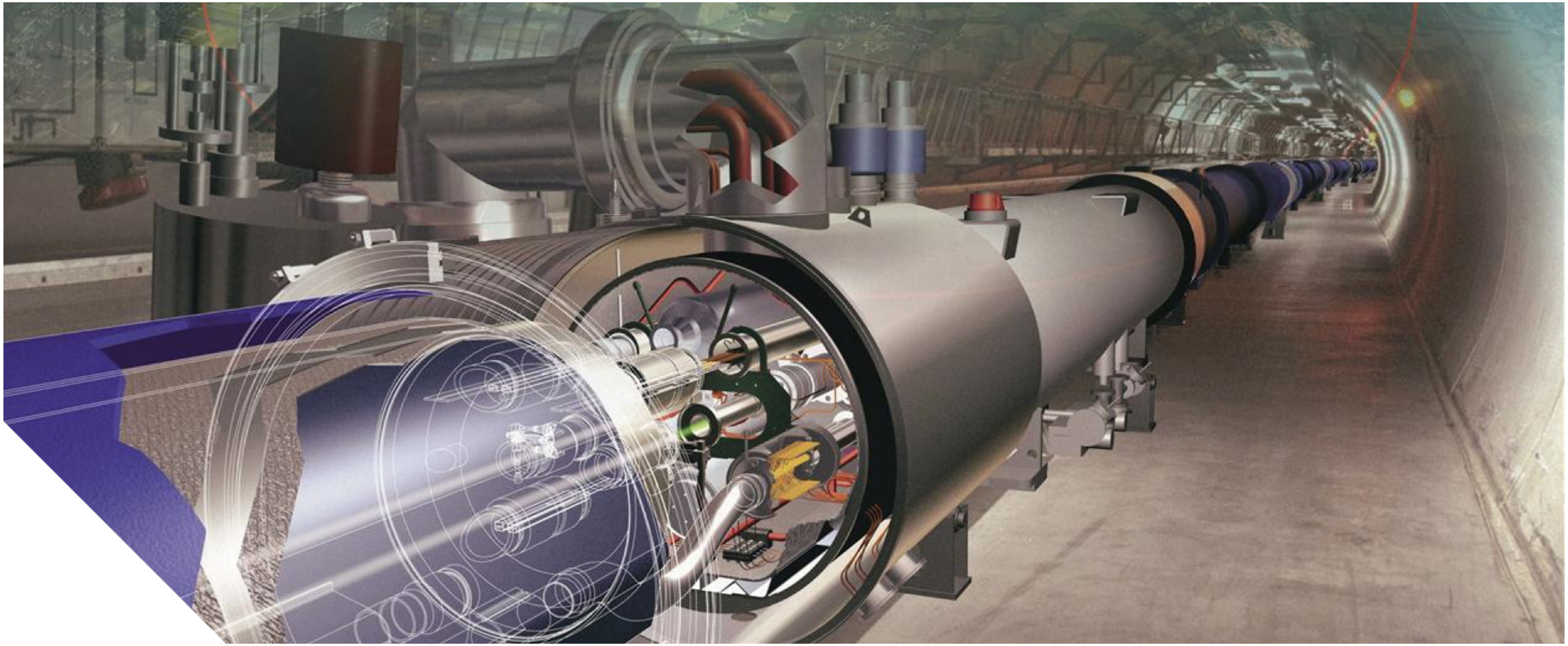


QCD – Lecture 7

implications for and constraints from the LHC, and Beyond

Claire Gwenlan, Oxford, HT

the SM is not as well known as you might think

in the QCD sector, PDFs limit our knowledge;

transport PDFs to hadron-hadron cross sections

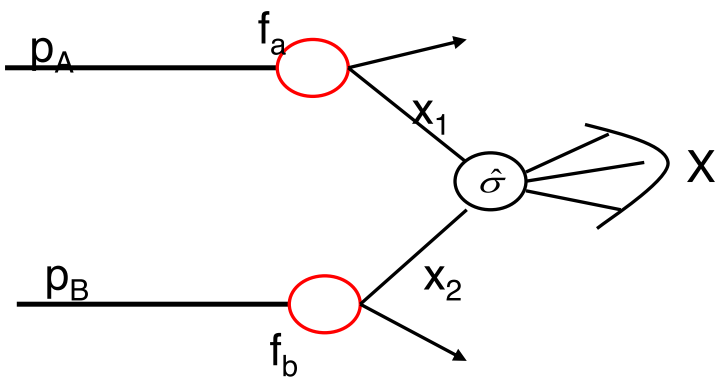
using **QCD factorisation theorem**

$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1, \mu_F^2)\, f_b(x_2, \mu_F^2)$$

$$\times\ \hat{\sigma}_{ab \to X}\left(x_1, x_2, \{p_i^\mu\}; \alpha_S(\mu_R^2), \alpha(\mu_R^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}\right)$$

where X = W, Z, H, t, jets, prompt-**γ**,…

and **σ** is known to some fixed order in pQCD, or in some leading logarithm approximation (LL, NLL) to all orders via resummation

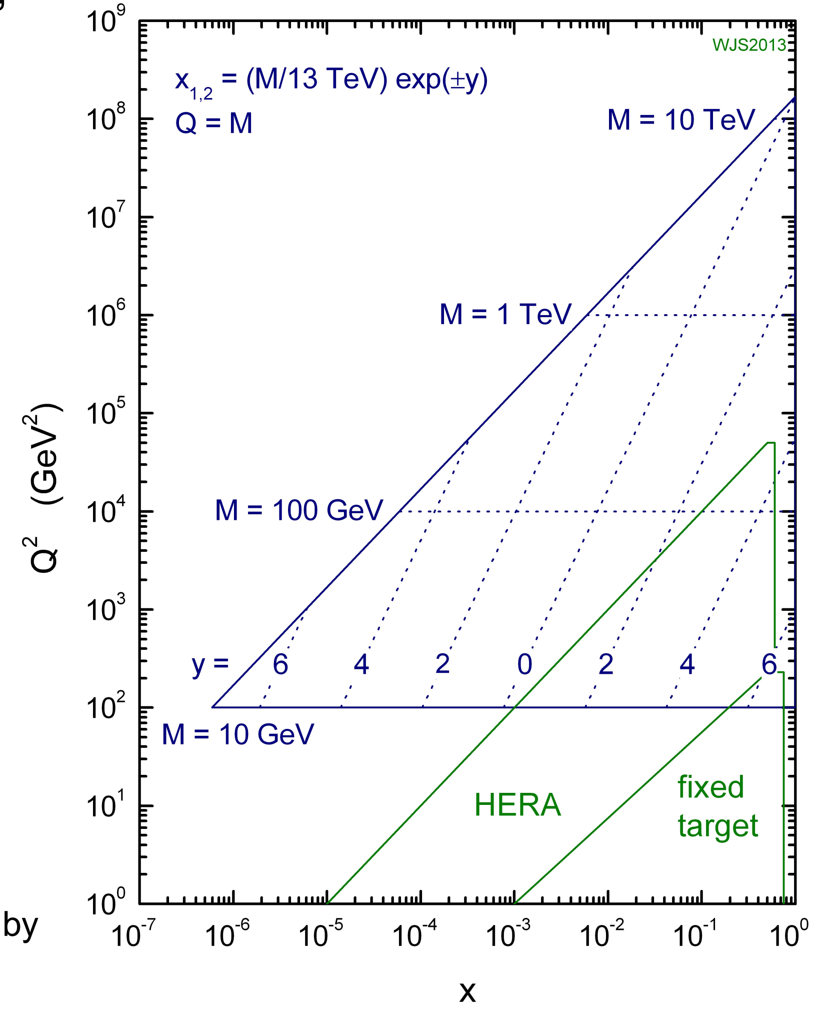


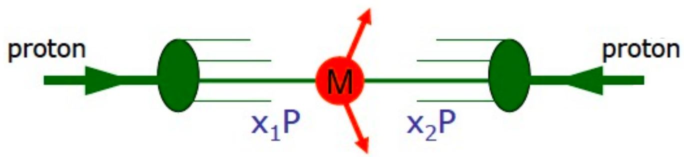
momentum fractions x1 and x2 determined by mass and rapidity of **X**

$$M = \sqrt{x_1 x_2 s}$$

$$y = \frac{1}{2} \ln \frac{x_1}{x_2}$$

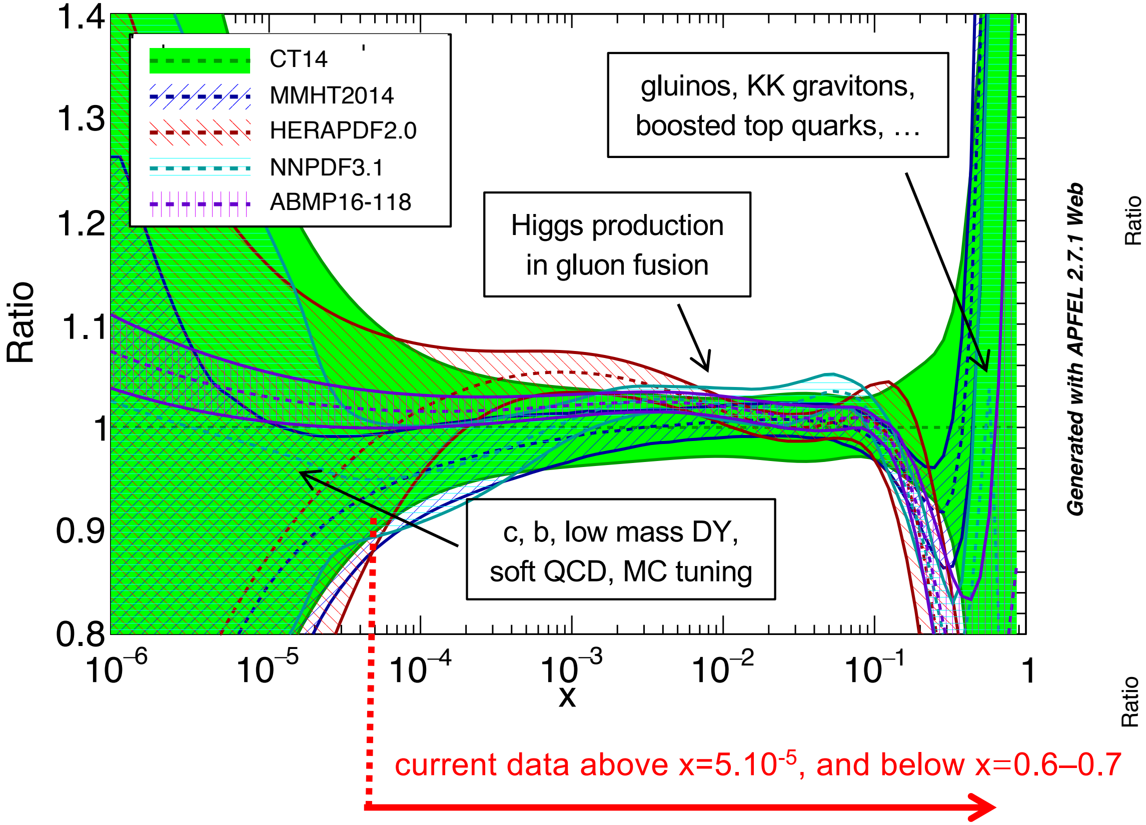
13 TeV LHC parton kinematics



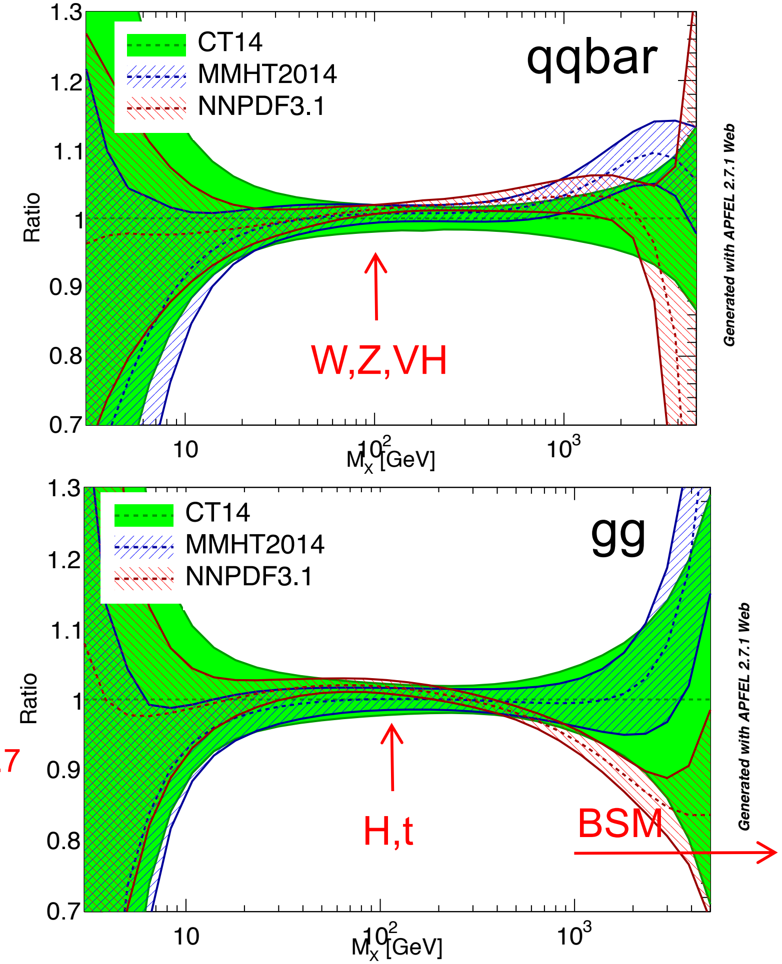


PDFs: the situation today

xg(x,Q), NNLO, Q^2=100 GeV^2, $\alpha_s(M_Z)$=0.118



pdf luminosities (LHC@14TeV)



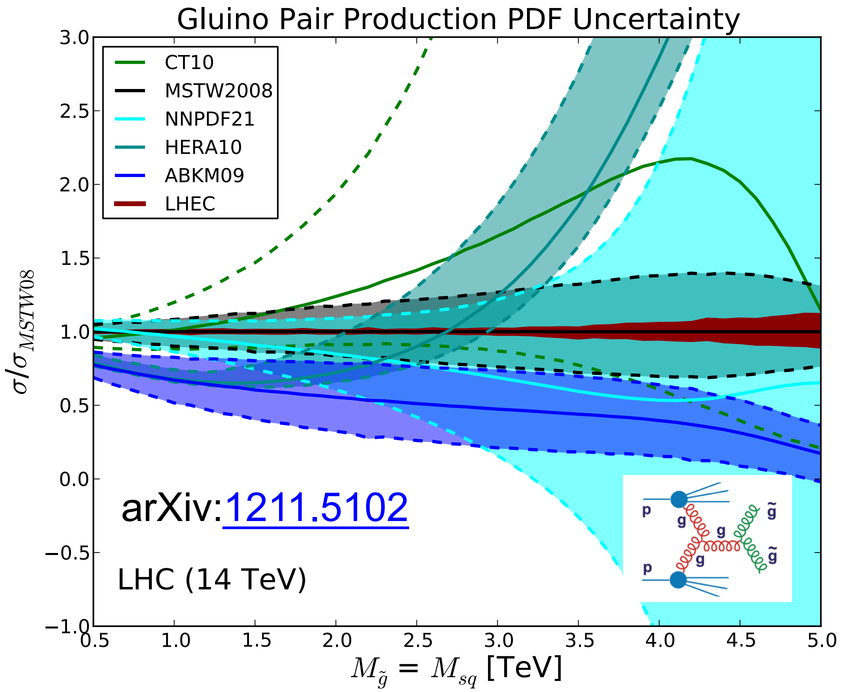
pdfs poorly known at **large** and **small x**

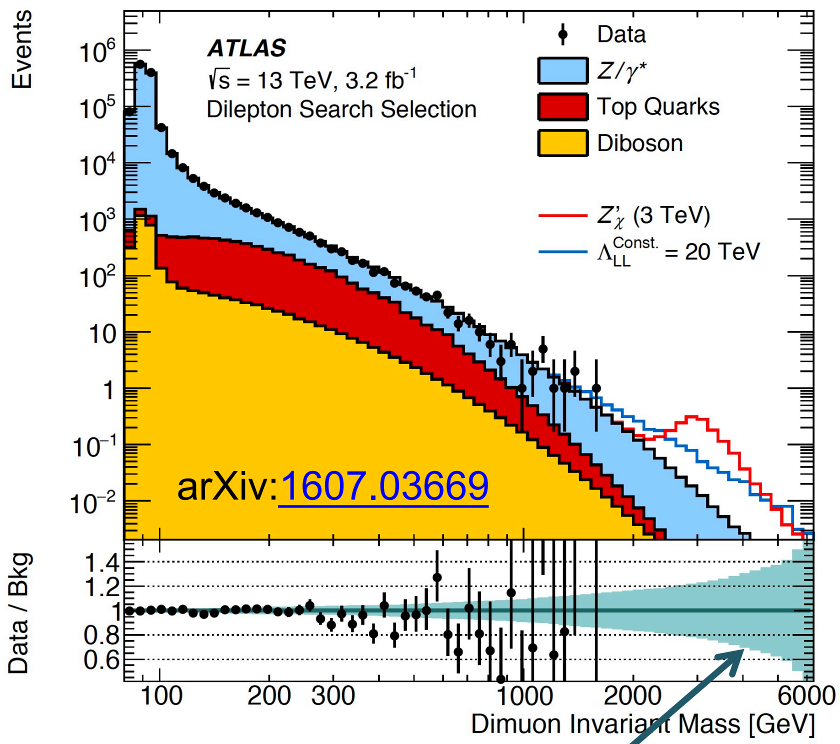
higher precision needed also for H, W, t

$$\frac{\partial \mathcal{L}_{ab}}{\partial \tau} = \int_0^1 dx_a dx_b \, f_a(x_a, M_X^2) f_b(x_b, M_X^2) \, \delta(x_a x_b - \tau) \quad (\tau = M_X^2/s)$$

why large x PDFs matter

BSM searches at LHC currently limited by (lack of) knowledge of large x PDFs





many interesting processes at LHC are **gg** initiated – top; Higgs; BSM, EG. gluino pair production, LQs etc.; …

pdf uncertainty dominates

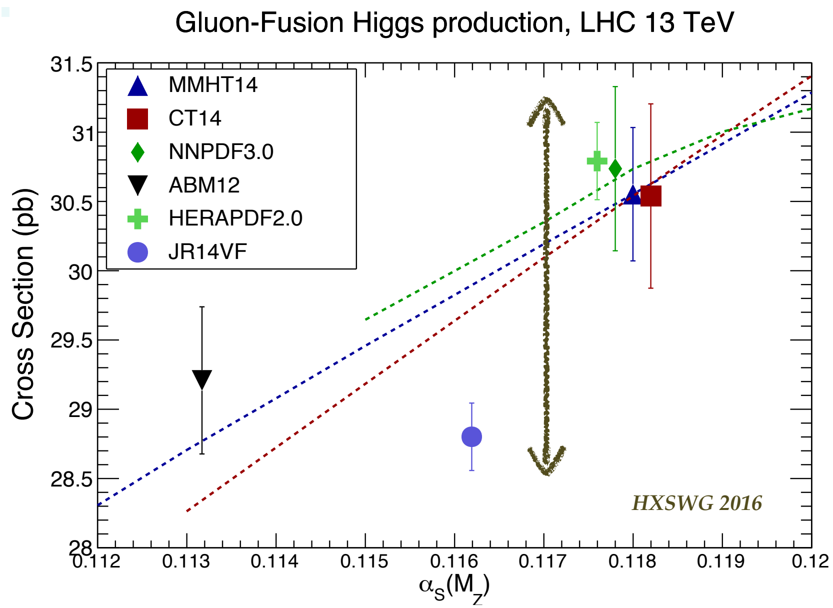
current BSM searches at high mass also limited by **large x valence** and **sea quark** uncertainties

and other LHC measurements …

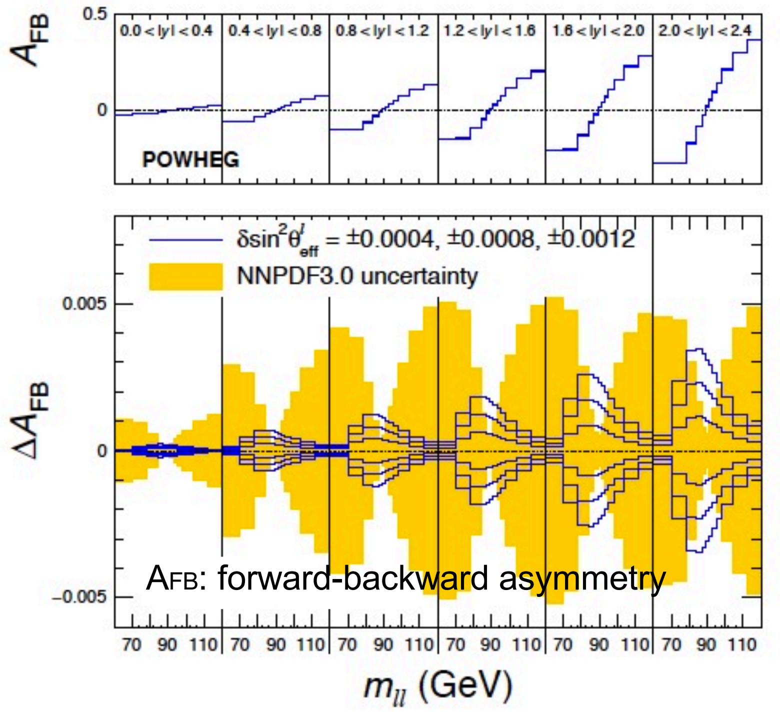
… such as precision M_W, $\sin^2\vartheta_W$ (where small discrepancies may indicate BSM physics) and Higgs, are also limited by **PDF uncertainties** at medium x, where we know PDFs best!

ATLAS M_W, arXiv:1701.07240

Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	−29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	−28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	−29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0



CMS $\sin^2\vartheta_W$, arXiv:1806.00863



BLUE: vary $\sin^2\vartheta_{eff}$ for fixed pdf

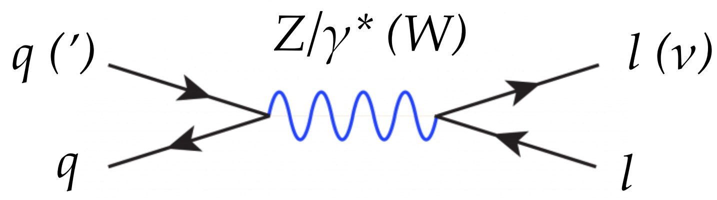
ORANGE: NNPDF3.0 pdf uncertainty for fixed $\sin^2\vartheta_{eff}$

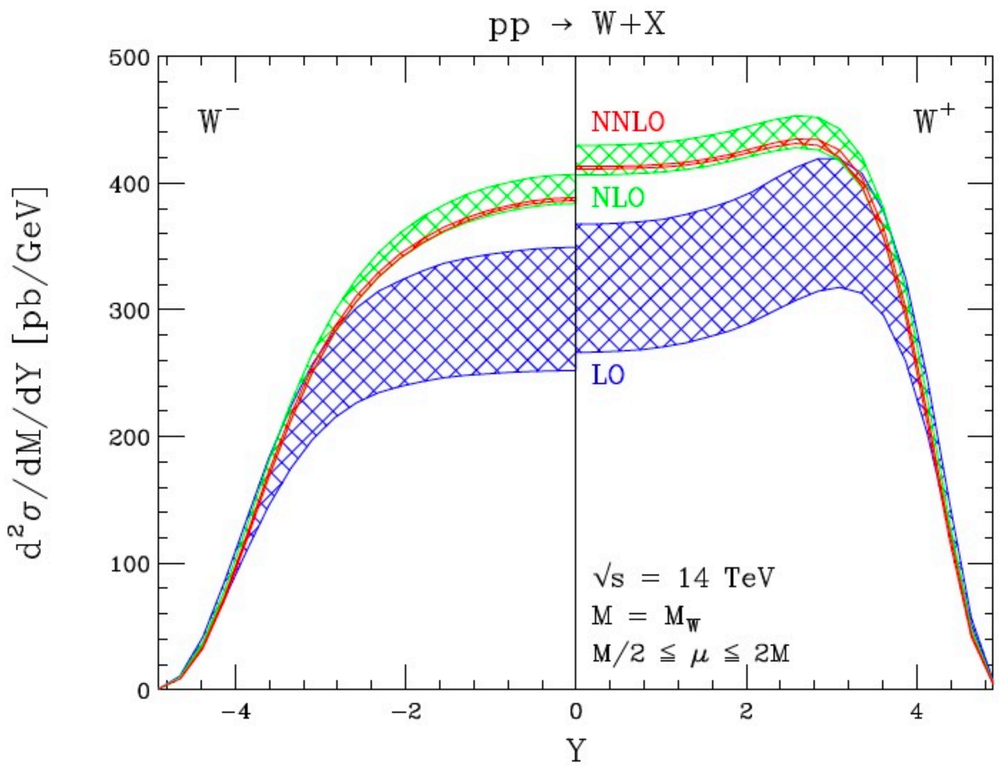
what do we know well in the SM?

W and Z production have been considered as good standard candle processes with small theoretical uncertainty; **can be used as a luminosity monitor?**

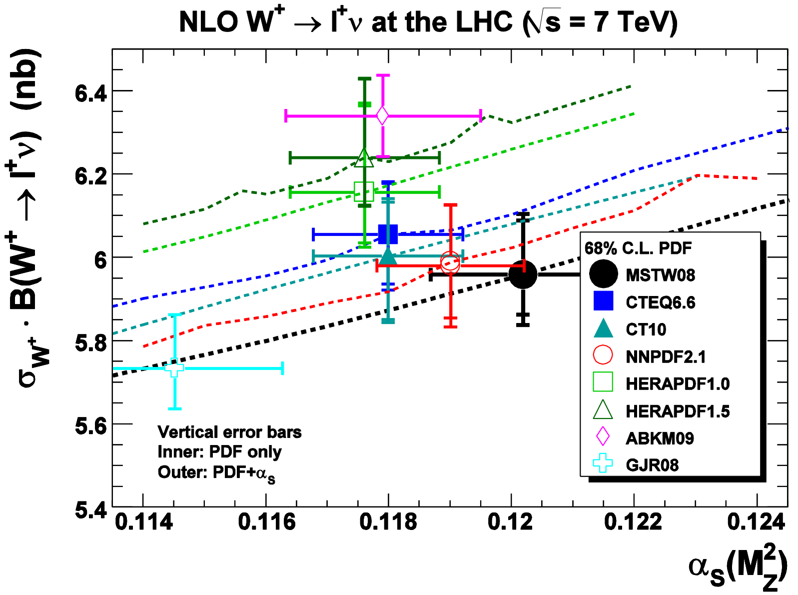
PDF uncertainty is THE dominant contribution; **most PDF groups quote uncertainties of about 3 – 4%**

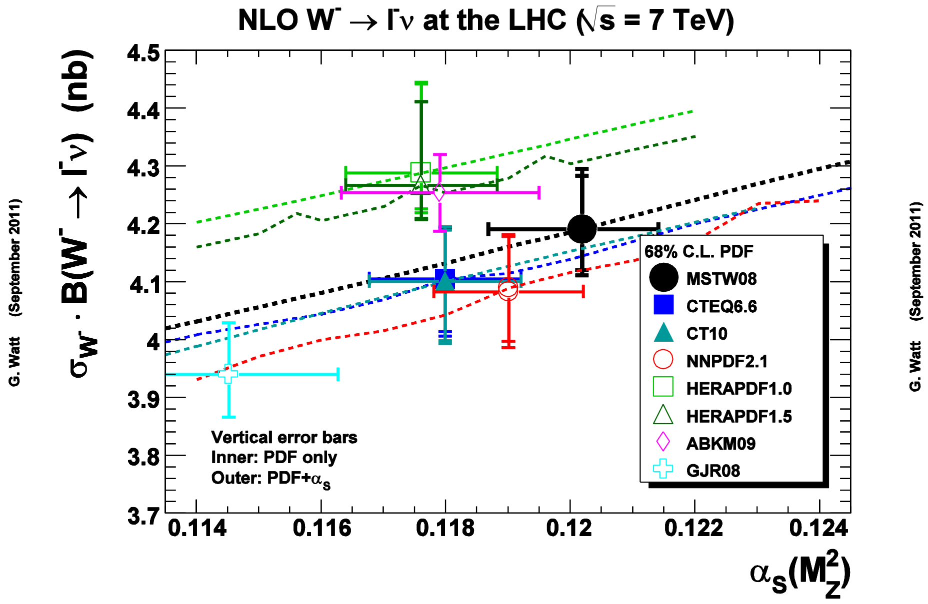
BUT PDF uncertainties from one group do not always cover differences BETWEEN groups!





just a few years ago predictions were coming into better agreement – CTEQ and MSTW predictions agreed well within their quoted uncertainties **BUT new PDF sets have come on to the 'market' which show stronger disagreements** …





Let's look at how PDFs have evolved since LHC startup

MSTW08 – now MSHT20

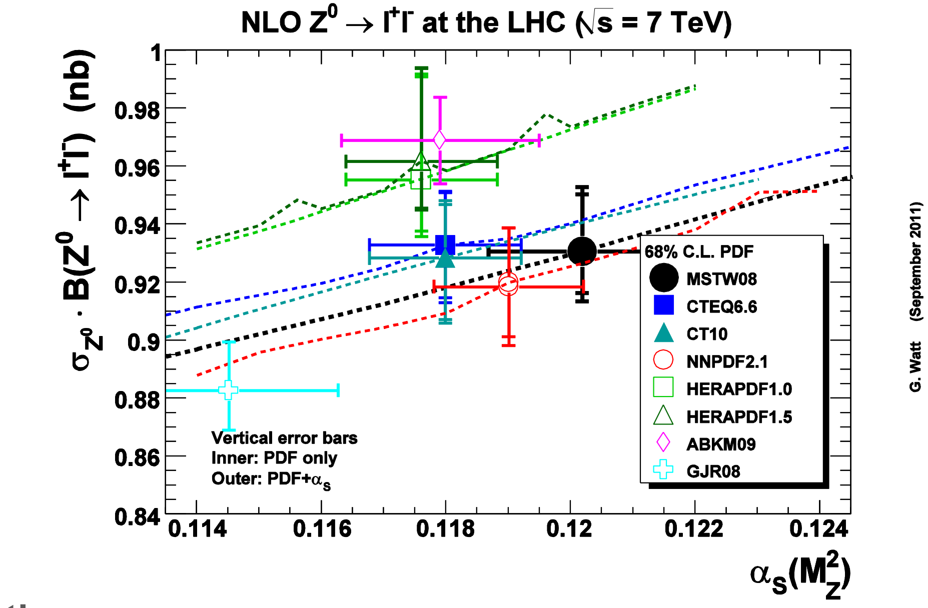
CTEQ66 – CT10, 14 – now CT18

NNPDF2.0 – 2.1, 2.3, 3.0 – now 3.1

HERAPDF1.0 – 1.5 – now 2.0

ABKM09 – ABM11, 12 – now ABMP16

GJR08 – now JR14



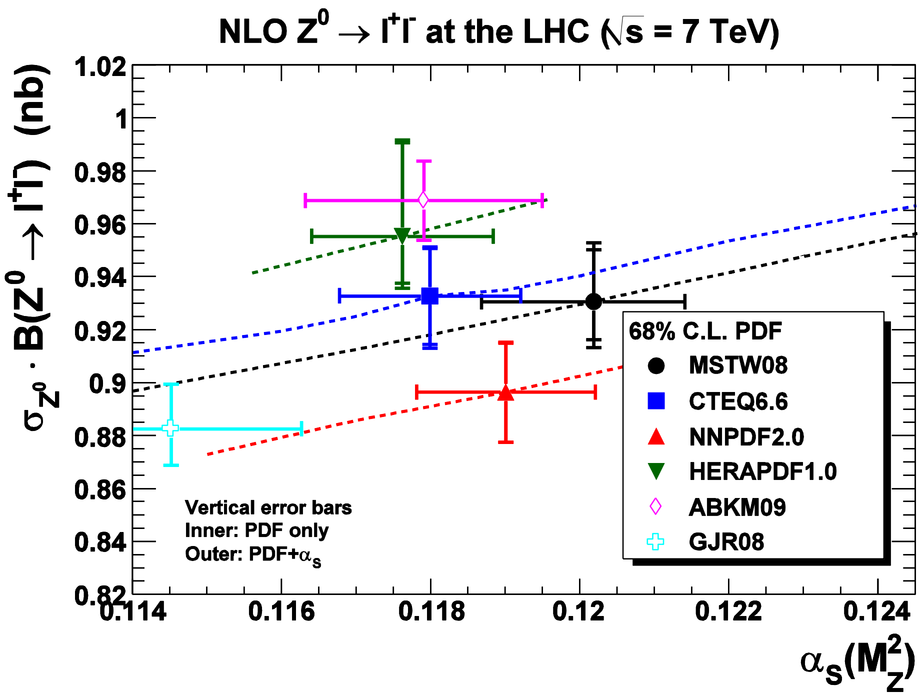
overall disagreement about 8% in W cross sections

