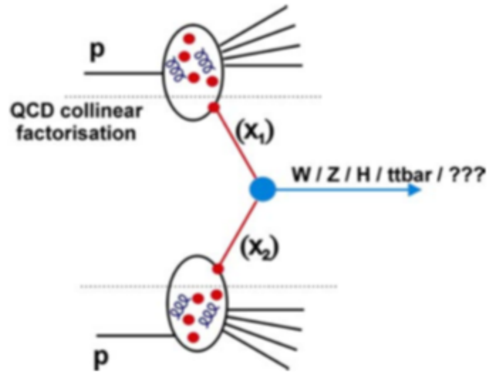
Towards Accuracy at Small x: Experimental Overview

Edinburgh, 10 September 2019



Paul Newman
(University of Birmingham)

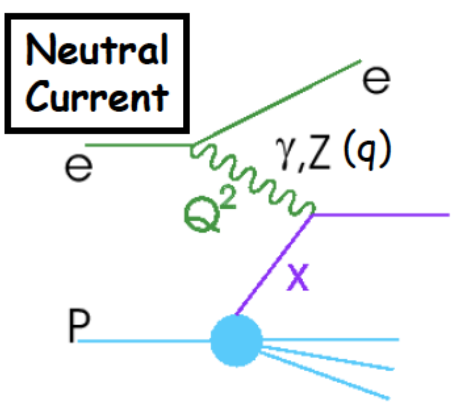
1) Where does HERA leave us?
2) Future DIS facilities
3) LHC observables v low x sea quarks and gluons
4) Diffractive observables
5) Other observables sensitive to novel low x effects

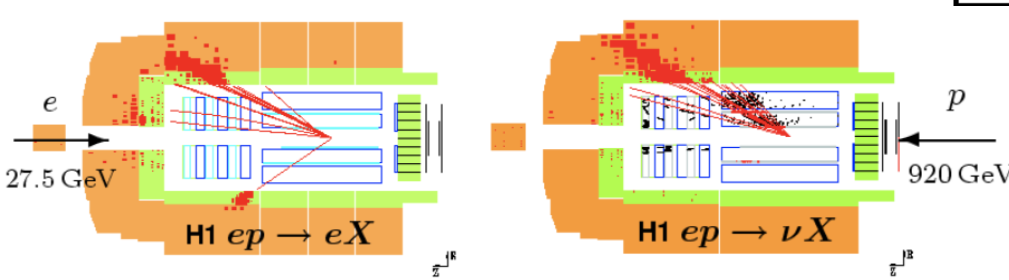
…birth of experimental low x physics

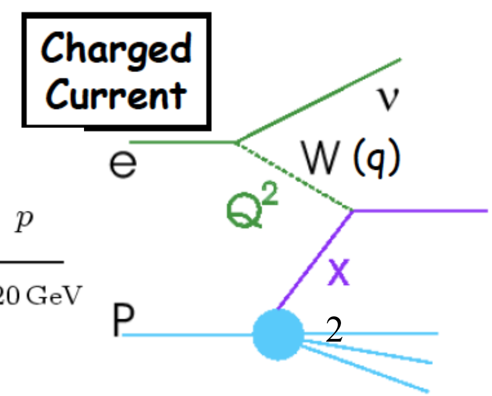
- The only ever collider of electron beams with proton beams:

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

- Still publishing papers, though main results are now out

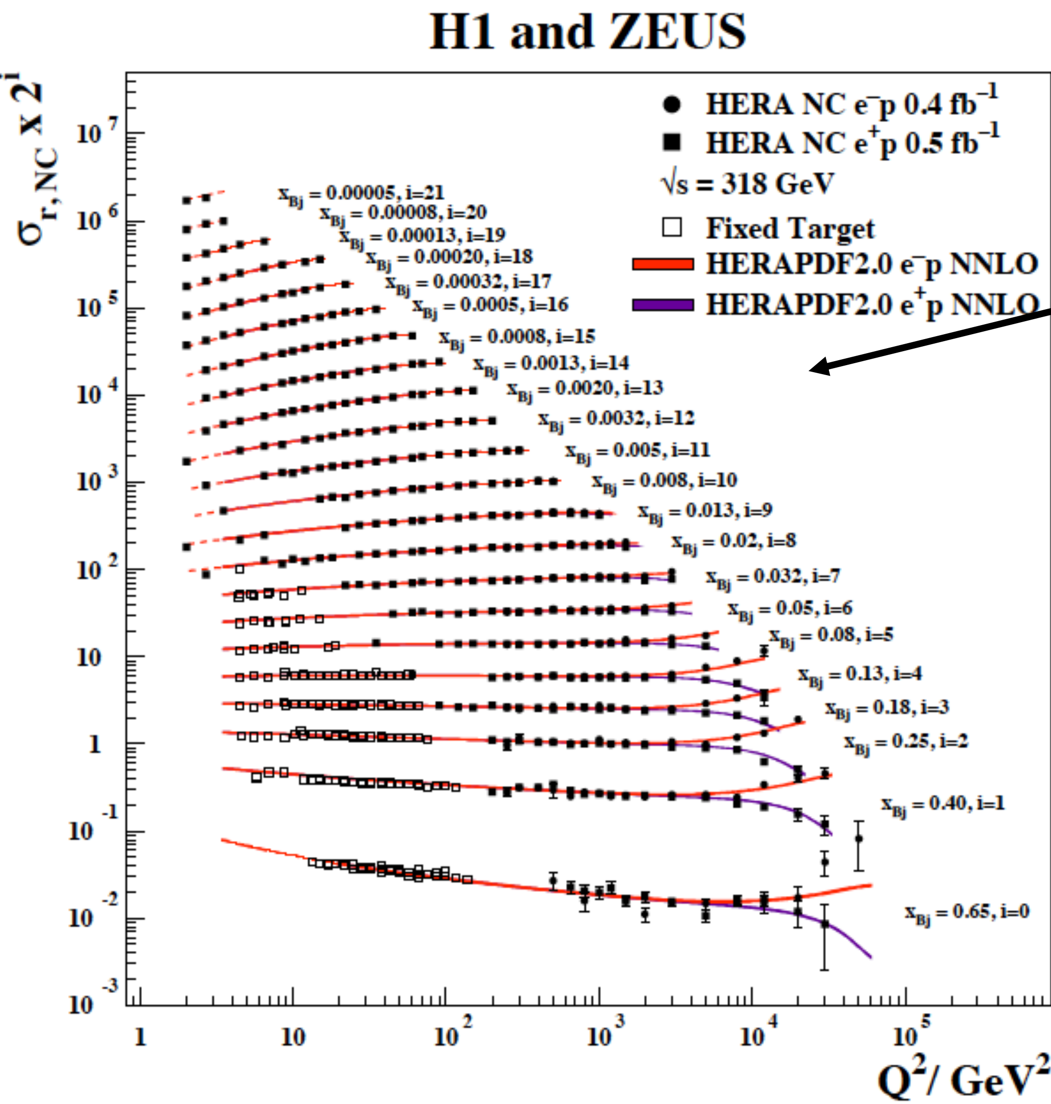




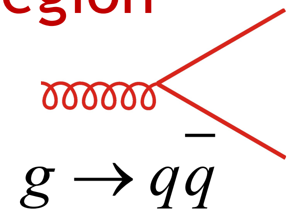


Low x Physics is Driven by the Gluon

… knowledge comes mainly from inclusive NC HERA data



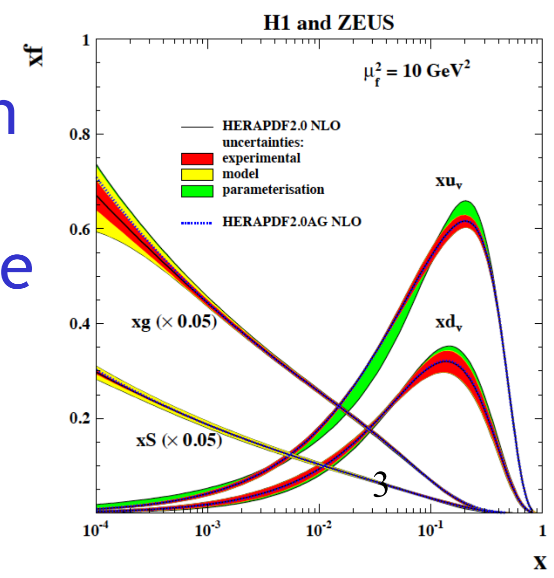
- NC Q^2 dependence in perturbative region driven by …



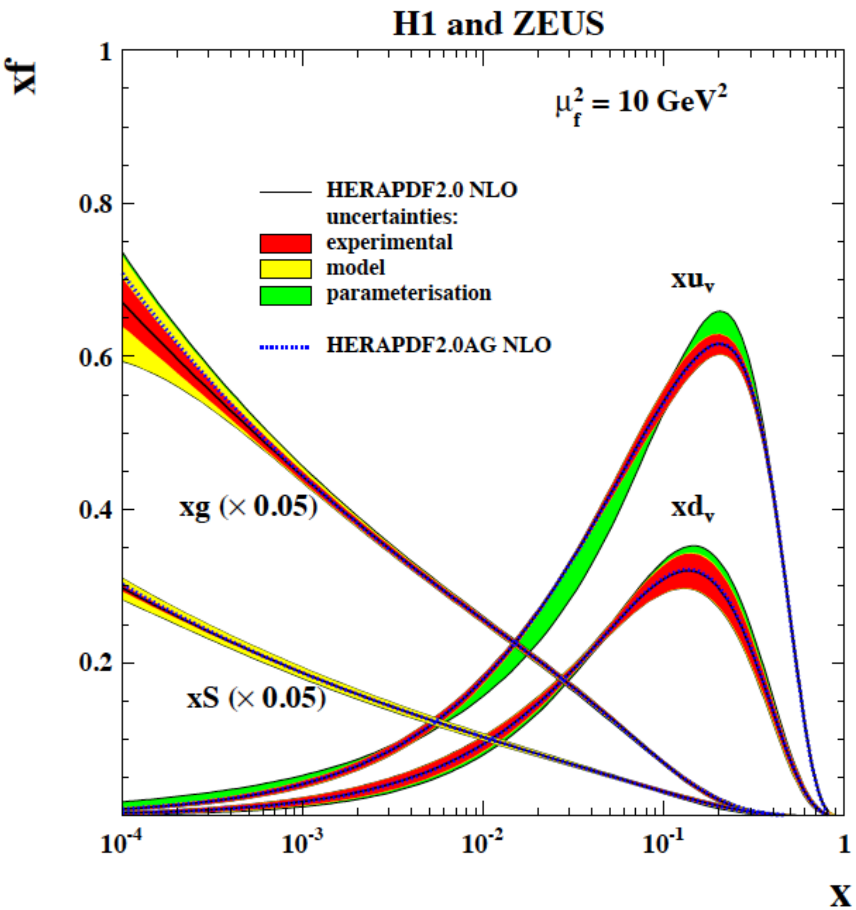
- e.g. Prytz approx:

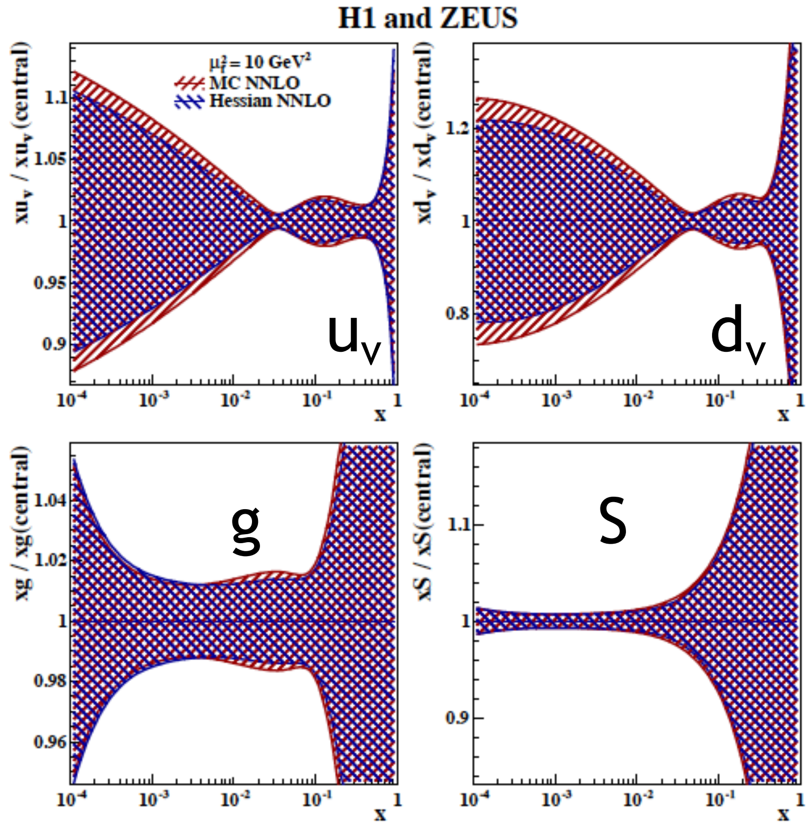
$$\frac{dF_2(x,Q^2)}{d\ln Q^2} \sim G(2x)$$

- needs lever-arm in Q^2 … reasonable precision only to $x \sim 10^{-3}$.



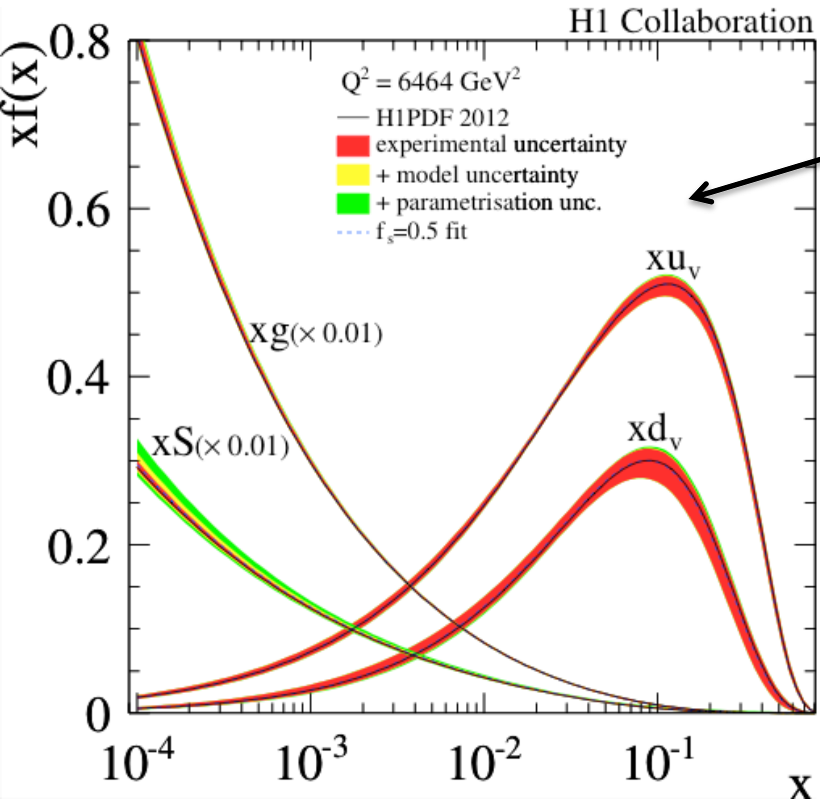
Final HERA Picture of Proton (HERAPDF2.0)



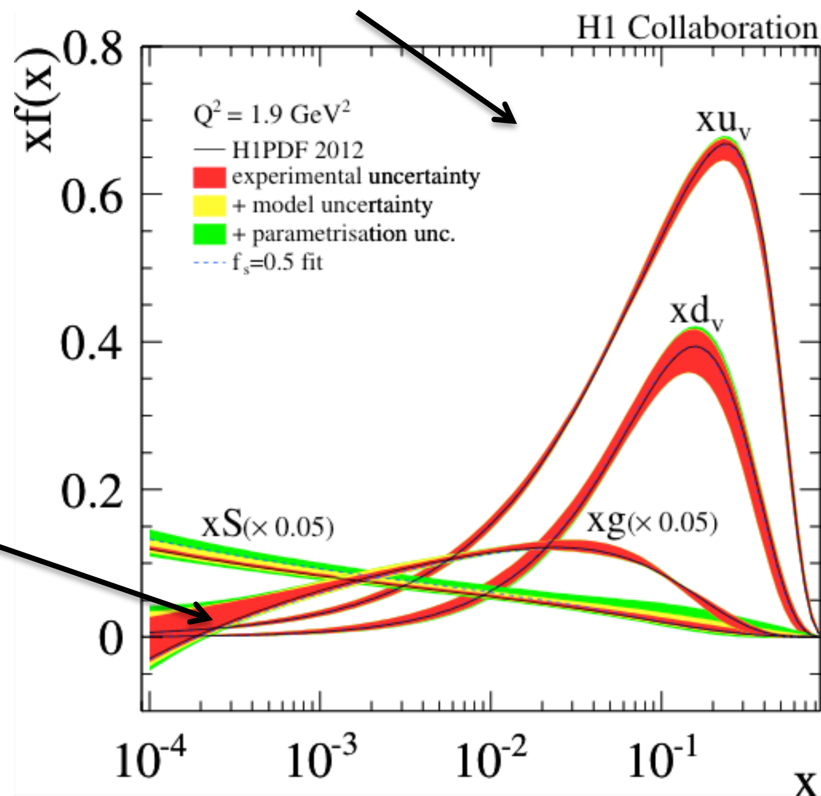


- ~2% precision on gluon for $10^{-3} < x < 10^{-1}$
- Gluon uncertainty explodes between $x=10^{-3}$ and $x=10^{-4}$
- Gluon itself is rising in a seemingly non-sustainable way …
- Note the 'Standard' presentation is at $Q^2 = 10$ GeV^2

Evolution to Other Scales



- Electroweak scale ~ M_Z^2 (LHC precision physics) … gluon rise gets sharper, error band shrinks
- Parameter scale ~ 1.9 GeV^2 (where lowest x data exist)



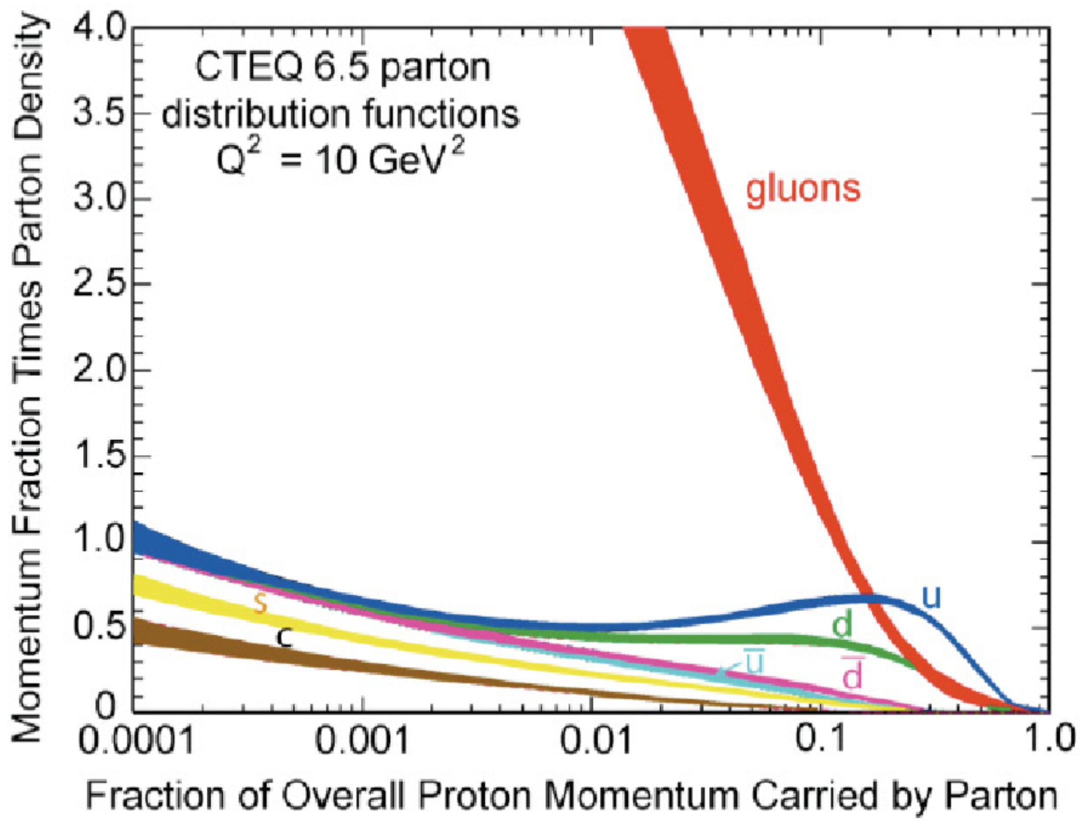
- Gluon in DGLAP approach is close to zero in region where e.g. saturation models are applied

The "Pathological" Gluon: Implications

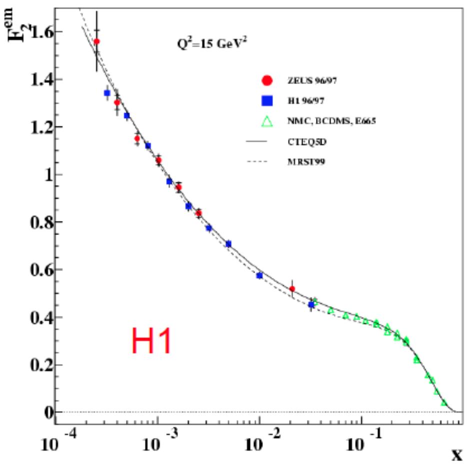
- **Fast growth of low x gluon appears unsustainable → new low x gluon-driven dynamics?**
  - Recombine (gg→g), non-linear / saturation / (density effects)?
  - Log(1/x) resummation (energy effects)?
  - Just DGLAP (+ Higher twists)?

→ The implications of the high density, small coupling, regime of parton dynamics are not well understood

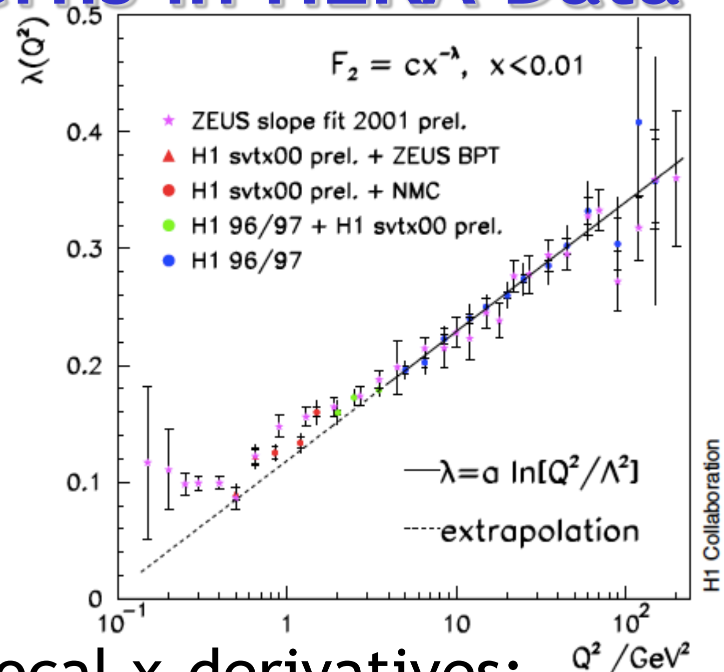
→ Is there any evidence for novel low x effects in HERA data?...

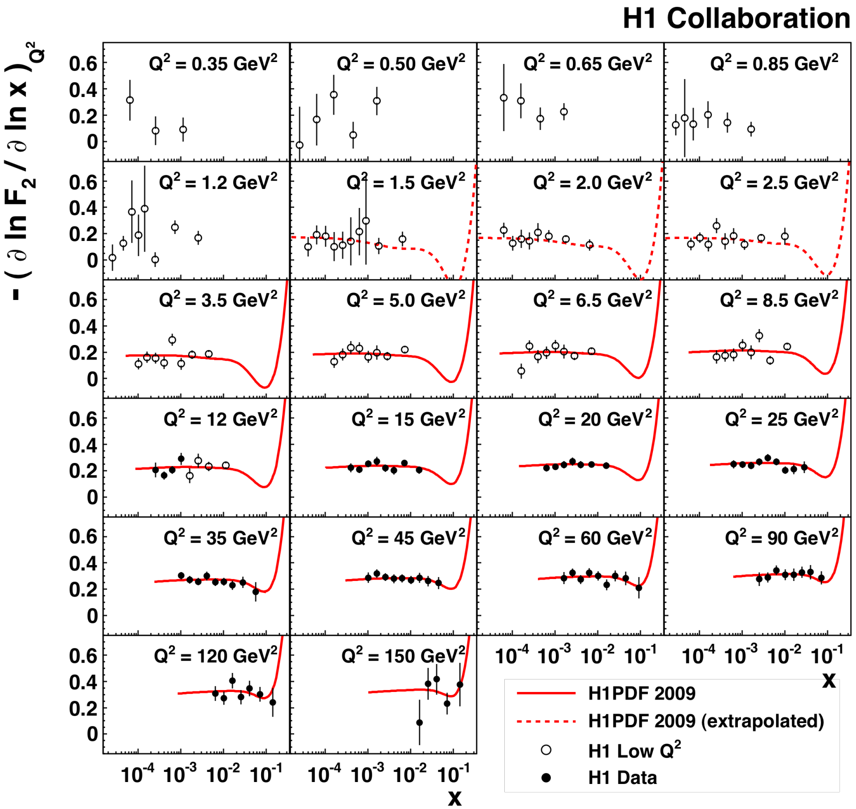


Looking for Changes in patterns in HERA Data



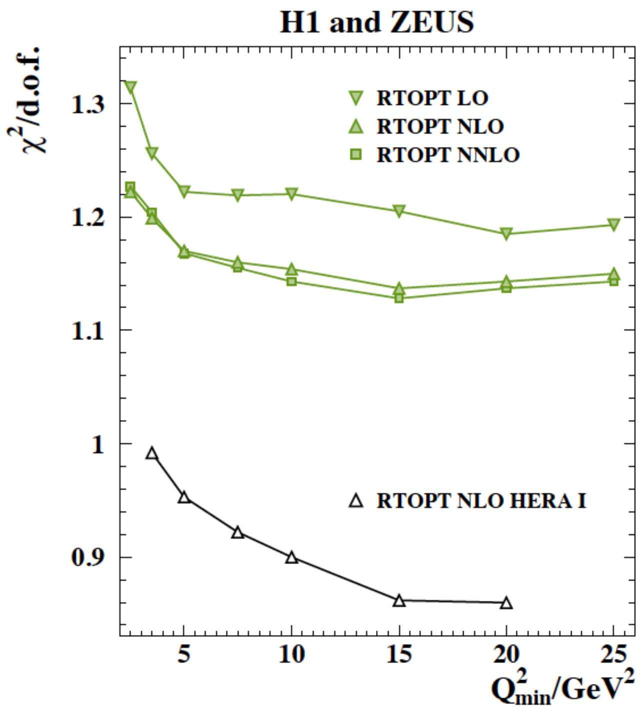
HERA inclusive data well described by $F_2 = Ax^{-\lambda(Q2)}$ with fixed A~0.2 for all Q^2 >~ 1 GeV^2





From 2D local x-derivatives: no evidence here for deviation from monatonic rise of structure functions towards low x in perturbative region.

... no smoking guns are directly available from the HERA data
→ effects are subtle

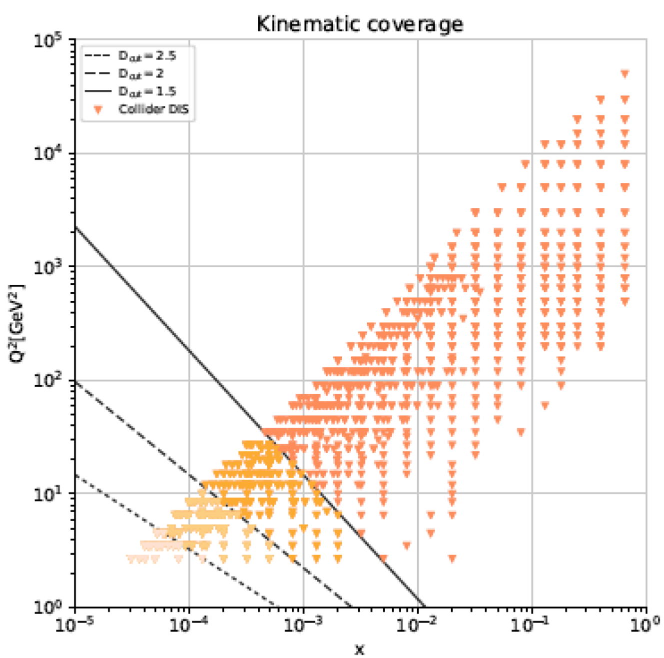


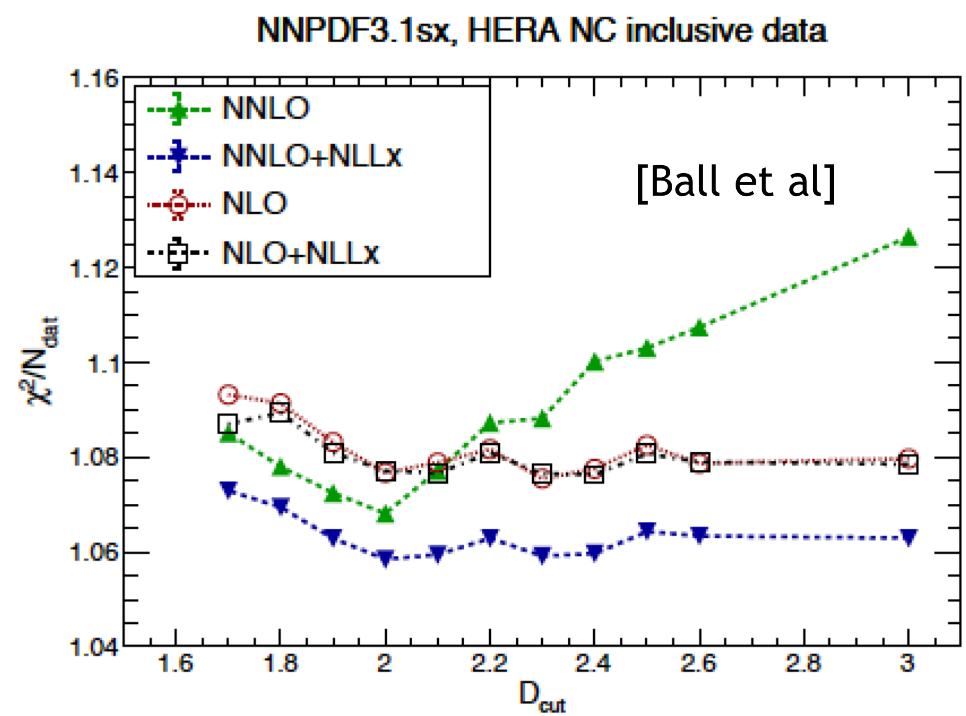
New Low x effects at HERA?

Final HERA-2 Combined PDF Paper:

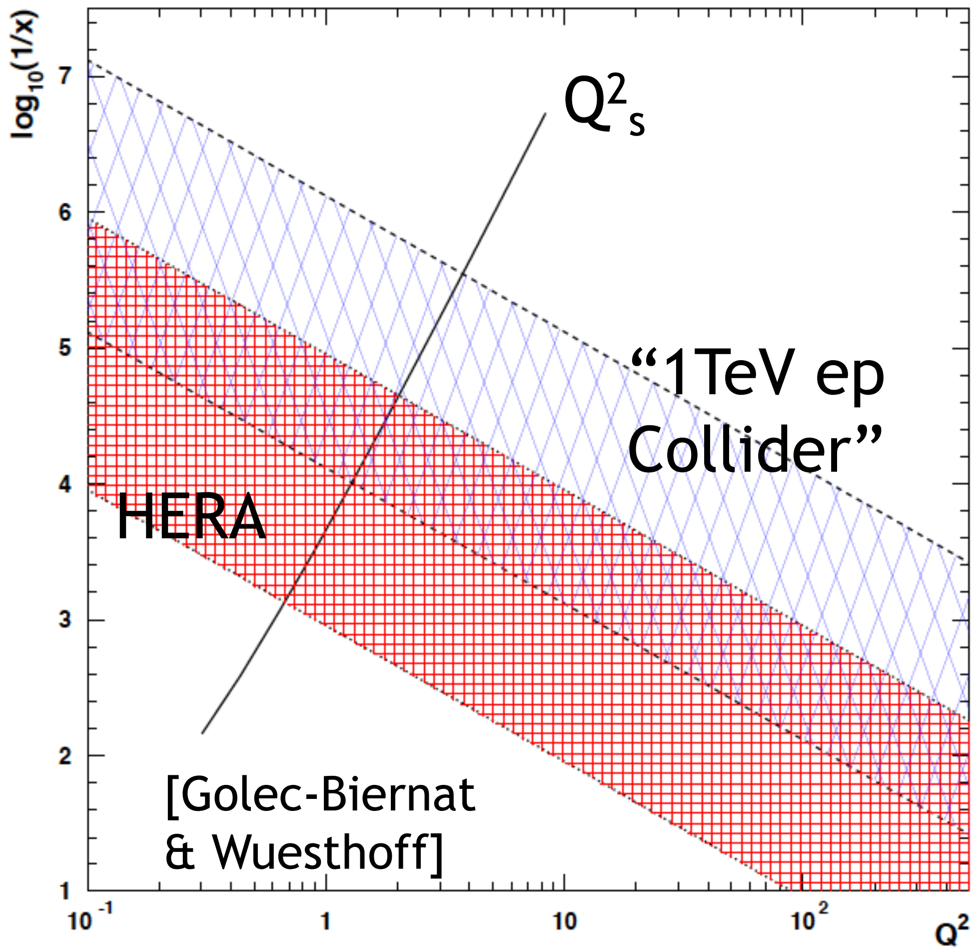
"some tension in fit between low & medium Q^2 data… not attributable to particular x region"
(though there is a kinematic correlation)

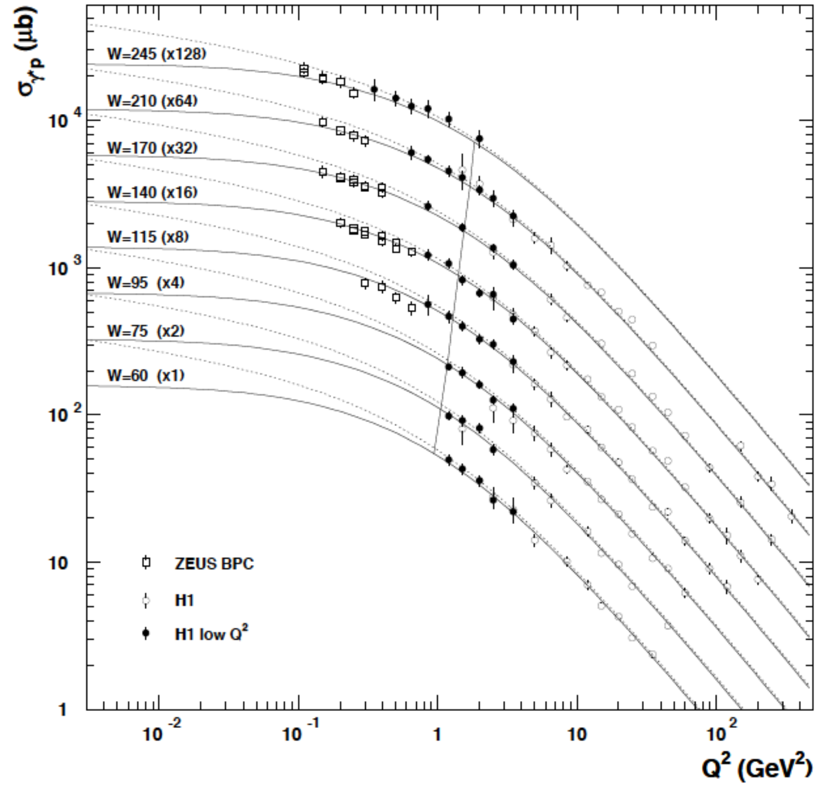
Including ln(1/x) resummation in fits improves χ^2 and describes difficult low x, low Q2 corner of kinematic plane





Q^2 < 1 GeV^2 data → Best description with Dipole Model, including saturation



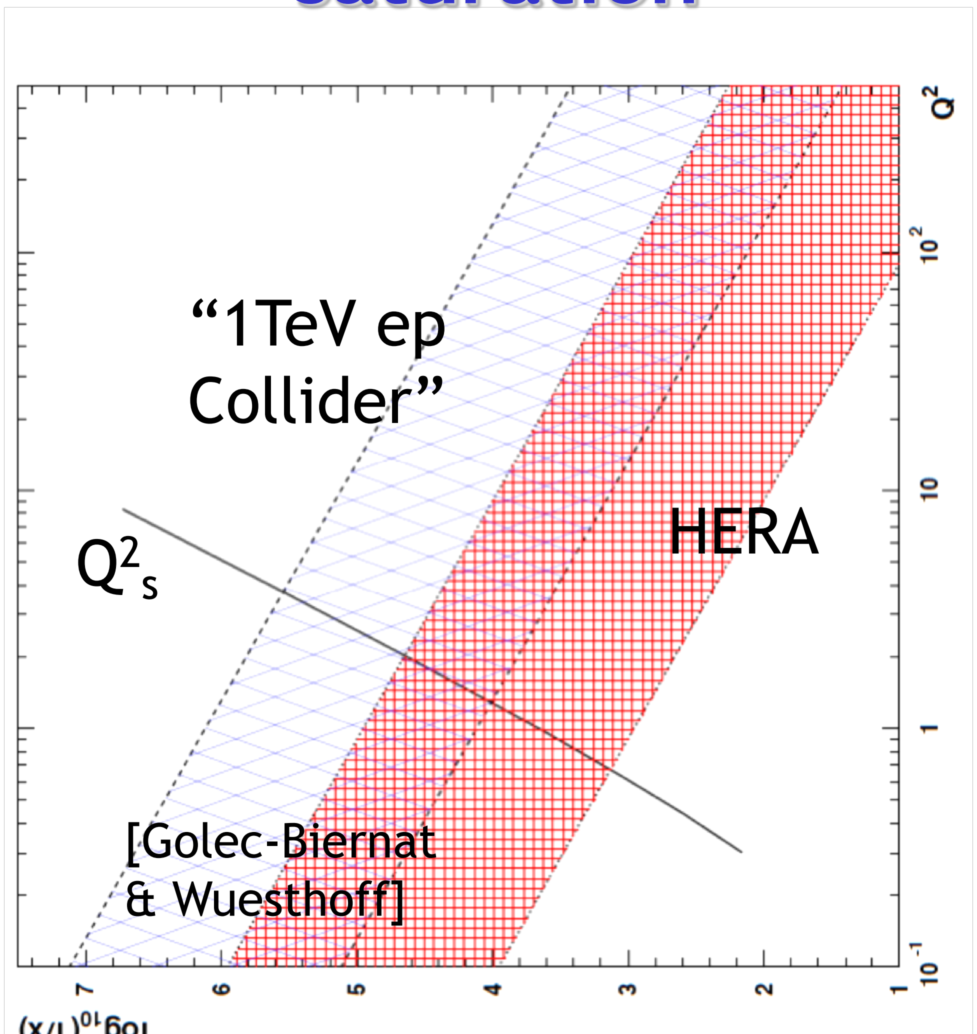


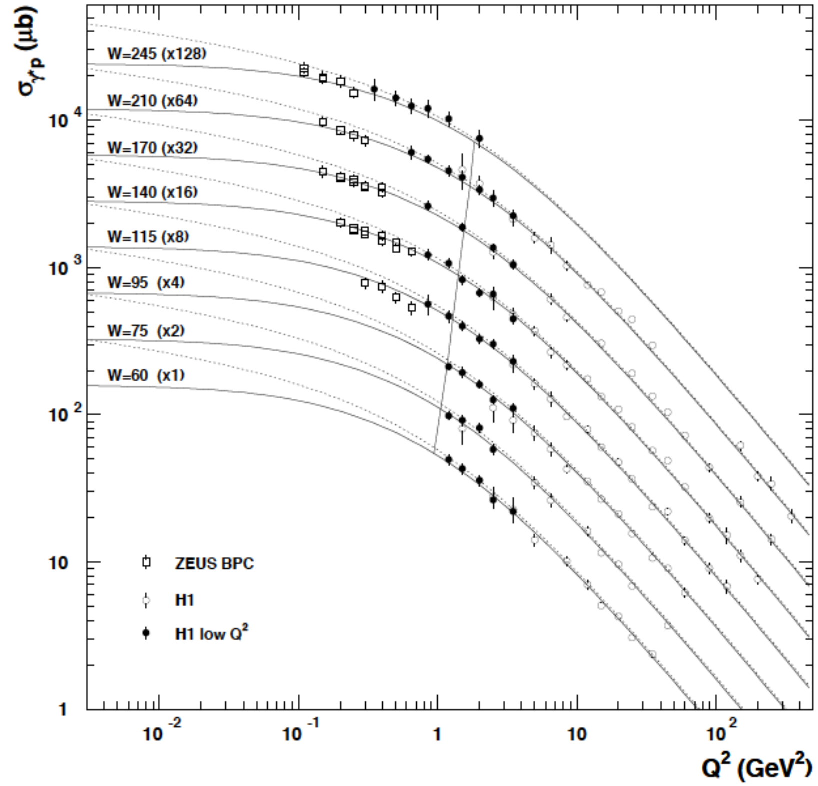
All data (Q^2 >~ 0.05 GeV^2) are well fitted in (dipole) models that include saturation effects

- x dependent "saturation scale", $Q^2_s(x)$

$$\frac{xG_A(x,Q_s^2)}{\pi R_A^2 Q_s^2} \sim 1 \Longrightarrow Q_s^2 \propto A^{1/3} x^{\sim -0.3}$$

Q^2 < 1 GeV^2 data → Best description with Dipole Model, including saturation





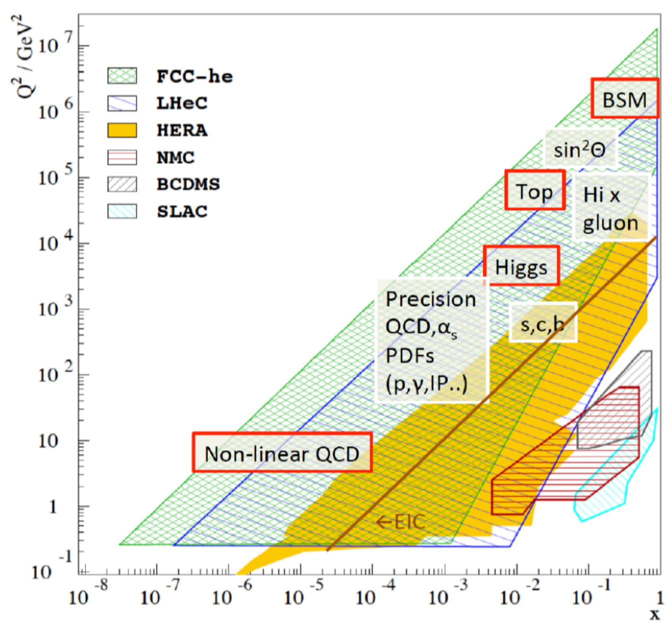
… at HERA, Q^2_s doesn't get above about 0.5 GeV^2

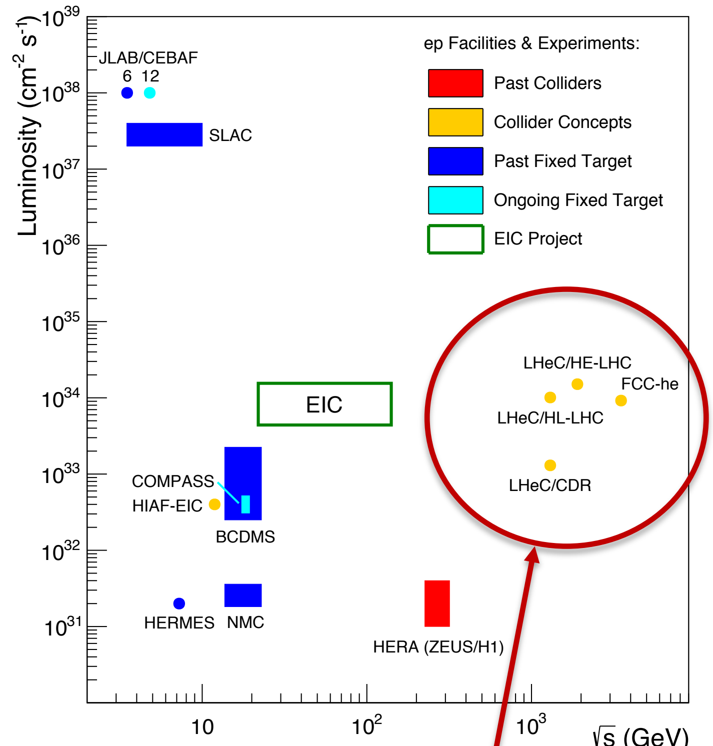
→Saturation may have been observed at HERA … but not in a region where quarks and gluons are reliable degrees of freedom

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 gluon precision
- No deuterons → limited quark flavour decomposition
- No nuclei → insensitive to nuclear effects
- No polarised targets (except HERMES) → limited access to spin, transverse structure

ALL addressed by complementary proposed future DIS projects





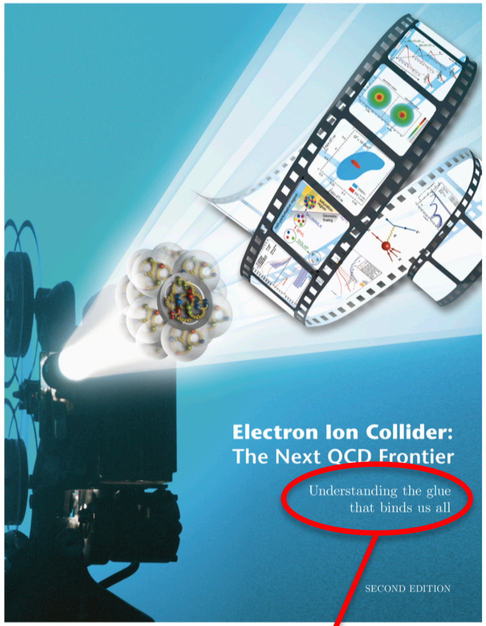
High energy, high luminosity via new e beam + LHC or FCC

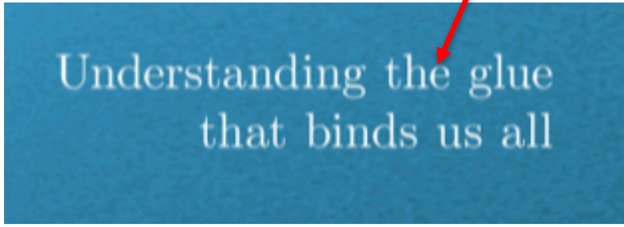
Electron Ion Collider

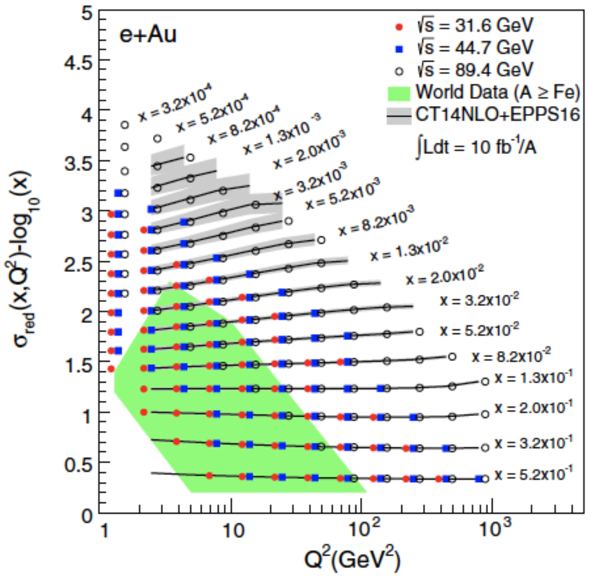
- Planned US ep and eA DIS facility

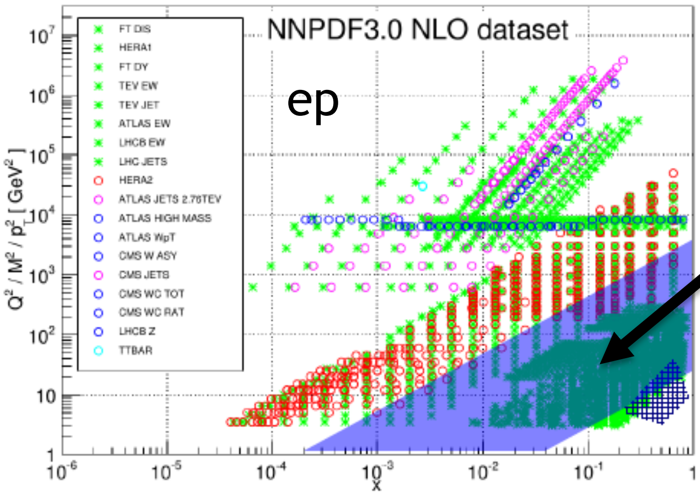
- $20 < \sqrt{s} < \sim 140$ GeV is lower than HERA

- Ion beams and polarised protons
 → physics programme focused on understanding gluons at medium-high x eg through TMDs / GPDs and approaching low x in eA









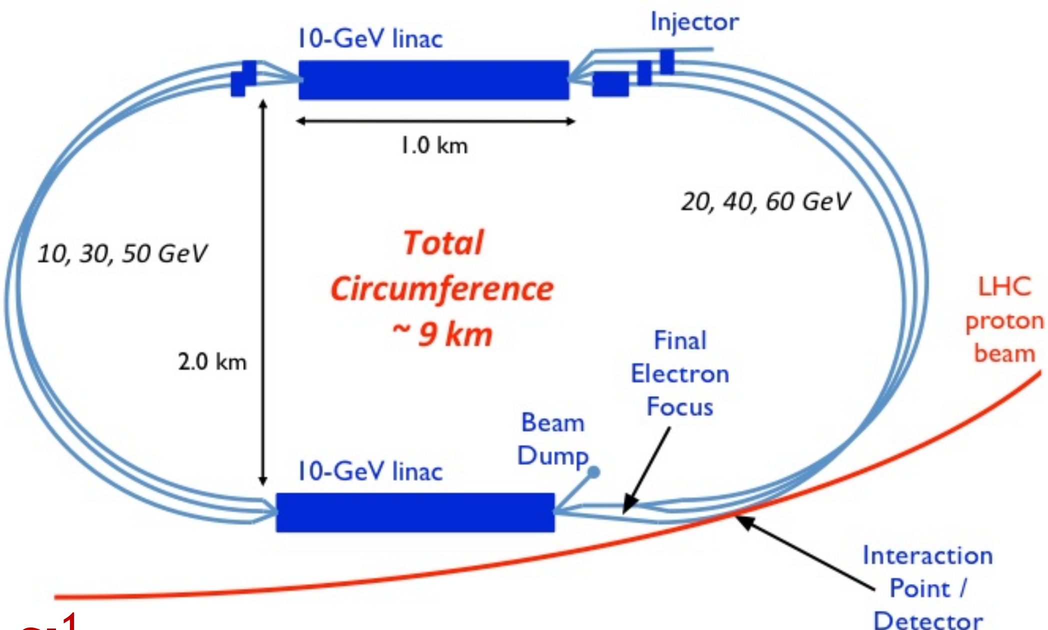
Approximate EIC coverage is shaded area.

