European Strategy for Particle Physics

PARALLEL 4 / **STRONG INTERACTIONS**

# Partonic dynamics in protons and nuclei: prospects with future measurements at HL-LHC and electron-hadron colliders

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23-27 JUNE 2025 Lido di Venezia

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1. **Introduction.**

2. **State-of-the-art and future physics goals:**
   - Collinear proton PDFs.
   - Collinear nuclear PDFs.
   - 3D structure: TMDs and GPDs.
   - Small-x physics.
   - Lattice QCD.

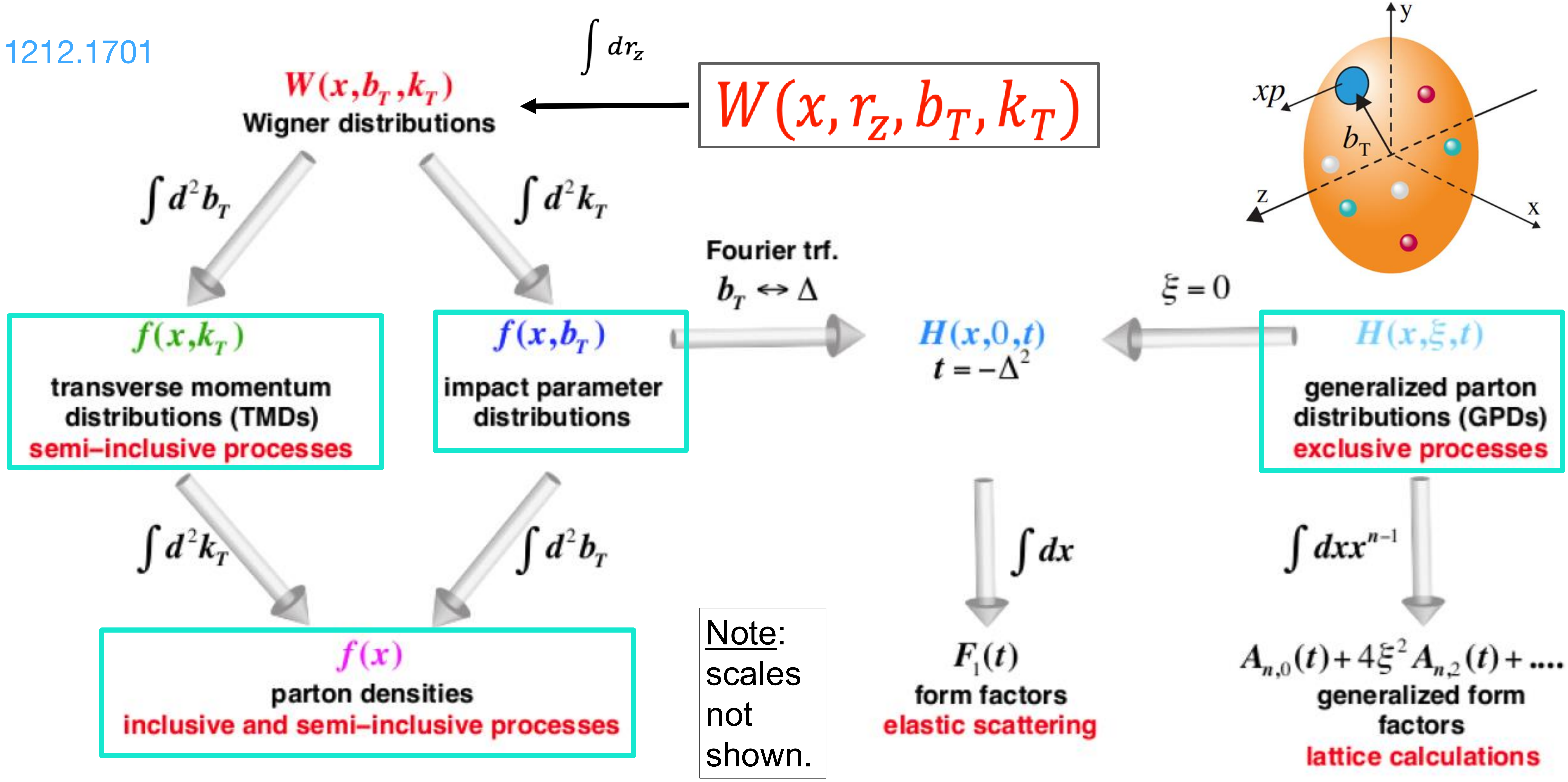
Talks by T. Cridge/C. Gwenlan/M.Ubiali, H. Paukkunen and V. Bertone at https://indico.cern.ch/event/1527574/#day-2025-05-28.

3. **Future facilities: kinematics and benchmark measurements.**
   - Collinear proton PDFs.
   - Collinear nuclear PDFs.
   - 3D structure: TMDs and GPDs.
   - Small-x physics.

4. **Conclusions.**

**Note**: no spin included; only protons and nuclei.

# Inner structure of protons and nuclei



# Inputs received

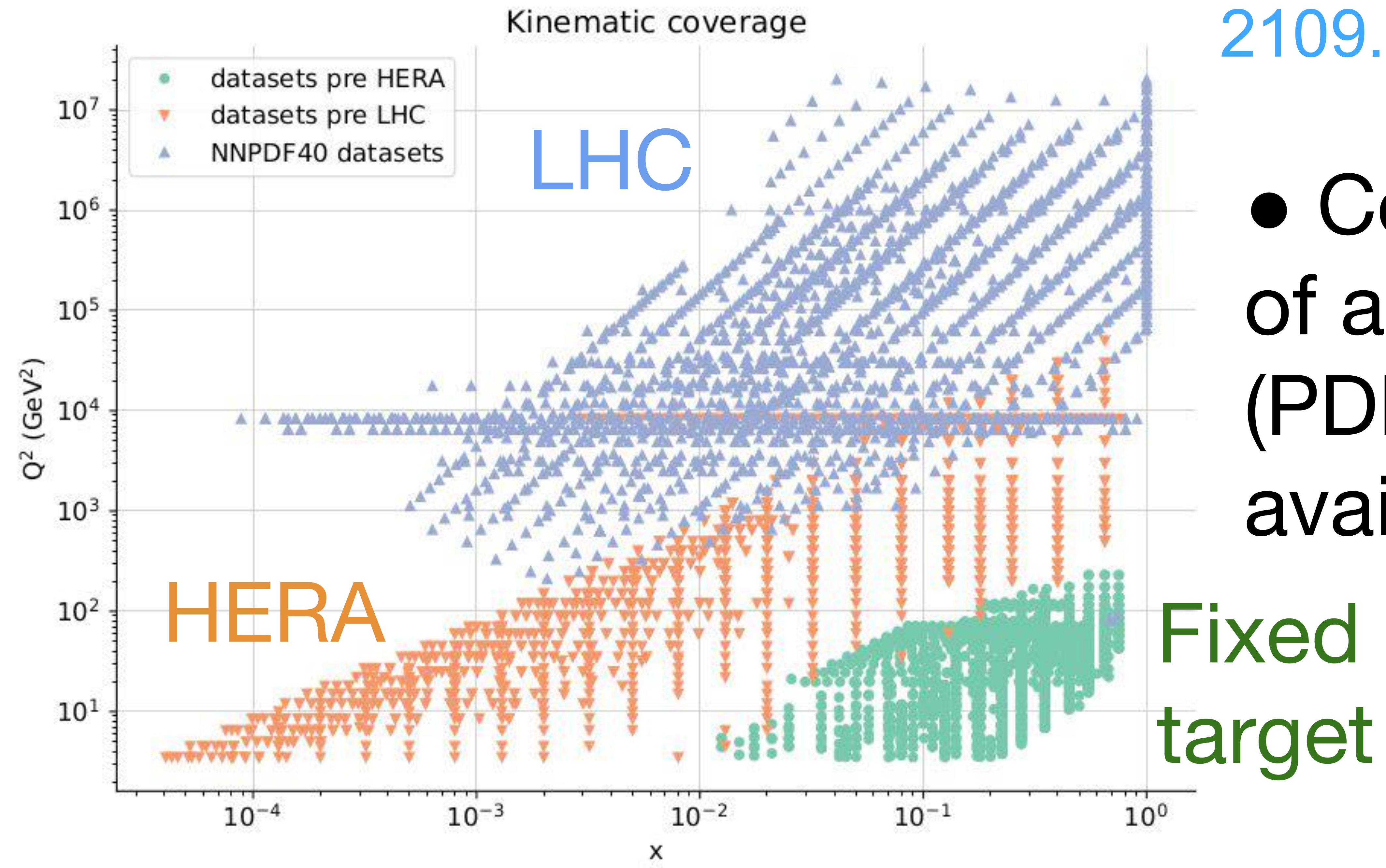
| Id | Title (link to file) | Type | Origin |
|---|---|---|---|
| 68 | Input from the ALICE Collaboration | A: Exp Collaboration | LHC ALICE |
| 170 | Highlights of the HL-LHC physics projections by ATLAS and CMS | A: Exp Collaboration | LHC ATLAS+CMS |
| 23 | Prospects and Opportunities with an upgraded FASER Neutrino Detector during the HL-LHC era: Input to the EPPSU | A: Exp Collaboration | LHC FASER |
| 19 | The Forward Physics Facility at the Large Hadron Collider | A: Exp Collaboration | LHC FPF |
| 82 | Heavy ion physics with LHCb Upgrade II | A: Exp Collaboration | LHC LHCb |
| 213 | LHCspin: a Polarized Gas Target for LHC | A: Exp Collaboration | LHC LHCb |
| 235 | Summary Report of the Physics Beyond Colliders Study at CERN | A: Exp Collaboration | SPS, ... PBC |
| 114 | Synergies between a U.S.-based Electron-Ion Collider and European Research in Particle Physics | B: Future Colliders | eh: EIC USA |
| 214 | The Large Hadron electron Collider (LHeC) as a bridge project for CERN | B: Future Colliders | eh: LHeC |
| 209 | FCC: QCD physics | B: Future Colliders | FCC |
| 227 | Prospects for physics at FCC-hh | B: Future Colliders | FCC |
| 241 | The FCC integrated programme: a physics manifesto | B: Future Colliders | FCC |
| 247 | FCC Integrated Programme Stage 2: The FCC-hh | B: Future Colliders | FCC |

| Id | Title (link to file) | Type | Origin |
|---|---|---|---|
| 69 | Future Opportunities with Lepton-Hadron Collisions | C: Community (specific) | DIS community |
| 224 | Community Support for Physics with high-luminosity proton-nucleus collisions at the LHC | C: Community (specific) | HI at HL-LHC |
| 2 | Light Ion Collisions at the LHC | C: Community (specific) | HI Light ions LHC |
| 29 | Strategy for the Future of Lattice QCD | C: Community (specific) | Lattice QCD |
| 103 | Nuclear Physics and the European Particle Physics Strategy Update 2026 | C: Community (specific) | NuPECC |
| 174 | Phase-One LHeC | D: Theory / Specific | Personal inputs on LHeC combined with HL-LHC |
| 5 | Prospective report of the French QCD community to the ESPPU 2025 with respect to the program of the LHC Run 5 and beyond and future colliders at CERN | E: National (specific) | France QCD |

20 contributions plus input from MuCol, contacts with the global (n)PDF and TMD groups, GPD community, and lattice groups.

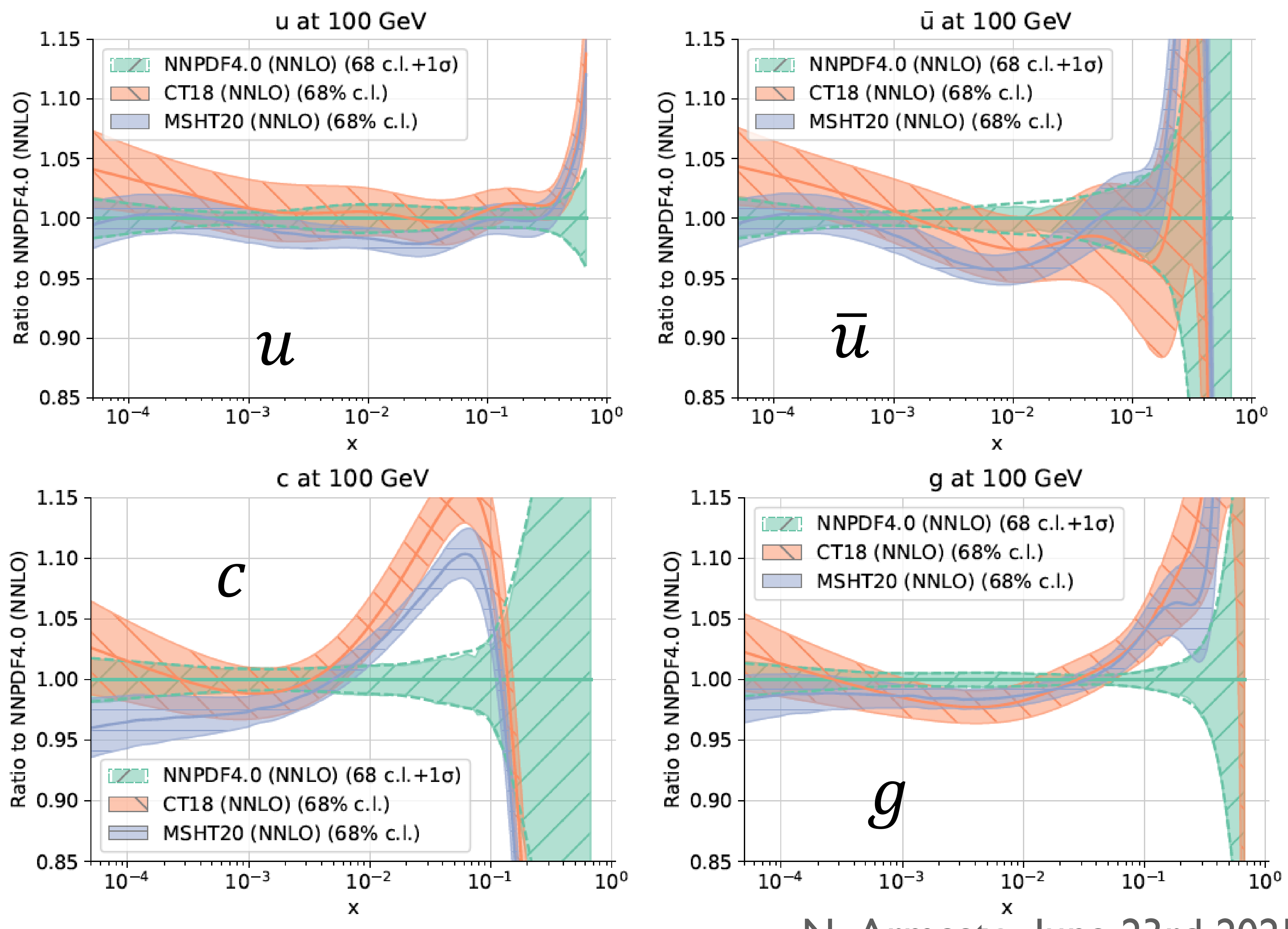
# Proton collinear PDFs: state-of-the-art

- **Methodology**: complex error analysis (CT, MSHT, NNPDF; HERAPDF, ABMP).
- **Theory**: approximate N3LO QCD PDFs + QED (MSHT, NNPDF); MHOUs.
- **Data**: $\mathcal{O}(5000)$ data points, complementarity between HERA, fixed target and LHC.
- **Challenges**:
  - Data: tension between datasets, need of information about systematics.
  - Parametrisation/methodology biases & uncertainty estimation: closure tests.
  - How the PDF sets absorb experimental and theoretical inconsistencies.
  - MHOs: nuisance parameters or inclusion of even higher orders: aN3LO QCD+QED, 2 sets available and combined.



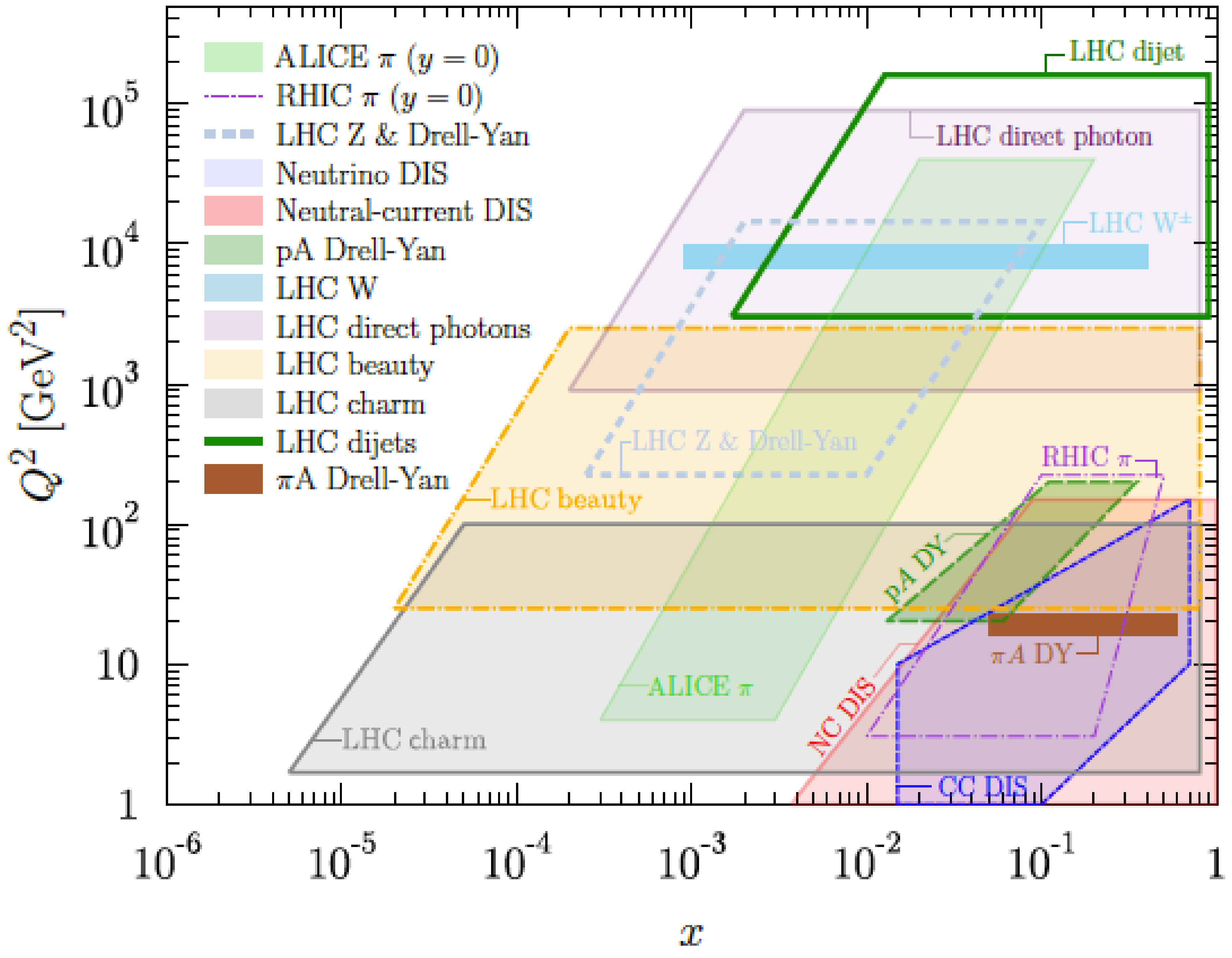

2109.02653

- Combination of analyses (PDF4LHC21) available.



# Nuclear collinear PDFs: state-of-the-art

- **Methodology**: complex error analysis (nCTEQ, EPPS, nNNPDF, TUJU, KSASG).
- **Theory**: NLO/NNLO.
- **Data**: $\mathcal{O}(2000)$ data points, complementarity between fixed-target eA & pA, and LHC.
- **Challenges**:
  - Data: Incompatibilities in some data (D's in pPb@LHC) and problems to use others (J/$\psi$ in UPCs).
  - Parametrisation biases & uncertainty estimation.
  - Sizeable differences up to a factor 2 between sets, within uncertainties.

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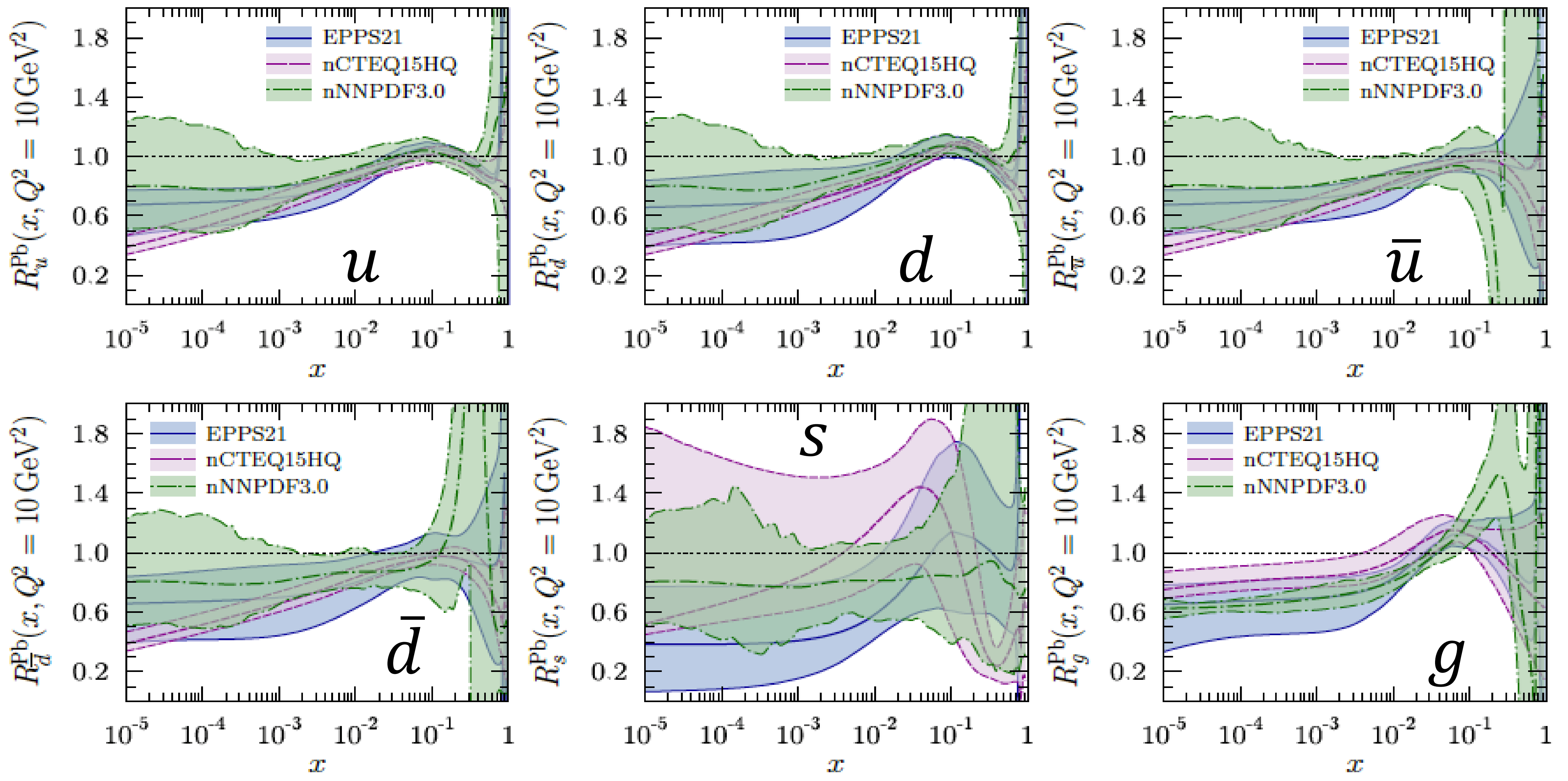


# Collinear PDFs: precision physics

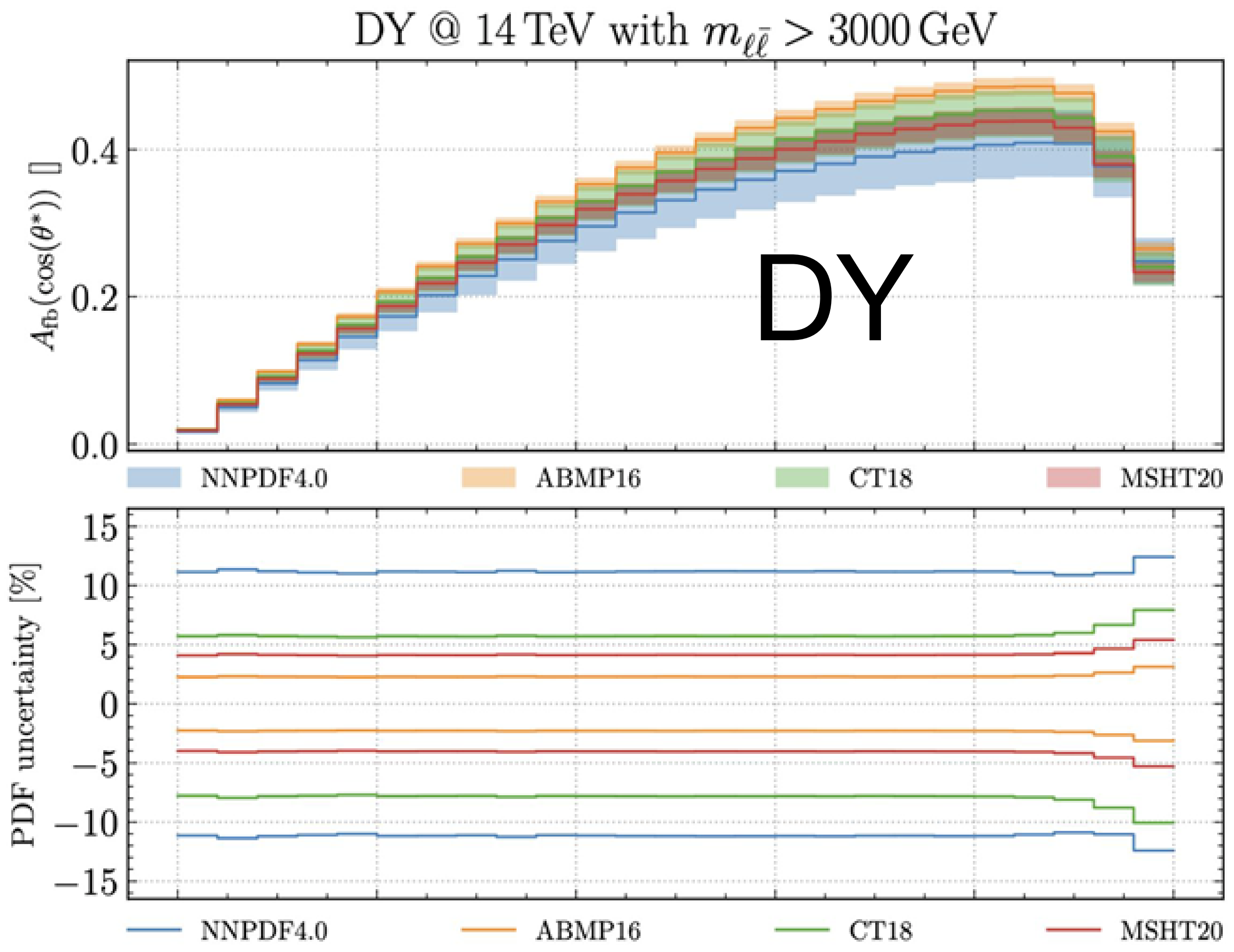
- PDFs **essential for precision** physics studies:
  - Dominant uncertainty of many SM parameters: ATLAS $\alpha_s$ (0.0005/0.0009), and CMS $M_W$ (4.4/9.9 MeV) and $\sin^2\theta_W$ (0.0027/0.0031).
  - Differences between PDF sets, profiling delicate, simultaneous PDF+SM parameter fits.

$$\alpha_{S,\mathrm{aN3LO}}(M_Z^2) = 0.1170 \pm 0.0016$$

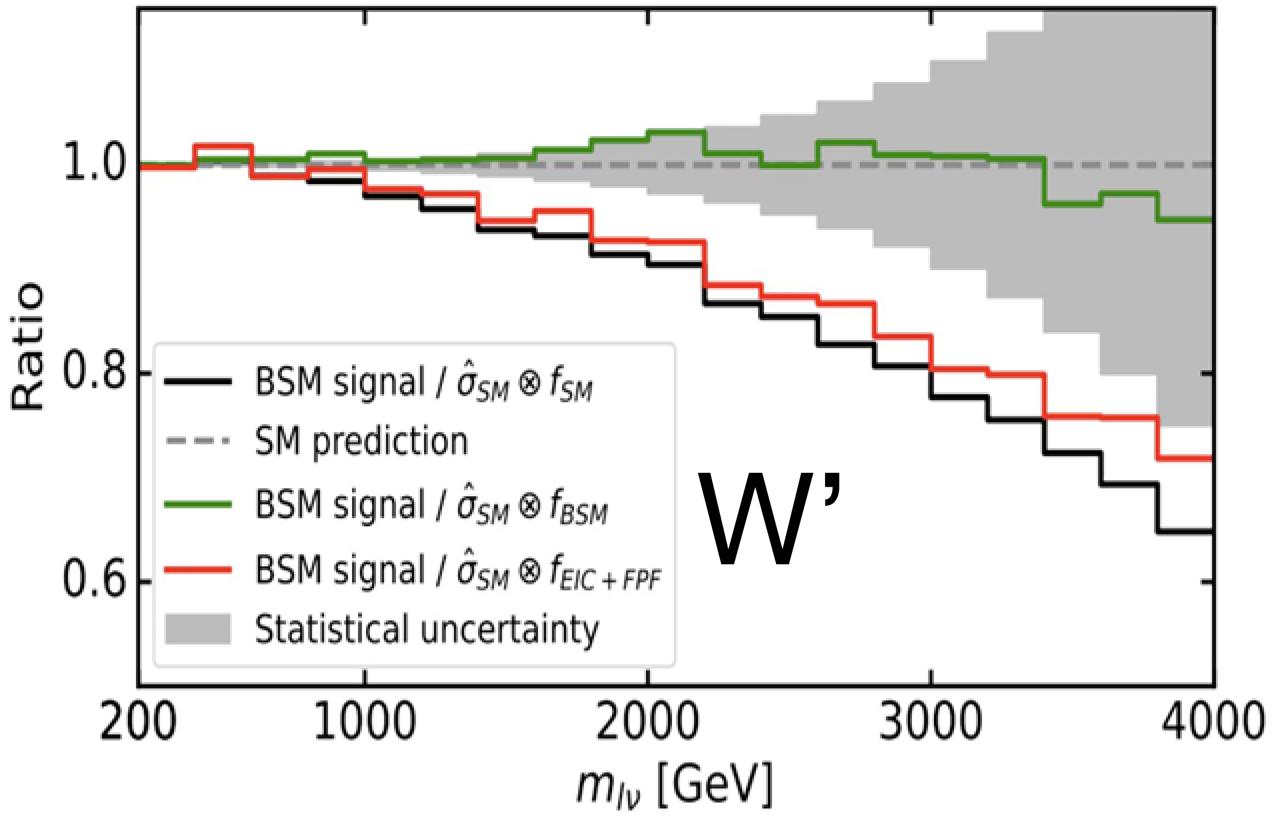
Consistent with (NNLO) World Average of $0.1180 \pm 0.0009$.

2404.02964

2209.08115

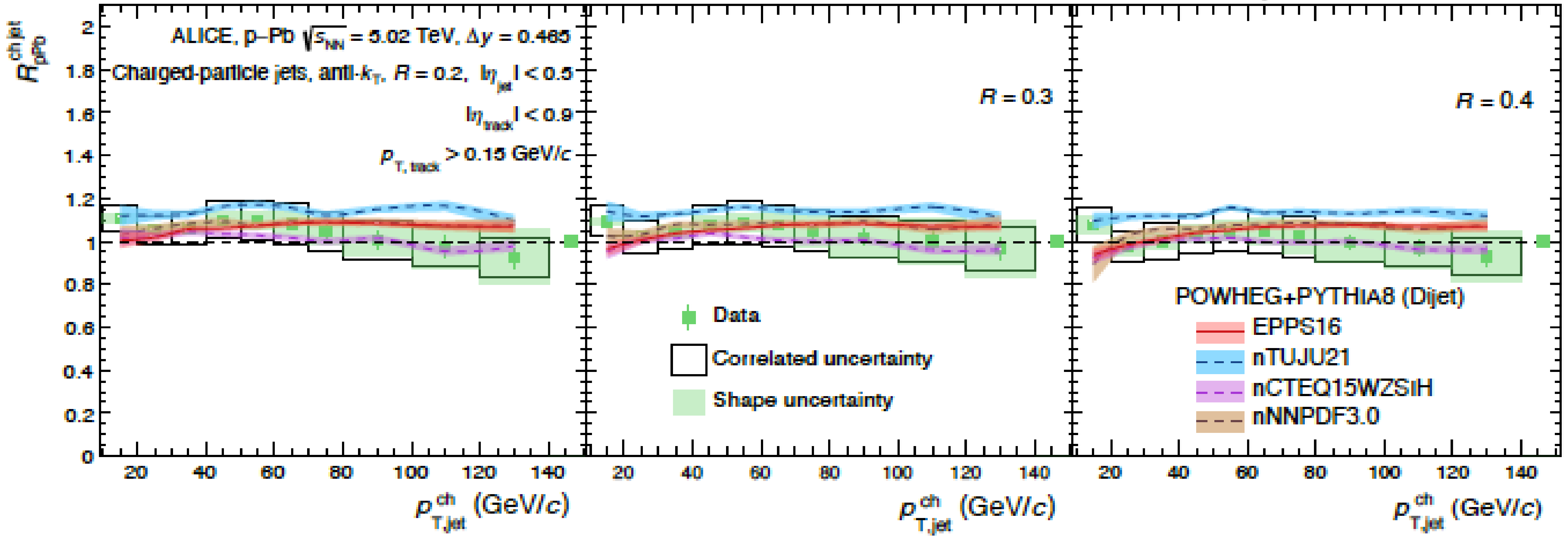



2410.00963




- High mass (large x): sizable uncertainties, BSM can be hidden in PDF uncertainties.

2307.10860 charged jets




- nPDFs may mask QGP-like effects in small systems, e.g., pPb or pp.
- nPDFs provide sizable uncertainties for QGP characterisation in PbPb.

# Collinear PDFs: goals and challenges

- **Data**: substantial progress expected from the complementarity of upcoming and proposed experiments ⇒ need of controlled systematics and correlations, inconsistencies?

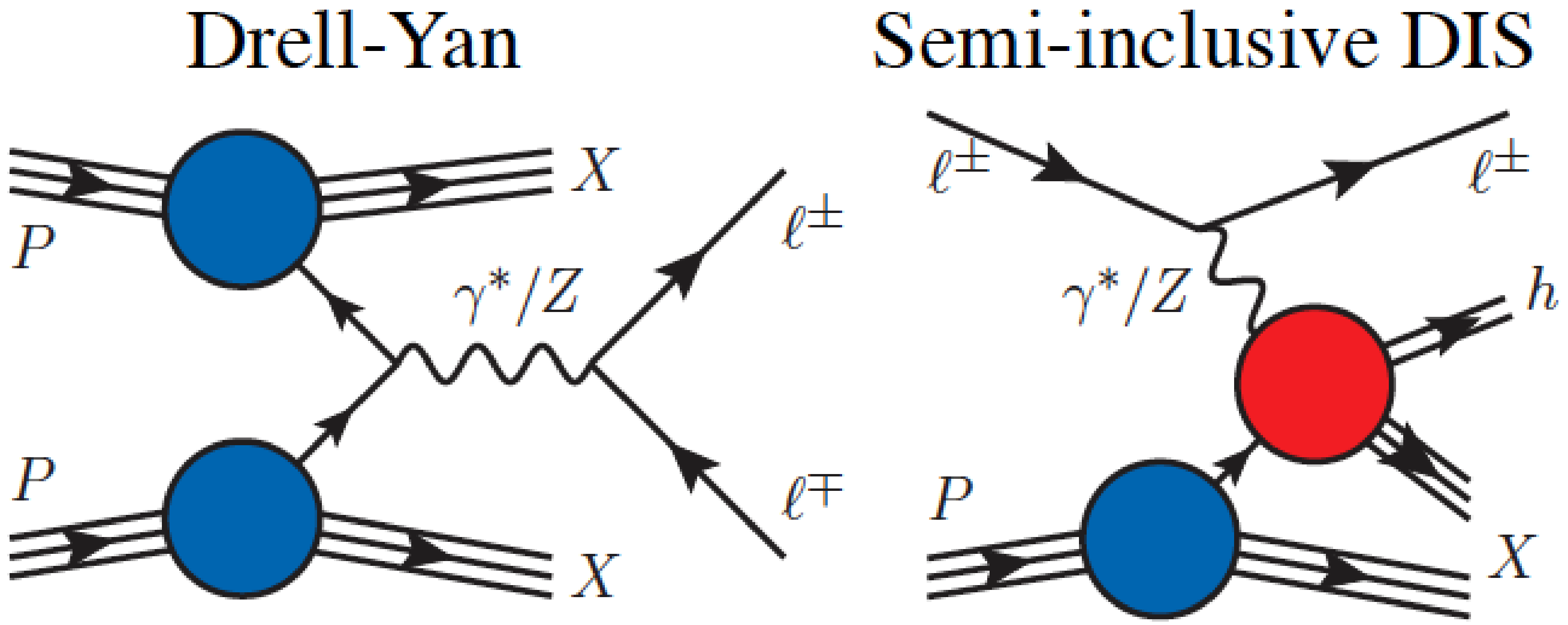
- **Methodology**: numerous developments, parametrisation ⇒ increasing complexity, need of control precisions, tolerance?

- **Theory**: N3LO PDFs coming, and inclusion of theoretical uncertainties, crucial to achieve the required precision ⇒ understanding of theoretical uncertainties and possibility of higher order calculations.

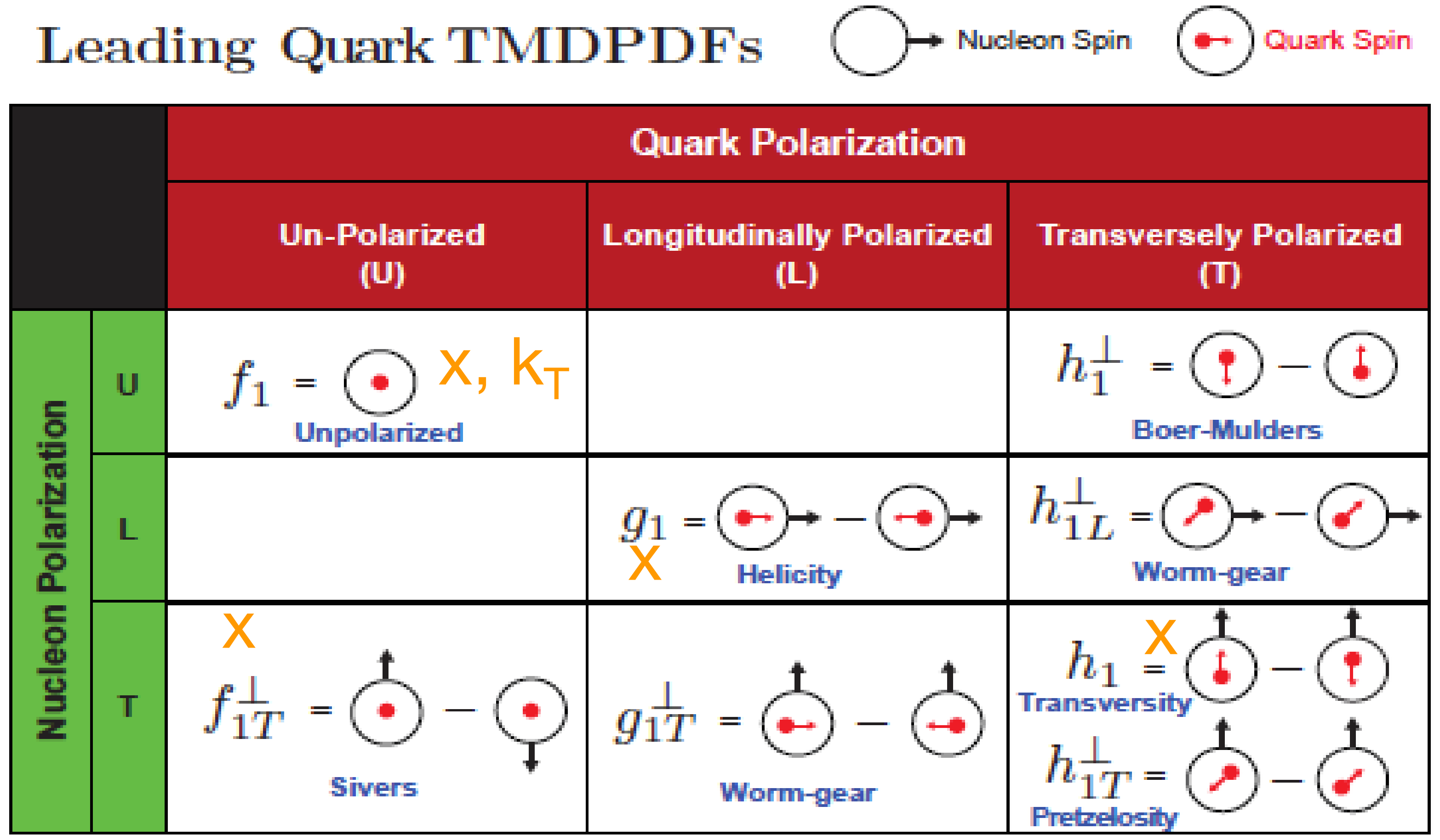
- **Standard Model/BSM Parameters (including QGP characterisation and the small system problem)**: driven by PDF precision/accuracy improvements ⇒ understanding the assumptions underlying profiling and their impact, separating out 'new' effects from PDFs, complementary data from multiple colliders required.

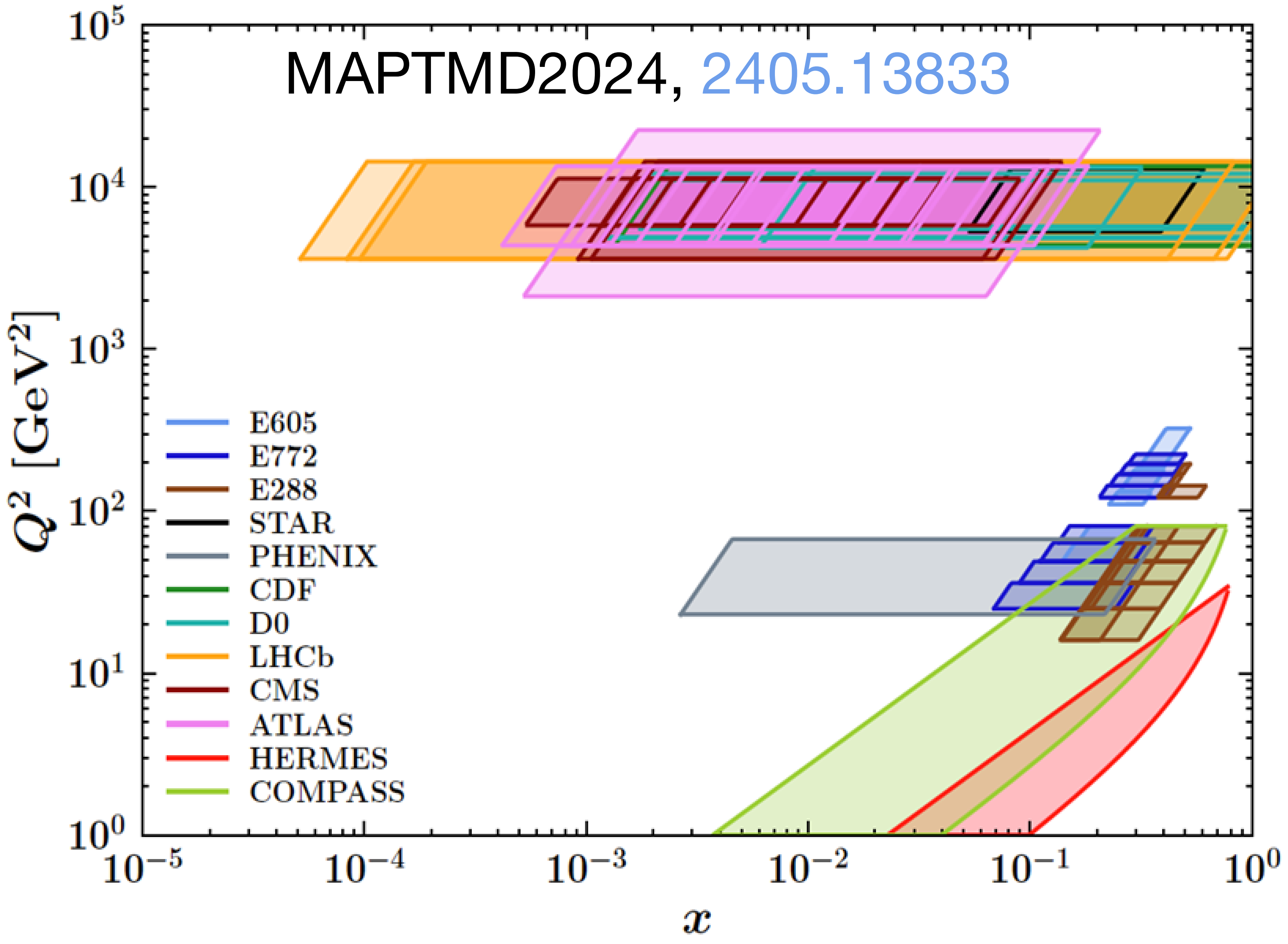
# TMDs: state-of-the-art

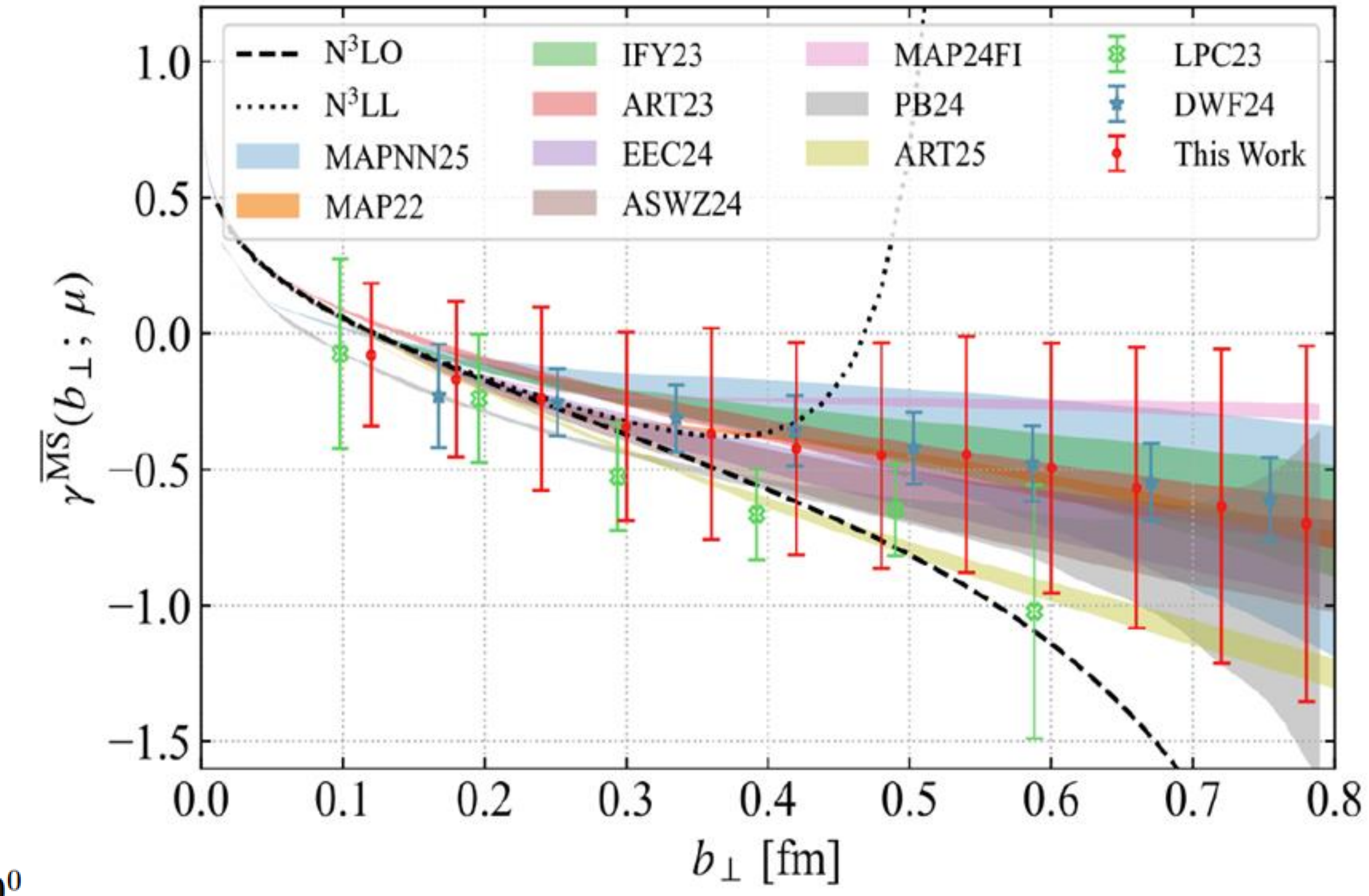
- TMD factorisation appears in **two-scale problems**, e.g., Q and $q_T$ in DY.
- TMDs contain perturbative & non-perturbative pieces; linked to collinear PDFs/FFs.
- Numerous sets/approaches, large perturbative accuracy (N4LL, required by data).
- Also extracted from lattice and related with small-x physics (CGC).
- Nuclear effects in TMD analyses through nPDFs.
- Different non-perturbative modelling and collinear PDFs ⟹ sets difficult to compare.




