PDFs in the high precision LHC Era

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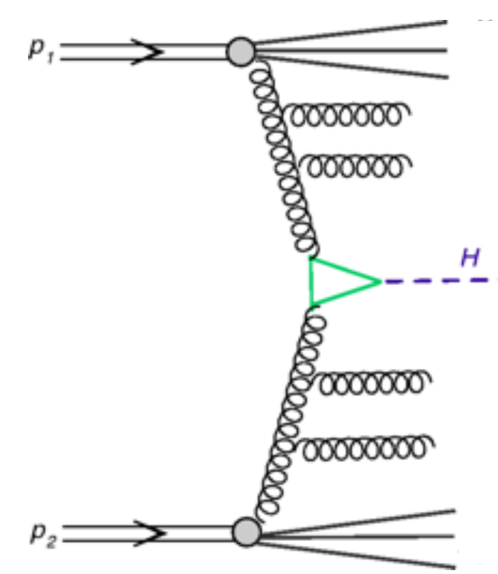
ATLAS SM Workshop, London, 5th September

Global PDF Fits

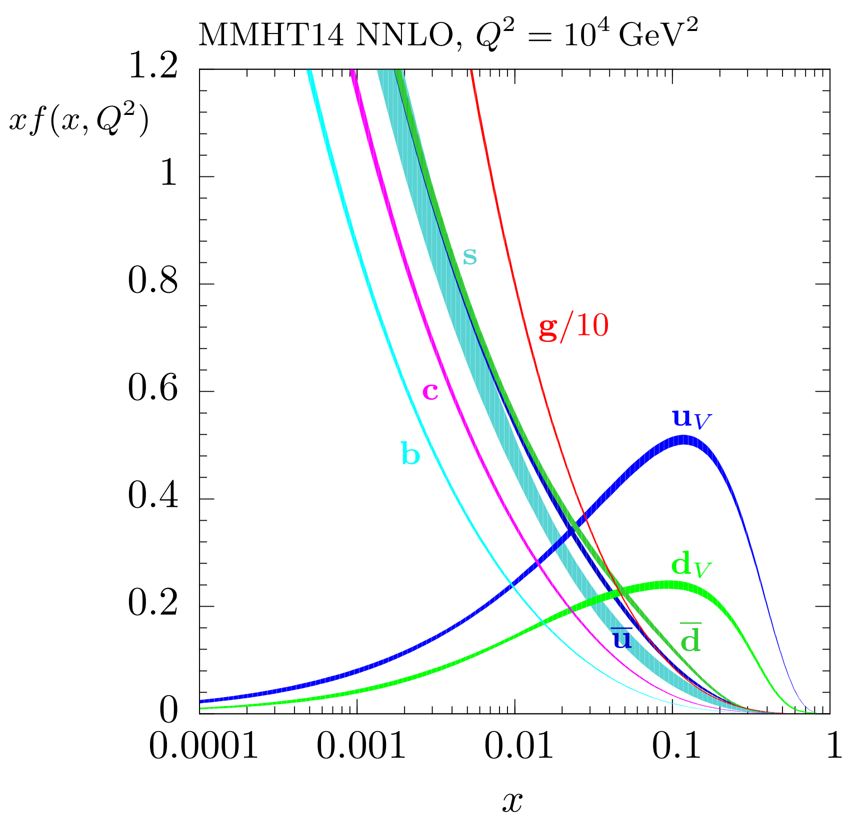
- LHC cross section given in terms of: $\sigma(pp \to h + X) \sim \sigma(gg \to h) \otimes g(x_1, Q^2) \otimes g(x_2, Q^2)$,

  $\sigma(gg \to h)$: parton-level cross section, apply pQCD.

  $g(x, Q^2)$: PDF for gluon with momentum fraction x and at scale Q .



- PDFs: cannot currently calculate $\Rightarrow$ extract from **global fit** to wide range of data (DIS, fixed nuclear targets with beams, hadron collider data - jets, W, Z, $t\bar{t}$ ...).



$\chi^2/\text{dof} \sim 1$

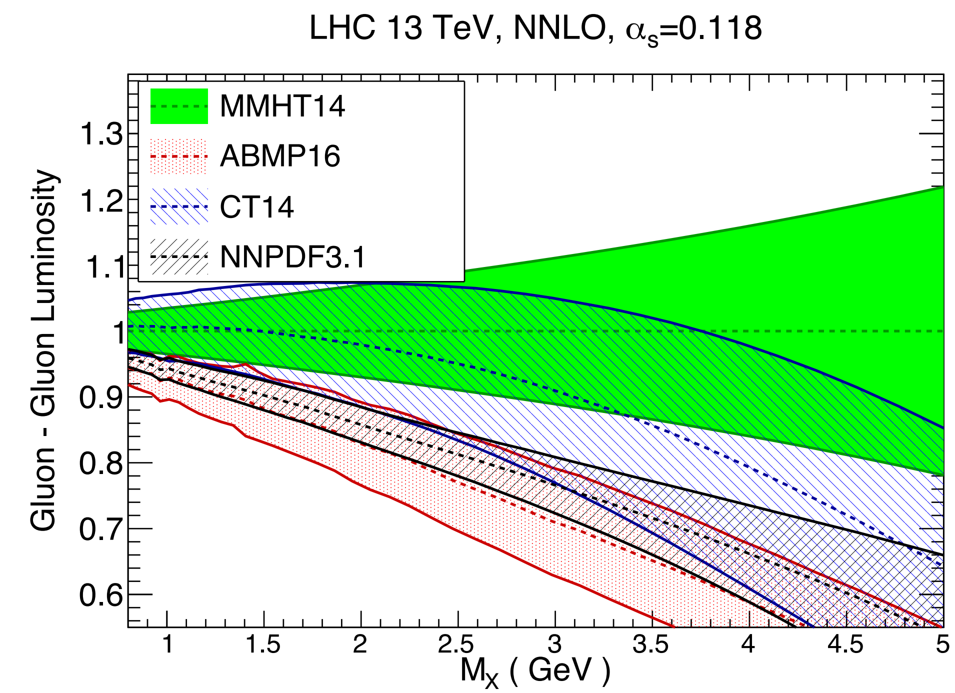
$\Rightarrow$ **Non-trivial check of QCD.**

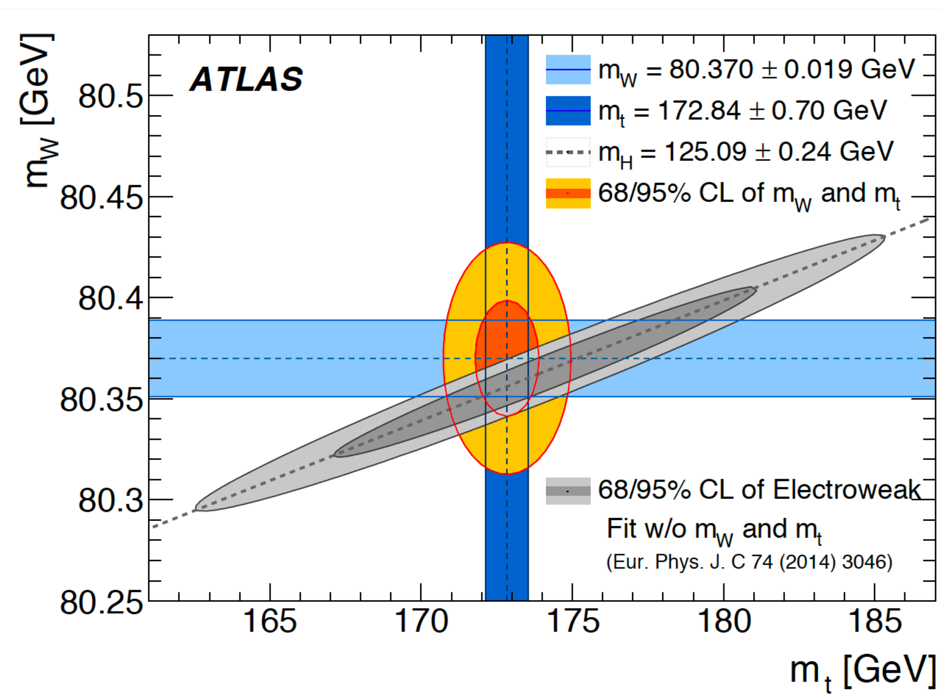
Data set	LO	NLO	NNLO
BCDMS μp F_2 [125]	162 / 153	176 / 163	173 / 163
BCDMS μd F_2 [19]	140 / 142	143 / 151	143 / 151
NMC μp F_2 [20]	141 / 115	132 / 123	123 / 123
NMC μd F_2 [20]	134 / 115	115 / 123	108 / 123
NMC $\mu n/\mu p$ [21]	122 / 137	131 / 148	127 / 148
E665 μp F_2 [22]	59 / 53	60 / 53	65 / 53
E665 μd F_2 [22]	52 / 53	52 / 53	60 / 53
SLAC ep F_2 [23, 24]	21 / 18	31 / 37	31 / 37
SLAC ed F_2 [23, 24]	13 / 18	30 / 38	26 / 38
NMC/BCDMS/SLAC/HERA F_L [20, 125, 24, 63, 64, 65]	113 / 53	68 / 57	63 / 57
E866/NuSea pp DY [88]	229 / 184	221 / 184	227 / 184
E866/NuSea pd/pp DY [89]	29 / 15	11 / 15	11 / 15
NuTeV νN F_2 [29]	35 / 49	39 / 53	38 / 53
CHORUS νN F_2 [30]	25 / 37	26 / 42	28 / 42
NuTeV νN xF_3 [29]	49 / 42	37 / 42	31 / 42
CHORUS νN xF_3 [30]	35 / 28	22 / 28	19 / 28
CCFR $\nu N \to \mu\mu X$ [31]	65 / 86	71 / 86	76 / 86
NuTeV $\nu N \to \mu\mu X$ [31]	53 / 40	38 / 40	43 / 40
HERA e^+p NC 820 GeV[61]	125 / 78	93 / 78	89 / 78
HERA e^+p NC 920 GeV[61]	479 /330	402 /330	373/ 330
HERA e^-p NC 920 GeV [61]	158/ 145	129/ 145	125 /145
HERA e^+p CC [61]	41 / 34	34 / 34	32 / 34
HERA e^-p CC [61]	29 / 34	23 / 34	21 / 34
HERA ep F_2^{charm} [62]	105 /52	72 / 52	82 / 52
H1 99–00 e^+p incl. jets [126]	77 / 24	14 / 24	—
ZEUS incl. jets [127, 128]	140/60	45 / 60	—
DØ II $p\bar{p}$ incl. jets [119]	125 / 110	116 / 110	119 / 110
CDF II $p\bar{p}$ incl. jets [118]	78 / 76	63 / 76	59 / 76
CDF II W asym. [66]	55 / 13	32 / 13	30 / 13
DØ II $W \to \nu e$ asym. [67]	47 / 12	28 / 12	27 / 12
DØ II $W \to \nu\mu$ asym. [68]	16 / 10	19 / 10	21 / 10
DØ II Z rap. [90]	34 / 28	16 / 28	16 / 28
CDF II Z rap. [70]	95 / 28	36 / 28	40 / 28
ATLAS W^+, W^-, Z [10]	94/30	38/30	39/30
CMS W asymm $p_T > 35$ GeV [9]	10/11	7/11	9/11
CMS asymm $p_T > 25$ GeV, 30 GeV[77]	7/24	8/24	10/24
LHCb $Z \to e^+e^-$[79]	76/9	13/9	20/9
LHCb W asymm $p_T > 20$ GeV[78]	27/10	12/10	16/10
CMS $Z \to e^+e^-$ [84]	46/35	19/35	22/35
ATLAS high-mass Drell-Yan [83]	42/13	21/13	17/13
CMS double diff. Drell-Yan [86]	—	372/132	149/132
Tevatron, ATLAS, CMS $\sigma_{t\bar{t}}$ [91]–[97]	53/13	7/13	8/13
ATLAS jets (2.76 TeV+7 TeV)[108, 107]	162/116	106/116	—
CMS jets (7 TeV) [106]	150/133	138/133	—
All data sets	**3706 / 2763**	**3267 / 2996**	**2717 / 2663**

Precise PDFs for the LHC

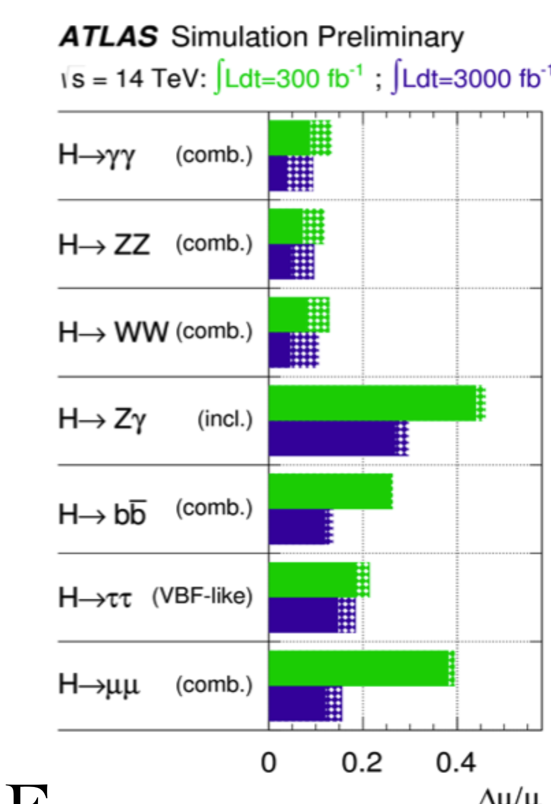
- Ultimate reach of LHC limited by knowledge of PDFs.

- **High mass searches** - PDFs in high region (currently constraints poor)





- **Higgs couplings** $\rightarrow$ need to model SM production precisely.



Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5

- **Precision SM** measurements - PDFs dominant uncertainty for e.g. W mass.

- Our understanding of **QCD** at LHC intricately linked to PDFs

PDFs: Recent Progress/Ideas

New Theory/ Methodology ⟷ **New Data in Fits**

★ High precision theory - NNLO now 'standard'.

★ Resummation (high/low x)

★ Photon PDF.

★ Intrinsic charm

★ Lattice (?).

★ Scale variations in fits.

★ Fast tools - APPLFAST.

★ Jets.

★ W, Z and proton strangeness.

★ W, Z $p_\perp$.

★ Isolated Photon

★ Differential $t\bar{t}$

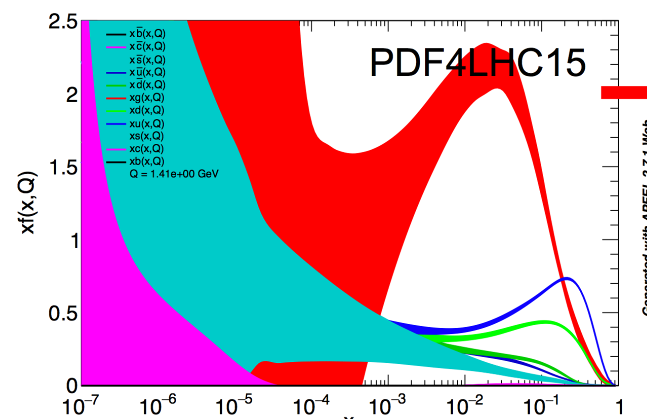
} Impact of LHC data crucial

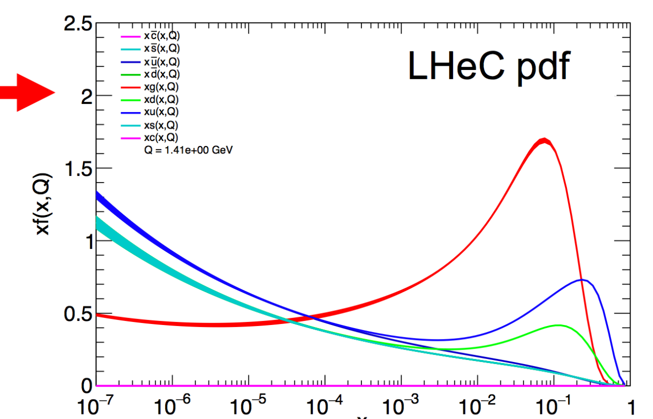
- Even within this non-exhaustive list I will not have time to cover everything - will discuss a few representative topics.
- Before considering the LHC now, what about the future?

