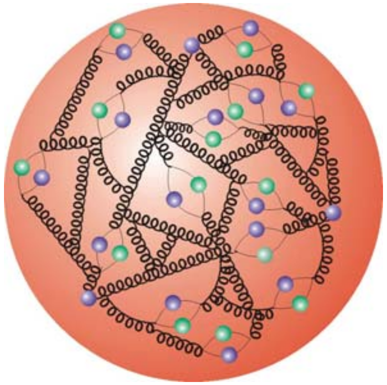
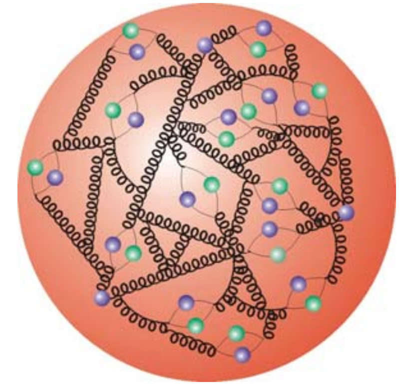
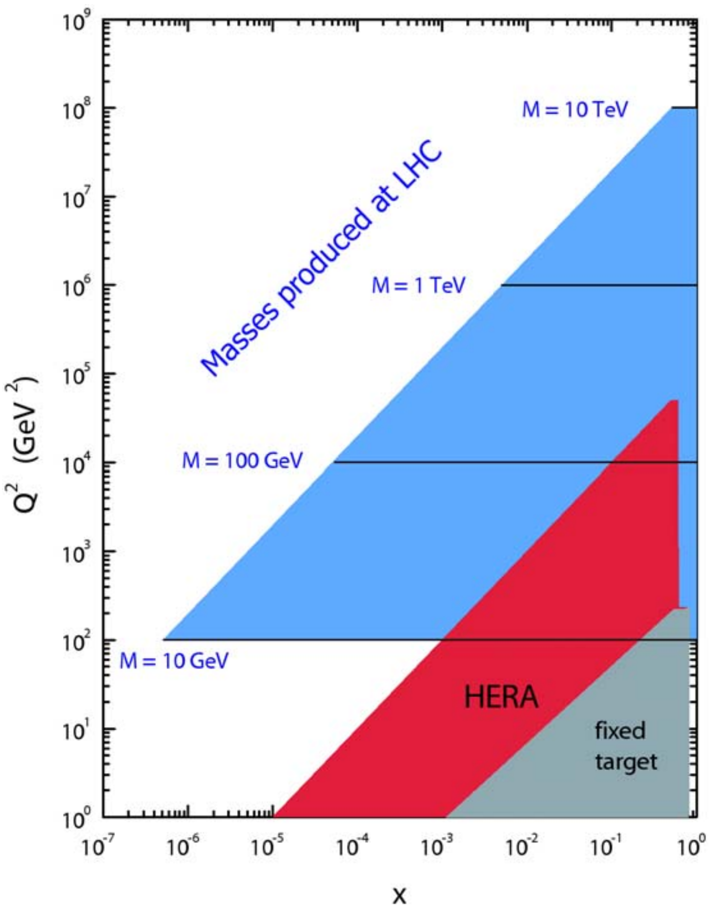
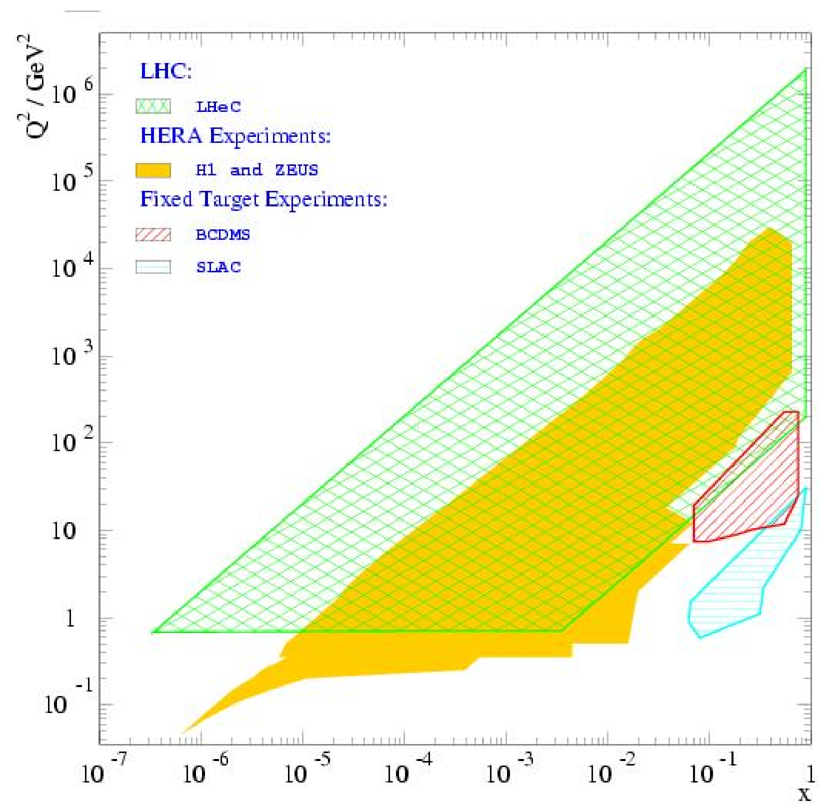


From HERA to the LHC and the Future of DIS

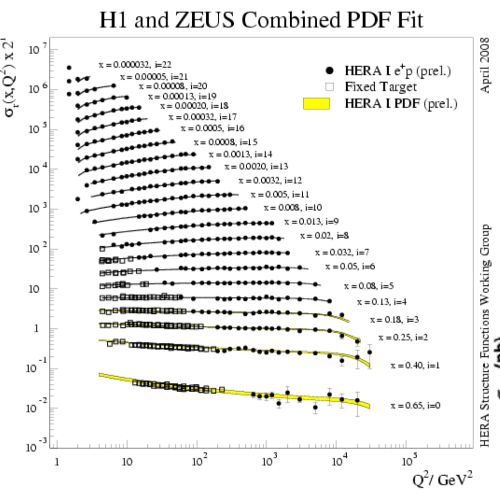


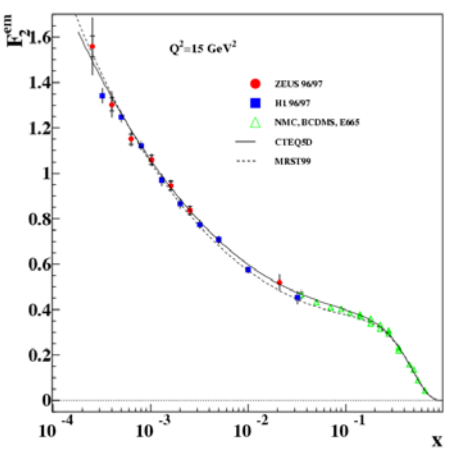
Paul Newman, University of Birmingham
"A Celebration of HERA and the UK Role"
RAL, 25 June 2008

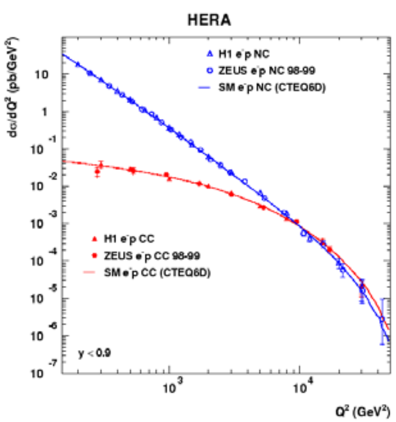


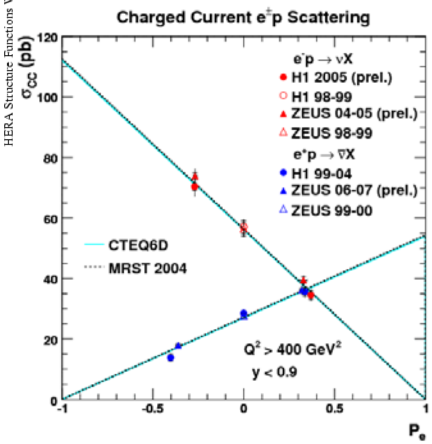


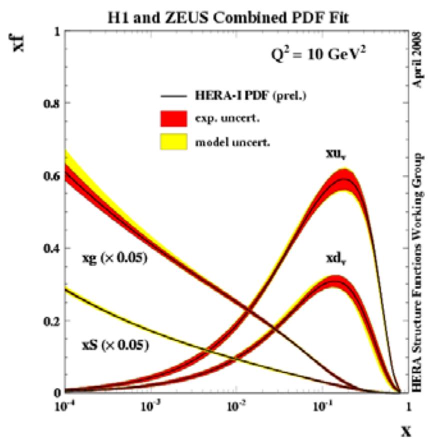
Collage of “Text-Book” HERA Plots

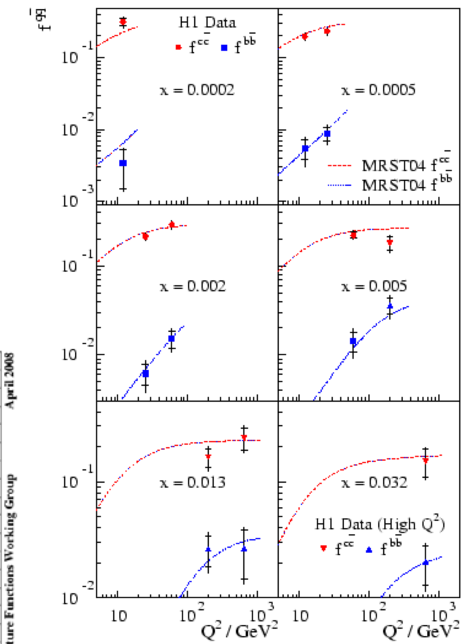


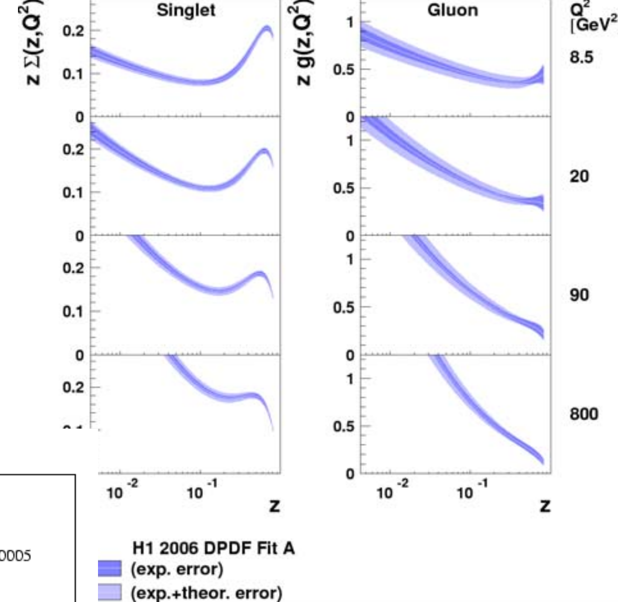


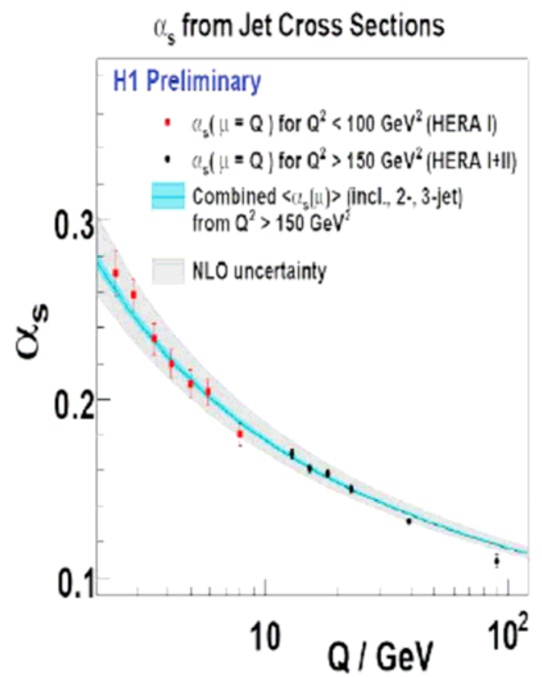












UK involvement everywhere!

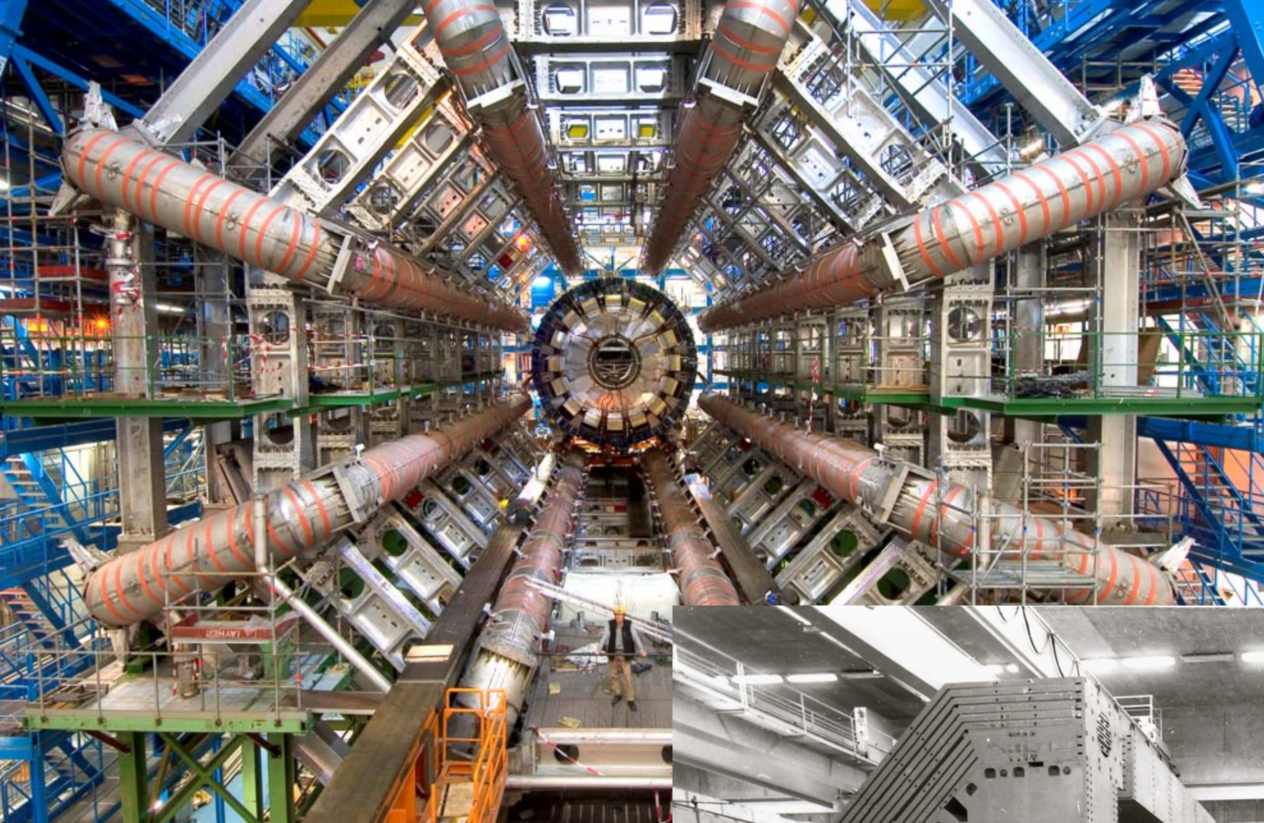
The LHC is the Future!

