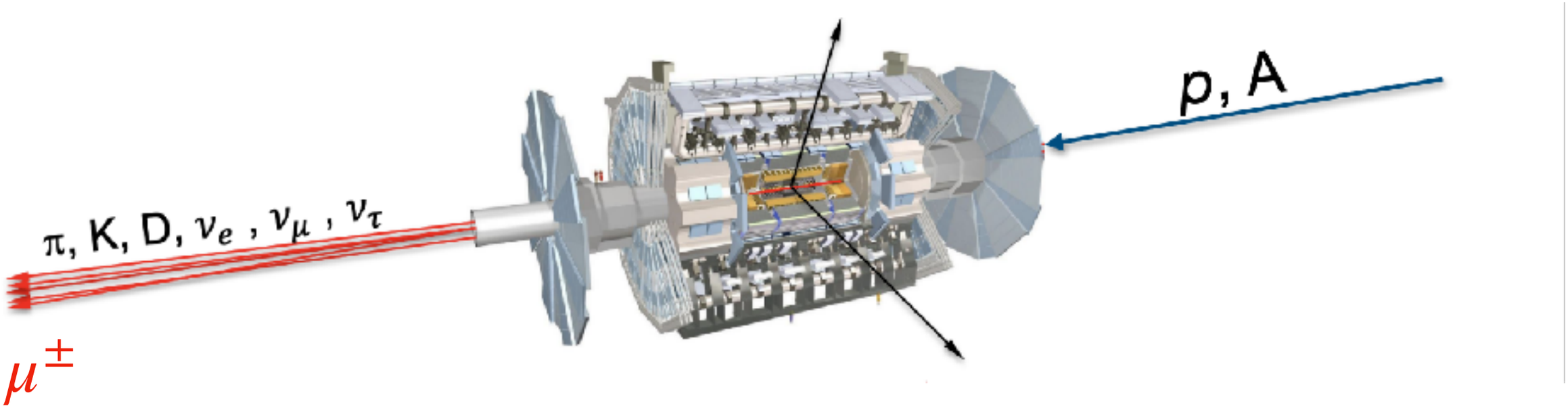
Muon DIS at the FPF

Peter Krack, VU Amsterdam & Nikhef



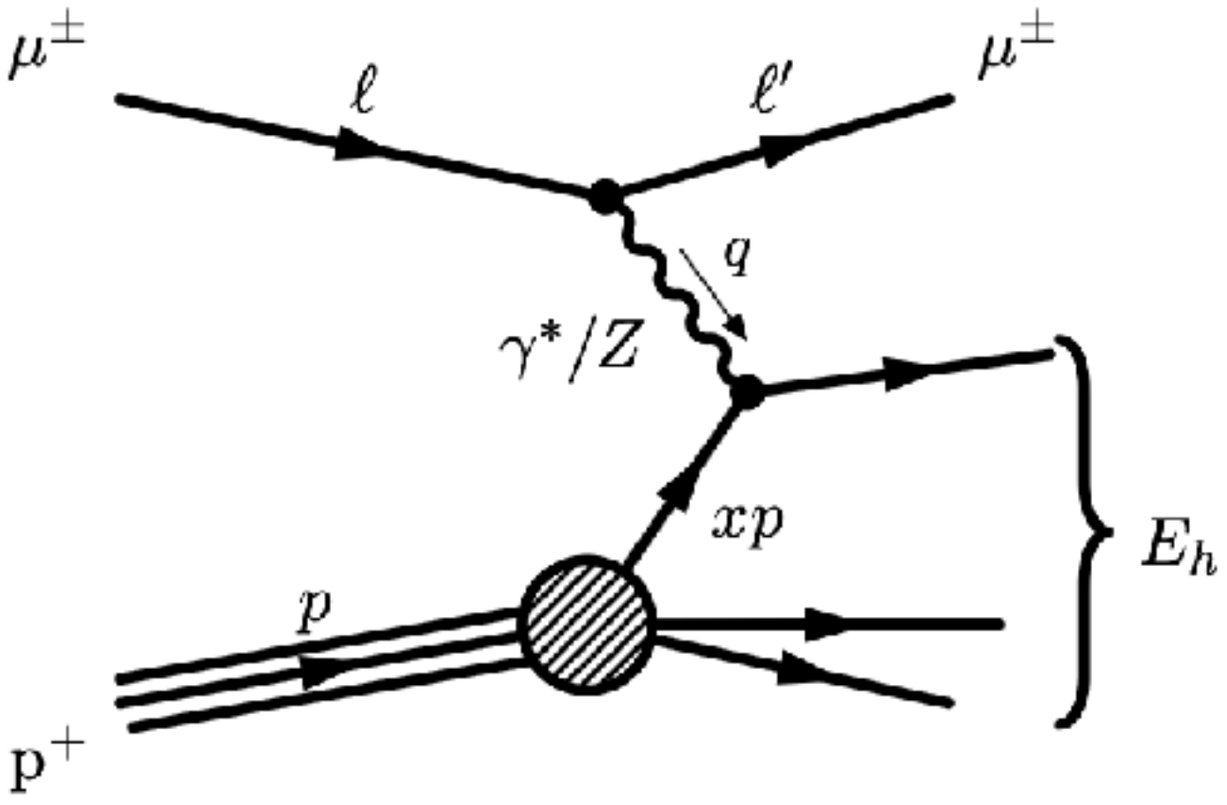
Deep-inelastic scattering at TeV energies with LHC muons

Reinaldo Francener, Victor P. Gonçalves, Felix Kling, Peter Krack, Juan Rojo

9th Forward Physics Facility meeting

Muon DIS and the Structure of the Proton

- Muon deep-inelastic scattering is a powerful probe of the proton's structure.



$$E_\ell = E_h + E'_\ell$$
$$Q^2 = 4(E_h + E'_\ell)E'_\ell \sin^2(\theta_\ell/2)$$
$$x = \frac{4(E_h + E'_\ell)E'_\ell \sin^2(\theta_\ell/2)}{2m_N E_h}$$

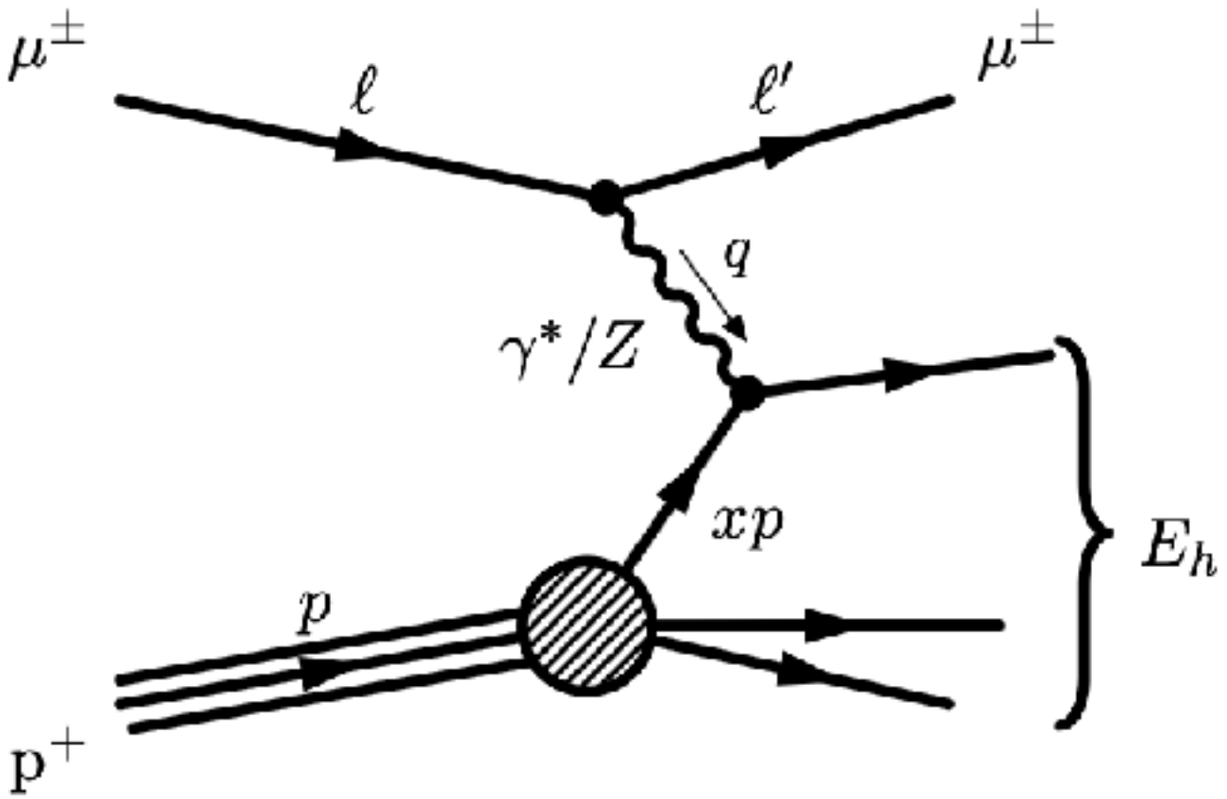
$$\sigma_{\mu^{\pm}u \to \mu^{\pm}X} = \hat{\sigma}_{\mu^{\pm}u \to \mu^{\pm}u} \otimes f_u(x, Q)$$

muon-proton scattering rate | **partonic cross-section** | **parton distribution function**

- Process is described by measuring the outgoing **muon** and the **energy of the hadronic system.** $(E'_\ell, \theta_{\ell'}, E_h)$

Muon DIS and the Structure of the Proton

- Muon deep-inelastic scattering is a powerful probe of the proton's structure.



$$\sigma_{\mu^{\pm}u\to\mu^{\pm}X} = \hat{\sigma}_{\mu^{\pm}u\to\mu^{\pm}u} \otimes f_u(x, Q)$$

muon-proton scattering rate

partonic cross-section

parton distribution function

- Kinematics also specified by the **incoming muon energy** and the angle and energy of the outgoing muon. $(E_\ell, E'_\ell, \theta_{\ell'})$

- No need to measure the hadronic final state.

