The LHC as a Neutrino-Ion Collider

Max Fieg w/

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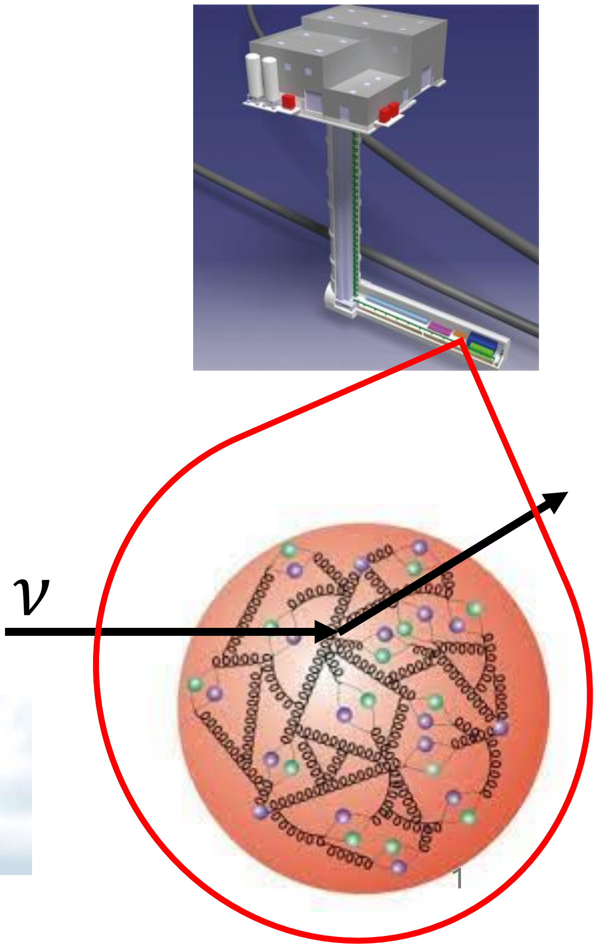
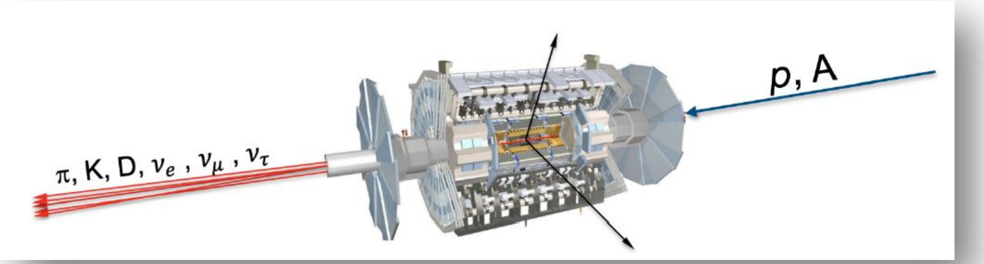


Forward Physics

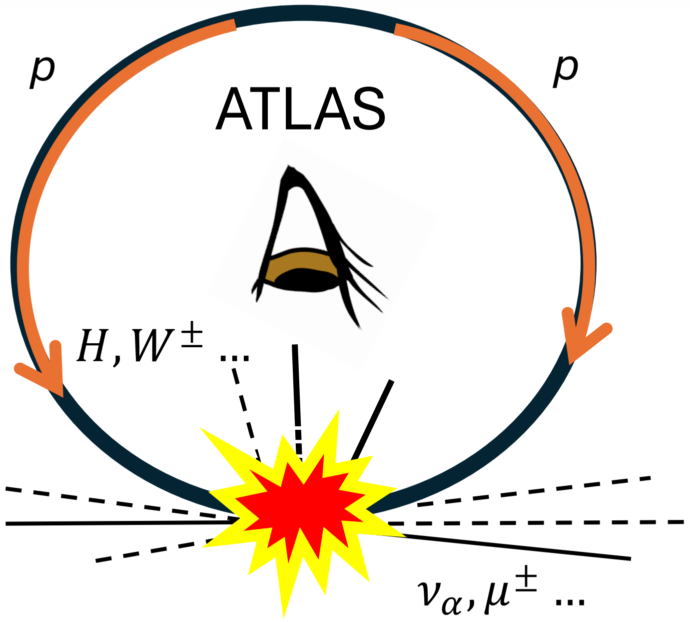


Historically, we've been interested in high p_T events

In the forward direction at the LHC there is an intense flux of particles

The forward direction has emerged as a highly important yet largely unseen area. Sensitive to:

- Plenty of BSM sensitivity
- Hadronic interaction modelling at energies relevant for neutrino telescopes (muon puzzle + prompt production)
- **Highest energy neutrino beam produced in a lab**



Forward Physics

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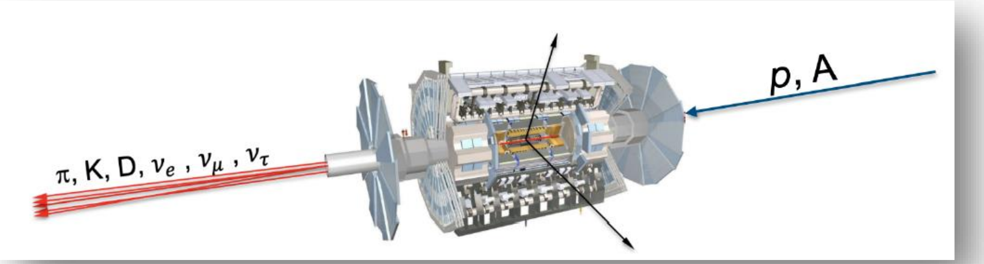
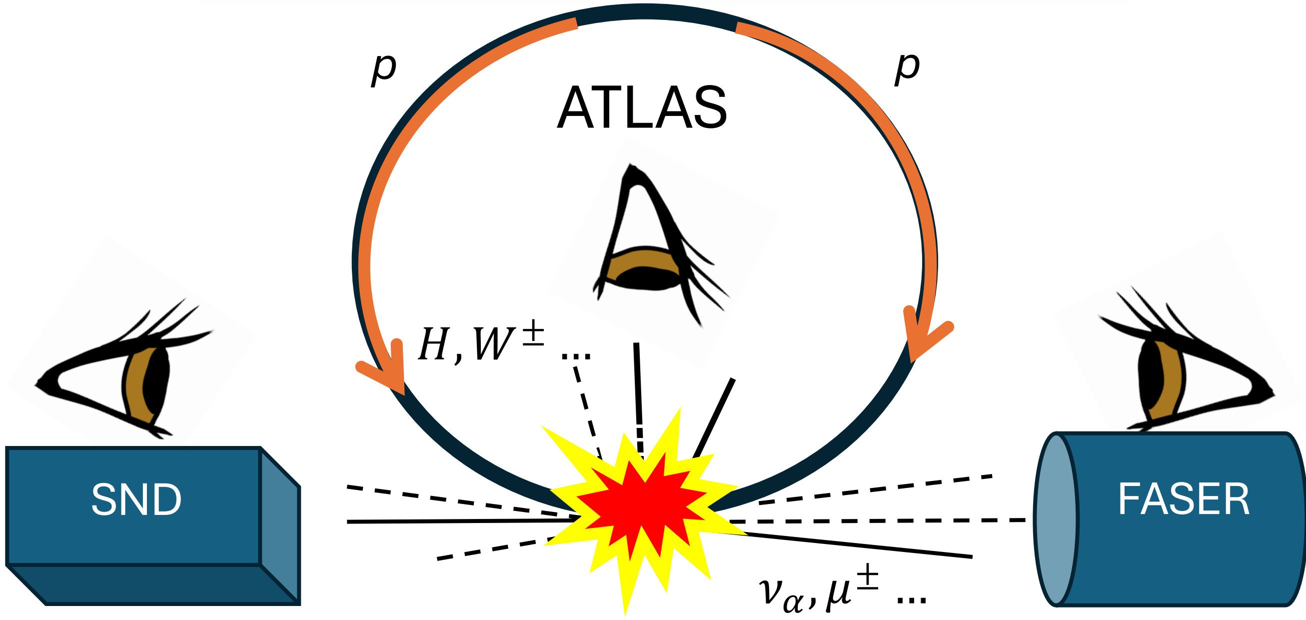
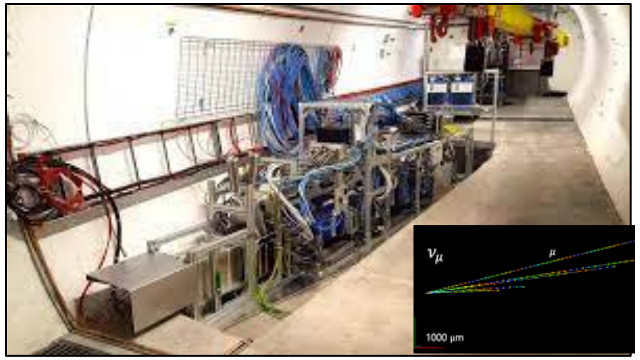
First collider neutrinos recently discovered, brings a **new** way to observe high energy LHC collisions

- Proposed **Forward Physics Facility** will greatly improve our observation of LHC collisions
  - $\approx$500k ν_e, 1M ν_μ, 10k ν_τ

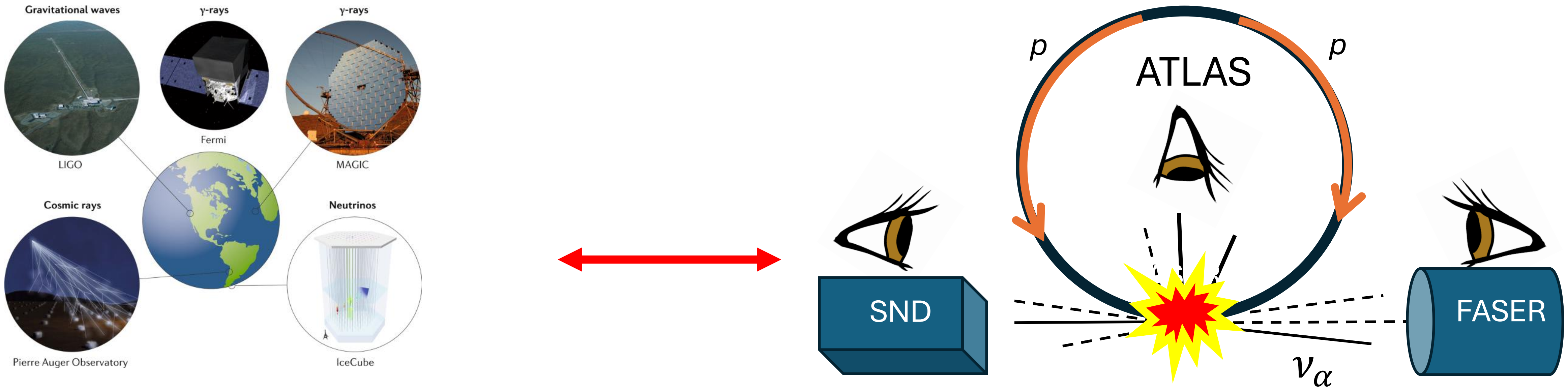






Astro

Collider



"These **sources** are complicated… Unless you have many ways to ***look*** at them, you're not going to figure them out"

