Quark mixing from muon collider neutrinos

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The most important slide

1. The high energy, collimated neutrino flux from muon decays at a MuC will enable highly precise forward target DIS measurements.

2. The setup will allow for exceptionally sensitive measurements of CKM matrix elements, surpassing current standards.

3. Even when including estimates of additional sources of uncertainty (theory, experiment), by exploiting the large event rates and the shape information across the kinematic coverage there are strong prospects for precision CKM measurements.

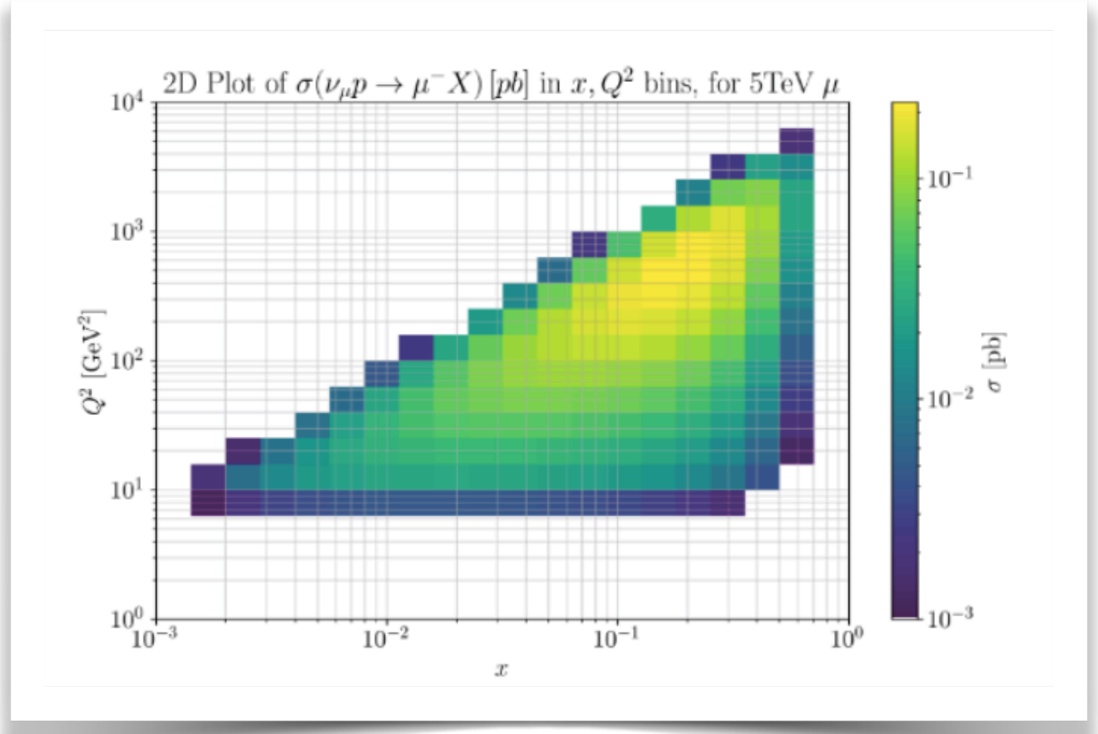
4. This analysis will benefit from parallel MuC studies:

    1. Additional observables and constraints.

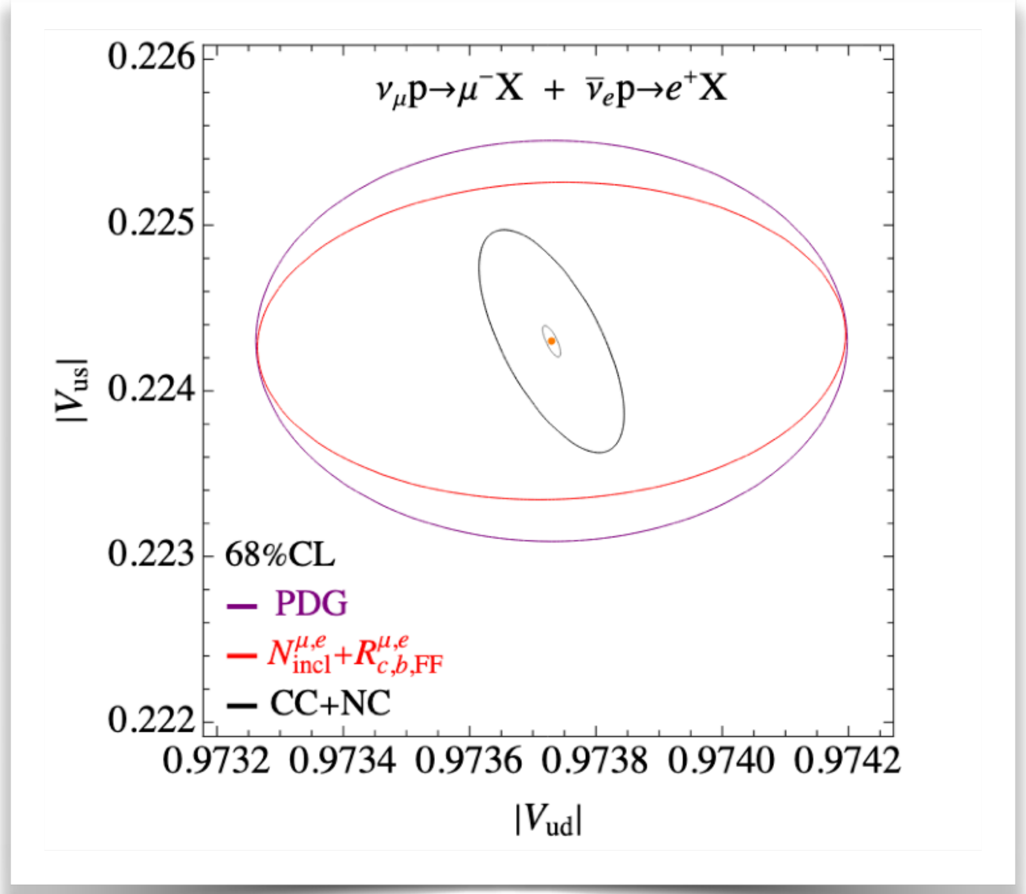
    2. Experiment design.

    3. Estimation of systematics, …

Outline



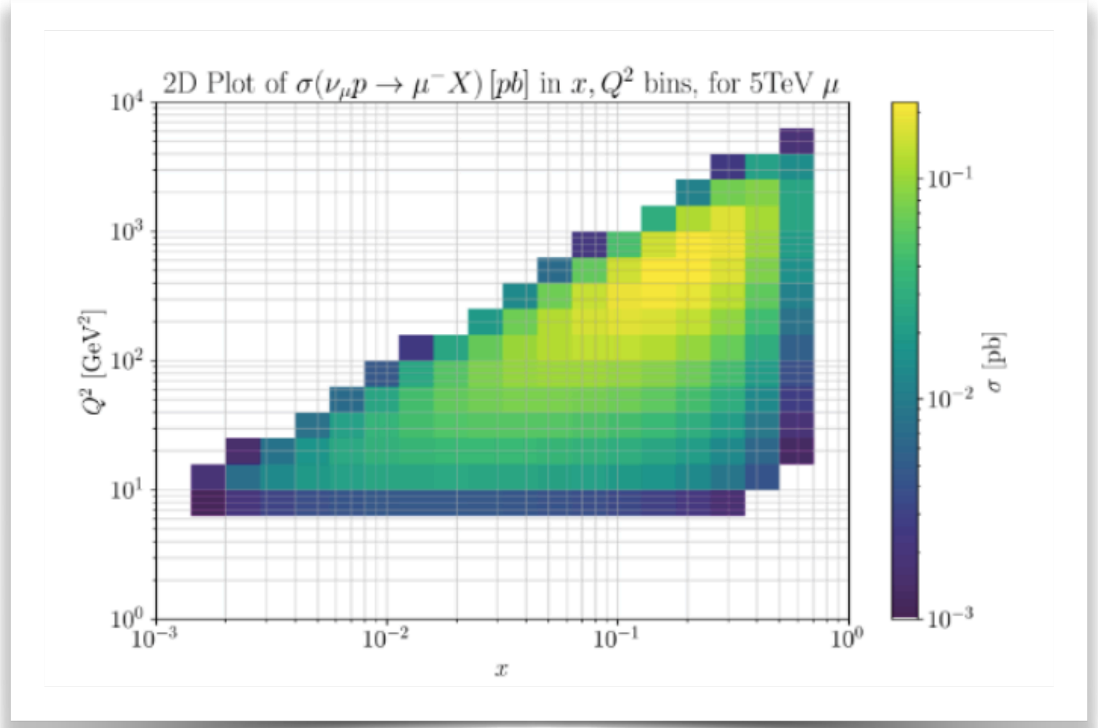
Background



CKM determination

Summary

Outline

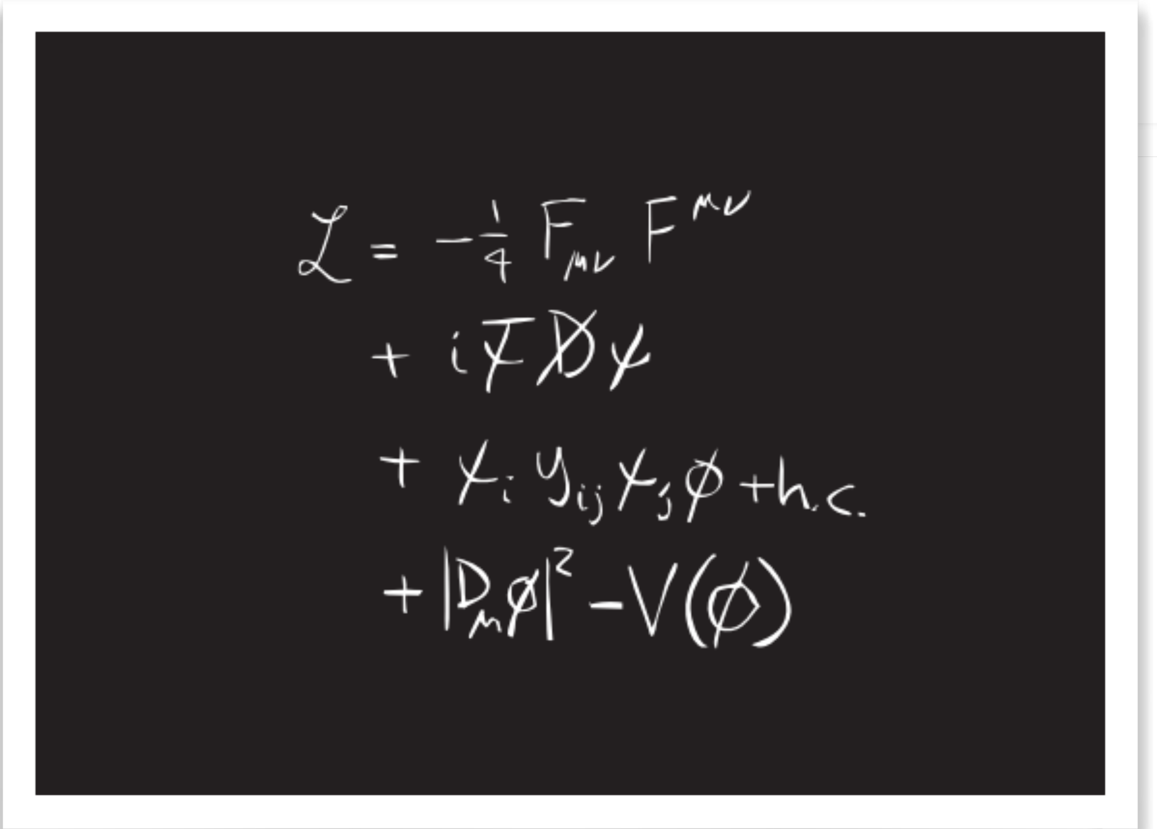


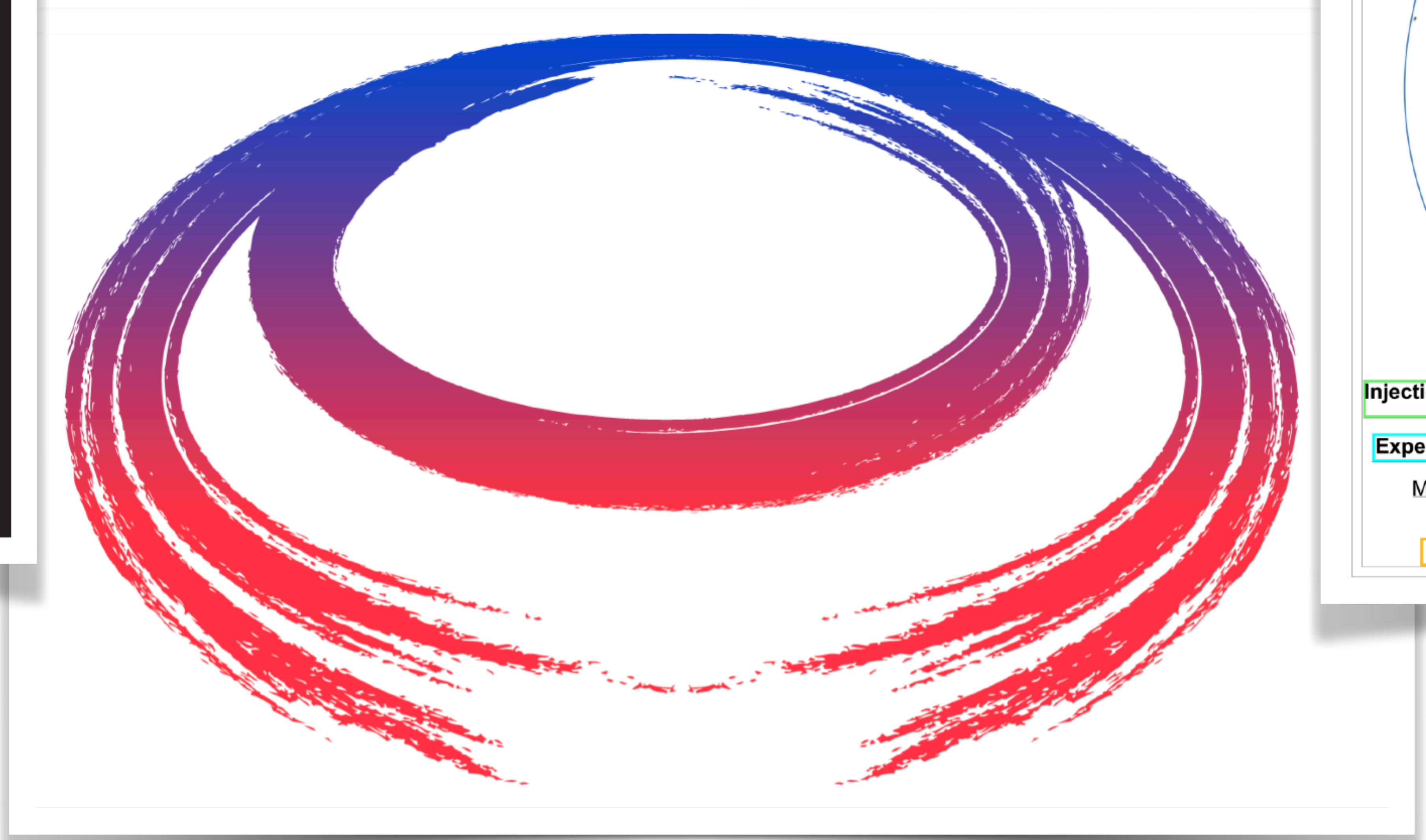
Background

MuC for the Standard Model and beyond

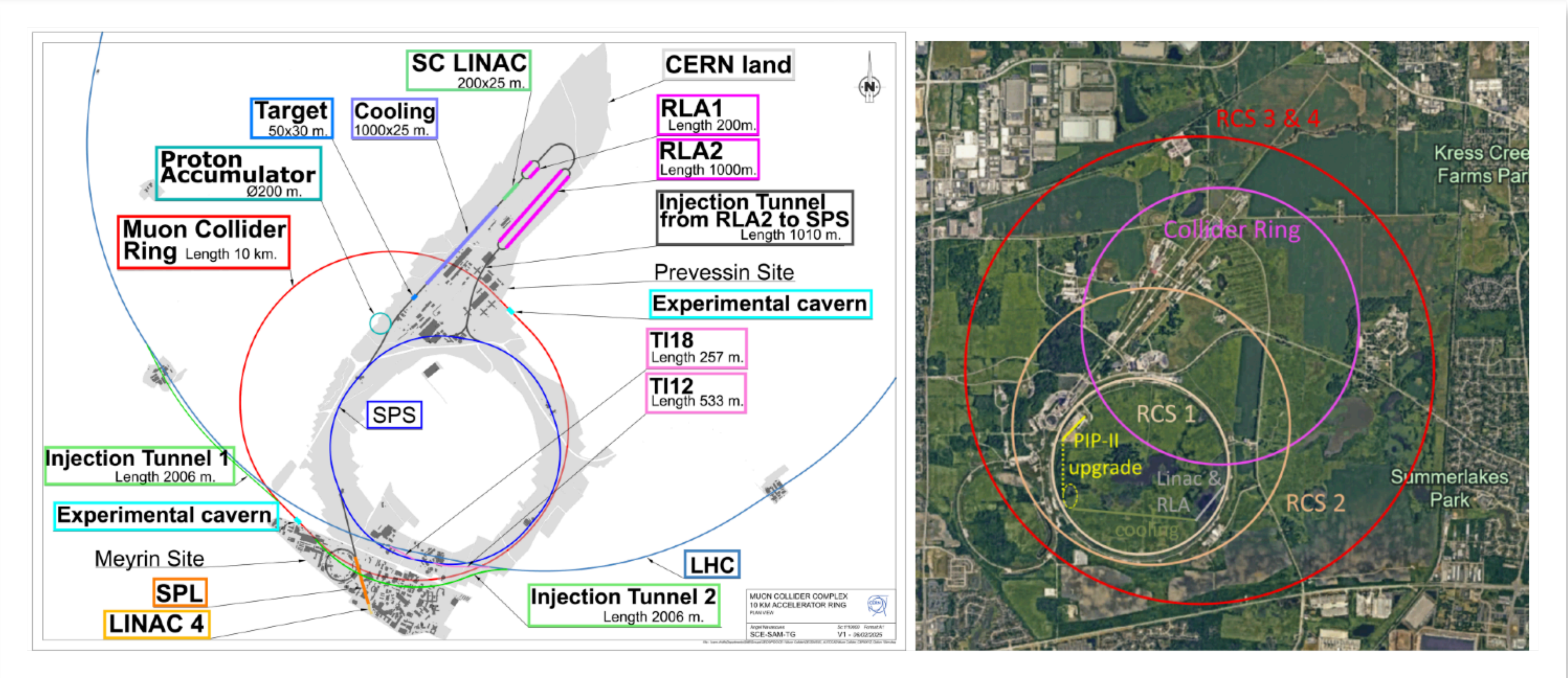
The MuC is a revolutionary proposal to explore the Universe at the most fundamental level.