- Muon initiated event are usually considered a **background,** but enables **novel physics opportunities.**

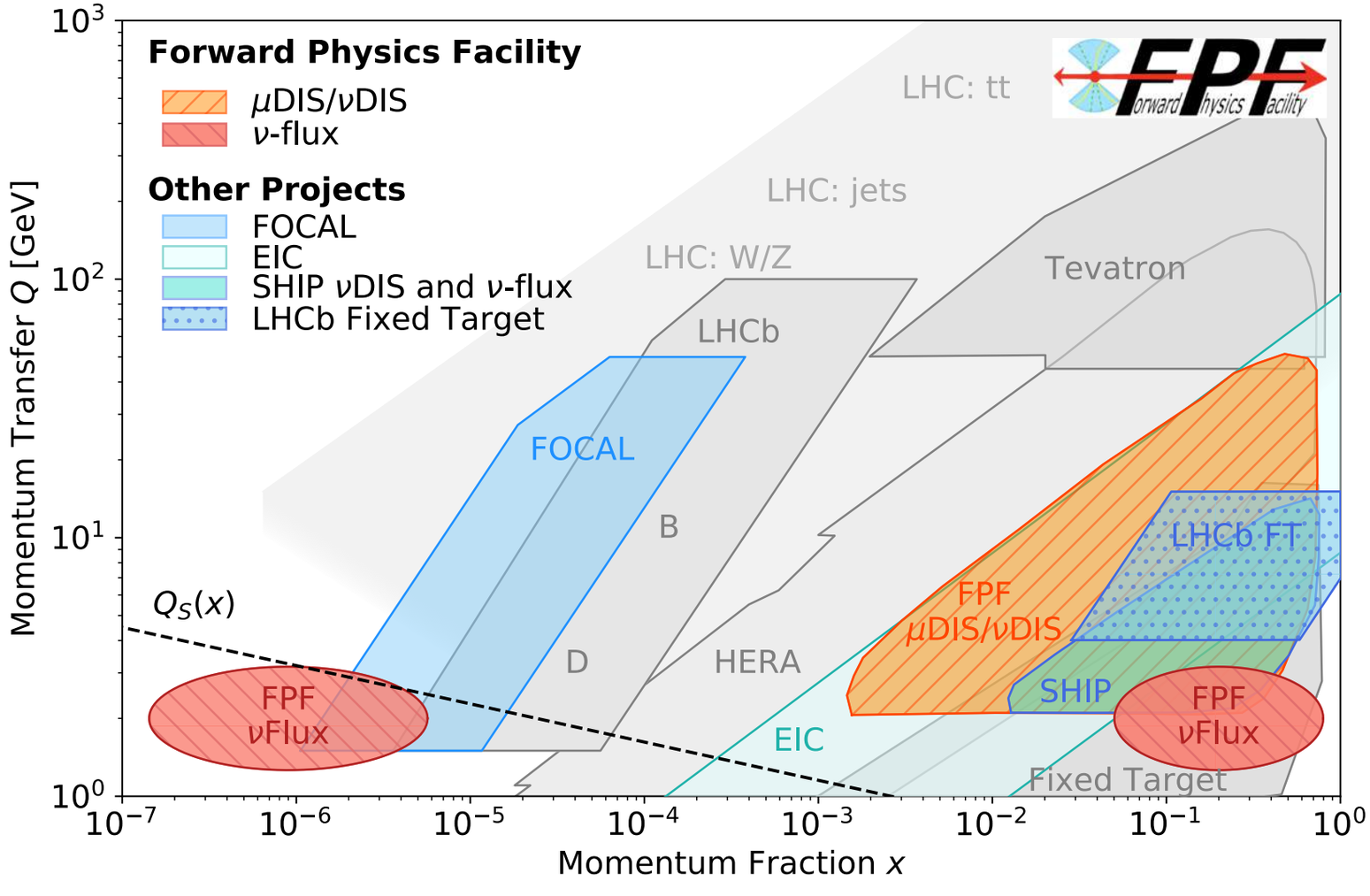
Muon DIS and the Structure of the Proton

- The **FPF** will be measuring **muon DIS** in a kinematic region overlapping with the **EIC** (>2032) for **electron DIS.**

- We expect $2.5 \cdot 10^7$ muon DIS interactions at FASERν2.

- Can measure multi-differential cross sections.

- Allows to probe the **charm** content of the proton **at large-x**

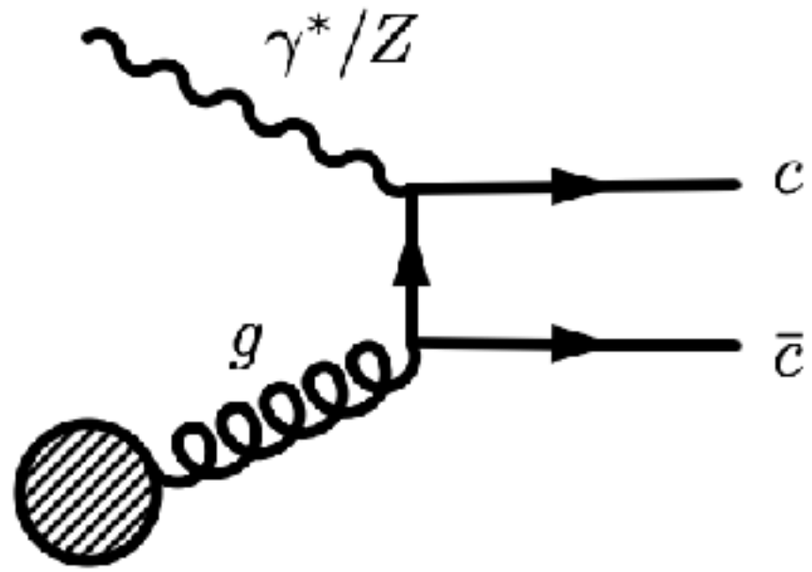


Charm Production in Muon DIS

- Muon DIS can probe the gluon and charm PDF.

Perturbative charm:

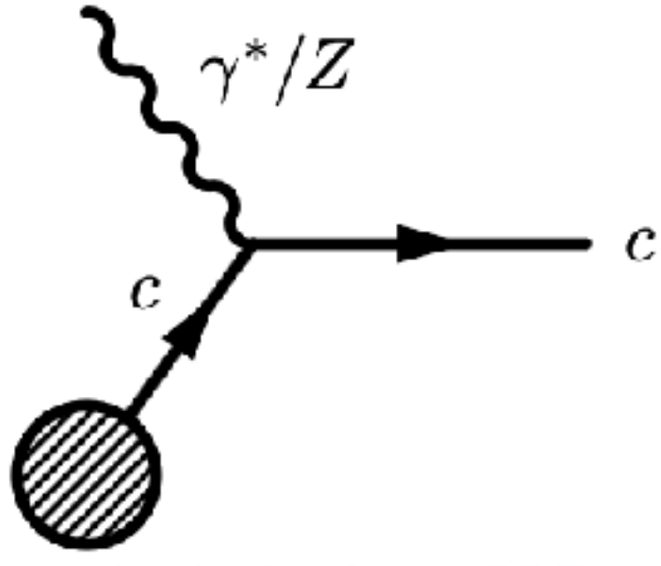
- From gluon splitting $g \to c + \bar{c}$
- Symmetric $c = \bar{c}$
- Vanishes for $Q^2 \to 0$
- Small at large-x



perturbative charm PDF

Intrinsic charm:

- Part of the protons wavefunction
- Exists at low scales
- Can be valence-like $c \neq \bar{c}$
- Present at large-x



