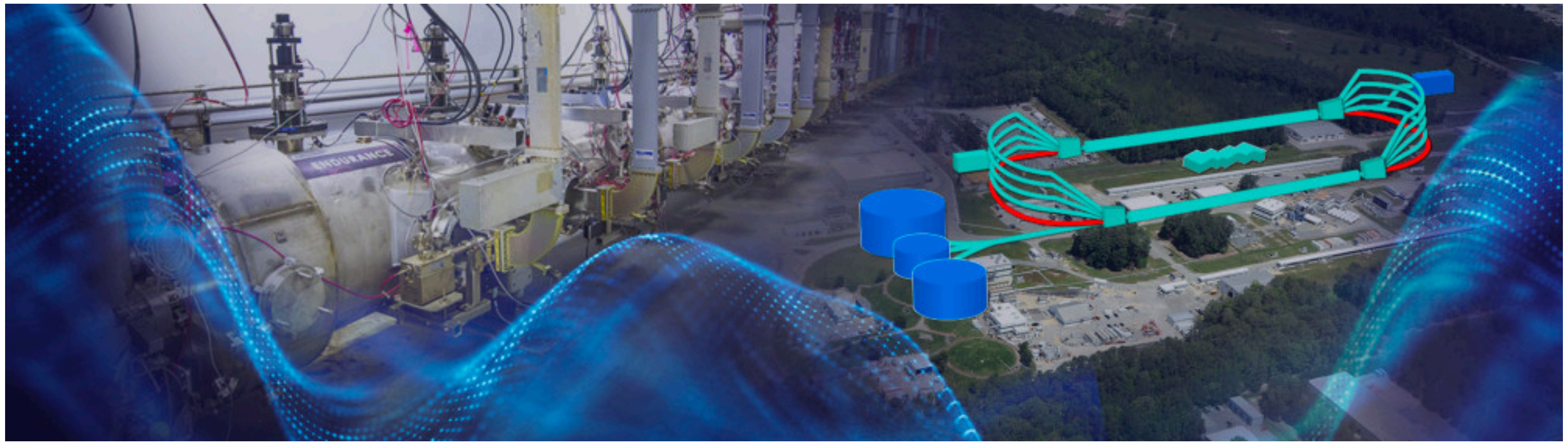
Unpolarised PDFs and the JLab upgrade at 22 GeV

Juan Rojo, VU Amsterdam & Nikhef

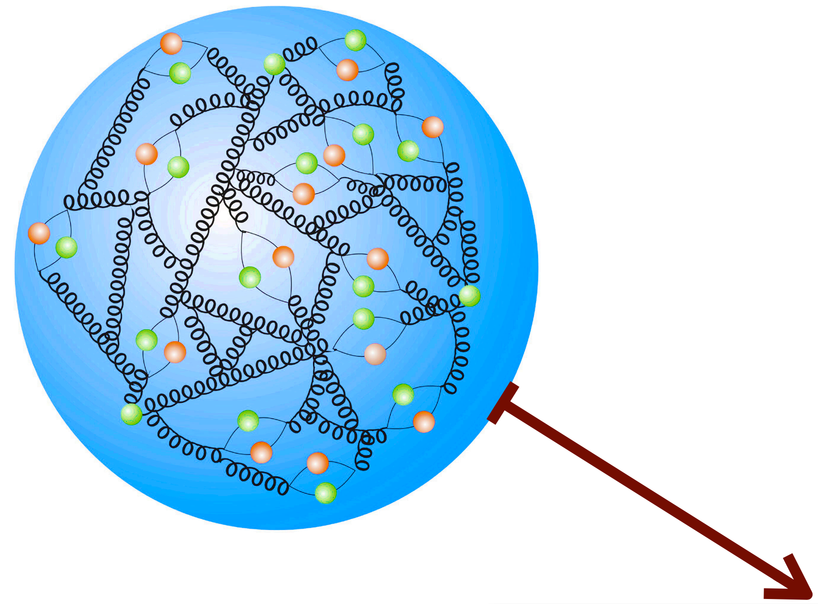


Science at the Luminosity Frontier: JLab at 22 GeV workshop

24th January 2023

Motivation

Why Nucleon Structure?

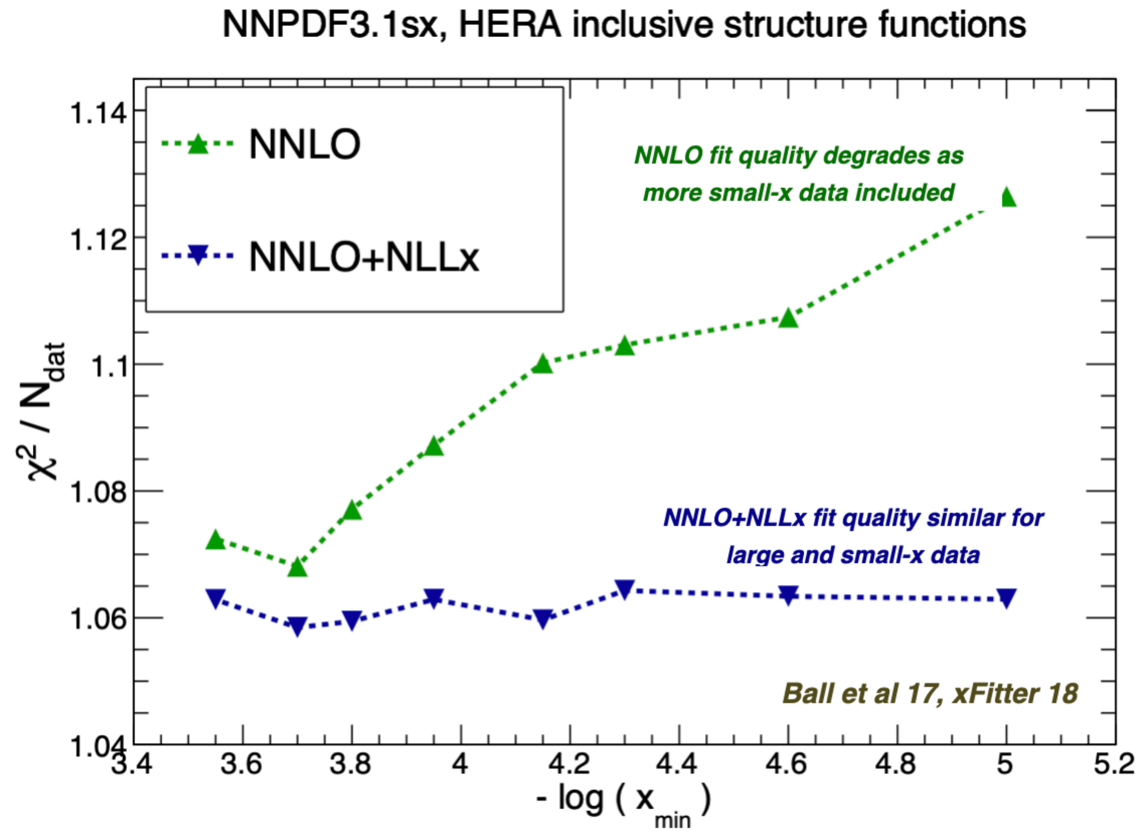


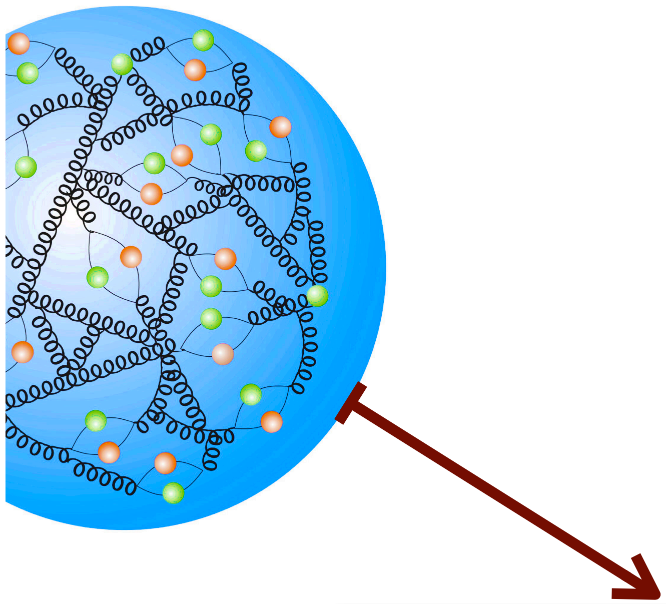
Address fundamental questions about Quantum Chromodynamics

- origin of mass & spin?
- **heavy quark** & **antimatter content?**
- 3D imaging?
- gluon-dominated matter?
- **nuclear modifications?**
- Interplay with BSM searches?

Why Nucleon Structure?

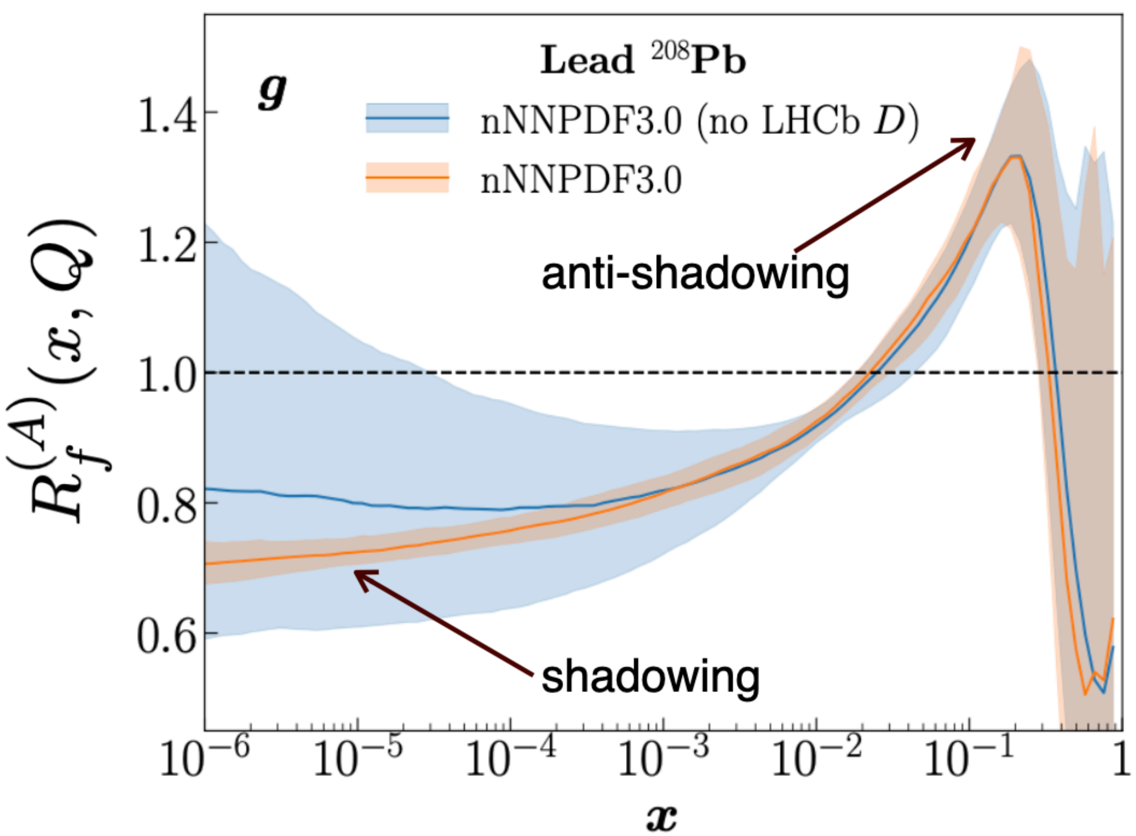
BFKL dynamics in HERA data





Address fundamental questions about Quantum Chromodynamics

Strong nuclear shadowing in lead gluons



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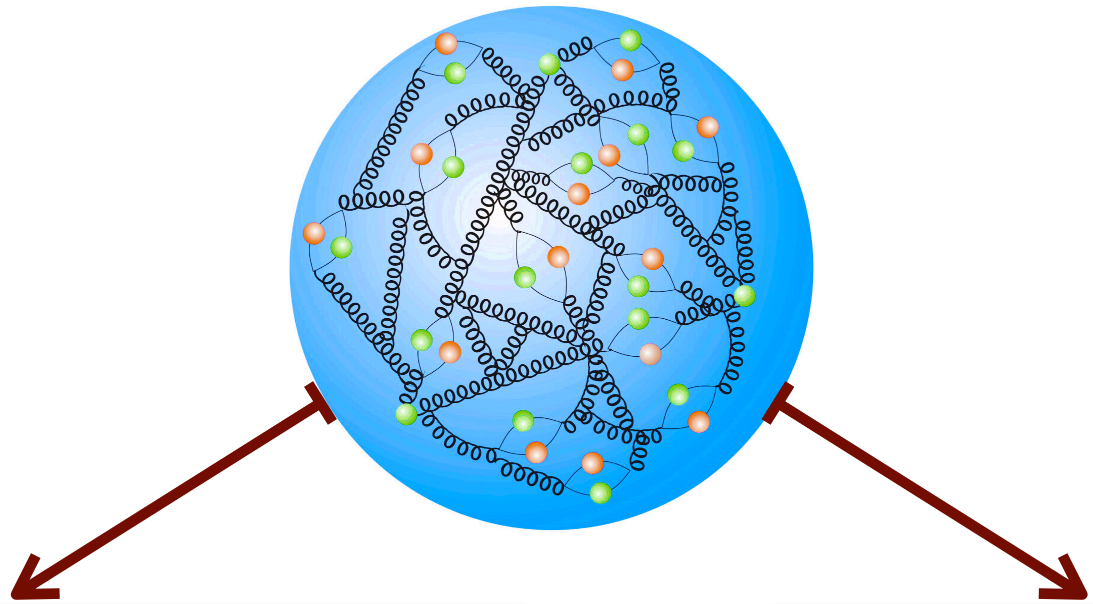

Key component of predictions for particle, nuclear, and astro-particle experiments

- **pp: ATLAS, CMS, LHCb, ALICE**
- ep: fixed target DIS, HERA
- neutrinos: IceCube, KM3NET, **Forward Physics Facility** @ LHC
- heavy ions: LHC Pb, LHC O, RHIC
- *pp (future): HL-LHC, FCC, SppS*
- ep (future): **Electron-Ion Collider,** LHeC, FCC-eh

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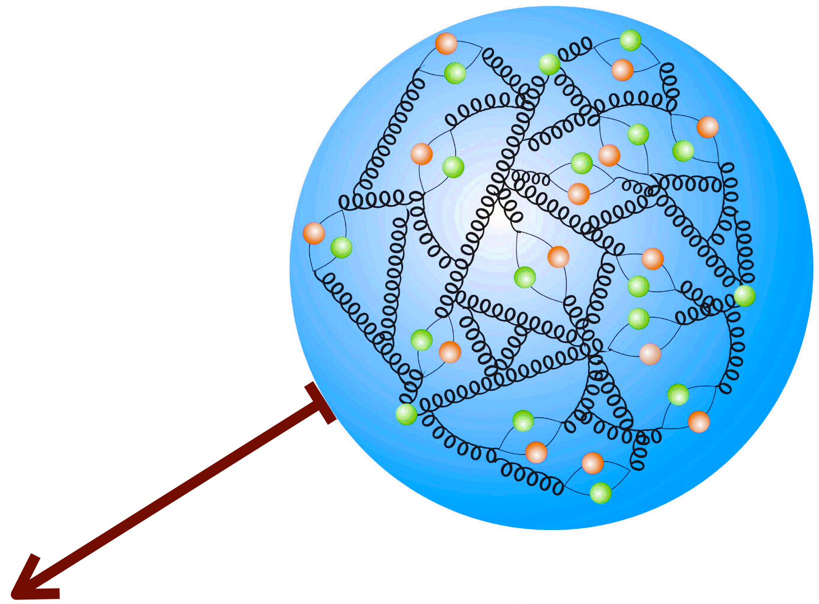

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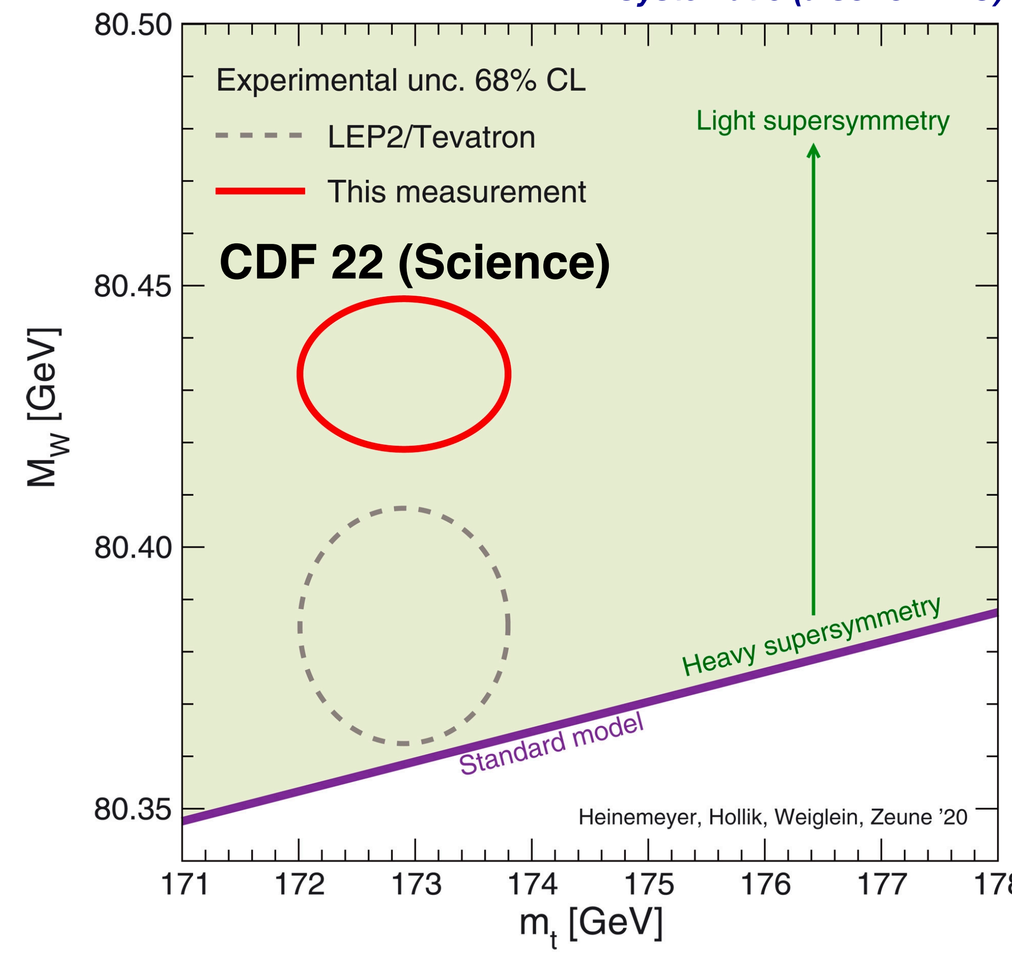
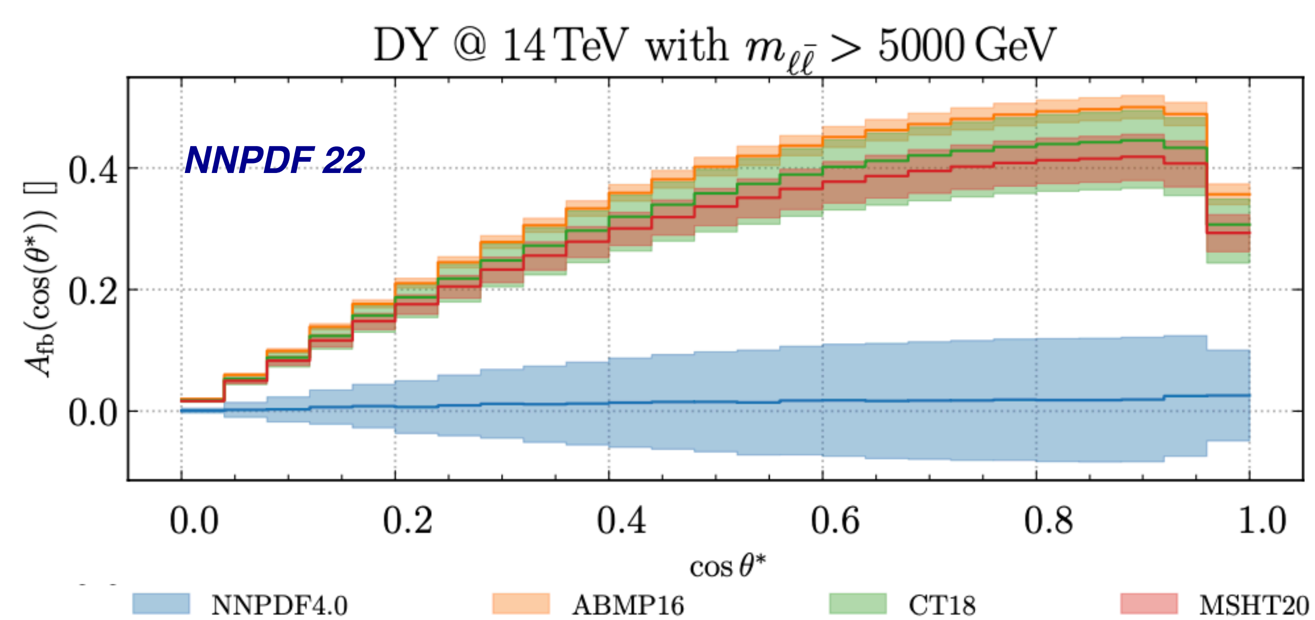
PDFs leading theory systematic (also for LHC)



high-mass Drell-Yan forward-backward asymmetry at LHC



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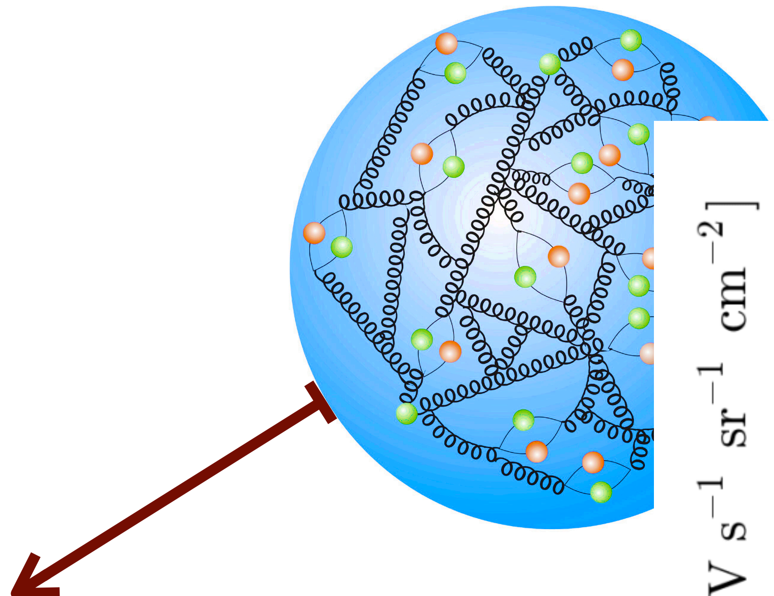