Theory





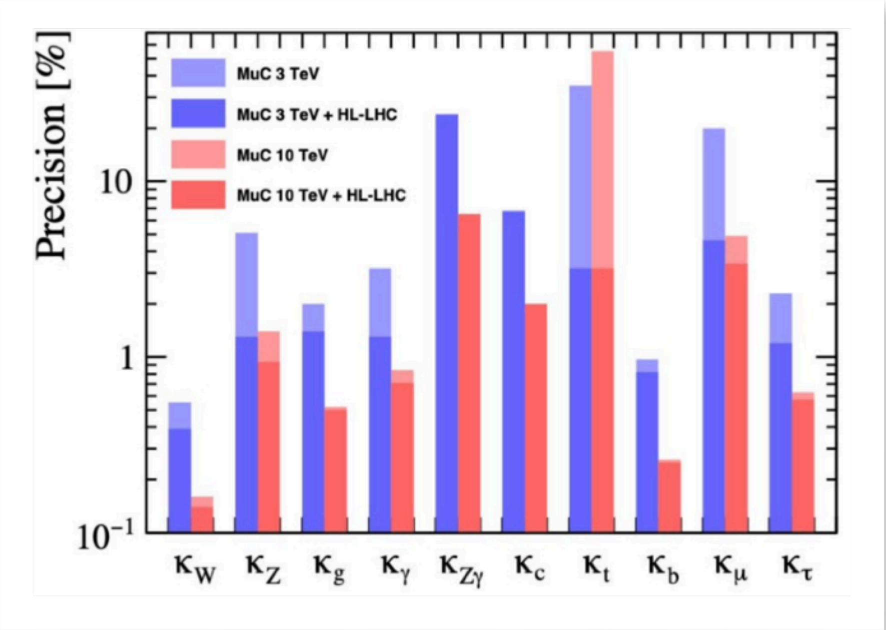
Experiment

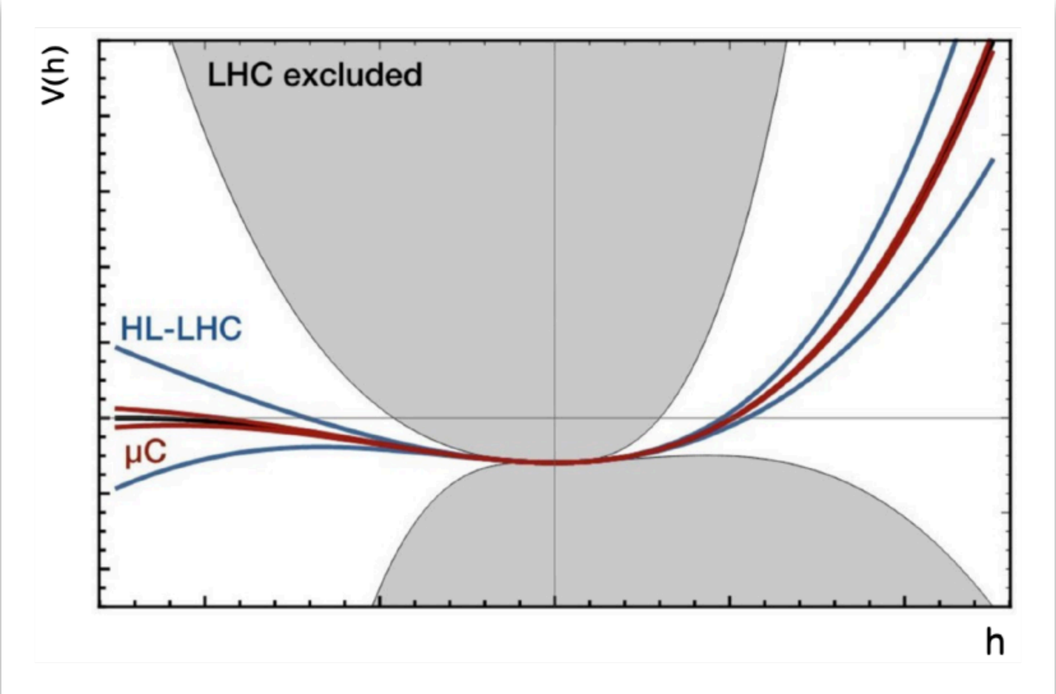


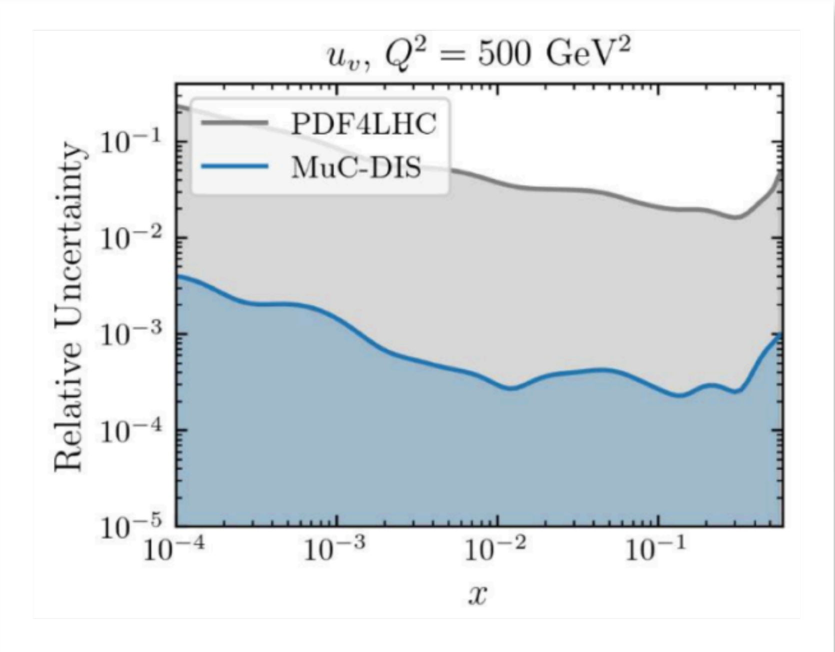
MuC for the Standard Model and beyond

The physics program at a MuC is very broad:

Precision SM measurements at high energies (Higgs physics, EW, …).

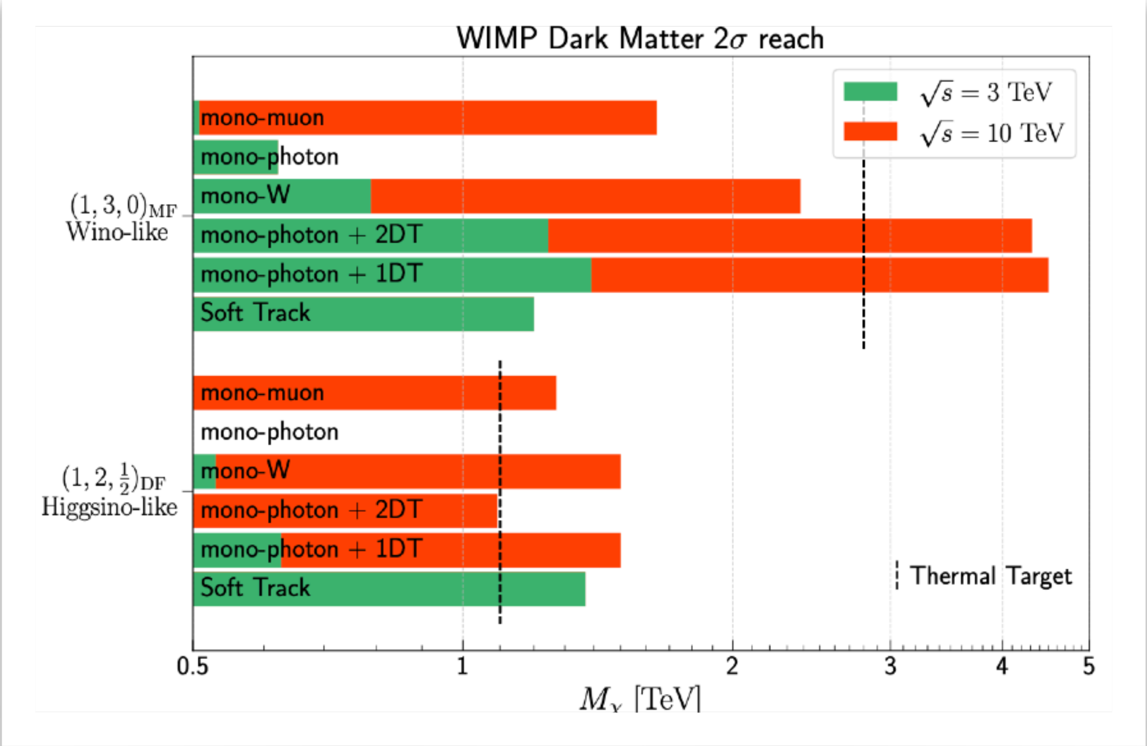


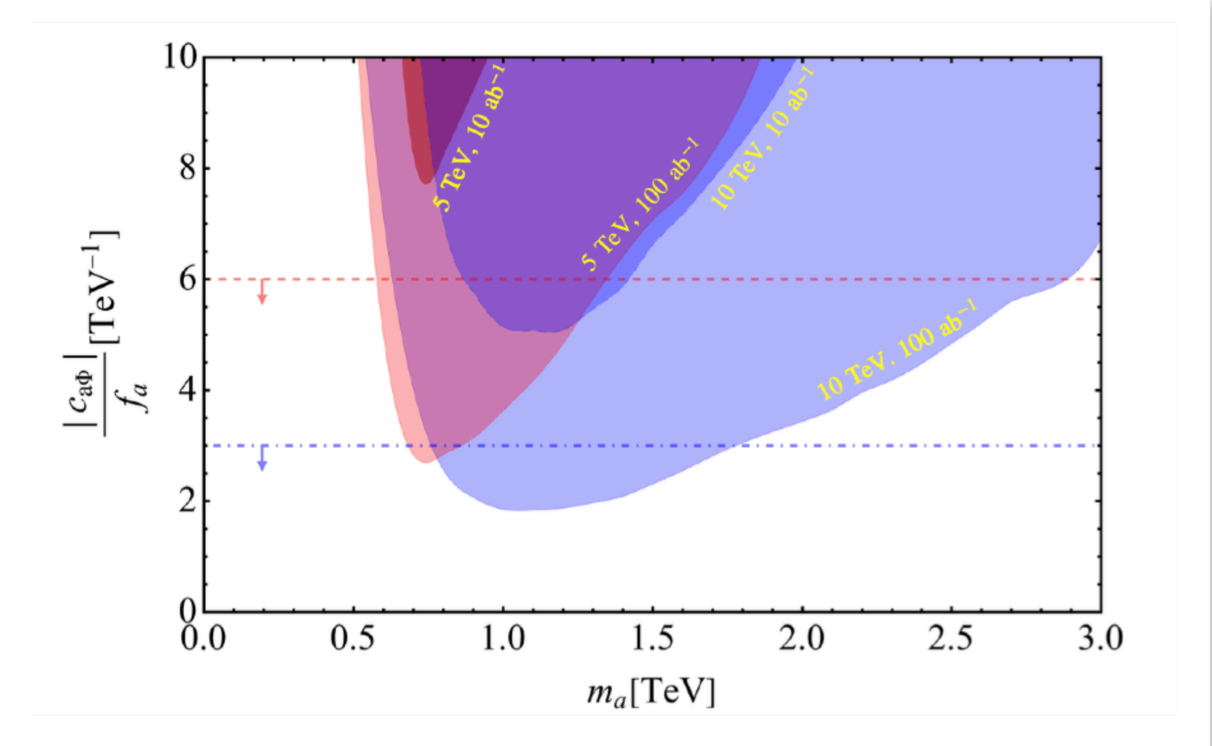




Direct and indirect searches of new physics (EFT, DM, ALPS, …).

Coefficient	MuC-10 [TeV^{-2}]	$\delta(\lvert g_\mu/g_e\rvert^2)$	$\delta(\lvert g_\tau/g_\mu\rvert^2)$	$\delta(\lvert g_\tau/g_e\rvert^2)$
$[C_{ll}]_{1221}$	$[-(136)^{-2},\ (139)^{-2}]$	0	3.3×10^{-6}	3.3×10^{-6}
$[C_{ll}]_{2332}$	$[-(96)^{-2},\ (100)^{-2}]$	6.6×10^{-6}	0	6.6×10^{-6}
$[C_{le}]_{1221}$	$[-(74)^{-2},\ (74)^{-2}]$	0	3.1×10^{-11}	3.1×10^{-11}
$[C_{le}]_{2332}$	$[-(62)^{-2},\ (62)^{-2}]$	6.2×10^{-11}	0	7.0×10^{-11}
$[C^{(3)}_{Hl}]_{22}$	$[-(183)^{-2},\ (183)^{-2}]$	3.6×10^{-6}	6.2×10^{-6}	1.1×10^{-6}





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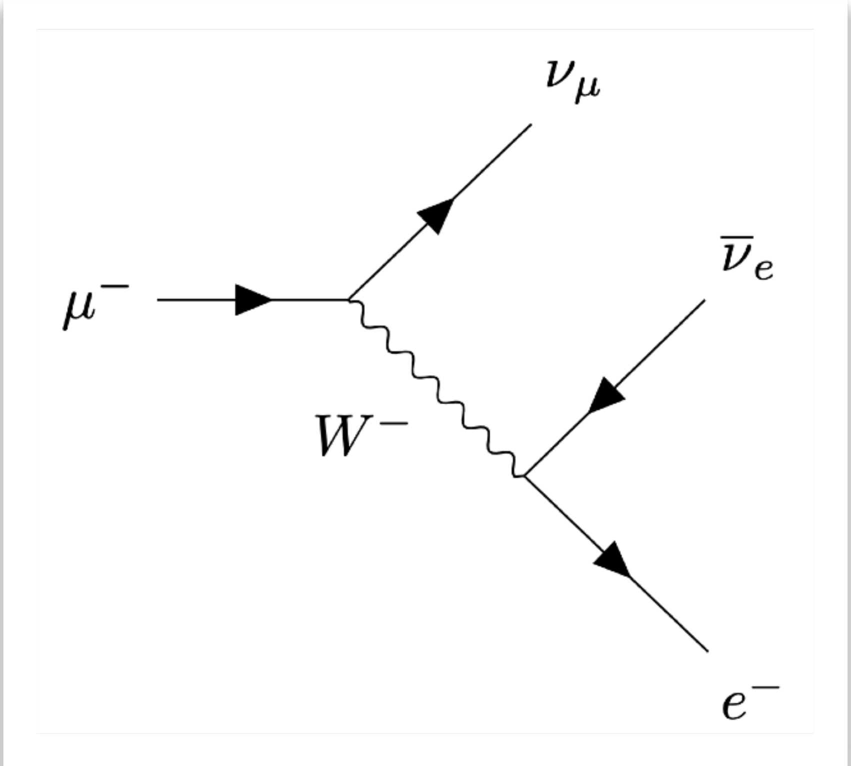
MuC neutrinos

