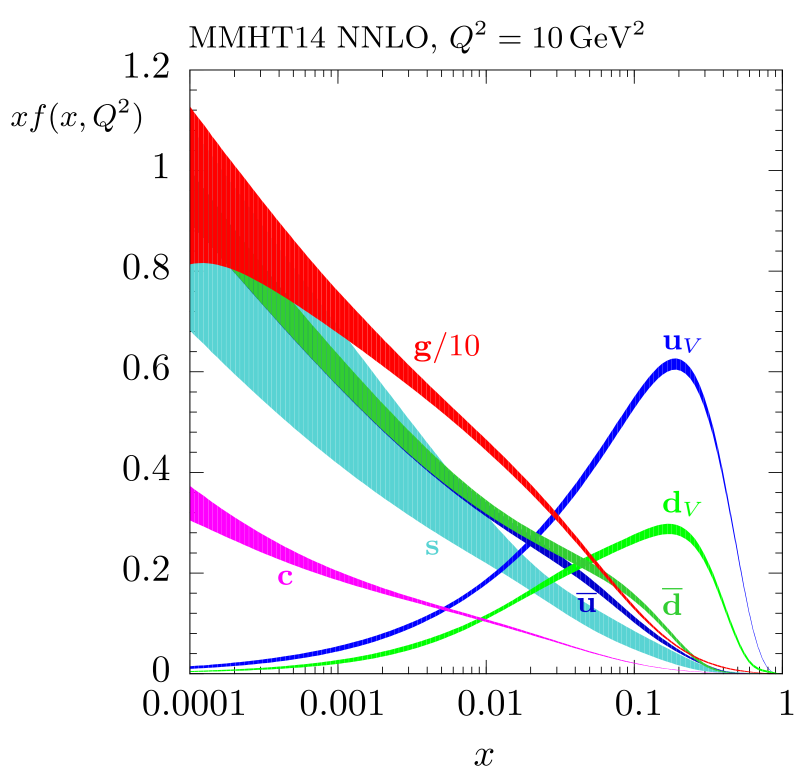
News From MMHT

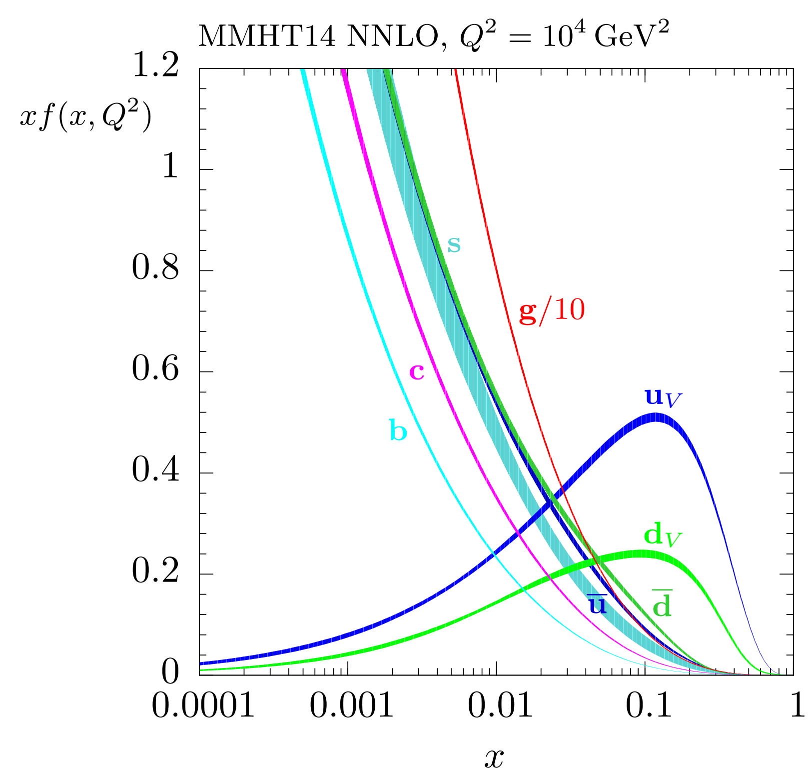
Lucian Harland-Lang, University of Oxford

PD4LHC Meeting, CERN, 13th December

Outline

- Recent work on including scale variations consistently in PDF fit and predictions.
- Brief summary of other MMHT work:
  - Dimuon production at NNLO.
  - $t\bar{t}$ production.
  - Photon PDF.
  - MMHT19

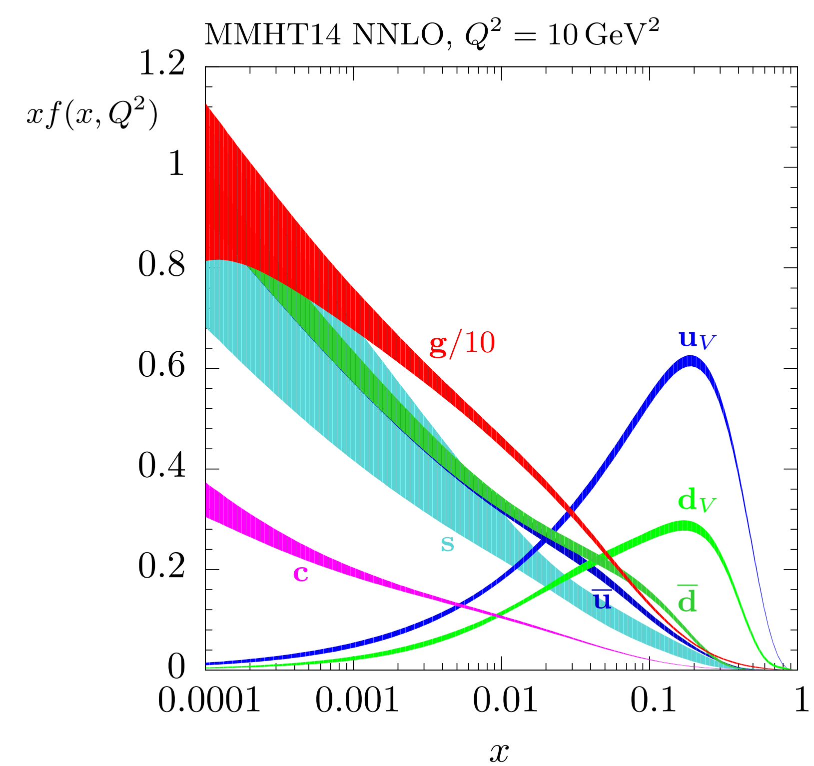




Consistent Scale Variations in PDF Fits and Predictions

Theoretical Uncertainties in PDFs

- Treatment of PDF uncertainties well developed. Two established methods - Hessian and MC replicas - and procedures for converting between the two.
- However this only concerns 'experimental' uncertainties, due to propagation of data errors through to fit.
- Other sources of error, due in particular to 'theory' in fit:
    - Value of strong coupling α_S, quark masses $m_{c,b}$.
    - Treatment of heavy flavour in cross sections.
    - Higher twists effects.
    - Nuclear corrections
    - ...
- Sources of these numerous, and focus of many studies.
- One source until recently never touched on - what is uncertainty due to fact we are using approximate fixed-order theory in the fit?



