



# Global analyses of nuclear parton distributions

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nCTEQ collaboration

ITP, WWU

SFB 1225 isoQuant



# Nuclear structure at high energies

Periodic Table of the Elements

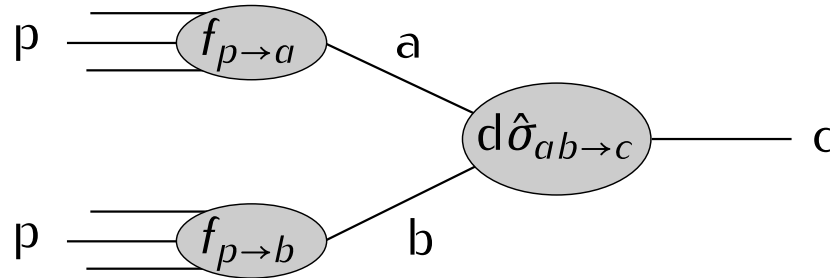
Nuclei with DIS data included in nCTEQ15 (Fig. by E. Godat)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
IA	IIA	IIIB	IVB	VB	VIB	VII	VIII	VIII	VIII	IB	IIB	IIIA	IIIA	VA	VIA	VIA	VIA
H Hydrogen 1.00794	He Helium 4.002602																
Li Lithium 6.941	Be Beryllium 9.0122											B Boron 10.811	C Carbon 12.011	N Nitrogen 14.007	O Oxygen 15.999	F Fluorine 18.998	Ne Neon 20.180
Na Sodium 22.990	Mg Magnesium 24.305											Al Aluminum 26.982	Si Silicon 28.086	P Phosphorus 30.974	S Sulfur 32.064	Cl Chlorine 35.453	Ar Argon 39.948
K Potassium 39.098	Ca Calcium 40.078	Sc Scandium 44.956	Ti Titanium 47.88	V Vanadium 50.942	Cr Chromium 51.996	Mn Manganese 54.938	Fe Iron 55.845	Co Cobalt 58.933	Ni Nickel 58.693	Cu Copper 63.546	Zn Zinc 65.38	Ga Gallium 69.723	Ge Germanium 72.64	As Arsenic 74.922	Se Selenium 78.972	Br Bromine 79.904	Kr Krypton 83.80
Rb Rubidium 84.464	Sr Strontium 87.62	Y Yttrium 88.906	Zr Zirconium 91.224	Nb Niobium 92.906	Mo Molybdenum 95.94	Tc Technetium 98.907	Ru Ruthenium 101.07	Rh Rhodium 102.906	Pd Palladium 106.42	Ag Silver 107.868	Cd Cadmium 112.411	In Indium 114.818	Sn Tin 118.71	Sb Antimony 121.760	Te Tellurium 127.6	I Iodine 126.905	Xe Xenon 131.29
Cs Cesium 132.905	Ba Barium 137.327		Hf Hafnium 178.49	Ta Tantalum 180.948	W Tungsten 183.85	Re Rhenium 186.207	Os Osmium 196.23	Ir Iridium 192.22	Pt Platinum 195.08	Au Gold 196.967	Hg Mercury 200.59	Tl Thallium 204.383	Pb Lead 207.2	Bi Bismuth 208.980	Po Polonium [209]	At Astatine 209	Rn Radon 222.018
Fr Francium [223]	Ra Radium [226]		Rf Rutherfordium [261]	Db Dubnium [262]	Sg Seaborgium [266]	Bh Bohrium [264]	Hs Hassium [277]	Mt Meitnerium [276]	Ds Darmstadtium [271]	Rg Roentgenium [272]	Cn Copernicium [285]	Uut Ununtrium [288]	Fl Flerovium [289]	Uup Ununpentium [288]	Lv Livermorium [293]	Uus Ununseptium [294]	Uuo Ununoctium [294]

- Nuclear parton distribution functions: proxy for nuclear structure at high energies
  - ▶ Point to fundamental  $q, g$  dynamics of  $p, n$  bound in nuclei
  - ▶ Set the initial conditions in creation of new state of matter: Color-glass condensate  $\rightarrow$  Quark-gluon plasma

# Theoretical framework

- Take for example proton-proton (pp) collisions in picture:



- Or in formula, in the collinear factorization framework:

$$d\sigma_{pp \rightarrow c} = \sum_{a,b} f_{p \rightarrow a}(x_a, \mu) \otimes f_{p \rightarrow b}(x_b, \mu) \otimes d\hat{\sigma}_{ab \rightarrow c}(\mu)$$
$$\mu \gtrsim 1 \text{ GeV}, x \in (0, 1)$$

- With  $\mu$ : factorization scale,  $x$ : fraction of parton  $a(b)$  momentum in proton  $p$

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- With  $\mu$ : factorization scale,  $x$ : fraction of parton  $a(b)$  momentum in proton  $p$
- Hard cross section  $d\hat{\sigma}_{ab \rightarrow c}(\mu)$ 
  - ▶ Process specific
  - ▶ Calculable in perturbative QCD (pQCD)
- Parton Distribution Functions (PDFs)  $f_{p \rightarrow a}(x, \mu)$ 
  - ▶ Universal
  - ▶ Not calculable from first principles (not yet)
- Similarly for  $lp$ ,  $\nu p$  and one-particle inclusive<sup>a</sup> processes

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<sup>a</sup>Which involve second factorization scale and convolution with fragmentation functions.

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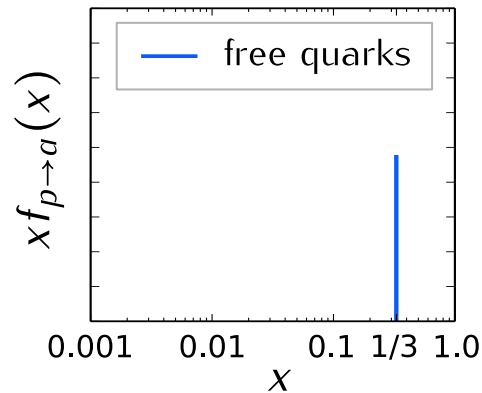
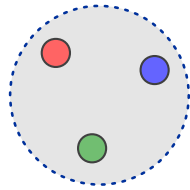
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# Parton Distribution Functions (PDFs)

- PDF[ $f_{p \rightarrow a}(x, \mu)$ ]: probability that parton  $a$  carries fraction<sup>a</sup>  $x$  of proton  $p$  momentum

Free partons



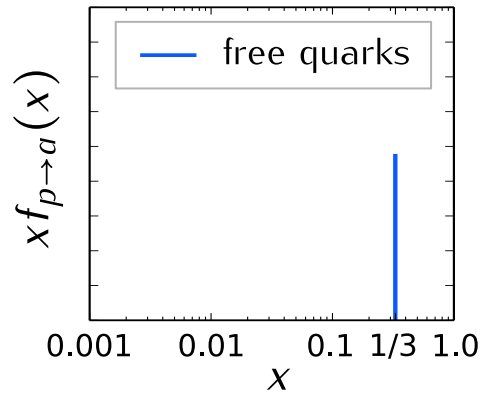
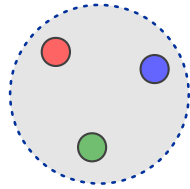
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<sup>a</sup>Longitudinal.

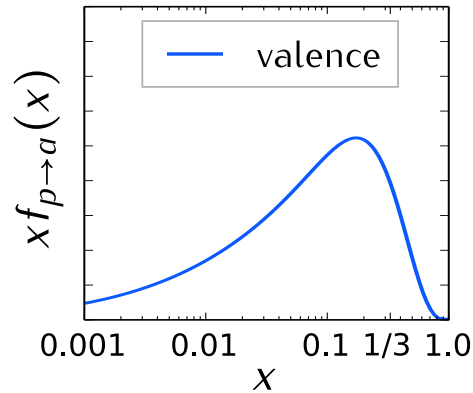
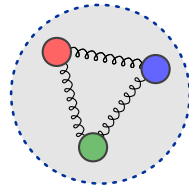
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Free partons



Bound partons

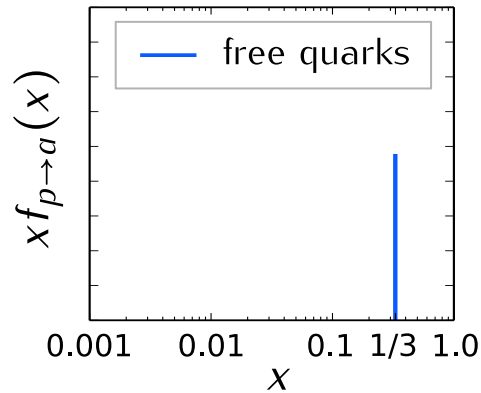
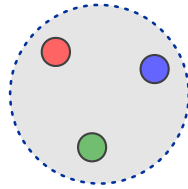


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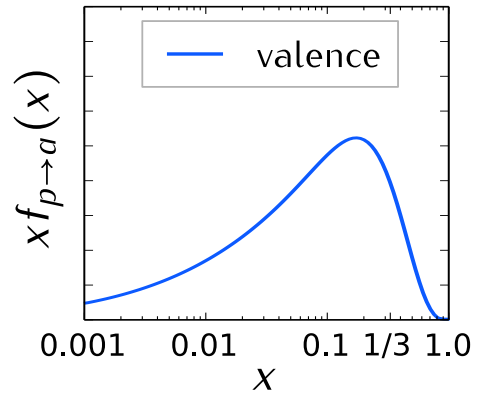
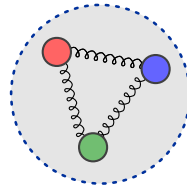
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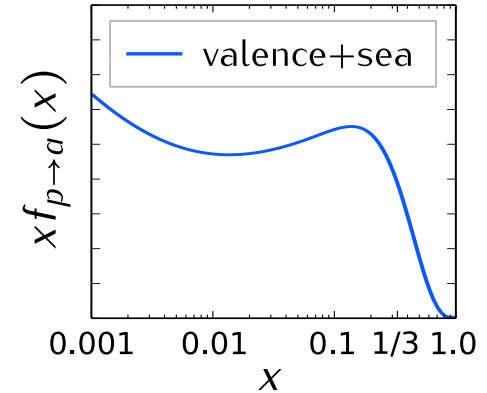
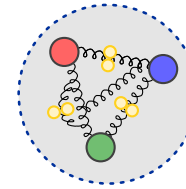
Free partons



Bound partons



Bound partons  
& QCD effects

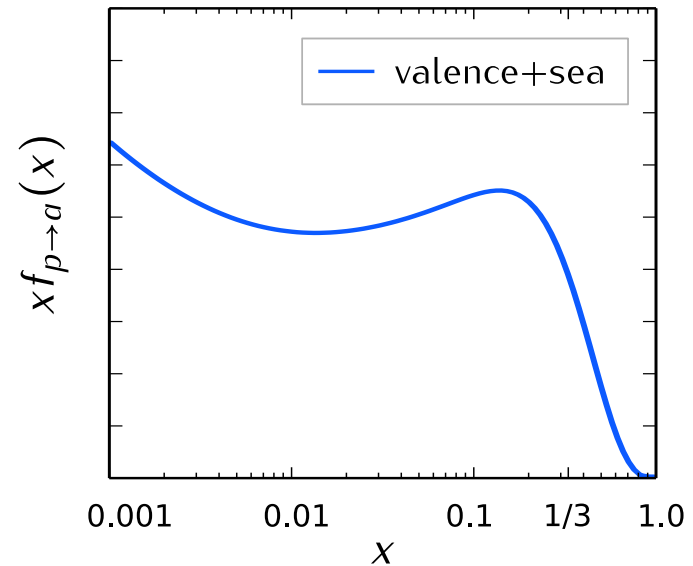
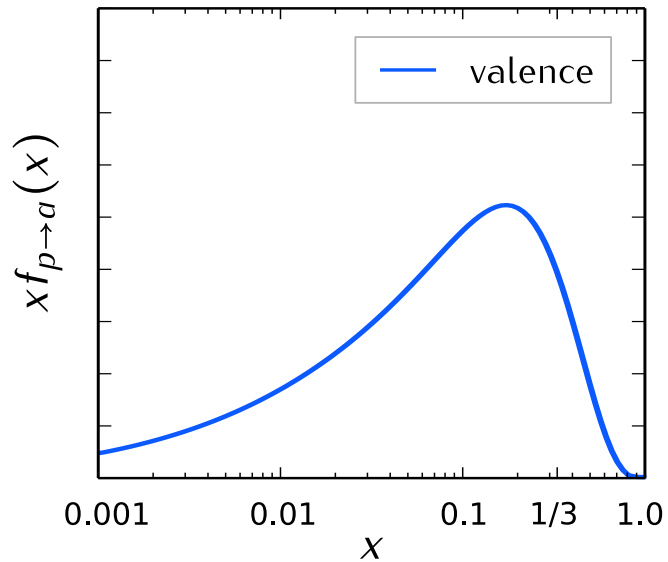


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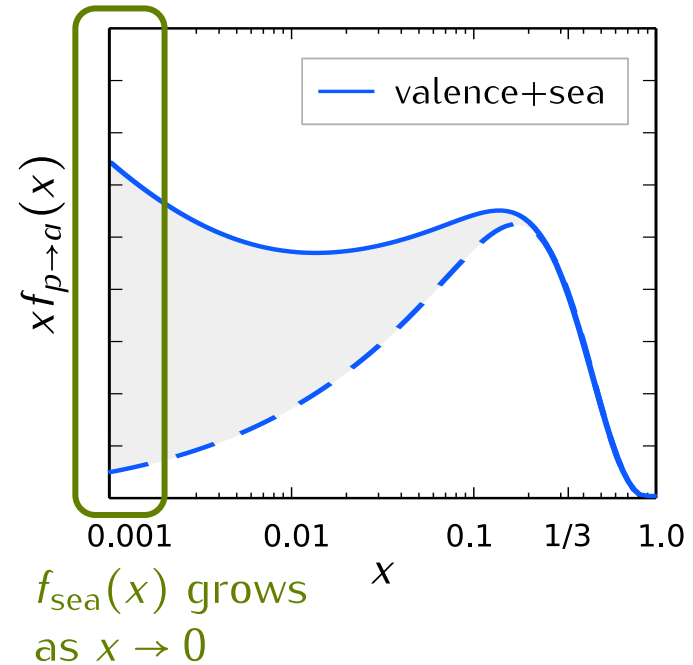
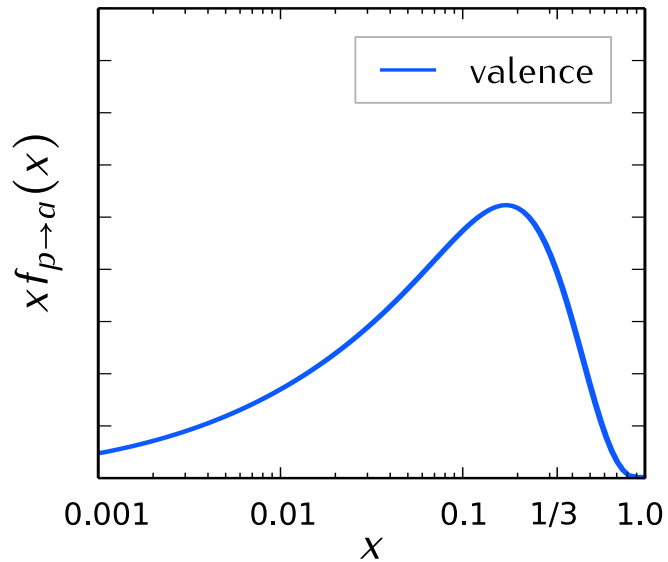


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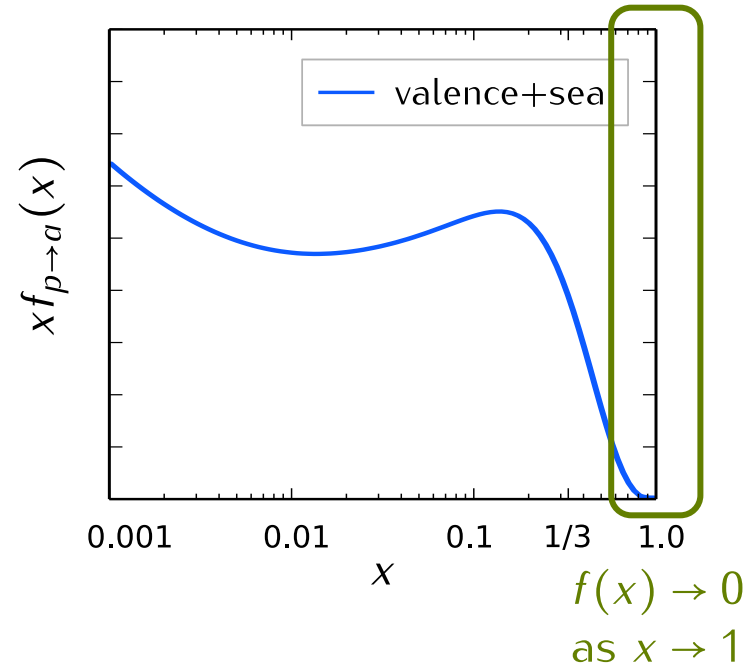
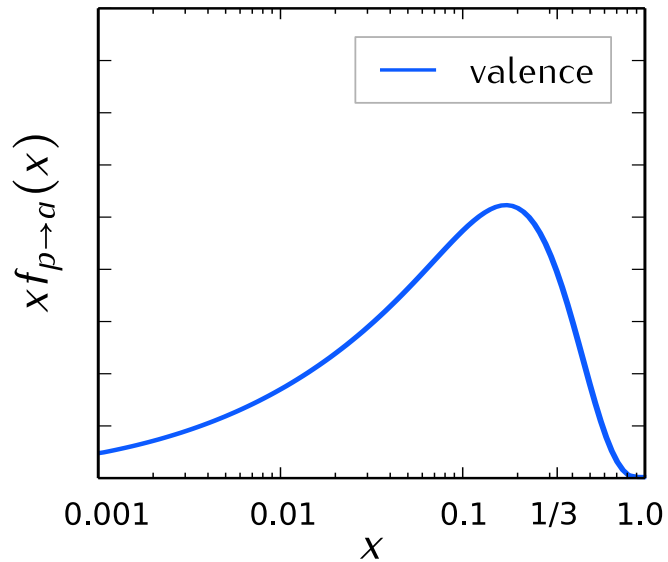
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# Parton Distribution Functions (PDFs)

- Universal: same PDF enters different processes (DIS, DY, SIH, HQ, ...)
- $x$  dependence not calculable in pQCD
  - ▶ Constrained through number and momentum sum rules
- $\mu$  dependence governed by DGLAP evolution equations

$$\frac{d}{d \log \mu^2} f_q(x, \mu^2) \sim (P_{qq} \otimes f_q)(x, \mu^2) + (P_{qg} \otimes f_g)(x, \mu^2)$$
$$\frac{d}{d \log \mu^2} f_g(x, \mu^2) \sim (P_{gg} \otimes f_g)(x, \mu^2) + (P_{gq} \otimes f_q)(x, \mu^2)$$

- ▶ Describe violations of Bjorken  $x$  scaling
- ▶ Different PDFs mix: set of  $(2n_f + 1)$  coupled integro-differential equations.

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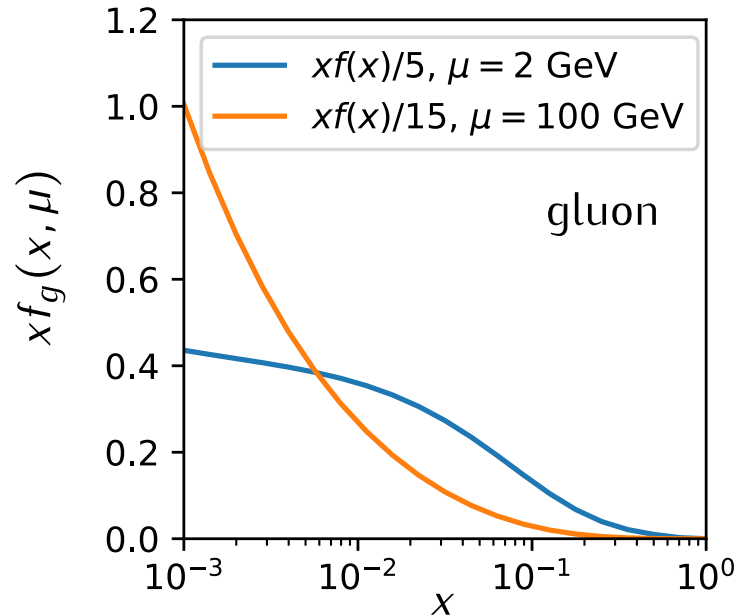
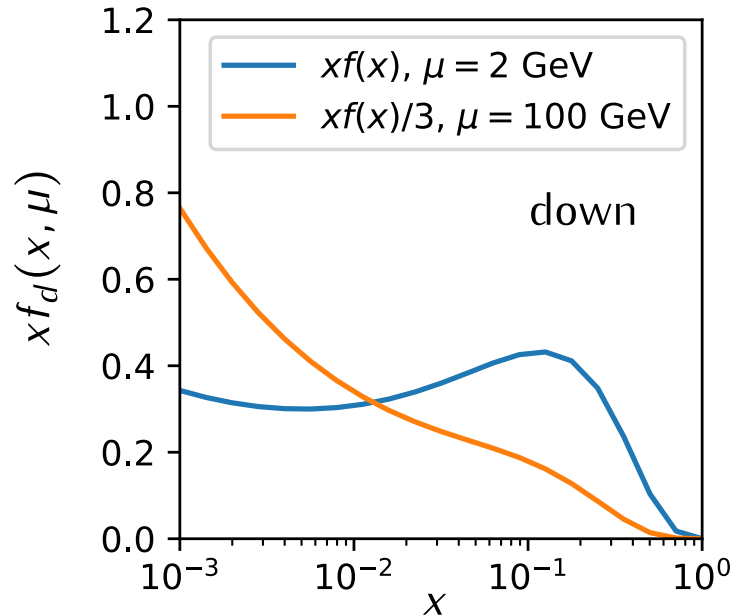
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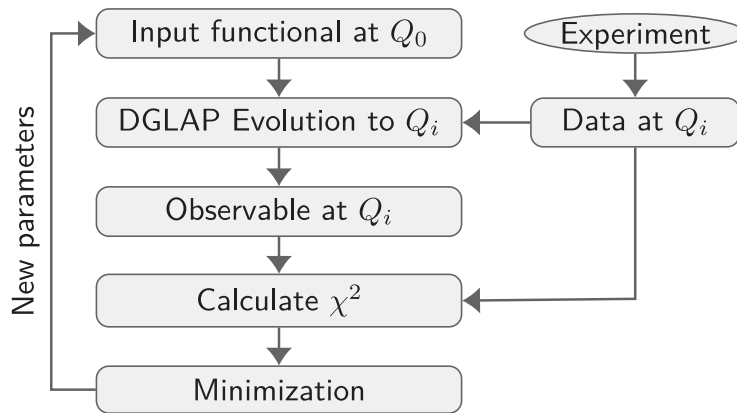
- ▶ Reduces valence and increases sea
- ▶ Mixes flavours

# Parton Distribution Functions (PDFs)

- $x$  dependence not calculable in pQCD:<sup>a</sup>
  - ▶ assume parametrization<sup>b</sup> in  $x$  at a chosen input scale  $Q_0$ :

$$xf_i(x, Q_0) = N(1-x)^{p_{i,1}} x^{p_{i,2}} P(x, p_{i,3}, \dots)$$

- ▶ set  $p_{i,j}$ , calculate theoretical predictions, compare to data, iterate:



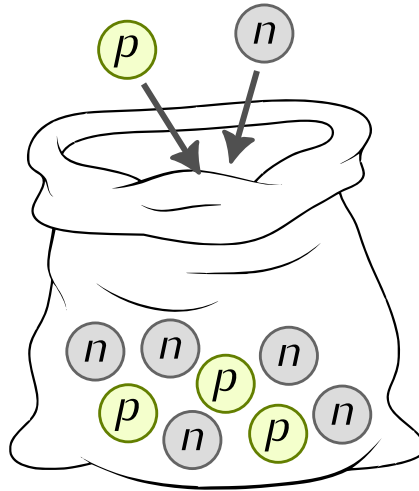
$$\chi^2 = \sum_{ij}^N (D_i - T_i) (C^{-1})_{ij} (D_j - T_j)$$

<sup>a</sup>Calculable in lattice QCD in near future?

<sup>b</sup>NNPDF collaboration use NN to avoid parametrization bias.

# Nuclear Parton Distribution Functions (nPDFs)

- Free nucleon approximation:

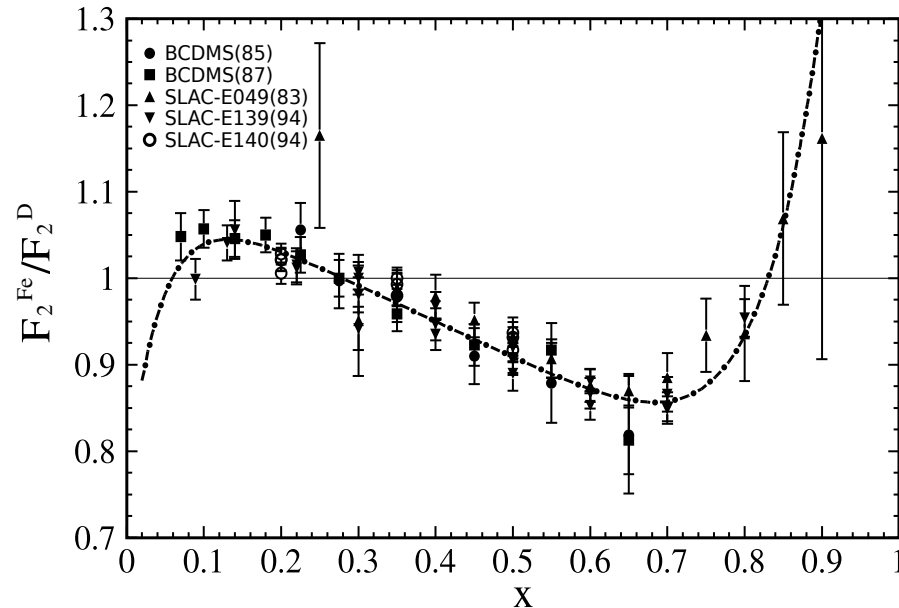


$$Af^A(x, \mu) \stackrel{?}{=} Zf^p(x, \mu) + Nf^n(x, \mu)$$



# Nuclear Parton Distribution Functions (nPDFs)

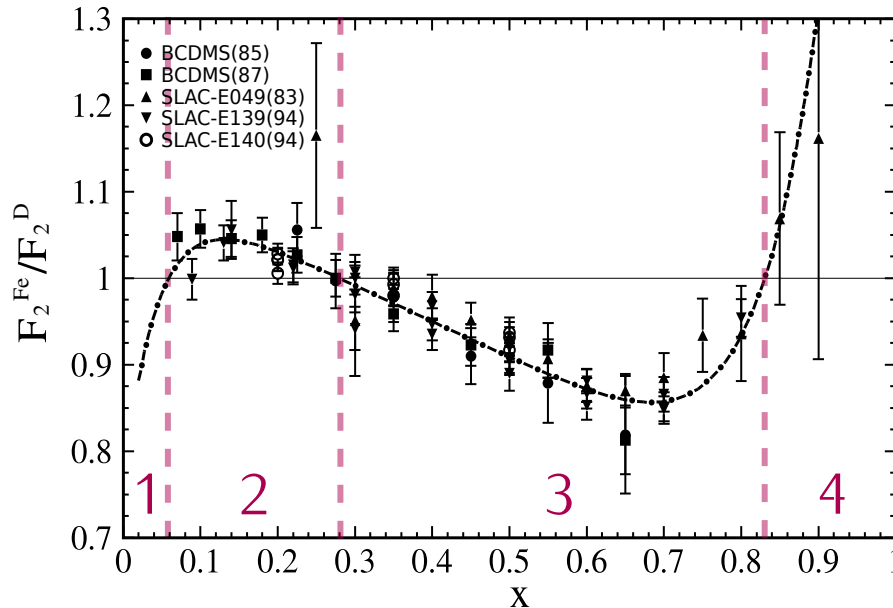
- Nuclear modification:



$$Af^A(x, \mu) \neq Zf^p(x, \mu) + Nf^n(x, \mu)$$

# Nuclear Parton Distribution Functions (nPDFs)

- Nuclear modification:



- ▶ 1 shadowing
- ▶ 2 anti-shadowing
- ▶ 3 EMC effect
- ▶ 4 Fermi motion

- ▶ Underlying dynamics still to be fully theoretically understood
- ▶ Can be parametrized and incorporated into nPDF fits

# Nuclear Parton Distribution Functions (nPDFs)

- Nuclear modification can be incorporated into the PDF framework:
  - ▶ Introduce the notion of bound proton PDF for flavour  $i$ :  $f_i^{p/A}(x, \mu, A)$
  - ▶  $x \in (0, A)$ , but  $x > 1$  region typically negligible
  - ▶  $f_i^{p/A}$  fulfils the usual evolution equations and sum rules
  - ▶  $f_i^{n/A}$  from isospin symmetry, i.e.  $f_{d,u}^{n/A} = f_{u,d}^{p/A}$

$$f_i^{(A,Z)}(x, \mu) = \frac{Z}{A} f_i^{p/A}(x, \mu, A) + \frac{A-Z}{A} f_i^{n/A}(x, \mu, A)$$

- ▶  $f_i^{(A,Z)}$  replaces  $f_i^p$  in the factorization formula<sup>a</sup>

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<sup>a</sup>Proof of factorization for collisions of nuclei not yet available.

# Global analyses of nPDFs

## ● EPPS

- EKS98: [hep-ph/9807297](#)
- EKPS07: [hep-ph/0703104](#)
- EPS08: [0802.0139](#)
- EPS09: [0902.4154](#)
- EPPS16: [1612.05741](#)
- EPPS21: [2112.12462](#)

## ● nNNPDF

- nNNPDF1.0: [1904.00018](#)
- nNNPDF2.0: [2006.14629](#)
- nNNPDF3.0: [2201.12363](#)

## ● nCTEQ

- nCTEQ09: [0907.2357](#)
- nCTEQ15: [1509.00792](#)
- nCTEQ15WZ: [2007.09100](#)
- nCTEQ15HiX: [2012.11566](#)
- nCTEQ15WZSIH: [2105.09873](#)
- nCTEQ15HQ: [2204.09982](#)
- nCTEQ15WZSIHdeut: [2204.13157](#)
- BaseDimuChorus: [2204.13157](#)

## ● TUJU

- TUJU19: [1908.03355](#)
- TUJU21: [2112.11904](#)

## ● KA

- KA15: [1601.00939](#)
- KSASG20: [2010.00555](#)

## ● nDS

- nDS03: [hep-ph/0311227](#)
- DSSZ12: [1112.6324](#)

## ● HKM/HKN

- HKM01: [hep-ph/0103208](#)
- HKN04: [hep-ph/0404093](#)
- HKN07: [0709.3038](#)

# Global analyses of nPDFs

Recent

## ● EPPS

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- KA15: [1601.00939](#)
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## Outdated

## ● nDS

- nDS03: [hep-ph/0311227](#)
- DSSZ12: [1112.6324](#)

## ● HKM/HKN

- HKM01: [hep-ph/0103208](#)
- HKN04: [hep-ph/0404093](#)
- HKN07: [0709.3038](#)

# Global analyses of nPDFs

Extract from a table by P. Paakinen

	KSASG	nCTEQ	TUJU	EPPS	nNNPDF
Order in $\alpha$	NLO & NNLO	NLO	NLO & NNLO	NLO	NLO
Error analysis	Hessian	Hessian	Hessian	Hessian	Monte Carlo
Free-proton PDFs	CT18	$\sim$ CTEQ6M	own fit	CT18A	$\sim$ NNPDF4.0
HQ treatment	FONLL	S-ACOT	FONLL	S-ACOT	FONLL

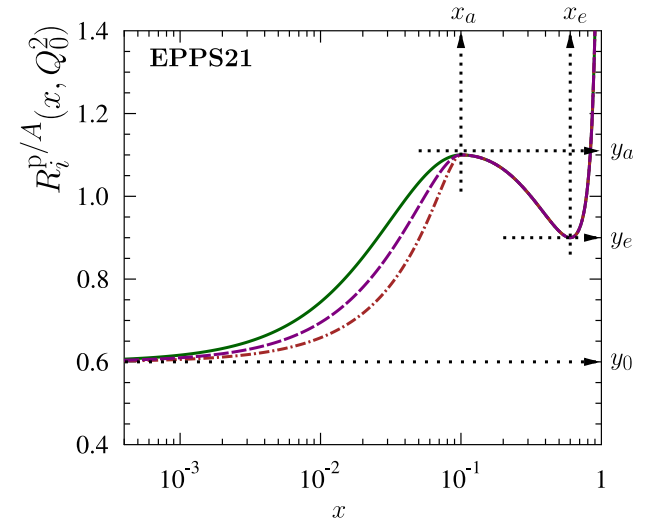
- Have in common: collinear factorisation, DGLAG evolution, sum rules, pQCD observables\*,  $\chi^2$  minimization, isospin symmetry,  $x > 1$  region neglected, ...
- Differ in:
  - ▶ **Parametrization:**  $R$  vs.  $f^A$ ; proton baseline; functional form vs. neural nets
  - ▶ **Data selection:** processes; cuts; correlations; normalisations
  - ▶ **Error analysis:** Hessian vs. monte carlo replicas;  $\Delta\chi^2$  tolerance; **proton baseline uncertainties**
  - ▶ **Other:** inputs ( $m_c$ ,  $m_b$ ,  $\alpha_S(M_Z)$ , ...); heavy flavour scheme; deuteron treatment; target mass corrections; **perturbative order**; ...

# Global analyses of nPDFs

- Perturbative order:
  - ▶ Protons: wealth of Hera, LHC pp data → 1% accuracy, need NNLO
  - ▶ Nuclei: mostly FT, some LHC pA → 10% accuracy, NLO sufficient
- Parametrization: ideally, results should be independent of it
  - ▶ EPPS: nuclear modification ratio;  $A$ ,  $x$  dependence mixing marginal

$$R_i^A(x, Q_0^2) = \begin{cases} a_0 + a_1(x - x_a) \left[ e^{-x a_2/x_a} - e^{-a_2} \right], & x \leq x_a \\ b_0 x^{b_1} (1-x)^{b_2} e^{x b_3}, & x_a \leq x \leq x_e \\ c_0 + c_1(c_2 - x)(1-x)^{-\beta}, & x_e \leq x \leq 1 \end{cases}$$

$$y_i(A) = 1 + \left[ y_i(A_{\text{ref}}) - 1 \right] \left( \frac{A}{A_{\text{ref}}} \right)^{\gamma_i}$$



Adapted from a figure by EPPS

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  - ▶ EPPS: nuclear modification ratio;  $A, x$  dependence mixing marginal
  - ▶ nNNPDF: nuclear PDF, NN parametrization;  $A, x$  dependence mix

$$xF(x, Q_0) = \mathcal{N}_F x^{\alpha_F} (1-x)^{\beta_F} \text{NN}_F(x, A)$$

$$F \in \{\Sigma^{(p/A)}, T_3^{(p/A)}, T_8^{(p/A)}, V^{(p/A)}, V_3^{(p/A)}, g^{(p/A)}\}$$



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  - ▶ KSASG, TUJU, nCTEQ: nuclear PDF, traditional parametrization;  $A$ ,  $x$  mix

e.g. in nCTEQ15

$$x f_i^{p/A}(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4 x})^{c_5}$$
$$c_k \rightarrow c_k(A) \equiv p_k + a_k (1 - A^{-b_k})$$

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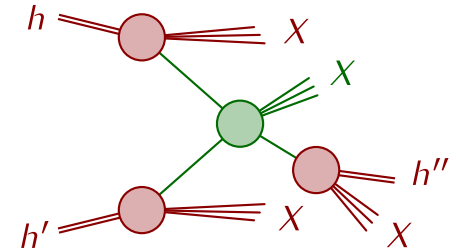
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  - ▶ KSASG, TUJU, nCTEQ: nuclear PDF, traditional parametrization;  $A$ ,  $x$  mix
- Data selection: guiding theme of the remainder of this talk

# Data: not covered today

- DIS NC ( $n_{\text{dat}} \in [451, 1227]$ ) and CC ( $n_{\text{dat}} \in [824, 2458]$ ) production
  - ▶ Bread and butter of PDF analyses (see backup slides)
- Fixed Target DY ( $n_{\text{dat}} \sim 100$ ) and LHC  $W, Z$  ( $n_{\text{dat}} \sim 150$ ) production
  - ▶ Important for strange distribution, also constrains gluon
  - ▶ Included in most analyses
- Single inclusive light flavours ( $n_{\text{dat}} \sim 300$ )
  - ▶ Gluon dominated at LHC
  - ▶ Almost 2/3 points in a very low  $p_T$  difficult to describe
  - ▶ Analysed by nCTEQ and also partly by EPPS
- Direct photon production ( $n_{\text{dat}} \sim 50$ )
  - ▶ Should provide extra handle on gluon
  - ▶ pPb/pp ratio described well, absolute pPb no that well

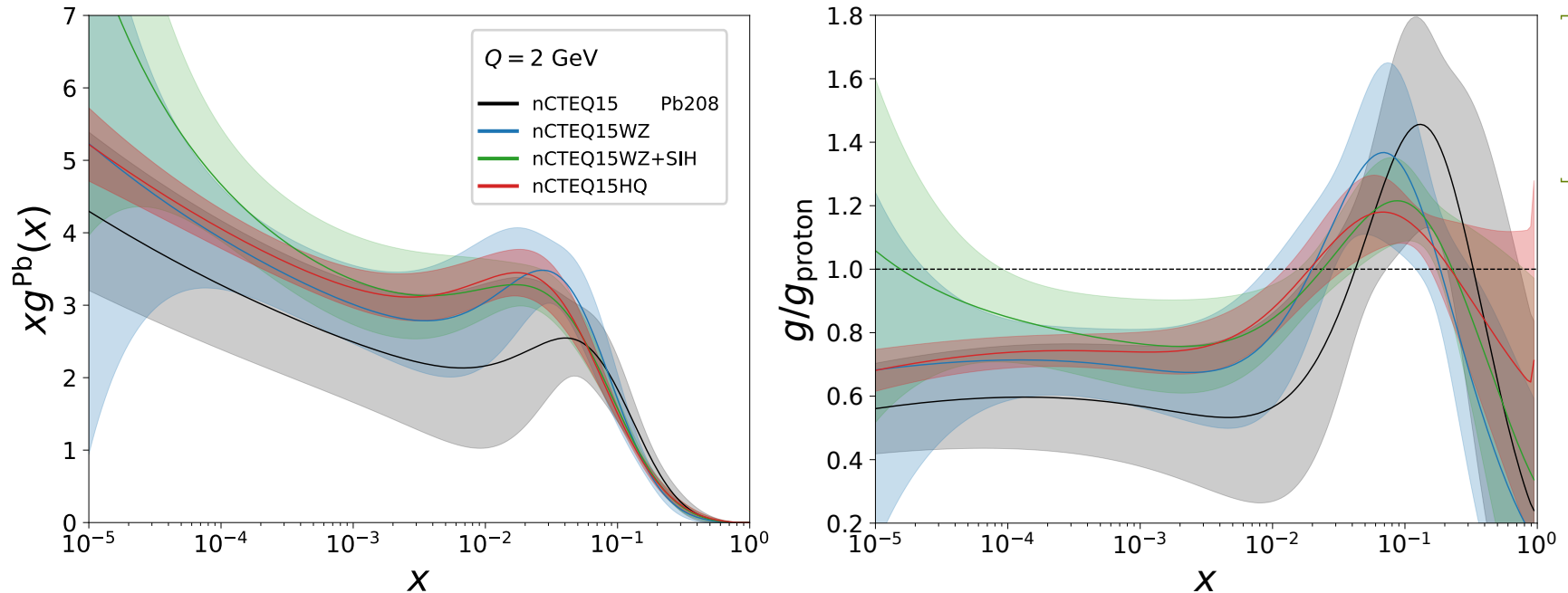
# Data: Heavy quark production

	KSASG20	TUJU21	EPPS21	nNNPDF3.0	nCTEQ15HQ
open HF	-	-	48	37	82
quarkonia	-	-	-	-	466



- Unprecedented low  $x$  reach
- Two very different production modes
  - ▶ Open heavy flavour production:  $D$
  - ▶ Quarkonia production:  $J/\psi, \Upsilon(1S), \psi(2S)$
- EPPS: only open HF, pQCD prediction with fragmentation
- nNNPDF: only open HF, pQCD prediction with GPMC hadronization
- nCTEQ: open HF and quarkonia, data driven approach based on a ME fit

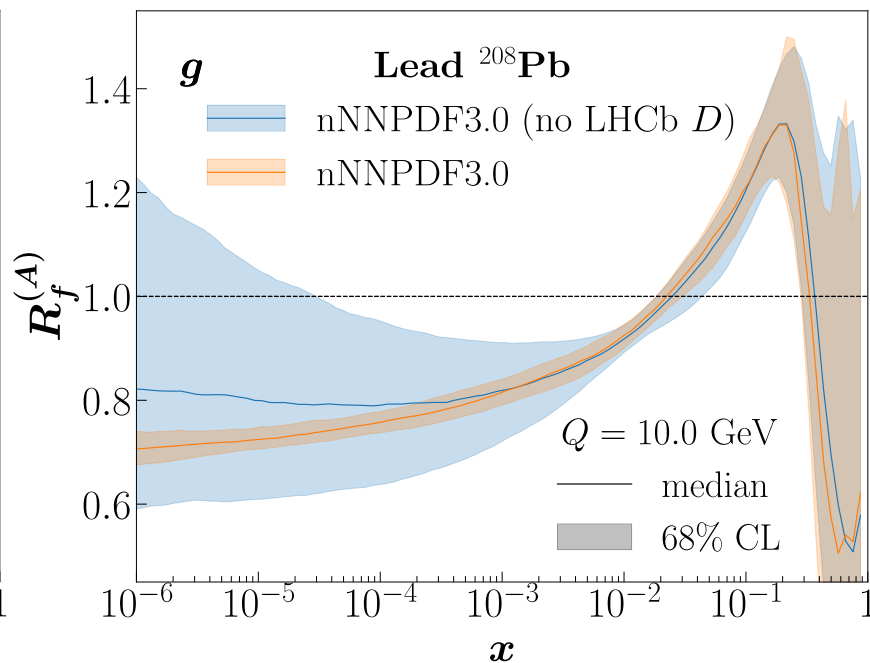
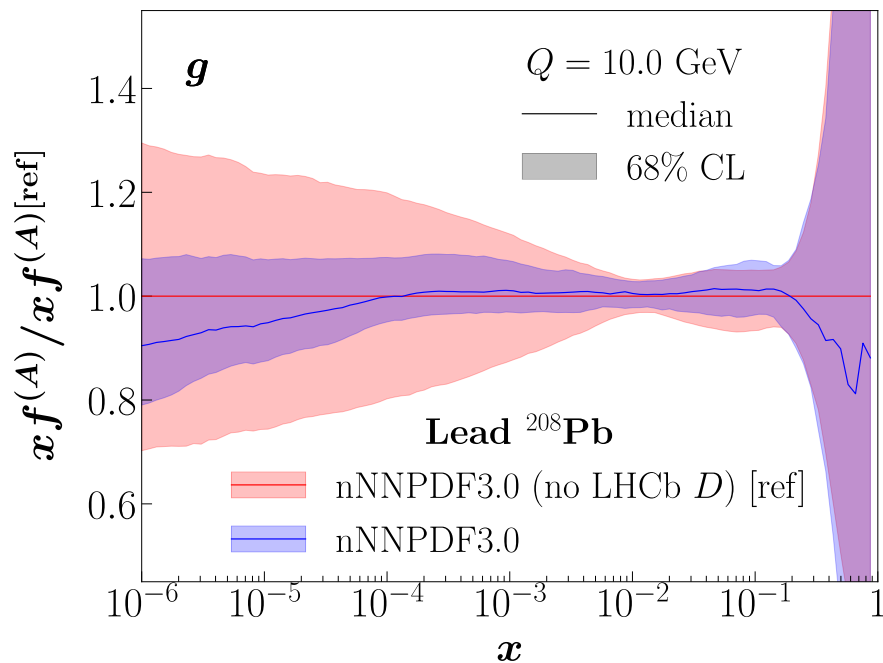
# Data: Heavy quark production



[2204.09982]

- Impressive reduction of uncertainties down to  $x \sim 10^{-5}$

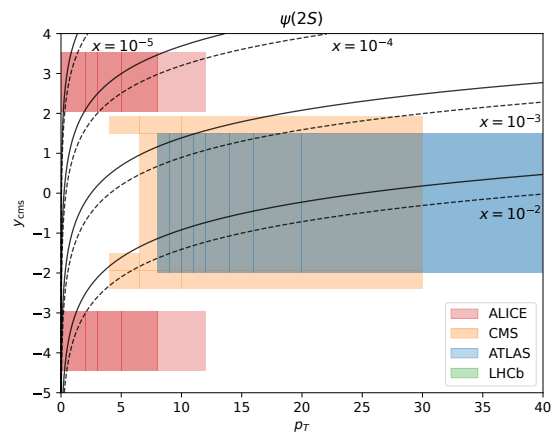
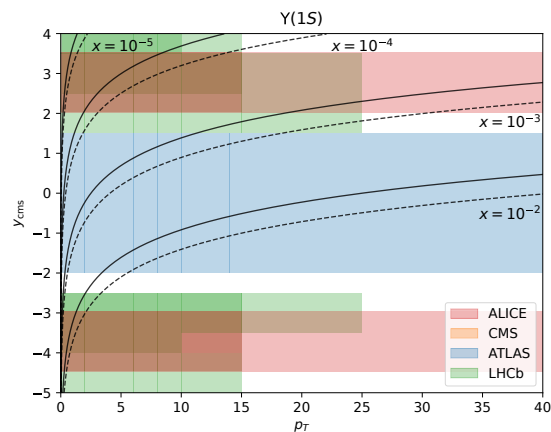
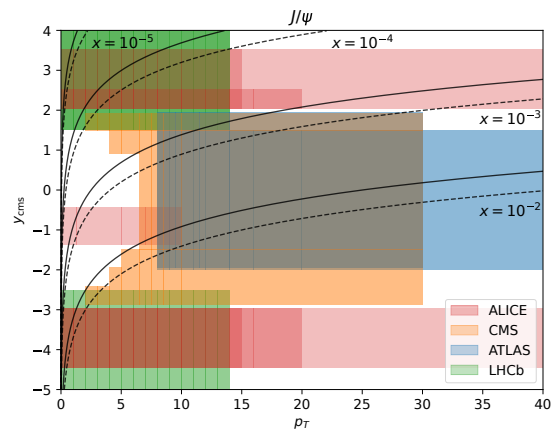
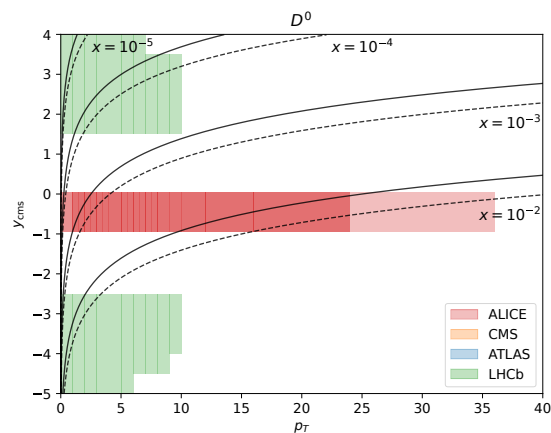
# Data: Heavy quark production



[2201.12363]

- Impressive reduction of uncertainties down to  $x \sim 10^{-6}$

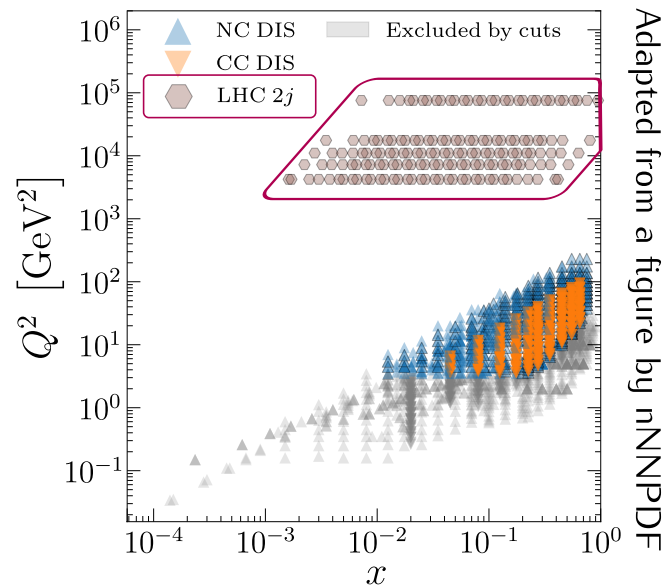
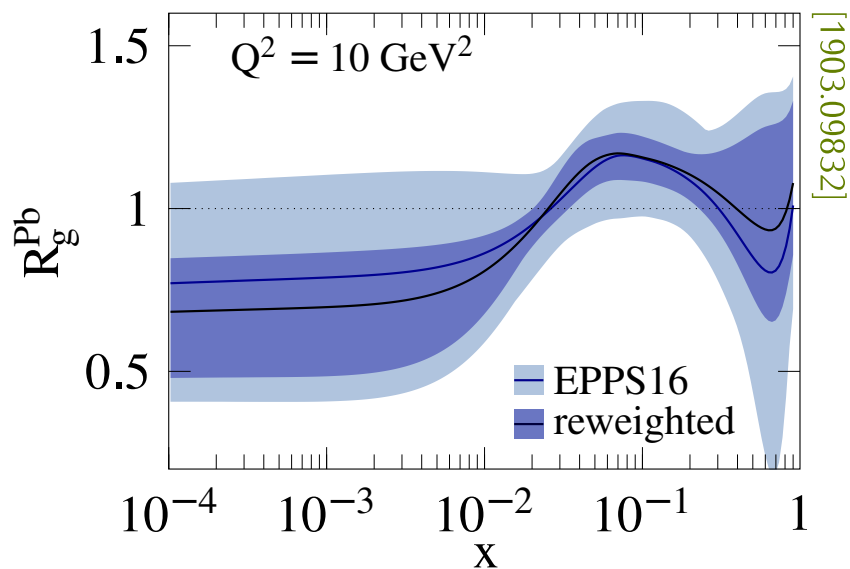
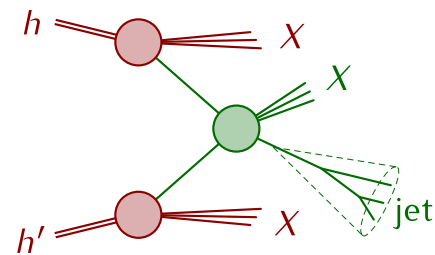
# Data: Heavy quark production



# Data: Jet production

	KSASG20	TUJU21	EPPS21	nNNPDF3.0	nCTEQ15HQ
dijet	-	-	83	84	-

- Great potential to constrain gluon distribution at low  $x$



Adapted from a figure by nNNPDF



# Data: Jet production

- pPb/pp ratios described well

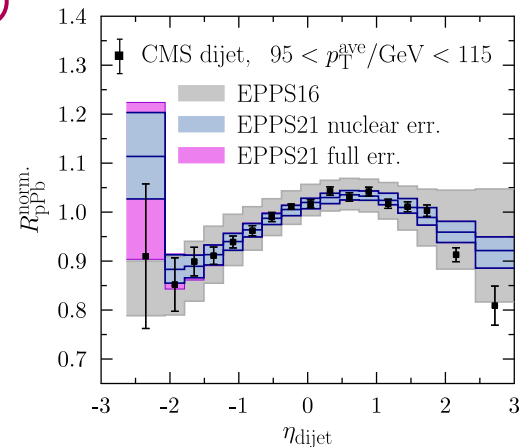
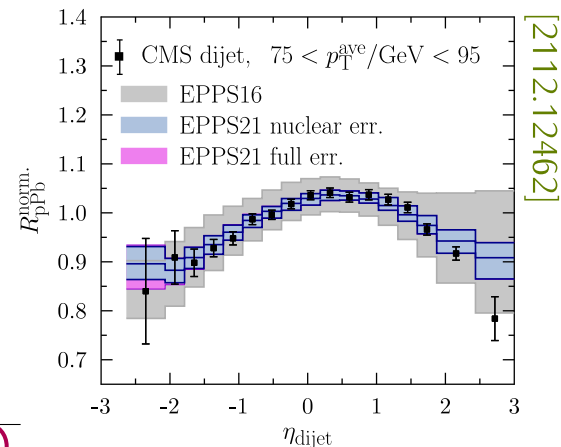
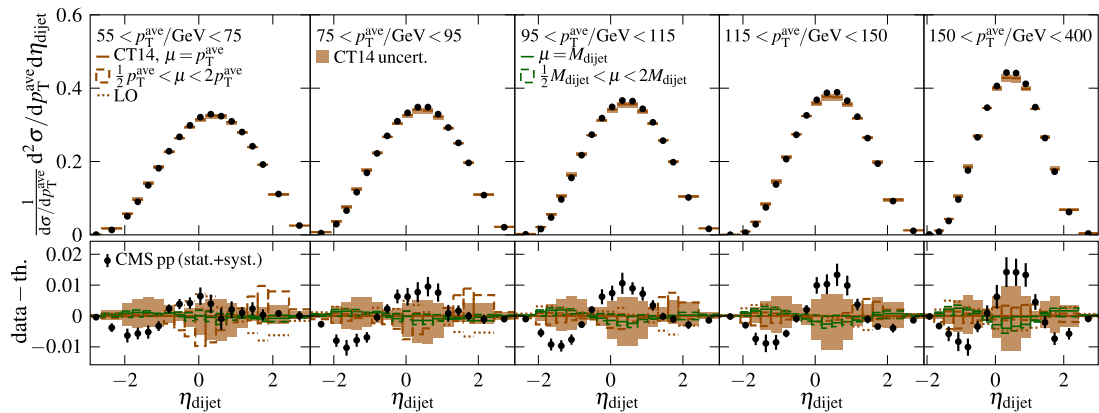
Experiment	Observable	Collisions	Data points	$\chi^2$
CERN CMS	dijet	pPb(208)	83	123.81

▶ EPPS:

Dataset	$n_{\text{dat}}$	$\chi^2/n_{\text{dat}}$
CMS dijet pPb/pp $\sqrt{s} = 5.02$ TeV	84	1.75

▶ nNNPDF:

- Not pp, pPb separately
- | Dataset                             | $n_{\text{dat}}$ | $\chi^2/n_{\text{dat}}$ |
|-------------------------------------|------------------|-------------------------|
| CMS dijet pPb $\sqrt{s} = 5.02$ TeV | 85               | [13.96]                 |



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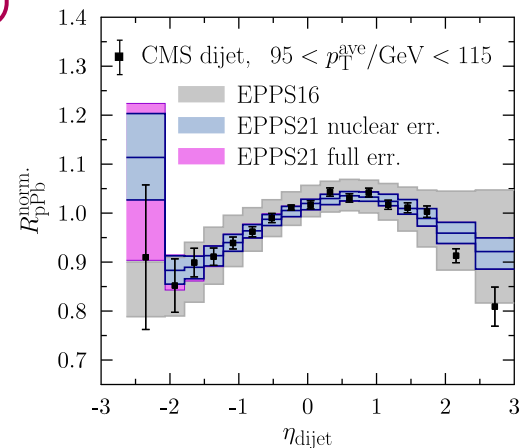
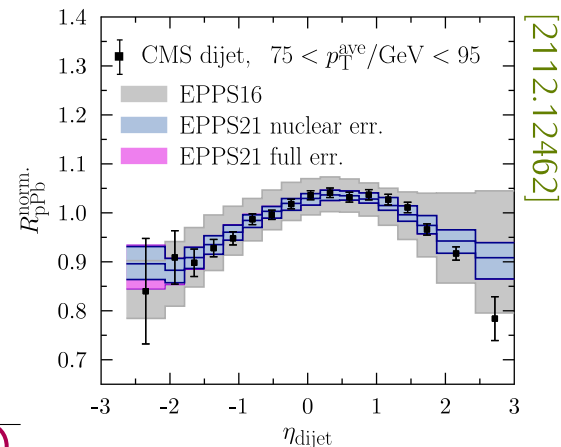
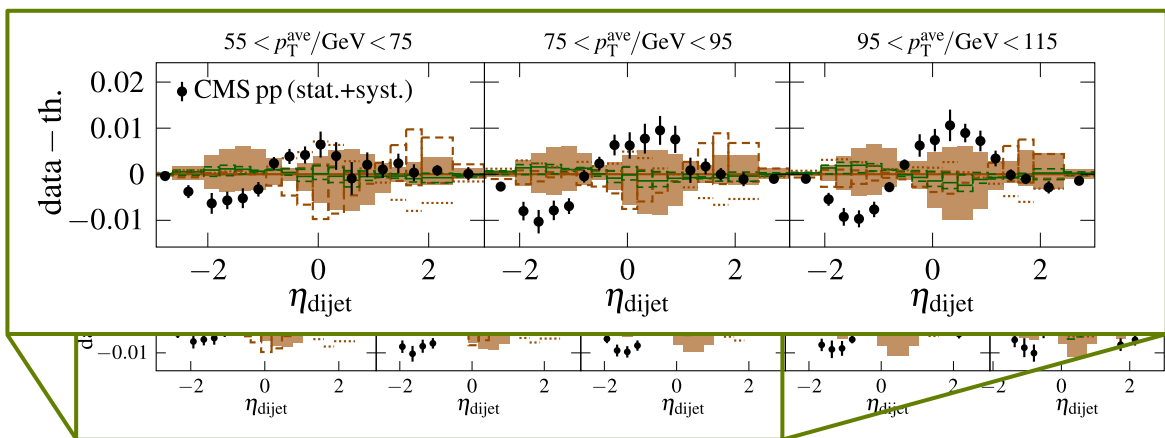
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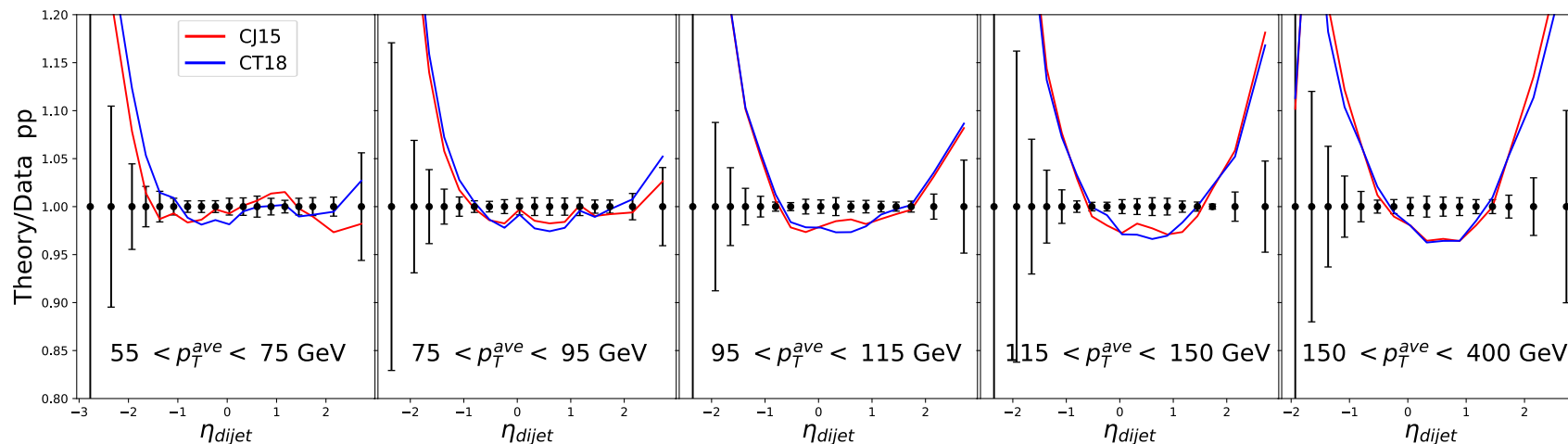
# Data: Jet production

- CMS dijet  $\sqrt{s} = 5.02$  TeV pp subset not included in proton PDF analyses

PDFs	MSHT20	NNPDF4.0	CT18	CJ15	CT14	ABMP16	NNPDF31
$\chi^2/N$	6.10	9.43	8.81	8.28	7.69	3.52	4.17

$$\mu_f = \mu_r = p_T^{\text{ave}} \dagger$$

- Can the data be included through reweighting?



$\dagger$  Setting  $\mu = m_{jj}$  does not help.

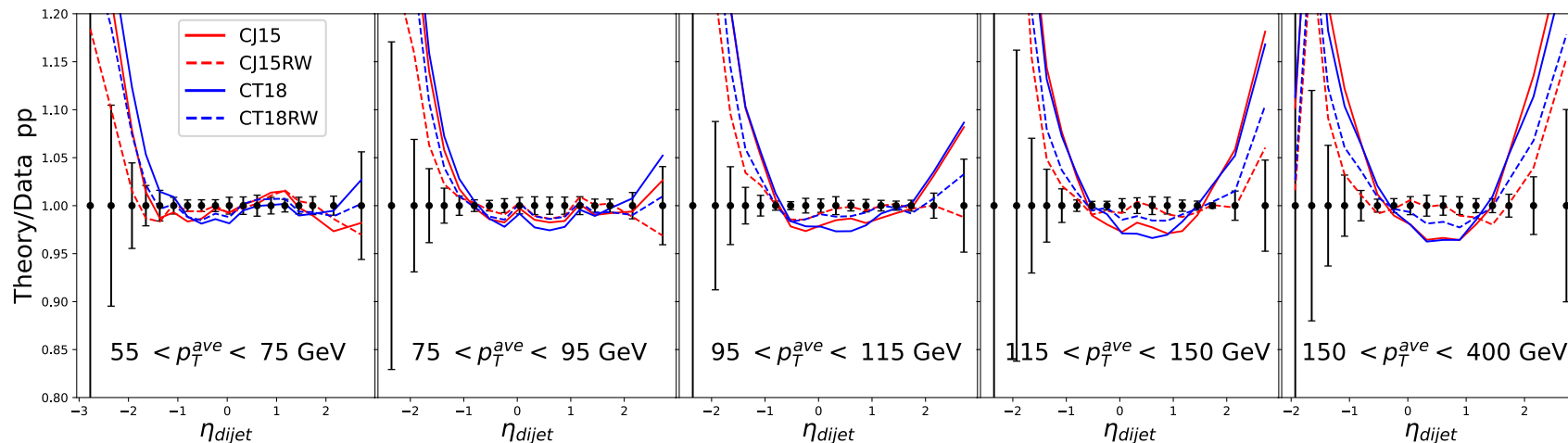
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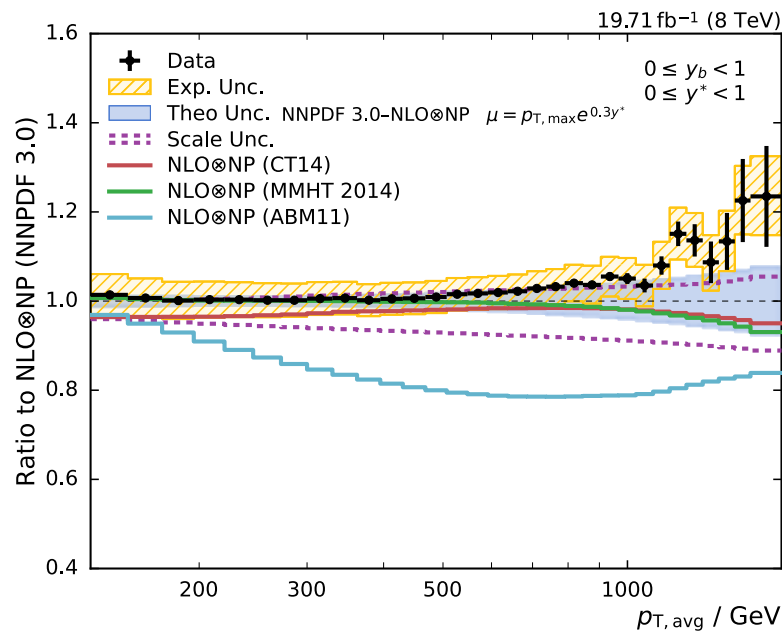
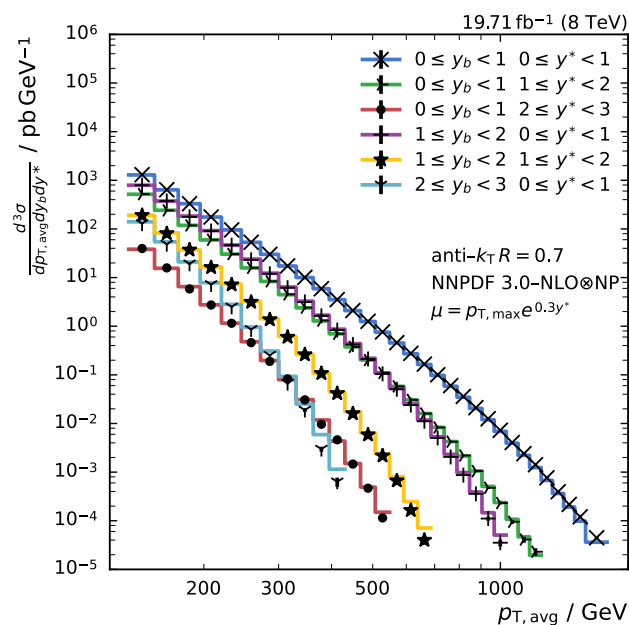
- Can the data be included through reweighting? ( $\chi^2/N$ : CJ15RW  $\sim 1.5$ , CT18RW  $\sim 3$ )



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# Data: Jet production

- For comparison: CMS dijet  $\sqrt{s} = 8$  TeV tripple differential cross sections

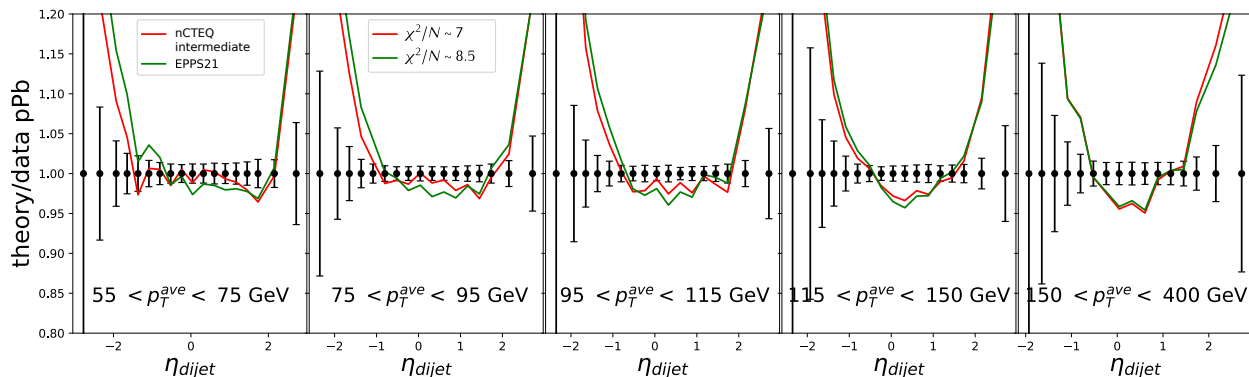


- Data described well once included in the fit:

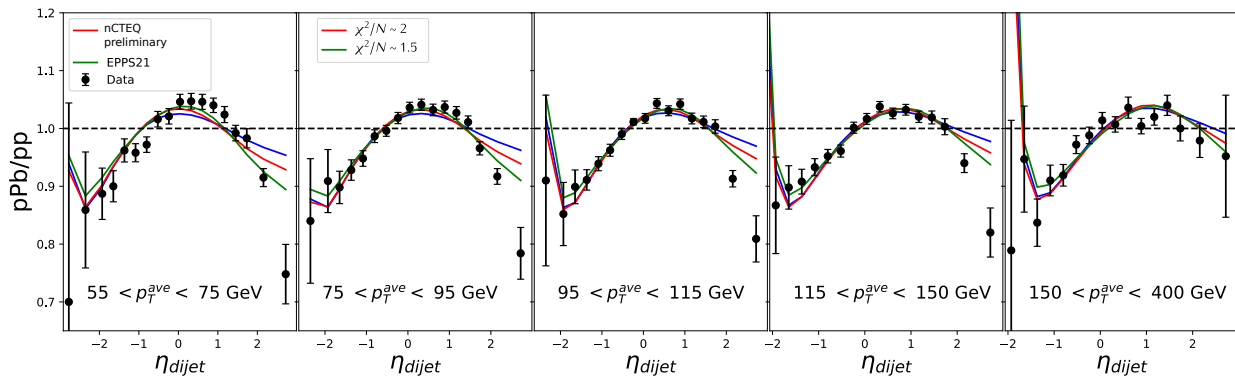
- ▶ HERA DIS [[arXiv:2207.13735](https://arxiv.org/abs/2207.13735)]: NLO 0.8(1.7<sup>†</sup>), NNLO 0.9(0.8<sup>†</sup>) (<sup>†</sup>  $\mu = m_{jj}$ )
- ▶ Global [[NNPDF4.0](https://arxiv.org/abs/2207.13735)]: NNLO 1.5 ( $\mu = |p_{T,j_1}| + |p_{T,j_2}|$ )

# Data: Jet production

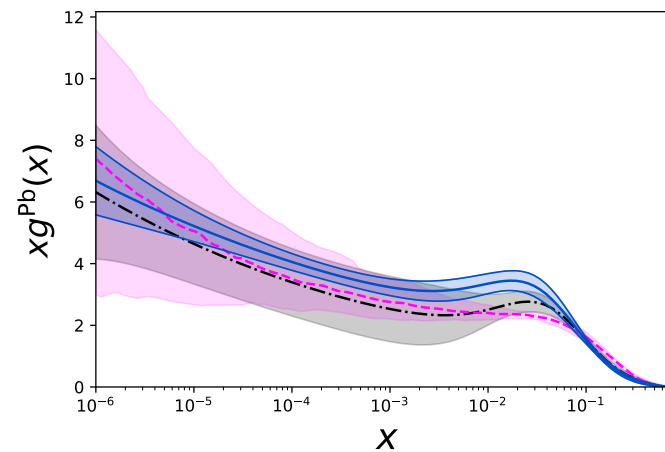
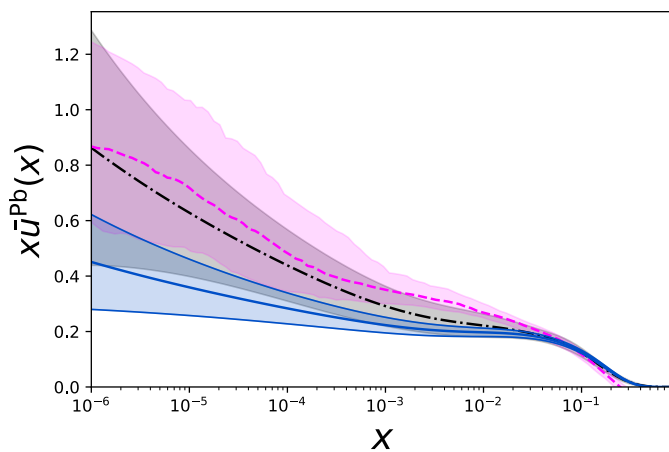
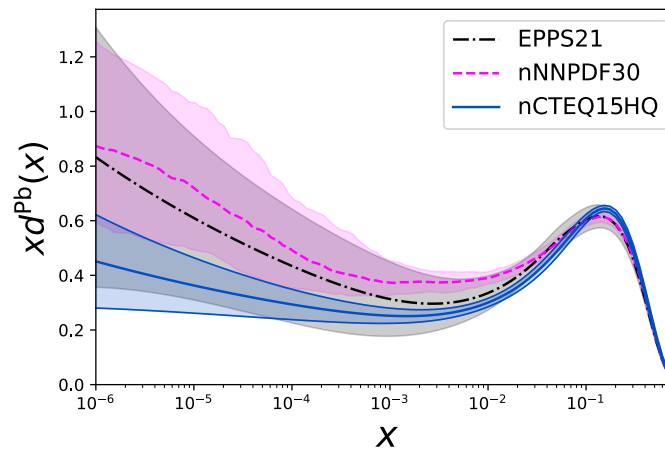
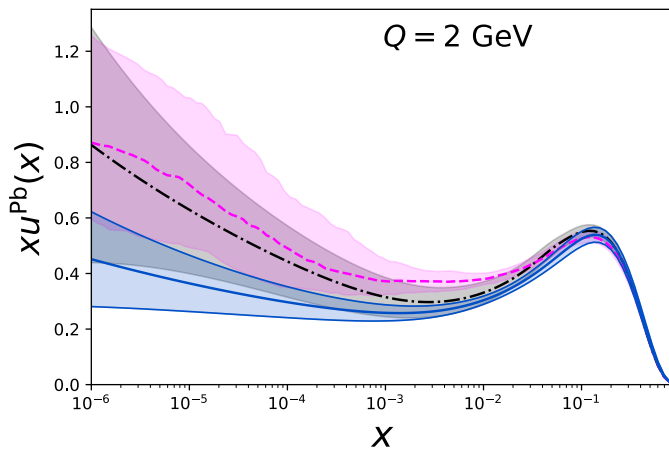
- CMS dijet  $\sqrt{s} = 5.02$  TeV pPb not described well either



- pPb/pp ratio



# Comparison of nPDFs



# Summary and outlook

- I reviewed:
  - ▶ The frameworks used in most recent global analyses of nPDFs
  - ▶ Some highlights on data inclusion
- New developments in the last ~two years:
  - ▶ Relaxed cuts (EPPS, KSASG, nCTEQ)
  - ▶ NC DIS: New JLAB CLASS and Hall-C data (EPPS, KSASG, nCTEQ)
  - ▶ CC DIS: Reanalysis confirms unreconcilable tension (nCTEQ)
  - ▶ New processes useful for gluon and low  $x$ :
    - ▷ Heavy quarks (EPPS, nCTEQ, nNNPDF)
    - ▷ Dijets (EPPS, nNNPDF)
    - ▷ Direct photons (nNNPDF)
- Personal wish list: (di-)jets, direct photons,  $t\bar{t}$ , low mass DY/W/Z, light hadrons
- Overall: nPDF extraction is a very active field with a rich future ahead

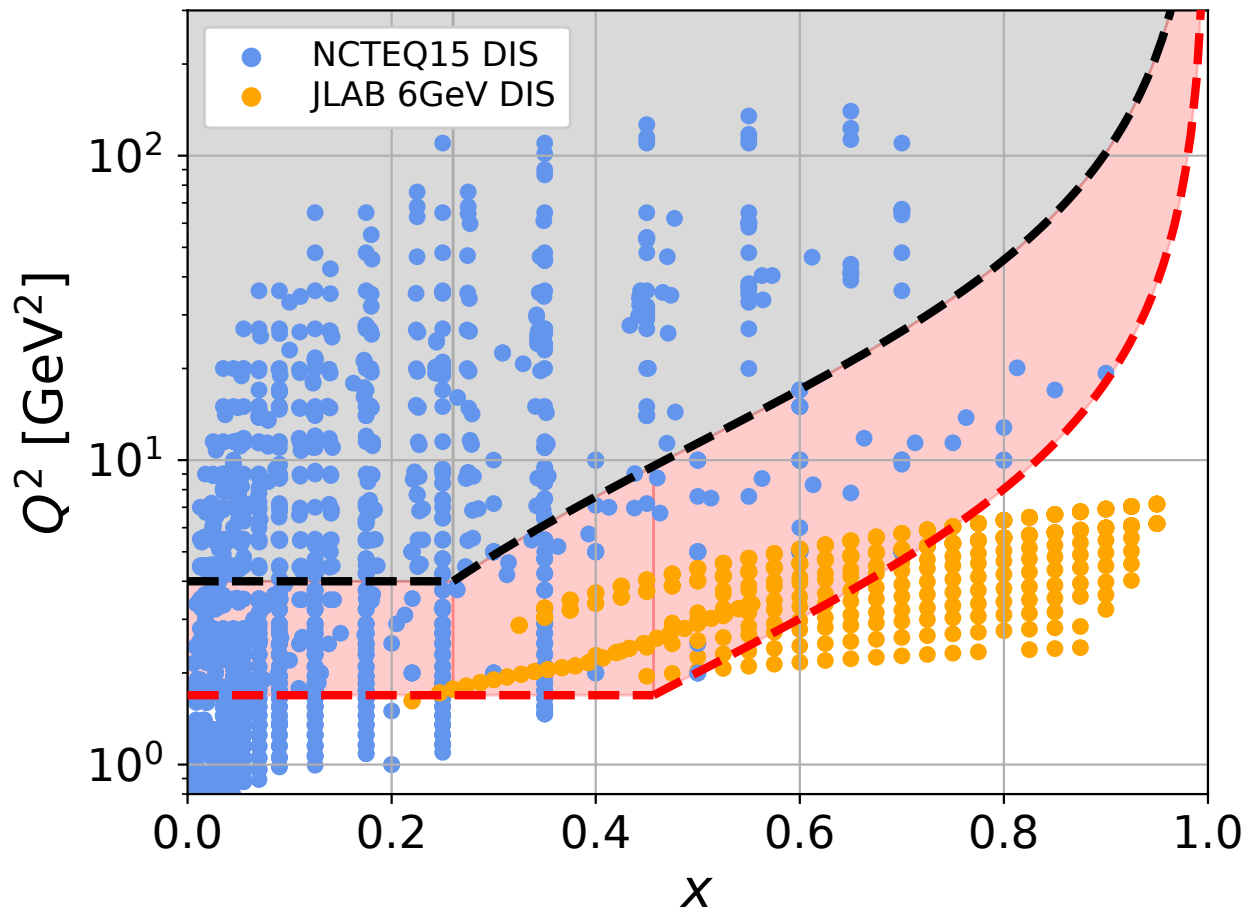


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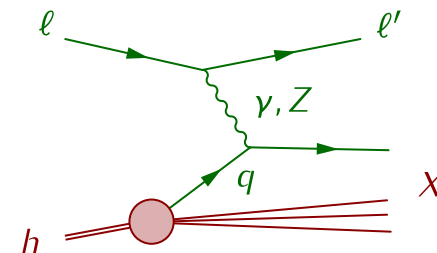
# Backup slides

# Data: Neutral current DIS

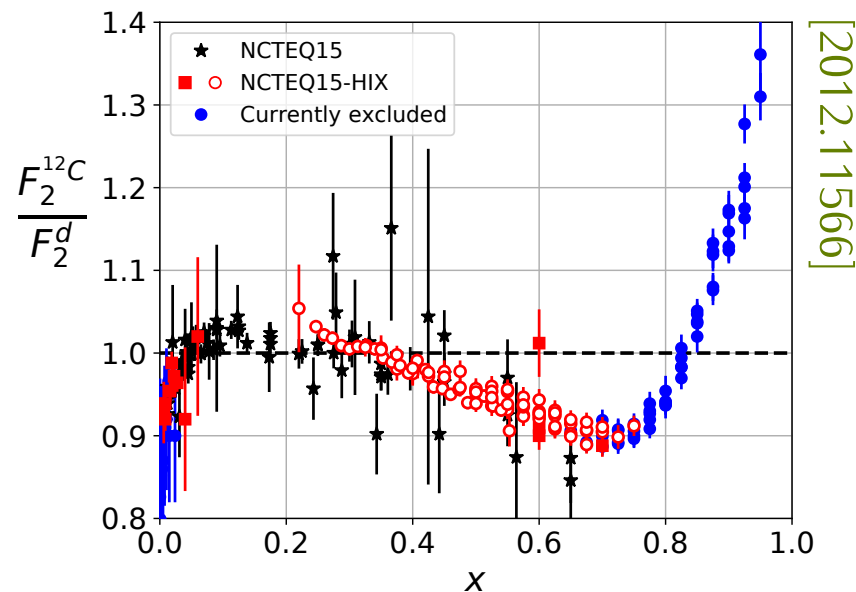


# Data: Neutral current DIS

	KSASG20	TUJU21	EPPS21	nNNPDF3.0	nCTEQ15HIX
NC DIS tot <sup>a</sup>	1274	459	1078	451	1227
JLAB only	199	-	160	-	336



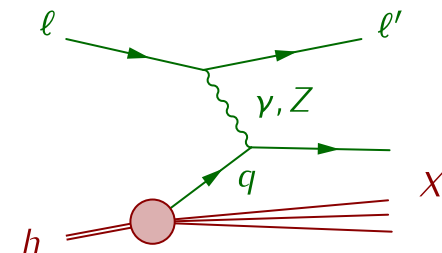
- Traditionally the bulk of data in nPDF analyses
- Constraints valence distributions across a broad  $x$  range
- NEW! JLab CLAS and Hall C data
  - ▶ Maps out the high- $x$  EMC region very precisely



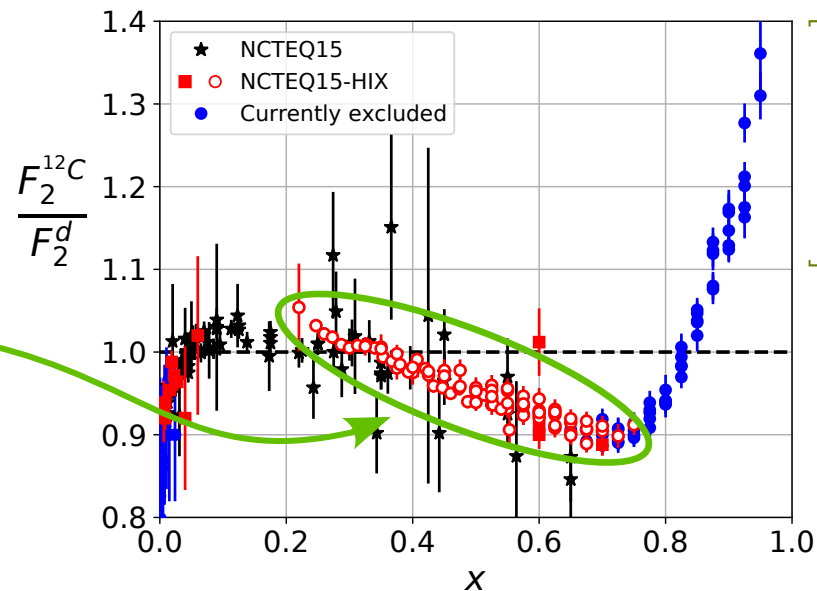
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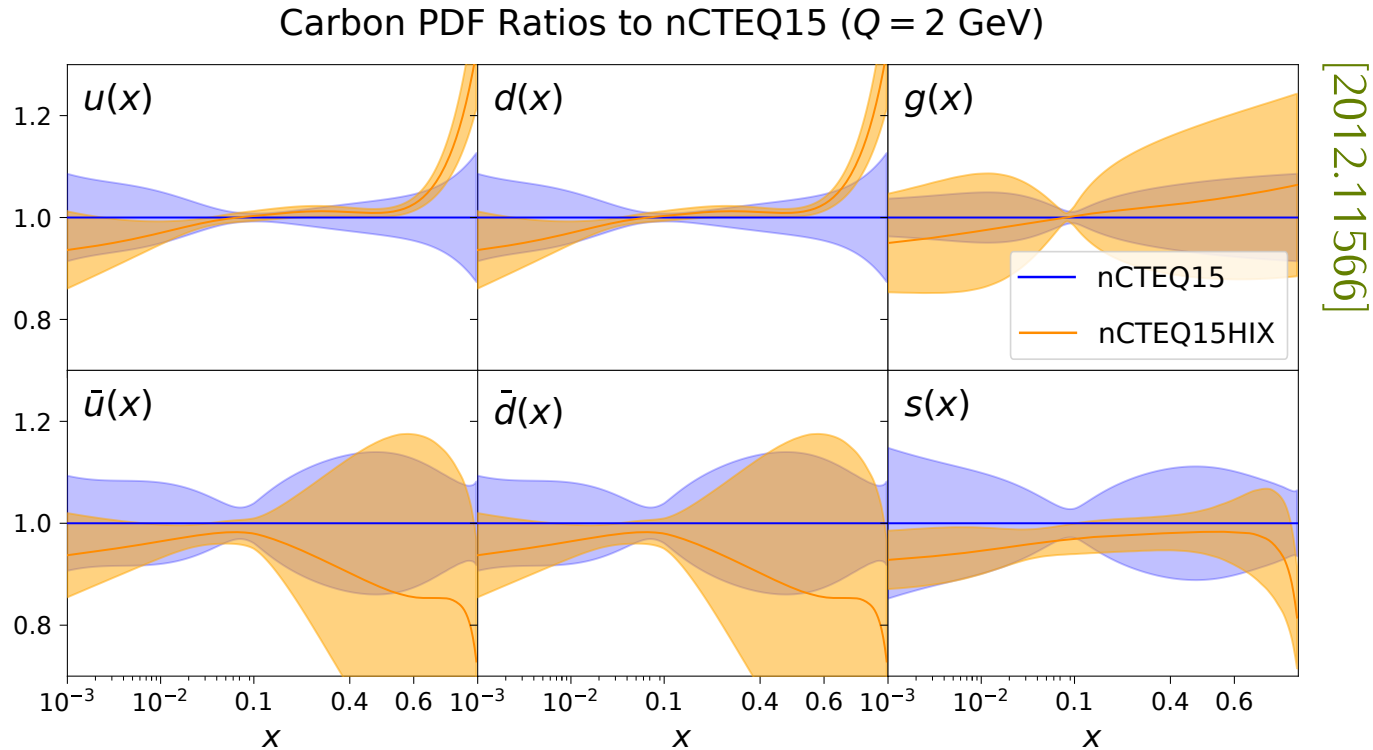
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[2012.11566]

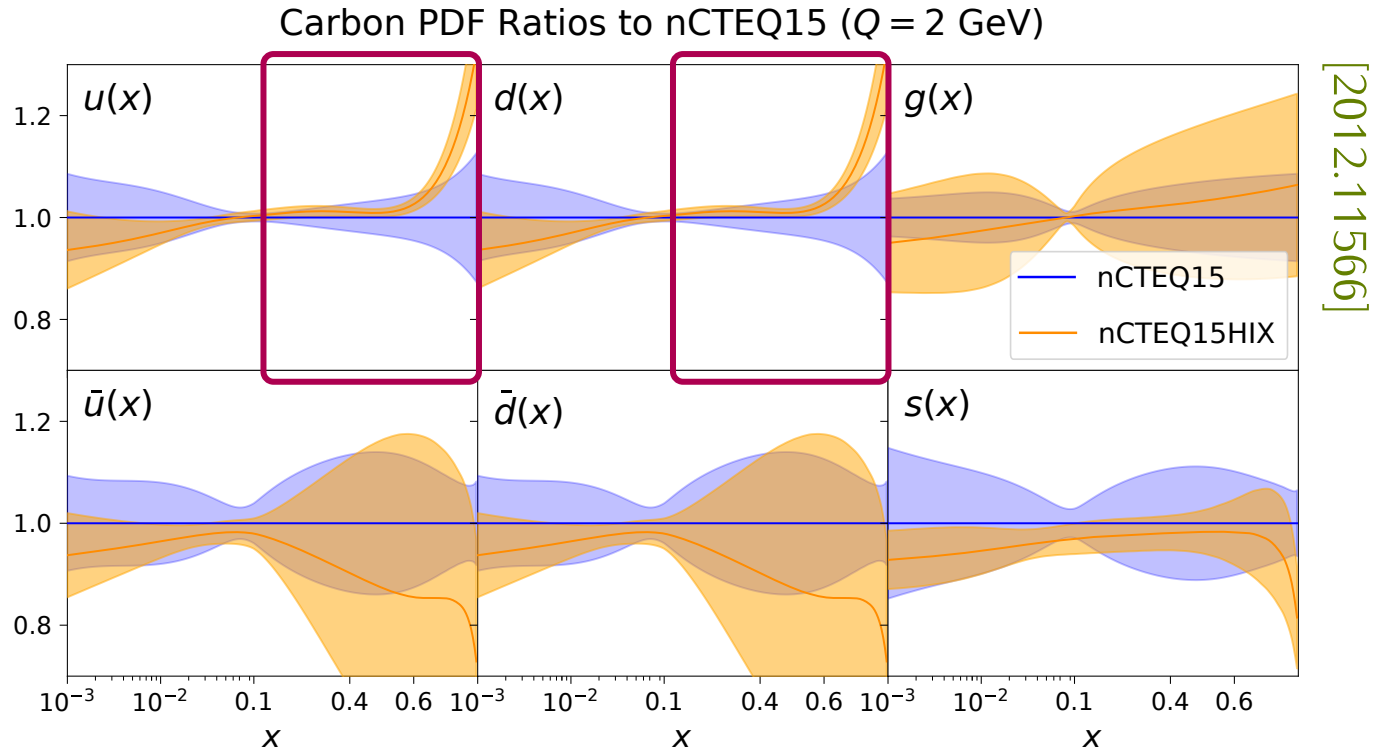
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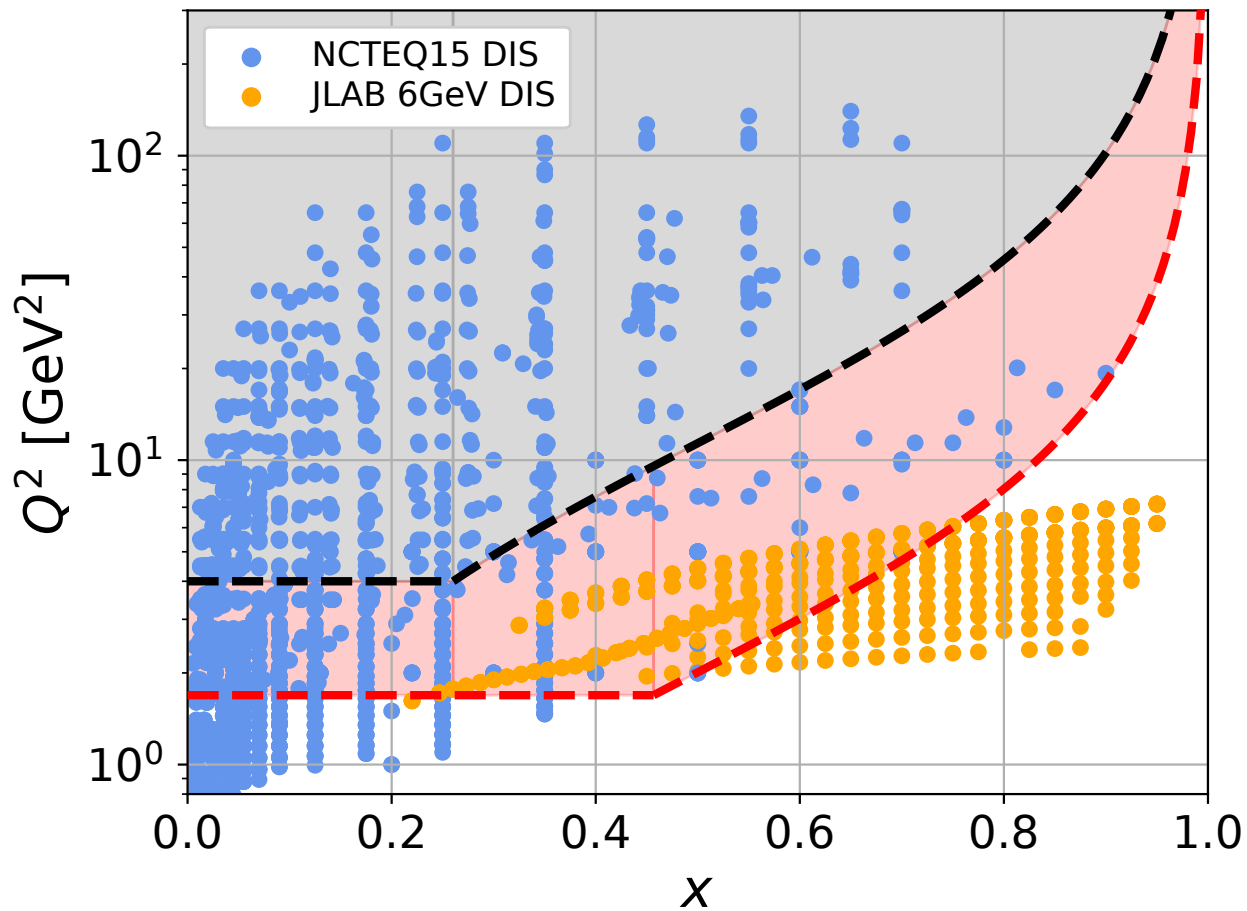
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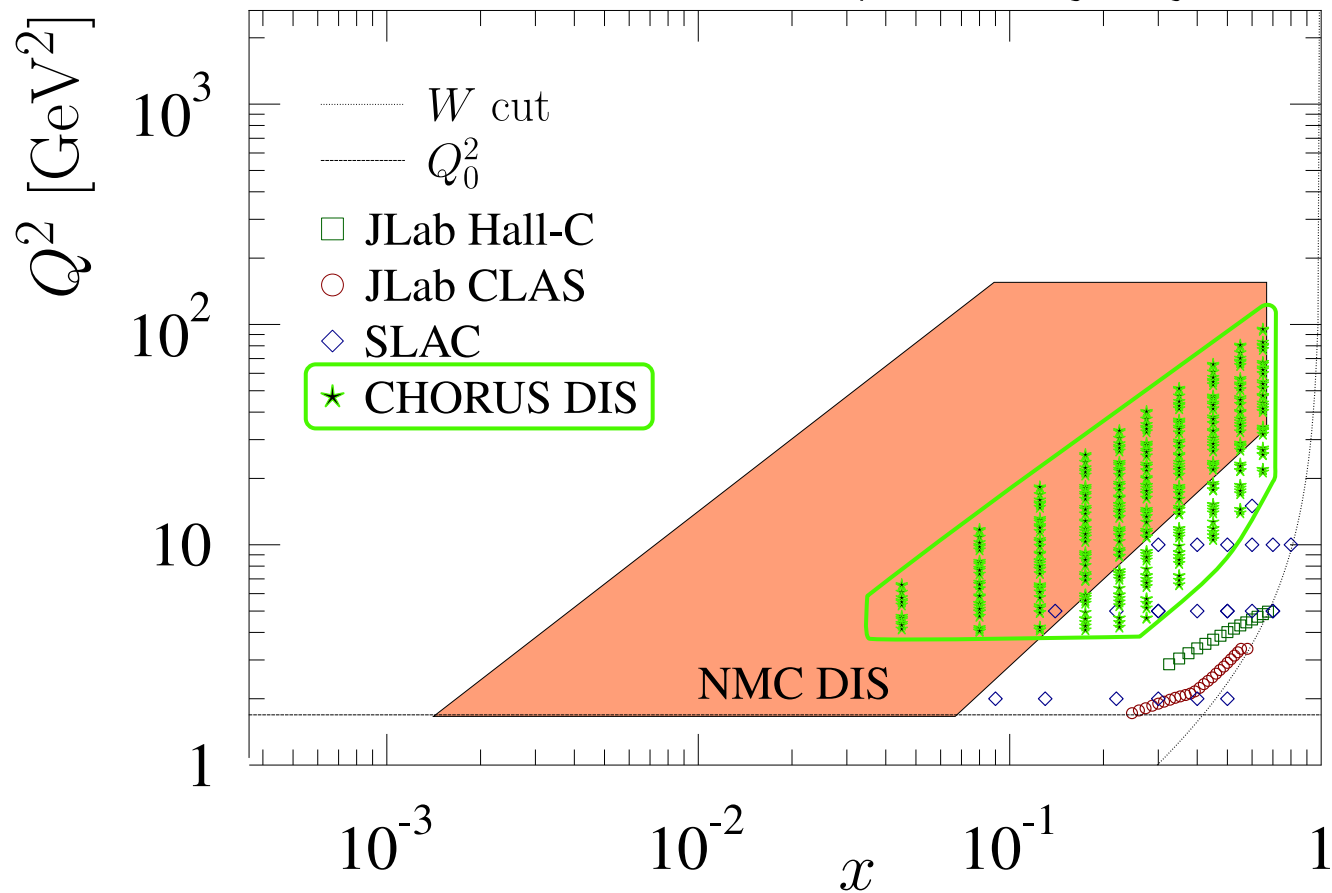
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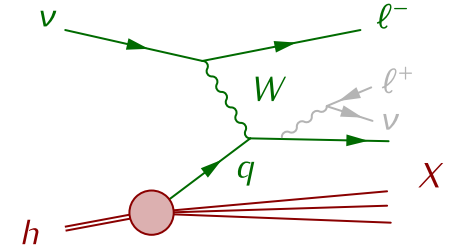
# Data: Charged current DIS

Adapted from a figure by EPPS21



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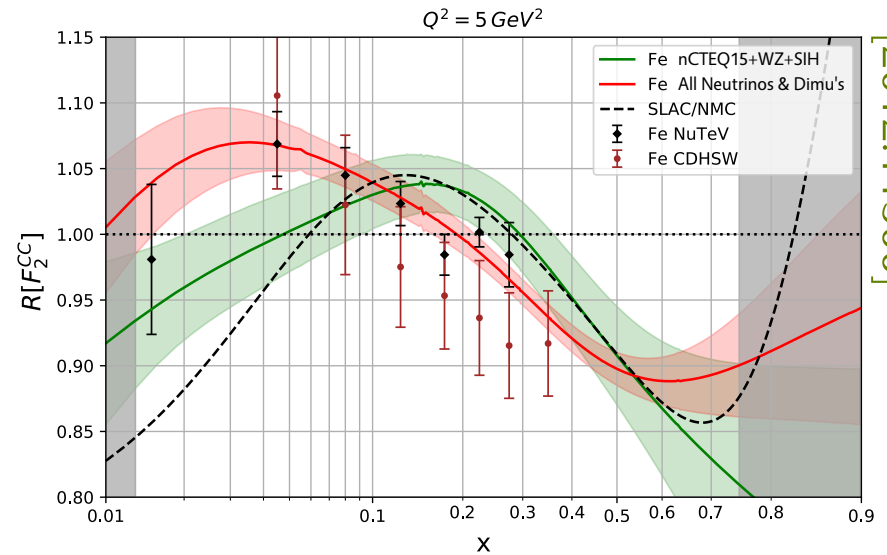
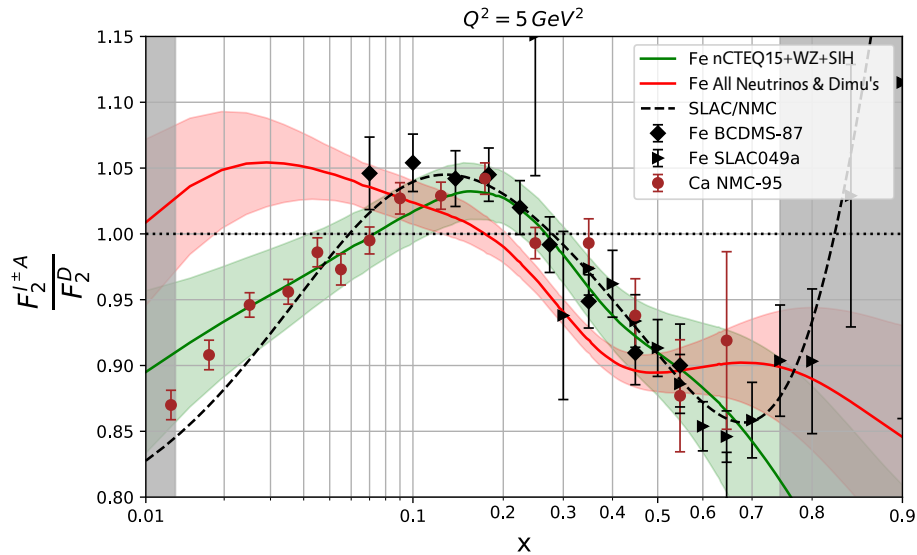
	KSASG20	TUJU21	EPPS21	nNNPDF3.0	nCTEQ15BDC <sup>a</sup>
CC DIS	2458	1736	824	922	974
di-muon only	-	-	-	76	150



- Important for flavour separation
- Constrains strange distribution
- Remarkably abundant and precise, but not universally included
  - ▶ Chorus (824 pts): mostly included
  - ▶ CDHSW (930 pts): sometimes included
  - ▶ CCFR & NuTeV (4343 pts): mostly excluded

<sup>a</sup>nCTEQ15BaseDimuChorus

# Data: Charged current DIS



[2012.11566]

- Nutev, CCFR and CDHSW data in tension with NC DIS data. Dropping correlations alleviates the tension but doesn't resolve it.

# Data: Charged current DIS

Adapted from a figure by EPPS21