2304.03302



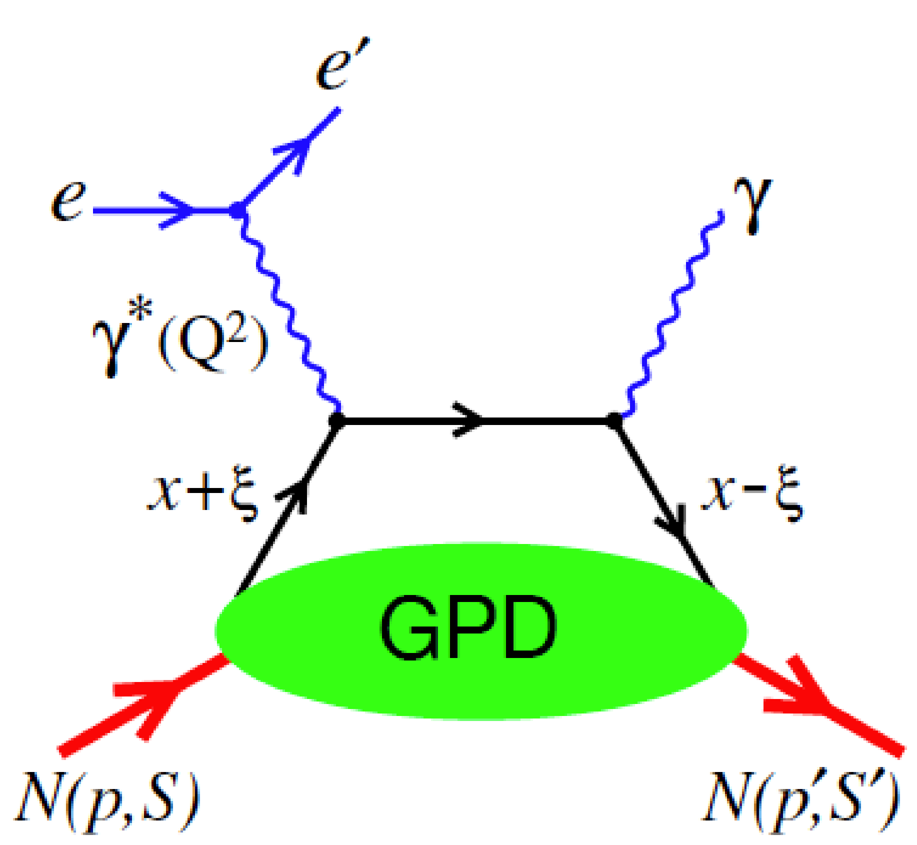



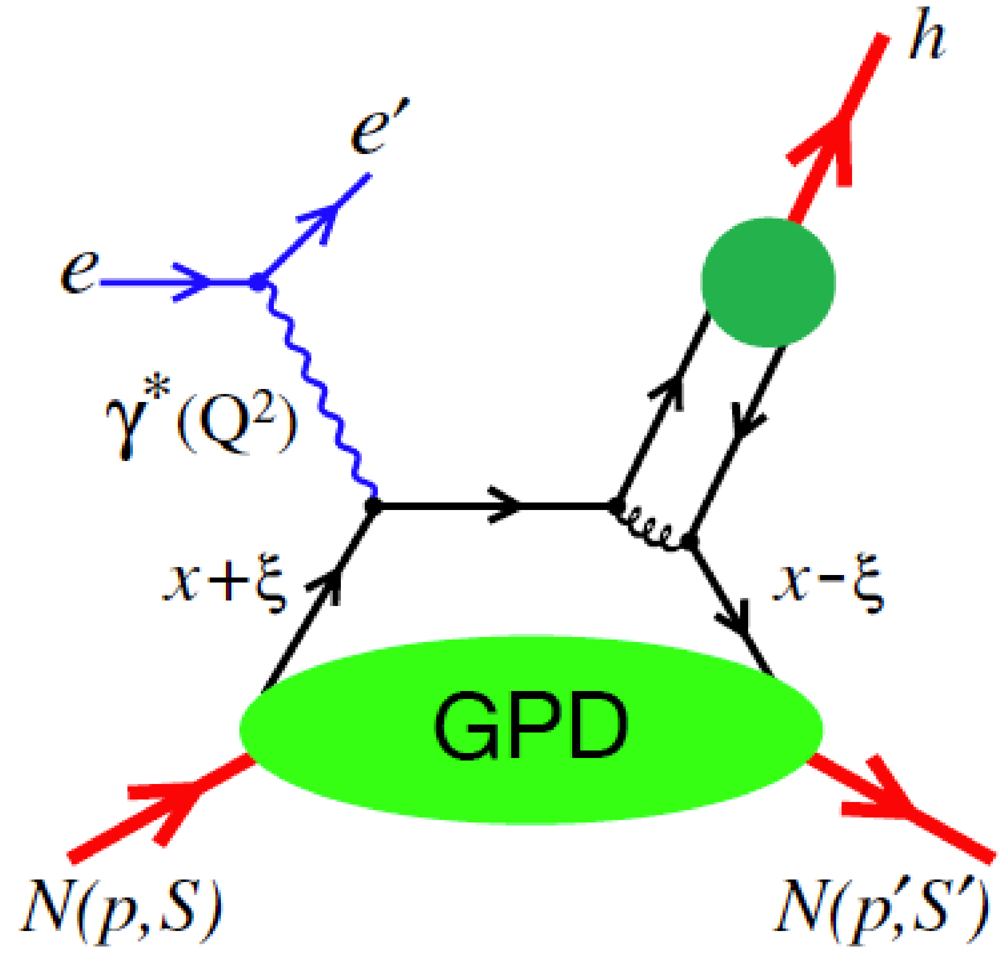



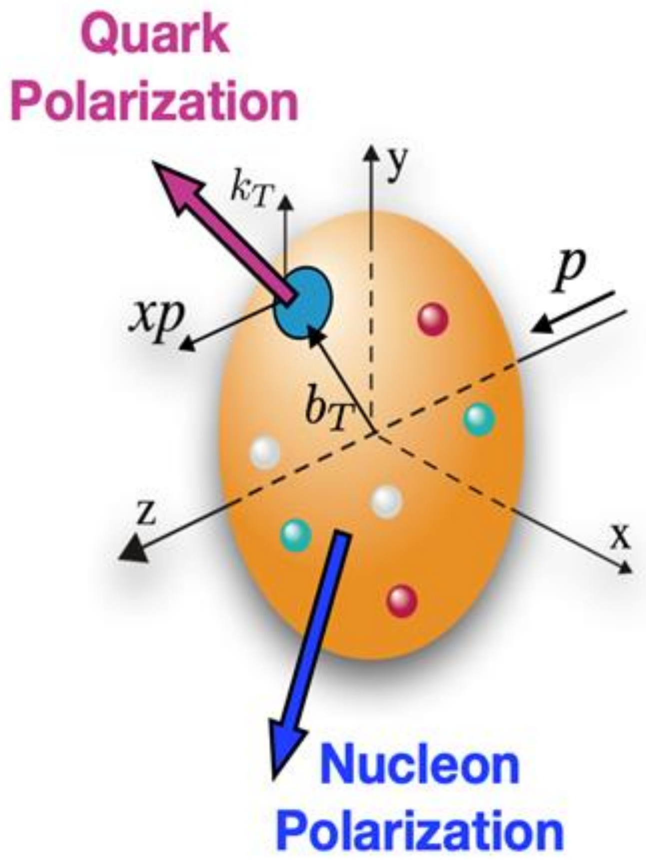

2504.04625, CS kernel

B. Pasquini @DIS2025

# GPDs: state-of-the-art



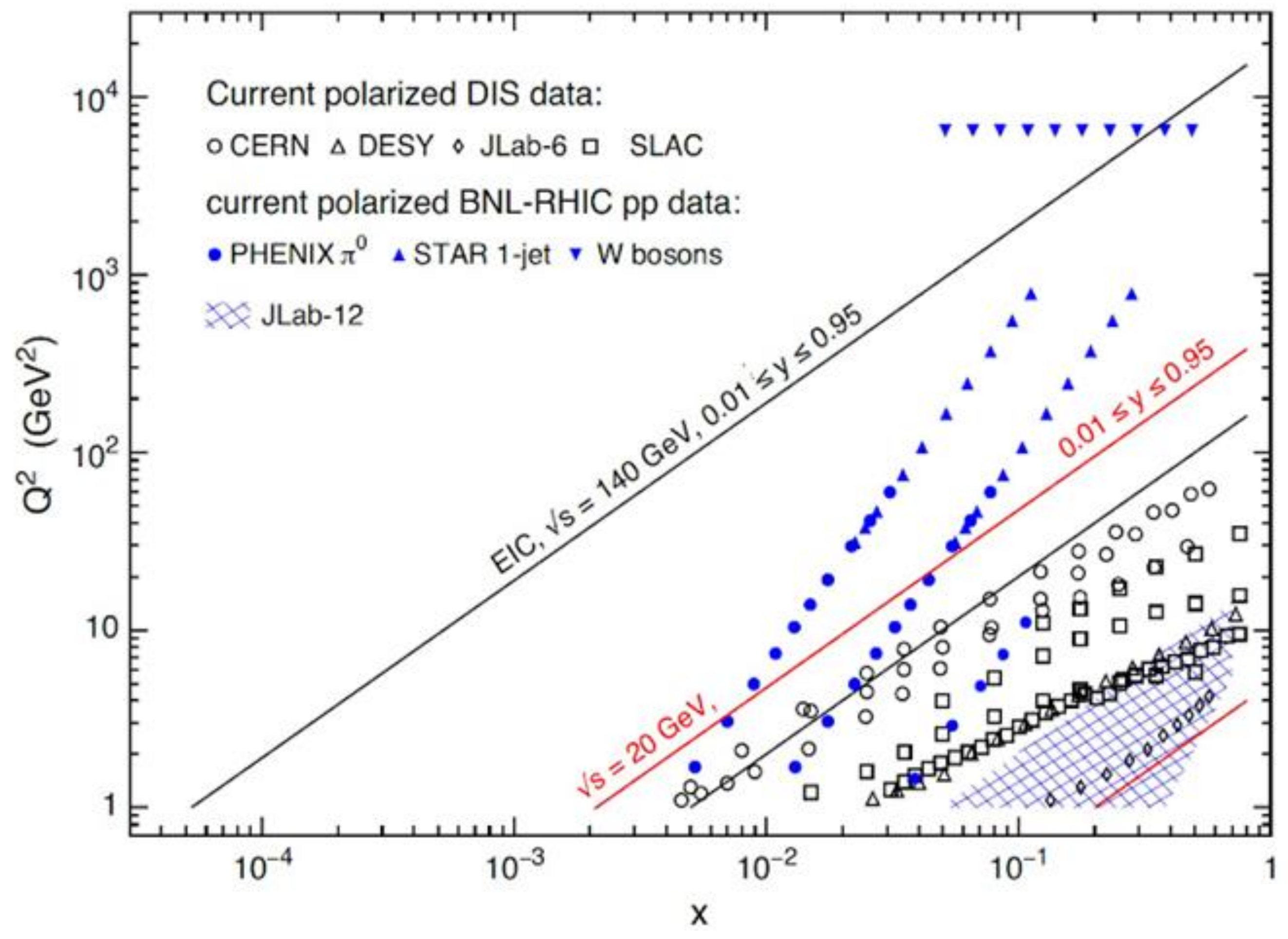



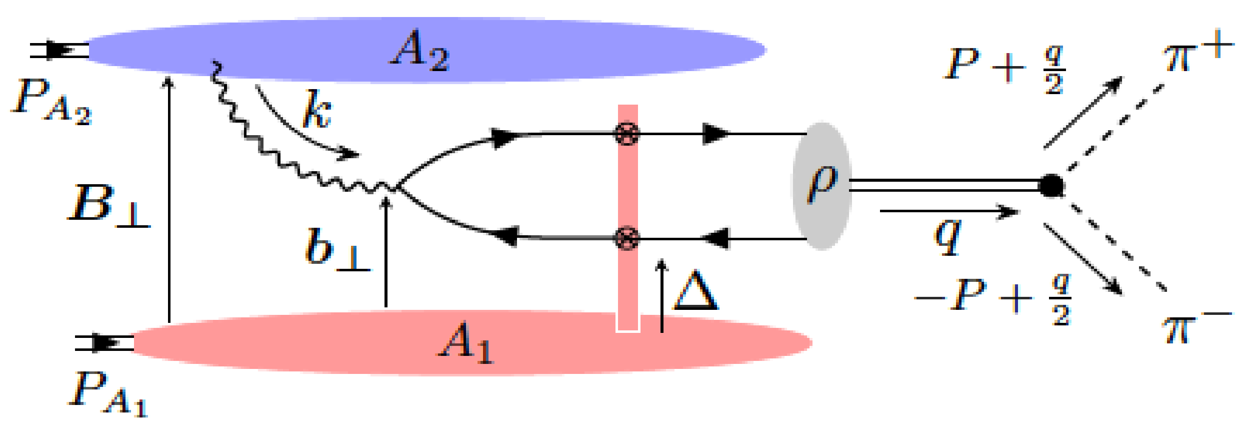

quark polarization

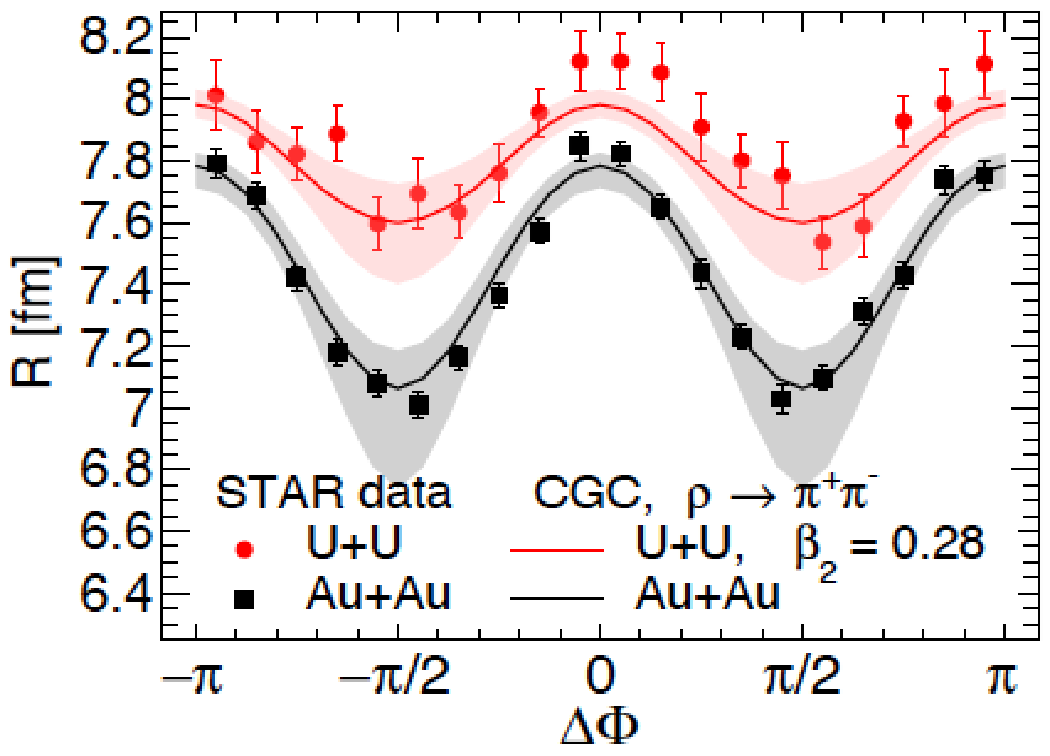
nucleon polarization

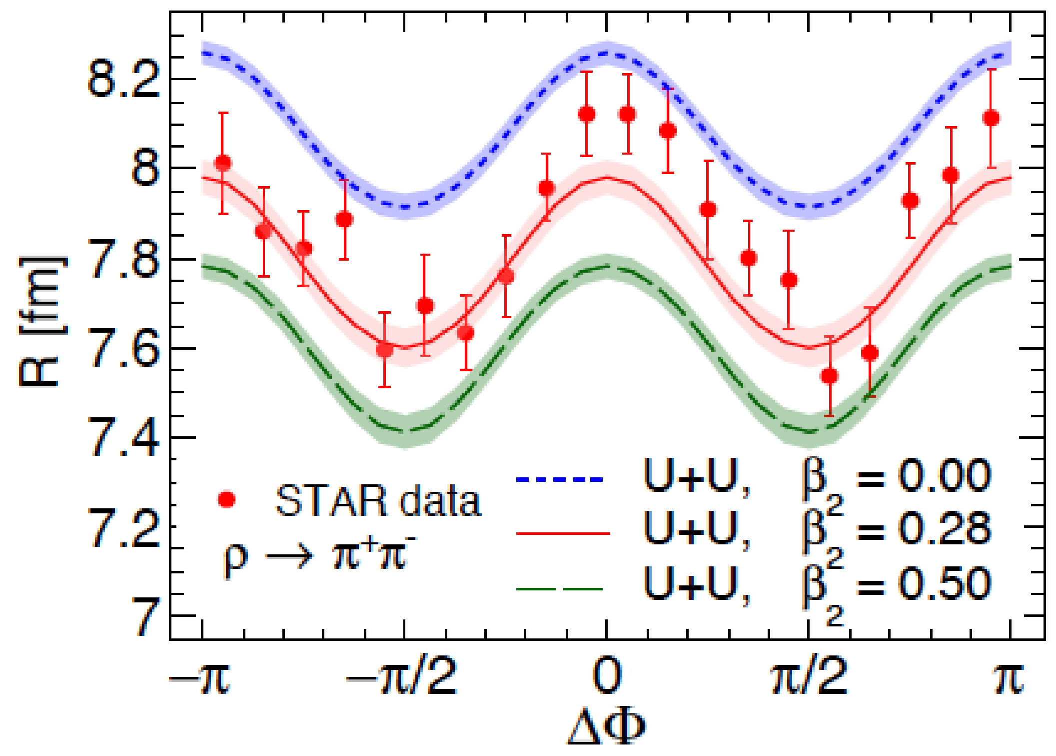
| GPD | $U$ | $L$ | $T$ |
|---|---|---|---|
| $U$ | $H$ | | $\mathcal{E}_T$ |
| $L$ | | $\tilde{H}$ | $\tilde{E}_T$ |
| $T$ | $E$ | $\tilde{E}$ | $H_T$, $\tilde{H}_T$ |

- Measured in **exclusive processes**: DVCS, TCS (NNLO), exclusive VM production (NLO?), DDVCS, 2 to 3 processes like $\gamma\gamma$ or $\gamma$-meson, transition GPDs/DAs,...
- Relation with the QCD energy-momentum tensor.
- The partonic profile of hadrons can be extracted dependent on x.




2310.15300, nuclear deformation

# TMDs and GPDs: goals and challenges

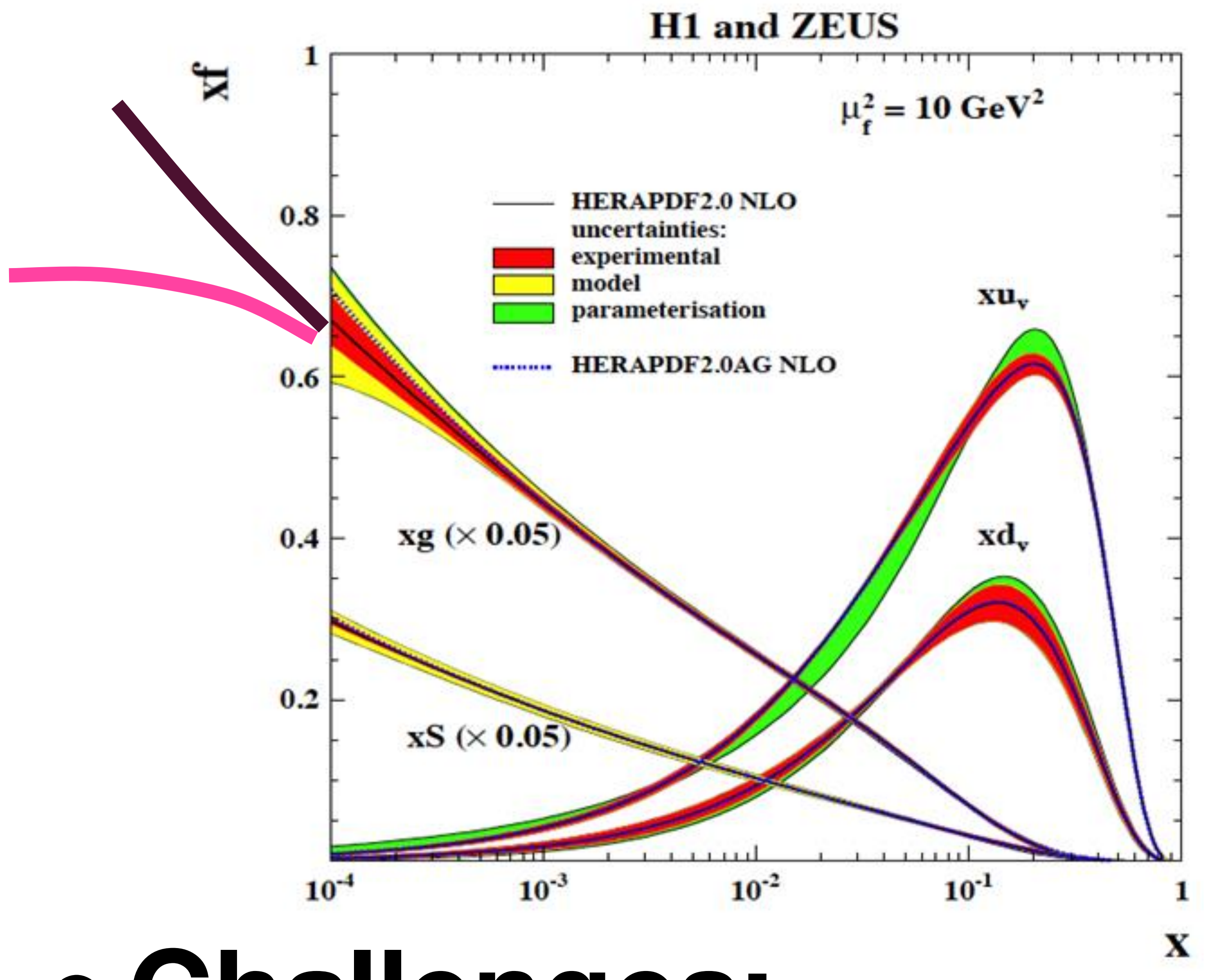
- **Data**: substantial progress expected from upcoming experiments (EIC) ⇒ need of large amounts from different observables in order to constrain the numerous TMDs and GPDs, e.g., gluon, flavour dependence.

- **Methodology**: many developments, several parameterisations, full method of extraction still lacking for GPDs ⇒ increasing complexity (TMD PDFs and FFs have to be included), interplay with collinear PDFs and FFs, extension to nuclei.

- **Theory**: for TMDs large perturbative accuracy available, crucial to achieve the required precision; for GPDs NNLO DVCS available but not yet full NLO evolution ⇒ understanding of theoretical uncertainties, extension to small x and relation with other formalisms, possibility of using non-perturbative information from lattice; completion of the missing pieces.

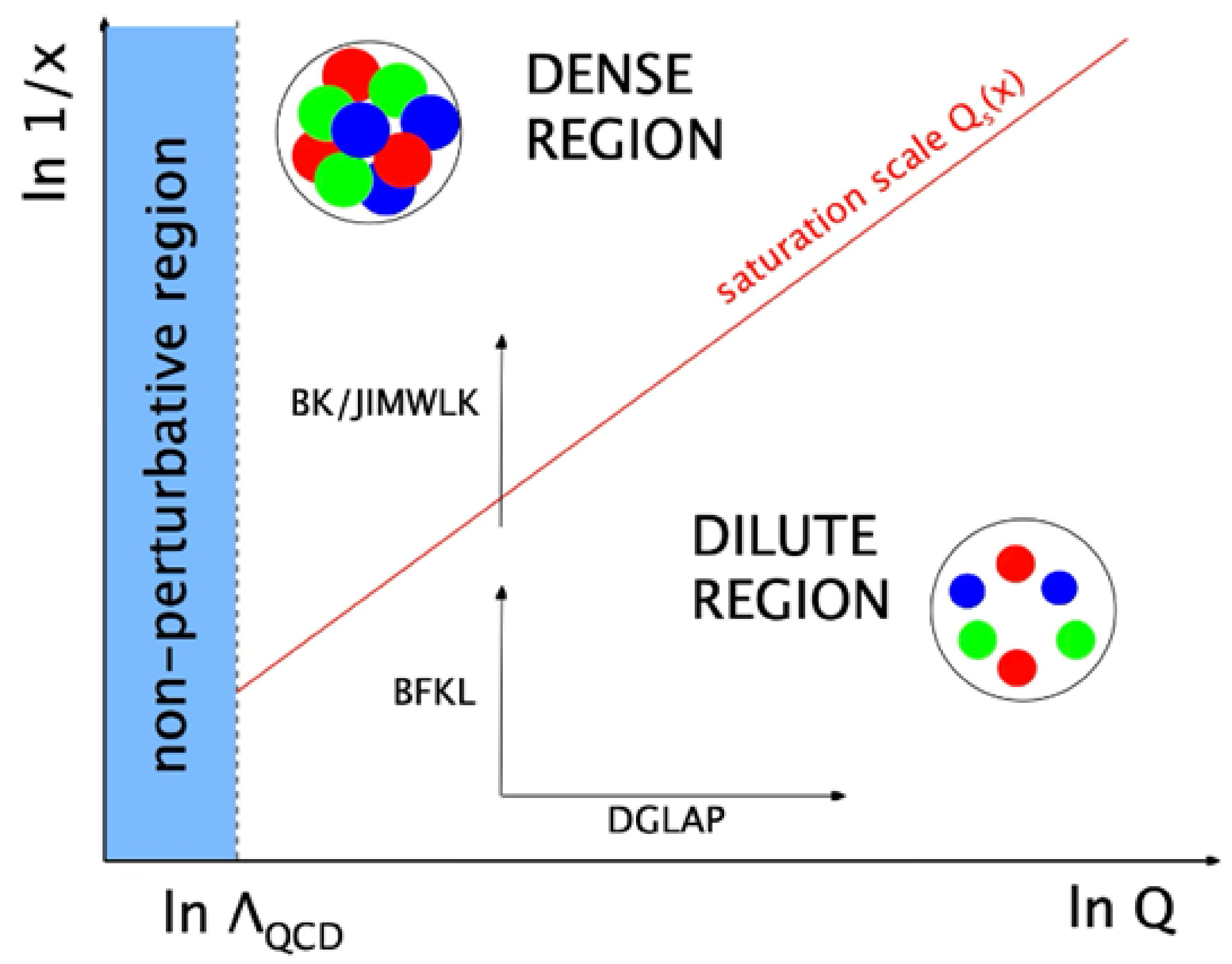
- **Precision**: $\alpha_s$ from low transverse momentum DY, $M_W$ in hadronic colliders,...

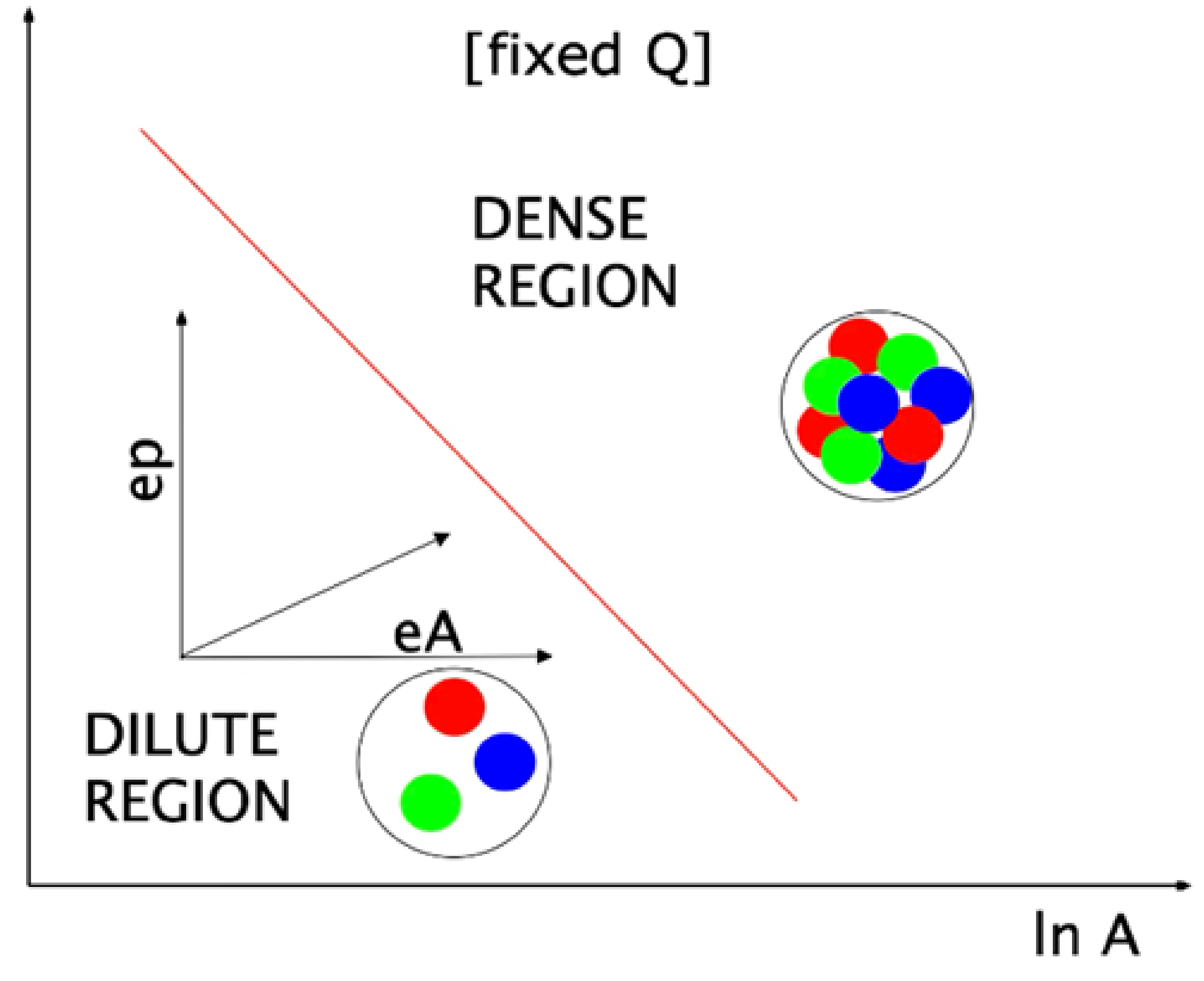
# Small x : state-of-the-art and challenges




- In **QCD at high energies**, fixed-order perturbation theory (linear, DGLAP) eventually fails $\Longrightarrow$ resummation, non-linear effects (saturation, driven by density).
- **NLO calculations** available in both regimes dilute (BFKL+coll. res., DIS and $\gamma\gamma$ cross sections, jet-gap-jet observables, H, heavy quarks) and dense (CGC: JIMWLK/BK+ coll. res., DIS cross sections including HQs, single particle/jet and DY+jet in pA, single hadron, dihadron and dijet in DIS, non-eikonal corrections).

- **Challenges:**
  - ❑ Experimental data inconclusive: lever arm in $Q^2$ at small x, proton and nuclei.
  - ❑ Complete NLO calculations: stability?; target modelling.
  - ❑ Relation with TMD factorisation, and search of unified evolution.



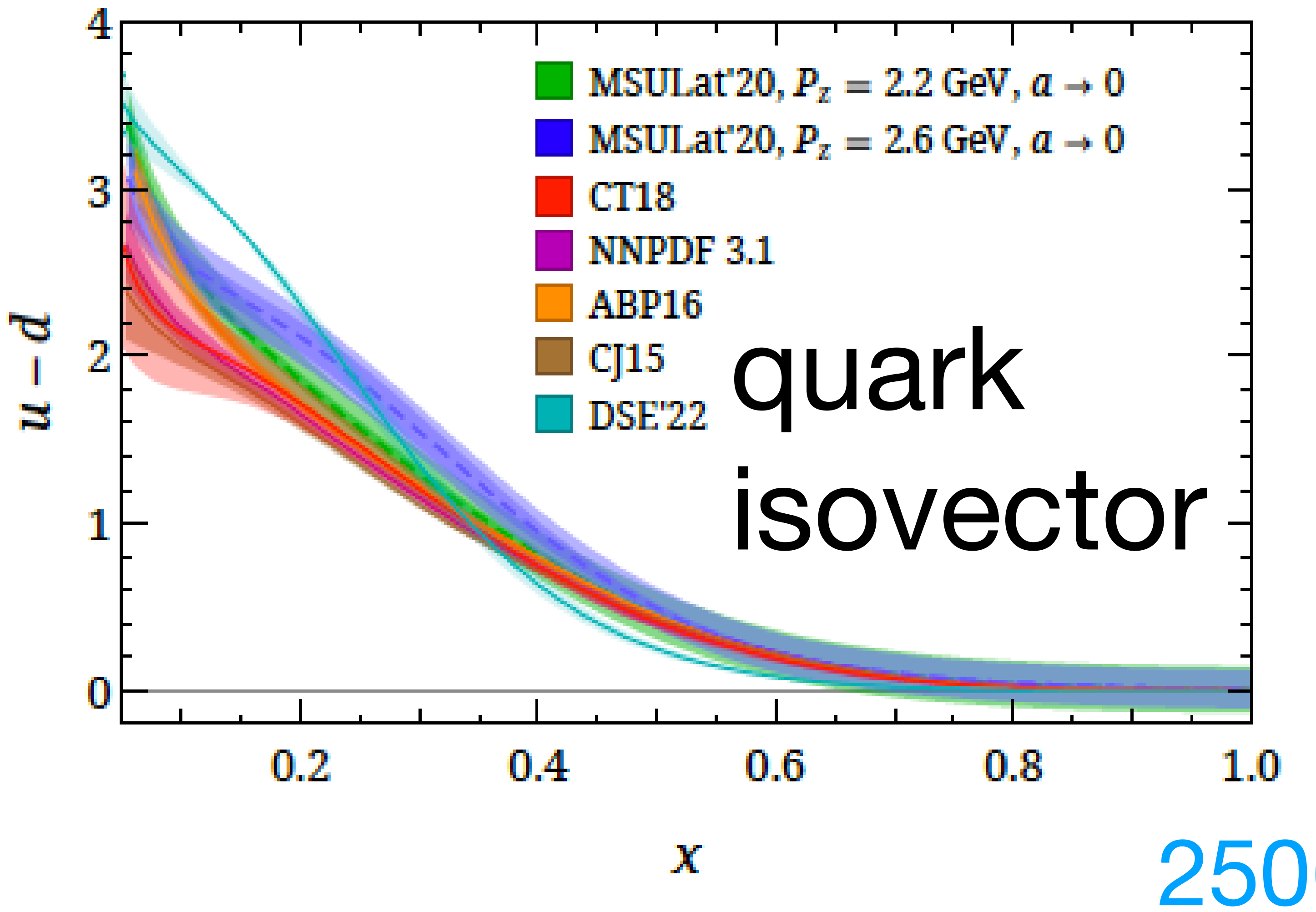



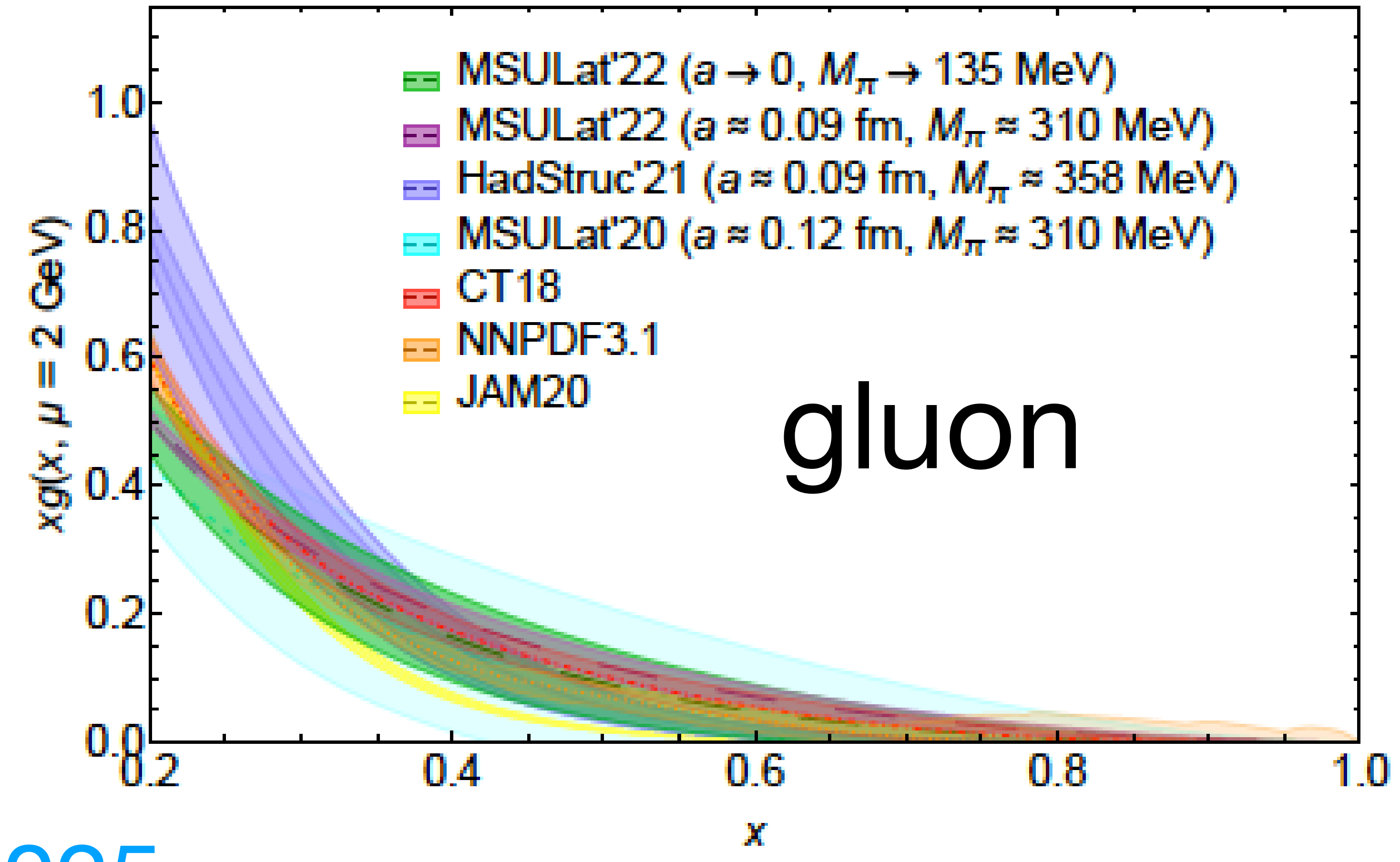


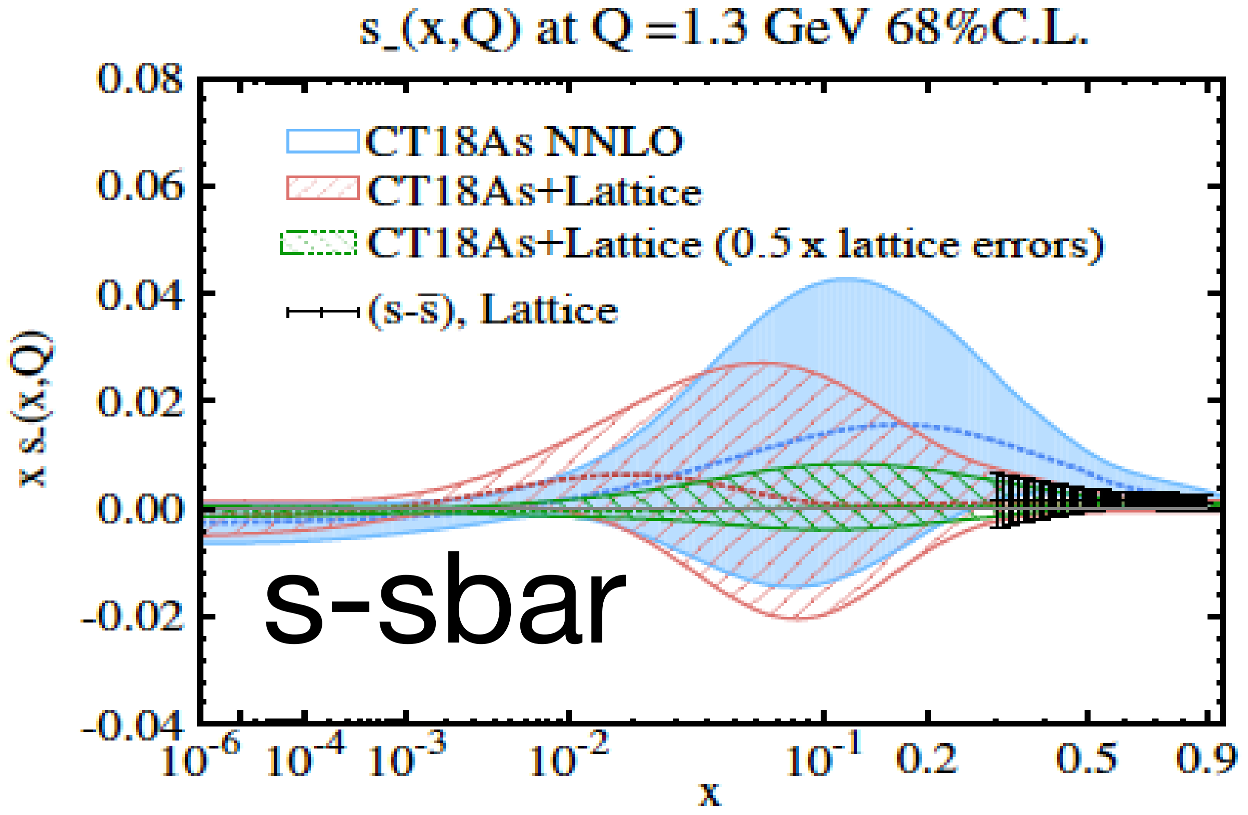

N. Armesto, June 23rd 2025

# Lattice: state-of-the-art and challenges

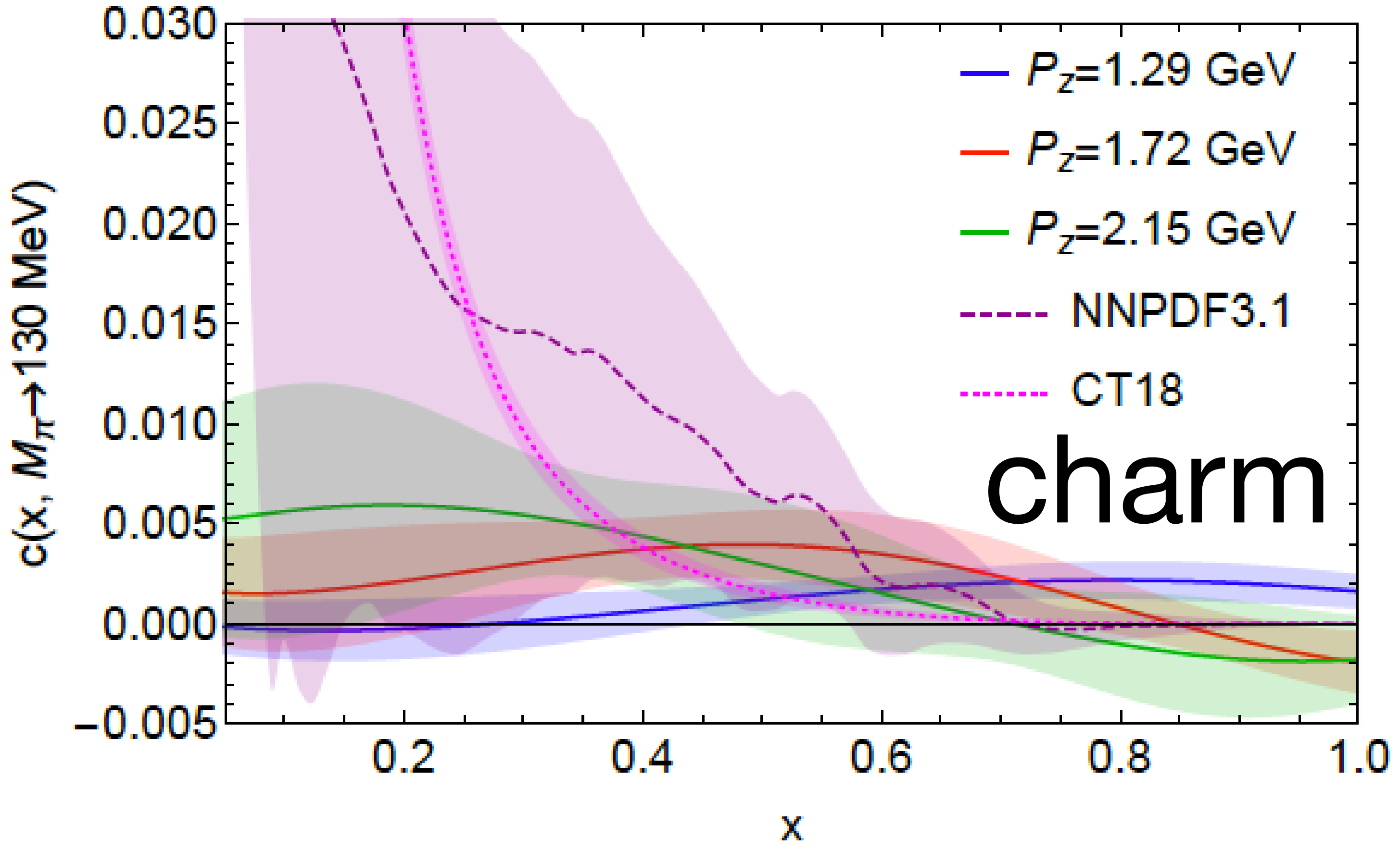
- **Since 2013, lattice QCD has provided 1st-principles PDFs, TMDs and GPDs.**
- 2+1(+1) flavors (physical $m_\pi$ for some quantities) achieved.
- **Challenges**: signal-to-noise ratios, extrapolation to physical $m_\pi$, uncertainties for large and small x; lattice results into global fits (already done for COMPASS transversity TMD).

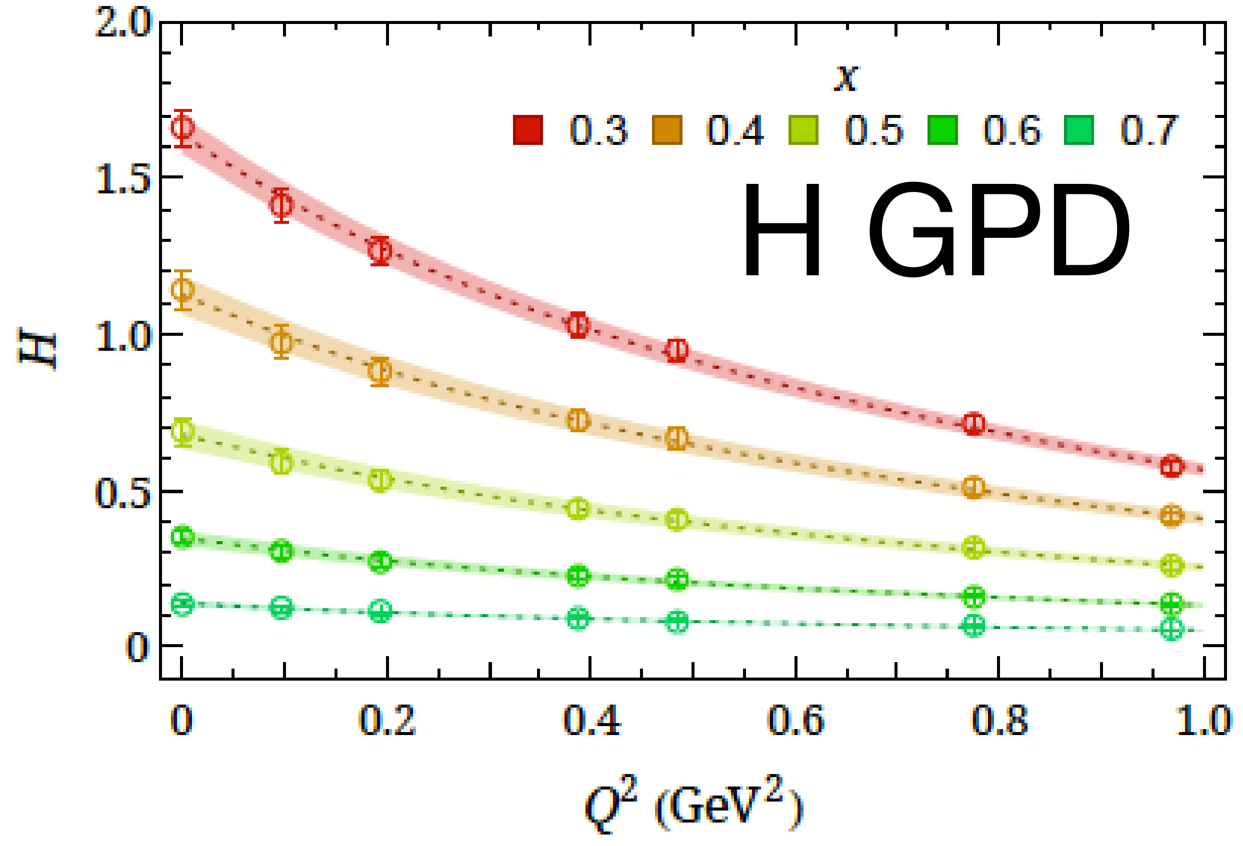


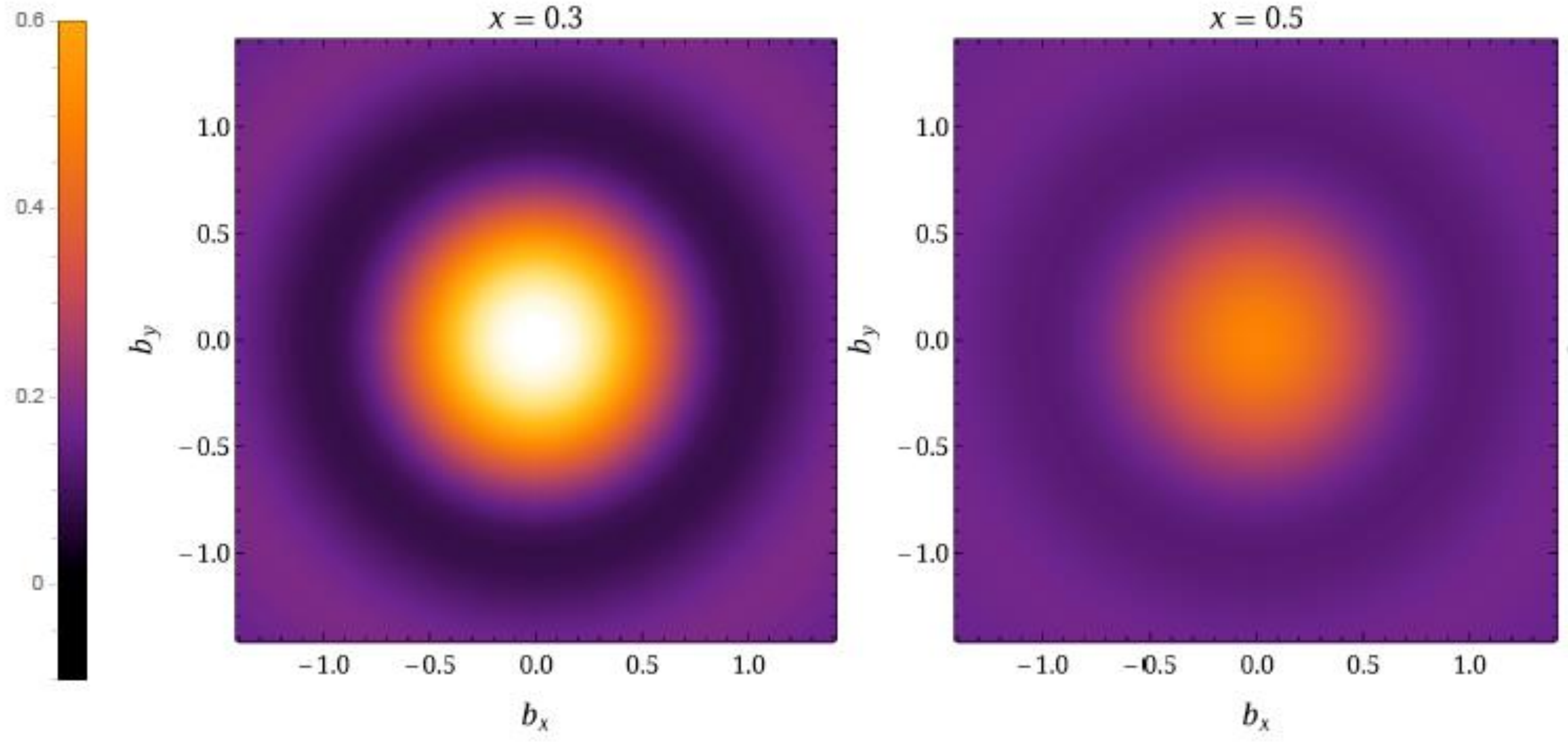




2506.05025



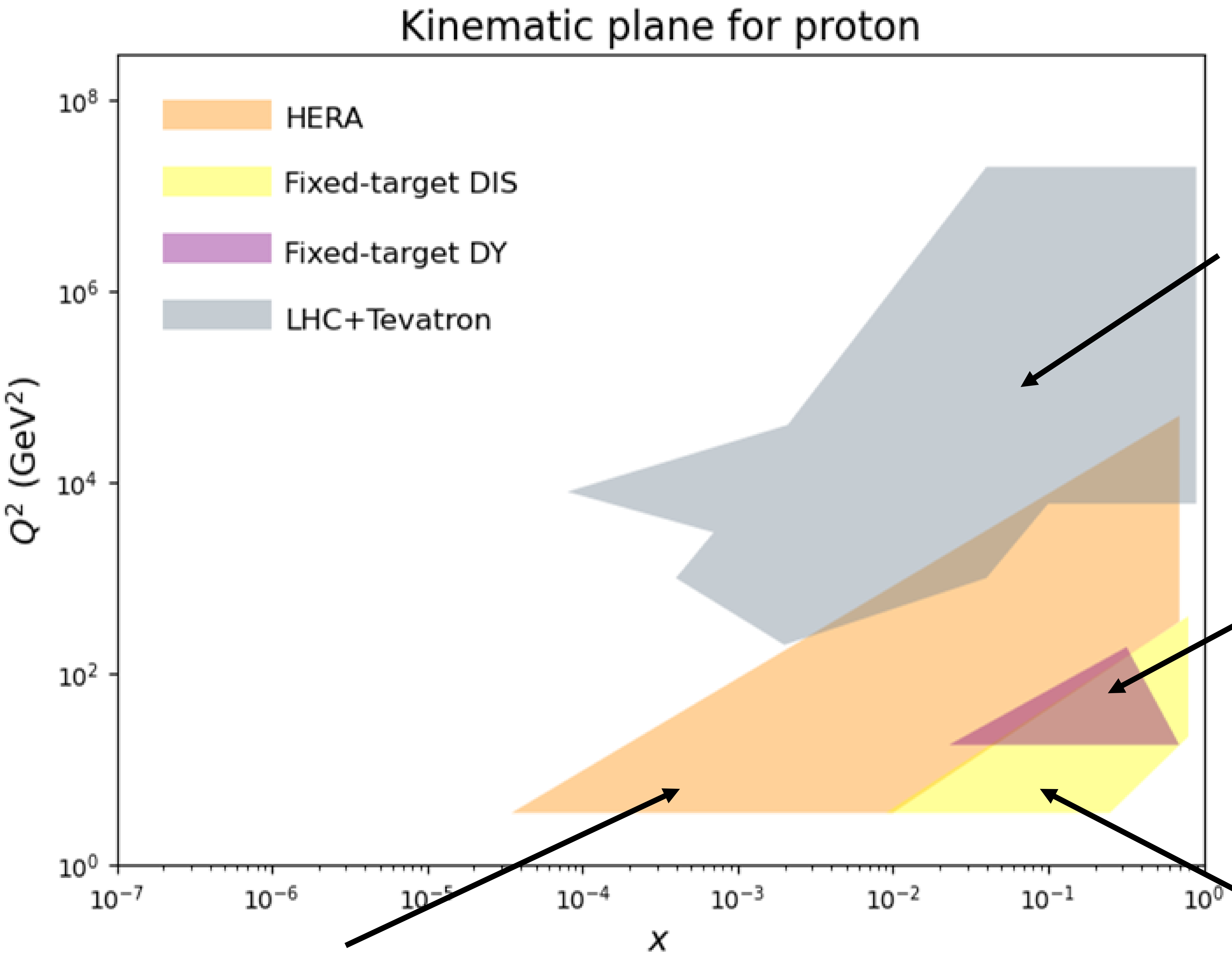




$$q(x, b) = \int \frac{d\mathbf{q}}{(2\pi)^2} H(x, \xi = 0, t = -\mathbf{q}^2) e^{i\mathbf{q}\cdot\mathbf{b}}$$

# Kinematic planes for proton

**NNPDF4.0:**
[arXiv: 2109.02653]




LHC: W(+jet), Z, DY, jets and dijets, single and top pairs (+jet), isolated photons

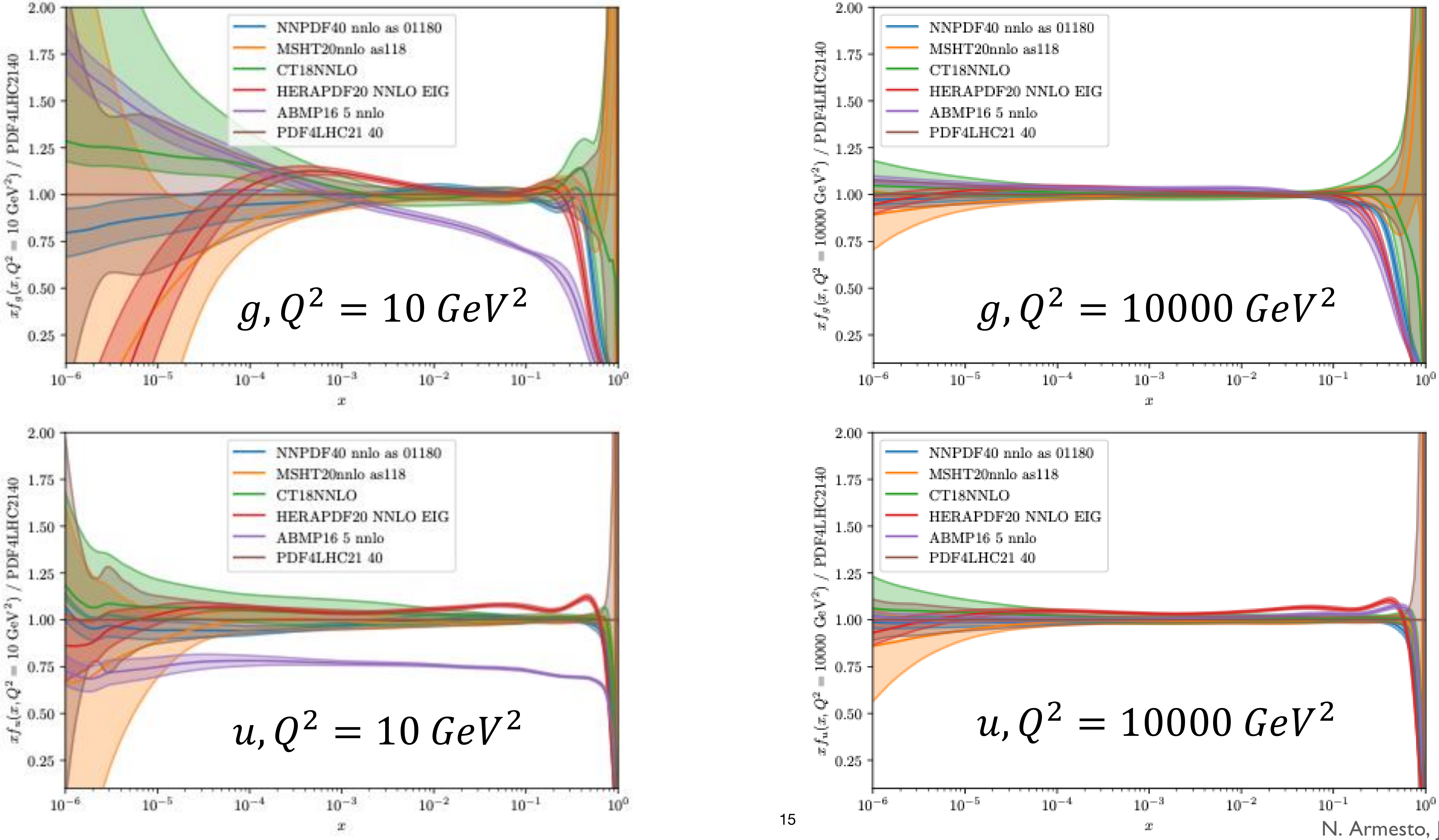
Tevatron data: W, Z

$p(\overline{p}) + p/d$ DY

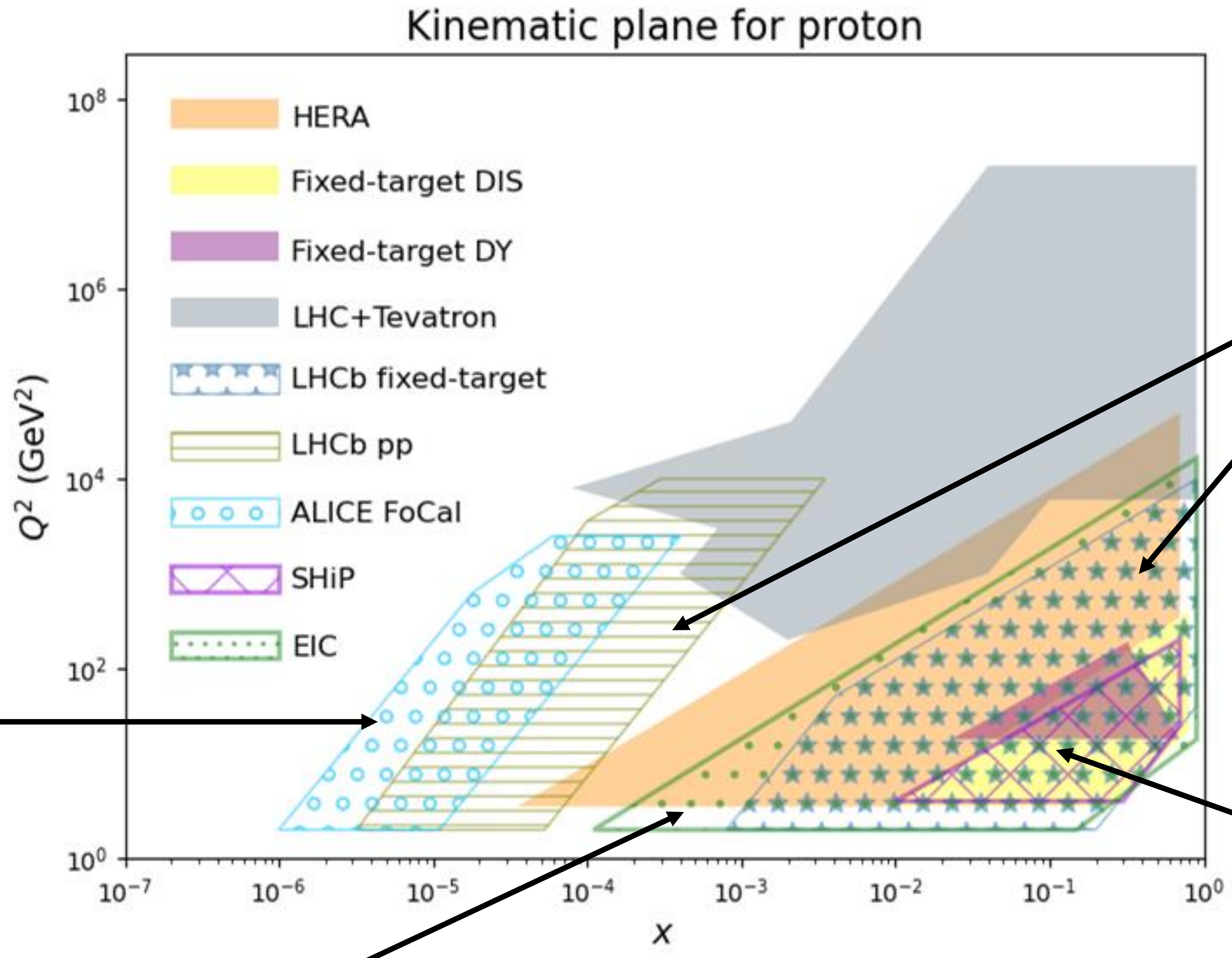
HERA: NC, CC and jets in DIS

NC($l^{\pm}$) and CC($\nu$) DIS

# Kinematic planes for proton



# Kinematic planes for proton




LHCb (wo/w upgr. II): D, B, quarkonia, light hadrons

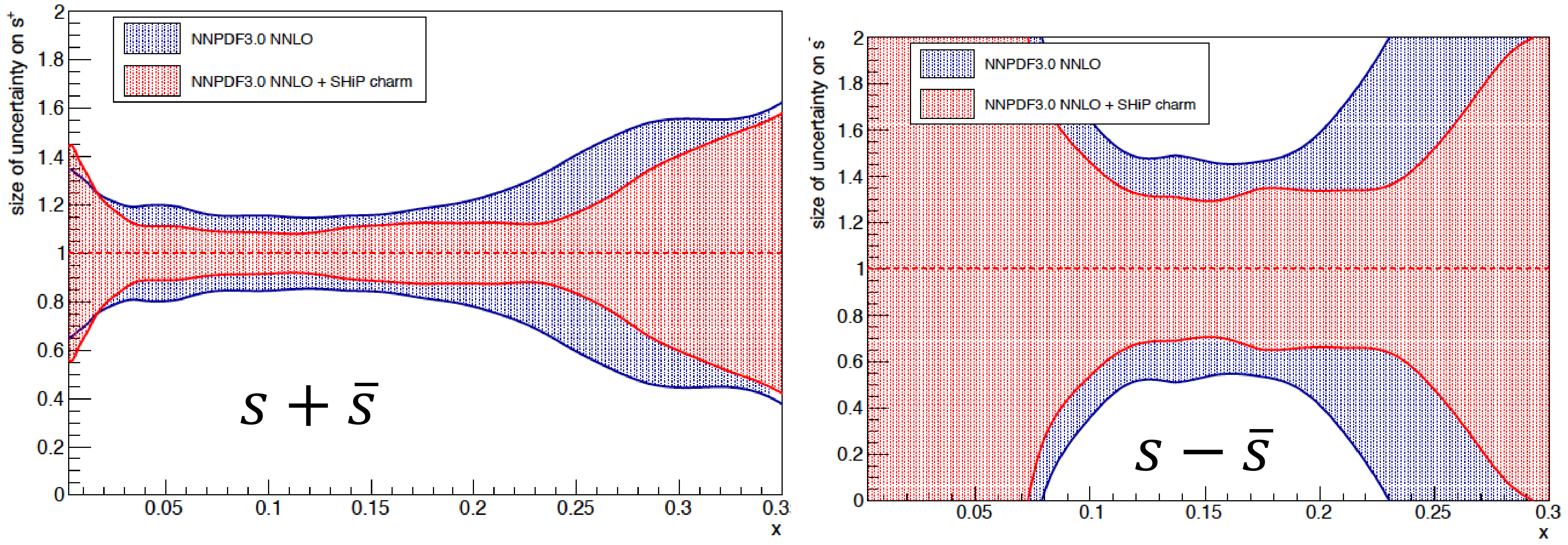
ALICE FoCal: photons, electrons (J/ψ) and jets