LHeC / FCC-eh 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



- LHeC ep lumi → 10^{34} cm^{-2} s^{-1}

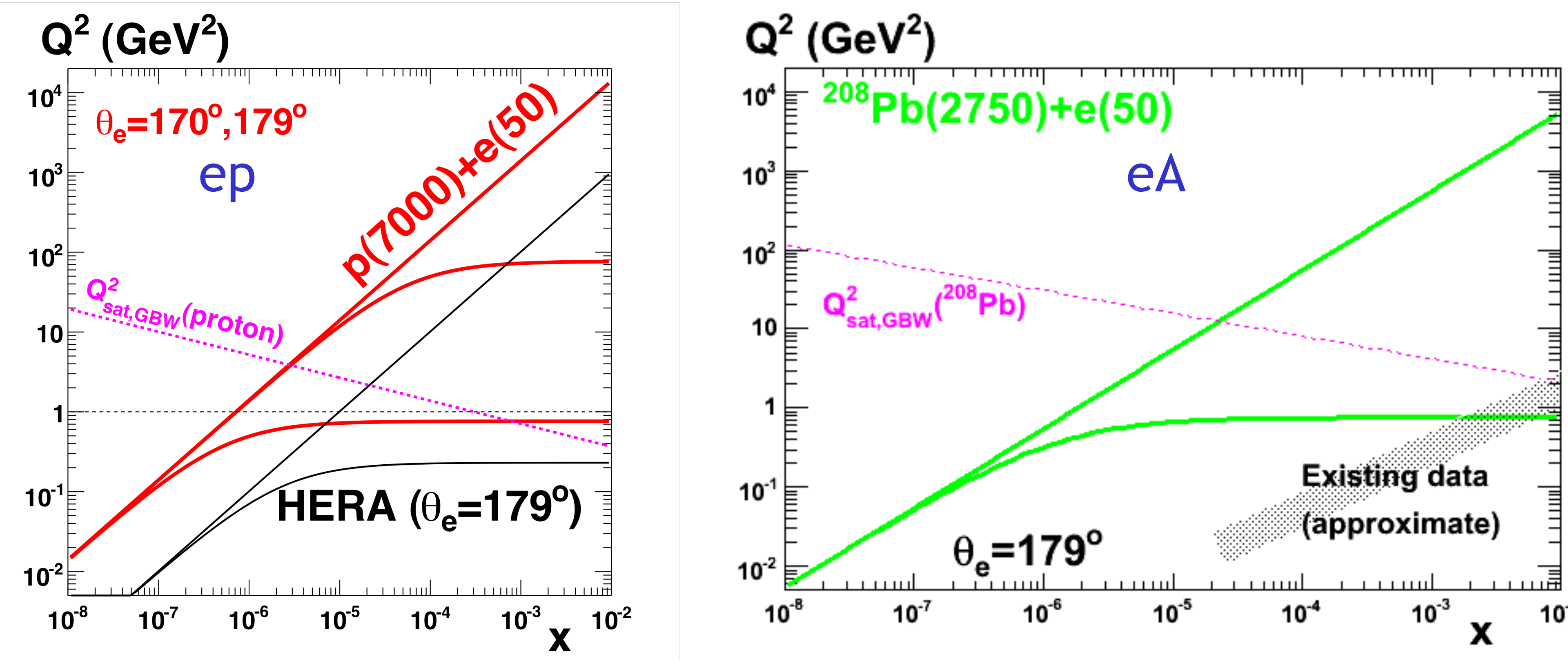
→ ~100 fb^{-1} per year →~1 ab^{-1} total

- e-nucleon Lumi estimates ~ 10^{31} (3.10^{32}) cm^{-2} s^{-1} for eD (ePb)

- **Similar schemes in collision with protons of 7 TeV (LHeC), 13 TeV (HE-LHeC) and 50 TeV (FCC-eh)**

Low x at LHeC: 2 orders of magnitude extension for ep, 4 for eA …

Testing saturation models at perturbative Q^2

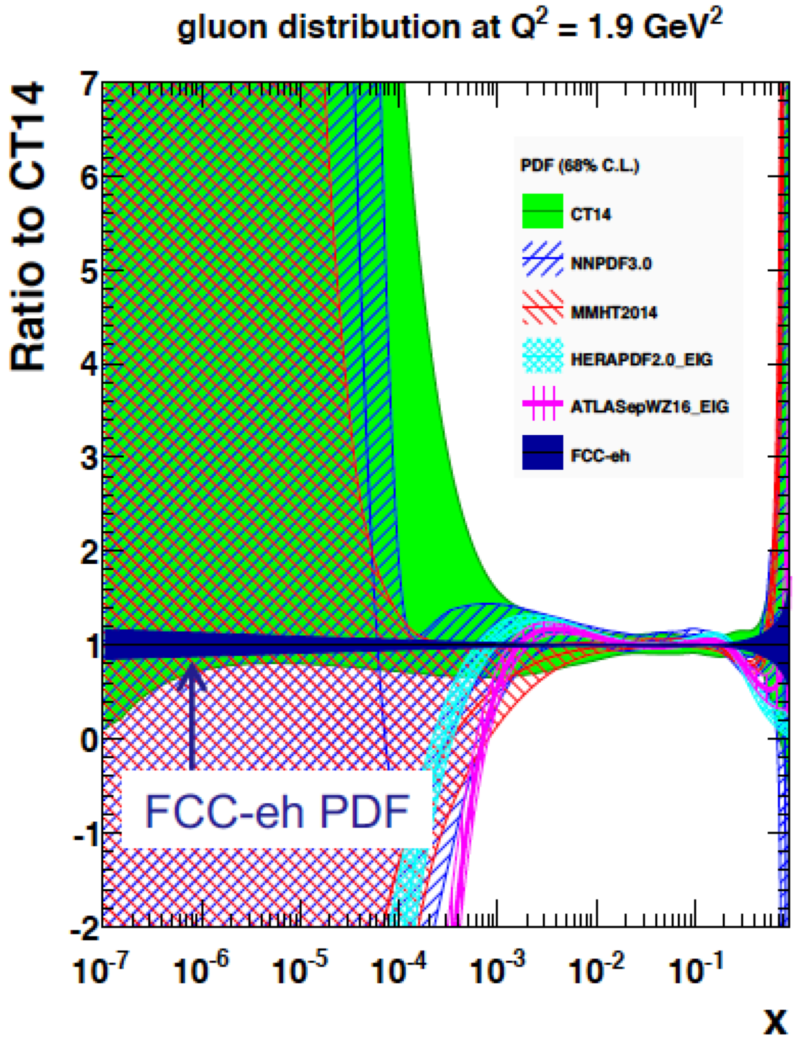


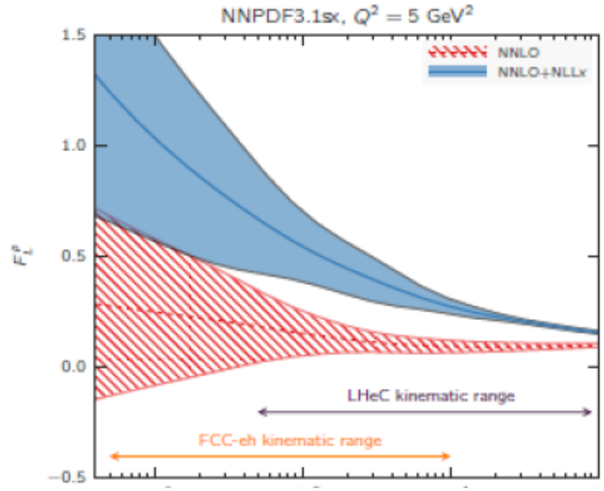
- Low x, Q^2 corner of phase space accesses expected saturated region in both ep & eA at perturbative Q^2 according to models

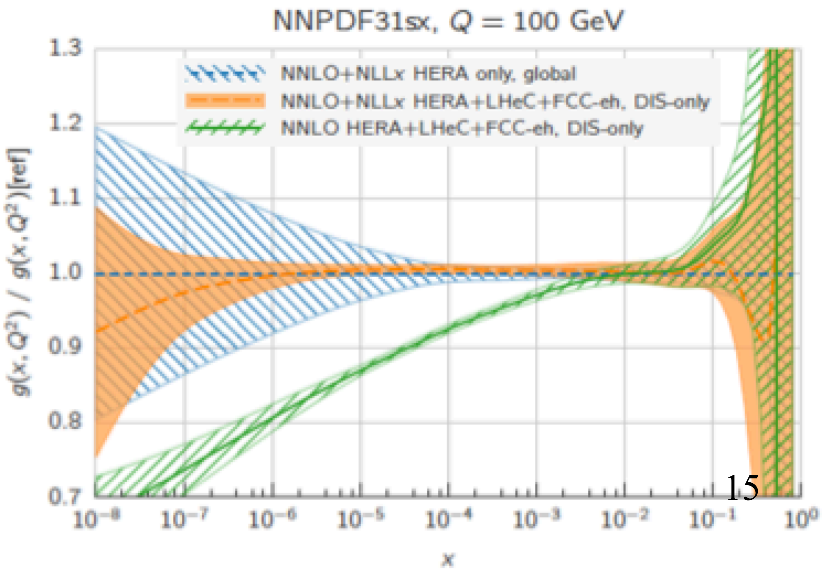
Potential of LHeC and FCC-eh

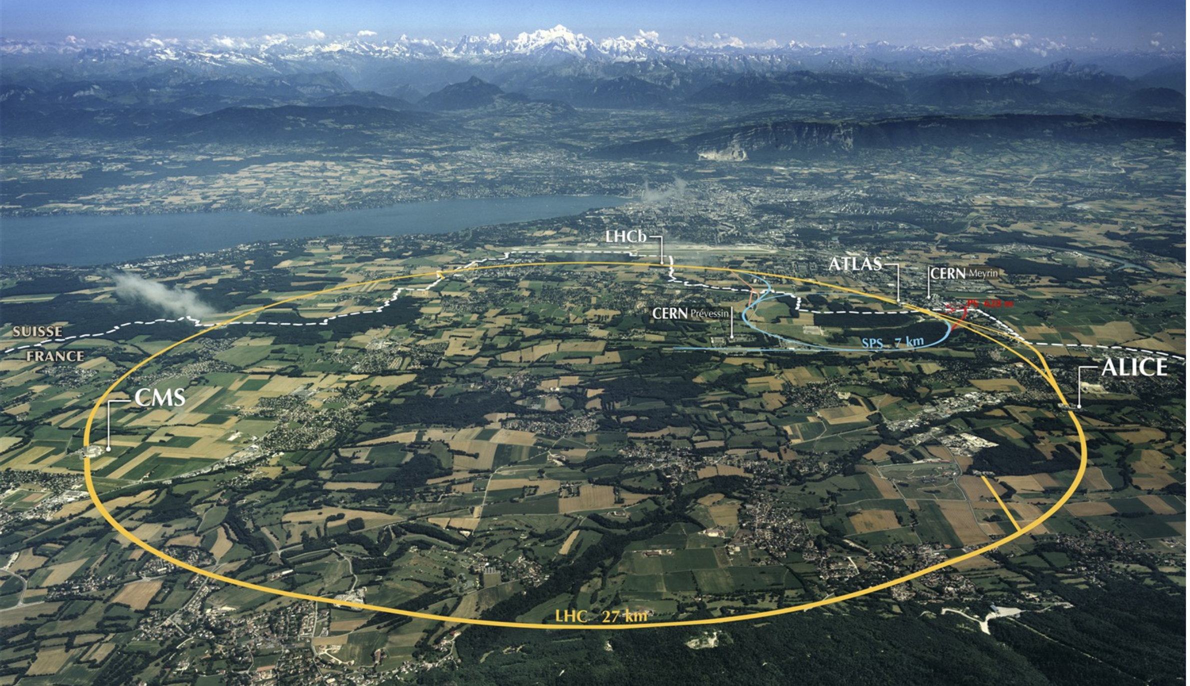
$x \rightarrow 10^{-7}$ at $Q^2 > 3$ GeV^2 for FCC-eh

Very large predicted effects from LL(1/x) resummation









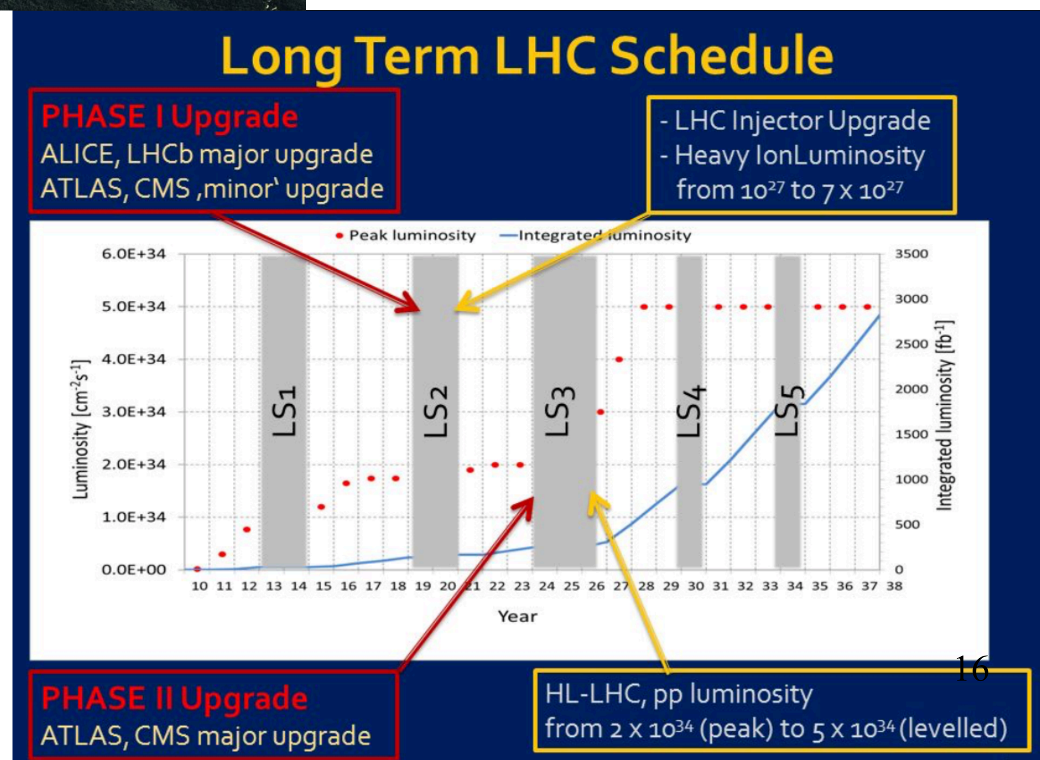
- Future high energy DIS is decades away
- Meantime …

Low x and the LHC

- LHC will run for another two decades

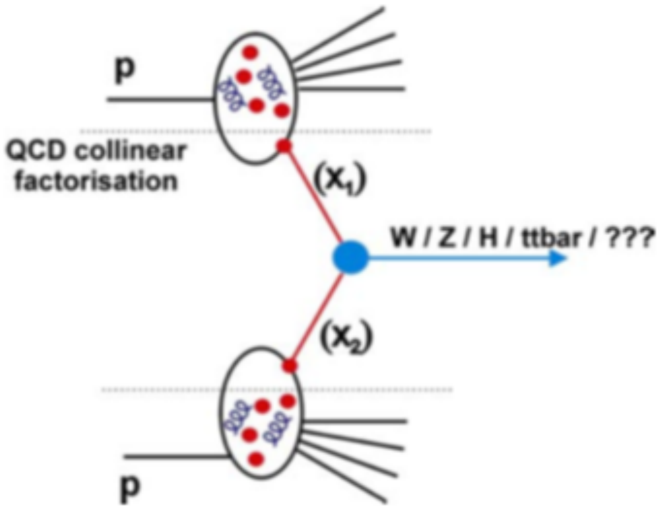
- Will remain the energy frontier for (a lot) longer

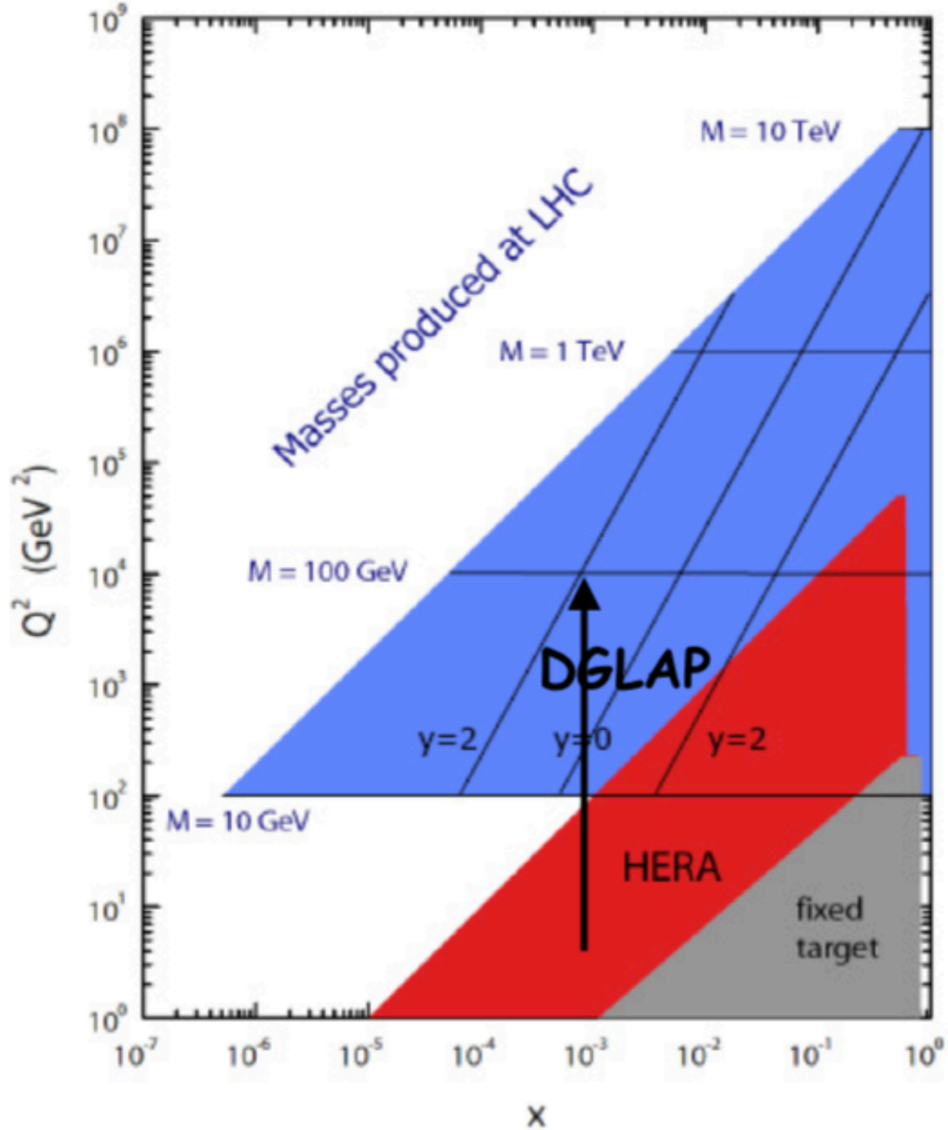
- Has capability to be a much better low-x facility than generally acknowledged



From HERA to LHC

Assuming collinear factorisation and a full understanding of low x dynamics …





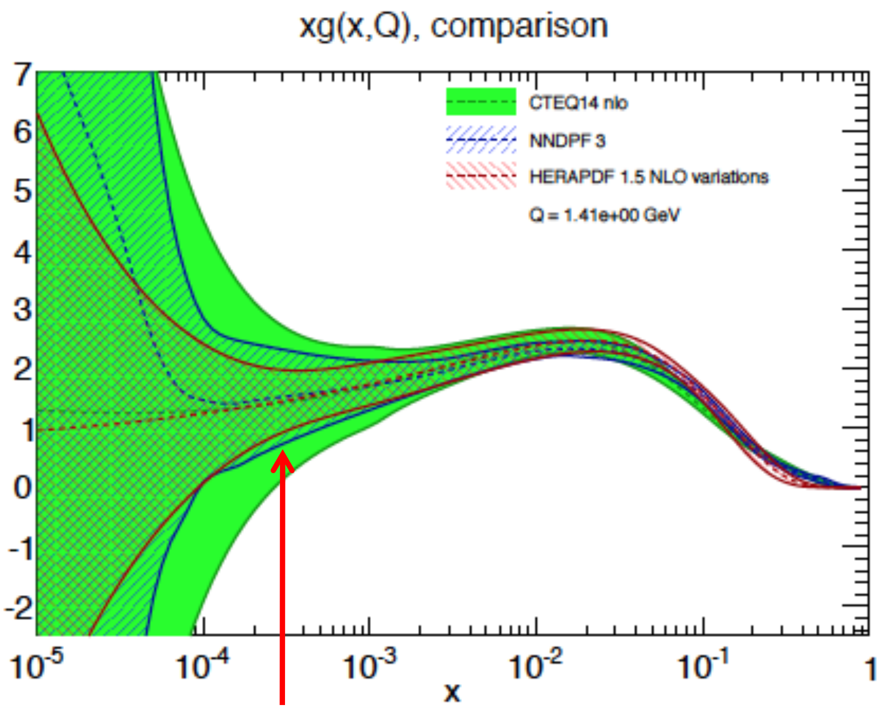
→ Need precise PDFs for interpretation of LHC physics

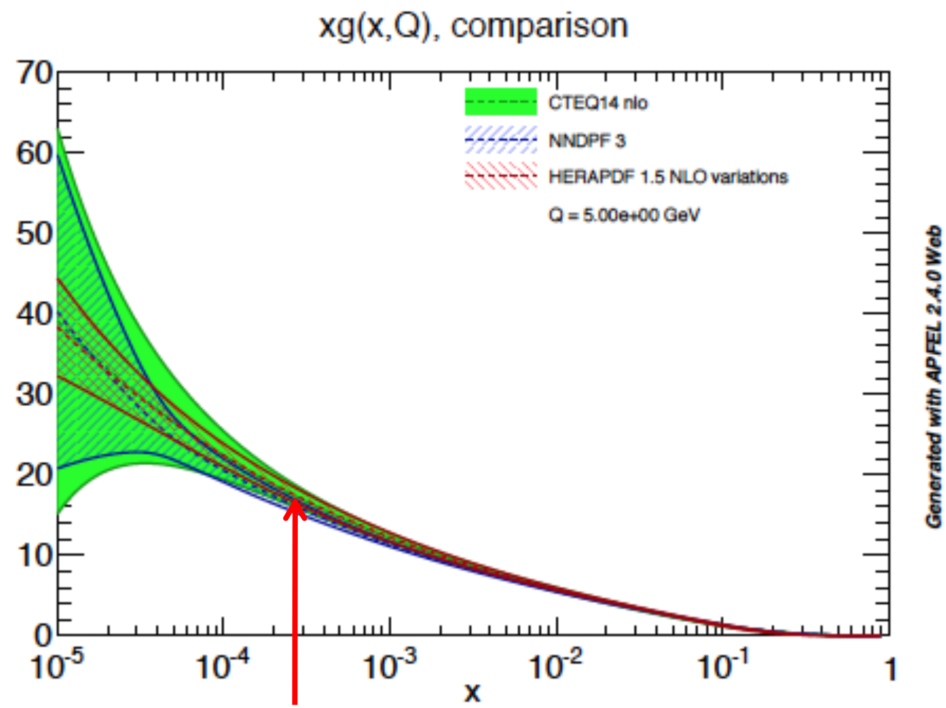
→ LHC has capability of improving PDF precision

… in principle, includes low x PDFs (as well as revealing any new underlying dynamics)

Why low x might cause dangers at the LHC

- Use of PDFs based purely on DGLAP Q^2 evolution at low(ish) x, high Q^2 at the LHC will give incorrect results if there are novel effects in the low x, low Q^2 data …

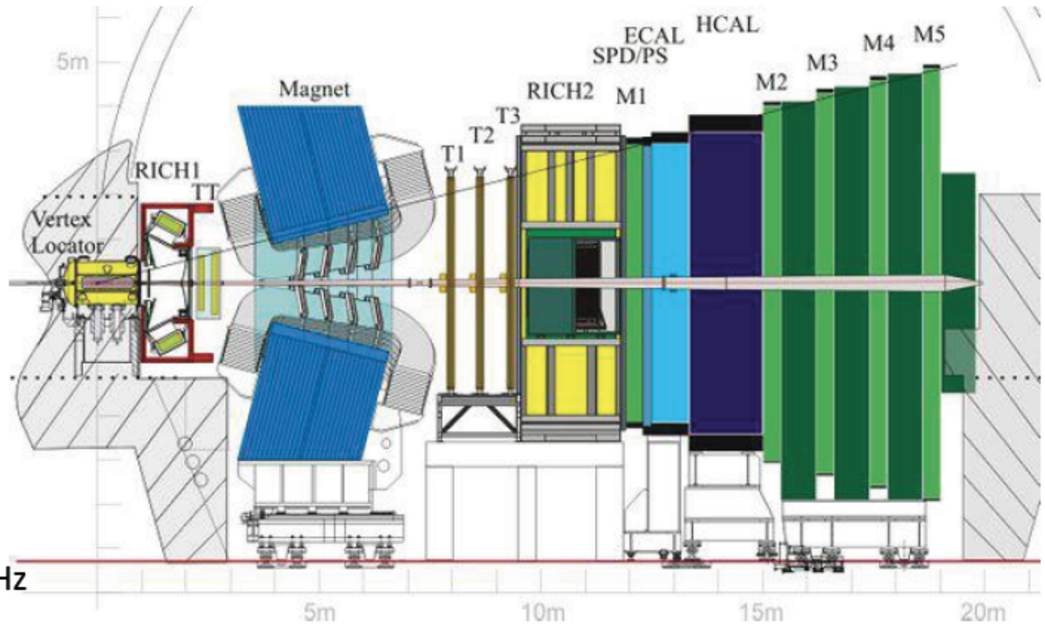




Constrained by HERA data

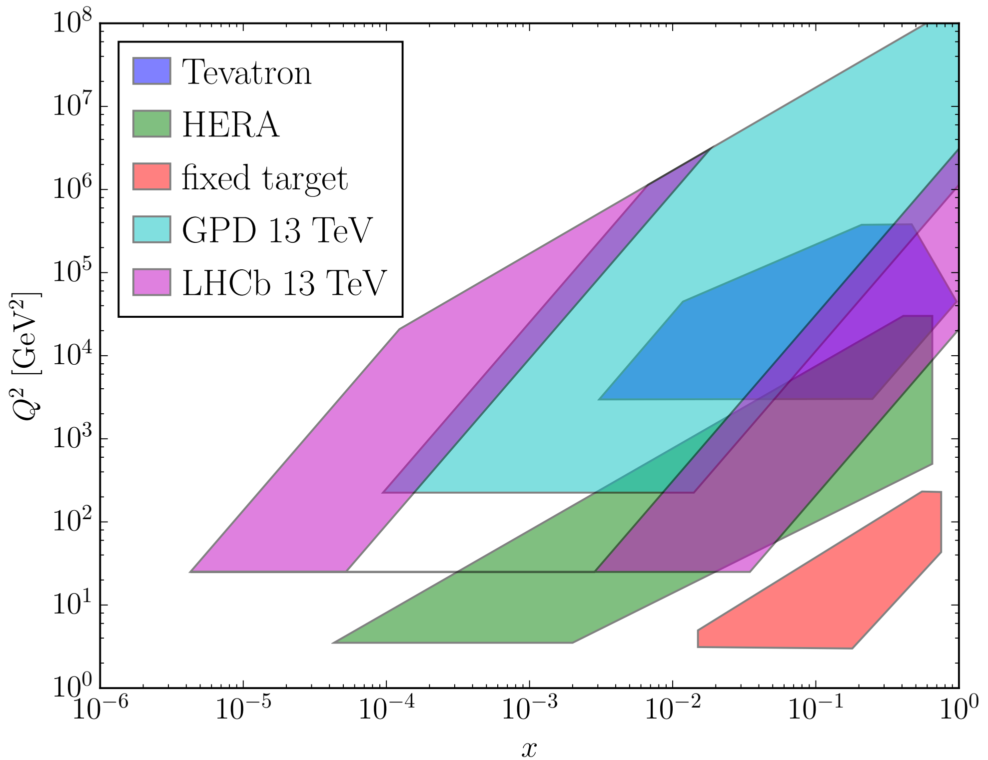
Not directly constrained by HERA data

- Convergence of solutions after DGLAP evolution may already be misleading at the LHC if there are novel evolution dynamics

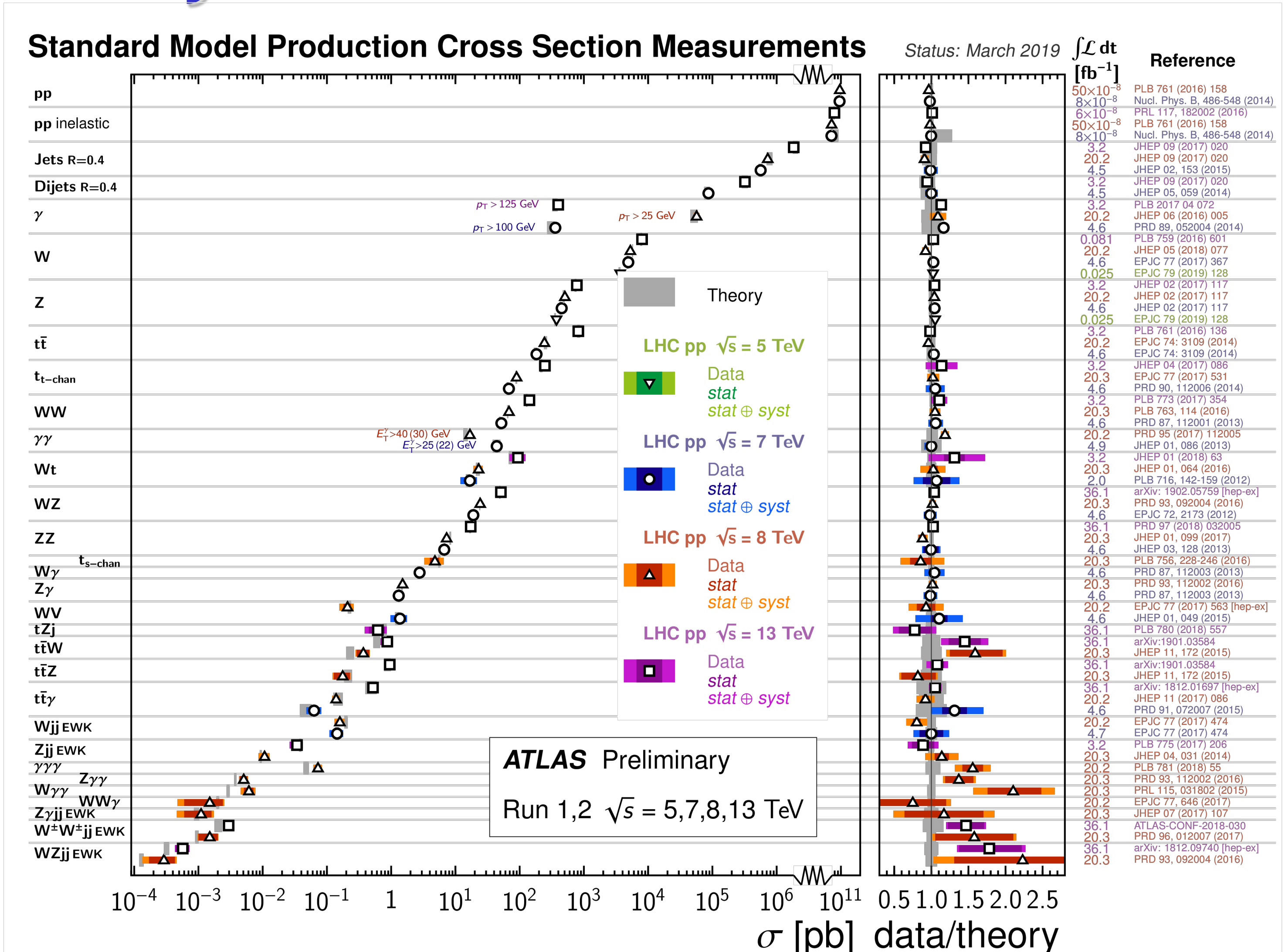


Uniquely Favourable Low x Kinematics at LHCb

- "Fixed target-like" forward instrumentation favours processes with asymmetric incoming x values, giving 'mainstream' sensitivity down to x~10^{-5}
- Even more pronounced in genuine fixed target mode (SMOG at LHCb, AFTER …)



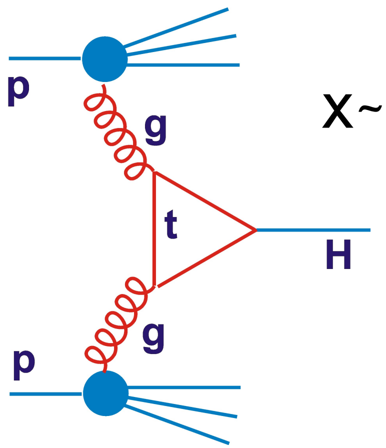
Theory v Data: inclusive variables at LHC



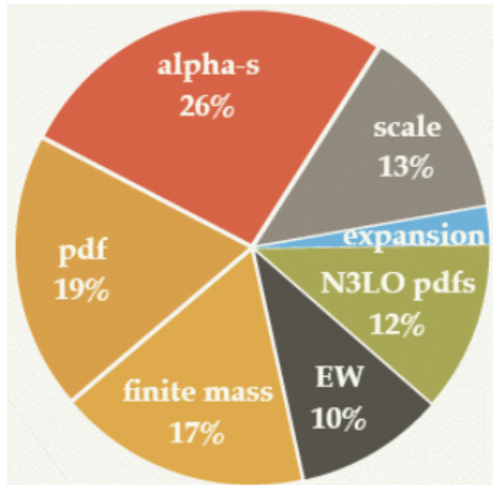
- PDFs are a vital ingredient in almost all predictions
- Factorisation between ep and pp works well overall!
- From LHC point of view, low-x is a small corner

High / Medium x: PDFs Limit LHC Physics

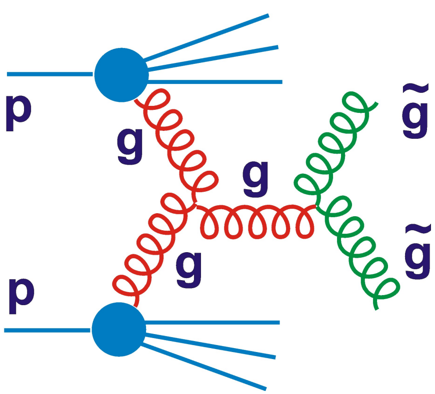
Higgs Cross Section Theory Uncertainties (at N³LO)

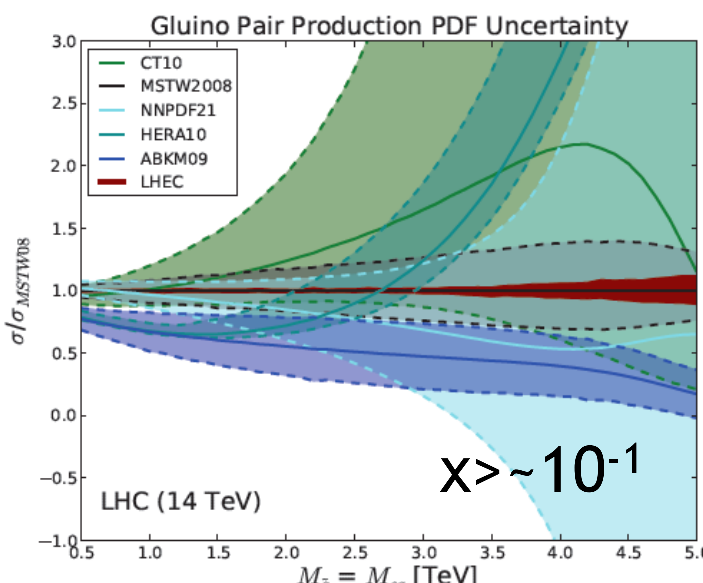


x~10^{-2}

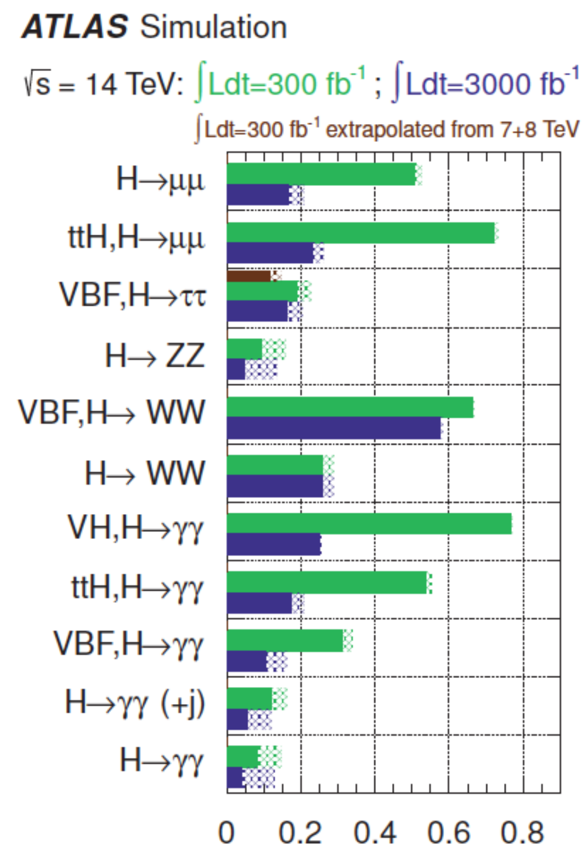


Searches → eg Gluino Pairs



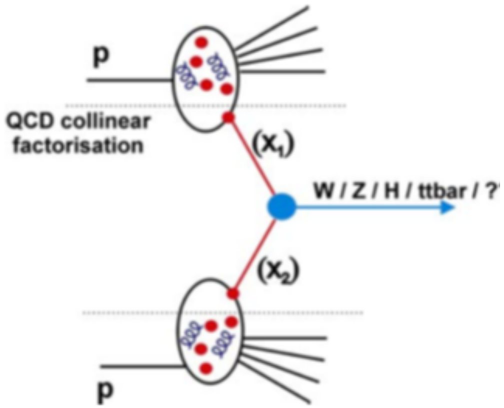


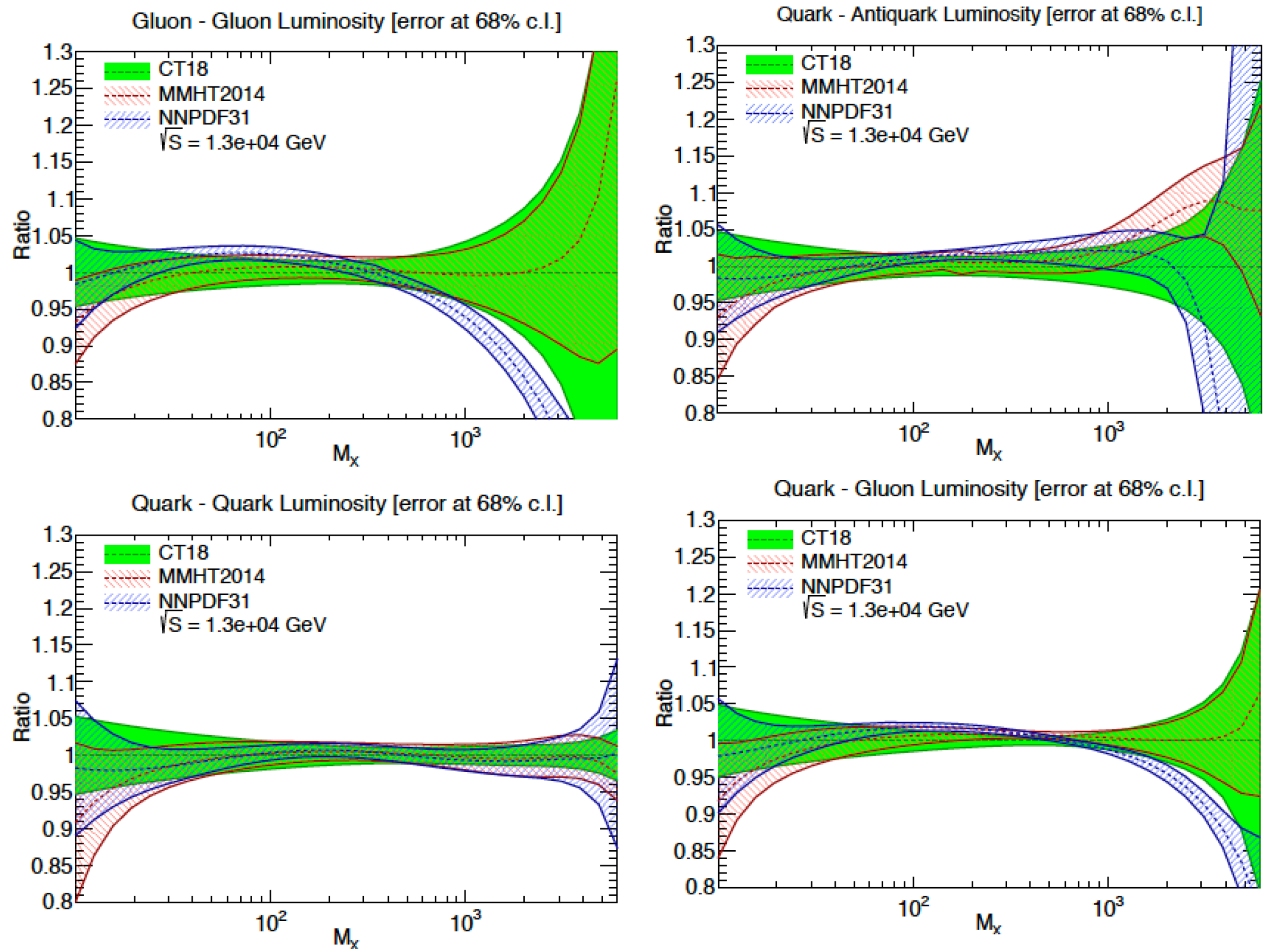
Projected Higgs Coupling Experimental Uncertainties



