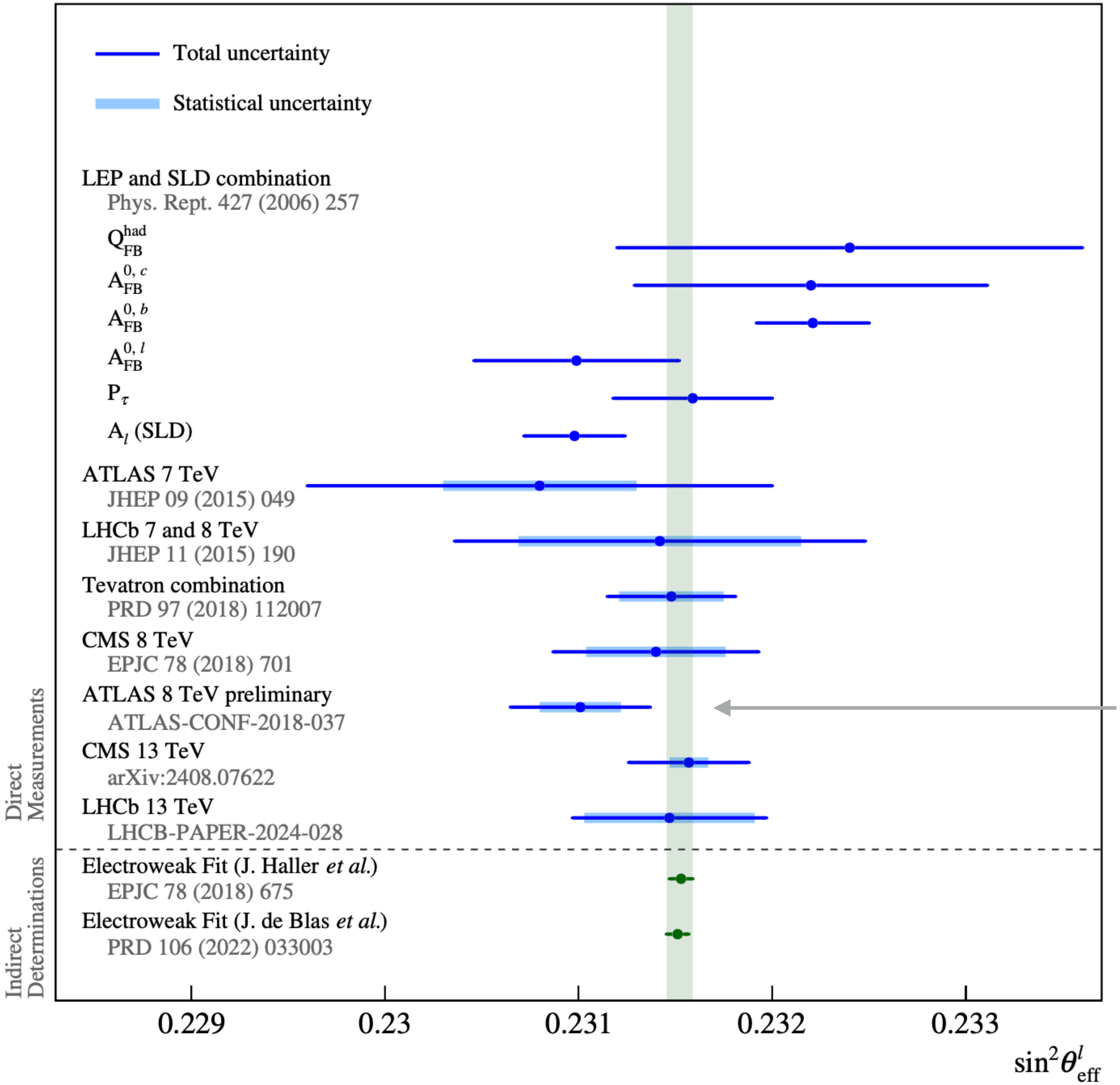
Weak Mixing Angle Measurements



Finalising ATLAS Run 1 measurement

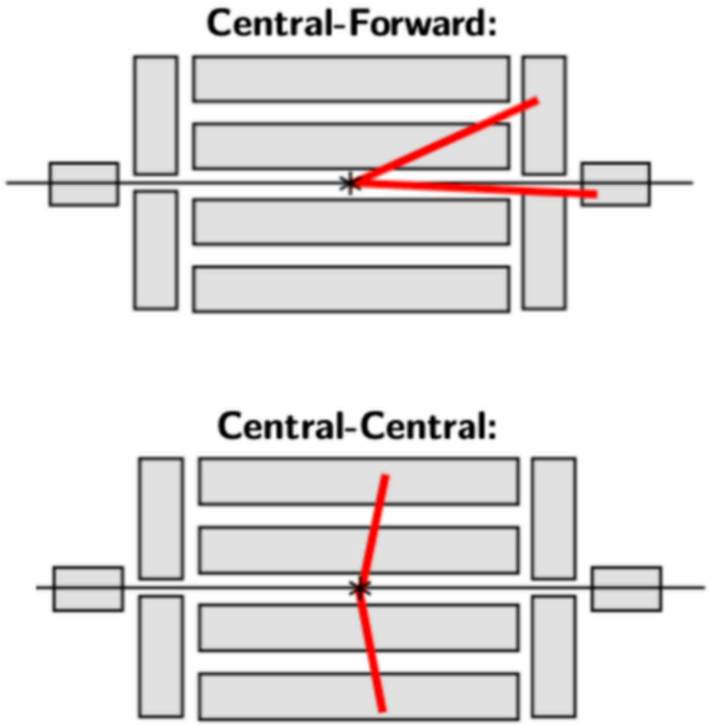
ATLAS Z/γ^* $d^3\sigma$ cross section $\sqrt{s}$ = 8 TeV

- Extraction of $\sin^2\theta^f_{\text{eff}}$ builds on ATLAS 3D (y_{ll}, M_{ll}, $\cos\theta^*$) DY cross section measurement at 8 TeV

- $d^3\sigma$ provides information on both A_{FB} and PDFs:

$$x_1 = \frac{m_{ll}}{\sqrt{s}} e^{yll}, x_2 = \frac{m_{ll}}{\sqrt{s}} e^{-yll}, Q^2 = m_{ll}^2 \rightarrow f(x, Q^2), \cos\theta^* \rightarrow A_{\text{FB}}(\cos\theta^*)$$