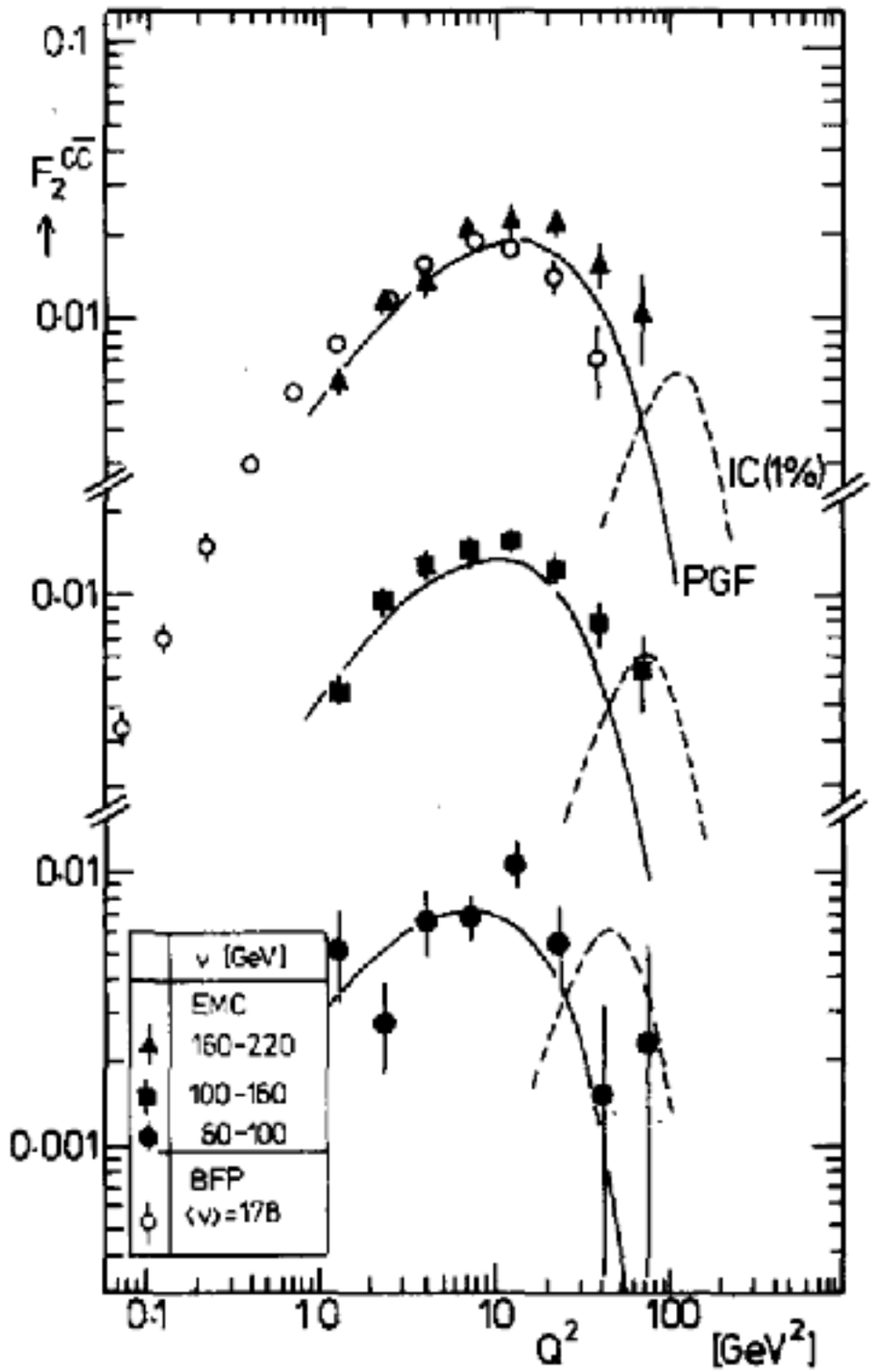
intrinsic charm PDF

Charm PDF at large-x

- The EMC measurement of the F_2^c structure function at large-x suggests **the presence of intrinsic charm** in the proton.

- This measurement (over 40 years old) has **never been reproduced.**

$$Q^2 = -q^2 = -(\ell - \ell')^2$$
$$\nu = p \cdot q / M = \underbrace{E_\mu - E'_\mu}_{\text{lab frame}}$$
$$x = \frac{Q^2}{2M\nu}$$

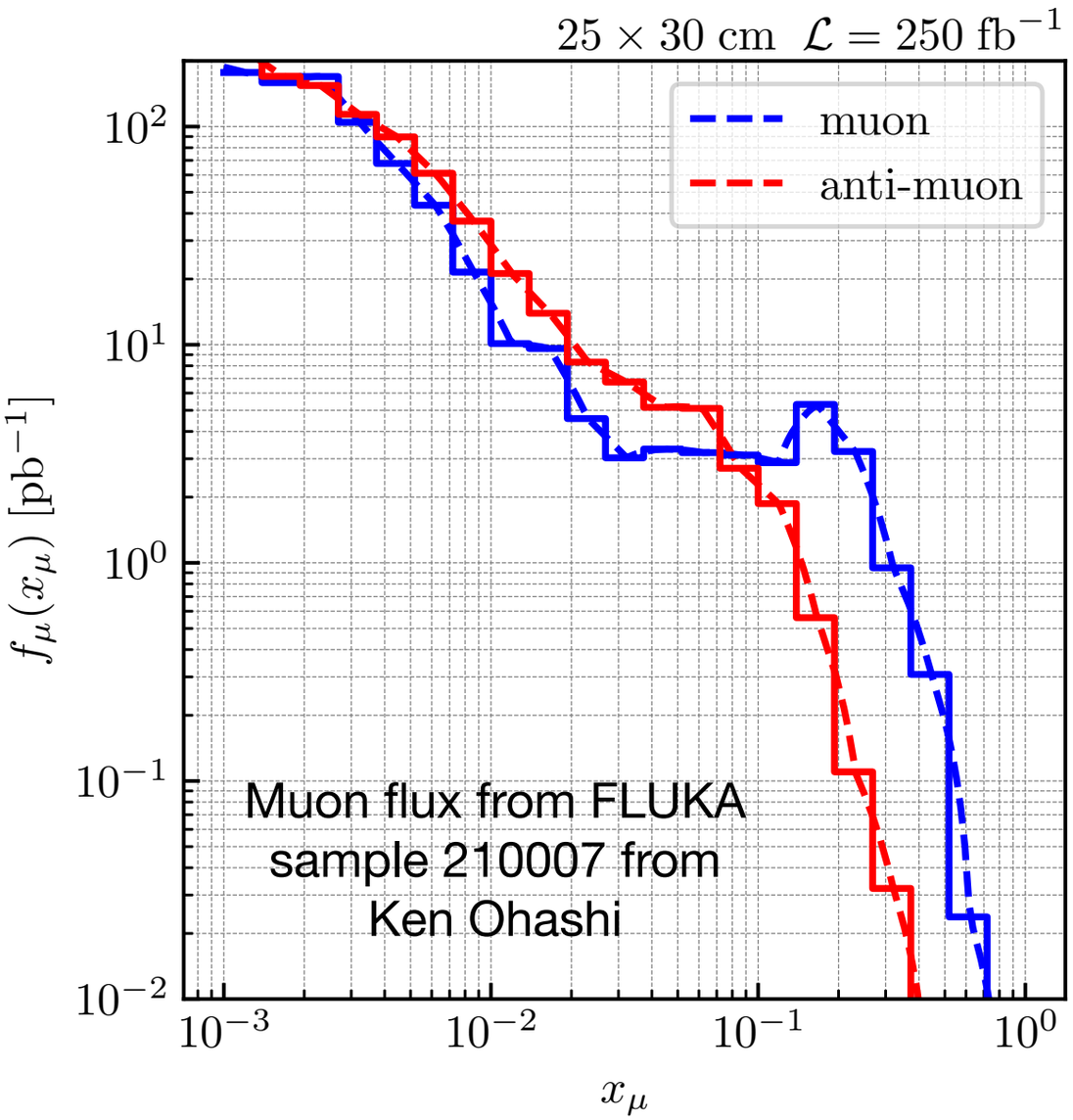


Simulation of Muon DIS

- **Input:** Predictions for the **muon flux** reaching the FASERν.

- The flux has **negligible modelling uncertainties.** Simulations of the flux can be validated independently of any cross-section measurements.

- Muon scattering and modelling of the final state are carried out in **POWHEG+Pythia8** at NLO in QCD using modern PDFs.



Can rescale the muon flux to obtain predictions for the FPF.

HL-LHC: $40\,\text{cm} \times 40\,\text{cm}$, $L_T = 6.2\,\text{m}$, $\mathscr{L}_{\text{int}} = 3\,\text{ab}^{-1}$

Event Yields at FASERν and FASERν2

Muon DIS neutral-current event yields at FASERν and FASERν2 for $\mathcal{L}_{\rm pp} = 3$ ab^{-1}

PDF set	Charm PDF	Process	FASERν	FASERν2
NNPDF4.0	Fitted charm	$\mu^\pm + W \to \mu^\pm + X$	2.0×10^6	2.5×10^7
		$\mu^\pm + W \to \mu^\pm + X + c(\bar{c})$	7.0×10^4	8.6×10^5
NNPDF4.0PC	Pert. charm	$\mu^\pm + W \to \mu^\pm + X$	2.1×10^6	2.6×10^7
		$\mu^\pm + W \to \mu^\pm + X + c(\bar{c})$	7.6×10^4	9.4×10^5
CT18 FC	Fitted charm (BHPS3)	$\mu^\pm + W \to \mu^\pm + X$	2.1×10^6	2.6×10^7
		$\mu^\pm + W \to \mu^\pm + X + c(\bar{c})$	1.4×10^5	1.7×10^6
CT18	Pert. charm	$\mu^\pm + W \to \mu^\pm + X$	2.0×10^6	2.5×10^7
		$\mu^\pm + W \to \mu^\pm + X + c(\bar{c})$	1.1×10^5	1.4×10^6