HERA-LHC Workshop … (see also PDF4LHC)

AIMS

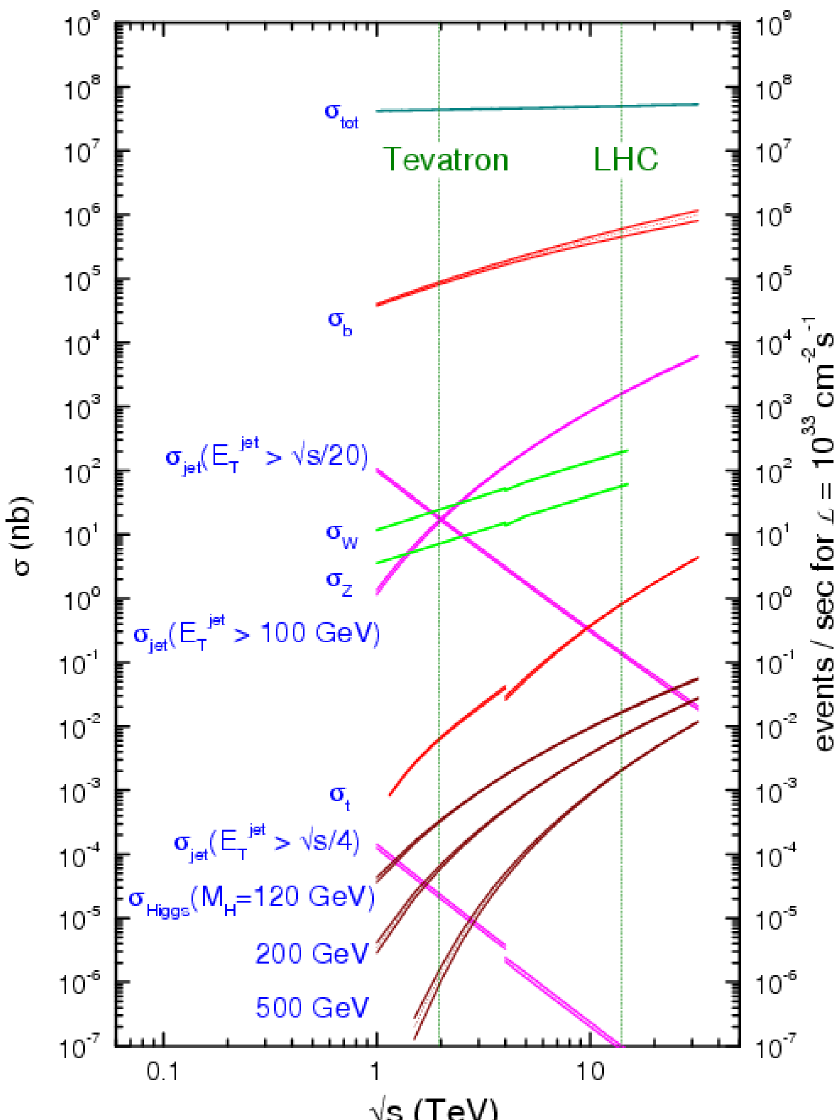
- Identify & prioritise HERA measurements needed for LHC
- Transfer of knowledge between HERA & LHC communities
- Establish ongoing interaction HERA & LHC communities
- Quantify implication of HERA results
- Develop new experimental / theoretical tools
- Encourage theory / phenomenology efforts

Scale:
H1 v
ATLAS



LHC Technology Challenges

proton - (anti)proton cross sections



- Up to a billion collisions per sec.
- A Higgs every 10s
  … and that's before Branchings
- Huge challenge for detector, trigger and read-out

(Bill Haynes)

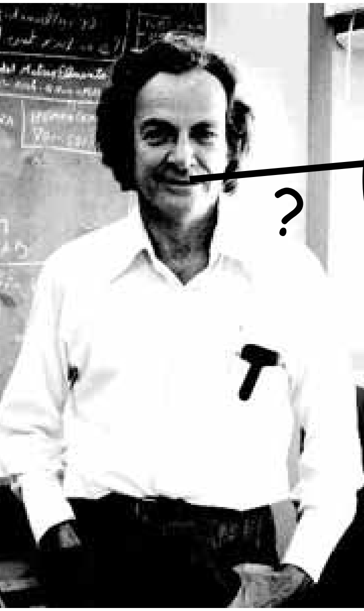
H1 & CMS Data Acquisition Parameters

A comparison of the main DAQ System parameters and the relevance of H1 into the future

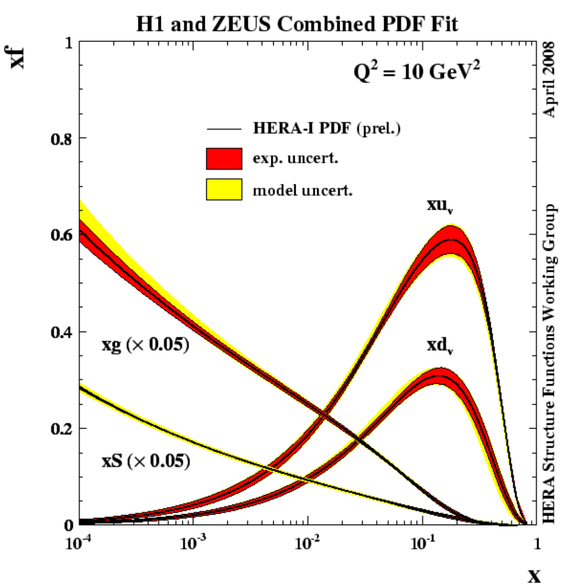
Parameter	*H1 1991 to 2006*	*CMS 2007 to 202?*
Bunch crossing interval	96 ns	25 ns
Level-1 Trigger Rate	100 - 300 Hz	100 kHz
Total no. of electronics channels	≈ 750,000	≈ 12,000,000
Average total final event size	≈ 100 kBytes	≈ 1 MByte
Average size from trackers	60 - 80 kBytes	≈ 300 kBytes
Number of Branch/RUs	12	256 / 512
Event builder bandwidth	≈ 25 MBytes/s	≈ 100 GBytes/s
Data production	≈ 10 GByte/day	≈ TByte/day
Number of readout crates	≈ 150	≈ 300
Number of electronics boards	≈ 2,000	≈ 5,000
Total Cost DAQ + Electronics	≈ $15 M	≈ $100 M

-HERA's challenge was probably as tough in 1992!…

Most Obvious Link: PDFs



"You don't find out how a watch works by throwing other watches at it!"



HERA

+

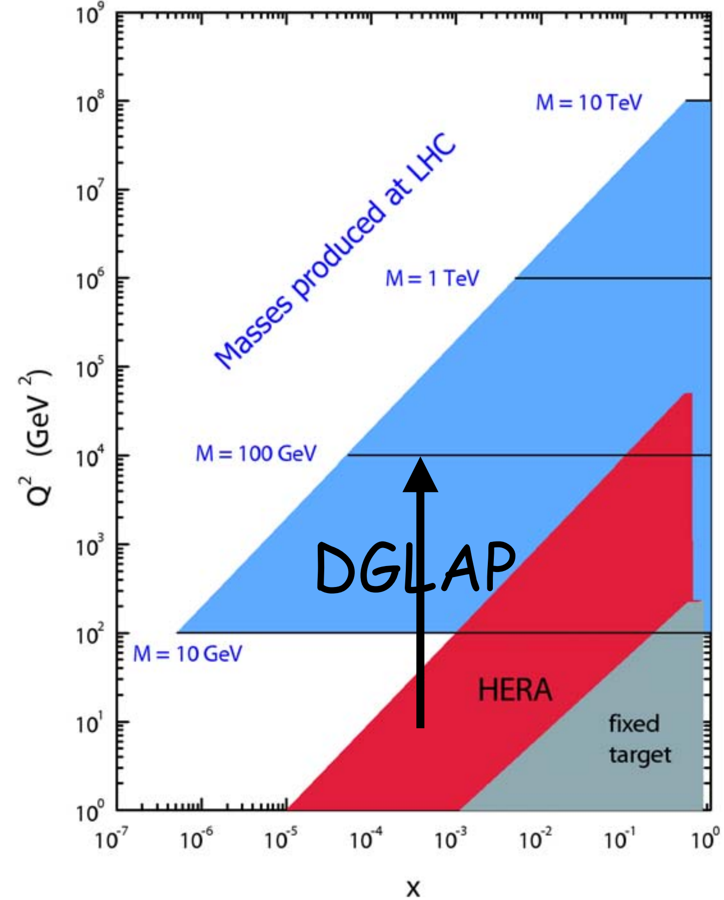
QCD Facⁿ

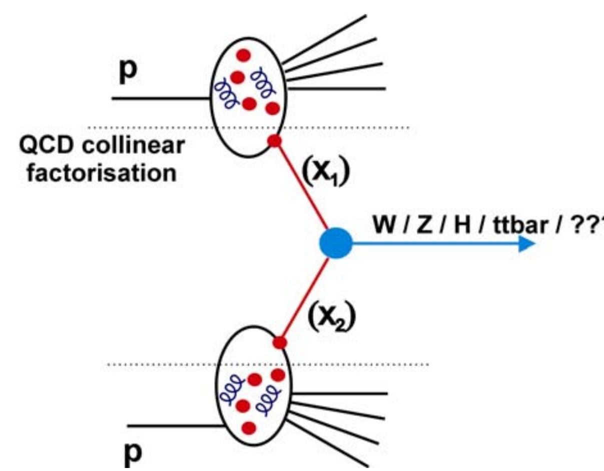
+

DGLAP

=

Initial state
At LHC





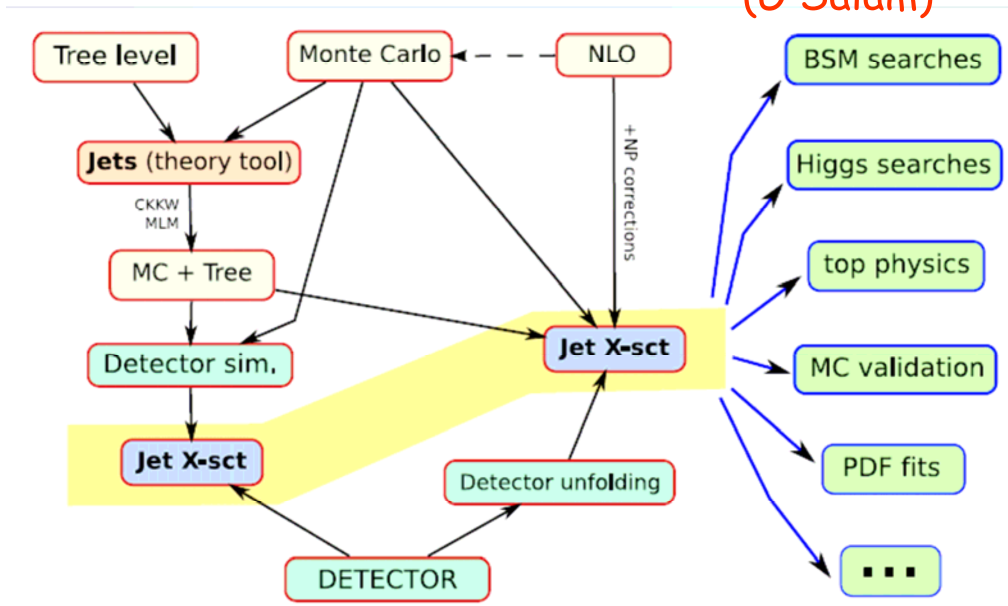
… but modelling hadronic production is much more complicated than just the PDFs!

- "Bewildering" list of generators to model interaction at N^kLO
- DGLAP, CCFM, uPDFs .
- Multiple interactions
- Hadronic jets are poor substitutes for partons

(E Laenen)

- PYTHIA, HERWIG, Ariadne, Sherpa, (in C++), high-order flexible LO codes (Alpgen, CompHep, MadEvent, Helac,...), twistor methods and BCF recursion relations, NLO packages (Grace, MCFM, PHOX,NLOJET++,VBFNLO), NLO Monte Carlo's (MC@NLO, POWHEG) , NNLO Higgs, NNLO thrust, 3-loop splitting functions, NNLO PDF's, NNLL resummation,...

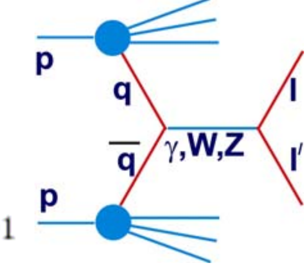
(G Salam)



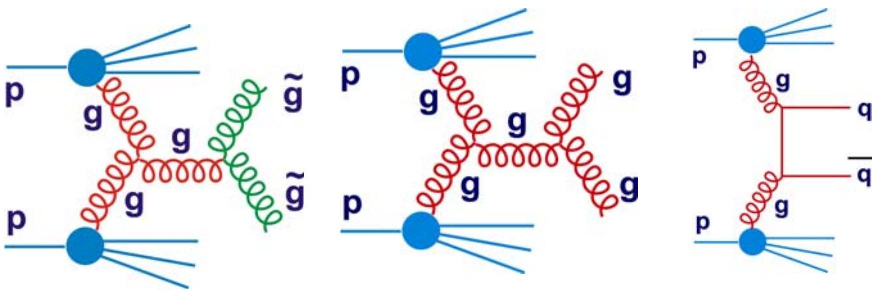
The simpler ep / γp hadronic environment of HERA has been used to tune and distinguish between these ingredients.

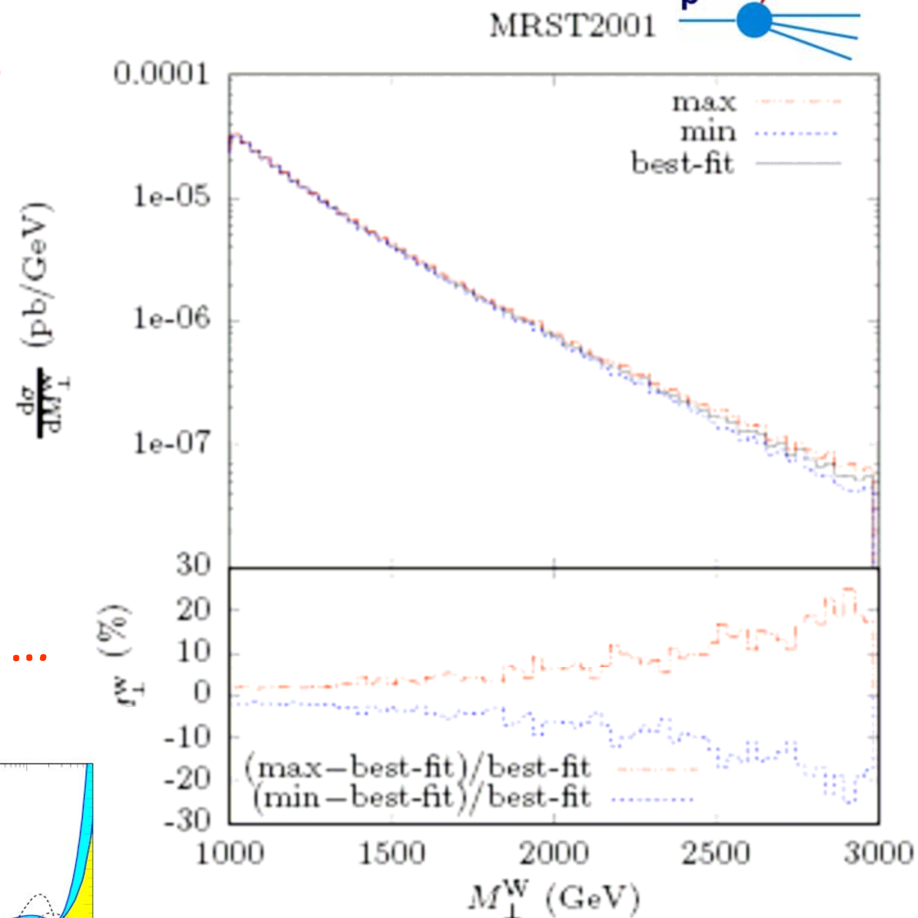
… but do we need to care?…

High x Parton Uncertainties

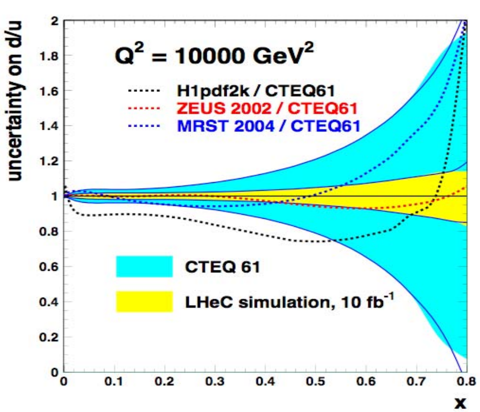


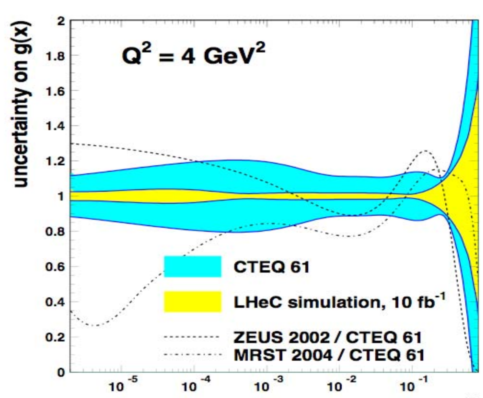
High x partons are initial state for both signal and background at energy frontier





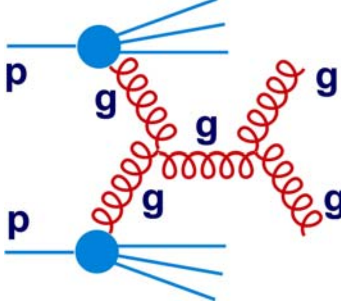
... still large PDF uncertainties ...