[Dashed regions = scale & PDF contributions

Current PDF Sets → LHC Kinematics & Low x





- LHC masses produced by low x partons are very low …

At mid-rapidity, $M_X = 2.x.E_p$

… e.g. two $x=10^{-4}$ partons produce M_X = 1.7GeV at mid-rapidity

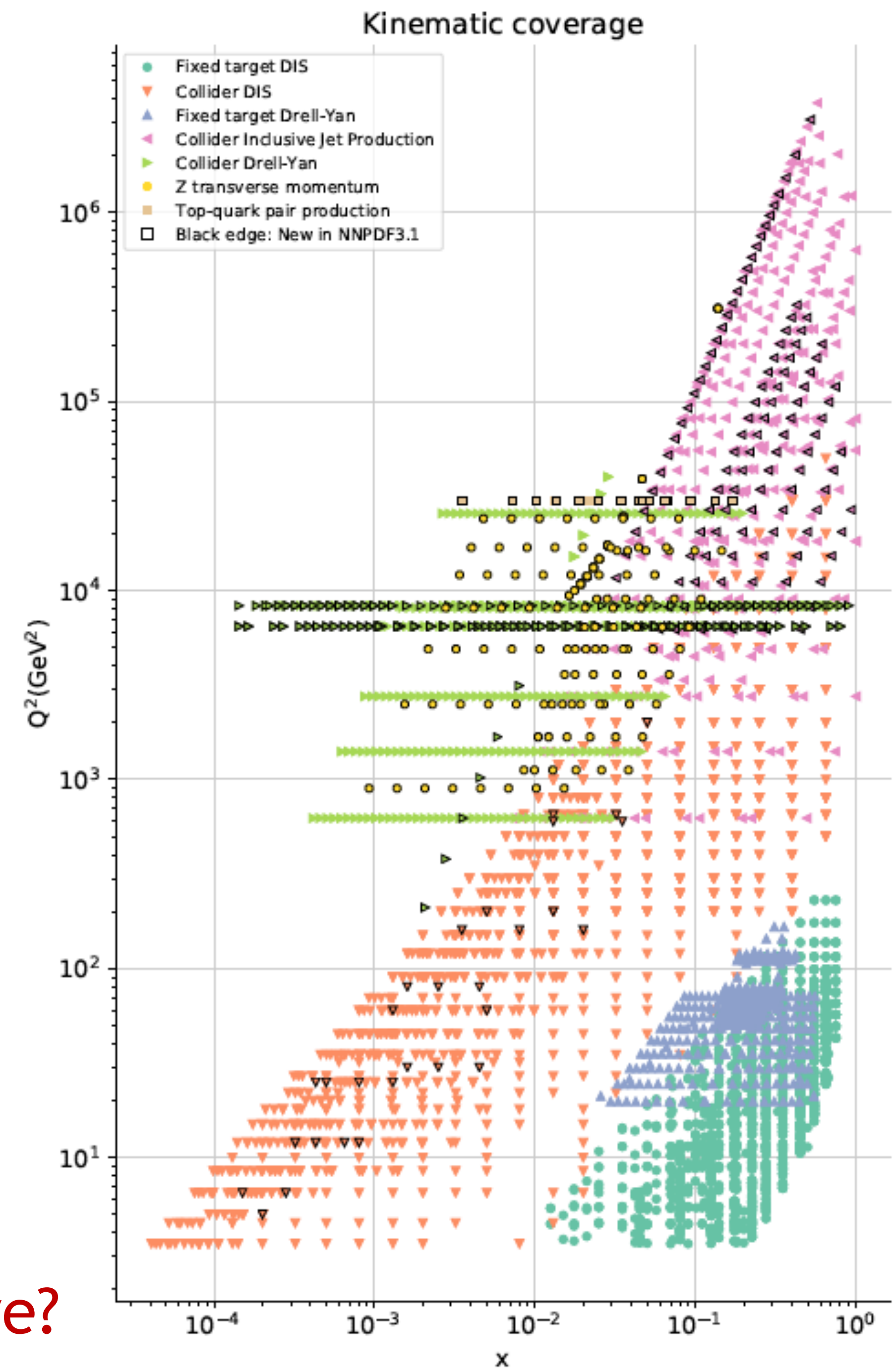
- … low x not very fashionable in LHC collider communnity

There are at Least Some Low-x Sensitive Data

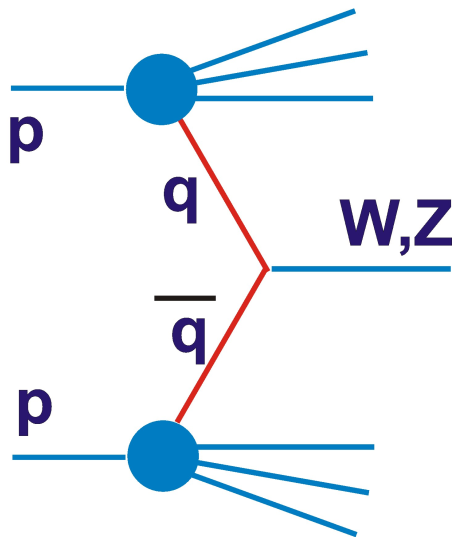
- Global fit ingredients include LHC W, Z, jets, top

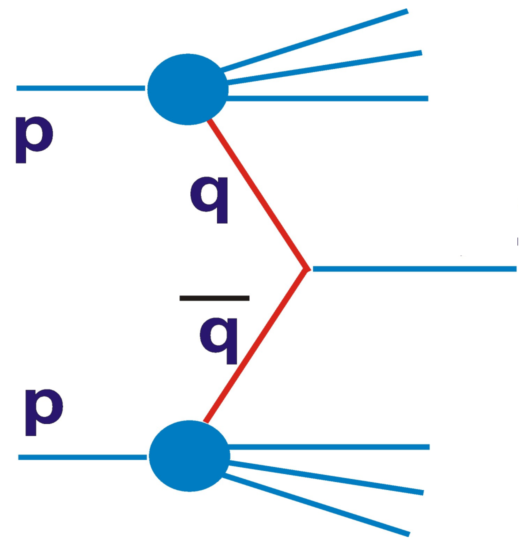
- Eg NNPDF 3.1 → some low-x sensitive observables
  → ATLAS low mass Drell-Yan
  → LHCb forward W & Z

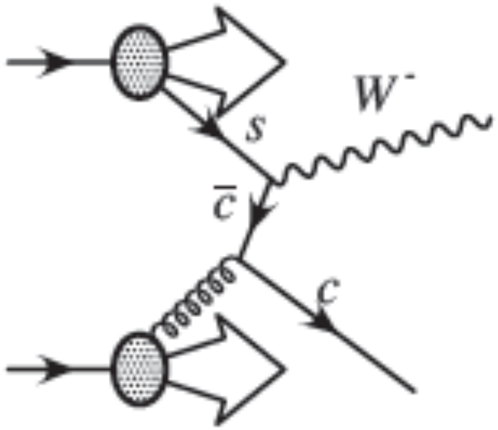
- But which PDFs are they sensitive to?...
- And what impact do they have?



QUARK SENSITIVE LHC OBSERVABLES





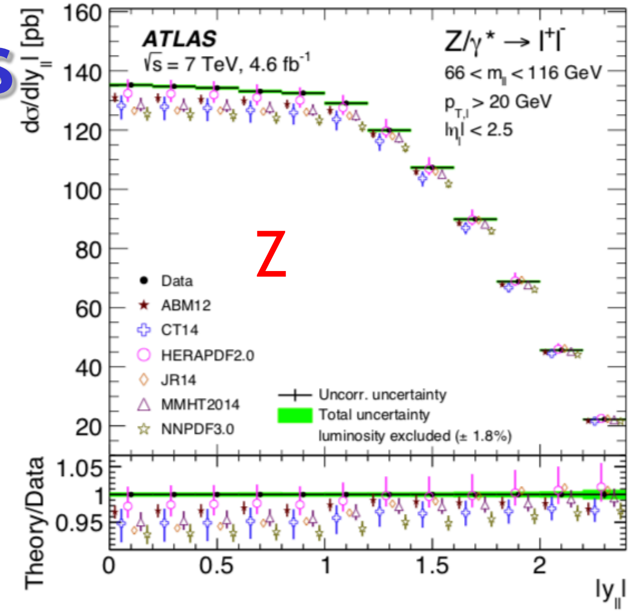


- Electroweak gauge boson production

- Drell Yan below the Z pole

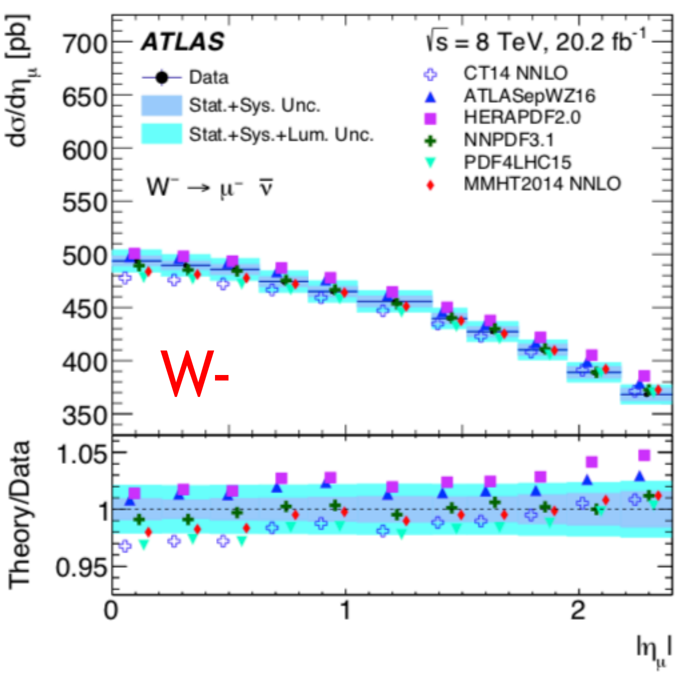
- W + charm

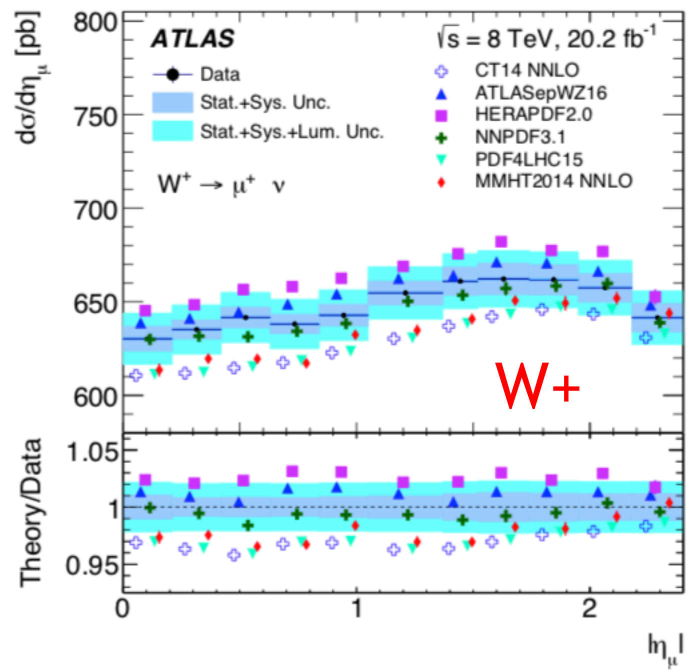
Differential W, Z Cross Sections



- Normalisation (~2% precision) already distinguishes PDF sets

- Differential distributions give added sensitivity, particularly to flavour decomposition …

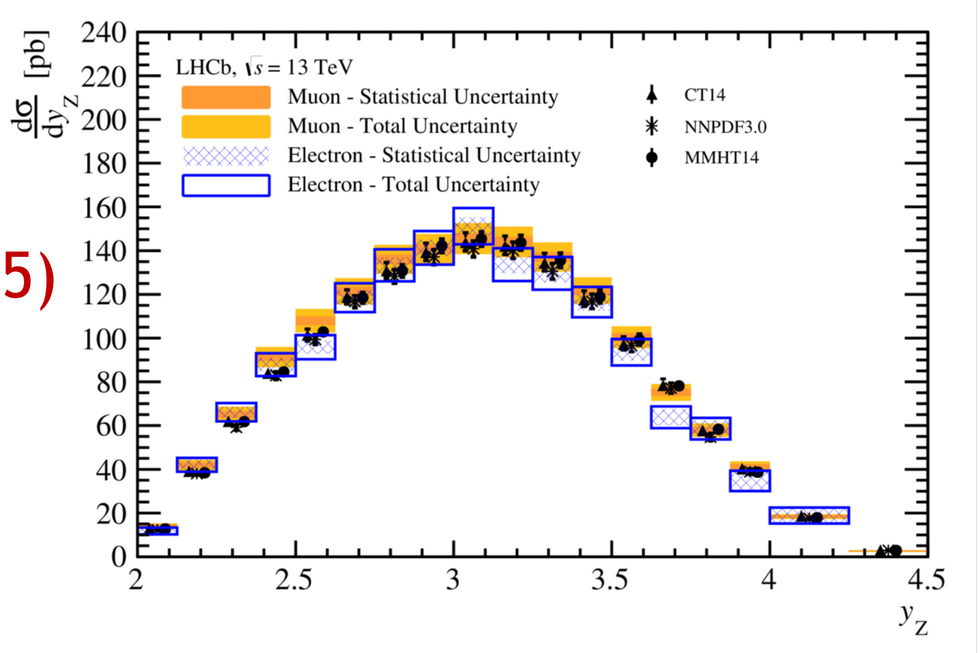


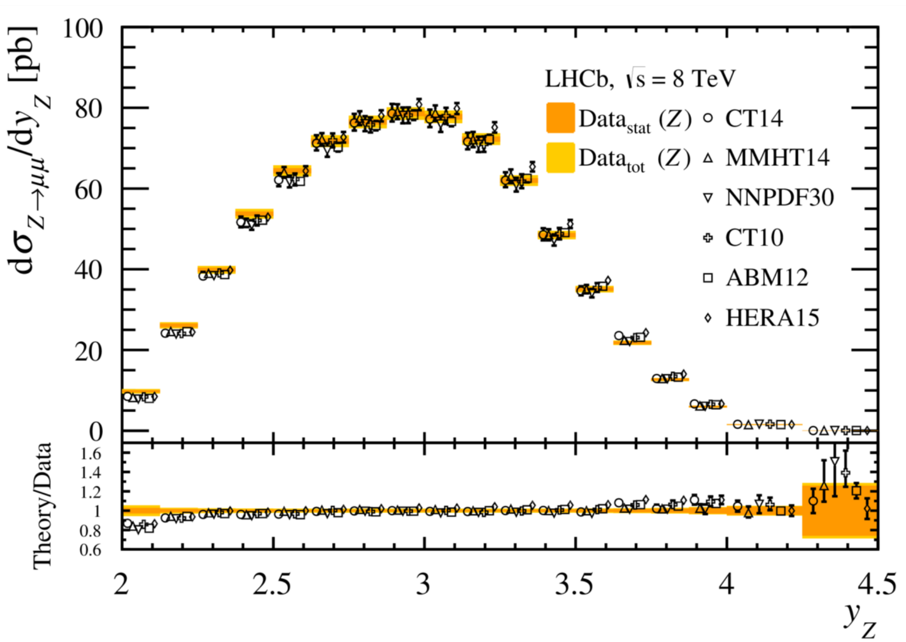


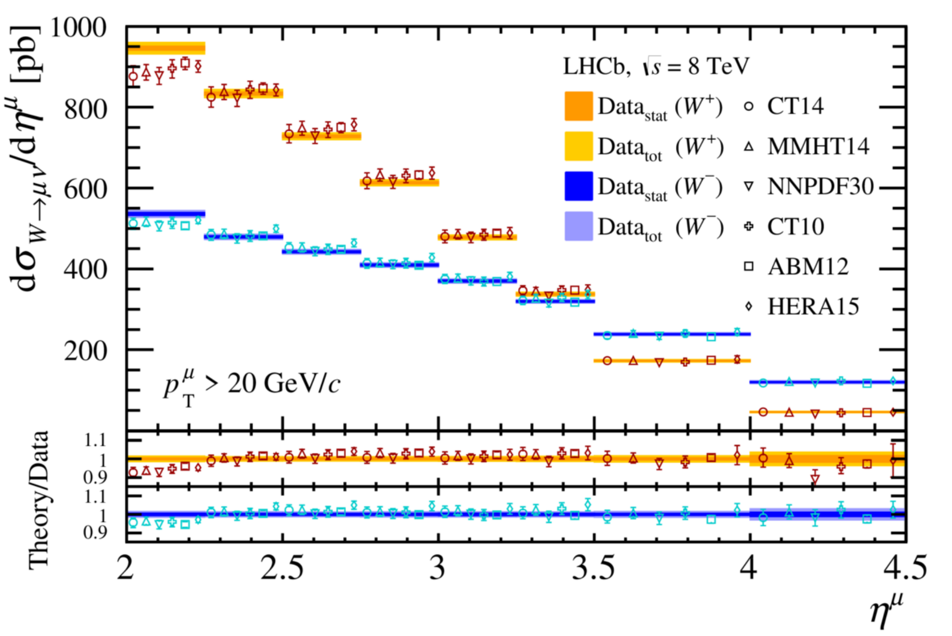
- Z p_T dist's also in NNPDF3.1 → consistency, but limited impact

LHCb W and Z

- Forward kinematics (2 < η < 4.5) promising
- Full Run 1 data (7TeV and 8TeV) included in PDF fits
- Run 2 data also now published

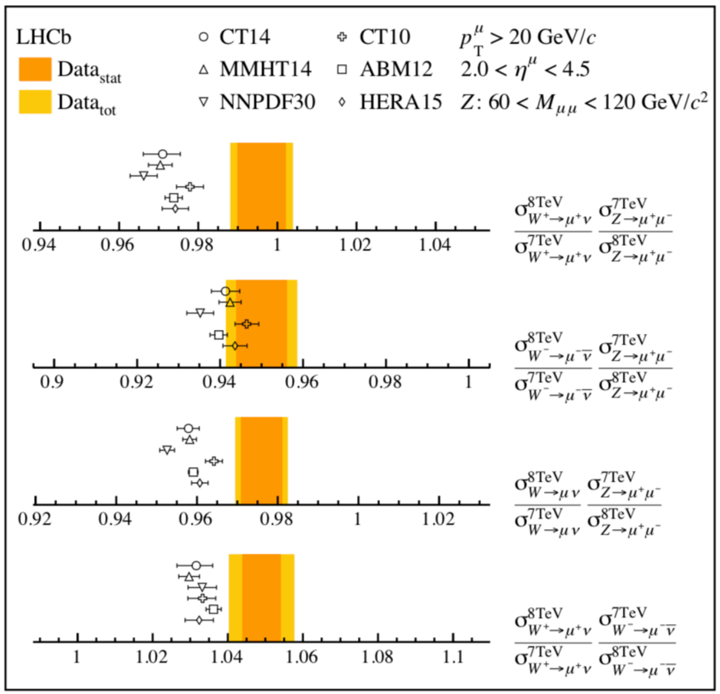


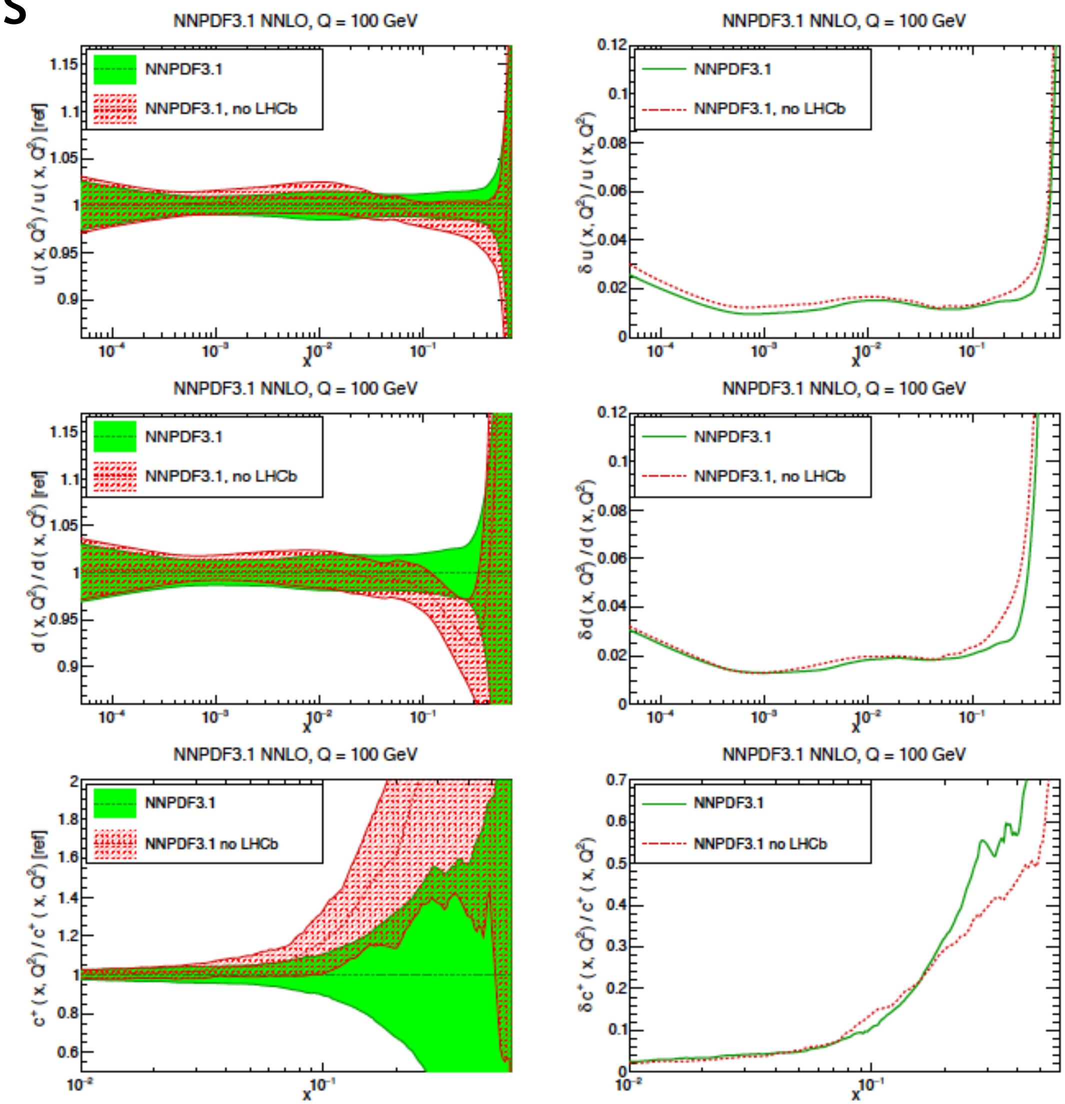




LHCb W and Z data

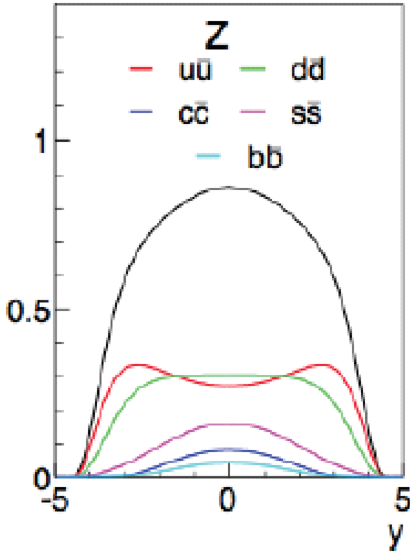
- Ratios W/Z (or ratios of ratios 8TeV/7TeV) look powerful!
- The data have an impact (see shifts in central values) and reductions in uncertainties



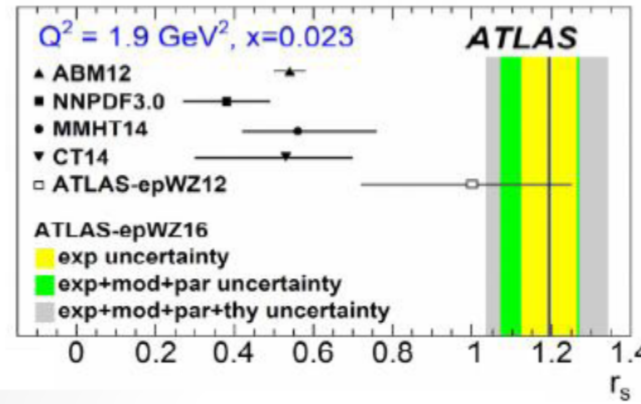


… BUT almost entirely restricted to large x

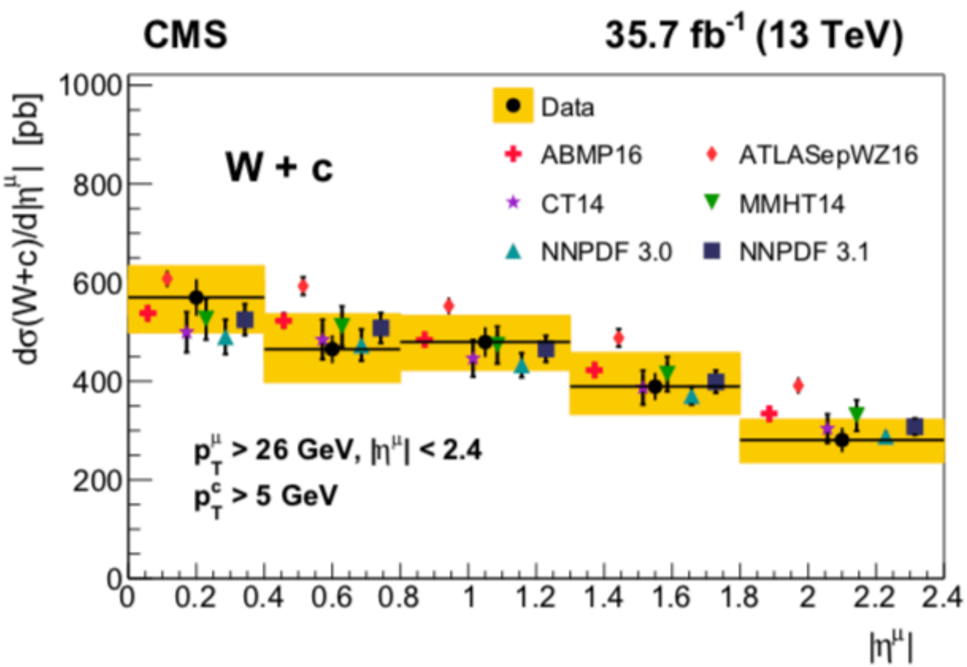
Strange Density



- Z differential rapidity distribution at central rapidity sensitive to s+sbar
- Suggested strange not suppressed relative to u,d

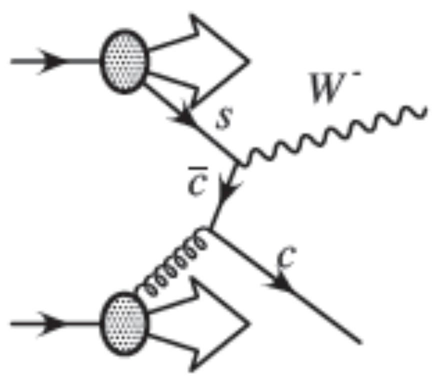


Final states with W + charm more directly sensitive to strange

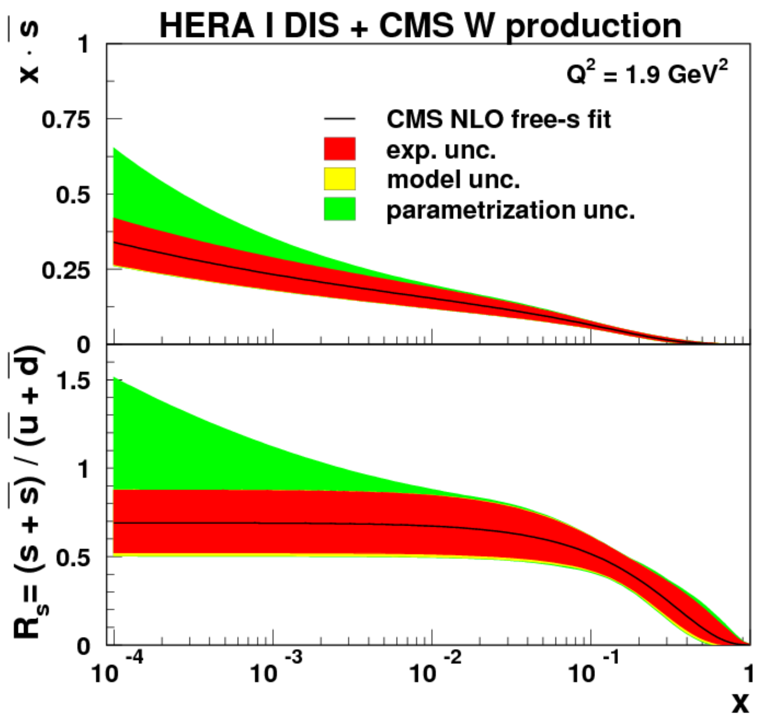


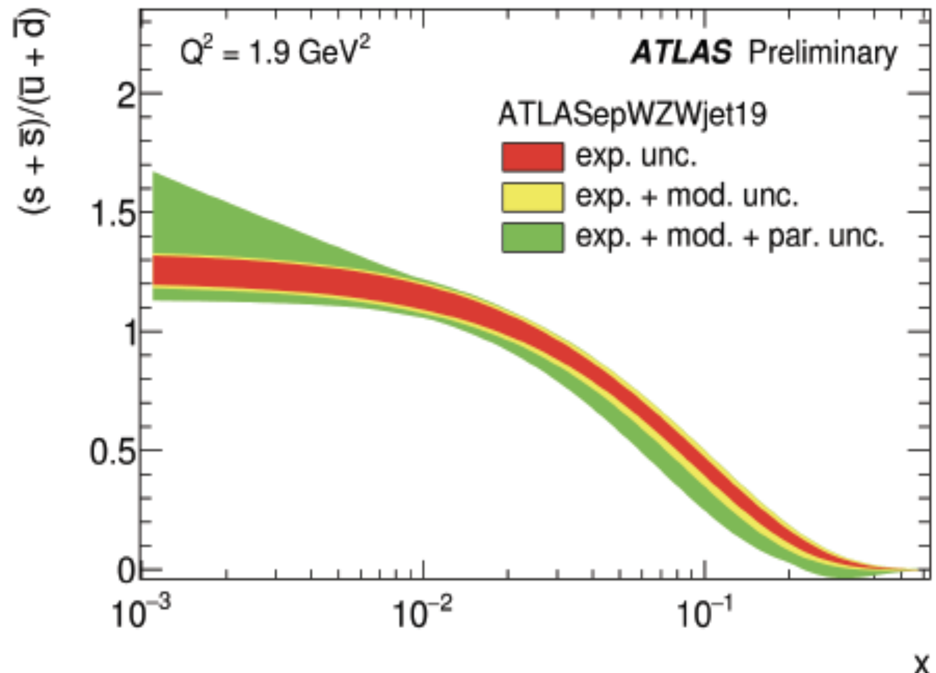
Measurements using fully reconstructed D(*) or leptons associated with jets.

Cross section comparisons at NLO …



Latest ATLAS / CMS Word on Strange PDFs Including W+jet data



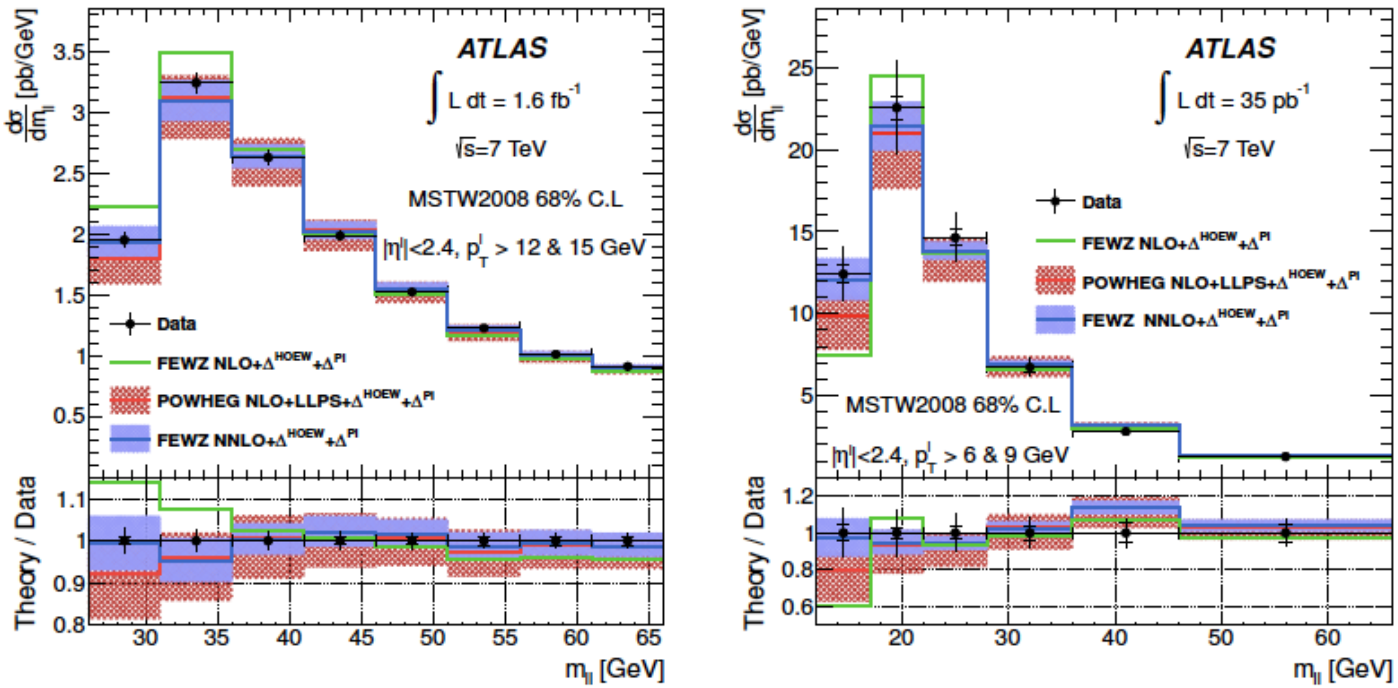


- Marginal agreement between ATLAS and CMS

- Plots extend to genuinely low x ☺

- Low x “parameterisation uncertainty” indicative of lack of direct constraints

Drell-Yan Below Z Pole



- Lowest x direct constraints come from DY q qbar→ l+l- at low m_{ll} → eg ATLAS dedicated sample down to m_{ll} = 12 GeV

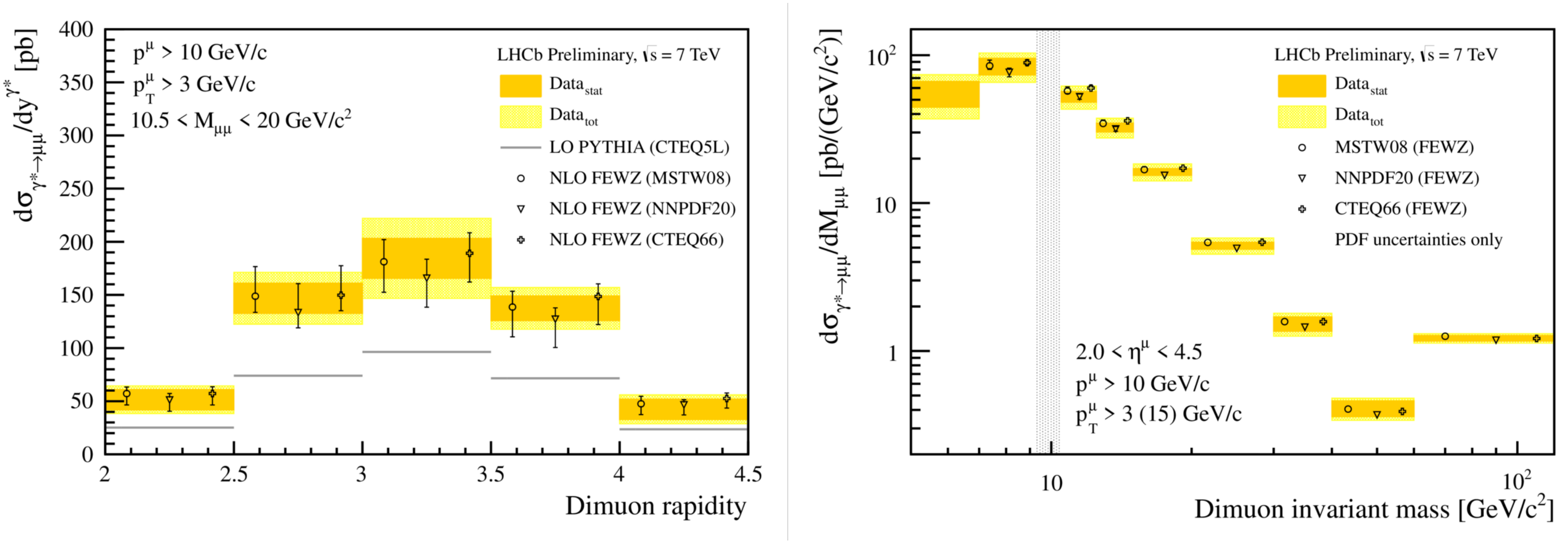
- Significant improvement in data description when NLO → NNLO

- MSTW2008 PDFs adequate to describe → well understood?...

- Now included in NNPDF3.1

Drell Yan at low mass in LHCb

- CONF note 2012 … still yet to be published?...

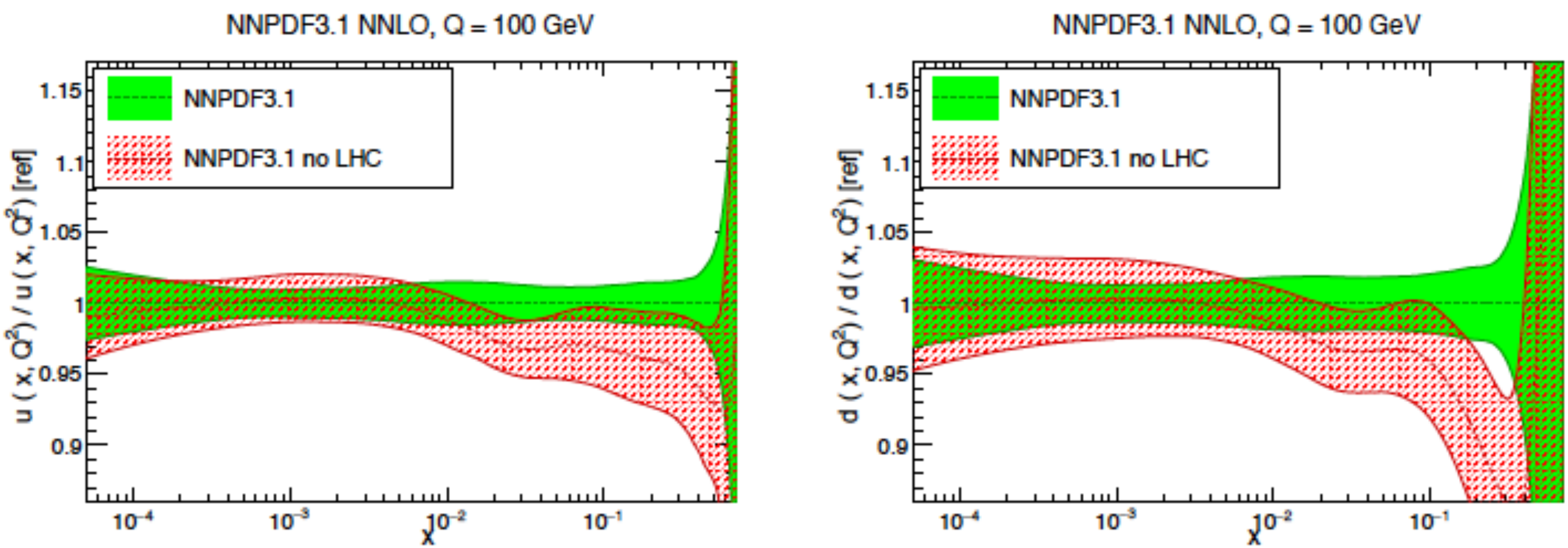


- Data extend to m_{ll} = 5 GeV at forward rapidities!

- (NLO) comparisons with previous generations of PDF sets don't show much distinguishing power

- Improved experimental precision may be possible?

