The LHC as a Neutrino-Ion Collider

Max Fieg w/

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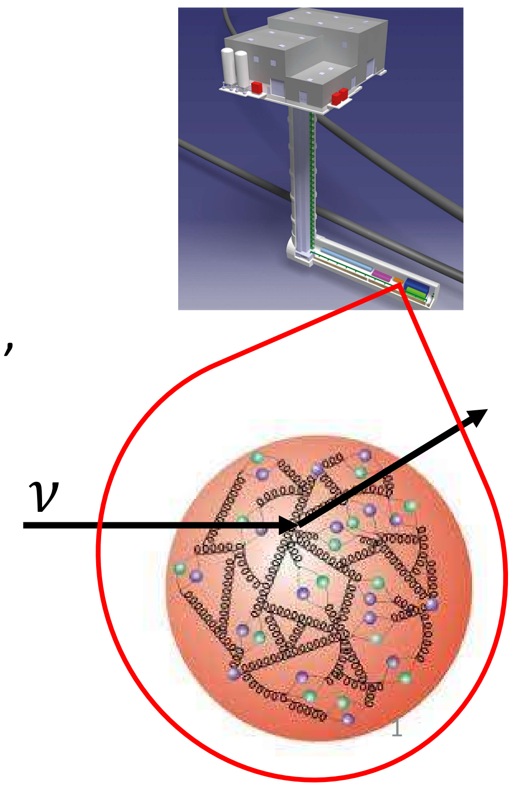
FLArE Forward Physics Working Group 11/7



Forward Physics

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ForwArd Search ExpeRiment at the LHC

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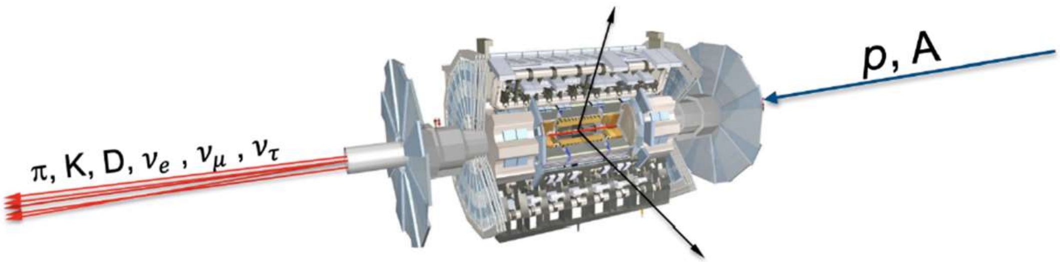


CERN-FASER-CONF-2023-001
29 March 2023

First Results from the Search for Dark Photons with the FASER Detector at the LHC

FASER Collaboration

Forward Physics at the LHC has become a very active topic

Many models predict an intense flux of BSM particles in the forward direction

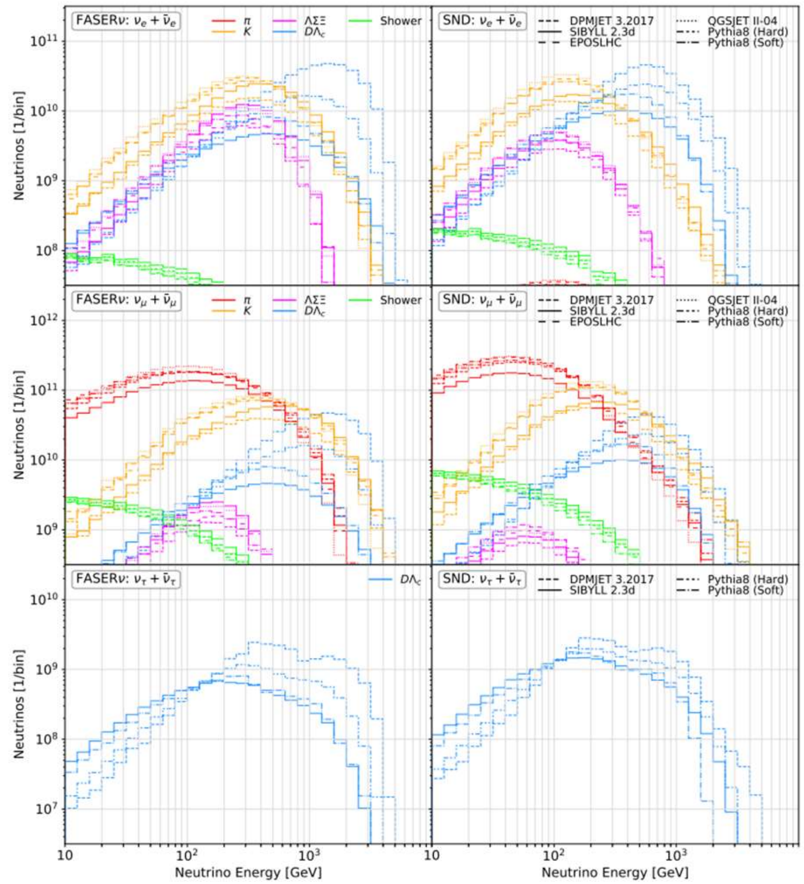
SM predicts intense neutrino beam of all 3 flavors

Forward Physics – Neutrinos

Neutrinos dominantly produced from hadron decays

Highest energy neutrinos made in a lab setting

In Run 3, $> 10^{11}$ neutrinos passing through FASERν, and O(1000) neutrino interactions



Forward Neutrinos

- Once a background,

- Now a signal, LHC neutrinos have been discovered at FASER and SND

- Can neutrinos be used as a tool?

A. Neutrino-Induced Backgrounds

"...a very forward detector might be able to detect a sizable number of neutrino events..."

First Direct Observation of Collider Neutrinos with FASER at the LHC

FASER Collaboration

Forward Physics
Neutrino-nucleon cross section

One of the primary targets is the neutrino cross section at uncharted neutrino energies

What more can we do with more statistics?

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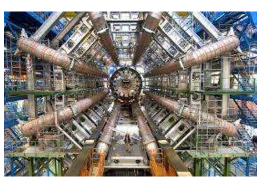
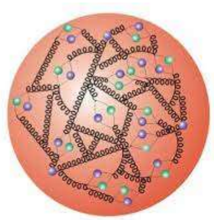
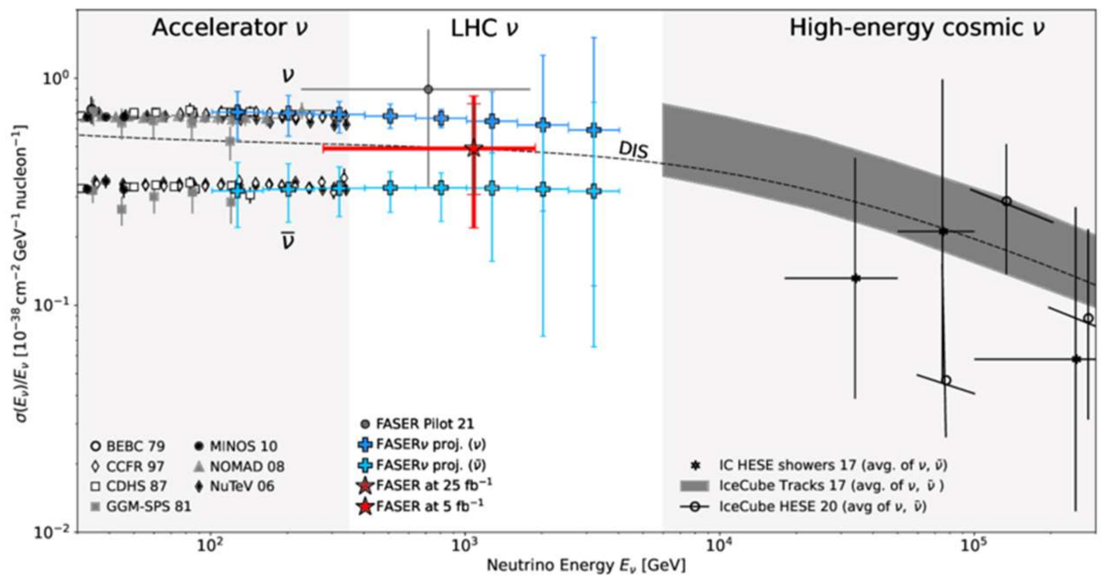


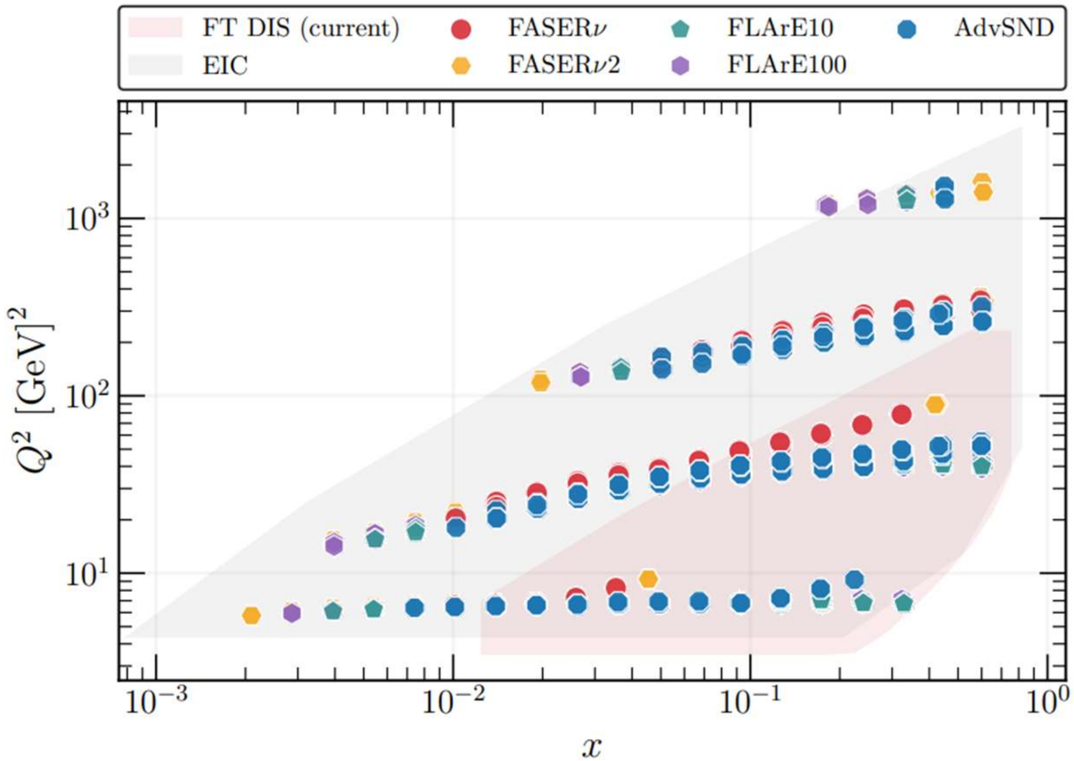
ν





Forward Physics at the LHC : A Neutrino Ion collider

- TeV neutrino energy offers new measurements in small Bjorken-x and high-Q^2 momentum transfer regime
- Complementary coverage as the proposed Electron-Ion Collider
- After boosting, the forward neutrino program at the LHC can be viewed as a neutrino-ion collider



