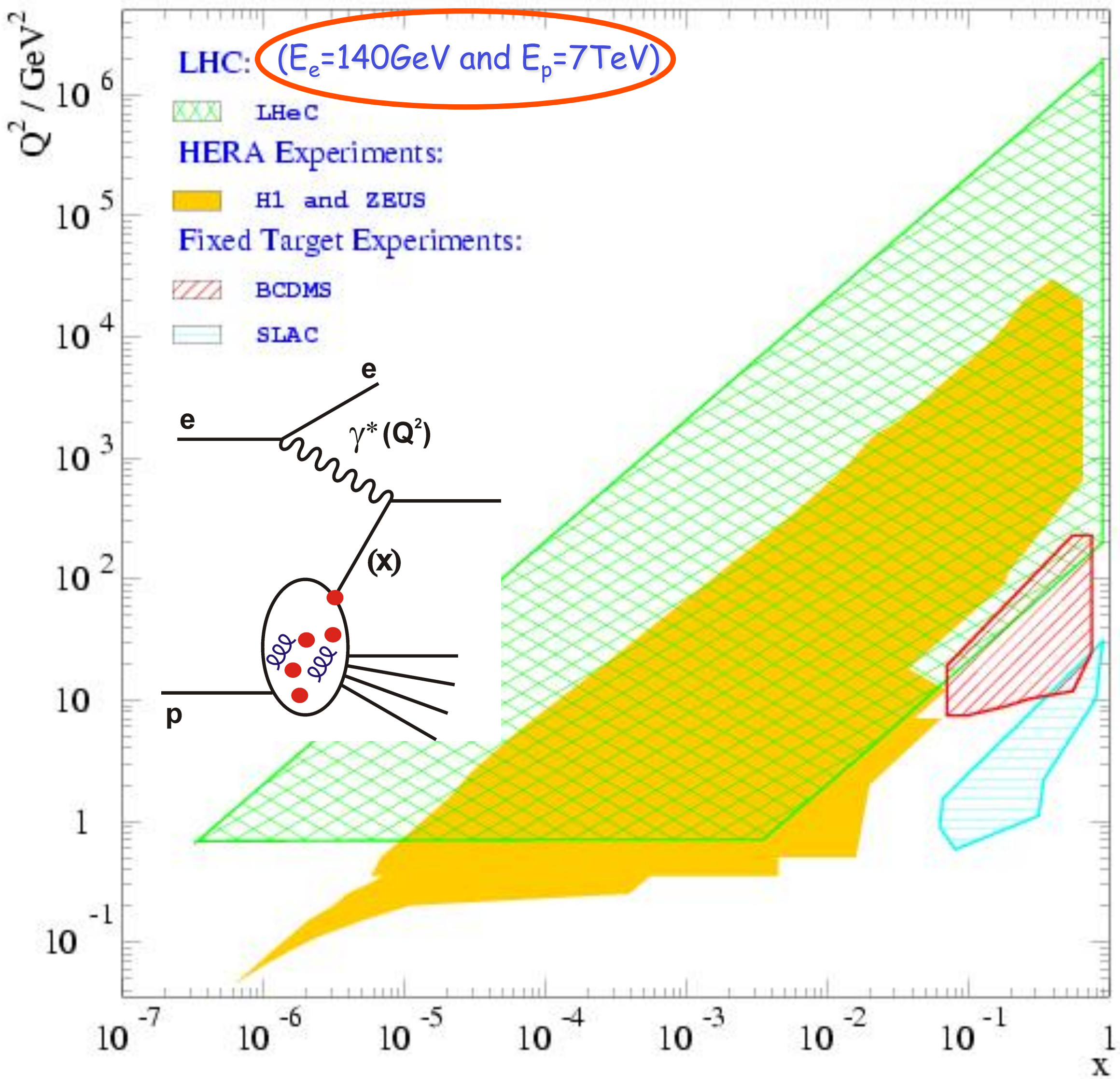
High Energy DIS after HERA?… The LHeC Project

Paul Newman
(Birmingham University)

Southampton Seminar
18 June 2010

… work in progress from ECFA/CERN/NuPECC workshop on ep/eA physics possibilities at the LHC



http://cern.ch/lhec

Overview

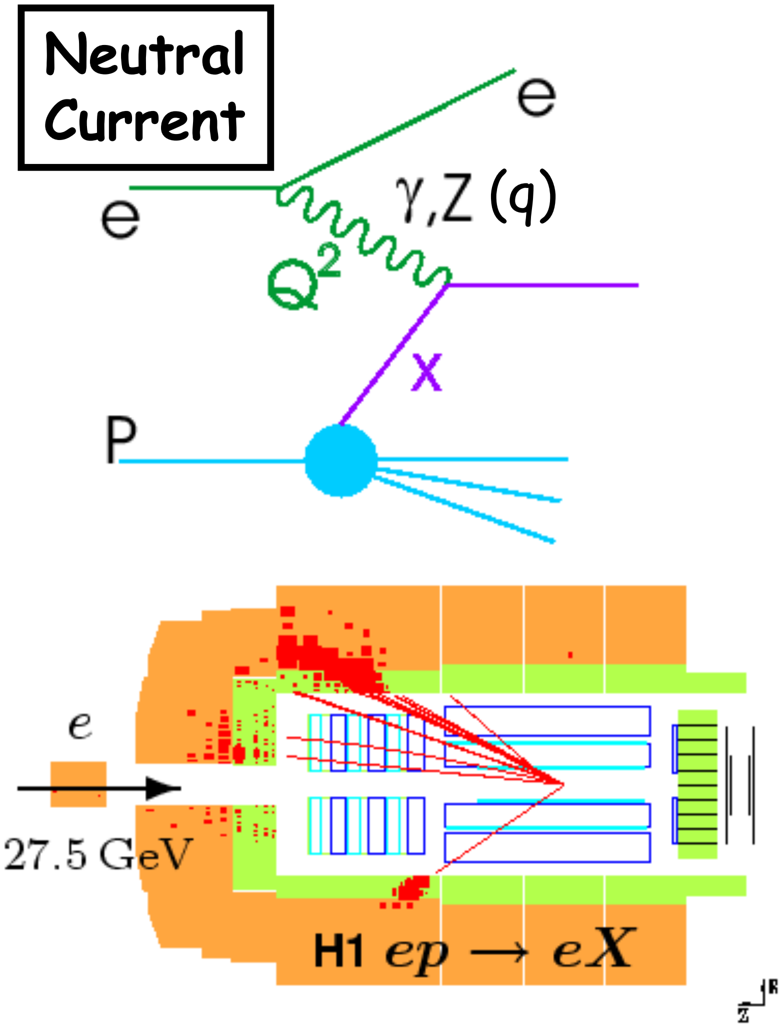
"Now we are entering the post-TeV era, jumping not one but two orders of magnitude to a lab equivalent of order 50 TeV at HERA. If the LHC is successfully commissioned in the LEP tunnel in 1997, then we may hope to see collisions between electrons from LEP and protons from the LHC in the next millenium giving a lab equivalent around 10 TeV (1 PeV). "

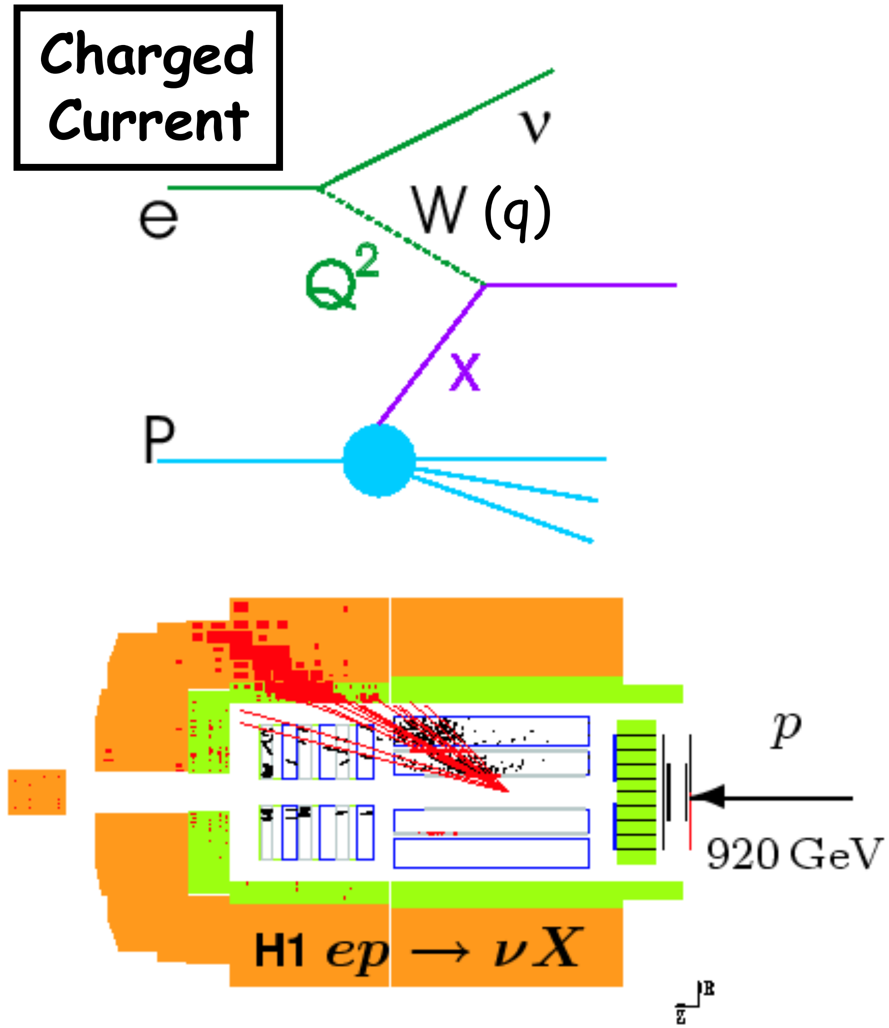
F.Close Singapor 1990

LHeC is the latest and most promising attempt to take ep Physics into the TeV centre-of-mass scale …

- Status of ep Physics after HERA
- How to build an ep Collider using the LHC
- Physics motivation
  - BSM physics
  - Precision QCD / EW
  - Low x / high parton densities
- Detector considerations
- Timeline and outlook

Basic Deep Inelastic Scattering Processes

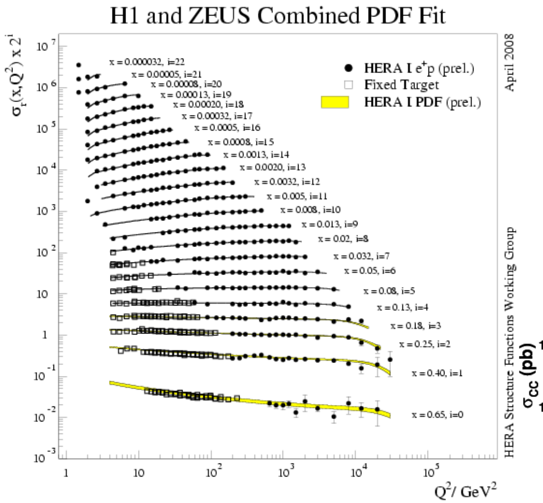


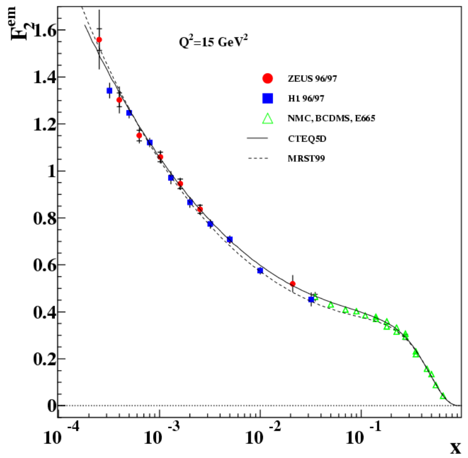


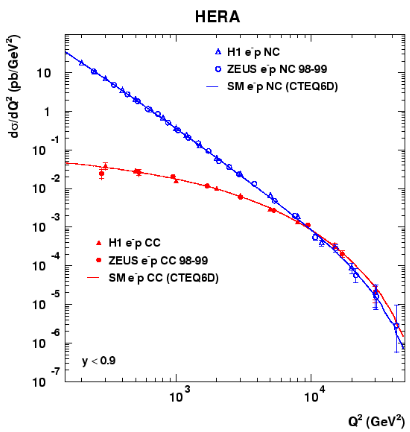
$Q^2 = -q^2$:resolving power of interaction

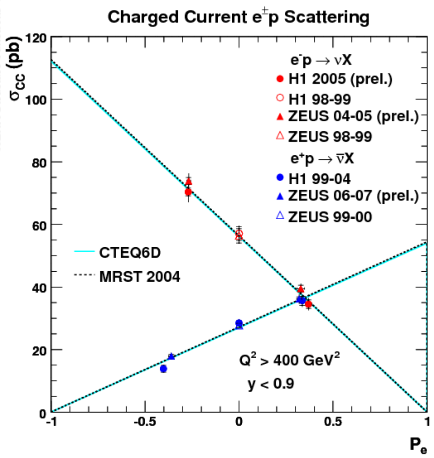
$x = Q^2 / 2q.p$: fraction of struck quark / proton momentum

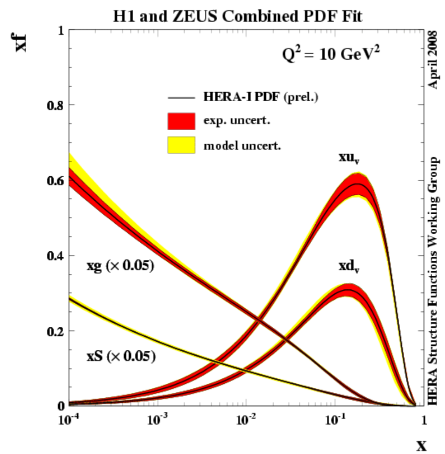
Collage of "Text-Book" HERA Plots

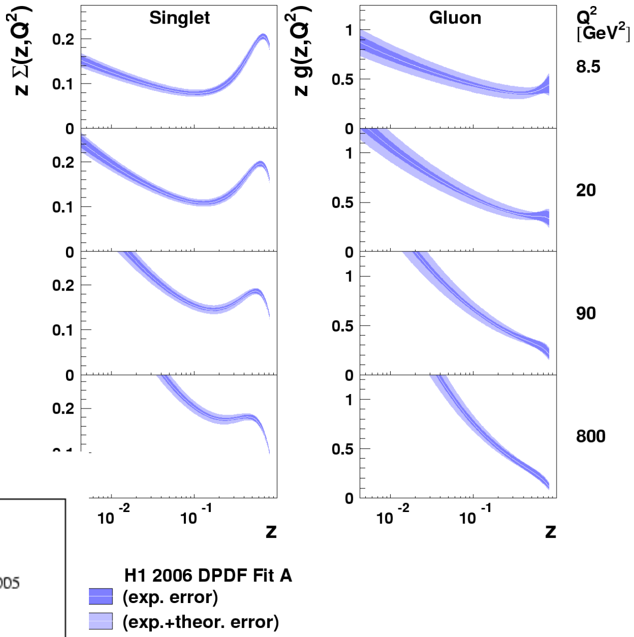


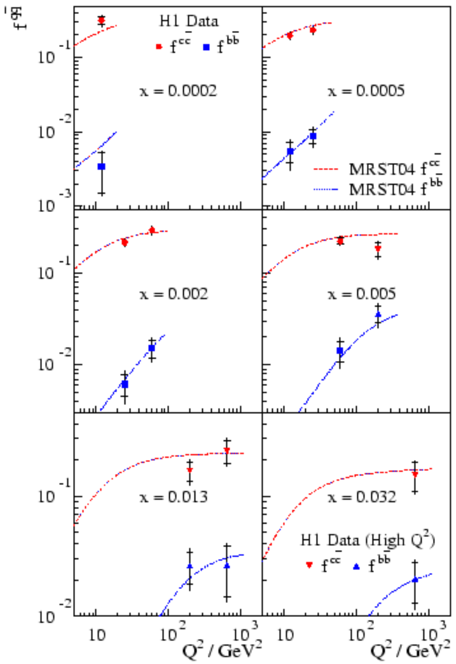


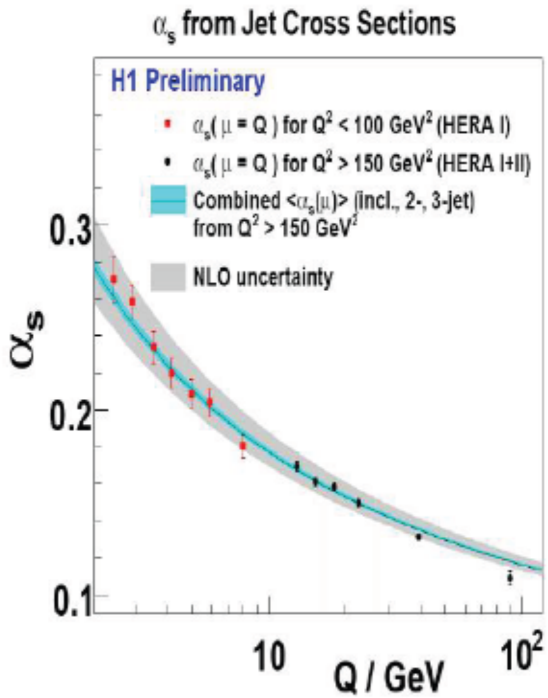




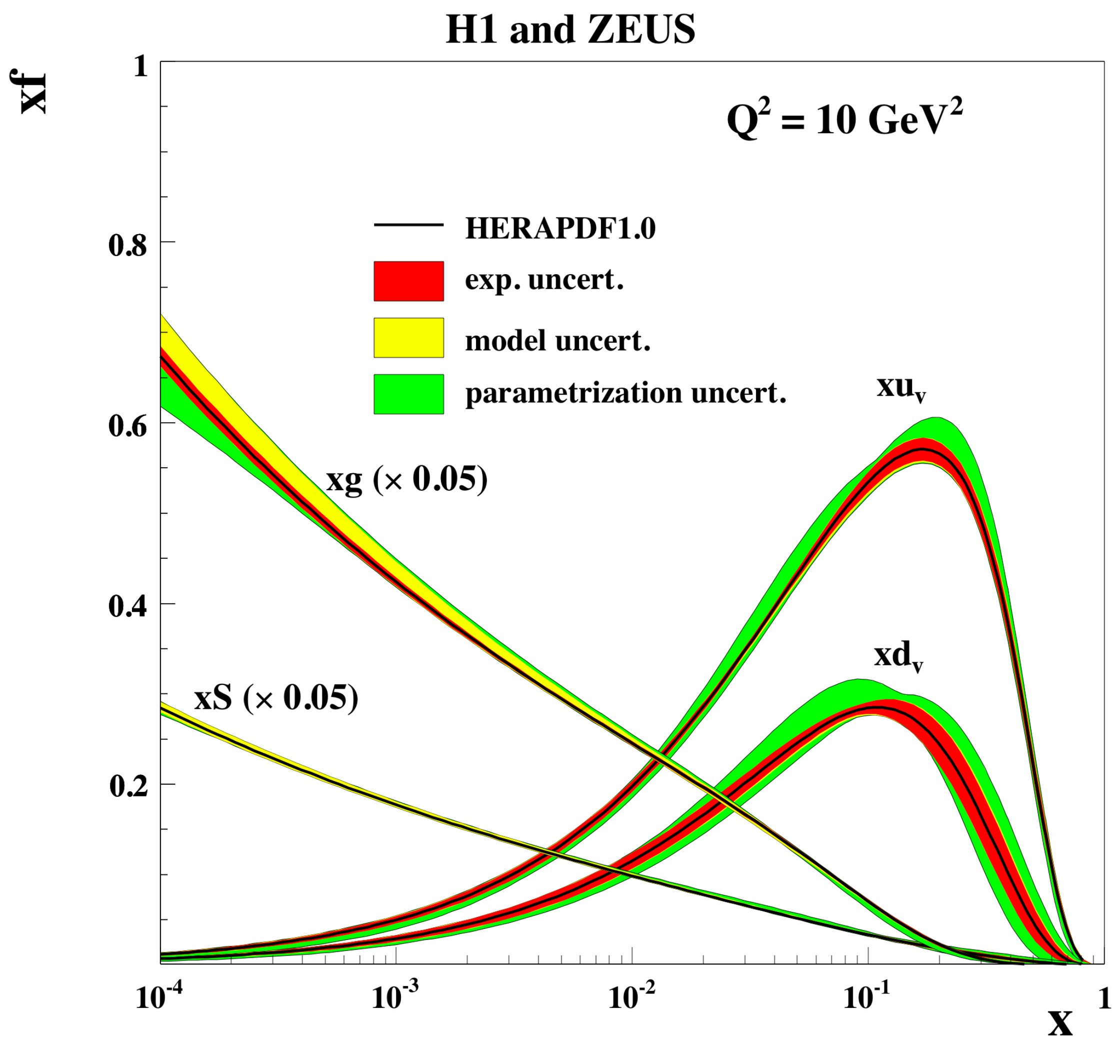








HERA's most famous legacy



Parton densities of proton in an x range well matched to the LHC rapidity plateau ☺

Some limitations:
- Insufficient lumi for high x precision
- No deuterons … u and d not separated
- No heavy ions
- No time to fully explore new concepts like GPDs, DPDFs, unintegrated PDFs

- H1/ZEUS/joint publications still coming for 1-2 years
- Further progress requires higher energy and luminosity …

HERA-LHC Workshop … (see also PDF4LHC)

<u>Workshop on the implications of HERA for the LHC</u>
(partons, jets, heavy flavours, diffraction, MC tools …)

807 pages!
(March 2009) →

Impressum

Proceedings of the workshop
HERA and the LHC
2nd workshop on the implications of HERA for LHC physics
2006 - 2008, Hamburg - Geneva

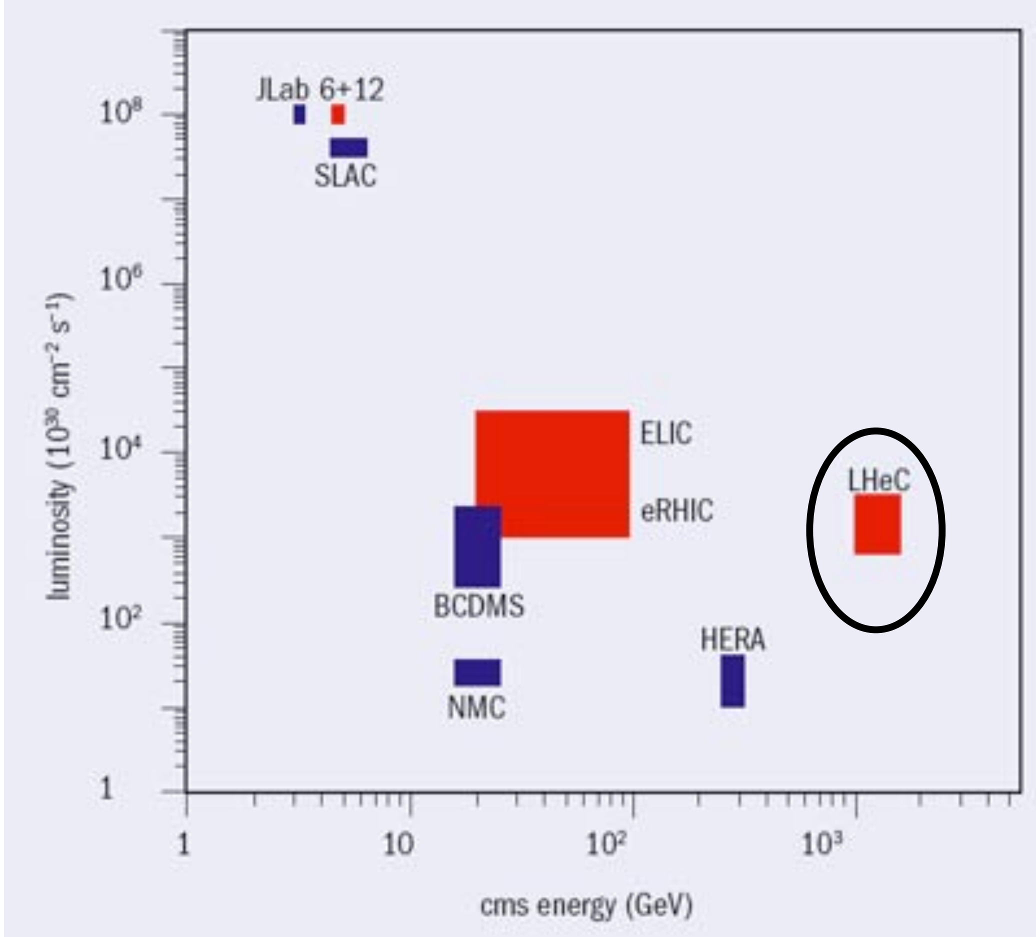
Conference homepage
http://www.desy.de/~heralhc

Online proceedings at
http://www.desy.de/~heralhc/proceedings-2008/proceedings.html

Currently Approved Future of High Energy DIS

Some LHeC Context

The LHeC is not the first proposal for TeV scale DIS, but it is the first with the potential for significantly higher luminosity than HERA …



DESY 06-006
Cockcroft-06-05

Deep Inelastic Electron-Nucleon Scattering at the LHC*

J. B. Dainton[1], M. Klein[2], P. Newman[3], E. Perez[4], F. Willeke[2]

[1] Cockcroft Institute of Accelerator Science and Technology, Daresbury International Science Park, UK
[2] DESY, Hamburg and Zeuthen, Germany
[3] School of Physics and Astronomy, University of Birmingham, UK
[4] CE Saclay, DSM/DAPNIA/Spp, Gif-sur-Yvette, France

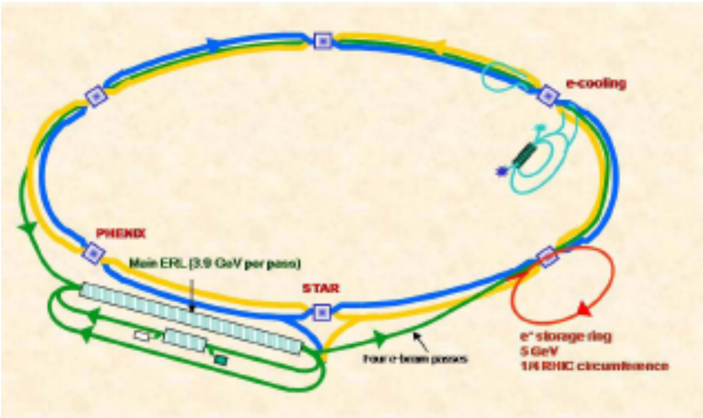
… achievable with a new electron accelerator at the LHC …

[JINST 1 (2006) P10001]

The Electron-Ion Collider (BNL / Jlab)

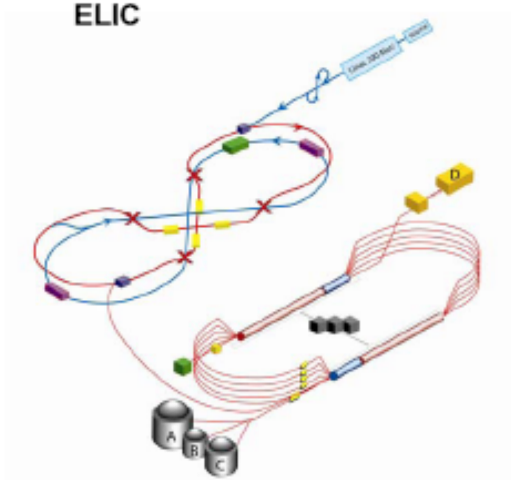
e.g. 10 GeV $e^{+/-}$ and 250 GeV polarised p/A

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 100 times HERA luminosity
- Polarised hadrons → **spin** → long-term successor to HERMES, COMPASS?...
- Heavy ions → huge step forward for eA kinematic range

[More info at http://web.mit.edu/eicc]

LHC is the future of the high energy frontier!

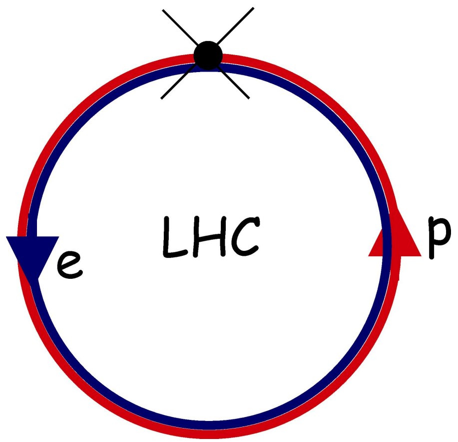
"… the LHeC is already half built" [J Engelen]

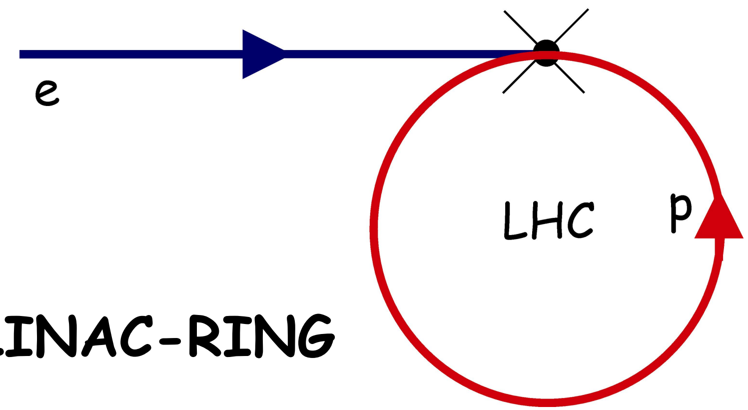
Can its unprecedented energy and intensity be exploited for DIS?

"… it would be a waste not to exploit the 7TeV beams for ep and eA physics at some stage during the LHC time"
[G. Altarelli]

How Could ep be Done using LHC?

