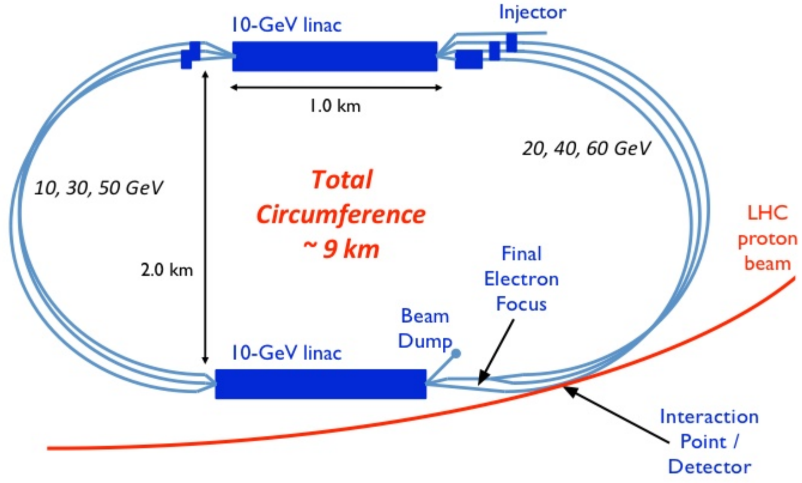
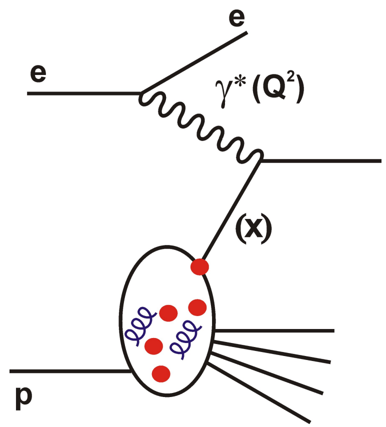
# Overview of the LHeC Project

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?*

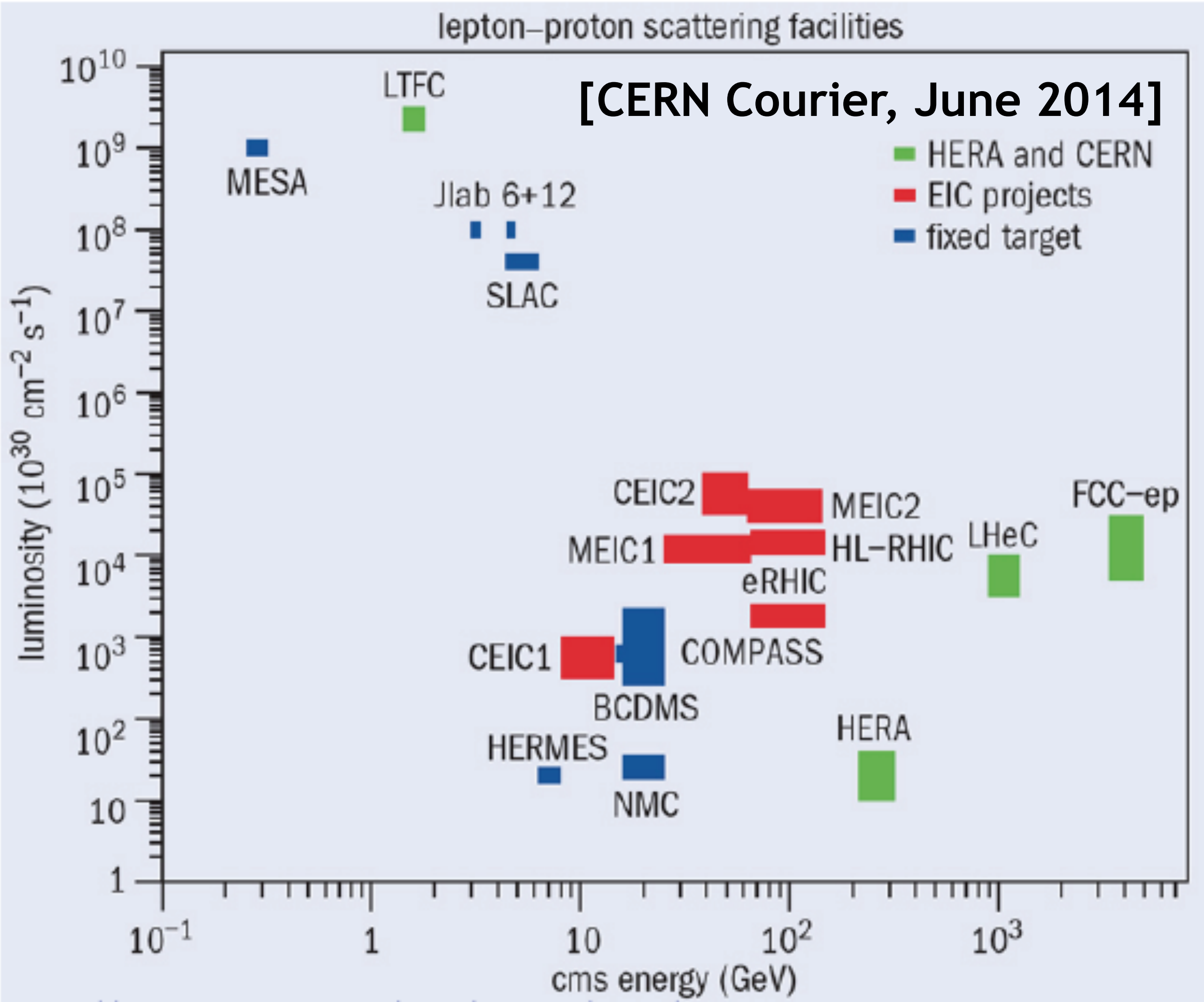



POETIC VI

September 7th-11th 2015
Palaiseau, France

6th International Conference on Physics Opportunities at an Electron-Ion Collider

# LHeC / FCC-he Context




**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

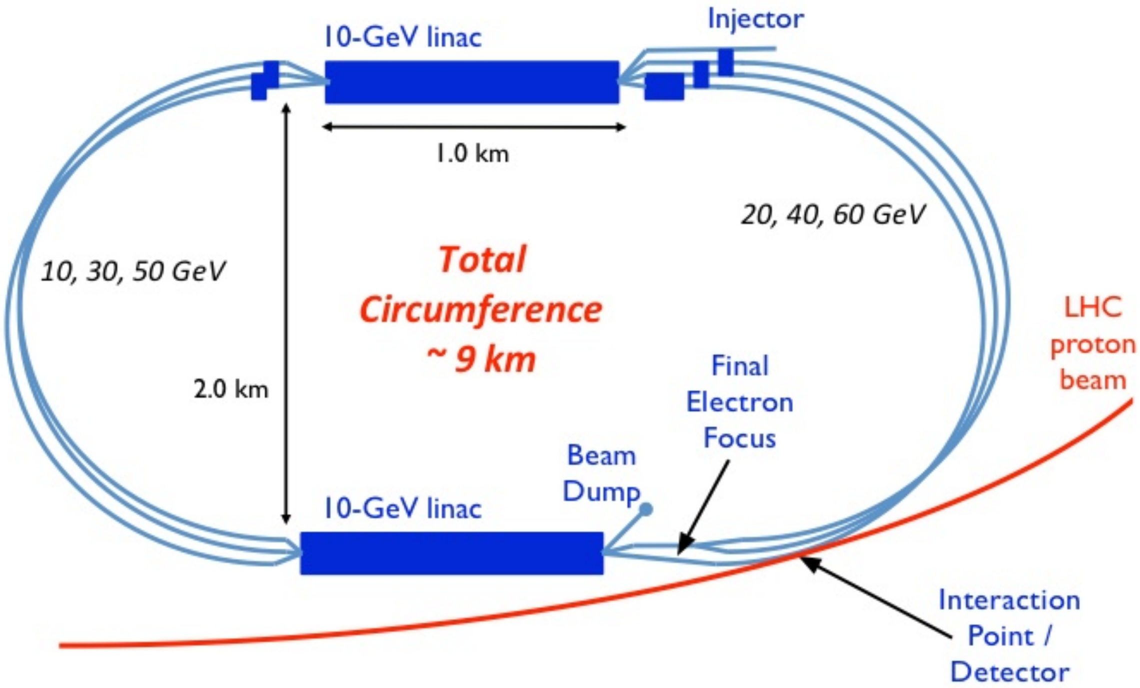
**FCC-he:** 60 GeV electrons x 50 TeV protons from FCC

# Baseline# Design (Electron "Linac")

**LHeC CDR, July 2012 [arXiv:1206.2913]**

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

# Recent Developments

**LHC programme runs to >2035. Longer term at CERN? → FCC?**

... CERN-sponsored ongoing work to evaluate how LHeC fits in.

→ Further develop physics aims, accelerator & detector, both LHeC & FCC

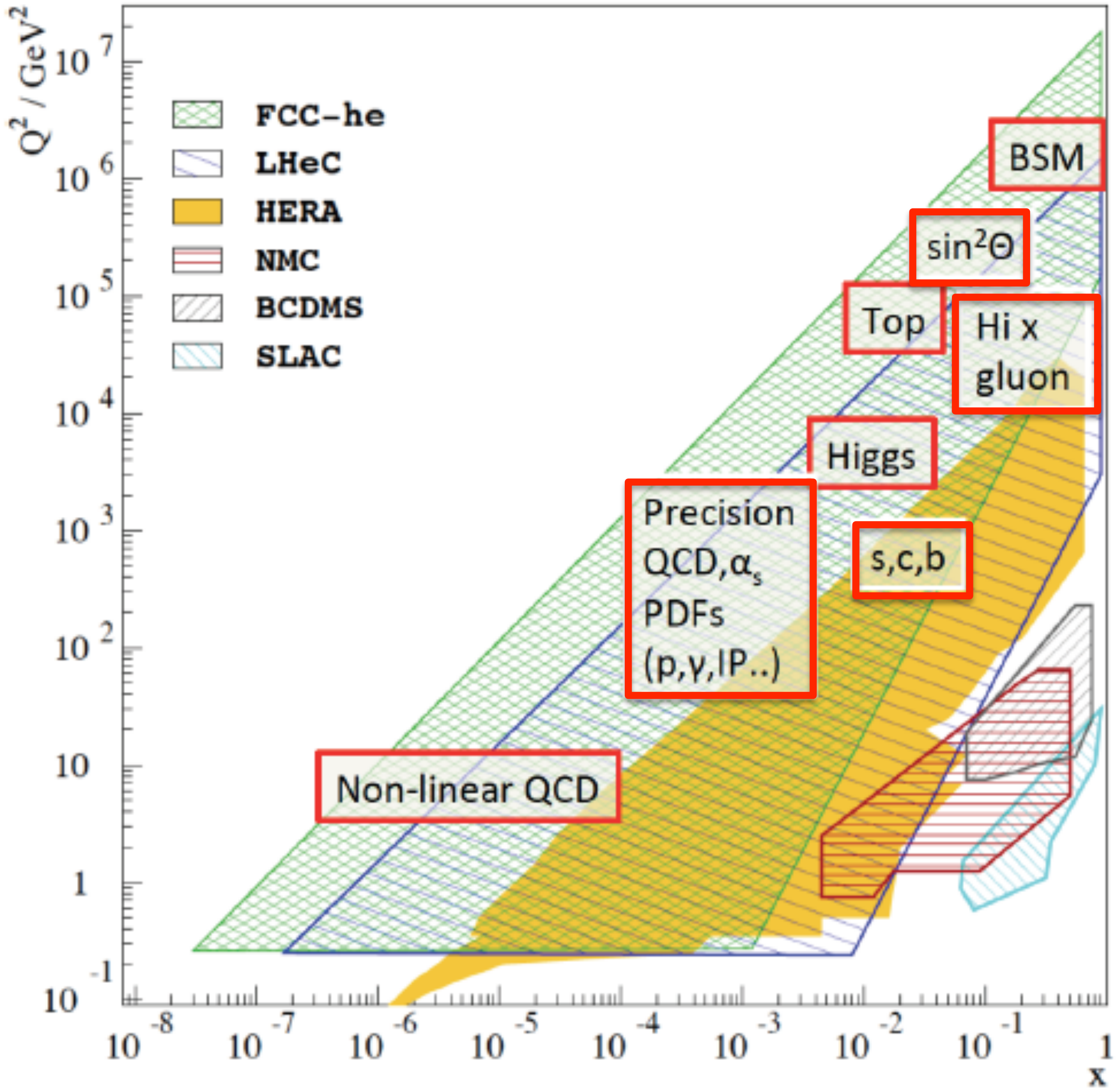
→ Continue building collaboration

→ Design ERL test facility @ CERN


**ERL Test Facility:**

- Test centre for accelerator development, LHeC prototype
- Most ambitious design (2 x 150 MeV linacs, 3 passes → 900 GeV) has significant physics potential of its own ($10^{40}$ cm$^{-2}$ s$^{-1}$ fixed target) … EW parameters, proton radius, photonuclear physics, dark photons …
- Conceptual Design Report by end 2015

# Physics Overview




- Next experimental facility to see Higgs?

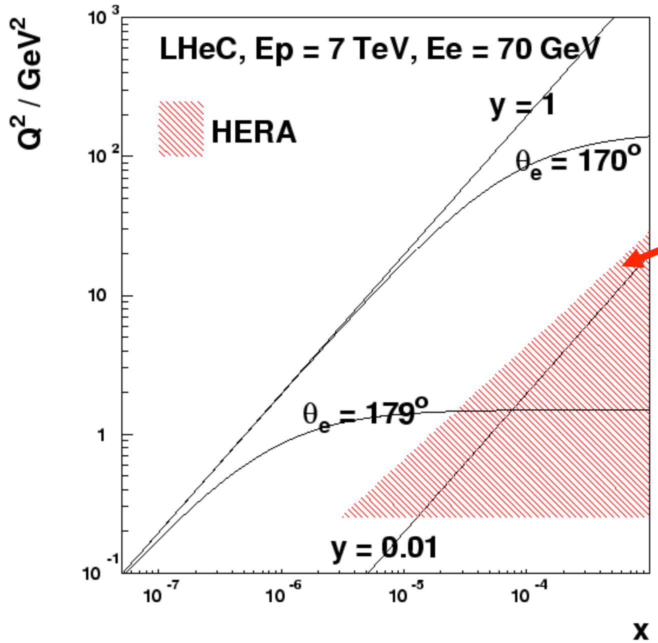
- Enhanced PDF precision enhances LHC new heavy particle sensitivity by ~0.5 TeV & transforms LHC precision at EW scale

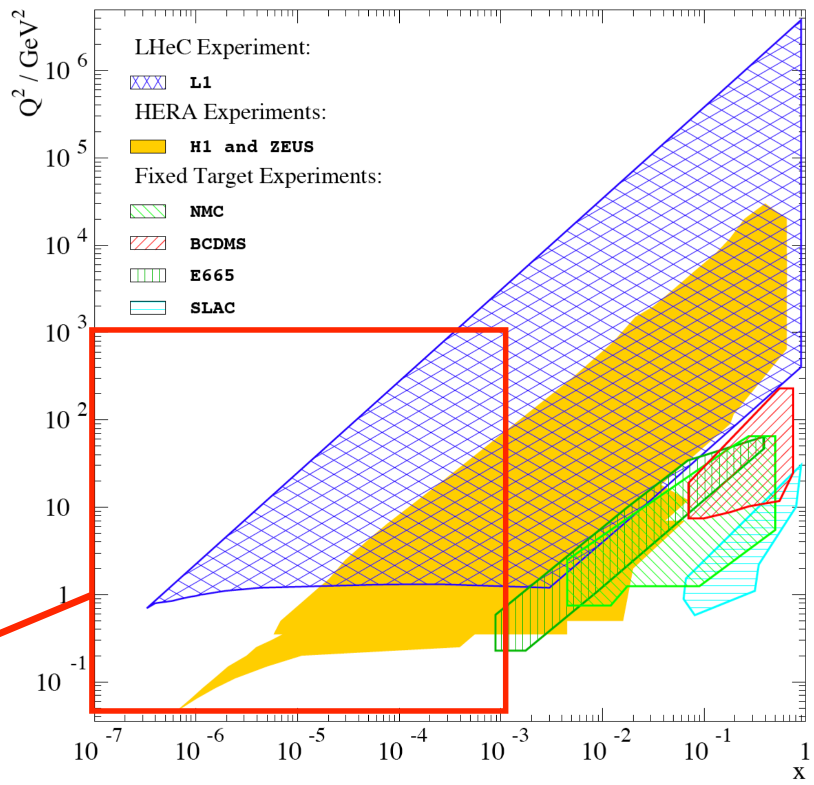
- Elucidates new low x dynamics in both ep and eA

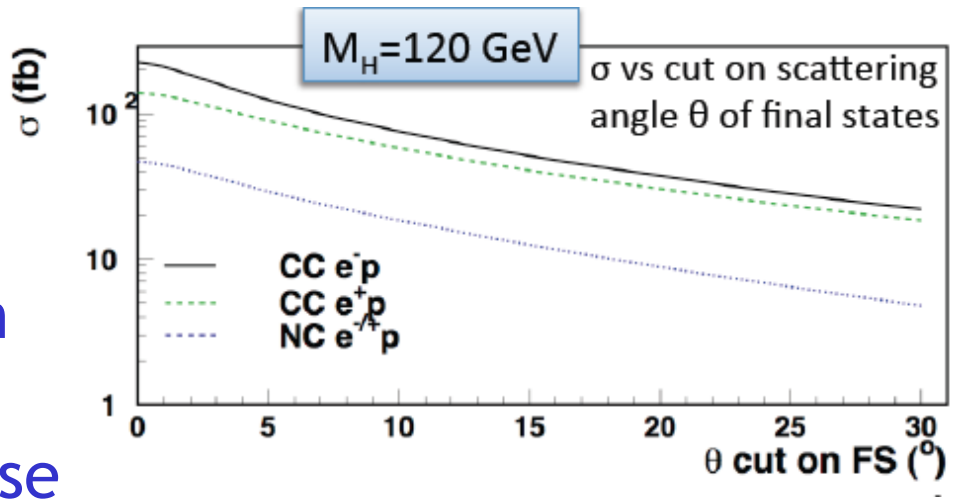
- Revolutionises knowledge of nuclear structure

# 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°

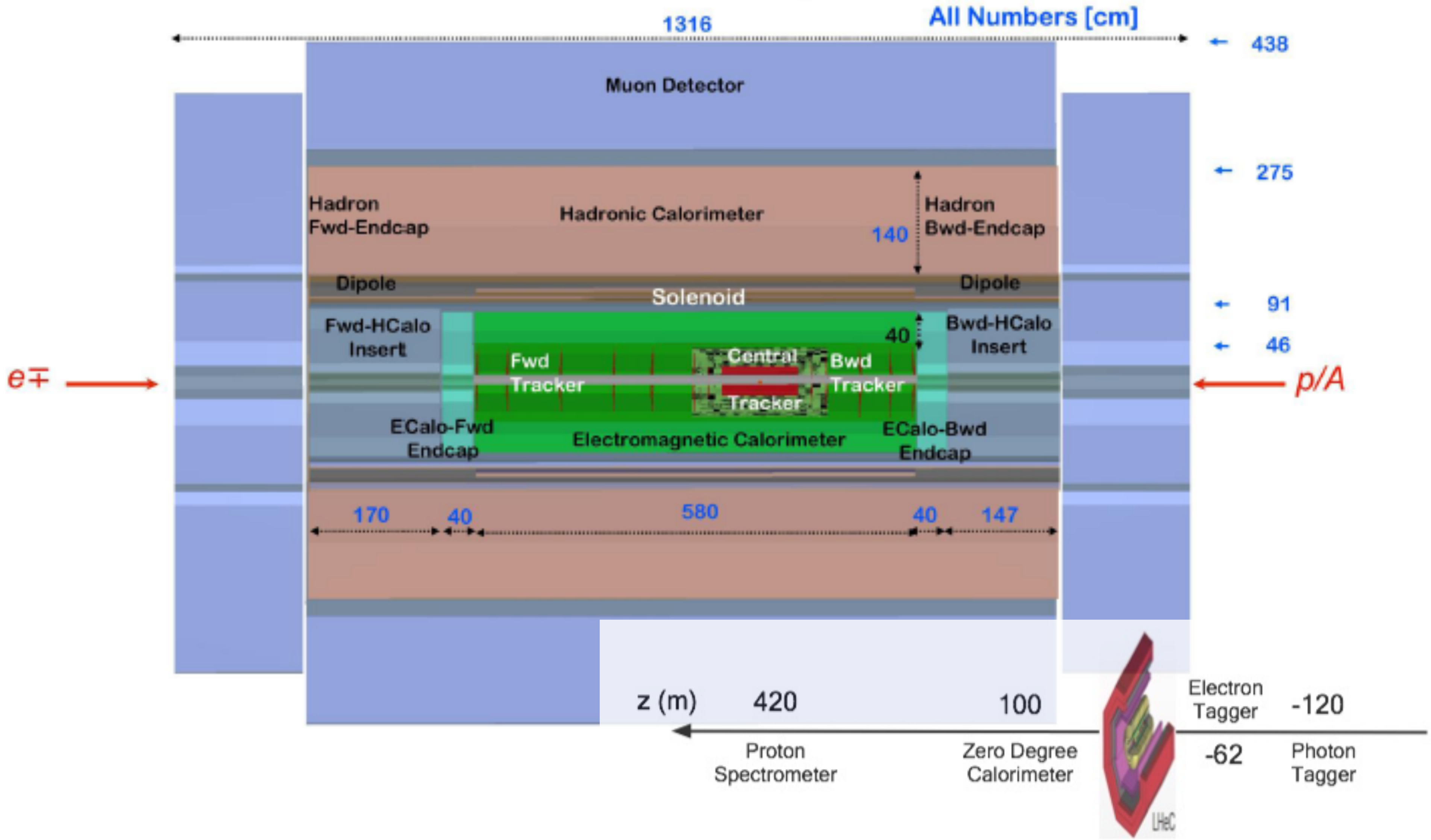



Also need 1° acceptance in proton direction to contain hadrons for kinematic reconstruction, maximise acceptance for H, new massive particles, Mueller-Navelet jets …

# Detector Design Overview



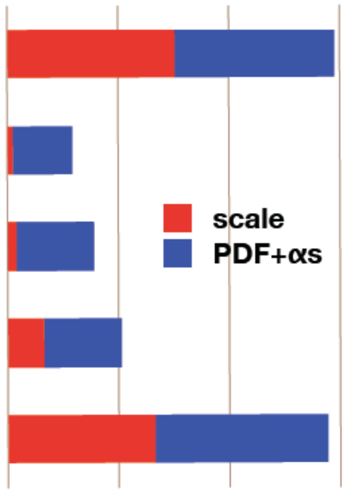

- Present size 13m x 9m (c.f. CMS 21m x 15m, ATLAS 45m x 25m)
- 1° tracking acceptance in both forward & backward directions
- Forward & backward beam-line instrumentation integrated

# Why PDFs? → Uncertainties for LHC Higgs

## Theory Cross Section Uncertainties

(125 GeV Higgs
J Campbell, ICHEP'12)

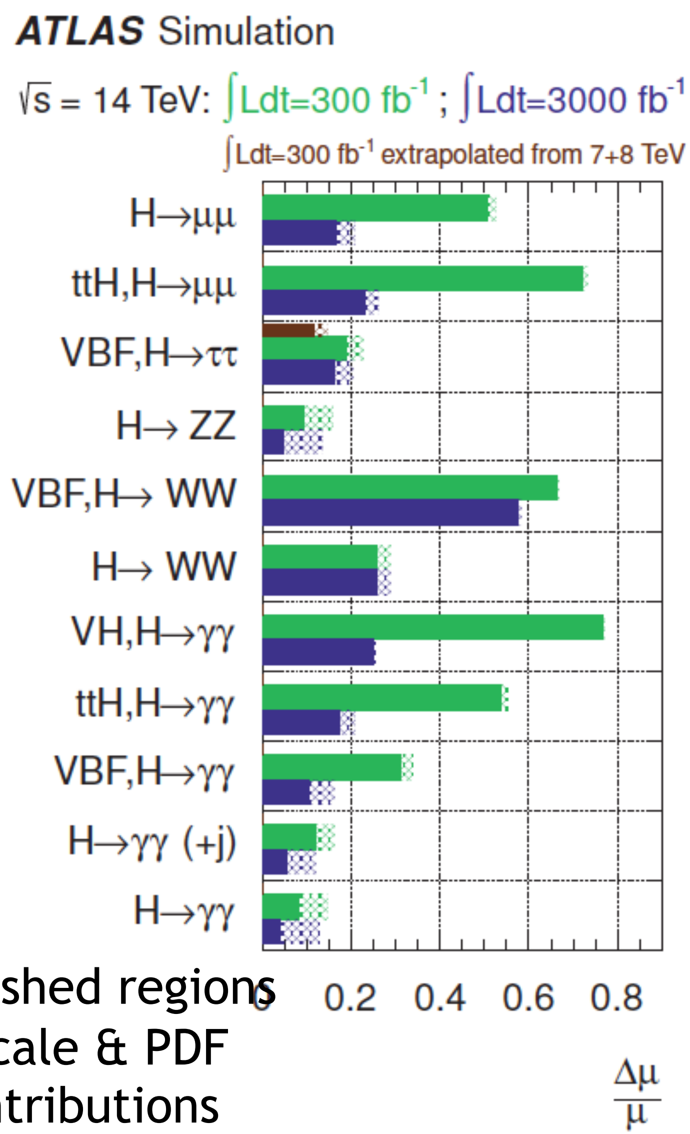
| Order | Process | σ (8 TeV) | uncertainty |
|---|---|---|---|
| NNLL QCD +NLO EW | gg→H | 19.5 pb | 14.7% |
| | VBF | 1.56 pb | 2.9% |
| NNLO QCD +NLO EW | WH | 0.70 pb | 3.9% |
| | ZH | 0.39 pb | 5.1% |
| NLO QCD | ttH | 0.13 pb | 14.4% |




Similarly fermionic modes (bbbar, ccbar)