Outline

1. DIS pseudodata generation
2. Forward Physics Experiments
3. (n)PDF fitting results
4. Phenomenology implications

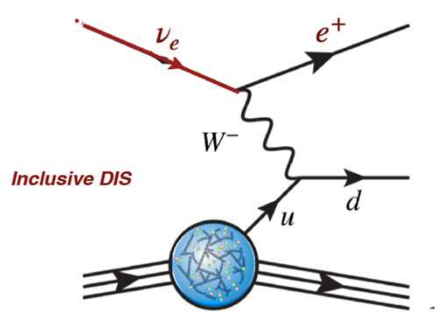
Deep-inelastic Scattering

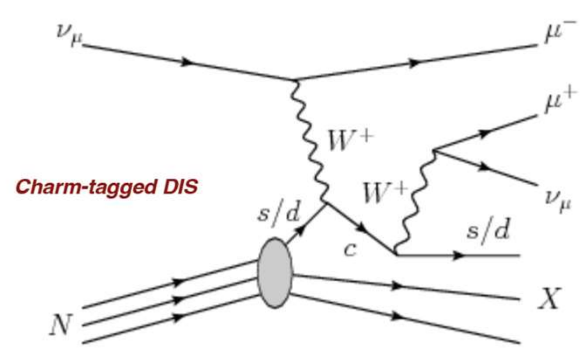
Neutrino scattering off a nucleon can be described via

- Bjorken-x momentum fraction, Q^2 momentum transfer, E_ν

Two processes of interest

- Inclusive DIS
- Charm-tagged DIS





Pseudodata Generation

- In bins of (x, Q^2, E_ν) can write the binned event rate as

$$N_{\text{ev}}^{(i)} = n_T L_T \int_{Q^{2(i)}_{\text{min}}}^{Q^{2(i)}_{\text{max}}} \int_{x^{(i)}_{\text{min}}}^{x^{(i)}_{\text{max}}} \int_{E^{(i)}_{\text{min}}}^{E^{(i)}_{\text{max}}} \frac{dN_\nu(E_\nu)}{dE_\nu} \left(\frac{d^2\sigma(x, Q^2, E_\nu)}{dx dQ^2} \right) \mathcal{A}(x, Q^2, E_\nu) dQ^2 dx dE_\nu$$

Incoming ν flux

Experimental acceptance

ν-nucleon cross-section

Pseudodata Generation (charm)

- In bins of (x, Q^2, E_ν) can write the binned event rate as

$$N^{(i)}_{\mathrm{ev,c}} = n_T L_T \int_{Q^{2(i)}_{\mathrm{min}}}^{Q^{2(i)}_{\mathrm{max}}} \int_{x^{(i)}_{\mathrm{min}}}^{x^{(i)}_{\mathrm{max}}} \int_{E^{(i)}_{\mathrm{min}}}^{E^{(i)}_{\mathrm{max}}} \frac{dN_\nu(E_\nu)}{dE_\nu} \left(\frac{d^2\sigma^{\nu N \to \ell + c + X}(x, Q^2, E_\nu)}{dx dQ^2} \right) \mathcal{A}(x, Q^2, E_\nu) dQ^2 dx dE_\nu$$

Incoming ν flux

Experimental acceptance

ν-nucleon cross-section

Neutrino Flux

- Well known that there are flux uncertainties in forward neutrino distribution
  - ν_μ is smallest at $\sim 10-20\%$

- Measurements constrain $\frac{\mathrm{dN}}{dE_\nu} \times \sigma$

- Future measurements and modeling will improve on this leading to better predictions of the flux

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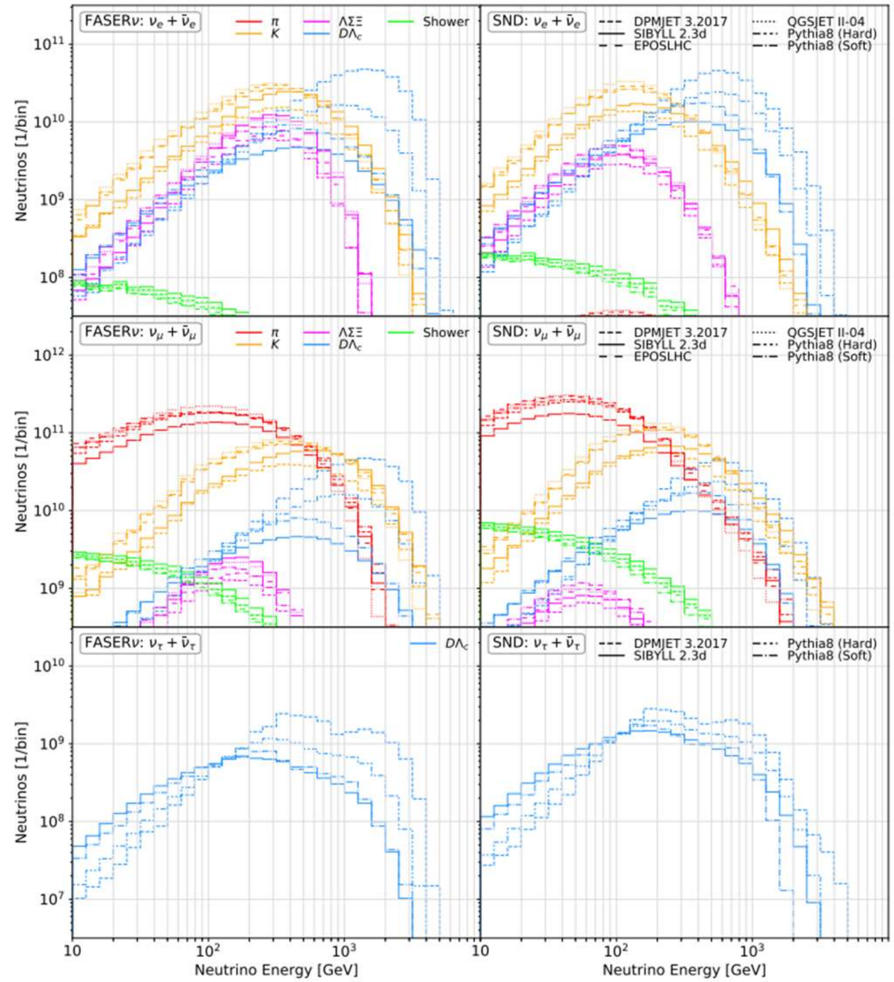


DIS structure functions

- Double differential cross-section for (anti-)neutrino free-nucleon CC scattering can be expressed with structure functions, $F_i^{\nu A}$

$$\frac{d^2\sigma^{\nu A}(x,Q^2,y)}{dxdy} = \frac{G_F^2 s/4\pi}{\left(1+Q^2/m_W^2\right)^2}\left[Y_+F_2^{\nu A}(x,Q^2) - y^2F_L^{\nu A}(x,Q^2) + Y_-xF_3^{\nu A}(x,Q^2)\right]$$

$$\frac{d^2\sigma^{\bar{\nu} A}(x,Q^2,y)}{dxdy} = \frac{G_F^2 s/4\pi}{\left(1+Q^2/m_W^2\right)^2}\left[Y_+F_2^{\bar{\nu} A}(x,Q^2) - y^2F_L^{\bar{\nu} A}(x,Q^2) - Y_-xF_3^{\bar{\nu} A}(x,Q^2)\right]$$

- Structure functions contain PDF information
- Different quark flavor dependencies between NC and CC

DIS structure functions – NC vs CC

- For illustration, with $n_f = 4$ and diagonal CKM, structure functions for CC neutrino NC lepton scattering can be expressed as (with $Q^2 \ll M_Z^2$)

- CC: $$F_2^{\nu p}(x, Q^2) = 2x \left(f_{\bar{u}} + f_d + f_s + f_{\bar{c}} \right)(x, Q^2)$$

$$f_{q^\pm} = f_q \pm f_{\bar{q}}$$

- NC: $$F_2^{\ell p}(x, Q^2) = x \left(\frac{4}{9} \left[f_{u^+} + f_{c^+} \right] + \frac{1}{9} \left[f_{d^+} + f_{s^+} \right] \right)(x, Q^2)$$

→ Best sensitivity on quark flavor separation is to use CC from FPF and NC from EIC

