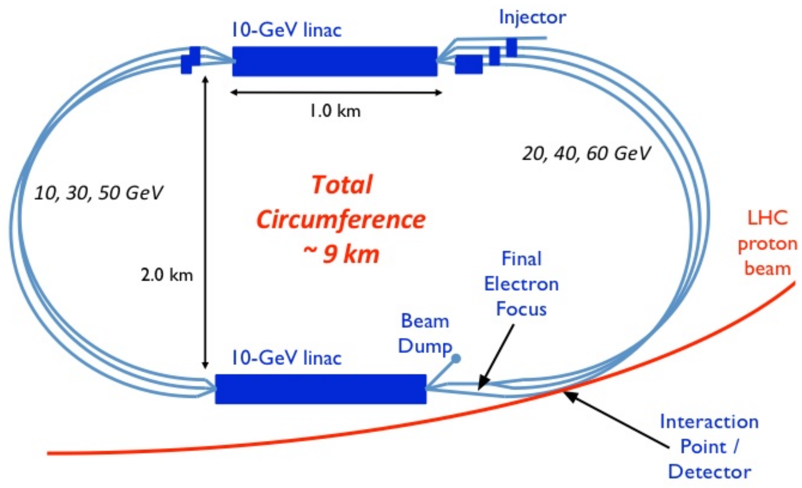
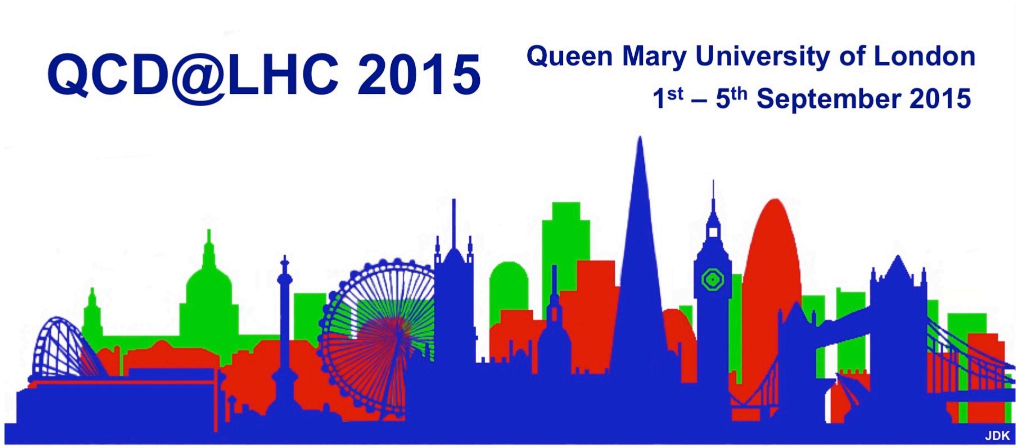
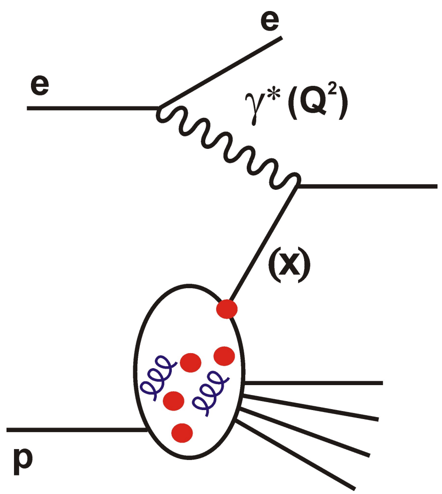
QCD @ LHeC

Paul Newman
Birmingham University

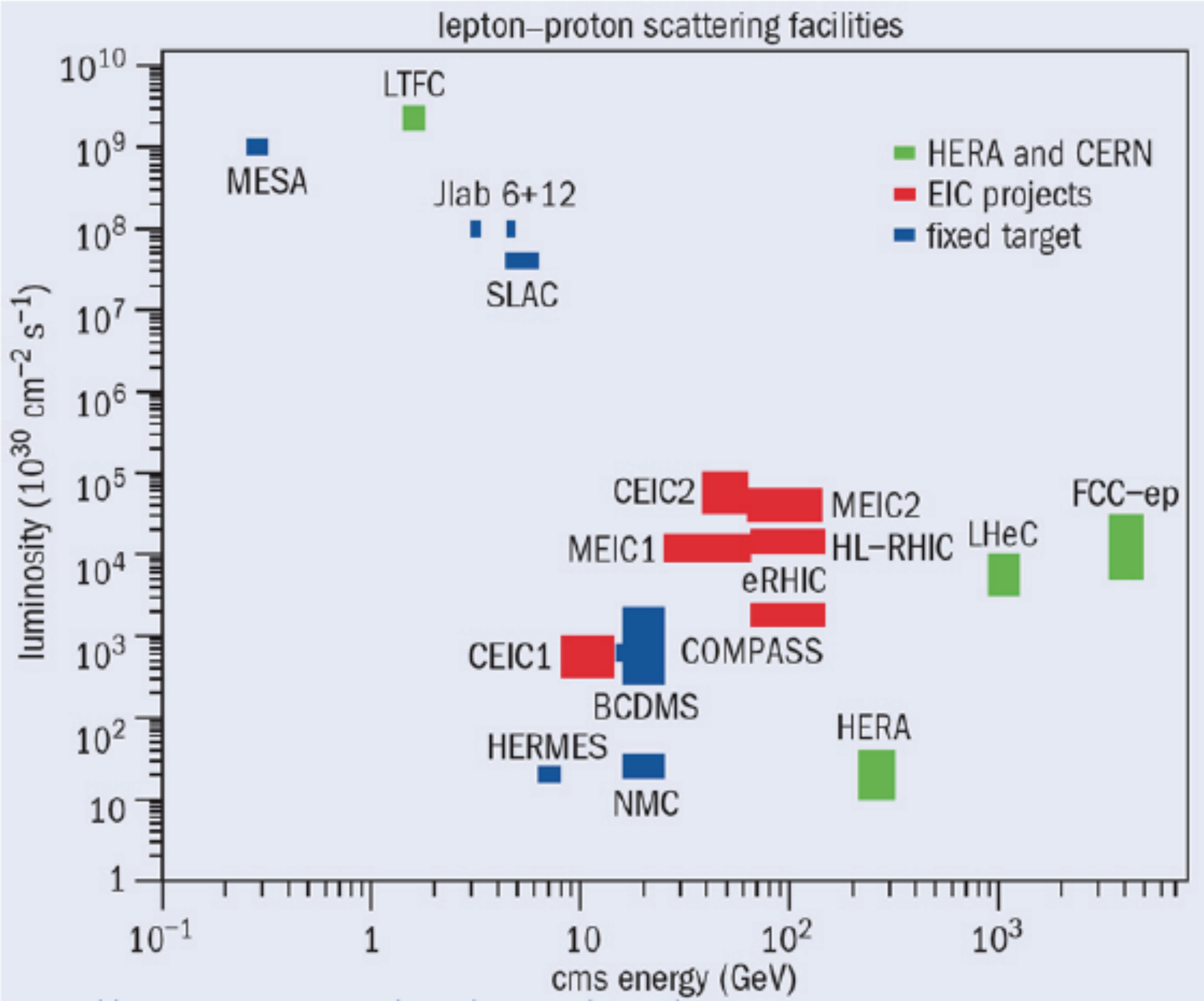


- *Lepton-hadron collider based on the high lumi LHC*
- *Can we add ep and eA collisions to the existing LHC pp, AA and pA programme?*





LHeC / FCC-he Context



LHeC CDR, July 2012 [arXiv:1206.2913]
CERN Courier, June 2014

Lepton-hadron scattering at the TeV scale …

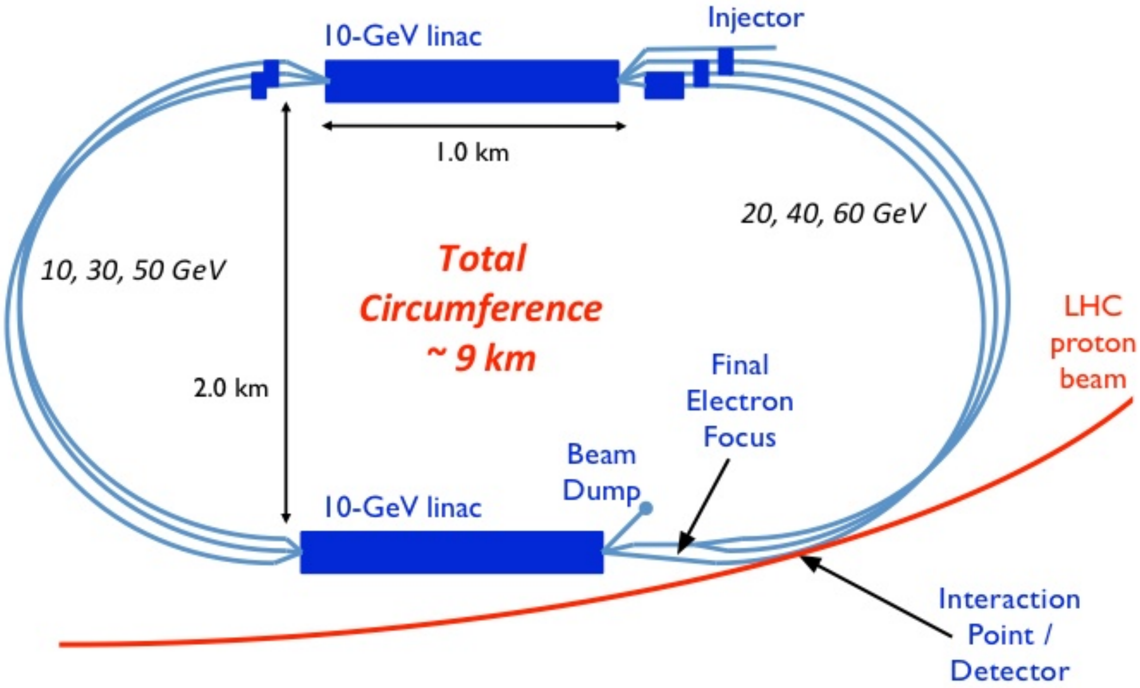
LHeC: 60 GeV electrons x LHC protons & ions
→ 10^{34} cm^{-2} s^{-1}
→ Simultaneous running with ATLAS / CMS sometime in HL-LHC period

FCC-he: 60 GeV electrons x 50 TeV protons from FCC

Baseline# Design (Electron "Linac")

Design constraint: power consumption < 100 MW → E_e = 60 GeV

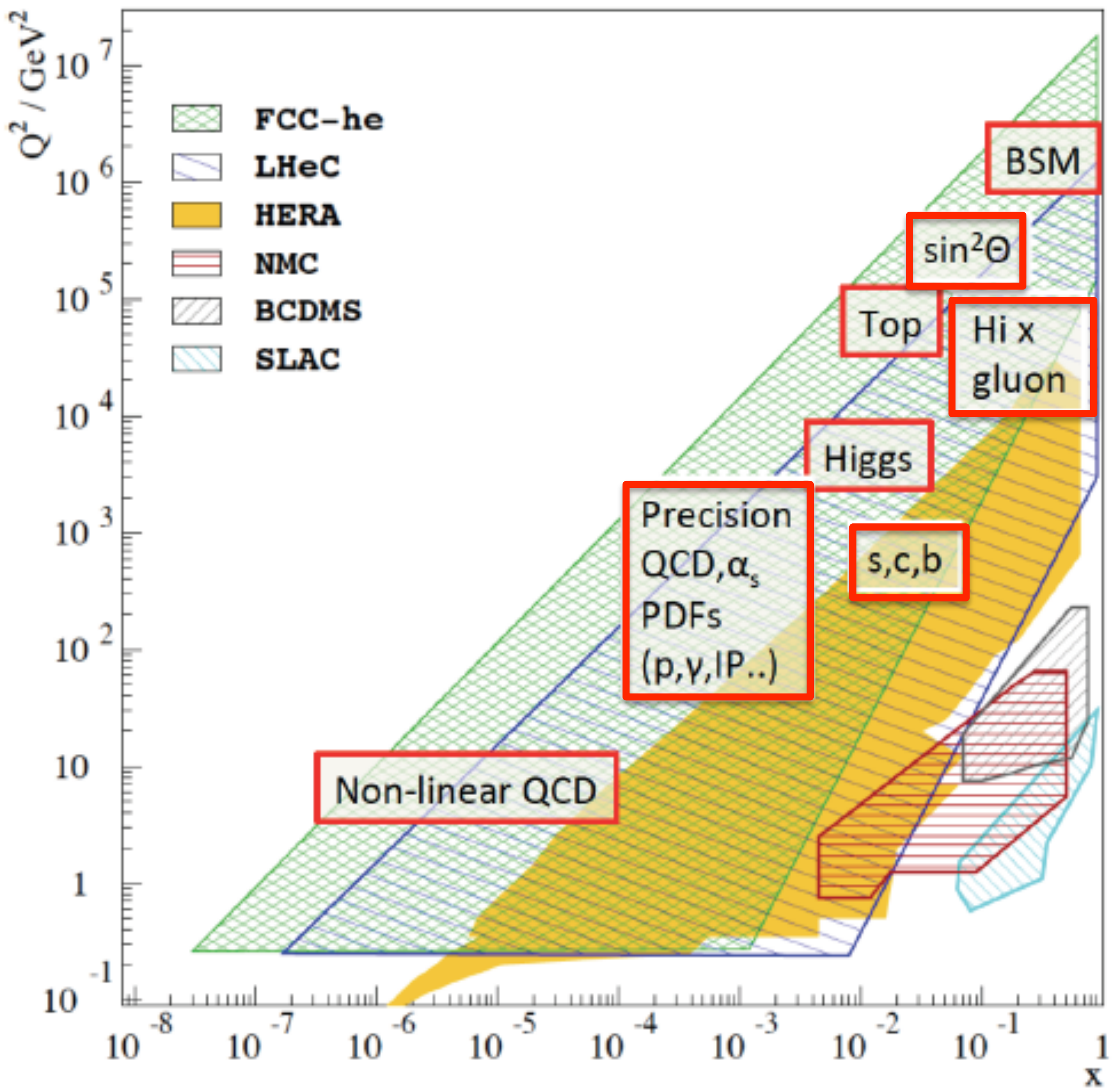
- Two 10 GeV linacs,
- 3 returns, 20 MV/m
- Energy recovery in same structures [CERN plans energy recovery prototype]

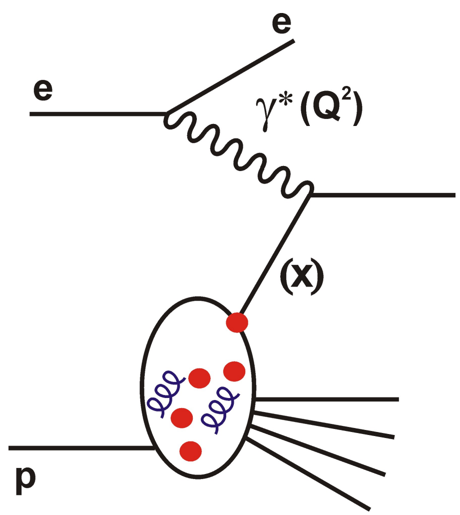


- ep lumi → 10^{34} cm^{-2} s^{-1}
→ ~100 fb^{-1} per year →~1 ab^{-1} total
- **eD and eA collisions have always been integral to programme**
- **e-nucleon Lumi estimates ~ 10^{31} (10^{32}) cm^{-2} s^{-1} for eD (ePb)**

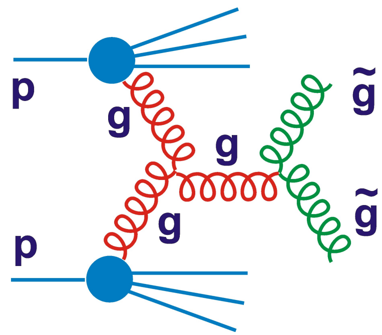
Alternative designs based on electron ring and on higher energy, lower luminosity, linac also exist

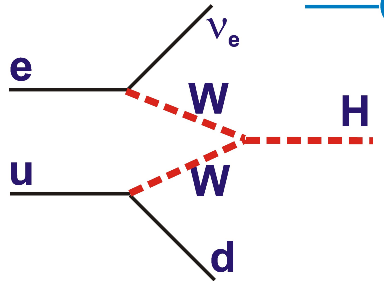
Physics Overview





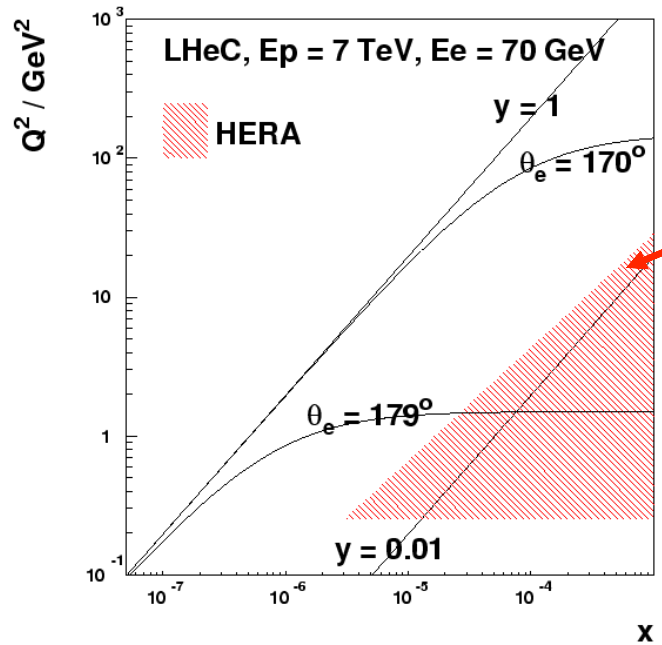
Diverse physics goals require precision throughout wide accessible kinematic region.