The muon beam offers excellent precision and discovery potential, but there is more …

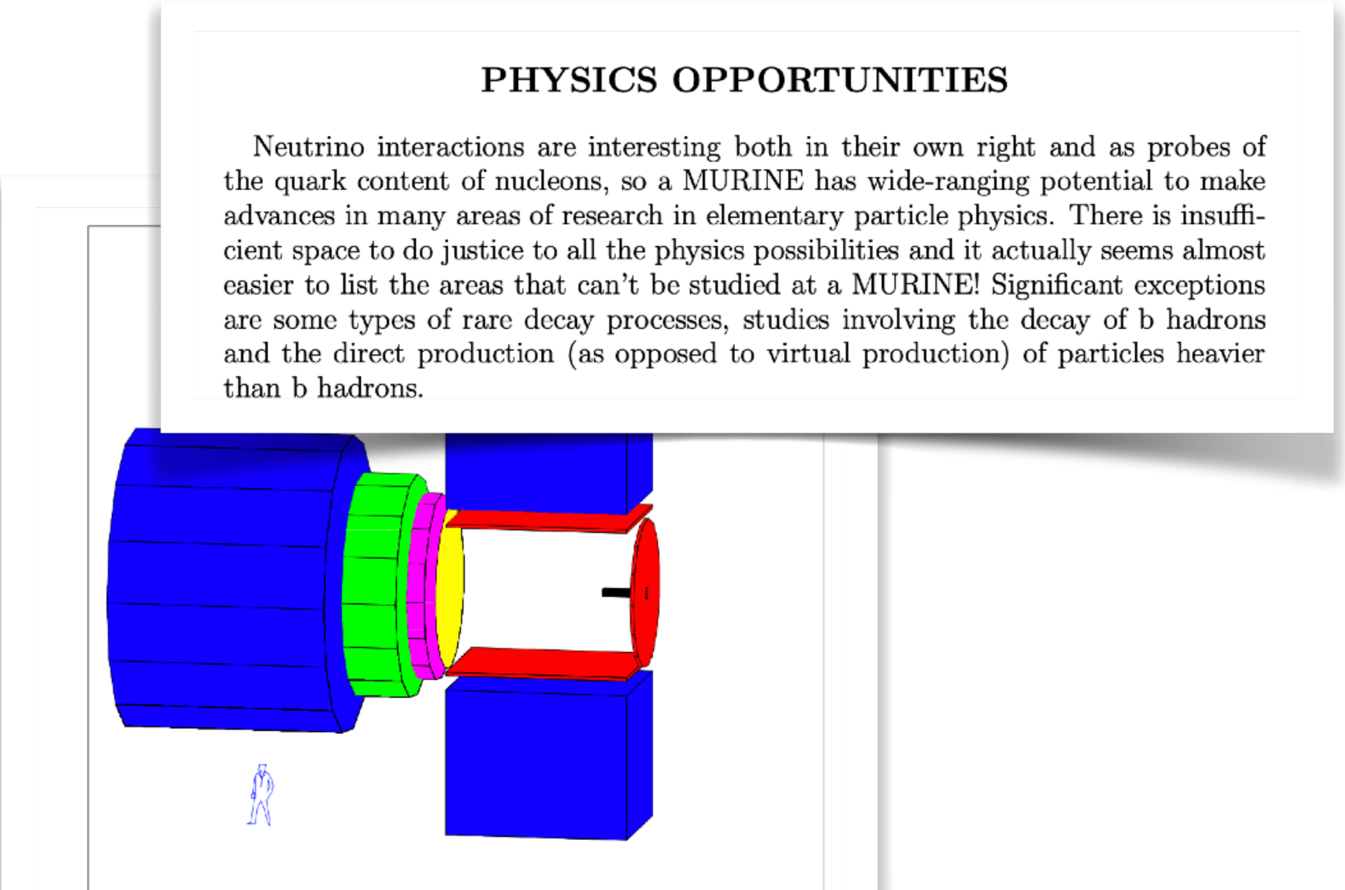


$$\mu^- \to \nu_\mu + e^- + \overline{\nu}_e$$

Via muon decay, we have access to *collimated, high energy, neutrino beams*.

The neutrino beam can interact with a forward target via *deep inelastic scattering* (DIS) and enable high precision measurements.

The potential of the physics opportunities using a neutrino beam from a MuC has been characterised in the past [e.g. 9907.033].



9907.033

In what follows, we will explore the potential of MuC neutrinos in the context of quark mixing via the *Cabibbo-Kobayashi-Maskawa* (CKM) matrix.

The CKM matrix

It can be regarded as a rotation between quark mass and weak eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

The elements of the matrix are *fundamental* SM parameters.

(We will devote our attention to the first 2 rows of the CKM matrix).

The CKM matrix

Why measure it?

- It mediates flavour changing transitions in quarks.
- Direct source of CP violation in the SM.
- Further constrain the Cabibbo angle anomaly: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \neq 1$
- Constrain new physics from rare meson decays: $|V_{cb}|$
- Shed light on the inclusive/exclusive tension in b to c transitions.
- …

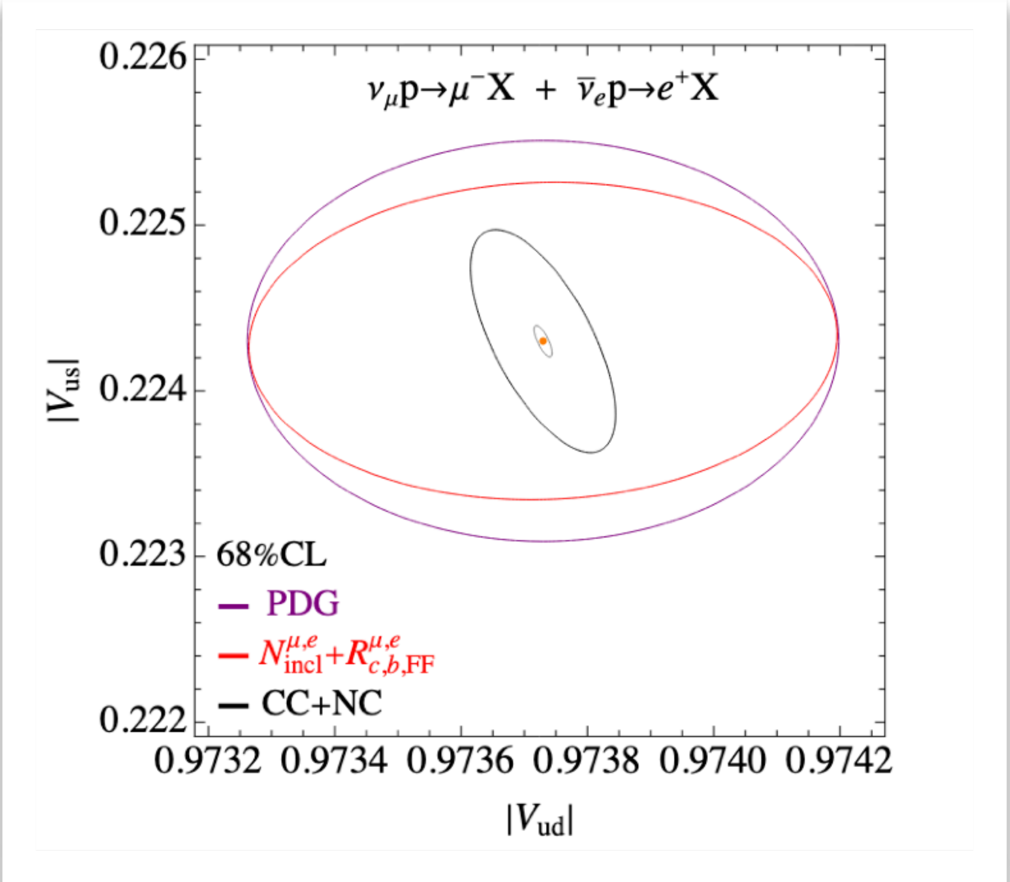
The CKM matrix

The current precision boundary:

δ_{CKM}	PDG
$\|V_{cs}\|$	0.62%
$\|V_{cd}\|$	1.8%
$\|V_{cb}\|$	3.4%
$\|V_{ub}\|$	5.2%
$\|V_{ud}\|$	3.2×10^{-4}
$\|V_{us}\|$	0.36%
s_W^2	1.7×10^{-4}

(We also include the weak mixing angle as our setting will also be able to constrain it)

Outline

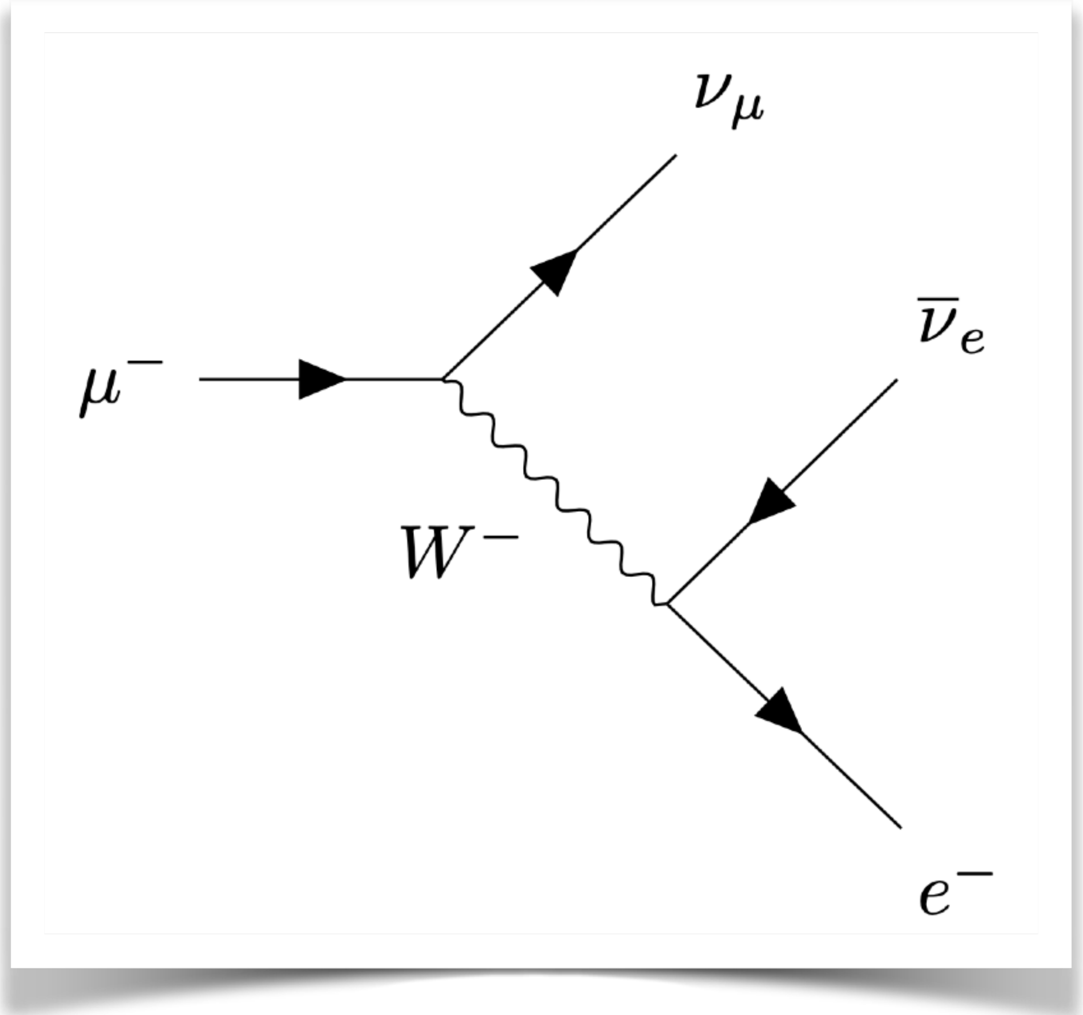


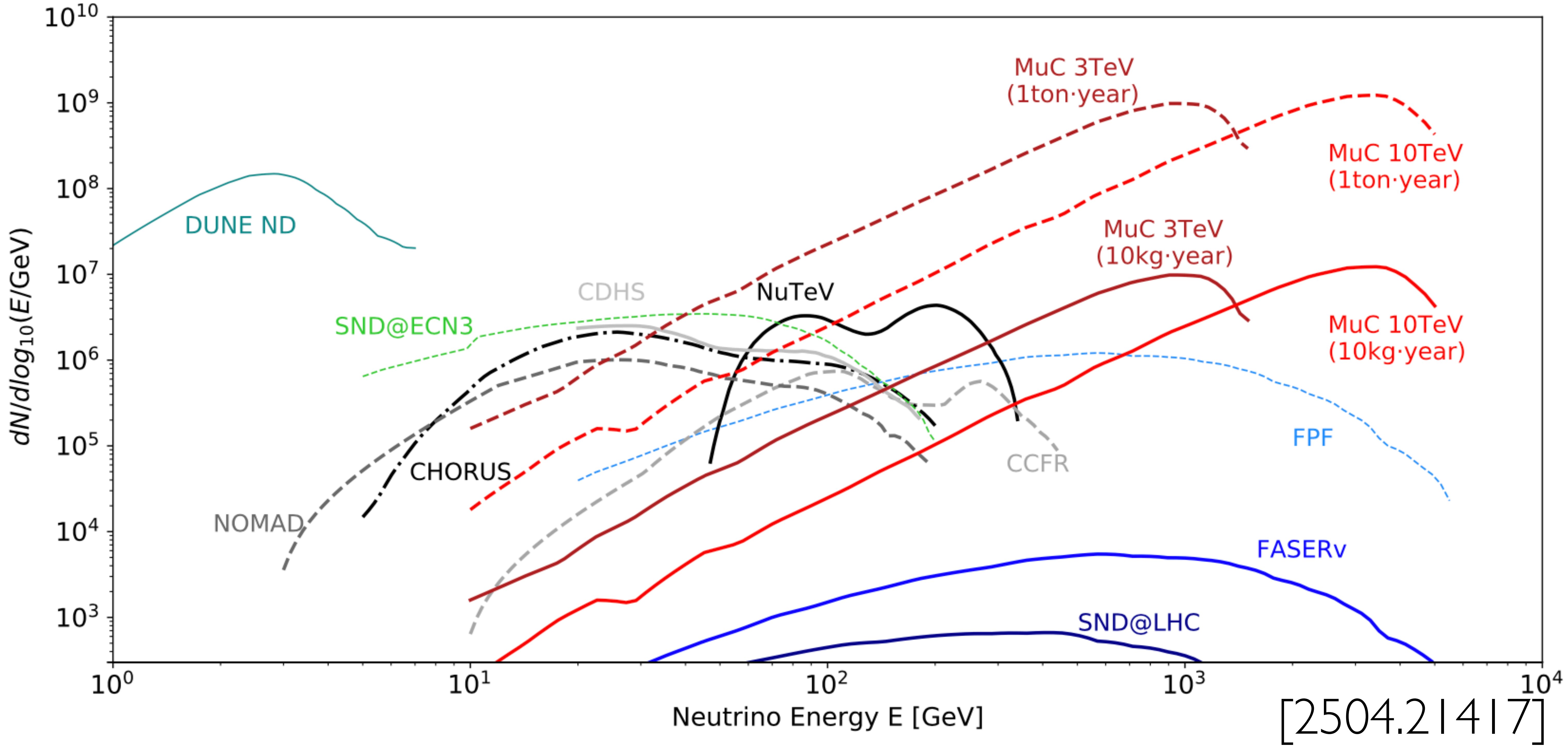
CKM determination

MuC neutrino flux

Muons decaying in the straight section near the MuC interaction point produce an extremely collimated high energy neutrino beam

$$\mu^- \to \nu_\mu + e^- + \overline{\nu}_e$$

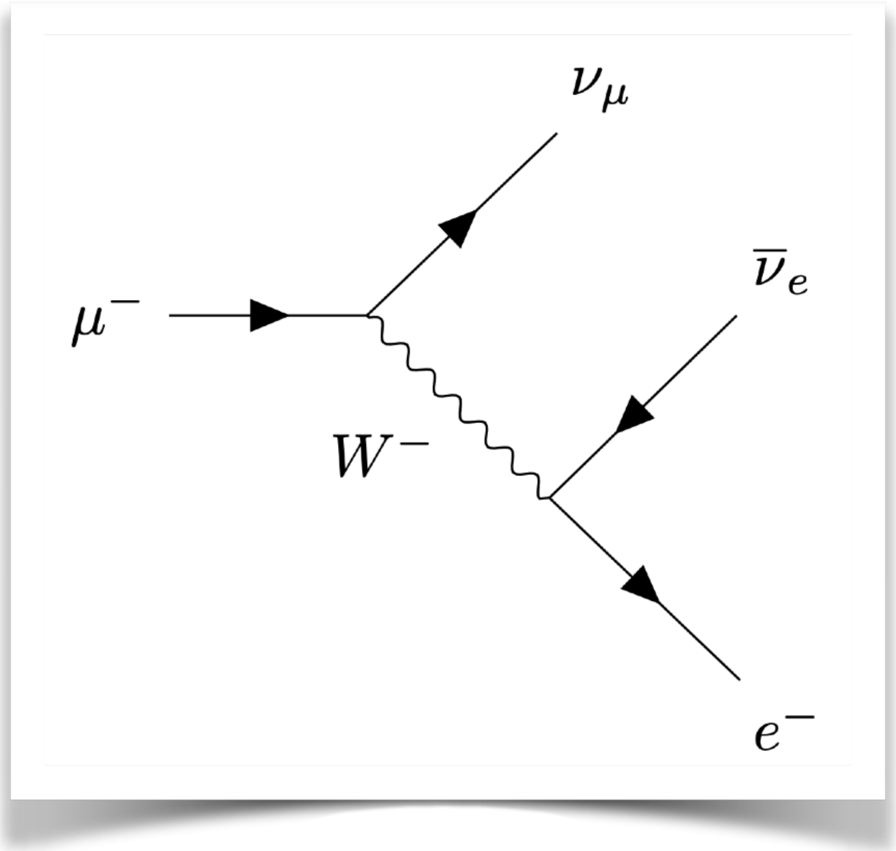




[2504.21417]

MuC neutrino flux

The number of neutrinos can estimated from the MuC target parameters [2504.21417].
We consider a 10 TeV MuC.