- 20.2 fb^{-1} of pp data at $\sqrt{s}$ = 8 TeV
- Two measurement regions:
  - central-central (CC): electrons and muons in seven $46 < m_{ll} < 200$ GeV, twelve $|y_{ll}| < 2.4$ and six $\cos\theta^*$ bins (2×504 bins)
  - central-forward (CF): one central and one forward electron in five $66 < m_{ll} < 150$ GeV, five $1.2 < |y_{ll}| < 3.6$ and six $\cos\theta^*$ bins (150 bins)
- Good agreement with theoretical predictions
  - $d^3\sigma$ reaches 0.5% precision near Z peak, barring luminosity uncertainty

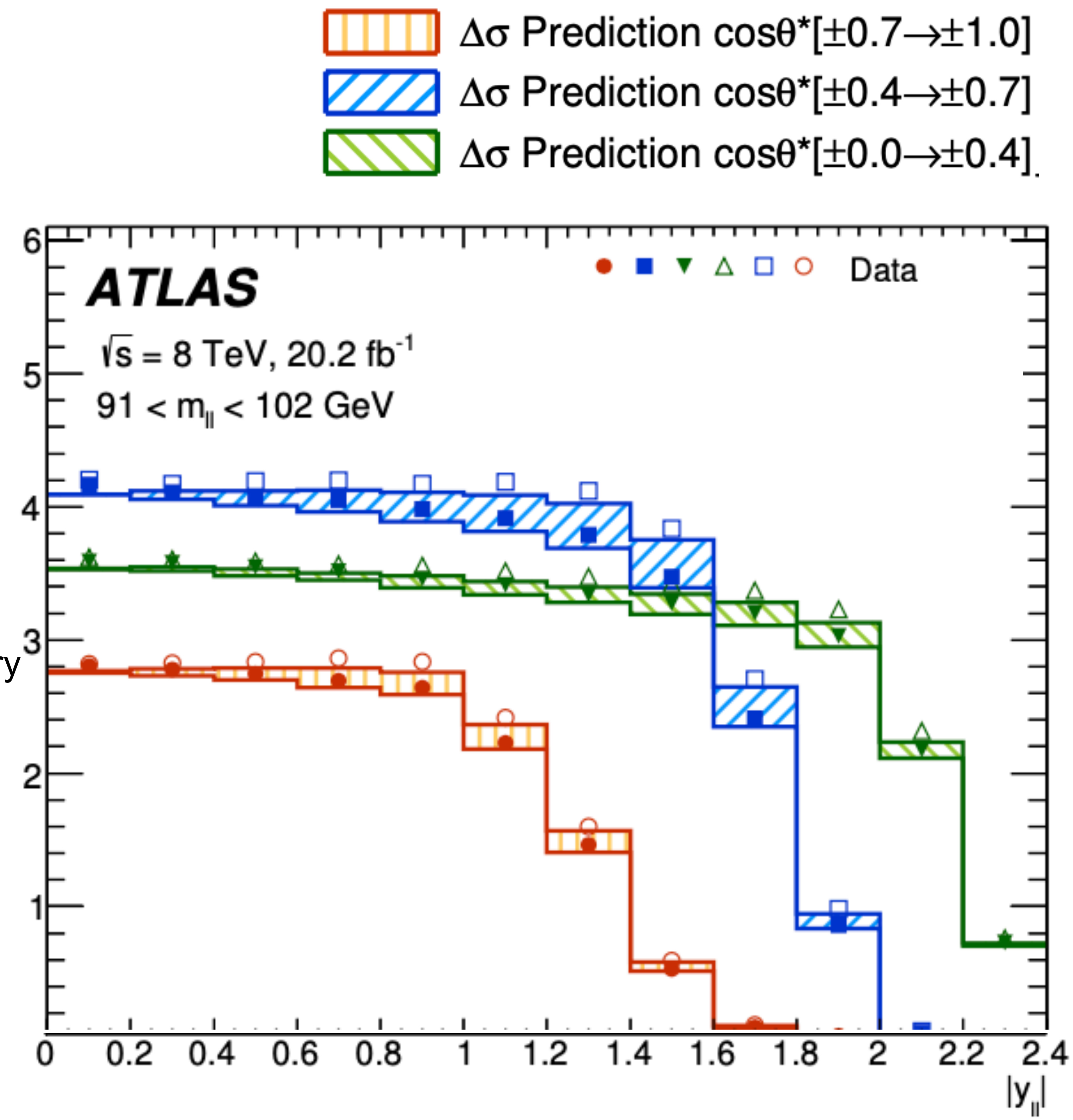


EW scheme using $\{\sin^2\theta^\ell_{eff}, G_\mu$ and $m_Z\}$ scheme → smaller EW corrections

Example mass bin:

91< m < 102 GeV

$$\frac{d^3\sigma}{dm_{\ell\ell}d|y_{\ell\ell}|d\cos\theta^*}$$



Plot as function of $|y_{\ell\ell}|$

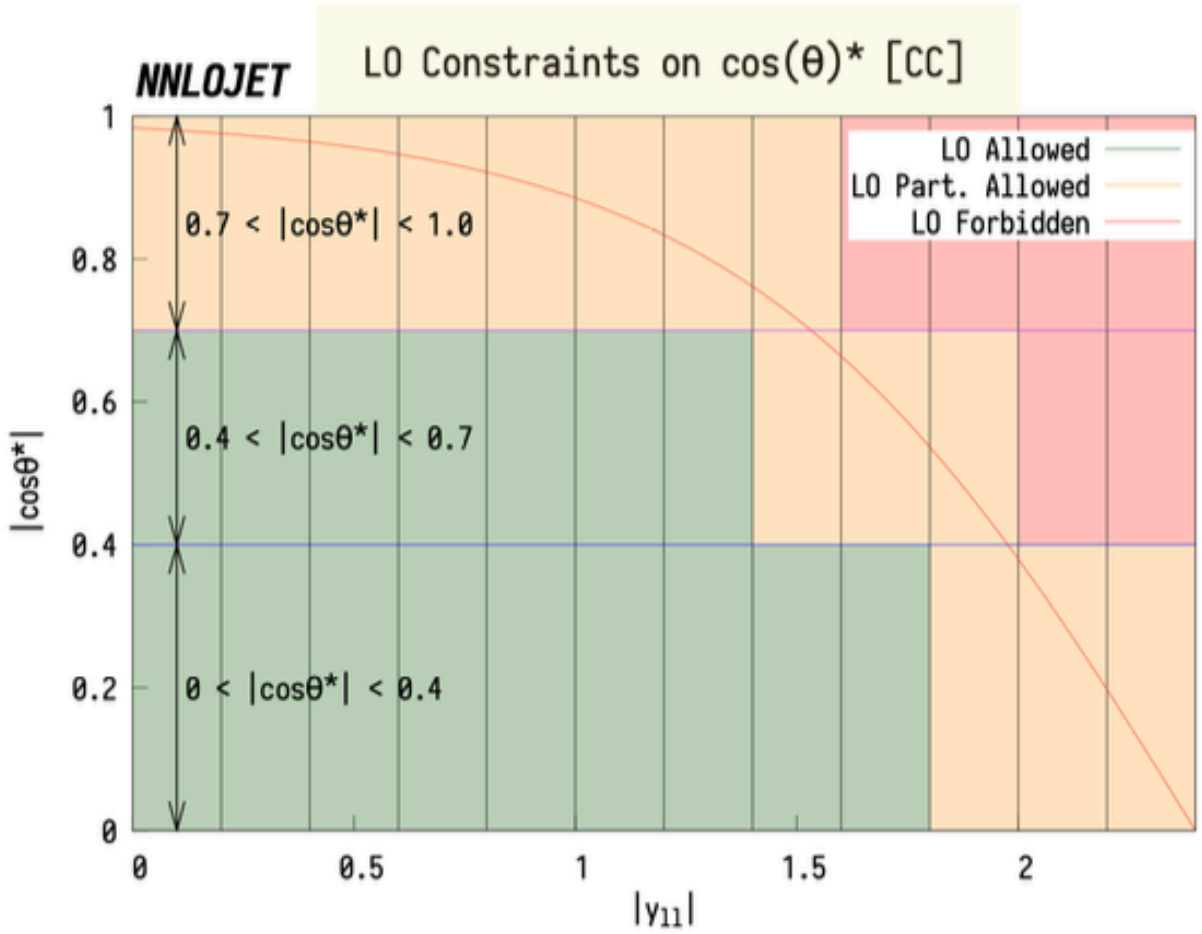
Overlay $\cos\theta^*$ bins

Shaded area indicate forward backward asymmetry

$$A_{\rm FB} = \frac{d^3\sigma(\cos\theta^* > 0) - d^3\sigma(\cos\theta^* < 0)}{d^3\sigma(\cos\theta^* > 0) + d^3\sigma(\cos\theta^* < 0)}$$

ATLAS Z/γ^* $d^3\sigma$ cross section $\sqrt{s}$ = 8 TeV

- Extraction of $\sin^2\theta^f_{\text{eff}}$ builds on ATLAS 3D ($y_{ll}, M_{ll}, \cos\theta^*$) DY cross section measurement at 8 TeV
  - Z3D kinematics and impact of fiducial cuts:
    - Rich and complex kinematic structure
    - Kinematic constraints from single lepton fiducial cuts restrict available phase space for di-lepton system



LO forbidden region sampled with Z vs jet recoil

⇒ Only populated at NLO ⇒ larger scale uncertainties

Divergent contributions at Q_T = 0 in partially allowed bins

⇒ phenomenology discussed here

Strategy:

- Fiducial acceptance = ratio of fid events / all events
- Fit $d^3\sigma$ for high acceptance bins ≥ 95%
- Fit A_{FB} forward backward asymmetry in low acceptance bins

ATLAS Z/γ^* $d^3\sigma$ cross section $\sqrt{s}$ = 8 TeV

LHCb: $\sin^2\theta^\ell_{\text{eff}}$ = 0.23147 ± 0.00044 (stat) ± 0.00005 (sys) ± 0.00023 (th. incl PDF)

CMS: $\sin^2\theta^\ell_{\text{eff}}$ = 0.23152 ± 0.00010 (stat) ± 0.00015 (sys) ± 0.00009 (theory) ± 0.00027 (PDF)

ATLAS (prel.): $\sin^2\theta^\ell_{\text{eff}}$ = 0.23140 ± 0.00021 (stat) ± 0.00016 (sys) ± 0.00024 (PDF)

Note: ATLAS Run1 analysis reaches same precision as recent CMS Run2 analysis

CMS $\sin^2\theta^\ell_{\text{eff}}$ measurement

Scale variations ~ ⅓ of PDF uncertainty
Similar for ATLAS

	χ^2_{min}	bins	$p(\%)$	$\sin^2\theta^\ell_{\text{eff}}$	stat	exp	th	PDF	MC	bg	eff	calib	other
$\ell\ell$	731	816	98	$23\,152 \pm 31$	10	15	8	27	8	4	6	6	3

Correlation of scales in A_{FB}
De-correlate numerator from denominator
Separate scales for shape vs norm
Use envelope of scale variations

$$A_{\text{FB}} = \frac{d^3\sigma(\cos\theta^* > 0) - d^3\sigma(\cos\theta^* < 0)}{d^3\sigma(\cos\theta^* > 0) + d^3\sigma(\cos\theta^* < 0)}$$

Questions

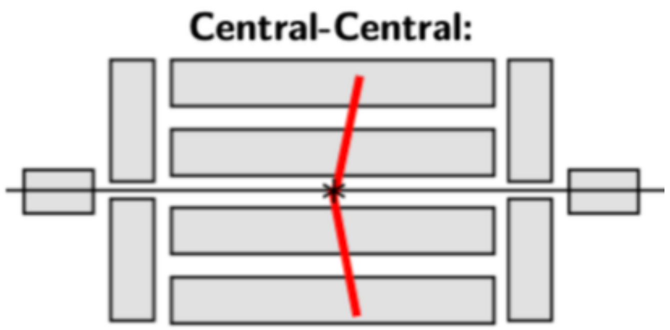
- How to handle scales in A_{FB}?
- What tools are available now to use theory nuisance parameters (TNPs)?
- How to handle TNPs in fixed order vs resummed parts of prediction

PDF Profiling & Tolerances

PDF sensitivity

- Unknown quark and anti-quark direction
- Rely on larger valence momentum
- This determines the boost of Z

  → better sensitivity to $\sin^2\theta^{\ell}_{\text{eff}}$



$|y_{\ell\ell}|$ = 0 ⇒ no sensitivity

Probe symmetric sea quarks

$|y_{\ell\ell}|$ ~ 3 ⇒ high sensitivity

Probe valence quarks

$d^3\sigma$ designed for PDF and $\sin^2\theta^{\ell}_{\text{eff}}$ sensitivity

$m_{\ell\ell}$: 46 — 200 GeV

$|y_{\ell\ell}|$: 0 — 3.6

→ constrain PDFs in-situ

Include PDF uncertainties via profiling
Approximation to performing full PDF fit

Introduce nuisance parameters for

- all correlated exp uncertainties
- global PDF uncertainties

Global fits use a tolerance criterion to define uncertainty

$\Delta\chi^2 = T^2$ for $T > 1$

e.g. CT use T ~ 10 or even more

Accommodates tensions in datasets / predictions
Effectively increases uncertainties

Question:

- How to accommodate tolerances in $\sin^2\theta^{\ell}_{\text{eff}}$ determination?

