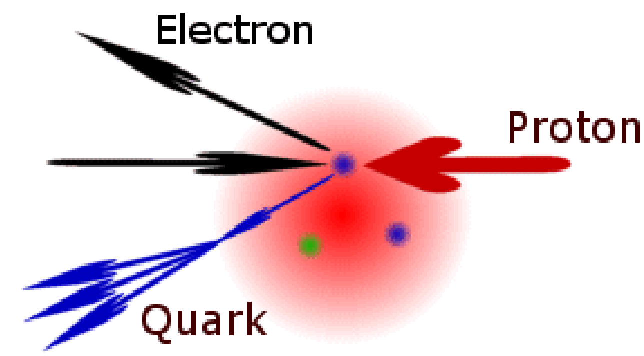
Studies of low-x higher twists @ HERA
&
strangeness @ ATLAS and CMS
(two separate analysis)

Both analyses done using xFitter & MandyFitter :)

K. Wichmann, A. Cooper-Sarkar, I. Abt, B. Foster, V. Myronenko, M. Wing, P. Gunnellini



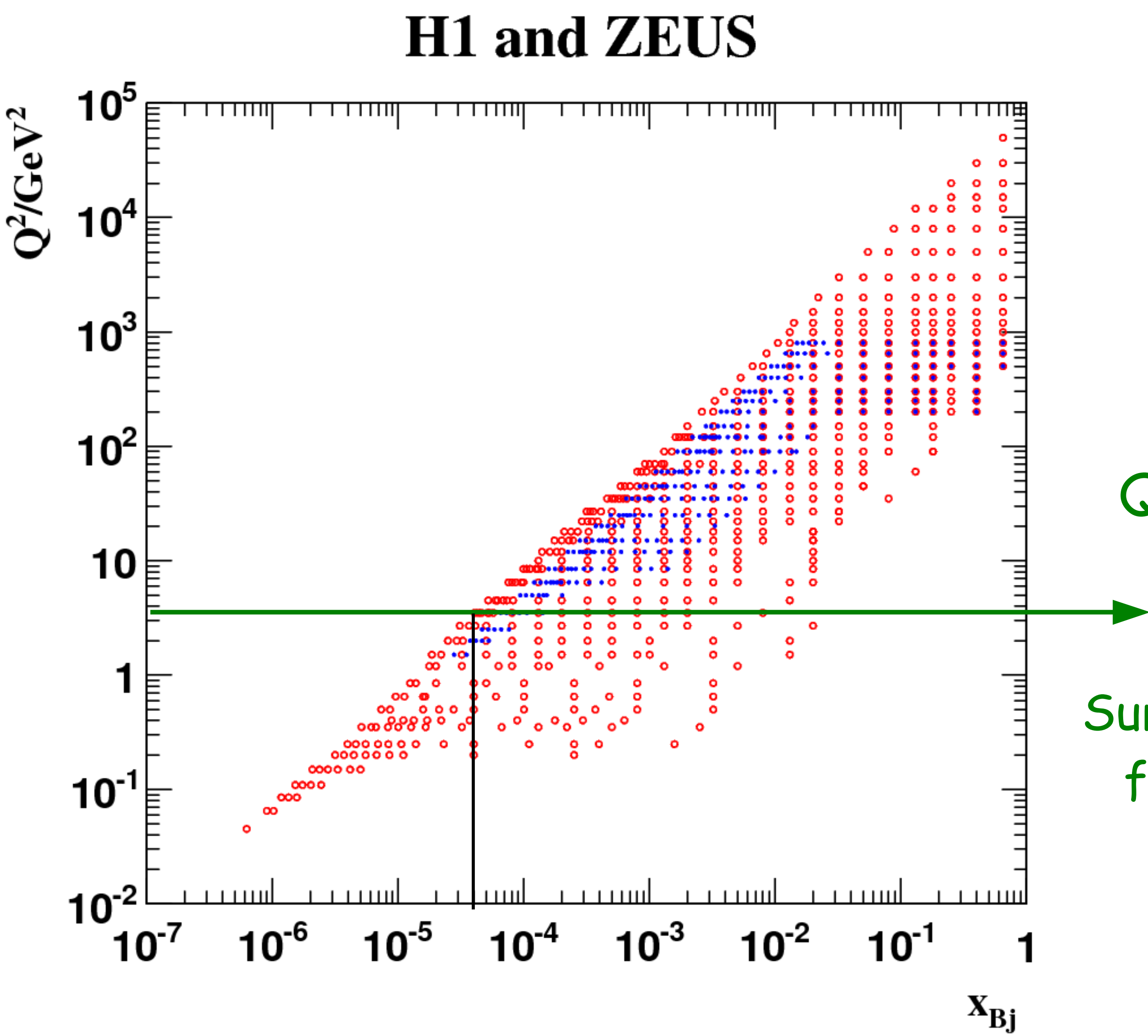
Low-x low-Q^2 higher twists @ HERA

K. Wichmann, A. Cooper-Sarkar, I. Abt, B. Foster, V. Myronenko, M. Wing

Phys. Rev. D 94, 034032 (2016), arXiv:1604.02299

Phys. Rev. D 96, 014001 (2017), arXiv:1704.03187

@ HERA low $Q^2 \rightarrow$ low x



$Q^2_{min} = 3.5\ GeV^2$

Surprisingly we can fit so low in Q^2

HERAPDF2.0 @ low Q^2 and low x

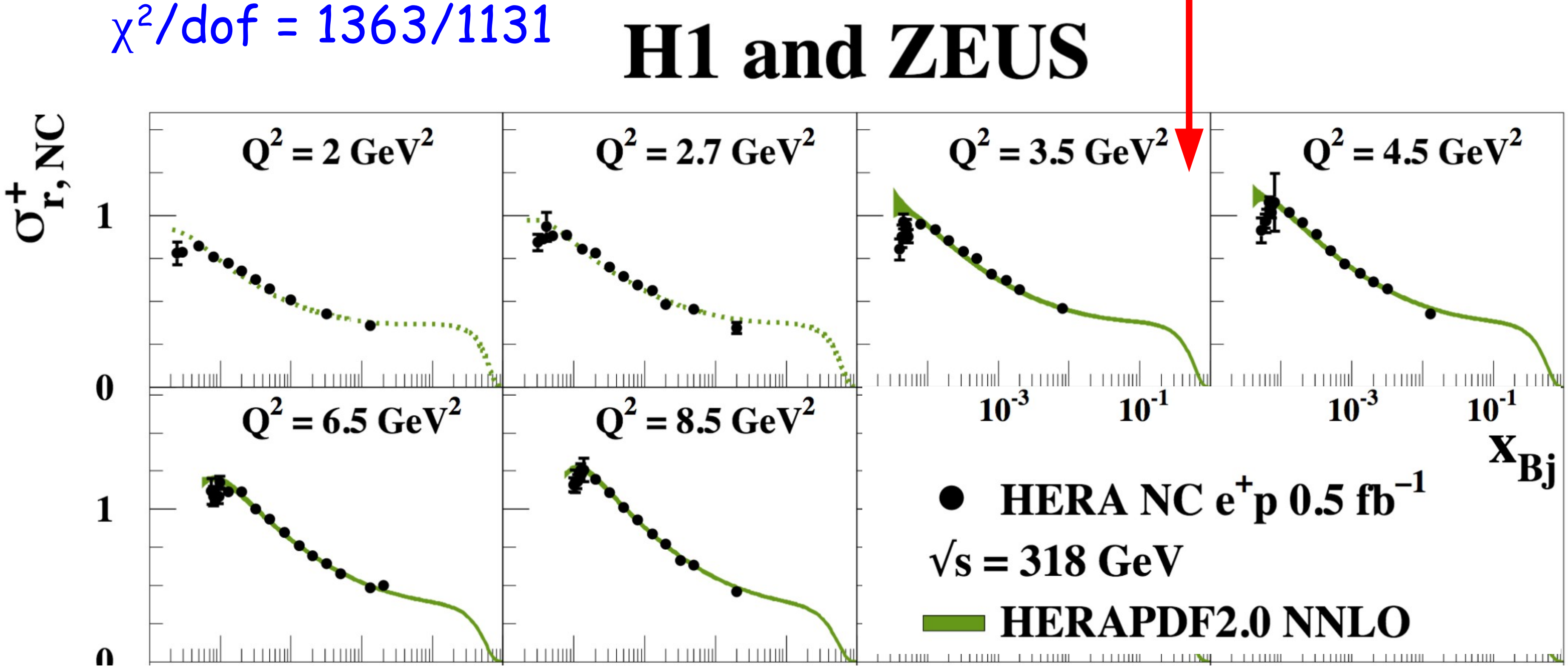
- NLO fit for Q^2_{min} = 3.5 GeV²

  χ^2/dof = 1357/1131

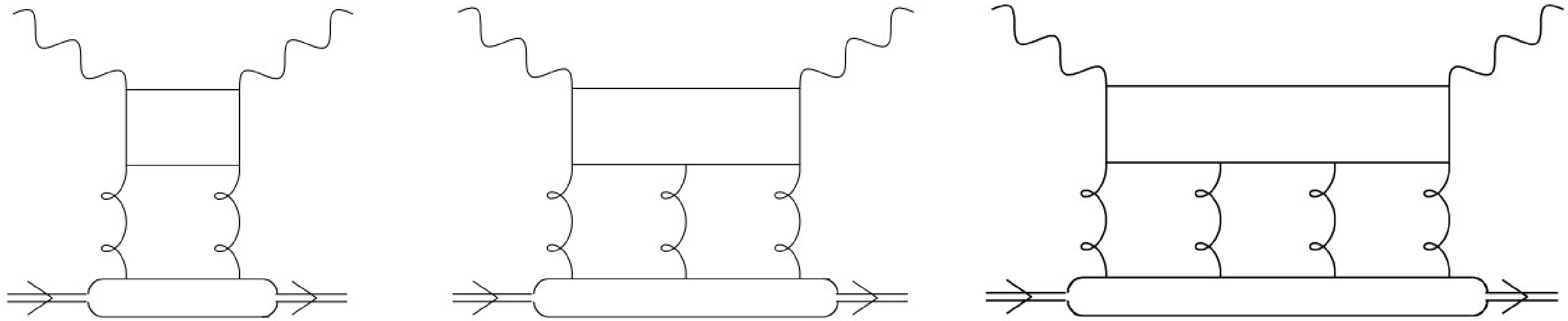
- NNLO fit for Q^2_{min} = 3.5 GeV²

  χ^2/dof = 1363/1131

- Let's see how HERA low Q^2, low x data are described by predictions
  - Not that great...

- 

Higher-twist corrections



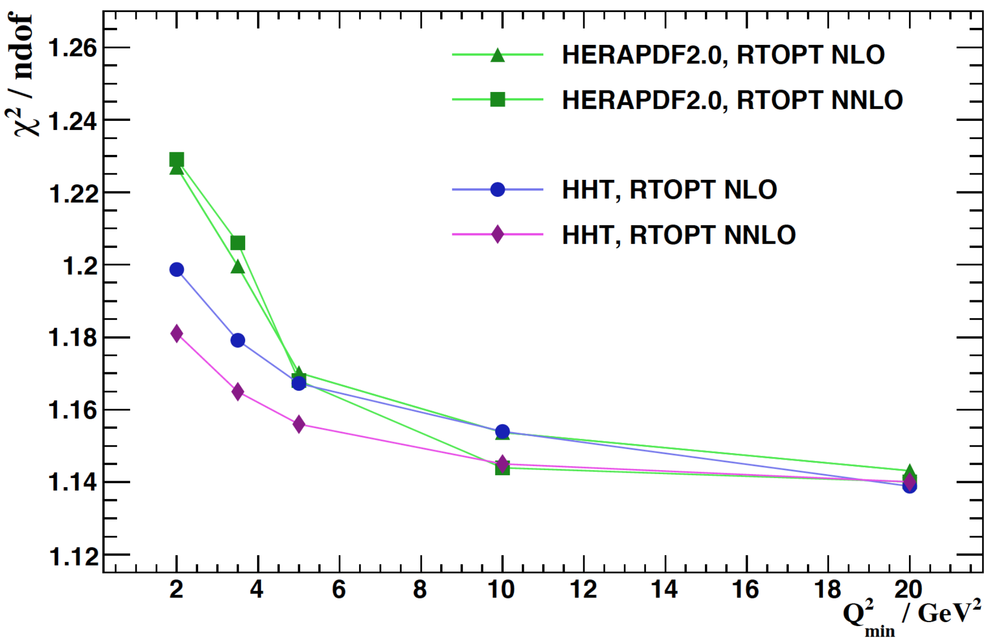
- higher twist terms acting at low-x considered
- their origin COULD be connected with the recombination of gluon ladders
- Bartels, Golec-Biernat, Peters suggested that such higher twist terms would cancel between σ_L and σ_T in F_2, but remain strong in F_L
- simplest possible modification to structure functions F_2 and F_L as calculated from HERAPDF2.0 formalism tried

$$F_2^{\mathrm{HT}} = F_2^{\mathrm{DGLAP}} (1 + \boxed{A_2^{\mathrm{HT}}}/Q^2)$$ has almost no effect

$$F_L^{\mathrm{HT}} = F_L^{\mathrm{DGLAP}} (1 + \boxed{A_L^{\mathrm{HT}}}/Q^2)$$ **helps a lot, A~4-5**

