Strong Interactions & QCD at the Energy Frontier

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European Strategy Preparatory Group

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Speaker's affiliations:

Strong Interactions and QCD

Open Fundmental Questions	Practical Concerns
- Confinement - Hadronic mass generation - High energy unitarity - Spin `Crisis' - 3 dimensional structure - Coupling unification - Strong CP / axions - QCD instantons - Bound states (glueballs, hybrids, pentaquarks?) - AdS/CFT connection to Super-gravity? - …	- Proton parton densities - Photon, pomeron, nuclear parton densities - Multi-parton / heavy flavour final states - (Non)-factorisation schemes - Hadronisat^{n} & fragmentat^{n} - Underlying event / MPI - Minimum bias (pile-up) - Boosted jets / substructure, - Jet vetoes - …

A rich and subtle theory with lots still to be discovered and many deeper tests of our understanding still needed

Talk Outline

1) Tour of relevant present and possible future facilities
2) Most pressing experimentally accessible targets
   - Proton & nuclear parton densities and α_s
   - High density QCD and non-linear evolution
   - Nucleon spin and 3D structure

Complied mainly from submitted documents: in particular:

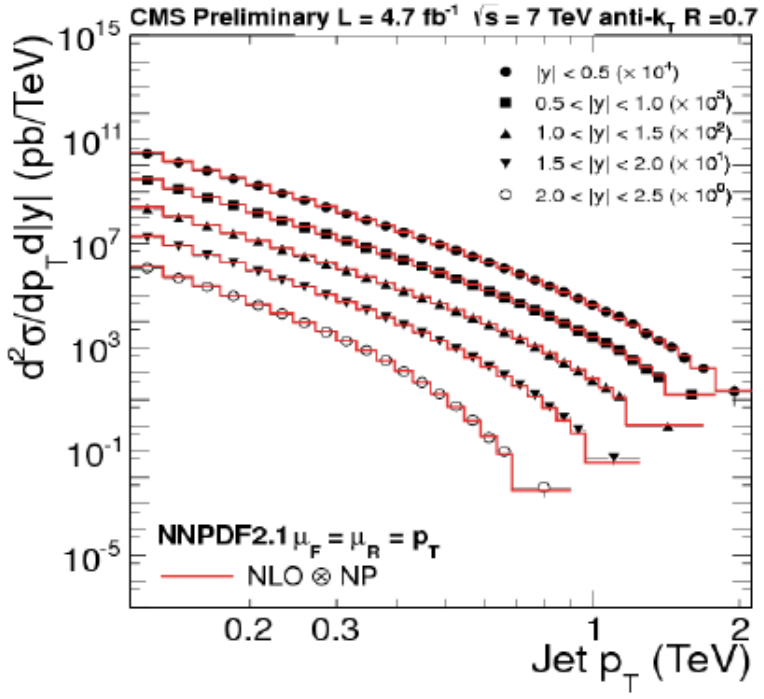
12) *Exploring Confinement* (W. Krasny)
30) *The Scientific Program in Particle and Nuclear Physics at the CERN injectors and its foreseable future* (CERN-PH)
36) *Nucleon Structure & QCD at High Energy* (A. Ferrero et al IN2P3 10 year plan)
60) *COMPASS planned measurements in the next five years and longer term perspectives on the study of the nucleon structure* (COMPASS Collaboration)
106) *The future of Monte Carlo Event Generators* (MCNet Collaboration)
117) *A Fixed-Target ExpeRiment at the LHC: AFTER @ LHC* (M. Anselmino et al)
119) *COMPASS Plans & Perspectives with Hadron Beams* (COMPASS Collaboration)
141) *Physics at a High-Luminosity LHC with ATLAS* (ATLAS Collaboration)
144) *CMS Submission to European Strategy Preparatory Group* (CMS Collaboration)
147) *A Large Hadron Electron Collider at CERN* (LHeC Study Group)

[and various national and institutional summaries]

LHC and HL-LHC

- Impressive, eclectic progress since LHC turn-on

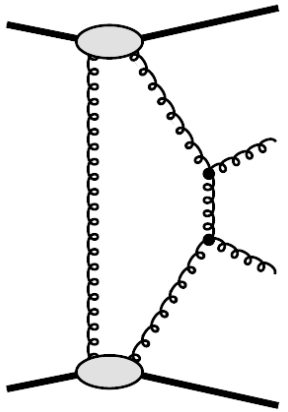
- … will continue @ √s=13 - 14 TeV

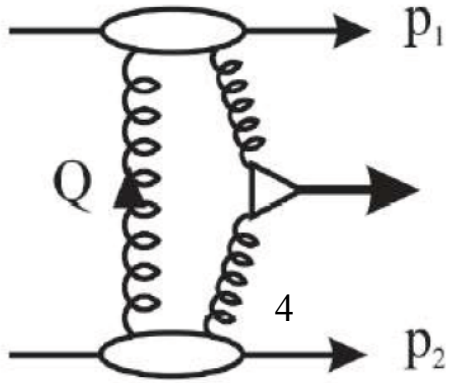


- Output rate will presumably decrease by the time HL-LHC approaches
  - Main observables covered
  - HL-LHC strongly focused on searches / Higgs sector
  - (Most) QCD does not need ab^{-1} luminosities
  - Pile-up ~ 200 may be prohibitive (JES, Etmiss …)

- Short dedicated runs for low x physics?

- Possible role for proton taggers (ATLAS-FP, 420m proton taggers …)





Higher Energy Proton-Proton Colliders

HE-LHC ($\sqrt{s}$ ~ 33 TeV) or pp in new 80km tunnel ($\sqrt{s}$ ~80 TeV) would continue / develop existing pp colliders QCD programme

Exciting extensions to kinematic range at high p_T and low x (e.g. reaching x ~ 2.10^{-6} on rapidity plateau for $\sqrt{s}$ ~ 33 TeV)

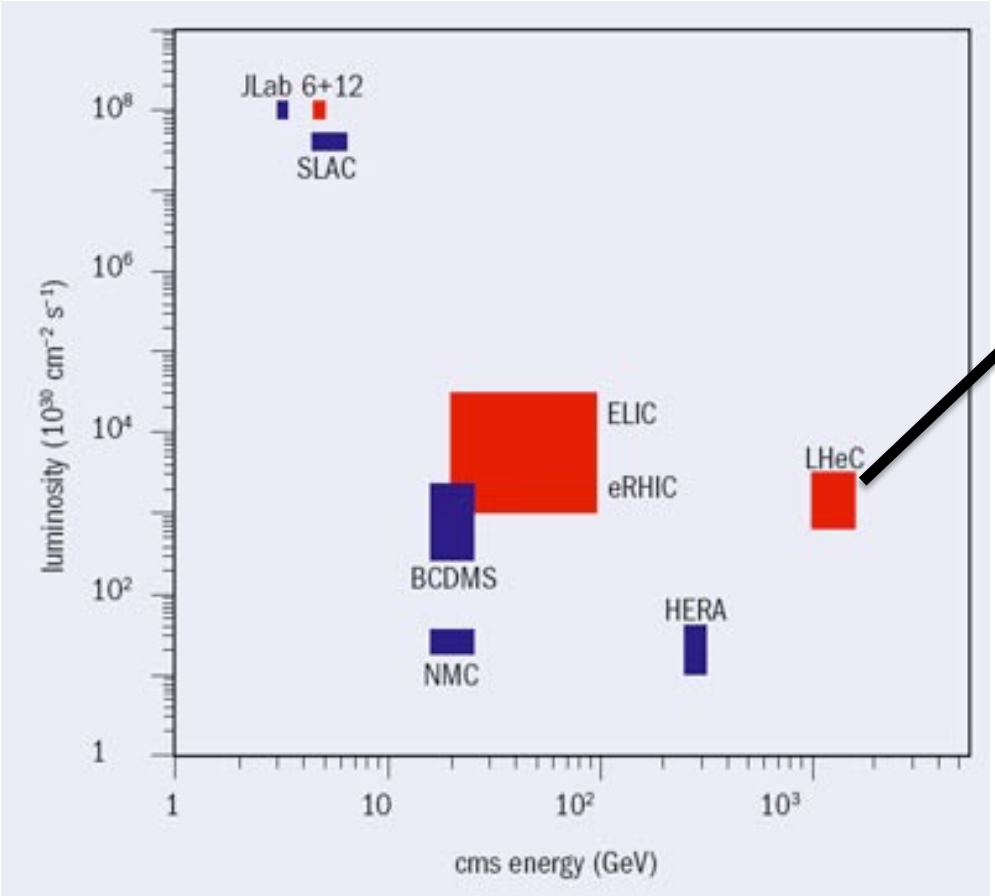
No dedicated QCD studies so far: not considered further here

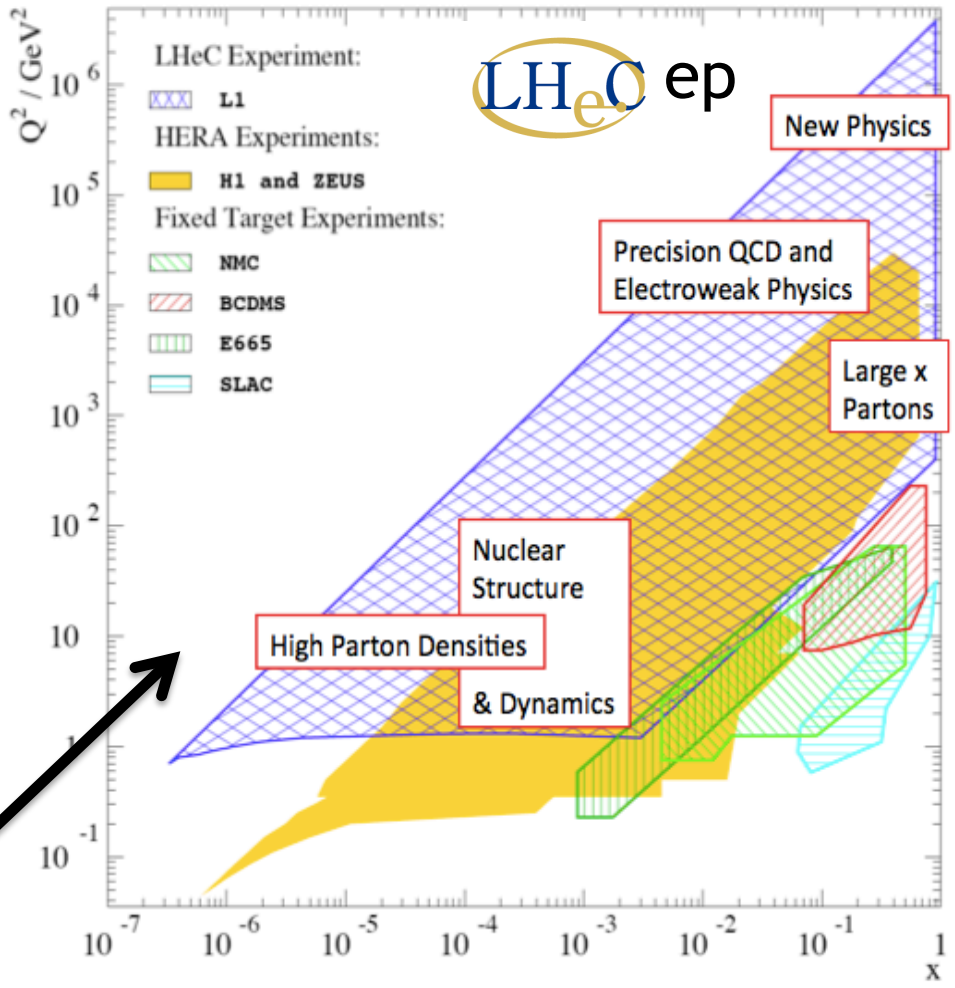
High Energy Lepton Collider

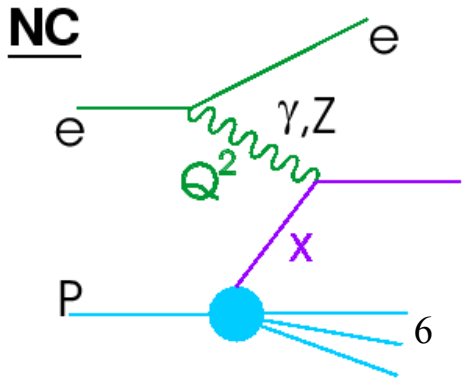
Various proposed lepton collider configurations would provide clean environment to measure α_s and other fundamental parameters via e.g. event shapes.
Also top quarks, multi-jets, other precision QCD topics.

→clean testing ground for NNLO, NN(N)LL, fragmentation, hadronisation etc

Past, Present and Future ep Colliders

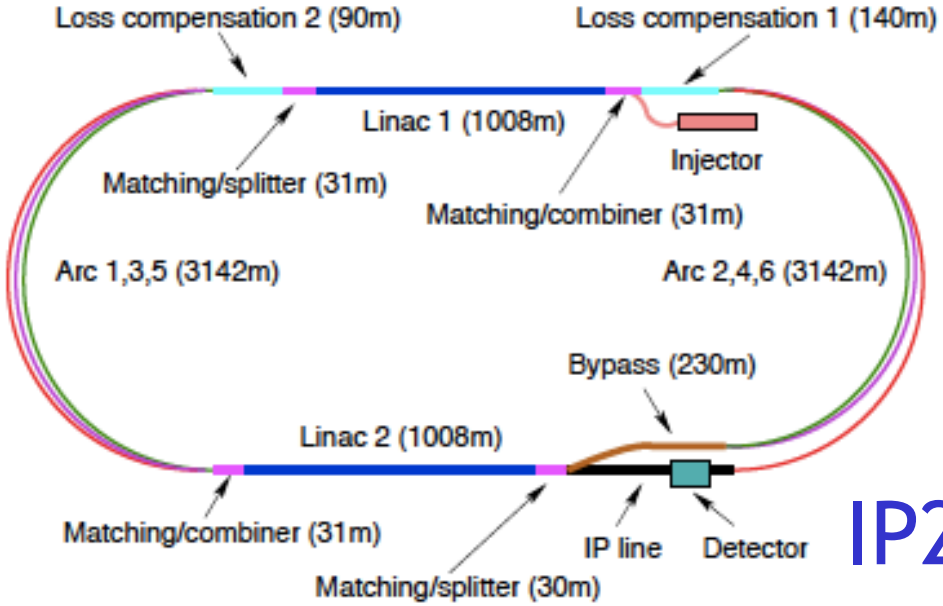






Large Hadron electron Collider (LHeC)

- 60 GeV electron beam colliding with LHC protons (ions) from mid 2020s
- Simultaneous with pp running
- Lumi ~10^{33} $cm^{-1}s^{-1}$ constrained by 100 MW power consumption,
  → ~100 fb-1 integrated
- `Medium scale LHC upgrade'



- **Mainly QCD & PDF-focused facility at the ep energy frontier**, attacking fundamental questions in QCD and providing a basis for LHC discovery potential near the kinematic limit

- Discovery potential, probing eq, eg vertices, excited leptons …
- Complementary to LHC in Higgs sensitivity (clean WW, ZZ production, bbbar decay, CP properties …)
- Precision electroweak measurements

Recently Completed LHeC CDR

~600 page document, commissioned by CERN, ECFA,NuPECC

~200 contributing authors.

- In final stages of ECFA evaluation
- Included in NuPECC Long Range Plan
- CERN Mandate (S. Bertolucci at closing workshop, Chavannes-de-Bogis, June 2012)

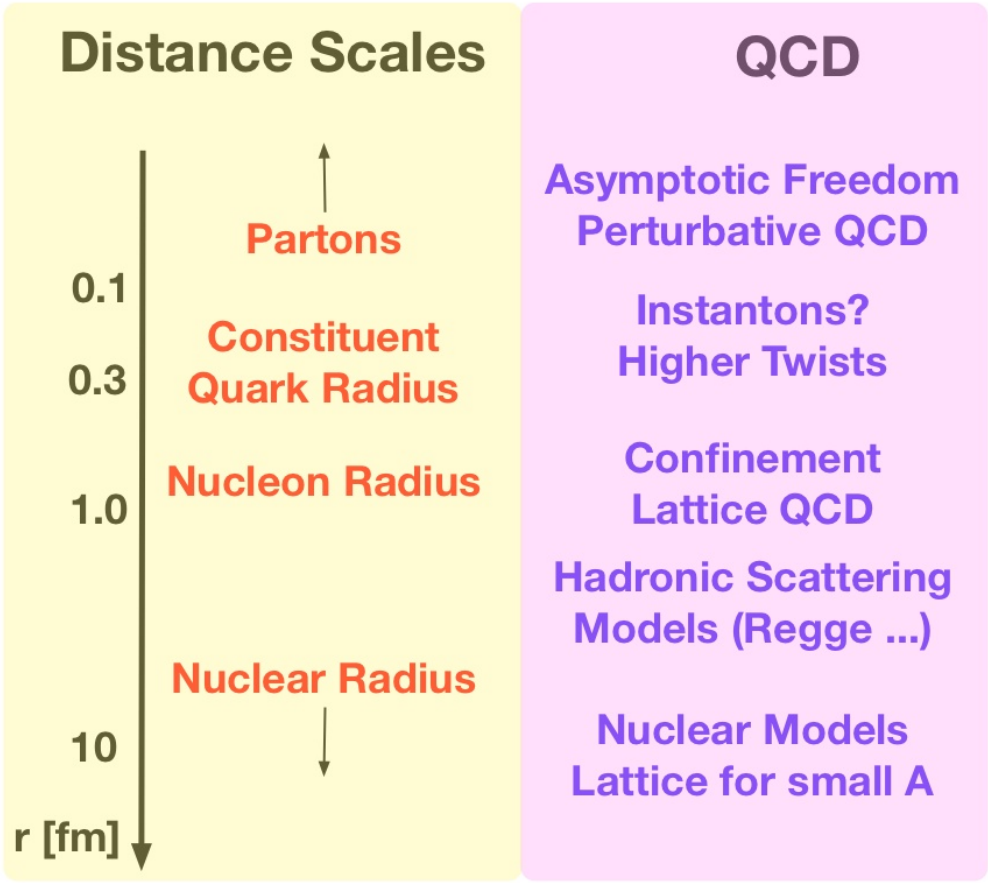
"**Next goal: TDR by ~2015.**

The LHeC study group has the mandate of **preparing in 2012, a proposal to the European Strategy Group, in which the LHeC project can be considered for evaluation as one of the future European collider projects**.