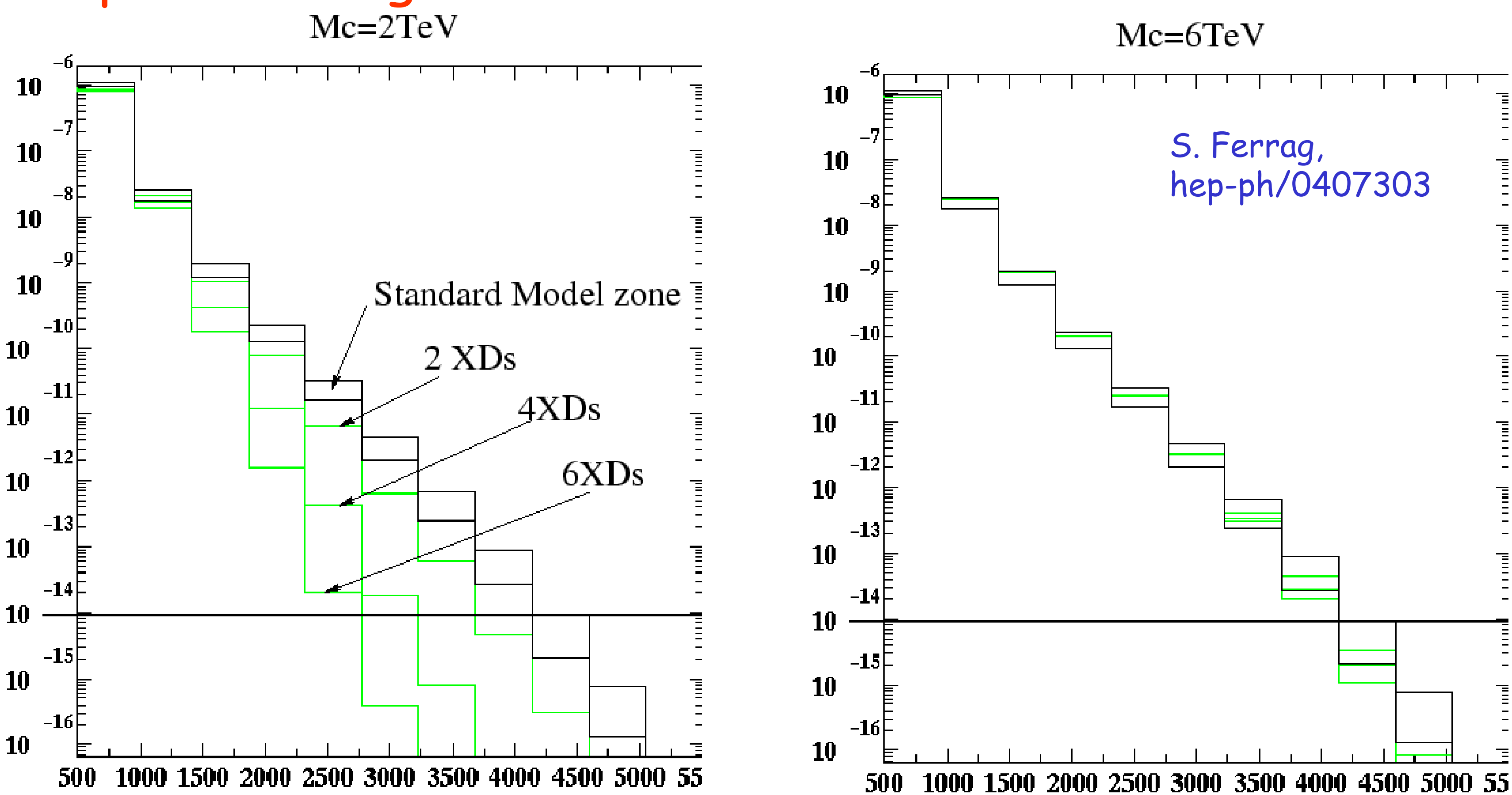


Improving constraints a matter of statistics to a large extent

Partons Limiting BSM Searches



Many BSM scenarios give deviations in high mass dijet spectra … e.g. a model with extra dimensions …

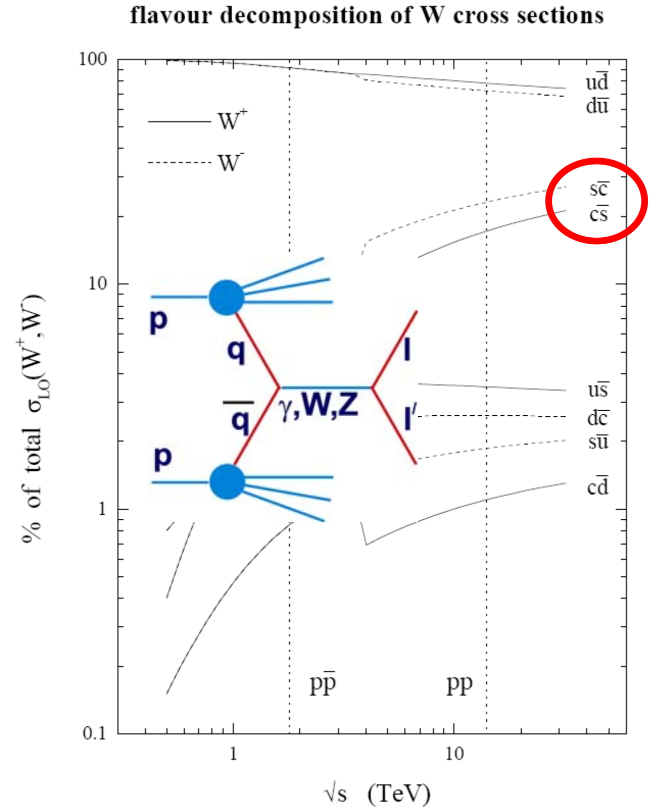


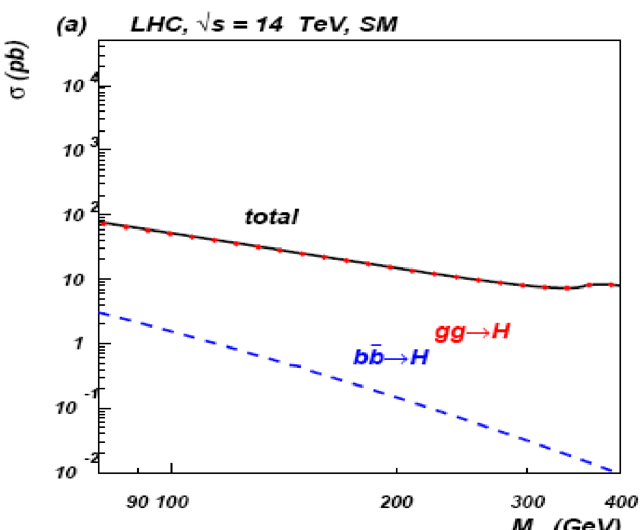
… in this example, high x PDF uncertainties reduce sensitivity to compactification scales from 6 TeV to 2 TeV for 2XDs

Heavy Quarks: HERA → LHC

- LHC predictions rely strongly on extrapolations and pQCD …wrong HF evolution HERA→LHC could result in big problems… e.g. σ(W)

- Knowing HF Component of initial state crucial to predictions. e.g. bbbar → H in SM & high tan β MSSM

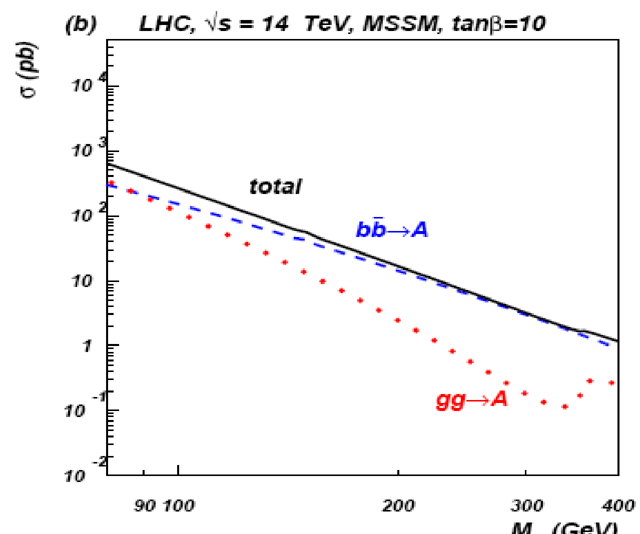




Higgs

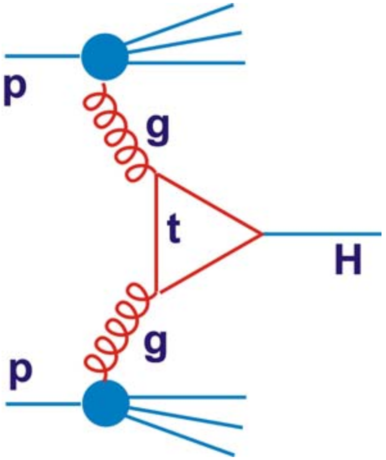
<-SM

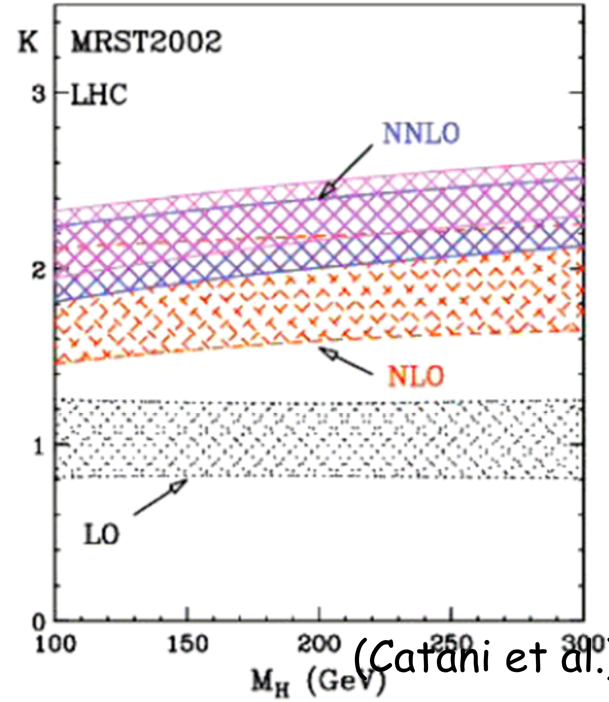
MSSM->



The Electroweak Scale

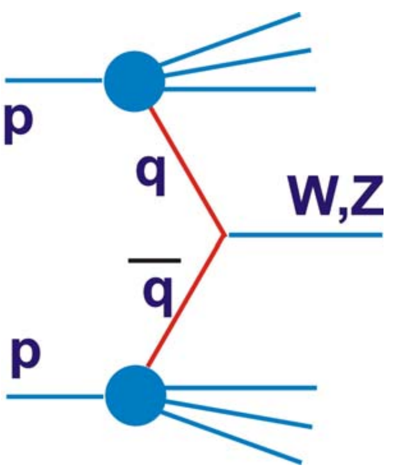
Higgs cross section
for m_H = 120 GeV,
- PDF uncertainty ~ 3%
- Scale uncertainty ~ 10%



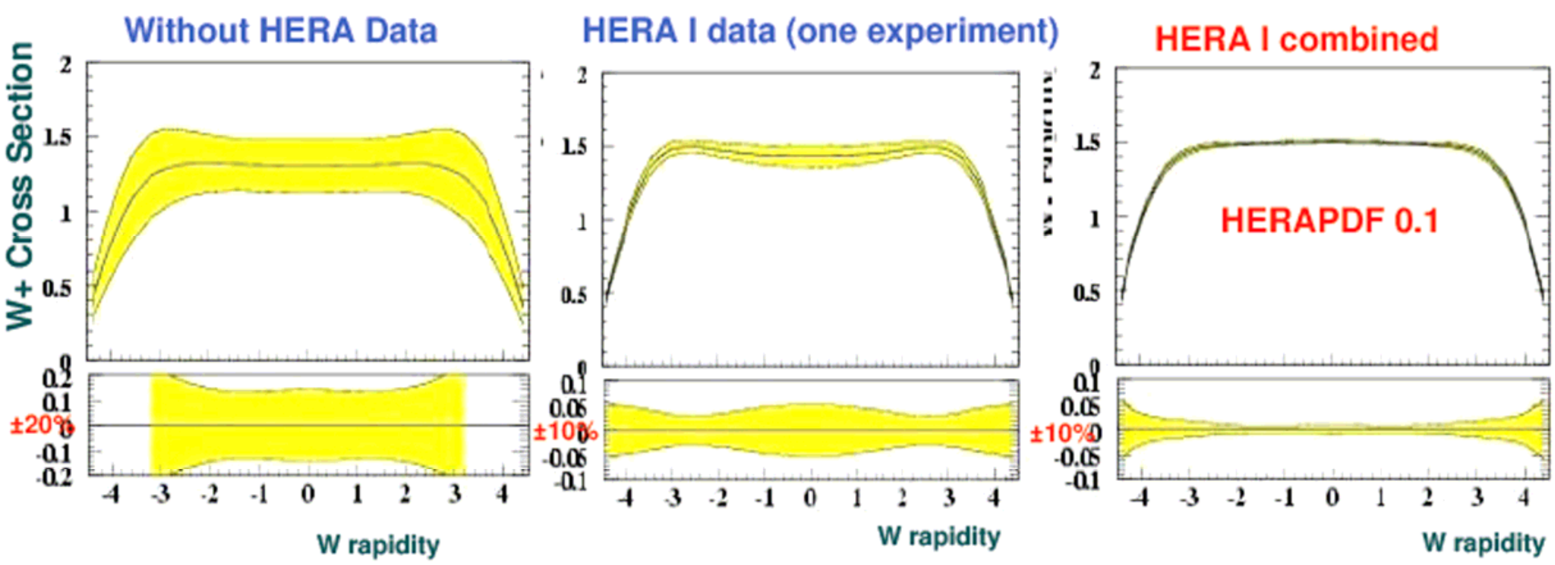


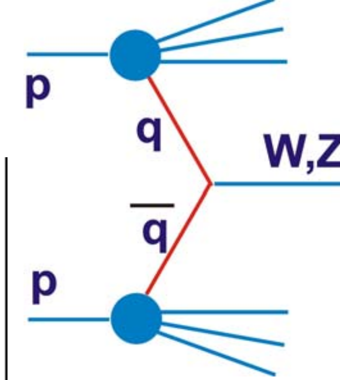
(Catani et al.)

'Standard Candle' processes required:
- Check formalism (QCD fac^n? DGLAP?)
- Calibrate our understanding
- Possibly provide a luminosity monitor?
- … and ultimately could improve PDFs directly at LHC



W & Z as "Standard Candles"

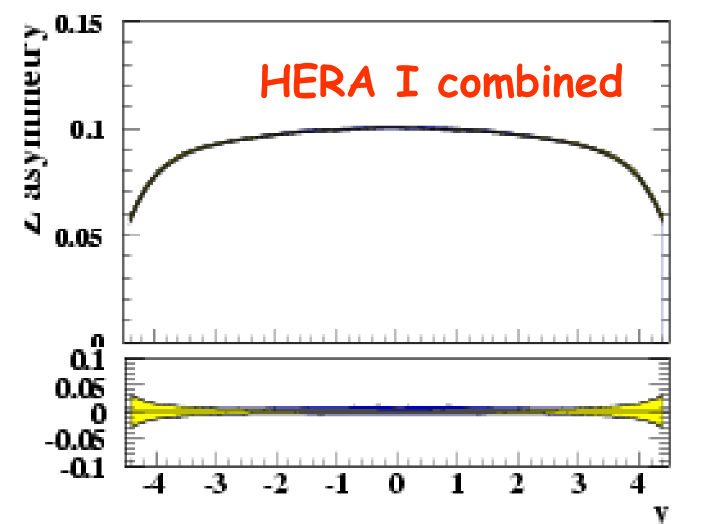




(A Cooper-Sarkar)

W Rapidity Spectra:

- Main improvement due to constraining low x gluon
- 1.5% experimental error in central region (… from HERA-I only!)
- … a further 3-4% from theoretical uncertainty

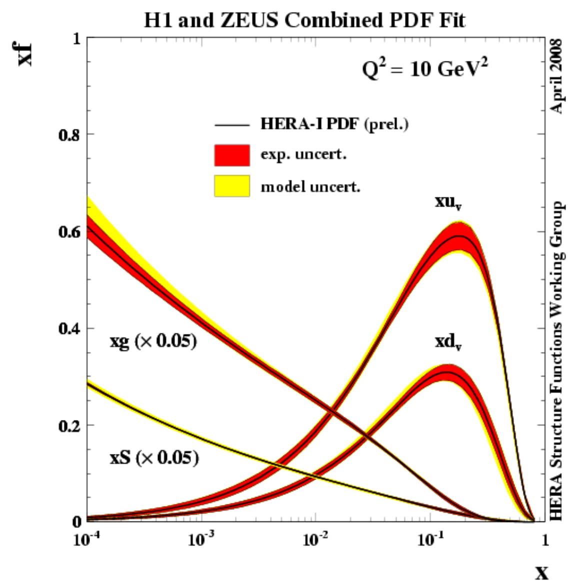


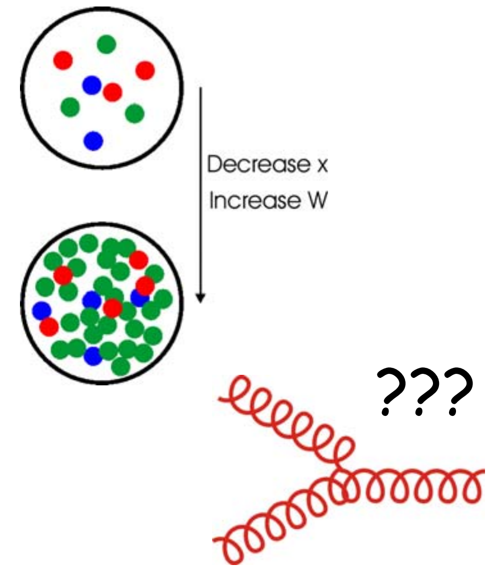
Z/W Ratio:

- → <2% total uncertainty …

Can the Rise of Gluon be True?