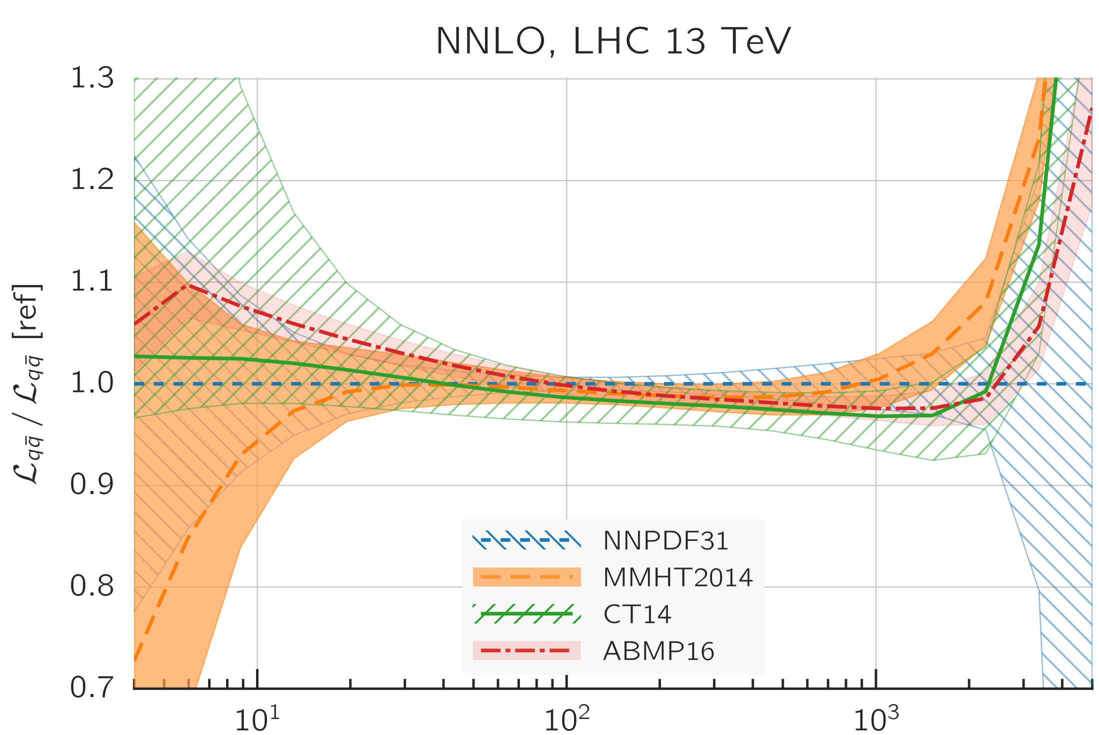
The Future - ‘Ultimate PDFs’

Ultimate PDFs - Motivation

- The HL-LHC will provide a vast range of data with a direct impact on the PDFs (in particular in poorly known high x region).
- **Question:** what exactly can we expect that impact to be?
- Collaborative effort to produce '**Ultimate**' PDF set for HL/HE-LHC Yellow report. LHAPDF files will be made available.
- Similar exercise has already been done for **LHeC**.

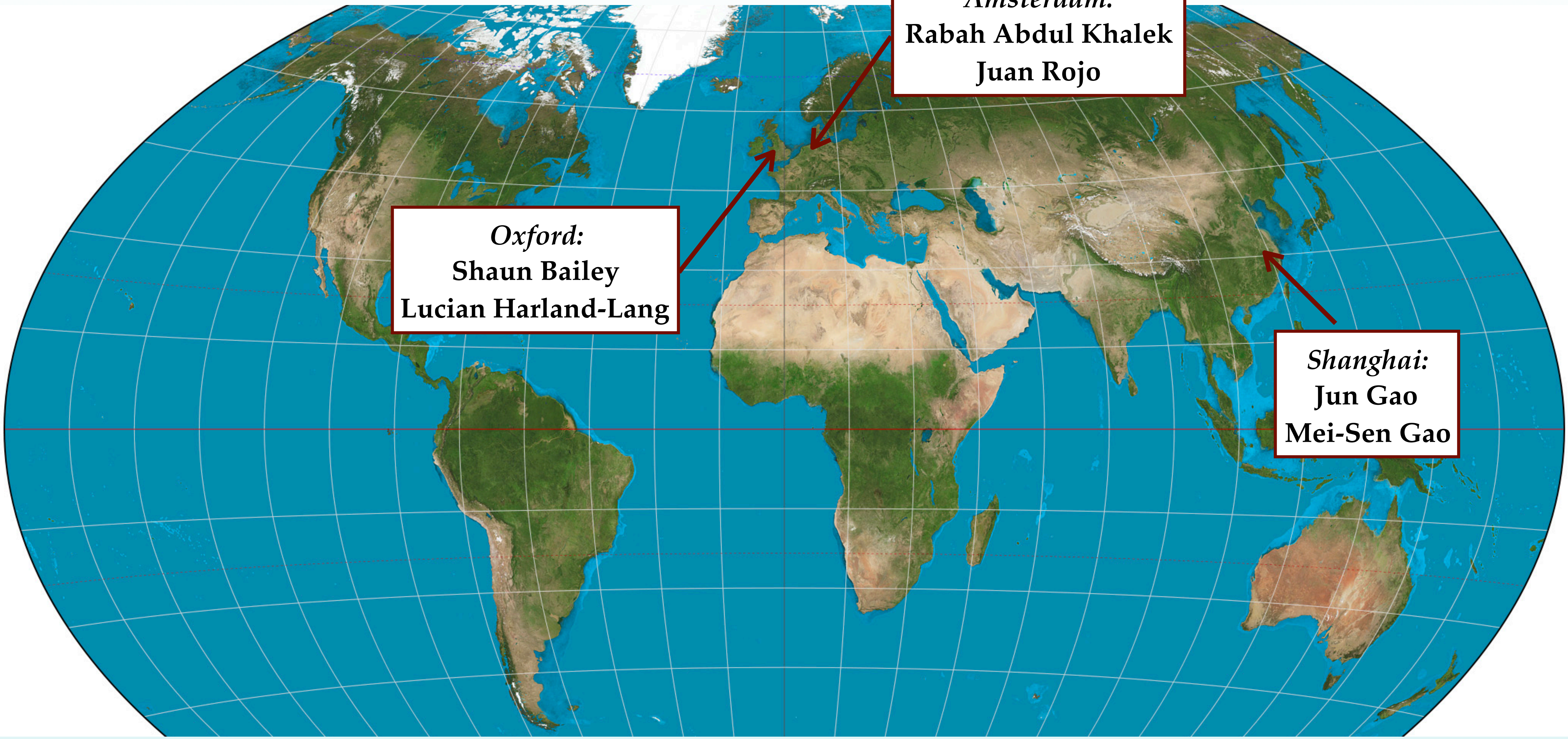






?

The team



Contactpersons within the LHC experiments:
Mario Campanelli, Claire Gwenlan (ATLAS)
Katerina Lipka (CMS)
William Barter, Stephen Farry (LHCb)

Basic Idea

Produce theory predictions for relevant processes, in kinematic region probed by HL-LHC

↓

Produce pseudodata - binned predictions, provided with corresponding statistical + systematic errors

↓

Perform initial profiling with PDF4LHC baseline to assess impact of HL-LHC pseudodata set

↓

Public release of 'Ultimate PDF' set

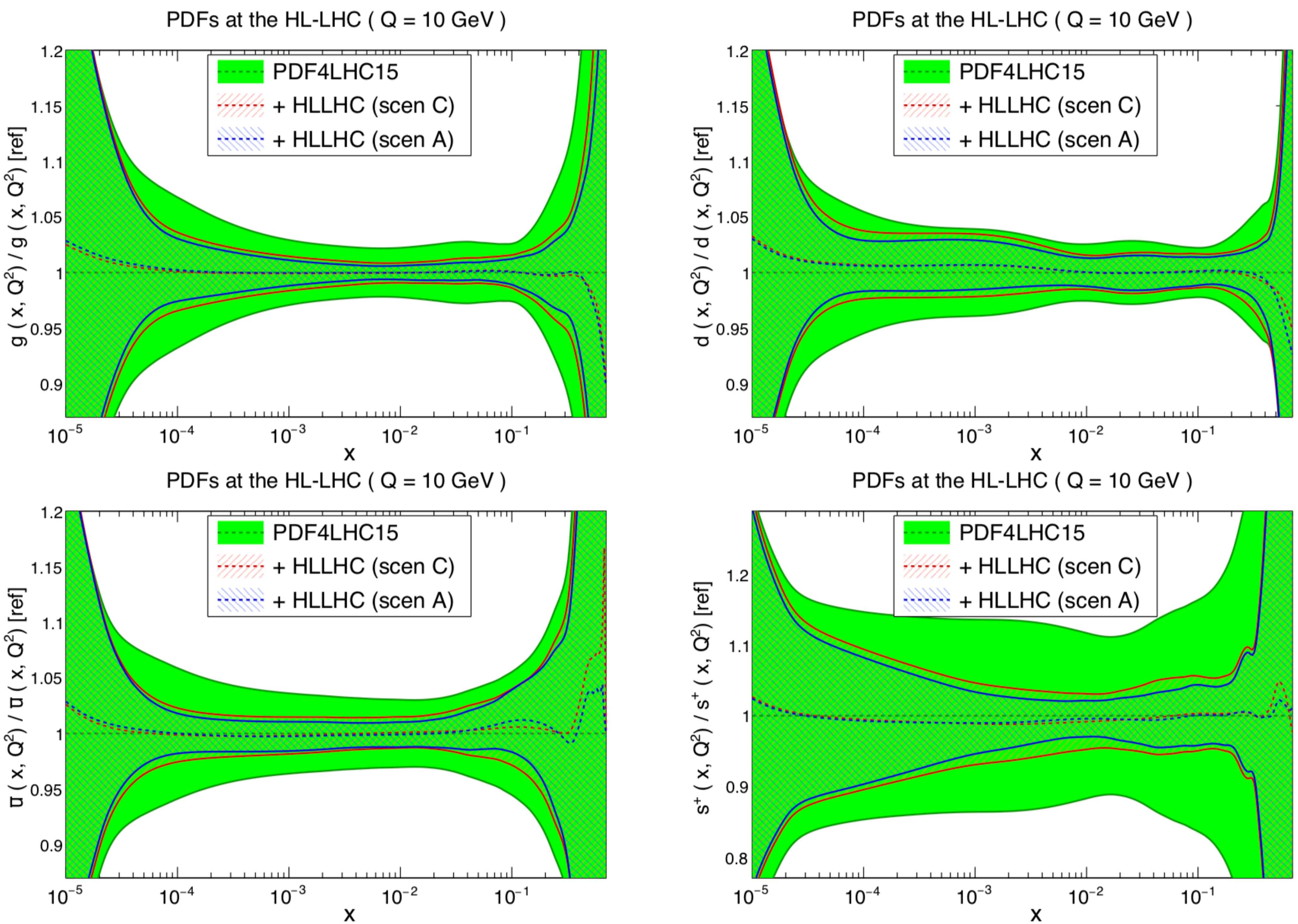
The HL-LHC dataset

- Non-exhaustive list of **HL-LHC** processes. Emphasis on high x region + measurements not already limited by systematic uncertainties.

Process	Kinematics	$N_{\rm dat}$	
$Z\ p_T$	$20\,{\rm GeV} \le p_T^{ll} \lesssim 3.5$ TeV $12\,{\rm GeV} \le m_{ll} \le 150$ GeV $\lvert y_{ll}\rvert \le 2.4$	130	→ *medium-x gluon*
high-mass Drell-Yan	$m_{ll} \ge 116\,{\rm GeV},\ \lvert\eta_l\rvert < 2.5$ $p_T^{l1(2)} \ge 40\ (30)$	21	→ *antiquarks*
top quark pair	$m_{t\bar{t}} \lesssim 5$ TeV, $\lvert y_t\rvert \le 2.5$	26	→ *large-x gluon*
W+charm (central)	$p_T^{\mu} \ge 26\,{\rm GeV},\ p_T^{c} \ge 5\,{\rm GeV},$ $\lvert\eta^{\mu}\rvert \le 2.4$	6	→ *strangeness*
W+charm (forward)	$p_T^{\mu} \ge 20\,{\rm GeV},\ p_T^{c} \ge 20\,{\rm GeV},\ p_T^{\mu+c} \ge 20\,{\rm GeV},$ $2 \le \eta^{\mu} \le 2.4,\ 2.2 \le \eta^{c} \le 3.2$	12	→ *strangeness*
Direct photon	$E_T^{\gamma} \lesssim 3$ TeV, $\lvert\eta_\gamma\rvert \le 2.5$	60	→ *medium-x gluon*
Forward W, Z	$p_T^{l} \ge 20\,{\rm GeV},\ 2.0 < \eta_l < 4.5$ $60 < m_{ll} < 120\,{\rm GeV},\ 2.0 < y_{ll} < 4.5$	90	→ *antiquarks*
Inclusive jets ($R = 0.4$)	$\lvert y_{\rm jet}\rvert \le 3,\ p_T^{\rm jet} \lesssim 4$ TeV	54	→ *large-x gluon*

- Generate pseudo-data for these using **PDF4LHC** set.
- Consider **conservative** (C) and **optimistic** (A) scenarios for future improvement in systematics.

PDF Luminosities



- **Significant error reduction** seen, with little dependence on scenario!
- This is the projection - how do we get there?

The Present - New LHC Data

New Data

- Global groups busily updating fits to include new LHC data. **ABMP16, NNPDF3.1** released, **MMHT18** and **CT17** on their way.

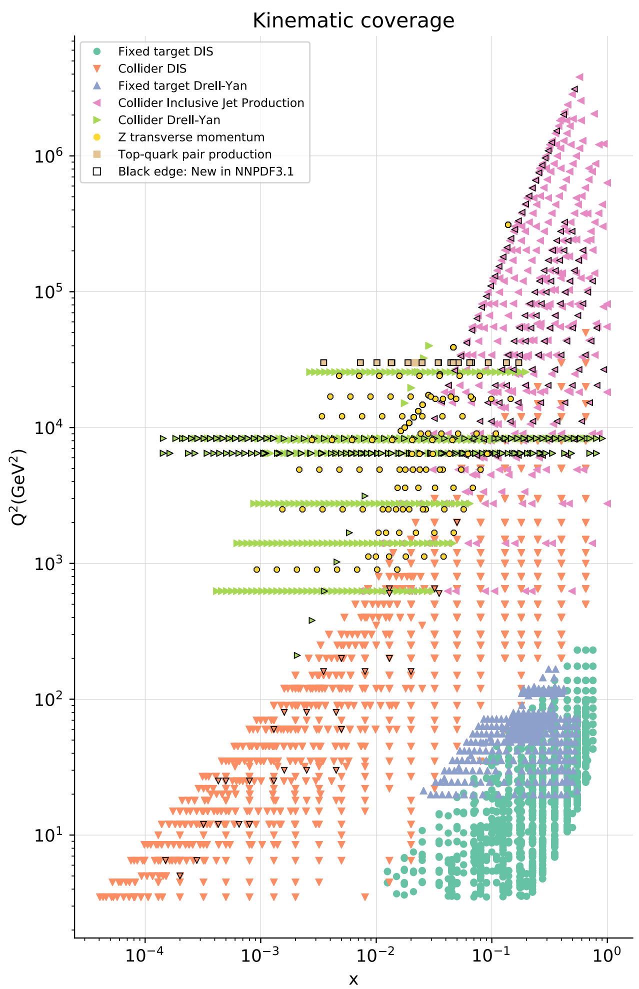
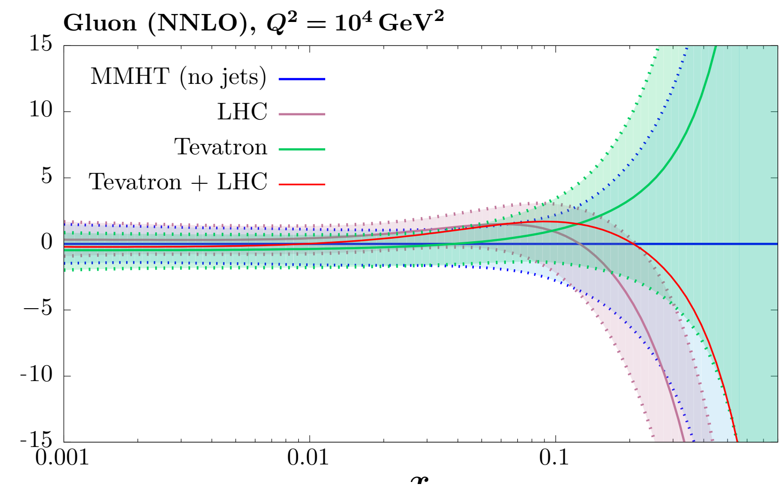


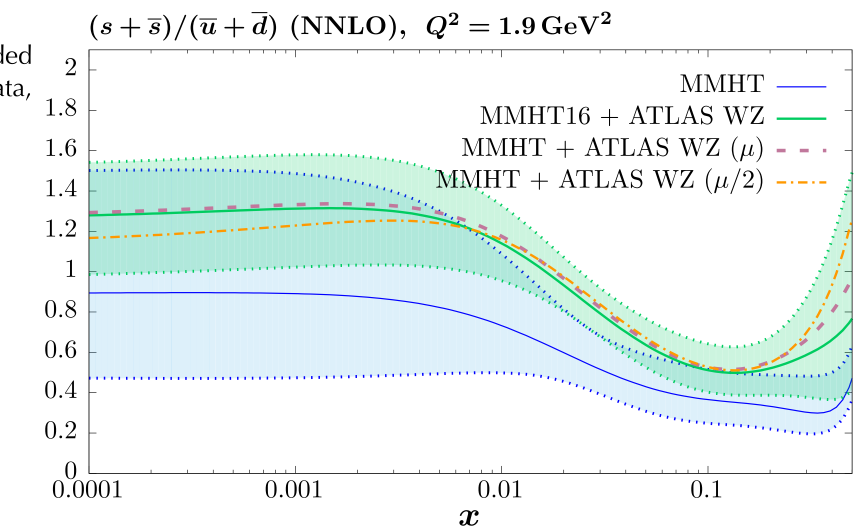
Figure 2.1: The kinematic coverage of the NNPDF3.1 dataset in the (x, Q^2) plane.