SHIP: $\nu$ flux from charm, NC and CC DIS (charm tagging)

EIC: NC, CC and jets in DIS, light- and heavy-flavour ID

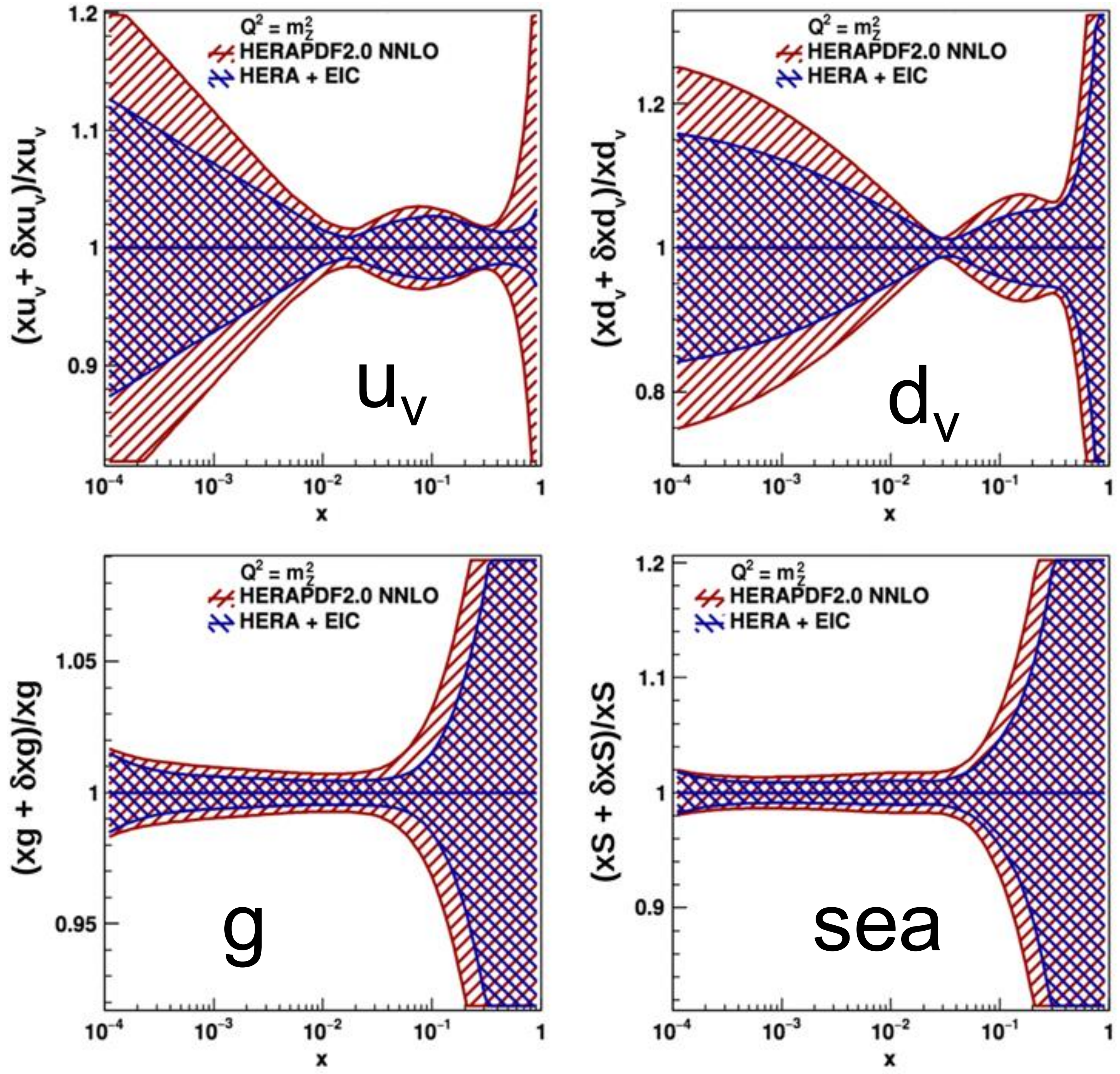
# Kinematic planes for proton

1504.04855, strangeness through charm tagging at **SHiP**




**EIC**

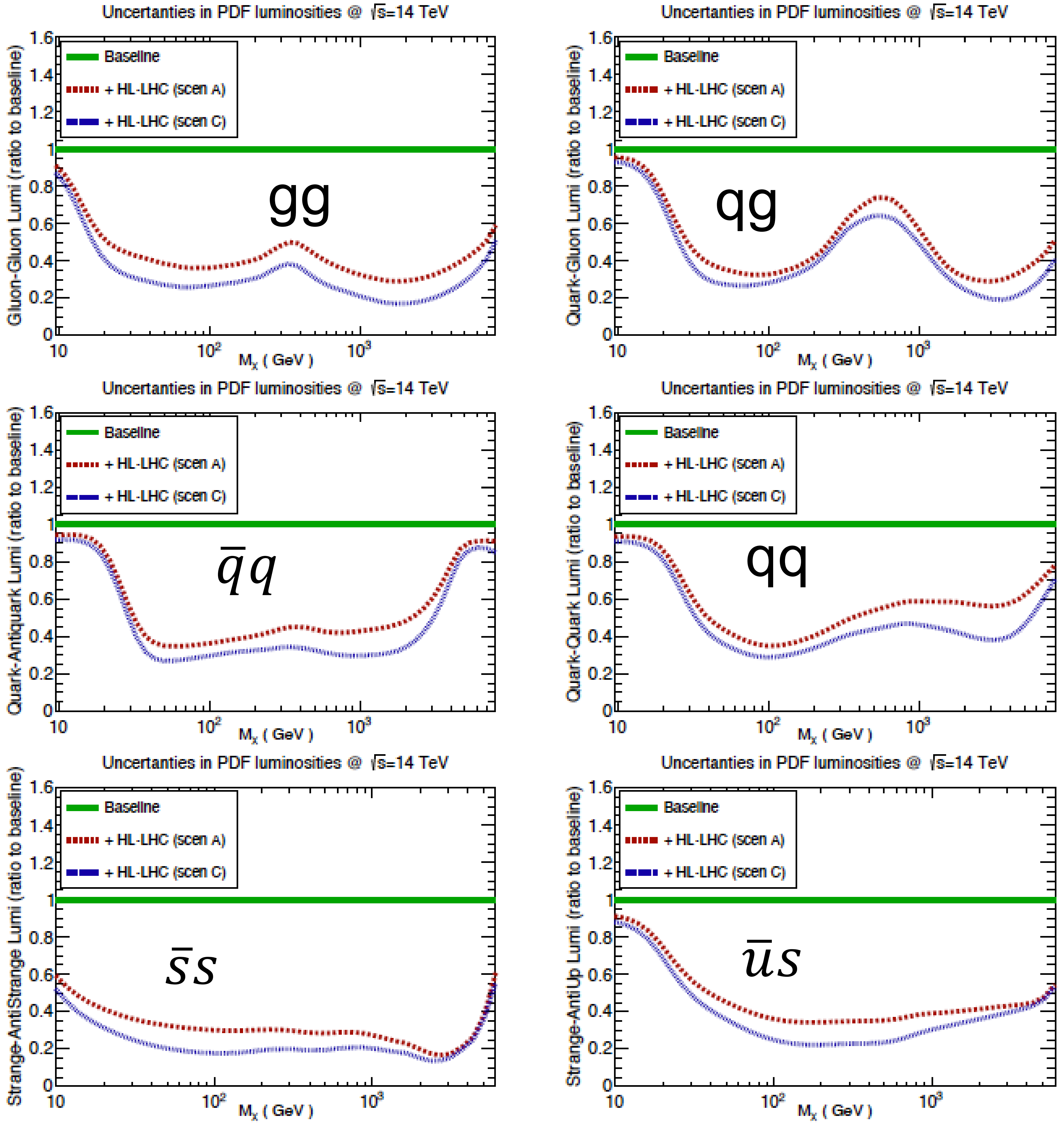
2309.11269



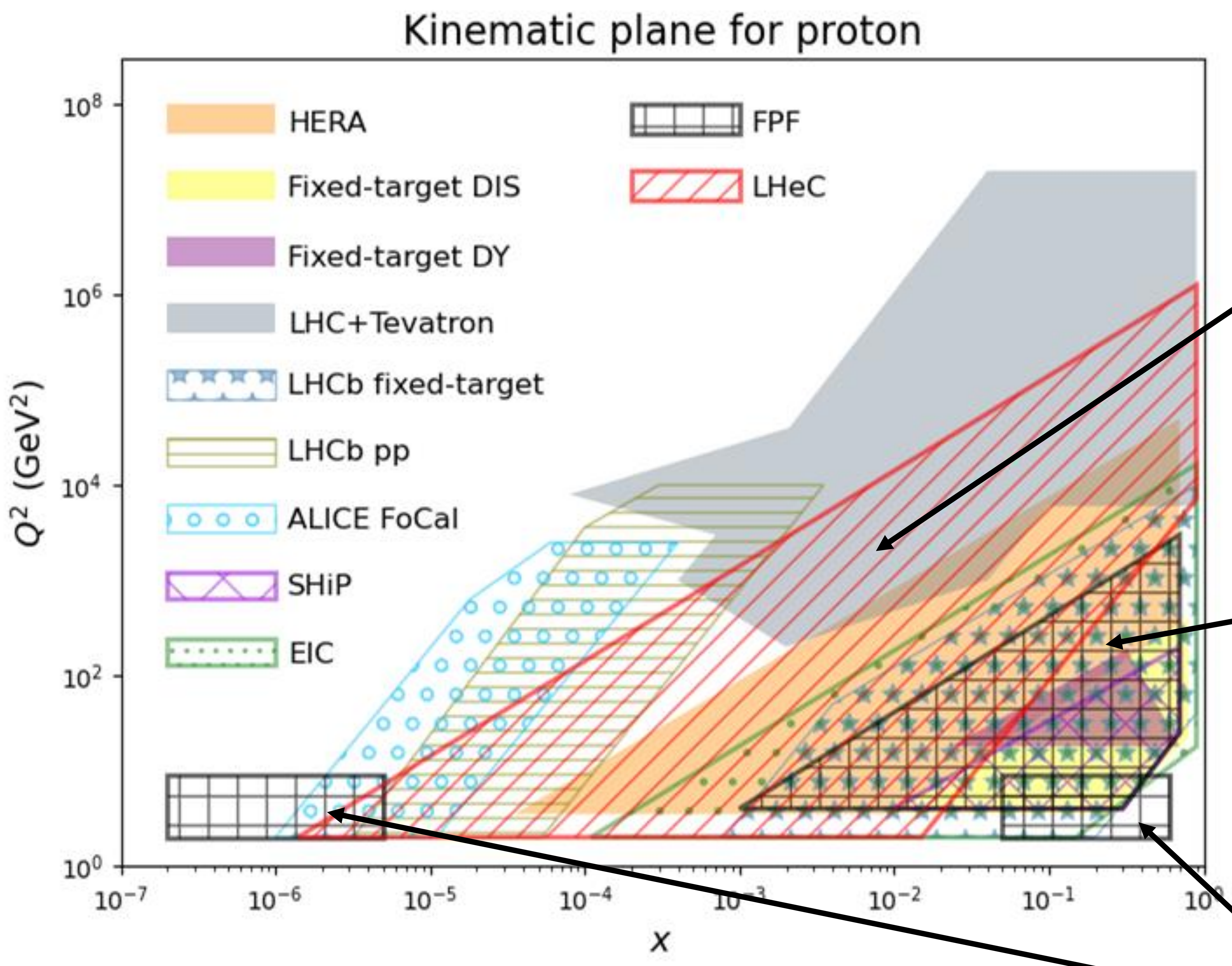

- Sizeable but modest impact from EIC, SHiP provides strangeness.
- Large impact from HL-LHC, but a large fraction of it already done (update needed).
- Note: timelines may be different.

1810.03639, **HL-LHC**

A: conservative (1/2); C: optimistic (1/5)



# Kinematic planes for proton



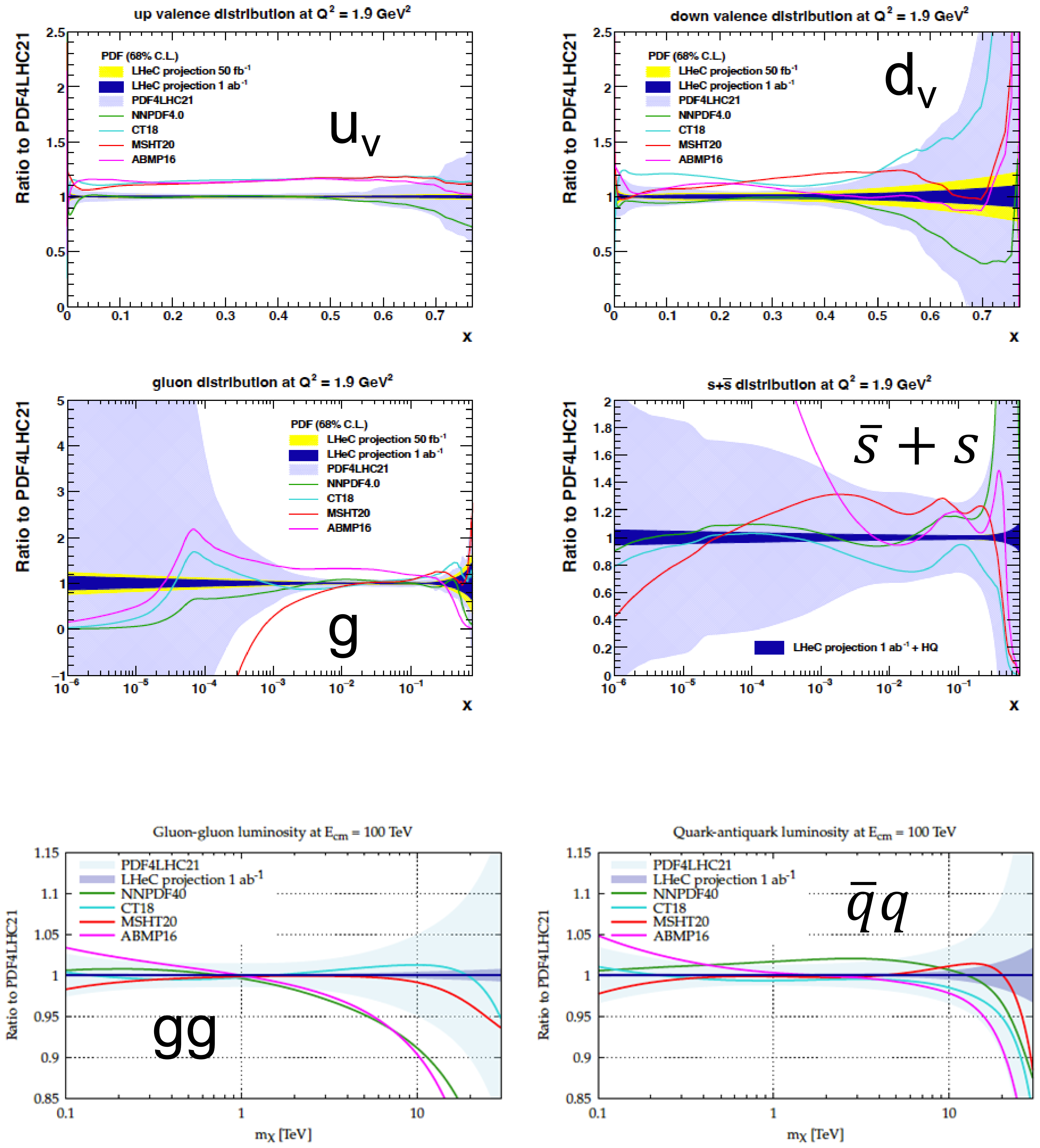

LHeC: NC, CC and jets in DIS, heavy flavour ID

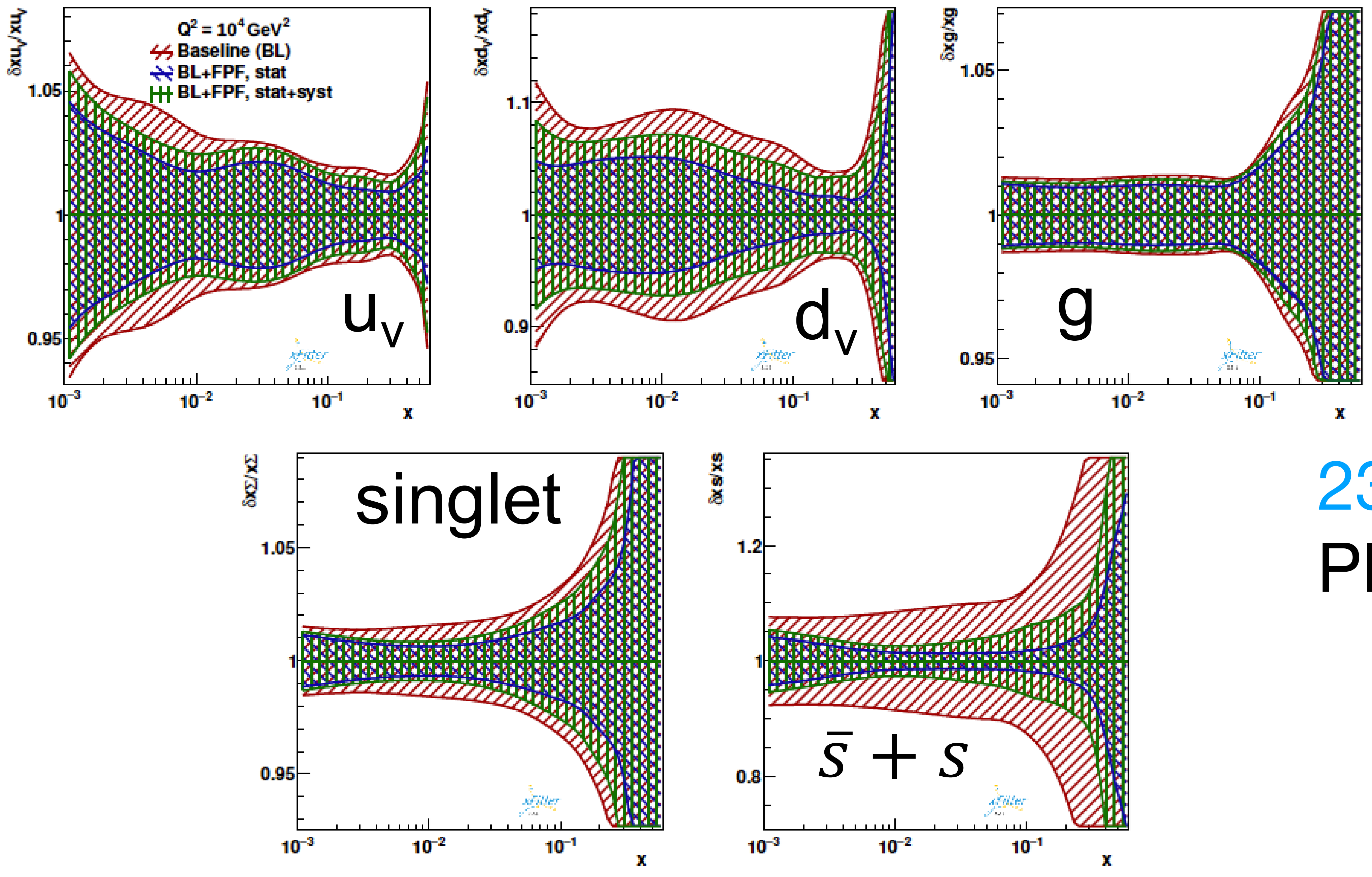
FPF:
NC and CC DIS

FPF:
$\nu$ flux from charm

# Kinematic planes for proton

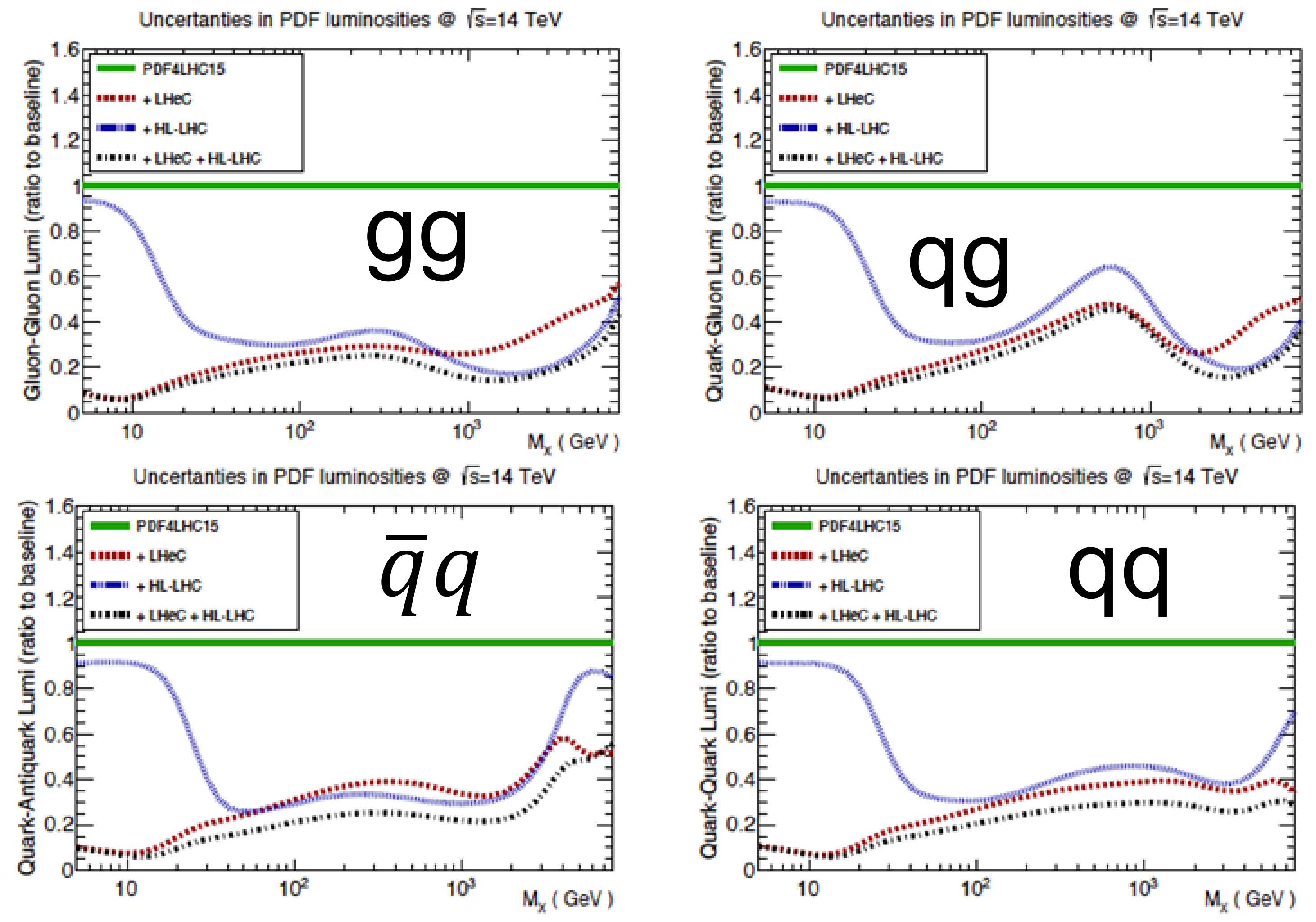
2503.17727, **LHeC**




2309.09581, **FPF**, PDF4LHC21

- Sizeable but modest impact from FPF,except strangeness!
- Large impact from LHeC.




1906.10127, **LHeC**



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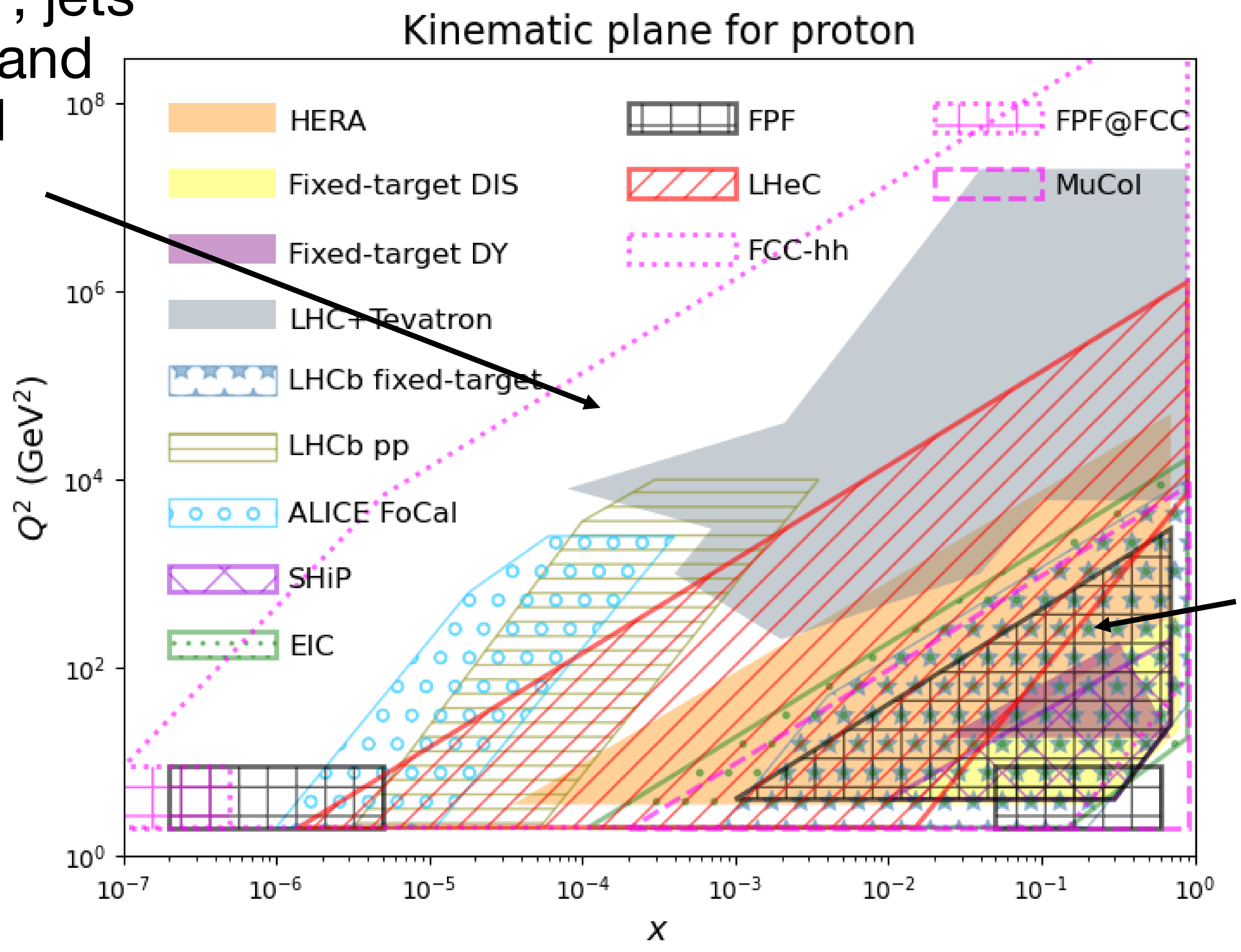
# Kinematic planes for proton

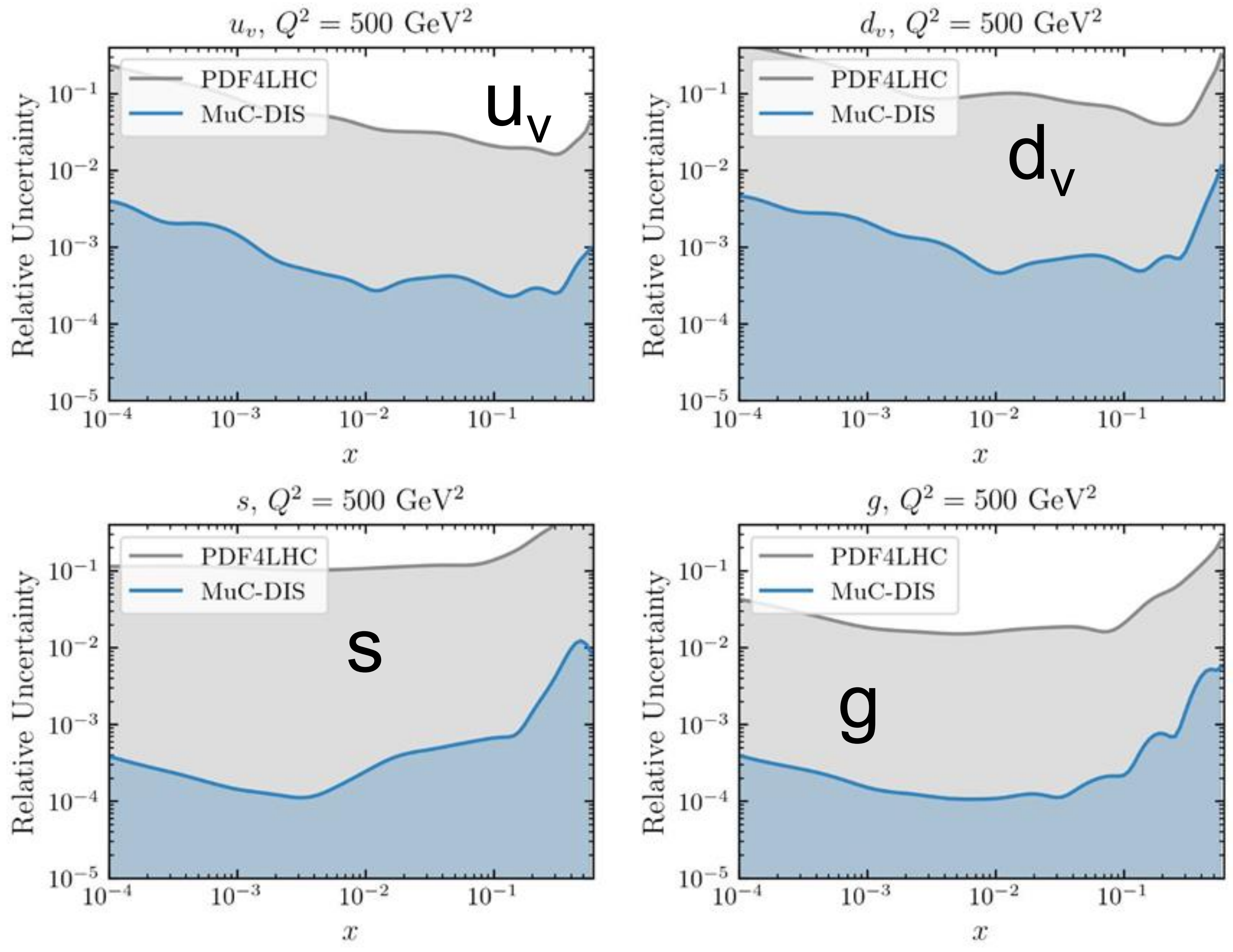
FCC-hh: W, Z, DY, jets and dijets, single and top pairs, isolated photons, D, B, quarkonia, light hadrons

FPF@FCC



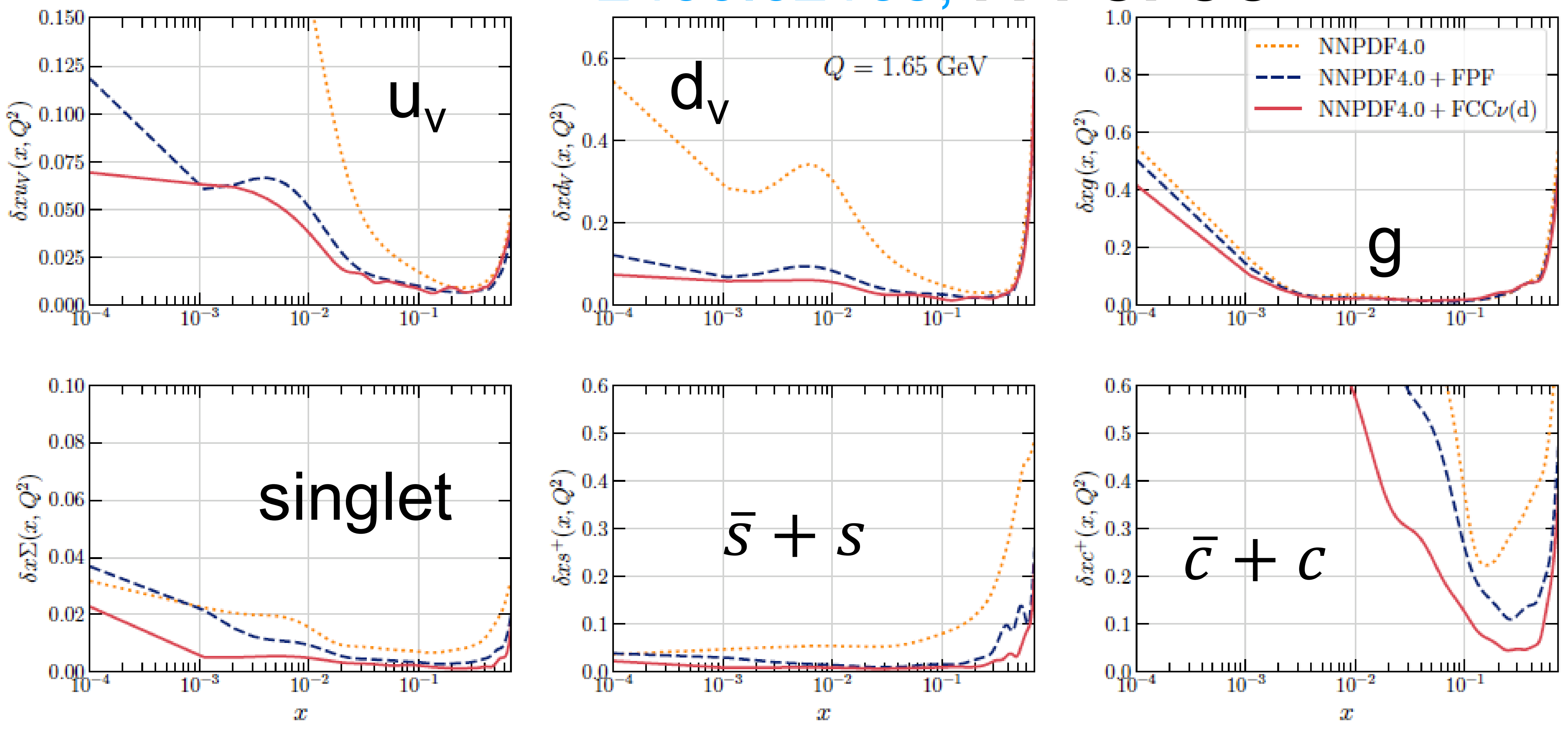

MuCol:
NC and CC DIS

# Kinematic planes for proton




2504.21417, **MuCol**

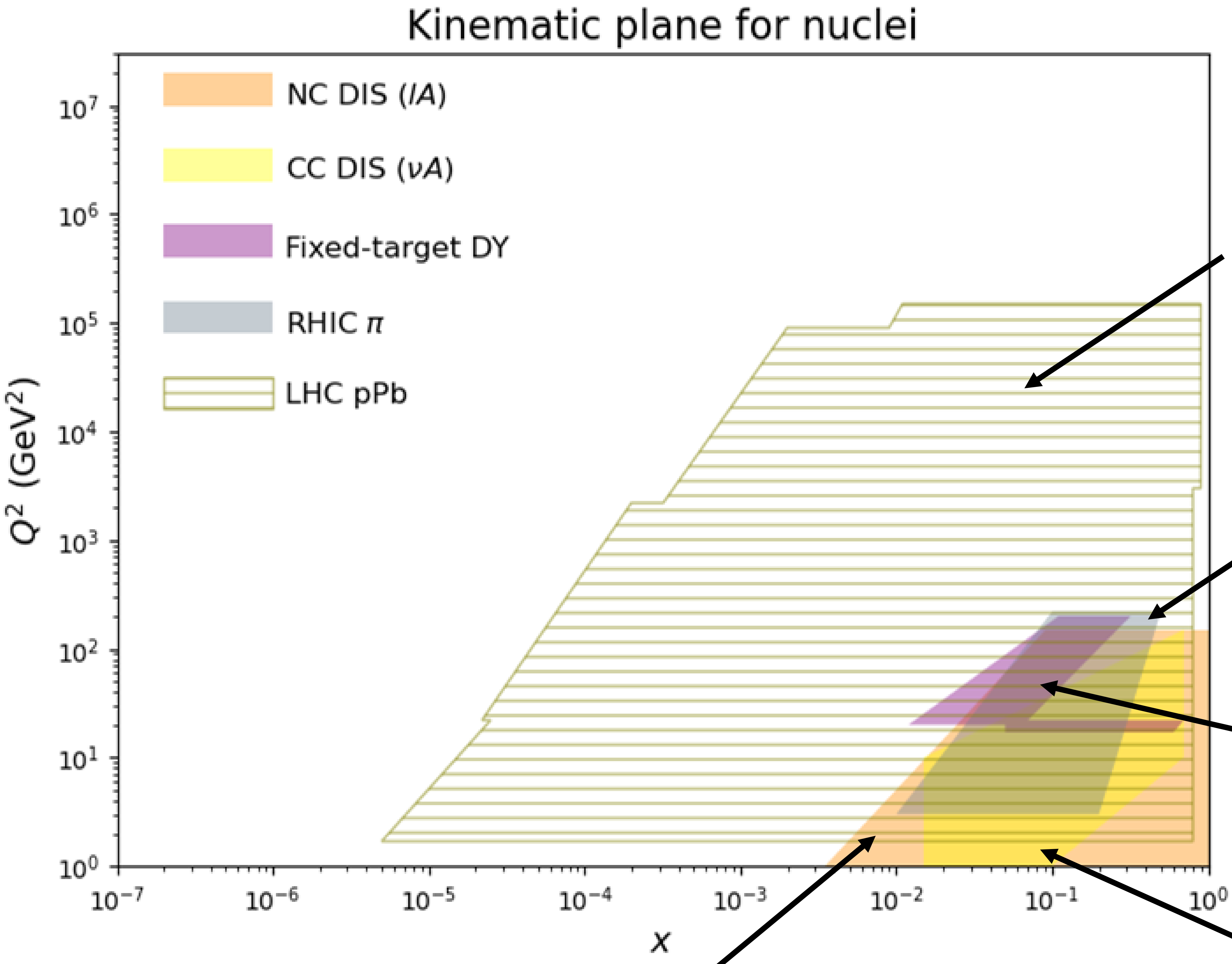
2409.02163, **FPF@FCC**




- Sizeable impact from FPF@FCC (valence), close to FPF@HL-LHC.
- Large impact from MuCol (statistics only).

**Review:** arXiv: 2311.00450

# Kinematic planes for nuclei




LHC: W, Z, jets, light hadrons, isolated photons, D mesons, quarkonia

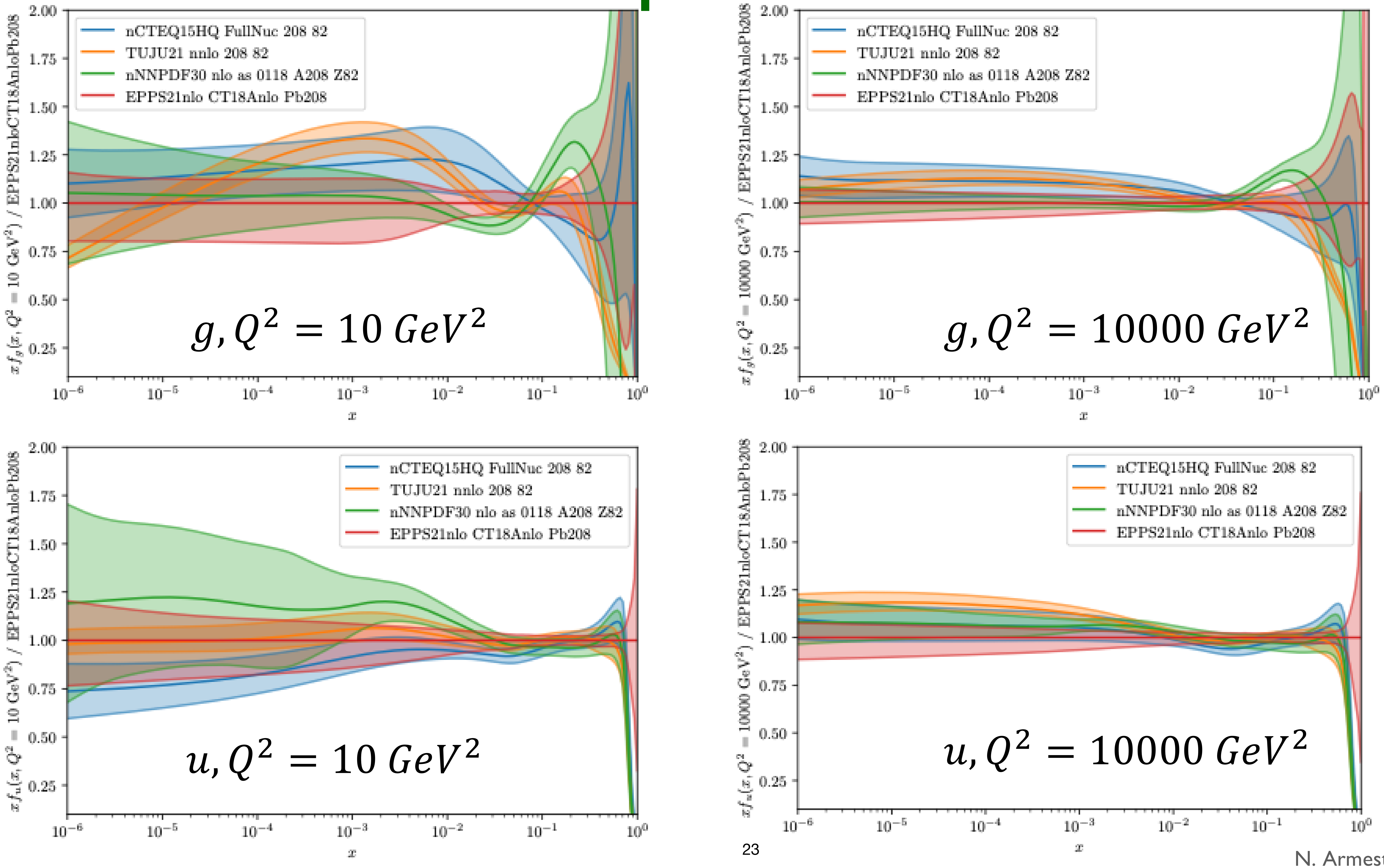
RHIC: pions

$pA$ and $\pi A$ DY

CC DIS

NC DIS with electrons and muons

# Kinematic planes for nuclei



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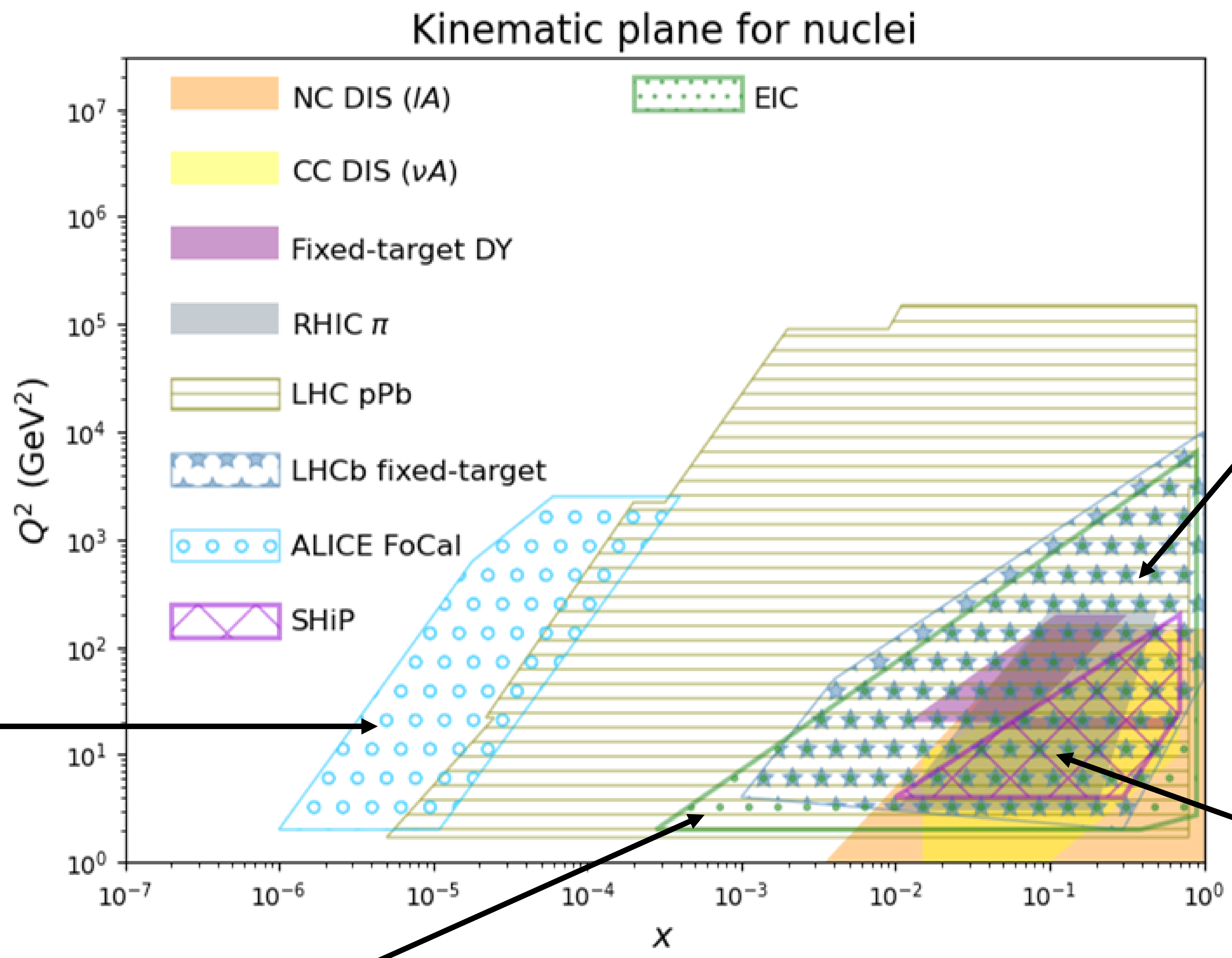
# Kinematic planes for nuclei




ALICE FoCal: photons, electrons (J/ψ) and jets

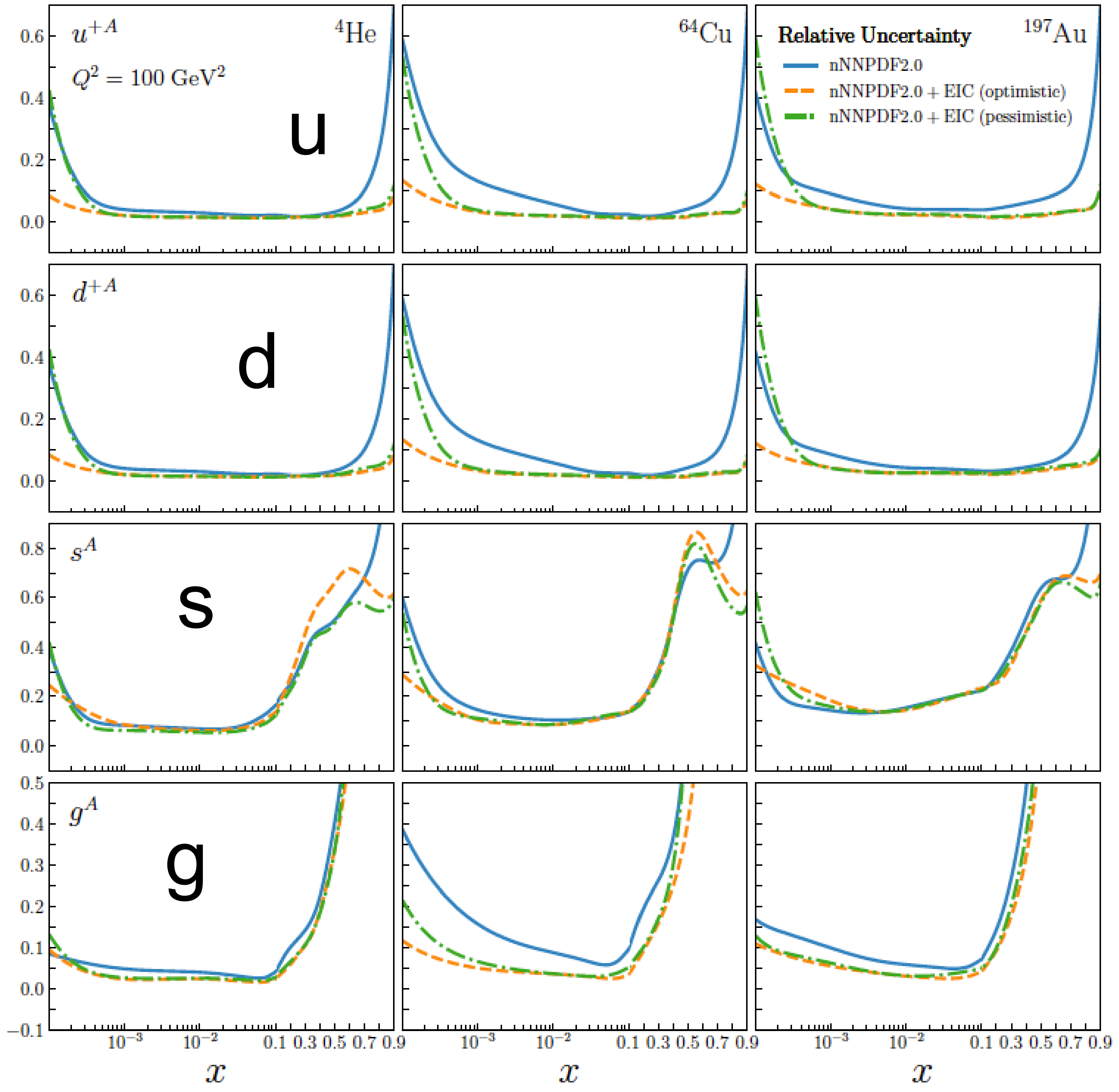
LHCb: D, B, quarkonia, light hadrons

SHiP: $\nu$ flux from charm, NC and CC DIS (charm tagging)

EIC: NC, CC and jets in DIS, light- and heavy-flavour ID

# Kinematic planes for nuclei

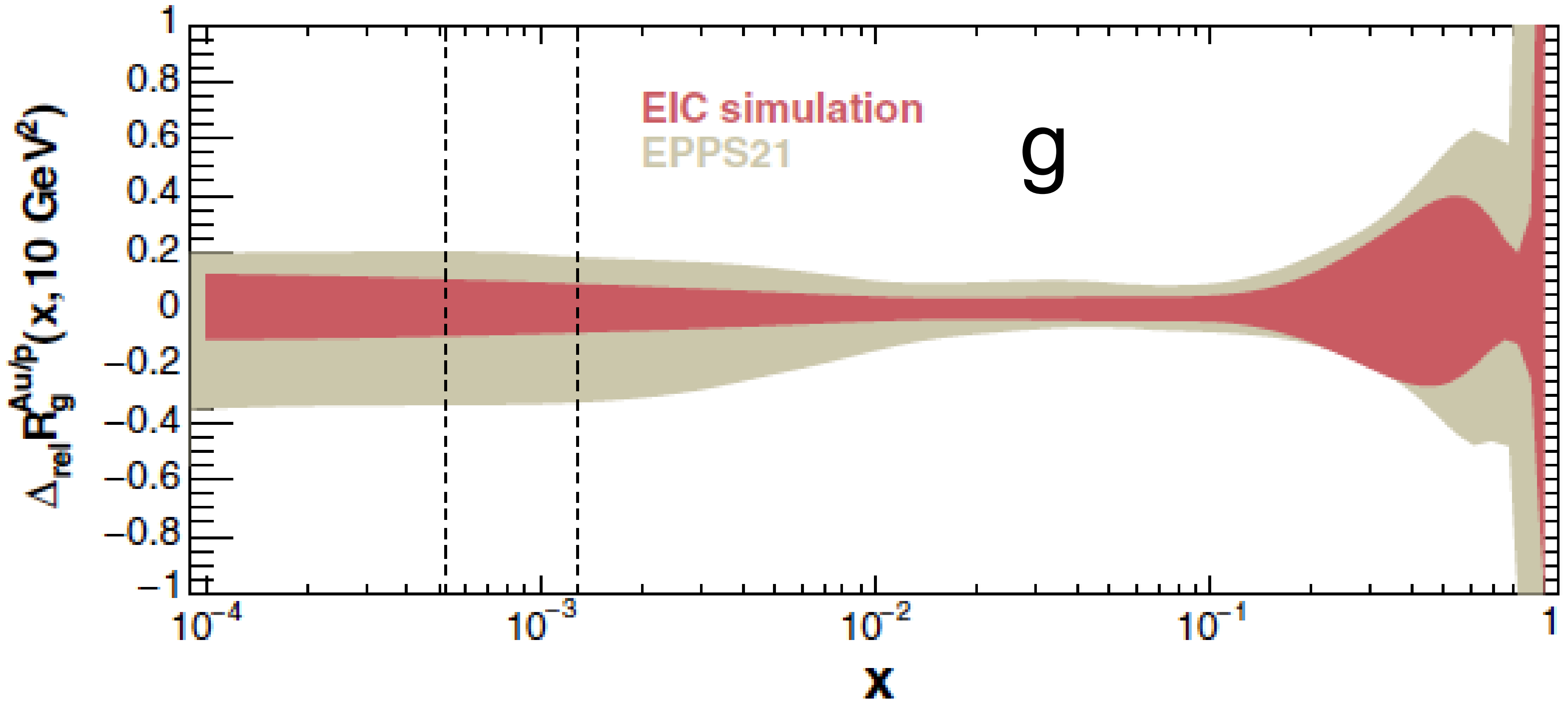
2102.00018



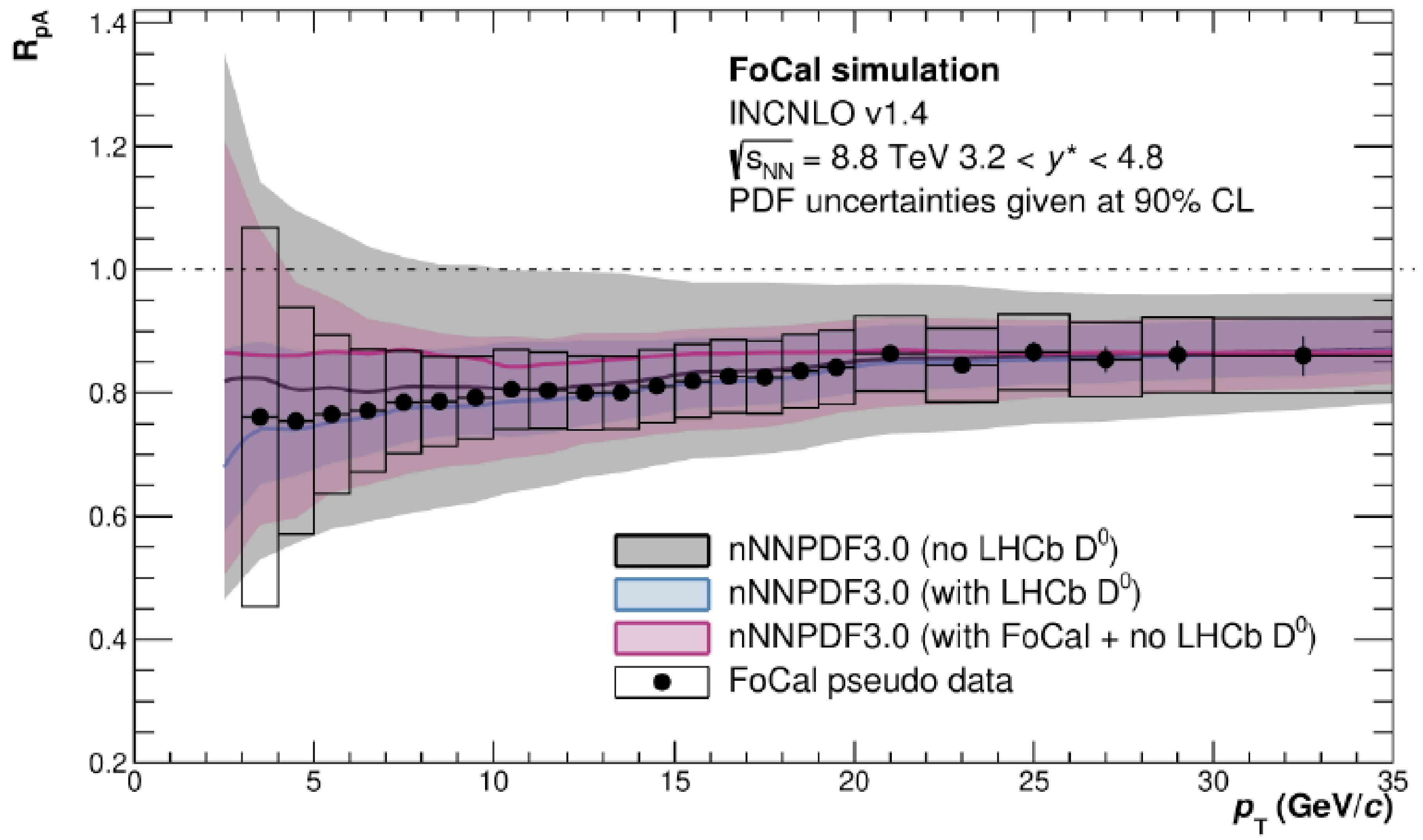

- Large impact from EIC.
- Sizable impact from LHCb SMOG2 and ALICE FoCal ($\gamma's \sim D's$).