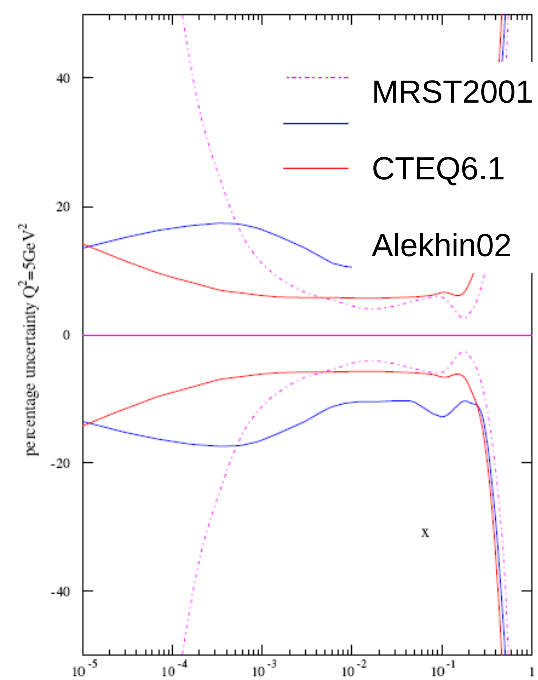
• Gluon density not well constrained directly at low x… but cannot rise indefinitely as x decreases (e.g. recombination gg→g)





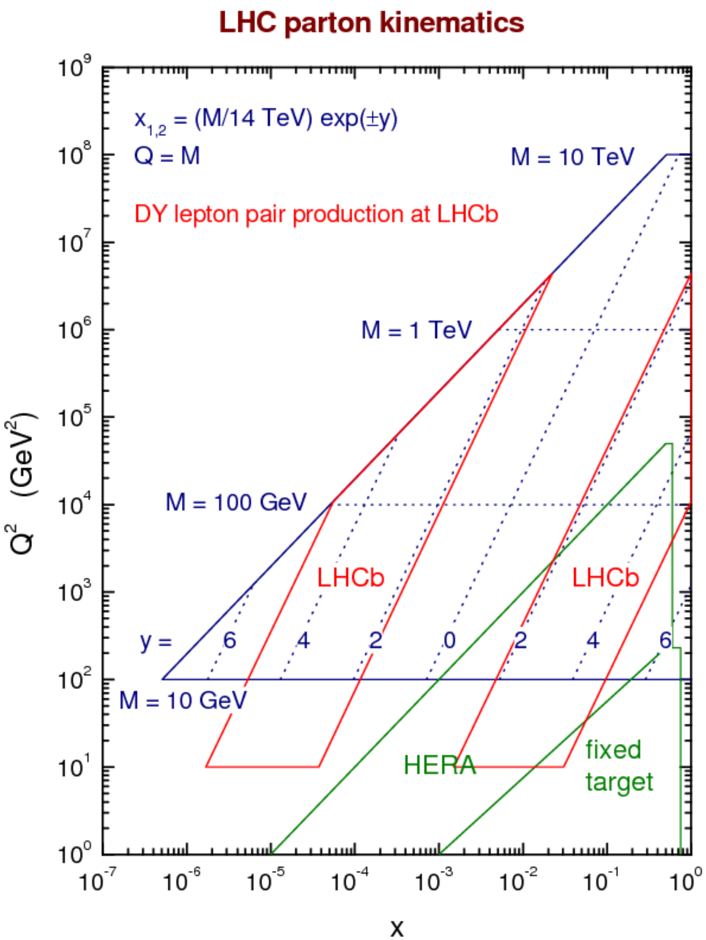
• DGLAP approximation to QCD evolution may become insufficient?

• Result is largely extrapolation from higher x.



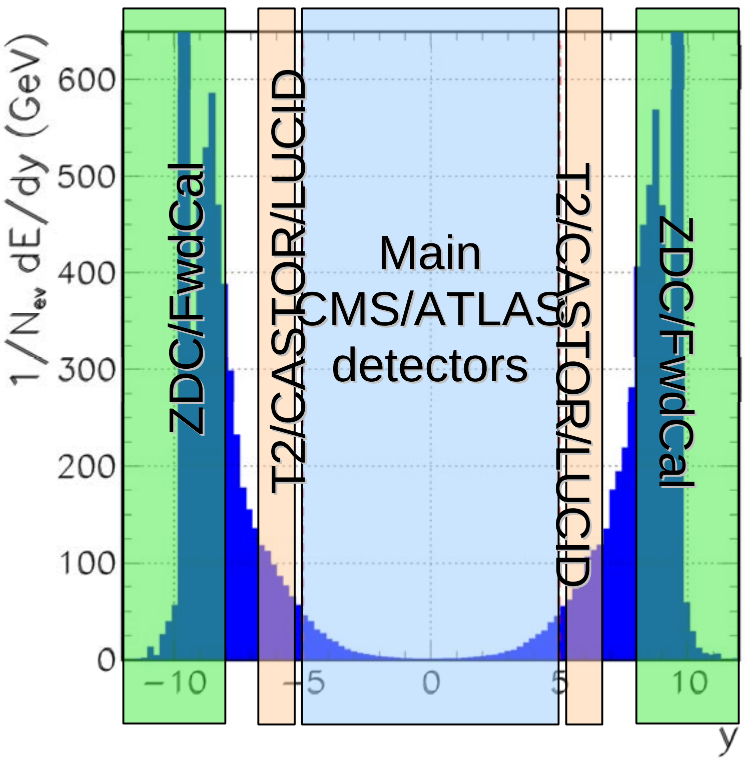
• Essential to test the gluon density at low x and "large" scales at LHC through direct measurement …

LHCb and Low x Partons



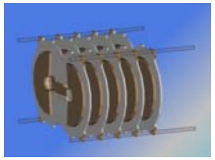
Saturation of PDFs unlikely to be visible on LHC rapidity plateau
… but may evolve there from saturated Region at same x, lower Q^2 at HERA

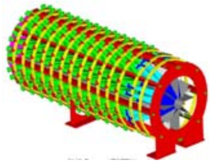
… asymmetric beams (LHCb) or very forward instrumentation (e.g. Totem acceptance to $|\eta|$=6.5 corresponds to $x \sim 10^{-6}$ at Q^2 = 100 GeV^2)

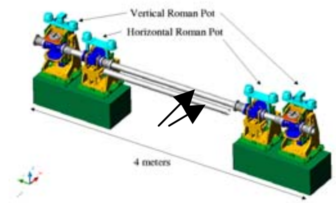


LHC Forward Instrumentation

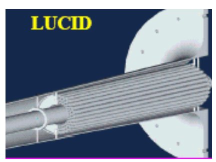
IP5

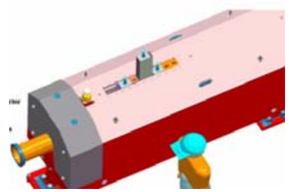


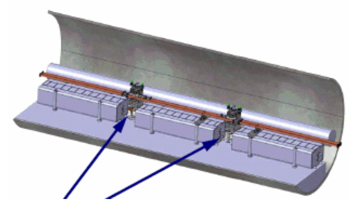


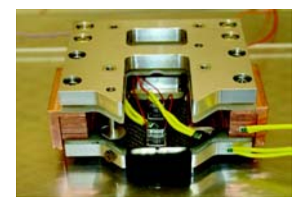


	TOTEM-T2	CASTOR	ZDC/FwdCal	TOTEM-RP	FP420
	14m	16m	140m	147-(180)-220m	420m
		LUCID	ZDC	ALFA/FP220	FP420







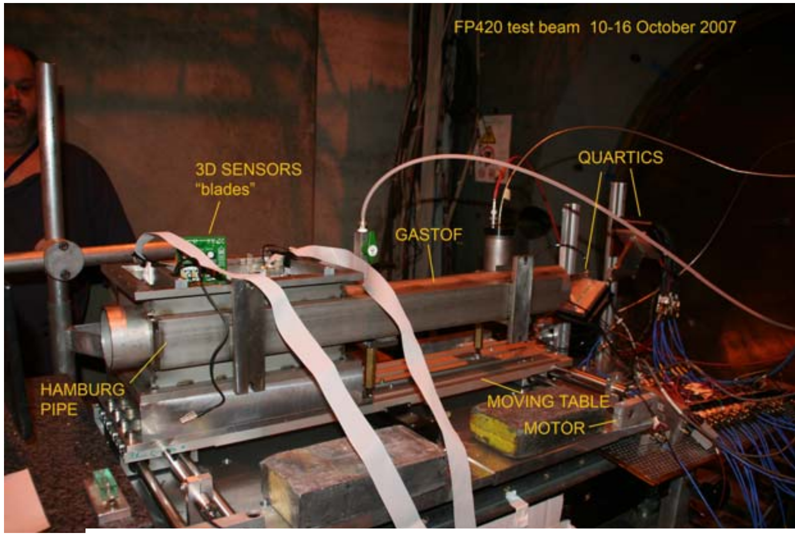


IP1

Impressive array of forward physics projects, providing high rapidity tracking / calorimetry and proton spectroscopy …

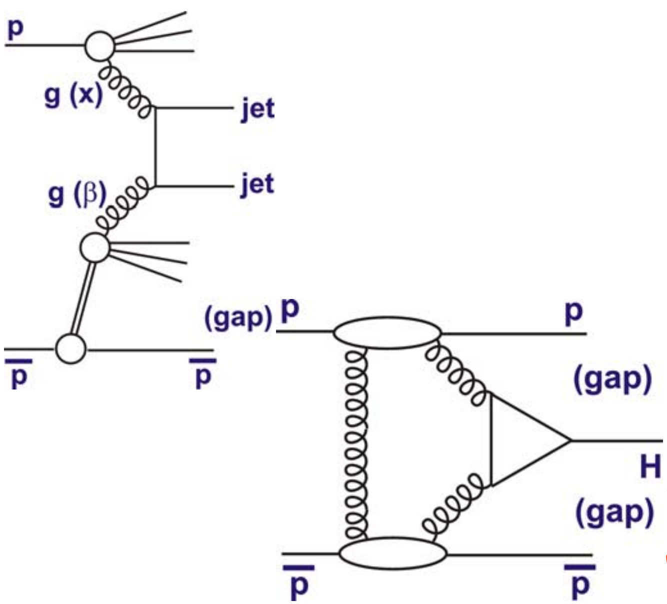
… the best instrumented forward beam-lines ever!

Diffraction & Forward Proton Spectrometry

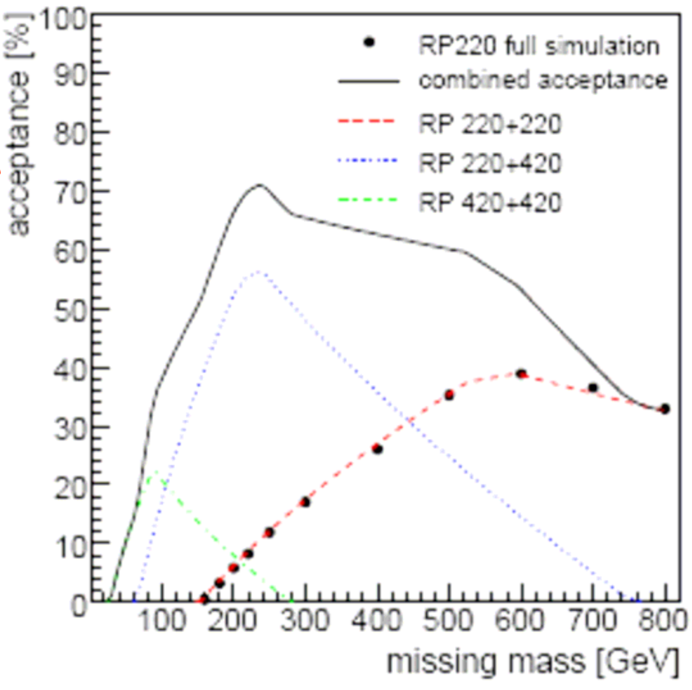


Pots up to 150m, 220m and 420m

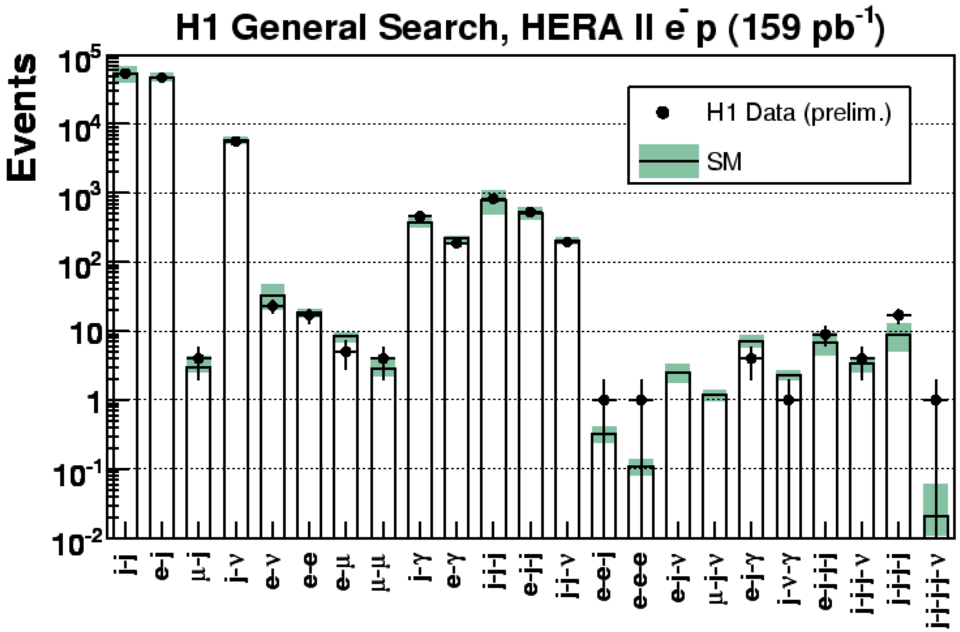
- CMS has 150m and 220m pots
- ATLAS 220m and both 420m to be approved
- Big UK involvement in FP420 R&D
- HERA DPDFs are a major input
- $\gamma\gamma$, γp, γIP as well as pIP
- Clean Higgs production?

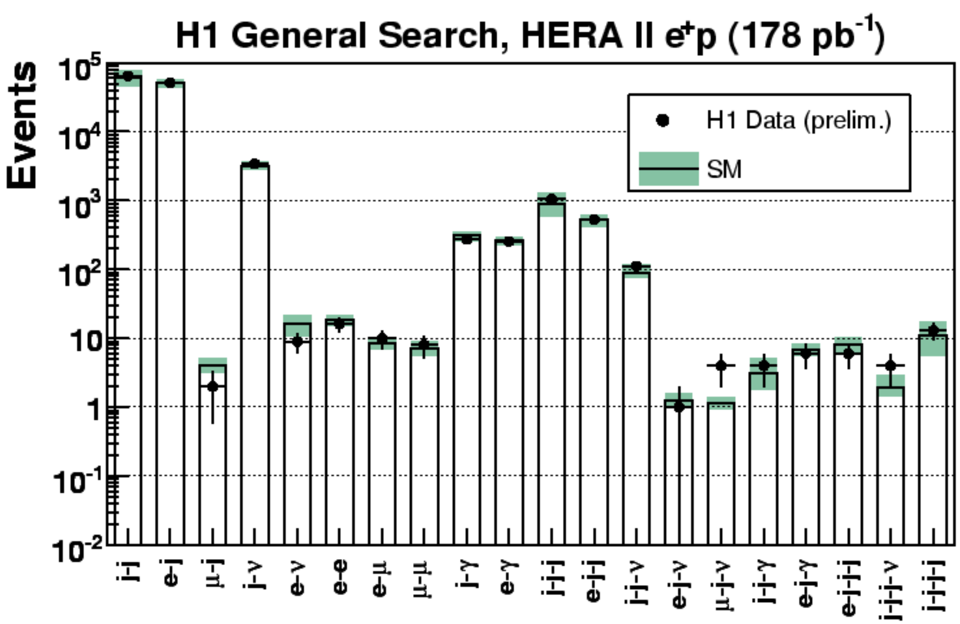


- Comprehensive M_H coverage with 220m, 420m combined … Higgs Mass resolution ~ 2-4 GeV over wide m_H range

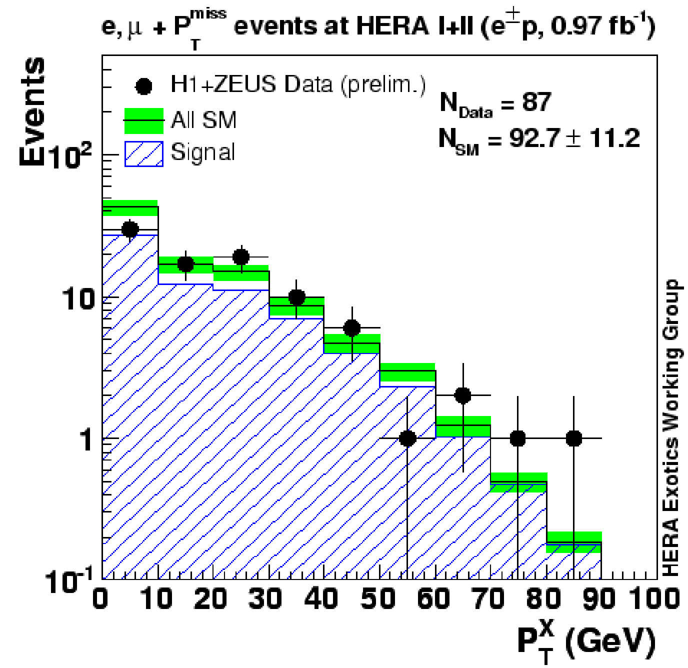


Celebrations usually at end … are we finished?