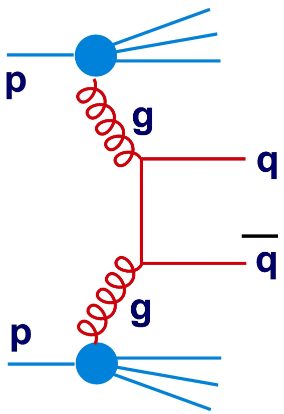
SUMMARY OF LHC IMPACT ON QUARKS

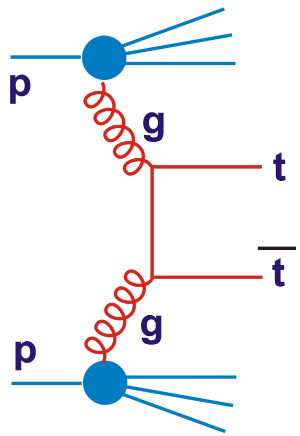


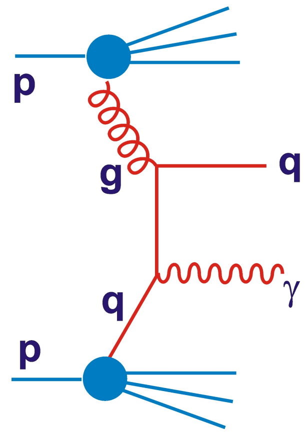
- LHC has contributed, mainly through low mass Drell-Yan, particularly to down density

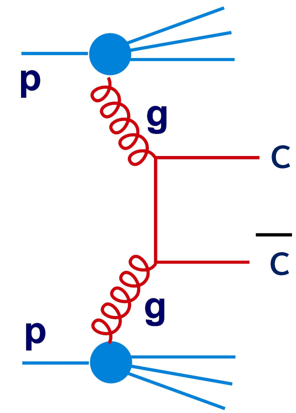
- Primary constraints still come from HERA

GLUON SENSITIVE LHC OBSERVABLES



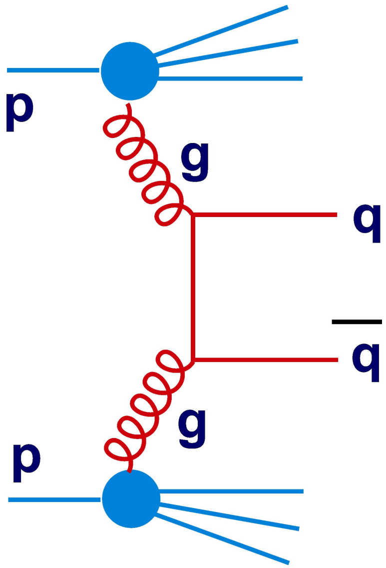


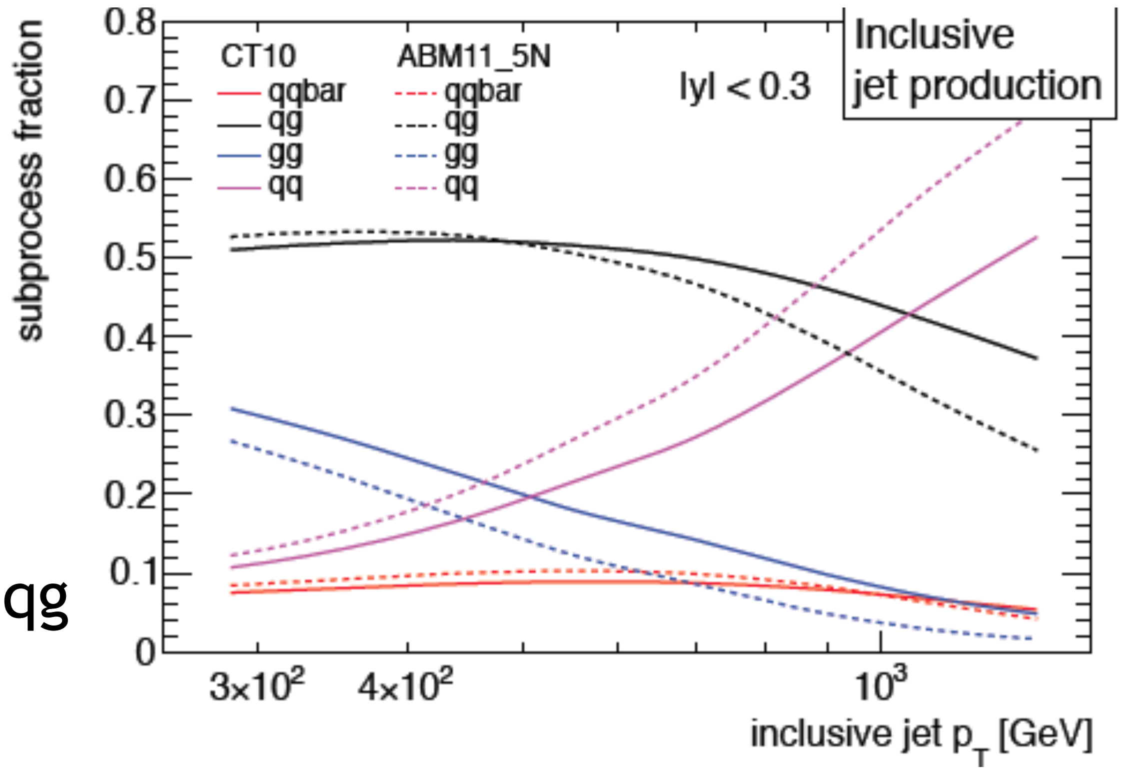




- Jet production
- Top Quarks
- Direct Photons
- Charm Production

Jet Production





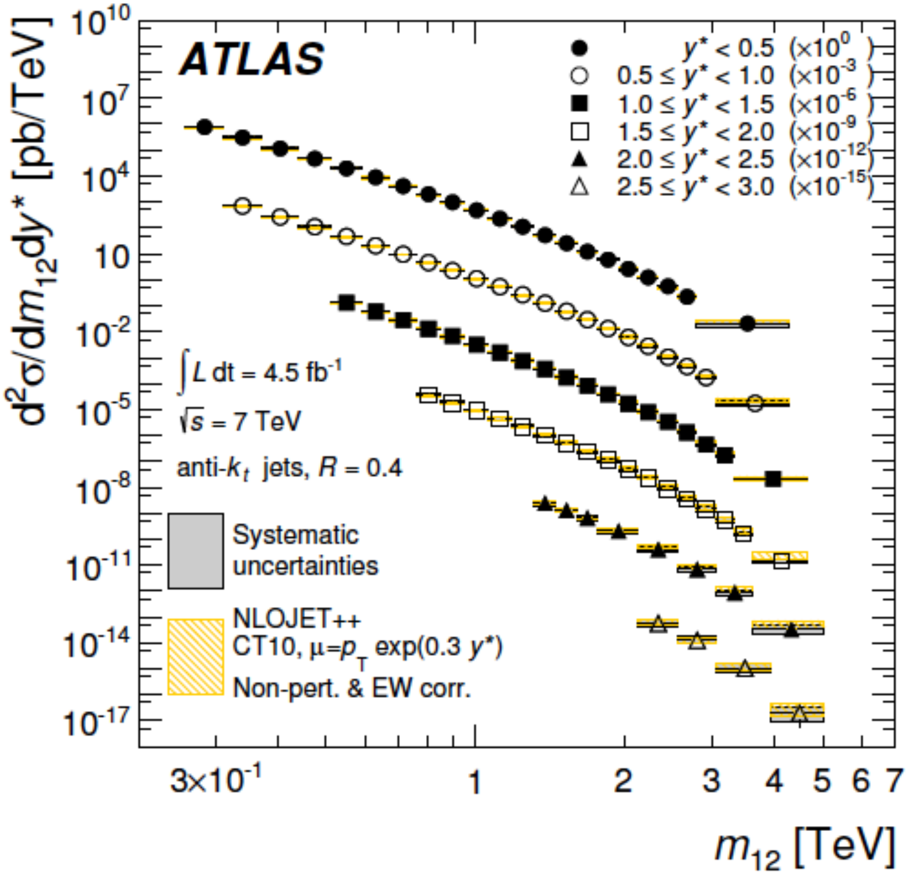
- Gluon-sensitive, though even at low(ish) p_T, qg → qg is larger than gg → gg

- Rates very high

- Limited experimentally by jet Energy Scale Uncertainty and non-perturbative corrections to the jets

- Recent availability of NNLO calculations increases interest

e.g. ATLAS Dijet Data



- Remarkable kinematic range

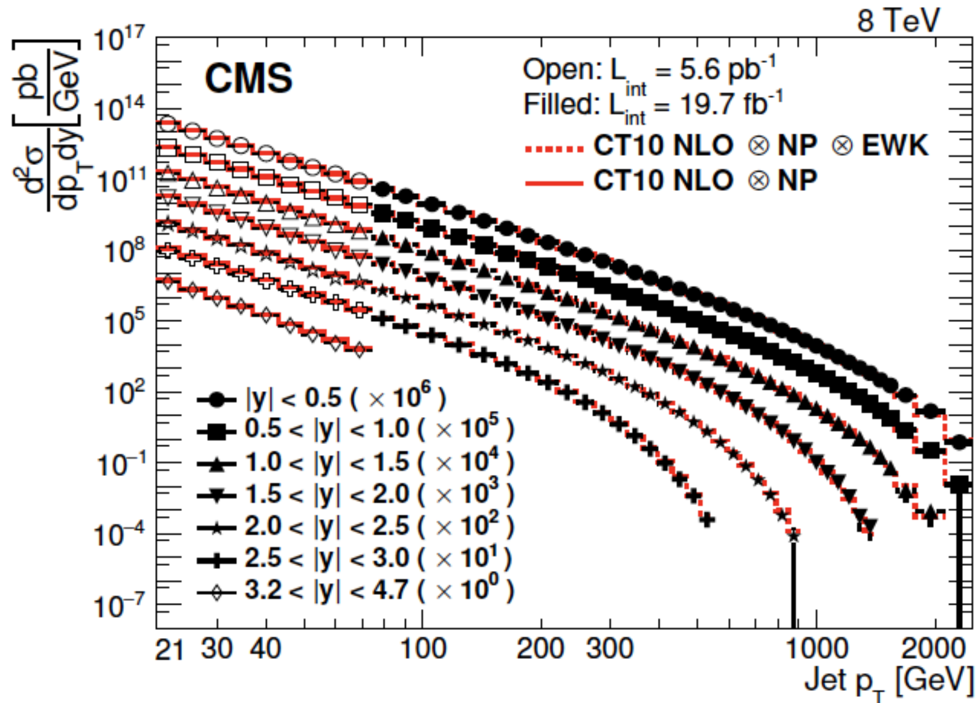
- ~2% jet energy scale uncertainty

- QCD does impressive job of describing data extending to dijet invariant masses 5 TeV

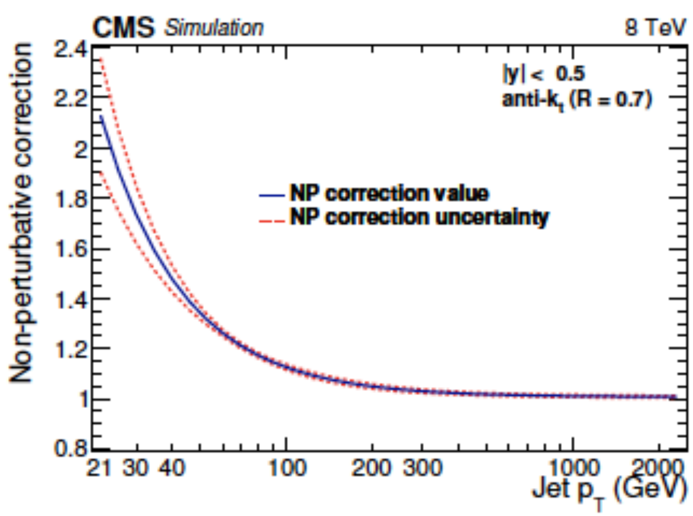
- BUT kinematic region of mainstream jet analyses is high p_T and large invariant masses → not generally well suited to low x physics

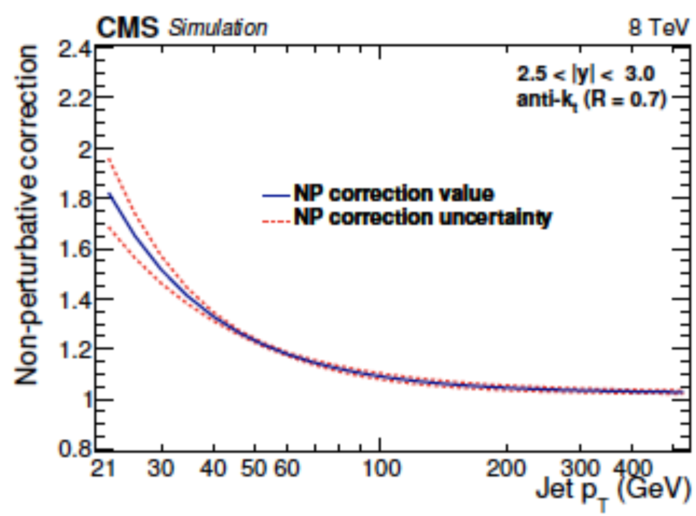
e.g. CMS 8 TeV Dijet Data

- Dedicated analysis in low pile-up sample leads to data at low(er) p_T and large $|\eta|$, with improved low-x sensitivity

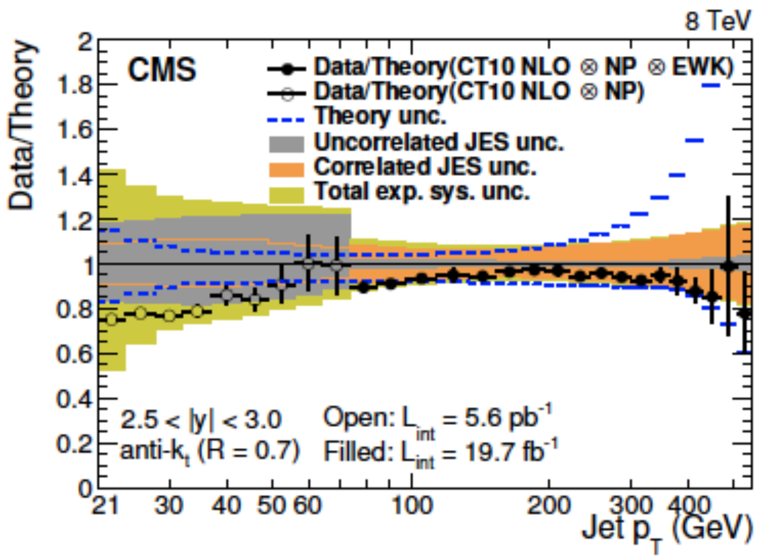


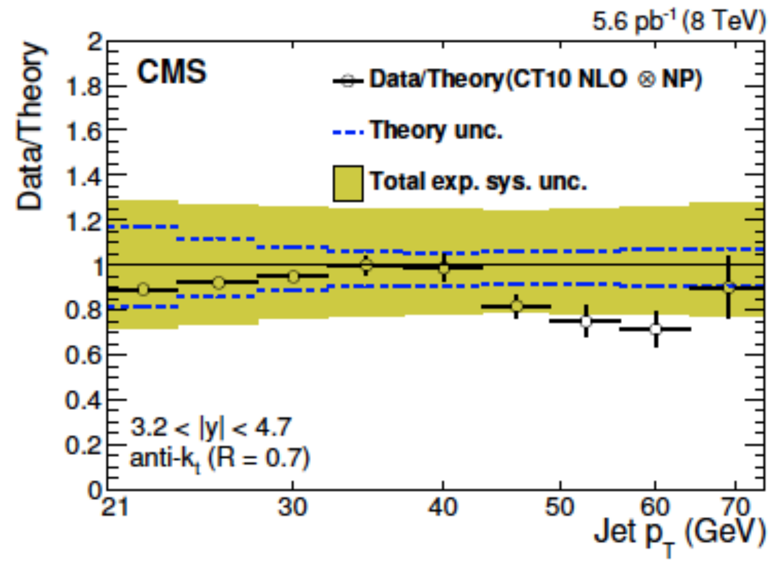
- Also brings bigger non-perturbative corrections and associated uncertainties (hadronization, underlying event)

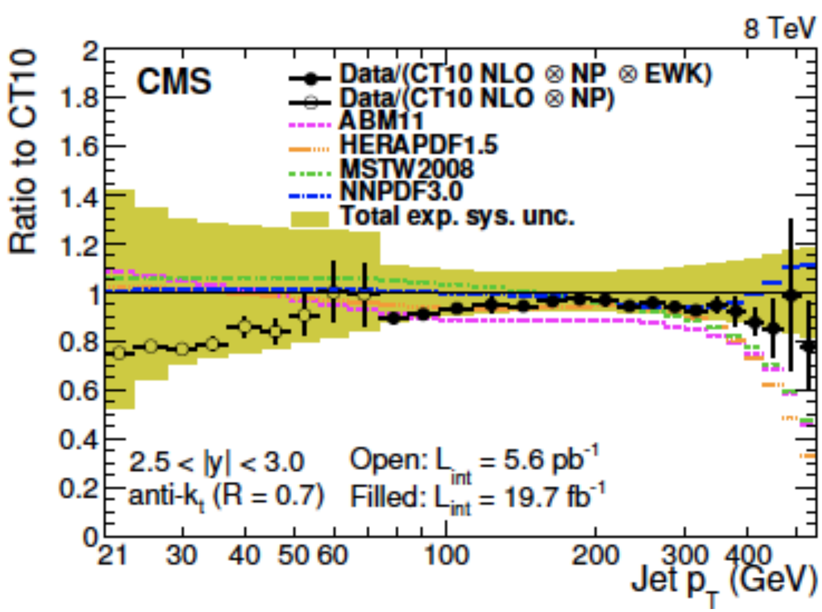




CMS 8 TeV Dijet Data



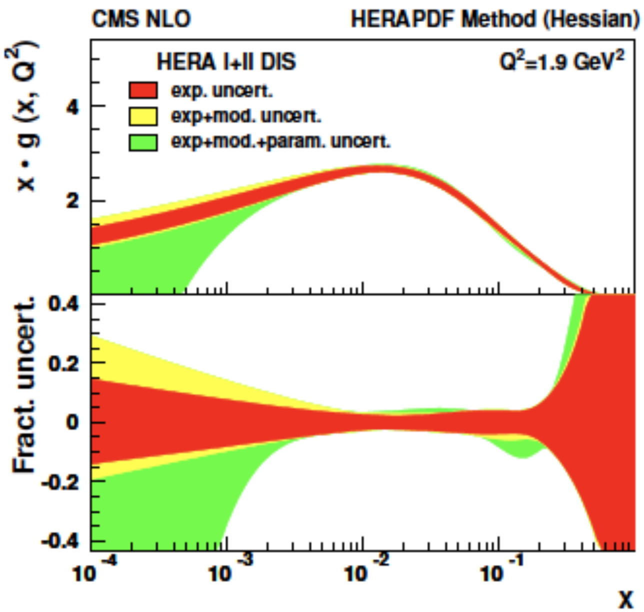


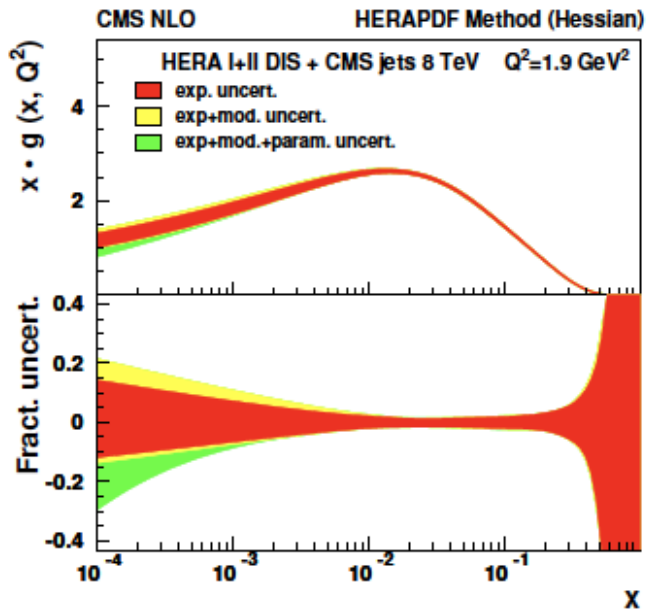


- In highest rapidity bins, low p_T data appear to deviate from all (NLO) predictions

- However, deviations are within the (large) experimental and theory uncertainties

CMS (NLO) QCD Analysis including jet data

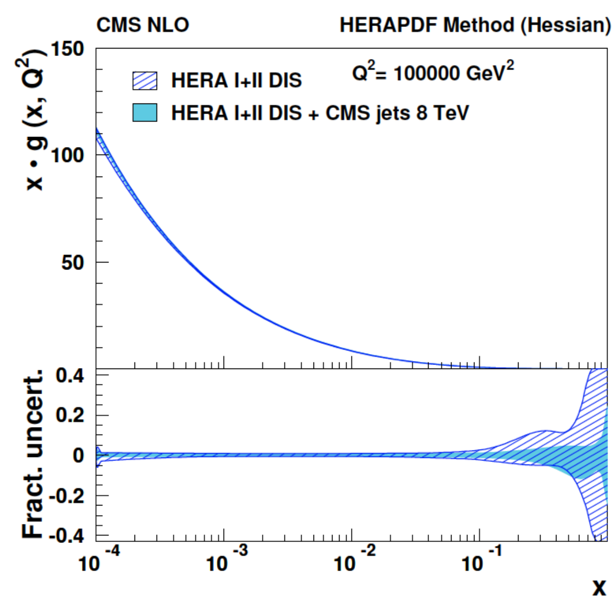




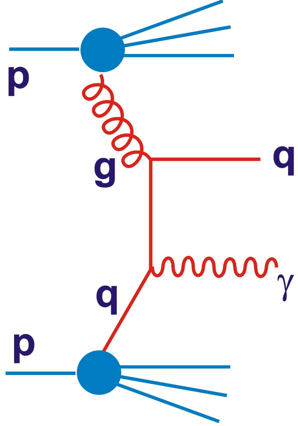
- Some impact at lowest x and parameterization scale, in terms of addressing HERA param'n uncertainty

- Low x influence washes out with DGLAP evolution to large scales

- High x influence survives

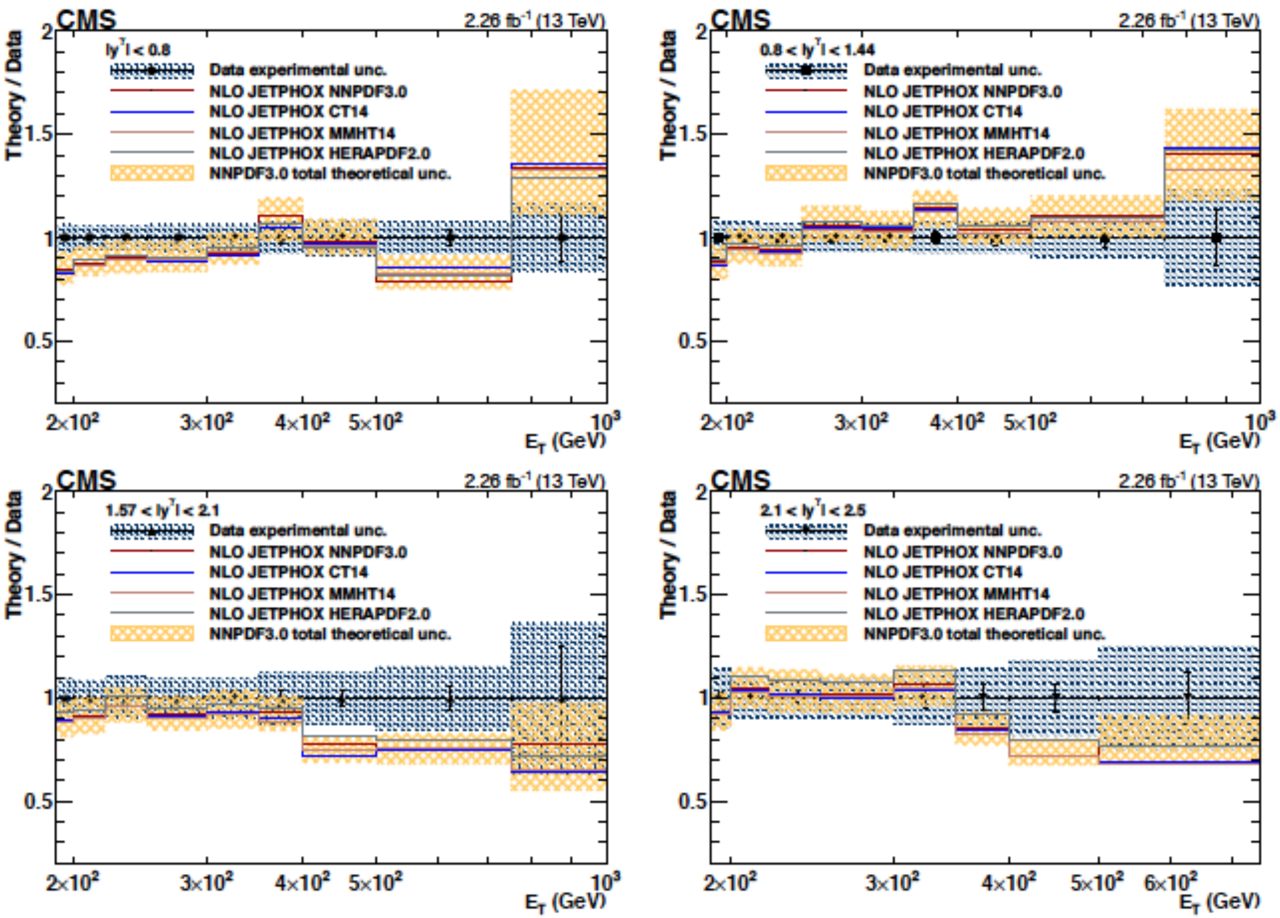


What about Direct Photons?



Dominant diagram is ug → uγ (~60% of cross section)

Previously limited by questionable agreement with NLO (eg Jetphox) … but NNLO now exists



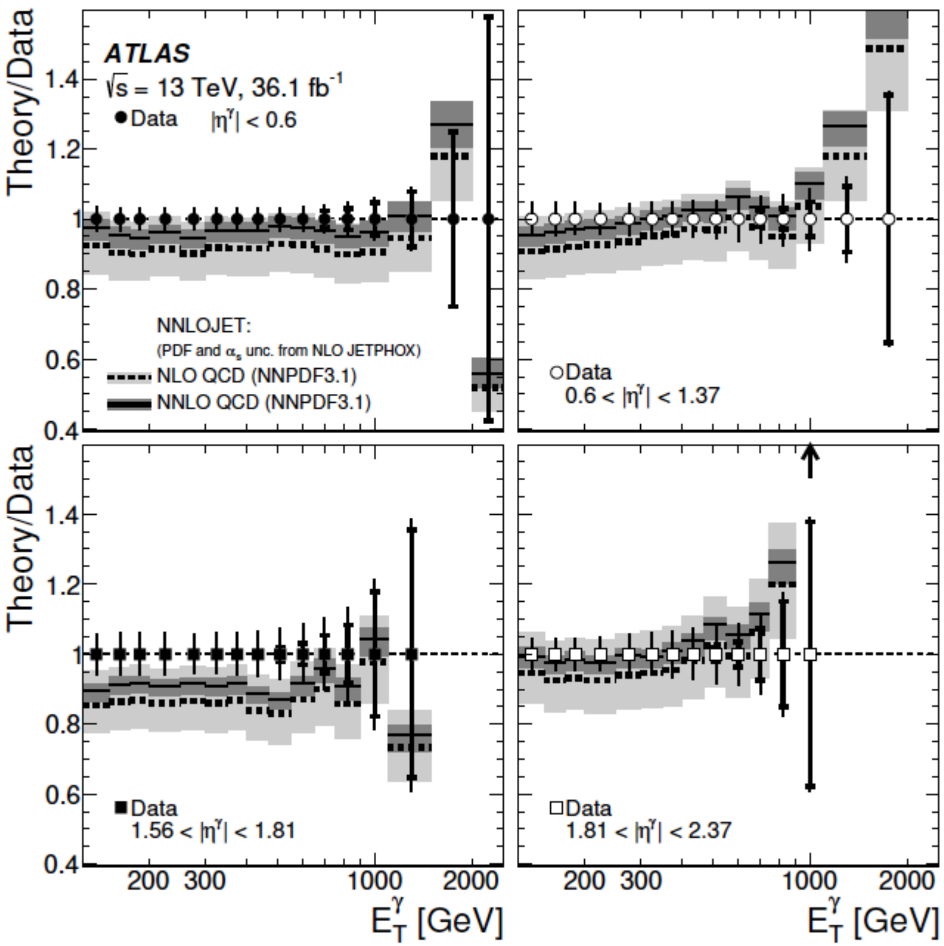
e.g. recent CMS 13 TeV data

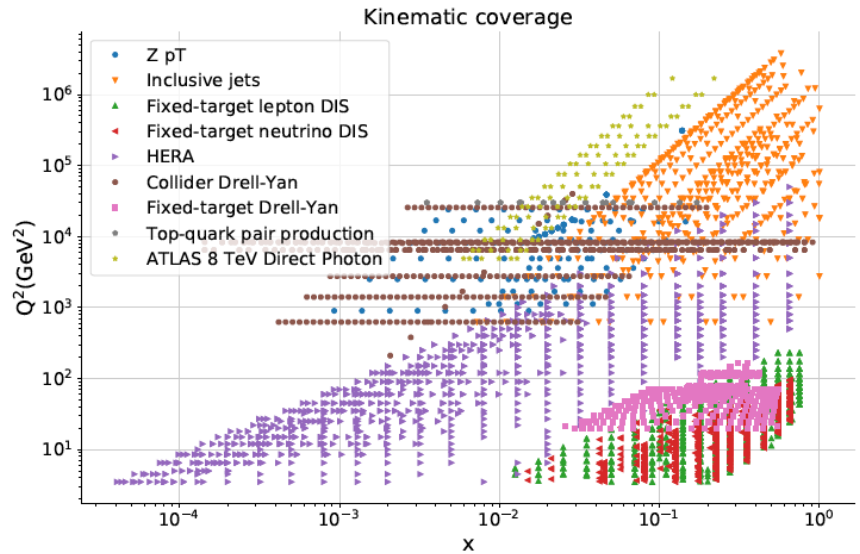
Deviations between PDF sets much smaller than deviation from NLO and theory uncertainty band

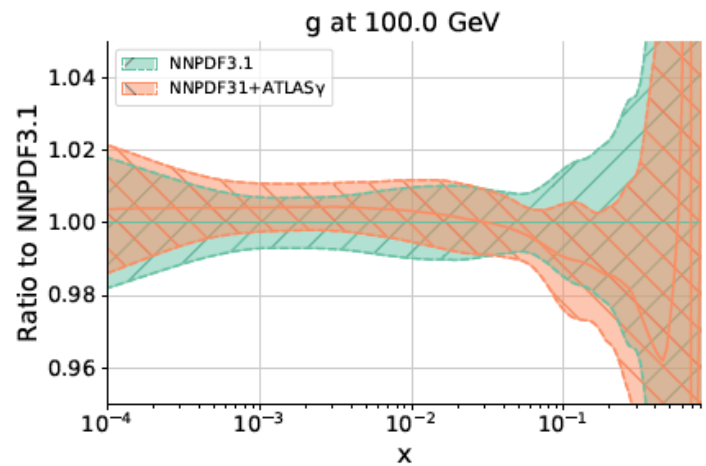
(this is highish x)

ATLAS Direct Photons and NNLO

NNLO scale variation uncertainties much reduced and agreement with data improves

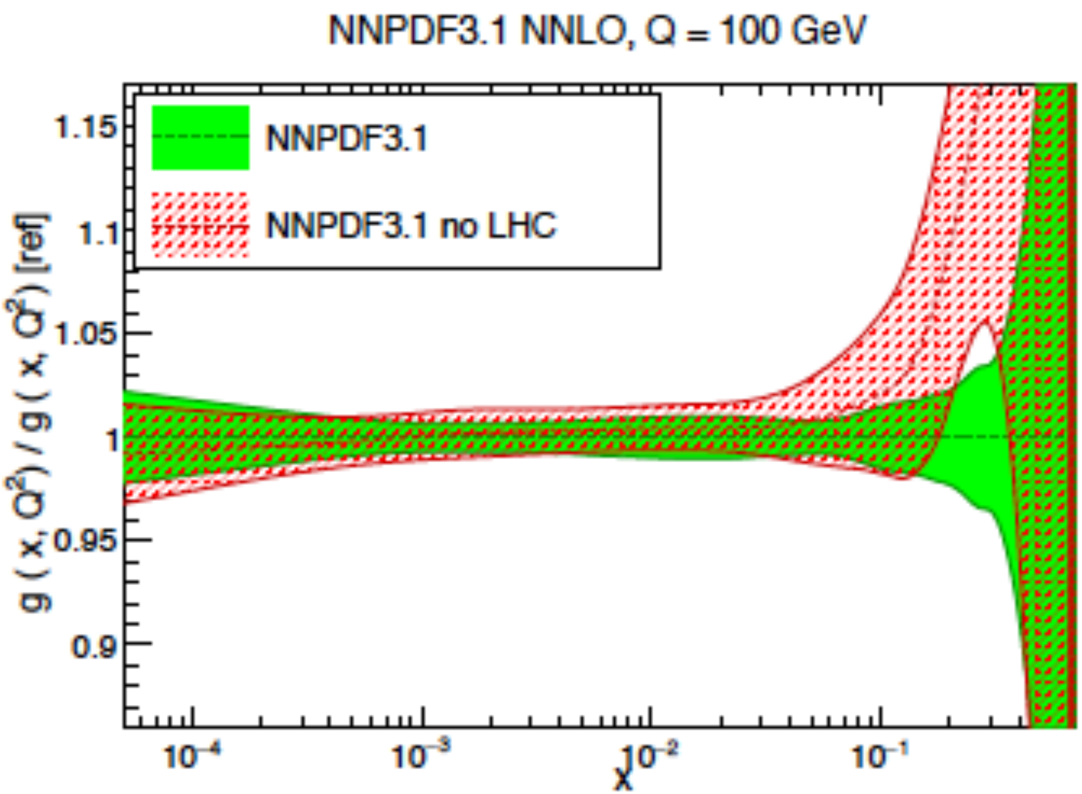


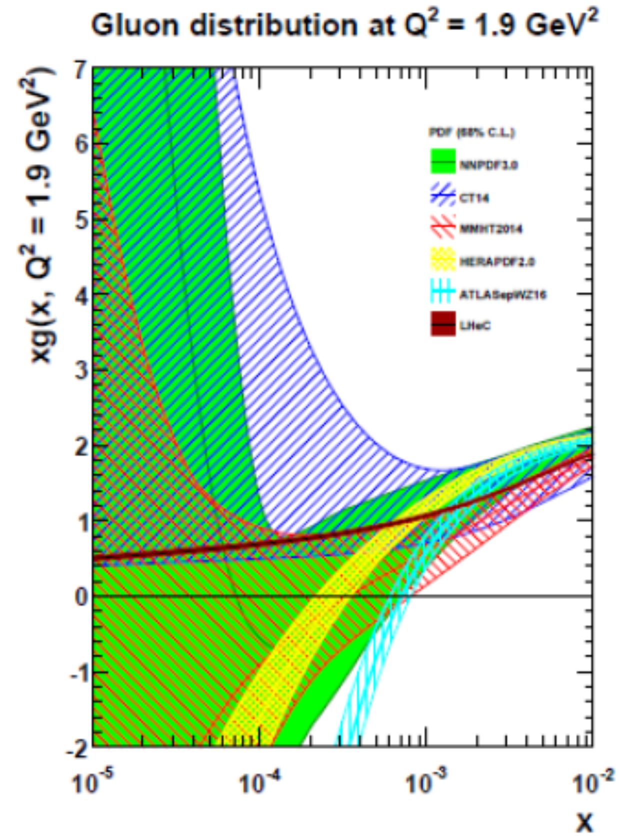




- Still $E_T(\gamma)$ > 125 GeV → sensitivity is at high x >~ 10^{-2}
- Extend to lower values? - Issues with isolation / γ from frag?)

SUMMARY OF LHC IMPACT ON GLUONS





- (Mainstream) LHC data don't extend (much) below 10^{-3}
- Current knowledge basically still comes from HERA

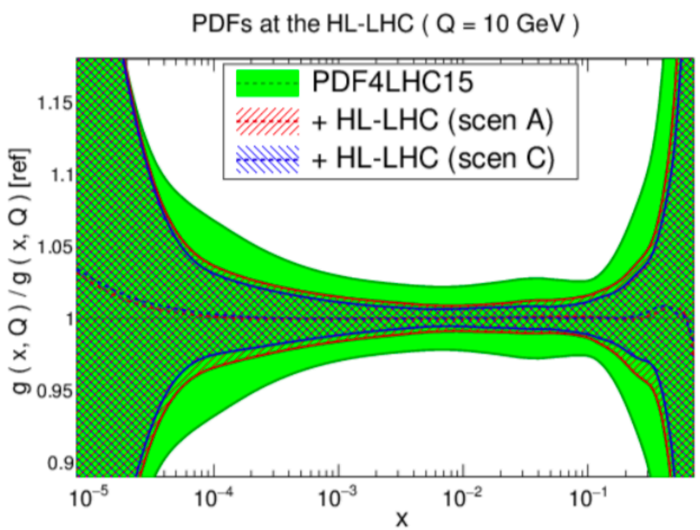
- Is there really no direct probe of gluon at lower x with well-controlled theory?...

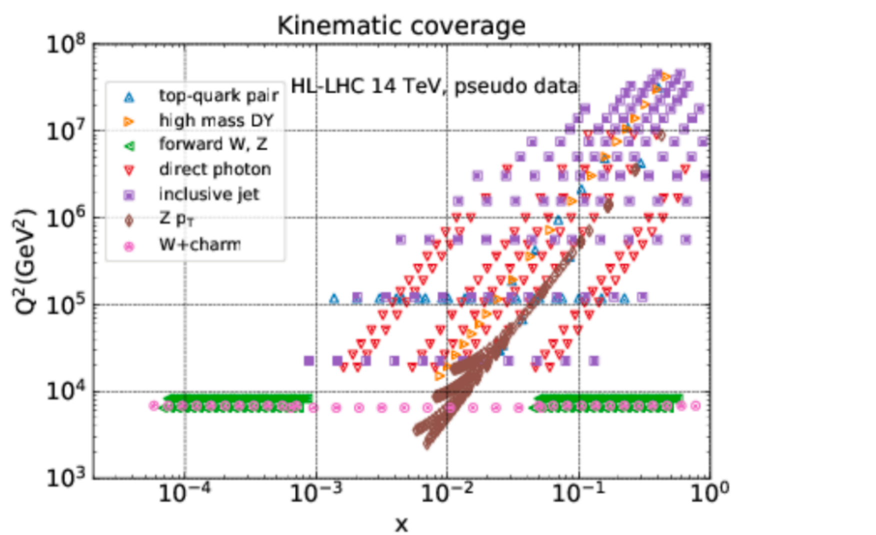
Can we Expect More from Mainstream LHC?

- With pile-up ever increasing (→ 200 at HL-LHC), systematics on 'standard candle' measurements unlikely to improve dramatically

- Kinematic range issues could be addressed with dedicated low p_T running and forward focus, but requires lots of work to reach good level of understanding and change of culture (always tensioned against loss of luminosity for searches etc)

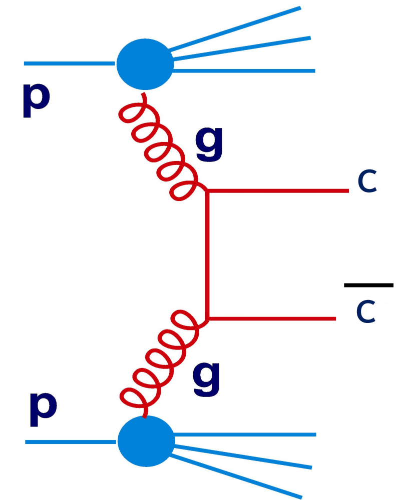
- HL-LHC projections in optimistic scenarios suggest some limited further improvement down to $x \sim 10^{-4}$ by end of LHC era





New Observables? - Gluons from Charm

- Exclusive production of D mesons is dominated by gg → ccbar



- Scale set by charm mass / p_T → LHC data at large rapidity are potentially highly sensitive to gluon

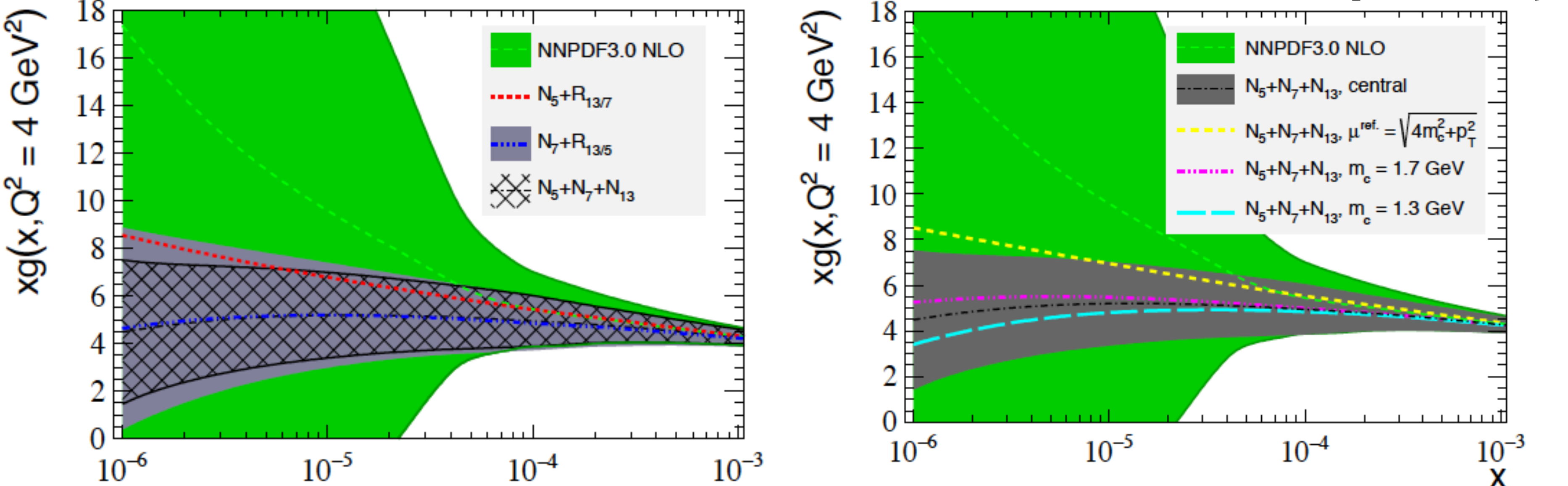
- Limited by charm cross section precision (exclusive D-meson reconstruction or inclusive secondary vertex tagging)

- Theory is NLO and subject to fragmentation uncertatinty
→ Partially offset by use of normalized distributions and ratios of results from different CMS energies

- Hard to do in ATLAS and CMS due to trigger thresholds, but fairly mainstream at LHCb

Study of Impact of Published LHCb D mesons

[Gauld + Rojo]



- N5 + N7 + N13 is normalised data from $\sqrt{s} = 5$, 7 & 13 TeV

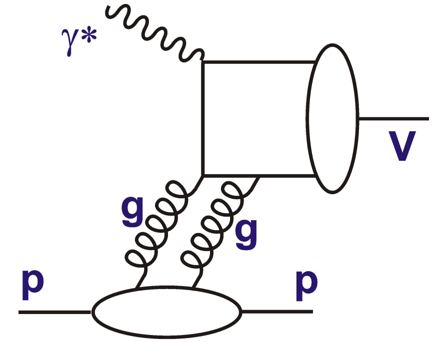
- Remarkable impact!

- Reasonable stability w.r.t. theory parameter variation

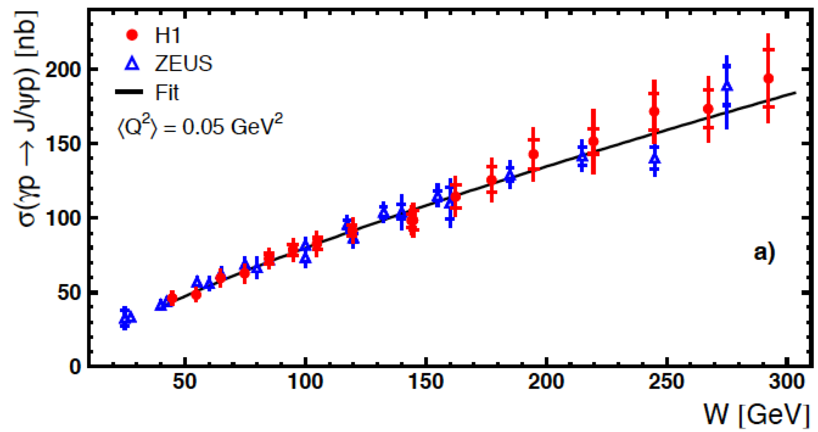
- “A future analysis at NNLO would be desirable”

- Are experimental issues fully under control?