EIC

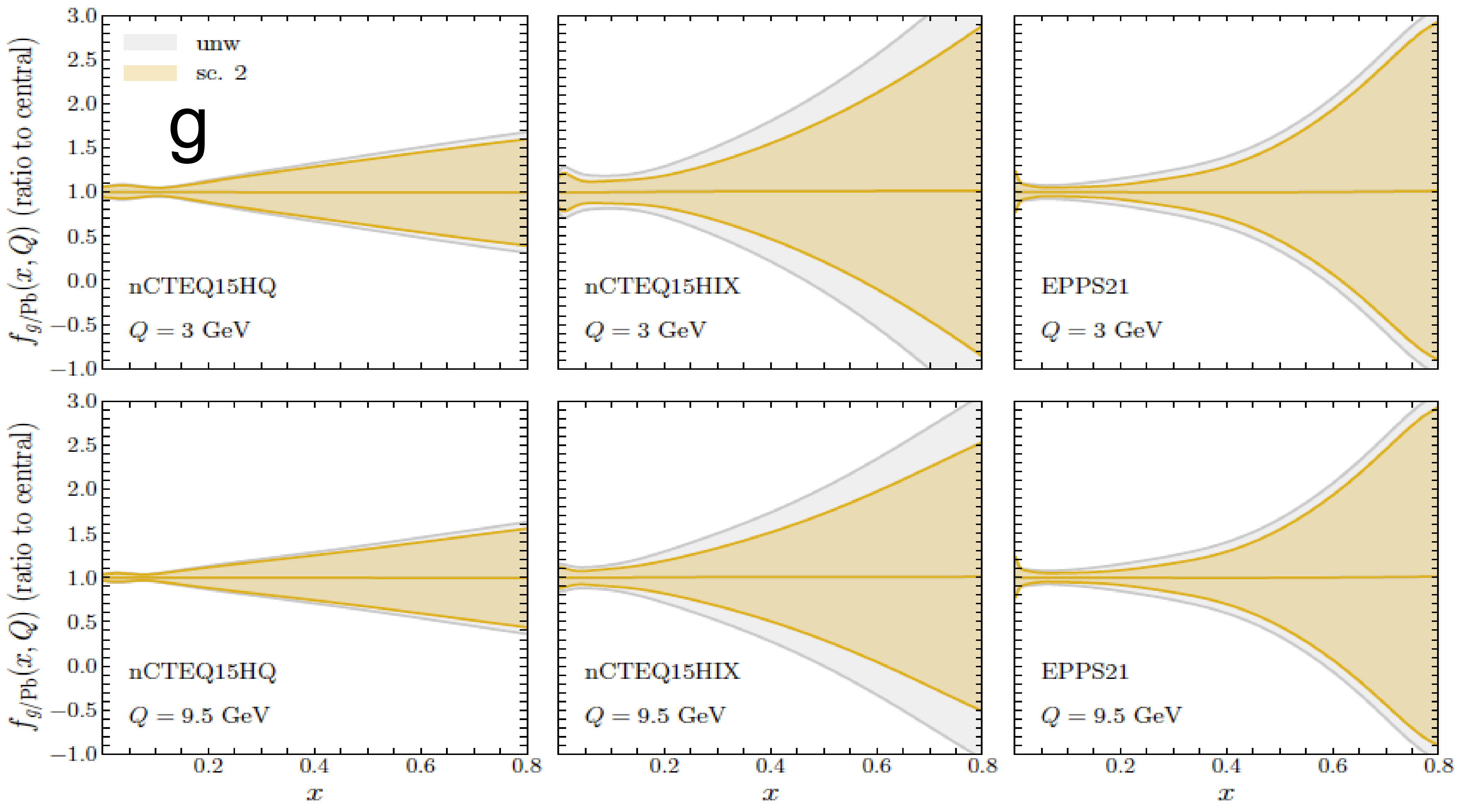
2309.11269



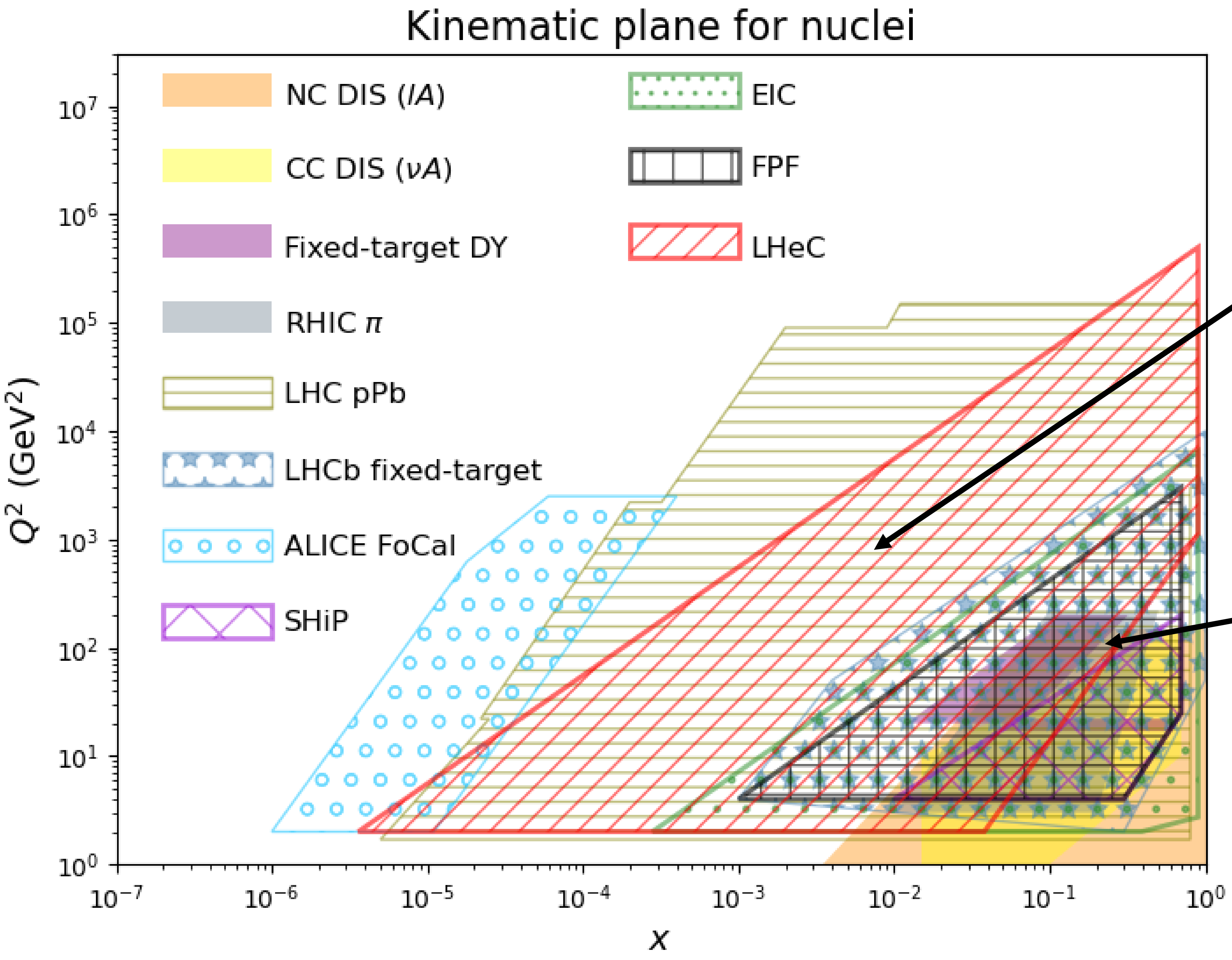

2407.13058, $\gamma$@ALICE **FoCal**




2503.21531, **LHCb SMOG2**



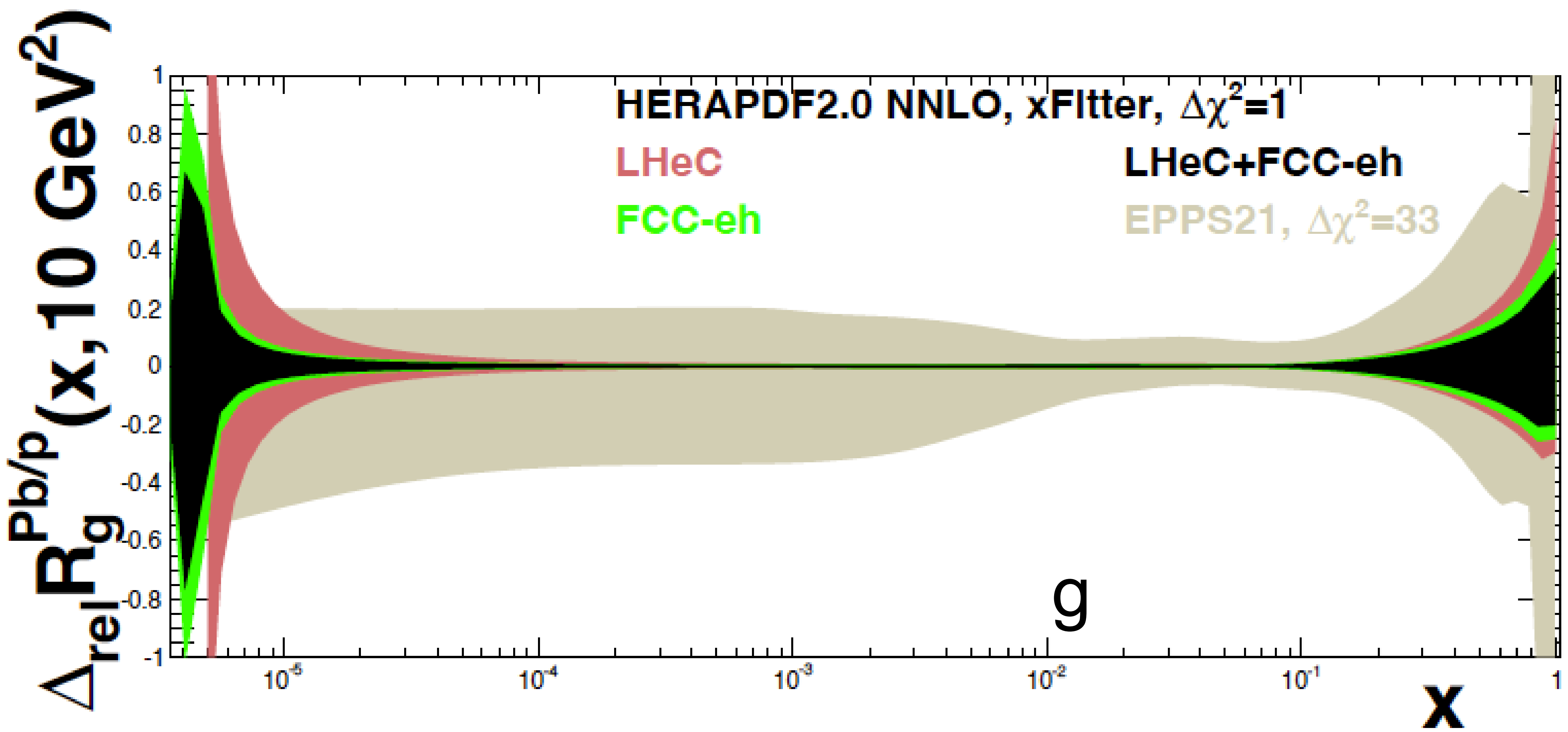
# Kinematic planes for nuclei



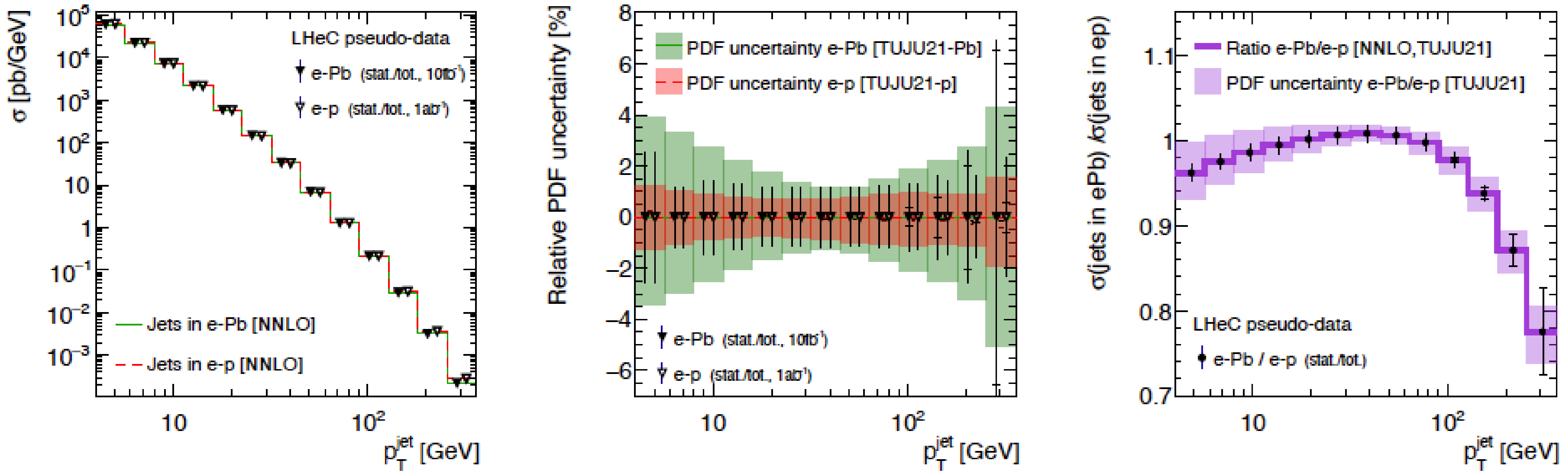

LHeC:NC, CC and jets in DIS, heavy-flavour ID

FPF:
NC and CC DIS

# Kinematic planes for nuclei

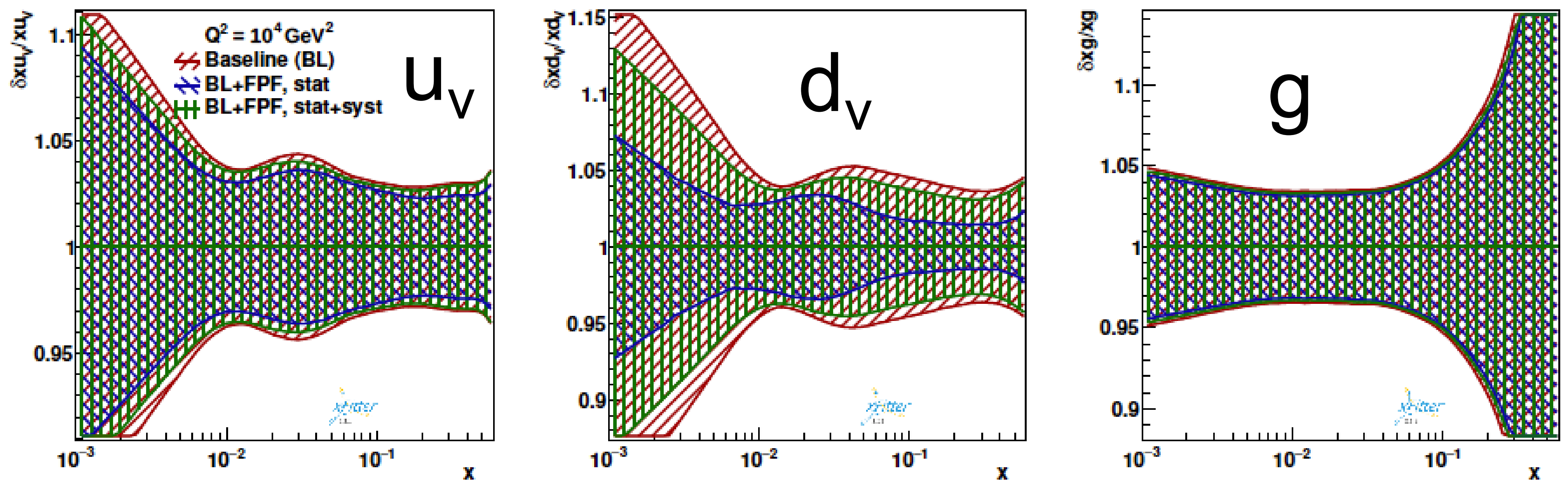



**LHeC**

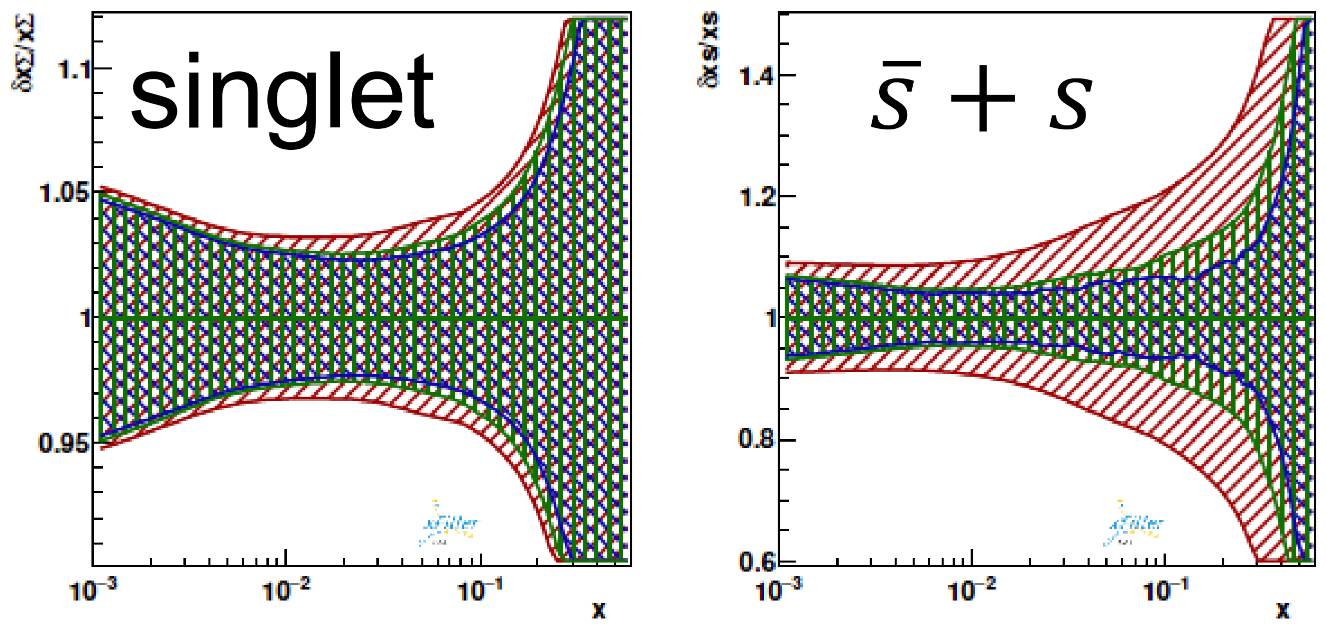



jets

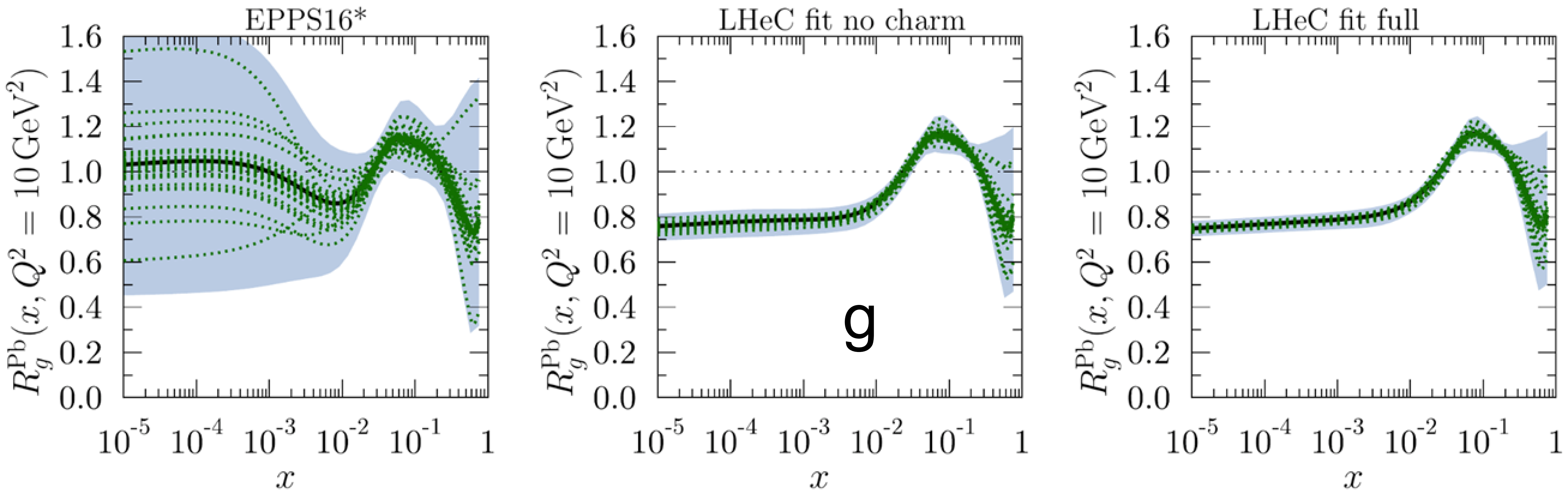
2309.09581, **FPF**, EPPS21




- Large impact from LHeC.
- Sizable impact from FPF.



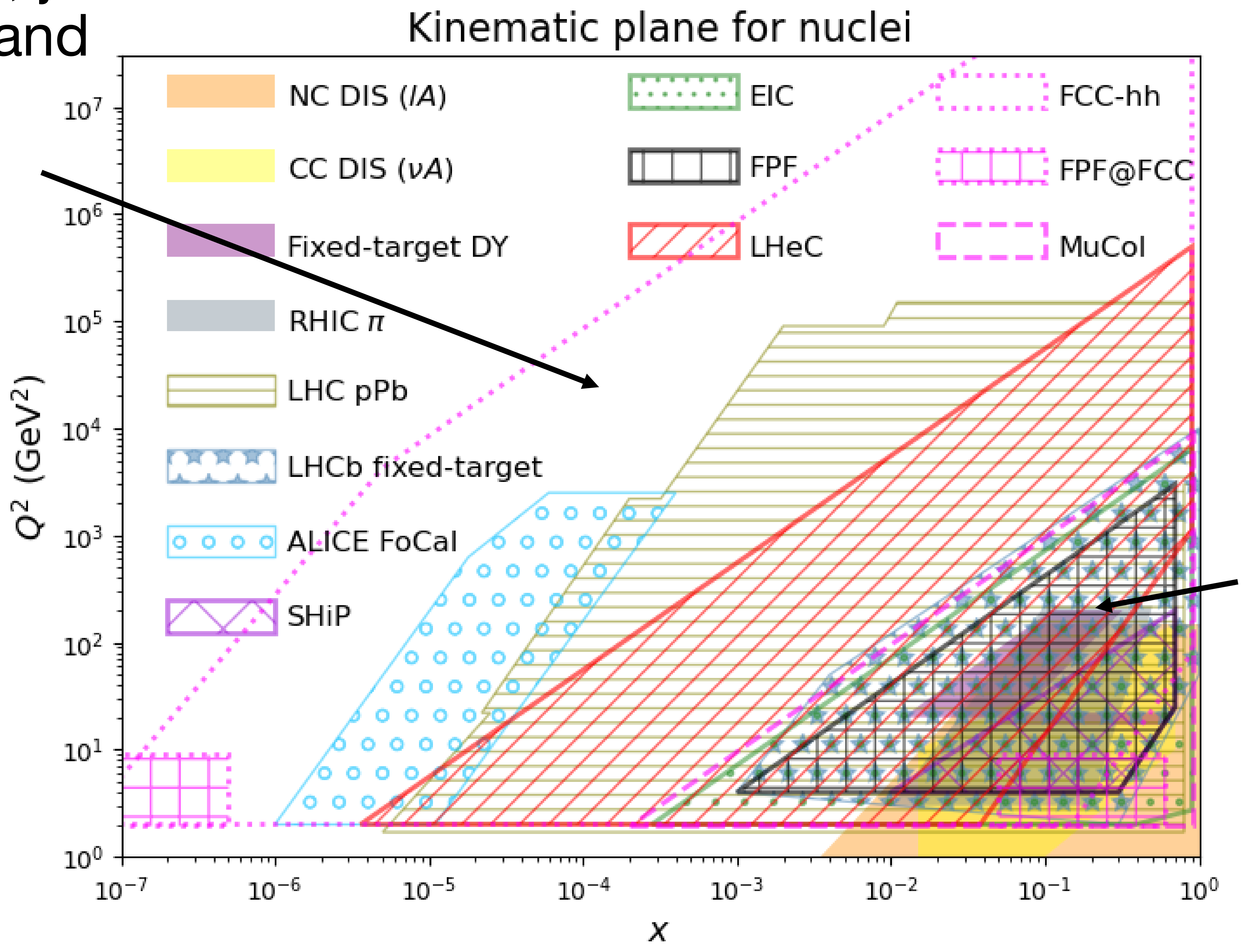

2007.14491, **LHeC**



# Kinematic planes for nuclei

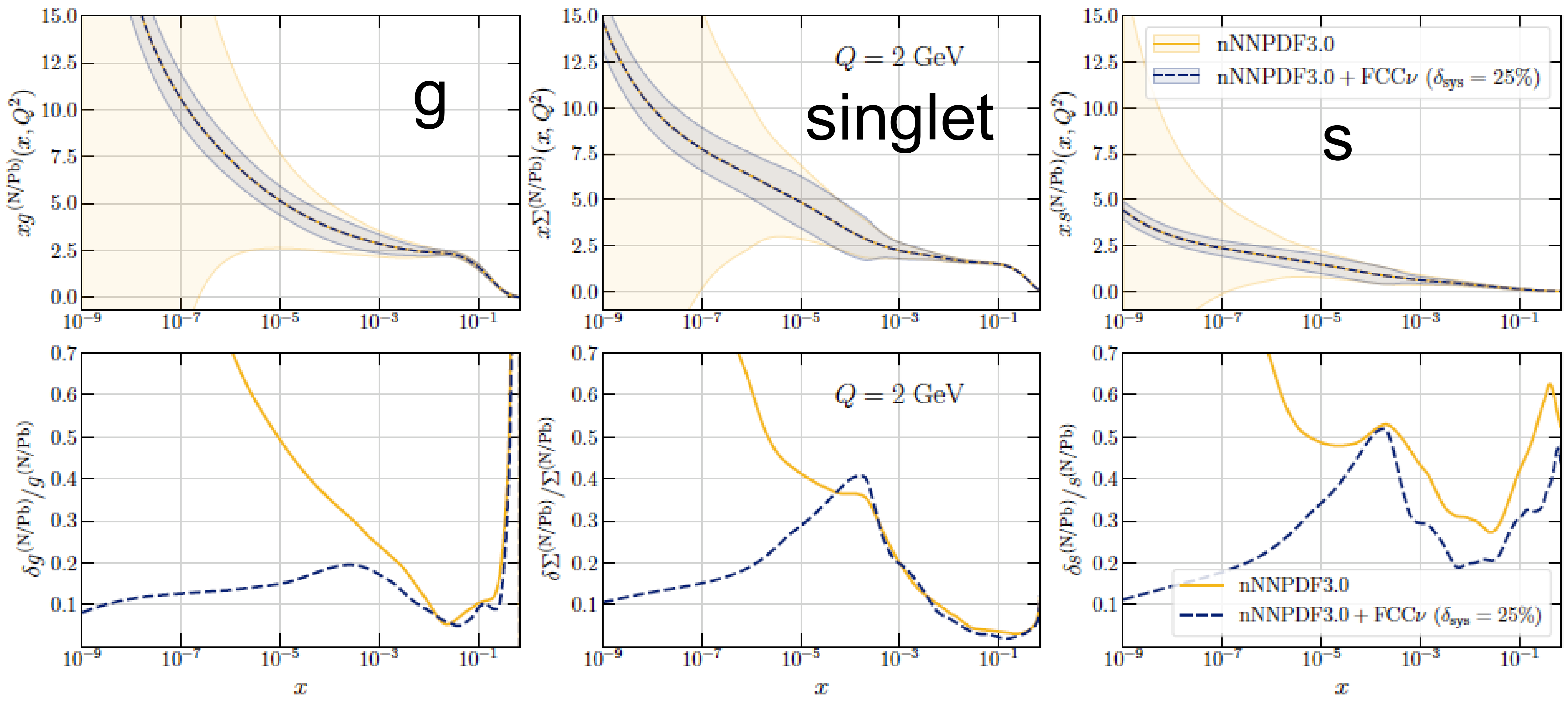
FCC-hh: W, Z, DY, jets and dijets, single and top pairs, isolated photons, D, B, quarkonia, light hadrons

FPF@FCC

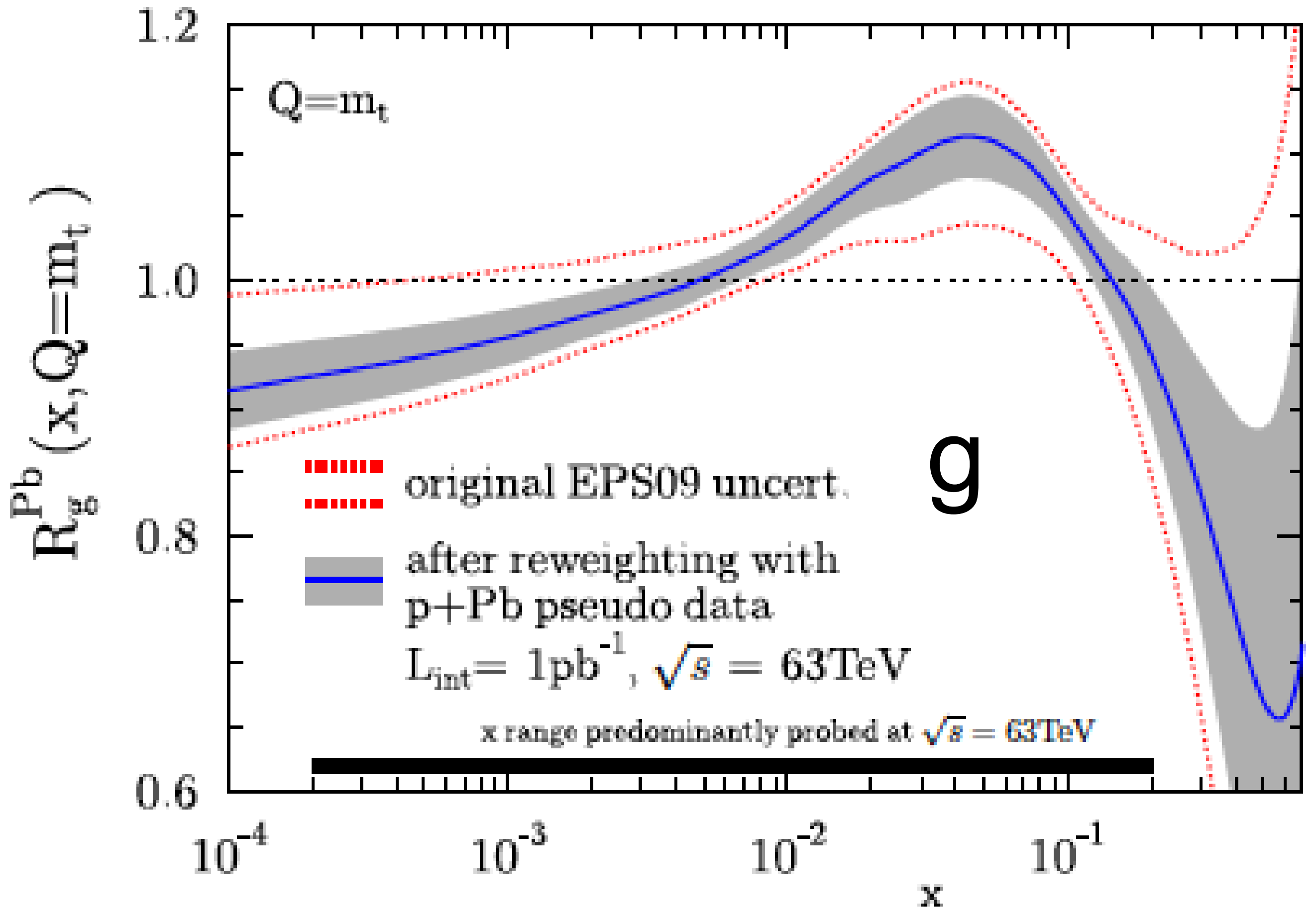



MuCol: NC ad CC DIS

# Kinematic planes for nuclei




2409.02163, **FPF@FCC**

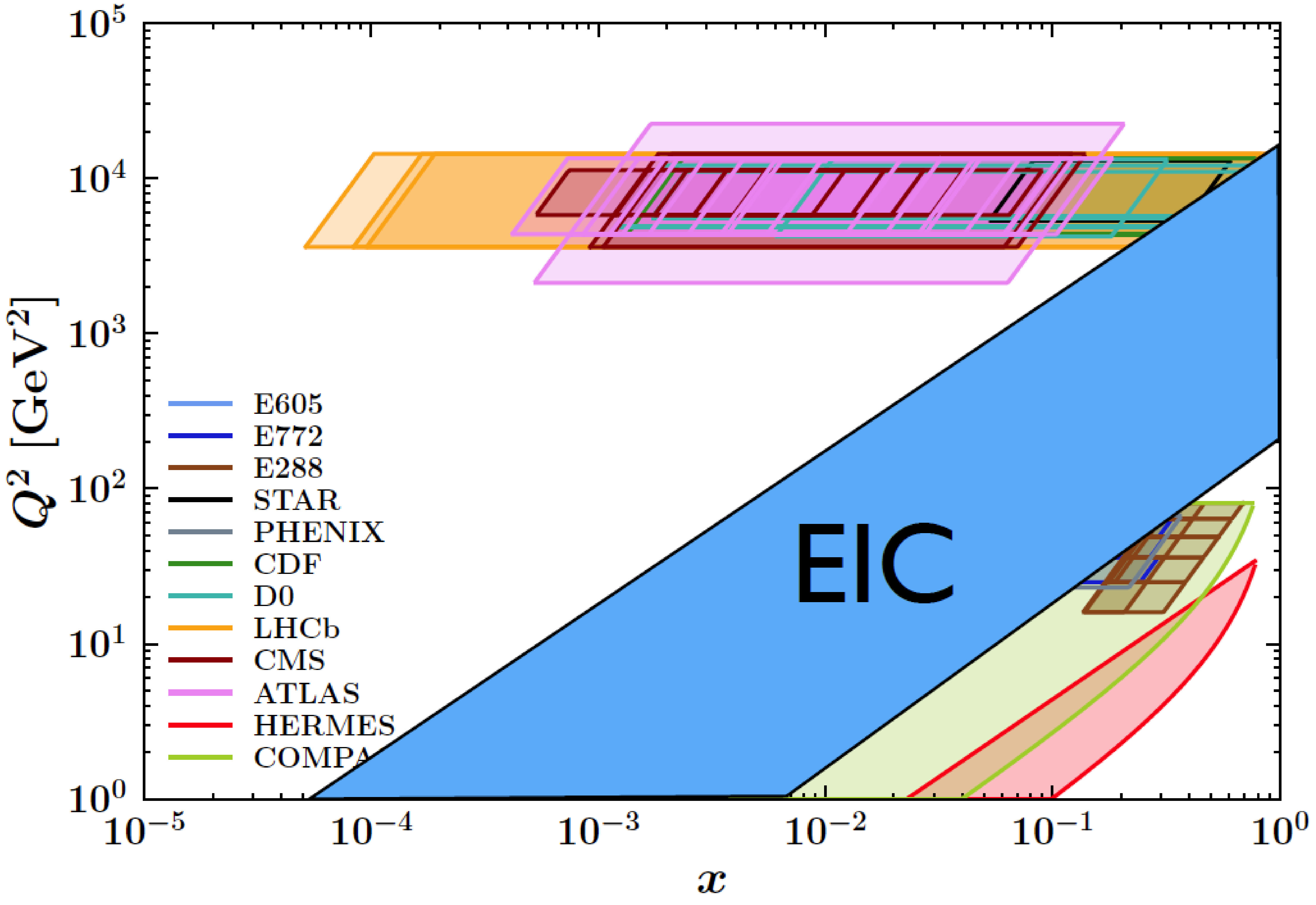



1501.05879, **FCC**, top

- Large impact from FPF@FCC, particularly at small x, and FCC.

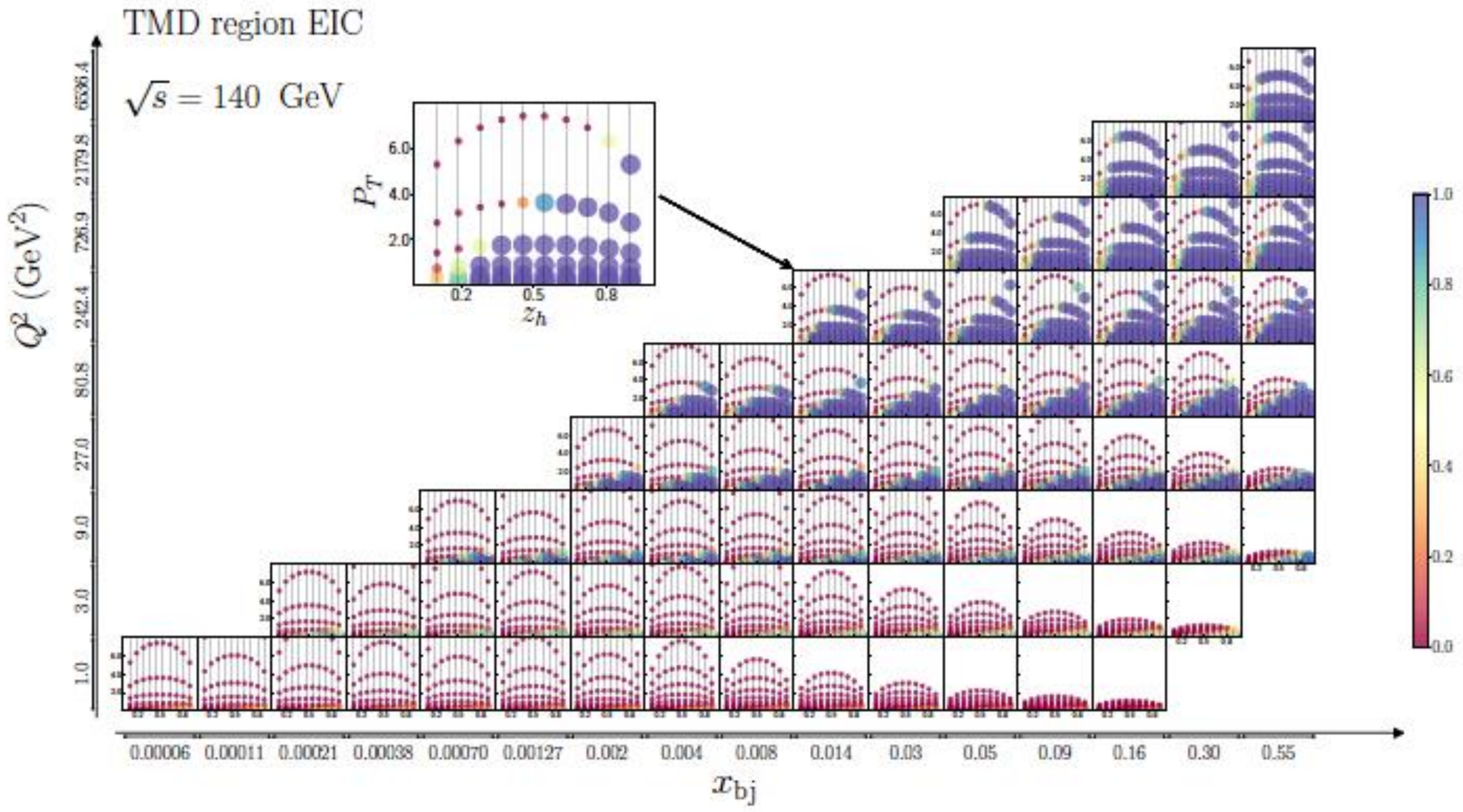
# TMDs: experimental prospects

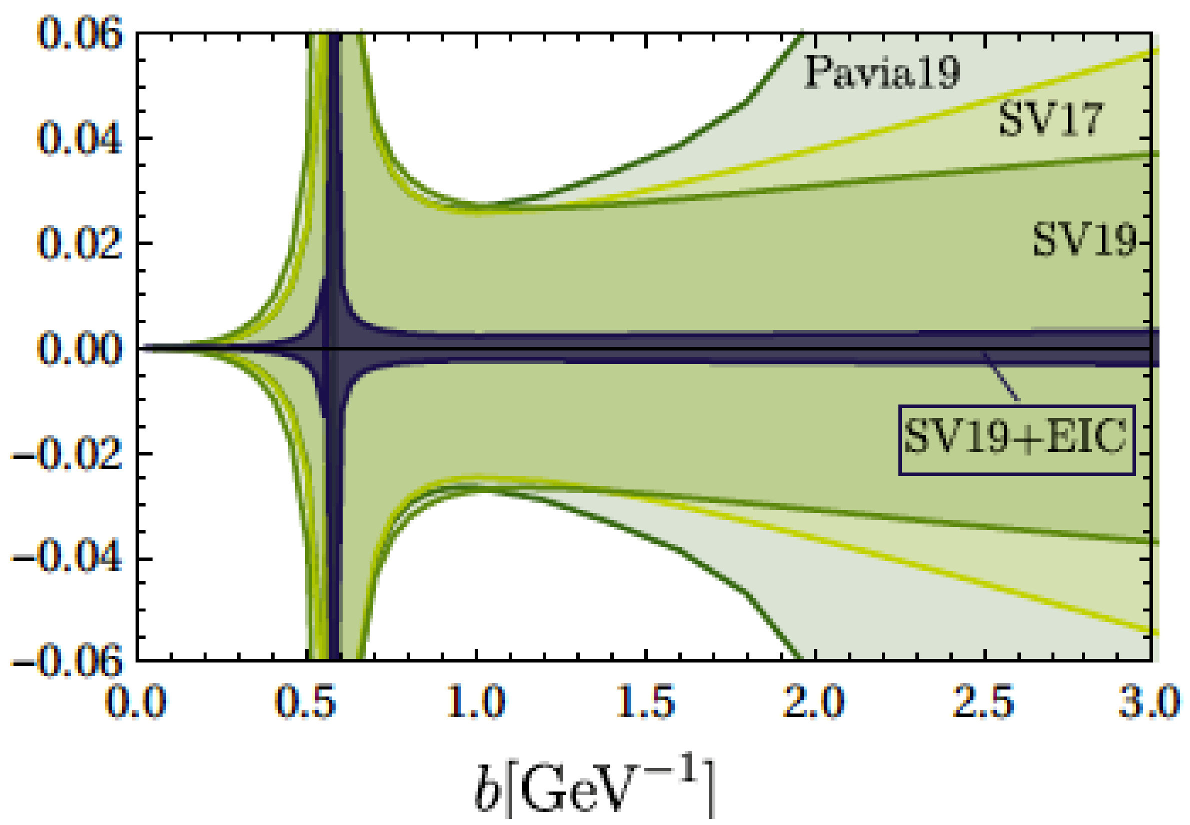
1601.01813



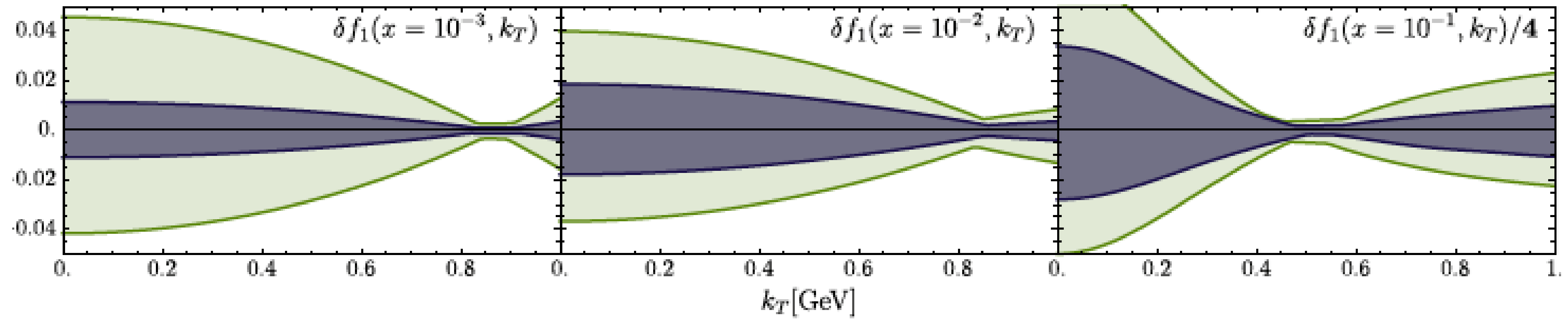

| | DIS & DY | SIDIS | $pA \to hX$ | $pA \to \gamma\,\mathrm{jet}\,X$ | Dijet in DIS | Dijet in $pA$ |
|---|---|---|---|---|---|---|
| $f_1^{g\,[+,+]}$ (WW) | × | × | × | × | √ | √ |
| $f_1^{g\,[+,-]}$ (DP) | √ | √ | √ | √ | × | √ |
| **Gluon unpol. and lin. pol. TMDs** | LHC, FCC-hh, EIC, LHeC | EIC, LHeC | LHC, FCC-hh | | EIC, LHeC | LHC, FCC-hh |

| | DIS & DY | SIDIS | $pA \to hX$ | $pA \to \gamma\,\mathrm{jet}\,X$ | Dijet in DIS | Dijet in $pA$ |
|---|---|---|---|---|---|---|
| $h_1^{\perp g\,[+,+]}$ (WW) | × | × | × | × | √ | √ |
| $h_1^{\perp g\,[+,-]}$ (DP) | × | × | × | × | × | √ |



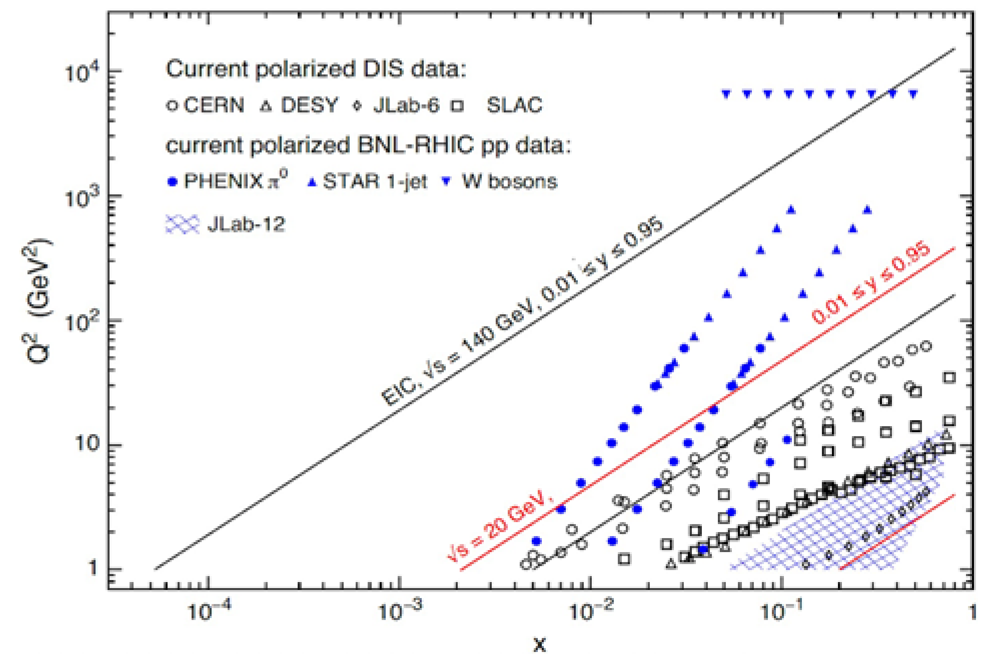




CS kernel, 2103.05419

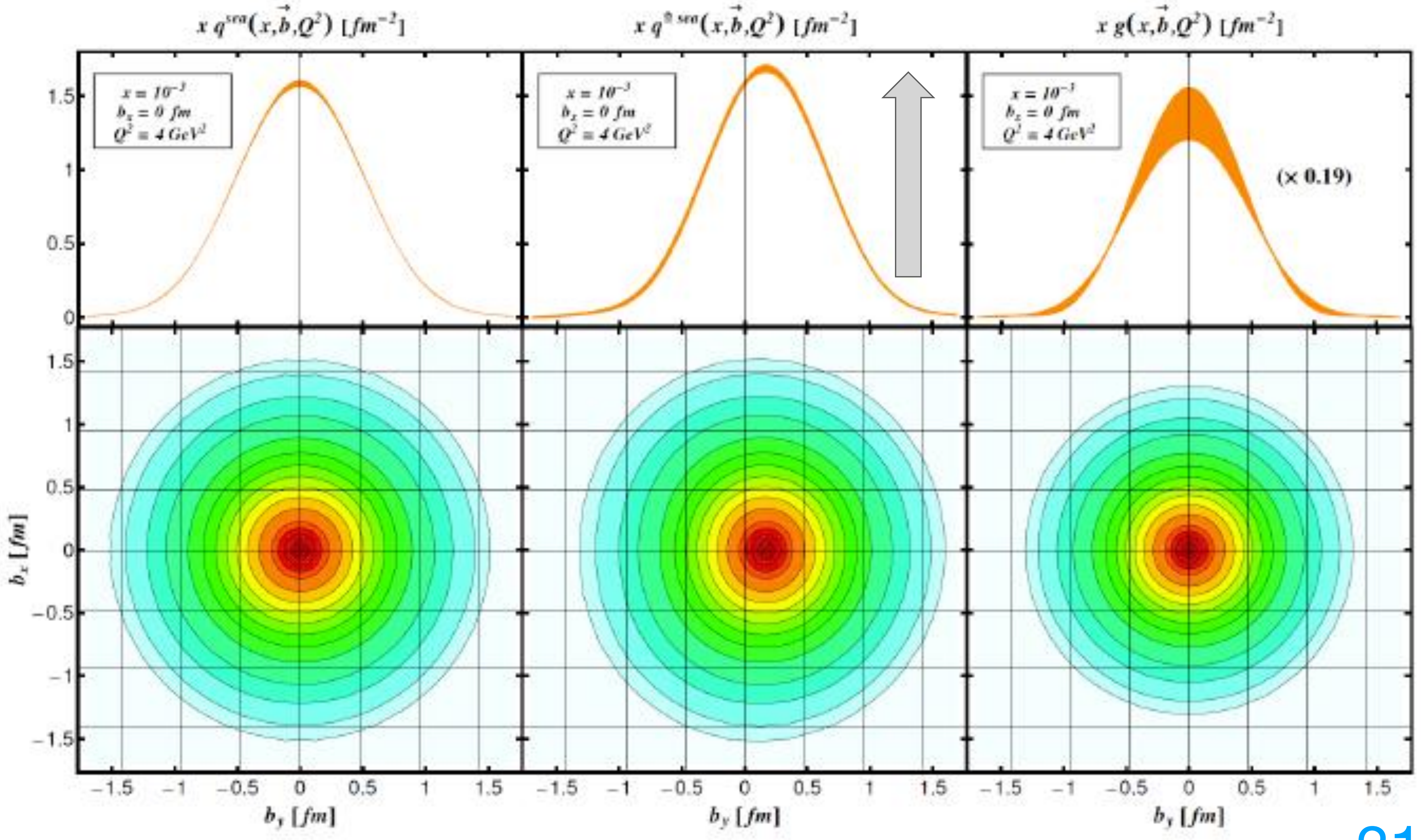



Quark TMD, SV19(+EIC), 2103.05419

# GPDs: experimental prospects

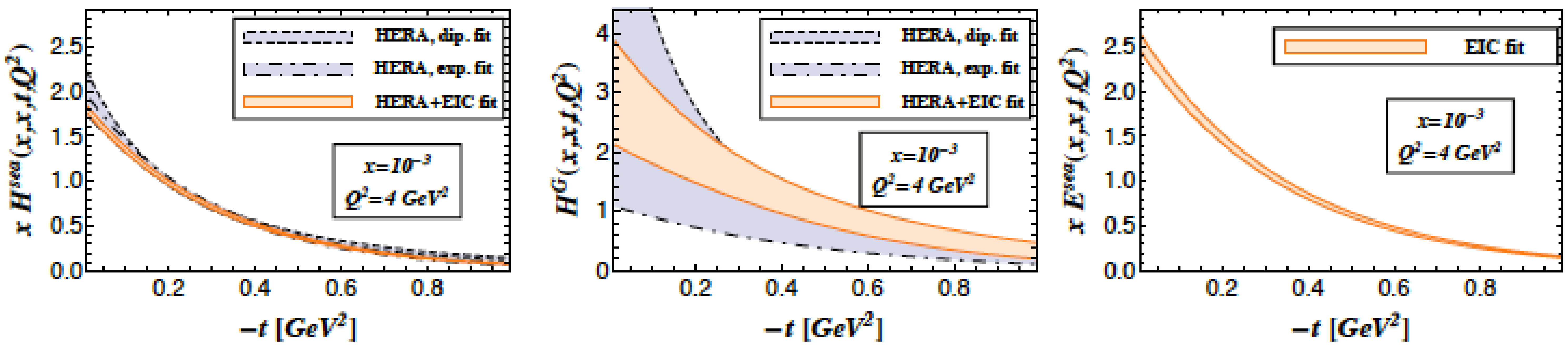



| Experiment<br>red = ESPP submissions | Observable | Access to |
|---|---|---|
| HL-LHC in collider and fixed-target mode | Exclusive quarkonium production and TCS in UPCs | Quark and gluon GPDs |
| LHCspin | TSSA in UPCs | |
| EIC | DVCS, exclusive VM production | Quark and gluon GPDs |
| LHeC | DVCS, exclusive VM production | Quark and gluon GPDs |
| FAIR | N+N⟶N+$\pi$(90$^0$)+B | Transition GPDs |
| Electron-Ion Collider in China | DVCS, DVMP | Quark and gluon GPDs |
| CLAS12 luminosity upgrade | Proton, neutron and nuclear DVCS, TCS, DVMP | Quark and gluon GPDs |
| SoLID | DVCS, TCS, DDVCS, exclusive meson production on polarised proton and nuclear targets | Quark and gluon GPDs |
| JLab22 | DVCS, … | Quark and gluon GPDs |

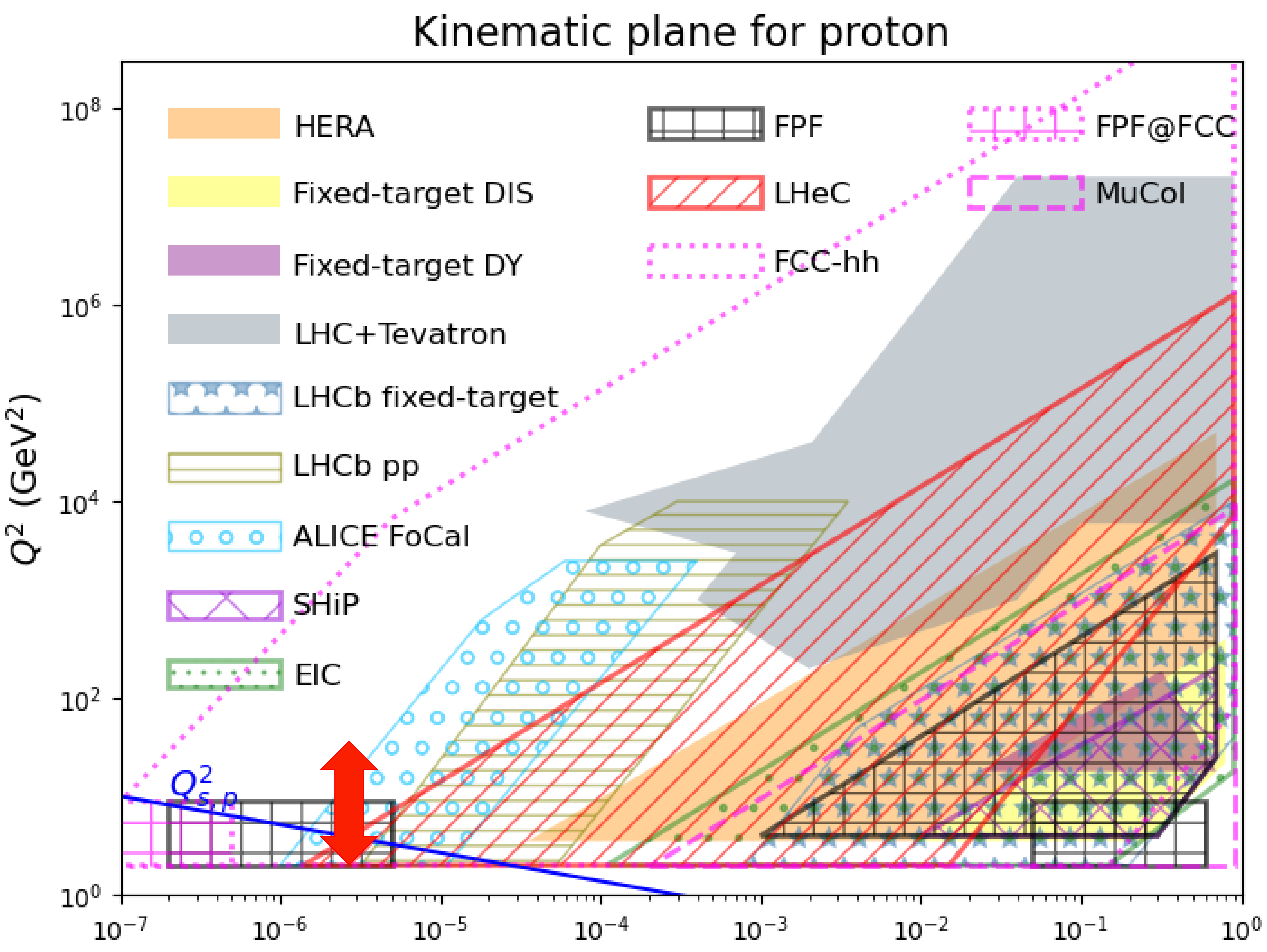


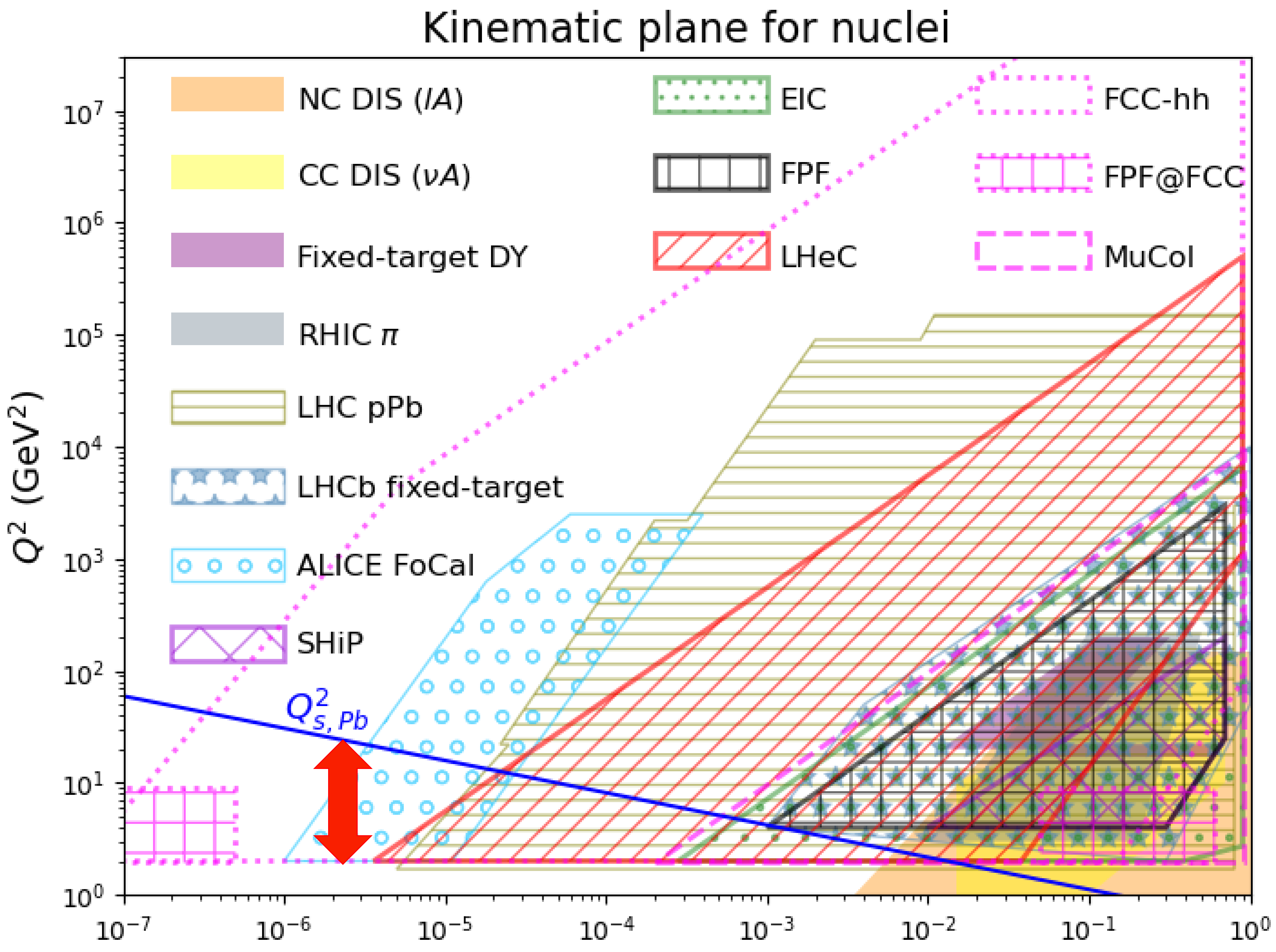

sea and g impact parameter distributions

2103.05419



# Small $x$: experimental prospects



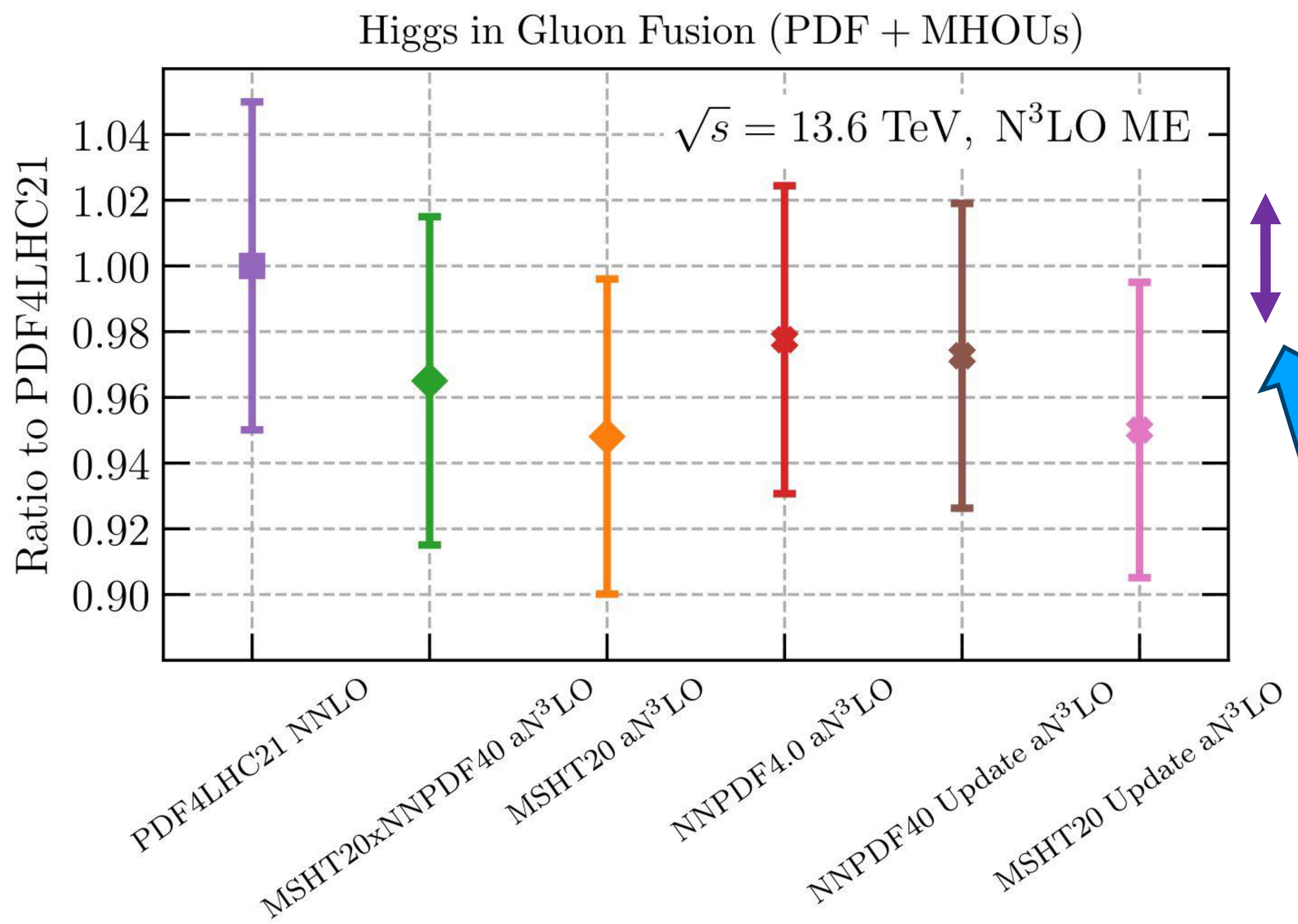




Saturation scale: GBW, scaled by $A^{1/3}$~6 for a Pb nucleus.