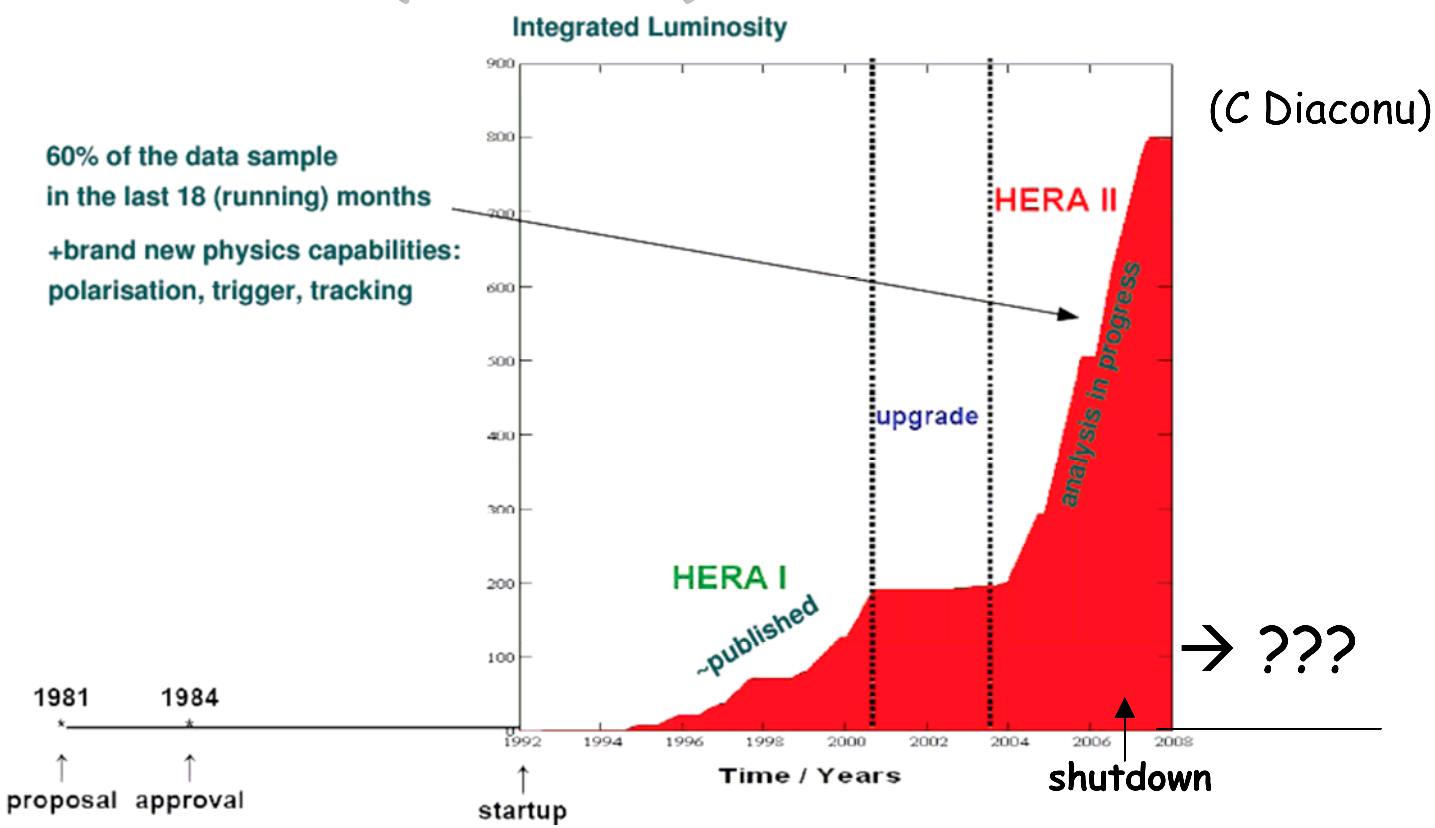


… perhaps yes for searches



- Combined HERA results clarify e.g. H1 isolated high pt leptons With missing pt
- No really significant signals
- Detectors well understood!

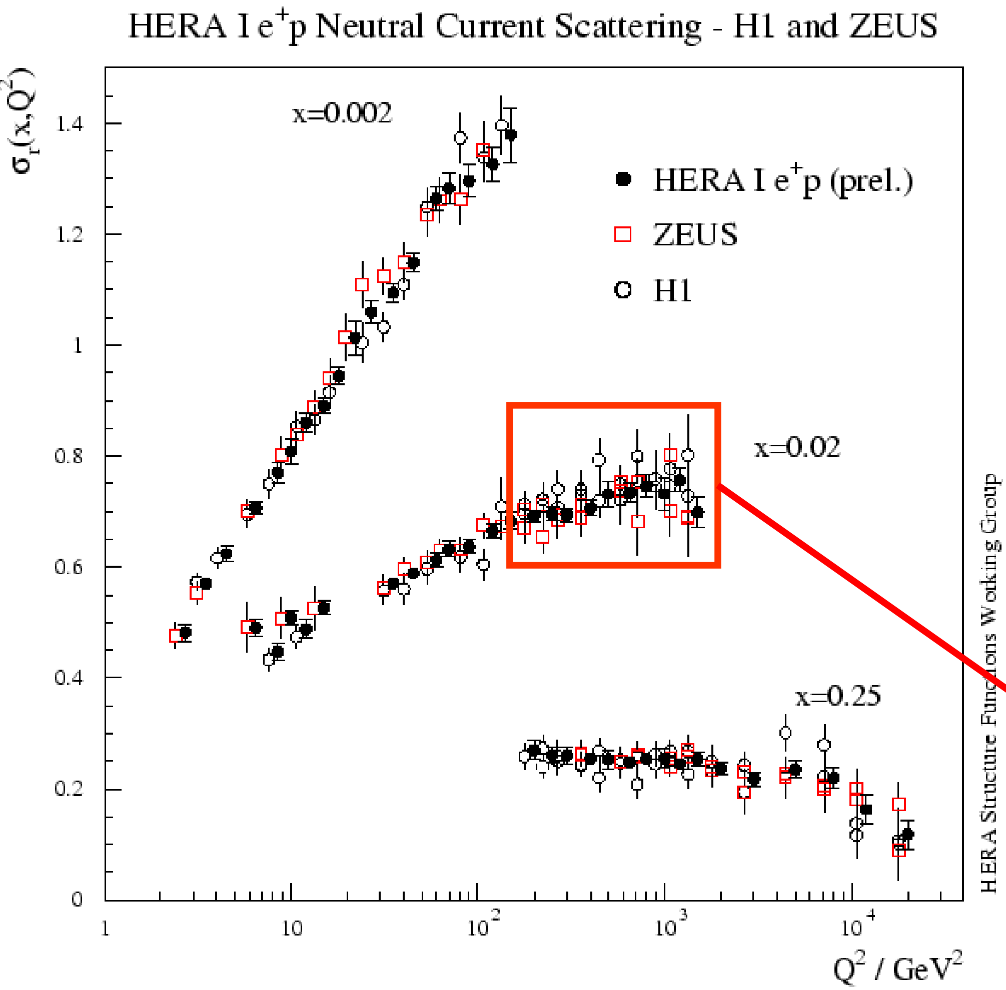
A(nother) HERA Timeline



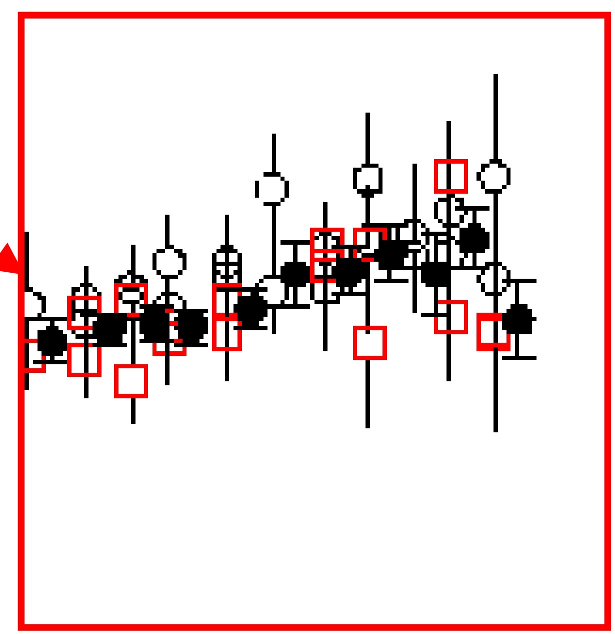
... very few publications on HERA-II so far!.. best still to come
... complicated final states take time (& UK experts) to analyse!

"UK physicists are still very much engaged in getting the most accurate data analysed and published on subjects of key importance for HERA, for QCD and in the preparation For the LHC. The projects require modest travel and common Fund support (mainly computing) in order to produce the final publications which capitalise on two decades of UK investment" [Particle Physics Consultation Panel to STFC Programmatic Review:]

Example: H1 + ZEUS Combinations



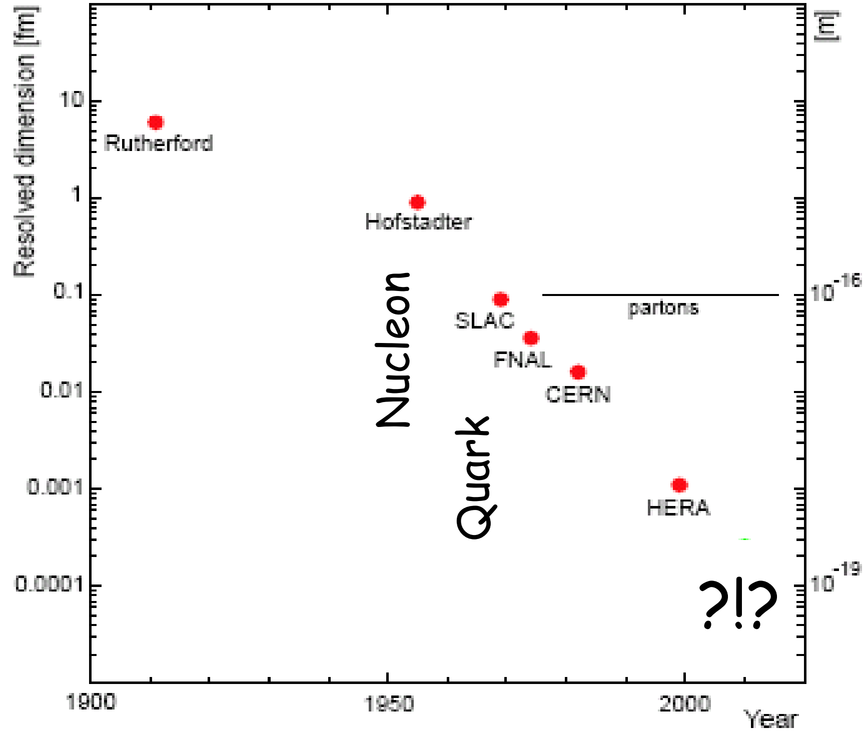
- Complementary dominant systematics lead to cross-calibration and big gains in syst precision
-Young technique, pushing boundaries of statistics
- Much more to come …

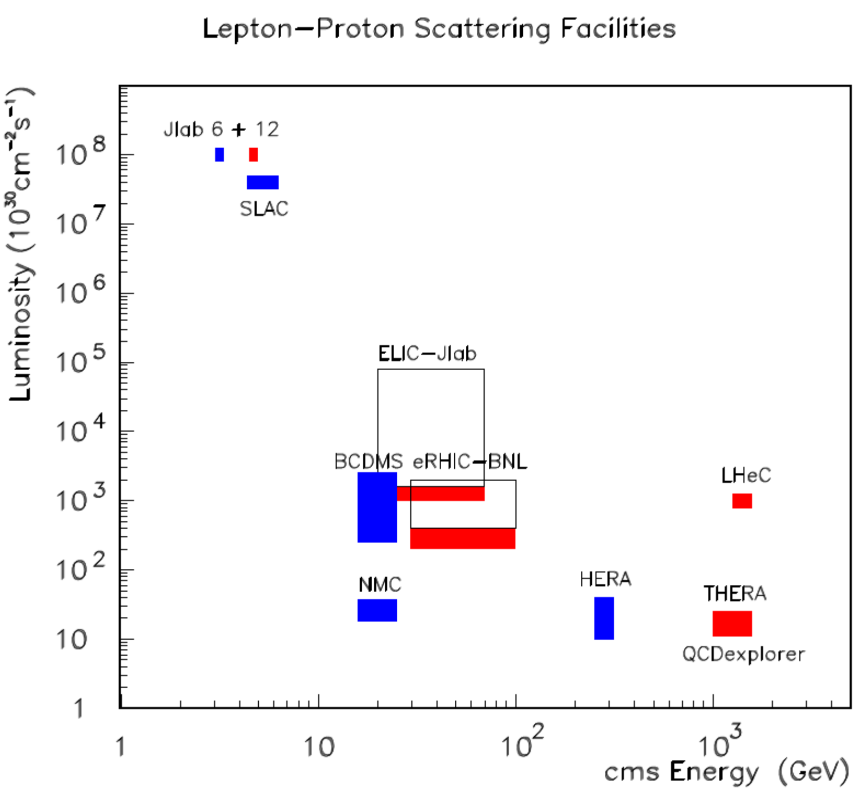


- Done only for HERA-I so far
- Also, α_s, final states, diffraction …

Possible DIS futures?