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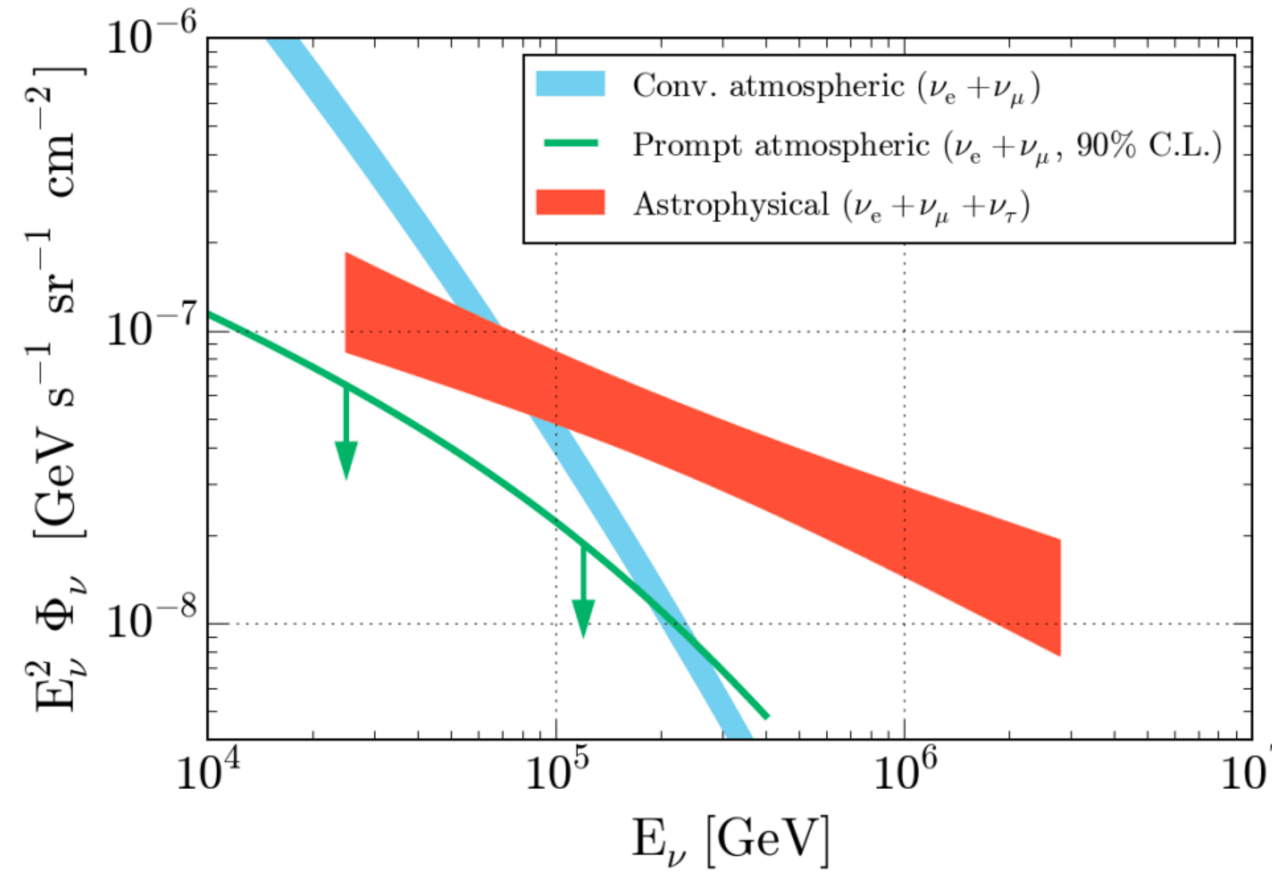
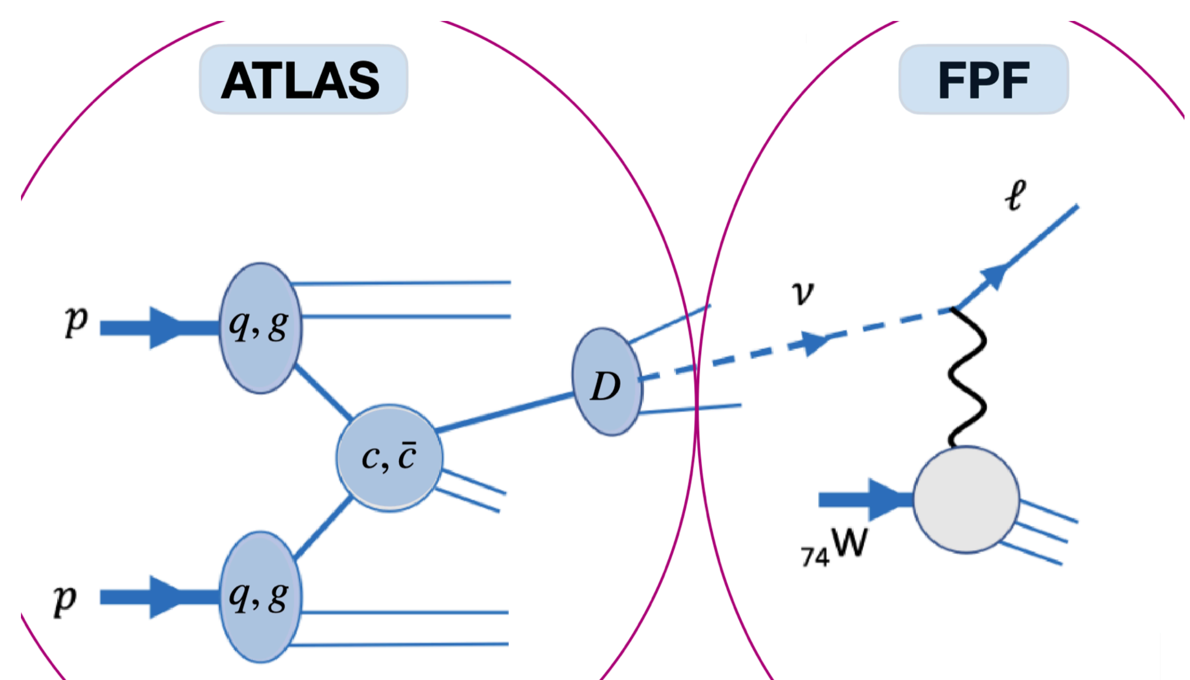
Neutrino cross-sections and prompt fluxes at IceCube



TeV Neutrino scattering at the LHC



From 11/12 GeV to 22 GeV

Fixed-target lepton-nucleon scattering

$$E_\ell = k_0 = k_3$$

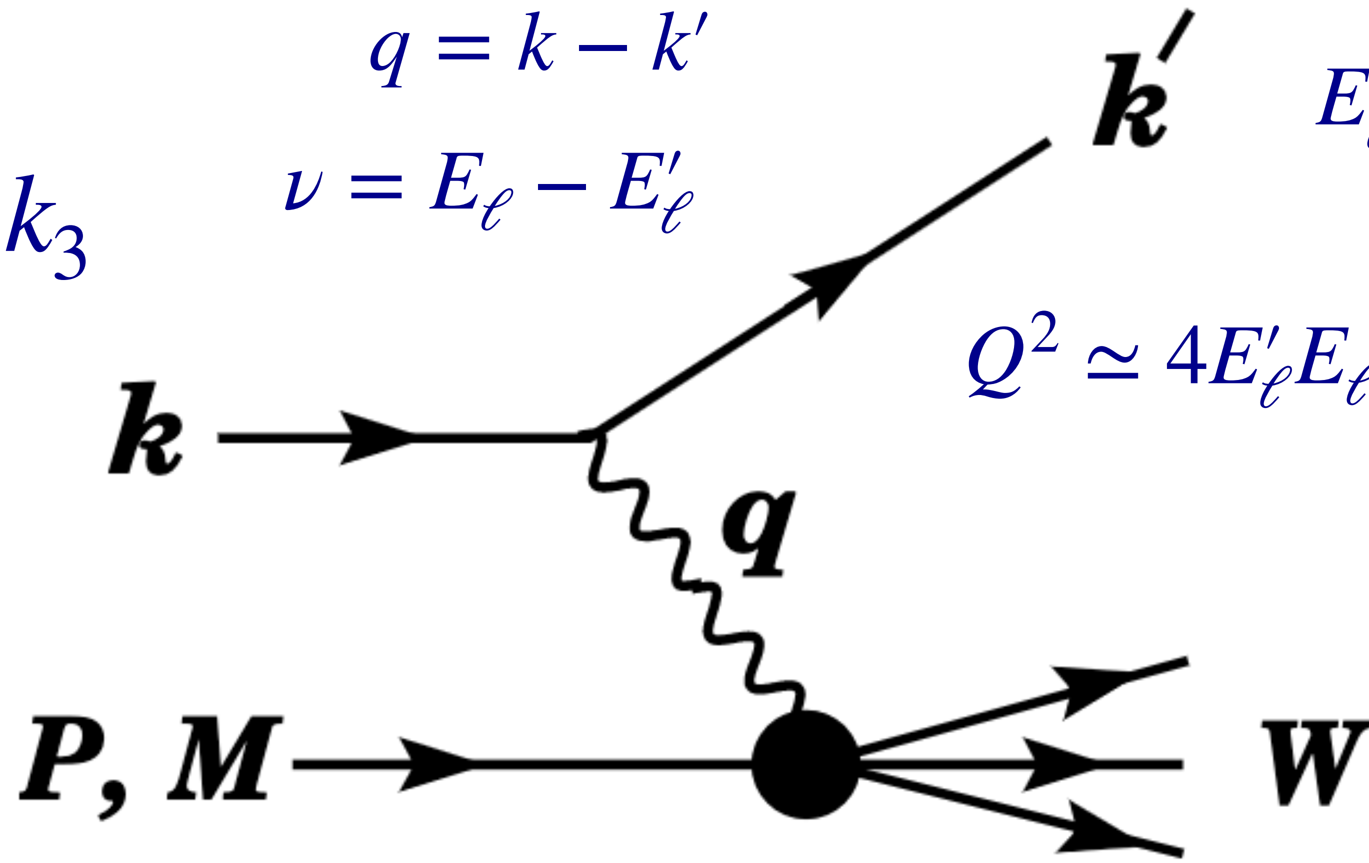
$$q = k - k'$$

$$\nu = E_\ell - E'_\ell$$

$$E'_\ell = k'_0$$

$$Q^2 \simeq 4E'_\ell E_\ell \sin^2(\theta/2)$$

$$y = \frac{\nu}{E_\ell} = 1 - \frac{E'_\ell}{E_\ell}$$



$$E_h = E_\ell - E'_\ell$$

$$x = \frac{Q^2}{2ym_N E_\ell}$$

$$W^2 = Q^2\frac{(1-x)}{x} = m_N^2 + 2m_N\nu - Q^2$$

- For **inclusive DIS measurements**, reconstructing the outgoing lepton provides all needed kinematic information
- For **semi-inclusive DIS** (*e.g.* charm production or kaon production) one needs also to access the **hadronic final state** (would this be possible at JLab22?

From 12 GeV to 22 GeV

$$q = k - k'$$

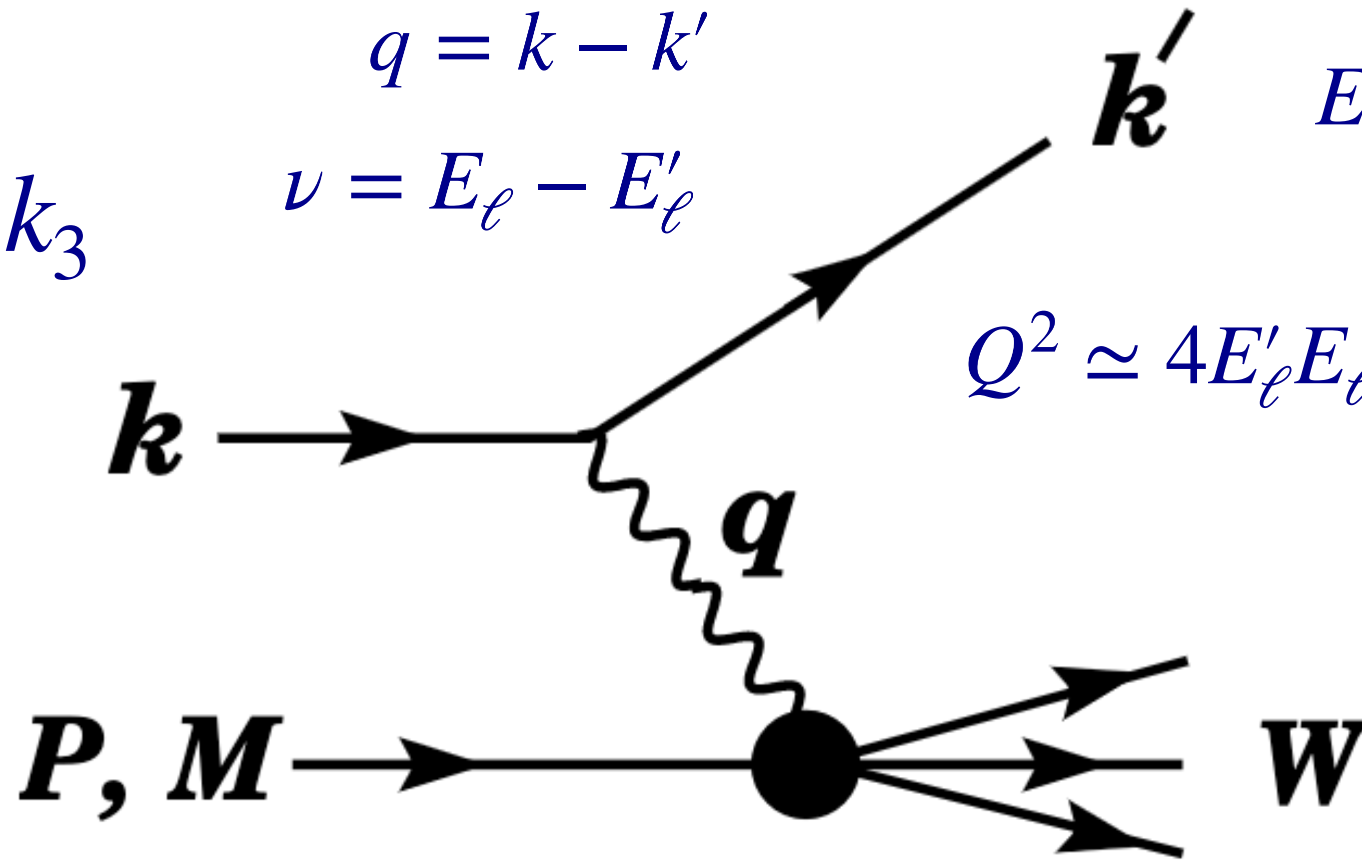
$$E'_\ell = k'_0$$

$$\nu = E_\ell - E'_\ell$$

$$E_\ell = k_0 = k_3$$

$$Q^2 \simeq 4E'_\ell E_\ell \sin^2(\theta/2)$$

$$y = \frac{\nu}{E_\ell} = 1 - \frac{E'_\ell}{E_\ell}$$



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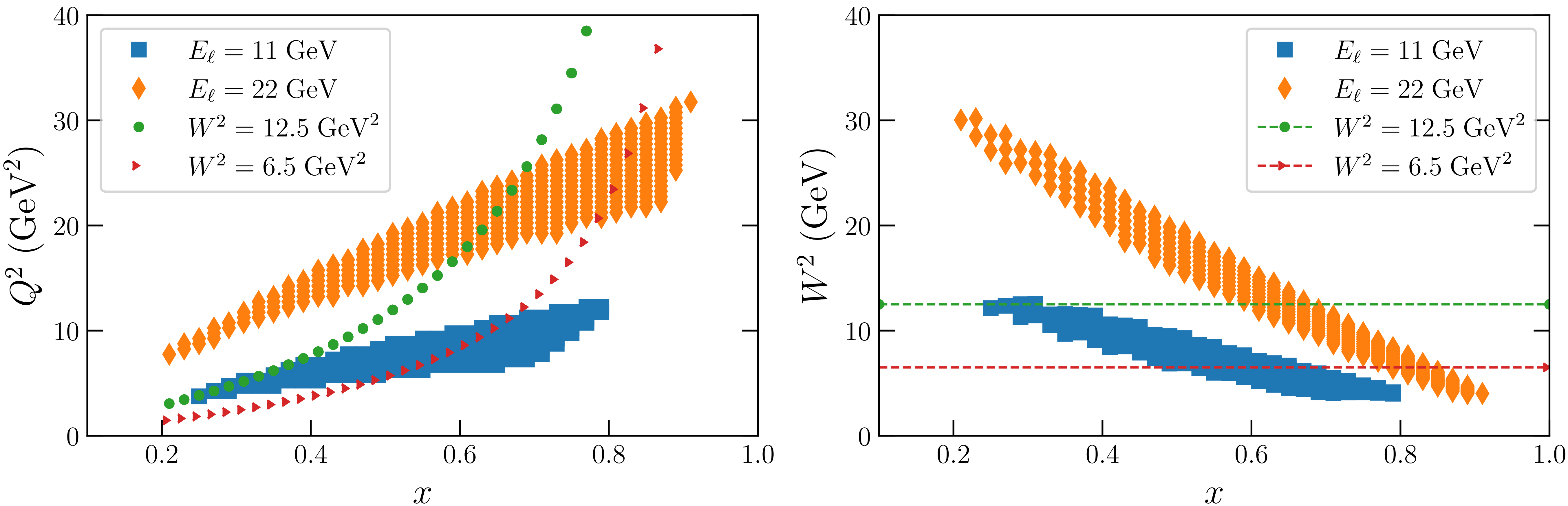
$$x = \frac{Q^2}{2ym_N E_\ell}$$

$$W^2 = Q^2\frac{(1-x)}{x} = m_N^2 + 2m_N\nu - Q^2$$

- For fixed *y* and *Q*², one has $x_{\rm min}^{(22\ {\rm GeV})} \sim 0.5 x_{\rm min}^{(12\ {\rm GeV})}$
- For fixed leptonic acceptance, one has $Q^{(22\ {\rm GeV})}_{\rm max} \sim 2Q^{(12\ {\rm GeV})}_{\rm max}$
- For fixed *x*, hadronic state invariant mass is $W^{2(22\ {\rm GeV})}_{\rm max} \sim 4W^{2(12\ {\rm GeV})}_{\rm max}$

From 11 GeV to 22 GeV

Pseudo-data for **SOLID@JLab** 22 GeV

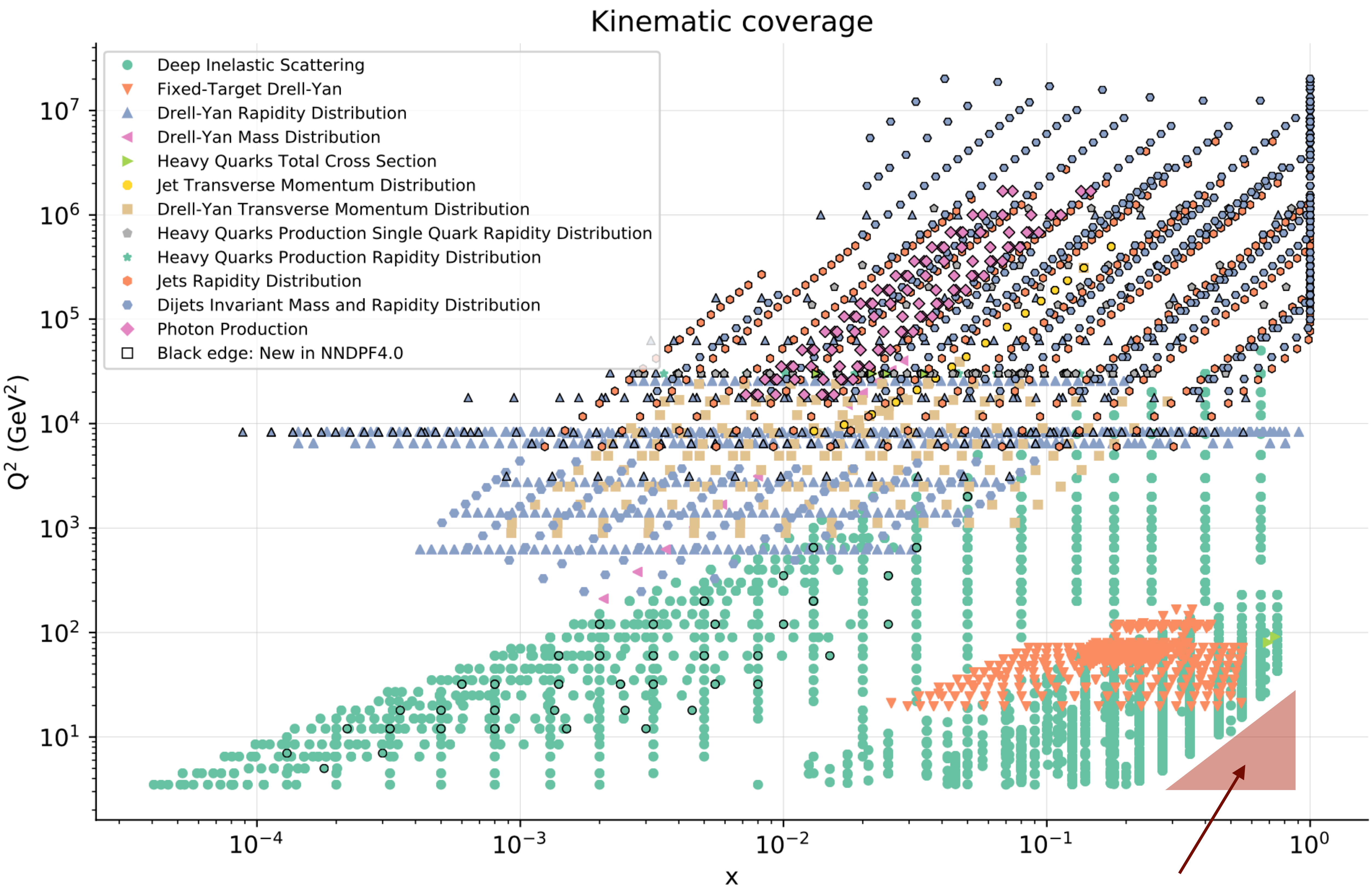


- At 22 GeV, we can access up to ***x* = 0.65 for *W*² > 12.5 GeV²**, the standard cut in most global PDF fits required to suppressed higher-twist corrections
- Hence we can access up and down quarks in *x* region **relevant for BSM searches at LHC**
- At 22 GeV, we can access **charm structure functions** in the same *x* region if **final-state charm can be tagged**, since one satisfies