- **Plus:** PPS2 at CMS in the HL-LHC, diffractive observables at the EIC and LHeC, photon-photon at LEP3/FCC-ee/CEPC/LC,…

# Examples of effect on observables: Higgs

2411.05373



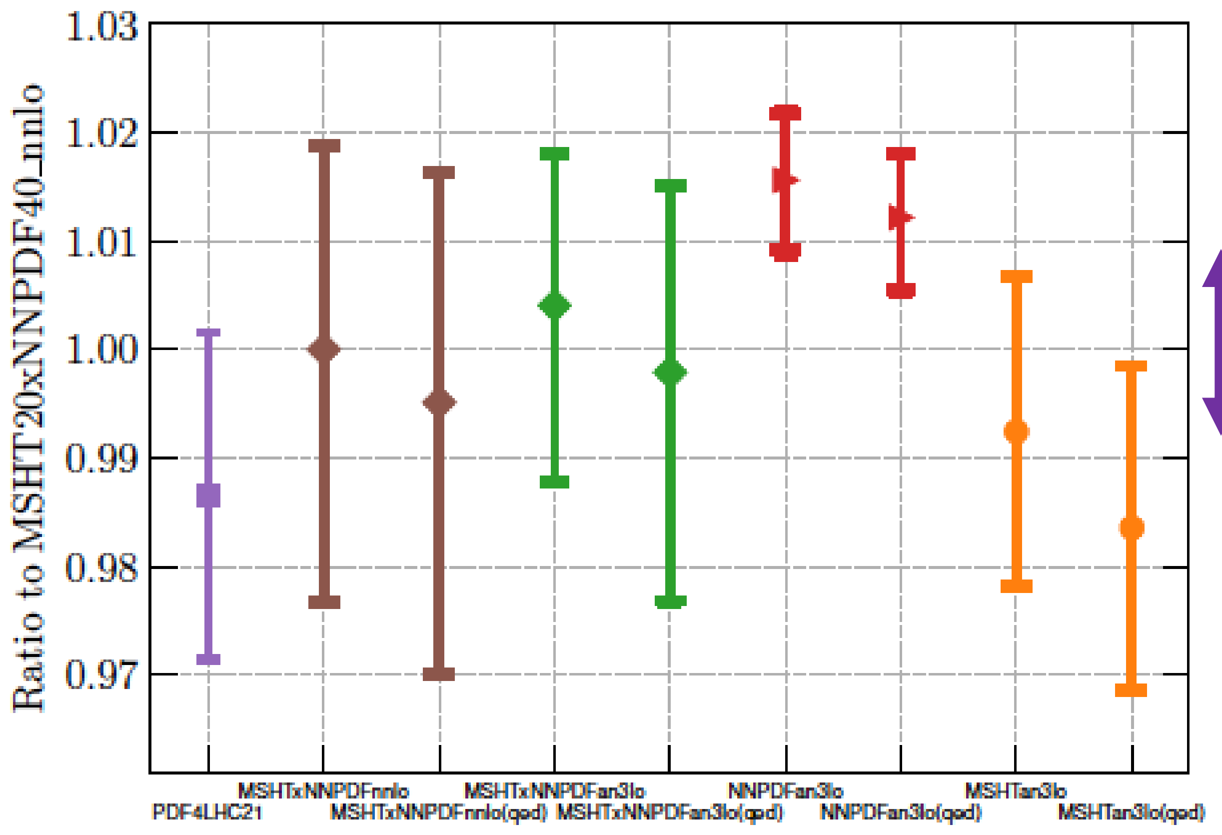

2309.11269, MSHT20+EIC total/PDF

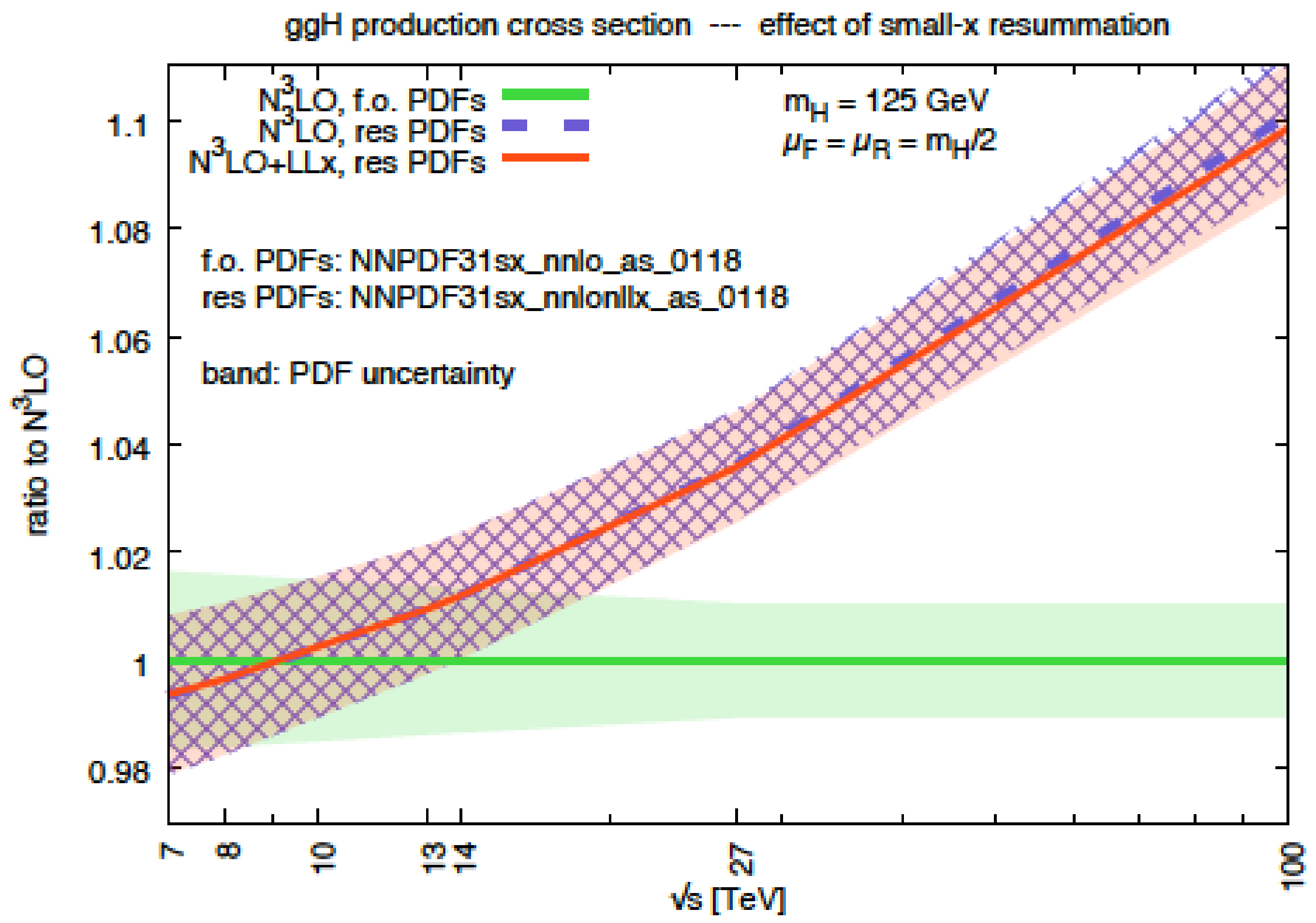
2503.17727, LHeC total/PDF+$\boldsymbol{\alpha}_s$

Higgs cross section at LHC: $gg \to H$ and HW$^+$ (VBF).

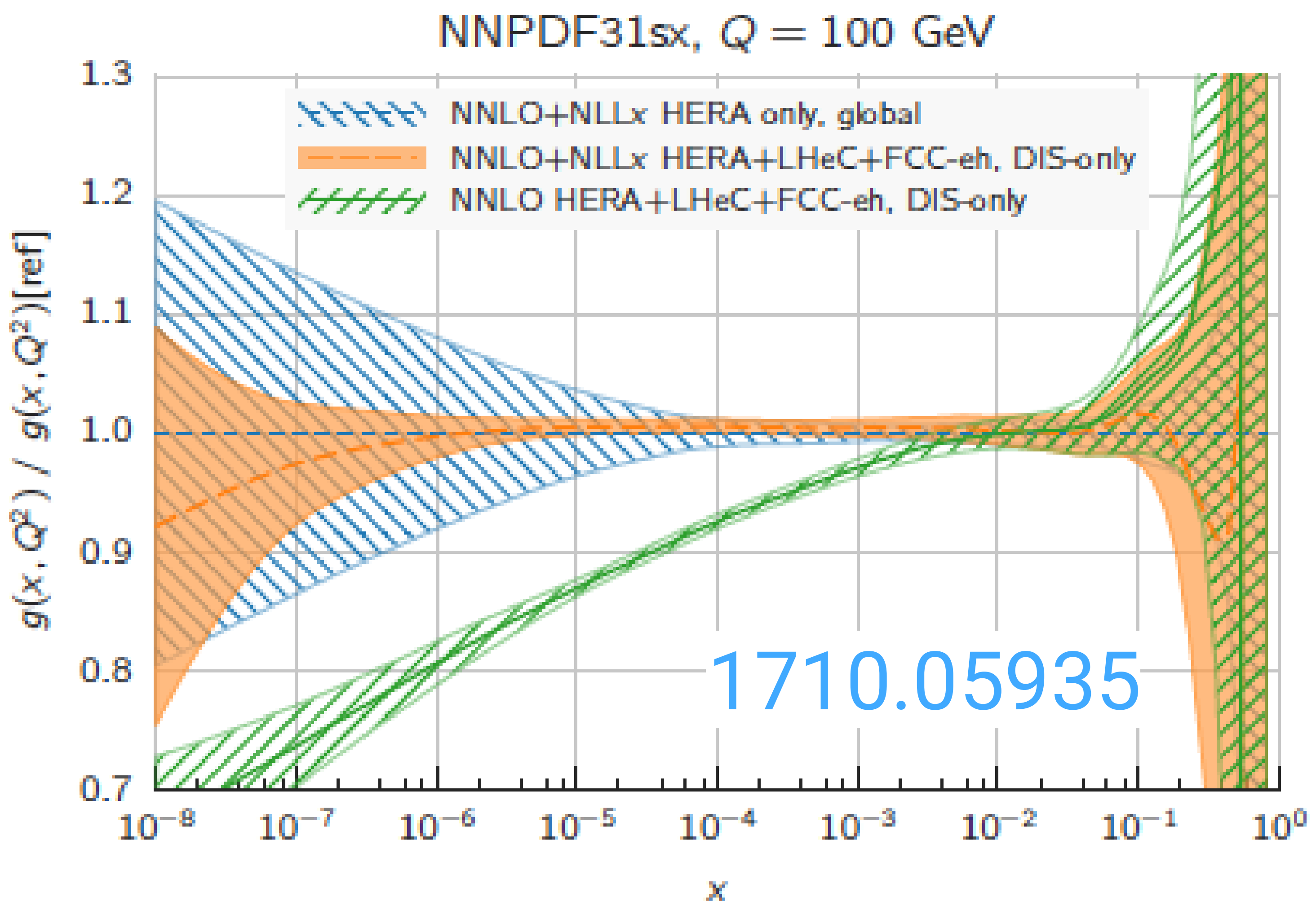
2411.05373

2503.19010, DIS@FPF (stat.)




1802.07758, effect of small-x resummation on $gg \to H$

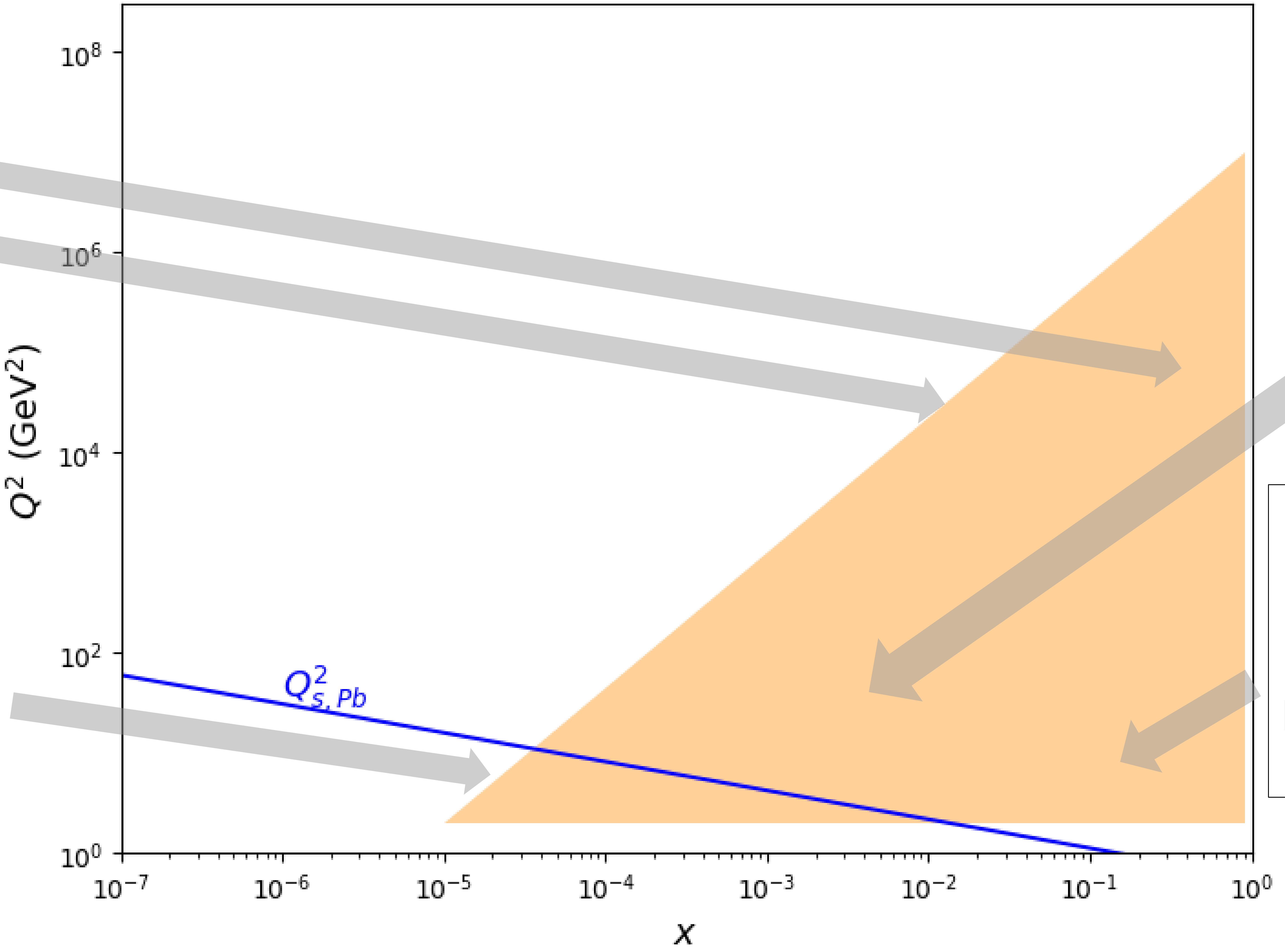



1710.05935

# Comparing different projects

HL-LHC collider
LHeC
FCC-hh

HL-LHC collider
ALICE FoCal
LHeC
FPF@FCC charm
FCC-hh




HL-LHC collider
EIC
FPF(@FCC) νDIS
LHeC
FCC-hh
MuCol

HL-LHC collider
LHCb fixed target
EIC
SHiP
FPF(@FCC) νDIS&charm
MuCol

**Dark green: Highest precision/breadth;** Light green: strong/focussed contributions.

# Comparing different projects

| **Quantity or question/ experiment** | **LHC in fixed target mode** D, B, quarkonium, light hadrons | **(HL-)LHC in collider mode** D, B, quarkonium, light hadrons, UPCs, DY | **ALICE FoCal** Photons, quarkonia and jets | **SHiP** $\nu$ flux from charm, NC and CC DIS | **EIC** NC, CC and jets in DIS, light and heavy flavour ID, exclusive diffraction | **FPF** $\nu$ flux from charm, NC and CC DIS | **LHeC** NC, CC and jets in DIS, heavy flavour ID, exclusive diffraction | **FCC-ee/ LEP3/ CEPC/LC** FFs of light and heavy quarks, jets, $\gamma\gamma$ | **MuCol** $\nu$ flux from muons | **FCC-hh** D, B, quarkonium, light hadrons, UPCs, DY |
|---|---|---|---|---|---|---|---|---|---|---|
| **PDFs** | | Most information available | Simultaneous fits of proton and nuclei | Simultaneous fits of proton and nuclei; $F_4$, $F_5$ | Covered by HERA | Simultaneous fits of proton and nuclei; $F_4$, $F_5$ | | | Simultaneous fits of proton and nuclei | Kinematic reach |
| **nPDFs** | | Most information available | Region overlapping with current pPb | | | | | | | Kinematic reach |
| **TMDs** | | DY, jets | Little PID | | | | Little PID in current project | FFs needed for PDFs, and TMD in jets | | DY, jets |
| **GPDs** | | Currently UPCs | | | | | | | | Currently UPCs |
| **Small-*x* dynamics** | Large x needed for small x | | | Large x needed for small x | Kinematic reach | Kinermatic reach | | $\gamma\gamma$ | Large x needed for small x | |

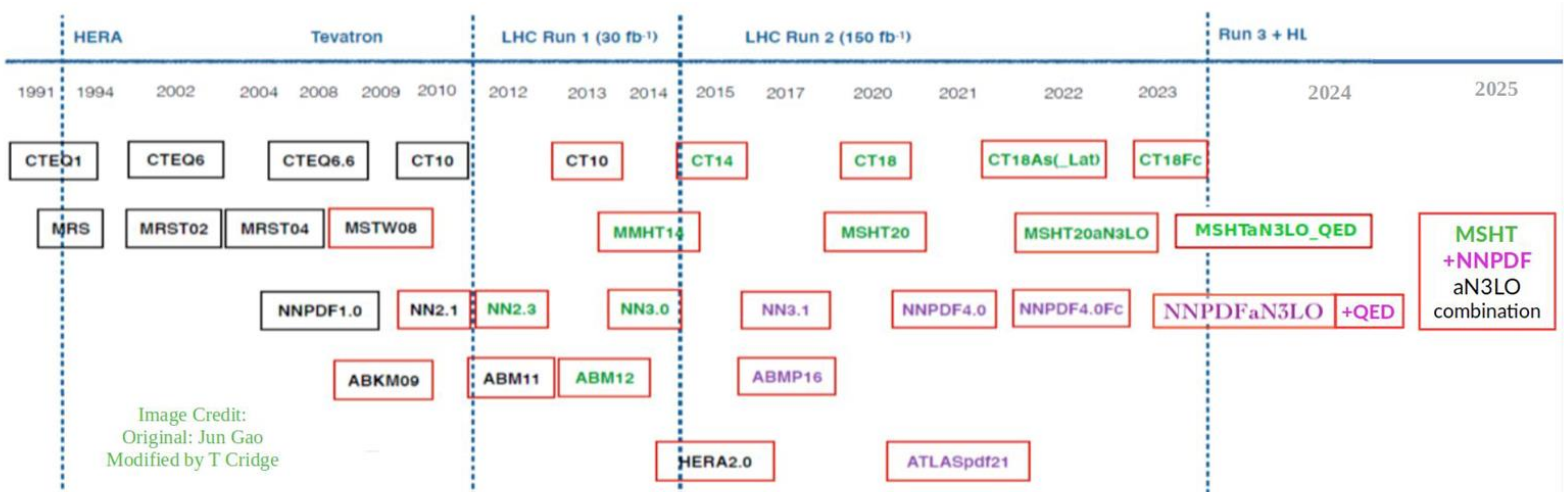
**Dark green: Highest precision/breadth;** Light green: strong/focussed contributions; White: no contribution.

Many thanks to the WG members, and to Constantia Alexandrou, Valerio Bertone, Tom Cridge, Abraham Gallas, Maria Vittoria Garzelli, Claire Gwenlan, Francesco Hautmann, Charlotte van Hulse, Florian Jonas, Marco Van Leeuwen, Heikki Mäntysaari, Saverio Mariani, Pavel Nadolsky, Hannu Paukkunen, Peter Petreczky, Juan Rojo, Paweł Sznajder, Robert Thorne, Maria Ubiali, María Vieites,…, for information and comments.

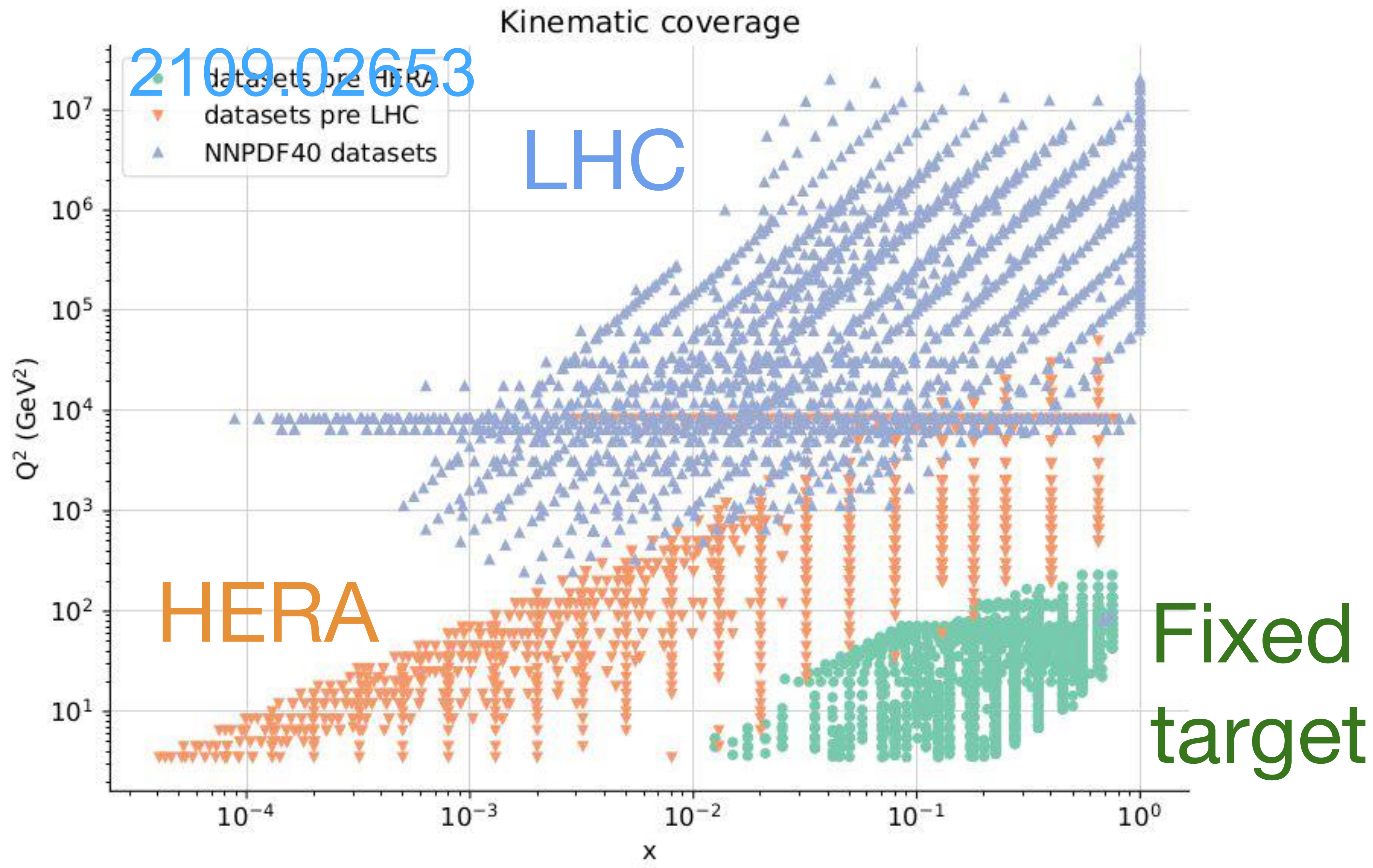
Thank you very much for your attention!!!

# Backup

# Proton collinear PDFs: state-of-the-art



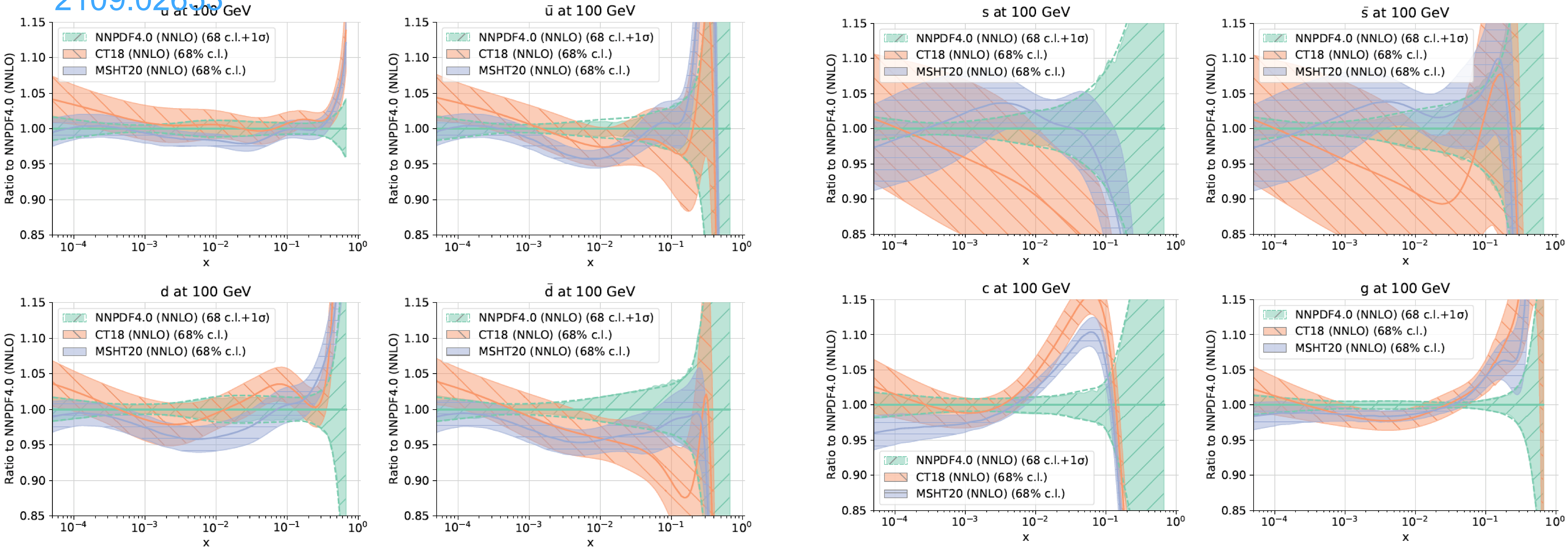

- Methodology: complex error analysis (CT, MSHT, NNPDF; HERAPDF, ABMP).
- Theory: approximate N3LO QCD PDFs + QED (MSHT, NNPDF); theoretical uncertainties from missing higher orders (MHOUs).




- Data - $\mathcal{O}$(5000) data points, complementarity:
  - HERA - valence quarks, some sea, low x gluon.
  - Fixed target (and others) - flavour decomposition.
  - LHC - sea quarks, flavour decomposition, medium-large x gluon.

# Proton collinear PDFs: state-of-the-art

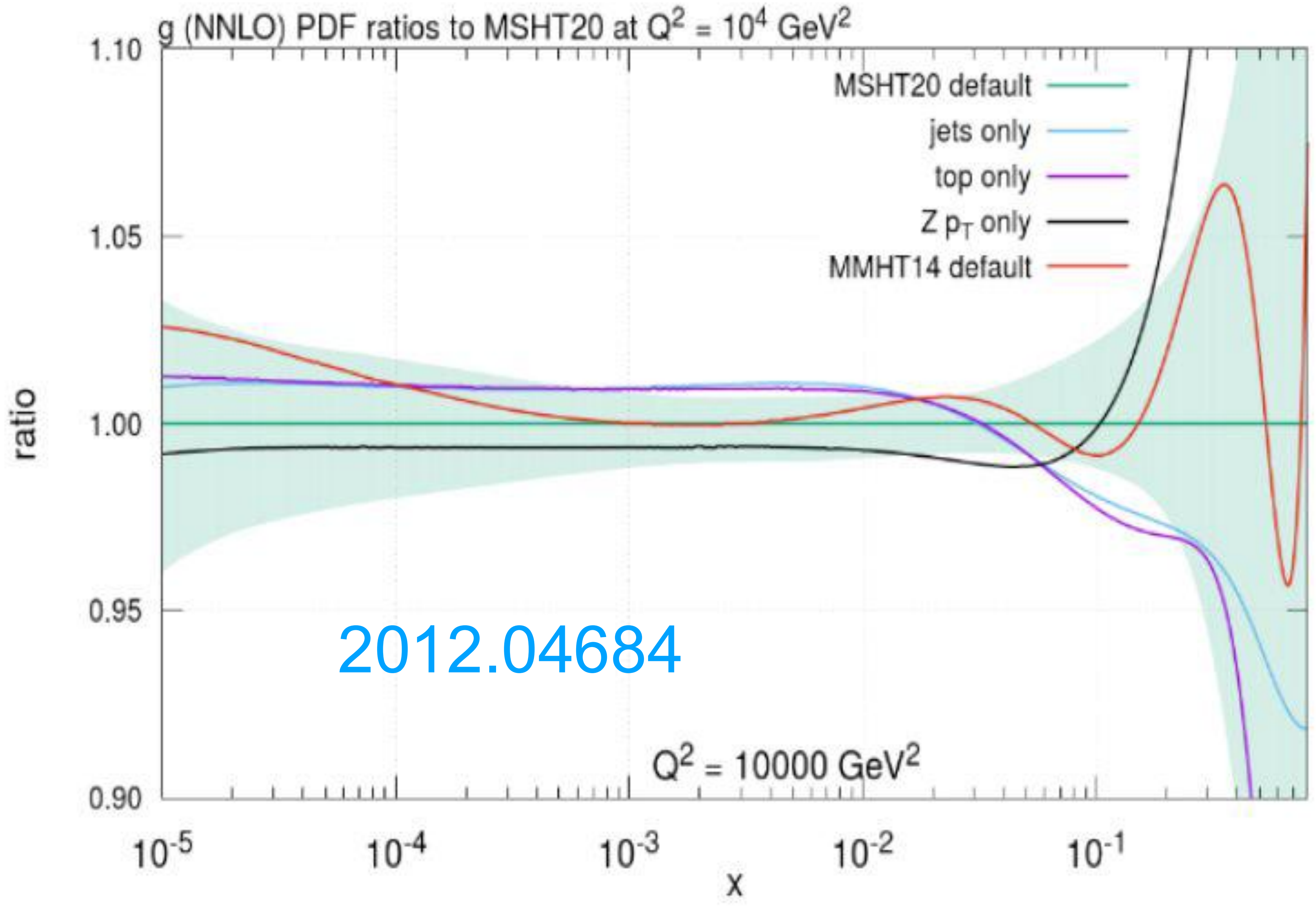
2109.02653



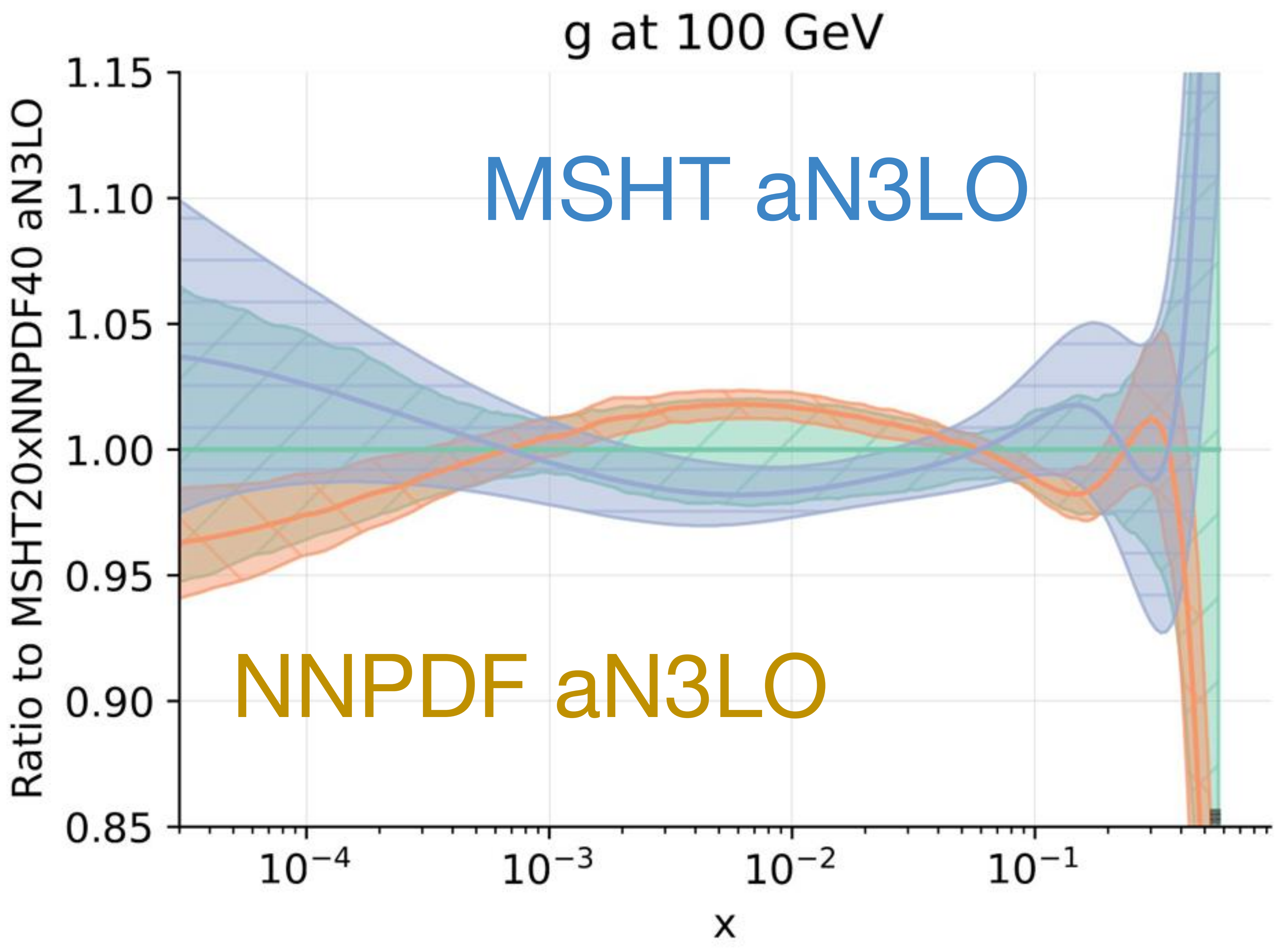

- Huge efforts to understand the differences between different sets, combination PDF4LHC21 available.

# Proton collinear PDFs: state-of-the-art

- Challenges:
  - Data: tension between datasets, need of information about systematics.
  - Parametrisation biases/different methodology & uncertainty estimation: closure tests.
  - How the PDF sets absorb experimental and theoretical inconsistencies.
  - Missing higher orders: nuisance parameters, or inclusion of higher orders: aN3LO QCD + QED, two sets available and combined.




2207.04739,
2402.18635



# Proton collinear PDFs: precision physics

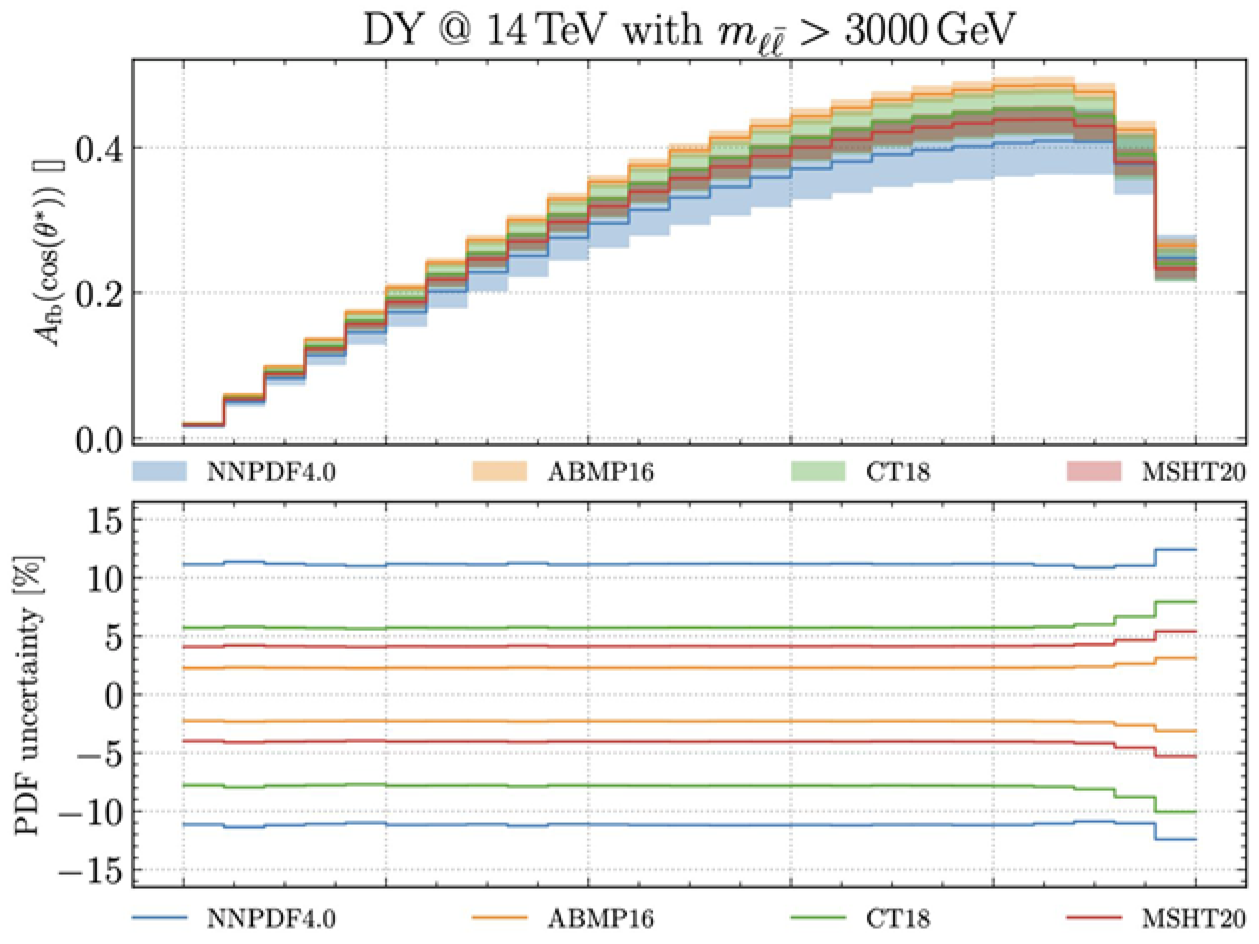
2411.05373, 2312.07665, 2406.01779, 2203.05506

- PDFs essential for precision physics studies:
  - Dominant uncertainty of many SM parameters: ATLAS $\boldsymbol{\alpha}_s$ (0.0005/0.0009), CMS $M_W$ (4.4/9.9 MeV) and $\sin^2\theta_W$ (0.0027/0.0031).
  - Differences between PDF sets, profiling delicate, simultaneous PDF+SM parameter fits.

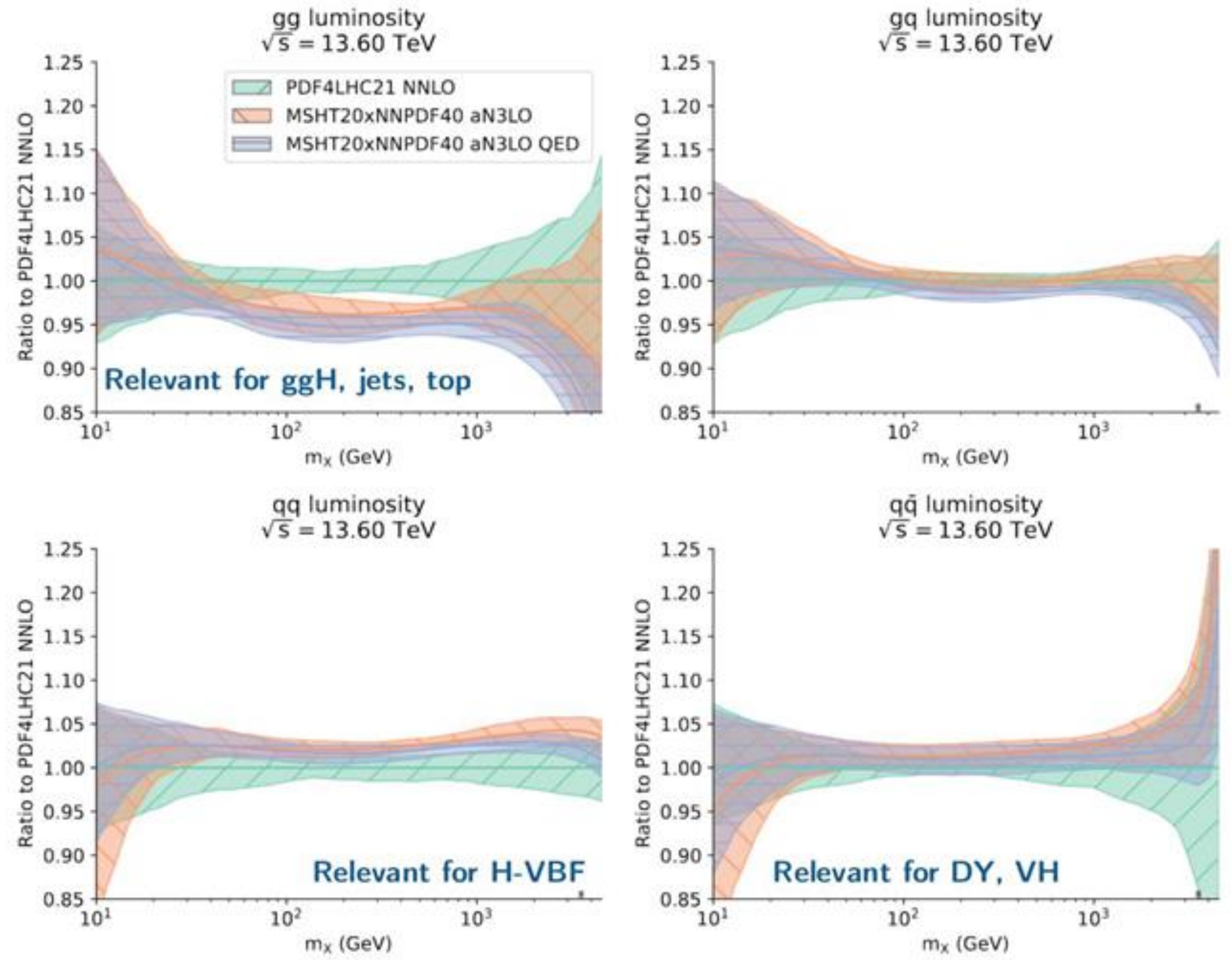
$$\alpha_{S,\mathrm{aN3LO}}(M_Z^2) = 0.1170 \pm 0.0016$$ Consistent with (NNLO) World Average of $0.1180 \pm 0.0009$.

2404.02964

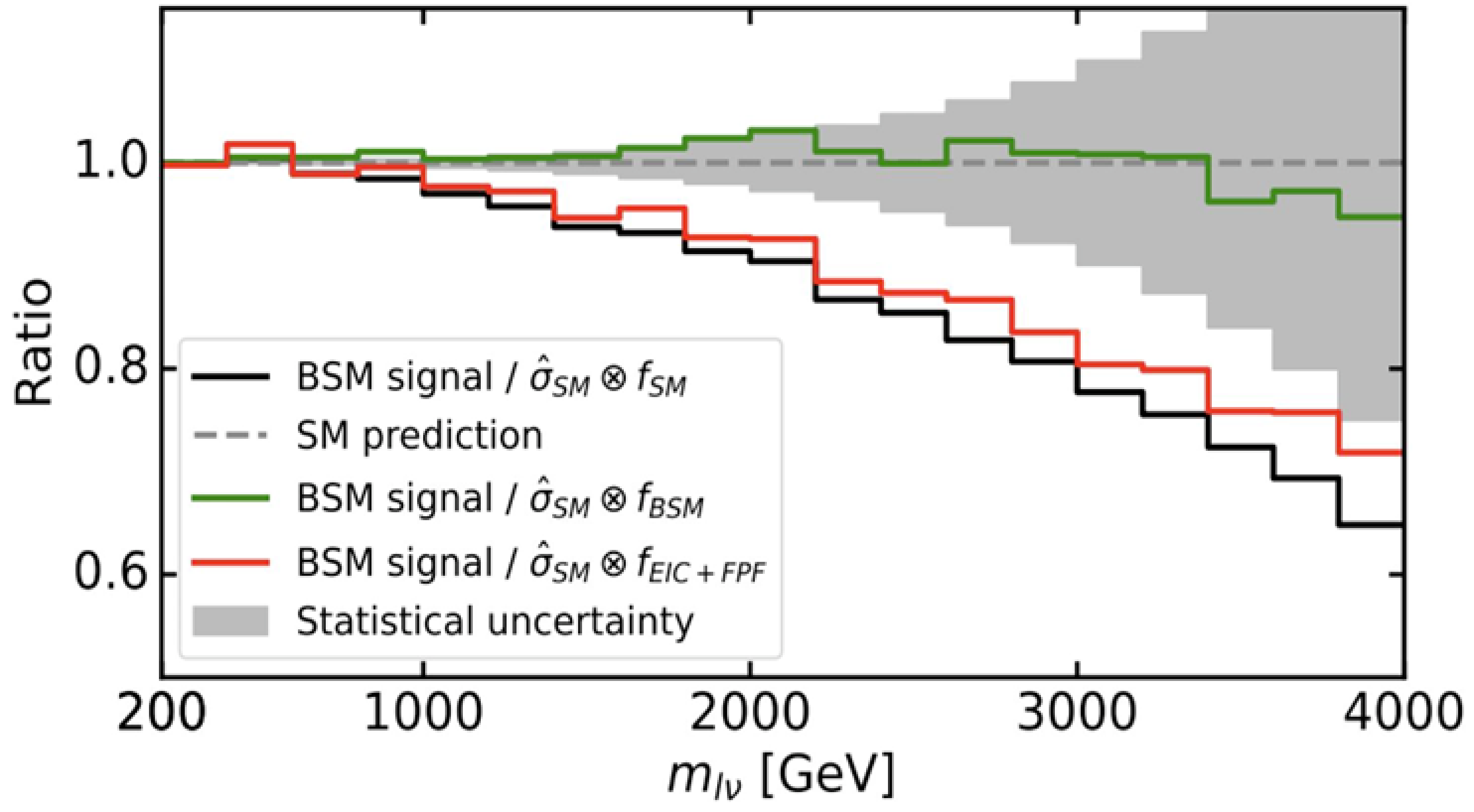
- High mass region dominated by large x partons: sizable uncertainties, BSM can be hidden in PDF uncertainties.