… **whilst allowing simultaneous ep and pp running** …

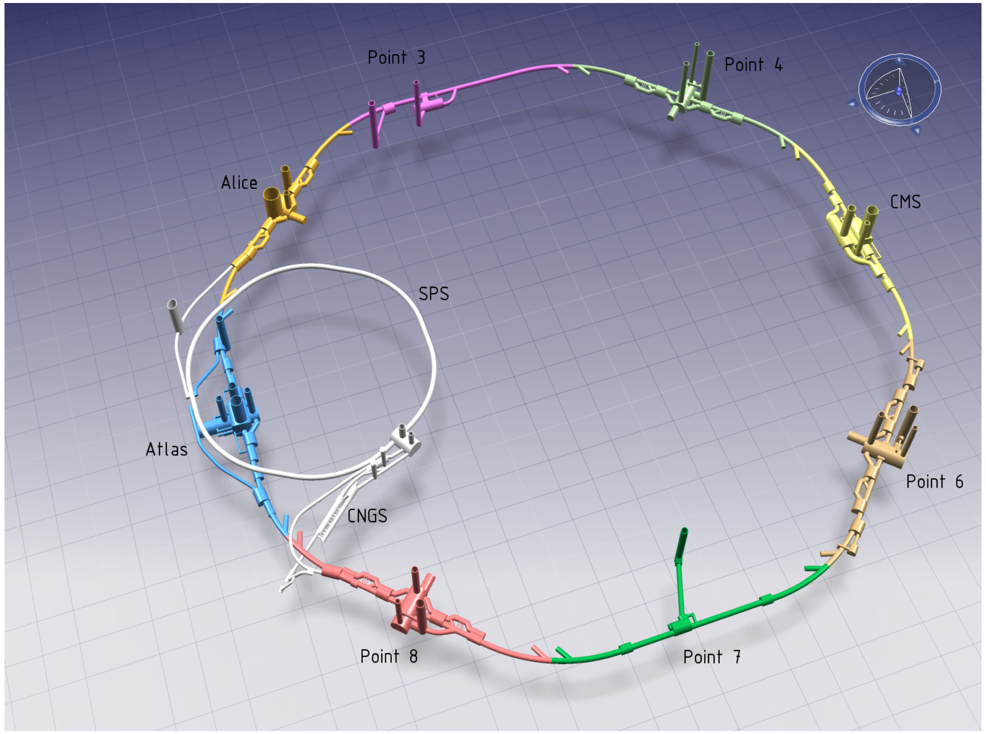


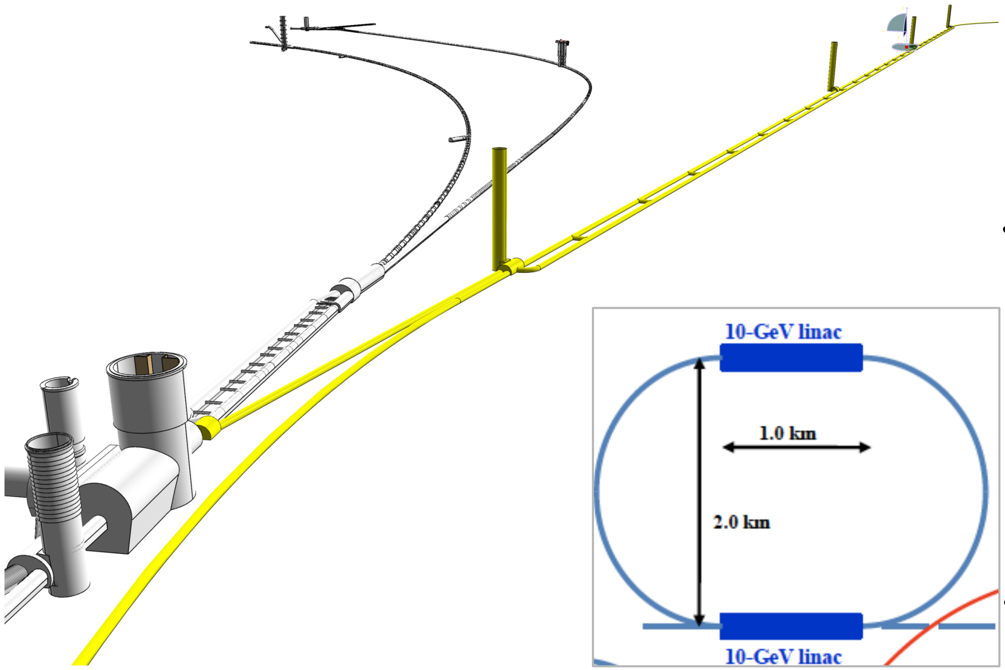


- First considered (as LEPxLHC) in 1984 ECFA workshop
- Main advantage: high peak lumi obtainable (~3.10^{33} cm^{-2} s^{-1})
- Main difficulties: building round existing LHC, e beam energy (60GeV?) and lifetime limited by synchrotron radiation

- Previously considered as `QCD explorer' (also THERA)
- Main advantages: low interference with LHC, high E_e (→ 150 GeV?) and lepton polarisation, LC relation
- Main difficulties: lower luminosity ~3.10^{32} cm^{-2} s^{-1} (?) at reasonable power, no previous experience exists

Accelerator Design





<u>Multi-Institute / Lab Involvement</u>

Novosibirsk, BNL, CERN Cockcroft, Cornell, DESY, EPFL Lausanne, KEK, Liverpool, SLAC, TAC Turkey

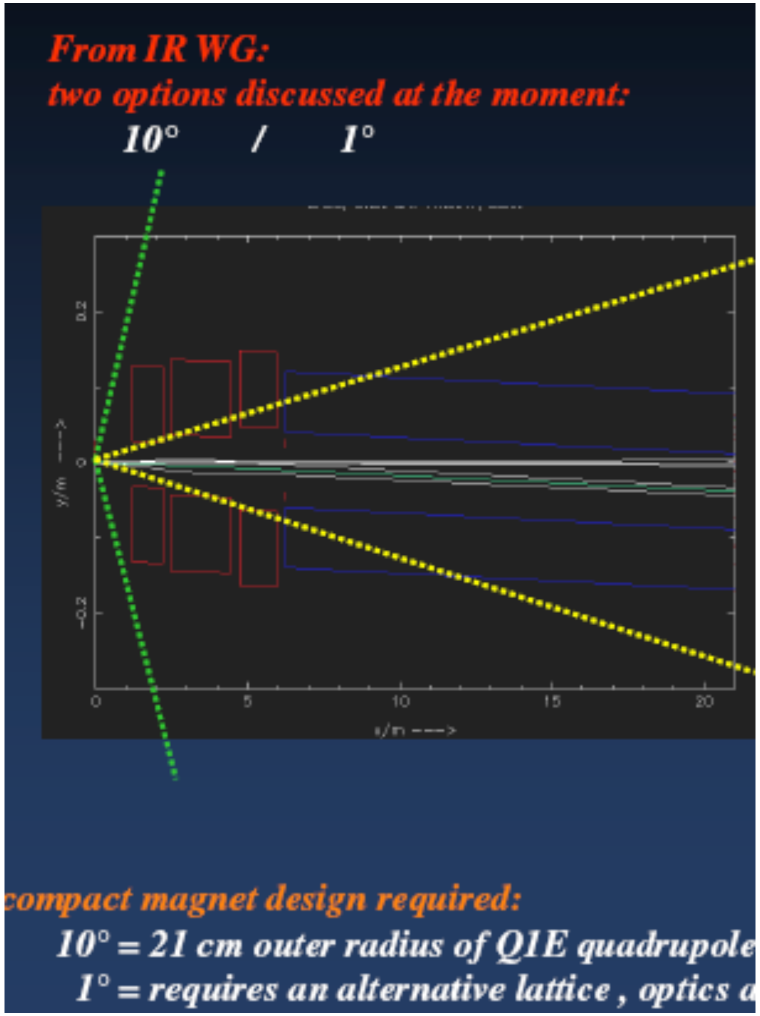
- Design constraints of simultaneous ep and pp running, power consumption < 100 MW

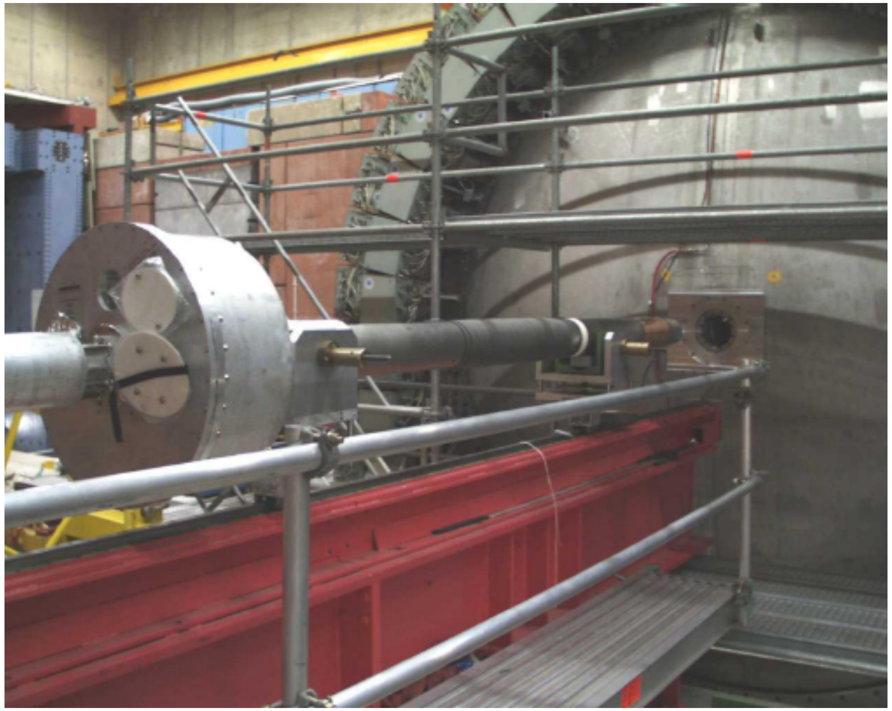
- 100 fb-1 at Ee = 60 GeV looks to be possible with a few years running

The Luminosity v Acceptance Question

- As for HERA-I v HERA-II, low β focusing beam elements around interaction region can improve lumi by a factor ~10
- However, acceptance near beam-pipe is compromised

→ loss of low x / Q^2 acceptance
→ loss of high M_{eq} acceptance
→ poorer HFS measurements





Beam Scenarios for First Physics Studies

Several scenarios under study … see later for justification

config.	E(e)	E(N)	N	$\int L(e^+)$	$\int L(e^-)$	|Pol|	$L/10^{32}$	P/MW	years	type
A	20	7	p	1	1	-	1	10	1	SPL
B	50	7	p	50	50	0.4	25	30	2	RR hiQ^2
C	50	7	p	1	1	0.4	1	30	1	RR lo x
D	100	7	p	5	10	0.9	2.5	40	2	LR
E	150	7	p	3	6	0.9	1.8	40	2	LR
F	50	3.5	D	1	1	--	0.5	30	1	eD
G	50	2.7	Pb	0.1	0.1	0.4	0.1	30	1	ePb
H	50	1	p	--	1	--	25	30	1	lowEp

ep Studies based on a 20-150 GeV electron beam
and lumi of 1-10 fb^{-1} / year

Scenario for Experimental Precision

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

[Klein, Kluge …]

The new collider …

- should be ~100 times more luminous than HERA

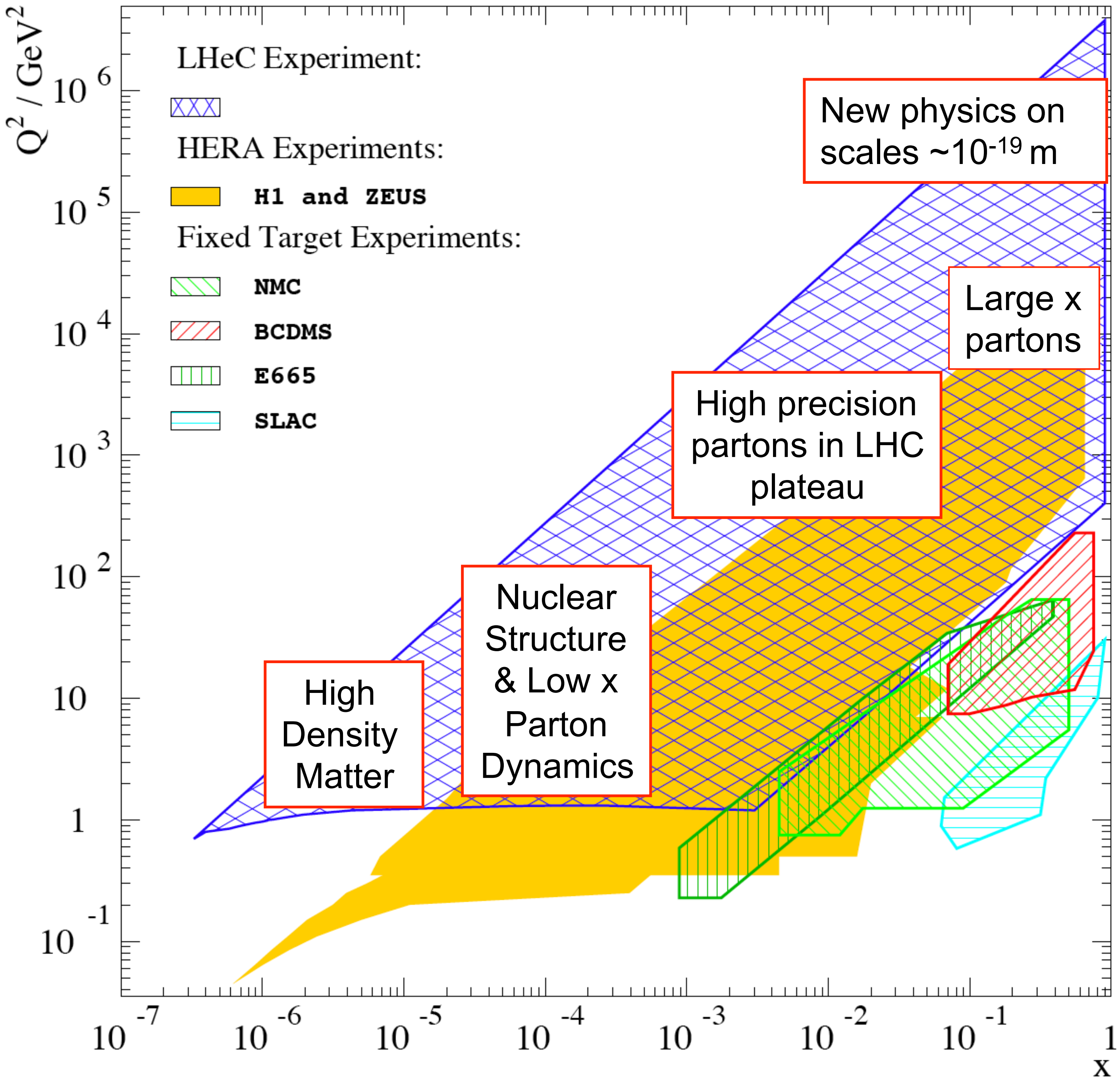
The new detector

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

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%)

First `pseudo-data' for F_2, F_L, F_2^D …produced on this basis …

Kinematics & Motivation (140 GeV x 7 TeV)



$\sqrt{s} = 2$ TeV

- High mass (M_{eq}, Q^2) frontier
- EW & Higgs
- Q^2 lever-arm at moderate & high x → PDFs
- Low x frontier → novel QCD …

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

Searches For New Physics

- The (pp) LHC has better discovery potential than the LHeC in the majority of scenarios (and is already running!)

- However, LHeC is competitive with (or better than) LHC in cases where initial state lepton is an advantage

THE UNCONFINED QUARKS AND GLUONS

Abdus Salam

International Centre for Theoretical Physics,
Trieste, Italy and Imperical College, London,
England

1. Introduction

Leptons and hadrons share equally three of the basic forces of nature: electromagnetic, weak and gravitational. The only force which is supposed to distinguish between them is strong. Could it be that leptons share with hadrons this force also, and that there is just one form of matter, not two?

… and who knows what will happen – nature may hold surprises!

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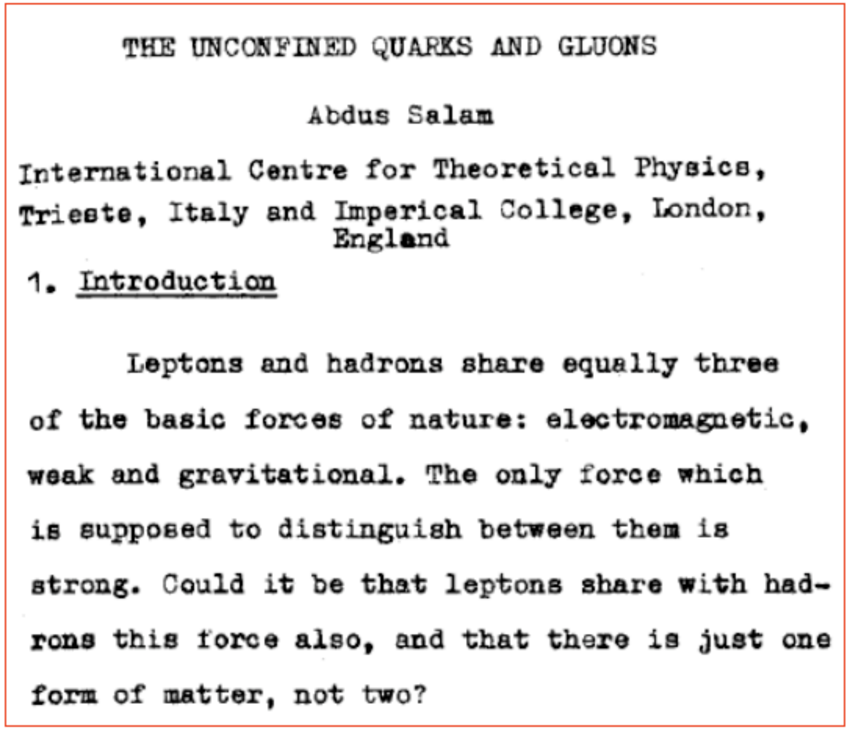

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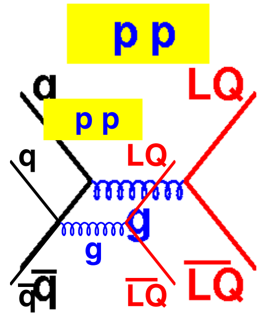
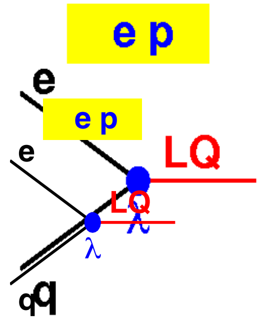
Lepton-quark Bound States





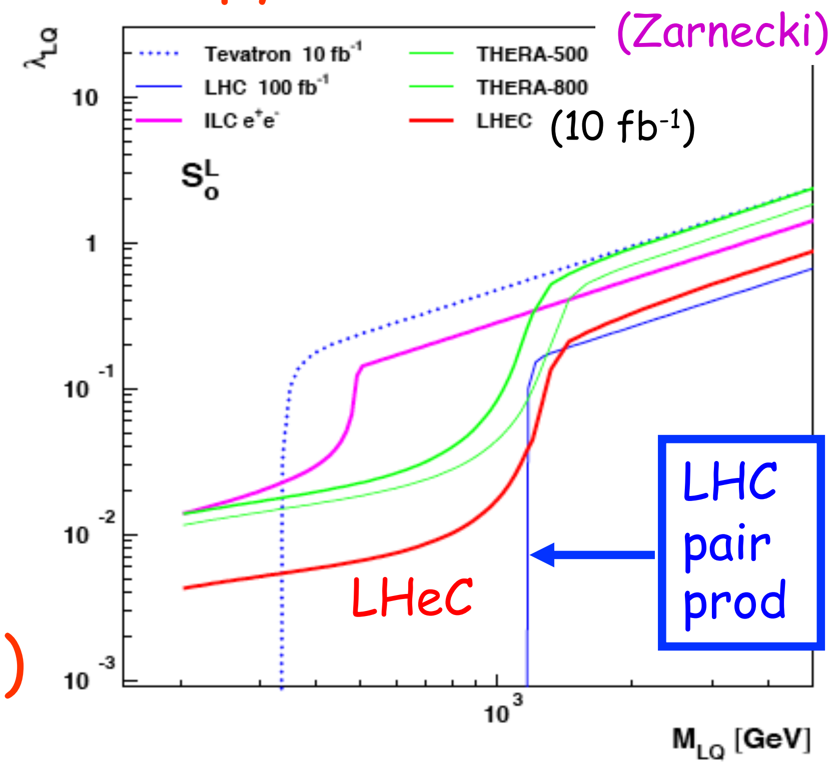
Yukawa coupling, λ

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

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

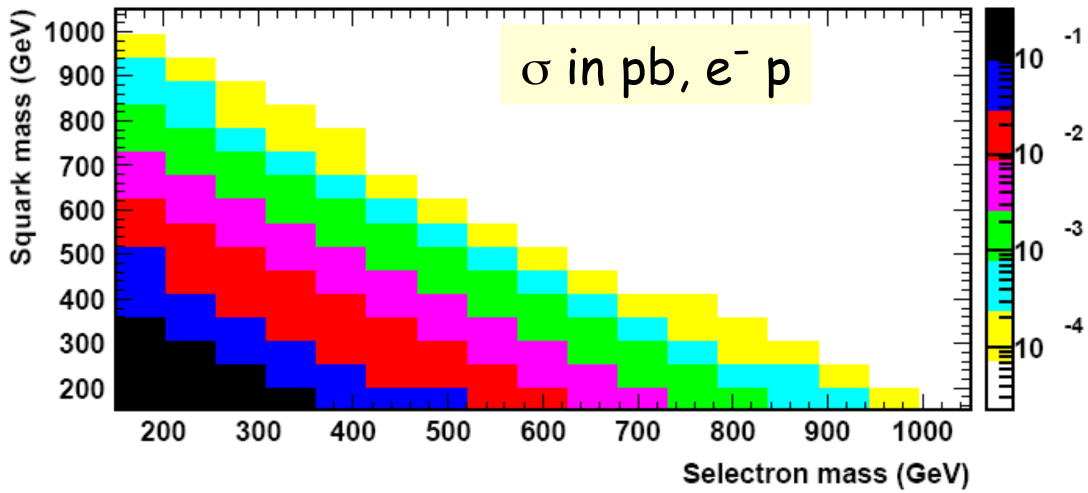
- (Mostly) pair produced in pp, single production in ep.

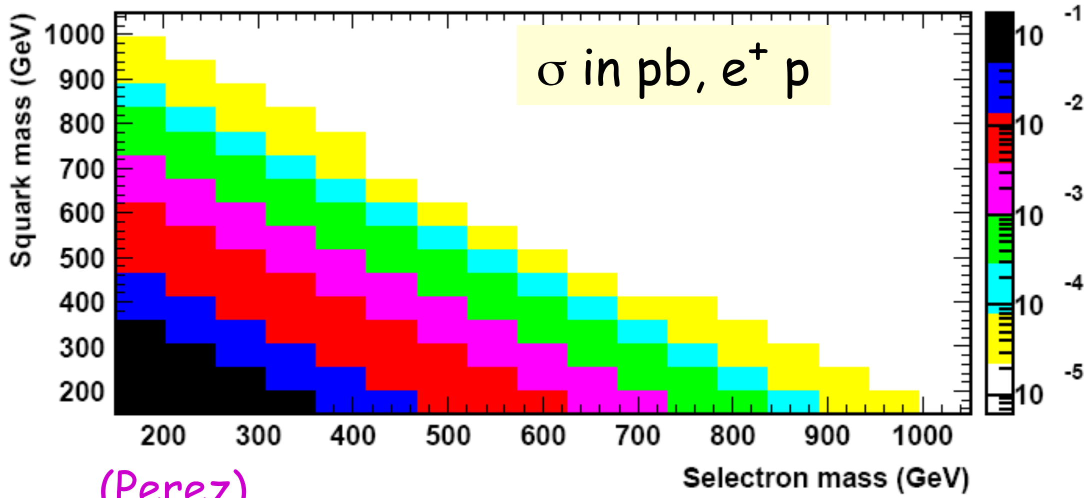
- LHeC sensitivity (to ~1.5 TeV) similar to LHC, but can determine quantum numbers / spectroscopy (fermion #, spin, chiral couplings …)



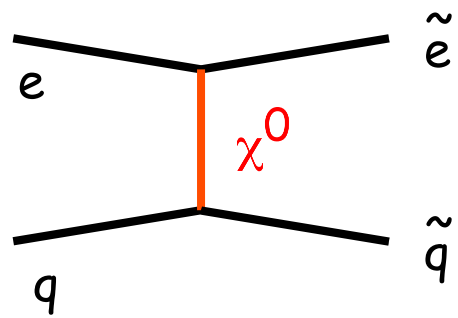
Rp Conserving Supersymmetry

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





(Perez)



Pair production via t-channel exchange of a neutralino.

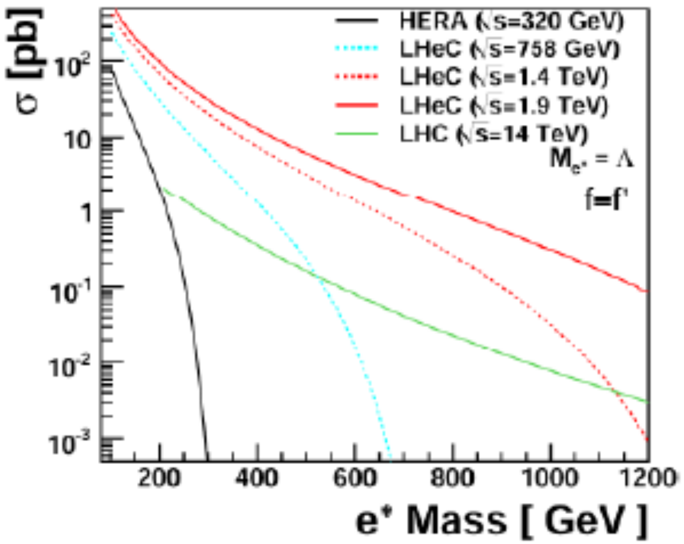
Cross-section sizeable for ΣM < 1 TeV

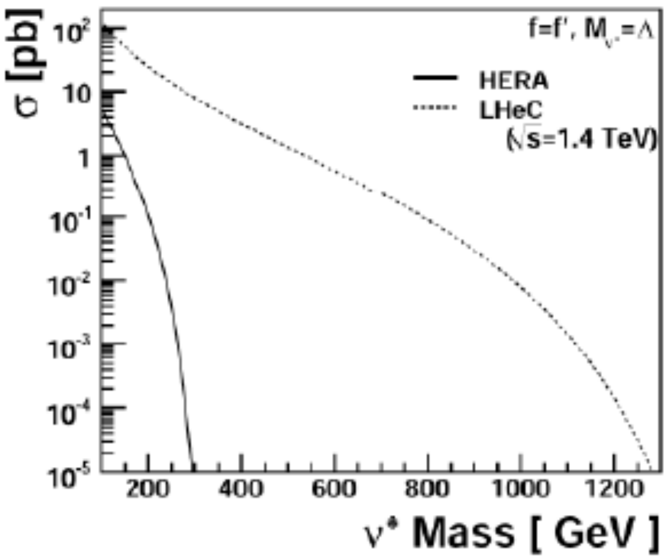
i.e. if squarks are "light", could observe selectrons up to ~ 500 GeV, a little beyond LHC?

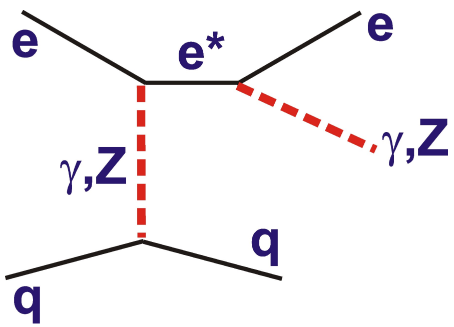
Excited Leptons

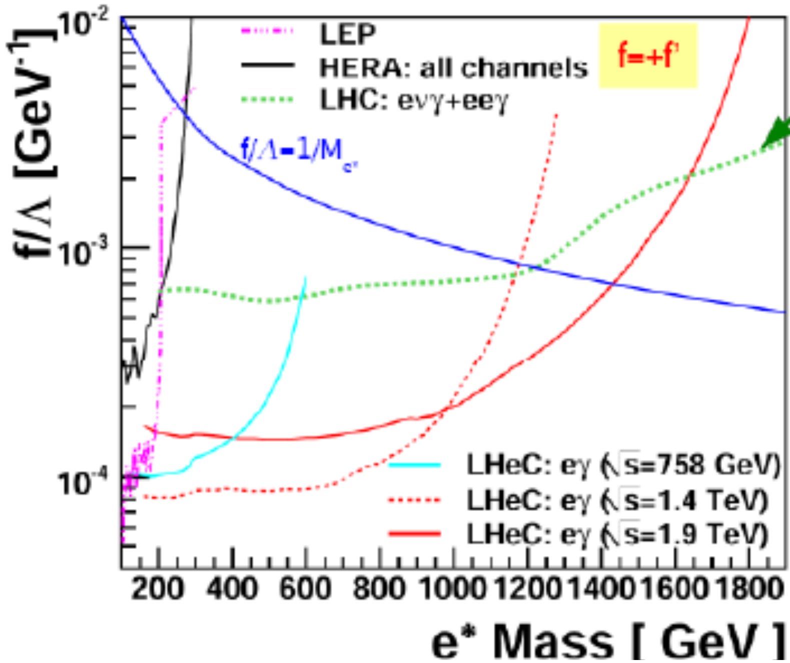
[Sauvan, Trinh]

- Total cross section for l* productions through GM interaction at LHeC, assuming M*=Λ
  - comparison with HERA and LHC









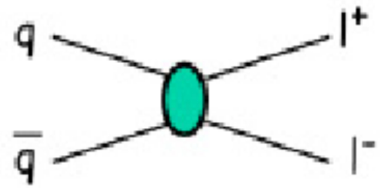
[Phys. Rev D 65 (2002) 075003]

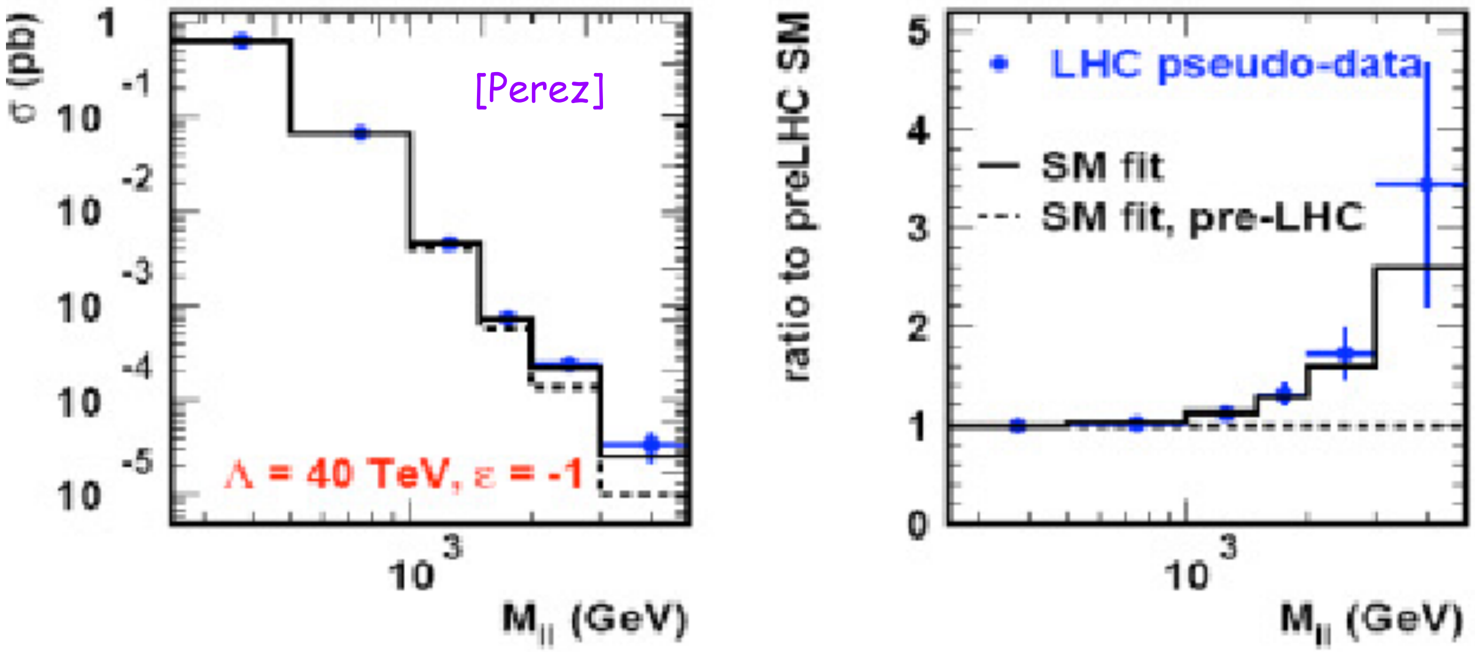
LHeC sensitivity, with L=10 fb⁻¹ for Ee=70/20 GeV with L=1 fb⁻¹ for Ee=140 GeV

LHeC gives best sensitivity in this scenario …

Complementarity between LHC and LHeC

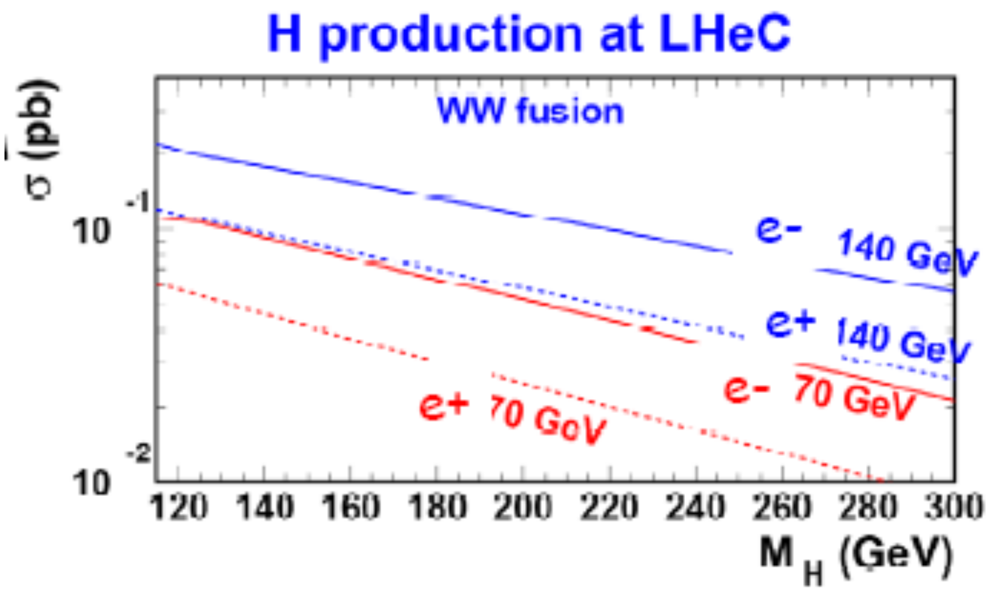
Contact interaction term introduced in LHC pseudo-data for high mass Drell-Yan

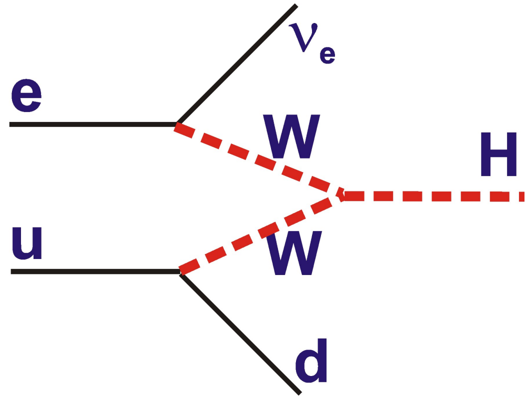




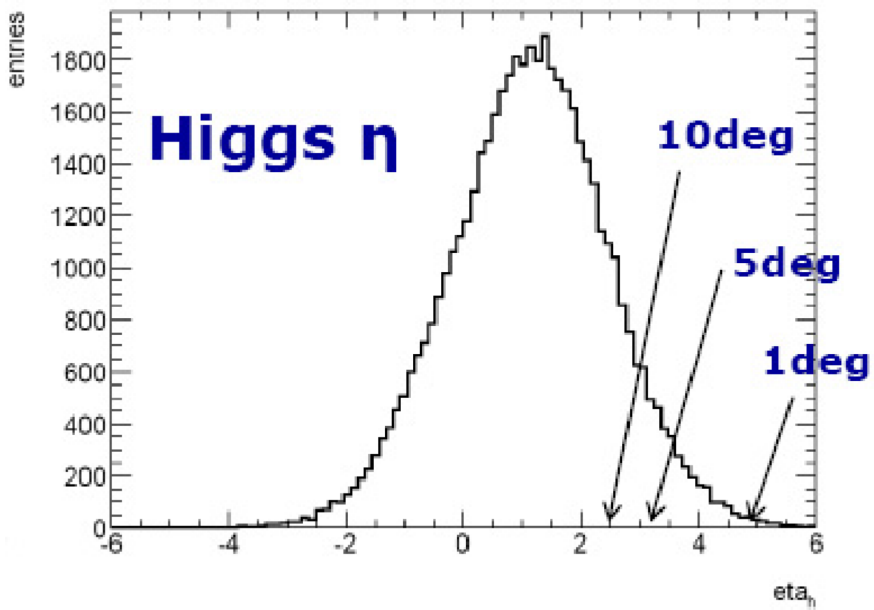
- Even if new physics looks rather different from SM, wide range of high x BSM effects can be accomodated in DGLAP fits due to poor current high x PDF constraints
- Better high x precision at high lumi LHeC could disentangle …

Higgs Production





[U Klein, Kniehl, Perez, Khuze]



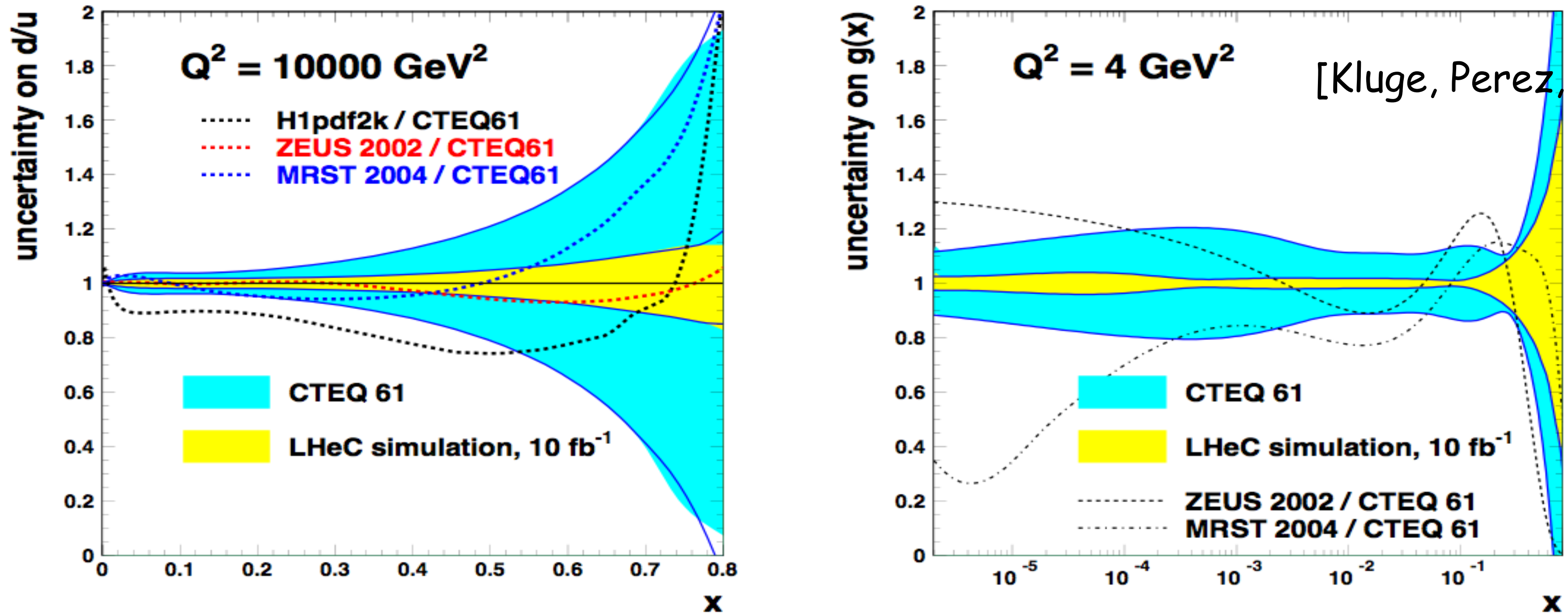
Sizeable CC (WW) x-section
~ few thousand events
Strongly dependent on m_H

→ Novel production mechanism
→ Clean(ish) … H + j + p_t^{miss}
→ bbbar coupling to light H?