-Francis Halzen on Multimessenger Astronomy Scientific American

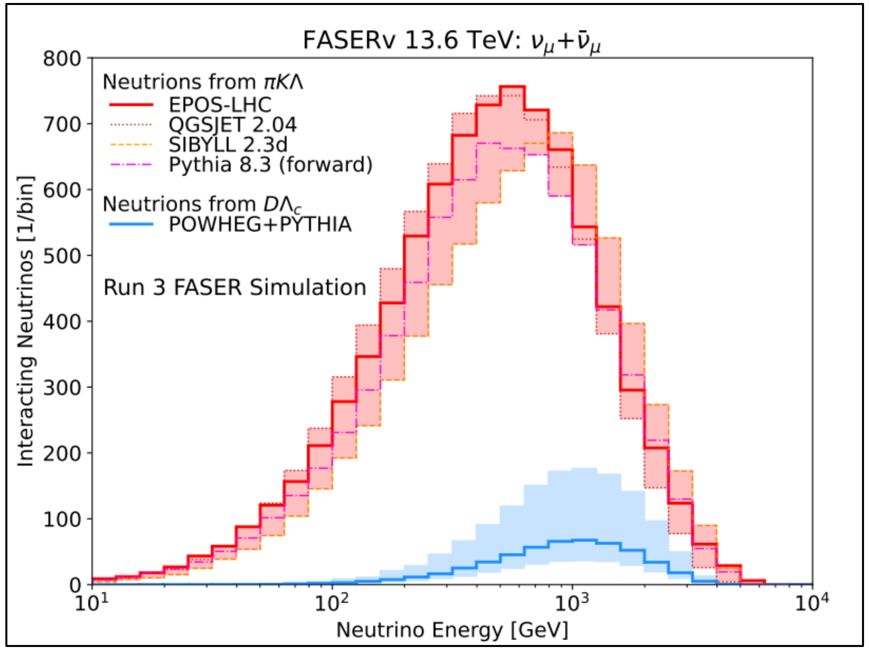
These **collisions** are complicated… Unless you have many ways to ***look*** at them, you're not going to figure them out

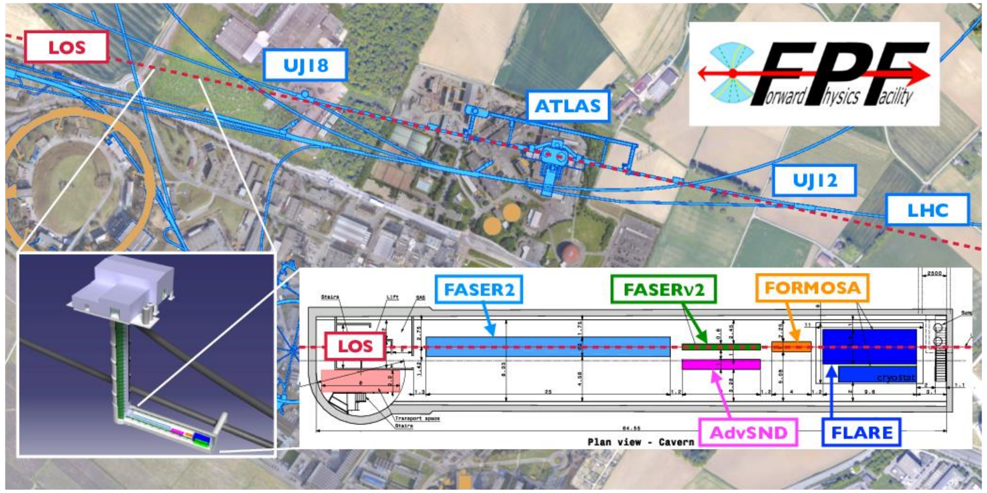
Multimessenger Collider Physics

Forward neutrinos can be used as a tool to better understand LHC collisions and answer fundamental questions in particle physics

Forward Neutrinos

- All flavors are copiously produced in the forward direction, dominantly from hadron decays, $E_\nu \approx$ TeV
- By the end of Run 3, expect $> 10^{12}$ neutrinos passing through FASERν, and ≈10,000 CC neutrino interactions (virtually all DIS)
- A proposed Forward Physics Facility (**FPF**) will house a suite of experiments, each with different strengths, that will operate during the HL-LHC
  - >100x the event rate!





Forward Physics Facility

FASER(ν)2 – Decay volume + Tungsten Emulsion
FLArE – Liquid Argon Detector
AdvSND – Off axis neutrino detector
FORMOSA – millicharged particle detector

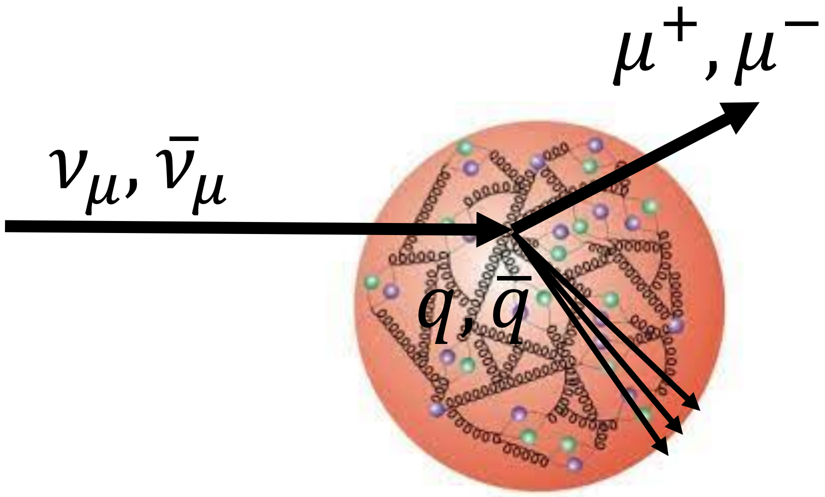
Detector				Number of CC Interactions		
Name	Mass	Coverage	Luminosity	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
FASERν	1 ton	$\eta \gtrsim 8.5$	150 fb^{-1}	901 / 3.4k	4.7k / 7.1k	15 / 97
SND@LHC	800kg	$7 < \eta < 8.5$	150 fb^{-1}	137 / 395	790 / 1.0k	7.6 / 18.6
FASERν2	20 tons	$\eta \gtrsim 8.5$	3 ab^{-1}	178k / 668k	943k / 1.4M	2.3k / 20k
FLArE	10 tons	$\eta \gtrsim 7.5$	3 ab^{-1}	36k / 113k	203k / 268k	1.5k / 4k
AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	3 ab^{-1}	6.5k / 20k	41k / 53k	190 / 754

- What can we do with all of these DIS events?

What can we learn from 1M DIS neutrino events?

Many things... ask me!

Here, I focus on using neutrinos to understand the quark content of proton



1. Answers a fundamental question of the proton
2. Parton Distribution Functions (PDFs) still have large uncertainties
   - Drives uncertainty for $\sigma(E_\nu = \mathrm{TeV})$
   - Better understanding of proton structure $\Longrightarrow$ Better understanding of LHC collisions

ν_μ CC DIS

- ν_μ flux dominant and the best understood
- With a magnet, CC allows us to identify ν vs $\bar{\nu}$ projectile
- Will study inclusive and semi-inclusive charm production at Run 3 and HL-LHC experiments

Detector			
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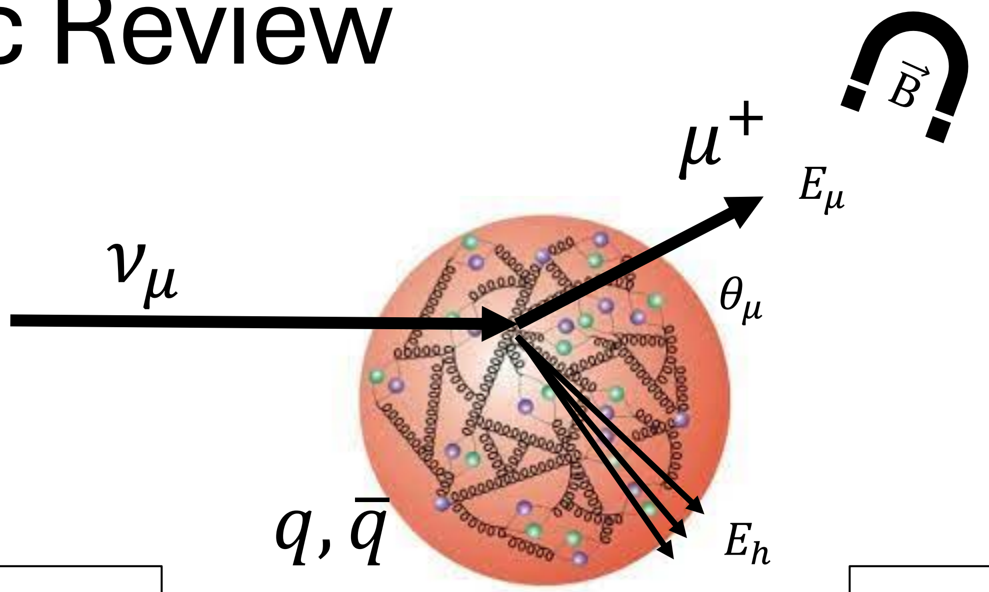
PDF Kinematic Review



PDF Kinematics

Neutrino energy E_ν

Momentum fraction, Bjorken-x

$$\frac{p_q}{E_N} = x$$

Momentum Transfer Q^2

$$(p_\mu - p_\nu)^2 = Q^2$$

Reconstruct w/ observables

Observables

Muon energy E_μ

Muon scattering angle θ_μ

Hadronic Energy deposited, E_h

$$E_\nu = E_\mu + E_h$$

$$Q^2 = 4(E_h + E_\mu)E_\mu \sin^2 \frac{\theta_\mu}{2}$$

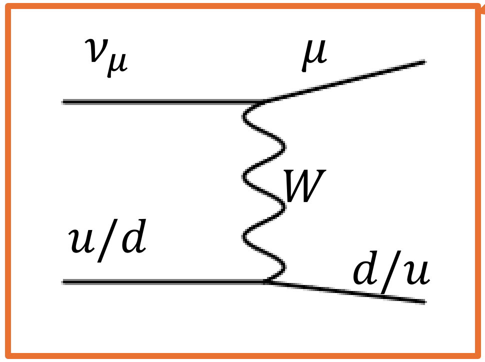
$$x = \frac{Q^2}{2m_N E_h}$$

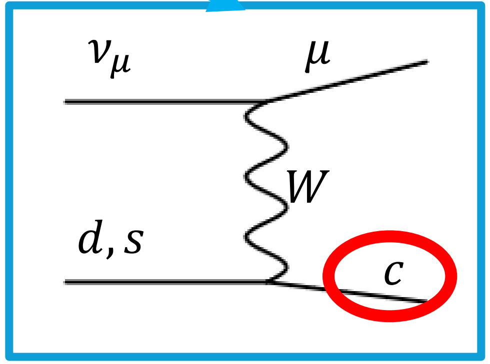
DIS Event Rate

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

Inclusive or Charm production can be written

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





Different techniques to ID charm events

(e.g. dimuon from D decay)