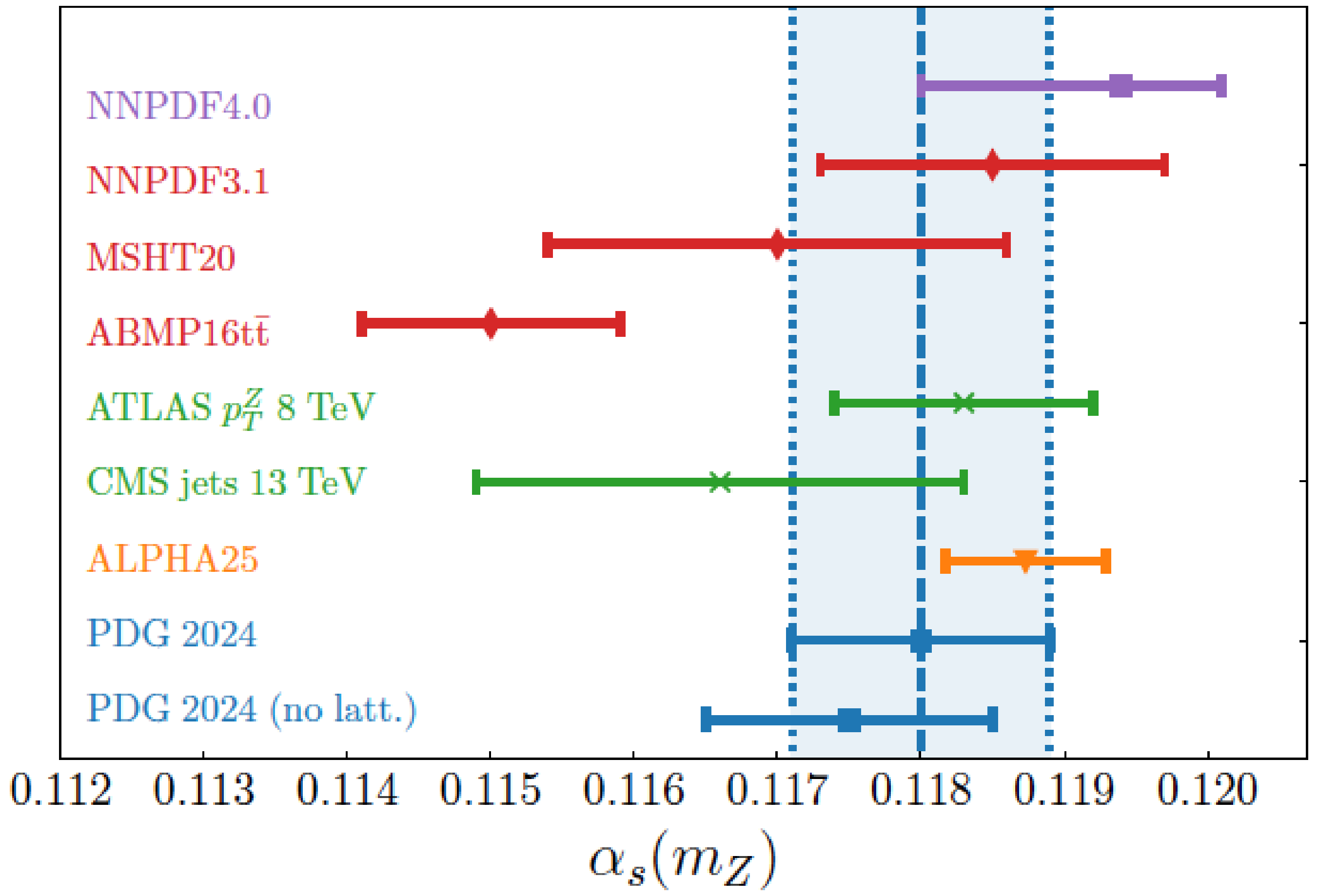



2209.08115




W' 2410.00963




2506.13871

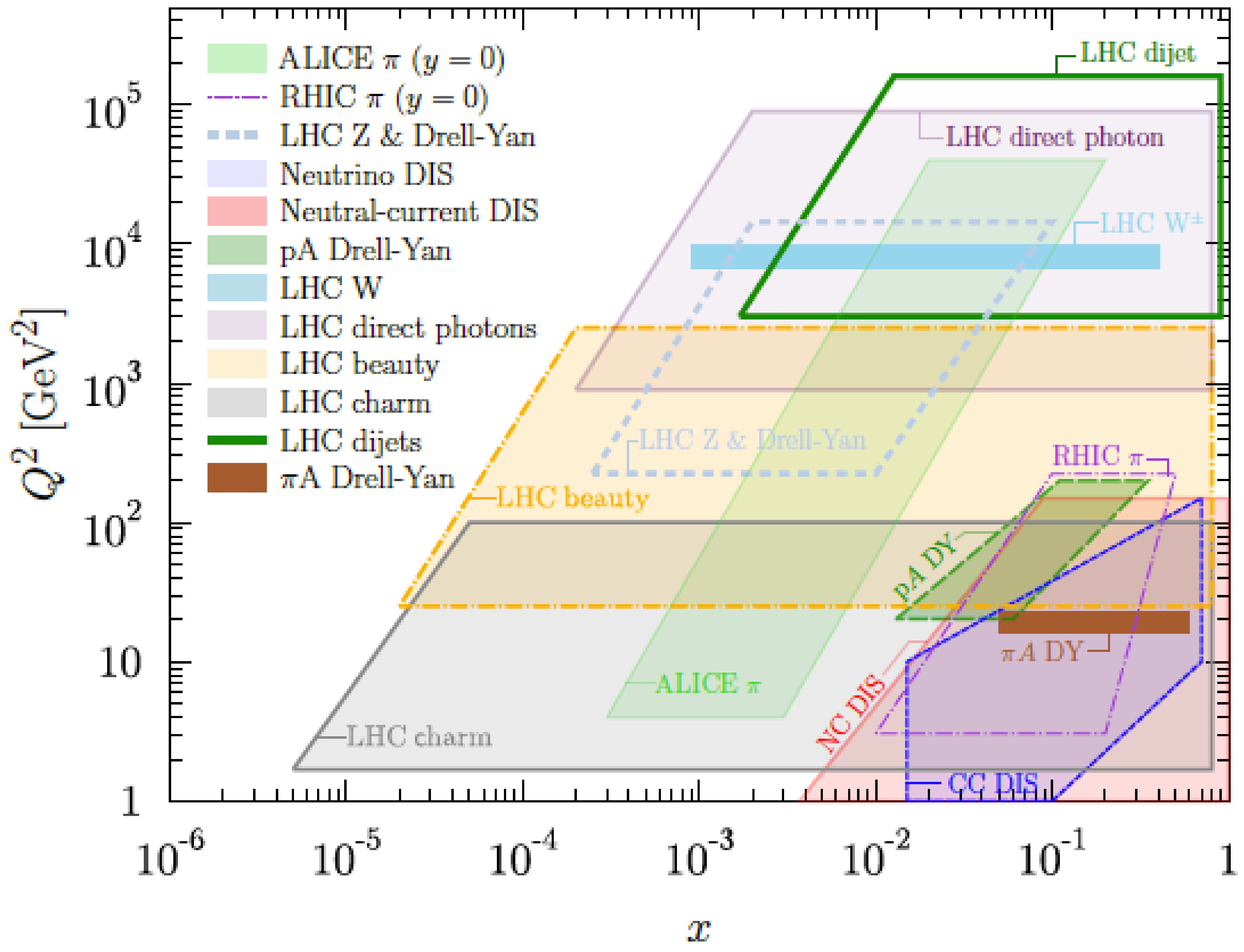
# Nuclear collinear PDFs: state-of-the-art

| Analysis | nCTEQ15HQ (50) | EPPS21 (51) | nNNPDF3.0 (52) | TUJU21 (80) | KSASG20 (81) |
|---|---|---|---|---|---|
| **Theoretical input:** | | | | | |
| Perturbative order | NLO | NLO | NLO | NNLO | NNLO |
| Heavy-quark scheme | SACOT$-\chi$ | SACOT$-\chi$ | FONLL | FONLL | FONLL |
| Value of $\alpha_s(M_Z)$ | 0.118 | 0.118 | 0.118 | 0.118 | 0.118 |
| Charm mass $m_c$ | 1.3 GeV | 1.3 GeV | 1.51 GeV | 1.43 GeV | 1.3 GeV |
| Bottom mass $m_b$ | 4.5 GeV | 4.75 GeV | 4.92 GeV | 4.5 GeV | 4.75 GeV |
| Input scale $Q_0$ | 1.3 GeV | 1.3 GeV | 1.0 GeV | 1.3 GeV | 1.3 GeV |
| Data points | 1484 | 2077 | 2188 | 2410 | 4353 |
| Independent flavors | 5 | 6 | 6 | 4 | 3 |
| Parameterization | Analytic | Analytic | Neural network | Analytic | Analytic |
| Free parameters | 19 | 24 | 256 | 16 | 18 |
| Error analysis | Hessian | Hessian | Monte Carlo | Hessian | Hessian |
| Tolerance | $\Delta\chi^2 = 35$ | $\Delta\chi^2 = 33$ | N/A | $\Delta\chi^2 = 50$ | $\Delta\chi^2 = 20$ |
| Proton PDF | ~CTEQ6.1 | CT18A | ~NNPDF4.0 | ~HERAPDF2.0 | CT18 |
| Proton PDF correlations | | ✓ | ✓ | | |
| Deuteron corrections | $(\checkmark)^{a,b}$ | $\checkmark^{c}$ | ✓ | ✓ | ✓ |
| **Fixed-target data:** | | | | | |
| SLAC/EMC/NMC NC DIS | ✓ | ✓ | ✓ | ✓ | ✓ |
| – Cut on $Q^2$ | 4 GeV$^2$ | 1.69 GeV$^2$ | 3.5 GeV$^2$ | 3.5 GeV$^2$ | 1.2 GeV$^2$ |
| – Cut on $W^2$ | 12.25 GeV$^2$ | 3.24 GeV$^2$ | 12.5 GeV$^2$ | 12.0 GeV$^2$ | |
| JLab NC DIS | $(\checkmark)^{a}$ | ✓ | | | ✓ |
| CHORUS/CDHSW CC DIS | $(\checkmark/\text{-})^{b}$ | ✓/- | ✓/- | ✓/✓ | ✓/✓ |
| NuTeV/CCFR 2$\mu$ CC DIS | $(\checkmark/\checkmark)^{b}$ | | ✓/- | | |
| $pA$ DY | ✓ | ✓ | ✓ | | ✓ |
| $\pi A$ DY | | ✓ | | | |
| **Collider data:** | | | | | |
| $Z$ bosons | ✓ | ✓ | ✓ | ✓ | |
| $W^\pm$ bosons | ✓ | ✓ | ✓ | ✓ | |
| Light hadrons | ✓ | $\checkmark^{d}$ | | | |
| – Cut on $p_T$ | 3 GeV | 3 GeV | | | |
| Jets | | ✓ | ✓ | | |
| Prompt photons | | | ✓ | | |
| Prompt D$^0$ | ✓ | ✓ | $\checkmark^{e}$ | | |
| – Cut on $p_T$ | 3 GeV | 3 GeV | 0 GeV | | |
| Quarkonia ($J/\psi$, $\psi'$, $\Upsilon$) | ✓ | | | | |

[a] nCTEQ15HIX (26); [b] nCTEQ15$\nu$ (114); [c] through CT18A; [d] only $\pi^0$ in DAu; [e] only forward ($y > 0$).

2311.00450

- Methodology: complex error analysis (nCTEQ, EPPS, nNNPDF, TUJU, KSASG).
- Theory: NLO/NNLO.
- Data - $\mathcal{O}(2000)$ data points, complementarity between data sets.

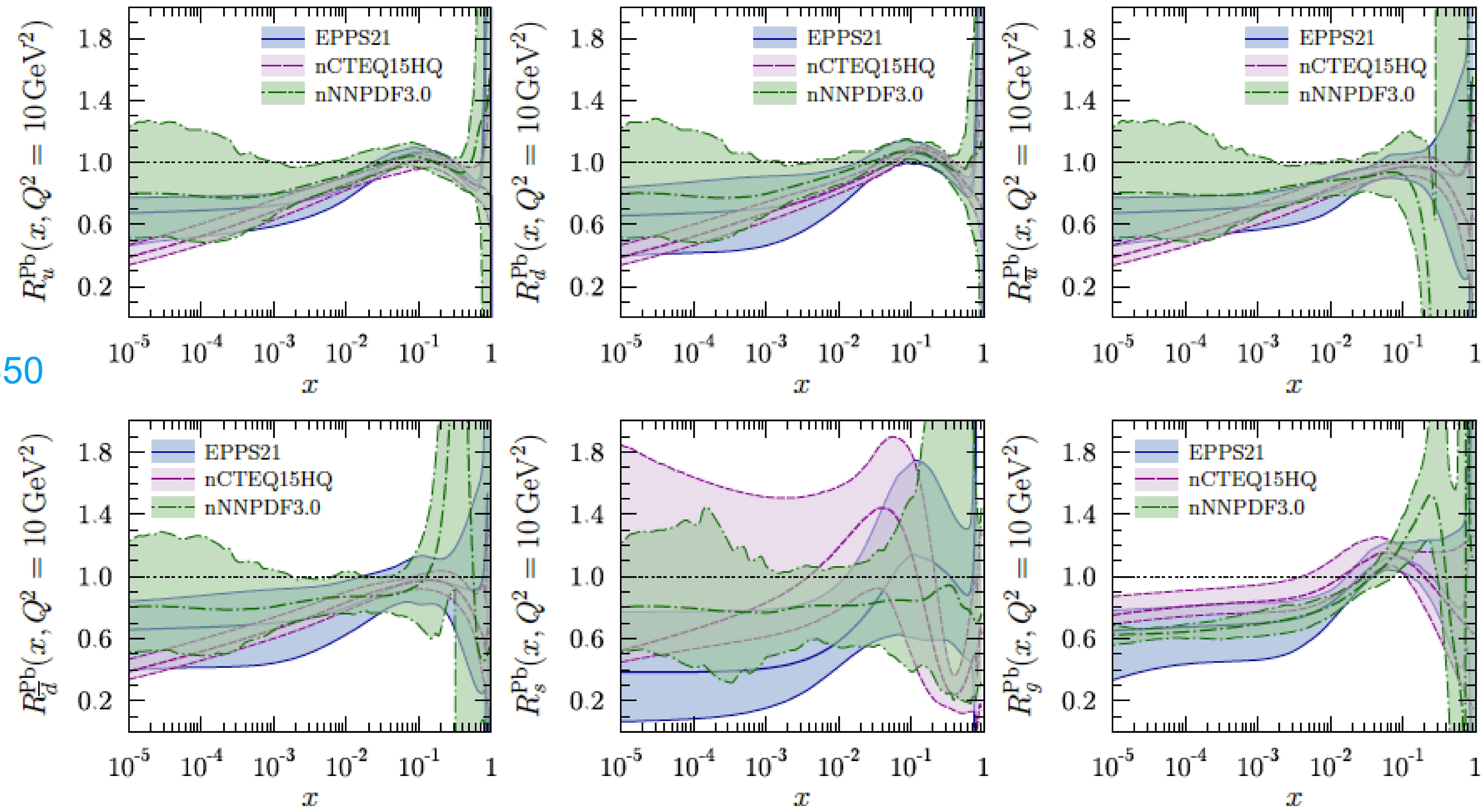





N. Armesto, June 23rd 2025

# Nuclear collinear PDFs: state-of-the-art

2311.00450



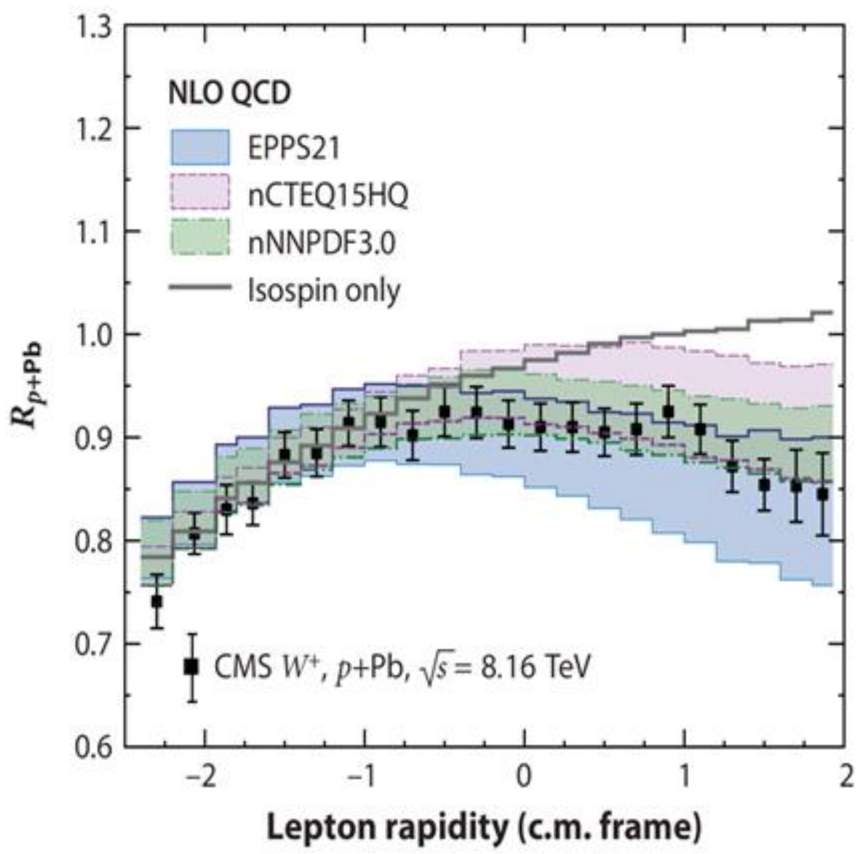

$$f^{\mathrm{Pb}}(x, Q^2)/[Z f^{\mathrm{proton}}(x, Q^2) + N f^{\mathrm{neutron}}(x, Q^2)]$$

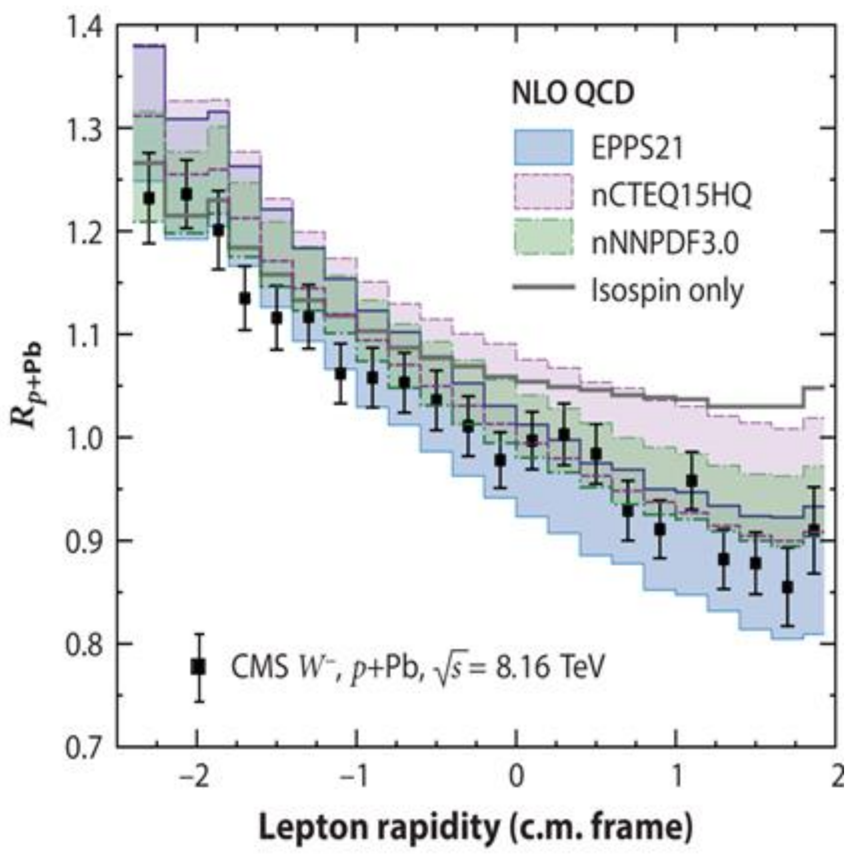
- Sizeable differences up to a factor 2, within uncertainties.

# Nuclear collinear PDFs: LHC data

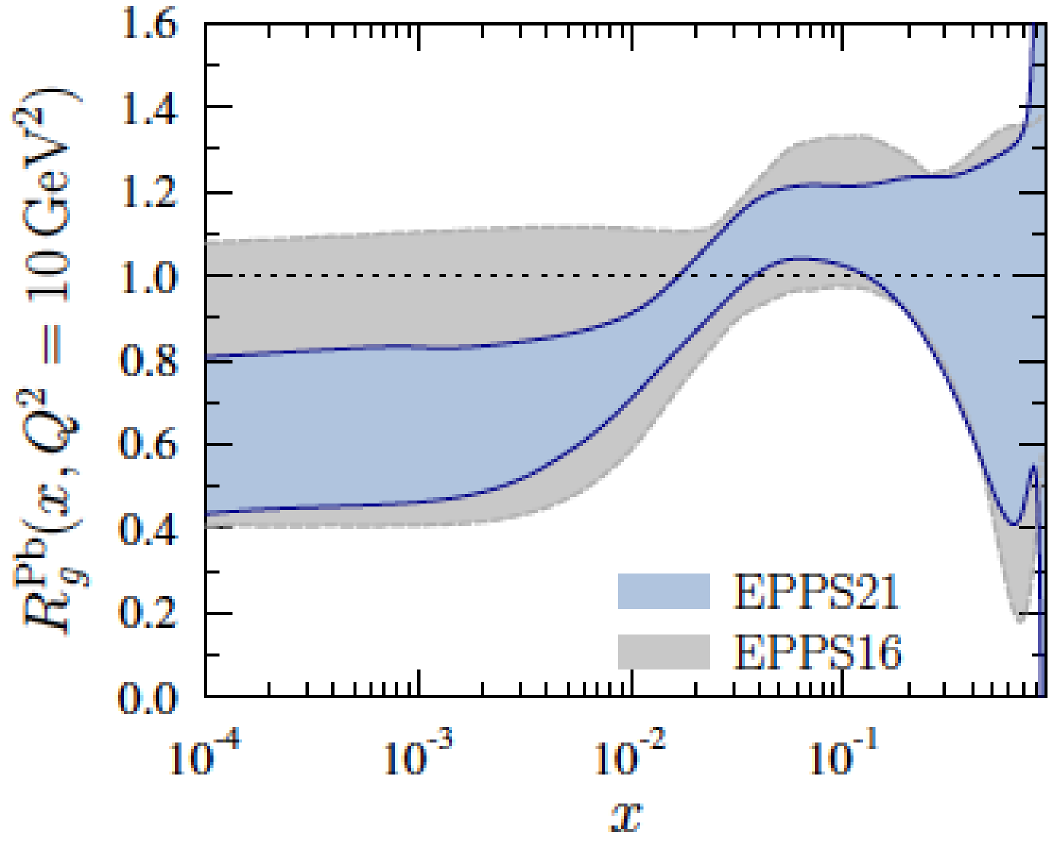
- EW bosons: W/Z to constrain the glue, larger statistics at the HL-LHC will improve.
- Dijets constrain the medium and large-x glue, statistics abundant, light ion runs to constrain A-dependence of nPDFs.

2311.00450

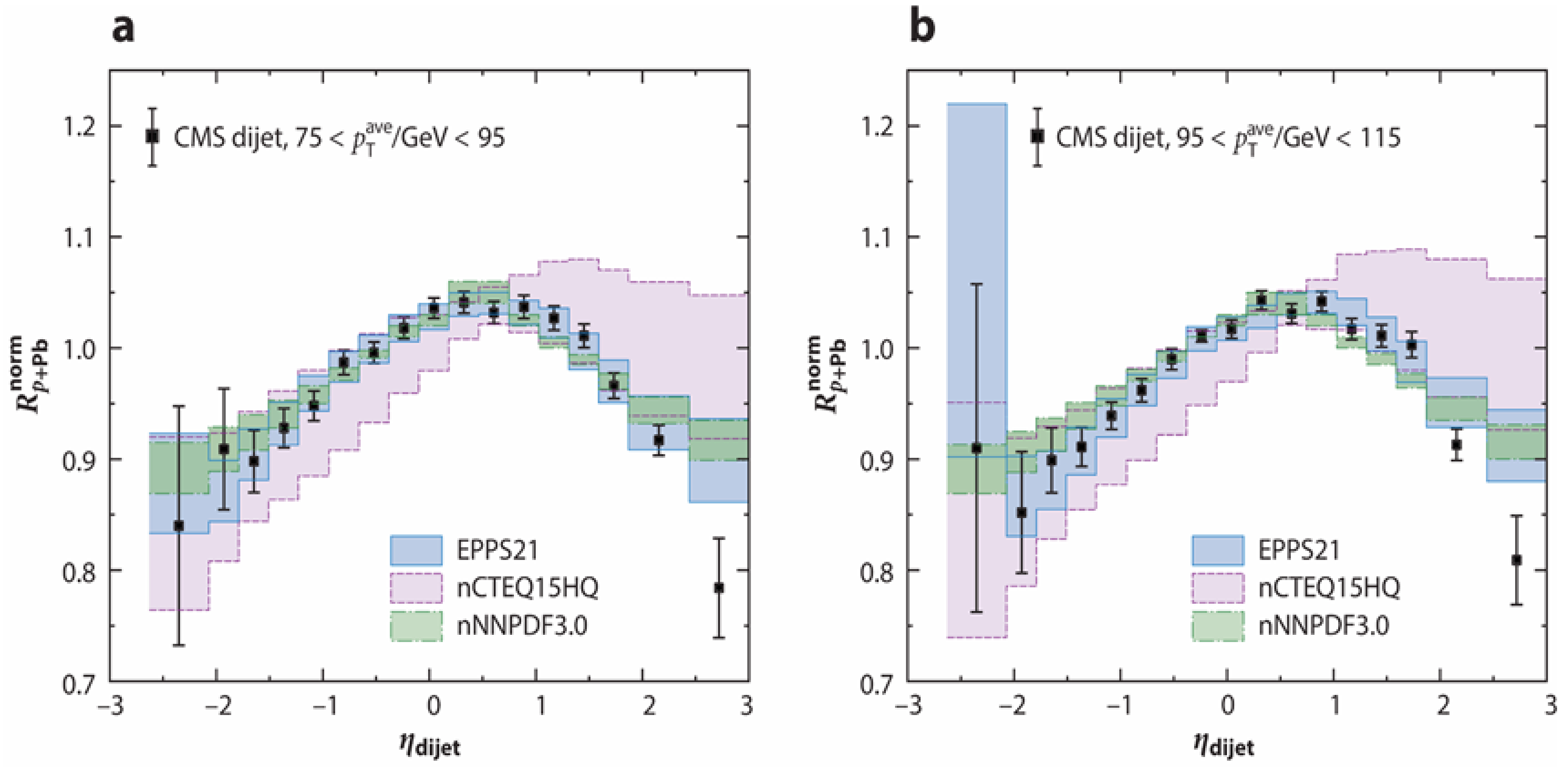


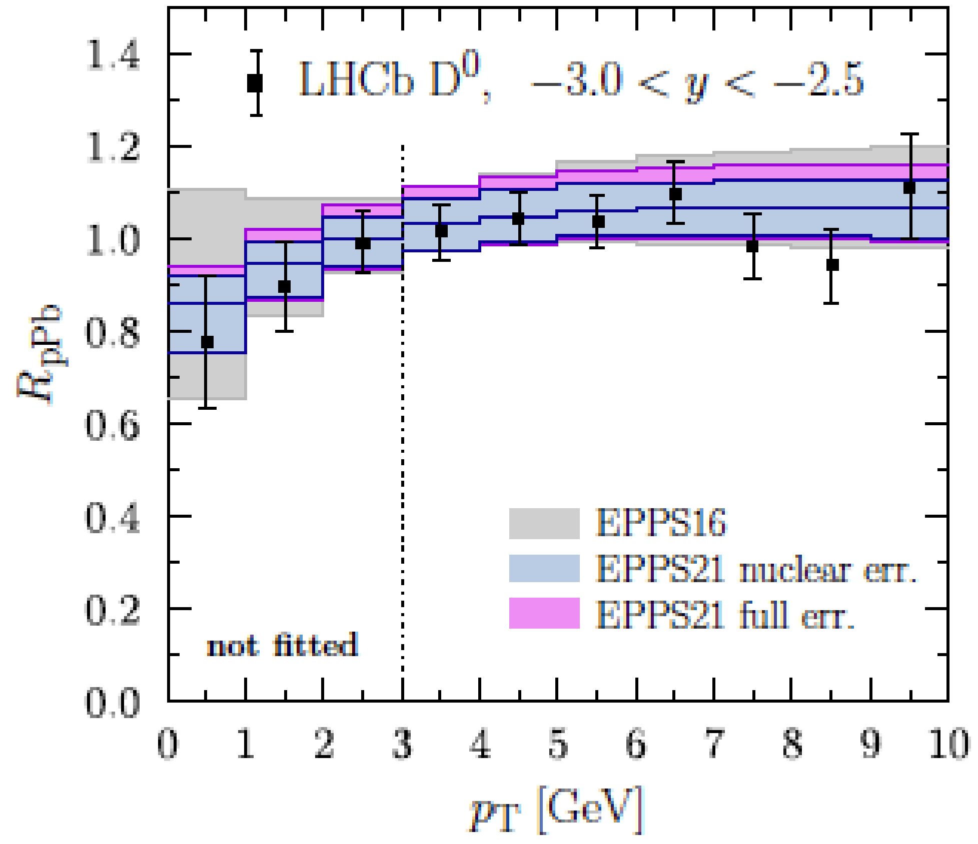

2112.12462



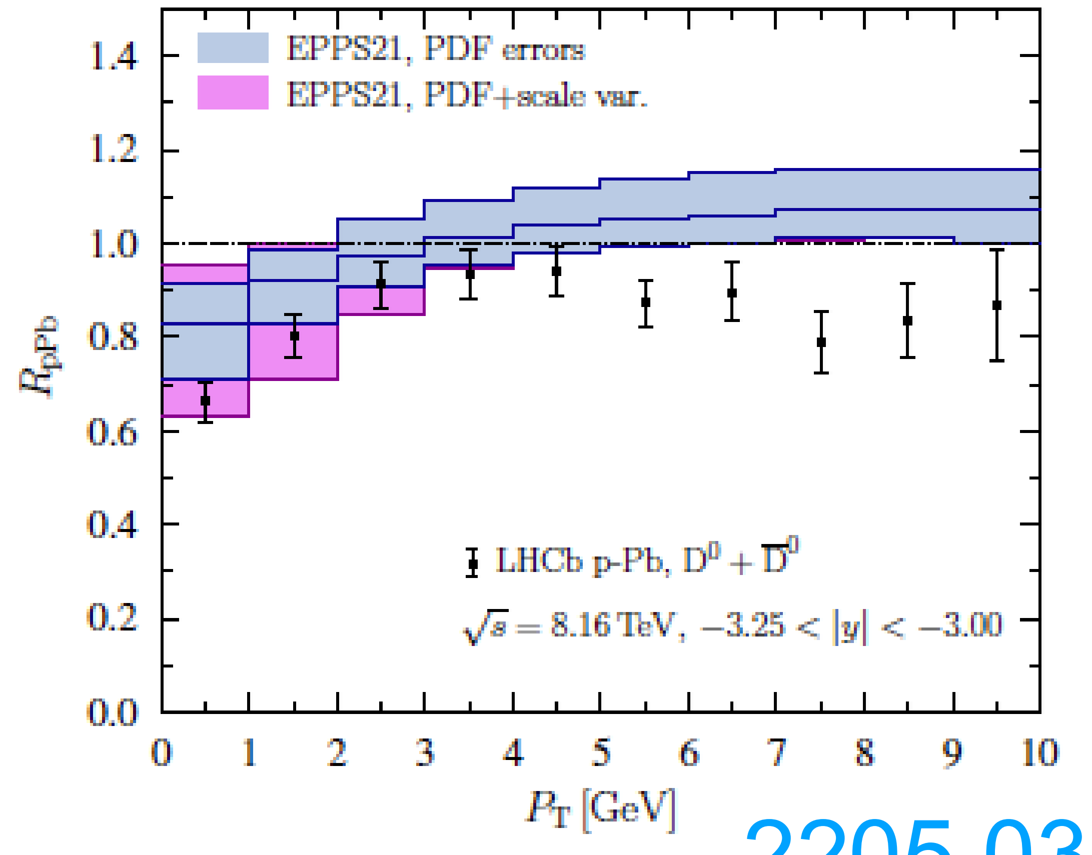

2311.00450




- Open heavy flavour constrains small-x glue, tension between 5 and 8.16 TeV LHCb backward D's: B's?
- (Anti)baryon enhancement, flow?
- VM (J/ψ) in UPCs: theory problems (GPDs, large scale dependence at NLO).



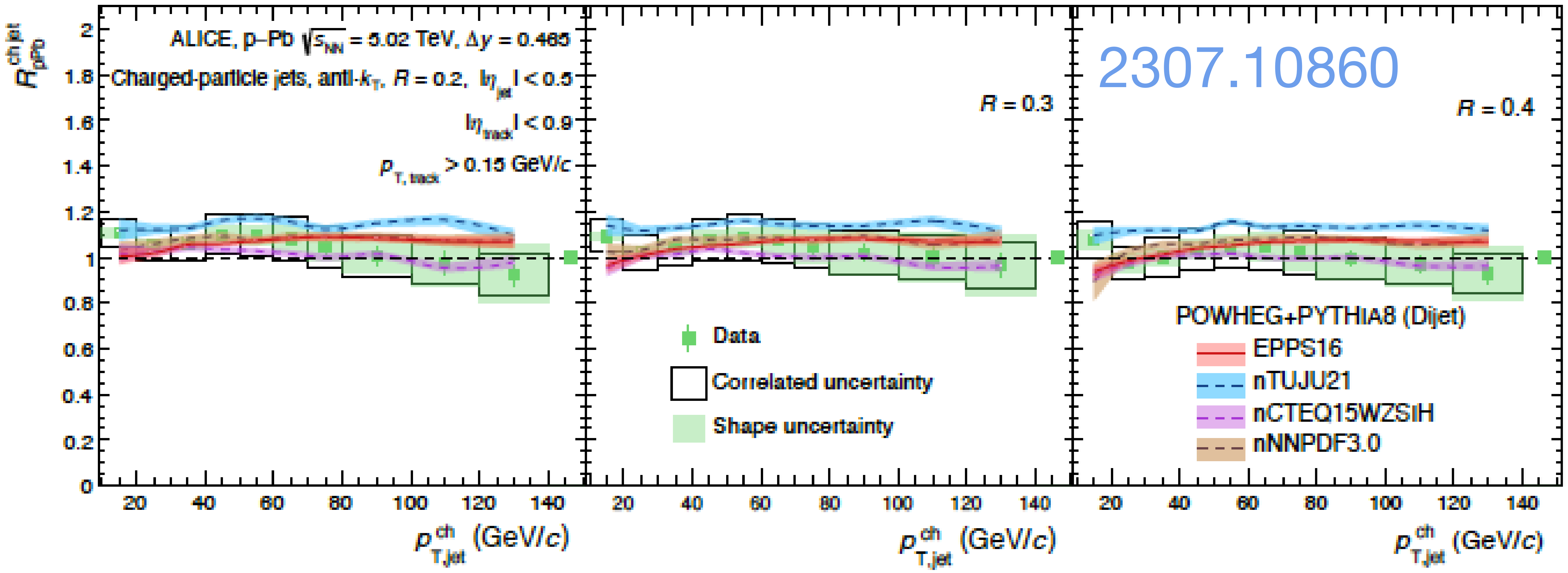

2112.12462



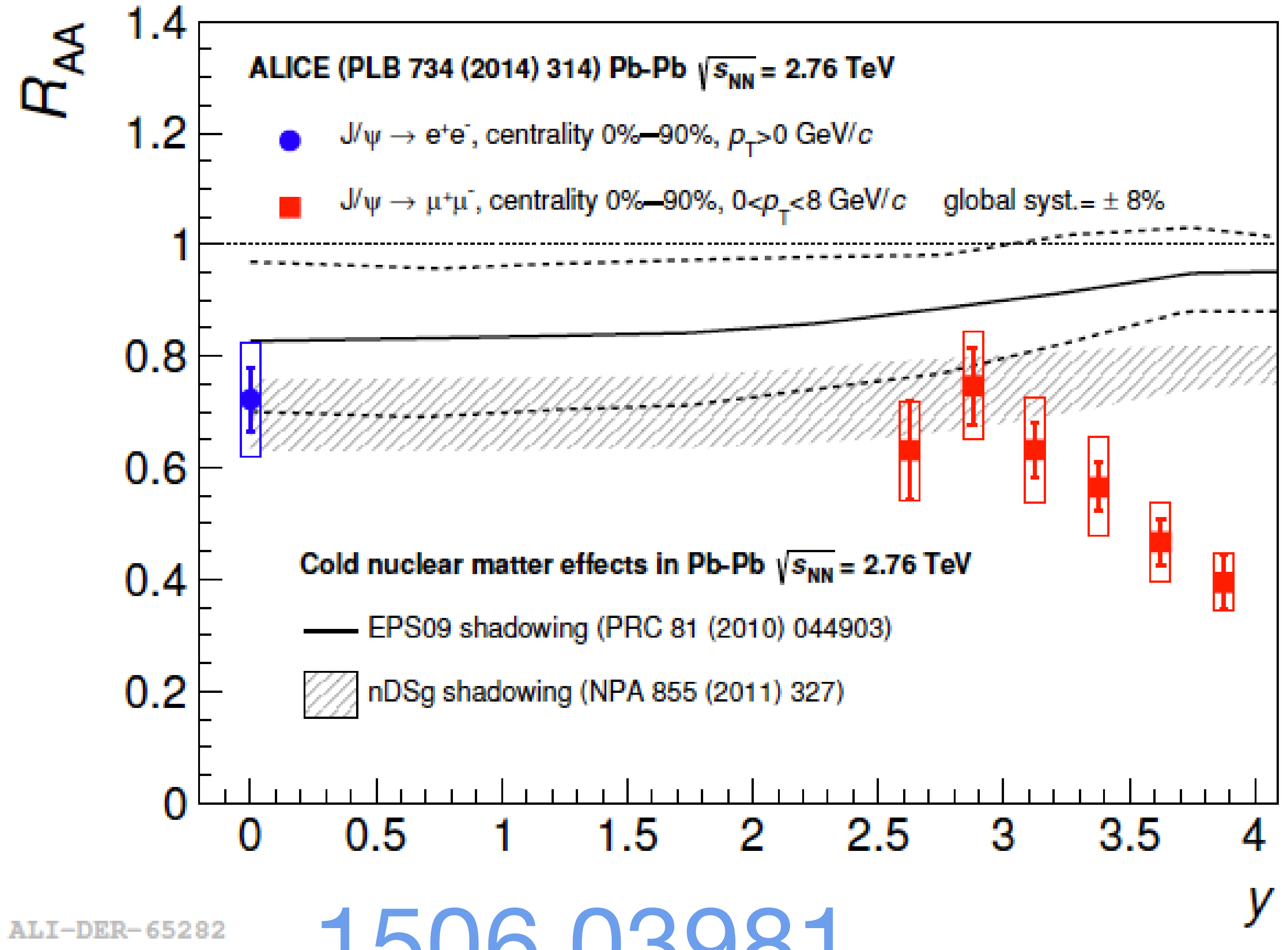

2205.03936

# Nuclear collinear PDFs: QGP search

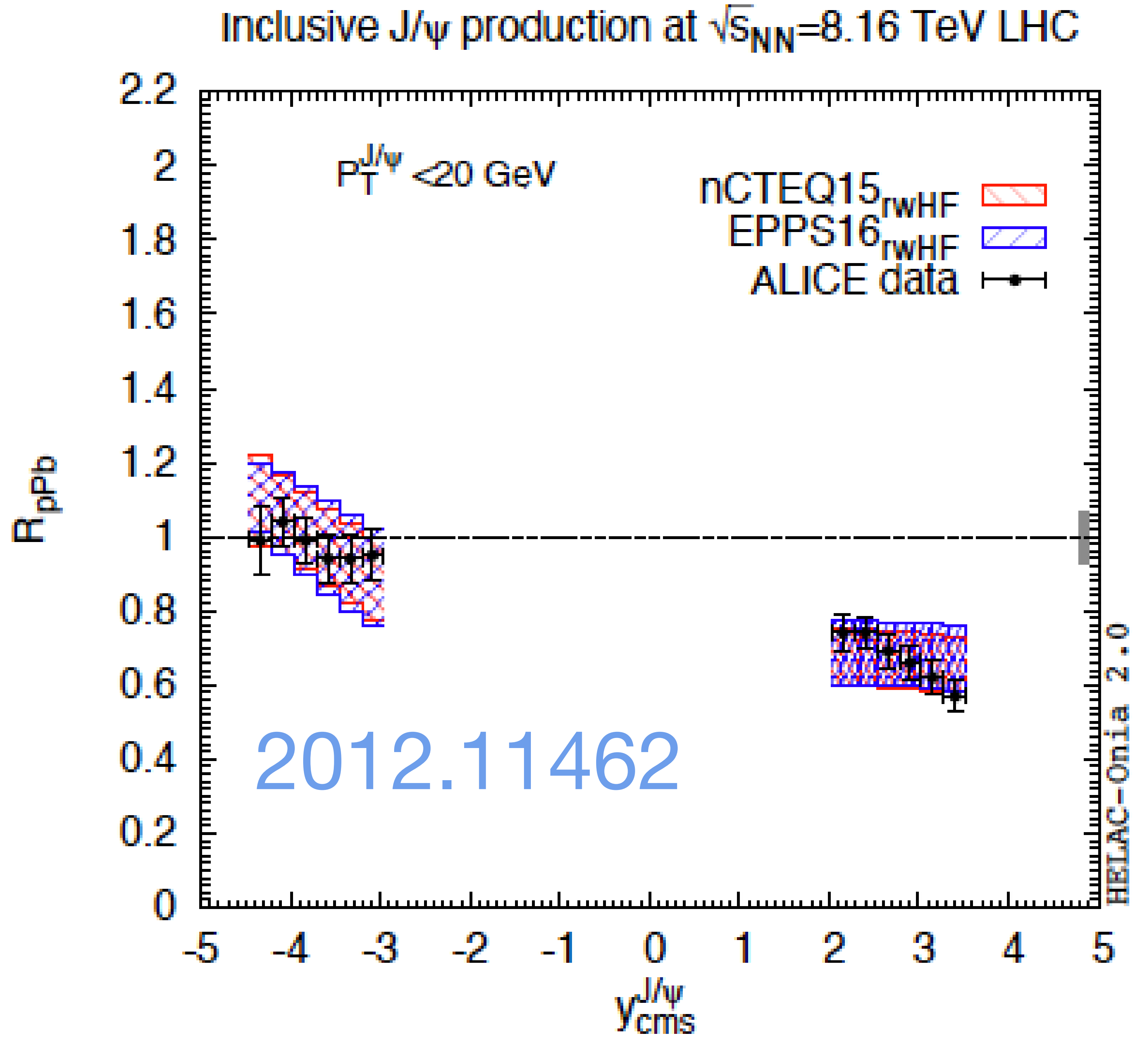
- PDFs may mask QGP-like effects in small systems, e.g., pPb or pp.




- nPDFs provide sizable uncertainties for QGP characterisation in PbPb.




1506.03981



# Collinear PDFs: goals and challenges

- **Data**: substantial progress expected from the complementarity of upcoming and proposed experiments ⇒ need of controlled systematics and correlations, inconsistencies?

- **Methodology**: numerous developments, parametrisation ⇒ increasing complexity, need of control precisions, tolerance?

- **Theory**: N3LO PDFs coming, and inclusion of theoretical uncertainties, crucial to achieve the required precision ⇒ understanding of theoretical uncertainties and possibility of higher order calculations.

- **Standard Model/BSM Parameters (including QGP characterisation and the small system problem)**: driven by PDF precision/accuracy improvements ⇒ understanding the assumptions underlying profiling and their impact, separating out 'new' effects from PDFs, complementary data from multiple colliders required.

# TMDs: state-of-the-art

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{res.}} \overset{\text{TMD}}{=} \sigma_0 H(Q) \int d^2\mathbf{b}_T e^{i\mathbf{b}_T\cdot\mathbf{q}_T} F_1(x_1,\mathbf{b}_T,Q,Q^2) F_2(x_2,\mathbf{b}_T,Q,Q^2) + \mathcal{O}\left[\left(\frac{q_T}{Q}\right)^m\right]$$

$$F_{f/P}(x,\mathbf{b}_T;\mu,\zeta) = \boxed{\sum_j C_{f/j}(x,b_{\boxed{*}};\mu_b,\mu_b^2)\otimes f_{j/P}(x,\mu_b)}$$

$$\times \boxed{\exp\left\{K(b_{\boxed{*}};\mu_b)\ln\frac{\sqrt{\zeta}}{\mu_b} + \int_{\mu_b}^{\mu}\frac{d\mu'}{\mu'}\left[\gamma_F - \gamma_K \ln\frac{\sqrt{\zeta}}{\mu'}\right]\right\}}$$

$$\times \boxed{\exp\left\{\underline{g_{j/P}(x,b_T)} + \underline{g_K(b_T)\ln\frac{\sqrt{\zeta_F}}{\sqrt{\zeta_{F,0}}}}\right\}}$$

- matching onto the collinear region at $b_T \ll 1/\Lambda_{QCD}$,
- factorises as *hard* (perturbative) and *longitudinal* (*i.e.* collinear, non-perturbative).

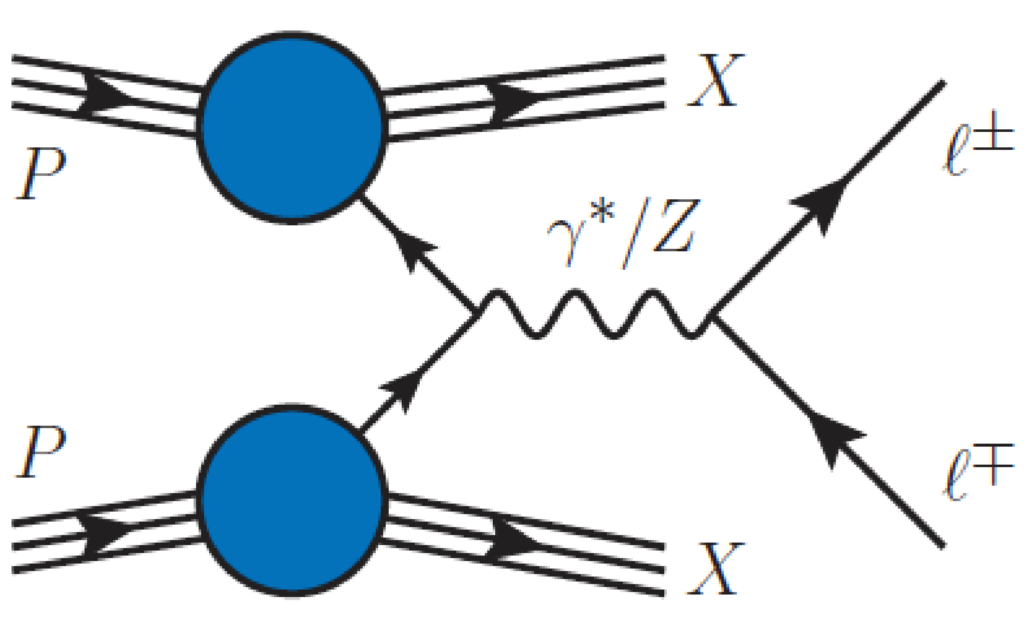
- avoid the Landau pole,
- $f_{NP}$ accounts for the introduction of $b_*$,
- $f_{NP}$ is non-perturbative thus **fit** to data.

- CS and RGE evolution,
- evolution in $\mu$ and $\zeta$,
- perturbative.

- TMD factorisation appears in two scale problems, e.g., Q and $q_T$ in DY.
- They include perturbative and non-perturbative pieces.
- They are linked to their collinear counterparts.

# TMDs: state-of-the-art

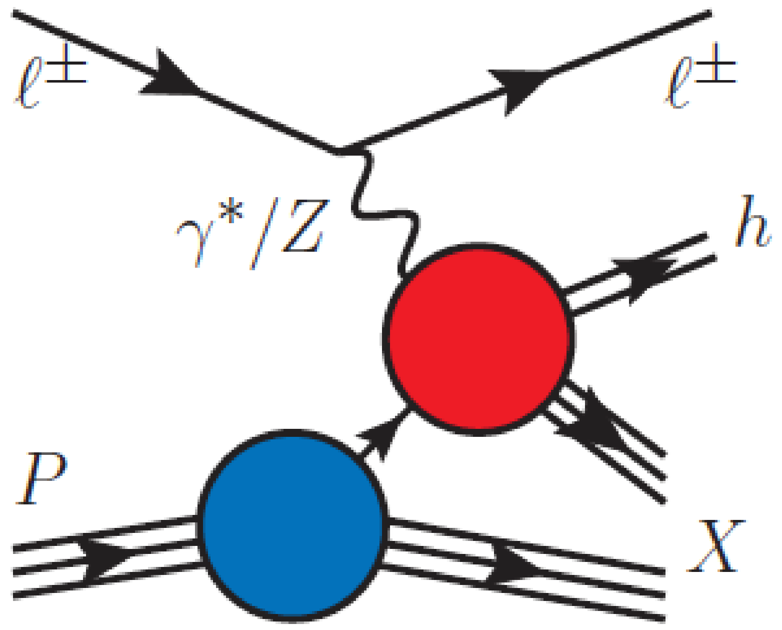
Drell-Yan




$PP \longrightarrow \ell^\pm \ell^\mp X$

- **Two** TMD **PDFs**:
- Lots of data:
  - low-energy: FNAL,
  - mid-energy: RHIC,
  - high-energy: Tevatron, LHC.

Semi-inclusive DIS

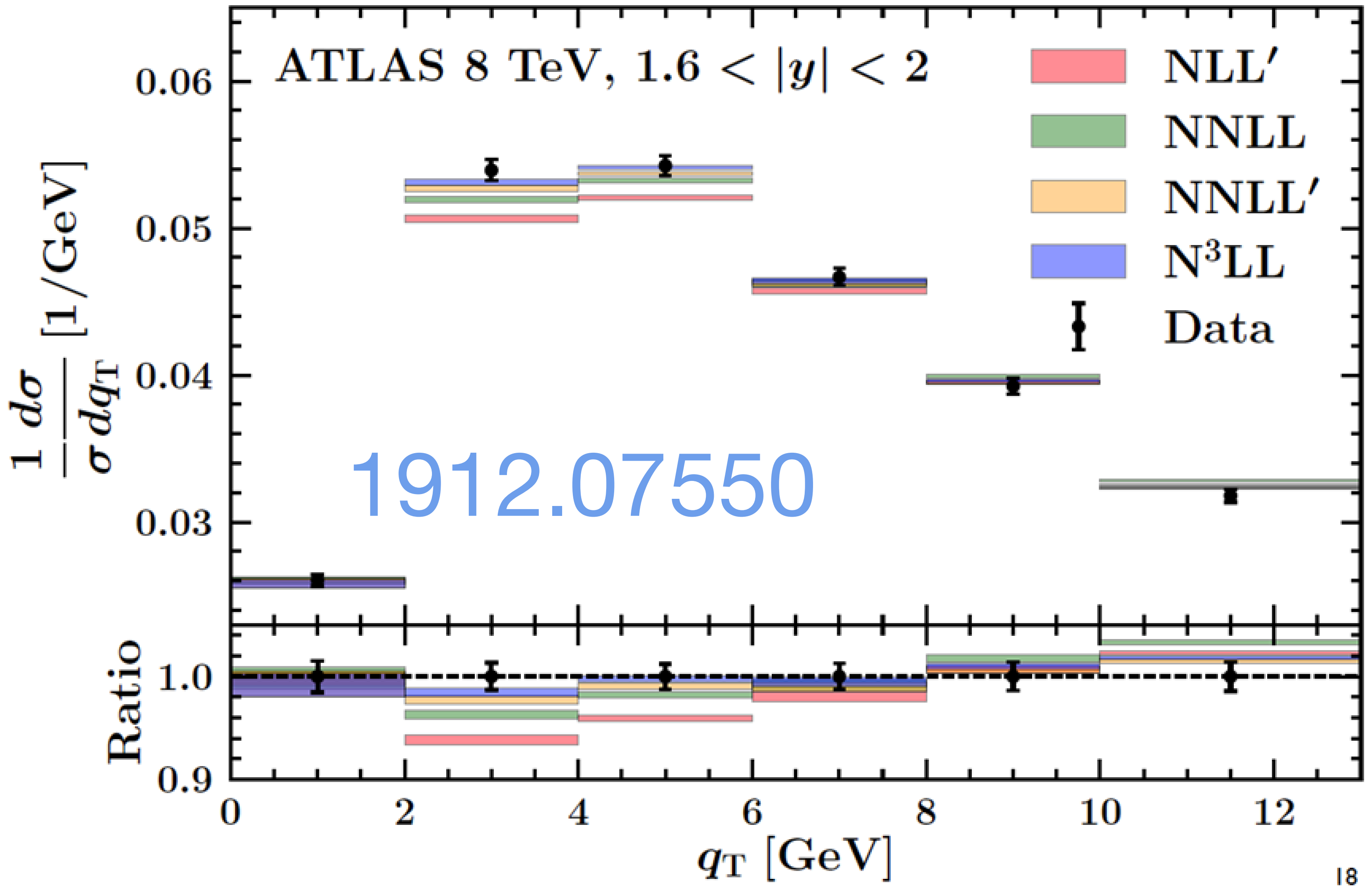



$P\ell^\pm \longrightarrow \ell^\pm h\ X$

- One TMD **PDF** one **FF**:
- many precise data points:
  - HERMES at DESY,
  - COMPASS at CERN.
- **EIC** will deliver precise data.

- Not yet used for extractions: W production in pp, dijet and heavy quark pair production in DIS, dijets in pp.

| | Accuracy | SIDIS | Drell-Yan | N. of points | Flavour dep. |
|---|---|---|---|---|---|
| DWS 1984, CERN-TH.3987/84 | NLL | ✘ | ✔ | a few | ✘ |
| BLNY 2003, hep-ph/0212159 | NLL'-NNLL | ✘ | ✔ | 116 | ✘ |
| Pavia 2017, 1703.10157 | NLL | ✔ | ✔ | 8059 | ✘ |
| SV 2017, 1706.01473 | N$^3$LL | ✘ | ✔ (LHC) | 309 | ✘ |
| SV 2019,1912.06532 | N$^3$LL$^{(-)}$ | ✔ | ✔ (LHC) | 1039 | ✘ |
| Pavia 2019, 1912.07550 | N$^3$LL | ✘ | ✔ (LHC) | 353 | ✘ |
| MAPTMD22, 2206.07598 | N$^3$LL$^{(-)}$ | ✔ | ✔ (LHC) | 2031 | ✘ |
| ART23, 2305.07473 | N$^4$LL$^{(-)}$ | ✘ | ✔ (LHC) | 627 | ✔ |
| MAPTMD24, 2405.13833 | N$^3$LL | ✔ | ✔ (LHC) | 2031 | ✔ |
| ART25, 2503.11201 | N$^4$LL$^{(-)}$ | ✔ | ✔ (LHC) | 1209 | ✔ |
| Neural Network TMDs (MAP) 2502.04166 | N$^3$LL | ✘ | ✔ (LHC) | 482 | ✘ |

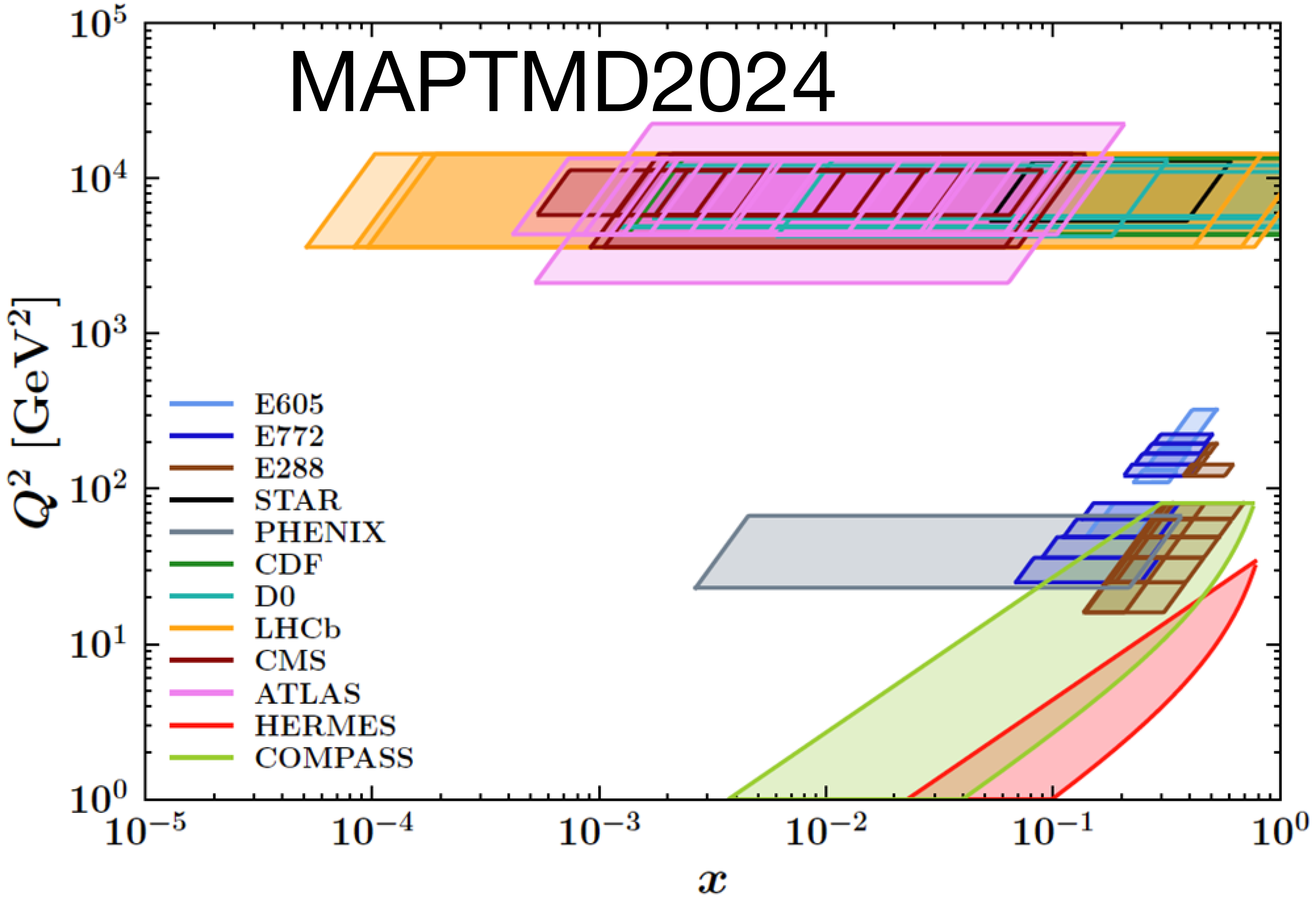



1912.07550

- Also other approaches, e.g., PMB, and relation with small-x physics (CGC).
- Extracted from lattice.
- Large perturbative accuracy computed (and required to describe data).
- Also contain spin information.