Forward acceptance is an issue

First background studies (jets in CC) underway …

LHeC Impact on High x Partons



[Kluge, Perez, Klein]

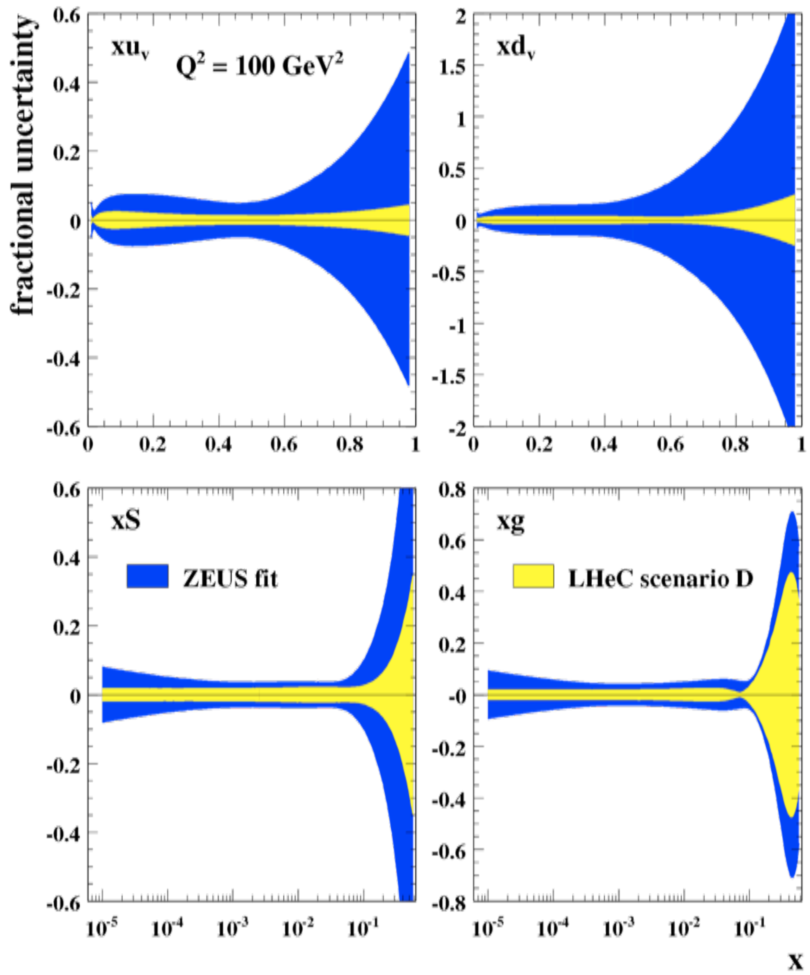
Full NC/CC sim (with systs giving per mille α_s) & NLO DGLAP fit using HERA technology…

… full flavour decomposition possible

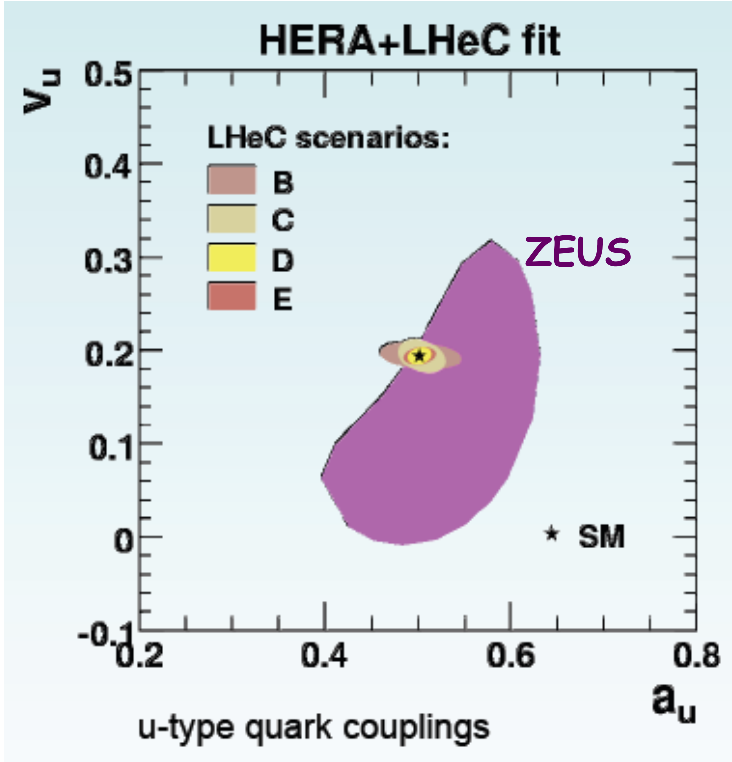
… high x pdfs → may help clarify LHC discoveries through interpretation of new states?

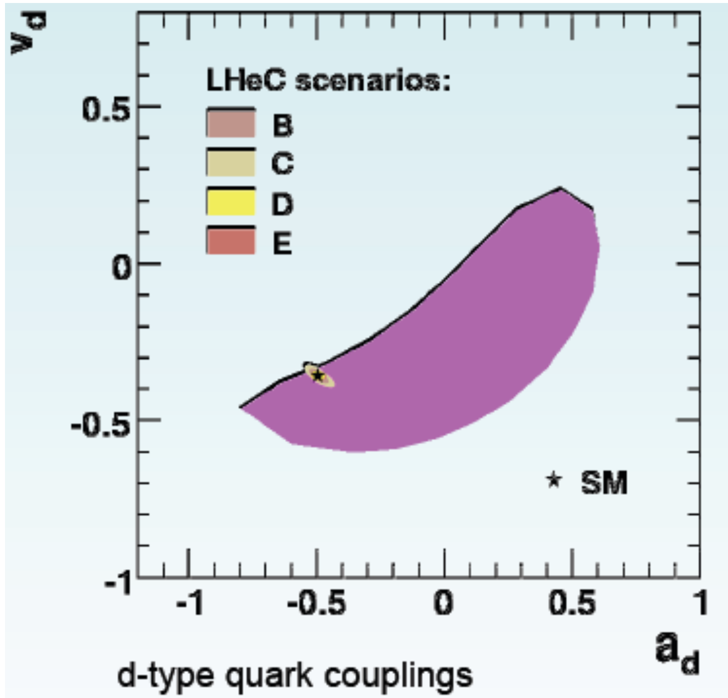
[Some of highest x improvement from param^n extrapolation]

PDFs & EW Couplings



[Gwenlan]

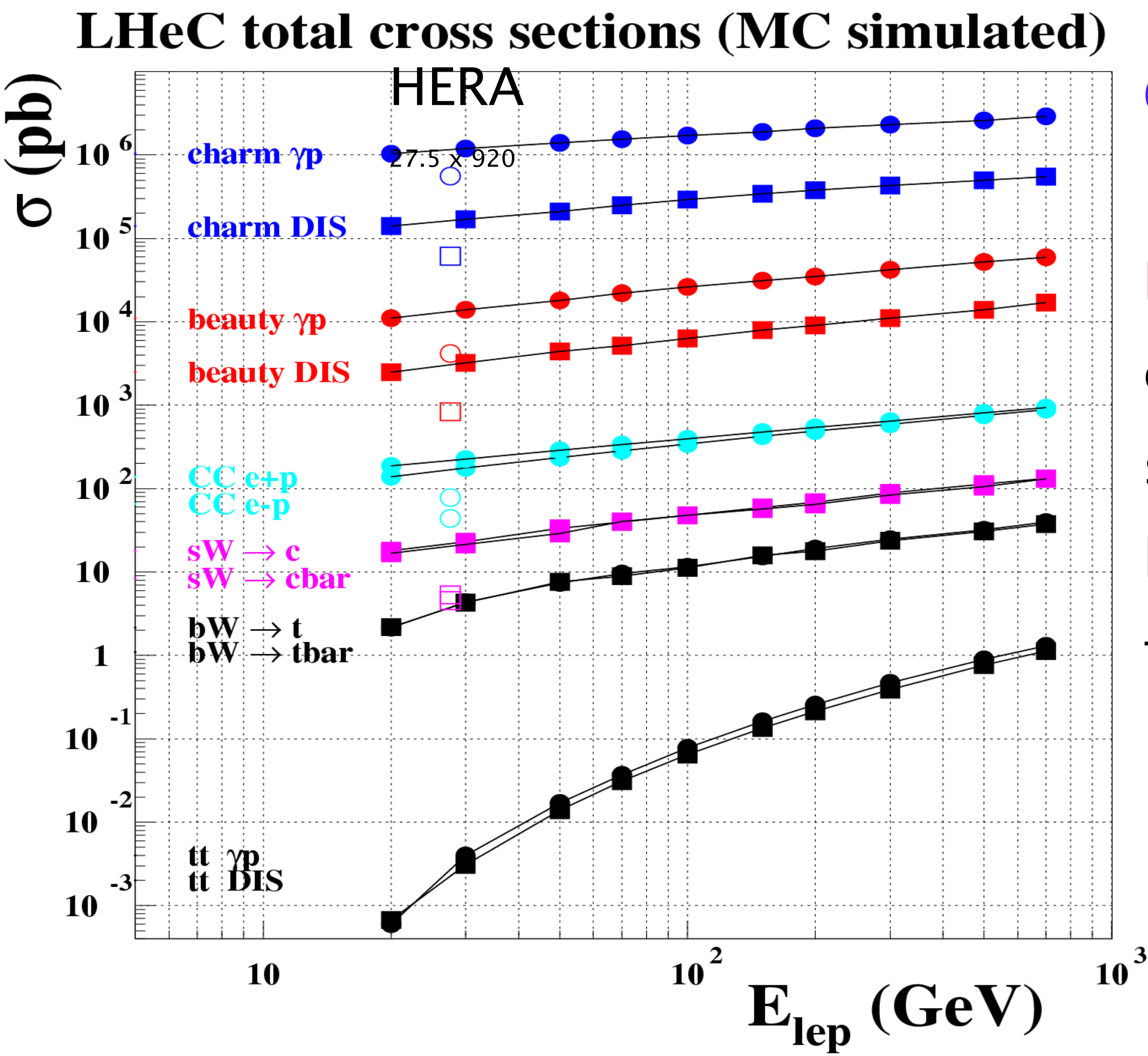




Using ZEUS fitting code, HERA + LHeC data … EW couplings free

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

Cross Sections and Rates for Heavy Flavours



Charm [Behnke]

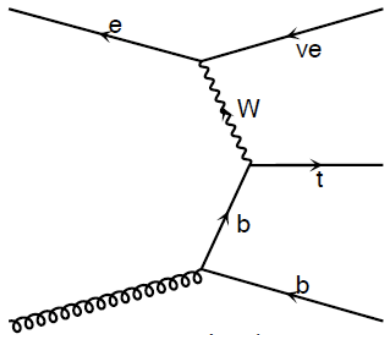
Beauty

cc

sW-> c

bW->top

ttbar

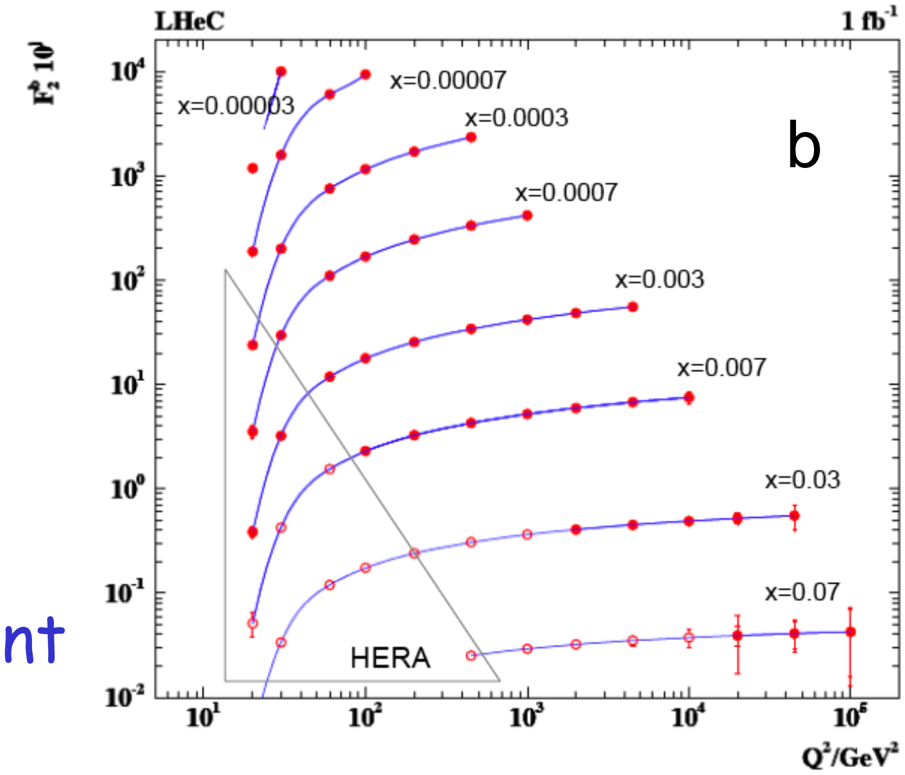


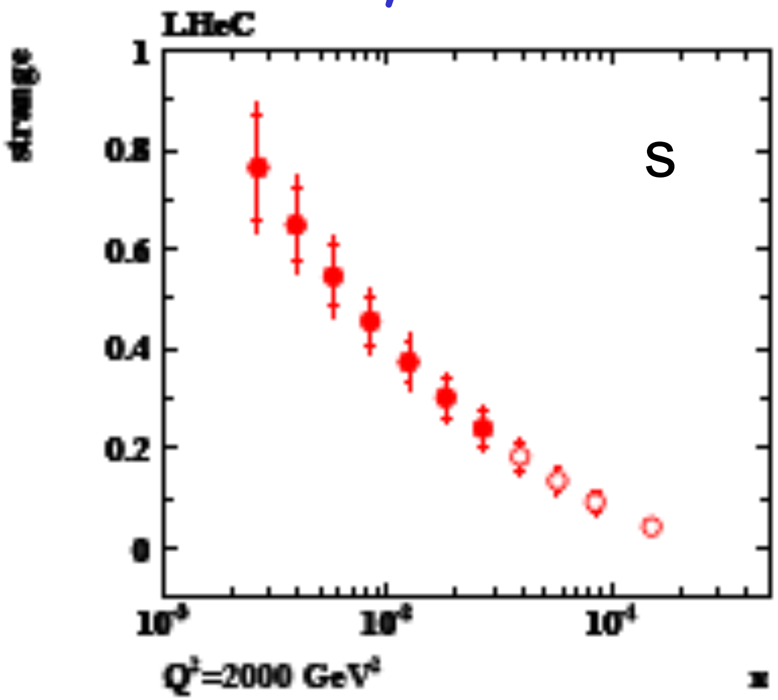
c.f. luminosity of ~10 fb-1 per year …

Flavour Decomposition

High precision c, b measurements
(modern Si trackers, beam spot 15 * 35 μm^2 , increased HF rates at higher scales).
Systematics at 10% level

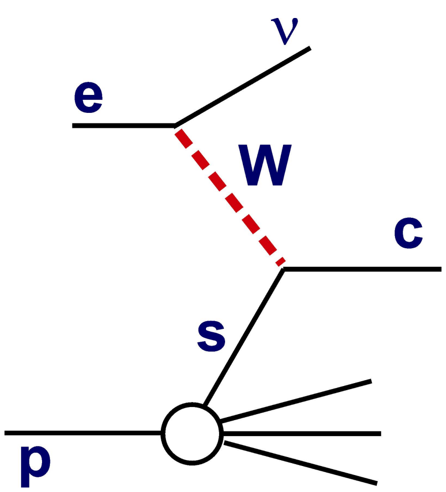
→beauty is a low x observable!
→s (& sbar) from charged current
→ Similarly Wb → t?





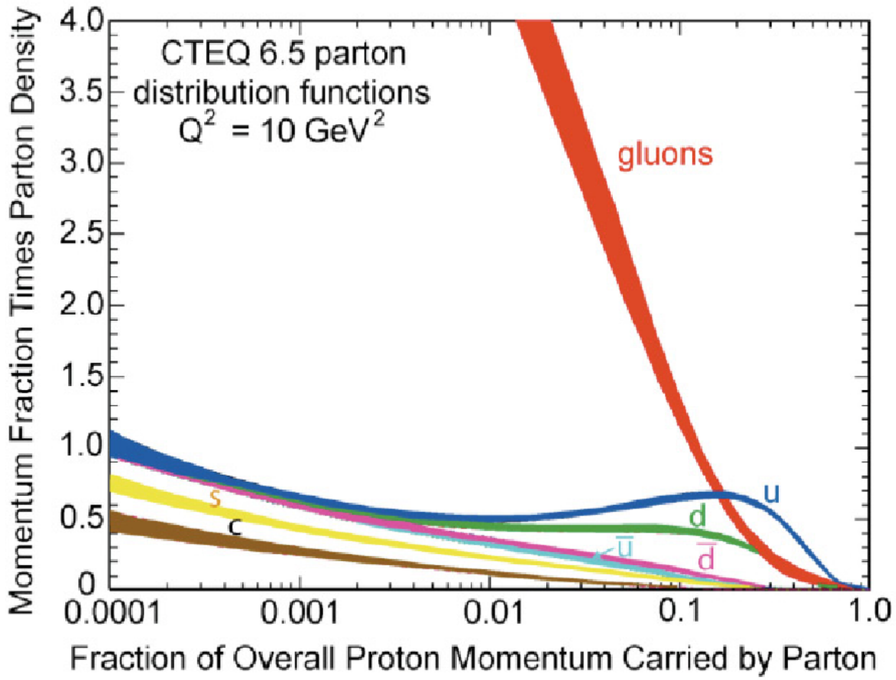
● LHeC 10° acceptance
○ LHEC 1° acceptance

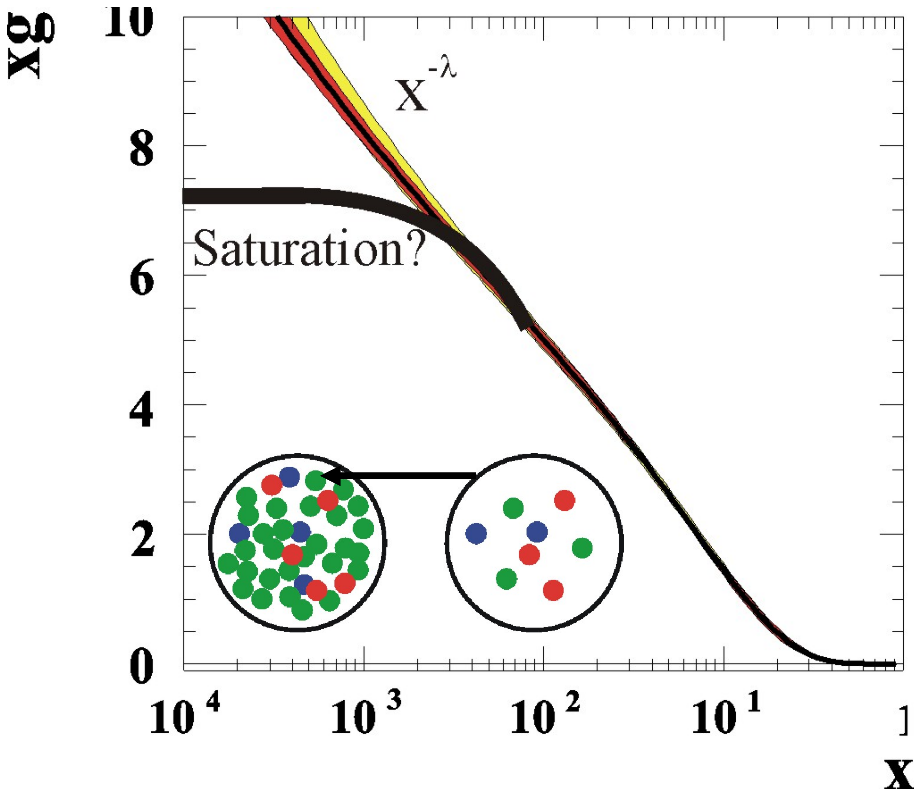
[Mehta, Klein]



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

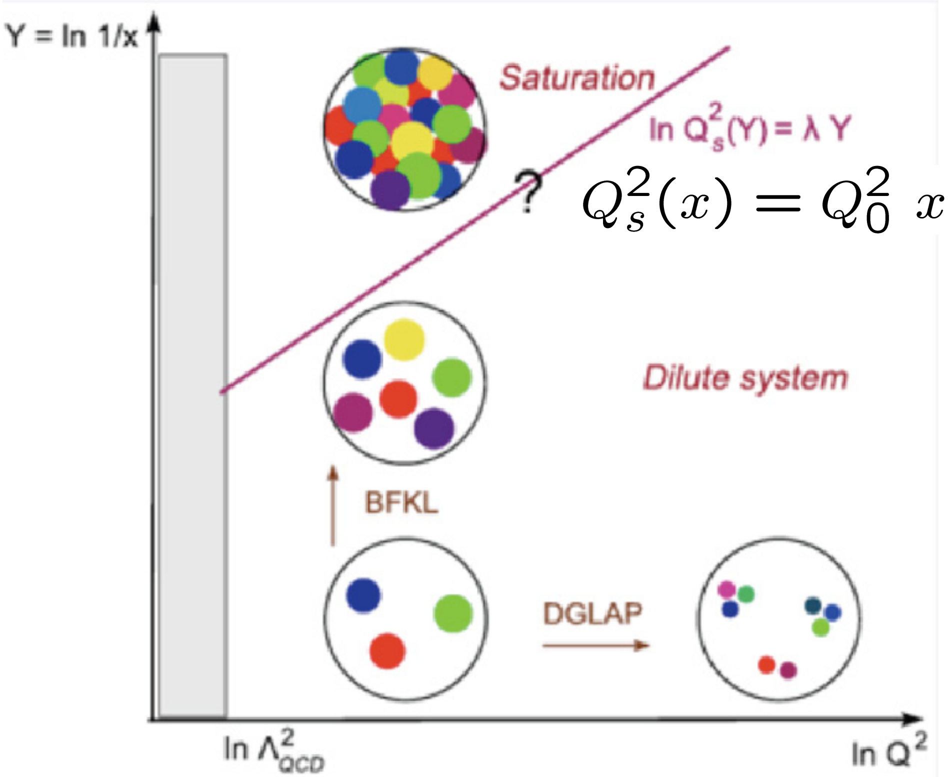
Low-x Physics and Non-linear Evolution





- Somewhere & somehow, the low x growth of cross sections must be tamed to satisfy unitarity … non-linear effects
- Dipole model language → **projectile $q\bar{q}$ multiply interacting**
- Parton level language → **recombination gg → g?**
- Usually characterised in terms of an x dependent "saturation scale", $Q^2_s(x)$, to be determined experimentally

Non-linear effects in HERA and eA Data?



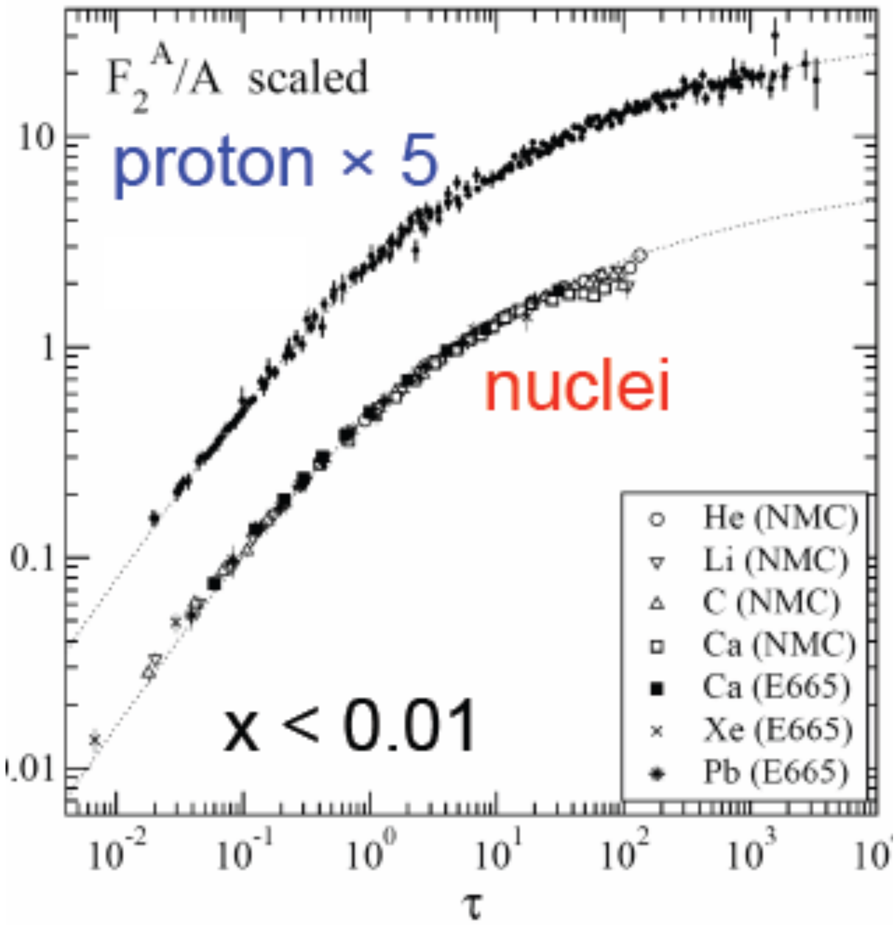
$$Q_s^2(x) = Q_0^2\ x^{-\lambda}$$

Something appears to happen around $\tau = Q^2/Q^2_s = 1\ \mathrm{GeV}^2$ (confirmed in many analyses)

BUT … Q^2 small for τ <~ 1 GeV^2 … not easily interpreted in QCD

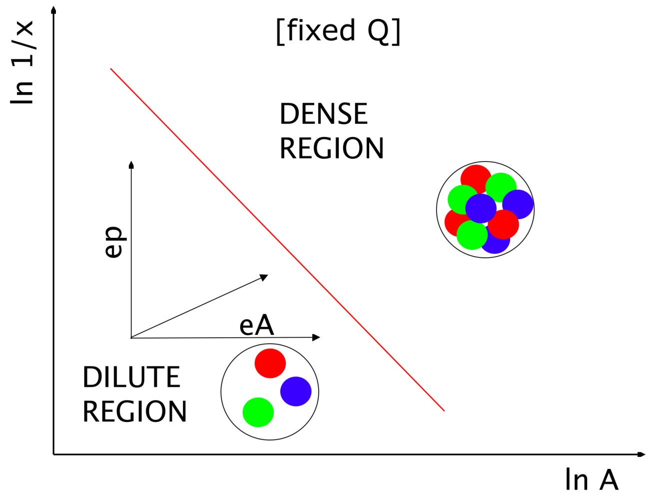
Lines of constant 'blackness' diagonal … scattering cross section appears constant along them … "Geometric Scaling"

$$\sigma_{tot}^{\gamma^* h \to X}(x, Q^2) = \sigma_{tot}^{\gamma^* h \to X}(Q^2/Q_s^2(x))$$



Strategy for making the target blacker

LHeC delivers a 2-pronged approach:



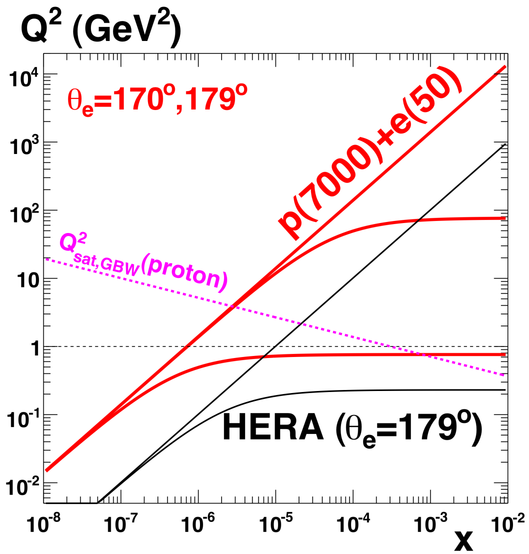
Enhance target `blackness' by:

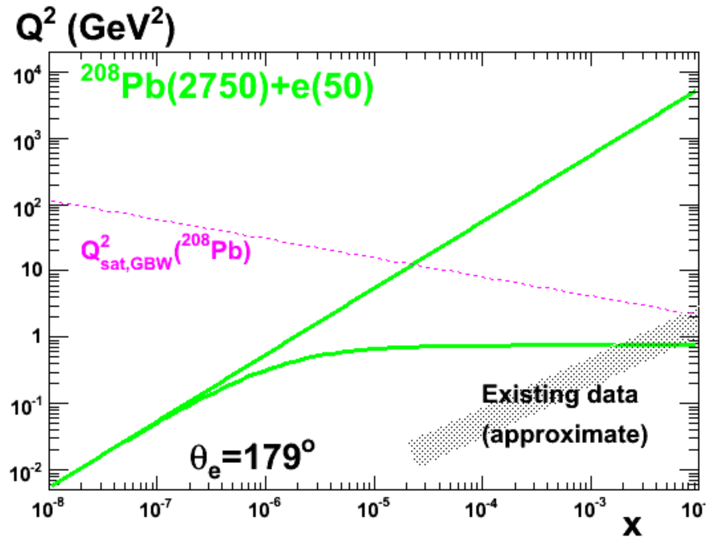
1) Probing lower x at fixed Q^2 in ep

[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]

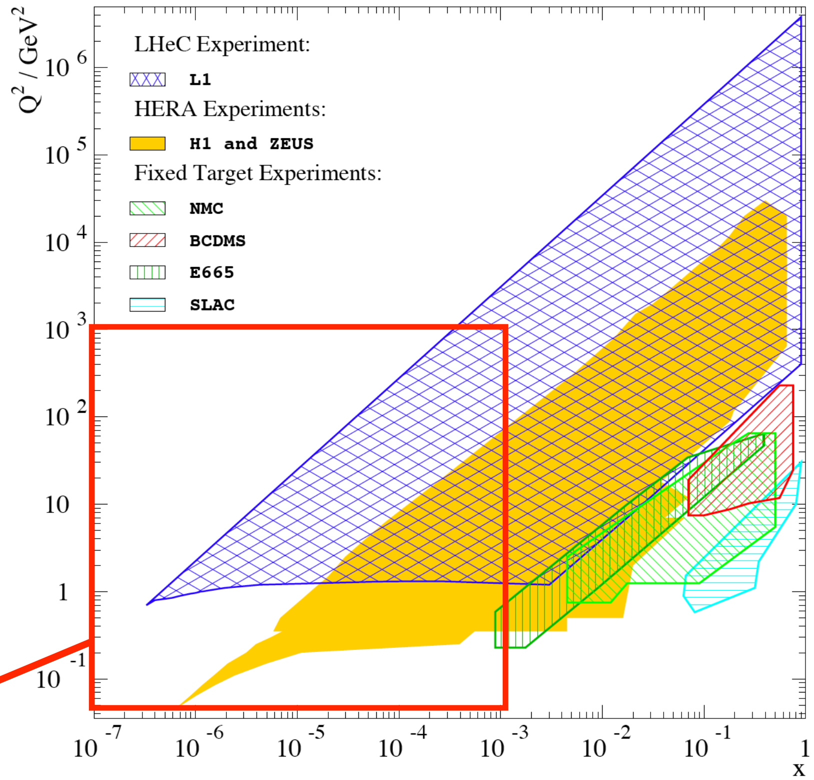


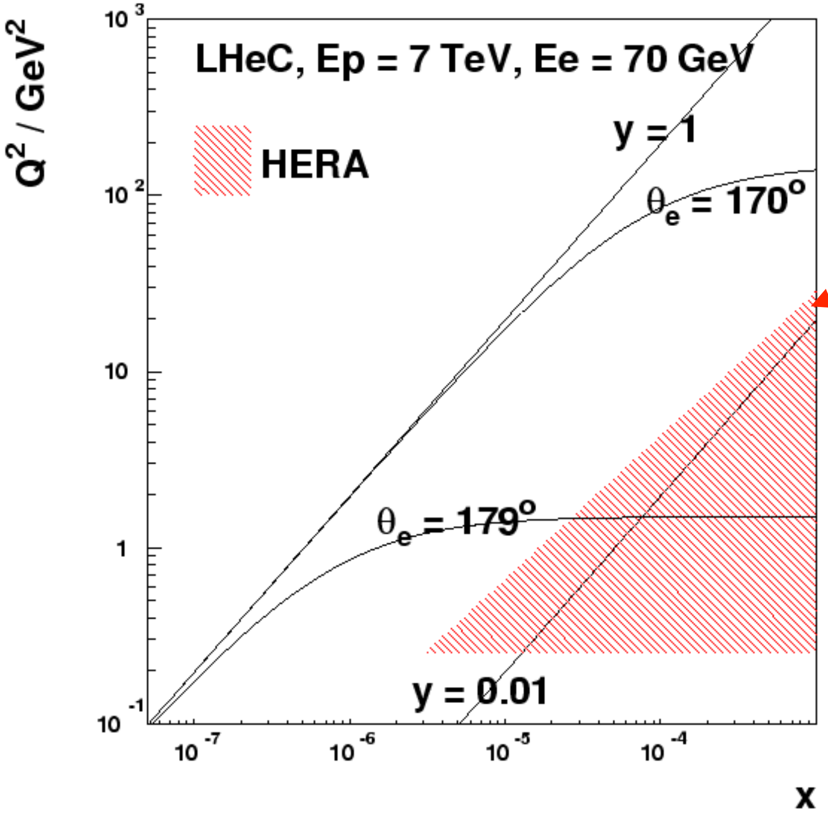


Basic Inclusive Kinematics / Acceptance

Access to Q^2=1 GeV^2 in ep mode for all x > 5 x 10^{-7} IF we have acceptance to 179° (and @ low E_e')