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

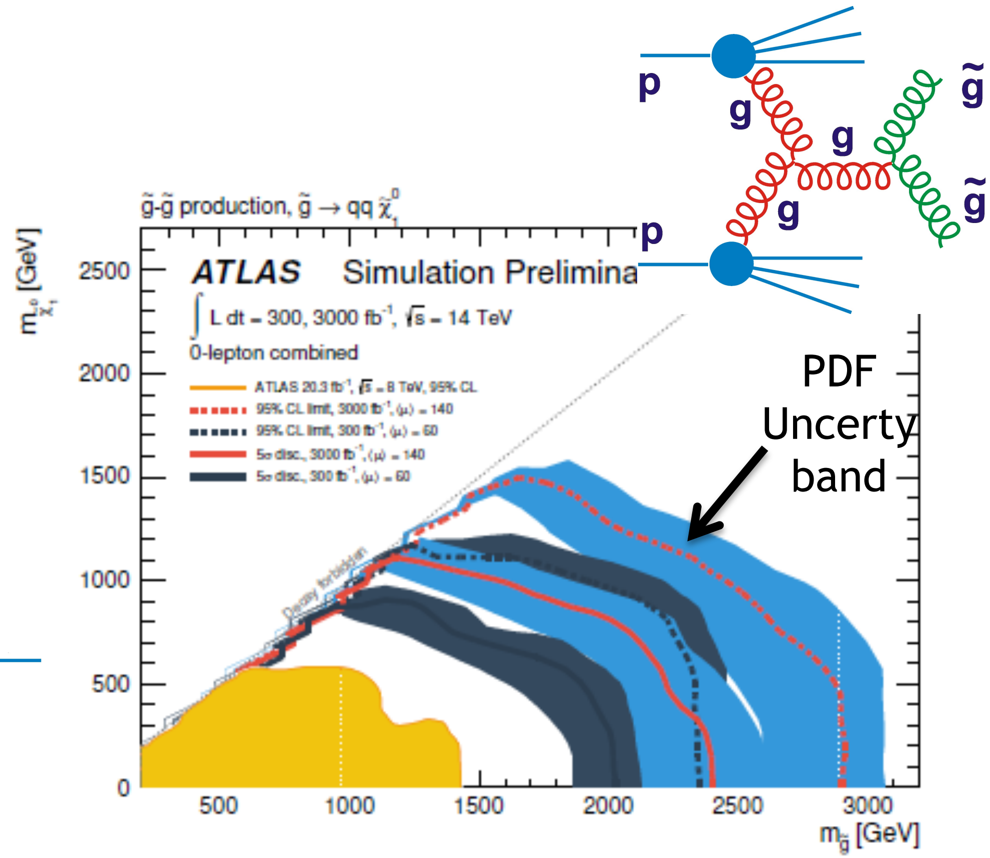
## Projected Experimental Uncertainties

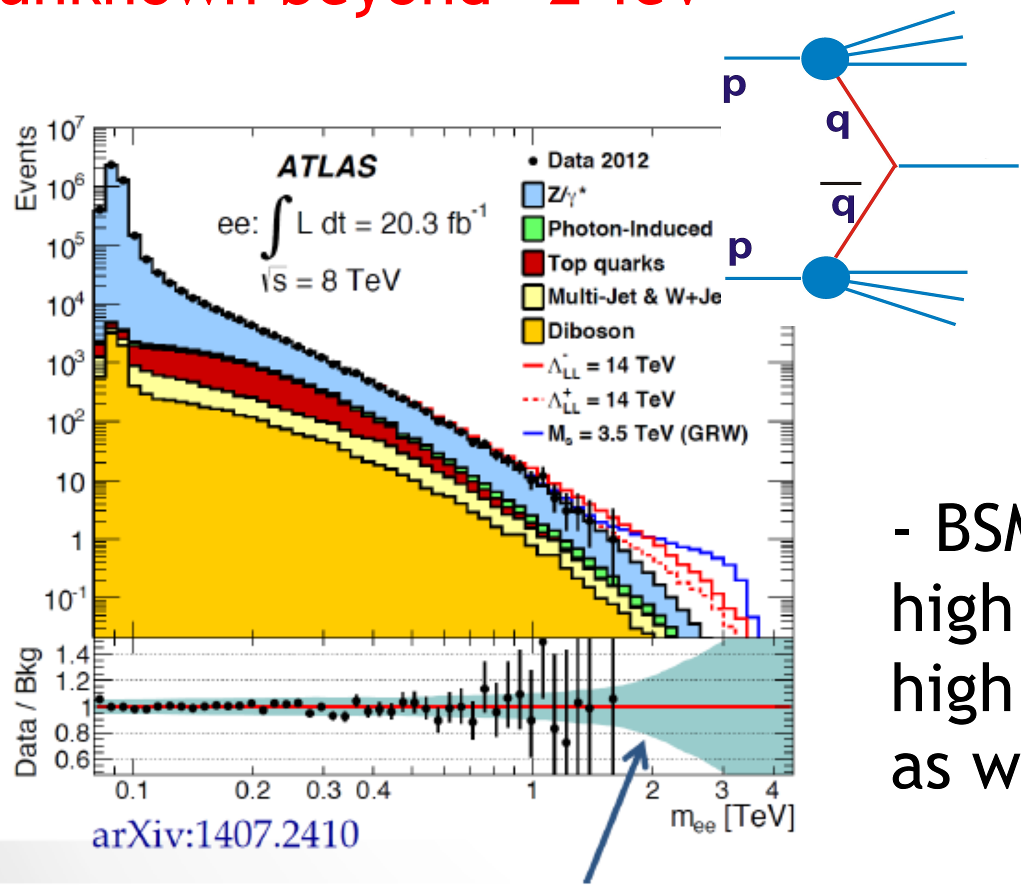



[Dashed regions = scale & PDF contributions

# PDFs → New High Mass LHC Particles

- Gluino signature is excess @ large invariant mass
- Both signal & background uncertainties driven by error on gluon density … essentially unknown beyond ~2 TeV



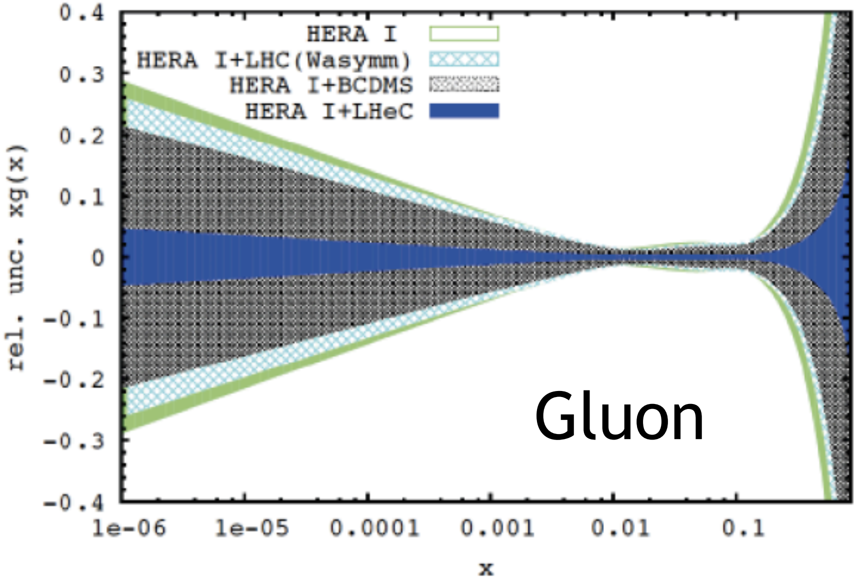



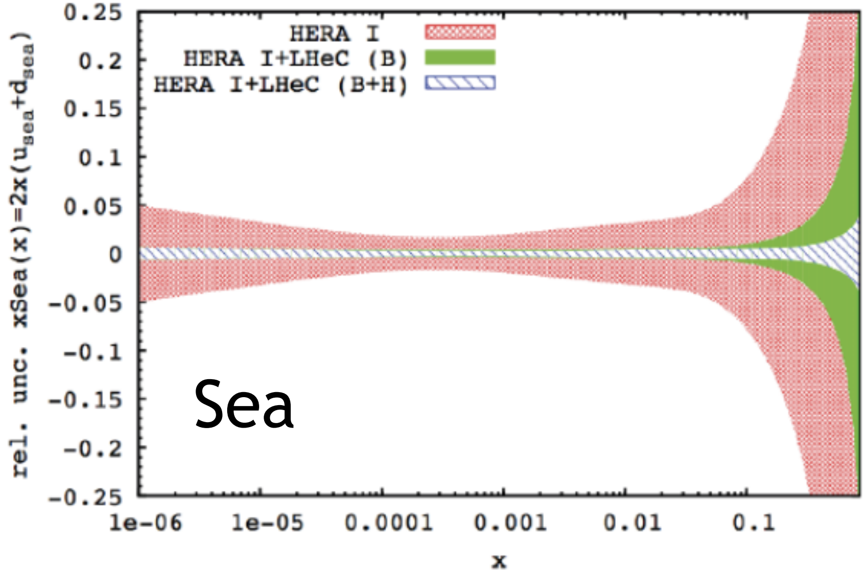

arXiv:1407.2410

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

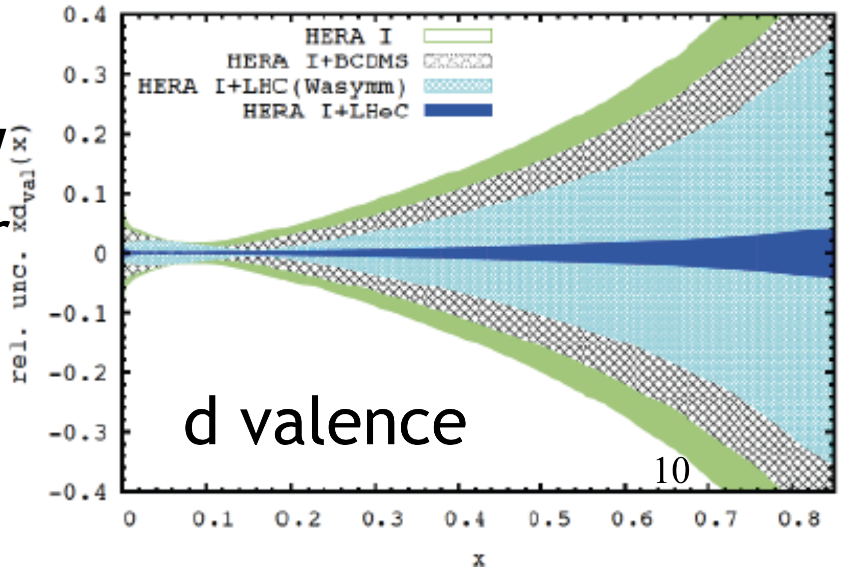
# PDF Constraints at LHeC

Full simulation of inclusive NC and CC DIS data, including systematics → NLO DGLAP fit using HERA technology…

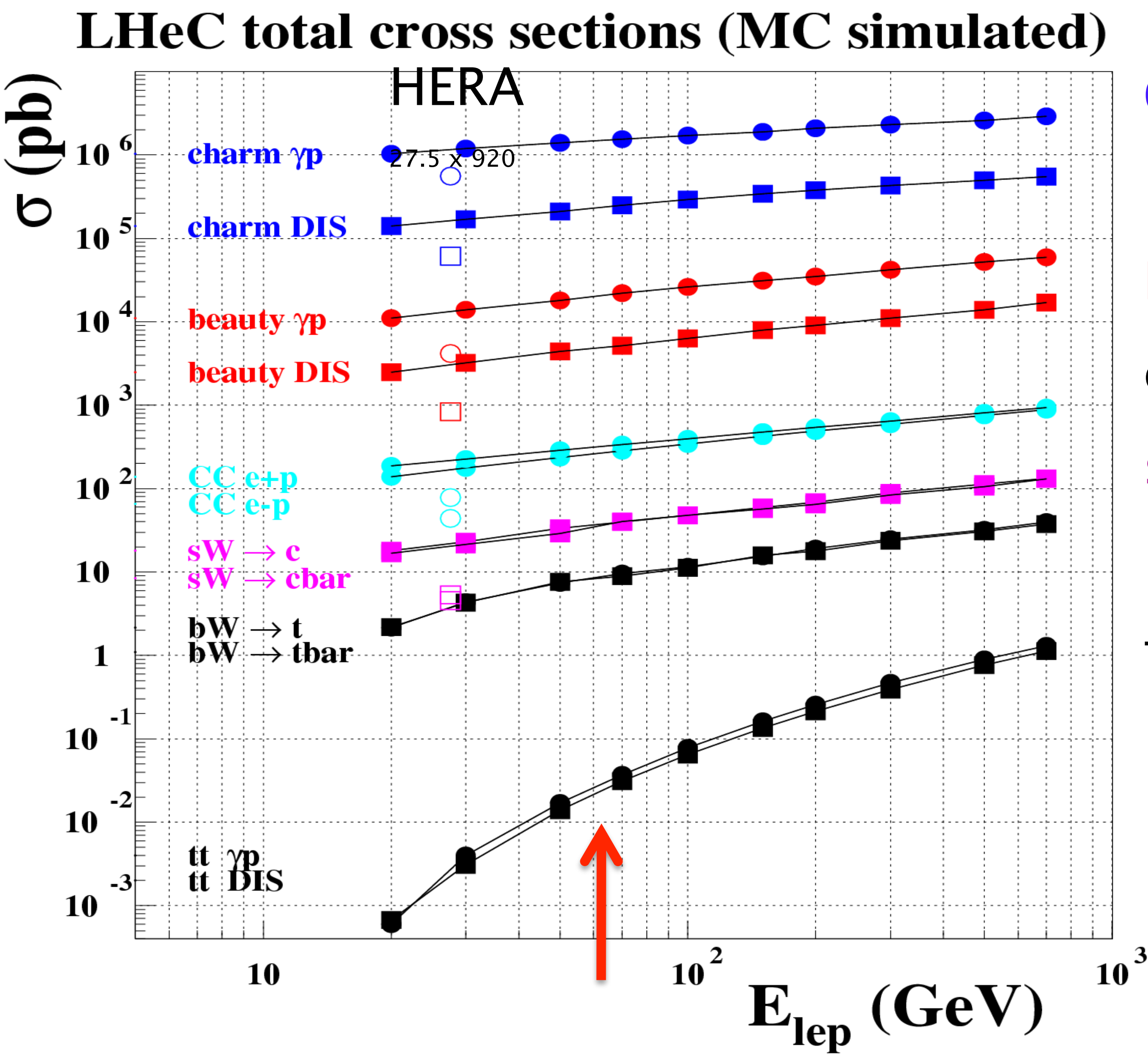



- Low x → novel QCD / unitarity
- Medium x → precision Higgs and EW
- High x → new particle mass frontier
- Per-mille experimental $\alpha_s$ precision
- Full Flavour decomposition



# Cross Sections and Rates for Heavy Flavours




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

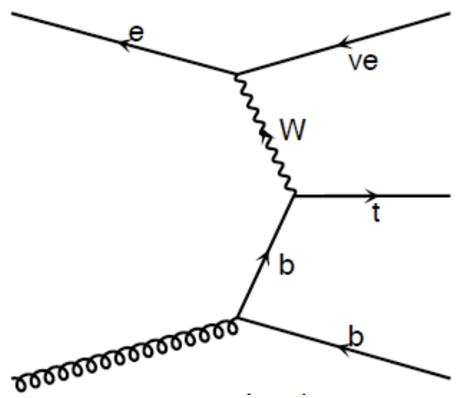
Beauty [$10^{8}$ / 10 $fb^{-1}$]

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

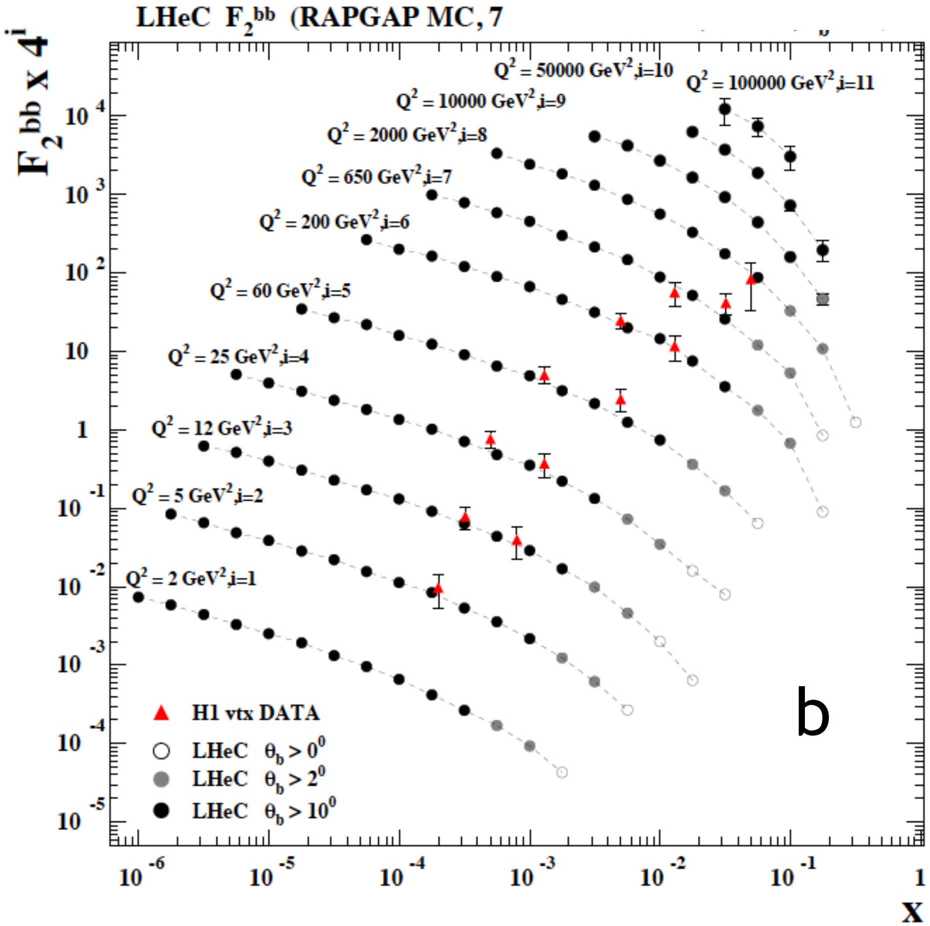
# Flavour Decomposition

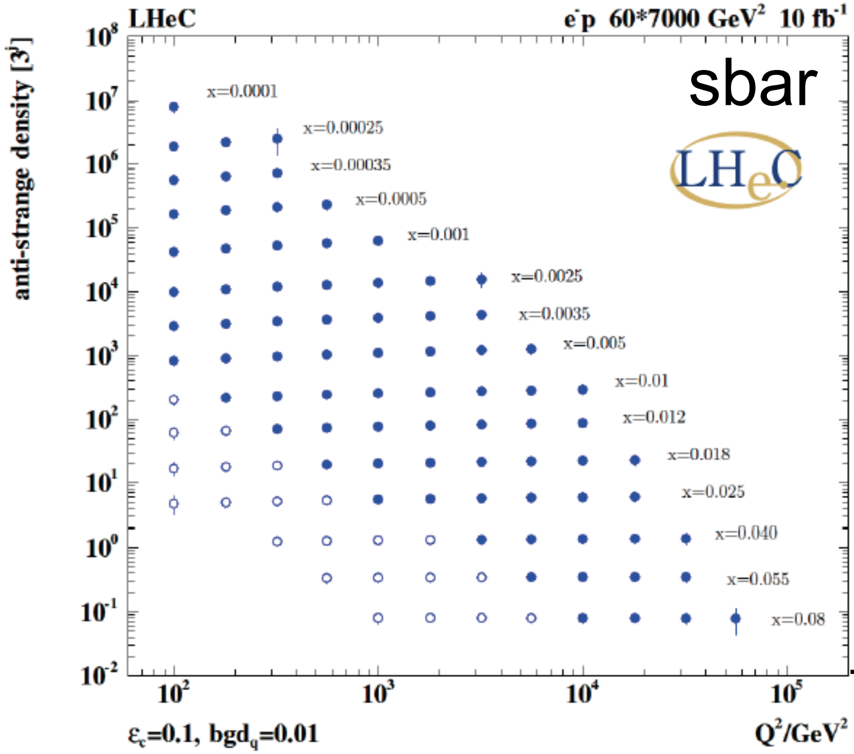
Precision c, b measurements (modern Si trackers, beam spot 15 * 35 $\mu m^2$ , increased HF rates at higher scales).

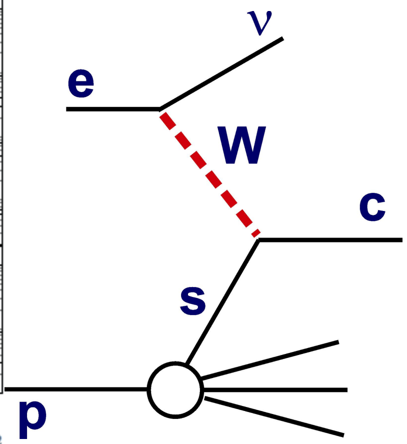
Systematics at 10% level

→beauty as a low x observable

→s, sbar from charged current

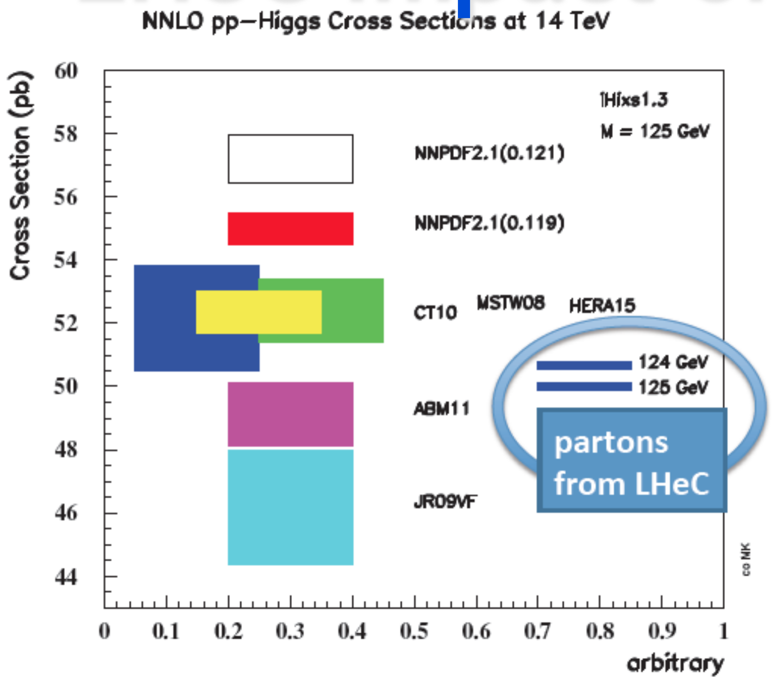



(Assumes 1 fb$^{-1}$ and
- 50% beauty, 10% charm efficiency
- 1% uds → c mistag probability.
- 10% c → b mistag)

# LHeC Impact on LHC Higgs PDF Unc'ty

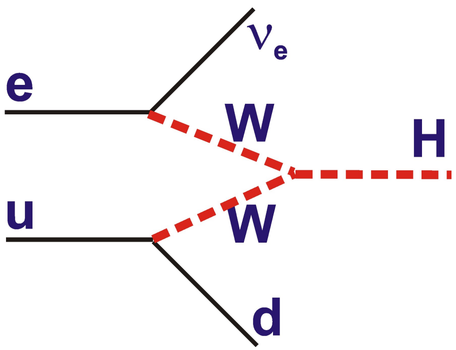



... needs $N^3LO$ Higgs calculation

... needs improved $\alpha_s$ measurement (also @ LHeC)

c.f. experimental uncertainty ~0.25%

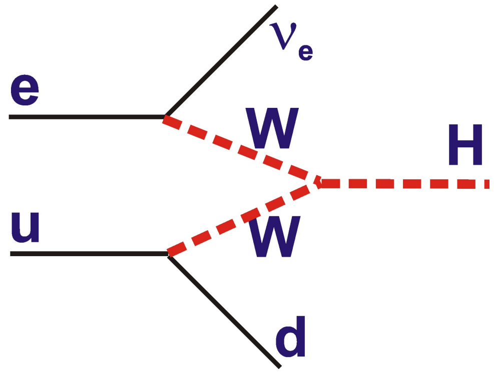
# Higgs Production at LHeC & FCC-eh




Estimated integrated yields ...

| Higgs in $e^-p$ | | CC - LHeC | NC - LHeC | CC - FHeC |
|---|---|---|---|---|
| Polarisation | | -0.8 | -0.8 | -0.8 |
| Luminosity [$ab^{-1}$] | | 1 | 1 | 5 |
| Cross Section [fb] | | 196 | 25 | 850 |
| Decay | BrFraction | $N^H_{CC}$ | $N^H_{NC}$ | $N^H_{CC}$ |
| $H \to b\bar{b}$ | 0.577 | 113 100 | 13 900 | 2 450 000 |
| $H \to c\bar{c}$ | 0.029 | 5 700 | 700 | 123 000 |
| $H \to \tau^+\tau^-$ | 0.063 | 12 350 | 1 600 | 270 000 |
| $H \to \mu\mu$ | 0.00022 | 50 | 5 | 1 000 |
| $H \to 4l$ | 0.00013 | 30 | 3 | 550 |
| $H \to 2l2\nu$ | 0.0106 | 2 080 | 250 | 45 000 |
| $H \to gg$ | 0.086 | 16 850 | 2 050 | 365 000 |
| $H \to WW$ | 0.215 | 42 100 | 5 150 | 915 000 |
| $H \to ZZ$ | 0.0264 | 5 200 | 600 | 110 000 |
| $H \to \gamma\gamma$ | 0.00228 | 450 | 60 | 10 000 |
| $H \to Z\gamma$ | 0.00154 | 300 | 40 | 6 500 |

# A Direct Higgs Study

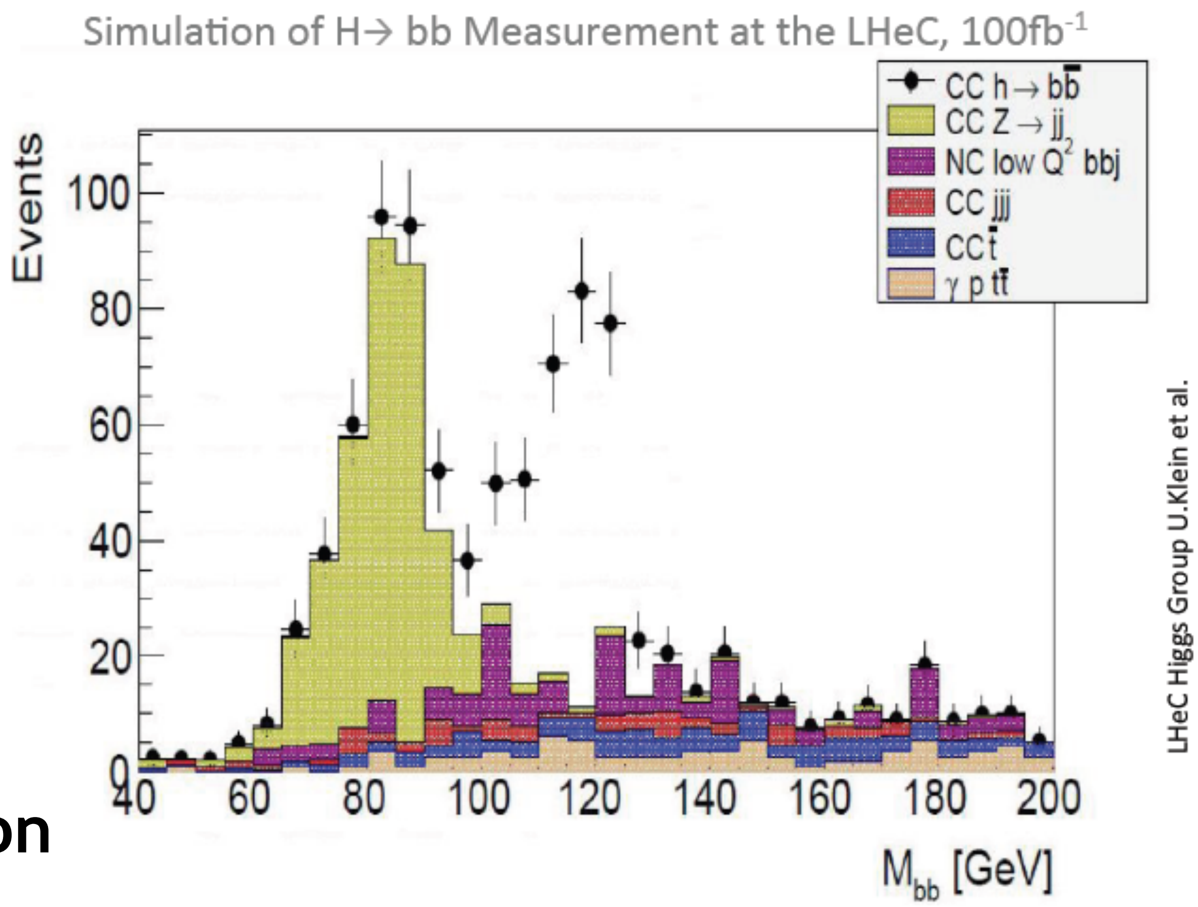



## Study of H → bbbar in generic simulated LHC detector

- 80% lepton polarisation enhances signal by factor 1.7

- Signal/Background ~ 1-2

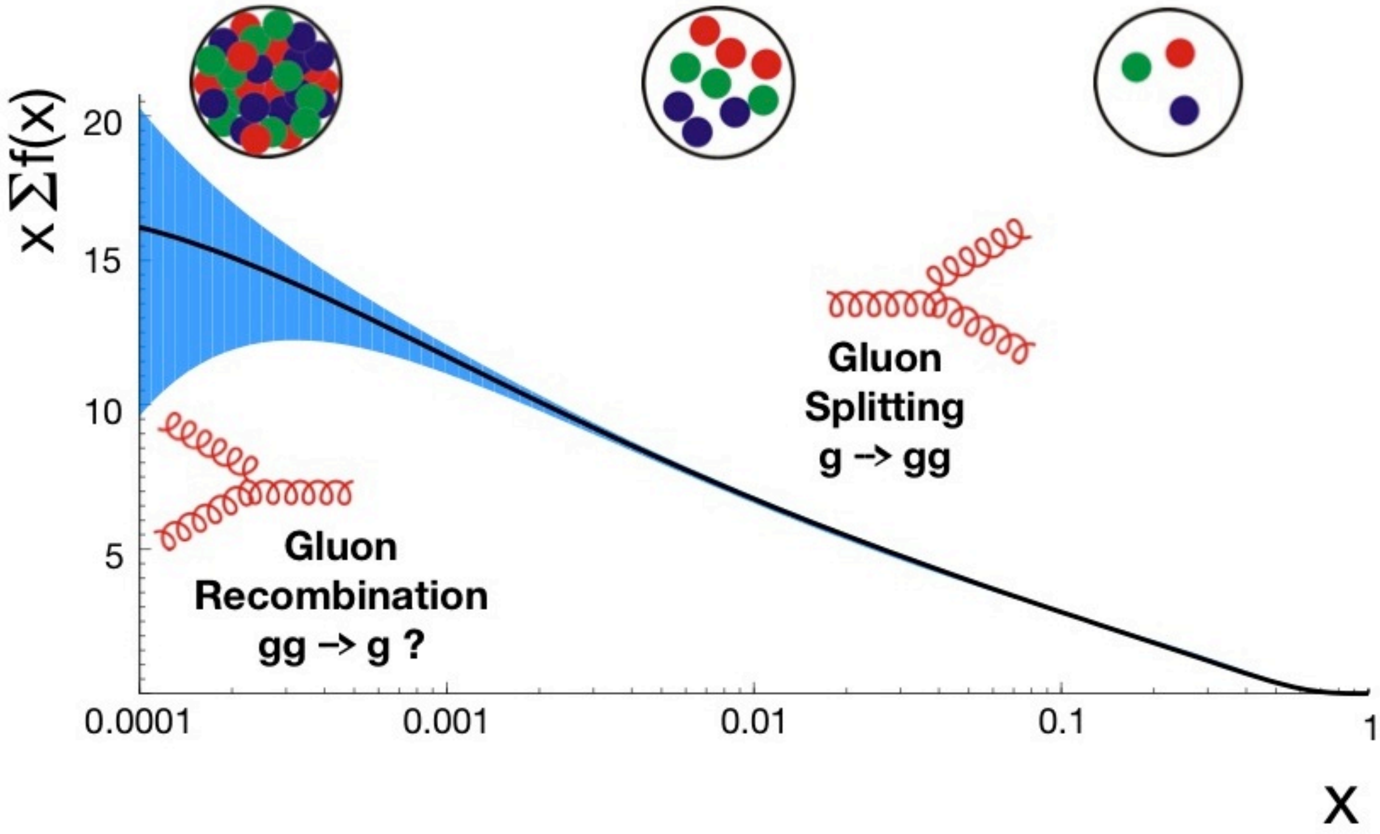
- With $10^{34}$ luminosity, x10 more data
  → ~1% H→bbbar coupling …
  **way beyond LHC precision**