MHO Uncertainties

- Generically in fit relate observables O to PDFs f via (schematically):

$$O \sim f \otimes \sigma \sim f \otimes \left(\sigma^{(0)} + \alpha_S \sigma^{(1)} + \cdots\right)$$

- Function of PDF fit is to invert this relation, giving $f(O\,;\,\sigma)$.
- But σ and therefore $f(O\,;\,\sigma)$ not known exactly - source of uncertainty due to the missing higher orders (MHOs) in theory (the `…').
- Typically these MHOs are estimated via scale variations. First concrete study including these have been recently performed by NNPDF. **See Juan's talk**
- Our aim is a little different - to try and consider from first principles how such uncertainties should/could be included in a fit.

LHL and R.S. Thorne, arXiv:1811.08434

On the Consistent Use of Scale Variations in PDF Fits and Predictions

L. A. Harland–Lang[1], R. S. Thorne[2],

[1]Rudolf Peierls Centre, Beecroft Building, Parks Road, Oxford, OX1 3PU, UK
[2]Department of Physics and Astronomy, University College London, WC1E 6BT, UK

Abstract

We present an investigation of the theoretical uncertainties in parton distribution functions (PDFs) due to missing higher–order corrections in the perturbative predictions used in the

Basic Idea

- PDFs themselves not observable. Can recast fit process purely in terms of fit and predicted observables, with no reference to PDFs.

Fit $$O_{\text{fit}} \sim f_i(\mu^2) \otimes \sigma_i(\mu^2) \sim f_i(\mu^2) \otimes \left(\sigma_i^{(0)}(\mu^2) + \alpha_S\, \sigma_i^{(1)'}(\mu^2) + \cdots\right)$$

$$\Big\downarrow \mathbf{A} \qquad\qquad \Big\downarrow \mathbf{B}$$

$$f_i$$

$$\Big\downarrow \mathbf{C}$$

$i:$ PDF type

Prediction $$O_{\text{pred}} \sim f_i(\mu^2) \otimes \sigma_i'(\mu^2) \sim f_i(\mu^2) \otimes \left(\sigma_i^{(0)'}(\mu^2) + \alpha_S\, \sigma_i^{(1)'}(\mu^2) + \cdots\right)$$

- Rule of thumb: vary scale $\mu \in \left(\frac{\mu_0}{2}, 2\mu_0\right)$. Can propagate through to PDFs. However, will traditionally then include such a variation **again** in prediction.
- If we interpret 'theory uncertainty' as that inherent in expressing predicted quantity in terms of measured one then varying at both **B** and **C** not obviously the right procedure.
- Recasting in terms of $O_1 \leftrightarrow O_2$ via **A** makes this concrete.

Simple Model

- Simplest thing we can consider- fit to non-singlet structure function $F_{\rm NS}$ and prediction of another $F'_{\rm NS}$. At NLO:

$$g\otimes f(x) = \int_x^1 \frac{{\rm d}z}{z} f(z) g\left(\frac{x}{z}\right) ,$$

Fit $$F_{\rm NS}(x,Q^2) = xq_{\rm NS}(x,a_iQ^2) + \tilde{\alpha}_S C_q^{(1)} \otimes xq_{\rm NS}(x,a_iQ^2) - \tilde{\alpha}_S \ln a_i P_{qq}^{(0)} \otimes xq_{\rm NS}(x,a_iQ^2)$$

Prediction $$F'_{\rm NS}(x,Q^2) = xq_{\rm NS}(x,a_fQ^2) + \tilde{\alpha}_S C_q^{(1)} \otimes xq_{\rm NS}(x,a_fQ^2) - \tilde{\alpha}_S \ln a_f P_{qq}^{(0)} \otimes xq_{\rm NS}(x,a_fQ^2)$$

- Here $a_{i,f} = \mu_{i,f}^2/Q^2$ reflects relative variation of factorization scale μ (renormalization scale fixed), so that rule of thumb variation is $a_{i,f} \in \left(\frac{1}{4},4\right)$
- 'Standard' fit - fix $a_i = 1$: $xq_{\rm NS}(x,\mu^2) = F_{\rm NS}(x,\mu^2) - \tilde{\alpha}_S C_q^{(1)} \otimes F_{\rm NS}(x,\mu^2)$,
- Predict:

$$F'_{\rm NS}(x,Q^2) = F_{\rm NS}(x,a_fQ^2) + \tilde{\alpha}_S\left(C_q'^{(1)} - C_q^{(1)}\right) \otimes F_{\rm NS}(x,a_fQ^2) - \tilde{\alpha}_S \ln a_f P_{qq}^{(0)} \otimes xF_{\rm NS}(x,a_fQ^2) ,$$

$\longrightarrow$ Direct $F_{\rm NS} \leftrightarrow F'_{\rm NS}$ relation, with MHO uncertainty on $\delta F'_{NS} : a_f \in \left(\frac{1}{4},4\right)$

- Straightforward to now consider MHO at fit stage - vary a_i . What do we find?