Nothing fundamentally new in LHeC low x physics with θ<170°





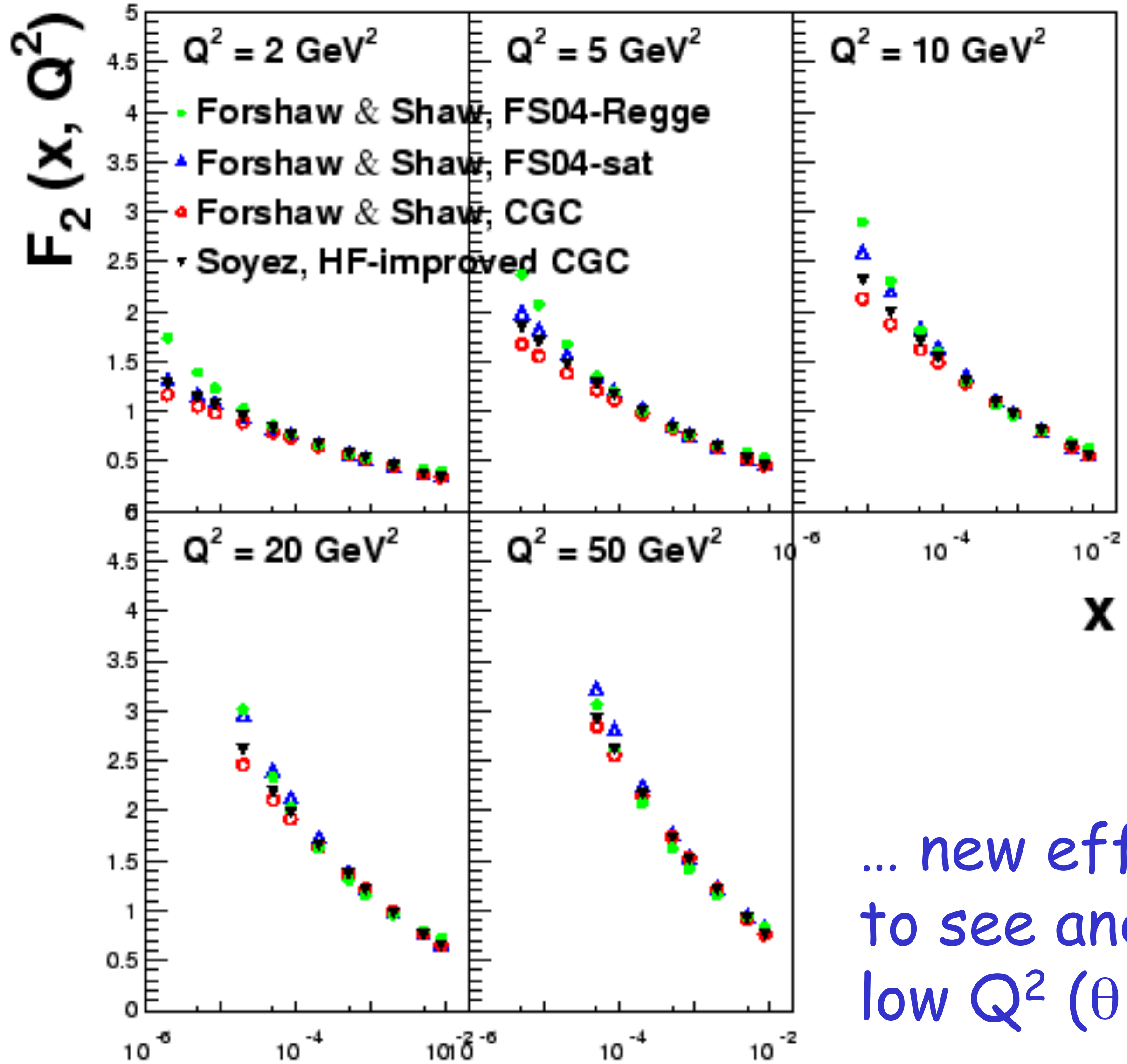
... low x cross sections are large!

... luminosity in all realistic scenarios ample for most low x measurements

Some models of low x F_2 with LHeC Data

With 1 fb^{-1} (1 year at 10^{33} cm^{-2} s^{-1}), 1^o detector:
stat. precision < 0.1%, syst, 1-3%

[Forshaw, Klein, PN, Soyez]



Precise data in LHeC region, x > ~10^{-6}

- Extrapolated HERA dipole models …
- FS04, CGC models including saturation suppressed at low x & Q^2 relative to non-sat FS04-Regge

… new effects may not be easy to see and will certainly need low Q^2 ($\theta \rightarrow 179^o$) region …

F_L Simulation

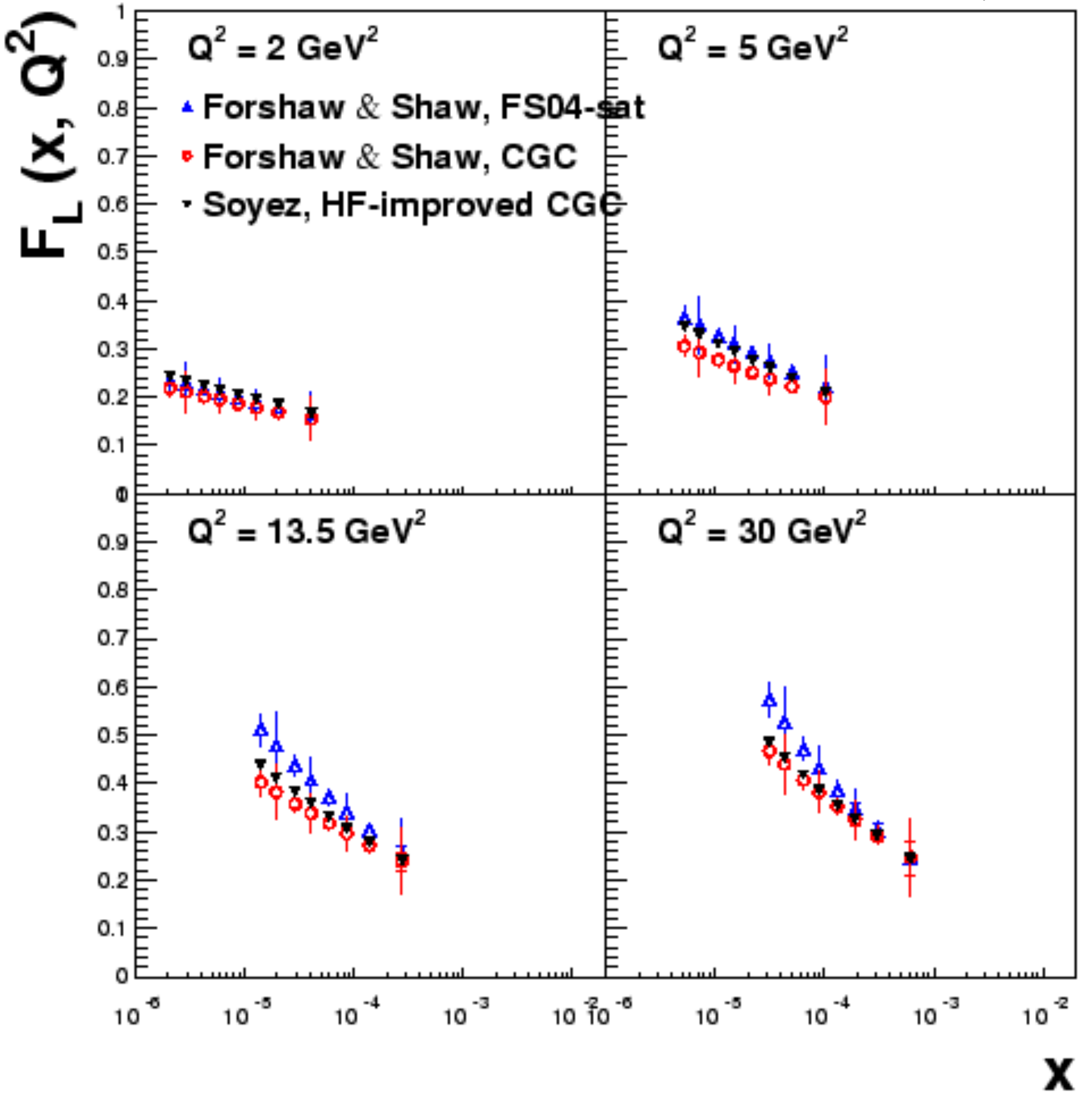
Vary proton beam energy
as recently done at HERA ?...
'direct' gluon measurement ...

E_p (TeV)	Lumi (fb^{-1})
7	1
4	0.8
2	0.2
1	0.05
[0.45	0.01]

... precision typically 5%
... stats limited for
Q^2 > 1000 GeV^2
... could also vary E_e ...

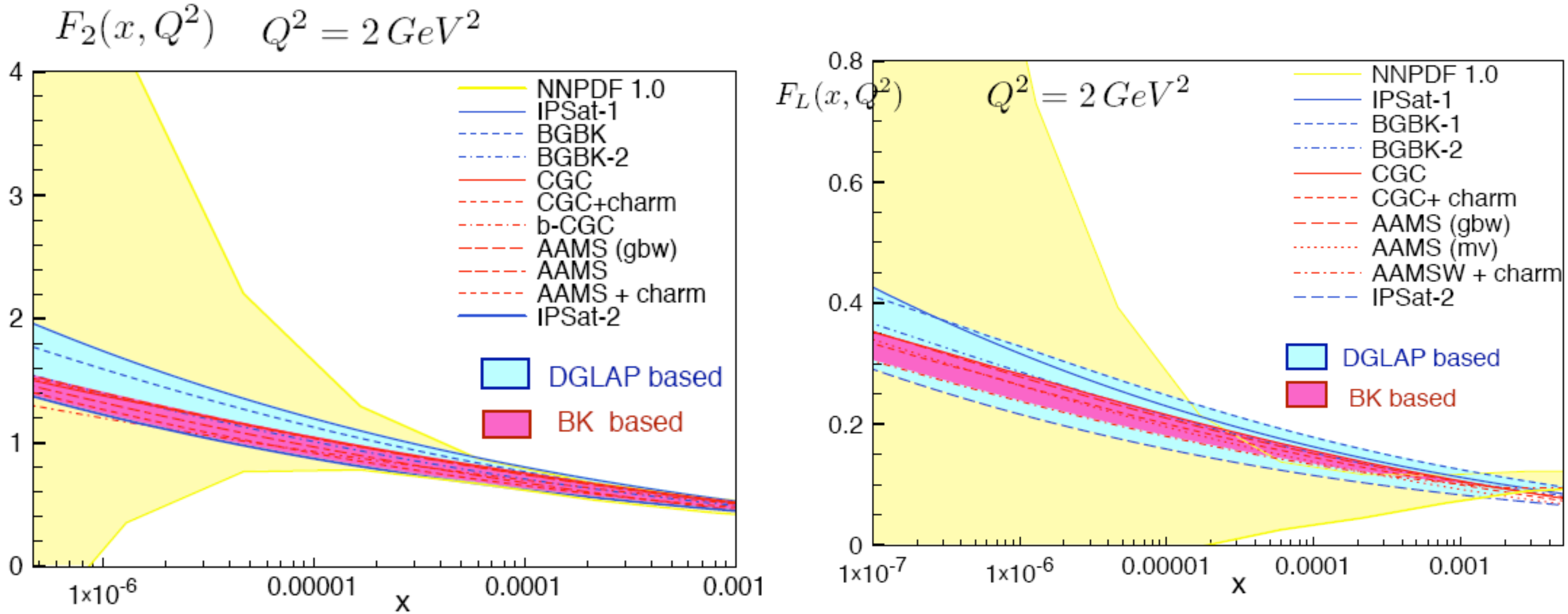
... selected lowest x data
compared with 3 dipole
models including saturation ...

[Forshaw, Klein, PN, Soyez]



Extrapolating HERA models of F_2 (Albacete)

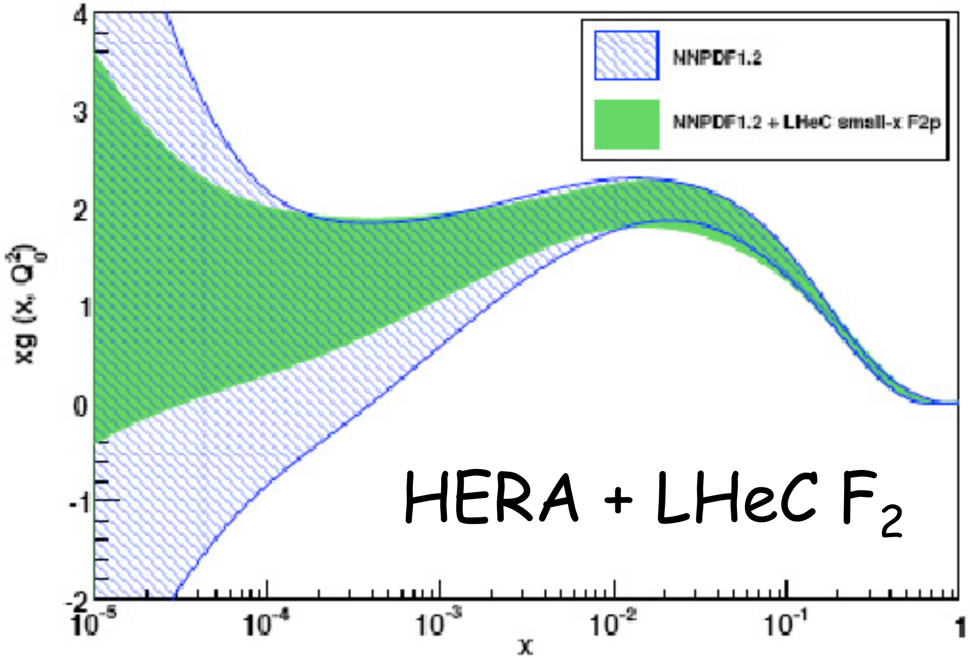
NNPDF NLO DGLAP uncertainties explode @ low x and Q^2
Formally, wide range of possibilities allowed, still fitting HERA

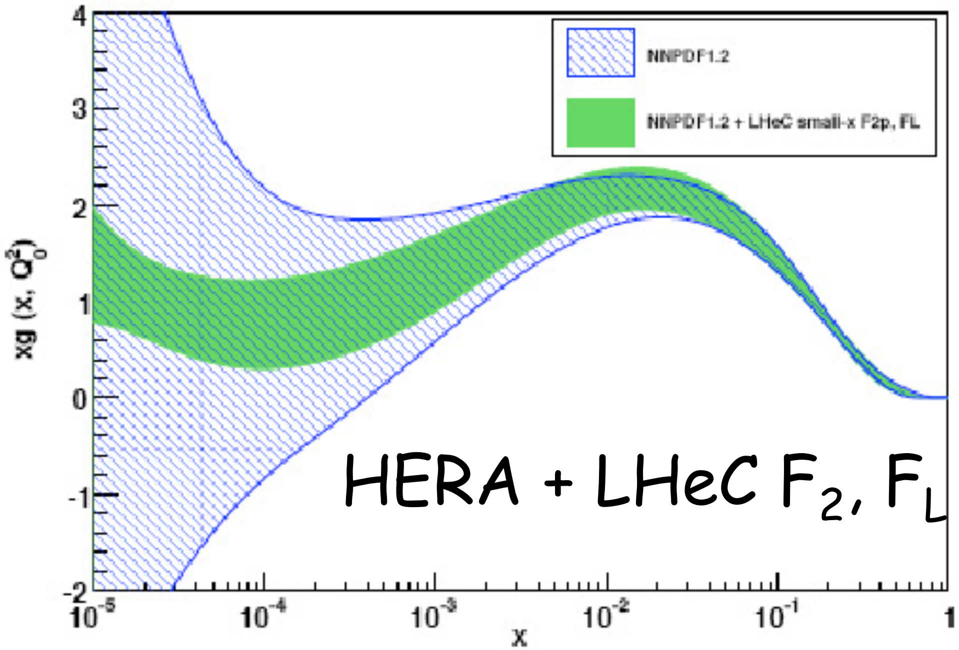


- 'Modern' dipole models, containing saturation effects & low x behaviour derived from QCD give a much narrower range
- c.f. 2% errors on LHeC F_2 pseudo-data, 8% on F_L pseudo-data

… we should be able to distinguish …

Fitting for the Gluon with LHeC F_2 and F_L (Gufanti, Rojo ...)





(Q^2 = 2 GeV^2)

Including LHeC data in NNPDF DGLAP fit approach ...

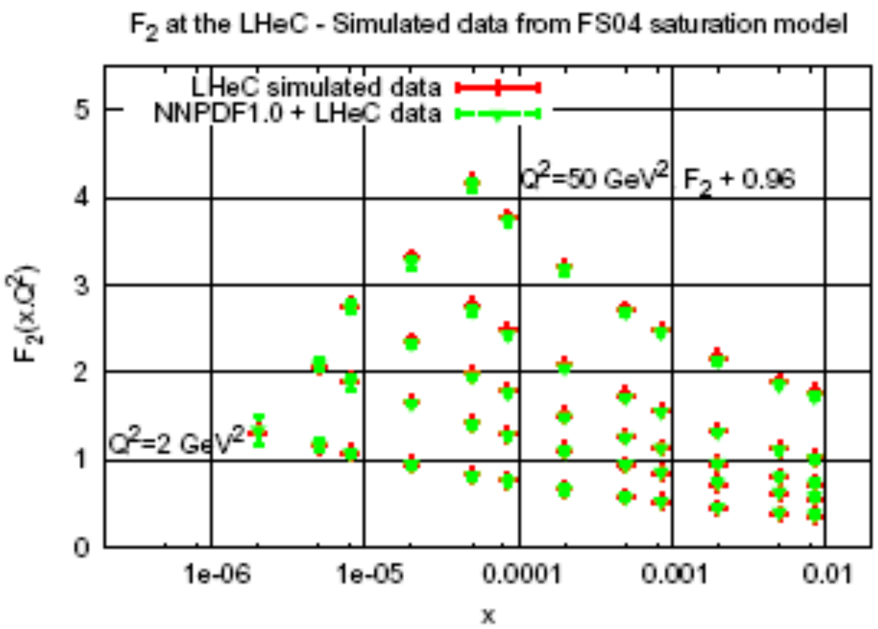
... sizeable improvement in error on low x gluon when both LHeC F_2 & F_L data are included.

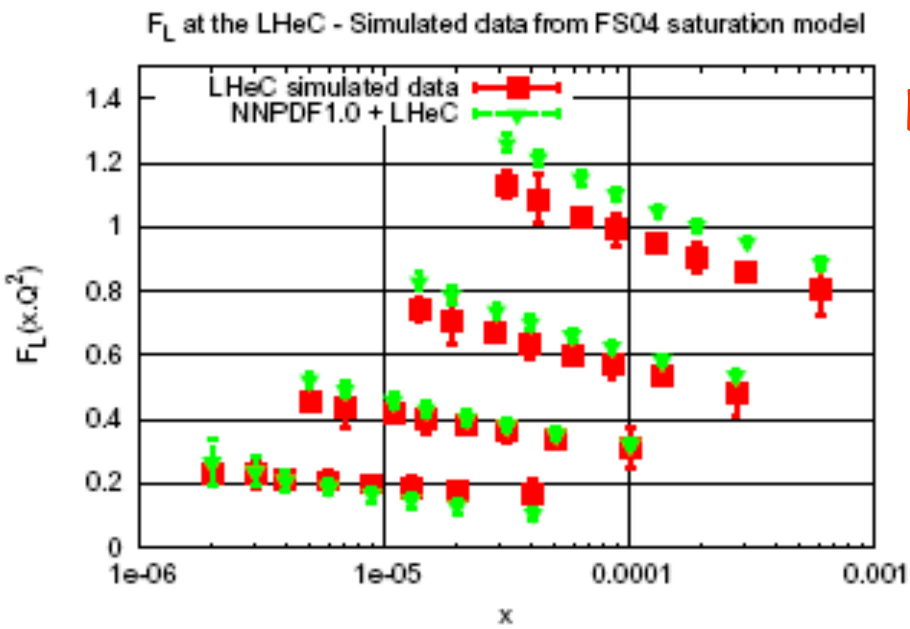
... but would DGLAP fits fail if non-linear effects present?

Can Parton Saturation be Established in ep @ LHeC?

Simulated LHeC F_2 and F_L data based on a dipole model containing low x saturation (FS04-sat)…

… NNPDF (also HERA framework) DGLAP QCD fits cannot accommodate saturation effects if F_2 and F_L both fitted

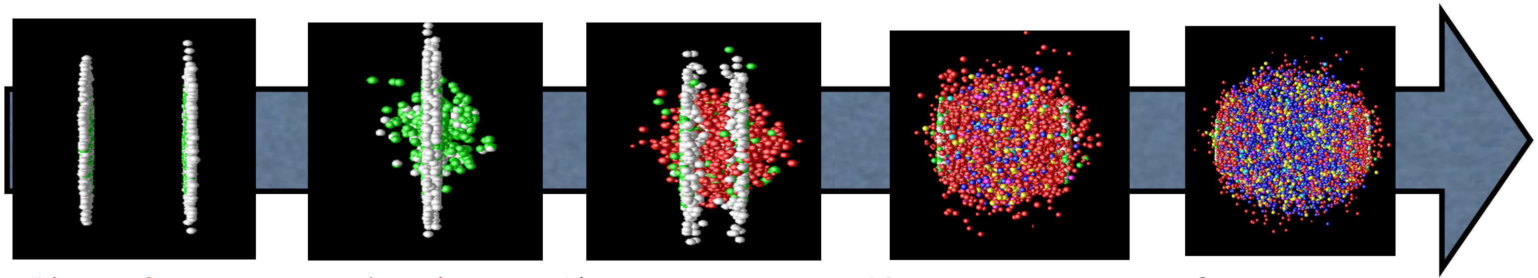




[Rojo]

Conclusion: clearly establishing non-linear effects needs a minimum of 2 observables … <u>(F_2^c may work in place of F_L)</u>…

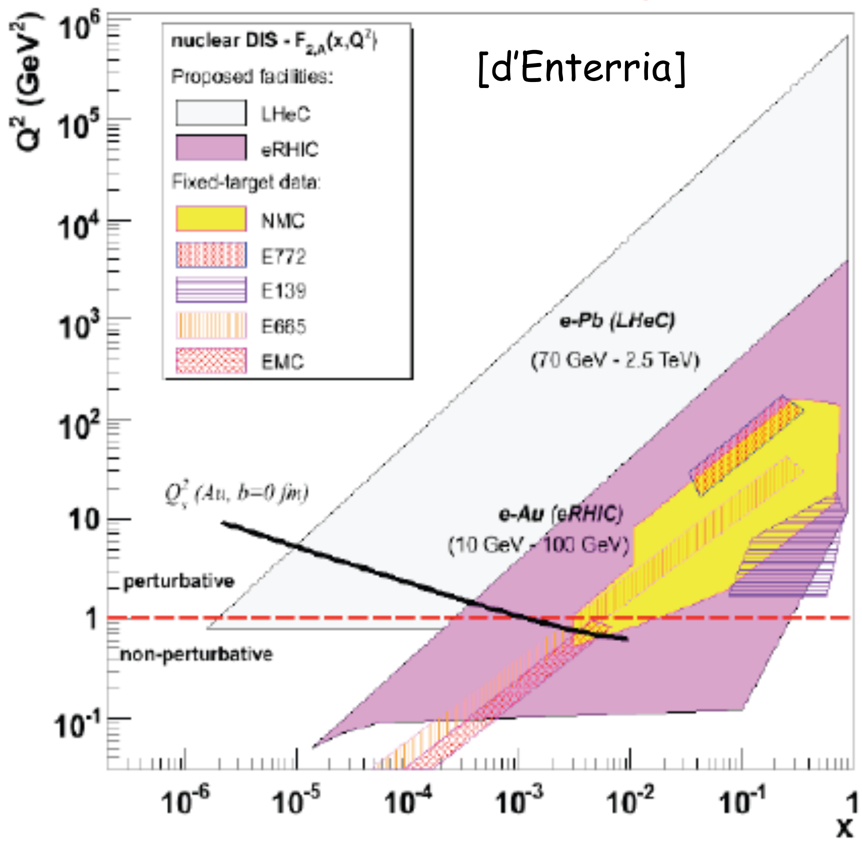
What is Initial State of LHC AA Collisions?



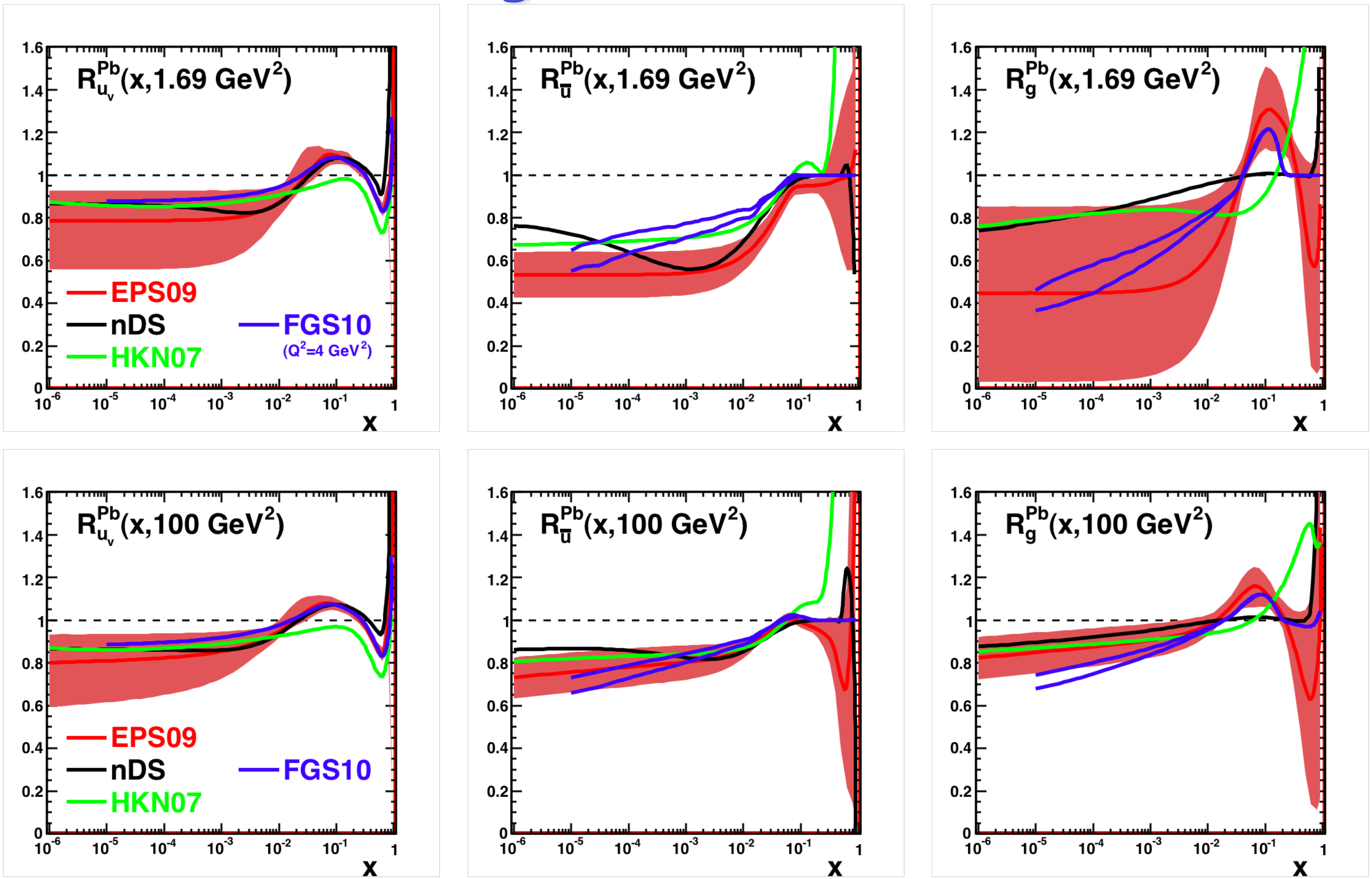
Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

- Very limited x, Q^2 and A range for F_2^A so far (unknown for x <~ 10^{-2}, gluon very poorly constrained)

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

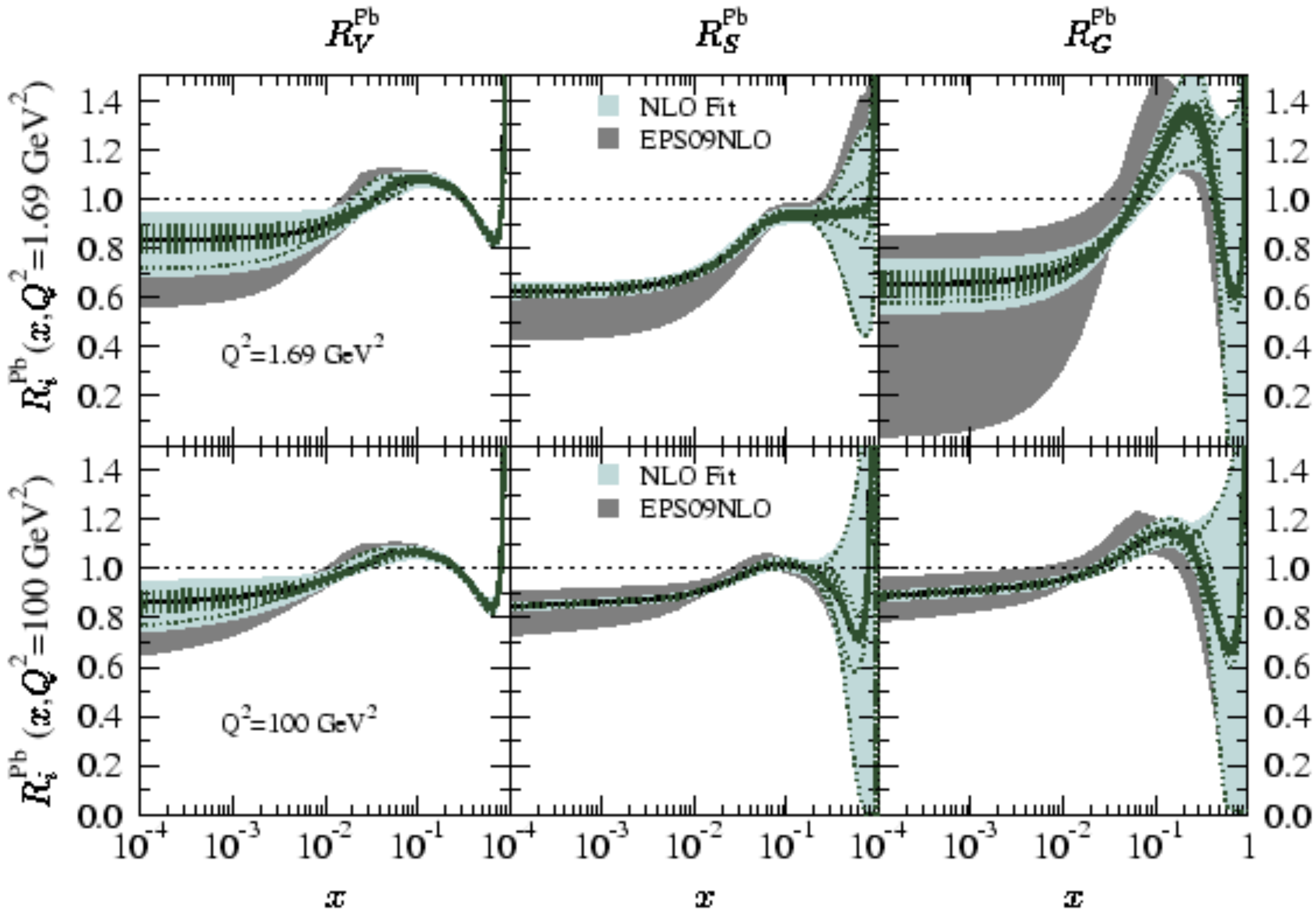


Current Knowledge: Nuclear Parton Densities



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

First Study of Impact of e-Pb LHC data

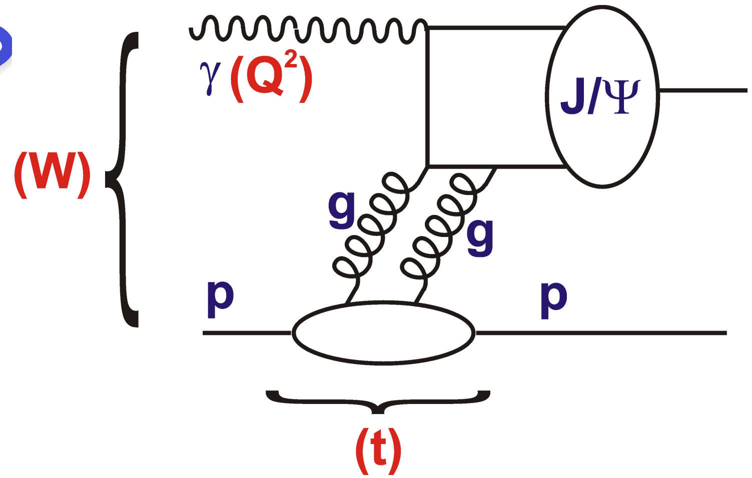


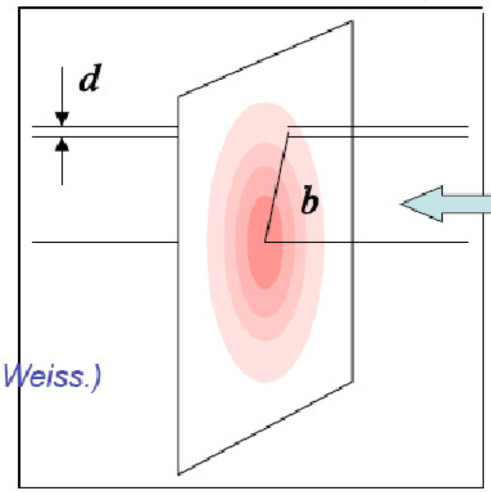
[Paukkunen, Armesto … in progress]

- Striking effect on quark sea and gluons in particular
- High x gluon uncertainty remains large
- Now working on flavour decomposition

What about Diffraction?