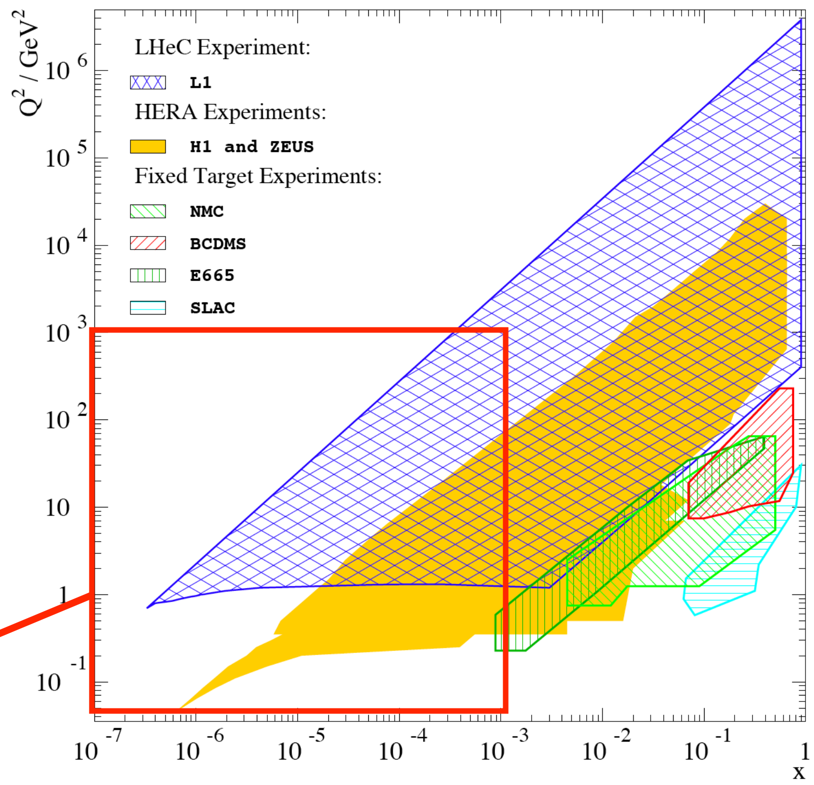


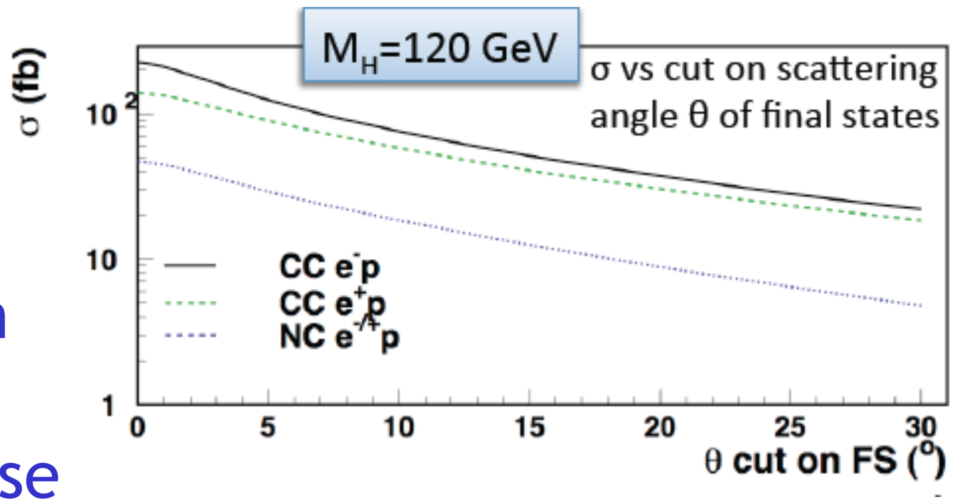


LHeC Kinematic Detector Requirements

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

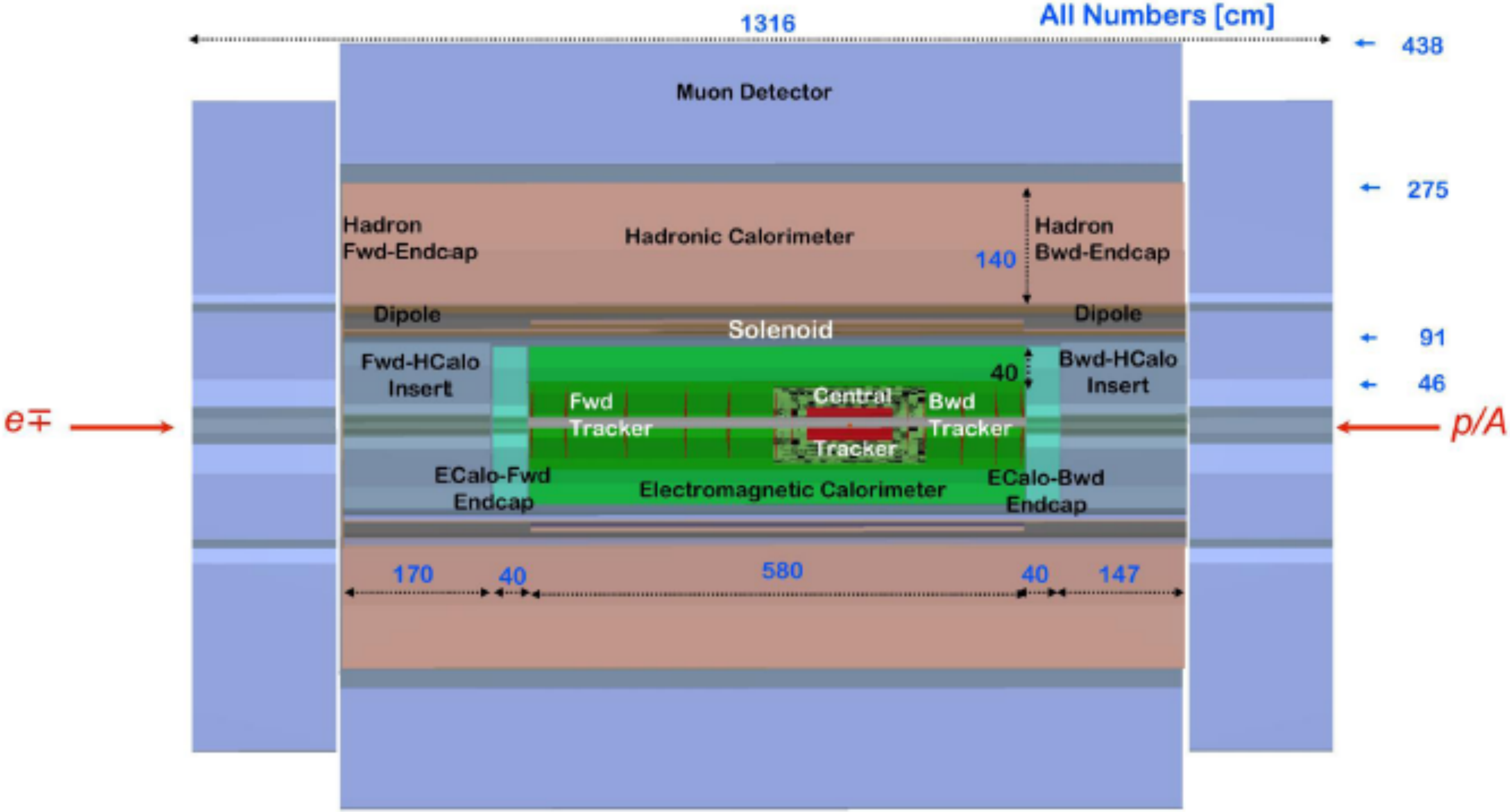






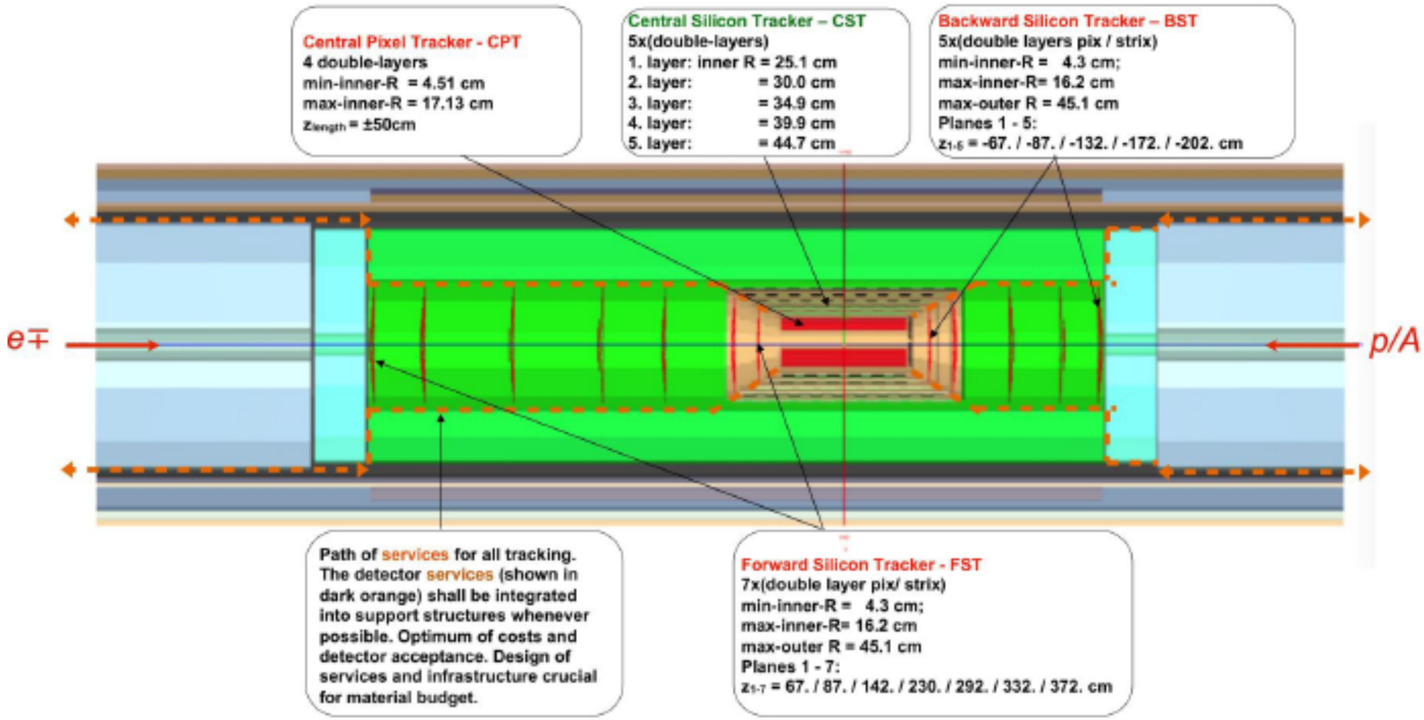
Also need 1° acceptance in proton direction to contain hadrons for kinematic reconstruction, maximise acceptance for H, new massive particles, Mueller-Navelet jets …

Detector Design Overview



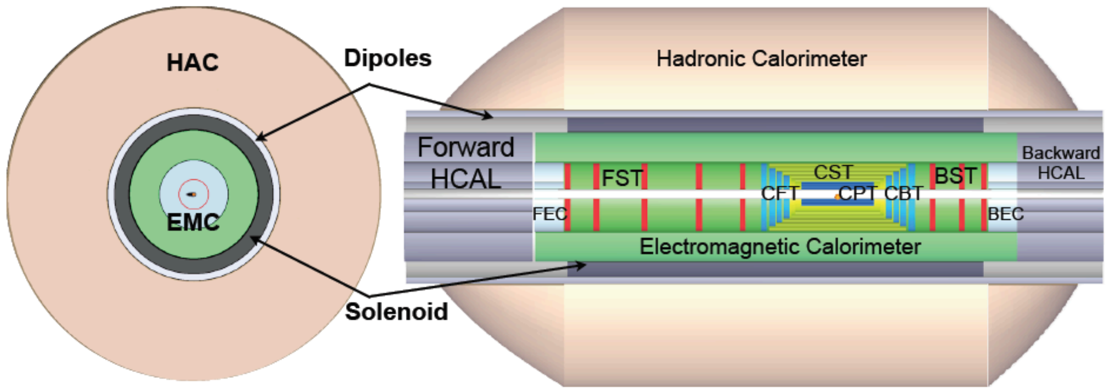
- Present size 13m x 9m (c.f. CMS 21m x 15m, ATLAS 45m x 25m)
- Forward / backward asymmetry reflecting beam energies
- Demanding tracking → high fraction of pixels, wide acceptance

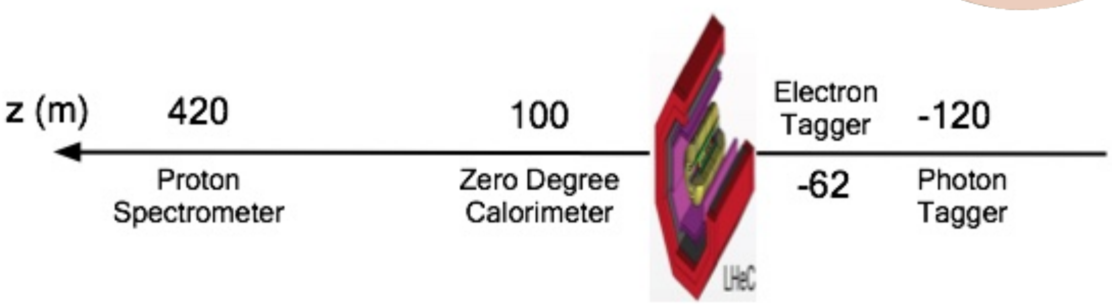
Detector Details



- Long tracking region (pixels + strips) → 1º electron hits 2 tracker planes

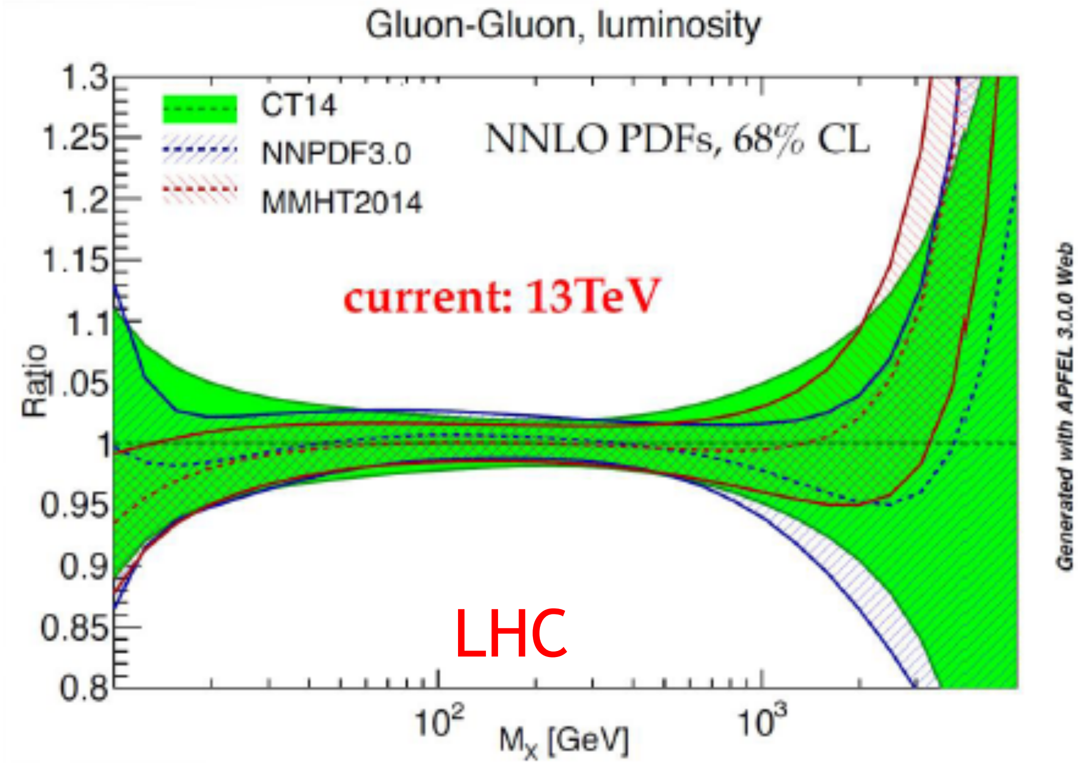
- Lar / Tile calorimeter leaning heavily on LHC experience



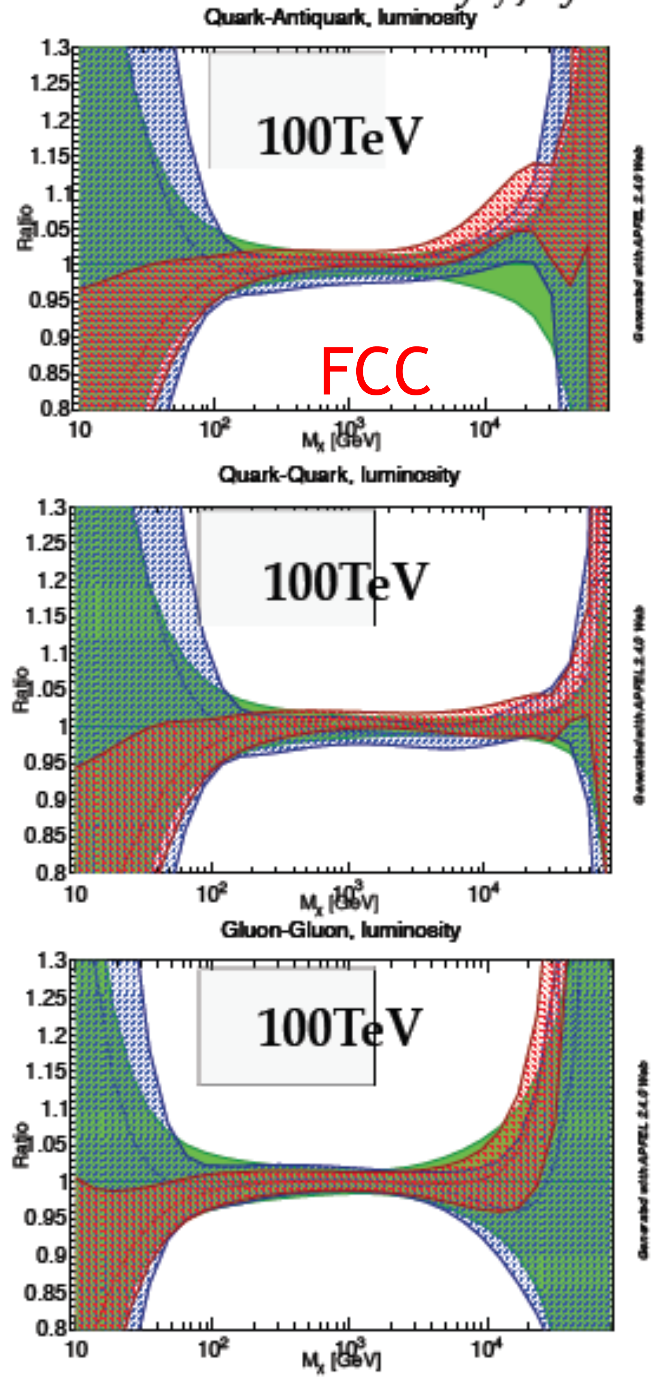


- Beamline insrumentation considered from outset.