- Doing this we find, with scale variation in:

Prediction only: $$F'_{\rm NS}(x,Q^2) = F_{\rm NS}(x,a_f Q^2) + \tilde\alpha_S \left(C_q'^{(1)} - C_q^{(1)}\right) \otimes F_{\rm NS}(x,a_f Q^2) - \tilde\alpha_S \ln a_f P_{qq}^{(0)} \otimes x F_{\rm NS}(x,a_f Q^2)\ ,$$

Fit & prediction: $$F'_{\rm NS}(x,Q^2) = F_{\rm NS}(x,a_{fi} Q^2) + \tilde\alpha_S \left(C_q'^{(1)} - C_q^{(1)}\right) \otimes F_{\rm NS}(x,a_{fi} Q^2) - \tilde\alpha_S \ln a_{fi} P_{qq}^{(0)} \otimes x F_{\rm NS}(x,a_{fi} Q^2)\ ,$$

where: $a_{fi} \equiv a_f/a_i$ $\qquad a_{i,f} = \mu^2_{i,f}/Q^2$

- Thus in this case effect of varying scale in prediction and fit is **completely equivalent** to variation in prediction alone (or fit):

$$a_i \in \left(\frac{1}{4},4\right) \sim a_f \in \left(\frac{1}{4},4\right) \qquad a_i \in \left(\frac{1}{4},4\right) \ \&\ a_f \in \left(\frac{1}{4},4\right) \sim a_{fi} \in \left(\frac{1}{16},16\right)$$

- Indeed in terms of fundamental $F_{\rm NS} \leftrightarrow F'_{\rm NS}$ relation:

$$F'_{\rm NS}(x,Q^2) = F_{\rm NS}(x,aQ^2) + \tilde\alpha_S \left(C_q'^{(1)} - C_q^{(1)}\right) \otimes F_{\rm NS}(x,aQ^2) - \tilde\alpha_S \ln a P_{qq}^{(0)} \otimes x F_{\rm NS}(x,aQ^2)$$

there is only one d.o.f. (‘a’), corresponding to difference in (squared) scale at which we evaluate $F_{\rm NS}$ and $F'_{\rm NS}$.

Interpretation

$$F'_{\rm NS}(x,Q^2) = F_{\rm NS}(x,aQ^2)+\tilde{\alpha}_S\left(C'^{(1)}_q - C^{(1)}_q\right)\otimes F_{\rm NS}(x,aQ^2)-\tilde{\alpha}_S \ln a P^{(0)}_{qq}\otimes x F_{\rm NS}(x,aQ^2)$$

- 'Rule of thumb' variation: one varies logarithms in a within specified range, to keep track of decreasing dependence with order, but keeping $a \sim O(1)$.
- Within context of basic $F_{\rm NS} \leftrightarrow F'_{\rm NS}$ relation, this leads to $a \in \left(\frac{1}{4},4\right)$. MHO uncertainty in PDF should reflect this.
- In this example: either vary in **fit** or **prediction** by set amount, but **not in both**.
- If one wished to argue for larger variation, this could still be performed with larger range in either fit or prediction - complete overlap between these.
- Note: can also extend idea to higher orders straightforwardly in Mellin space, and extension to DY cross section works in same way.

$$F'_{\rm NS}(j,Q^2) = \frac{f'_q(j,\tilde{\alpha}_s)}{f_q(j,\tilde{\alpha}_s)}\left(\frac{Q^2}{\mu^2}\right)^{\tilde{\alpha}_s\gamma_{qq}(j,\tilde{\alpha}_s)} F_{\rm NS}(j,\mu^2)$$

- Clearly **global PDF** fit much more complex. Can we take this idea further?

Extension

- Next step towards generality, included coupled q, g evolution. Toy model - fit to two structure function observables:

$$F(Q^2) = \Sigma_+(\mu^2)\left(\frac{Q^2}{\mu^2}\right)^{\tilde{\alpha}_S\gamma_+} F_+ + \Sigma_-(\mu^2)\left(\frac{Q^2}{\mu^2}\right)^{\tilde{\alpha}_S\gamma_-} F_- \ ,$$

1 quark flavour

$$H(Q^2) = \Sigma_+(\mu^2)\left(\frac{Q^2}{\mu^2}\right)^{\tilde{\alpha}_S\gamma_+} H_+ + \Sigma_-(\mu^2)\left(\frac{Q^2}{\mu^2}\right)^{\tilde{\alpha}_S\gamma_-} H_- \ ,$$

and prediction of a third, $K(Q^2)$. Effect of coupled DGLAP simplified here by moving to diagonal basis.

- Leaving details to our paper, varying in fit ($a_{f,h}$) and prediction (a_k), get:

$$K(Q^2) \sim \left(K_1 + \tilde{\alpha}_S \ln\left(\frac{a_f}{a_k}\right) K_2 + \tilde{\alpha}_S \ln \underline{\left(\frac{a_h}{a_f}\right)} K_3\right) F\left(\frac{a_k}{a_f}Q^2\right) + \underset{a_f \leftrightarrow a_h}{F \leftrightarrow H}$$

- Situation no longer so simple - have introduced **completely new** logarithmic dependence on a_h/a_f. Variation in prediction alone would instead give:

$$K(Q^2) \sim (K_1 - \tilde{\alpha}_S \ln(a_k) K_2)\, F\left(a_k Q^2\right) + F \leftrightarrow H$$

- What does this tell us?

Prediction only:

$$K(Q^2) \sim (K_1 - \tilde{\alpha}_S \ln(a_k) K_2)\, F\left(a_k Q^2\right) + F \leftrightarrow H$$

Fit & prediction:

$$K(Q^2) \sim \left(K_1 + \tilde{\alpha}_S \ln\left(\frac{a_f}{a_k}\right) K_2 + \tilde{\alpha}_S \ln\left(\frac{a_h}{a_f}\right) K_3\right) F\left(\frac{a_k}{a_f} Q^2\right) + F \leftrightarrow H$$

- Including MHO uncertainty in fit has introduced genuinely new d.o.f. in $K \leftrightarrow F, H$ relation - **cannot** in general include via variation in **fit/prediction alone**.
- However, things do simplify if one considers low/high x regions:

$$F(Q^2) = \Sigma_+(\mu^2)\left(\frac{Q^2}{\mu^2}\right)^{\tilde{\alpha}_S \gamma_+} F_+ + \Sigma_-(\mu^2)\left(\frac{Q^2}{\mu^2}\right)^{\tilde{\alpha}_S \gamma_-} F_- \,,$$

★ High x : $\Sigma_+(j,\mu^2) = g(j,\mu^2)$, $\Sigma_-(j,\mu^2) = \Sigma_q(j,\mu^2)$

★ Low x : $g(j,\mu^2) \sim q(j,\mu^2) \sim \Sigma_+(j,\mu^2)$

- In both cases, dominance of single eigenvector/separation of q, g means that we revert back to original 'non-singlet' case.
- For example: fit to processes sensitive to high x gluon (jets, $t\bar{t}$ ...) and prediction of other ~ one scale d.o.f - vary fit/prediction but not both.
- We find if one assumes variations fully correlated in fit could equally include in prediction (but implicitly assumes correlated there as well).

