The EIC and Collinear Factorization Physics

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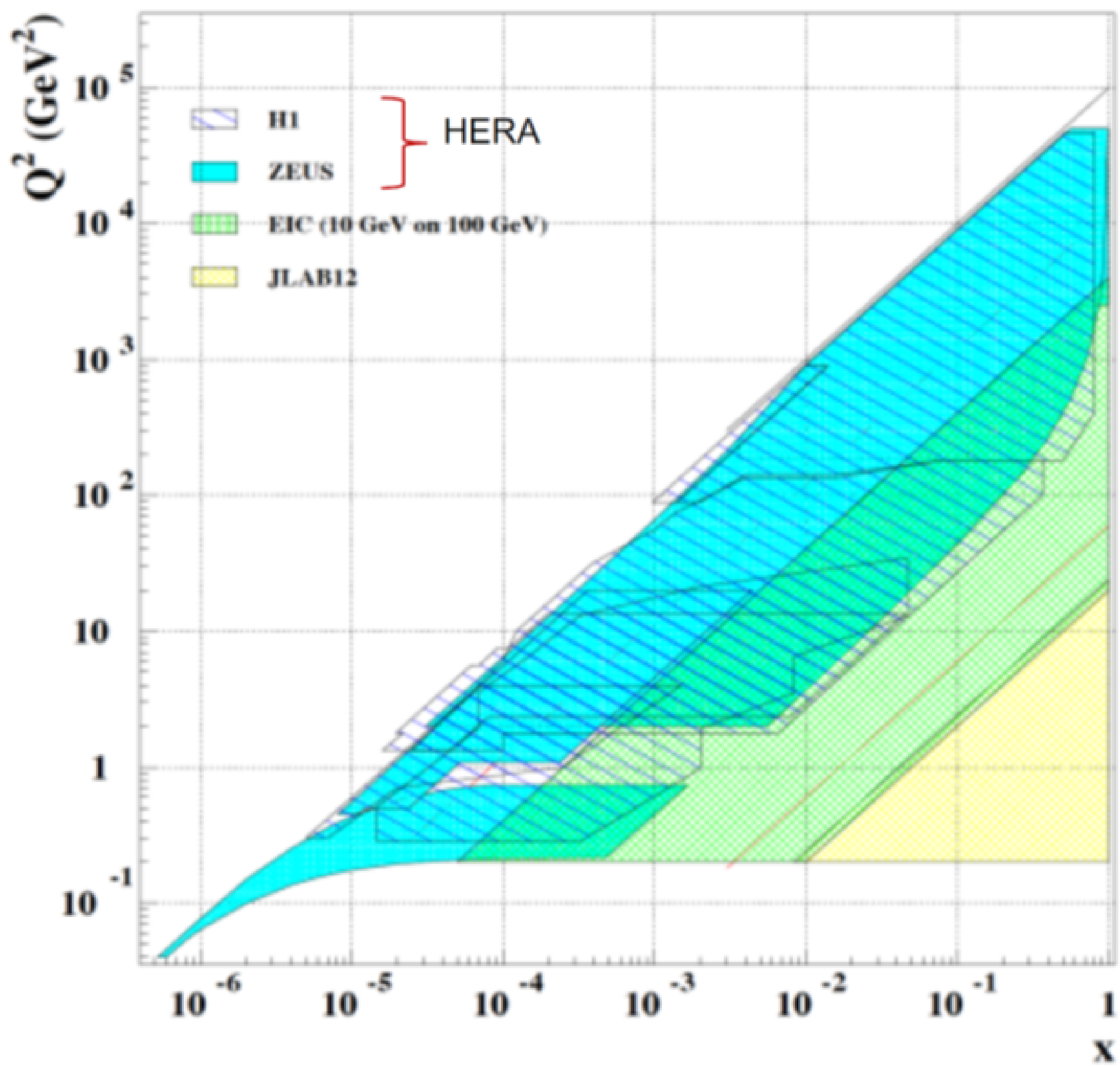
I will discuss what opportunities we envision for learning about PDFs and related physics from data at the EIC.

I will focus on unpolarised and polarised proton PDFs from electron(positron)-proton (and deuteron) scattering, and only touch on nuclear PDFs - covered by other speakers.

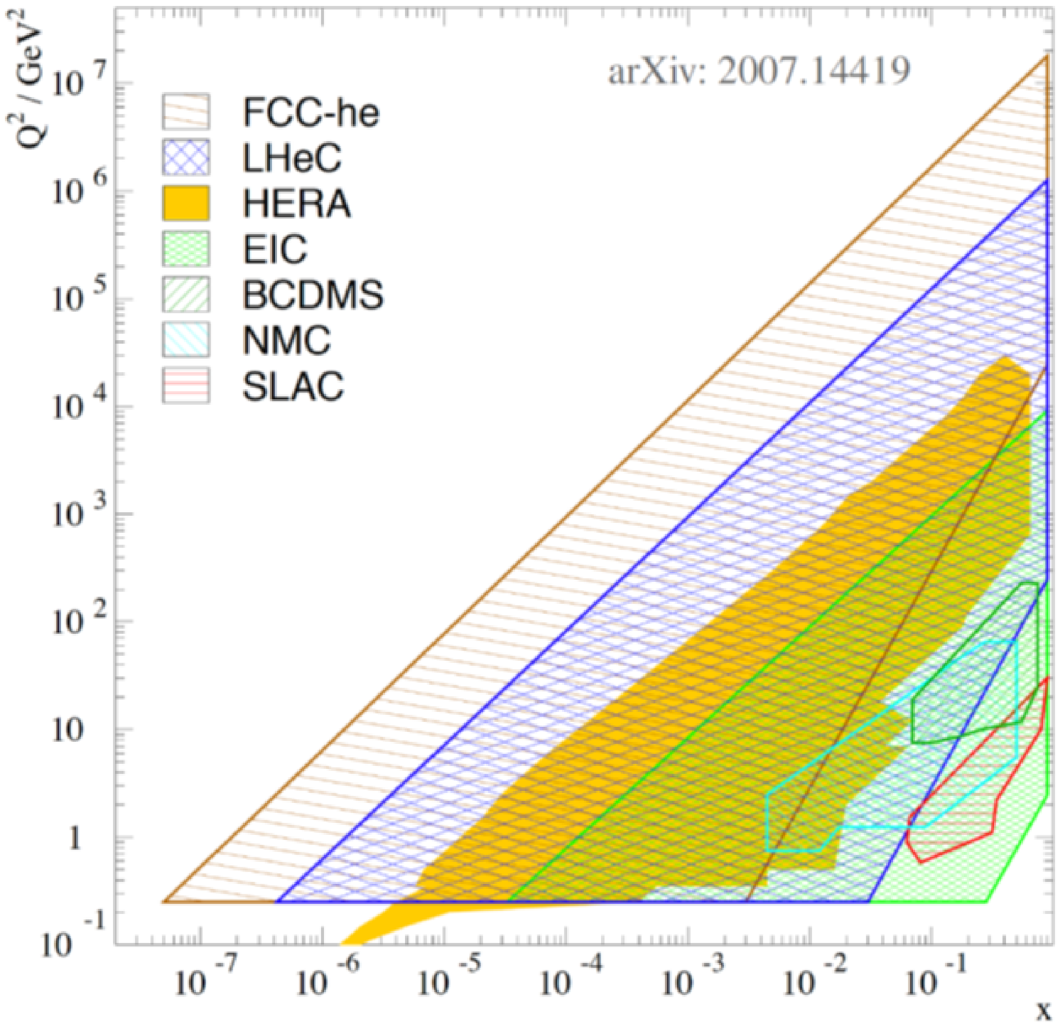
Similarly, TMDs, GPDs covered in other talks.

EIC kinematic range compared to HERA (plot from Y. Furletova).



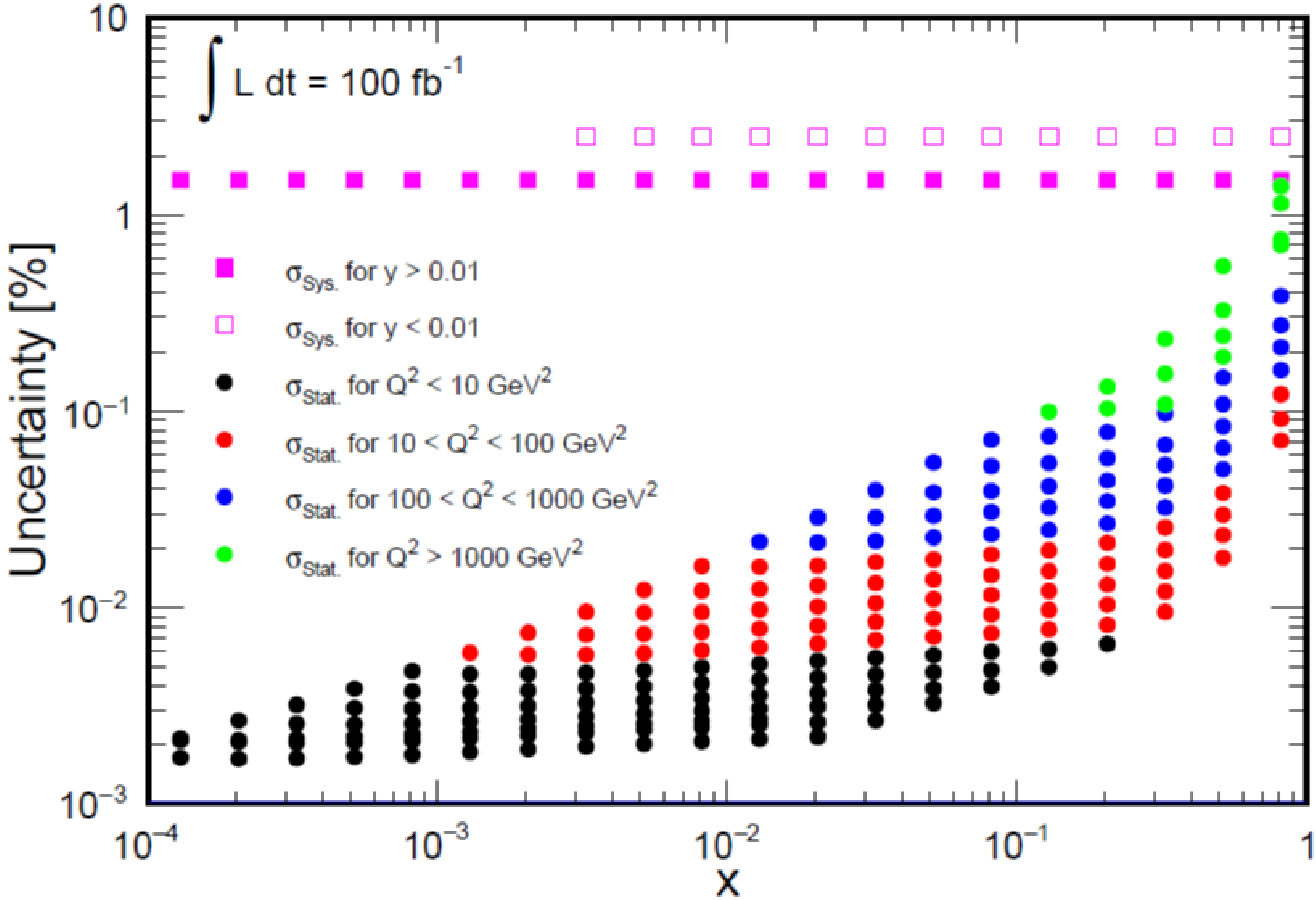
Some overlap. EIC clearly generally at higher x and lower Q^2.

EIC constraints on PDFs.



Compare with other experiments providing unpolarized PDF constraints.

Much better than previous experiments at high x but not too low ($\leq 15\mathrm{GeV}^2$) W^2 – less higher twist contamination.



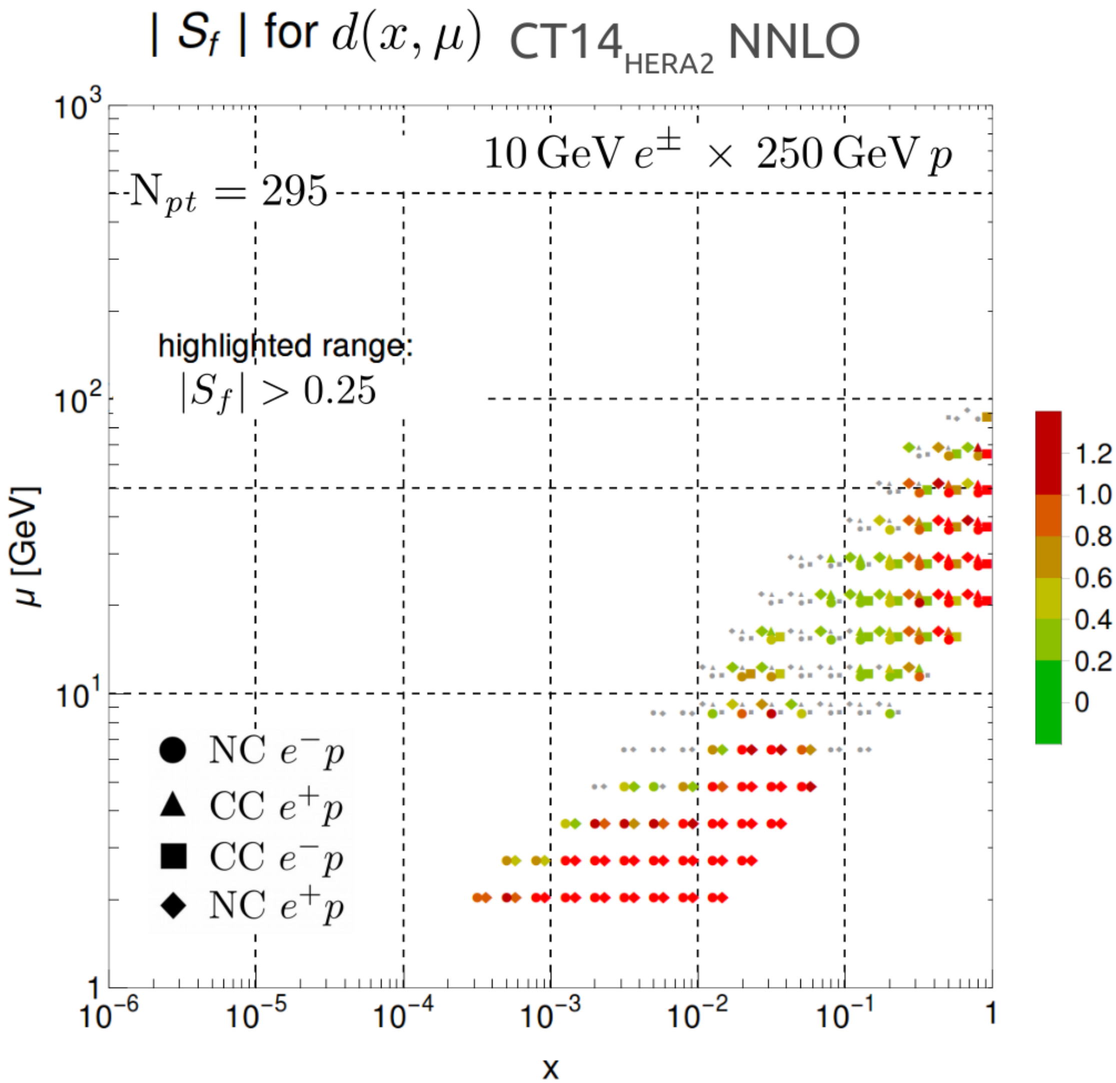
Dominated by systematic rather than statistical uncertainties. Latter projected to be much better than previous DIS experiments.

CT group use sensitivity study to infer potential impact of EIC proton data on PDFs.

$$S_f \sim C_f\left(\frac{|D_i - T_i|}{\sigma_i}\right)$$

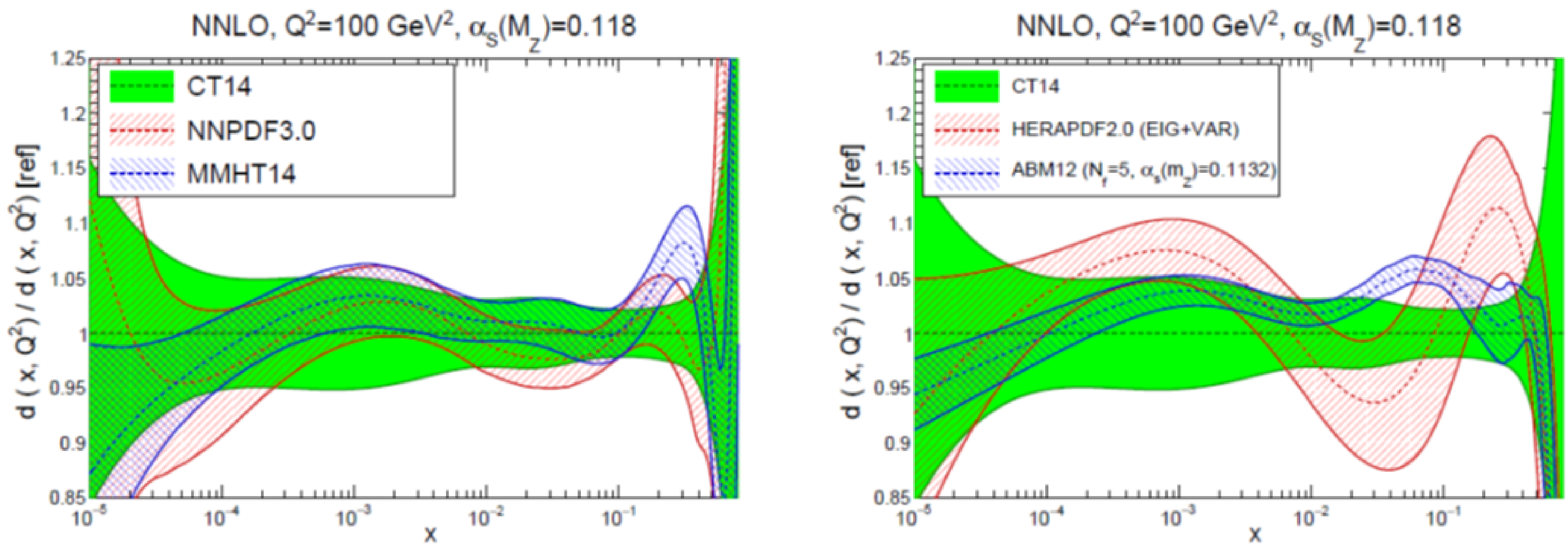
i.e. typical deviation between PDF uncertainty and data divided by typical data uncertainty weighted by correlation of data to the PDF.

Down quark known much less precisely that up quark, so more sensitivity.



Plot from https://arxiv.org/abs/2001.07862.

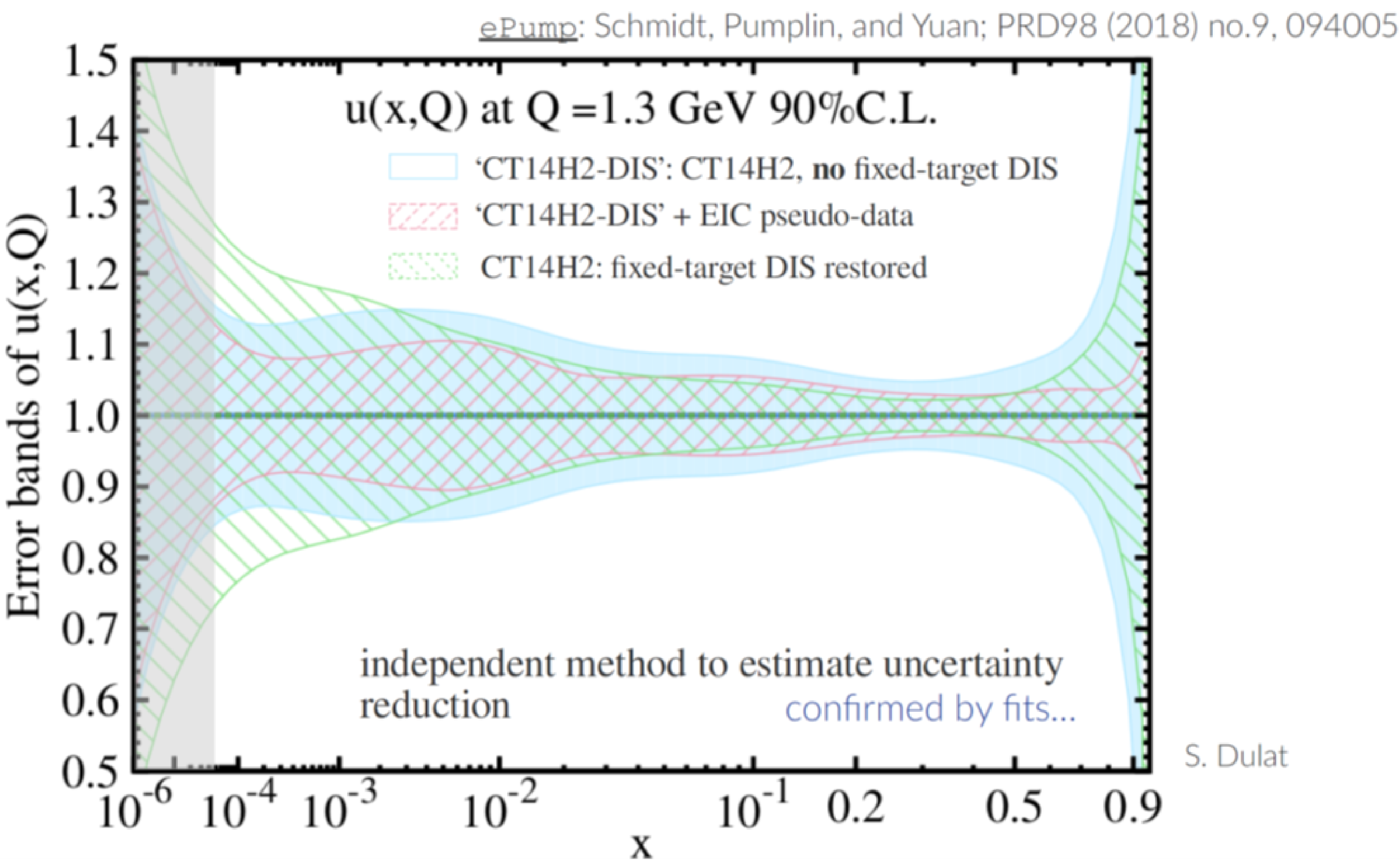
Uncertainty and variation in $d(x, Q^2)$.



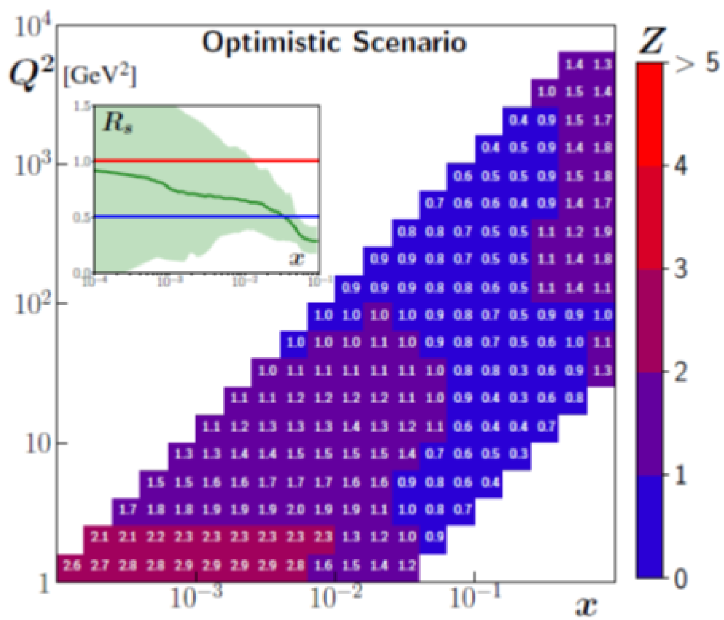
Can see that uncertainty, and even more-so variation between PDF sets, expands rapidly above $x \sim 0.2$.

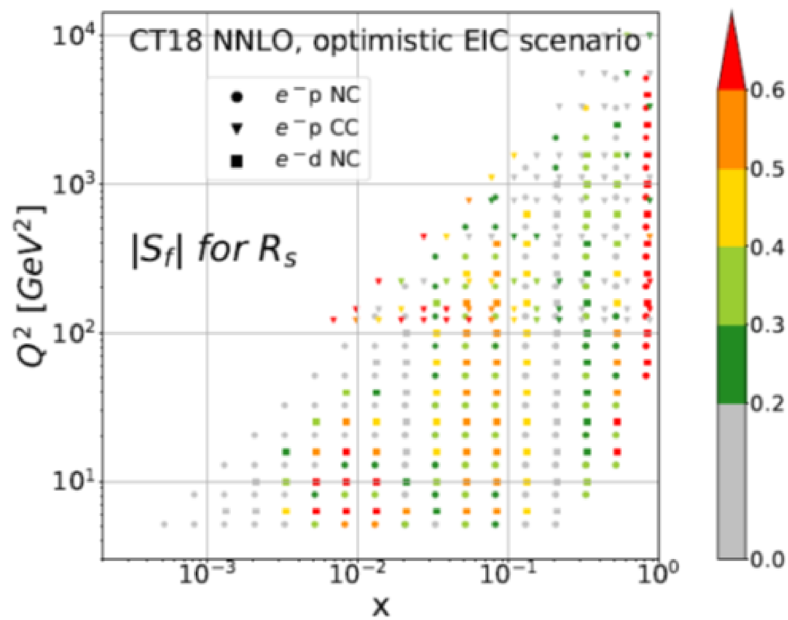
Differences due to variations in data constraints, and/or manner in which deuteron corrections are treated.

At very high x clean data also provides better constraints on even the up quark.



Conversely, the strange quark is not as well known, so very precise data can improve this even without very direct constraint.