DIS Acceptance Cuts

$Q \geq 1.65\,\text{GeV}$

$W^2 \geq 4\,\text{GeV}^2$

Detector Acceptance Cuts

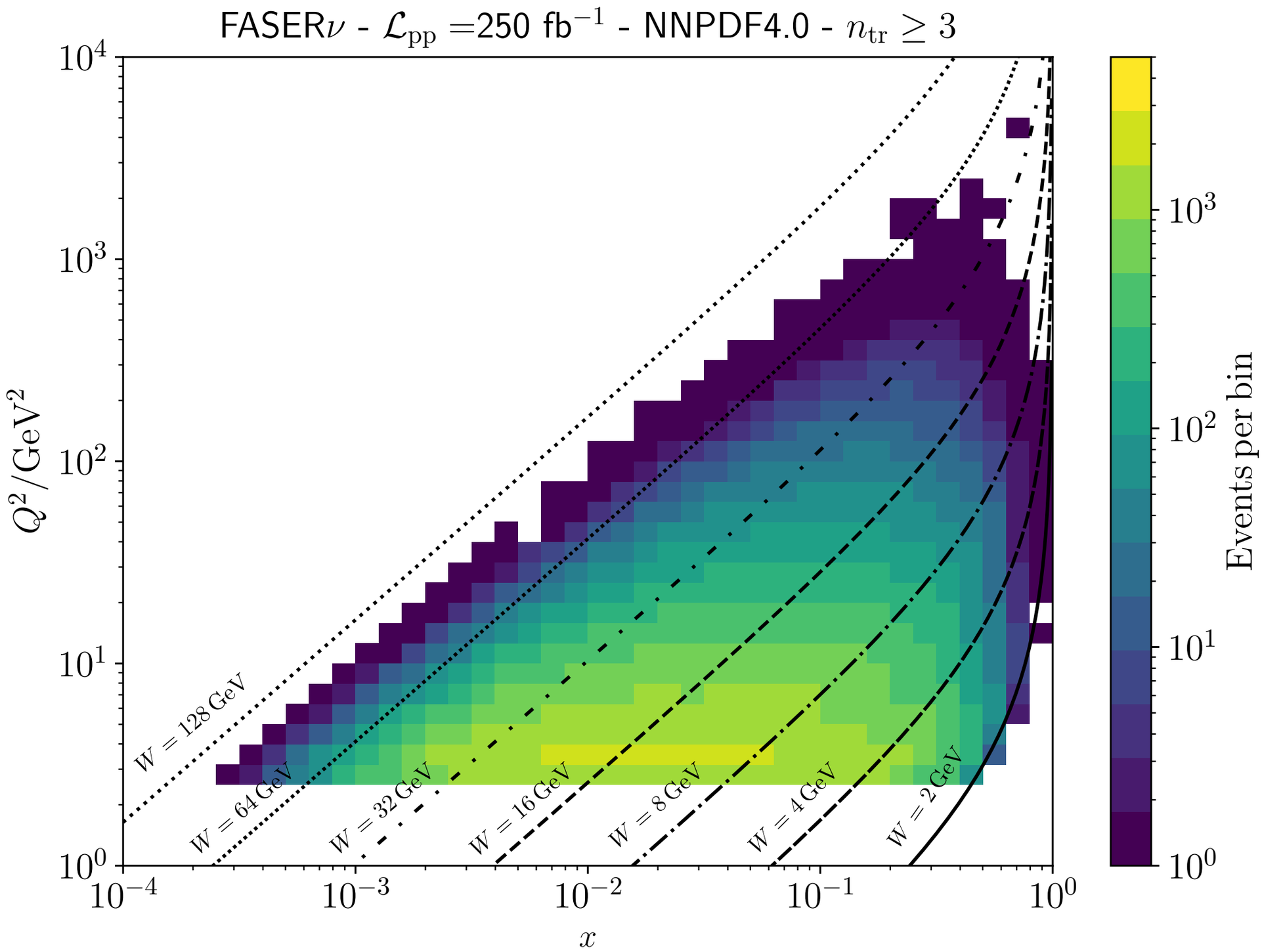
$E'_\ell \geq 100\,\text{GeV}$

$n_{\rm tr} = 3,4,5$

$E_{\rm track} \geq 1\,\text{GeV}$

Assuming charm tagging efficency of $\epsilon_c = 70\,\%$

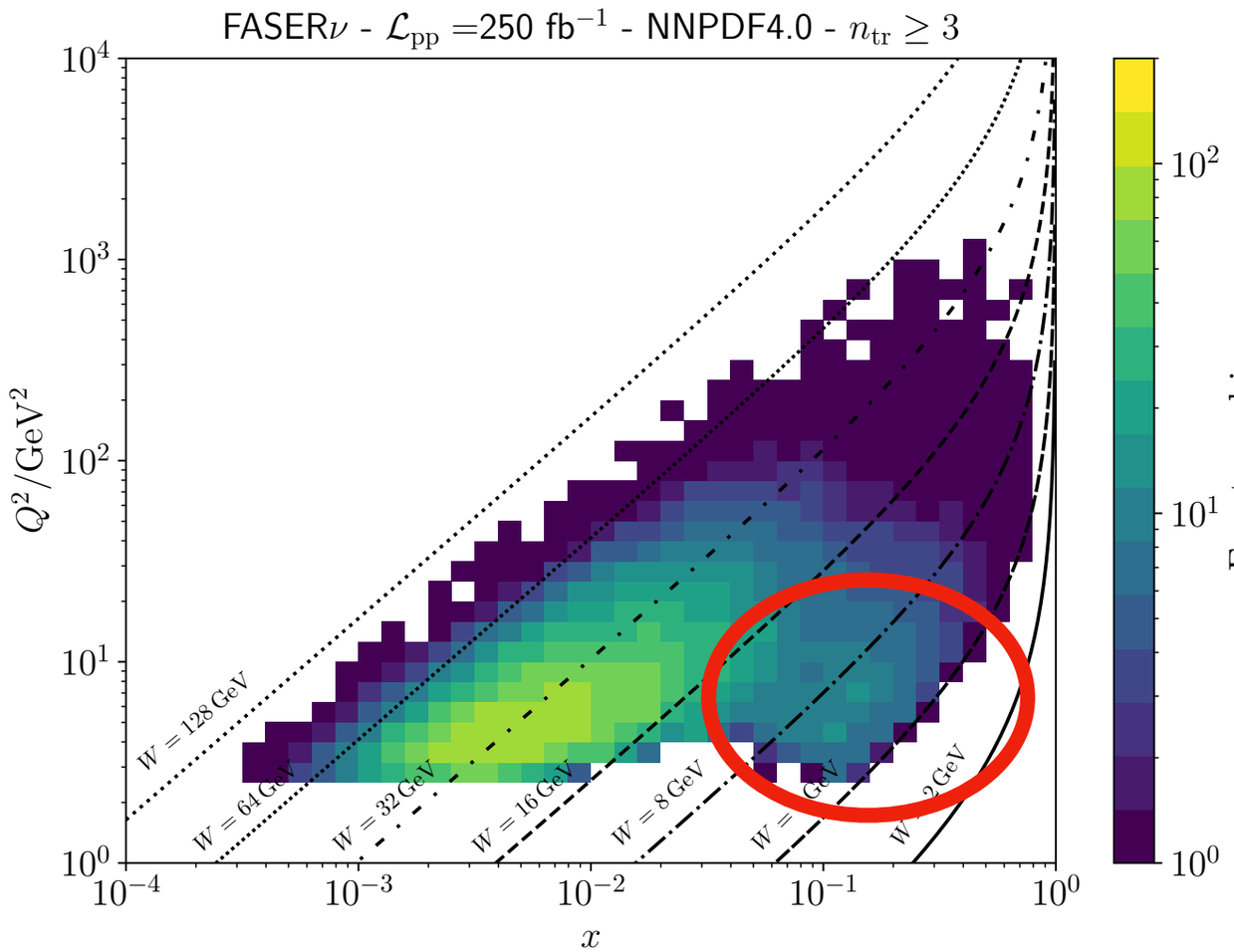
