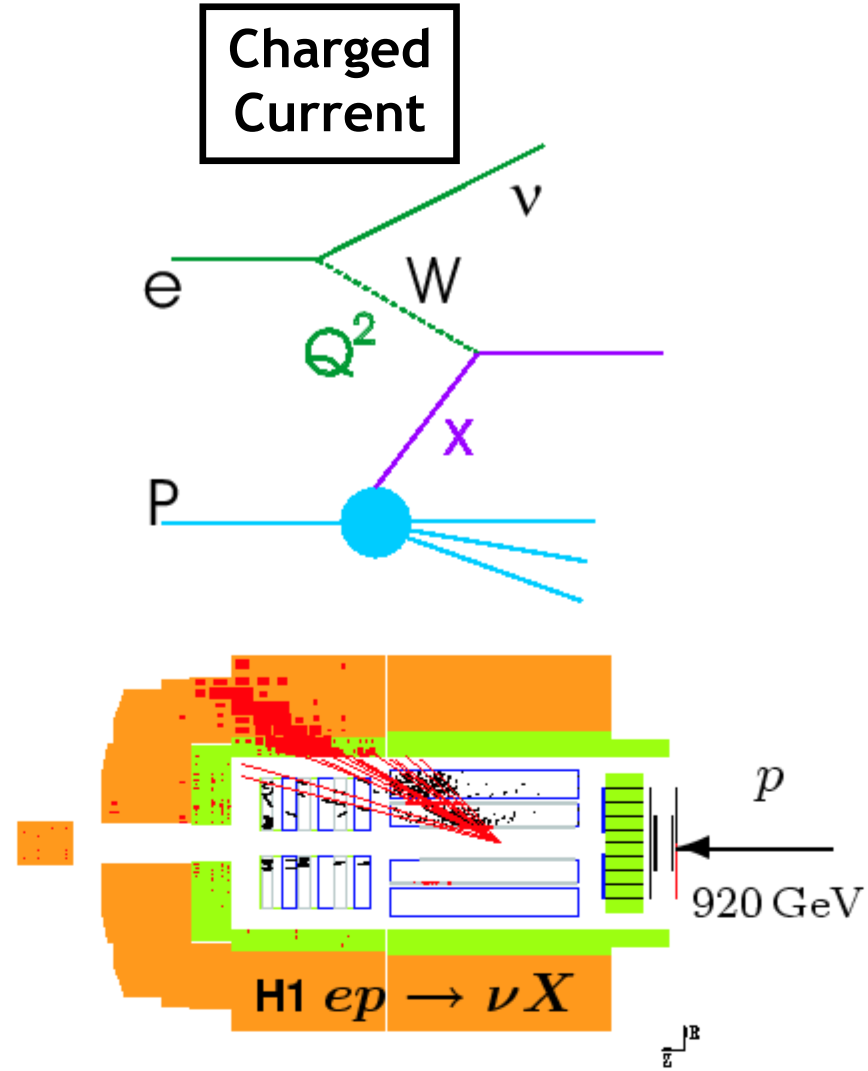
… birth of experimental low x physics



Basic Deep Inelastic Scattering Processes

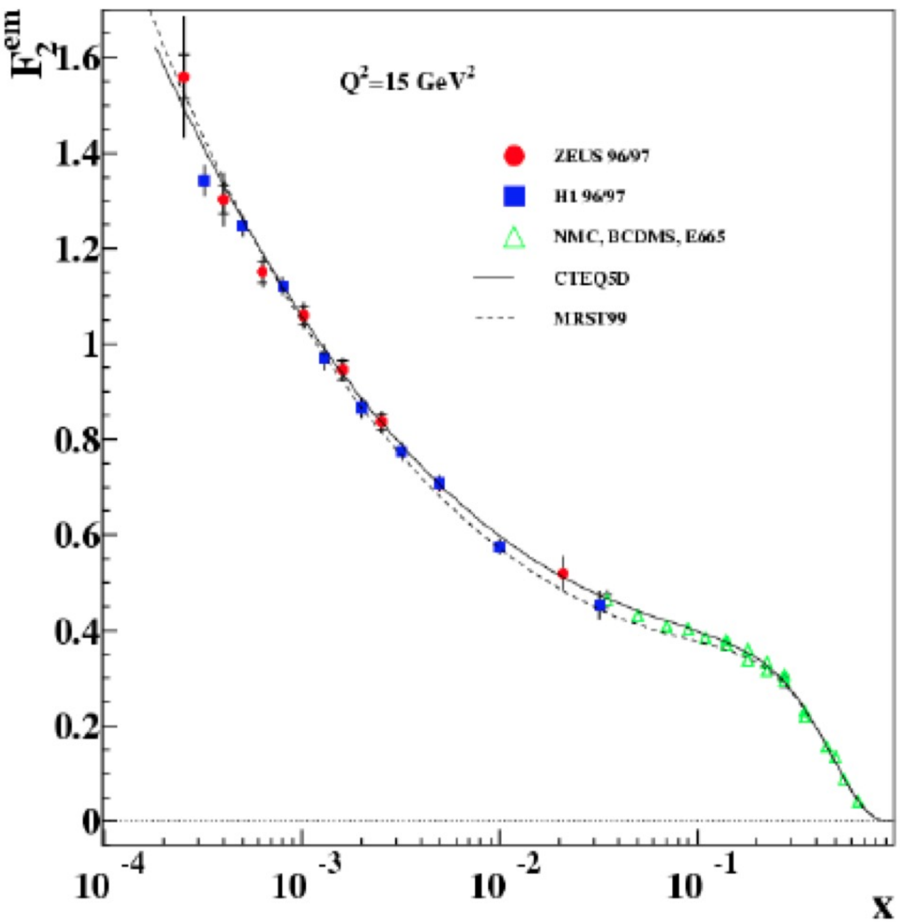


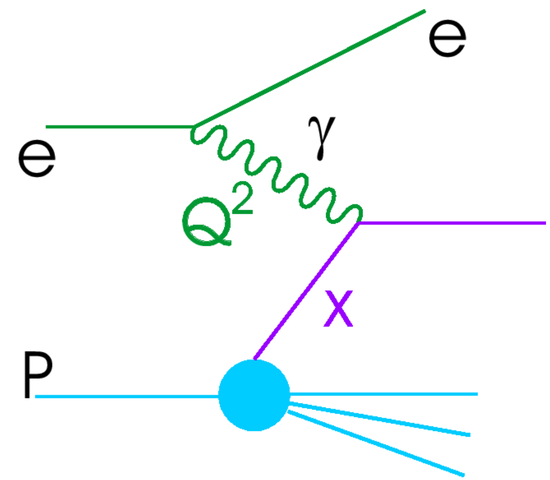


We will only be concerned with Neutral Currents here

Example Inclusive Neutral Current Data

Fixed target and (early) HERA data
at a single Q^2 value (15 GeV^2)





- Photon-exchange component of NC data measures

$$\frac{d\sigma}{dxdQ^2} \sim F_2 = \sum_q e_q^2 \, x \, (q + \bar{q})$$

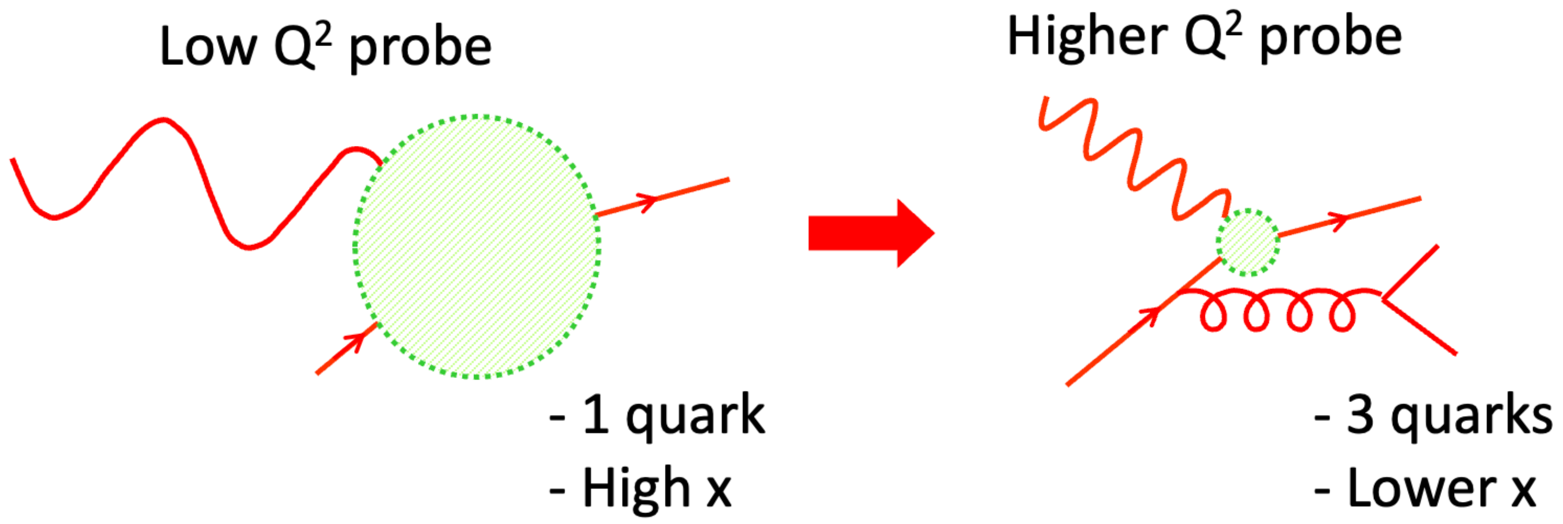
- Due to e_q^2 photon coupling, this mainly constrains **u & ubar**

… shape of quark densities already qualitatively apparent

QCD Evolution

- Variations of the cross sections / structure functions with Q^2 tell us about the role of gluons.

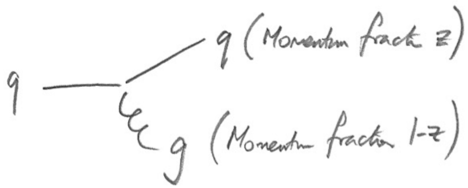
- … a higher Q^2 probe will see more structure than a lower Q^2 probe.

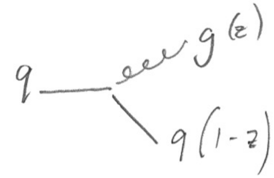


- DGLAP equations formalise this via splitting functions …

DGLAP in 1 Slide

Splitting functions are functions of momentum-share z … calculable in QCD …





$$P_{qq}(z) = \frac{4}{3}\left(\frac{1+z^2}{1-z}\right)$$

$P_{gq}(z)$

$P_{qg}(z)$

$P_{gg}(z)$

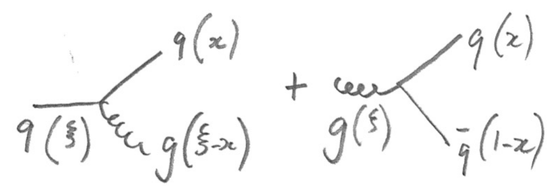
- So that (with similar expression for gluons):

$$\frac{\partial q(x,Q^2)}{\partial \ln Q^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{d\xi}{\xi}\left[P_{qq}\left(\frac{x}{\xi}\right)q(\xi,Q^2) + P_{qg}\left(\frac{x}{\xi}\right)g(\xi,Q^2)\right]$$