Backup

In Summary

- By considering a global PDF fit as a relationship between different observables we find that:

  - ⋆ Including factorization scale variation in both fit and prediction leads to overestimate of error in certain regimes (simplified model - low/high x).
  - ⋆ Only varying in predictions does not fully account for theory error inherent in the relationship between observables.
  - ⋆ Assuming a full correlation between factorization scales at the fit stage also misses this (and if fully correlated in fit, why not in prediction as well?).

- A possible route forward (future work):

  - ⋆ Vary factorization scale at fit stage.
  - ⋆ Do not vary factorization scale at prediction stage.
  - ⋆ Apply a phenomenological approach for dealing with correlation between different processes entering fit.

Caveats

★ **Caveat 1** : This all relies on us trusting scale variation as the correct approach. Our results might even be taken as indication that it is not. But result of working in physical basis should apply in any case.

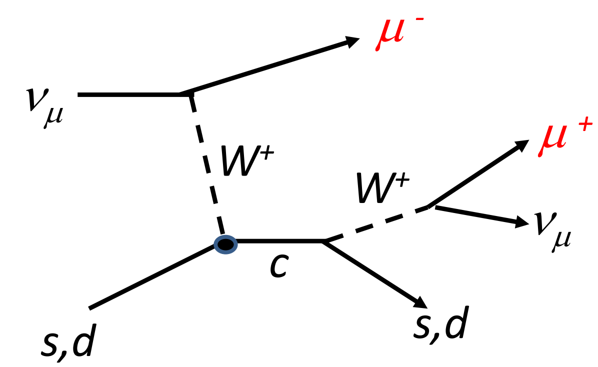
★ **Caveat 2** : Only applies to factorization scale. We find renormalization scale is different, with no clear fit/prediction overlap (i.e. should include both). However correlations between related processes (e.g. W, Z) in fit/prediction in principle as important as in fit.

Backup

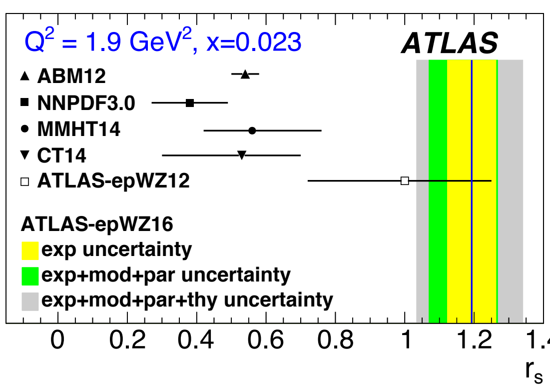
MMHT: Other Updates

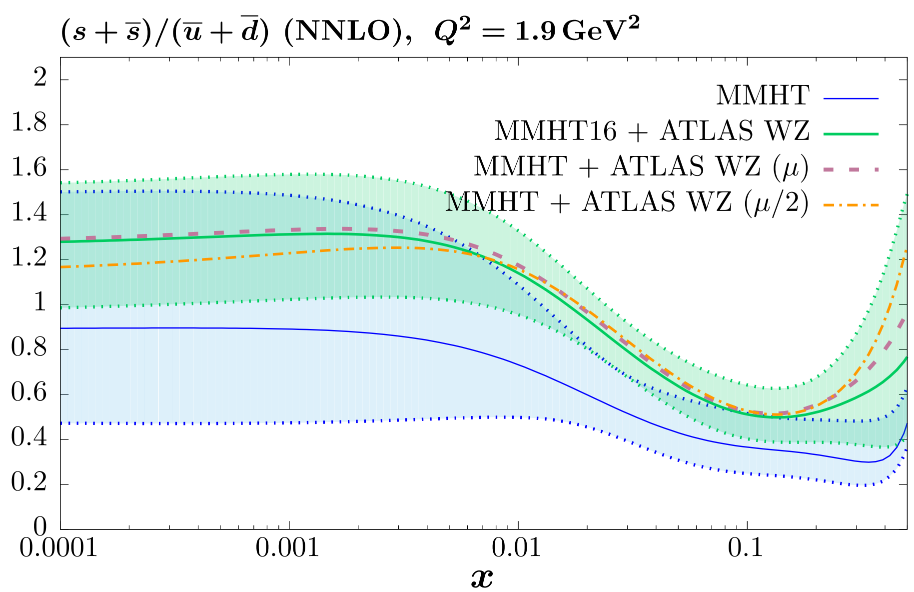
Dimuon production - NNLO

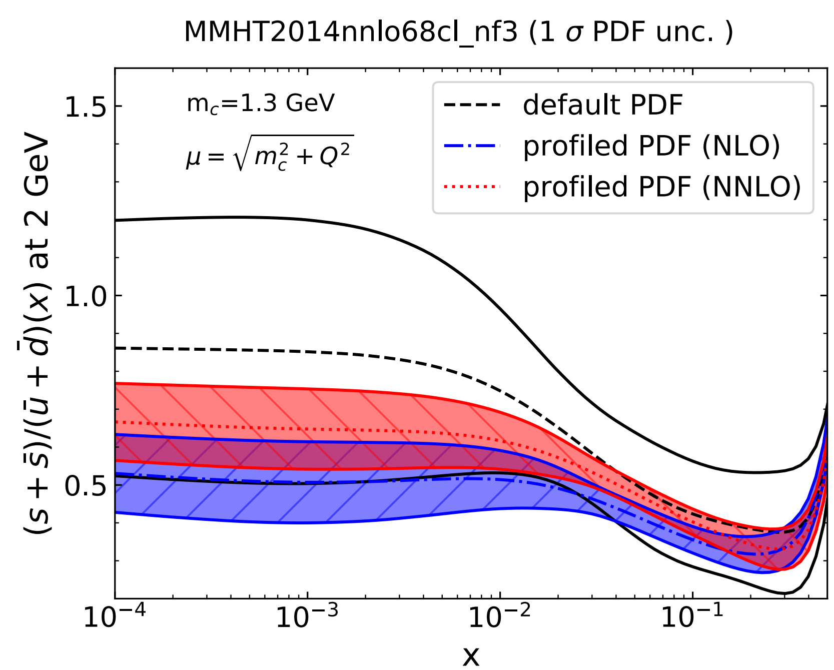
- Known degree of tension between ATLAS data and dimuon production on strangeness (though can both be accommodated in MMHT).