Event Yields at FASERν and FASERν2

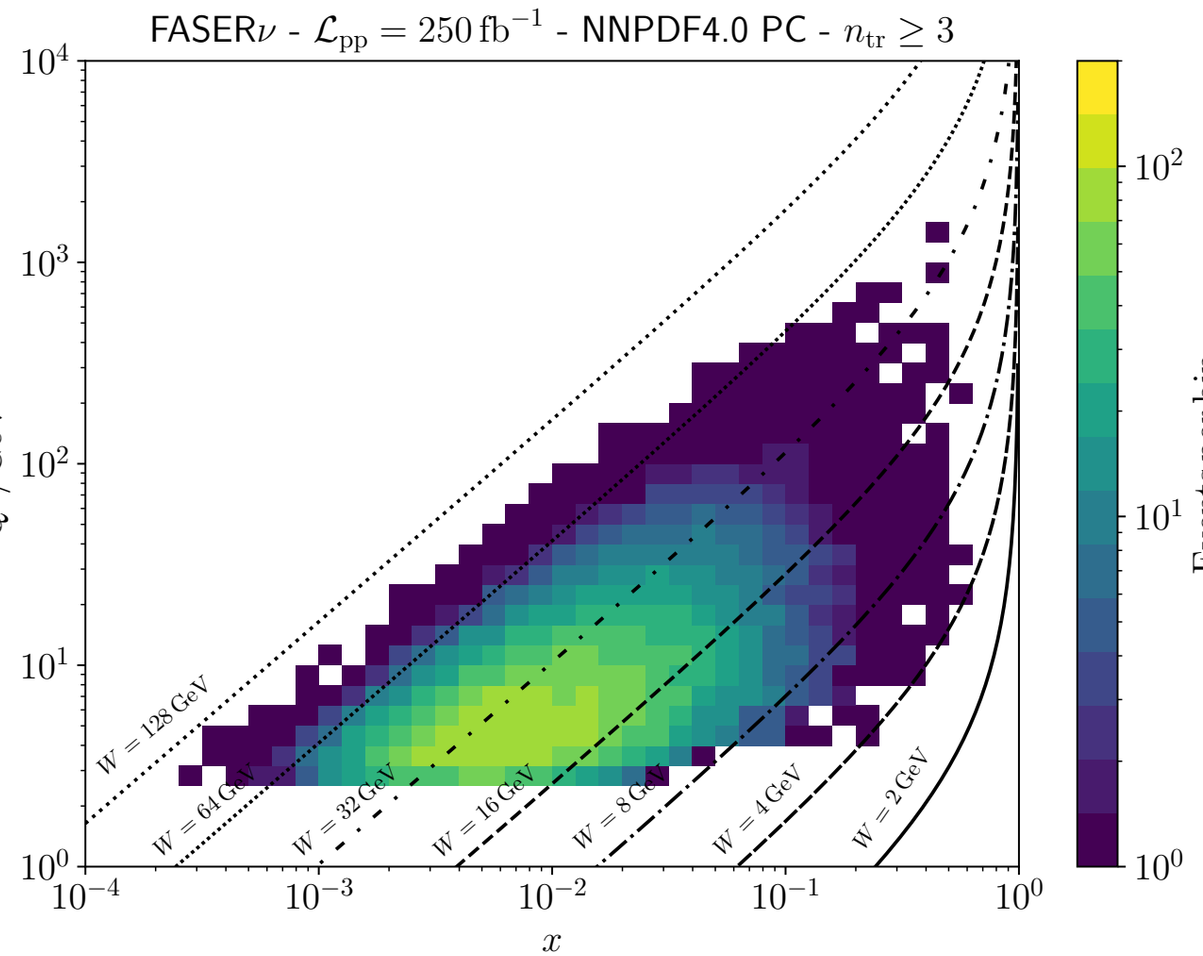


Muon DIS dominated by low-Q scattering events

Event Yields at FASERν and FASERν2

Comparing NNPDF4.0 IC to NNPDF PC for charm tagged events.

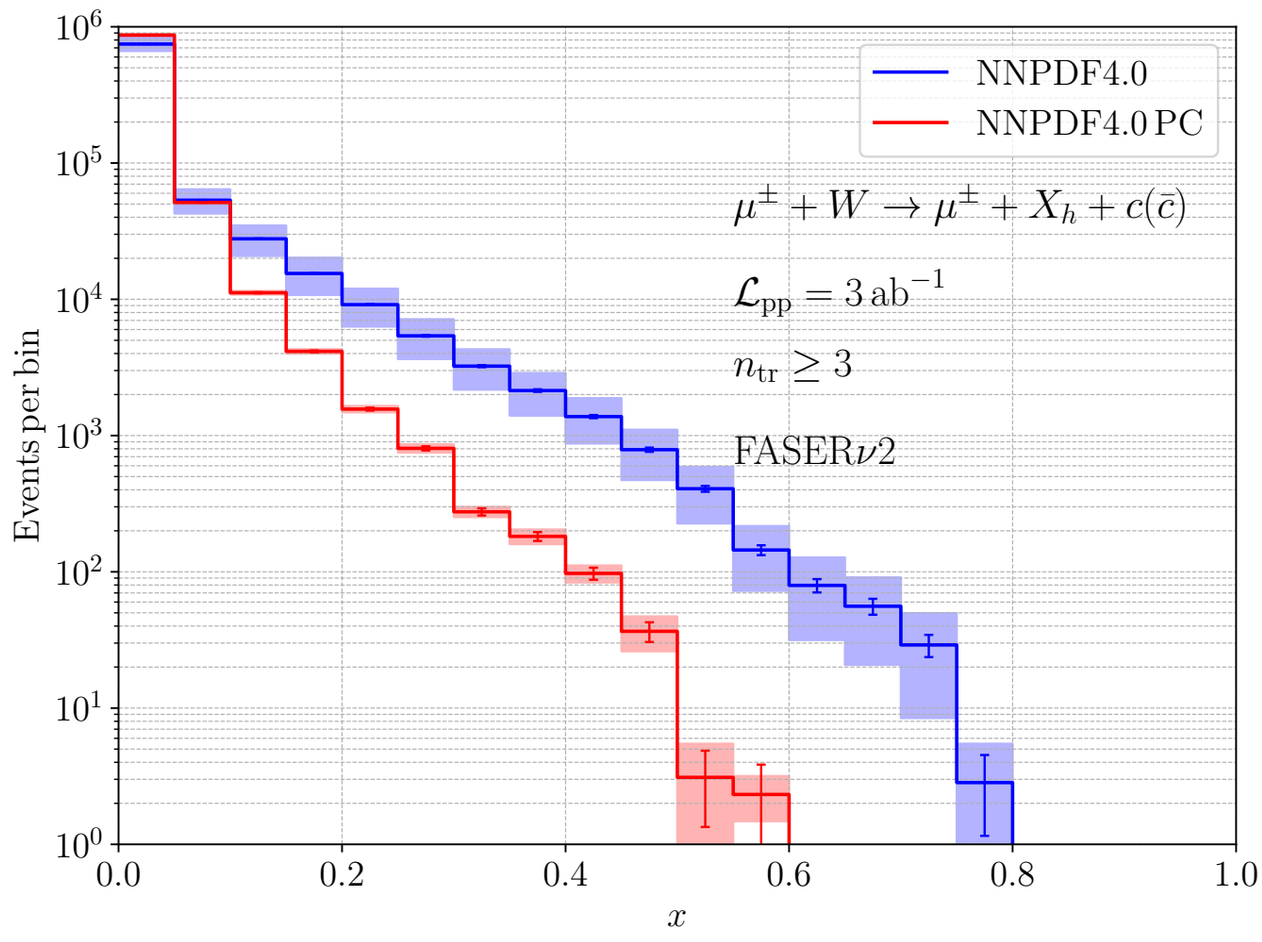




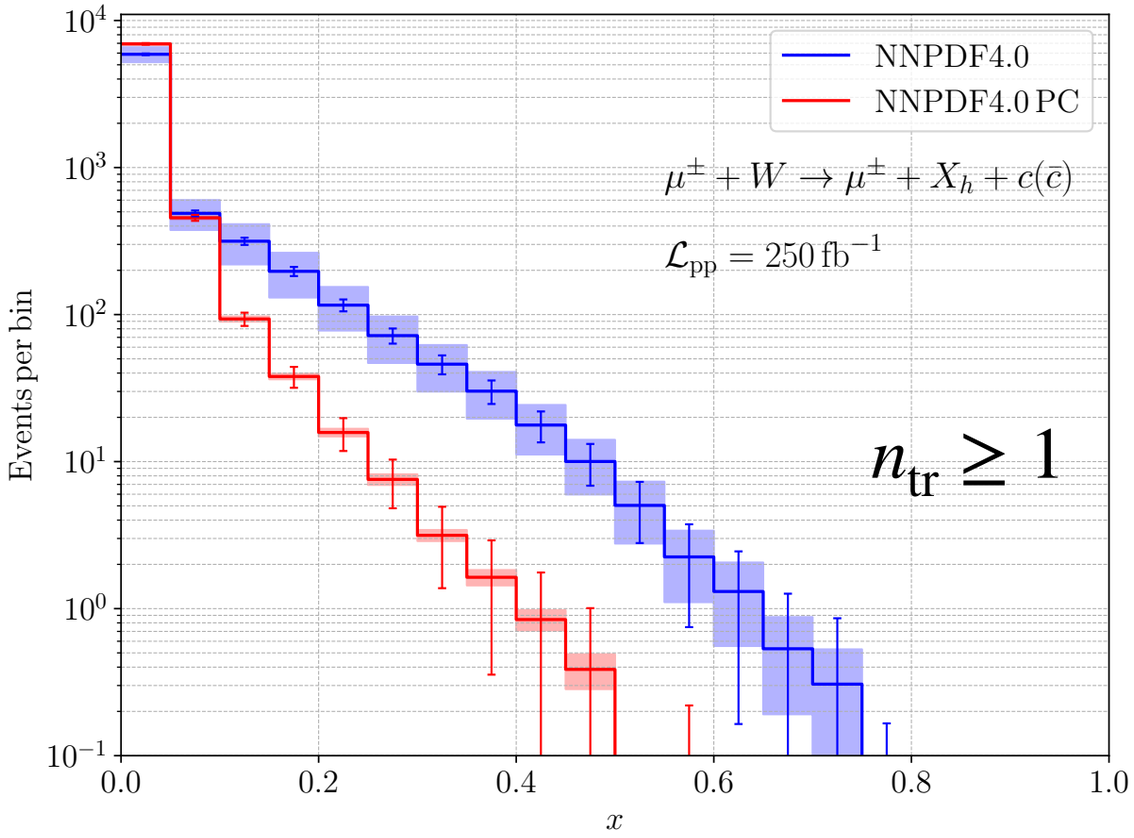
Large-x region sensitive to intrinsic charm