  Large tolerances used to determine PDFs

  PDF uncertainties provided for T = 1

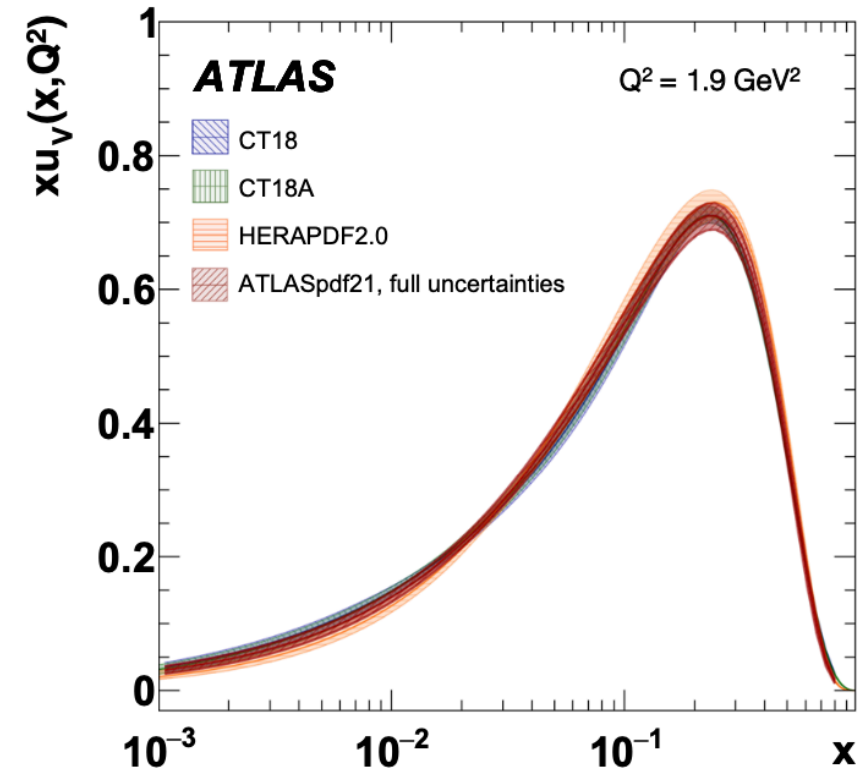
Dedicated PDF $\otimes \sin^2\theta^{\ell}_{eff}$ Fit

Alternative approach: simultaneous PDF $\otimes \sin^2\theta^{\ell}_{eff}$ fit using XFitter

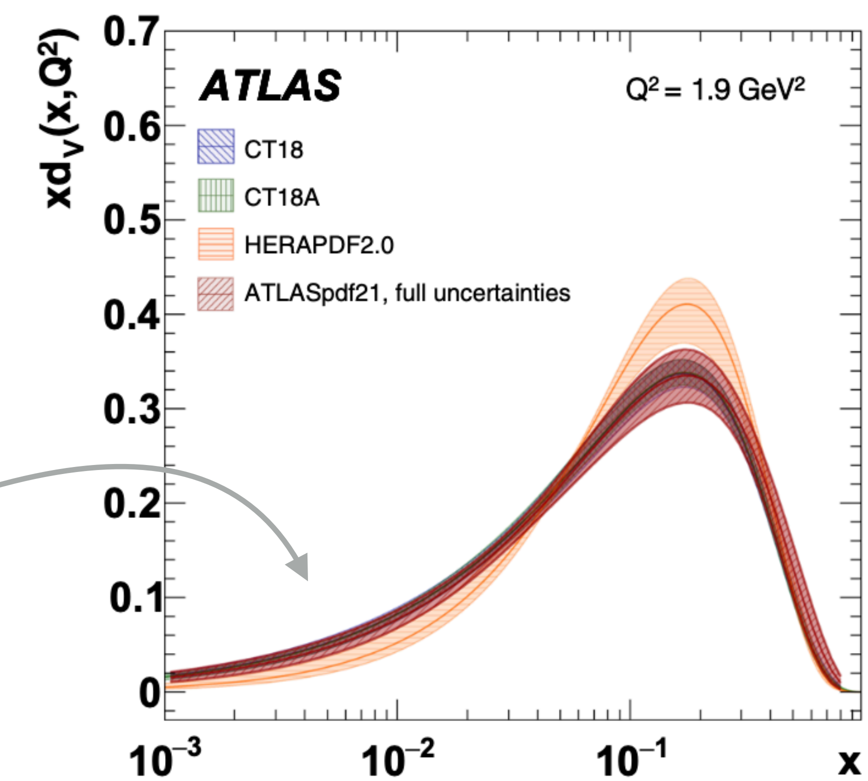
Use ATLASPDF and HERAPDF approach:

- Use minimal well understood data sets
- HERA DIS data (combined NC and CC)
- ATLAS precision W/Z data (7 TeV)
- ATLAS $d^3\sigma$ measurements
- Considering ATLAS W+jets / W asymmetry (8 TeV)
- Consistent NNLO QCD & NLO-EW predictions