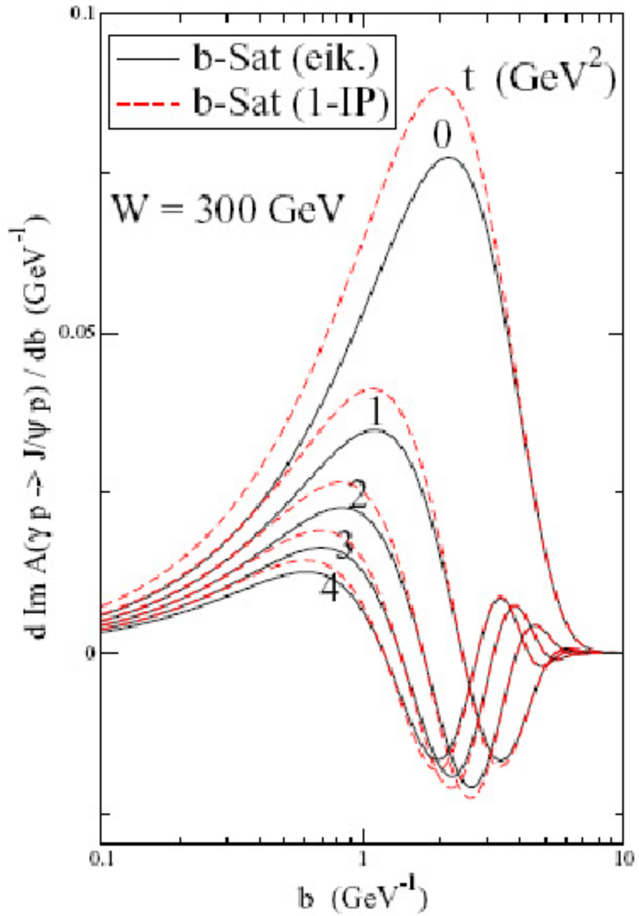
Additional variable t gives access to impact parameter (b) dependent amplitudes





(figure from C. Weiss.)

Central black region growing with decrease of x.



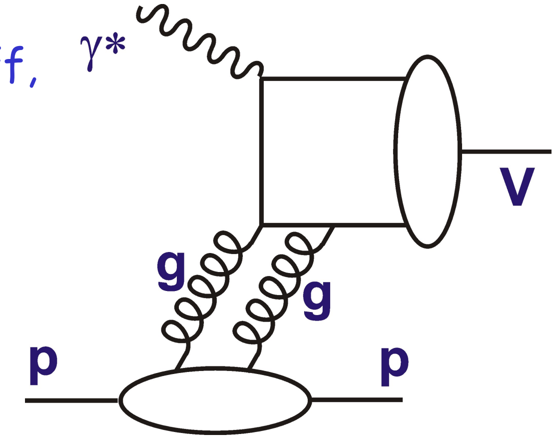
Large t (small b) probes densest packed part of proton?
c.f. inclusive scattering probes median $b \sim 2\text{-}3\ \mathrm{GeV}^{-1}$

Dipole Model of J/ψ Photoproduction

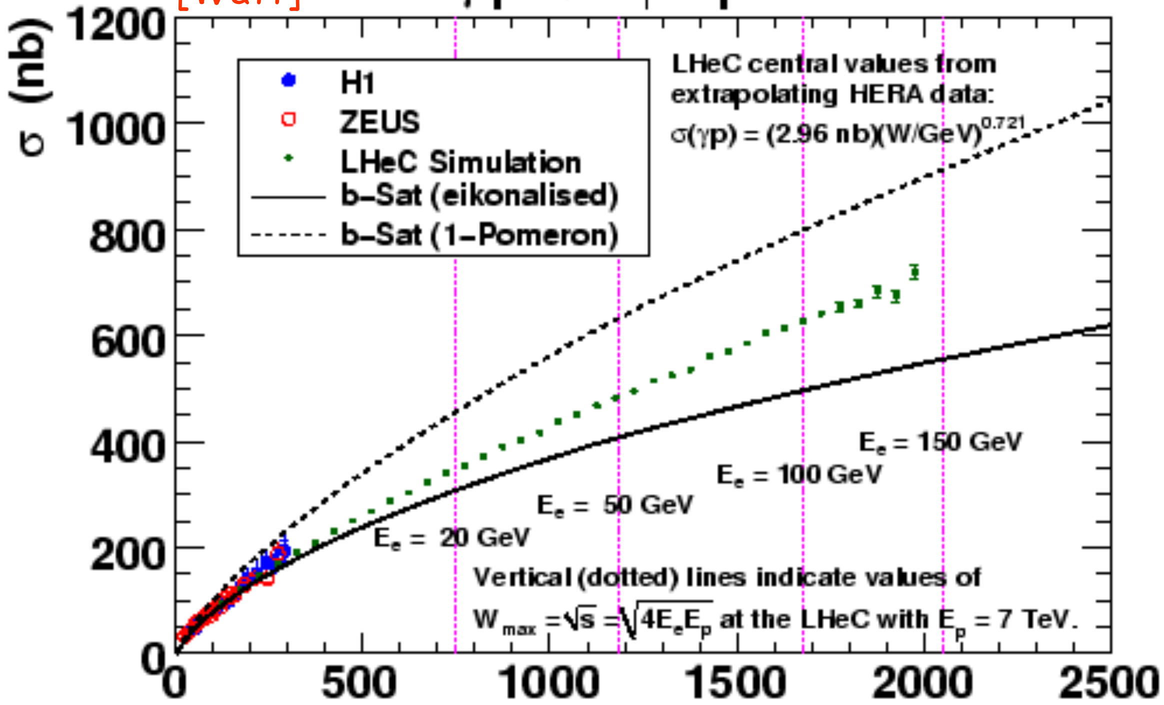
e.g. "b-Sat" Dipole model [Golec-Biernat, Wuesthoff, Bartels, Teaney, Kowalski, Motyka, Watt] ...

"eikonalised": with impact-parameter dependent saturation

"1 Pomeron": non-saturating



[Watt]

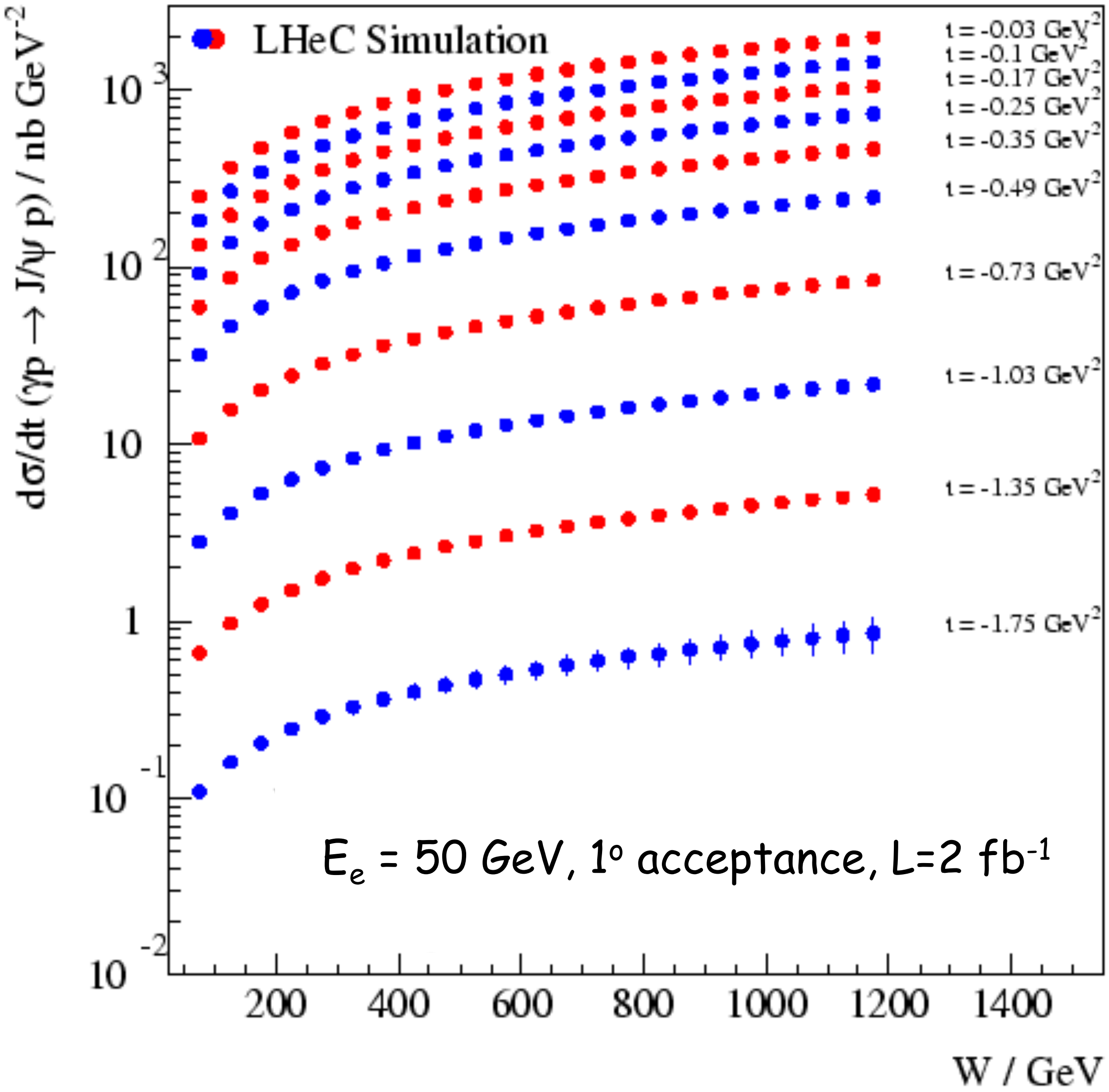


[2 years in low x configuration]

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

→ Sat^n smoking gun?

Elastic J/ψ Production more Differentially



J/ψ photoproduction double differentially in W and t …

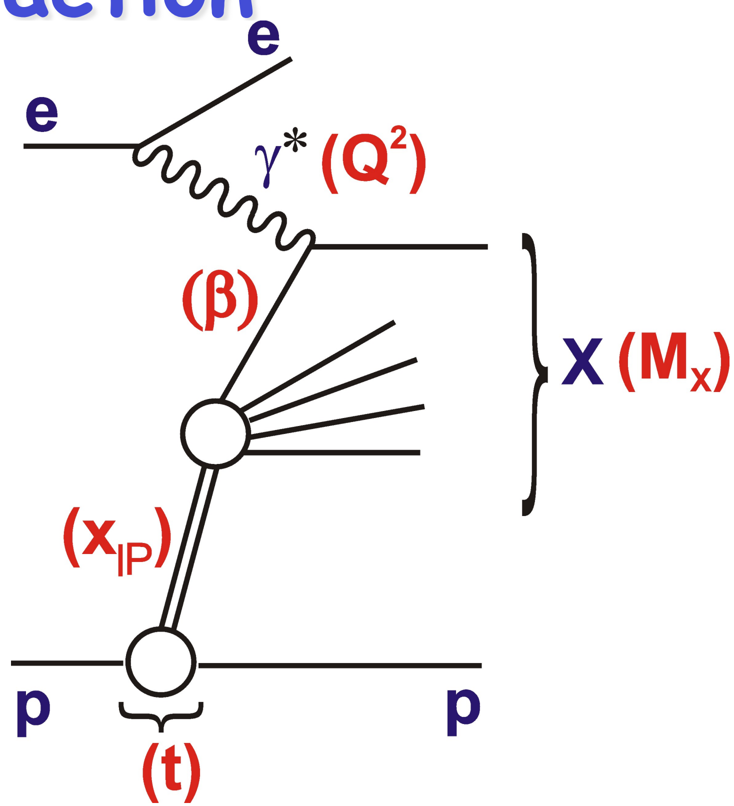
Cross sec probes to $x_g \sim 6.10^{-6}$

$Q^2 \sim 3\ GeV^2 \sim m_\psi^2/4$

Precise t dependence will help to reveal sat^n effects!

Also possible in several Q^2 bins and for Upsilon, DVCS …

Inclusive Diffraction



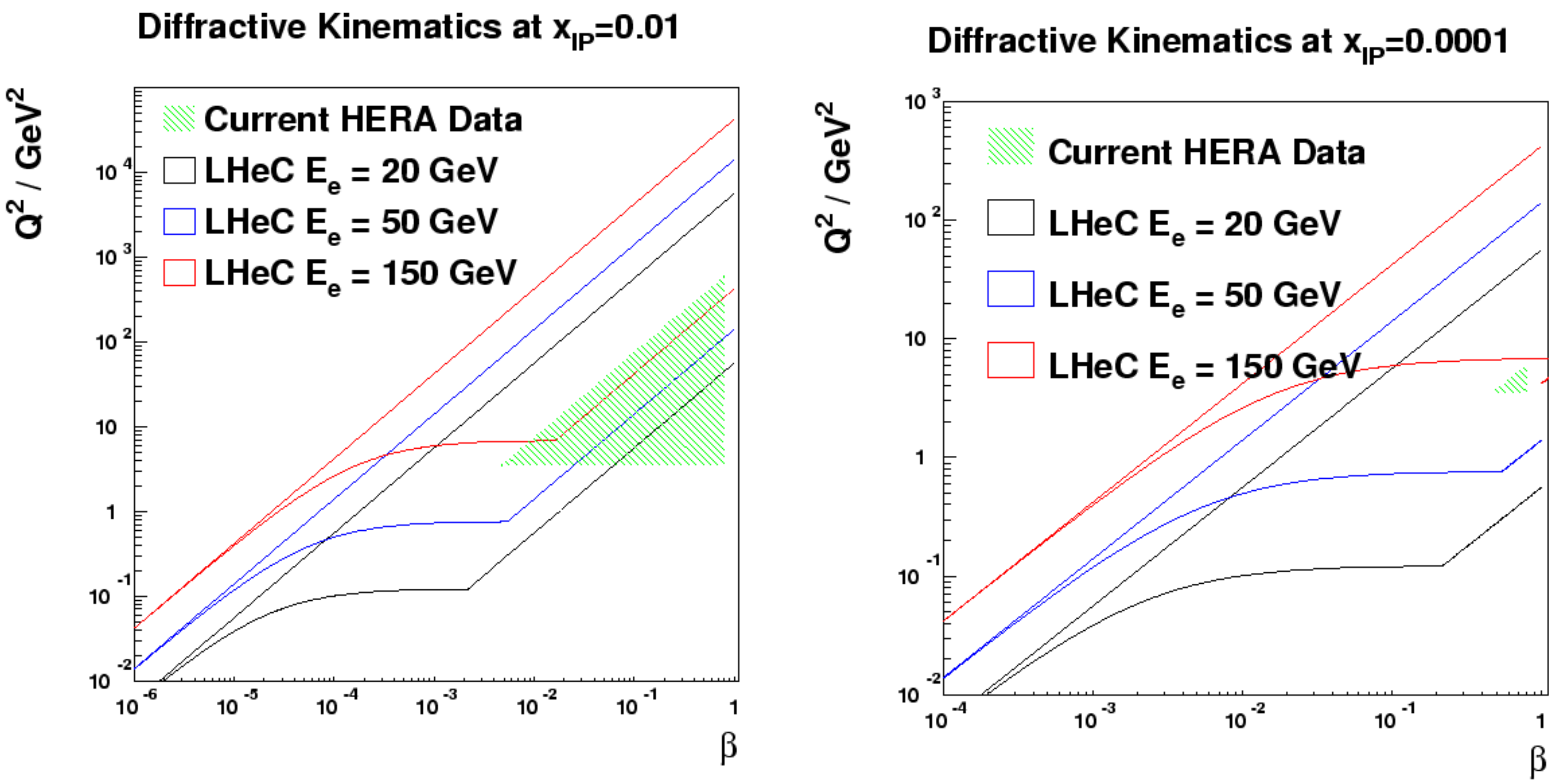
Additional variables …

x_{IP} = fractional momentum loss of proton (momentum fraction IP/p)

$\beta = x / x_{IP}$ (momentum fraction q / IP)

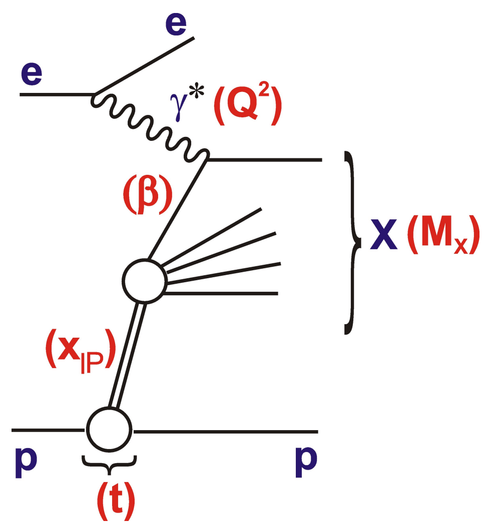
→ Further sensitivity to saturation phenomena
→ Diffractive parton densities in much increased range
→ Sensitivity to rapidity gap survival issues
→ Can relate ep diffraction to eA shadowing
… Control for interpretation of inclusive eA data

Diffractive Kinematic Plane at LHeC

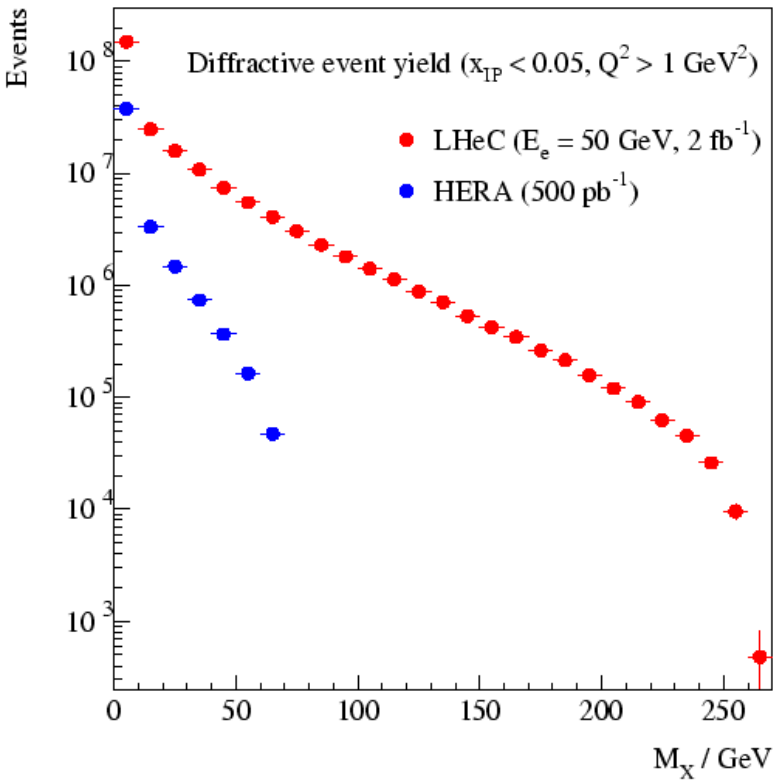


- Higher E_e yields acceptance at higher Q^2 (pQCD), lower x_{IP} (clean diffraction) and β (low x effects)
- Similar to inclusive case, 170° acceptance kills most of plane

Simulated Diffractive DIS Data

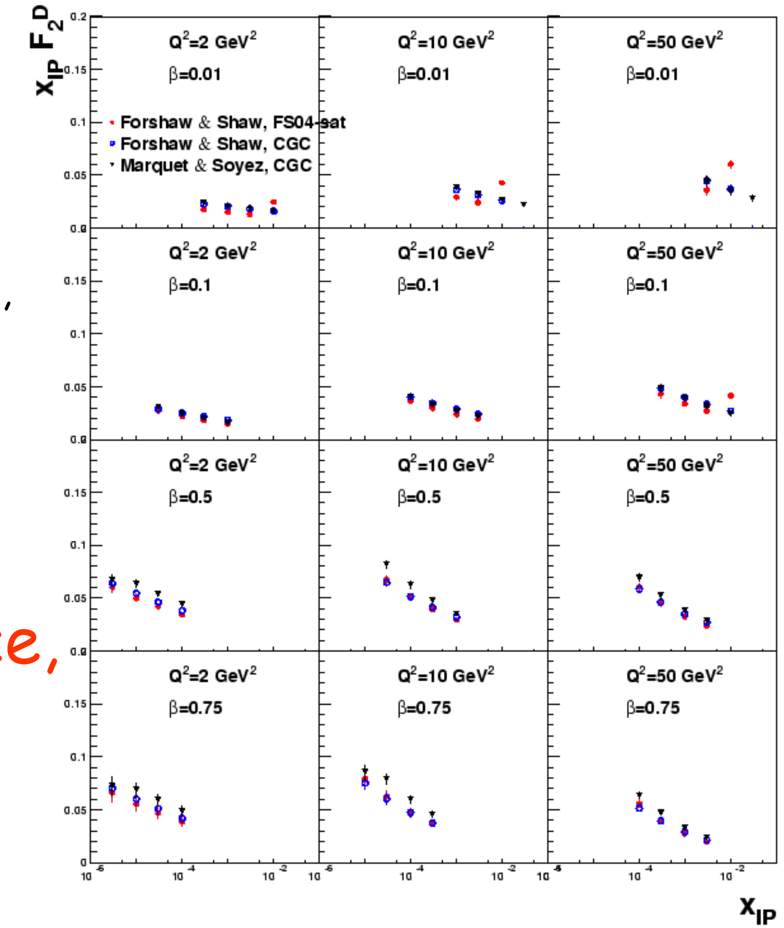


- 5-10% data, depending on detector
- DPDFs / fac'n in much bigger range
- Enhanced parton satn sensitivity?
- Exclusive production of any 1^- state with Mx up to ~ 250 GeV
  → X including W, Z, b, exotics?



[Forshaw, Marquet, PN]

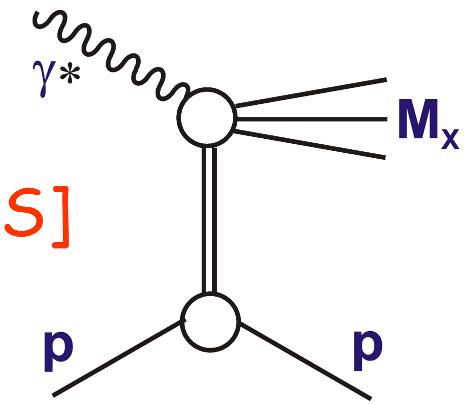
1° acceptance, 2 fb^{-1}

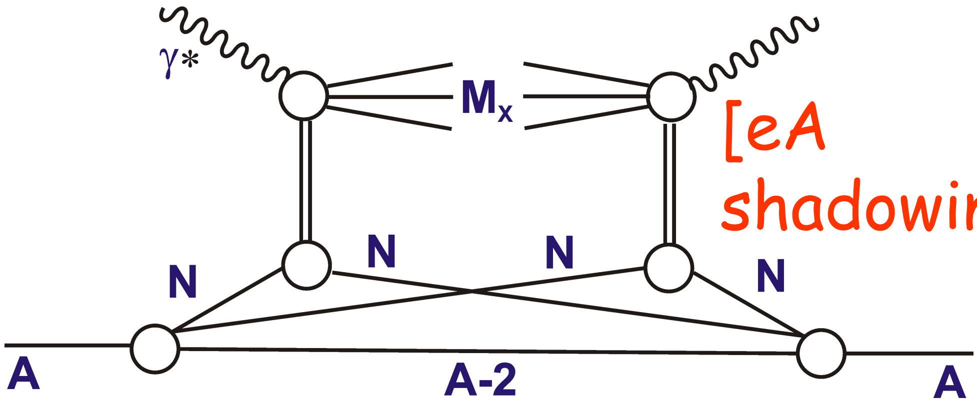


F_2^D and Nuclear Shadowing

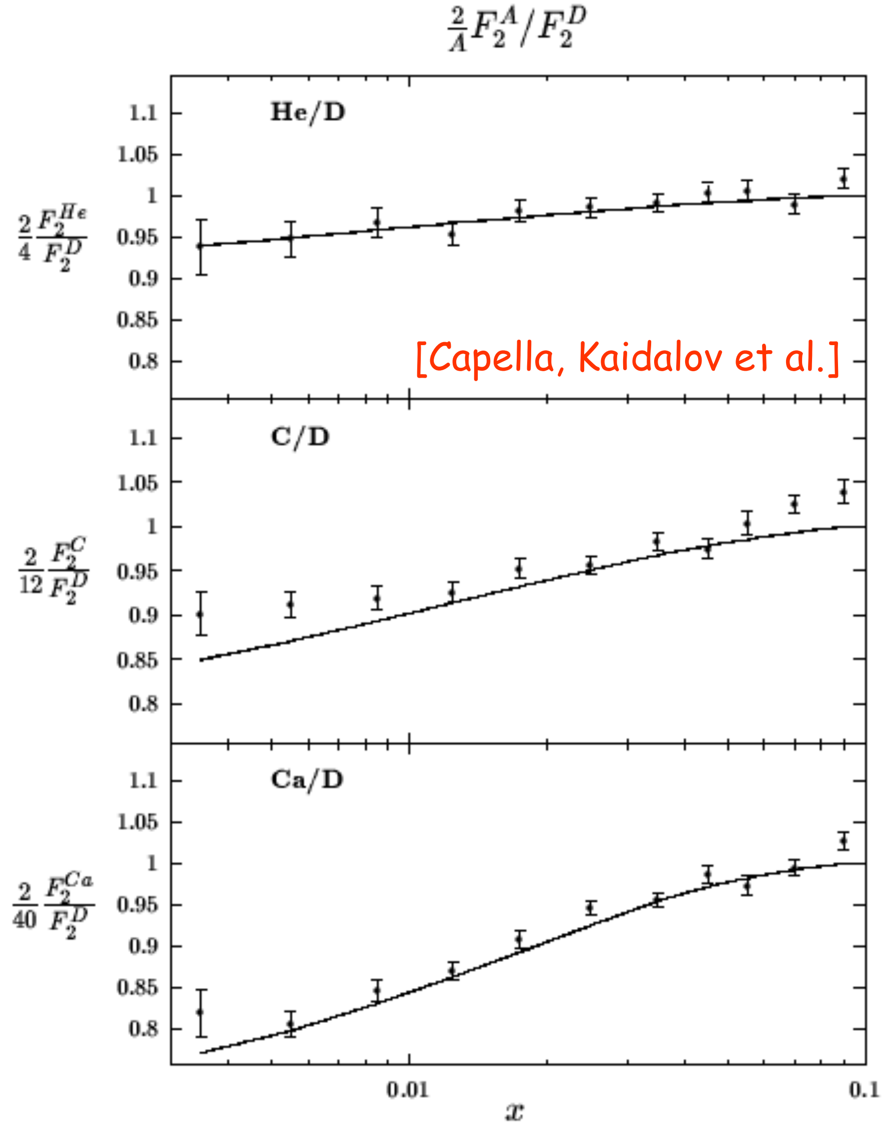
Nuclear shadowing can be described (Gribov-Glauber) as multiple interactions, starting from ep DPDFs

[Diff DIS]



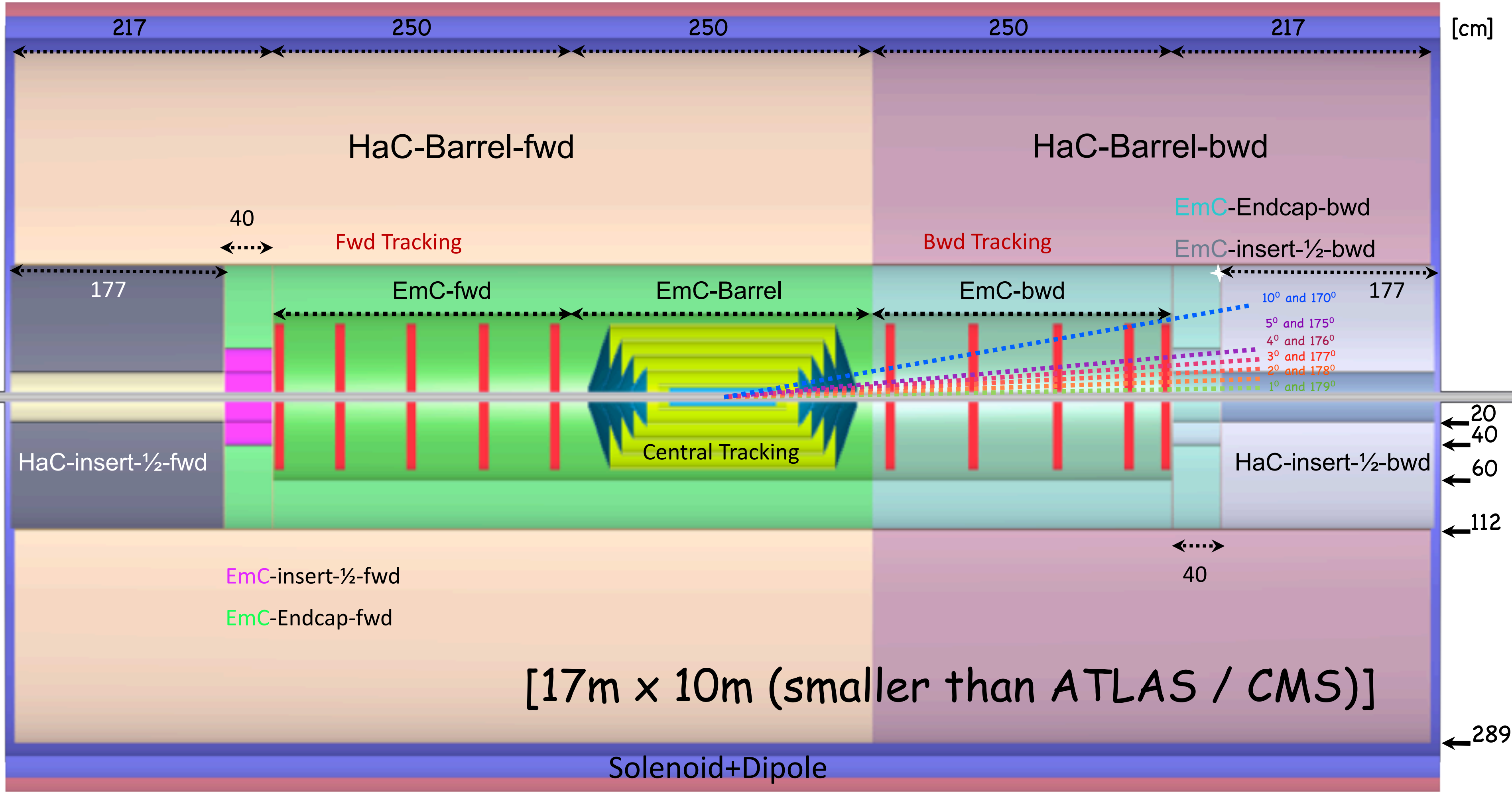


[eA shadowing]



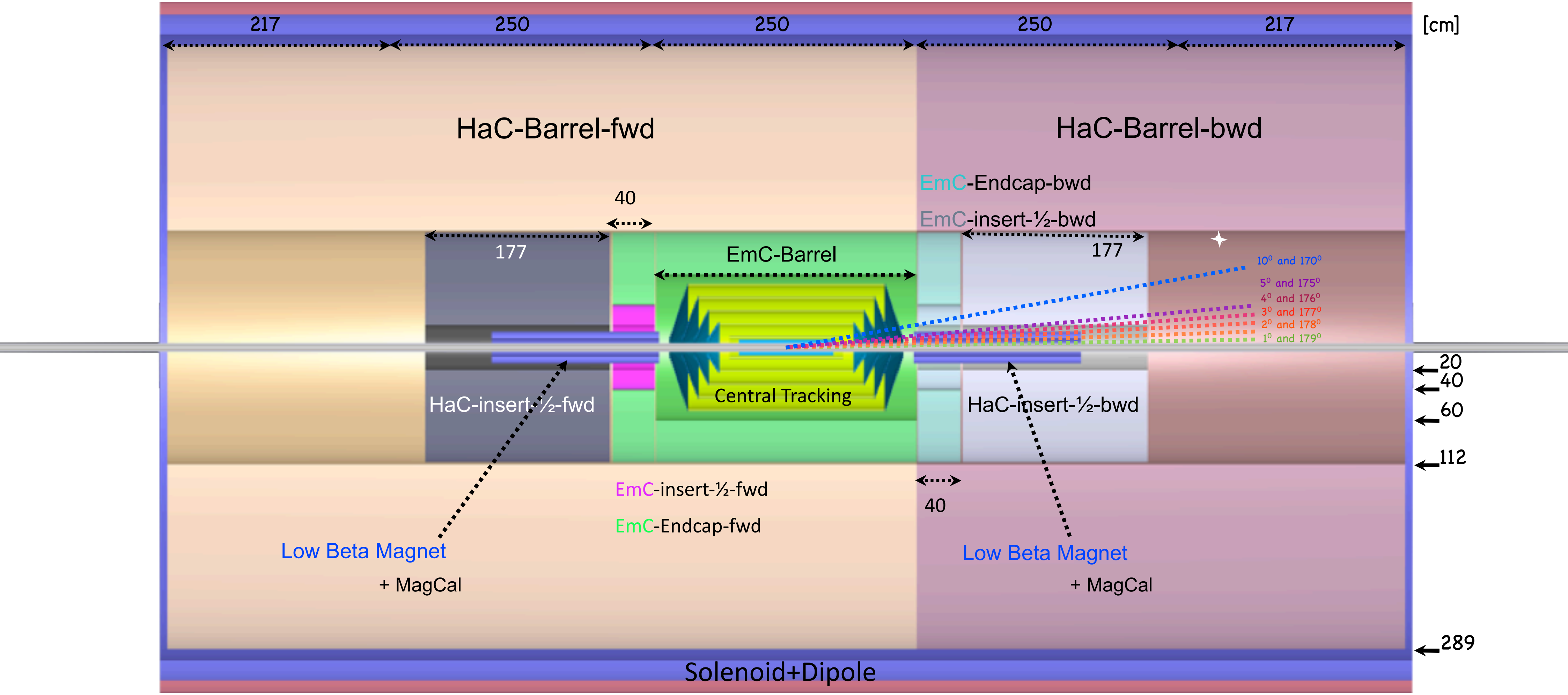
… starting point for extending precision LHeC studies into eA collisions

First Detector Concepts - Low x Optimised



- Full angular coverage, long tracking region → 1°
- Dimensions determined by synchrotron radiation fan
- Modular Low material budget High precision
- Technologies under discussion (lots of ideas!)