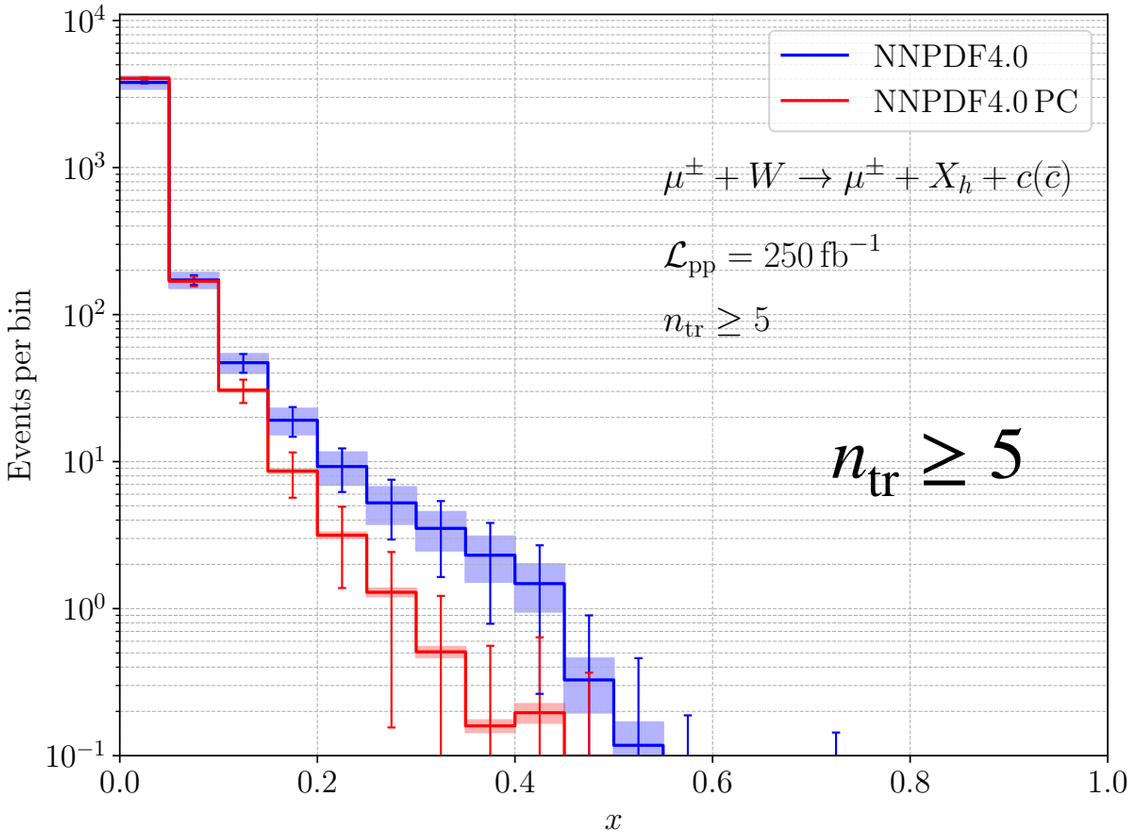
Results

- Error bands indicate the 68% CL PDF uncertainties.
- Error bars indicate the statistical uncertainties.
- Clear signal for **intrinsic charm**
- Can confirm or falsify intrinsic charm.
- Can study multi-differential distributions with **over 2000 events** for $x \geq 0.4$.



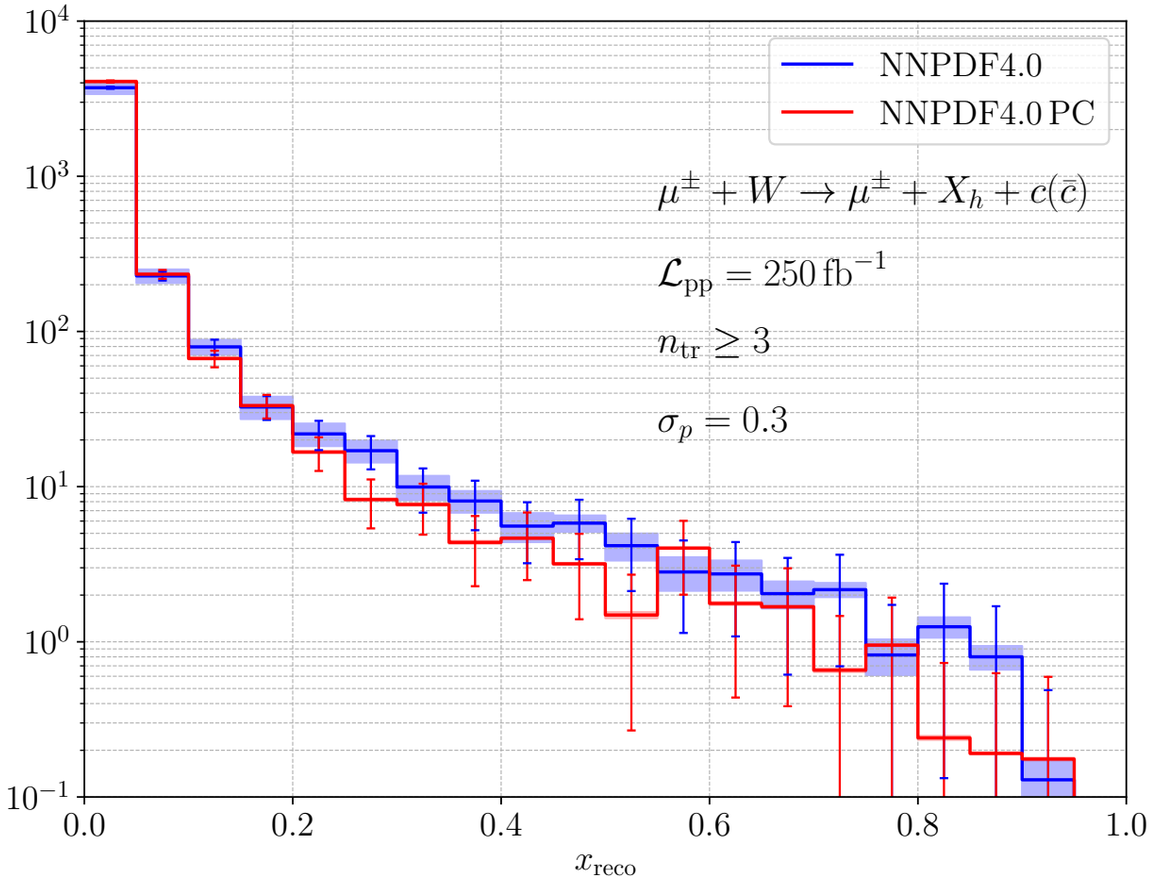
Impact of Acceptance Cuts



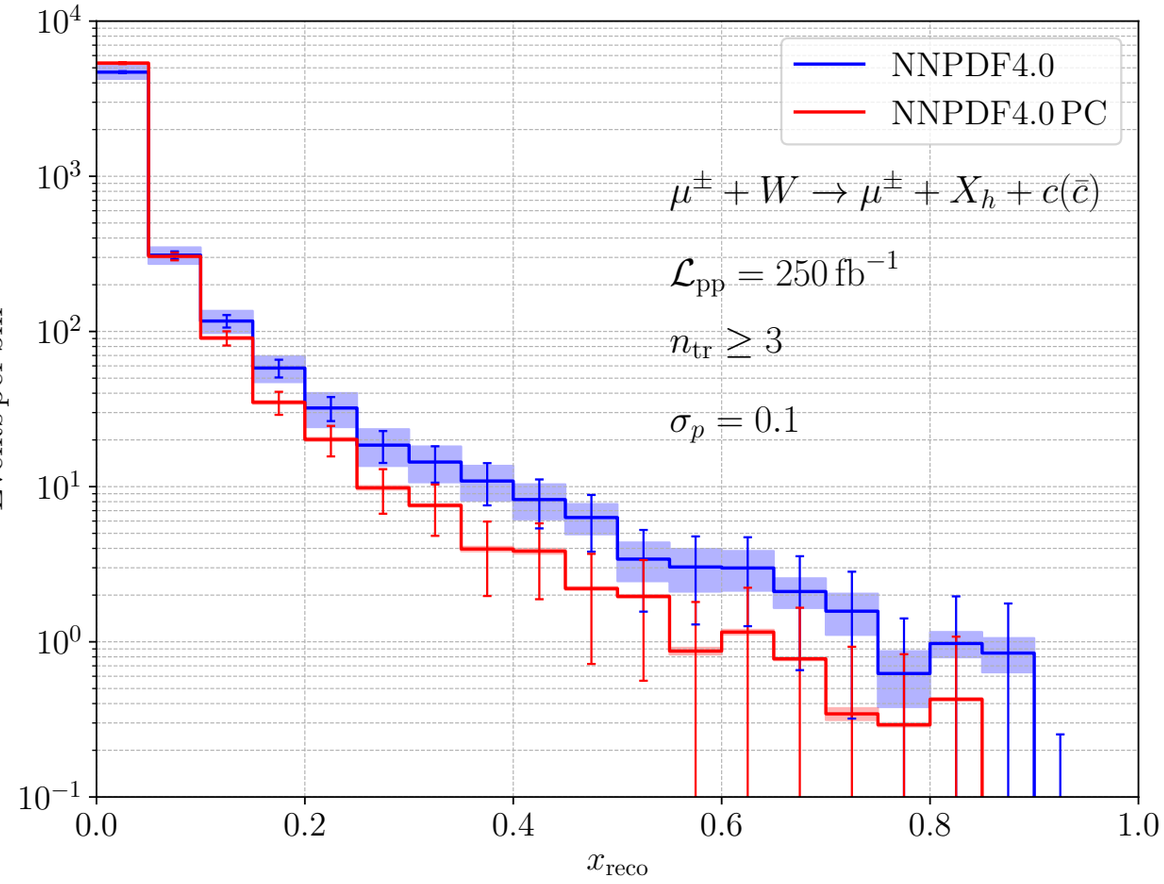


- Muon DIS dominated by low-Q^2 events.
- A too stringent cut in $n_{\rm tr}$ with $E_{\rm tr} \geq 1\,{\rm GeV}$ reduces the event sample in the large-x region.
- FASERν vertex finding algorithm currently **requires** $n_{\rm tr} \geq 5$. Improvements to lower the threshold are being considered.