… ongoing studies of LHeC H→ccbar and FCC-eh possibilities

# Low-x Physics and Parton Saturation

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

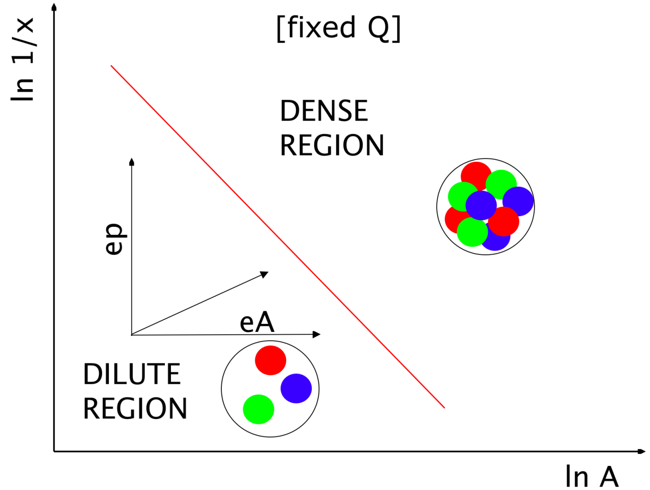



→ new high density, small coupling parton regime of non-linear parton evolution dynamics (e.g. Colour Glass Condensate)? …
… gluon dynamics → confinement and hadronic mass generation

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

# LHeC: Accessing saturation region at large $Q^2$

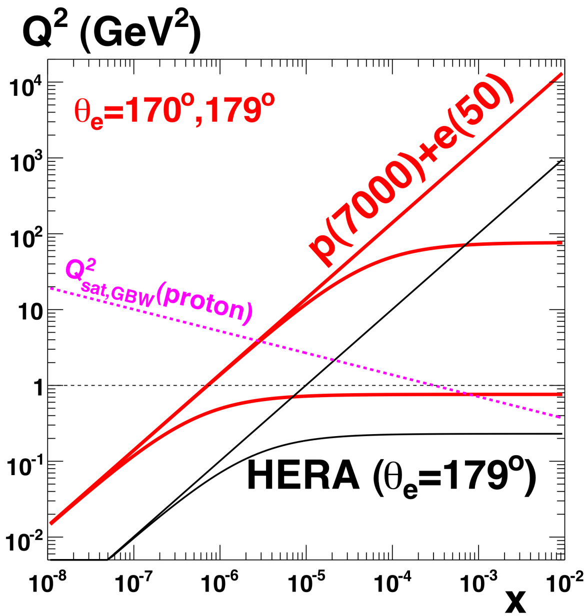
LHeC delivers a 2-pronged approach:

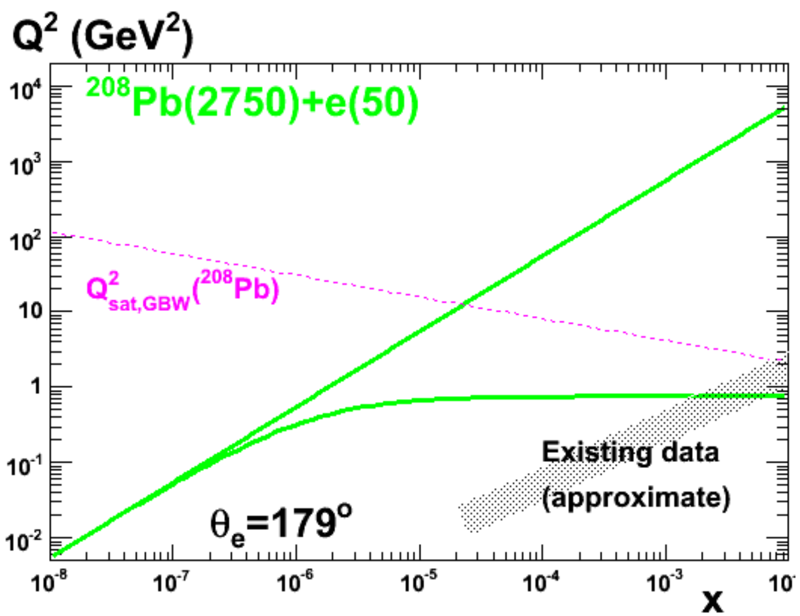



Enhance target `blackness' by:

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]



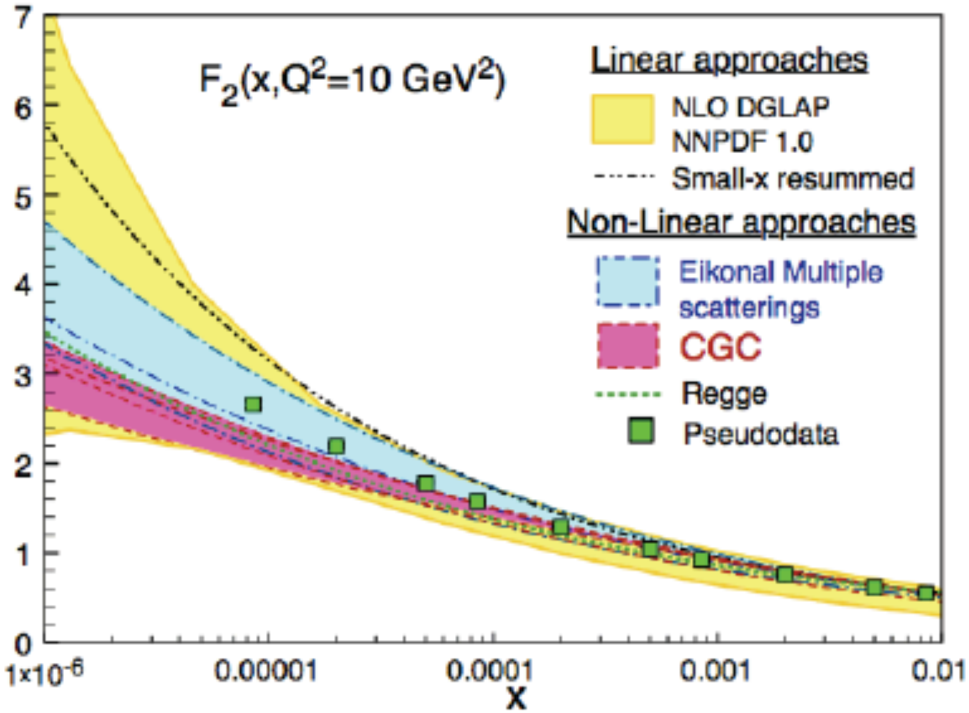



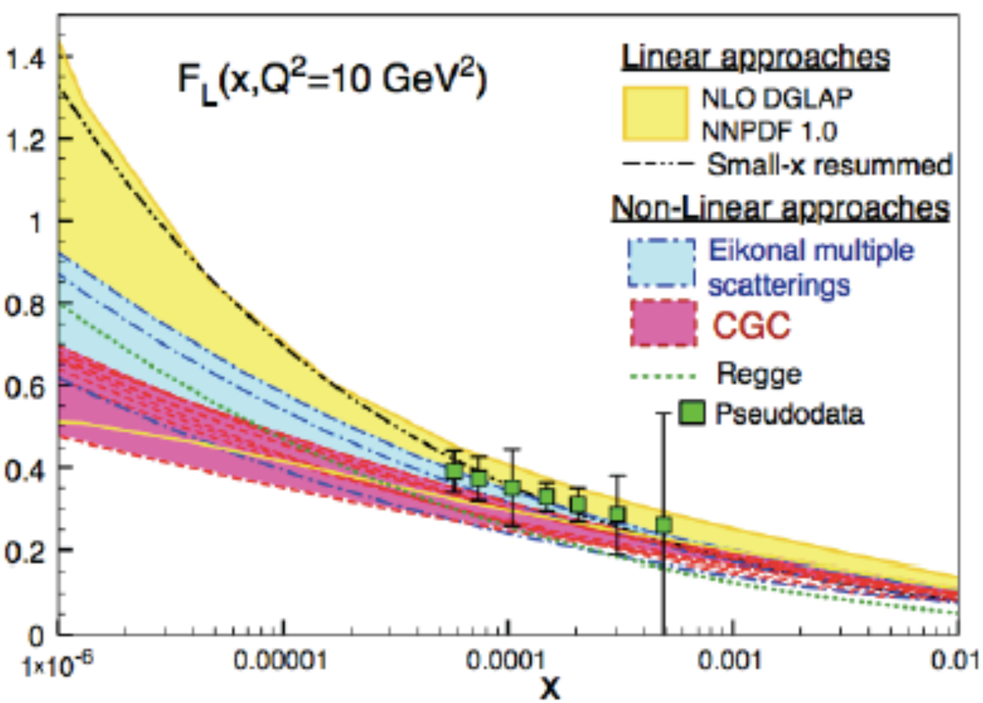

… Reaches saturated region in both ep & eA inclusive data according to models

# 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 $E_p$

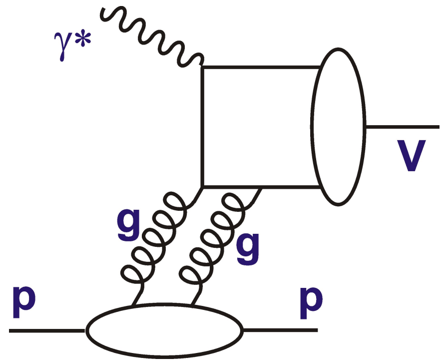


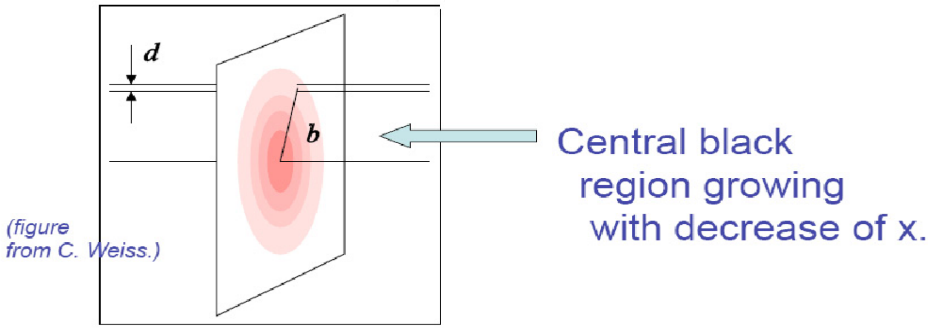

- LHeC can distinguish between different QCD-based models for the onset of non-linear dynamics
- Unambiguous observation of saturation will be based on tension between different observables e.g. $F_2$ v $F_L$ in ep or $F_2$ in ep v eA

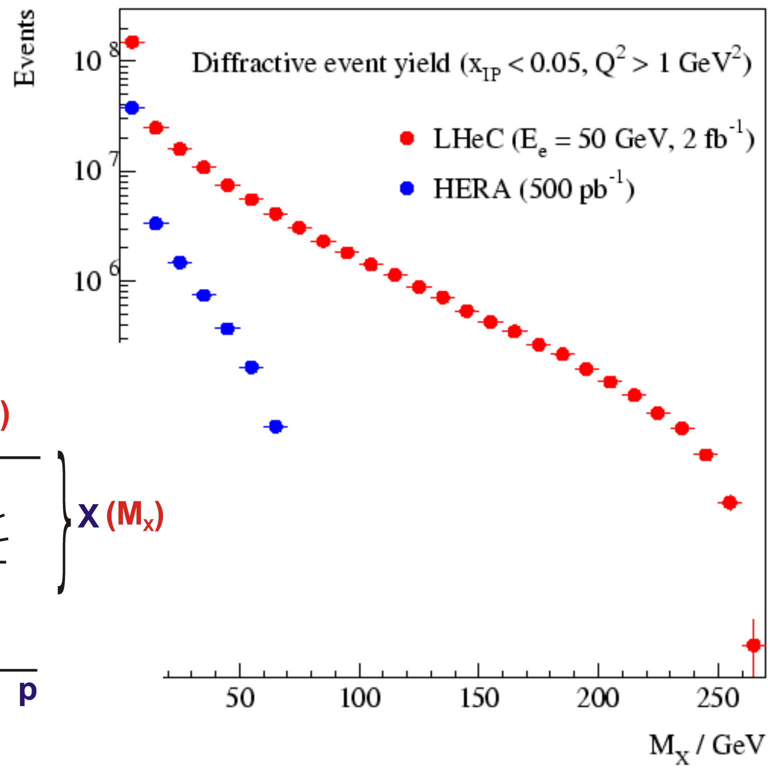
# Exclusive / Diffractive Channels and Saturation

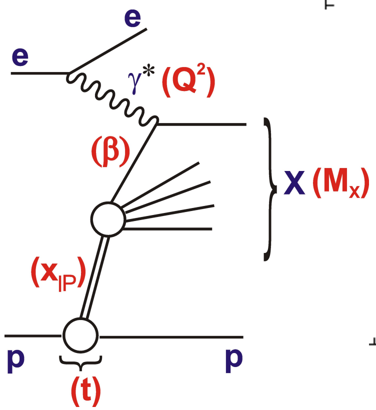
• [Low-Nusinov] interpretation as 2 gluon exchange → enhanced low x gluon sensitivity




• Additional variable t provides impact parameter (b) dependent amplitudes → Large t (small b) probes densest region of proton



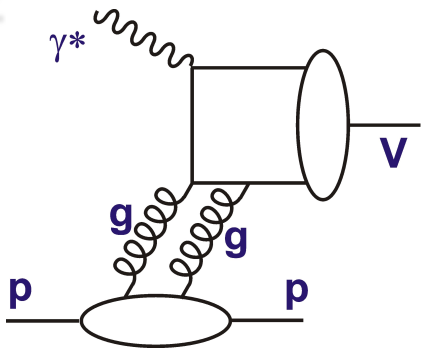




→ Investigations of exclusive VM production, DVCS, inclusive diffraction & diffractive dijets

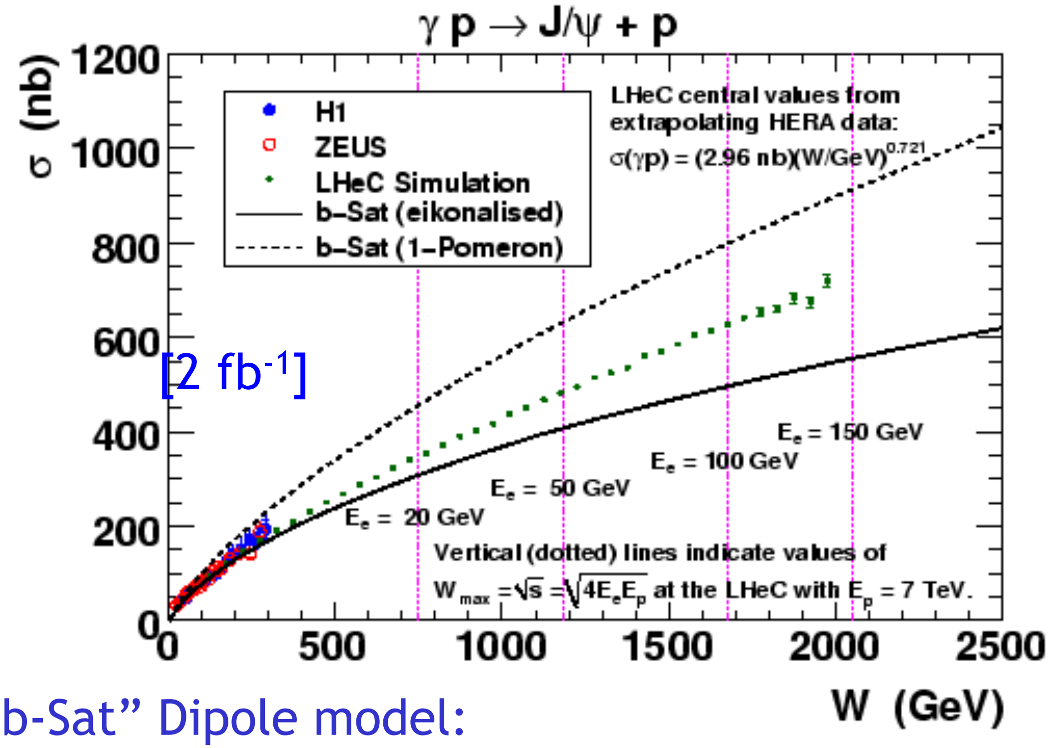
→ Any $1^-$ system with mass up to 250 GeV accessible

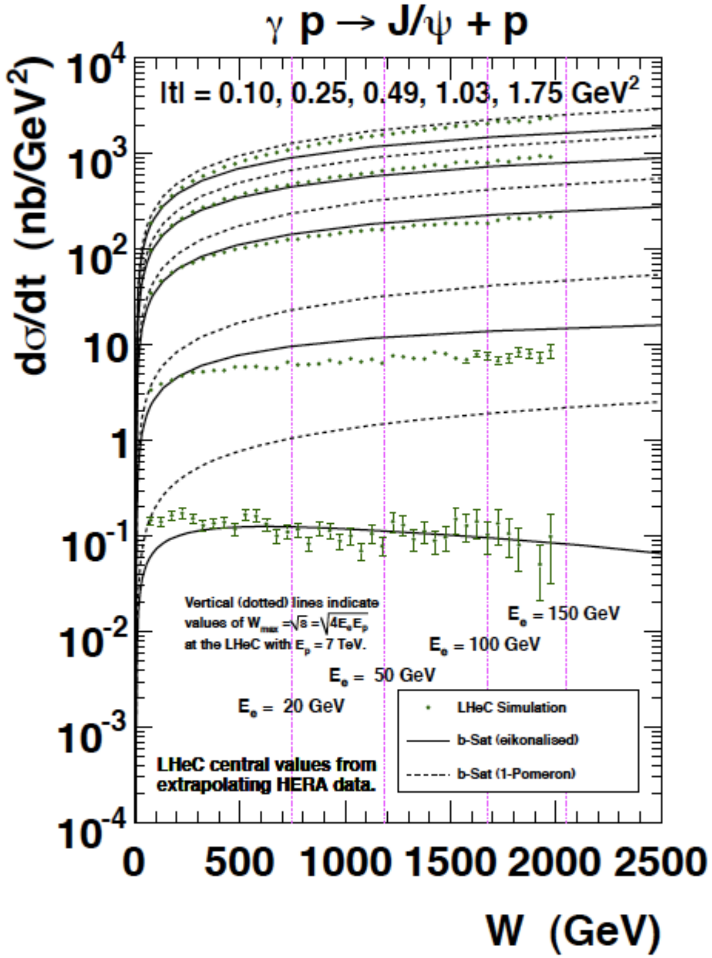
# e.g. J/ψ Photoproduction v W, t & $Q^2$




Precise kinematic reconstruction from decay μ tracks over wide W and $Q^2$ range to |t| ~ 2 $GeV^2$

• Significant non-linear effects expected in LHeC kinematic range

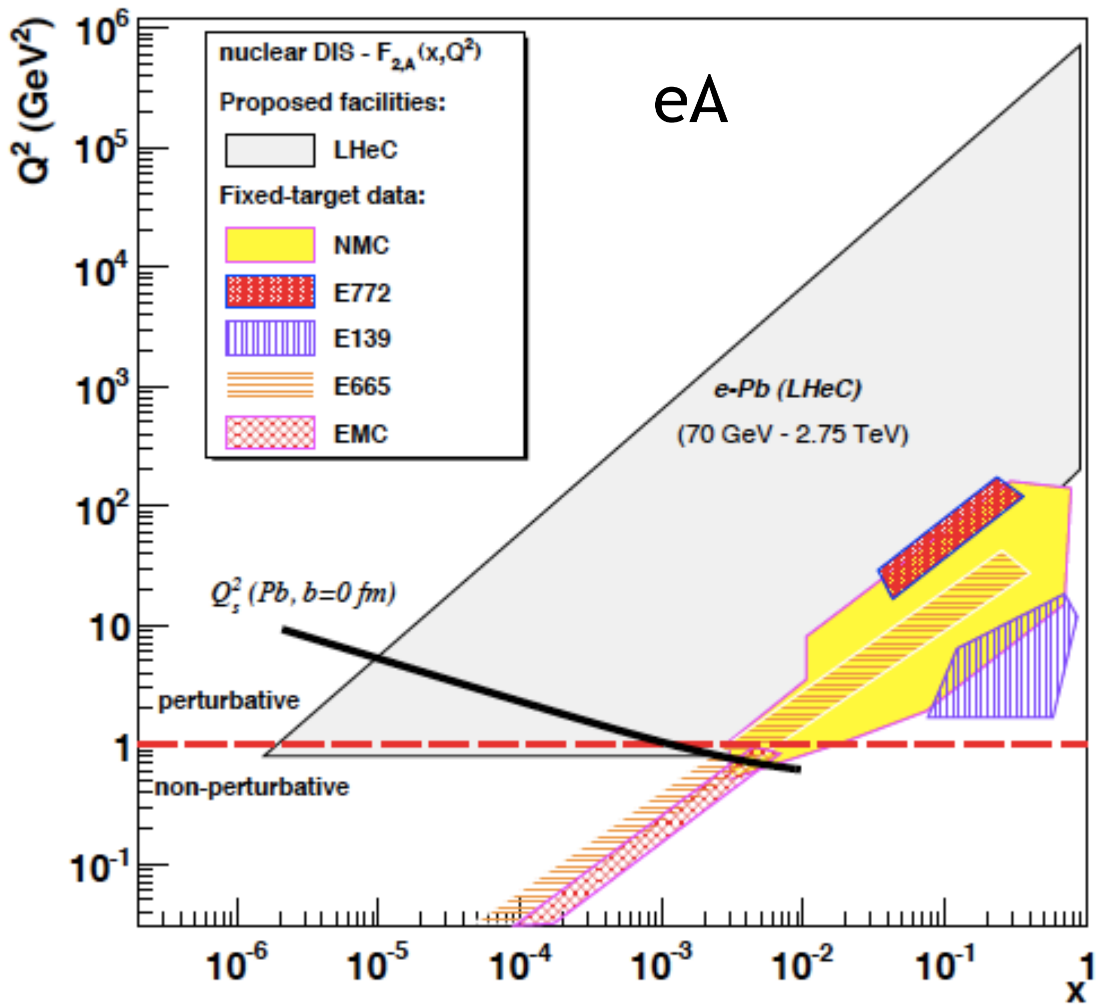



"b-Sat" Dipole model:
- "eikonalised" – with IP-dependent saturation
- "1 Pomeron": non-saturating