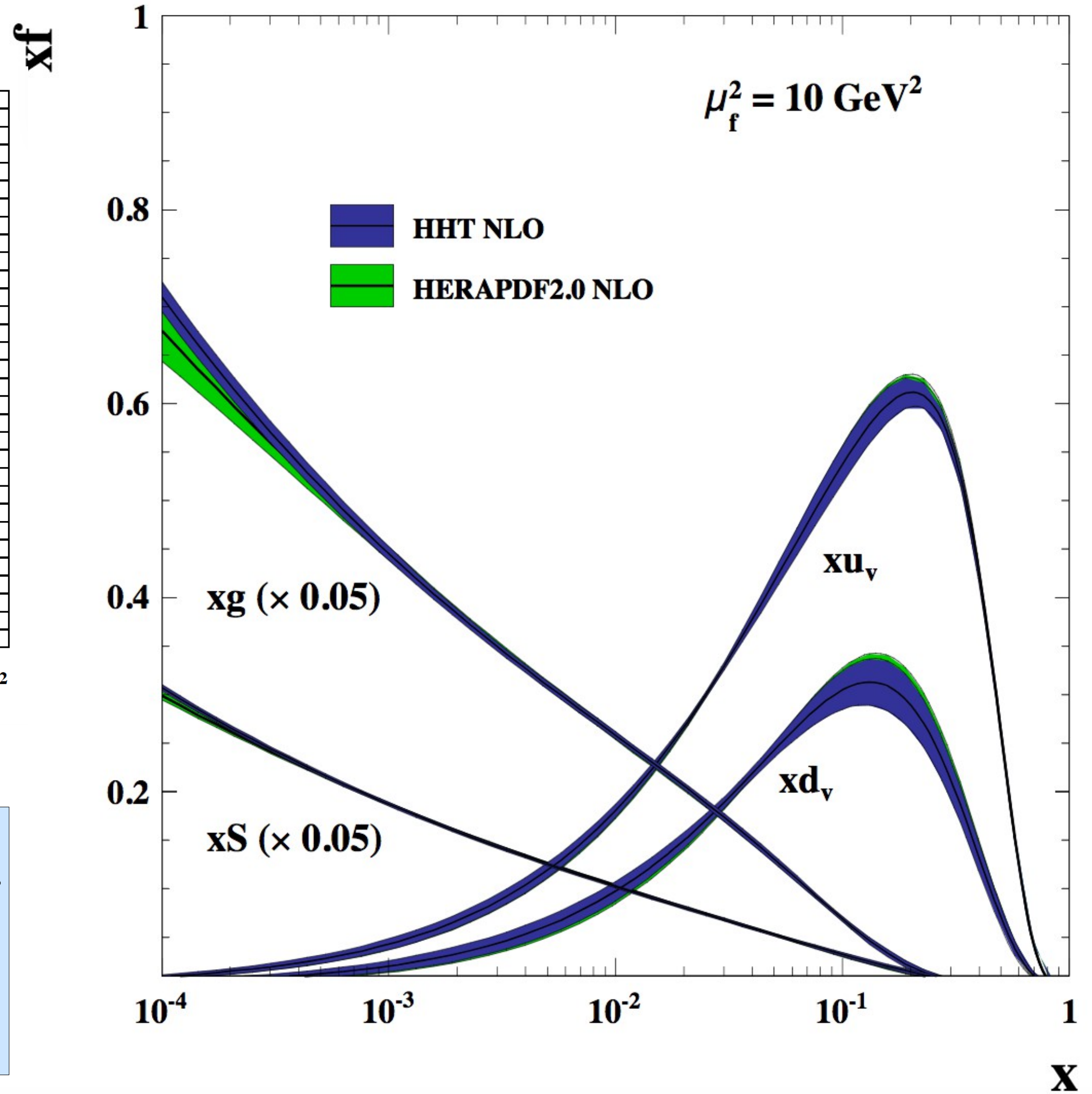
Higher-twist effects

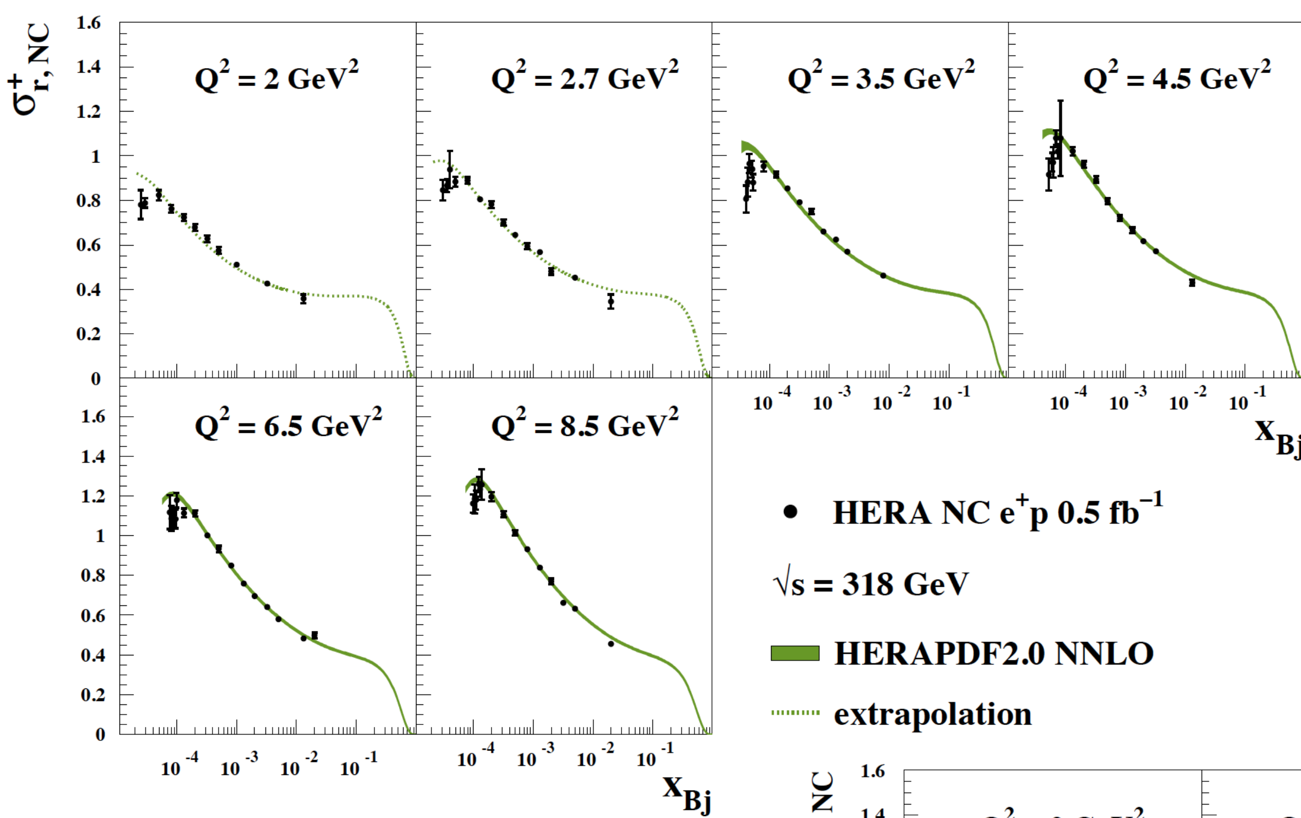
- Q^2 dependence flattens



higher twist modification does not affect high-scale LHC physics

- PDFs similar





- Low-Q^2 data description much improved
- including extrapolation down to $Q^2 = 2$ GeV^2
- NNLO does better then NLO

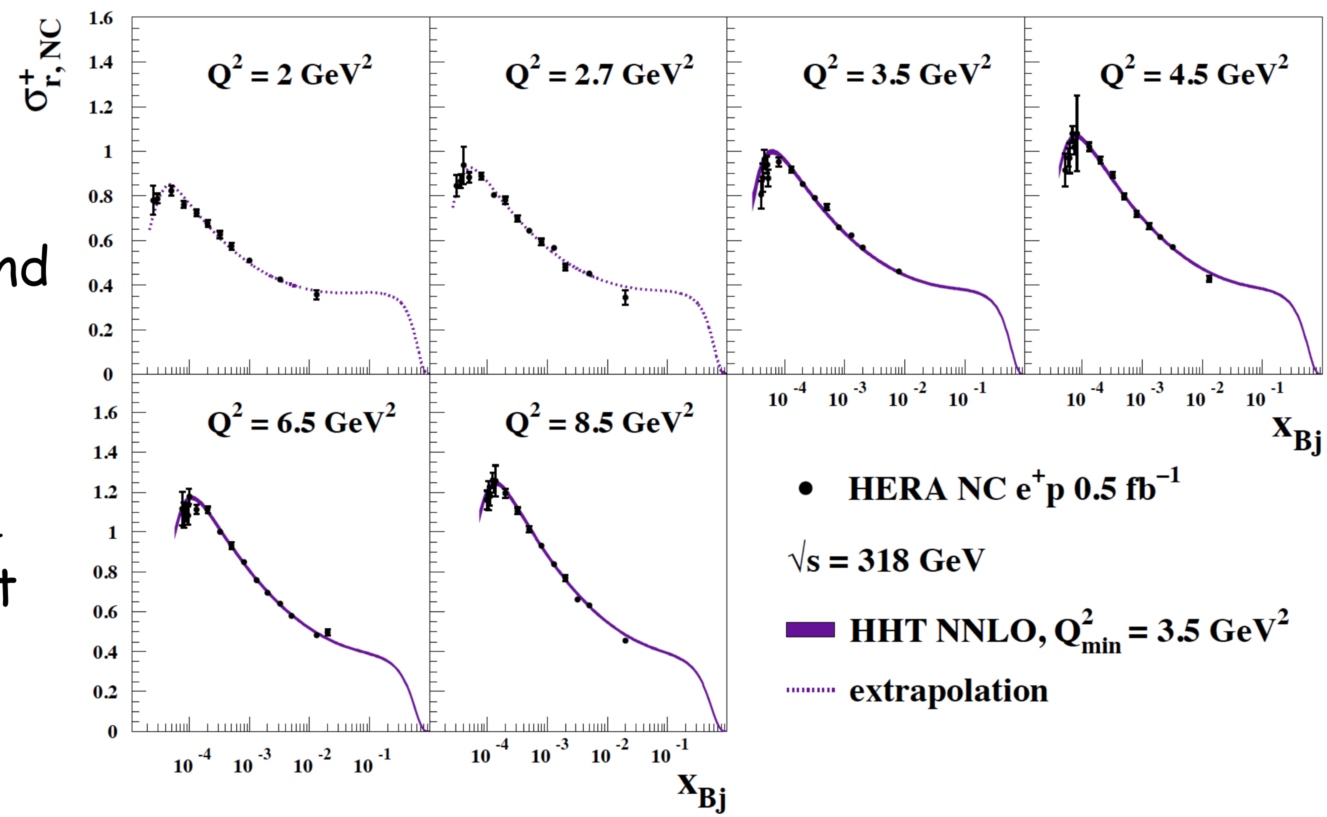
why HHT fits do so well?

K. Wichmann

- HHT describes turn-over and slope better

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

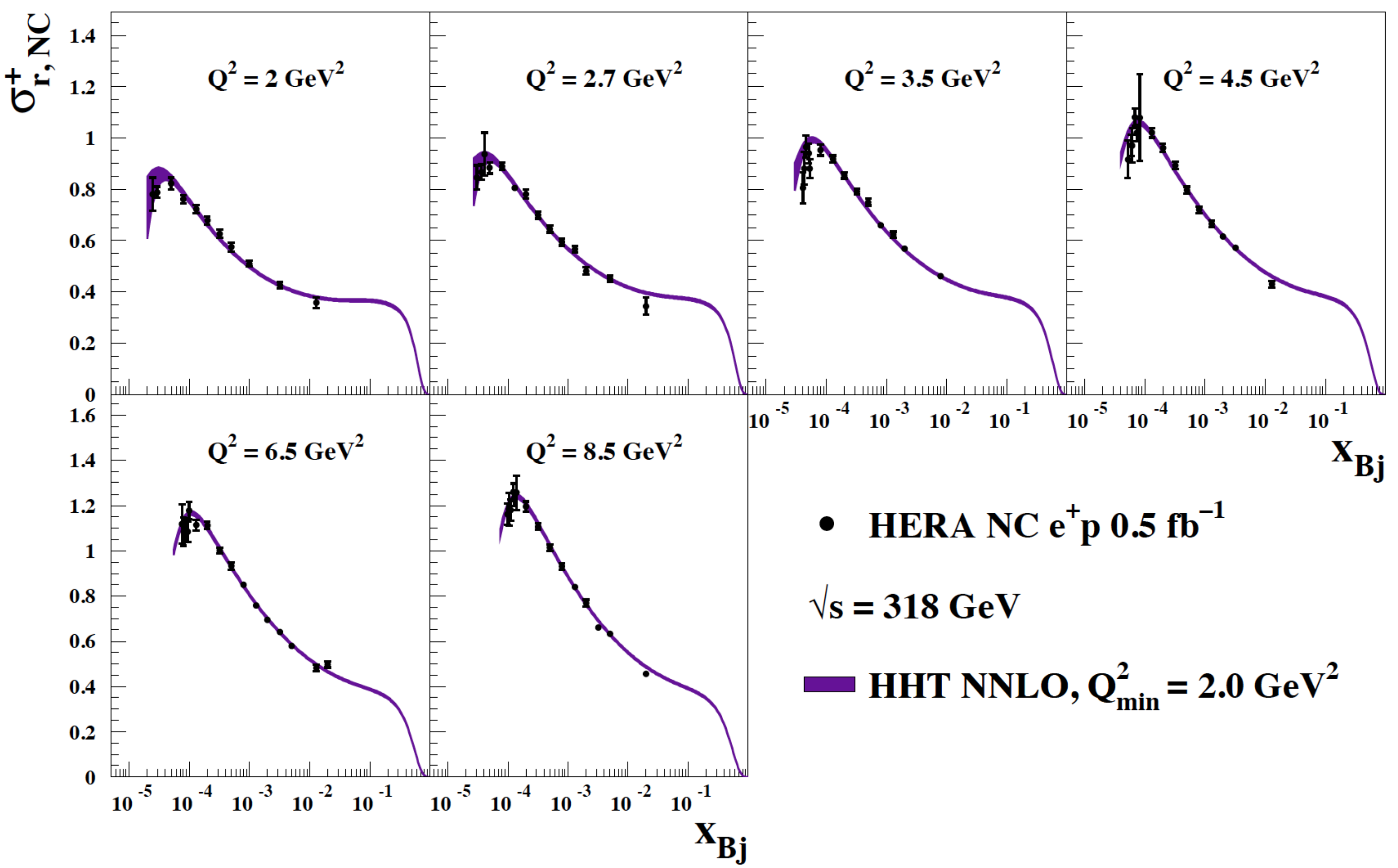
- data clearly wants larger F_L
  - this is what higher twist term provides



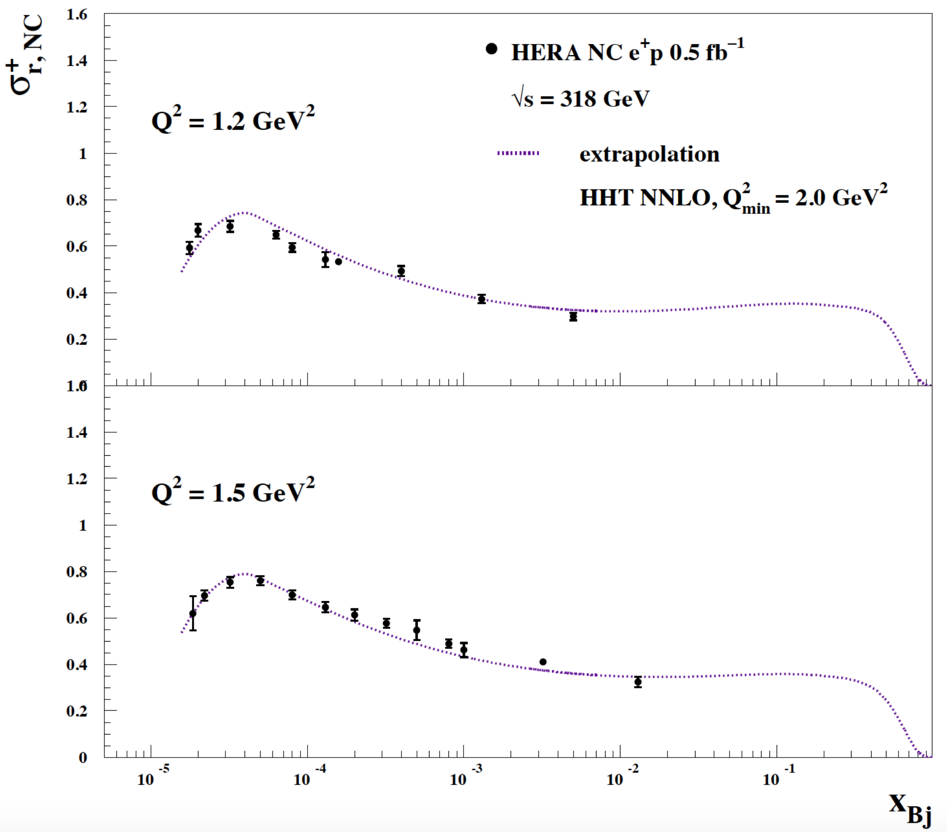
Let's be bold and fit from $Q^2 = 2\ GeV^2$

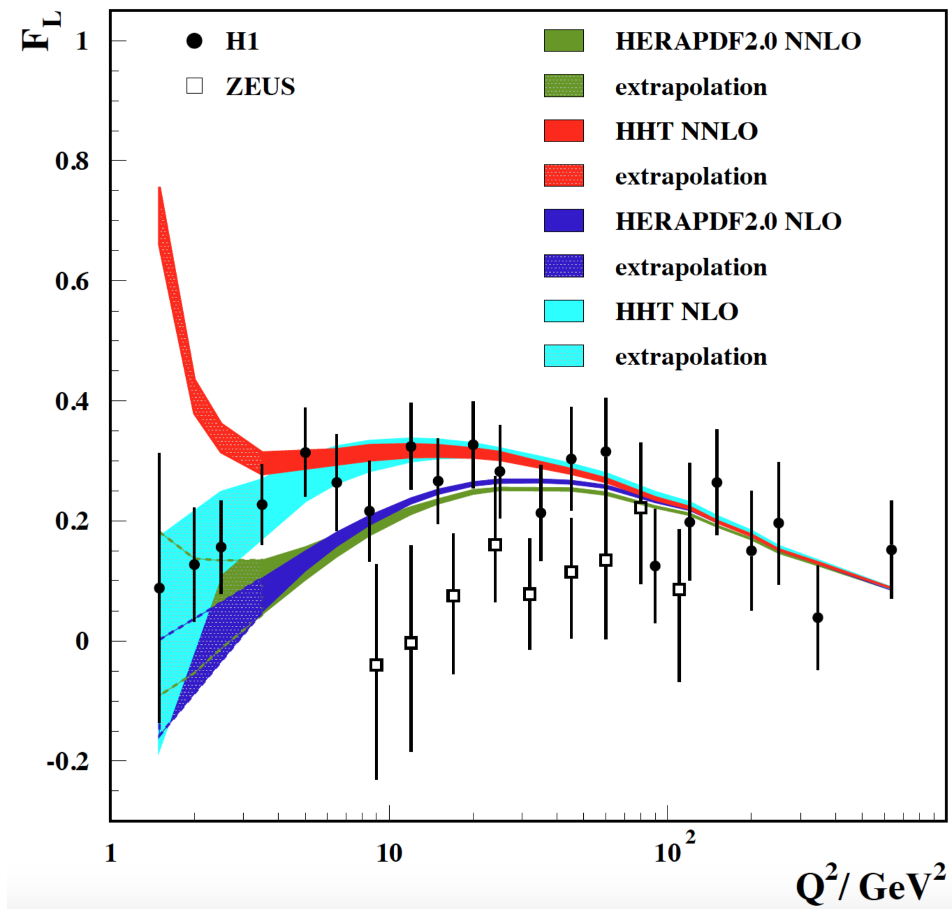
	$Q^2_{min} = 3.5\ GeV^2$		$Q^2_{min} = 2\ GeV^2$
NLO	$A_L^{HT} = 4.2 \pm 0.7\ GeV^2$	→	$A_L^{HT} = 4.0 \pm 0.6\ GeV^2$
NNLO	$A_L^{HT} = 5.5 \pm 0.6\ GeV^2$	→	$A_L^{HT} = 5.2 \pm 0.7\ GeV^2$