Tag down,strange targets

Structure fxns. encode PDF, σ(PDF)

$$\mathrm{PDF} = \mathrm{f}(\mathrm{x}, \mathrm{Q}^2)$$

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

$$\frac{d^2\sigma^{\nu A}(x,Q^2,y)}{dx\,dy} = \frac{G_F^2 s/4\pi}{(1+Q^2/m_W^2)^2}\left[Y_+ F_2^{\nu A}(x,Q^2) - y^2 F_L^{\nu A}(x,Q^2) + Y_- x F_3^{\nu A}(x,Q^2)\right]$$

Neutrino flux $\frac{dN_\nu}{dE_\nu}$, +
differential cross sections w/ PDF $d^2\sigma_{I,C}$ +
exp. acceptance $A(x, Q^2, E_\nu)$ =
compute the event rate for all proposed FPF experiments
(and current experiments)

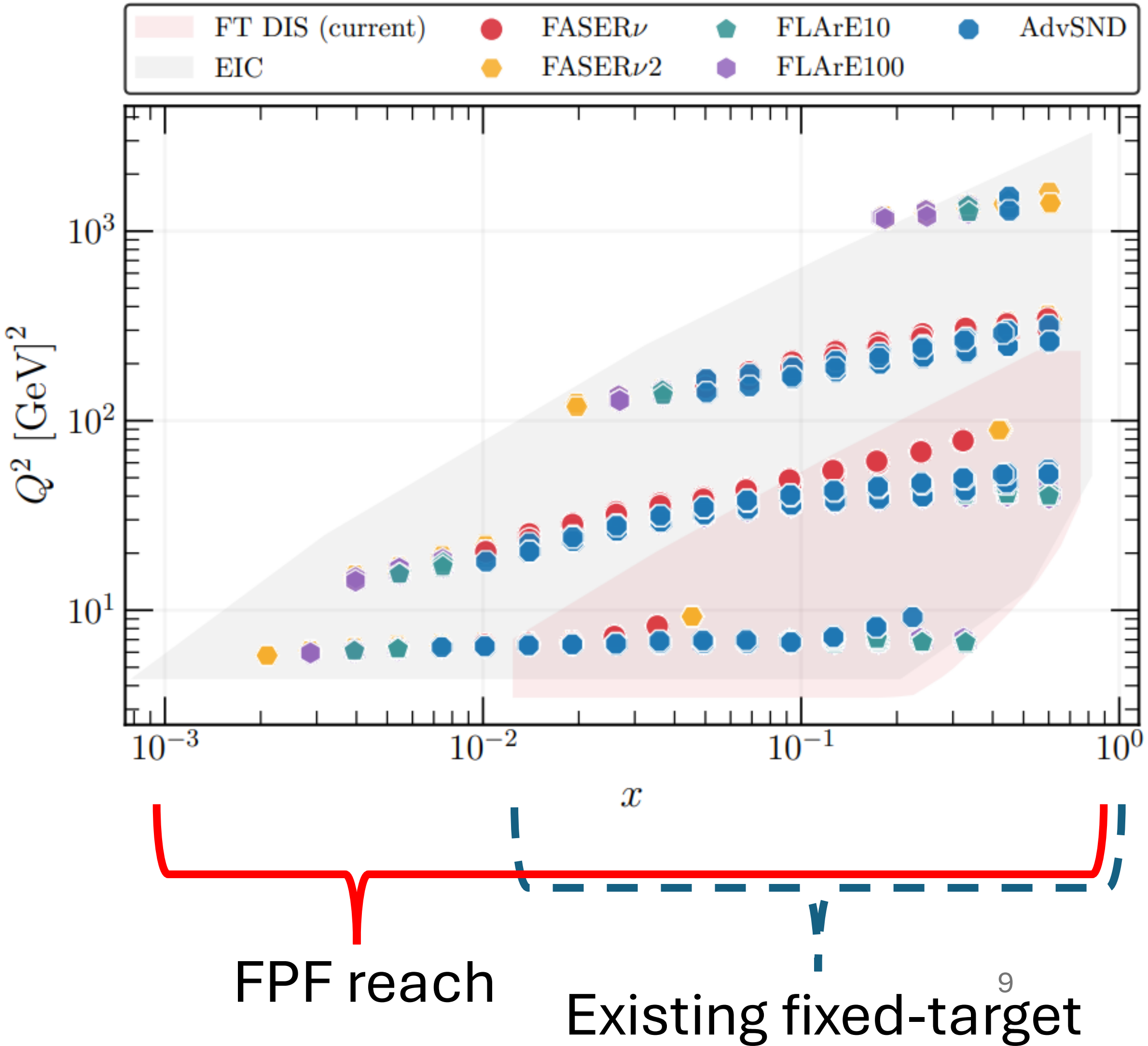
PDFs - kinematic coverage

- TeV neutrino energy brings measurements at unprobed, small Bjorken-x and Q^2 momentum transfer regimes

- Complementary coverage as the proposed Electron-Ion Collider.

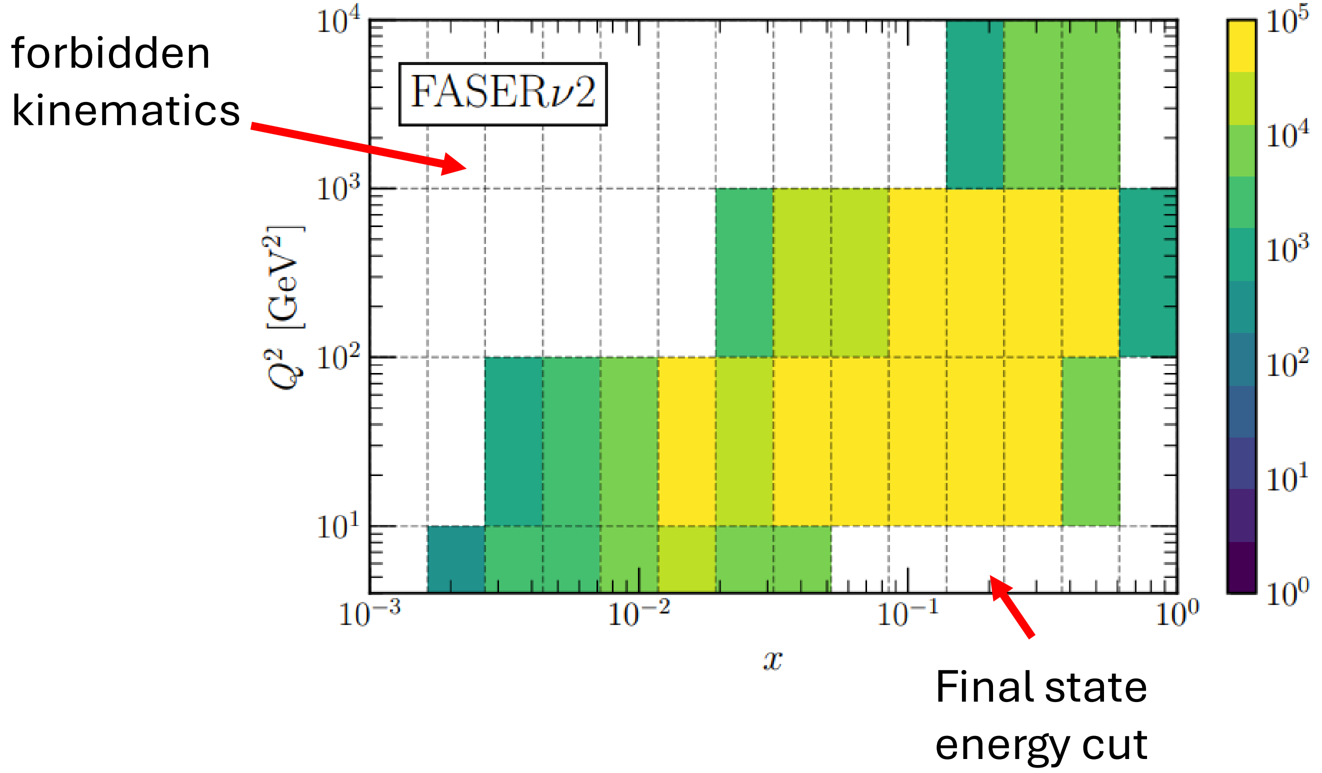
- Upon a boost, the forward neutrino program at the LHC can be viewed as a neutrino-ion collider ☺

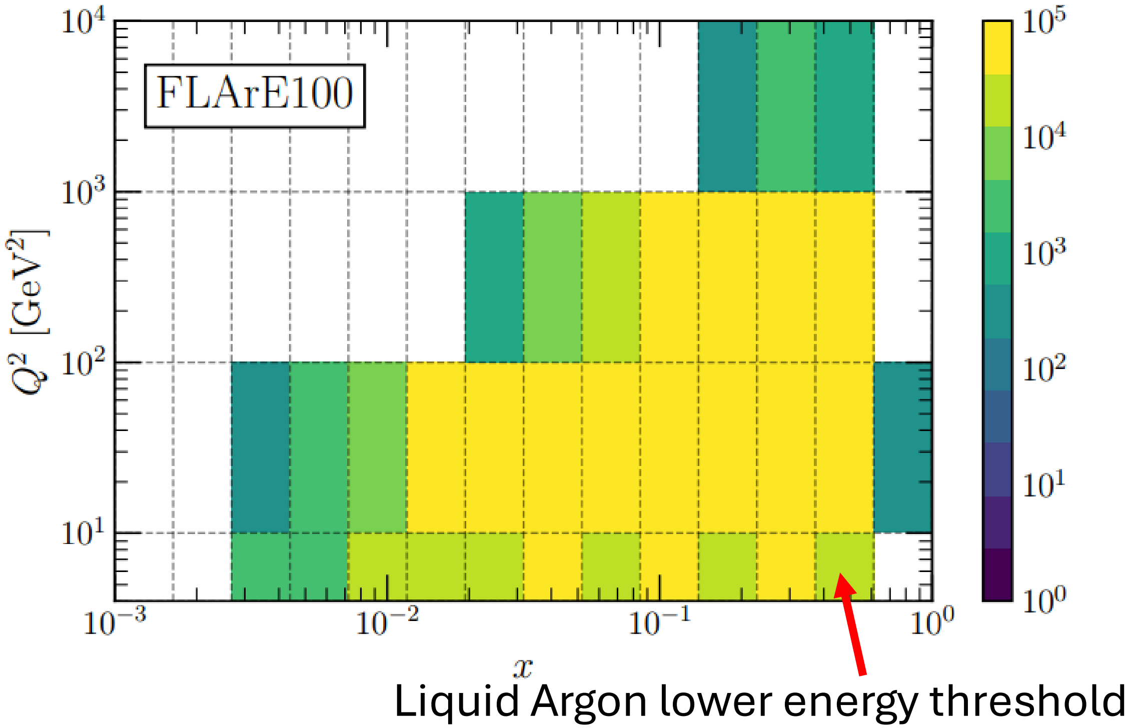
- Let's look at the event rate in this plane