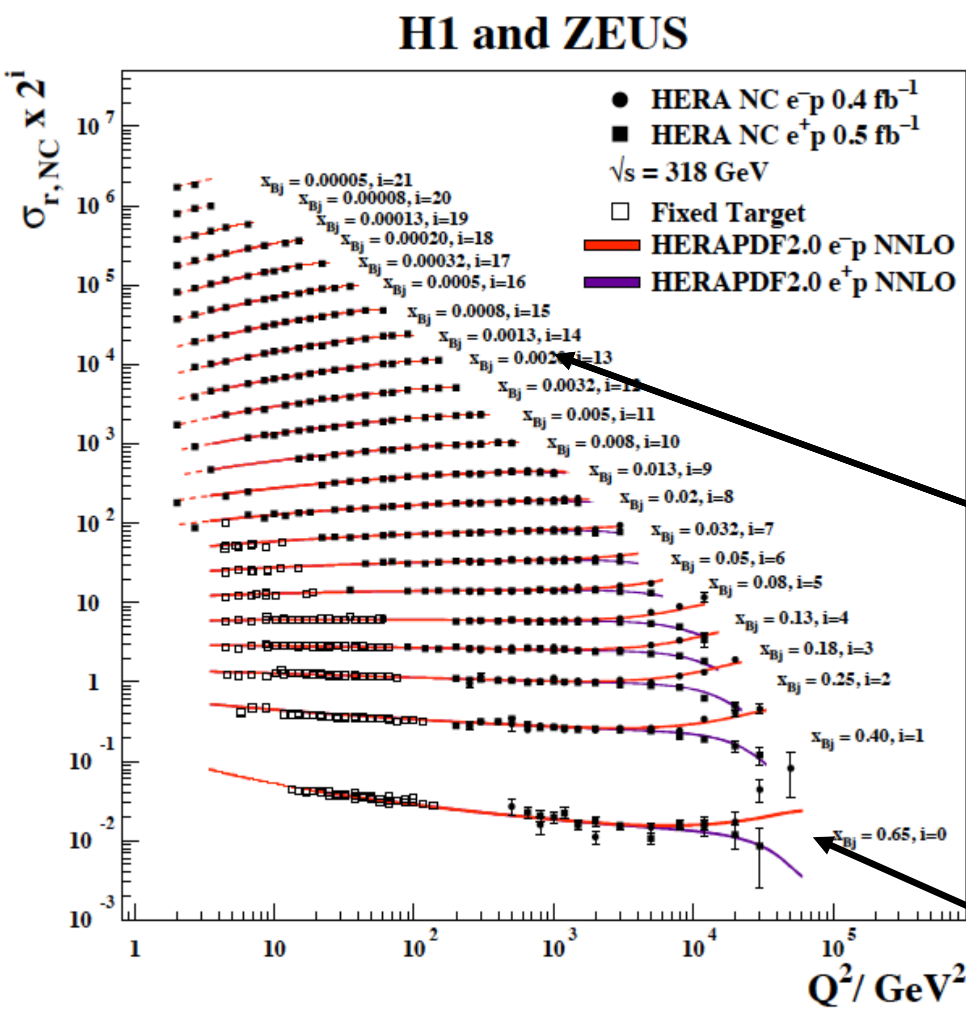
ξ is the x value of the parent parton … could have been anything from x to 1

Splitting functions × parent quark or gluon distributions

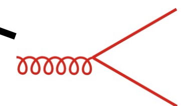
i.e. we are integrating $x < \xi < 1$ for …



Simple Model of QCD Evolution in HERA Data



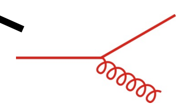
Valence quarks split to produce gluons ($q \to qg$)
… which split to produce more gluons ($g \to gg$) … and more …
… until at some point they split to produce quarks that couple to the photon ($g \to q\bar{q}$)



dominates $\frac{\partial q}{\partial \ln Q^2}$ at low x

Approximately (‘Prytz’):

$$\frac{d\, F_2(x,Q^2)}{d \ln Q^2} \approx G(2x, Q^2)$$

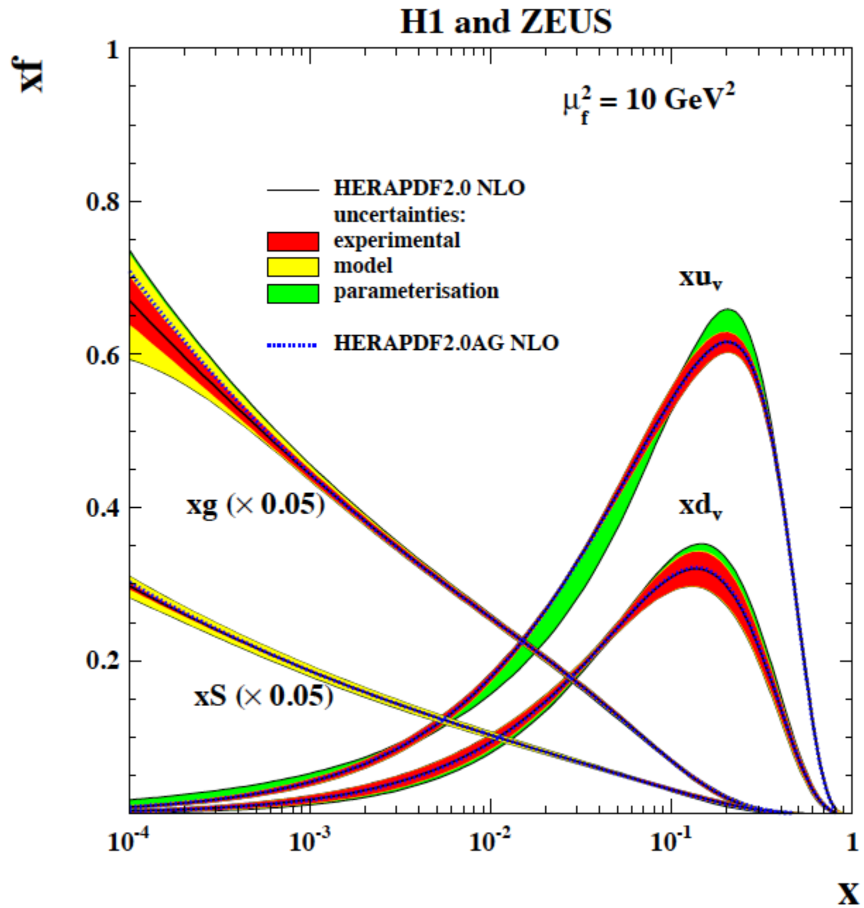


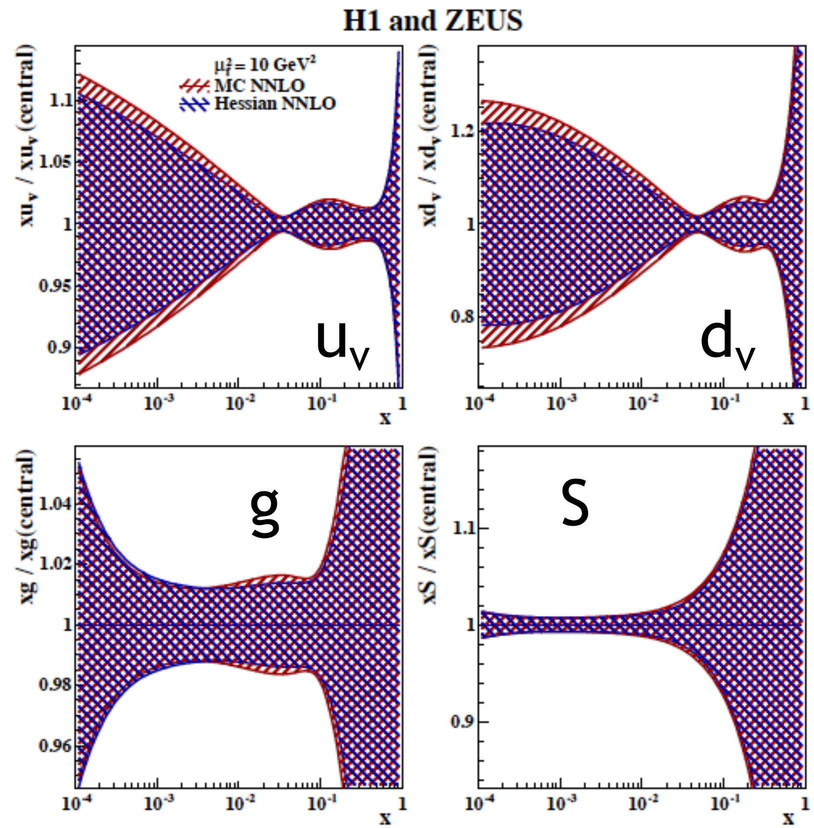
dominates $\frac{\partial q}{\partial \ln Q^2}$ at x→1

- NC Q² evolution yields low-medium x gluon via $g \to q\bar{q}$
- High x gluon is tougher, because $q \to qg$ dominates!

→ Other observables needed …

Final HERA Picture of Proton (HERAPDF2.0)





- ~2% precision on gluon for $10^{-3} < x < 10^{-1}$
- Gluon uncertainty explodes between $x=10^{-3}$ and $x=10^{-4}$
- **Gluon itself is rising in a seemingly non-sustainable way!...**
- Note the ‘Standard’ presentation is at $Q^2 = 10\ GeV^2$

The “Pathological” Gluon: Implications

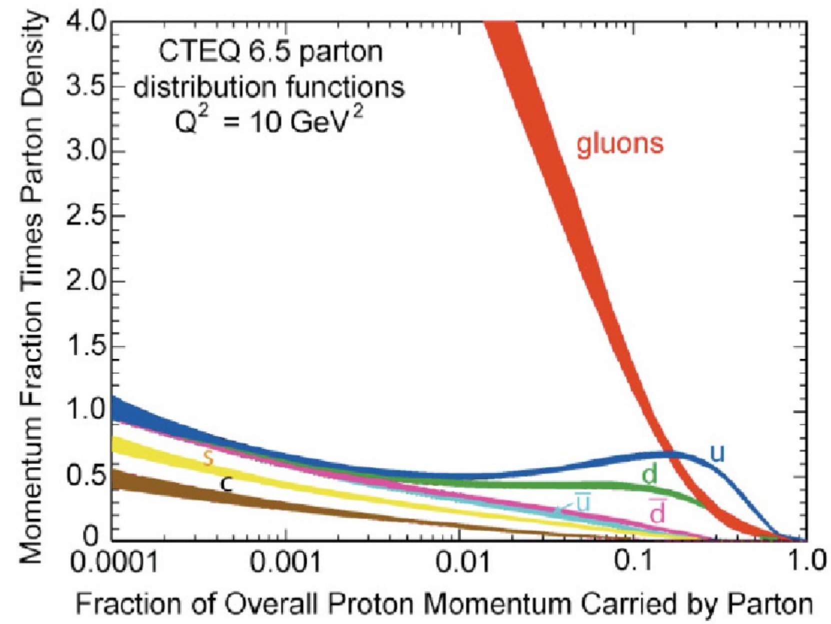
- Fast growth of low x gluon appears unsustainable → expect new low x gluon-driven dynamics …

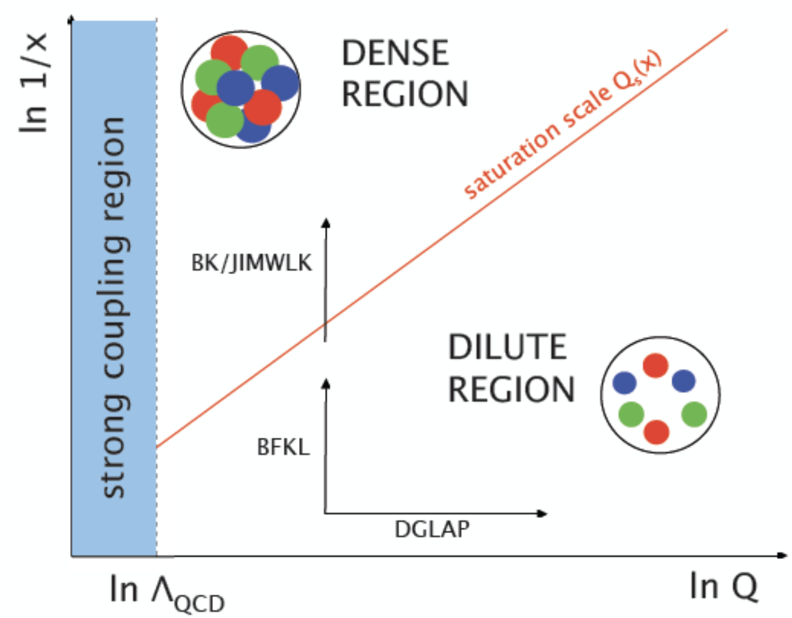
- Two different types of effect:

1) High energy …
   - $\ln(^1/_x)$ resummation (BFKL) leads to deviations from pure DGLAP evolution

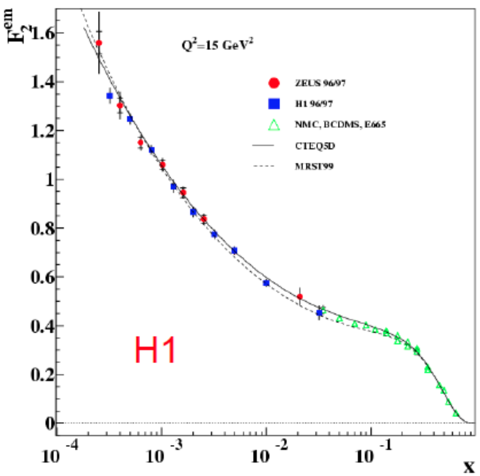
2) High density …
   - Recombination $(gg \to g)$?
     → Non-linear evolution
   - And other density-driven models yielding saturation / taming the low-x growth

… Rich phenomenology!
… But what do we see in HERA data?...