Look at the excellent description at low Q^2



Extrapolation down to $Q^2 \sim 1$ GeV^2





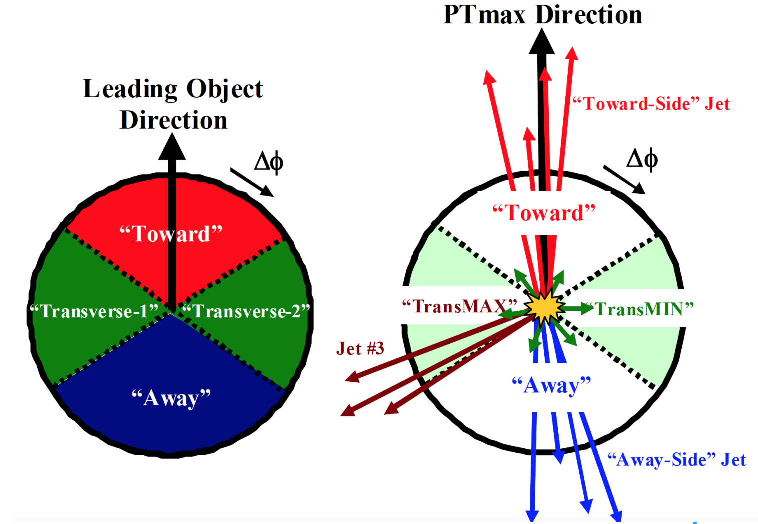
But beware… is this actually reasonable?

What does F_L itself look like?

- NNLO HHT FL prediction untamed at low Q^2
- this approach can't be pushed too far
- this comes from NNLO coeff. functions and the $1/Q^2$ term makes it worse

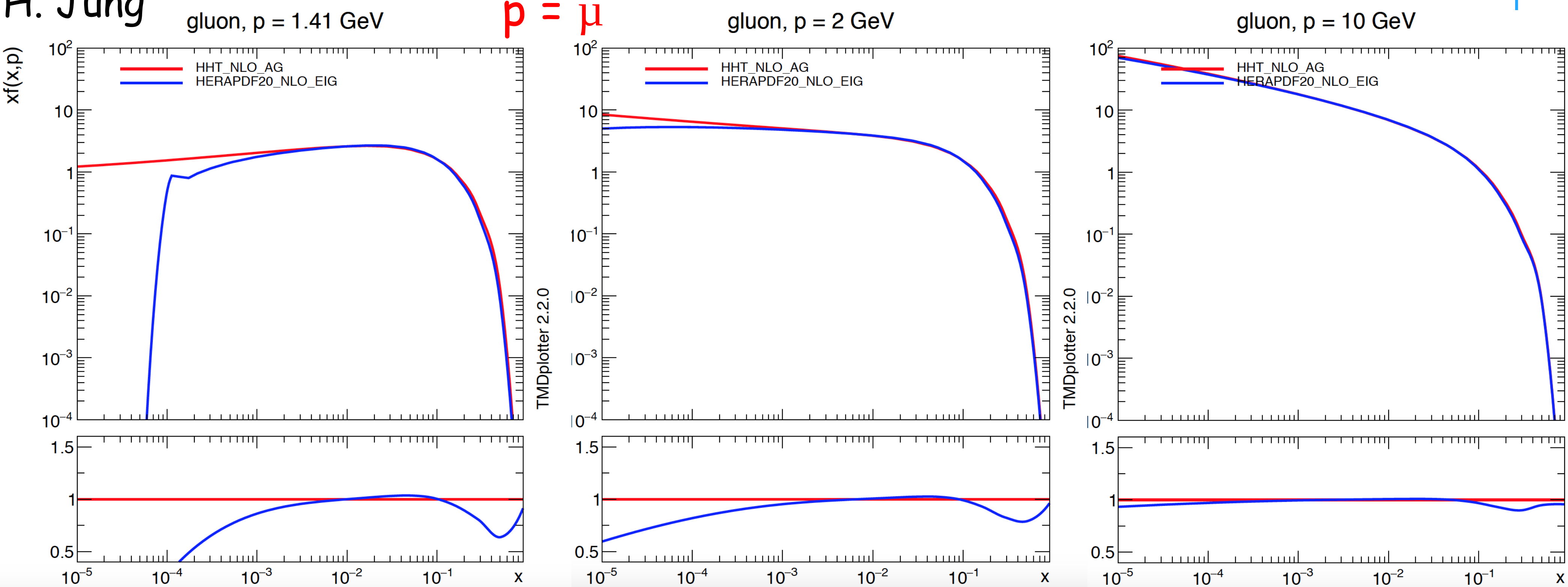
Used in MC tuning: underlying event

- Interest in MC community for PDF describing data well down to lowest possible Q^2
  - HHT NLO AG can be used → AG (alternative gluon): no negative gluon term
  - First use: tune for underlying event, private work done in CMS