FPF experiments – ν_μ event distribution at FASERv2 and FLArE

- Event rate in x, Q^2 plane
- O(1M) total event rate → ~500k after acceptance cuts





- We also estimate systematic uncertainties due to imperfect detector resolution
  - Fluctuate MC event sample about E_h, E_ℓ, θ_ℓ resolutions

Overview of PDF fits

We make lots of comparisons in the paper

- Different PDF Base sets
  - PDF4LHC21
  - NNPDF - Consistent and robust results
  - EPPS21 - Tungsten Nucleus
- FASERv2
  - Statistics vs systematics
  - Charm ID vs no charm ID
  - Charge ID vs no charge ID
- Experimental comparison
  - FASERv2 vs AdvSND, FLArE10
  - Total FPF data

} I will highlight a few.

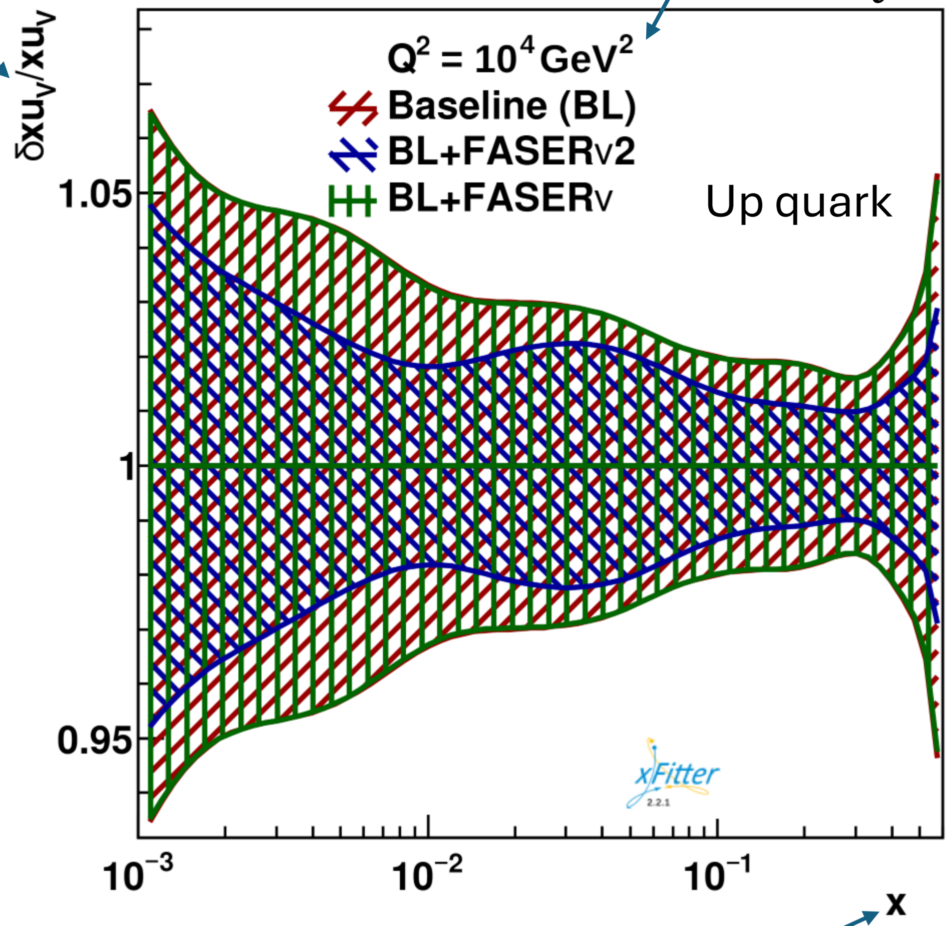
PDF fits – FASERν Run3 vs FASERν2 HL

- Run 3 statistics too small to be sensitive to PDF fit…
- Need FPF + HL-LHC measurements to make progress on PDF fits
- But data still useful! There are no measurements in this range, and measured FASERν data may reveal inconsistencies with old data

Let's look at FASERν2 results

PDF uncertainty

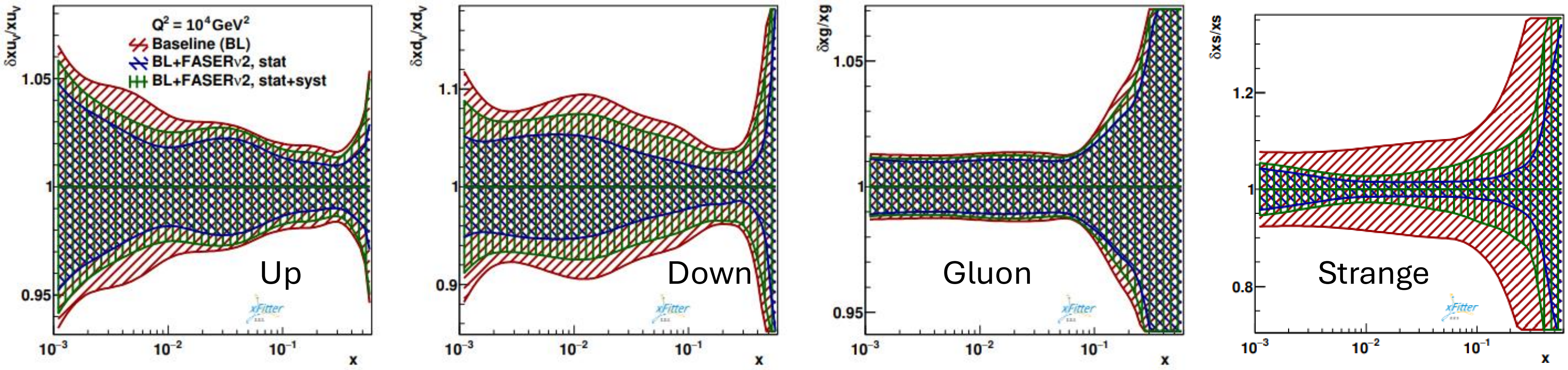
at fixed Q^2



Up quark

As a fxn of momentum fraction

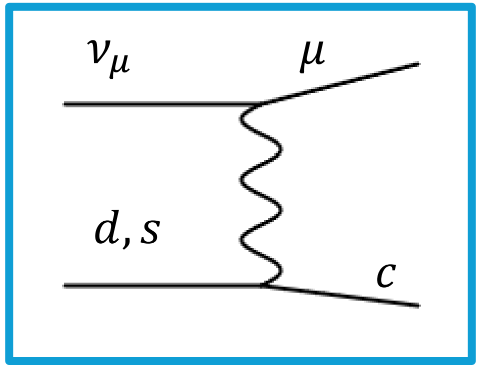
PDF fits – FASERv2 stat and systematics



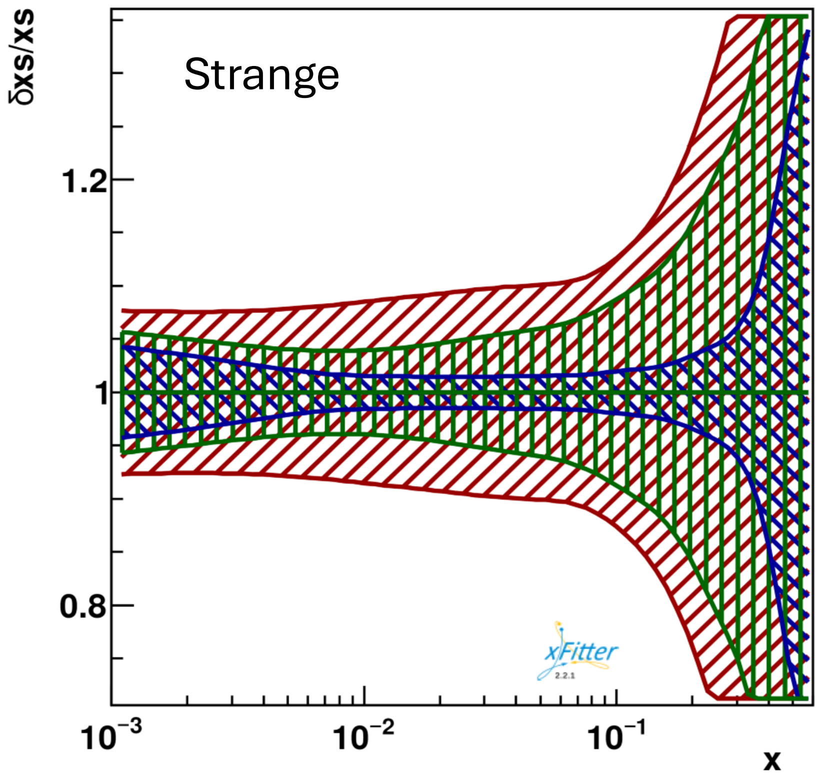
- PDF base set includes existing neutrino DIS measurements
    - FPF still manages to improve!
- Huge improvement in strange quark
    - Consequence of charm tagging!
- Systematics weaken fits but do not erase them
- Gluon PDF unaffected→ expected for a neutrino scattering experiment

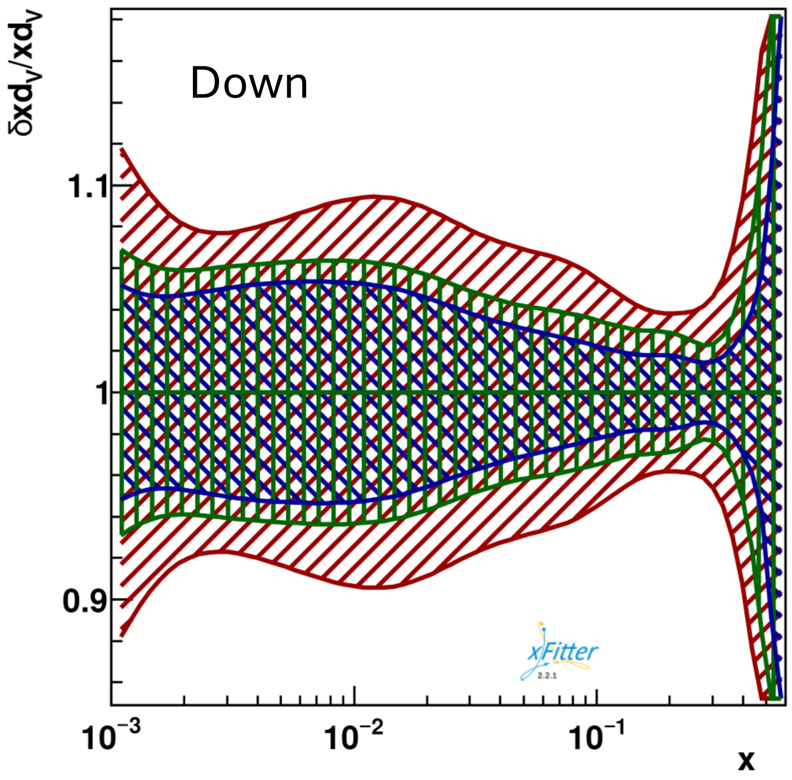
How do fits look without charm ID?