Ultra-peripheral J/Ψ (Photo)-Production

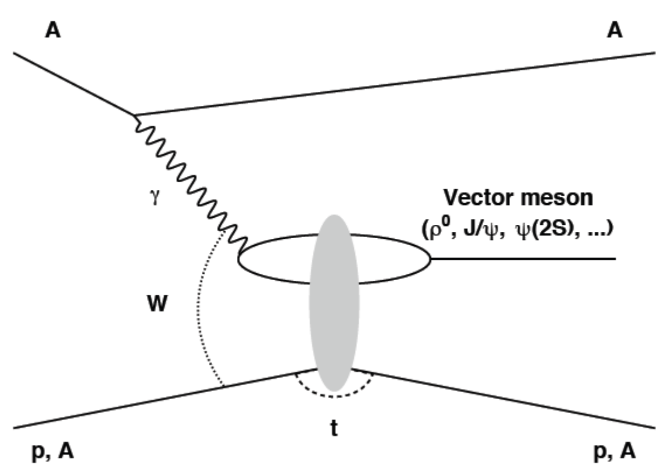


- [Low-Nussinov] interpretation as 2 gluon exchange enhances sensitivity to low x gluon (at least for exclusives)



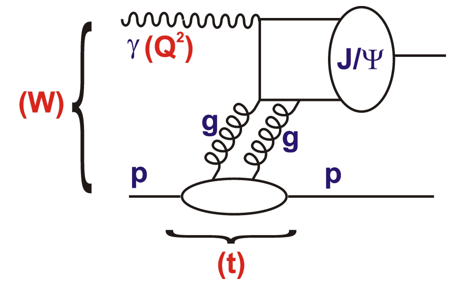
- Long studied in ep at HERA including unfolding σ_T, σ_L …

- LHC contributes via ultraperipheral collisions, which are also driven by photon exchange



- pA collisions are best-suited due to massively enhanced γ coupling to high Z nucleus

Attractions of J/Ψ Photoproduction



- Clean experimental signature (just 2 leptons)
→ good data from HERA and LHC!

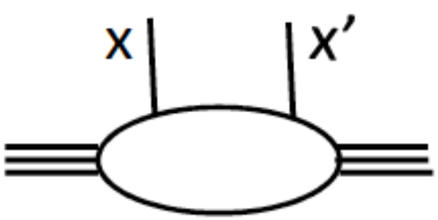
- Scale $Q^2 \sim (Q^2 + M_V^2) / 4 \;>\!\sim 3\ \mathrm{GeV}^2$ ideally suited to reaching lowest possible x whilst remaining in perturbative regime

… eg L<u>HC</u> reach extends to: $x_g \sim (Q^2 + M_V^2) / (Q^2 + W^2) \sim 10^{-5}$

Difficulties with J/Ψ Photoproduction

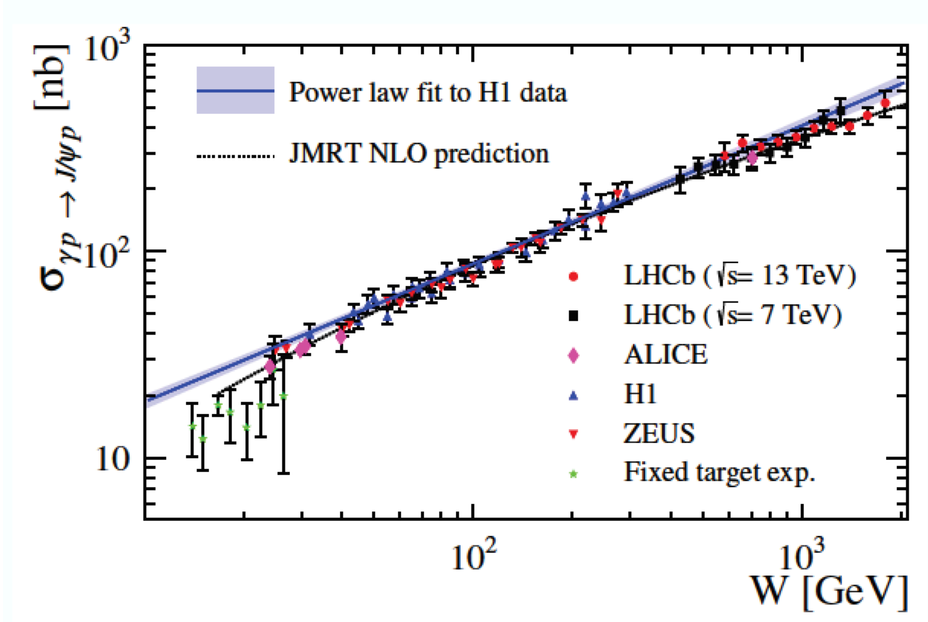
- Vector meson wavefuction

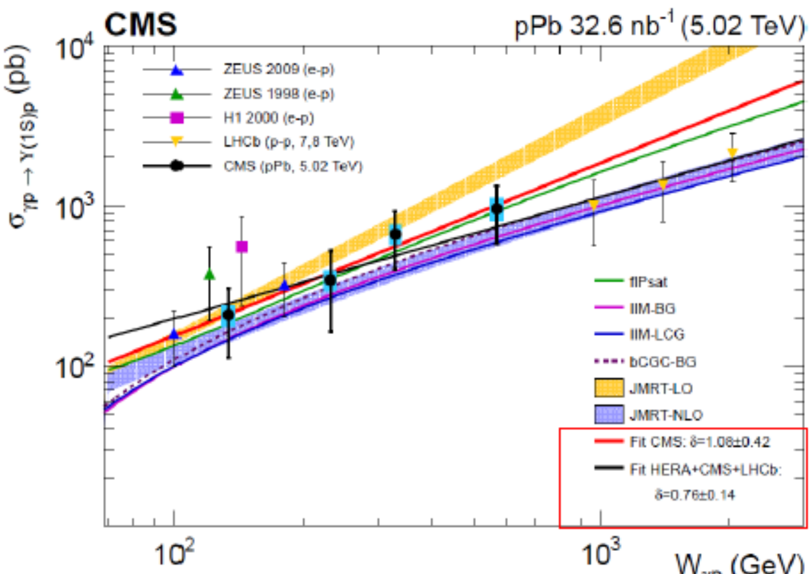
- Process requires GPDs (OK for x' << x << 1, but theoretically not at same level)

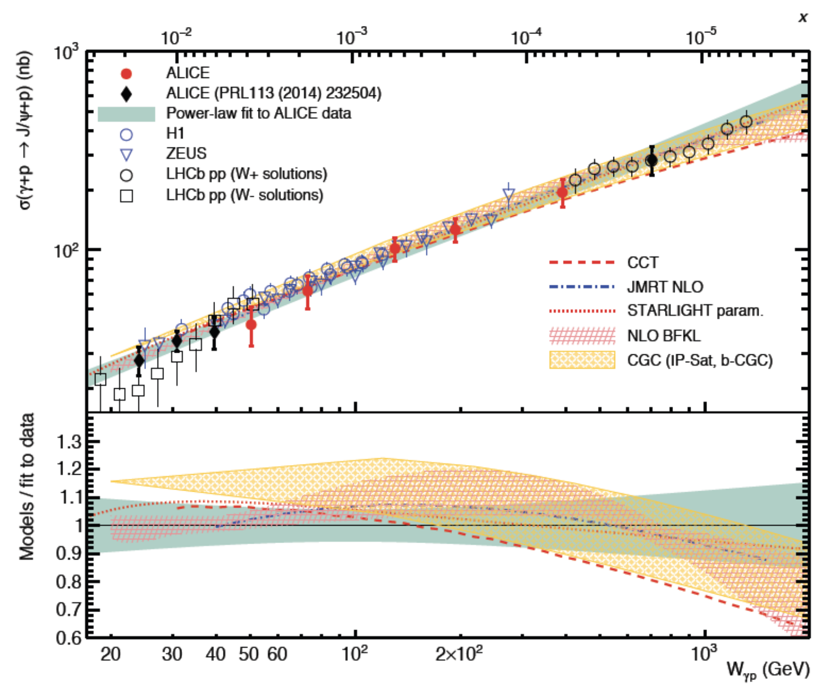


- Large scale uncertainties in collinear factorization approach (NLO v LO convergence)

Ultraperipheral J/Ψ Latest from LHC

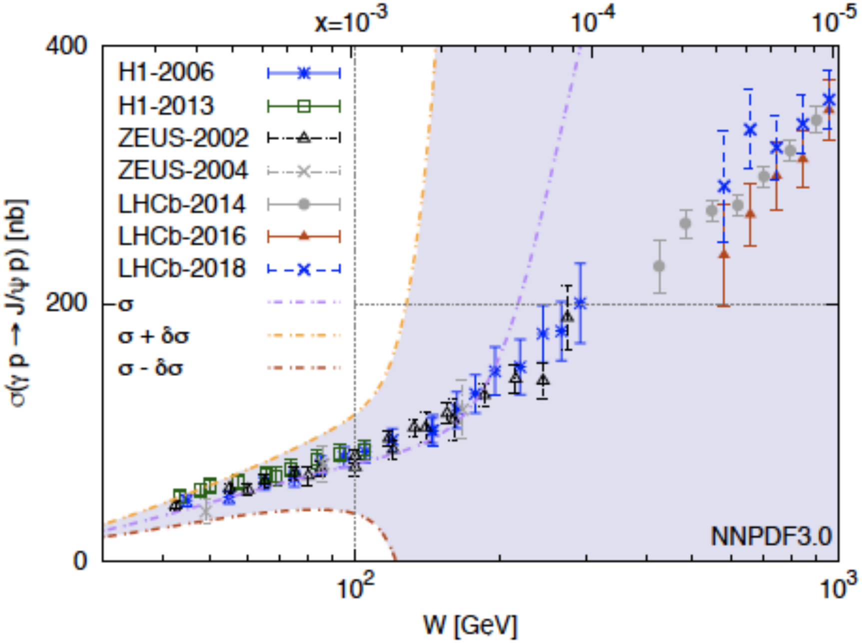






- JMRT NLO gives excellent 'out-of-box' prediction (k_T fac^n)
- There is power to add to these data

Interpretation in JMRT

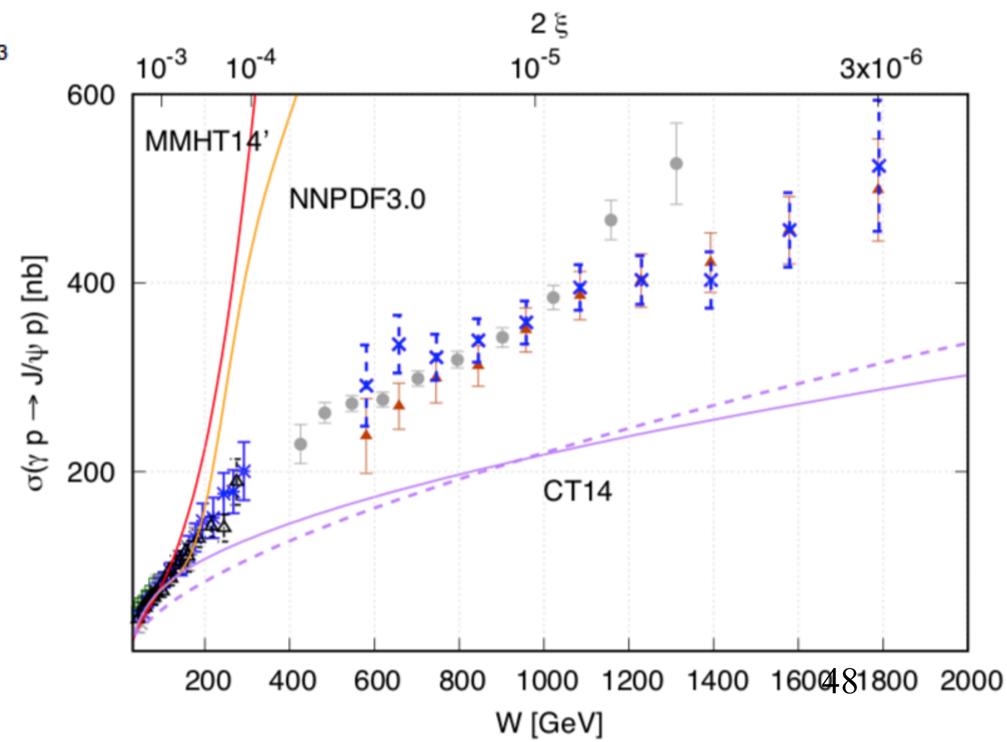


- JMRT k_T factorization model (attempts to) overcome scale problems etc → see recent Flett et al. paper

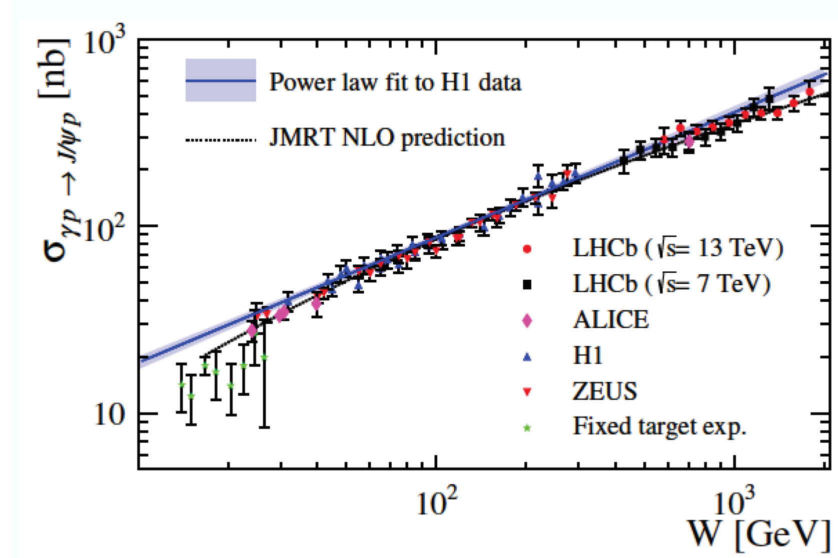
- Data uncertainties much smaller than PDF theory uncert's (band)

- Remarkable sensitivity to choice of PDF

- Not well established theoretically, but surely worth pursuing!

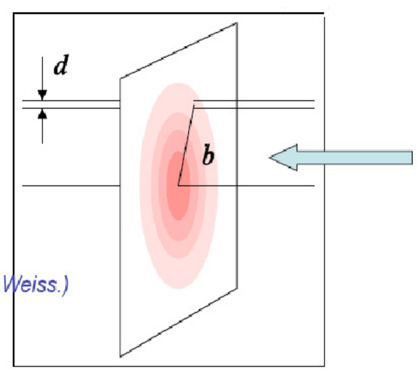


Any evidence for Saturation?



- No clear evidence in exclusive J/Ψ photoproduction for deviation from monatomic rise with increasing W (decreasing x).

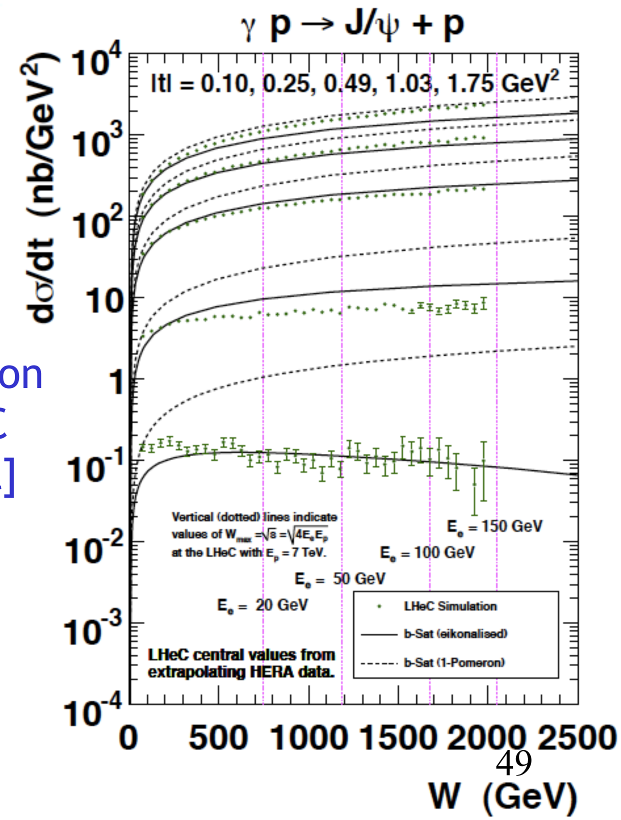
- Additional variable t gives access to impact parameter (b) dependent amplitudes



(figure from C. Weiss.)

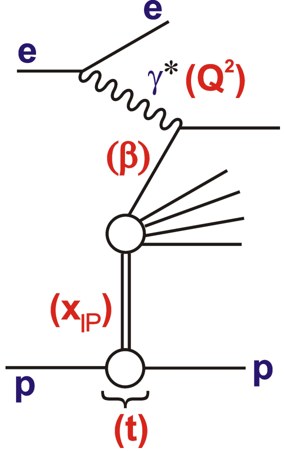
Central black region growing with decrease of x.

[Simulation in LHeC Context]

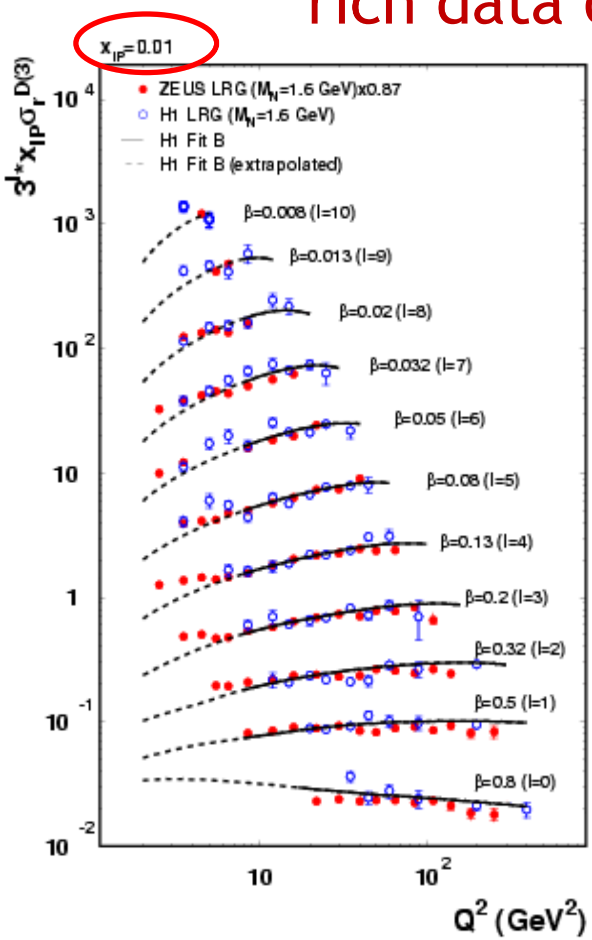


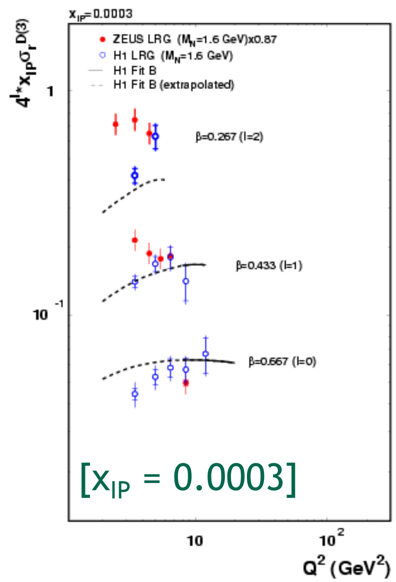
- … can in principle be studied at LHC …

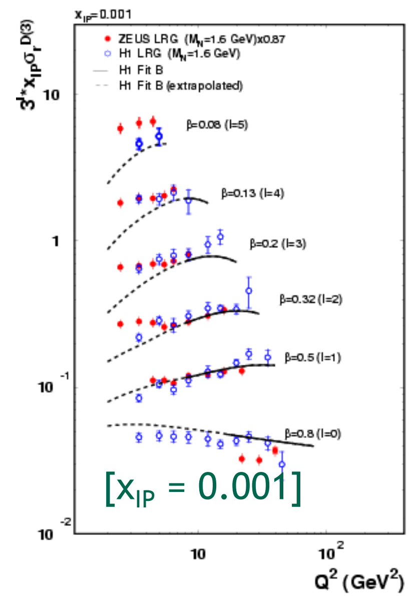
Inclusive Diffraction at HERA and Semi-Inclusive (Diffractive) PDFs

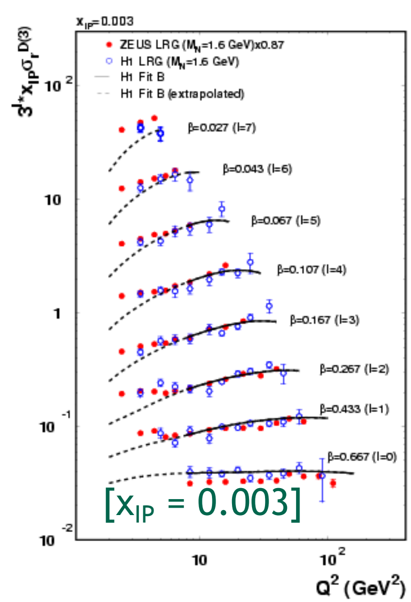


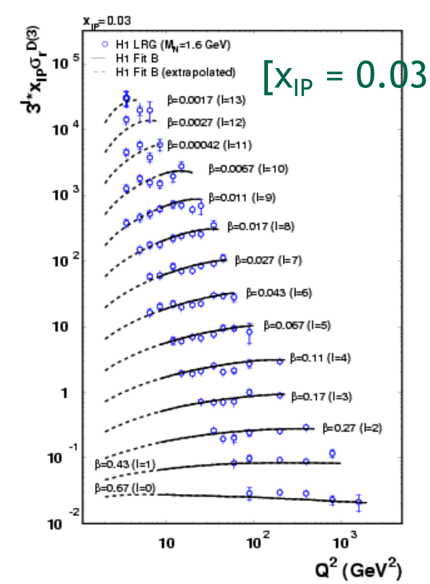
- Leading twist and ~10% of total x-sec
- Huge topic with rich data outputs



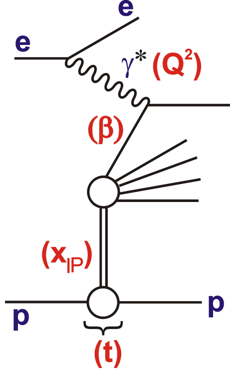




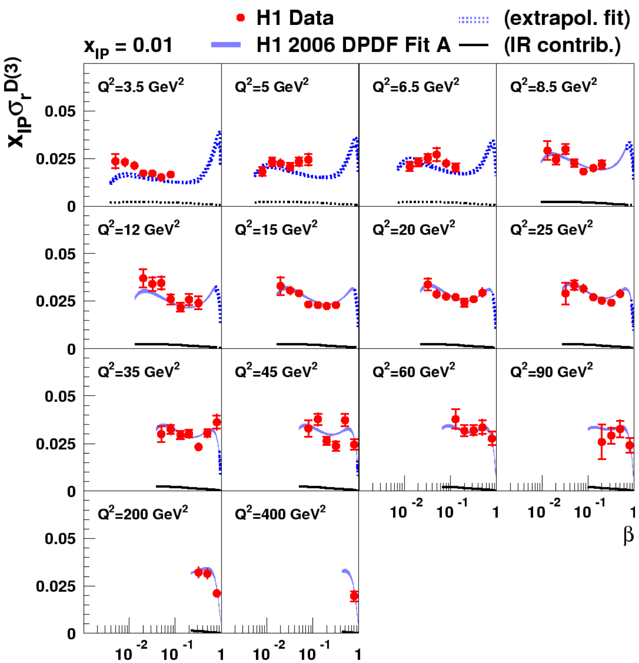


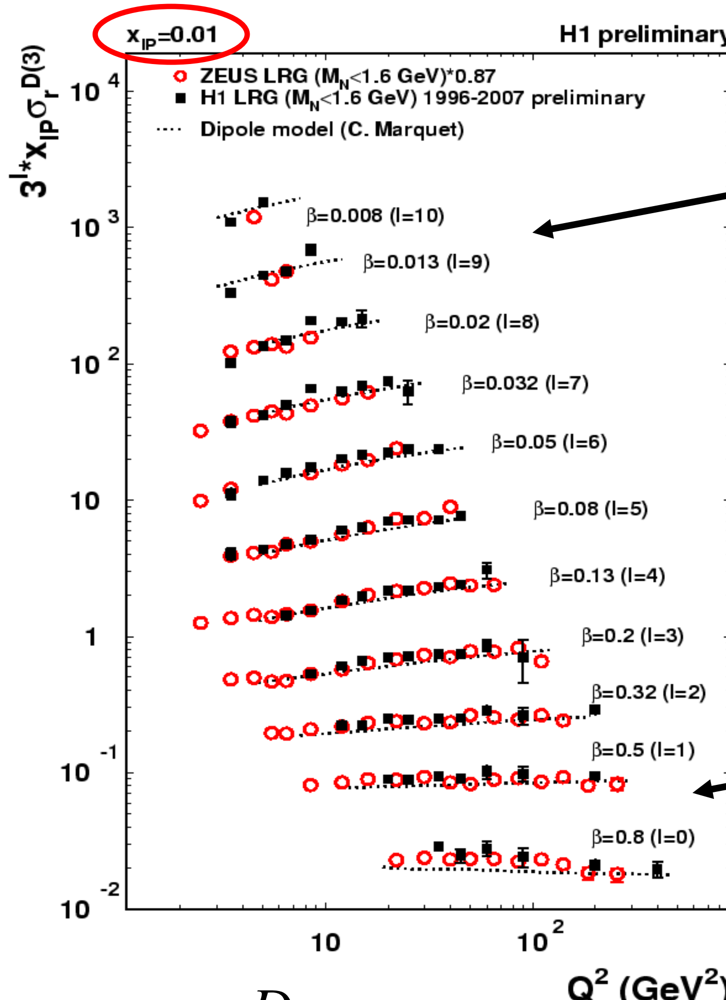


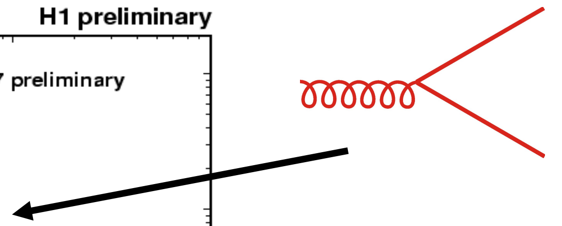
Sensitivity to Diffractive Quarks & Gluons



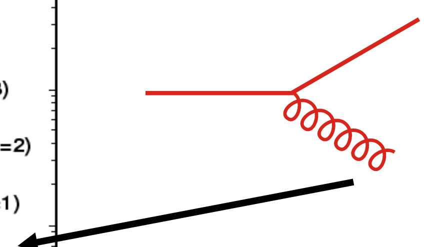
Similarly to Inclusive DIS …







Q^2 dependence tells us gluon density via DGLAP eqns

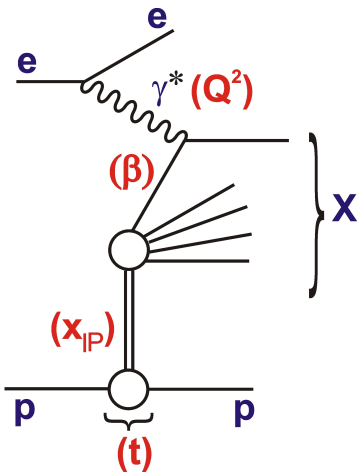


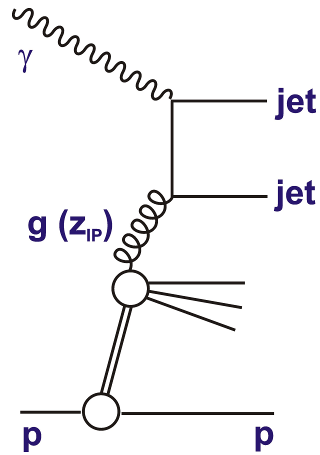
Diffractive cross section measures quark density

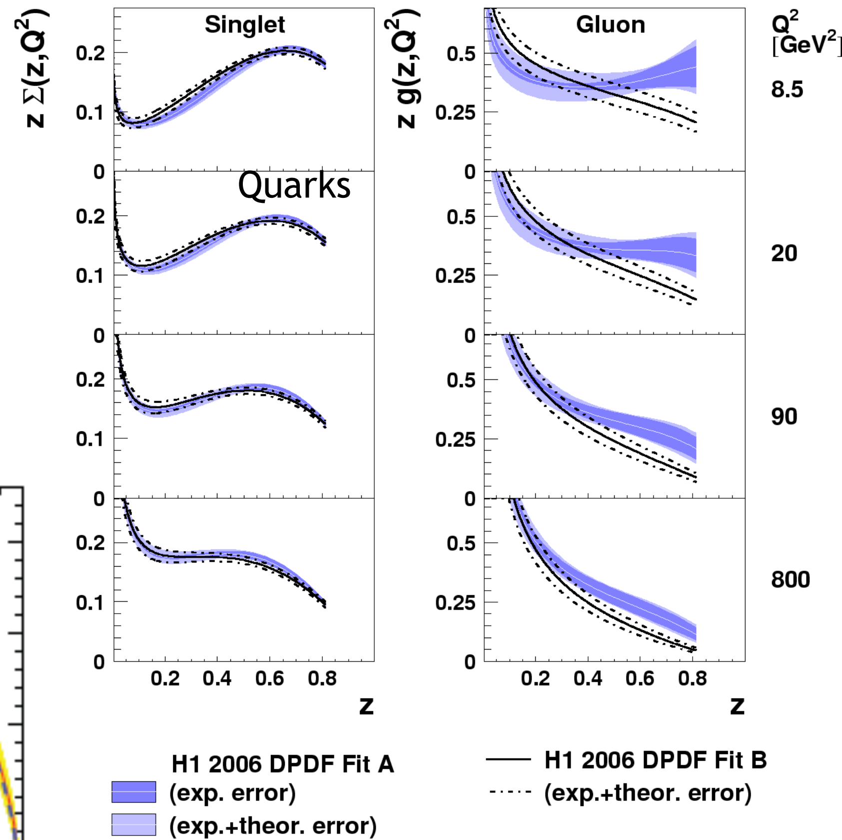
$$F_2^D = \sum_q e_q^2 \, \beta \, (q + \bar{q})$$

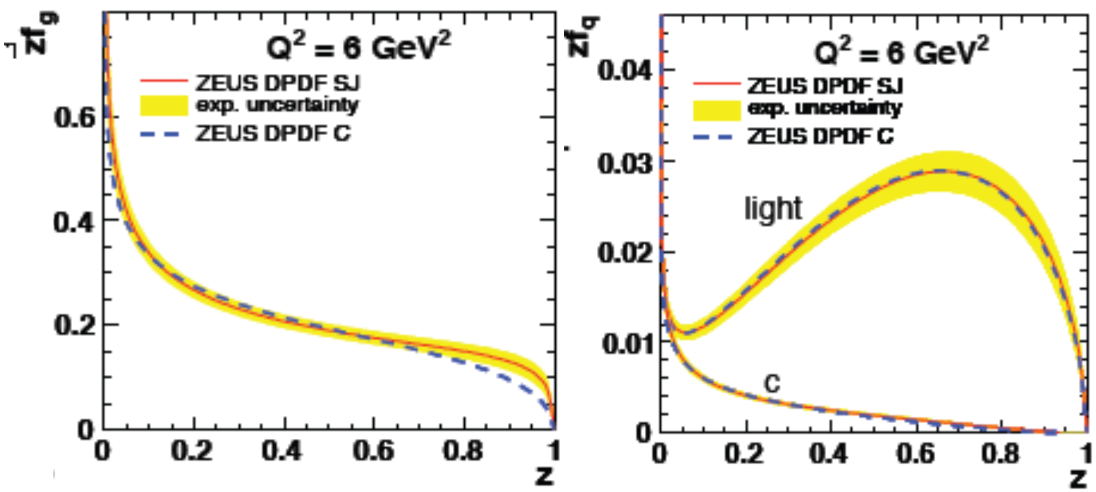
$$\frac{d\sigma_r^D}{d \ln Q^2} \sim \frac{\alpha_s}{2\pi} \left[P_{qg} \otimes g + P_{qq} \otimes q \right]$$

Diffractive Parton Densities (DPDFs)







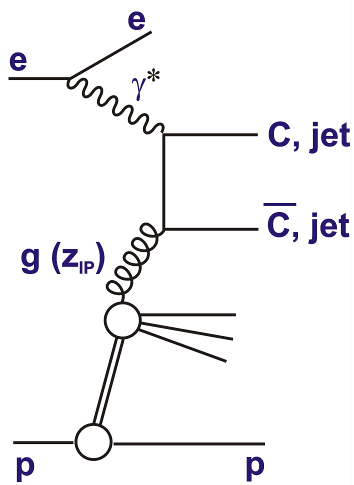


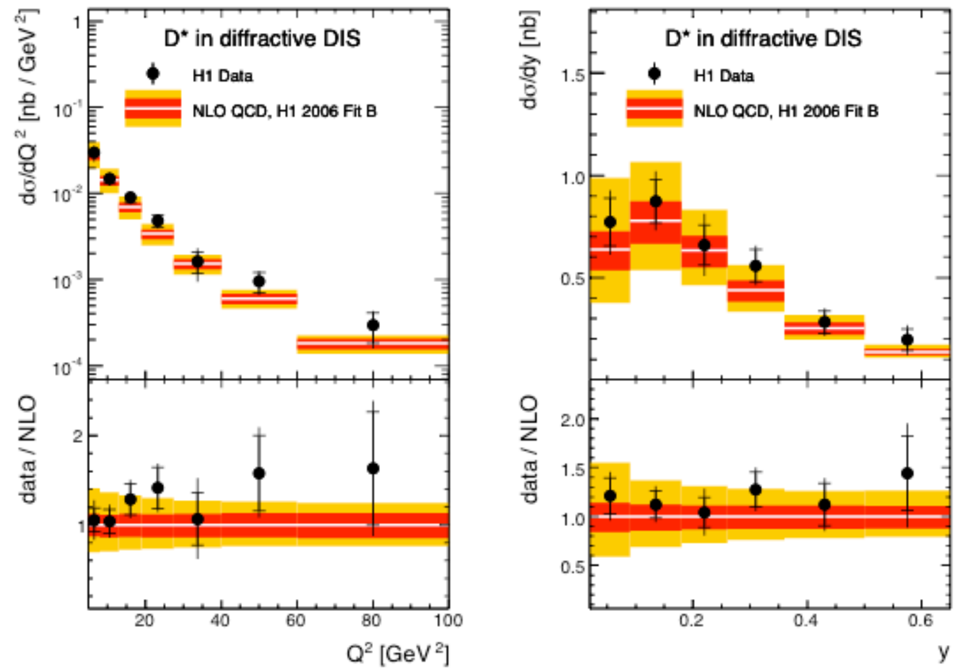
- … DPDFs extracted from HERA inclusive (F_2^D) data are PDFs, subject to constraint of leading proton (semi-inclusive fac^n)

- Recently also extracted at NNLO (Khanpour, H1-prelim)

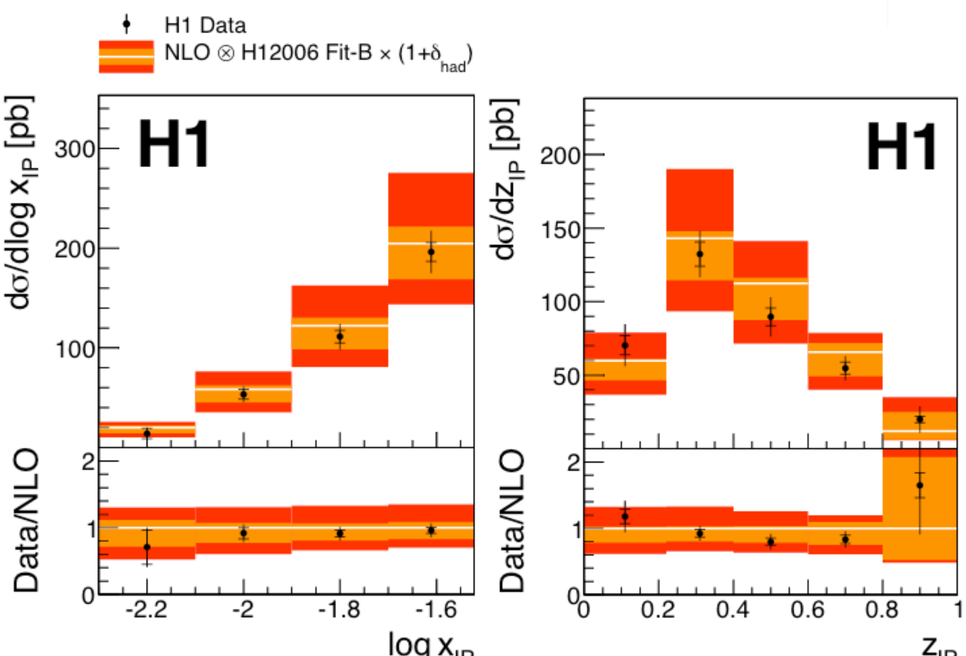
Testing Factorisation; HERA Jets & Charm

Remarkably good description of all variables over a wide kinematic range

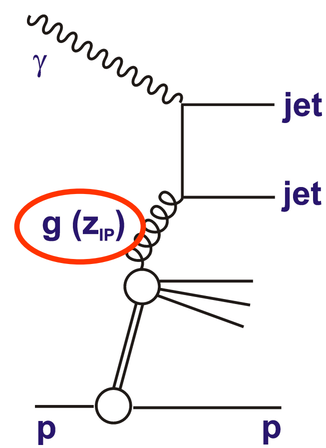




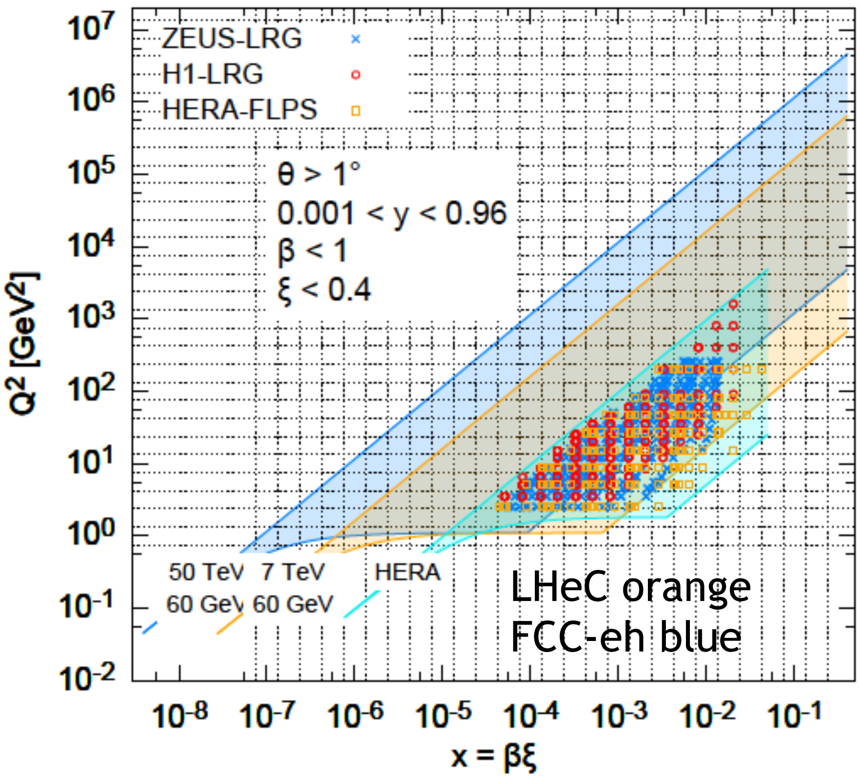
Charm in DIS



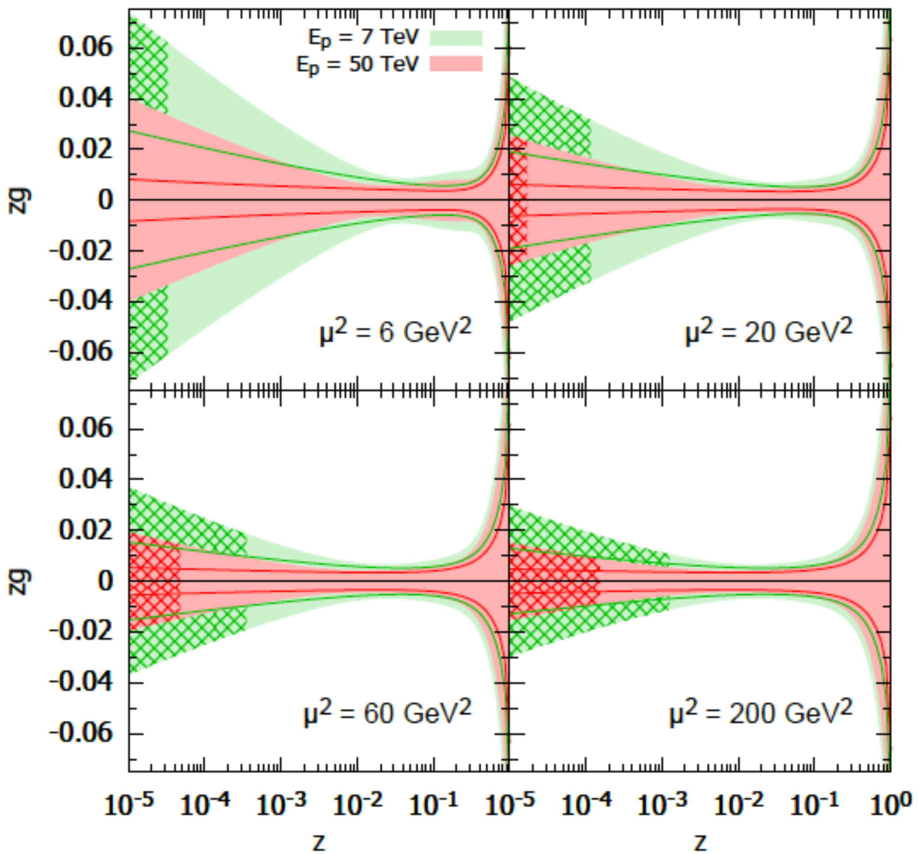
Dijets in DIS



LHeC and FCC-eh would be Transformational



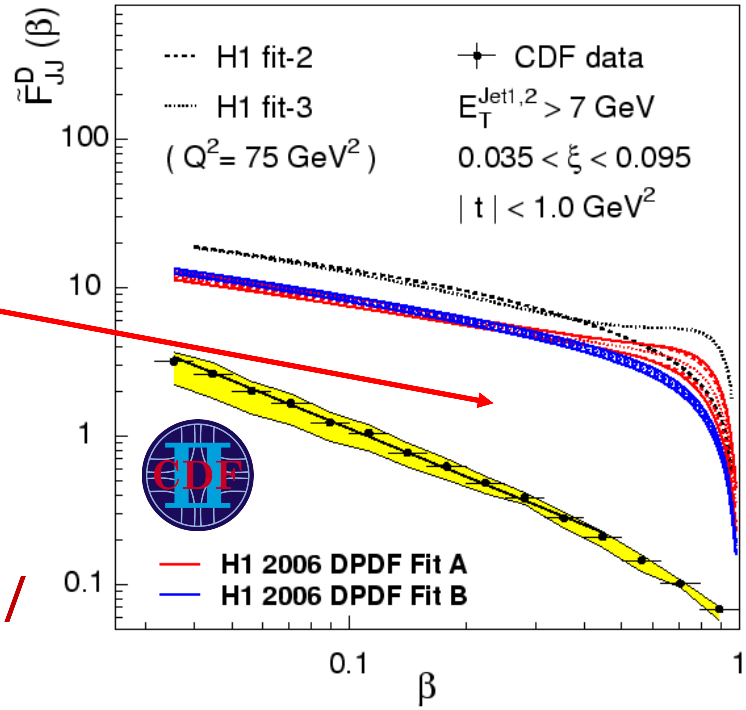
- Fits to simulated LHeC and FCC-eh Neutral Current inclusive diffraction data lead to well-constrained DPDFs down to $\beta=10^{-4} - 10^{-5}$



- Quark density directly constrained → 2% precision
- Gluon uncertainty propagated from experimental data few %
- Param'n and other theory uncertainties not yet included

… but in pp(bar)

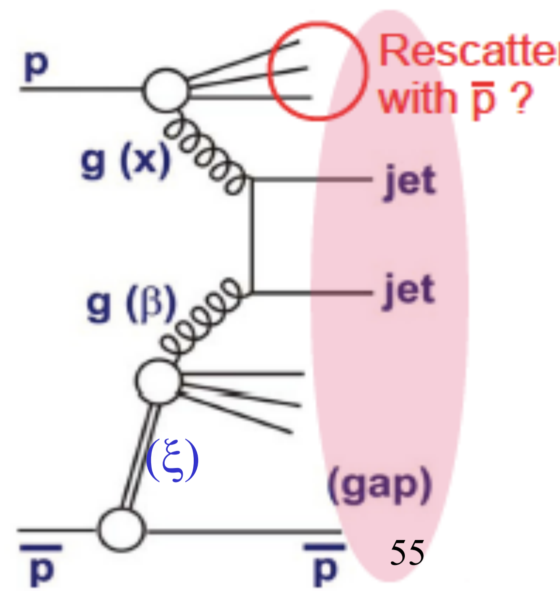
Spectacular failure in comparison of Tevatron proton-tagged diffractive dijets with HERA DPDFs [PRL 84 (2000) 5043]



… rescattering (absorptive corrections / related to Multi Parton Interactions …) breaks factorisation …

`*rapidity gap survival probability*' ~ 0.1

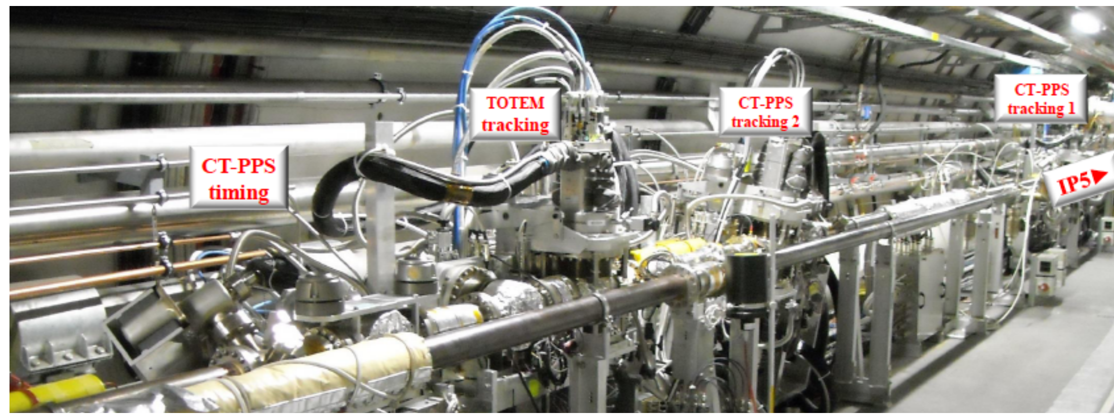
Gap survival probability needs to be understood to interpret all LHC hard diffraction data.