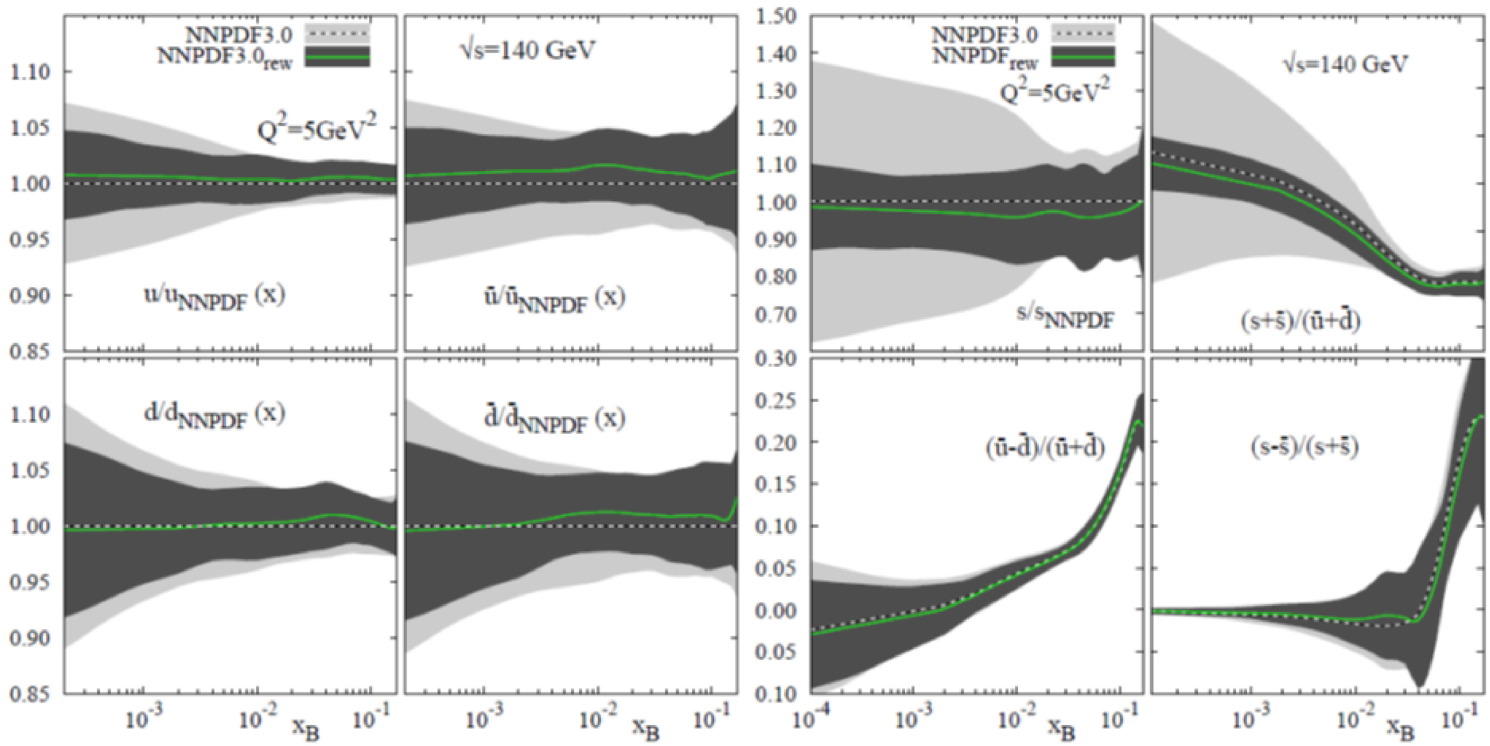


Left, NNPDF study on sensitivity where Z score measures statistical separation in units of σ of cross section hypotheses.

Right, CT study similar ro previous slides.

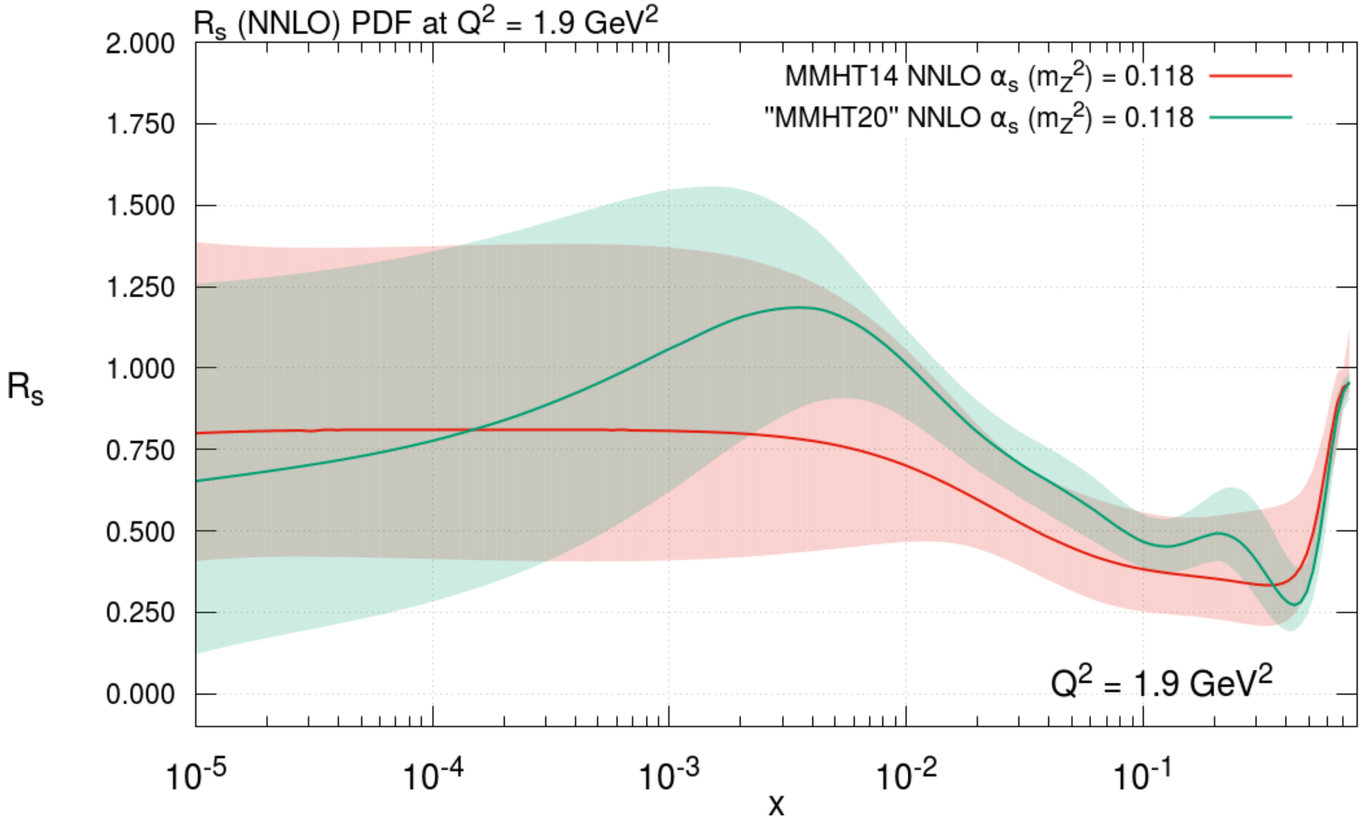
Low x and Q^2 or high x have best potential.

Semi-Inclusive DIS



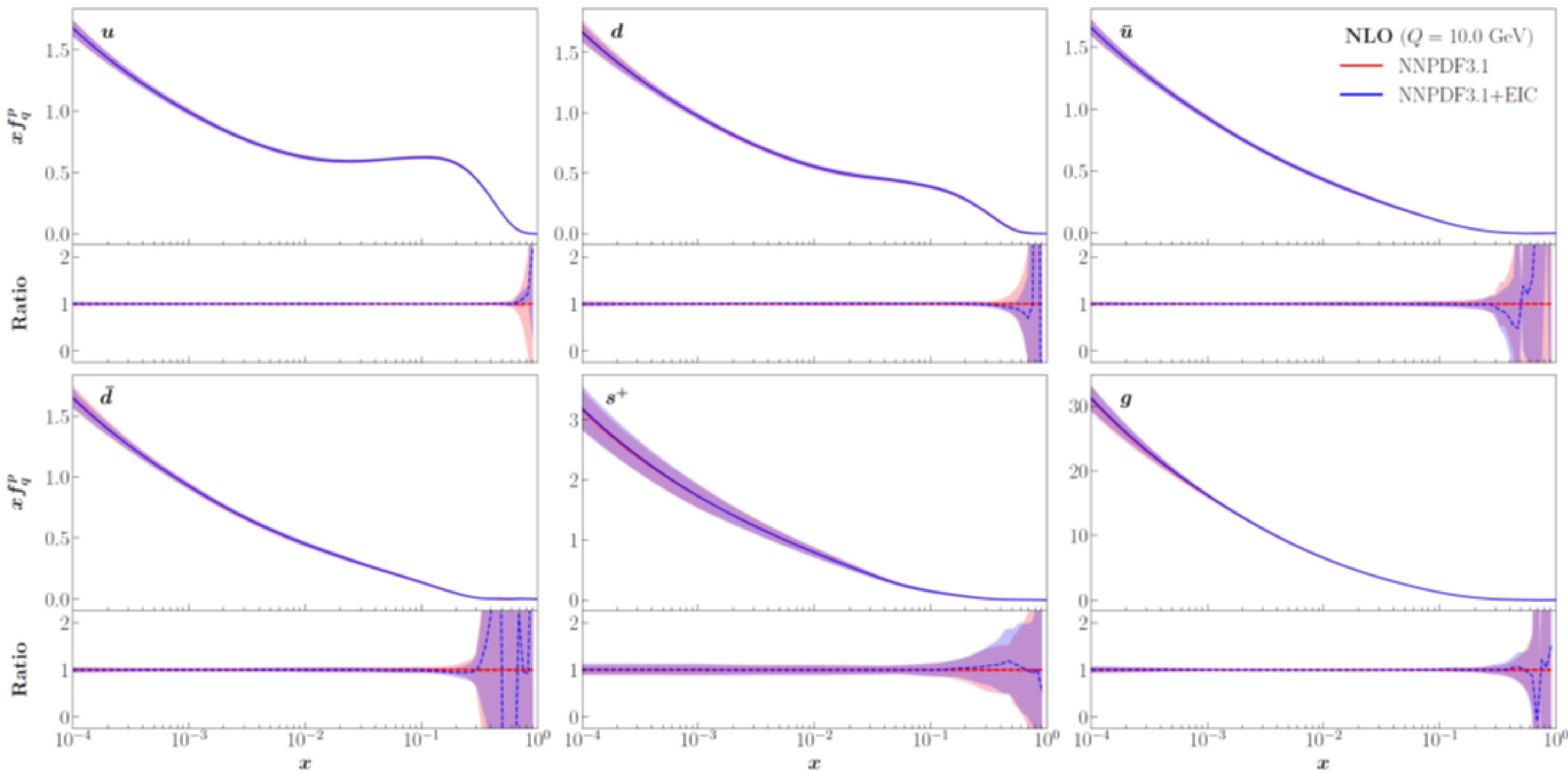
Also an impact, particularly on strange from kaon production, though tied to uncertainty on fragmentation functions PysRevD.990094004.

Look at impact of LHC data $R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$.



Comes from different between Z and W production in Drell Yan.

Potential PDF constraints viewed in slightly different way for NNPDF.

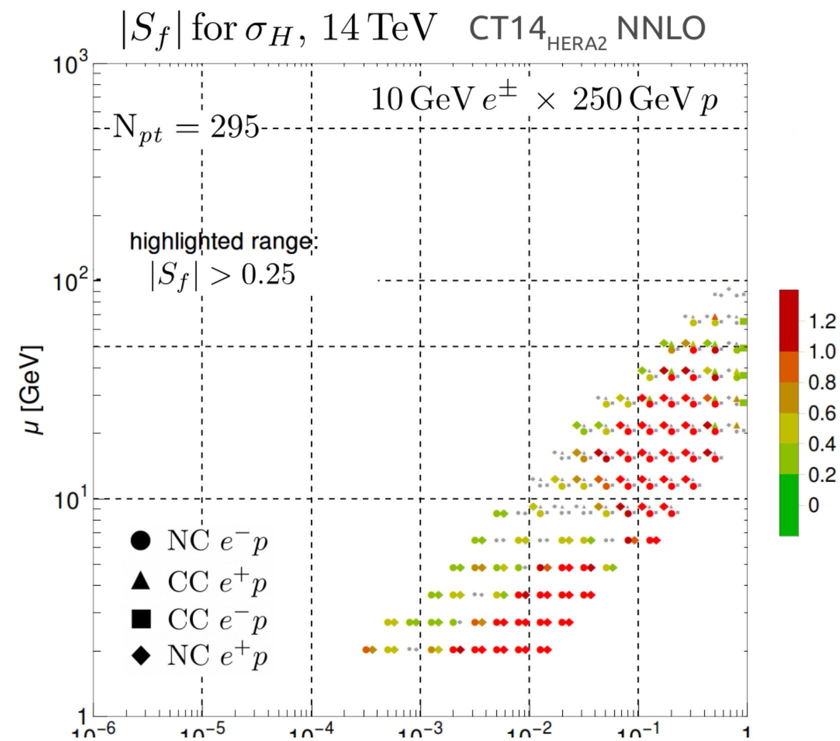


CT also look at sensitivity study for LHC Higgs cross section.

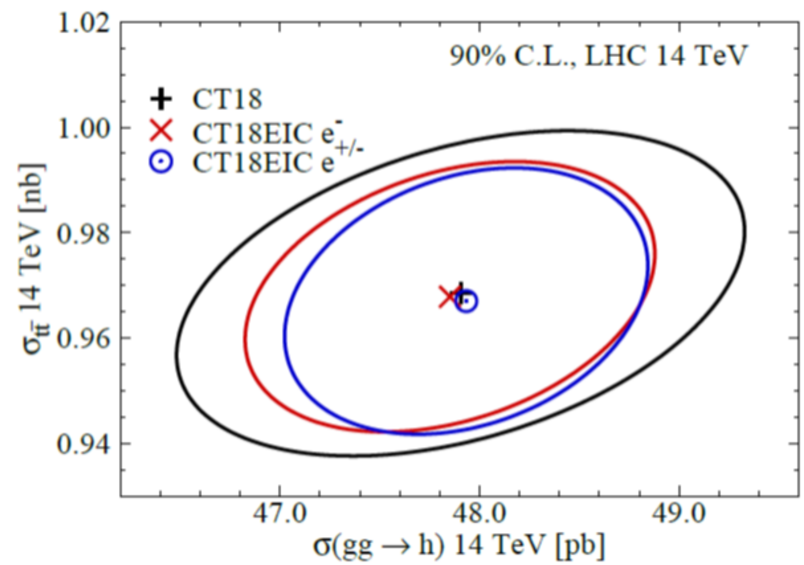
Strongly correlated to the gluon.

Primary sensitivity due to evolution of the structure function driven by the gluon.

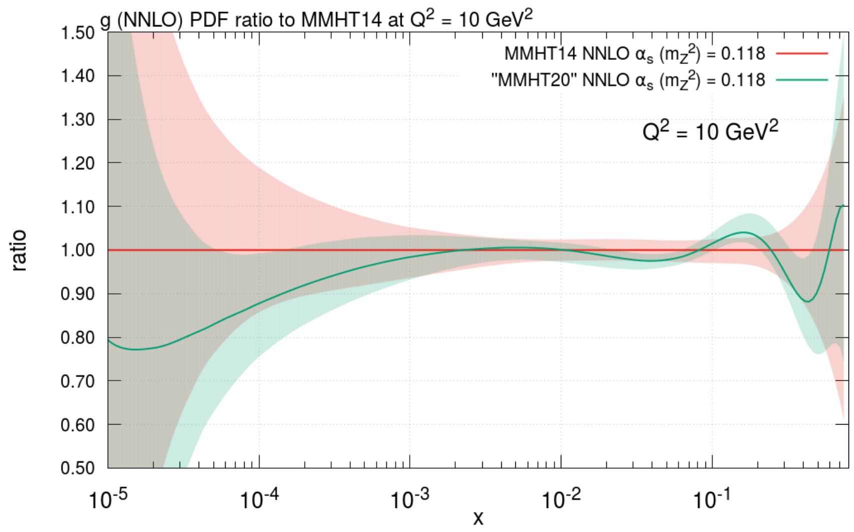
Plot from 2001.07862.

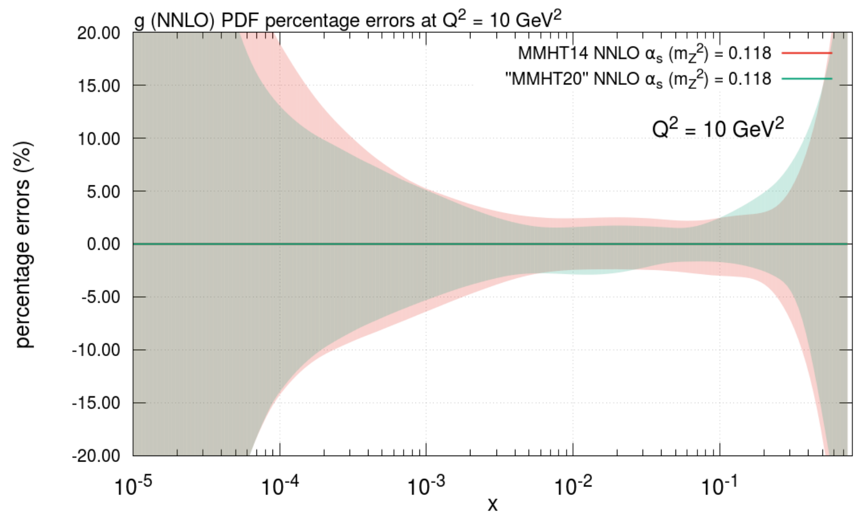


Direct visualisation of Higgs impact.



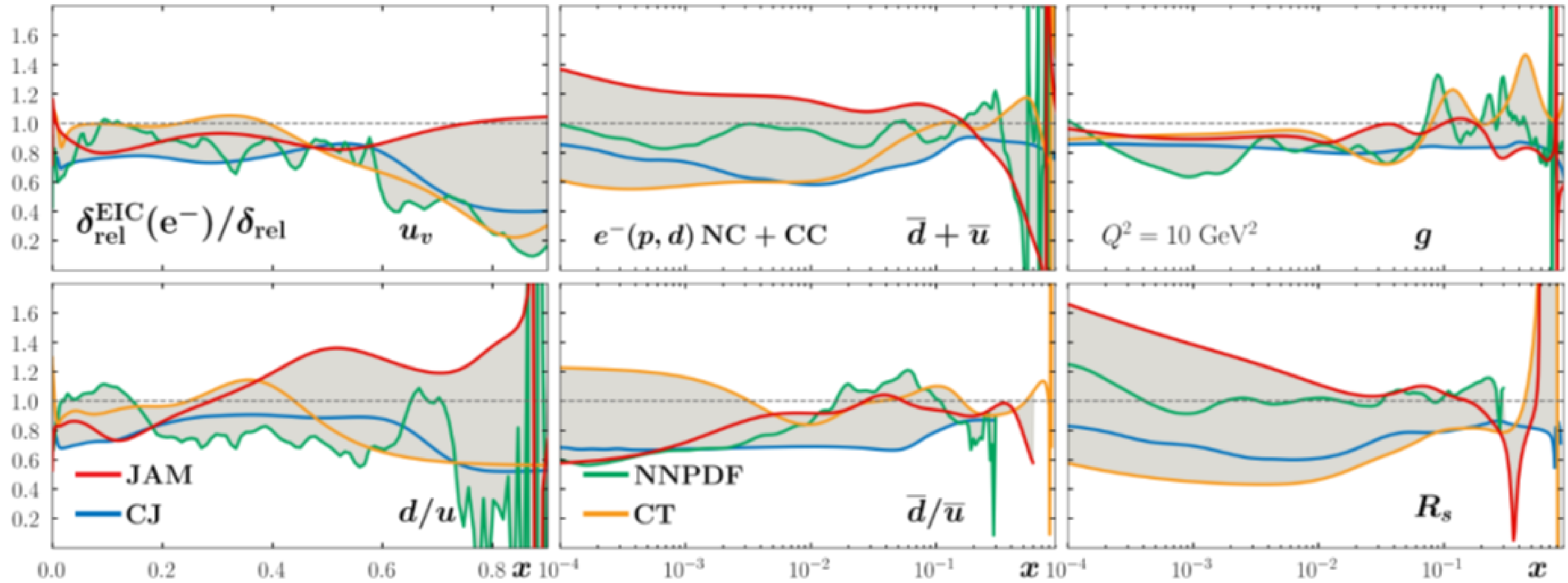
Lower Q^2.





The gluon $g(x, Q^2)$ is more uncertain at low Q^2.

Again precision data on evolution of structure functions at $x \sim 0.01$ at low Q^2 can make an impact on this.

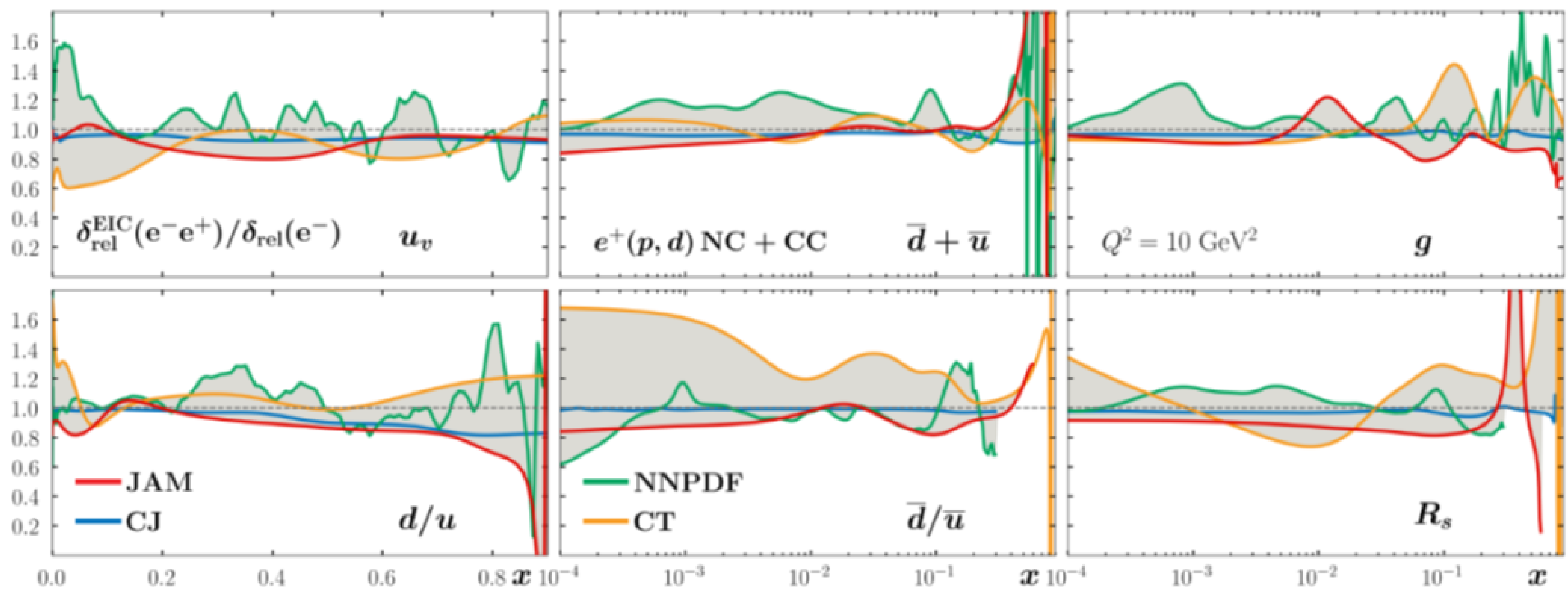


Alternative illustration in Yellow Report, but different PDFs give rather different answers. JAM provides some slightly odd results in my view.

Depends what other data was already in the fit.

Also the possibility of running with e^+

In principle alternative charged current (W^+ rather than W^-) gives more info. on flavour separtion.

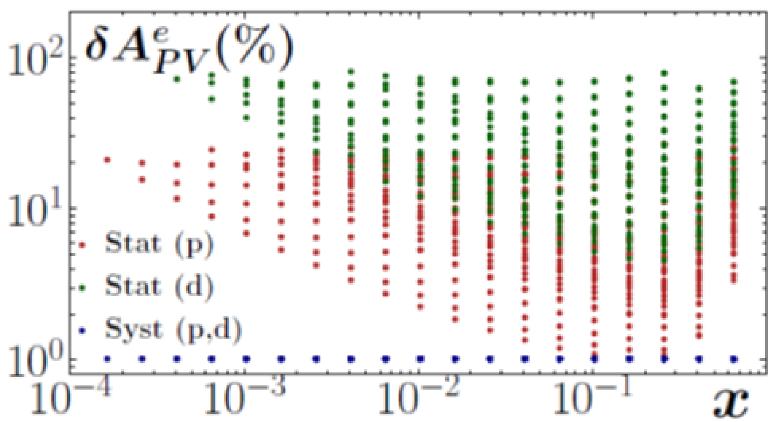


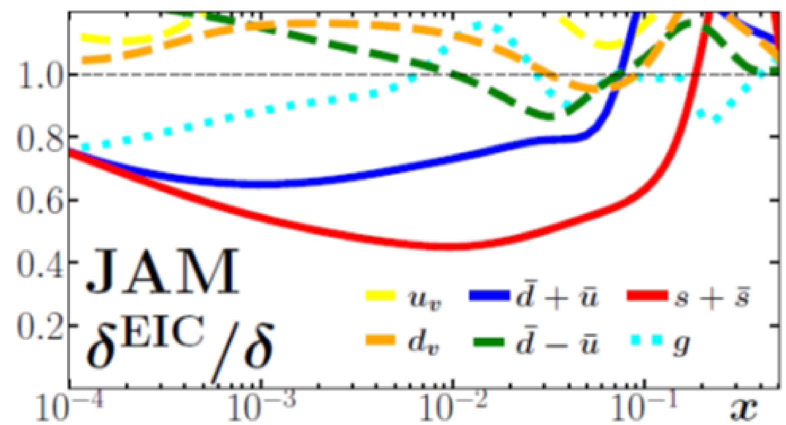
Looks rather marginal in practice.