First Detector Concepts - High Q^2 Optimised



- Sacrifice low angle acceptance to beam focusing magnets
- Calorimeter inserts slide inwards
- 2 phases of operation a la HERA?
- Alternatively 2 interaction points (RR only)?

Schedule and Remarks

- Aim to start operation by 2020/22 [new phase of LHC]

  → cf HERA: Proposal 1984 – Operation 1992. LEP: Proposal 1983 – Operation 1989

- The major accelerator and detector technologies exist

- Cost is modest in major HEP project terms

- Steps: Conceptual Design Report, early 2011
  Evaluation within CERN / European PP/NP strategy
  If positive, more professional effort torward a
  Technical Design Report 2013/14

- In an optimistic long term perspective, a 140 GeV electron linac beam coupled with a 16 TeV Super-LHC' beam would mean CMS energy of 3 TeV and x ~10^{-7} ☺

Summary

• LHC is a totally new world of
•energy and luminosity! LHeC proposal aims to exploit it for TeV lepton-hadron scattering
… ep complementing next generation pp, ee facilities

• Ongoing ECFA/CERN/NuPECC workshop has gathered many accelerator, theory & experimental colleagues
… still lots to do, even for CDR!

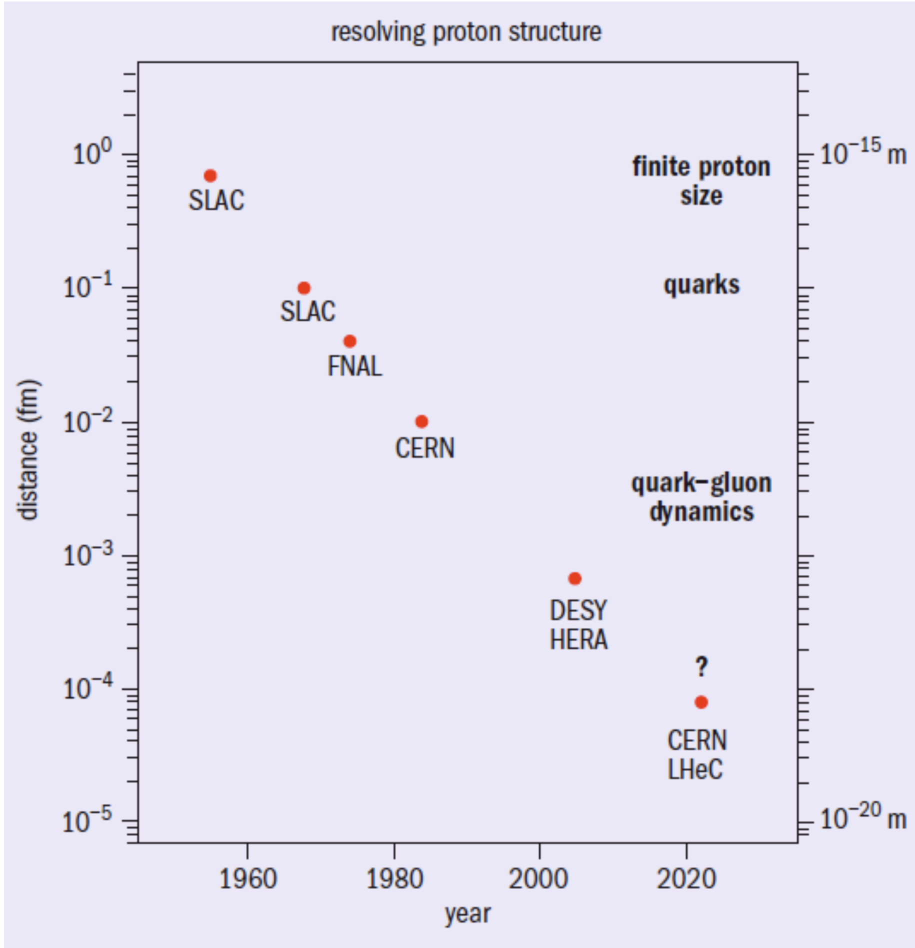


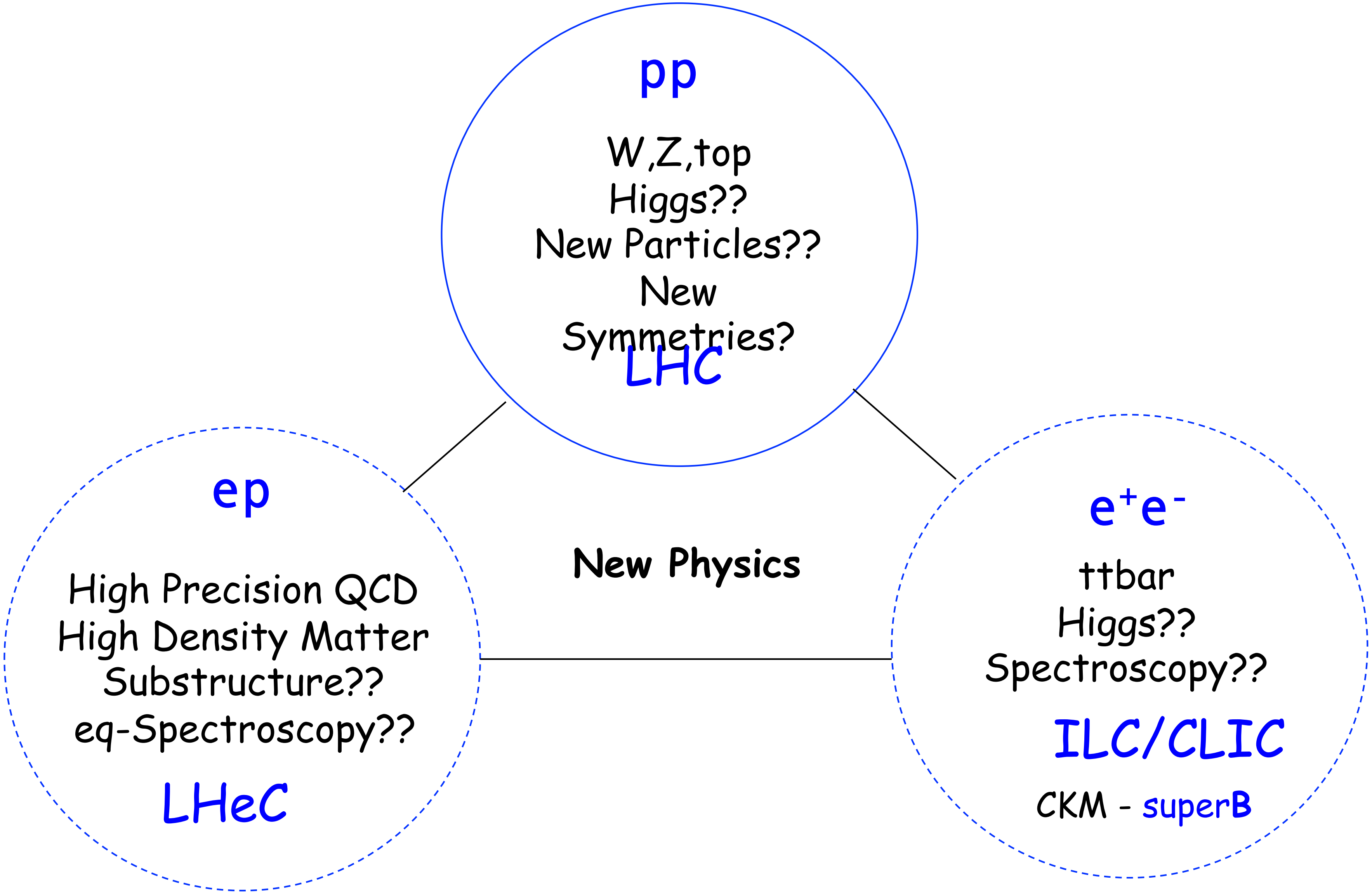
Fig. 1. Distance scales resolved in successive lepton–hadron scattering experiments since the 1950s, and some of the new physics revealed.

• Next major workshop planned for October '10 .All ideas and involvement welcome!

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

Back-Ups Follow

The TeV Scale [2010-2035..]



Organisation for the CDR

Scientific Advisory Committee

Guido Altarelli (Rome)
Sergio Bertolucci (CERN)
Stan Brodsky (SLAC)
Allen Caldwell -chair (MPI Munich)
Swapan Chattopadhyay (Cockcroft)
John Dainton (Liverpool)
John Ellis (CERN)
Jos Engelen (CERN)
Joel Feltesse (Saclay)
Lev Lipatov (St.Petersburg)
Roland Garoby (CERN)
Roland Horisberger (PSI)
Young-Kee Kim (Fermilab)
Aharon Levy (Tel Aviv)
Karlheinz Meier (Heidelberg)
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Tatsuya Nakada (Lausanne, ECFA)
Guenther Rosner (Glasgow, NuPECC)
Alexander Skrinsky (Novosibirsk)
Anthony Thomas (Jlab)
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Bernd Surrow	(MIT)
Katsuo Tokushuku	(KEK)
Urs Wiedemann	(CERN)
Frank Zimmermann	(CERN)

Working Group Convenors

Accelerator Design [RR and LR]

Oliver Bruening (CERN),

John Dainton (CI/Liverpool)

Interaction Region and Fwd/Bwd

Bernhard Holzer (DESY),

Uwe Schneeekloth (DESY),

Pierre van Mechelen (Antwerpen)

Detector Design

Peter Kostka (DESY),

Rainer Wallny (UCLA),

Alessandro Polini (Bologna)

New Physics at Large Scales

George Azuelos (Montreal)

Emmanuelle Perez (CERN),

Georg Weiglein (Durham)

Precision QCD and Electroweak

Olaf Behnke (DESY),

Paolo Gambino (Torino),

Thomas Gehrmann (Zuerich)

Claire Gwenlan (Oxford)

Physics at High Parton Densities

Nestor Armesto (Santiago),

Brian Cole (Columbia),

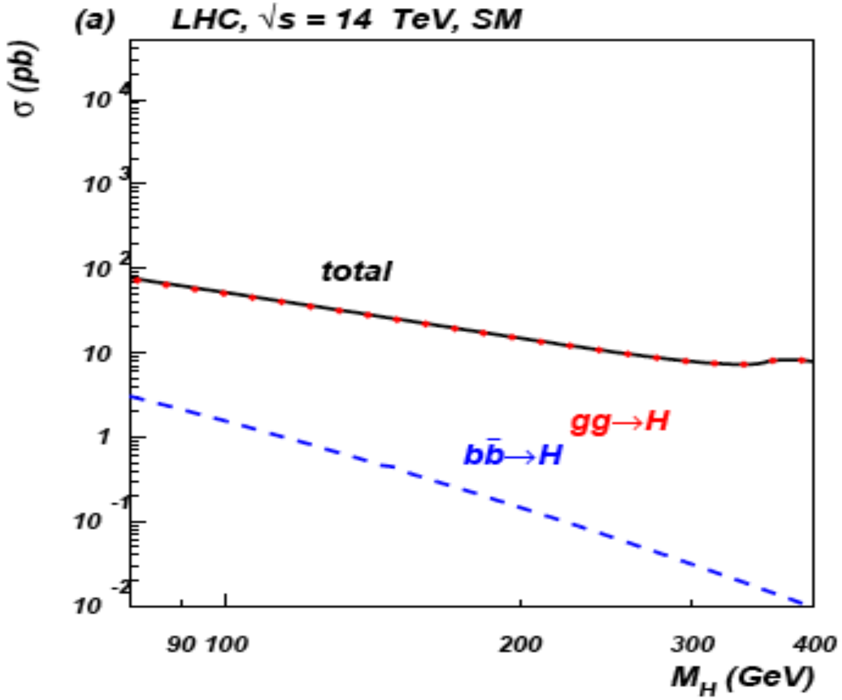
Paul Newman (Birmingham),

http://cern.ch/lhec

Heavy Quarks: HERA → LHC

• HERA HF information limited by kinematic range and lumi (reasonable charm, some beauty, almost no strange)

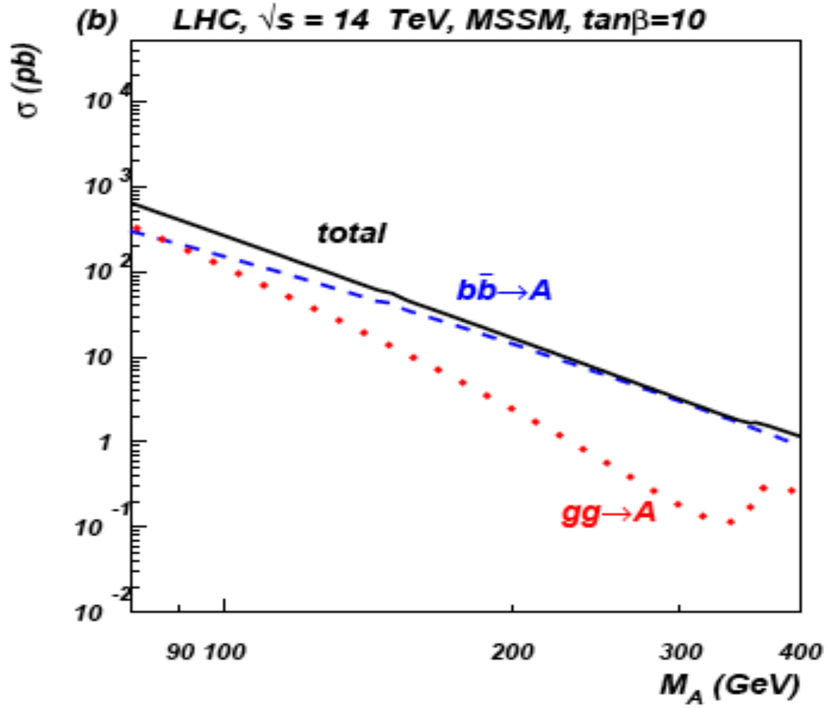
• Crucial for understanding LHC initial state for new processes (e.g. bbbar->H) and backgrounds.



Higgs

<-SM

MSSM->



• LHC predictions rely strongly on extrapolations and pQCD (e.g. CTEQ: 7% effect on W,Z rates varying HF treatment).

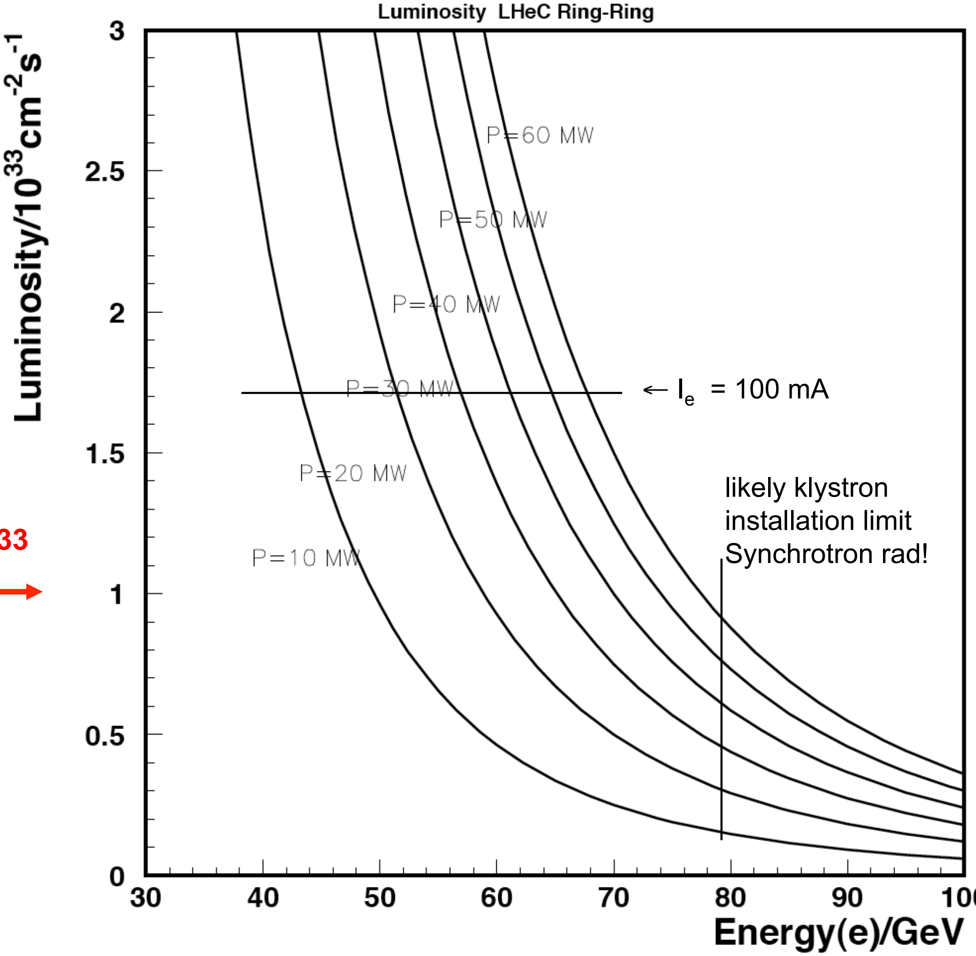
Luminosity: Ring-Ring

$$L = \frac{N_p \gamma}{4\pi e \varepsilon_{pn}} \cdot \frac{I_e}{\sqrt{\beta_{px}\beta_{py}}} = 8.3 10^{32} \cdot \frac{I_e}{50mA} \frac{m}{\sqrt{\beta_{px}\beta_{pn}}} cm^{-2}s^{-1}$$

$\varepsilon_{pn} = 3.8\mu m$
$N_p = 1.7 \cdot 10^{11}$
$\sigma_{p(x,y)} = \sigma_{e(x,y)}$
$\beta_{px} = 1.8m$
$\beta_{py} = 0.5m$

$$I_e = 0.35mA \cdot \frac{P}{MW} \cdot \left(\frac{100GeV}{E_e}\right)^4$$

10^{33} →



10^{33} can be reached in RR
E_e = 40-80 GeV & P = 5-60 MW.

HERA was 1-4 10^{31} cm^{-2} s^{-1}
huge gain with SLHC p beam

F.Willeke in hep-ex/0603016:
Design of interaction region
for 10^{33} : 50 MW, 70 GeV

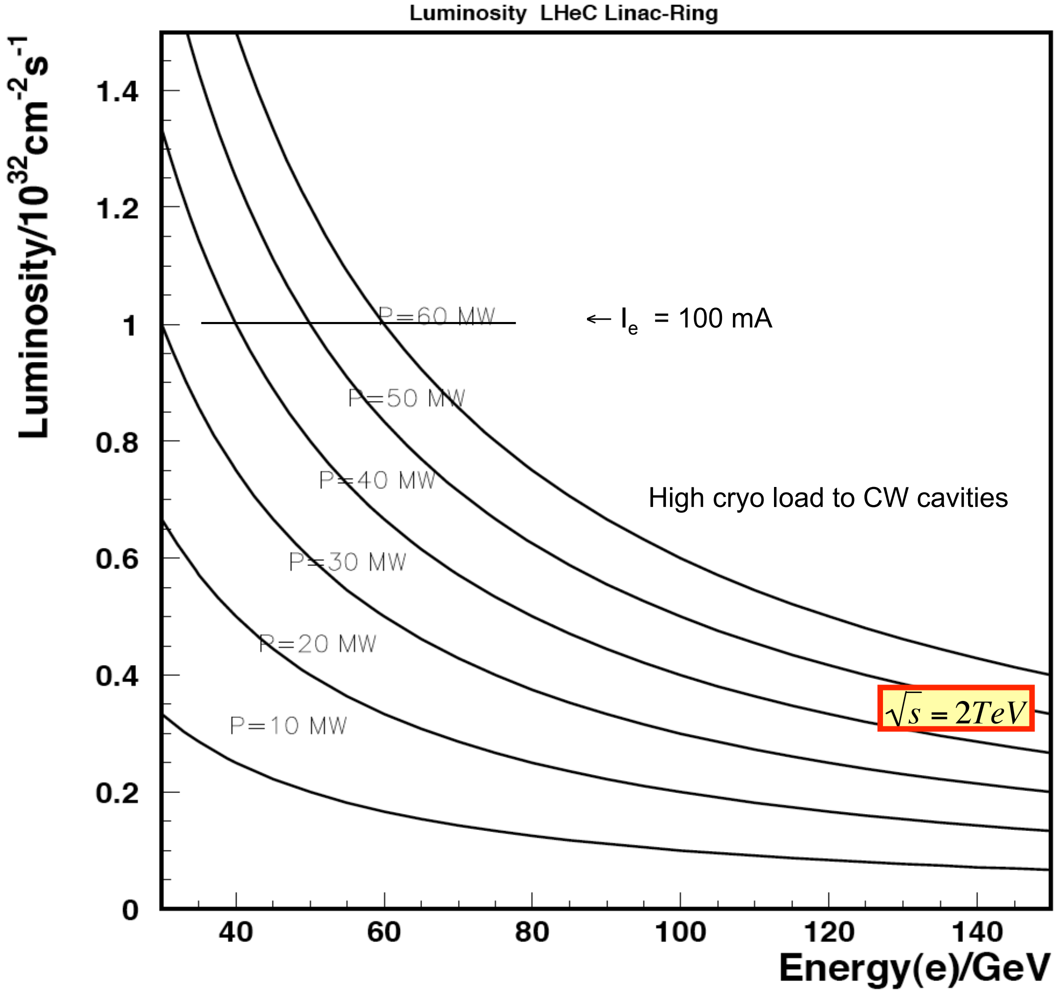
May reach 10^{34} with ERL in bypasses, or/and reduce power.
R&D performed at BNL/eRHIC

cf also A.Verdier 1990, E.Keil 1986

Luminosity: Linac-Ring

$$L = \frac{N_p \gamma}{4\pi e \varepsilon_{pn} \beta^*} \cdot \frac{P}{E_e} = 1 \cdot 10^{32} \cdot \frac{P/MW}{E_e/GeV} cm^{-2} s^{-1}$$

$$\varepsilon_{pn} = 3.8 \mu m$$
$$N_p = 1.7 \cdot 10^{11}$$
$$\beta^* = 0.15 m$$



$$I_e = 100 mA \cdot \frac{P}{MW} \cdot \frac{GeV}{E_e}$$

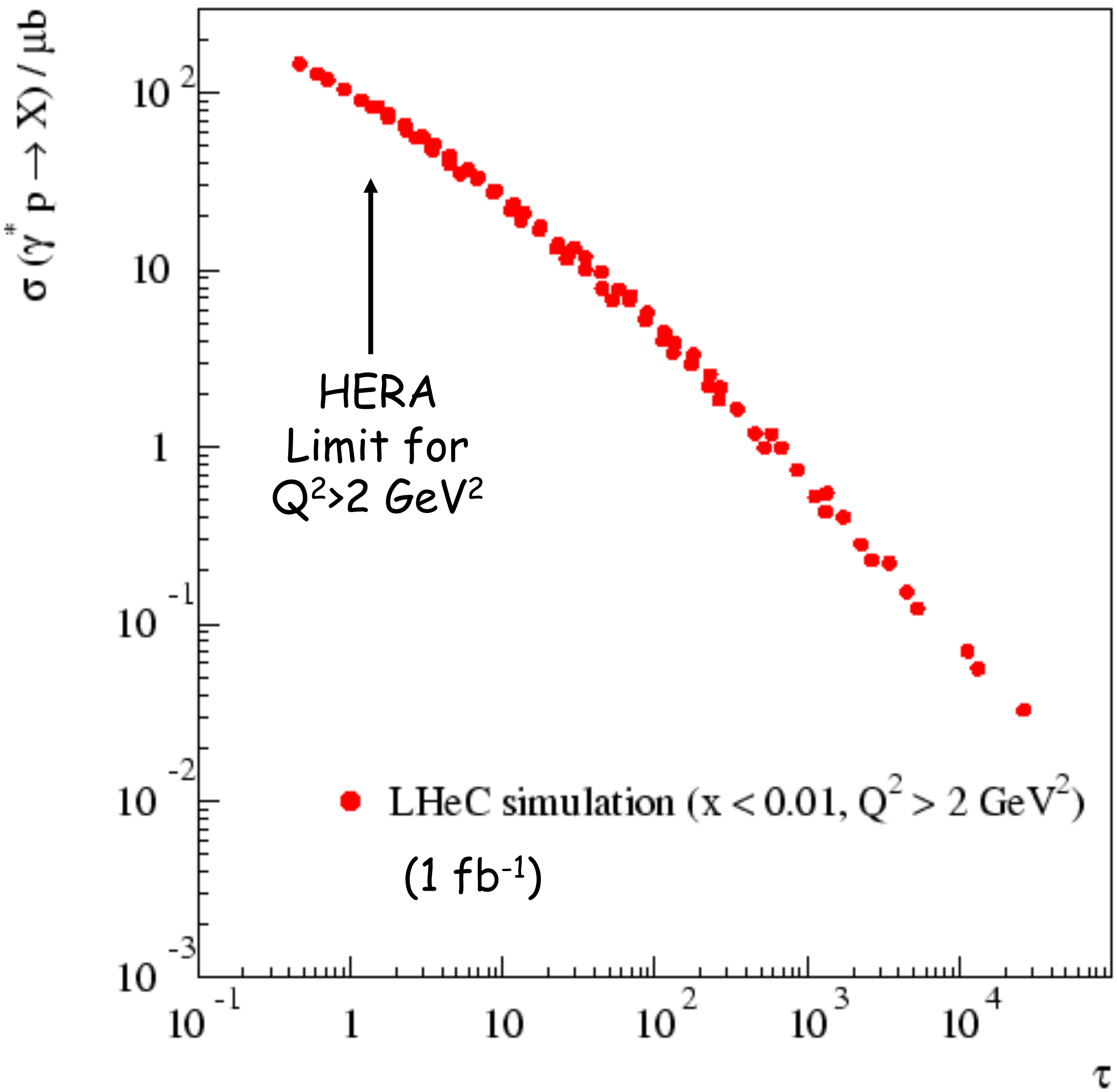
LHeC as Linac-Ring version
can be as luminous as HERA II:

4 10^{31} can be reached with LR:
E_e = 40-140 GeV & P=20-60 MW
LR: average lumi close to peak

140 GeV at 23 MV/m is 6km +gaps

Luminosity horizon: high power:
ERL (2 Linacs?)

Geometric Scaling at the LHeC



LHeC reaches $\tau \sim 0.15$ for Q^2=1 GeV^2 and $\tau \sim 0.4$ for Q^2=2 GeV^2

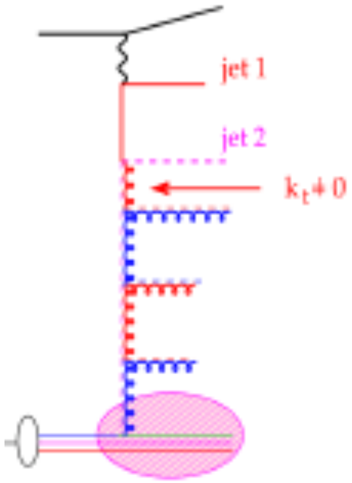
Some (though limited) acceptance for $Q^2 < Q^2_s$ with Q^2 "perturbative"

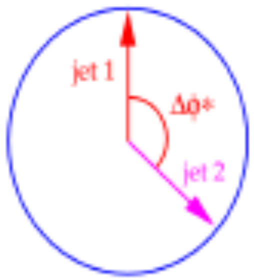
Could be enhanced with nuclei.

$Q^2 < 1$ GeV^2 accessible in special runs?

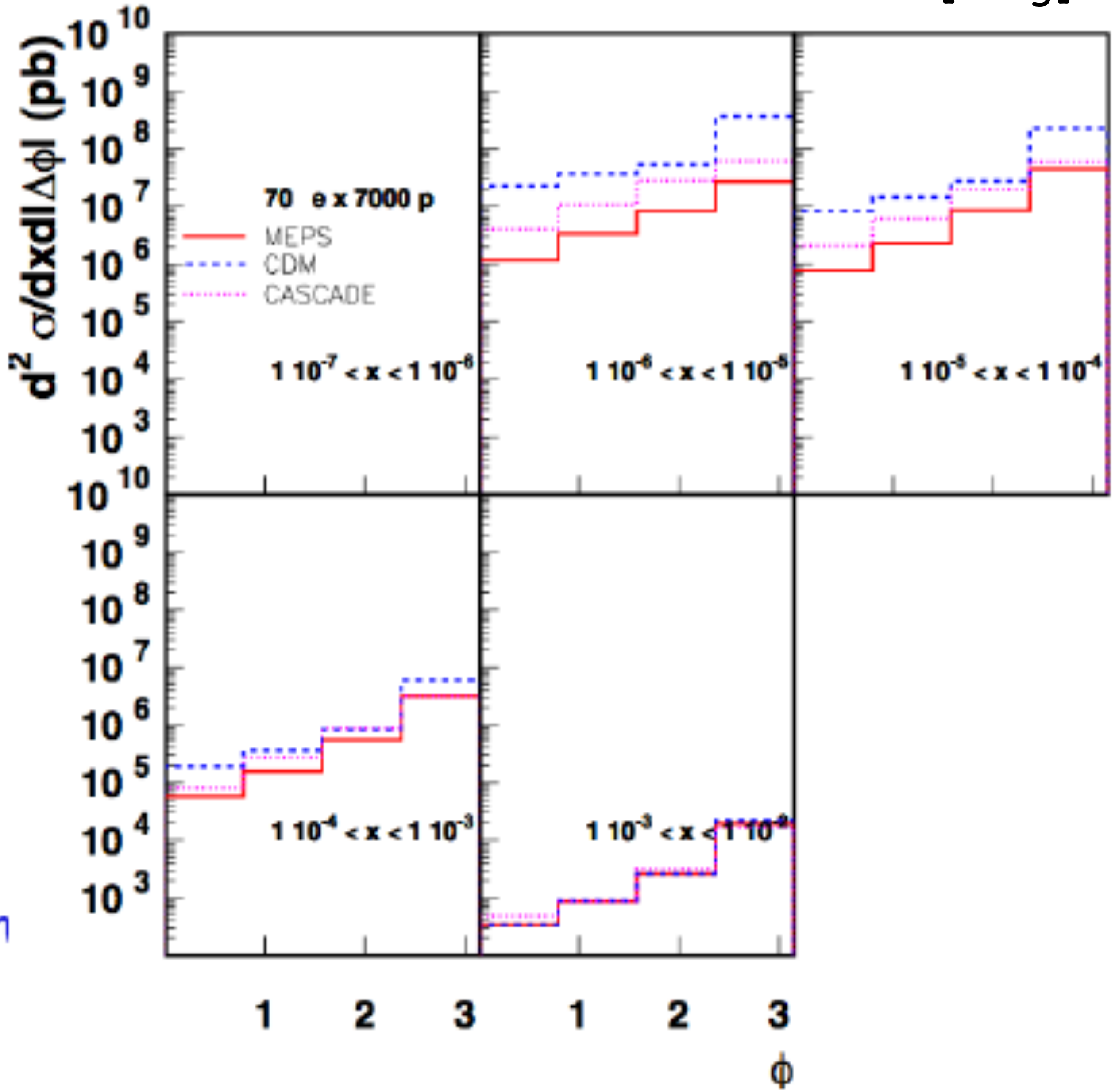
Azimuthal (de)correlations between Jets

[Jung]

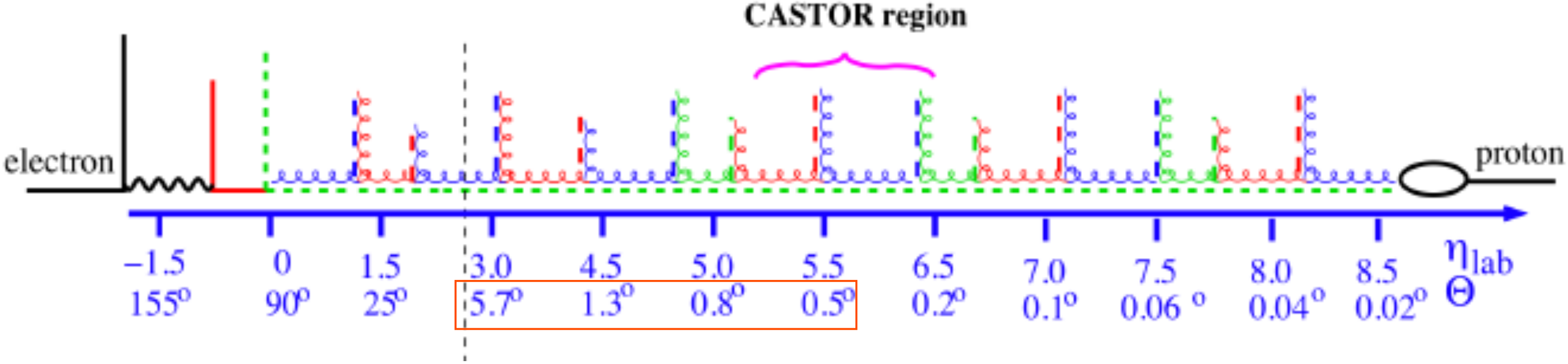




- $5 < Q^2 < 100 \text{ GeV}^2$
  $-1 < \eta < 2.5$
  $E_T > 5 \text{ GeV}$
- small $k_t \rightarrow \Delta\phi \sim 180$
- large k_t from evolution