CT17p — data to be included

✦ Previous LHC and HERA 1 data included in CT14 will be superseded by updated Run 1 and HERA 1+2 data; adding new LHC data, especially on Z boson p_T and top quark differential distributions

- Combined HERA1+2 DIS [1506.06042] update
- LHCb 7 TeV Z, W muon rapidity dist. [1505.07024] update
- LHCb 8 TeV Z rapidity dist. [1503.00963] update
- ATLAS 7 TeV inclusive jet [1410.8857] update
- CMS 7 TeV inclusive jet (extended y range)[1406.0324] update
- ATLAS 7 TeV Z pT dist. [1406.3660] new
- LHCb 13 TeV Z rapidity dist. [1607.06495] update
- CMS 8 TeV Z pT and rapidity dist. (double diff.) [1504.03511] new
- CMS 8 TeV W, muon asymmetry dist. [1603.01803] update
- ATLAS 7 TeV W/Z, lepton(s) rapidity dist. [1612.03016] update
- CMS 7,8 TeV tT differential distributions new
- ATLAS 7,8 TeV tT differential distributions new



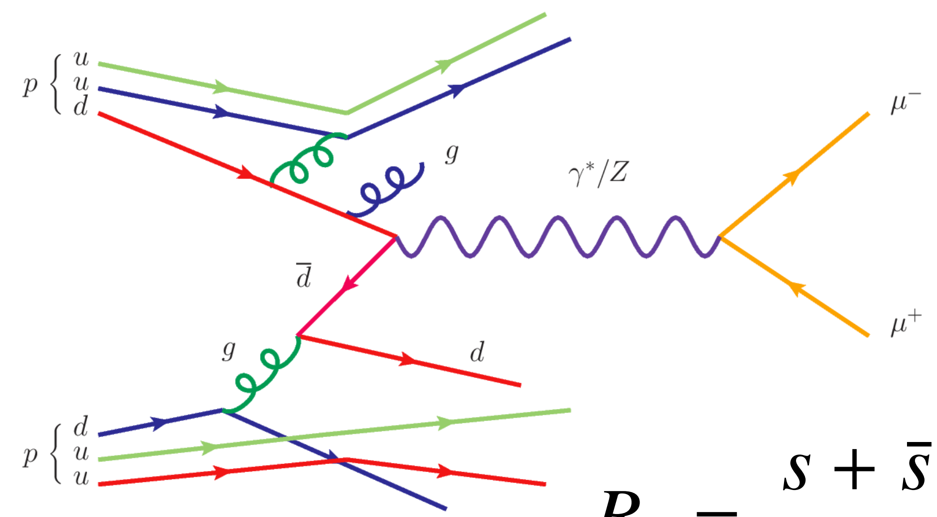
- Focus now on precise LHC data with precise (NNLO) theory: determine proton flavour structure, and push to higher x.
- In (some) more detail: proton strangeness, ATLAS $t\bar{t}$, 7 TeV jets…

Proton Strangeness

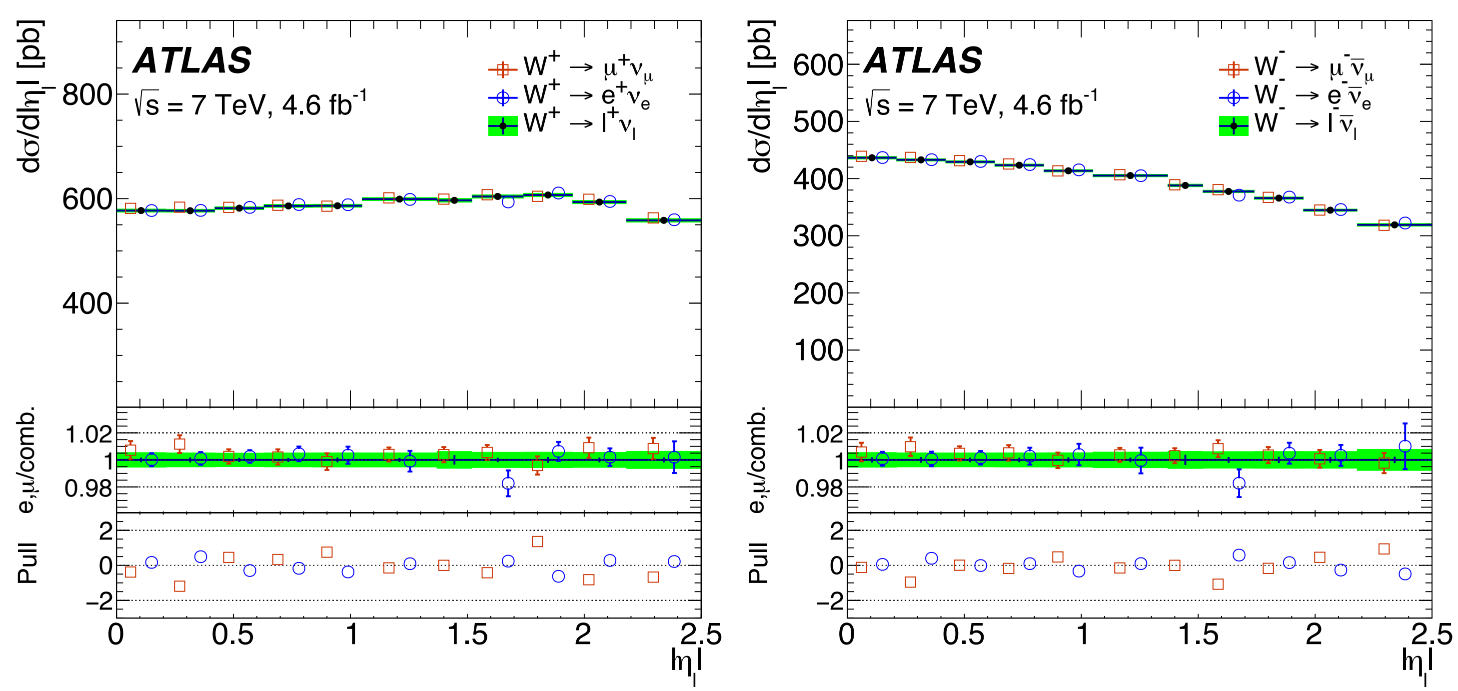
Proton strangeness

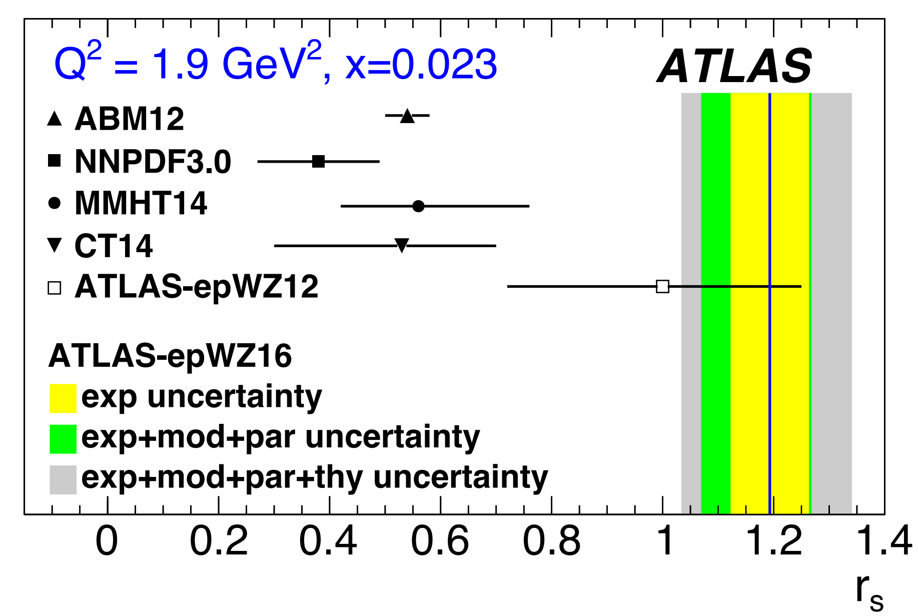
- Historically constraint on strangeness from neutrino-induced **DIS** ($\overline{\nu} s \to l c$), but high precision **DY** can also pin this down.
- Such data available from **ATLAS** - prefers higher $s, \bar{s}$ vs. previous fits.

$$u\bar{d},\ c\bar{s} \quad (u\bar{s},\ c\bar{d}) \to W^+ ,$$
$$d\bar{u},\ s\bar{c} \quad (s\bar{u},\ d\bar{c}) \to W^- ,$$
$$q\bar{q} \to Z/\gamma^* ,$$



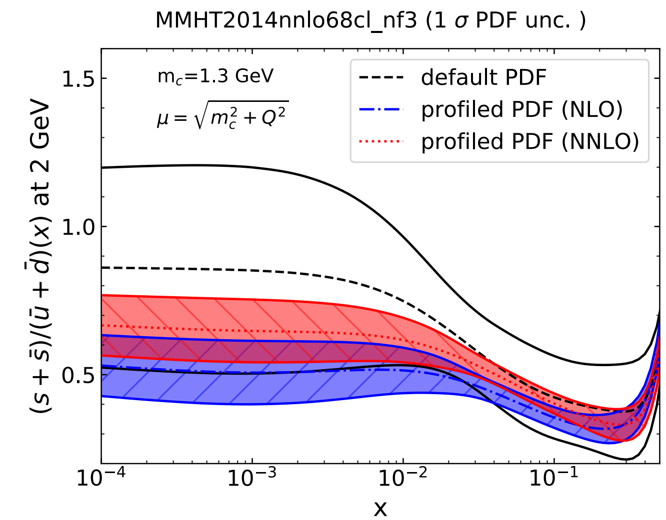
$$R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}}$$





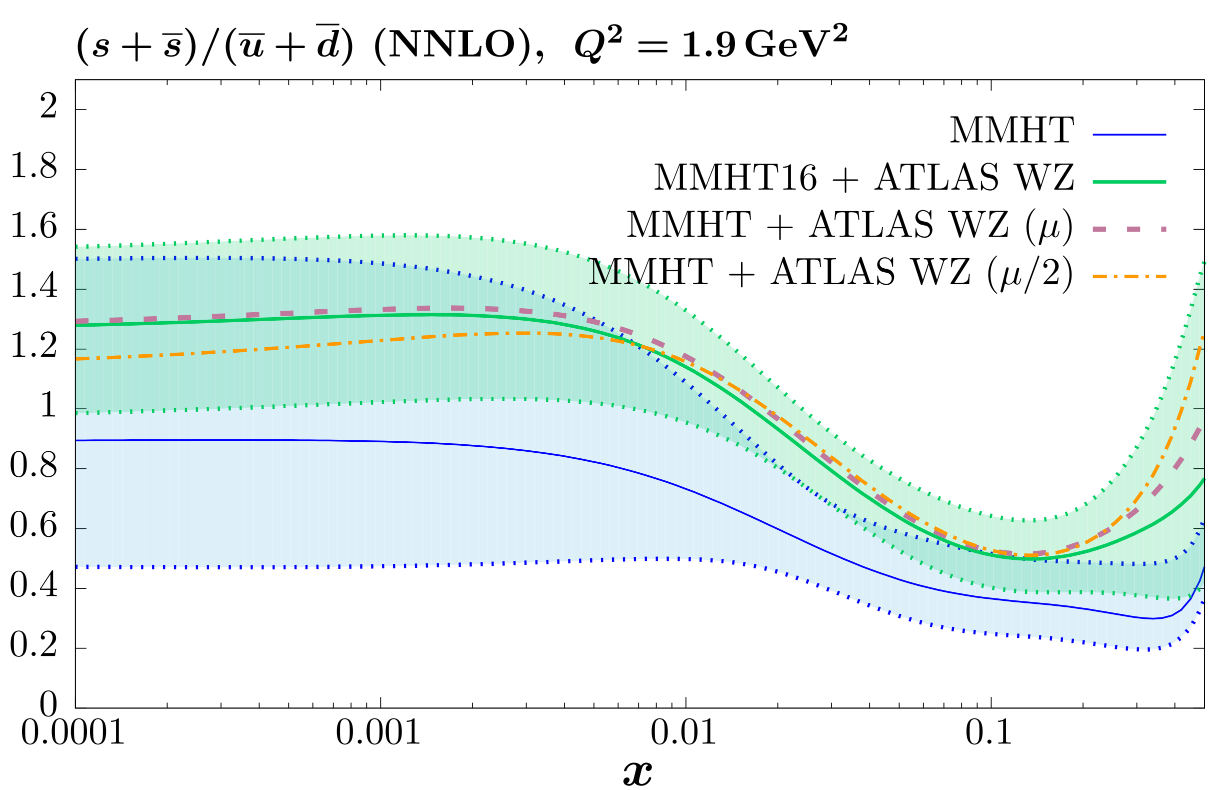
Proton strangeness

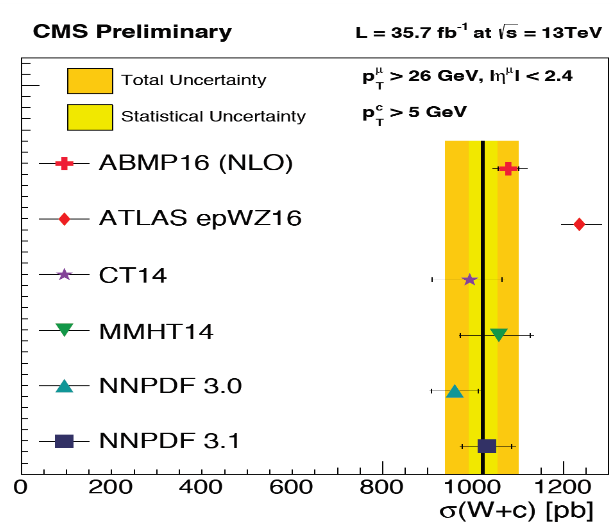
- What is impact within global (**MMHT**) fit?
- Find some **tension** with neutrino-induced DIS (deterioration in χ^2), but new $s+\bar{s}$ consistent with old, with smaller uncertainties.
- Not the end of the story: full **NNLO** corrections to (massive) neutrino-induced DIS now available. Suggests may reduce tension.



- **CMS** TeV W + c (new 13 TeV data) prefer lower strangeness.

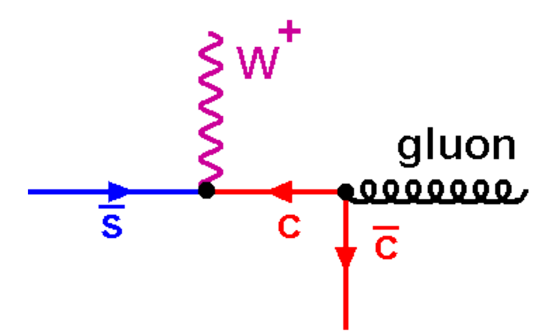
→ **Full study** in order (and underway)!





B. Bilin, DIS18

J. Gao, JHEP 1802 (2018) 026



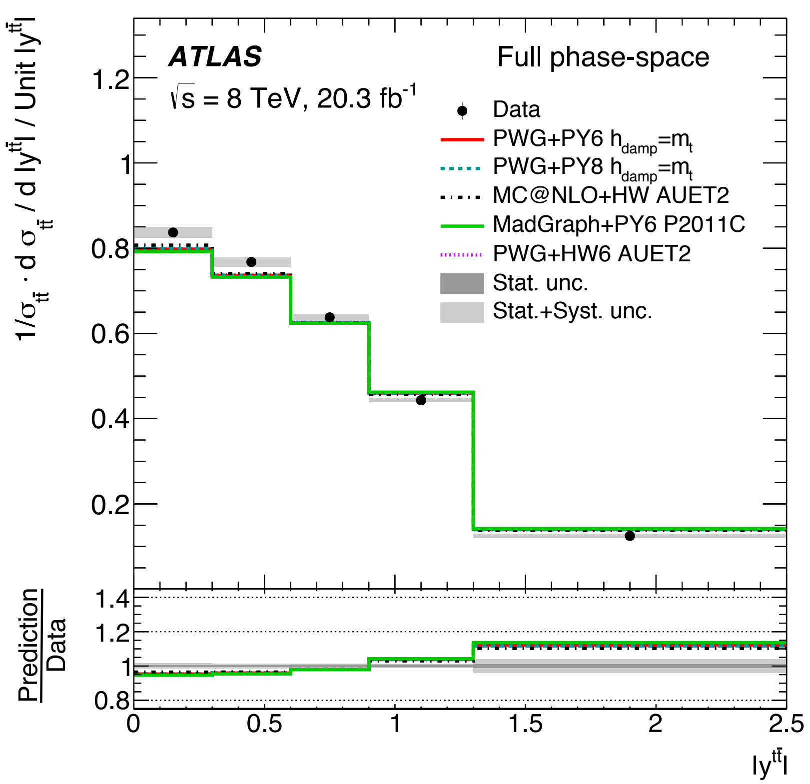
Fitting top quark pair production

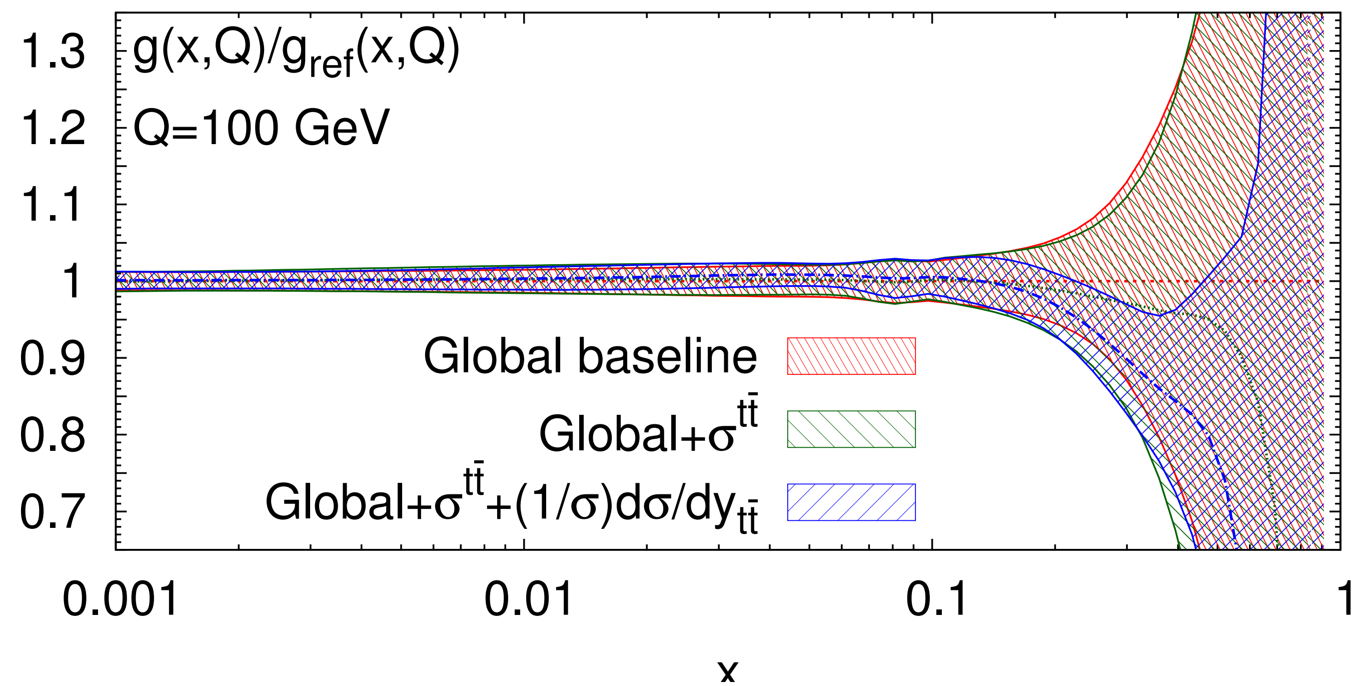
Differential Top

- Top quark pair production- sensitive to gluon PDF. Differential ⇒ increase impact in poorly determined high x region.
- NNLO theory performed and readily available (fastnlo).
- ATLAS 8 TeV data - full statistical correlations recently released.