PDF4LHC recommendation (arXiv:1510.03865) takes envelope of NNPDF, MMHT, CTEQ predictions – but even this may not be enough!

arXiv:1201.1295

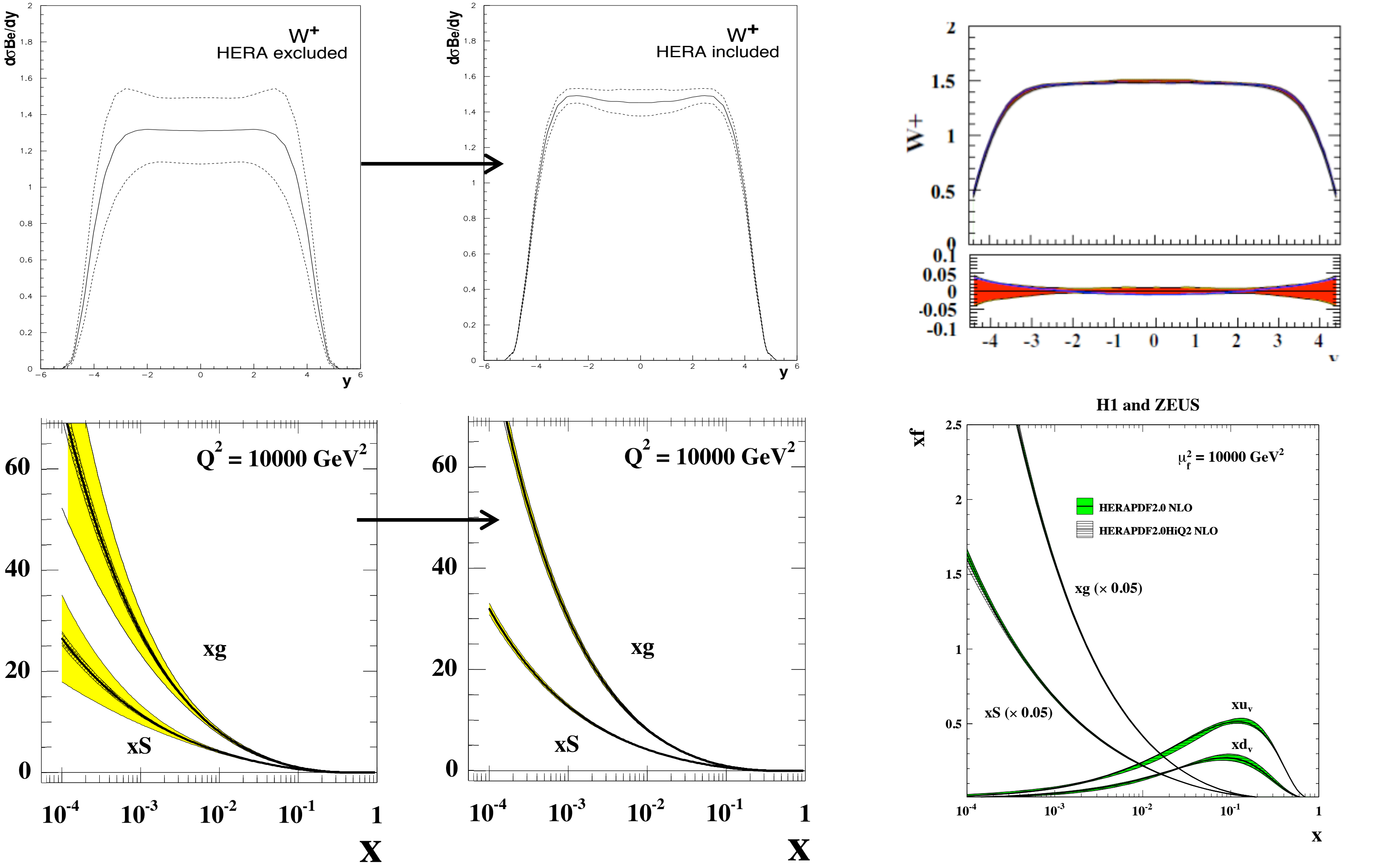
why these disagreements ?

1. use of different **αs(MZ) values**; a common value would bring some of the predictions into better agreement
2. different ways of accounting for **heavy quark production** and different values of the **heavy quark mass**
3. different **input datasets** (or different cuts on data sets), with different levels of consistency and different hidden systematics, EG. evaluation of nuclear target corrections for data taken on heavy targets
4. there are differences in philosophy regarding choices of **PDF parameterisation** and **model prejudices** which are imposed



impact of HERA on LHC – one example

No HERA data | separate H1+ZEUS | NOW, HERA combined 2015



improvement comes from improvement in low x gluon; at the LHC, the qqbar which make the boson are mostly sea partons at low x, and **at high scale $Q^2 \sim M_W^2$, sea is driven by g → qqbar splitting**

NOTE only experimental uncerts. shown – model are not included – so final uncertainties larger than shown

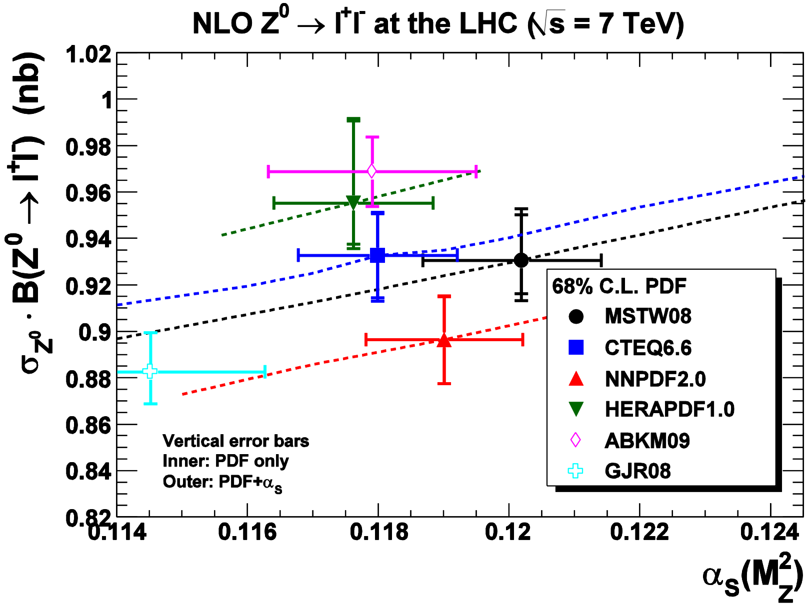
impact of HQ scheme

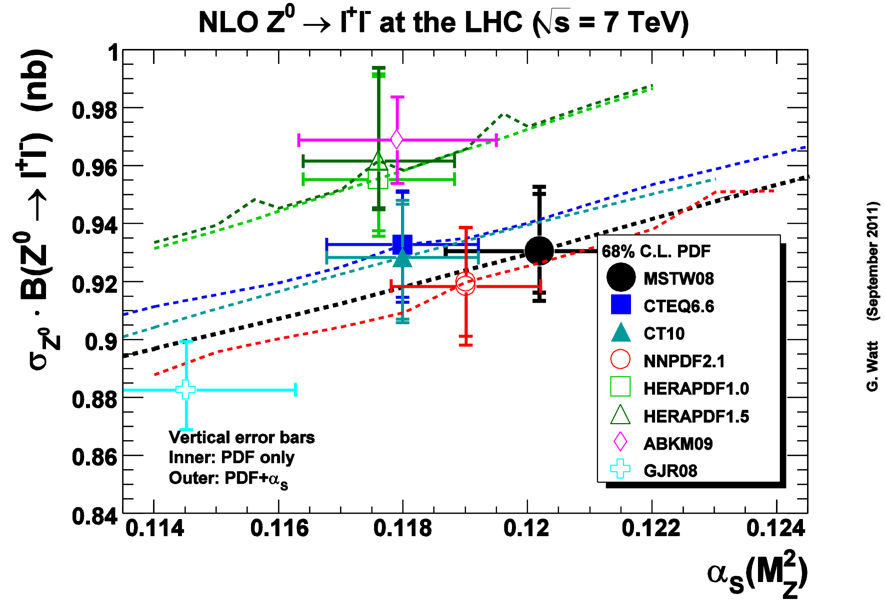
HQ scheme choice certainly accounts for some of the difference between NNPDF2.0 (**ZMVFN**) and CTEQ/MSTW cf. update to NNPDF2.1 (**GMVFN**) below

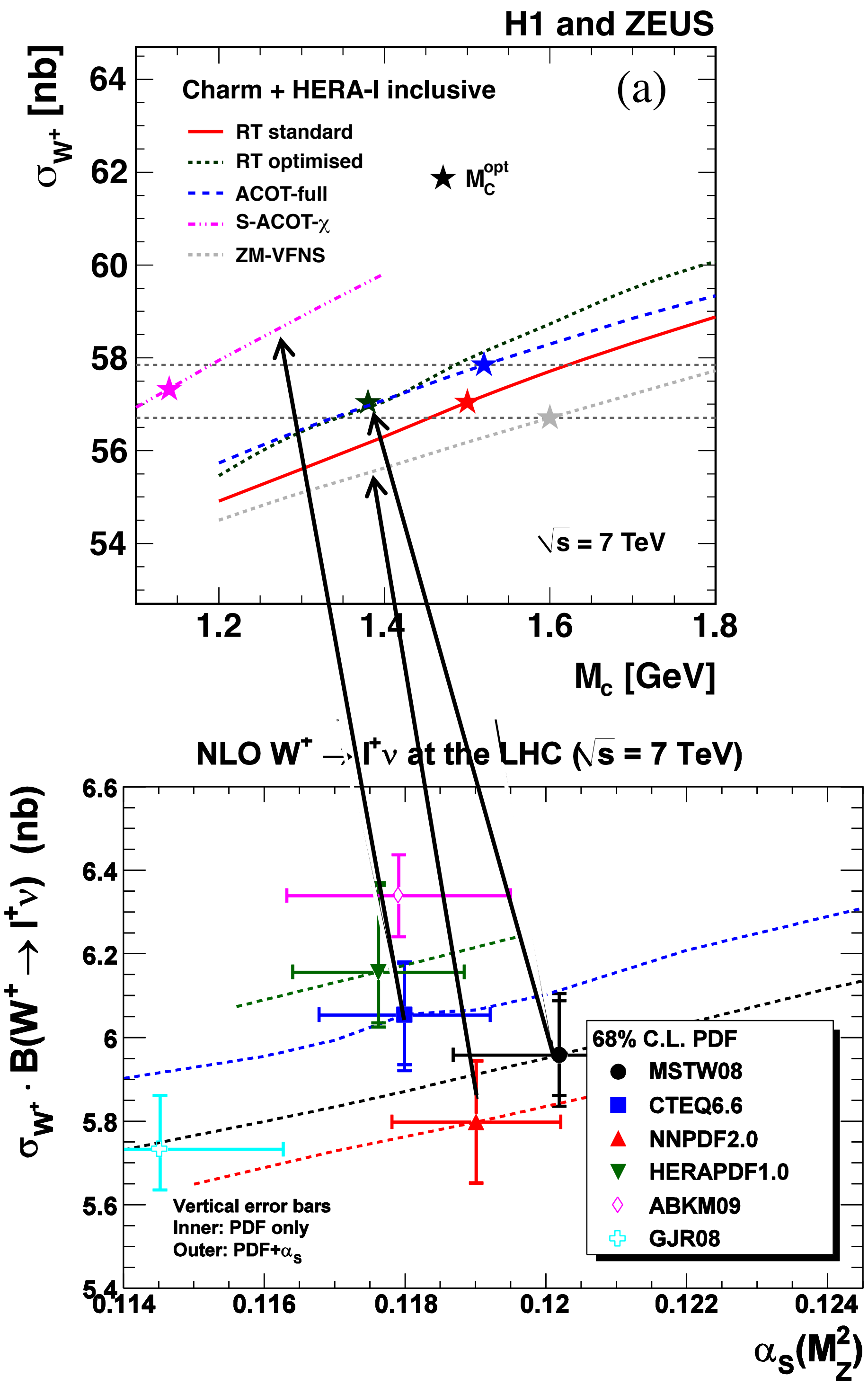
if quarks **massive** then charm production suppressed at threshold and light quark densities increase to compensate – since what is fitted is low-scale DIS data – this in turn leads to slightly larger W/Z cross sections

same effect means a larger choice of charm mass leads to a larger predicted W/Z cross sections

HQ treatment also explains much of difference in ABKM result cf. CTEQ/MSTW, since ABKM treatment is closest to a fully **FFNS** treatment







LHC W and Z cross section predictions (at 7 TeV) as a function of charm mass using different HQ schemes

if **fixed Mc** used, spread is considerable BUT if each prediction taken at its **own optimal mass** (determined by treating Mc as a free parameter in the fit – see Lecture 5), spread dramatically reduced

PDFs MSTW08, CTEQ6.6, NNPDF2.0 do NOT use charm mass parameters at the optimal values – this partly explains the differing predictions

(Note, NNPDF has now moved up – GMVFN scheme now used)

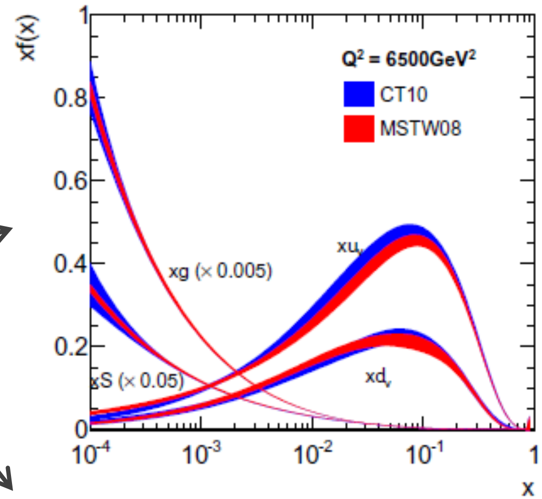
W asymmetry

since PDF uncertainty feeding into all of W+, W- and Z is dominated by the **gluon**, strong correlation in uncertainties, which can be **reduced by taking ratios**,

EG W asymmetry: $A_W = (W^+ - W^-)/(W^+ + W^-)$

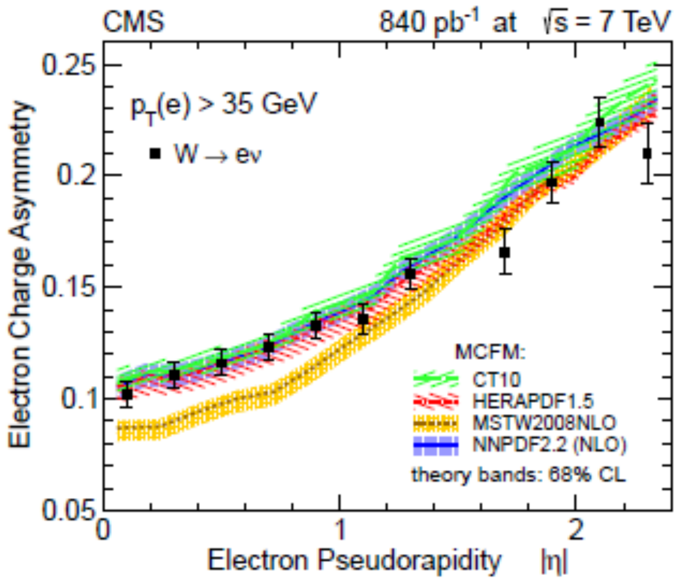
which tells us about valence quarks $\rightarrow (u_v - d_v)/(u_v + d_v + \bar{u} + \bar{d})$

at central rapidity, x1=x2, and assuming ubar=dbar



valence quark differences translate into differences in W asymmetry, and thus the W-lepton asymmetry that we measure

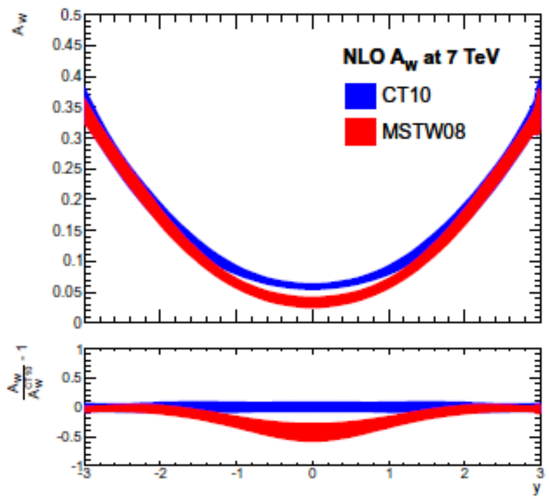
LHC probes precisely the x range $10^{-3} < x < 10^{-1}$ where differences maximal



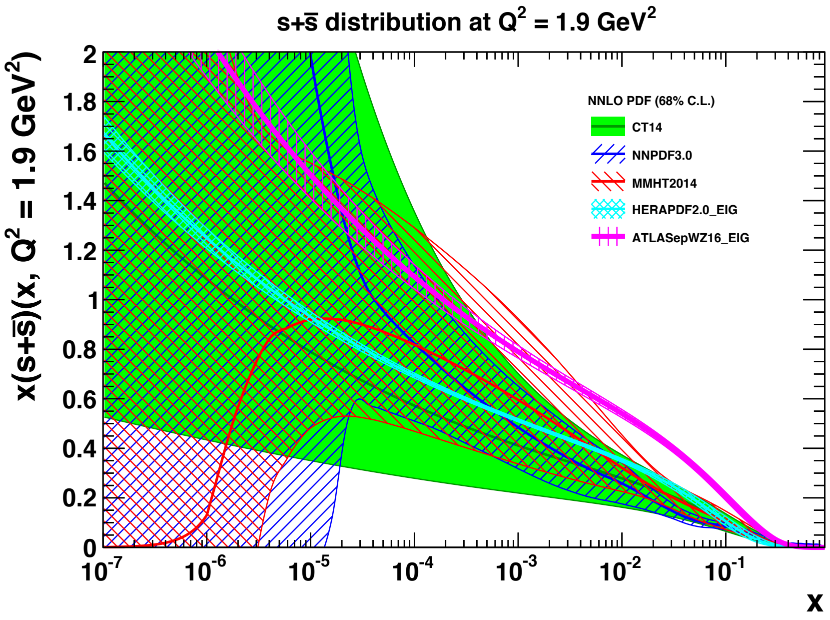
what we saw

(we actually measure the lepton asymmetry)

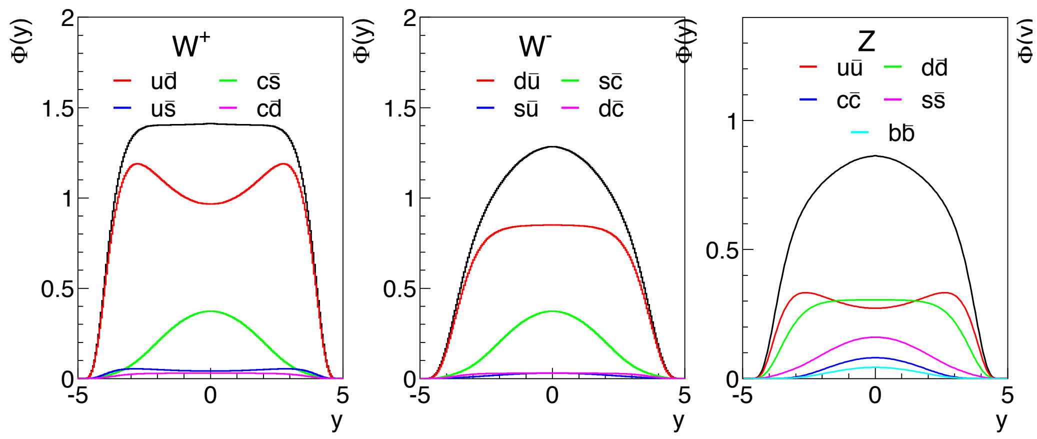
MSTW08 clearly disfavoured – update to MMHT14!



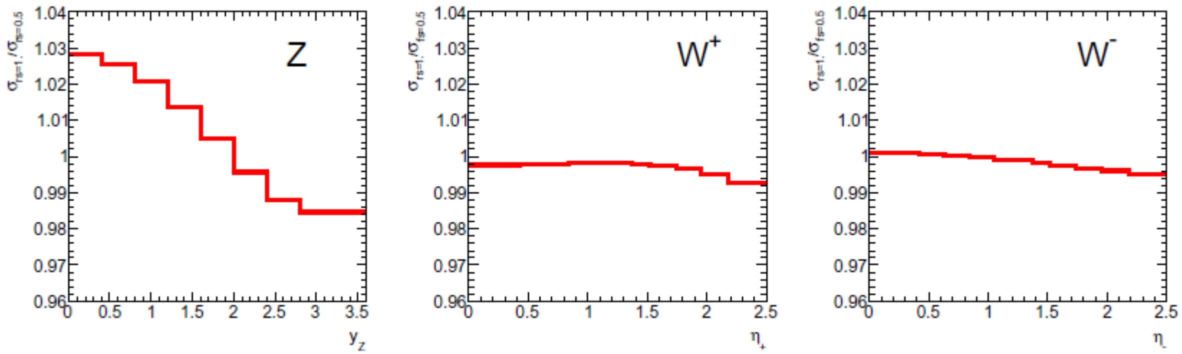
LHC W and Z production and the strange sea



the strange PDF is poorly known!



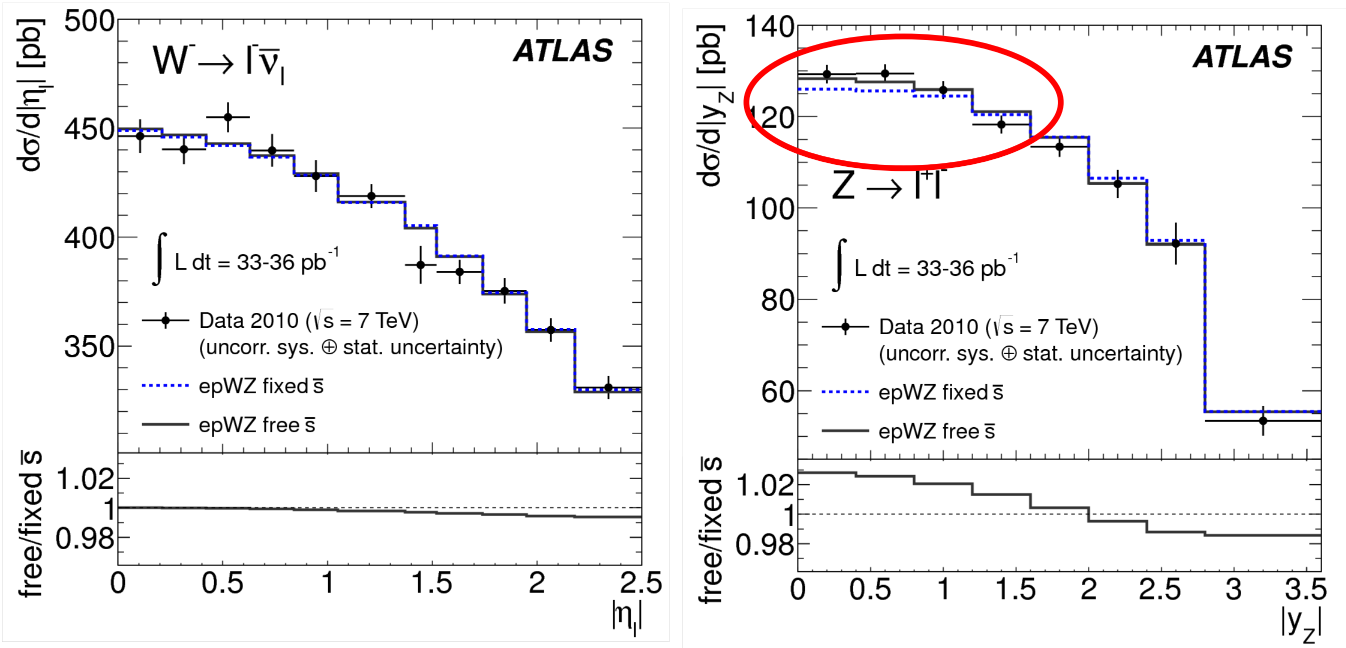
contribution to W and Z by quark flavour for usual assumption that strange sea is suppressed, ~ ½ of the d-type sea



shown are the ratios of
(strange = d-type sea) /
(strange = 0.5 × d-type sea)
for W and Z production

this is a small effect ~4% –
can we see it?

ATLAS inclusive W and Z production

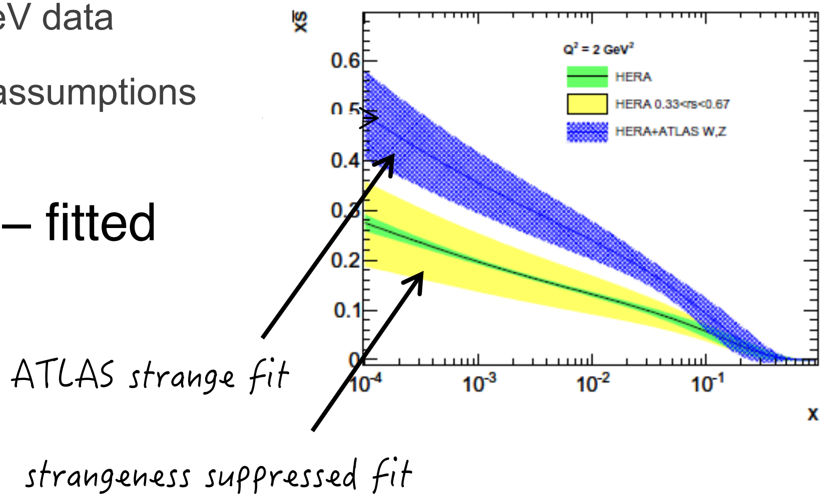


YES we can: ATLAS W, Z from 37 pb^{-1} 2010 7 TeV data

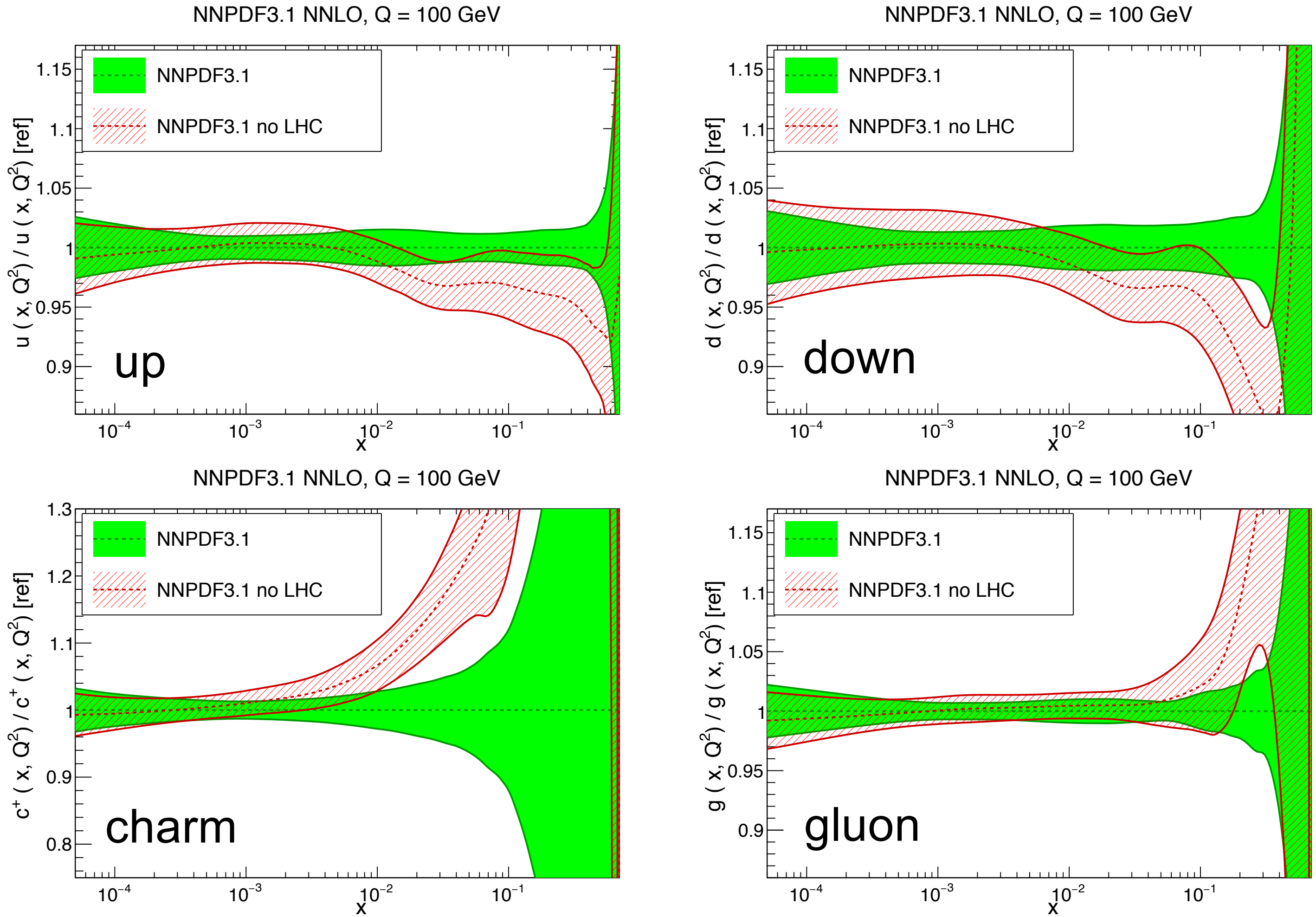
shown are NNLO predictions for these data for two assumptions on strangeness:

$s/d = 0.5$ fixed and $s/d = r_s (1-x)^{(Cs-Cd)}$ – fitted

fit gives $r_s = 1.0 \pm 0.25$



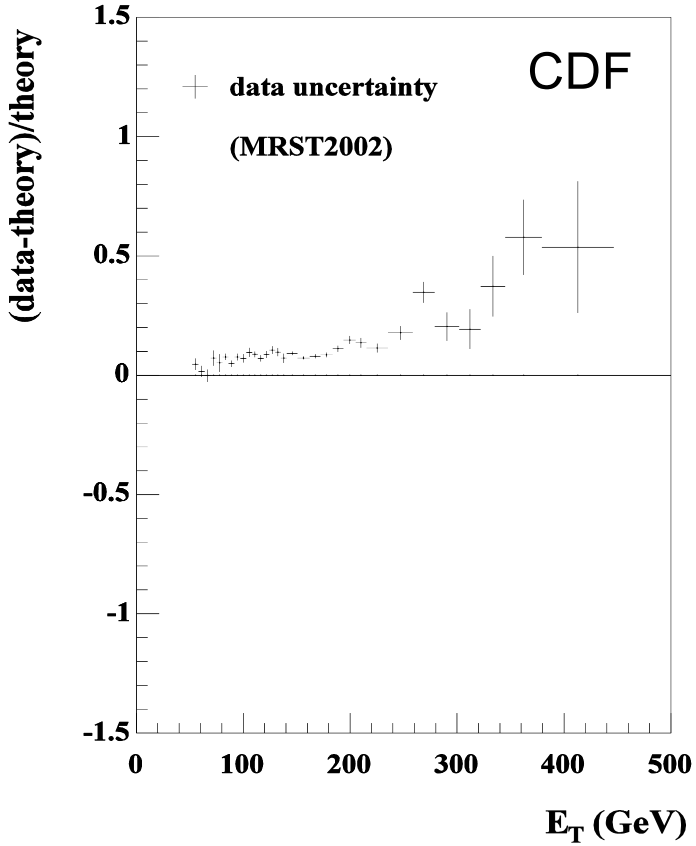
impact of LHC on today's PDFs



arXiv:[1706.00428](1706.00428)

(**NNPDF3.1** includes modern √s=7 and 8 TeV LHC data on W,Z+top+jets+ZPt)

BSM physics – what do we not know well?