J. Gao, JHEP 1802 (2018) 026

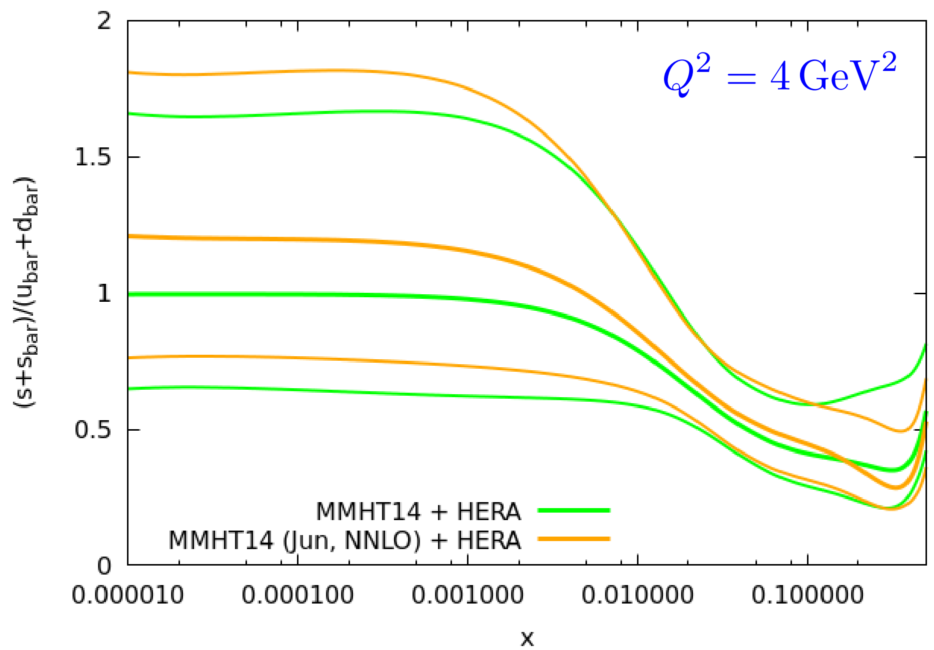


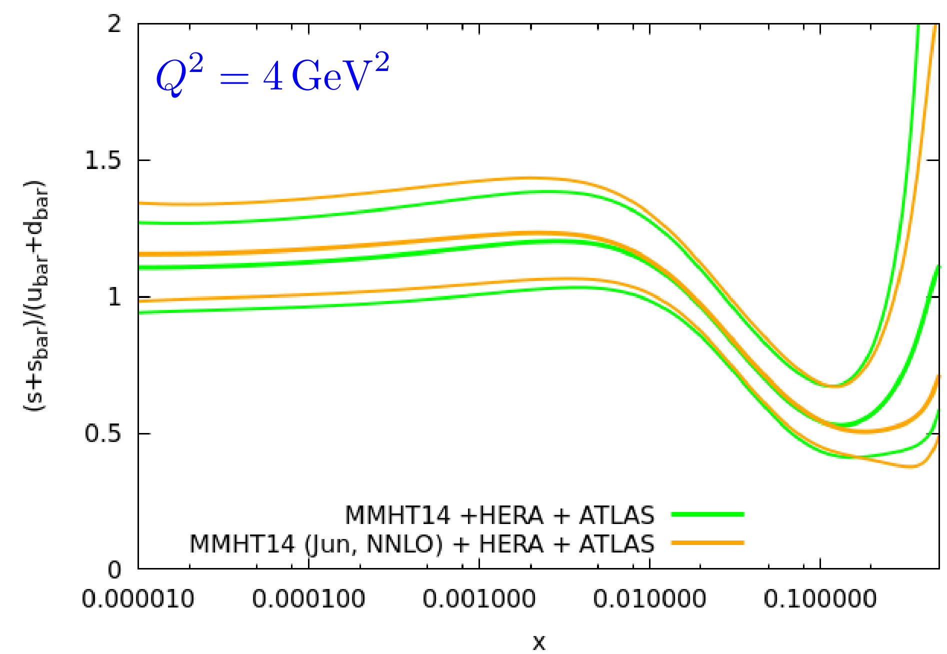




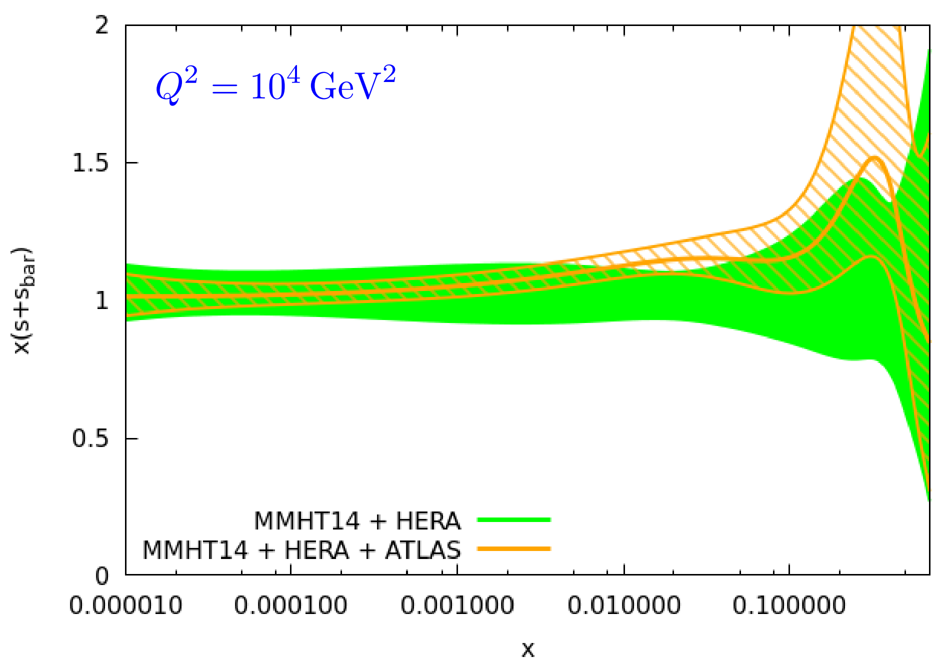
- Now full NNLO calculation available for dimuon production (including mass effects). Profiling study indicates this may reduce tension.
- Work ongoing to include in fit (with Shaun Bailey).