Muons per bunch: $N \approx 10^{12}$

Injected every: $1/f_r \approx 0.2\ \mathrm{sec}$

The # of neutrinos that decay in the straight section:

per second: $9 \cdot 10^9$

per year: $9 \cdot 10^{16}$

Angular spread $\sim 0.1\ \mathrm{mrad}$

MuC neutrino flux

Each neutrino crossing the target has a probability of interaction of

$$p_{\rm int} \simeq 6 \times 10^{-12} \frac{\rho \cdot L}{\rm g\ cm^{-2}} \frac{E_\nu}{\rm TeV}$$

It increases with the mass of the fixed target and the energy of the neutrino.

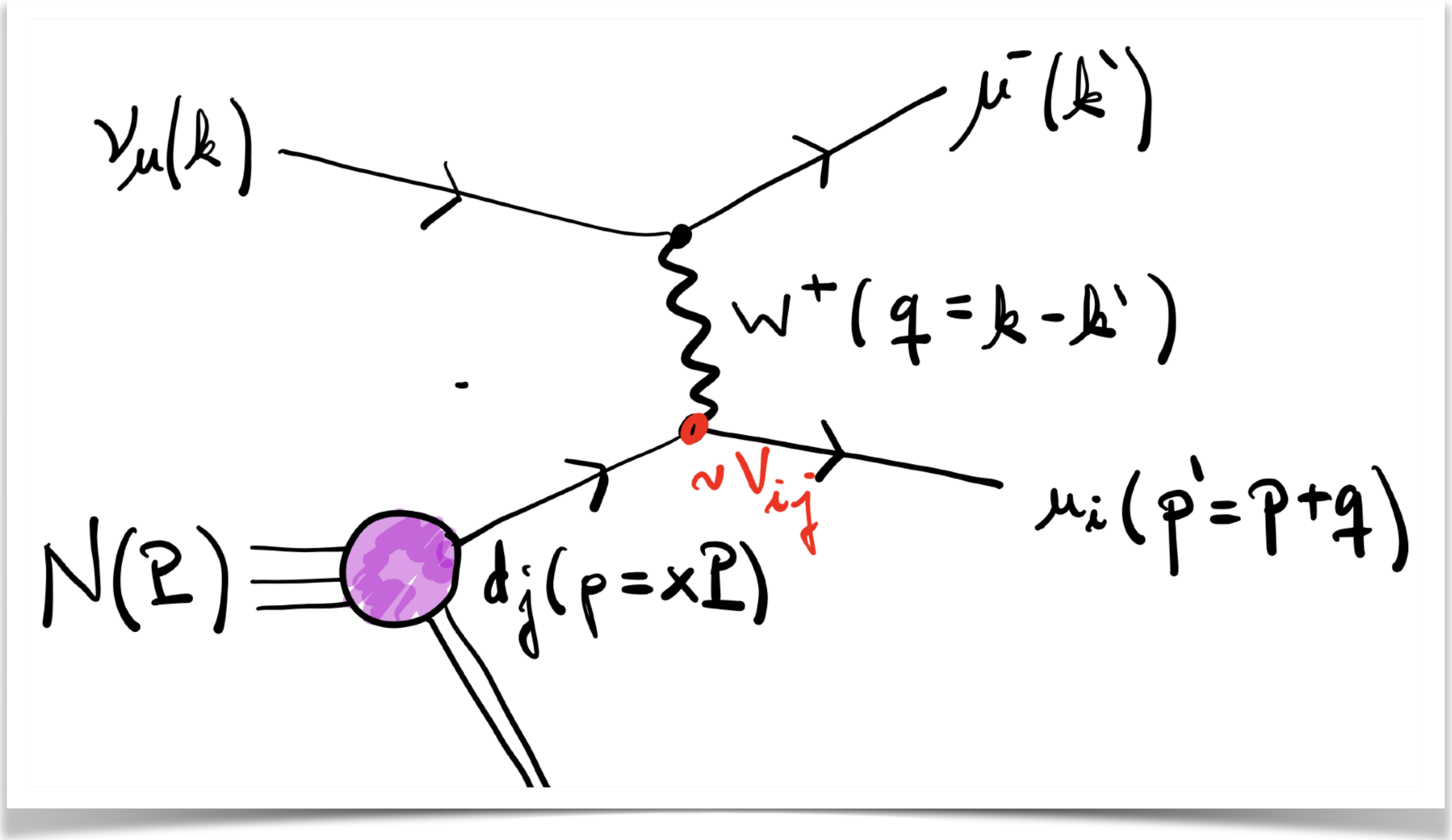
At present, no neutrino detector design exists for this forward target experiment (glad to discuss!)

In what follows, we consider a target of 1 ton (similar to current experiments, e.g. FASERnu at the LHC).

Now, some kinematics…

Neutrino DIS

Consider the charged current (CC) diagram:



With the kinematics:

$$q = k - k'$$

$$Q^2 = -q^2 \qquad \text{(Momentum transfer)}$$

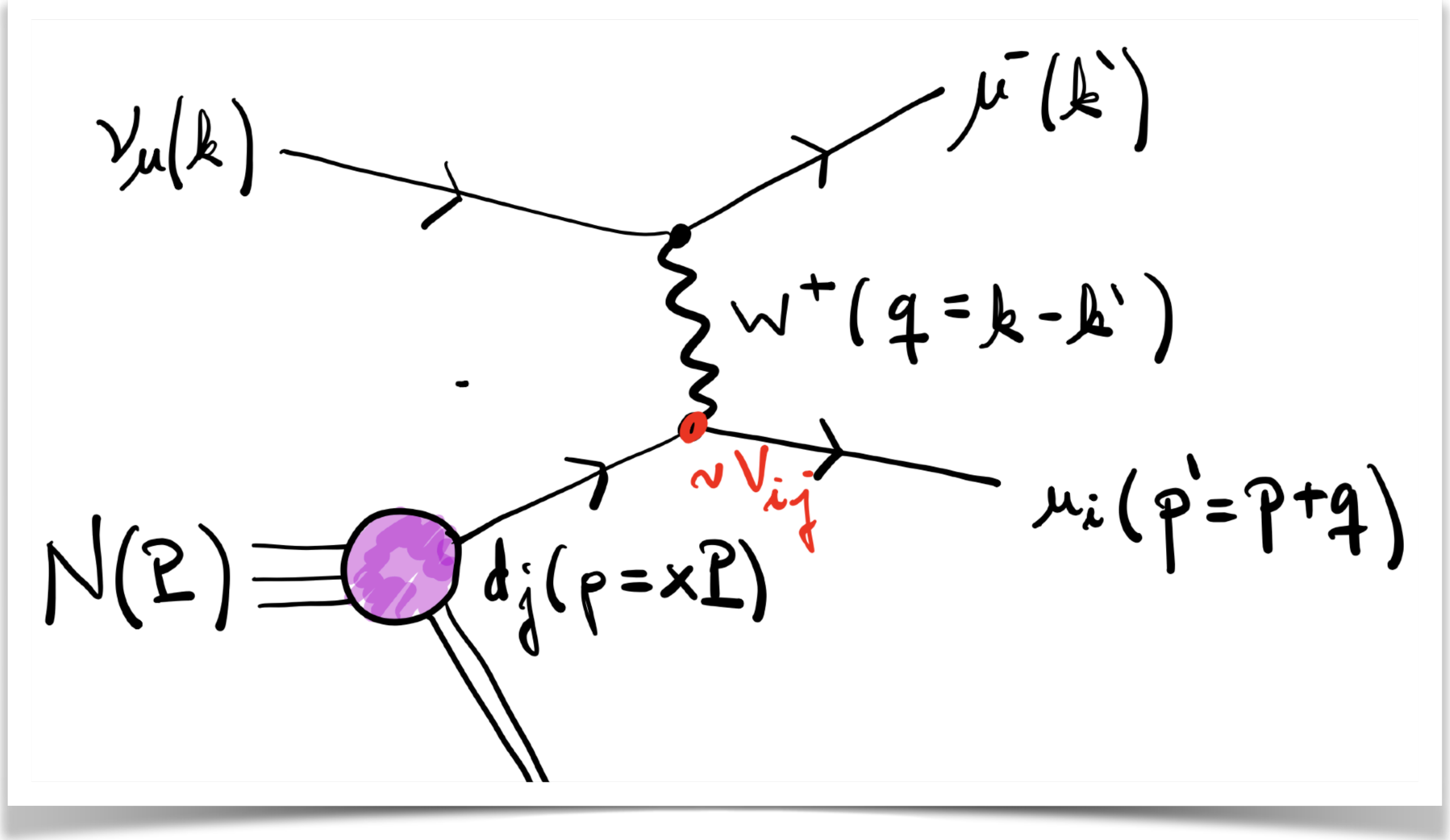
$$x = \frac{Q^2}{2P \cdot q} \qquad \text{(Parton momentum fractions)}$$

DIS double differential cross section:

$$\frac{d\sigma}{dx dQ^2} \Leftrightarrow \frac{d\sigma}{dx dy} \qquad (Q^2 = 2ME_\nu xy)$$

Neutrino DIS

We have both (muon and antielectron) neutrino contributions…



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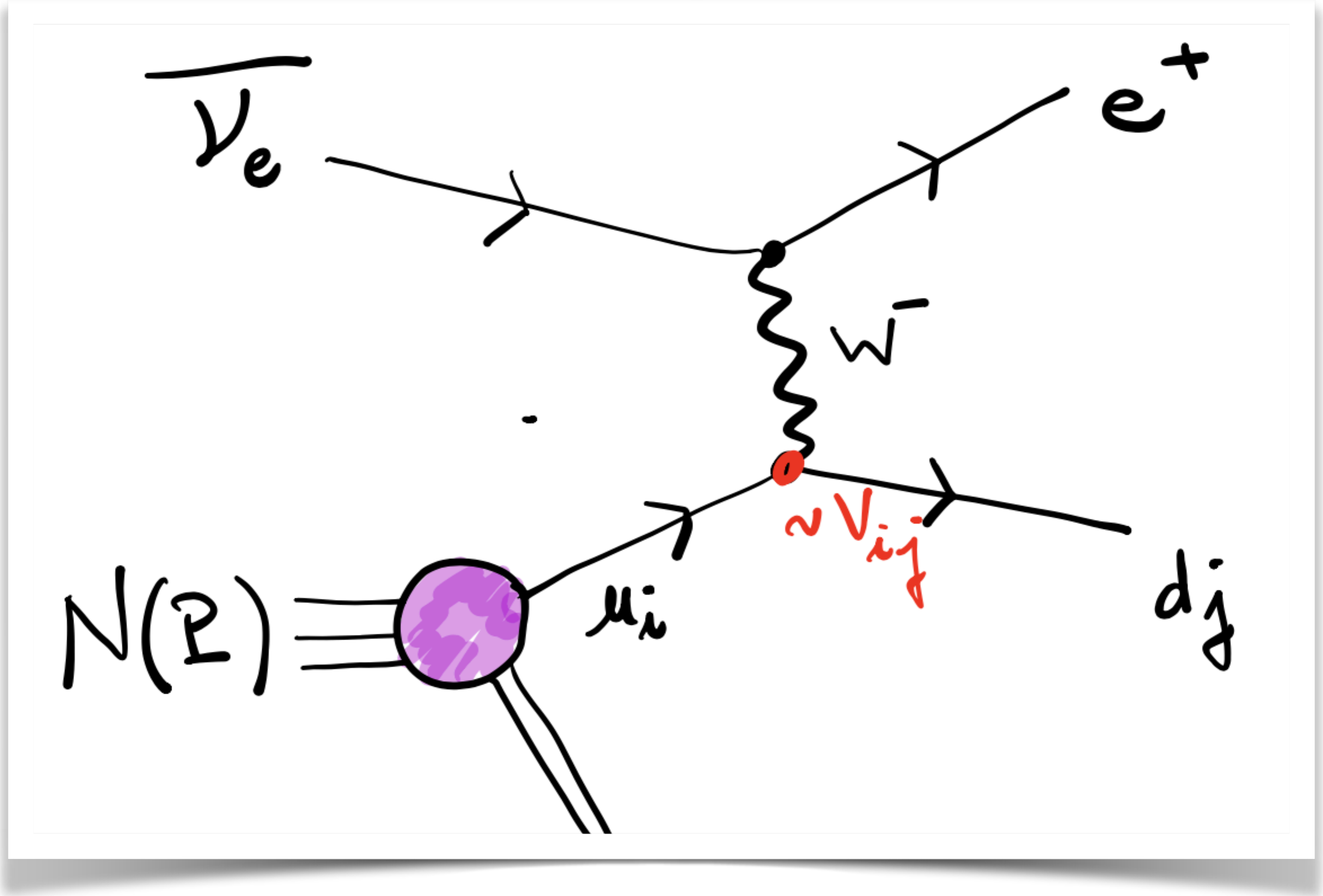
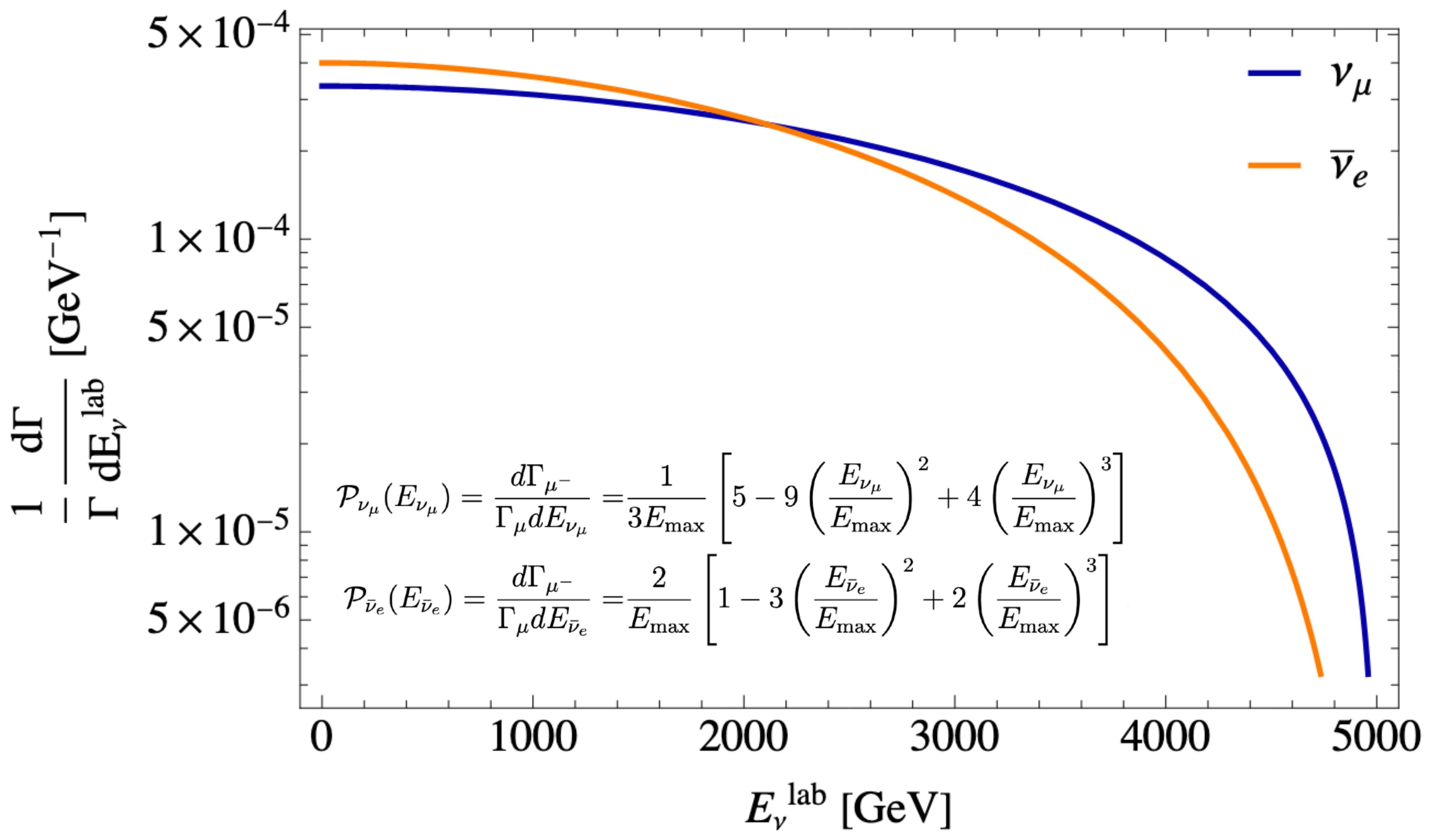


… and *also* the *neutral current* contributions!