$$W^2 > W^2_{c\bar{c}} = 4m_c^2 \sim 10 \text{ GeV}$$

very challenging at JLab11

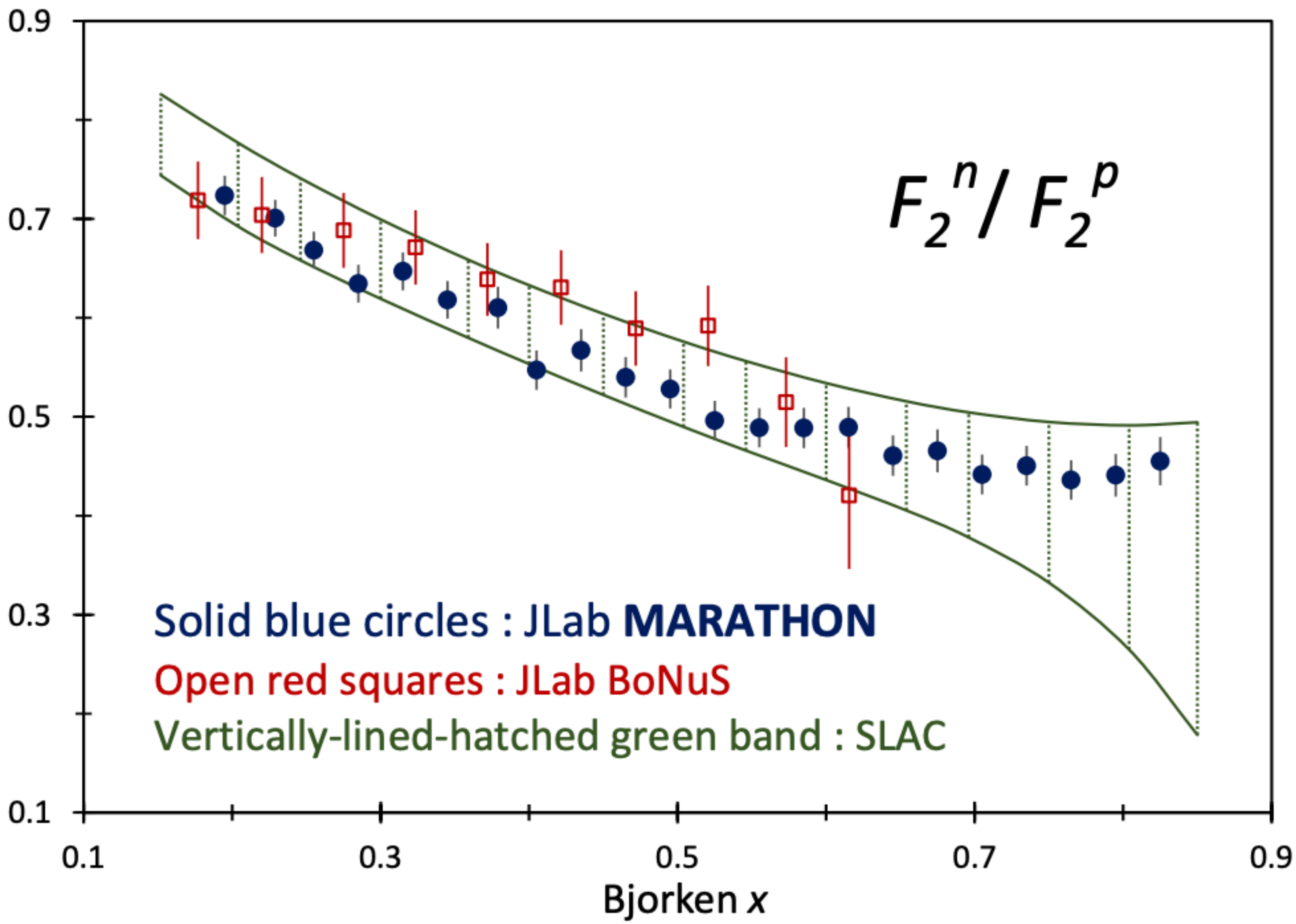
From 11 GeV to 22 GeV



JLab11 data excluded by W2 cut

most JLab22 data would pass the cut

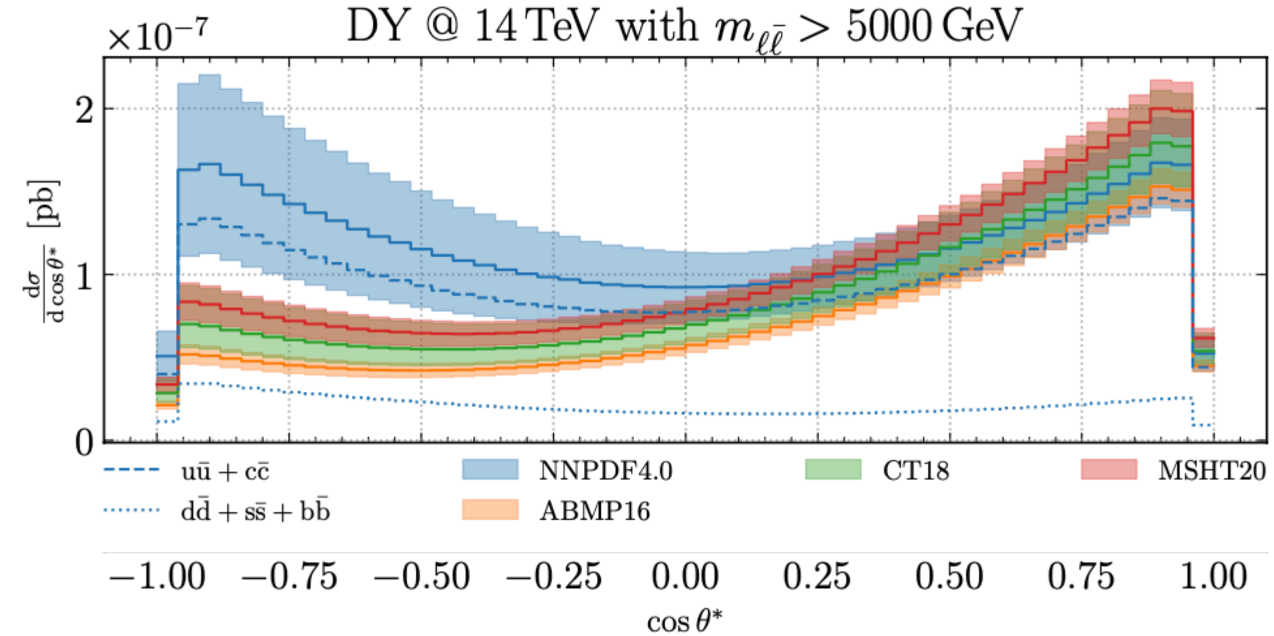
Key results from JLab12



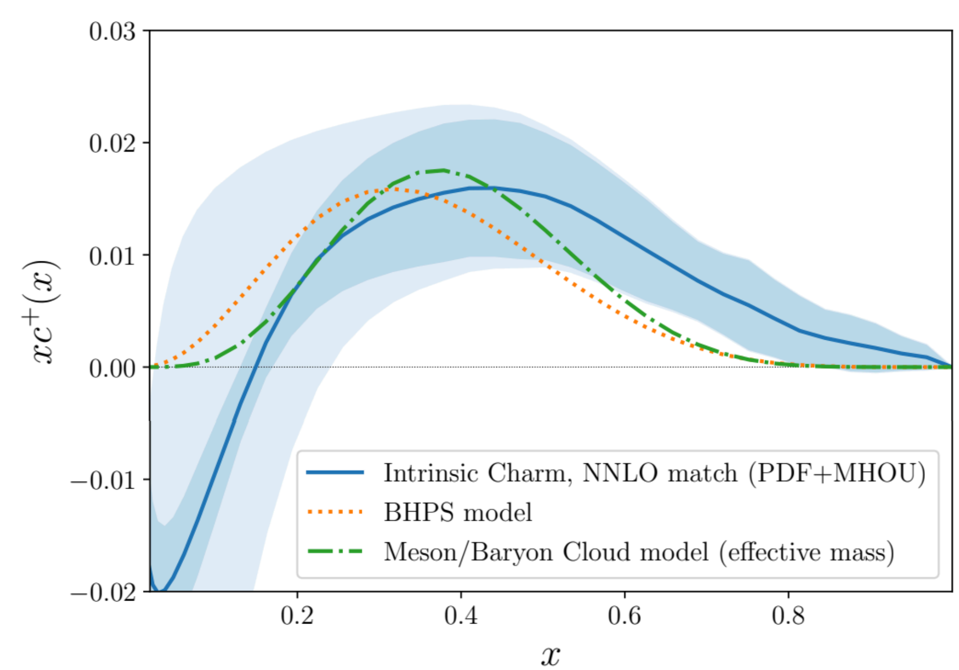
- Constraints on **up vs down valence quark flavour separation** at large-x
- Complications from **TMC / higher-twists** largely removed by going to 22 GeV

PDF drivers for JLab 22 GeV upgrade

- Clean access to **large-*x* up and down quarks** (wo TMCs/HTs) via inclusive structure functions, key input for many high-mass BSM searches at LHC



- Potential access to large-*x* charm structure function and hence probe of **intrinsic charm**



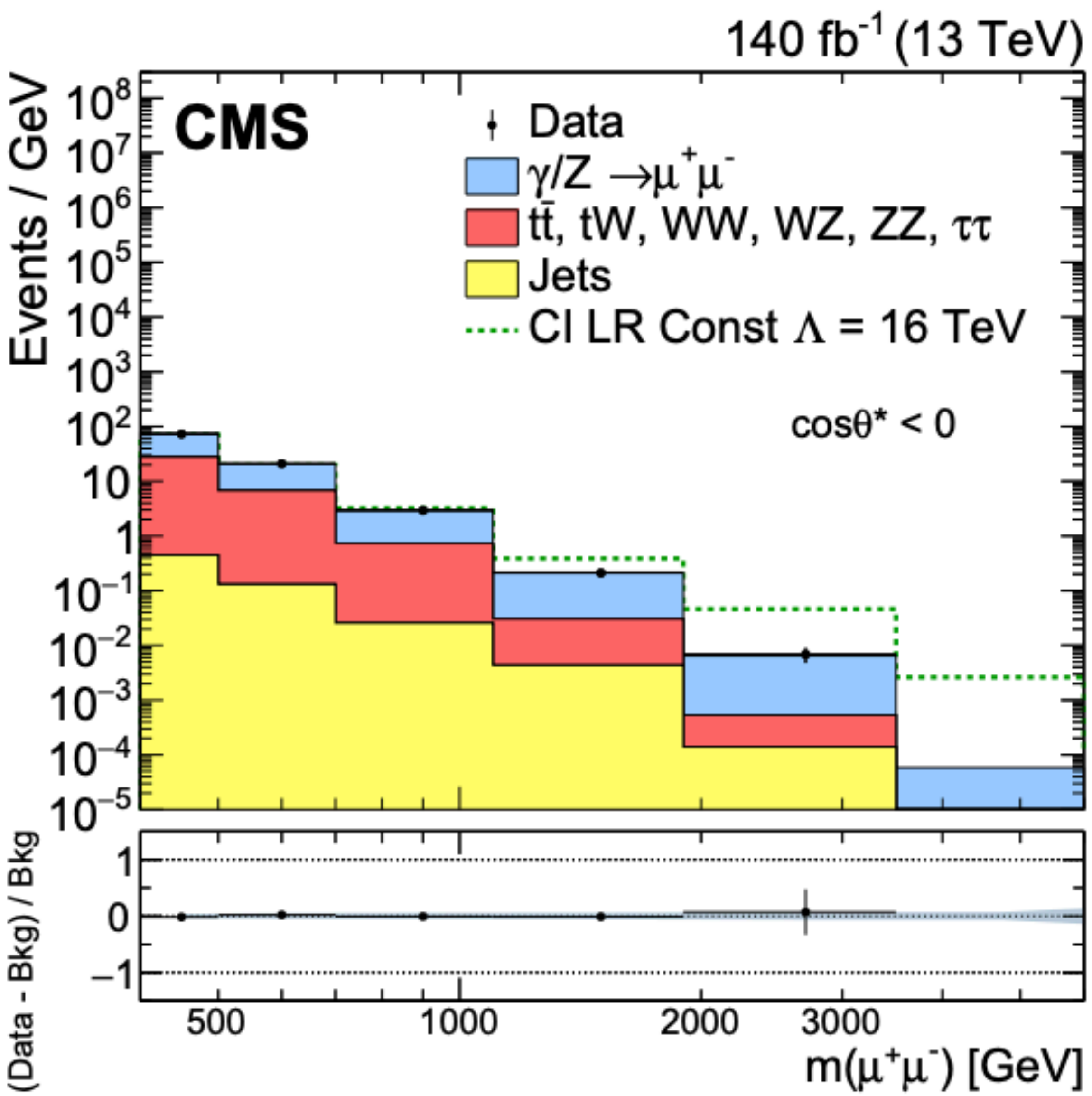
- **Parity-violating DIS** structure functions to access large-*x* antiquarks, also relevant for BSM searches

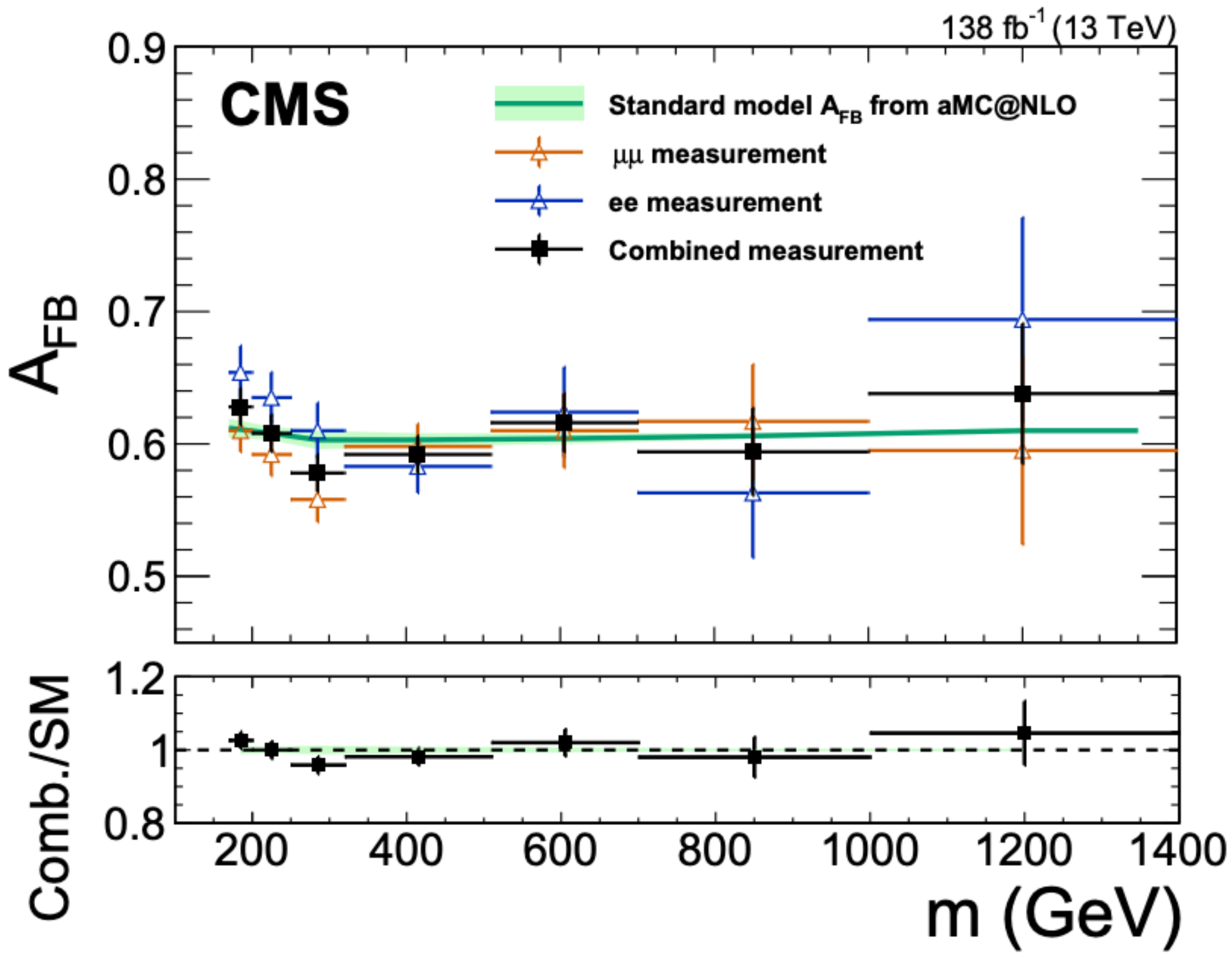
$$F_3^{\gamma Z} = 2\sum_f e_{q_f} (g_A)_{q_f} (q_f - \bar{q}_f).$$

New Physics at the LHC and the Forward-Backward Asymmetry

BSM Searches with High-Mass Drell-Yan

- High-mass neutral-current Drell-Yan is a very sensitive processes for BSM searches
- **Resonant** and **EFT new physics** can be probed with the invariant mass distributions, while **off-shell interference** (e.g. Z' boson) one can use the **Forward-Backward asymmetry**





- Current understanding of **large-*x* PDFs**: robust enough for present and future searches in DY?

Neutral-Current Drell-Yan

- Express in terms of **symmetric** and **antisymmetric** parton luminosities

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}m_{\ell\bar\ell}\,\mathrm{d}y_{\ell\bar\ell}\,\mathrm{d}\cos\theta^*} = \frac{\pi\alpha^2}{3m_{\ell\bar\ell}s}\left((1+\cos^2(\theta^*))\sum_q S_q\mathcal{L}_{S,q}(m_{\ell\bar\ell},y_{\ell\bar\ell}) + \cos\theta^*\sum_q A_q\mathcal{L}_{A,q}(m_{\ell\bar\ell},y_{\ell\bar\ell})\right)$$

dilepton invariant mass

dilepton rapidity

Collins-Soper angle

symmetric effective coupling

antisymmetric effective coupling

$$\mathcal{L}_{S,q}(m_{\ell\bar\ell},y_{\ell\bar\ell}) \equiv f_q(x_1,m_{\ell\bar\ell}^2)f_{\bar q}(x_2,m_{\ell\bar\ell}^2) + f_q(x_2,m_{\ell\bar\ell}^2)f_{\bar q}(x_1,m_{\ell\bar\ell}^2)\,,$$

$$\mathcal{L}_{A,q}(m_{\ell\bar\ell},y_{\ell\bar\ell}) \equiv \mathrm{sign}(y_{\ell\bar\ell})\left[f_q(x_1,m_{\ell\bar\ell}^2)f_{\bar q}(x_2,m_{\ell\bar\ell}^2) - f_q(x_2,m_{\ell\bar\ell}^2)f_{\bar q}(x_1,m_{\ell\bar\ell}^2)\right]$$

invariant under $x_1 \leftrightarrow x_2$

- The Collins-Soper angle is defined in the **hadronic CoM frame**

$$\cos\theta^* = \mathrm{sign}(y_{\ell\bar\ell})\cos\theta\,,$$

$$\cos\theta \equiv \frac{p_\ell^+ p_{\bar\ell}^- - p_\ell^- p_{\bar\ell}^+}{m_{\ell\bar\ell}\sqrt{m_{\ell\bar\ell}^2 + p_{\mathrm{T},\ell\bar\ell}^2}}, \quad p^\pm = p^0 \pm p^3$$

coincides with the lepton scattering angle in the **partonic CoM frame**

Neutral-Current Drell-Yan

- Express in terms of **symmetric** and **antisymmetric** parton luminosities

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}m_{\ell\bar{\ell}}\,\mathrm{d}y_{\ell\bar{\ell}}\,\mathrm{d}\cos\theta^*} = \frac{\pi\alpha^2}{3m_{\ell\bar{\ell}}s}\left((1+\cos^2(\theta^*))\sum_q S_q\mathcal{L}_{S,q}(m_{\ell\bar{\ell}},y_{\ell\bar{\ell}}) + \cos\theta^*\sum_q A_q\mathcal{L}_{A,q}(m_{\ell\bar{\ell}},y_{\ell\bar{\ell}})\right)$$

dilepton invariant mass

dilepton rapidity

Collins-Soper angle

symmetric effective coupling

antisymmetric effective coupling

even under

$\cos(\theta^*) \to -\cos(\theta^*)$

odd under

$\cos(\theta^*) \to -\cos(\theta^*)$

- Combination of **symmetric** and **antisymmetric contributions** in the Collins-Soper angle
- A **forward-backward (FB) asymmetry** arises when antisymmetric lumi is non-zero

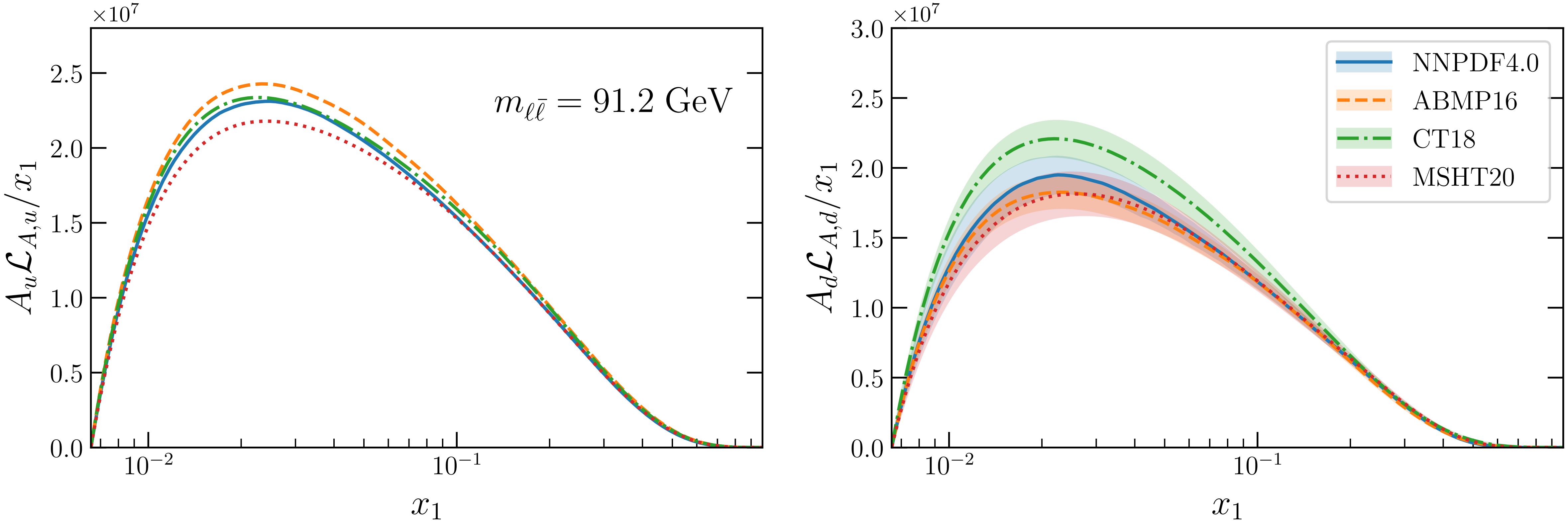
$$\left.\frac{d^3\sigma}{dm_{\ell\bar{\ell}}dy_{\ell\bar{\ell}}d\cos(\theta^*)}\right|_{\mathrm{FB}} = \left.\frac{d^3\sigma}{dm_{\ell\bar{\ell}}dy_{\ell\bar{\ell}}d\cos(\theta^*)}\right|_{\cos\theta^*} - \left.\frac{d^3\sigma}{dm_{\ell\bar{\ell}}dy_{\ell\bar{\ell}}d\cos(\theta^*)}\right|_{-\cos\theta^*}$$

$$\left.\frac{d^3\sigma}{dm_{\ell\bar{\ell}}dy_{\ell\bar{\ell}}d\cos(\theta^*)}\right|_{\mathrm{FB}} = \frac{2\pi\alpha^2\cos(\theta^*)}{3m_{\ell\bar{\ell}}s}\sum_q A_q\mathscr{L}_{A,q}$$