Current PDF Uncertainties



Courtesy of Joey Huston



Low x / M_x → novel QCD / unitarity

Medium x / M_x → precision H and EW

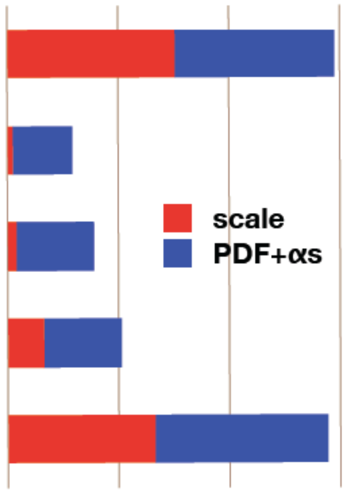
High x / M_x → new particle mass frontier

Should we care? PDF Unc's for LHC Higgs

Theory Cross Section Uncertainties

(125 GeV Higgs
J Campbell, ICHEP'12)

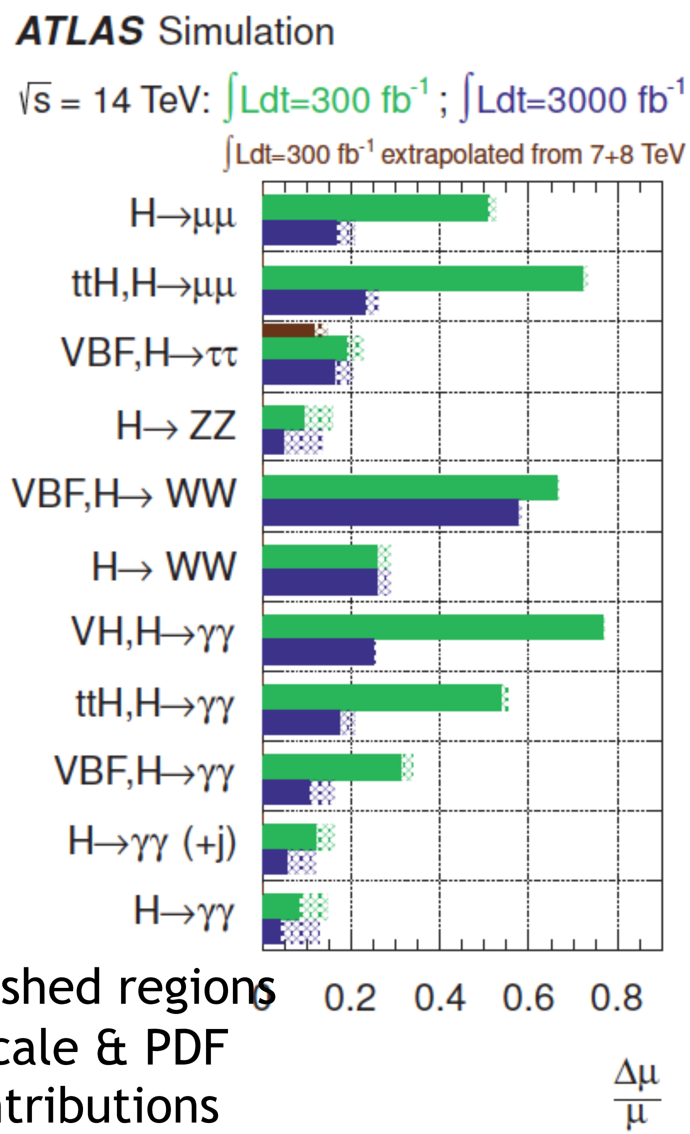
	Process	σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
	VBF	1.56 pb	2.9%
NNLO QCD +NLO EW	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%



Similarly fermionic modes (bbbar, ccbar)

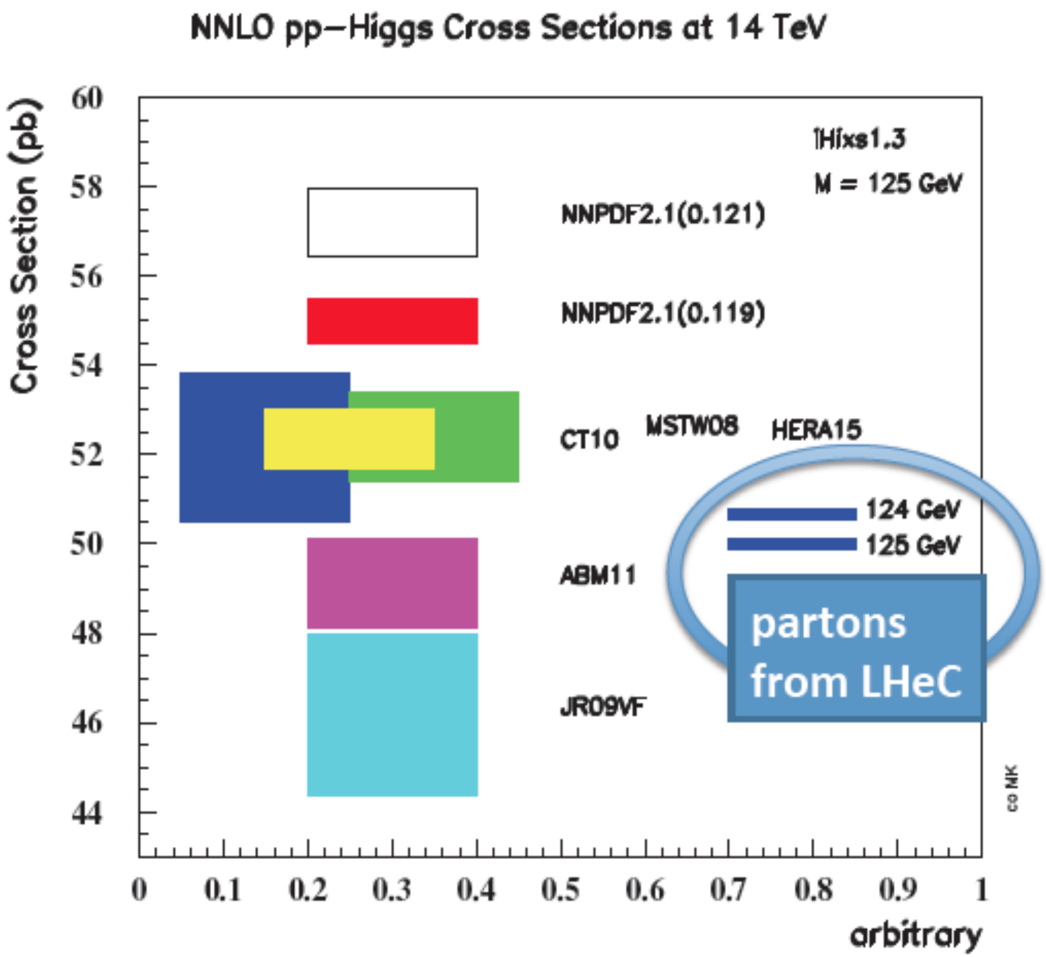
... tests of Standard Model in Higgs sector become limited by knowledge of PDFs in HL-LHC era

Projected Experimental Uncertainties



[Dashed regions = scale & PDF contributions

LHeC Impact on LHC Higgs PDF Unc'ty



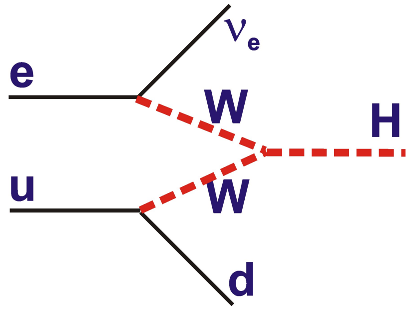
... needs N^{3}LO Higgs calculation

... needs improved α_s measurement (also @ LHeC)

c.f. experimental uncertainty of 0.25%

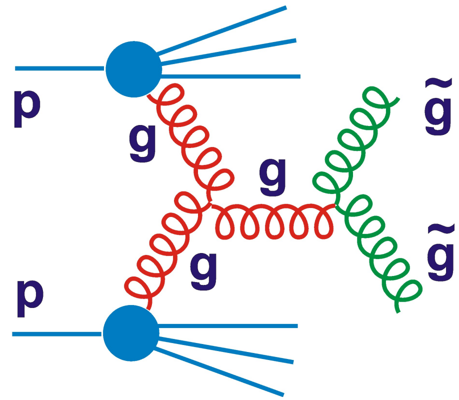
Aside:

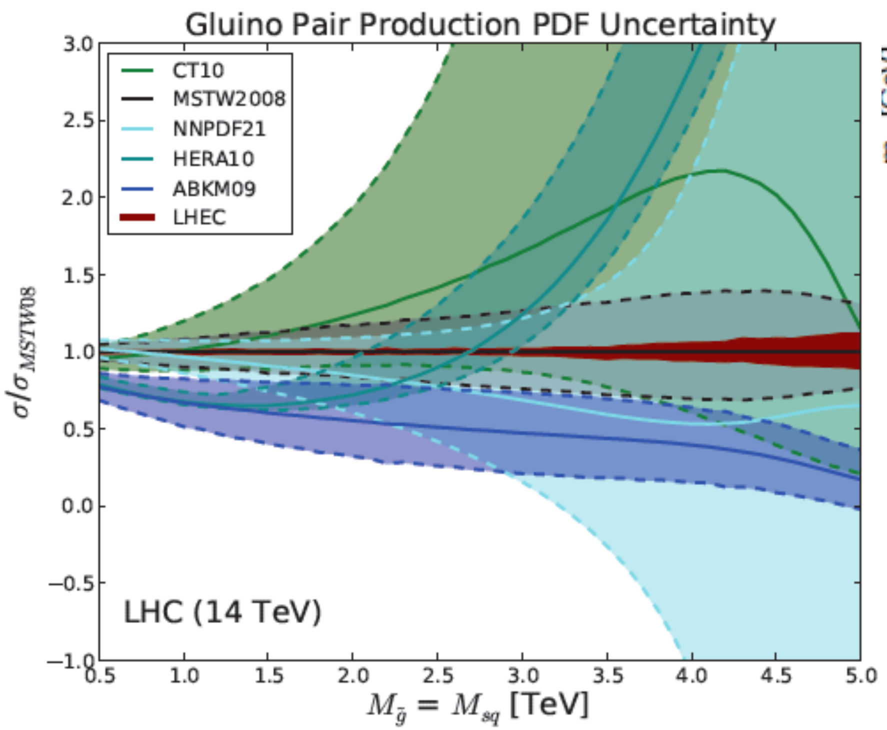
LHeC at 10^{34} cm^{-2}s^{-1} is also a significant Higgs factory, offering e.g. ~1% H→bbbar coupling,

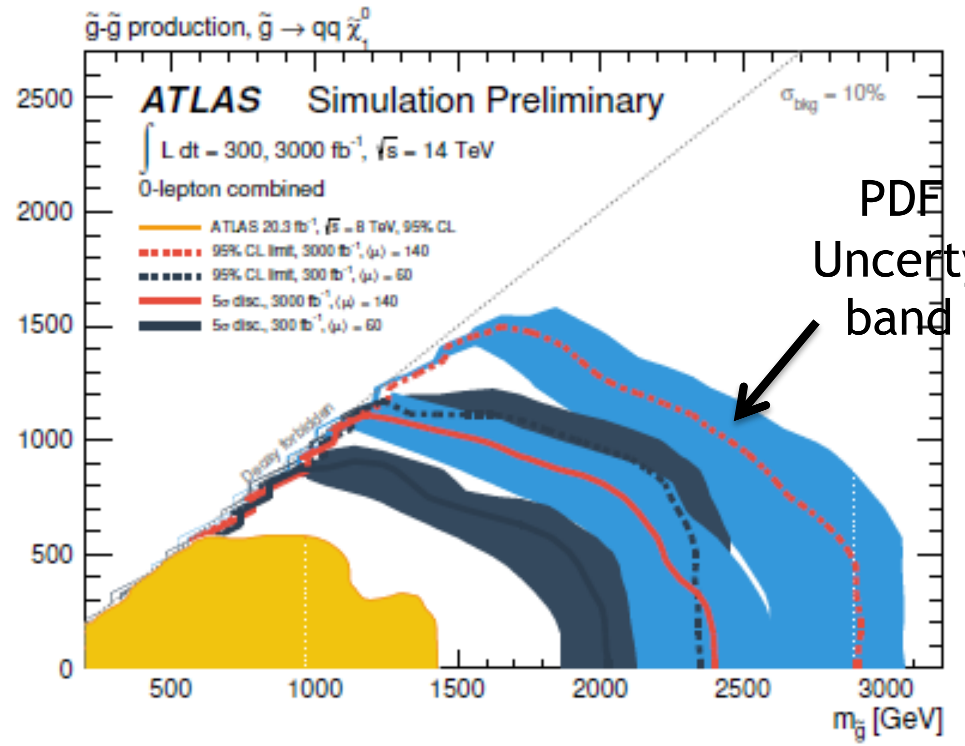


e.g. High Mass 2 Gluino Production

- Signature is excess @ large invariant mass
- Expected SM background (e.g. gg → gg) poorly known for s-hat > 1 TeV.
- Both signal & background uncertainties driven by error on gluon density … essentially unknown for masses much beyond 2 TeV

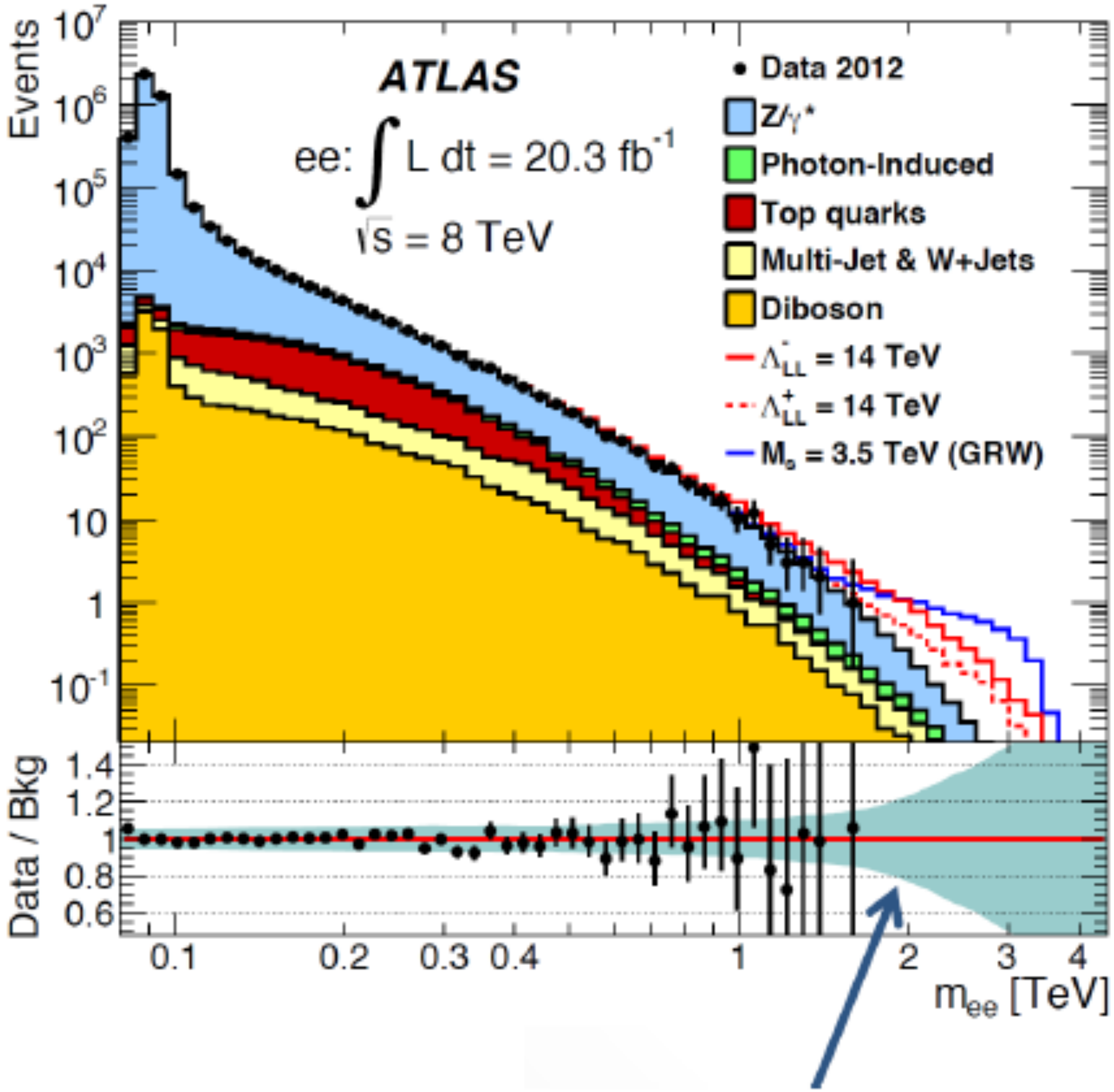






PDF Uncerty band

Limitations from High x Sea Quarks



BSM sensitivity through excess in high mass Drell-Yan limited by high x antiquark uncertainties as well as valence