PDF uncertainties matter for BSM physics

EG. Tevatron jet data originally taken as evidence for BSM

something seemed to be going on at high E_T;

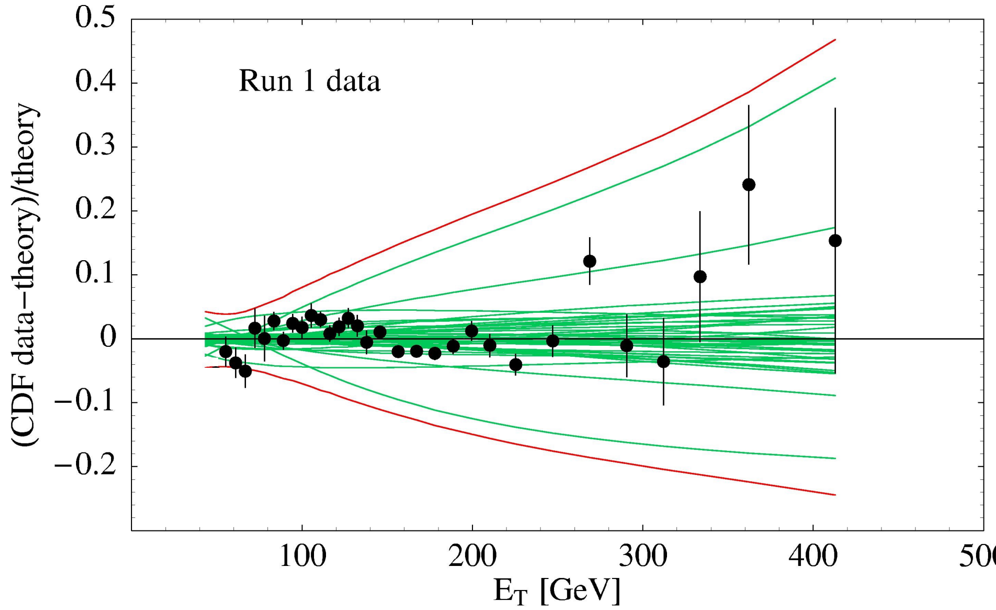
special PDFs like CTEQ4/5HJ were even tuned to describe it better, though quality of fit to other data deteriorated

BUT this was all before PDF uncertainties were seriously considered!

Tevatron jet data is today considered to lie within PDF uncertainties

(EG. CTEQ; arXiv:0303013)

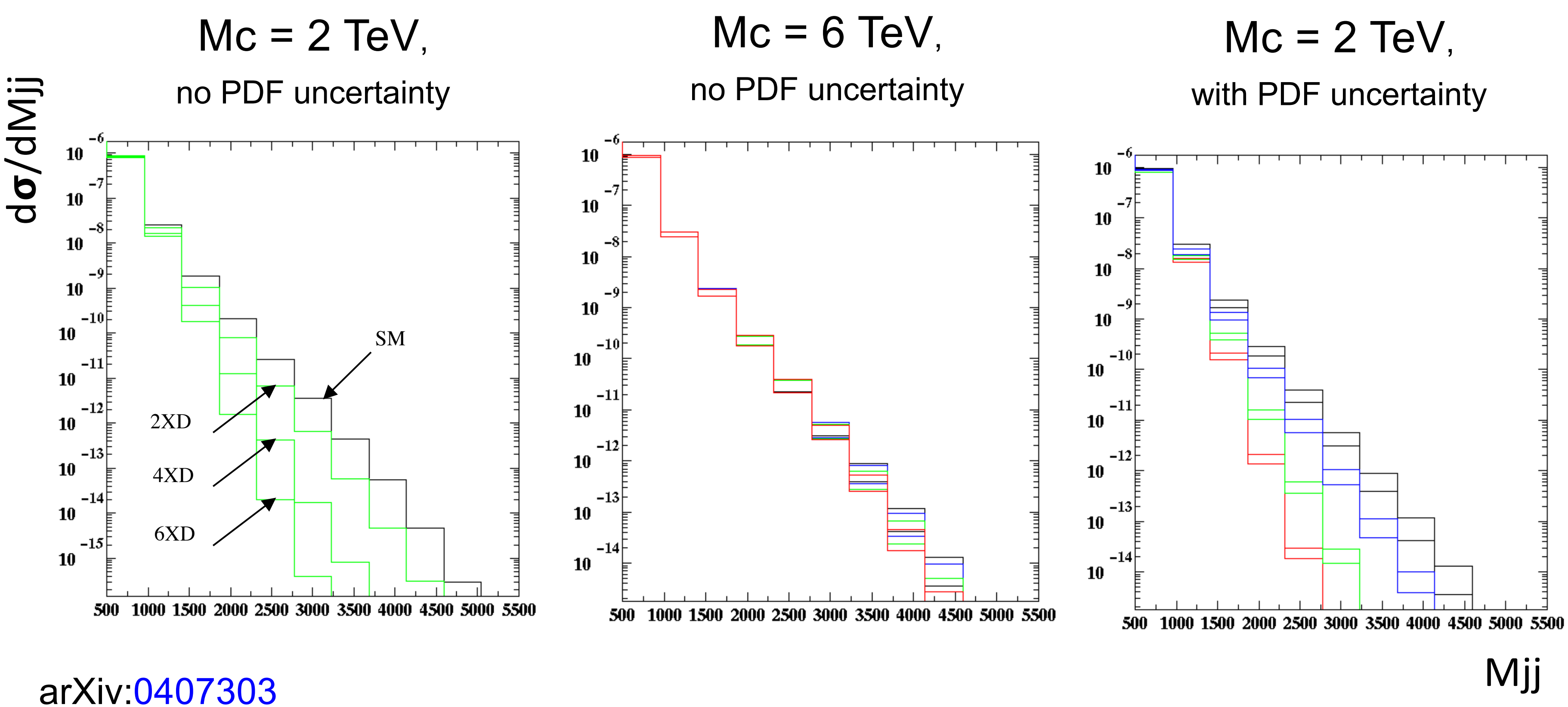
we can decompose PDF uncertainties into eigenvector combinations of fit parameters – largest uncertainty in this case is from eigenvector 15, dominated by high x gluon



why large x PDFs matter

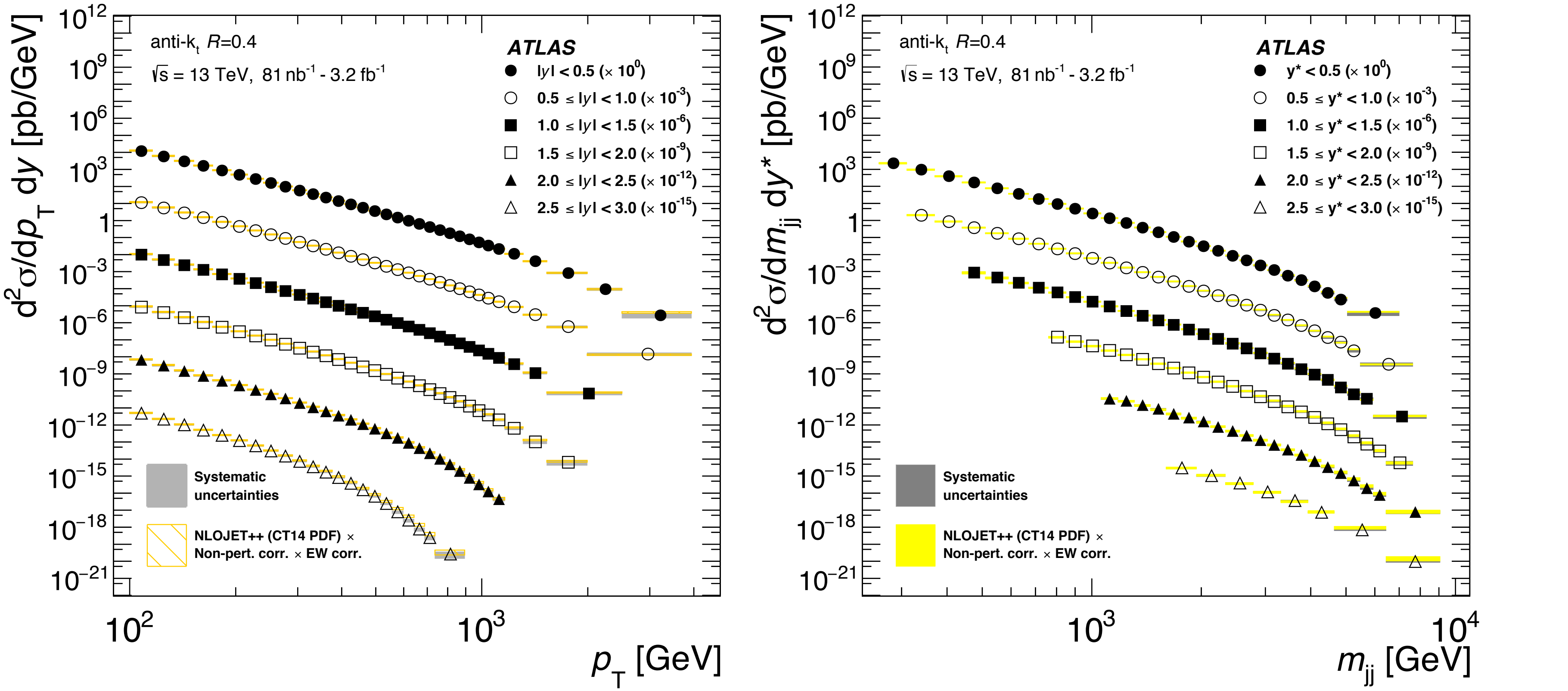
what consequences might our lack of knowledge of the large x gluon have?

EG. such PDF uncertainties in jet cross sections compromise the LHC potential for discovery of new physics; one example: dijet cross section potential sensitivity to compactification scale of **extra spatial dimensions** (Mc) reduced from about 6 → 2 TeV



arXiv:0407303

what about LHC jet data?

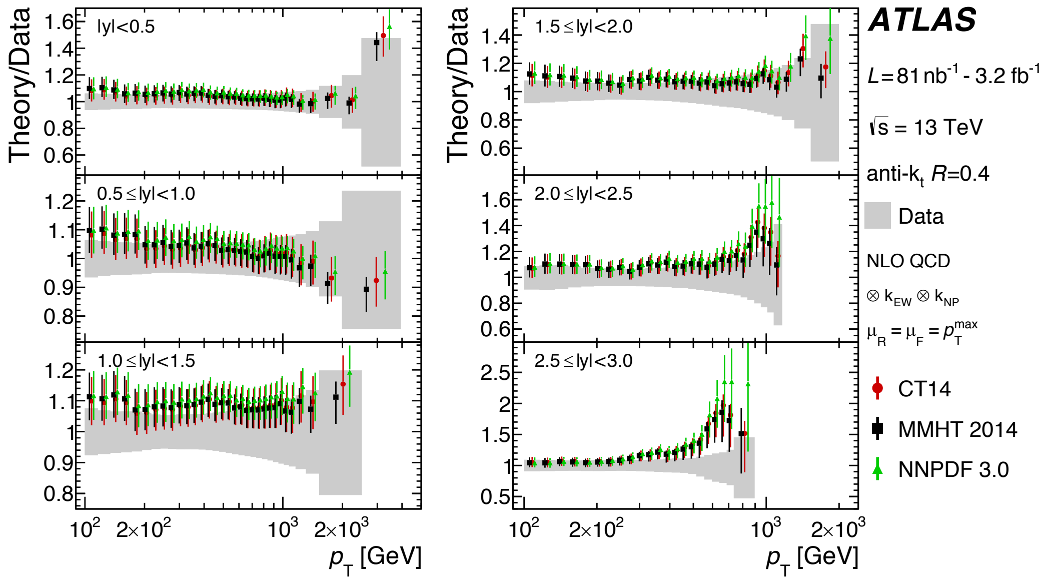


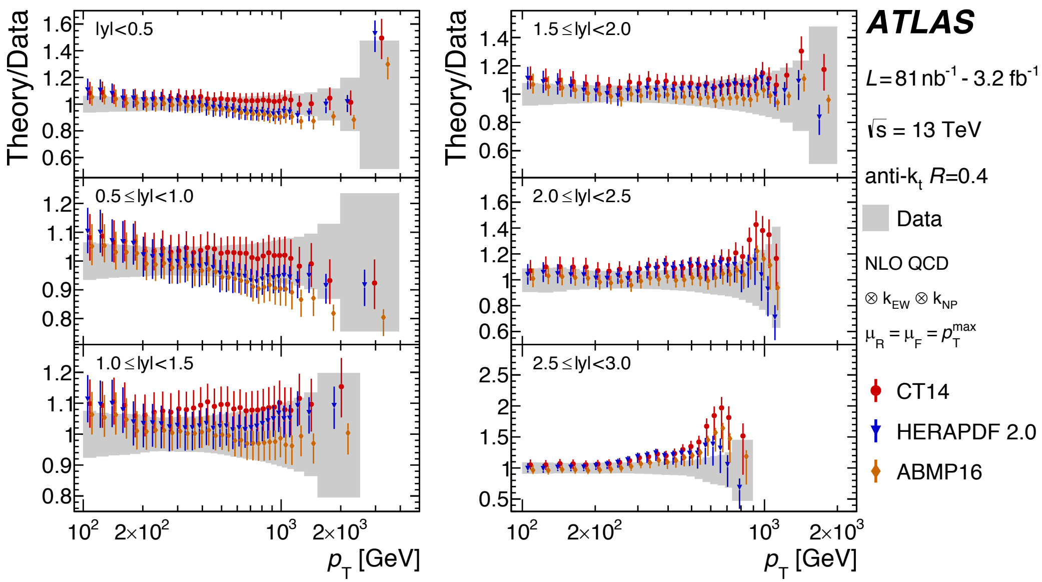
arXiv:1711.02692

ATLAS inclusive jet cross sections at 7, 8 and 13 TeV, now probing up to pt ~ 3.5 TeV and dijet cross sections up to invariant masses mjj ~ 9 TeV !

(there are also three-jet and four-jet measurements) – and nothing NEW seen so far

LHC jet cross section measurements





arXiv:1711.02692

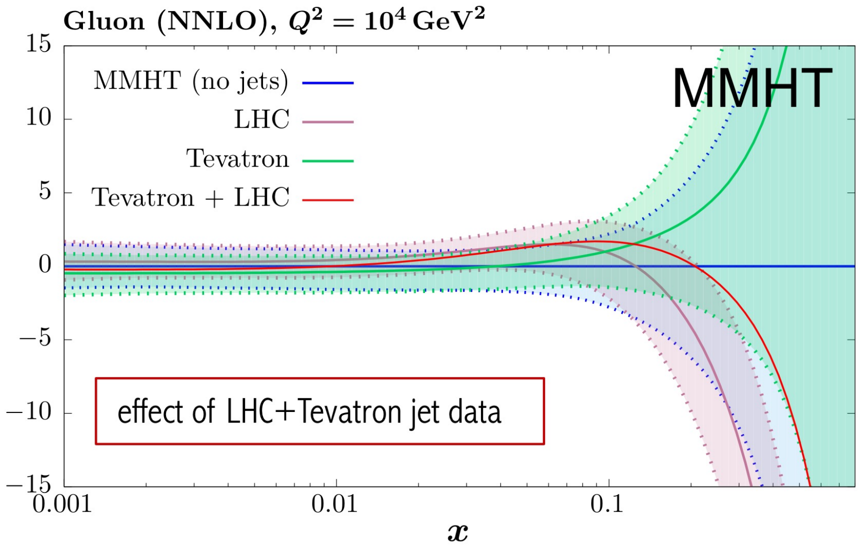
measurements have been quantitatively compared to **NLO QCD predictions using different PDFs**

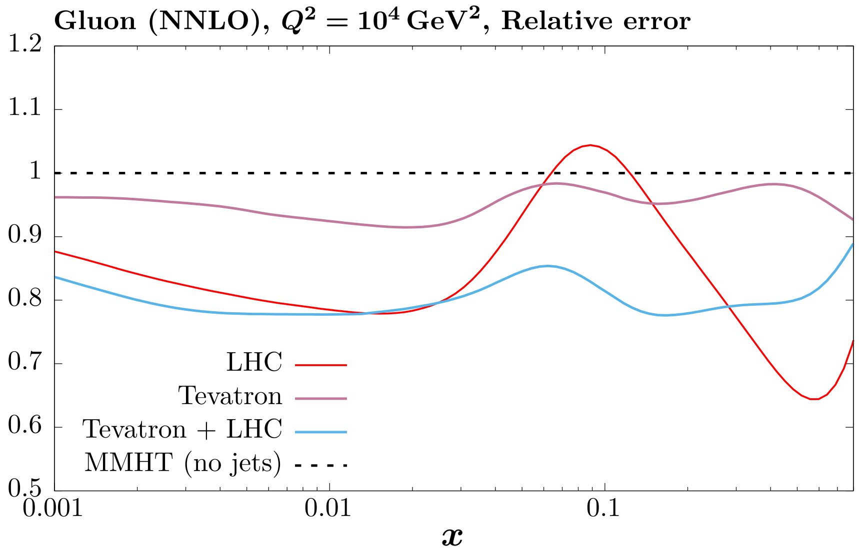
there is progress in both range and precision of measurements, AND in different PDF predictions, EG. previously ABM11 was very bad (see arXiv:1410.8857), ABMP16 is not

NNLO QCD calculations also now available (arXiv:1611.01460, 1705.10271)

can we use these data to **improve our knowledge of PDFs?**

LHC jet data: impact on global PDF fit





EG. MMHT PDF (arXiv:1711.05757)

impact on **gluon PDF** from inclusion of inclusive jet data from

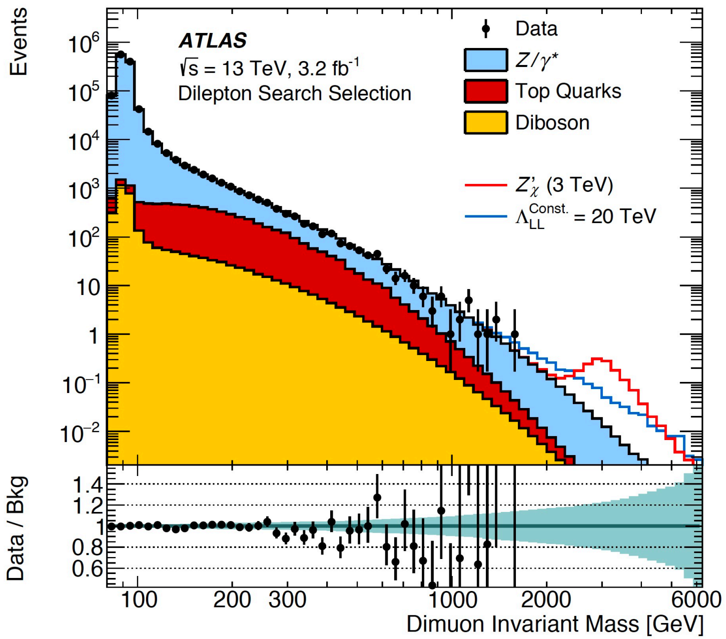
ATLAS (arXiv:1410.8857),
CMS (arXiv:1406.0324),
Tevatron (arXiv:1110.3771, 0701051)

treatment of correlated systematic uncertainties must be carefully considered for ATLAS jet data, and fitting all data together has proved problematic (MMHT decorrelated certain systematics; issue also seen by ATLAS, CT, NNPDF)

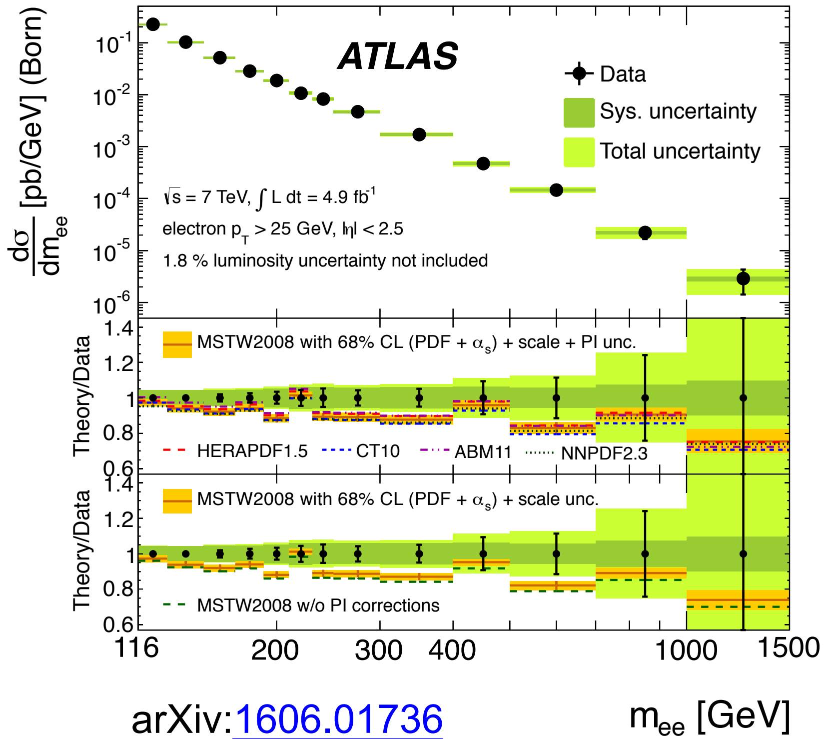
can also take ratios of jet cross sections at different CM energies, EG. arXiv:1304.4739
– exp. uncerts. reduced in ratio; PDF sensitivity remains since different beam energies probe different x,Q2 for same pt and y

HM Drell-Yan and the photon PDF

High mass Drell-Yan data can also be searched for BSM effects



arXiv:1607.03669



arXiv:1606.01736

arXiv:1305.4192

if/when none found, then a precision measurement can improve the knowledge of **high x sea quark PDFs**

LHC measurements at √s=7,8 TeV showed little PDF discrimination BUT evidence for a QED effect – some events are photon induced, **ie. there is a photonic component in the proton**

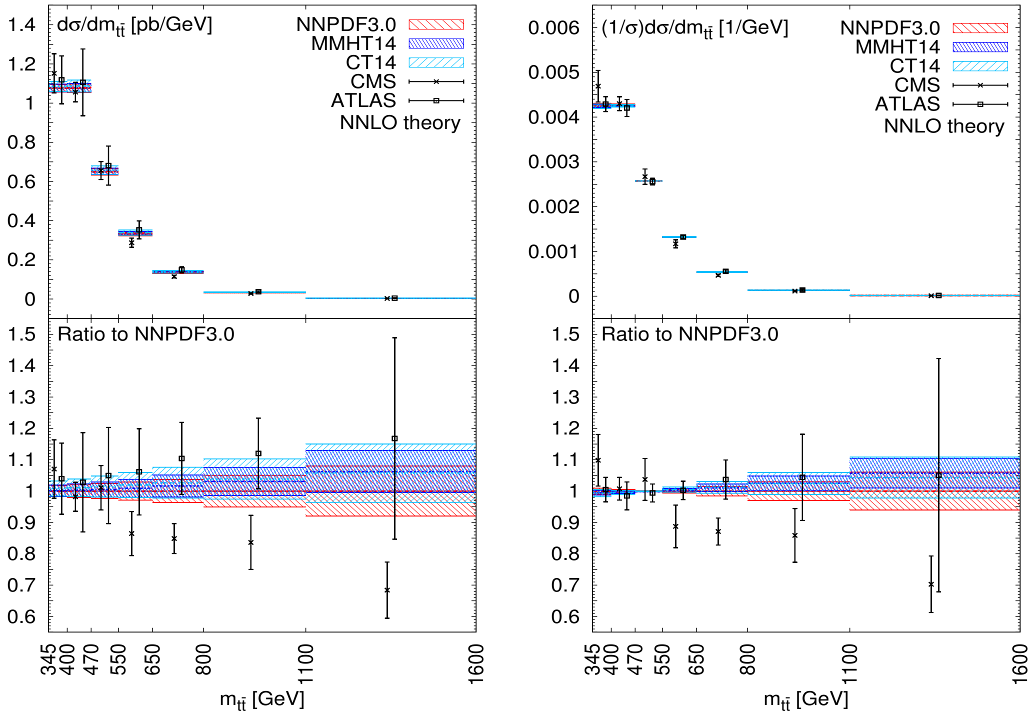
top-quark pair production

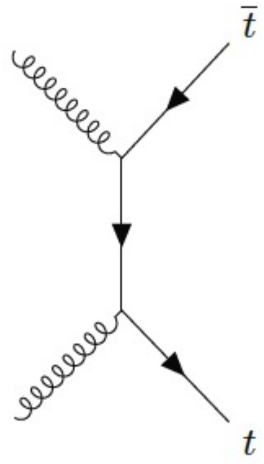
LHC top quark pair data have sensitivity primarily to **high x gluon** BUT

ATLAS/CMS agreement not very good – particularly for mtt

(and even within a single experiment there are discrepancies when fitting different spectra, see EG. arXiv:1909.10541)

PDF groups are making choices for these measurements; they use some spectra and not others



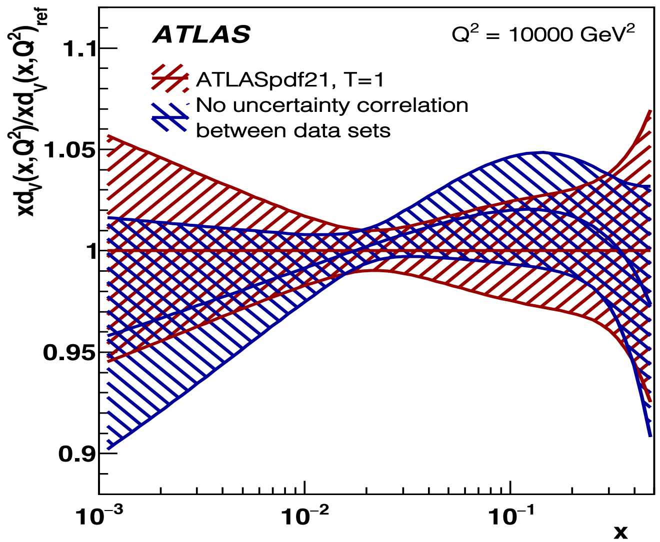


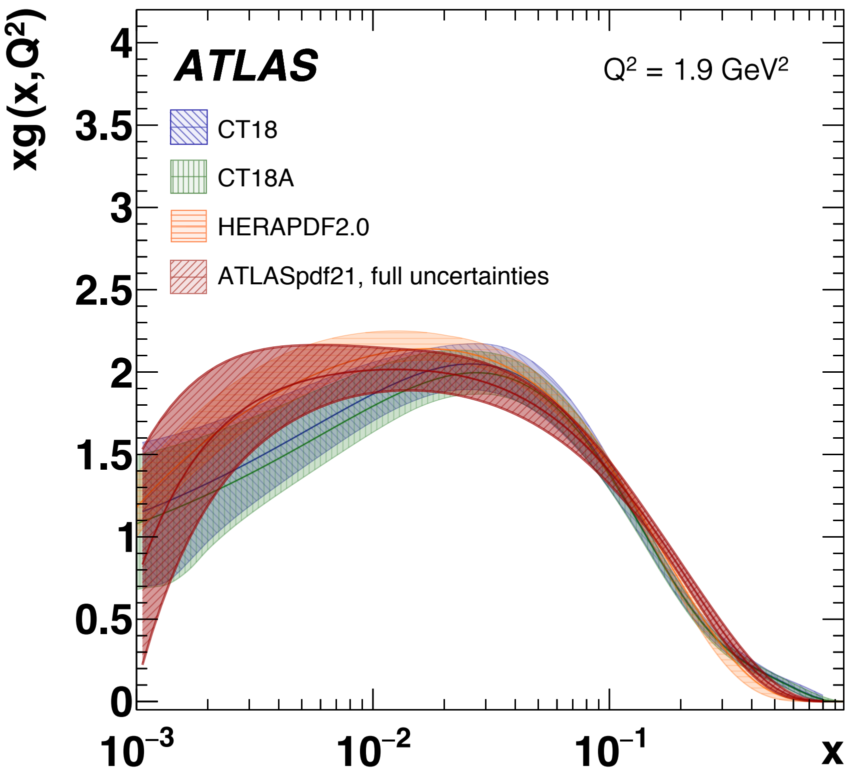
arXiv:1611.08609

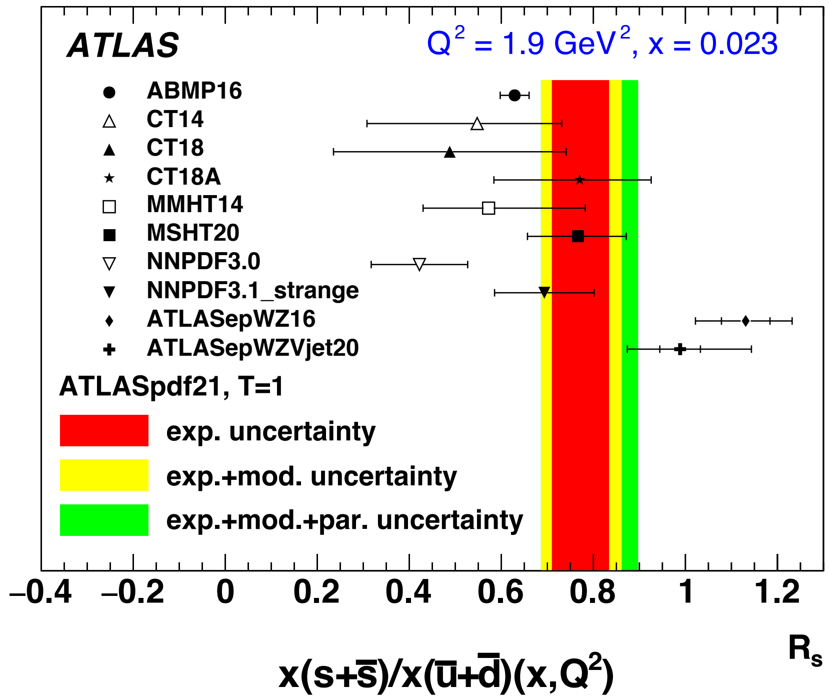
PDF set	ATLAS $d\sigma/dm_{t\bar{t}}$	CMS $d\sigma/dm_{t\bar{t}}$	ATLAS $(1/\sigma)d\sigma/dm_{t\bar{t}}$	CMS $(1/\sigma)d\sigma/dm_{t\bar{t}}$
NNPDF3.0	0.77 (0.38)	5.73 (4.36)	1.57 (0.10)	10.6 (3.87)
MMHT14	0.58 (0.24)	7.32 (5.74)	1.01 (0.05)	13.5 (4.93)
CT14	0.61 (0.19)	7.28 (6.06)	1.09 (0.05)	13.5 (4.82)

ATLASpdf21

- NEW **ATLASpdf21** fit – arXiv:[2112.11266]
- HERA + diverse set of ATLAS measurements (inclusive V, V+Jets, ttbar, QCD jets, direct-**γ**)
- taking account of statistical and systematic correlations within and between datasets
- some example results:

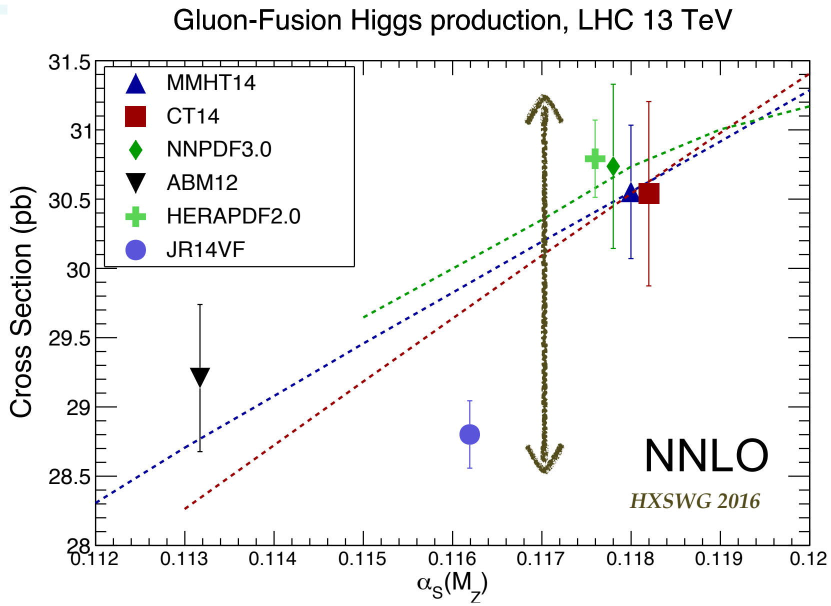


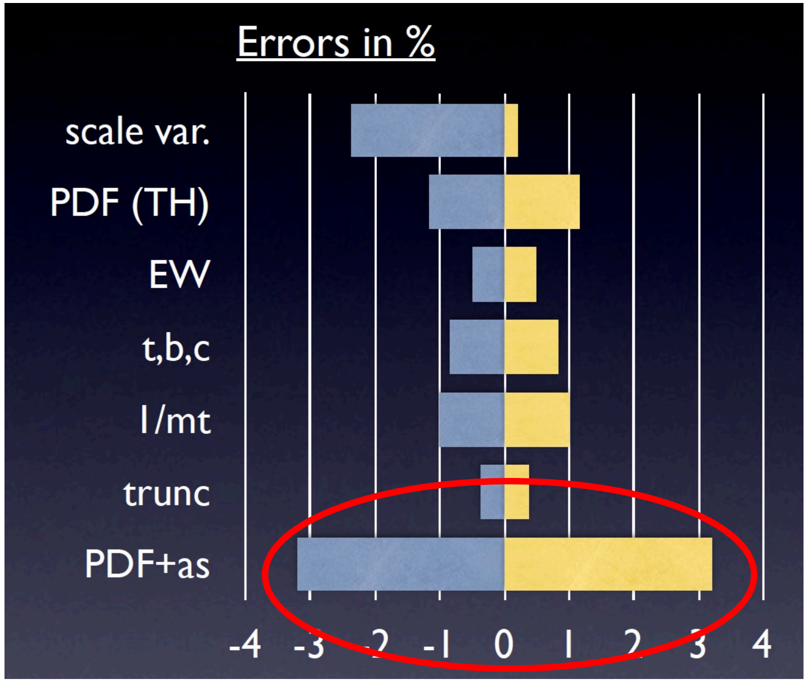




Higgs – is it the SM Higgs?

what the SM predicts depends on which PDF you chose





Must use (at least) NNLO calculations and PDFs

– differences to NLO are LARGE (for ggH, N^3LO QCD now available)

inclusive H production uncertainties

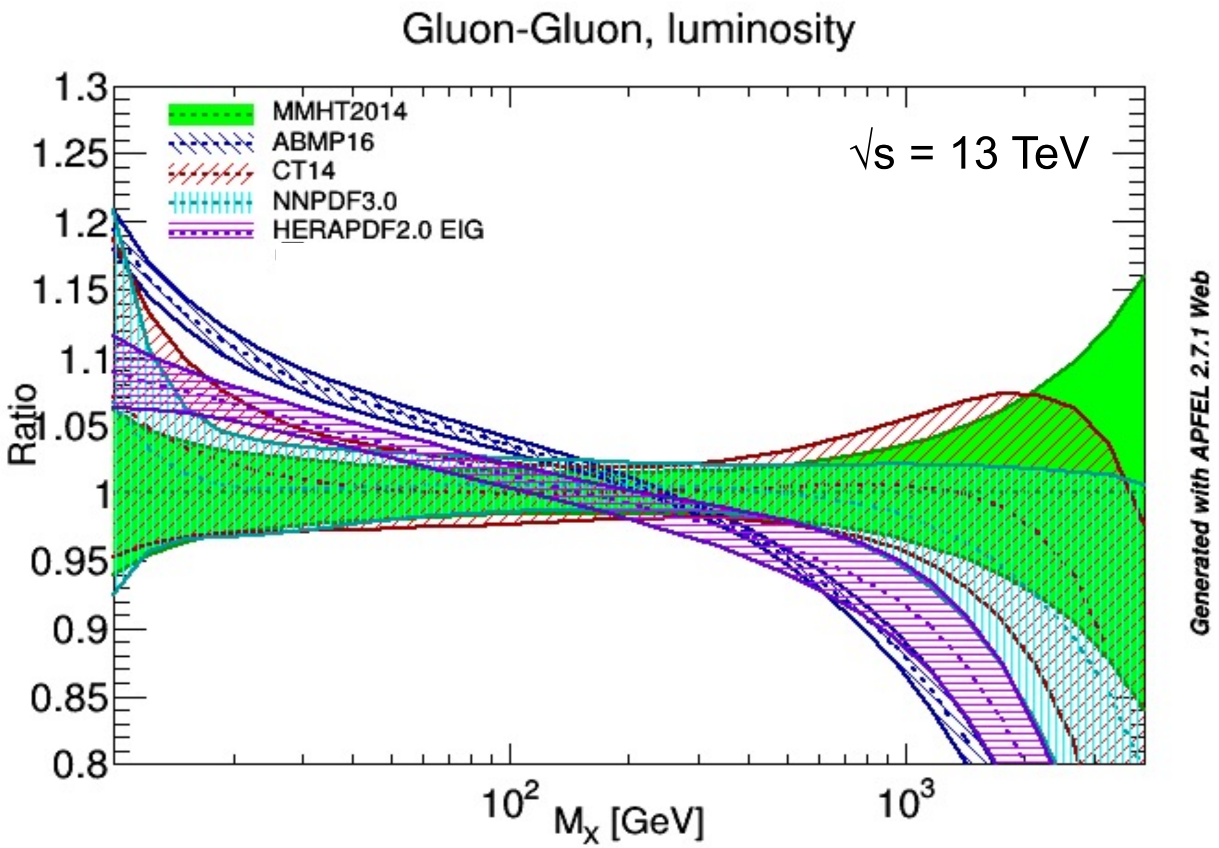
(arXiv:1602.00695)

Also note the strong αs dependence;

this is a contentious issue; a recent bench-marking study gets better agreement by taking all NNLO PDFs at **α**s(MZ) =0.118

PDF+αs dominant theory uncertainty on calculations of H cross sections

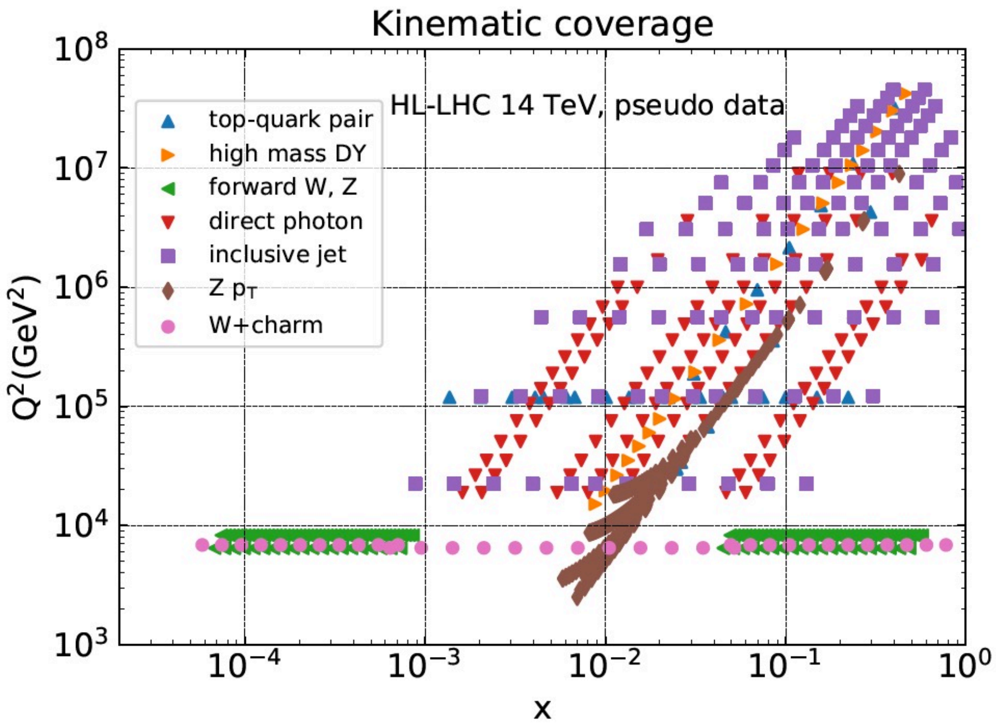
Higgs – is it the SM Higgs?



Higgs production depends on gg luminosity, which also differs between PDF groups;

H(125) is about as good as it gets – still a spread in ggH cross section of $\mathcal{O}$(10%)

what we might expect in the future: HL-LHC PDFs



study PDF constraints expected from LHC measurements **by end of the HL-LHC phase (2026 ~ 2038)**

ATLAS+CMS **3 ab^{-1}**

LHCb **0.3 ab^{-1}**

(studies in arXiv:1810.03639; prepared for CERN Yellow Report, arXiv:1902.04070)

concentrate on datasets sensitive to mid-to-high-x; and not already systematics dominated

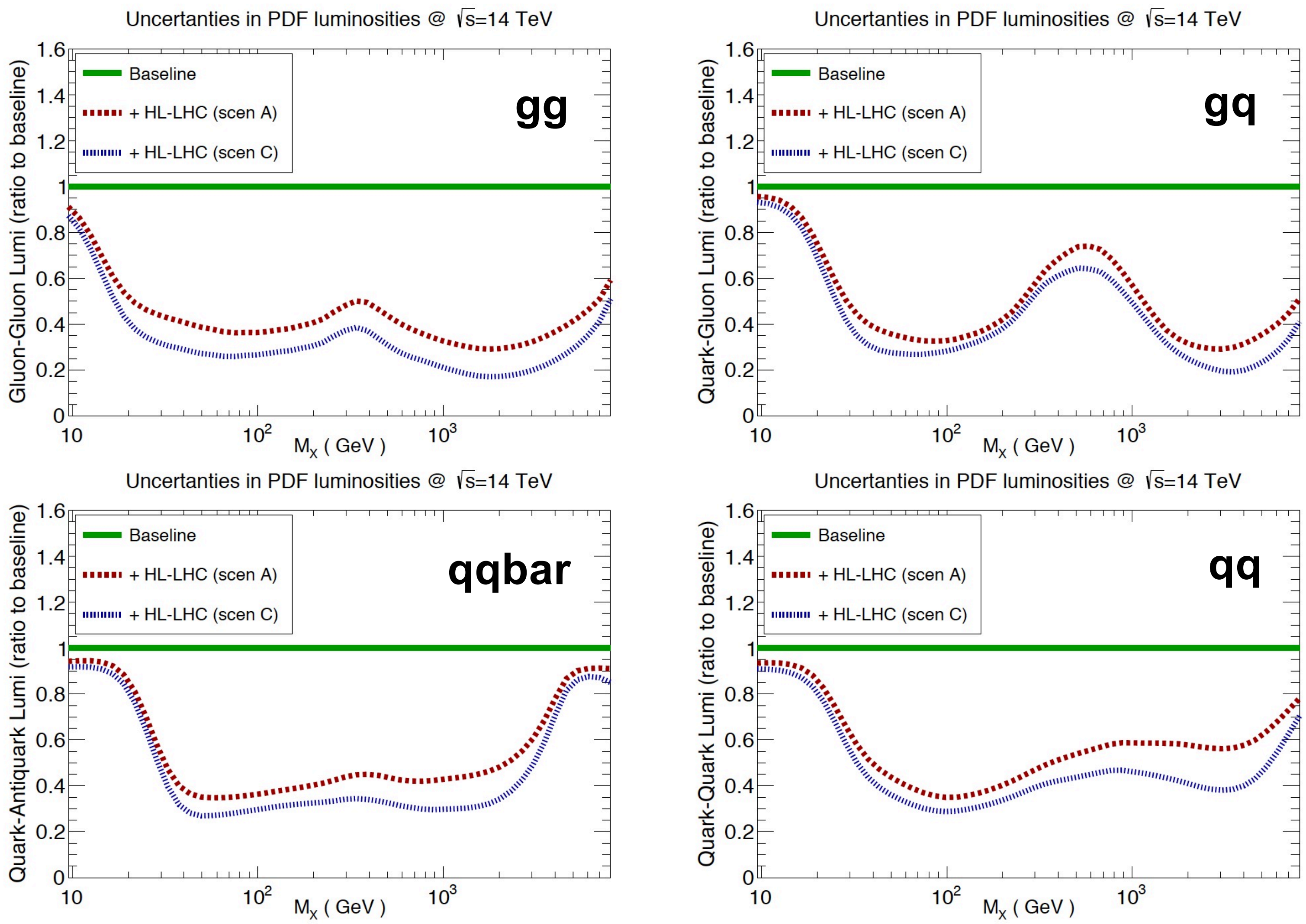
$$\mathrm{sys}(14\ \mathrm{TeV}) \sim f_{\mathrm{corr}} \times f_{\mathrm{red}} \times \mathrm{sys}(8/13\ \mathrm{TeV})$$

Hessian profiling of PDF4LHC15
with tolerance T=3

- systematic uncertainties taken from existing data;
- treated as uncorrelated, with factor **fcorr=0.5**, chosen to approximately reproduce effect of syst. correlations in existing measurements;
- variable factor **fred** to estimate improvement to systs.

HL-LHC parton luminosities

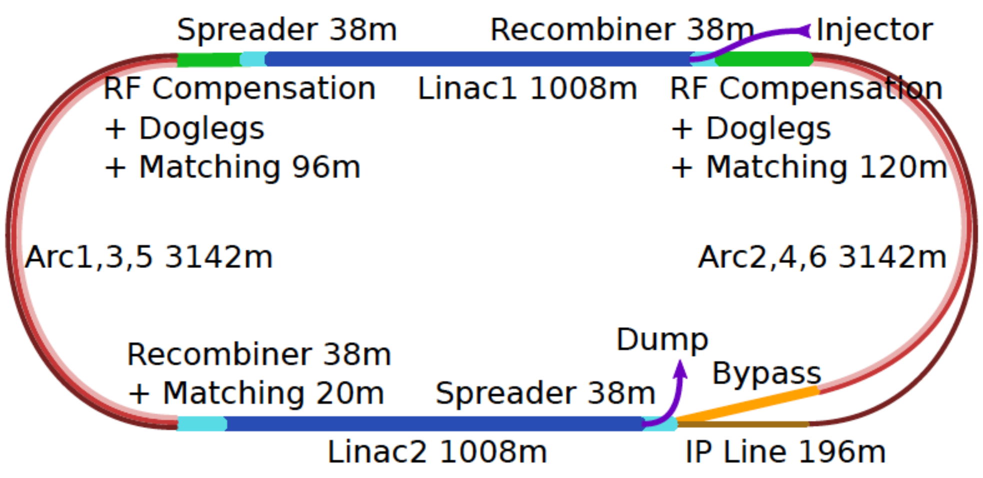
arXiv:1810.03639



$$f_{red} = \begin{cases} 1/0.5\ (8/13)\mathrm{TeV} & \text{scenario A: conservative} \\ 0.4/0.2\ (8/13)\mathrm{TeV} & \text{scenario C: optimistic} \end{cases}$$

(together with **intermediate** scenario B, all are available in lhapdf format)

can we do better? ep colliders!

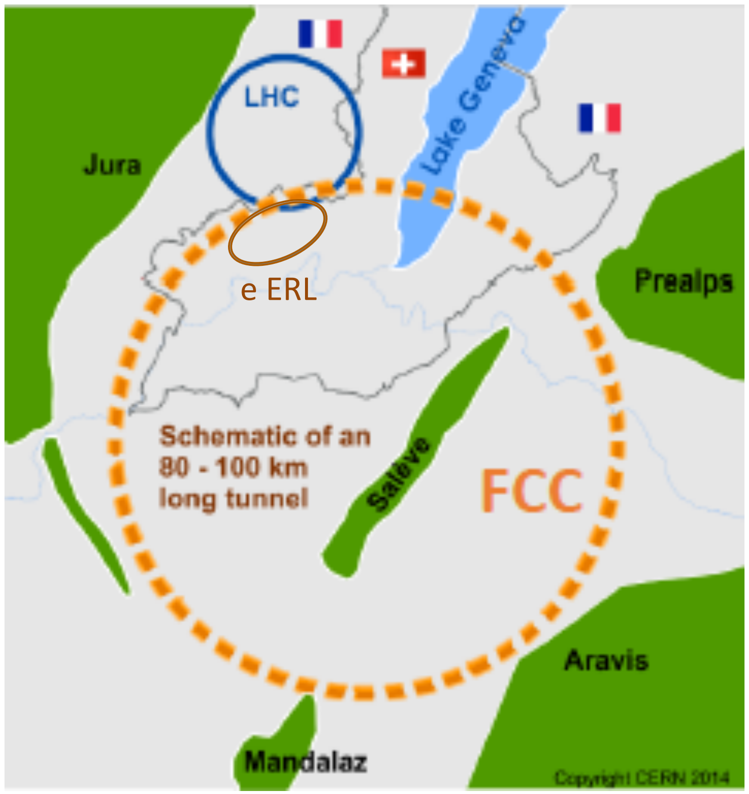


proposed **ep** colliders: **LHeC**, **FCC-eh**

energy recovery LINAC

e beam: up to 60 GeV

Lint ⟶ 1 ab^{-1} (1000× HERA ; per 10 yrs)

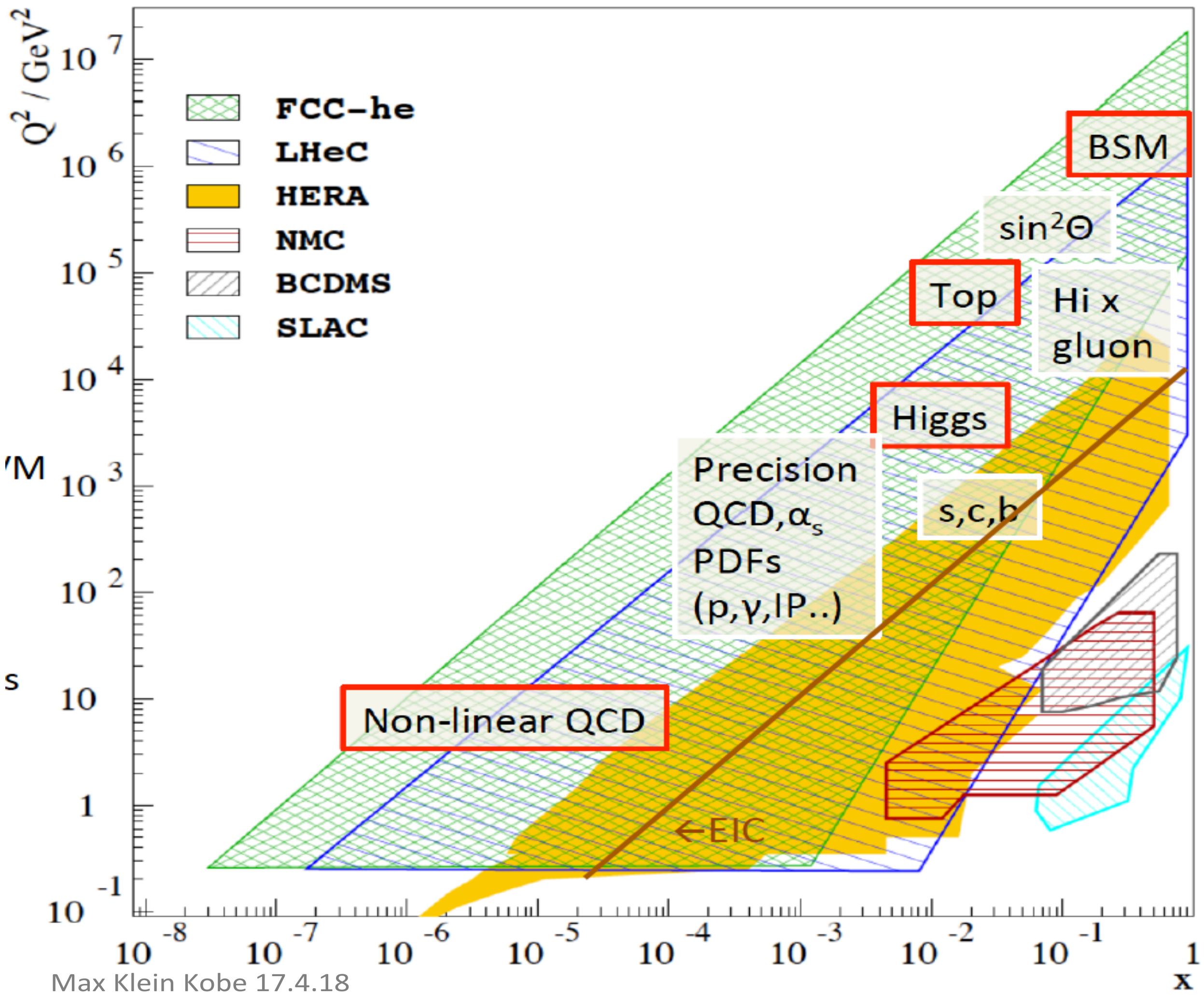


operating **synchronously** with and using p beam from:

- the **HL-LHC** (or HE-LHC)
  p: 7 (14) **TeV, $\sqrt{s} \approx$ 1.3** (1.8) **TeV**
- and/or later using an **FCC** (LE)
  p: 50 (20) **TeV, $\sqrt{s} \approx$ 3.5** (2.2) **TeV**

† **FCC (LE):** a lower energy configuration that could operate earlier in an FCC tunnel, using current magnet technology

kinematic coverage



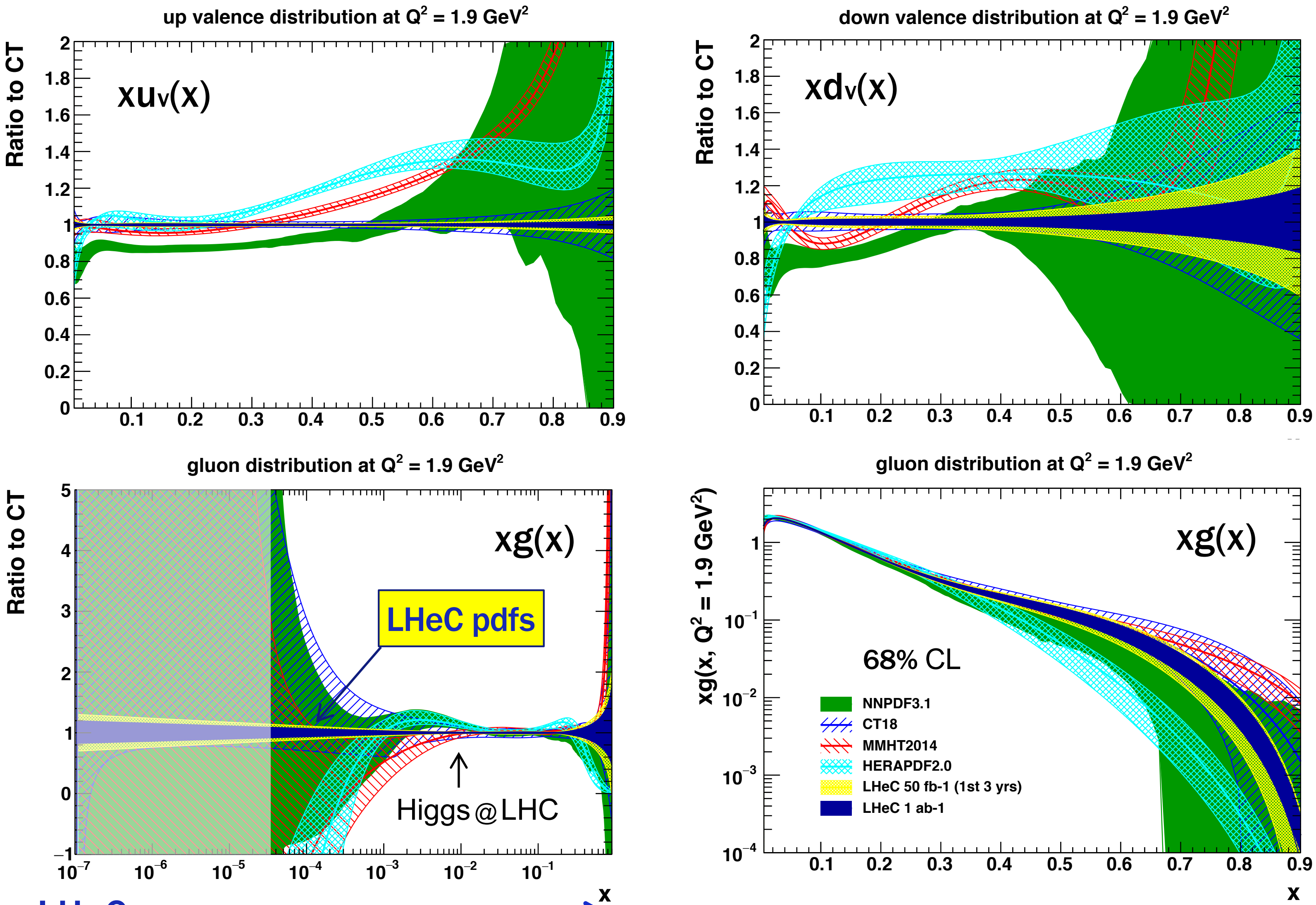
opportunity for **unprecedented increase in DIS kinematic reach**; ×1000 increase in lumi. cf. HERA

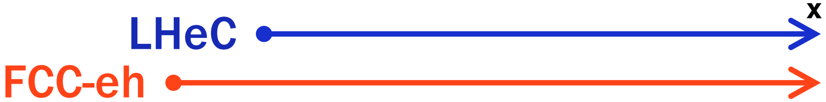
no nuclear corrections, free of symmetry assumptions, N^3LO theory possible, …

precision pdfs up to x→1, and exploration of small x regime; plus extensive additional physics programme

×**15**/**120** extension in Q^2,1/x reach vs **HERA** arXiv:[2007.14491](https://arxiv.org/abs/2007.14491)

quark and gluon pdfs

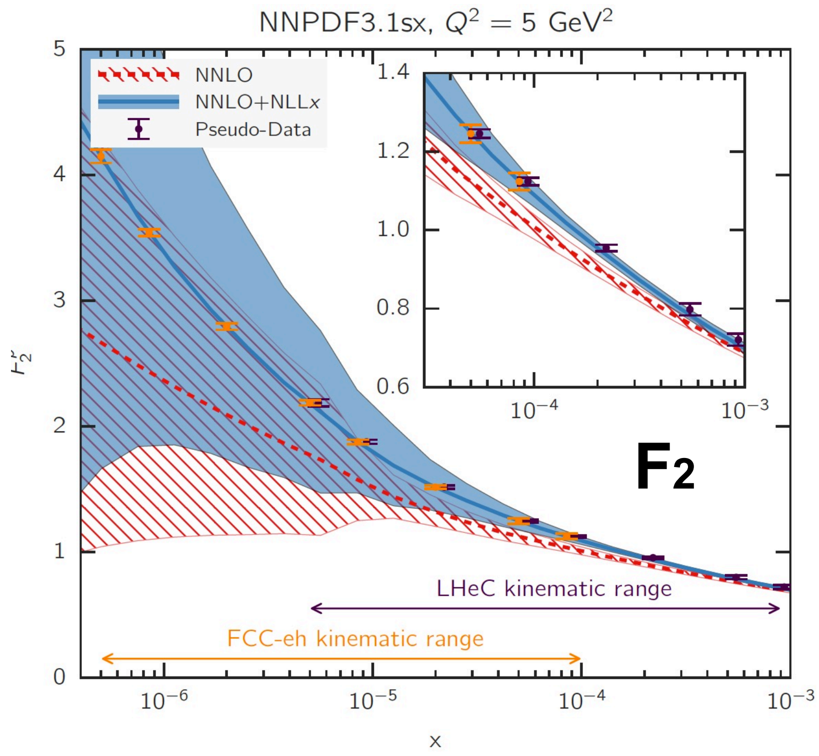


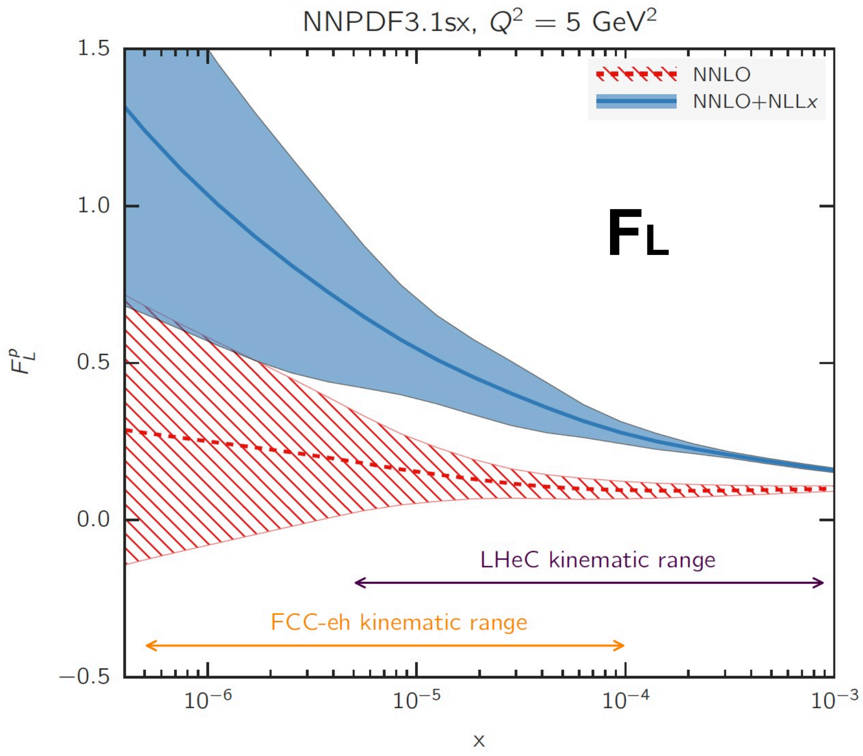


in addition, semi-inclusive measurements of s,c,b,t disentangles all flavours; jets for improvement to xg etc.