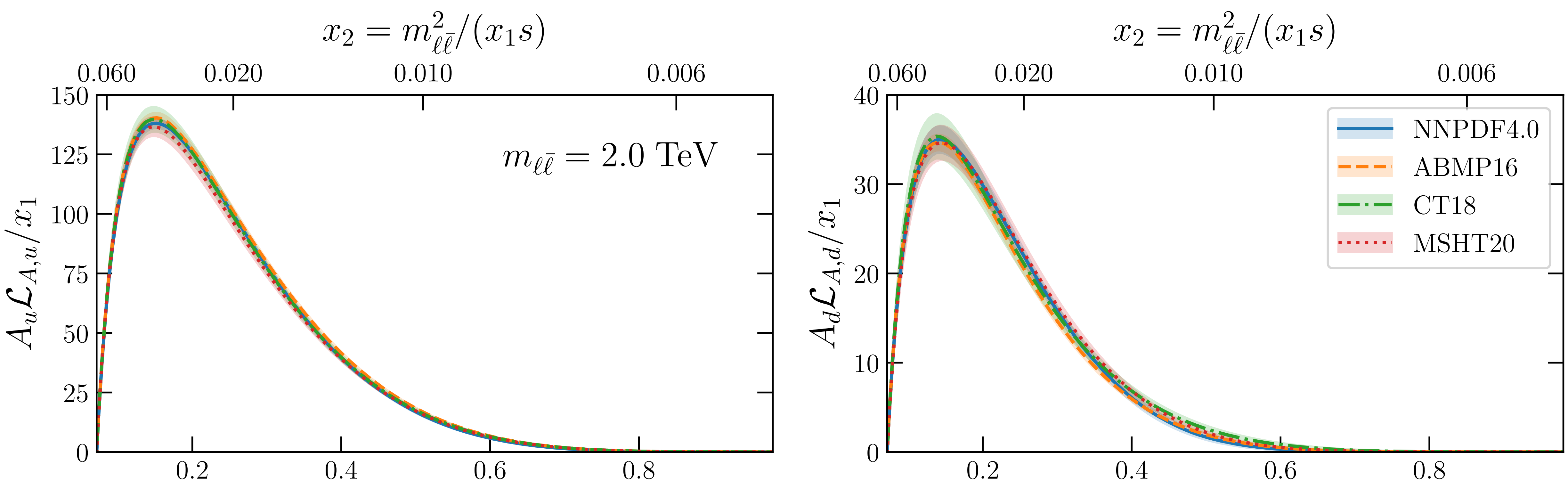
At LO, properties of forward-backward asymmetry dictated by antisymmetric parton luminosity

Antisymmetric PDF luminosities

- At the **Z-peak region** we probe **valence PDFs:** antisymmetric parton lumis behave valence-like



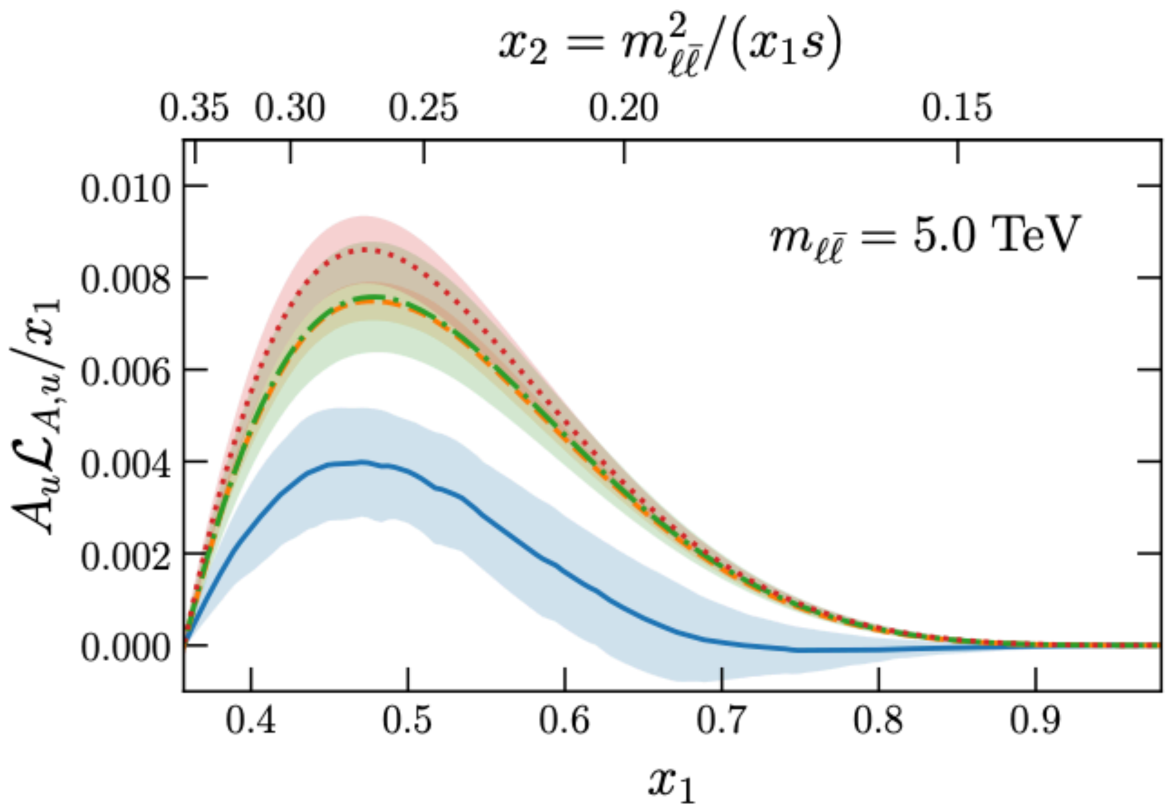
- Same as we go to **2 TeV**, and note good agreement between PDF fits

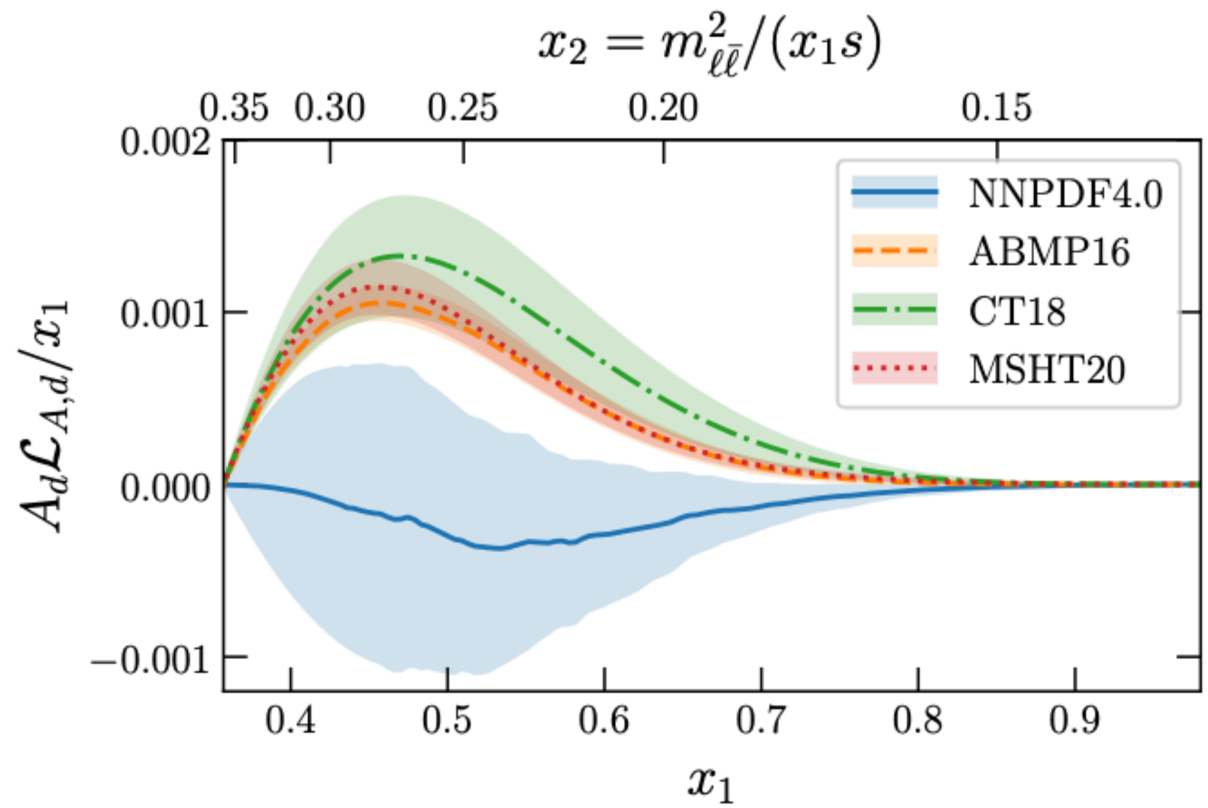


extrapolation to yet higher invariant masses trivial?

Antisymmetric PDF luminosities

- At **5 TeV**, very different behaviour in NNPDF4.0: ***A*_*FB*** may not be positive definite after all





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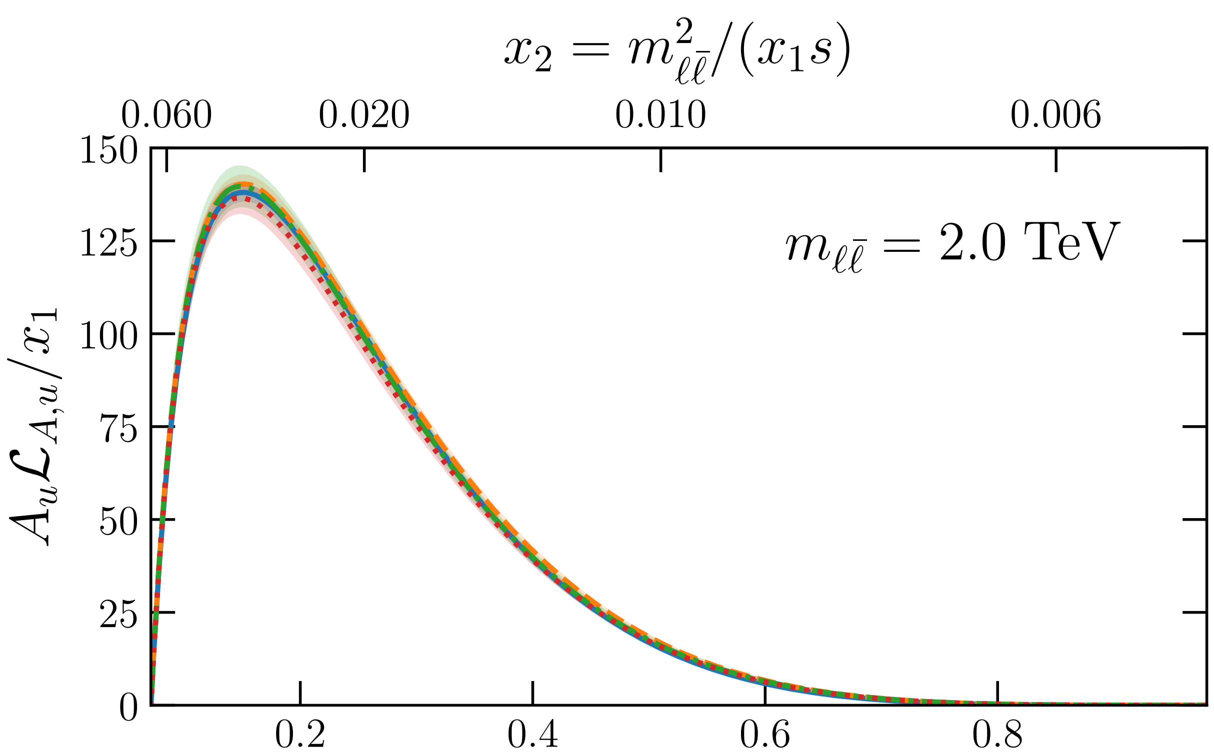
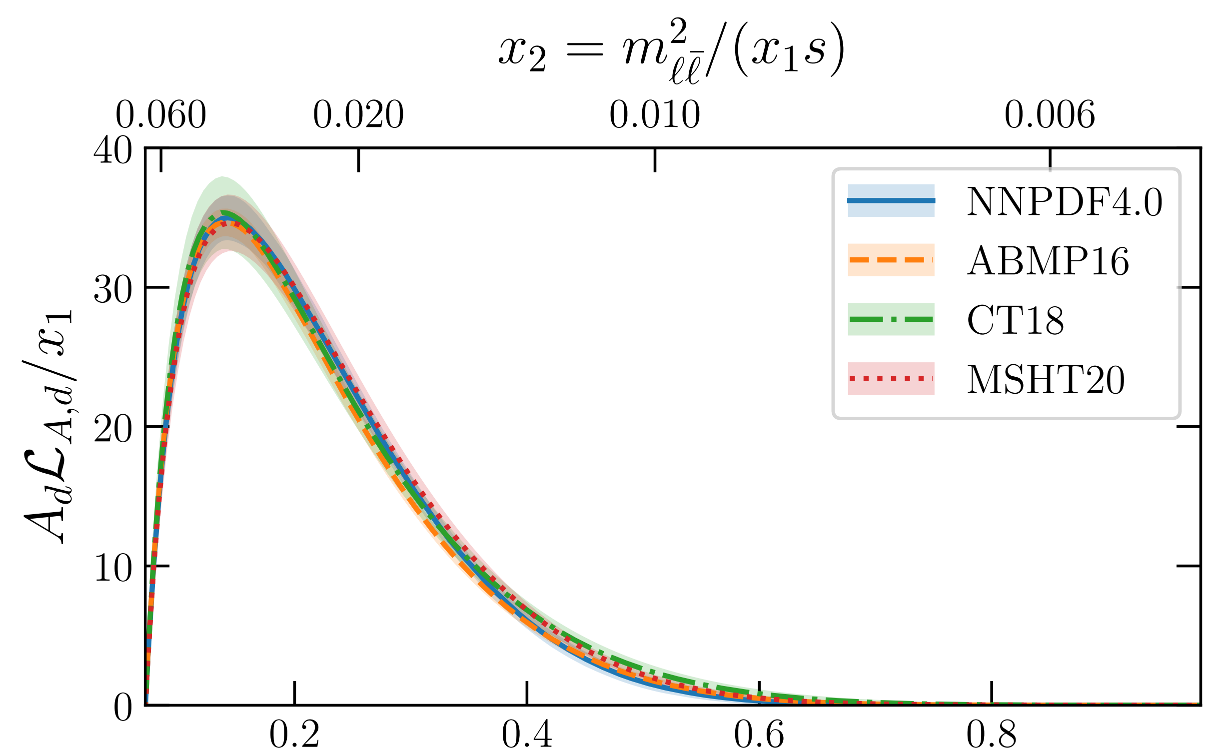
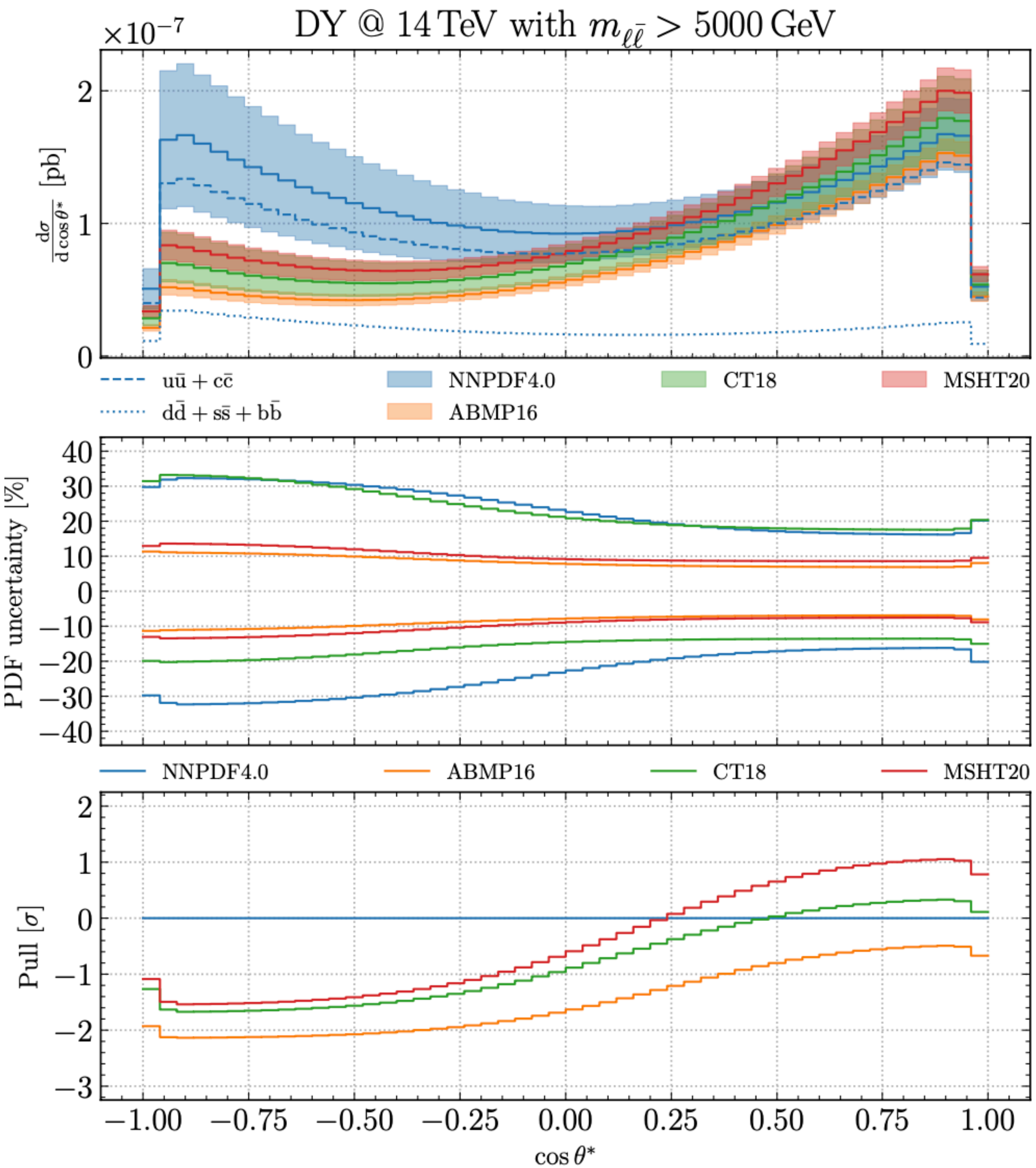


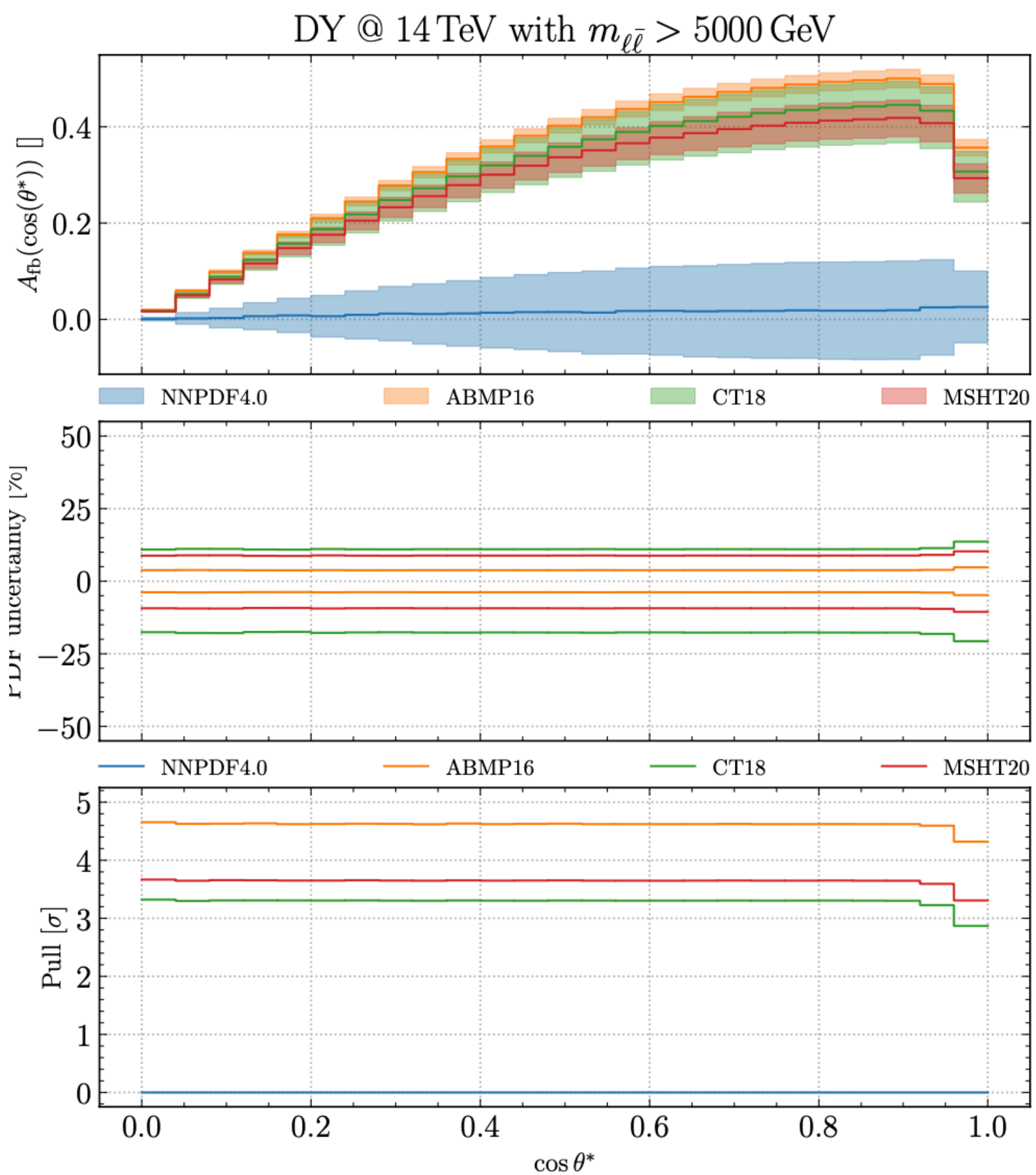


x_1 ***extrapolation to yet higher invariant masses trivial?*** x_1

LHC phenomenology

- For dilepton masses > 5 TeV, $\boldsymbol{A_{FB}}$ vanishes for NNPDF4.0, while other groups extrapolate





Further data required, Jlab 22 GeV upgrade would be perfect for this

Scrutinising the charm content of the proton

The charm content of the proton

common assumption in PDF fits: the static proton wave function does not contain charm quarks: the proton contains **intrinsic up, down, strange (anti-)quarks** but **no intrinsic charm quarks**

the charm PDF is **generated perturbatively** (DGLAP evolution) from radiation off gluons and quarks

$$f_c^{(n_f)} = 0 \quad \rightarrow \quad f_c^{(n_f+1)} \propto \alpha_s \ln \frac{Q^2}{m_c^2} \left(P_{qg} \otimes f_g^{(n_f+1)} \right) + \mathcal{O}\left(\alpha_s^2\right)$$

