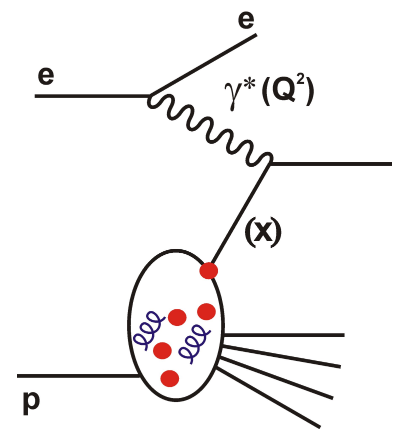
Complementarity of the Electron-Ion Collider and the (High Luminosity)-Large Hadron Collider



Paul Newman
(University of Birmingham)

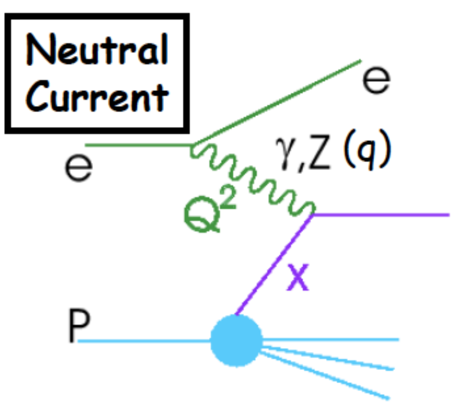
1) Where did HERA leave us?
2) High x partons and LHC energy frontier discovery
3) Medium x partons and LHC precision
4) Flavour decomposition
5) Low x partons and novel parton dynamics
6) Possibilities from EIC

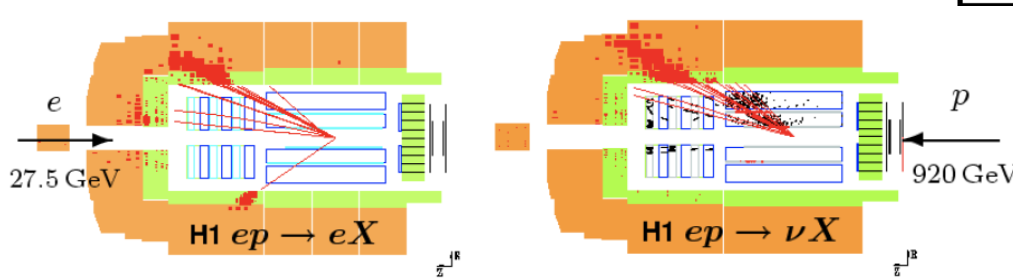
EICUG
Electron-Ion Collider User Group Meeting
2019 JULY 22-26 PARIS
École Nationale Supérieure de Chimie

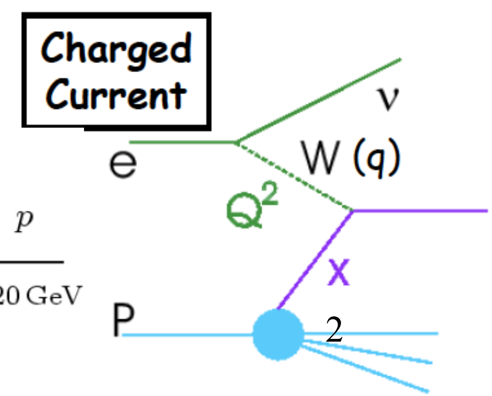
- The only ever collider of electron beams with proton beams:

$$\sqrt{s_{ep}} \sim 300 \text{ GeV}$$

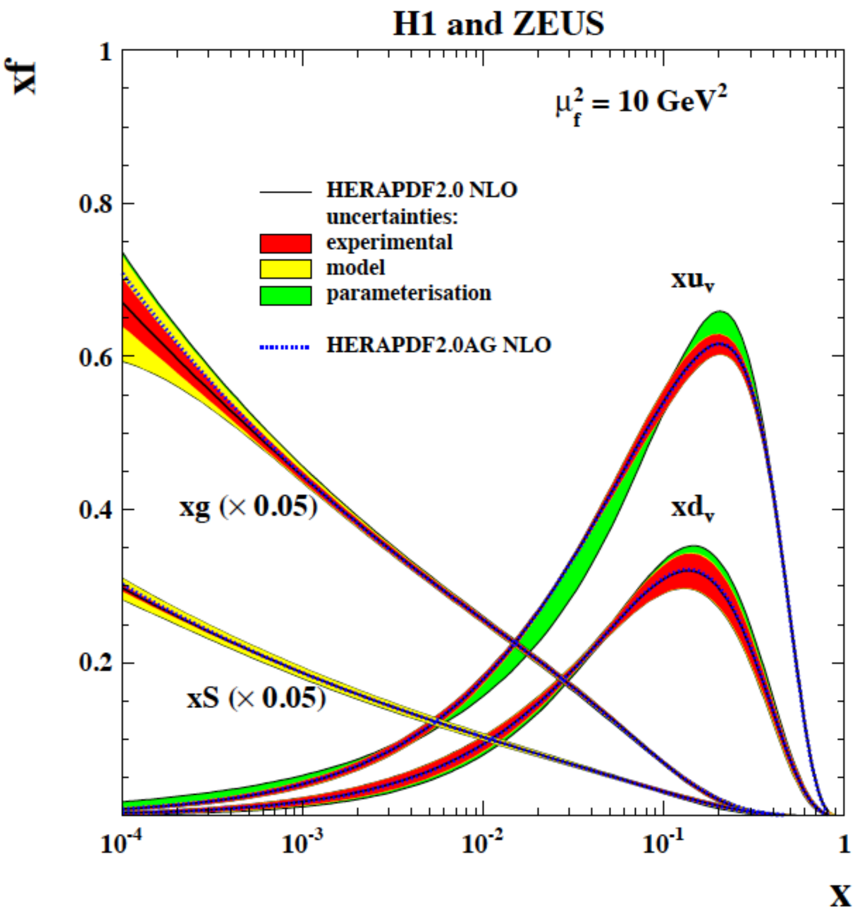
- ~0.5 fb^{-1} per exp't
- Both lepton charges and polarisations
- Protons unpolarised

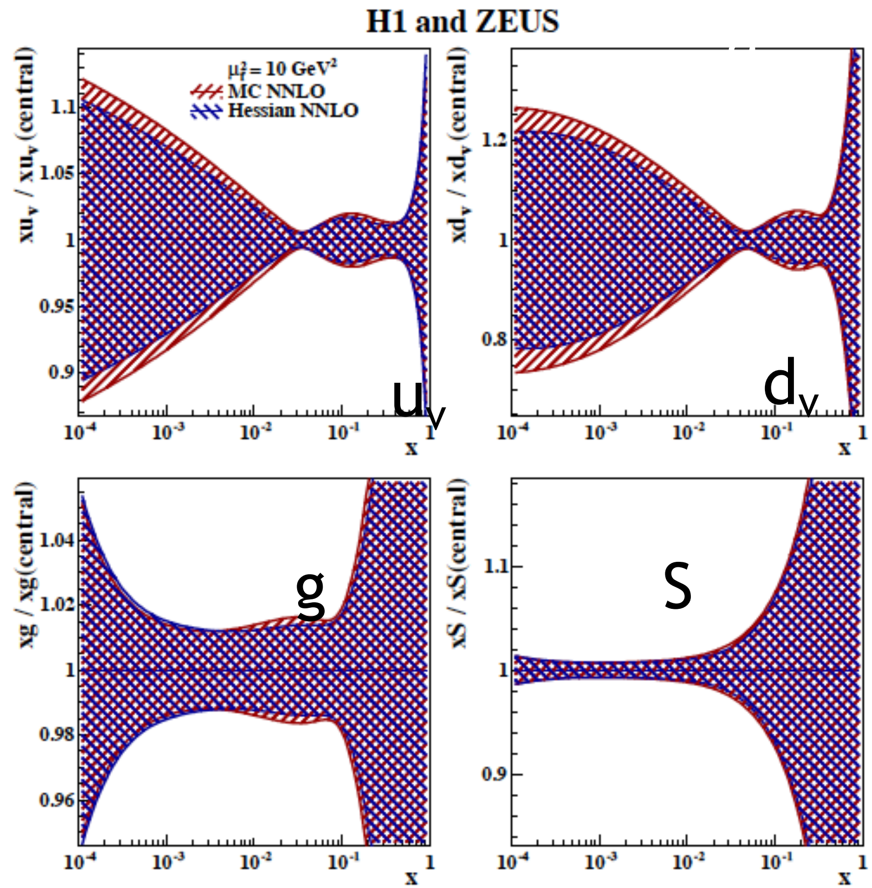






Final HERA Picture of Proton (HERAPDF2.0)





- ~2% gluon precision, 1% on sea quarks for x ~ 10^{-2}
- Uncertainty explodes above x=10^{-1} and below x=10^{-3}
- Low x gluon rising in a non-sustainable way at large Q^2 …

[Note ‘Standard’ presentation is at Q^2 = 10 GeV^2]

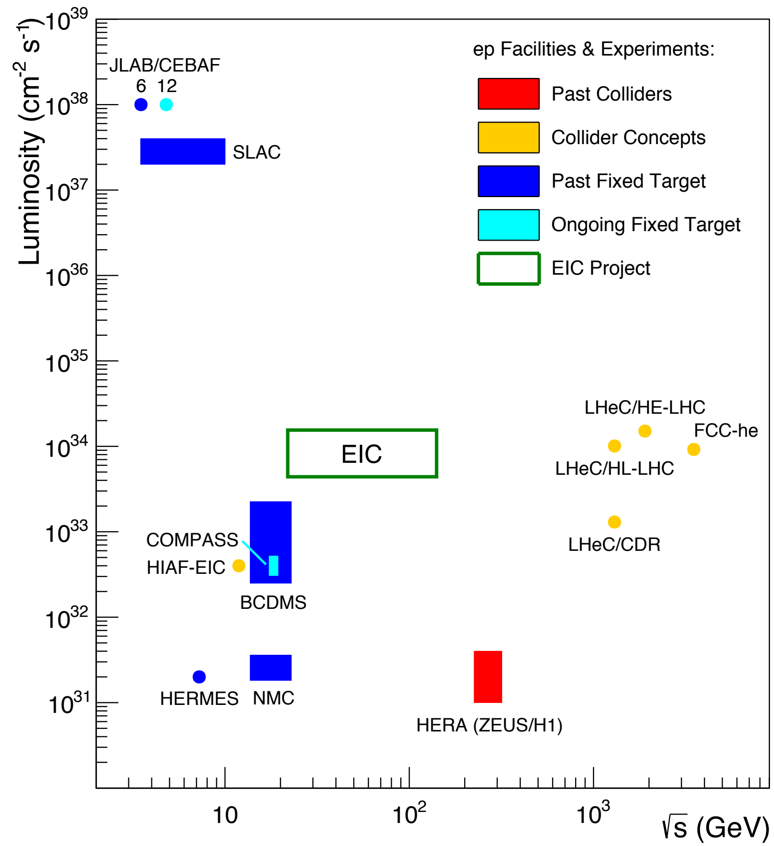
HERA's Limitations

- Limited lumi → restricts searches and precision at high x, Q^2
- Lack of Q^2 lever-arm at low x → restricts low x interpretation
- No deuterons → limited quark flavour decomposition
- No nuclei → insensitive to nuclear effects
- No polarised targets (except HERMES) → limited access to spin, transverse structure