Studies with Simulated LHeC Data

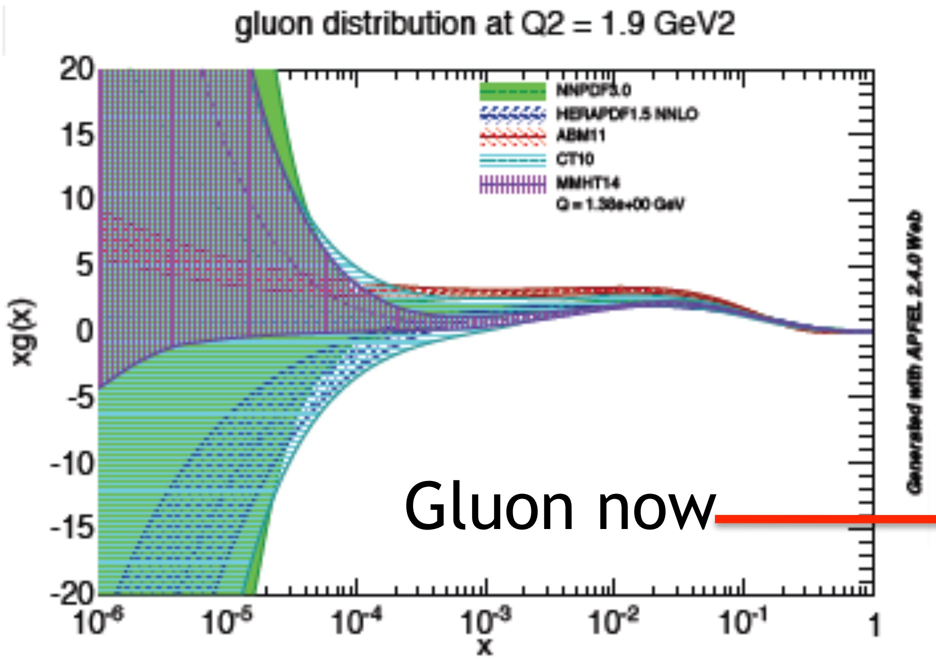
- First generation simulated `pseudo-data' produced with reasonable assumptions on systematics (typically 2x better than H1 and ZEUS at HERA).

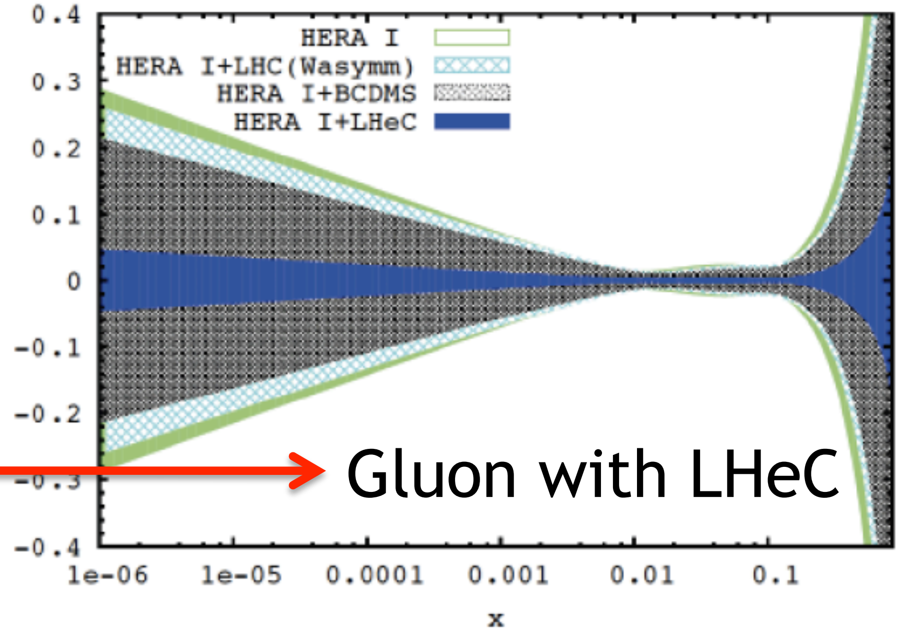
-Second generation pseudo-data (with full detector simulation) in progress

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

- NLO DGLAP fit using HERAPDF1.0, including:
    - LHeC NC and CC e^+p and e^-p cross sections
    - HERA-1 combined H1+ZEUS data
    - Fixed target BCDMS data with W>15 GeV (where stated)
    - ATLAS 2010 W, Z data (where stated)

Gluon and Sea Quarks at LHeC

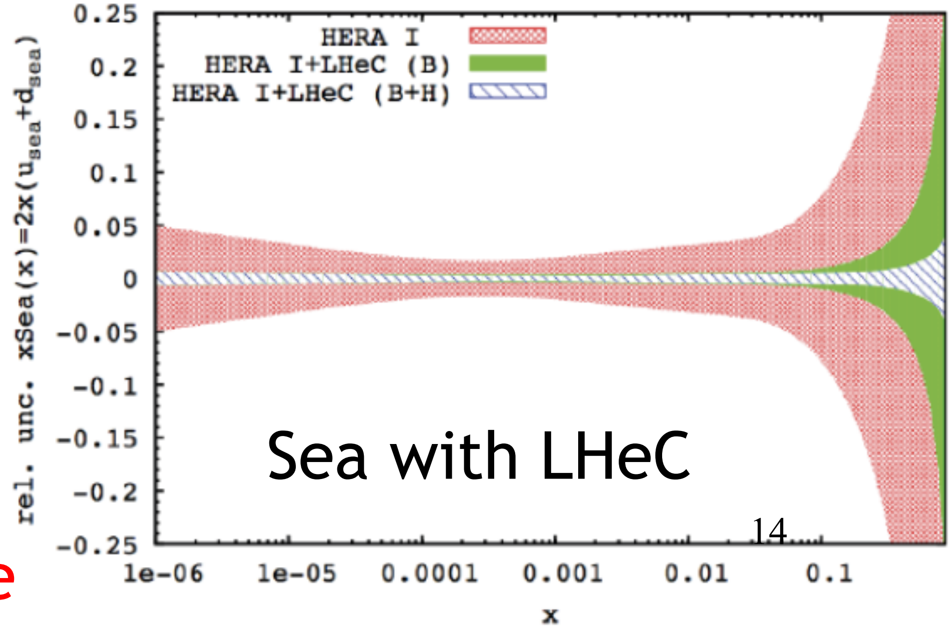




- No current gluon constraints below x~10^{-4}. LHeC goes to x~10^{-6} with < 5% precision

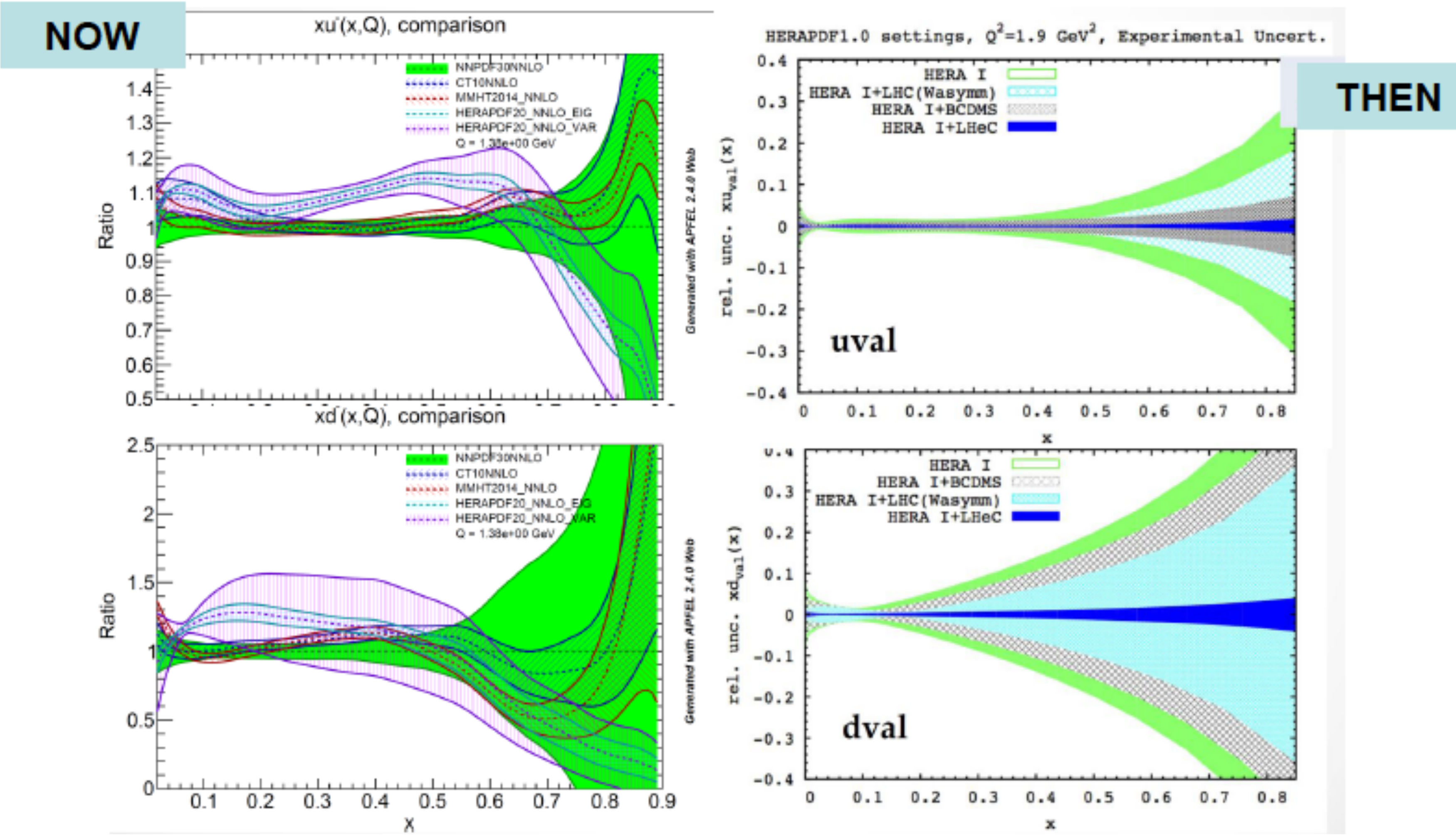
- High x poorly known (current PDF sets differ) → searches …

- Sea intimately connected to glue



Valence Quarks at LHeC

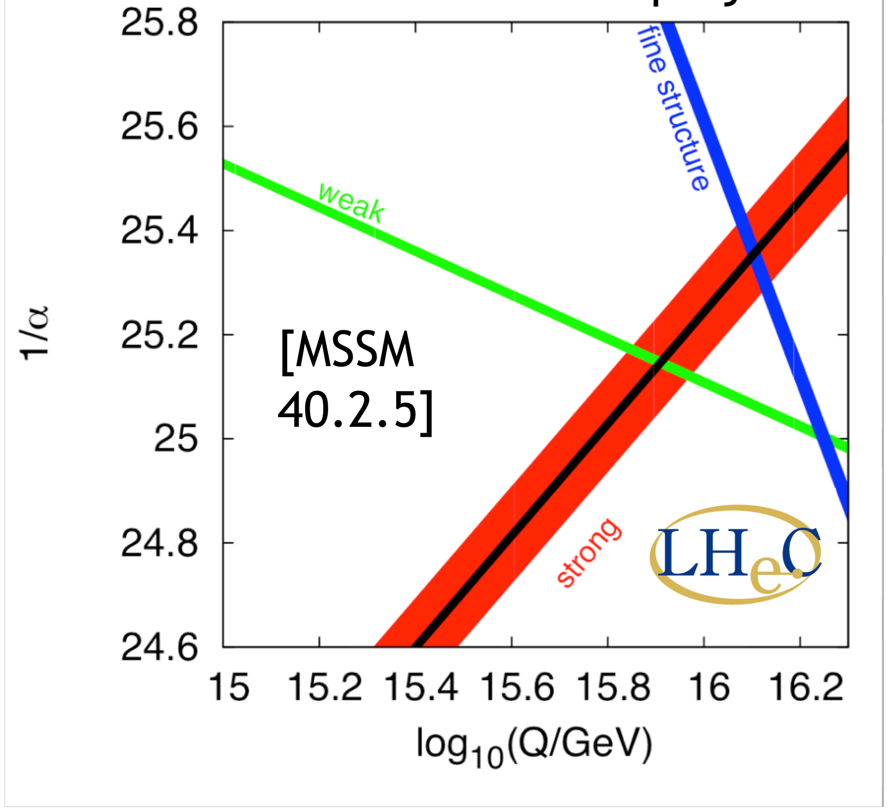
Disentangle sea and valence through CC, xF_3 etc



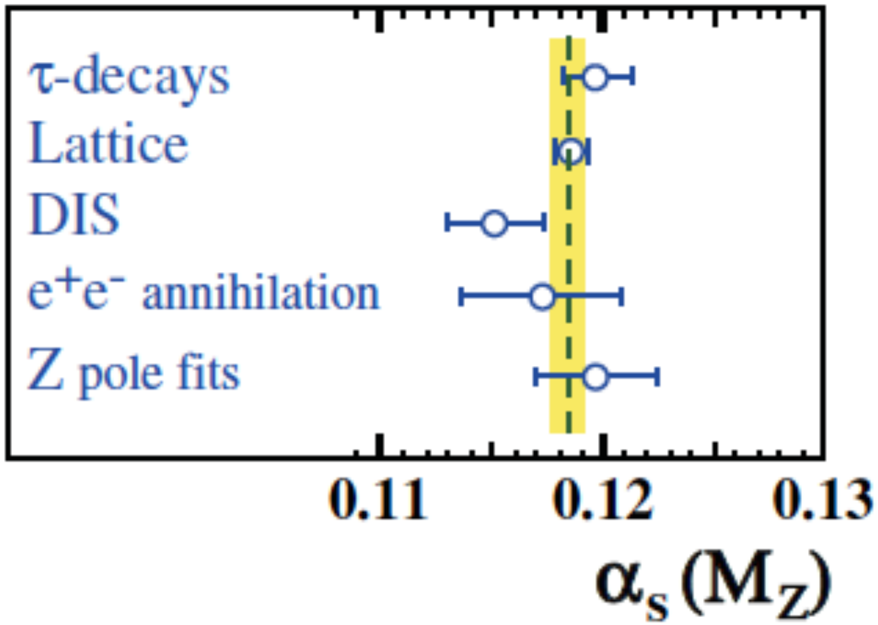
- Also, precision light quark axial / vector couplings, weak mixing angle, α_s and full flavour decomposition …

Precision α_s

Red = current world average
Black = LHeC projected



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



- Simulated LHeC precision from fitting inclusive data
→ per-mille (experimental)
→ also requires improved theory