- Progress in HEP has previously combined ppbar, e^+e^- and ep
- Natural to think of next steps for lepton-hadron scattering



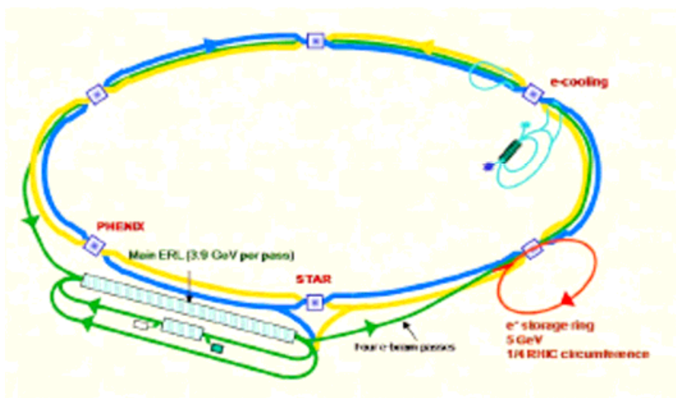


- No future high energy ep/eA physics approved…
- **LHeC** latest of several ideas to take ep physics into the TeV energy range … with unprecedented lumi
- **EIC** builds on RHIC & Jlab → spin

The Electron-Ion Collider (BNL / Jlab)

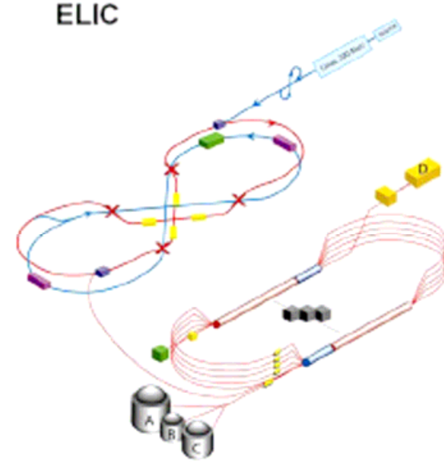
e.g. 5 GeV e+/- and 250 GeV polarised p/A

eRHIC



Peak lumi ~ 2.6 x 10^{33}cm^{-2}s^{-1}

ELIC



Peak lumi ~ 6 x 10^{34}cm^{-2}s^{-1}

- Limited in energy, but
  - high luminosity
  - heavy ions → low x saturation
  - polarised hadrons → spin
- The only long-term successor to HERMES!...
- UK involvement through Glasgow
- NuPeCC study group

"An electron-ion collider with polarised beams has been embraced by the US nuclear science community … QCD frontier of strong colour fields in nuclei and precisely imaging the gluons in the Proton." [NSAC 2007 Long Range Plan]

Motivation for TeV Scale DIS: LHeC

-New Physics of eq Bound States, ν^*, Selectrons …

leptoquarks, RP violating SUSY, quark compositeness

-The Low x Limit of Quantum Chromodynamics

high parton densities with low coupling

`saturating; the parton growth, new evolution dynamics

diffraction and confinement

quark-gluon dynamics and the origin of mass

-Precision Proton Structure for the LHC and elsewhere

essential to know the initial state precisely (b, g …)

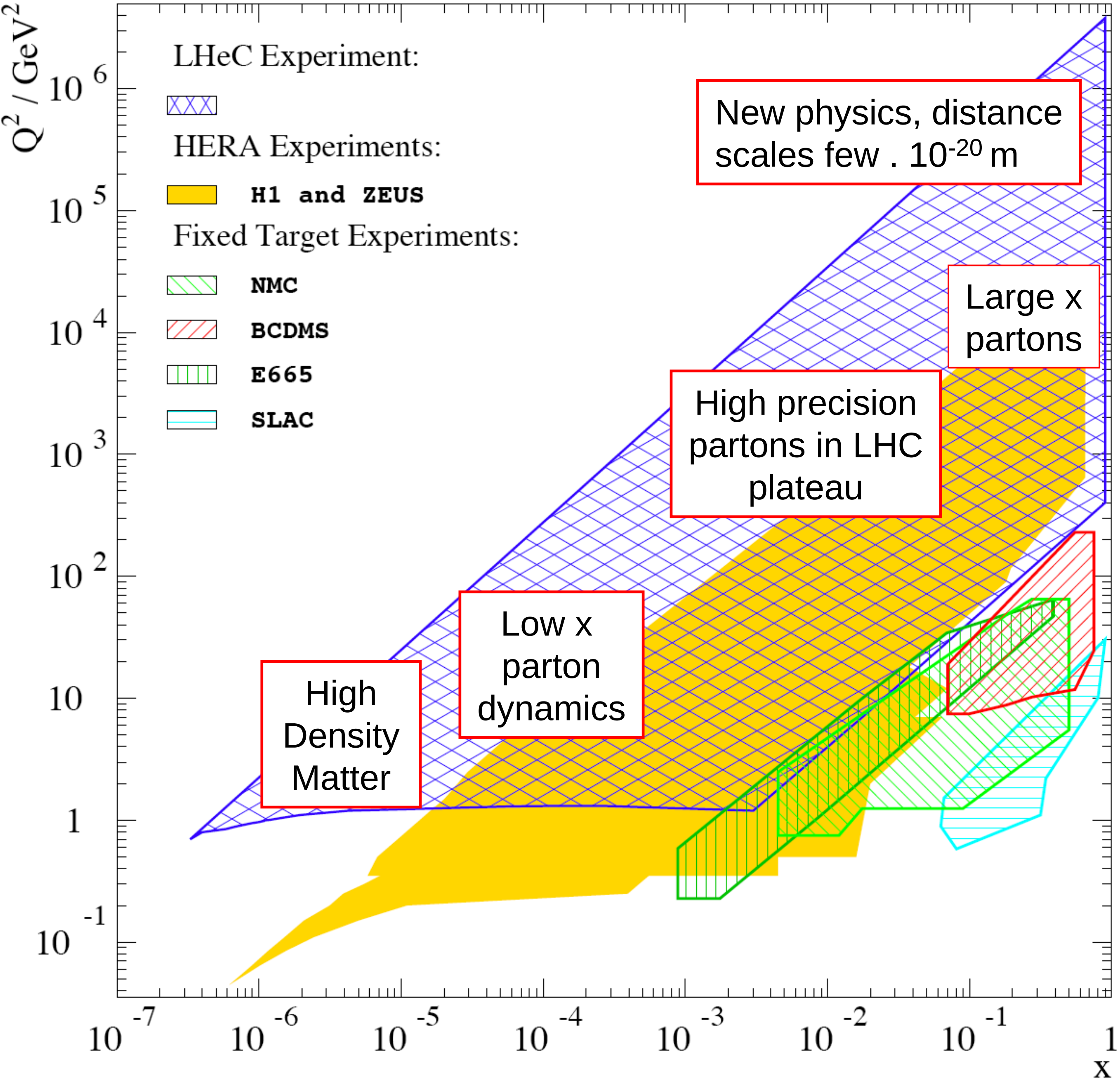
-Nuclear Parton Densities

eA with AA -> partons in nuclei, Quark Gluon Plasma

… some considerations follow with E_e = 70 GeV, E_p = 7 TeV,

lumi ~ 10^{33} cm^{-2} s^{-1} (~ 10 fb^{-1} $year^{-1}$)…

Inclusive Kinematics for 70 GeV x 7 TeV



$$\sqrt{s} = 1.4\ \text{TeV}$$

$$W \leq 1.4\ \text{TeV}$$

$$x \geq 5.10^{-7} \text{ at } Q^2 \leq 1\ \text{GeV}^2$$

- High mass (Q^2) frontier $M_{eq} \rightarrow 1.4\text{TeV}$
- Q^2 lever-arm at moderate x
- Low x (high W) frontier

Systematic Precision Requirements

e.g. Requirements based on reaching per-mil α_s (c.f. 1-2% now)

The new collider …

- should be 100 times more luminous than HERA …

… achievable using low β focusing quad's (acceptance → 170°)

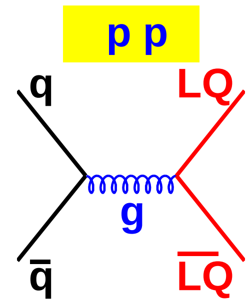
The new detector

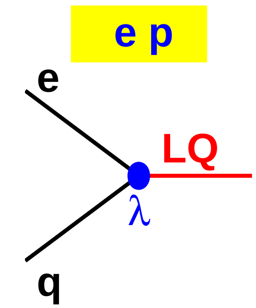
- should be at least 2 times better than H1 / ZEUS

Redundant determination of kinematics from e and X
is a huge help in calibration etc!

Lumi = 10^{33} cm^{-2} s^{-1}	(HERA 1-5 x 10^{31} cm^{-2} s^{-1})
Acceptance 10-170° (→179°?)	(HERA 7-177°)
Tracking to 0.1 mrad	(HERA 0.2 – 1 mrad)
EM Calorimetry to 0.1%	(HERA 0.2-0.5%)
Had calorimtry to 0.5%	(HERA 1%)
Luminosity to 0.5%	(HERA 1%)

Lepton-quark Bound States





- Leptoquarks appear in many extensions to SM… explain apparent symmetry between lepton and quark sectors.

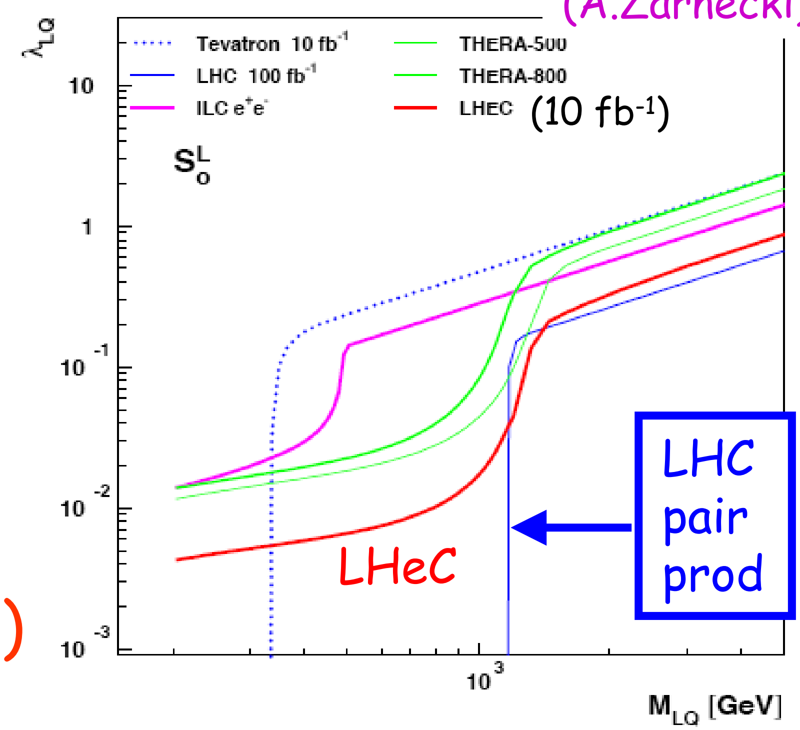
Yukawa coupling, λ

- Scalar or Vector color triplet bosons carrying L, B and fractional Q, complex spectroscopy?

- (Mostly) pair produced in pp, single production in ep.

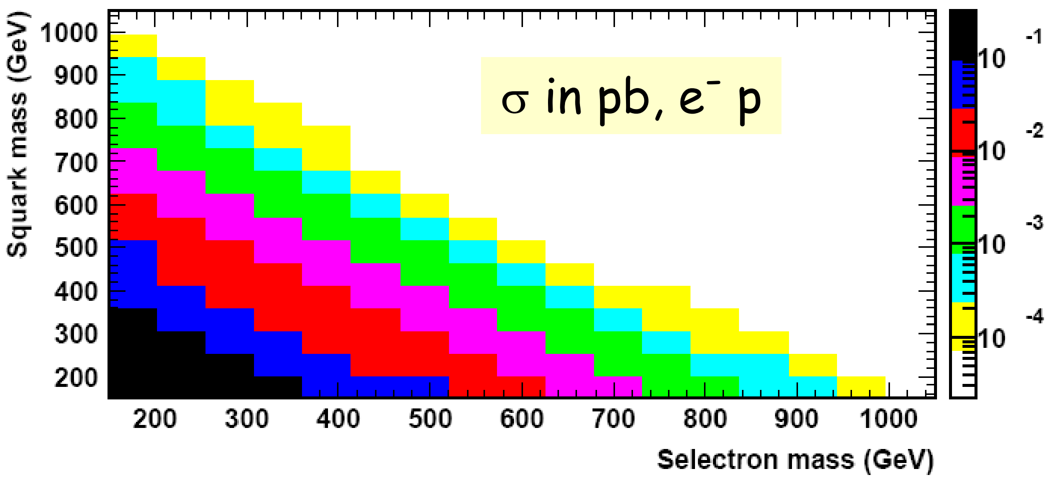
- LHeC sensitivity (to ~1.5 TeV) similar to LHC, but can determine quantum numbers / spectroscopy (fermion #, spin, chiral couplings …)

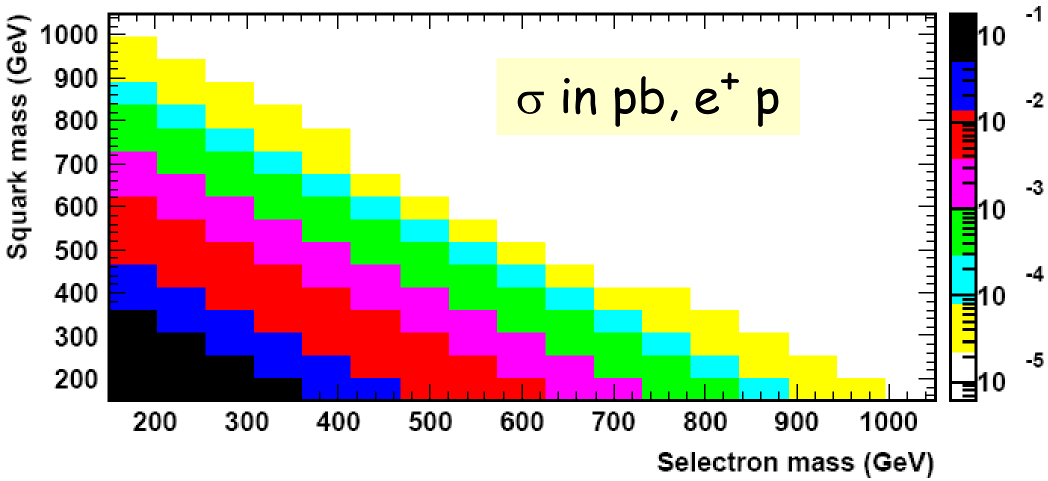
(A.Zarnecki)



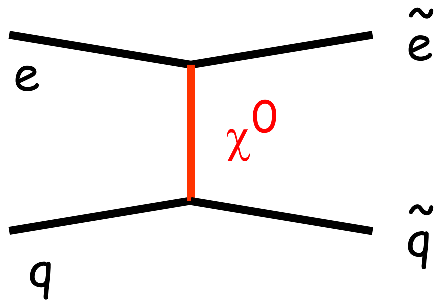
Supersymmetry

tan β = 10, M_2 = 380 GeV, μ = -500 GeV





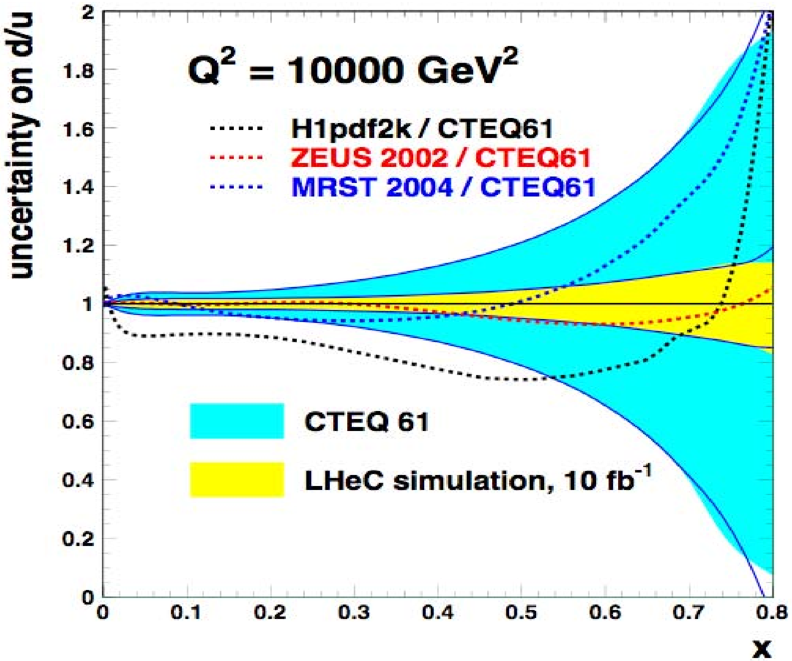
(E.Perez)

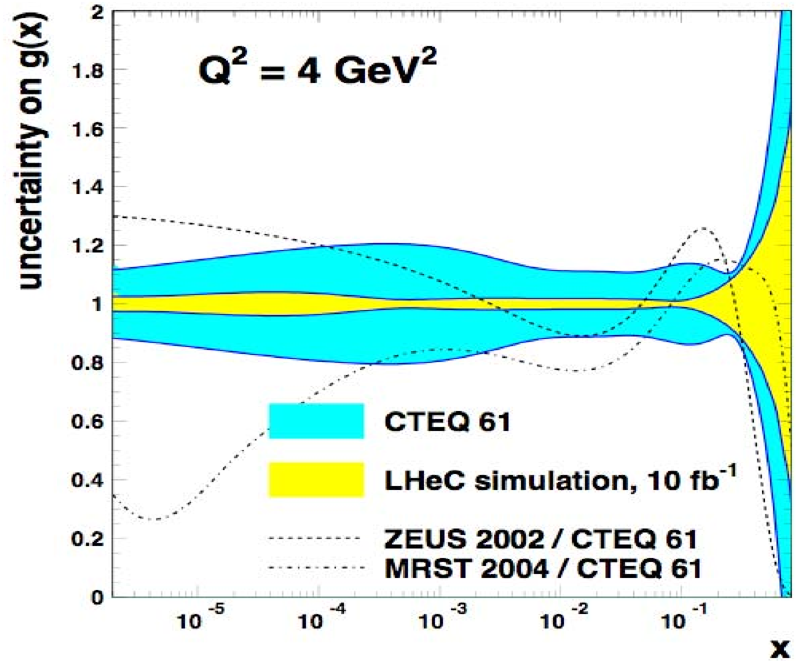


Pair production via t-channel exchange of a neutralino.

Cross-section sizeable for $\Sigma M < 1$ TeV i.e. if squarks are "light", could observe selectrons up to ~ 500 GeV, a little beyond LHC?

LHeC Impact on High x Partons and α_s





Full NC/CC sim (with systs giving per mil α_s) & NLO DGLAP fit using standard HERA technology…

… high x pdfs → May help clarify LHC discoveries through interpretation of new states?