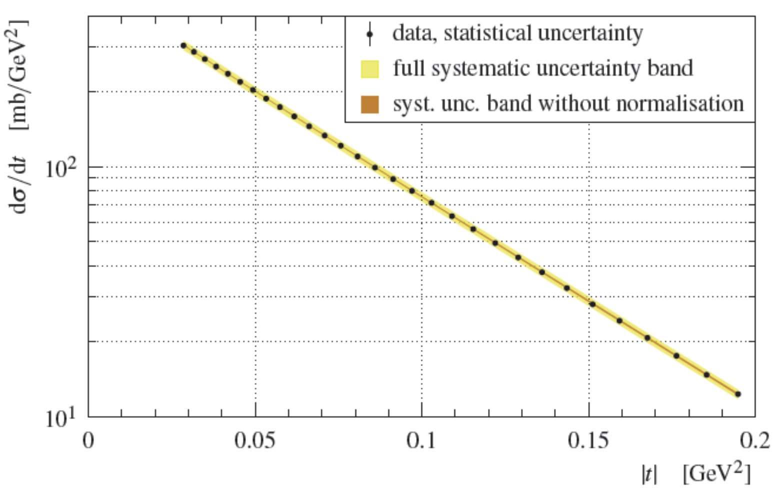


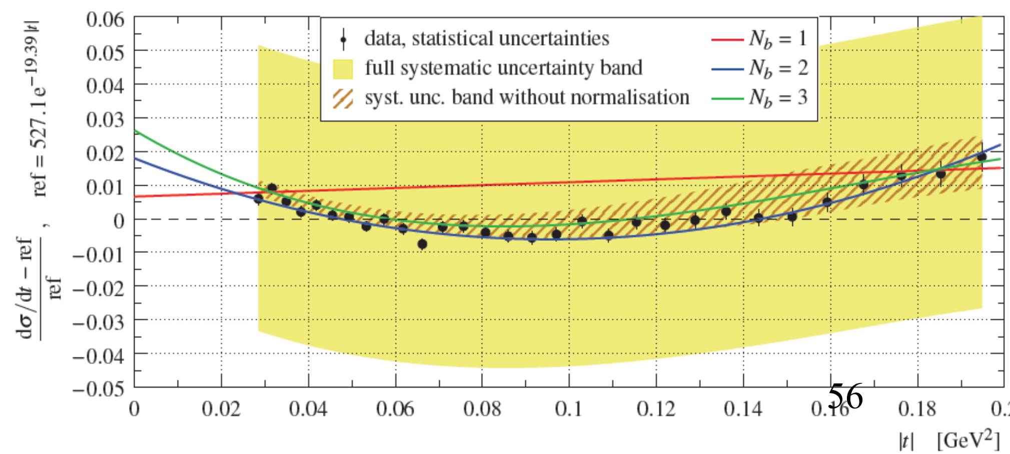
Diffraction at LHC: Proton Spectrometers Come of Age

LHC experiments (TOTEM, ALFA@ATLAS) have shown that it's possible to make precision measurements and cover wide kinematic range with Roman pots.

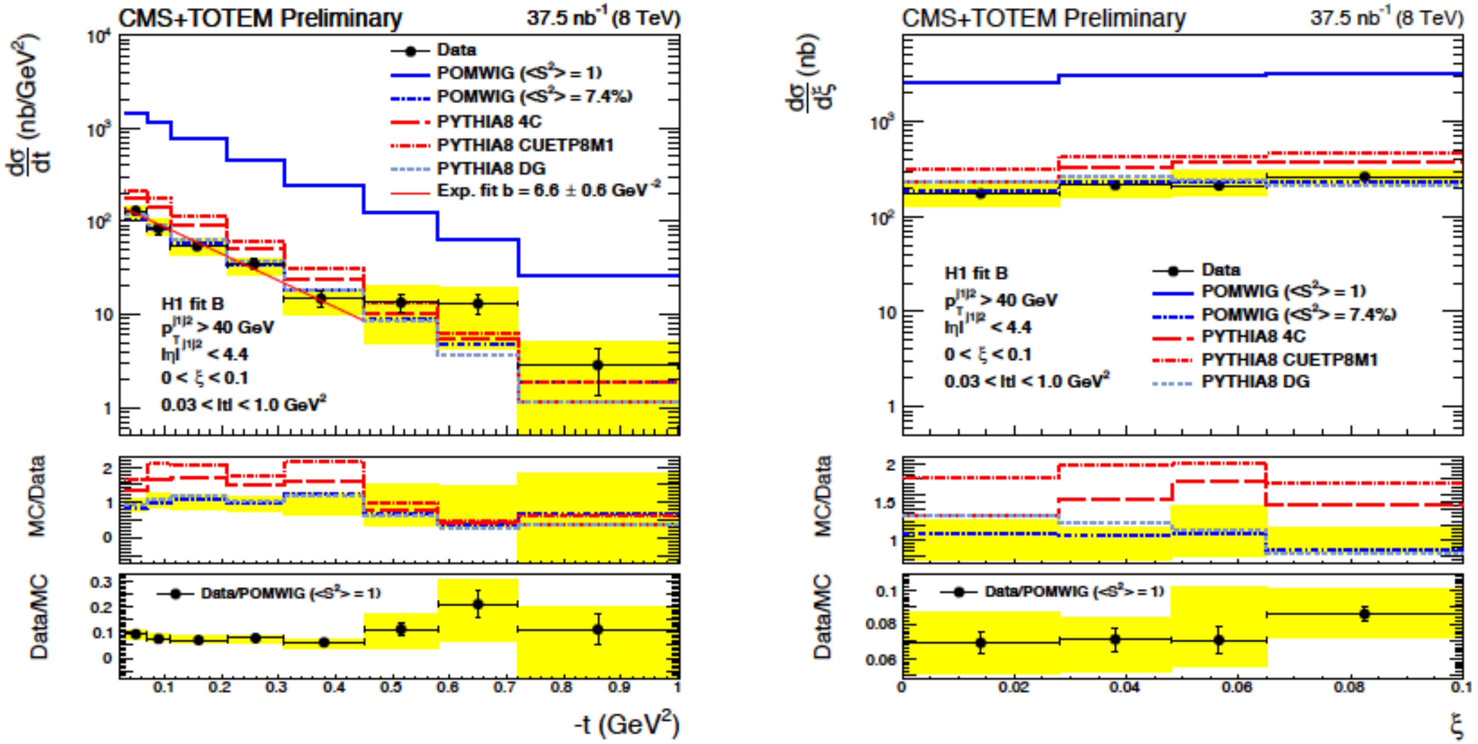
e.g. TOTEM operated 14 pots in 2017, with several at full LHC lumi (~50ps timing and precision tracking detectors) → Sensitivity to subtle new effects eg non-exponential t dep …







Proton-tagged LHC Diffractive Jets

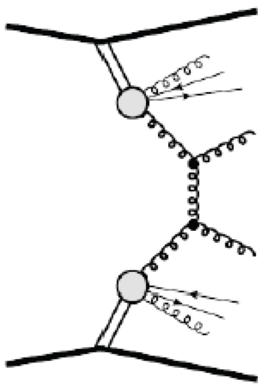


- Proton tagging removes the double dissociation and non-diffractive backgrounds that limited understanding with previous LHC rapidity gap measurements
- Predictions based on HERA DPDFs require <S²> ~7.4%
- Dynamic Gap Survival Model in PYTHIA (based on Simultaneous description of MPI) reproduces data

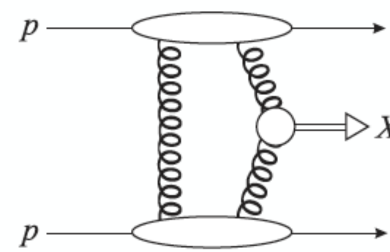
→ Lots more potential here!

Future Diffraction at LHC

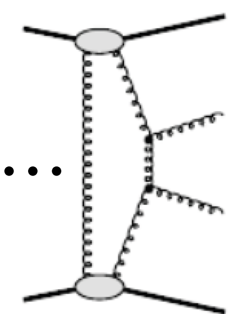
- Most of the future diffractive programme will involve Roman Pot tagging in normal running conditions
- In practice this means we will study double tags (pp→ppX), suppressing pile-up background by constraining interaction vertex using precision timing of protons

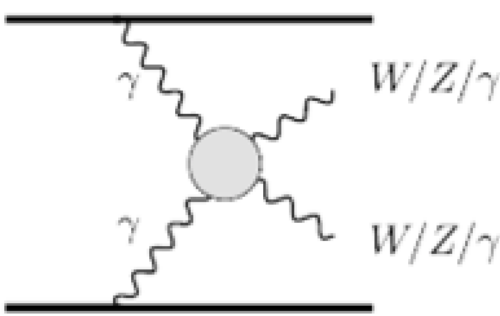


- **Inclusive central production**
pomeron-pomeron hard scattering with jets, HF, W, Z signatures



- **Central Exclusive QCD Production**
of dijets, γ-jet and other strongly produced high mass systems … Higgs?...





- **Two photon physics** → exclusive dileptons, dibosons & anomalous multiple gauge couplings …
[Dominates at large masses]

First P-tagged $\gamma\gamma$ Results

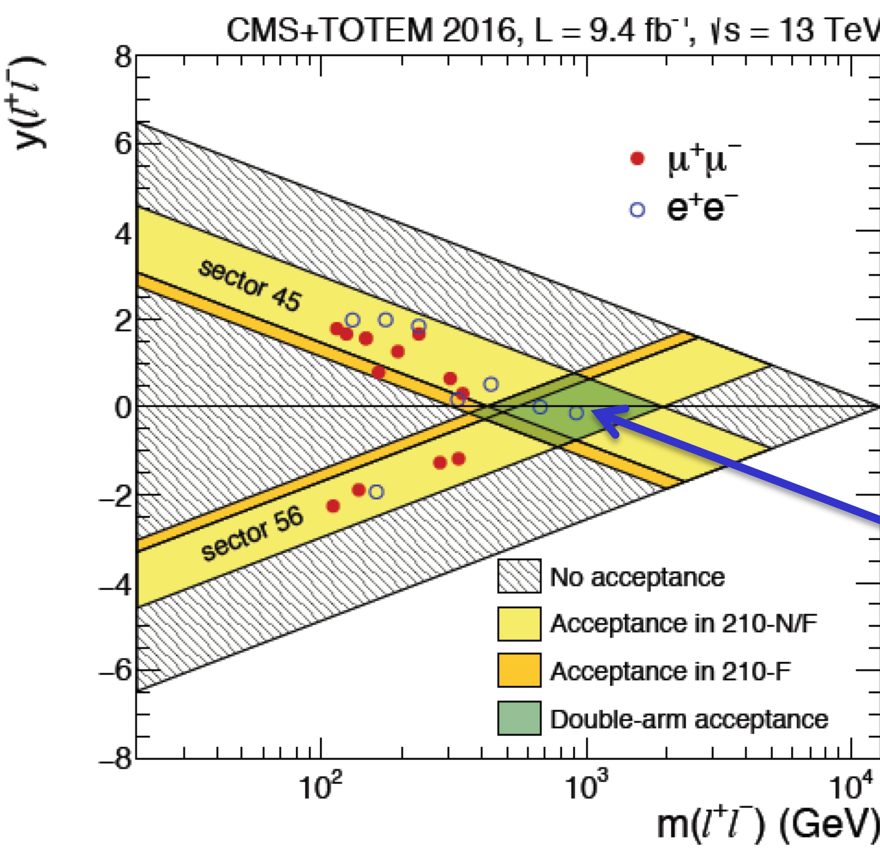
- CT-PPS fully installed from 2016, AFP from 2017
- Total of 110 fb^{-1} accumulated by CT-PPS, 81 fb^{-1} by AFP.

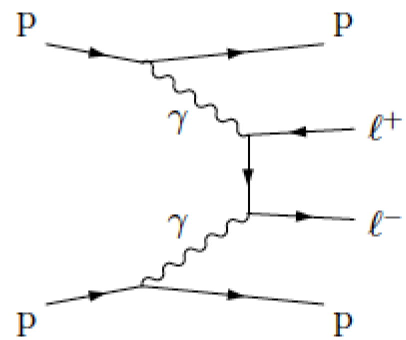
→ Transformational lumi compared with previous Roman pots

→ Commissioning and data understanding ongoing

→ First results obtained (with single tags so far)

$\gamma\gamma$ → ee or $\mu\mu$



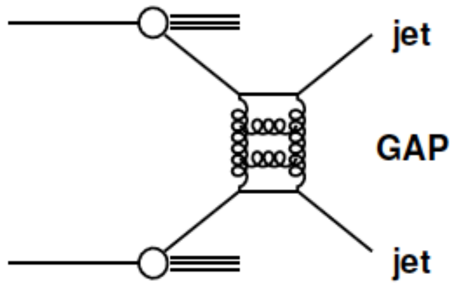


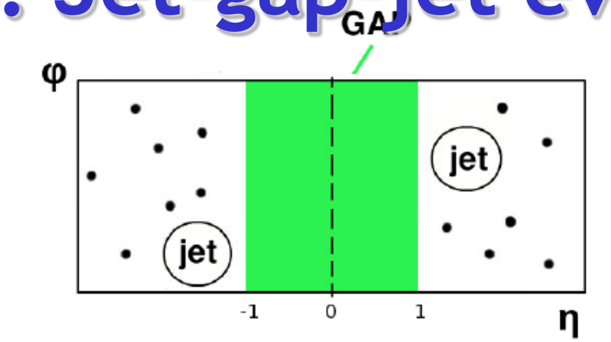
Potential region for double tagging: 350GeV <~ m(ll) <~ 2TeV

5σ observation.

Highest mass m(ee) = 917 GeV

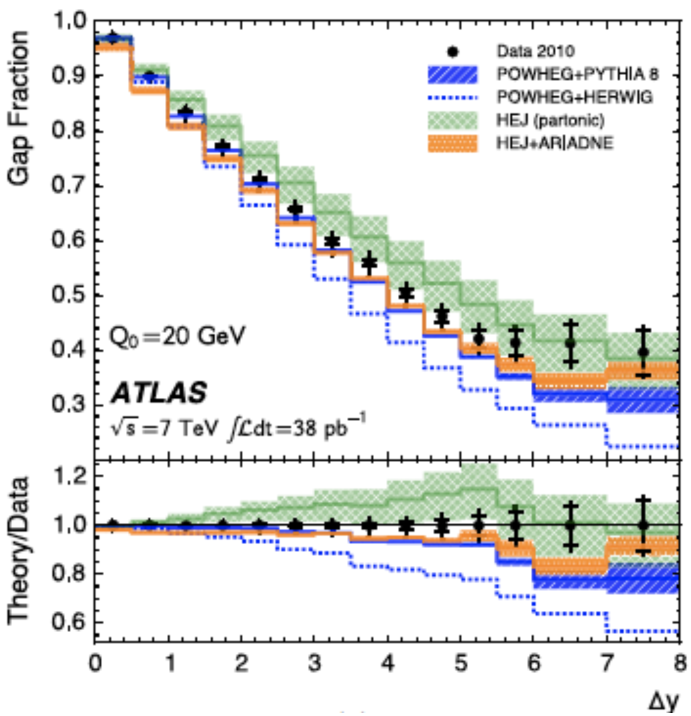
LHC Searches for BFKL Dynamics: Jet-gap-jet events

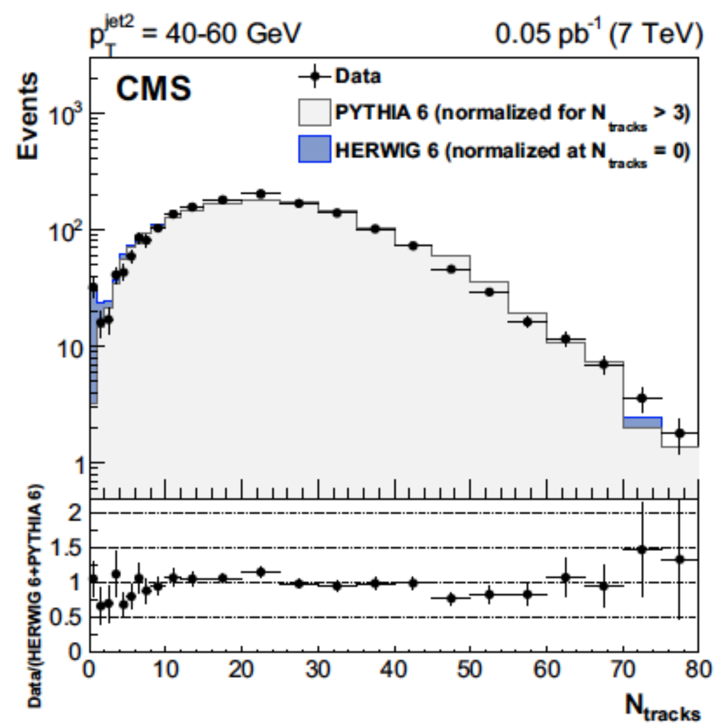




- Gaps between jets are a classic Signature for BFKL dynamics

- Complicated experimentally by difficulty of defining signal, theoretically by rapidity gap survival probability

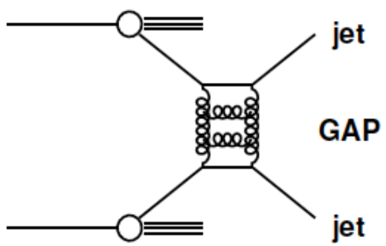


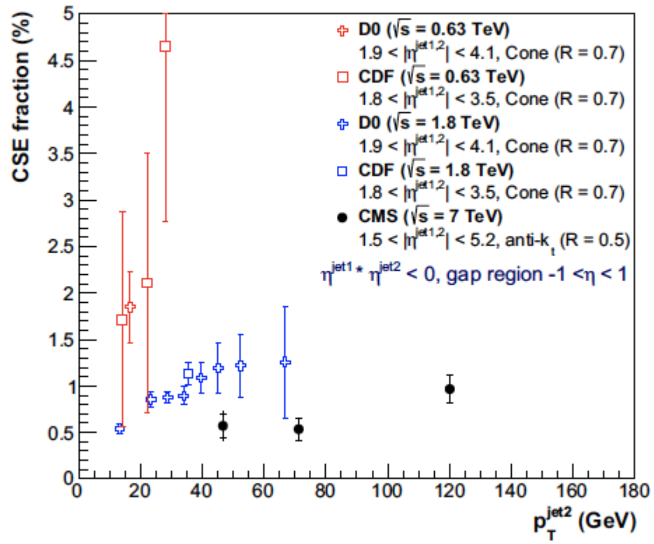


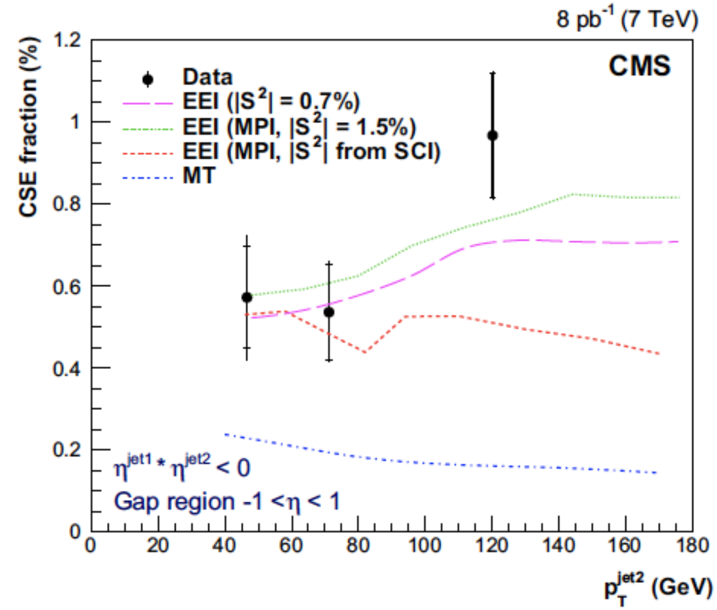
[Tracks with pT > 200 MeV, |η| < 1]

Jet-gap-jet events and BFKL

Clear signal in case where there is no (visible) radiation in gap



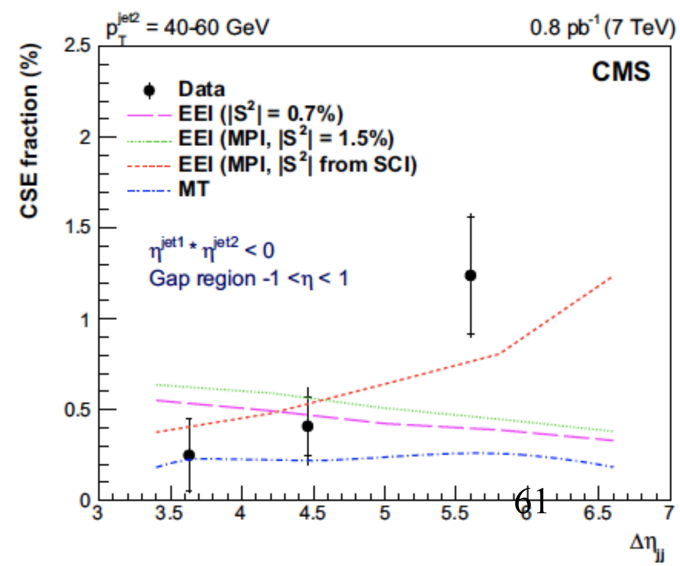




- Comparison with Tevatron shows that gap survival falls with CMS energy

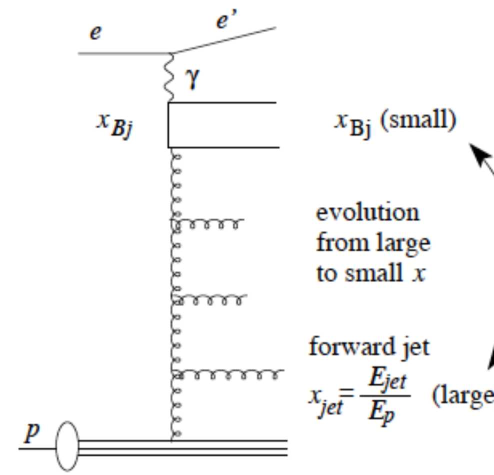
- BFKL-based calculations (EEI and MT) broadly successful with $<S^2> \sim 1\%$, including Dynamic model in PYTHIA

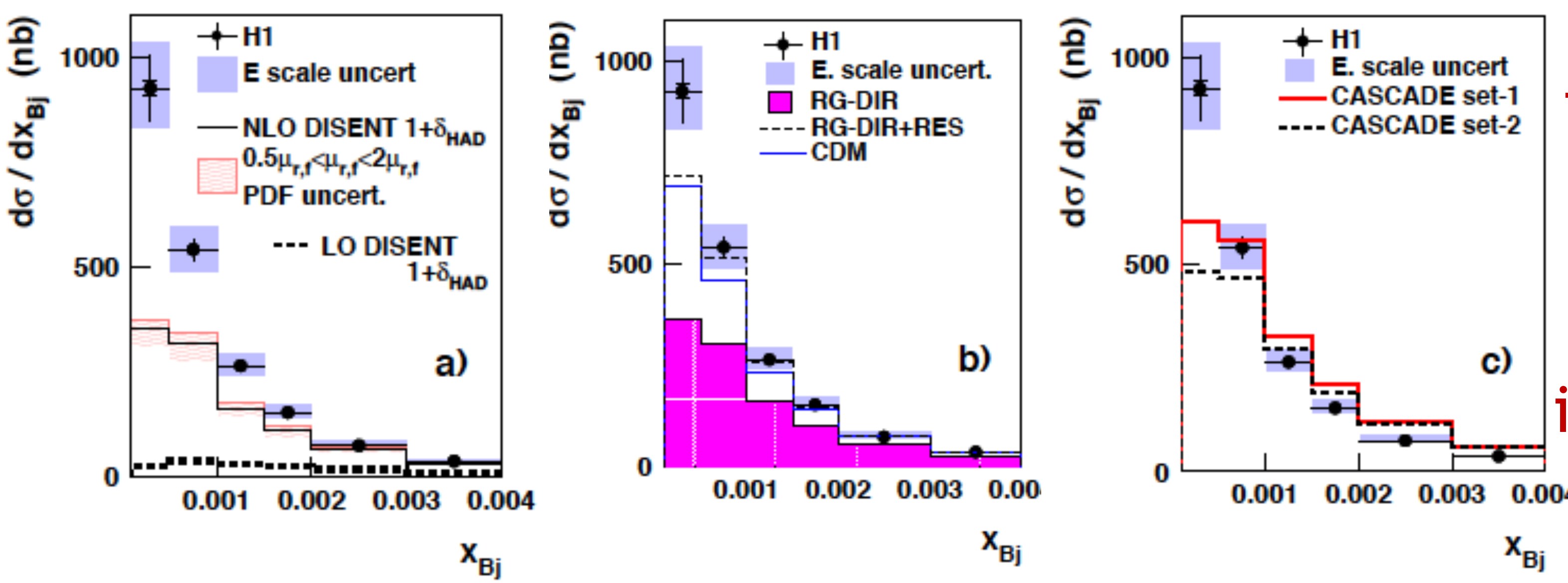
- Not yet a precision activity …



Observables Sensitive to Novel Dynamics

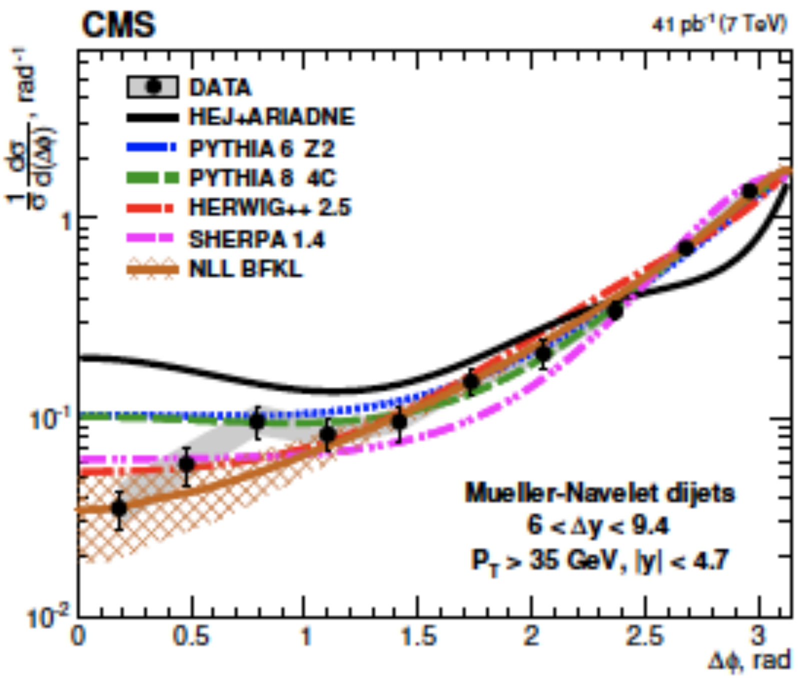
- (Very) forward jet, particle production and energy flow
- Mueller-Navelet forward-backward jet pairs
- Azimuthal decorrelations between jets
- Jet broadening
- Correlations / p_T ordering of hadrons



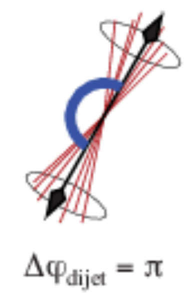


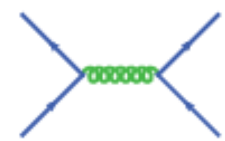
Some interesting effects … not easily interpreted

LHC Example combining different signatures: Azimuthal Decorrelations between M-N jets



- Choice of Forward-backward highest E_T jets with comparable energy suppresses phase-space for DGLAP evolution
- Sensitivity enhanced at large azimuthal decorrelation due to multiple emissions





- Jets separated by up to $\Delta y = 9.4$ units!
- DGLAP-based models with appropriate tuning (LL parton showers and colour-coherence) can describe data
- LL BFKL model (HEJ) overestimates decorrelations
- Analytic NLL BFKL calculation agrees well with data

→ Will be increasingly interesting at higher CMS energy

Summary

• HERA leaves us with many questions about low x physics

- Implications of fast-rising gluon?
- Novel dynamics?

• While we wait for the next energy frontier DIS facility, can we exploit LHC?

- Current mainstream LHC data have some impact on low x quarks, but little on low x gluon
- Dedicated (big!) effort could address this in some areas
- New observables (charm-related) may be key?

• Diffraction at LHC bearing fruit → opens up new CEP topics?...

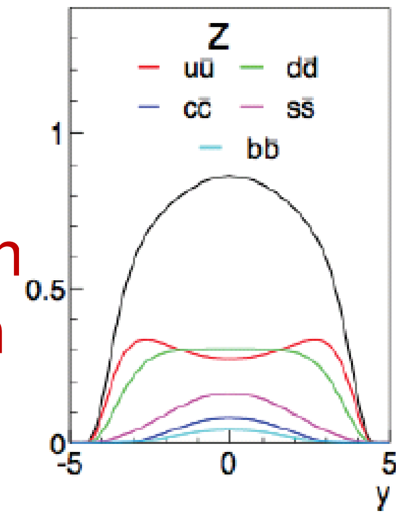
Sooner or later, (FCC-hh), 'mainstream' will have to move to lower x …

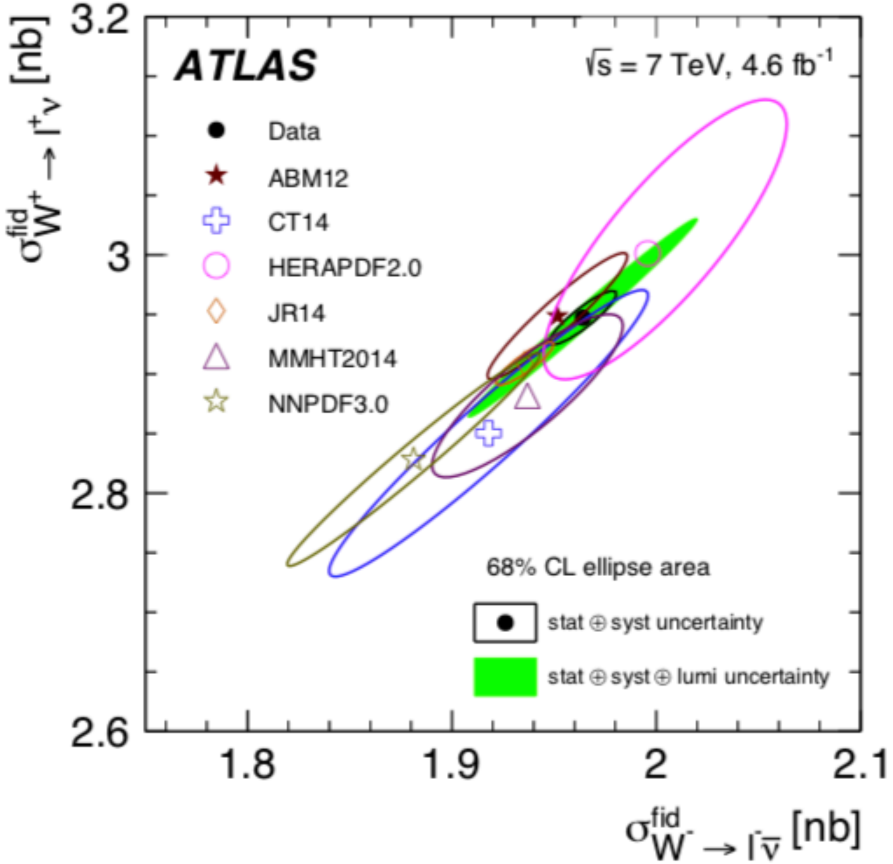
[Sincere apologies for the many topics that I omitted and for the lack of accreditation of work taken from elsewhere … if only there were more time!]

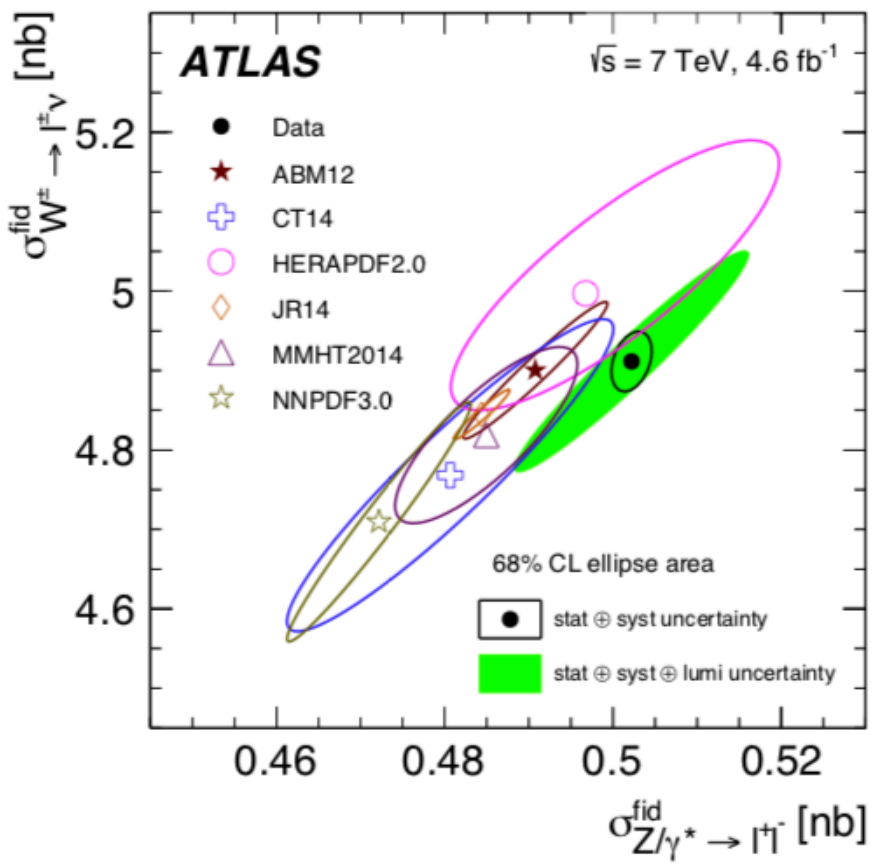
Back-Ups Follow

Inclusive W, Z Cross Sections

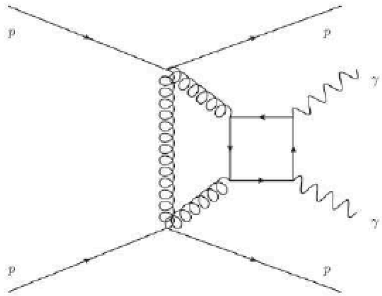
- Inclusive data show some discriminatory power between PDF sets → tighten low(ish) x decompositon
- W^+ / W^- plane sensitive to u / d in sea quark region
- W / Z plane sensitive to sea flavour asymmetries

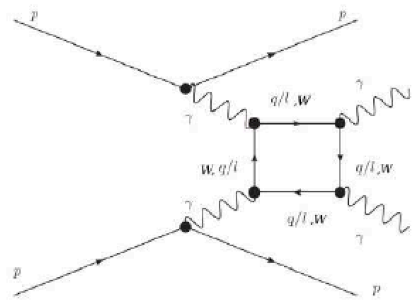






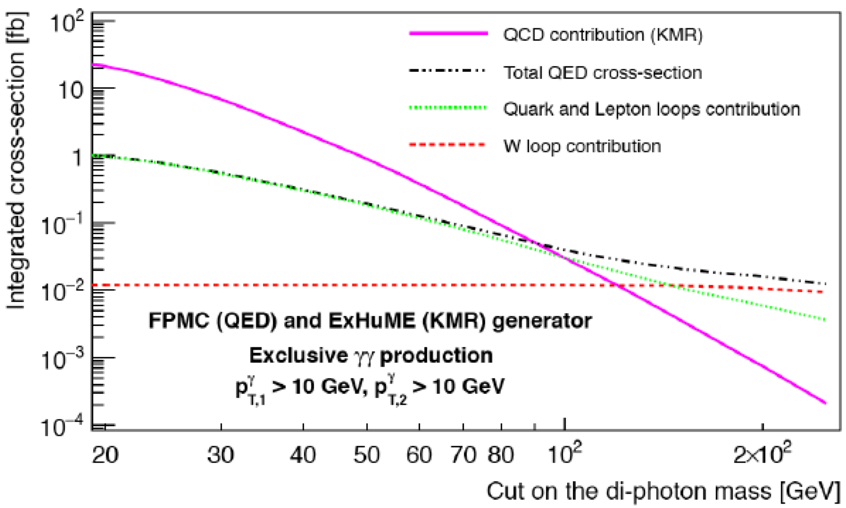
e.g. Strong Interactions v Photon-photon

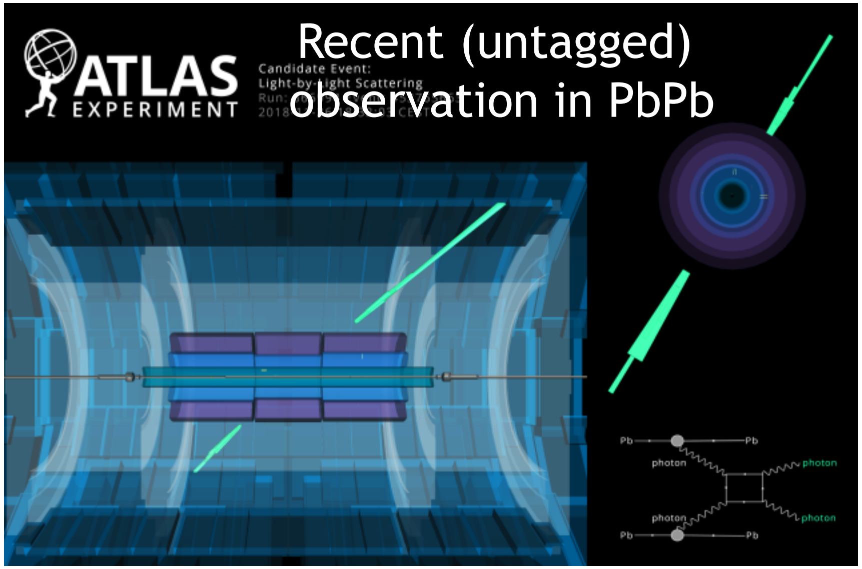




- QCD production dominates at low central system masses

- QED production (light-by-light) takes over at larger central system masses





… extensive programme of probing $\gamma\gamma$ vertex …

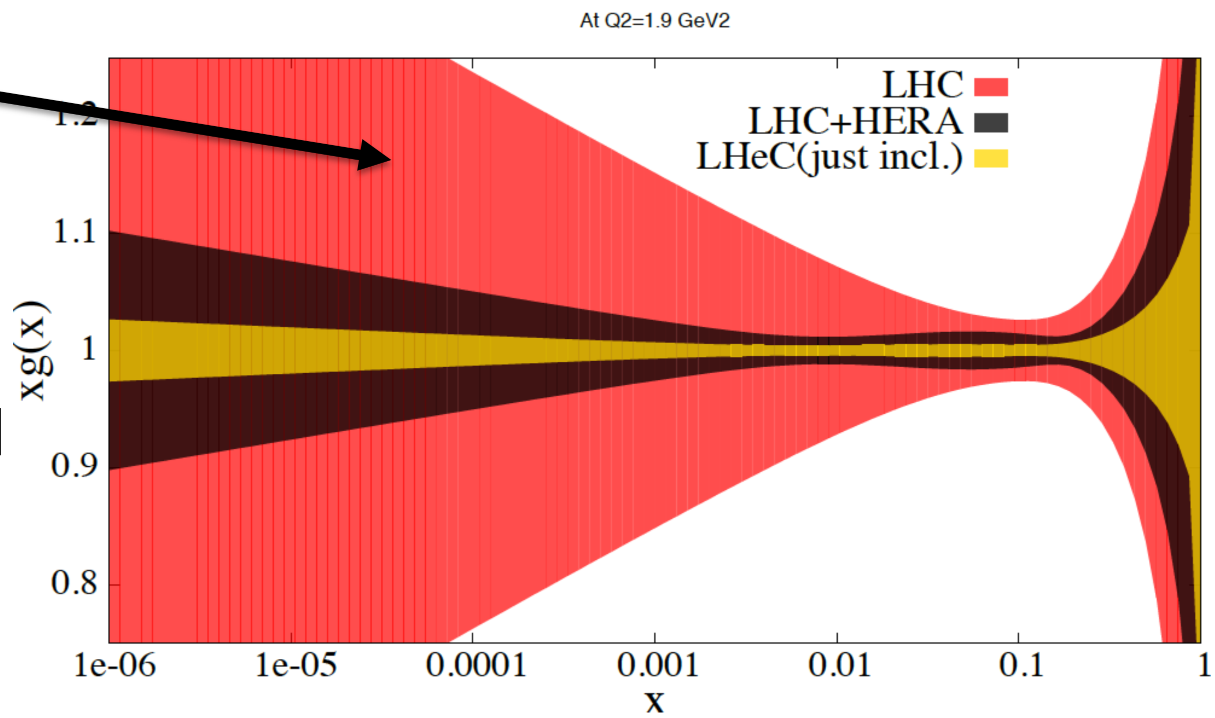
→ ZZ, WW, $\gamma\gamma$ final states …

→ Competitive sensitivity to anomalous quartic gauge couplings in large mass region

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 ...