FPF Experiments

We consider experiments for Run 3 and HL-LHC

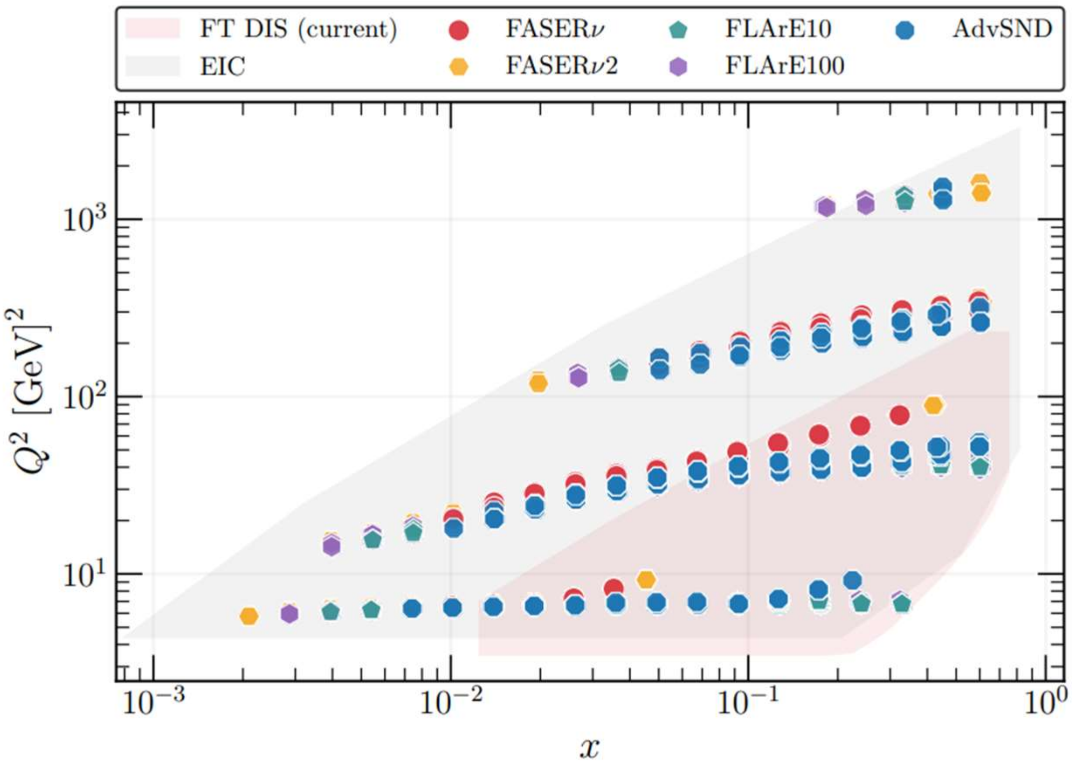
- Run 3 : FASERv and SND
- HL-LHC / FPF : FASERv2, AdvSND, FLArE-10, FLArE-100

- We assess the uncertainties and acceptances related with reconstructing (x, Q^2, E_ν) or equivalently $(E_\ell, E_h, \theta_\ell)$

$$
\begin{aligned}
E_\nu &= E_h + E_\ell \,, \\
Q^2 &= 4(E_h + E_\ell)E_\ell \sin^2(\theta_\ell/2) \\
x &= \frac{4(E_h + E_\ell)E_\ell \sin^2(\theta_\ell/2)}{2m_N E_h}
\end{aligned}
$$

FPF Experiments - kinematic coverage

- Increase reach in x and Q^2 by almost an order of magnitude in each direction
- Comparable reach of the highest energy proposed at EIC
- Small-x region relevant for heavy boson production in central region



FPF Experiments – systematics

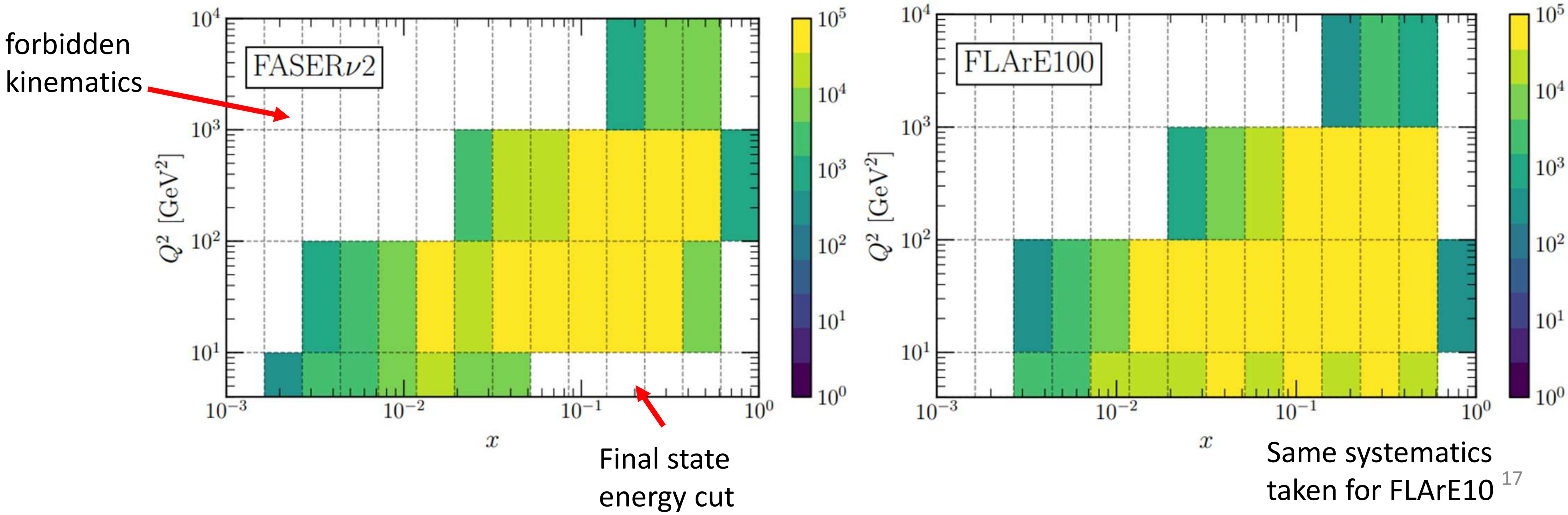
- We study DIS event rate for electron and muon neutrinos using some benchmark systematics
  - Cut on E_h, E_ℓ, θ_ℓ
- We also study the impact of charge ID and charm ID
- For FLArE-10(0), we measure muon charge and energy using FASER magnet
  - Imposes angular cut

Detector	Rapidity	Target	Charge ID	Acceptance	Performance
FASERν	$\eta_\nu \geq 8.5$	Tungsten (1.1 tonnes)	muons	$E_\ell, E_h \gtrsim 100$ GeV $\tan\theta_\ell \lesssim 0.025$ (charge ID) reco E_h & charm ID	$\delta E_\ell \sim 30\%$ $\delta\theta_\ell \sim 0.06$ mrad $\delta E_h \sim 30\%$
SND@LHC	$7.2 \leq \eta_\nu \leq 8.4$	Tungsten (0.83 tonnes)	n/a	$E_\ell, E_h \gtrsim 20$ GeV $\theta_\mu \lesssim 0.15, \theta_e \lesssim 0.5$	n/a
FASERν2	$\eta_\nu \geq 8.5$	Tungsten (20 tonnes)	muons	$E_\ell, E_h \gtrsim 100$ GeV $\tan\theta_\ell \lesssim 0.05$ (charge ID) reco E_h & charm ID	$\delta E_\ell \sim 30\%$ $\delta\theta_\ell \sim 0.06$ mrad $\delta E_h \sim 30\%$
AdvSND-far	$7.2 \leq \eta_\nu \leq 8.4$	Tungsten (5 tonnes)	muons	$E_\ell, E_h \gtrsim 20$ GeV $\theta_\mu \lesssim 0.15, \theta_e \lesssim 0.5$ reco E_h	n/a
FLArE (*)	$\eta_\nu \geq 7.5$	LAr (10, 100 tonnes)	muons	$E_\ell, E_h \gtrsim 2$ GeV, $E_e \lesssim 2$ TeV $\theta_\mu \lesssim 0.025$, $\theta_e \lesssim 0.5$ reco E_h	$\delta E_e \sim 5\%$, $\delta E_\mu \sim 30\%$ $\delta\theta_\ell \sim 15$ mrad $\delta E_h \sim 30\%$

$$N_{\rm ev}^{(i)} = n_T L_T \int_{Q^{2(i)}_{\rm min}}^{Q^{2(i)}_{\rm max}} \int_{x^{(i)}_{\rm min}}^{x^{(i)}_{\rm max}} \int_{E^{(i)}_{\rm min}}^{E^{(i)}_{\rm max}} \frac{dN_\nu(E_\nu)}{dE_\nu} \left(\frac{d^2\sigma(x,Q^2,E_\nu)}{dx\,dQ^2}\right) \boxed{\mathcal{A}(x,Q^2,E_\nu)}\, dQ^2\,dx\,dE_\nu$$

FPF experiments – ν_μ event distribution at FASERv2 and FLArE*

- O(1M) total event rate → ~500k after acceptance cuts
- Reach x~10^{-3}
- Lower energy thresholds at FLArE



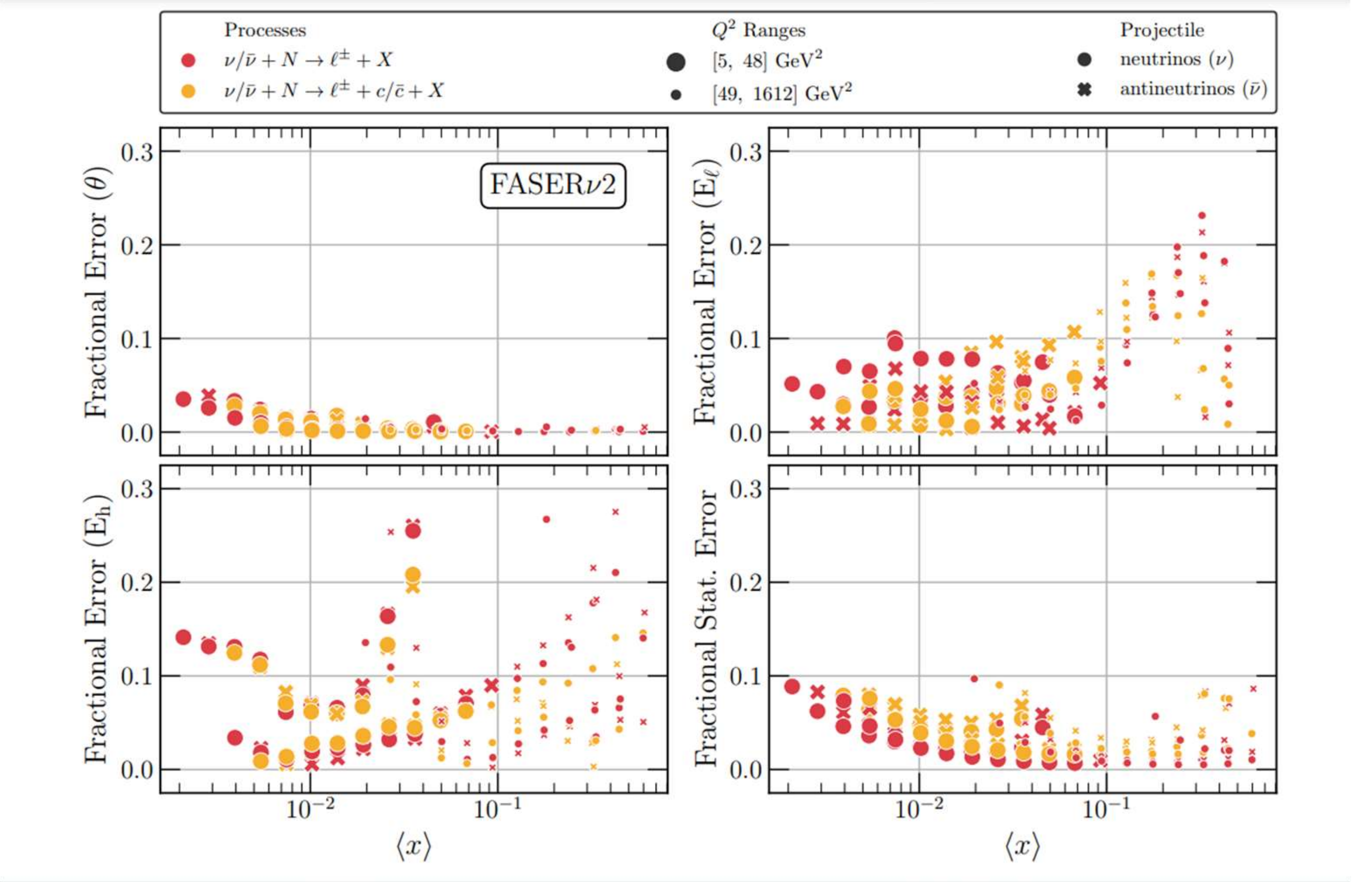
FPF experiments – inclusive (charm) event rates