# LHeC as an Electron-Ion Collider

**Four orders of magnitude increase in kinematic range over previous DIS experiments → Wide ranging programme …**

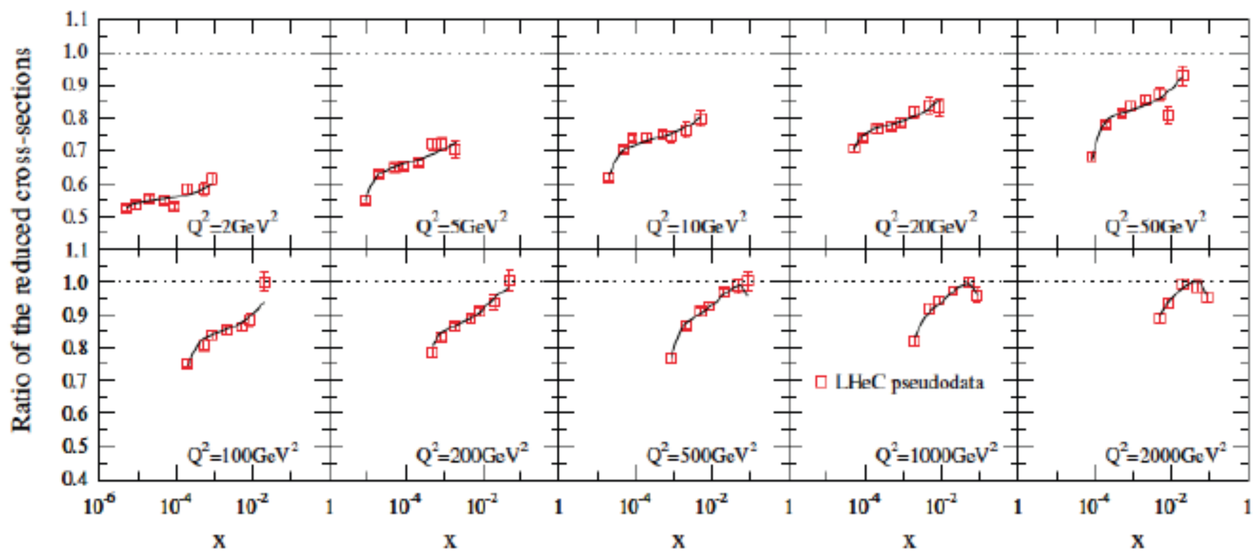



→ Revolutionises knowledge of nuclear partonic structure

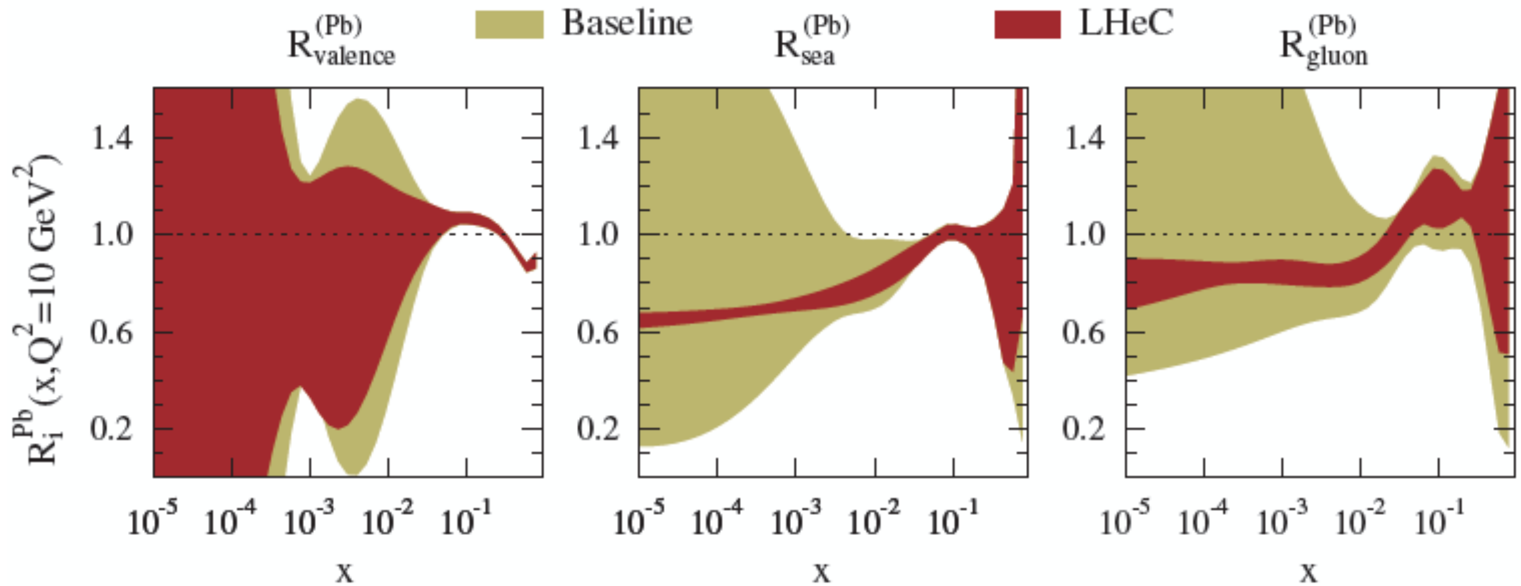
→ Low x / diffactive eA programme gives additional lens on densely packed, weakly coupled, partons

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

# Impact of Simulated ePb LHeC $F_2$ & $F_L$ data

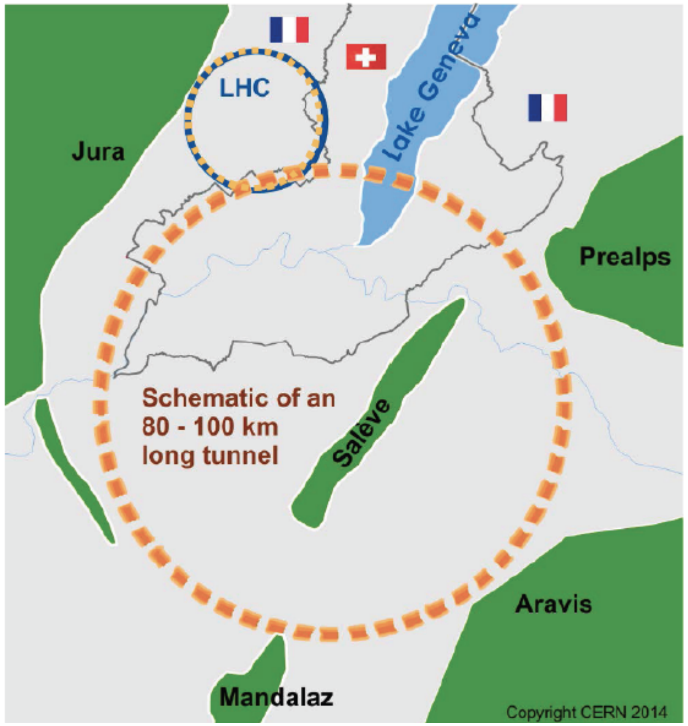



- Studies in context of EPS'09 nPDF set, with more flexible low x parameterisation at starting scale …
- LHeC data have huge impact on low x gluon & sea uncertainties






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

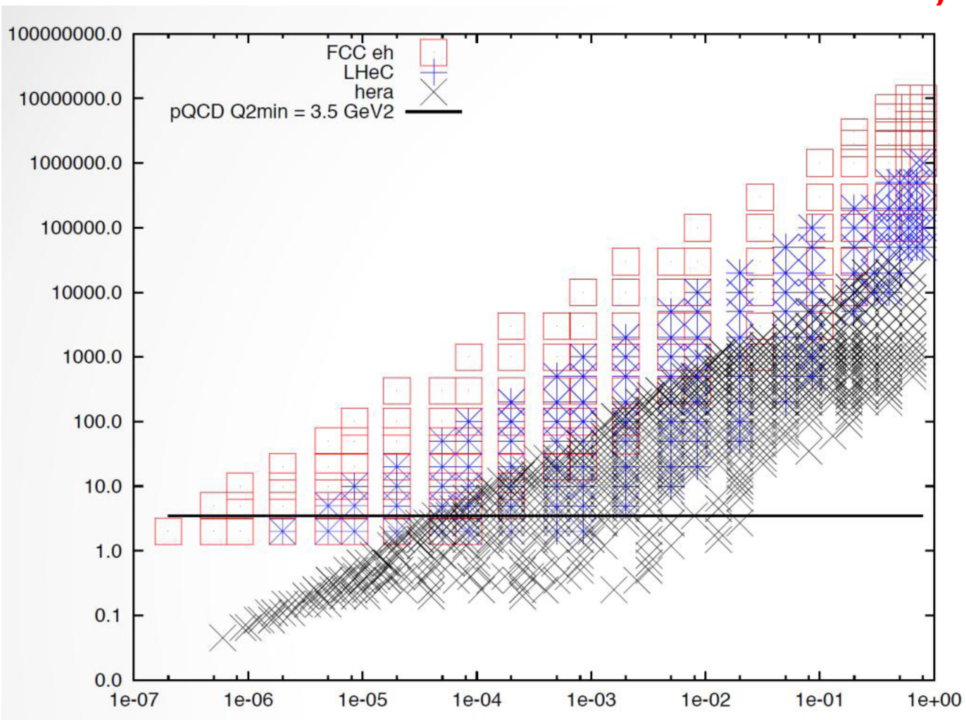



# First Thoughts on FCC-he

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]

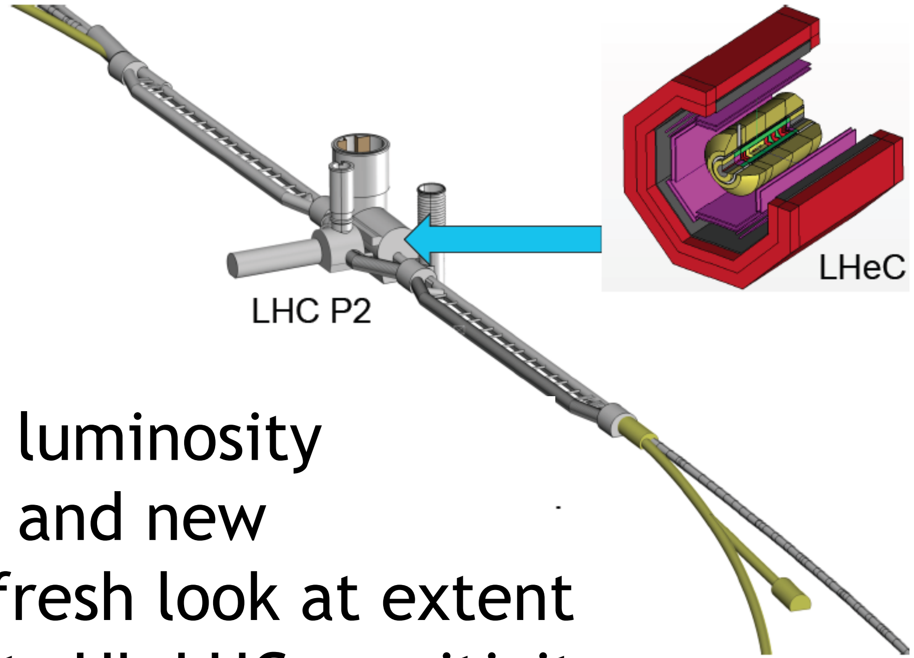
-Total FCC-he H x-sec ~ 1 pb, lumi ~ $10^{34}$ $cm^{-2}s^{-1}$, H→HH x-sec ~0.5 fb in range?...




- 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



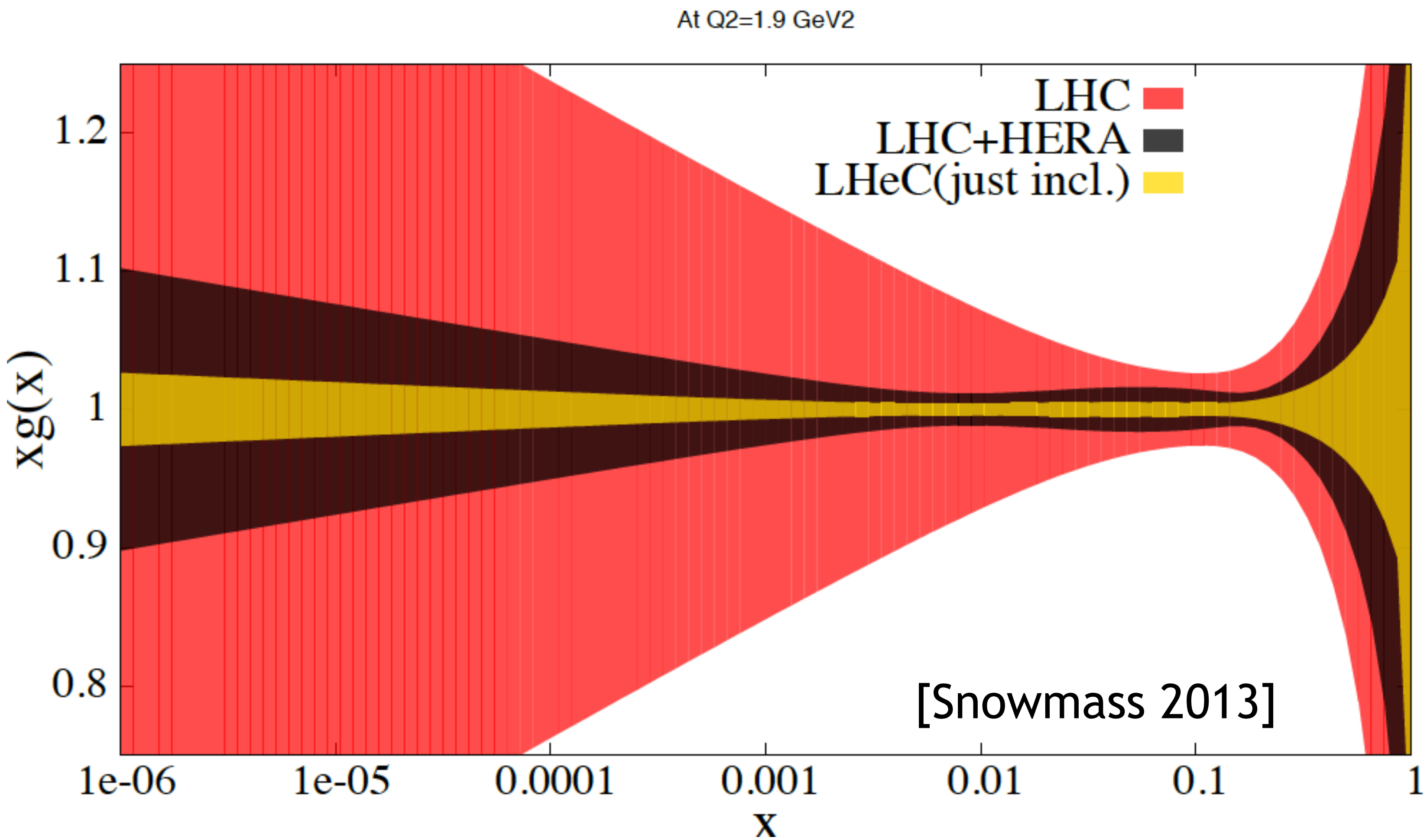

- LHeC CDR 2012 + ongoing work

- 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)
  4) Longer term perspective of LHC and possibility of FCC

- For more on recent updates, see also:
  - POETIC'15: (Nestor Armesto, Claire Gwenlan, Max Klein)
  - Slides from recent LHeC Chavannes Workshop (June 2015)
  - LHeC web: http://lhec.web.cern.ch

# Back-Ups Follow

# What can be done with LHC alone?



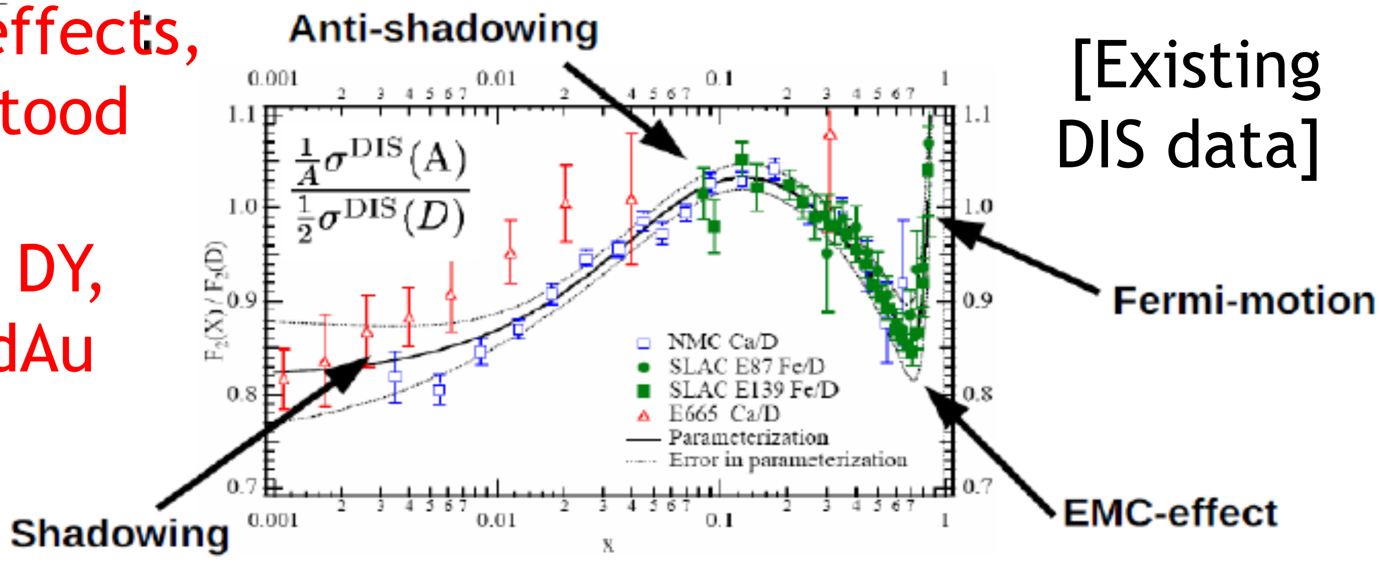

- LHC = current LHC W, Z and jet data
- Remarkable what can be achieved with LHC data alone
- Can we improve substantially? – Often already systs limited

# Current Status of Nuclear Parton Densities

- Complex nuclear effects, not yet fully understood

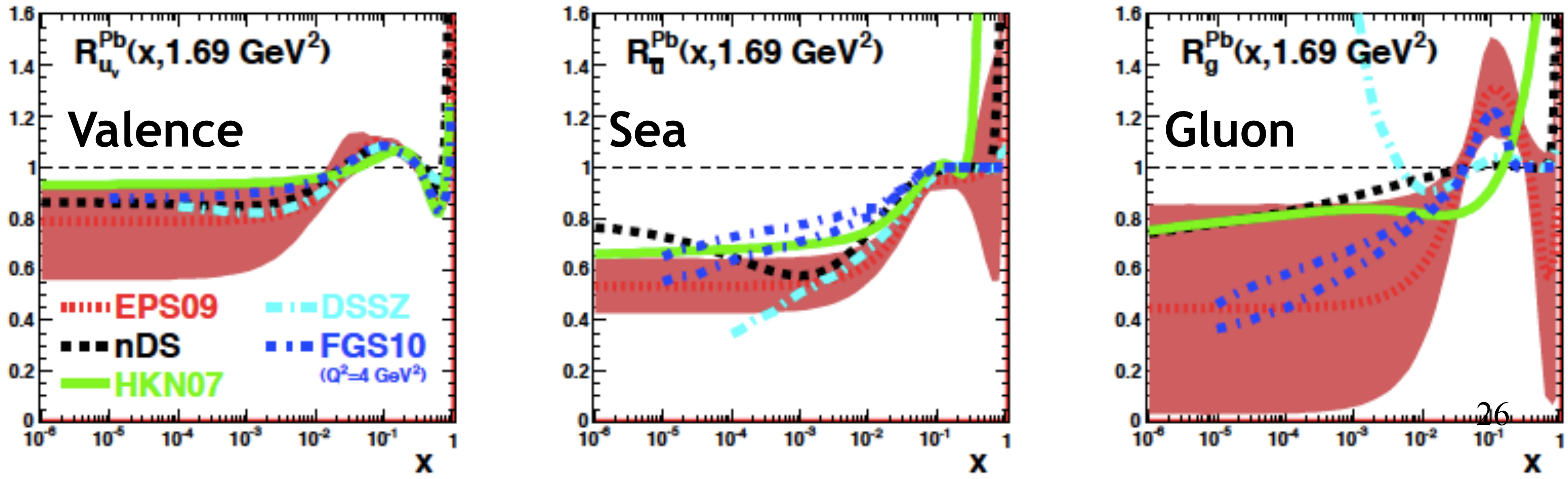
- Quarks from DIS & DY, Gluon mainly from dAu single $\pi^0$ rates

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

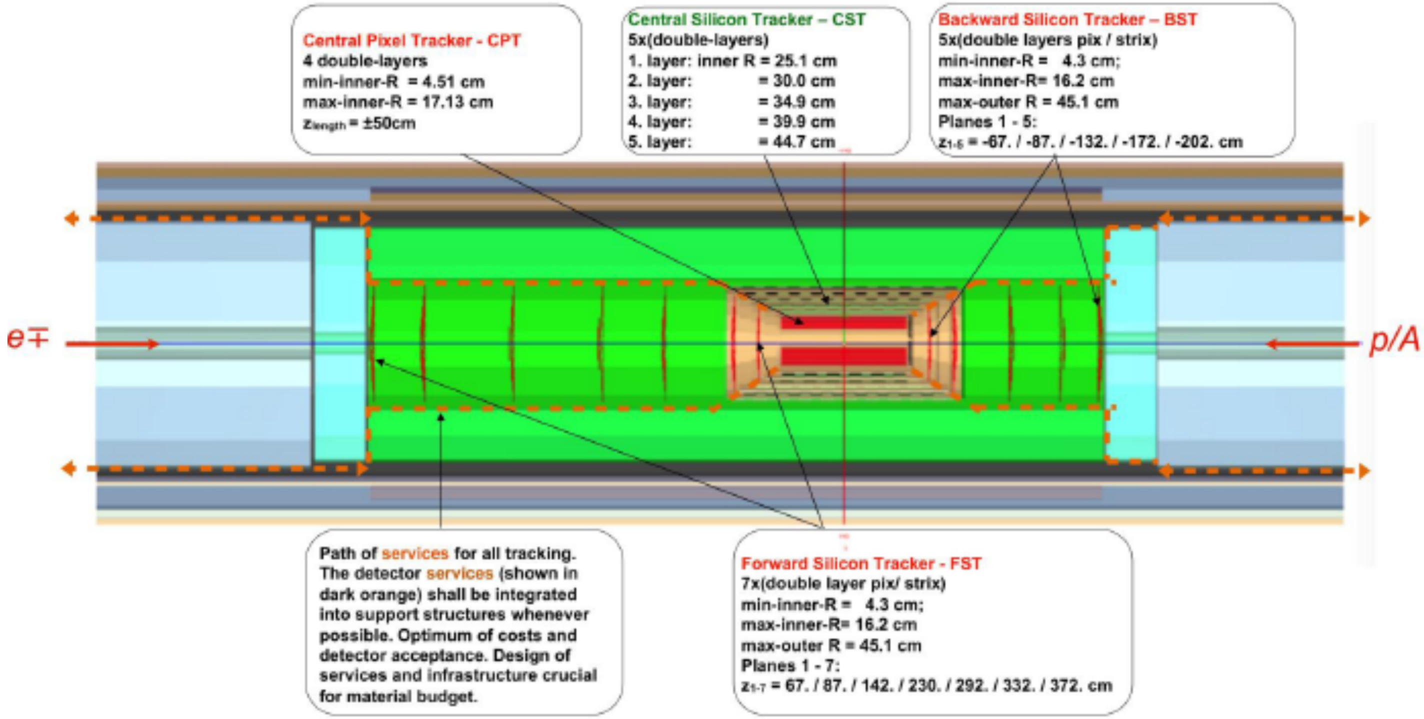



[Existing DIS data]

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

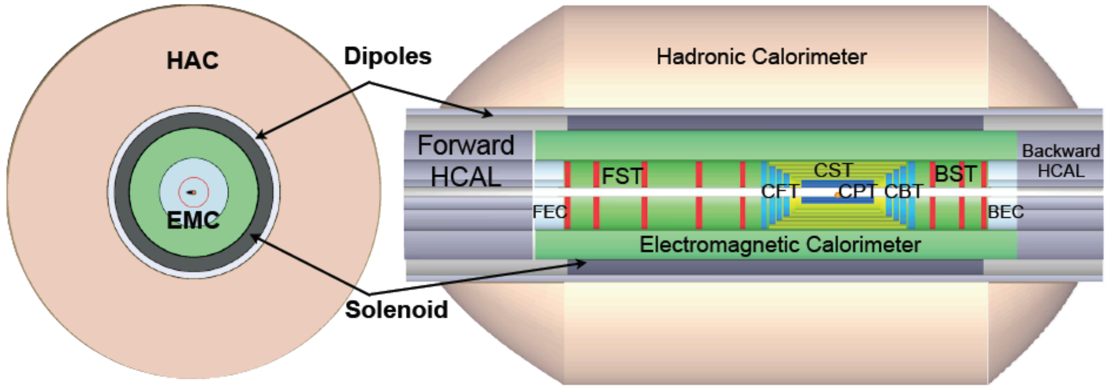


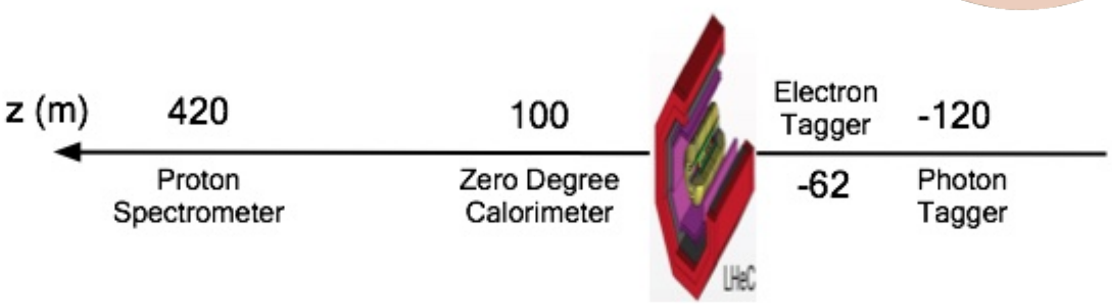
# Detector Details




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

- Lar / Tile calorimeter leaning heavily on LHC experience



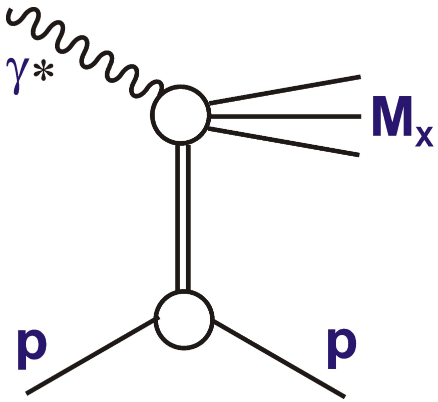



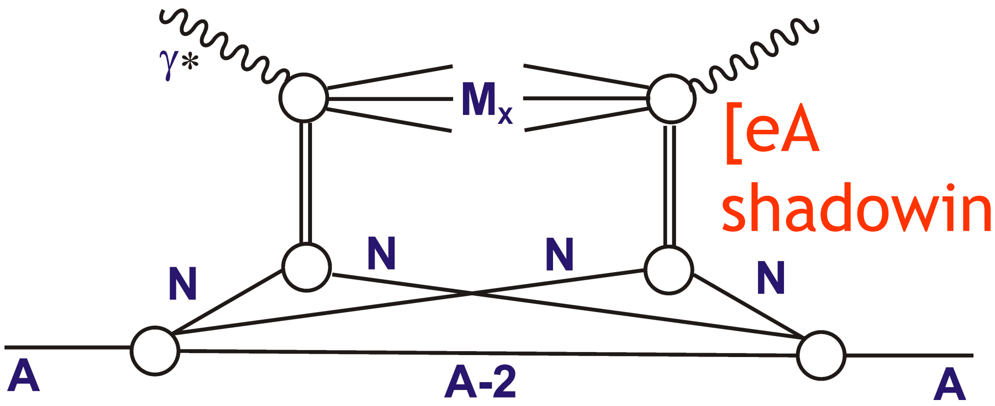

- Beamline insrumentation considered from outset.