This will entail, over the coming three years, **the development of the key technological components required for the Linac-Ring option, such that a final decision on the project can be taken at the time in which first results of the LHC 13-14 TeV operation will become available.**"

Important to Probe wide Range of Energies / Distance Scales

- QCD has rich phenomenology over wide range of energies and scales
- Requires corresponding range of experiments – not only highest energies possible.
- Confinement transition on scales ~ 1fm.



e.g. 20 GeV electron beam on at SPS with relatively low lumi, mapping strong force over range 0.1 → 10 fm, $4 \times 10^{-6} < Q^2 < 400\ \mathrm{GeV}^2$ could already be interesting for eA in particular

[Krasny: Detailed studies yet to be performed]

COMPASS: past, present and future

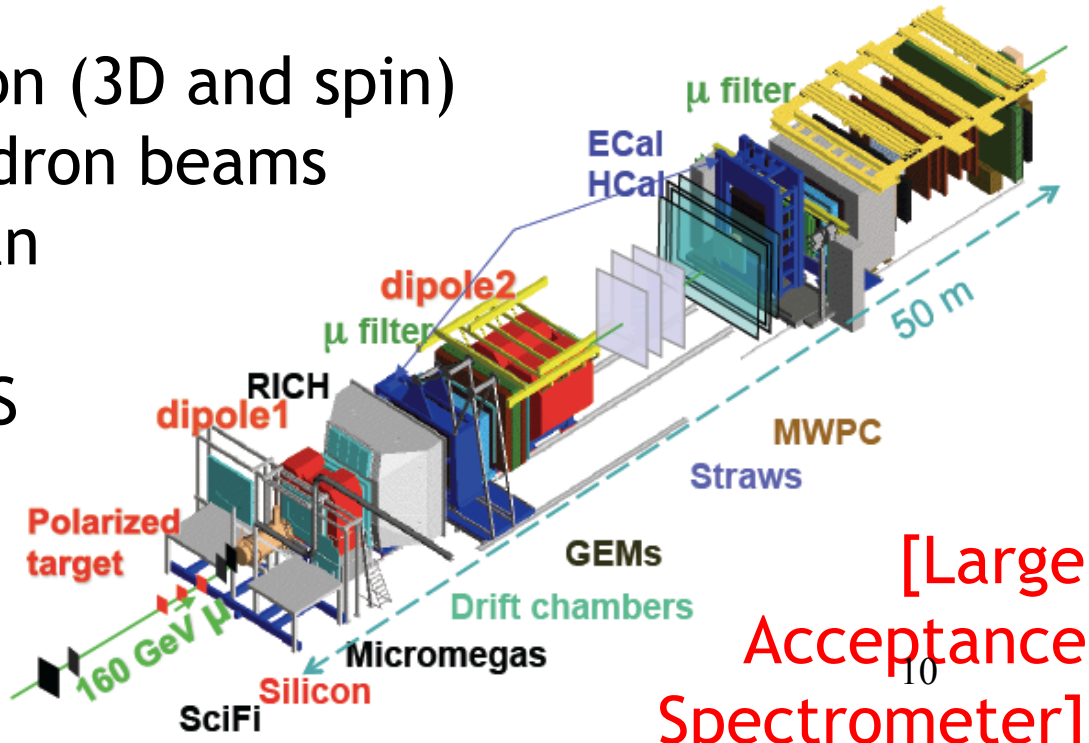
100-200 GeV secondary / tertiary SPS muon and hadron beams on various fixed targets (LH2, Polarized NH_3, ^6LiD, Nuclei…)

- 2002-7, 2010-11: Muon beam, polarised targets (nucleon spin)

- 2008-9: Diffractive and central reactions with hadron beam (hadron spectroscopy)

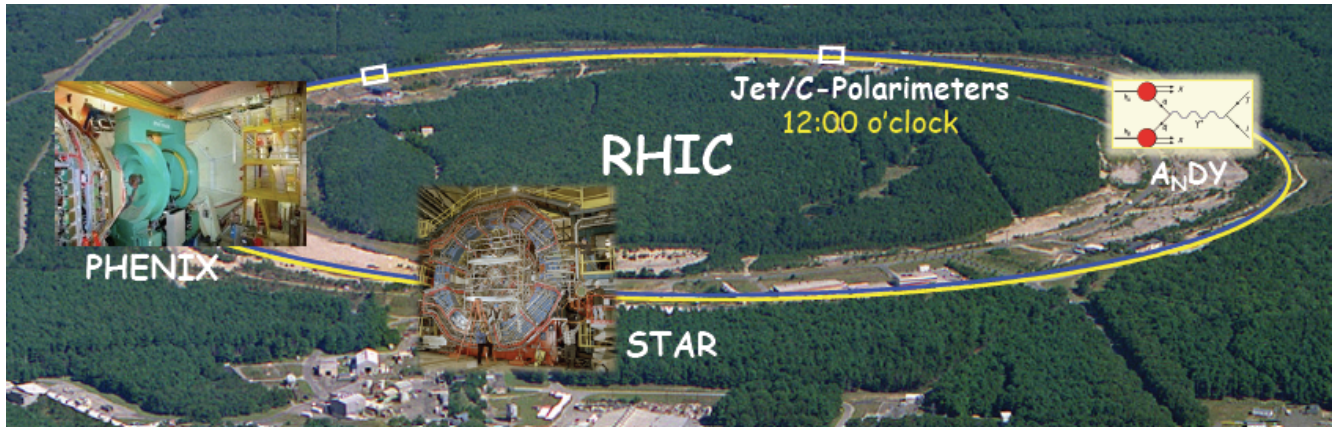
- 2014-17 [Approved]: Nucleon (3D and spin) structure using muon and hadron beams
  - TMDs via polarised Drell-Yan
  - GPDs via DVCS etc
  - (un)polarised semi-incl. DIS

- Planning further programme on all topics beyond 2017



[Large Acceptance Spectrometer]

Polarised Proton Programme @ RHIC



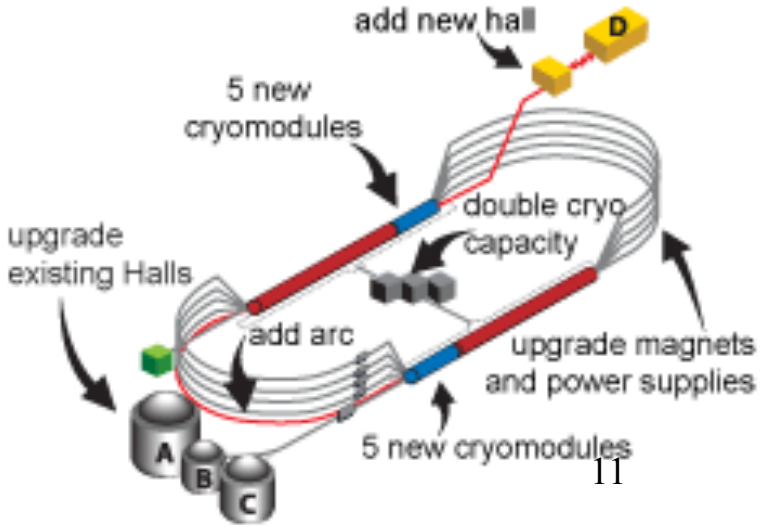
Polarised pp with $\sqrt{s}$ = 500 GeV : current highest energy spin and nucleon tomography programme

Detector Upgrade programme ~ 2016-18

(Approved) J-Lab CEBAF 12 GeV Upgrade

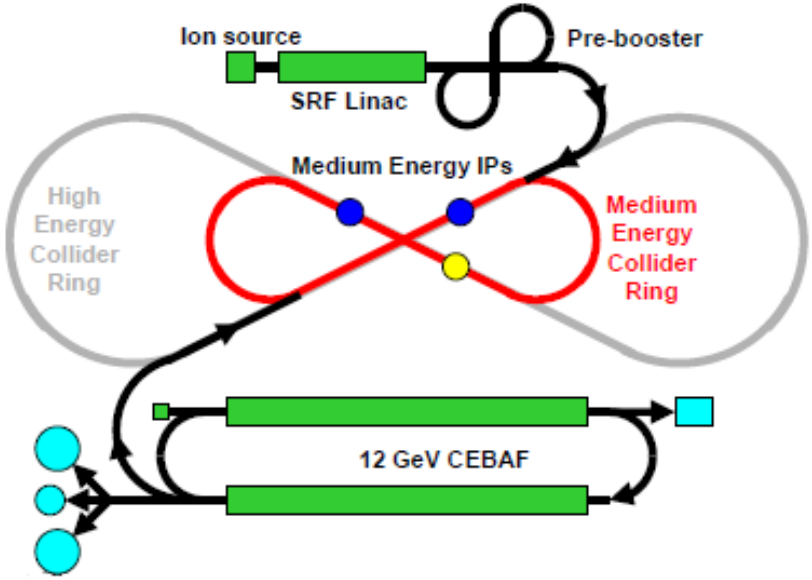
Intense 12 GeV electron beam on fixed targets

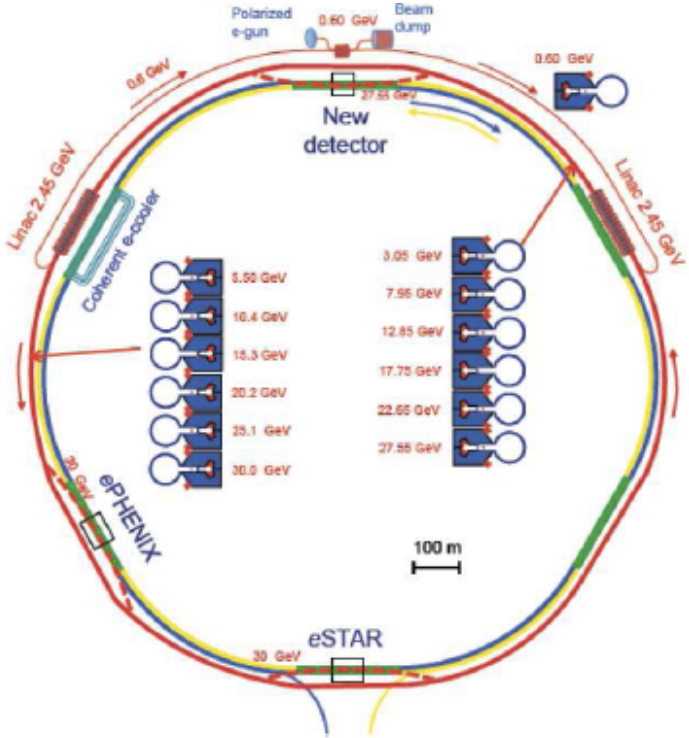
High x nucleon and nuclear structure, nucleon tomography, meson spectroscopy, confinement …



(Proposed) US Electron Ion Collider (EIC)

- MEIC/ELIC @ Jlab: Add figure of 8 hadron rings to CEBAF
- eRHIC @ BNL: Add energy recovery LINAC in RHIC tunnel



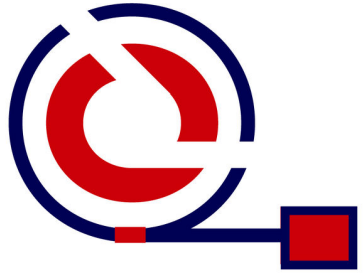


E_e <~ 20 GeV, E_p <~ 250 GeV,
$\sqrt{s_{NN}}$ <~ 140 GeV, Lumi > 10^{33} cm^{-2} s^{-1}

- Limited in energy, but >100 times HERA luminosity
- Polarised hadrons → **DIS spin, 3D structure in new regime**
- Heavy ions → **large step forward for eA kinematic range**

AFTER @ LHC

Multi-purpose proposed experiment with LHC p, Pb beams on various polarised and unpolarised fixed targets.



- pp $\sqrt{s}$ = 115 GeV (comparable to RHIC) ; $\sqrt{s_{NN}}$ = 72 GeV in Pb A.

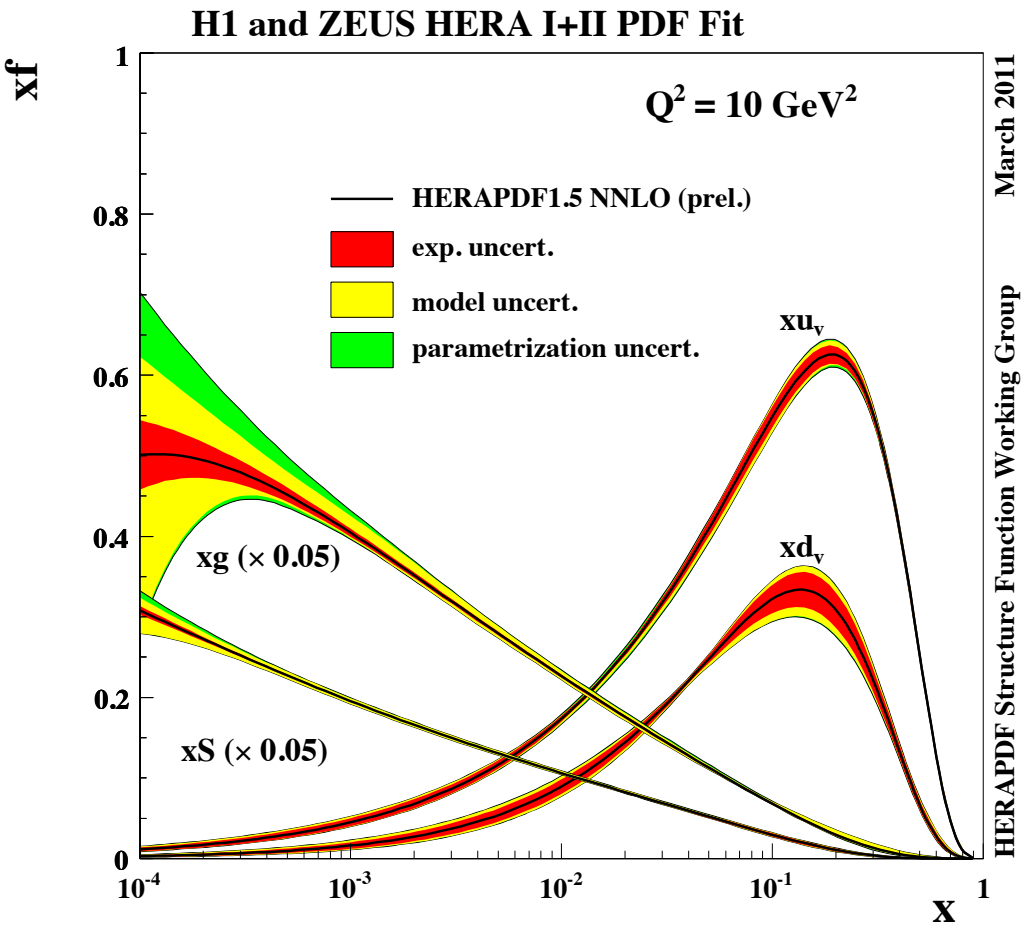
- Full backward access (to x_F = -1)

- Potentially high luminosity ("slow extraction" 5.10^8 protons/sec)

  - Proton, neutron, nuclear structure (gluon, dbar-ubar, HQ)
  - 3D structure through e.g. TMDs (Sivers function from SSAs)
  - Complementary deconfinement observables in heavy ions
  - Ultra-peripheral quasi-elastic gamma-p, diffraction …

Relatively small cost extension to LHC programme.
No timeline yet, but LHCC recommended further studies.