PDF fits – With and Without Charm ID



- Massive improvement in strange PDF, reduced to 1-5% for $x < \frac{1}{3}$

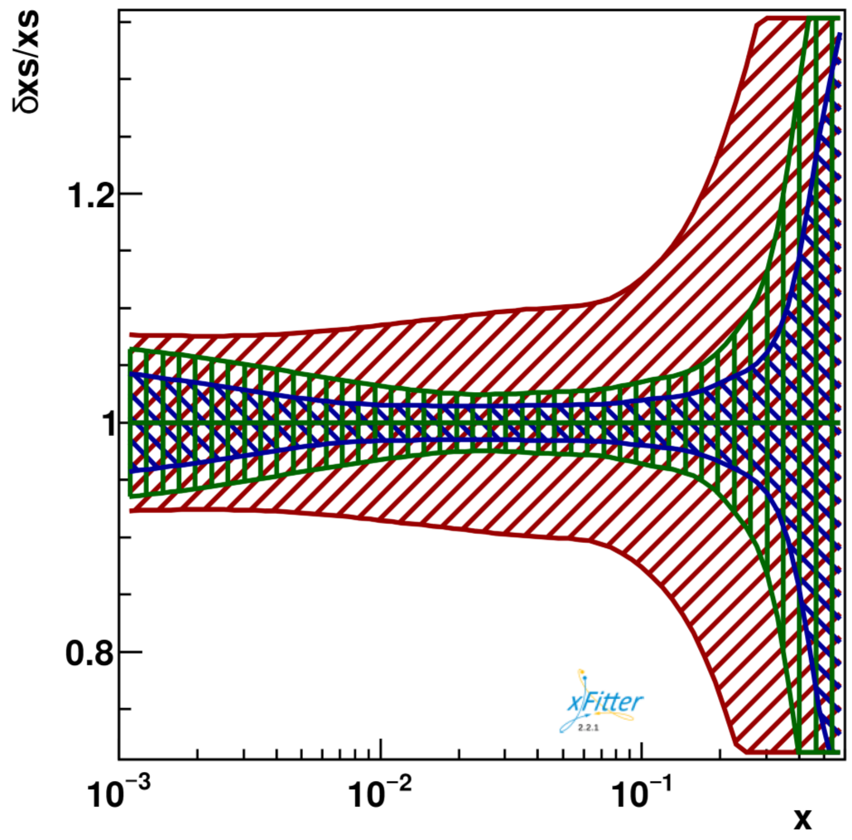




Phenomenology Implications

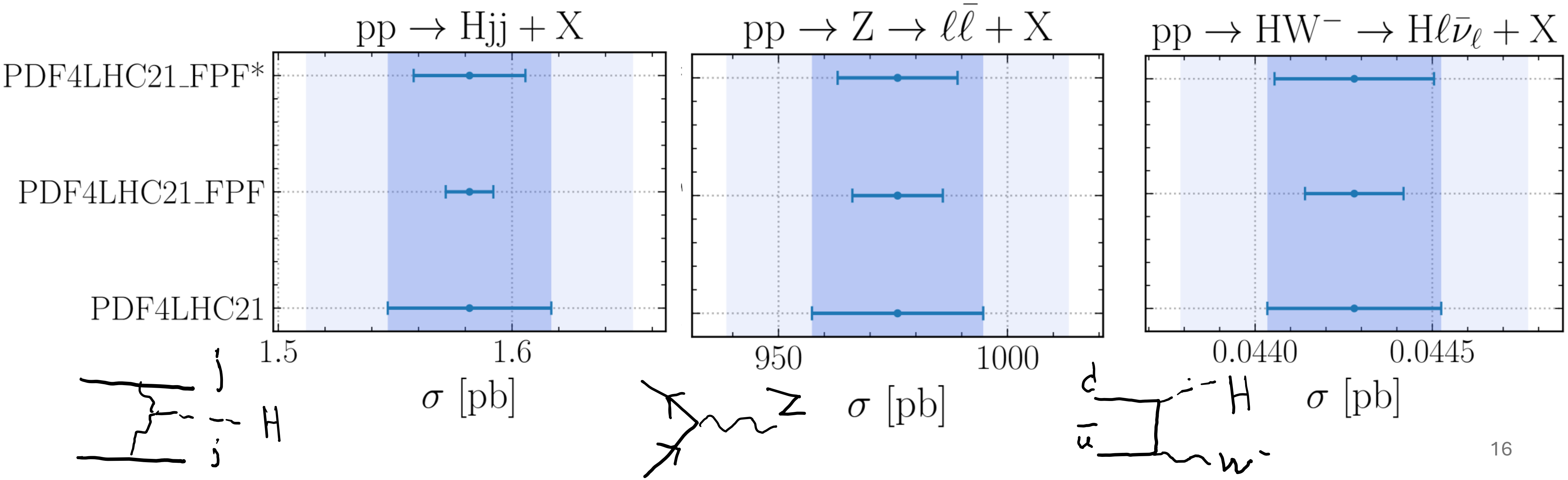
- What can we do with these improved PDF fits, what is the point?

- Look at quark-initiated processes of heavy bosons at LHC!
- Expect reduced uncertainties in heavy particle production!
  - Excellent complementarity between FPF and ATLAS/CMS



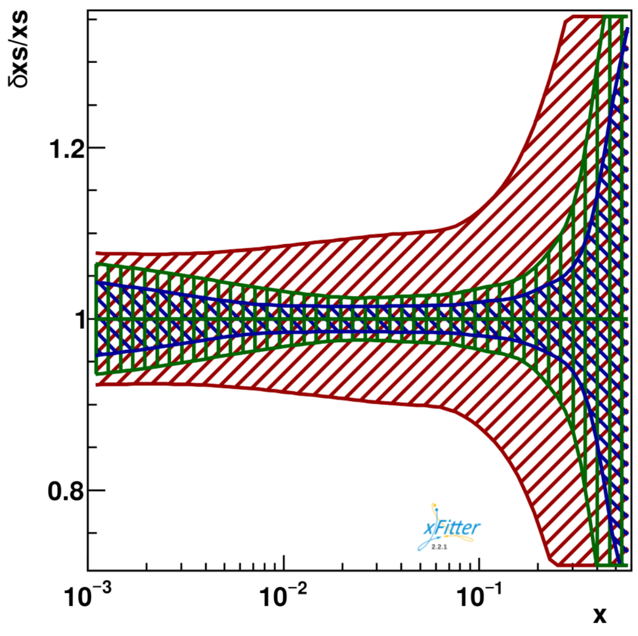
Phenomenology Implications

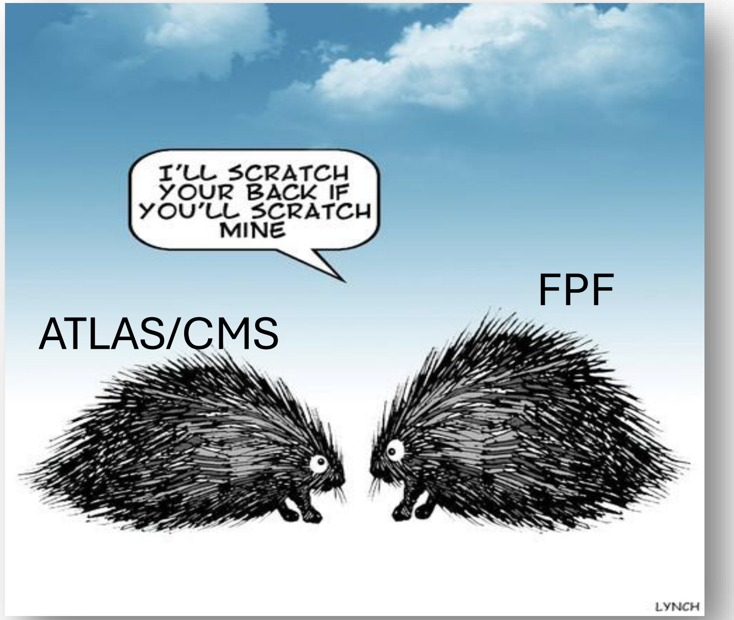
- Baseline vs systematics (FPF*) vs stat only (FPF)
- Forward measurements improve central predictions!
  - Including process relevant for m_W , and $\sin^2\theta_W$ measurements



Summary

- 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 help us understand LHC collisions and make better predictions at ATLAS
- Future work includes using gluon PDF at small-x to constrain prompt production