ATL-PHYS-PUB-2018-017

M. Czakon et al., JHEP 1704 (2017) 044





ATLAS collab., EPJC76 (2016) no. 10, 538

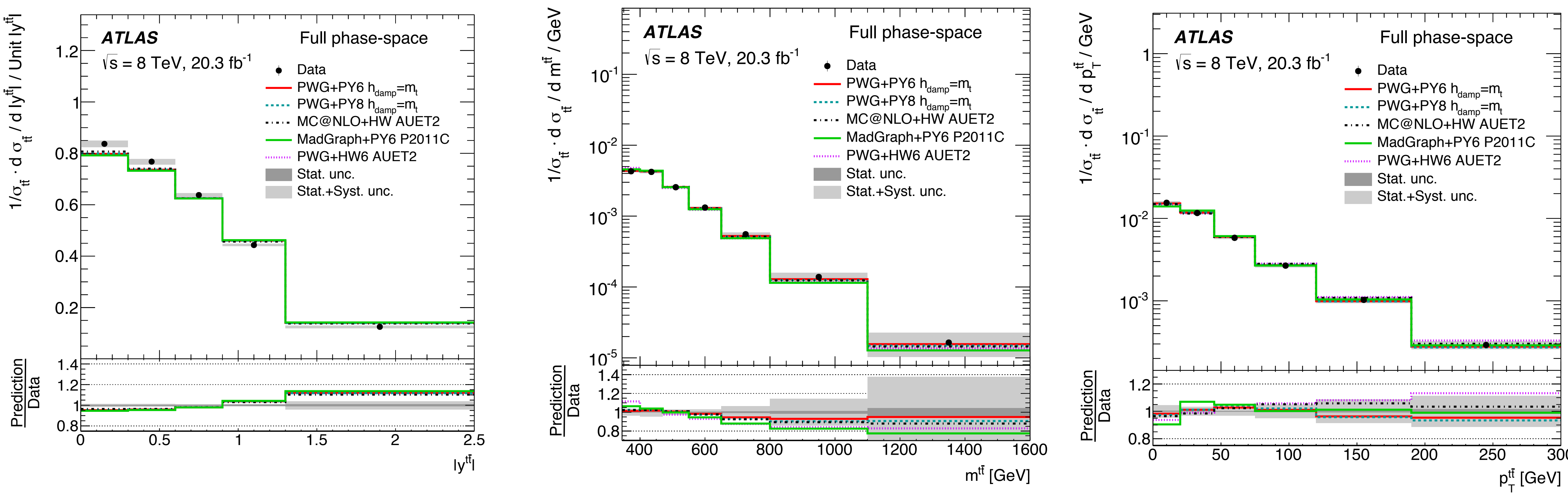
See also http://www.precision.hep.phy.cam.ac.uk/results/ttbar-fastnlo/

- In more detail…

ATLAS data

- ATLAS 8 TeV data available differential in 4 variables of interest for PDF fitting:

$$y_t,\ y_{t\bar{t}},\ p_\perp^t,\ M_{t\bar{t}}$$



- Consider impact in MMHT fit individually, and in combination…

Fitting Quality

- Fitting the distributions individually
  - very good for $p_\perp$, $M_{t\bar{t}}$, but for $y_t, y_{t\bar{t}}$ find large $\chi^2/N_{\rm pts} \sim 3 - 3.5$!
- Fit all distributions together*: fit quality deteriorates in all cases, total $\chi^2/N_{\rm pts} \sim 3$.

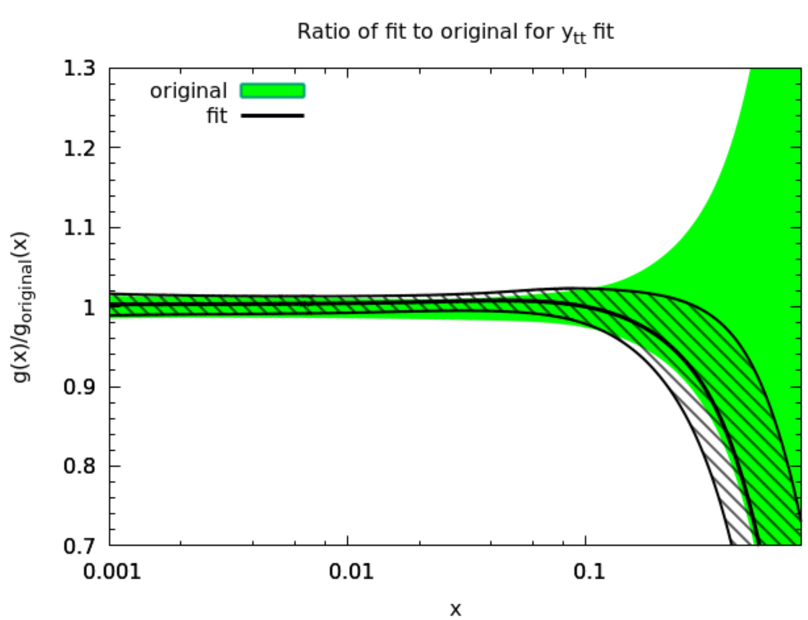
Individual

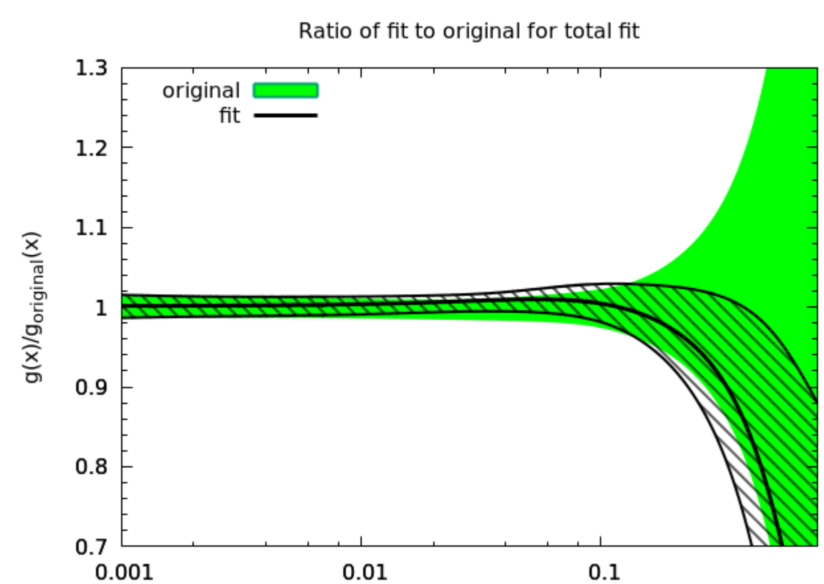
Contribution	Fitted data set(s): p_T	y_t	$y_{t\bar{t}}$	$M_{t\bar{t}}$
p_T	0.08			
y_t		1.23		
$y_{t\bar{t}}$			1.09	
$M_{t\bar{t}}$				0.29
Penalty	0.24	1.83	2.35	0.17
Total	0.32	3.06	3.44	0.47

Combined

Contribution	
p_T	2.38
y_t	1.84
$y_{t\bar{t}}$	2.22
$M_{t\bar{t}}$	1.81
Penalty	0.88
Total	2.96

- $y_{t\bar{t}}$ most constraining, combined fit similar to this.





- How to interpret/deal with poor fit quality?

Study prior to release of stat. correlations- should not affect conclusions significantly, but will include in final analysis (c.f. ATL-PHYS-PUB-2018-017).

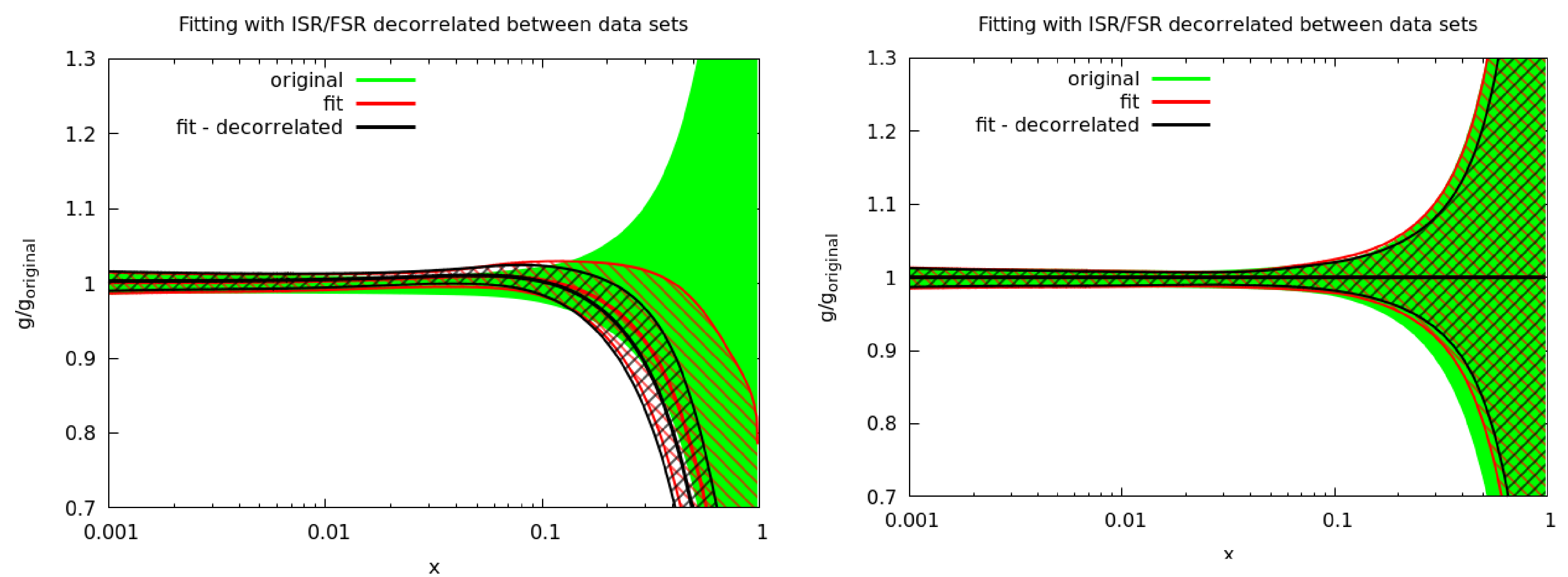
A Closer Look

- Systematics dominated data - fit quality sensitive to correlations.
- Three largest (~ 3-10%) systematics: hard-scattering modelling, ISR/FSR and parton-shower. Correction assumed to lie in a fully correlated way somewhere between two models/MCs.

	Before decorrelating	After decorrelating
pT	2.38	0.81
yt	1.84	1.11
ytt	2.21	1.86
mtt	1.81	0.50
pen	0.88	0.67
tot	2.96	1.67

- Decorrelating ISR/FSR between distributions, find significant improvement in fit quality.

- Gluon relatively stable, but not entirely.



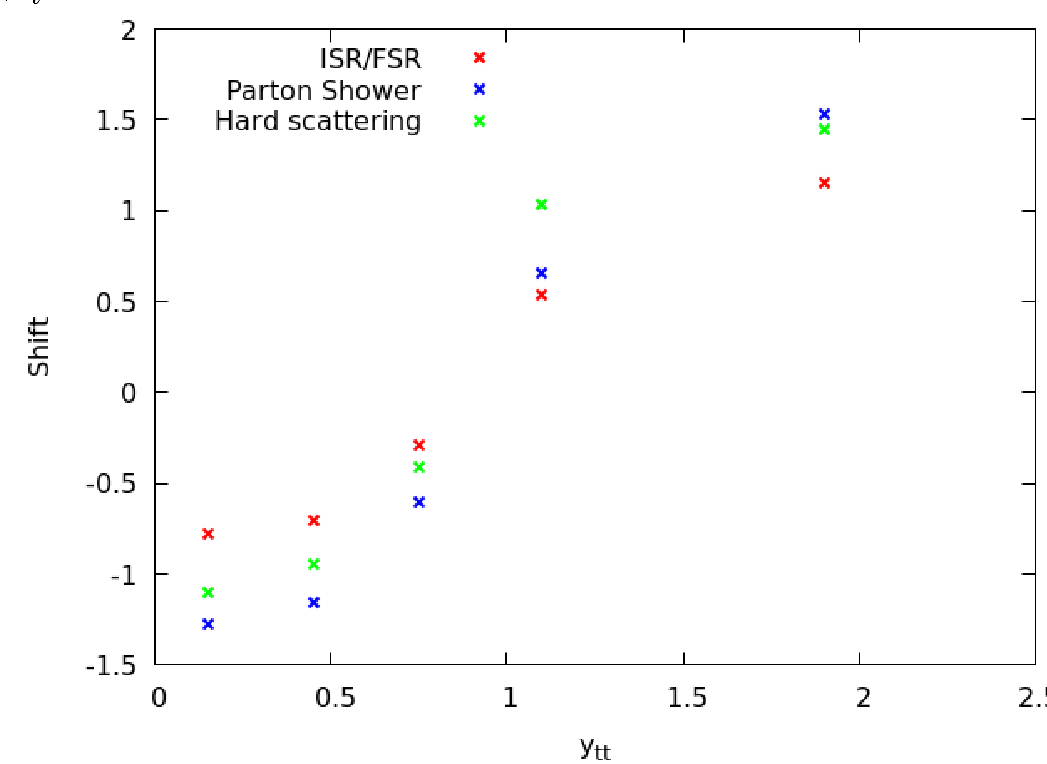
- Results ~ consistent with ATL-PHYS-PUB-2018-017.

Returning to y_t, $y_{t\bar{t}}$

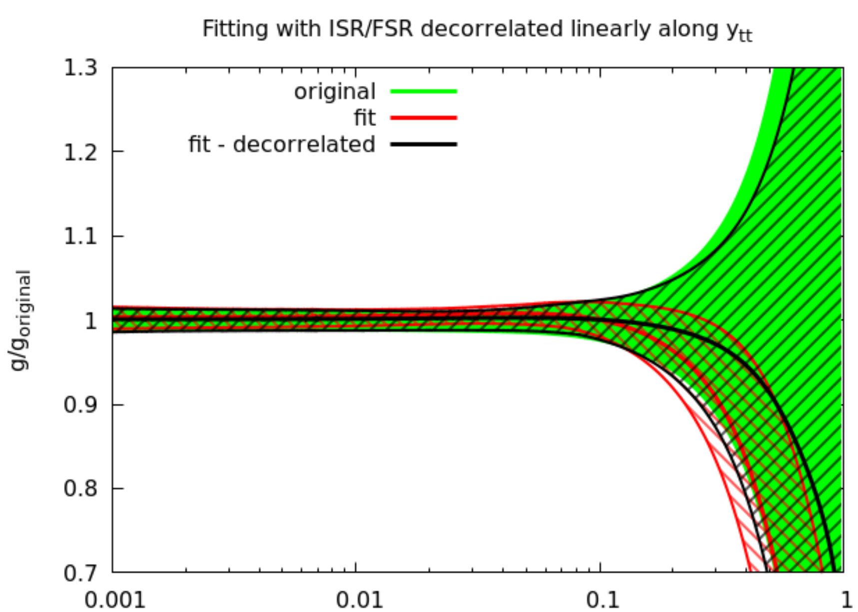
- Tempting to reconsider poor fit quality to y_t, $y_{t\bar{t}}$ in light of two-point systematics dominance.
- Consider further breakdown into two subcomponents:

χ^2/N_{pts}		Fitted data set(s)			
		p_T	y_t	$y_{t\bar{t}}$	$M_{t\bar{t}}$
Contribution	p_T	0.08			
	y_t		1.23		
	$y_{t\bar{t}}$			1.09	
	$M_{t\bar{t}}$				0.29
	Penalty	0.24	1.83	2.35	0.17
	Total	0.32	3.06	3.44	0.47

$$\beta_i^1 = \left(\frac{y_{tt,i} - y_{tt,min}}{y_{tt,max} - y_{tt,min}}\right)\beta_i^{\text{tot}}, \quad \beta_i^2 = \left[1 - \left(\frac{y_{tt,i} - y_{tt,min}}{y_{tt,max} - y_{tt,min}}\right)\right]^{\frac{1}{2}}\beta_i^{\text{tot}}$$



- Take $y_{t\bar{t}}$ - clear trend preferred in fit, with $\chi^2/N_{\text{pts}} \sim 3.5 \to 2$.