Context of Precision α_s

Snowmass13 report – arXiv:1310.5189

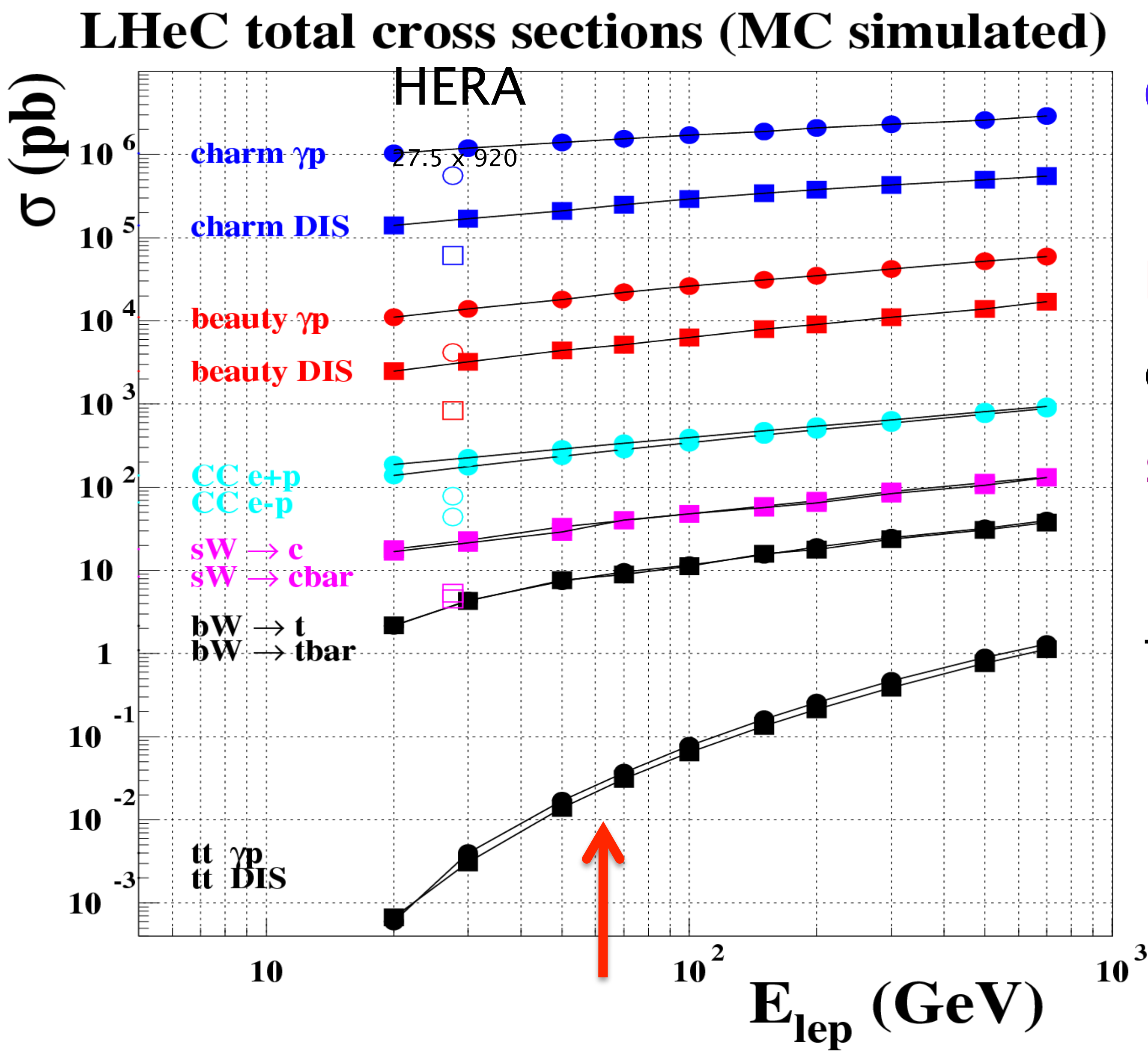
Method	Current relative precision	Future relative precision
e^+e^- evt shapes	expt $\sim 1\%$ (LEP) thry ~ 1–3% (NNLO+up to N^{3}LL, n.p. signif.) [27]	$< 1\%$ possible (ILC/TLEP) $\sim 1\%$ (control n.p. via Q^2-dep.)
e^+e^- jet rates	expt $\sim 2\%$ (LEP) thry $\sim 1\%$ (NNLO, n.p. moderate) [28]	$< 1\%$ possible (ILC/TLEP) $\sim 0.5\%$ (NLL missing)
precision EW	expt $\sim 3\%$ (R_Z, LEP) thry $\sim 0.5\%$ (N^{3}LO, n.p. small) [9,29]	0.1% (TLEP [10]), 0.5% (ILC [11]) $\sim 0.3\%$ (N^{4}LO feasible, ~ 10 yrs)
τ decays	expt $\sim 0.5\%$ (LEP, B-factories) thry $\sim 2\%$ (N^{3}LO, n.p. small) [8]	$< 0.2\%$ possible (ILC/TLEP) $\sim 1\%$ (N^{4}LO feasible, ~ 10 yrs)
ep colliders	~ 1–2% (pdf fit dependent) [30,31], (mostly theory, NNLO) [32,33]	0.1% (LHeC + HERA [23]) $\sim 0.5\%$ (at least N^{3}LO required)
hadron colliders	$\sim 4\%$ (Tev. jets), $\sim 3\%$ (LHC $t\bar{t}$) (NLO jets, NNLO $t\bar{t}$, gluon uncert.) [17,21,34]	$< 1\%$ challenging (NNLO jets imminent [22])
lattice	$\sim 0.5\%$ (Wilson loops, correlators, ...) (limited by accuracy of pert. th.) [35–37]	$\sim 0.3\%$ (~ 5 yrs [38])

per mille (precision EW)

per mille (ep colliders)

… tensions between lattice and DIS α_s results as a sensitive probe of new physics?...

Cross Sections and Rates for Heavy Flavours



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

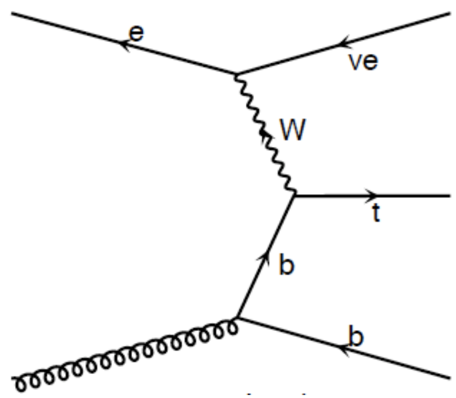
Beauty $[10^{8} / 10\ fb^{-1}]$

cc

sW → c $[4.10^{5} / 10\ fb^{-1}]$

bW → t $[10^{5} / 10\ fb^{-1}]$

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



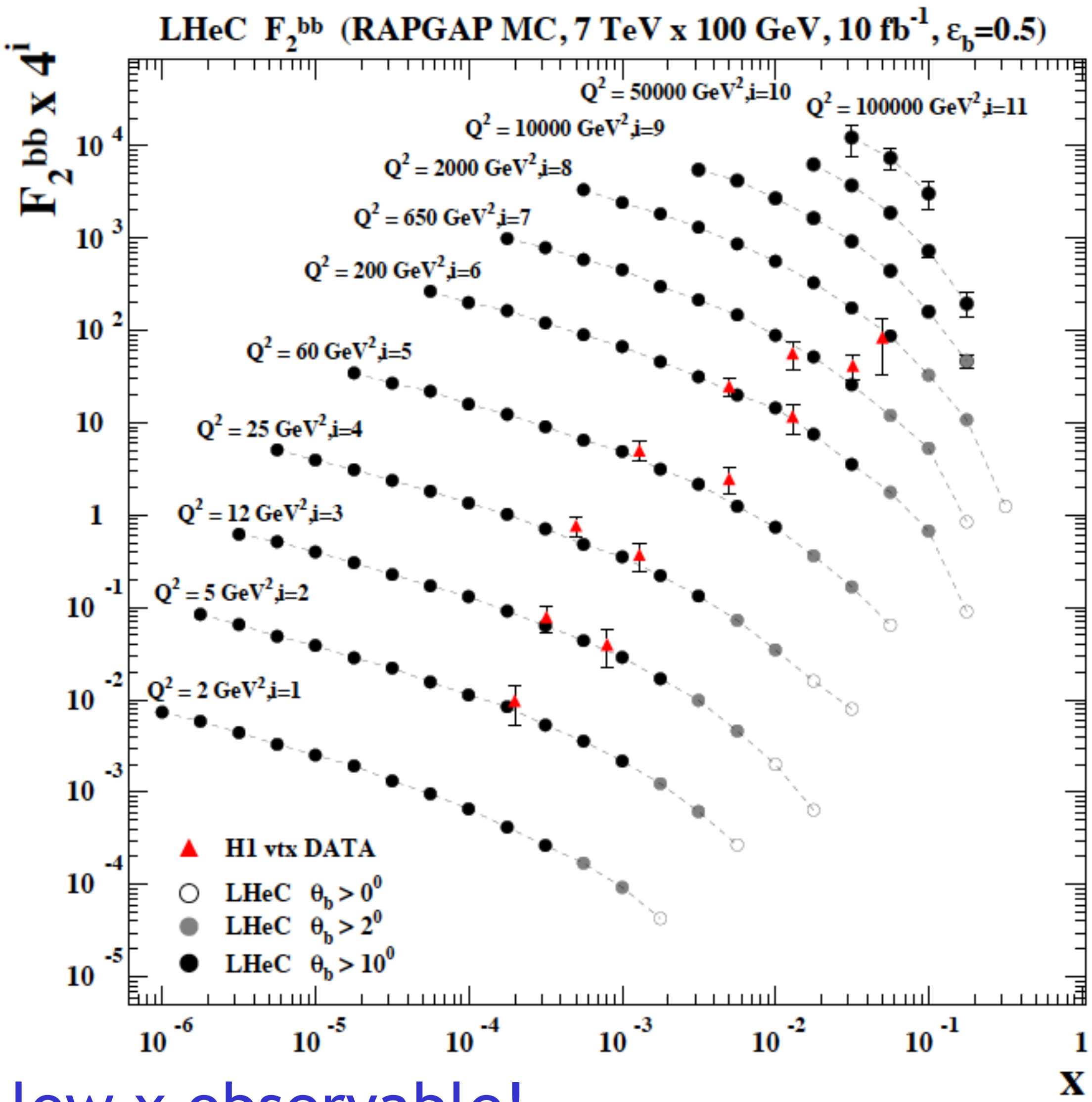
c.f. luminosity of ~10-100 fb^{-1} per year

e.g. Beauty Production

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

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

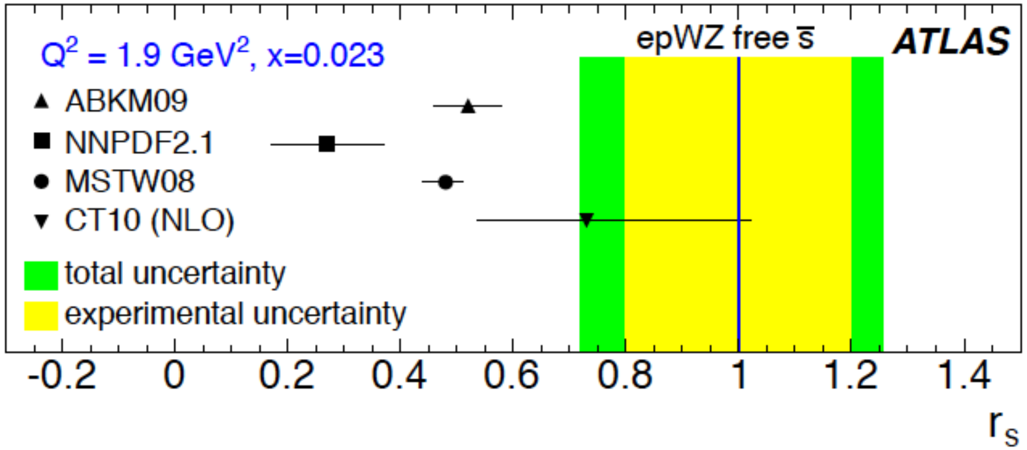
Systematics at 10% level

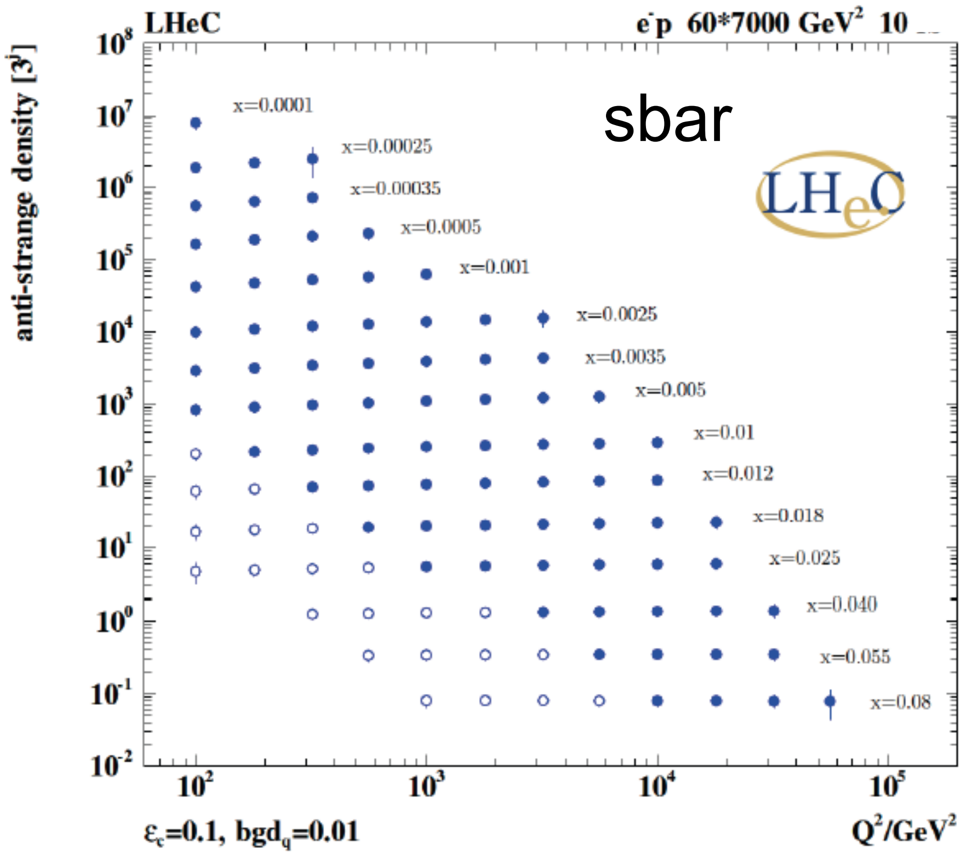


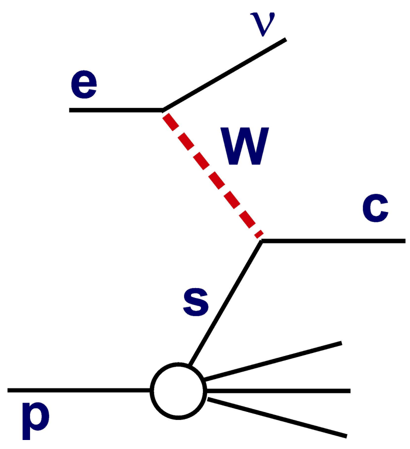
→beauty as a low x observable!

e.g. Strange and Anti-strange Quarks

Evidence from LHC that strange density is larger than thought: SU(3) symmetric sea?...



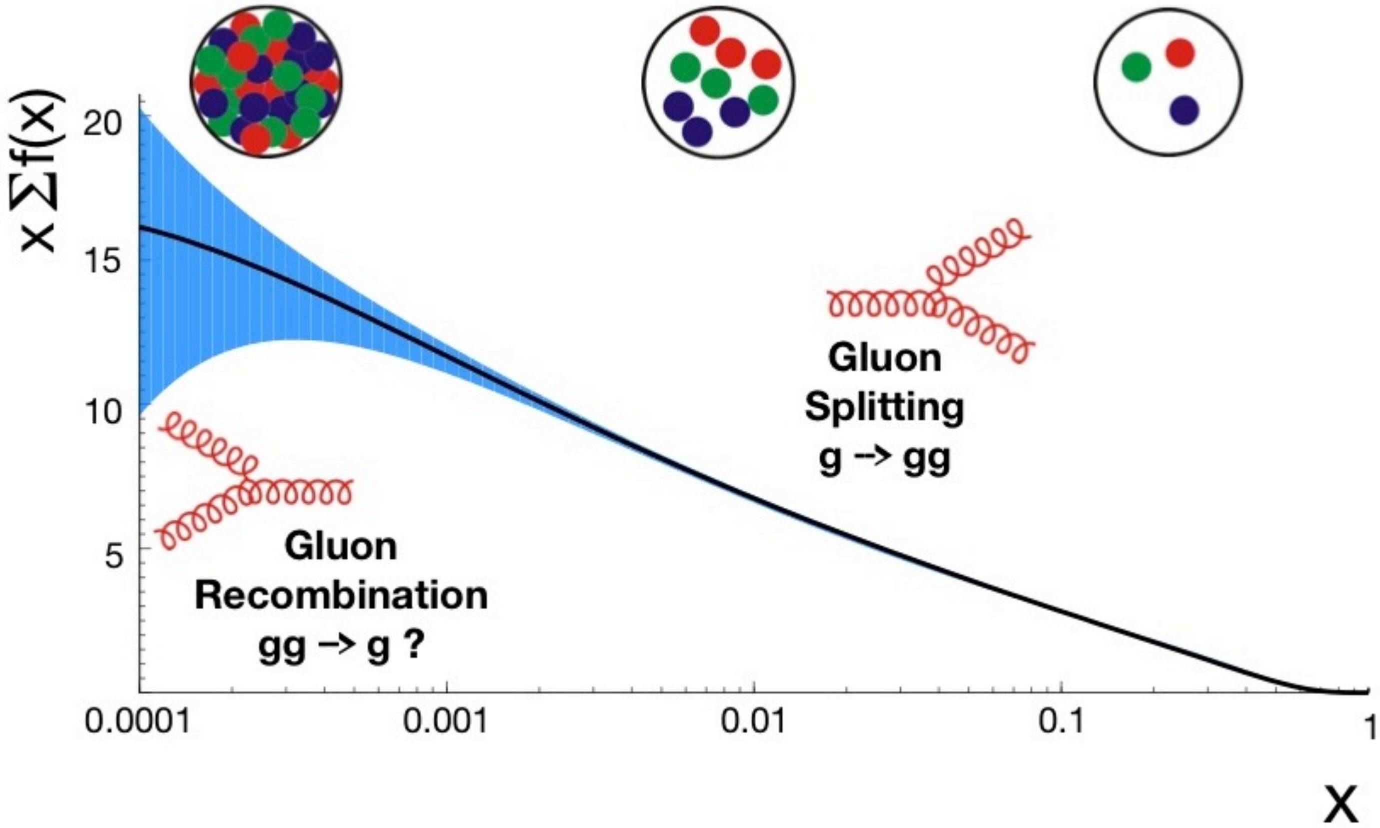




Assuming 10% charm tagging efficiency, 1% light quark background

Low-x Physics and Parton Saturation

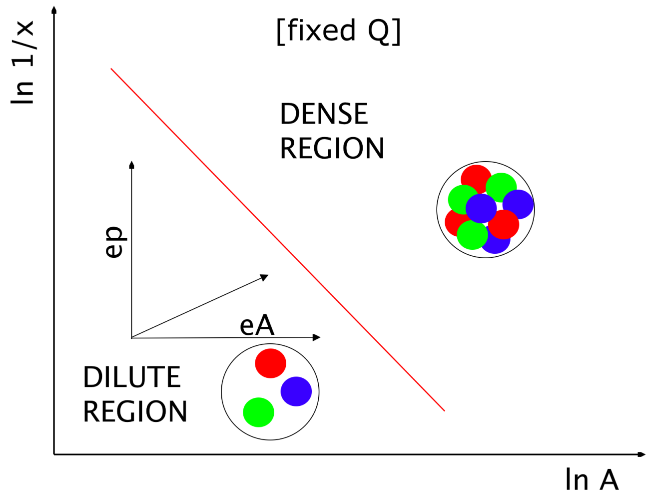
- Somewhere & somehow, the low x growth of cross sections must be tamed to satisfy unitarity … non-linear effects