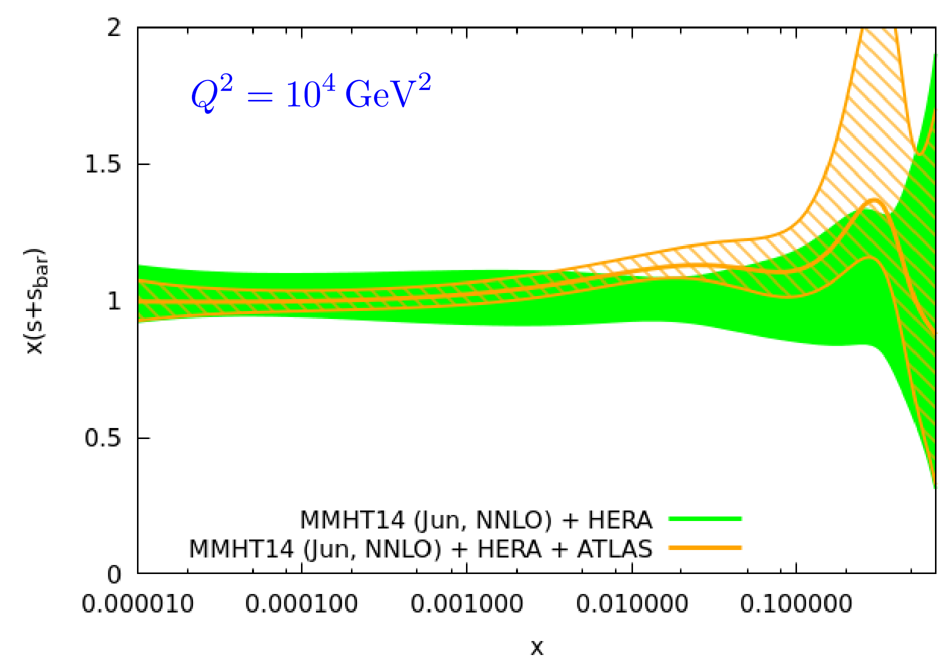
Preliminary





- Indeed in fit see increased strangeness, both with/without ATLAS (more marked without).





  - And see somewhat smoother impact of adding ATLAS at high x.
- So far, only FFS theory used- result with VFS corrections being finalised.
- Future work: including all $W + c$ within fit.

ATLAS $t\bar{t}$ data

ATL-PHYS-PUB-2018-017

- Motivated by release of full statistical correlations across y_t, $y_{t\bar{t}}$, $p_\perp^t$, $M_{t\bar{t}}$- look at impact in fit (with Shaun Bailey).
- (Very) briefly, find similar issues with:
  - ★ Fitting all distributions y_t, $y_{t\bar{t}}$, $p_\perp^t$, $M_{t\bar{t}}$ together.
  - ★ Fitting $y_t, y_{t\bar{t}}$ individually.

Seen by MMHT, CT, ATLAS. Not seen by NNPDF. (??)

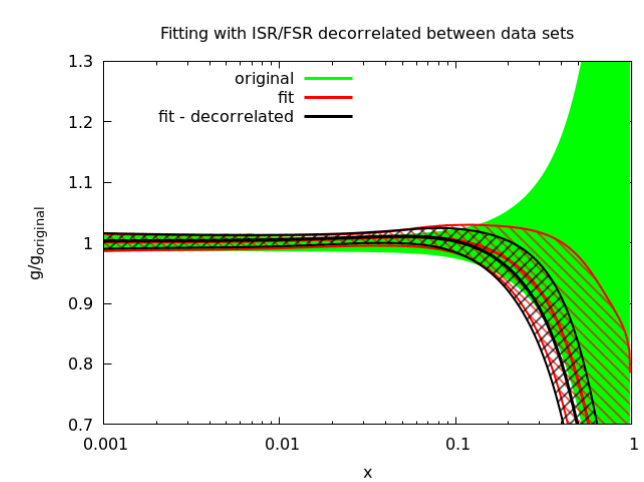
Individual

		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

Combined

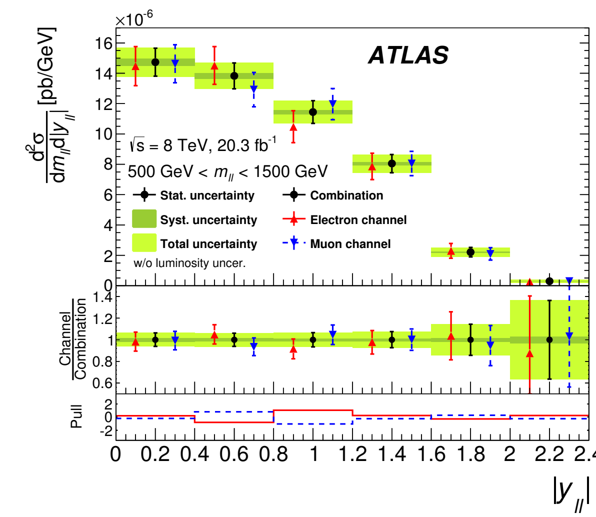
Contribution	p_T	2.38
	y_t	1.84
	$y_{t\bar{t}}$	2.22
	$M_{t\bar{t}}$	1.81
	Penalty	0.88
	Total	2.96

- As with ATLAS, combined fit quality highly sensitive to correlations in 3 largest (~ 3-10%) systematics: hard-scattering modelling, ISR/FSR & parton-shower.
- We also see similar sensitivity in individual $y_t, y_{t\bar{t}}$ fits.
- Investigate decorrelating, find relative (though not complete) insensitivity in extracted gluon.
- NB: first look: all of the above excludes the stat. correlations. Expected to be small impact, but work ongoing to include.