Detector	N_{ν_e}	$N_{\bar{\nu}_e}$	$N_{\nu_e} + N_{\bar{\nu}_e}$	N_{ν_μ}	$N_{\bar{\nu}_\mu}$	$N_{\nu_\mu} + N_{\bar{\nu}_\mu}$
FASERν	400 (62)	210 (38)	610 (100)	1.3k (200)	500 (90)	1.8k (290)
SND@LHC	180 (22)	76 (11)	260 (32)	510 (59)	190 (25)	700 (83)
FASERν2	116k (17k)	56k (9.9k)	170k (27k)	380k (53k)	133k (23k)	510k (76k)
AdvSND-far	12k (1.5k)	5.5k (0.82k)	18k (2.3k)	40k (4.8k)	16k (2.2k)	56k (7k)
FLArE10	44k (5.5k)	20k (3.0k)	64k (8.5k)	76k (10k)	38k (5.0k)	110k (15k)
FLArE100	290k (35k)	130k (19k)	420k (54k)	440k (60k)	232k (30k)	670k (90k)

- ν_μ dominates the event rate over ν_e by a factor of 2-3
- HL/FPF brings ~ 250x more events beyond Run 3 counterpart
- Charm production is ~15% of event rate → strange PDF

Systematics uncertainties at FASERv2

- Uncertainties of $\sim 10 - 30\%$
- Dominated by energy reconstruction
- Statistical errors $\leq 10\%$



PDF fitting strategy

- PDF4LHC21 - proton
  - *xFitter* with Hessian profiling with prior proton PDF sets
- NNPDF4.0 - proton
  - Direct inclusion into global PDF fit
  - Cross-check for robustness and stability with PDF4LHC21
- EPPS21 – Tungsten Nucleus
  - Nucleus correction

→

We take two cases

1. Statistical uncertainty only
   - $\delta N = \sqrt{N}$
2. With systematic uncertainties added in quadrature

*See paper for PDF fitting details

PDF fit summary

We make lots of comparisons in the paper

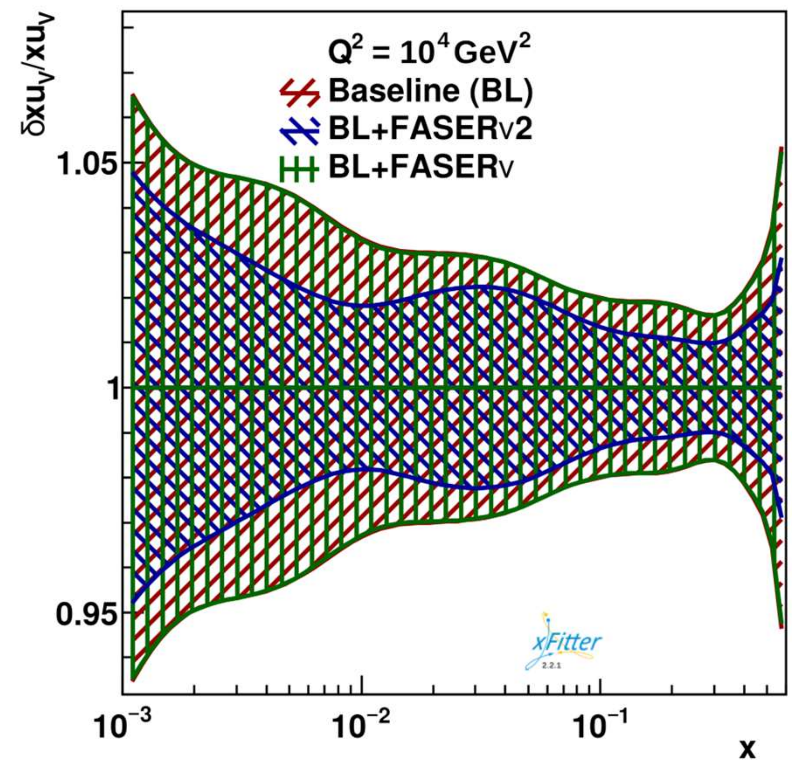
- FASERν(2)
  - Statistics vs systematics
  - Charm ID vs no charm ID
  - Charge ID vs no charge ID
- Experimental comparison
  - FASERν2 vs AdvSND, FLArE10
  - Total FPF data
- NNPDF
  - Consistent and robust results
- EPPS21
  - Tungsten Nucleus
  - qualitatively similar to proton PDF improvement

} I will highlight a few

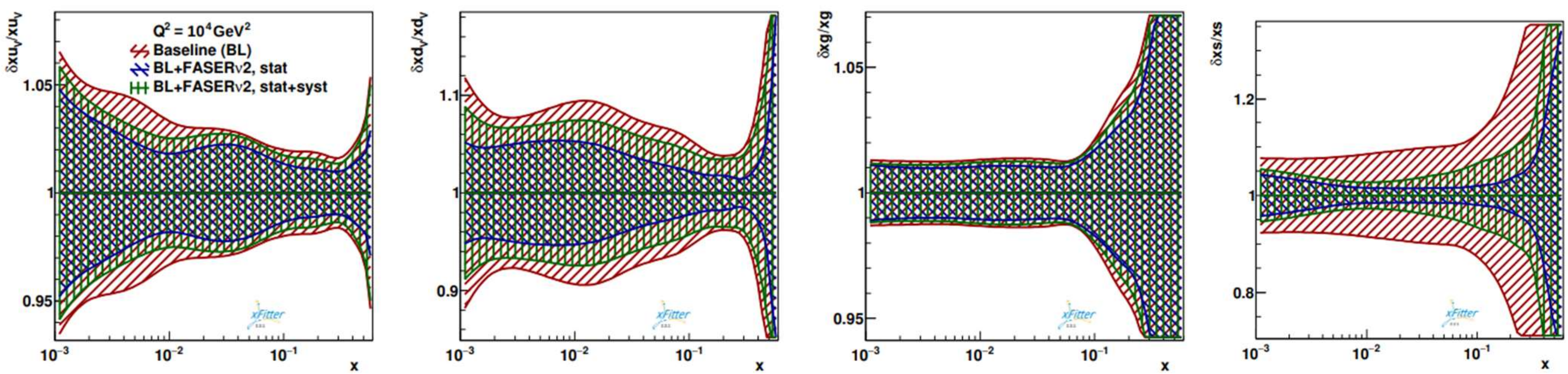
PDF fits – FASERv vs FASERv2

- Run 3 statistics too small to be sensitive to PDF fit…

- Not a surprise, let's look at FPF

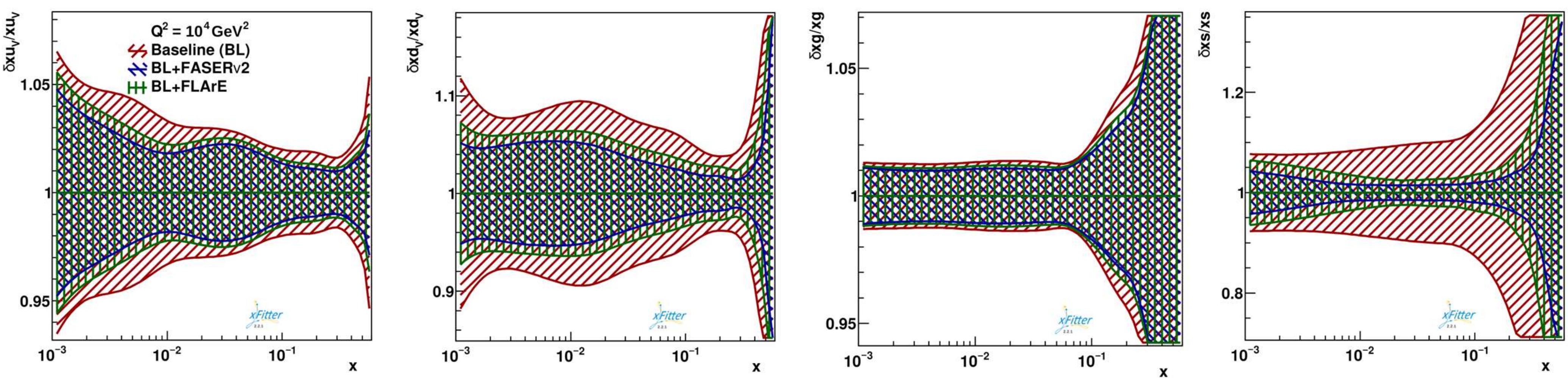


PDF fits – FASERv2 stat vs systematics



- PDF4LHC21 includes existing neutrino DIS measurements
  - FPF still manages to improve!
- Gluon PDF unaffected → expected for a neutrino scattering experiment
- Huge improvement in strange quark
  - Consequence of charm tagging!