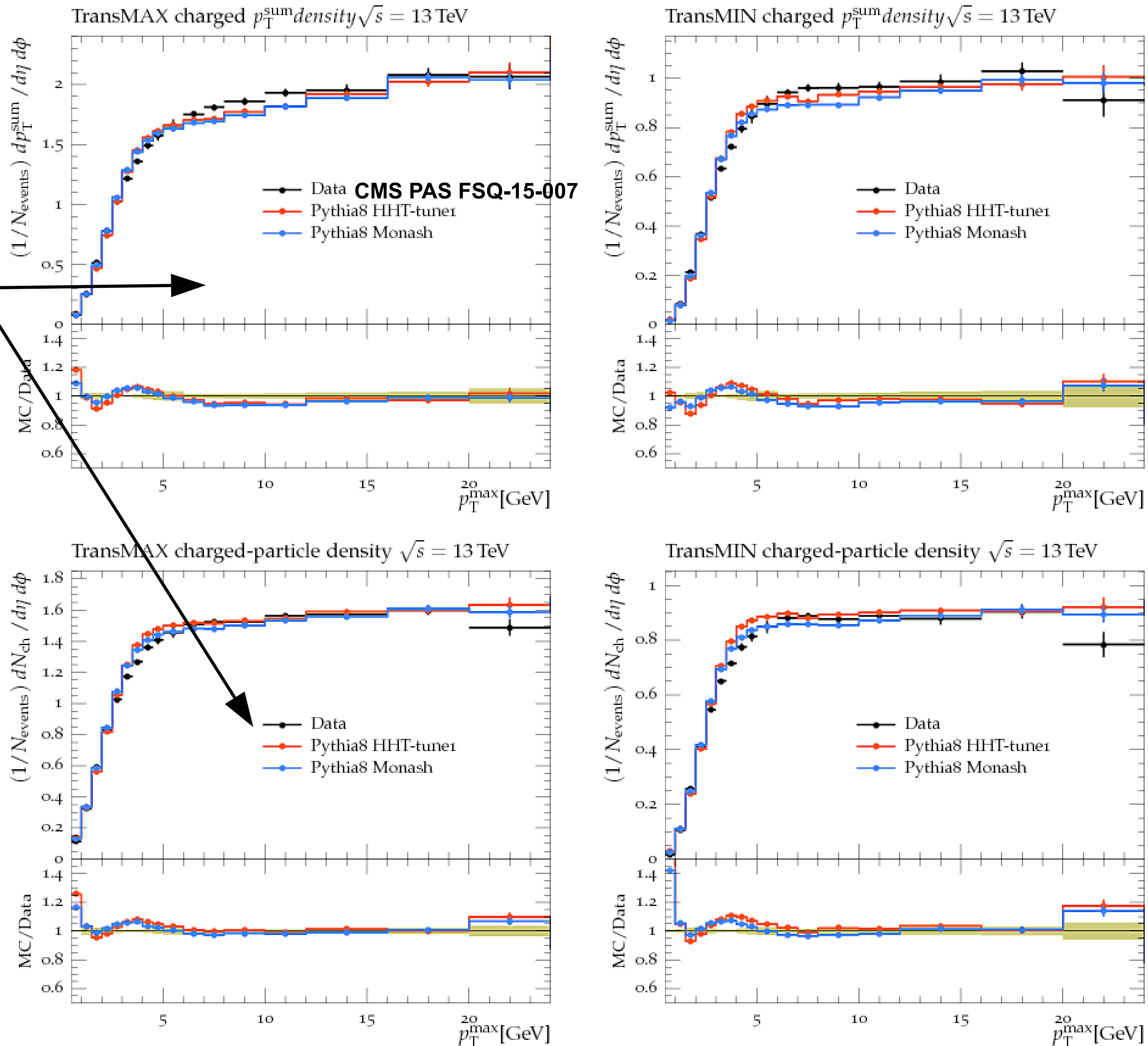
H. Jung

p = μ



MC tuning: underlying event

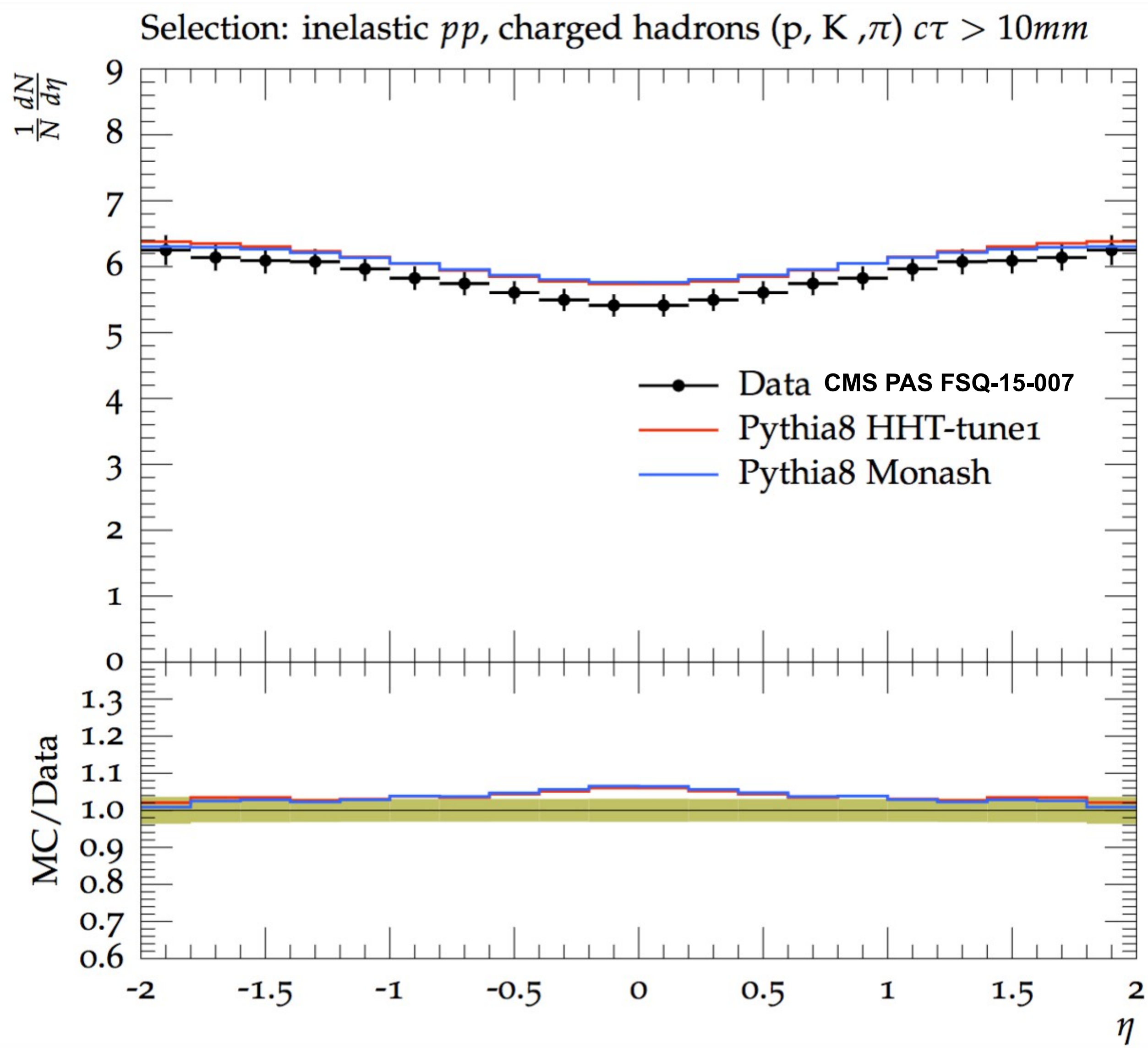
- 4 tuned variables
- 1 tuned parameter



P. Gunnellini, private communication

MC tuning

- Global variable: compares well with standard Monash tune with NNPDF

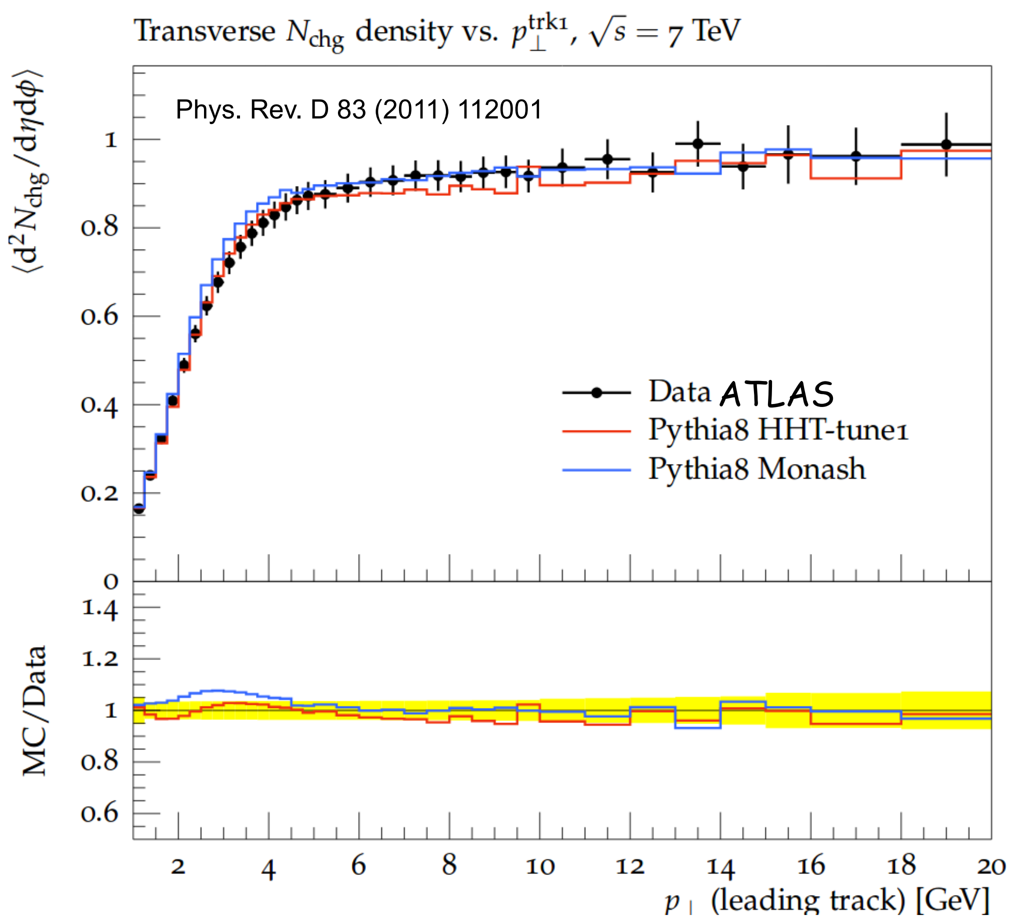


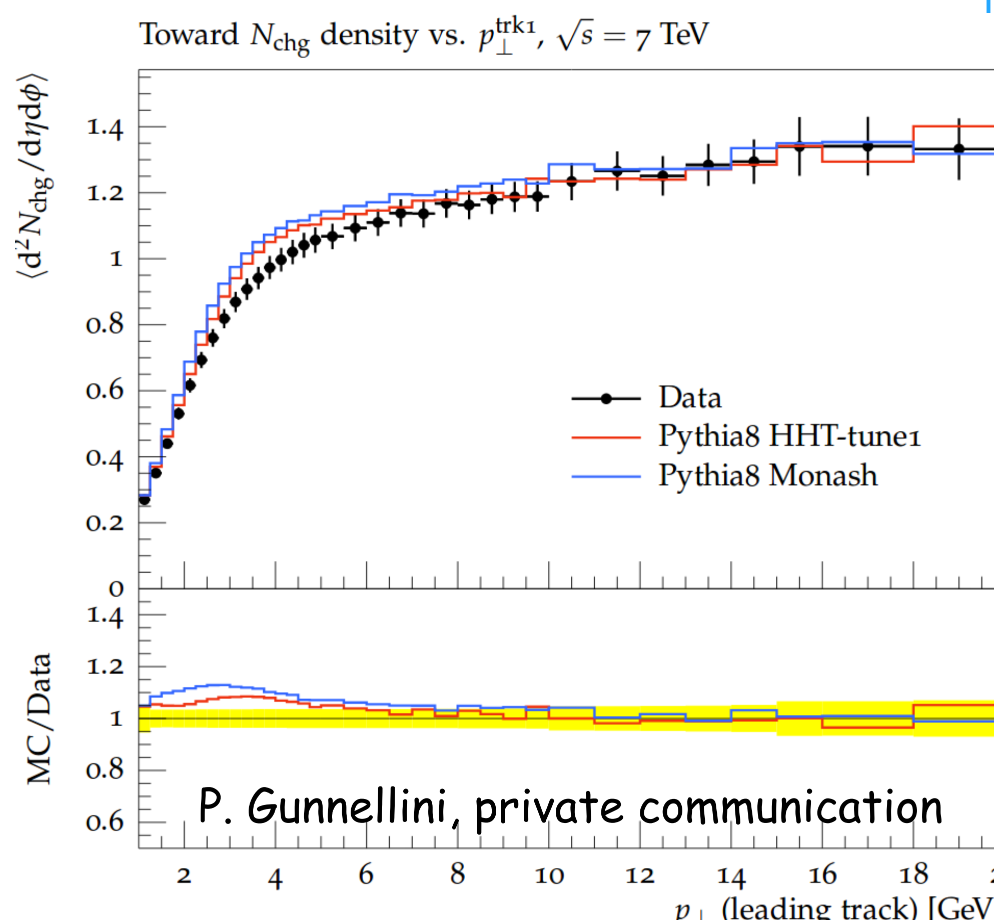
P. Gunnellini, private communication

MC tuning: comparison to ATLAS data

Phys. Rev. D 83 (2011) 112001

- Compares well with standard Pythia Monash tune
  - Sometimes better / sometimes a bit worse





- Work in progress → hope that for tunes with lower energies PDF better describing low Q^2 will be beneficial

QCD analysis of the ATLAS and CMS W± and Z cross-section measurements and implications for the strange sea density

arXiv:1803.00968

K. Wichmann, A. Cooper-Sarkar

Motivation

- In PDF fits x ~ 0.01 primarily constrained by HERA data: light flavor quarks and antiquarks
- flavor composition of total light sea not well determined using HERA data alone

  → in particular little is known about strange sea
- Neutrino data suggest suppression of strange sea: sbar(x) = 0.5 dbar(x)
  - CMS W+charm analysis supports suppression
  - ATLAS W+charm analysis finds no suppression
  - Interpretation of neutrino data is sensitive to uncertainties from charm fragmentation and nuclear corrections
  - Analysis of W+c data involve assumptions on charm jet fragmentation and hadronisation
- Drell-Yan process and DIS are theoretically best understood processes

→ Interesting to investigate if this disagreement is present for the inclusive Drell Yan data of ATLAS and CMS

Input data sets additionally to HERA DIS

- CMS
  - Z at 7 TeV → full covariance matrix for uncertainties

    CMS Collaboration, JHEP 12 (2013) 030, [arXiv:1310.7291].
  - W asymmetries at 7 TeV → systematic correlations

    CMS Collaboration, Phys. Rev. D 90 (2014) 032004, [arXiv:1312.6283].
  - W^{+-} cross sections (cross-checked with W asymmetries) at 8 TeV → systematic correlations

    CMS Collaboration, Eur. Phys. J. C 76 (2016) 469, [arXiv:1603.01803].
  - Z at 8 TeV → full covariance matrix for uncertainties → cross-check

    CMS Collaboration, Eur. Phys. J. C 75 (2015) 147, [arXiv:1412.1115].
- ATLAS
  - W and Z cross sections from one data sets – correlations → correlated systematic uncertainties as nuisance parameters

    ATLAS Collaboration, Eur. Phys. J. C 77 367 (2017), [arXiv:1612.03016]

→ for Z data we use only Z-mass-peak measurements

→ off-peak data added for cross-check

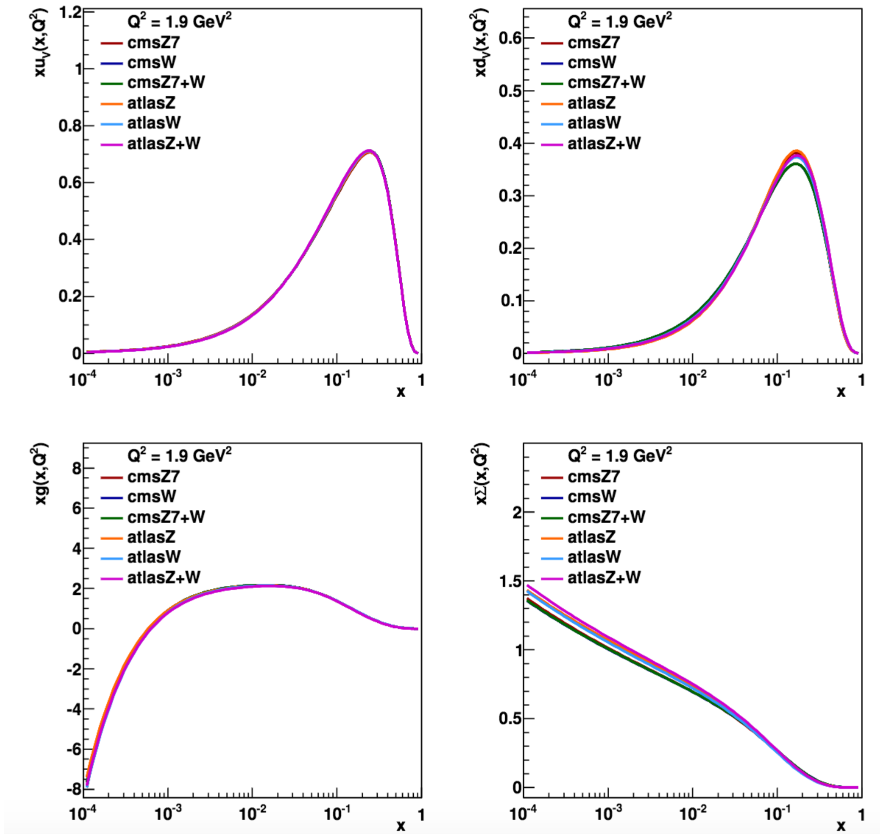
QCD analysis

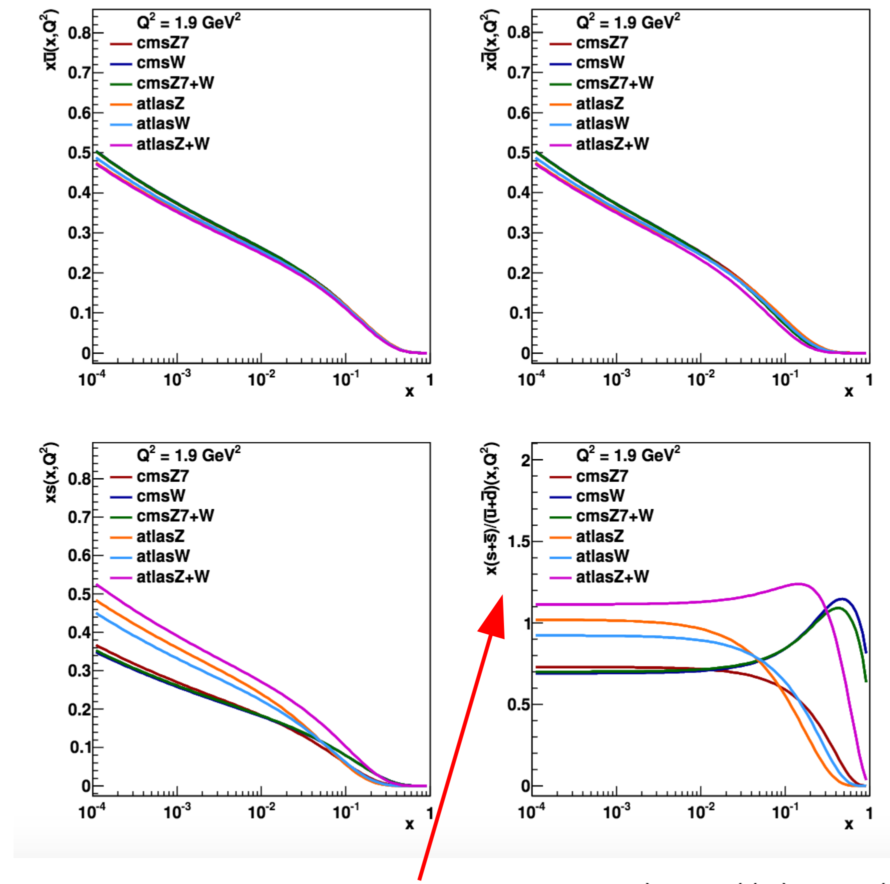
- QCD analysis at NNLO, following ATLAS paper, using xFitter + independent code
  - RTOPT, Q^2 of HERA data from 7.5 GeV^2
  - K-factors, APPLGRID predictions
- Parameterisation: 15 free parameters, 2 for strange sea
  - Chosen after parameterisation scan

$$
\begin{aligned}
xu_v(x) &= A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1 + E_{u_v} x^2)\,, \\
xd_v(x) &= A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}}\,, \\
x\bar{u}(x) &= A_{\bar{u}} x^{B_{\bar{u}}} (1-x)^{C_{\bar{u}}}\,, \\
x\bar{d}(x) &= A_{\bar{d}} x^{B_{\bar{d}}} (1-x)^{C_{\bar{d}}}\,, \\
xg(x) &= A_g x^{B_g} (1-x)^{C_g} - A'_g x^{B'_g} (1-x)^{C'_g}\,, \\
x\bar{s}(x) &= A_{\bar{s}} x^{B_{\bar{s}}} (1-x)^{C_{\bar{s}}}\,,
\end{aligned} \tag{22}
$$

where $A_{\bar{u}} = A_{\bar{d}}$ and $B_{\bar{s}} = B_{\bar{d}} = B_{\bar{u}}$. Given the enhanced sensitivity to the strange-quark distribution through the ATLAS data, $A_{\bar{s}}$ and $C_{\bar{s}}$ appear as free parameters, assuming $s = \bar{s}$. The experimental data uncertainties are propagated to the extracted QCD fit parameters using the asymmetric Hessian method based on the iterative procedure of Ref. [128], which provides an estimate of the corresponding PDF uncertainties.

Fits to CMS & ATLAS data separately

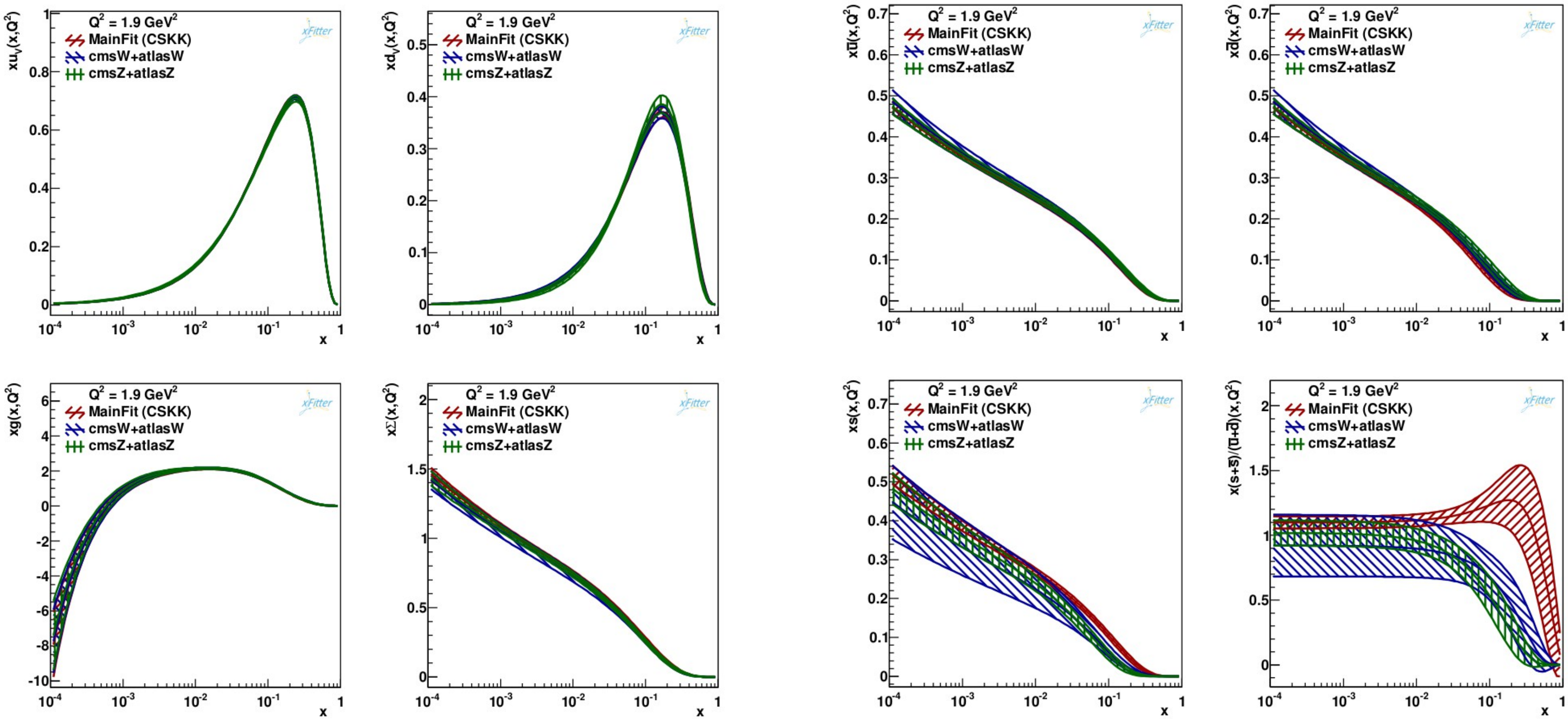




This ratio is unity if strange quarks are not suppressed in relation to light quarks and is ~ 0.5 for the conventional level of suppression.