pinning down the low x behaviour

arXiv:1710.05935





F2 and FL predictions for simulated kinematics of **LHeC** and **FCC-eh**

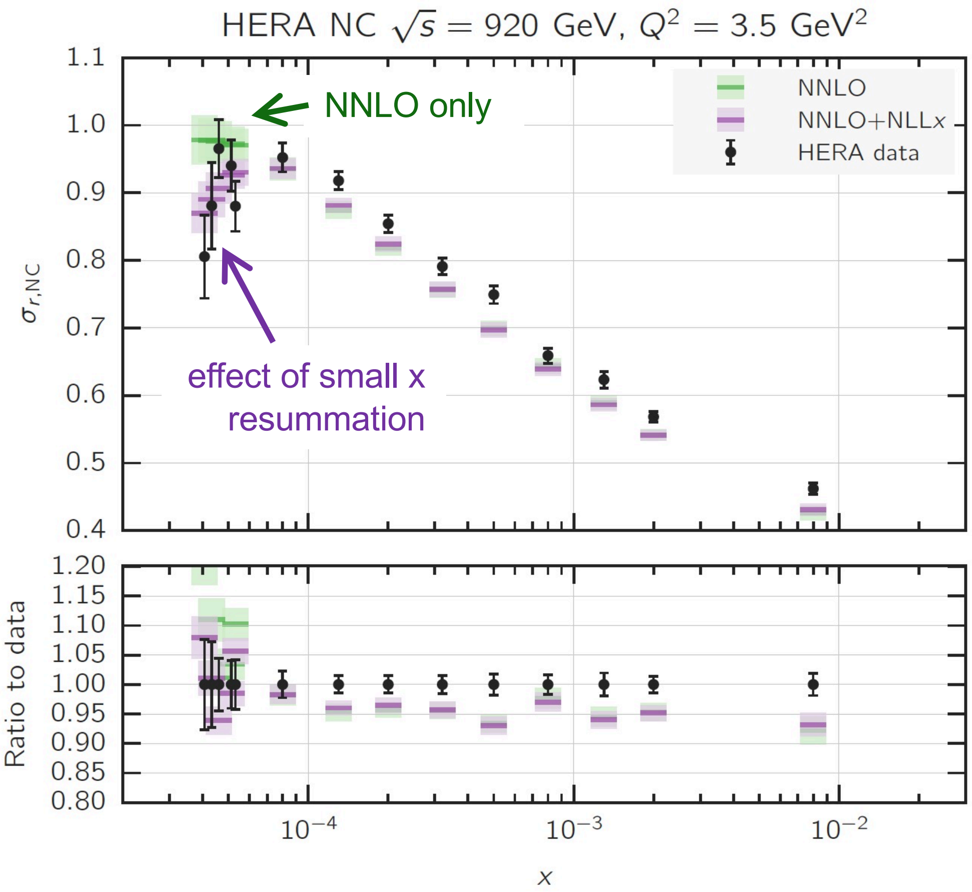
ep simulated data very precise – significant constraining power to discriminate between theoretical scenarios of small x dynamics

measurement of FL has a critical role to play

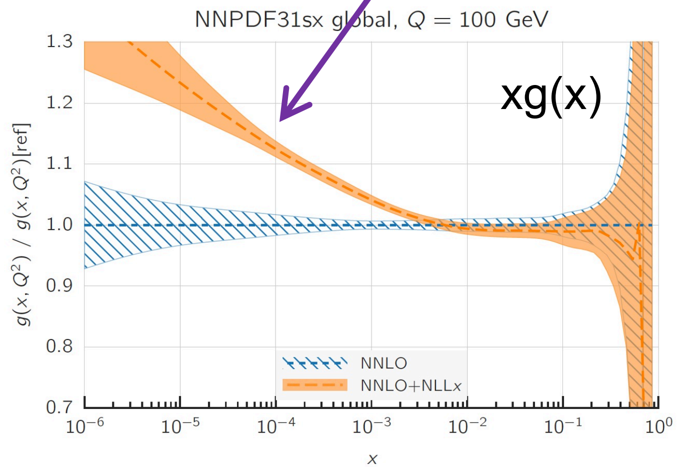
see also arXiv:1802.04317

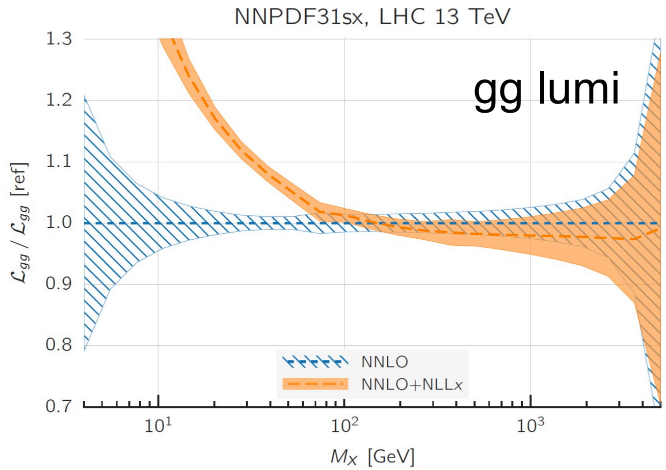
why small x matters

arXiv:1710.05935 ; confirmed in, arXiv:1802.00064



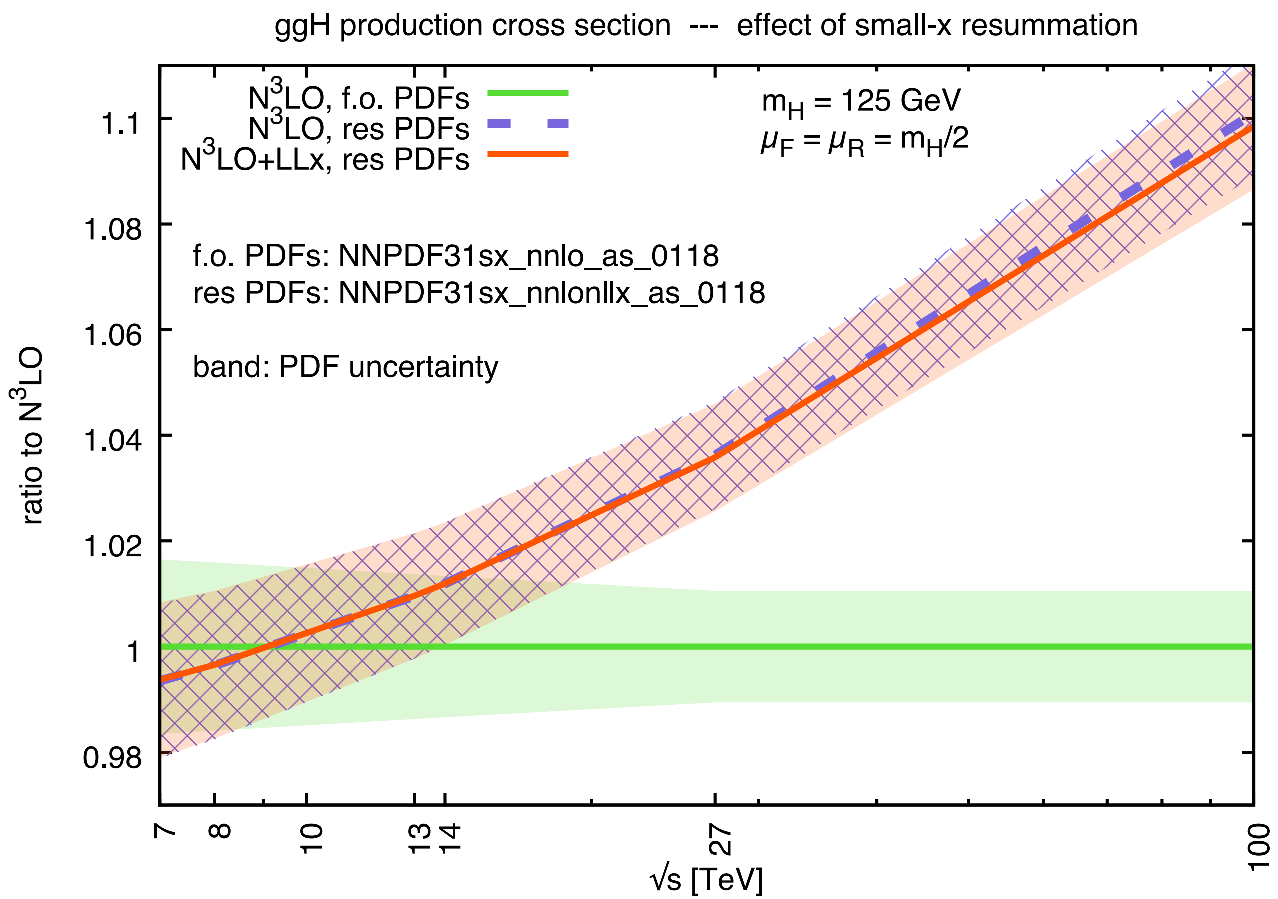
effect of small x resummation





- RECALL: recent evidence for onset of BFKL dynamics in HERA inclusive data
- **impact for LHC and most certainly at ultra low x values probed at FCC**

implications for observables at the LHC and beyond

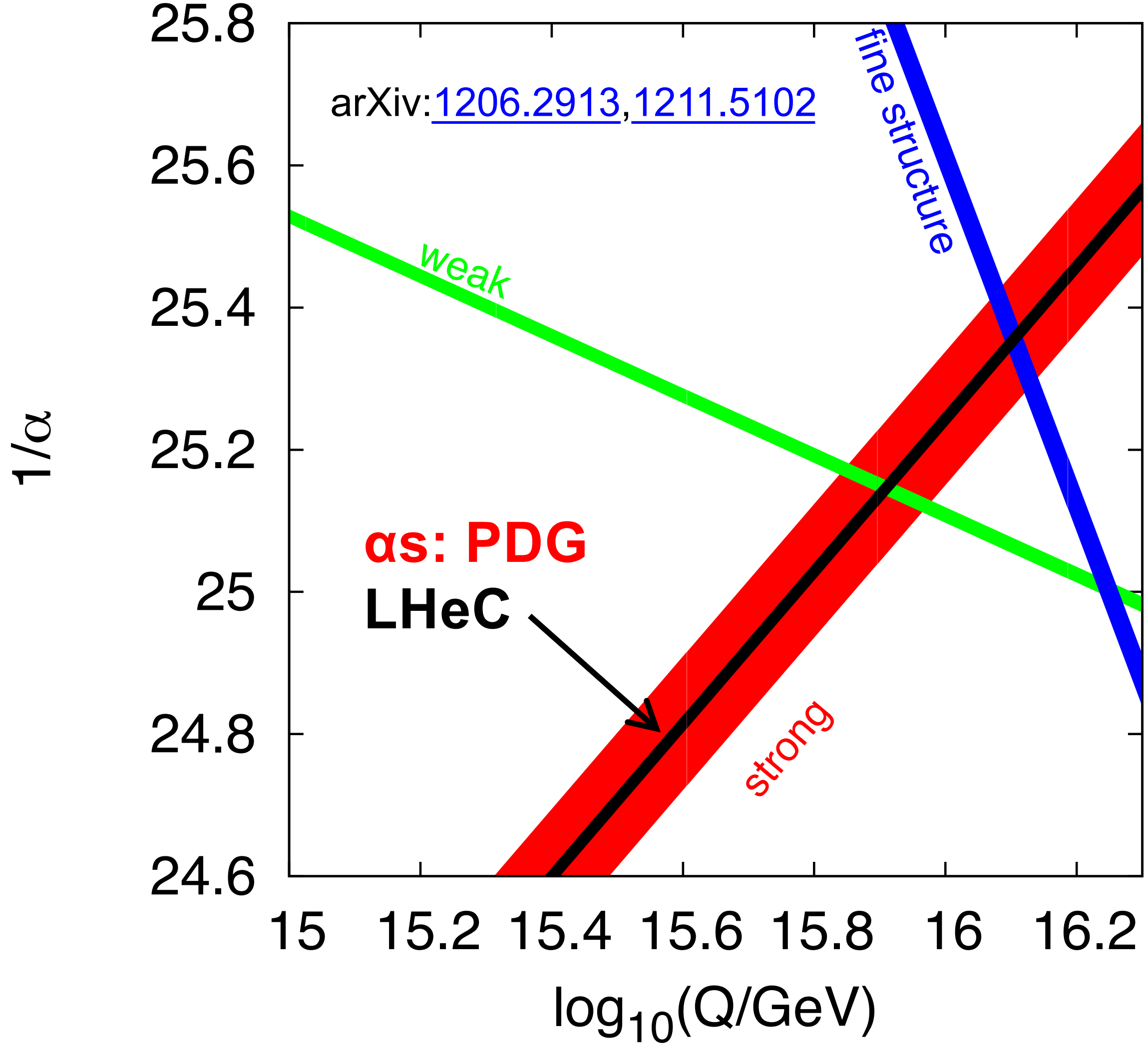


effect of small x resummation on ggH cross section for LHC, HE-LHC, FCC

impact on other EW observables could be of similar size

arXiv:[1802.07758](1802.07758); also recent work on forward Higgs production, arXiv:[2011.03193](2011.03193); and other processes in progress

strong coupling, αs at the LHeC

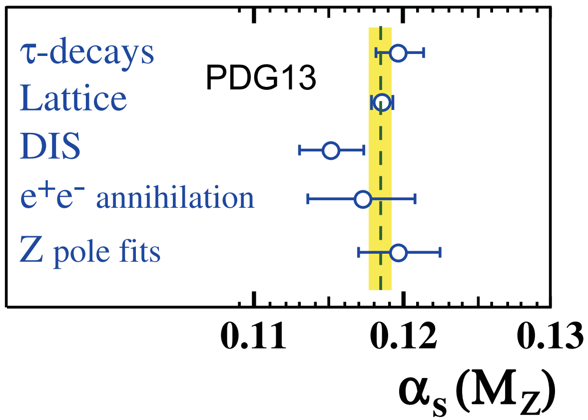


αs is least well known coupling constant

PDG21:

αs = 0.1175 ± 0.0010

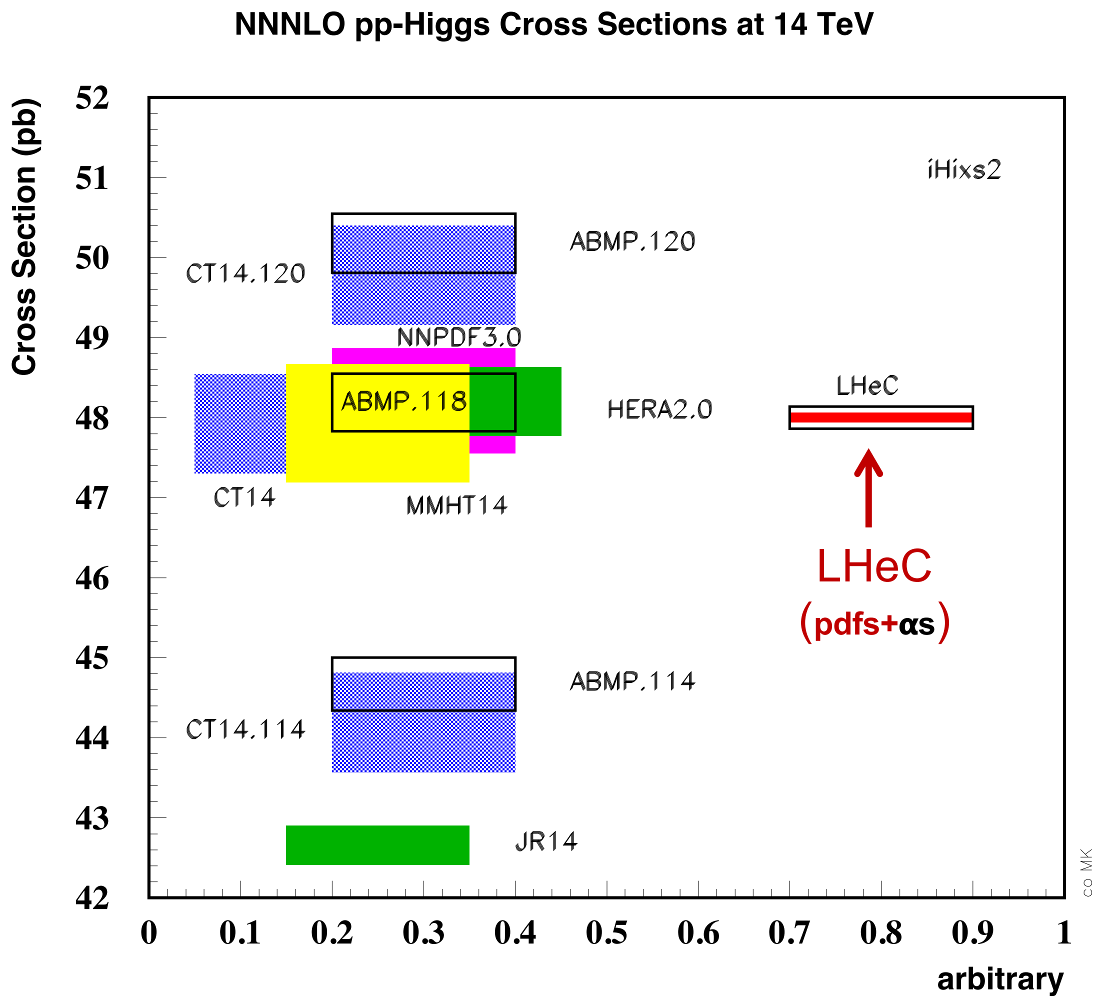
current measurements not all consistent!



accurate and precise **αs** needed:

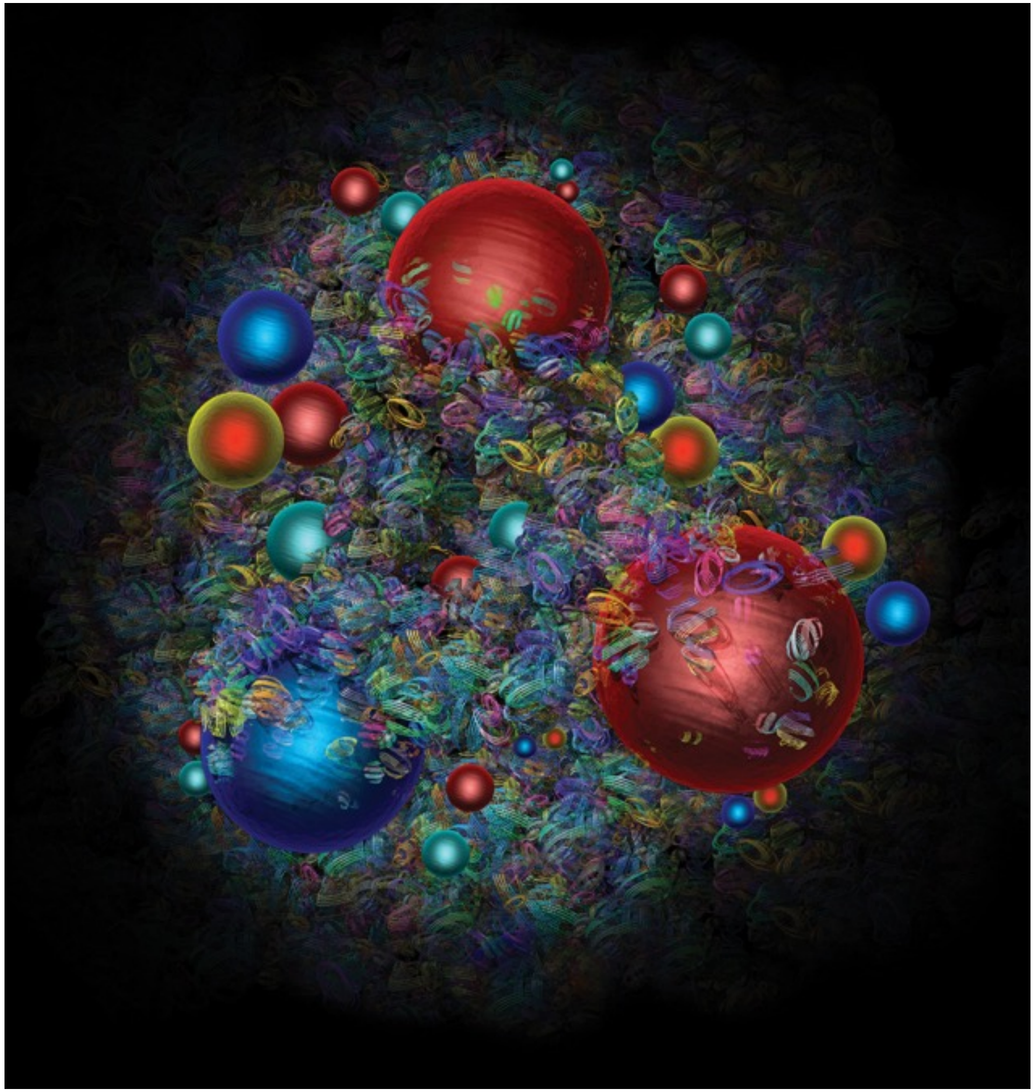
to constrain GUT scenarios; for cross section predictions, including Higgs; …

Higgs

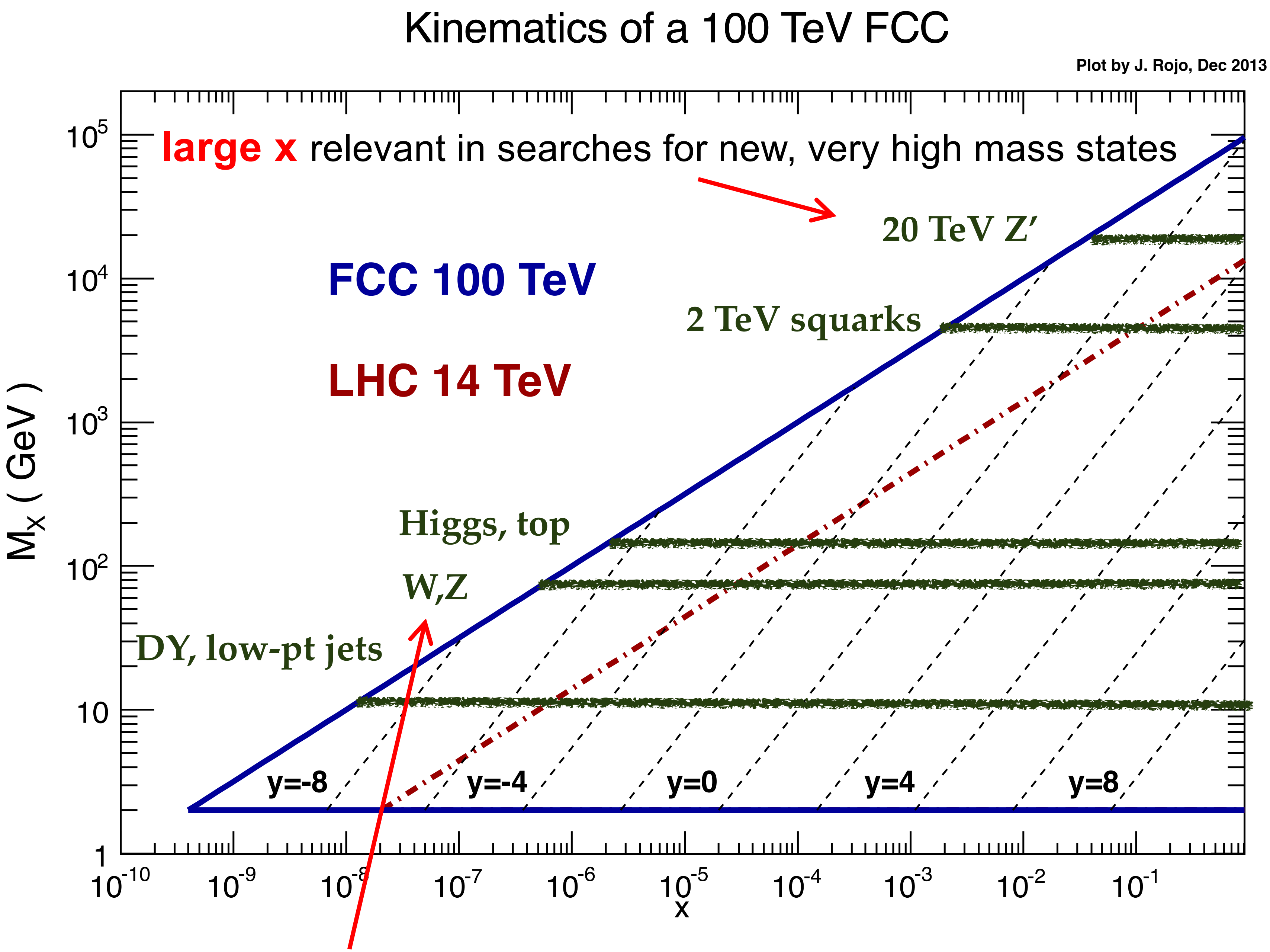


as well as αs to potentially permille precision …

LHeC also has an extensive Higgs program in its own right



extras

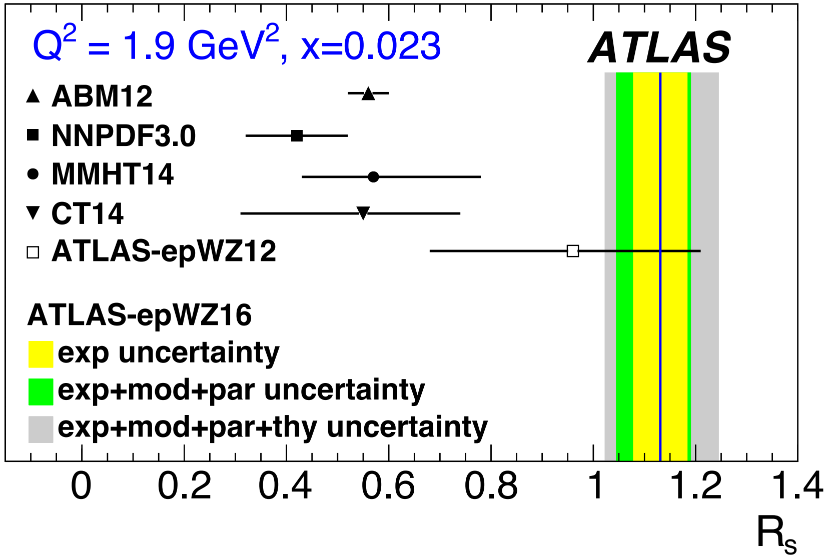


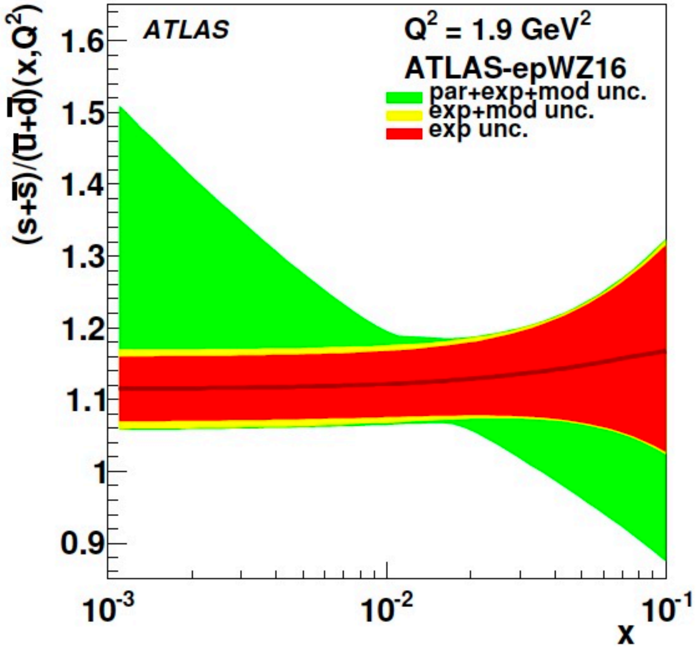
small x becomes relevant even for “common” physics (EG. W, Z, H, t)

the strange sea

confirmed in most precise published ATLAS W,Z data (arXiv:1612.03016)

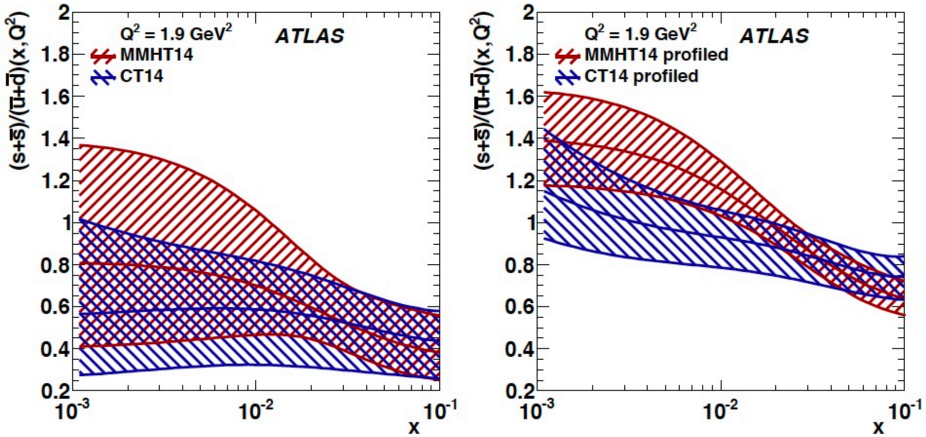
ATLAS sees unsuppressed strange at small x



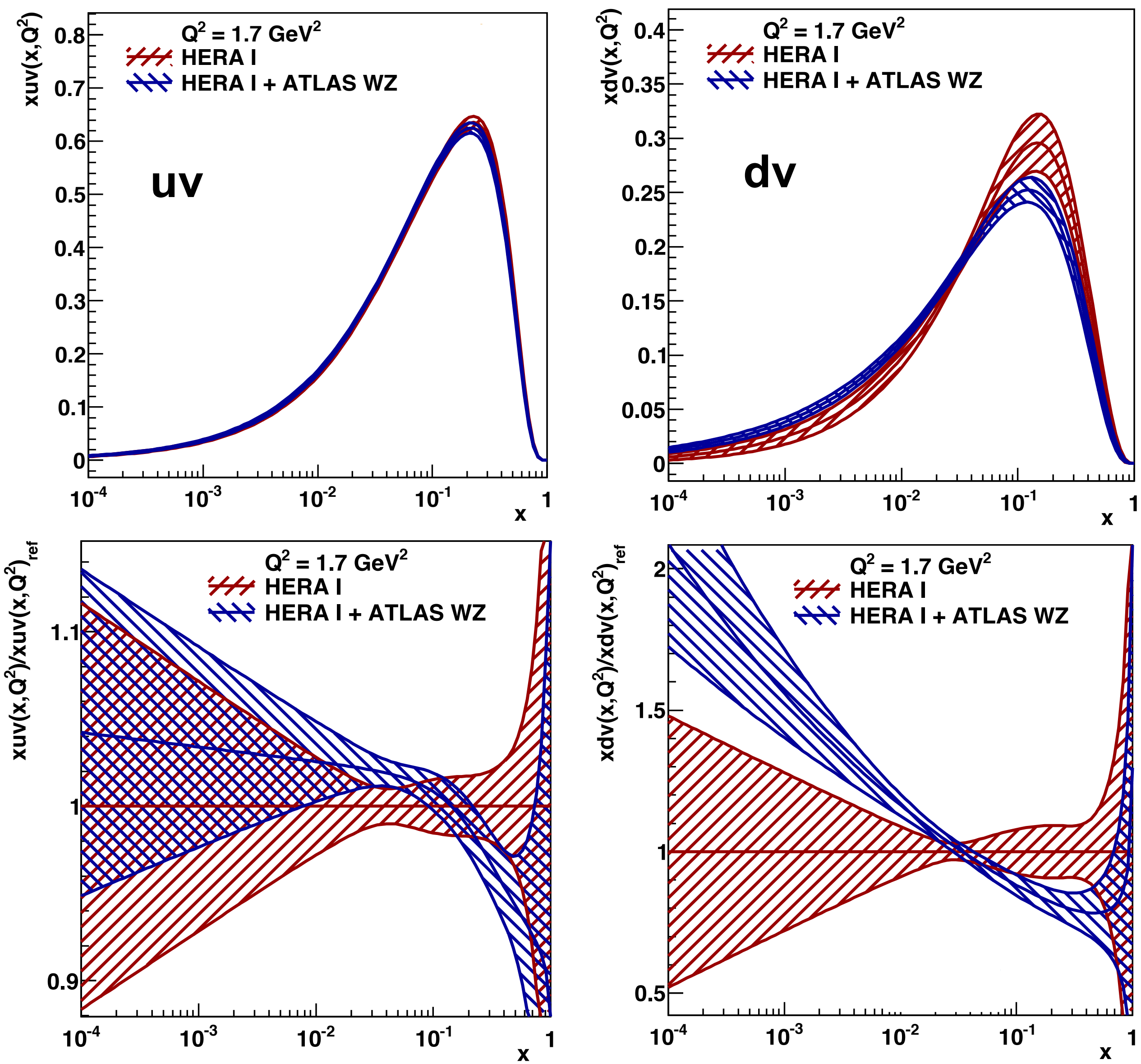


profiling other PDF sets tells the same story – more strange at low x

$$R_s(x,Q^2) = \frac{s(x,Q^2)+\bar{s}(x,Q^2)}{\bar{u}(x,Q^2)+\bar{d}(x,Q^2)} \begin{cases} \approx 0.5 \text{ (from neutrino)} \\ \approx 1.0 \text{ (from ATLAS W,Z)} \end{cases}$$

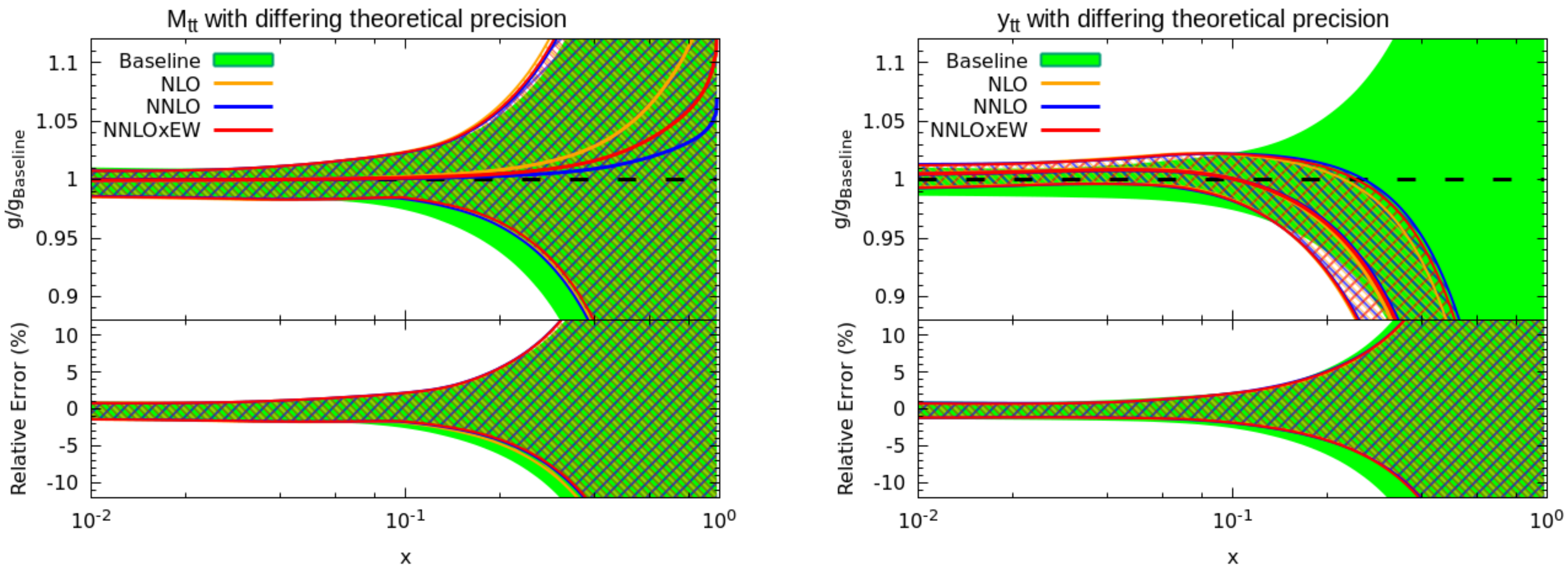


impact on valence quarks from ATLAS W and Z



top-quark pair production

even within a **single experiment** there are discrepancies, EG.