Physics Aims 1: Parton Densities and α_s



HERA's great legacy, but some limitations:

- Insufficient lumi for high x precision

- Low x lack of Q^2 lever-arm for precision on gluon

- Assumptions on quark flavour decomposition

- No deuterons … u and d not separated

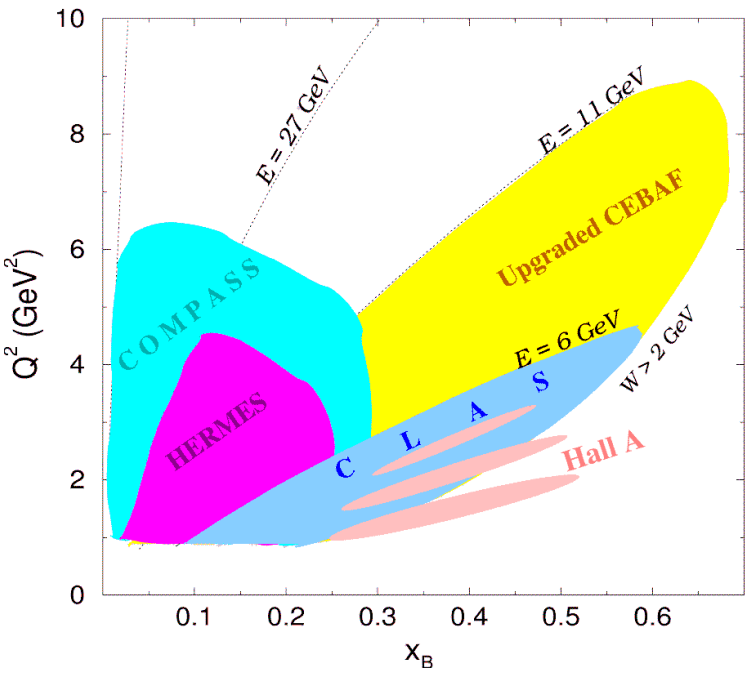
- No heavy ions

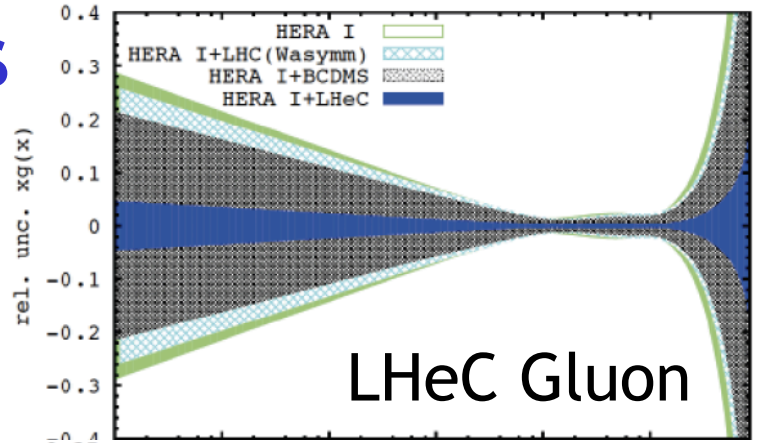
New Proton PDF Constraints

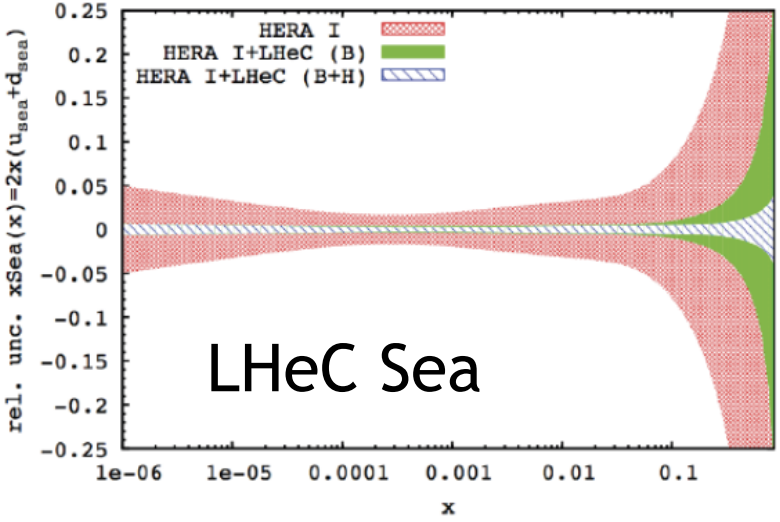
LHeC: huge impact at low x (kinematic range) and high x (lumi). Full flavour decomposition without assumptions

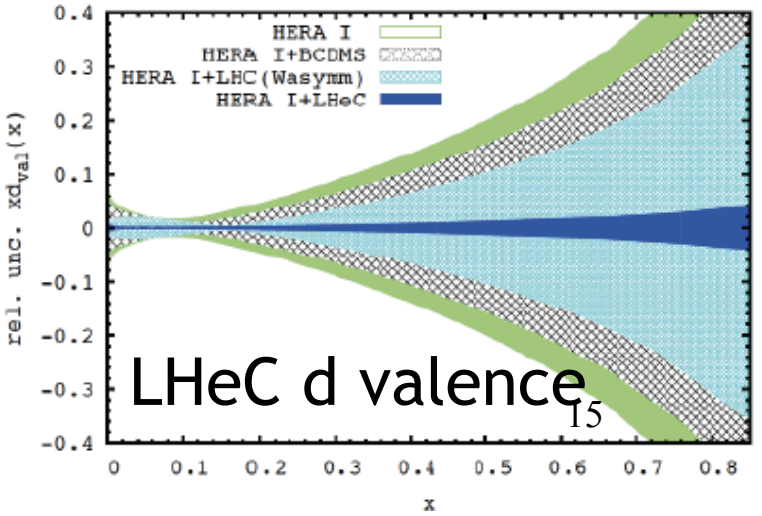
LHC: complementary information in limited range (W, Z, direct γ, DY …)

Fixed Target (Jlab, COMPASS): flavour sensitivity (semi-incl' DIS) and high x, low Q^2 for quark density





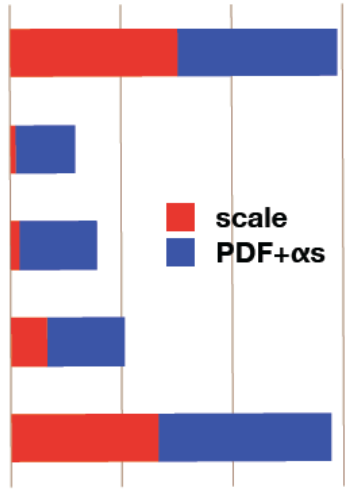




PDF Uncertainties for Higgs Physics

Theory Cross Section Uncertainties (125 GeV Higgs J Campbell, ICHEP'12)

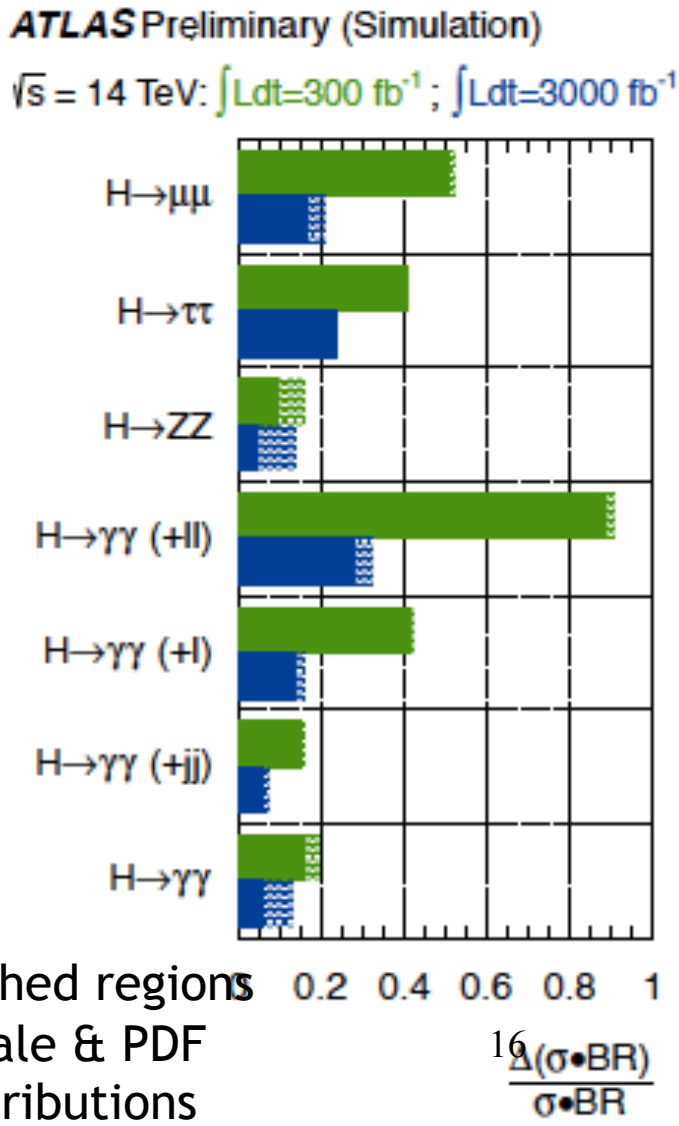
		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
	VBF	1.56 pb	2.9%
NNLO QCD +NLO EW	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%



Similarly fermionic modes (bbbar, ccbar)

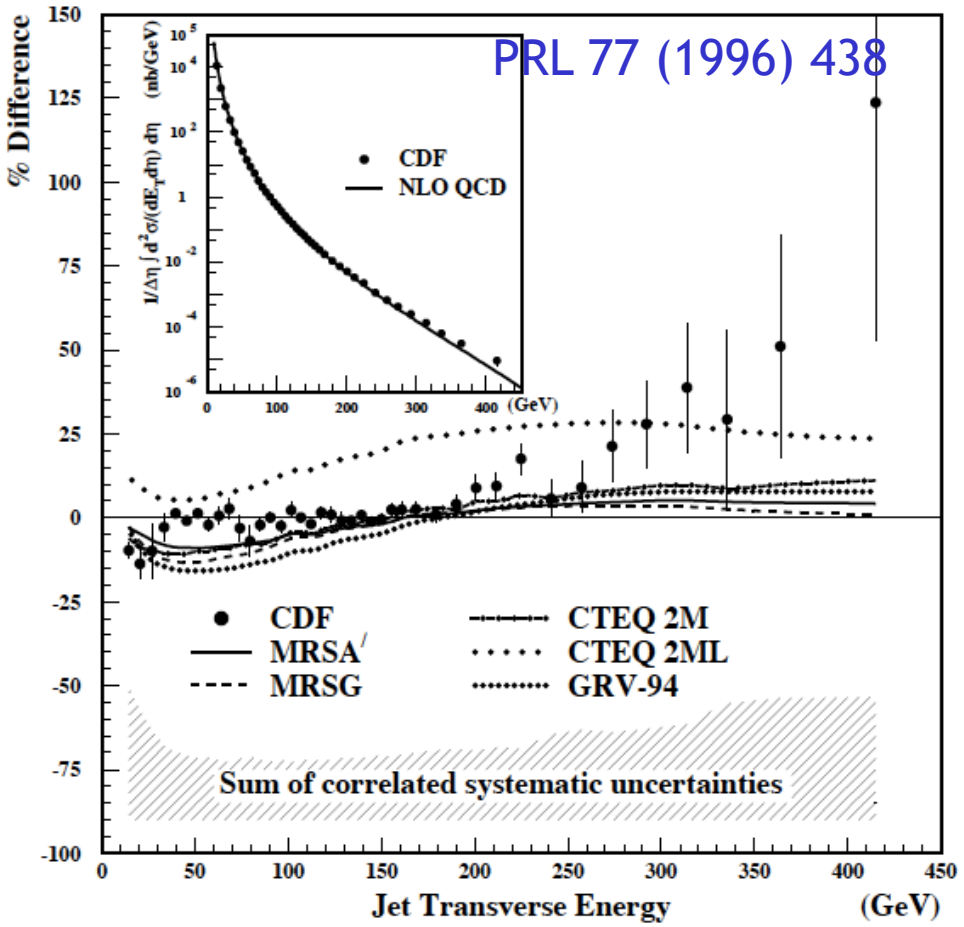
… tests of Standard Model in Higgs sector may become limited by knowledge of PDFs in HL-LHC era

Projected Experimental Uncertainties



[Dashed regions = scale & PDF contributions

New Physics Near Kinematic Limit



Ancient history (HERA, Tevatron)

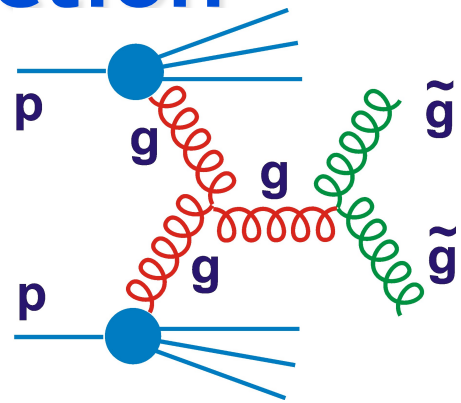
- Apparent excess in large E_T jets at Tevatron turned out to be explained by too low high x gluon density in PDF sets

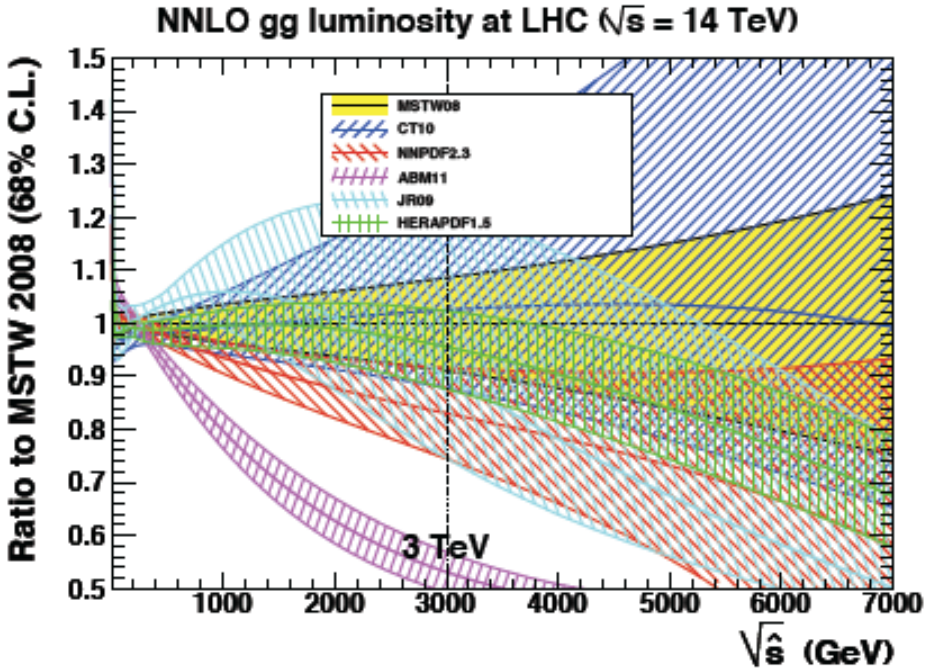
- Confirmation of (non-resonant) new physics near LHC kinematic limit relies on breakdown of factorisation between ep and pp

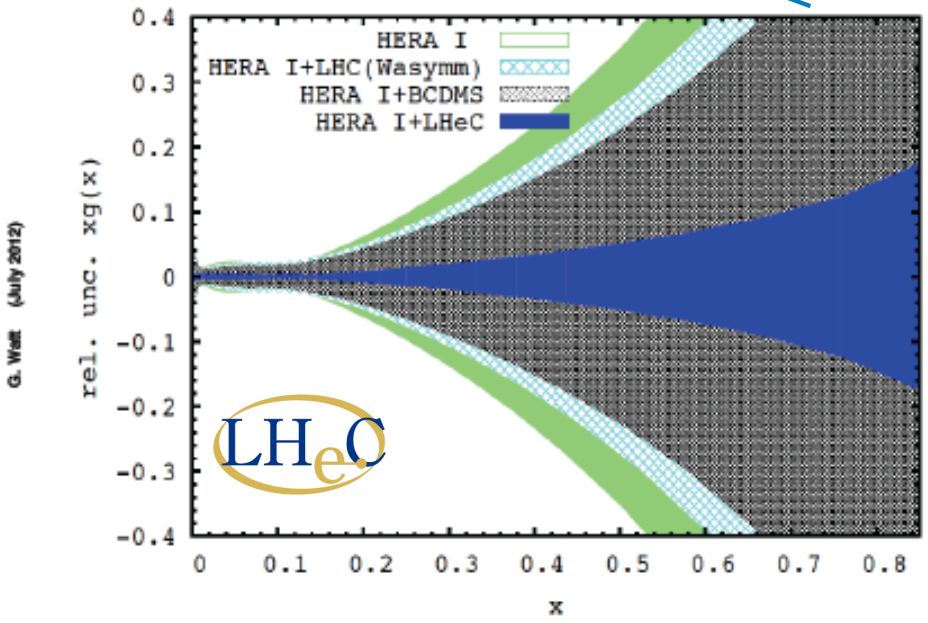
Searches near LHC kinematic boundary may ultimately be limited by knowledge of PDFs (especially gluon as x → 1)

e.g. High Mass Gluino Production

- Signature is excess @ large invariant mass
- Expected SM background (e.g. gg → gg)
  poorly known for s-hat > 1 TeV.

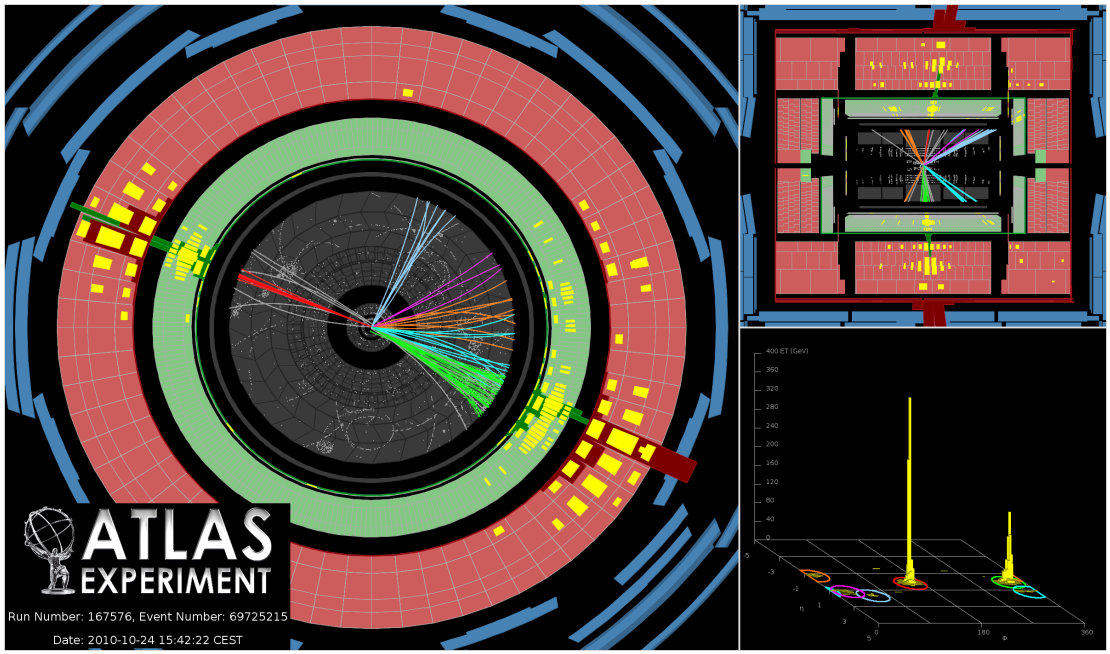






- Both signal & background uncertainties driven by error on gluon density
- Similar conclusions for other non-resonant LHC signals involving high x partons (e.g. contact interactions signal in Drell-Yan)

(Lumi Limited) High pT QCD at the LHC



LHC processes sensitive to PDFs @ x → 1

- Jets with p_T → √s/2
- Large mass Drell Yan
- Di-bosons

Cross sections fall rapidly with increasing x

With 3000 fb^{-1} at 14 TeV, x ~ 0.6 accessible with central jets at the LHC.