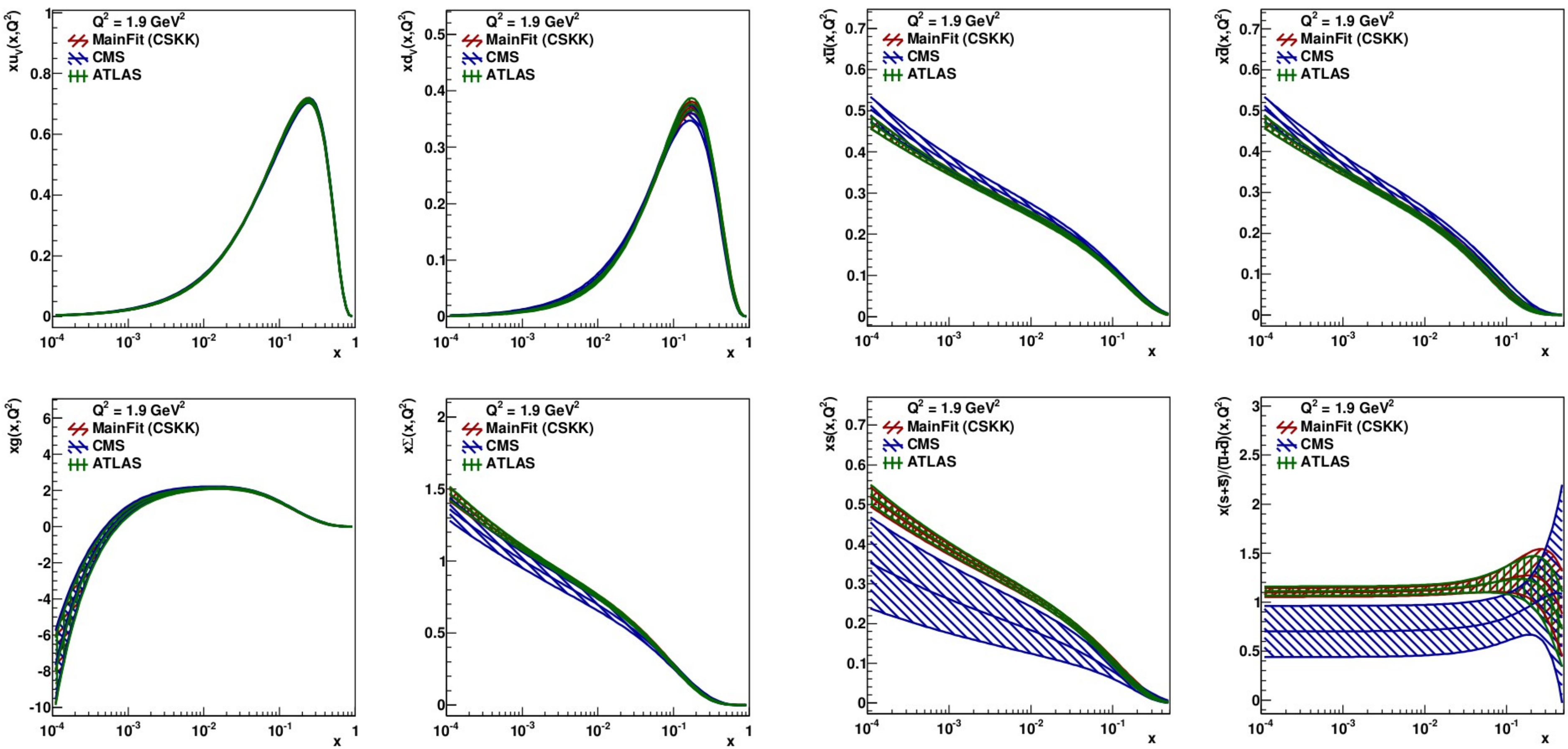
- Valence, gluon and total sea similar
- Break-up of sea – sensitive to LHC data – different for CMS and ATLAS
- at small x neither data support conventional level of suppression
- For x > 0.1 parameterisation uncertainties usually large

Fits to CMS & ATLAS data together



- Valence, gluon and total sea similar
- Flavor break up of sea is similar at small x for W and Z data separately
- Both data sets support unsuppressed strangeness
  - Most information comes from Z data
  - For ATLAS correlations between Z and W important
- For $x > 0.1$ parameterisation uncertainties become large

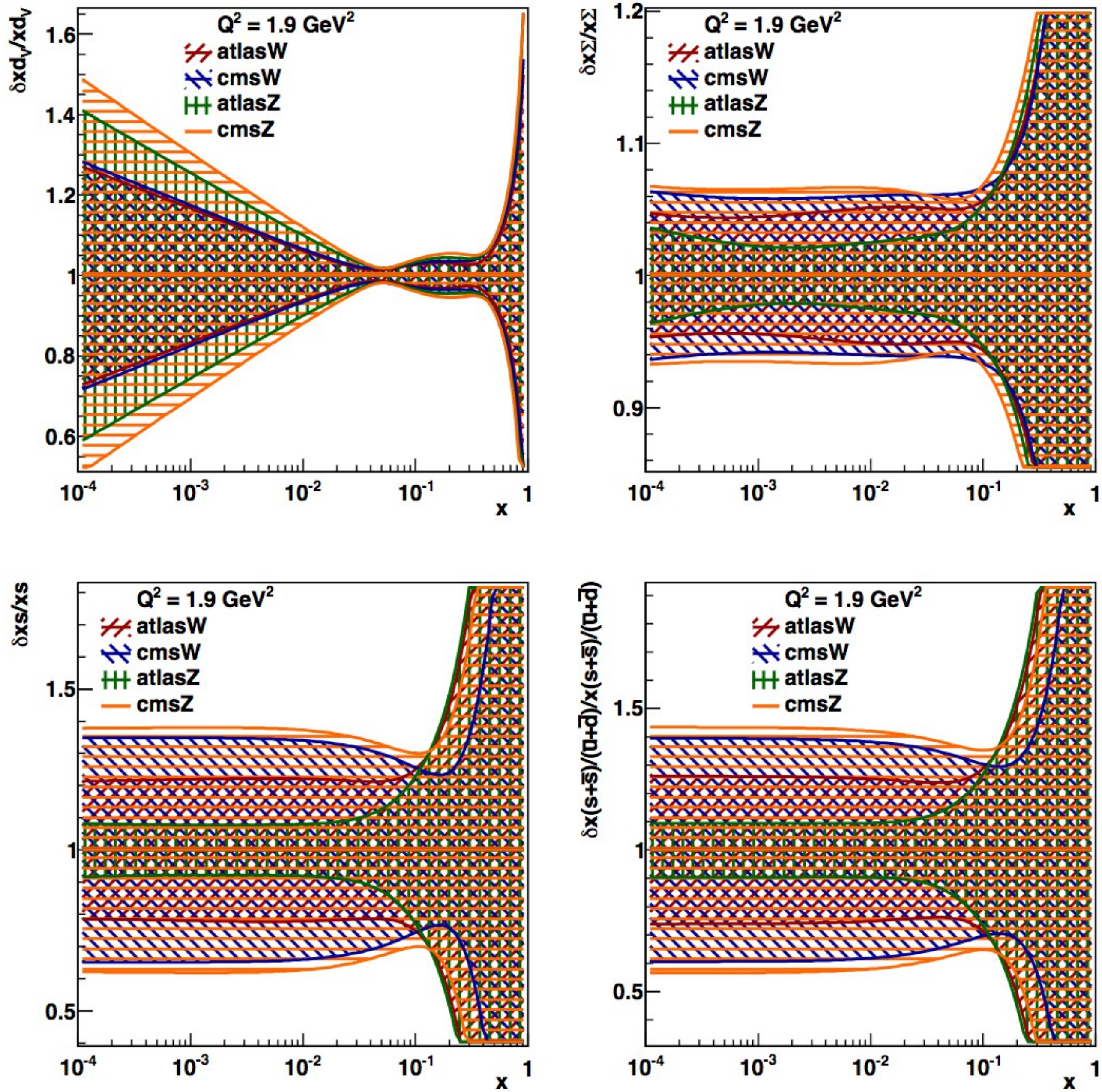
CMS vs ATLAS vs both



- Experimental uncertainties
- Valence, gluon and total sea are similar for PDFs from ATLAS and CMS data, small differences well within uncertainties
- Strange distributions differ
- For x ~ 0.01 CMS ratio 1-2 sigma lower then ATLAS ratio

Constraining power of various datasets

- Valence quarks best constrained by both CMS and ATLAS W data
- For total sea Σ ATLAS Z most constraining
  - followed by ATLAS W, CMS W and CMS Z
- Same ordering seen for ubar and dbar and is most pronounced for s and R_s



Fit quality

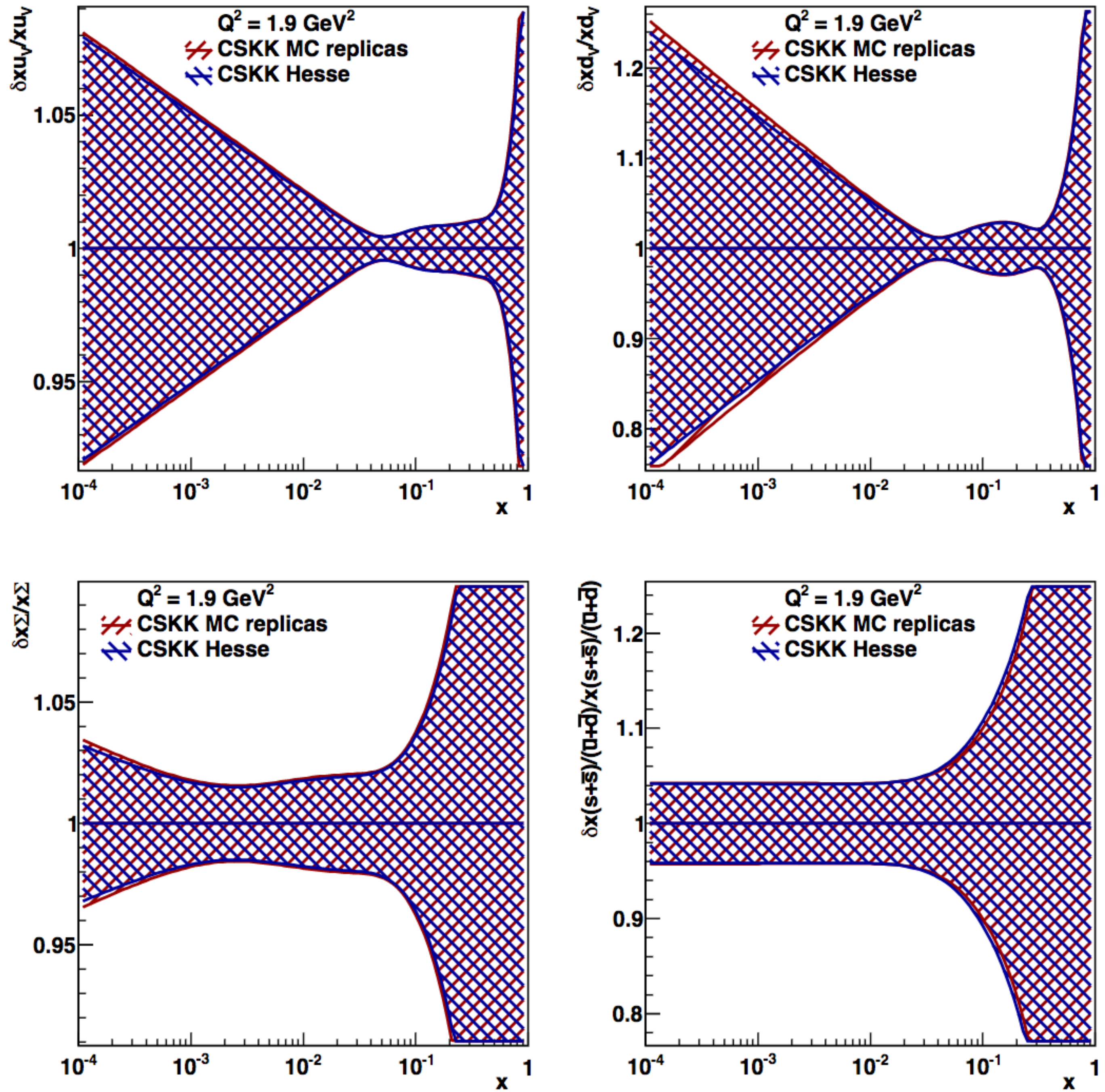
- Total and partial χ^2s for W/Z data samples good
- ATLAS + CMS with central Z fit → MainFit → CSKK
- clear that greater accuracy of ATLAS data dominates CSKK fit
  - combined fit has unsuppressed strangeness
  - CMS data are not in tension with this result → χ^2 for CMS data is still very good

	ATLAS and CMS W	ATLAS and CMS Z	ATLAS and CMS W and Z, CSKK fit
Total χ^2/NDF	1265/1096 = 1.15	1244/1086 = 1.15	1308/1141 = 1.15
Data set, χ^2/NDP			
HERA	1159/1056	1157/1056	1163/1056
ATLAS W^+	12/11		13/11
ATLAS W^-	8/11		9/11
ATLAS central CC Z		14/12	16/12
ATLAS central CF Z		9/9	7/9
CMS 7 TeV central Z		12/24	$\boxed{12/24}$
CMS 7 TeV W-asym.	13/11		$\boxed{14/11}$
CMS 8 TeV W^+, W^-	6/22		$\boxed{5/22}$

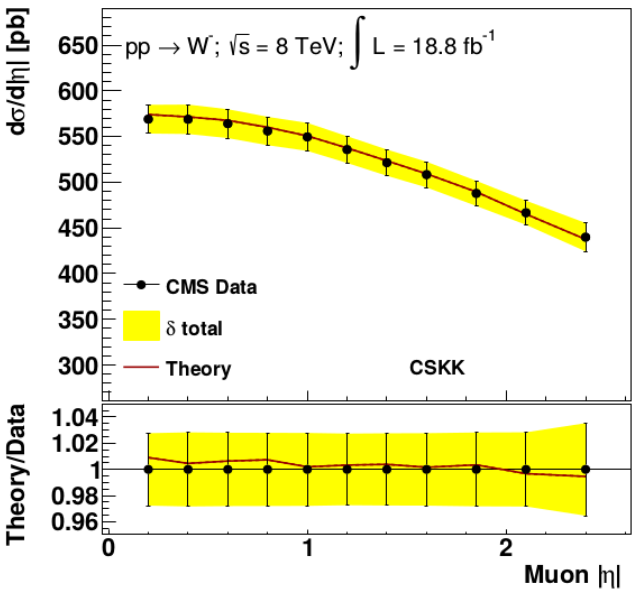
	CMS Z7	CMS W7,8	CMS Z7 + W7,8
Total χ^2/NDF	1218/1965	1225/1074	1236/1098
Data set, χ^2/NDP			
HERA	1156/1056	1157/1056	1157/1056
CMS 7 TeV central Z	11/24		$\boxed{11/24}$
CMS 7 TeV W-asymmetry		13/11	$\boxed{13/11}$
CMS 8 TeV W^+, W^-		4/22	$\boxed{4/22}$

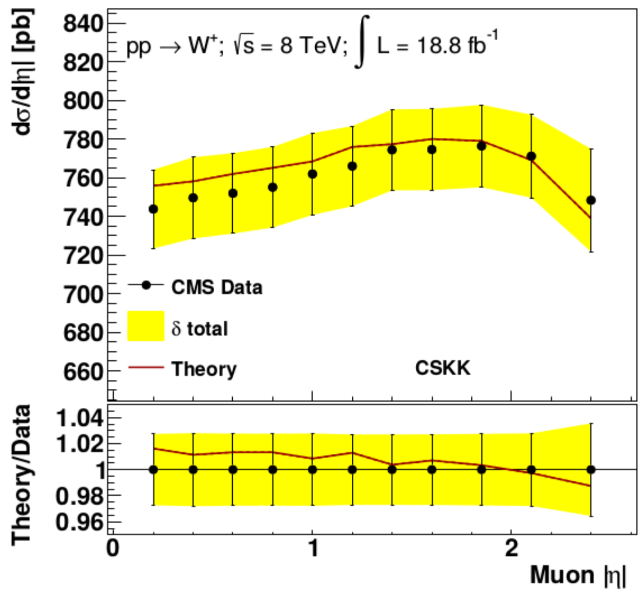
Hesse uncertainty .vs. MC replicas

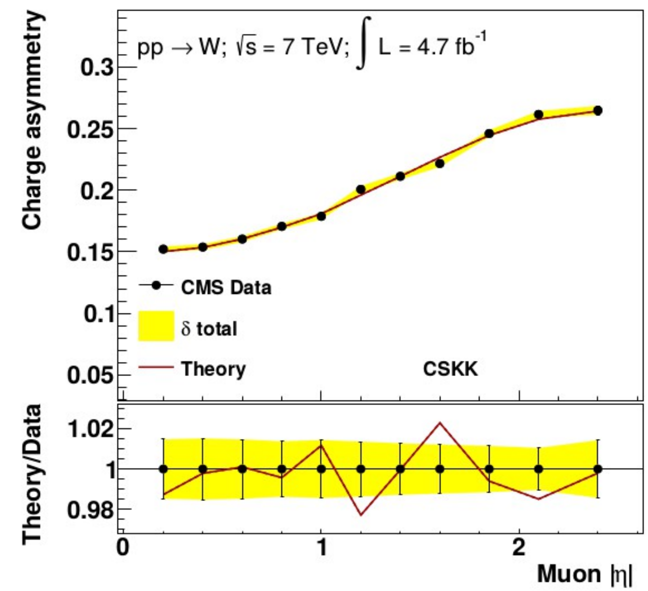
- Main method of experimental uncertainty estimation: Hesse
- Cross check done using MC replicas
- PDFs obtained with both methods agree well
- Uncertainties compatible