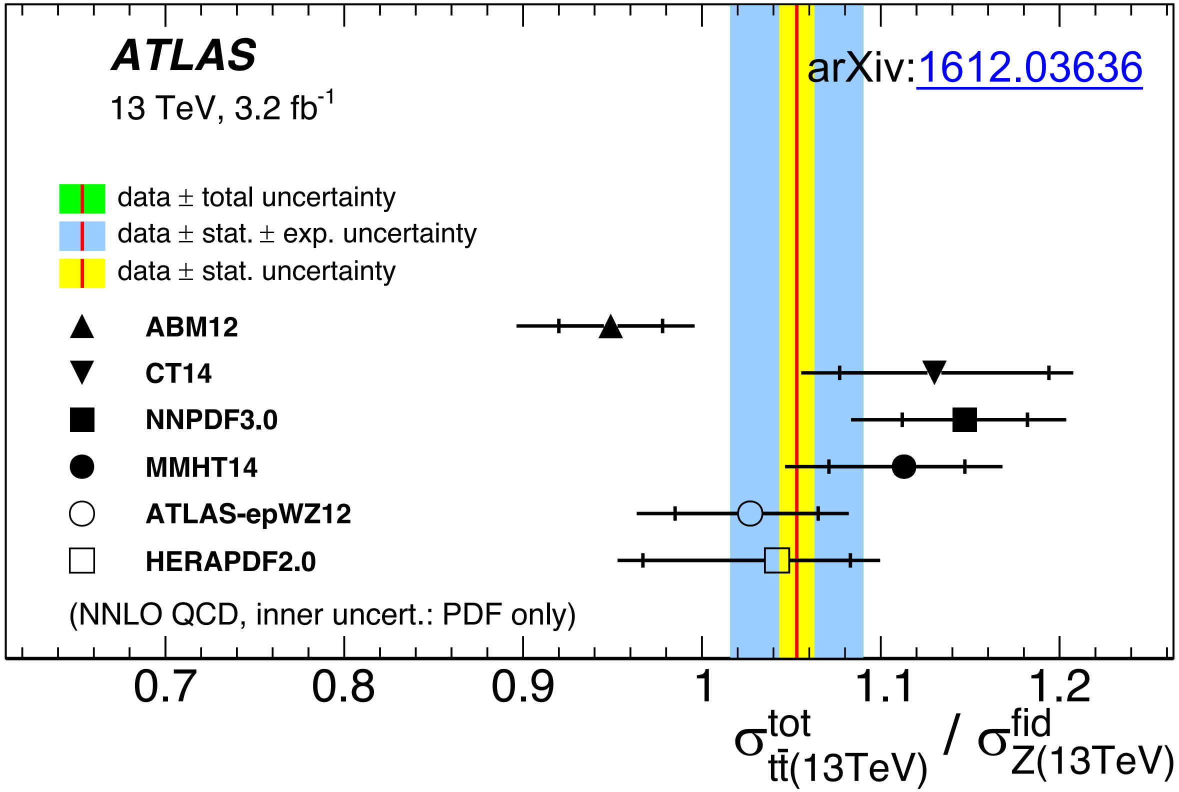


arXiv:1909.10541

- ATLAS 8 TeV ttbar (in lepton+jet decay channel)
- cross section measurements exist differential in several observables, EG. Mtt, ytt
- **Mtt wants harder gluon, ytt a softer gluon and is in tension with some other datasets**
- these findings have been observed also by other groups: ATLAS, CT, NNPDF …

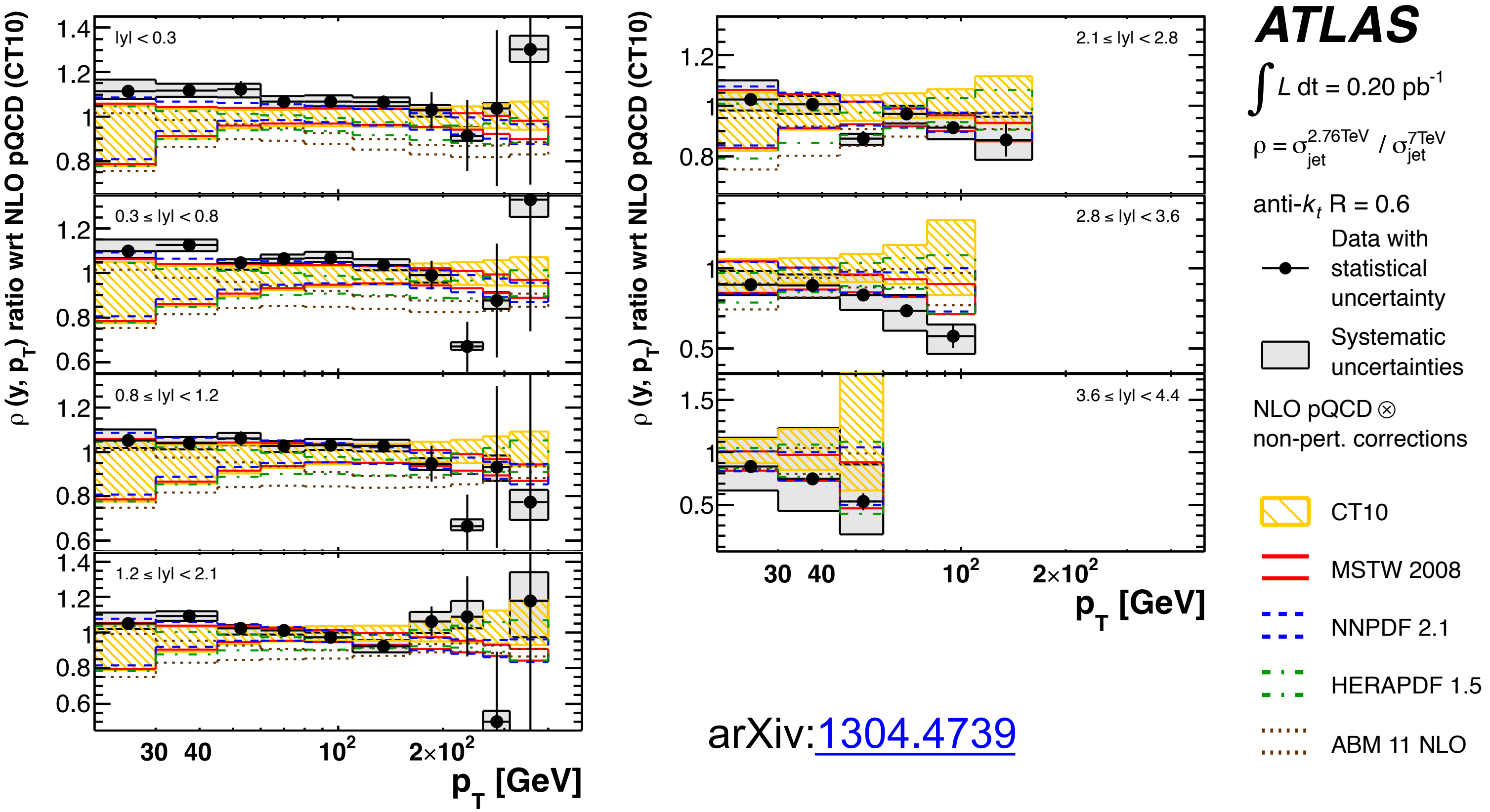
top-quark pair to Z cross section ratios

- measuring ratios has also been suggested as a good discriminator



EG. **ATLAS ttbar/Z ratio at 13 TeV**: ttbar mostly relates to gluon, Z mostly to quarks; ABM12 too little gluon, many other PDFs not enough Z (recall strangeness study)

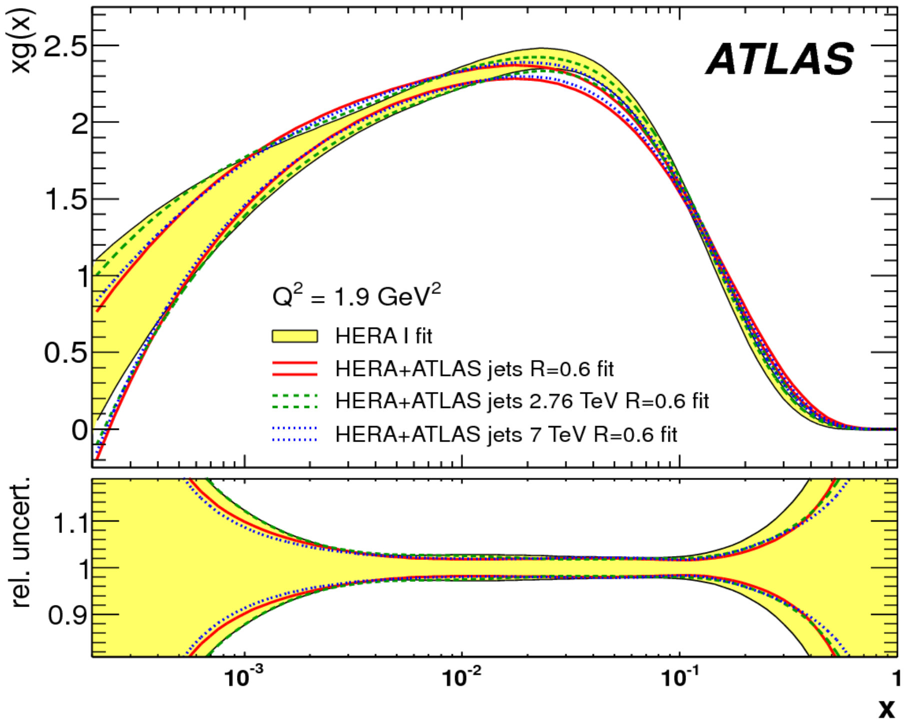
jet cross section ratio measurements



arXiv:[1304.4739]

- even better: **take ratios of jet measurements at different CM energies**
- EG. ratio of ATLAS 2.76 to 7 TeV inclusive jet cross sections (itself shown as a ratio to NLO QCD)
- experimental uncerts. reduced in ratio and generally smaller than theory uncerts.
- potential for **PDF discrimination/constraint** since different beam energies probe **different x, Q2** values for **same pt and y range**

jet cross section ratios



arXiv:[1304.4739]

this is an older result with relatively small statistics, but stands as a proof-of-principle

comparison of **gluon PDF** for fits using only HERA data compared to using HERA+ATLAS 2.76 and 7 TeV inclusive jets

gluon becomes harder, uncertainties are reduced

impact stronger than if either 2.76 or 7 TeV data used individually

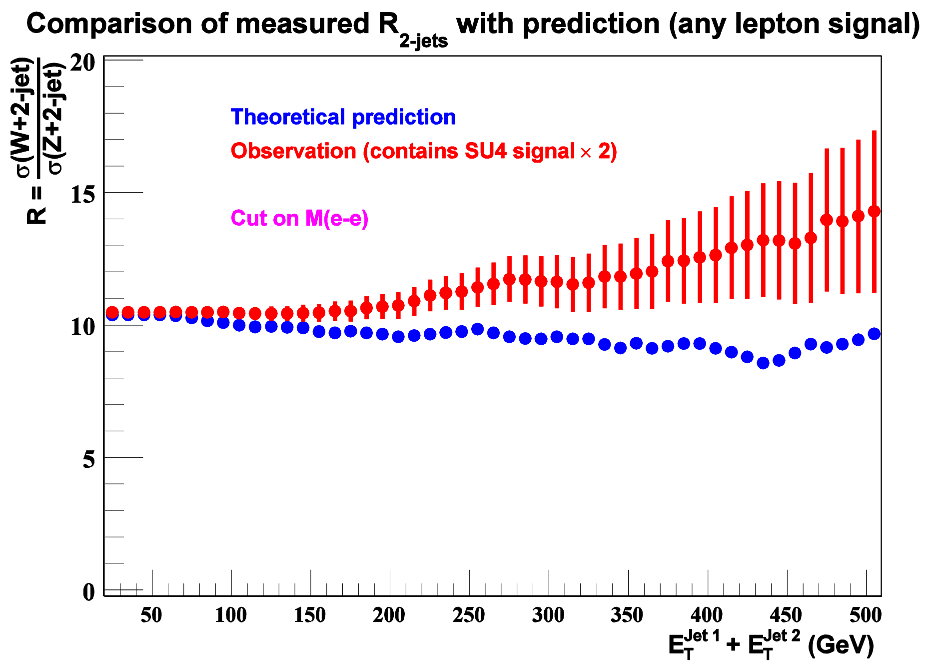
treatment of correlated systematic uncertainties must be carefully considered for ATLAS jet data; 87 separate sources of correlated uncertainty in this example! Jet energy scale uncertainty down to 3% but taking the ratio is what really helps control it

V+jets

W/Z+Jets is a channel which bridges from SM to BSM physics

EG. looking at ratios such as: W+N-Jets/W+(N–1)-Jets or Z+N-Jets/W+N-Jets

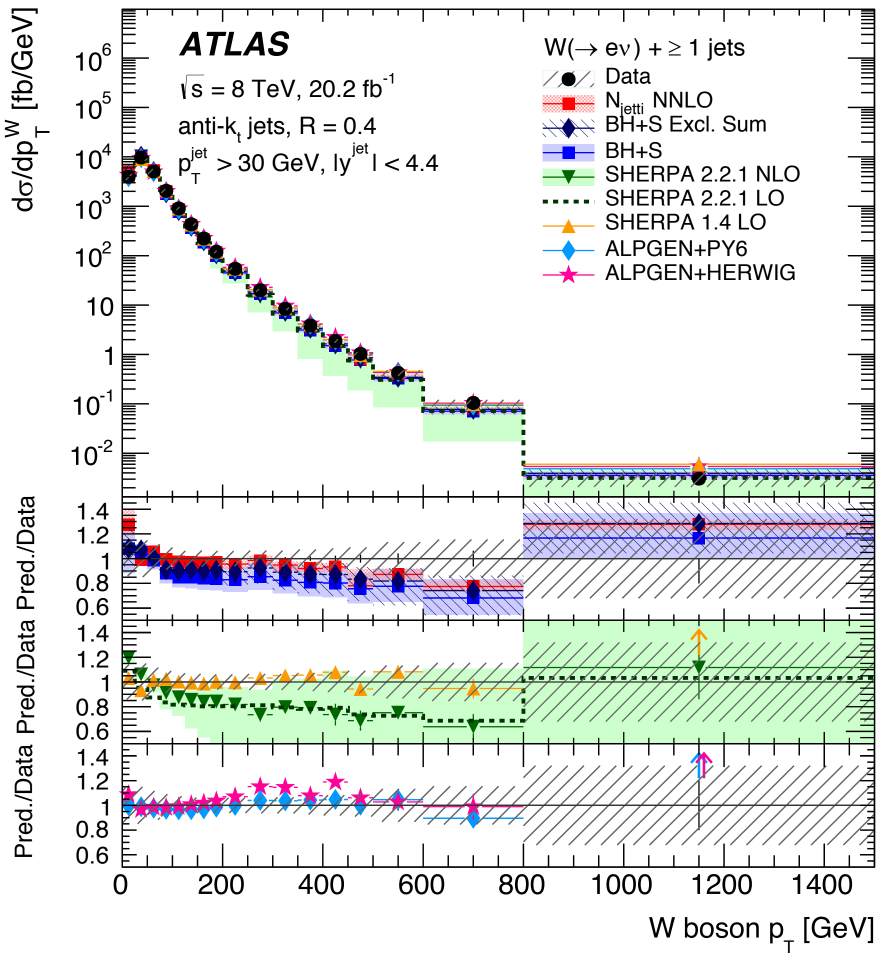
is a good way to search for BSM signals while reducing common systematic uncertainties



Illustrated is MSugra SU(4) compared to Standard Model for $200pb^{-1}$ of data in the W/Z +2 jets channel

V+jets

arXiv:1711.03296

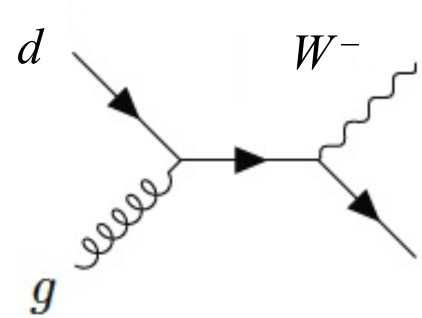


BUT nothing has been seen

current measurements mainly used for testing Monte Carlo modelling of QCD (Sherpa, ALPGEN, MC@NLO, BlackHat)

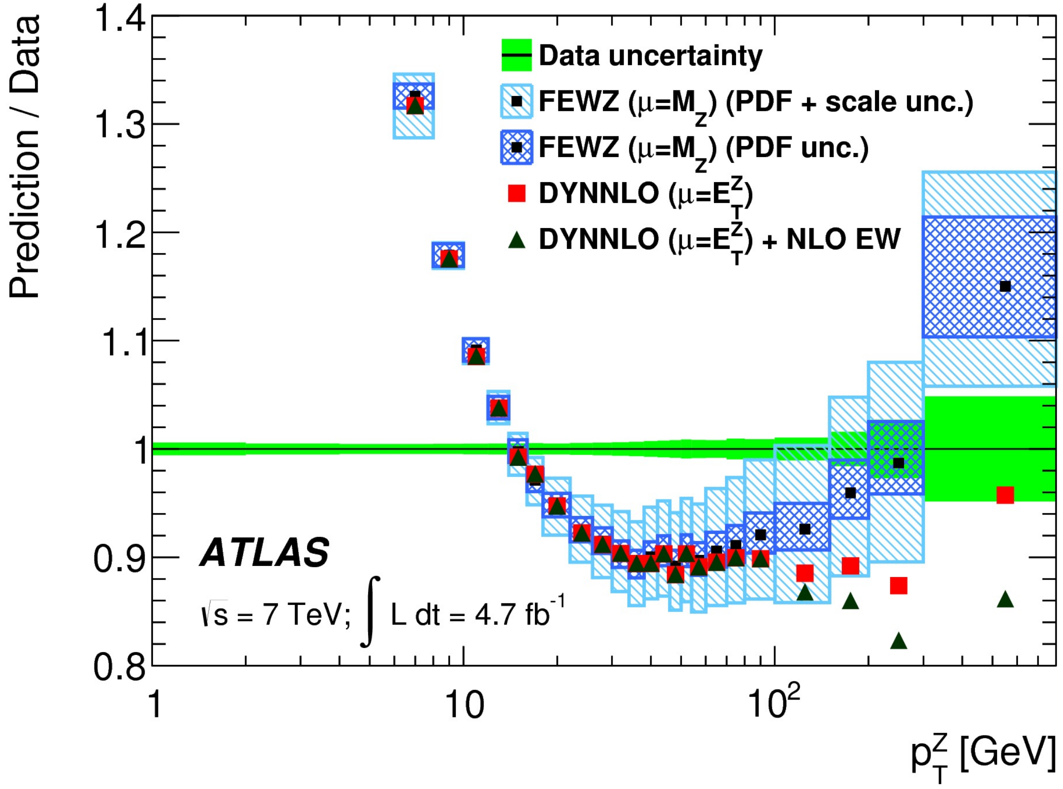
PDF fits using such measurements have been very recently performed, EG. arXiv:2101.05095

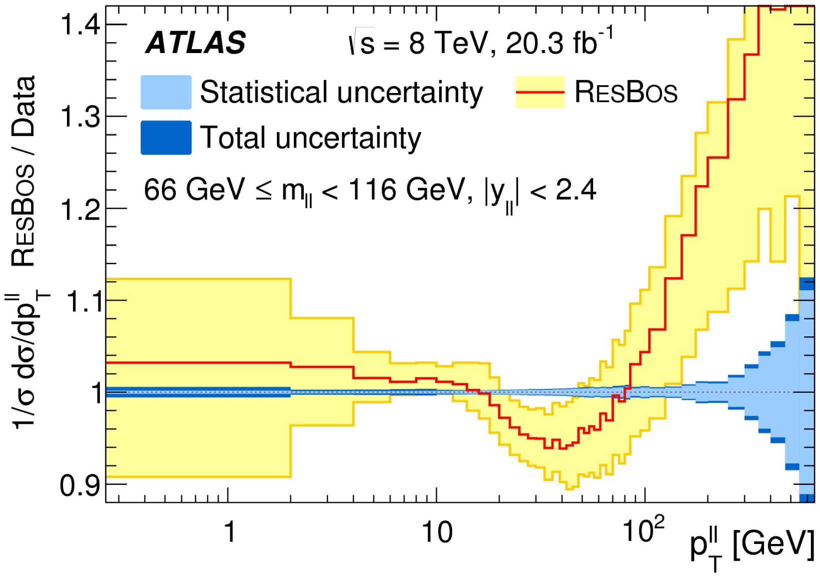
so far, main impact on **d** and **s** sea quarks; in principle sensitivity also to gluon

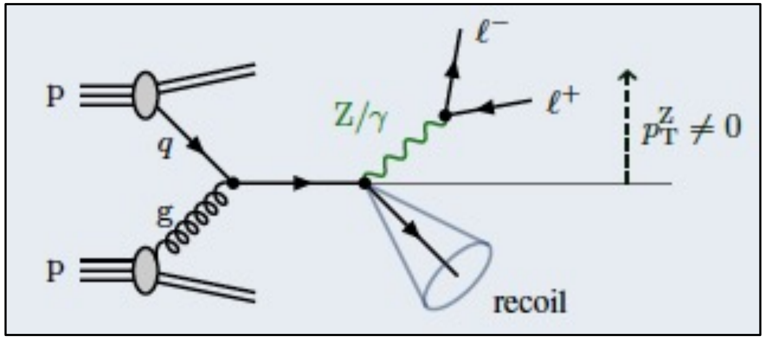


ptZ

JHEP09 (2014) 145
EPJ C76 (2016) 291







sensitive to **pdfs**, especially gluon

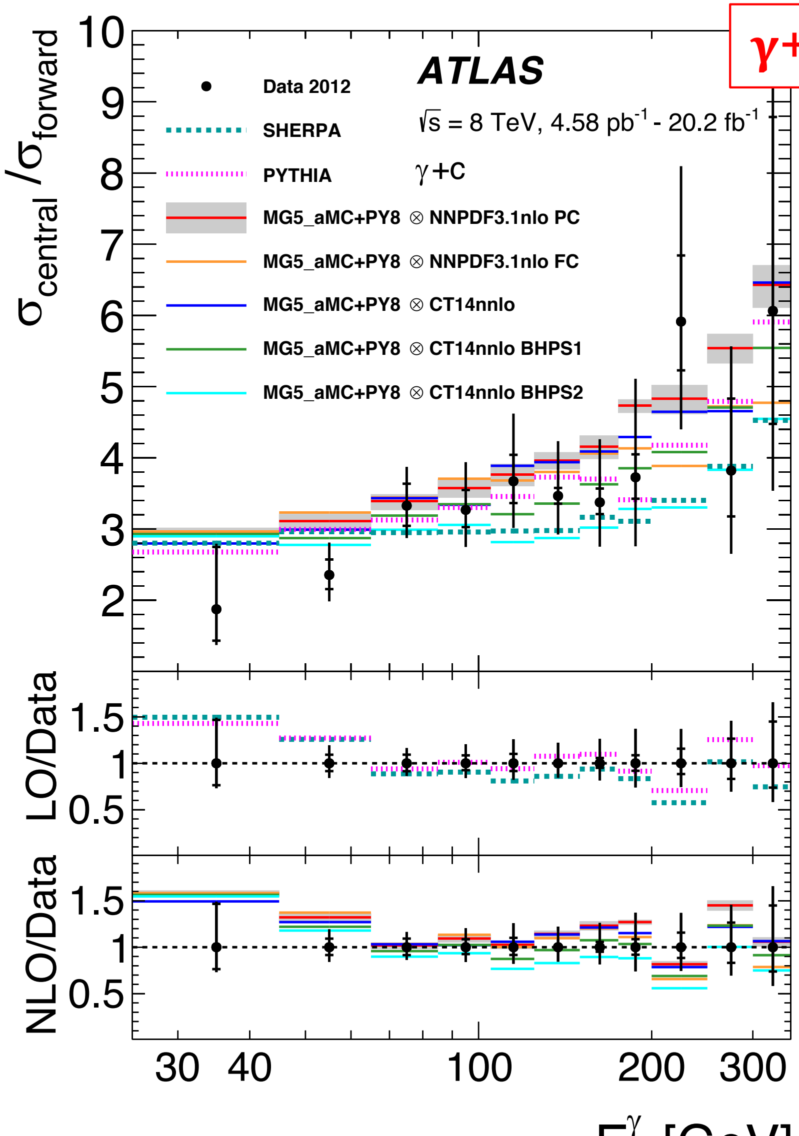
experimentally, very precise

ATLAS: ee, μμ channels; combined precision better than 0.5% precision for pt < 100 GeV

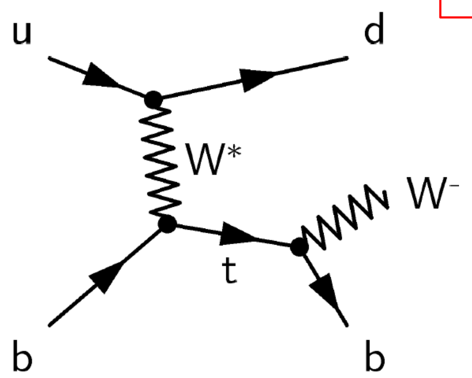
theoretically challenging – low pt region dominated by soft particle emission (resummation, shower models); high pt region dominated by emission of hard partons (pdfs)

examples of heavy quark data

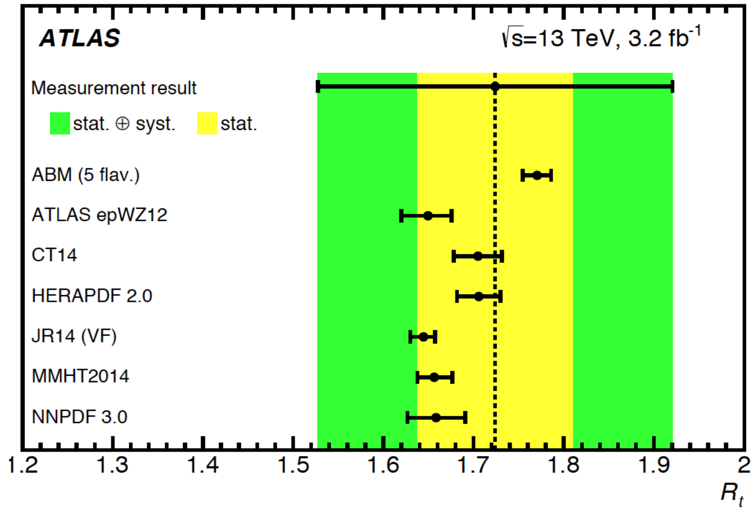
γ+c



single top



Rt = σ(tq)/σ(tbarq)