Two most constraining ATLAS datasets



Example from ATLASPDF21



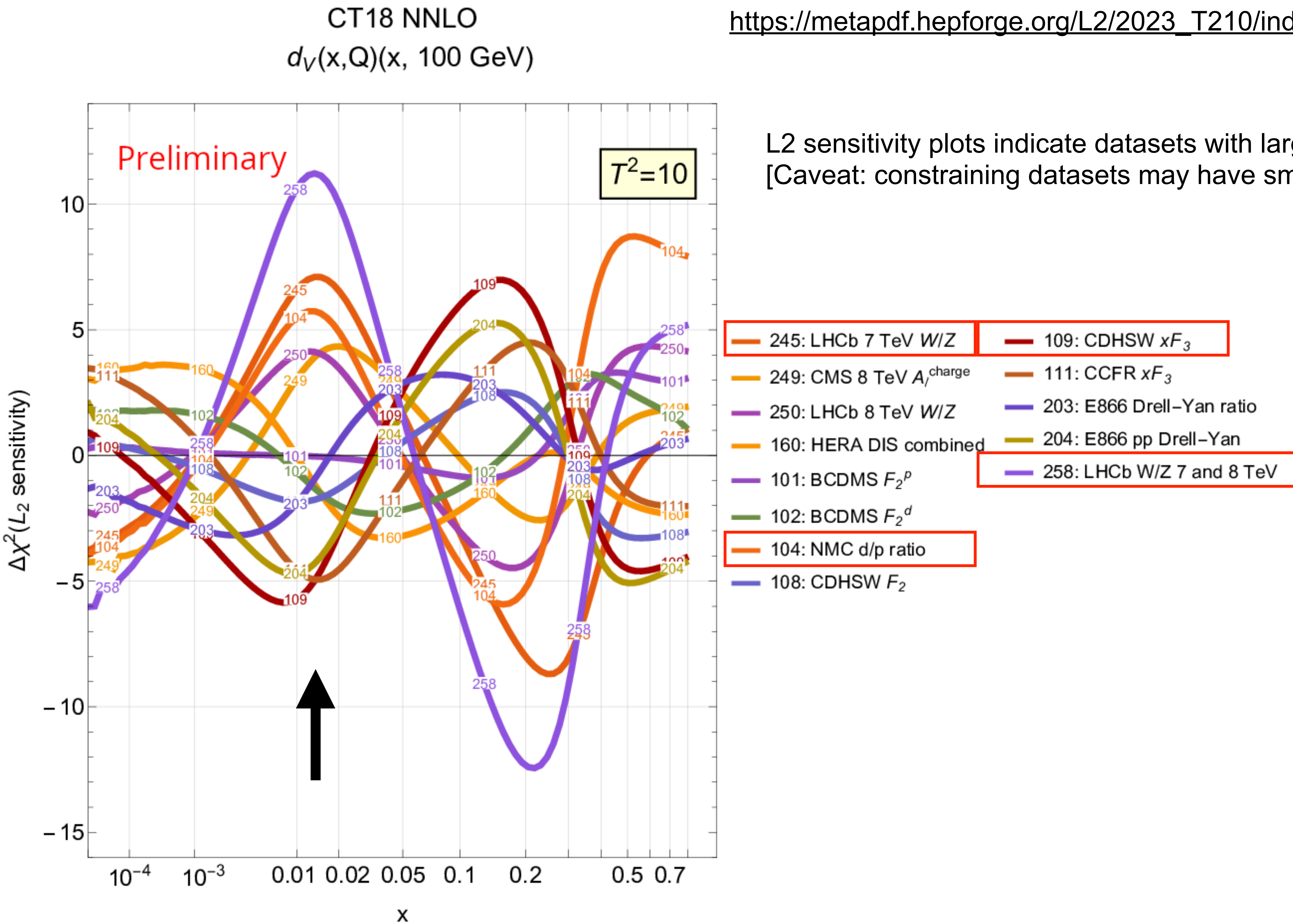
- Avoids use of many partially discrepant datasets
- Can use $\Delta\chi^2 = 1$ criterion (no need for tolerances)
- Cost: fewer reduced PDF constraints

Observe unexpected $\sin^2\theta^{\ell}_{eff}$ sensitivity to xd_v at x ~ 10^{-2}
Linked to behaviour in peak region via sum rules

Question:
- What are the constraining datasets for d_v at med x?
- How large are tensions between datasets in global fits?

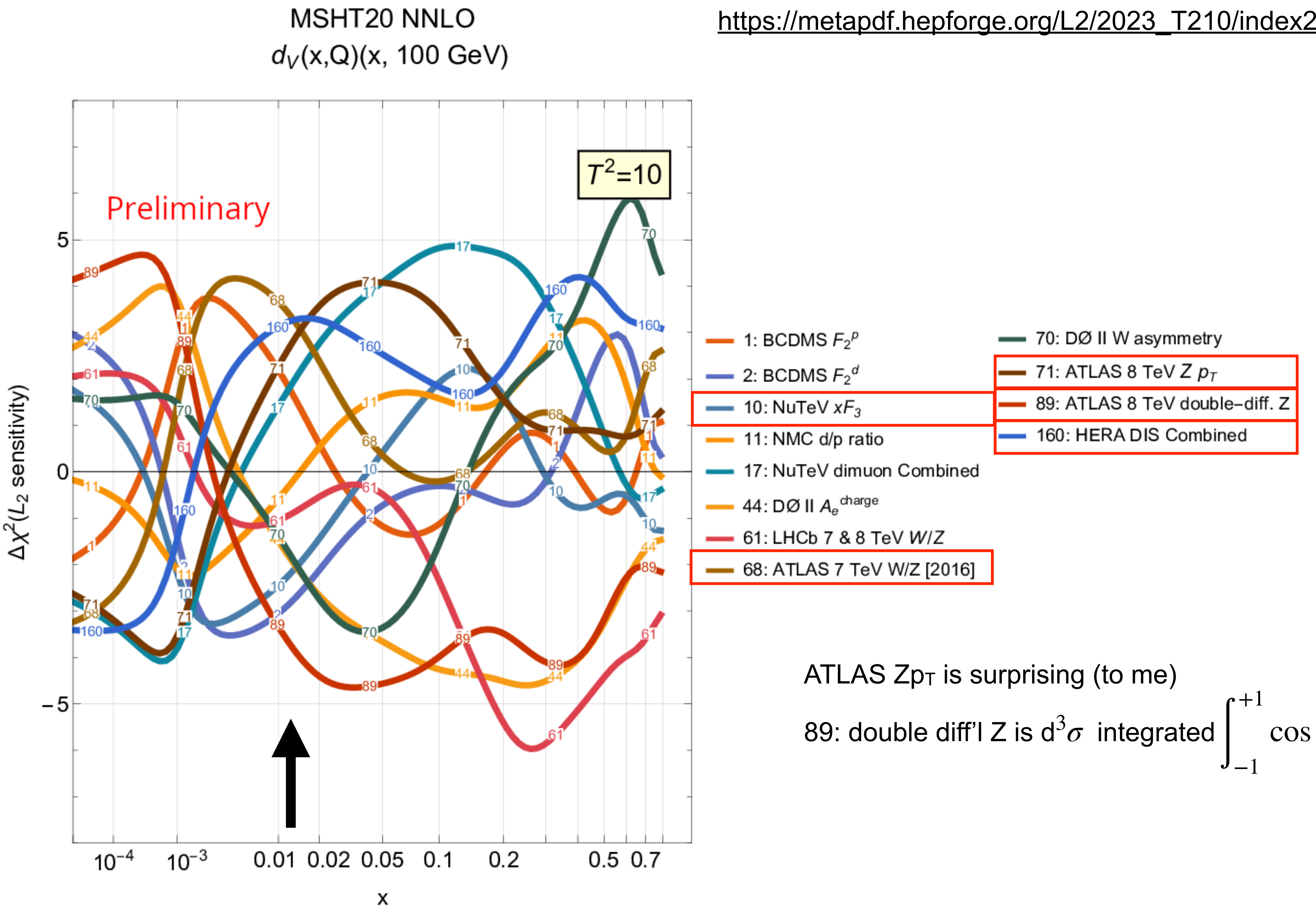
CT L2 Sensitivity Plot fo xd_v

https://metapdf.hepforge.org/L2/2023_T210/index2.html



L2 sensitivity plots indicate datasets with largest pulls
[Caveat: constraining datasets may have small pulls]