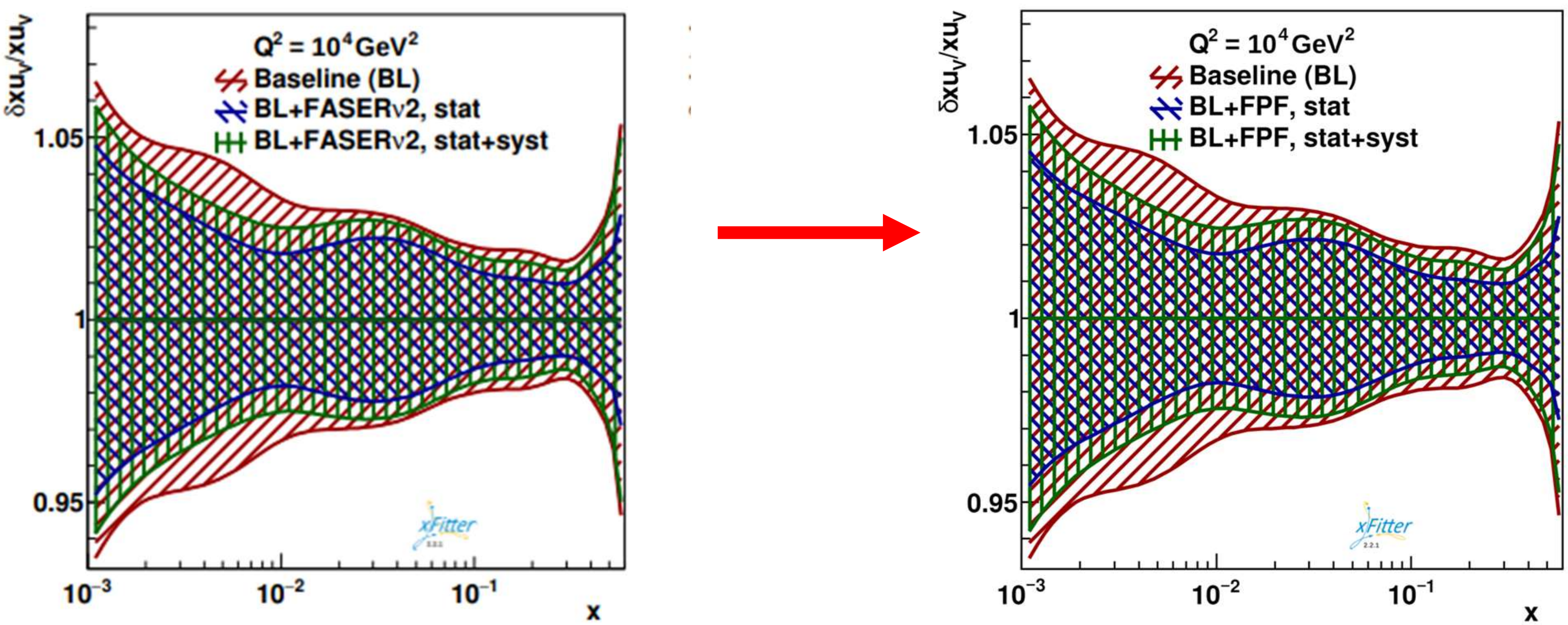
PDF fits – FASERv2 vs FLArE-10 (stat only)



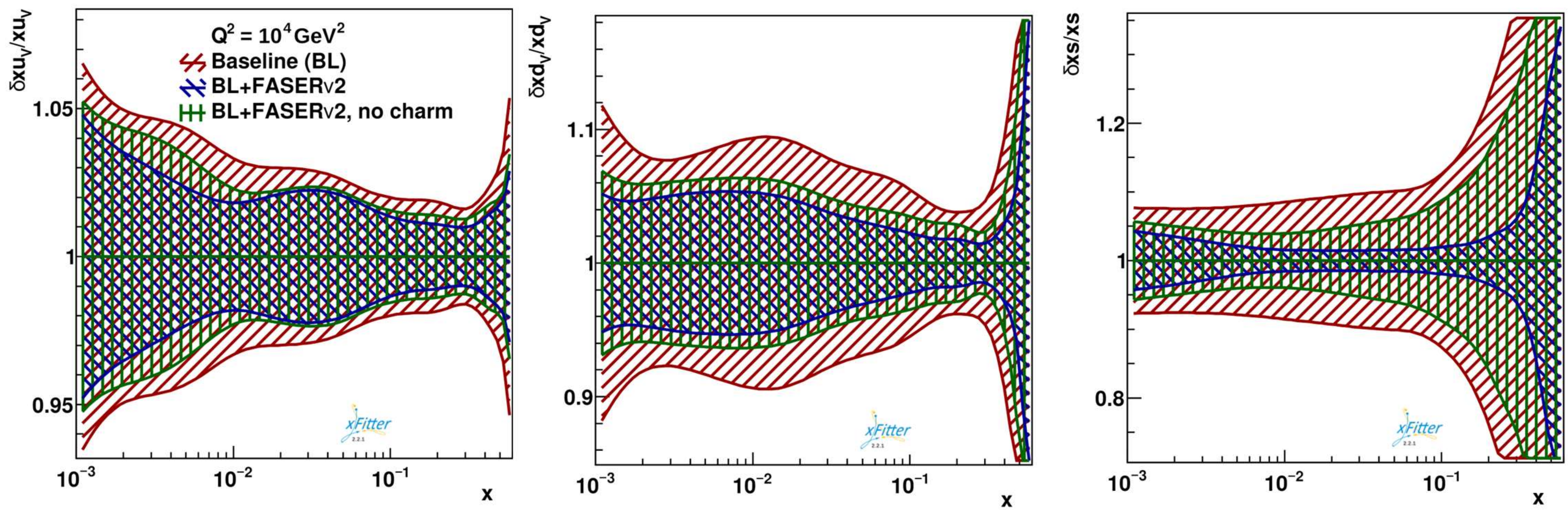
- At $Q^2 = 10^4$ GeV², have somewhat comparable sensitivities
- FLArE would have sensitivity at small recoils

PDF fits – total FPF

- Results marginally improved with inclusion of additional data
  - → Experiment with largest statistics dominates

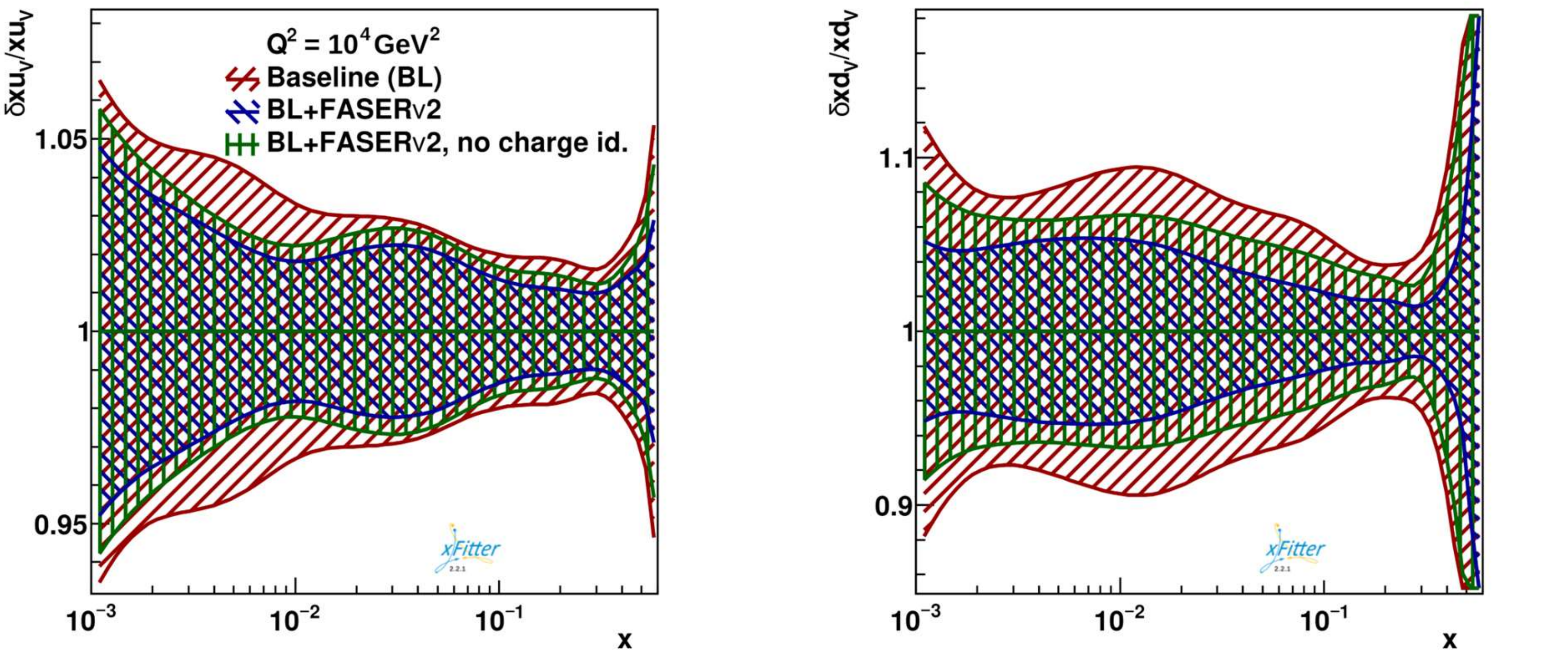


PDF fits –charm ID



- Small improvement in up quark PDF
- Massive improvement in strange PDF!