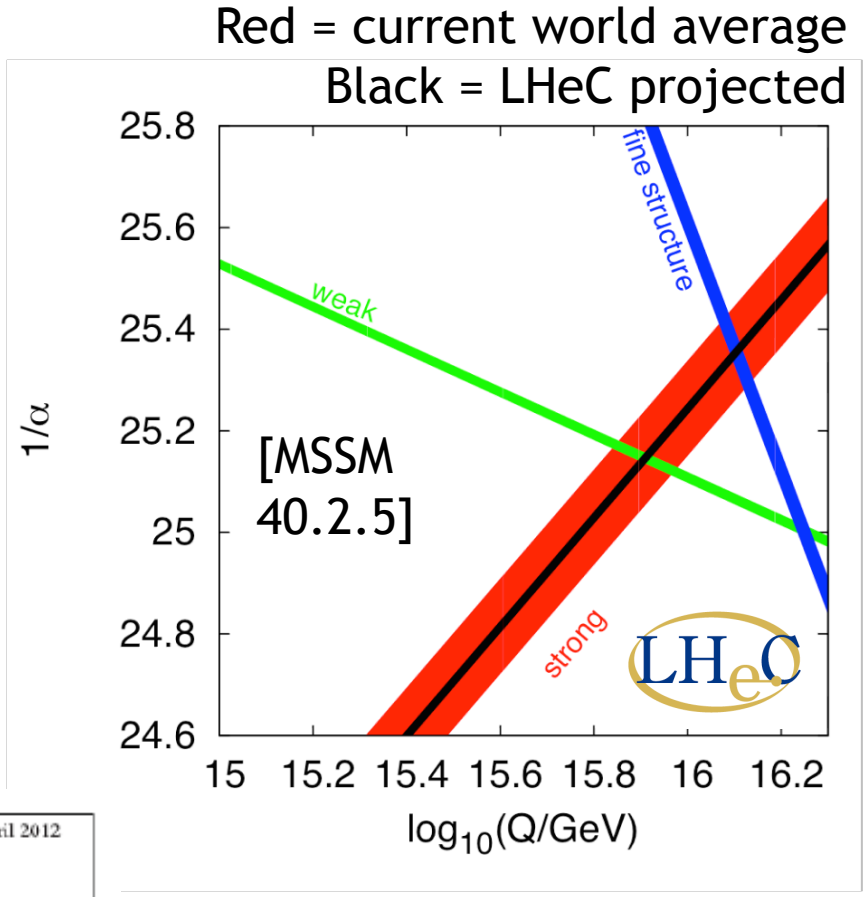
[CMS Calculations]

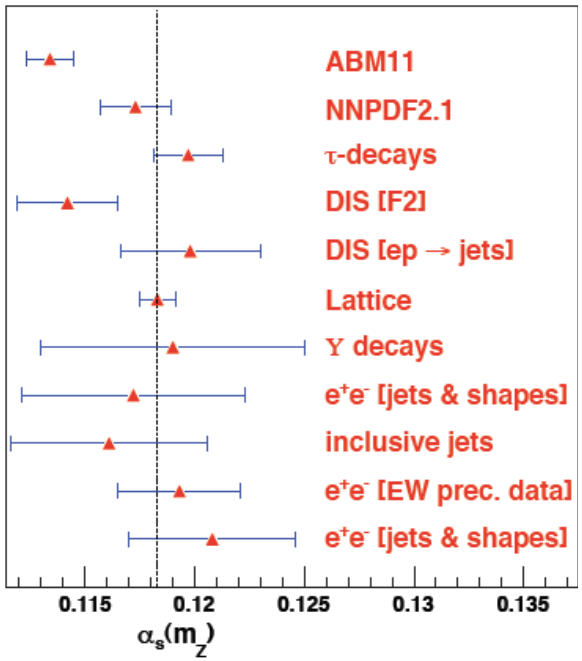
	$\sigma(pp \to j + j + X)$[fb]	
$\bar{x} = \frac{2p_T}{\sqrt{s}}$	$\sqrt{s} = 14$ TeV	$\sqrt{s} = 33$ TeV
0.5	$2 \cdot 10^{-1}$	$1 \cdot 10^{-2}$
0.6	$4 \cdot 10^{-3}$	$5 \cdot 10^{-4}$
0.7	$7 \cdot 10^{-5}$	$9 \cdot 10^{-6}$
0.8	$4 \cdot 10^{-7}$	$4 \cdot 10^{-8}$
0.9	$7 \cdot 10^{-11}$	$8 \cdot 10^{-12}$

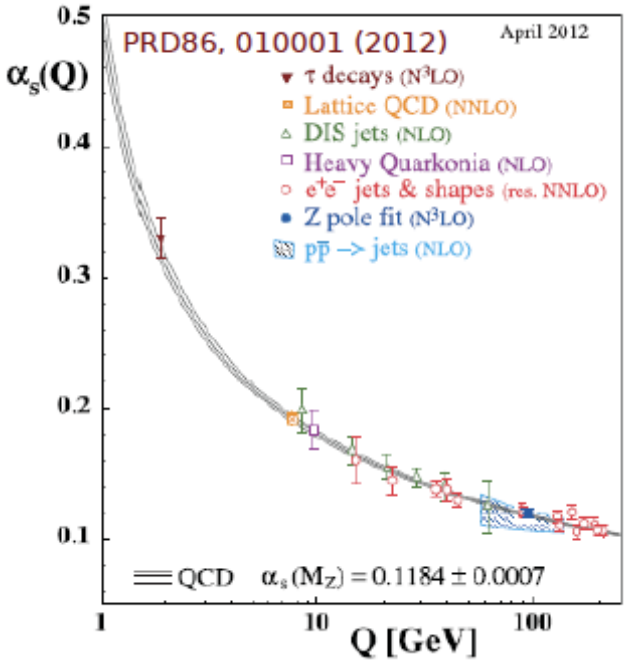
HL-LHC and LHeC combining in 2020s to fully exploit full kinematic mass range for direct new particle production at LHC

Measuring α_s

- Least constrained fundamental coupling by far (known to ~1%)
- Do coupling constants unify (with a little help rom SUSY?)
- Future measurement precision
→ per-mille (experimental) with LHeC, high energy lepton colliders





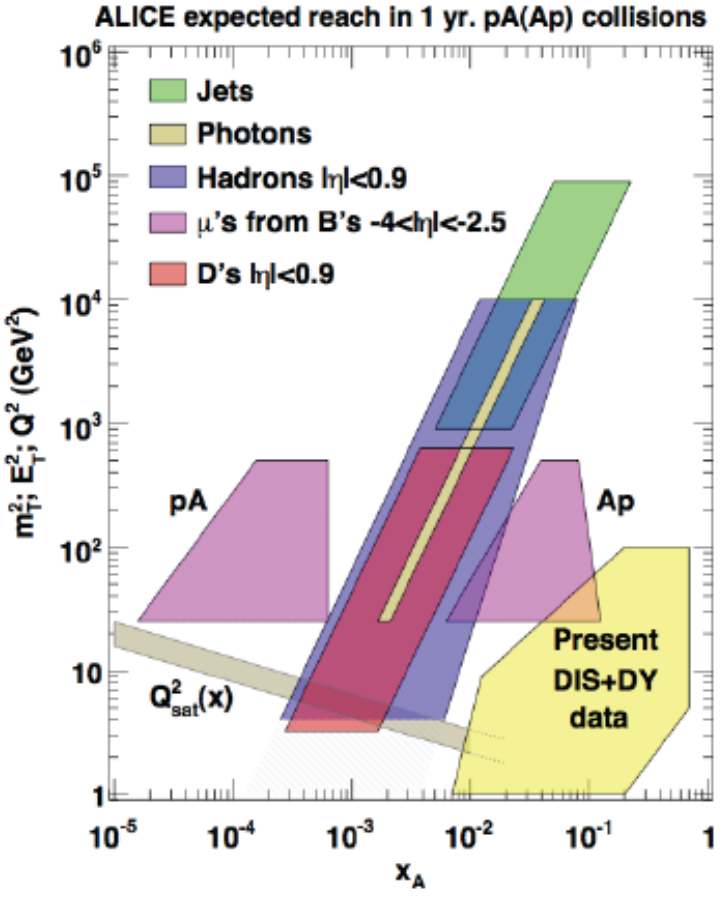


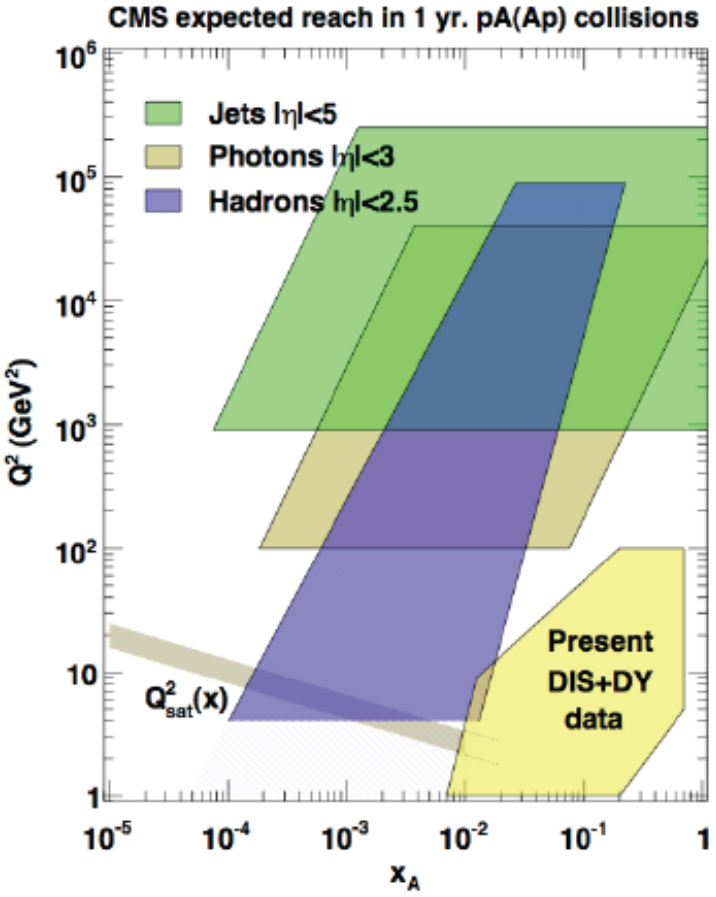
- Important to check compatibility between different experiments (and lattice)
- Scale dependence (running) also sensitive to new effects

Nuclear Parton Densities: pA

Improved knowledge essential for understanding of collective, high parton density effects in nuclei, to constrain initial state of heavy ion collisions and characterise the produced medium.

Currently ~ unknown @ x <~ 10^{-2}; gluon very poorly constrained



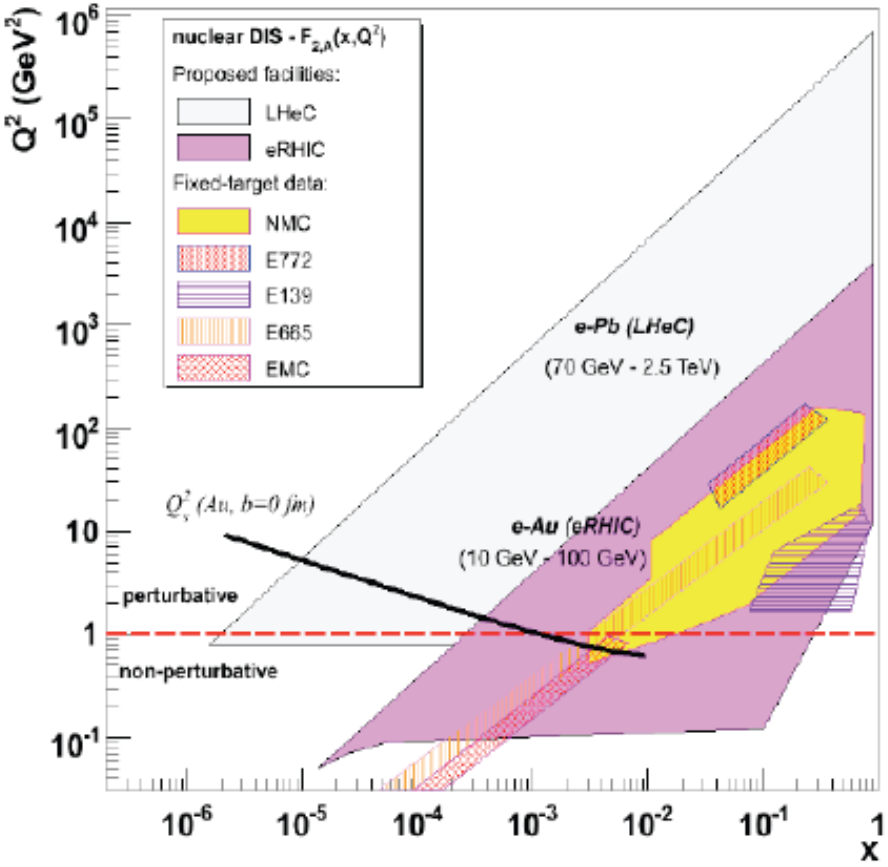


… goal of LHC pA programme

… may be sufficient for practical needs in AA programme at LHC

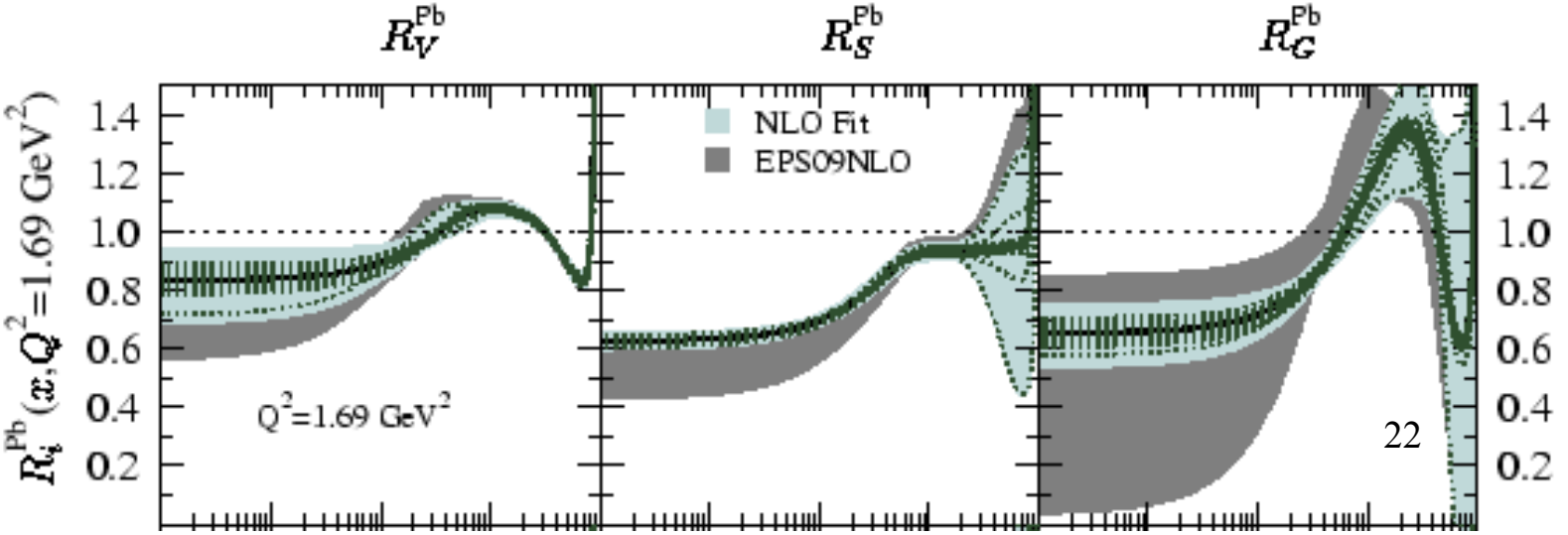
Nuclear PDFs: eA

- eA offers access to lower x than easily achievable in pA at LHC
LHeC (EIC) extends x range by 3-4 (1-2) orders of magnitude
- Clean final states / theoretical control - to (N)NLO in pQCD

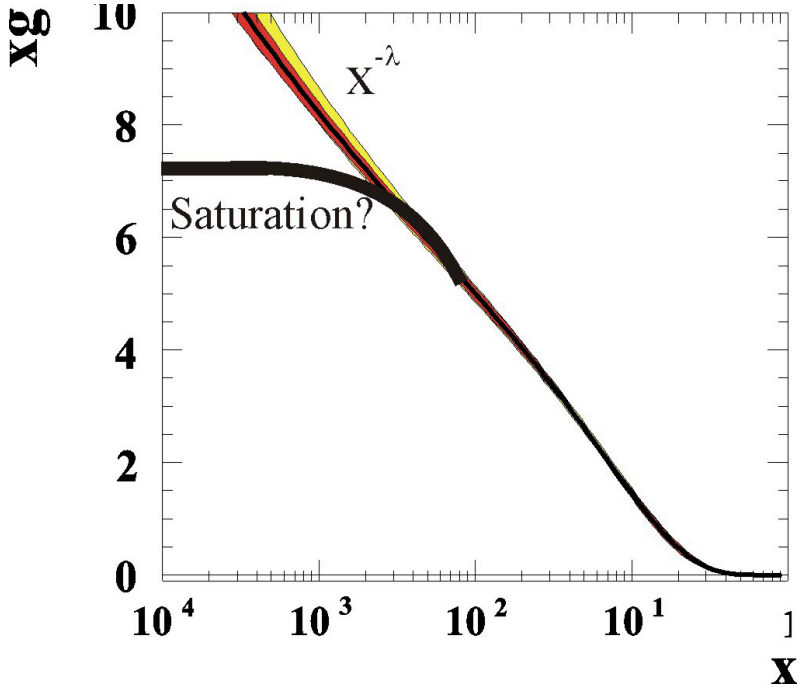


- New effects anyway likely to be revealed in tensions between eA and pA, AA (breakdown of factorisation)