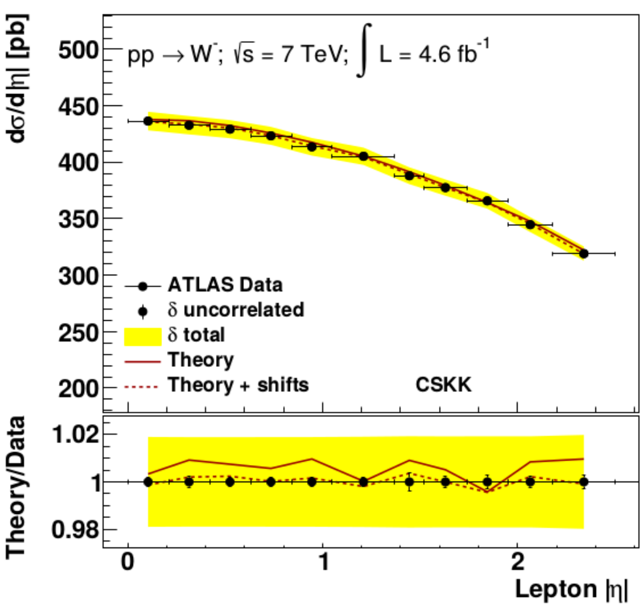


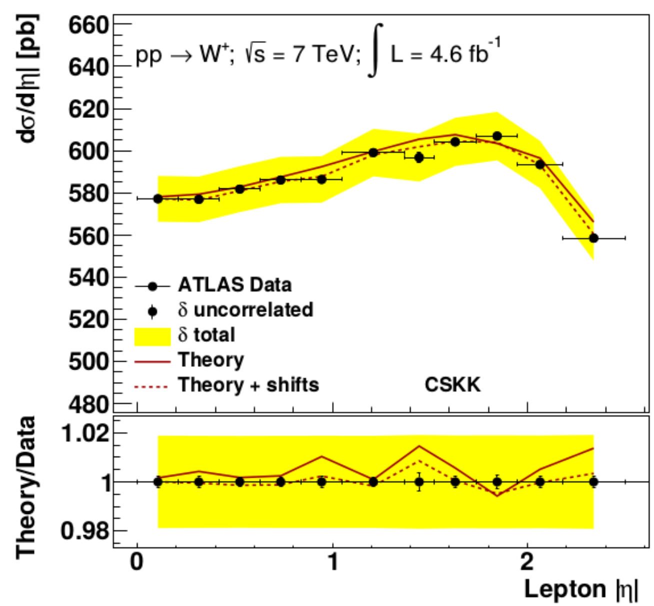
Data description: W



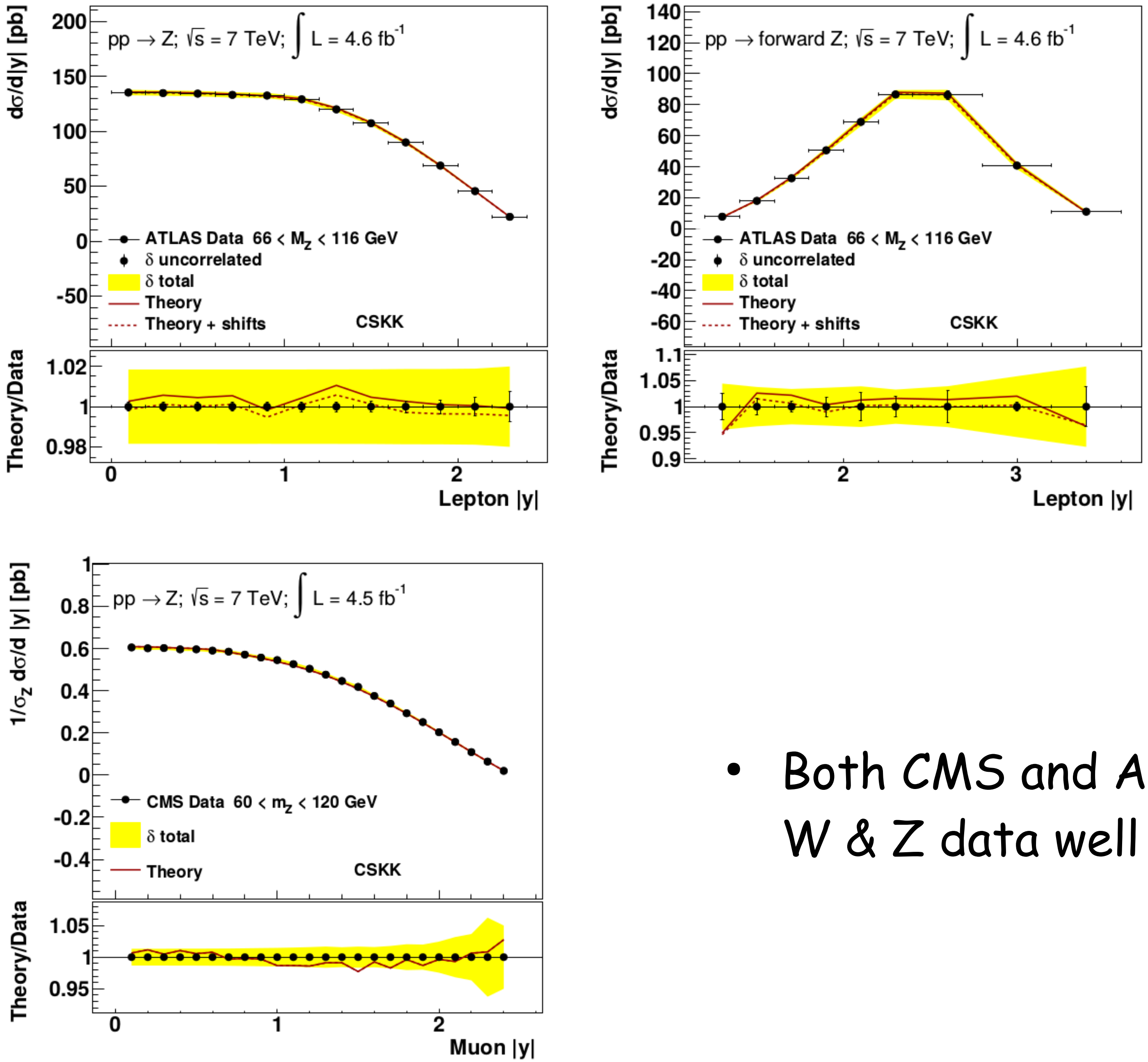








Data description: Z

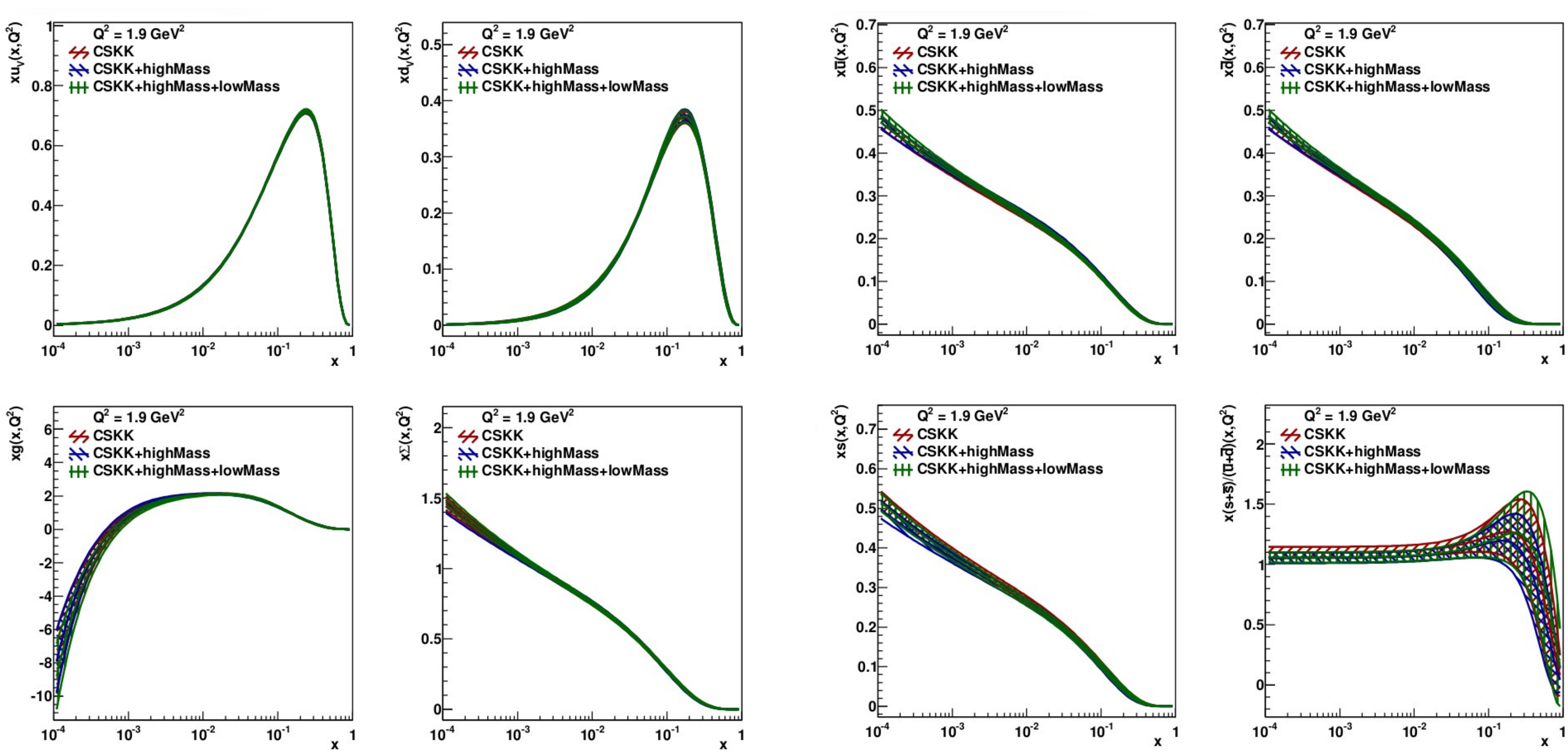


- Both CMS and ATLAS and W & Z data well described

Adding Z off-peak data

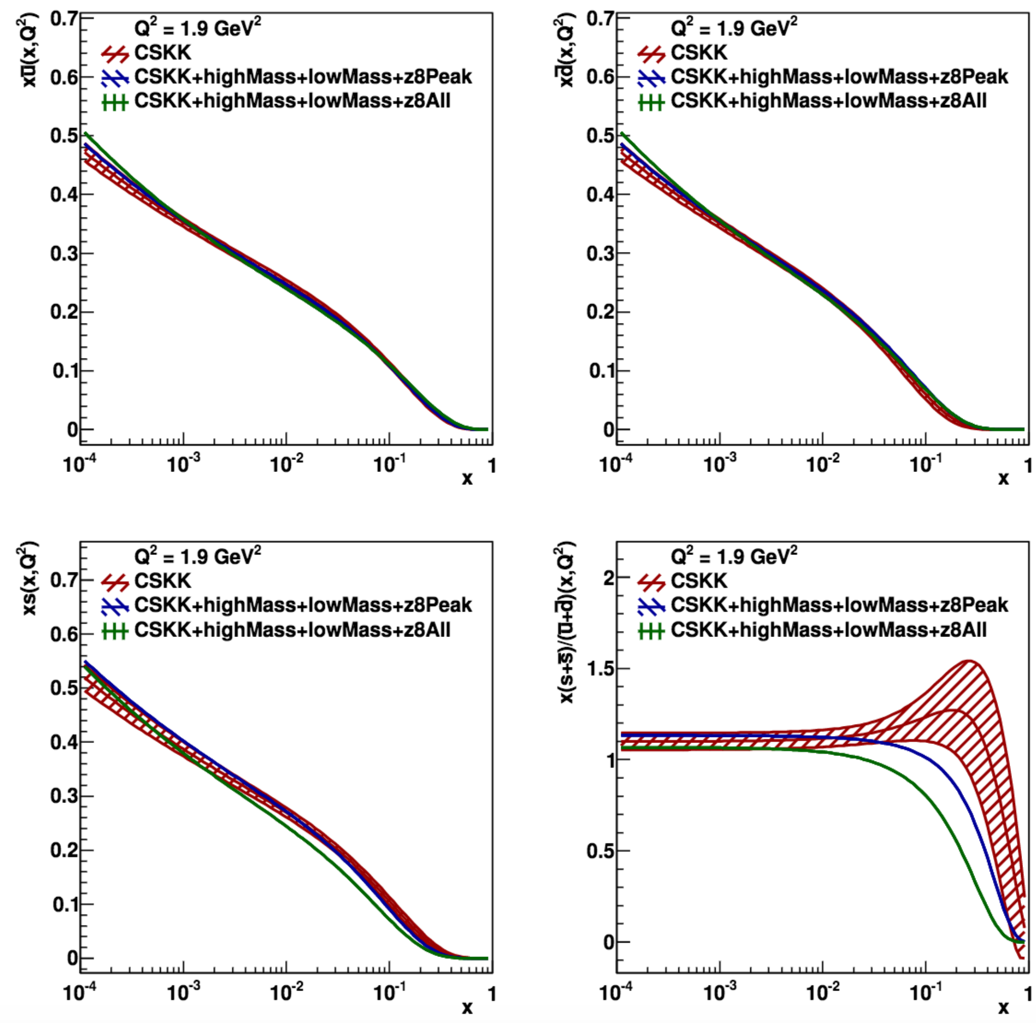
- We added off-peak Z data → high mass first and then low mass
- results not changed substantially
- experimental uncertainties are also not much reduced

→ larger theoretical uncertainties, from electroweak effects and photon induced processes → MainFit CSKK contains peak data only



Adding CMS Z @ 8 TeV

- CMS Z @ 8 TeV peak data + low/high mass added
- These data also do not change the result substantially
  - Valence, gluon, sea – very similar
  - Strangeness consistent
- In fact the CMS 8 TeV Z-peak data favor even larger strangeness than CSKK for small x



Main fit: CSKK

- We consider CSKK as our main fit
  - HERA inclusive data + W data + Z peak data
- Our main conclusion about data sets

→ There is no tension between the HERA data and the LHC data or between the LHC data sets

- We consider $R_s = \frac{s+\bar{s}}{\bar{d}+\bar{u}}$ distribution our main result
  - For comparison with ATLAS result we also calculate R_s at certain x and Q^2 values
  - Results with experimental, model and parameterisation uncertainties