Better prospects from looking at Parity Violating effects, i.e.

$$\frac{\sigma(e^{\uparrow}p)-\sigma(e^{\downarrow}p)}{\sigma(e^{\uparrow}p)+\sigma(e^{\downarrow}p)} \propto F_2^{\gamma Z} = 2Q_q g_V^q x(q(x)+\bar{q}(x)),$$

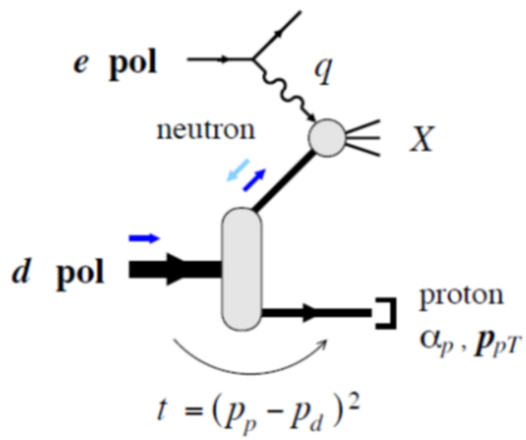
which gives up and down type quarks roughly equal weight.

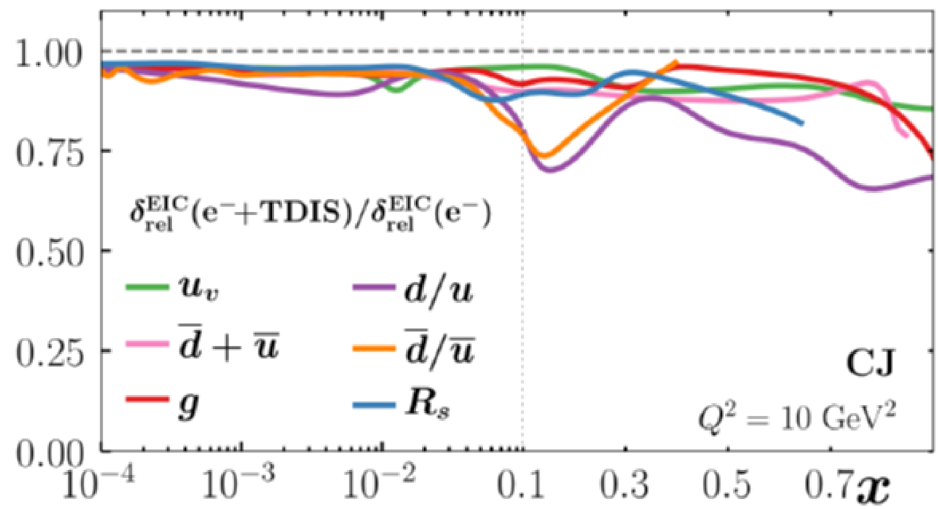




Possibility of tagging a final state neutron in deuteron scattering.

As $t - m_N^2 \rightarrow 0$ corresponds to scattering of neutron, i.e. "onshell extrapolation".

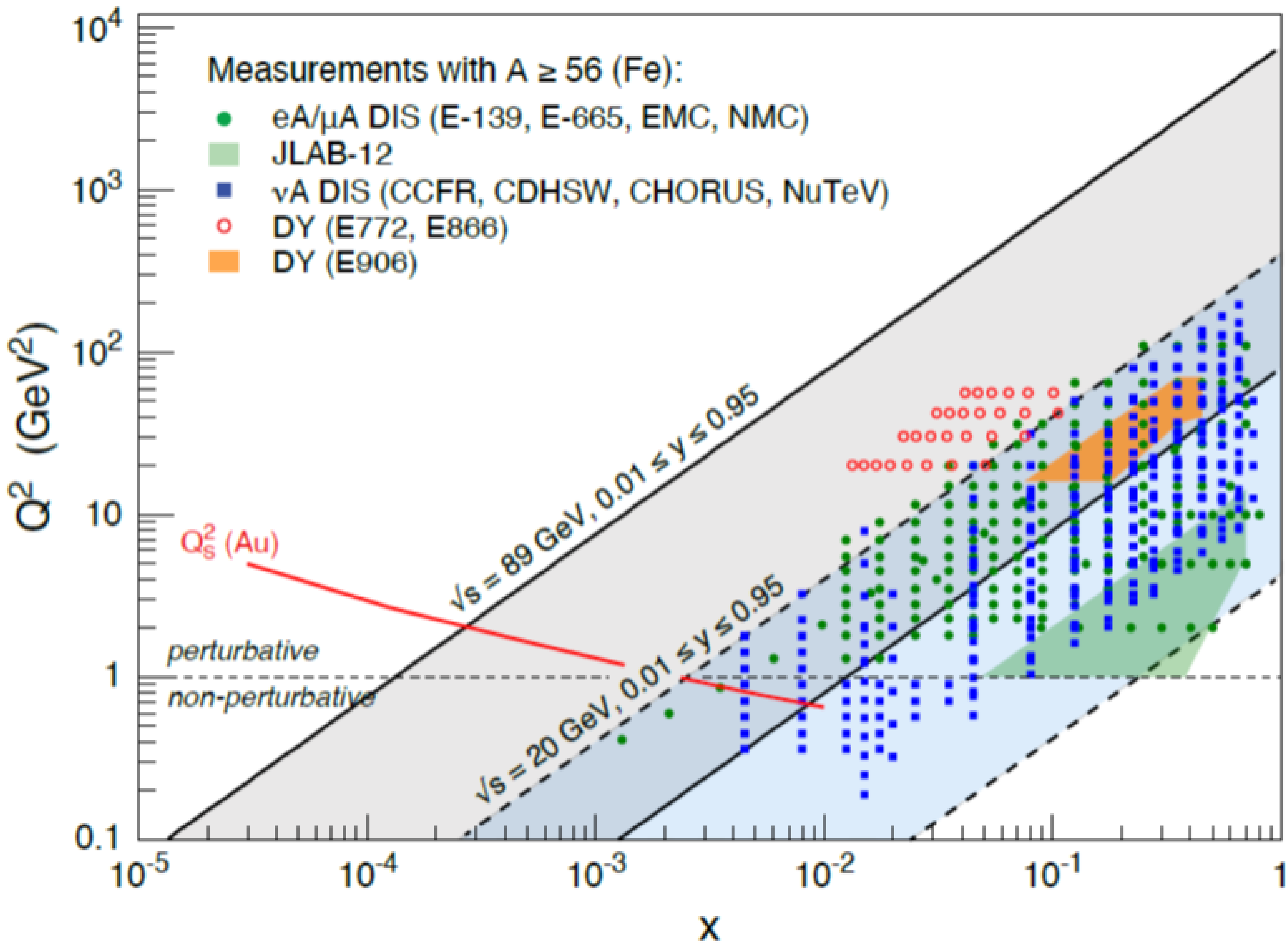




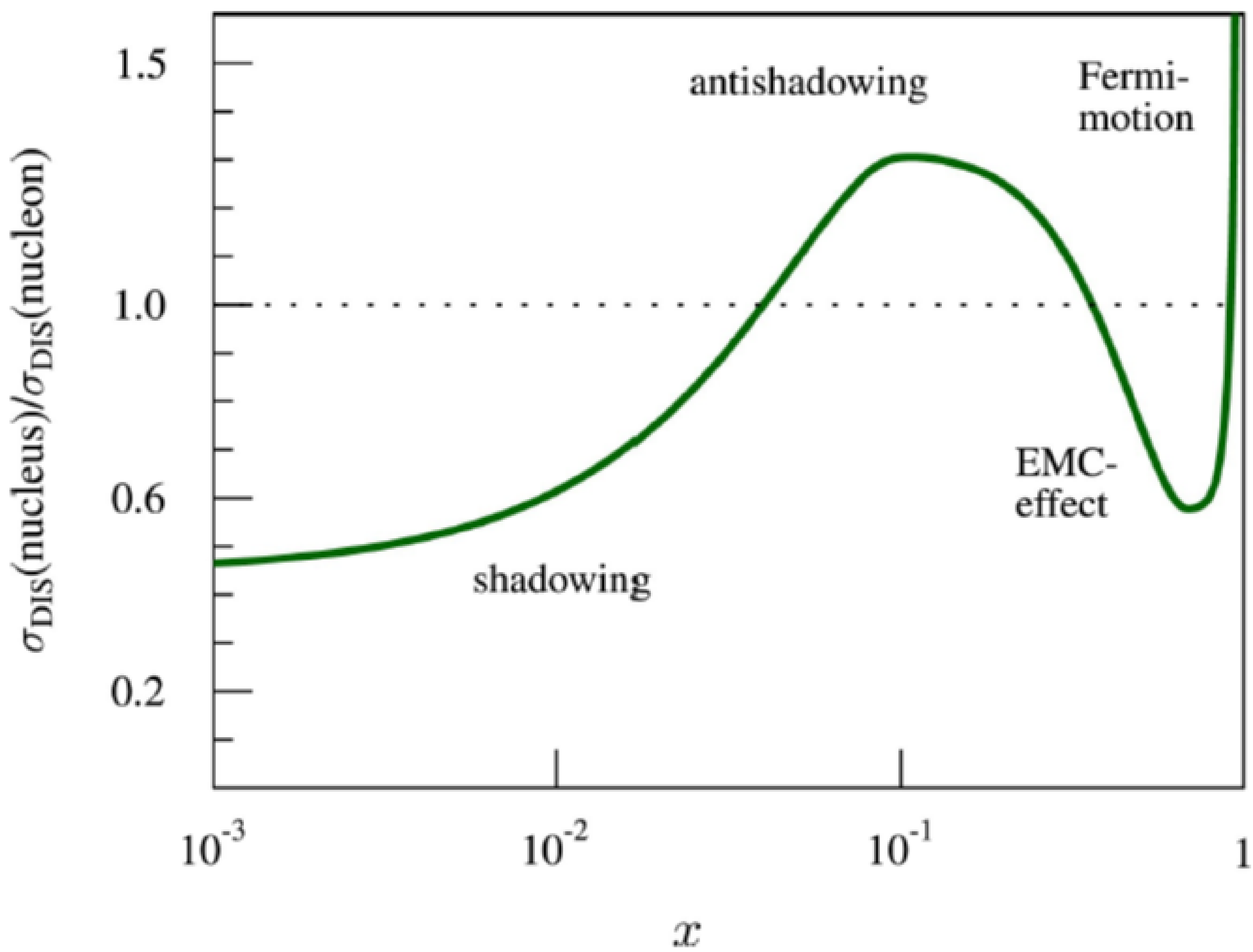
Elimates uncertainty in deuteron correction to sum of free p, n distributions.

Can possibily start testing isospin symmetry.

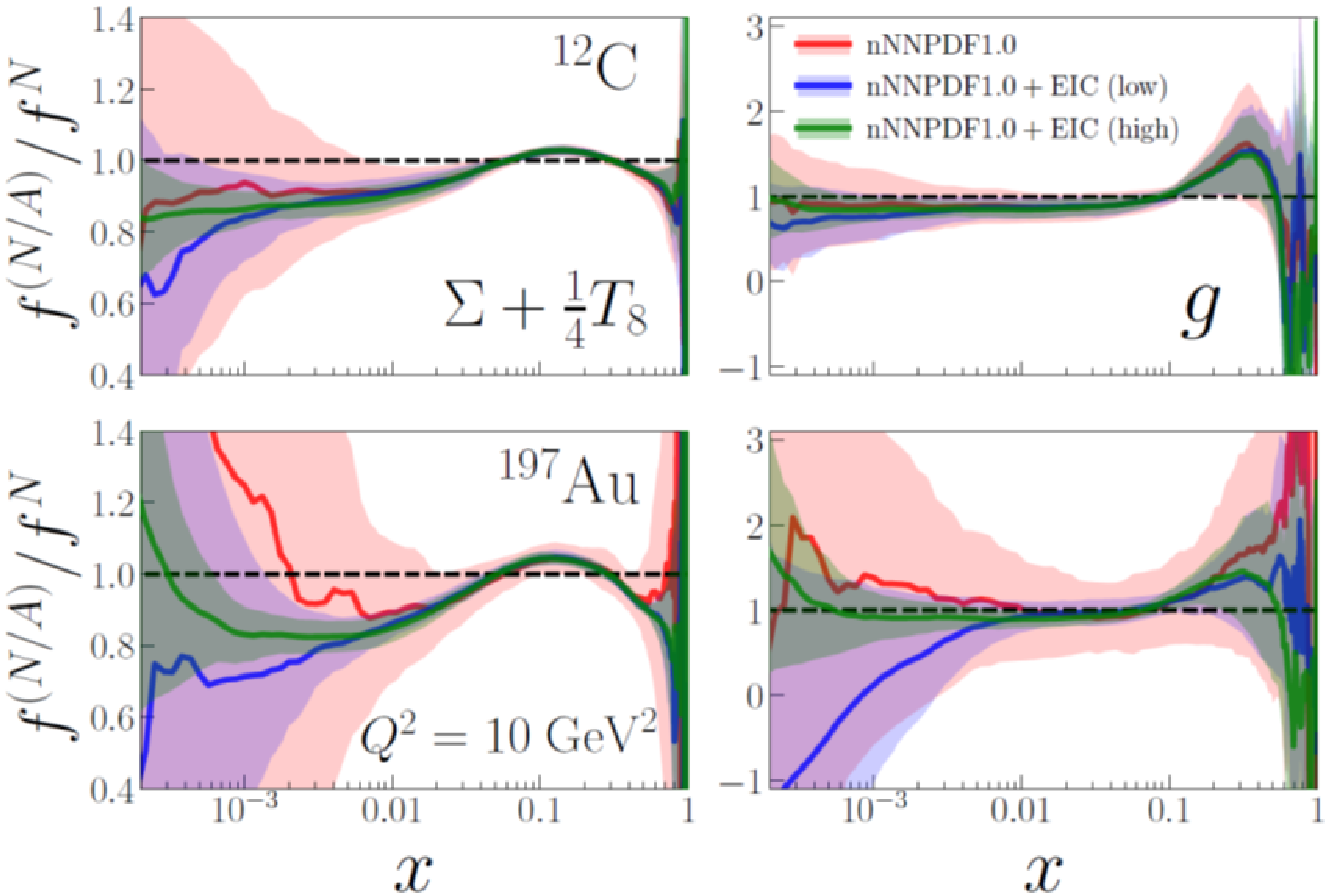
Big impact on Nuclear PDFS



Test the nuclear corrections in much more detail



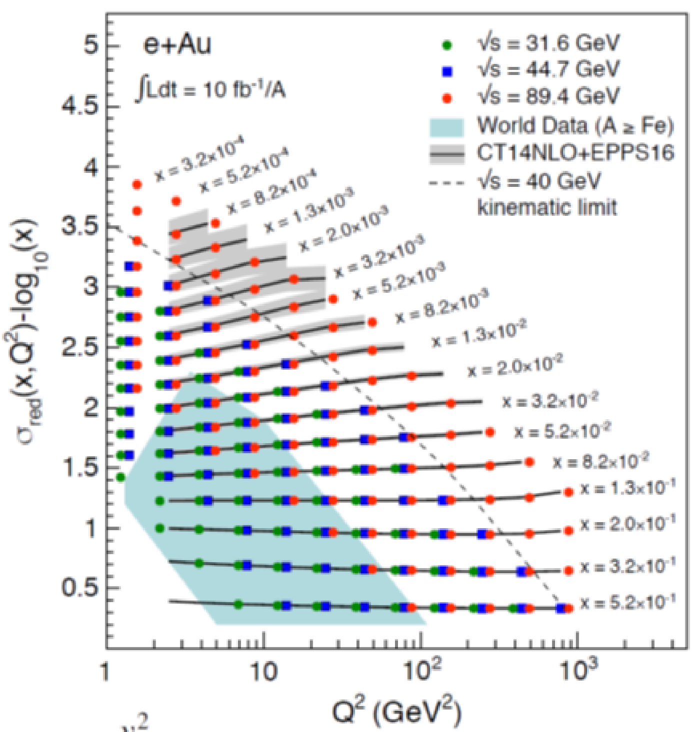
Covered in detail in other talks. See however an example of the possible improvement in NNPDF nuclear PDFs Phys.Rev.D 103 (2021) 9.

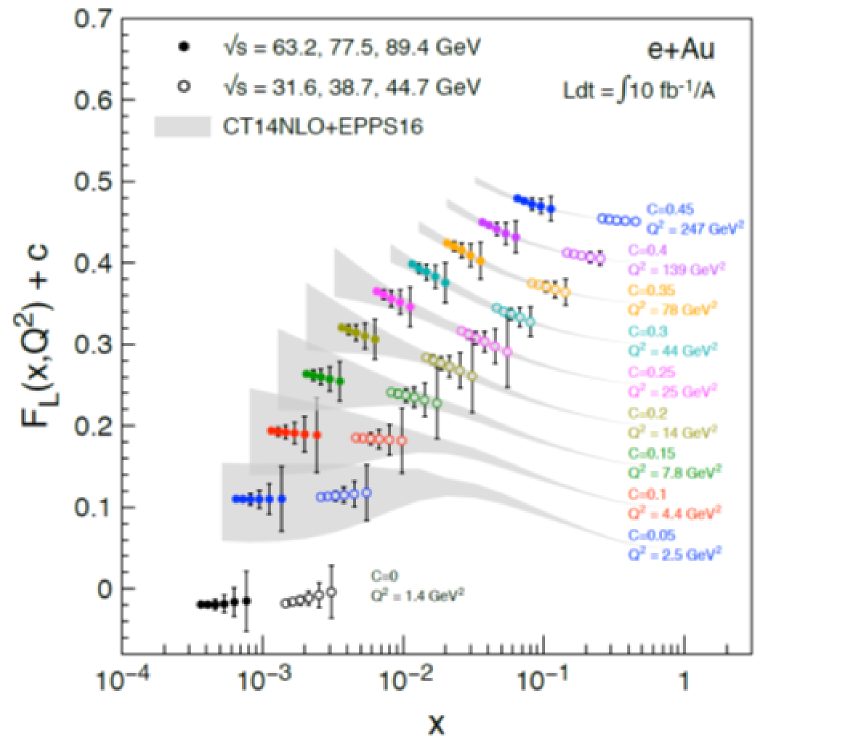


Projection for possible EIC heavy flavour data.

- Inclusive eA scattering measurements

arXiv:1708.01527

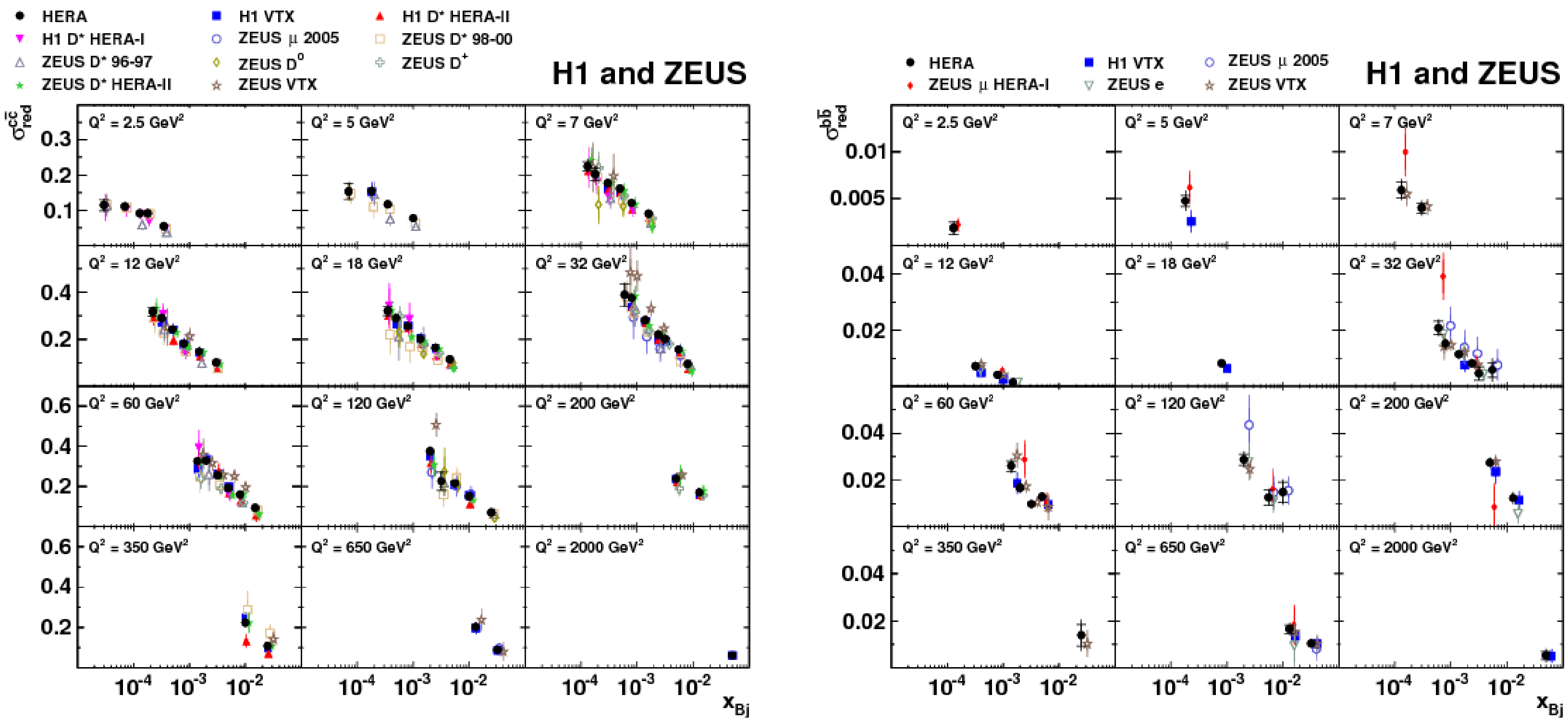




$$\sigma_{\rm red} = F_2 - \frac{y^2}{Y_+} F_L$$

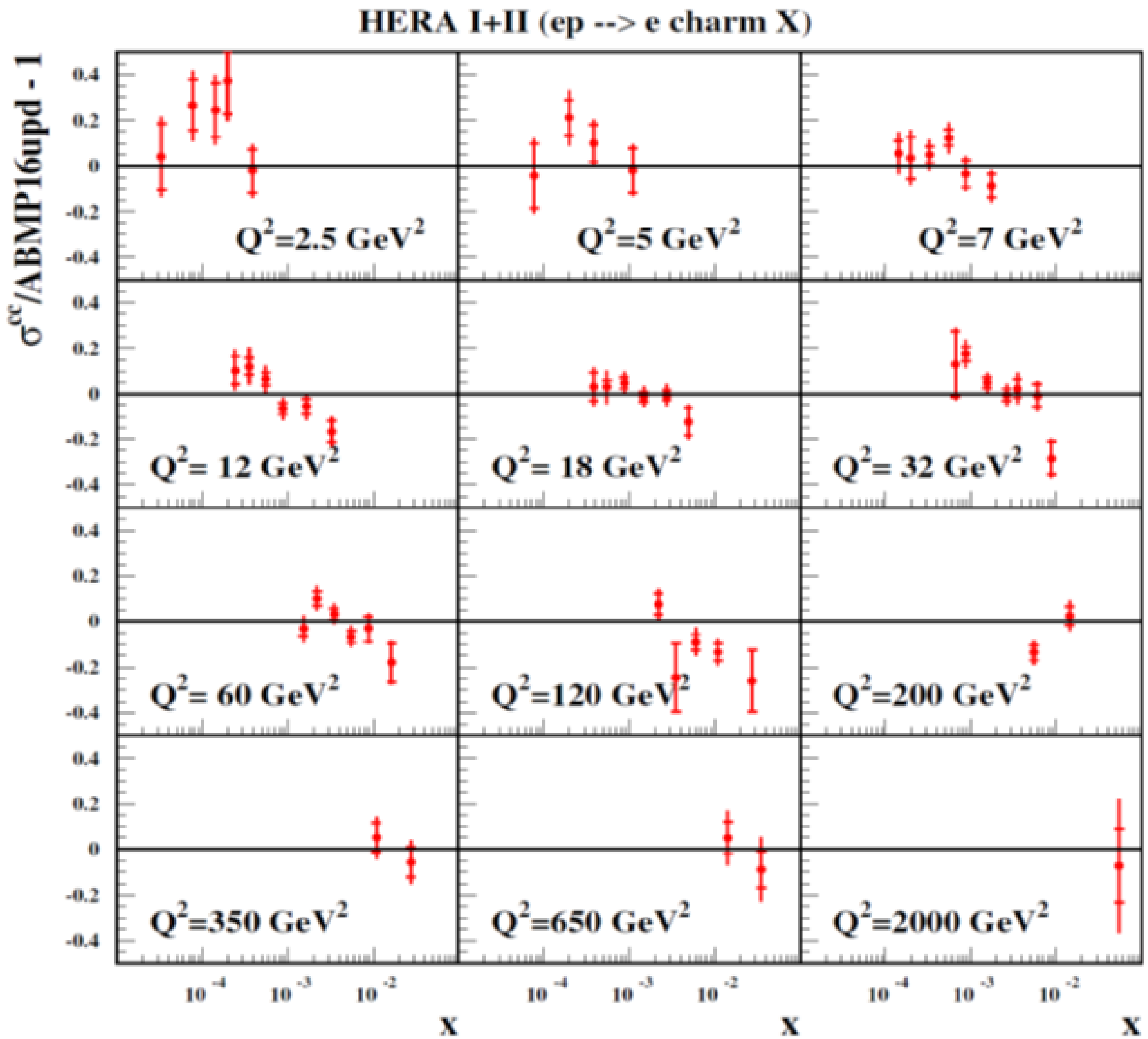
$$\left(\frac{d^2\sigma}{dx\,dQ^2}\right) = \frac{2\pi\alpha^2 Y_+}{xQ^4}\left(F_2 - \frac{y^2}{Y_+}F_L\right)$$

Up to 40% of inclusive cross section is from heavy flavours, mainly charm (EPJC 78 (2018) 6, 473).