NLO matching

3FNS charm → ***4FNS charm***, ***4FNS gluon***

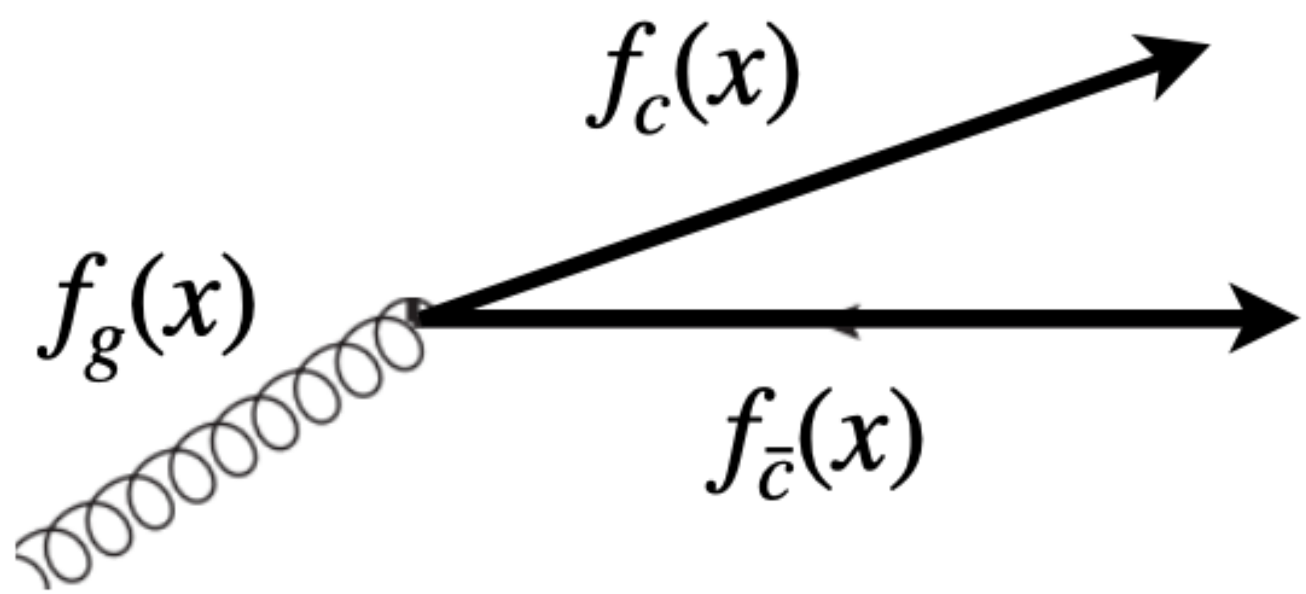
4 flavour scheme, $Q > m_c$

$u^{(4)}, d^{(4)}, s^{(4)}, c^{(4)} g^{(4)}$

$\updownarrow \quad \updownarrow$

3 flavour scheme, $Q < m_c$

$u^{(3)}, d^{(4)}, s^{(3)}, g^{(3)}$



If charm is **perturbatively generated**, the charm PDF is **trivial**

The charm content of the proton

common assumption in PDF fits: the static proton wave function does not contain charm quarks: the proton contains **intrinsic up, down, strange (anti-)quarks** but **no intrinsic charm quarks**

It does not need to be so! An **intrinsic charm component** predicted in many models

THE INTRINSIC CHARM OF THE PROTON

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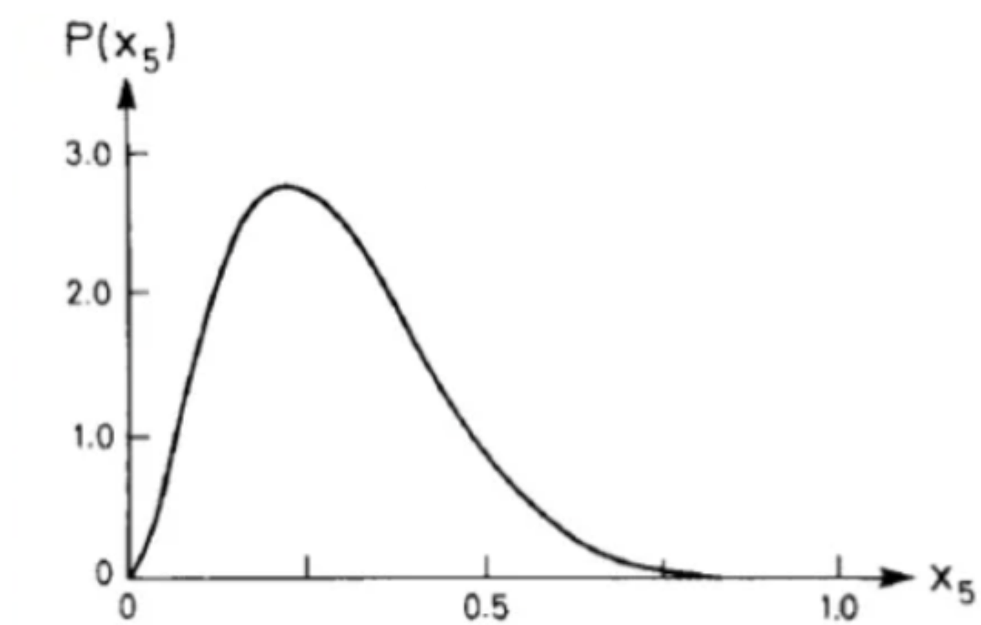
Received 22 April 1980



$$|p\rangle = \mathscr{P}_{3q}\,|uud\rangle + \mathscr{P}_{5q}\,|uudc\bar{c}\rangle + \ldots$$

Recent data give unexpectedly large cross-sections for charmed particle production at high x_F in hadron collisions. This may imply that the proton has a non-negligible $uudc\bar{c}$ Fock component. The interesting consequences of such a hypothesis are explored.

40 years of extensive searches for intrinsic charm: no unambiguous evidence ….

Disentangling intrinsic charm

$$c^{(n_f=4)}(x,Q) \simeq c^{(n_f=4)}_{\rm (pert)}(x,Q) + c^{(n_f=4)}_{\rm (intr)}(x,Q)$$

Extracted phenomenologically from data

from pQCD evolution and matching

from intrinsic component $c^{(n_f=3)}_{\rm (intr)}(x) \neq 0$

4FNS CHARM PDF CONSTRAINED BY EXPERIMENTAL DATA FOR $Q > Q_0$

- NNPDF4.0 dataset
- NNLO QCD calculations

QCD evolution

starting point: NNPDF 4.0 methodology

4FNS CHARM PDF PARAMETRISED AT Q_0

- Deep-learning parametrisation
- Monte Carlo representation of uncertainties

$Q_0 =$ 1.65 GeV

Disentangling intrinsic charm

$$c^{(n_f=4)}(x,Q) \simeq c^{(n_f=4)}_{\text{(pert)}}(x,Q) + c^{(n_f=4)}_{\text{(intr)}}(x,Q)$$

Extracted phenomenologically from data

from pQCD evolution and matching

from intrinsic component $c^{(n_f=3)}_{\text{(intr)}}(x) \neq 0$

4FNS Charm PDF constrained by experimental data for $Q > Q_0$

- NNPDF4.0 dataset
- NNLO QCD calculations

QCD evolution

starting point: NNPDF 4.0 methodology

$Q_0 =$ 1.65 GeV

4FNS Charm PDF parametrised at Q_0

- Deep-learning parametrisation
- Monte Carlo representation of uncertainties

QCD evolution

subtract perturbative component

4FNS to 3FNS transformation

NNLO or N^{3}LO matching conditions

$$c^{(n_f=3)}(x,Q) = c_{\text{(intr)}}(x)$$

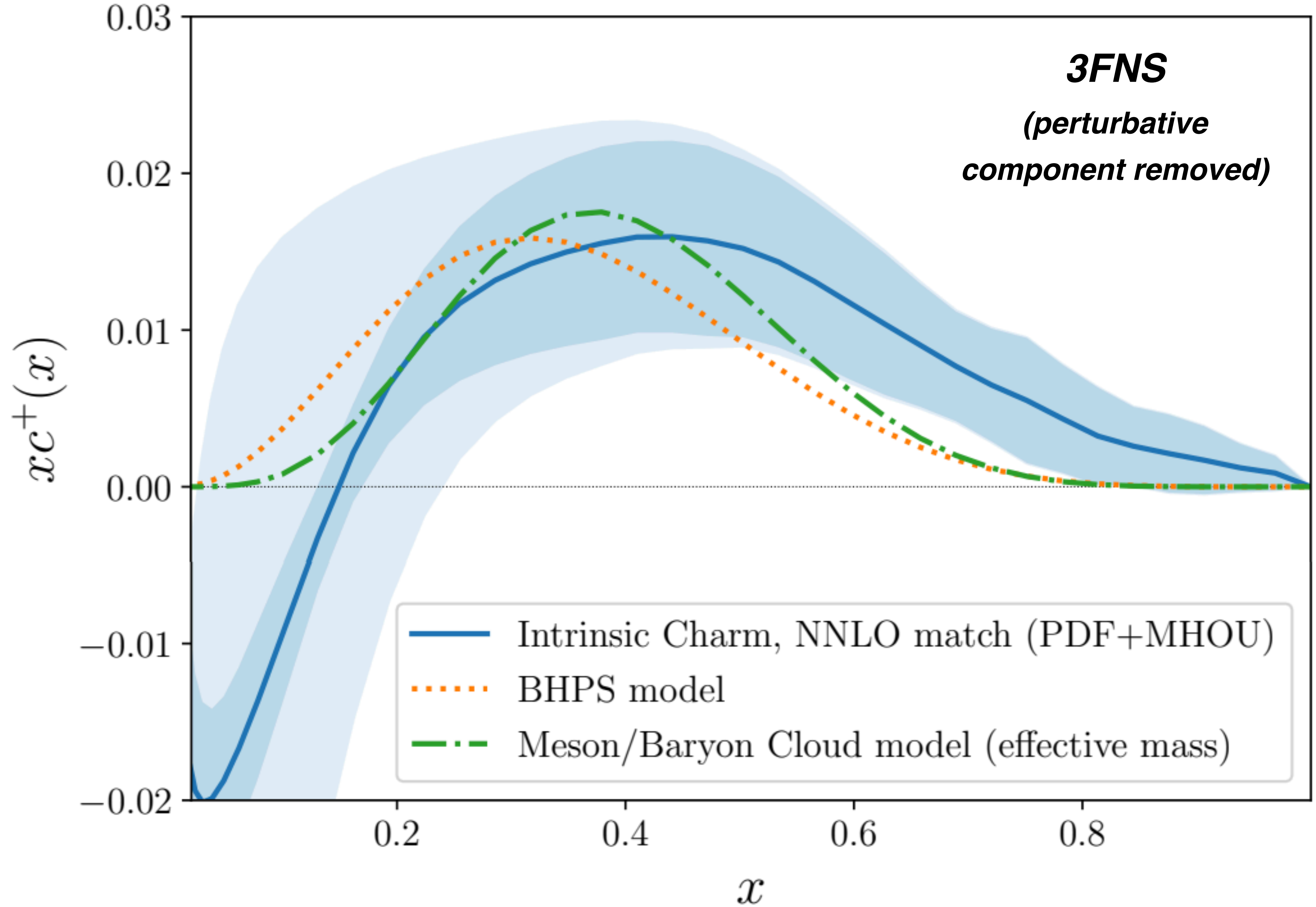
Intrinsic (3FNS) Charm

- Scale-independent
- PDF and MHO uncertainties

EKO

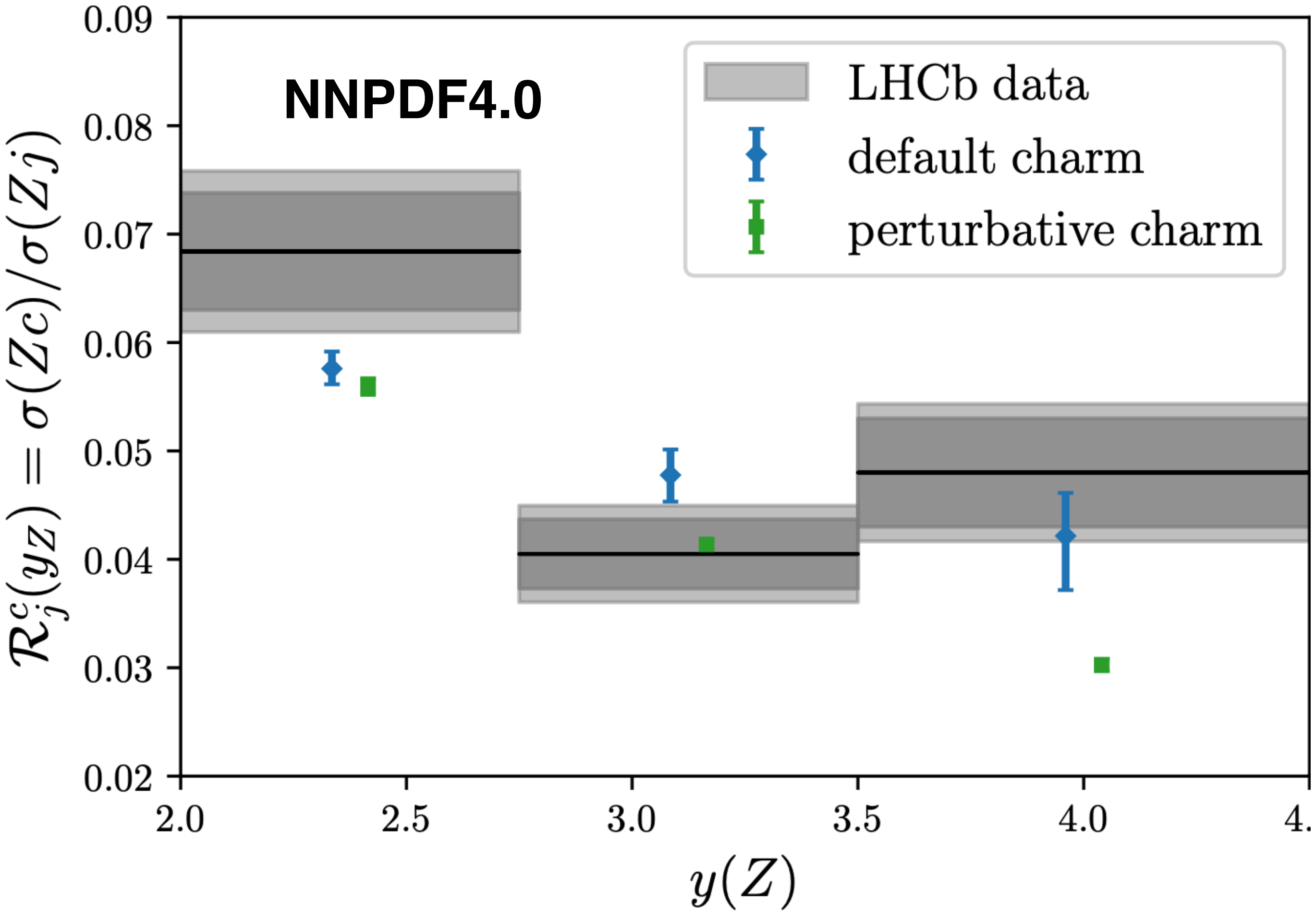
Evolution Kernel Operators

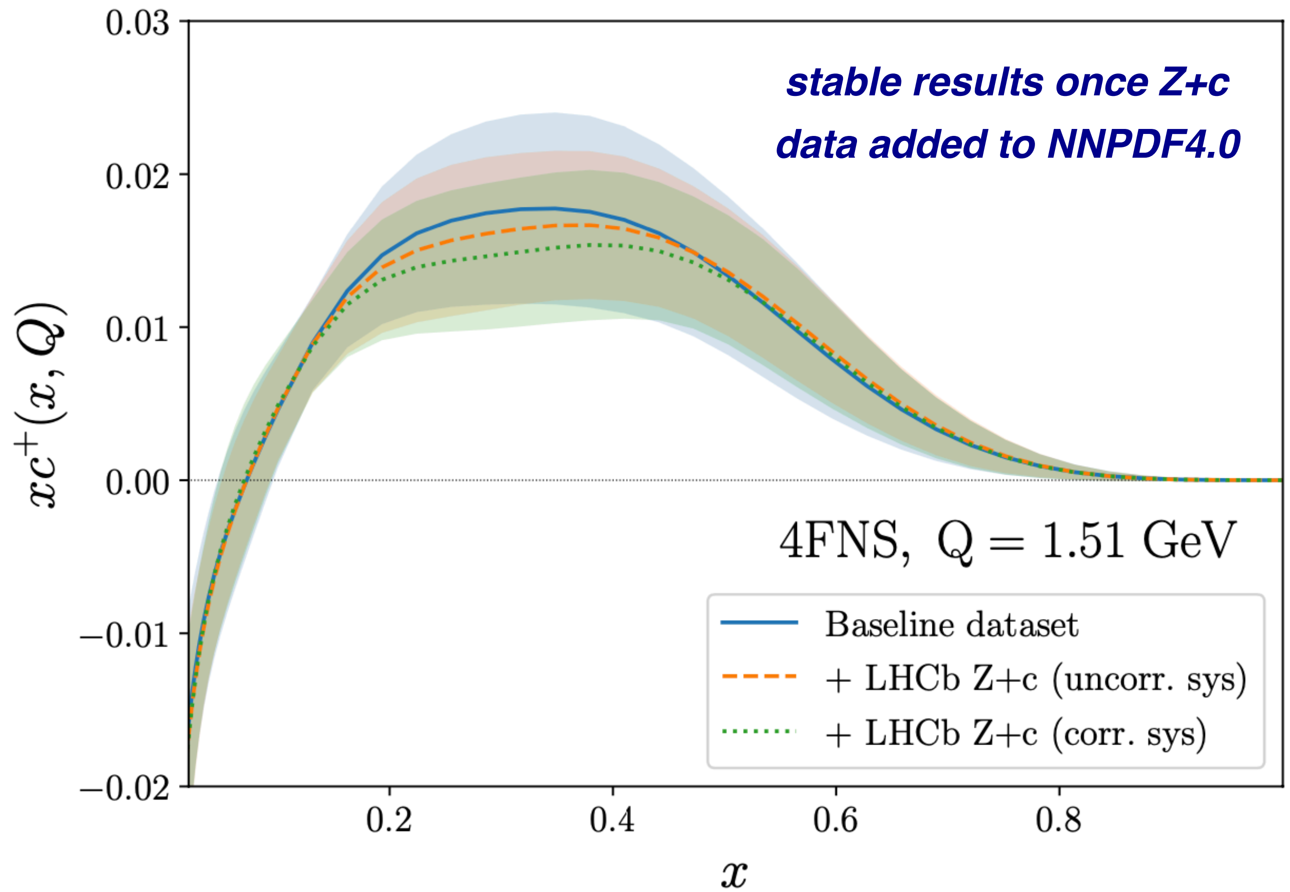
4FNS to 3FNS transformation



The 3FNS charm PDF displays **non-zero component** peaked at large-*x* which can be identified with **intrinsic charm**

Z+charm @ LHCb





- Calculations settings: **NLO+Pythia8 via the POWHEG-BOX** (charm fragmentation from shower), accounting for MHO and PDF uncertainties (MHOUs cancel partially in ratio)
- Charm jets defined by **overlap of anti-k_t jets with reconstructed *D*-mesons** to reproduce experimental analyses: includes contribution from g => c+cbar splittings
- However, there are *i)* suppressed in forward region where IC effects stronger and *ii)* do not affect shape
- Fixed-order QCD cannot be used to compare with (current) data due to **lack of flavour IR-safe definition**

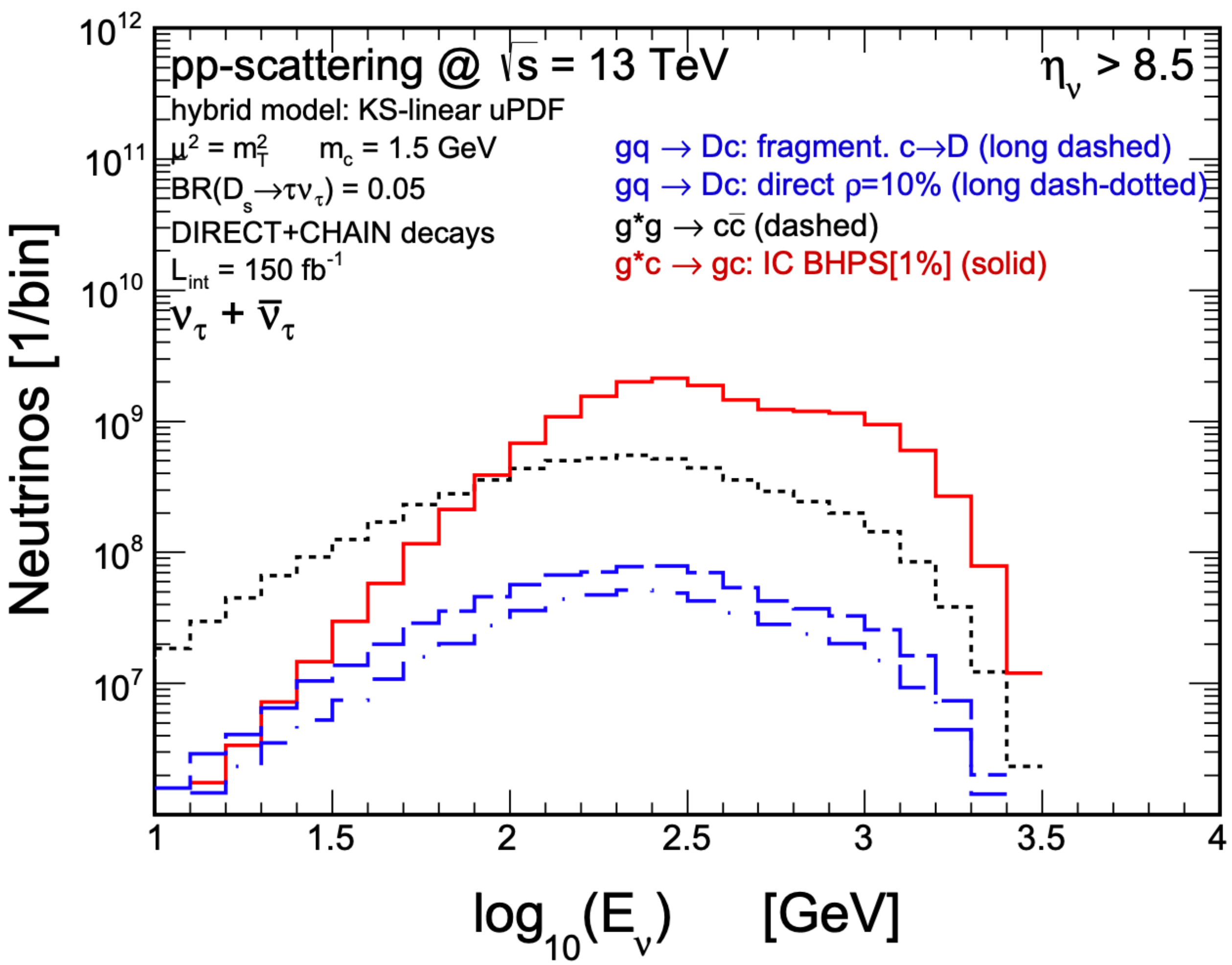
Further testing intrinsic heavy quarks

- With more LHC data, study also the possibility of **intrinsic bottom quarks** and of an **intrinsic charm - anticharm asymmetry**

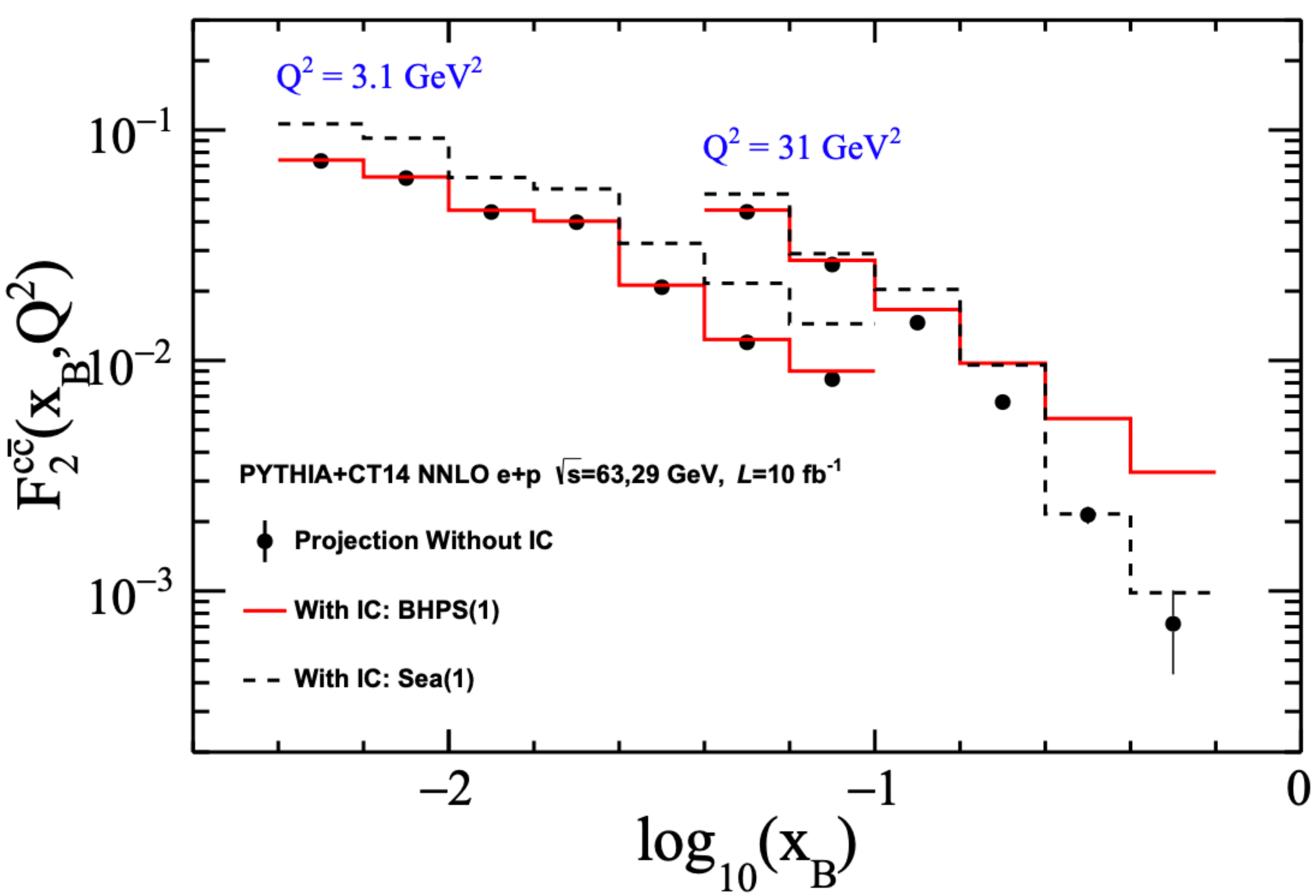
- Better charm structure function measurements to become available at **Electron Ion Collider -** but maybe also at a **22 GeV upgrade of JLab!**

- IC will also affect rates for **prompt neutrino fluxes** in neutrino telescopes, main background for extraterrestrial high-energy neutrinos

forward charm production



charm @ Electron Ion Collider

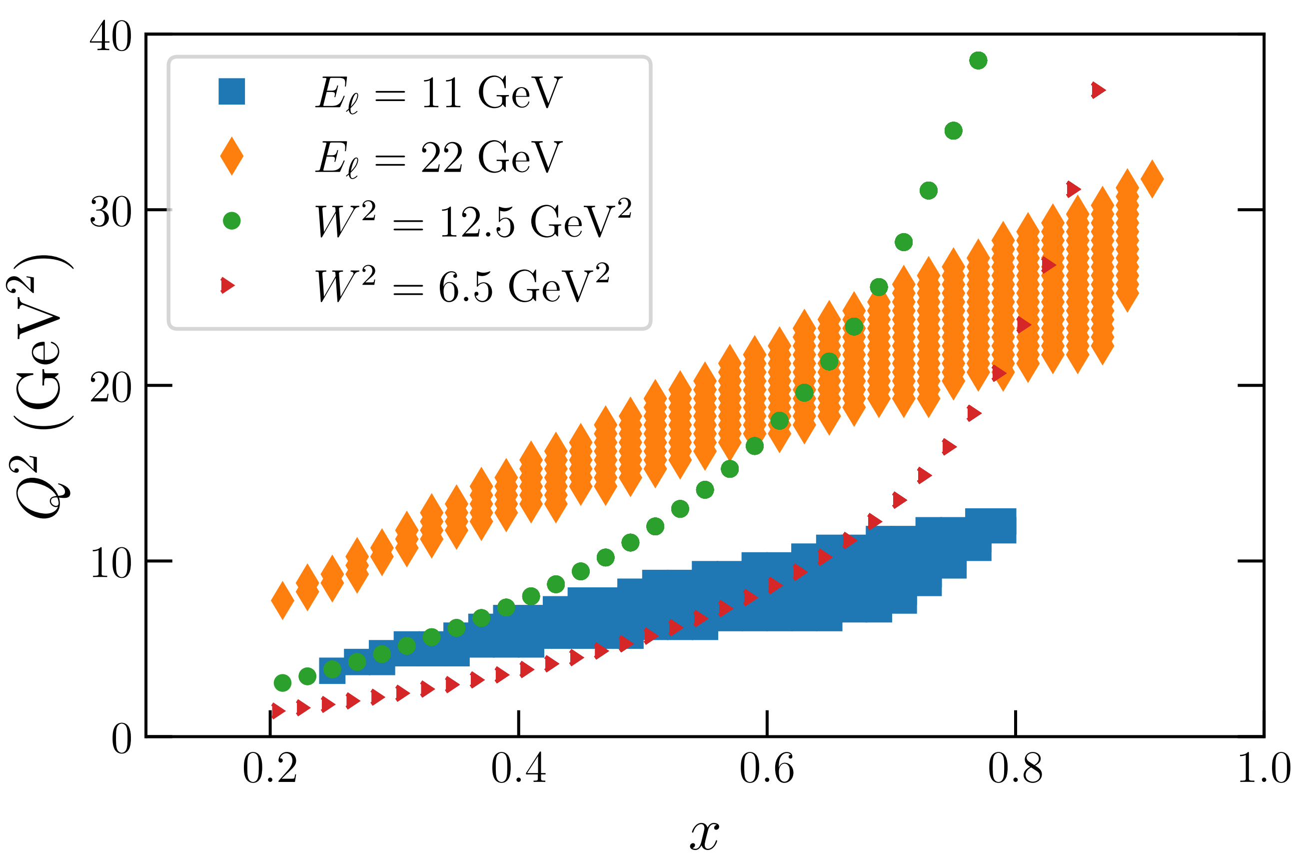


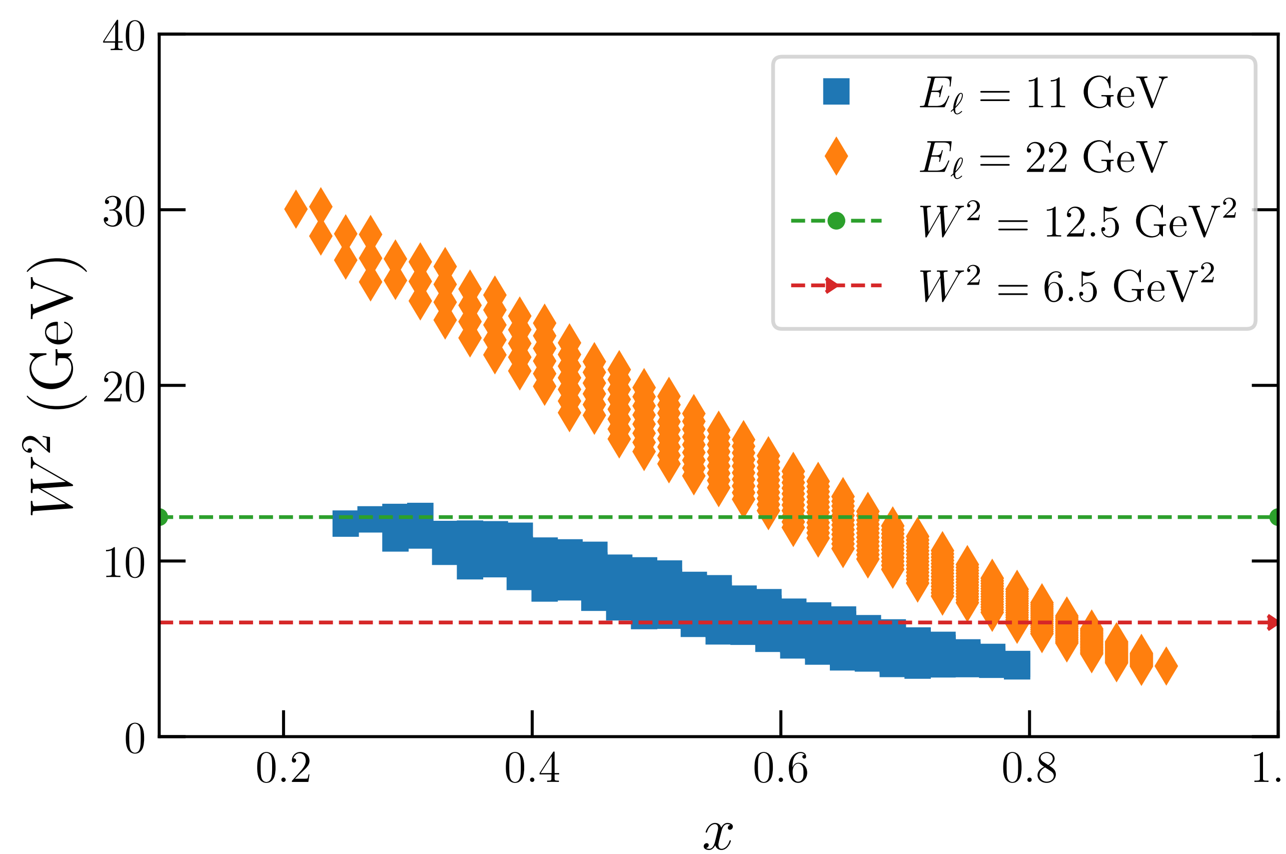
Summary and outlook

- The availability of 22 GeV beam at JLab opens new science opportunities for hadronic physics

- Jlab22 data probes large-x quark and antiquark PDFs in a region where LT dominates and a clean pQCD interpretation is possible: direct input for **New Physics searches at the (HL-)LHC**

- Jlab22 can access charm production: test predictions for **intrinsic heavy quarks** in the nucleon



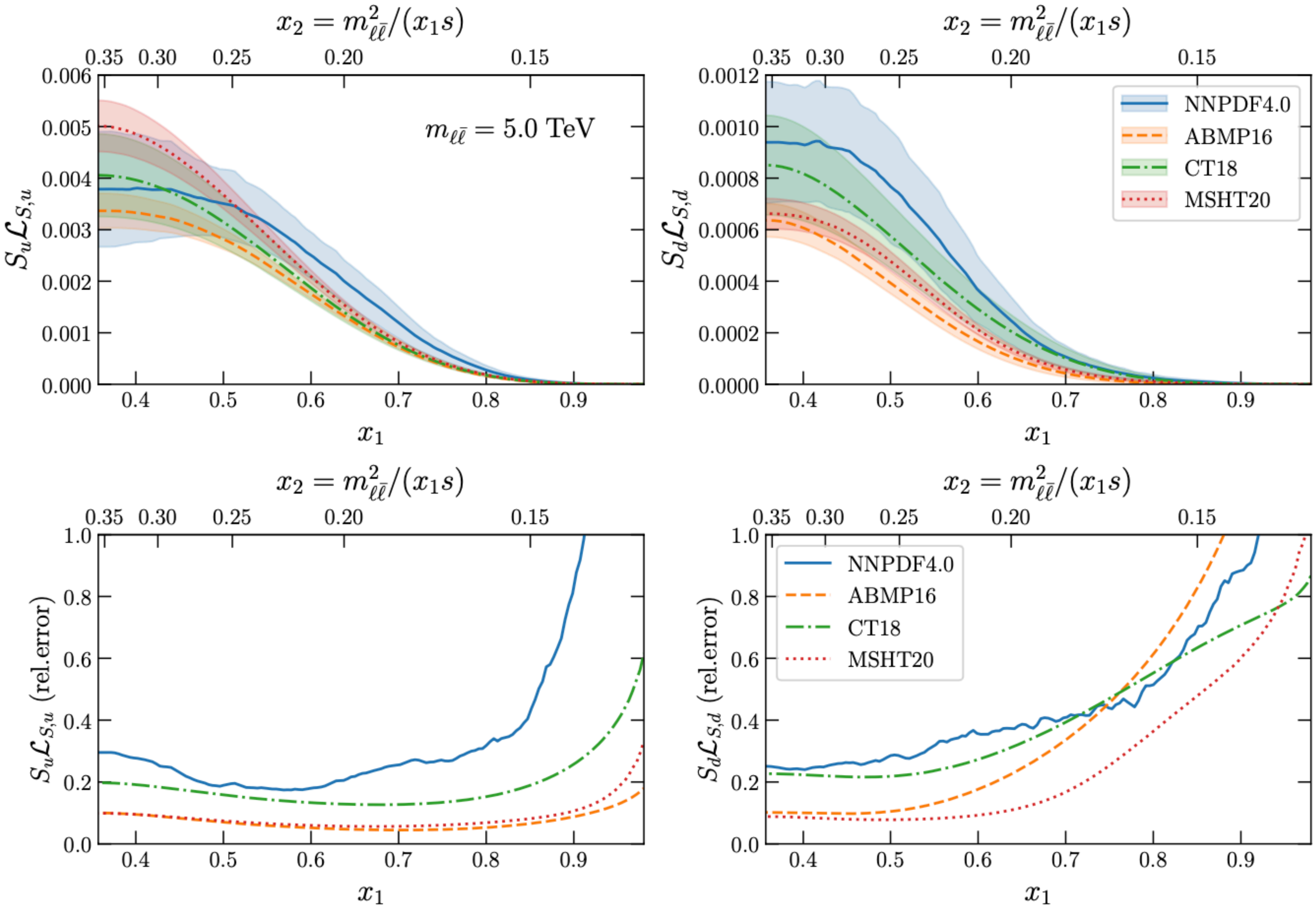


just an initial sketch, quantitative studies needed to further strengthen physics case

Extra Material

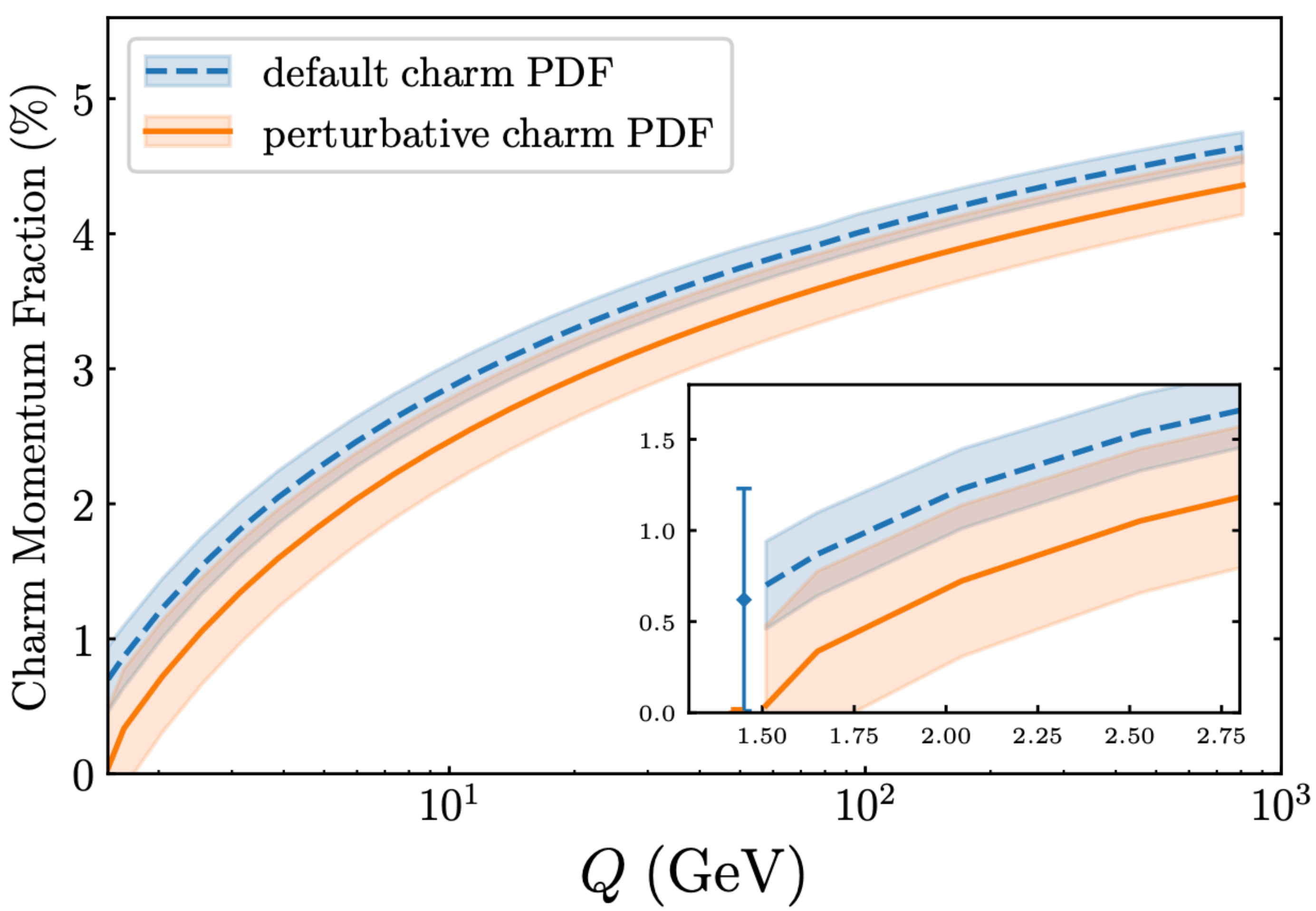
Symmetric PDF luminosities

- On the other hand, symmetric parton luminosities are in **good qualitative agreement** even at very high masses, with **NNPDF4.0** displaying the largest PDF uncertainties



The charm momentum fraction

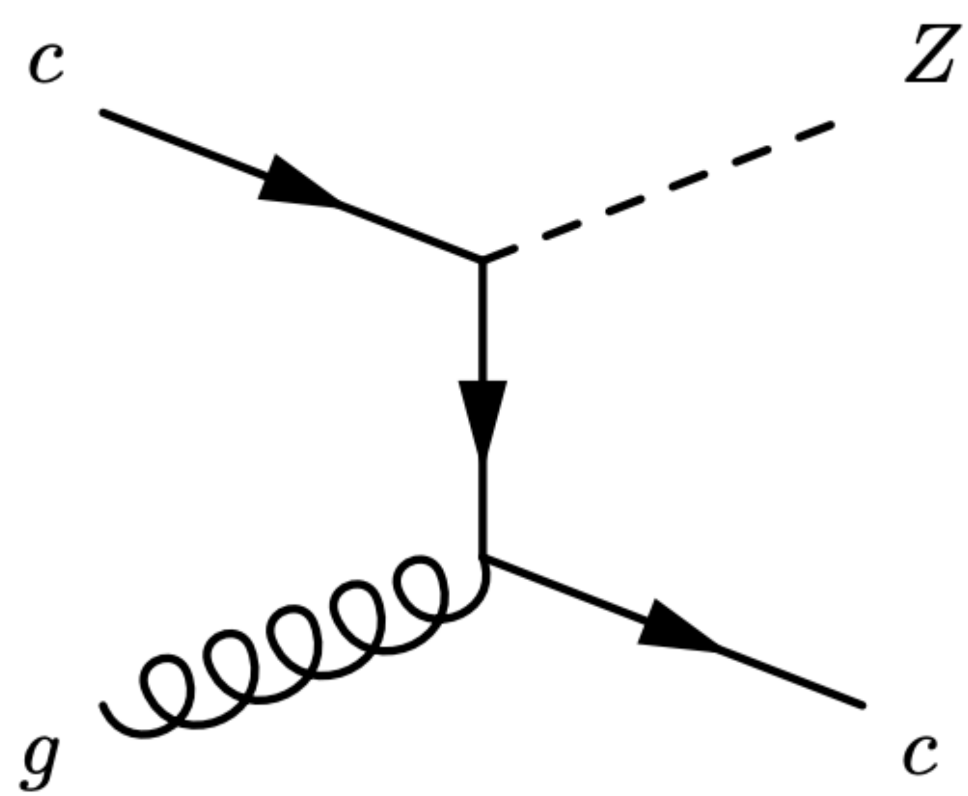
Scheme	Q	Charm PDF	m_c	$[c]$ (%)
3FNS	–	default	1.51 GeV	$0.62 \pm 0.28_{\rm pdf} \pm 0.54_{\rm mhou}$
3FNS	–	default	1.38 GeV	$0.47 \pm 0.27_{\rm pdf} \pm 0.62_{\rm mhou}$
3FNS	–	default	1.64 GeV	$0.77 \pm 0.28_{\rm pdf} \pm 0.48_{\rm mhou}$
4FNS	1.65 GeV	default	1.51 GeV	$0.87 \pm 0.23_{\rm pdf}$
4FNS	1.65 GeV	default	1.38 GeV	$0.94 \pm 0.22_{\rm pdf}$
4FNS	1.65 GeV	default	1.64 GeV	$0.84 \pm 0.24_{\rm pdf}$
4FNS	1.65 GeV	perturbative	1.51 GeV	$0.346 \pm 0.005_{\rm pdf} \pm 0.44_{\rm mhou}$
4FNS	1.65 GeV	perturbative	1.38 GeV	$0.536 \pm 0.006_{\rm pdf} \pm 0.49_{\rm mhou}$
4FNS	1.65 GeV	perturbative	1.64 GeV	$0.172 \pm 0.003_{\rm pdf} \pm 0.41_{\rm mhou}$

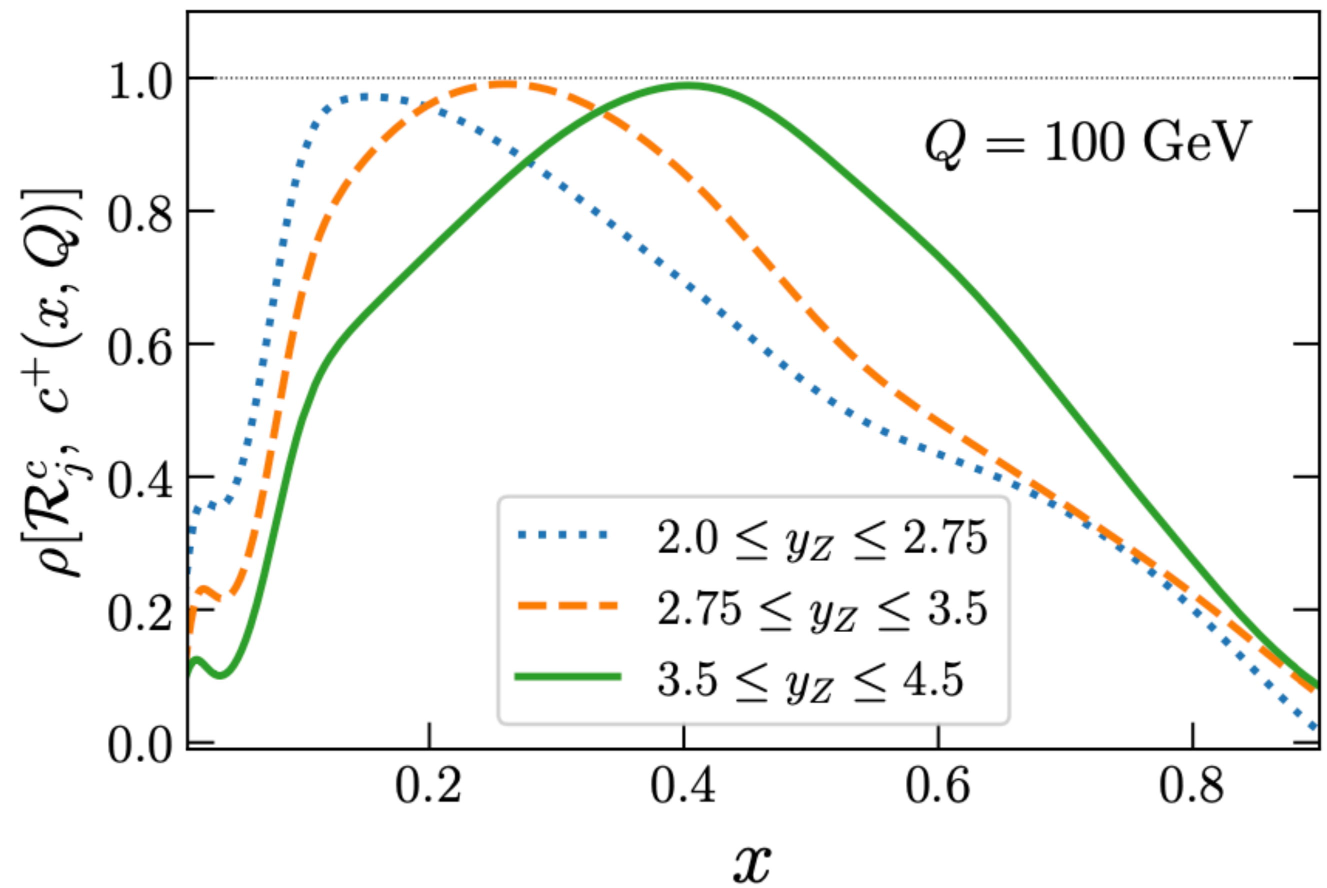


Intrinsic charm carries around **0.5%** of the proton's total momentum

Z+charm @ LHCb

Direct handle on the **charm content of the proton**

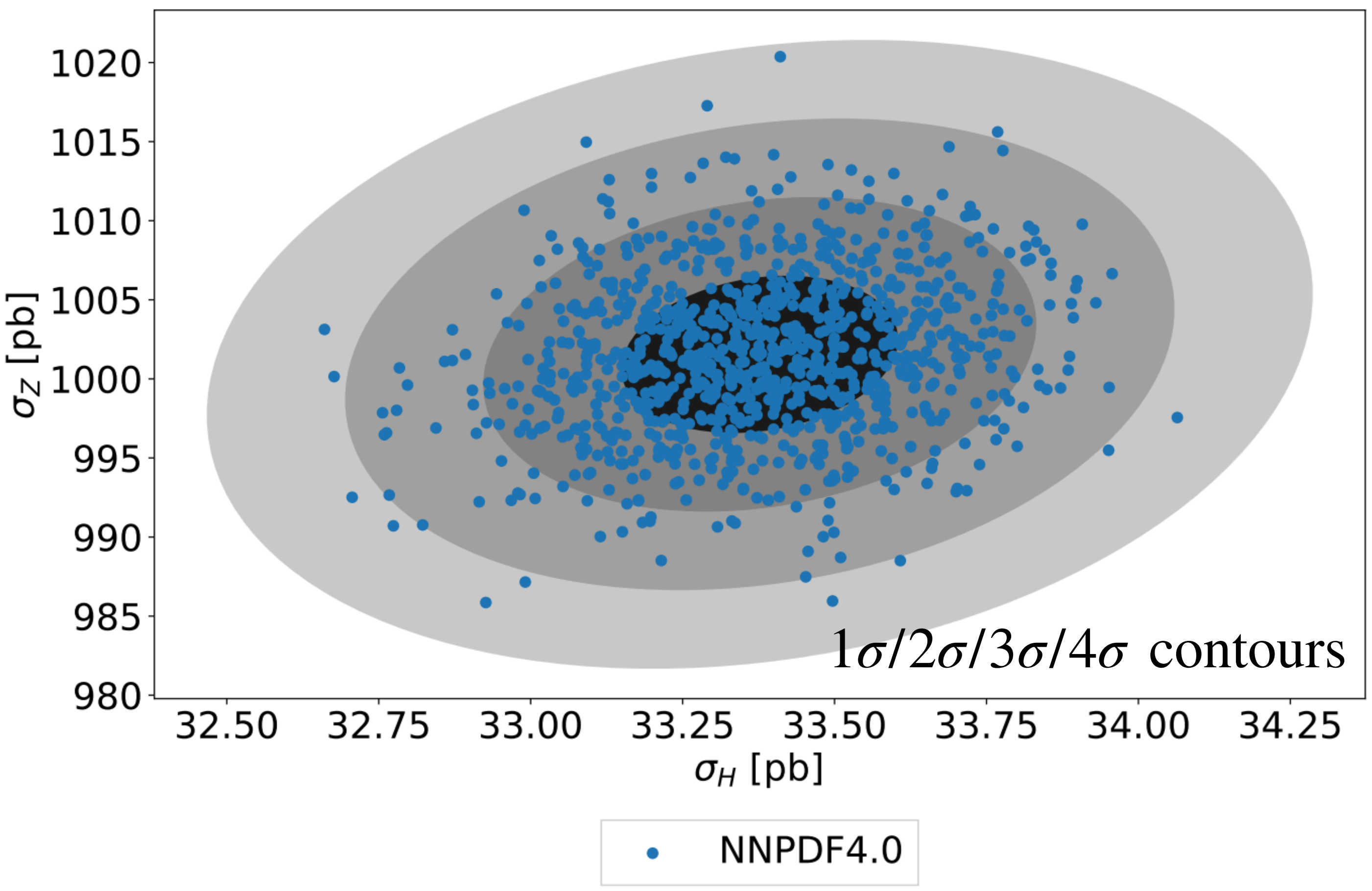


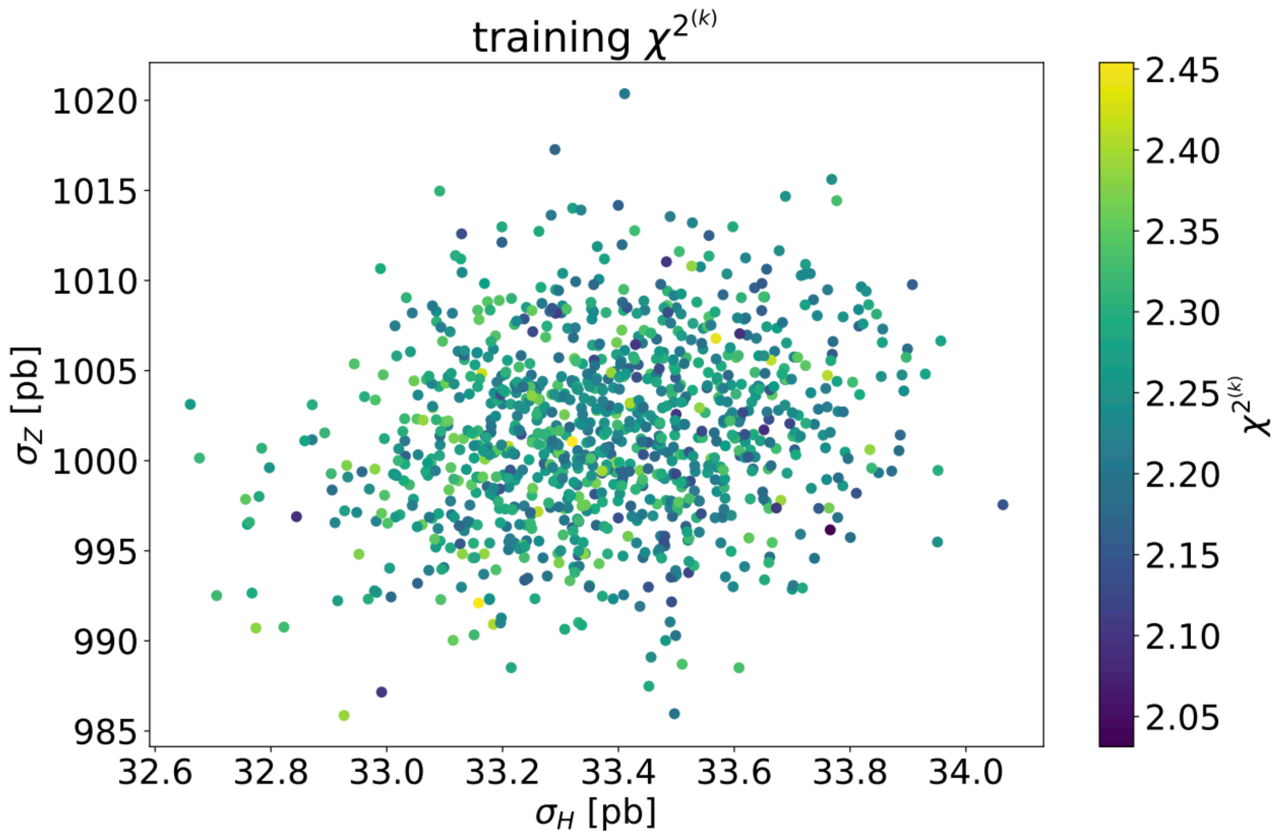


$$\mathcal{R}_j^c(y_Z) \equiv \frac{N(c \text{ tagged jets}; y_Z)}{N(\text{jets}; y_Z)} = \frac{\sigma(pp \to Z + \text{charm jet}; y_Z)}{\sigma(pp \to Z + \text{jet}; y_Z)}$$

Z+charm at forward rapidities (LHCb) sensitive to the **charm PDF up to *x*=0.5**

Representative sampling in NNPDF



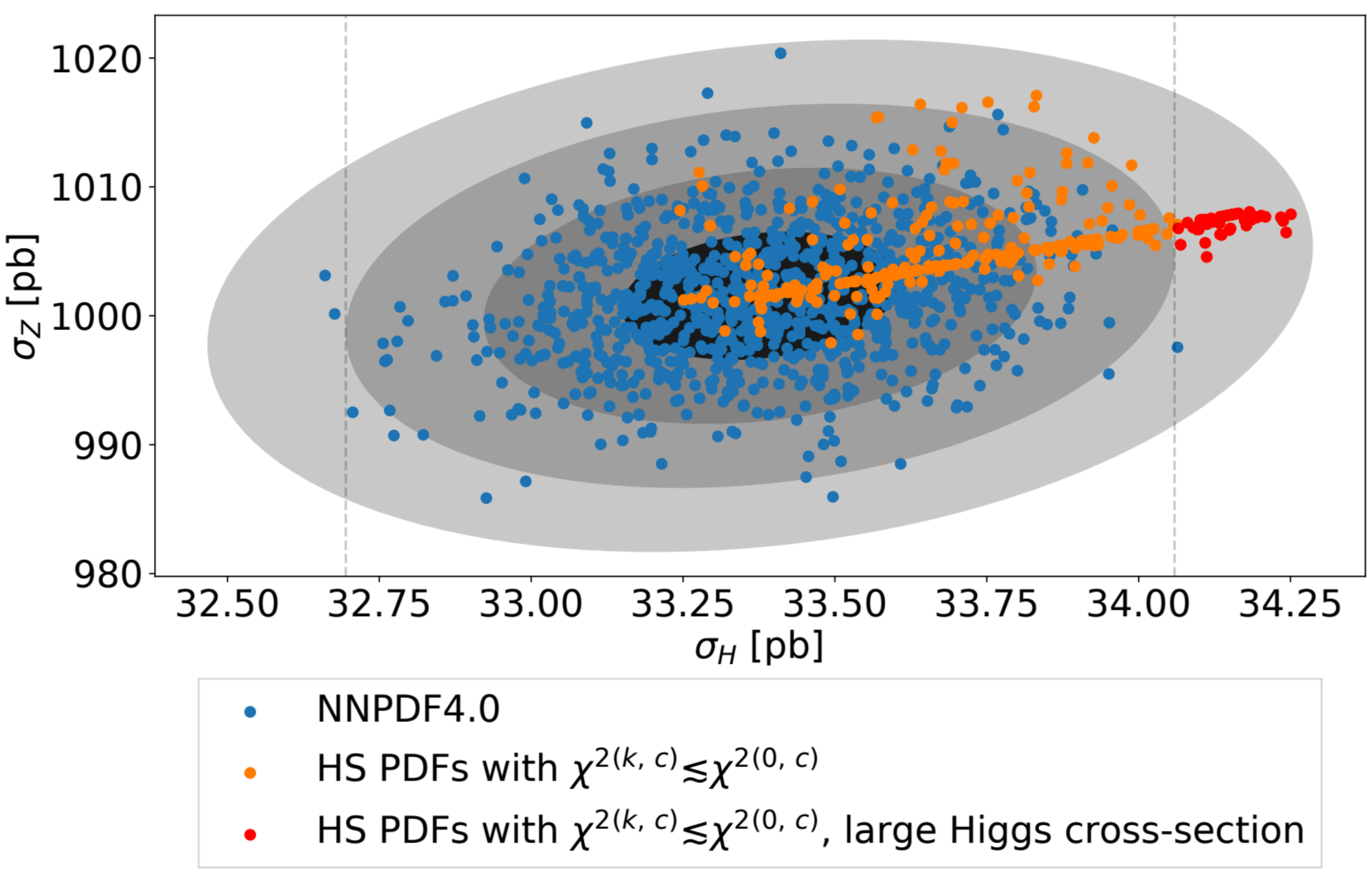


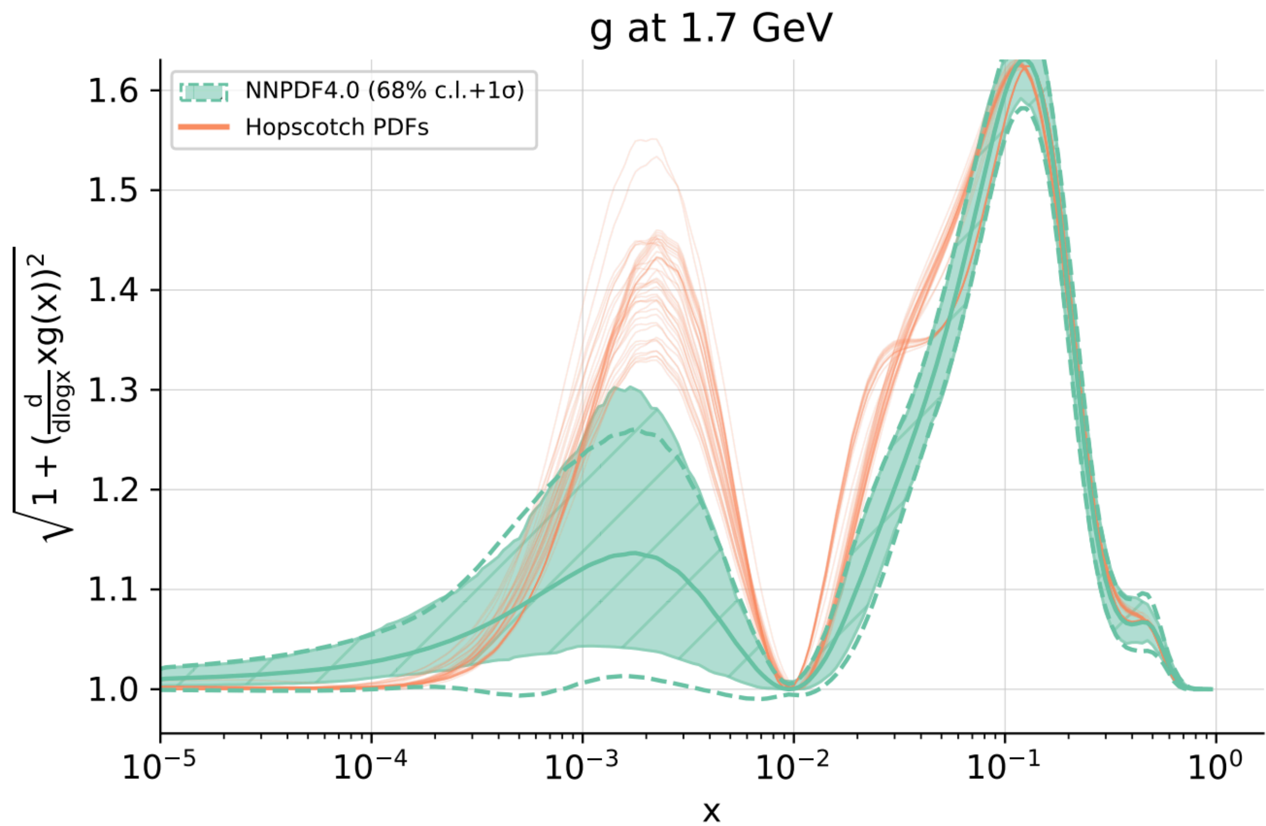
- NNPDF4.0 replicas behave as expected for **representative sampling** e.g. around 50 replicas out of a sample of 1000 fall outside 95% CL contours
- The χ^2 is **not the only measure of the likelihood of a replica**, theory and methodological constraints (e.g. integrability, smoothness) are also accounted for
- For a sufficiently large number of sampled replicas, **solutions with lower χ^2** than the ``central'' (average) replica are guaranteed to be found

The hopscotch PDFs

CT Hopscotch (HS) PDFs: arXiv:2205.10444

- **Linear combinations of NNPDF4.0 replicas**, some of them with lower χ^2 than the average NNPDF4.0 PDF set, constructed using NNPDF open-source code





- HS PDFs **do not provide representative sampling,** *e.g.* cannot be used to determine PDF errors
- Similar PDFs can be found with the NNPDF methodology, albeit with **very low probability**
- **Kinetic energy** (local measure of non-smoothness) systematically higher in HS PDFs

Large-x extrapolation

- Reliable estimates of **PDF uncertainties at large-x** crucial for BSM searches at LHC
- Take the **forward-backward asymmetry** in high-mass neutral current Drell-Yan as case study

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}m_{\ell\bar{\ell}}\,\mathrm{d}y_{\ell\bar{\ell}}\,\mathrm{d}\cos\theta^*} = \frac{\pi\alpha^2}{3m_{\ell\bar{\ell}}s}\left(\underbrace{(1+\cos^2(\theta^*))\sum_q S_q\mathcal{L}_{S,q}(m_{\ell\bar{\ell}},y_{\ell\bar{\ell}})}_{\textit{symmetric in }\cos\theta^*} + \underbrace{\cos\theta^*\sum_q A_q\mathcal{L}_{A,q}(m_{\ell\bar{\ell}},y_{\ell\bar{\ell}})}_{\textit{antisymmetric in }\cos\theta^*}\right)$$

$$\mathcal{L}_{S,q}(m_{\ell\bar{\ell}},y_{\ell\bar{\ell}}) \equiv f_q(x_1,m^2_{\ell\bar{\ell}})f_{\bar{q}}(x_2,m^2_{\ell\bar{\ell}}) + f_q(x_2,m^2_{\ell\bar{\ell}})f_{\bar{q}}(x_1,m^2_{\ell\bar{\ell}})\,,$$
$$\mathcal{L}_{A,q}(m_{\ell\bar{\ell}},y_{\ell\bar{\ell}}) \equiv \mathrm{sign}(y_{\ell\bar{\ell}})\left[f_q(x_1,m^2_{\ell\bar{\ell}})f_{\bar{q}}(x_2,m^2_{\ell\bar{\ell}}) - f_q(x_2,m^2_{\ell\bar{\ell}})f_{\bar{q}}(x_1,m^2_{\ell\bar{\ell}})\right]$$

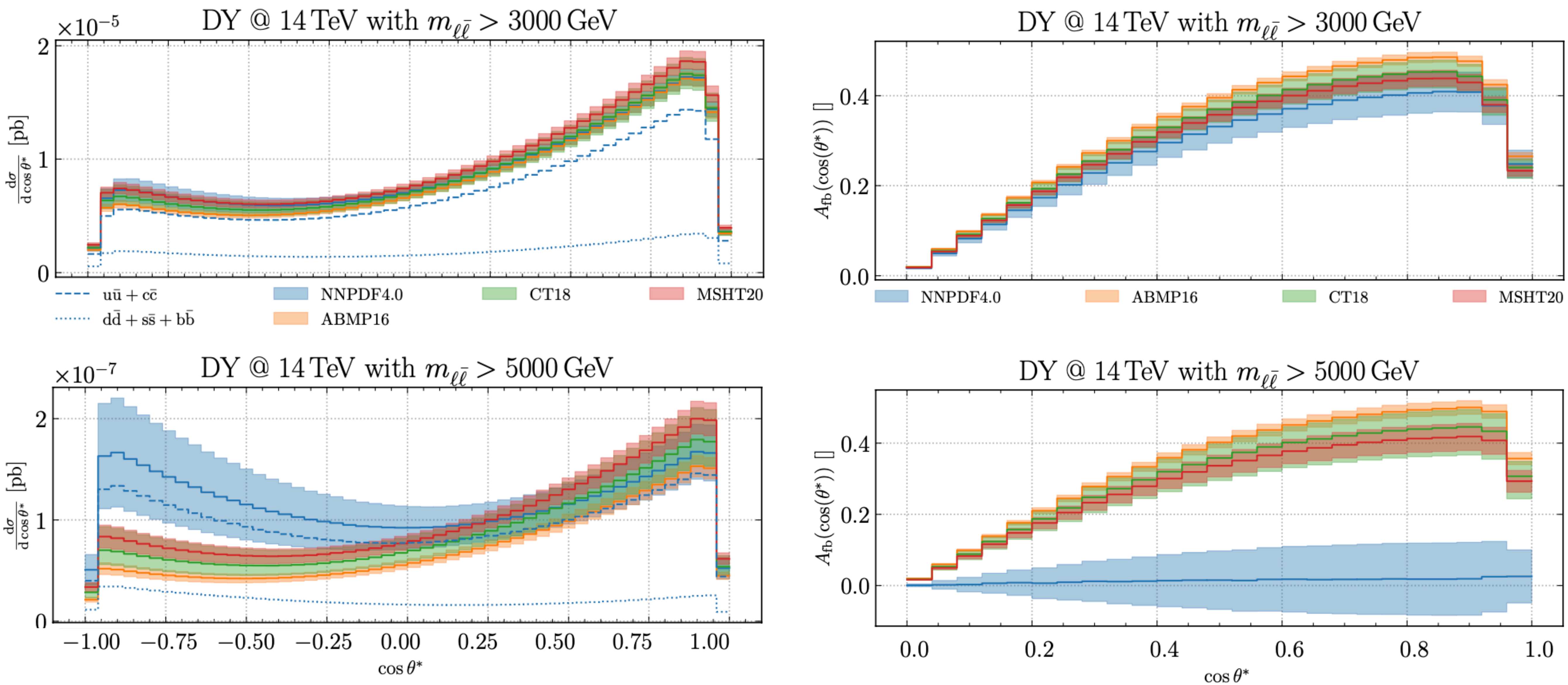
- Relevant for non-resonant BSM searches and for determination of precision SM parameters

$$A_{\mathrm{fb}}(\cos\theta^*) \equiv \frac{\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*}(\cos\theta^*) - \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*}(-\cos\theta^*)}{\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*}(\cos\theta^*) + \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*}(-\cos\theta^*)}\,, \quad \cos\theta^* > 0\,,$$