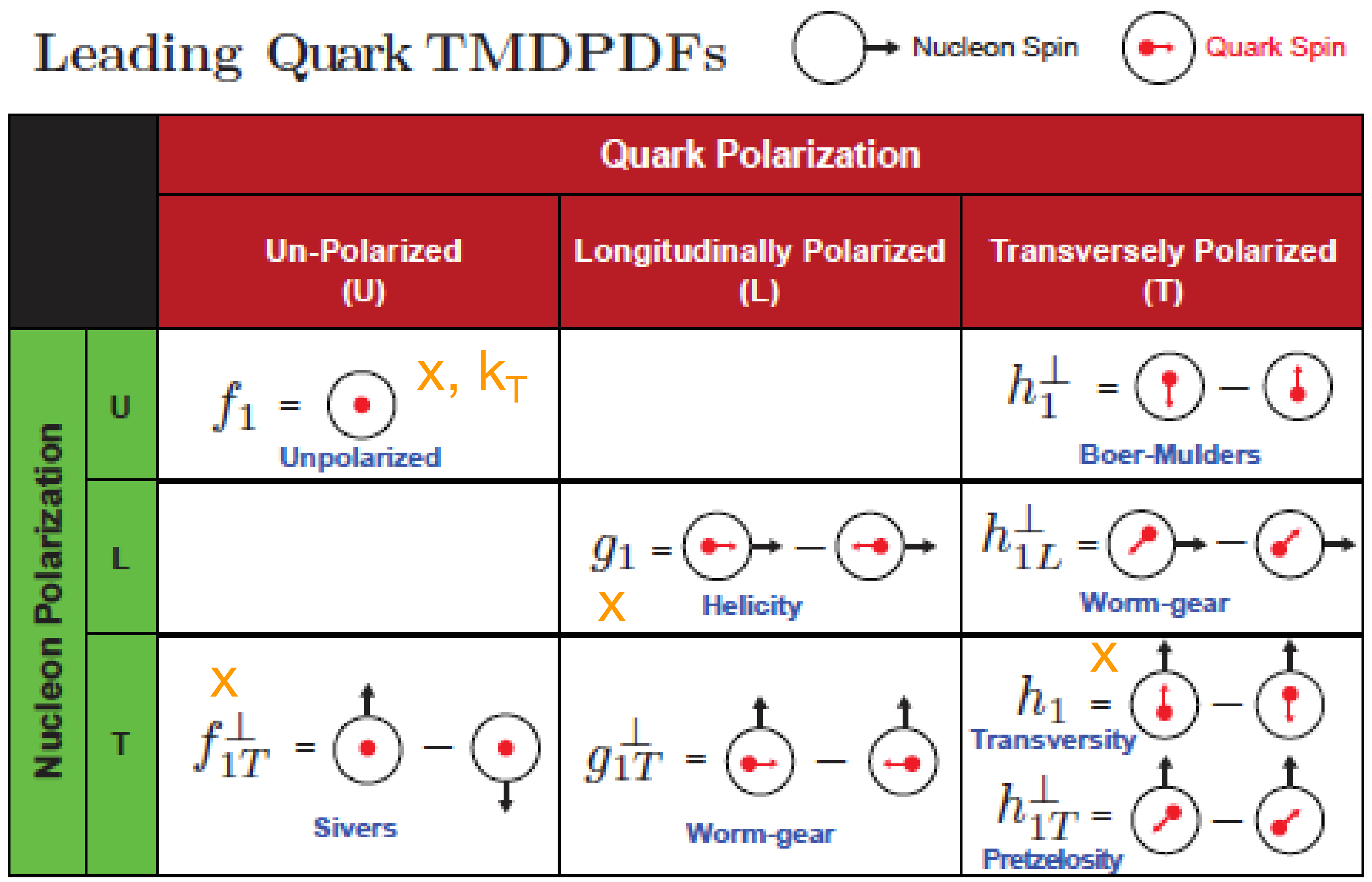
# TMDs: state-of-the-art

2405.13833

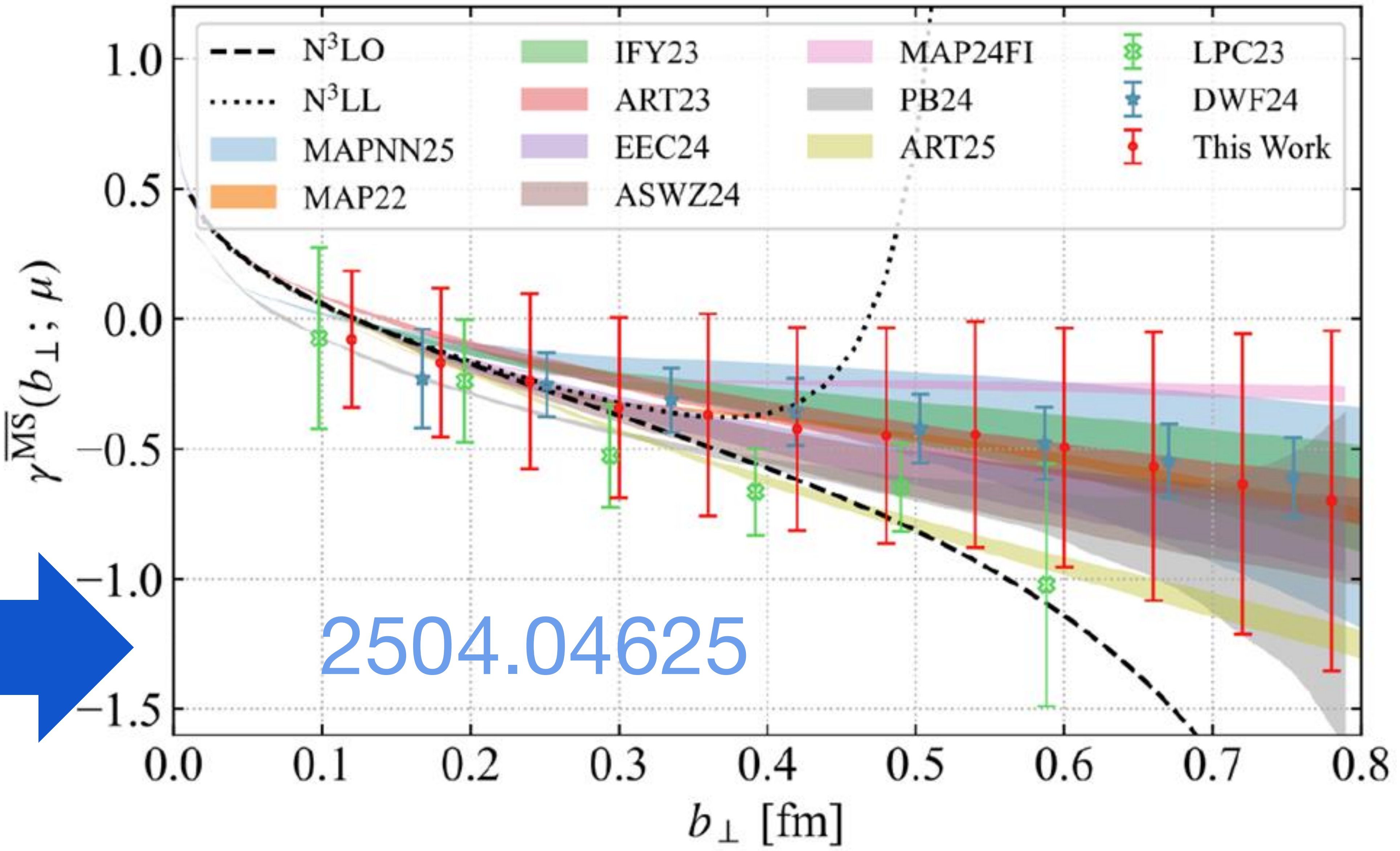



| Data set | $N_{\rm dat}$ | N³LL $\chi^2_D$ | $\chi^2_\lambda$ | $\chi^2_0$ |
|---|---|---|---|---|
| Tevatron total | 71 | 1.10 | 0.07 | 1.17 |
| LHCb total | 21 | 3.56 | 0.96 | 4.52 |
| ATLAS total | 72 | 3.54 | 0.82 | 4.36 |
| CMS total | 78 | 0.38 | 0.05 | 0.43 |
| PHENIX 200 | 2 | 2.76 | 1.04 | 3.80 |
| STAR 510 | 7 | 1.12 | 0.26 | 1.38 |
| *DY collider total* | 251 | 1.37 | 0.28 | 1.65 |
| E288 200 GeV | 30 | 0.13 | 0.40 | 0.53 |
| E288 300 GeV | 39 | 0.16 | 0.26 | 0.42 |
| E288 400 GeV | 61 | 0.11 | 0.08 | 0.19 |
| E772 | 53 | 0.88 | 0.20 | 1.08 |
| E605 | 50 | 0.70 | 0.22 | 0.92 |
| *DY fixed-target total* | 233 | 0.63 | 0.31 | 0.94 |
| *DY total* | 484 | 1.02 | 0.29 | 1.31 |
| HERMES total | 344 | 0.81 | 0.24 | 1.05 |
| COMPASS total | 1203 | 0.67 | 0.27 | 0.94 |
| *SIDIS total* | 1547 | 0.70 | 0.26 | 0.96 |
| **Total** | **2031** | **0.81** | **0.27** | **1.08** |

2304.03302




- Large sets of data but much more information to extract than for collinear PDFs.
- Use of different modeling for the non-perturbative pieces and collinear PDFs make TMDs difficult to compare: better the CS kernel (also computed in lattice).

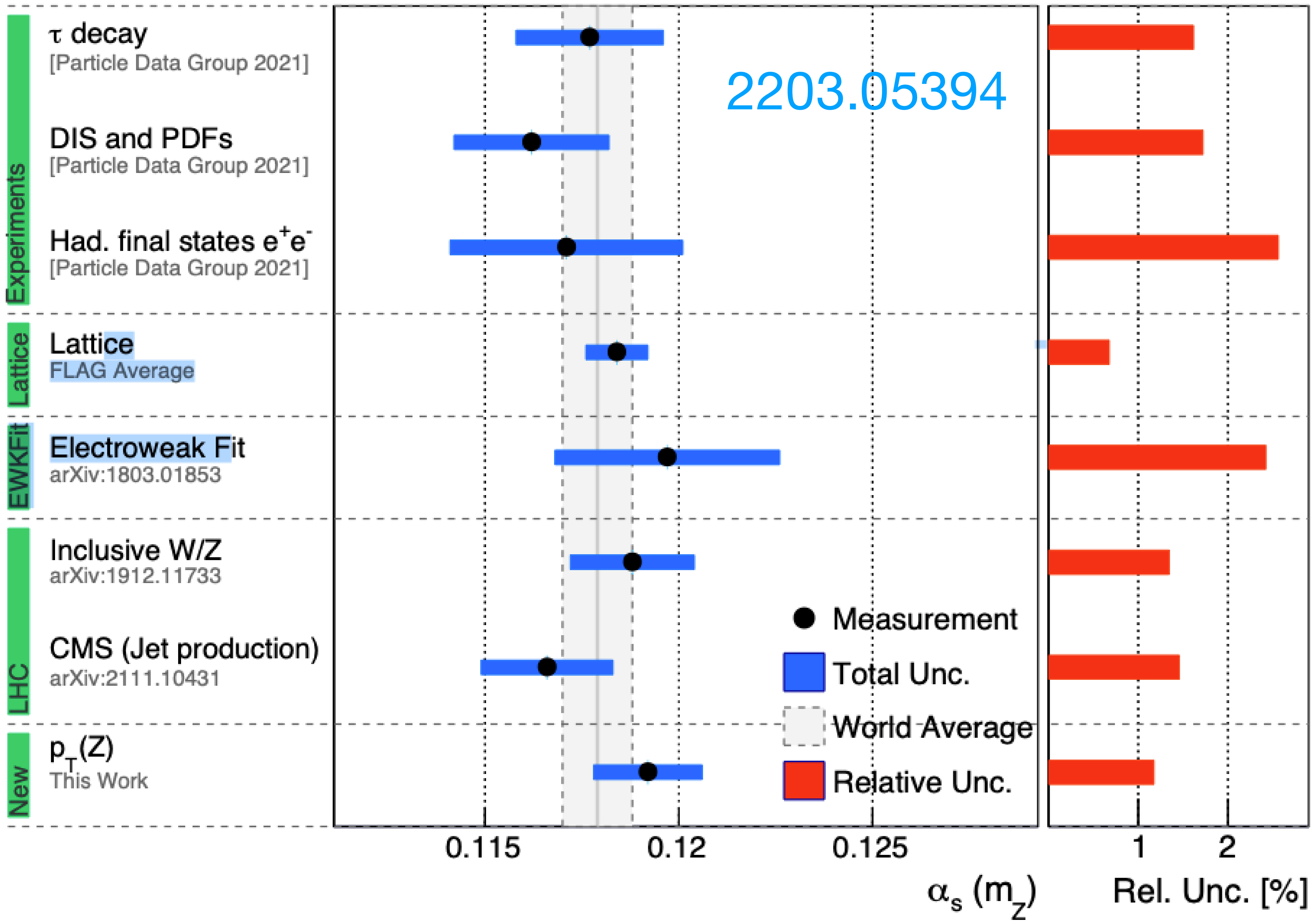





N. Armesto, June 23rd 2025

# TMDs: implications

- Extraction of $\alpha_s$ from low transverse momentum DY: huge potential at the LHC.

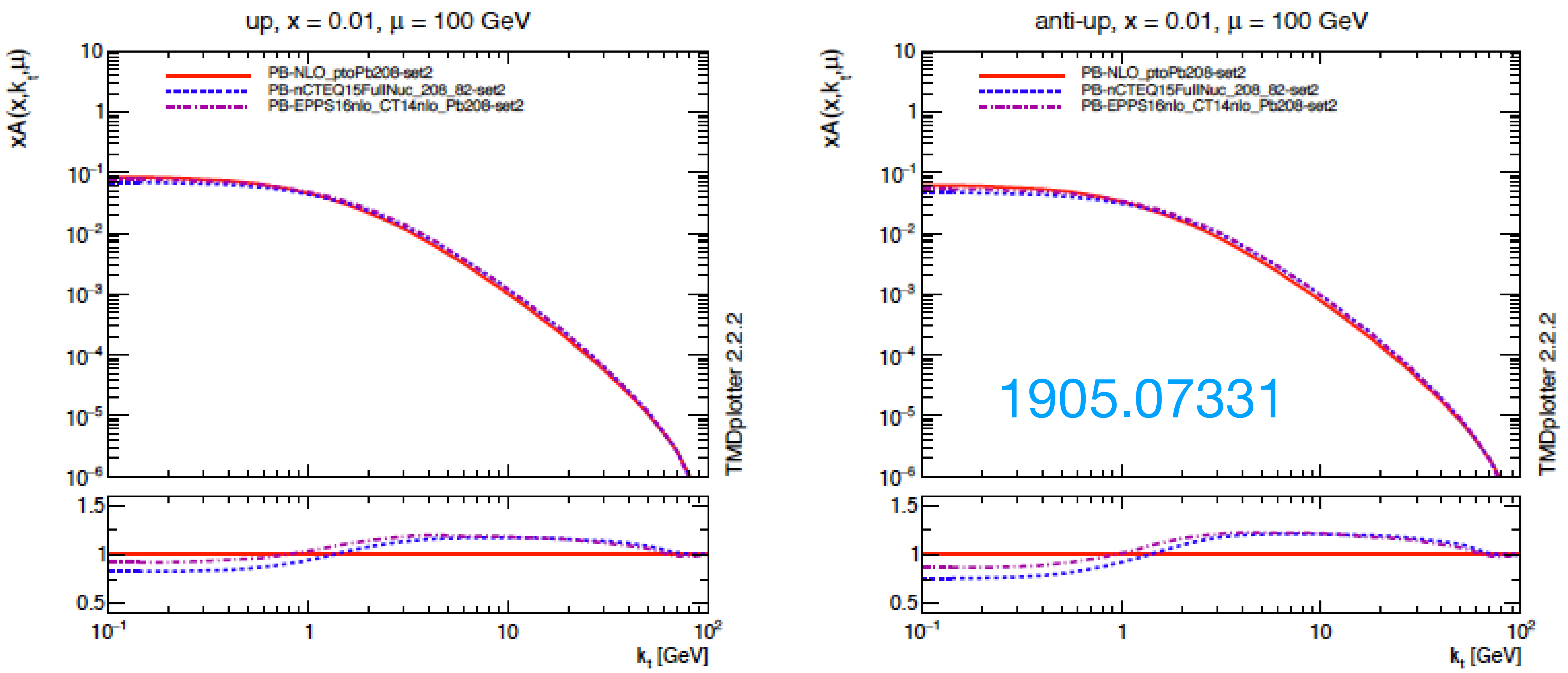



- Nuclear effects in TMD analyses through nPDFs.

- Determination of the W-mass in hadronic colliders, which relies on templates: uncertainties coming from our knowledge of the Z spectrum, coming mainly from TMDs (PDFs).

2506.13871

$$\frac{d\sigma^W}{dq_T} = \left(\frac{d\sigma^W/dq_T}{d\sigma^Z/dq_T}\right)_{\mathbf{exp.}} \left(\frac{d\sigma^Z}{dq_T}\right)_{\mathbf{th.}}$$

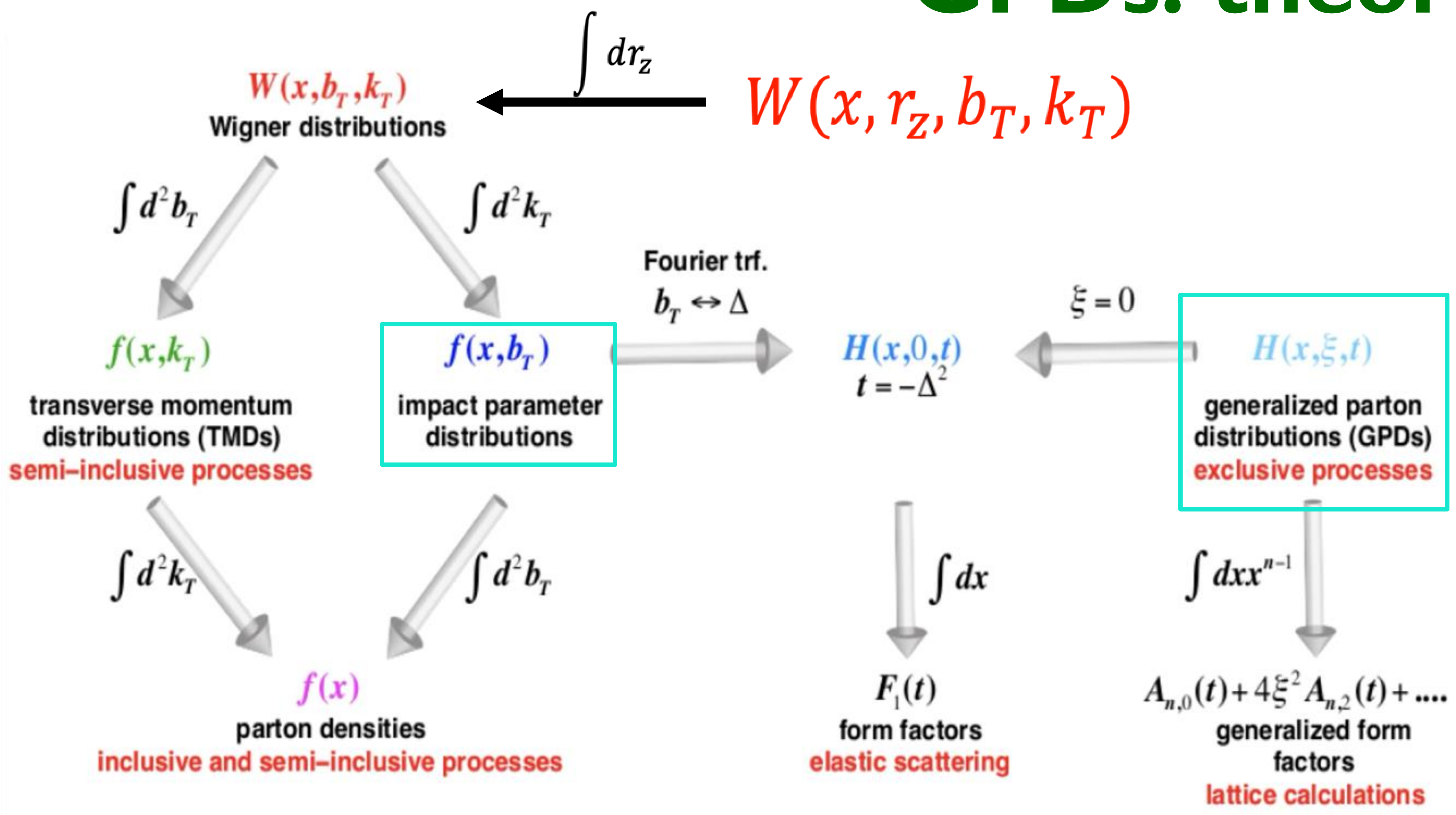


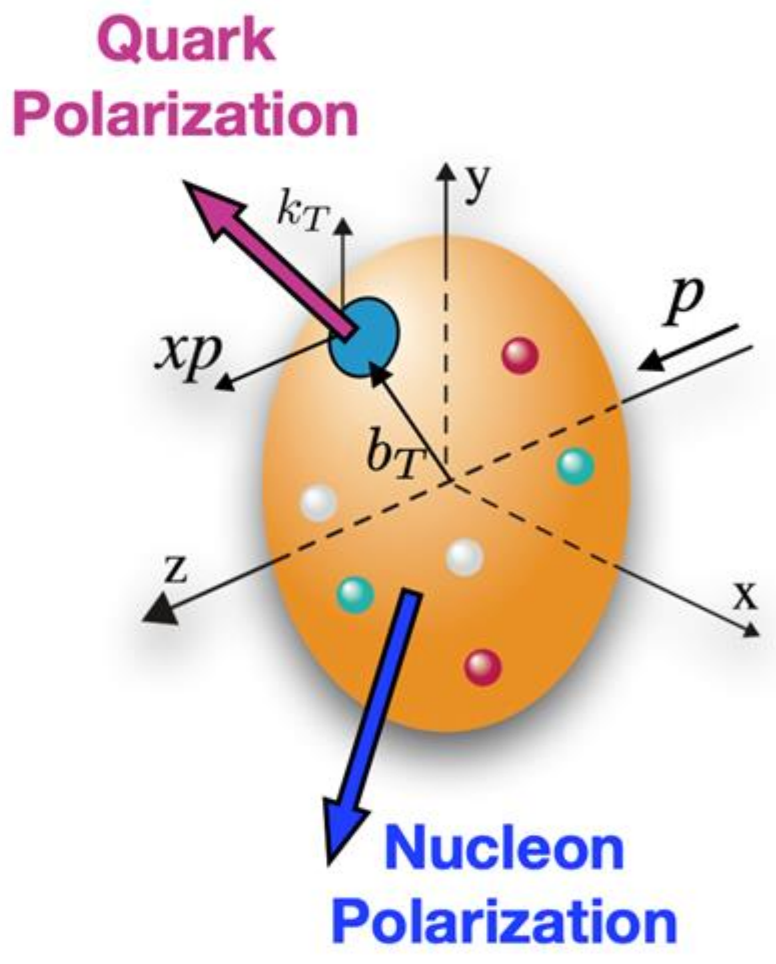



N. Armesto, June 23rd 2025

# GPDs: theory

B. Pasquini at DIS2025



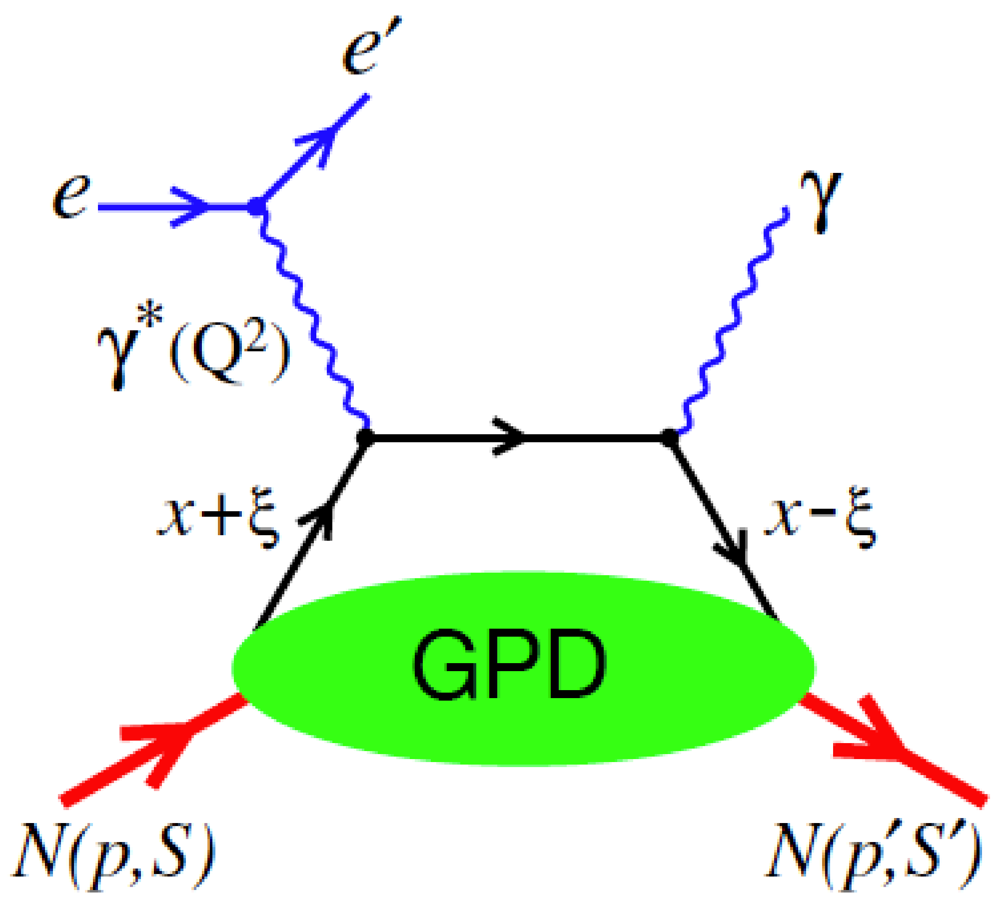



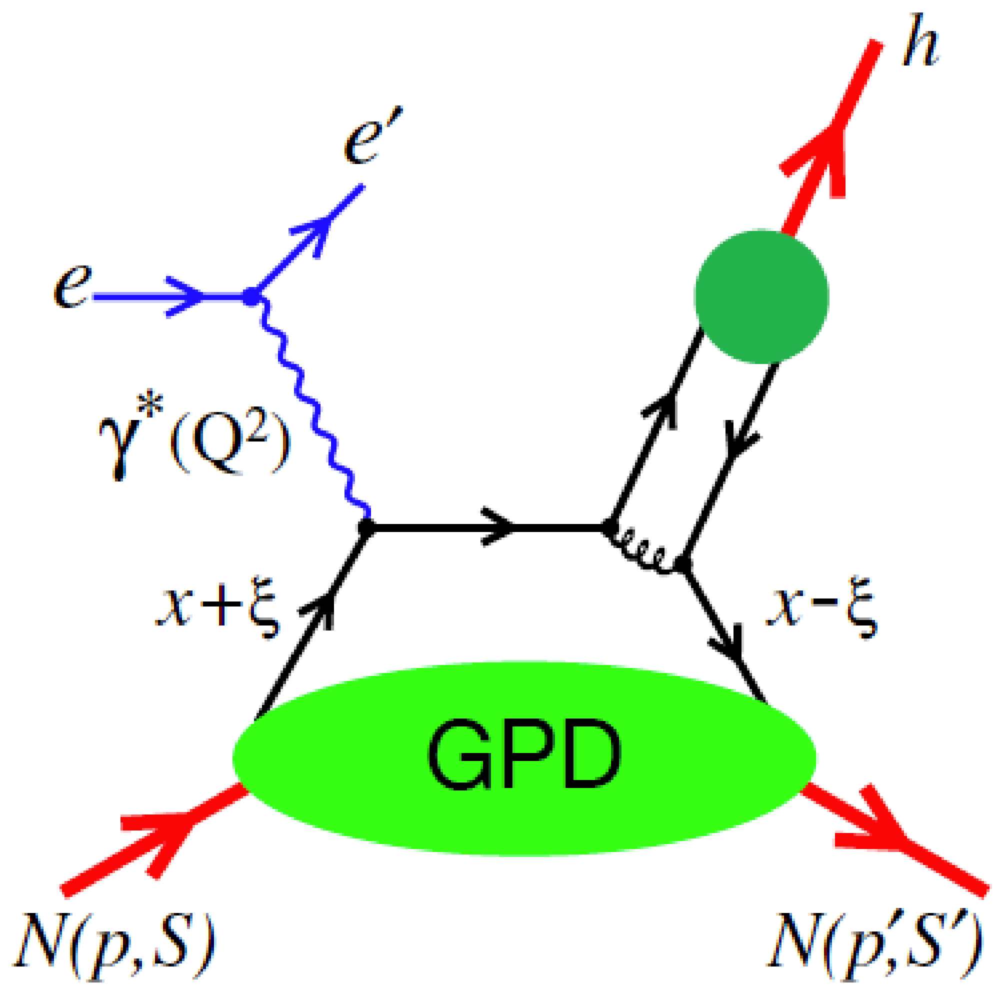

quark polarization (columns); nucleon polarization (rows)

| GPD | $U$ | $L$ | $T$ |
|---|---|---|---|
| $U$ | $H$ | | $\mathcal{E}_T$ |
| $L$ | | $\tilde{H}$ | $\tilde{E}_T$ |
| $T$ | $E$ | $\tilde{E}$ | $H_T,\ \tilde{H}_T$ |


**Measured in exclusive processes:**

- DVCS, TCS at NNLO.
- Exclusive VM production: studies to stabilise at NLO.
- Besides DDVCS, 2 to 3 processes like diphoton or photon-meson.
- Target: transition GPDs/DAs.
- Pion, light nuclei,...



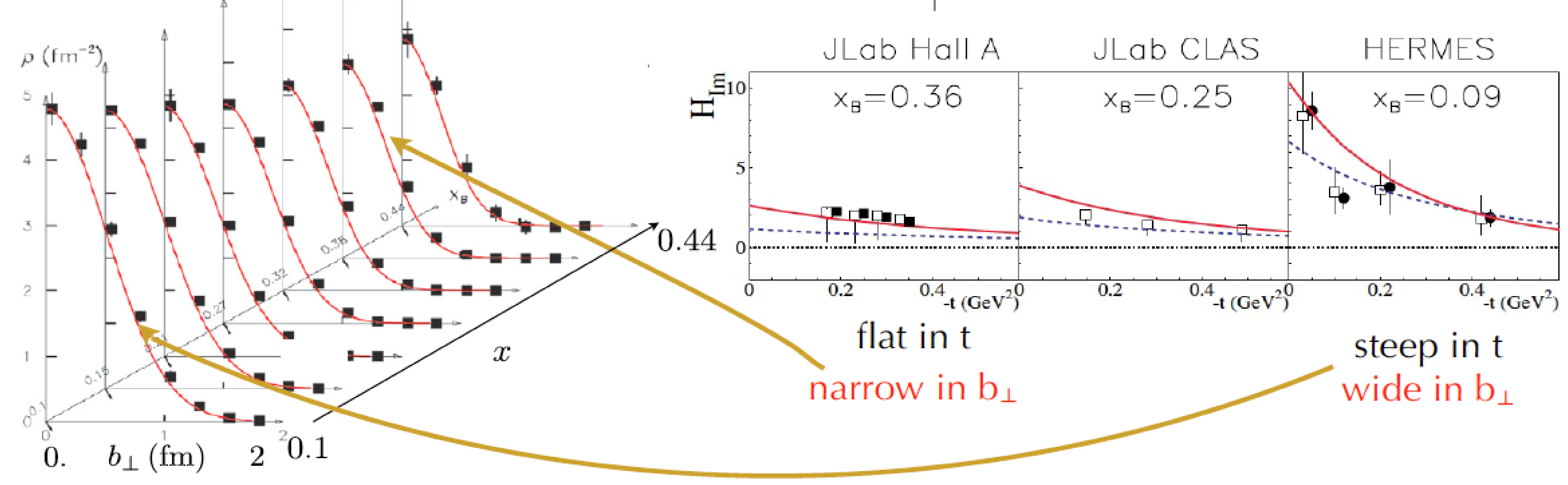



# GPDs: theory

- The partonic profile of hadrons can be extracted dependent on *x*.

- Relation with the energy-momentum tensor.

$$H^q(x,0,\vec{b}_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} H^q(x,0,t) e^{-i\vec{b}_\perp\cdot\vec{\Delta}_\perp} \longrightarrow \int dx\, H^q(x,0,\vec{b}_\perp) = F_1(\vec{b}_\perp)$$




B. Pasquini at DIS2025

$$\langle p|\, T_{\mu\nu}\, |p'\rangle = \bar{u}(p')\left[A(t)\frac{P_\mu P_\nu}{M_N} + J(t)\frac{i(P_\mu\sigma_{\nu\rho}+P_\nu\sigma_{\mu\rho})\Delta^\rho}{2M_N} + D(t)\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{5M_N}\right]u(p)$$

Relation with second-moments of GPDs:

$$\int dx\, x\, H(x,\xi,t) = A(t) + \frac{4}{5}D(t)\xi^2$$

$$\int dx\, x\, E(x,\xi,t) = 2J(t) - A(t) - \frac{4}{5}D(t)\xi^2$$

"Charges" of the EMT Form Factors at t=0

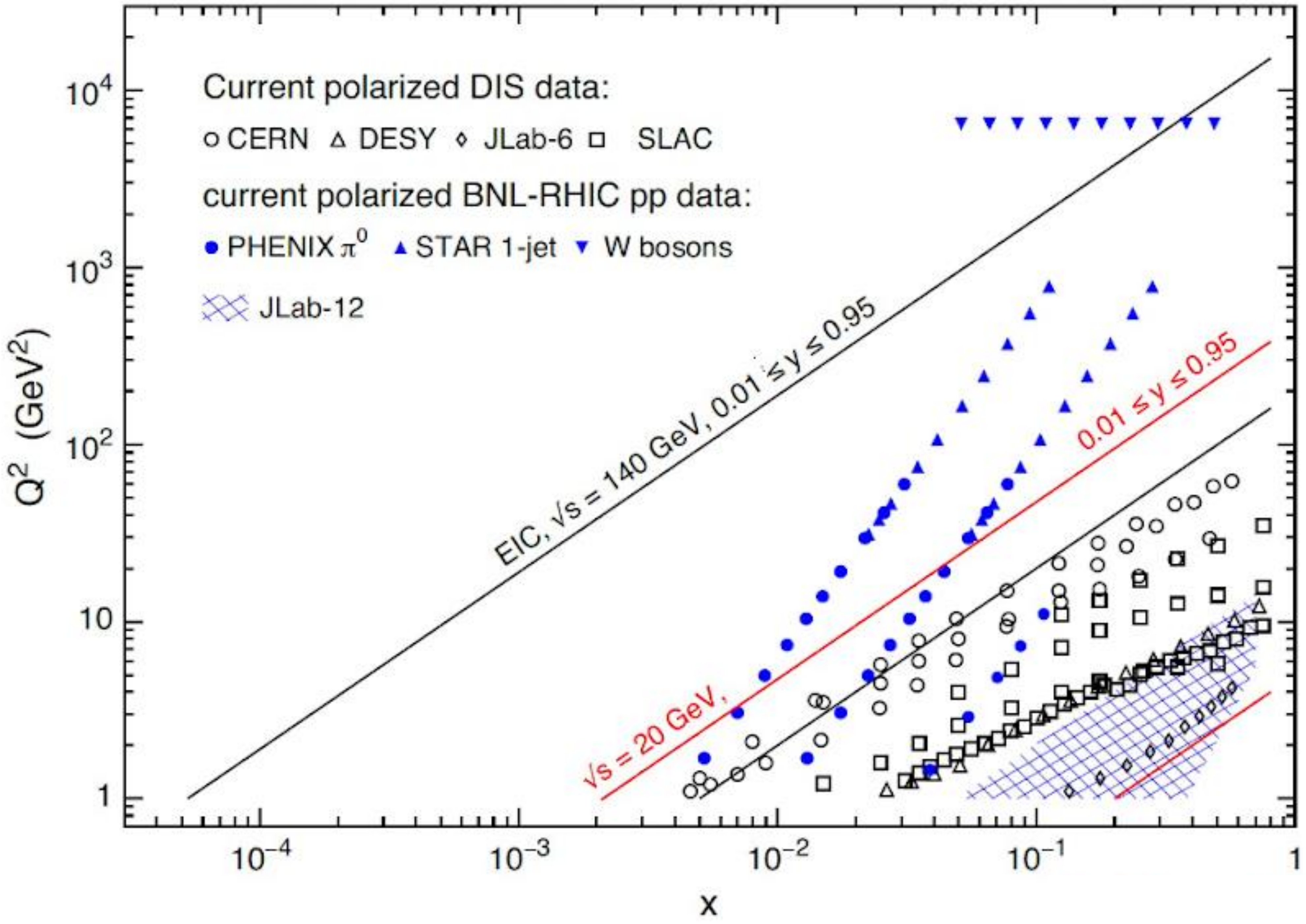
$A^{Q,G}(0)$ nucleon momentum carried by parton

$J^{Q,G}(0)$ angular momentum of partons

$D^{Q,G}(0)$ D-term ("stability" of the nucleon)

# GPDs: existing data

C. Keppel
at DIS2025

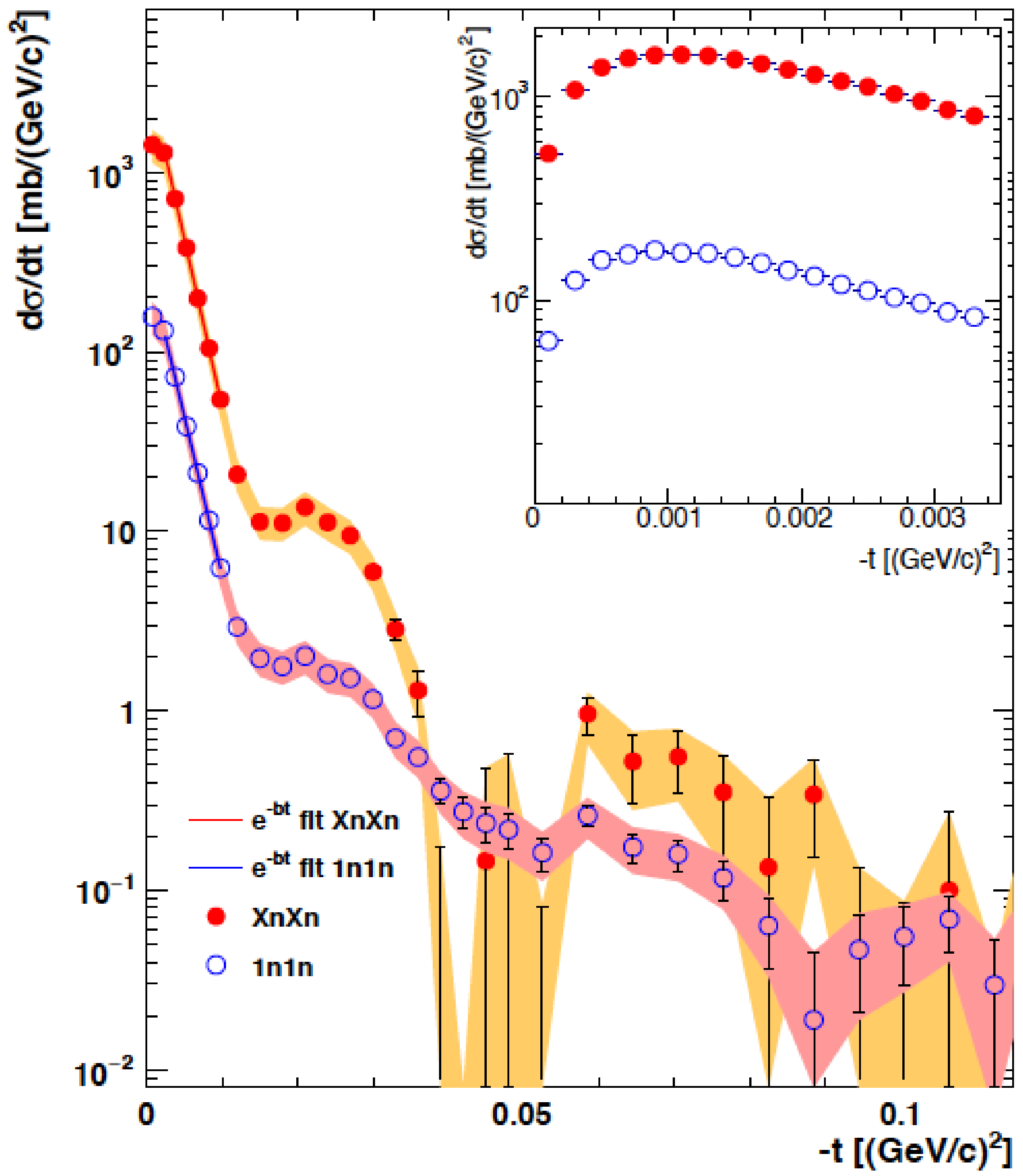



| Experiment | Ref. | Target | Analysis | $W$ (GeV) | $x_{Bj}$ | $Q^2$ ($GeV^2$) |
|---|---|---|---|---|---|---|
| E80 (SLAC) | [101] | p | $A_1$ | 2.1 to 2.6 | 0.2 to 0.33 | 1.4 to 2.7 |
| E130 (SLAC) | [102] | p | $A_1$ | 2.1 to 4.0 | 0.1 to 0.5 | 1.0 to 4.1 |
| EMC (CERN) | [103] | p | $A_1$ | 5.9 to 15.2 | $1.5 \times 10^{-2}$ to 0.47 | 3.5 to 29.5 |
| SMC (CERN) | [250] | p, d | $A_1$ | 7.7 to 16.1 | $10^{-4}$ to 0.482 | 0.02 to 57 |
| E142 (SLAC) | [244] | $^3$He | $A_1$, $A_2$ | 2.7 to 5.5 | $3.6 \times 10^{-2}$ to 0.47 | 1.1 to 5.5 |
| E143 (SLAC) | [245] | p, d | $A_1$, $A_2$ | 1.1 to 6.4 | $3.1 \times 10^{-2}$ to 0.75 | 0.45 to 9.5 |
| E154 (SLAC) | [246, 247] | $^3$He | $A_1$, $A_2$ | 3.5 to 8.4 | $1.7 \times 10^{-2}$ to 0.57 | 1.2 to 15.0 |
| E155/x (SLAC) | [248, 249] | p, d | $A_1$, $A_2$ | 3.5 to 9.0 | $1.5 \times 10^{-2}$ to 0.75 | 1.2 to 34.7 |
| HERMES (DESY) | [253, 254] | p, $^3$He | $A_1$ | 2.1 to 6.2 | $2.1 \times 10^{-2}$ to 0.85 | 0.8 to 20 |
| E94010 (JLab) | [256] | $^3$He | $g_1$, $g_2$ | 1.0 to 2.4 | $1.9 \times 10^{-2}$ to 1.0 | 0.019 to 1.2 |
| EG1a (JLab) | [257] | p, d | $A_1$ | 1.0 to 2.1 | $5.9 \times 10^{-2}$ to 1.0 | 0.15 to 1.8 |
| RSS (JLab) | [258, 259] | p, d | $A_1$, $A_2$ | 1.0 to 1.9 | 0.3 to 1.0 | 0.8 to 1.4 |
| COMPASS (CERN) DIS | [251] | p, d | $A_1$ | 7.0 to 15.5 | $4.6 \times 10^{-3}$ to 0.6 | 1.1 to 62.1 |
| COMPASS (CERN) low-$Q^2$ | [280] | p, d | $A_1$ | 5.2 to 19.1 | $4 \times 10^{-5}$ to $4 \times 10^{-2}$ | 0.001 to 1. |
| EG1b (JLab) | [260, 261, 262, 263] | p, d | $A_1$ | 1.0 to 3.1 | $2.5 \times 10^{-2}$ to 1.0 | 0.05 to 4.2 |
| E99-117 (JLab) | [264] | $^3$He | $A_1$, $A_2$ | 2.0 to 2.5 | 0.33 to 0.60 | 2.7 to 4.8 |
| E99-107 (JLab) | [265] | $^3$He | $g_1$, $g_2$ | 2.0 to 2.5 | 0.16 to 0.20 | 0.57 to 1.34 |
| E01-012 (JLab) | [266, 267] | $^3$He | $g_1$, $g_2$ | 1.0 to 1.8 | 0.33 to 1.0 | 1.2 to 3.3 |
| E97-110 (JLab) | [268] | $^3$He | $g_1$, $g_2$ | 1.0 to 2.6 | $2.8 \times 10^{-3}$ to 1.0 | 0.006 to 0.3 |
| EG4 (JLab) | [269] | p, n | $g_1$ | 1.0 to 2.4 | $7.0 \times 10^{-3}$ to 1.0 | 0.003 to 0.84 |
| SANE (JLab) | [271] | p | $A_1$, $A_2$ | 1.4 to 2.8 | 0.3 to 0.85 | 2.5 to 6.5 |
| EG1dvcs (JLab) | [270] | p | $A_1$ | 1.0 to 3.1 | $6.9 \times 10^{-2}$ to 0.63 | 0.61 to 5.8 |
| E06-014 (JLab) | [272, 273] | $^3$He | $g_1$, $g_2$ | 1.0 to 2.9 | 0.25 to 1.0 | 1.9 to 6.9 |
| E06-010/011 (JLab) | [278] | $^3$He | single spin asy. | 2.4 to 2.9 | 0.16 to 0.35 | 1.4 to 2.7 |
| E07-013 (JLab) | [72] | $^3$He | single spin asy. | 1.7 to 2.9 | 0.16 to 0.65 | 1.1 to 4.0 |
| E08-027 (JLab) | [309] | p | $g_1$, $g_2$ | 1. to 2.1 | $3.0 \times 10^{-3}$ to 1.0 | 0.02 to 0.4 |

+ polarised RHIC

# Impact-parameter distributions: nuclear shape & deformation

- Exclusive VM production in UPCs in AA allows the extraction of nuclear shape, including deformation.

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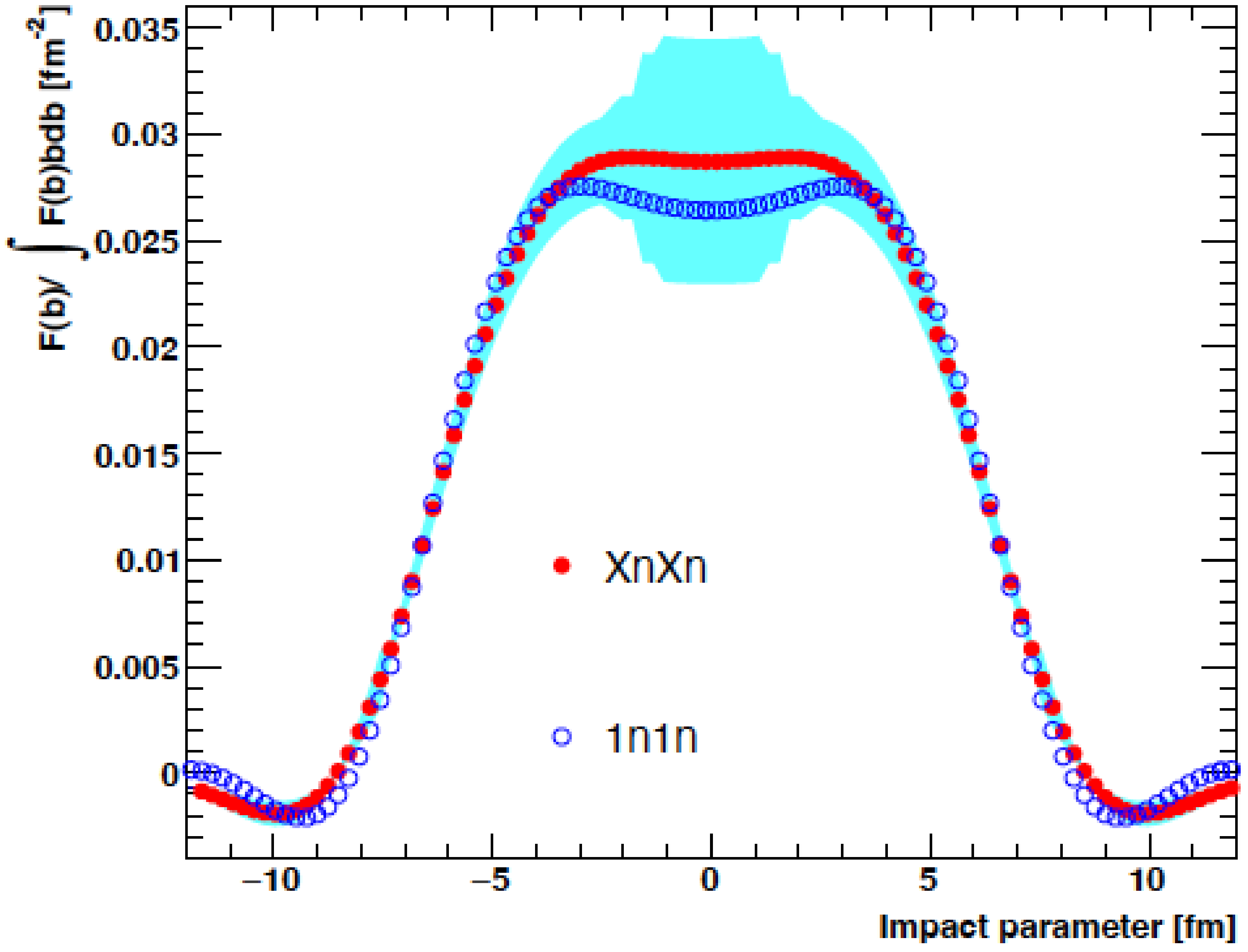
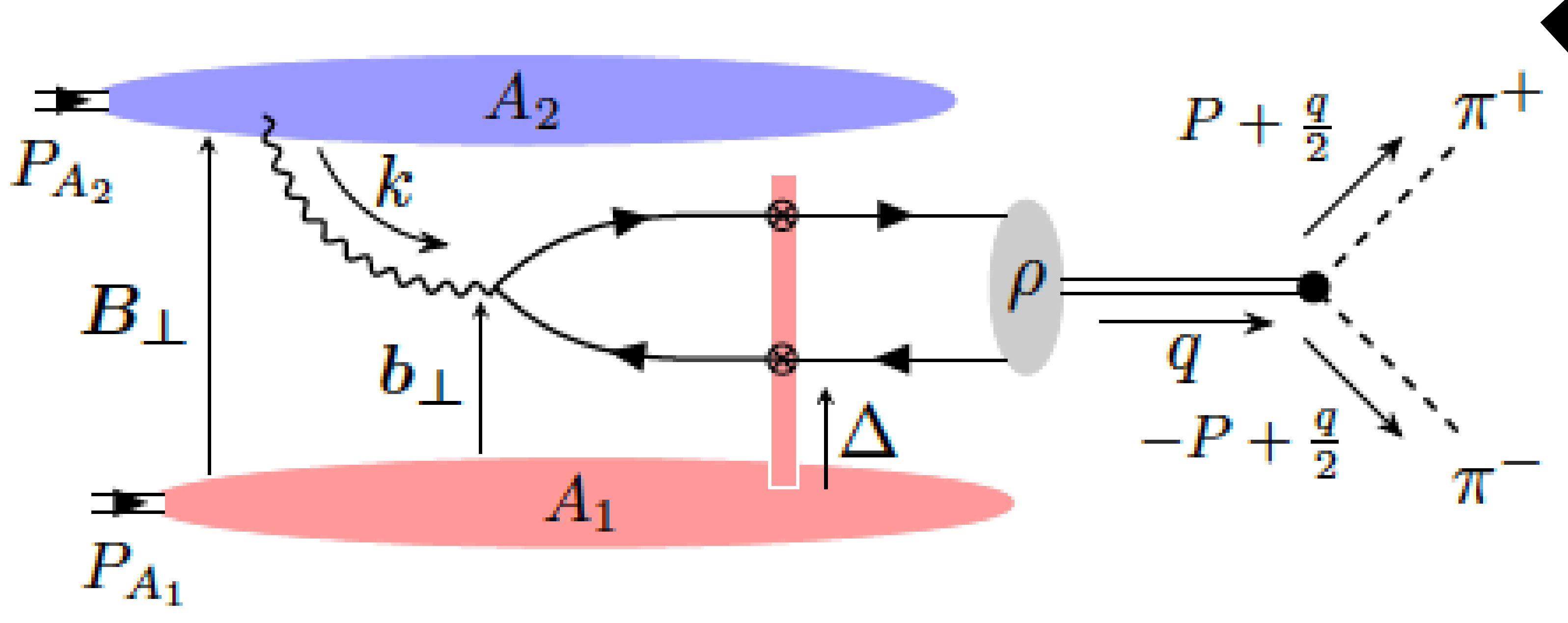
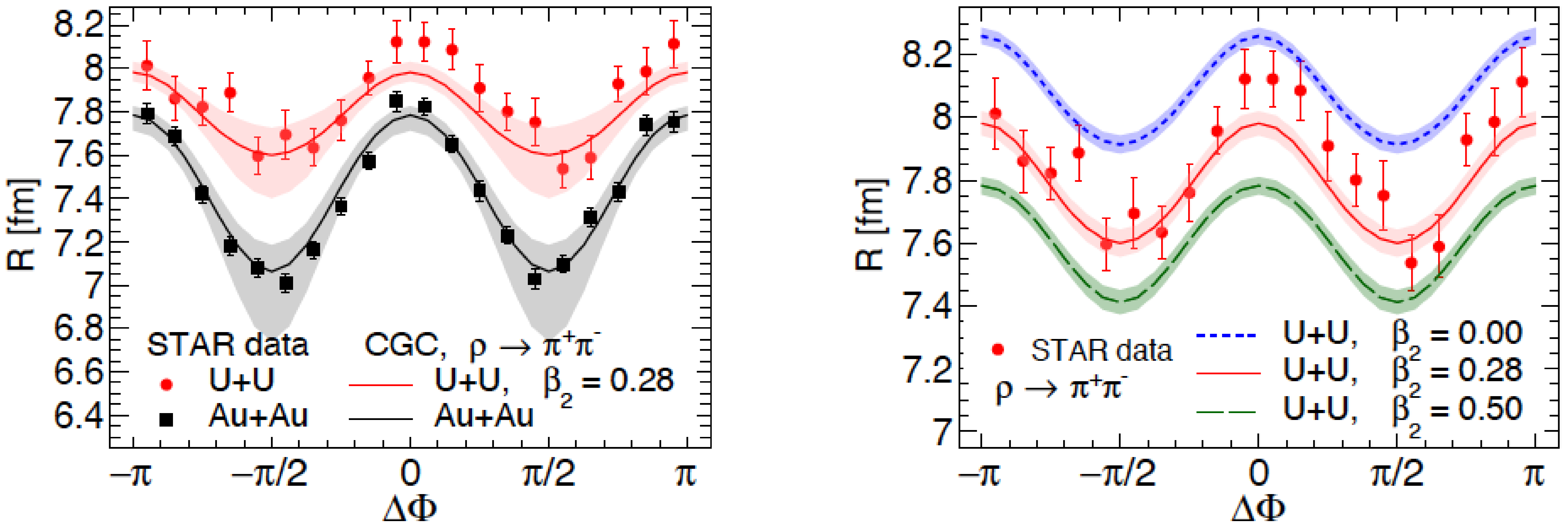



2310.15300



# TMDs and GPDs: goals and challenges

- **Data**: substantial progress expected from upcoming experiments (EIC) ⇒ need of large amounts from different observables in order to constrain the numerous TMDs and GPDs, e.g., gluon, flavour dependence.

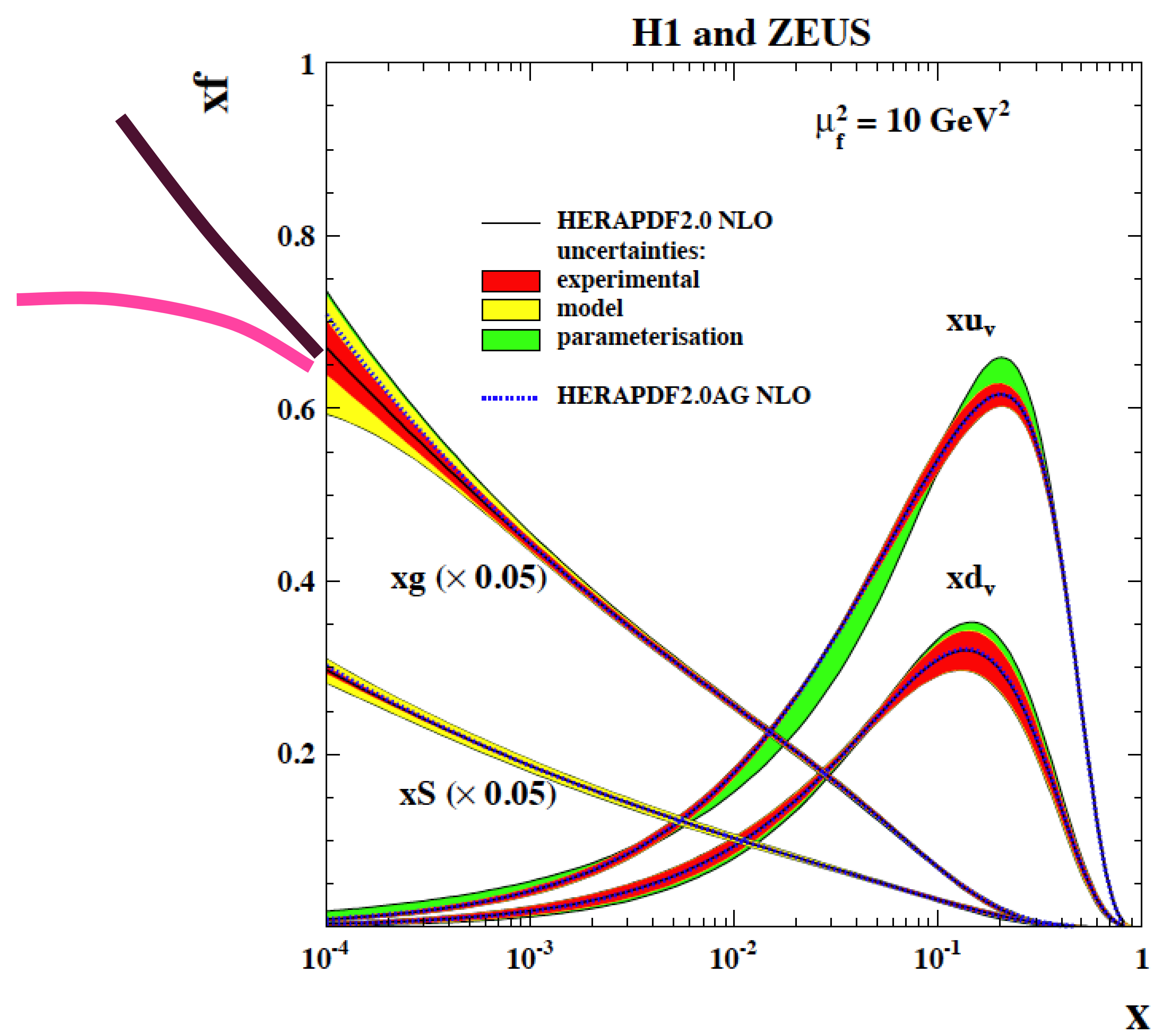
- **Methodology**: many developments, several parameterisations, full method of extraction still lacking for GPDs ⇒ increasing complexity (TMD PDFs and FFs have to be included), interplay with collinear PDFs and FFs, extension to nuclei.

- **Theory**: for TMDs large perturbative accuracy available, crucial to achieve the required precision; for GPDs NNLO DVCS available but not yet full NLO evolution ⇒ understanding of theoretical uncertainties, extension to small x and relation with other formalisms, possibility of using non-perturbative information from lattice; completion of the missing pieces.