Systematic Uncertainties



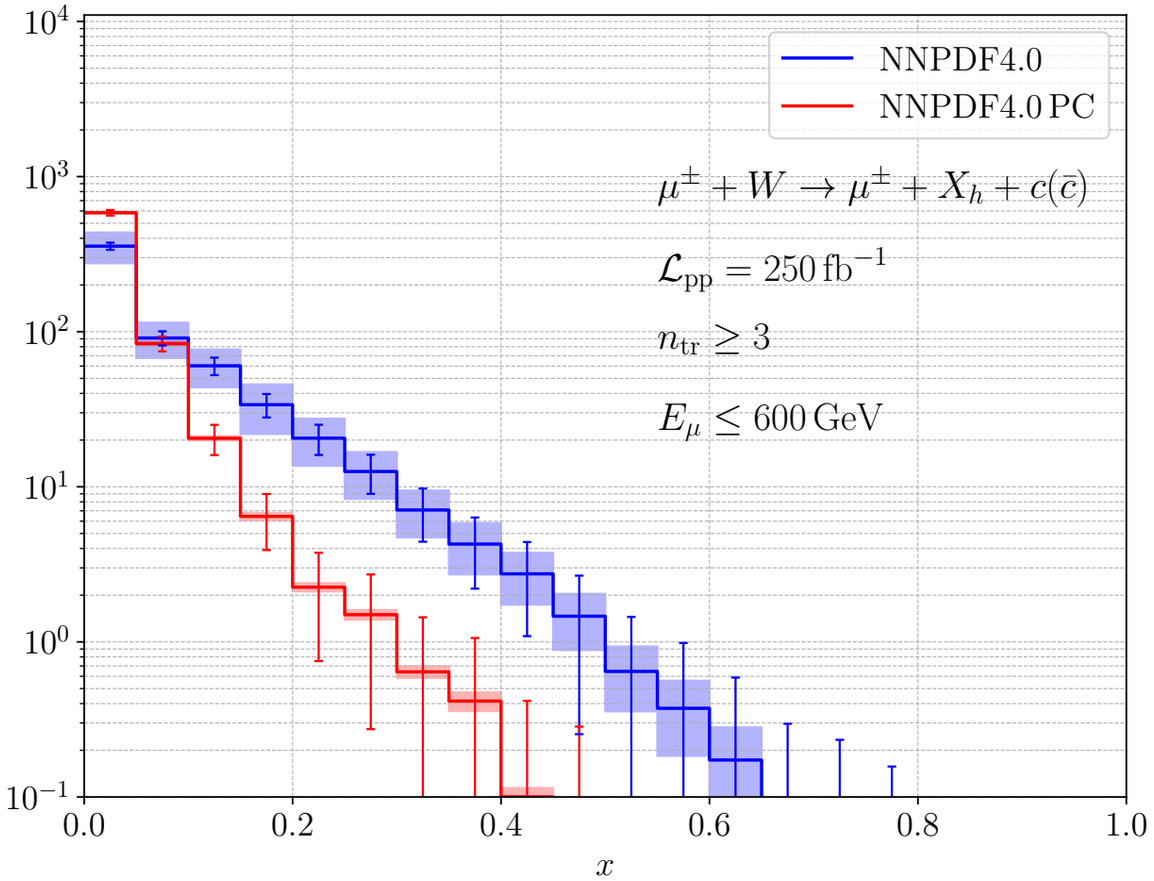
30% smearing



10% smearing

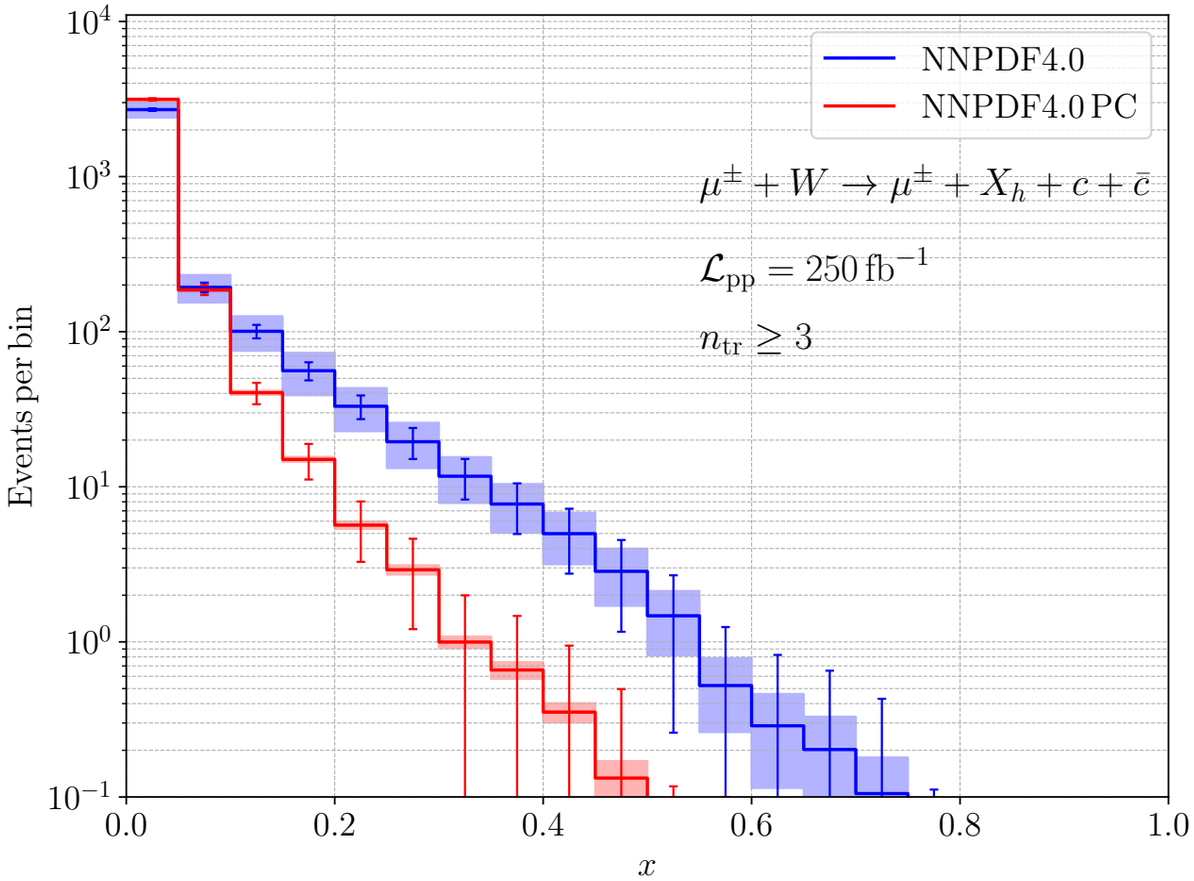
- Need to measure the energy if the i**ncoming and outgoing** muon in the detector volume.
- The energy is determined form the curvature of the track, Uncertainties become larger for higher energies.
- FASERν has a resolution of around 30% for measurements of the muon energy,
- Applying smearing (30% and 10%) to the energy shows that the difference between pert. and intr. charm washes out.