PDF fits –charge ID

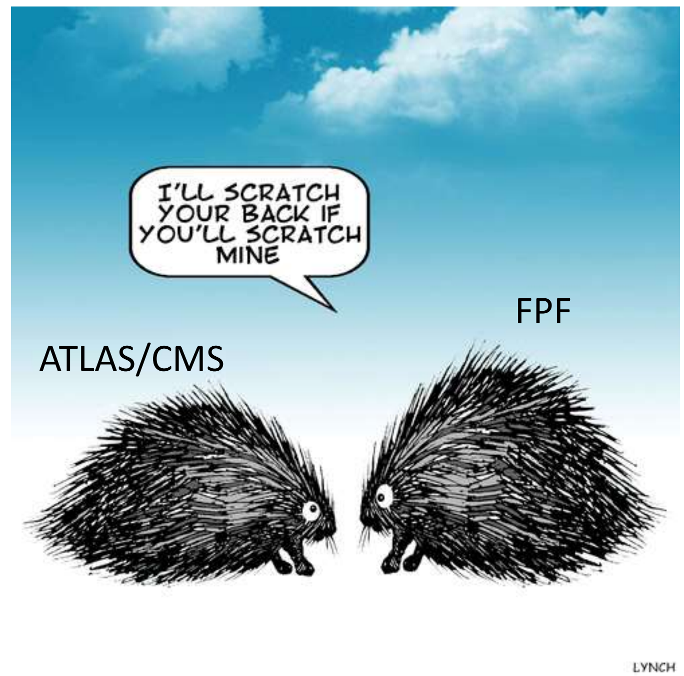


- Small improvement up, down
- Negligible improvement in remaining → charge ID not important

Phenomenology Implications

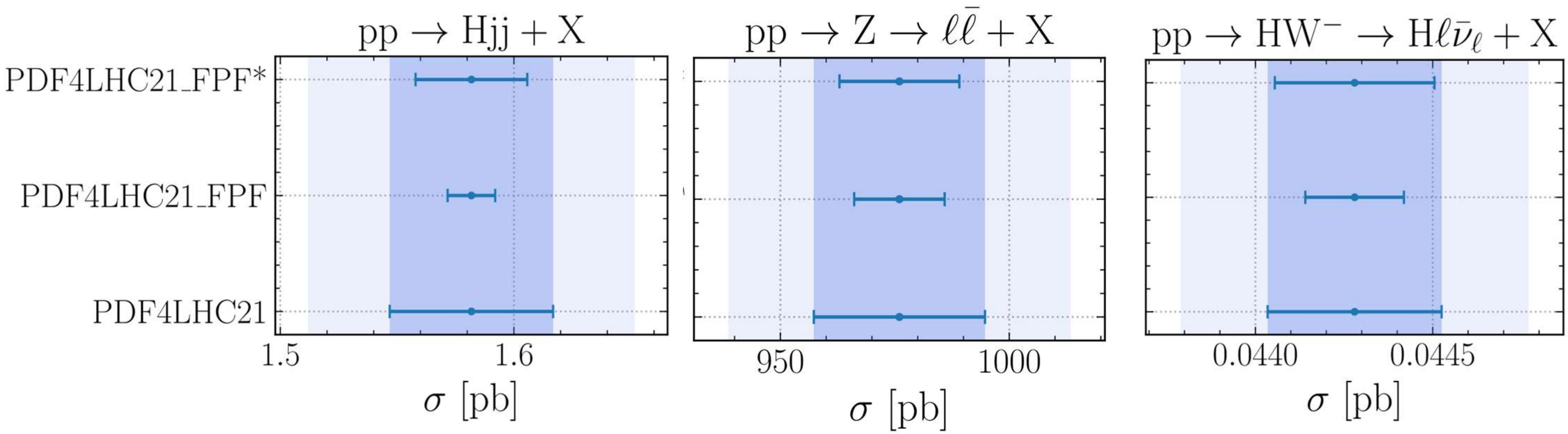
- What can we do with improved PDF fits from FPF data?
  - With collected data, have improved understanding of proton quark content

- Look at quark-initiated processes of heavy bosons at LHC!
  - Excellent complementarity



Phenomenology Implications

- Baseline vs systematics (FPF*) vs stat only (FPF)
- Forward measurements improve central predictions!
  - Including process relevant for m_W , and $\sin^2\theta_W$ measurements



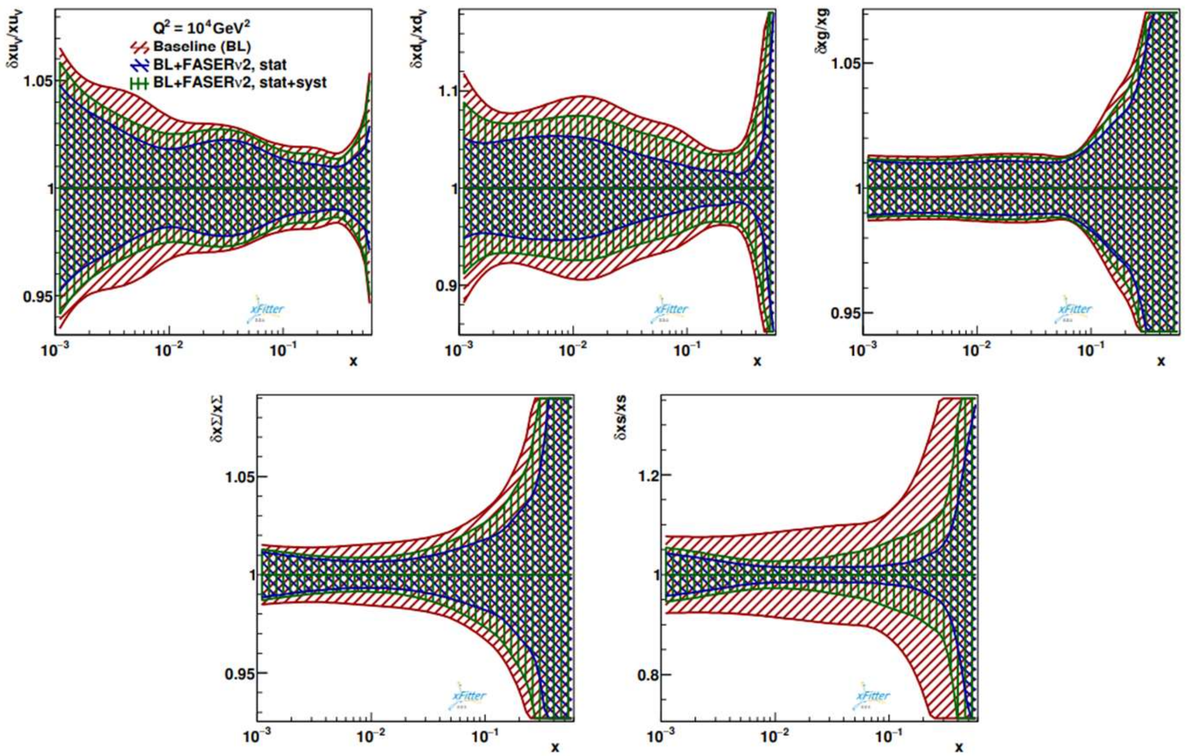
Conclusions

- We calculate neutrino scattering rates at the FPF, with detection systematics folded in
  - Neutrinos are a target and a tool for FPF
- We explore the impact that DIS measurements at Run 3 and the FPF can improve PDF fits
  - Despite wealth of existing data, FPF still manages to improve PDF
  - Greatest gains in strange content due charm tagging
  - Charge ID has small improvement
- Fits from FPF can improve predictions at ATLAS
- Future work includes using gluon PDF at small-x to constrain production

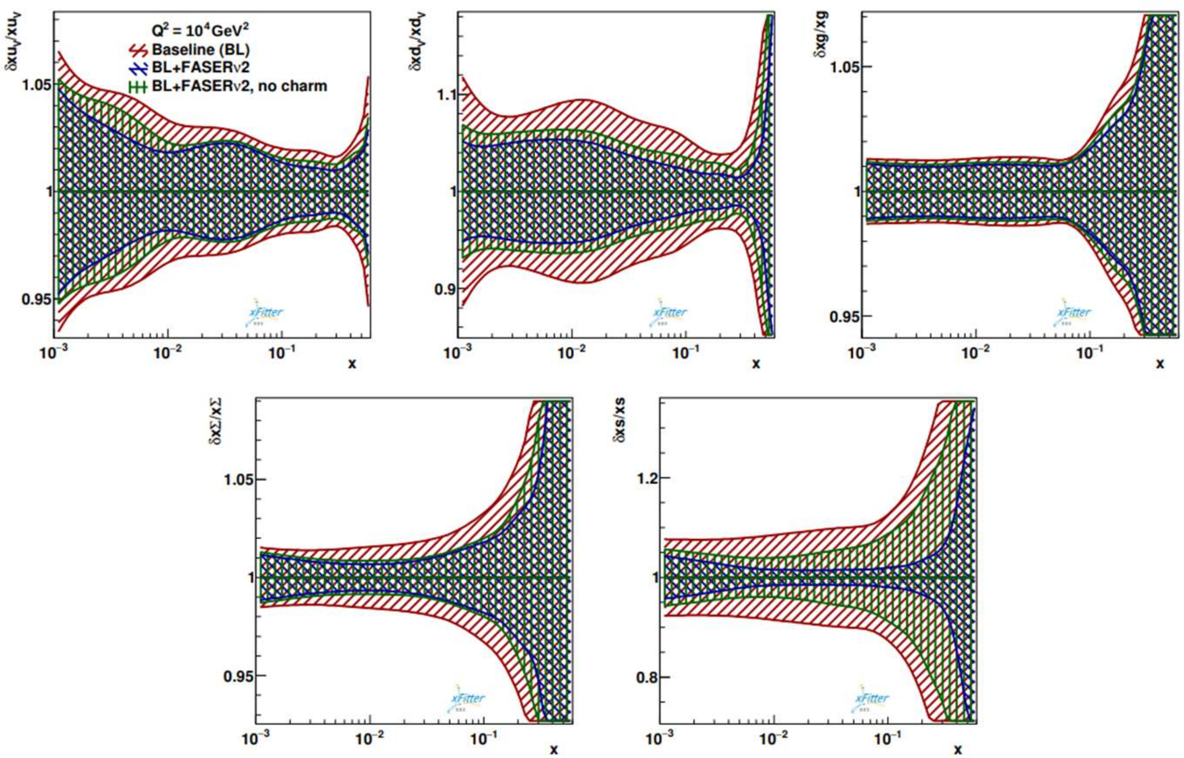
Thank you!