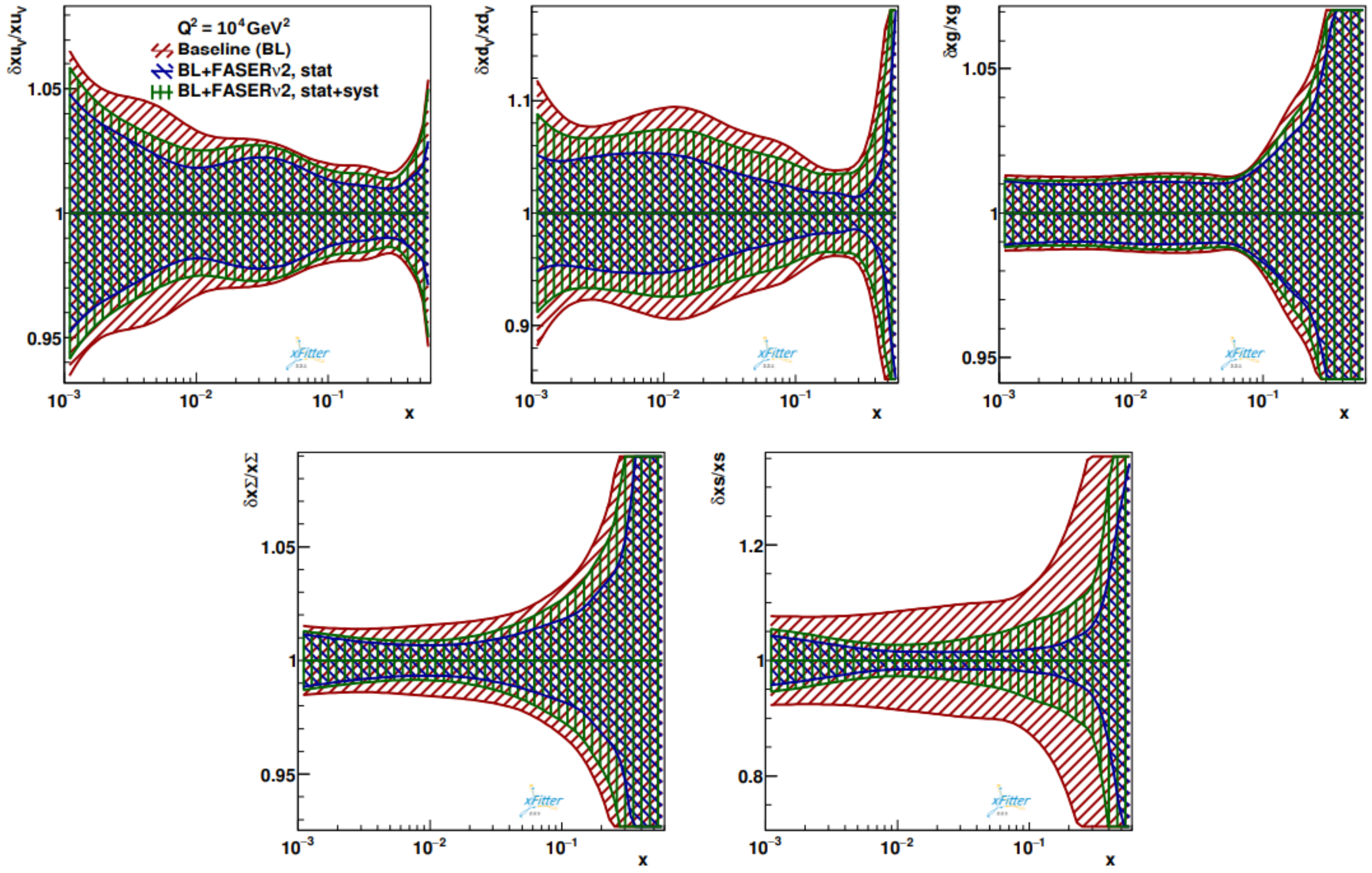




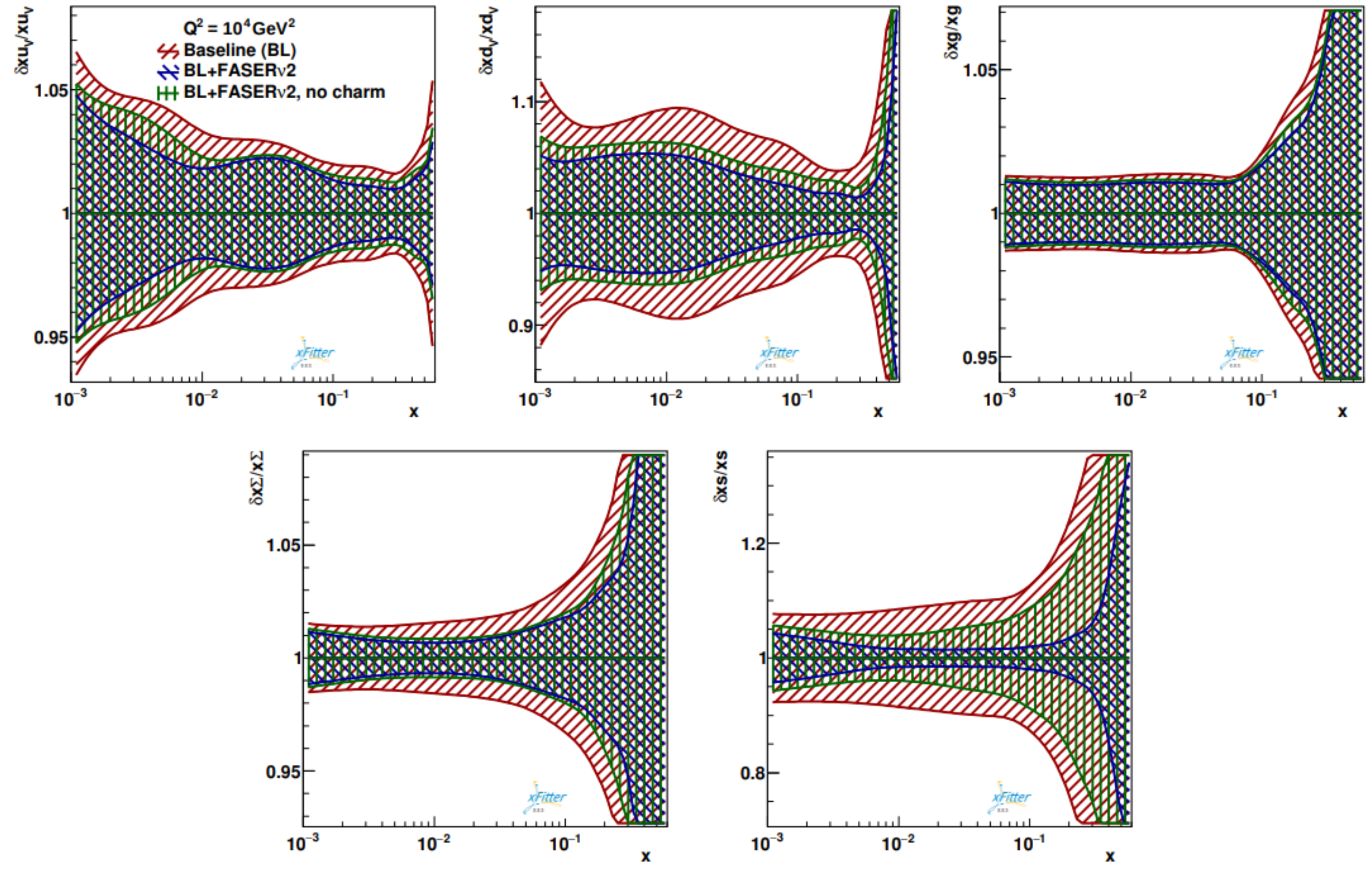
Thank you!