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

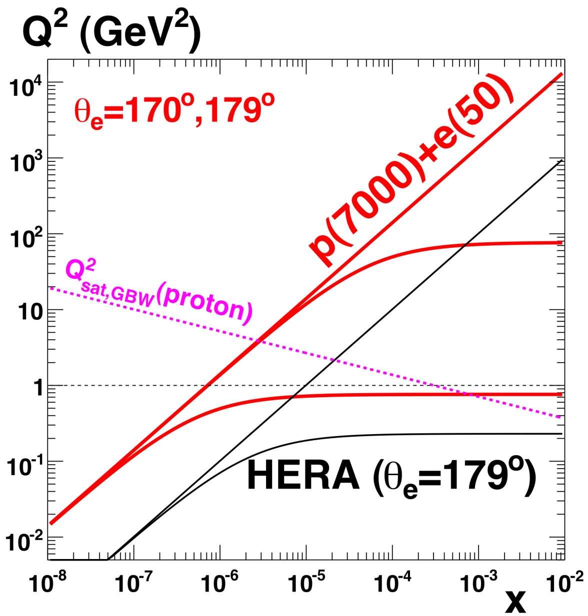
Some limited evidence from HERA, LHC picture (e.g pPb) unclear

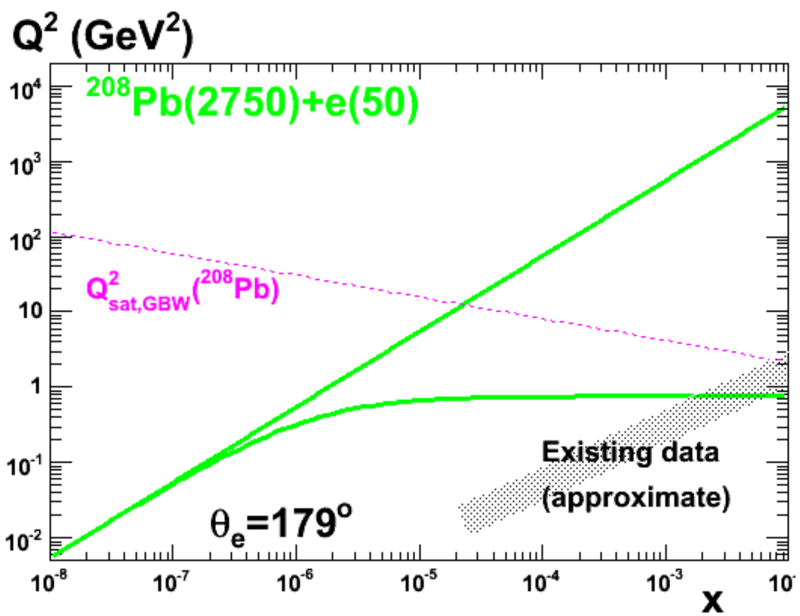
LHeC: Accessing saturation region at large Q^2



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]



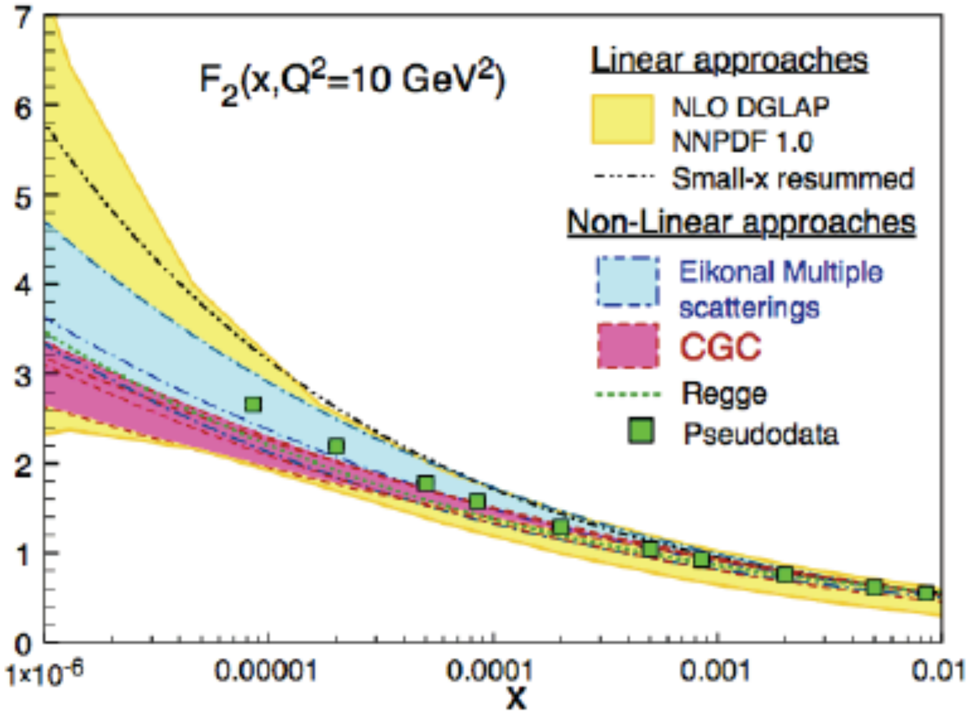


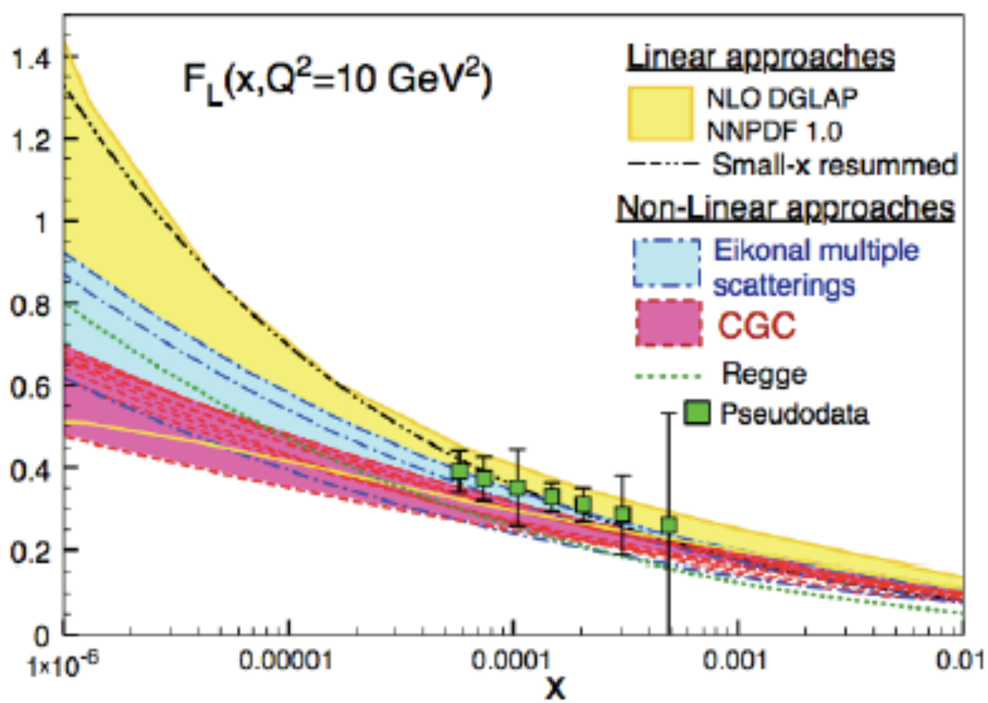
… Reaches saturated region in both ep & eA inclusive data according to models

Establishing and Characterising Saturation

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

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





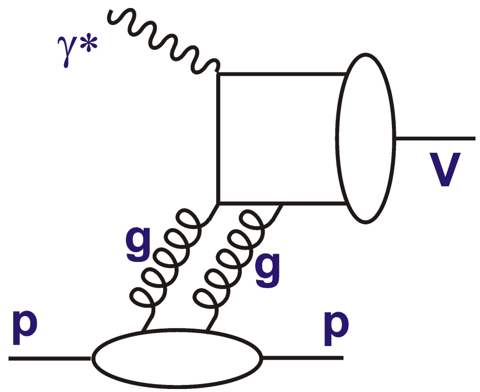
- LHeC can distinguish between different QCD-based models for the onset of non-linear dynamics
- Unambiguous observation of saturation will be based on tension between different observables e.g. F_2 v F_L in ep or F_2 in ep v eA

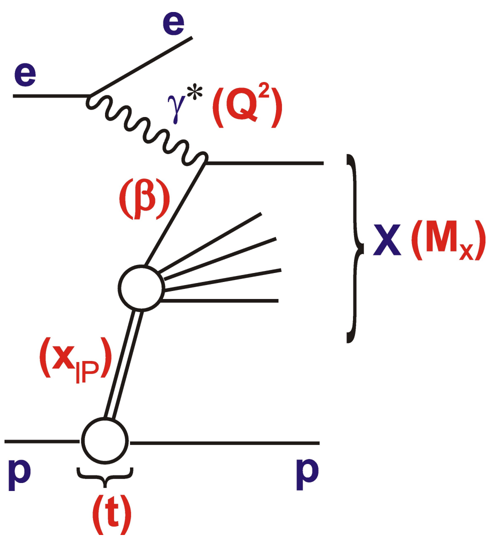
Exclusive / Diffractive Channels and Saturation

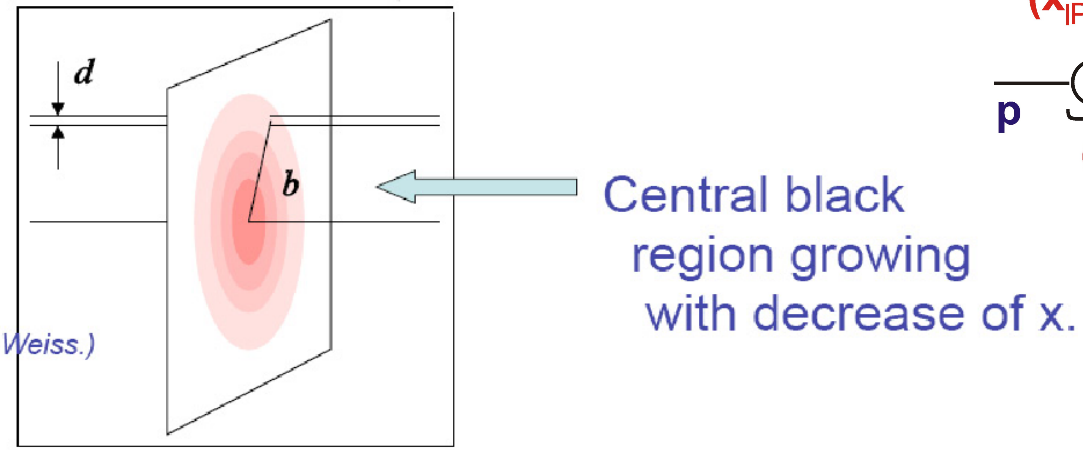
1) [Low-Nussinov] interpretation as 2 gluon exchange enhances sensitivity to low x gluon

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

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



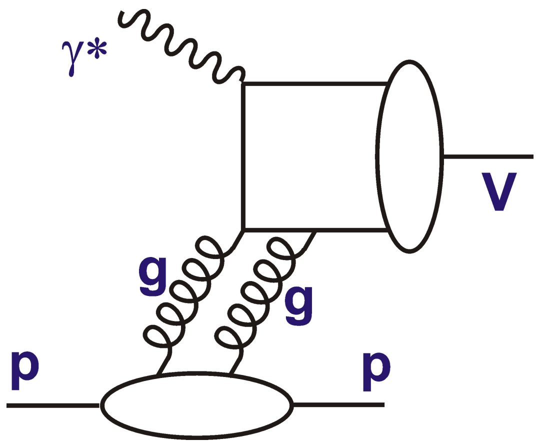


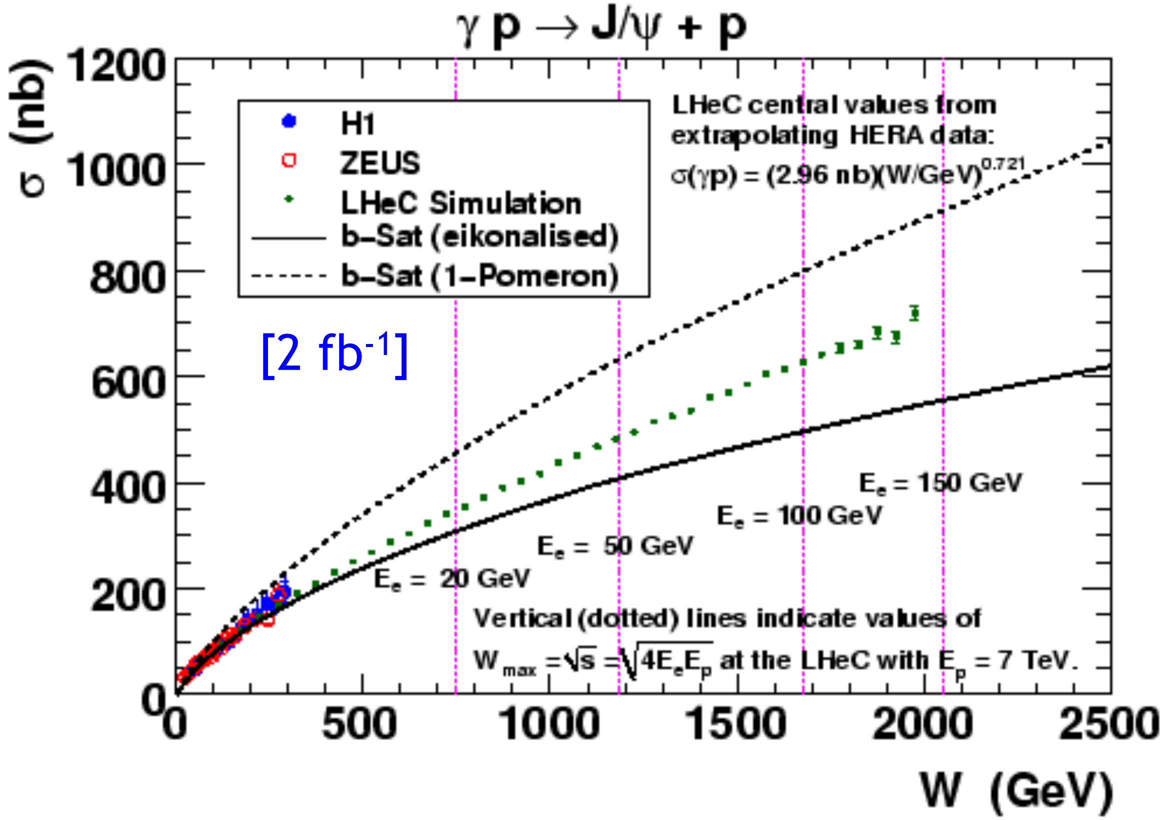


(figure from C. Weiss.)

e.g. J/ψ Photoproduction

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

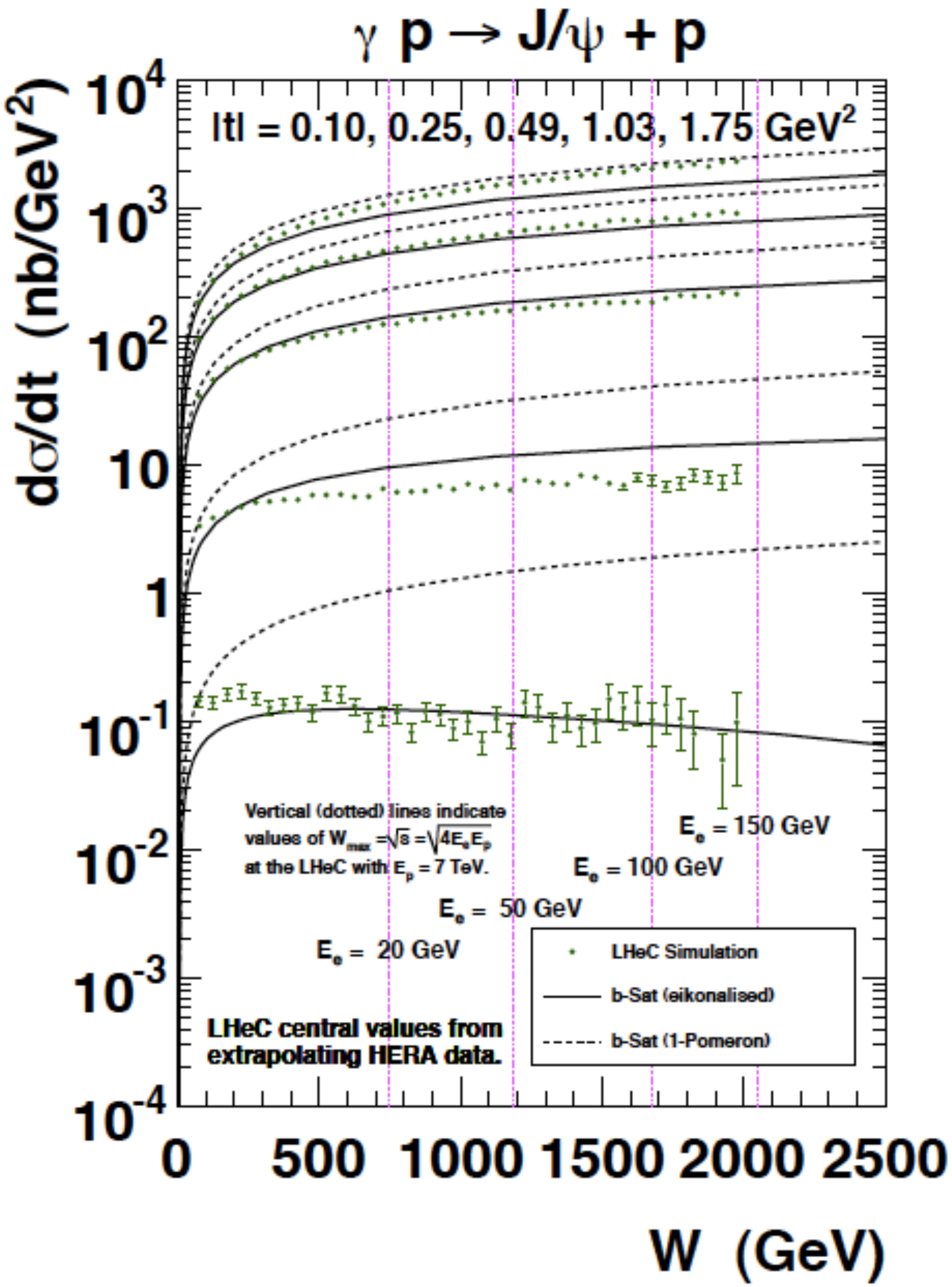




- Significant non-linear effects expected in LHeC kinematic range.