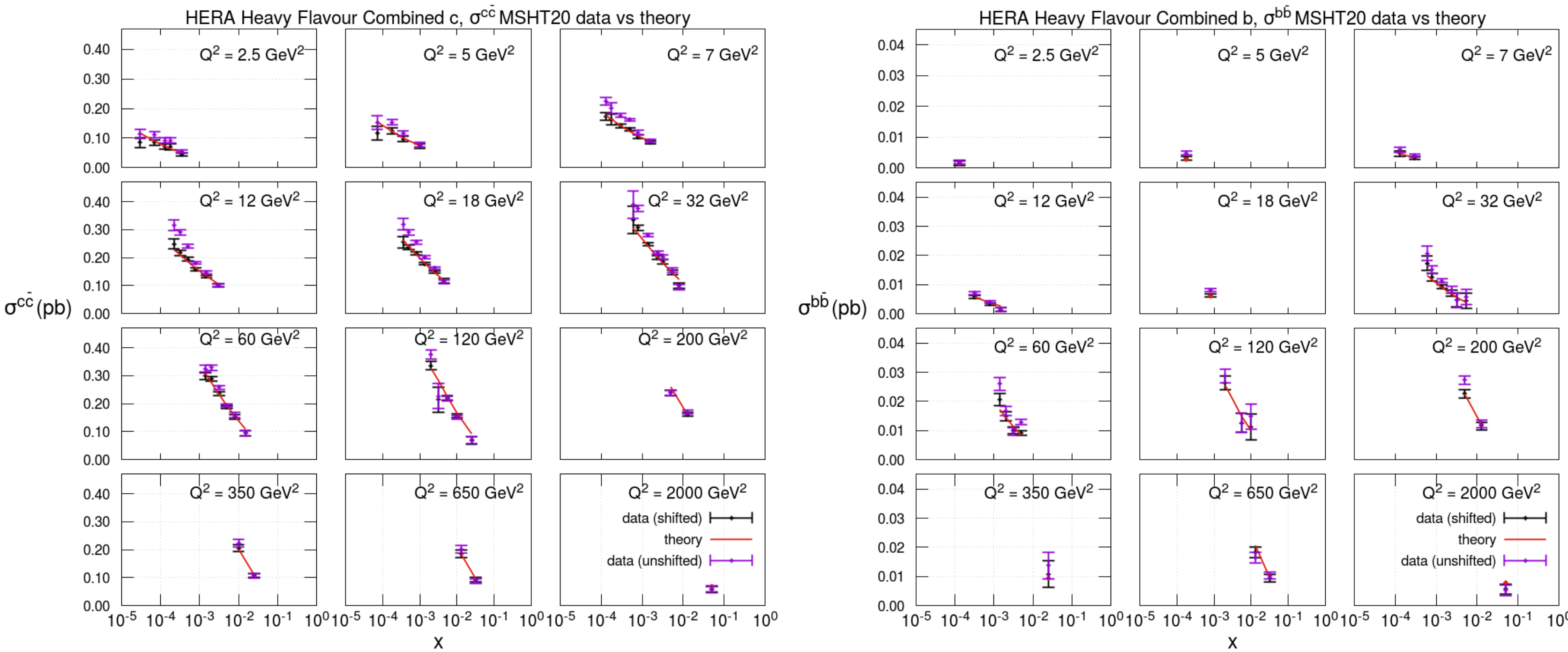
Must fit taking into account contribution to total σ and also directly fit heavy flavour cross section.

ABM charm fit (1909.03533)



Fit not bad, but slope with x not steep enough at low x, Q^2.

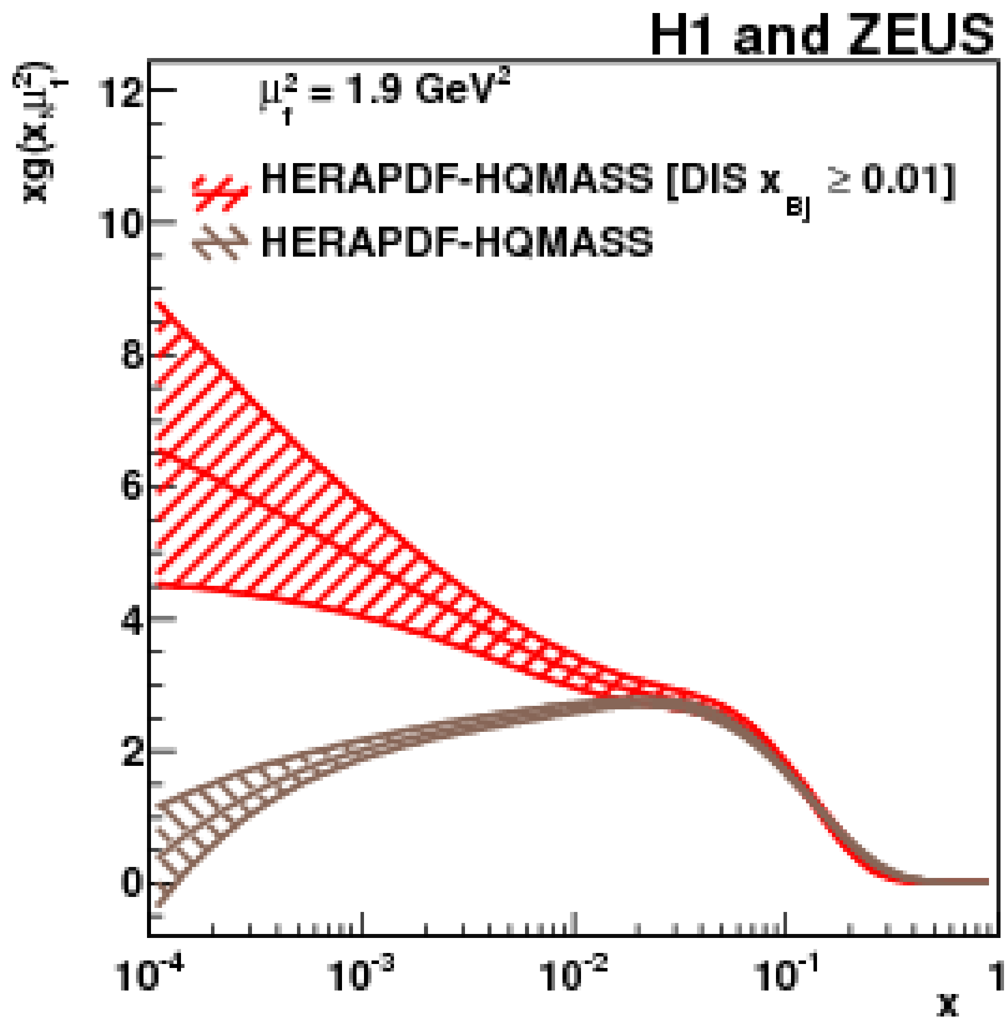
MSHT heavy flavour fit



Similar issue with fit, total $\chi^2 \approx 130/79$. Similar in other fits and comparisons, not really a FFNS – GMVFNS difference.

Tensions between inclusive structure function data and heavy flavour.

Latter prefers steeper gluon – (EPJC 78 (2018) 6, 473).



The EIC will get into this range where tension is seen.

Intrinsic charm

Formally of higher twist, i.e. $\mathcal{O}(\Lambda^2/m_c^2)$.

Proposed that it could be enhanced at high x by Brodsky et al in 1983.

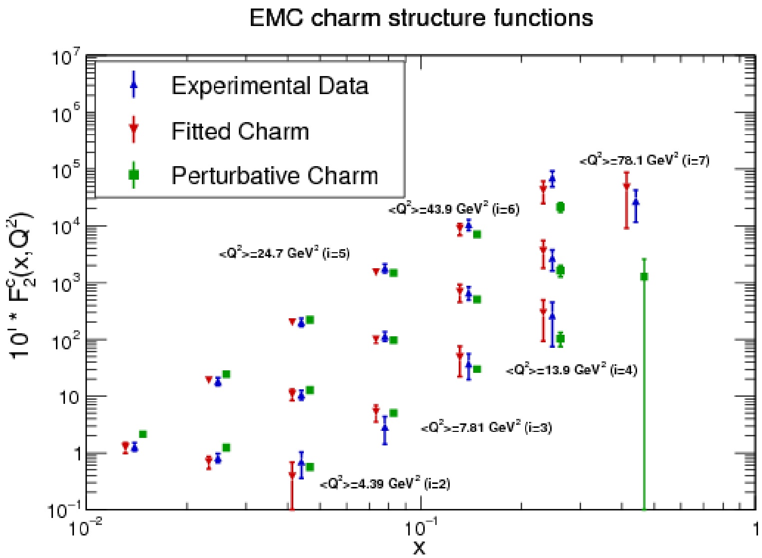
$$\hat{c}(x) = Ax^2[6x(1+x)\ln x + (1-x)(1+10x+x^2)]$$

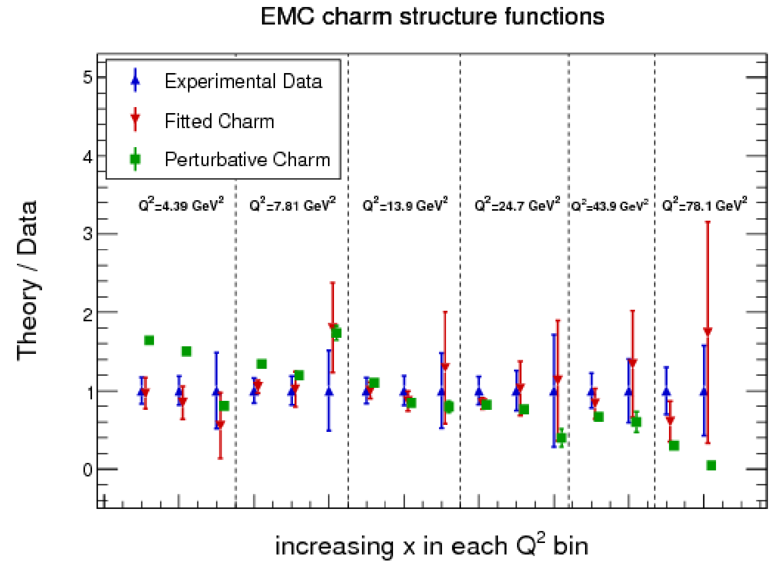
Rather definite form predicted. Enhancement at high x.

Additional issue of unknown higher order corrections to boundary condition for charm PDF at low Q^2.

Also leads to non-zero charm input at low Q^2 but entirely perturbative – not intrinsic charm.

In some NNPDF fits try fitting old EMC data (NPB 213 (1983) 31-64).





Clearly prefers supression at smaller x, and also some enhancement as $x \rightarrow 1$.

Consistent with suggestions from LHC data sensitive to flavours (W, Z).

Note however, EMC data relied on large corrections using LO theory generators and extremely basic PDFs. Significant question mark.

MSTW tried fitting EMC data. Overshoot lower x data even at NLO with dynamical charm.

High-x intrinsic charm with modified coefficient functions, $m_c^2 \to m_c^2 + \Lambda^2$, at threshold works ok.

At low Q^2 and W^2 we likely need to worry about nonperturbative or higher twist effects beyond just that of intrinsic charm.

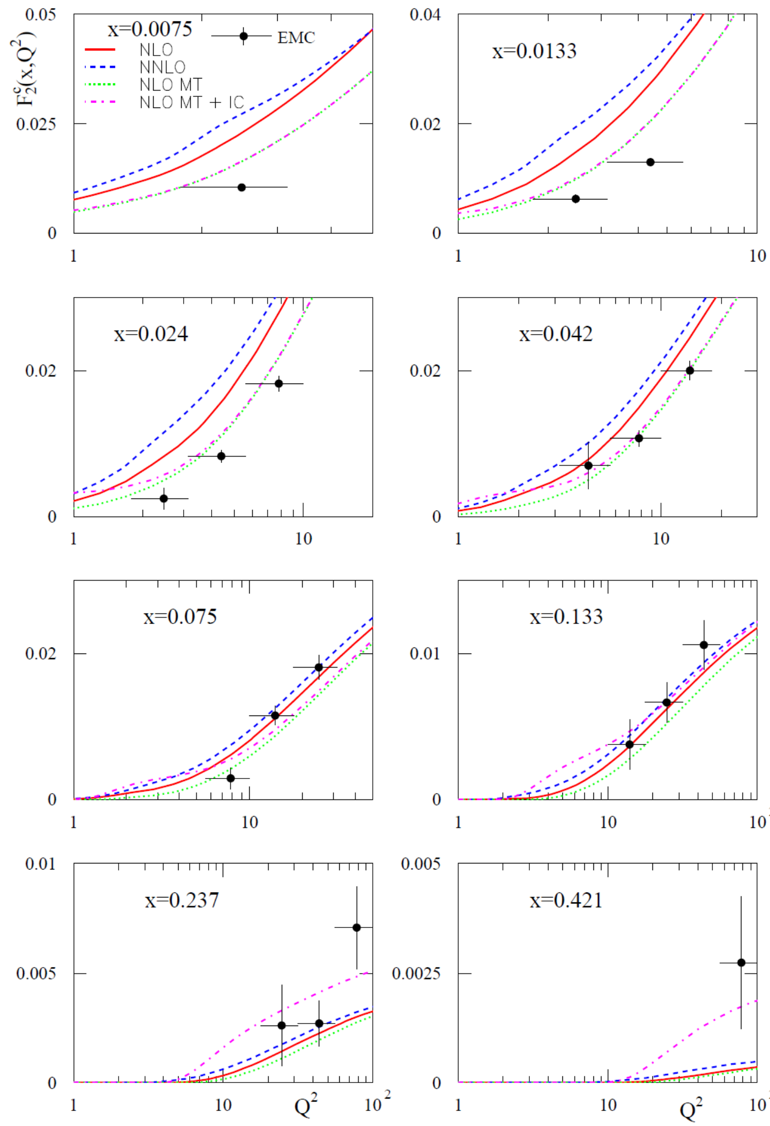
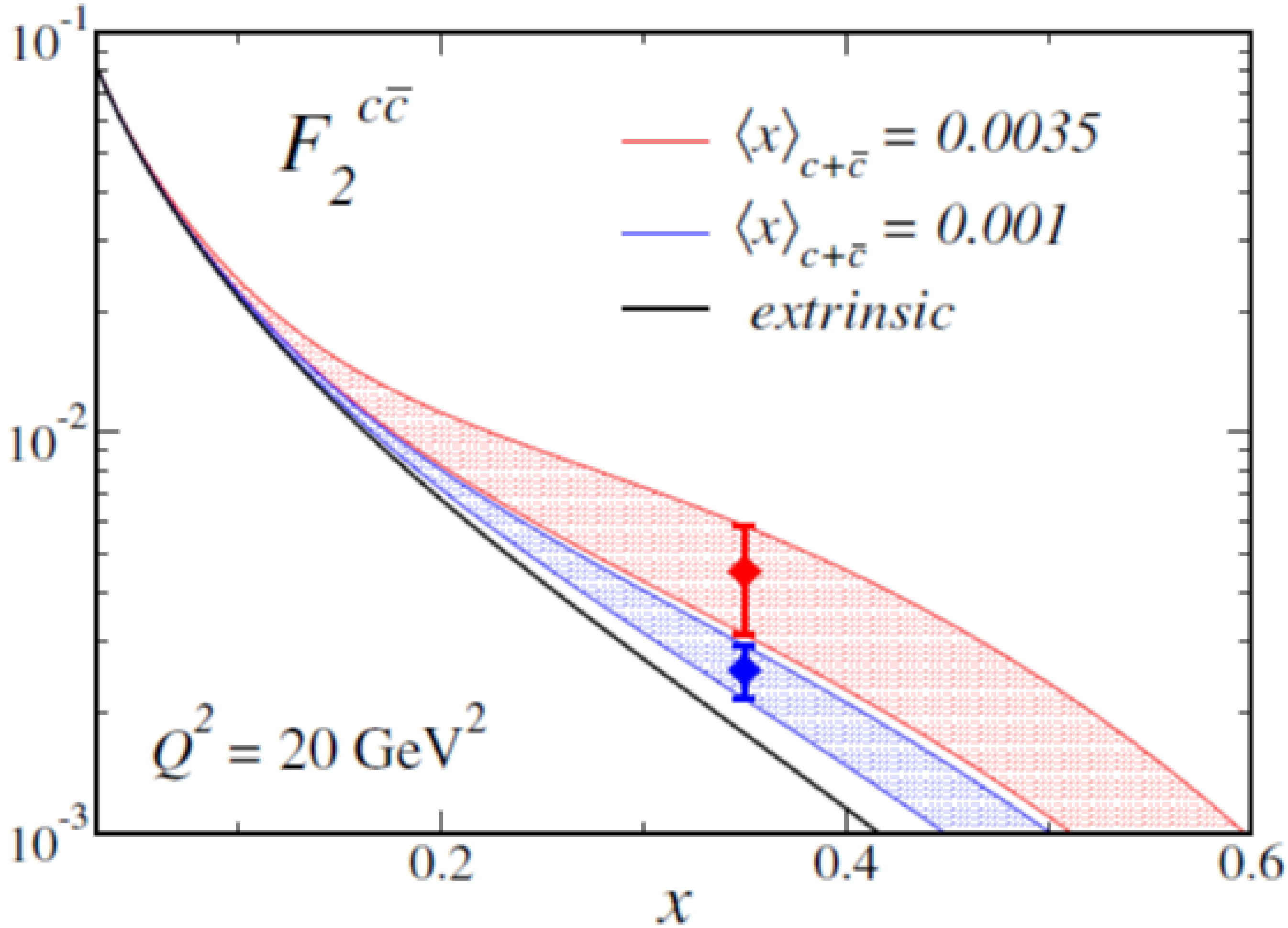


Figure 39: The comparison of the EMC charm data [165] to our predictions at NLO and NNLO. MT stands for the modified threshold approach and IC stands for inclusion of intrinsic charm.



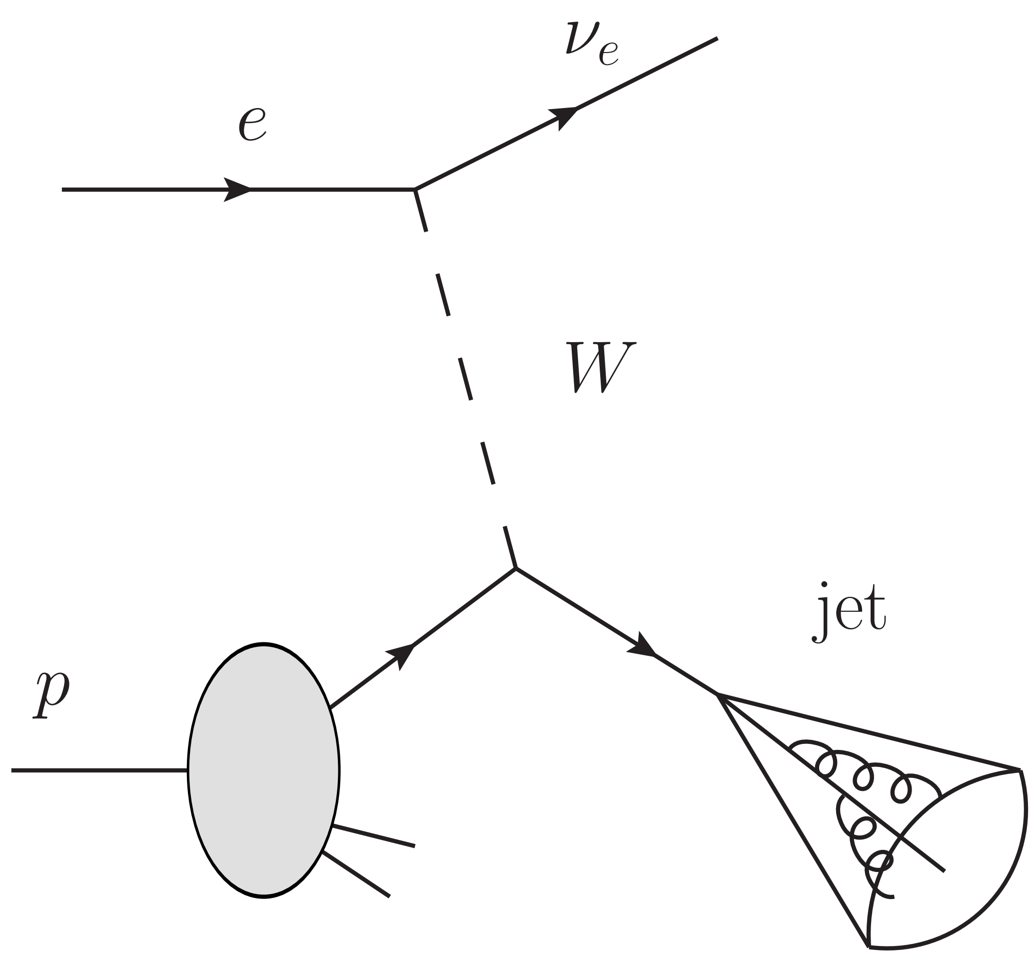
YR contains precision needed to get a test at high x. Theoretically complicated.

High-x Strange Quark.

There is also the possibility of looking at the less well know strange quark via charm quark jets.

Requires dealing with fragmentation (but so do some current methods at some level).

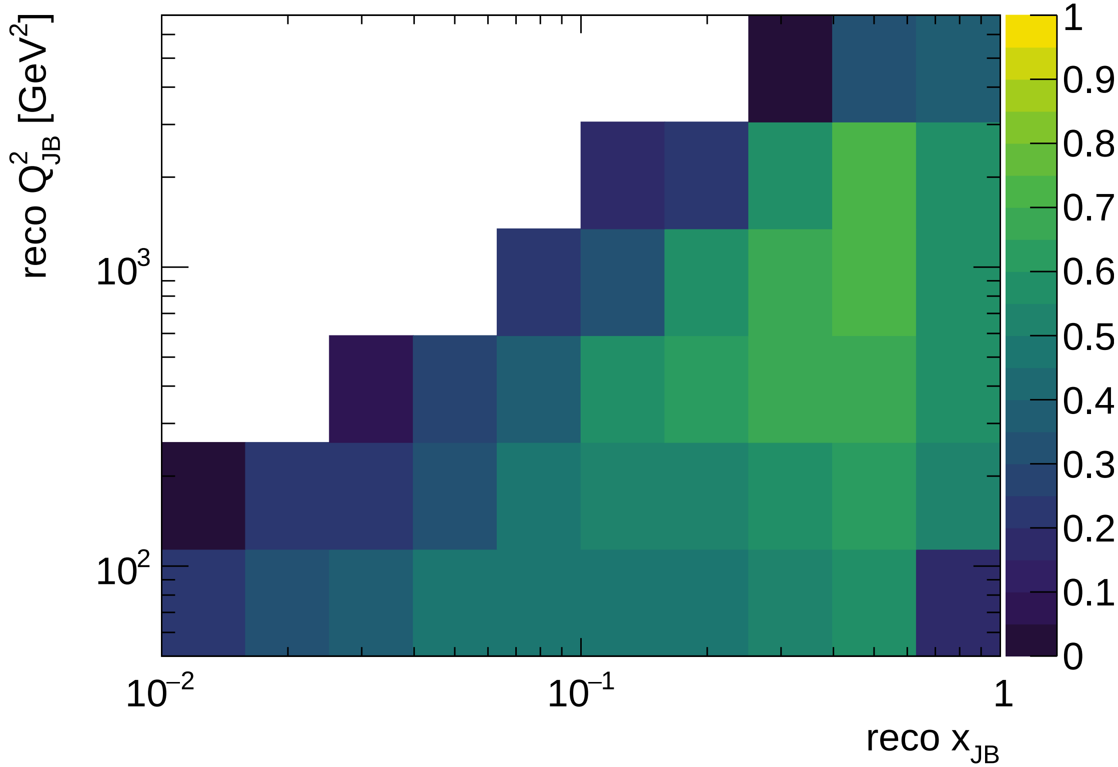
Similar type of data from neutrino scattering on iron targets from CCFR/NuTeV already used.



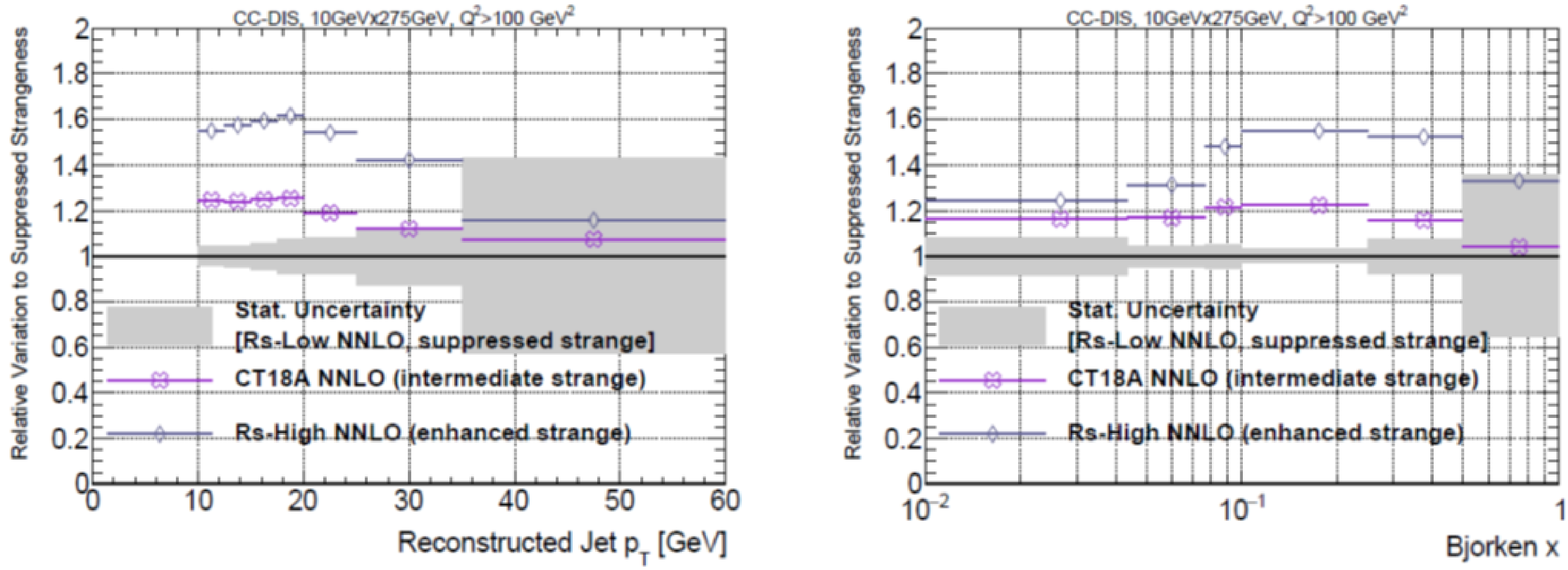
Plot from `https://arxiv.org/abs/2006.12520`.