The LHeC for Low x Investigations

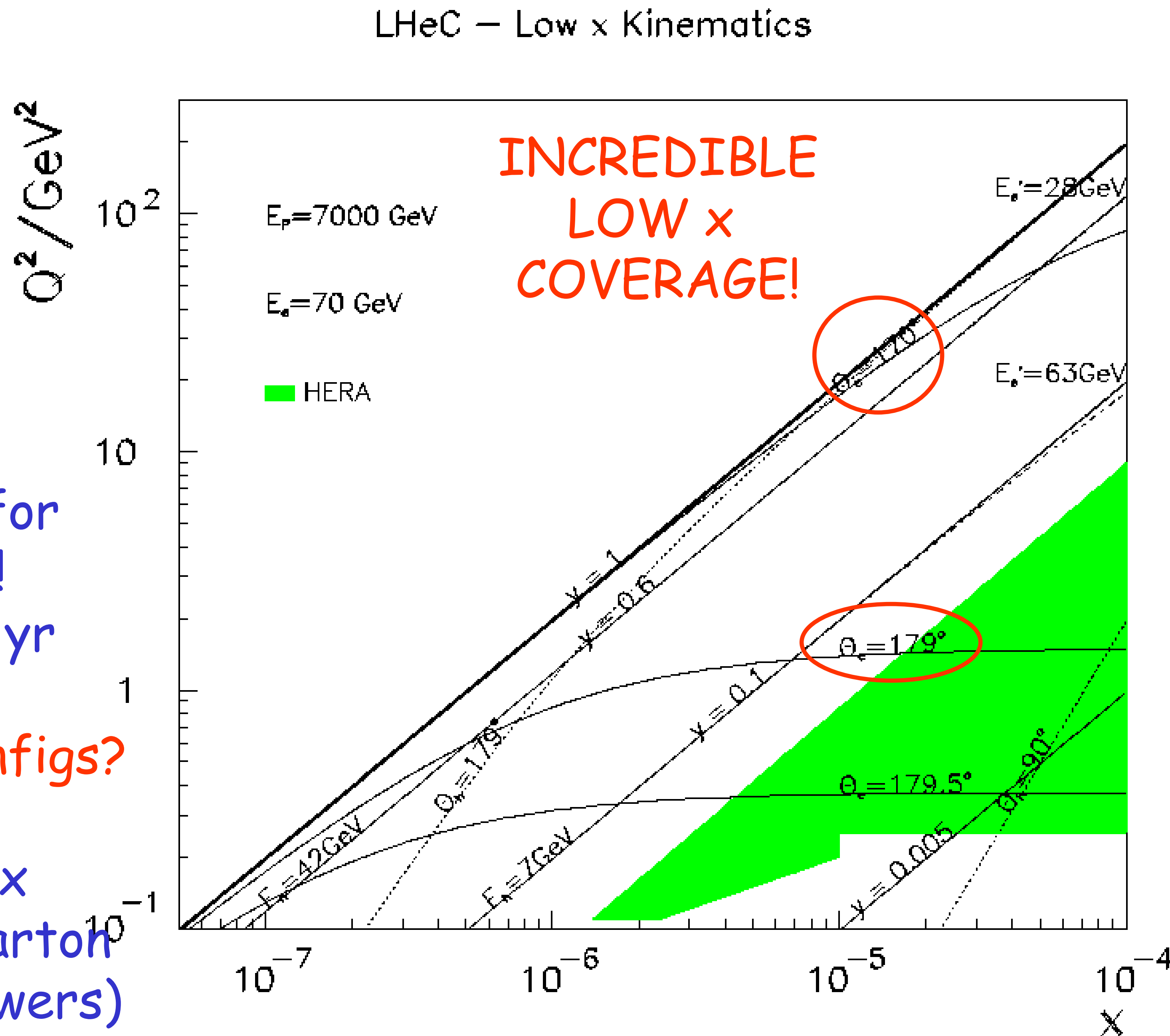
Requires detectors close to beam pipe

Acceptance to 179° → access to Q^2=1 GeV^2 for all x > 5 x 10^{-7} !

Lumi ~ 1 fb^{-1} / yr

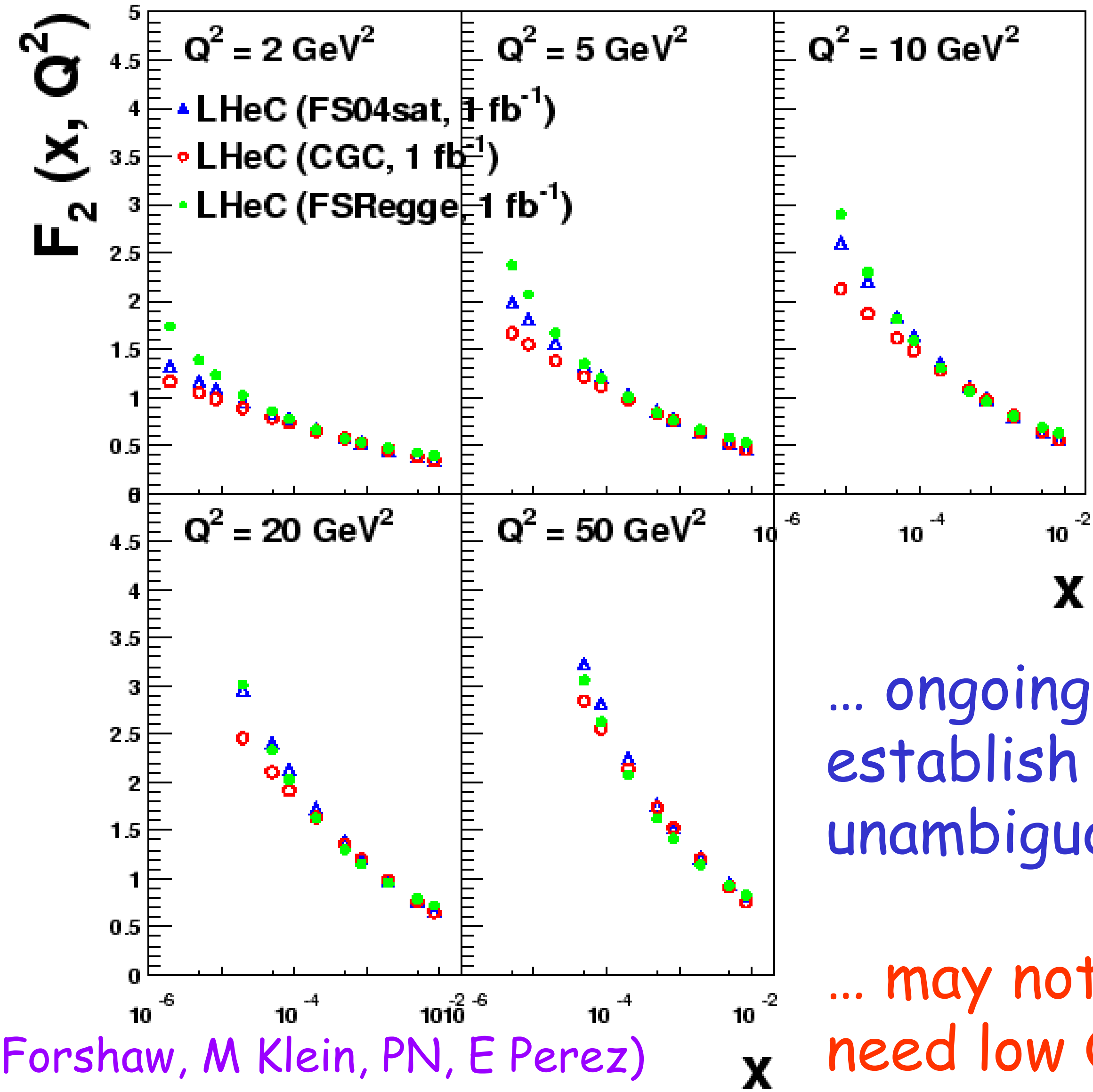
2 detector configs?

Definitive low x facility (e.g. parton saturation answers)



Example low x F_2 with LHeC Data

Stat. precision < 0.1%, syst, 1-3%



Precise data in LHeC region, x > ~10^{-6} (detector → 1°)

- Extrapolated dipole FS04, CGC models including sat'n suppressed at low x, Q^2

… ongoing work on how to establish saturation partons unambiguously …

… may not be easy and will need low Q^2 ($\theta \rightarrow 179°$) region

(J Forshaw, M Klein, PN, E Perez)

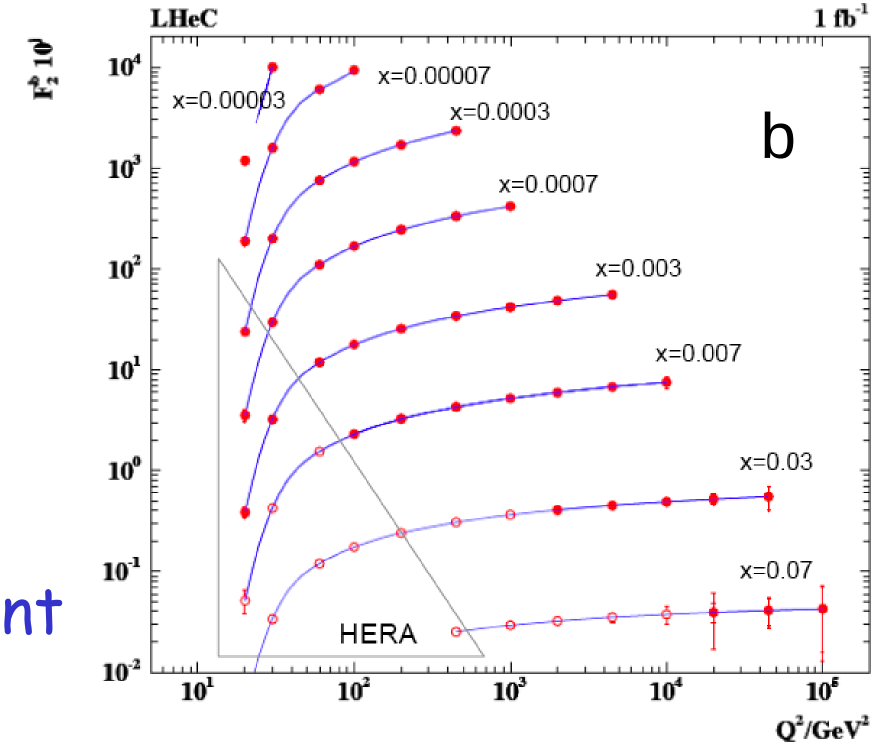
Heavy Quarks: LHeC

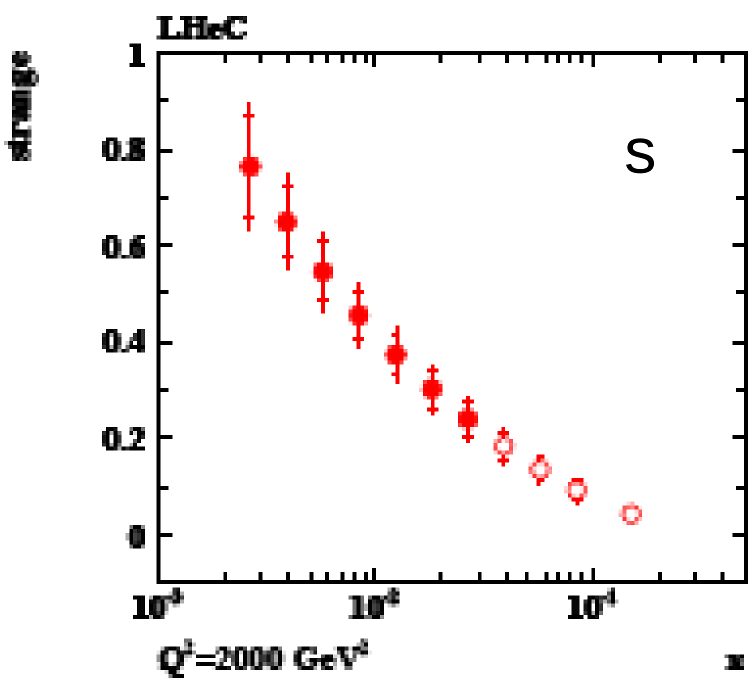
High precision c, b measurements (modern Si trackers, beam spot 15 * 35 μm^2 , increased rates at larger scales).

Systematics at 10% level

→beauty is a low x observable!

→s (& sbar) from charged current

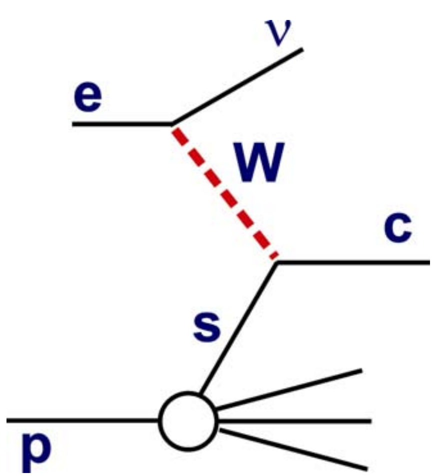




● LHeC 10° acceptance

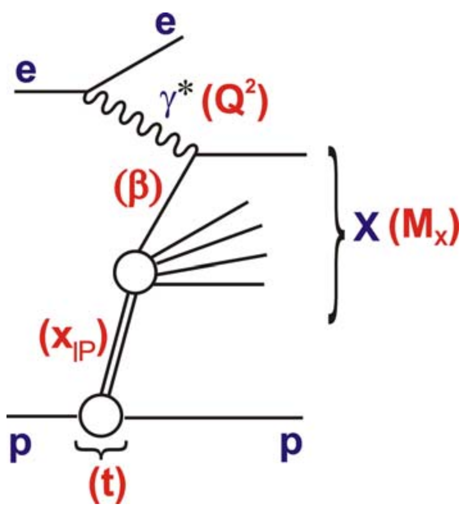
○ LHEC 1° acceptance

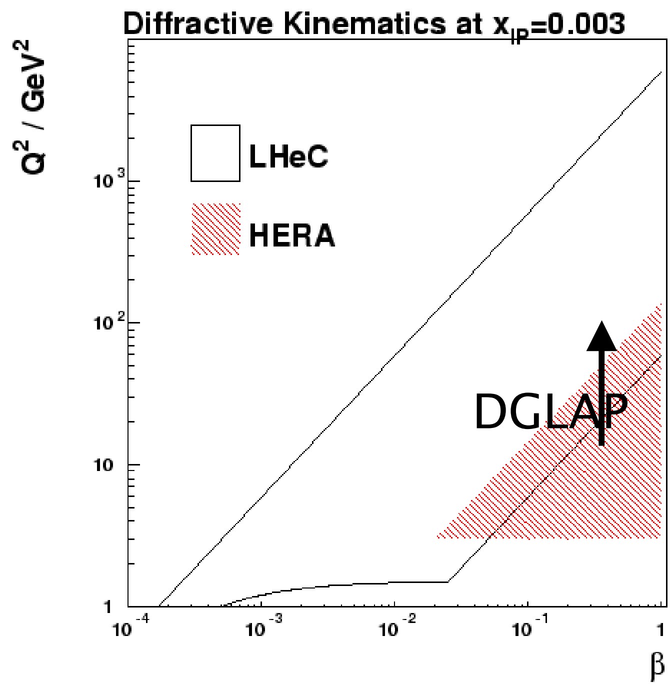
(A. Mehta, M. Klein)

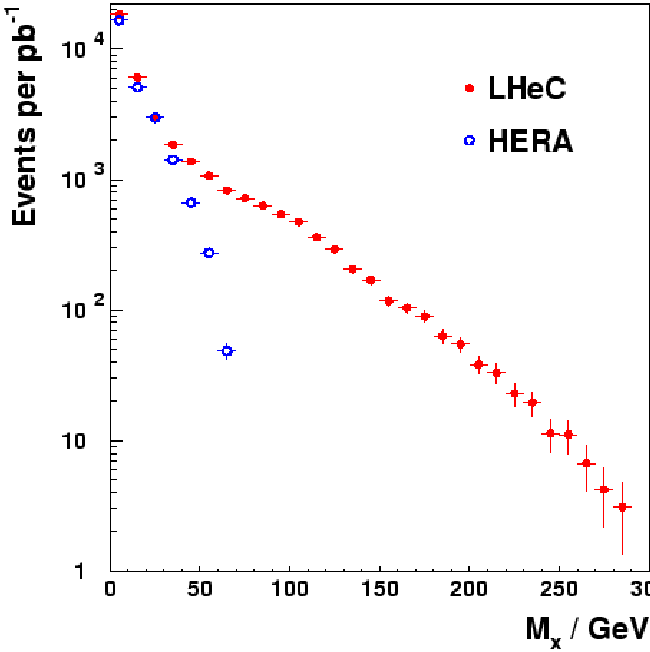


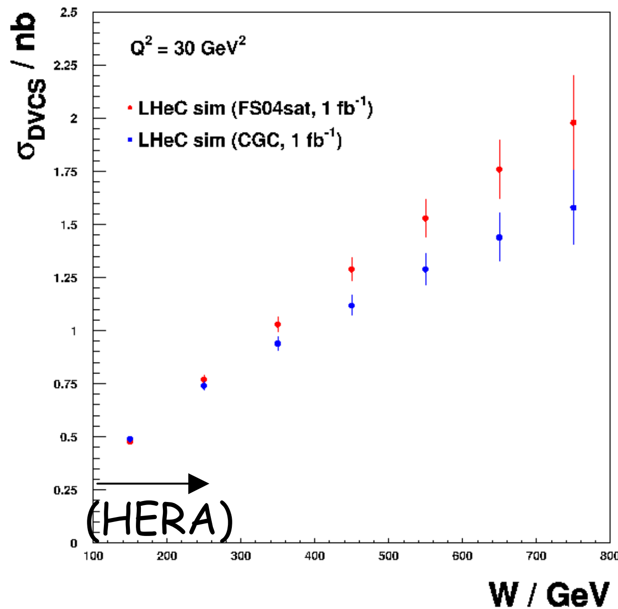
(Assumes 1 fb^{-1} and
- 50% beauty, 10% charm efficiency
- 1% uds → c mistag probability.
- 10% c → b mistag)