- Data shown are extrapolations of HERA power law fit

t Dependence of Elastic J/ψ Photoproduction



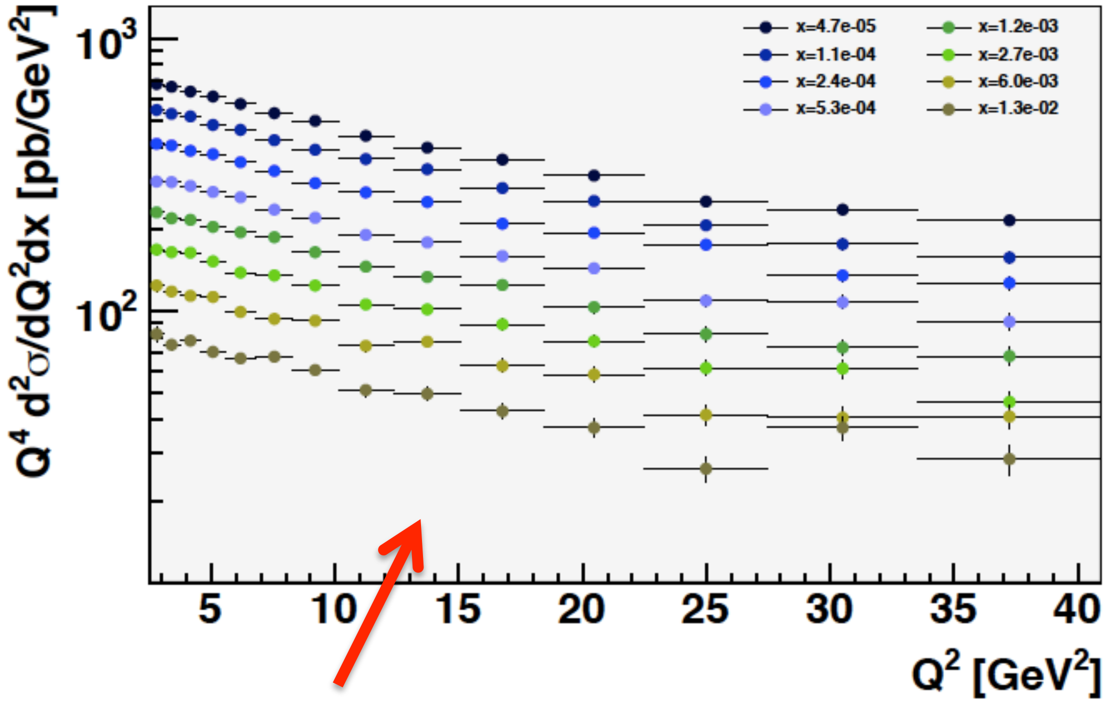
- J/ψ photoproduction double differentially in W and t …

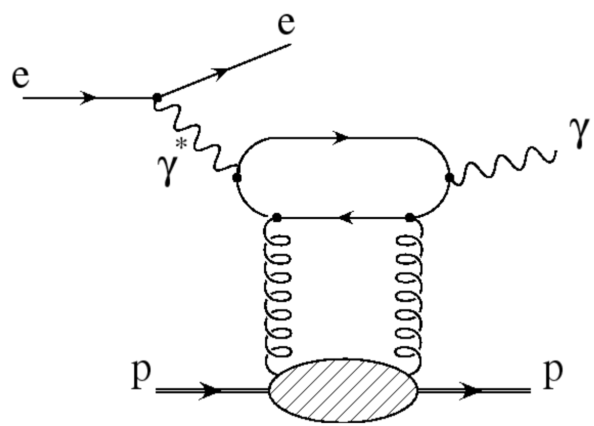
- Precise t measurement from decay μ tracks over wide W range extends to |t| ~ 2 GeV^2 and enhances sensitivity to saturation effects

- Measurements also possible in multiple Q^2 bins

… powerful probe!

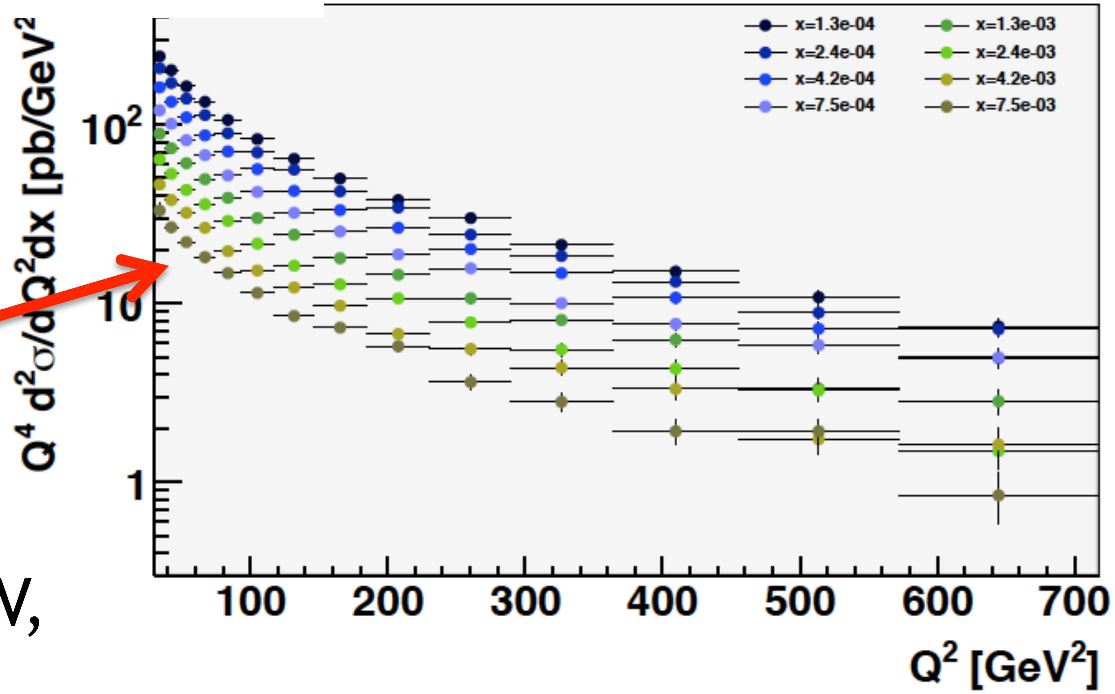
e.g. DVCS (MILOU simulation)





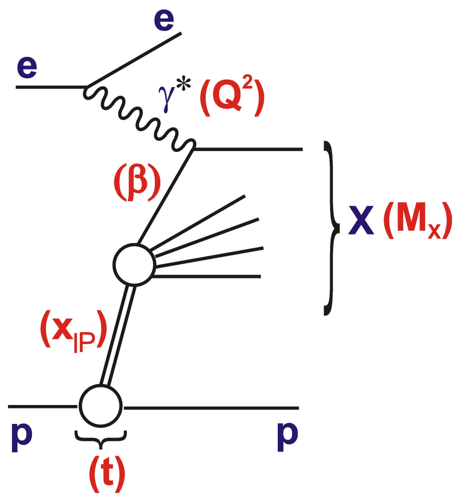
$1\ \mathrm{fb}^{-1}$, $E_e = 50$ GeV,
1° acc'nce, $p_T^{\gamma} > 2$ GeV

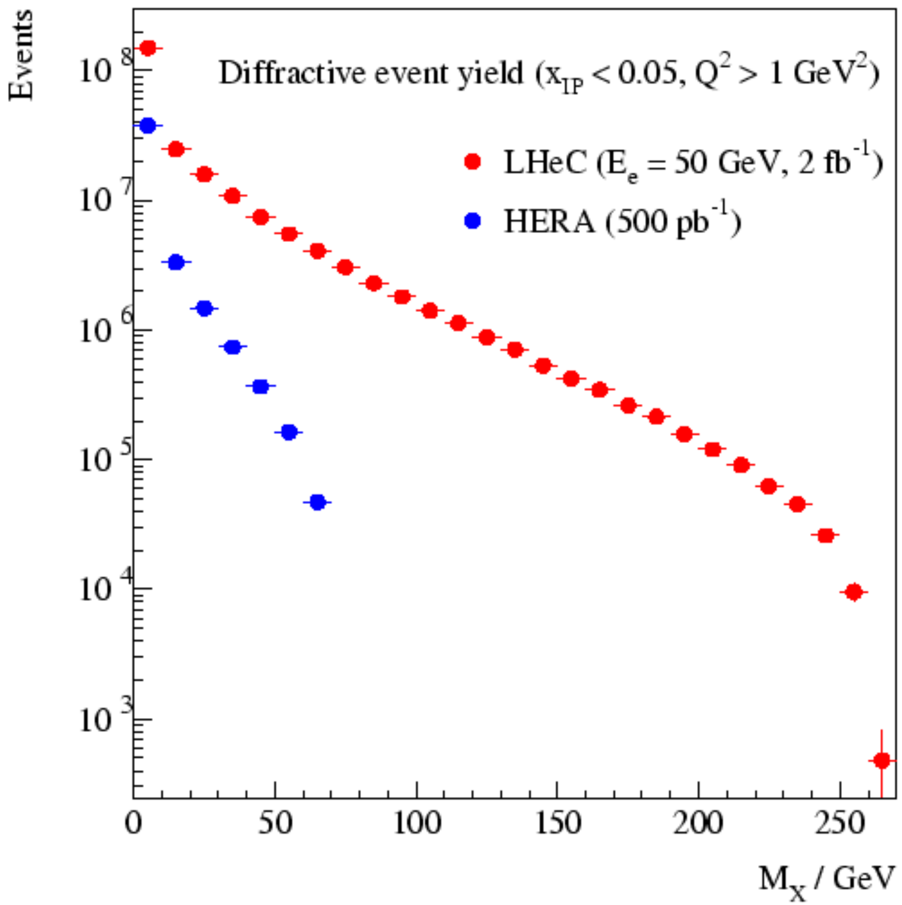
$100\ \mathrm{fb}^{-1}$, $E_e = 50$ GeV,
10° acc'nce, $p_T^{\gamma} > 5$ GeV

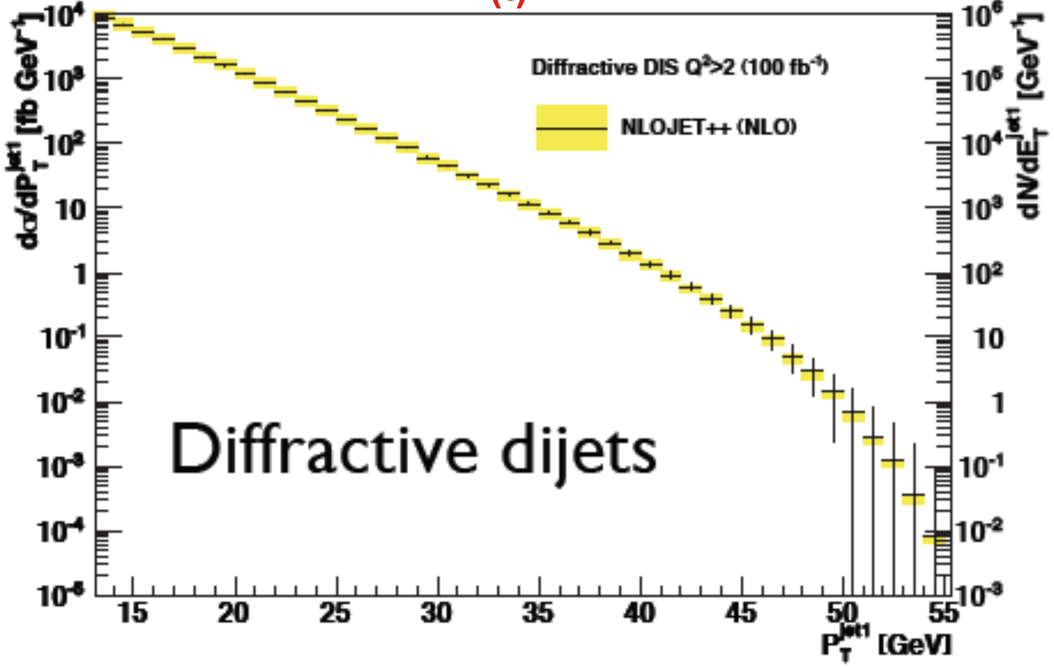


Precise data with W → 1 TeV,
Q^2 → 700 GeV^2, x → 5.10^{-5}

Large Diffractive Masses



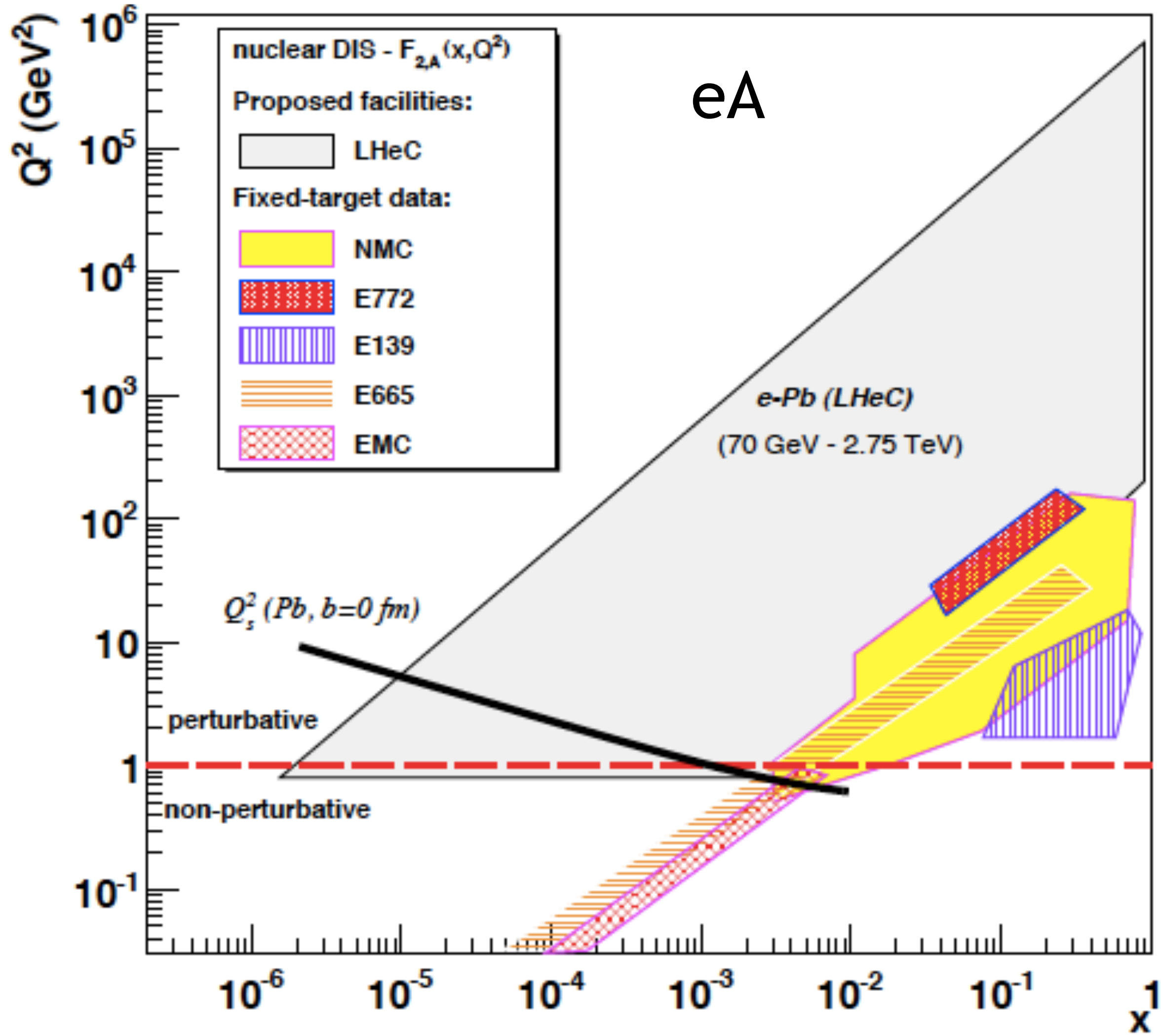




- `Proper' QCD (e.g. large E_T) with jets and charm accessible
- New diffractive channels … beauty, W / Z bosons
- Unfold quantum numbers / precisely measure new 1^- states

LHeC as an Electron-Ion Collider

Four orders of magnitude increase in kinematic range over previous DIS experiments.