From the same CT study one can see the likely x and Q^2 range likely to be covered.

Higher x than the main constraints from the LHC, and from the most precise dimuon measurements.



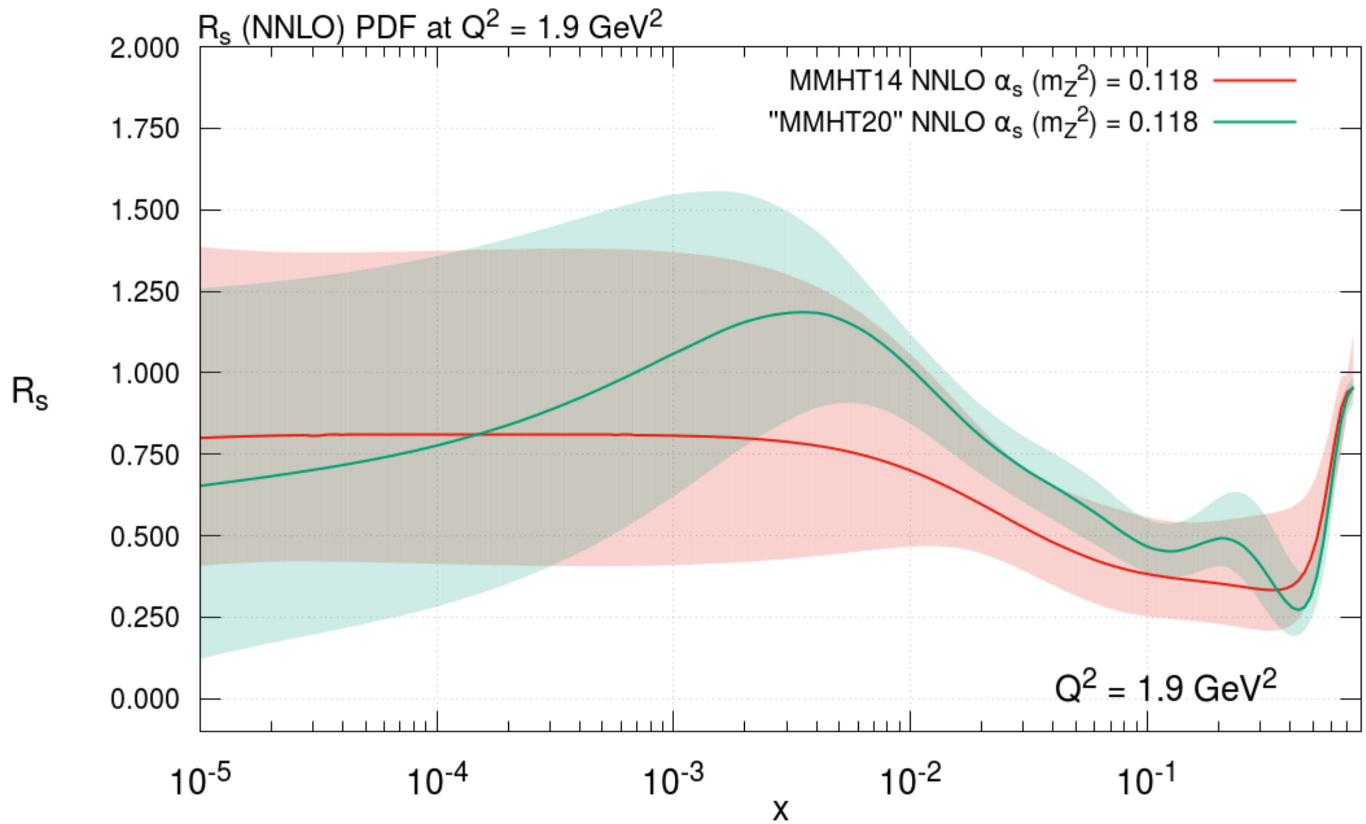
Plot from https://arxiv.org/abs/2006.12520.



Comparison between precision and results using different strange models.

New PDFs compared to MMHT2014 at NNLO.

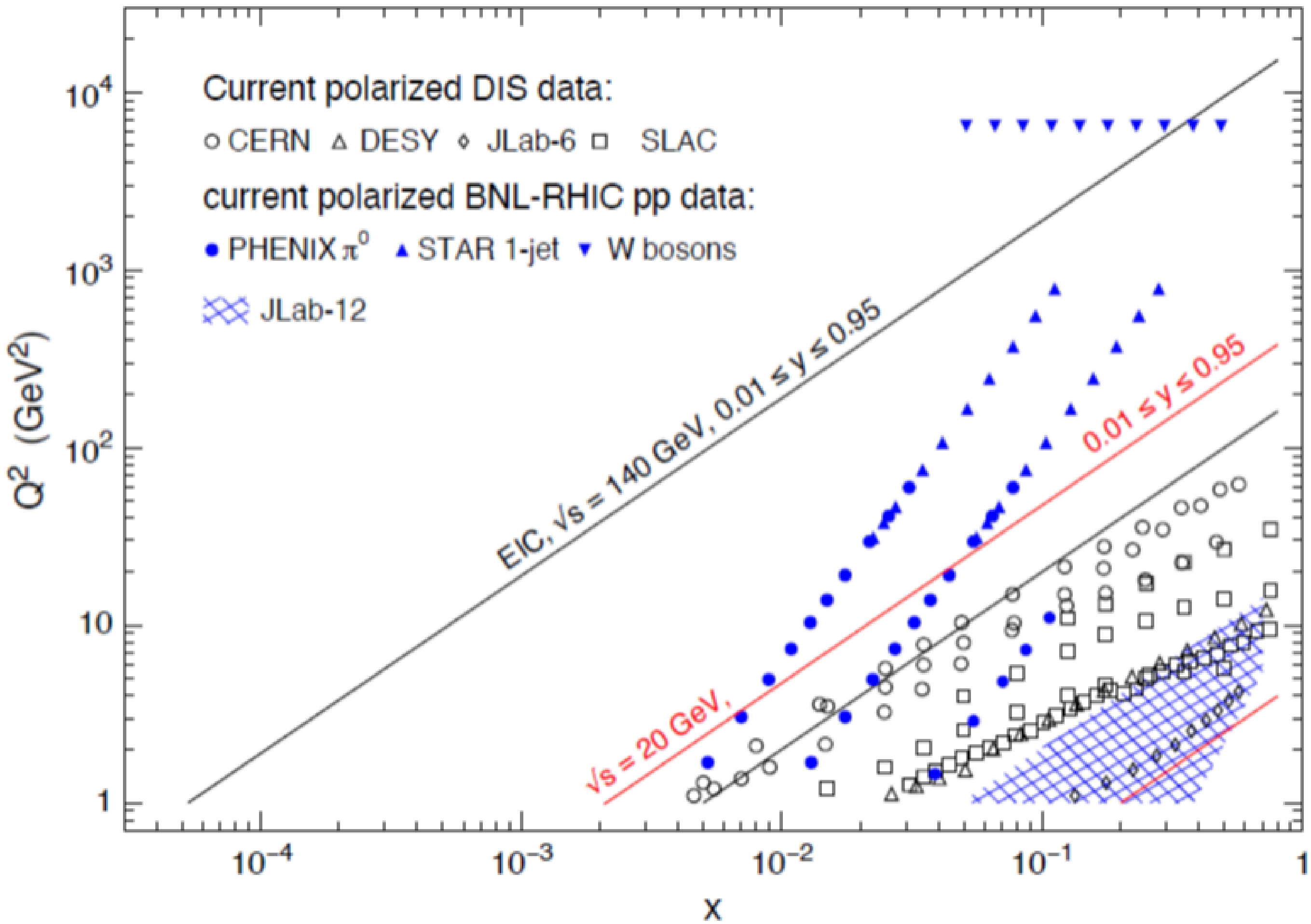
Reminder about tensions in current fits.



Currently an increase in the strange quark below $x = 0.1$ due to W, Z data (mainly ATLAS 7, 8 TeV).

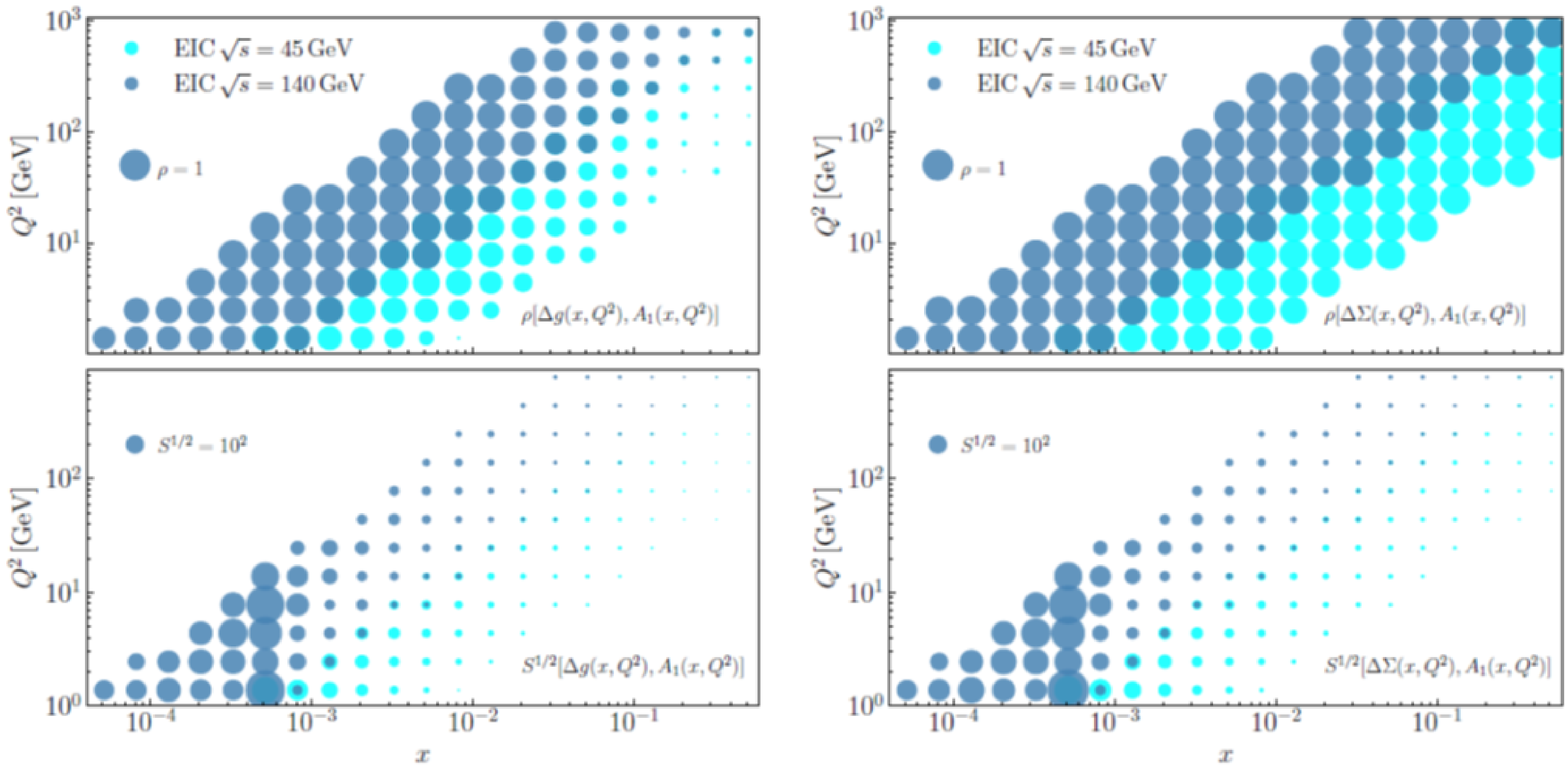
Still significant uncertainty, and some tension, at higher x. Important constraint from the EIC possible.

Polarized PDFs.



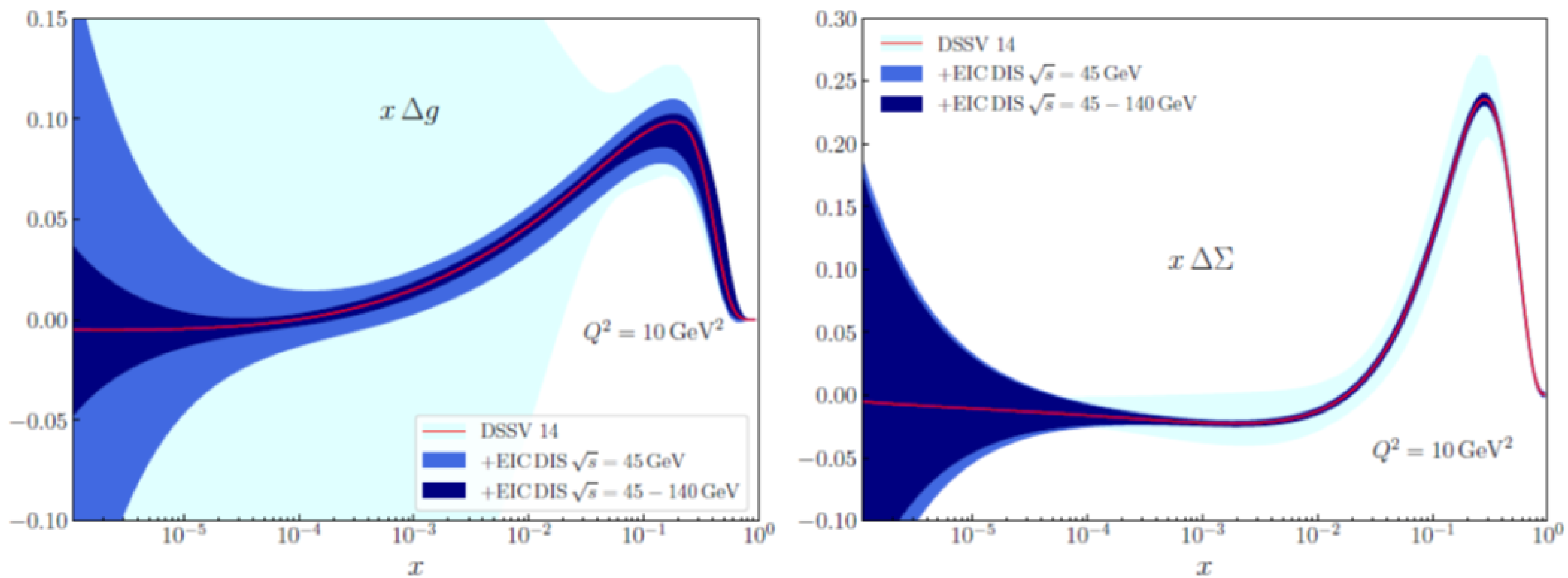
Very significant expansion of coverage to small x, as well as higher Q^2 at high x.

Very useful visualization of correlation btween data and the PDFs that are constrained PhysRevD.102.094018, Borsa et al.



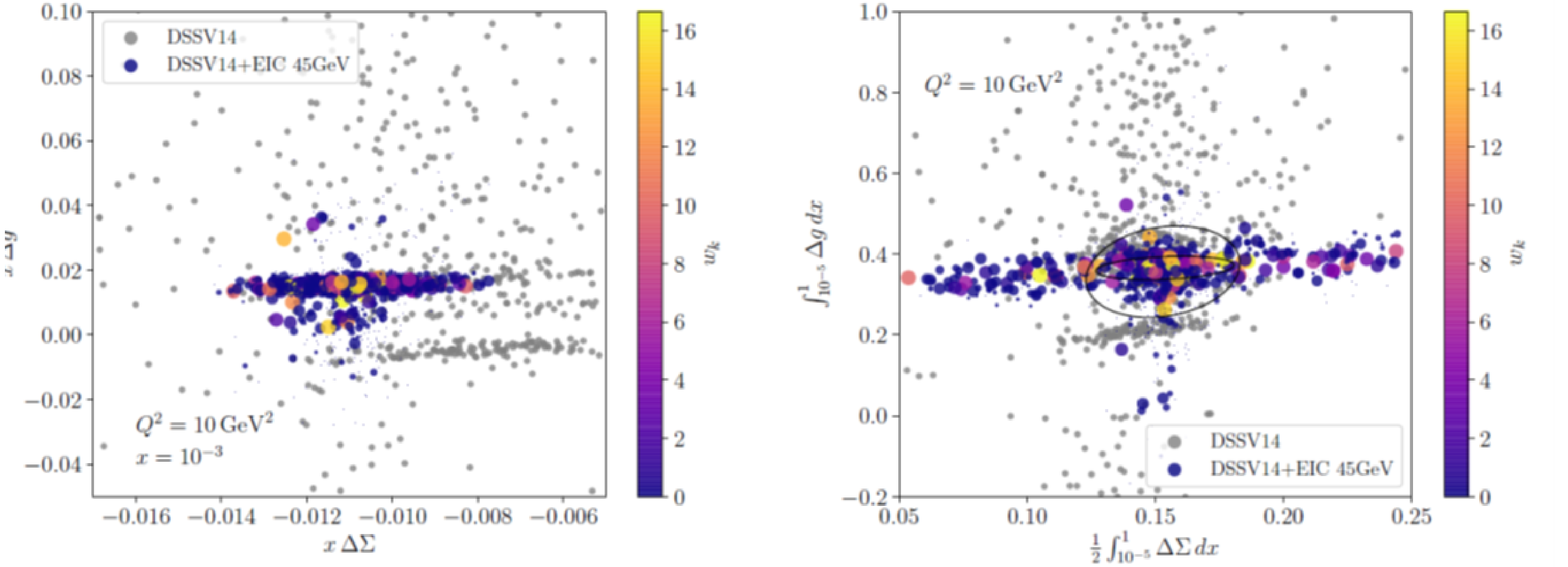
Fairly direct relationship for quarks, but increasing at smaller x for the gluon since it comes from evolution effects $(\partial g_1(x, Q^2)/\partial \ln Q^2) \sim -\Delta g(x, Q^2)$.

Leads directly to the below improvements in PDFs.



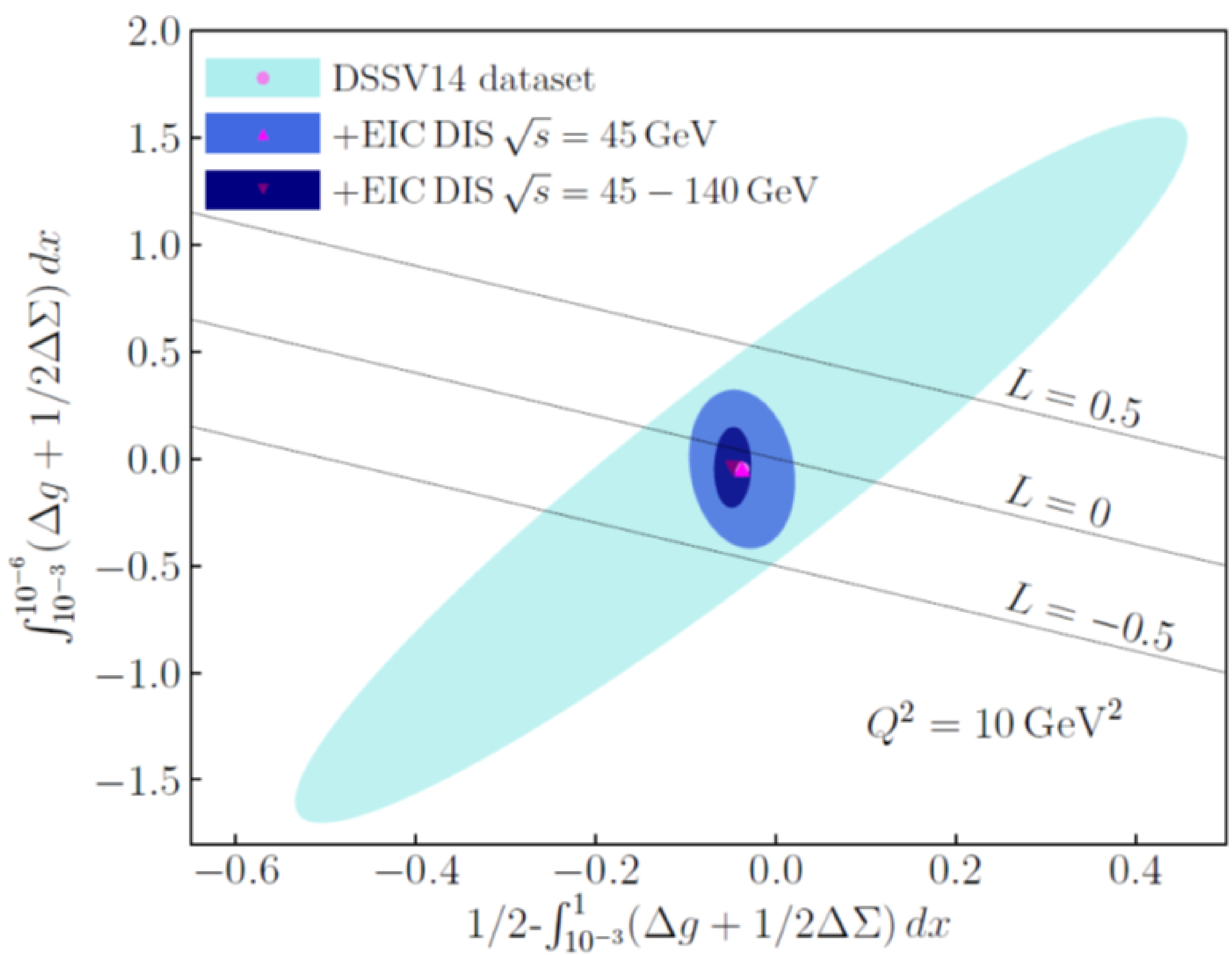
Slight caveat, need care that parameterization flexibilty consistent with precision of data and pseudodata – PDFs have 5 parameters here, probably sufficient.

A direct example of how PDF replicas are selected and focussed by the potential new data.

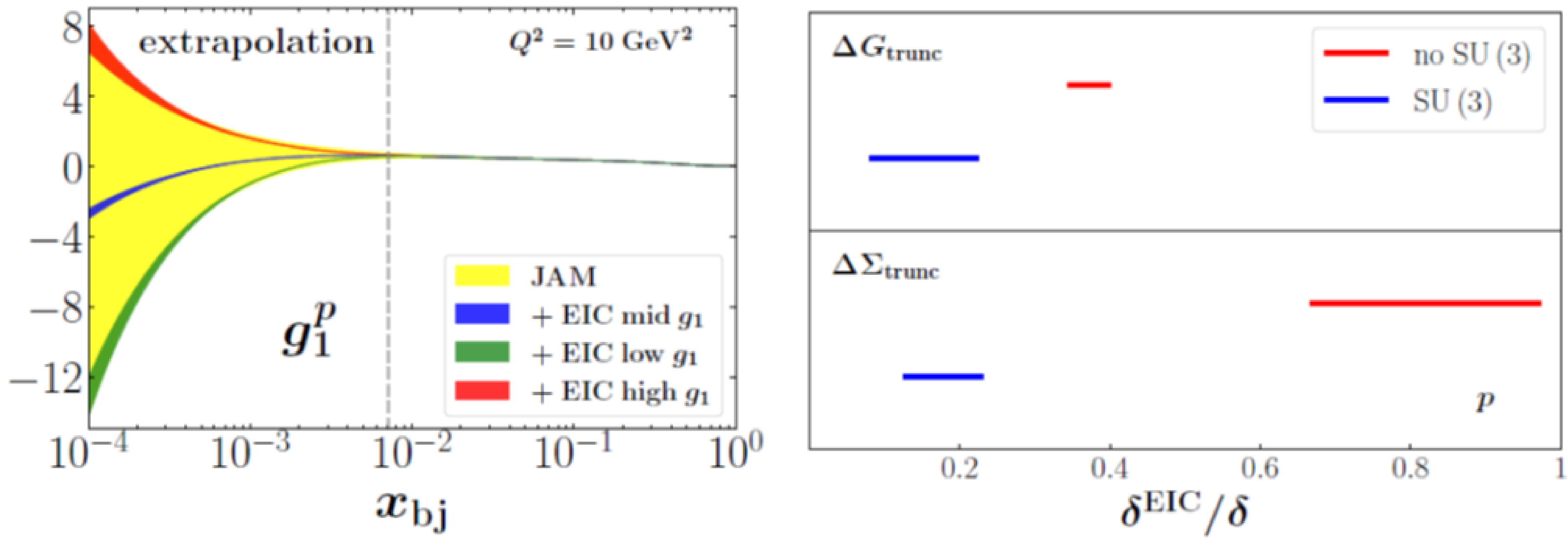


Distinct bunching, but also variation of weight within reduced set of PDFs.

Related to this is the possible impact on the knowledge of the sum rule.



Of course the new central PDF depends on exactly where the correct physics lies, not necessarily the centre of the current best fit Phys.Rev.D 104 (2021) 3, JAM collaboration...



Also, some dependence on whether $SU(3)$ symmetry relations to baryon decay constants are imposed or not.

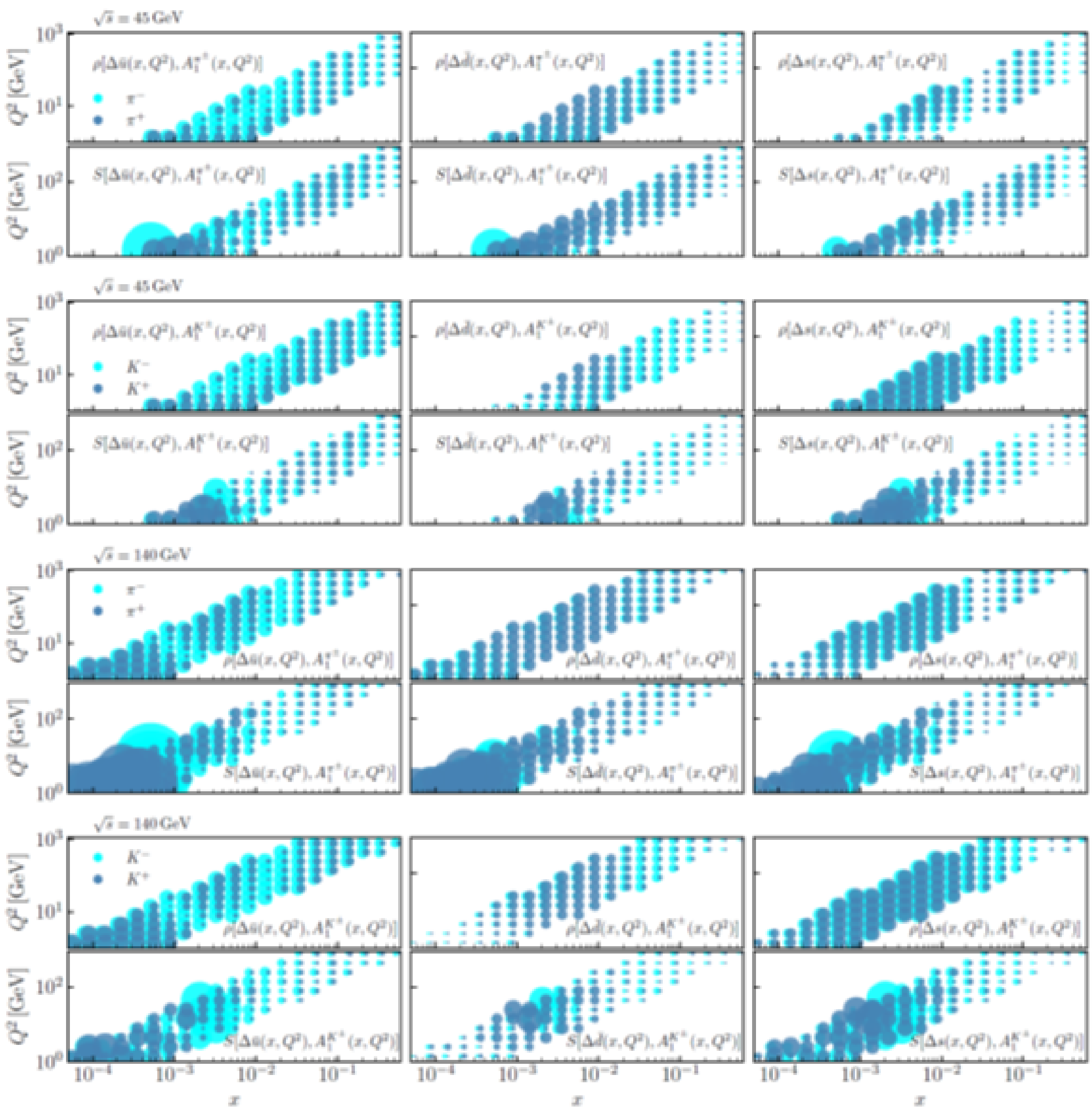
$$\Delta\Sigma_u^1 - \Delta\Sigma_d^1 = (F+D)[1+\epsilon_{SU(2)}],$$

$$\Delta\Sigma_u^1 + \Delta\Sigma_d^1 - 2\Delta\Sigma_s^1 = (3F-D)[1+\epsilon_{SU(3)}],$$

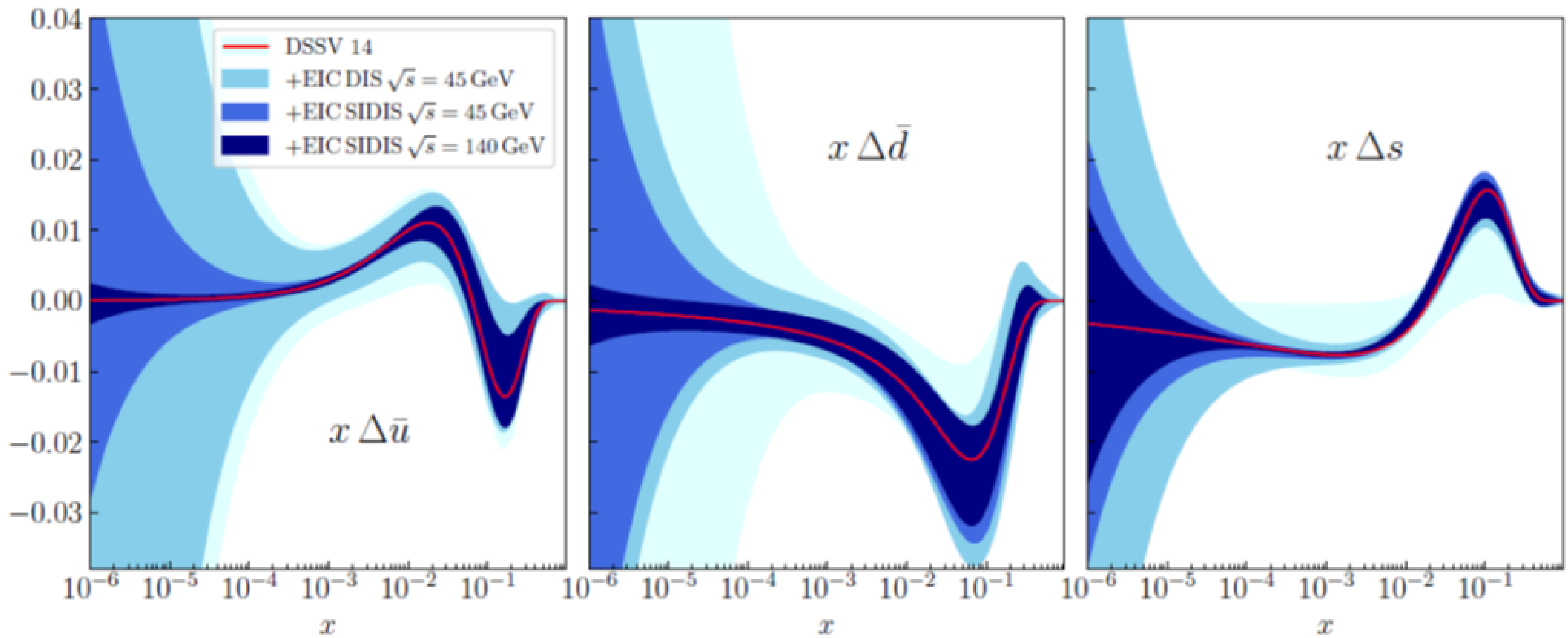
$$\Delta\Sigma_i^1 = \int_0^1 (\Delta f_i + \Delta\bar{f}_i)\,dx,$$

$$(F+D) = g_a = 1.269(3), (3F-D) = a_8 = 0.586(31).$$

Additional direct constraints by use of SIDIS data PhysRevD.102.094018, Borsa et al.



Also leads to large potential improvements in PDFs.

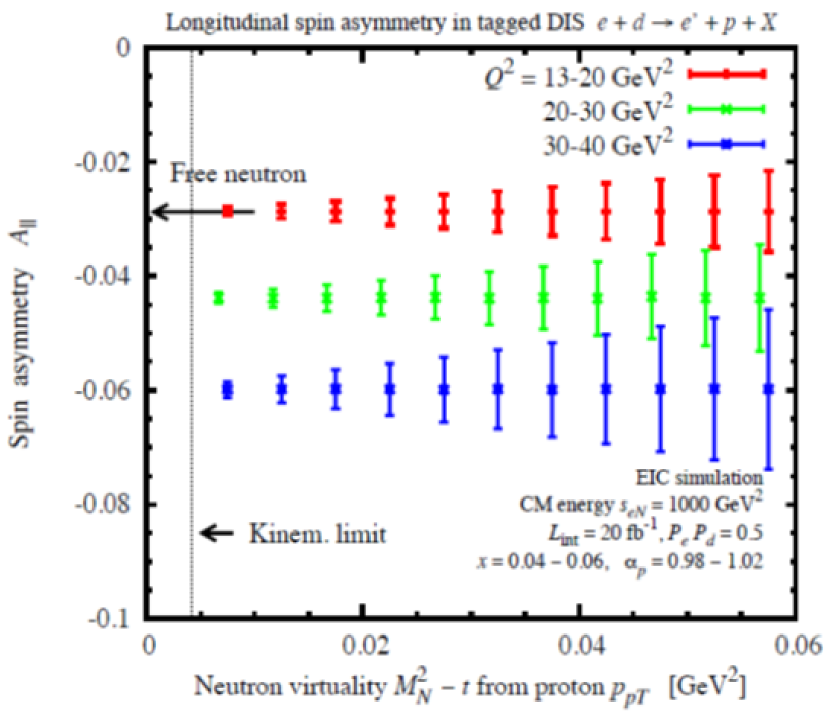


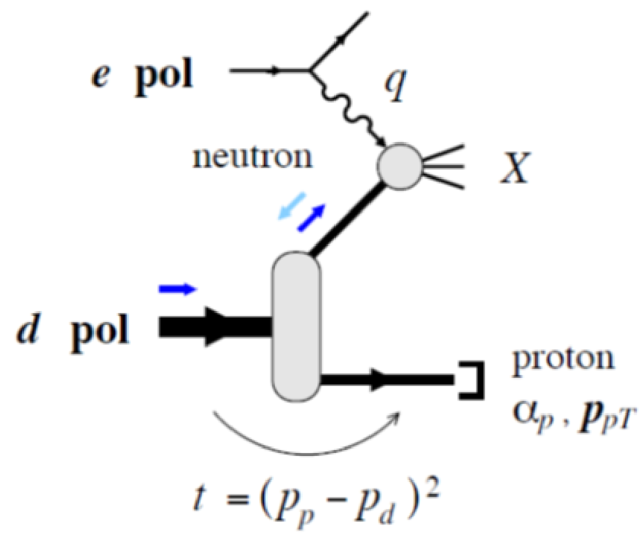
In this case particularly in the flavour decomposition.

As for unpolarised data some extra sensitivity may be acheived probing neutron PDFs in d or He^3 scattering.

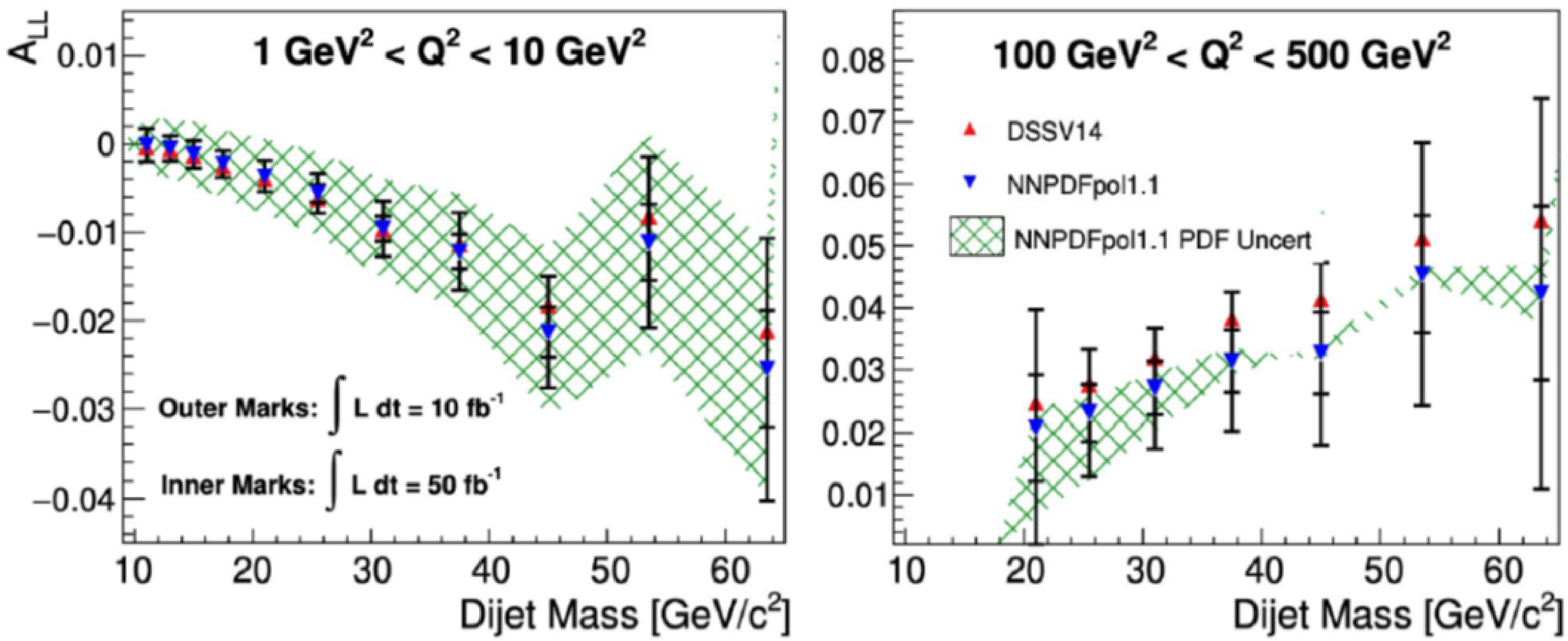
Helps to separate singlet $g_p^1 + g_n^1$ and nonsinglet $g_p^1 - g_n^1$, and hence the gluon as well as flavours.

Again precision can be improved by by tagging of the neutron.





Direct constraints on gluon polarization

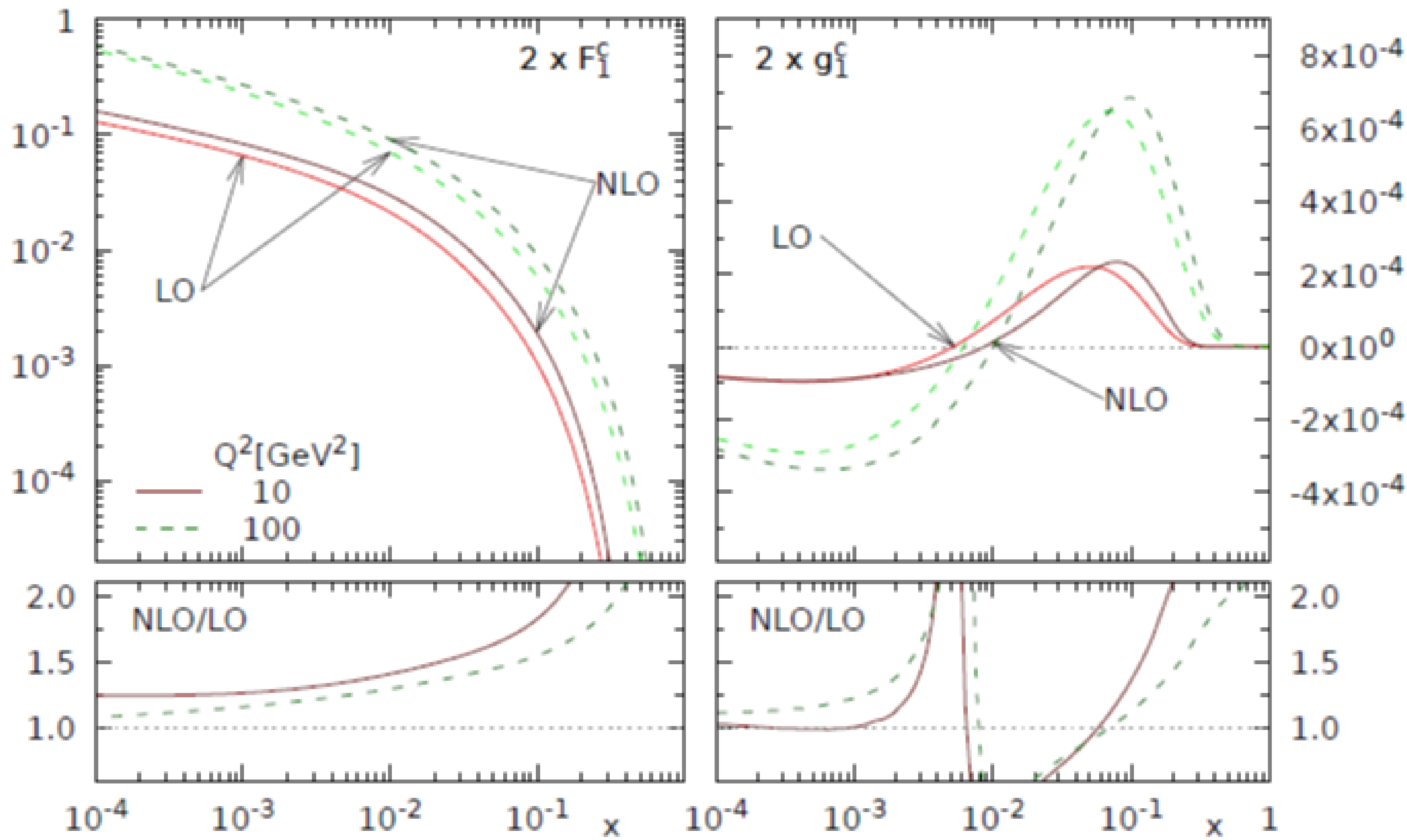


Data type already used in polarised fits, and for unpolarised PDFs –dijet data Page et al. PhysRevD.101.072003.

In DIS sensitive to gluon from gluon photon fusion.

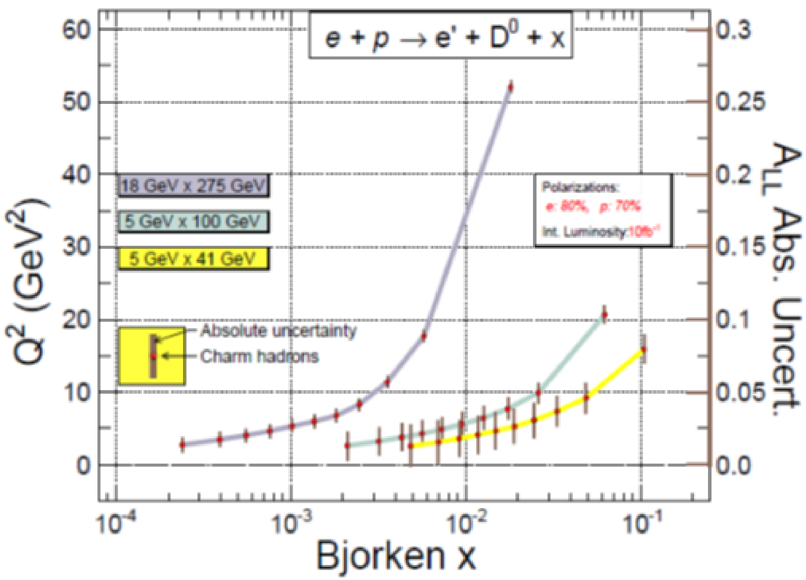
Low-Q^2 data provides good potential constraint.

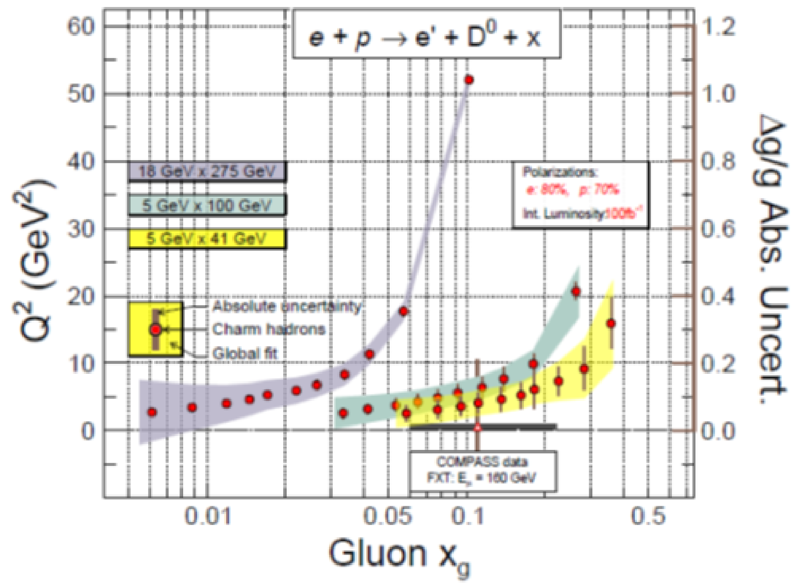
Similar process – corrections to polarised charm production know at NLO and (relatively) under control Hekhorn and Stratmann, Phys. Rev. D 98 (1) (2018) 014018.



More directly gluon sensitive from again photon-gluon fusion.

Potential constraining data here from meson production Adolph et al. Phys. Rev. D 87 (5) (2013) 052018.





Currently only studied at LO.

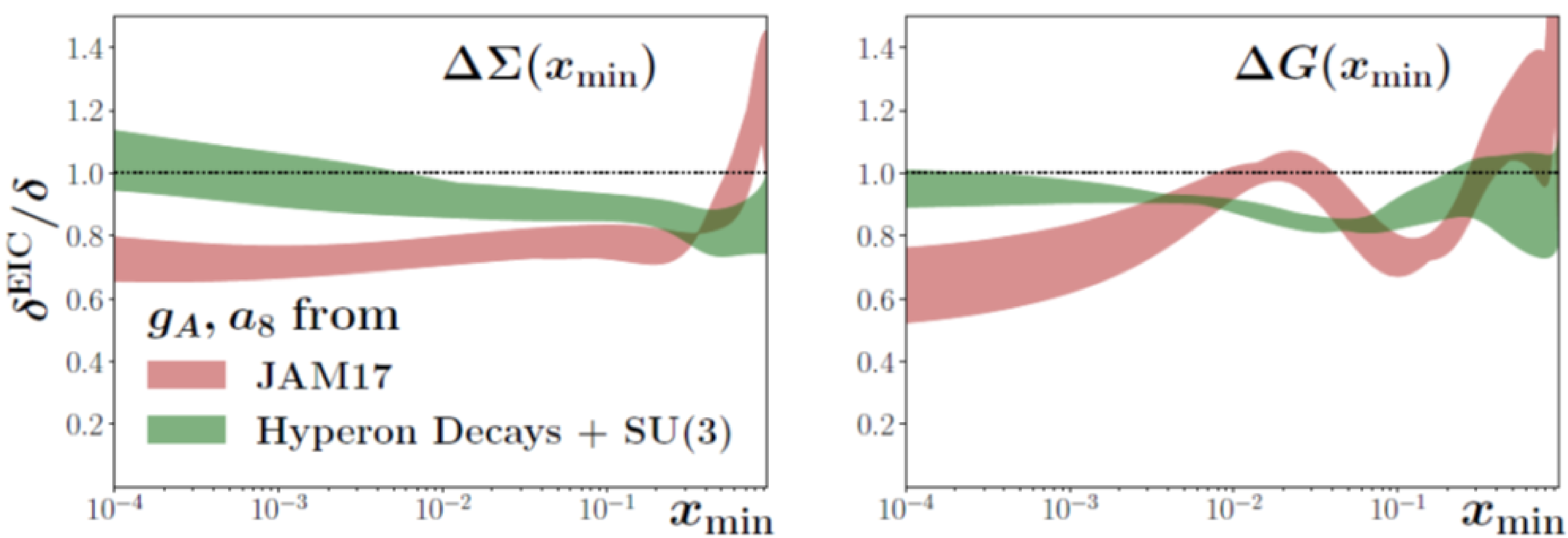
Parity Violation.

$$\frac{\sigma(ep^{\uparrow}) - \sigma(ep^{\downarrow})}{\sigma(ep^{\uparrow}) + \sigma(ep^{\downarrow})} \propto g_A^e Y^- g_1^{\gamma Z} + g_V^e g_V^e Y^+ g_5^{\gamma Z},$$

g_V^e is very small, and $g_5^{\gamma Z} \propto \sum_q \Delta(q - \bar{q})$, which vanishes at small x.

Therefore depends on $g_1^{\gamma Z} \approx \sum_q e_q g_V^q \Delta(q + \bar{q}) \approx 1/9 \Delta\Sigma$.

Good constraint, but again depends on $SU(3)$ symmetry assumptions.



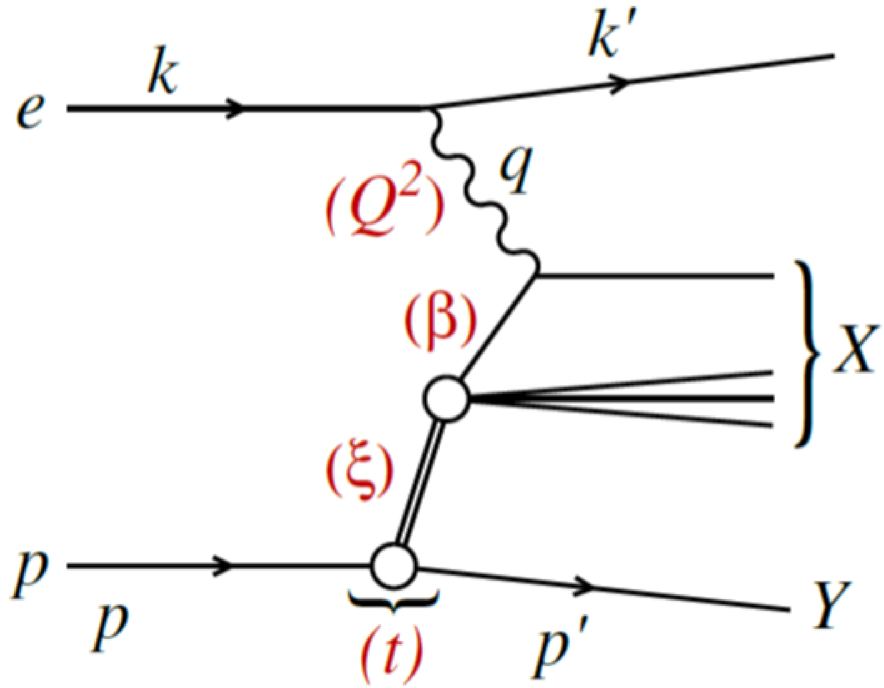
Diffraction

Diffractive events defined by tagged final hadron or large rapidity gap.