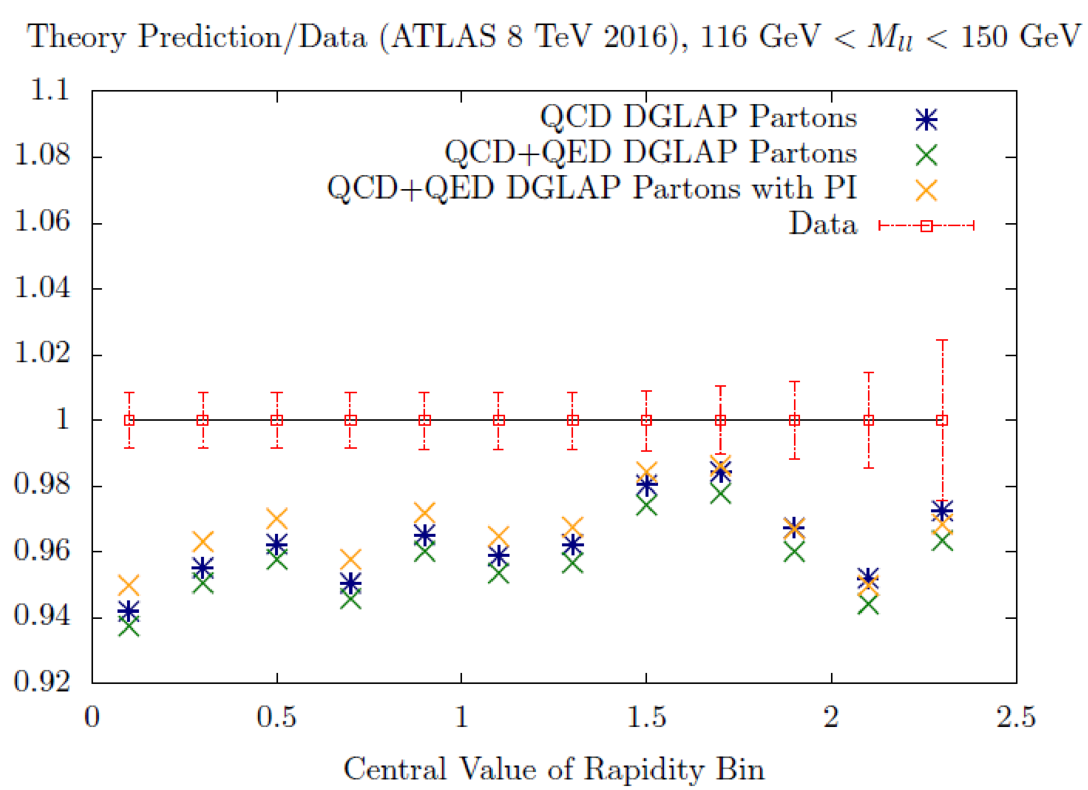


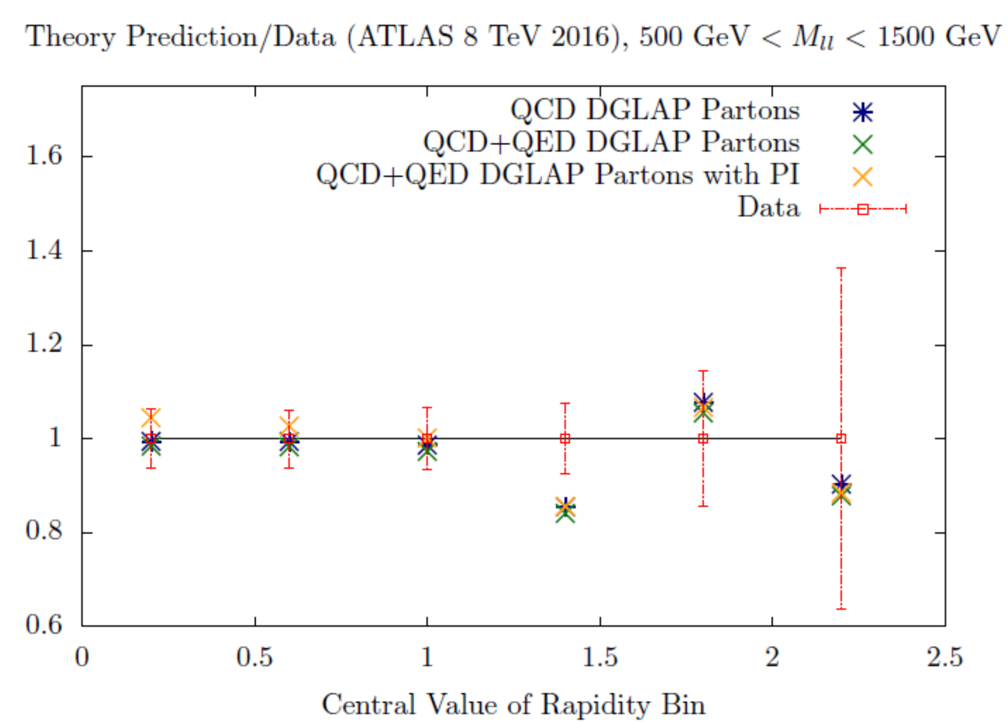
Photon PDF

- Work ongoing to include photon within LUXqed ($\gamma \sim F_{2,L}$) framework.
- Now fully implemented in MMHT code, currently looking at pheno. implications, e.g. for ATLAS high mass DY.
- Find impact of QED evolution on other partons as important as explicit PI contributions in some data bins.
- More to come very soon- stay tuned!