Model and α_s uncertainties

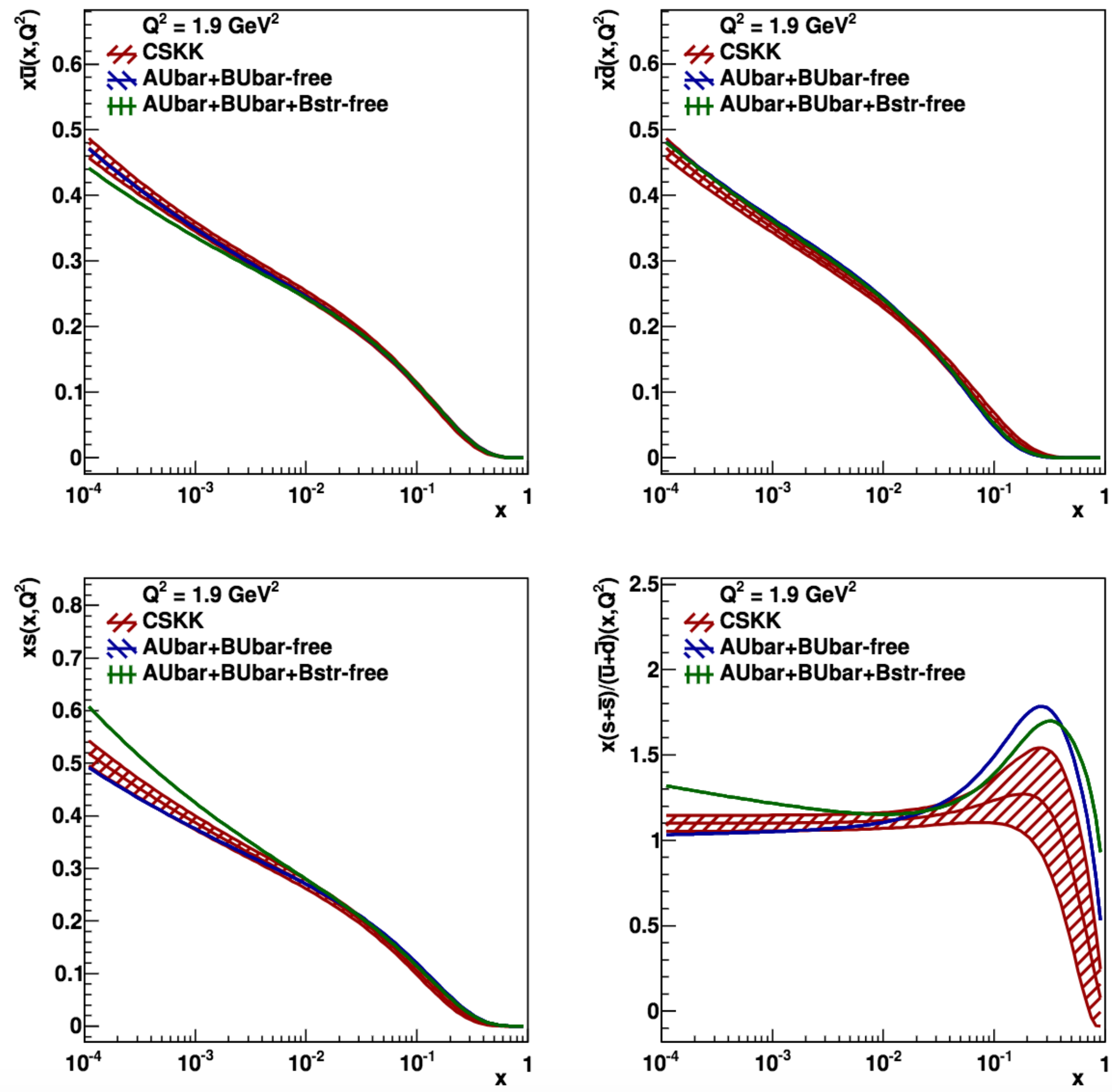
Variation	Total χ^2/NDF	$R_s = \frac{s+\bar{s}}{\bar{d}+\bar{u}}$	
		$x = 0.023$, $Q_0^2 = 1.9$ GeV^2	$x = 0.013$, $Q_0^2 = 8317$ GeV^2
Nominal CSKK fit	1308 / 1141	1.14	1.05
Model variations			
$Q^2_{\mathrm{min}} = 5$ GeV^2	1375 / 1188	1.14	1.06
$Q^2_{\mathrm{min}} = 10$ GeV^2	1251 / 1101	1.14	1.05
$m_b = 4.25$ GeV	1307 / 1141	1.12	1.04
$m_b = 4.75$ GeV	1310 / 1141	1.16	1.06
$\mu^2_{f0} = 1.6$ GeV^2 and $m_c = 1.37$ GeV	1312 / 1141	1.16	1.06
$\mu^2_{f0} = 2.2$ GeV^2 and $m_c = 1.49$ GeV	1308 / 1141	1.12	1.05
$\alpha_s(M_Z)$ variations			
$\alpha_s(M_Z) = 0.116$	1308 / 1141	1.12	1.04
$\alpha_s(M_Z) = 0.117$	1308 / 1141	1.13	1.05
$\alpha_s(M_Z) = 0.119$	1309 / 1141	1.14	1.06
$\alpha_s(M_Z) = 0.120$	1310 / 1141	1.15	1.06

Parameterisation uncertainty

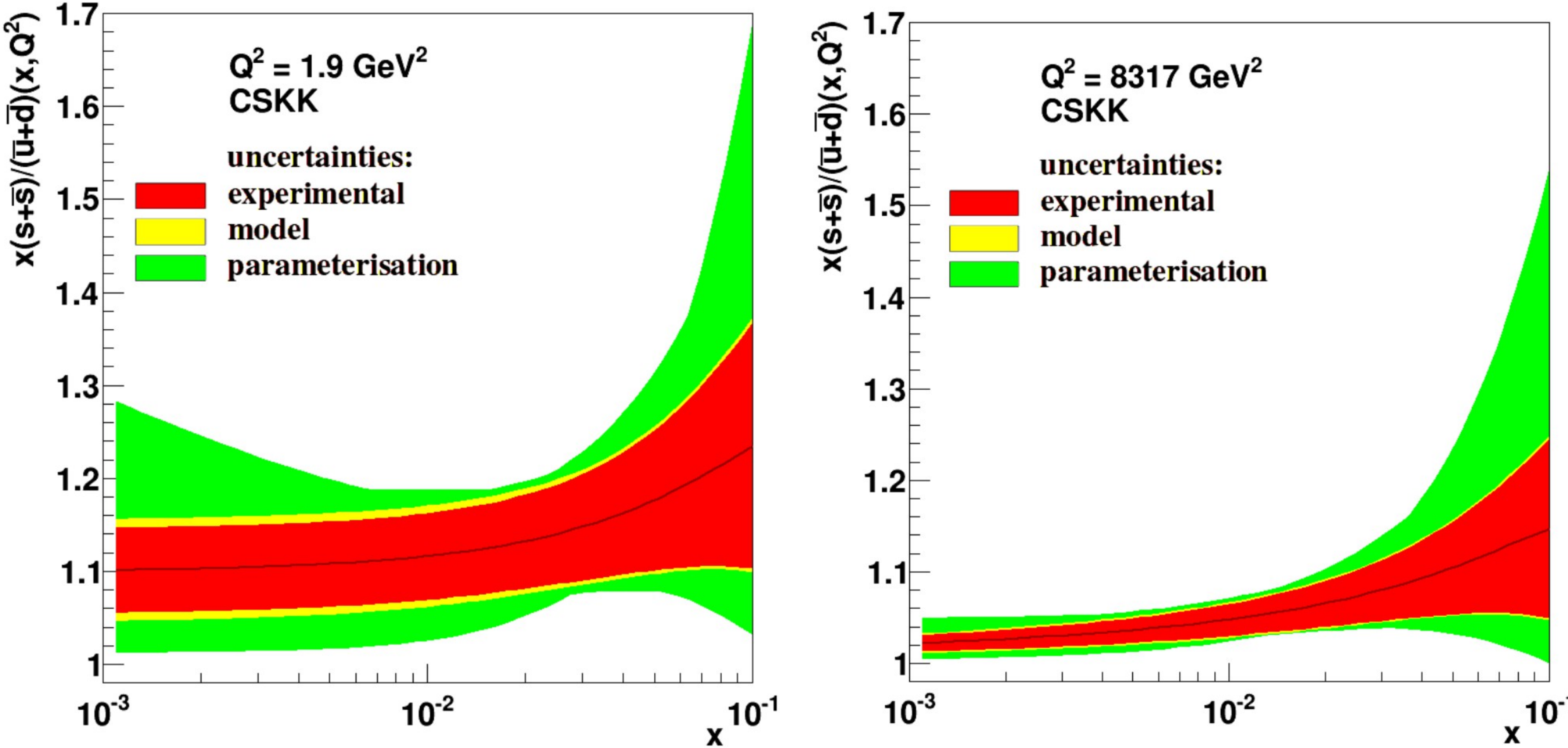
Variation	Total χ^2/NDF	$R_s = \frac{s+\bar{s}}{\bar{d}+\bar{u}}$	
		$x = 0.023$,	$x = 0.013$,
		$Q_0^2 = 1.9$ GeV^2	$Q_0^2 = 8317$ GeV^2
Nominal CSKK fit	1308 / 1141	1.14	1.05
Parameterisation variations			
$B_{\bar{s}}$	1308 / 1140	1.12	1.05
D_{u_v}	1308 / 1140	1.13	1.05
D_{d_v}	1308 / 1140	1.14	1.05
D_g	1306 / 1140	1.15	1.06
$D_{\bar{u}}$	1305 / 1140	1.15	1.06
$D_{\bar{d}}$	1302 / 1140	1.09	1.04
E_{d_v}	1308 / 1140	1.14	1.05
$A_{\bar{u}}$ and $B_{\bar{u}}$ free	1306 / 1139	1.17	1.07
$A_{\bar{u}}$ and $B_{\bar{u}}$ and $B_{\bar{s}}$ free	1306 / 1138	1.17	1.07

Parameterisation study

- valence and gluon PDFs do not differ much
- low-x Dbar distribution consistent with Ubar for AUbar and BUbar free and for additional Bstr free
- strangeness ratio still consistent with unity for both



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



- Total uncertainty dominated by parameterisation uncertainty for most of x range
- R_s consistent with unity at low x

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

- R_s at $x = 0.023$ and $Q^2 = 1.9\ \mathrm{GeV}^2$
  - Highest sensitivity at starting scale

$$R_s = 1.14 \pm 0.05\,(\mathrm{experimental}) \pm 0.03\,(\mathrm{model})\, ^{+0.03}_{-0.05}\,(\mathrm{parameterisation})\, ^{+0.01}_{-0.02}\,(\alpha_\mathrm{s})$$

- R_s at $x = 0.013$ and $Q^2 = M_Z^2$
  - Maximal sensitivity for LHC data

$$R_s = 1.05 \pm 0.02\,(\mathrm{experimental})\, ^{+0.02}_{-0.01}\,(\mathrm{model})\, ^{+0.02}_{-0.01}\,(\mathrm{parameterisation}) \pm 0.01\,(\alpha_\mathrm{s})$$

- Compared to ATLAS result at $x = 0.023$ and $Q^2 = 1.9\ \mathrm{GeV}^2$

$$R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}} = 1.13 \pm 0.05\,(\mathrm{exp}) \pm 0.02\,(\mathrm{mod})\, ^{+0.01}_{-0.06}\,(\mathrm{par})$$

Additional parameterisation study

- For the CSKK fit, dbar-ubar at x~0.1 is negative, 2-3 sigma away from positive value suggested by E866 fixed-target Drell-Yan data
- Maybe if positive (dbar-ubar) imposed on the fit → strangeness decreases → larger dbar is correlated to smaller strangeness in the current parameterisation
  - However E866 observation made at x~0.1, whereas the LHC data have largest constraining power at x~0.01
- Cross-check made with a parameterisation which forces (dbar–ubar) to be in agreement with the E866 data
  - $R_s = 0.95 \pm 0.07$ (experimental) at $x = 0.023$ and $Q^2 = 1.9$ GeV^2
  - Still consistent with unity, however ~2 sigma lower than central result
- not included in parameterisation variations → not a good fit
  - χ^2/NDF of this fit is 1363/1141 compared to 1308/1141 for CSKK

Instead of summary: thank you for your patience :)

Higher-twist effects

HERAPDF2.0

NLO $\frac{\chi^2}{ndf}=\frac{1356}{1131}\approx 1.20$

NNLO $\frac{\chi^2}{ndf}=\frac{1363}{1131}\approx 1.21$

→ Introducing $F_2^{HT}=F_2^{DGLAP}(1+\frac{A_2^{HT}}{Q^2})$ has almost no effect

HHT@F_2

NLO $\frac{\chi^2}{ndf}=\frac{1354}{1130}\approx 1.20$

NNLO $\frac{\chi^2}{ndf}=\frac{1357}{1130}\approx 1.20$

A_2^{HT} = 0.14 ± 0.10 GeV^2

A_2^{HT} = 0.12 ± 0.07 GeV^2

factors consistent with 0

→ Introducing $F_L^{HT}=F_L^{DGLAP}(1+\frac{A_L^{HT}}{Q^2})$ helps a lot

HHT@F_L

NLO $\frac{\chi^2}{ndf}=\frac{1329}{1130}\approx 1.18$

NNLO $\frac{\chi^2}{ndf}=\frac{1316}{1130}\approx 1.16$

$\Delta\chi^2=27$

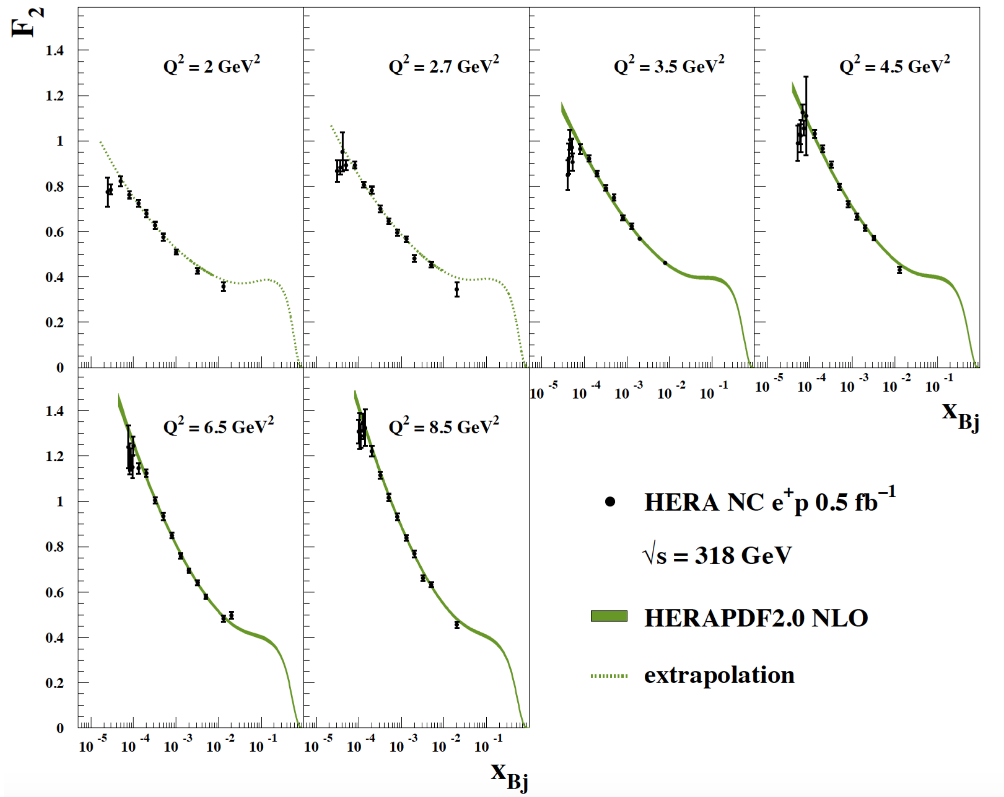
$\Delta\chi^2=47$

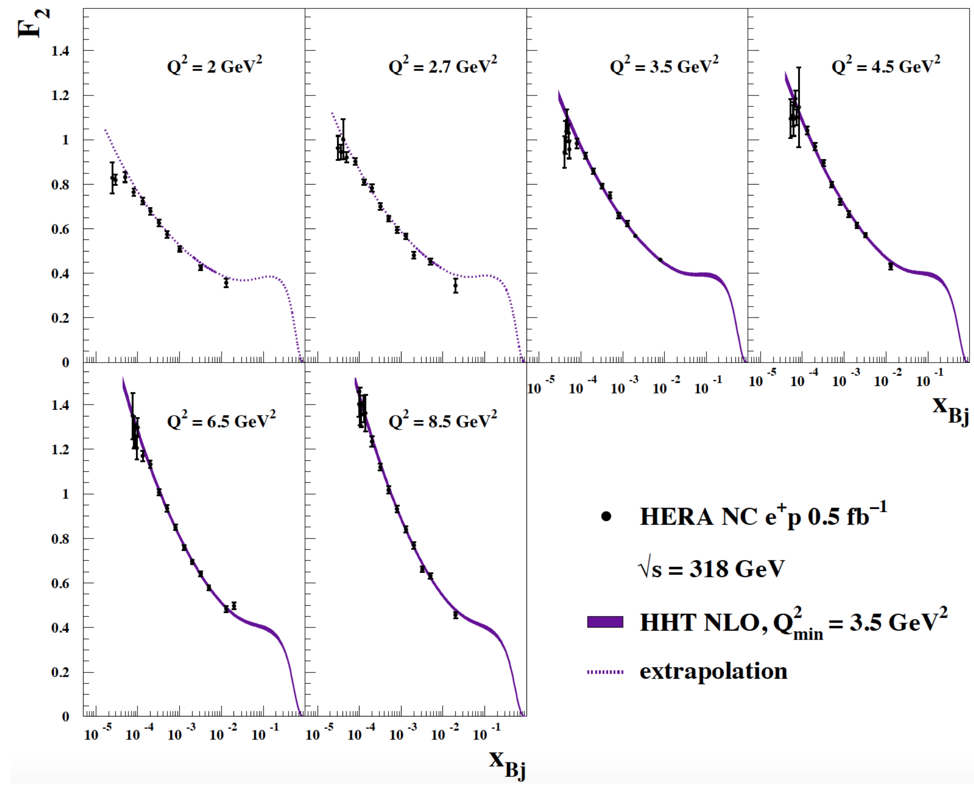
A_L^{HT} = 4.2 ± 0.7 GeV^2

A_L^{HT} = 5.5 ± 0.6 GeV^2

→ Trying to F_L and F_2 together gives the same conclusion

Look at $F_2^{extracted} = F_2^{predicted}\ \sigma_{red}^{measured} / \sigma_{red}^{predicted}$