Neutrino DIS

An additional consideration: the neutrino beam is *not* monochromatic, we need to account for the energy distribution of the neutrinos.



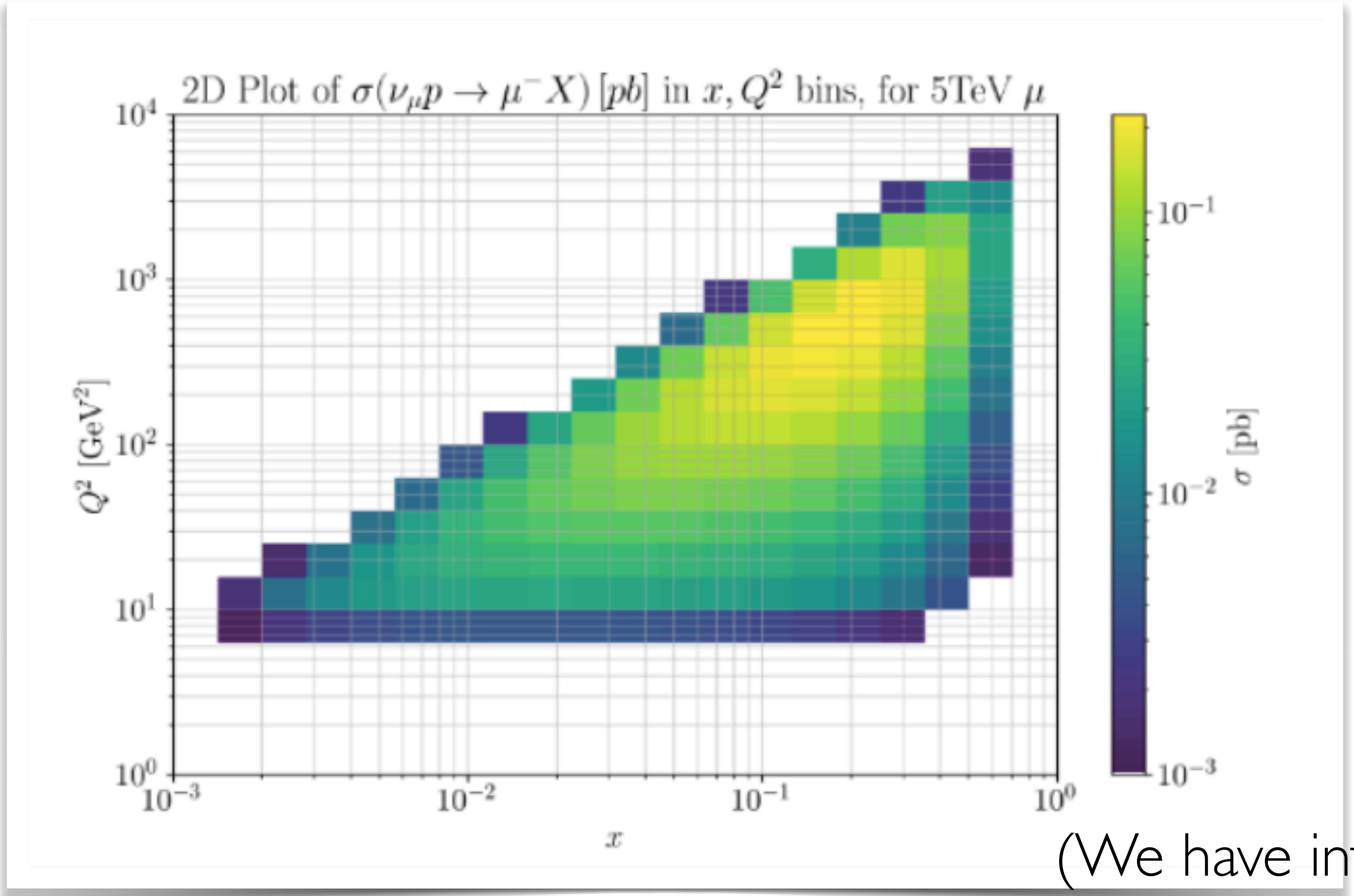
The cross section acquires an extra kinematic dependence due to the variable neutrino energy:

$$\frac{d\sigma}{dxdy} \to \frac{d\Sigma}{dEdxdy}$$

Neutrino DIS

A representative distribution would look like:

$$\frac{d\sigma}{dx dQ^2} \Leftrightarrow \frac{d\sigma}{dx dy}$$



So far, we have been modelling the neutrino beam, but we are still missing a key ingredient: the target.

We can describe it in terms of *parton distribution functions* (PDFs).

(We have integrated over the neutrino spectrum!)

Parton distribution functions

- PDFs describe the structure of protons (nuclei) in terms of elementary constituents.

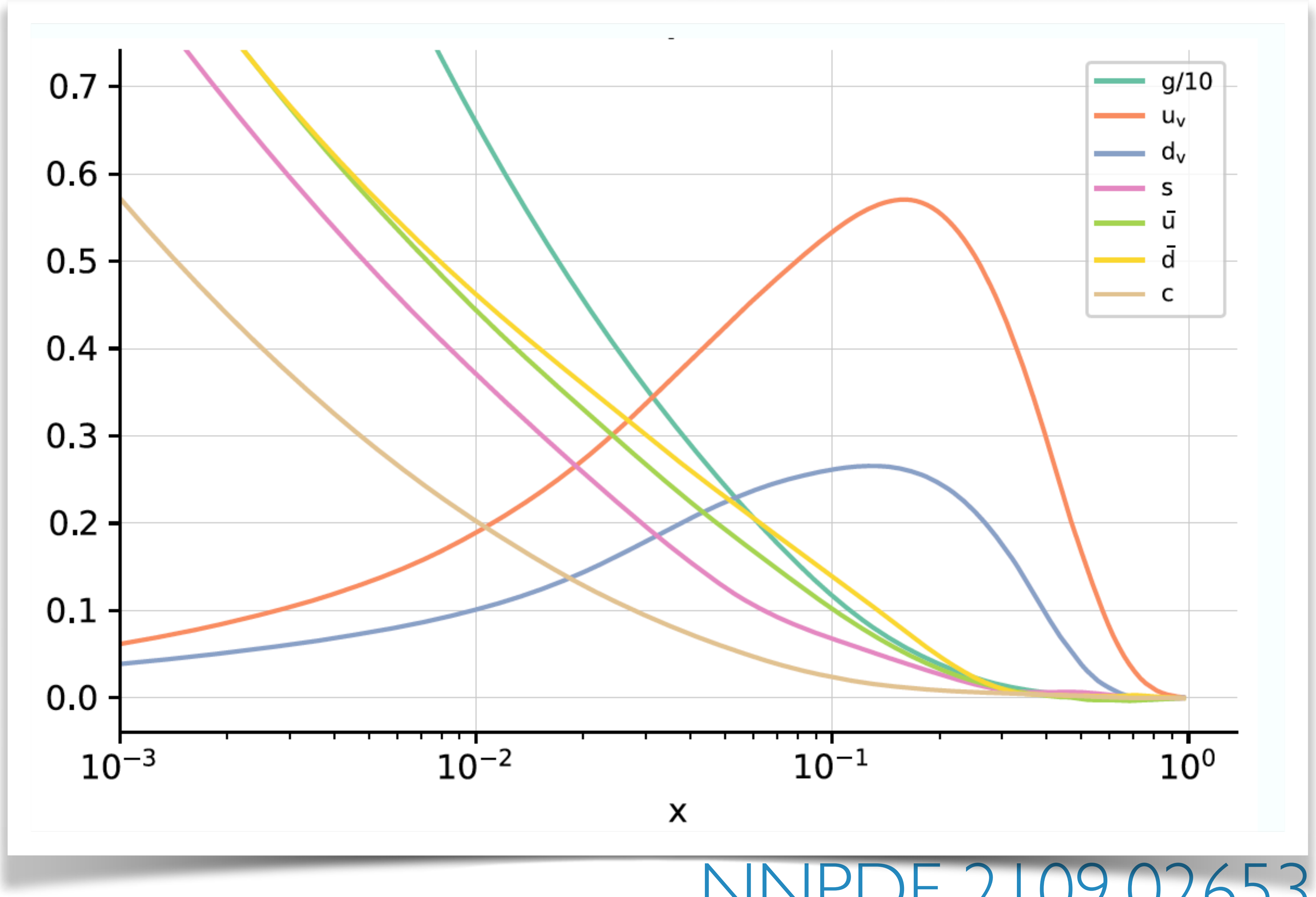
- Some intuition. Consider the proton PDF of the up quarks:

$$f_u(x) = u(x)$$

$u(x)$ → PDF: the 'probability' of finding an up-quark in the proton carrying a fraction x of the momentum of the proton.

$u(x)dx$ → # of up quarks carrying a momentum fraction between x and x +dx

NNPDF4.0 NNLO Q= 100.0 GeV



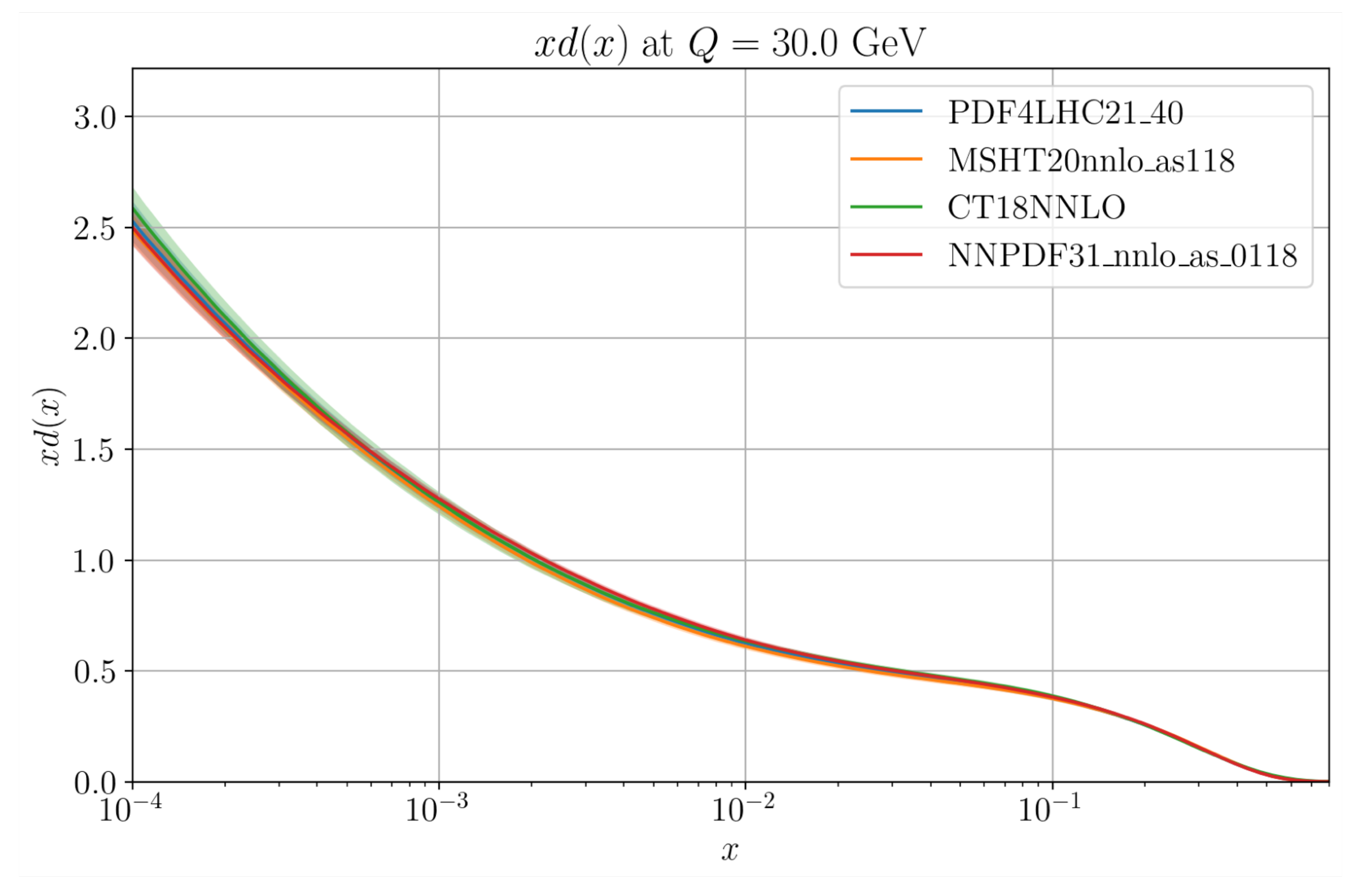
NNPDF, 2109.02653

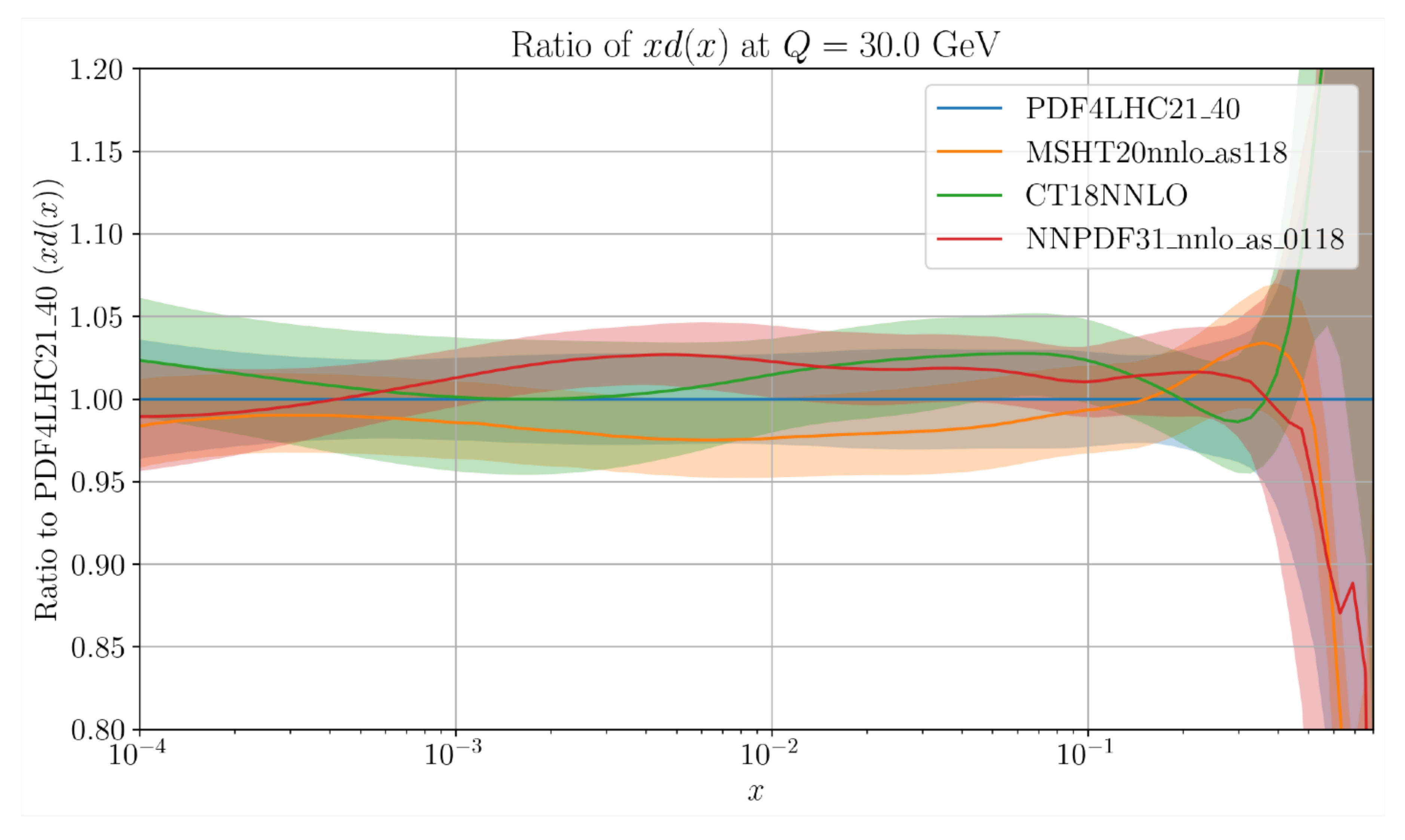
- PDFs are *dynamical* quantities $f_i(x) \to f_i(x, Q^2)$ … and are very important in our setup.