Current knowledge for x <~ 10^{-2} almost zero.

→LHeC revolutionises our view of partonic structure of nuclei.

→ Study interactions of densely packed, but weakly coupled, partons

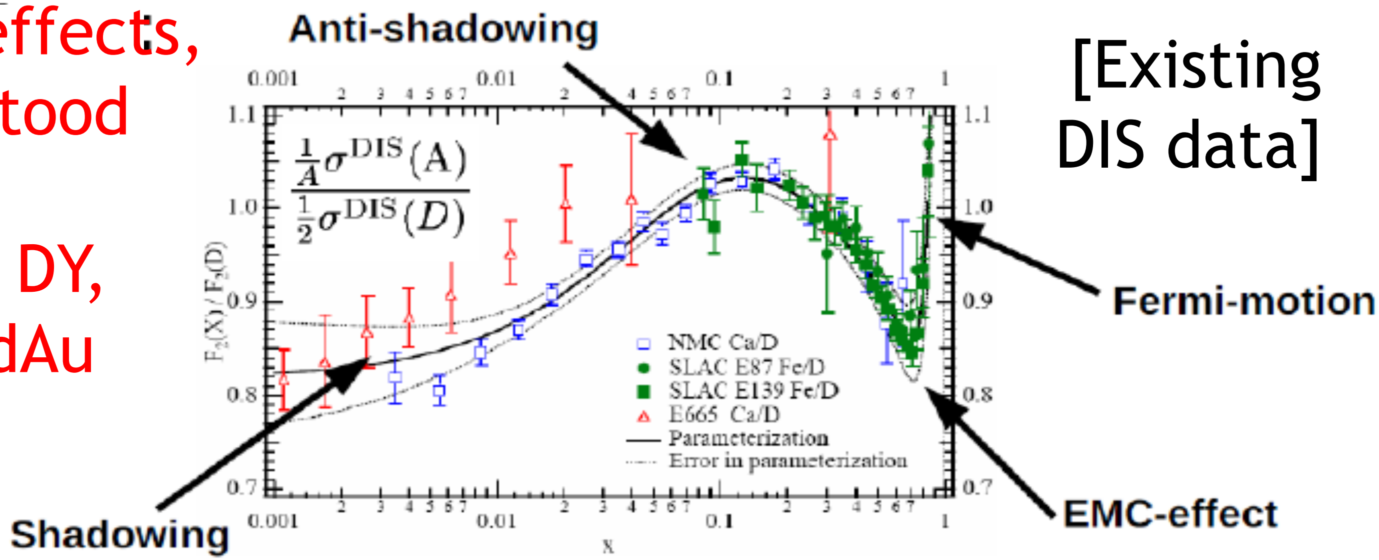
→Ultra-clean probe of passage of `struck' partons through cold nuclear matter

Current Status of Nuclear Parton Densities

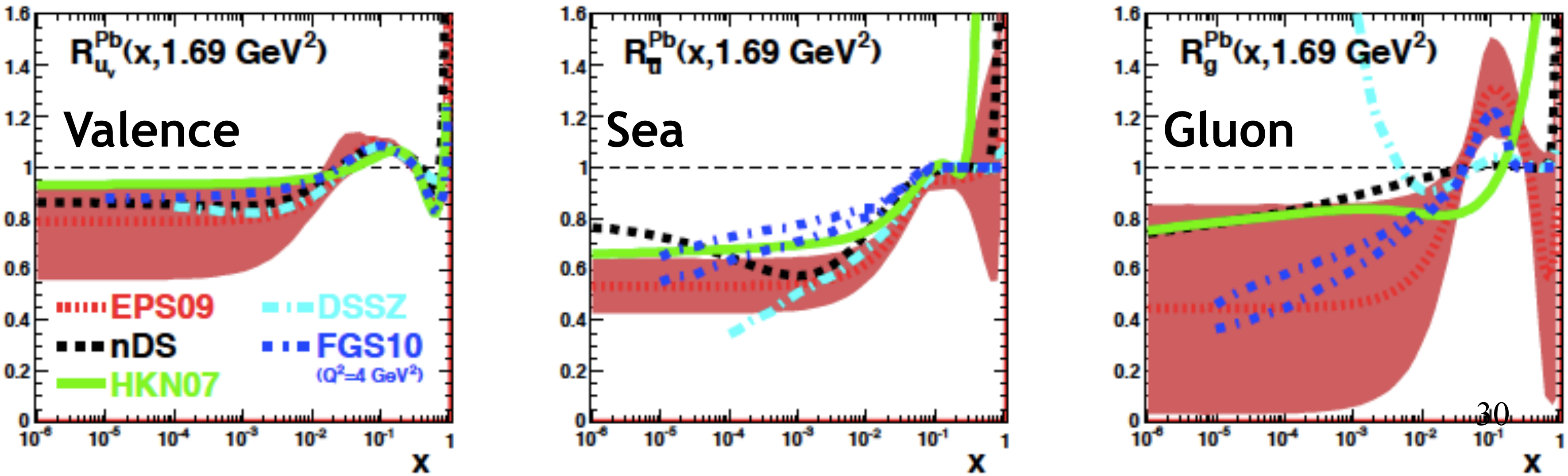
- Complex nuclear effects, not yet fully understood

- Quarks from DIS & DY, Gluon mainly from dAu single π^0 rates

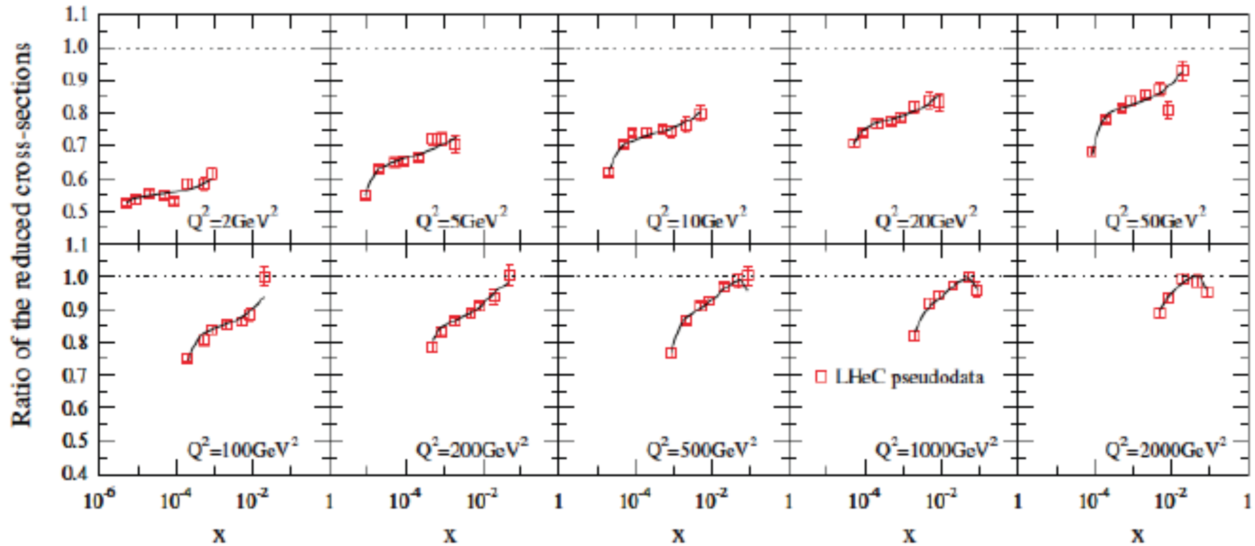
- All partons poorly constrained for $x < 10^{-2}$



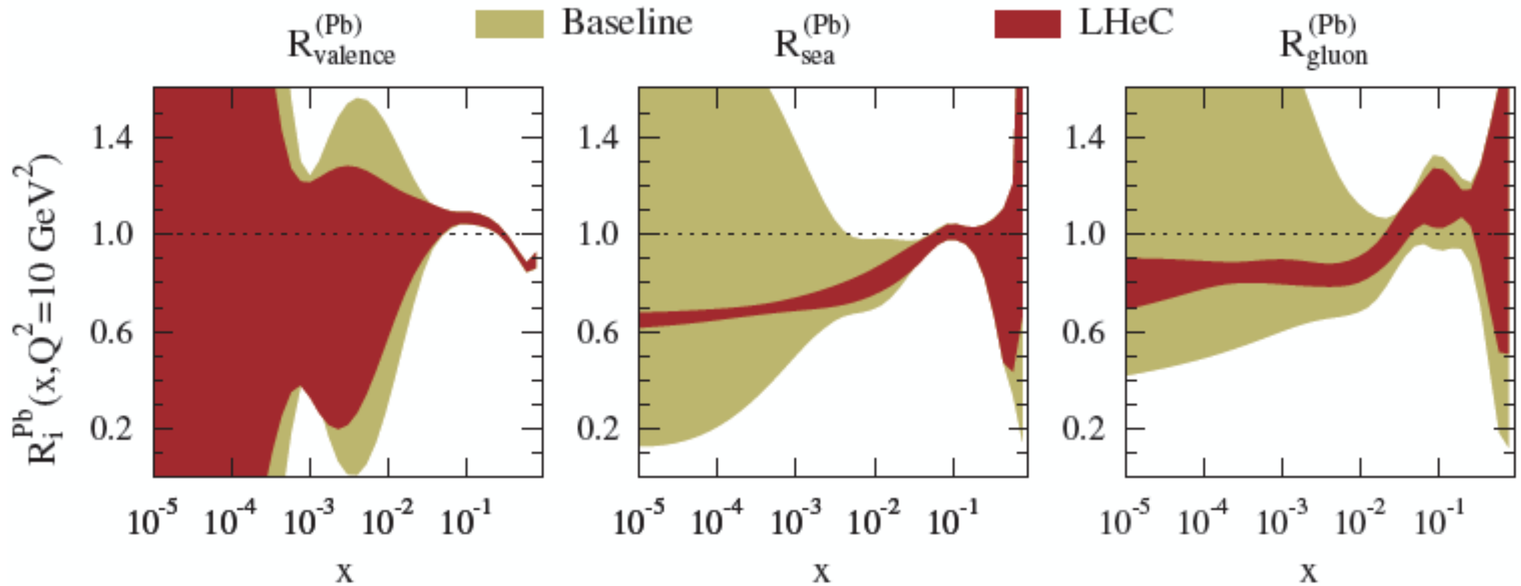
R_i = Nuclear PDF i / (A * proton PDF i)

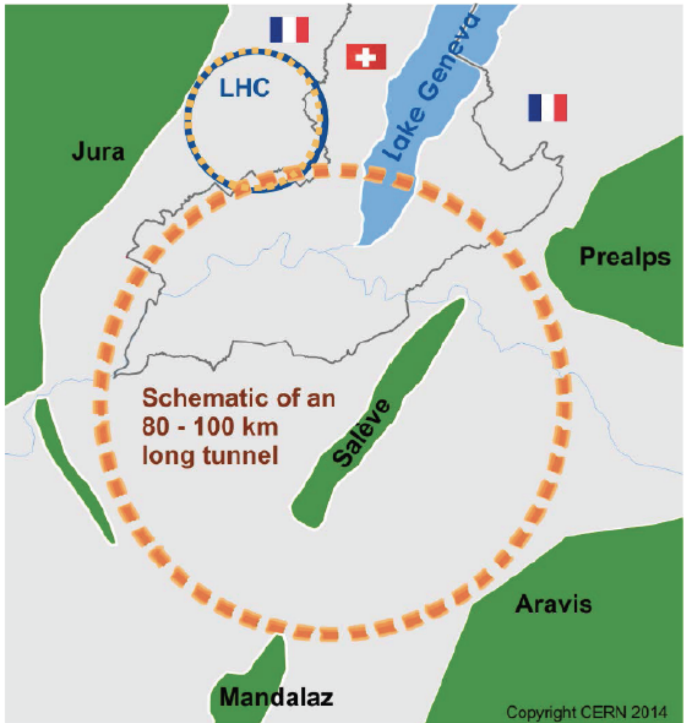


Impact of Simulated ePb LHeC F_2 & F_L data



- Studies in context of EPS'09 nPDF set, with more flexible low x parameterisation at starting scale …
- LHeC data have huge impact on low x gluon & sea uncertainties



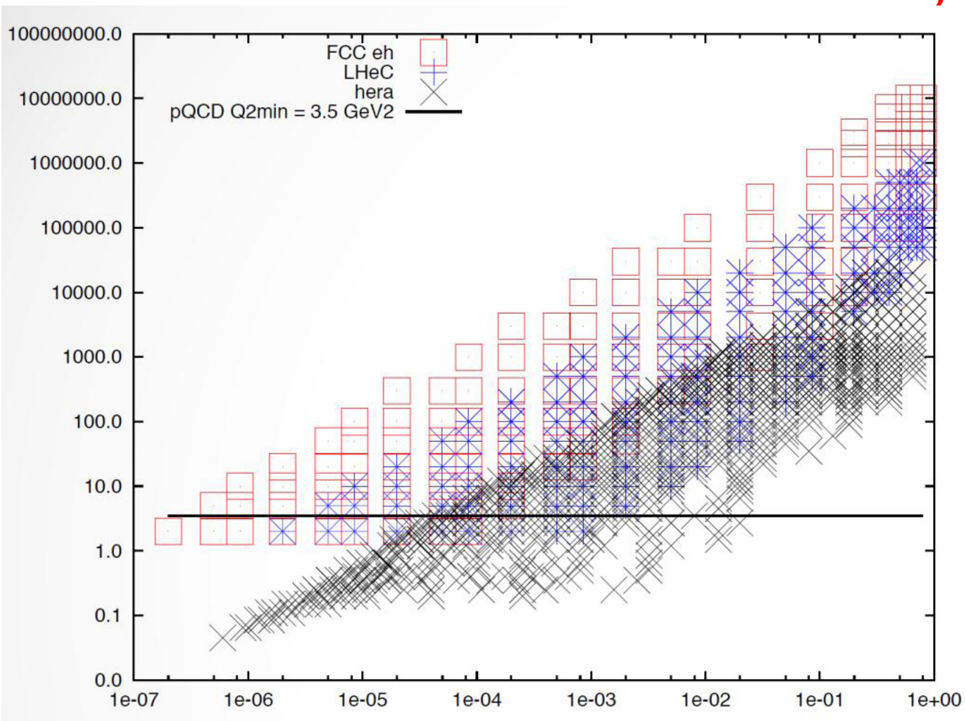


First Thoughts on FCC-he

Ongoing work based on similar electron ERL to LHeC, with 50 TeV protons

Detector is scaled-up version of LHeC [shower depths x ln(50/7)~2]

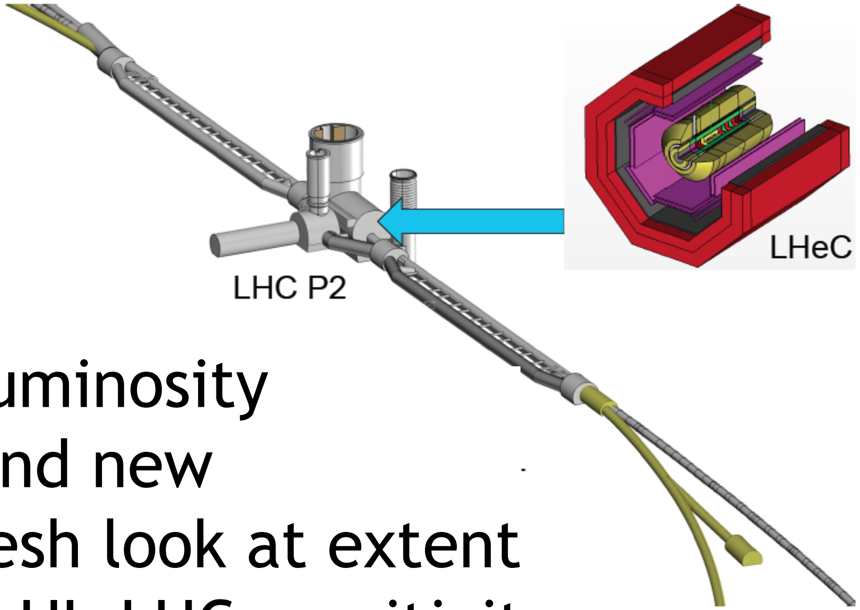
-Total FCC-he H x-sec ~ 1 pb, lumi ~ 10^{34} cm^{-2}s^{-1}, H→HH x-sec ~0.5 fb in range?...



- Sensitive to quark density down to x~10^{-7} for Q^2>1 GeV^2,
- Gluons to ~10^{-6},
- Hadronic final state to W → 4 TeV

... Studies just beginning

Summary



- LHeC CDR 2012 + ongoing work

- Renewed interest following
    1) Possibility of 10^{34} cm^{-2} s^{-1} luminosity
    2) Higgs discovery, searches and new measurements at LHC→ fresh look at extent to which PDFs / QCD limits HL-LHC sensitivity.
    3) Associated technical developments (High gradient cavities, Energy recovery linacs)

- New Committee and Working Group structure set up by CERN, to further develop LHeC, also in context of FCC.

- More in parallel session talks (Nestor Armesto, Claire Gwenlan), in slides from recent LHeC Chavannes Workshop (June 2015) and at LHeC web: http://lhec.web.cern.ch,