LHeC Simulation



Physics Aims 2:
The high energy (low x) problem -
High Density QCD,
Forward Physics & Diffraction



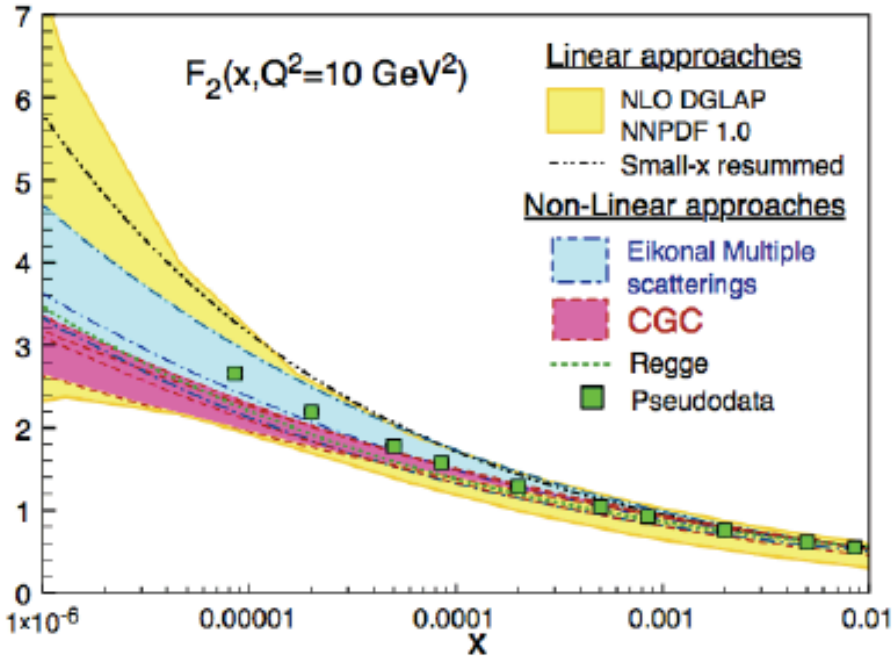
A fundamental QCD problem is looming … rise of low x parton densities cannot continue

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

… new high density, small coupling parton regime of non-linear parton evolution dynamics (e.g. Colour Glass Condensate)? …

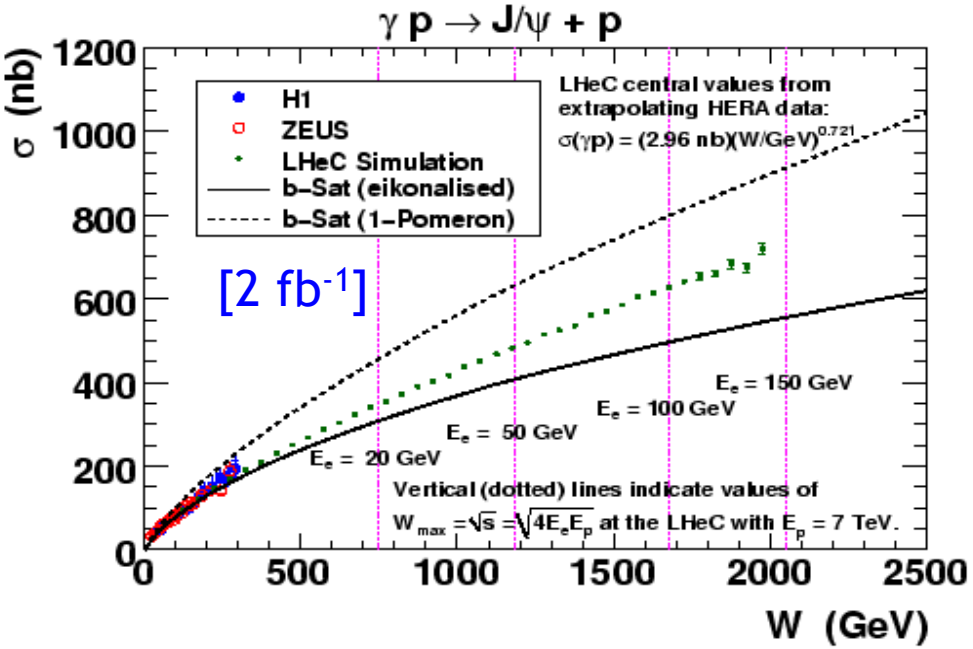
… gluon dynamics → confinement and hadronic mass generation

Precision Low x Physics at LHeC

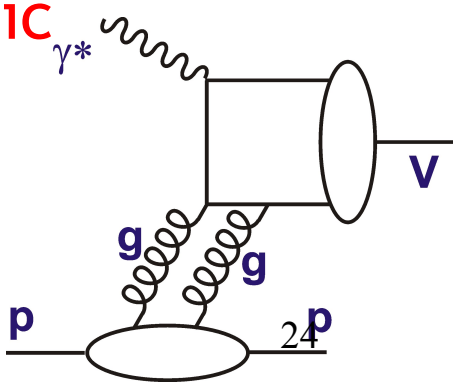


• LHeC can distinguish between different QCD-based models for the onset of non-linear dynamics

• 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



• Significant non-linear effects expected in diffraction in LHeC kinematic range, even for ep → eJ/Ψp - even more so in eA …



Physics Aims 3: Spin Degrees of Freedom & 3 Dimensional View of Hadrons ("Nucleon Tomography")

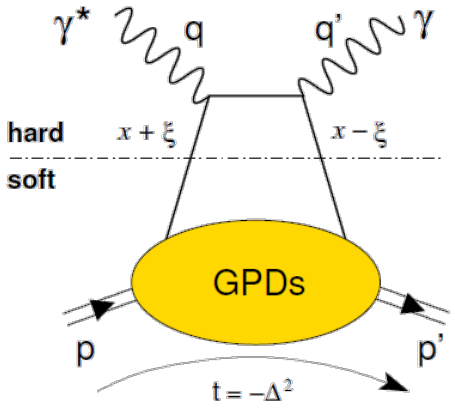
Basic Questions:

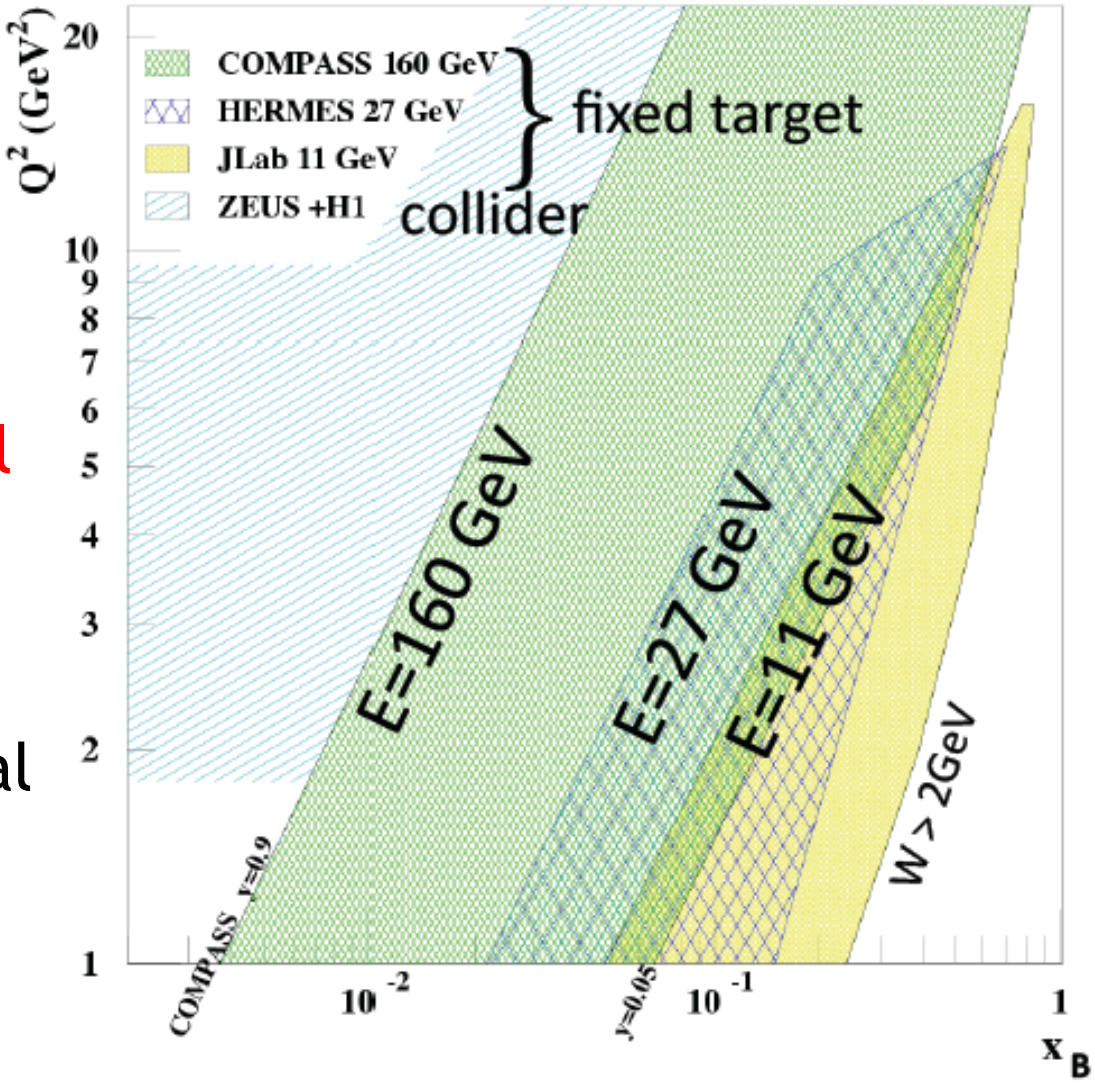
- How do quark and gluon spin and angular momentum conspire to guarantee spin ½ nulceons?
- Are quark and gluon radii of hadrons the same?
- What correlations are there between the spatial positions of partons (Generalised Parton Densities - GPDs)?
- What correlations are there between parton momenta (Transverse Momentum Distributions – TMDs)?

Emphasis shifted from longitudinal spin structure functions to observables sensitive to correlations between partons

Spatial tomography: GPDs and DVCS

DVCS,
ep→eγp





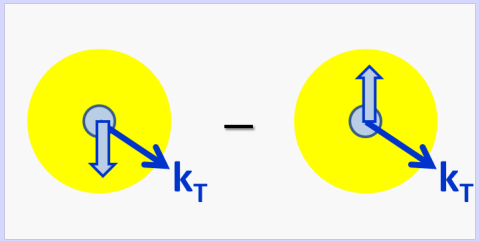
- GPDs correlate longitudinal momenta of partons with their transverse positions

- Measure with Deeply Virtual Compton Scattering (DVCS) or Hard Exclusive Meson Production in DIS

- Covering kinematic plane requires COMPASS, Jlab and HERA
- Also a major motivation for Jlab-12, EIC, LHeC

Beyond Collinear Factorisation: Momentum Tomography

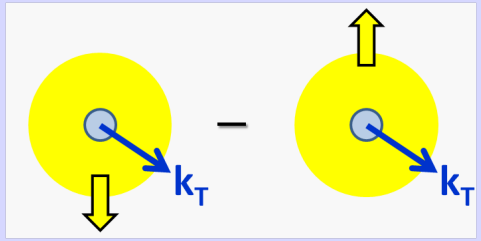
The **Boer-Mulders** function



correlates the quark k_T and the quark transverse spin (unpol N)

2 examples of TMDs

The **Sivers** function

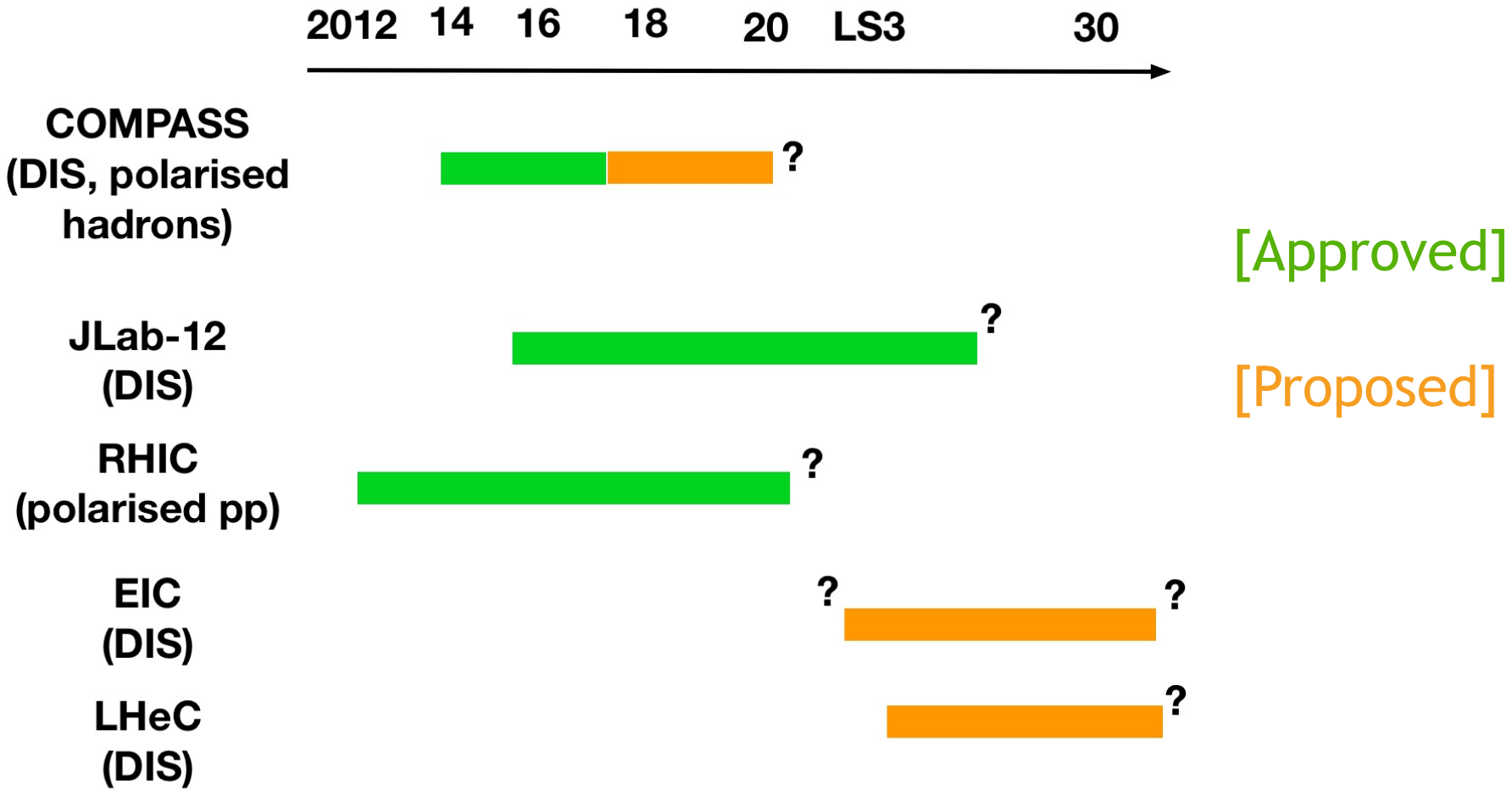


correlates the quark k_T and the nucleon spin (transv. Pol. N)

Measure with spin / azimuthal asymmetries in
1] polarised Drell-Yan (COMPASS πp, RHIC pp, AFTER@LHC?..)
2] semi-inclusive DIS (COMPASS, JLab)

- Important tests of QCD: e.g. Sivers and Boer-Mulders functions should change sign between polarised DIS and polarised Drell-Yan (initial → final state interactions)
- Multiple measurements in different kinematic regions needed.
- Also strong motivating factor for EIC

Rough Timeline of Main Projects Discussed Here



We cannot afford so much uncertainty about the future when we meet again in 2018!

