# Parton and gluon distributions in nucleons and nuclei: a summary


**Convenors:**

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Maria Żurek (Argonne National Laboratory)

Pía Zurita (Universität Regensburg)

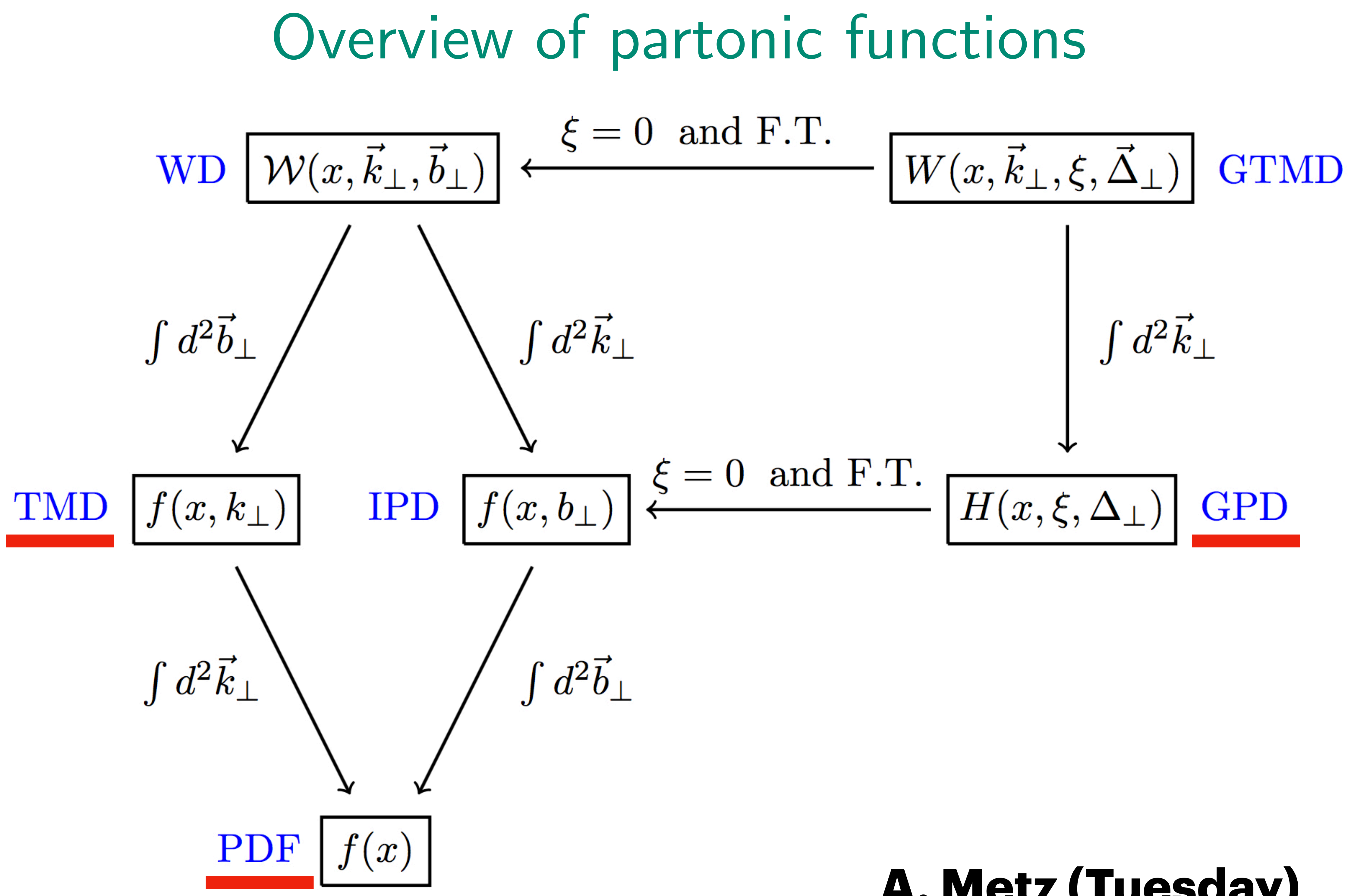


CIPANP2022

September 4th 2022, Orlando, FL, EE.UU.