Backup

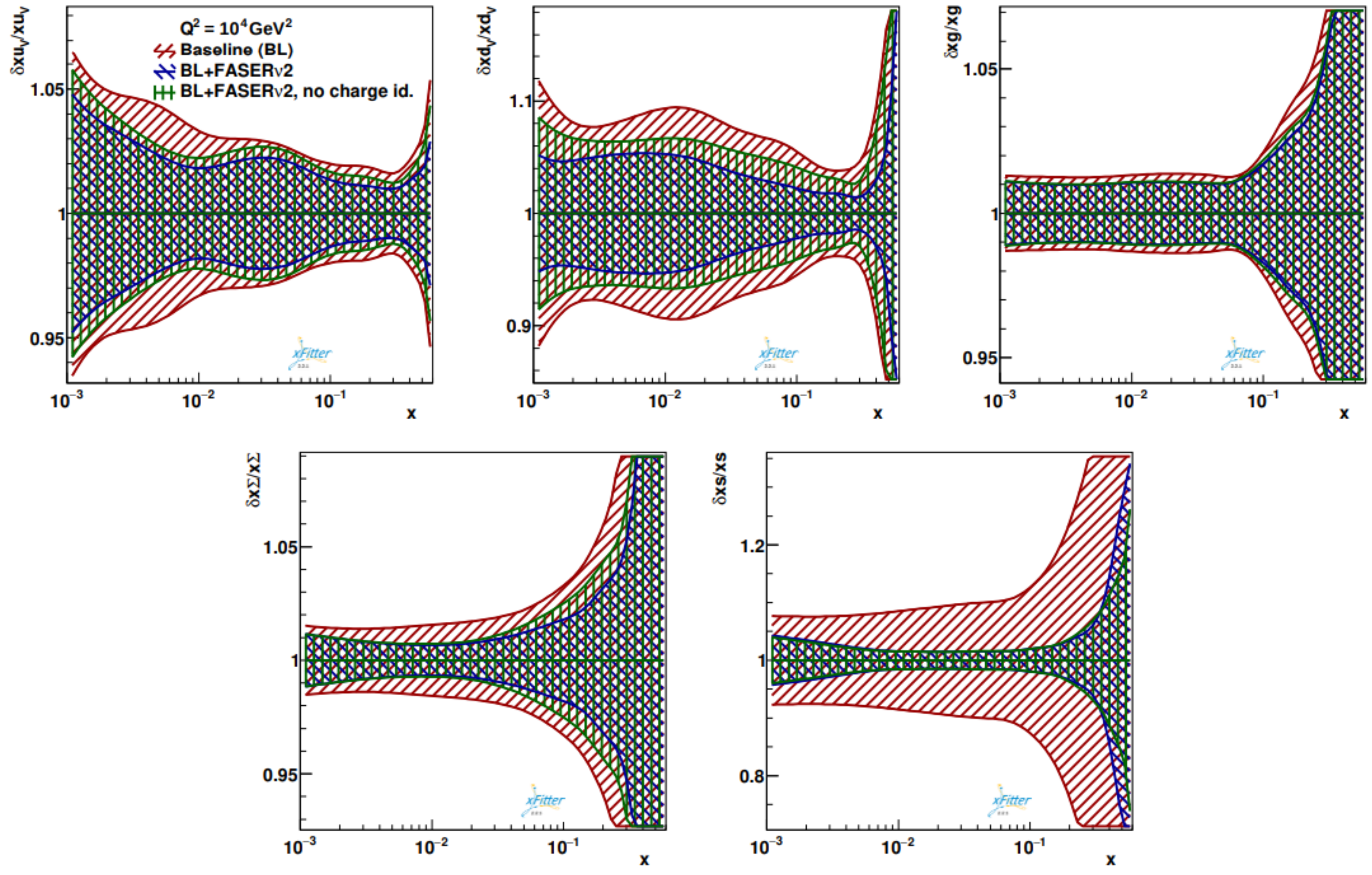
Faserv2 stat vs sys



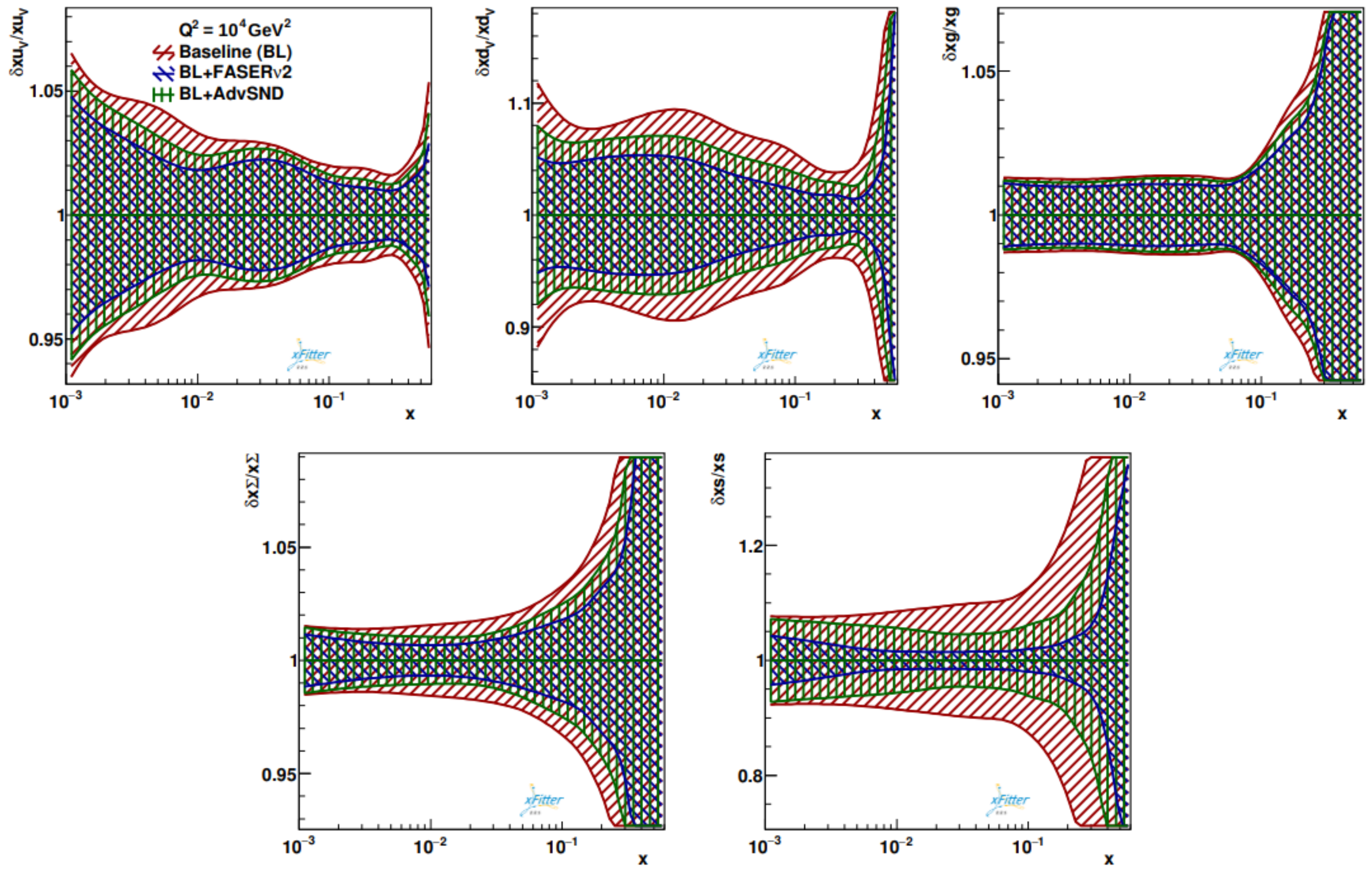
Faserv2 charm vs no charm



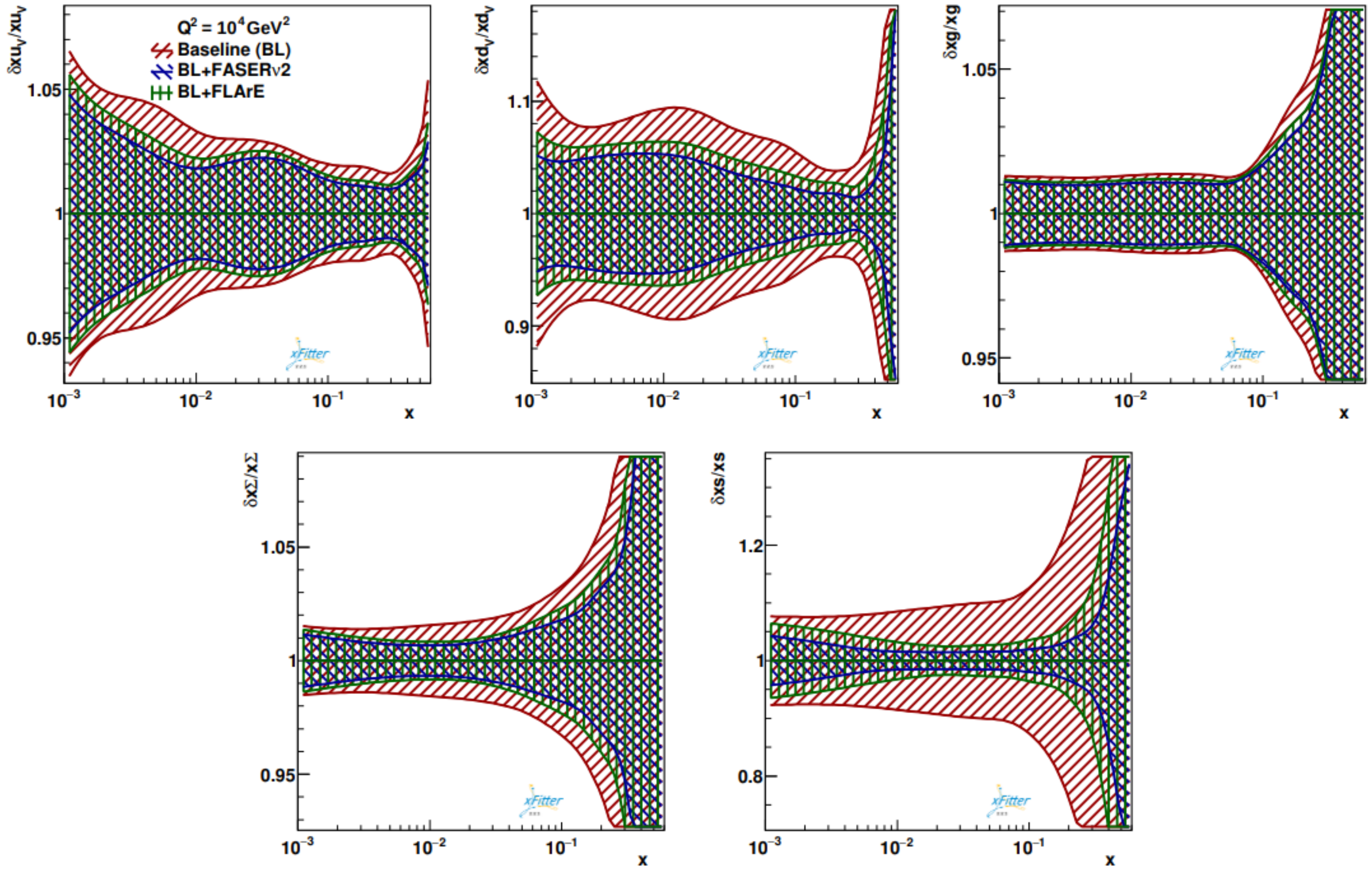
Faserv2 charge vs no charge



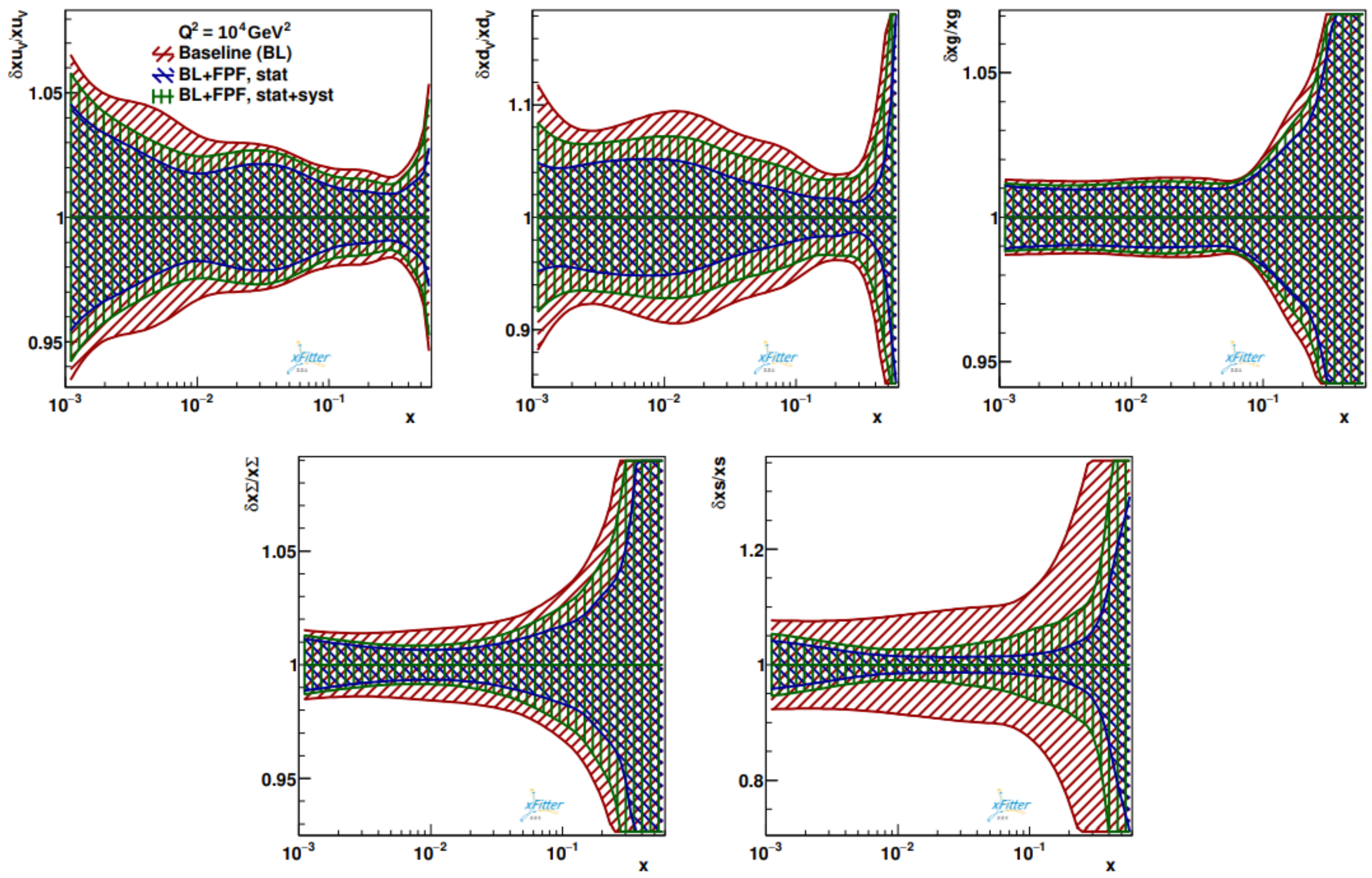
Faserv2 vs AdvSND



Faserv2 vs flare

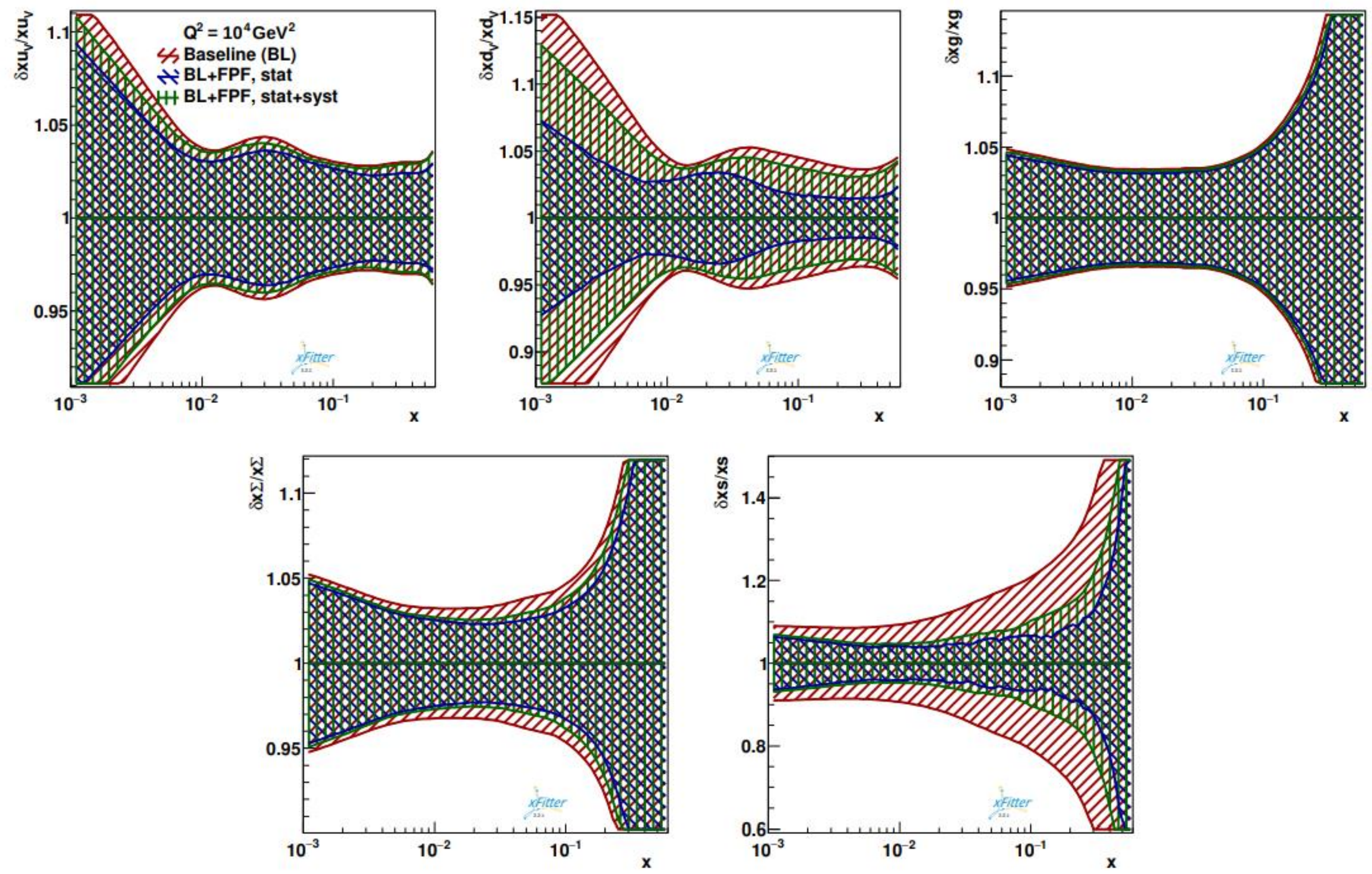


Fpf total



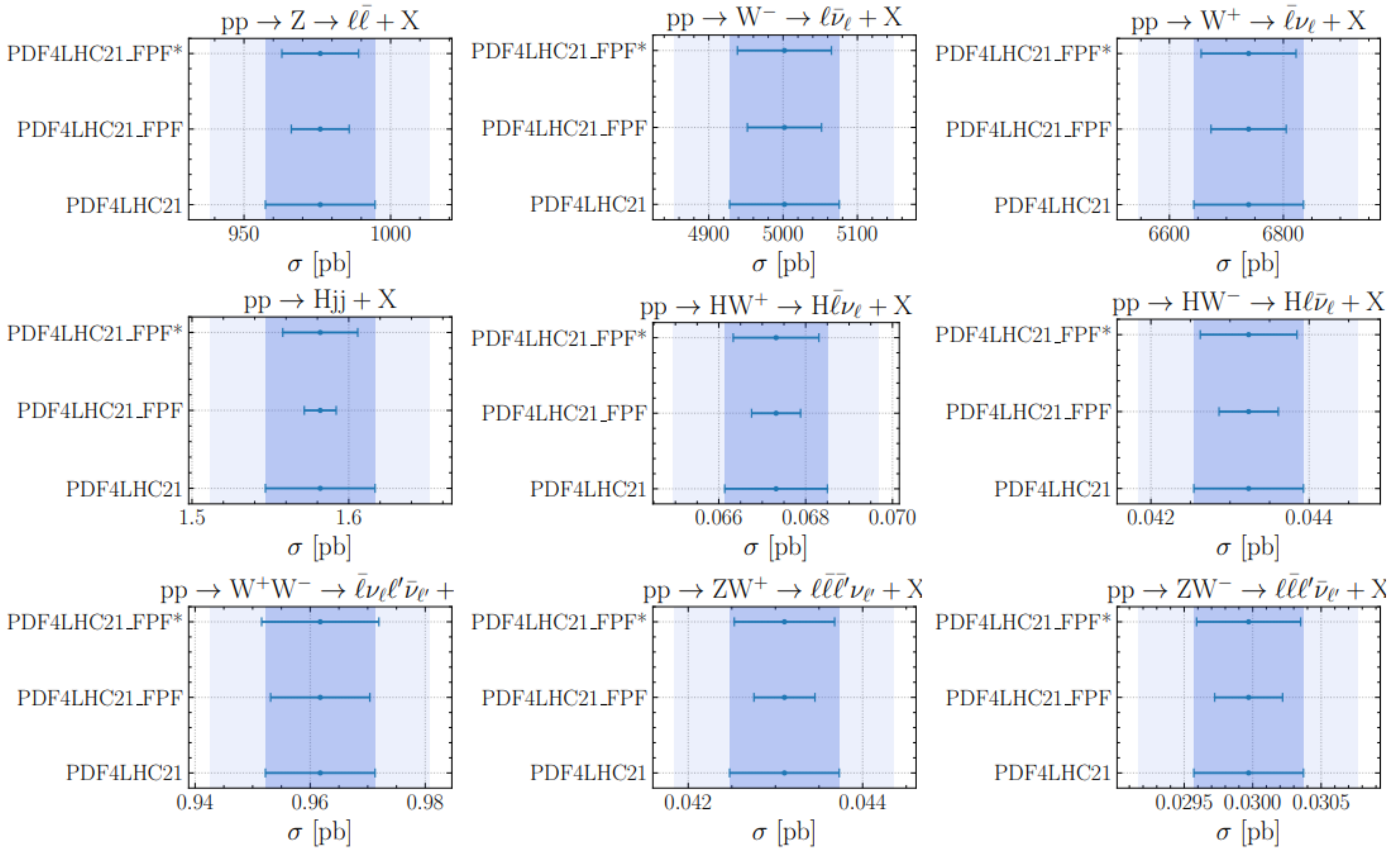