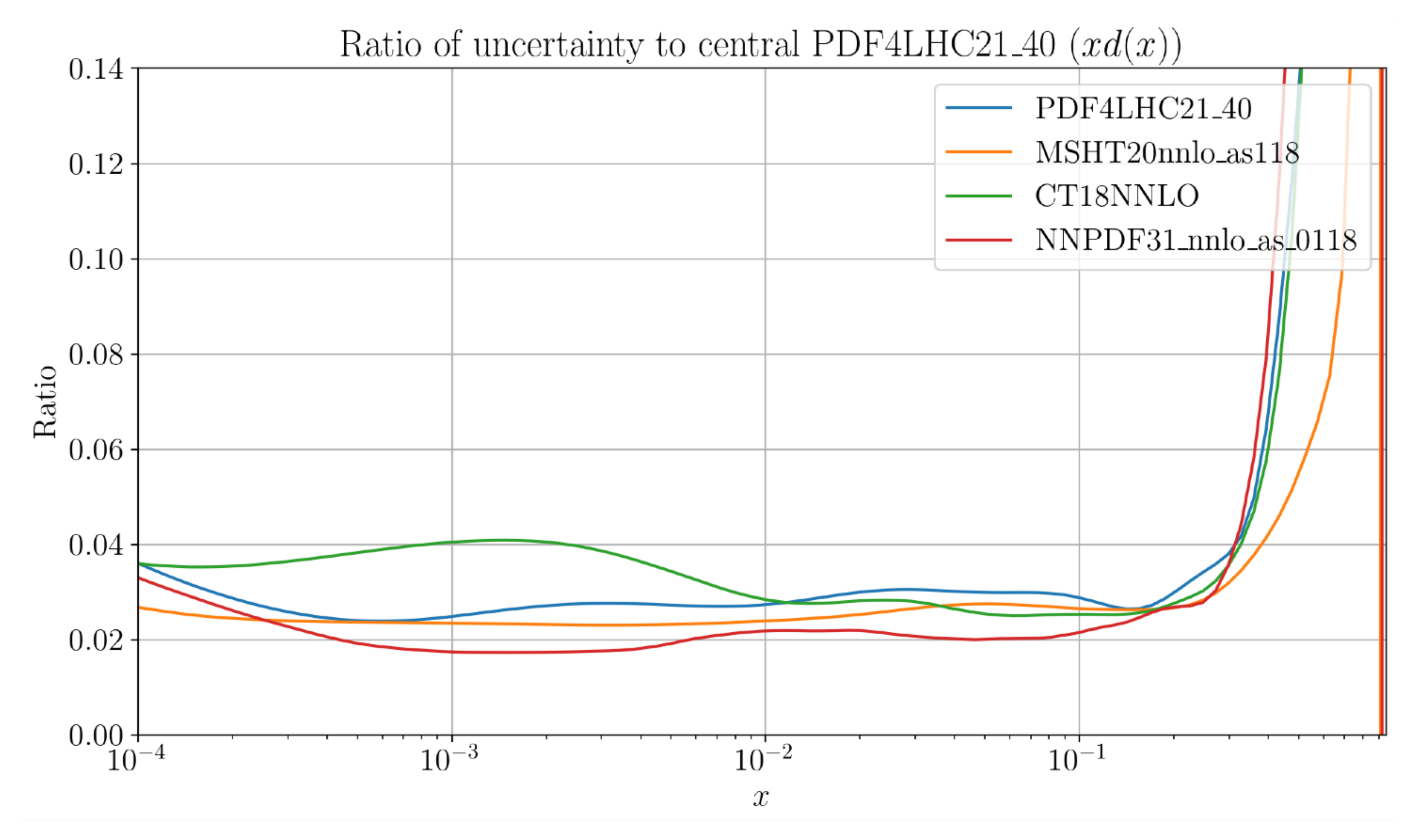
Parton distribution functions

PDFs cannot be calculated from first principles and have to be extracted from fits to data.

For our analysis we adopt PDF4LHC21, a combined PDF fit of individual collaborations.





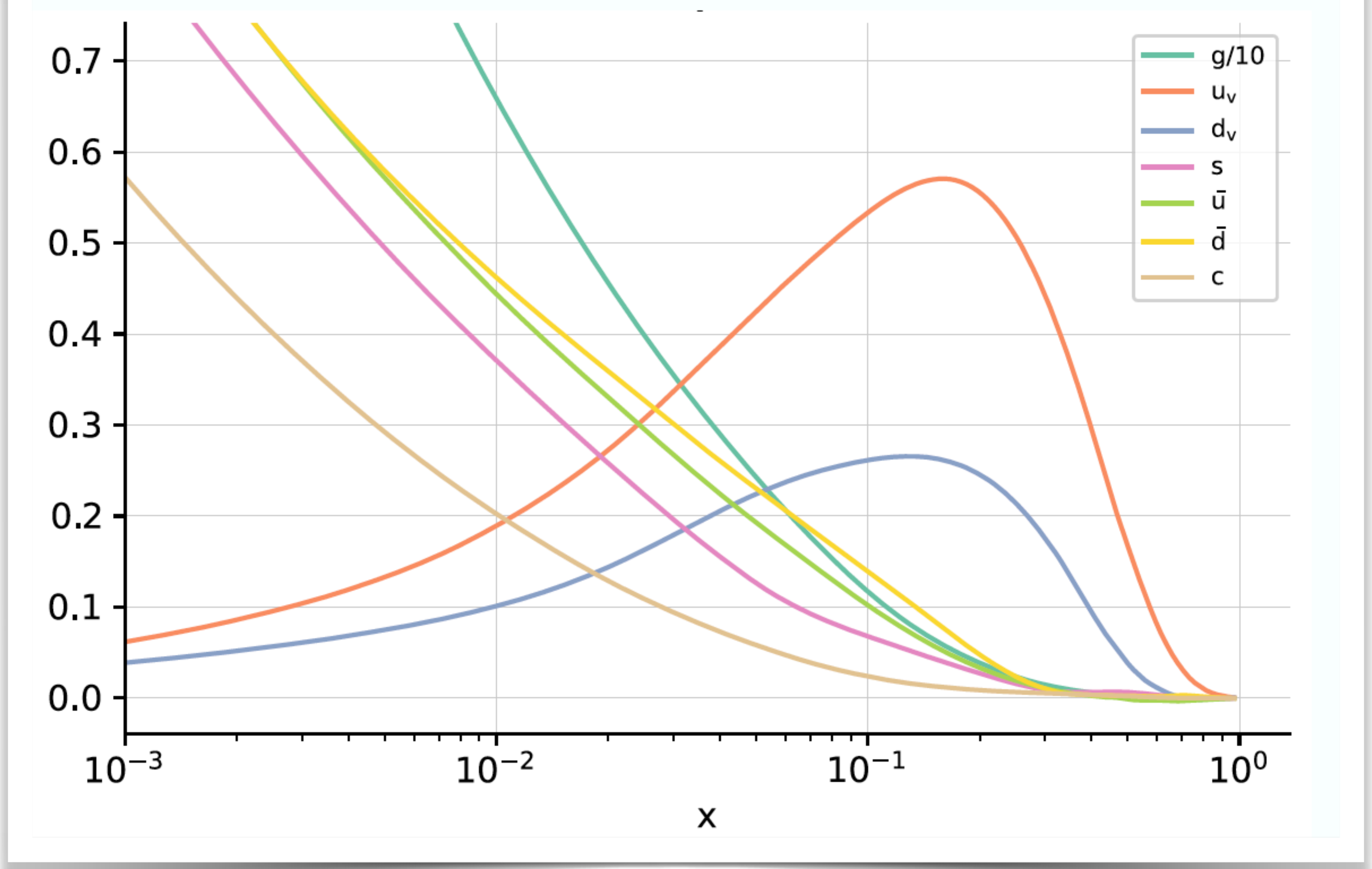


Parton distribution functions

Finally, we can model proton targets and isoscalar targets.

The latter case is just built from linear combinations of the proton PDF.

Proton PDFs, Q = 100 GeV



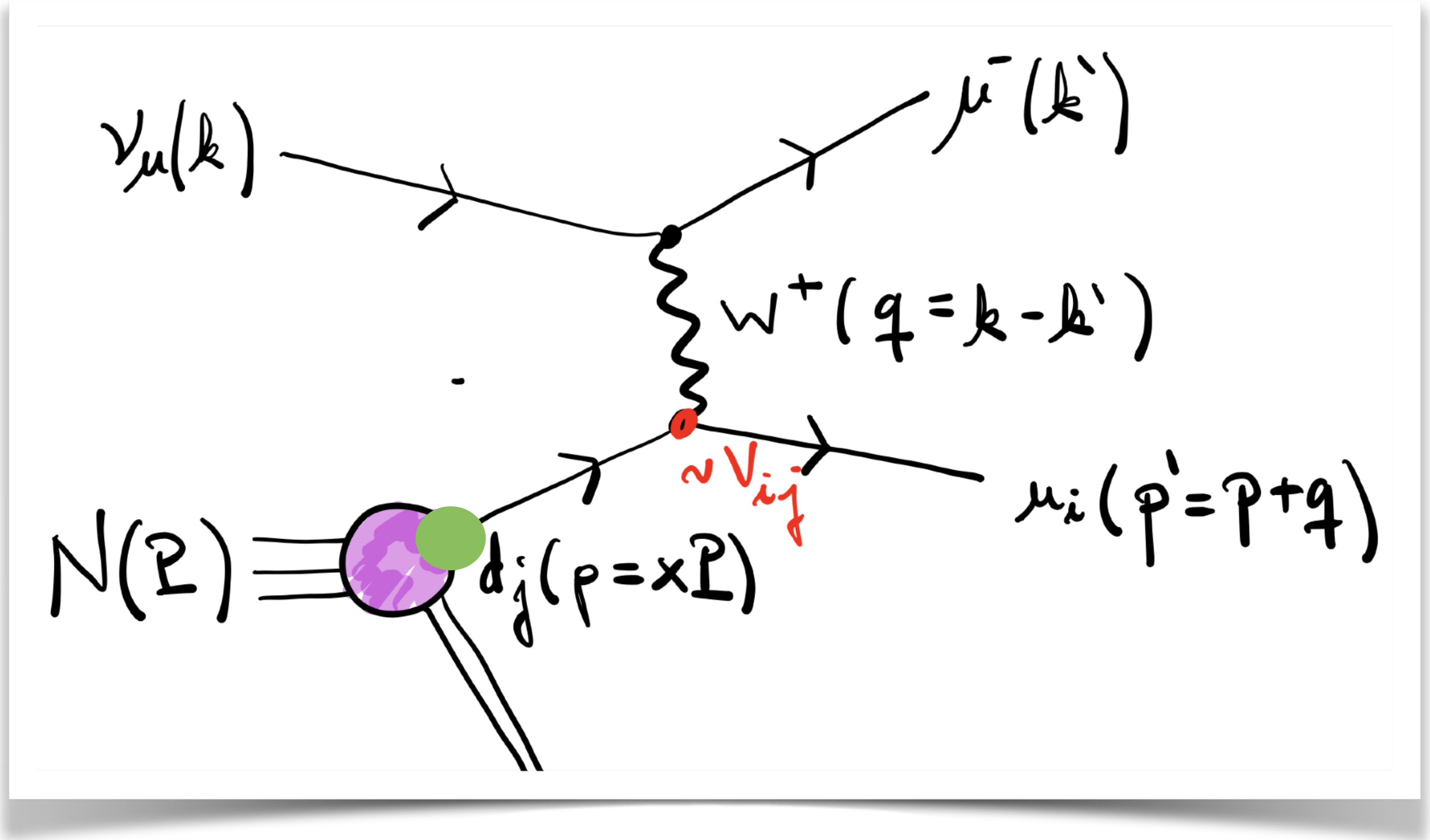
Isoscalar target

$$
\begin{aligned}
u(x,Q^2) &= (u_p(x,Q^2) + d_p(x,Q^2))/2\,,\\
d(x,Q^2) &= (d_p(x,Q^2) + u_p(x,Q^2))/2\,,\\
\bar{u}(x,Q^2) &= (\bar{u}_p(x,Q^2) + \bar{d}_p(x,Q^2))/2\,,\\
\bar{d}(x,Q^2) &= (\bar{d}_p(x,Q^2) + \bar{u}_p(x,Q^2))/2\,,\\
s(x,Q^2) &= s_p(x,Q^2)\,,\\
\bar{s}(x,Q^2) &= \bar{s}_p(x,Q^2)\,,\\
c(x,Q^2) &= c_p(x,Q^2)\,,\\
\bar{c}(x,Q^2) &= \bar{c}_p(x,Q^2)\,.
\end{aligned}
$$

Going back to the observable…

Neutrino DIS

The final CC muon neutrino distribution is given by



$$\frac{d\Sigma^{\mathrm{DIS}}_{\nu_\mu}}{dEdxdy} = \underbrace{\mathcal{P}_{\nu_\mu}(E)}_{\text{spectrum}}\underbrace{\frac{2G_F^2 MEx}{\pi(1+Q^2/m_W^2)^2}}_{\text{parton kin.}} \times \left(\sum_{f=u,c}\sum_{i=d,s} \underbrace{|V_{fi}|^2}_{\text{CKM}} \underbrace{f_i(x,Q^2)}_{\text{PDF}} + \sum_{f=\bar{d},\bar{s},\bar{b}}\sum_{i=\bar{u},\bar{c}} \underbrace{|V_{fi}|^2}_{\text{CKM}} \underbrace{f_i(x,Q^2)}_{\text{PDF}}(1-y)^2 \right)$$

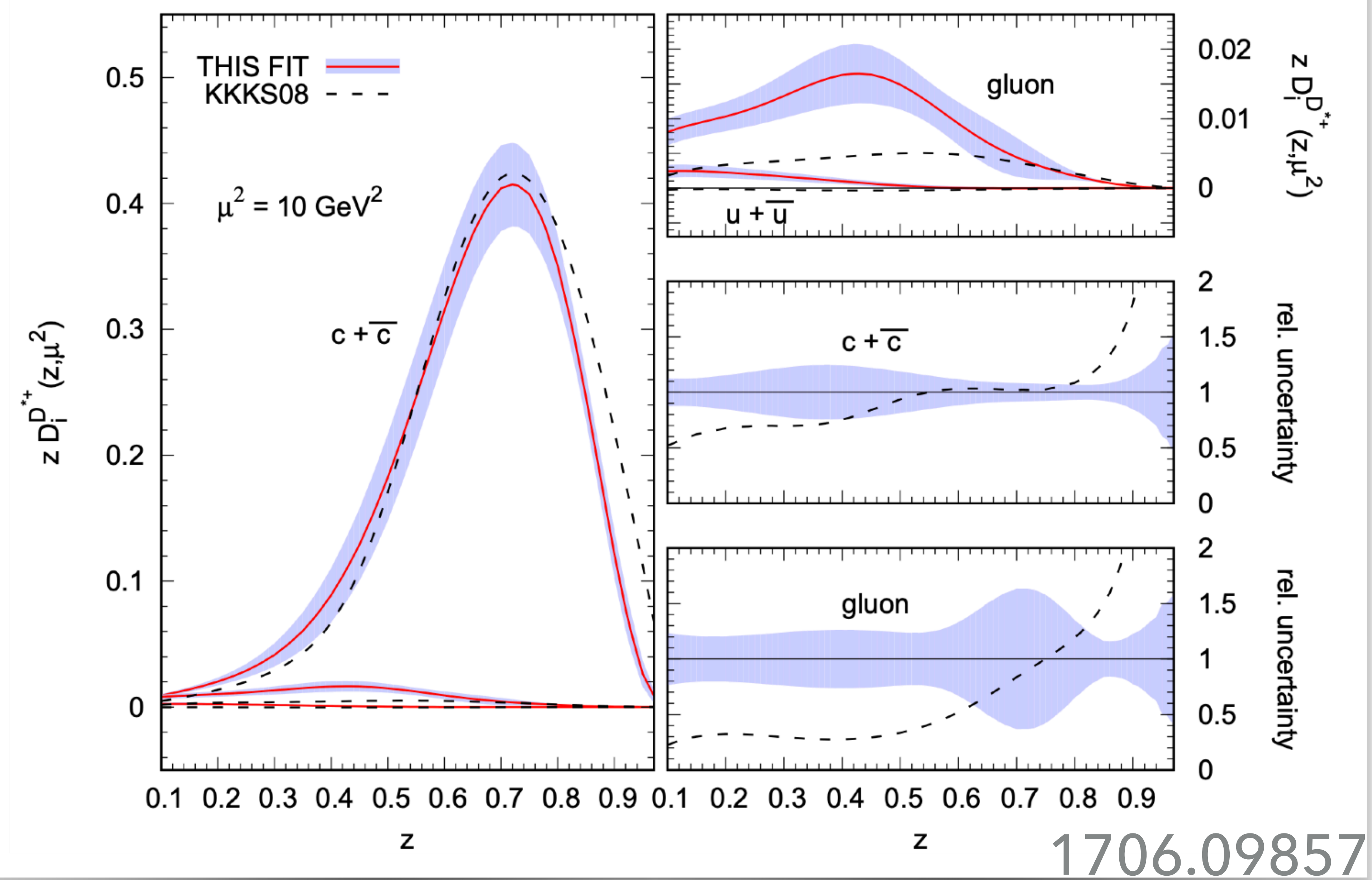
And analogous for electron antineutrino (change spectrum and parton channels).