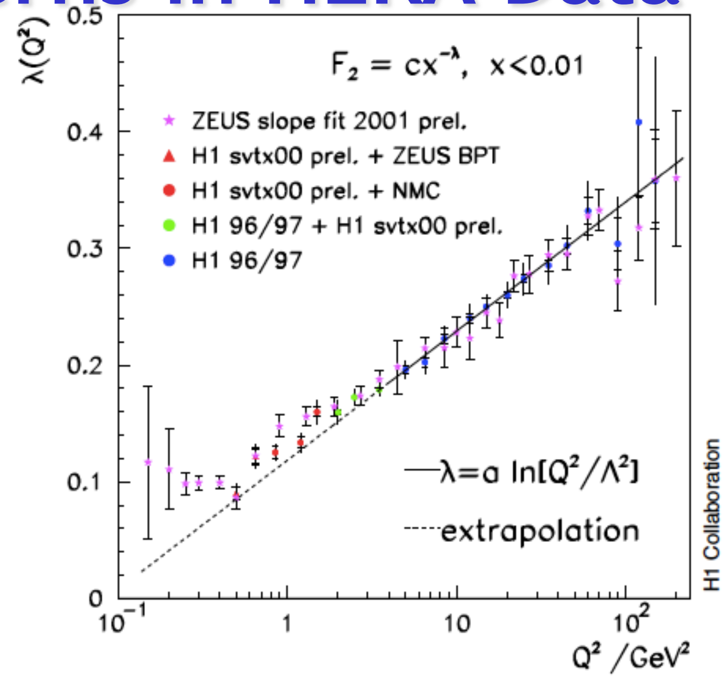
Looking for Changes in patterns in HERA Data

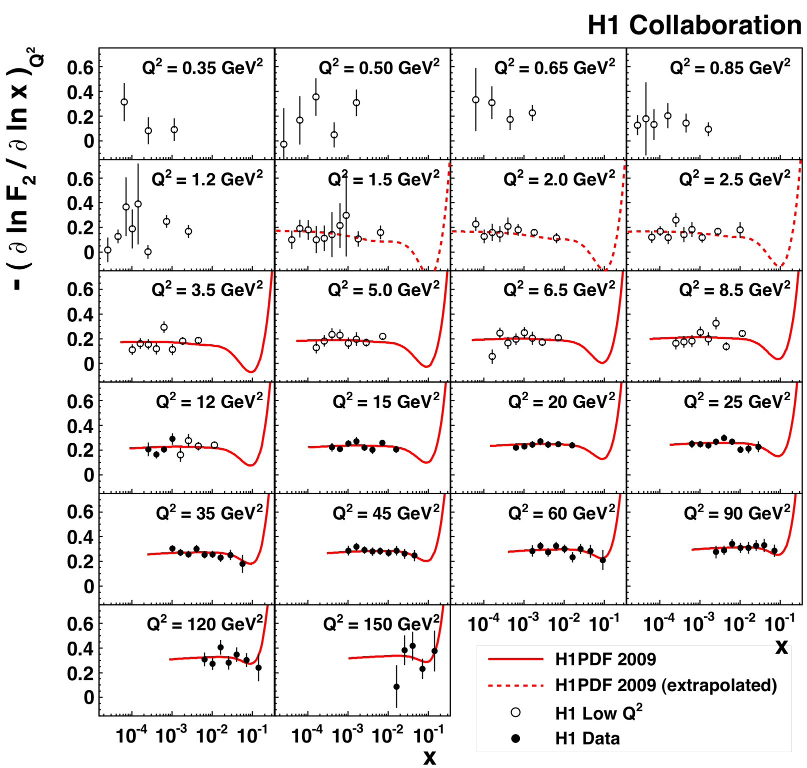


HERA inclusive data quite well parameterized by …

$$F_2 = Ax^{-\lambda(Q2)}$$

with fixed A~0.2 for all Q^2 >~ 1 GeV^2





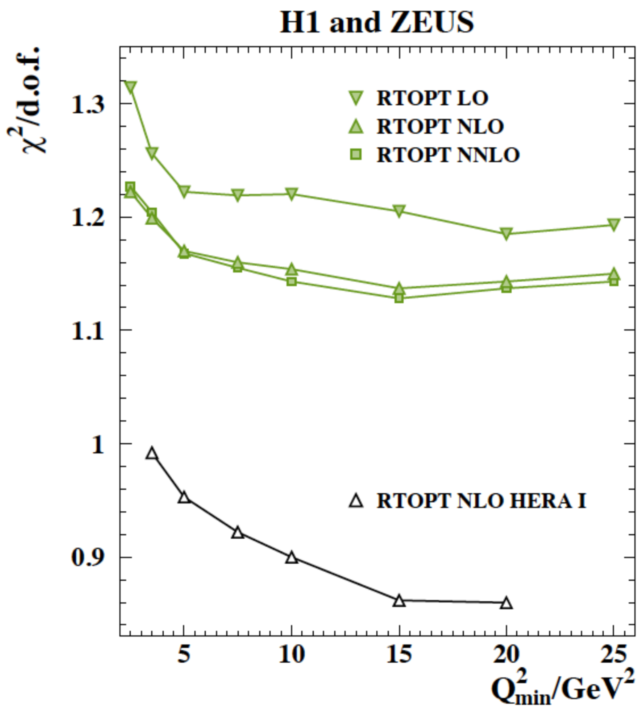
Also from 2D local x-derivatives:

… no evidence for deviation from monatonic rise of structure functions at low x in perturbative region.

… no smoking guns

→ any effects are subtle

Subtle Low x effects at HERA?

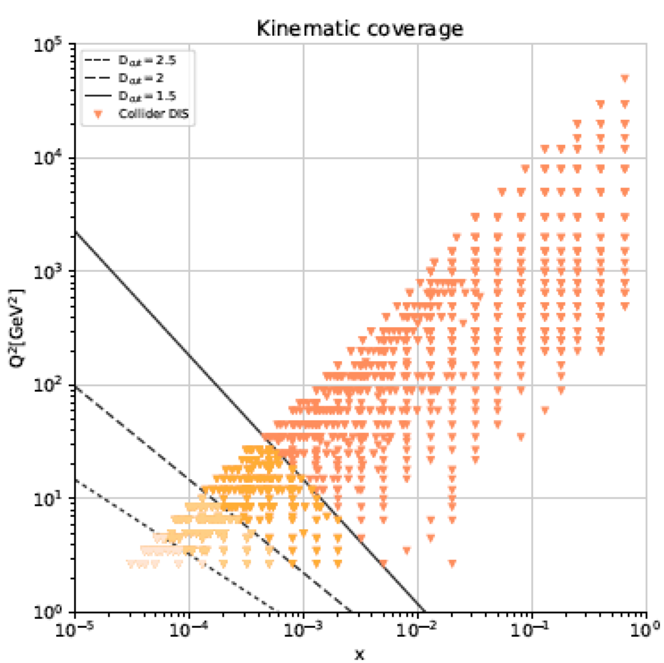


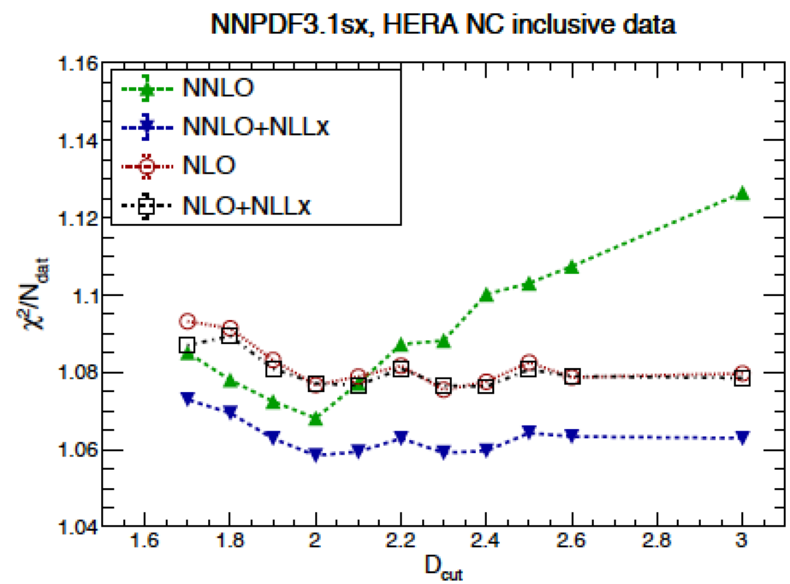
Final HERA-2 Combined PDF Paper:

- Quality of DGLAP PDF fit deteriorates as minimum Q^2 of data is reduced
- Could be a low x effect, since x and Q^2 are kinematically correlated

Including ln(1/x) resummation:

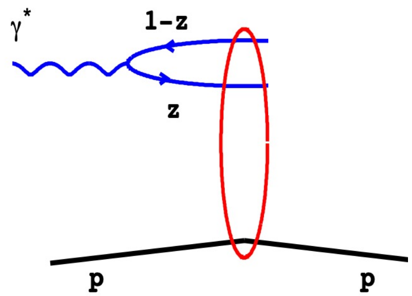
… improves χ^2 and describes low x, low Q^2 corner

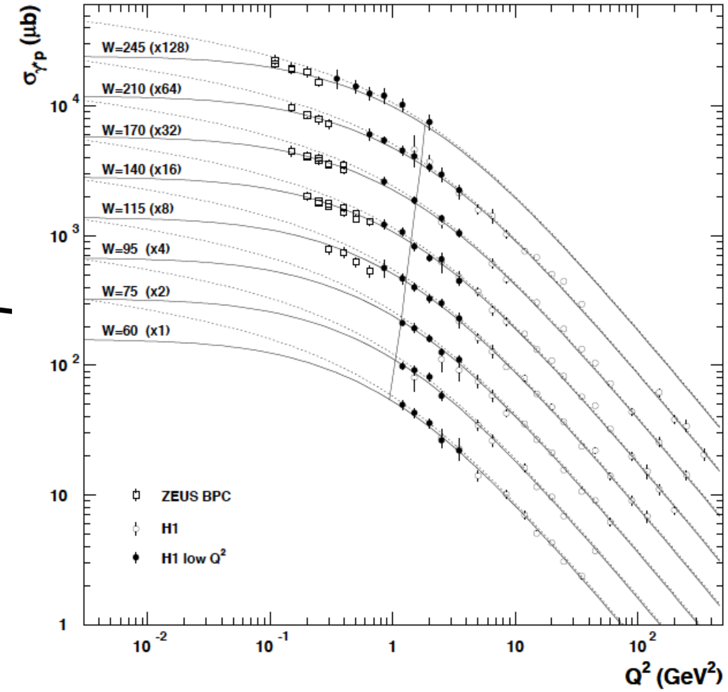


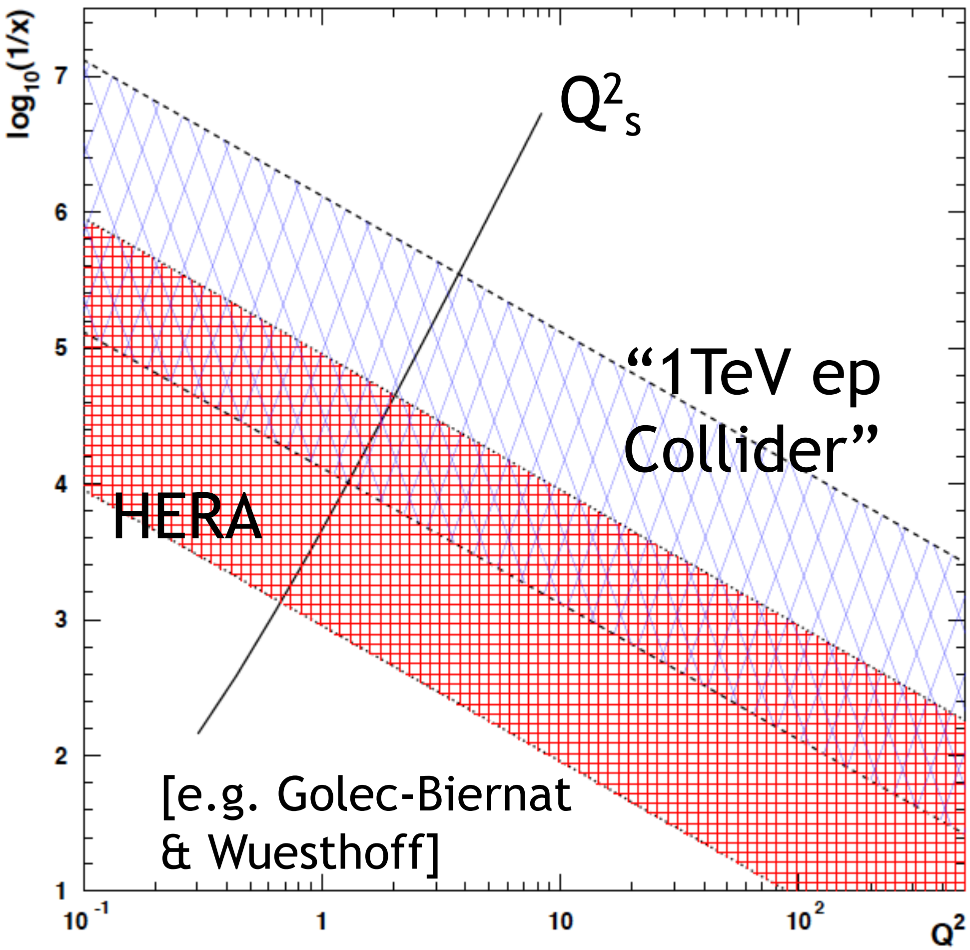


Going lower in x means going lower in Q^2 …

$Q^2 < 1$ GeV^2 data & Dipole Models (with saturation)