Backup

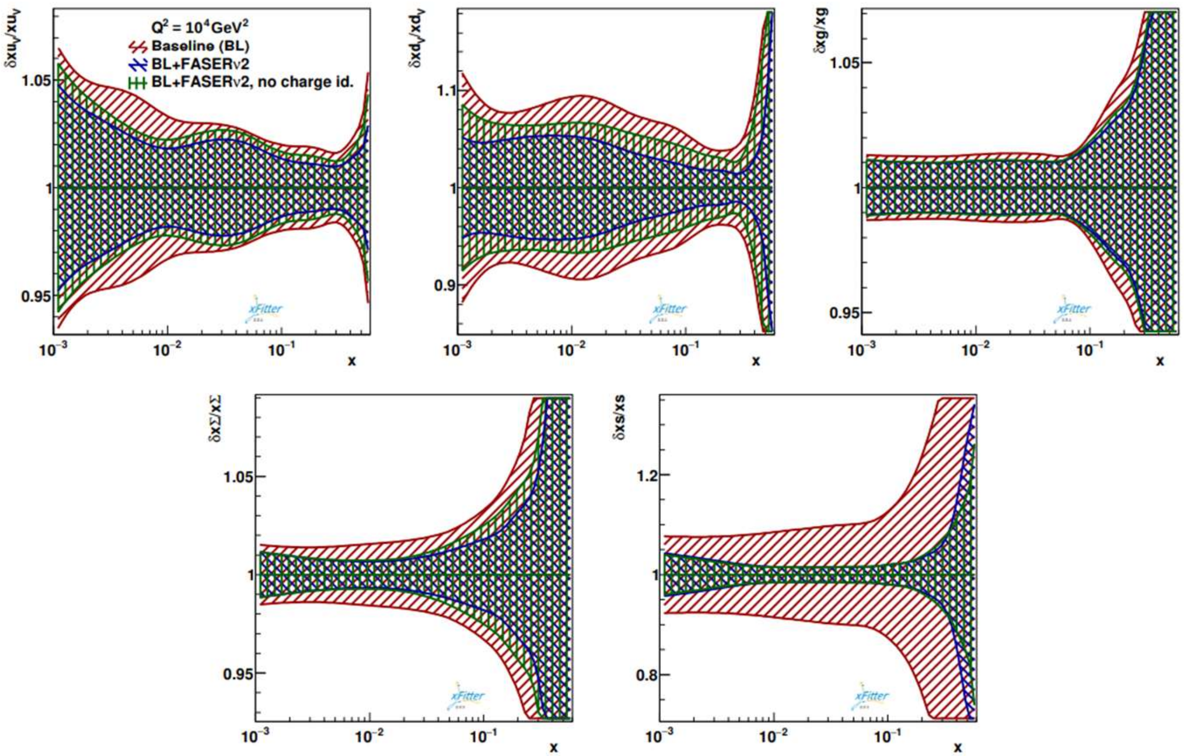
Faserv2 stat vs sys



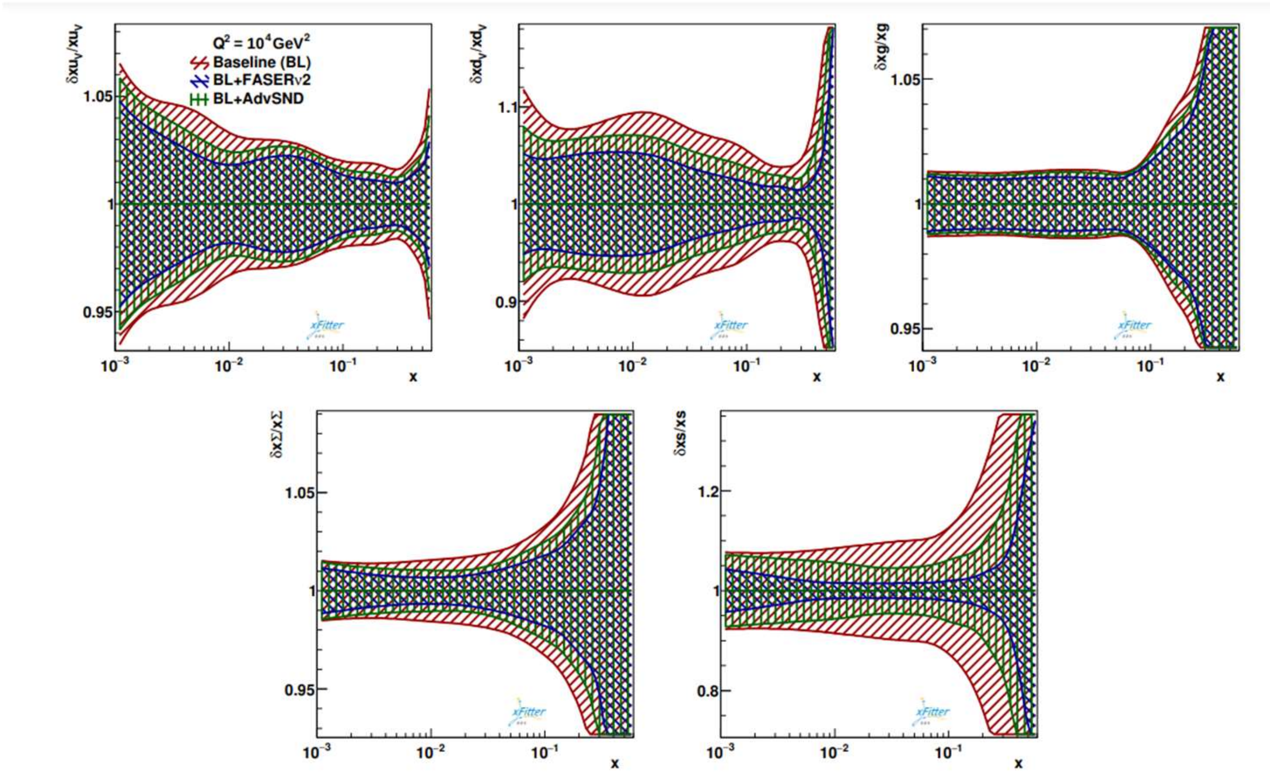
Faserv2 charm vs no charm



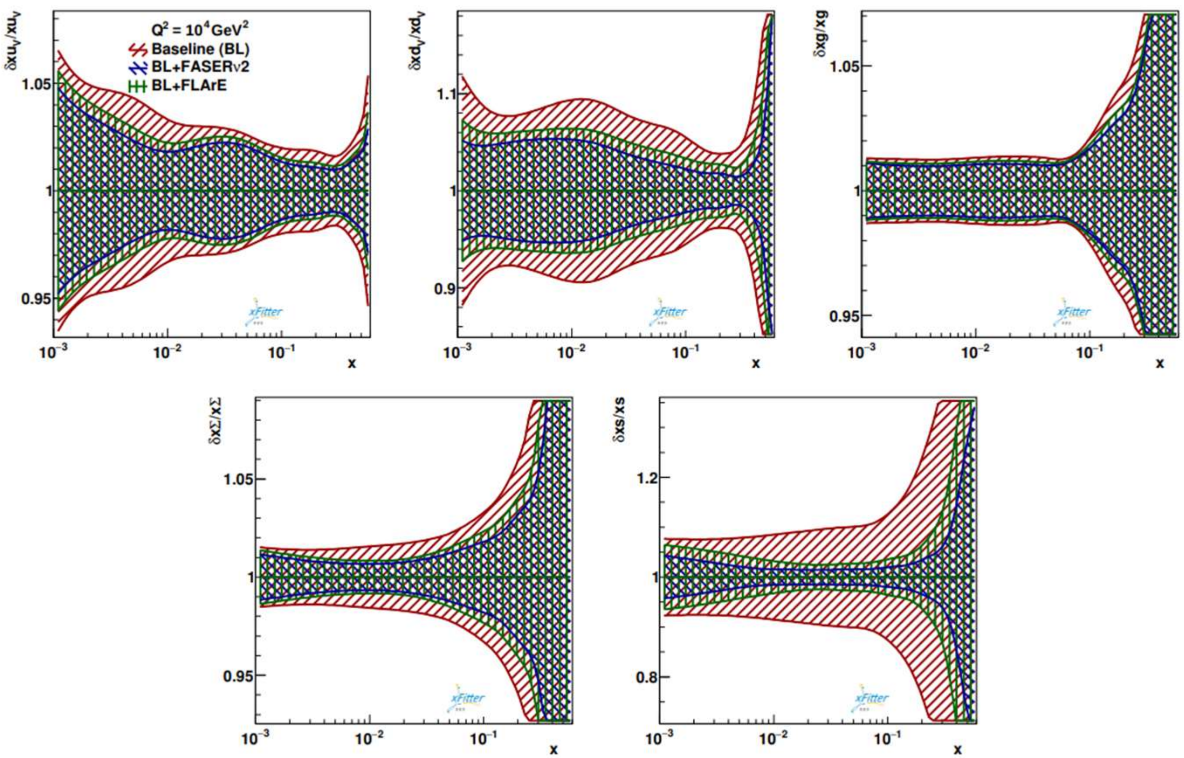
Faserv2 charge vs no charge



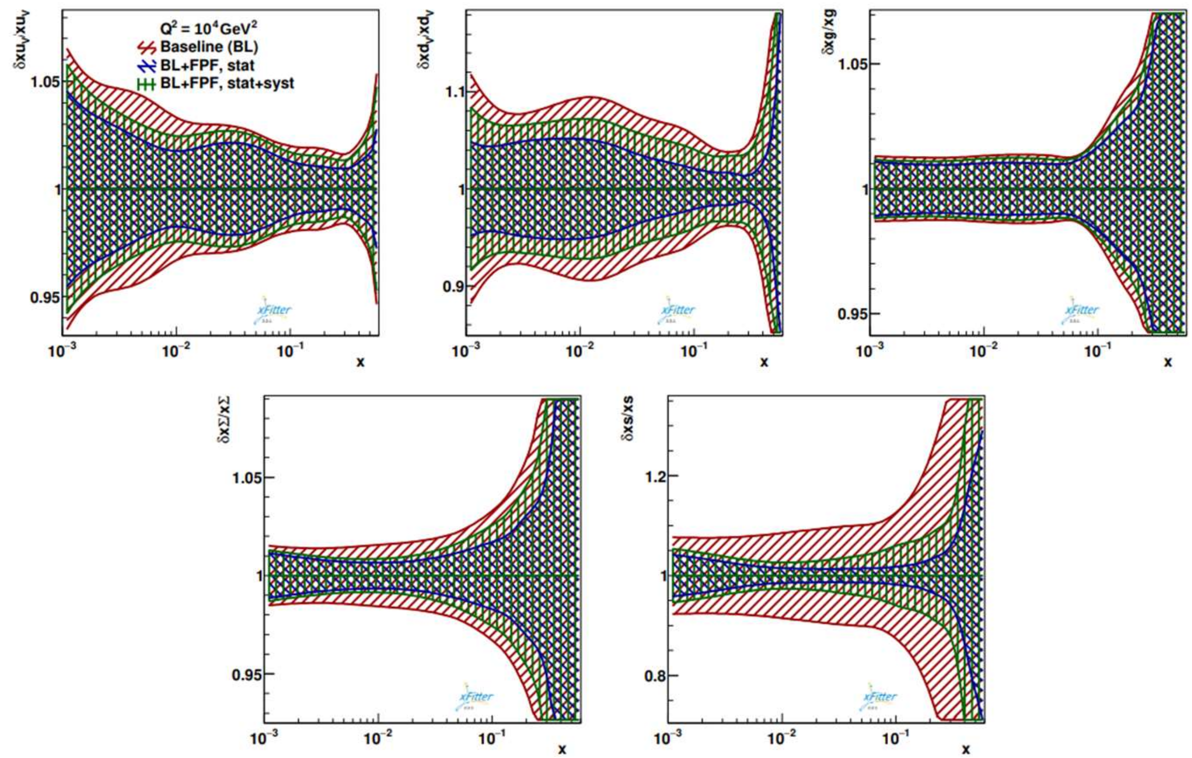
Faserv2 vs AdvSND



Faserv2 vs flare

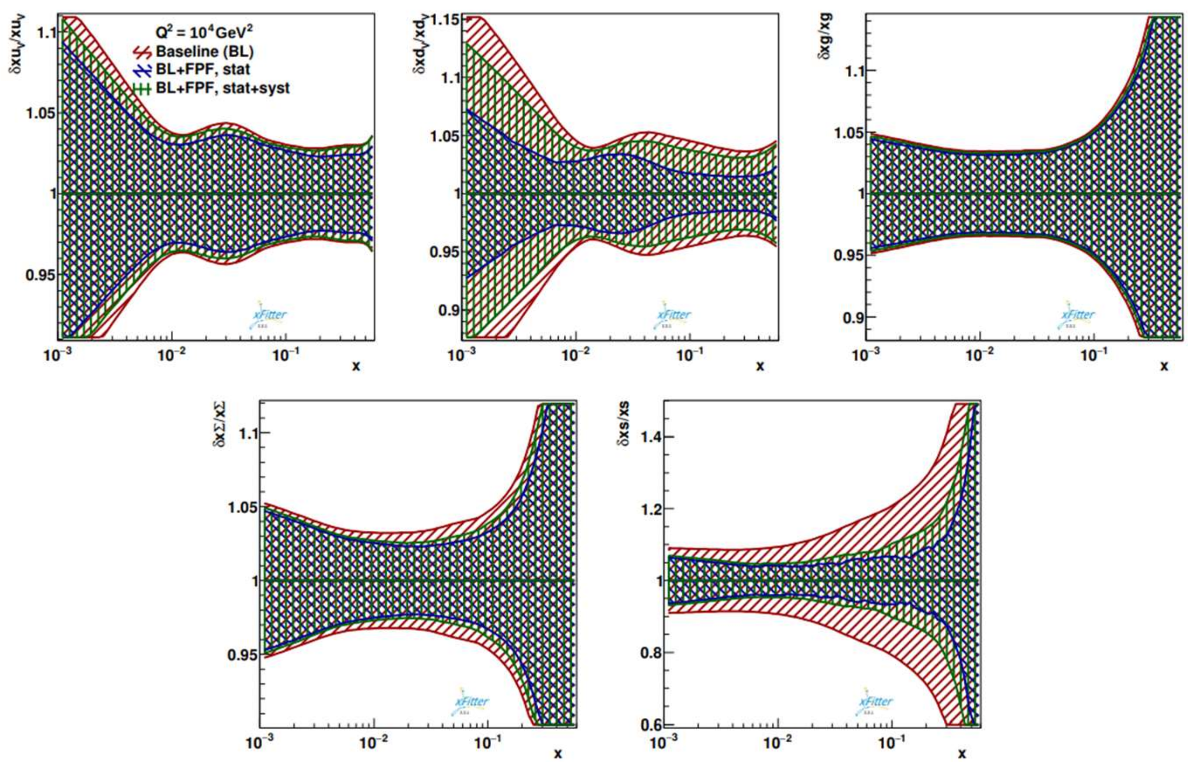


Fpf total



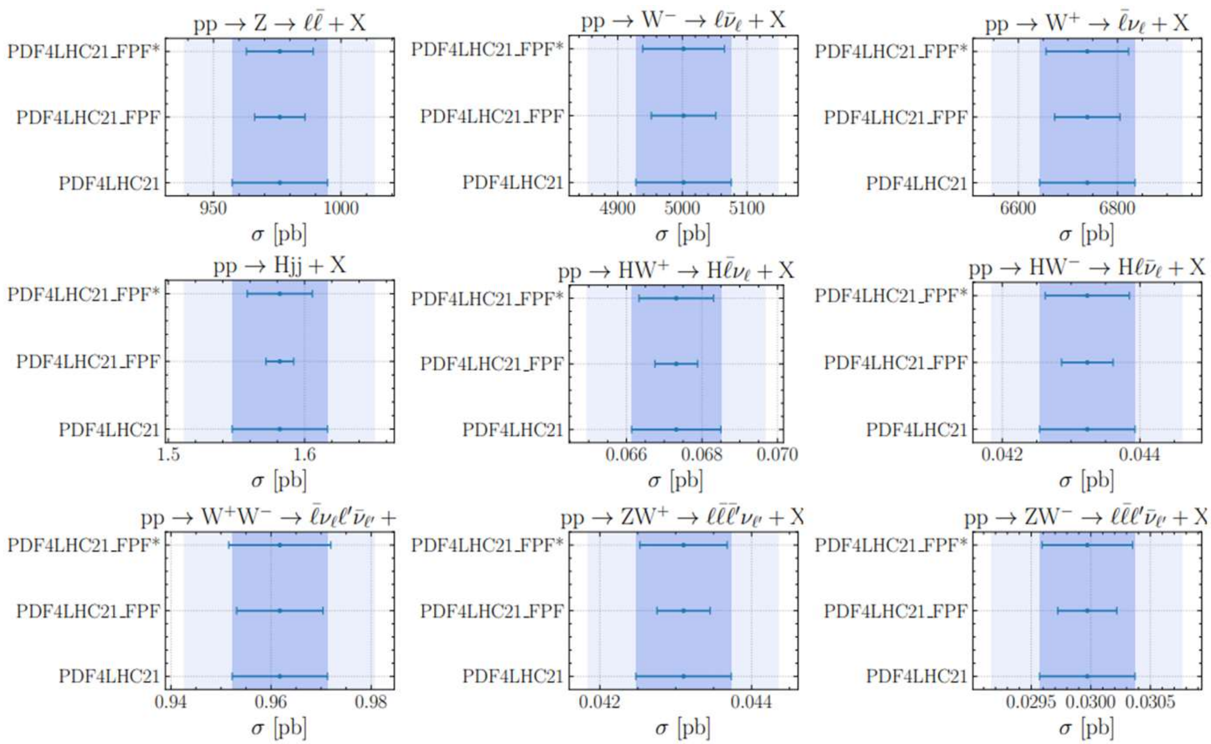
$Q^2 = 10^4 GeV^2$
Baseline (BL)
BL+FPF, stat
BL+FPF, stat+syst
$\delta xu_v/xu_v$