# $F_2^D$ and Nuclear Shadowing

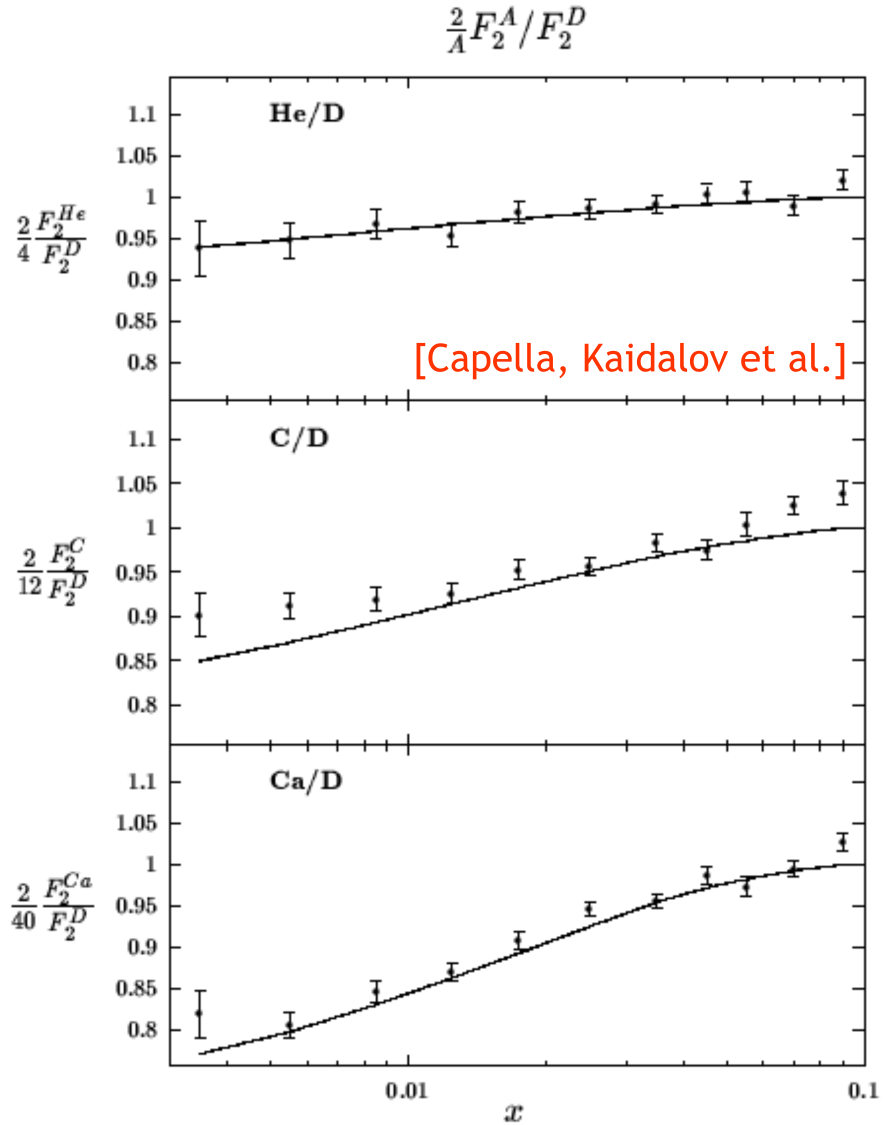
Nuclear shadowing can be described (Gribov-Glauber) as multiple interactions, starting from ep DPDFs

[Diff DIS]




[eA shadowing]

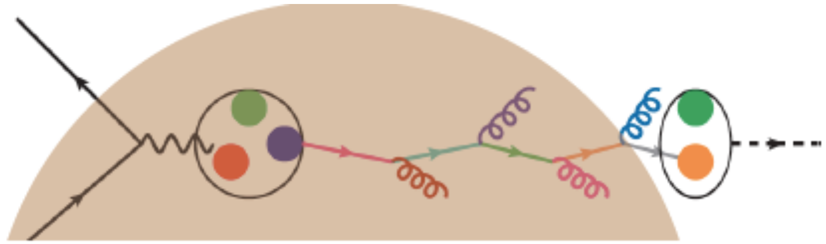


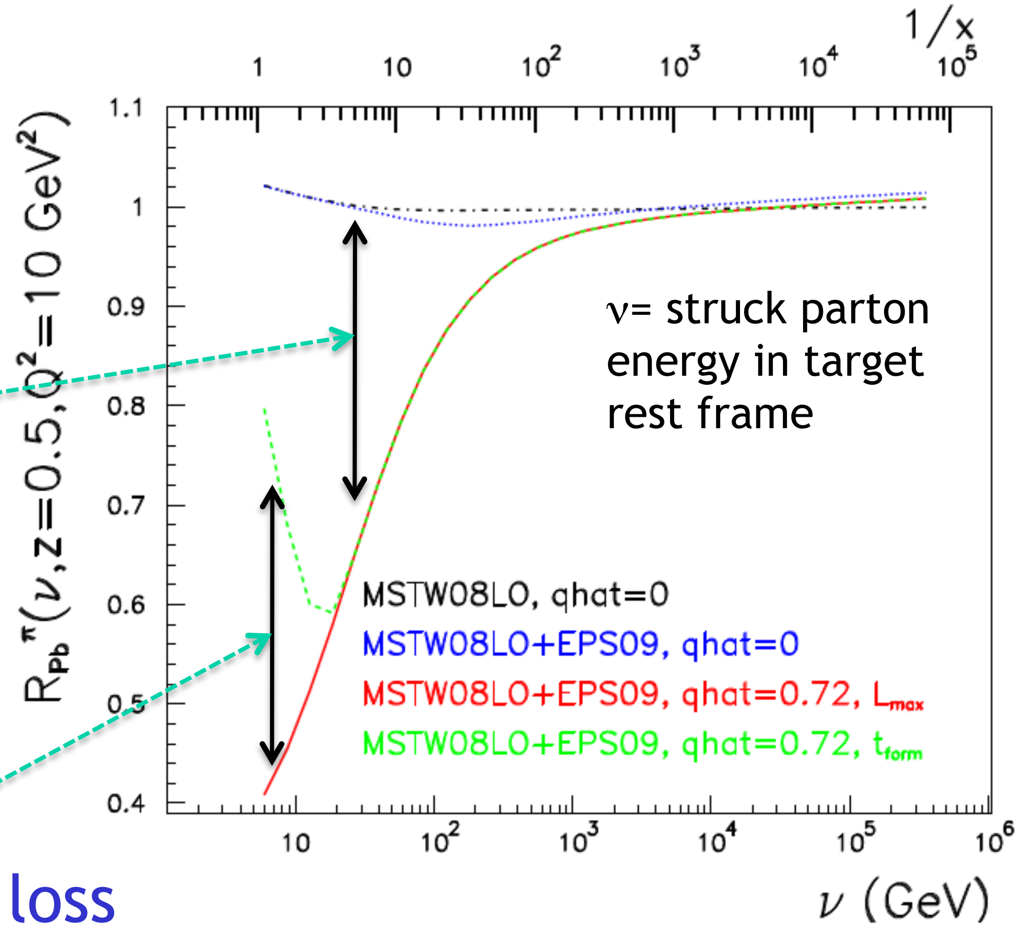

… starting point for extending precision LHeC studies into eA collisions

# In-medium radiation and hadronisation effects

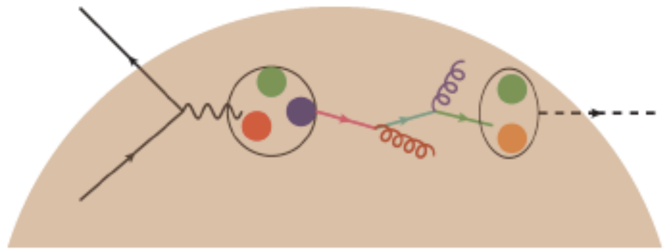
How do virtual parton probes lose Virtuality and colour to hadronise?

Ratio of $\pi^0$ frag$^n$ functions Pb / p (Armesto et al.)






Large ν: Hadronisation beyond medium. Partonic energy loss

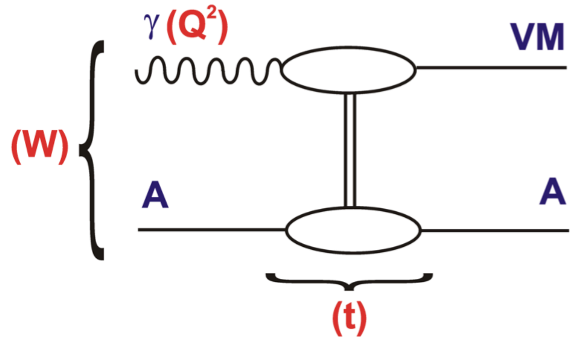


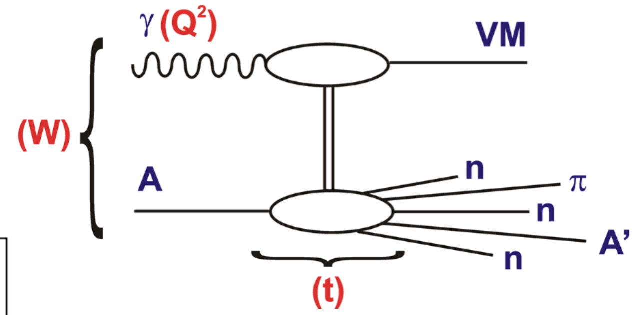
Small ν: Hadron formation may be inside. Hadronic energy loss

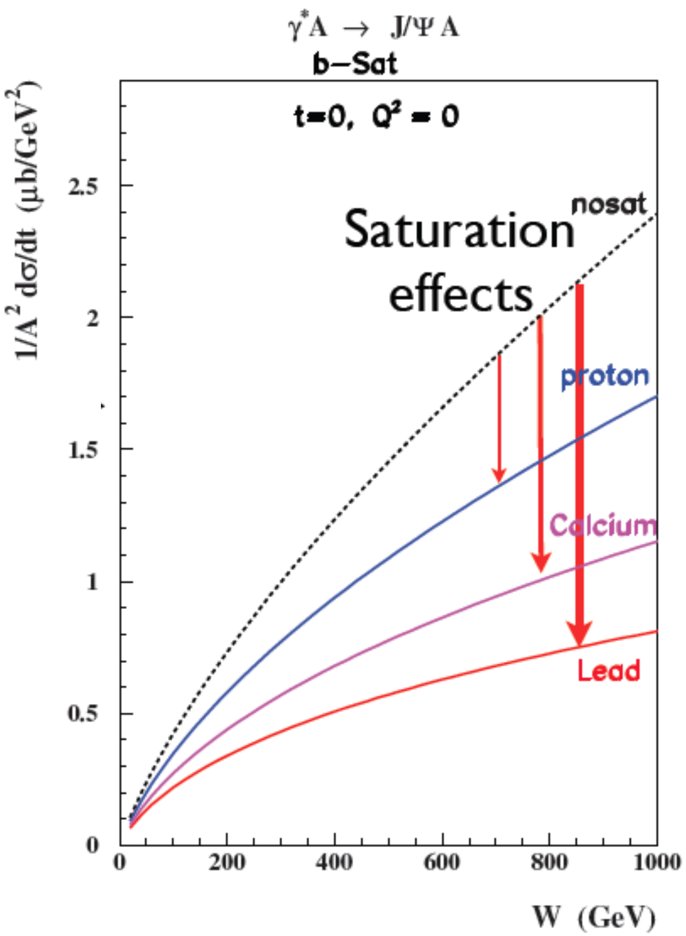
LHeC most sensitive to partonic loss. → Baseline `cold matter' input to use energy loss mechanisms to characterise QGP

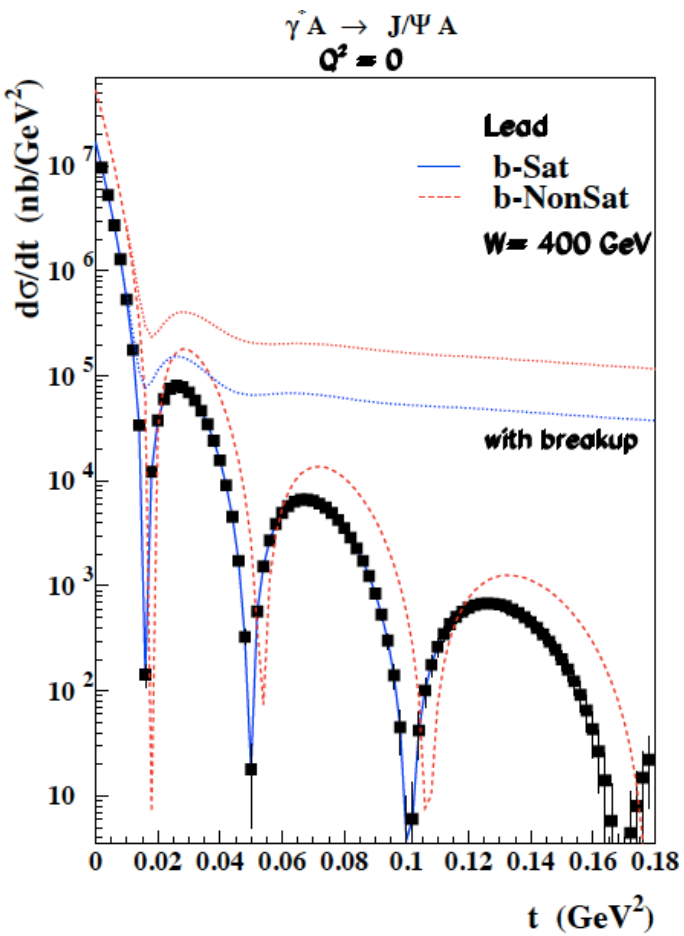
# Exclusive Diffraction in eA

Experimentally clear signatures and theoretically cleanly calculable saturation effects in coherent diffraction case (eA → eVA)



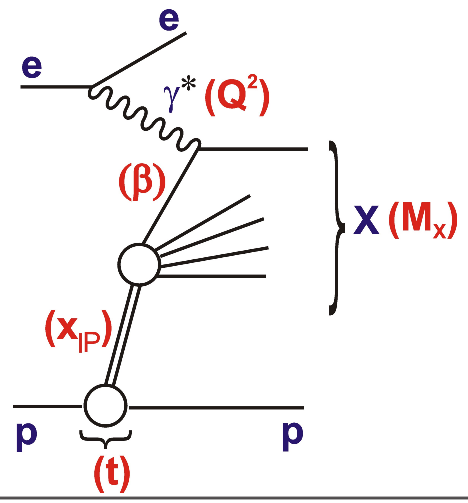



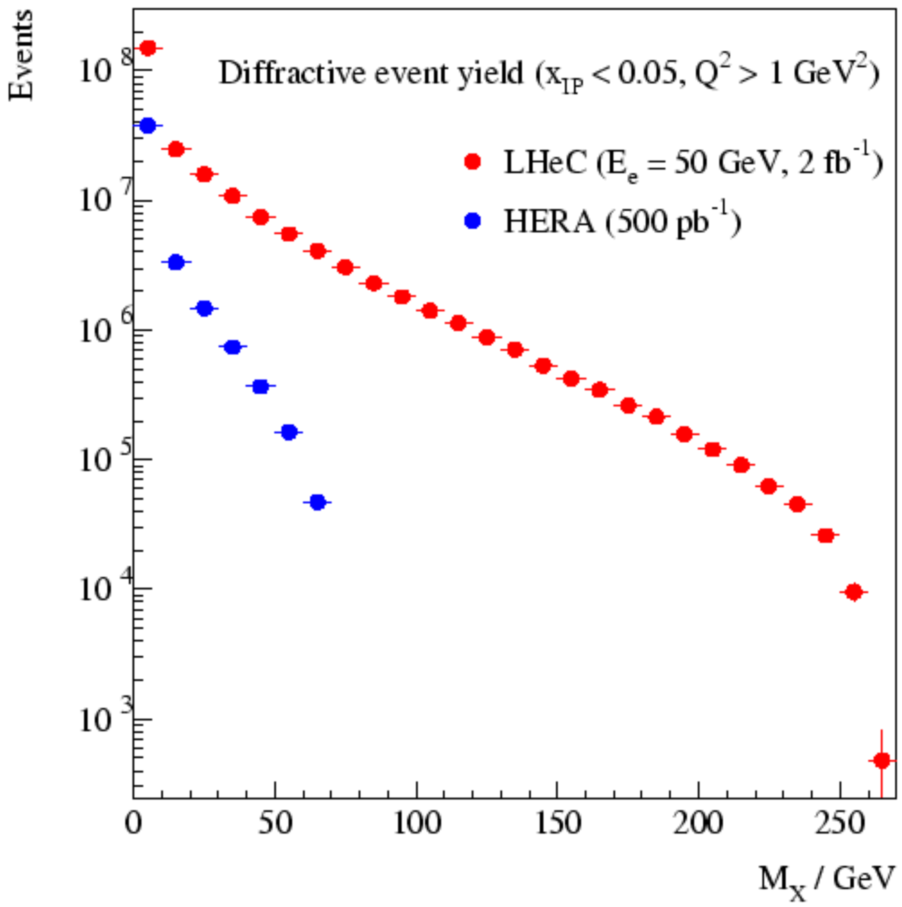



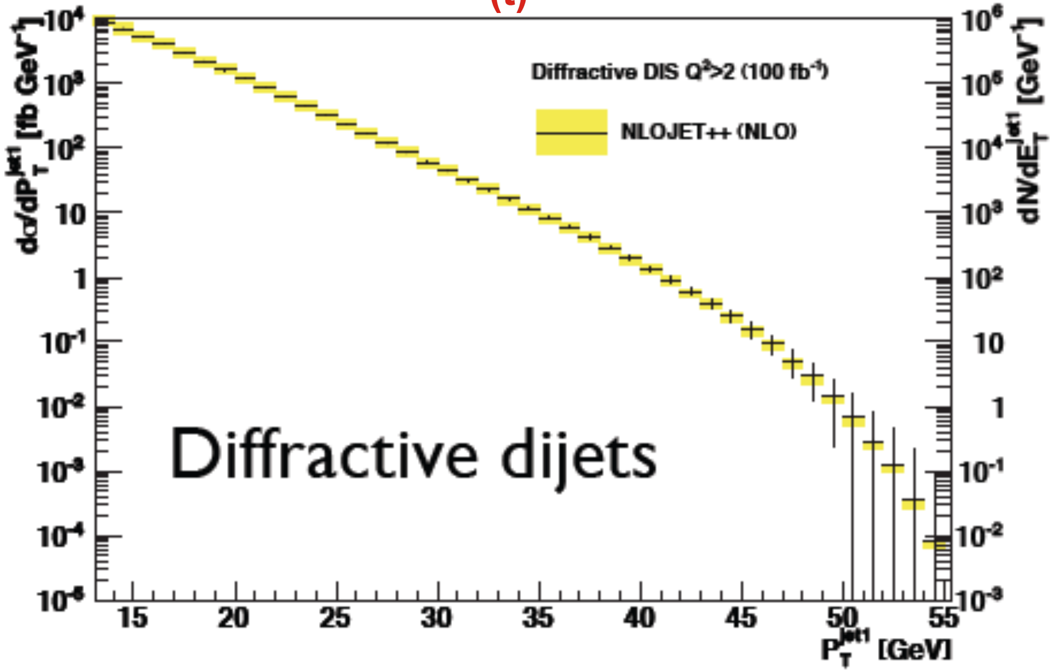




Experimental separation of incoherent diffraction based mainly on ZDC

# Large Diffractive Masses

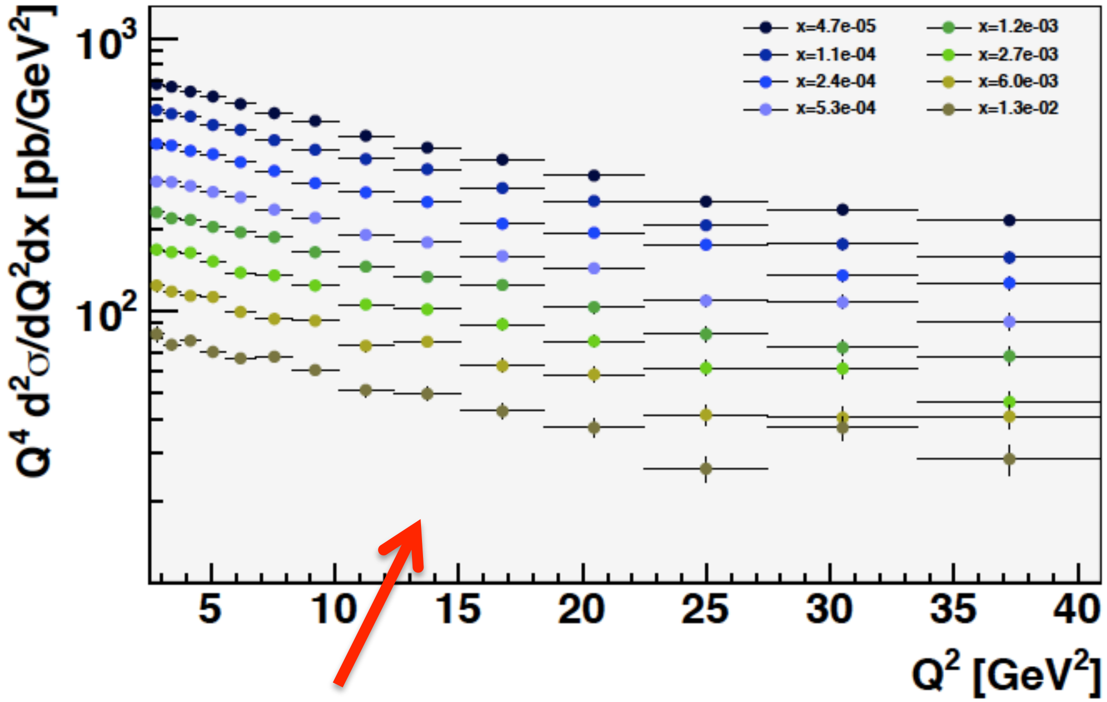


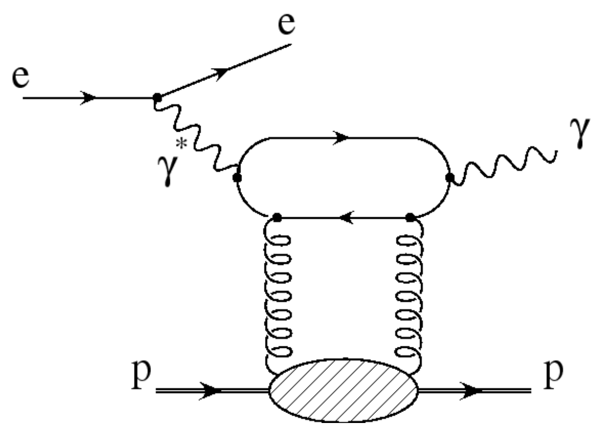



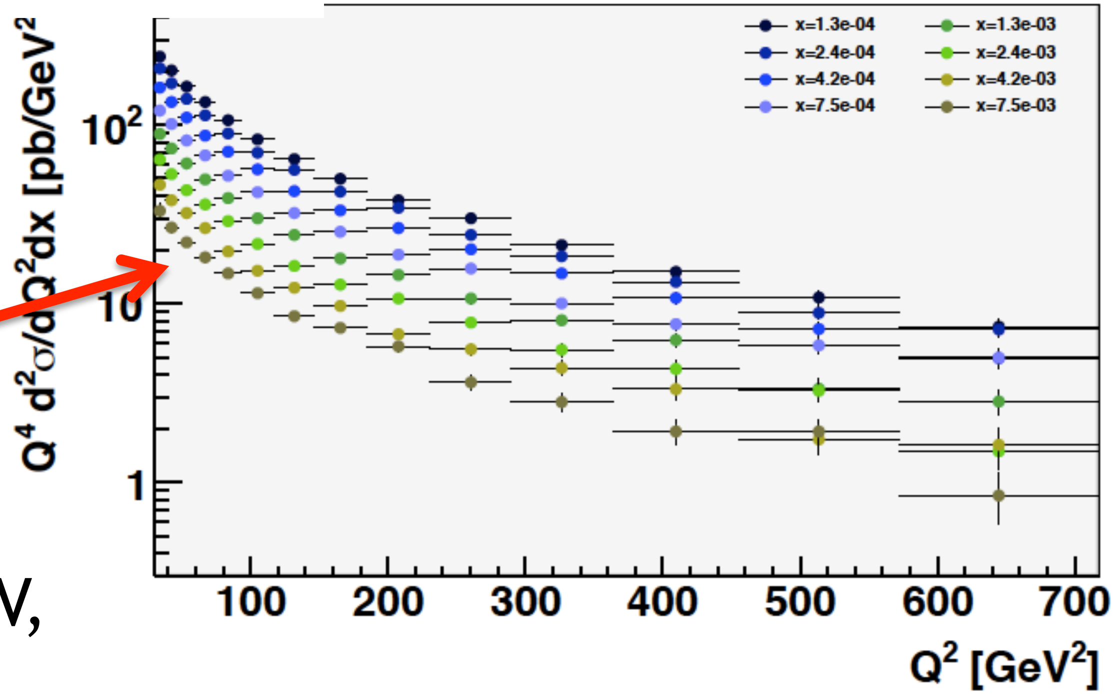

- \`Proper' QCD (e.g. large $E_T$) with jets and charm accessible
- New diffractive channels … beauty, W / Z bosons
- Unfold quantum numbers / precisely measure new $1^-$ states

# e.g. DVCS (MILOU simulation)




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




100 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$^{-5}$

# 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)

## Tentative parameters

PERLE | Powerful energy recovery linac experiments

2 $10^9$ e/bunch, 25ns, 10cm hydrogen target → **L(ep) ~ 3 $10^{40}$ $cm^{-2}$ $s^{-1}$**

| GAMMA BEAM PARAMETERS | |
|---|---|
| Energy | 30 MeV |
| Spectral density | $9*10^4$ γ/s/eV ← *or much higher!* |
| Bandwidth | < 5% |
| Flux within FWHM bdw | $7*10^{10}$ ph/s |
| ph/$e^-$ within FWHM bdw | $10^{-6}$ |
| Peak Brilliance | $3*10^{21}$ ph/s*$mm^2$*$mrad^2$ 0.1% bdw |

→ **Huge physics potential – a new fixed target programme at CERN possibly**
$G_E$, $G_M$, $r_p$, $\sin^2\theta_W$, dark photons, photonuclear physics: today plenary 6.15pm

Courtesy by Alessandra Valloni, Name by Erk Jensen with the Support of OB+MK [+ you?]

# CERN-Jlab Cavity + Cryomodule Collaboration

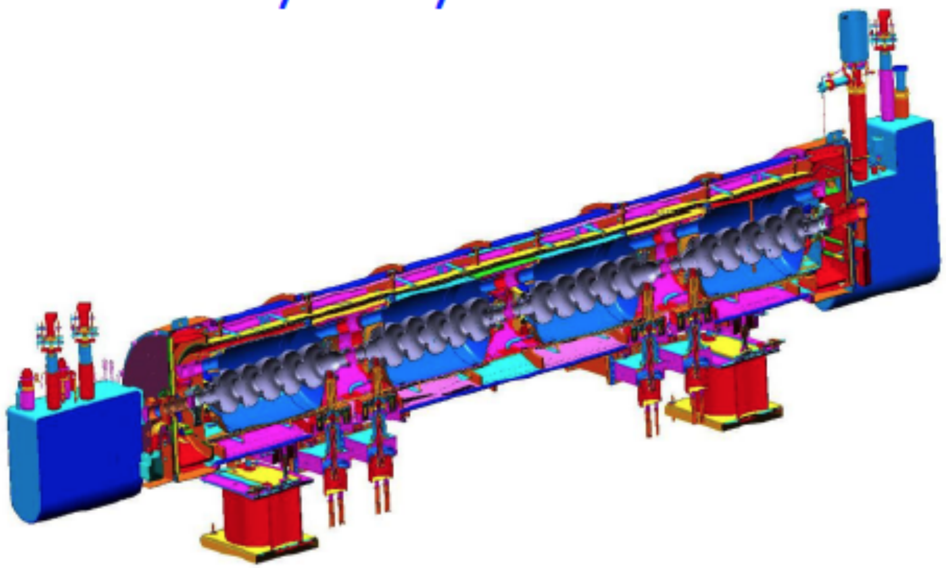


Figure 3.9: SNS high $\beta$ module adapted to house $\beta$ =1 5-cell cavities for LHeC.