To summarise …

- Hadronic QCD is full of open questions (practical & fundamental)

- Potentially large international experimental community (HERA was ~1000 at its peak)

- Next generation frontier machine needs to step forward in luminosity as well as energy to tackle LHC PDF uncertainties on Higgs couplings and at high x (LHeC)

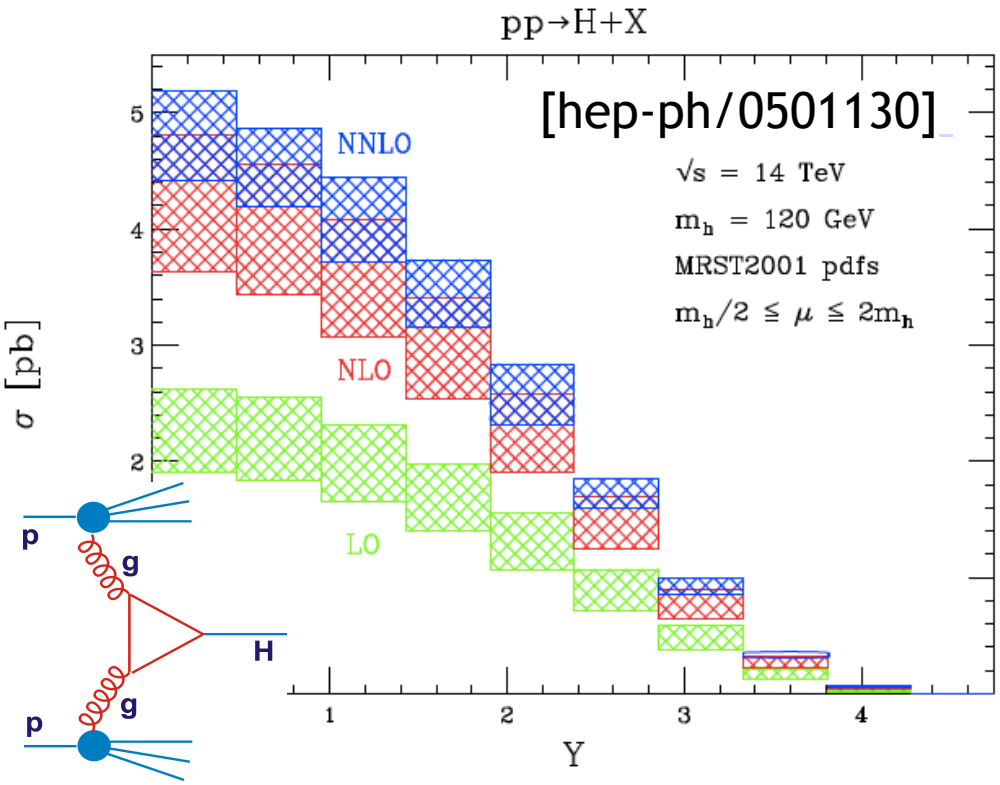
- Require facilities sensitive to a range of scales, from nuclear, hadronic, through confinement to partonic, and beyond to energy frontier, probing 3D structure as well as standard observables (COMPASS, JLab12, RHIC, EIC, AFTER@LHC …)

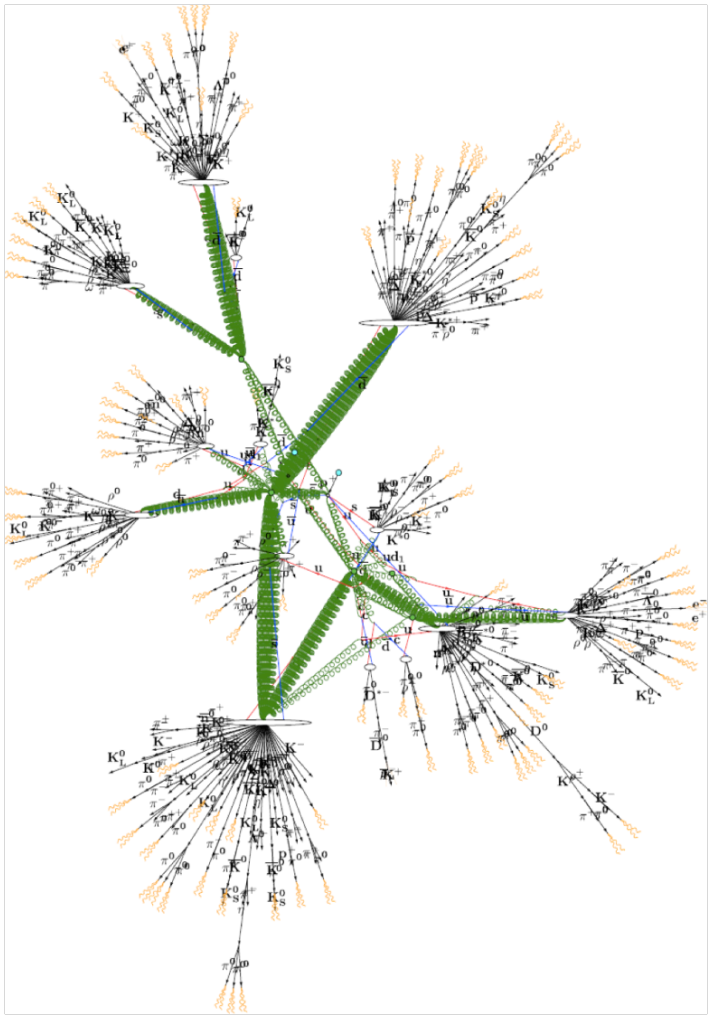
Thanks to E Aschenauer, N Armesto, P Braun-Munzinger, A Bressan, J Butterworth, J Campbell, D Charlton, A de Roeck, A Glazov, M Klein, U Klein, W Krasny, F Kunne, P Laycock, A Stasto, N Watson, G Watt, A Zarnecki

Back-ups

Theory & Phenomenology (Monte Carlo)

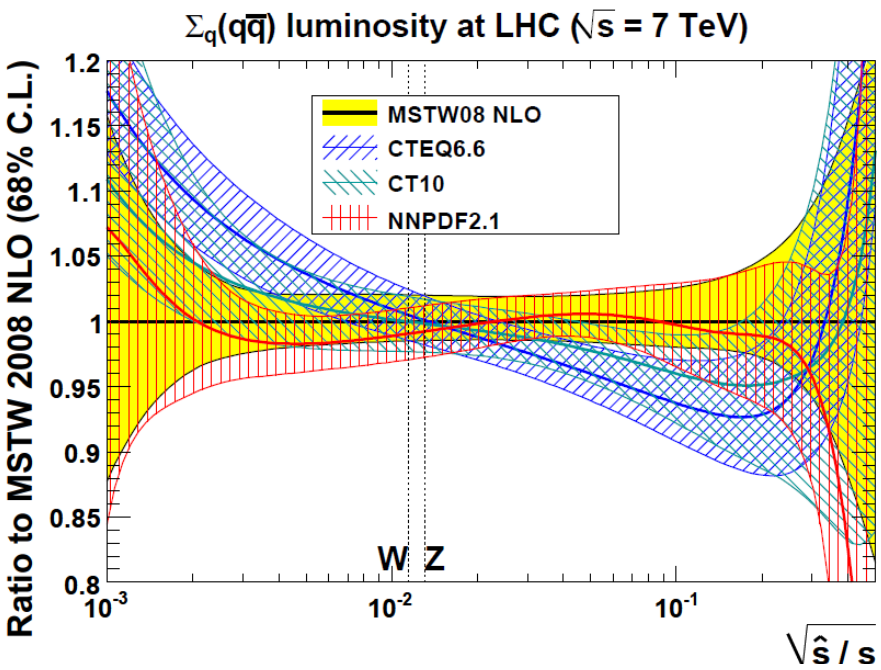
Progress at all suggested facilities relies on developments in both
- formal theory (N^nLO, N^nLL, resummations …)
- Monte Carlo modelling.





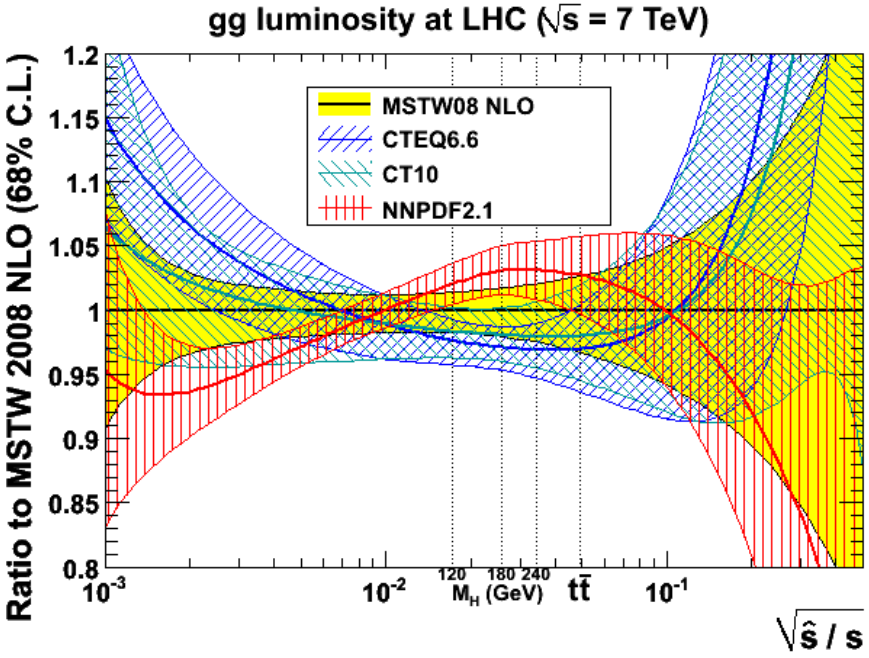
"minimum bias" pp event in PYTHIA8 at √s=7 TeV (MCViz)

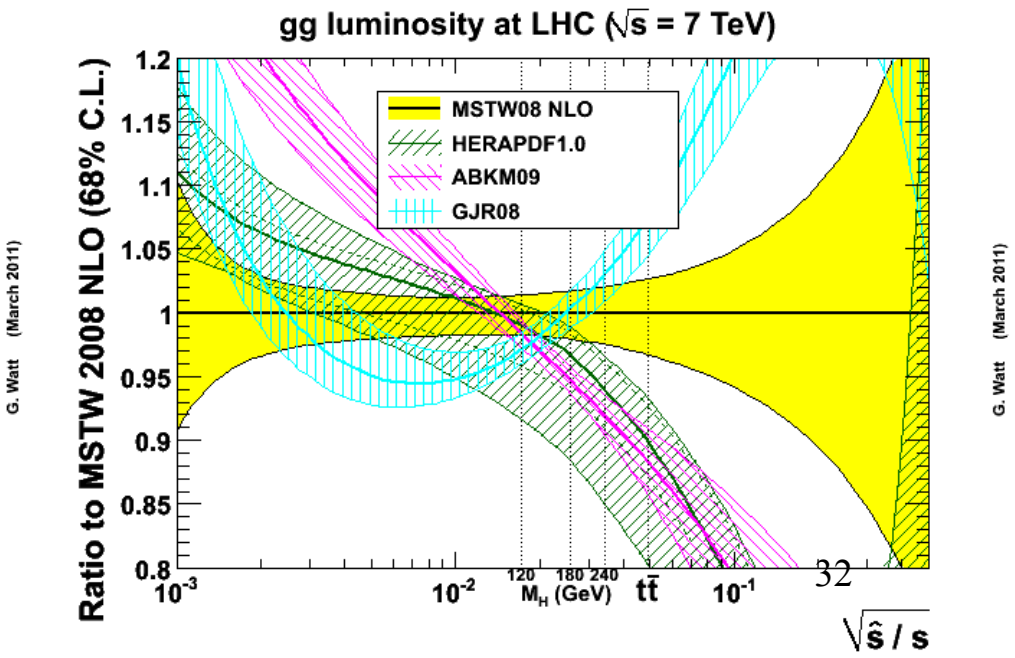
Parton Densities



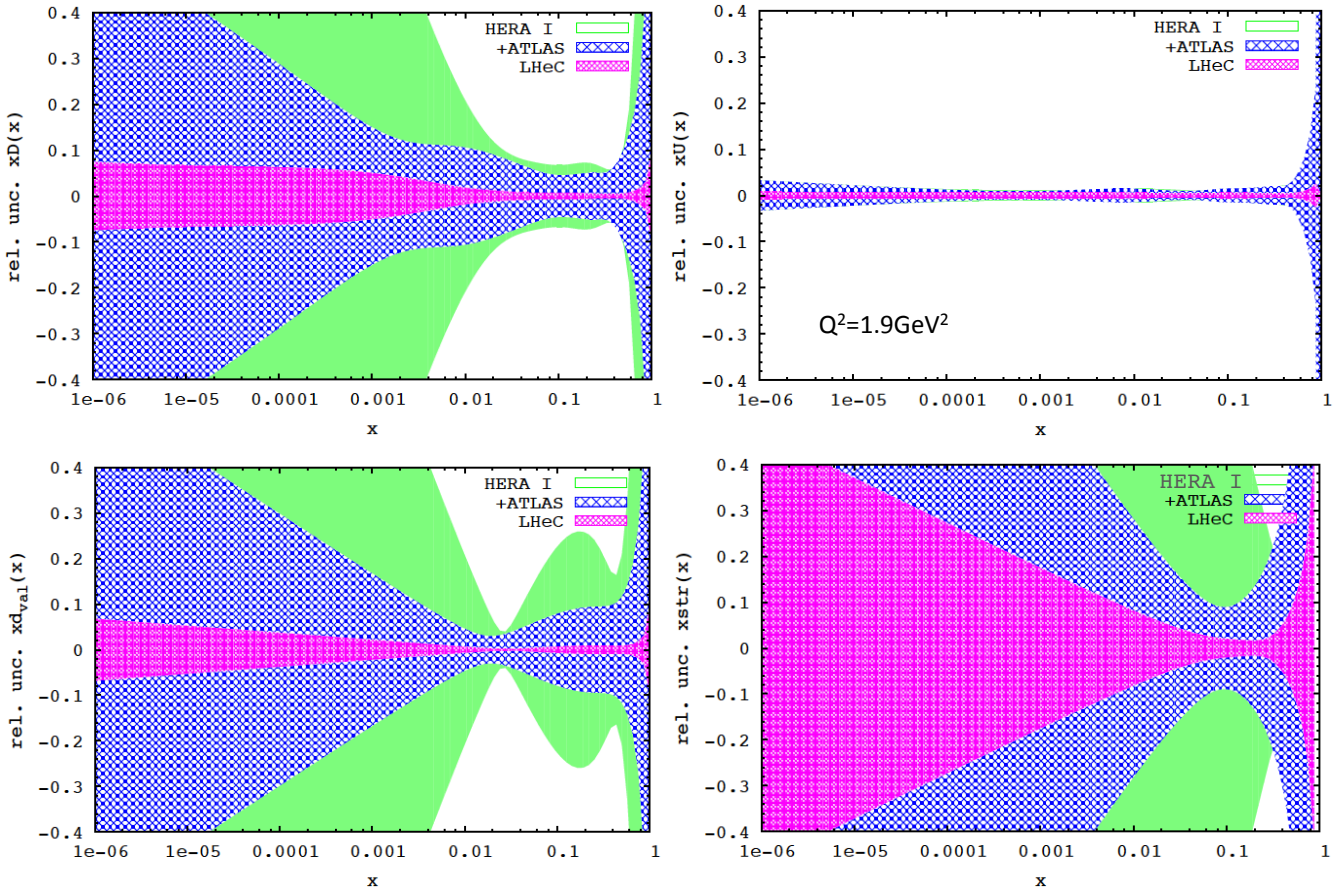
Current uncertainties due to PDFs for particles on LHC rapidity plateau (NLO):

- Most precise for quark initiated processes around EW scale
- Gluon initiated processes less well known
- All uncertainties explode for largest masses





LHC / LHeC Complementarity for PDFs

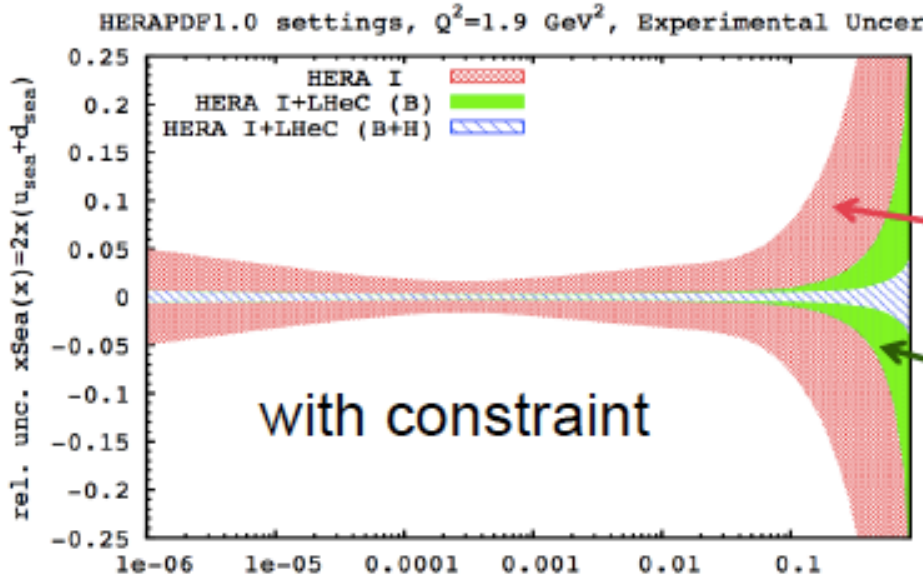


Study with u,d,s assumed all independent

In general, LHC has good sensitivity in narrow range from W,Z and has already contributed to e.g. strange.
elsewhere: limited. Low x DY has large scale uncertainty, at large x you would rather discover something.