https://metapdf.hepforge.org/L2/2023_T210/index2.html

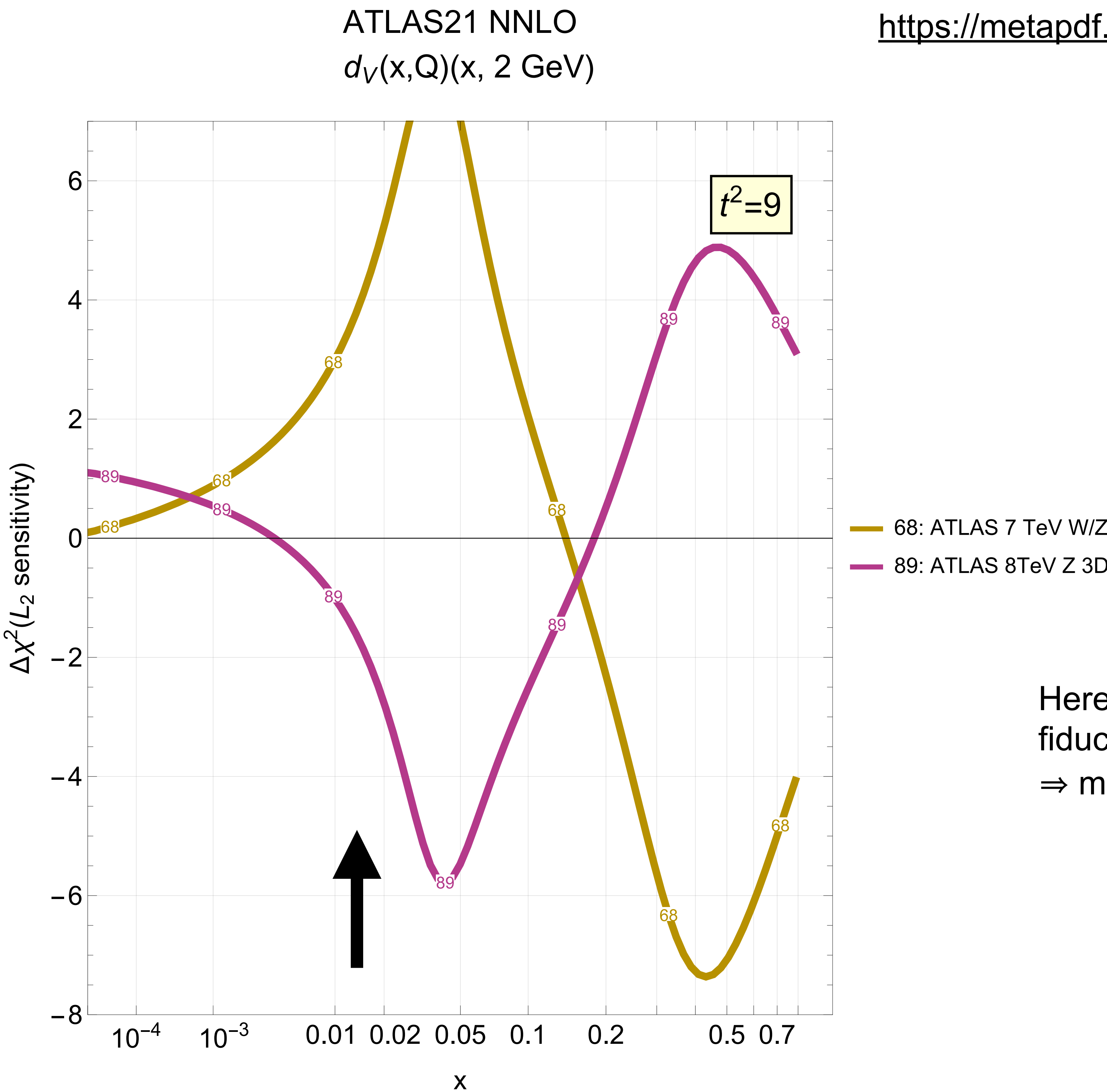


ATLAS Zp$_T$ is surprising (to me)

89: double diff'l Z is $d^3\sigma$ integrated $\int_{-1}^{+1} \cos\theta^*$

ATLASPDF21 L2 Sensitivity Plot fo xd_v

https://metapdf.hepforge.org/L2/2023_T210/index2.html



Here the $d^3\sigma$ are included where fiducial acceptance ≥ 95%
⇒ mostly data for $|y_{\ell\ell}| \leq 2.4$

Back-up

Fit Model

18 PDF parameters + $\sin^2\theta^\ell_{eff}$

$$xg(x) = A_g x^{B_g}(1-x)^{C_g}(1+D_g x) - A'_g x^{B'_g}(1-x)^{C'_g}$$

$$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1+D_{u_v}x+E_{u_v}x^2)$$

$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}(1+D_{d_v}x)$$

$$x\bar{u}(x) = A_{\bar{u}} x^{B_{\bar{u}}}(1-x)^{C_{\bar{u}}}$$

$$x\bar{d}(x) = A_{\bar{d}} x^{B_{\bar{d}}}(1-x)^{C_{\bar{d}}}$$

$$x\bar{s}(x) = r_s A_{\bar{d}} x^{B_{\bar{s}}}(1-x)^{C_{\bar{s}}}$$

C'_g: set to 25 to suppress negative contributions at high-x

$$r_s = \frac{s+\bar{s}}{2\bar{d}}$$

Assumption: $s = \bar{s}$

(green): constrained by sum rules
- Partons carry all the proton's momentum
- Proton = 2 valence up + 1 valence down