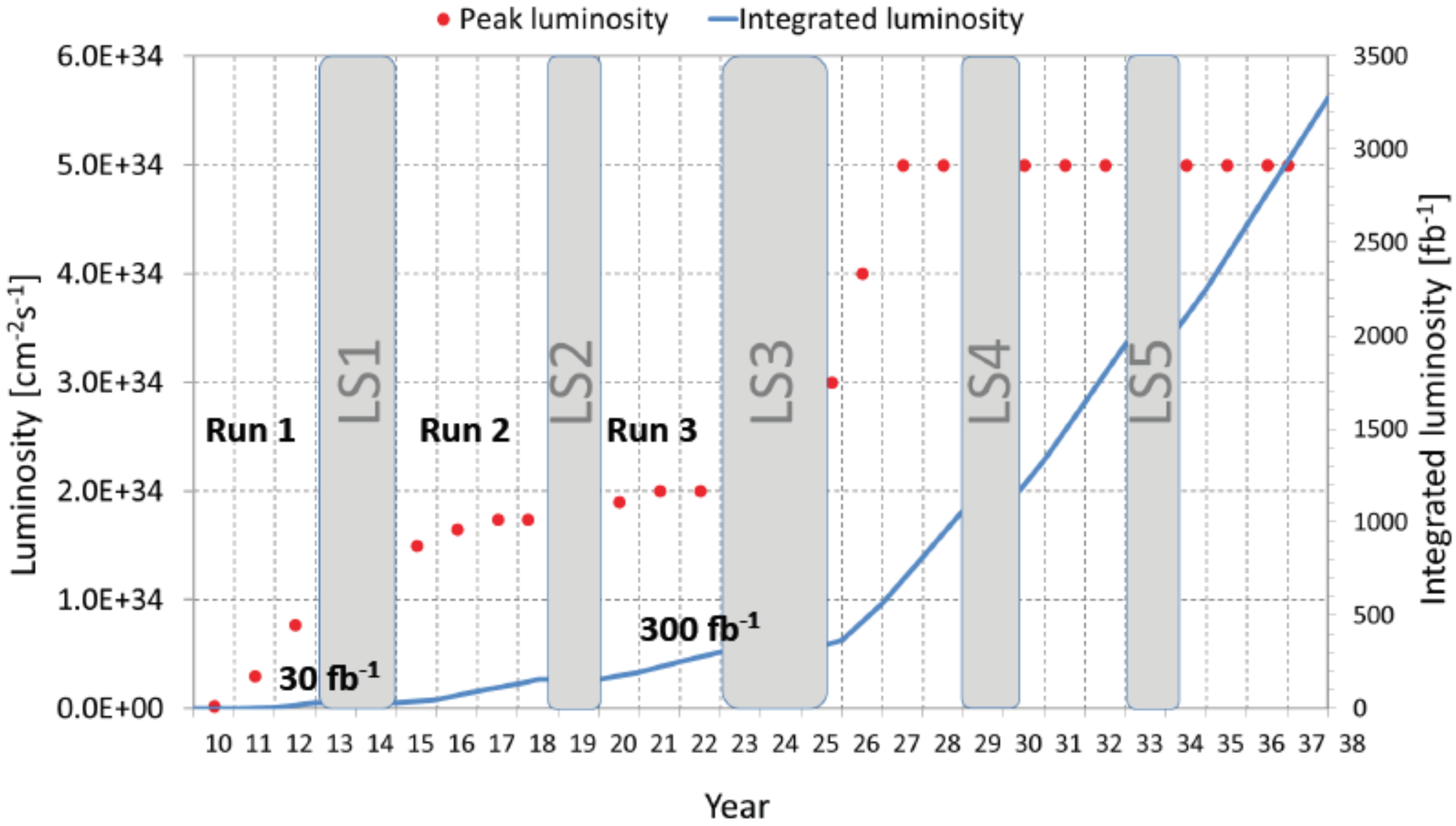
Magic Ms
..MoU..
..MTP..
Cavity 1
in 2016

The ERL test facility will need up to four cryomodules each containing four 802 MHz five cell cavities. A convenient concept for these can be developed by simply adapting the four-cavity SNS high beta cryomodule designed by JLab [39], to accommodate 5-cell $\beta$=1 cavities, as shown in Fig. 3.9. Since the cavities are almost the same length as the original 805 MHz $\beta$= 0.81 6-cells no major changes to the module would be required. This

From PERLE CDR 24.6.2015

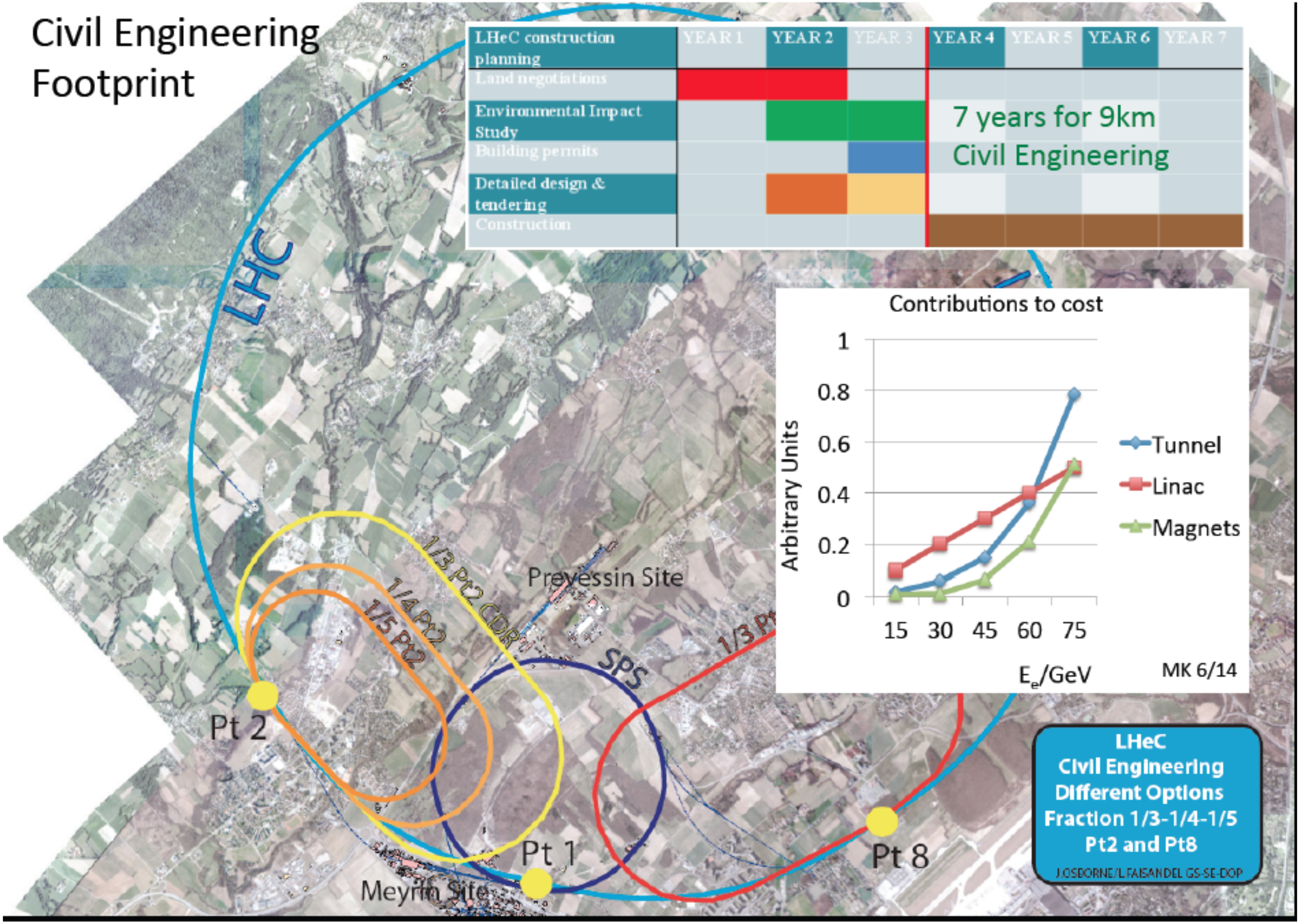
# Formal Status

## Current Long Term Planning of the LHC Operation




F. Bordry at the FCC Workshop at Washington DC March 2015

# Civil Engineering Footprint

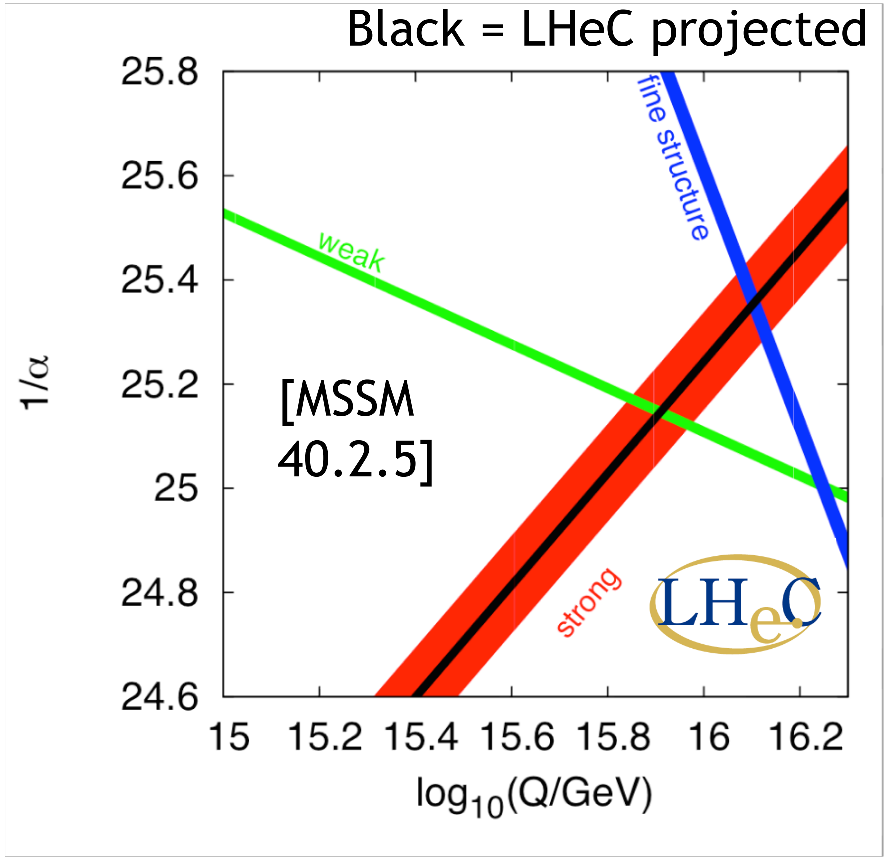


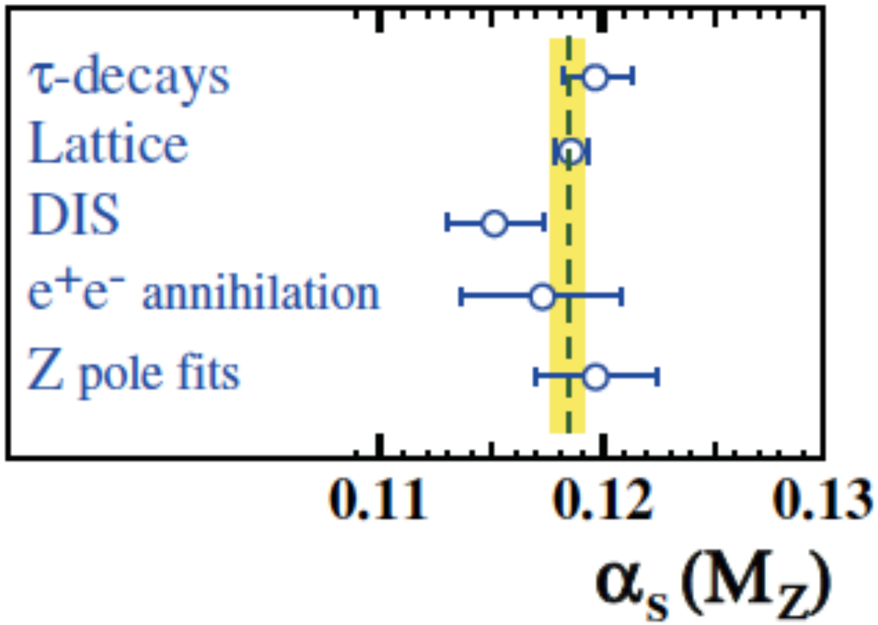

| LHeC construction planning | YEAR 1 | YEAR 2 | YEAR 3 | YEAR 4 | YEAR 5 | YEAR 6 | YEAR 7 |
|---|---|---|---|---|---|---|---|
| Land negotiations | | | | | | | |
| Environmental Impact Study | | | | | | | |
| Building permits | | | | | | | |
| Detailed design & tendering | | | | | | | |
| Construction | | | | | | | |

# Precision $\alpha_s$

- 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?

Red = current world average
Black = LHeC projected




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

# Context of Precision $\alpha_s$

Snowmass13 report – arXiv:1310.5189

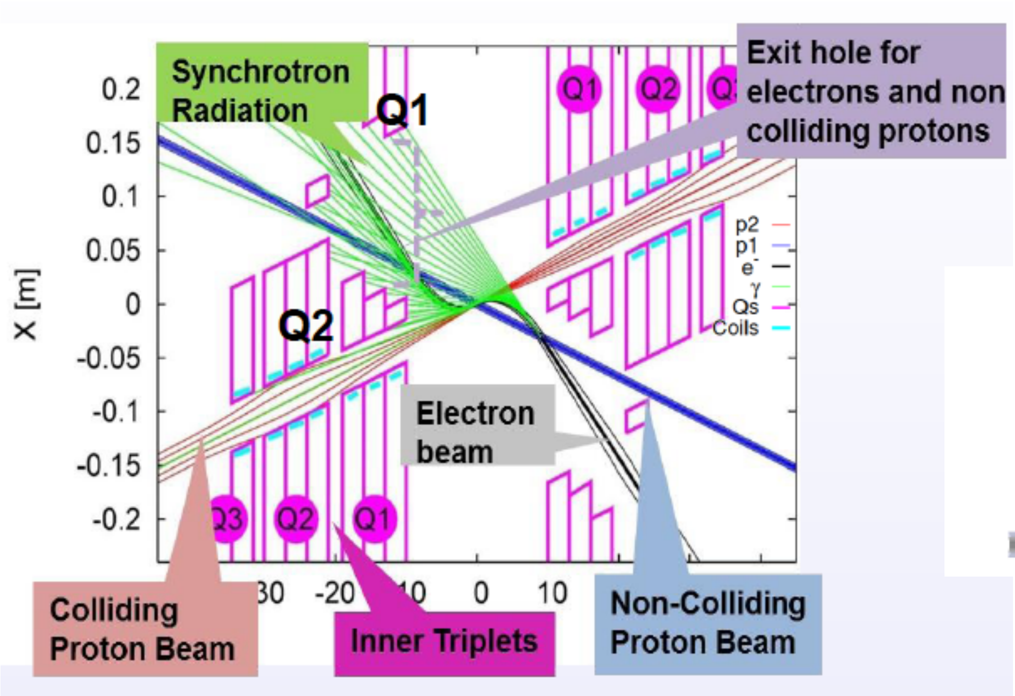
| Method | Current relative precision | Future relative precision |
|---|---|---|
| $e^+e^-$ evt shapes | expt $\sim 1\%$ (LEP)<br>thry $\sim 1$–$3\%$ (NNLO+up to N$^3$LL, n.p. signif.) [27] | $< 1\%$ possible (ILC/TLEP)<br>$\sim 1\%$ (control n.p. via $Q^2$-dep.) |
| $e^+e^-$ jet rates | expt $\sim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

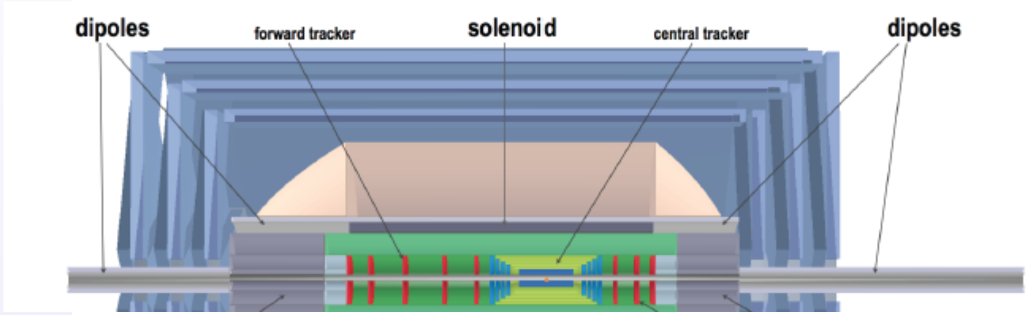
per mille (precision EW)

per mille ($ep$ colliders)

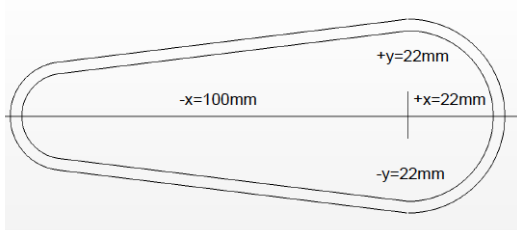
… tensions between lattice and DIS $\alpha_s$ results as a sensitive probe of new physics?...

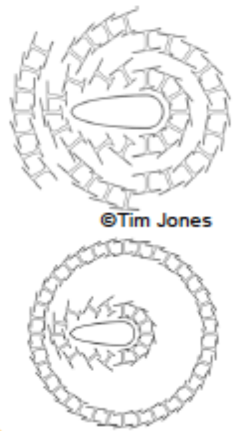
# Interaction Region & Magnets



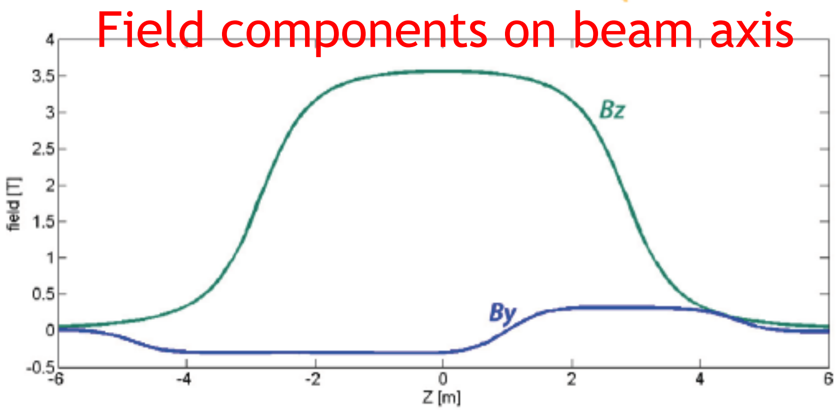

- Dual dipole magnets (0.15 – 0.3 T) throughout detector region (|z| < 14m) bend electrons into head-on collisions



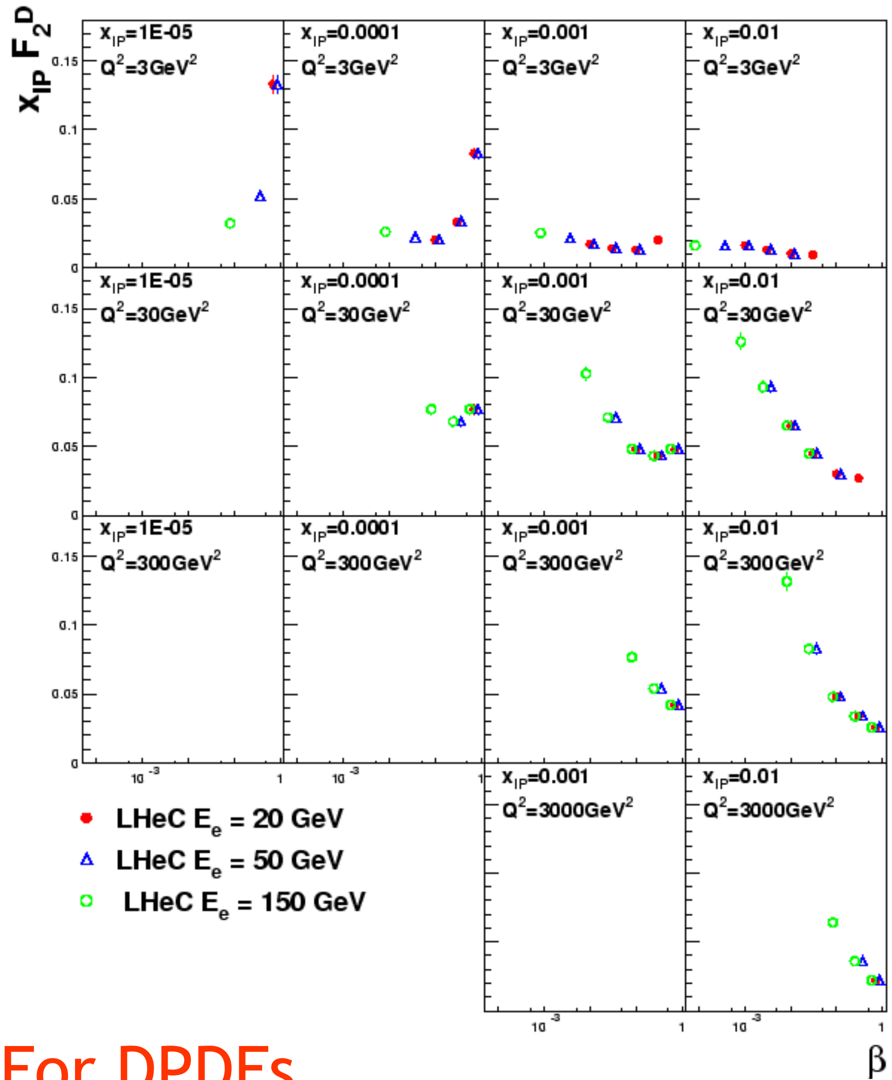



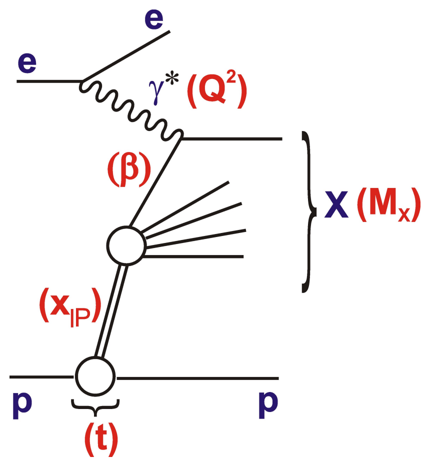

- Eliptical beampipe (6m x 3mm Be) accommodates synchrotron fan

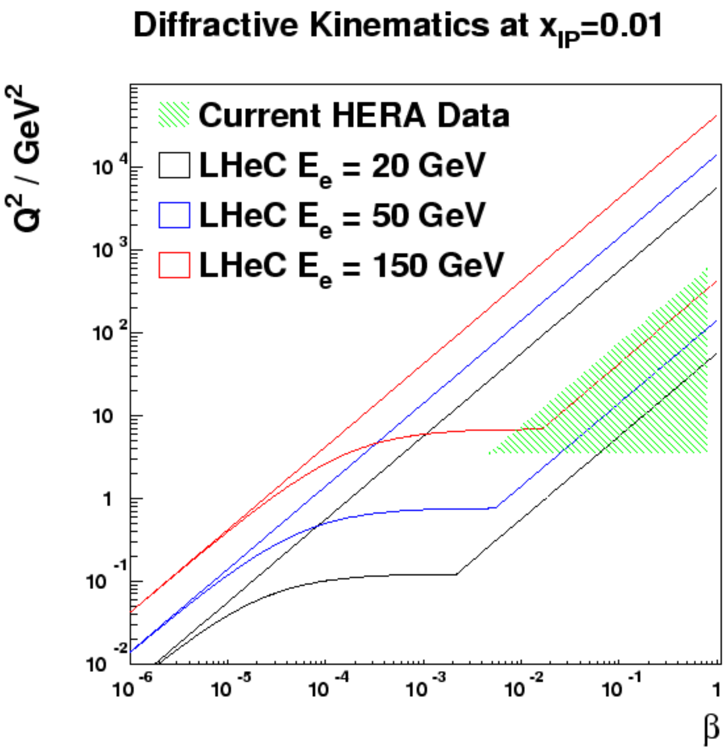
- 3.5 T Superconducting NbTi/Cu Solenoid in 4.6K liquid helium cryo.



# Inclusive Diffraction / Diffractive PDFs




For DPDFs …

- Low $x_{IP}$ → cleanly separate diffraction
- Low β → Novel low x DPDF effects /non-linear dynamics?
- High $Q^2$ → Lever-arm for gluon, Flavour separation via EW

# Machine Parameters

| $10^{34}$ $cm^{-2}$ $s^{-1}$ Luminosity reach | PROTONS | ELECTRONS |
|---|---|---|
| Beam Energy [GeV] | 7000 | 60 |
| Luminosity [$10^{33}cm^{-2}s^{-1}$] | 16 | 16 |
| Normalized emittance $\gamma\varepsilon_{x,y}$ [μm] | 2.5 | 20 |
| Beta Function $\beta^*_{x,y}$ [m] | 0.05 | 0.10 |
| rms Beam size $\sigma^*_{x,y}$ [μm] | 4 | 4 |
| rms Beam divergence $\sigma'_{x,y}$ [μrad] | 80 | 40 |
| Beam Current [mA] | 1112 | 25 |
| Bunch Spacing [ns] | 25 | 25 |
| Bunch Population | $2.2*10^{11}$ | $4*10^{9}$ |
| Bunch charge [nC] | 35 | 0.64 |

HL-LHC proton beam parameters

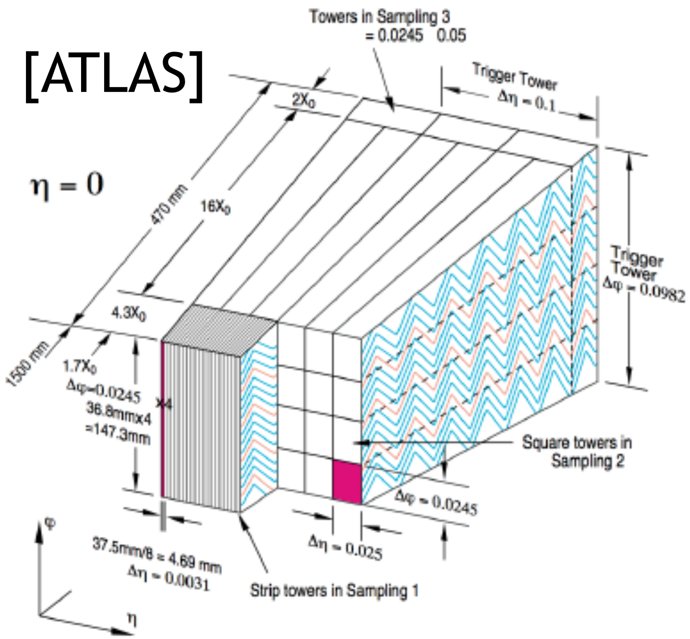
1000 times HERA Luminosity and 4 times cms Energy

# Barrel EM Calorimeter

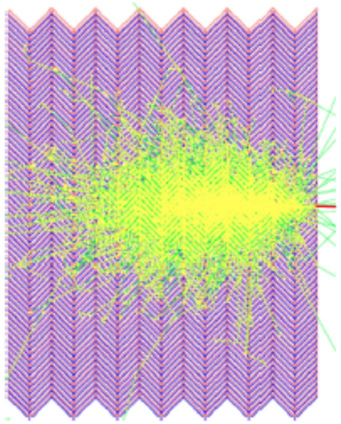
Liquid Argon Barrel EM Calorimeter
inside coil

- -2.3 < η < 2.8
- Possibly accordion geometry
- 2.2mm lead + 3.8mm LAr layers
- Total depth ~ 20 $X_0$

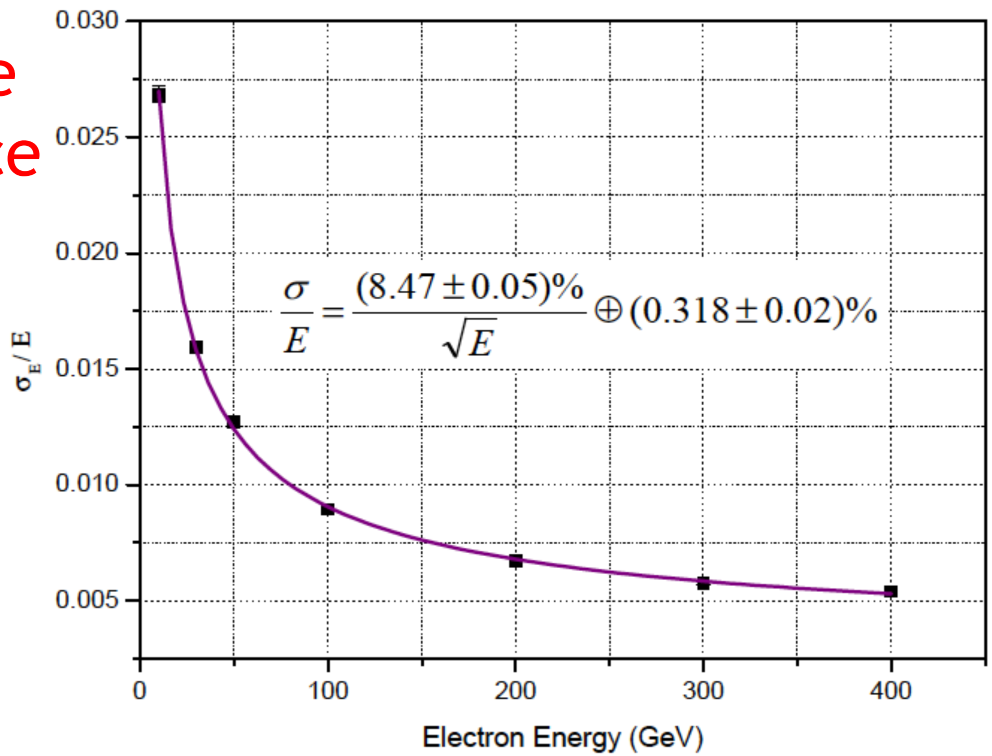
[ATLAS]