Q² = 10⁴ GeV²
Baseline (BL)
BL+FPF, stat
BL+FPF, stat+syst
δxu_v/xu_v
δxd_v/xd_v
δxg/xg
δxΣ/xΣ
δxs/xs
x
xFitter

Tungsten

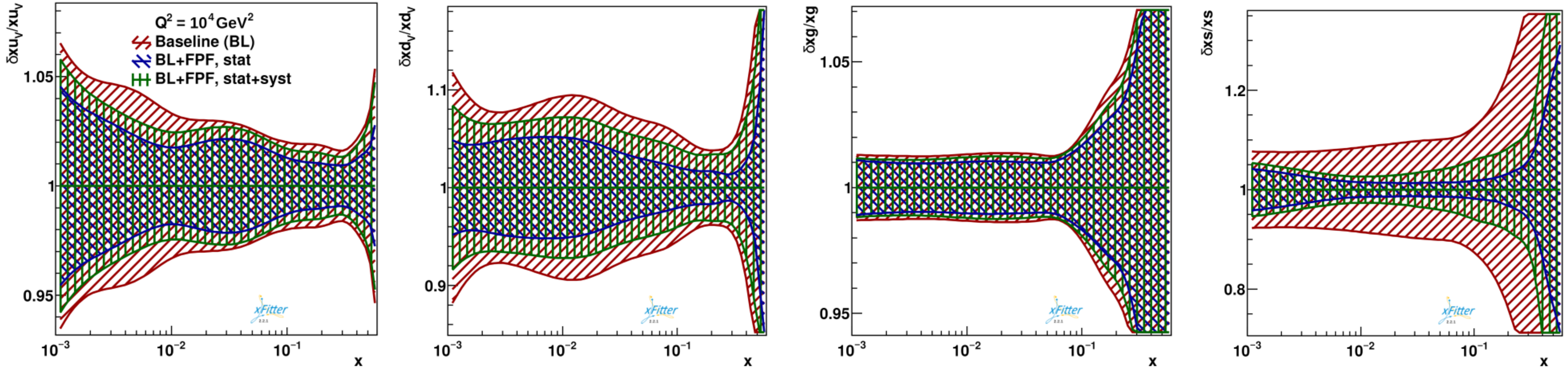


$Q^2 = 10^4 GeV^2$
Baseline (BL)
BL+FPF, stat
BL+FPF, stat+syst
$\delta xu_v/xu_v$
$\delta xd_v/xd_v$
$\delta xg/xg$
$\delta x\Sigma/x\Sigma$
$\delta xs/xs$
x

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