(yellow): set equal

(blue): set equal

Assumption:
$\bar{u} = \bar{d}$ as $x \to 0$

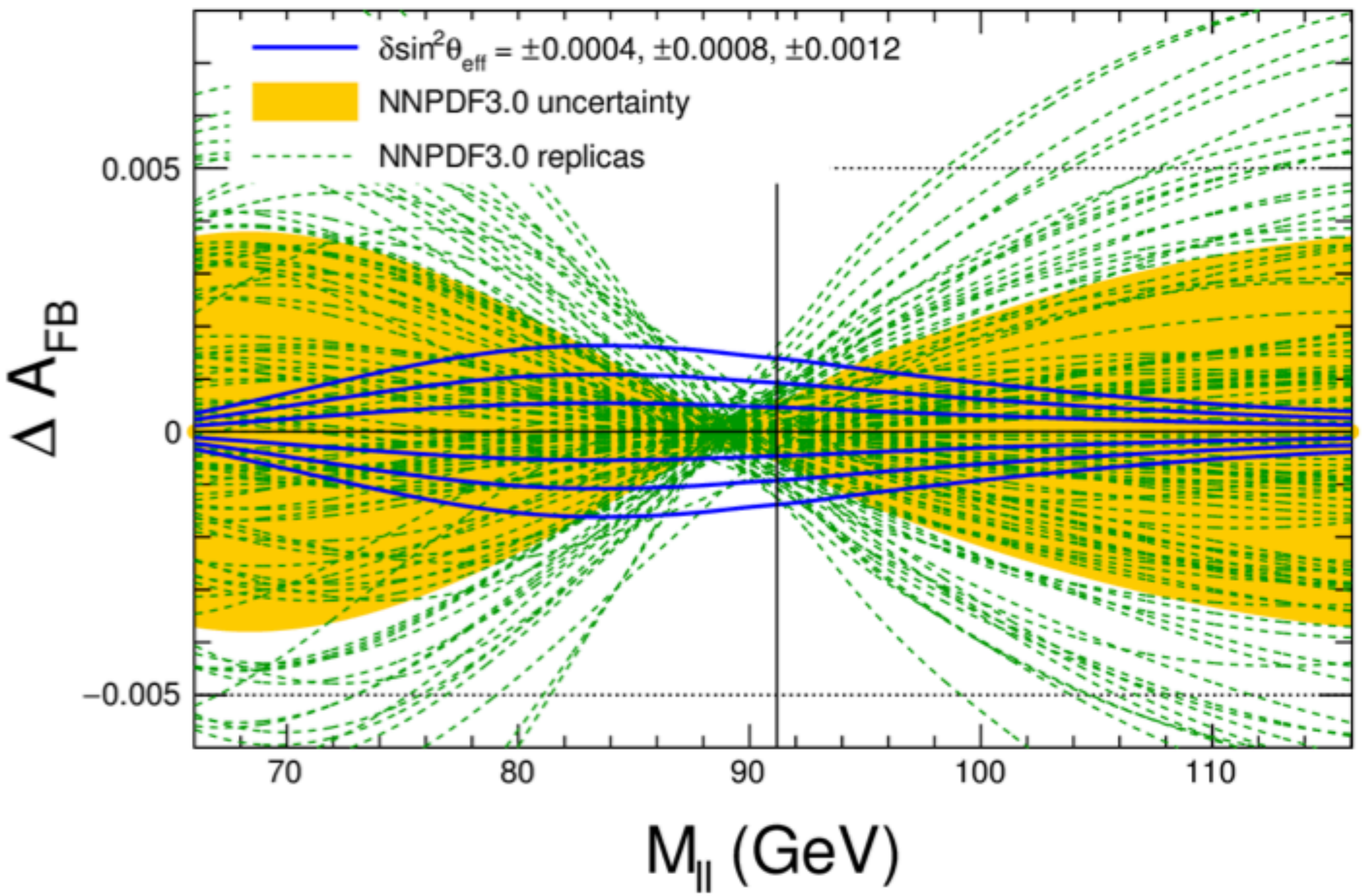
Fit Model (II)

- 19 parameters: 18 PDF parameters + $\Delta \sin^2\theta^{l}_{eff}$ parameter
- $\alpha_s(m_Z)$ = 0.118
- Heavy quark masses: m_c = 1.41 GeV, m_b = 4.2 GeV
- Initial scale Q^2_0 = 1.9 GeV^2
- Minimum cut on HERA data Q^2_{min} = 10 GeV^2

All these assumptions are varied to estimate uncertainties

PDF dependenance v $\sin^2\theta^{\ell}_{eff}$ dependance

Illustrative CMS plot
Difference dependancies allow simultaneous PDF and $\sin^2\theta^{\ell}_{eff}$