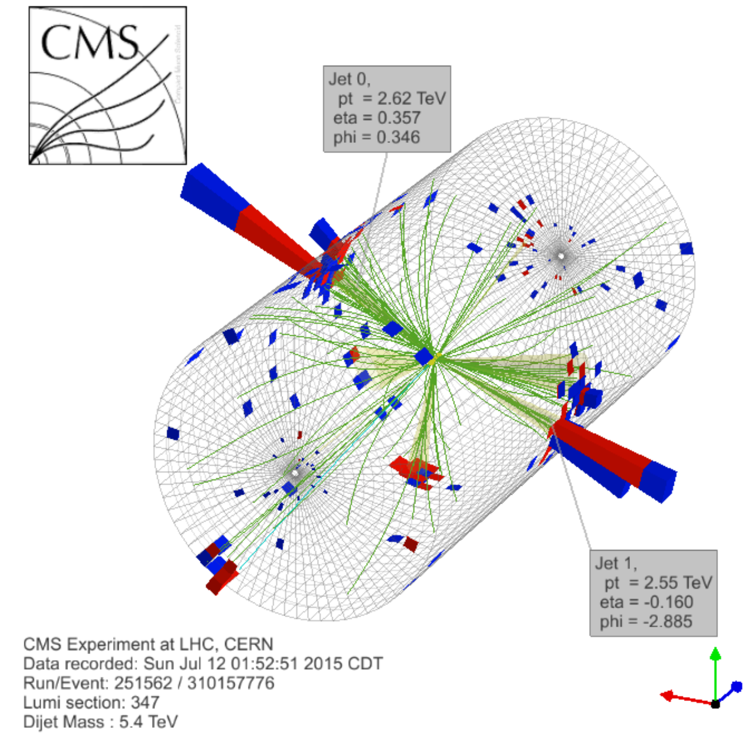
- However, impact on gluon rather large. Hope for stability in combined fit - under investigation.

Jets at NNLO

Jets at NNLO

- **LHC jets** - dominated by gluon-initiated production:

$$gg \to gg,\ gg \to q\bar{q},\ gq \to gq,\ q\bar{q} \to gg\ ,$$



- Sensitive to high x as jet $p_\perp$ increases. Region where PDF uncertainties high, and important for e.g. high mass BSM searches.

- Recent full **NNLO** calculation completed and made available for first time consider PDF impact at this high precision level.

NNLO QCD predictions for single jet inclusive production at the LHC

J. Currie[a], E.W.N. Glover[a], J. Pires[b]
[a] *Institute for Particle Physics Phenomenology, University of Durham, Durham DH1 3LE, England*
[b] *Max-Planck-Institut für Physik, Föhringer Ring 6 D-80805 Munich, Germany*

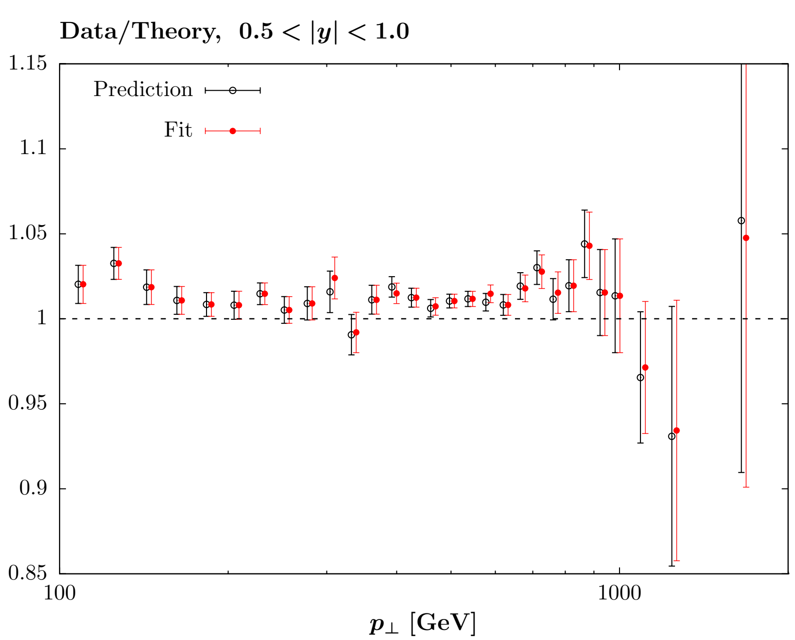
We report the first calculation of fully differential jet production in all partonic channels at next-to-next-to leading order (NNLO) in perturbative QCD and compare to the available ATLAS 7 TeV data. We discuss the size and shape of the perturbative corrections along with their associated scale variation across a wide range in jet transverse momentum, p_T, and rapidity, y. We find significant effects, especially at low p_T, and discuss the possible implications for Parton Distribution Function fits.

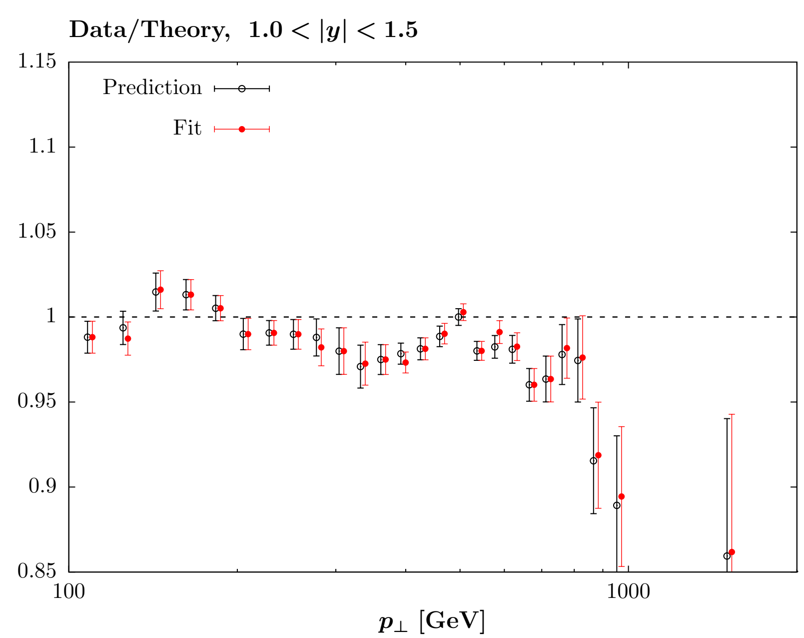
J. Currie et al., Phys.Rev.Lett. 118 (2017) no.7, 072002

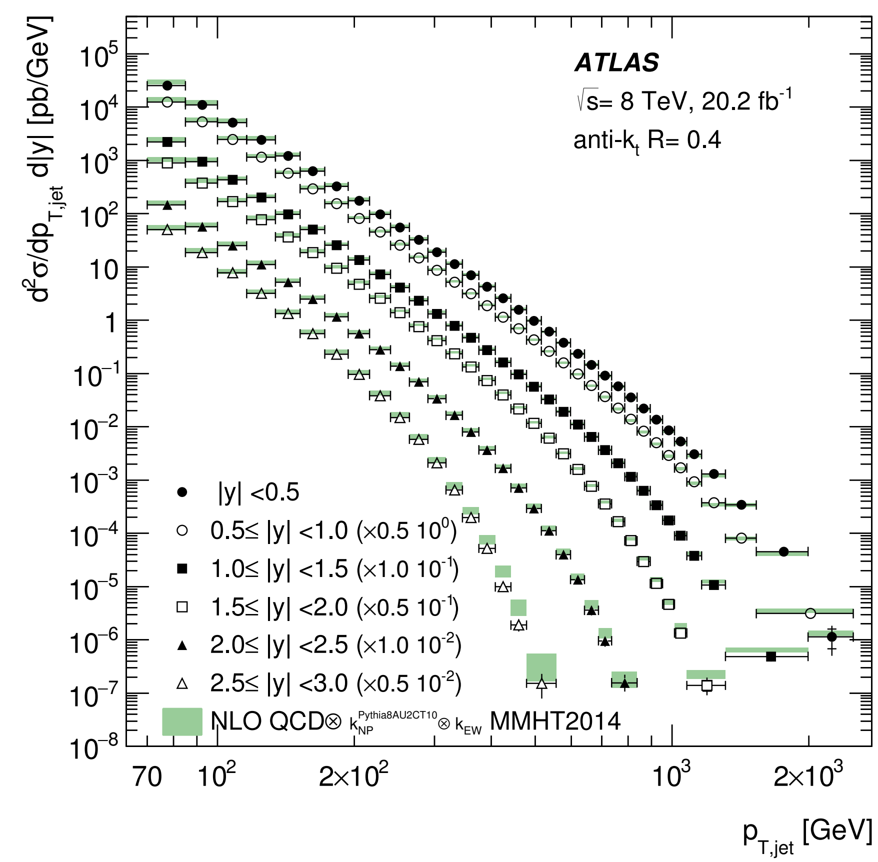
Jets at NNLO

LHL, A.D. Martin, R.S. Thorne EPJC 78 (2018) no.3, 248

- **MMHT** study at **NNLO**, including **ATLAS/CMS** 7 TeV data.
- Complication - despite 'by eye' good description, issues in describing ATLAS jet data well across all rapidity bins.
- Find **mismatch** between neighbouring rapidity bins, despite being sensitive to PDFs of same flavour at similar x, Q^2.
- Does not improve with **NNLO**.







Boughezal et al., JHEP 1707 (2017) 130

- Data completely systematics dominated - fit quality intimately tied to systematic errors and their correlations. **See backup**
- With loosening of correlations, get large improvement in χ^2, but with fitted **gluon** remaining **stable**. Overall encouraging results:

More complete study: ATLAS, JHEP 09, 020 (2017)

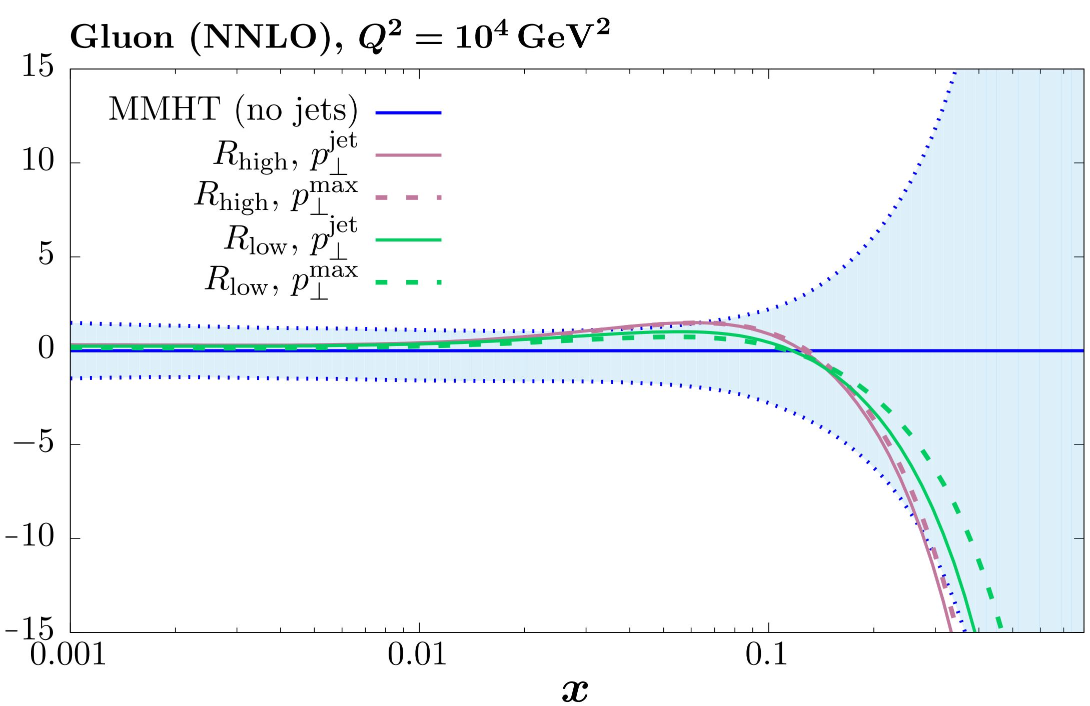
‣ **Improvement** in description from **NLO** to **NNLO** - pQCD working as it should.

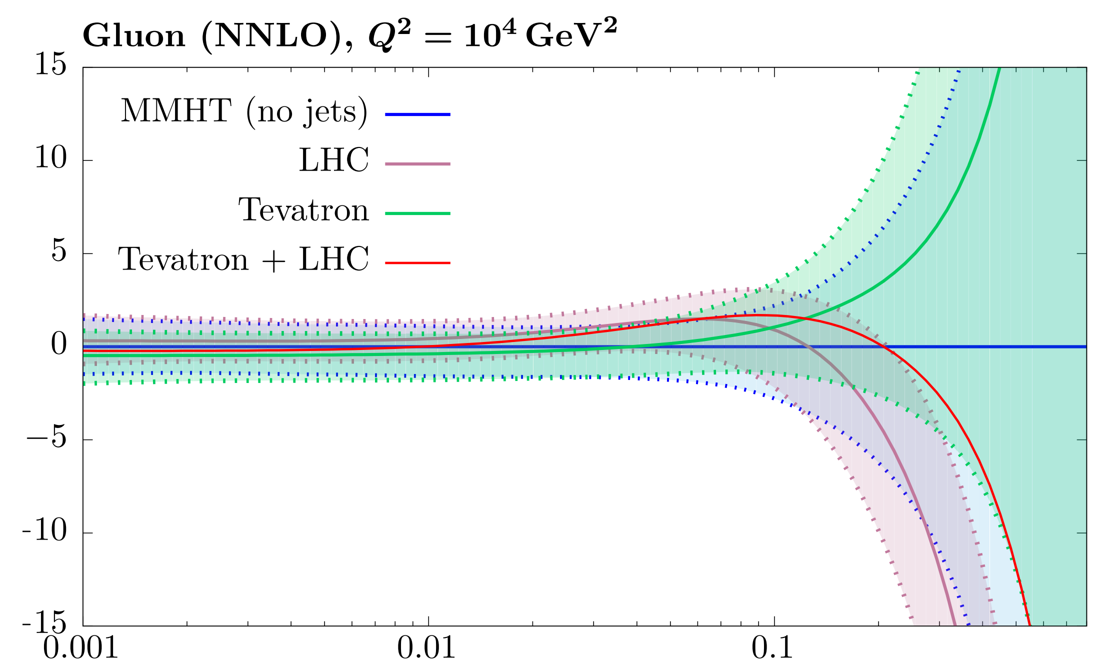
χ^2

	NLO theory	NNLO
ATLAS, $R_{\rm low}$	215.3	172.3
ATLAS, $R_{\rm high}$	159.2	149.8
CMS, $R_{\rm low}$	194.2	177.8
CMS, $R_{\rm high}$	198.5	182.3

‣ Relative insensitivity to scale choice ($p_\perp^{\rm jet}, p_\perp^{\rm max}$), up to ~ 30% reduction in relative uncertainty at high x .

‣ Pull **opposite** to **Tevatron**, but this misses full NNLO. Might that help?