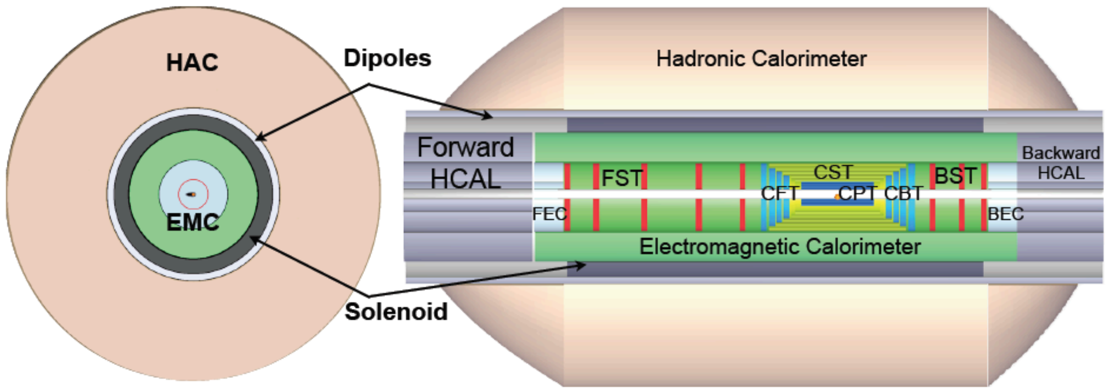

- Geant4 simulation of response to electrons at normal incidence [cf ATLAS: 10%/√E + 0.35%]



[20 GeV electron]



# Calorimeters Overview

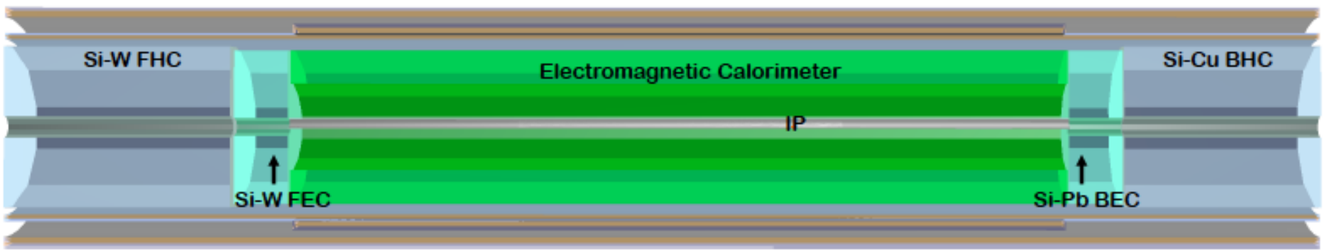



Current design based on (experience with) ATLAS (and H1), re-using existing technologies

- Barrel HAD calorimeter, outside coil
  → 4mm Steel + 3mm Scintilating Tile
  → 7-9 $\lambda$, $\sigma_E/E \sim 30\%/\surd E + 9\%$ [~ ATLAS]

- Forward end-cap silicon + tungsten, to cope with highest energies & multiplicities, radiation tolerant EM → $30X_0$, Had→9$\lambda$

- Backward end-cap
Pb+Si for EM ($25X_0$)
Cu+Si for HAD (7$\lambda$)

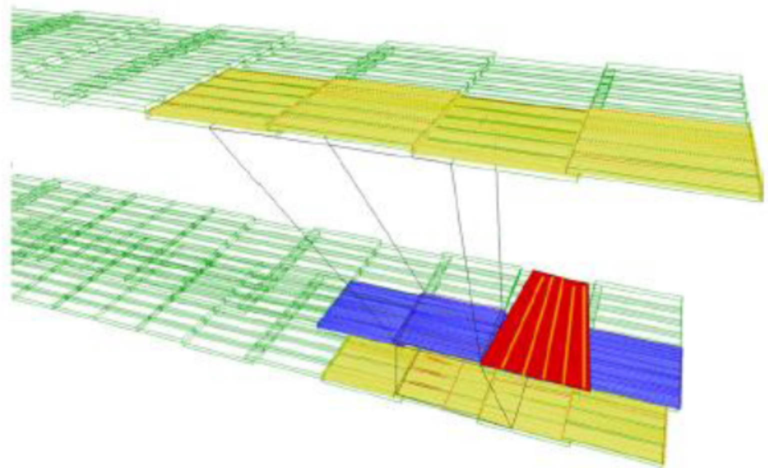


# Muon System

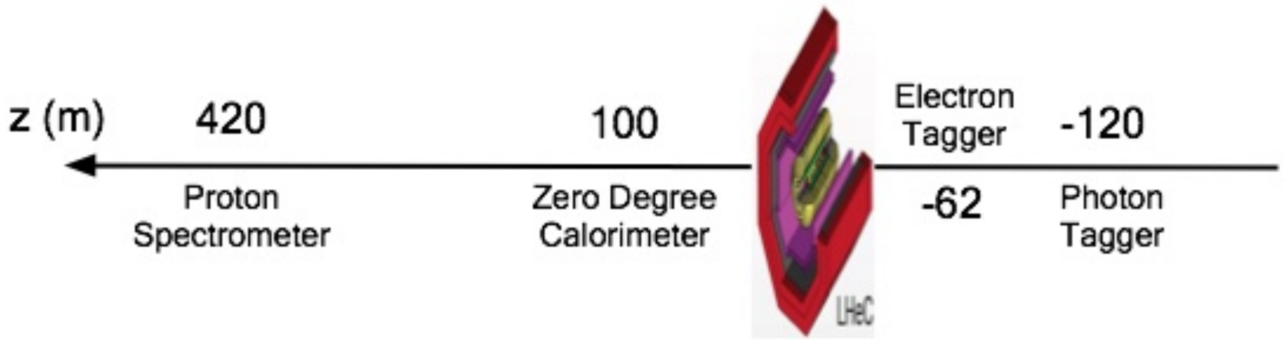
Baseline: Provides tagging, but not momentum measurement
: Angular coverage → 1° vital eg for e.g. elastic J/Ψ
: Technologies used in LHC GPDs and their upgrades
(more than) adequate

- 2 or 3 Superlayers

- Drift tubes / Cathode strip chambers → precision
- Resistive plate / Thin Gap chambers → trigger + 2nd coord]



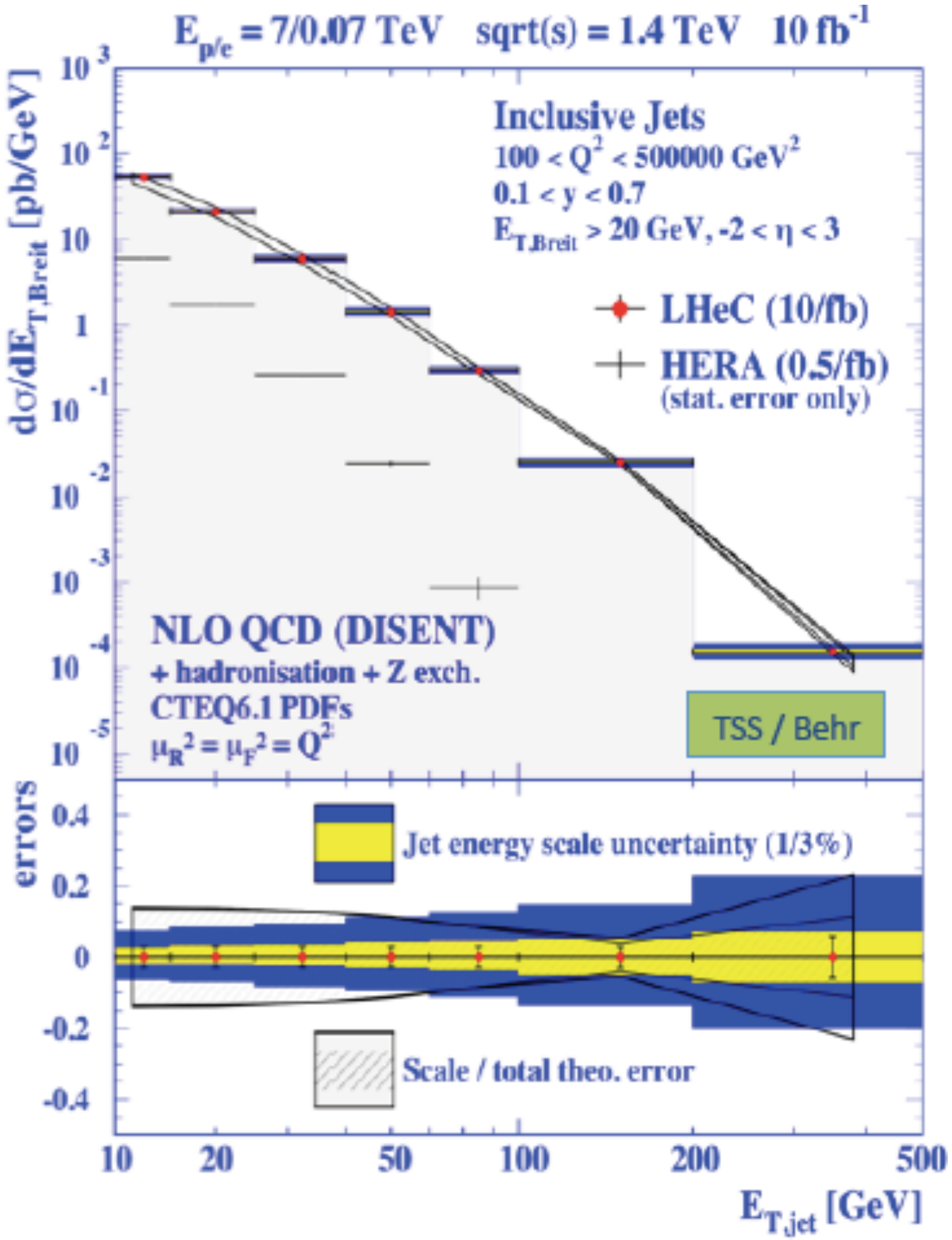
# Beamline Instrumentation




- Forward proton & neutron tagging

-Backward electron tagging & luminosity monitoring (ep→epγ)

# Inclusive Jets & QCD Dynamics

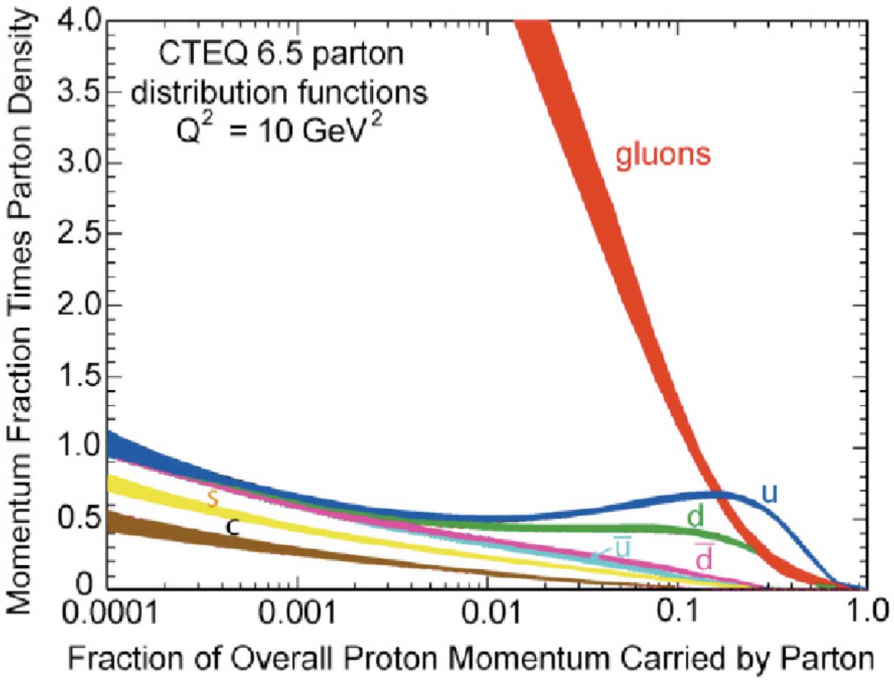



Also differential in $Q^2$ with high precision to beyond $Q^2 = 10^5$ $GeV^2$

$\alpha_s$ up to scale ~ 400 GeV

Detailed studies of QCD dynamics, including novel low x effects in regions not probed at HERA and (probably) not at LHC

# Low-x Physics and Parton Saturation



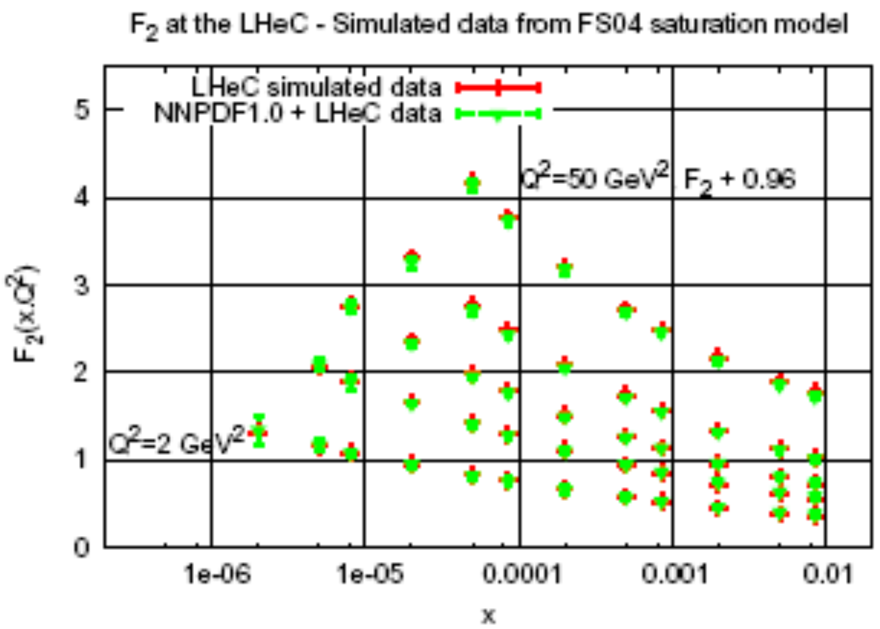

A fundamental QCD problem is looming … rise of low x parton densities cannot continue

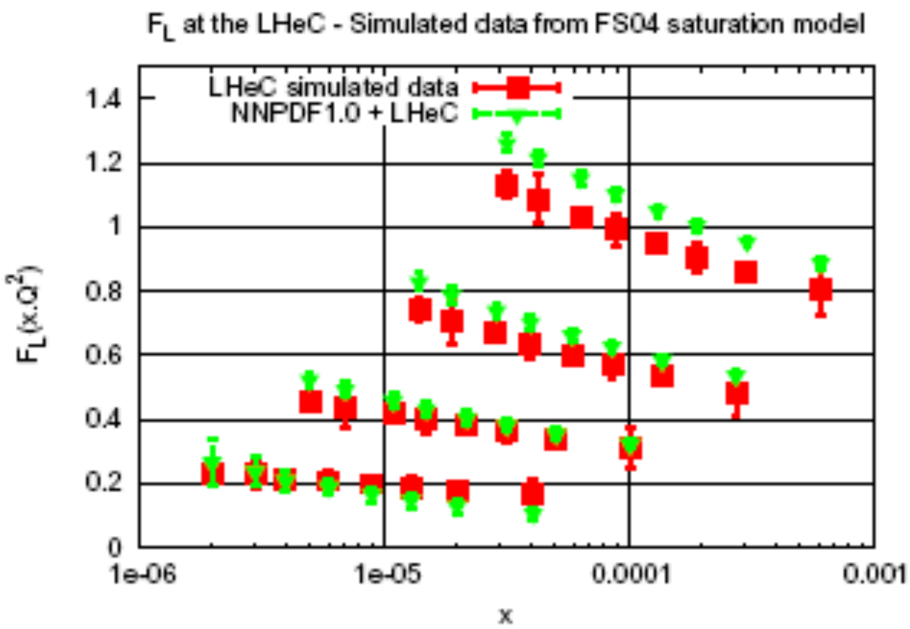
… High energy unitarity issues reminiscent of longitudinal WW scattering in electroweak physics:

# 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)…

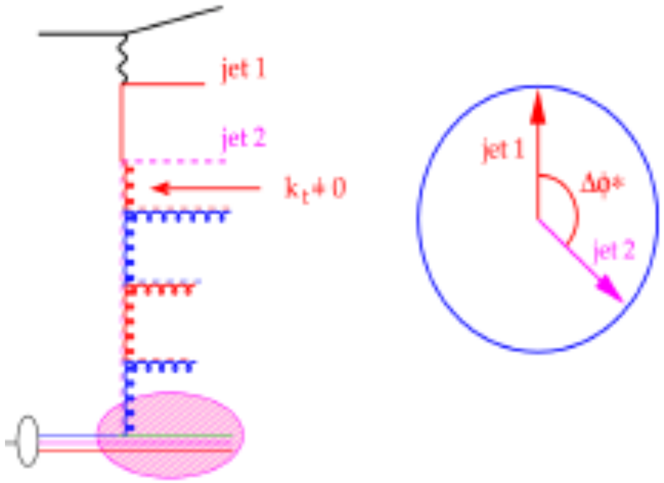
… NNPDF (also HERA framework) DGLAP QCD fits cannot accommodate saturation effects if $F_2$ and $F_L$ both fitted



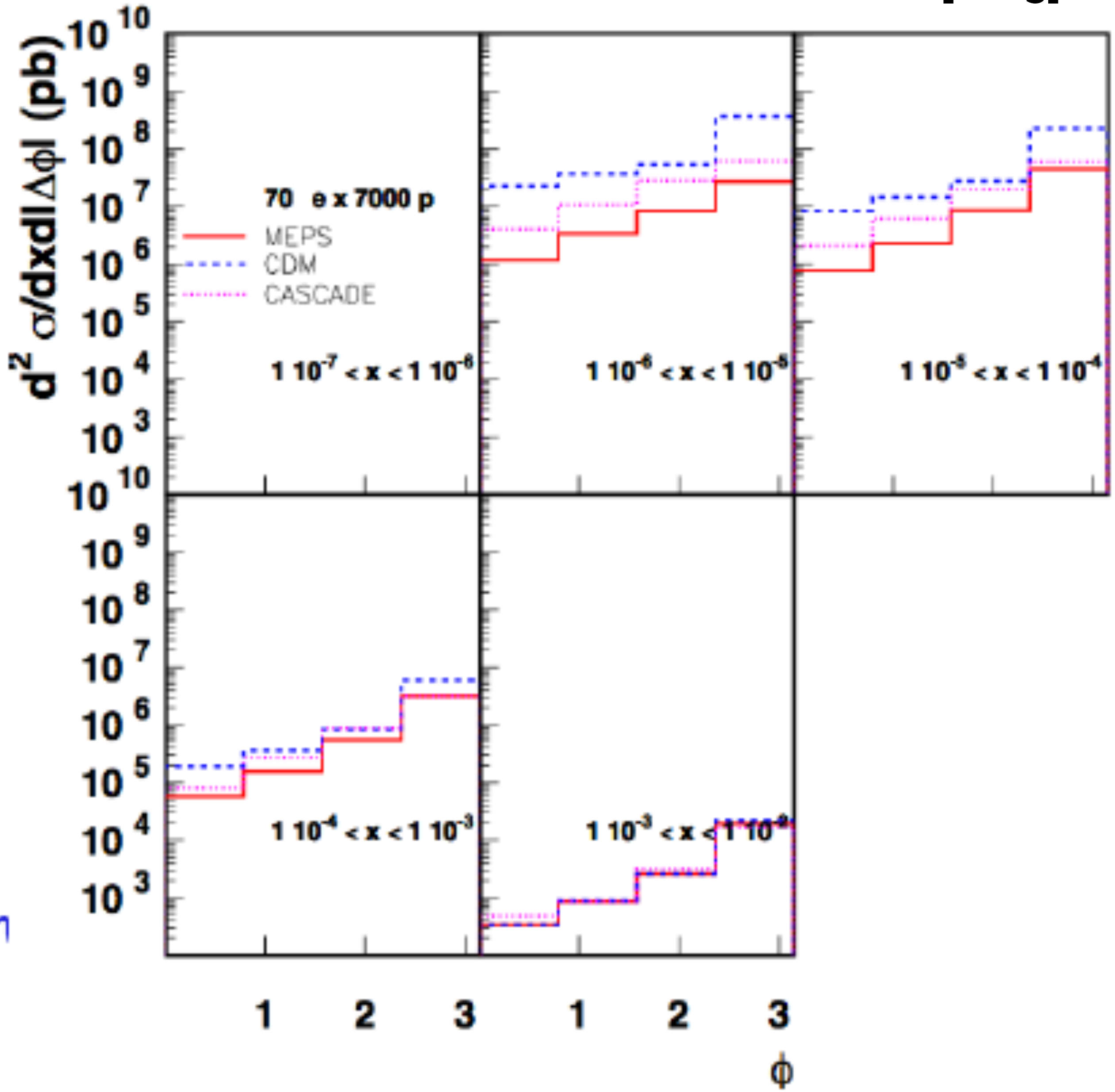

Conclusion: clearly establishing non-linear effects needs a minimum of 2 observables … <u>($F_2^c$ may work in place of $F_L$)</u>…

# Azimuthal (de)correlations between Jets

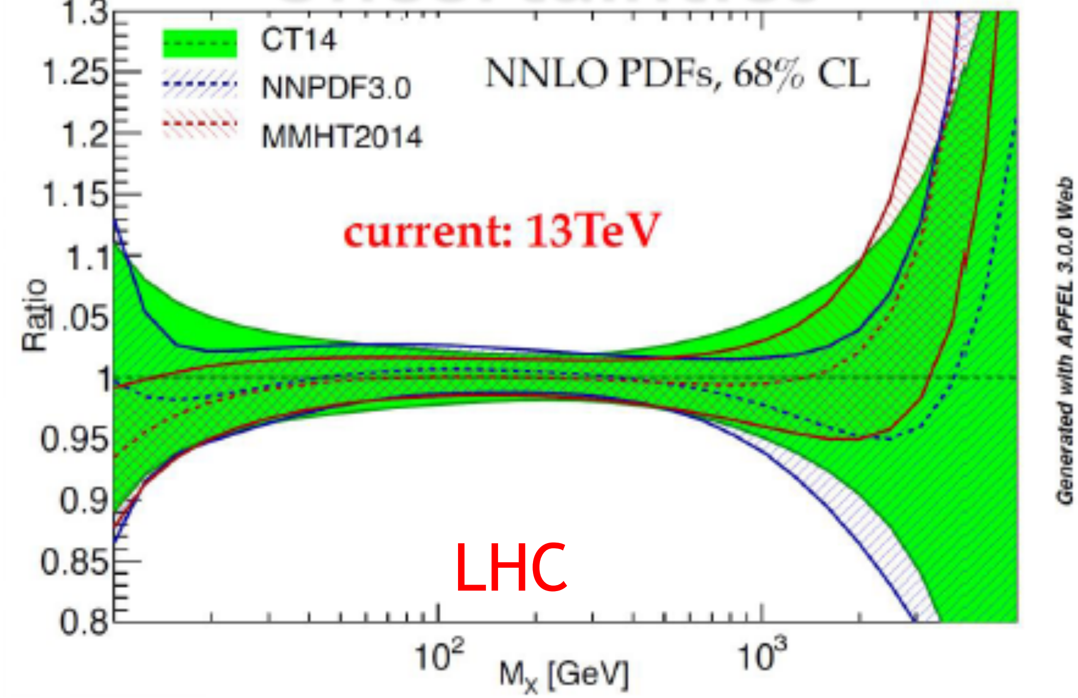



- $5 < Q^2 < 100\ \text{GeV}^2$
  $-1 < \eta < 2.5$
  $E_T > 5\ \text{GeV}$
- small $k_t \rightarrow \Delta\phi \sim 180$
- large $k_t$ from evolution

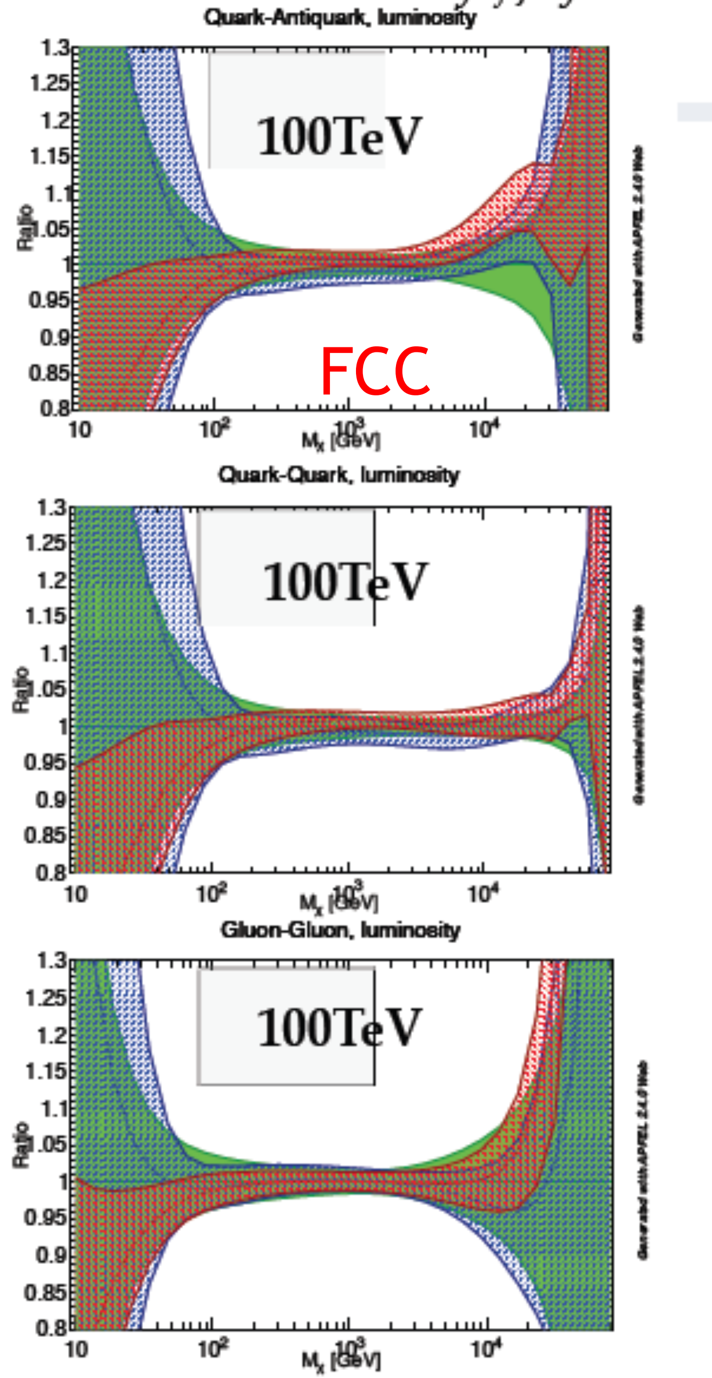
[Jung]