Additional PDF sensitivity in $\cos\theta^*$ spectrum

$\cos\theta^*$ distribution also contains PDF sensitivity eg. for qqbar vs qg

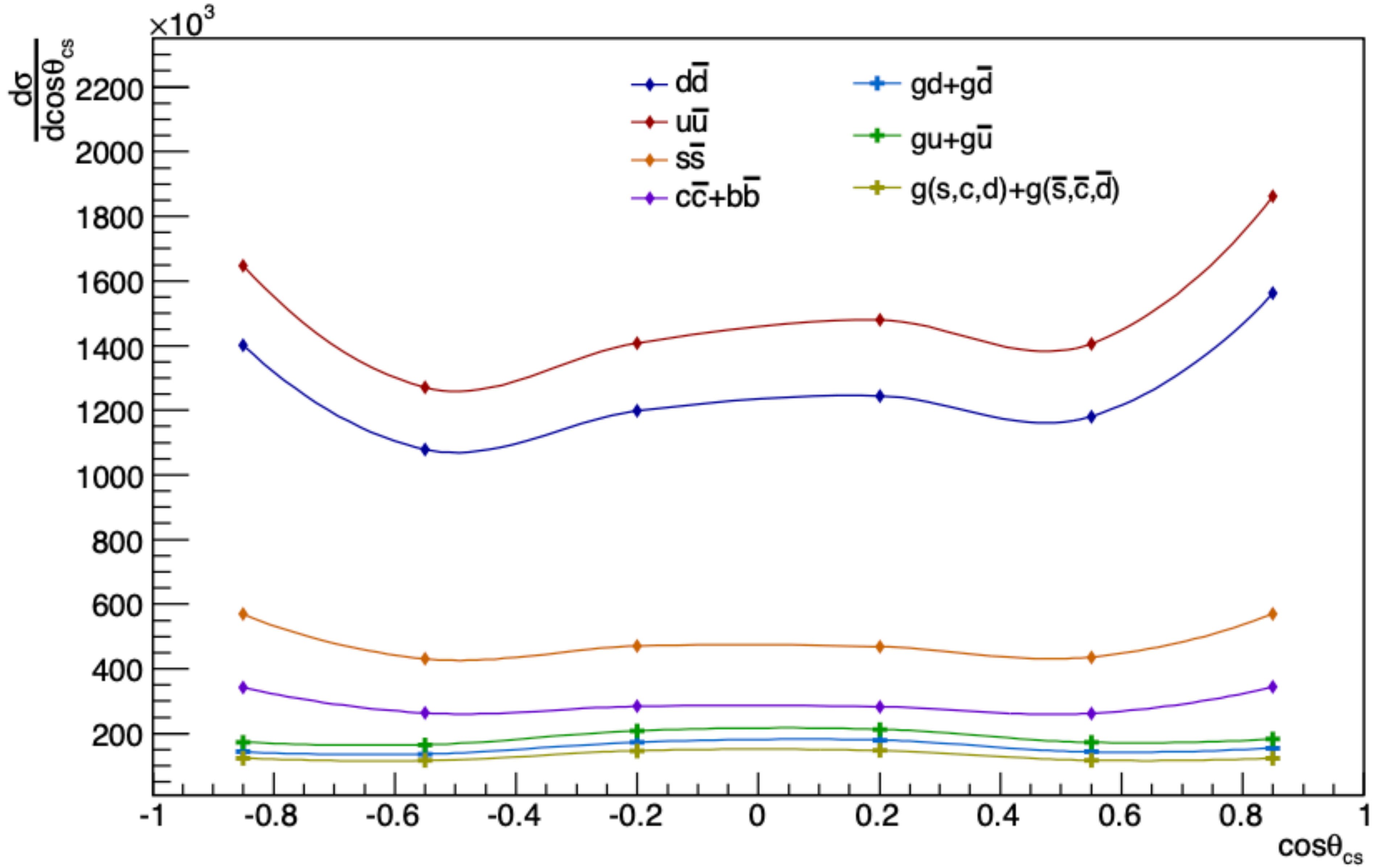
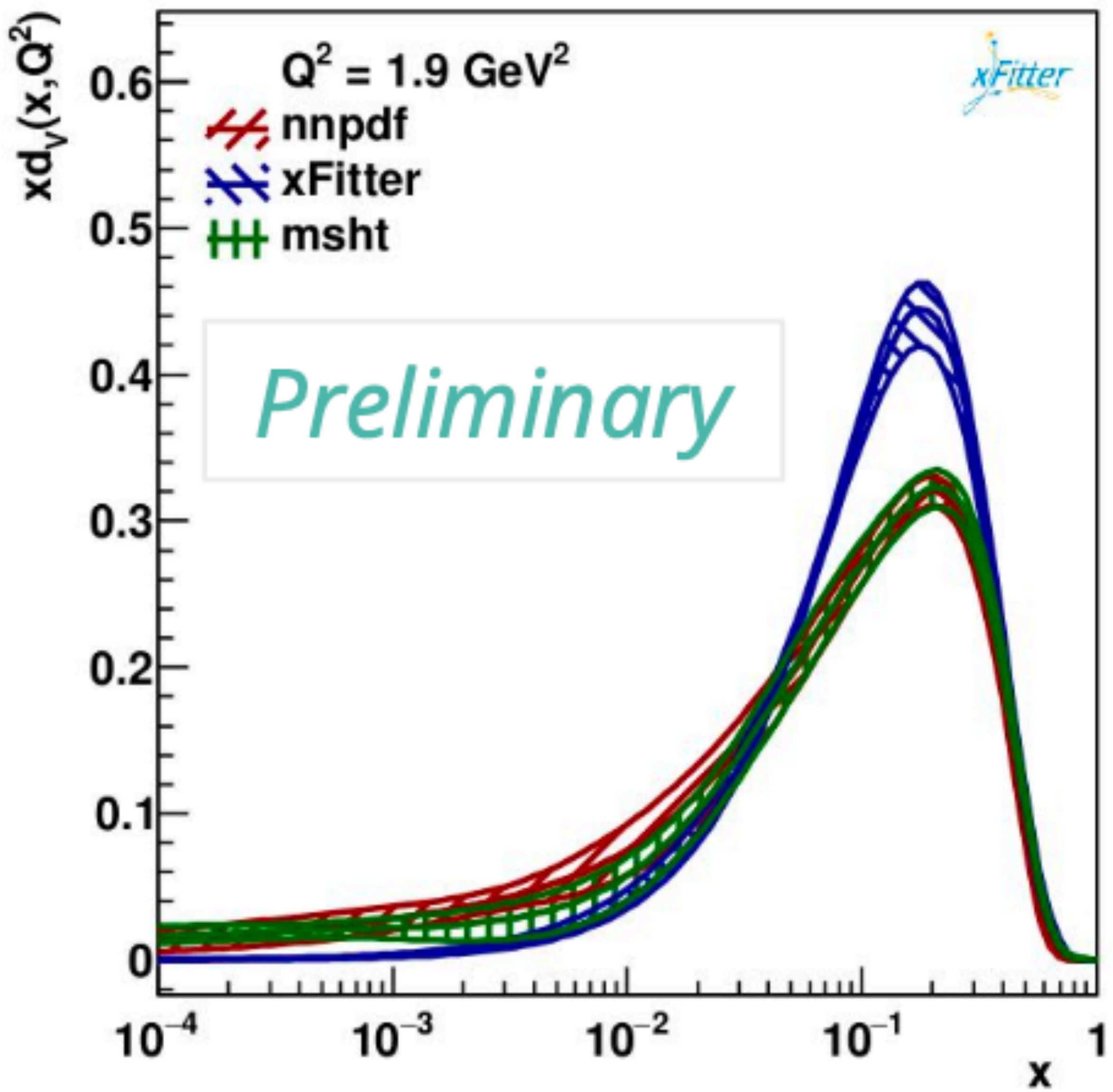


Figure 4: Parton contributions to the cross-section as a function of $\cos\theta^*$.

Dedicated PDF $\otimes \sin^2\theta^{\ell}_{eff}$ Fit

Recent xFitter study

Initial look at simple HERA fit
Performed at aN3LO



Questions and issues

- Large PDF / theory uncertainties ==> sin2thw, mw
- forbidden phase space regions
- scales ==> AFB
    - how do PDF fits use scale errors?
        - sin2thw uses envelope
        - ATLASPDF21 uses profiling
        - MSHT20 aN3LO drops this and adds new error fro MHOU
        - NNPDF4.0
    - scales unc. enters sub-leading in MC bg subtractions
- theory nuisance parameters?
    - practically what is available now?
    - Huss / Bonvini ==> other approaches to scale uncertainties

- dv constraints
- impact of N3LO or aN3LO
- can we get full N3LO pdfs soon?
- why are nnpdf4.0 error bands so small ?

- PDF tolerances
- profiling vs fits - new approaches?

- how are scale uncertainties used in the Ai analysis?
- what are the goals / requirements from PDFs ?