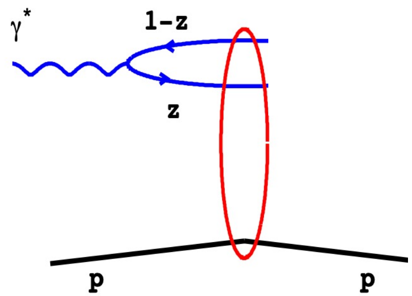


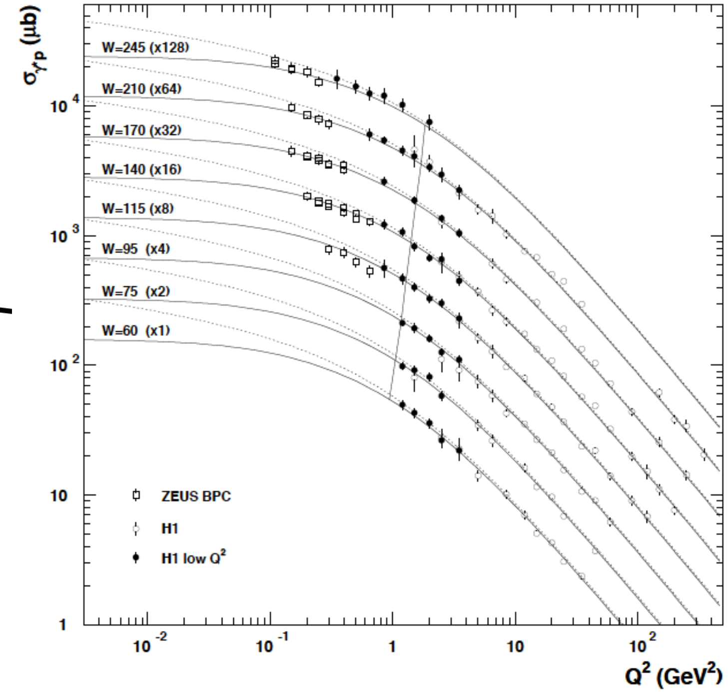
- Virtual photon fluctuates to $q\bar{q}$ dipole, which scatters from proton according to dipole cross section

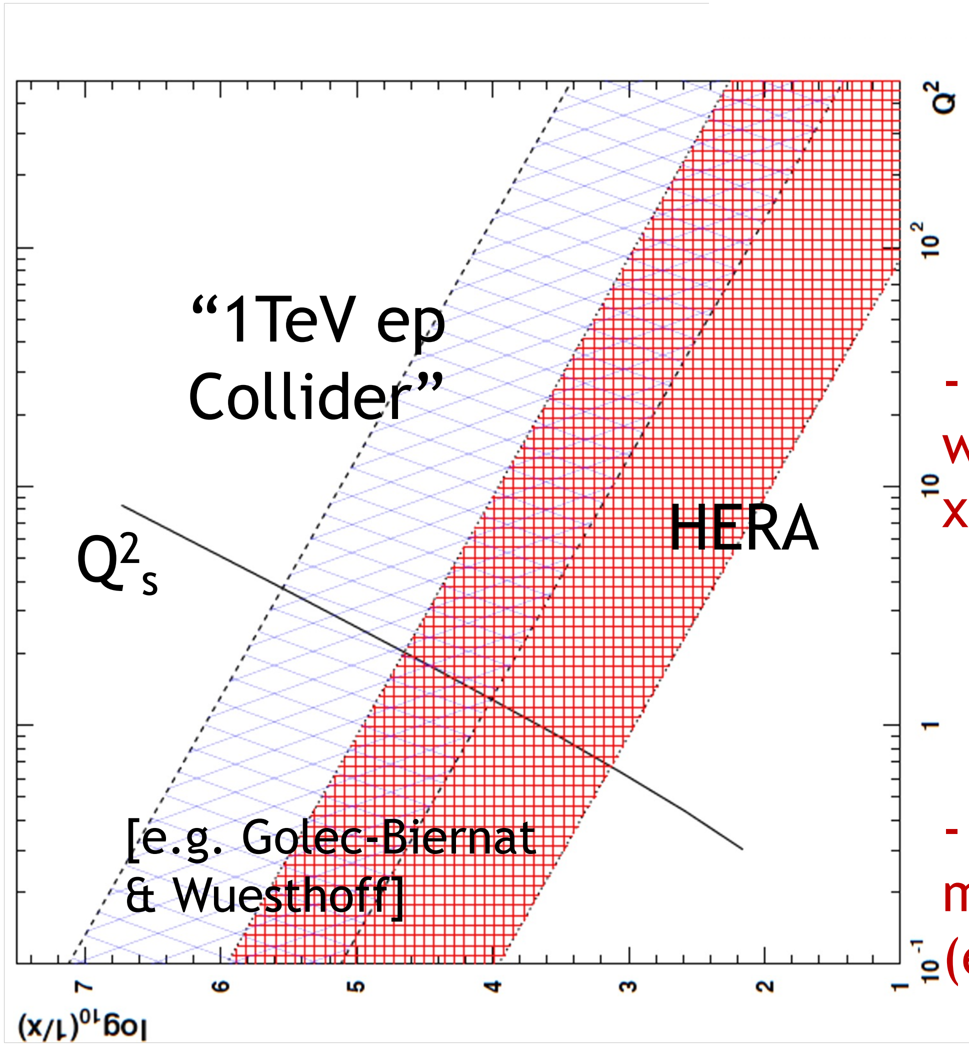
- All data (Q^2 >~ 0.05 GeV^2) well fitted when dipole cross section saturates at x dependent "saturation scale" $Q^2_s(x)$

$$\frac{xG_A(x,Q_s^2)}{\pi R_A^2 Q_s^2} \sim 1 \Longrightarrow Q_s^2 \propto A^{1/3} x^{\sim -0.3}$$

Q^2 < 1 GeV^2 data & Dipole Models (with saturation)







- All data (Q^2 >~ 0.05 GeV^2) well fitted when dipole cross section saturates at x dependent "saturation scale" $Q^2_s(x)$

$$\frac{xG_A(x,Q_s^2)}{\pi R_A^2 Q_s^2} \sim 1 \Longrightarrow Q_s^2 \propto A^{1/3} x^{\sim -0.3}$$

- See also more dynamically motivated dipole cross sections (eg Colour-Glass Condensate)

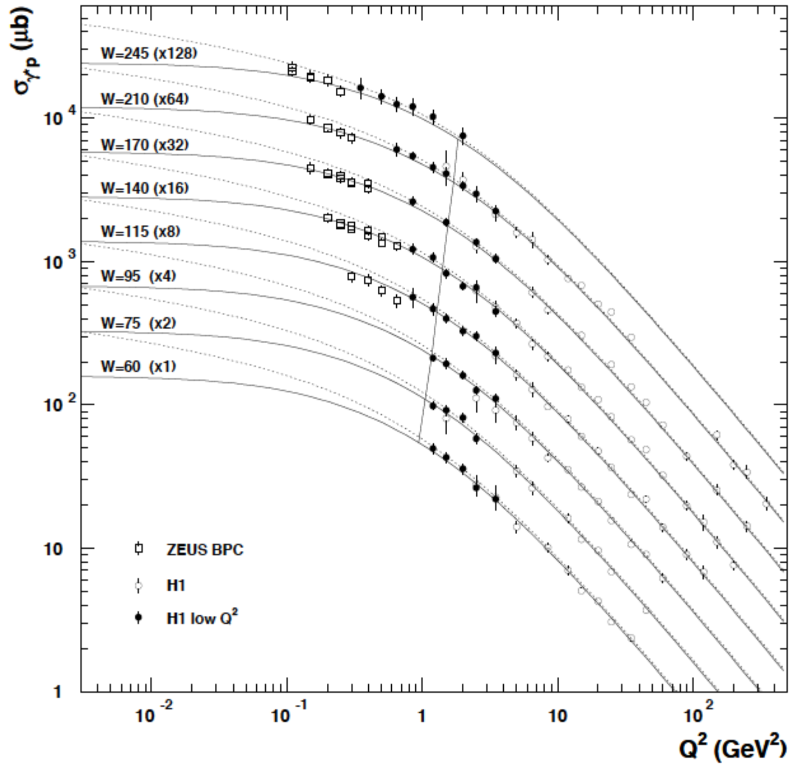
Ways Forward?

- BFKL effects visible at the limits of HERA perturbative acceptance

- Saturation of dipole cross section evident at HERA

- However, Q^2_s doesn't get above about 0.5 GeV^2

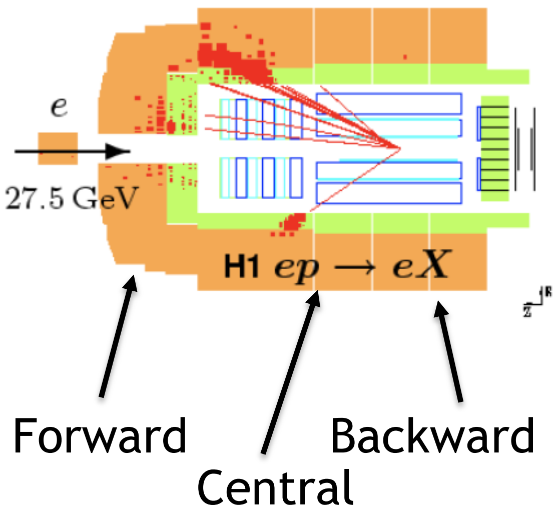
… below the range of perturbative QCD
… quarks and gluons are not reliable
degrees of freedom



Possible approaches to better constrain low-x at perturbative scales …

→ Higher energy DIS Colliders? [Lecture 3]
→ Scattering from heavy ions instead of protons [Lecture 3]
→ Consider hadron colliders [Lecture 1,2]
→ Consider more ep observables, not just inclusive DIS [Lecture 1]

Relation of Low x to 'Forward' Physics

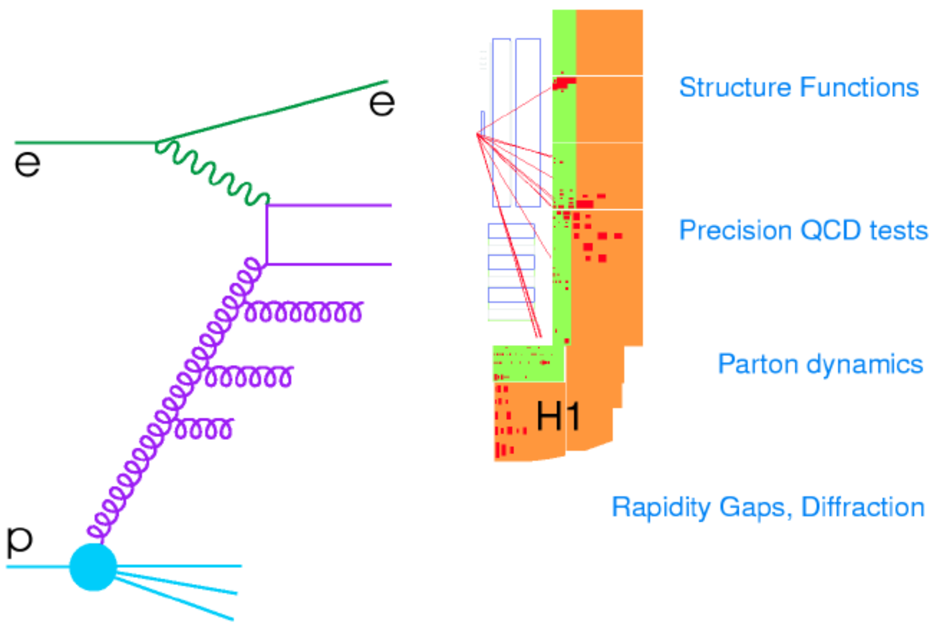


The 'forward' region is defined as the outgoing proton direction (high pseudorapidity, η)

Turning the H1 detector on its side and considering a 'parton cascade' …

Looking at hadrons produced more and more forward, we are sensitive to more and more parton emissions

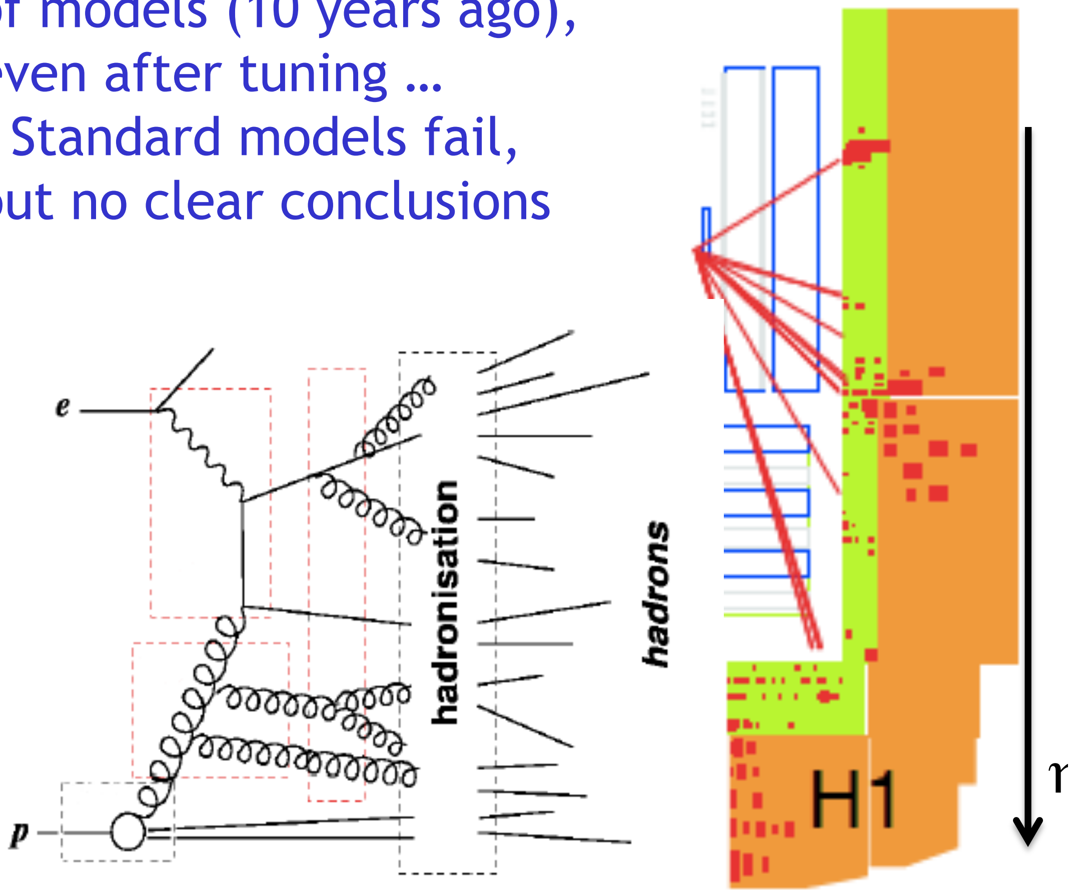
… i.e. how high x partons evolve to produce low x partons

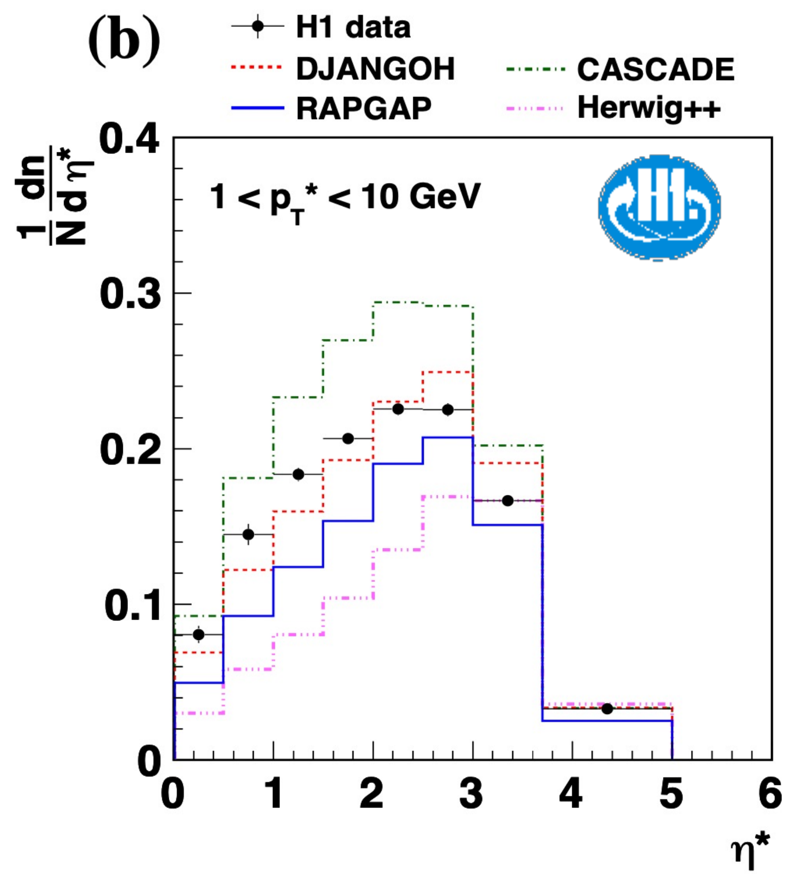


e.g. Where does the Energy / Particles Go?

- Many measurements of energy flow and charged particle production, including some increasingly novel observables
- e.g. numbers of charged particles versus pseudorapidity in γ^*p CMS frame:

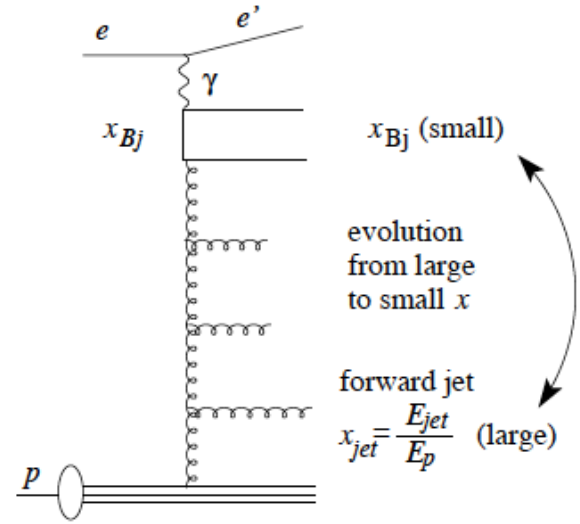
- Data often way ahead of models (10 years ago), even after tuning …
- Standard models fail, but no clear conclusions

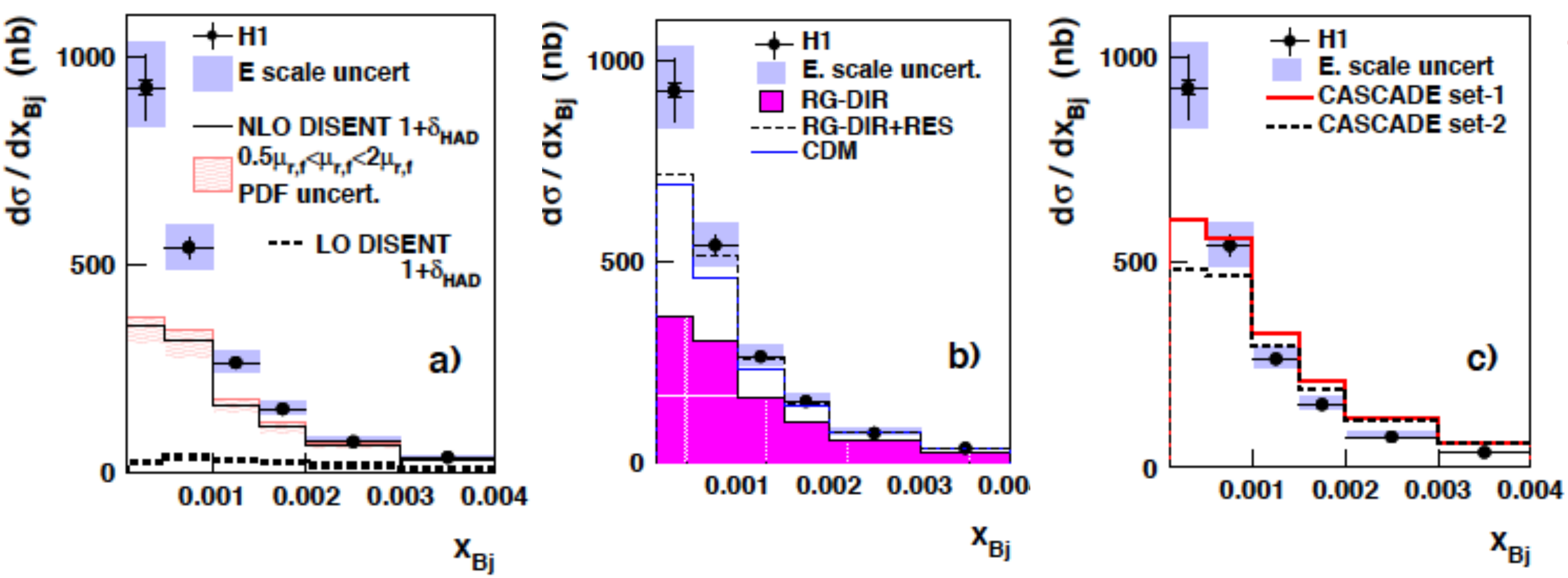




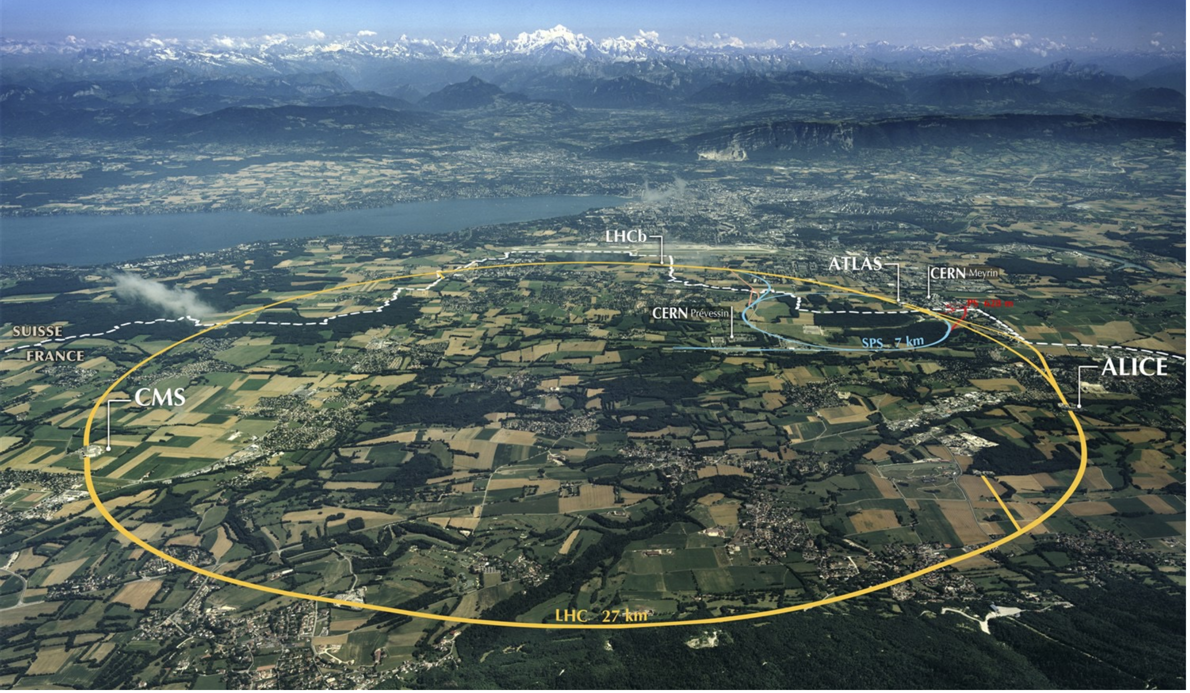
More Observables Sensitive to Novel Dynamics

- (Very) forward jet, particle production and energy flow
- Mueller-Navelet forward-backward jet pairs
- Azimuthal decorrelations between jets
- Jet broadening
- Correlations / p_T ordering of hadrons





e.g. Forward Jets … Very interesting effects … but not easily interpreted



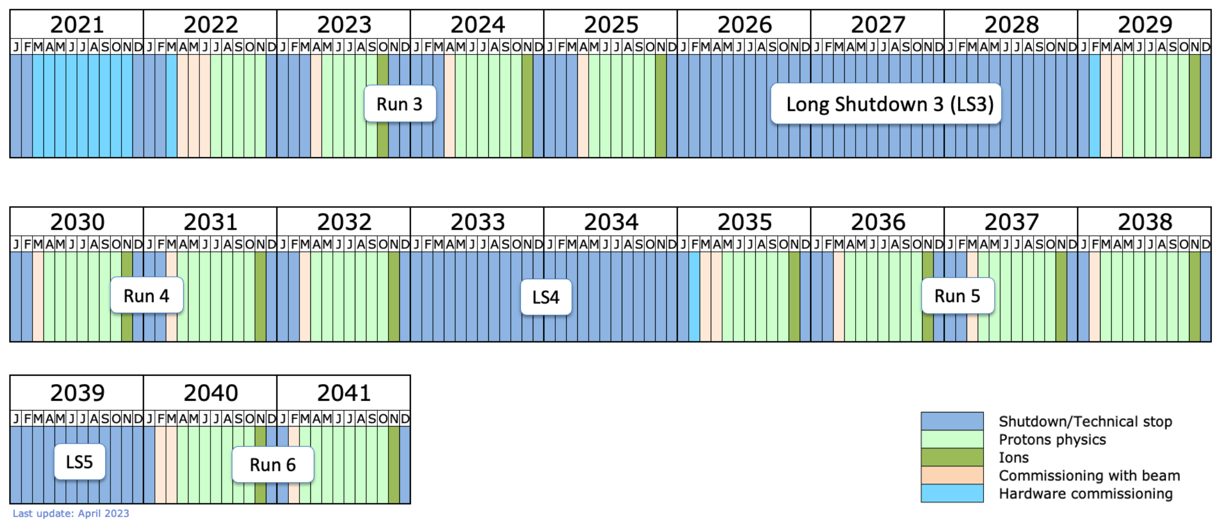
- Future high energy DIS is decades away (see lecture 3)
- Meantime …

Low x and the LHC …

- LHC will run for another two decades

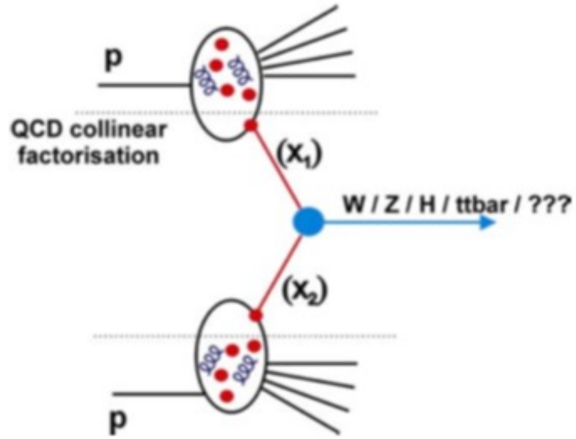
- Will remain the energy frontier for (a lot) longer

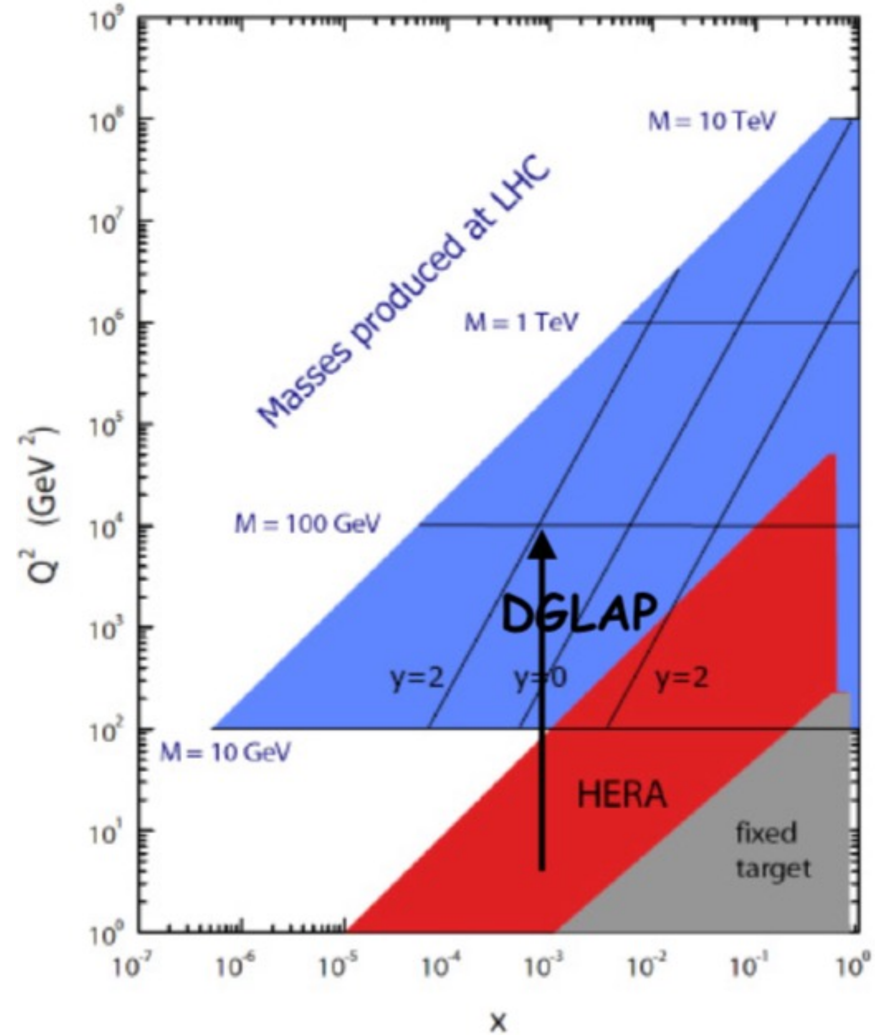
- Has capability to be a low-x facility …



From HERA to LHC

DGLAP evolution links HERA and LHC in a remarkably similar x range





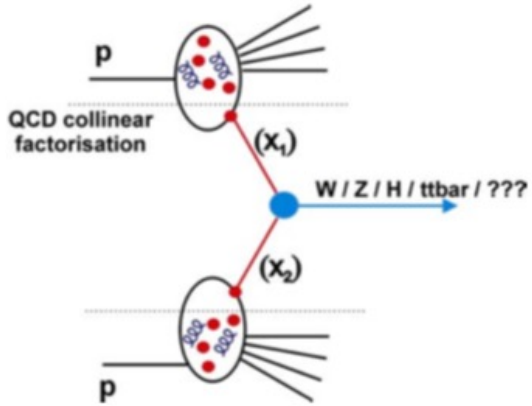
Usually, scale Q^2 replaced by invariant mass M^2 of the particle or system of particles produced by the partons

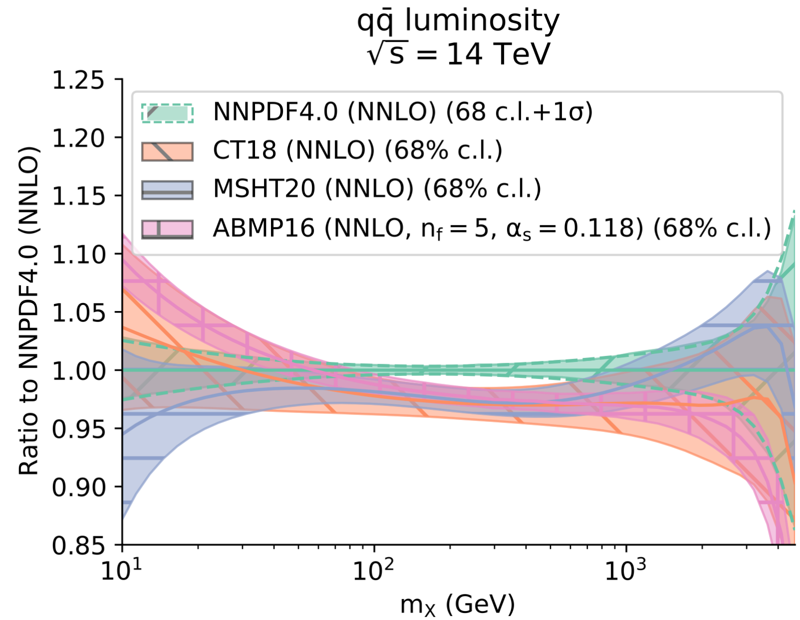
Kinematics … $x_1 = e^{y} \frac{M}{\sqrt{s}}$ $\quad x_2 = e^{-y} \frac{M}{\sqrt{s}}$ $\quad$ where rapidity, $y = \frac{1}{2} \ln \frac{(E+p_z)}{(E-p_z)}$

Central systems (with M near y=0) have symmetric x values.

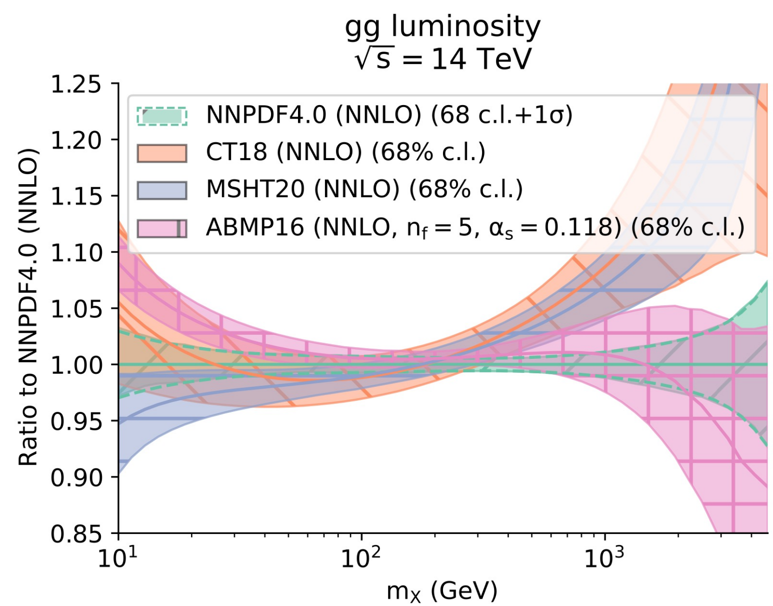
Forward systems (large |y|) probe asymmetric x values (one high, one low)

Low x Kinematics at the LHC





[NNPDF4.0 , arXiv:2109.02653]



- LHC masses produced by low x partons are very small …

- At mid-rapidity (y=0, central system):

$$M_X = 2xE_p$$

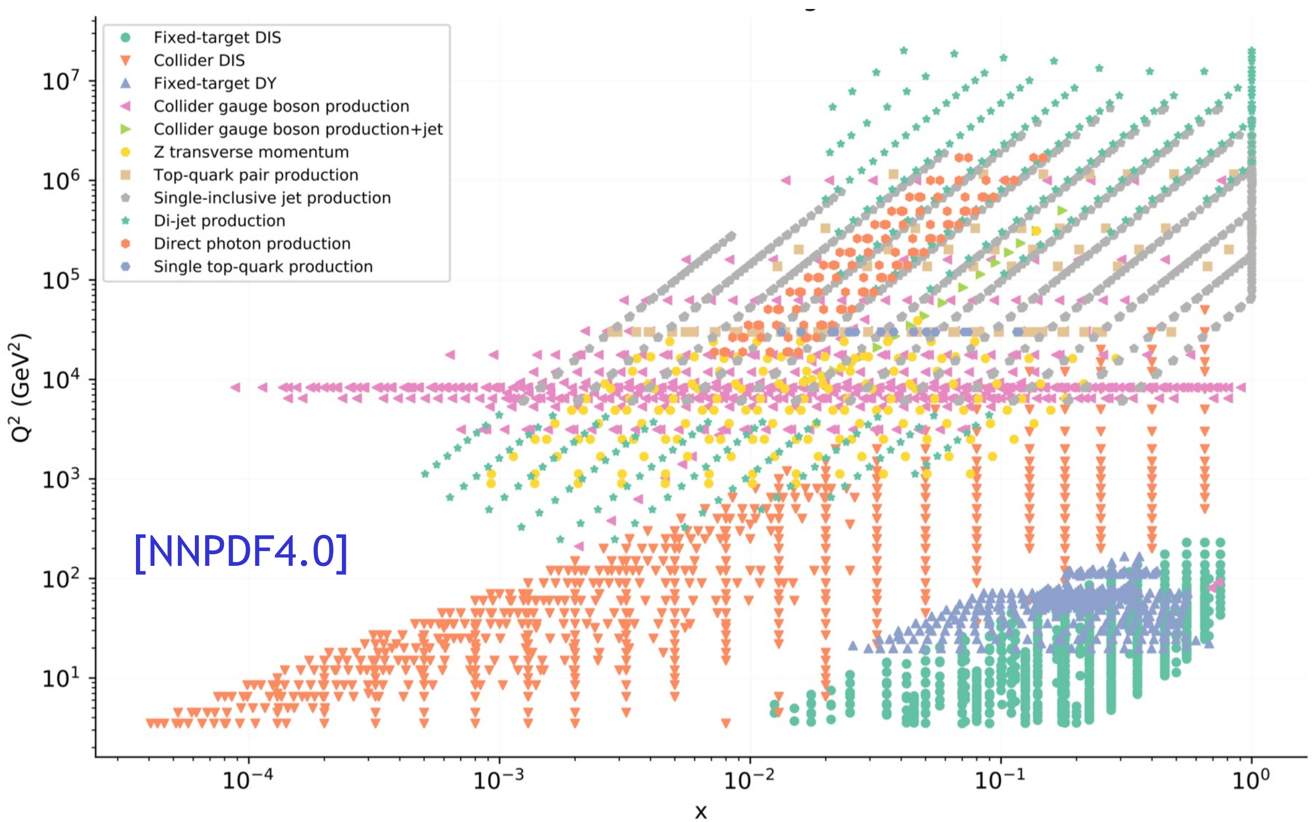
… e.g. two x=10^{-4} partons produce M_X = 1.4 GeV at mid-rapidity
→ Not even triggered
→ Not even on parton lumi plots

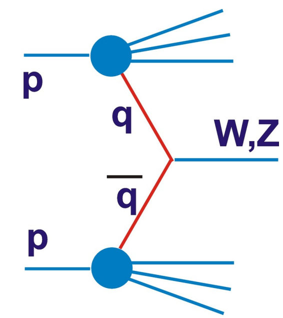
- Asymmetric configurations are essential → forward physics

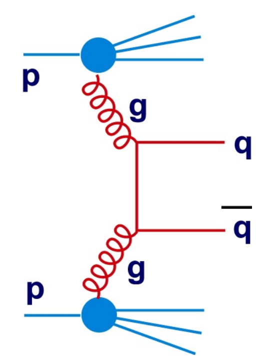
Constraining PDFs with LHC Data

→ Need precise PDFs for interpretation of LHC physics BUT ALSO

→ LHC can tell us more about PDFs … in principle, including new low-x dynamics, at perturbative Q^2 values





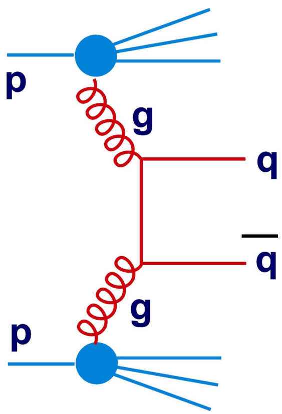


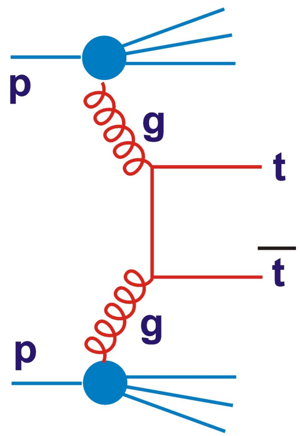
Main observables included in global fits that constrain low x …

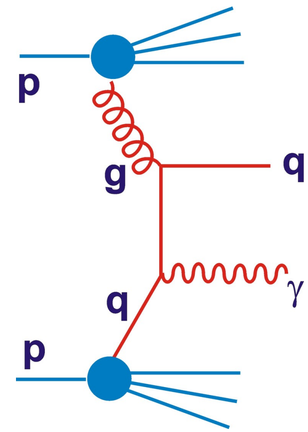
- Electroweak gauge bosons (and Drell Yan) → quarks
- Jet production → gluons

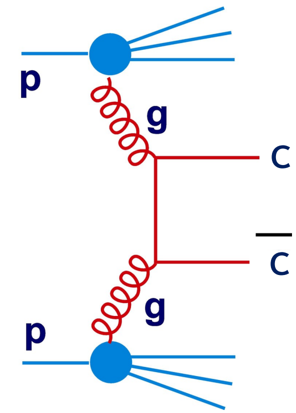
… the more forward (i.e. high $|\eta|$), the better!

MAINSTREAM GLUON SENSITIVE LHC OBSERVABLES





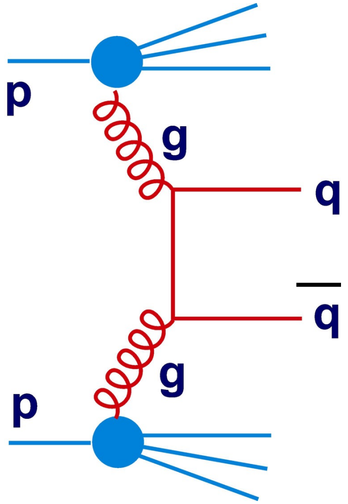




- Jet production
- Direct Photons
- Top Quarks
- Charm Production

[See also Ultra-Peripheral Collisions – Lecture 3]

e.g. LHC Gluons: Jet Production

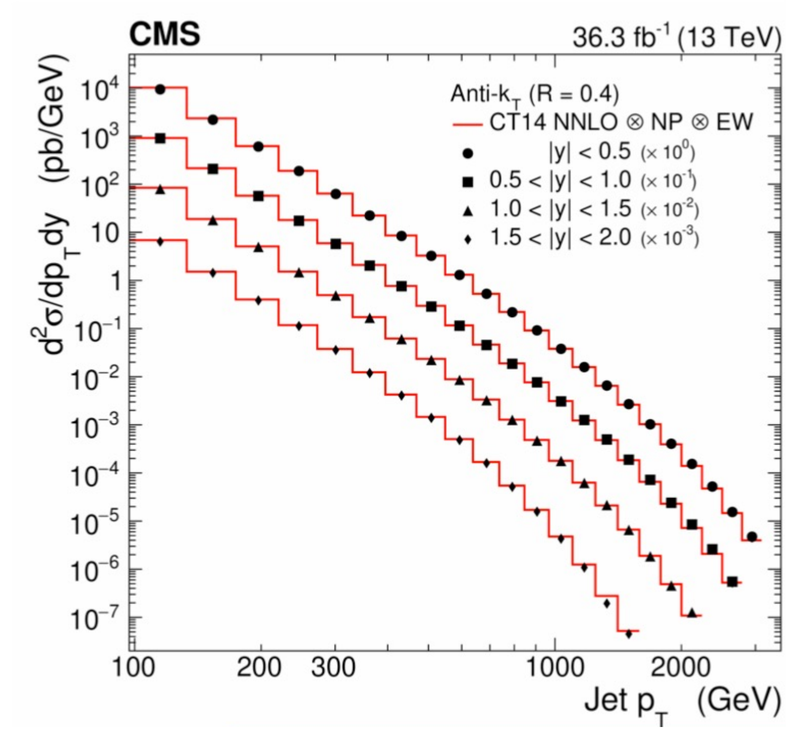


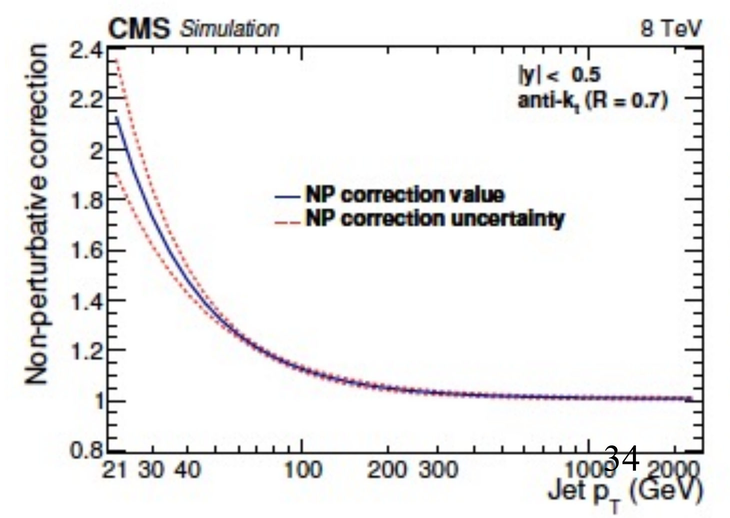
Gluon-sensitive, though
even at low(ish) p_T, qg → qg
is larger than gg → gg

- Recent availability of NNLO calculations increases interest

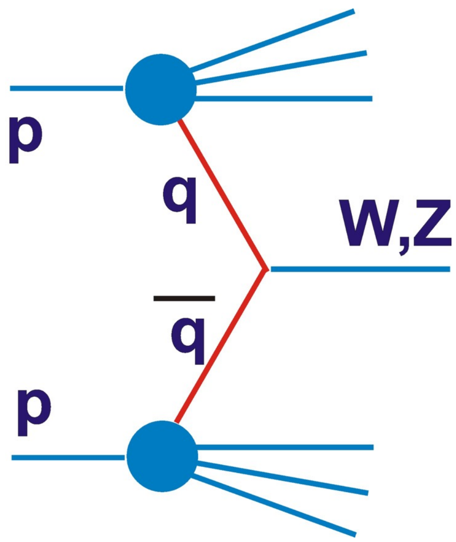
- Remarkable kinematic range, but high p_T
→ **not really a low x observable**

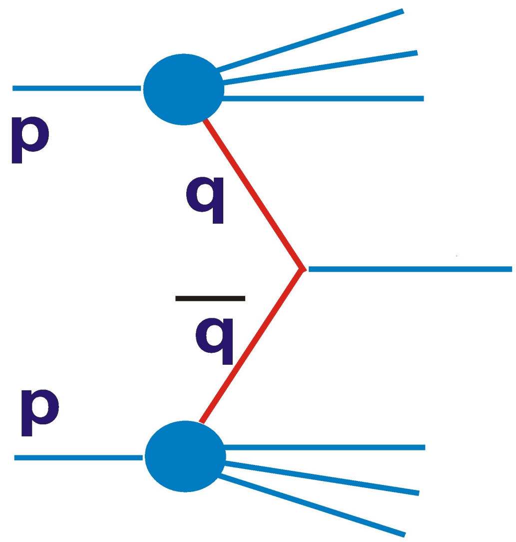
- Low p_T region limited experimentally by jet energy scale uncertainty and non-perturbative corrections to the jets