# Current Proton PDF Uncertainties




*Courtesy of Joey Huston*

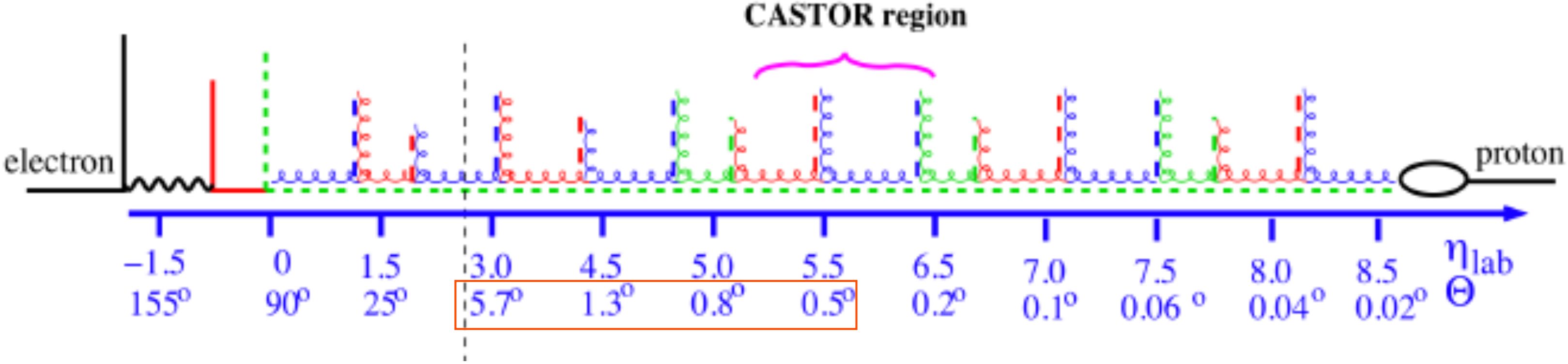



Low x / $M_x$ → novel QCD / unitarity

Medium x / $M_x$ → precision H and EW

High x / $M_x$ → new particle mass frontier

# Forward Instrumentation and Jets




[Jung]

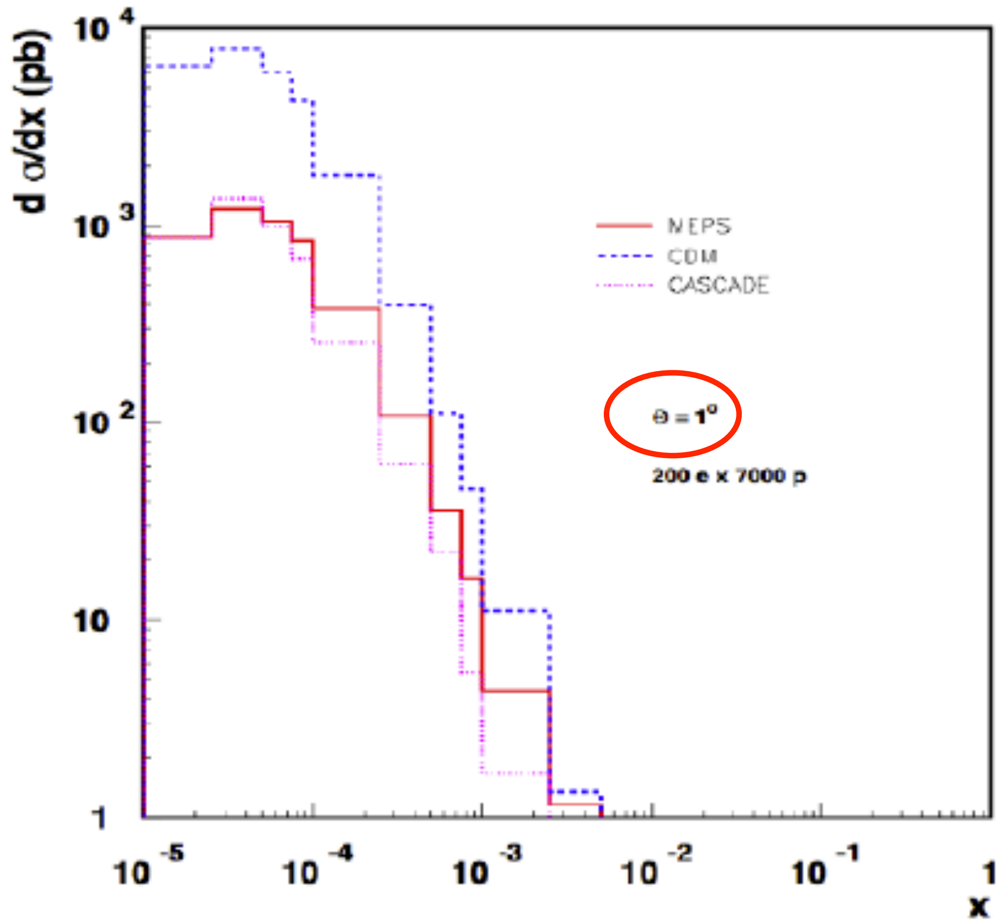
- DIS and forward jet:

$x_{jet} > 0.03$

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

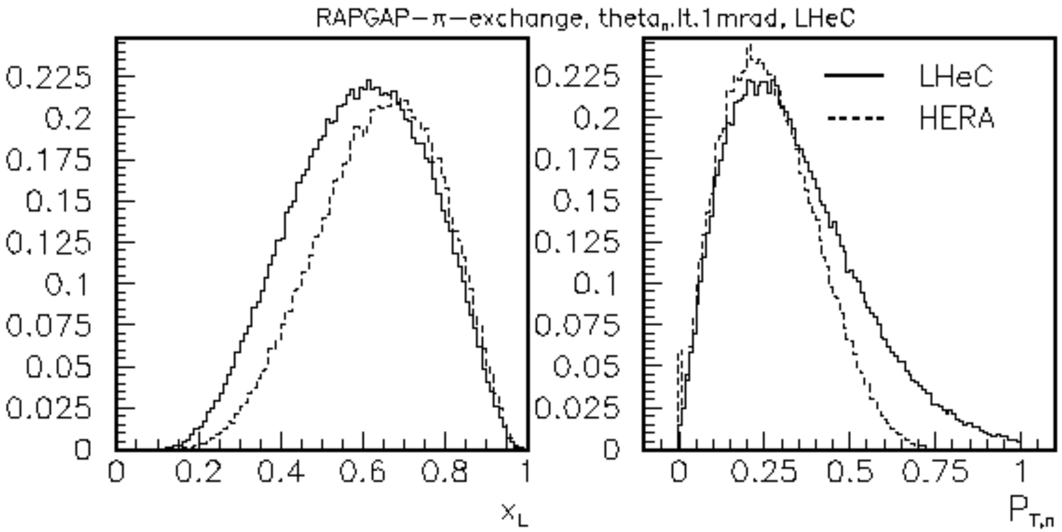
x range (and sensitivity to novel QCD effects) strongly depend on θ cut

Similar conclusions for Δϕ decorrelations between jets

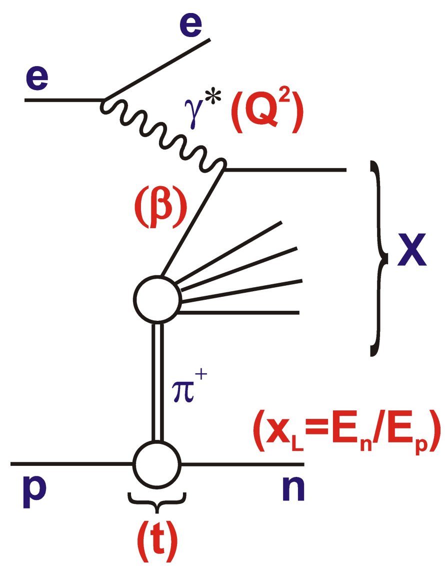


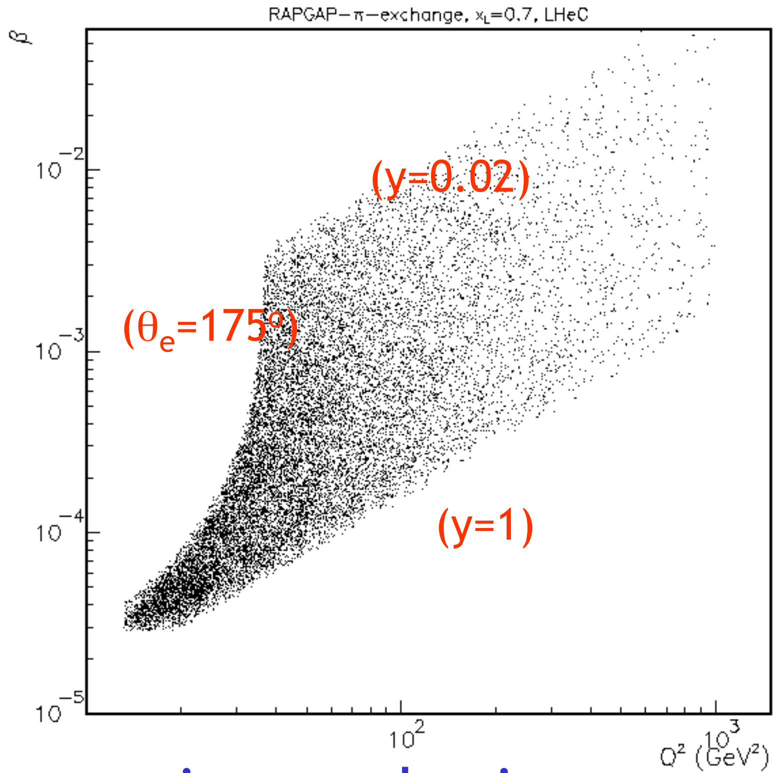
# π Structure with Leading Neutrons

[Bunyatyan]




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




• With $\theta_n$ < 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. → $F_2^\pi$ At $\beta<5.10^{-5}$ (cf HERA reaches $\beta\sim10^{-3}$)

Also relevant to absorptive corrections, cosmic ray physics …

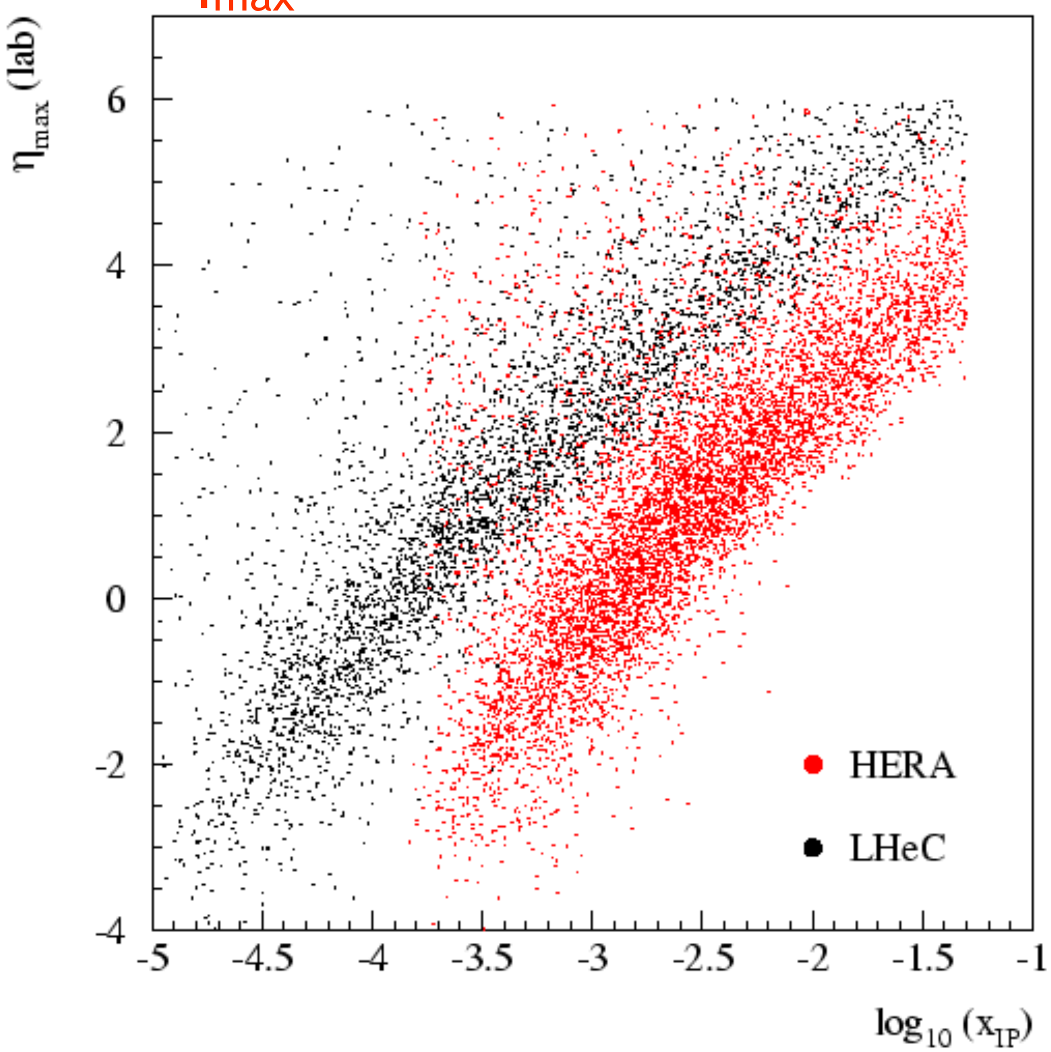
# Forward and Diffractive Detectors

- 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 $\eta_{max}$ cut around 5 …forward instrumentation essential!

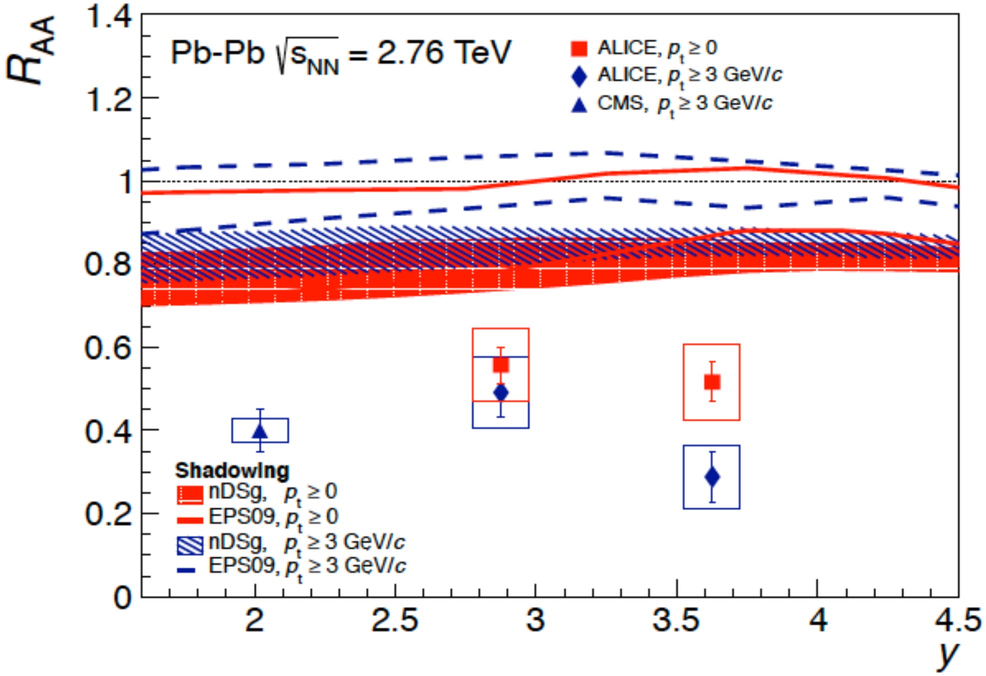
- Roman pots, FNC should clearly be an integral part.
  - Also for t measurements
  - Not new at LHC ☺
  - Being considered integrally with interaction region

$\eta_{max}$ from LRG selection …



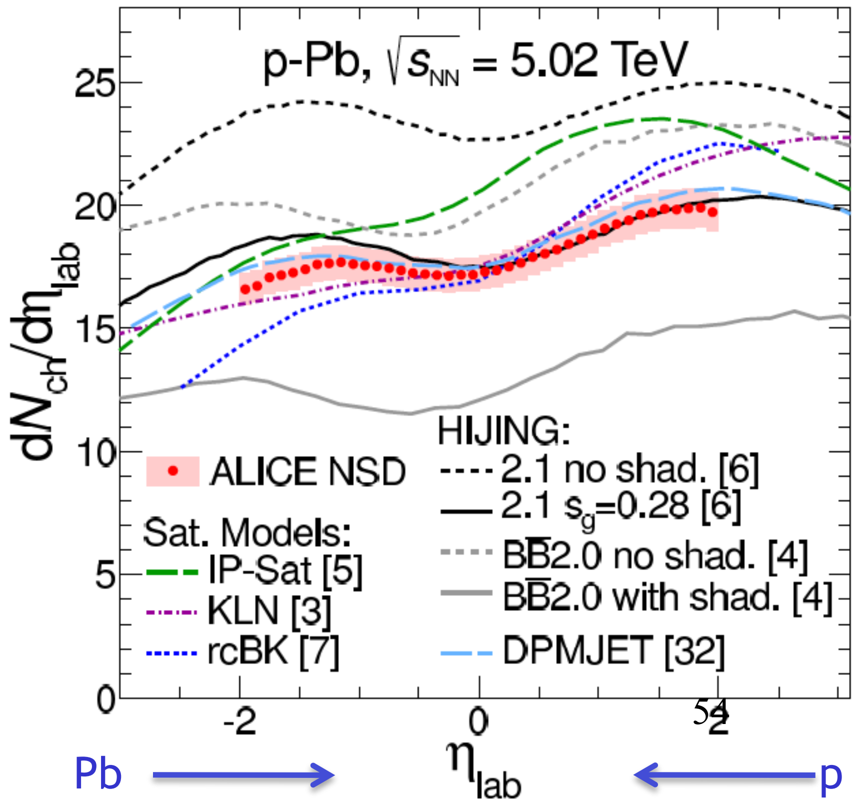
# Current Low x Understanding in LHC Ion Data

## Inclusive J/Ψ AA data




Uncertainties in low-x nuclear PDFs preclude precision statements on medium produced in AA (e.g. extent of screening of c-cbar potential)

## Minimum Bias pA data

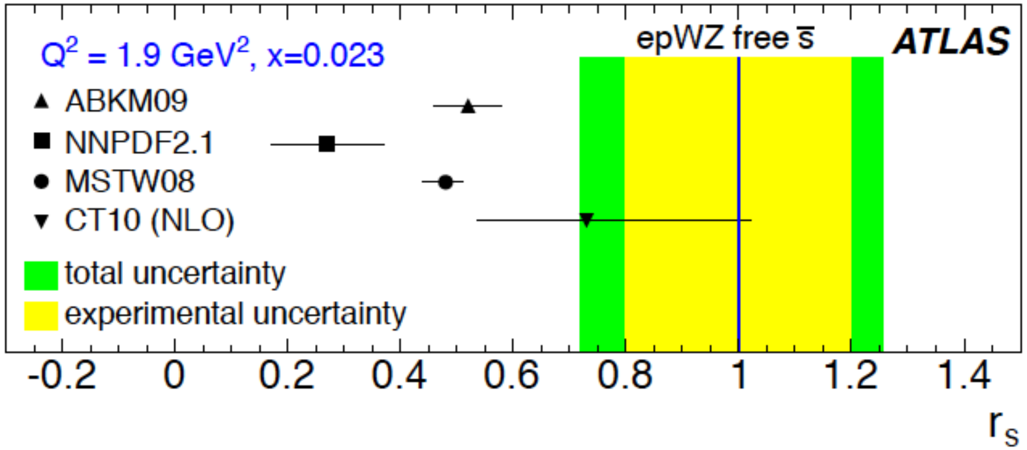


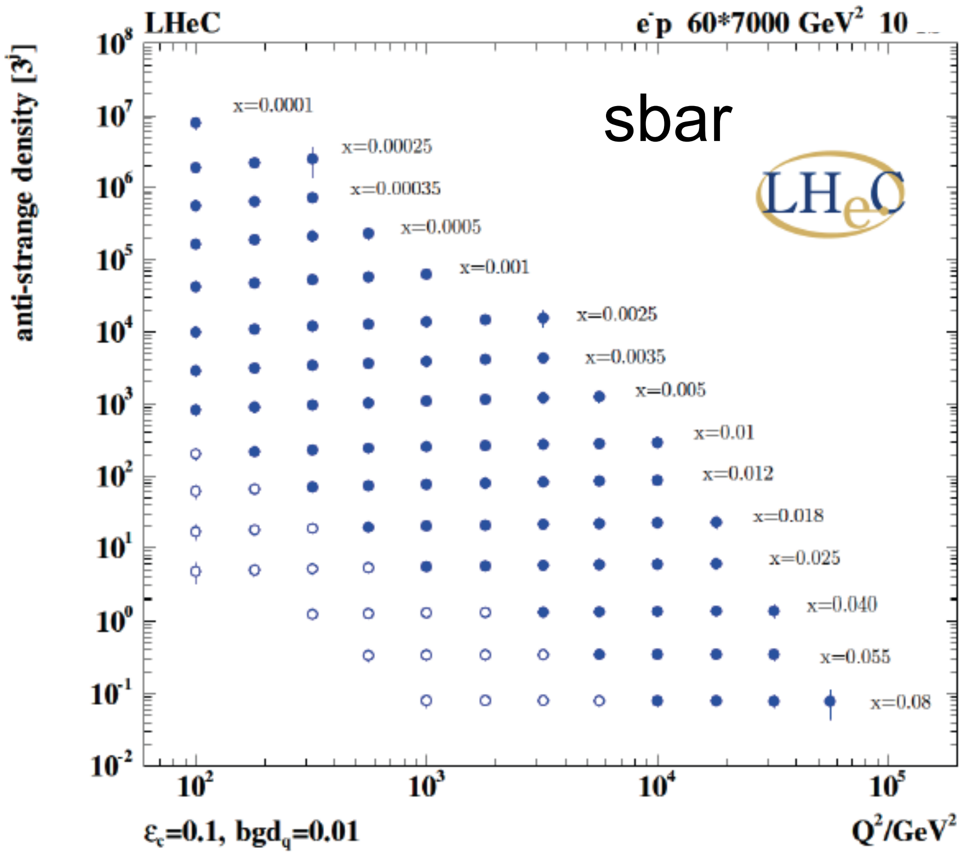

η dependence of pPb charged particle spectra best described by shadowing-only models (saturation models too steep?)

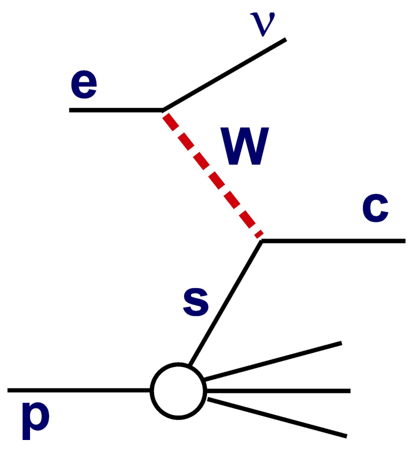
… progress with pPb, but uncertainties still large, detailed situation far from clear

# 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

… with thanks to many experimentalist, theorist
& accelerator science colleagues, especially
Nestor Armesto, Max Klein, Uta Klein and Anna Stasto …

LHeC study group …

J.L.Abelleira Fernandez[16,23], C.Adolphsen[57], P.Adzic[74], A.N.Akay[03], H.Aksakal[39], J.L.Albacete[52], B.Allanach[73], S.Alekhin[17,54], P.Allport[24], V.Andreev[34], R.B.Appleby[14,30], E.Arikan[39], N.Armesto[53,a], G.Azuelos[33,64], M.Bai[37], D.Barber[14,17,24], J.Bartels[18], O.Behnke[17], J.Behr[17], A.S.Belyaev[15,56], I.Ben-Zvi[37], N.Bernard[25], S.Bertolucci[16], S.Bettoni[16], S.Biswal[41], J.Blümlein[17], H.Böttcher[17], A.Bogacz[36], C.Bracco[16], J.Bracinik[06], G.Brandt[44], H.Braun[65], S.Brodsky[57,b], O.Brüning[16], E.Bulyak[12], A.Buniatyan[17], H.Burkhardt[16], I.T.Cakir[02], O.Cakir[01], R.Calaga[16], A.Caldwell[70], V.Cetinkaya[01], V.Chekelian[70], E.Ciapala[16], R.Ciftci[01], A.K.Ciftci[01], B.A.Cole[38], J.C.Collins[48], O.Dadoun[42], J.Dainton[24], A.De.Roeck[16], D.d'Enterria[16], P.DiNezza[72], M.D'Onofrio[24], A.Dudarev[16], A.Eide[60], R.Enberg[63], E.Eroglu[62], K.J.Eskola[21], L.Favart[08], M.Fitterer[16], S.Forte[32], A.Gaddi[16], P.Gambino[59], H.García Morales[16], T.Gehrmann[69], P.Gladkikh[12], C.Glasman[28], A.Glazov[17], R.Godbole[35], B.Goddard[16], T.Greenshaw[24], A.Guffanti[13], V.Guzey[19,36], C.Gwenlan[44], T.Han[50], Y.Hao[37], F.Haug[16], W.Herr[16], A.Hervé[27], B.J.Holzer[16], M.Ishitsuka[58], M.Jacquet[42], B.Jeanneret[16], E.Jensen[16], J.M.Jimenez[16], J.M.Jowett[16], H.Jung[17], H.Karadeniz[02], D.Kayran[37], A.Kilic[62], K.Kimura[58], R.Klees[75], M.Klein[24], U.Klein[24], T.Kluge[24], F.Kocak[62], M.Korostelev[24], A.Kosmicki[16], P.Kostka[17], H.Kowalski[17], M.Kraemer[75], G.Kramer[18], D.Kuchler[16], M.Kuze[58], T.Lappi[21,c], P.Laycock[24], E.Levichev[40], S.Levonian[17], V.N.Litvinenko[37], A.Lombardi[16], J.Maeda[58], C.Marquet[16], B.Mellado[27], K.H.Mess[16], A.Milanese[16], J.G.Milhano[76], S.Moch[17], I.I.Morozov[40], Y.Muttoni[16], S.Myers[16], S.Nandi[55], Z.Nergiz[39], P.R.Newman[06], T.Omori[61], J.Osborne[16], E.Paoloni[49], Y.Papaphilippou[16], C.Pascaud[42], H.Paukkunen[53], E.Perez[16], T.Pieloni[23], E.Pilicer[62], B.Pire[45], R.Placakyte[17], A.Polini[07], V.Ptitsyn[37], Y.Pupkov[40], V.Radescu[17], S.Raychaudhuri[35], L.Rinolfi[16], E.Rizvi[71], R.Rohini[35], J.Rojo[16,31], S.Russenschuck[16], M.Sahin[03], C.A.Salgado[53,a], K.Sampei[58], R.Sassot[09], E.Sauvan[04], M.Schaefer[75], U.Schneekloth[17], T.Schörner-Sadenius[17], D.Schulte[16], A.Senol[22], A.Seryi[44], P.Sievers[16], A.N.Skrinsky[40], W.Smith[27], D.South[17], H.Spiesberger[29], A.M.Stasto[48,d], M.Strikman[48], M.Sullivan[57], S.Sultansoy[03,e], Y.P.Sun[57], B.Surrow[11], L.Szymanowski[66,f], P.Taels[05], I.Tapan[62], T.Tasci[22], E.Tassi[10], H.Ten.Kate[16], J.Terron[28], H.Thiesen[16], L.Thompson[14,30], P.Thompson[06], K.Tokushuku[61], R.Tomás García[16], D.Tommasini[16], D.Trbojevic[37], N.Tsoupas[37], J.Tuckmantel[16], S.Turkoz[01], T.N.Trinh[47], K.Tywoniuk[26], G.Unel[20], T.Ullrich[37], J.Urakawa[61], P.VanMechelen[05], A.Variola[52], R.Veness[16], A.Vivoli[16], P.Vobly[40], J.Wagner[66], R.Wallny[68], S.Wallon[43,46,f], G.Watt[69], C.Weiss[36], U.A.Wiedemann[16], U.Wienands[57], F.Willeke[37], B.-W.Xiao[48], V.Yakimenko[37], A.F.Zarnecki[67], Z.Zhang[42], F.Zimmermann[16], R.Zlebcik[51], F.Zomer[42]