ATLAS Collab., JHEP 1608 (2016) 009



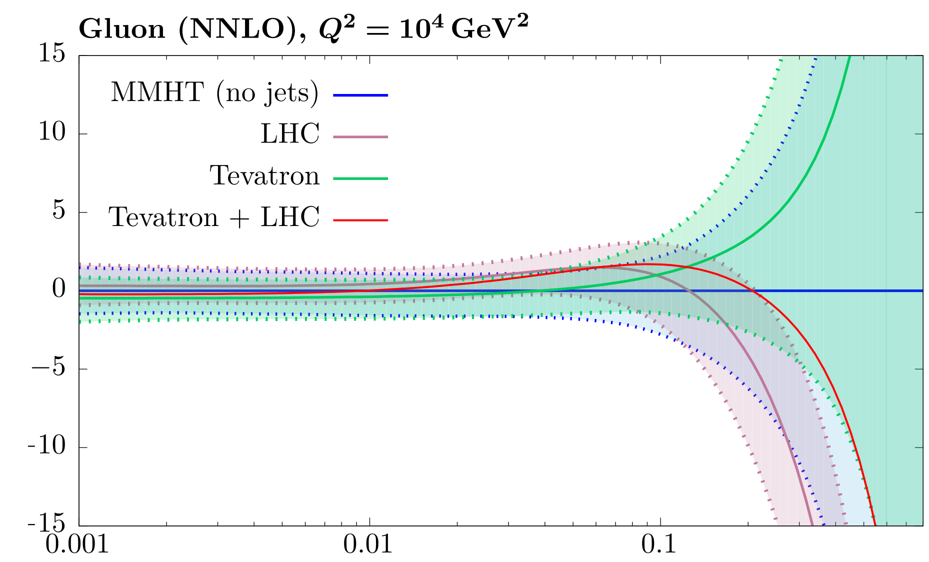


‘MMHT’19

- Since MMHT14, range of new LHC data + various fit improvements have been implemented, with in some cases rather large impacts.
- New release timely- work actively ongoing. Will include:

★ All **LHC Run I** data:

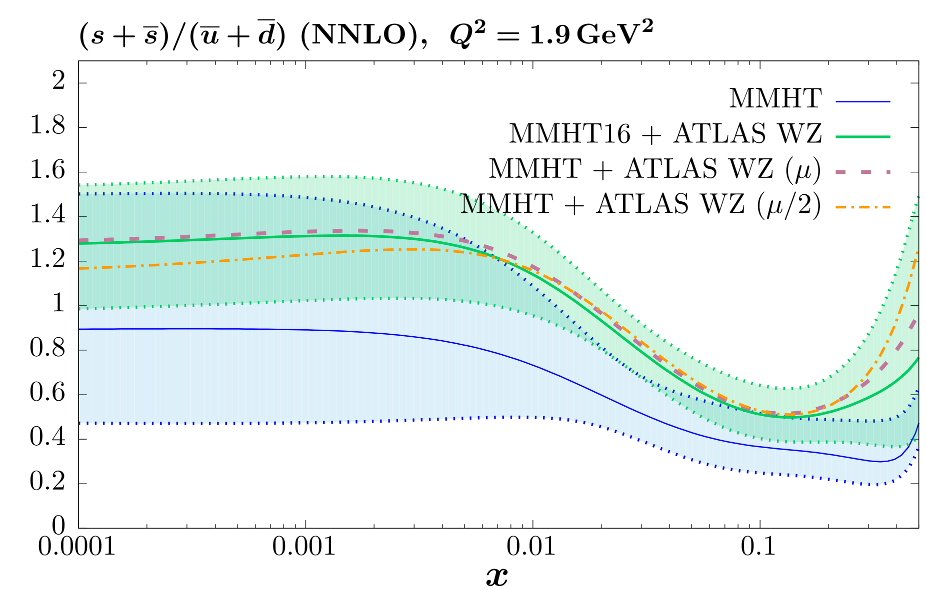
- Inclusive W, Z.
- Jets.
- Differential top.
- W+c
- …



★ Final HERA I+II inclusive and heavy flavour structure data.

★ All with **updated theory**, in most cases NNLO (W,Z, jets, top, neutrino-induced DIS…) - **APPLfast**.

★ Precise photon included by default.



Thank you for listening!

Backup

Renormalization Scale

- Consider within very simple toy model, fit to and predict :

$$A(Q^2) = \tilde{\alpha}_S(\mu_i^2) A_1 \left[1 + \frac{\tilde{\alpha}_S(\mu_i^2)}{A_1}\left(A_2 + \beta^{(0)} A_1 \ln a_i\right)\right] q(Q^2) \, .$$

$$B(Q^2) = \tilde{\alpha}_S(\mu_f^2) B_1 \left[1 + \frac{\tilde{\alpha}_S(\mu_f^2)}{B_1}\left(B_2 + \beta^{(0)} B_1 \ln a_f\right)\right] q(Q^2)$$

- If we write $\alpha_S \leftrightarrow A(Q^2)$, then in fact find similar situation to factorization scale. But not what we are interested in here (fit to PDFs).

- In that case, no simple breakdown of scales as before (fact. scale fixed here):

$$B(Q^2) = \frac{B_1 A(Q^2)}{A_1} \frac{\tilde{\alpha}_S(\mu_f^2)}{\tilde{\alpha}_S(\mu_i^2)} \left[1 + \beta^{(0)} \left(\tilde{\alpha}_S(\mu_f^2) \ln a_f - \tilde{\alpha}_S(\mu_i^2) \ln a_i\right) + \frac{B_2}{B_1} \tilde{\alpha}_S(\mu_f^2) - \frac{A_2}{A_1} \tilde{\alpha}_S(\mu_i^2)\right] \, .$$

- On the other hand for two related processes (e.g. W, Z):

$$\frac{A_2}{A_1} \sim \frac{B_2}{B_1} \equiv C_{\rm NLO}$$

and to maintain stability of $A(Q^2)/B(Q^2)$ under renormalization scale variations, need to take $\mu_i \sim \mu_f$ in relation between fit/predicted observables.

Correlated Scale Variations

$$K(Q^2) \sim \left(K_1 + \tilde{\alpha}_S \ln\left(\frac{a_f}{a_k}\right) K_2 + \tilde{\alpha}_S \ln\left(\frac{a_h}{a_f}\right) K_3\right) F\left(\frac{a_k}{a_f} Q^2\right) + F \leftrightarrow H$$

- If one assumes all factorization scale variation is correlated across observables, have $a_f = a_h$, and:

$$K(Q^2) \sim (K_1 - \tilde{\alpha}_S \ln(a_{kf}) K_2)\, F\left(a_{kf} Q^2\right) + F \leftrightarrow H$$

compare with variation in prediction alone:

$$K(Q^2) \sim (K_1 - \tilde{\alpha}_S \ln(a_k) K_2)\, F\left(a_k Q^2\right) + F \leftrightarrow H$$

- Thus again we reduce back to case where variation could be included in either fit or prediction, but not both (n.b. correlation in fit observables $\Rightarrow$ correlation in predicted ones).
- However such an assumption appears to be overly strong, missing some of the genuine d.o.f inherent in the $K \leftrightarrow F, H$ relation.