Systematic Uncertainties



Additional cut of $E_{\mu} \leq 600\,\mathrm{GeV}$

Reduction by around a factor of three

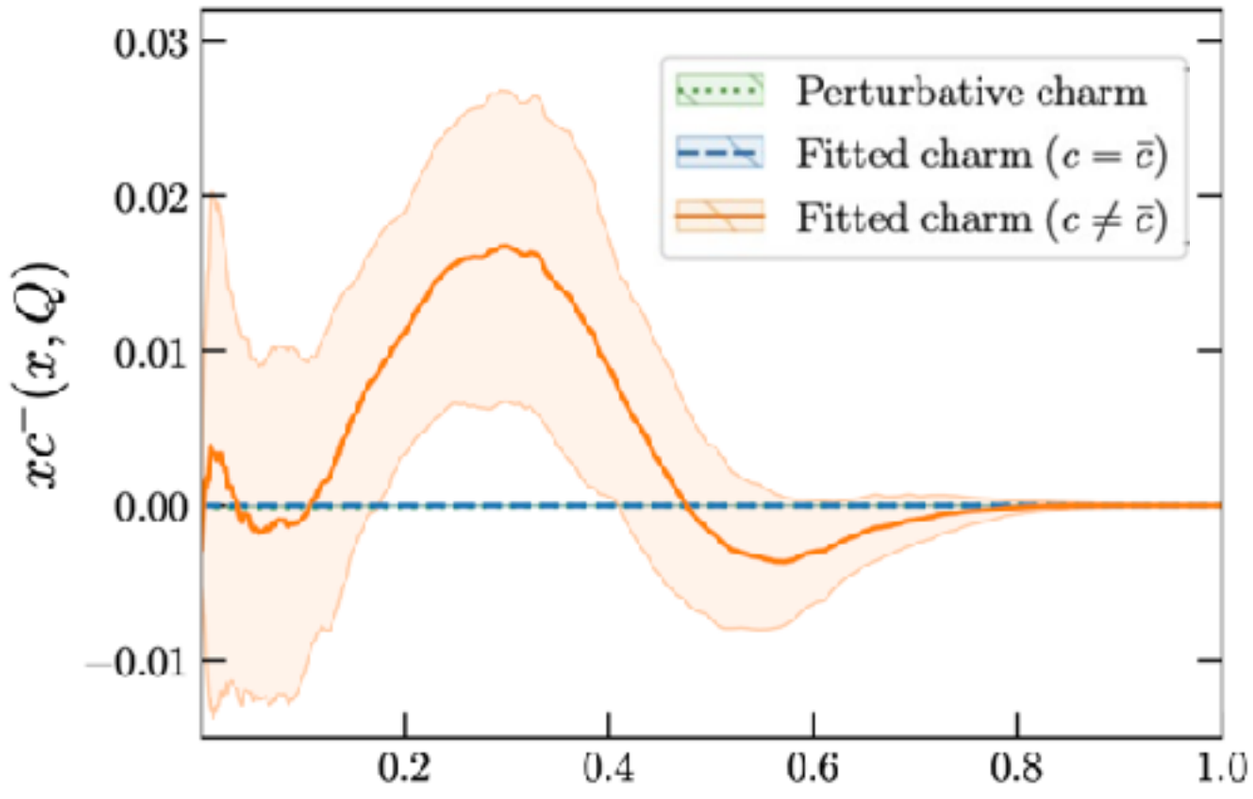


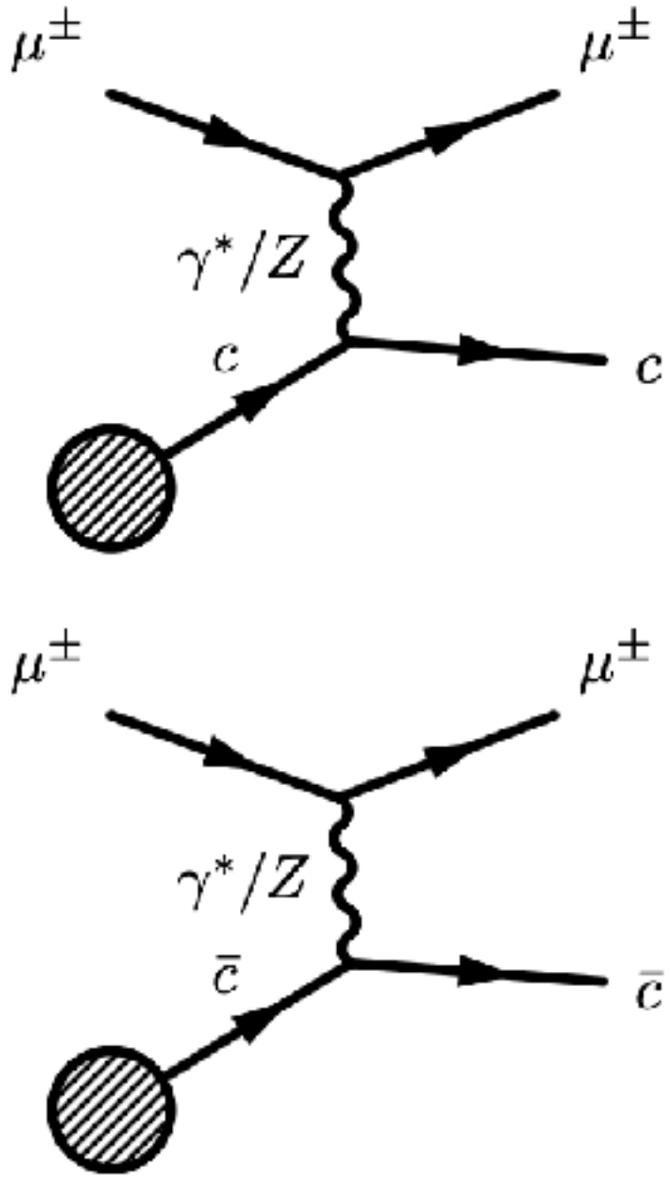
Double charm tagging

- Introduce an additional cut on the energy of the muon.
- Background from secondary hadron interactions can be suppressed by requiring double charm tagging.

Charm Asymmetry

- No correlation between charge of the muon and charge of the charm quark.
- If the charge of the charm quark can be determined, the charm asymmetry can be measured.
- Perturbative charm is symmetric $c = \bar{c}$.





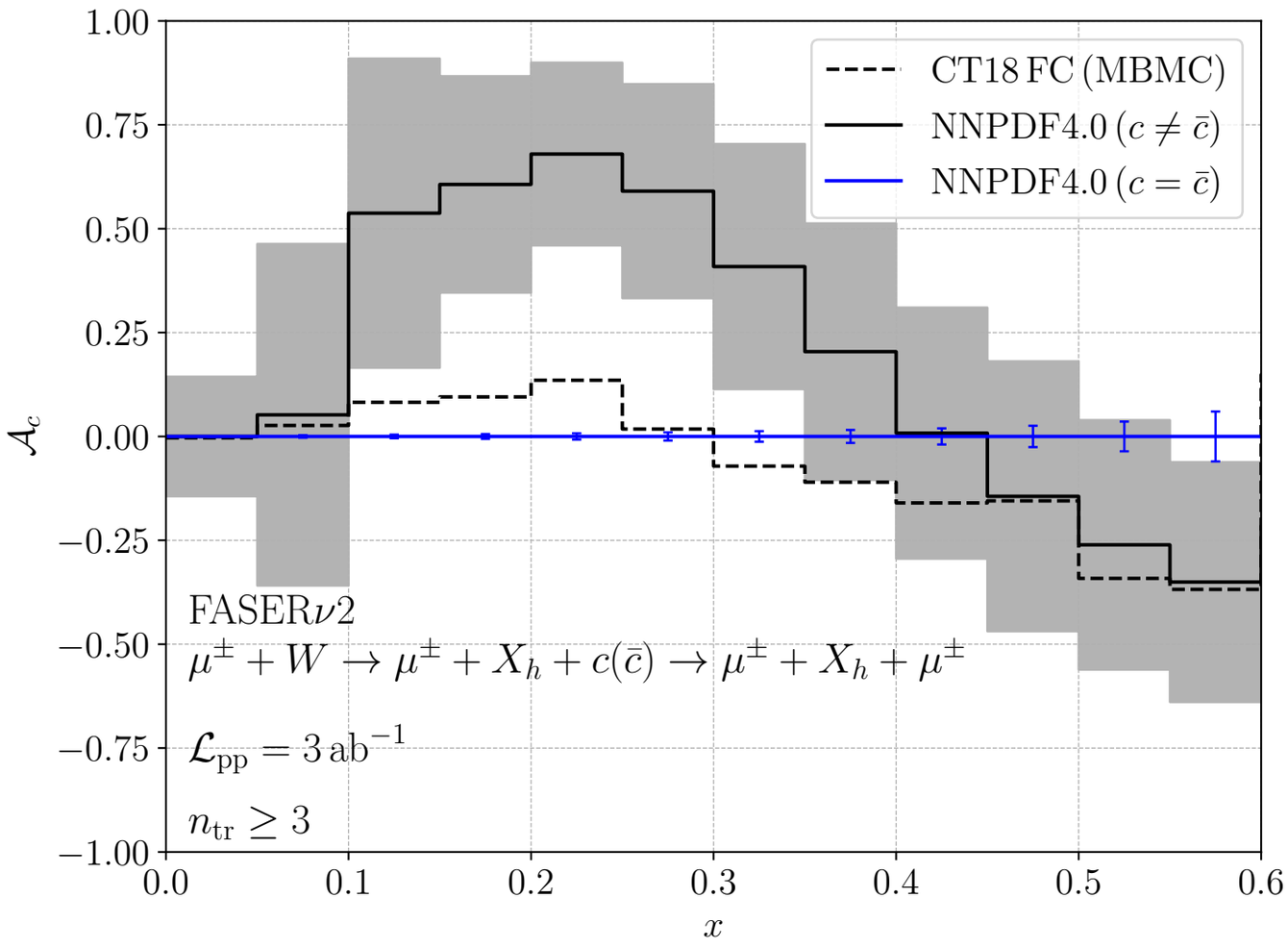
Measuring a **charm PDF asymmetry** is the ultimate smoking gun for intrinsic charm

Charm Asymmetry

- Muon DIS at large-x measured by FASERν2 is only sensitive to the total charm content of the proton.

- FASERν2 alone cannot disentangle charm and anti-charm. However, **FASER2 can identify the charge.**

$$\mathscr{A}_c = \frac{N_{\mathrm{DIS}}(c) - N_{\mathrm{DIS}}(\bar{c})}{N_{\mathrm{DIS}}(c) + N_{\mathrm{DIS}}(\bar{c})}$$



$$\mathrm{BR}(\mathrm{c} \to \ell^+ + \mathrm{X}) = \mathrm{BR}(\bar{\mathrm{c}} \to \ell^- + \mathrm{X}) = 0.096 \pm 0.004$$

Signature: A muon DIS event **tagged in the emulsion detector** correlated to a **di-muon event in the electronic detector**.
The second muon from the decay of the charm-hadron taking place in the FASERν2 volume.

Conclusion

- With $2.5 \cdot 10^7$ events at FASERν2 the event yields at the FPF for muon DIS are significantly higher than for neutrino DIS.

- Muon DIS at the FPF can probe intrinsic charm and resolve the discussion surrounding the EMC measurement.

- Combining information from FASER2 and FASERν2 allows to measure the asymmetry between the charm and anti-charm PDF.