Sea quark uncertainties and usual constraint ubar=dbar for x→0

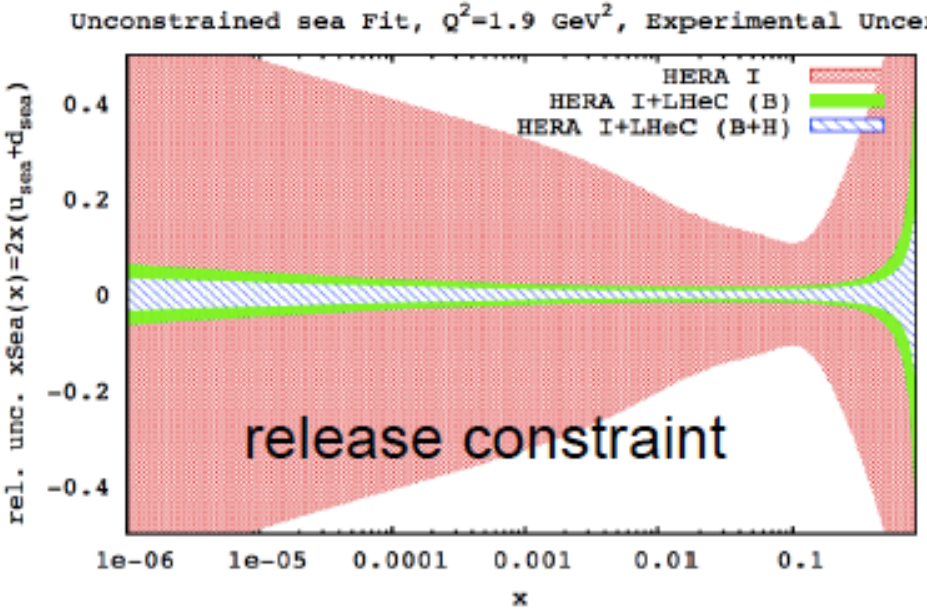
Voica Radescu



HERA only

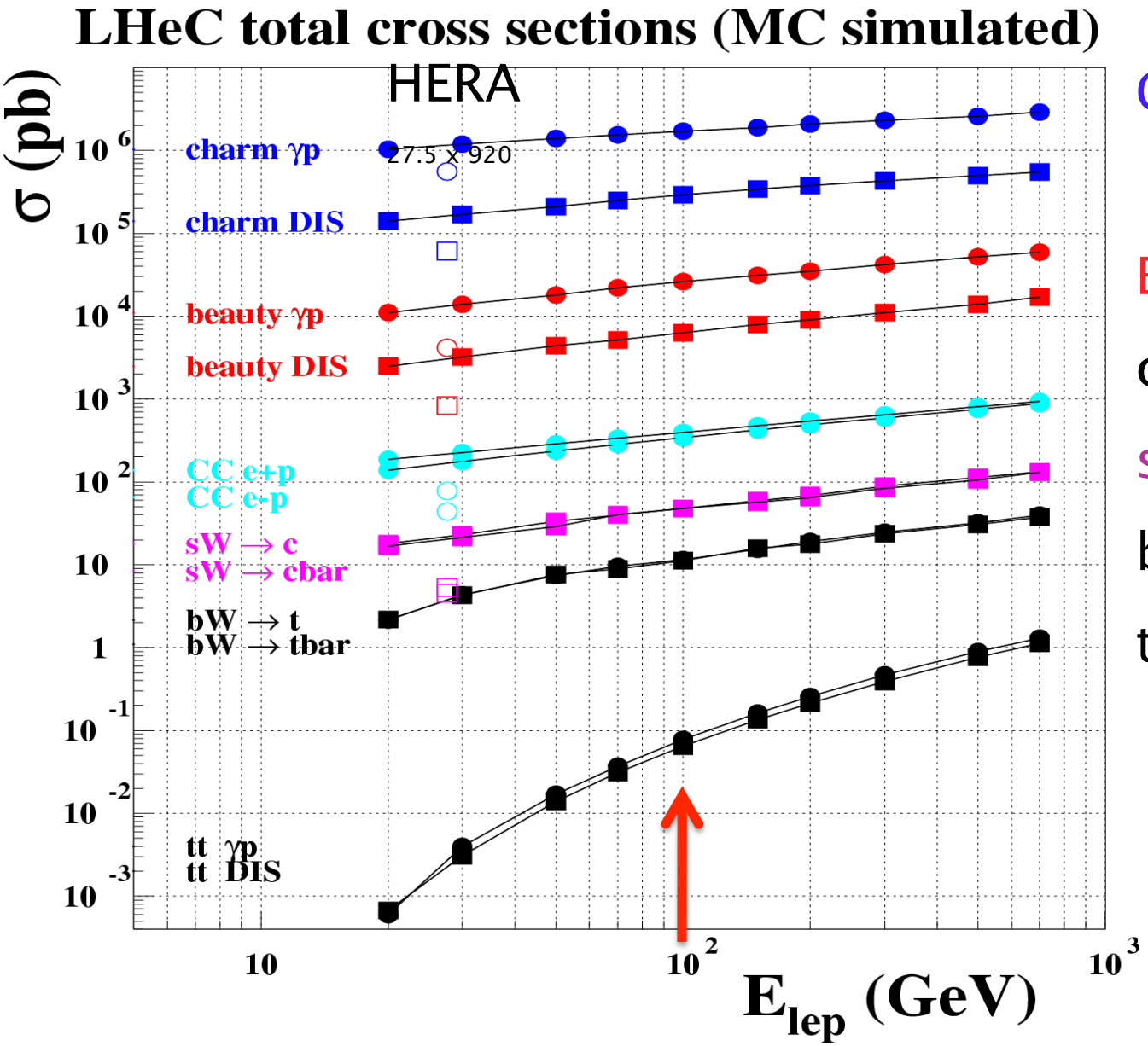
Adding LHeC

DROP



With LHeC can get rid of such assumptions

Cross Sections and Rates for Heavy Flavours



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

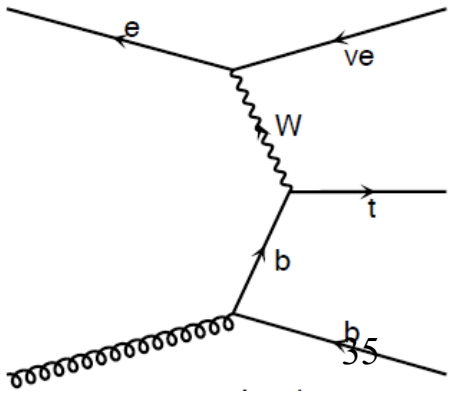
Beauty [10^{8} / 10 fb^{-1}]

cc

sW → c [4.10^{5} / 10 fb^{-1}]

bW → t [10^{5} / 10 fb^{-1}]

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

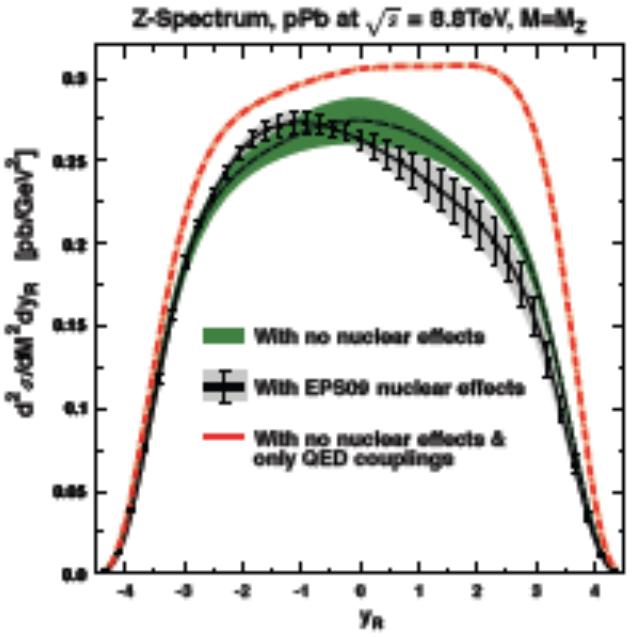


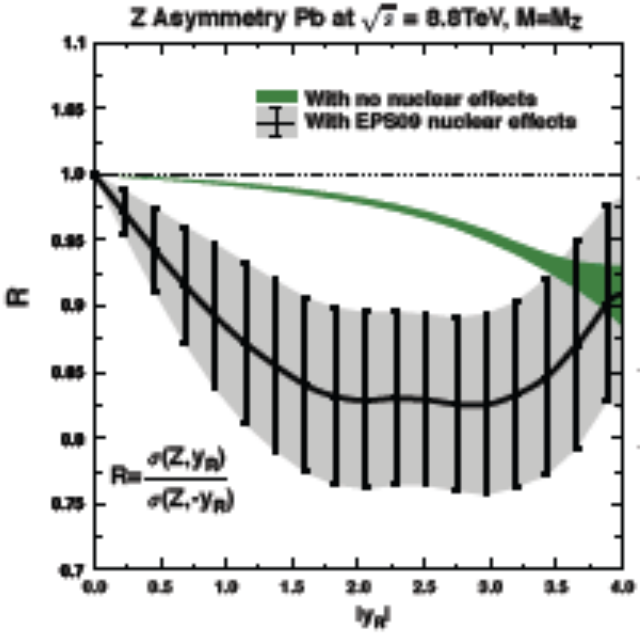
c.f. luminosity of ~10 fb^{-1} per year …

Nuclear PDFs

Fixed target pA and RHIC dAu data already play a role in nuclear PDF determinations.

pA at LHC will give new constraints at low x



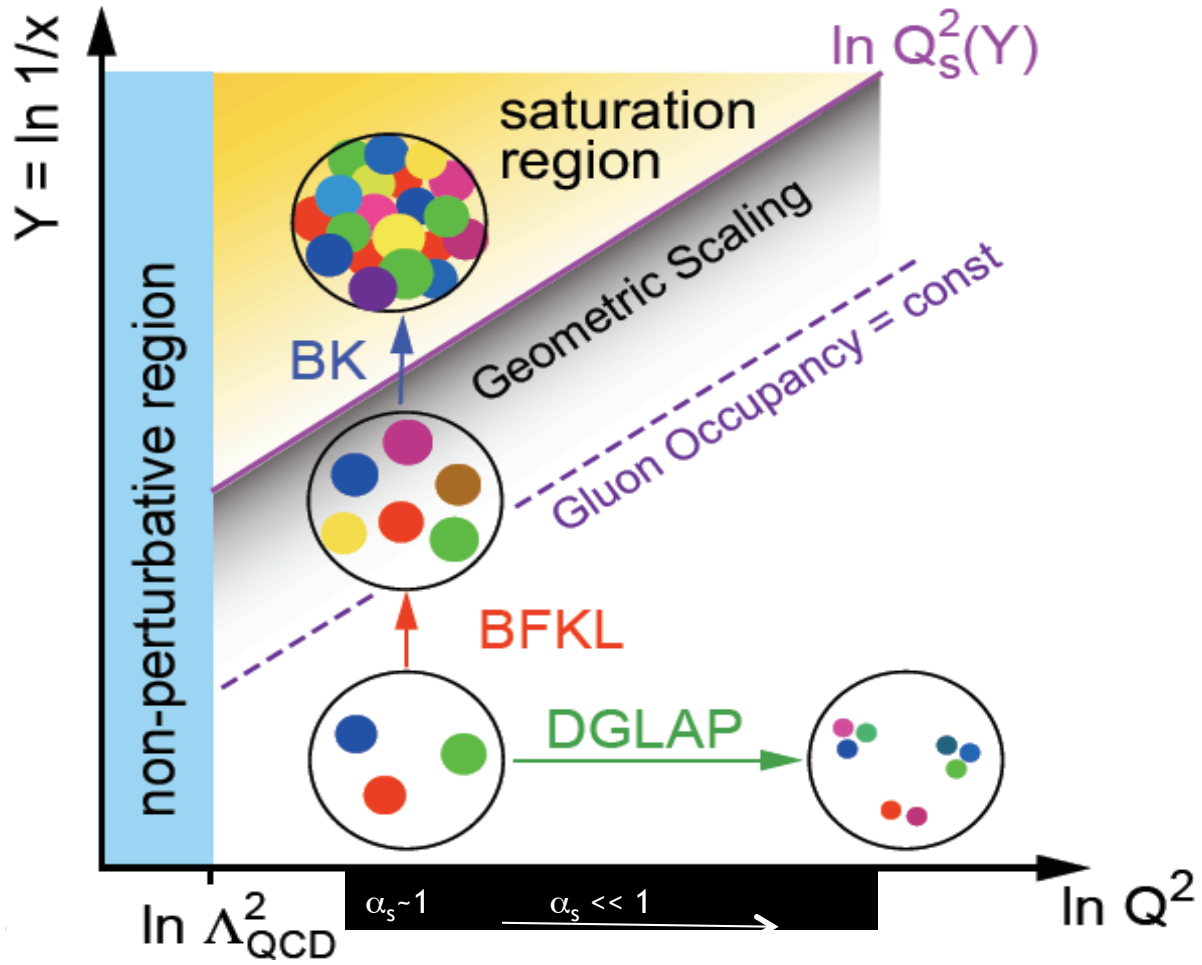


[Paukkunen, Salgado 2011]

… implementation of observables in fitting code non-trivial and uncertainties often large

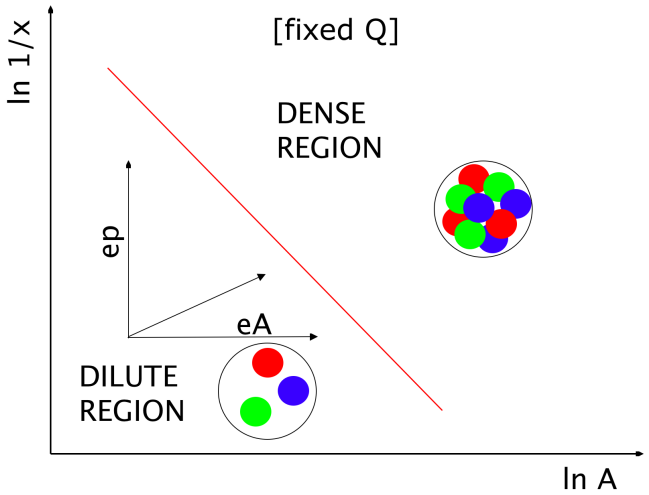
No substitute for low x DIS data

Schematic Kinematic Plane



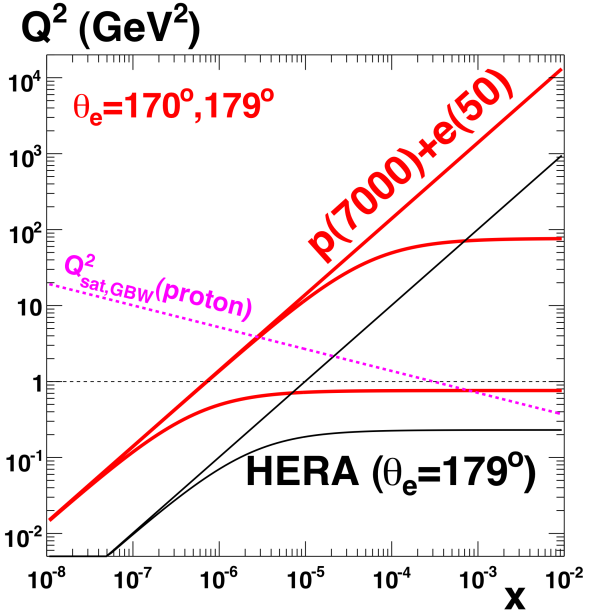
LHeC Sensitivity to Saturation Region

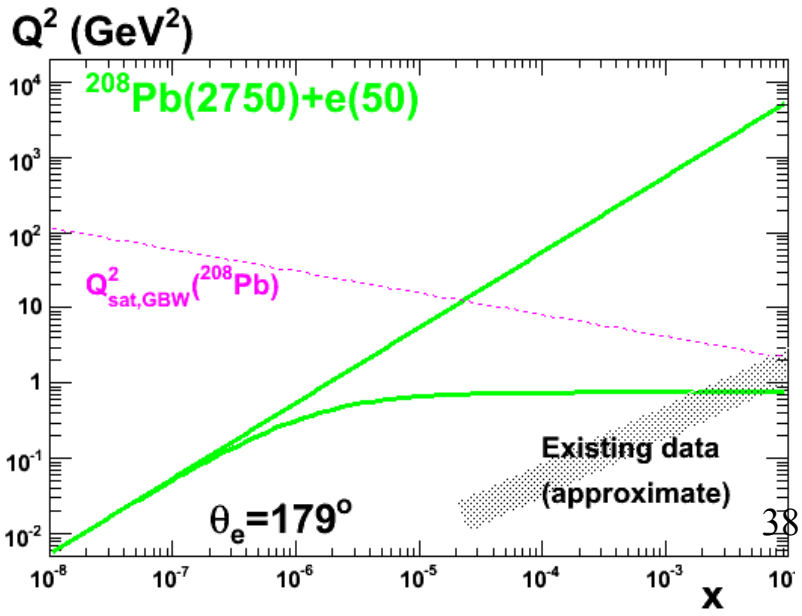
LHeC delivers a 2-pronged approach:



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]

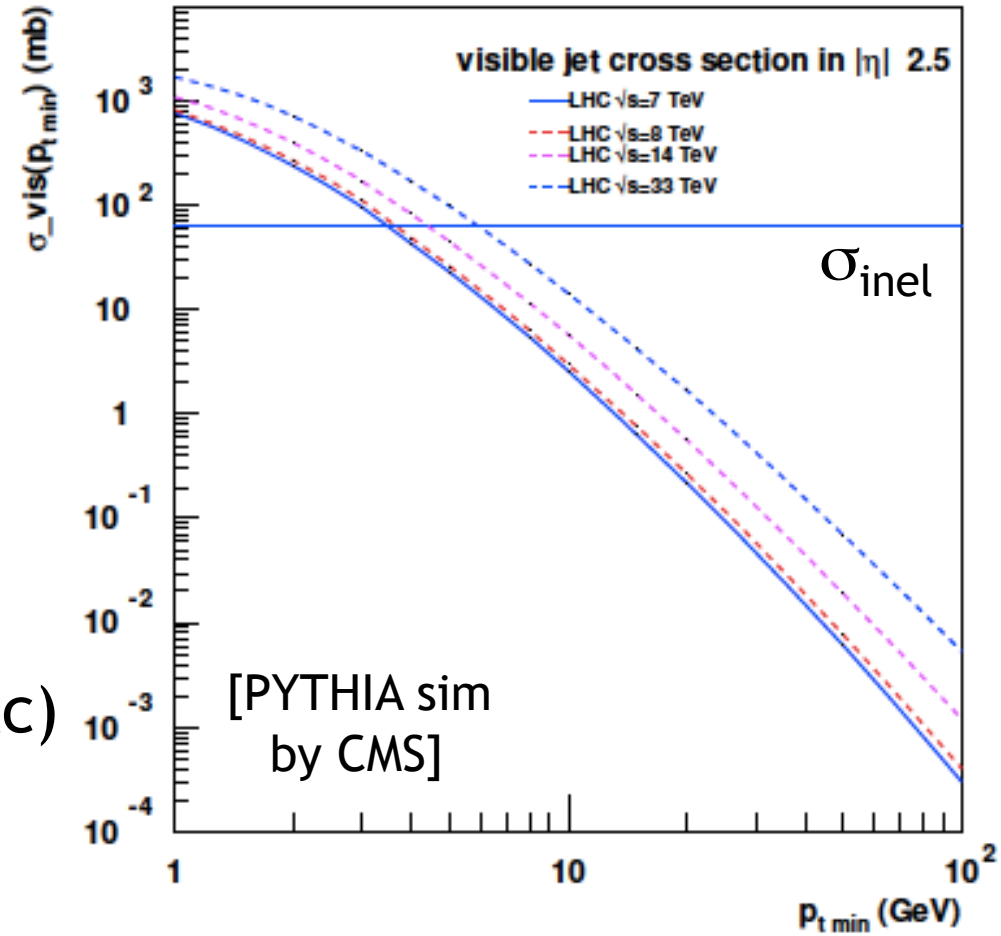




Low x (fwd) Physics @ LHC (energy limited)

e.g.
"Mini"-jets violating unitarity when integrated down to modest pt values.