Forward Instrumentation and Jets



[Jung]

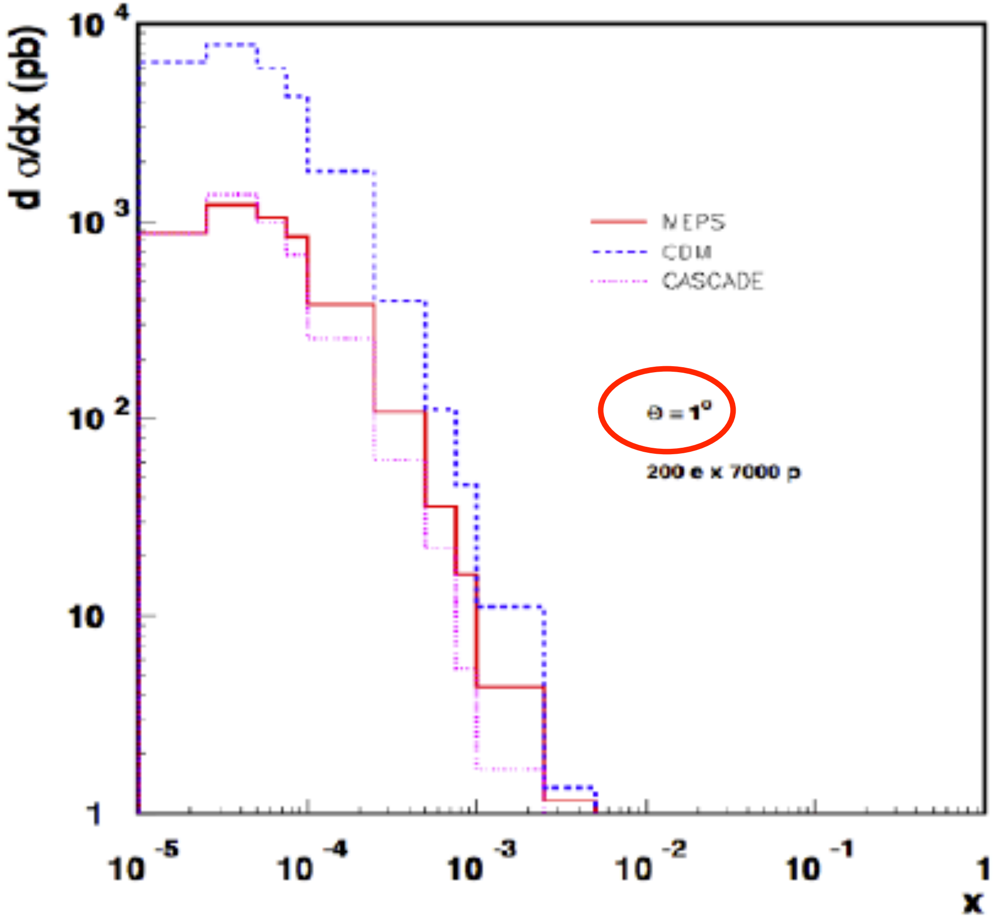
- DIS and forward jet:

$$x_{jet} > 0.03$$

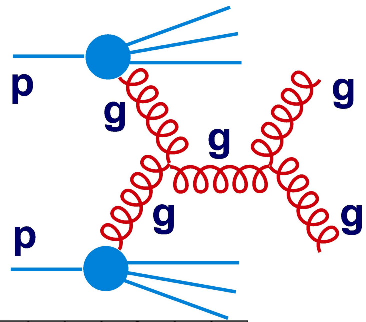
$$0.5 < \frac{p_{t\ jet}^2}{Q^2} < 2$$

x range (and sensitivity to novel QCD effects) strongly depend on θ cut

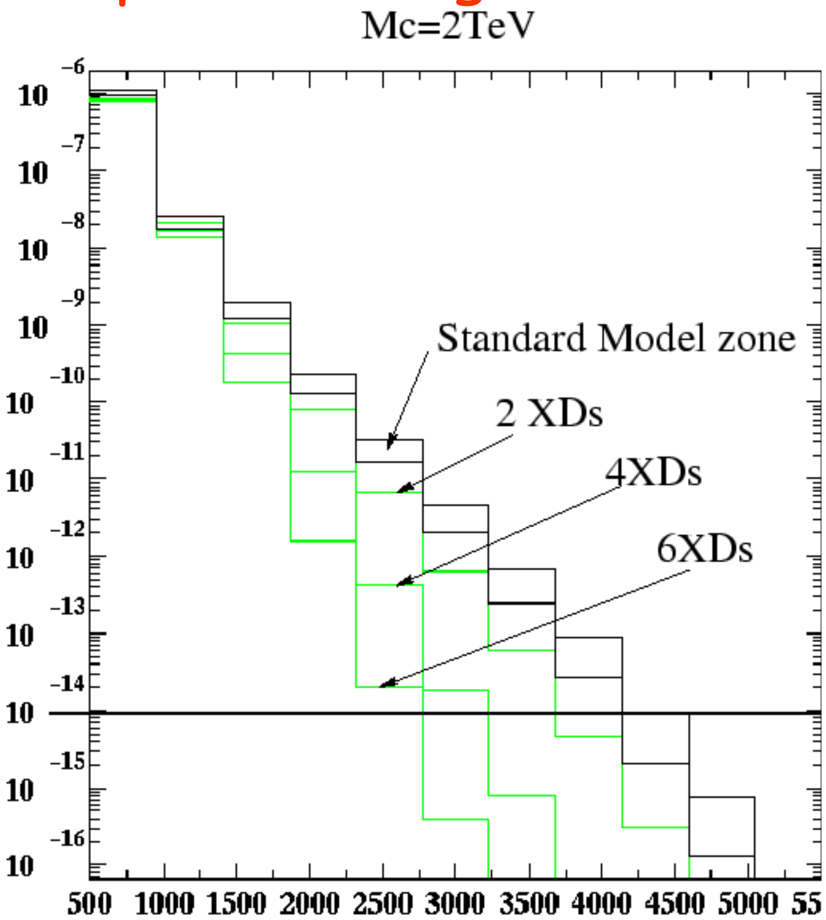
Similar conclusions for Δϕ decorrelations between jets

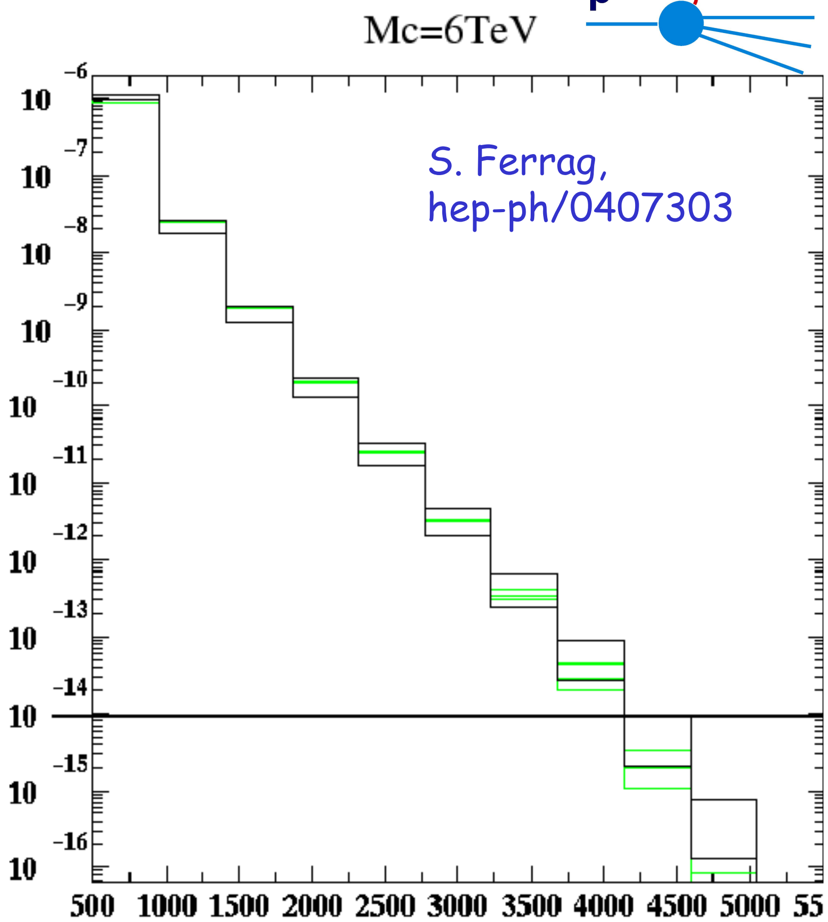


High x Partons Limiting LHC Searches



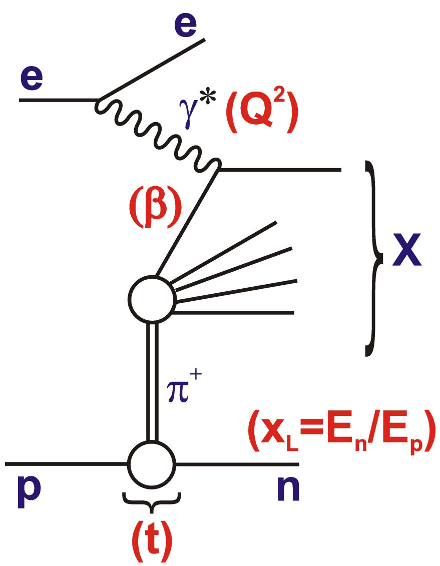
Some BSM scenarios give deviations in high mass dijet spectra … e.g. a model with extra dimensions …



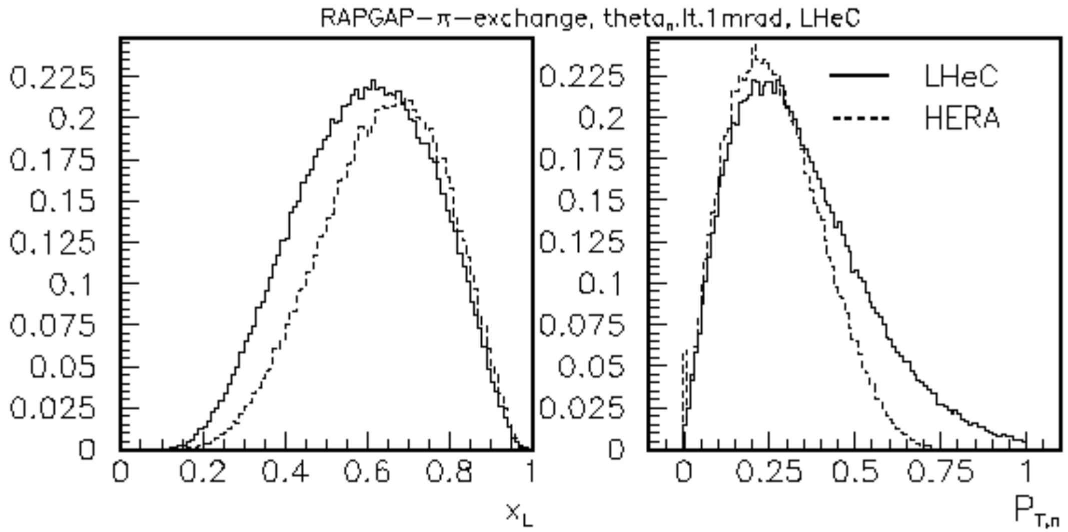


… in this example, high x PDF uncertainties reduce sensitivity to compactification scales from 6 TeV to 2 TeV for 2XDs

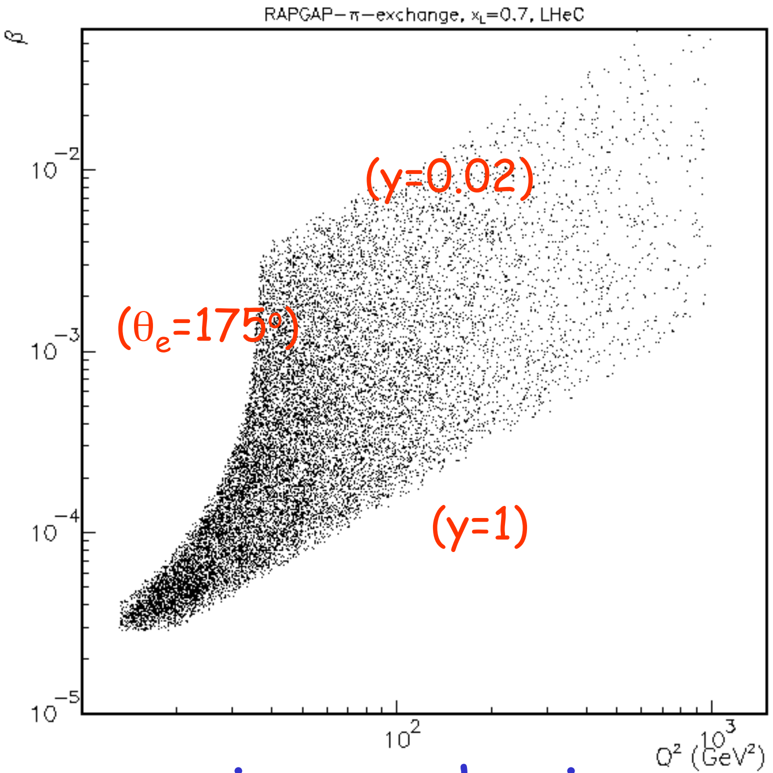
π Structure with Leading Neutrons



[Bunyatyan]



(RAPGAP MC model, E_p=7TeV, E_e=70GeV)

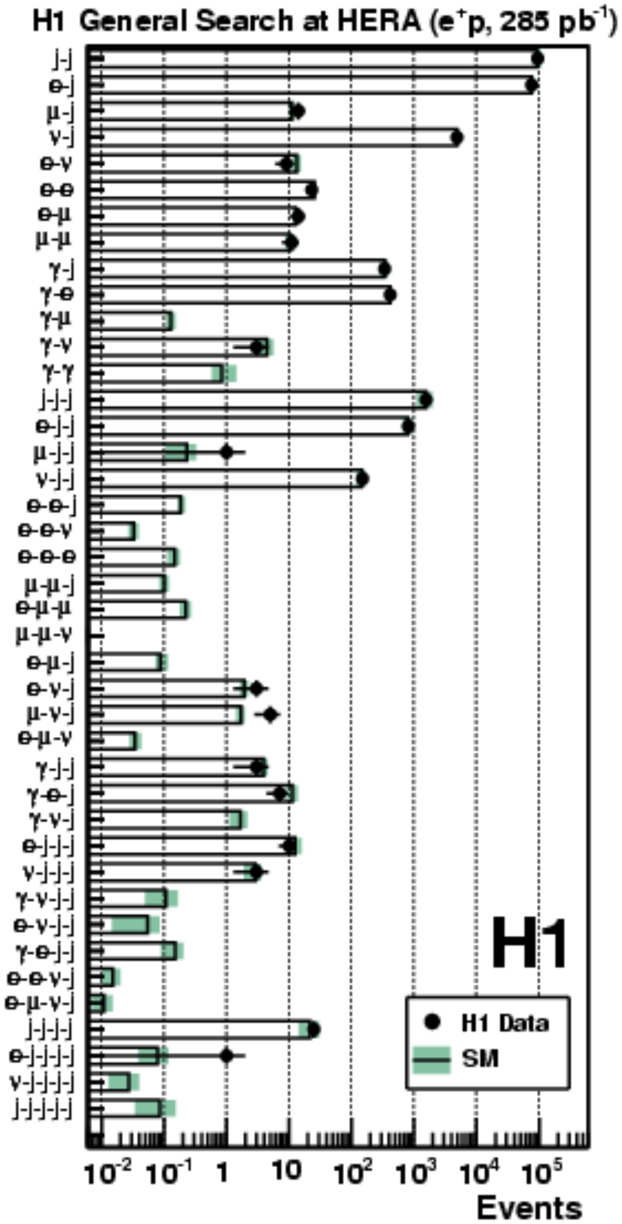


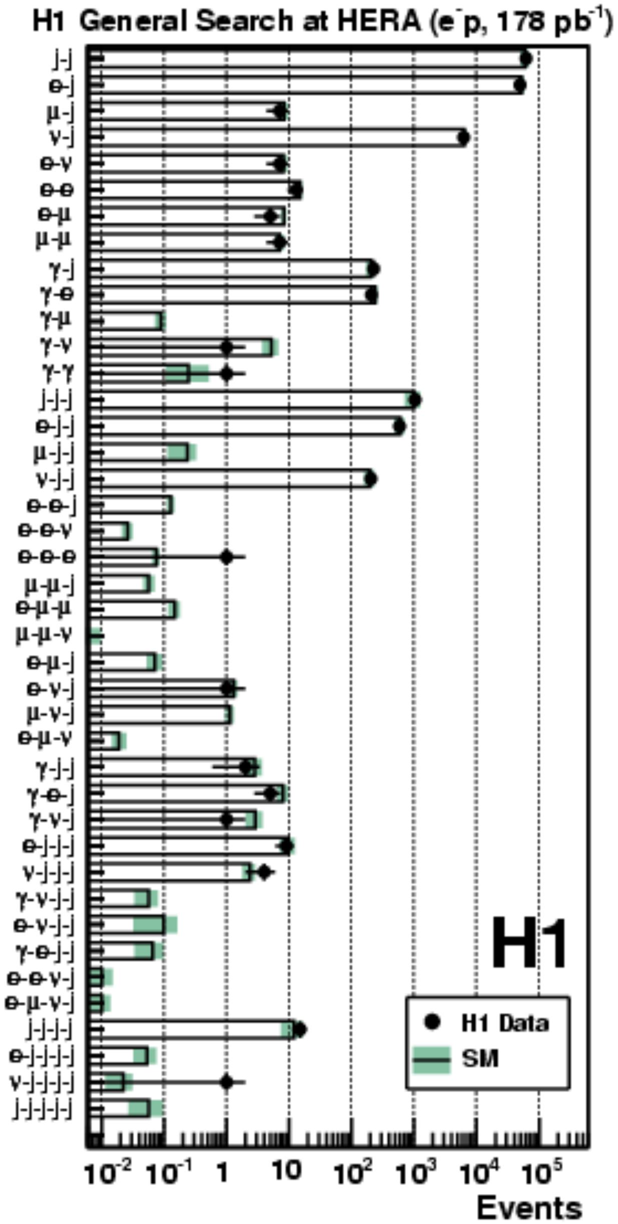
- With θ_n < 1 mrad, similar x_L and p_t ranges to HERA (a bit more p_t lever-arm for π flux).

- Extentions to lower β and higher Q^2 as in leading proton case. → F_2^{π} At $\beta < 5.10^{-5}$ (cf HERA reaches $\beta \sim 10^{-3}$)

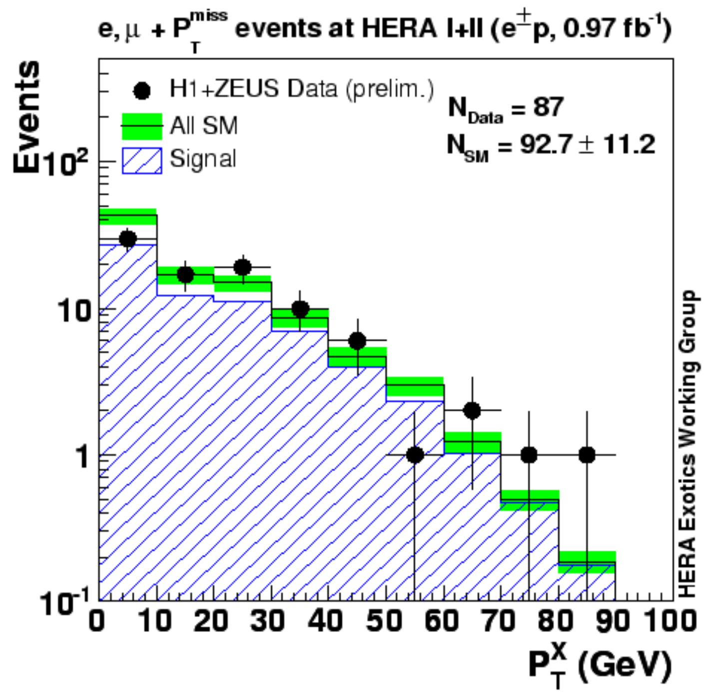
Also relevant to absorptive corrections, cosmic ray physics …

Is HERA Finished? - H1 high pt Summary





... perhaps yes for searches ...



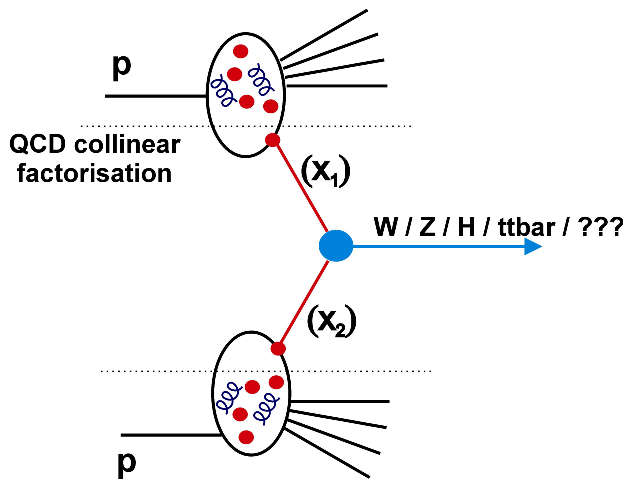
- Detectors and physics processes well understood!

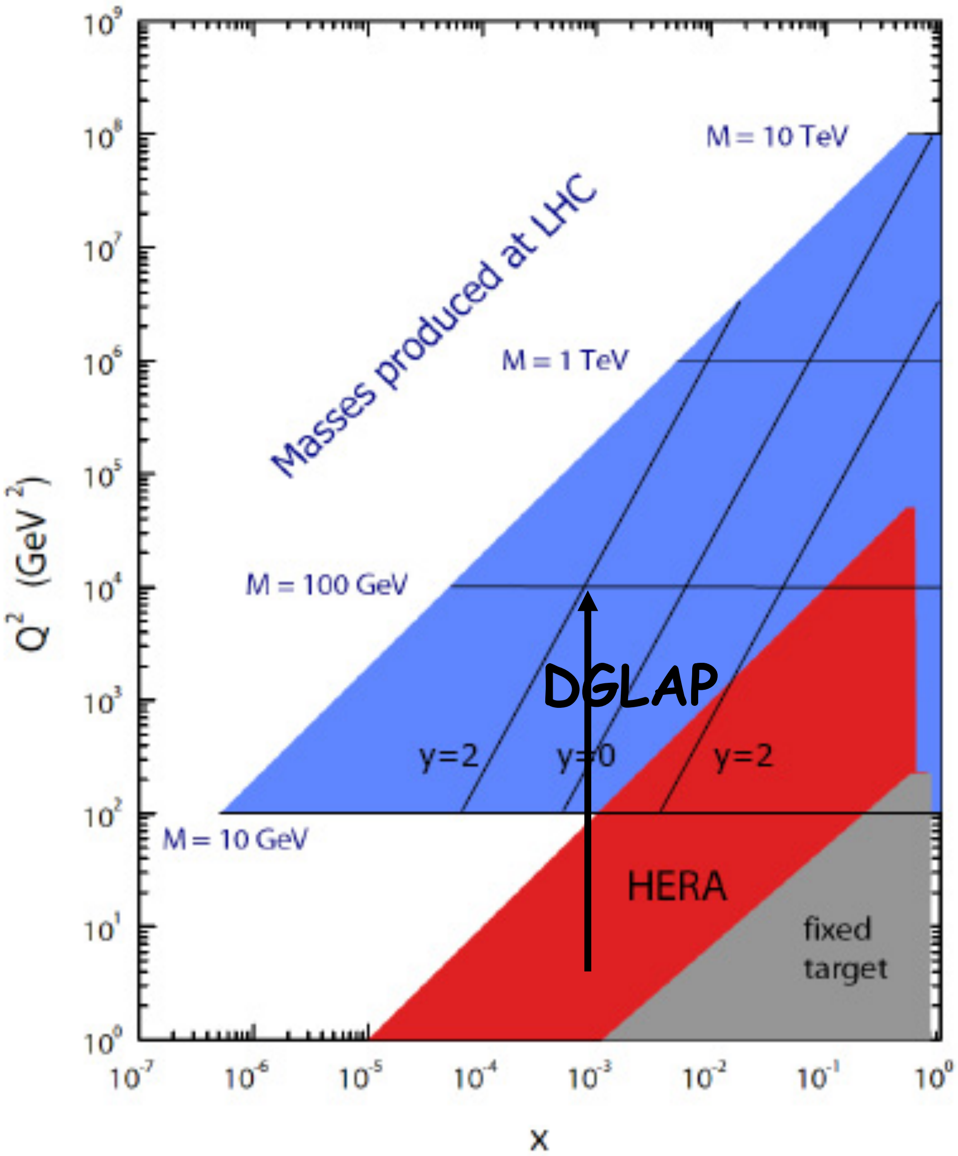
The Standard Model & HERA part as good friends!

HERA Input to LHC

- Unprecedented low x and high Q^2 coverage in DIS

- HERA + **QCD factorisation** → parton densities in full x range of LHC rapidity plateau





- Well established **`DGLAP' evolution** equations generalise to any scale (for not too small x)

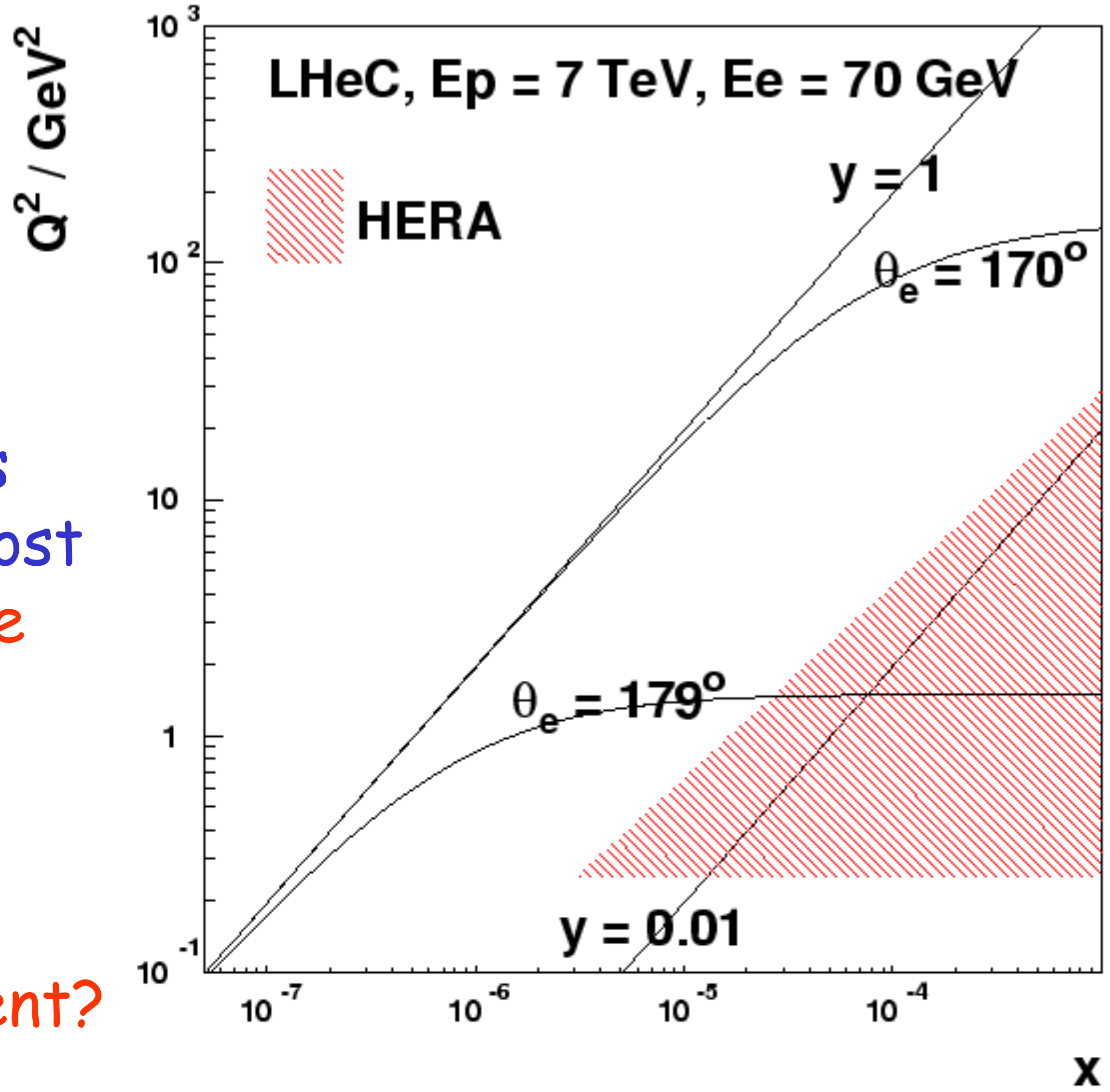
e.g. pp dijets at central rapidity: $x_1=x_2=2p_t / \sqrt{s}$

LHeC Kinematics for Low x Investigations

Access to Q^2=1 GeV^2 in ep mode for all $x > 5 \times 10^{-7}$ IF we have acceptance to 179°

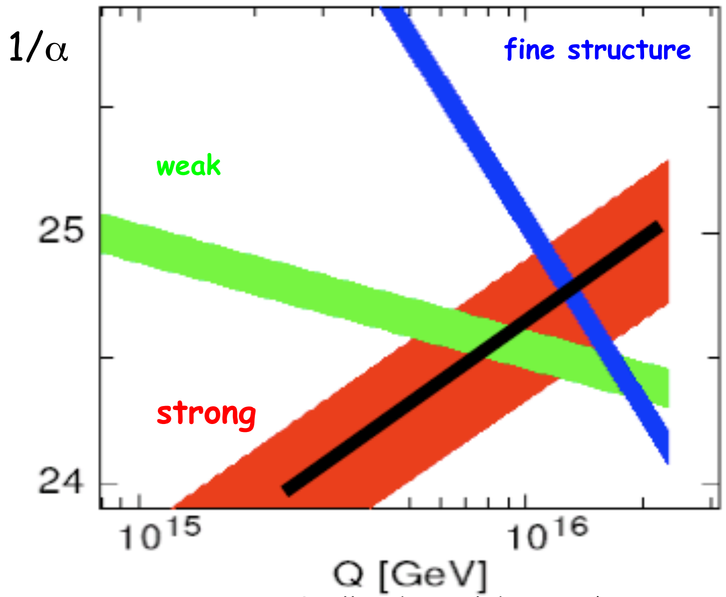
→Without low β magnets ~ 1 fb^{-1} / yr ample for most low x studies … definitive low x facility!

→parton saturation
→novel QCD evolution
→Relations to confinement?
→…



Strong Coupling Constant

Simulation of α_s measurement at LHeC



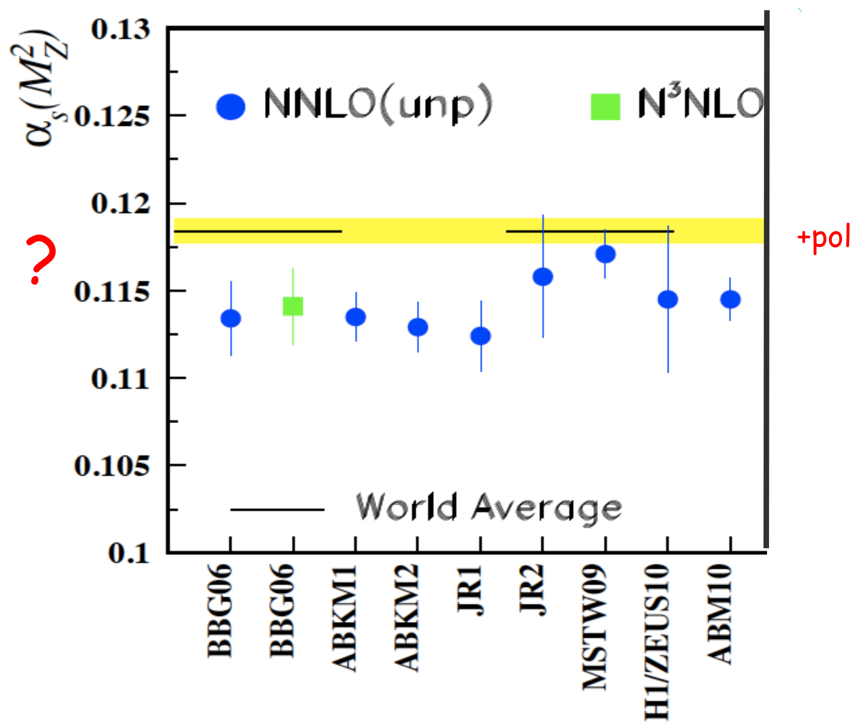
MSSM - B.Allnach et al, hep-ex/0403133

DATA	exp. error on α_s
NC e^+ only	0.48%
NC	0.41%
NC & CC	**0.23% :=(1)**
(1) $\gamma_h > 5°$	0.36% :=(2)
(1) +BCDMS	0.22%
(2) +BCDMS	0.22%
(1) stat. *= 2	0.35%

α_s least known of coupling constants
Grand Unification predictions suffer from $\delta\alpha_s$

DIS tends to be lower than world average

LHeC: per mille accuracy indep. of BCDMS.
Challenge to experiment and to h.o. QCD

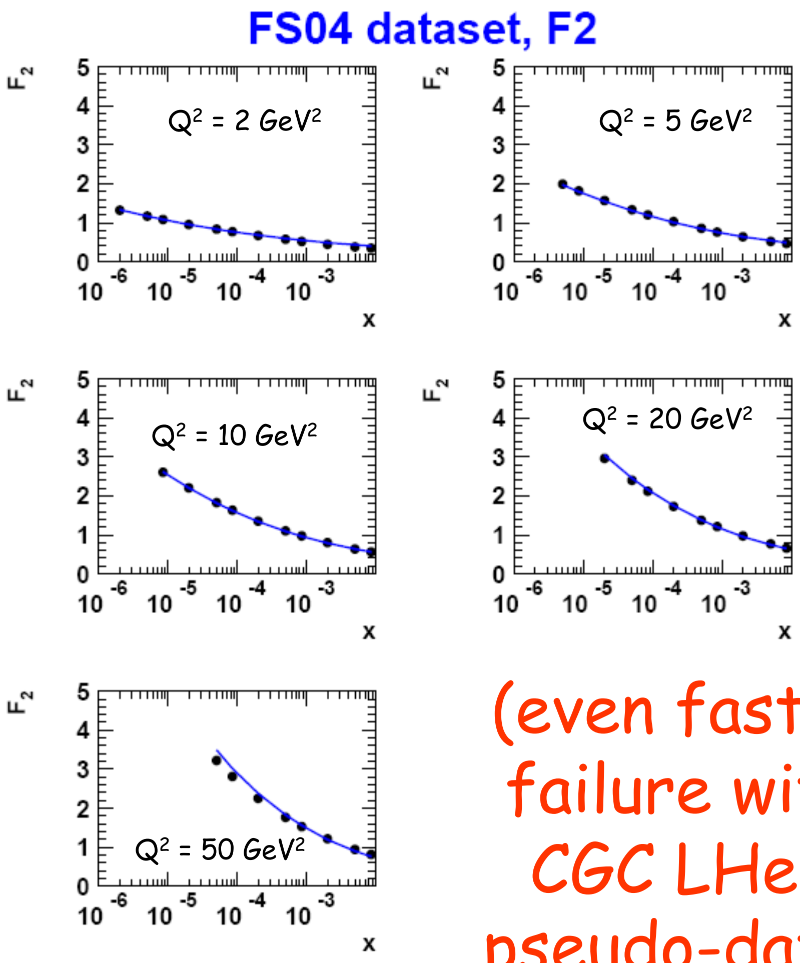


J.Bluemlein and H. Boettcher, arXiv 1005.3013 (2010)

Can DGLAP adjust to fit LHeC sat models?