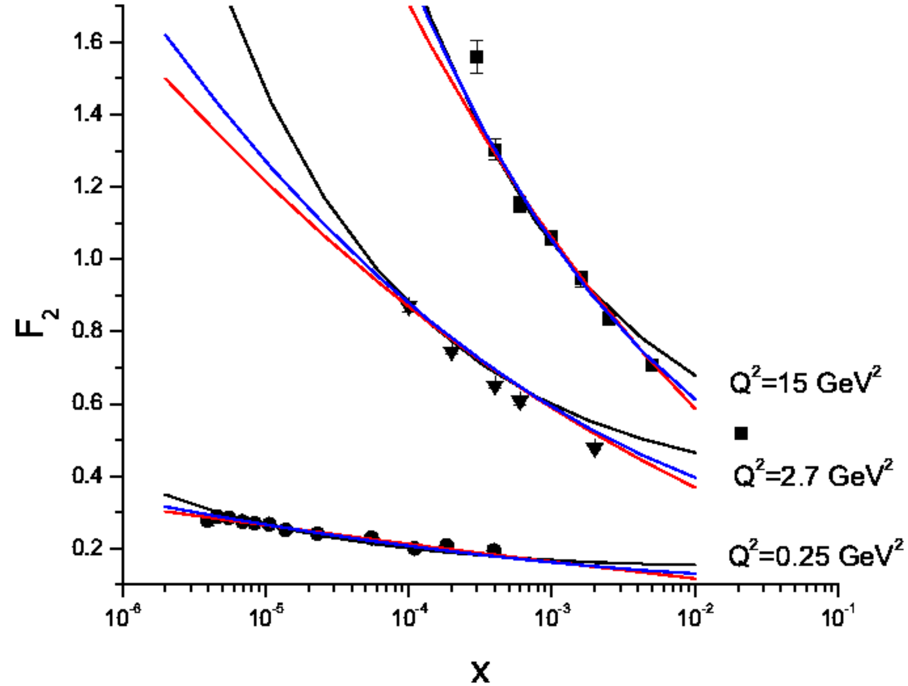
→ You can't use the same data to constrain parton densities and to discover new physics through deviations from predictions using those PDFs

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

Parton Saturation after HERA?

e.g. Forshaw, Sandapen, Shaw
hep-ph/0411337,0608161
… used for illustrations here

Fit inclusive HERA data
using dipole models
with and without parton
saturation effects



FS04 Regge (~FKS): 2 pomeron model, no saturation

FS04 Satn: Simple implementation of saturation

CGC: Colour Glass Condensate version of saturation

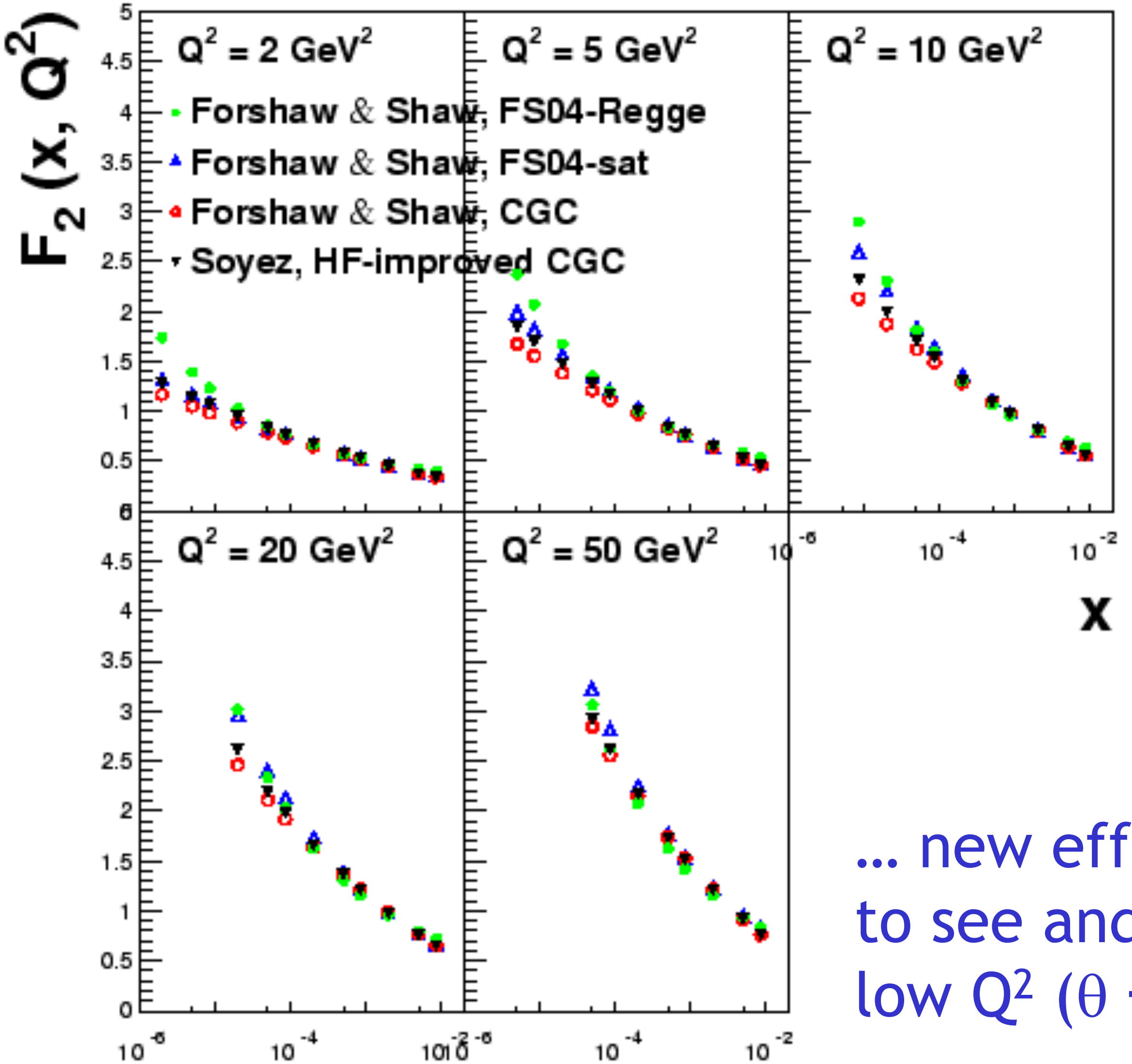
- All three models can describe data with $Q^2 > 1\text{GeV}^2$, $x < 0.01$
- Only versions with saturation work for $0.045 < Q^2 < 1\ \text{GeV}^2$

… any saturation at HERA not easily interpreted partonically

Some models of low x F_2 with LHeC Data

With 1 fb^{-1} (1 year at 10^{33} cm^{-2} s^{-1}), 1° detector:
stat. precision < 0.1%, syst, 1-3%

[Forshaw, Klein, PN, Soyez]



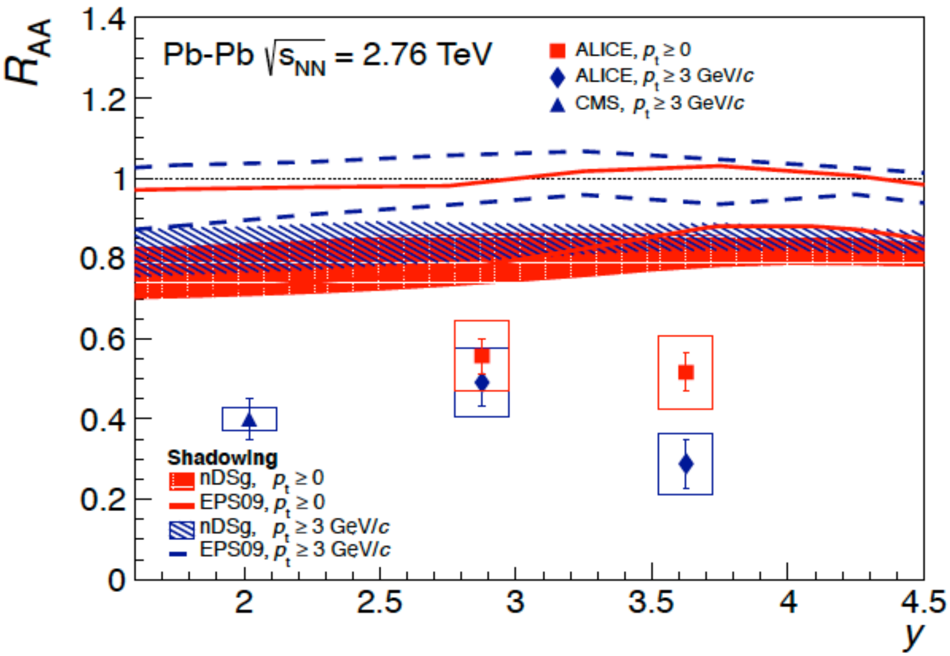
Precise data in LHeC region, x > ~10^{-6}

- Extrapolated HERA dipole models …
- FS04, CGC models including saturation suppressed at low x & Q^2 relative to non-sat FS04-Regge

… new effects may not be easy to see and will certainly need low Q^2 ($\theta \rightarrow 179°$) region …

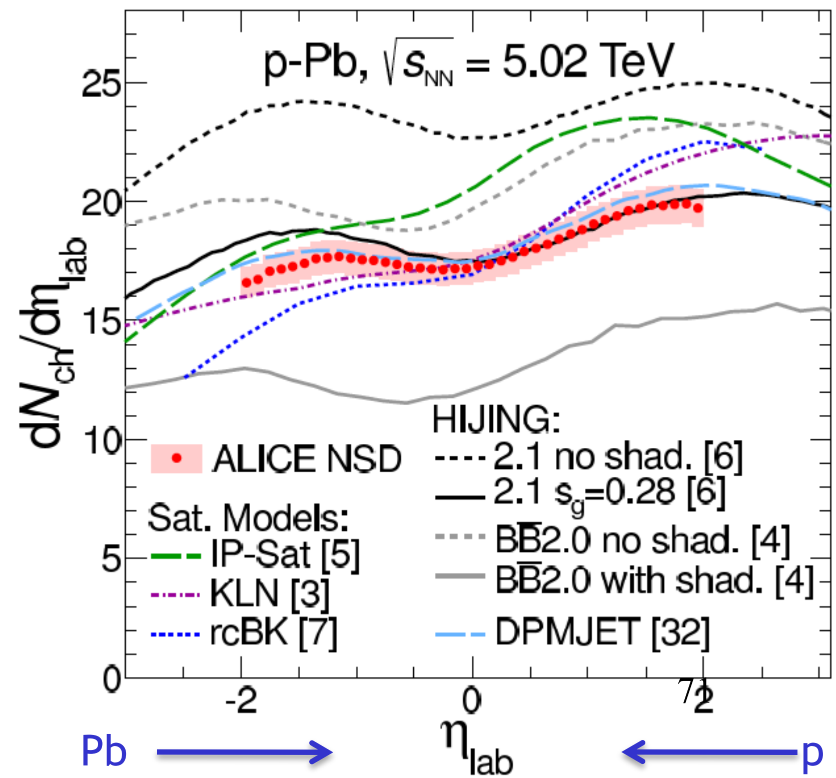
Current Low x Understanding in LHC Ion Data

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)

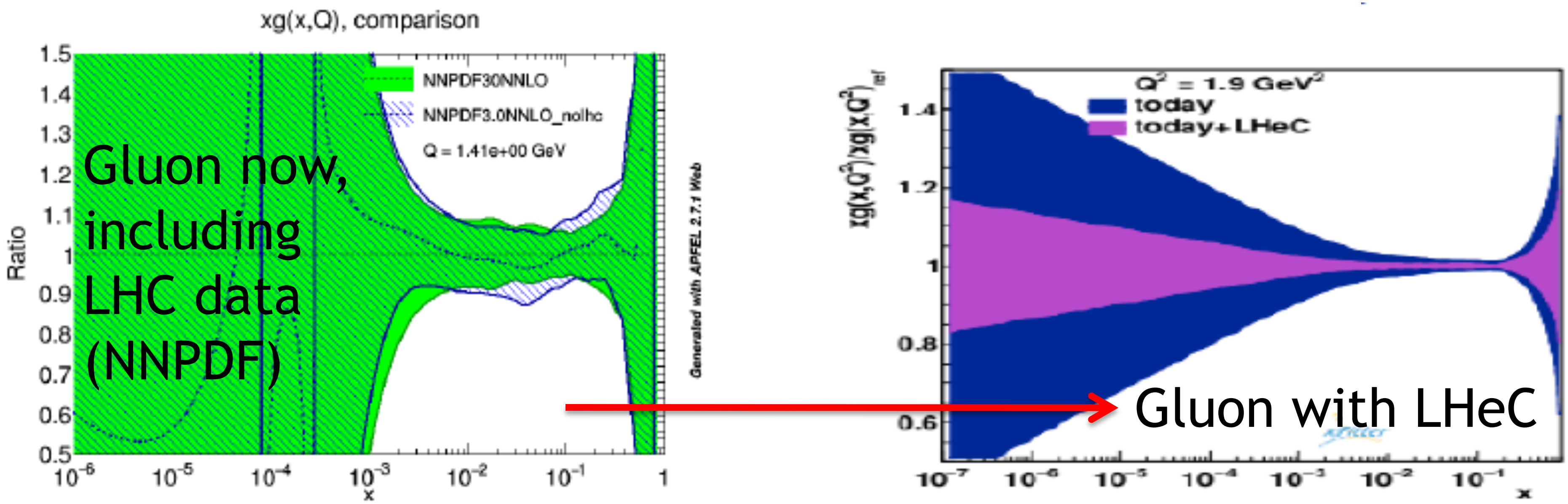
Minimum Bias pA data



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

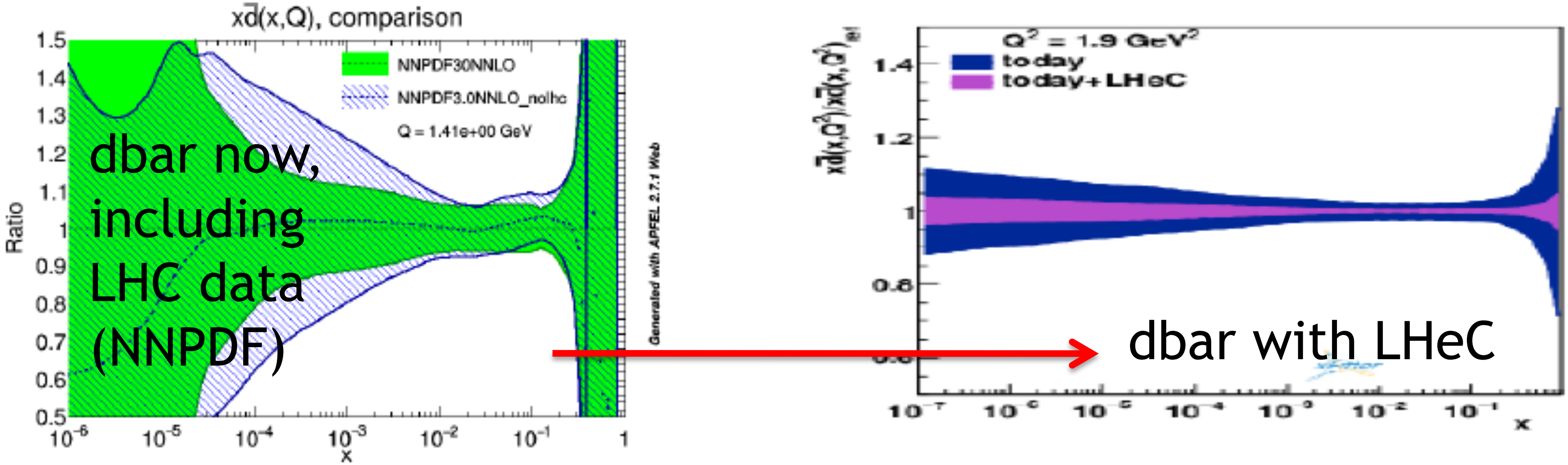
Low x Gluon with LHC, with and without LHeC



<u>Standard LHC channels do not help much:</u>

- ATLAS and CMS constraints as currently included in PDF fits (jets, top) don’t extend below $x \sim 10^{-3}$.
- Other channels may help if theoretical issues can be overcome (LHCb c,b, maybe even exclusive J/Ψ)
- Current knowledge basically comes from HERA: stops at $x \sim 5.10^{-4}$
- LHeC gives constraints to $x \sim 10^{-6}$ from scaling violations and F_L

Low x Sea with LHC, with and without LHeC

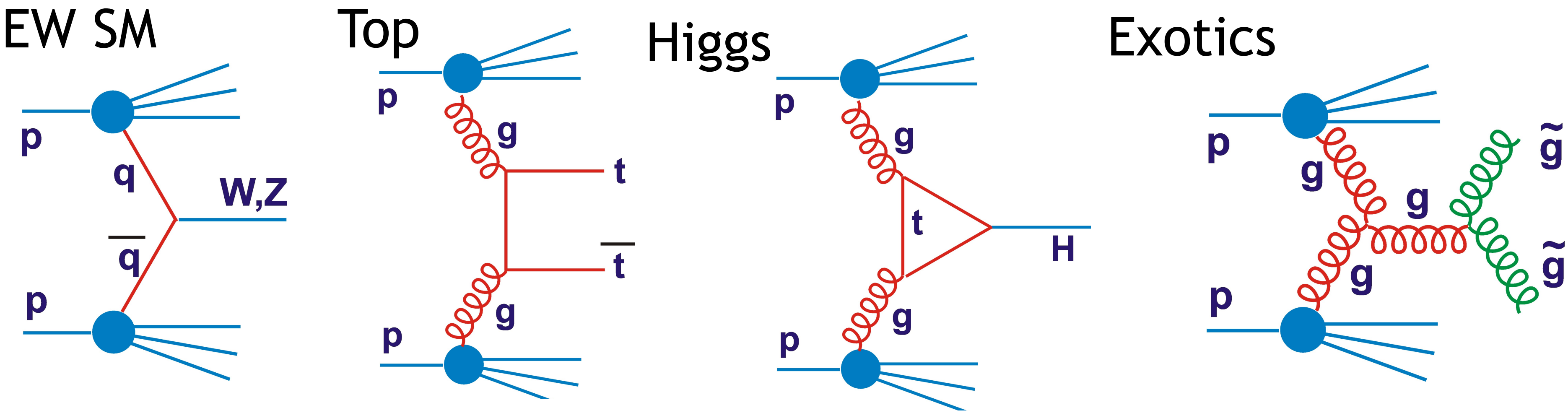


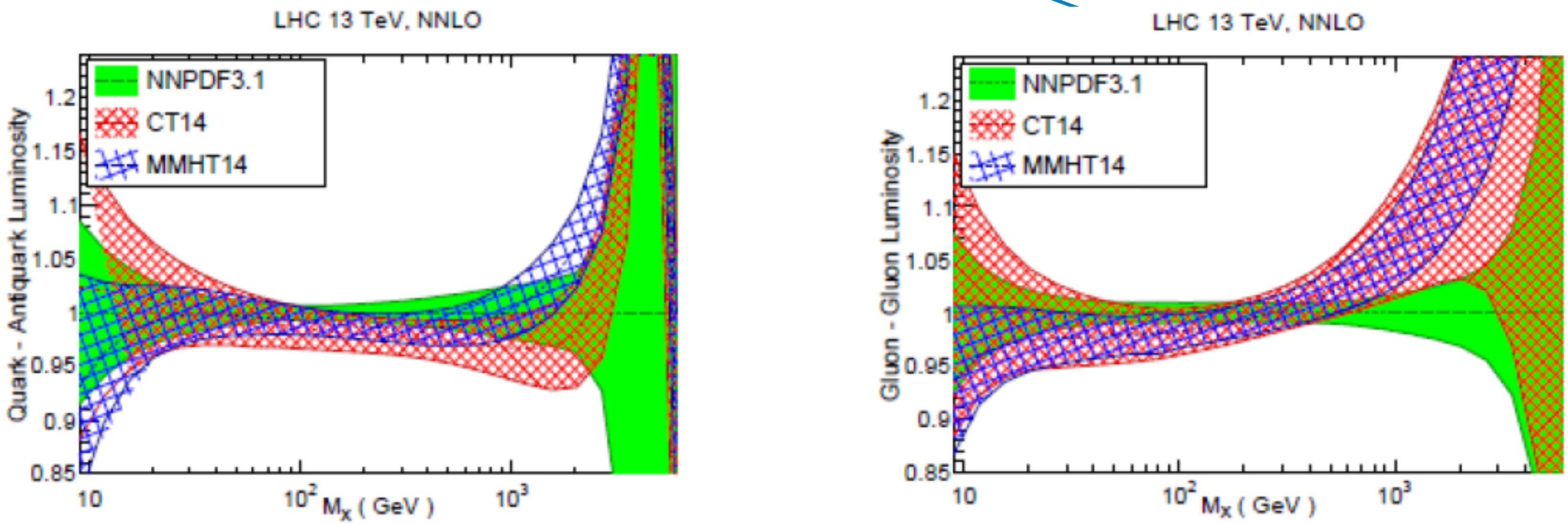
<u>**LHC channels help, but not on same level as LHeC:**</u>

- ATLAS and CMS low mass Drell-Yan data have an impact
- Also potentially LHCb Drell-Yan
- Other channels may help (see eg ALICE direct photon / FOCAL)
- LHeC goes to $x \sim 10^{-6}$, directly from F_2

… this is what DIS does best …

Closer look at Quality of LHC Predictions…

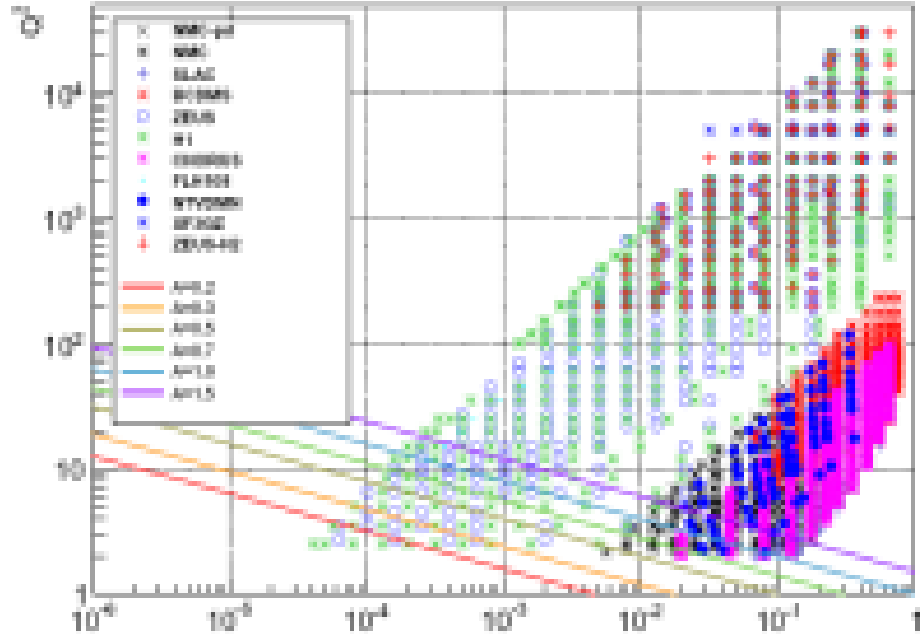




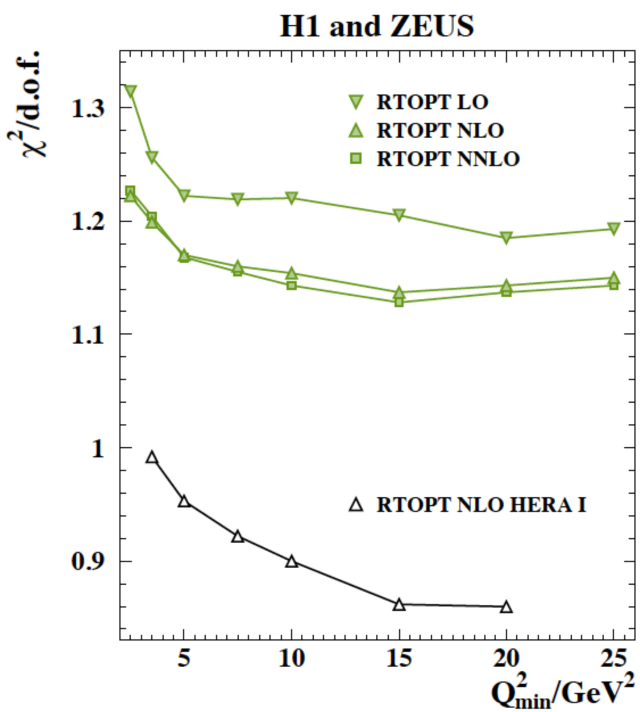
- Pretty good at electroweak scales (intermediate x)
- Still some differences (~5%) between global fits
- More limited at low and high x

Different Approaches and improved data in Perturbative region

e.g. NNPDF: NLO DGLAP description deteriorates when adding data in lines $Q^2 > Ax^{-0.3}$ parallel to 'saturation' curve in x/Q^2.



A	$\chi^2_{\text{without cuts}}/d.o.f.$	$\chi^2_{\text{cut}}/d.o.f$
0.5	$19.68/25 = 0.79$	$106.22/25 = 4.25$
1.0	$54.41/44 = 1.24$	$138.24/44 = 3.14$
1.5	$62.31/59 = 1.06$	$860.65/59 = 14.6$

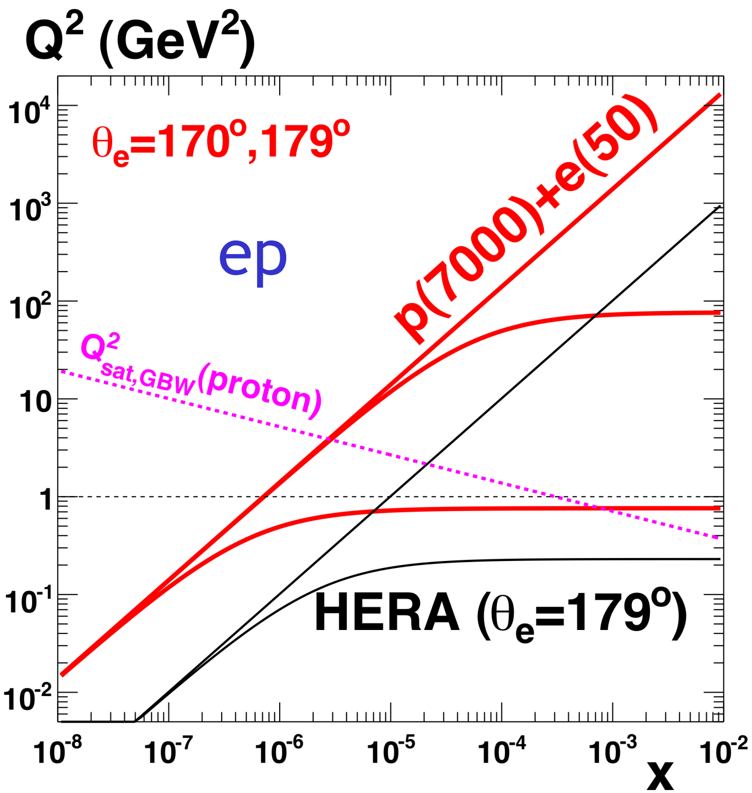


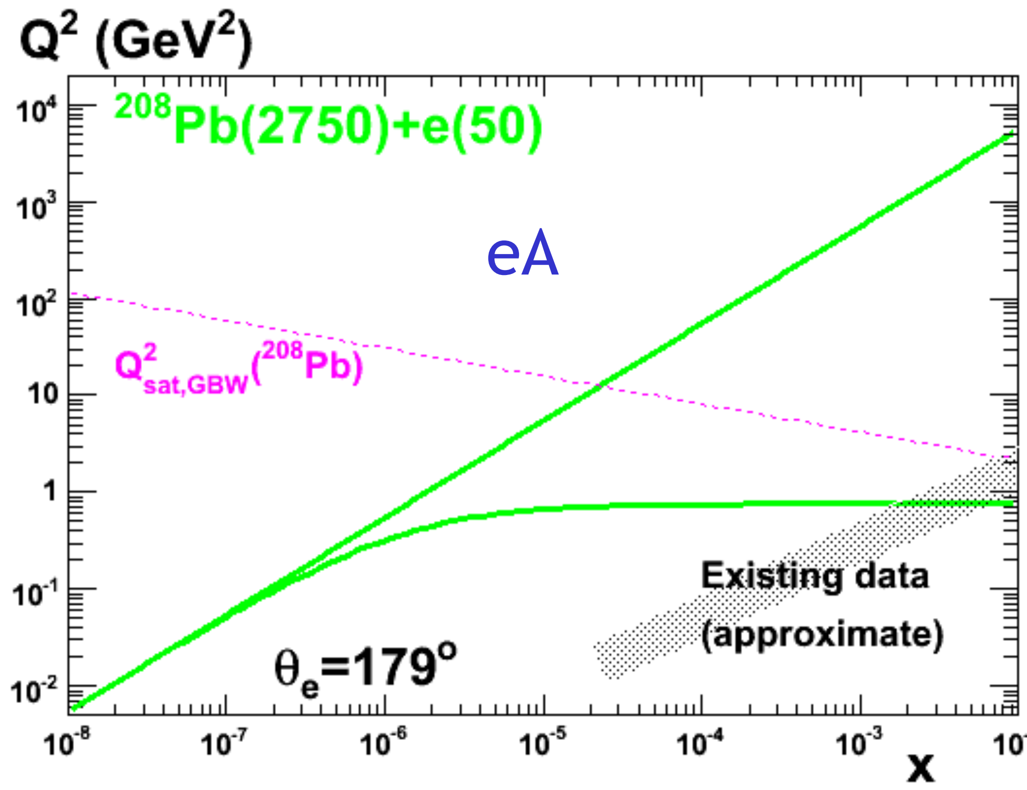
Final HERA-2 Combined PDF Paper:
"some tension in fit between low & medium Q^2 data… not attributable to particular x region" (though kinematic correlation)

… something happens … interpretation?

LHeC: Accessing low x at large Q^2

- Extending Q^2 range vital to fully unravel complex low x region
- Comparing eA and ep allows energy and density effects to be disentangled

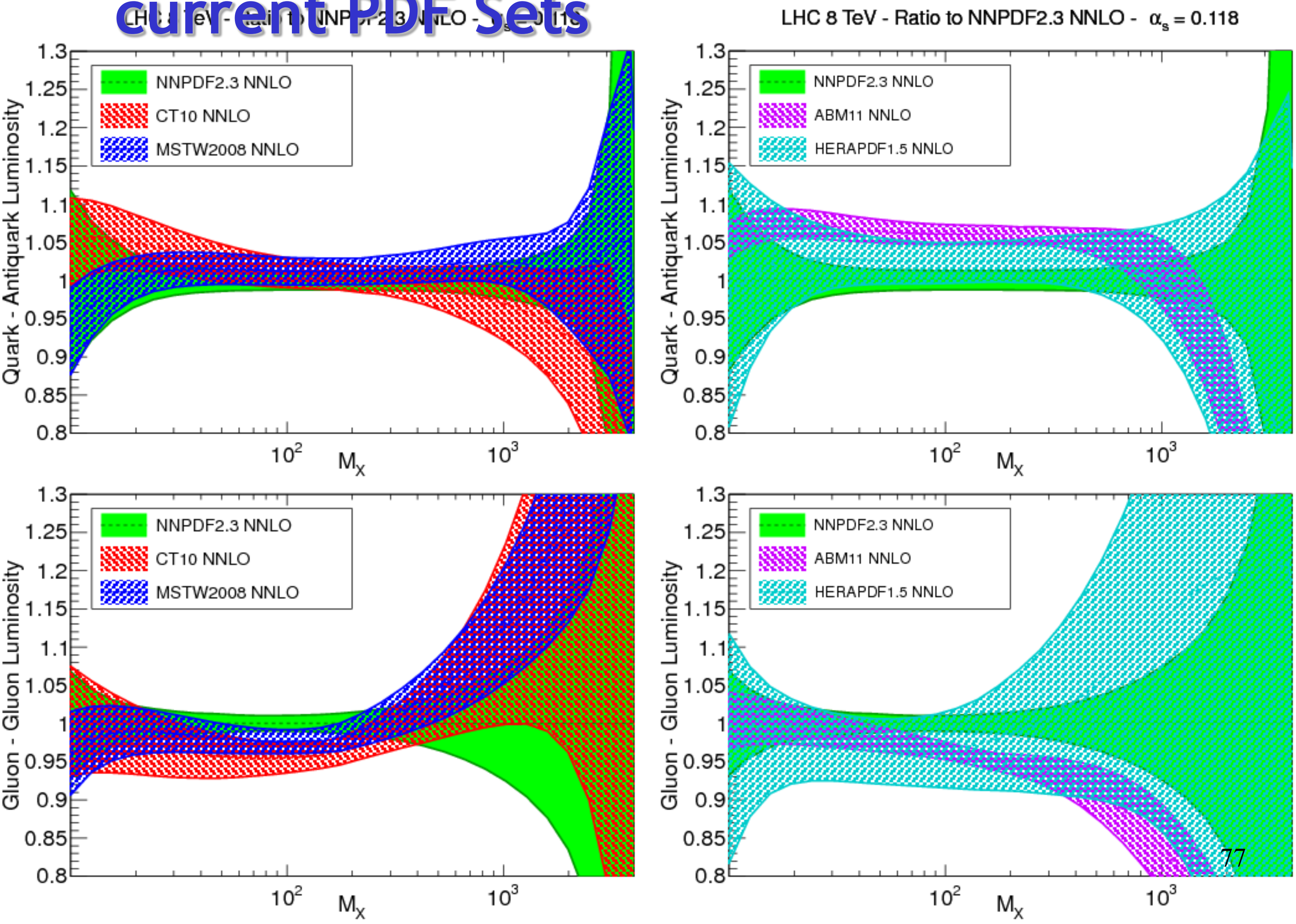




… LHeC reaches saturated region in both ep & eA at perturbative Q2 according to models

Others - not quite so current PDF Sets

[R. Ball et al., JHEP 1304 (2013) 125]



THIS MIGHT BE HANDY (CTEQ PG28)

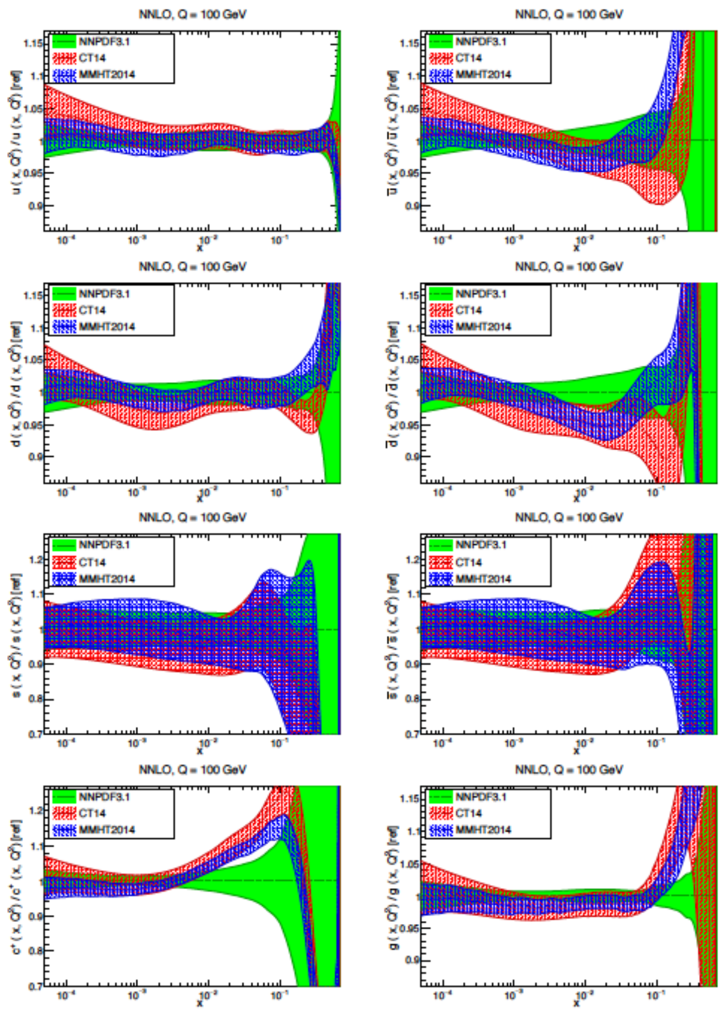
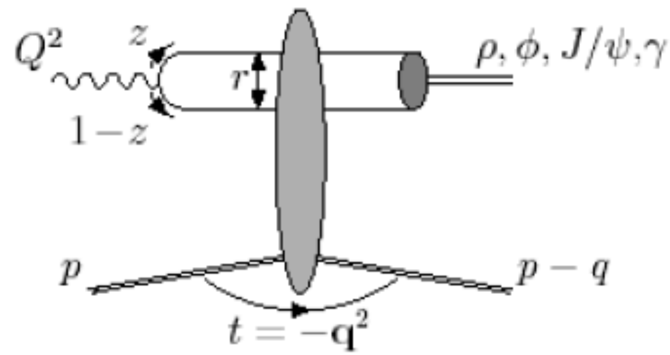


Figure 3.5: Comparison between NNPDF3.1, CT14 and MMHT2014 NNLO PDFs. The comparison is performed at $Q = 100$ GeV, and results are shown normalized to the central value of NNPDF3.1; the PDFs are as in Fig. 3.3.

Describing Vector Mesons in terms of Partons

Factorisation theorem



Dipole Models

step 1. γ fluctuation into $q\bar{q}$ dipole

step 2. dipole – proton interaction $A = \int dr^2\, dz\, \Psi_\gamma\, \sigma(dip-p)\, \Psi_V$

step 3. pair recombination into VM

1. γ wave function

well known : $\Psi(z, k_t)$

however : large $|t|$ studies -> chiral odd contributions

- Basically known

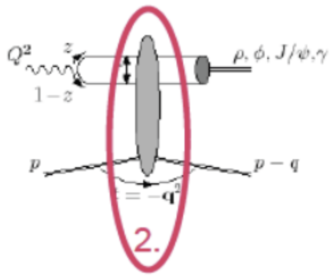
3. pair recombination into VM

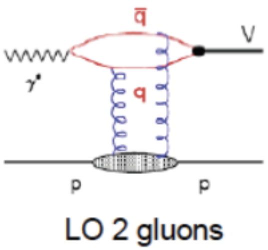
- VM wave function description ?
- role on σ_L / σ_T and helicity amplitudes

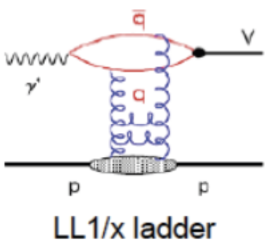
- Limits theoretical precision

The Dipole-Proton Interaction

2. dipole – proton interaction - The interesting physics





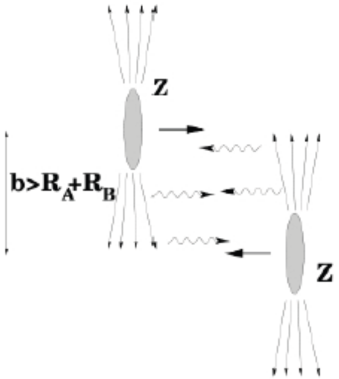


In principle, VM production is a promising candidate to learn about the gluon distribution in the proton

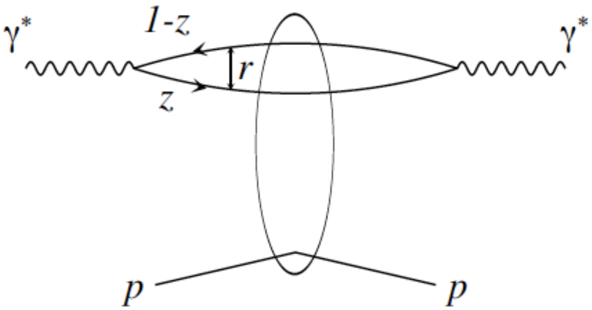
Many models on the details of $\sigma(r)$!

What is the relevant scale?... r depends on Q^2 and M_V^2

$$Q^2_{eff} = z\,(1-z)\,(Q^2+M_V^2) \sim (Q^2+M_V^2)\;/\;4$$ [MRT...]

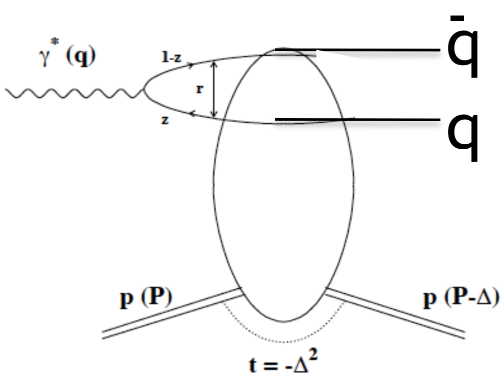


Advantage of Diffractive DIS: Dipole Language



Inclusive Cross Section

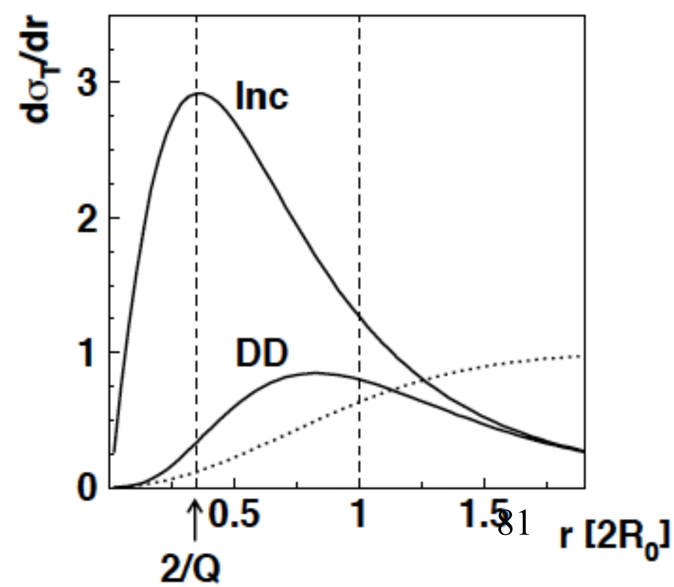
$$\sigma_{T,L}(x,Q^2) = \int d^2\mathbf{r} \int_0^1 d\alpha \, |\Psi_{T,L}(\alpha,\mathbf{r})|^2 \hat{\sigma}(x,r^2)$$



Diffractive DIS

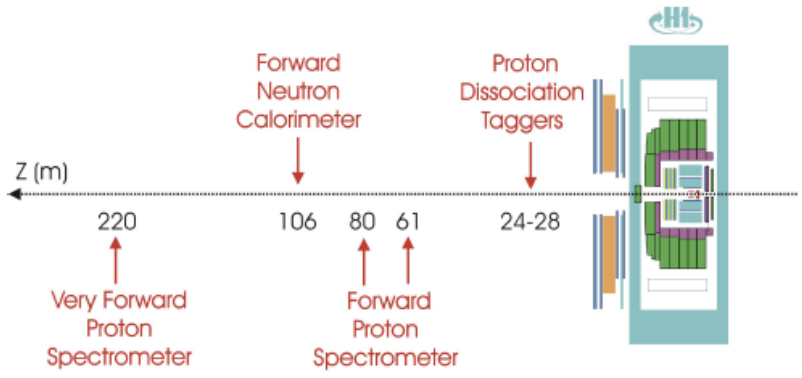
$$\left.\frac{d\sigma^D_{T,L}}{dt}\right|_{t=0} = \frac{1}{16\pi} \int d^2\mathbf{r} \int_0^1 d\alpha \, |\Psi_{T,L}(\alpha,\mathbf{r})|^2 \hat{\sigma}^2(x,r^2)$$

3) Extra factor of dipole cross section weights DDIS cross section towards larger dipole sizes → enhanced sensitivity to saturation effects.