ALL of these limitations are addressed by complementary proposed future DIS projects

EIC particularly sensitive to 3D structure, flavour, high x, nuclear effects, low x in eA

This talk (mostly) restricted to collinear PDFs

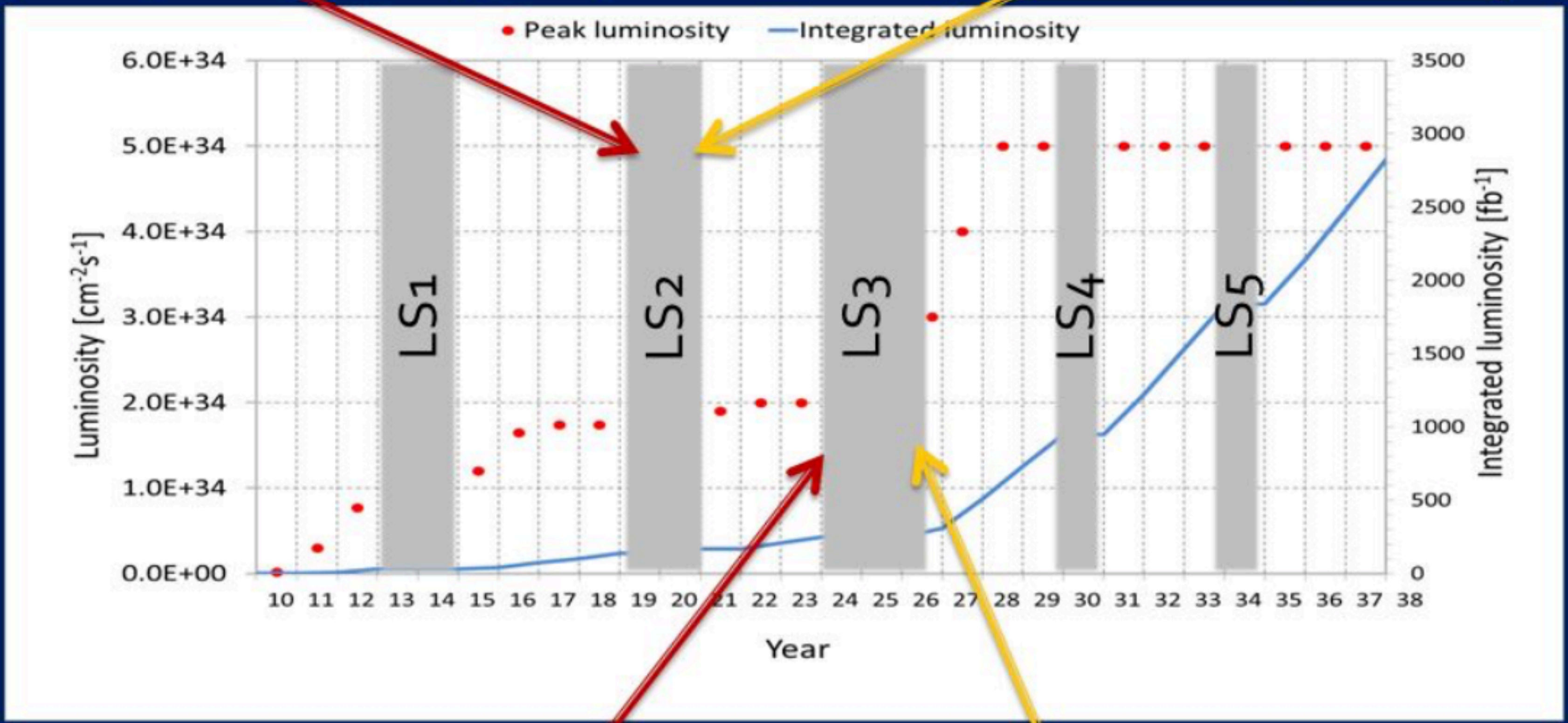


EIC and LHC in common time-frame

Long Term LHC Schedule

PHASE I Upgrade
ALICE, LHCb major upgrade
ATLAS, CMS ‚minor' upgrade

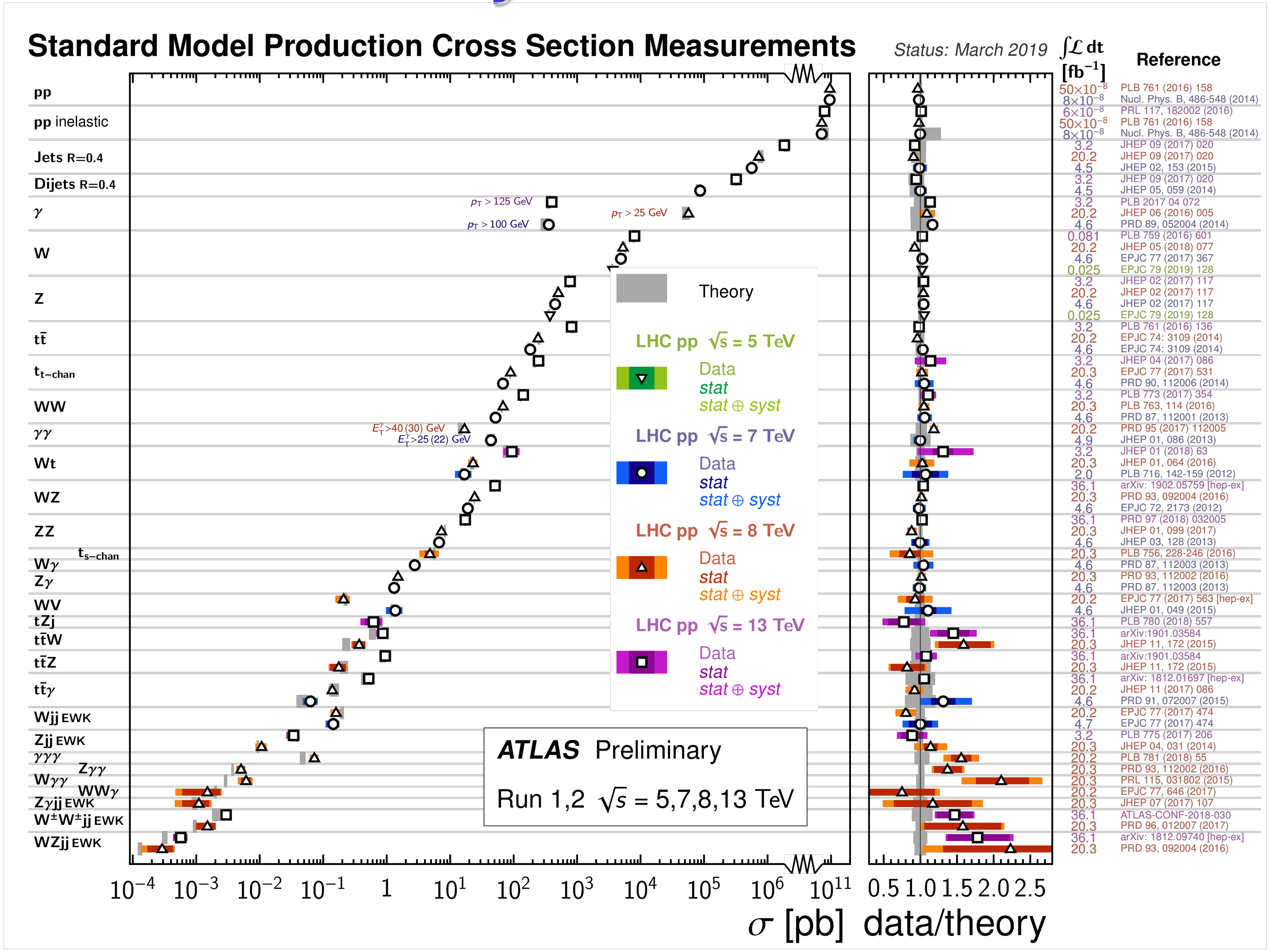
- LHC Injector Upgrade
- Heavy IonLuminosity from 10^{27} to 7×10^{27}



PHASE II Upgrade
ATLAS, CMS major upgrade

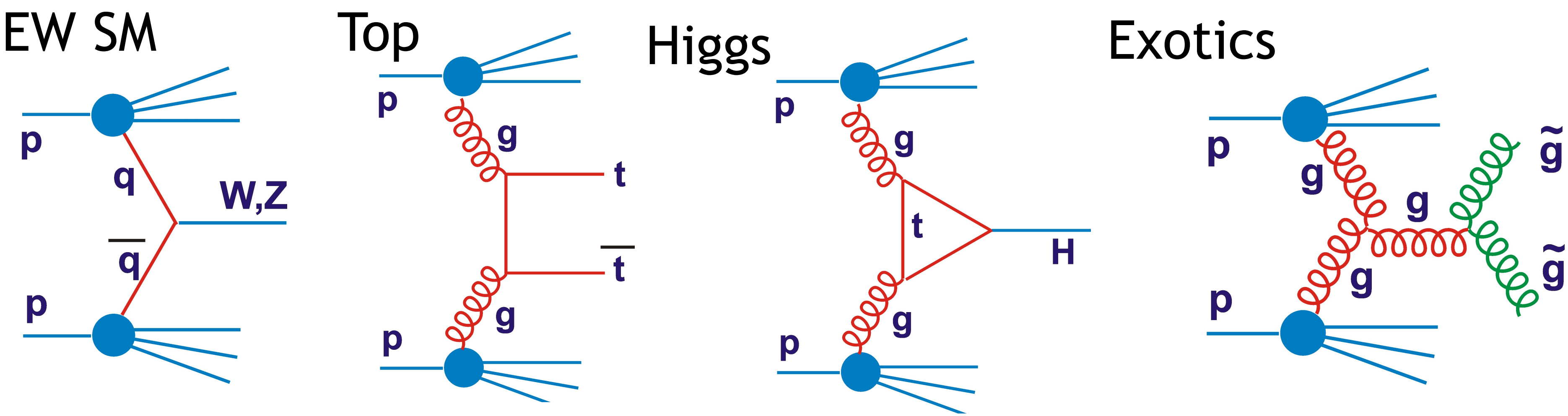
HL-LHC, pp luminosity
from 2×10^{34} (peak) to 5×10^{34} (levelled)