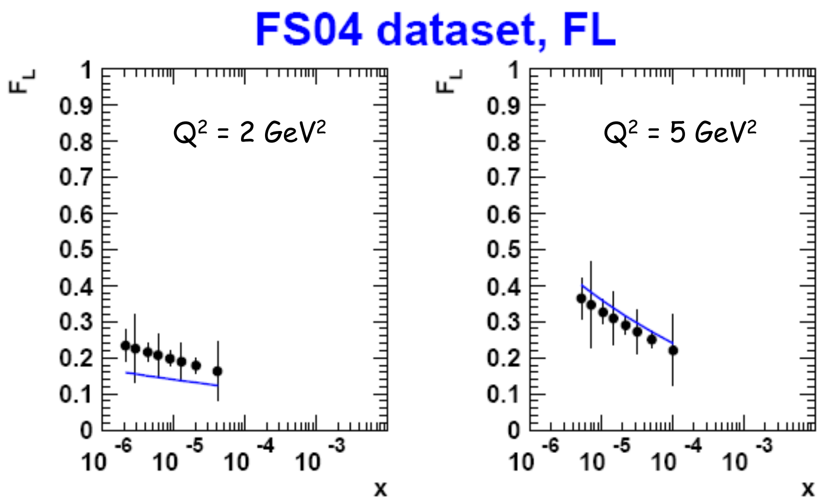
[Forshaw, Klein, PN, Perez]

- Attempt to fit ZEUS and LHeC saturated pseudo-data in increasingly narrow (low) Q^2 region until good fit obtained
- Use dipole-like (GBW) gluon parameterisation at Q_0^2



$$xg(x, Q_0^2) = A_g \left(1 - \exp\left[-B_g \log^2\left(\frac{x}{x_0}\right)^{\lambda} \right] \right) (1-x)^{C_g}$$

- Fitting F_2 only, a good fit cannot be obtained beyond the range $2 < Q^2 < 20$ GeV^2
- This fit fails to describe F_L



(even faster failure with CGC LHeC pseudo-data)

A high x Detector Acceptance Consideration

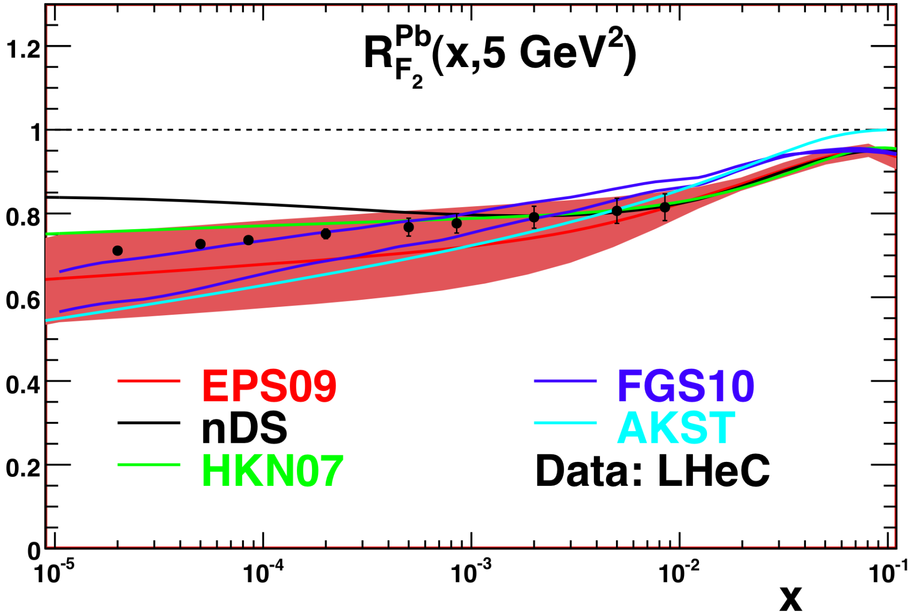
HERA	E_e=30GeV	E_p=920GeV
	→	←
LHeC	E_e=70GeV	E_p=7000GeV

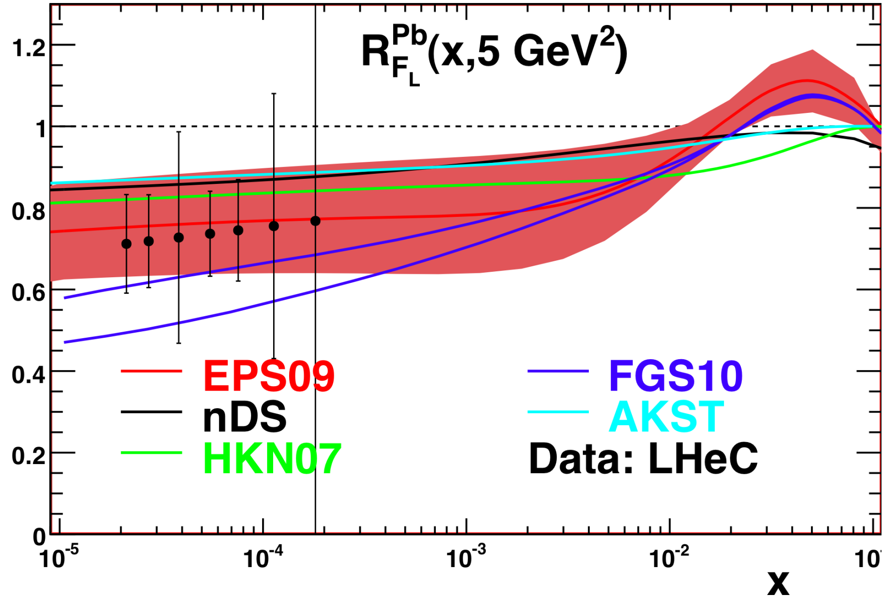
- Considerably more asymmetric beam energies than HERA!
  - Hadronic final state at newly accessed lowest x values goes central or backward in the detector ☺
  - As x grows at fixed Q^2, hadronic final state is boosted more and more in the forward direction … and hadrons are needed for good kinematic reconstruction as x gets large & electron method resolution deteriorates

- Ideally need sensitivity to energy flow in outgoing proton direction <u>for hadrons to ~1°</u>

2.2 ctd) eA models compared with pseudodata

[Armesto, Tywoniuk … in progress]





EPS09 bands reasonable estimates, but no direct constraints

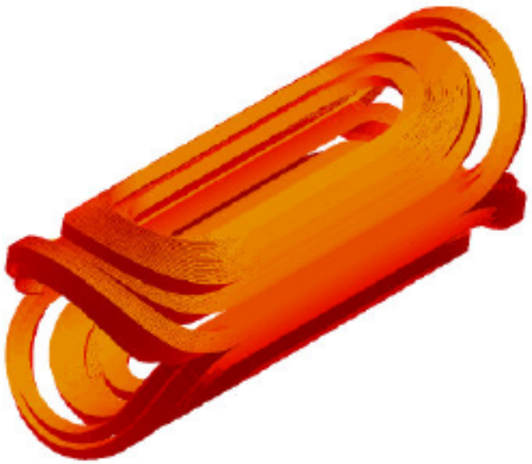
LHeC pseudodata show F_2 would give a first real and strong constraint on nuclear F_2 ratio At low x

F_L data also studied

Developing a Combined Function "Magcal"?

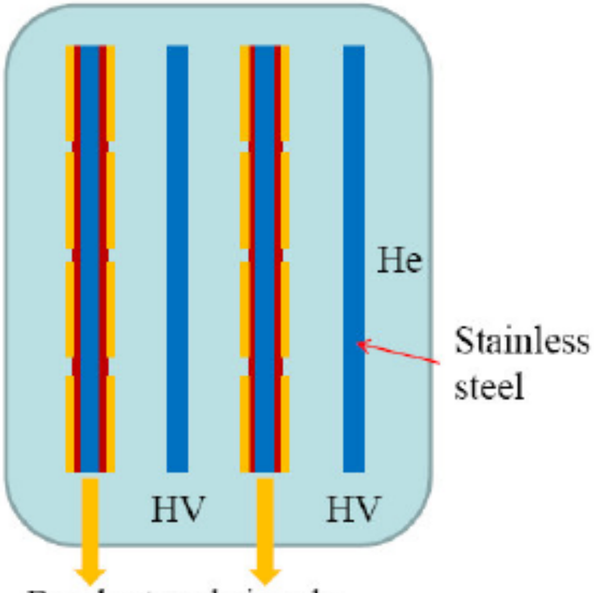
[Greenshaw]

- Helium cooled SC magnet.
- Coils in He bath.



- Space for calorimeter using He as active component?

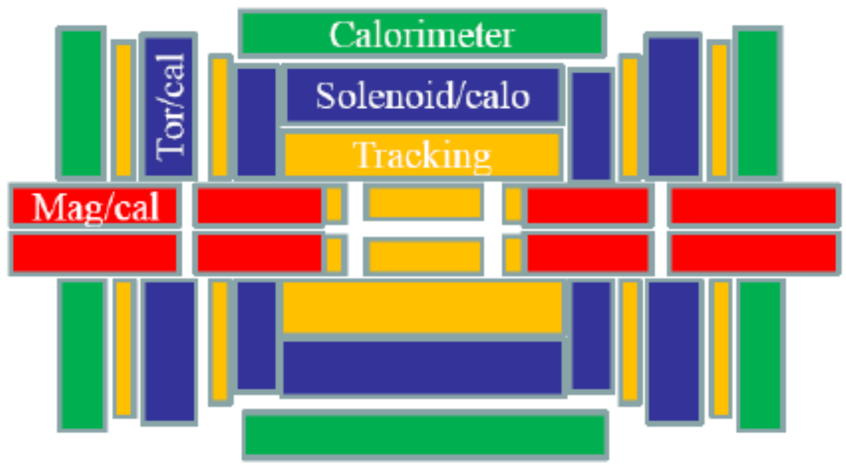
- Could add stainless steel plates as absorber with readout pads:



Use scintilation of liquid He to get signal?…
… Calo is all edges!…
→ What sort of resolution is achievable?
→What is influence on final beam focus?
→ …?

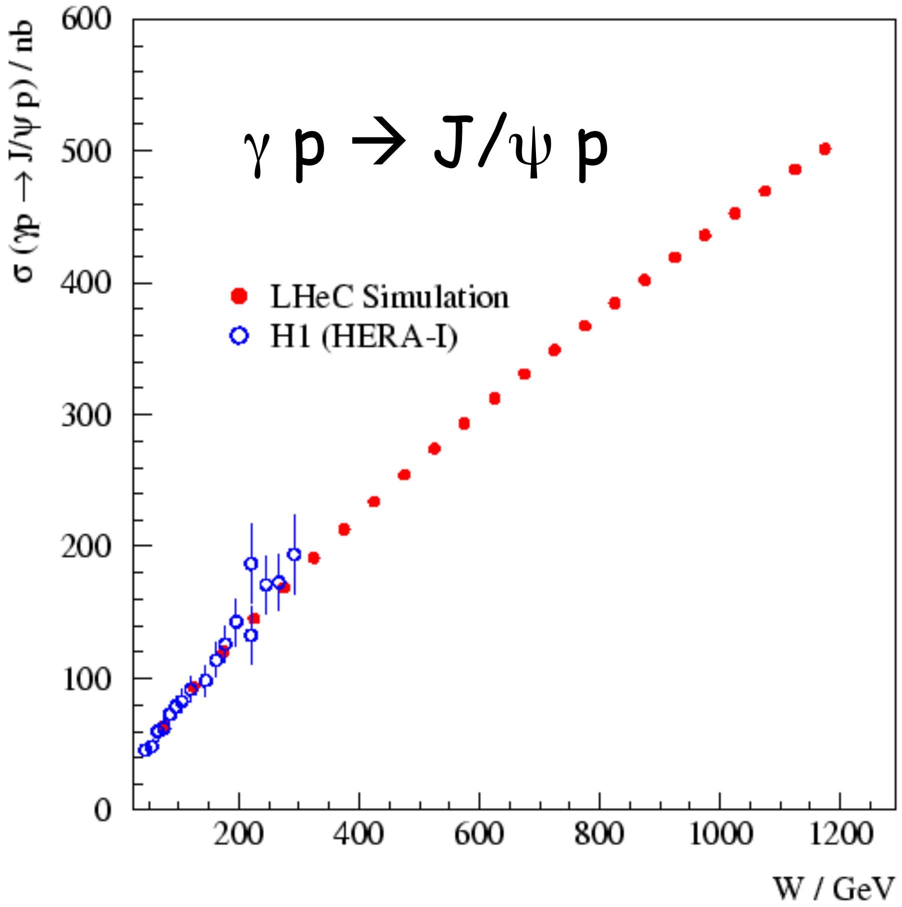
… also potentially interesting for medical physics and elsewhere?

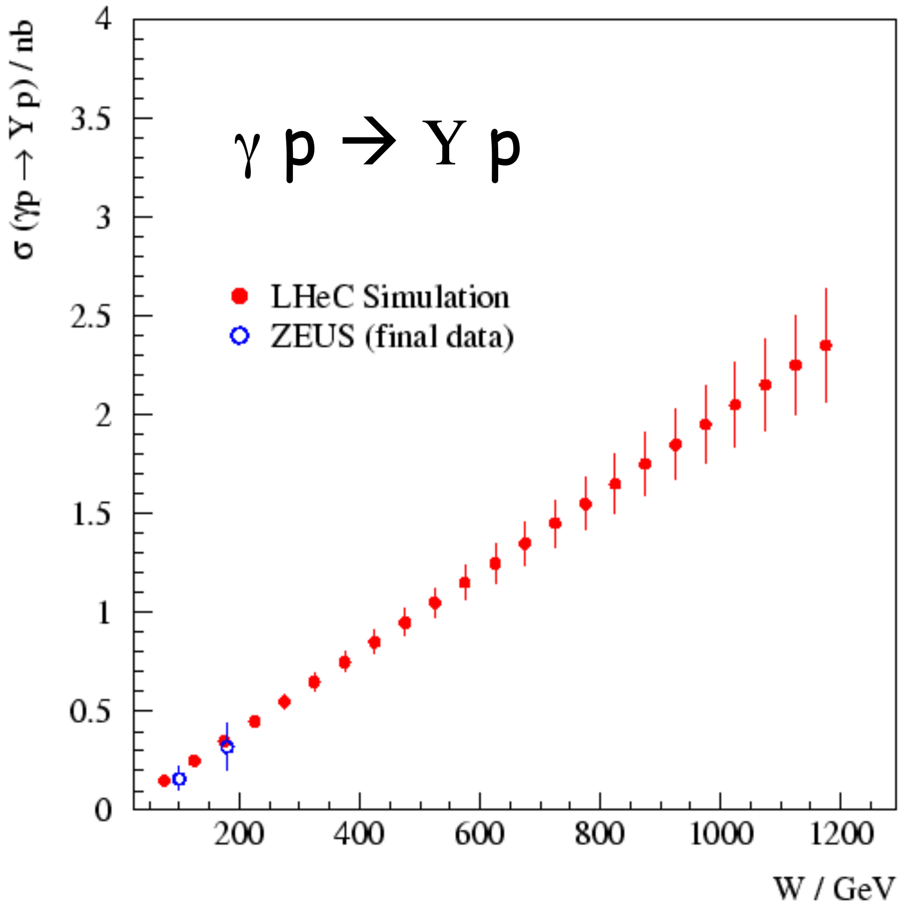
… could even think of doing the same with solenoids / toroids?



LHeC J/ψ & Υ Photoproduction Simulation

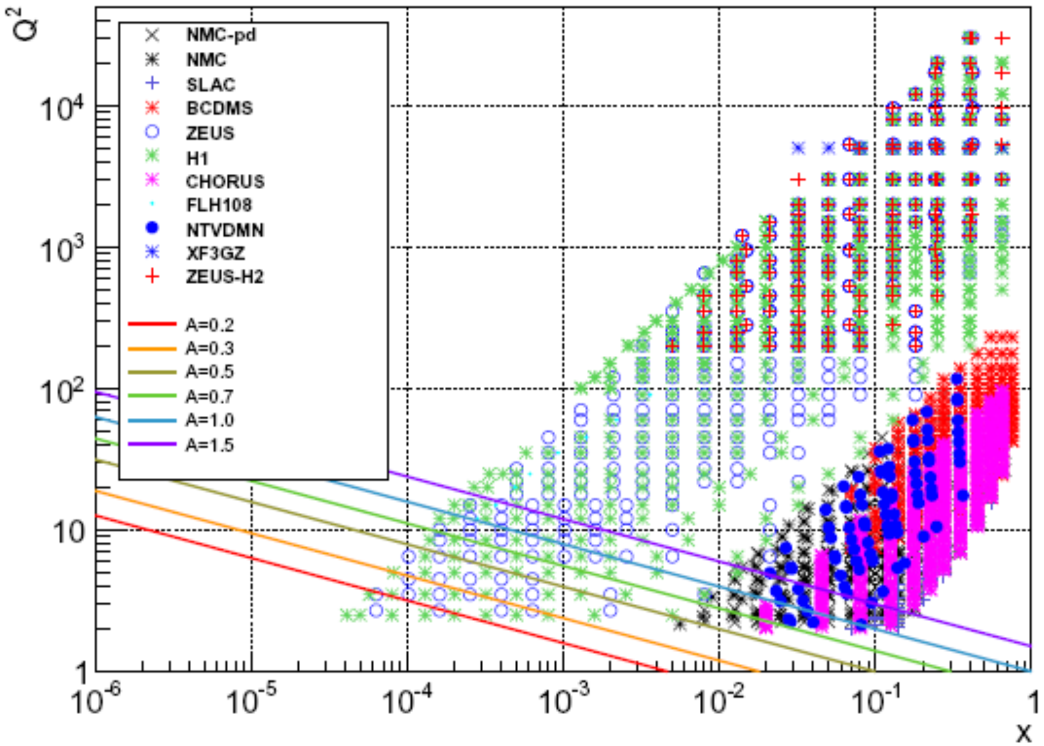
- Simulated data with heavy vector meson decays to μμ.
- Detector acceptance to within 1° of beampipe,
- Lumi = 2 fb^{-1} (2 years) E_e = 50 GeV

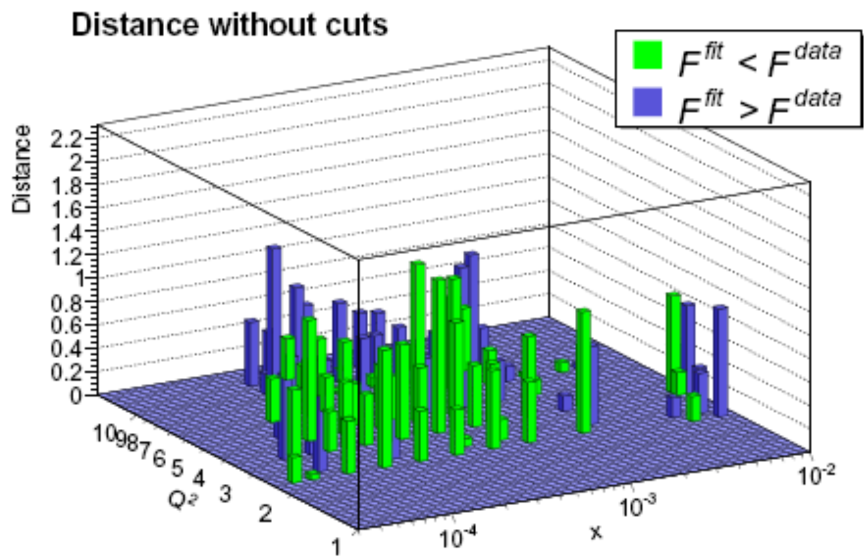




Precise measurements (even for Υ) well into sensitive region

e.g. NNPDF study of low Q^2 NLO DGLAP





- Fit HERA data in limited regions above lines of $Q^2 > Ax^{-0.3}$
  → backwards evolve to lower scales and compare χ^2
- Signed pulls show backward evolution consistently above data

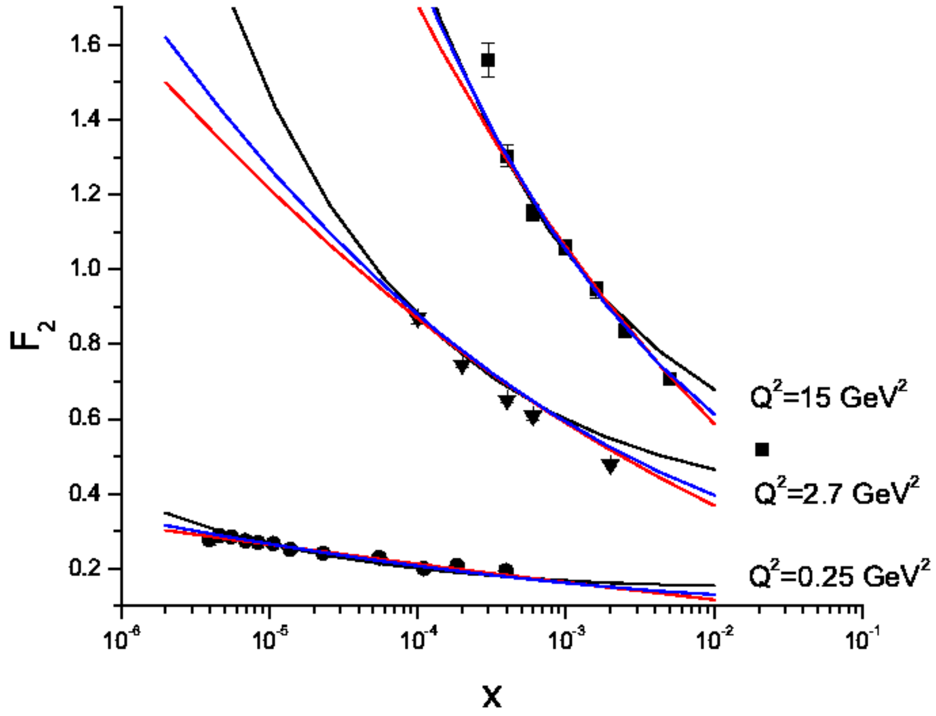
… something happens, but not easily interpreted …

A	$\chi^2_{\text{without cuts}}/d.o.f.$	$\chi^2_{\text{cut}}/d.o.f$
0.5	19.68/25 = 0.79	106.22/25 = 4.25
1.0	54.41/44 = 1.24	138.24/44 = 3.14
1.5	62.31/59 = 1.06	860.65/59 = 14.6

Parton Saturation after HERA?

e.g. Forshaw, Sandapen, Shaw
hep-ph/0411337,0608161
… used for illustrations here

Fit inclusive HERA data
using dipole models
with and without parton
saturation effects



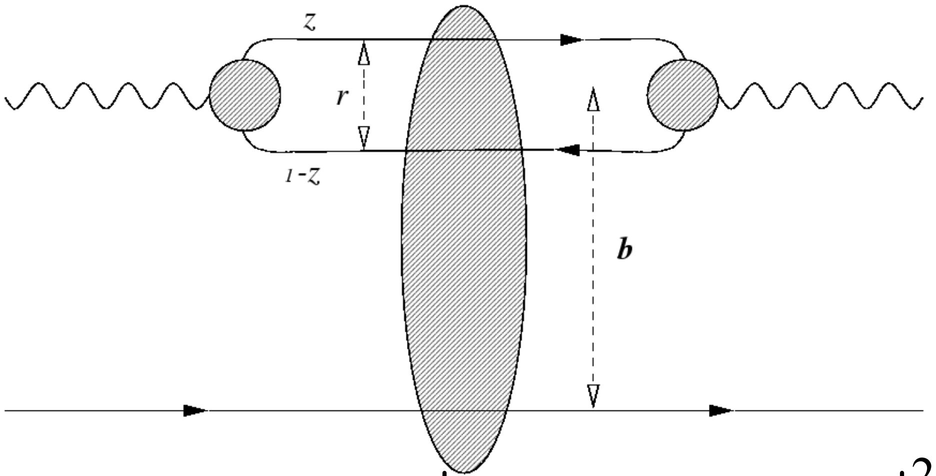
FS04 Regge (~FKS): 2 pomeron model, <u>no saturation</u>
FS04 Satn: <u>Simple implementation of saturation</u>
CGC: <u>Colour Glass Condensate version of saturation</u>

- All three models can describe data with $Q^2 > 1 GeV^2$, $x < 0.01$
- Only versions with saturation work for $0.045 < Q^2 < 1$ GeV^2

<u>… any saturation at HERA not easily interpreted partonically</u>

Reminder : Dipole models

• Unified description of low x region, including region where Q^2 small and partons not appropriate degrees of freedom …



$$\sigma_{\gamma^* p}^{T,L}(x,Q^2) \sim \int dz\, d^2r\, \left|\psi_{\gamma^*}^{T,L}(z,r,Q^2)\right|^2 \sigma_{dipole}(x,r,z)$$

• Simple unified picture of many inclusive and exclusive processes … strong interaction physics in (universal) dipole cross section σ_{dipole}. Process dependence in wavefunction Ψ Factors

• qqbar-g dipoles also needed to describe inclusive diffraction

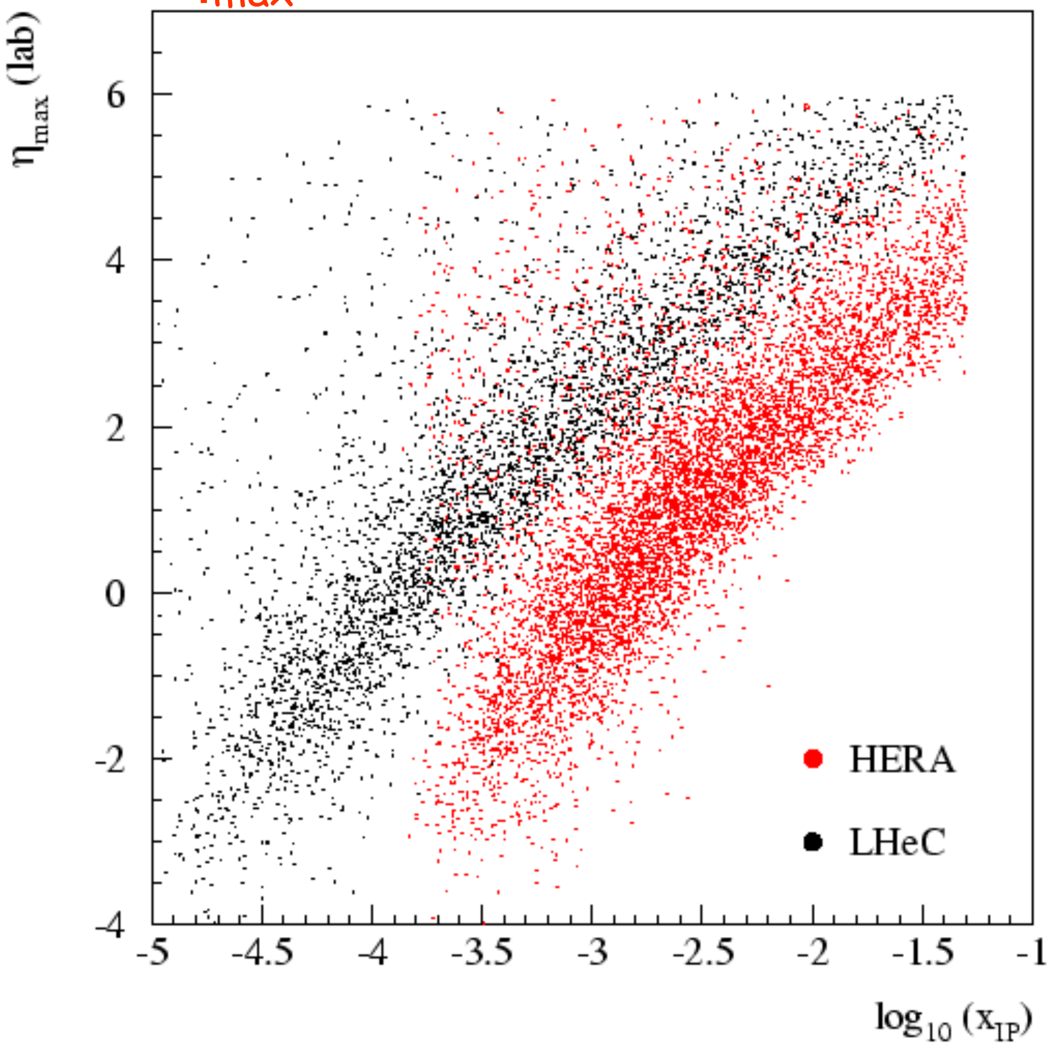
Forward and Diffractive Detectors

- Very forward tracking / calorimetry with good resolution …
- Proton and neutron spectrometers …

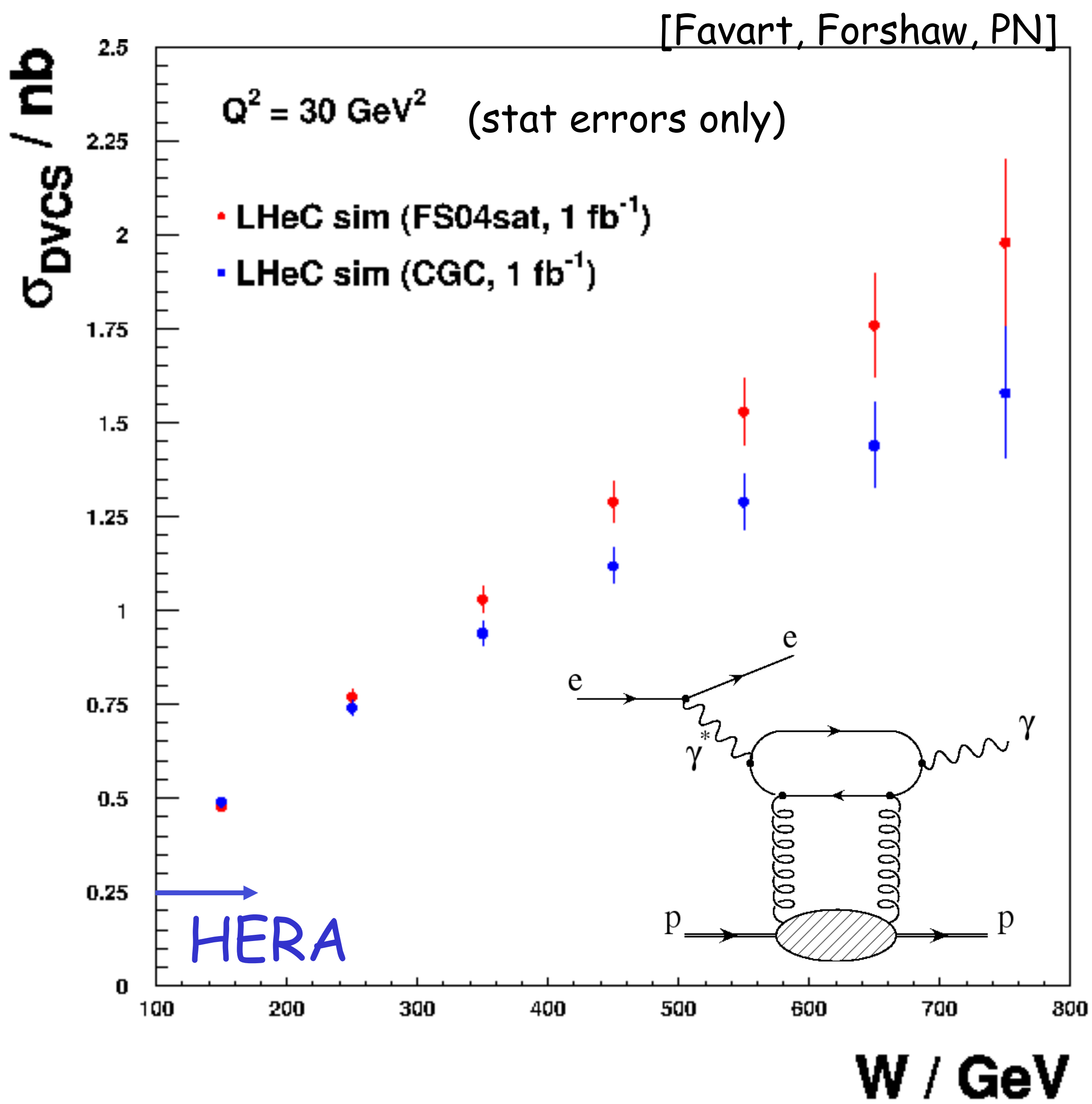
- Reaching $x_{IP} = 1 - E_p'/E_p = 0.01$ in diffraction with rapidity gap method requires η_{max} cut around 5 …forward instrumentation essential!

- Roman pots, FNC should clearly be an integral part.
  - Also for t measurements
  - Not new at LHC ☺
  - Being considered integrally with interaction region

η_{max} from LRG selection …



DVCS at LHeC



(1^o acceptance)

Statistical precision with $1fb^{-1}$ ~ 2-11%

With F_2, F_L, DVCS could help establish saturation and distinguish between different models which contain it?

Cleaner interpretation in terms of GPDs at larger LHeC Q^2 values