- PDF sets based on fixed-functional forms and NNPDF agree for symmetric (in Collins-Soper angle) distributions, **different results for antisymmetric ones like A_{FB}**

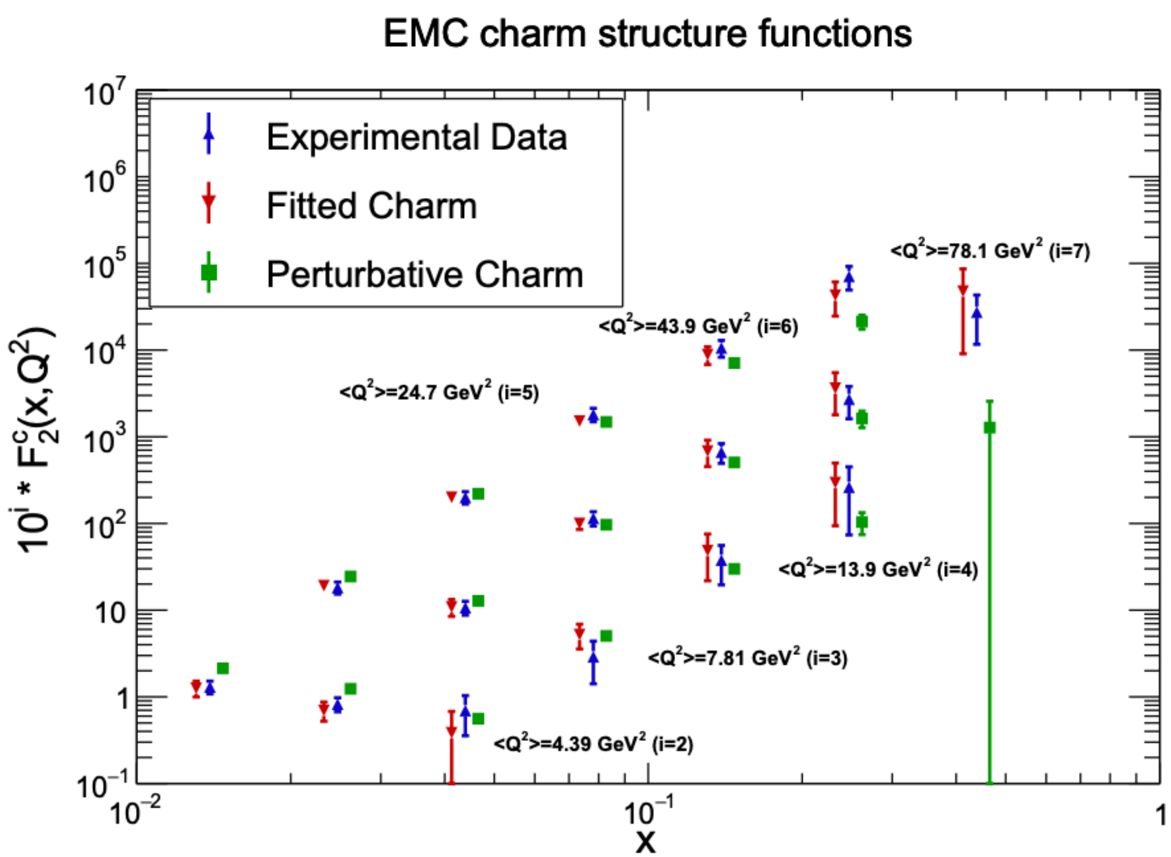
NNPDF, arXiv:2209.08115

Large-x extrapolation

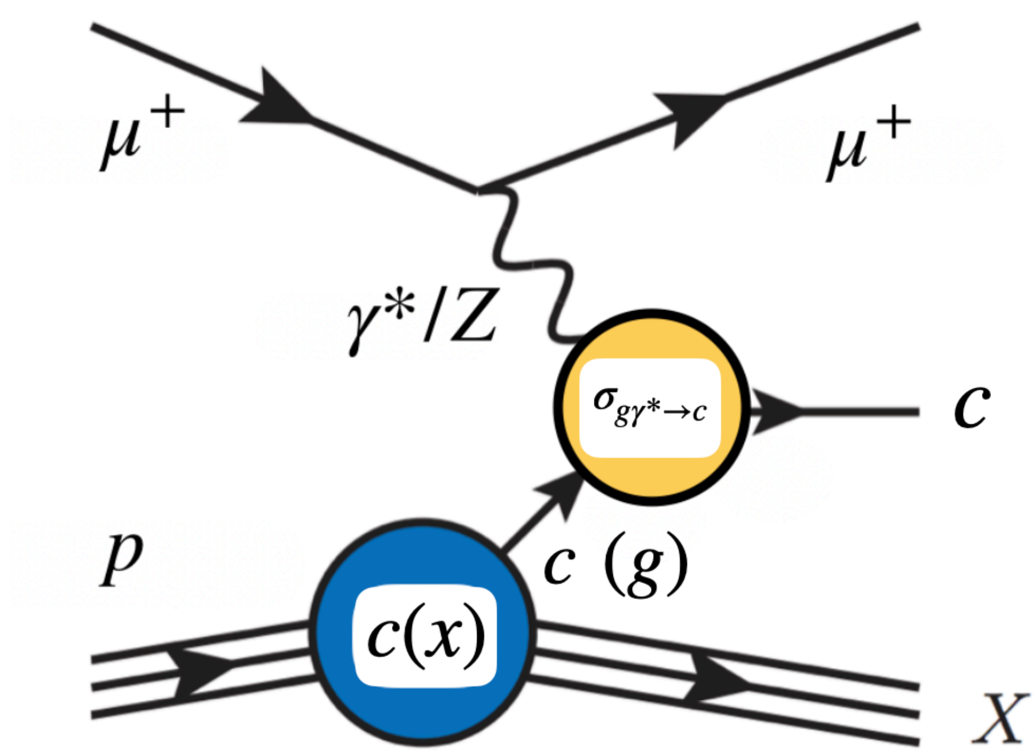


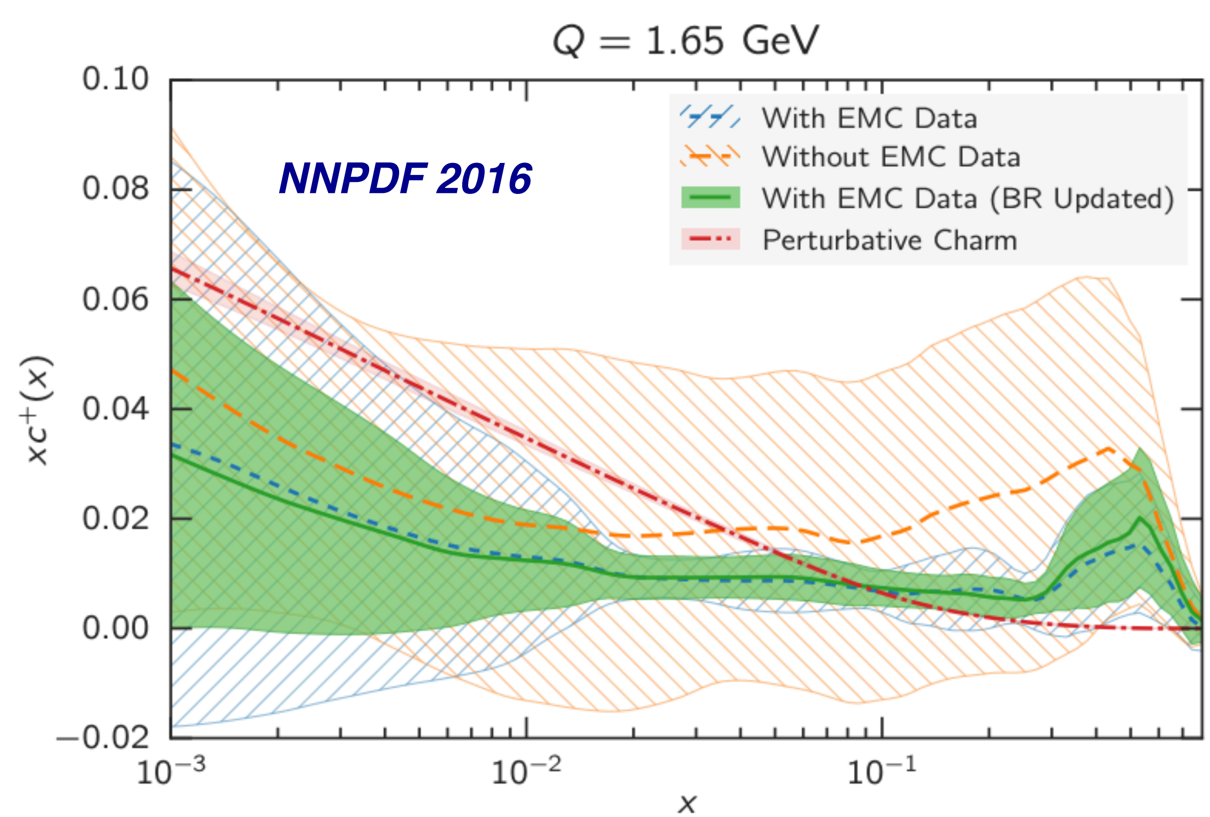
- Extrapolation of CT, MSHT, ABMP determined by **choice of large-*x* functional form**, not the case in NNPDF (verified by computing effective large-*x* exponents)
- The forward-backward asymmetry is hence **not positive-definite in the SM,** unlike what is assumed in some LHC searches
- NNPDF4.0 displays the **largest PDF uncertainties** in extrapolation region

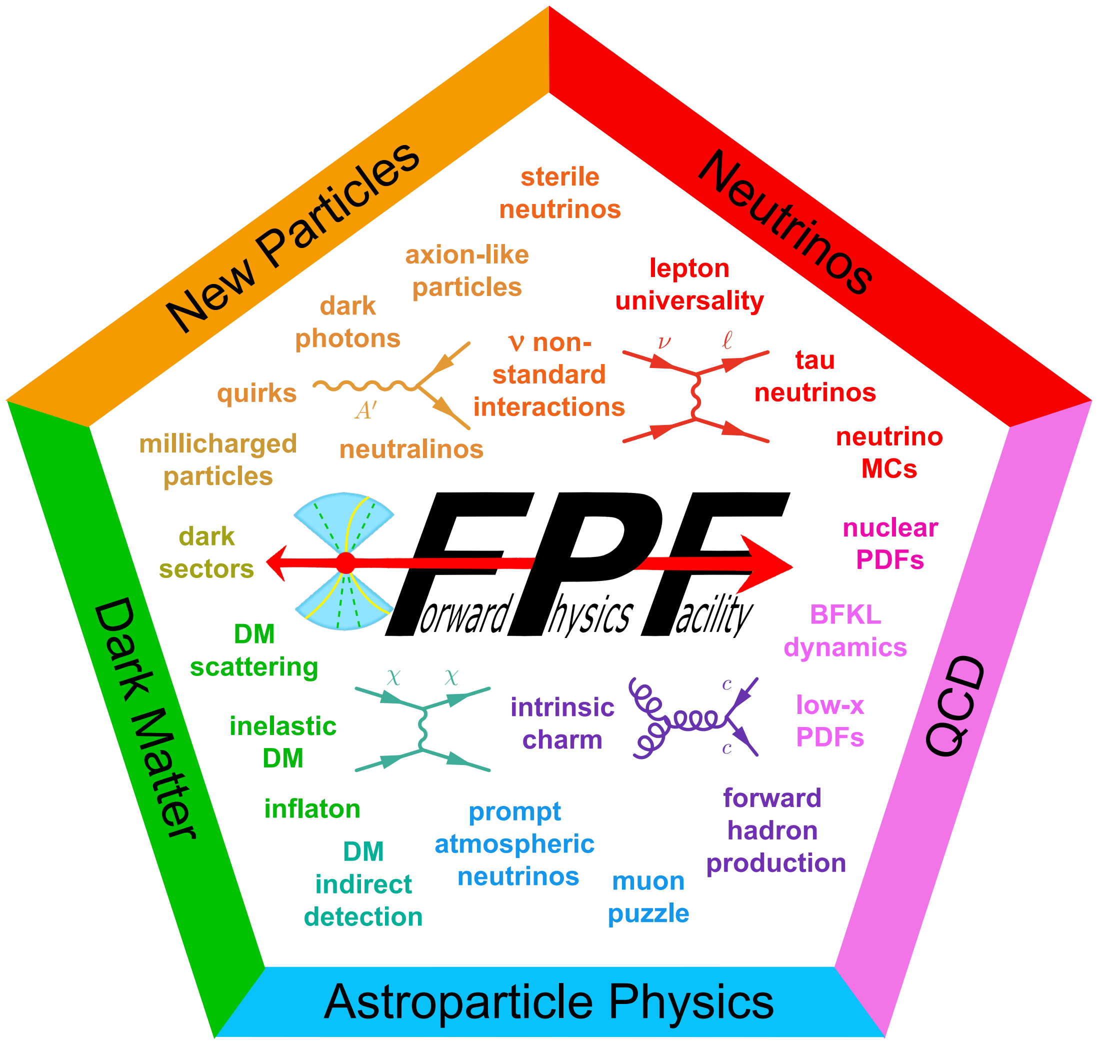
Back to the future



- **EMC charm structure functions** (1981): one of original motivations of intrinsic charm
- A purely perturbative charm PDF disfavoured by the data
- A model-independent determination of the charm PDF describes well the EMC data, but **limited statistical significance**







arXiv:2203.05090v1 [hep-ex] 9 Mar 2022

- **430 pages** describing scientific case, infrastructure, detectors, and simulations
- Several **Working Groups** now assembled towards preparing a CDR: **get in touch if you want to contribute!**

FPF Forward Physics Facility

The Forward Physics Facility at the High-Luminosity LHC

High energy collisions at the High-Luminosity Large Hadron Collider (LHC) produce a large number of particles along the beam collision axis, outside of the acceptance of existing LHC experiments. The proposed Forward Physics Facility (FPF), to be located several hundred meters from the ATLAS interaction point and shielded by concrete and rock, will host a suite of experiments to probe Standard Model (SM) processes and search for physics beyond the Standard Model (BSM). In this report, we review the status of the civil engineering plans and the experiments to explore the diverse physics signals that can be uniquely probed in the forward region. FPF experiments will be sensitive to a broad range of BSM physics through searches for new particle scattering or decay signatures and deviations from SM expectations in high statistics analyses with TeV neutrinos in this low-background environment. High statistics neutrino detection will also provide valuable data for fundamental topics in perturbative and non-perturbative QCD and in weak interactions. Experiments at the FPF will enable synergies between forward particle production at the LHC and astroparticle physics to be exploited. We report here on these physics topics, on infrastructure, detector, and simulation studies, and on future directions to realize the FPF's physics potential.

Snowmass Working Groups
EF4,EF5,EF6,EF9,EF10,NF3,NF6,NF8,NF9,NF10,RP6,CF7,TF07,TF09,TF11,AF2,AF5,IF8

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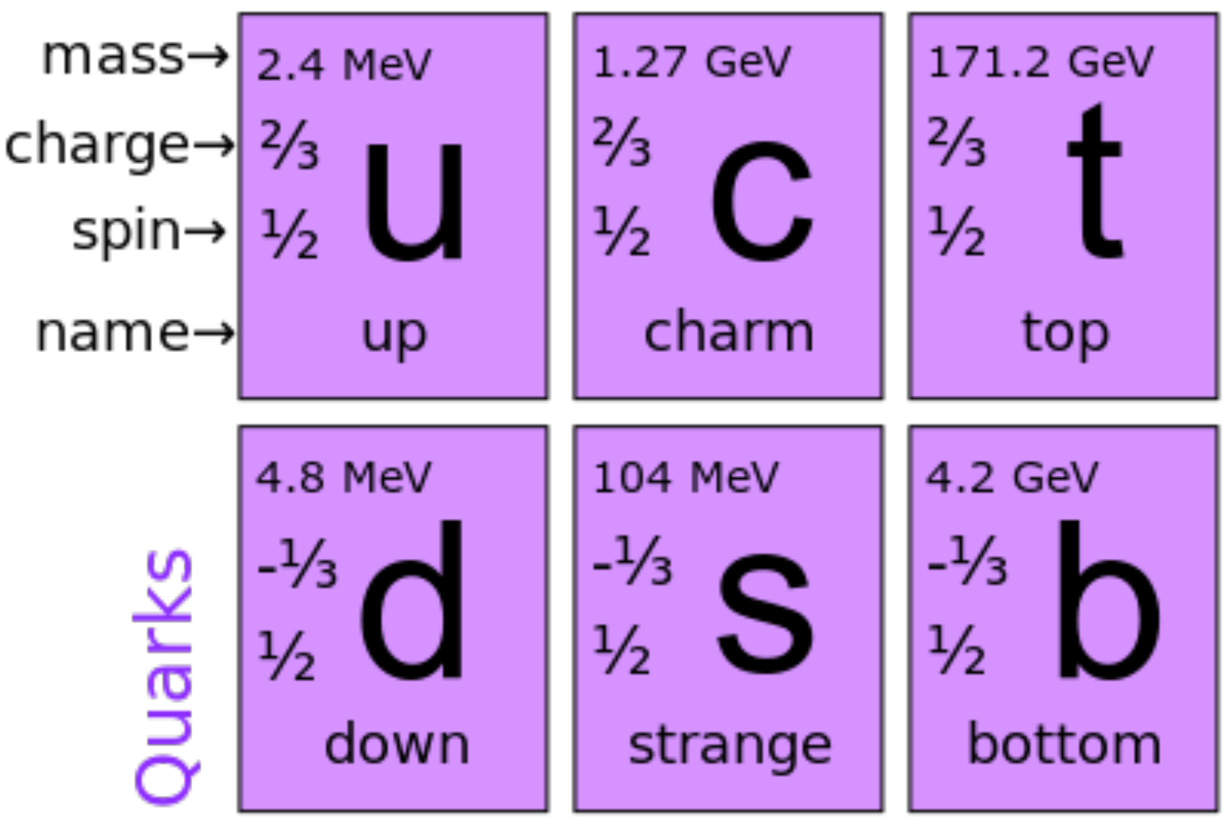
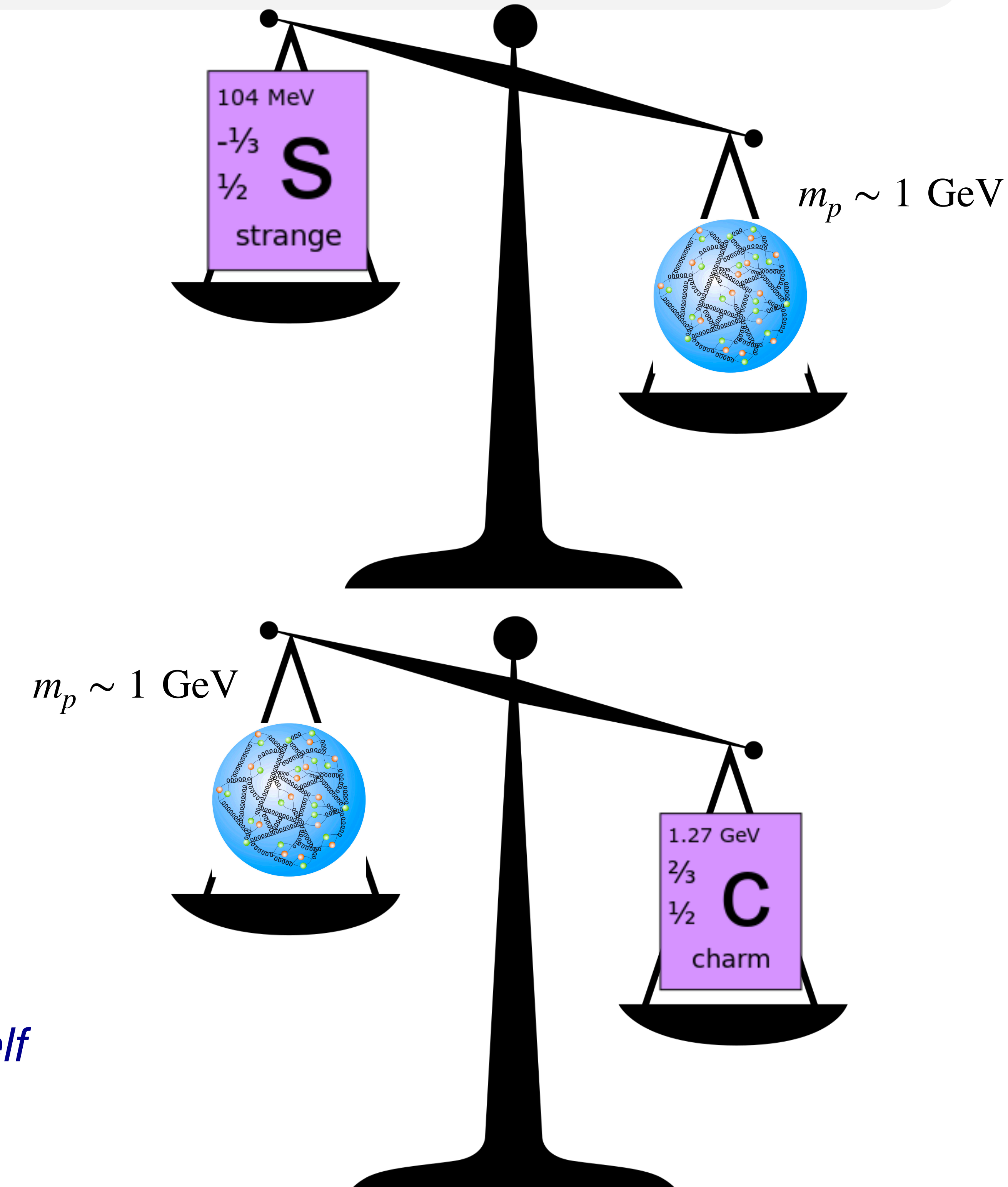
The charm content of the proton

common assumption in PDF fits: the static proton wave function does not contain charm quarks:
the proton contains **intrinsic up, down, strange (anti-)quarks** but **no intrinsic charm quarks**





charm quarks heavier than the proton itself