$\delta xd_v/xd_v$
$\delta xg/xg$
$\delta x\Sigma/x\Sigma$
$\delta xs/xs$
x
xFitter

Tungsten

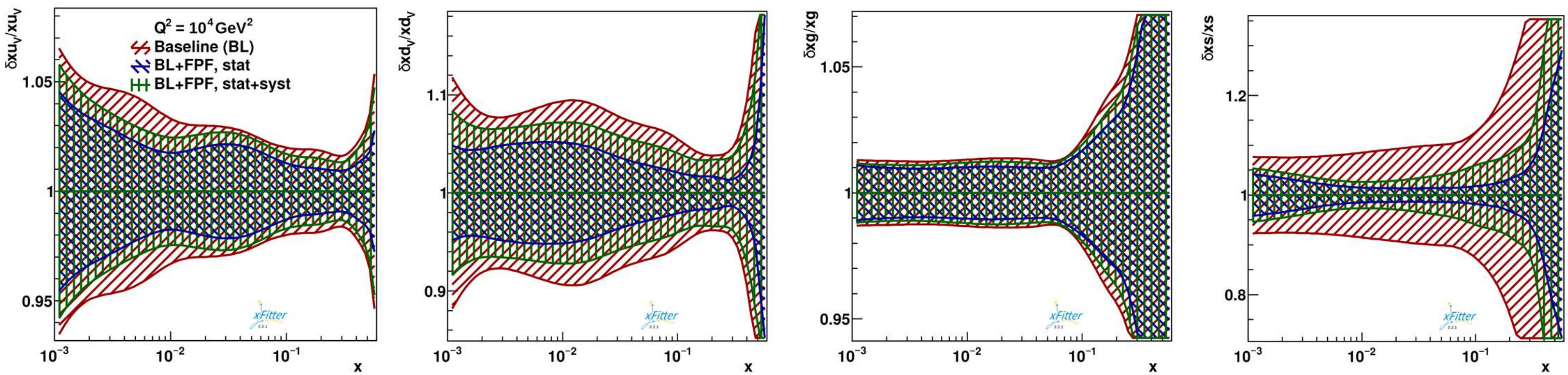


$Q^2 = 10^4 GeV^2$
Baseline (BL)
BL+FPF, stat
BL+FPF, stat+syst
$\delta xu_v/xu_v$
$\delta xd_v/xd_v$
$\delta xg/xg$
$\delta x\Sigma/x\Sigma$
$\delta xs/xs$
x
xFitter

Pheno pdf4lhc21



PDF fits –FPF


$Q^2 = 10^4 GeV^2$
Baseline (BL)
BL+FPF, stat
BL+FPF, stat+syst
$\delta xu_v/xu_v$
$\delta xd_v/xd_v$
$\delta xg/xg$
$\delta xs/xs$
x
xFitter