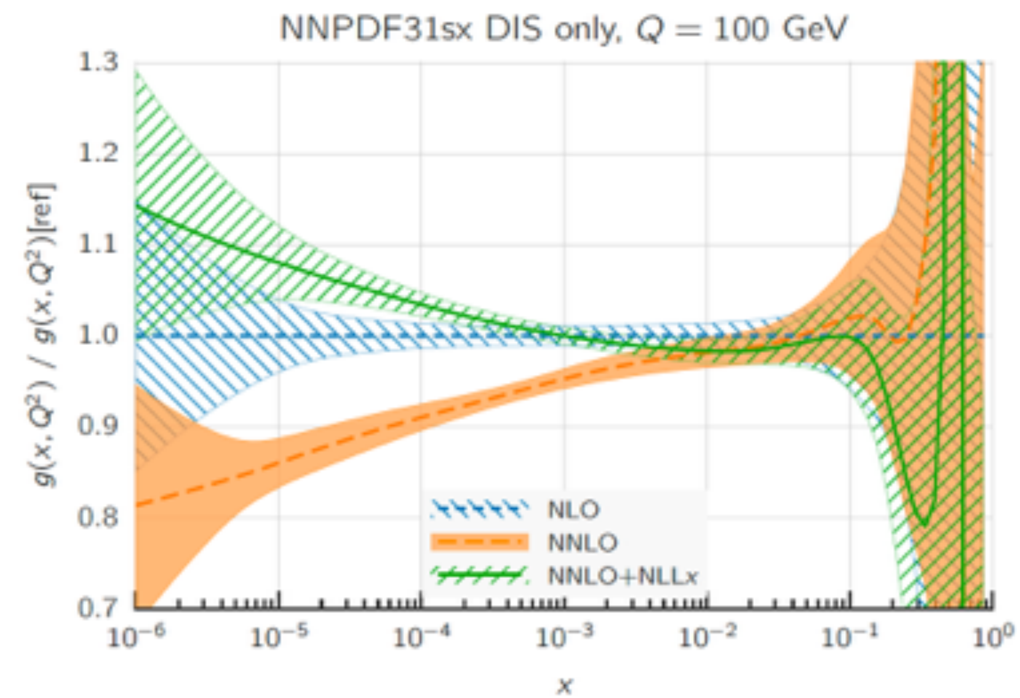
New Ideas - Resummation

Low x resummation

- Recent revival of low x resummation studies $\Rightarrow$ stabilise pQCD by summing $\ln\frac{1}{x}$ terms to all orders:

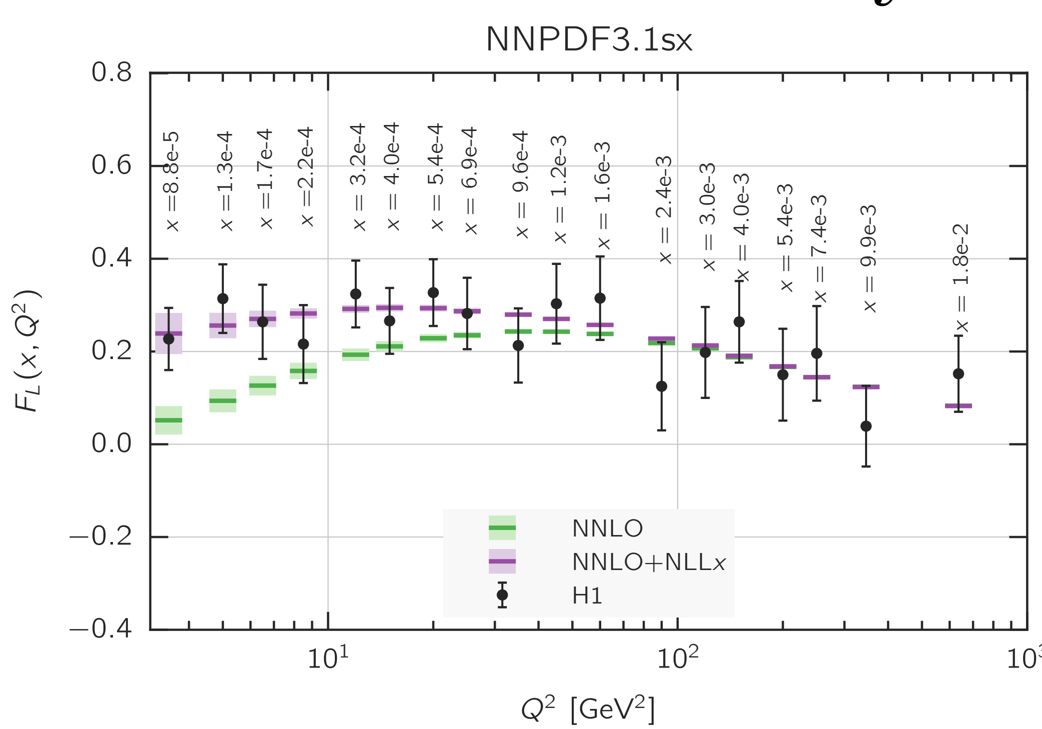
$$P_{ij}^{\mathrm{N}^k\mathrm{LO}+\mathrm{N}^h\mathrm{LL}x}(x) = P_{ij}^{\mathrm{N}^k\mathrm{LO}}(x) + \Delta_k P_{ij}^{\mathrm{N}^h\mathrm{LL}x}(x),$$

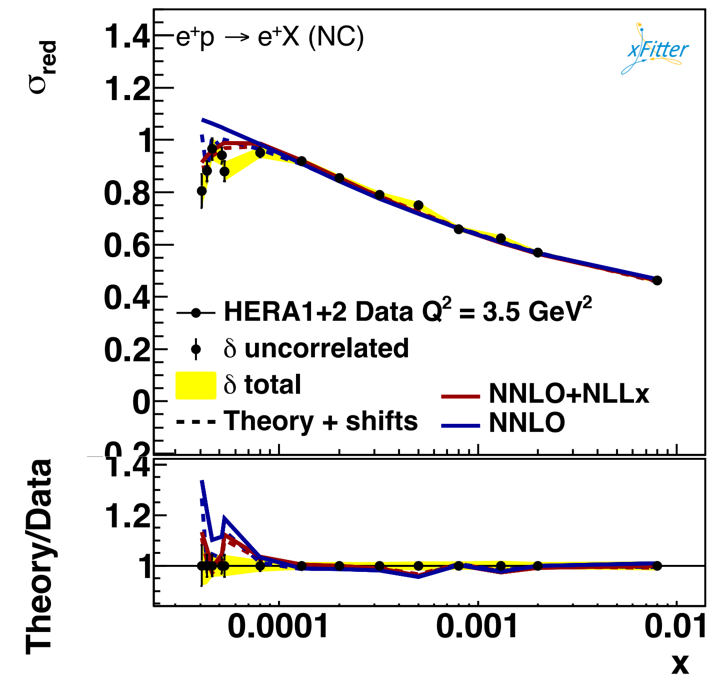
R.D. Ball el al., EPJC78 (2018) no.4, 321



- Inclusion in (semi) global fit considered recently for first time.
- Gives significant improvement in low x (Q^2) HERA inclusive structure function data. Confirmed by xFitter.

xFitter dev. team, EPJC78 (2018) no.8, 621





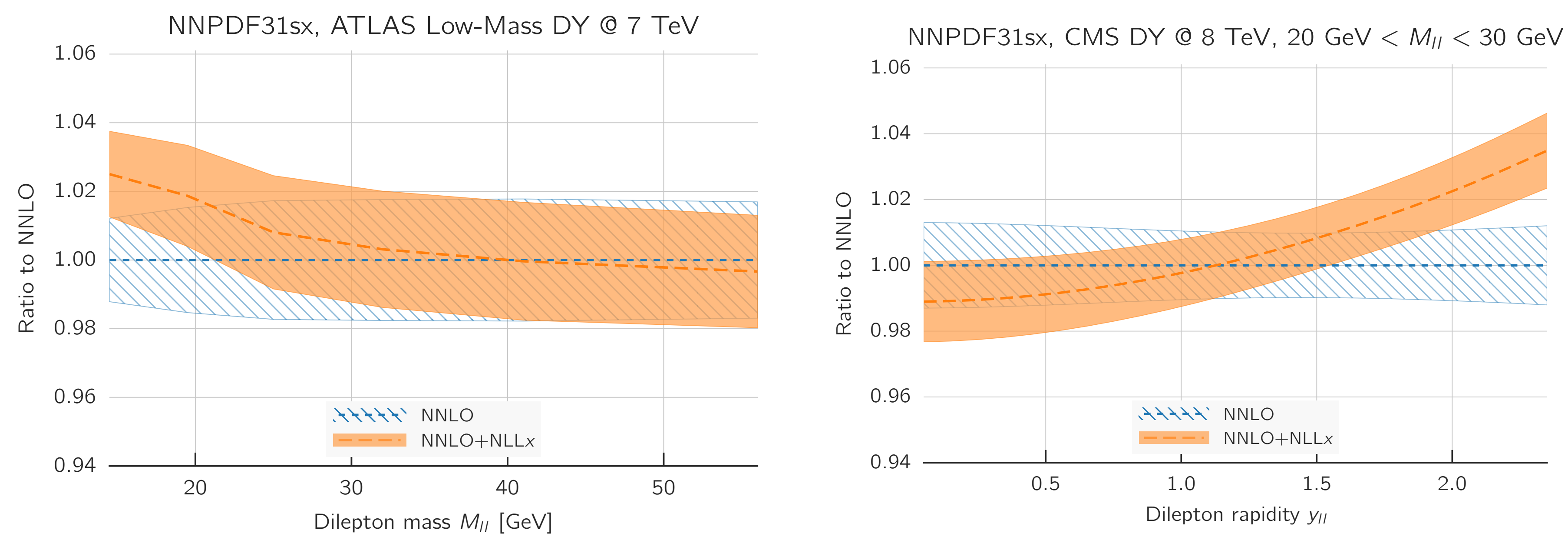
LHC impact?

LHL et al., EPJC76 (2016) no.4, 186

- Impact at HERA clear, though limited to low x and Q^2 by kinematics (can also improved with higher twist $\sim 1/Q^2$ corrections).
- Are we sensitive at LHC? What information can it provide?

NB: no resummation in cross section available yet

- First look in DY case suggests double differential more sensitive:



R.D. Ball el al., EPJC78 (2018) no.4, 321

- Clearly largest effects will be at LHCb, and at HE-LHC (FCC…).
- Impact at current level of precision small, but not negligible. Future fits with low + high x resummation foreseen in the long term

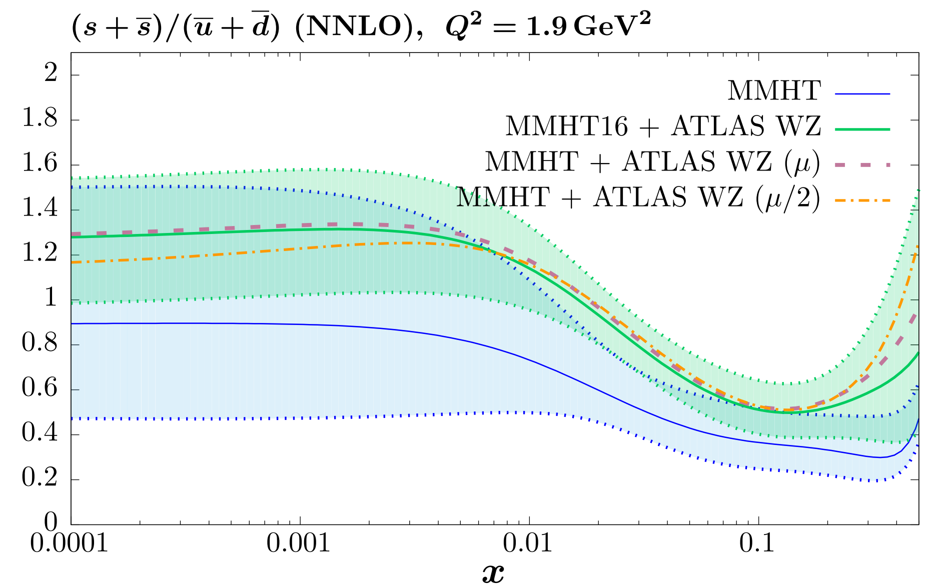
New Ideas - Theory Uncertainties

Theory uncertainties

ATLAS, JHEP 09, 020 (2017)

- Recall issues with fit to ATLAS jet data. Independent of experimental systematics - some improvement in χ^2 seen by varying QCD scales μ_R, μ_F.

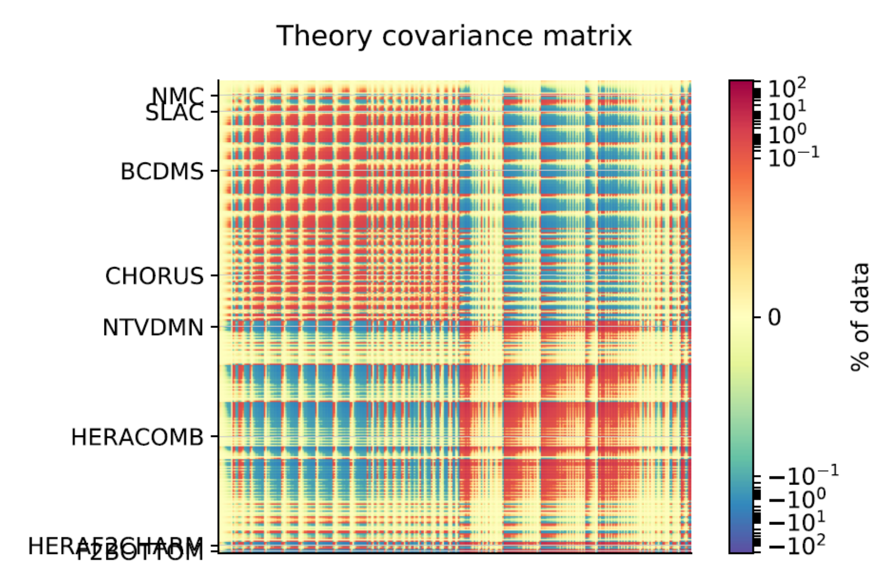
  - ATLAS W,Z : some improvement in fit quality ($\chi^2/N : 2.2 \to 1.8$) to all masses, when $\mu \to \mu/2$.



$\longrightarrow$ Clearly at/approaching stage where we should worry about this in PDF fits!

S. Forte, Cern July 2018

- First look by NNPDF: build 'theoretical' covariance matrix due to scale variation, and include in fit. So far - DIS only.

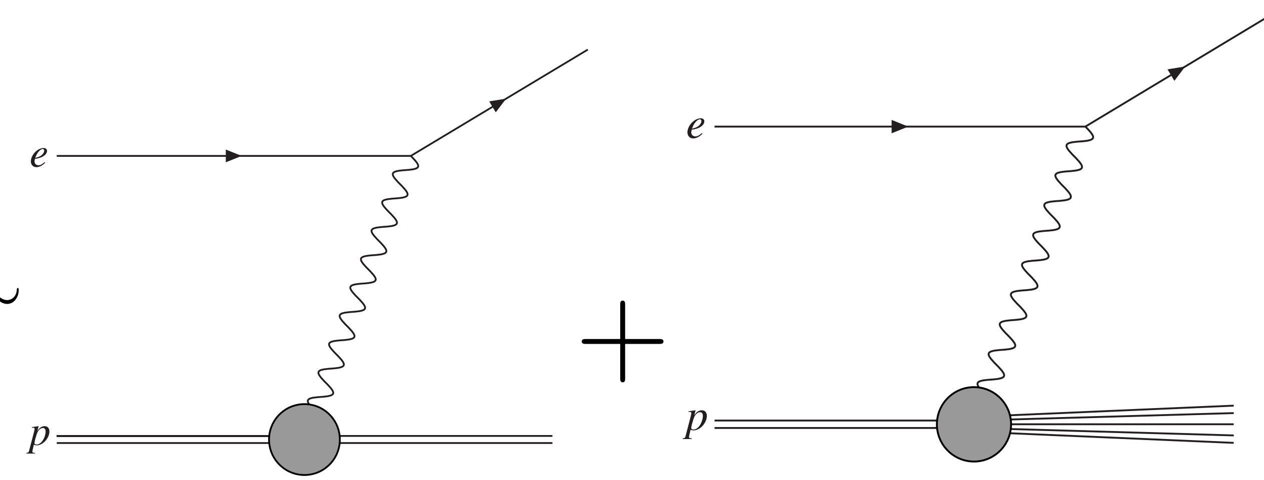


New Ideas - Photon PDF

Photon PDF

- Photon-initiated processes - relevant in precision era ($\alpha_S^2(M_Z) \sim \alpha(M_Z)$). Require introduction of 'photon PDF'.
- Precise photon PDF determination - photon exchange in elastic/inelastic ep scattering precisely same process as that generating $\gamma(x, Q^2)$:

$\gamma(x, Q^2) \sim$



Elastic **Inelastic**

LHL eta al., Phys. Rev. D94 (2016) no.7, 074008

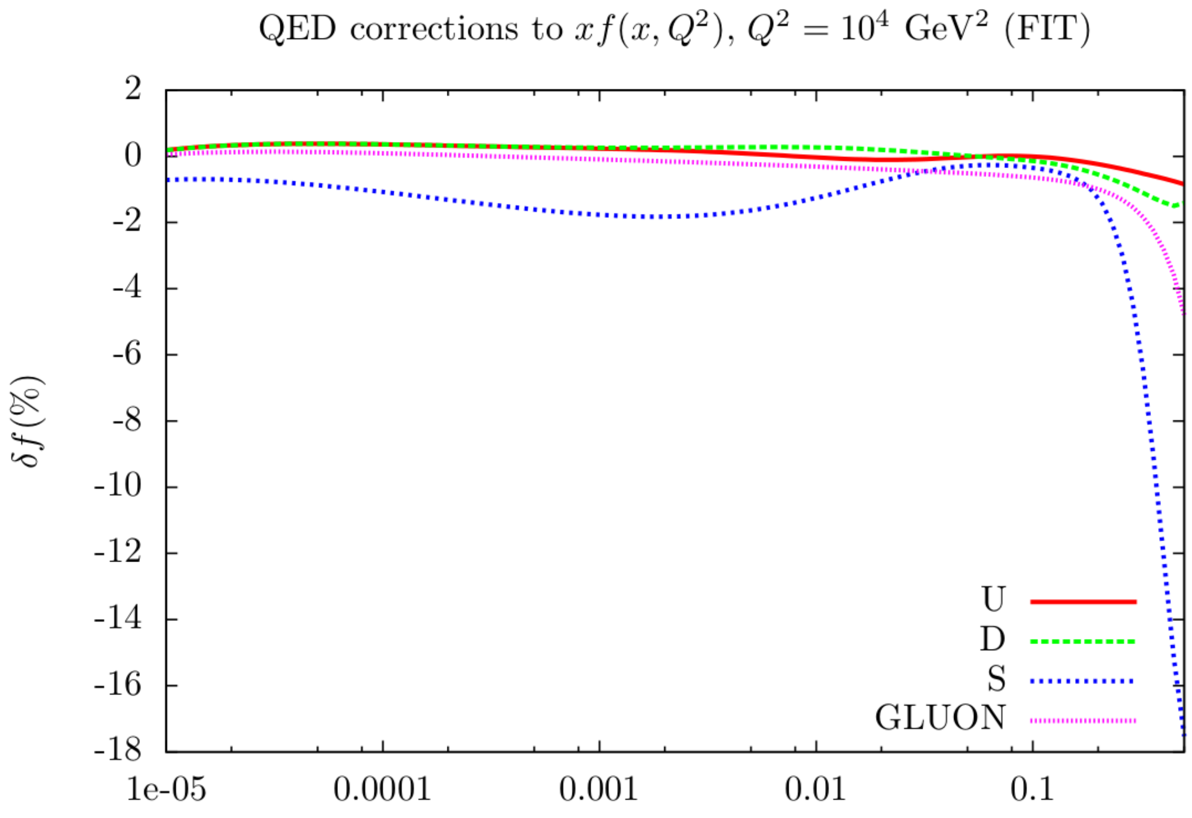
- Complete quantitative result provided by **LUXqed**:
- Photon v. well determined. Emphasis on consistent inclusion in global fit.