However, to reconstruct the outgoing parton we need to be able to account for *fragmentation functions.* The aim is to estimate uncertainties coming from the tagging of the final state.

Fragmentation functions

Some intuition:

$D_q^H(z, Q^2)$: the 'probability' that a parton of type q hadronises into a hadron of type H carrying a fraction z of its momentum at an energy scale Q2.



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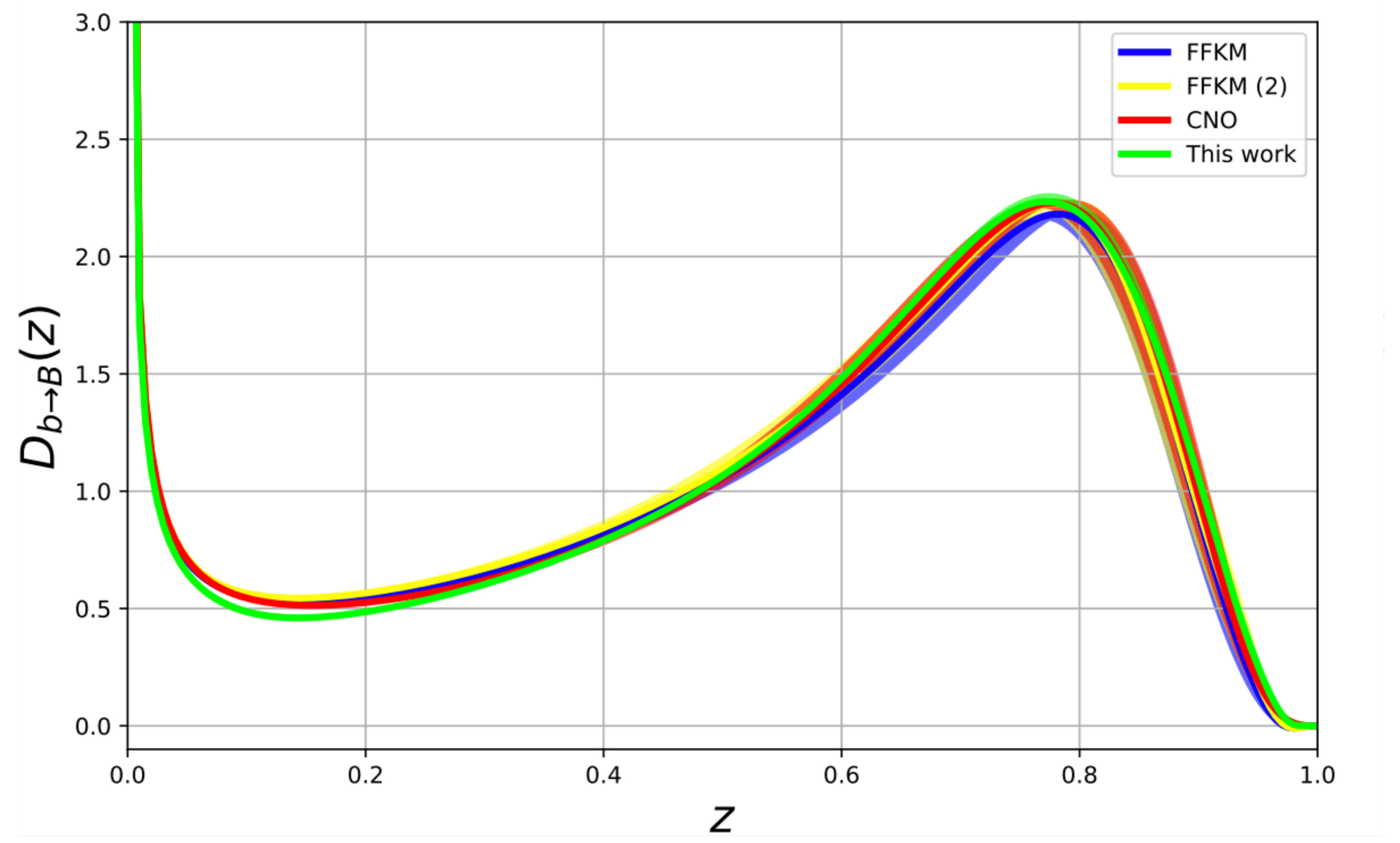
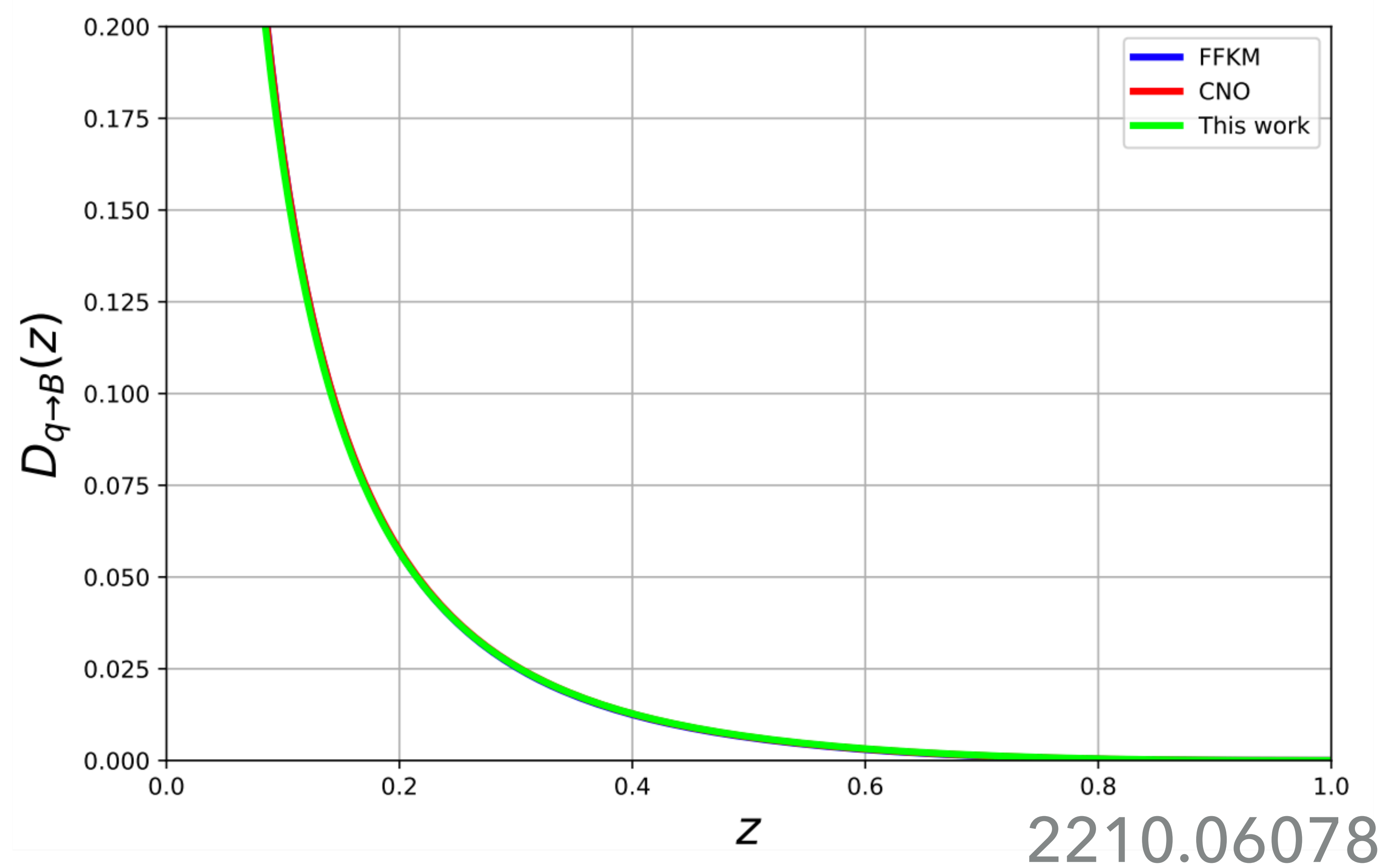
We work with D* meson and B-hadron fragmentations.





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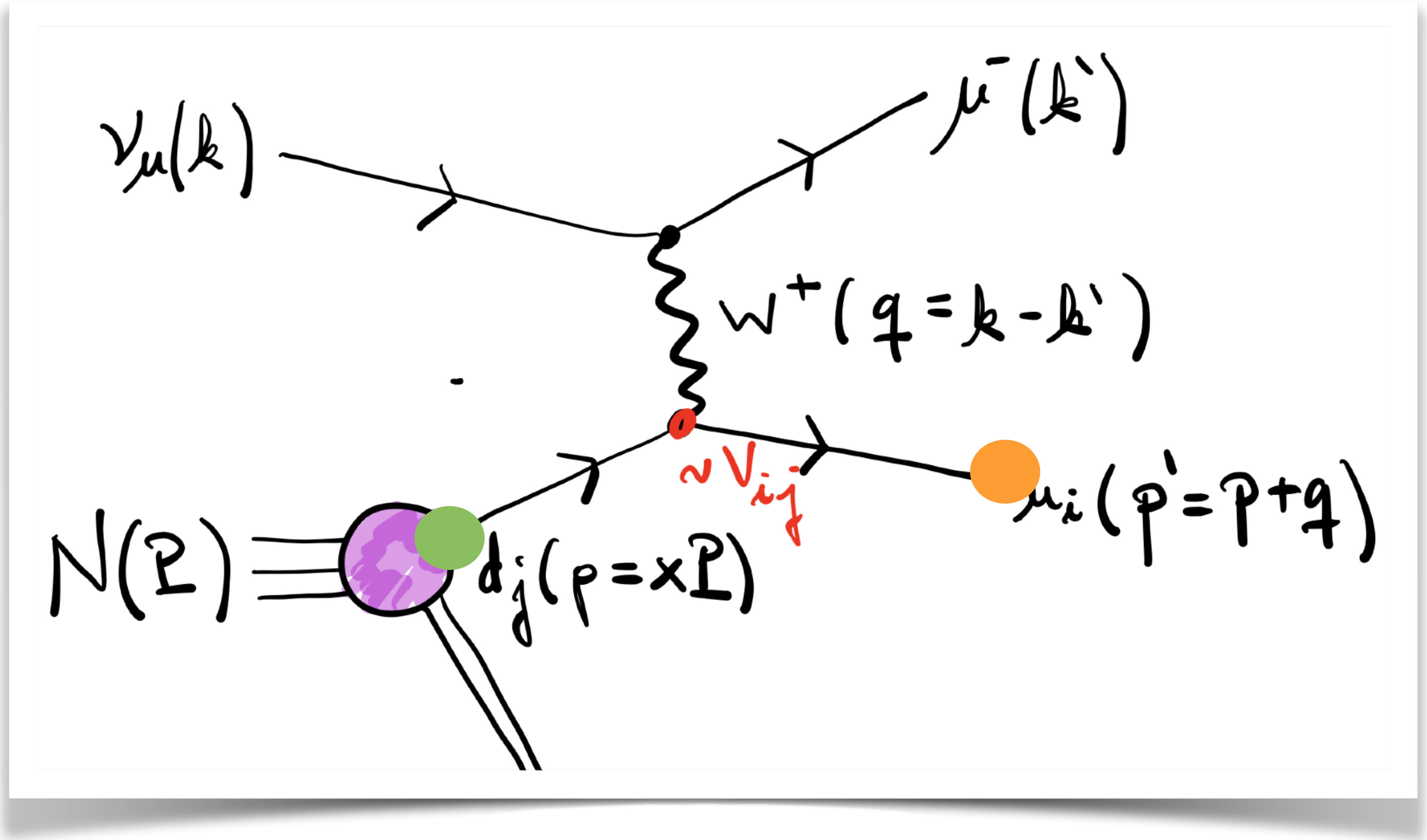
Neutrino DIS complete



Going back to our CC example:

spectrum parton kin.

$$\frac{d\Sigma^{\text{SIDIS}}_{\nu_\mu \to H}}{dEdxdydz} = \underbrace{\mathcal{P}_{\nu_\mu}(E)}_{\text{spectrum}} \underbrace{\frac{2G_F^2 MEx}{\pi(1+Q^2/m_W^2)^2}}_{\text{parton kin.}} \times$$

$$\left(\sum_{f=u,c} \sum_{i=d,s} \underbrace{|V_{fi}|^2}_{\text{CKM}} \underbrace{f_i(x,Q^2)}_{\text{PDF}} \underbrace{D_f^H(z,Q^2)}_{\text{Fr.}} + \sum_{f=\bar{d},\bar{s},\bar{b}} \sum_{i=\bar{u},\bar{c}} \underbrace{|V_{fi}|^2}_{\text{CKM}} \underbrace{f_i(x,Q^2)}_{\text{PDF}} \underbrace{D_f^H(z,Q^2)}_{\text{Fr.}} (1-y)^2 \right)$$

And we are ready to carry out the statistical analysis.

Observables

In bins of (x, Q^2, E_ν) :

In CC:

- Inclusive counts $N^{\nu_\mu,\overline{\nu}_e}$
- Ratio of c- and - tagged events over the inclusive count $R_{c,b}^{\nu_\mu,\overline{\nu}_e}$

In NC:

- Inclusive counts N^{ν}
- Ratio of c- and - tagged events over the inclusive count $R_{c,b}^{\nu}$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Nuisance parameters account for PDF, fragmentation, luminosity uncertainties, etc.