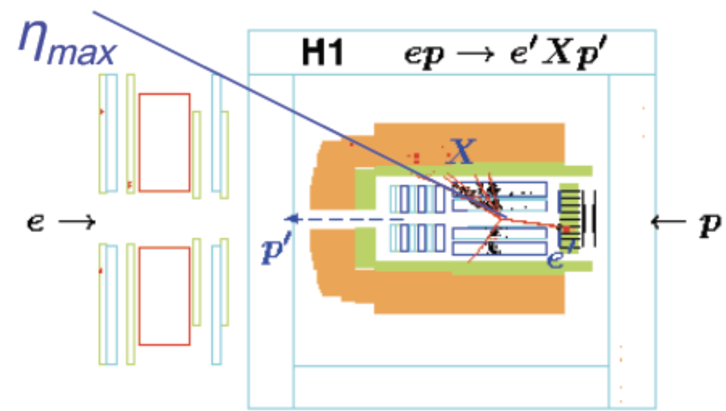
Signatures and Selection Methods

Scattered proton in Leading Proton Spectrometers **(LPS)**



Limited by statistics and p-tagging systematics

`Large Rapidity Gap' **(LRG)** adjacent to outgoing (untagged) proton

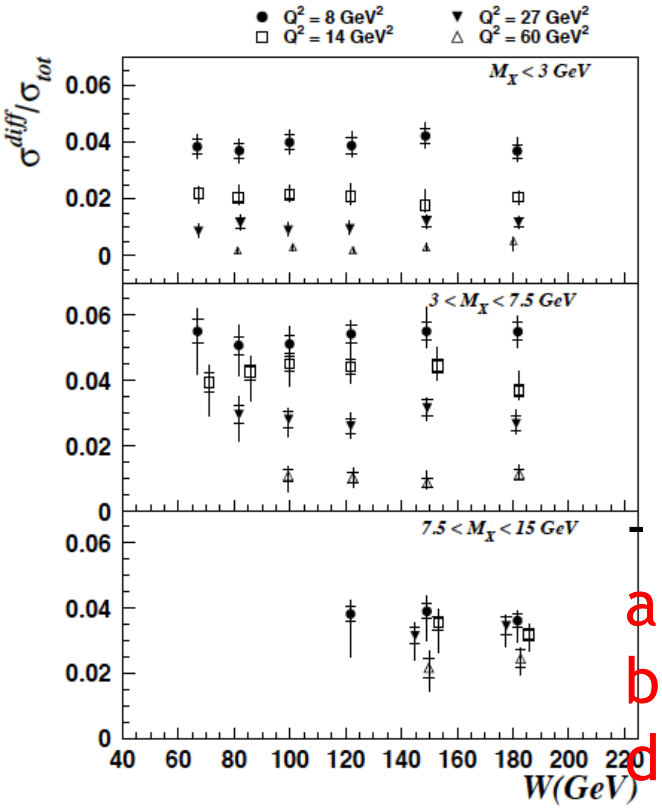


Limited by p-diss systematics

- The 2 methods have very different systematics

21

Diffractive : Inclusive Ratio



- Famous HERA plot … Rather flat diffractive/inclusive ratio v x at fixed Q2, taken as evidence for saturation

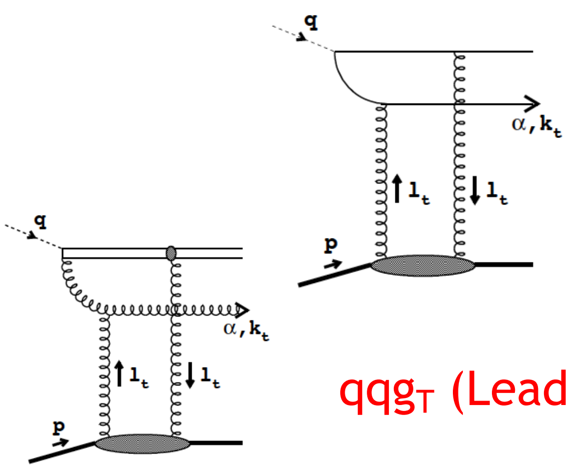
- **Rather flat diffractive/inclusive ratio** and failure of diffractive PDF fits to data below $Q^2 \sim 5$ GeV^2 best described by dipole models incorporating saturation …

BOTTOM LINE … HERA not conclusive on location or dynamics of onset and LHC has not given greater clarity

Diffractive DIS & Dipole Models

– χ^2 / ndf increases systematically in H1 DPDF fits when data of Q^2 < 8.5 GeV^2 are included (slightly lower in ZEUS)
… low Q^2 breakdown of pure Leading Twist DGLAP approach

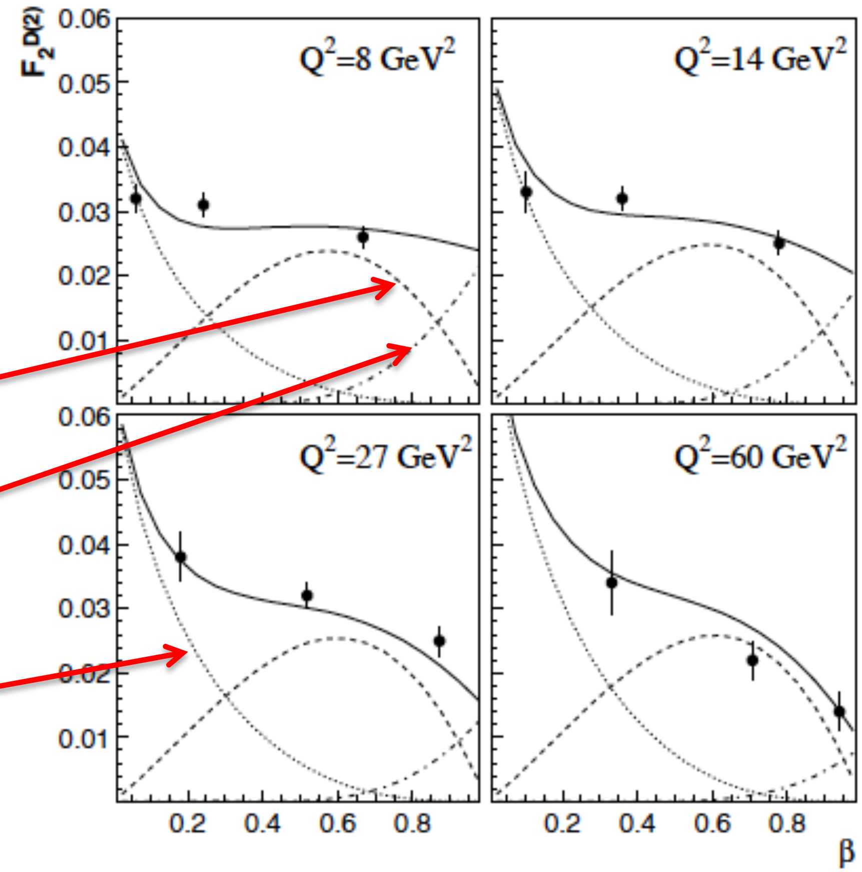
- Dipole models also applied, but need qqbar-g terms (and perhaps higher Fock states)



qq_T (Leading Twist)

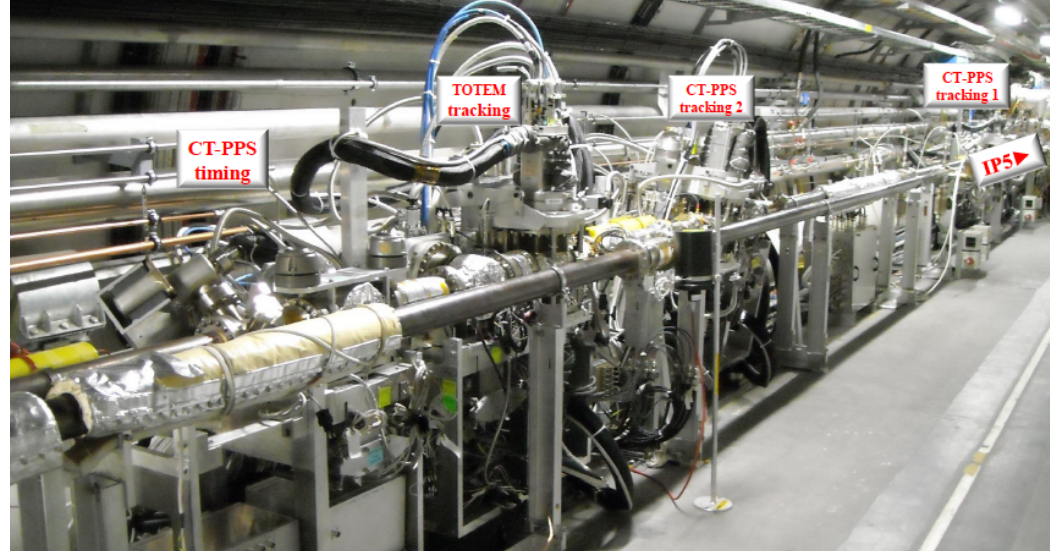
qq_L (Higher Twist)

qqg_T (Leading Twist)



- Not yet describing fine detail
- Unravelling this rich phenomonology can yield big rewards!

New Generation of Roman Pots

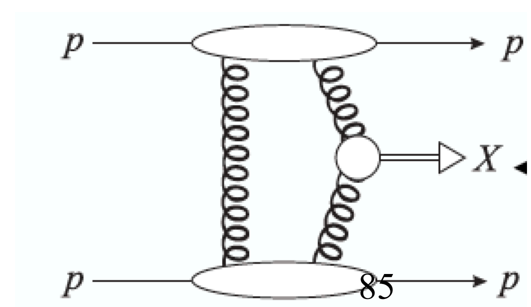


Future LHC diffractive Physics based on CT-PPS (CMS/TOTEM) & AFP (ATLAS)
- Operated in Run 2 and will remain in Run 3 (and possibly be upgraded for HL-LHC)

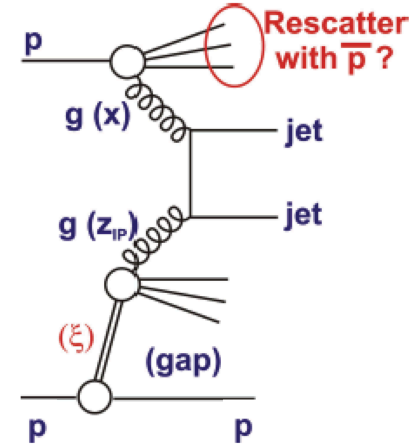
- Precision (fairly) radiation hard silicon pixel spatial detectors
- Time of Flight detectors with ~ 25ps timing precision from Cerenkov light in diamond (CT-PPS) and quartz (AFP)

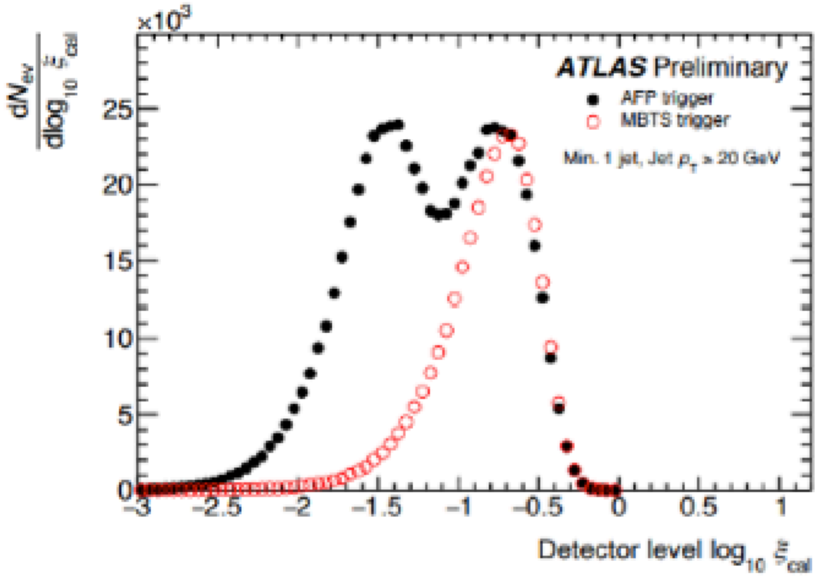
→ Operate in normal LHC runnning conditions

→ Optimised for double proton-tagged processes, where vertex can be located to ~1mm from proton ToF, suppressing pile-up



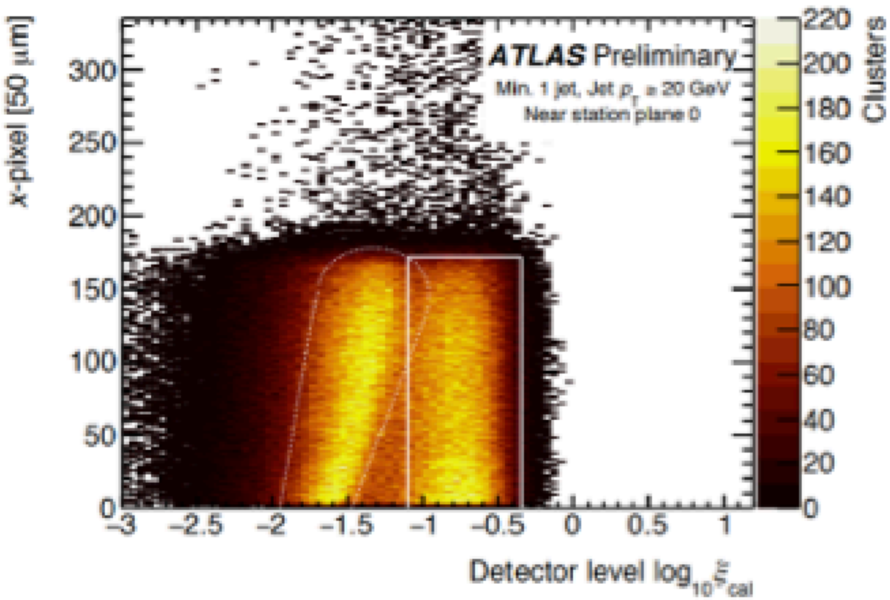
AFP Observation of Single Diffractive Dijet Signal





- Single proton tagged sample with ξ measured in main ATLAS calorimeter

- Strong enhancement in low ξ_{Cal} diffractive region for AFP-triggered data over MBTS data + common pile-up contribution

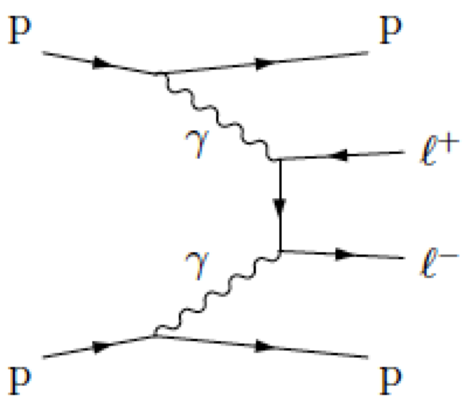


Low ξ data exhibit expected x-y correlation in AFP pixels and correlation between pixel x position and ξ_{Cal}

→ Clear diffractive signature

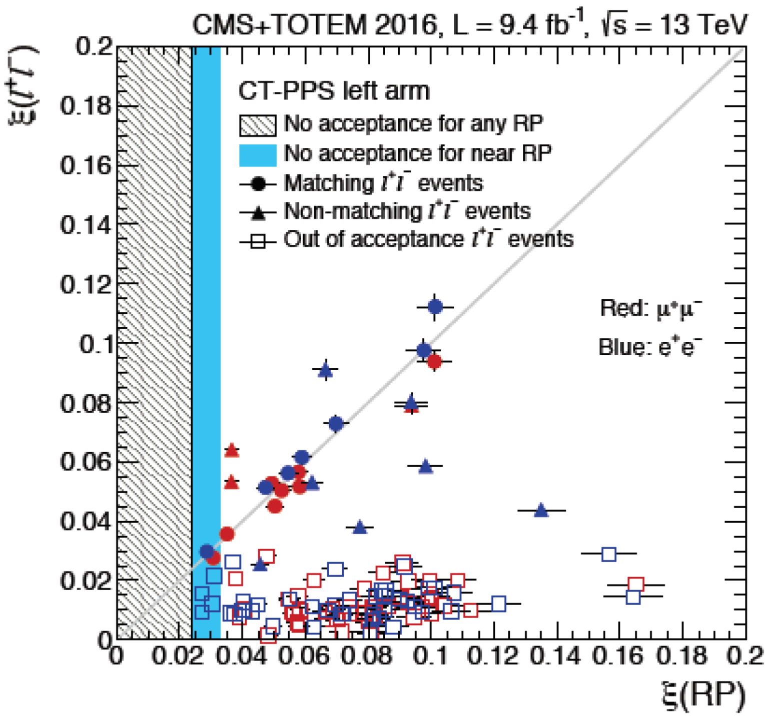
First High Lumi Study @ CT-PPS (9.4 fb^{-1})

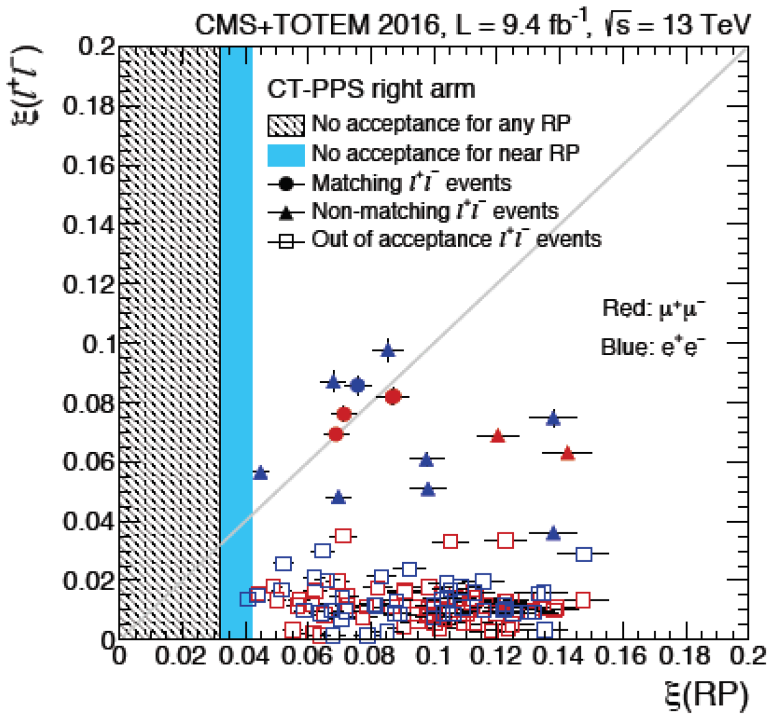
$\gamma\gamma \rightarrow$ ee or $\mu\mu$



- Single proton tagged (so far)
- Dileptons required to be back to back
- Study correlation between ξ from proton and from l^+l^- pair …

12 $\mu\mu$ events match in ξ (1.5±0.5 background)
8 ee events match in ξ (2.4±0.5 background)





5.1σ signal

[arXiv: 1803.04496]

ATLAS JET VETO and decorrelations ETC

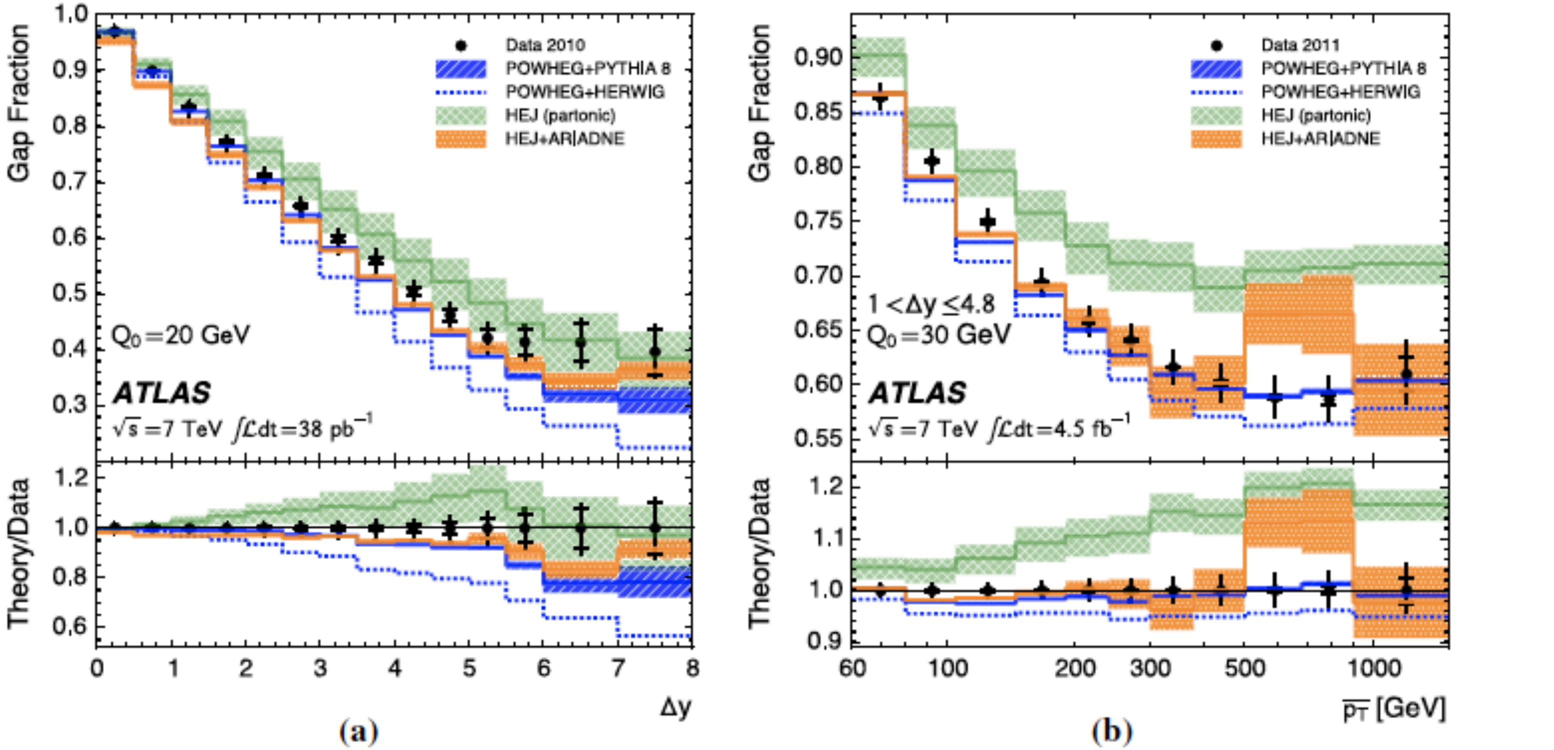
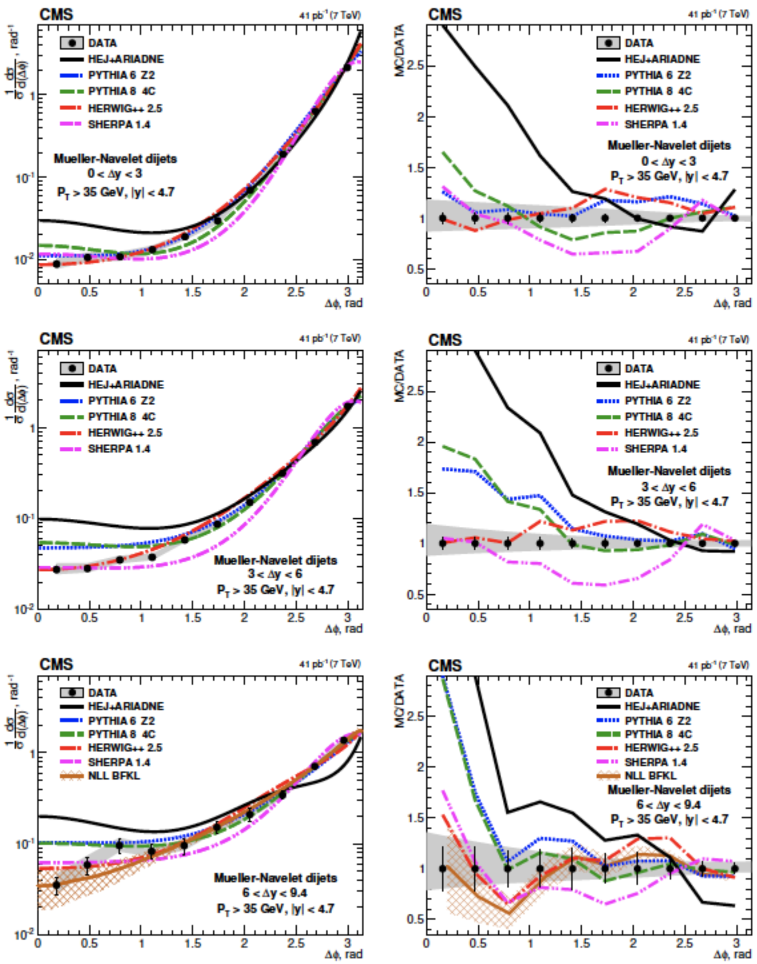
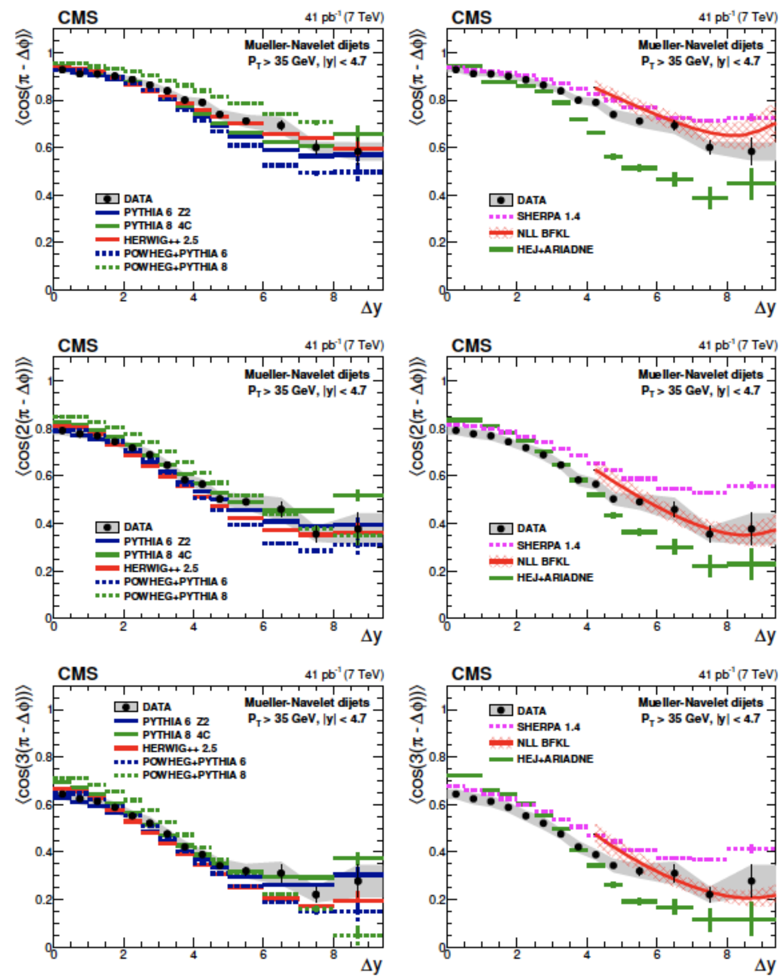


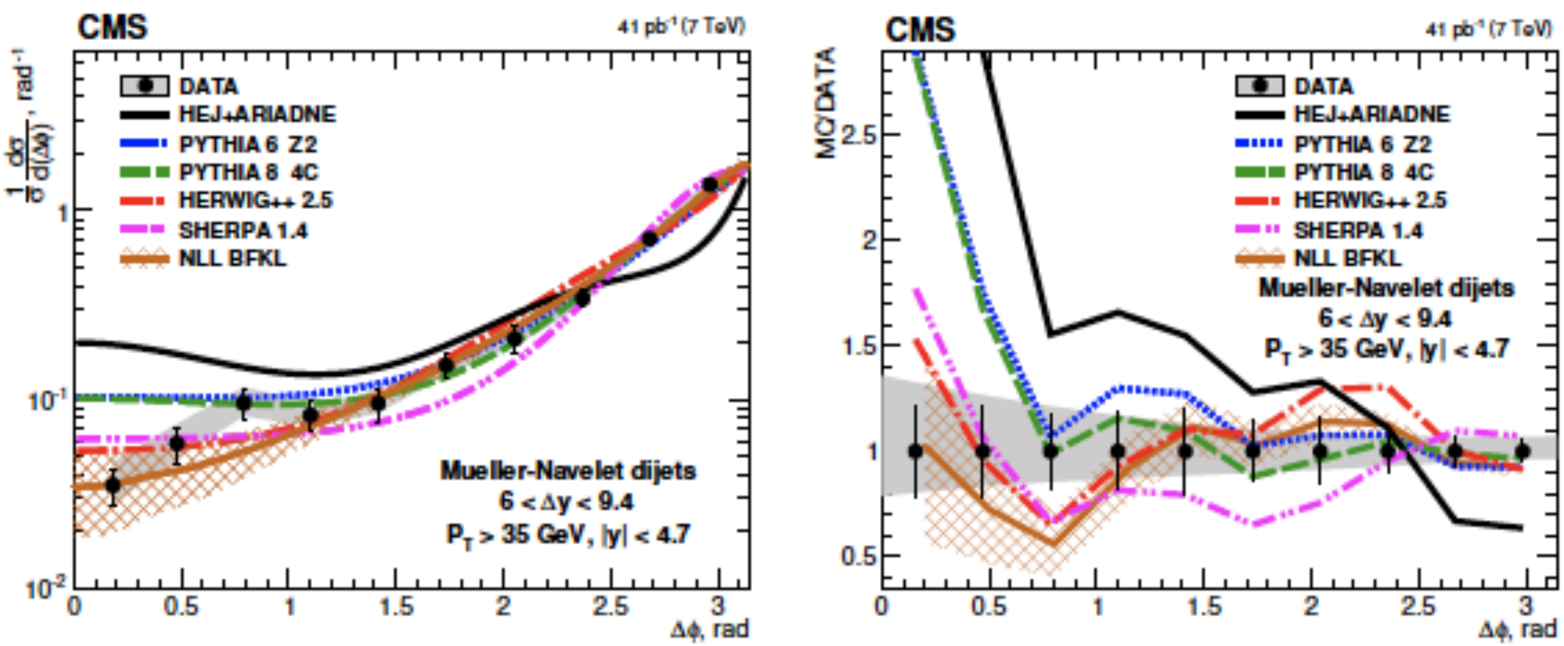
Fig. 3 The measured gap fraction (*black dots*) as a function of **a** Δy and **b** $\overline{p_T}$. The *inner error bars* represent statistical uncertainty while the *outer error bars* represent the quadrature sum of the systematic and statistical uncertainties. For comparison, the predictions from parton-level HEJ (*light-shaded cross-hatched band*), HEJ+ARIADNE (*mid-shaded dotted band*), POWHEG+PYTHIA 8 (*dark-shaded hatched band*) and POWHEG+HERWIG (*dotted line*) are also included. The ratio of the theory predictions to the data is shown in the *bottom panel*

LHC Example combining different signatures: Azimuthal Decorrelations between M-N jets





LHC Example combining different signatures: Azimuthal Decorrelations between M-N jets

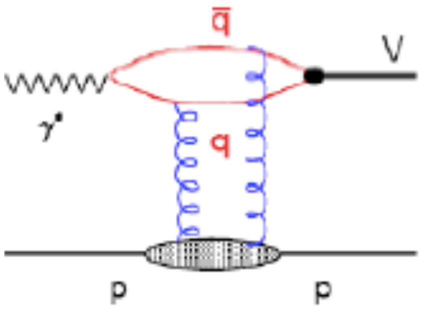


- Jets separated by up to Δy = 9.4 units
- DGLAP-based models with appropriate tuning (LL parton showers and colour-coherence) can describe data
- LL BFKL model (HEJ) overestimates decorrelations
- Analytic NLL BFKL calculation agrees well with data

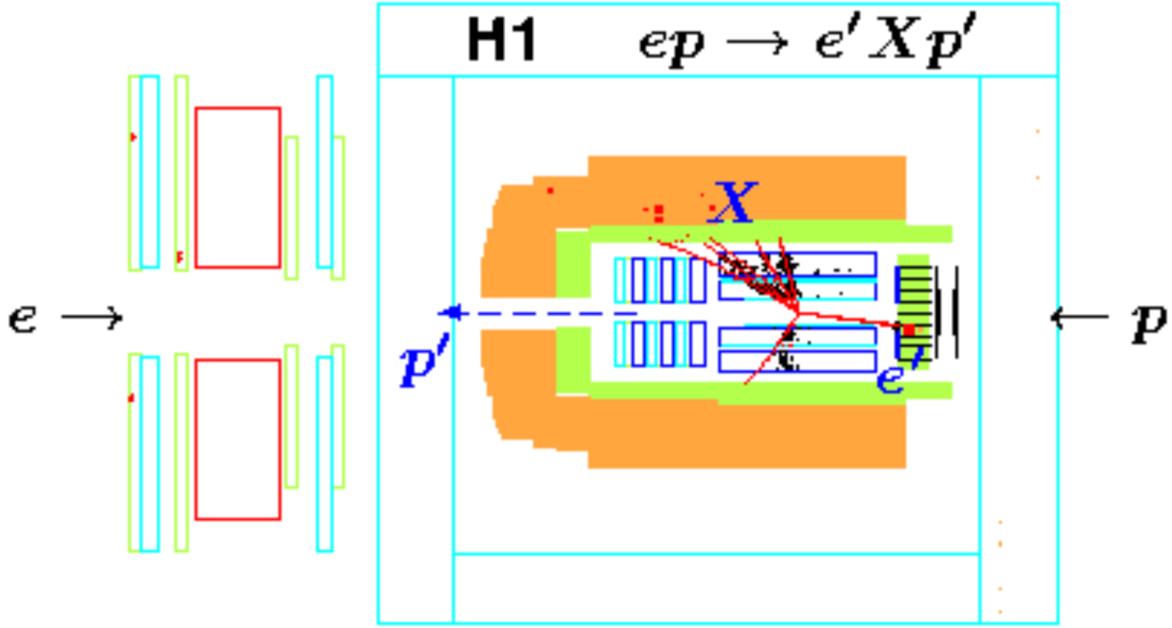
→ Will be increasingly interestin at higher CMS energies

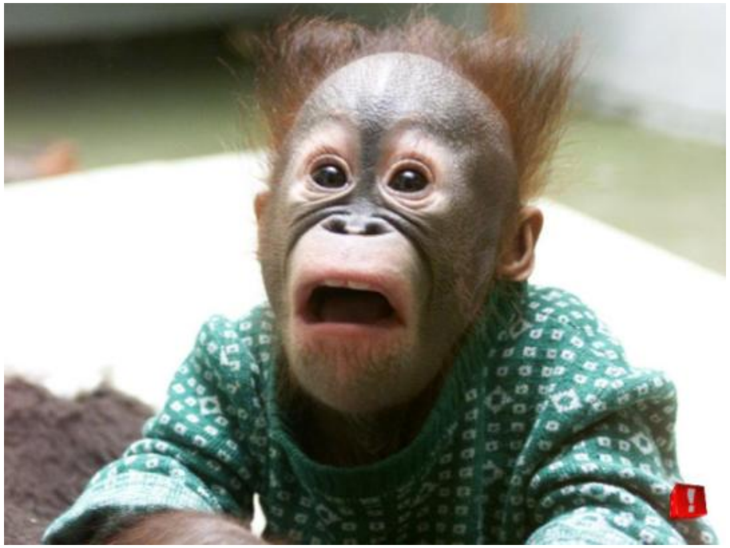
Inclusive Diffraction, Semi-Inclusive PDFs and Rapidity Gap Survival Probabilities

Vector meson production is a ‘higher twist’ (Q^2 suppressed) process



There are ‘leading twist’ diffractive processes with same Q^2 dependence as the bulk DIS cross section …





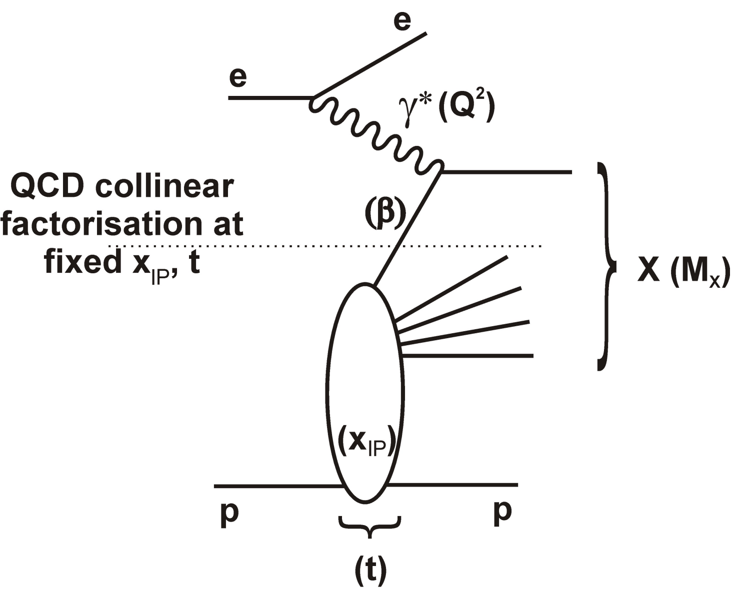
~10% of DIS events have no forward energy flow

Measurements and Observables

Main observable is the Diffractive `reduced cross section' …

$$\sigma_r^{D(3)}(\beta, Q^2, x_{IP}) = F_2^{D(3)} - \frac{y^2}{Y_+} F_L^{D(3)} \approx F_2^{D(3)}$$

… cross section (or structure fn.) dependent on 3 variables
… 4 if you also include t → $\sigma_r^{D(4)}(\beta, Q^2, x_{IP}, t)$
… can only realistically study 1 (maybe 2) variables at a time!



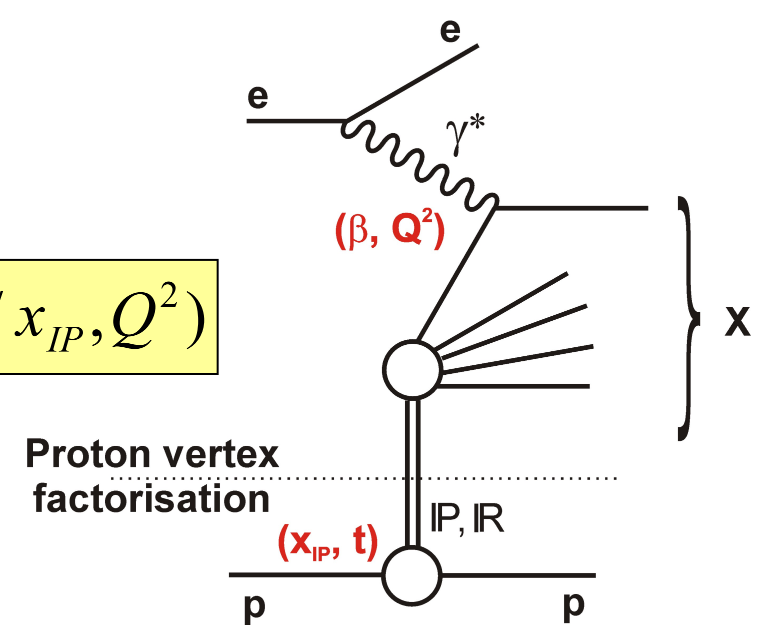
"Semi-inclusive QCD Factorisation"

$$d\sigma_{\text{parton } i}(ep \rightarrow eXY) = f_i^D(x, Q^2, x_{IP}, t) \otimes d\hat{\sigma}^{ei}(x, Q^2)$$

-i.e. can define
diffractive PDFs (DPDFs), f_i^D…
- At fixed (x_{IP}, t), DPDF Q^2 evolution is same as inclusive PDFs!

A deeper factorisation?

‘Proton vertex’ factorisation
… completely separate (x_{IP}, t) from (β, Q^2) dependences.



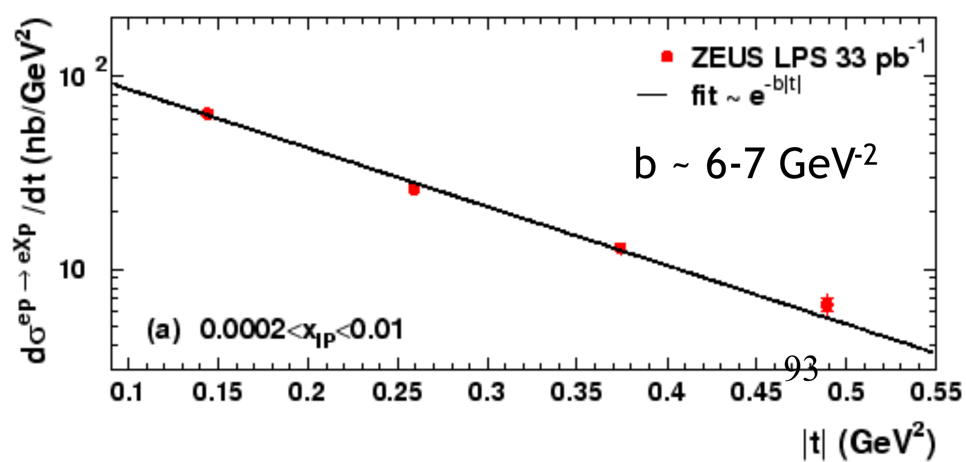
$$f_i^D(x, Q^2, x_{IP}, t) = f_{IP/p}(x_{IP}, t) \cdot f_i^{IP}(\beta = x / x_{IP}, Q^2)$$

No firm QCD basis, but consistent with all experimental data

… Regge-based parameterisation works well → Ingelman-Schlein

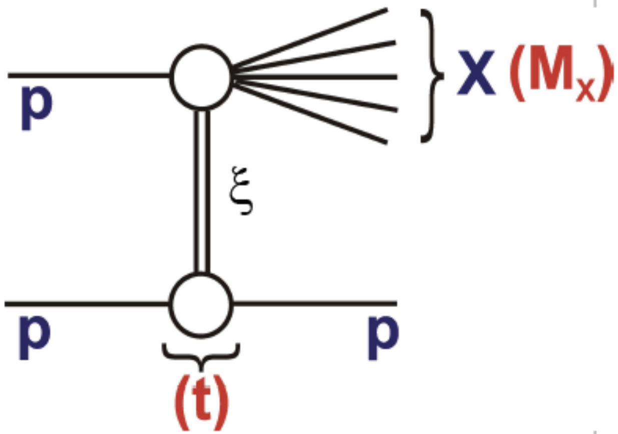
$$f_{IP/p}(x_{IP}, t) = \frac{e^{B_{IP} t}}{x_{IP}^{2\alpha_{IP}(t) - 1}}$$

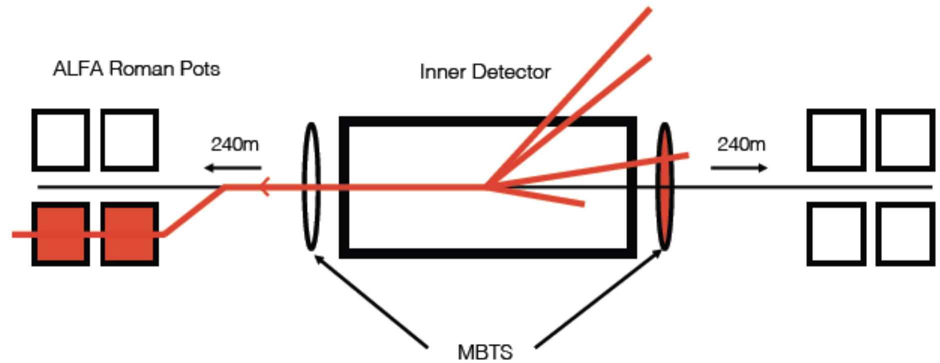
DPDFs f_i^{IP} then measure partonic structure of the exchanged system (IP)

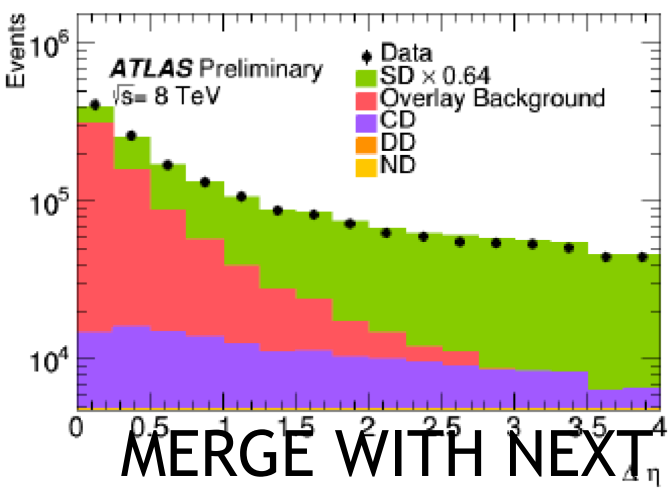


SD Cross Section with Tagged Protons

NEW!



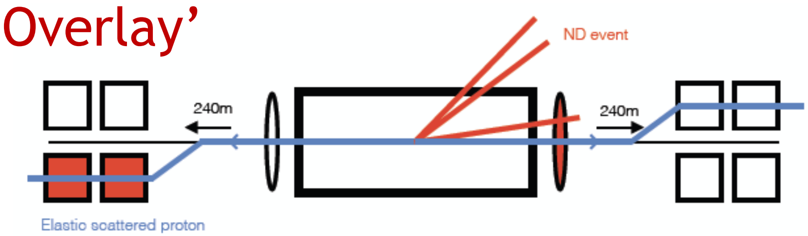




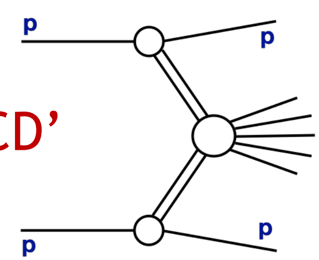
- Reconstruct scattered protons in ALFA, X system in inner tracker
  - ND and DD backgrounds negligible
  - New: ‘overlay’ background
    … uncorrelated ALFA, ID signals
- Also signigificant `Central Diffraction’ background

MERGE WITH NEXT OR DROP!

`Overlay’



`CD’

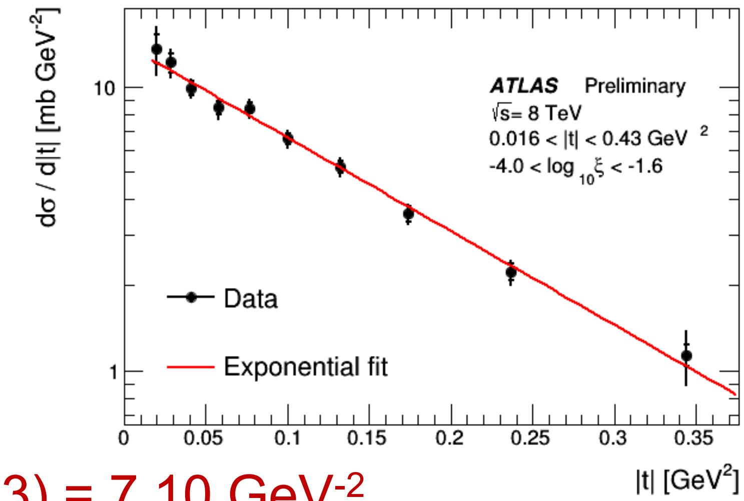


SD Cross Section v |t| and ξ

- Data consistent with expected exponential

$$\frac{d\sigma}{dt} = Ae^{Bt}$$

- B = 7.60 ± 0.23(stat.) ± 0.22(syst.) GeV^{-2}
- High precision, consistent with expectations:
- B(PYTHIA8 A2) = 7.82 GeV^{-2}, B(PYTHIA8 A3) = 7.10 GeV^{-2}



- Expected approximate $^{d\sigma}/_{d\xi}$ α $^{1}/_{\xi}$ dependence

holds over two orders of magnitude in ξ

- Further interpreted in `triple pomeron' model:

$$\frac{d\sigma_{SD}}{d\log_{10}(\xi)} \propto \left(\frac{1}{\xi}\right)^{\alpha(0)-1} \frac{1}{B}\left(e^{Bt_{\mathrm{high}}} - e^{Bt_{\mathrm{low}}}\right)$$

α(0) = 1.07 ± 0.02(stat.) ± 0.06(syst.) ± 0.06(α')

… compatible with value describing elastic cross section → universality

… compatible with models (PYTHIA8 A3: 1.14, PYTHIA8 A2 (SS): 1.00)