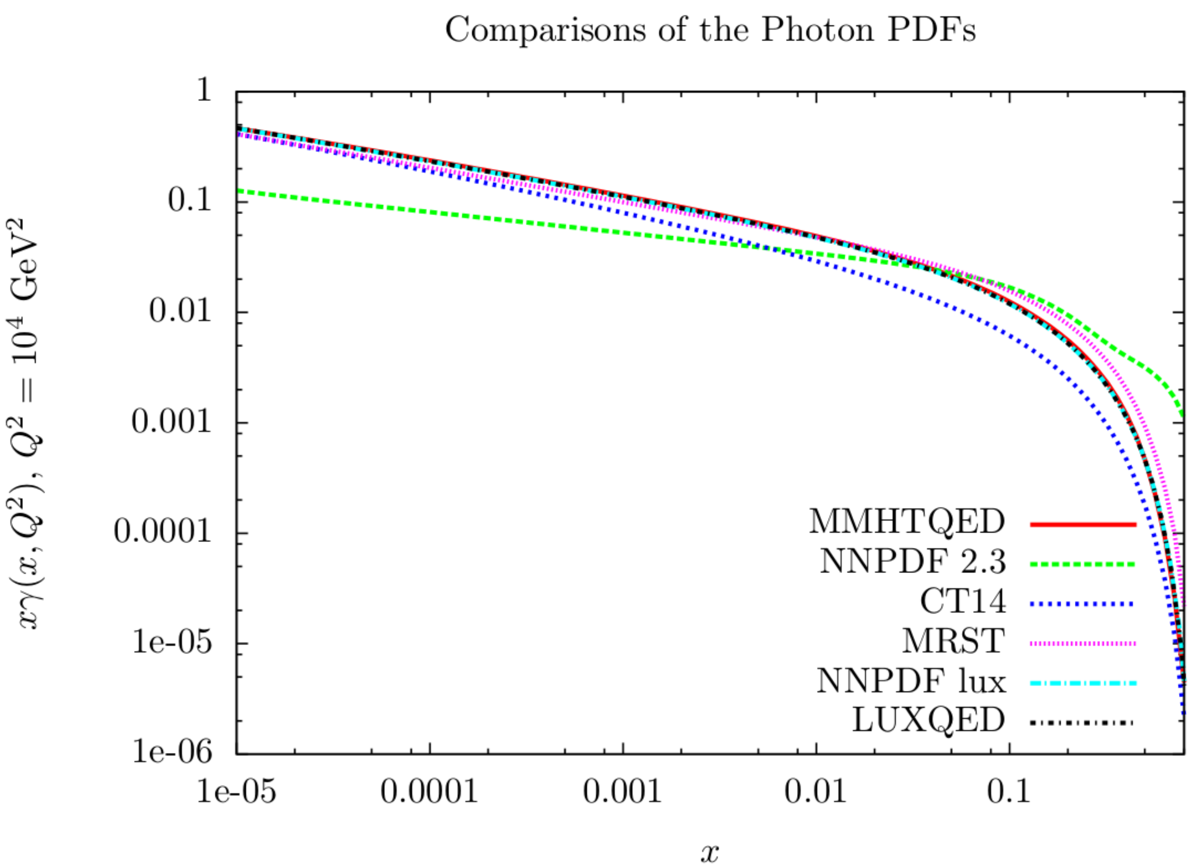
$$x f_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)} \int_x^1 \frac{dz}{z} \left\{ \int_{\frac{x^2 m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2} \alpha^2(Q^2) \left[\left(z p_{\gamma q}(z) + \frac{2x^2 m_p^2}{Q^2} \right) F_2(x/z, Q^2) - z^2 F_L\left(\frac{x}{z}, Q^2\right) \right] - \alpha^2(\mu^2) z^2 F_2\left(\frac{x}{z}, \mu^2\right) \right\}, \quad (6)$$

A. Manohar et al., JHEP 1712 (2017) 046
A. Manohar et al., Phys. Rev. Lett. 117 (2016) no.24, 100001

Photon in MMHT global PDF fit

- Input PDF $\gamma(x, Q_0)$ parameterised at low $Q_0 \sim 1\,\mathrm{GeV}$. For photon we do not leave free - take from adapted **LUXqed** expression.
- $\gamma - q/g$ coupling in DGLAP incorporated for both proton and neutron.



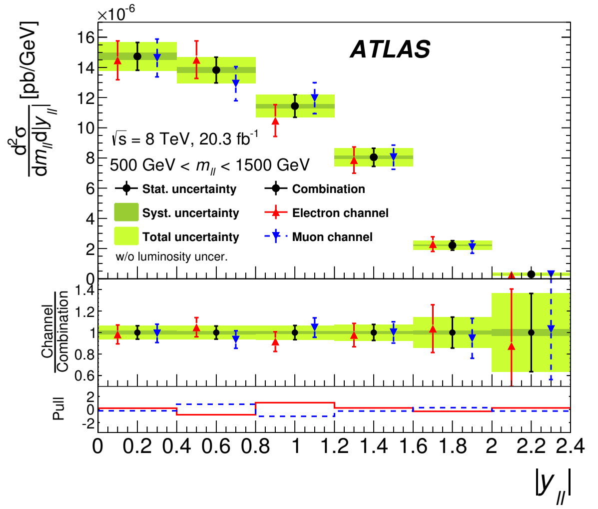


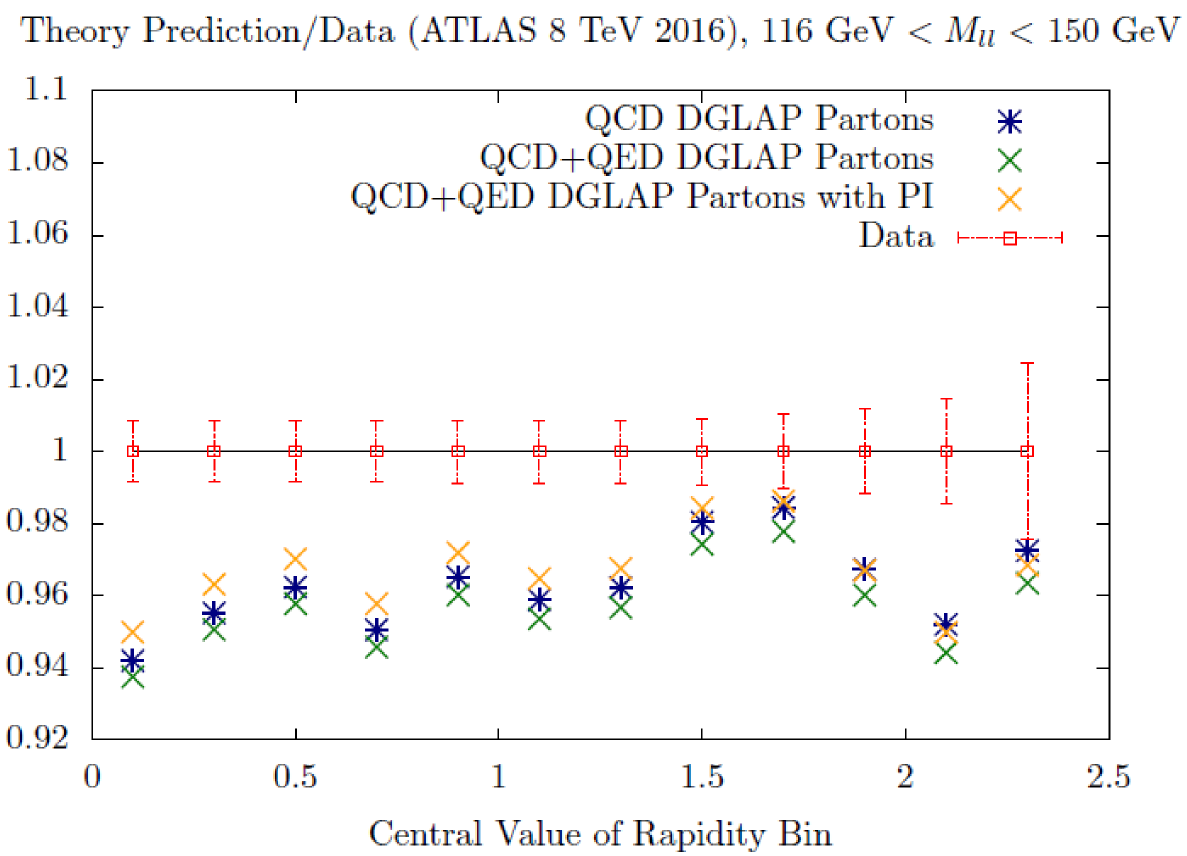
- (Left) Impact on other partons (after fit): loss of momentum to γ at high x, effect on strangeness largest.
- (Right) **MMHTQED** photon close to **LUX/NNPDFlux**. Variation in outdated/historical sets larger - these are no longer relevant!

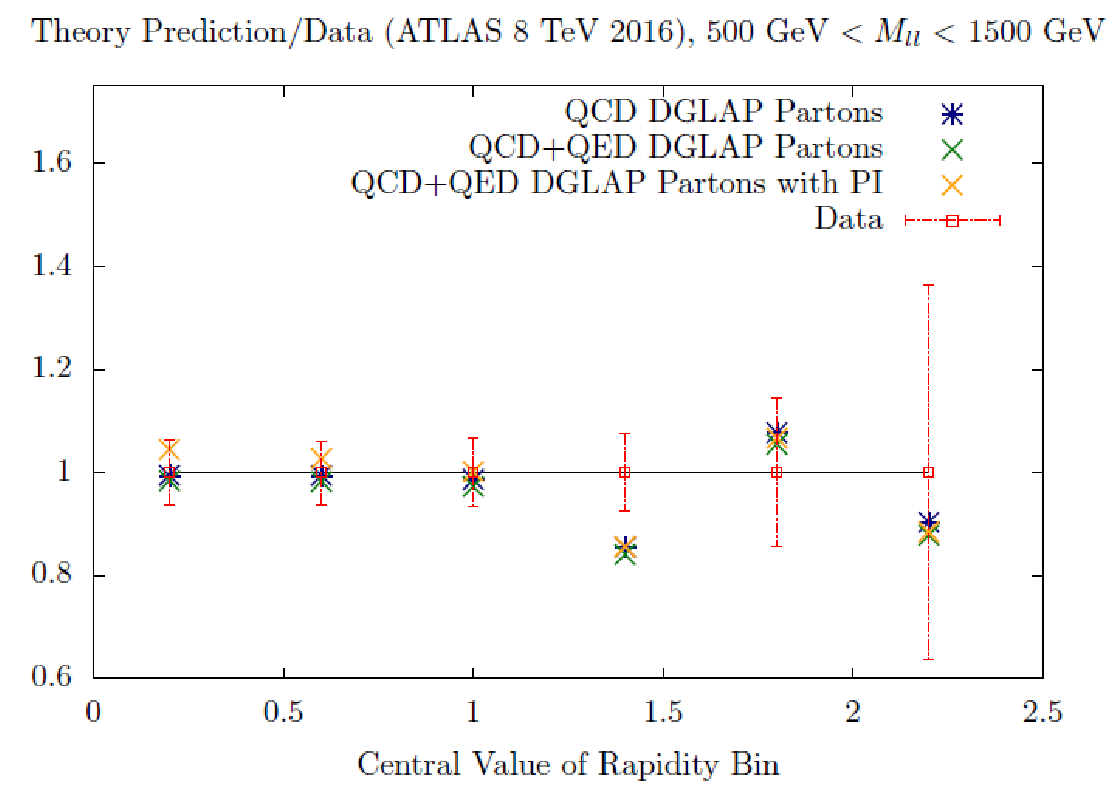
Data impact - high mass DY

ATLAS Collab., JHEP 1608 (2016) 009

- Fit to ATLAS high mass DY including photon.
- Fit quality good, but impact of photon **relatively minor** within current precision.
- Impact of QED **evolution** on other partons as important as explicit photon-initiated contribution.



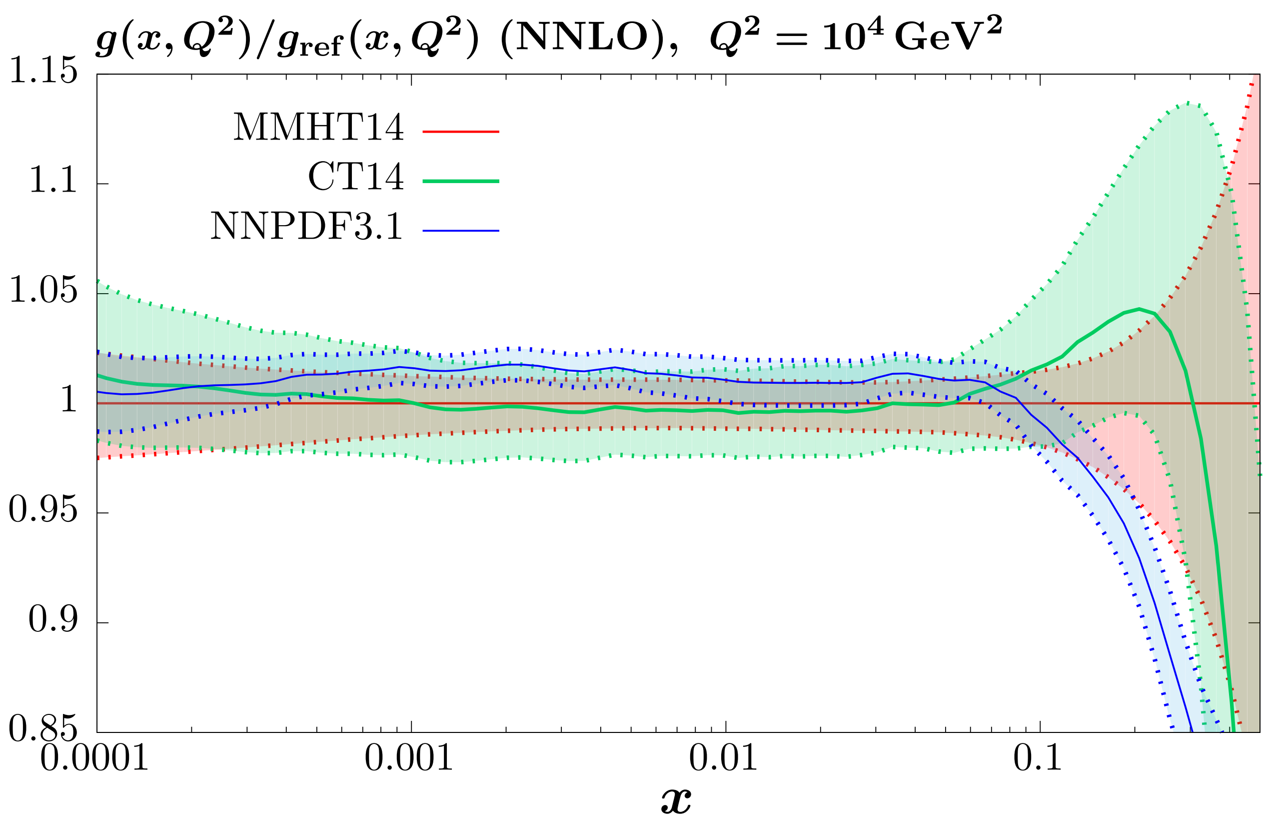


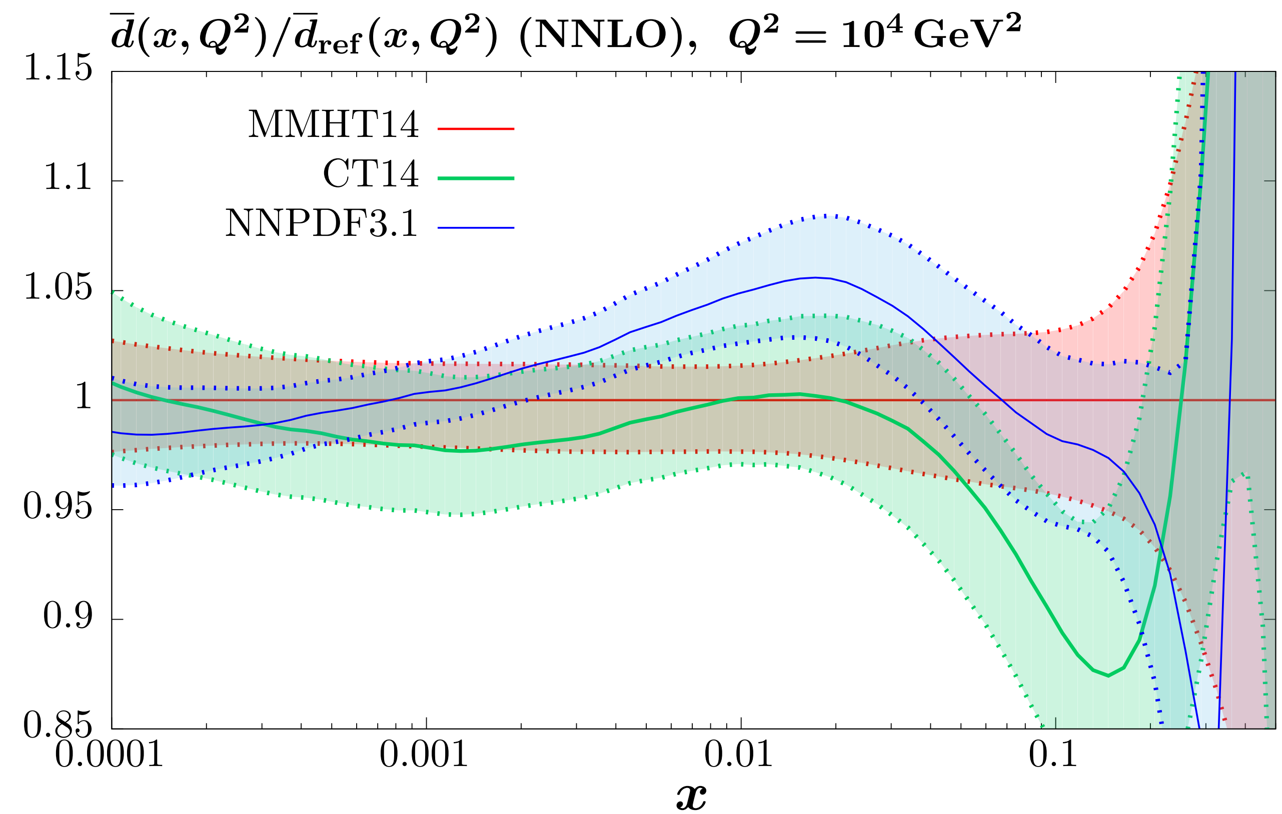


Lumi error not shown

PDFs - Where do we Stand?