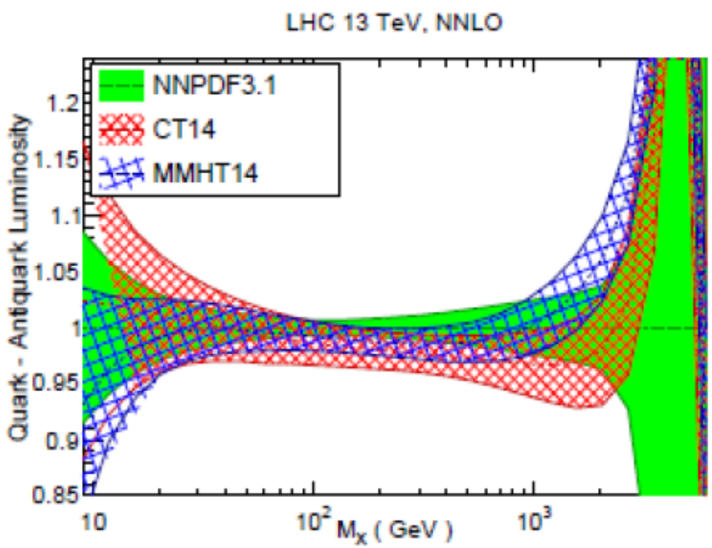
Theory v Data at LHC

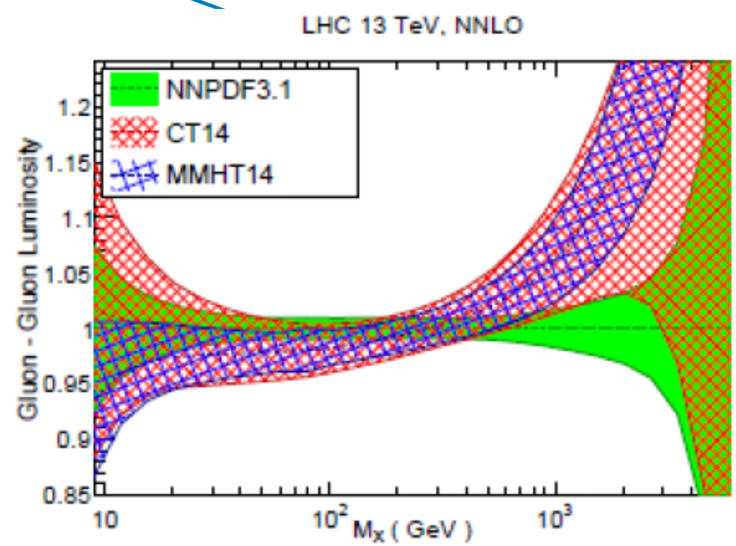


- PDFs are a vital ingredient in almost all predictions
- Factorisation between ep and pp works!

Closer look at Quality of LHC Predictions…

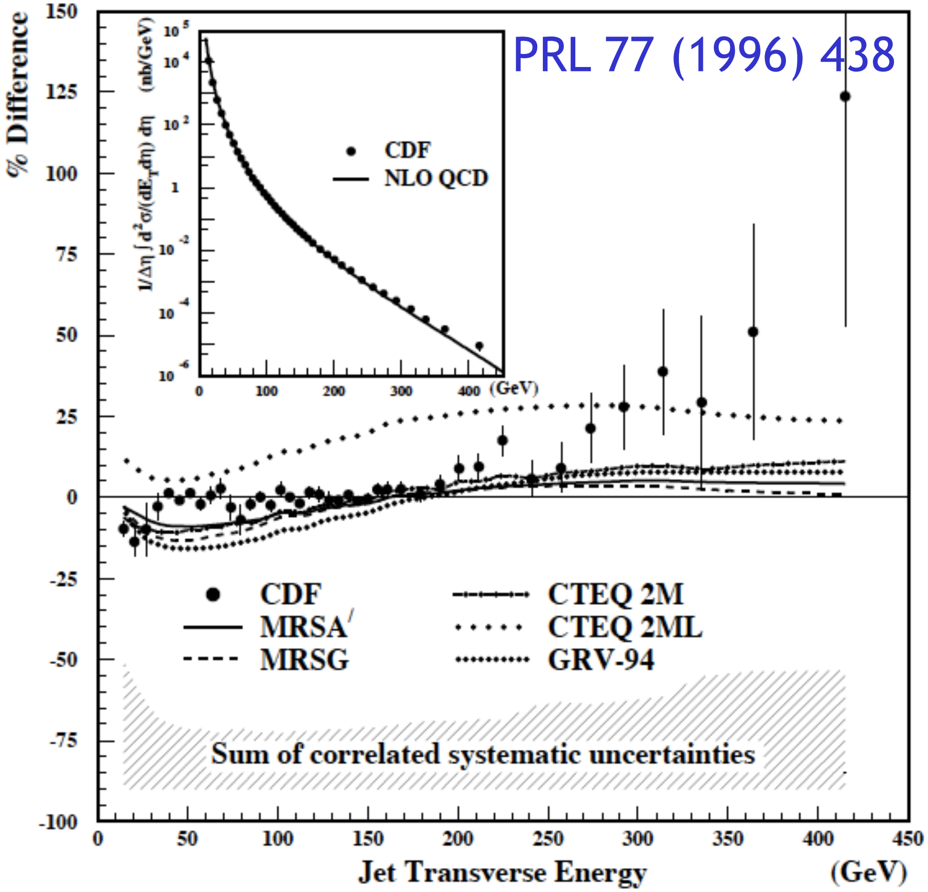






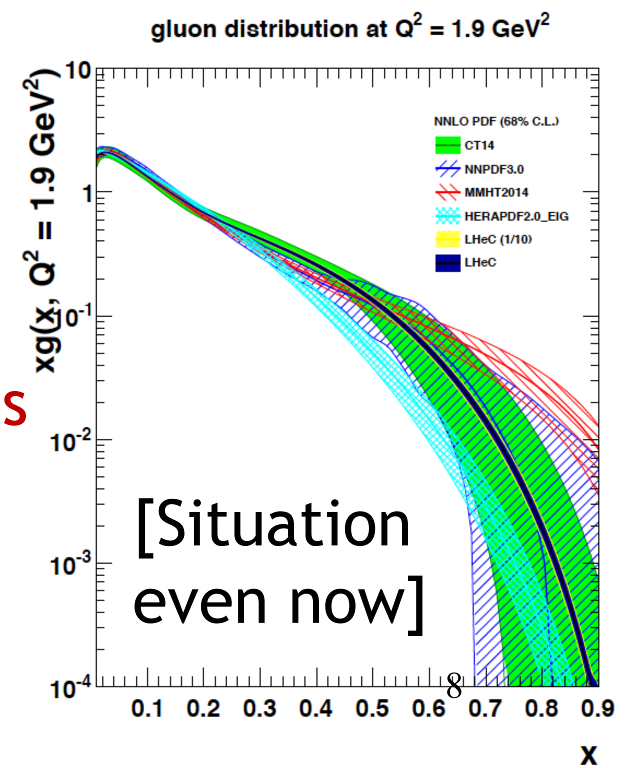
- Pretty good at electroweak scales (intermediate x)
- Still some differences (~5%) between global fits
- More limited at low and high x

Precision at High x Matters …



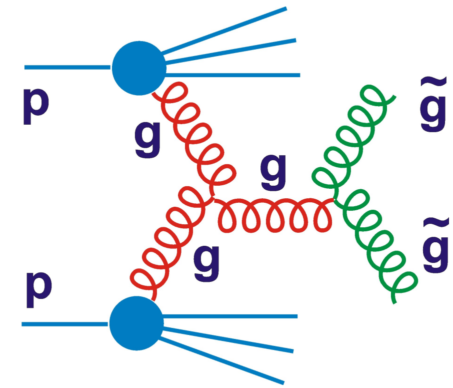
Ancient history (HERA v Tevatron)

- Apparent excess in large E_T jets at Tevatron turned out to be well within uncertainties on high x gluon …

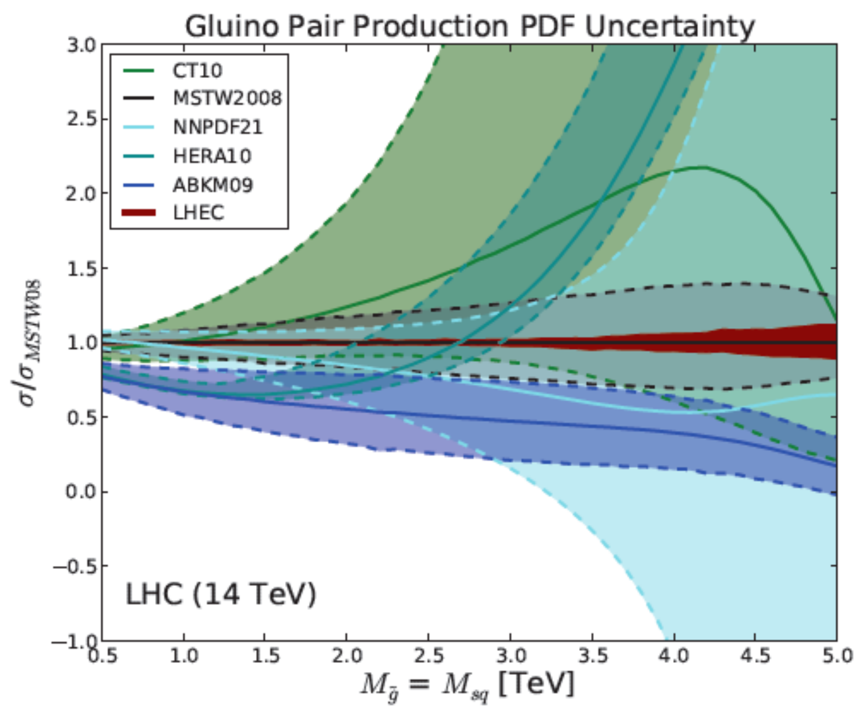


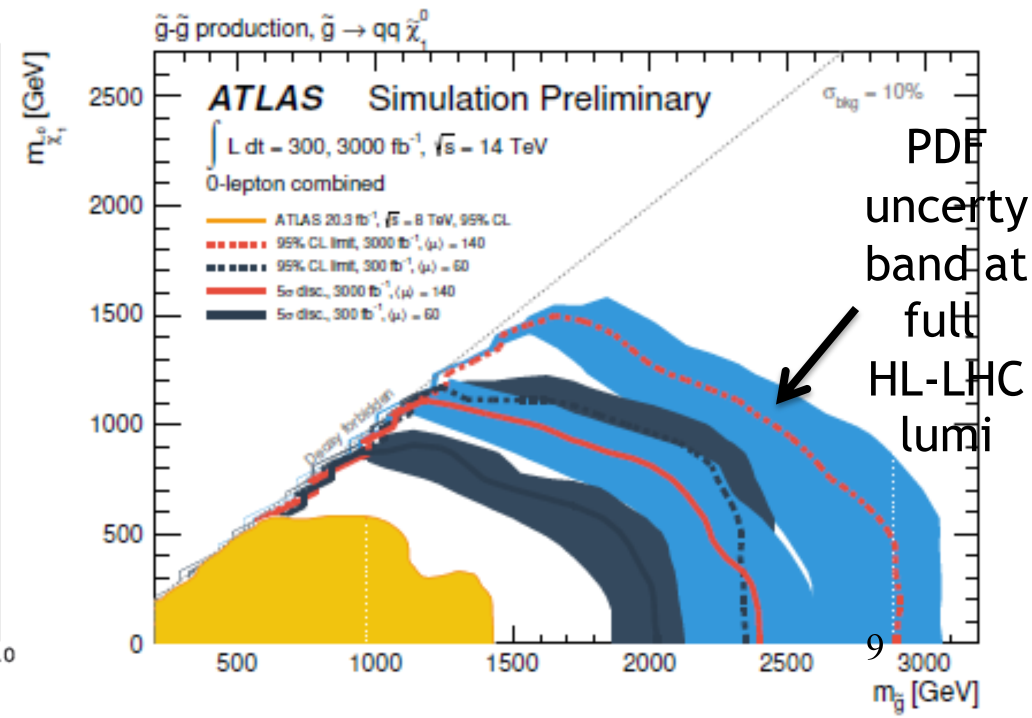
- Confirmation of (non-resonant) new physics near kinematic limit will require breakdown of factorisation between ep and pp …
- Needs best possible precision and careful uncertainty analysis

e.g. High Mass 2 Gluino Production

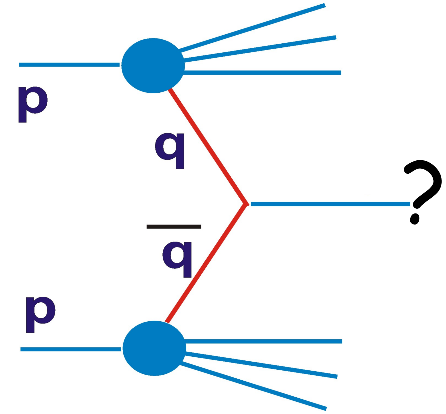


- Signature is excess @ large invariant mass over SM background (e.g. from gg → gg)
- Both signal & background uncertainties driven by error on high x gluon density … **essentially unknown for masses much beyond 2 TeV**
- Translates into a reduction in the mass range of sensitivity

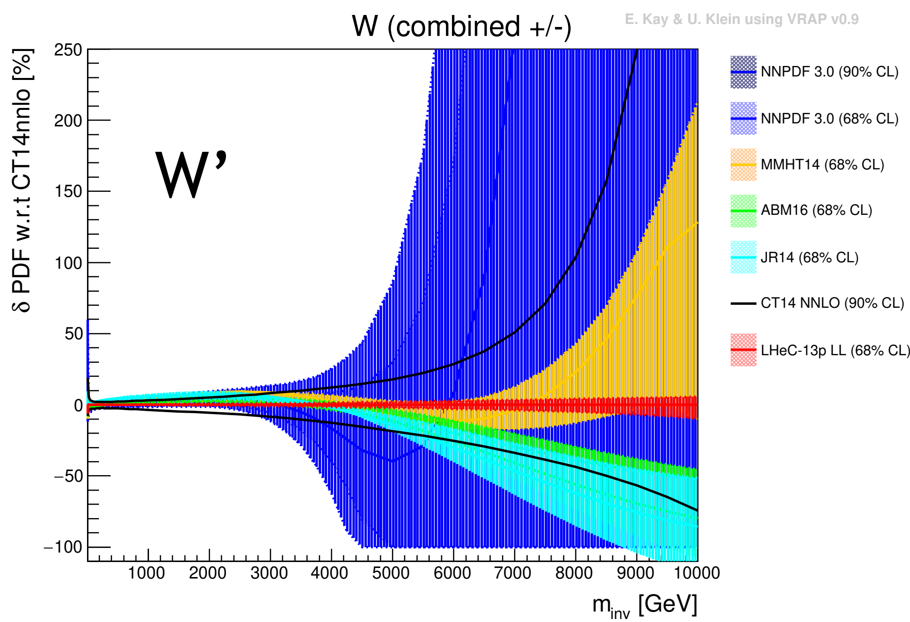


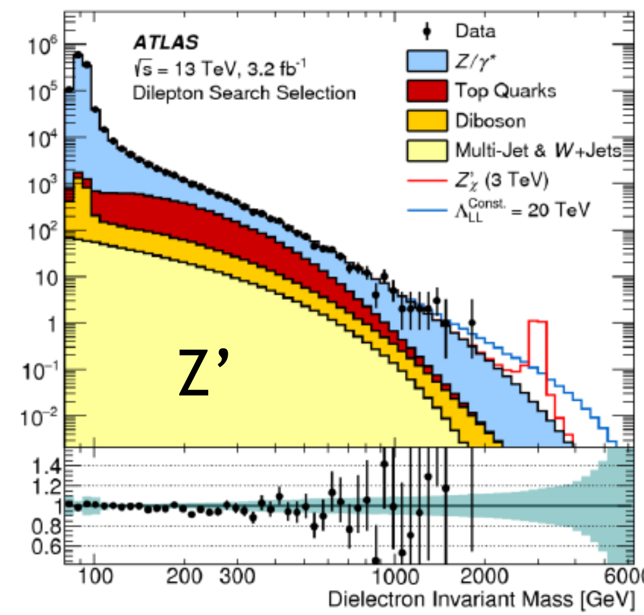


High x (anti)- quarks



- Sensitivity to BSM heavy W boson through excess in high mass lν or jj already limited by PDFs through background prediction (high x valence quark and antiquark entering Drell-Yan)



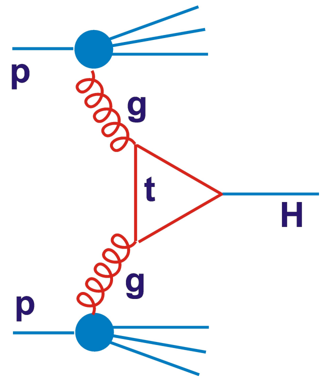


Many more examples in recent ‘*Report on the Physics at the HL-LHC …*’, ATLAS and CMS, CERN-LPCC-2019-01

… much of the LHC search programme will become limited by high x parton density uncertainties as time progresses

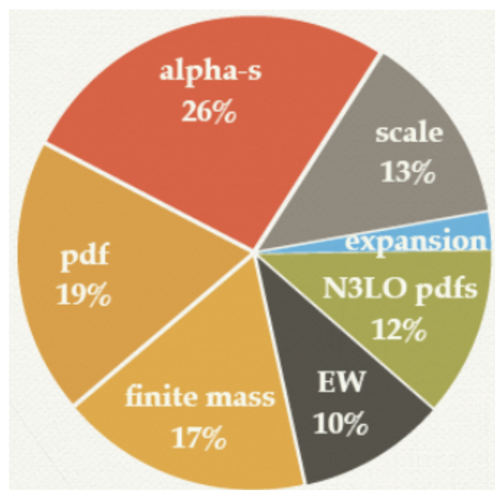
Higgs X-Section / Coupling PDF Uncertainties

… much of Higgs sector becomes PDF limited in HL-LHC era … ($x \sim 10^{-2}$)



Theoretical Uncertainties

After N^{3}LO calculation of gluon-fusion Higgs cross section:

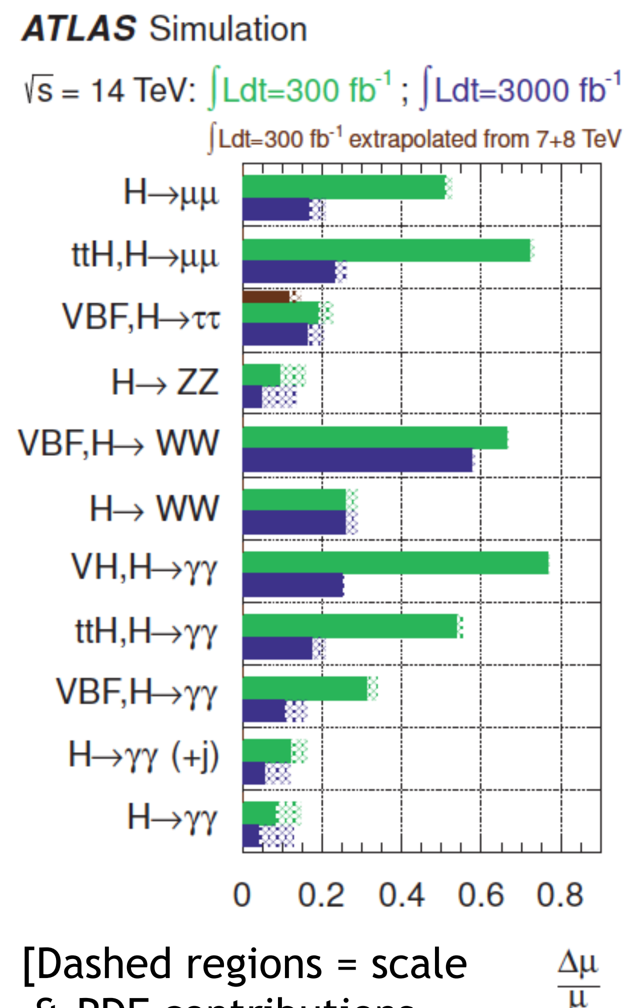


… largest sources of unertainty:

- PDFs
- `N3LO PDFs'
- α_s

Anastasiou et al [1503.06056]

Projected Experimental Uncertainties

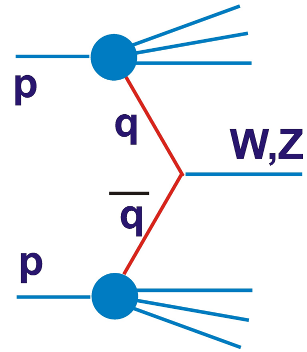


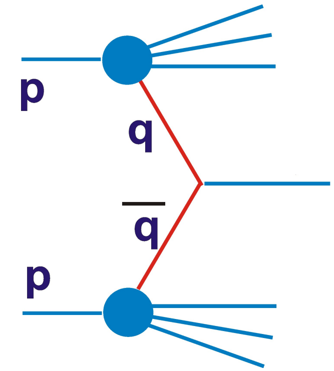
[Dashed regions = scale & PDF contributions]

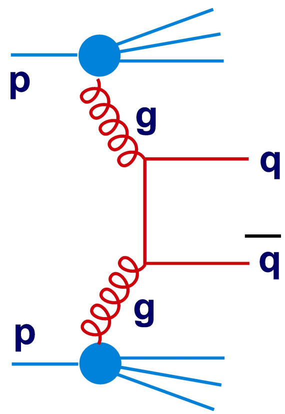
Why not constrain PDFs with LHC Data?...

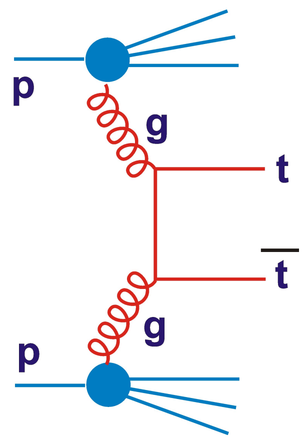
- Many pp processes are sensitive to PDFs …

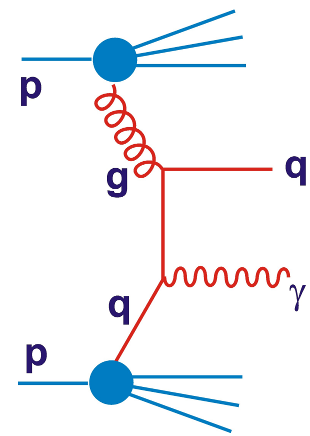
- Electroweak gauge boson production
- Drell Yan (away from Z pole)
- High pT jet production
- Top Quarks
- Direct Photons
- …





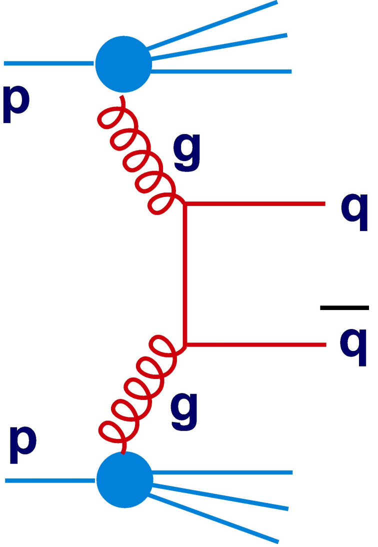




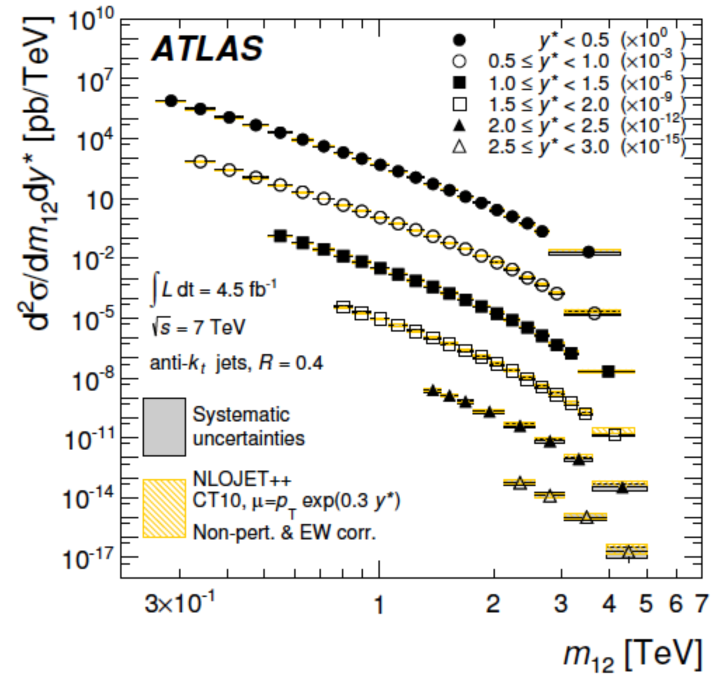


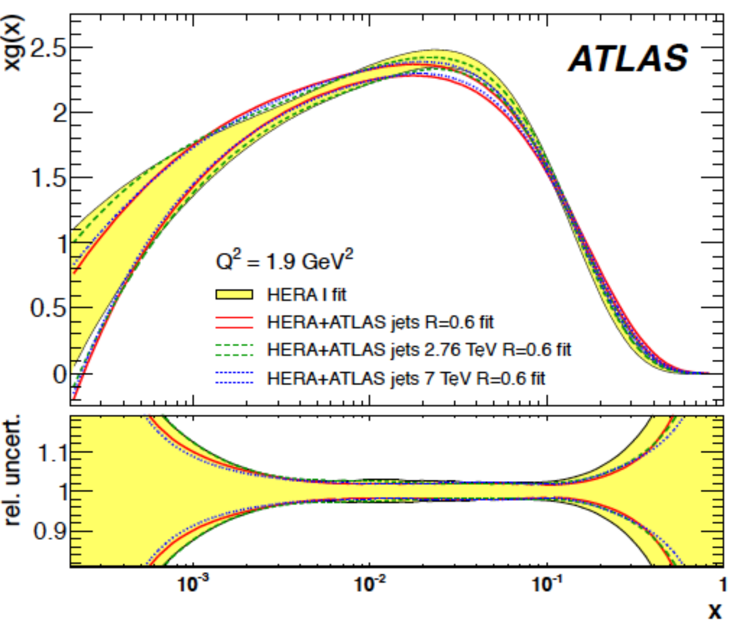
Serious ongoing programme to better constrain the PDFs with LHC data

e.g. LHC Jet Data and the Gluon



- Rates very high
- In principle sensitive to highest x
- Limited experimentally by jet Energy Scale Uncty
- Limited theoretically by no NNLO corrections, underlying event …





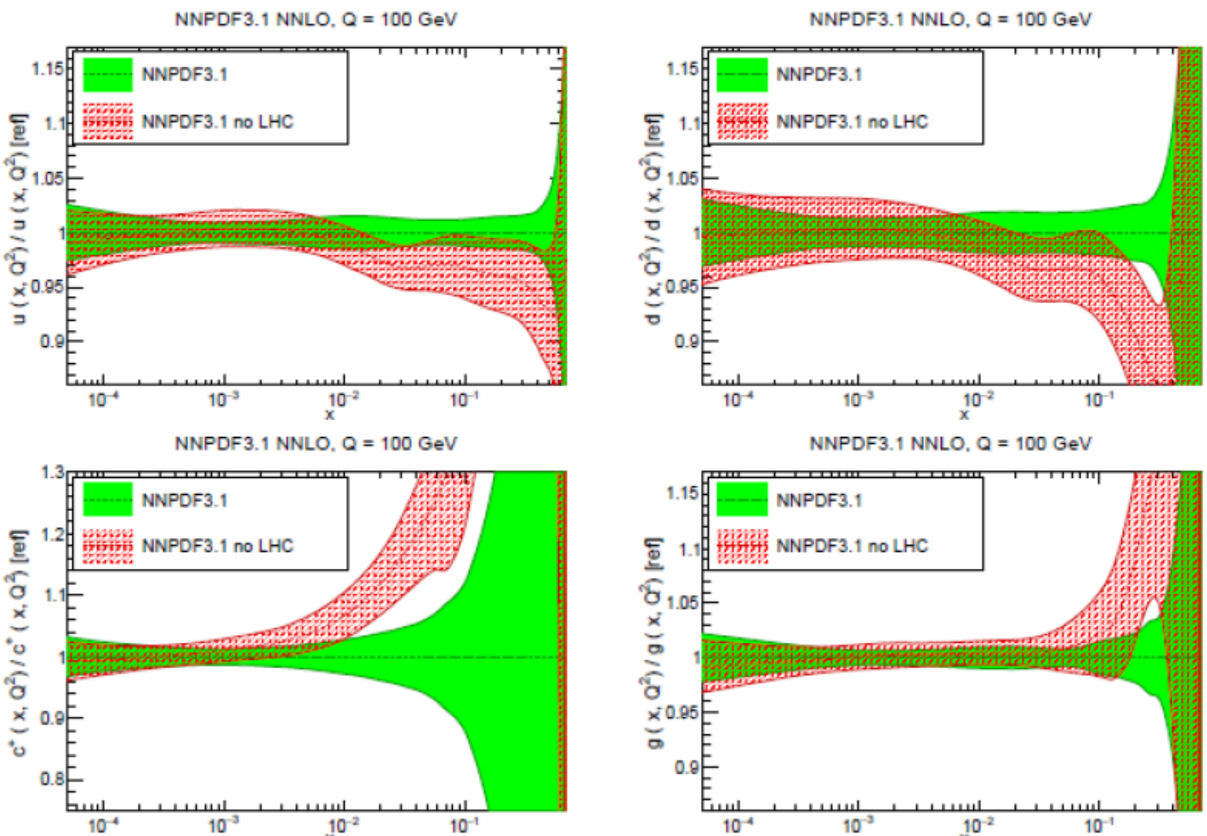
Influence of LHC jets relative to HERA-only is to make gluon slightly harder and to reduce its uncertainty somewhat

… large uncertainties remain on the high x gluon, particularly at modest scales

Quantitative Summary of LHC Impact

Theoretical Limitations:
- Hadronisation and Underlying Event
- Missing higher orders (QCD & EW)
- Large logs needing resummations

Experimental Limitations:
- Systematics (energy scale …)
- Correlations between measurements



NNPDF3.1 includes LHC W,Z, jets,top

PDFs with v without including LHC data

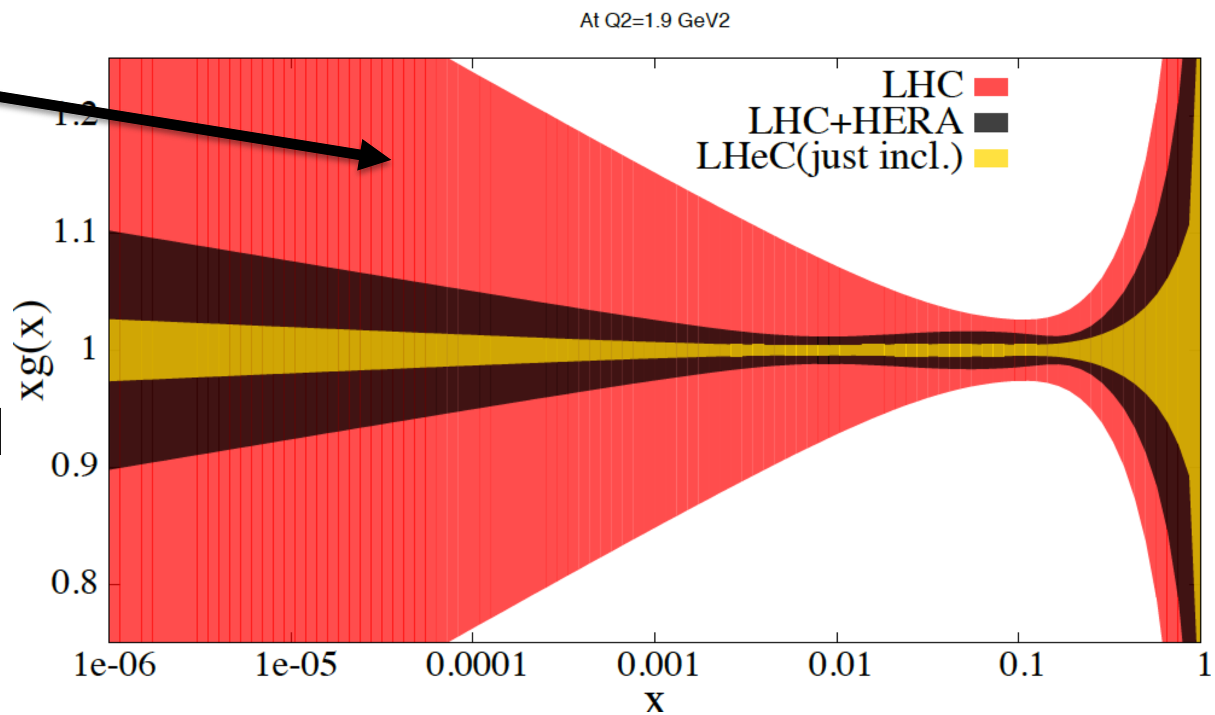
Some impact, but not transformational

Some deviations …

Asking the Question the Other Way Around

- "LHC" = current LHC W, Z and jet data

… Parton densities are best constrained in lepton-hadron scattering

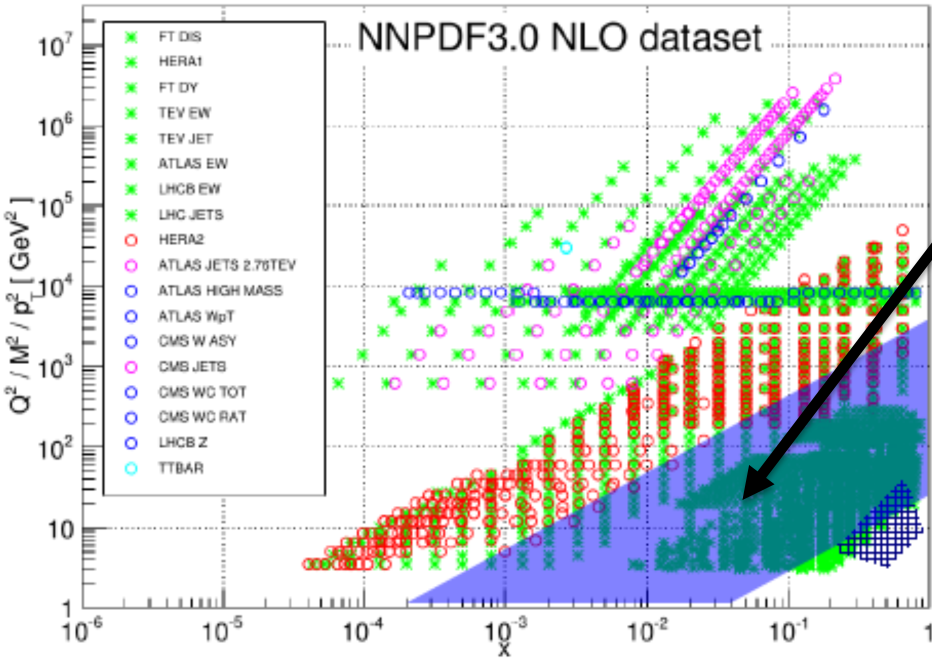


A more philosophical point …

→ You can't use the same data to constrain parton densities and to discover new physics through deviations from predictions using those PDFs

→ New physics likely to be seen in tension between predictions with non-LHC PDFs and LHC data

PDFs and the EIC

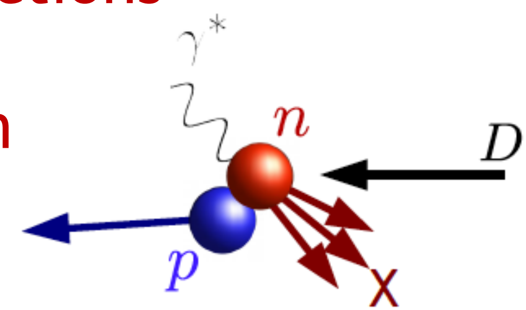


Approximate EIC coverage.

- High lumi → high x precision improved over HERA

- Some proton targets → avoid nuclear corrections

- Deuterons with and without spectator proton tagging → d/u unfolding with redundancy



- Nuclei → understanding of nuclear effects (also for FT)

- Precision tracking, performant particle ID, charged current scattering → full flavor decomposition

... first studies have been performed ...

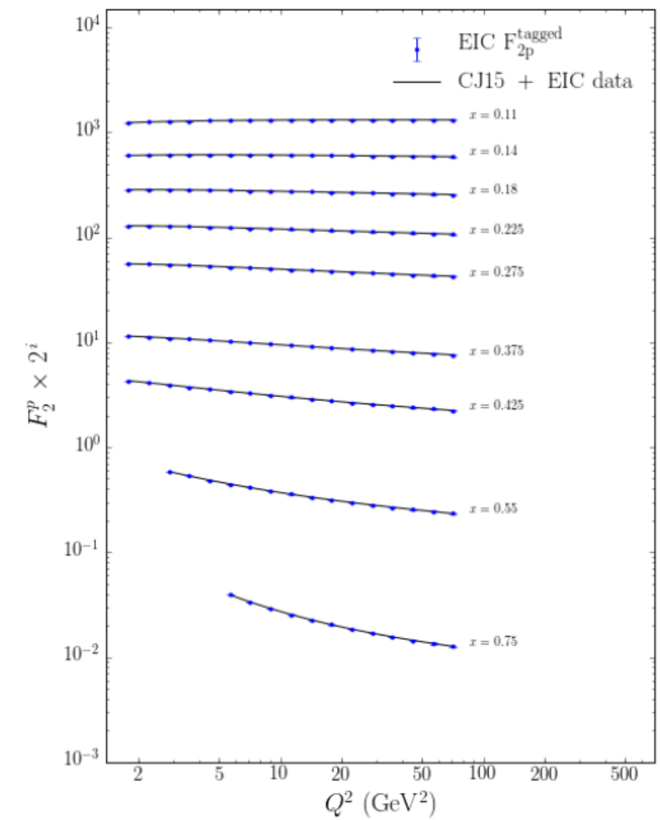
Recent dedicated High x Study

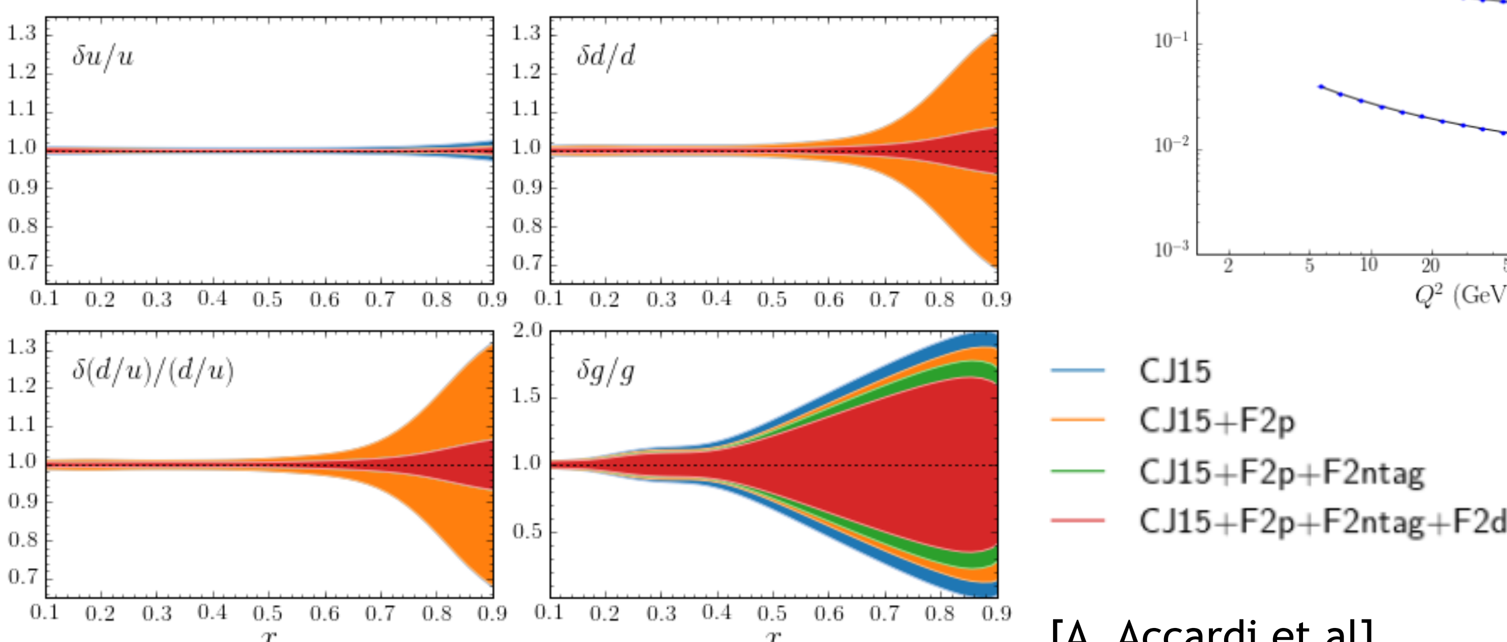
- Simulated inclusive high x EIC data

[E_e = 10 GeV, E_p = 100 GeV, 100fb^{-1}]

  - Proton,
  - Neutron from deuterons with tagged protons
  - Deuterons directly (p+n)

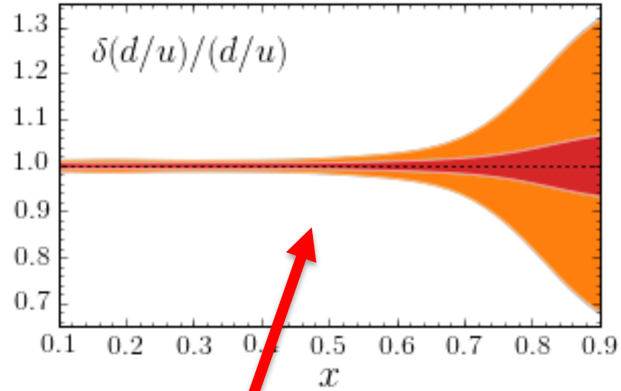
- CTEQ-Jlab ("CJ15") fitting framework

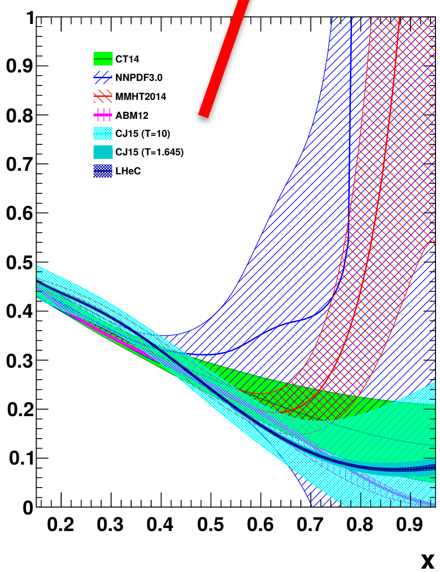


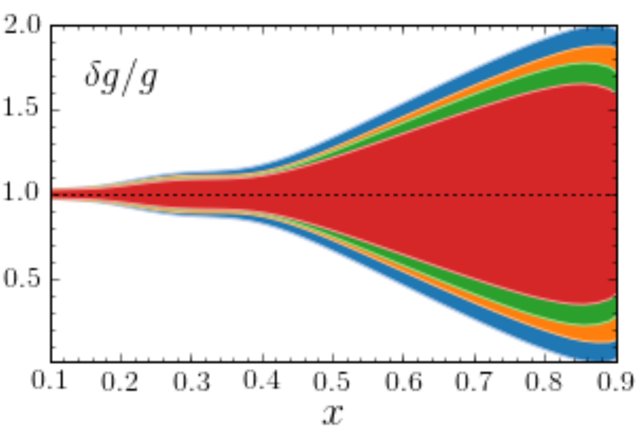


[A. Accardi et al]

High x results







- d quark precision reaches % level up to x~0.6 … resolves long-standing mystery of d/u as x → 1

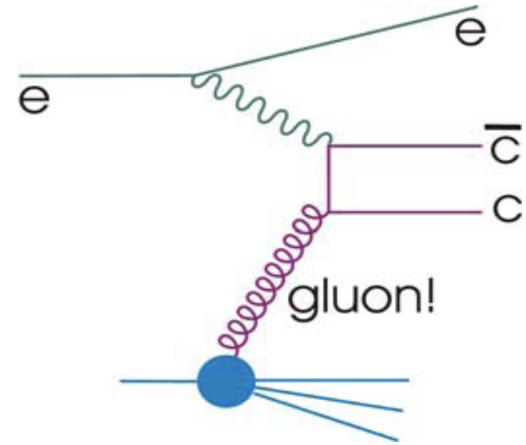
- D/(p+n) in a single experiment is starting point to understand nuclear corrections.

- Gluon improvement too, but more modest (high x scaling violations driven by q→qg, not g→qqbar?)

… motivation for other gluon-sensitive observables (jets, charm…)

PDFs from Charm at EIC

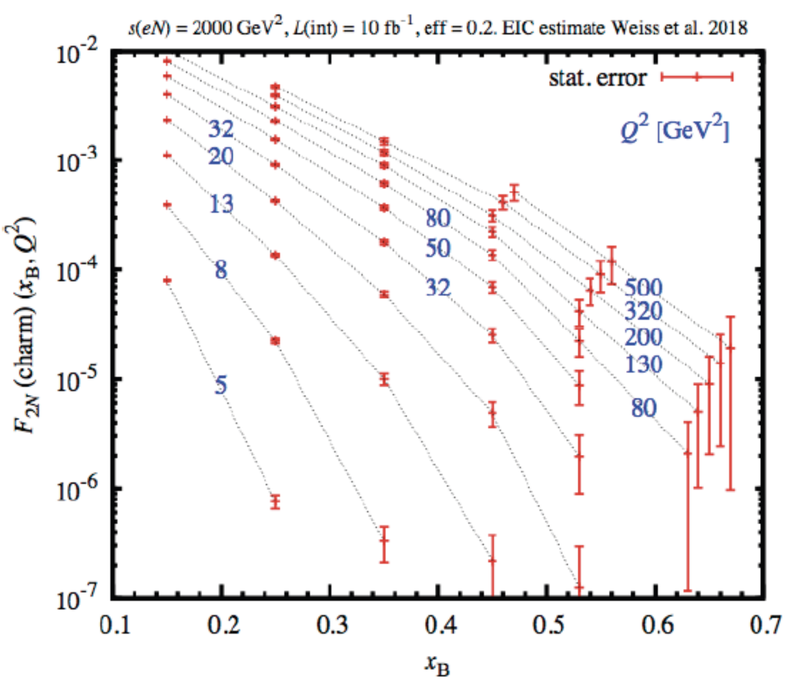
- Charm cross sections sensitive to gluon density through boson-gluon fusion
- Also addresses question of intrinsic charm



- Production rates fall rapidly as x→1

Requires : High luminosity

: Excellent charm identification (exclusive D-meson reconstruction or inclusive secondary vertex tagging)



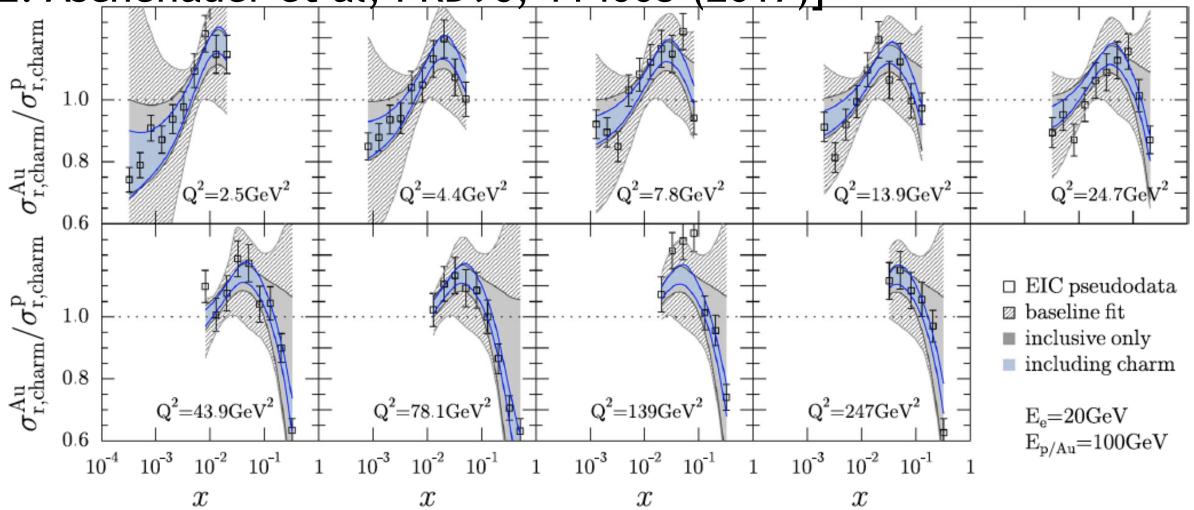
[F2(charm) = charm contribution to F2]

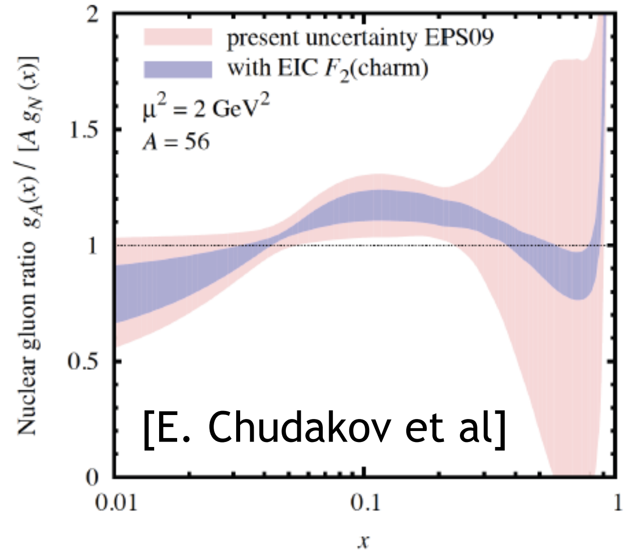
With sufficient lumi, high x charm can be tackled in ep at EIC [impact on gluon density to be confirmed]

[E. Chudakov et al]

Charm and the Nuclear Gluon Density

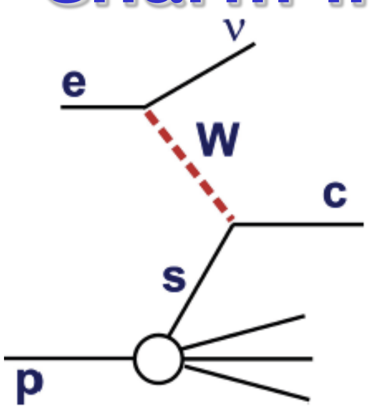
[E. Aschenauer et al, PRD96, 114005 (2017)]



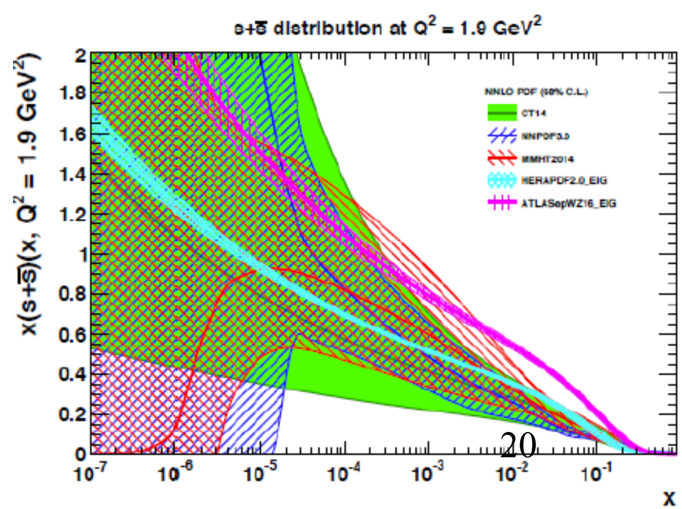


Ratio of charm cross section in eA / ep has a poweful impact on nuclear gluon density particularly at high x

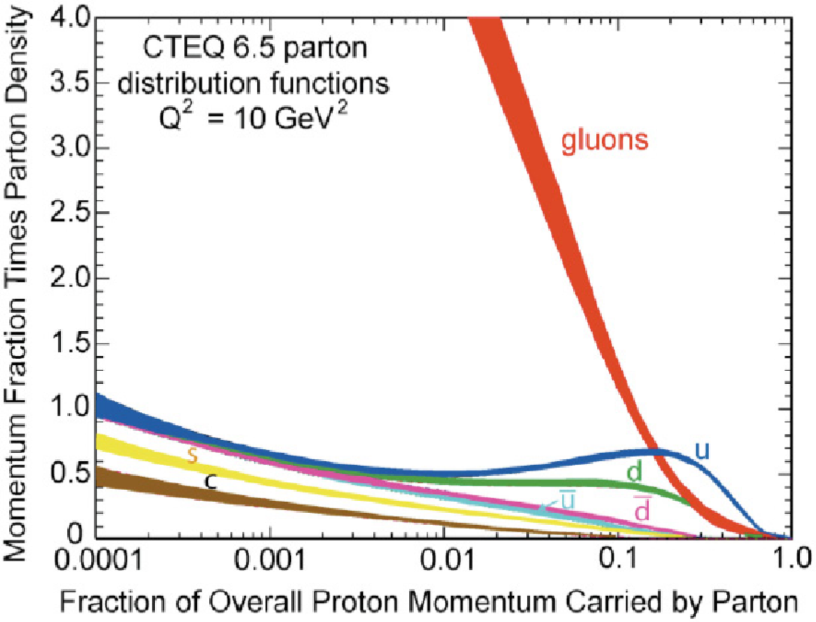
Charm in Charged Current



... tackles long-standing issue of strange density



Low x: the "Pathological" Gluon



New low x gluon-driven dynamics?

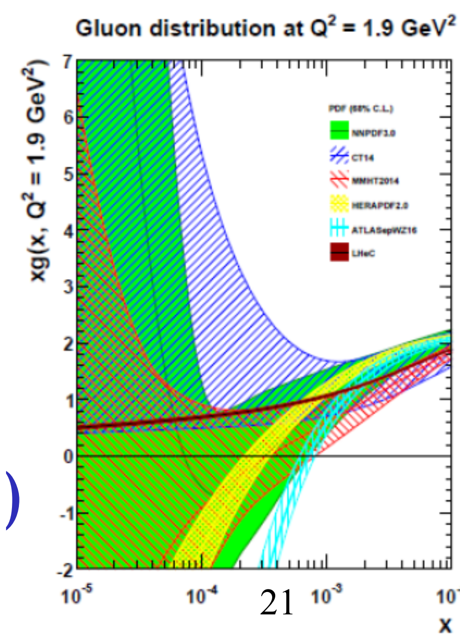
- Recombination (gg→g) ?
- Resummation?
- Just N(N)LO DGLAP + HT?

→towards new high density, small coupling, parton regime with non-linear parton evolution (e.g. CGC)?

→ HERA inconclusive

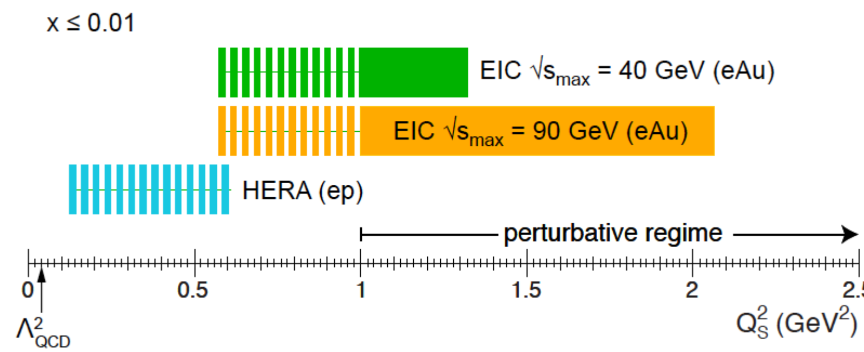
Constraints from LHC so far?...

- Gluon density poorly known below $x \sim 10^{-3}$
- LHC has limited impact in standard PDF sets
  - → more focused on high / medium x
  - → Lack of good observales (maybe UPCs…)
- LHCb unique kinematics → increasing impact



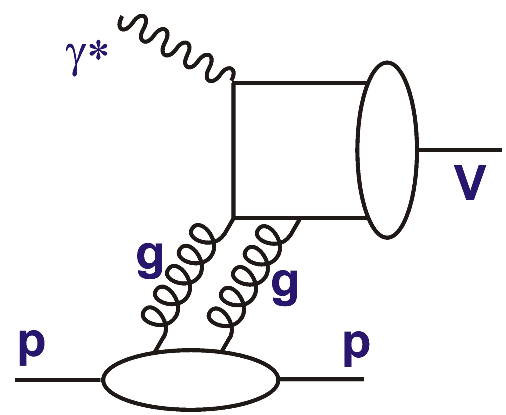
Accessing High Density Low x Partons at EIC

1) Use nuclear target



→ Overlap many sources;
enhance density ~ $A^{1/3}$ ~ 6 for Au …
[EIC may get to region where saturation effects expected up to sclaes Q^2_s ~ 2 GeV^2]

2) Use diffractive observables

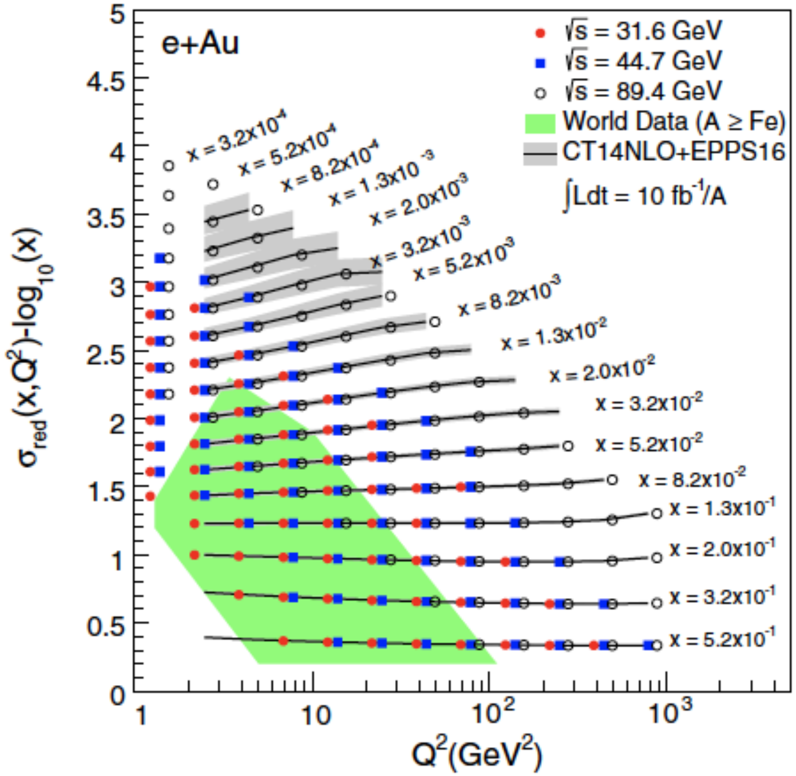


→ [Low-Nussinov] interpretation as 2 gluon exchange enhances sensitivity to low x gluon (at least for exclusives)

→ 4-momentum transfer squared (t) dependence varies impact paramerter and scans target transversely

Low x PDFs from eA at EIC

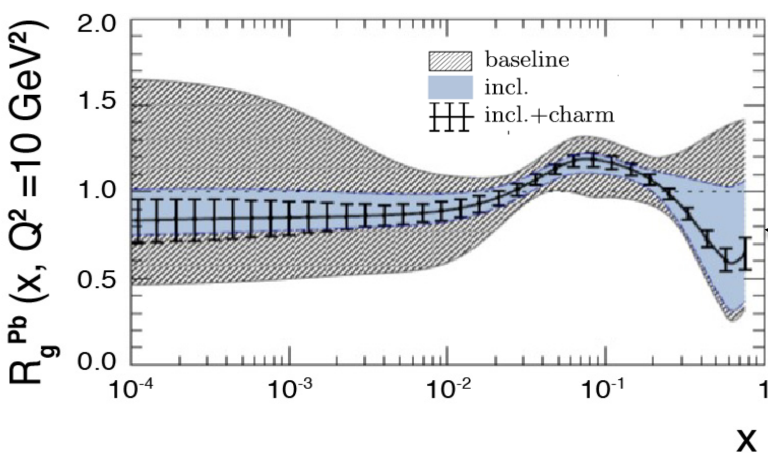
[E. Aschenauer et al, PRD96, 114005 (2017)]

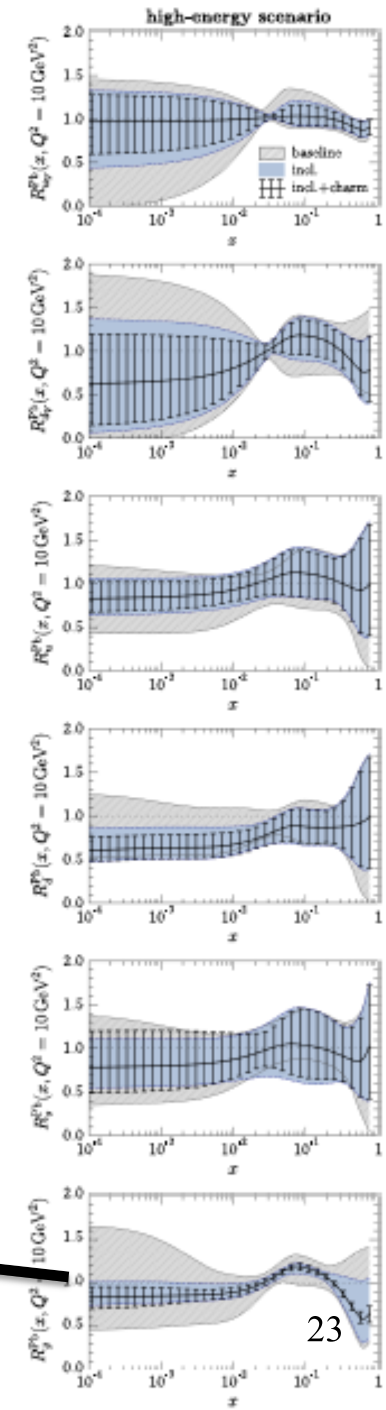


Coverage may extend to x~10^{-4} for Q^2 > 1 GeV^2

EIC inclusive and charm pseudodata at various $\sqrt{s}$ included in EPPS16 nuclear PDF fitting framework

→ transformational impact on nuclear modification ratio





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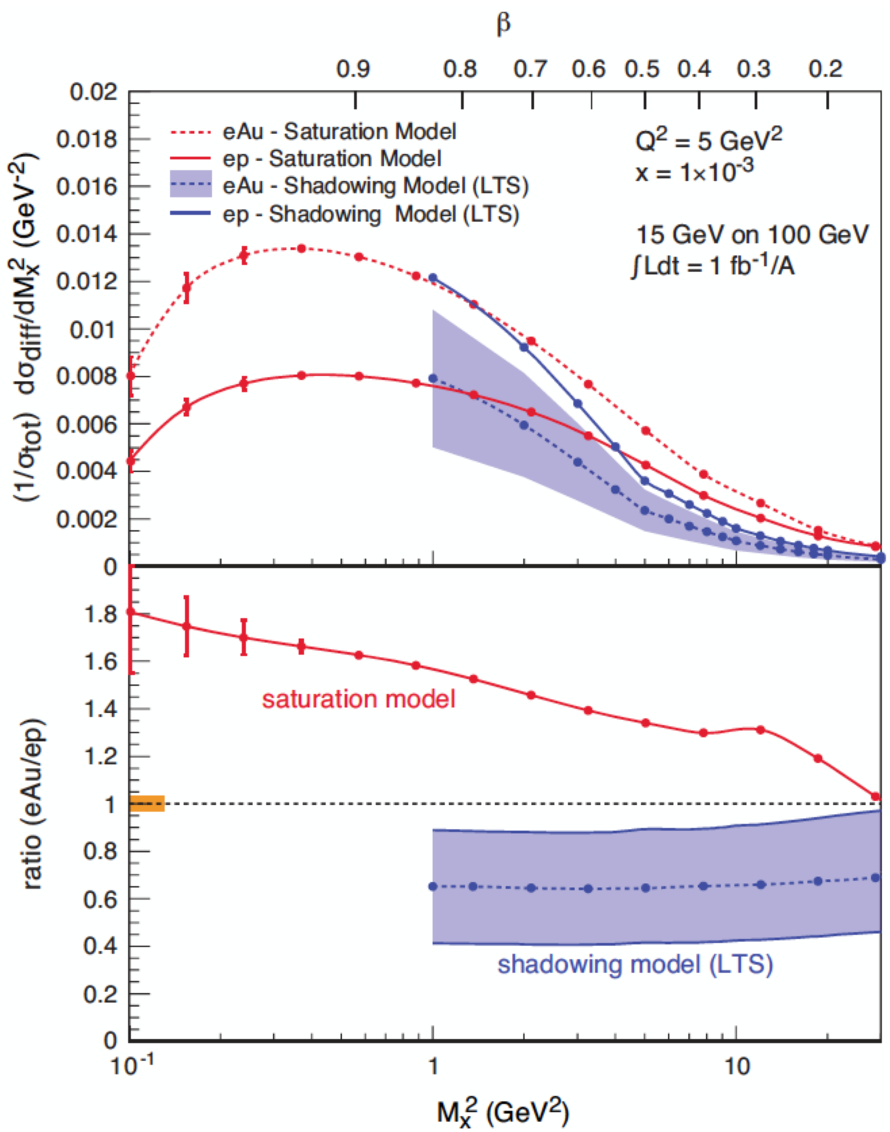
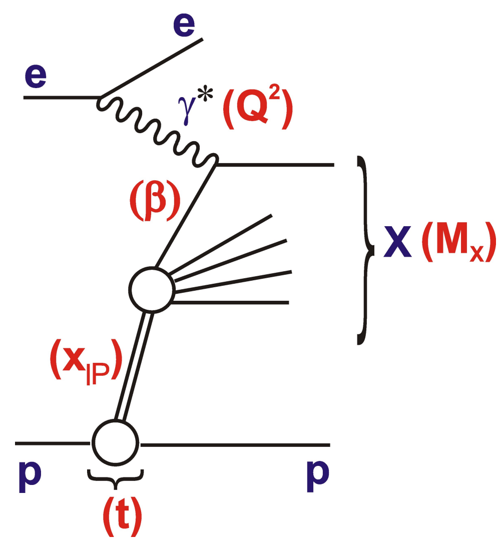
Low x Dynamics from Diffraction in early EIC data: one example





- Unfolding nuclear effects from new low x parton dynamics probably requires multiple observables … eg diffractive to inclusive ratio in ep and eA …

Summary

- Unpolarised collinear PDFs maybe not the most interesting way to characterise proton structure (see later talks), but highly relevant to high scale LHC physics

  → PDF uncertainties limit LHC searches for new heavy particles, dominate theory uncertainties in Higgs physics and limit precision measurements such as M_W

- A high lumi EIC can have a significant impact on LHC at large and intermediate x and in flavor decomposition, as well as on fundamental questions in nuclear / low x PDFs

  → First studies shown here – much more can be done

  → Lots of uncovered topics (diffraction, jets, multi-parton interactions, pion, kaon structure …)

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