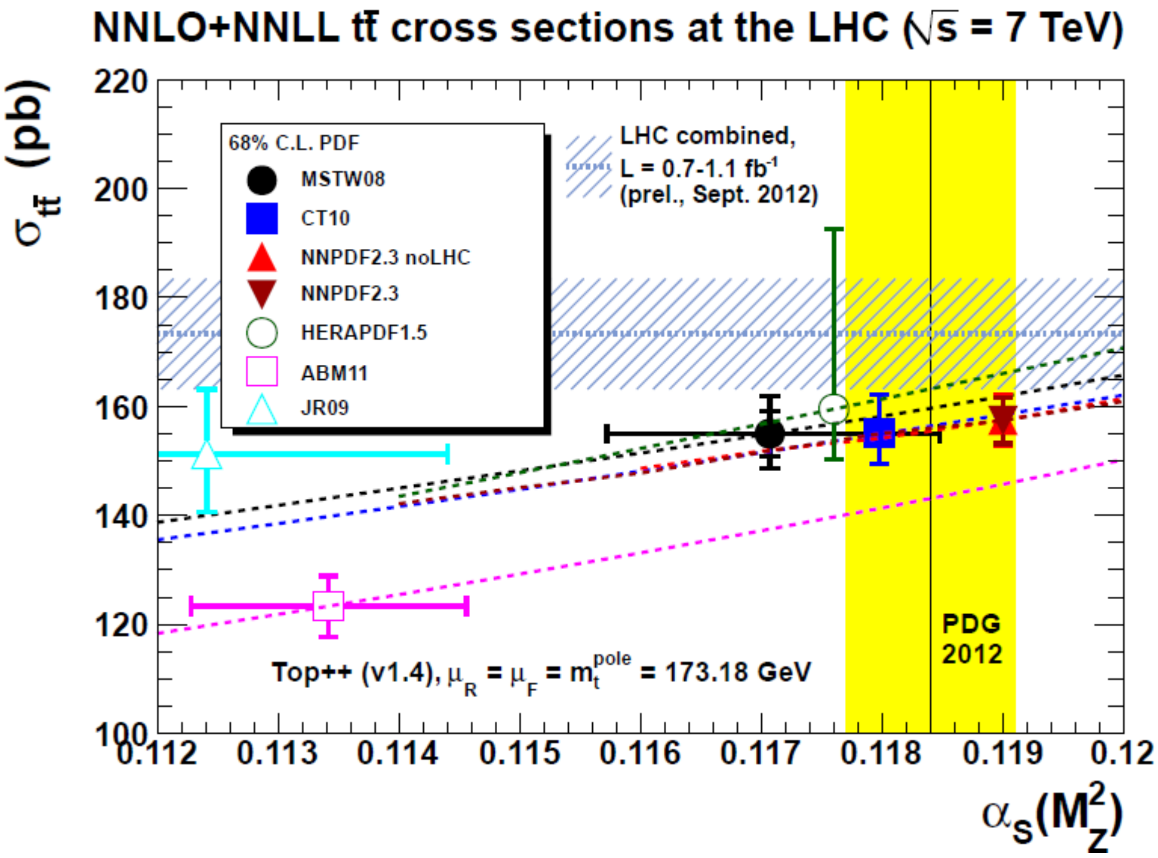


γ+c,b: PLB 776 (2018) 295

Z+b: JHEP10 (2014) 141

JHEP04 (2017) 086

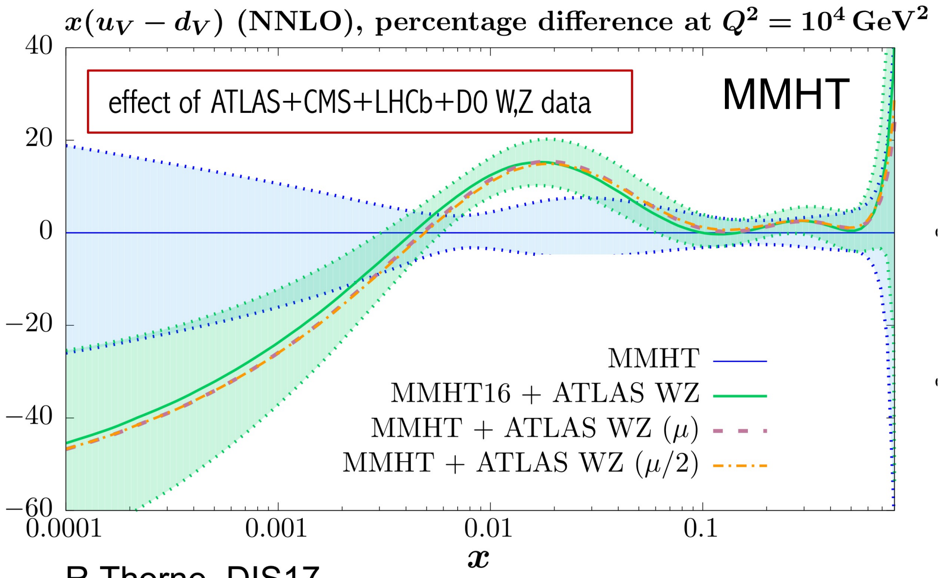
top-quark pair total cross sections



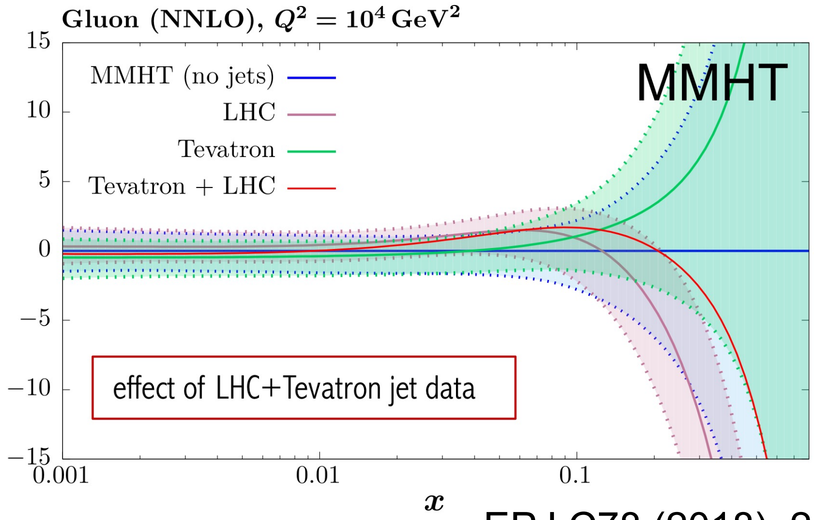
… already yield PDF discrimination? top cross sections strongly dependent on **gg luminosity** and on **αs(MZ)**; PDFs which get it right for top should be getting it right for Higgs

BUT calculation also depends on **top quark mass** and whether running mass or pole mass is used

impact of LHC data on modern global PDF fits



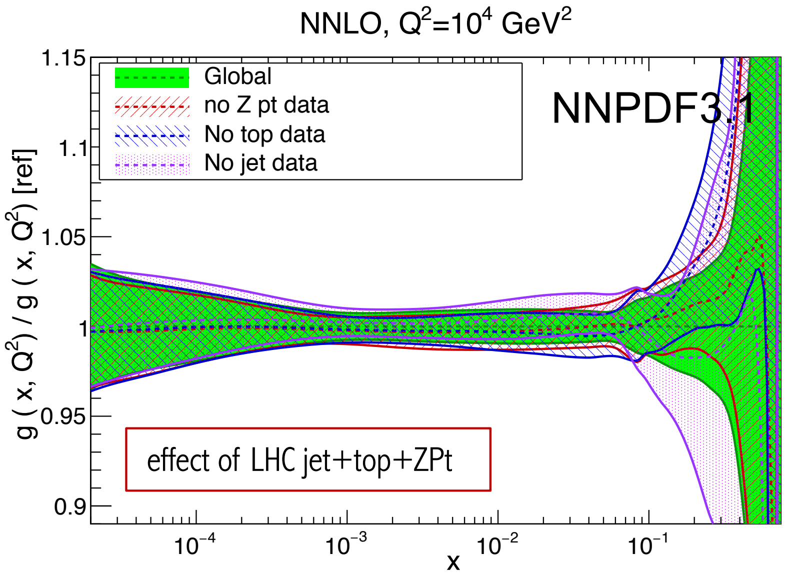
R.Thorne, DIS17



EPJ C78 (2018), 248

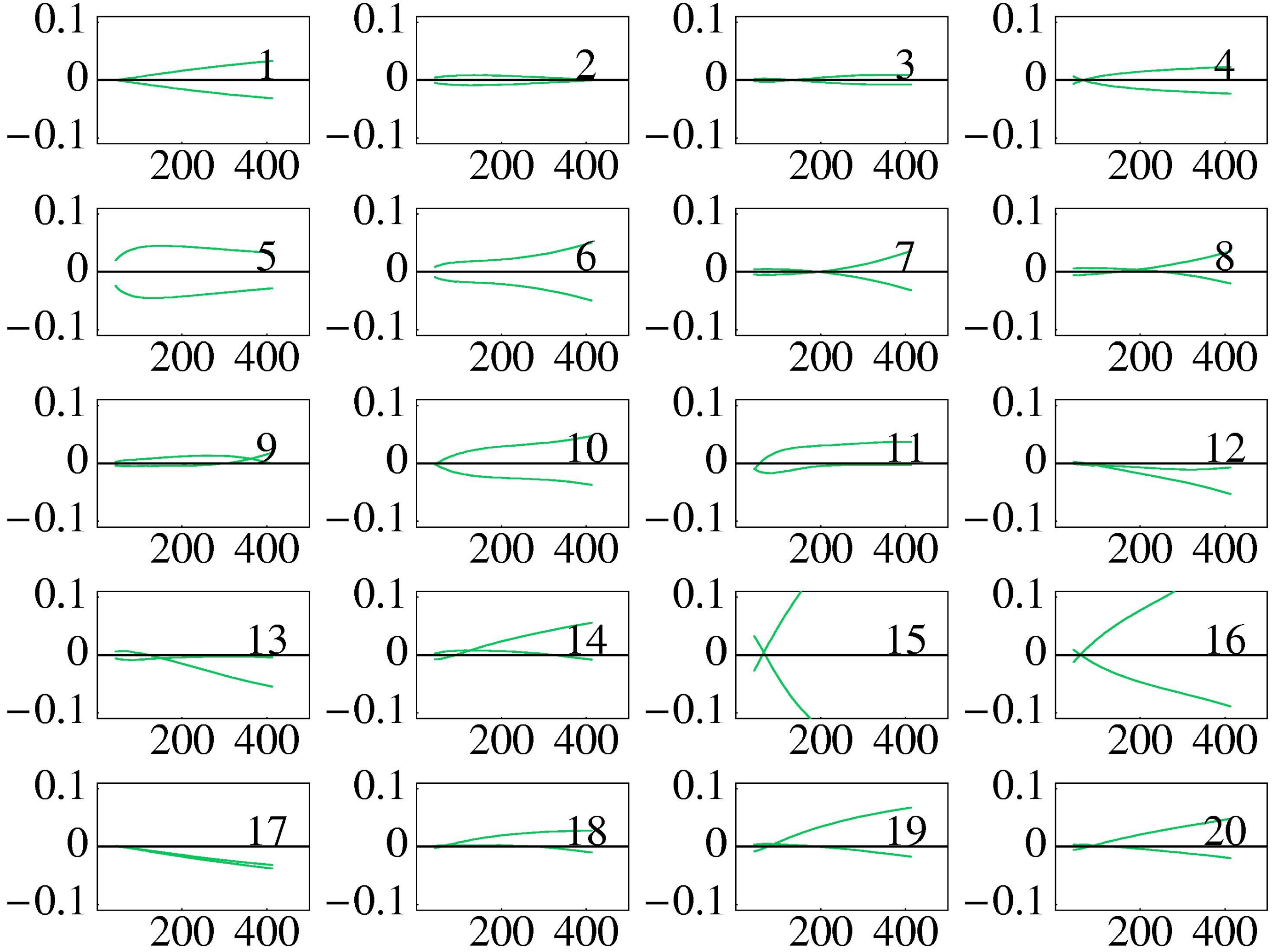
global pdf fitters actively including LHC data from **ATLAS**, CMS and LHCb

much more still to come…

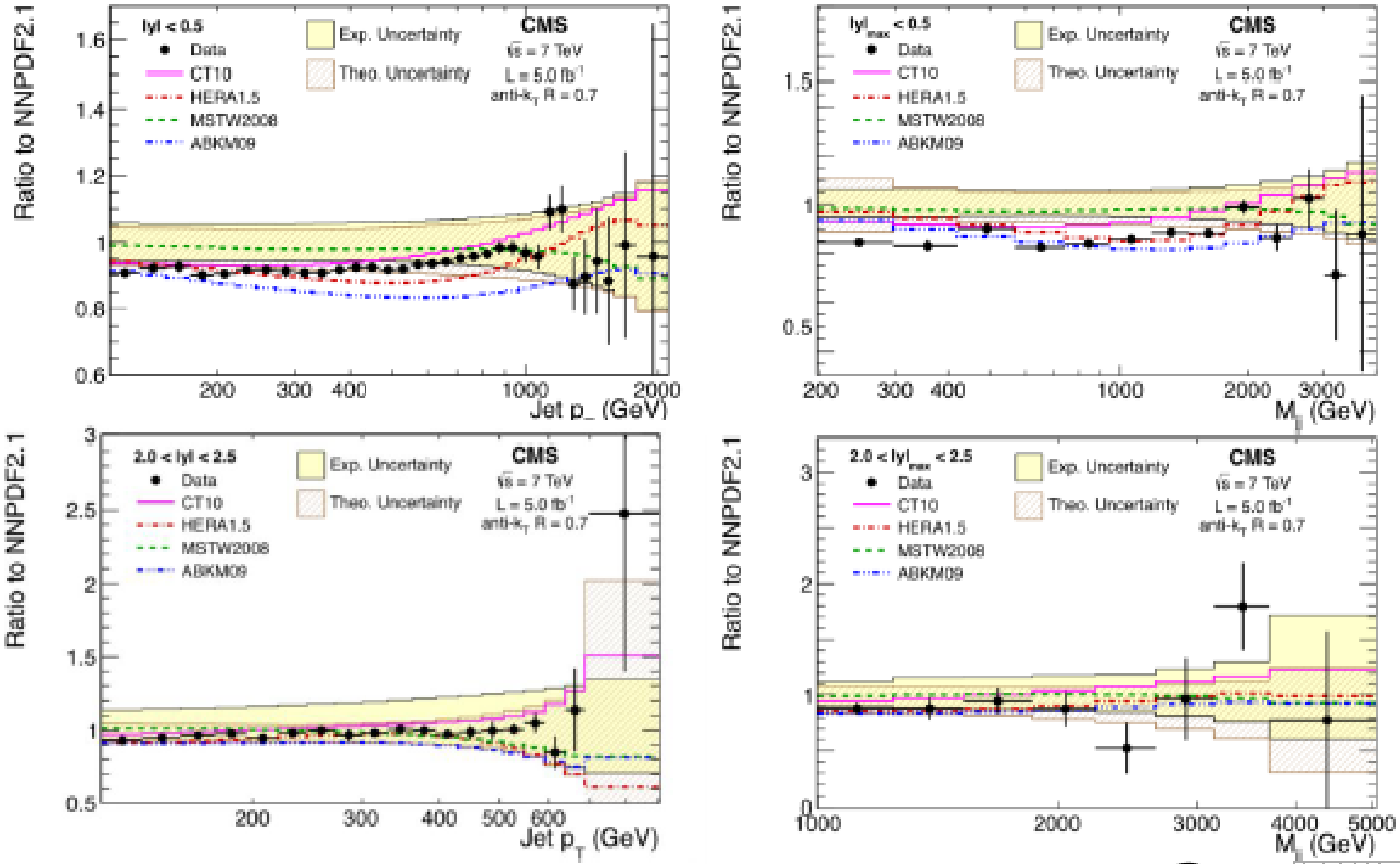


EPJ C77 (2017), 663

EG. CTEQ; arXiv/0303013

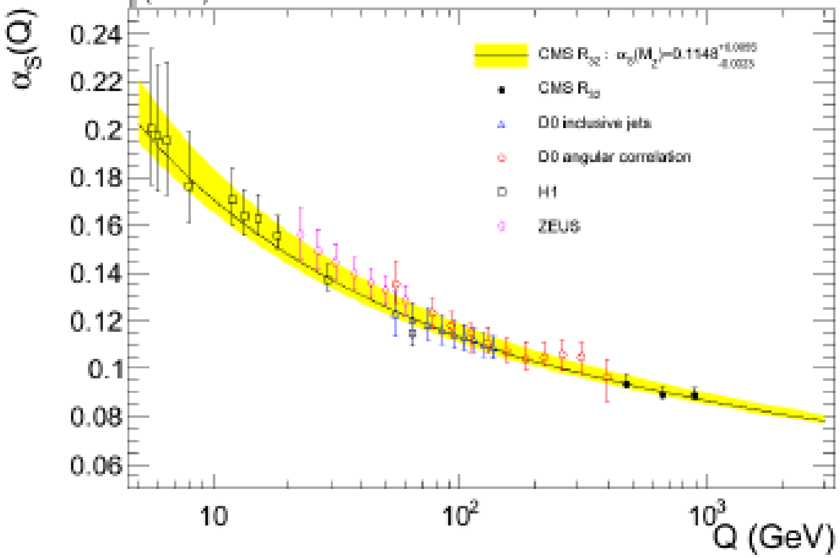


There are CMS inclusive jet and di-jet data from 5fb^{-1} of 2011 data

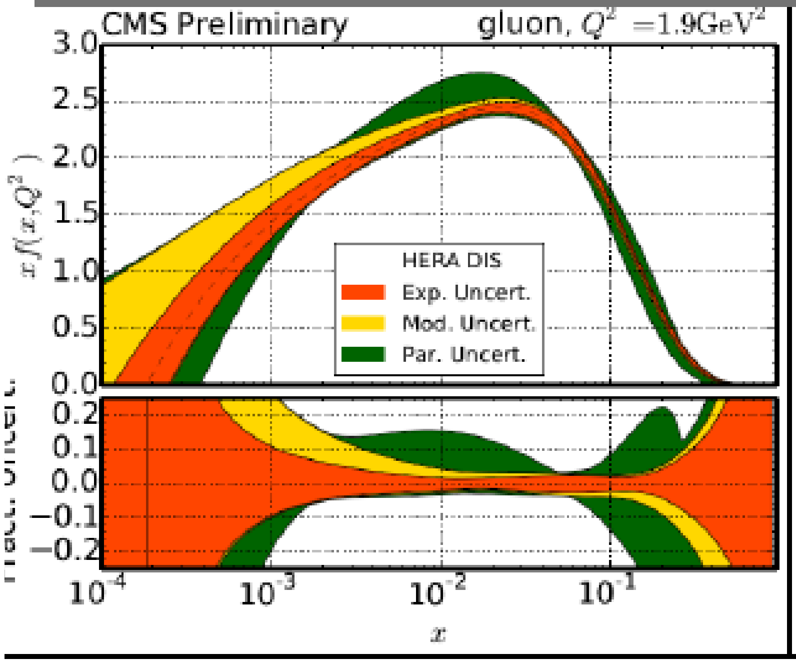


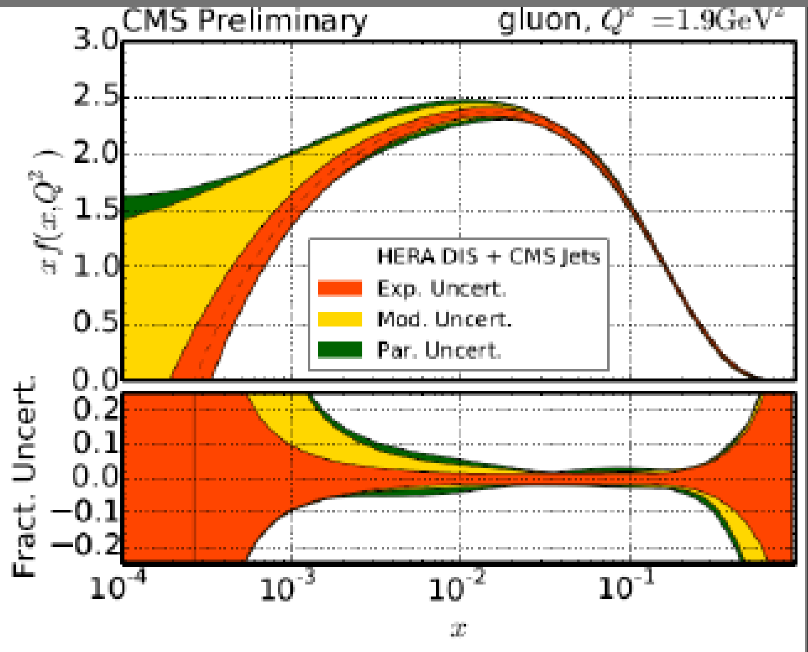
The strong coupling constant from the inclusive data (using fixed PDFs) is

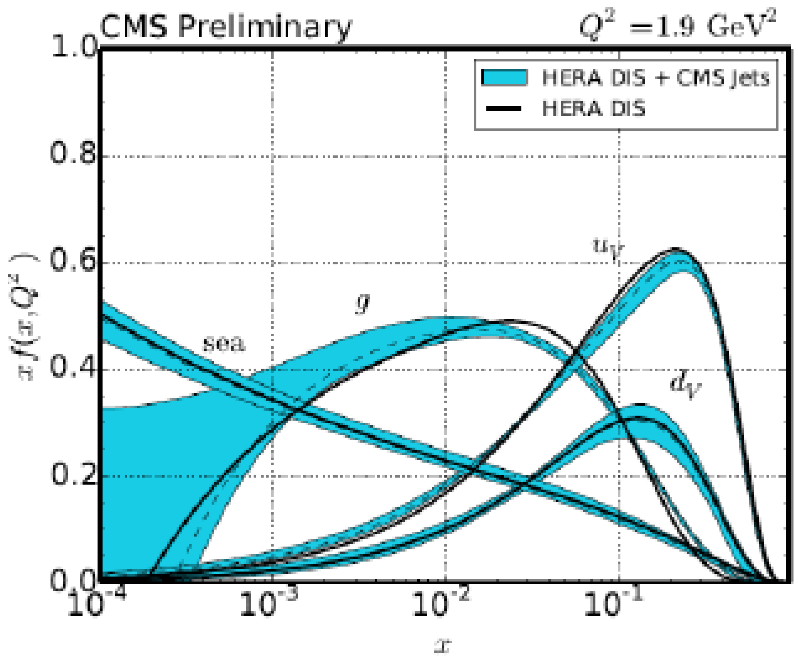
$$\alpha_S(M_Z) = 0.1185 \pm 0.0019(\text{exp}) \pm 0.0028(\text{PDF})\,{}^{+0.0055}_{-0.0022}(\text{scale})$$



A PDF fit of these CMS inclusive jet data together with the combined HERA-I inclusive deep inelastic scattering (DIS) data **(JHEP 1001 -109)** shows the potential of the CMS data to constrain PDFs, in particular the gluon

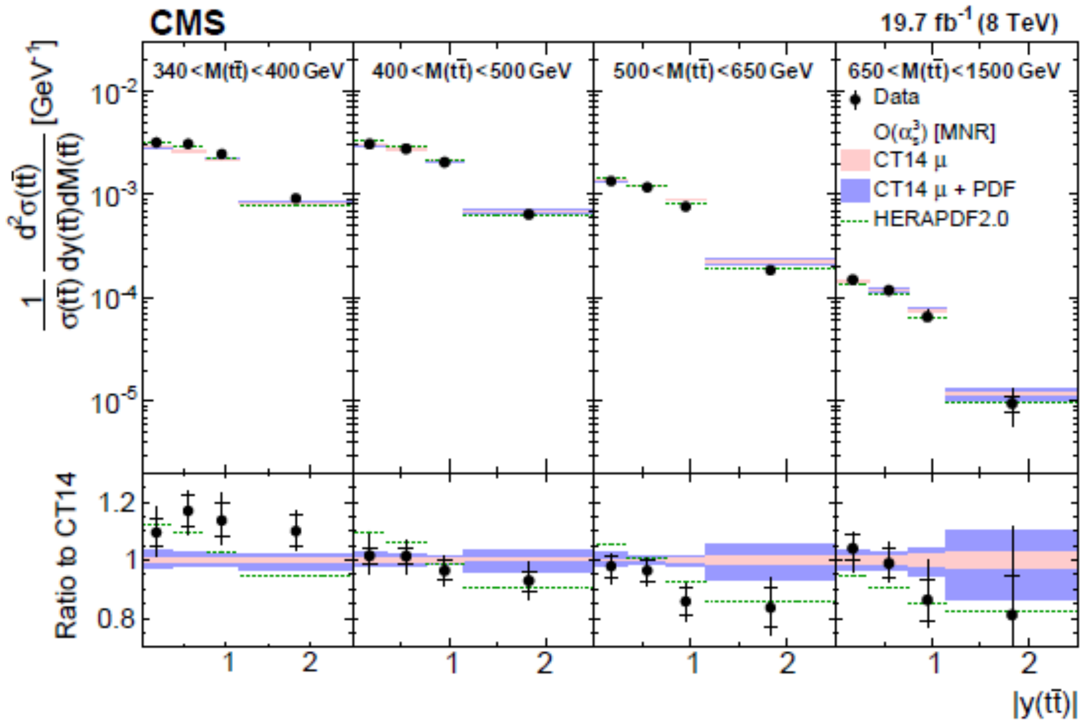


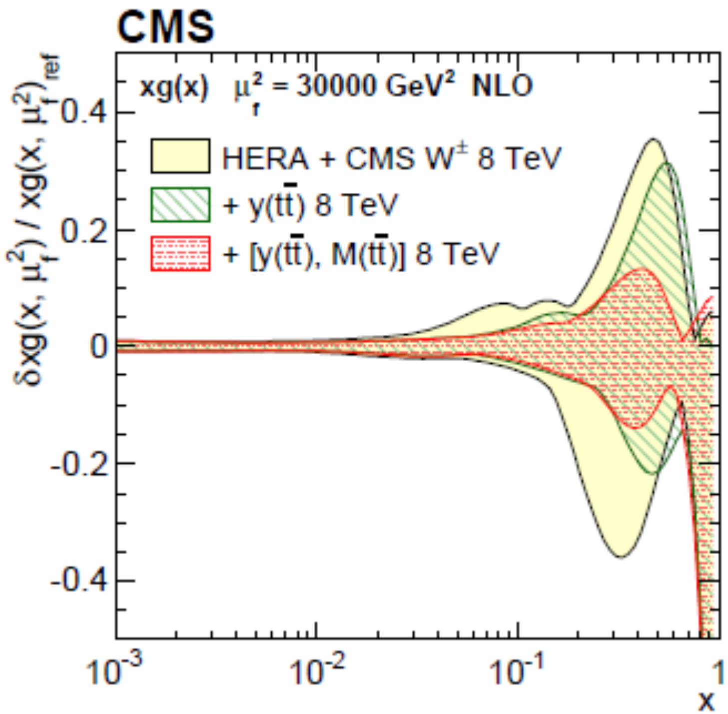




Note reduced uncertainty and change of shape of both gluon and u-valence
The strong coupling constant from a simultaneous fit of PDFs and $\alpha_S(M_Z)$ is
$\alpha_S(M_Z) = 0.1192 \pm 0.0016$(exp/NP)

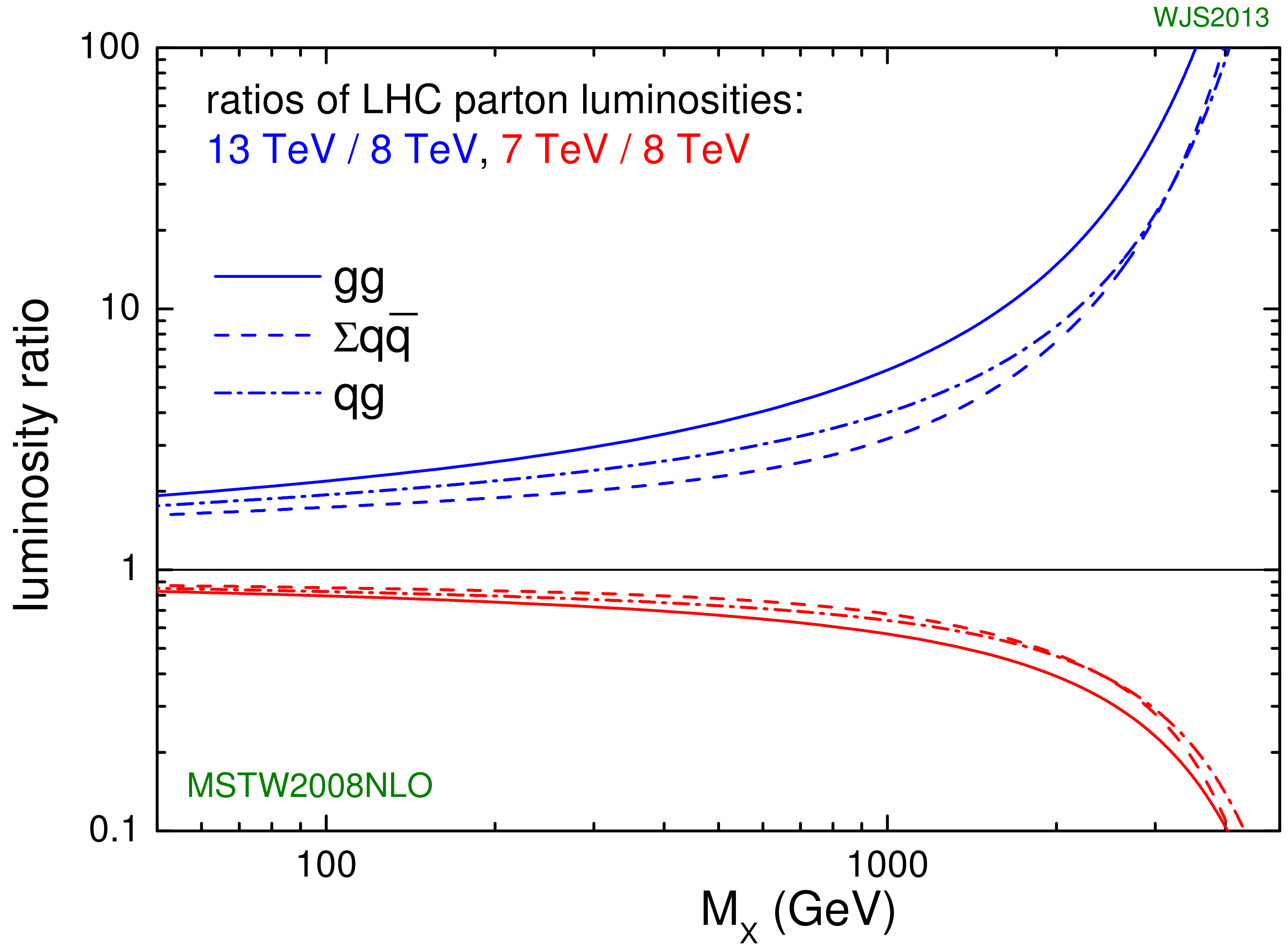
CMS have recently (arXiv:1703.01630) presented double differential top distributions in mass and rapidity of the t-tbar pair



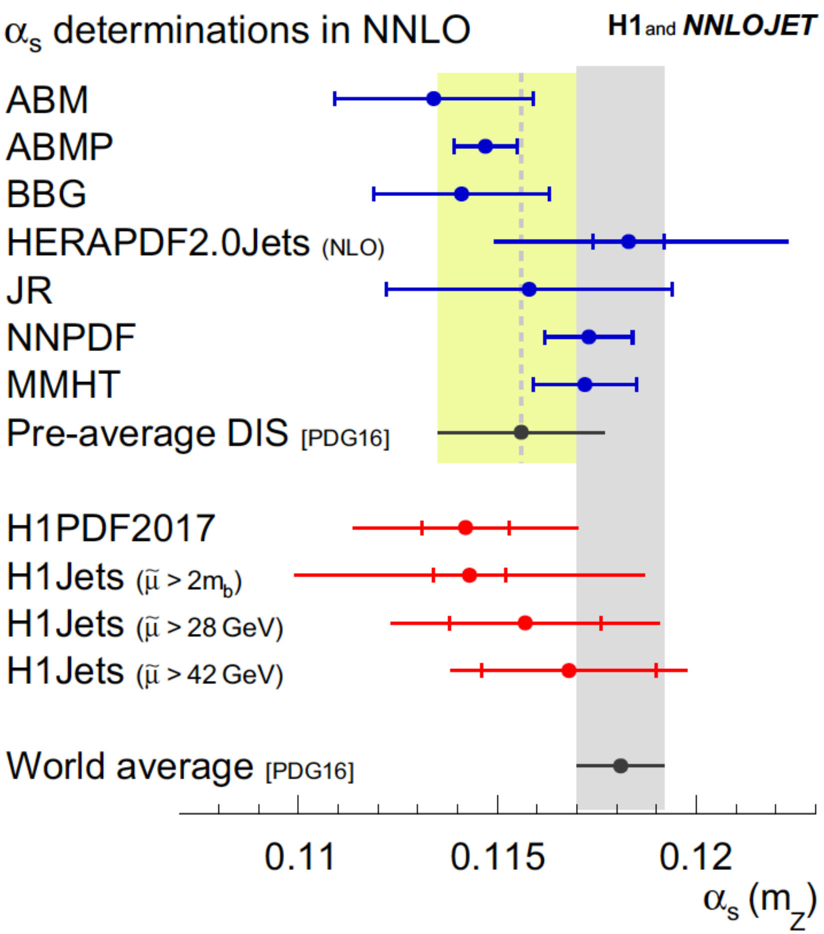


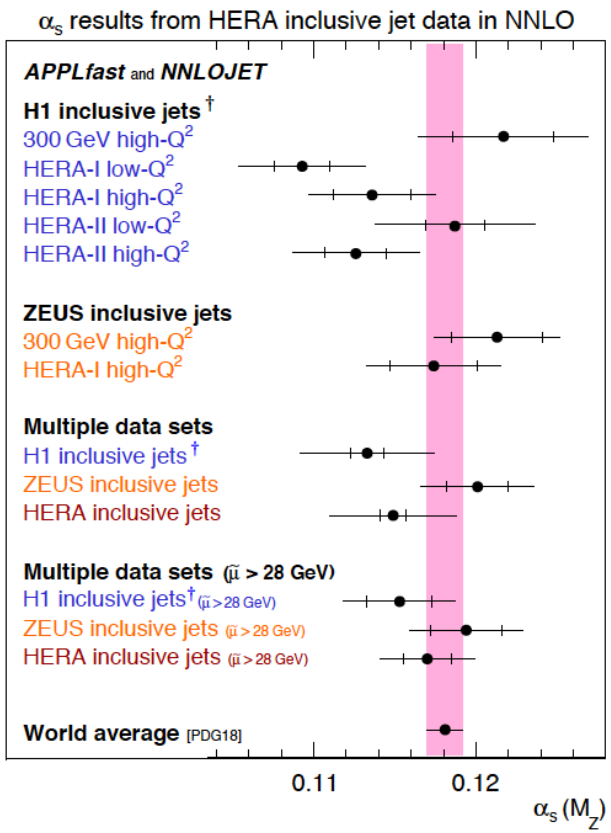
When input to a PDF fit these double differential is much more constraining than the single BUT analysis can only be done at NLO presently since there are no predictions at NNLO for the double differential distributions