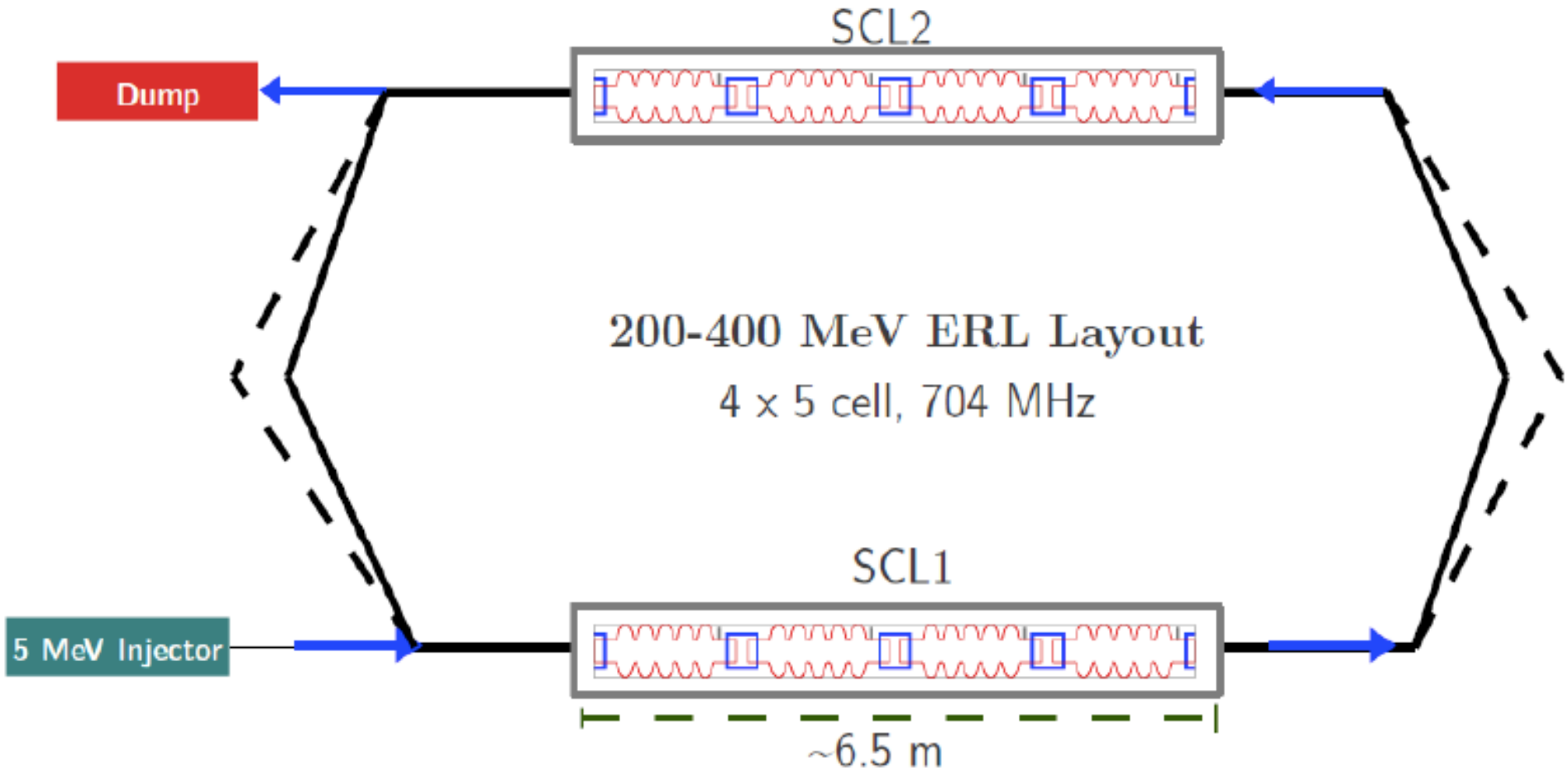
Also forward jets, fwd/bwd correlations etc (parton evolution dynamics, BFKL etc)



- CMS propose short dedicated ppruns (~100 nb-1) with low luminosity / pile-up to allow studies of this region.

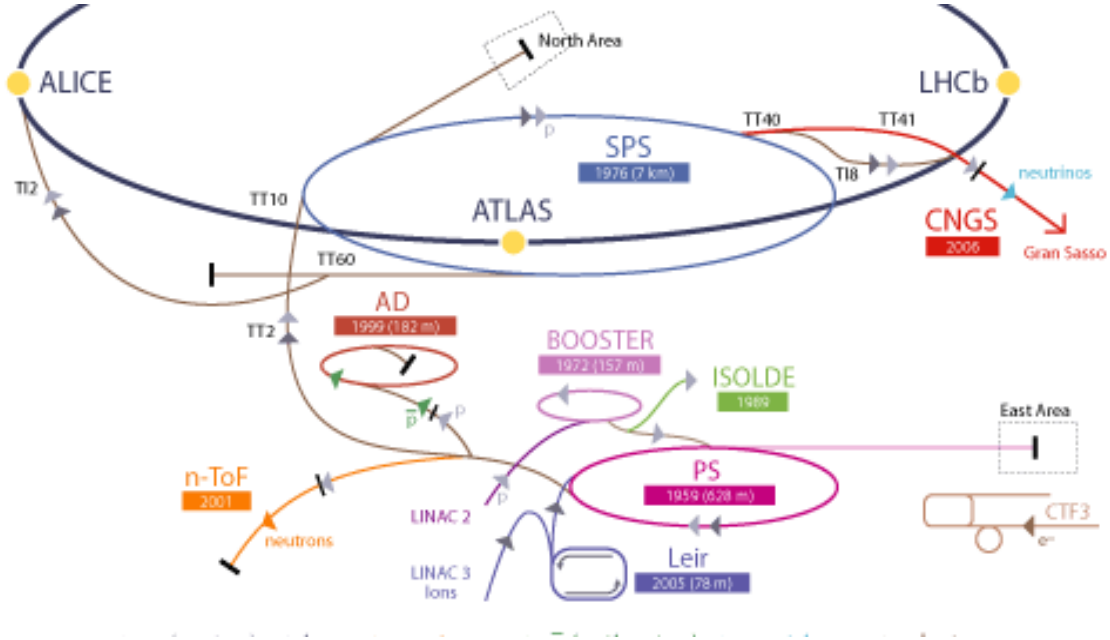
- pA collisions enhance sensitivity to saturation effects

CERN Planned Energy Recovery LINAC Test Facility



Non-LHC Physics at CERN

~1200 current CERN users on non-LHC experiments



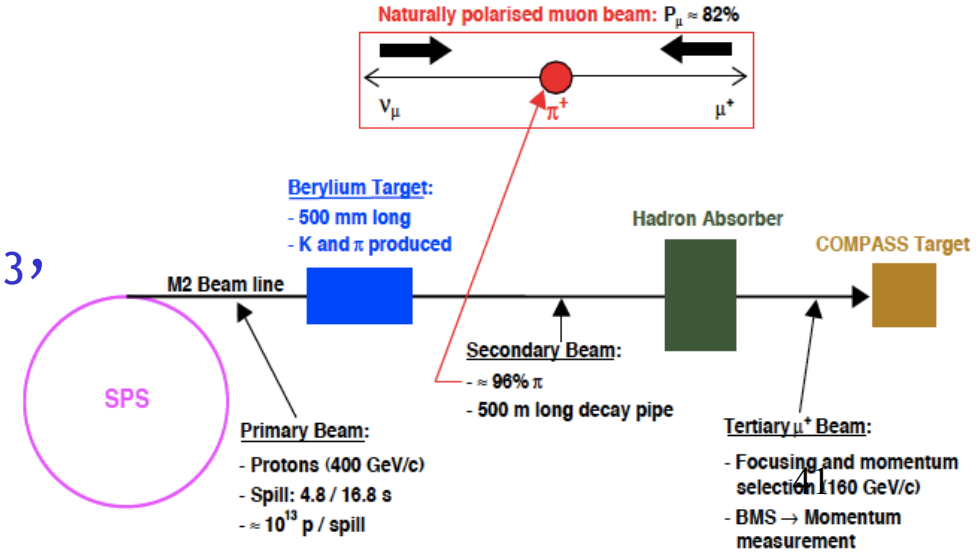
Several QCD-focused (DIRAC NA61, SHINE …)

"unique opportunities for at least another decade"

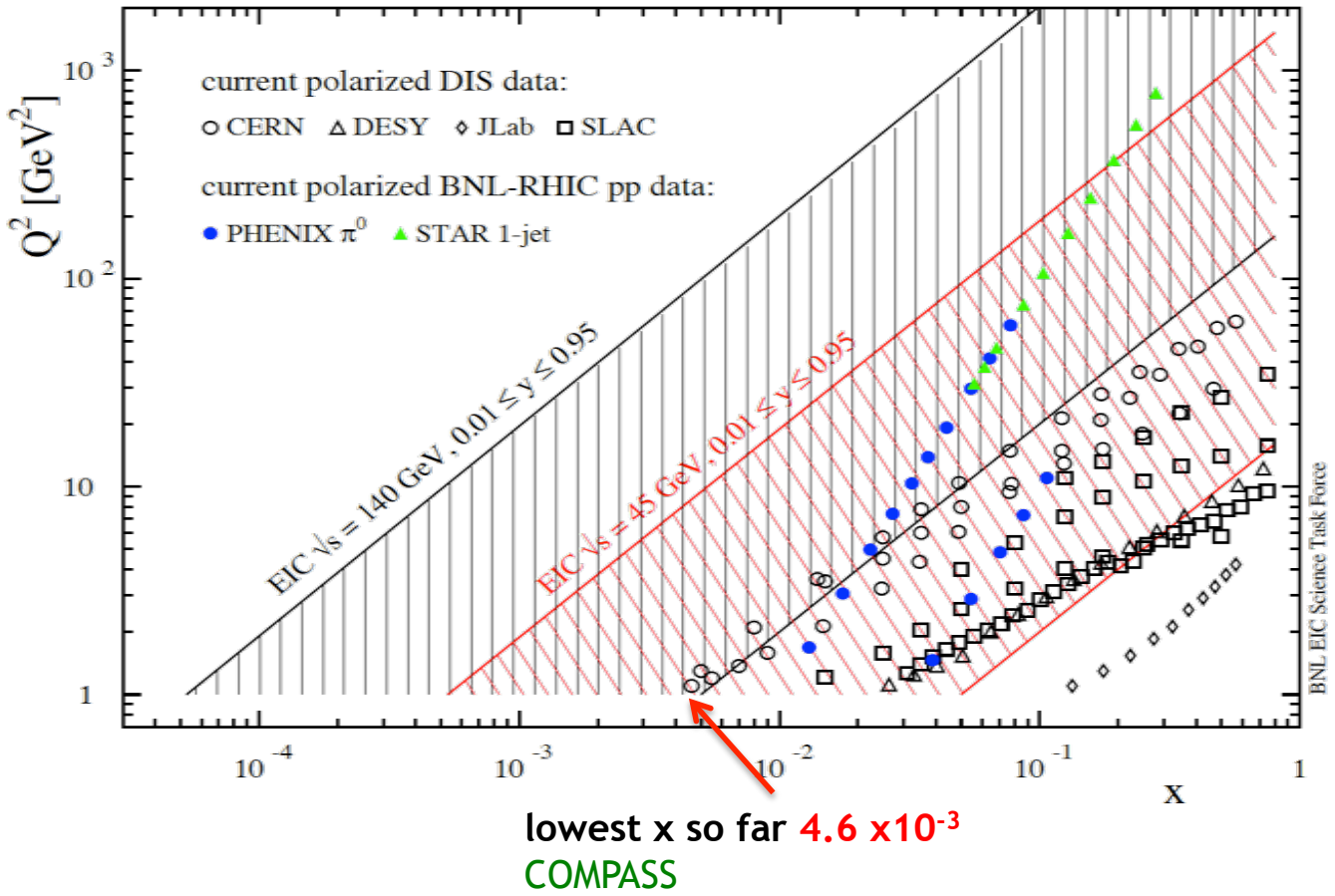
See 2009 `New opportunities in CERN Physics Landscape' w'shop

- **COMPASS:** 100-200 GeV muon and hadron beams on various Fixed targets (LH2, Polarized NH_3, ^6LiD, Nuclei…)

… nucleon structure, spin, hadron spectroscopy …



Polarised PDFs and Proton Spin Crisis



lowest x so far 4.6×10^{-3}
COMPASS

Large x quarks contribute surprisingly little to proton spin.

$\Delta g(x,Q^2)$ now known to be small for $x >\sim 0.05$

Is nucleon spin hiding at lower x?

Polarised structure function measurements currently limited to $x >\sim 10^{-2}$ in DIS regime

Would be revolutionised by colliding beam facility (EIC)

COMPASS Physics Programme in Detail

Table 2: Summary of the different physics items for the far and near future. Already approved measurements are in bold.

	physics item	key aspects of the measurement
GPD	**H**	**RPD, Beam Charge and Spin Asymmetries**
	***t*-slope parameter B**	$\boldsymbol{d\sigma/dt}$
	E	transversely polarized proton target
SIDIS	**hadron multiplicities for π and K**	**PID and absolute acceptance**
	$\boldsymbol{h_{1,u}^{\perp}}$, $\boldsymbol{h_{1,d}^{\perp}}$	**azimuthal modulations and PID**
	h_1^d with same accuracy as h_1^u	transversely polarized deuteron target
	$f_1^{\perp}$ evolution	100 GeV and transversely polarized proton target
DY	**sign change for $f_1^{\perp}$ and $h_1^{\perp}$**	**transversely polarized proton target**
	universality of TMD PDFs	higher statistics with transversely polarized proton target
	flavor separation	transversely polarized deuteron target
	test of the Lam-Tung relation	hydrogen target
	EMC effect in DY	different nuclear targets

Physics Aims 4: Hadron Spectroscopy

Lots of progress with heavy states in particular in recent years (Babar, Belle, Tevatron, CLEO, BES, Daphne, COMPASS, Now LHC]
Still many mysteries at low masses – glueball spectrum, Hybrid mesons etc – needed to validate lattice

- COMPASS >=2016 (after spin), increased SPS beam momentum to 280 GeV (?) enhances glue-rich states (single, double pom) → Glueballs
Tagged kaon beam → strange hadrons

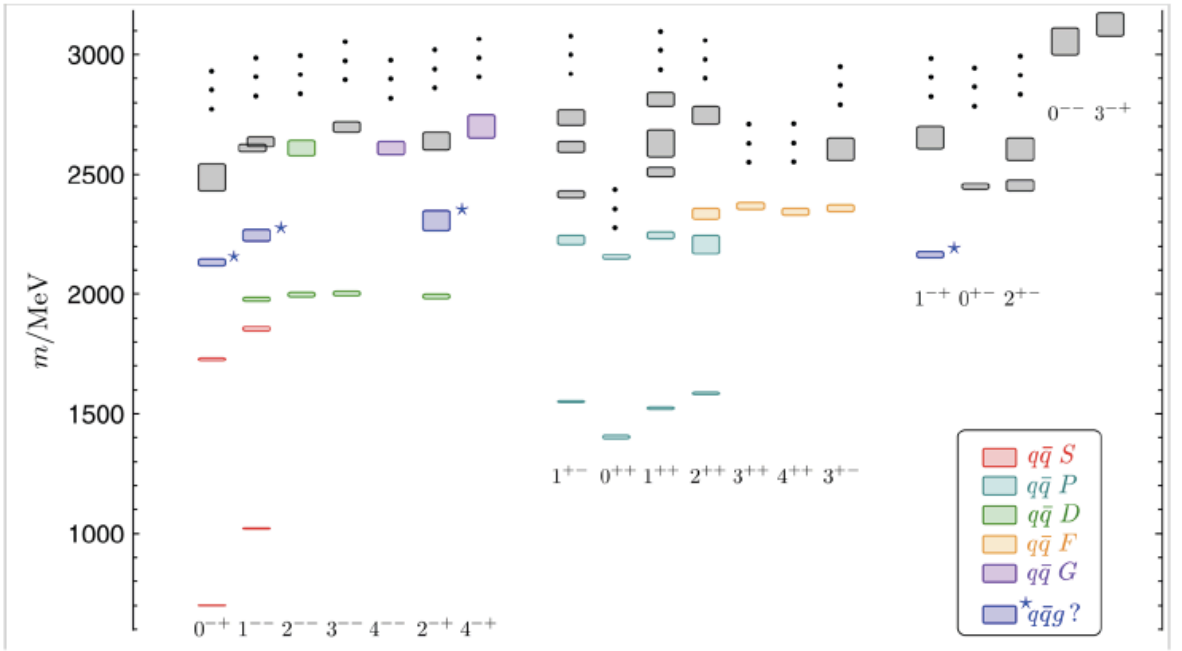


Figure 1: Spectrum of light isovector mesons resulting from a state-of-the-art lattice calculation [2], sorted by their quantum numbers J^{PC}. The colors indicate the dominant structure of the states. The pion mass used in these calculations is 700 MeV/c^2.

From `Discussion Document' of 2006 European Strategy Exercise

"QCD plays a multiple role in particle physics.

On one side, QCD is one of the cornerstones of the Standard Model, and in spite of its phenomenological successes, more work is necessary to fully establish its quantitative predictions

...

On the other side, QCD is a crucial tool for the measurement of the electroweak parameters of the SM as well as to search for BSM phenomena … where the production of new heavy particles may be hidden by large QCD backgrounds and often manifests itself in the form of multijet signatures."

Impressive, eclectic progress since 2006