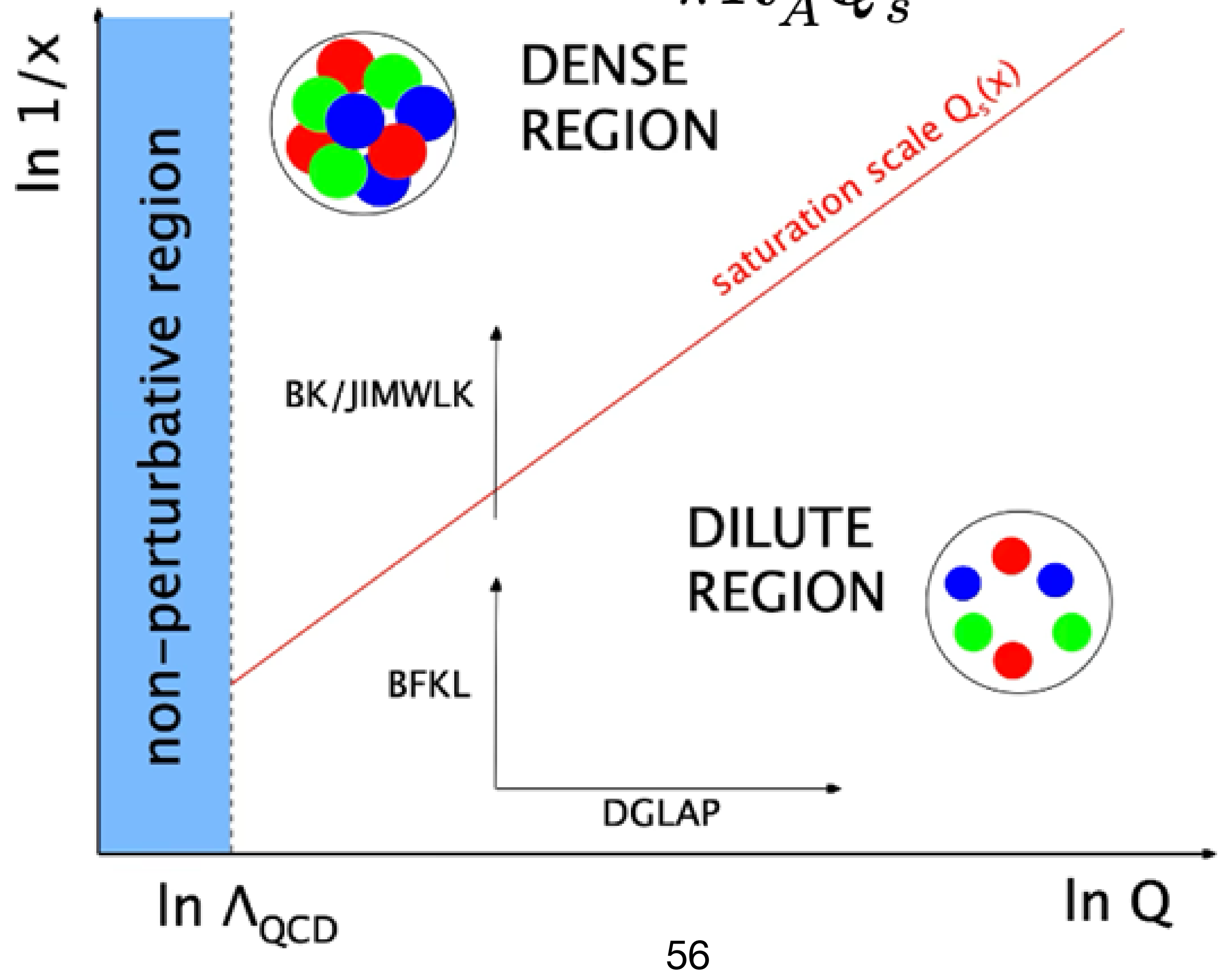
# Small $x$: motivation

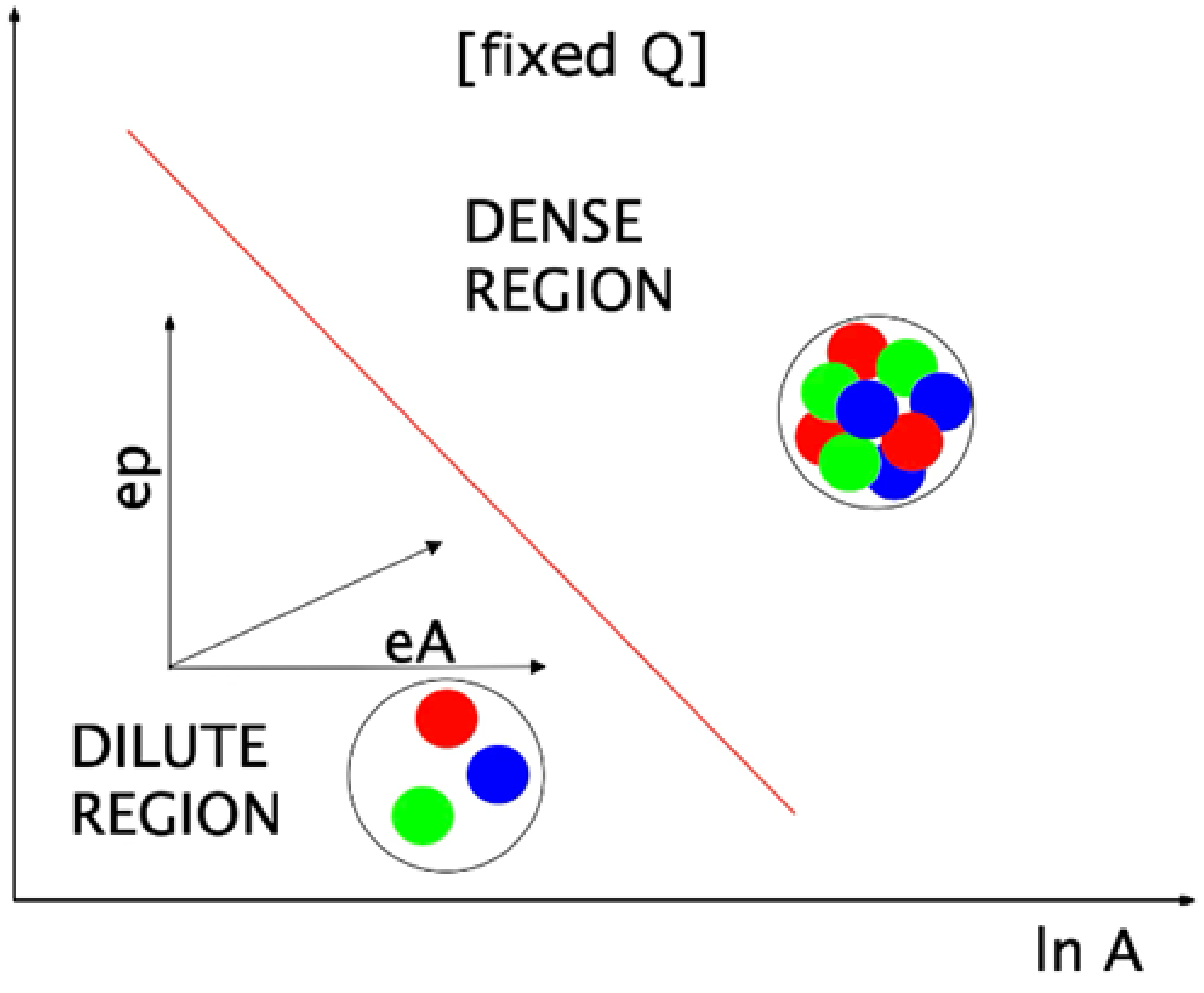
- **In QCD at high energies, standard fixed-order perturbation theory (DGLAP, linear evolution) must eventually fail**:
  → Large logs, e.g., $\alpha_s \ln 1/x \sim 1$: resummation (BFKL, CCFM, ABF, CCSS).
  → High density ⇒ linear evolution cannot hold: saturation, either perturbative (CGC) or non-perturbative.

- **Non-linear effects driven by density**, different from resummation: $x\downarrow$, A↑.




$$\frac{xG_A(x,Q_s^2)}{\pi R_A^2 Q_s^2} \sim 1 \Longrightarrow Q_s^2 \propto A^{1/3} x^{\sim -0.3}$$



# Small $x$: theory status

- LO calculations (single particle and correlations) do not allow a conclusive comparison with data.
- **NLO calculations in the dilute regime: BFKL at NLL (with coll. resummation)**
  - DIS cross sections.
  - Photon-photon cross sections.
  - Jet-gap-jet observables (Mueller-Navelet).
  - Resummations for some observables: Higgs, heavy quarks.
- **NLO calculations in the dense regimen (CGC): JIMWLK/BK at NLL (with collinear resummation)**
  - DIS cross sections: impact factors including HQs.
  - Single particle/jet, and DY+jet, in pA: problems with stability; <u>missing dijet and $\gamma$+jet</u>.
  - Single hadron, dihadron and dijet in DIS: Sudakov resummation, relation with TMDs at small $x$ and link with CSS/DGLAP.
  - Non-eikonal corrections.
- **Relation with TMD factorisation, and search of unified evolution.**
- **Target still simply modeled, characterisation from data not yet fully achieved.**

# Small $x$: experimental situation

- **Experimental observables where small-$x$ effects (resummation, saturation) have been claimed, none of them considered conclusive:**
  - DIS cross sections at HERA at small to moderate $Q^2$: resummation has been suggested as alternative to DGLAP fits, but several models are able to reproduce data.
  - Two-particle correlations in the forward direction at RHIC: $x$ not really small, and competes with standard gluon shadowing.
  - Two-particle correlations in small systems: theory lacks ingredients and presently contradicts some features of data.
  - Exclusive VMs in UPCs: competition with unknown gluon distributions, theoretical caveats.
  - Jet-gap-jet (Tevatron, LHC) and photon-photon (LEP): inconclusive differences between NLL BFKL and DGLAP.

**Lever-arm in $Q^2$ at small $x$ essential!!!**

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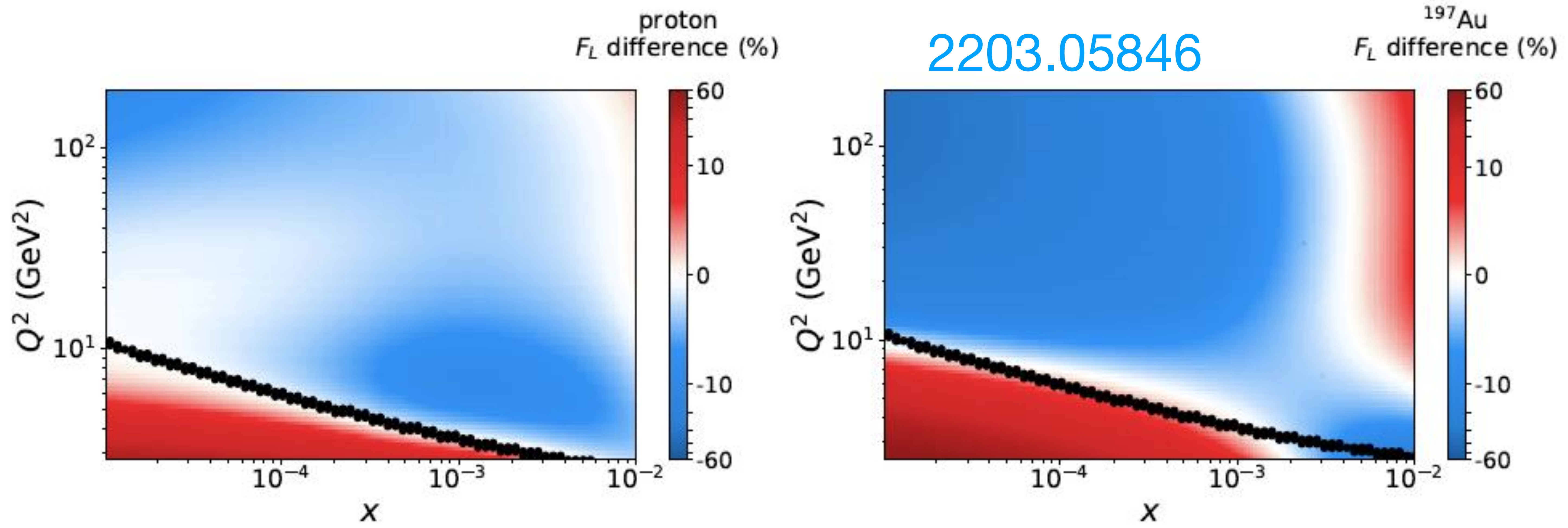

# Lattice: method

- **Since 2013, lattice QCD has provided 1st-principles PDFs, TMDs and GPDs.**

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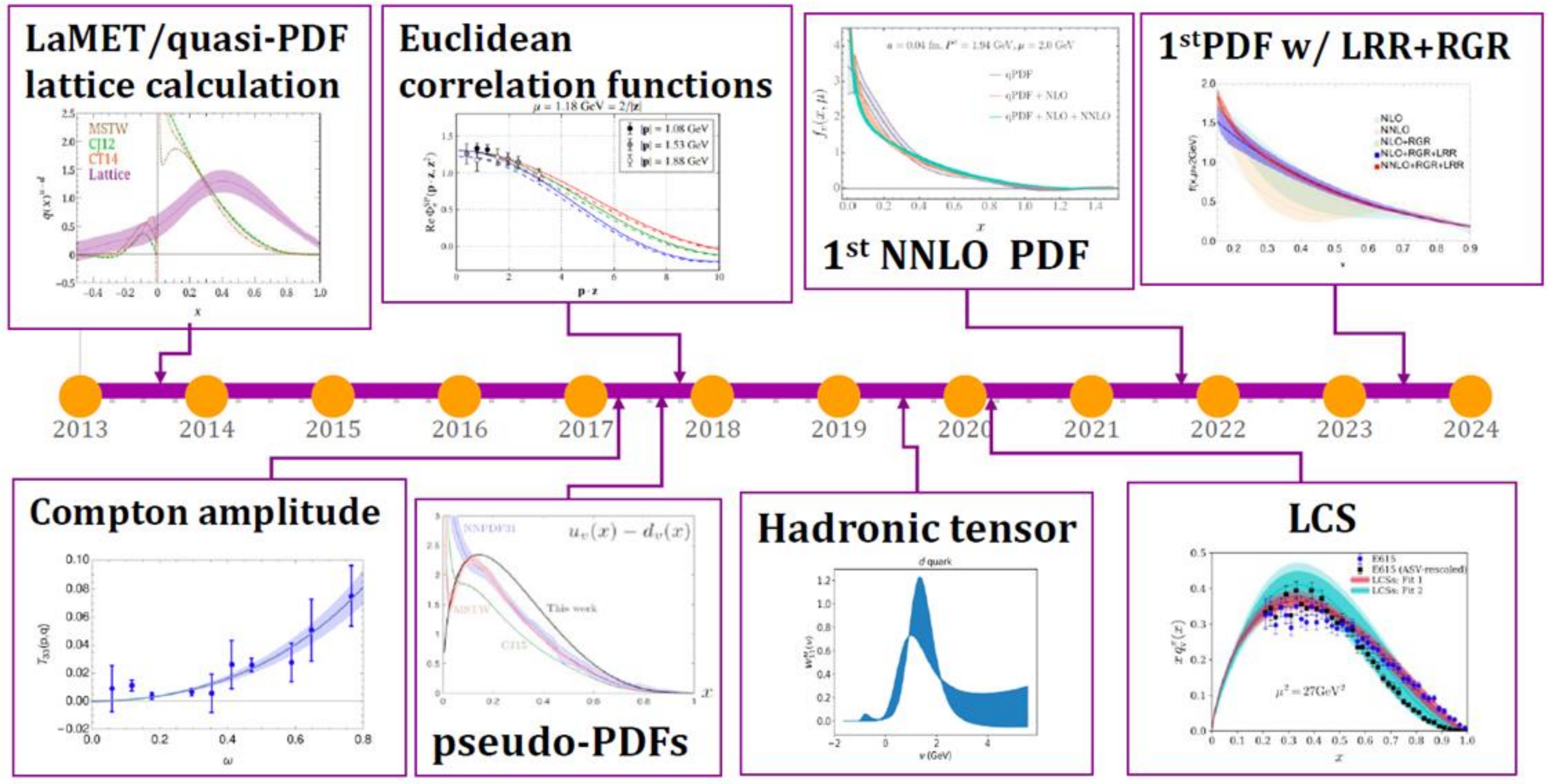


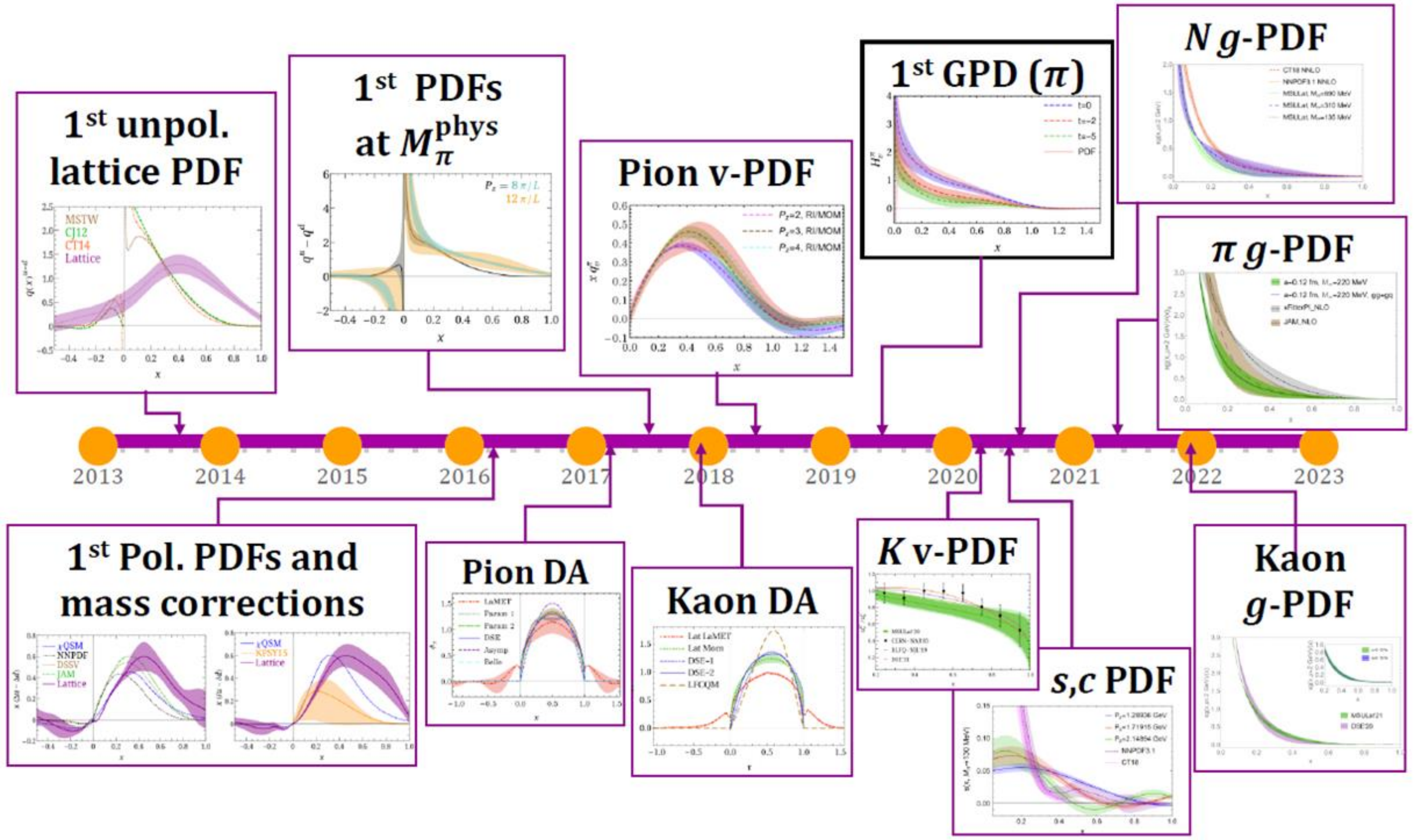


- Equivalence between different methods established, and improved renormalisation schemes.
- 2+1(+1) flavors (physical $m_\pi$ for some quantities) achieved.
- Requires matching perturbative coefficients.

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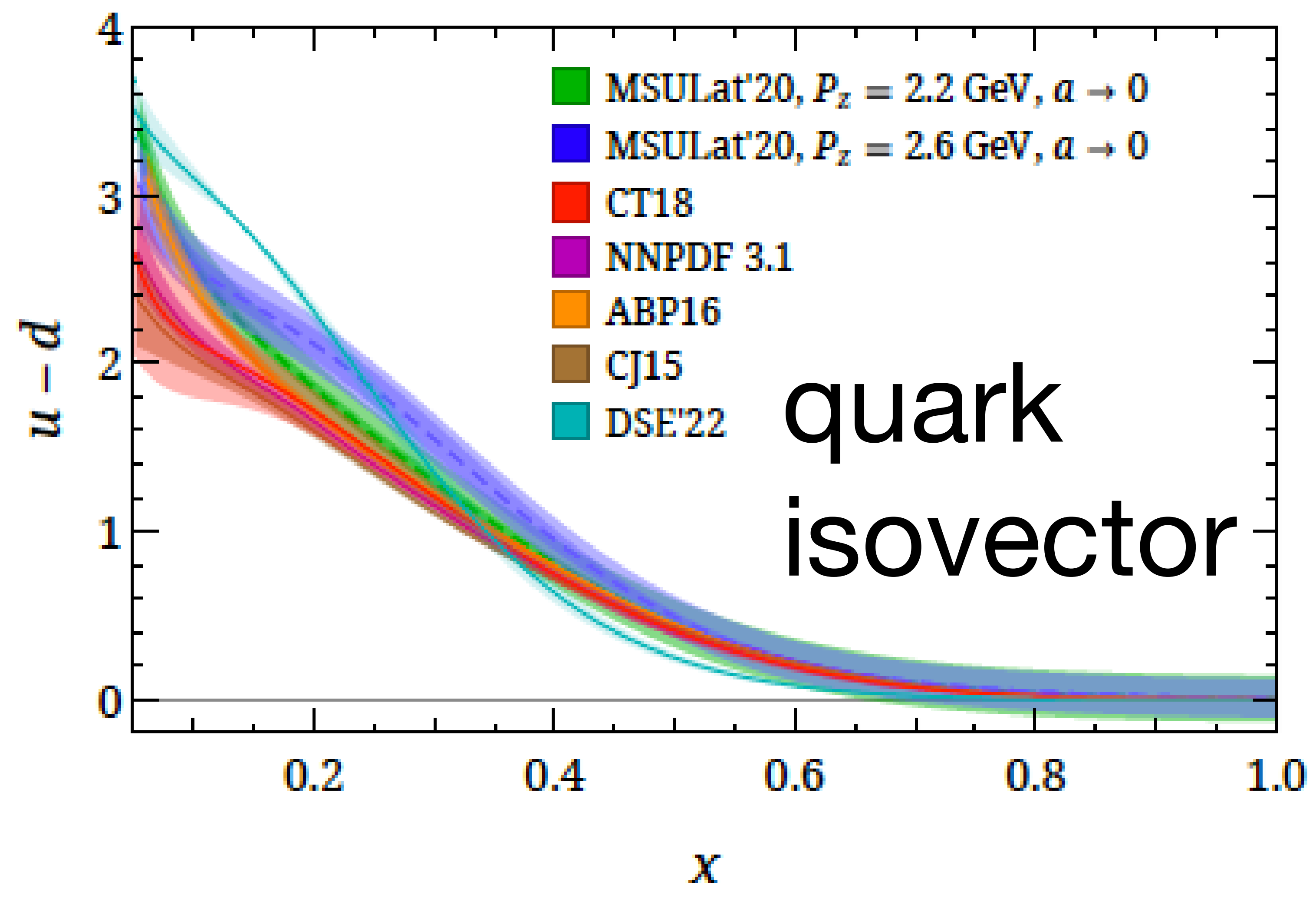
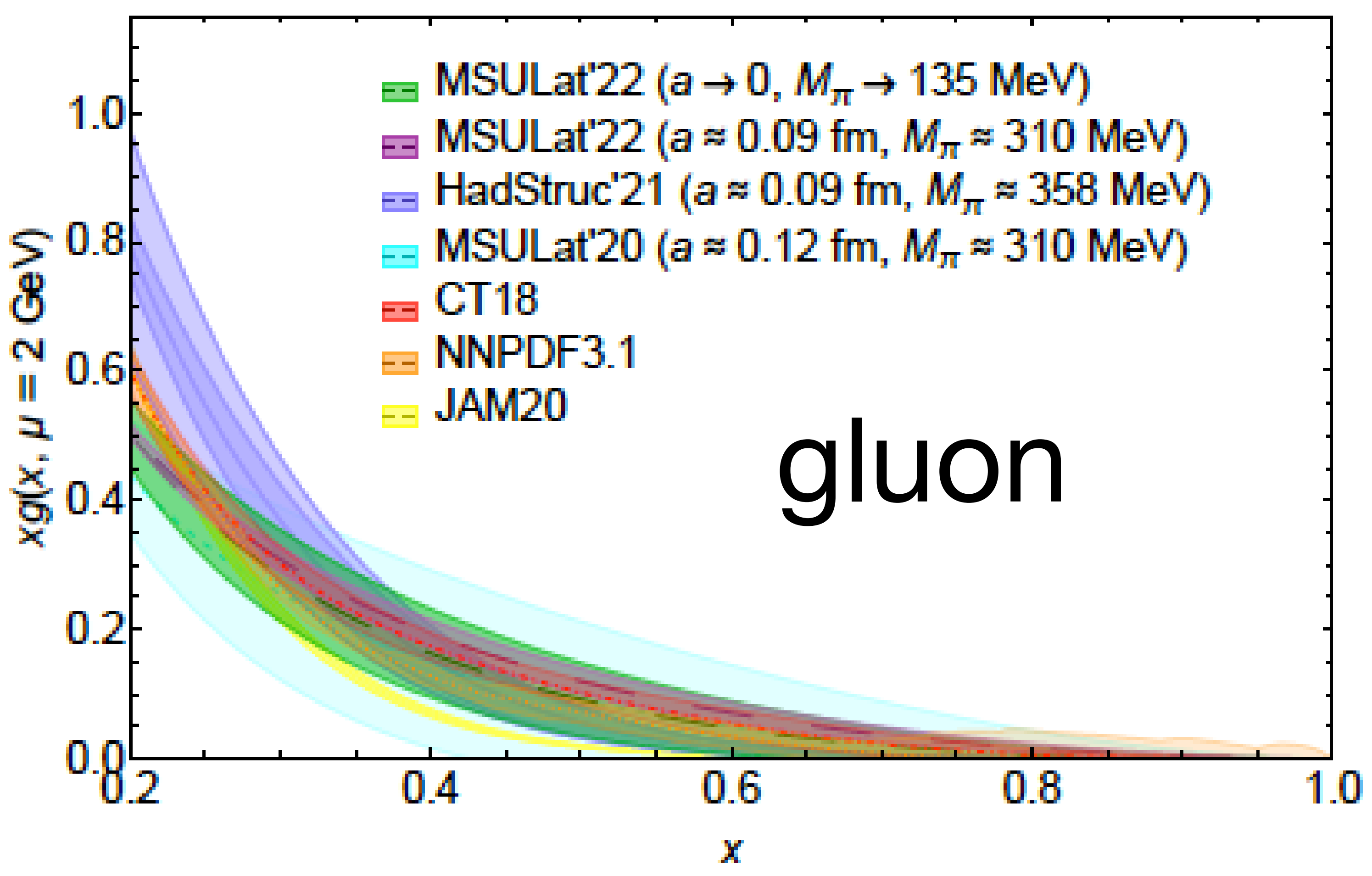
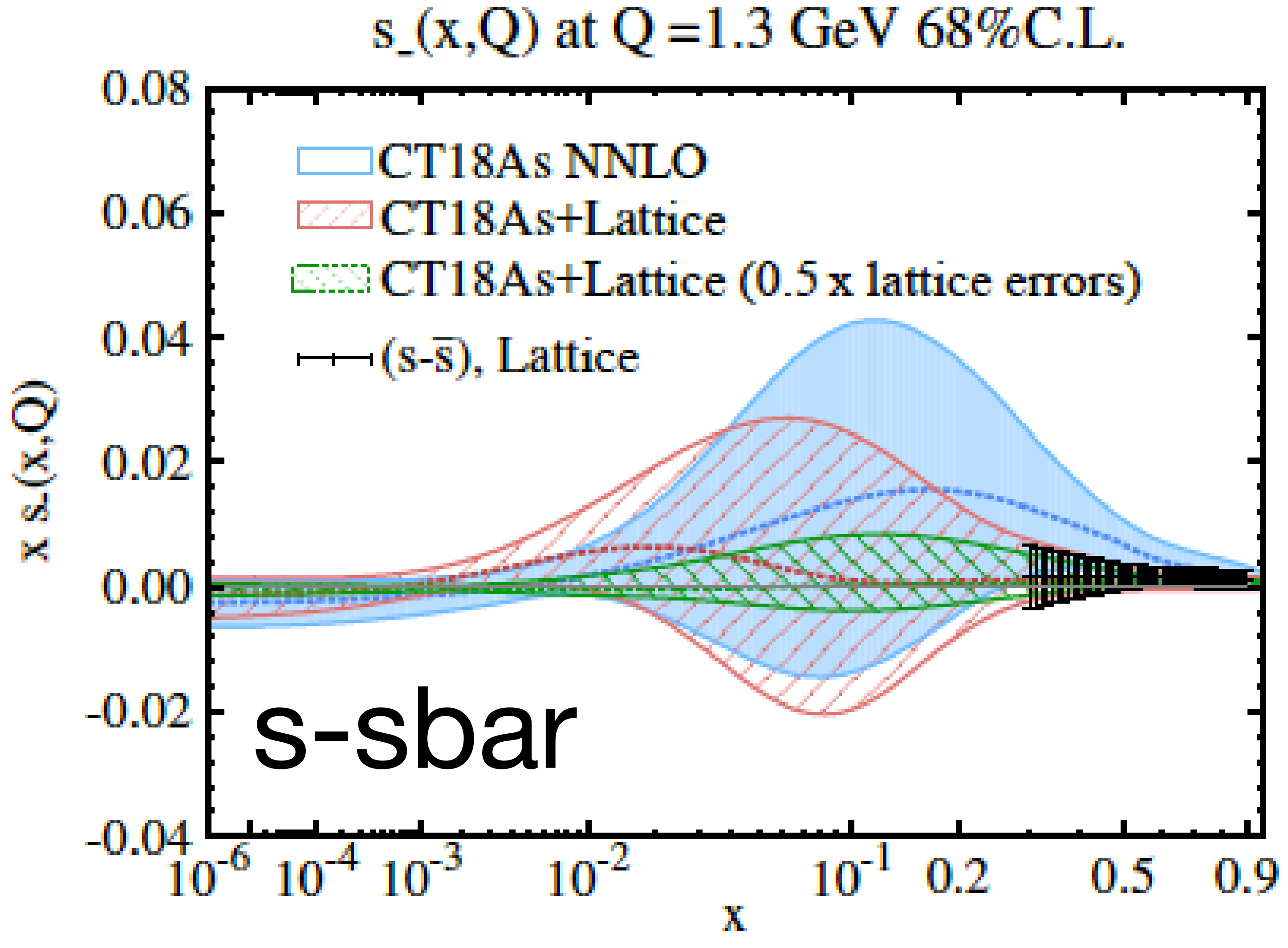
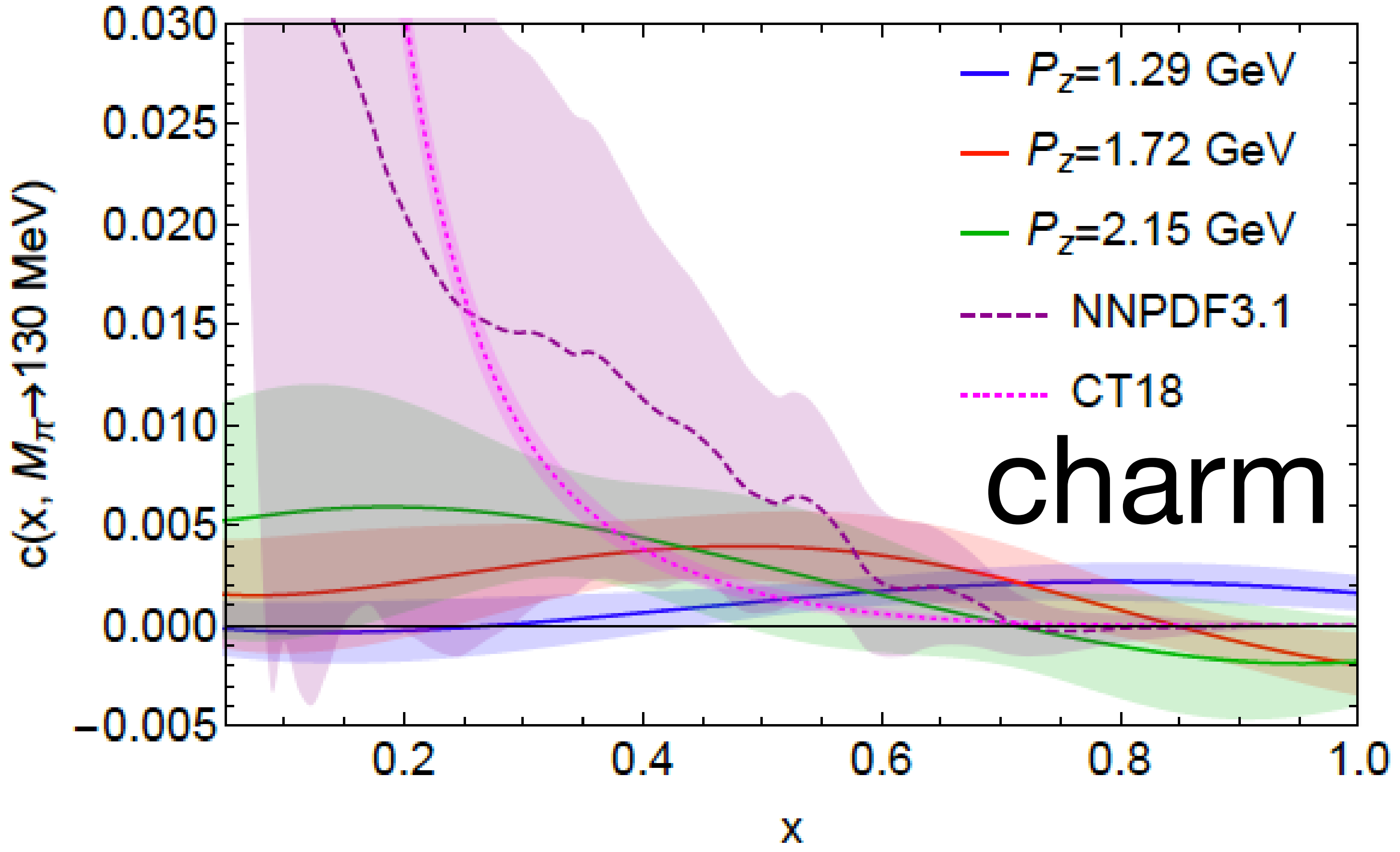
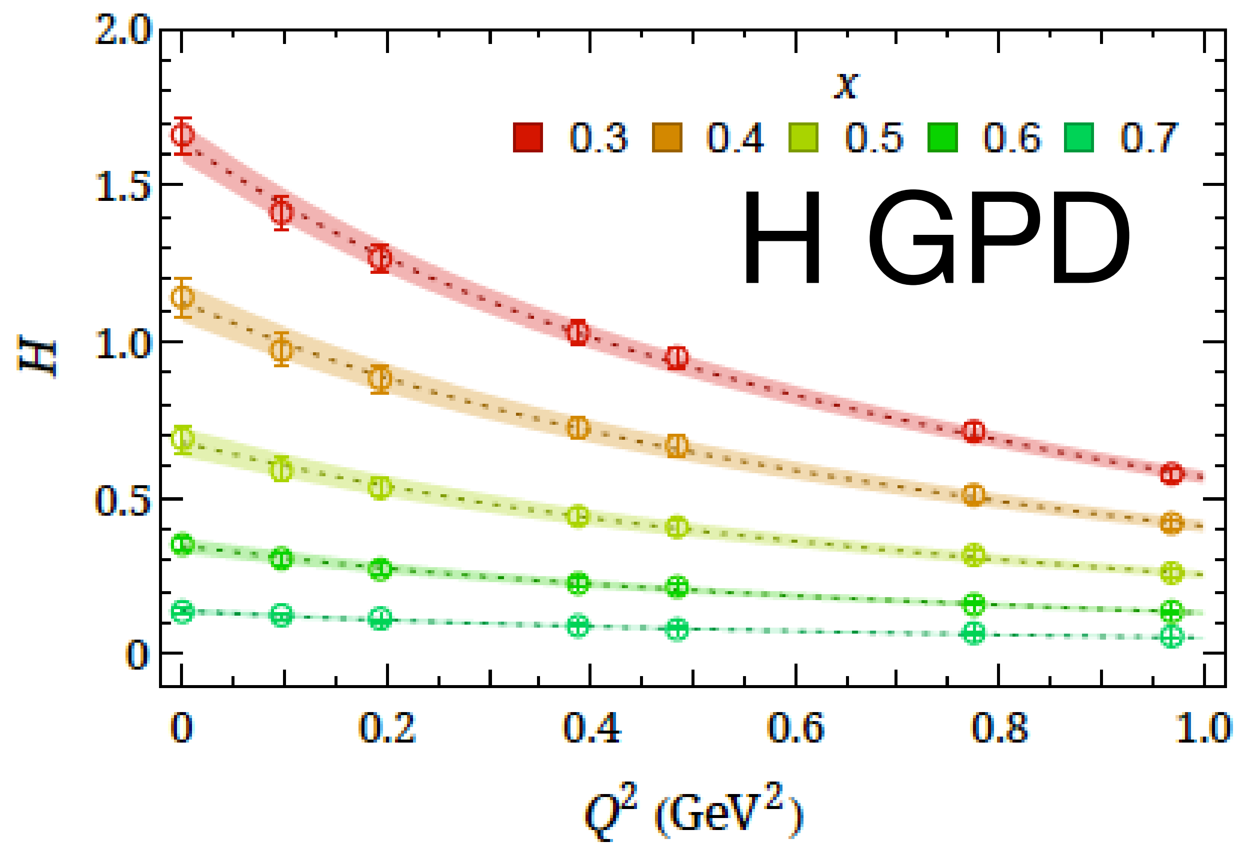
# Lattice: results

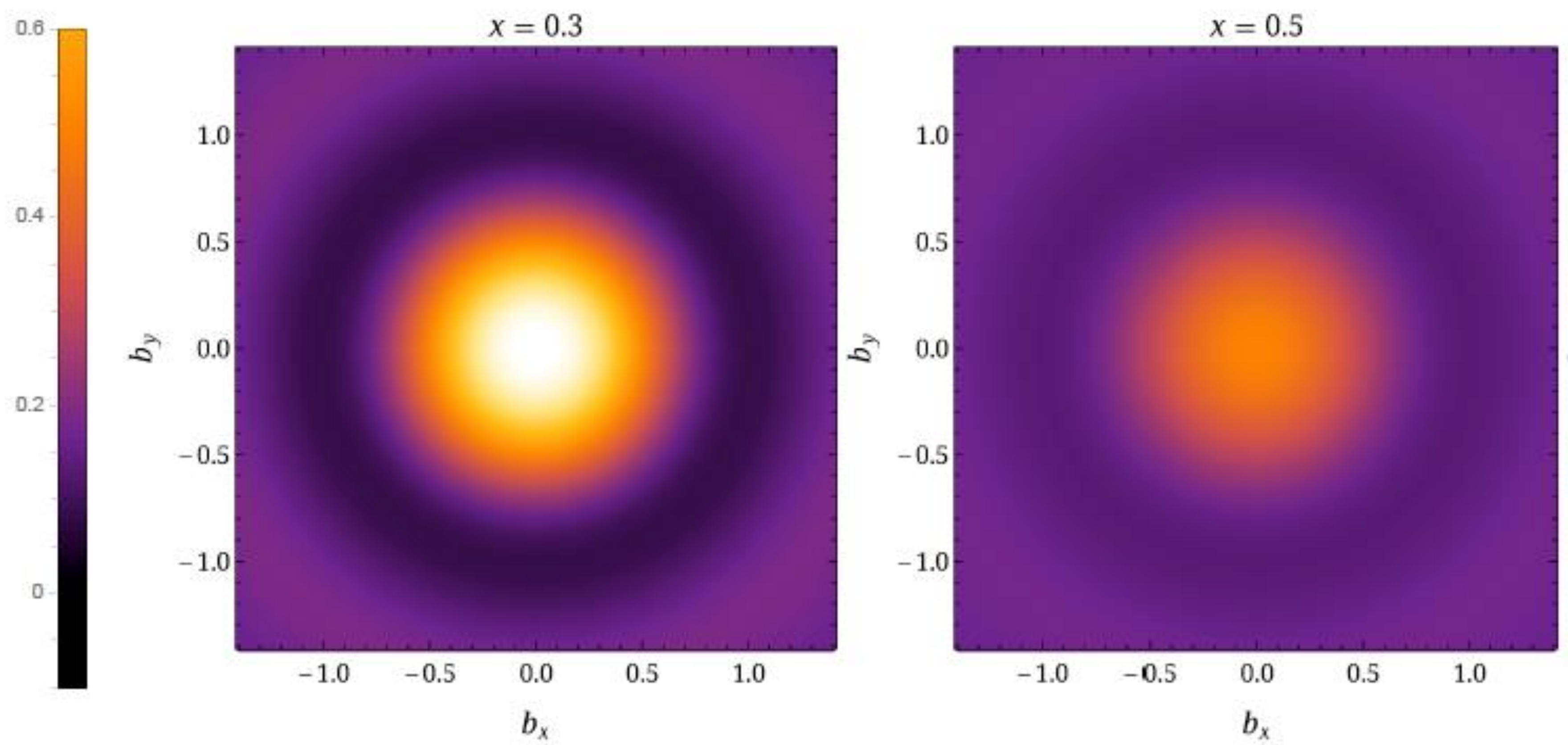


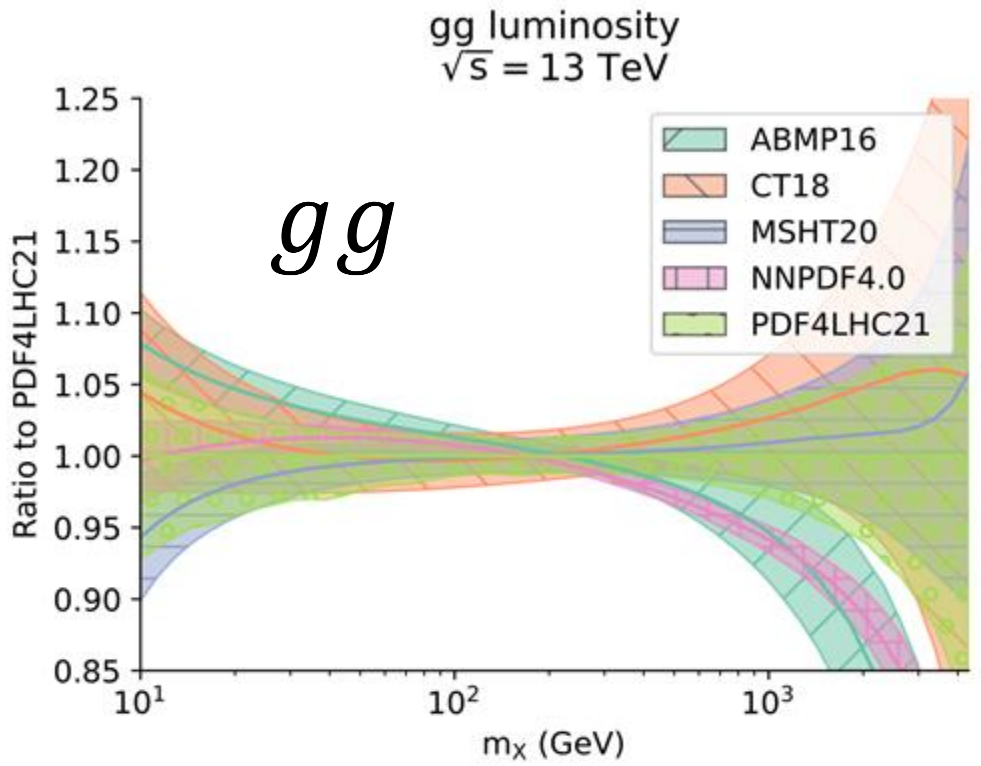



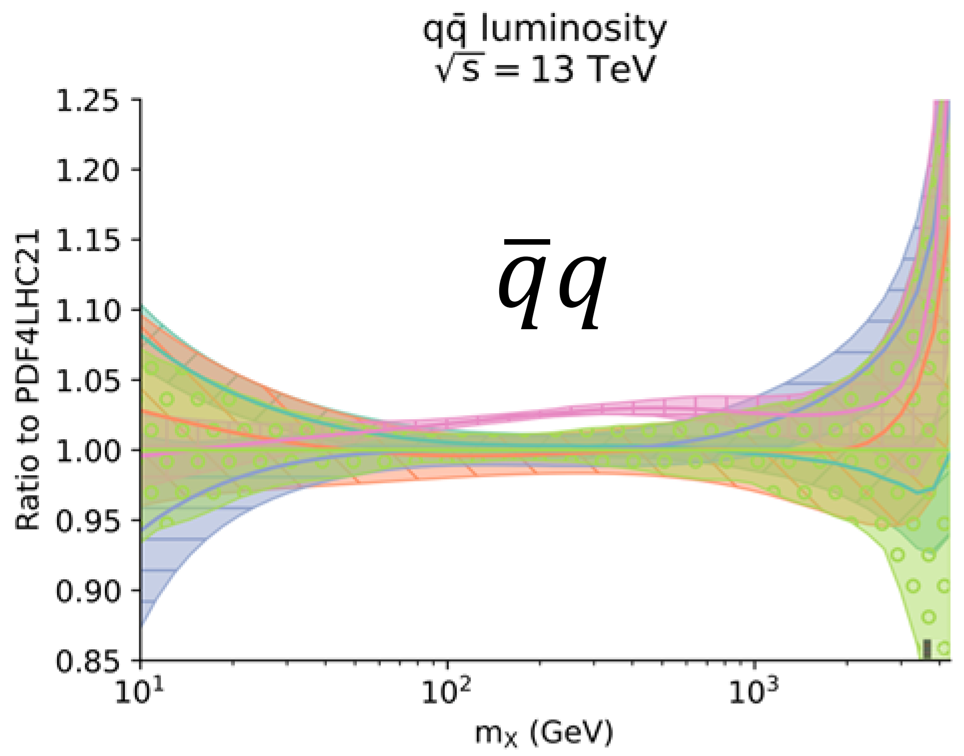

$$q(x, b) = \int \frac{dq}{(2\pi)^2} H(x, \xi = 0, t = -\mathbf{q}^2) e^{i\mathbf{q}\cdot\mathbf{b}}$$

- **Challenges**: signal-to-noise ratios, extrapolation to physical $m_\pi$, suppress systematic uncertainties for large and small x; incorporation of lattice results into global fits (as already done for COMPASS transversity TMD).

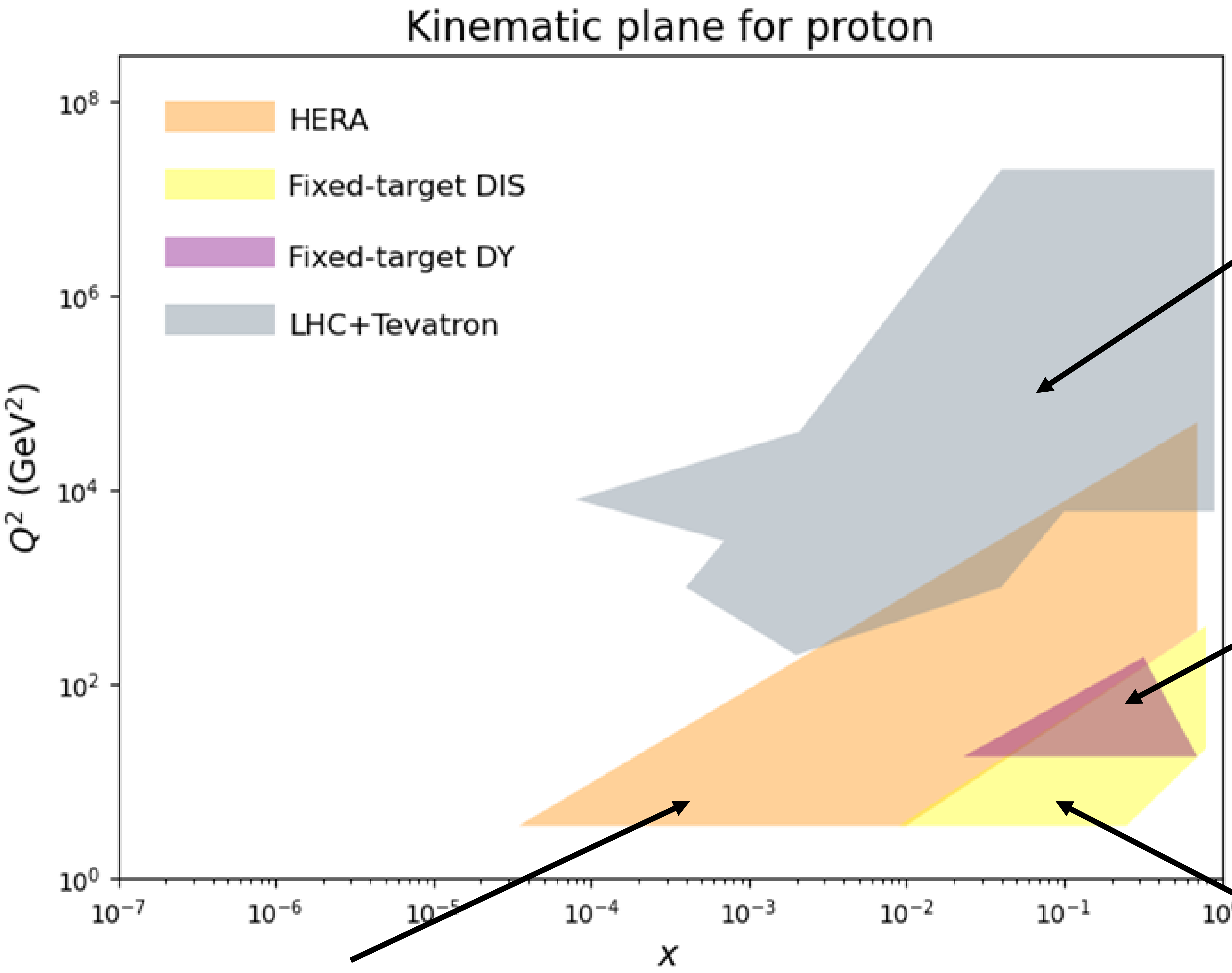
# Kinematic planes for proton

**NNPDF4.0:**
[arXiv: 2109.02653]




2411.05373, 2312.07665, 2406.01779, 2203.05506




LHC: W(+jet), Z, DY, jets and dijets, single and top pair (+jet), isolated photons

Tevatron data: W, Z

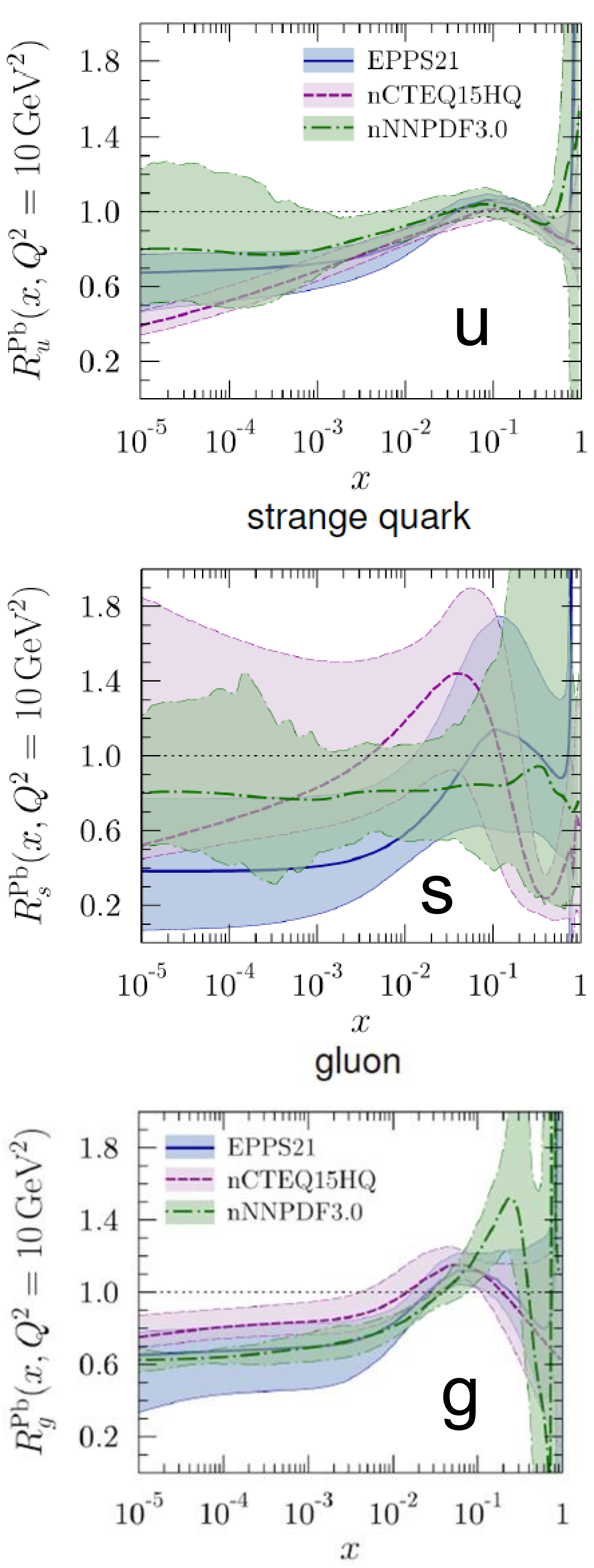
$p(\overline{p}) + p/d$ DY

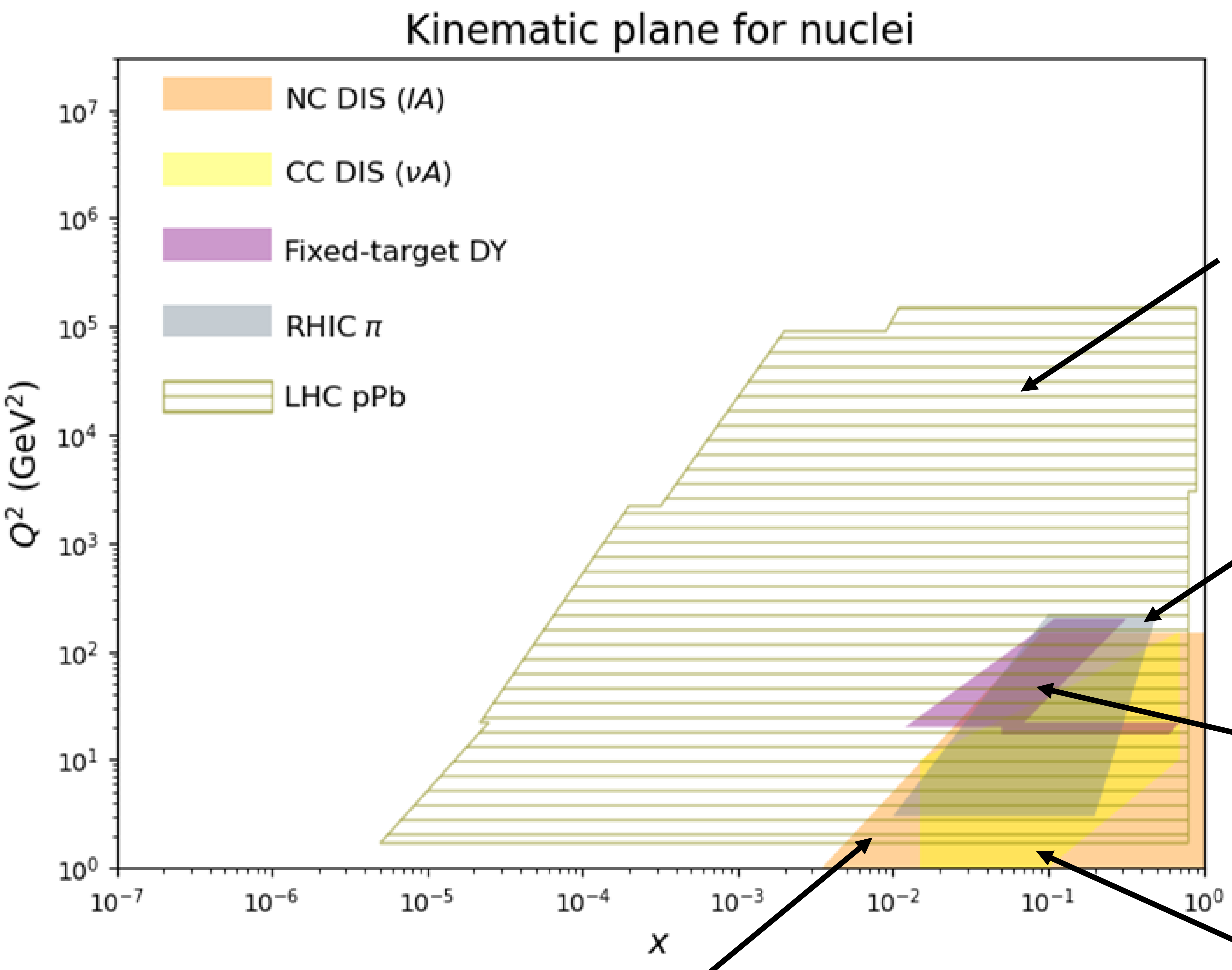
NC($l^{\pm}$) and CC($\nu$) DIS

HERA: NC, CC and jets in DIS

**Review:**
arXiv: 2311.00450

# Kinematic planes for nuclei




LHC: W, Z, jets, light hadrons, isolated photons, D mesons, quarkonia

RHIC: pions

$pA$ and $\pi A$ DY

CC DIS

NC DIS with electrons and muons