CKM determination

More specifically,

δ_{CKM}	PDG
$\lvert V_{cs}\rvert$	0.62%
$\lvert V_{cd}\rvert$	1.8%
$\lvert V_{cb}\rvert$	3.4%
$\lvert V_{ub}\rvert$	5.2%
$\lvert V_{ud}\rvert$	3.2×10^{-4}
$\lvert V_{us}\rvert$	0.36%
s_W^2	1.7×10^{-4}

CKM determination

More specifically,

δ_{CKM}	PDG	CC (stat)
$\lvert V_{cs}\rvert$	0.62%	0.0026%
$\lvert V_{cd}\rvert$	1.8%	0.0088%
$\lvert V_{cb}\rvert$	3.4%	0.30%
$\lvert V_{ub}\rvert$	5.2%	1.8%
$\lvert V_{ud}\rvert$	3.2×10^{-4}	7.0×10^{-6}
$\lvert V_{us}\rvert$	0.36%	0.028%
s_W^2	1.7×10^{-4}	–

CKM determination

More specifically,

δ_{CKM}	PDG	CC (stat)	CC
$\lvert V_{cs}\rvert$	0.62%	0.0026%	0.065%
$\lvert V_{cd}\rvert$	1.8%	0.0088%	0.24%
$\lvert V_{cb}\rvert$	3.4%	0.30%	0.71%
$\lvert V_{ub}\rvert$	5.2%	1.8%	1.9%
$\lvert V_{ud}\rvert$	3.2×10^{-4}	7.0×10^{-6}	3.2×10^{-4}
$\lvert V_{us}\rvert$	0.36%	0.028%	0.092%
s_W^2	1.7×10^{-4}	–	–

CKM determination

More specifically,

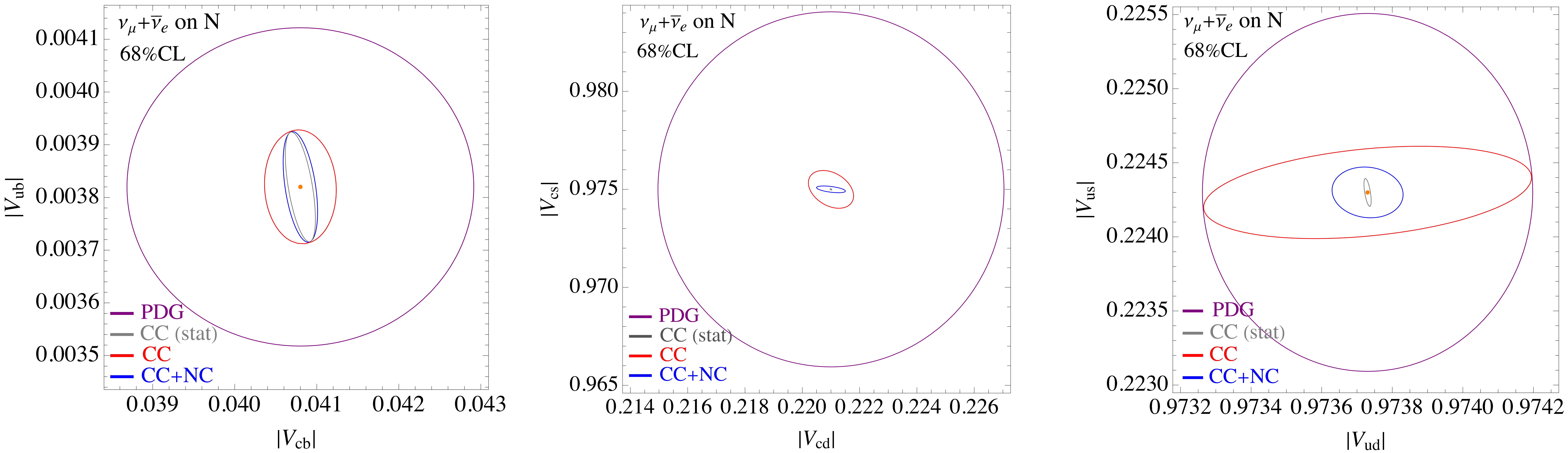
δ_{CKM}	PDG	CC (stat)	CC	CC+NC
$\lvert V_{cs} \rvert$	0.62%	0.0026%	0.065%	0.012%
$\lvert V_{cd} \rvert$	1.8%	0.0088%	0.24%	0.15%
$\lvert V_{cb} \rvert$	3.4%	0.30%	0.71%	0.34%
$\lvert V_{ub} \rvert$	5.2%	1.8%	1.9%	1.8%
$\lvert V_{ud} \rvert$	3.2×10^{-4}	7.0×10^{-6}	3.2×10^{-4}	0.68×10^{-4}
$\lvert V_{us} \rvert$	0.36%	0.028%	0.092%	0.051%
s_W^2	1.7×10^{-4}	–	–	5.8×10^{-5}

We see a strong improvement in precision (even in with extra sources of uncertainty).

This improvement is driven by the high statistics of the neutrino flux and the exploitation of correlations and shape information (from the PDFs, spectrum, parton level kinematics)

CKM determination

Constraints on CKM elements (profiled over the nuisance and other elements):



We see a good improvement in precision (even in the presence of systematics).

CKM determination - proton target

We find similar results (except a mild deterioration of $|V_{us}|$ to be further studied).

δ_{CKM}	PDG	CC (stat)	CC	CC+NC
$\|V_{cs}\|$	0.62%	0.0027%	0.051%	0.015%
$\|V_{cd}\|$	1.8%	0.013%	0.26%	0.17%
$\|V_{cb}\|$	3.4%	0.27%	0.69%	0.32%
$\|V_{ub}\|$	5.2%	1.4%	1.6%	1.5%
$\|V_{ud}\|$	3.2×10^{-4}	9.5×10^{-6}	3.2×10^{-4}	0.84×10^{-4}
$\|V_{us}\|$	0.36%	0.028%	0.28%	0.22%
s_W^2	1.7×10^{-4}	–	–	3.5×10^{-5}

Still, the improvement over current precision is very strong.

CKM determination

To be further explored:

- Additional sources of theory uncertainties (higher order contributions, mass effects, …)
- Reconstruction of event kinematics and tagging/fragmentation….
- Nuclear corrections in parton densities, isospin symmetry breaking effects…
- …

The analysis we have presented goes forward in parallel with other aspects of the MuC physics programme.

Outline

Summary

Summary - the most important slide

1. The high energy, collimated neutrino flux from muon decays at a MuC will enable highly precise forward target DIS measurements.

2. The setup will allow for exceptionally sensitive measurements of CKM matrix elements, surpassing current standards.

3. Even when including estimates of additional sources of uncertainty (theory, experiment), by exploiting the large event rates and the shape information across the kinematic coverage there are strong prospects for precision CKM measurements.

4. This analysis will benefit from parallel MuC studies:

    1. Additional observables and constraints.

    2. Experiment design.

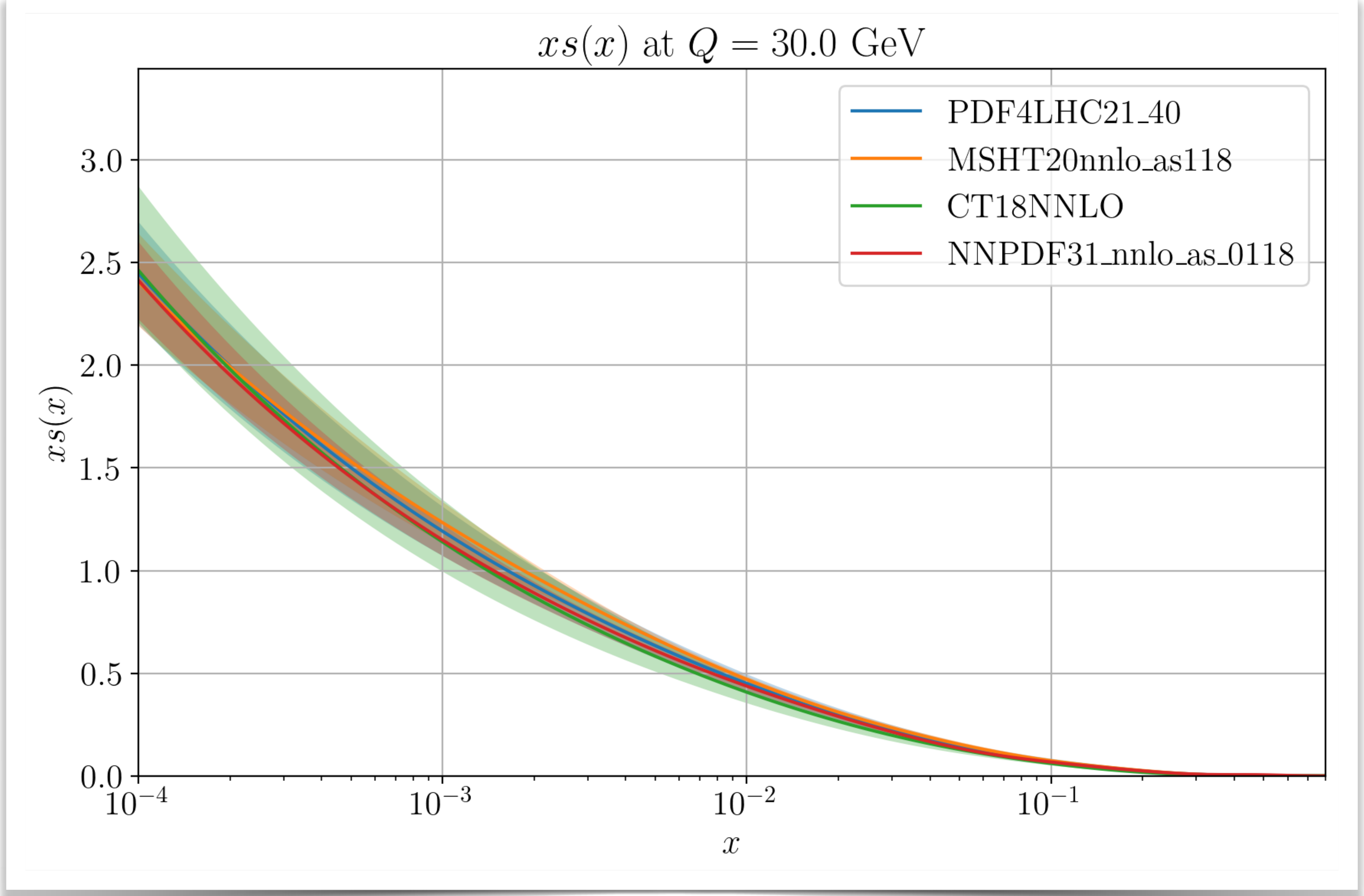
    3. Estimation of systematics, …

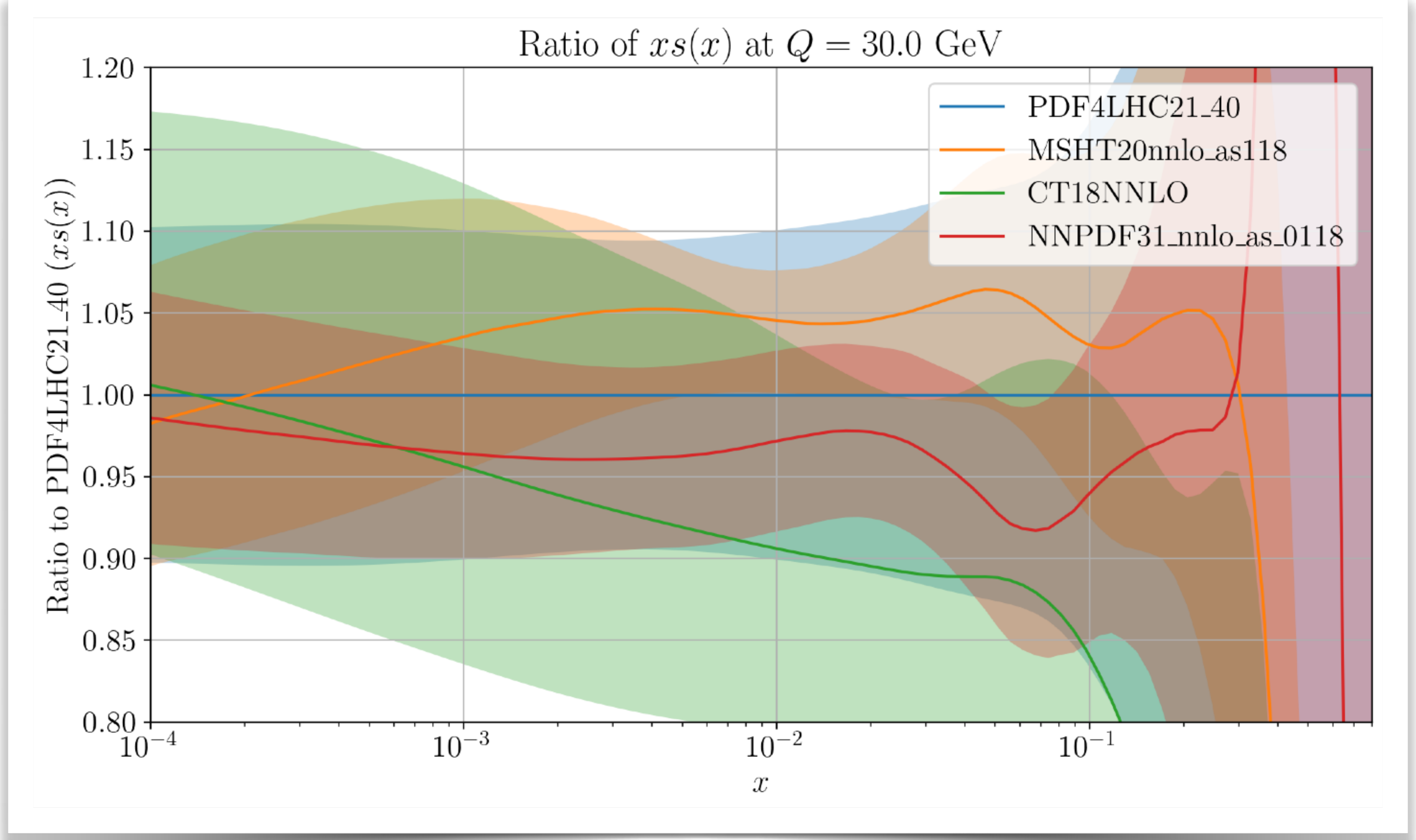
Thank you for your attention!

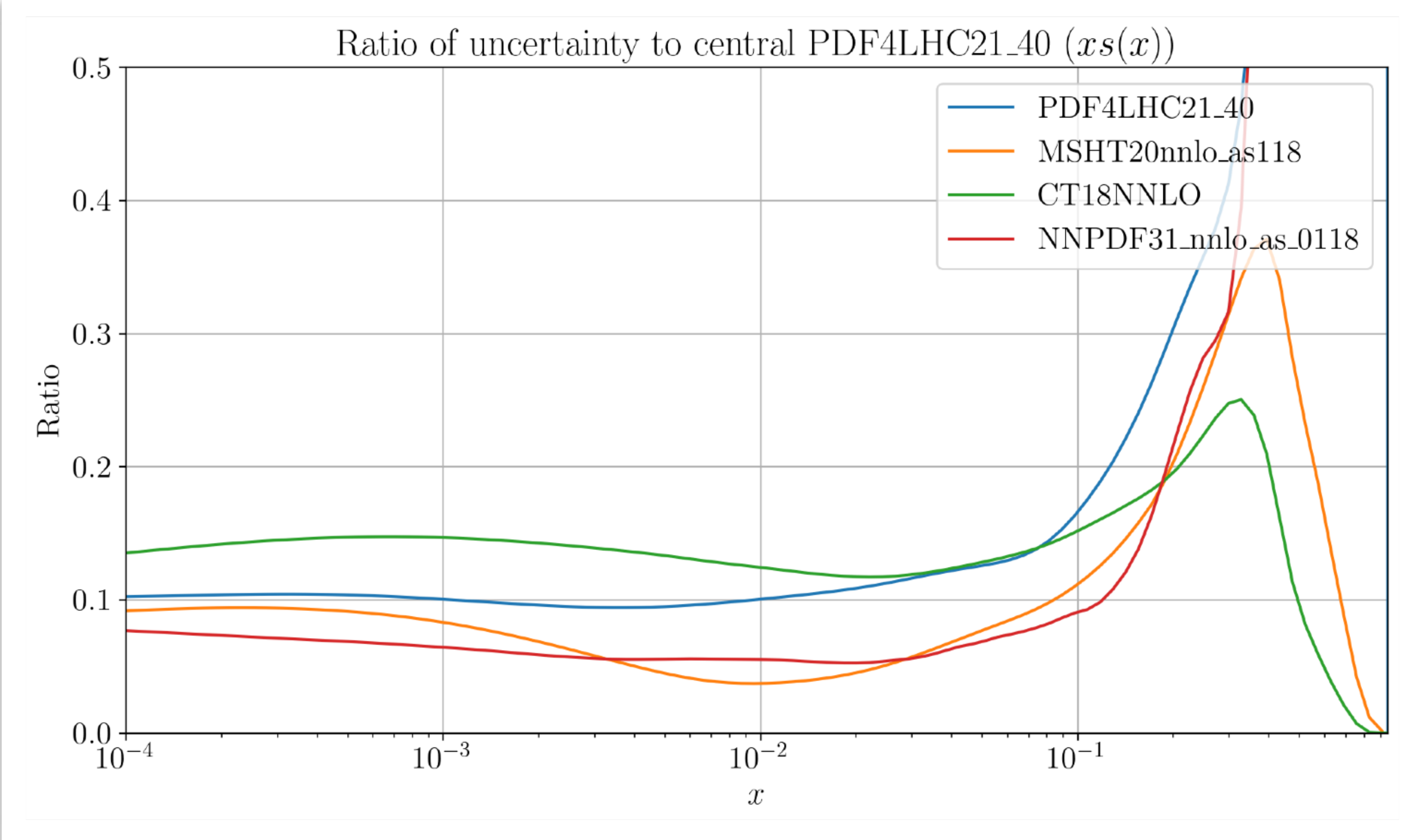
Extra

PDFs - strangeness

To marginalise over methodological uncertianty we adopt the recommended PDF4LHC21 set







MuC PDFs

Considerable reduction of uncertainties predicted.