PDF Luminosities



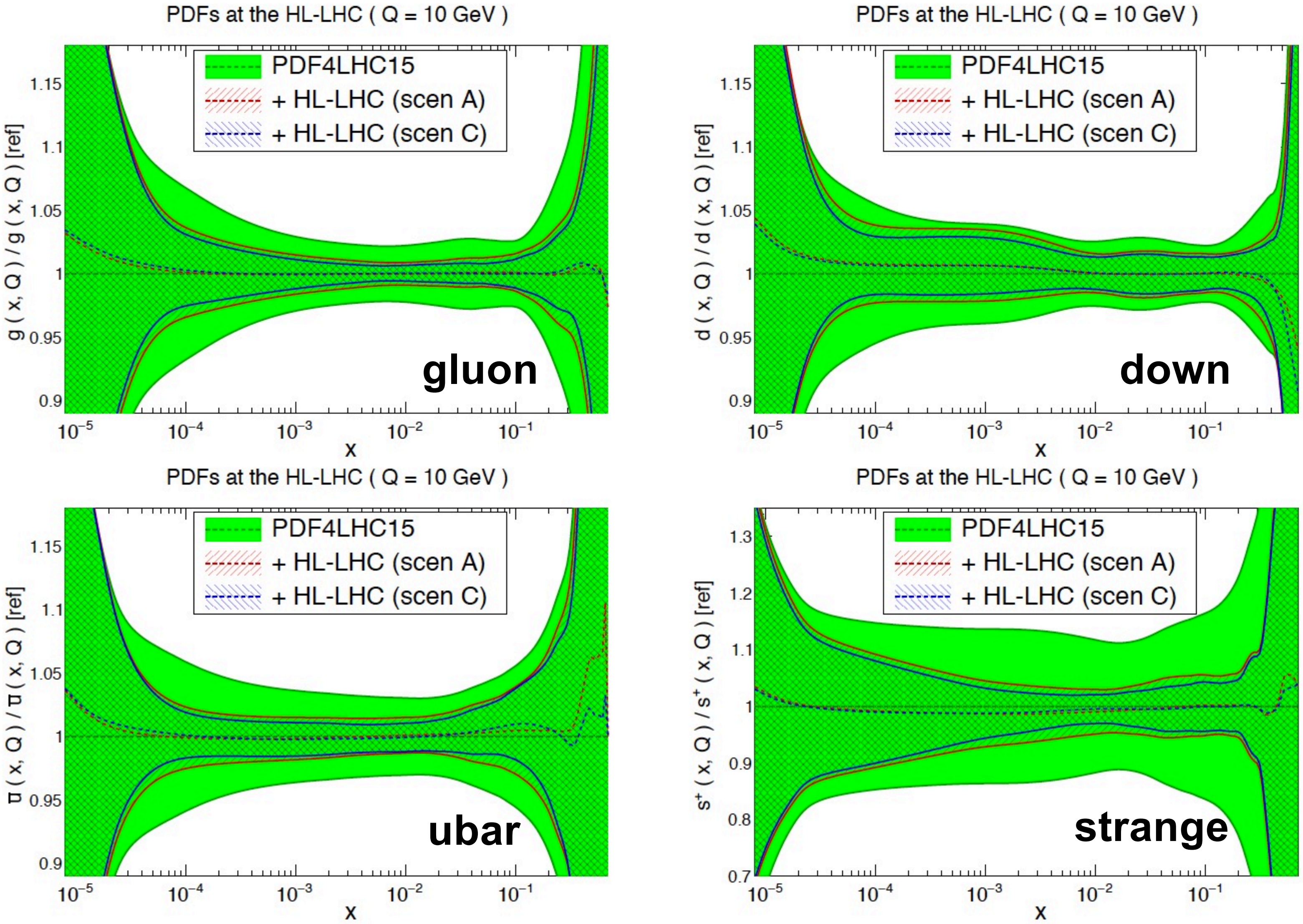
other αs determinations from QCD fits





HL-LHC PDFs

arXiv:1810.03639



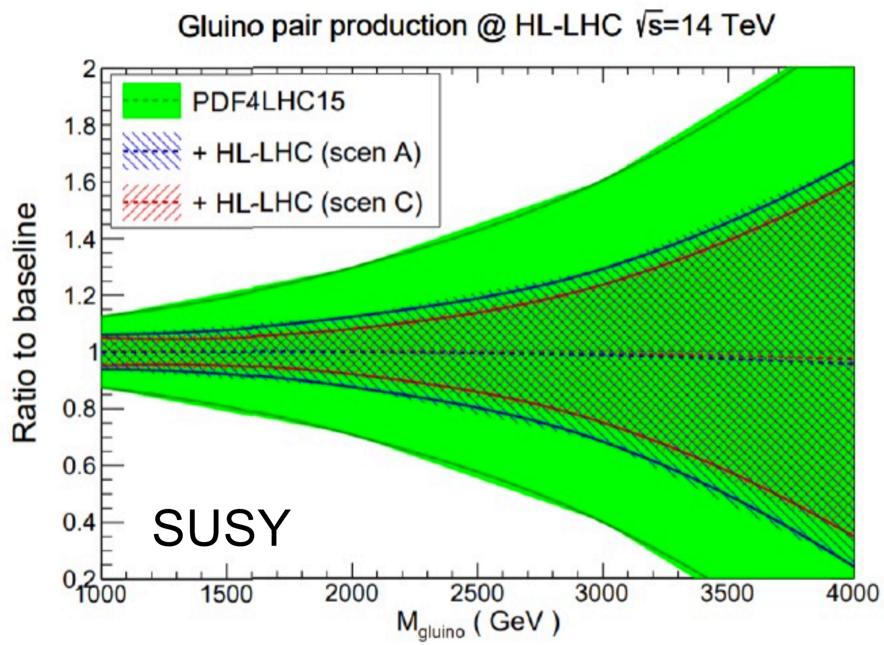
$$f_{red} = \begin{cases} 1/0.5\ (8/13)\text{TeV} \\ 0.4/0.2\ (8/13)\text{TeV} \end{cases}$$

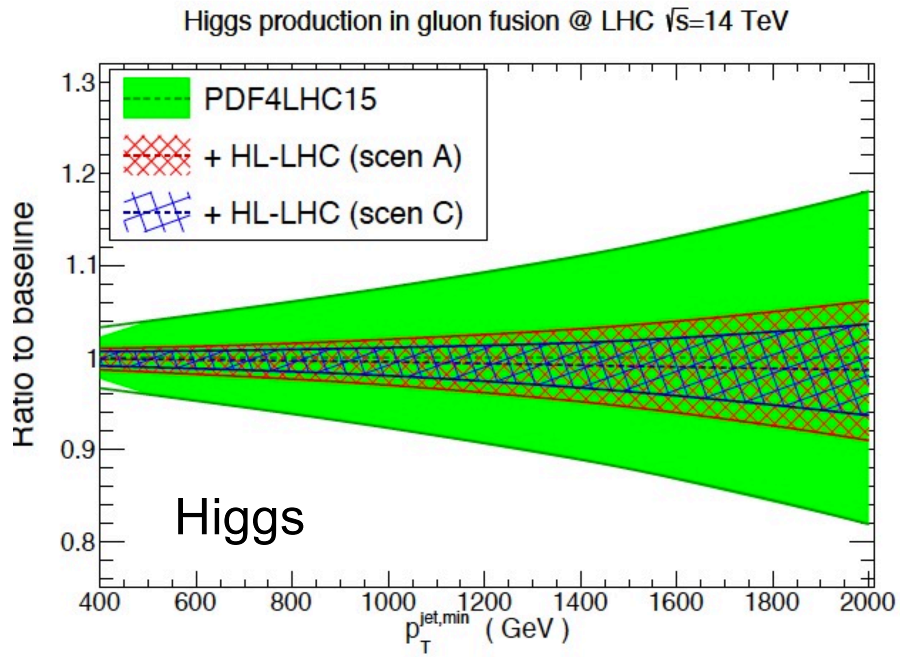
scenario A: **conservative**

scenario C: **optimistic**

(together with **intermediate** scenario B, all are available in lhapdf format)

impact on LHC phenomenology

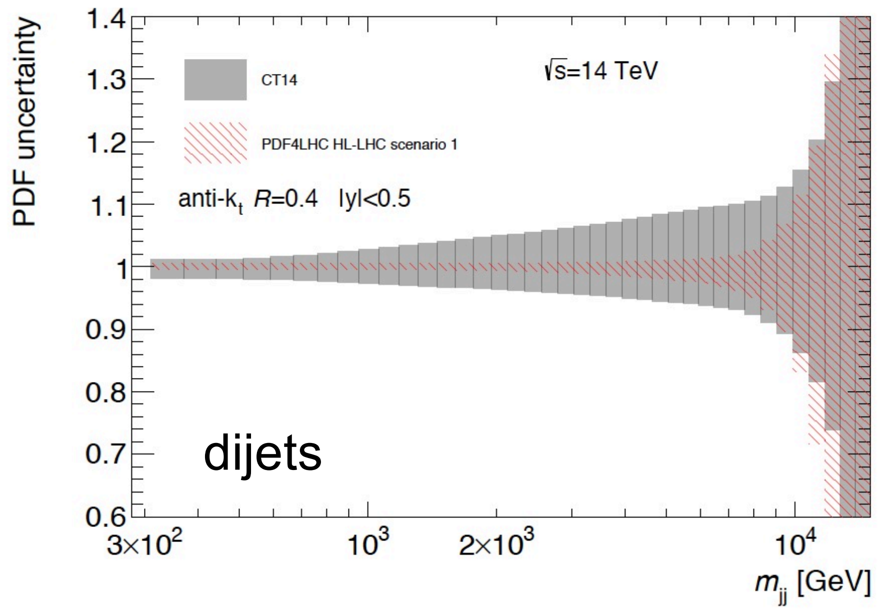




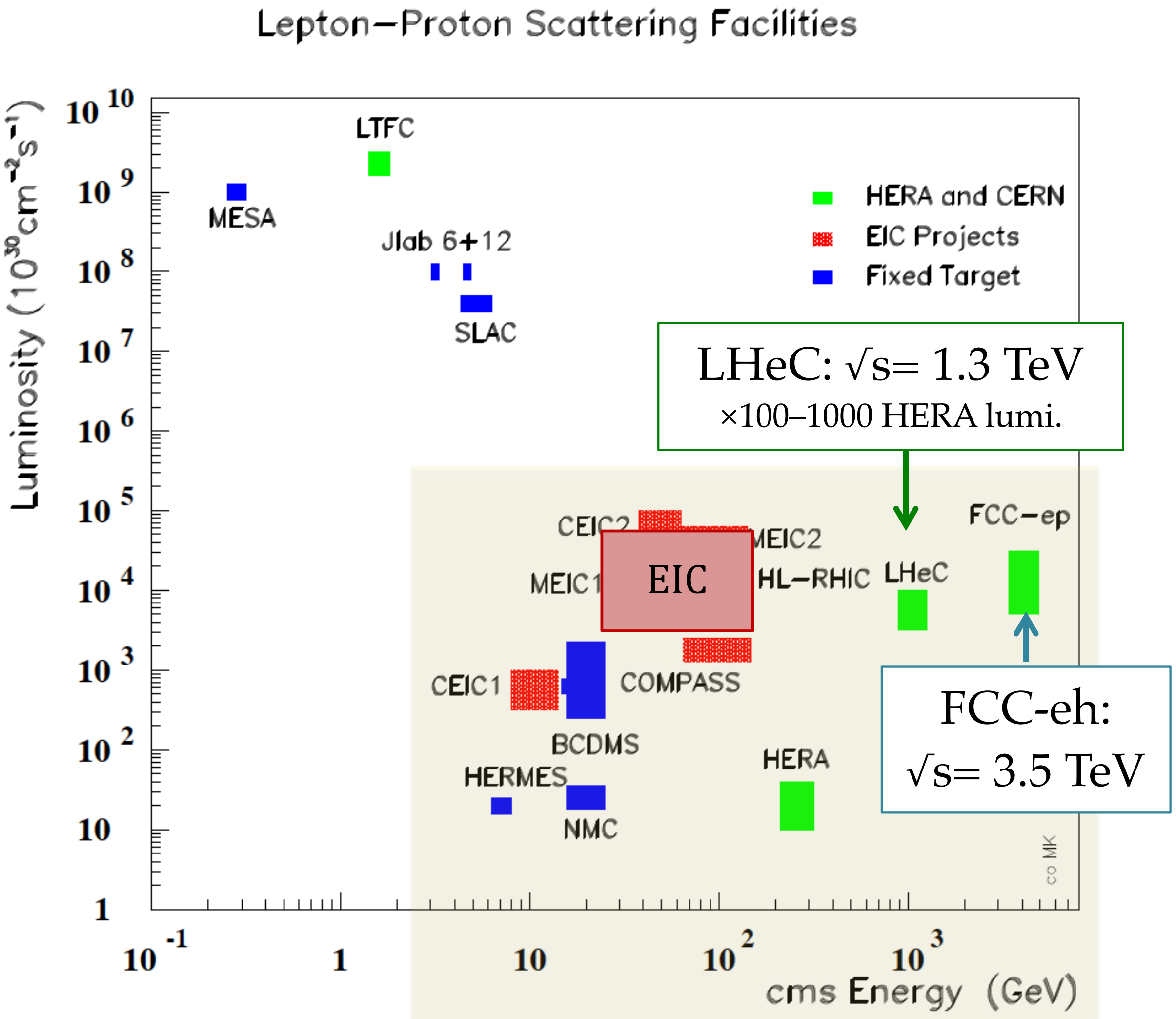
arXiv:[1810.03639](https://arxiv.org/abs/1810.03639)

and CERN yellow report,

arXiv:[1902.04070](https://arxiv.org/abs/1902.04070)



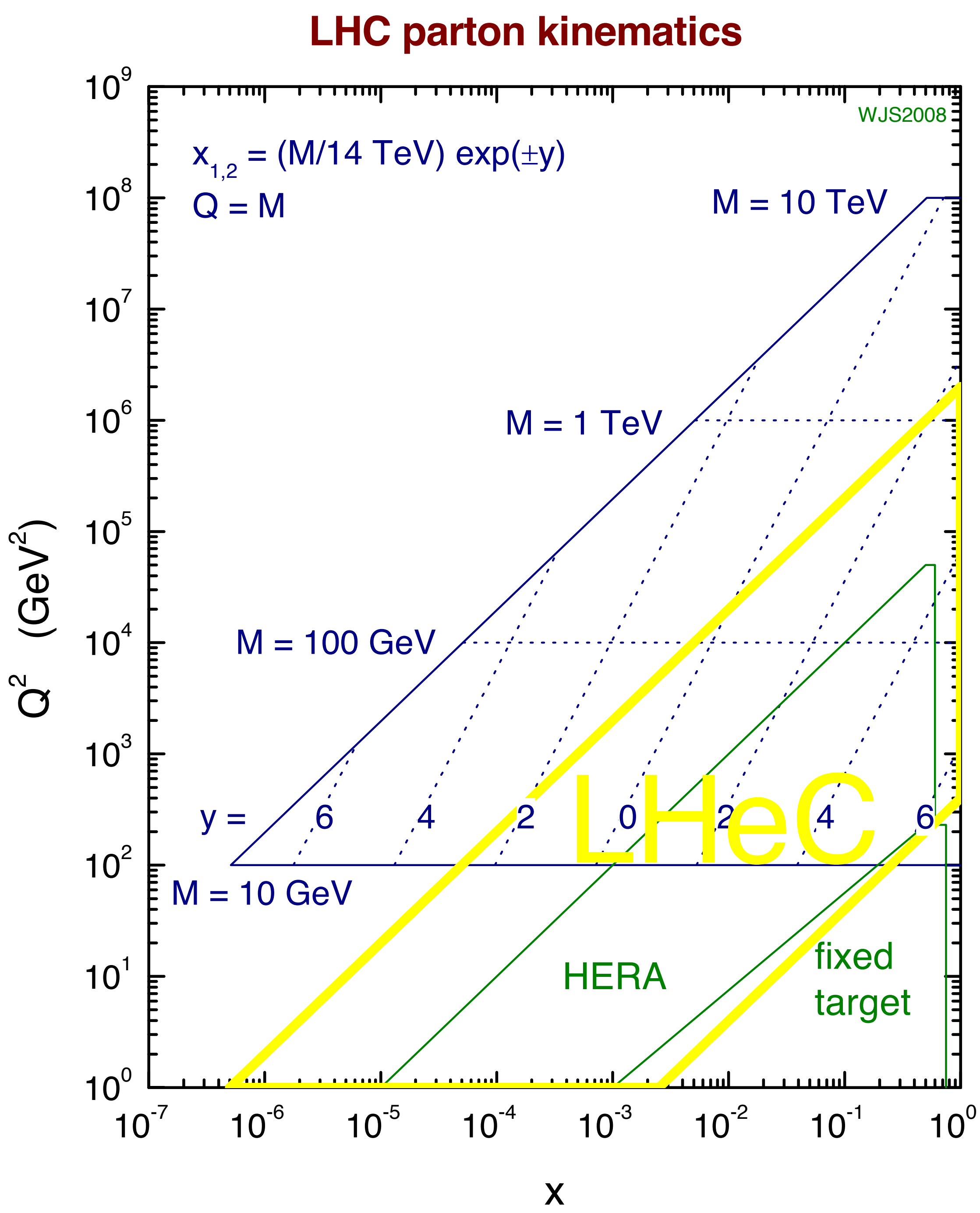
ep colliders



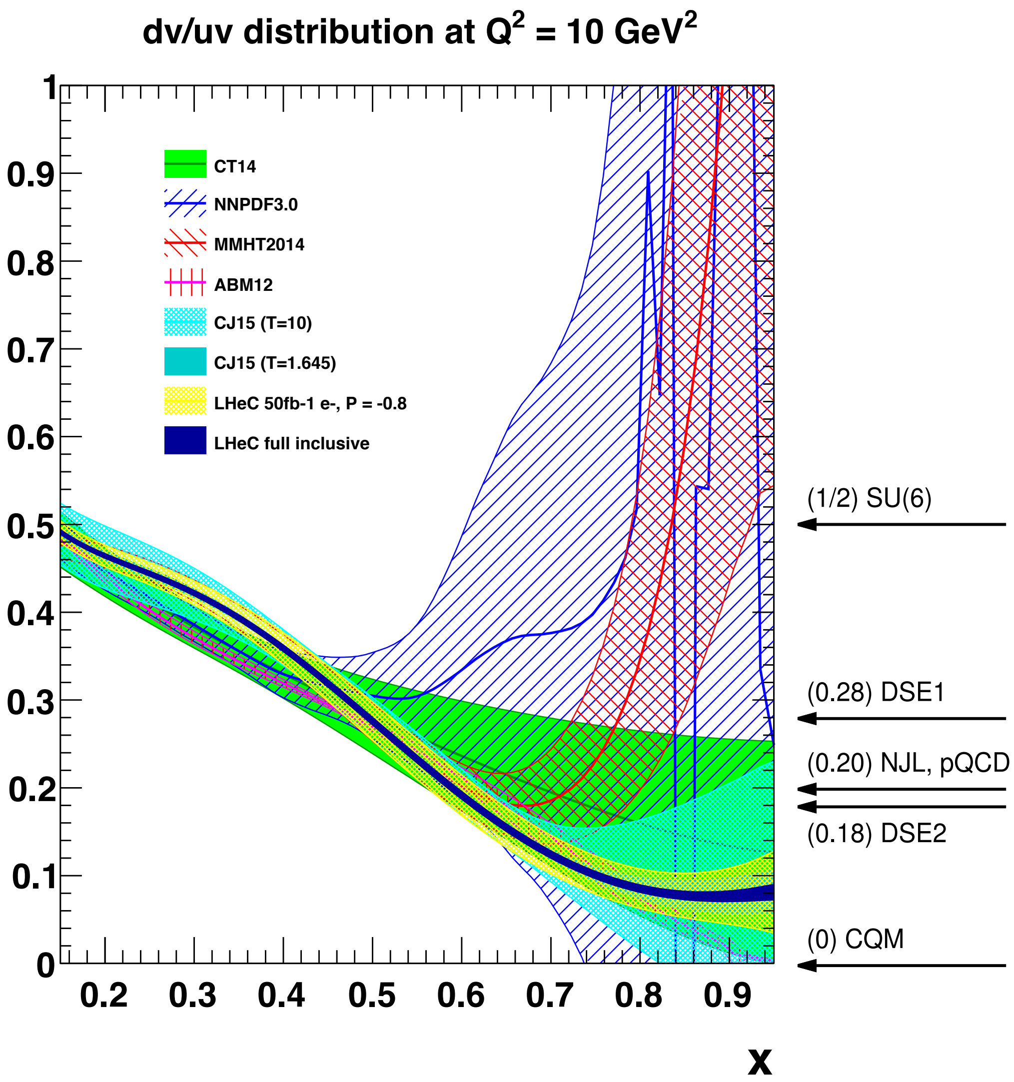
HERA: world's first and still only ep collider (√s ≃ 300 GeV)

LHeC: future ep (eA) collider, proposed to run concurrently with HL/HE-LHC; CDR arXiv:1206.2913 (complementary to LHC; extra discovery channels; Higgs; precision pdfs and **α**s)

FCC-eh: further future ep (eA) collider, integrated with FCC (further kinematic extension wrt **LHeC**)


LHC parton kinematics
WJS2008
x1,2 = (M/14 TeV) exp(±y)
Q = M
M = 10 TeV
M = 1 TeV
M = 100 GeV
M = 10 GeV
y =
6
4
2
0
2
4
6
LHeC
HERA
fixed
target
Q2 (GeV2)
x
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
10^0

d/u ratio at large x



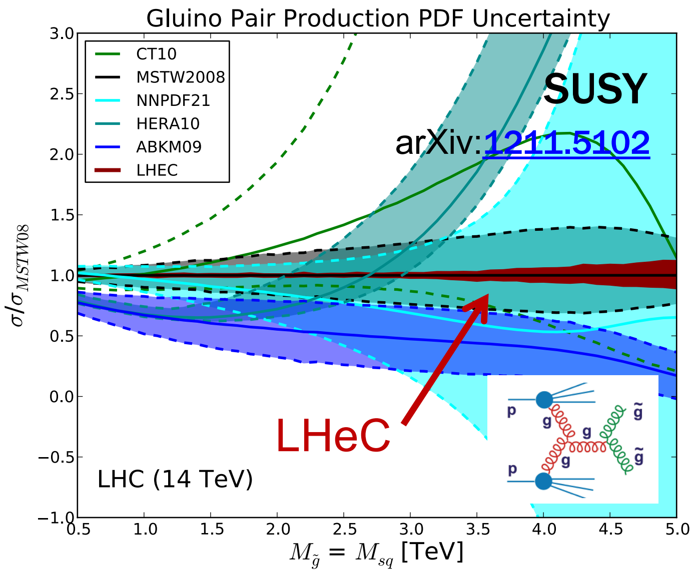
RECALL, d/u essentially unknown at large x (see Lecture 4)

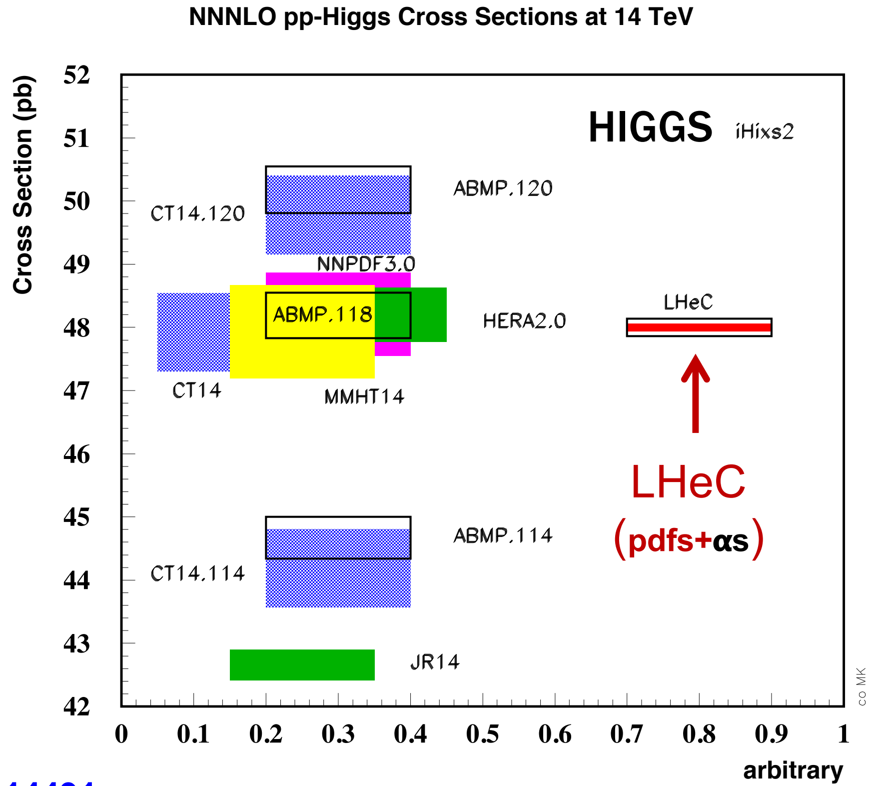
no predictive power from current pdfs;
conflicting theory pictures;
data inconclusive, large nuclear uncertainties

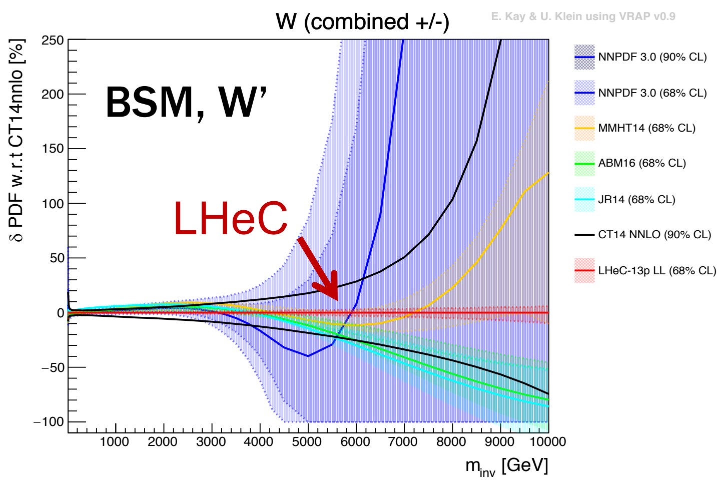
resolve long-standing mystery of **d/u ratio** at **large x**

LHeC empowering the LHC: Higgs and BSM

external, reliable, precise **pdfs** needed for **range extension** and **interpretation**





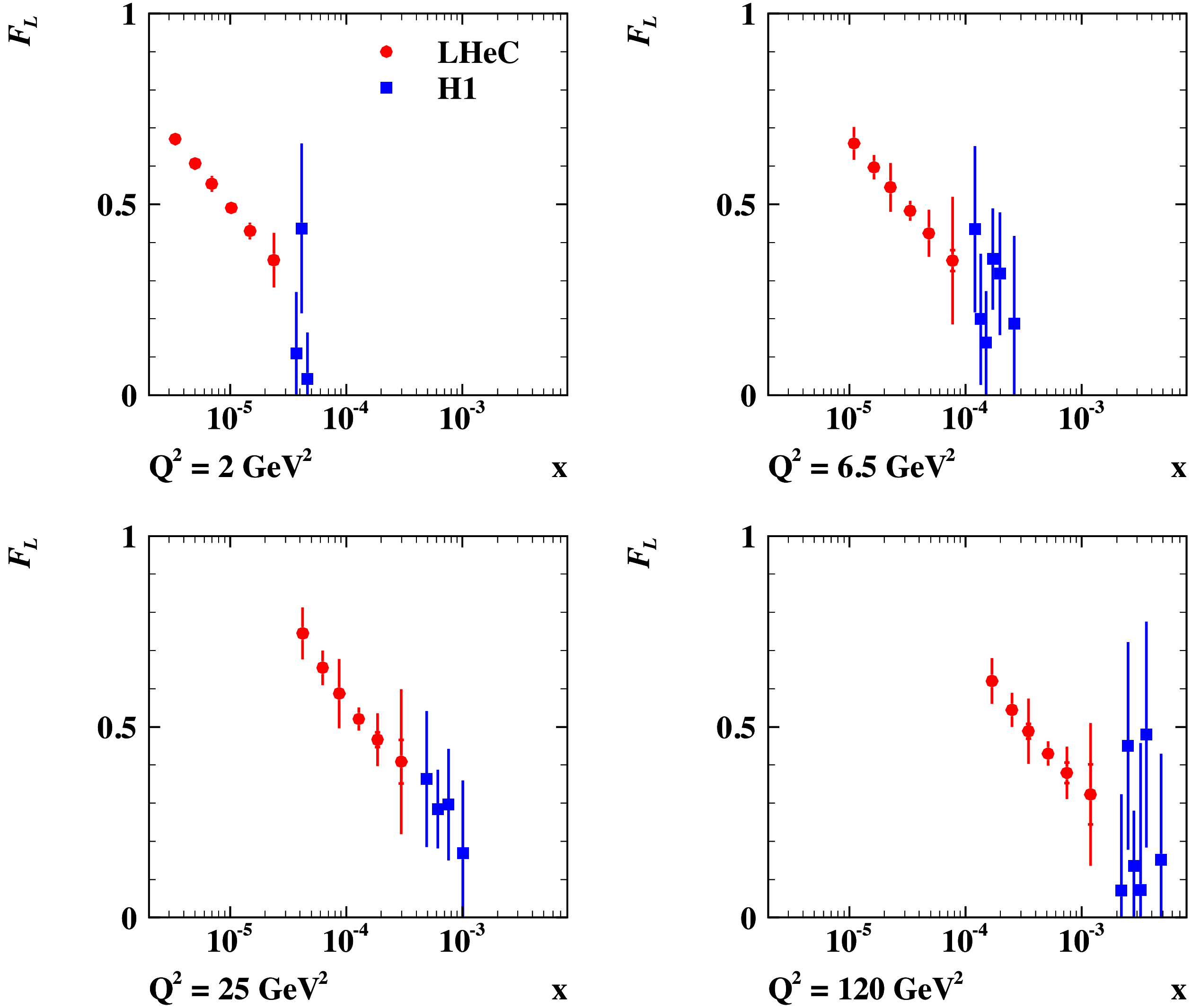


arXiv:2007.14491

CONTACT INTERACTIONS: $\mathcal{L}_{\rm CI} = \frac{g^2}{\Lambda^2}\eta_{ij}(\bar{q}_i\gamma_\mu q_i)(\bar{\ell}_i\gamma^\mu \ell_i)$

Model	ATLAS (Ref. [702])	HL-LHC	
	$\mathcal{L} = 36\,\mathrm{fb}^{-1}$ (CT14nnlo)	$\mathcal{L} = 3\,\mathrm{ab}^{-1}$ (CT14nnlo)	$\mathcal{L} = 3\,\mathrm{ab}^{-1}$ (LHeC)
LL (constr.)	28 TeV	58 TeV	96 TeV
LL (destr.)	21 TeV	49 TeV	77 TeV
RR (constr.)	26 TeV	58 TeV	84 TeV
RR (destr.)	22 TeV	61 TeV	75 TeV
LR (constr.)	26 TeV	49 TeV	81 TeV
LR (destr.)	22 TeV	45 TeV	62 TeV

F_L at LHeC



M. Klein, arXiv:1802.04317