Some Kinematics for Diffractive DIS



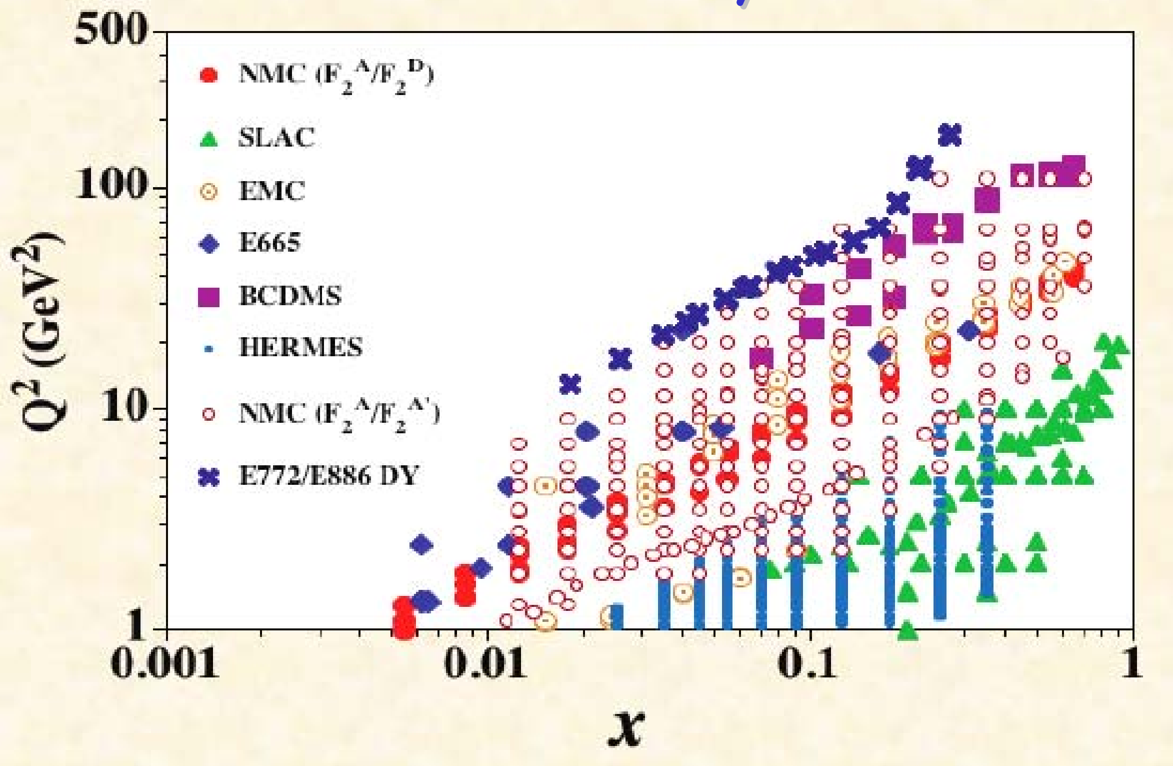






- 5-10% data, depending on detector
- (D)PDFs / fac'n in much bigger range
- Enhanced parton satn sensitivity?
- Mx → 200 GeV … X including W, Z, b
- Exclusive production of any 1^- state
- …

With AA at LHC, LHeC is also an eA Collider



- Very limited x and Q^2 range so far (unknown for $x <\sim 10^{-2}$, gluon poorly constrained)

- LHeC extends kinematic range by 4 orders of magnitude

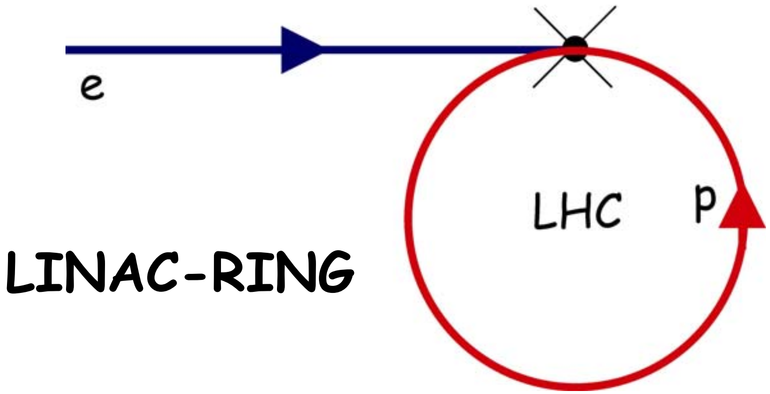
- With wide range of x, Q^2, A, opportunity to extract and understand nuclear parton densities in detail

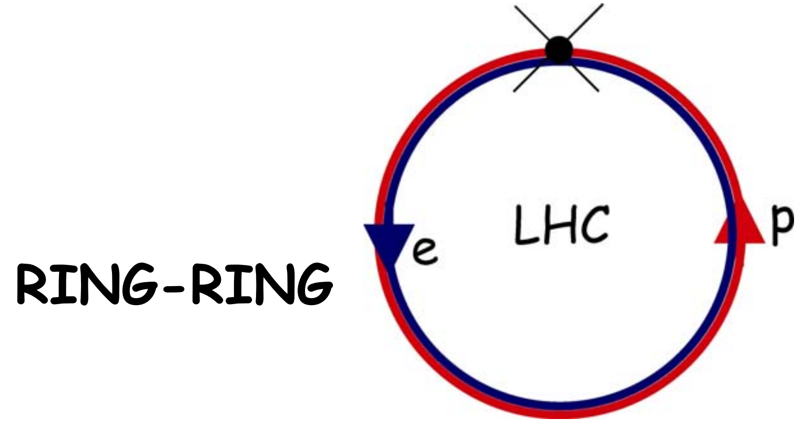
- e.g. enhanced sensitivity to low x gluon saturation

- c.f. ions at ALICE, RHIC … initial state in quark-gluon plasma production is presumably made out of saturated partons

How Could it be Done using LHC?

… essential to allow simultaneous ep and pp running …



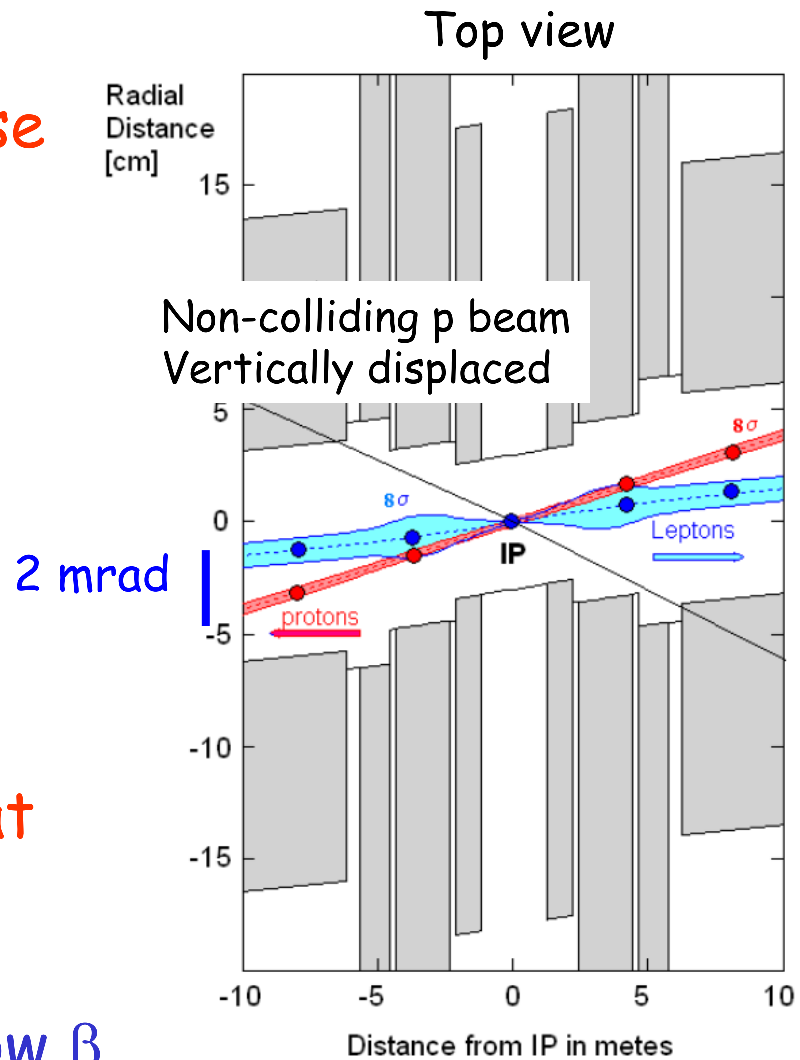


- Previously considered as `QCD explorer' (also THERA)
- Reconsideration (Chattopadhyay & Zimmermann) with CW cavities began
- Main advantages: low interference with LHC, $E_e \rightarrow$ 140 GeV, LC relation
- Main difficulty: peak luminosity only ~0.5.10^{32} cm^{-2} s^{-1} at reasonable power

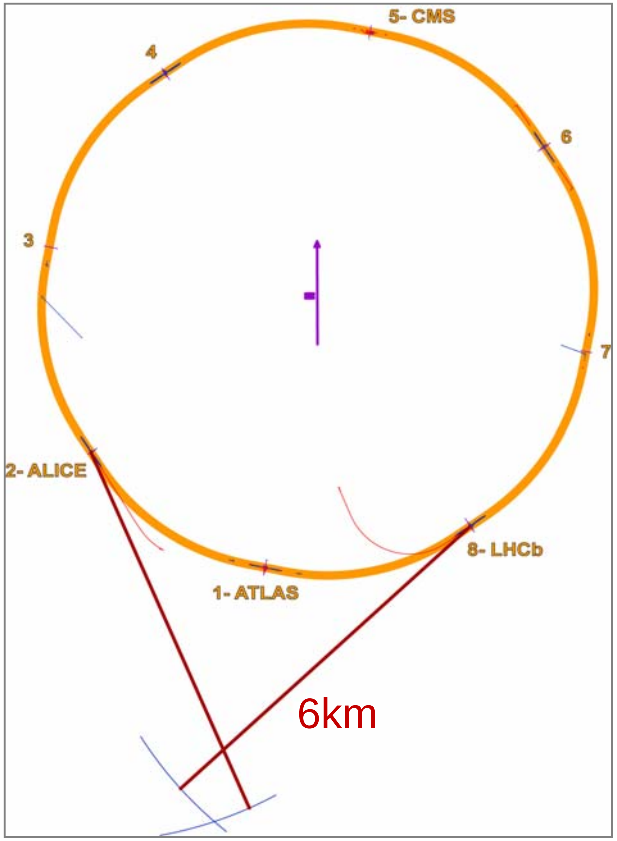
- First considered (as LEPxLHC) in 1984 ECFA workshop
- Recent detailed re-evaluation with new e ring (Willeke)
- Main advantage: high peak lumi obtainable (10^{33} cm^{-2} s^{-1})
- Main difficulties: building it around existing LHC, e beam life

Detailed Ring-Ring Study [hep-ex/0603016]

- LHC fixes p beam parameters
- 70 GeV electron beam, (compromise energy v synchrotron → 50 MW)
- Match e & p beam shapes, sizes
- Fast separation of beams with tolerable synchrotron power requires finite crossing angle
- 2 mrad angle gives 8σ separation at first parasitic crossing
- High luminosity running requires low β focusing quadrupoles close to IP (1.2 m)

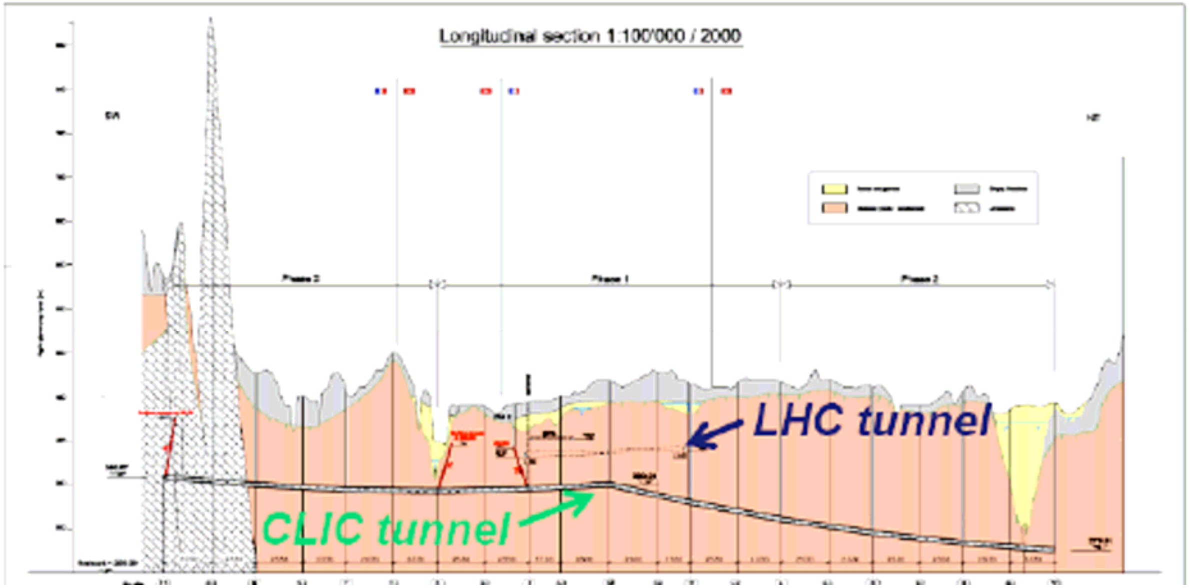


First Linac-Ring Design Ideas



• 140 GeV electron beam at 23 MV/m is 6km + gaps → CMS energy of 2 TeV!

• Relatively low peak luminosity, but good average luminosity



Synergy with Linear Collider?...

Not yet ... e.g. both ILC and CLIC tunnel studies require deeper tunnels than at LHC

First Low x Detector Considerations

- Low x studies require electron acceptance to 1° to beampipe

HERA	E_e=30GeV	E_p=920GeV
	→	←
LHeC	E_e=70GeV	E_p=7000GeV

- Considerably more asymmetric beam energies than HERA!
  - Hadronic final state at newly accessed lowest x values goes central or backward in the detector ☺
  - At x values typical of HERA (but larger Q^2), hadronic final state is boosted more in the forward direction.

- Study of low x / Q^2 and of range overlapping with HERA, with sensitivity to energy flow in outgoing proton direction requires forward acceptance for hadrons to 1°

- More forward hadrons: Roman pots essential for diff'n

ECFA/ CERN Workshop September 08

Planned Working Groups:

- Accelerator Design (ring-ring and linac-ring)
- Interaction region, Forward and Backward Detectors
- Detector Design
- New Physics at Large Scales
- Precision QCD and Electroweak Interactions
- Physics at High Parton Densities (low x, eA)

See http://www.lhec.org.uk & contact convenors if interested

Durham HERA Workshop, March 1993

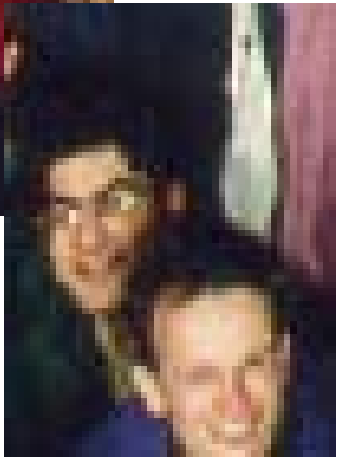






An Early H1 Collaboration Mugshot

Early H1 Mugshot



Summary

From the LHC to HERA …

LHC is a totally new world of energy and luminosity, which will Dominate our field for the forseeable future…

- HERA data provide essential, unique input
- Quantified and developed through HERA-LHC W/S
- Ongoing process … still much more to be gained!

… and back to the LHC …

LHeC proposal aims to exploit LHC this for TeV scale lepton-hadron scattering…

- More and better PDFs in LHC range
- Clarification of LHC pp and AA discoveries?
- Extending low x and high Q^2 frontiers of ep physics
- Encouraging first machine and physics considerations
- Workshop: 1-3 September, l'Esplanade du Lac, Divonne

[Huge thanks to many HERA colleagues for great fun and collaboration over past 16 years!]