- Gluon:
  - Despite varying approaches, global fits ~ **consistent** (not true in past). Uncertainties $\sim 2\%$ in some regions.
  - Biggest difference at high x, with NNPDF3.1 lower - includes more LHC data ($t\bar{t}$, jets…). Expect updates from other groups soon.
- $\bar{d}$:
  - **More variation**, in particular at high x (less constraints), more sensitive to methodological differences in this region.
- Reasonable agreement for other PDFs. Not perfect - **still work to do**.





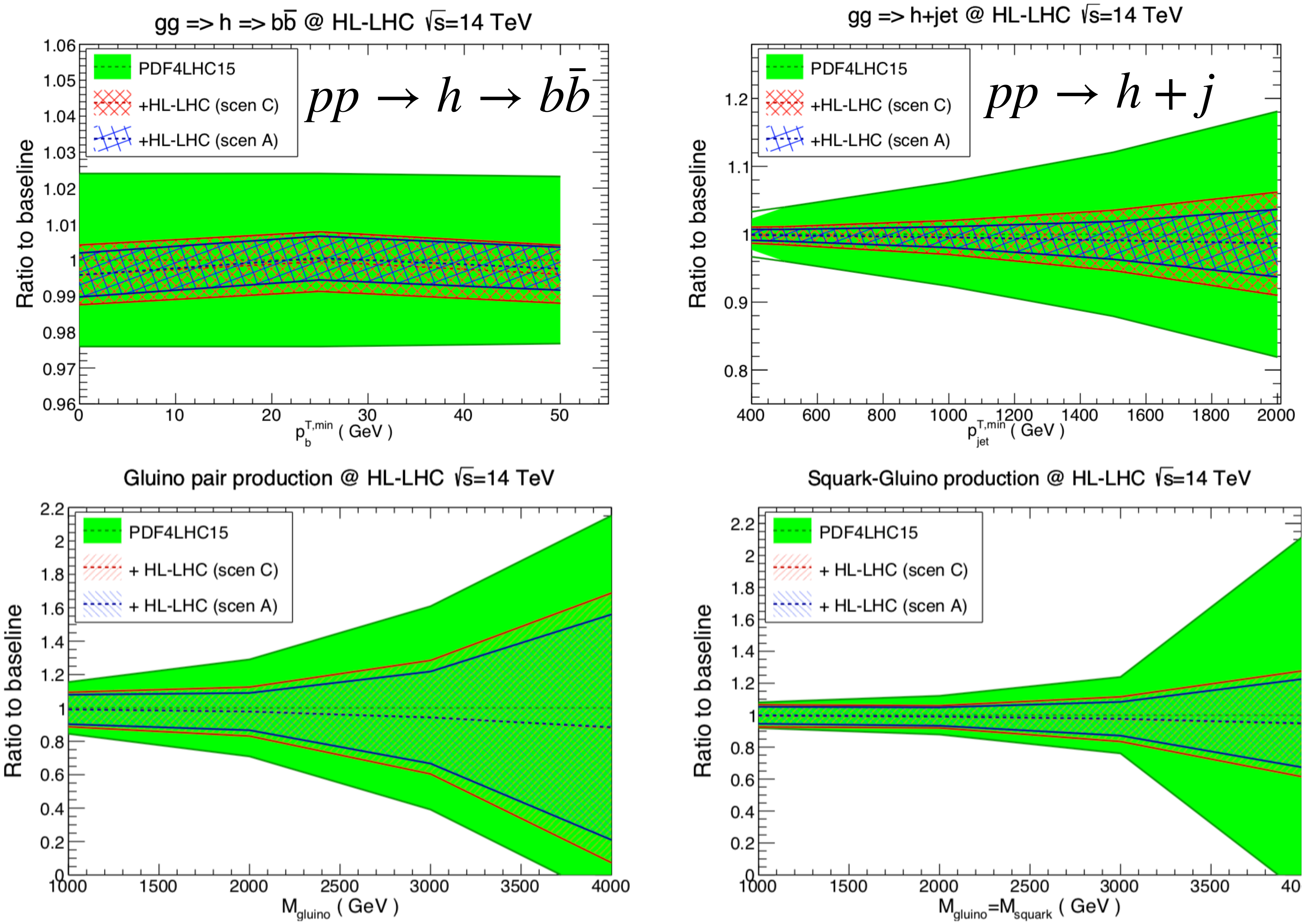
Summary/Outlook

- PDFs an essential part of LHC precision program. Have presented **a few selective examples**.
- High precision LHC data represents both a **opportunity and challenge** for PDF fitters.
- **Opportunity** - the highest ever precision measurements of standard candle SM processes playing significant role in PDF fit
- **Challenge** - confronting theory with such data not always simple. Delicate issues related to e.g. theoretical uncertainties and experimental systematics coming to the fore.
- Much progress ongoing other areas: resummation, photon PDF, theory uncertainties.
- Work on MMHT18 and MMHTQED ongoing- stay tuned!

Thank you for listening!

Backup

Ultimate PDFs - Cross sections



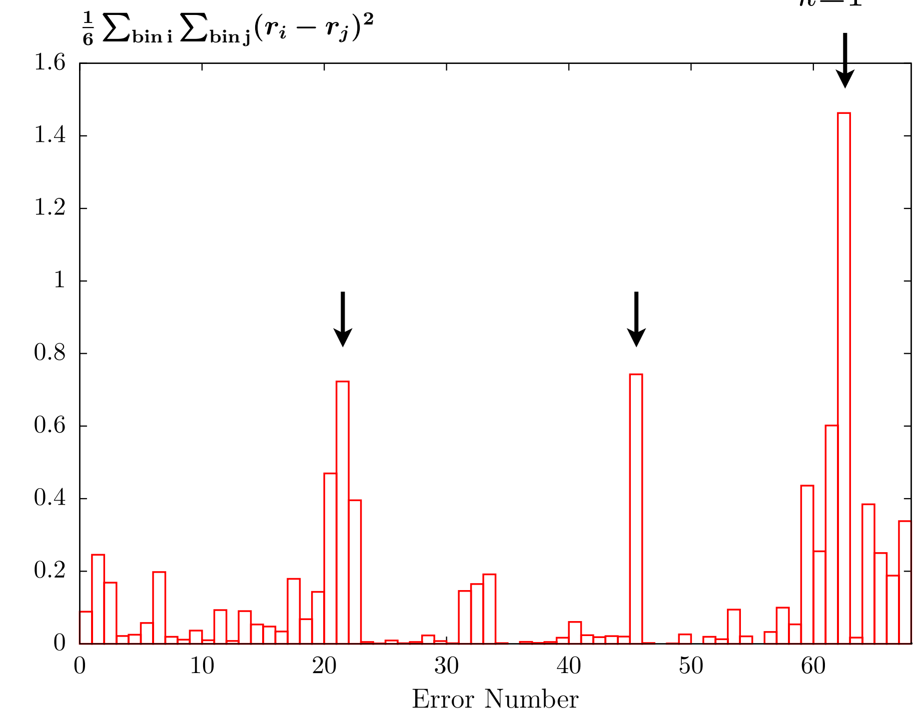
- Improvement in parton luminosities feeds through to impact on LHC cross sections, in particular gluon-initiated.

Jets correlations - in more detail

$$D_i \to D_i + \sum_{k=1}^{N_{\rm corr}} r_k \sigma_{k,i}^{\rm corr}$$

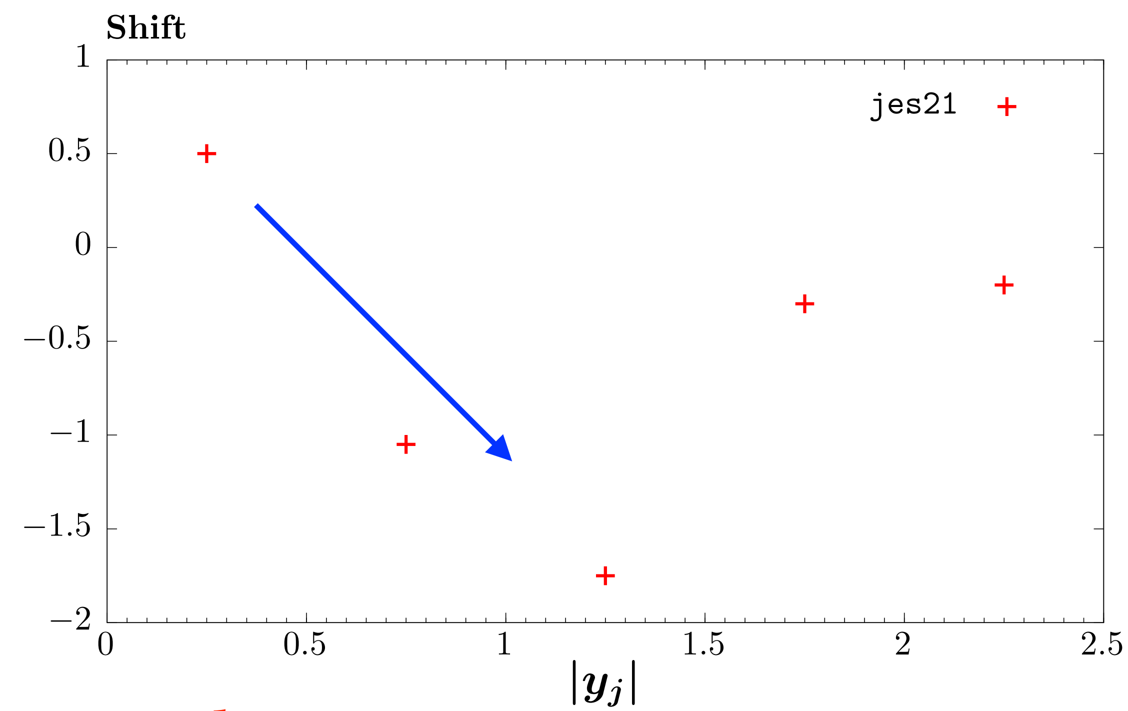
- Mismatch in neighbouring rapidity bins leads to poor fit quality.
- Decorrelating with y_j - small number of shifts prefer very different directions.
- Simple approach- decorrelate two systematics across y_j . Find dramatic improvement in χ^2.

ATLAS, JHEP 09, 020 (2017)



	Full	21	62	21,62
$\chi^2/N_{\rm pts.}$	2.85	1.58	2.36	1.27

- Clearly over-simplified (first investigation), but more complete approach $\longrightarrow$ similar gluon stability.
- Mapping out shift for `jes21` (largest impact) see clear trend in dominant y_j bins that should be picked out by more controlled decorrelation.



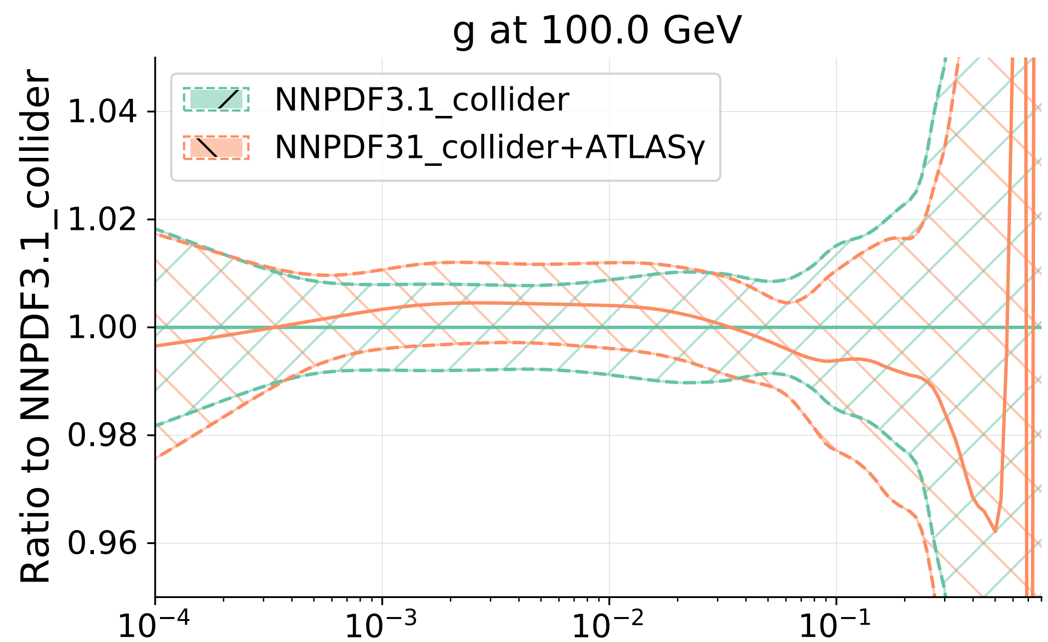
21: multijet balance asym.

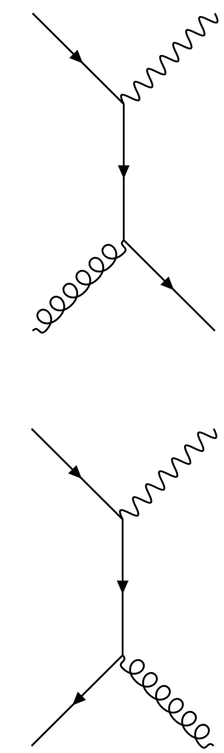
62: JES (close-by jets)

NB: errors not shown!

Other LHC Processes of Interest

- **Direct photon**: sensitivity to gluon at intermediate/high x.
- New NNLO calculations allows possibility for inclusion in precision fits.

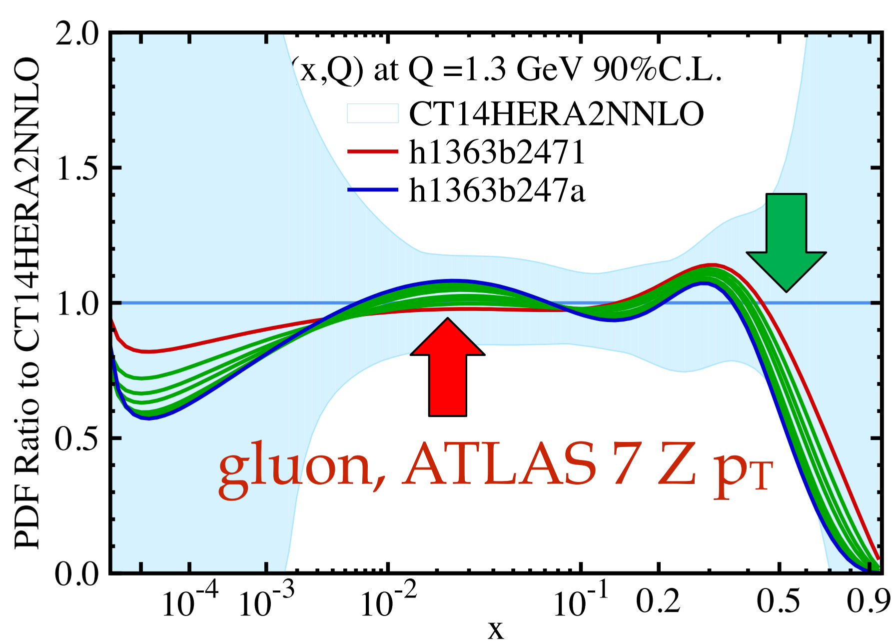




J. Gao, "Progress on CTEQ-TEA PDFs", DIS2017

J.M. Campbell et al., arXiv:1802.03021

CT17p best-fit vs. CT14 HERA2



- **Z boson $p_\perp$ distribution**. Sensitive to gluon at high . New NNLO calculation allows constraints on PDFs at this order.

Boughezal et al., Phys. Rev. Lett. 116 (2016) no 15 152001

Top differential

- Impact on gluon, fitting individually: