# Nuclear PDFs

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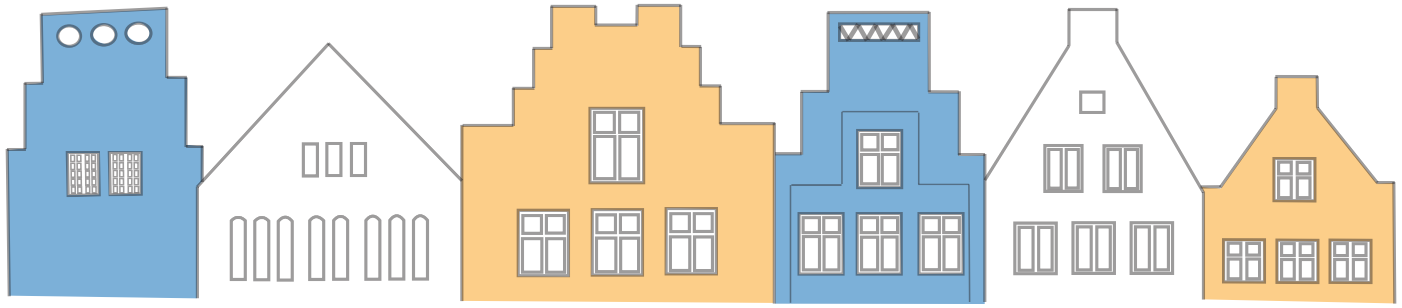
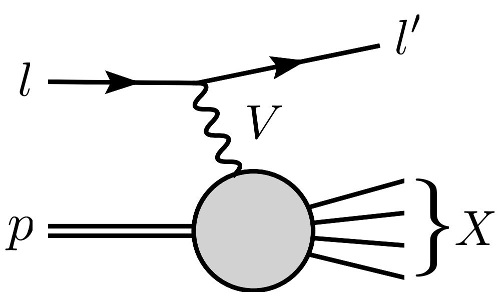


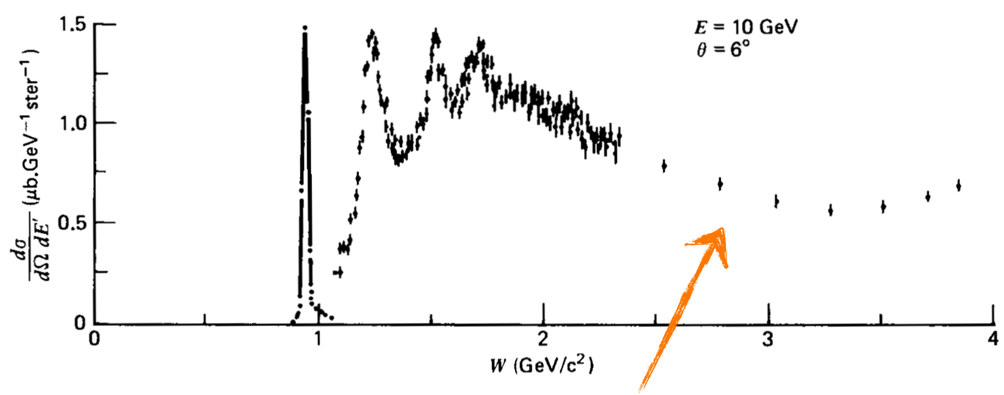
2024 CTEQ summer school on QCD and EW phenomenology

# Recap

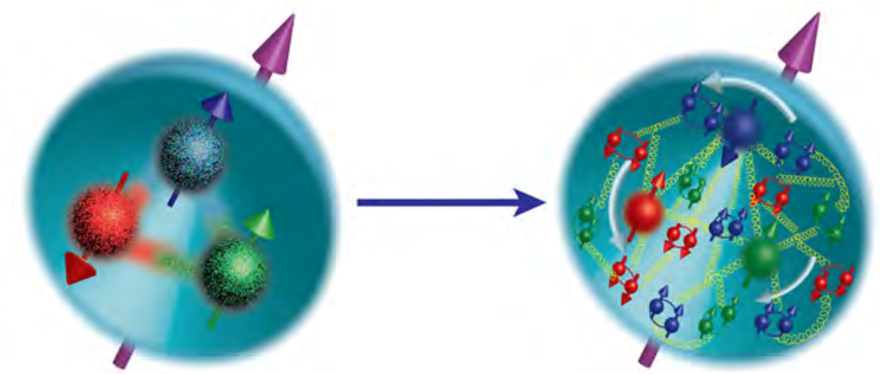
- Want to discover the inner structure of the proton? BREAK IT UP **HARD**




$$l(k) + p(p) \rightarrow l'(k') + X$$




Deep Inelastic Scattering (DIS)



- Distinguishing between elastic & inelastic scattering

$$W^2 = (p'_1 + p'_2 + \ldots + p'_n)^2 = m_p^2 + Q^2 \frac{(1-x)}{x}$$

  - if $W^2 = m_p^2$ elastic scattering
  - if $W^2 \gg m_p^2$ inelastic scattering

- Kinematic variables either $E', \theta$ or $x, Q^2$

$$Q^2 = -(k-k')^2 \overset{\text{lab}}{=} 4EE'\sin^2\frac{\theta}{2} \qquad x = \frac{Q^2}{2p.q} \overset{\text{lab}}{=} \frac{2EE'\sin^2\frac{\theta}{2}}{M(E-E')} \qquad y = \frac{p.q}{p.k} \overset{\text{lab}}{=} \frac{E-E'}{E}$$

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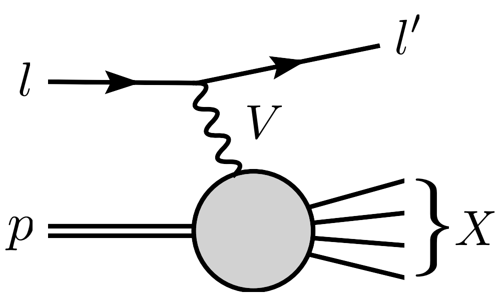


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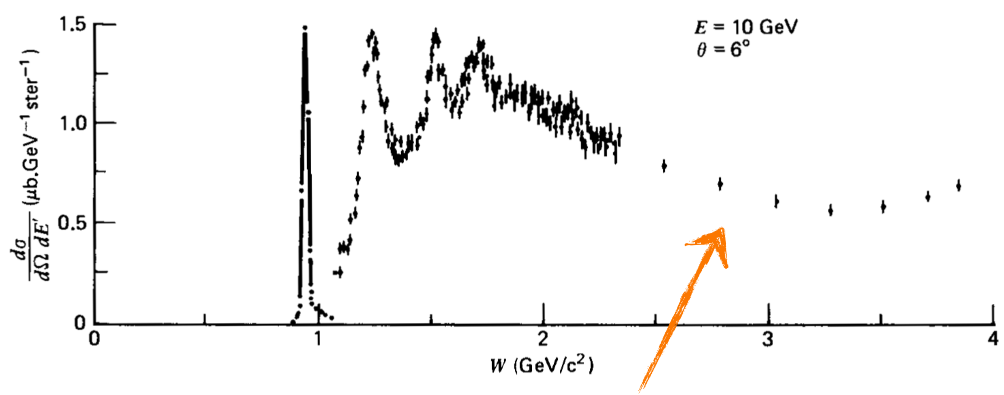
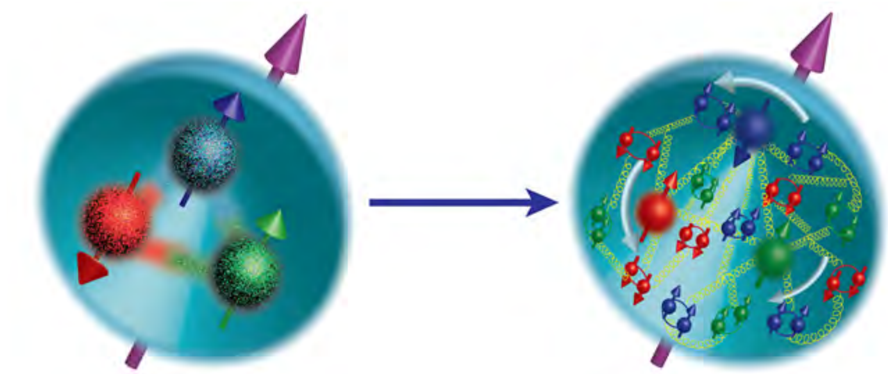


Deep Inelastic Scattering (DIS)

- DIS cross-section & structure functions (photon exchange)

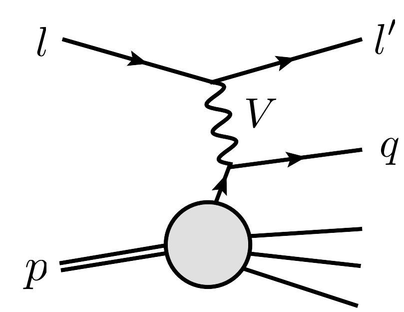
$$\frac{d\sigma}{dE'd\Omega} = \frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} \left( \frac{2F_1(x,Q^2)}{M} \sin^2 \frac{\theta}{2} + \frac{F_2(x,Q^2)}{E-E'} \cos^2 \frac{\theta}{2} \right)$$

or $$\frac{d\sigma}{dx\,dQ^2} = \frac{4\pi\alpha^2}{xQ^2} \left[ xy^2 F_1(x,Q^2) + (1-y)\,F_2(x,Q^2) \right]$$

- Assuming elastic scattering on partons in the proton - inelastic scattering an incoherent sum of elastic scatterings on proton constituents

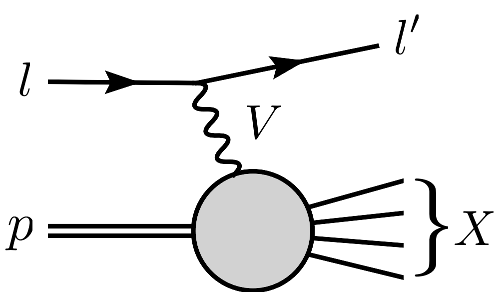
$$\frac{d\sigma}{dx\,dQ^2} = \sum_q \int \mathrm{d}\xi\, f_q(\xi) \left( \frac{d\sigma^{eq}}{dx\,dQ^2} \right)_{\text{el.}}$$

parton distribution function

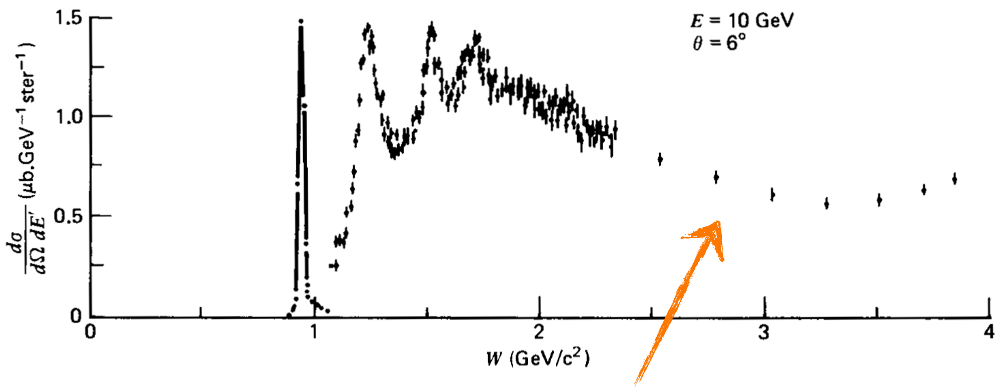


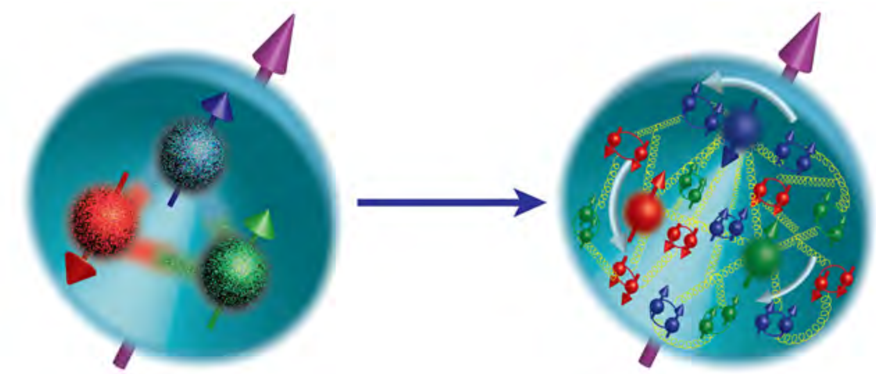
# Recap

- Want to discover the inner structure of the proton? BREAK IT UP **HARD**




$l(k) + p(p) \rightarrow l'(k') + X$



Deep Inelastic Scattering (DIS)

- DIS cross-section & structure functions

$$\frac{d\sigma}{dE'd\Omega} = \frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} \left( \frac{2F_1(x,Q^2)}{M} \sin^2 \frac{\theta}{2} + \frac{F_2(x,Q^2)}{E - E'} \cos^2 \frac{\theta}{2} \right)$$

or $$\frac{d\sigma}{dx\, dQ^2} = \frac{4\pi\alpha^2}{xQ^2} \left[ xy^2 F_1(x,Q^2) + (1-y)\, F_2(x,Q^2) \right]$$

- Assuming elastic scattering on partons in the proton - the structure function (at LO) is

$$F_2(x,\cancel{Q^2}) = 2xF_1(x,\cancel{Q^2}) = \sum_i e_i^2 \int \mathrm{d}\xi\, \xi\, f_i(\xi)\, \delta\left(\xi - \frac{Q^2}{2p.q}\right) = \sum_q e_q^2 x(f_q(x) + f_{\bar{q}}(x))$$

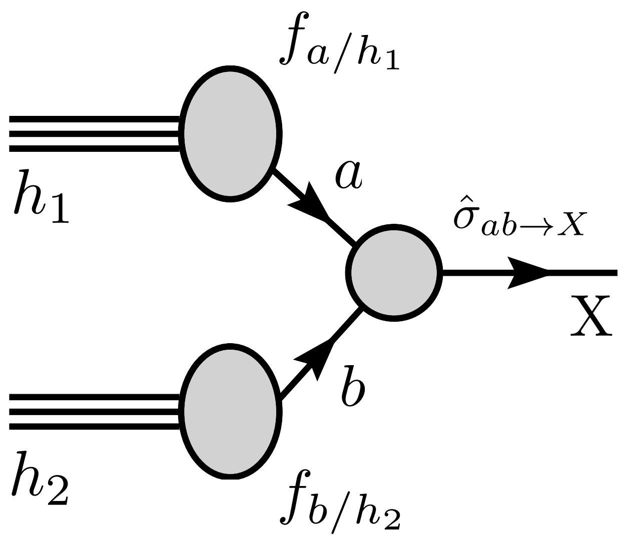
quark have spin 1/2

parton distribution function (PDF)

mom. fraction $\xi = x$ kinematic variable

# Recap

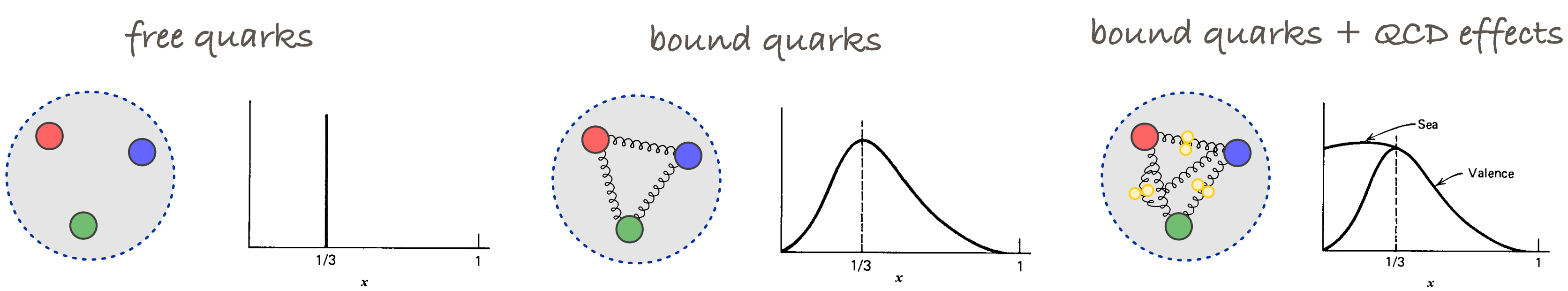
- Parton distribution functions are universal




$$\sigma = \sum_{a,b} \int dx_1 dx_2 \; f_{a/h_1}(x_1, Q^2) f_{b/h_2}(x_2, Q^2) \; \hat{\sigma}_{ab\to X}(x_1 x_2 s)$$

PDFs from experiment — from pQCD

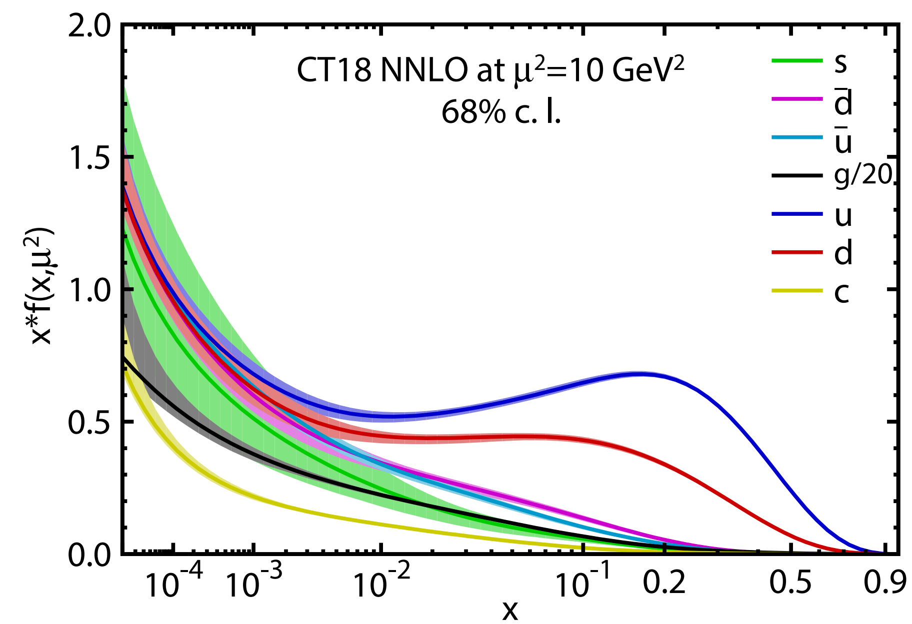
- In parton distribution functions the quark model is connected with QCD




for proton

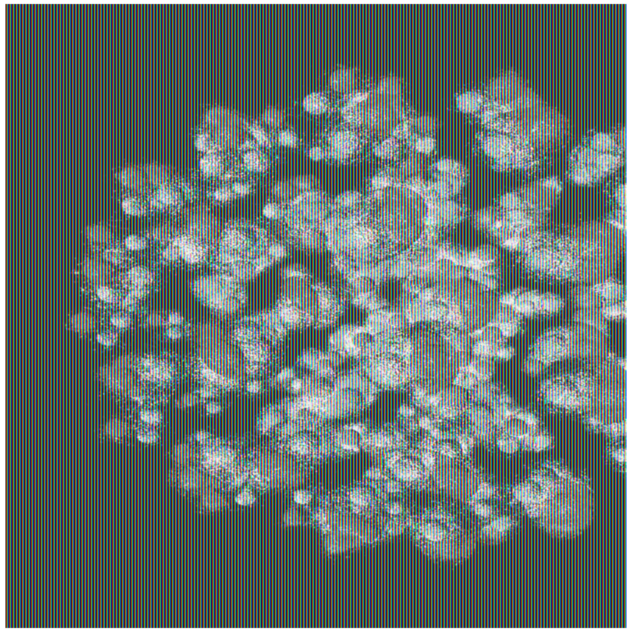
$$\int_0^1 dx \left[u(x) - \bar{u}(x)\right] = 2 \qquad \int_0^1 dx \left[d(x) - \bar{d}(x)\right] = 1$$

valence quark sum rules



# Nuclei

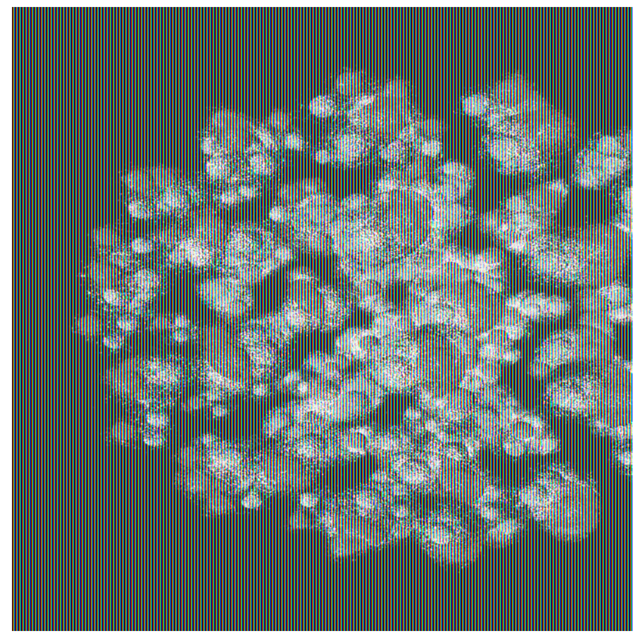
- Explanation of attraction between like-charged protons - strong force - QCD



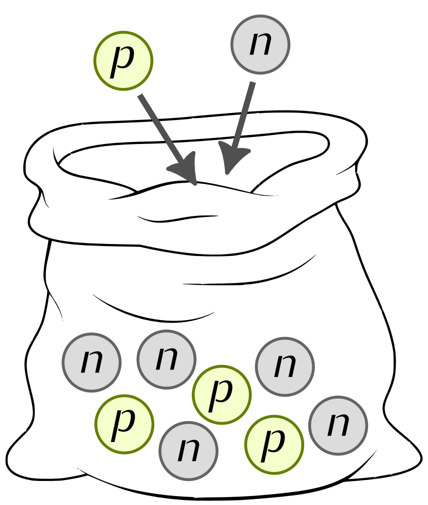
- Can we use the same language of PDFs to talk about the nucleus?

# Nuclei

- Explanation of attraction between like-charged protons - strong force - QCD



- Can we use the same language of PDFs to talk about the nucleus? YES we can



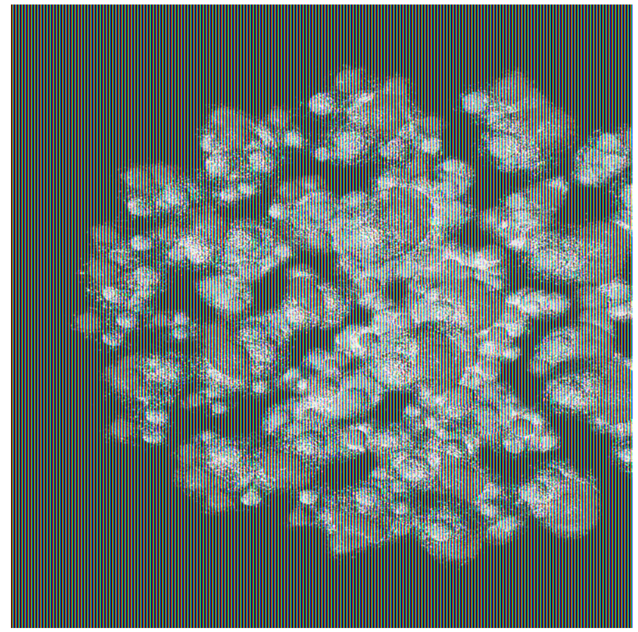

- *Free nucleon approximation* - nuclear binding effects assigned democratically to each nucleon in nucleus (A,Z)

$$f_i^N(x, Q^2)$$

↑ PDF of nucleus

# Nuclei

- Explanation of attraction between like-charged protons - strong force - QCD



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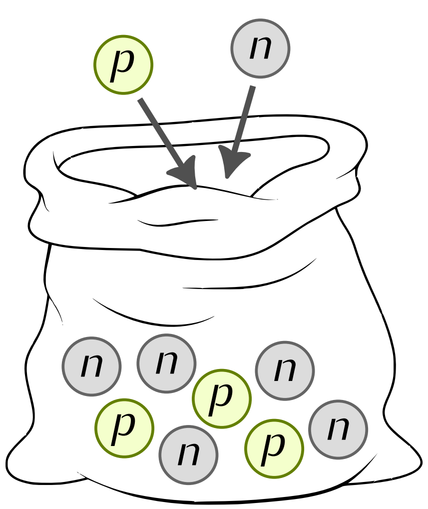



- *Free nucleon approximation* - nuclear binding effects assigned democratically to each nucleon in nucleus (A,Z)

$$f_i^N(x,Q^2) = A\, f_i^{(A,Z)}(x,Q^2) = Z\, f_i^{p/A}(x,Q^2) + (A-Z)\, f_i^{n/A}(x,Q^2)$$

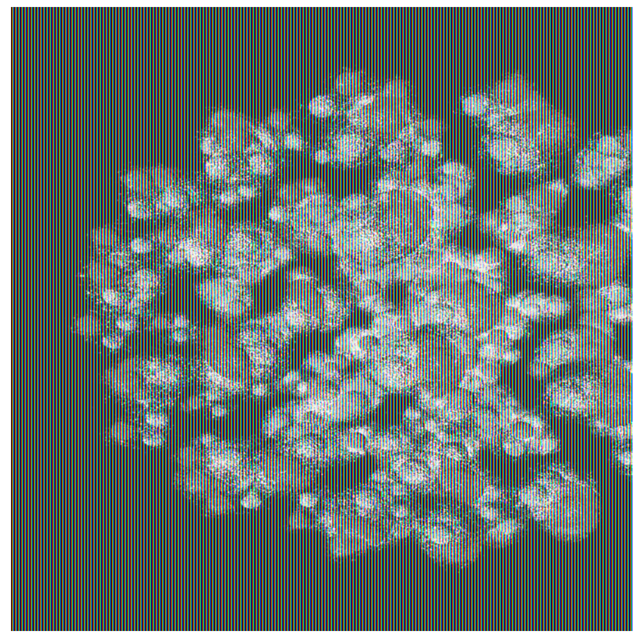
PDF of nucleus

PDF of average nucleon

PDF of bound proton

# Nuclei

- Explanation of attraction between like-charged protons - strong force - QCD



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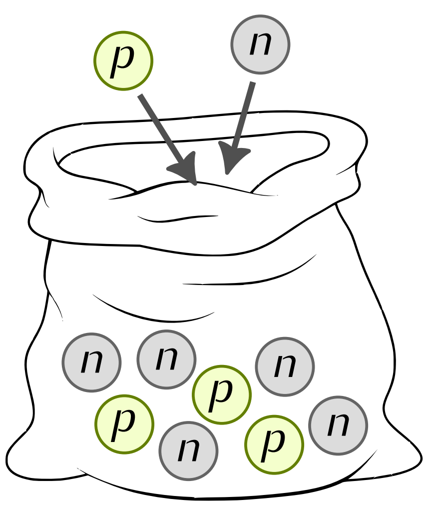



- *Free nucleon approximation* - nuclear binding effects assigned democratically to each nucleon in nucleus (A,Z)

$$f_i^N(x,Q^2) = A\, f_i^{(A,Z)}(x,Q^2) = Z\, f_i^{p/A}(x,Q^2) + (A-Z)\, f_i^{n/A}(x,Q^2)$$

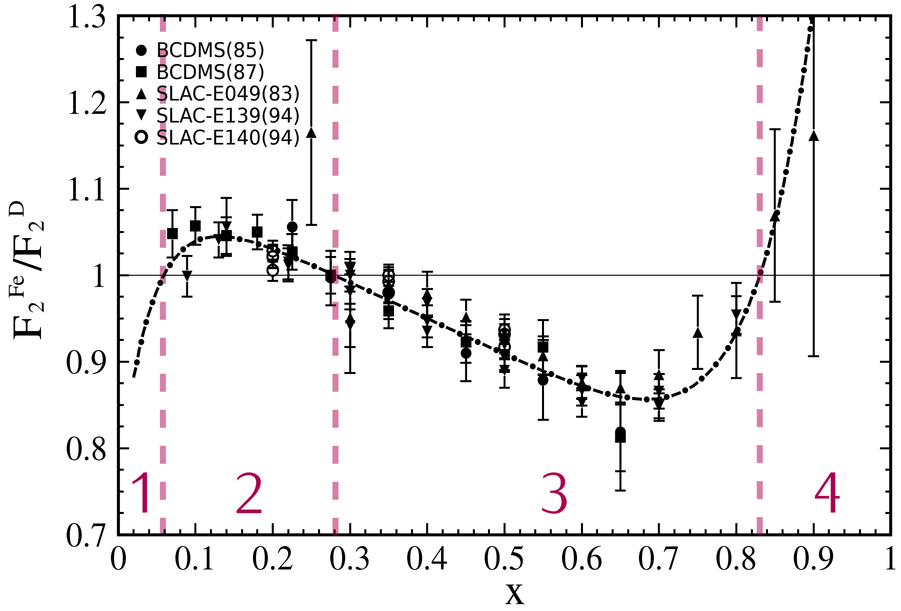
PDF of nucleus ($f_i^N$) — PDF of average nucleon ($f_i^{(A,Z)}$)

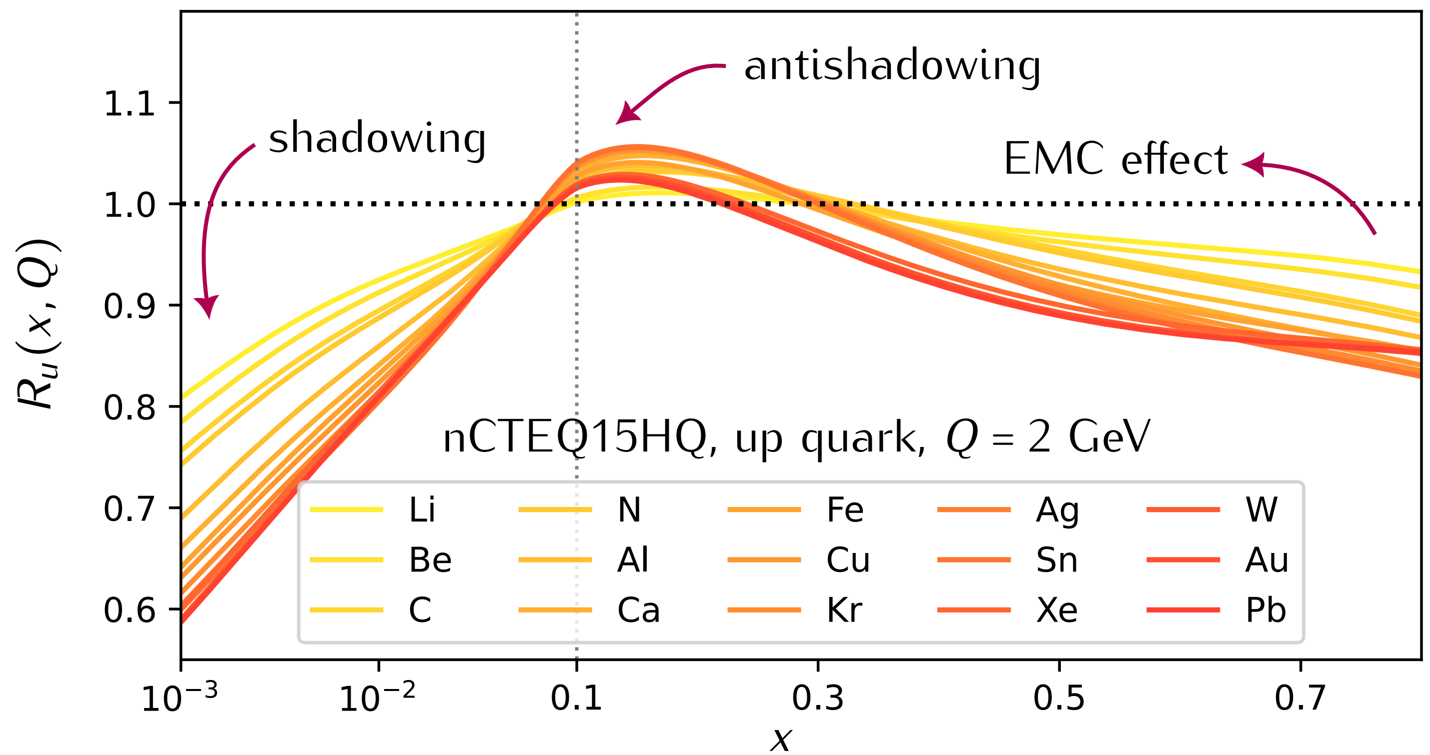
neutron structure related to proton via isospin

$$(u^{n/A}, d^{n/A}) = (d^{p/A}, u^{p/A})$$

# Nuclear binding

- How large are the nuclear binding effects? Are they uniform?




- Nuclear binding effects as correction factors R
  - many different possibilities to define R

$$R_{F_2}(x,Q) = \frac{F_2^A(x,Q)}{F_2^D(x,Q)}$$

$$R_u(x,Q) = \frac{u^{p/A}(x,Q)}{u^p(x,Q)}$$

- Different regions in x of the nuclear binding effects were given names

  *1. Shadowing*

  *2. Anti-shadowing*

  *3. EMC effect*

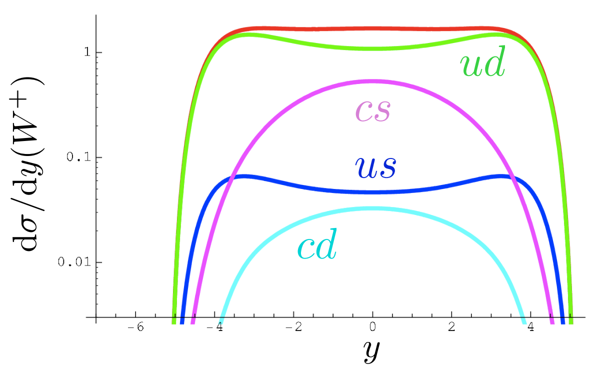
  *4. Fermi-motion*

# Nuclear effects

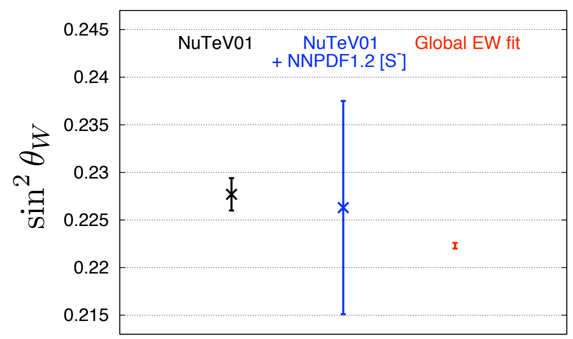
- Where/When are nuclear effects relevant/useful ?

*1. Strange quark content of the proton*

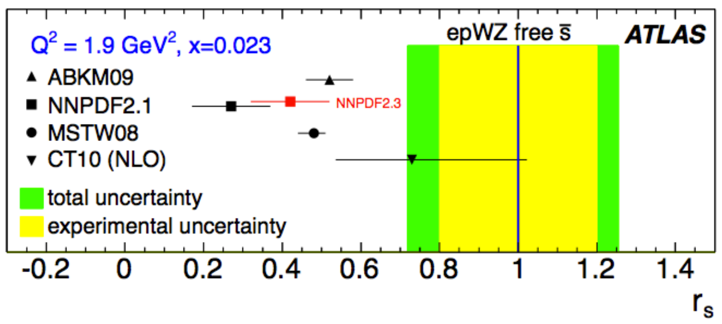
(anti-)strange PDF from (anti-)neutrino DIS with heavy nuclei - nuclear effects important




W-boson production @ LHC

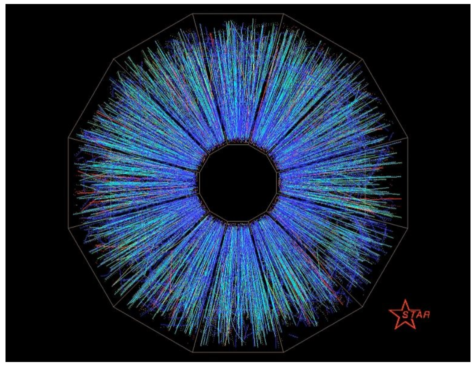


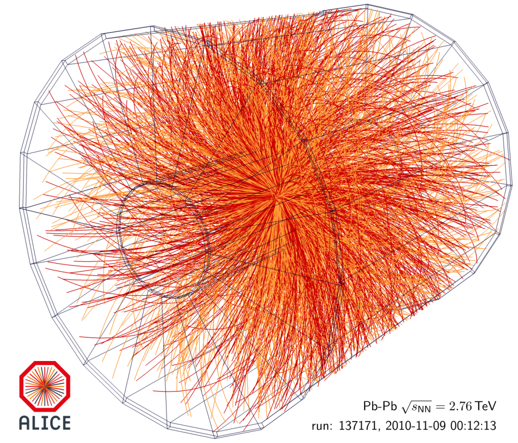

weak mixing angle from NuTeV experiment




*2. Heavy ion collisions @ RHIC, LHC*

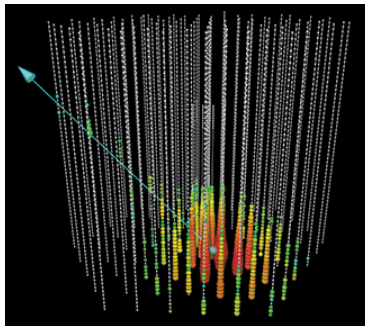
lead & gold heavy nuclei - nuclear effects in gluon PDF substantial

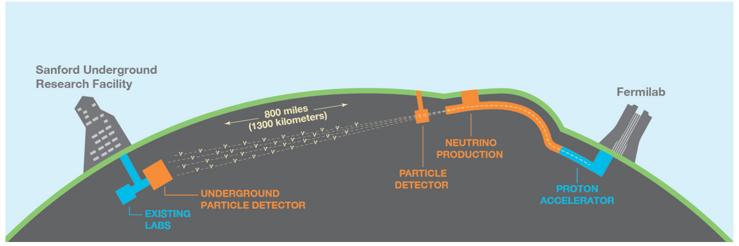





*3. Neutrino physics*

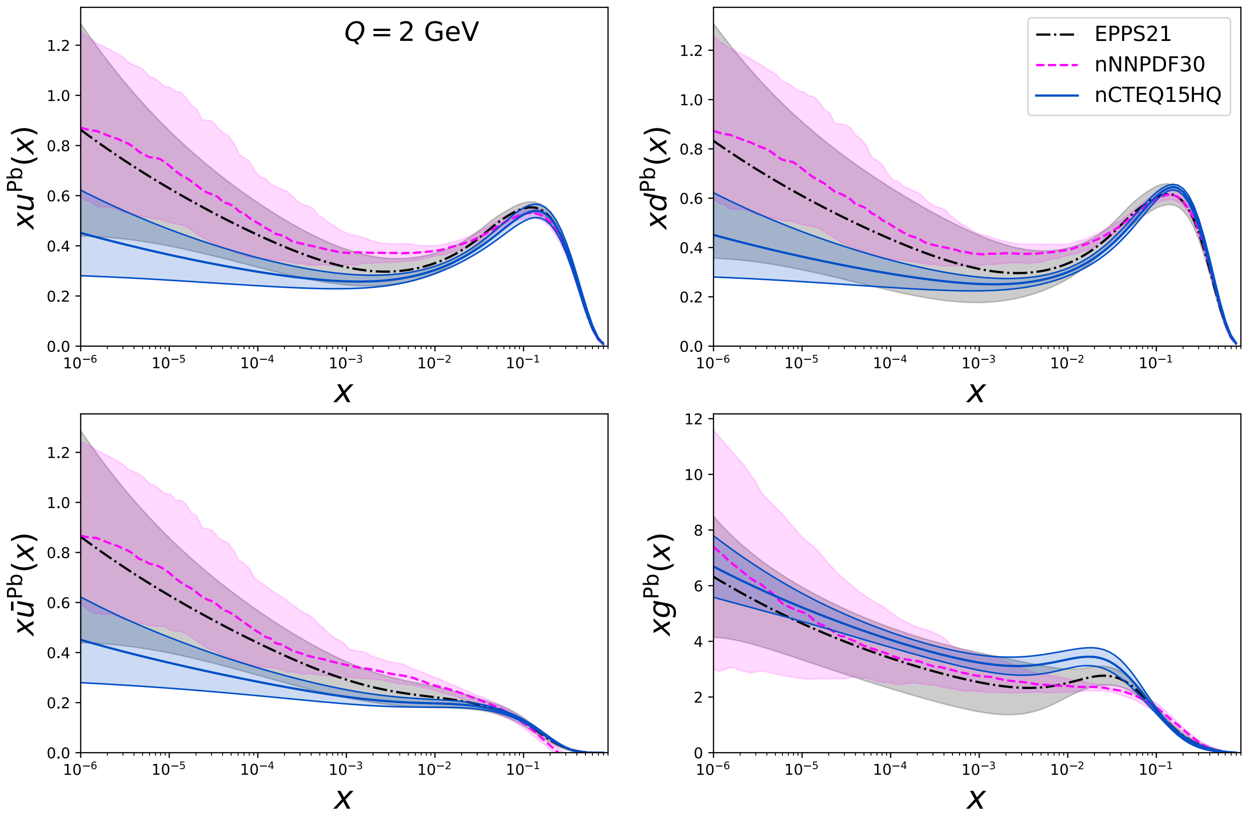
neutrinos interact only weakly - heavy targets required for sufficient count - IceCube (ice), DUNE (argon)





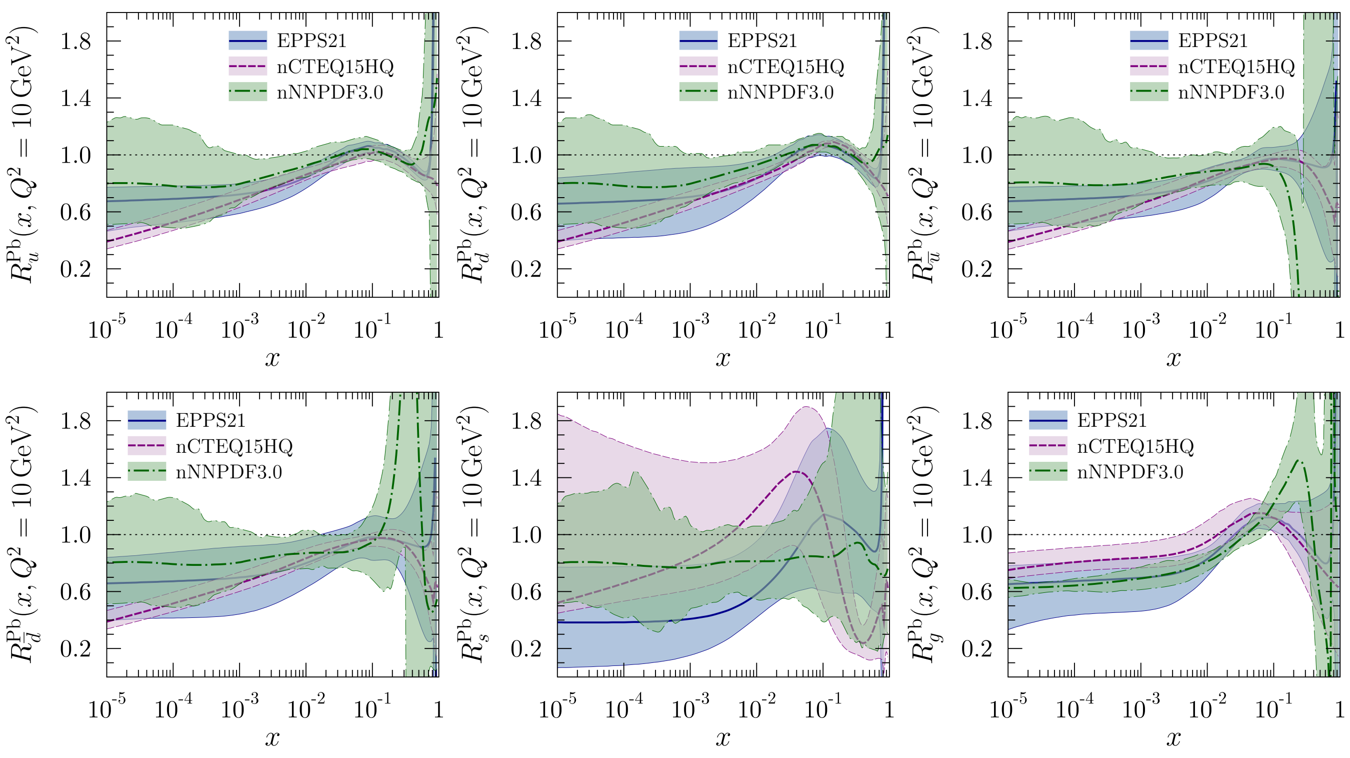
# Nuclear PDFs - results

- Nuclear PDFs similar in shape to the proton PDFs



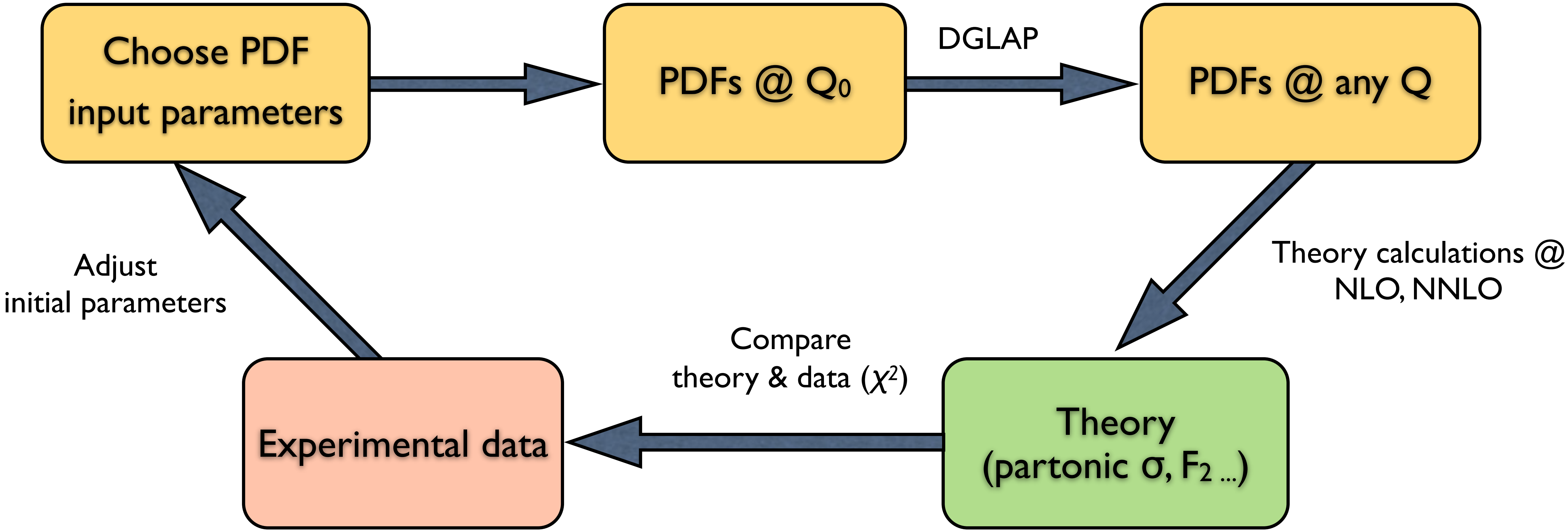

- Nuclear effects are similar in most partons

[2311.00450]



# Determining nPDFs

- Determining (nuclear) parton distribution functions
  - how do we determine them ? What are the moving parts in a typical PDF fitting-machine ?



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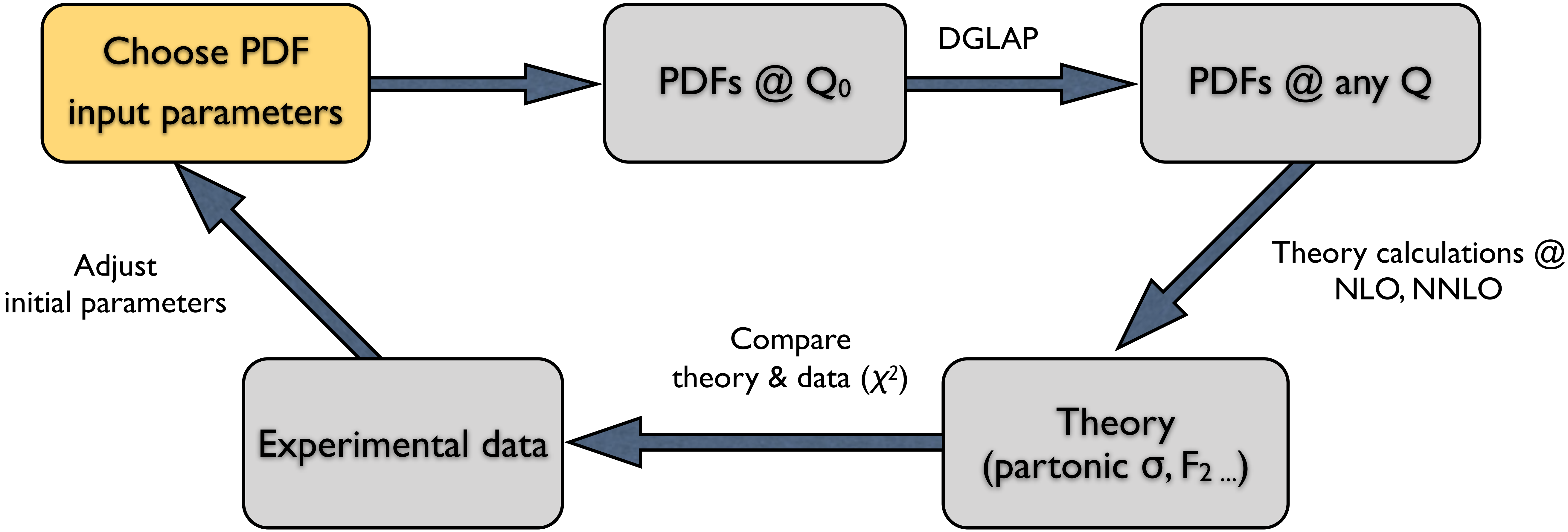


# Nuclear PDFs

- Nuclear effects in PDFs

*1. Multiplicative nuclear correction factor*

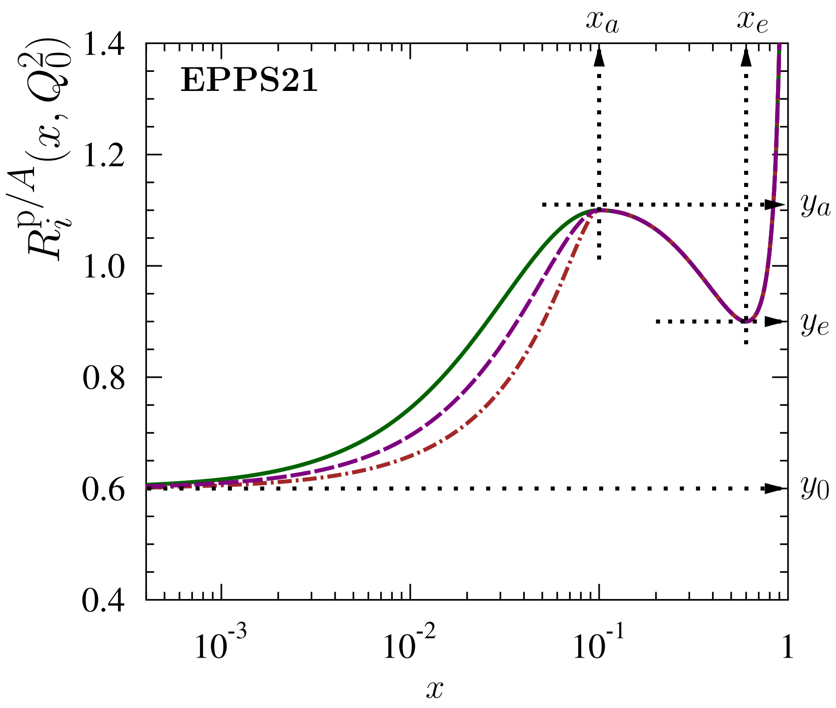
$$f_i^{p/A}(x_N, Q_0^2) = R_i^{p/A}(x_N, Q_0, A, Z) f_i^p(x_N, Q_0^2)$$

$$i = u_v, d_v, g, \bar{u} + \bar{d}, s, \bar{s}$$

bound parton density

free parton density

HKN07 - Hirai, Kumano, Nagai [PRC76(2007)065207] arXiv: 0709.0338
EPS09 - Eskola, Paukkunen, Salgado [JHEP0904(2009)065] arXiv: 0902.4154
DSSZ - de Florian, Sassot, Stratmann, Zurita [PRD85(2012)074028] arXiv: 1112.6324
KSASG20 - Khanpour et al. [PRD104(2021)3] arXiv: 2010.00555
EPPS21 - Eskola, Paakkinen, Paukkunen, Salgado [EPJC82(2022)413] arXiv: 2112.12462




- Complicated piecewise-parametrised nuclear correction factor (A-dependence in stitching conditions)

$$R_i^{p/A}(x, Q_0^2) = \begin{cases} a_0 + a_1(x - x_a)\left[e^{-xa_2/x_a} - e^{-a_2}\right] & x \le x_a \\ b_0 x^{b_1}(1-x)^{b_2} e^{x b_3} & x_a \le x \le x_e \\ c_0 + c_1(c_2 - x)(1-x)^{-\beta} & x_e \le x \le 1 \end{cases}$$

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

# Nuclear PDFs

- Nuclear effects in PDFs

*2. Nuclear PDF with neural network*

$$f_i^{p/A}(x_N, Q_0^2) = f_i(x_N, A, Q_0^2) \qquad f_i^{p}(x_N, Q_0^2) = f_i(x_N, A=1, Q_0^2)$$

bound parton density

free parton density

nNNPDF1.0 - Khalek et. al. [EPJC 79(2019)471] arXiv: 1904.00018

nNNPDF2.0 - Khalek et. al. [JHEP 09(2020)183] arXiv: 2006.14629

nNNPDF3.0 - Khalek et. al. [EPJC 82(2022)507] arXiv: 2201.12363

- functional form for bound protons same as for free proton PDF

$$x f_k(x, Q_0) = x^{\alpha_k}(1-x)^{\beta_k}\mathrm{NN}_k(x, A) \qquad f_k = \{\Sigma^{p/A}, T_3^{p/A}, T_8^{p/A}\}$$

$$x f_i(x, Q_0) = B_i\, x^{\alpha_i}(1-x)^{\beta_i}\mathrm{NN}_i(x, A) \qquad f_i = \{V^{p/A}, V_3^{p/A}, g^{p/A}\}$$

- In the evolution basis - singlet $\Sigma$, non-singlet sea quark $T_i$ , valence $V_i$

$$\Sigma = u + \bar{u} + d + \bar{d} + s + \bar{s} \qquad V = (u-\bar{u}) + (d-\bar{d}) + (s-\bar{s})$$

$$T_3 = (u+\bar{u}) - (d+\bar{d}) \qquad V_3 = (u-\bar{u}) - (d-\bar{d})$$

$$T_8 = (u+\bar{u}+d+\bar{d}) - 2(s+\bar{s}) \qquad V_8 = (u-\bar{u}+d-\bar{d}) - 2(s-\bar{s})$$

# Nuclear PDFs

- Nuclear effects in PDFs

*3. Traditional nuclear PDF*

$$f_i^{p/A}(x_N, Q_0^2) = f_i(x_N, A, Q_0^2) \qquad f_i^{p}(x_N, Q_0^2) = f_i(x_N, A=1, Q_0^2)$$

bound parton density

free parton density

nCTEQ15 - Kovarik et. al. [PRD93(2016)085037] arXiv: 1509.00792

nCTEQ15WZ, nCTEQ15HQ and other nCTEQ analyses

TUJU21 - Helenius, Walt, Vogelsang [PRD105(2022)9] arXiv: 2112.11904

- functional form for bound protons same as for free proton PDF

$$x\, f_k(x, Q_0) = c_0\, x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4} x)^{c_5}$$

$$k = u_v, d_v, g, \bar{u} + \bar{d}, s, \bar{s}$$

$$\bar{d}(x, Q_0)/\bar{u}(x, Q_0) = c_0\, x^{c_1} (1-x)^{c_2} + (1 + c_3 x)(1-x)^{c_4}$$

- coefficients with A-dependance (reduces to proton for A=1)

$$c_k \to c_k(A) \equiv c_{k,0} + c_{k,1}\left(1 - A^{-c_{k,2}}\right), \quad k = \{1, \ldots, 5\}$$

# Nuclear PDFs

| | proton | order | HQ | params | Uncert. |
|---|---|---|---|---|---|
| EPPS | CT18A | NLO | GM-VFNS (s-ACOT) | 7 indep. PDFs (24 params) | Hessian ($\Delta\chi^2$=33) |
| nCTEQ | CTEQ6 | NLO | GM-VFNS (s-ACOT) | 7 indep. PDFs (19 params) | Hessian ($\Delta\chi^2$=35) |
| nNNPDF | NNPDF4.0 | NLO | GM-VFNS (FONLL) | 6 indep. PDFs (neural network) | Monte Carlo |
| TUJU | own | NLO<br>NNLO | GM-VFNS (FONLL) | 7 indep. PDFs (16 params) | Hessian ($\Delta\chi^2$=50) |
| KSASG | CT18 | NLO<br>NNLO | GM-VFNS (FONLL) | 7 indep. PDFs (18 params) | Hessian ($\Delta\chi^2$=20) |

# Determining nPDFs

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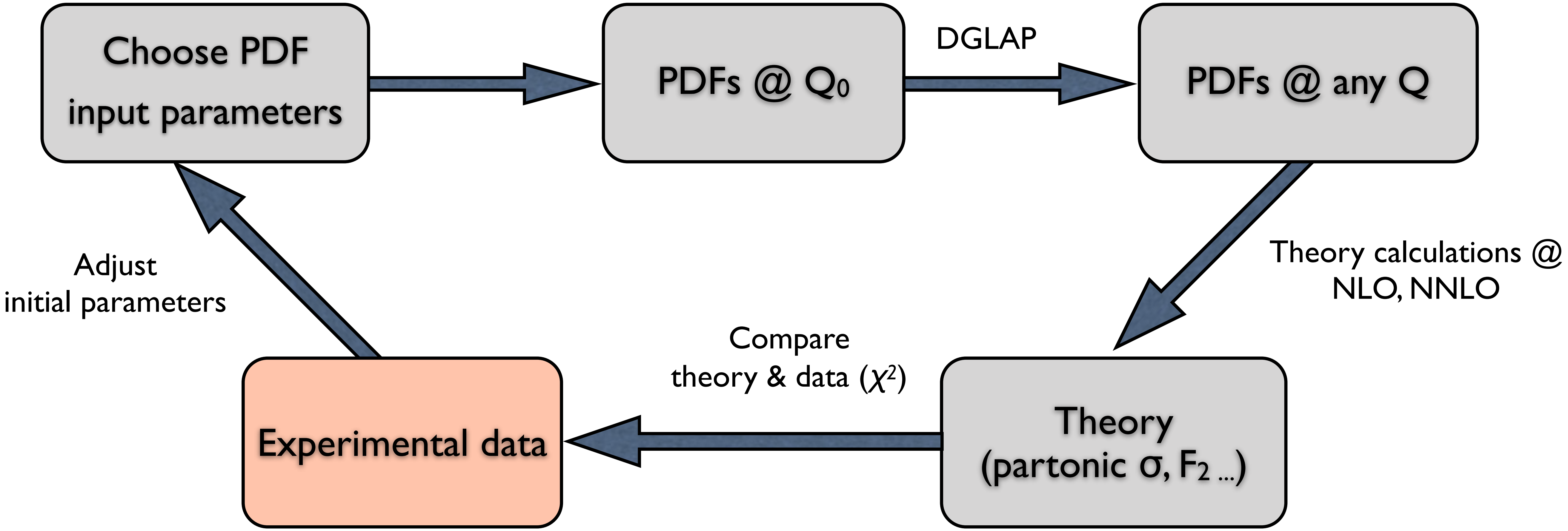
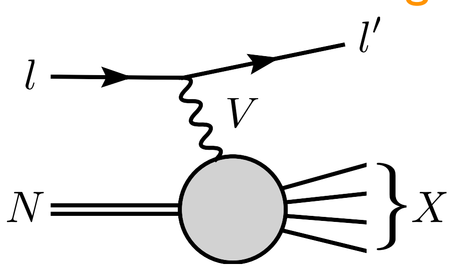


# Nuclear data

- Data for nuclear PDFs
  - Deep Inelastic Scattering (NC)




$$l + N \to l' + X$$

CERN BCDMS & EMC & NMC

$N = (\mathrm{D, Al, Be, C, Ca, Cu, Fe, Li, Pb, Sn, W})$

SLAC E-139 & E-049

$N = (\mathrm{D, Ag, Al, Au, Be, C, Ca, Fe, He})$

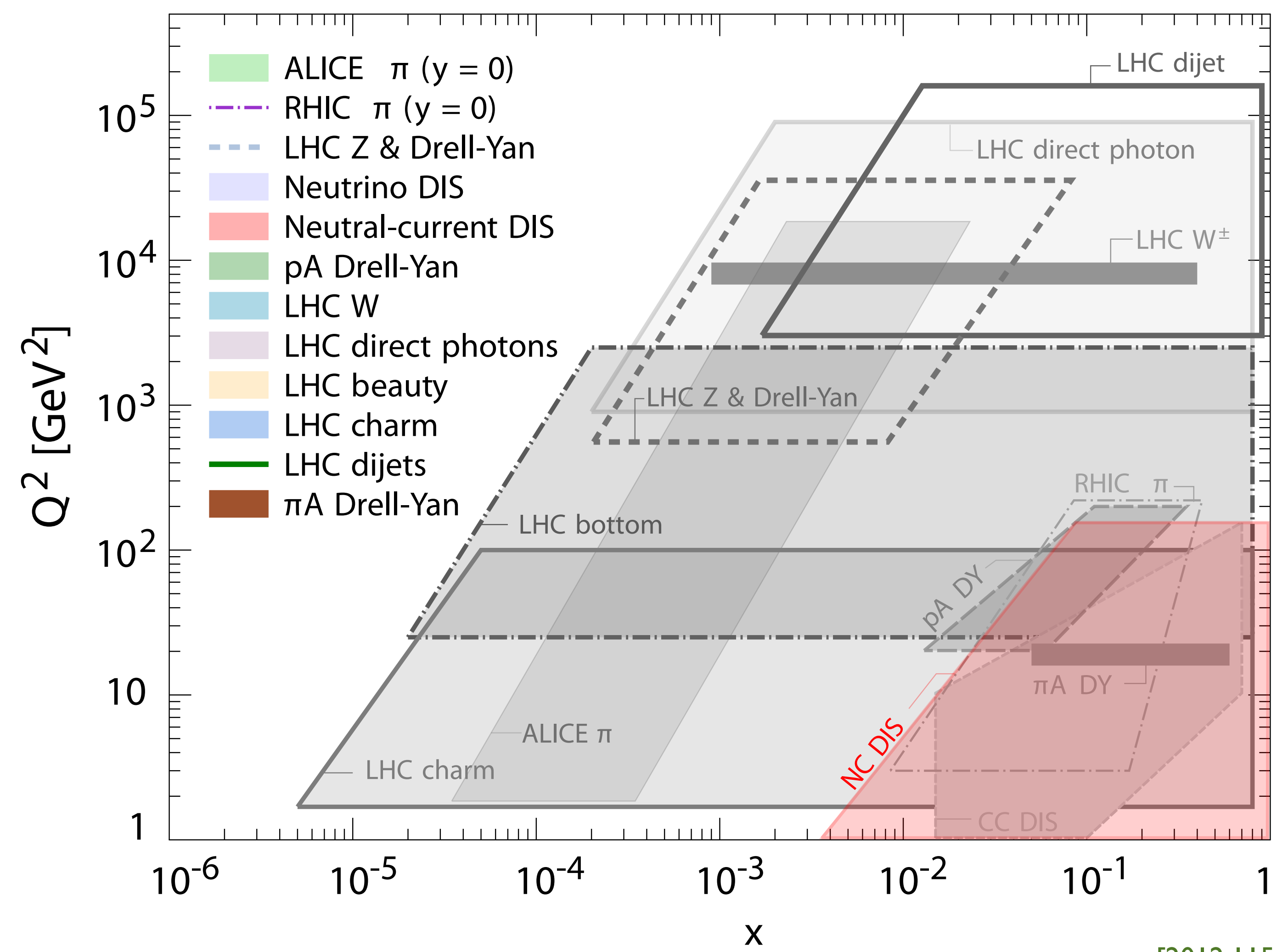
DESY Hermes

$N = (\mathrm{D, He, N, Kr})$

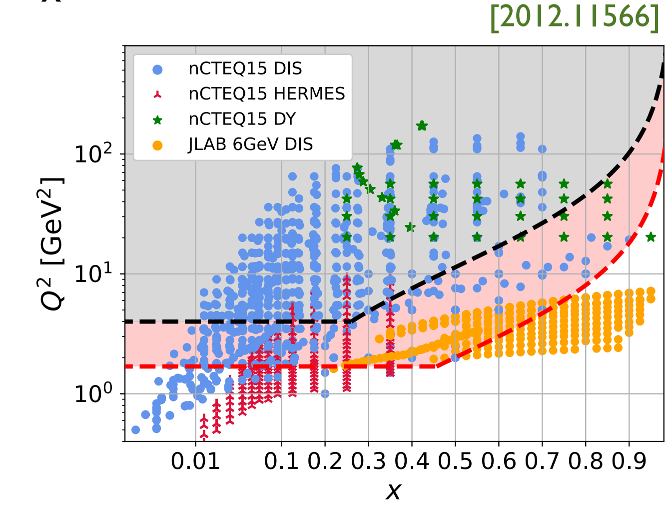
JLab CLAS & Hall C

$N = (\mathrm{He,\ Be,\ C,\ Al,\ Fe,\ Cu,\ Au,\ Pb})$

[2311.00450]



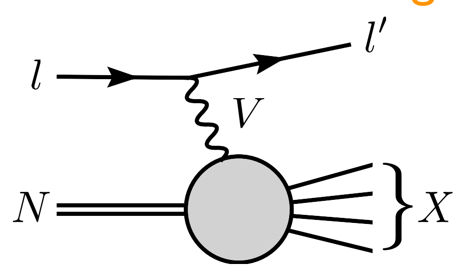

[2012.11566]



# Nuclear data

- Data for nuclear PDFs

  Deep Inelastic Scattering (NC)




$$l + N \to l' + X$$

**CERN BCDMS & EMC & NMC**

$N = (\mathrm{D, Al, Be, C, Ca, Cu, Fe, Li, Pb, Sn, W})$

**SLAC E-139 & E-049**

$N = (\mathrm{D, Ag, Al, Au, Be, C, Ca, Fe, He})$

**DESY Hermes**

$N = (\mathrm{D, He, N, Kr})$

**JLab CLAS & Hall C**

$N = (\mathrm{He,\ Be,\ C,\ Al,\ Fe,\ Cu,\ Au,\ Pb})$

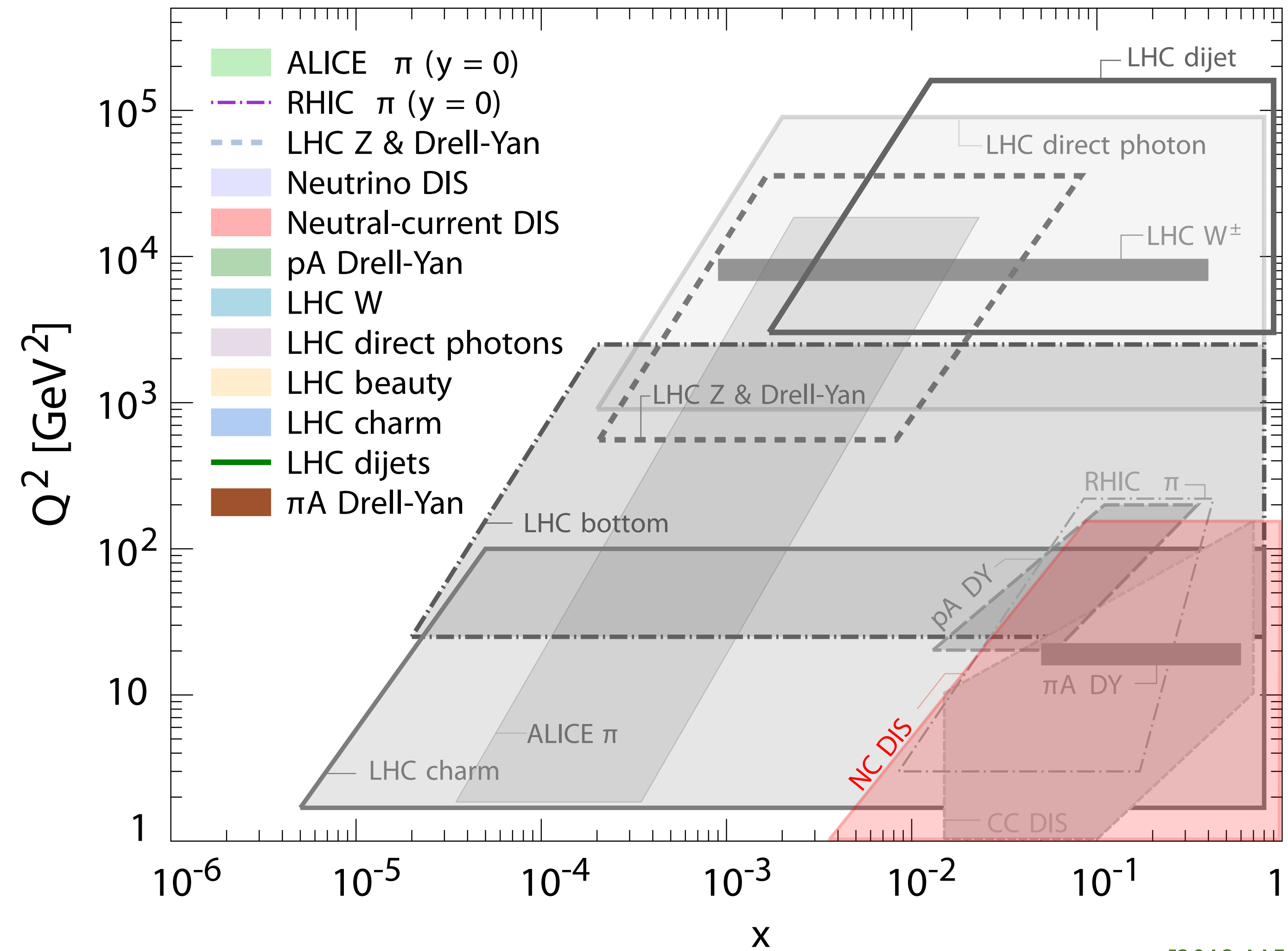
- Only photon exchange relevant - at leading order the structure function

$$F_2(x, Q^2) = \sum_q e_q^2\, x \left[q(x, Q^2) + \bar{q}(x, Q^2)\right]$$

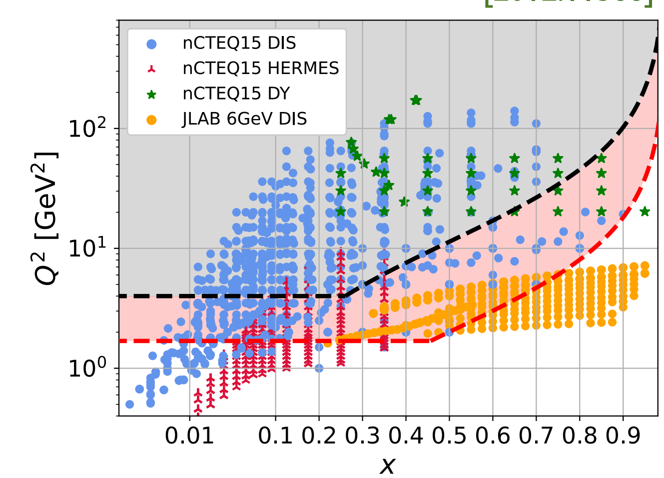
- Mainly constrains lin. combinations of (anti-)quark PDFs
- Many different nuclear targets, from *600 to 1350 data points* depending on cuts

$$Q^2 > 4\,\mathrm{GeV}^2 \quad W > 3.5\,\mathrm{GeV} \qquad \text{or} \qquad Q^2 > 1.69\,\mathrm{GeV}^2 \quad W > 1.7\,\mathrm{GeV}$$

[2311.00450]



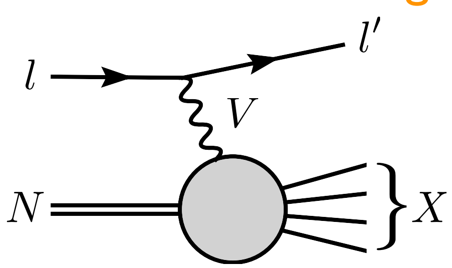

[2012.11566]



# Nuclear data

- Data for nuclear PDFs

  Deep Inelastic Scattering (NC)




$$l + N \to l' + X$$

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SLAC E-139 & E-049

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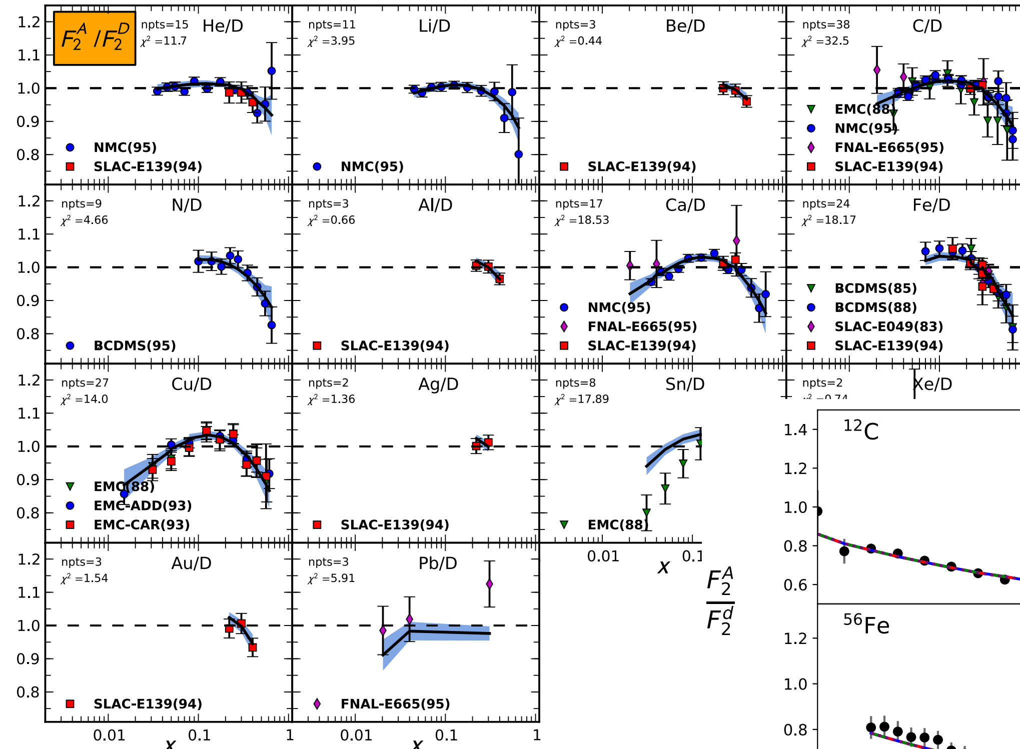
DESY Hermes

$$N = (\mathrm{D, He, N, Kr})$$

JLab CLAS & Hall C

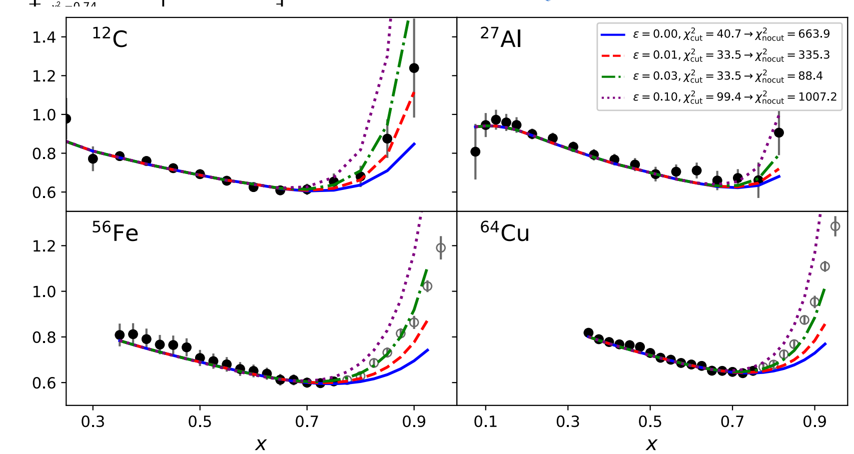
$$N = (\mathrm{He,\ Be,\ C,\ Al,\ Fe,\ Cu,\ Au,\ Pb})$$

[1509.00792]

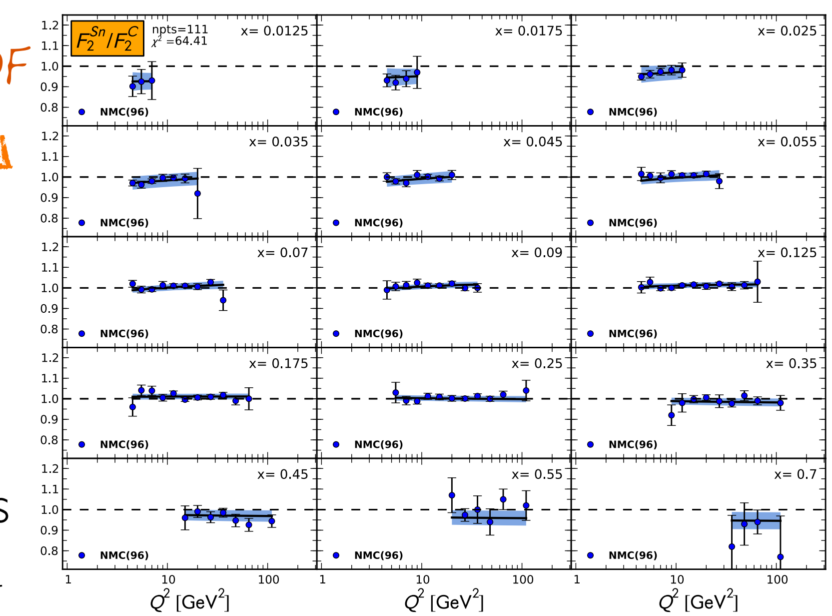



high-x JLab data

[2012.11566]




sensitive to gluon PDF




- Only photon exchange relevant - at leading order the structure function

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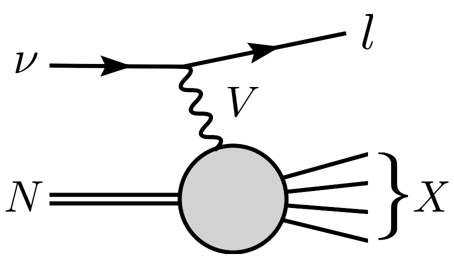
# Nuclear data

- Data for nuclear PDFs

  **Deep Inelastic Scattering (CC)**




$$\nu(\bar{\nu}) + N \to l + X$$

**CDHSW & CCFR & NuTeV**

$N = \mathrm{Fe}$

**Chorus**

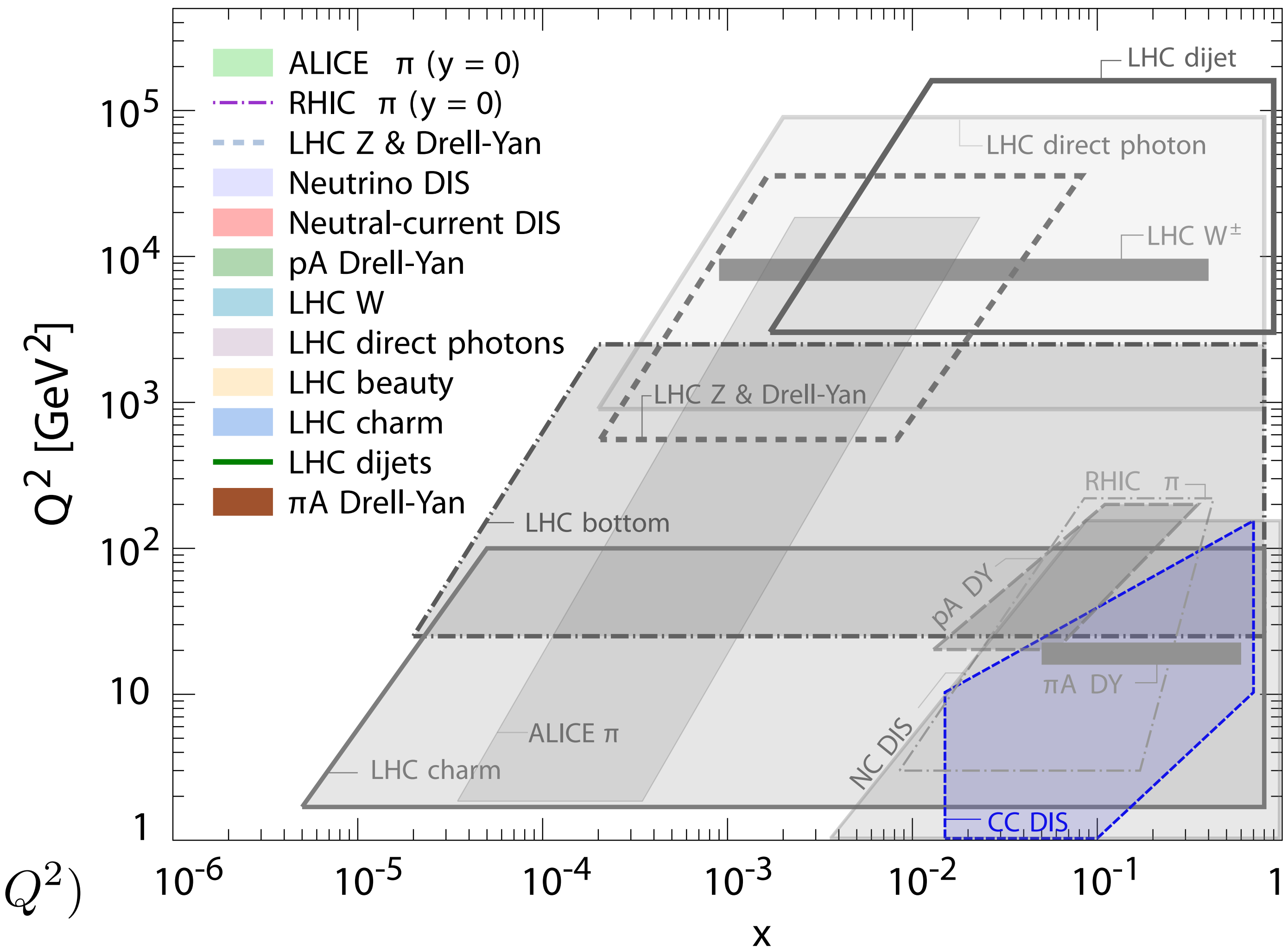
$N = \mathrm{Pb}$

- neutrino DIS contributes to $F_2(x, Q^2)$ and $F_3(x, Q^2)$
- different PDF combinations contribute to flavor separation together with NC DIS

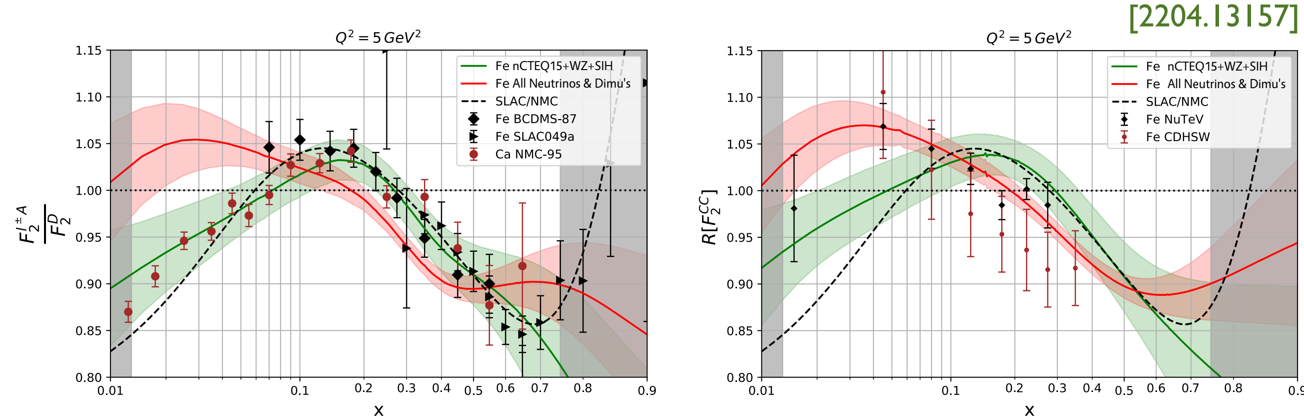
$$F_2(x, Q^2) = x \sum_q \left[q(x, Q^2) + \bar{q}(x, Q^2)\right]$$

$$xF_3(x, Q^2) = x \sum_q \left[q(x, Q^2) - \bar{q}(x, Q^2)\right]$$

[2311.00450]



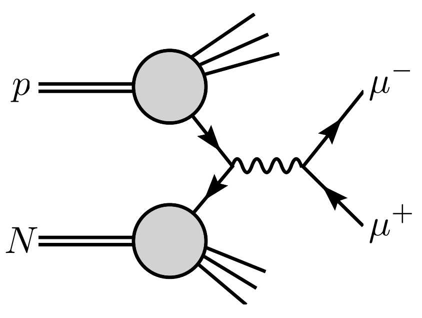

[2204.13157]



# Nuclear data

- Data for nuclear PDFs

  Drell-Yan process




$p + N \to \mu^+ \mu^- + X$

**FNAL E-665**

$N = (\mathrm{D}, \mathrm{C}, \mathrm{Ca}, \mathrm{Pb}, \mathrm{Xe})$

**FNAL E-772 & E-886**

$N = (\mathrm{D}, \mathrm{C}, \mathrm{Ca}, \mathrm{Fe}, \mathrm{W})$

**LHC Run I - ATLAS, CMS $Z^0, W^+, W^-$**

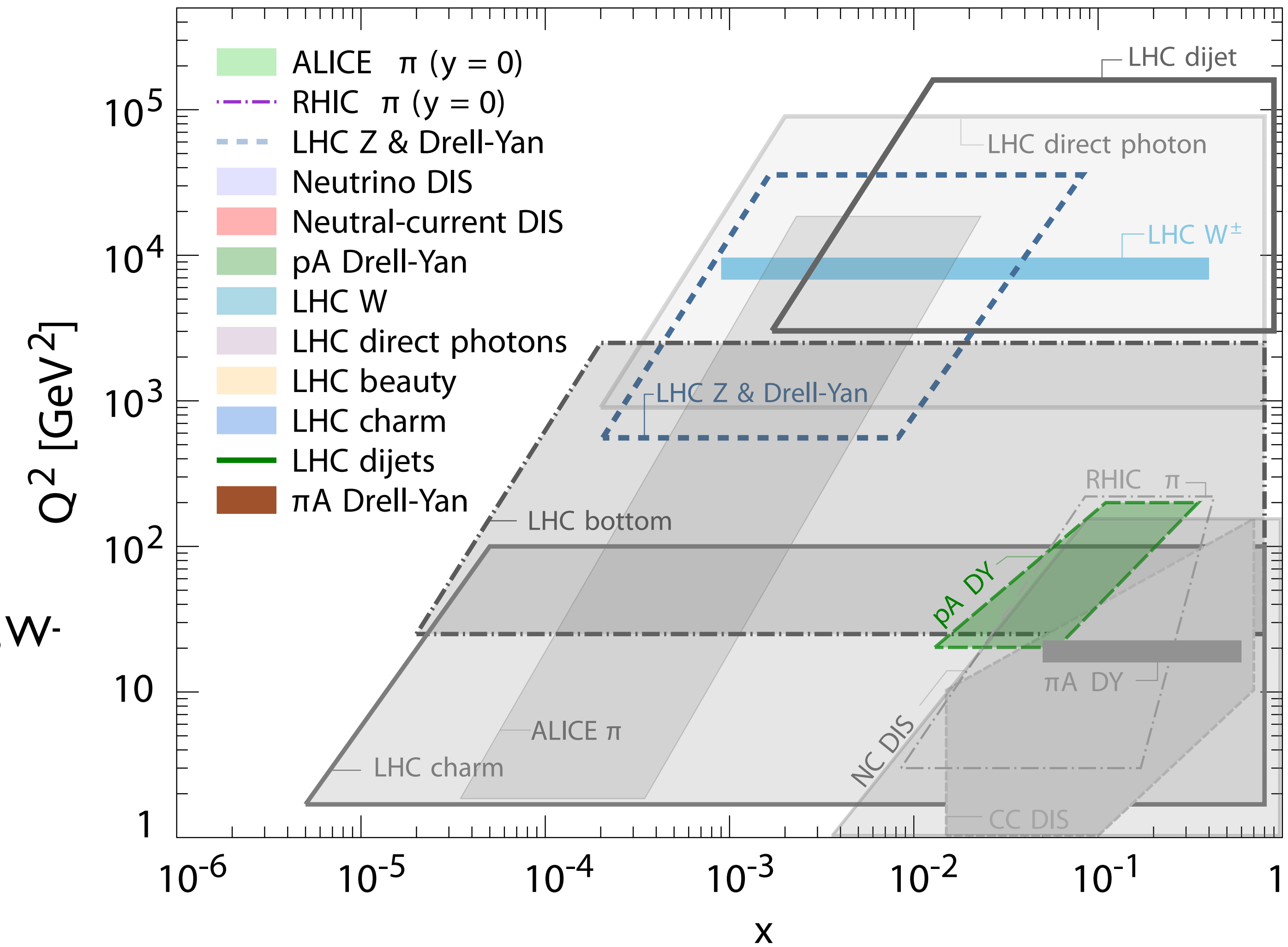
**- ALICE $W^+, W^-$**

**- LHCb $Z^0$**

**LHC Run II - CMS $W^+, W^-$**

$N = \mathrm{Pb}$

[2311.00450]




- DY dominated by photon exchange away from W & Z resonances

$$\frac{\mathrm{d}\sigma}{\mathrm{d}Q^2\mathrm{d}y} = \frac{4\pi\alpha^2}{9Q^2 s}\sum_i e_i^2\left[q_i(x_a,Q^2)\bar{q}_i(x_b,Q^2) + a \leftrightarrow b\right] \qquad Q^2 = (p_l + p_{\bar{l}})^2 \qquad x_{a,b} = \frac{Q}{\sqrt{s}}\exp(\pm y)$$

- DY at the W & Z resonances - different PDF combinations

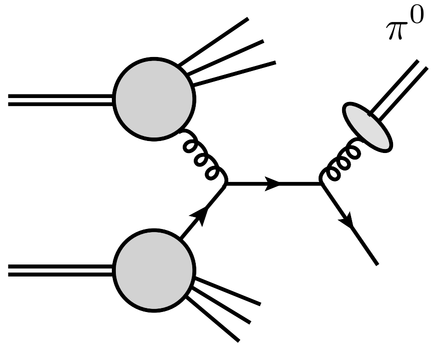
$$\frac{\mathrm{d}\sigma^W}{\mathrm{d}y} = \frac{\sqrt{2}\pi G_F m_W^2}{3s}\sum_{i,j}|V_{ij}^{\mathrm{CKM}}|\left[q_i(x_a,Q^2)\bar{q}_j(x_b,Q^2) + a \leftrightarrow b\right] \qquad \frac{\mathrm{d}\sigma^Z}{\mathrm{d}y} = \frac{\sqrt{2}\pi G_F m_Z^2}{3s}\sum_i \left(V_i^2 + A_i^2\right)\left[q_i(x_a,Q^2)\bar{q}_i(x_b,Q^2) + a \leftrightarrow b\right]$$

# Nuclear data

- Data for nuclear PDFs

  Single hadron production

$\pi^0\ \pi^\pm\ K^\pm\ \eta$

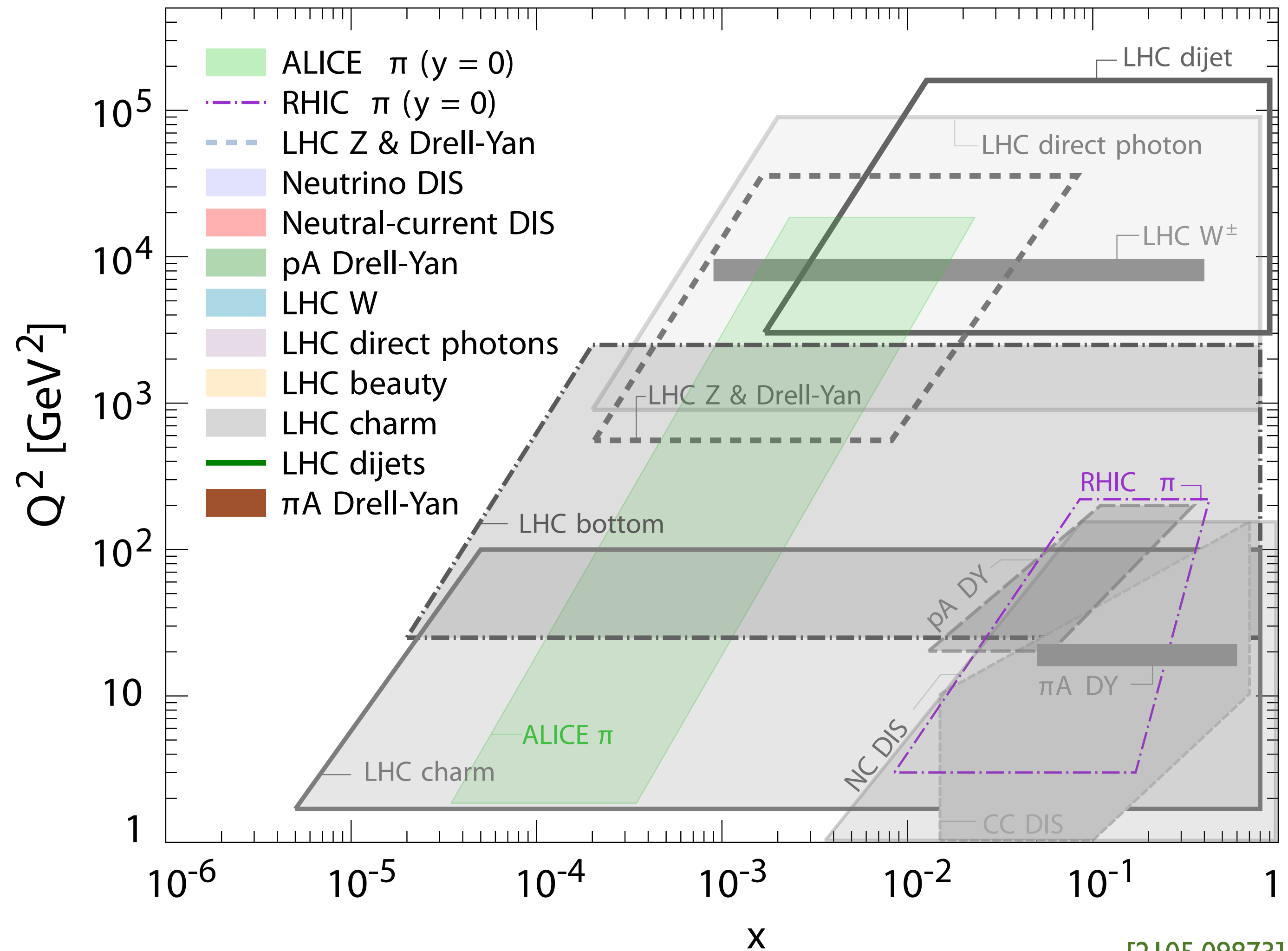


RHIC - PHENIX $\pi^0\ \pi^\pm\ K^\pm\ \eta$
$N = \mathrm{Au}$

RHIC - STAR $\pi^0\ \pi^\pm\ \eta$
$N = \mathrm{Au}$

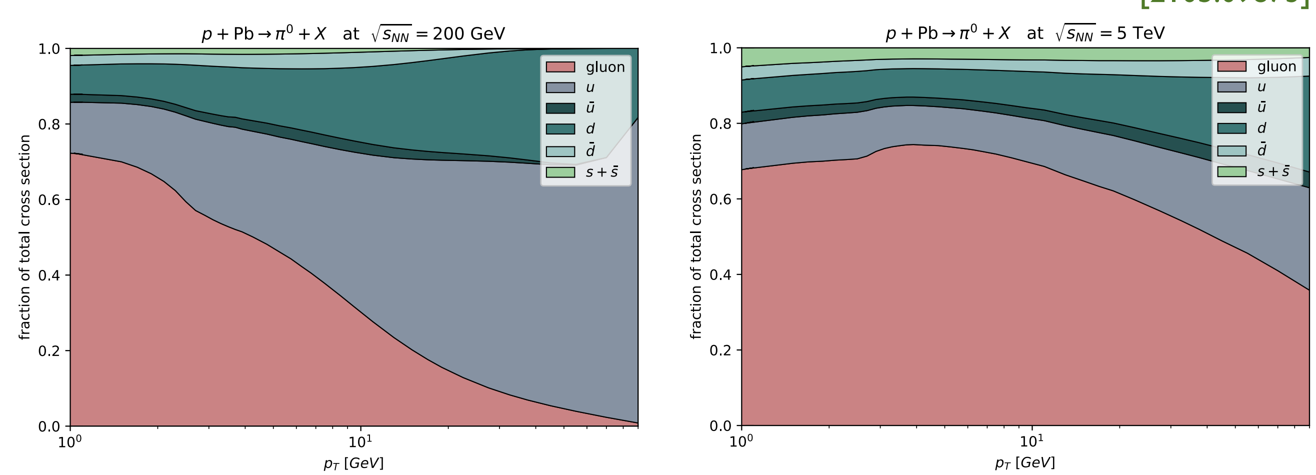
LHC - ALICE $\pi^0\ \pi^\pm\ K^\pm\ \eta$
$N = \mathrm{Pb}$

[2311.00450]




- can constrain gluon PDF (for lower pT RHIC, any pT LHC), abundant data
- pQCD cannot be used for very low pT (pT<3 GeV)
- fragmentation functions necessary for any prediction

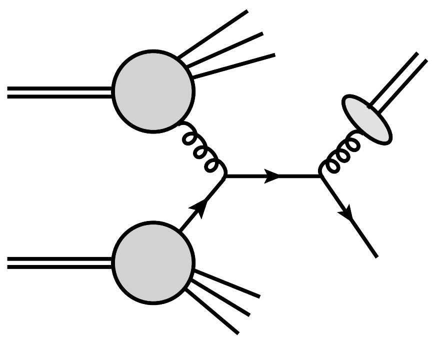
[2105.09873]



# Nuclear data

- Data for nuclear PDFs

  Heavy quark production

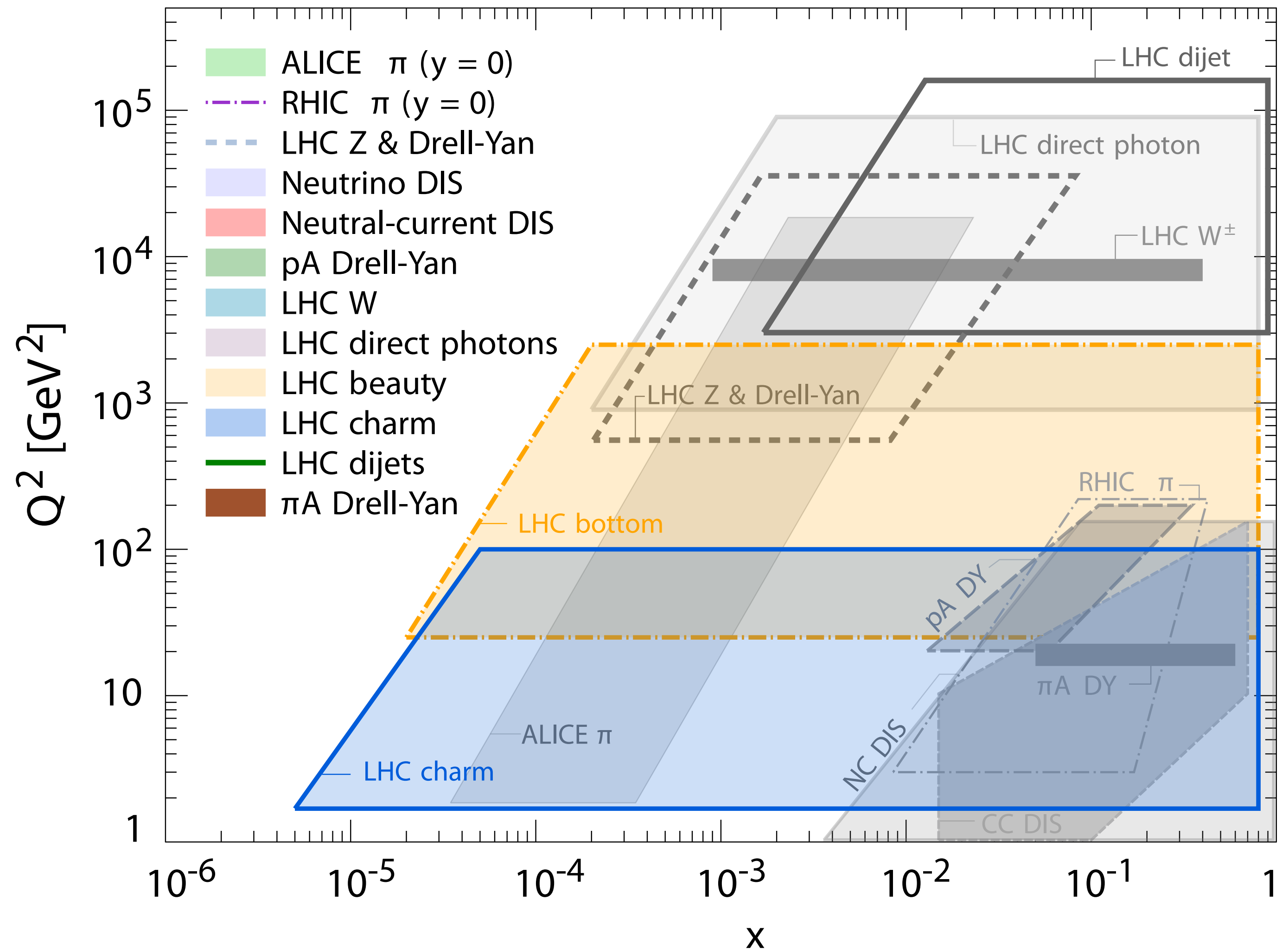



LHC - ATLAS $J/\psi$ $\Upsilon(1S)$ $\psi(2S)$

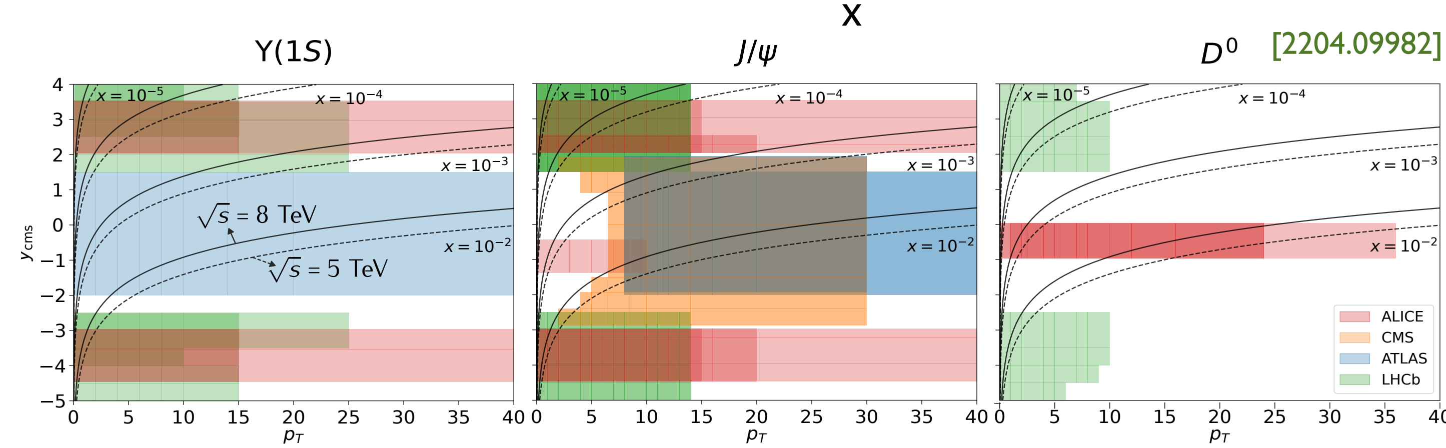
- CMS $J/\psi$ $\Upsilon(1S)$ $\psi(2S)$
- LHCb $D^0$ $J/\psi$ $\Upsilon(1S)$
- ALICE $D^0$ $J/\psi$ $\Upsilon(1S)$ $\psi(2S)$

$N = \mathrm{Pb}$

[2311.00450]




[2204.09982]




quarkonia $Q\bar{Q}$–bound states

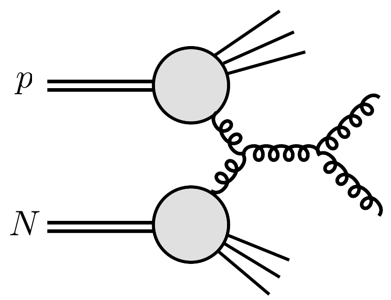
open HQ – $Q\bar{q}$ states

- sensitive to gluon PDF down to extremely low x
- pQCD cannot be used for quarkonia
  - NRQCD eff. field theory required
- fragmentation functions necessary for open HQ predictions

# Nuclear data

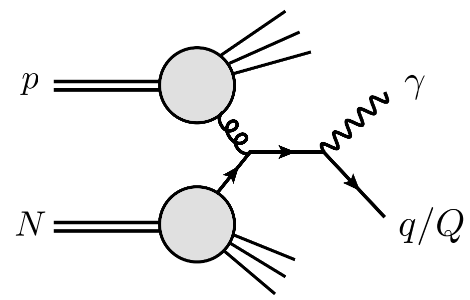
- Data for nuclear PDFs

*Di-jet production*



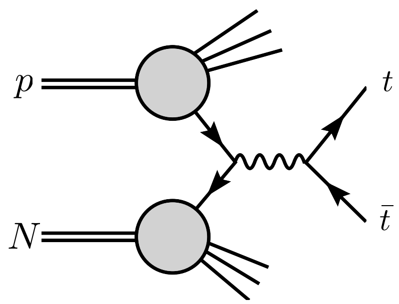

$p + N \to 2 \text{ jets} + X$

*Direct photon production*



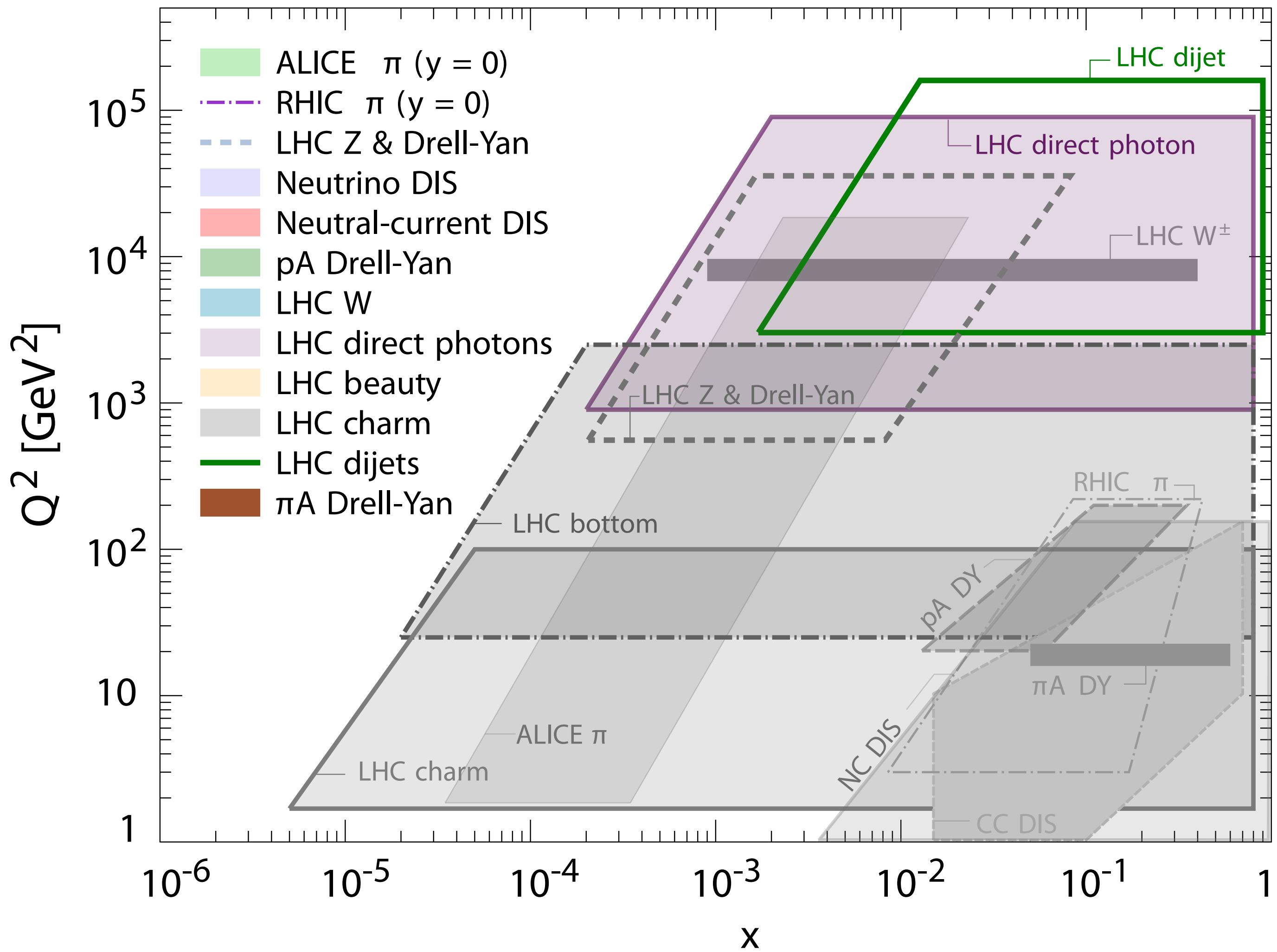

$p + N \to \gamma \; q/Q + X$

Top-quark production

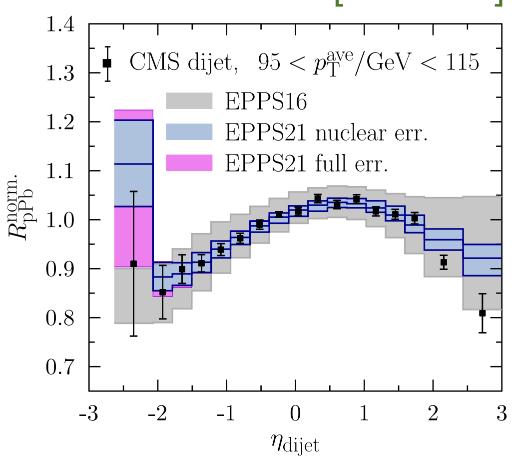



$p + N \to t\,\bar{t} + X$

[2311.00450]




[2112.12462]




- *Di-jet data* - promising - can reduce gluon PDF uncertainty

  ***BUT*** pp and pPb data not described well (only ratios)

- *Direct photon data* - additional constraint of the gluon PDF

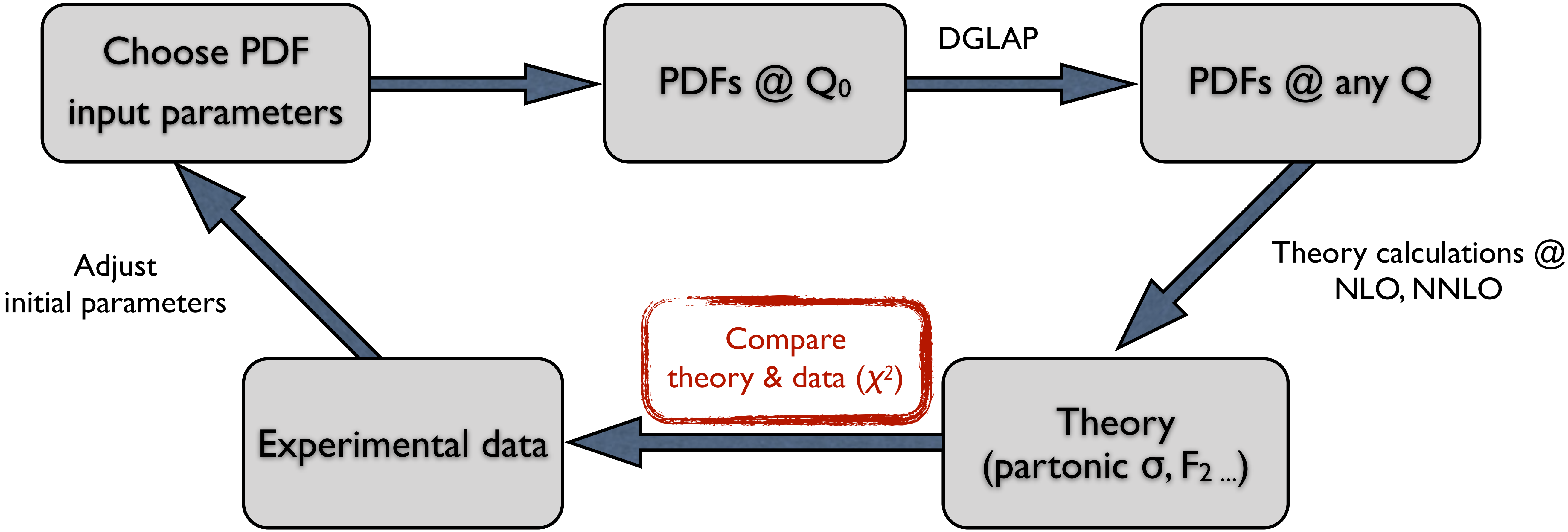
  ***BUT*** precision of the data cannot compete with HQ

- *Top quark data* - ultimate constraint of the gluon PDF

  ***BUT*** only 2 data points - total cross-section

# Determining nPDFs

- Determining (nuclear) parton distribution functions
  - how do we determine them ? What are the moving parts in a typical PDF fitting-machine ?

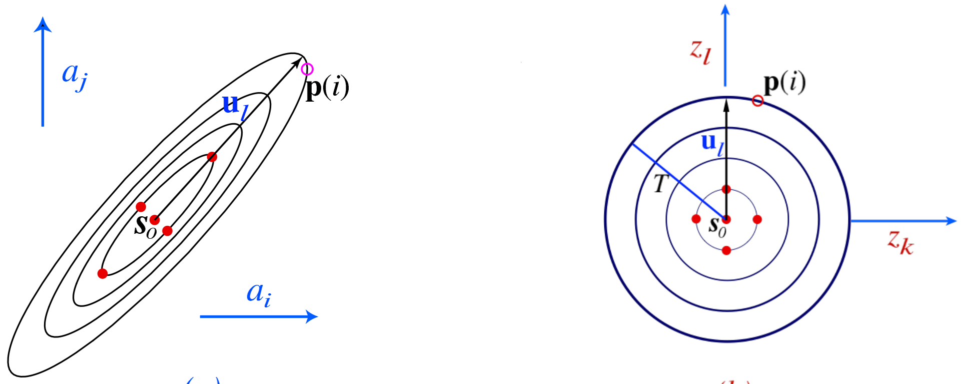


# Uncertainties

- Uncertainties of (nuclear PDF)
  - Hessian approach to uncertainties

Hessian — diagonal Hessian

$$\chi^2(a) = \chi_0^2 + \frac{1}{2}\frac{\partial\chi^2}{\partial a_i \partial a_j}(a-a_0)_i(a-a_0)_j + \ldots \rightarrow \chi_0^2 + \sum_i z_i^2$$




(a) *Original parameter basis* (b) *Orthonormal eigenvector basis*

  - Choice of $\Delta\chi^2 = \chi^2 - \chi_0^2$: $\Delta\chi^2 \sim 20 - 50$
  - Construct error PDFs for each parameter in 2 directions (#error PDF sets = $2N_{par}$):

error PDFs

$$z_i = \pm\sqrt{\Delta\chi^2} \qquad i = 1,\ldots,N_{\rm par} \qquad X_i^{\pm}(z) = X_i^{\pm}(0,0,\ldots,\pm\sqrt{\Delta\chi^2},\ldots,0,0) \qquad X = f_k(x,Q_0^2)$$