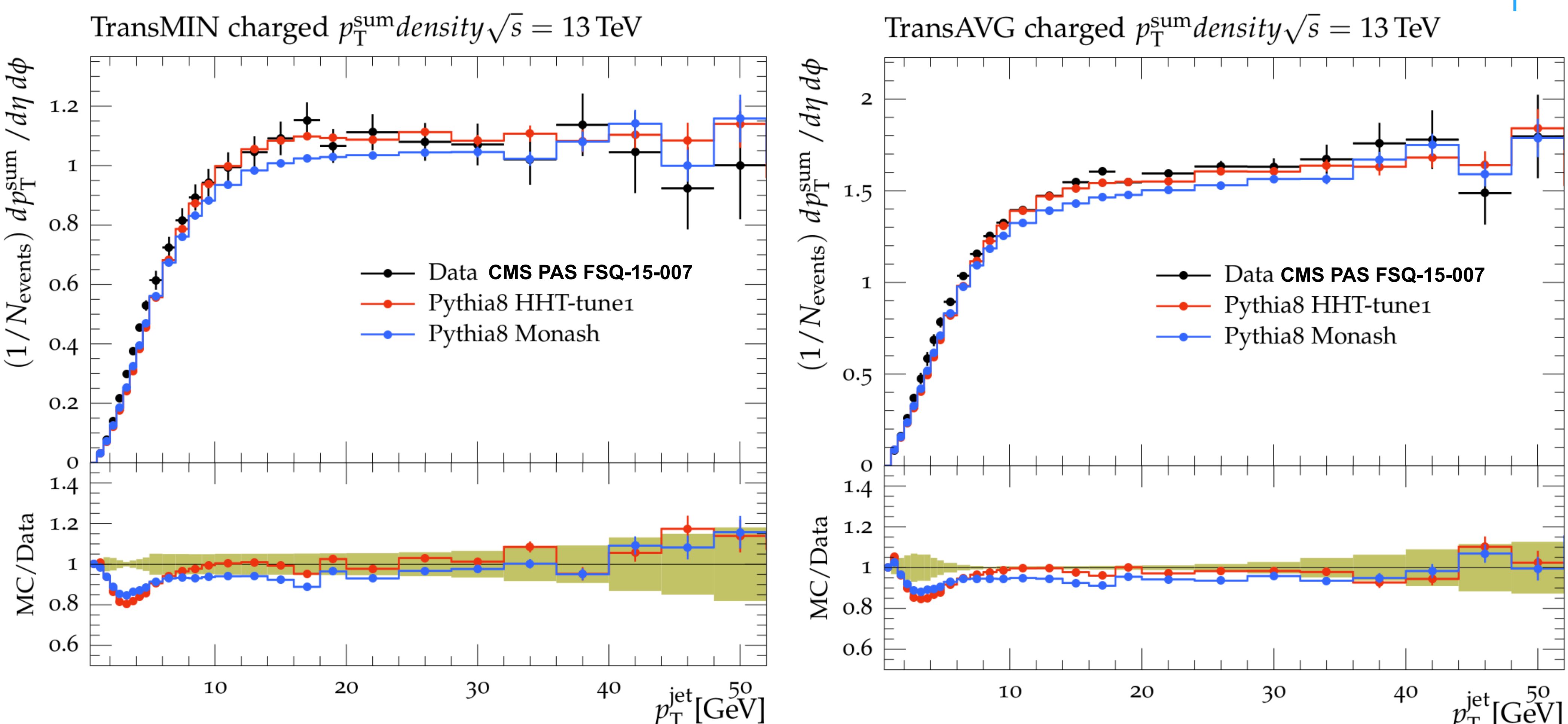




- F_2 obtained by correcting σ_{red} with predicted F_L $\quad F_2 = \sigma_{red} + y^2/Y_+ F_L$
- predicted F_L too small → F_2 also too small → seen in HERAPDF2.0 F_2 at low x, Q^2
    - **extracted F_2 takes a turn over!**
    - not what pQCD F_2 predictions say
- HHT predictions for F_L gives F_2 extracted much closer to F_2 predictions
- F_2 predictions very similar → they depend ONLY on very similar PDFs

MC tuning

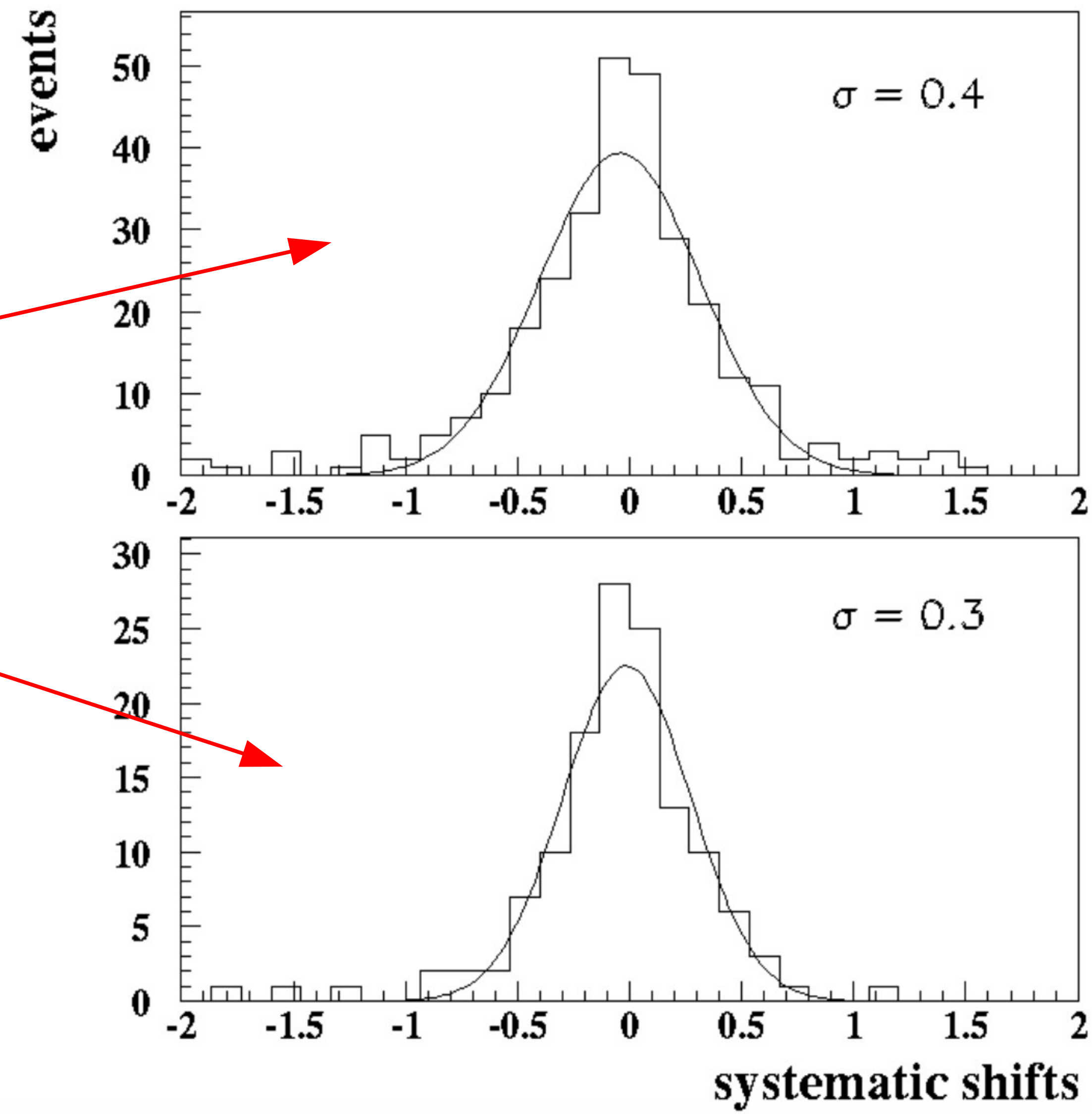
- Compares well with standard Pythia Monash tune – with NNPDF
  - Examples of better description for some variables



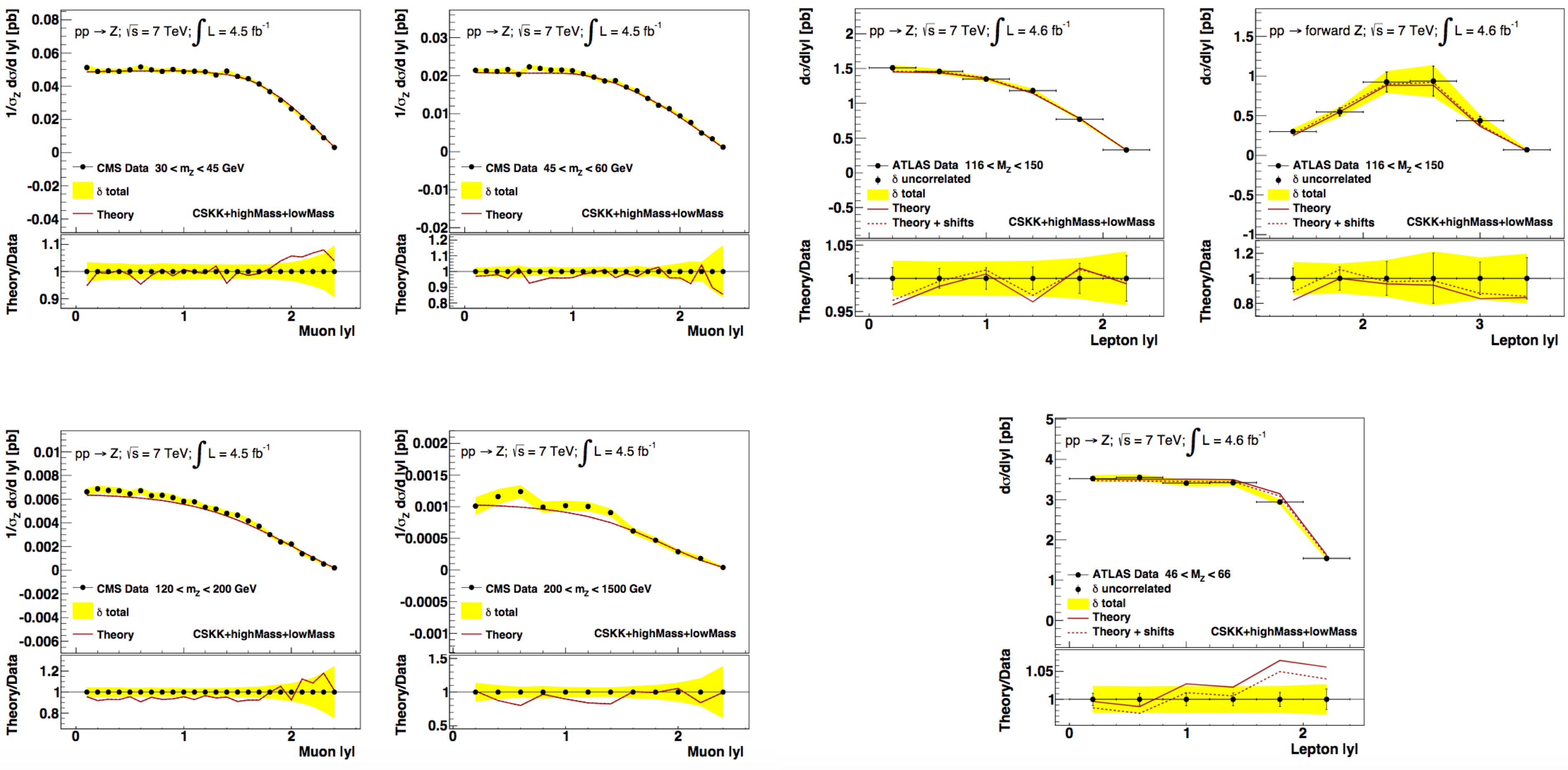
P. Gunnellini, private communication

Fit quality – shifts of systematic uncertainties

- Shifts of correlated systematic uncertainties (treated as nuisanc parameters)
- HERA + ATLAS
- ATLAS only
- Looks OK



Adding Z off-peak data



- Not very good agreement for CMS off-peak data and ATLAS low-mass (seen in ATLAS analysis as well)
- There are larger theoretical uncertainties for off-peak mass regions coming from electroweak effects and photon induced processes
  → we use only peak data for nominal CSKK fit

CMS Z @ 8 TeV data

	ATLAS and CMS W and all Z bins		CMS W and
	Z at 7 TeV	Z at 7 and 8 TeV	all Z bins
Total χ^2/NDF	1481/1243 = 1.19	1814/1351 = 1.34	1596/1290 = 1.24
Data set, χ^2/NDP			
HERA	1163/1056	1178/1056	1186/1056
ATLAS W^+	13/11	12/11	
ATLAS W^-	9/11	15/11	
ATLAS central CC Z	15/12	26/12	
ATLAS central CF Z	7/9	8/9	
ATLAS CC Z, $116 < M_z < 150$ GeV	8/6	7/6	
ATLAS CF Z, $116 < M_z < 150$ GeV	4/6	4/6	
ATLAS CC Z, $46 < M_z < 66$ GeV	28/6	34/6	
CMS 7 TeV W-asym.	14/11	14/11	18/11
CMS 8 TeV W^+, W^-	5/22	7/22	5/22
CMS 7 TeV Z central	12/24	13/24	16/24
CMS 7 TeV Z, $120 < M_z < 200$ GeV	31/24	28/24	25/25
CMS 7 TeV Z, $200 < M_z < 1500$ GeV	20/12	19/12	17/12
CMS 7 TeV Z, $30 < M_z < 45$ GeV	35/24	35/24	36/24
CMS 7 TeV Z, $45 < M_z < 60$ GeV	22/24	20/24	20/24
CMS 8 TeV Z central		74/24	66/24
CMS 8 TeV Z, $120 < M_z < 200$ GeV		73/24	56/24
CMS 8 TeV Z, $200 < M_z < 1500$ GeV		14/12	12/12
CMS 8 TeV Z, $30 < M_z < 45$ GeV		38/24	37/24
CMS 8 TeV Z, $45 < M_z < 60$ GeV		29/24	20/24

- CMS Z @ 8 TeV are not well described
- Found by NNPDF too
- some tension with ATLAS central mass & rapidity Z appears
- not well fitted even when fitted together with just HERA and other CMS data