Can be triple or quadruple differential.

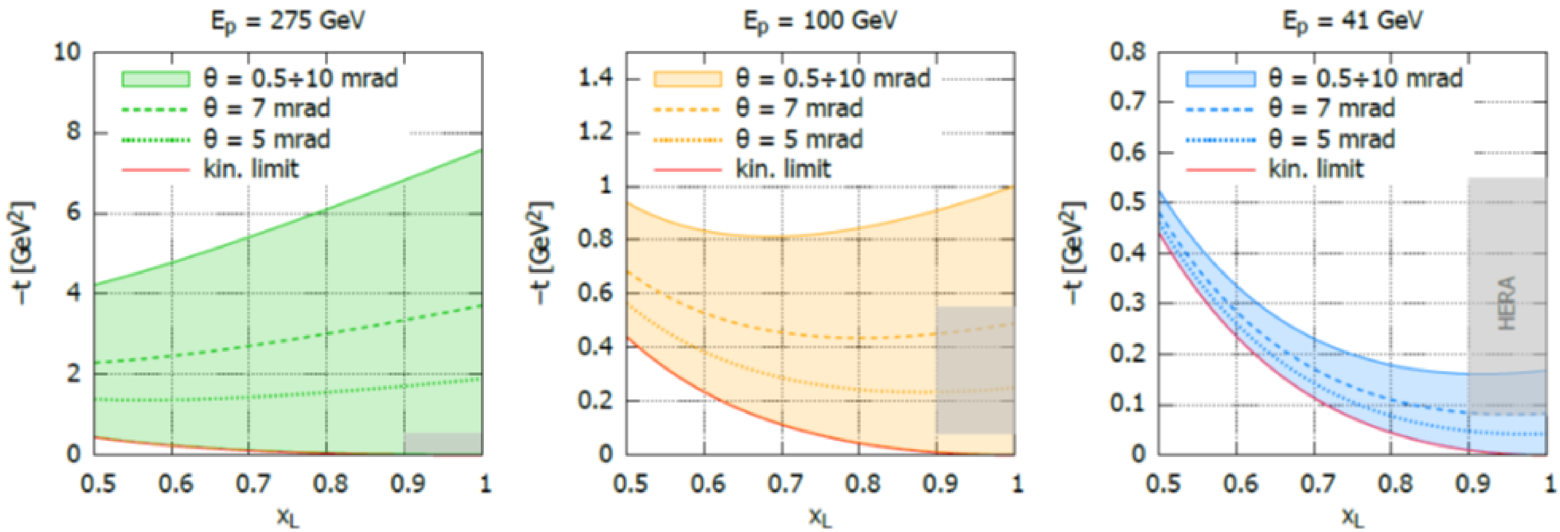
$\sigma_{red}^{D(3)} = F_2^{D(3)}(\beta, \xi, Q^2) - \frac{y^2}{Y_+} F_L^{D(3)}(\beta, \xi, Q^2)$.

$\sigma_{red}^{D(4)} = F_2^{D(4)}(\beta, \xi, Q^2, t) - \frac{y^2}{Y_+} F_L^{D(3)}(\beta, \xi, Q^2, t)$.



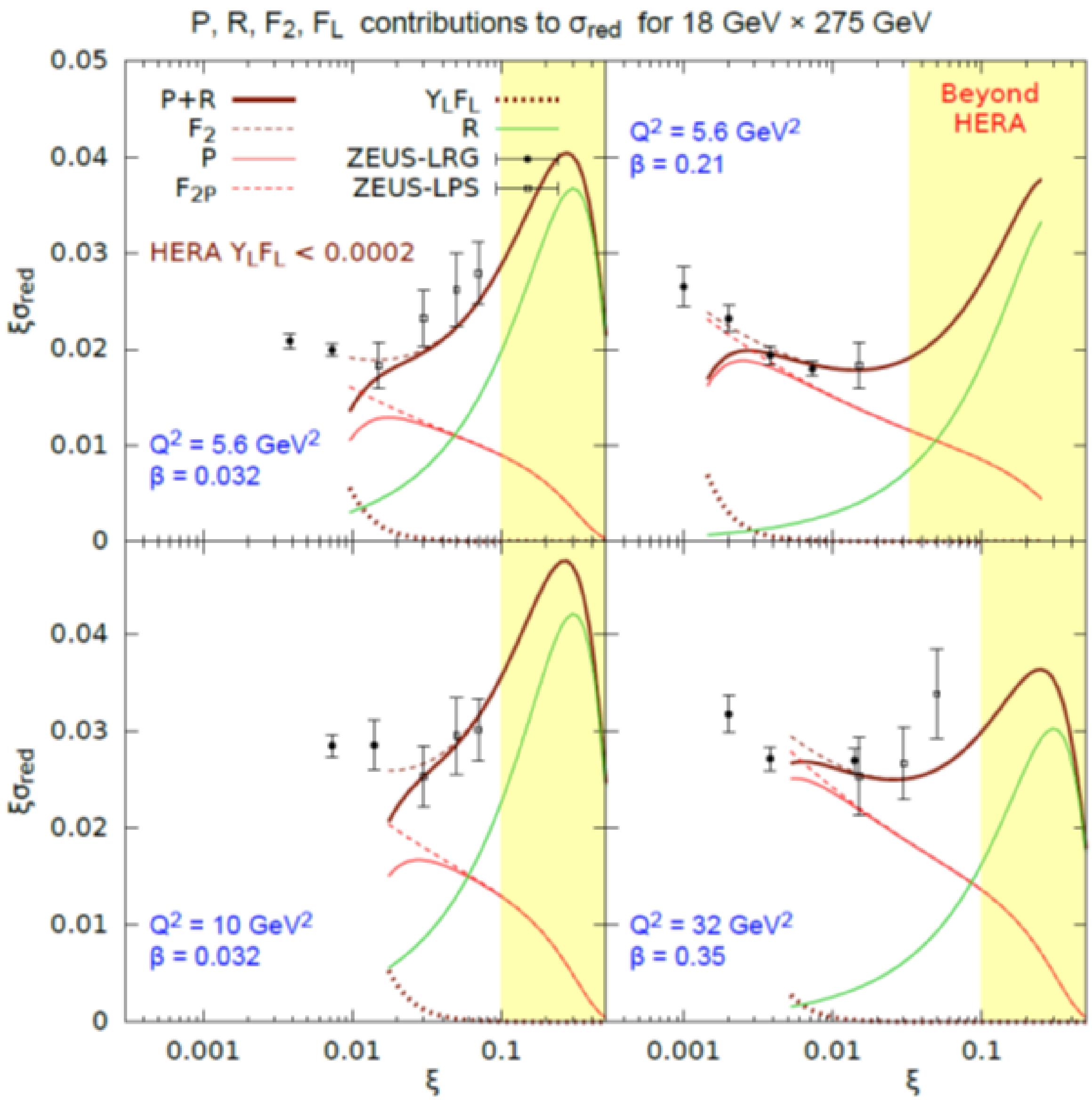
Where $\xi = \frac{Q^2+M_X^2-t}{Q^2+W^2}, \beta = \frac{Q^2}{Q^2+M_X^2-t}, x = \beta\xi$

Normally assumed to factorize into Pomeron(Reggeon) distribution $f_i^{\mathbb{P},\mathbb{R}}(\beta, Q^2)$ and flux factor $f_p^{\mathbb{P},\mathbb{R}}(\xi, t)$.



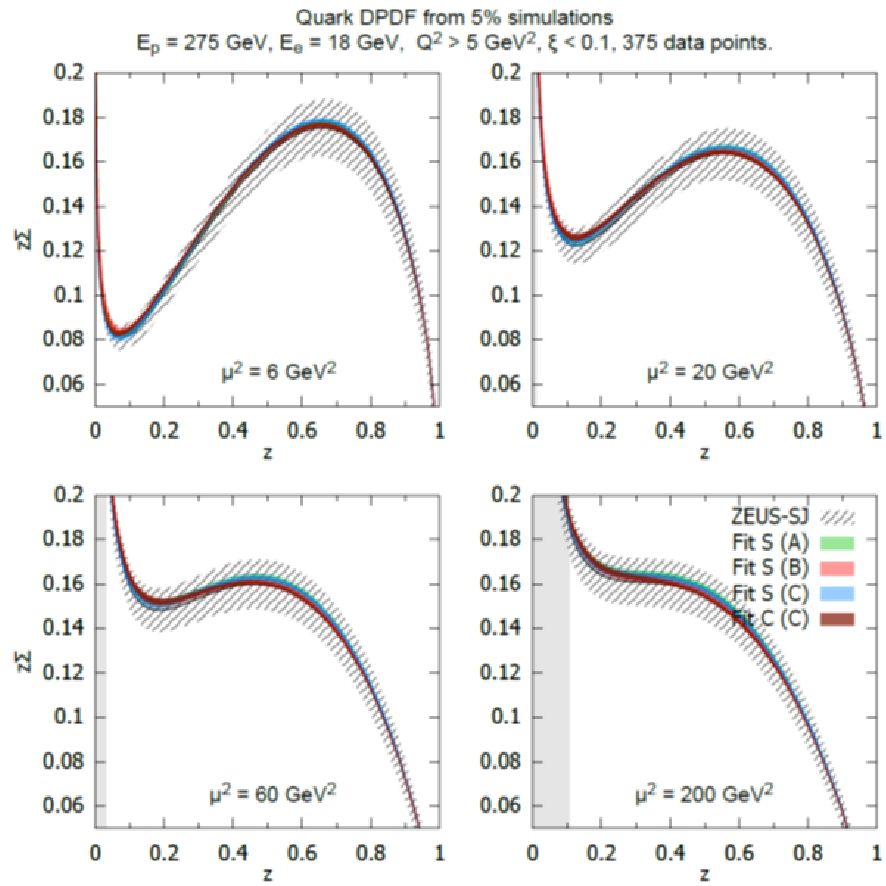
Experimental coverage potentially much better than HERA

Range of t and x_L shown as a function of the small angle acceptance of the final state proton.

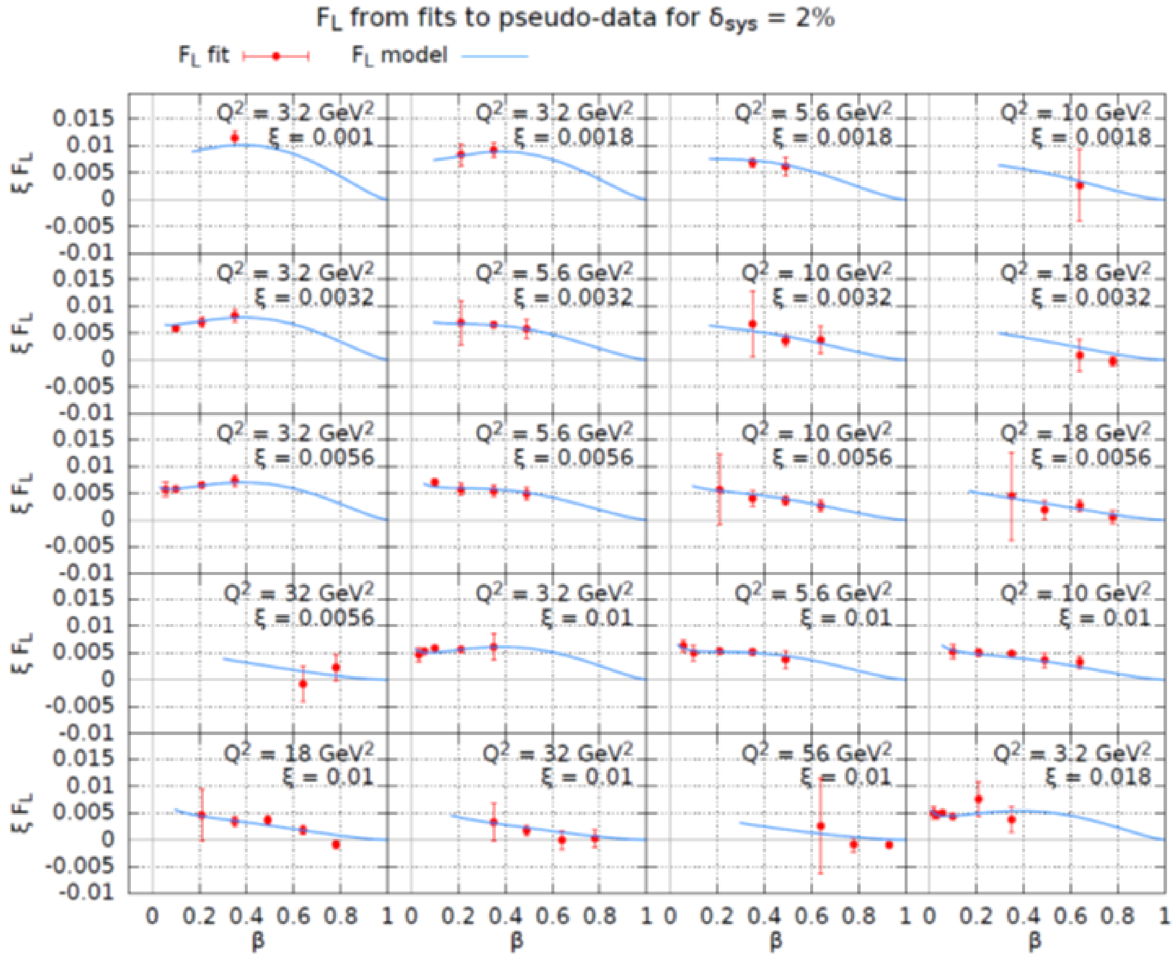


Will allow extension up to much larger ξ than HERA where the Reggeon contribution is far more important.

Example of the possible improvement in diffractive PDFs based on HERA-like parameterizations H1 Eur. Phys. J C 48 (2006) 715, ZEUS Nucl. Phys B 831 (2010) 1.



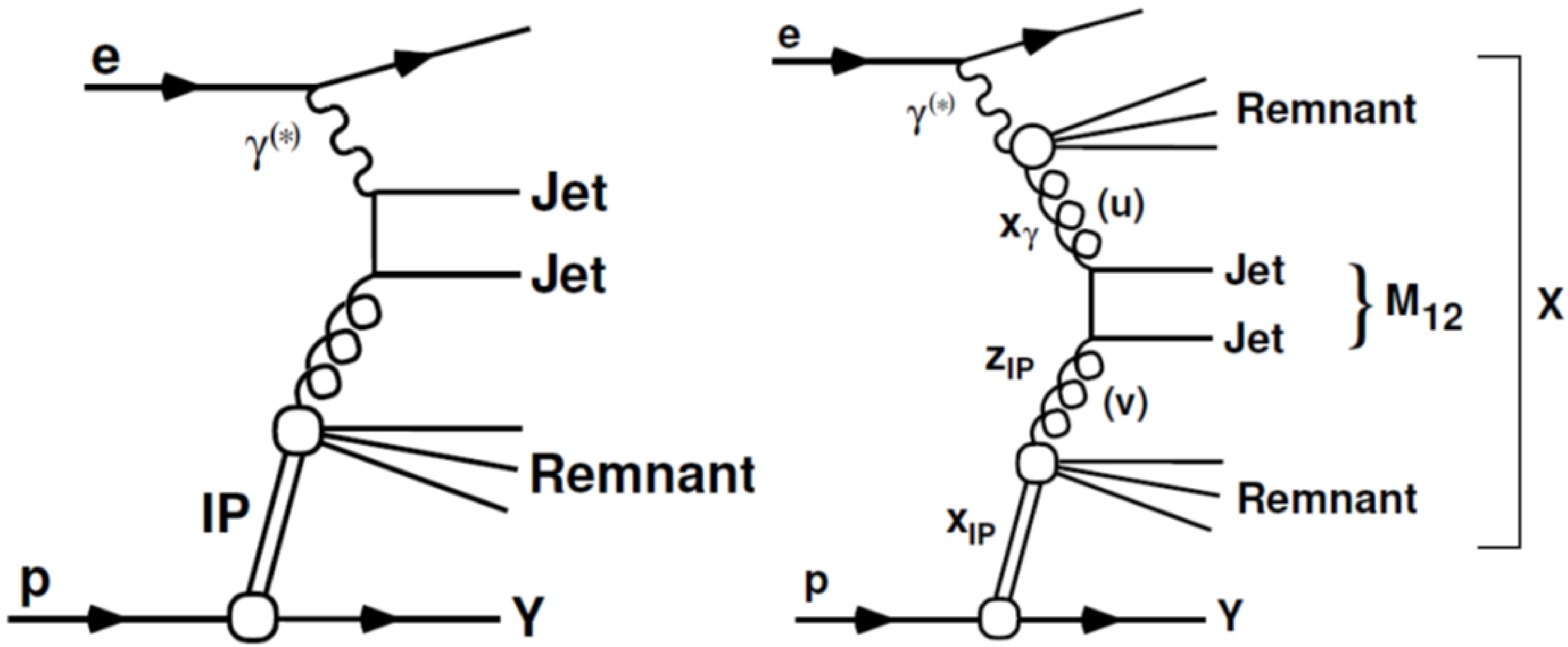
Stronger caveat on more flexible parameterization (only three parmeters) to estimate true constraints from precise data. Reduction possibly overestimated.



Enormous improvement in $F_L^{D(3)}$ possible from running at various energies.

Note that here 3 electron $\times$ 6 proton energies assumed - may be optimistic.

Dijet photoproduction



Made up of direct (left) and resolved (right) components.

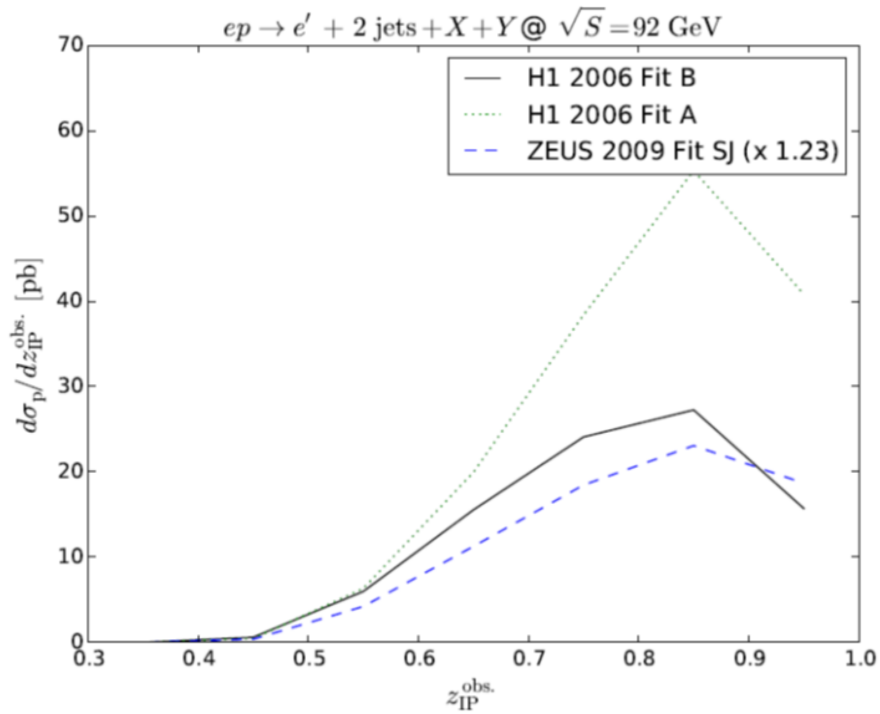
From HERA data factoriation known to ne broken at level 0.4 - 0.7 if both components or a little lower if resolved component only Guzey and Klasen, JHEP 05 (2020) 074.

Interpreted as gap survival probability.

In principle a good probe of the gluon diffractive PDF.

$$d\sigma = \sum_{a,b} \int dy \int dx_\gamma \int dt \int dx_{I\!P} \int dz_{I\!P} f_{\gamma/e}(y) f_{a/\gamma}(x_\gamma, M_\gamma^2) f_{I\!P/p}(x_{I\!P}, t) f_{b/I\!P}(z_{I\!P}, M_{I\!P}^2) d\hat{\sigma}_{ab}^{(n)}.$$

where $f_{\gamma/e}(y)$ is the photon flux $f_{a/\gamma}(y)(x_\gamma, M_\gamma^2)$ is the PDF of the photon and $d\hat{\sigma}$ is known at NLO.



Predictions at the EIC shown Guzey and Klasen, JHEP 05 (2020) 074.

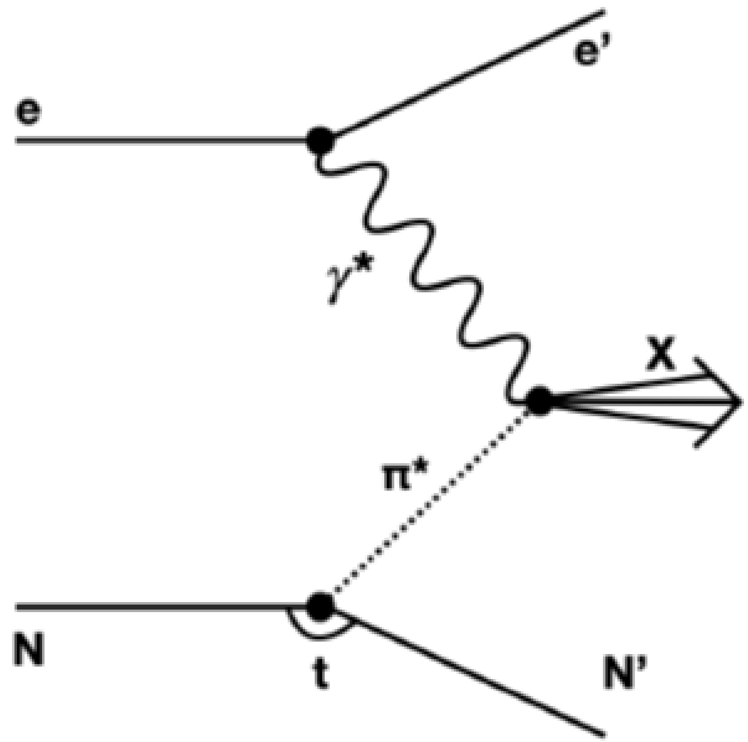
Potential sensitivity, particularly at large z_p^{obs}.

Pion Structure Function

Accessed via the mechanism

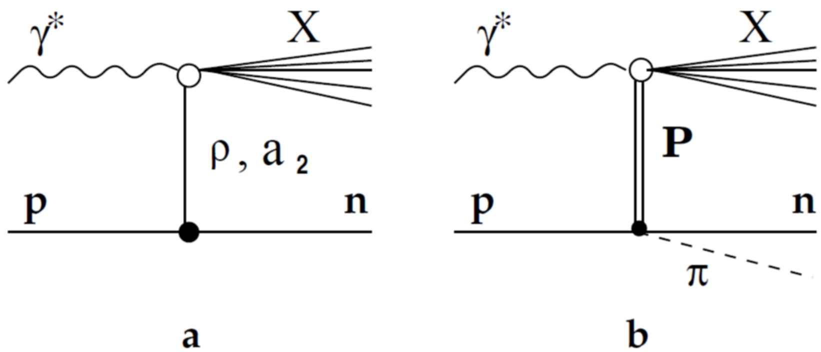
$e + p \rightarrow e' + X + N, Y$

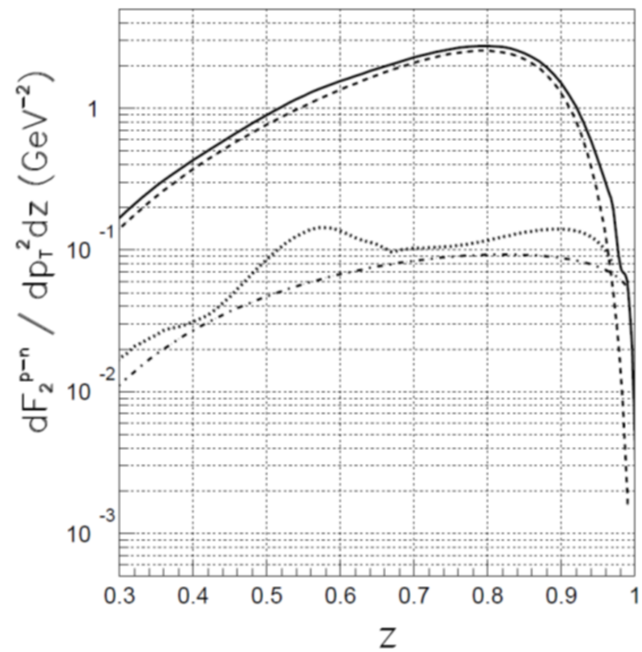
where N, Y is a nucleon or resonance.



Happens about 10^{-3} of the time in DIS

In the limit $t \rightarrow 0$ provides information on the pion (or possibly kaon) structure function, and hence PDFs.



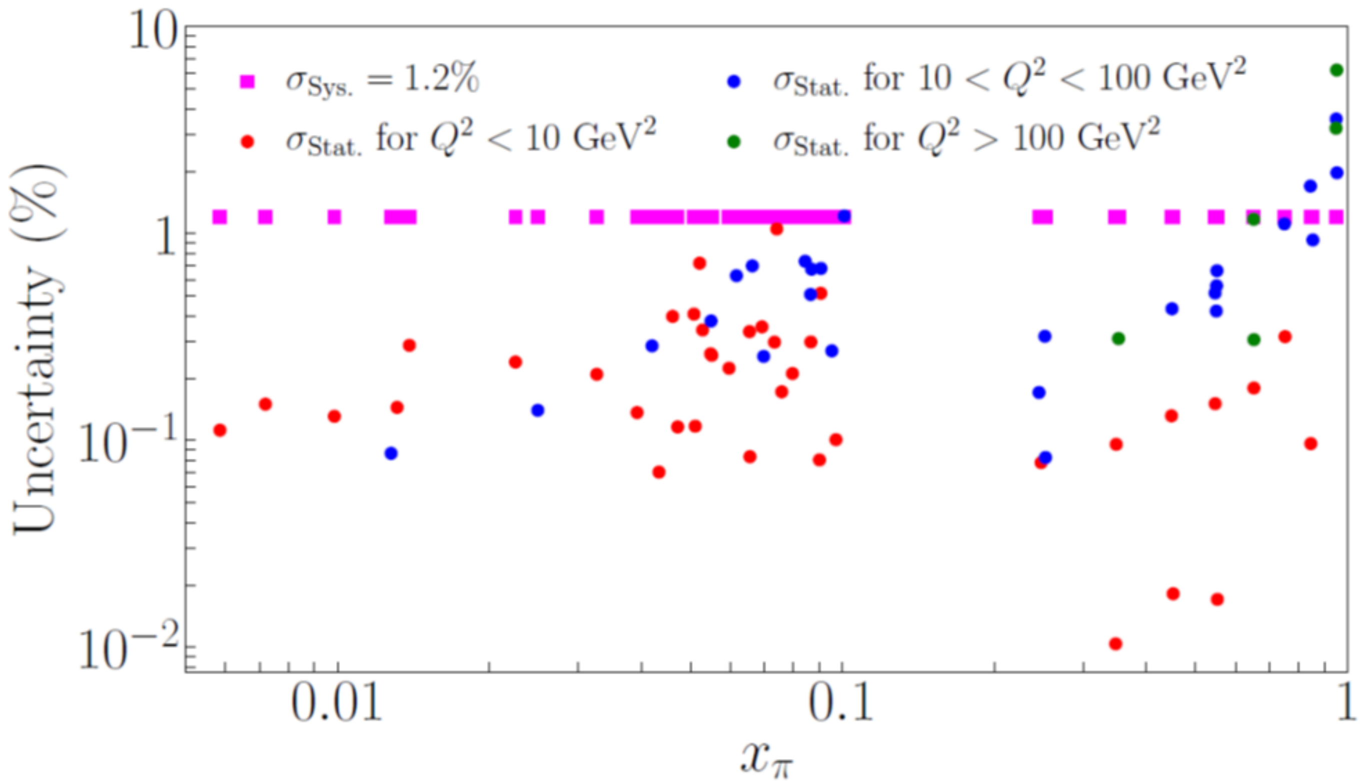


In practice there are backgrounds to this mechanism.

Non-pion intermediate particles, absorptive effects and uncertainties in the pion flux.

Considered in detail in e.g. Kopeliovich et al., Z. Phys. C 73 (1996) 125. Dominant (signal) and sub-dominant contributions shown.

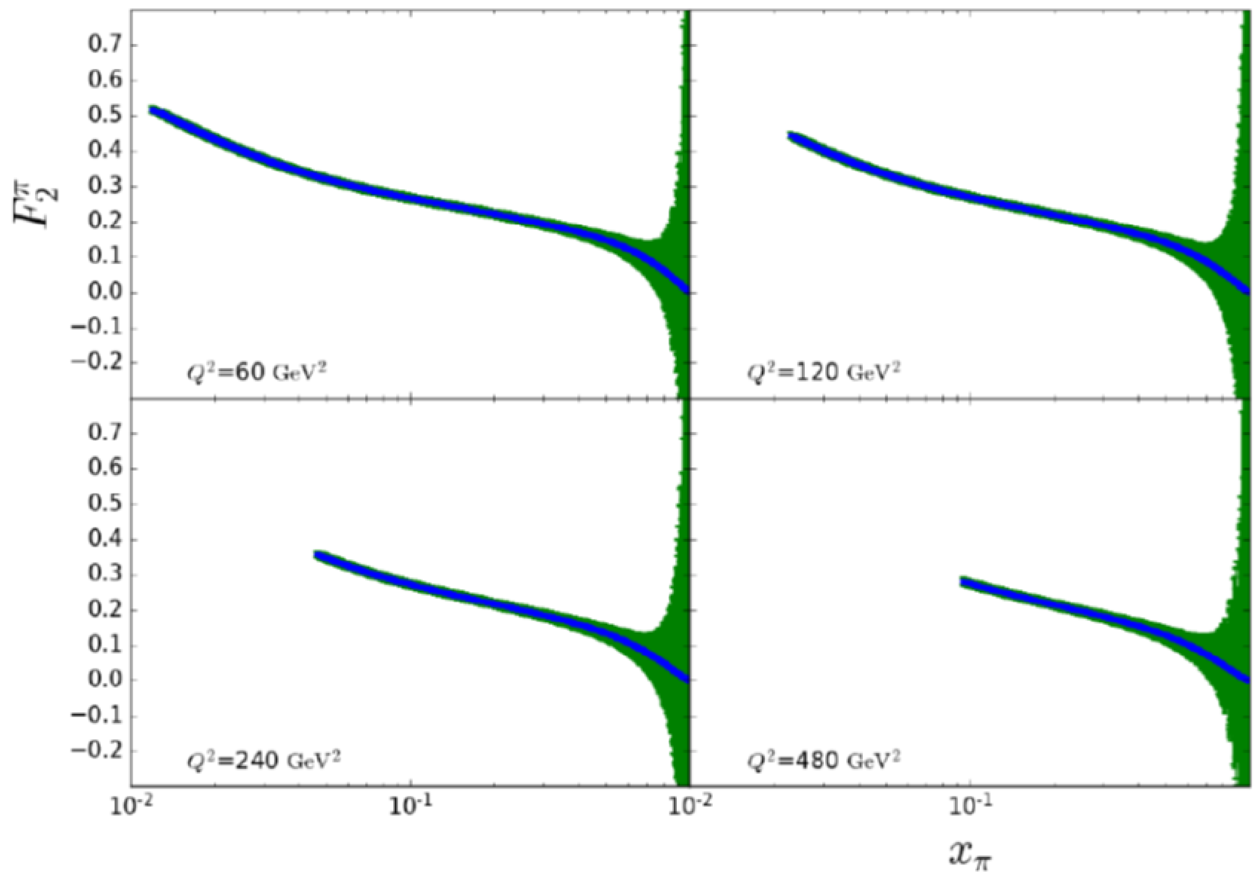
Of order 25% systematic theoretical uncertainty, much due to the pion flux uncertainty.



Fractional uncertainties of the cross section for projected data (J. Arrington et al., J.Phys.G 48 (2021) 7, 075106).

Simultaneously fit the pion structure function and the flux factor.

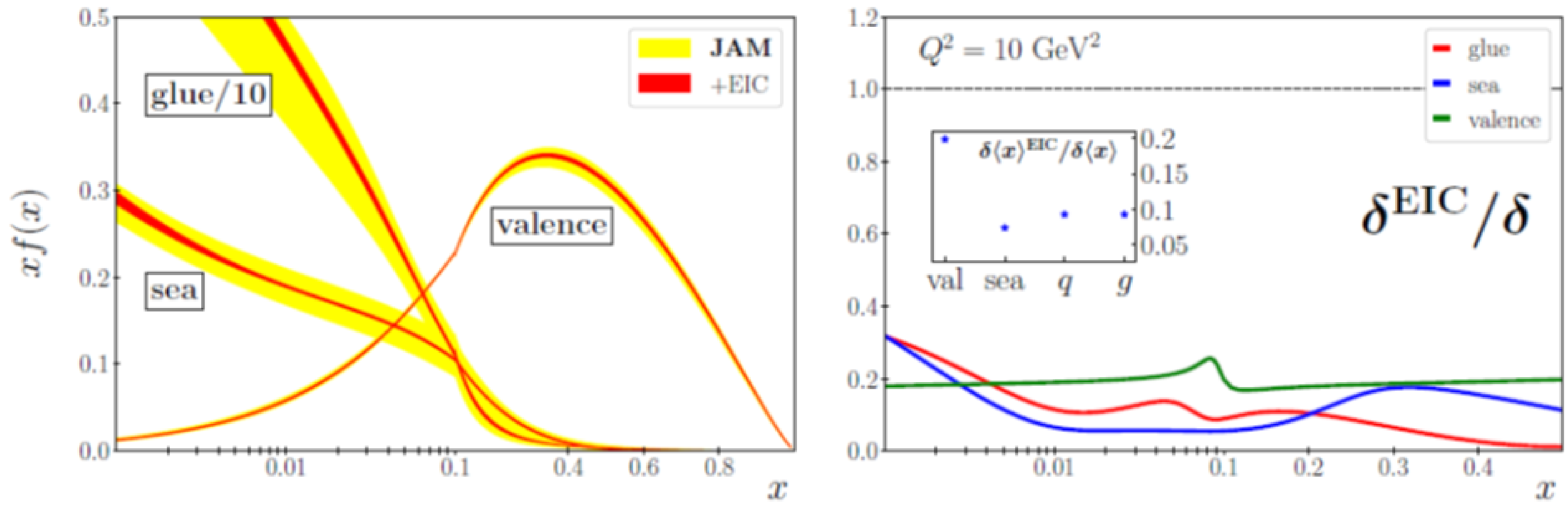
Ideally supplemented by other data , i.e. pionic Drell-Yan.



Projections of the pion structure function at the EIC

Bin sizes of 0.001 and $10\mathrm{GeV}^2$ in x, Q^2

Green band shows statistical uncertainty for $100 fb^{-1}$.



Possible improvement compared to current knowledge in terms of absolute (left) and fractional (right) uncertainties (P. Barry et al., arxiv:2108.05822).

Fit to pseudodata and real data done at NLL and using Drell Yan and F_2 data.

Would give information on the gluon contribution to pion mass (x. Ji, Phys. Rev. D 52, (1995) 271).

$\alpha_S(M_Z^2)$ determinations

Some processes at the EIC are very sensitive to the value of the strong coupling.

One example, event shapes, e.g. thrust, i.e. how well collimated hadrons (jets) are along the primary axis.

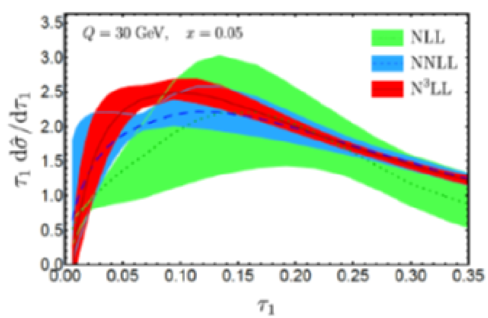
$$\tau = 1 - T \qquad T = \frac{1}{E} \max_{\hat{\mathbf{t}}} \sum_{i \in X} |\hat{\mathbf{t}} \cdot \mathbf{p_i}| = \frac{\mathbf{2}}{\mathbf{E}} \mathbf{P_z^A},$$

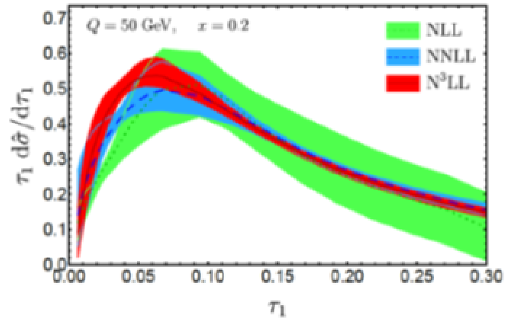
where P_Z^A is the total z momentum in the $+$ direction.

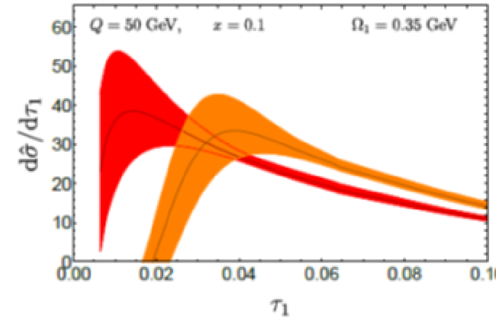
In DIS in the Breit frame the incoming current defines the z-axis.

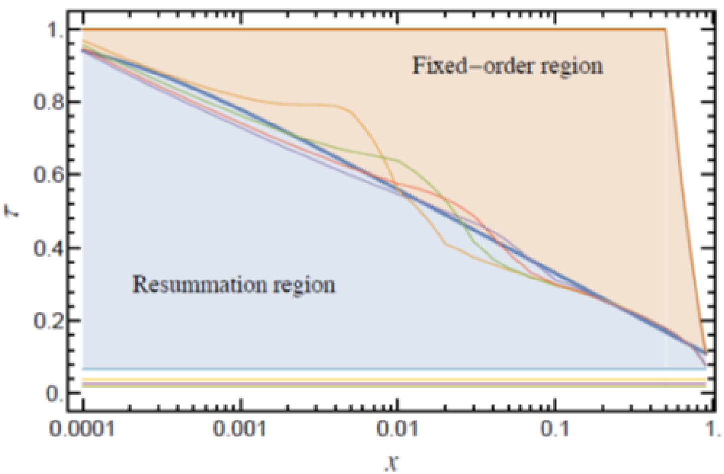
$$\tau_Q = 1 - \frac{2}{Q} \sum_{i \in \mathcal{H}_C} \mathbf{p_z^i}$$

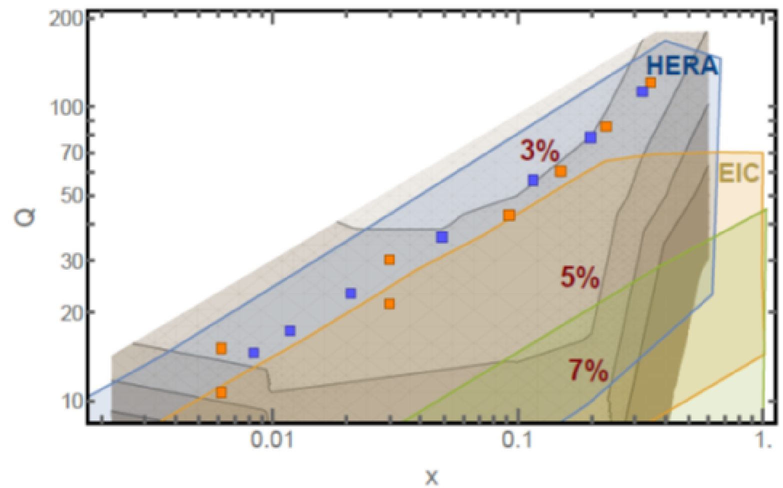
where $\mathcal{H}_C$ is the current hemisphere.







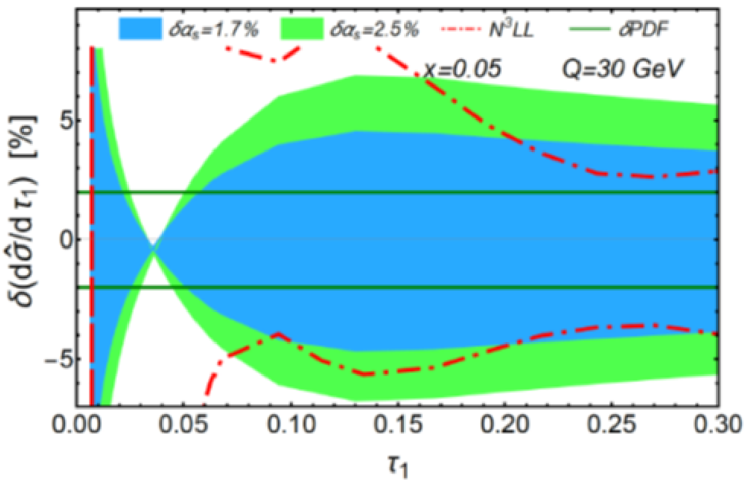


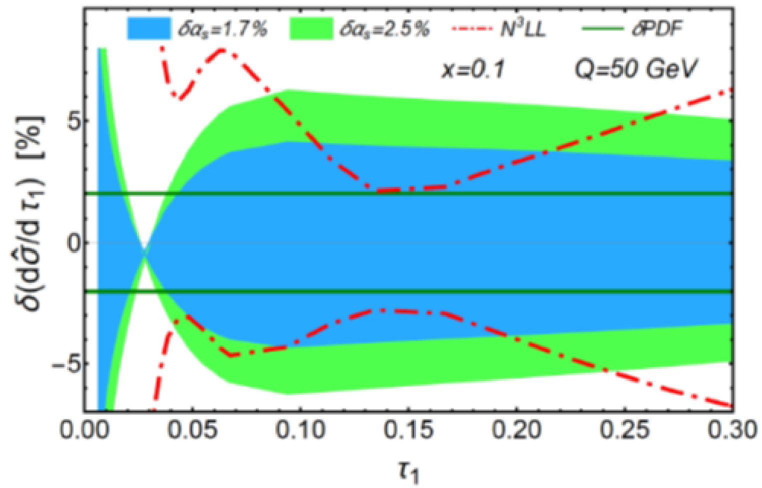


Can perform a resummation (Antonelli et al., JHEP 02 (2000) 001).

Now done at $N^3LL + \mathcal{O}(\alpha_S)$ (Kang et al., PoS DIS2015 142).

$$\sigma(\tau) = C(\alpha_S)e^{[Lg_{LL}(\alpha_S,L)+g_{NLL}(\alpha_S,L)+\alpha_S g_{NNLL}(\alpha_S,L)+\cdots]} + D(\alpha_S, L), \quad L = \ln(\tau).$$



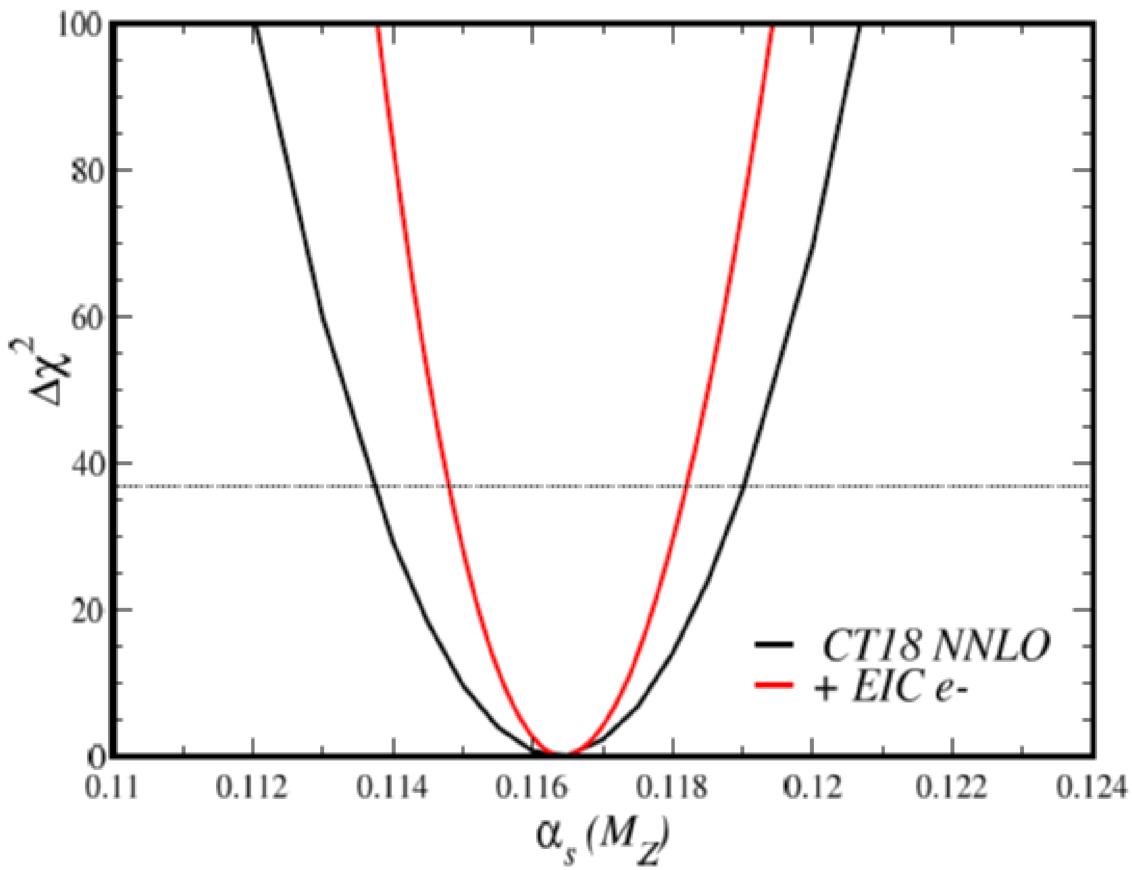


Current theoretical uncertainties in predictions along with PDF uncertainties compared to changes in cross sections due to given $\alpha_S(M_Z^2)$ variations.

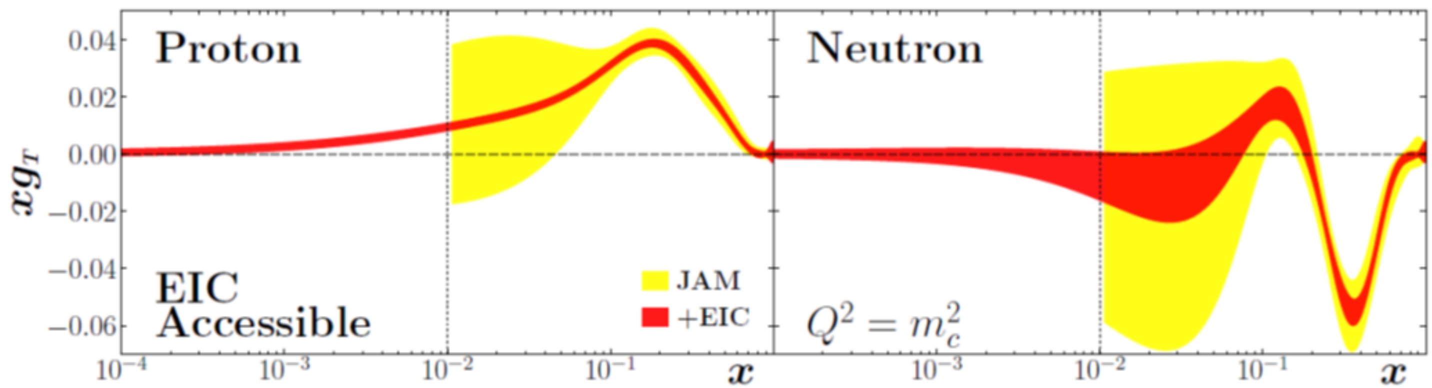
Measurements at various x, Q^2 values could give $\alpha_S(M_Z^2)$ determination of about a couple of percent or better.

Also possible improvement via increased constraints on structure function evolution, particularly (effective) nonsinglet at high x.

$$\frac{dF_2^{NS}(x,Q^2)}{d\ln Q^2} = P_{qq}^{NS}(\alpha_S) \otimes C_2^{NS}(\alpha_S) \otimes q^{NS} + \frac{\partial C_2^{NS}(\alpha_S)}{\partial \ln Q^2} \otimes q^{NS}.$$



Twist-3 structure function



Strucure function $g_2(x,Q^2) = -g_1(x,Q^2) + \int_x^1 \frac{dy}{y} g_2(y,Q^2) + \tilde{g}_2(x,Q^2)$, where $\tilde{g}_2(x,Q^2)$ is twist-3, and represents a quark-gluon correlation function (Jaffe, Nucl. Part. Phys. 19 (1990) 239).

Can be extracted from the longitudinal-transverse double spin asymmetry (Sato et al, Phys. Rev. D. 93 (216) 074005) in a global fit.

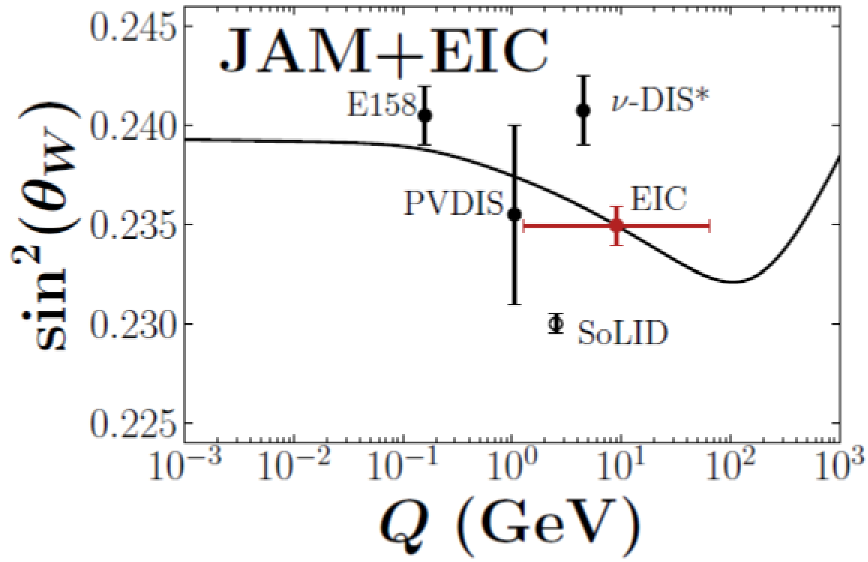
$$A_{LT}\frac{\sigma^{\downarrow\Rightarrow} - \sigma^{\uparrow\Rightarrow}}{\sigma^{\downarrow\Rightarrow} + \sigma^{\uparrow\Rightarrow}} \propto \frac{g_1(x,Q^2) + g_2(x,Q^2)}{F_1(x,Q^2)}.$$

Possible improvement at EIC shown above.

$\sin^2\theta_W$ **below** Z **pole.**

A measurement can be made via the $\gamma - z$ interference contribution to the asymmetry

$$A^e_{PV} = \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R}$$



Results shown assuming $100 fb^{-1}$ and $10 fb^{-1}$ with proton and deuteron targets.

Tests the running of $\sin^2\theta_W$ (Zhao et al, Eur. Phys. J A 53 (2017) 55).

Sensitive to presence of a dark photon.

Conclusions

Precision EIC structure function data can make a real impact on the (particularly down) quarks at very high x. Can also make an impact on the gluon both and strange quark at very high x, and at $x \sim 0.01$.

Interplay with constraints on $\alpha_S(m_Z^2)$, as well as possible direct constraints.

A dedicated study on charm jets, mainly produced in the quite far-forward direction, can also improve our knowledge of the strange quark at high x. Other interesting results from heavy flavour likely.

Very significant improvement in polarised PDFs at smaller x and via SIDIS also flavour decomposition. Much improved knowlege of spin sum rules.

Details of diffractive PDFs can be improved and Pomeron/Reggeon contributions and nature of factorization elucidated.

Huge improvement in pion PDFs likely.

Various routes into alternative physics issues.

Back-up