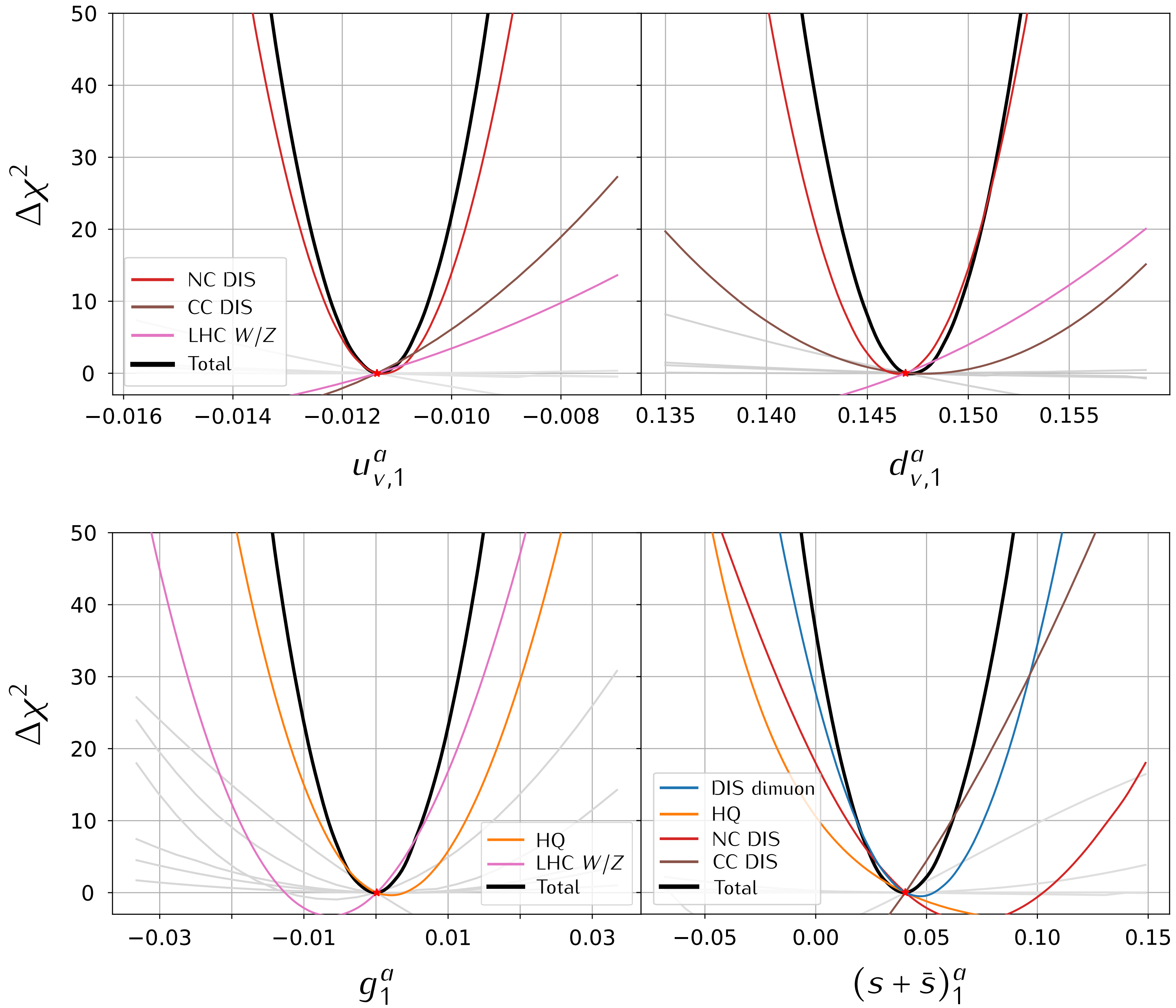
  - Calculate PDF uncertainty of cross-section

$$(\Delta\sigma)^2 \approx \frac{1}{4}\sum_i^{N_p}\Big(\sigma(X_i^+) - \sigma(X_i^-)\Big)^2$$

# Uncertainties

- Uncertainties of (nuclear PDF)
  - subsets of data constrain different PDFs at different x
  - sensitivity can be made visible by $\chi^2$-scans for single experiments

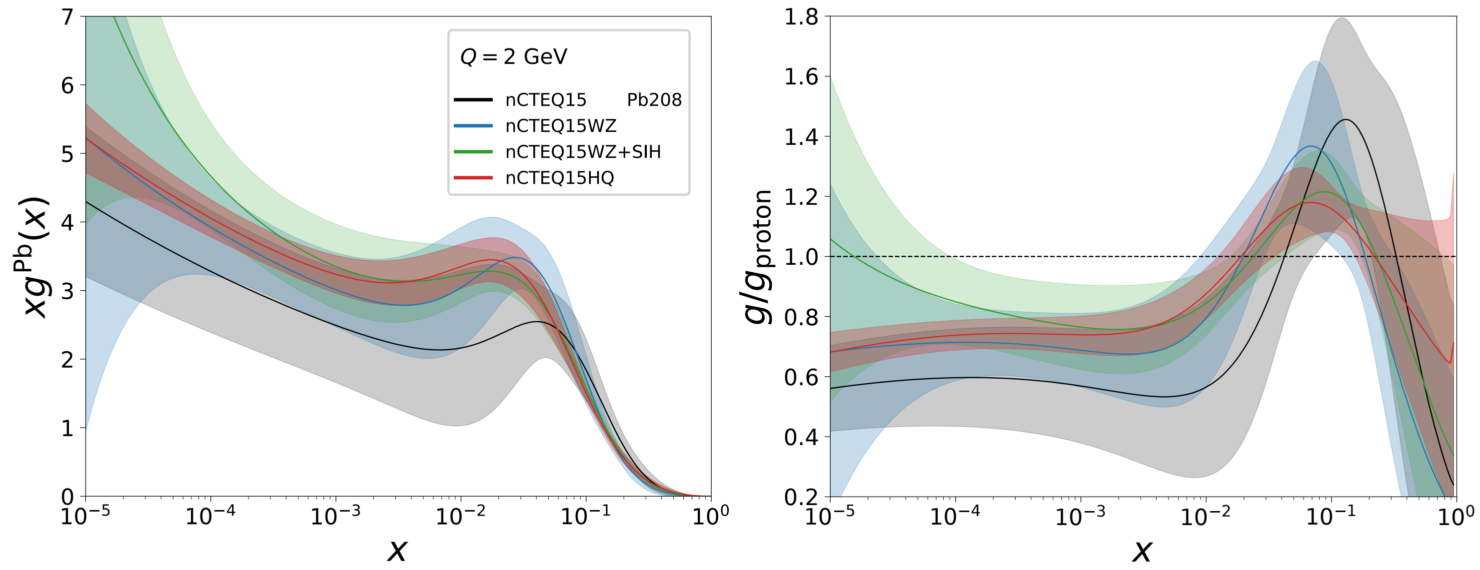
- NC & CC DIS constrain up & down quark PDFs
- W/Z Drell-Yan and HQ data constrain gluon PDFs
- di-muon CC DIS are very sensitive to the strange PDF



# Nuclear PDFs

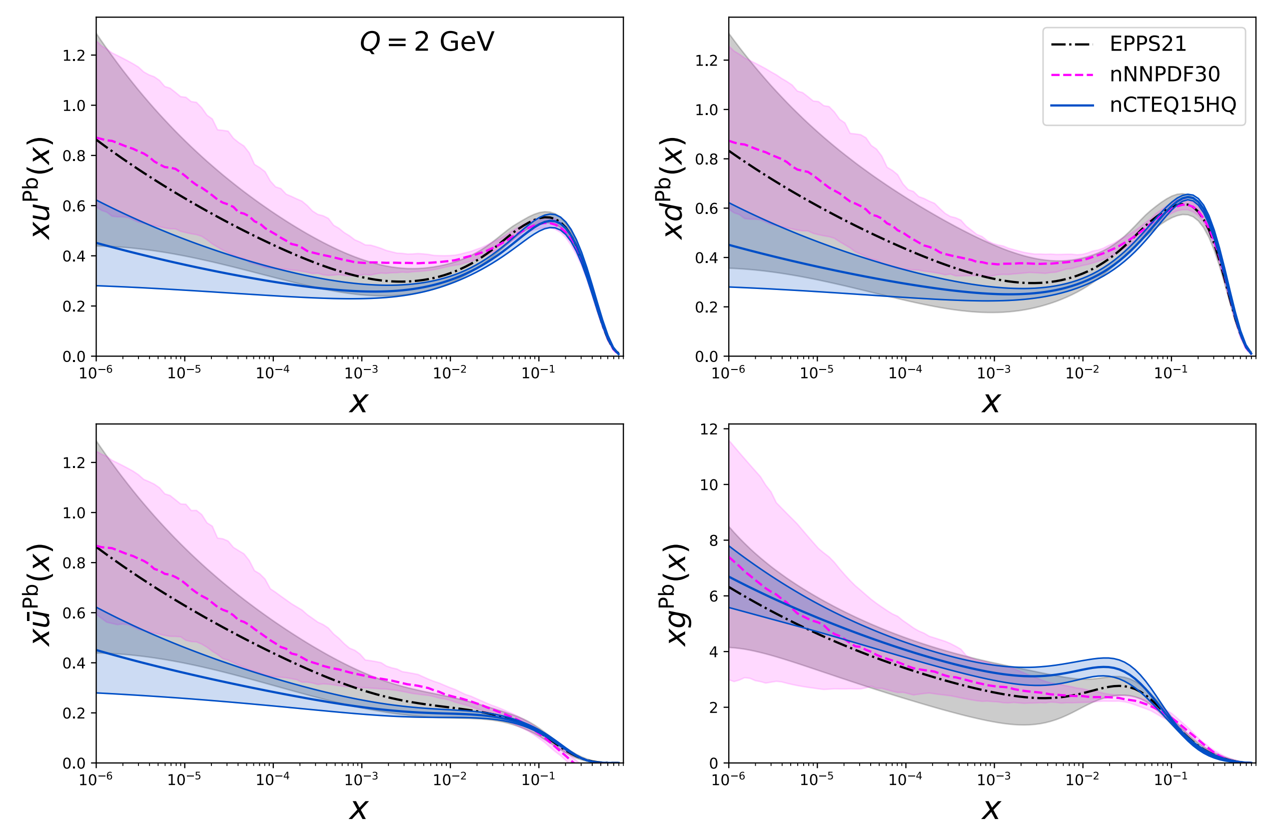
- Current nPDF analyses
  - adding more precise LHC pPb data improves the uncertainty
  - *framework*, *fitting approaches* and also *data selection* very different - different nPDF analyses can seem incompatible

[2204.09982]



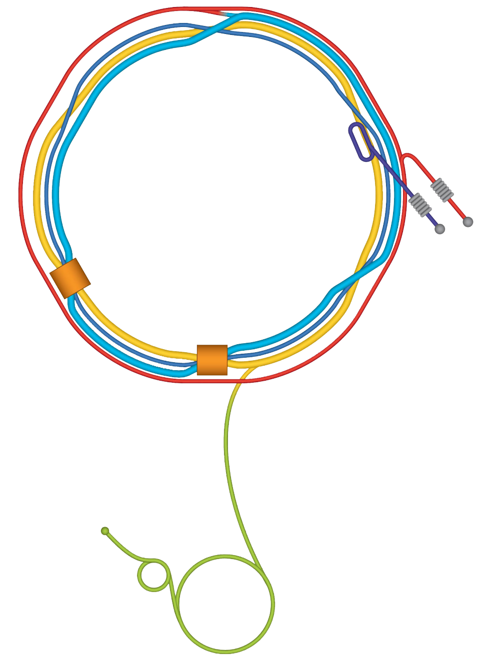

more to come from LHC

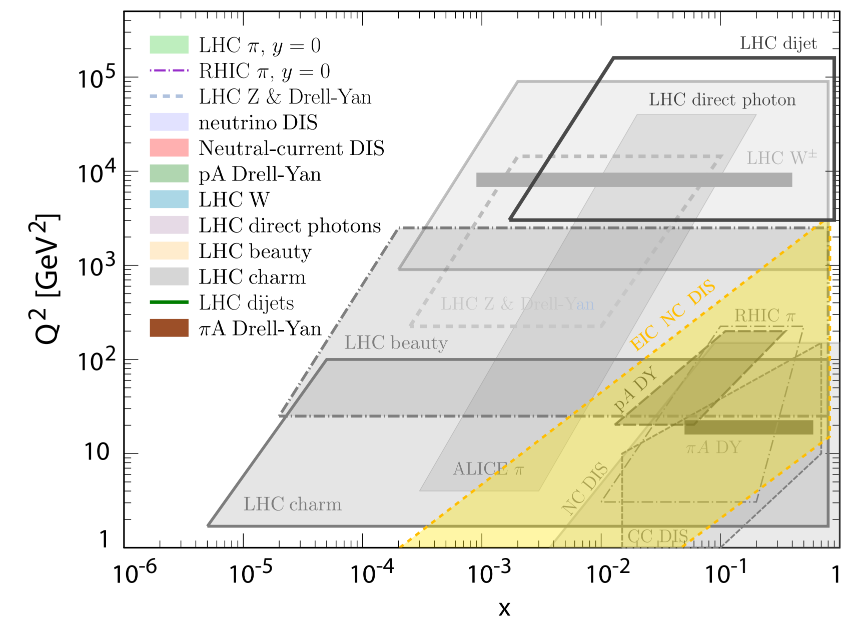
but above all ...



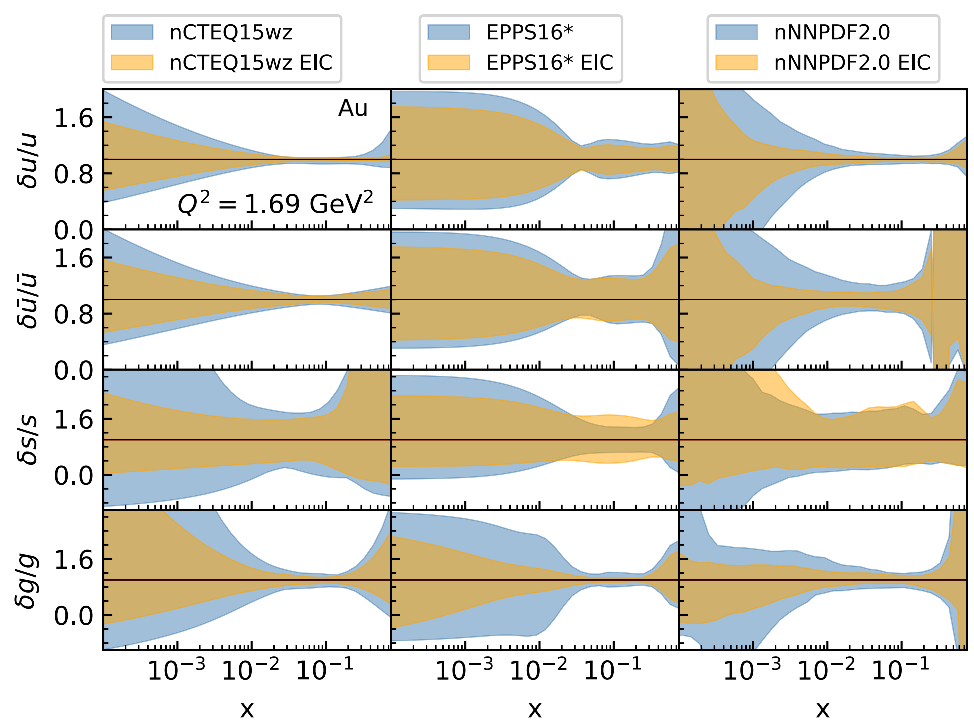
# Future of nPDFs

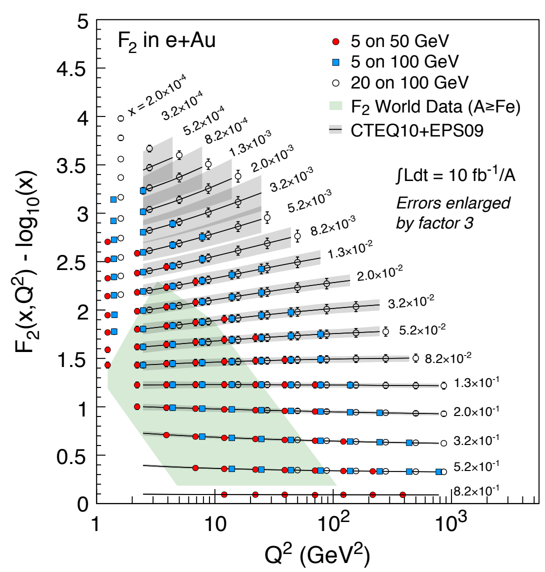
- Electron-Ion collider (EIC)
  - in preparation in BNL - start ~ 2030
  - main goal - spin & flavor structure of nucleon
  - center-of-mass energy ~ 100 GeV
  - high-luminosity ~ $10^{34}$ $cm^{-2}s^{-1}$

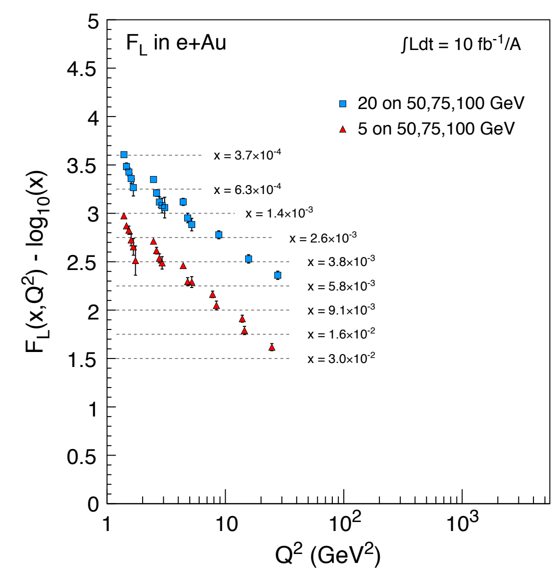





- very precise DIS on nuclei - same as HERA for protons



# Thanks