MAINSTREAM QUARK SENSITIVE LHC OBSERVABLES

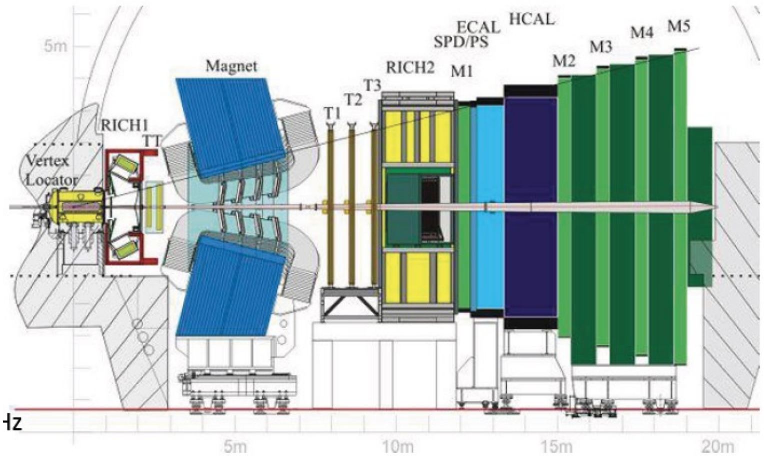




- Electroweak gauge boson production

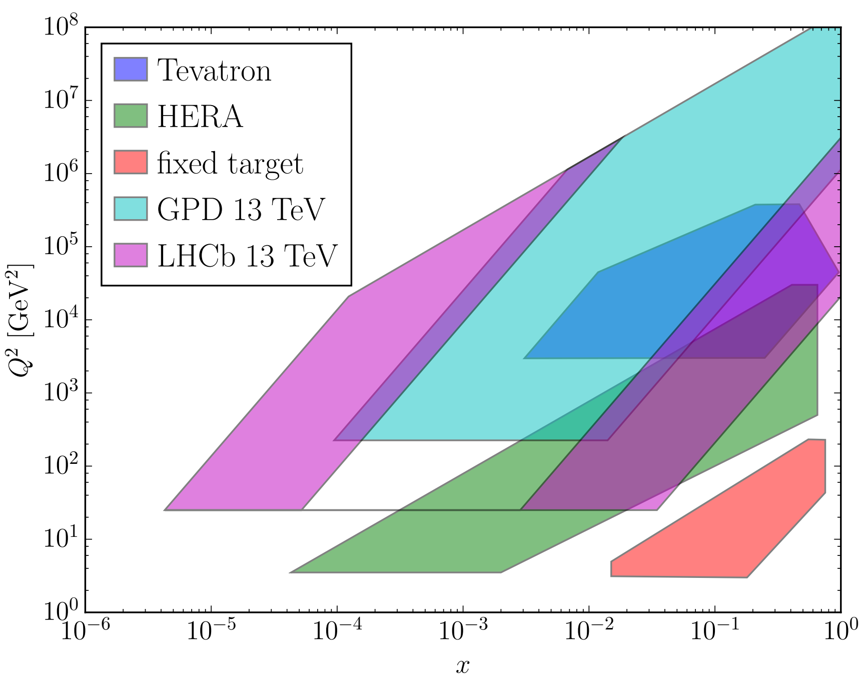
- Drell Yan ($q\bar{q} \to e^+e^-$ or $q\bar{q} \to \mu^+\mu^-$)

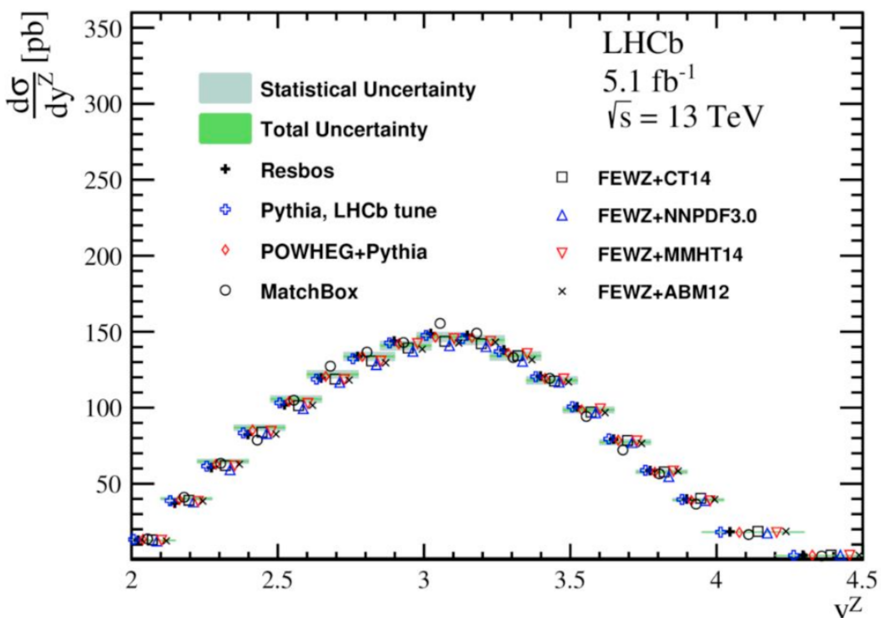
Favourable LHCb Kinematics for Low x Physics



- "Fixed target-like" forward instrumentation ($2 < \eta < 4.5$) → probes asymmetric x values
  - … to $x \sim 10^{-5}$ in perturbative domain
  - … also genuine fixed target (SMOG)

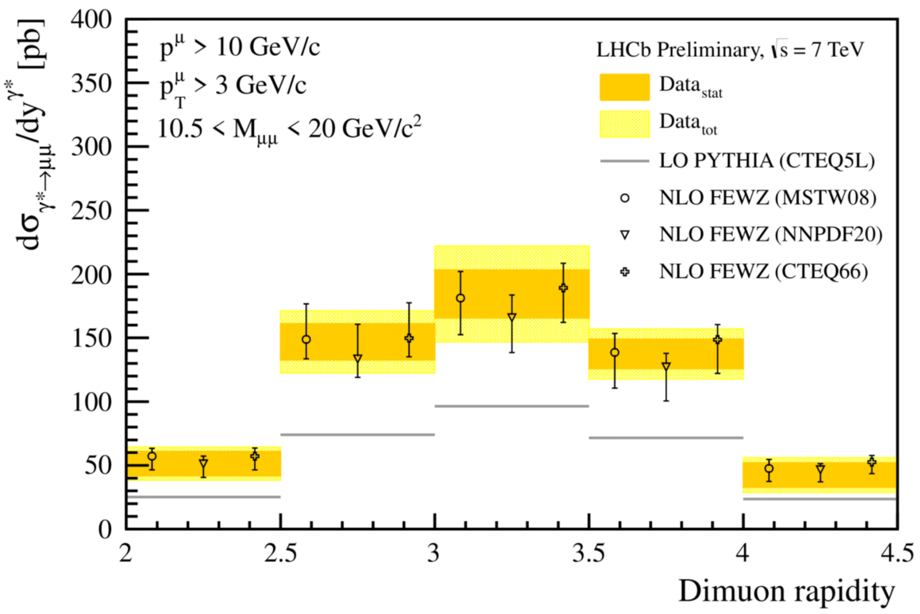
- e.g. inclusive Z production shows some interesting shape deviations from NLO theory

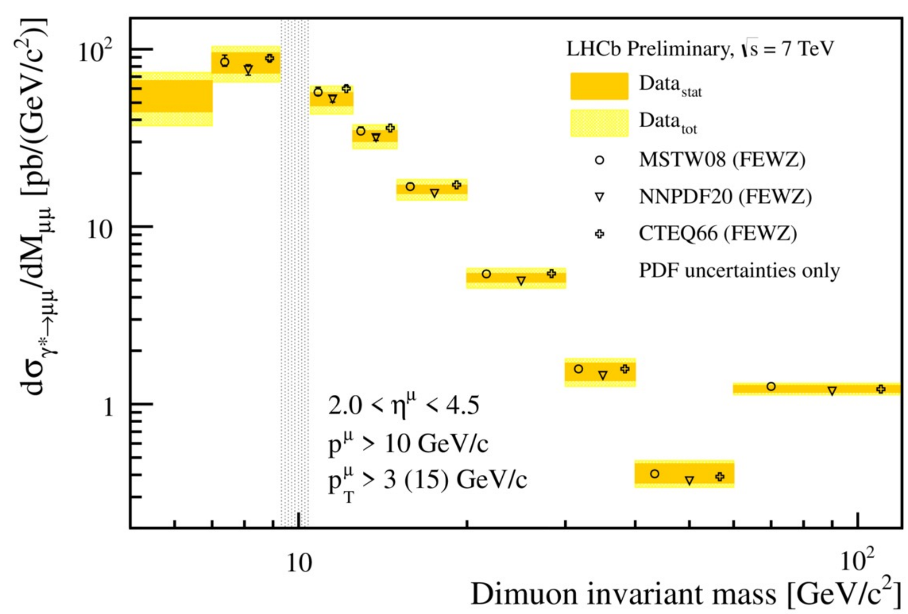




[arXiv:2112.07458]

Lowest x 'Mainstream' LHC data so far?... LHCb Drell Yan at very low masses



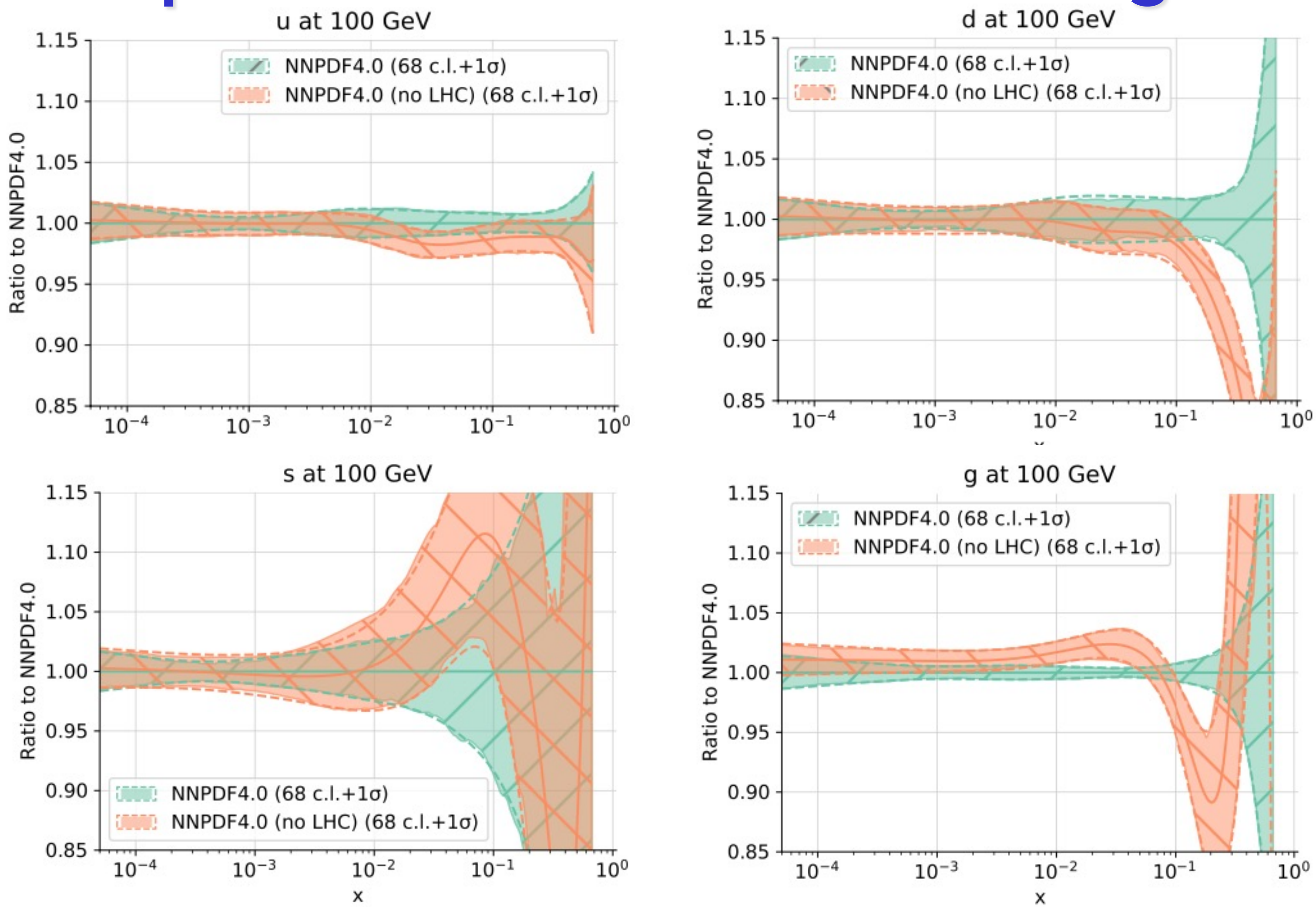


- Data extend to m_{ll} = 5 GeV at forward rapidities.

- Preliminary data look compatible with previous generations of PDF sets (NLO comparisons)

[CONF note 2012] … hard to imagine pushing further with standard processes

LHC Impact on Global Fits according to NNPDF



- LHC has contributed at all x, but the most significant impact is at large x
- Available data not expected to change fundamentally in the future

[Very different situation in nuclear PDFs
→ LHC pA transformational]

Summary

- HERA opened up low x physics
  - Fast-rising gluon with decreasing x
  - Evidence of need for BFKL-resummation at lowest x
  - Evidence for saturation, but in non-perturbative region

- While we wait for the next DIS facilities, can we exploit LHC?
  - Limited progress with ‘mainstream’ observables

Next Lecture

- Dedicated Low-x Observables in LHC Physics

- Elastic and Diffractive Processes in pp Collisions