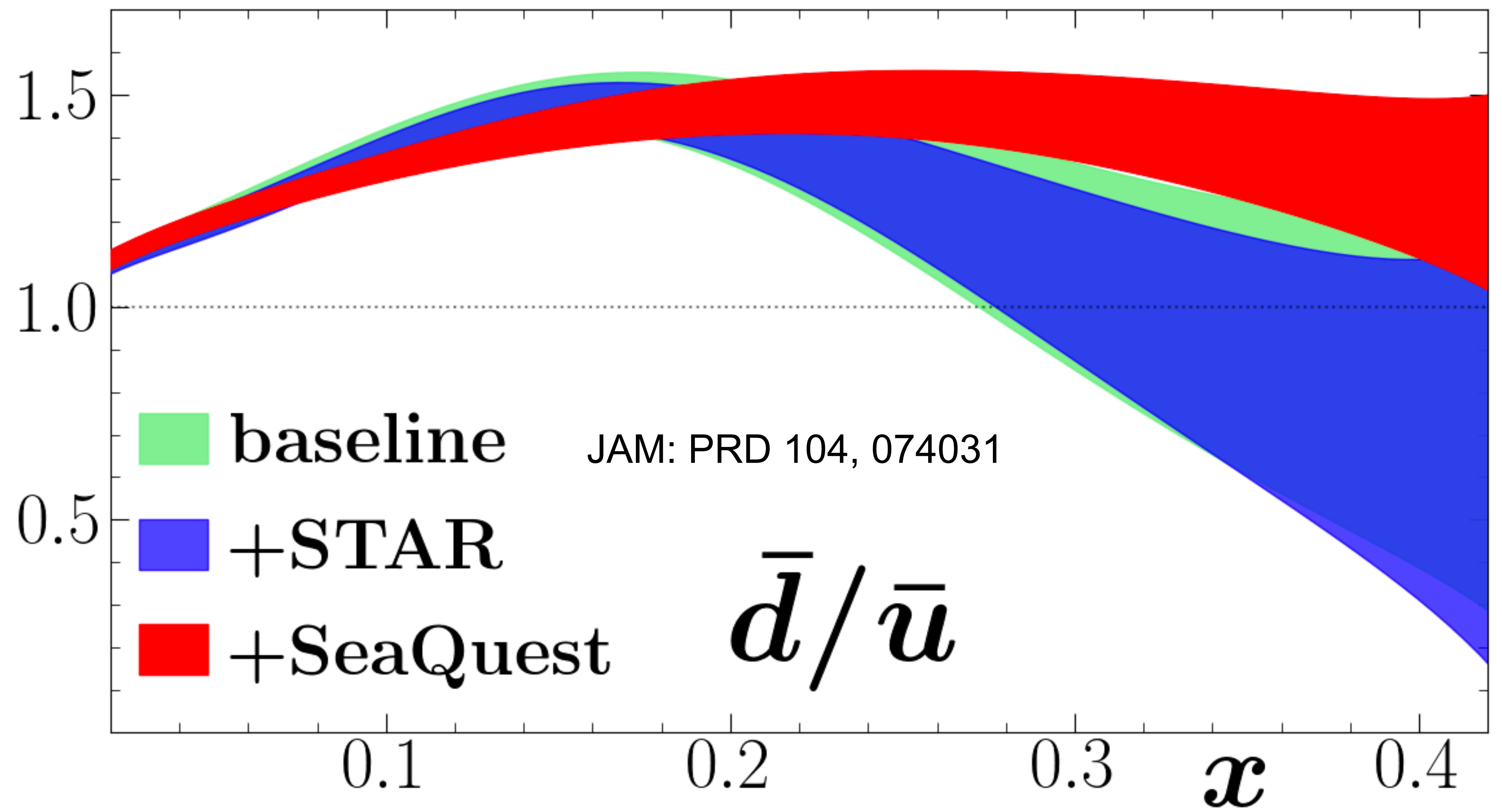
# Summary

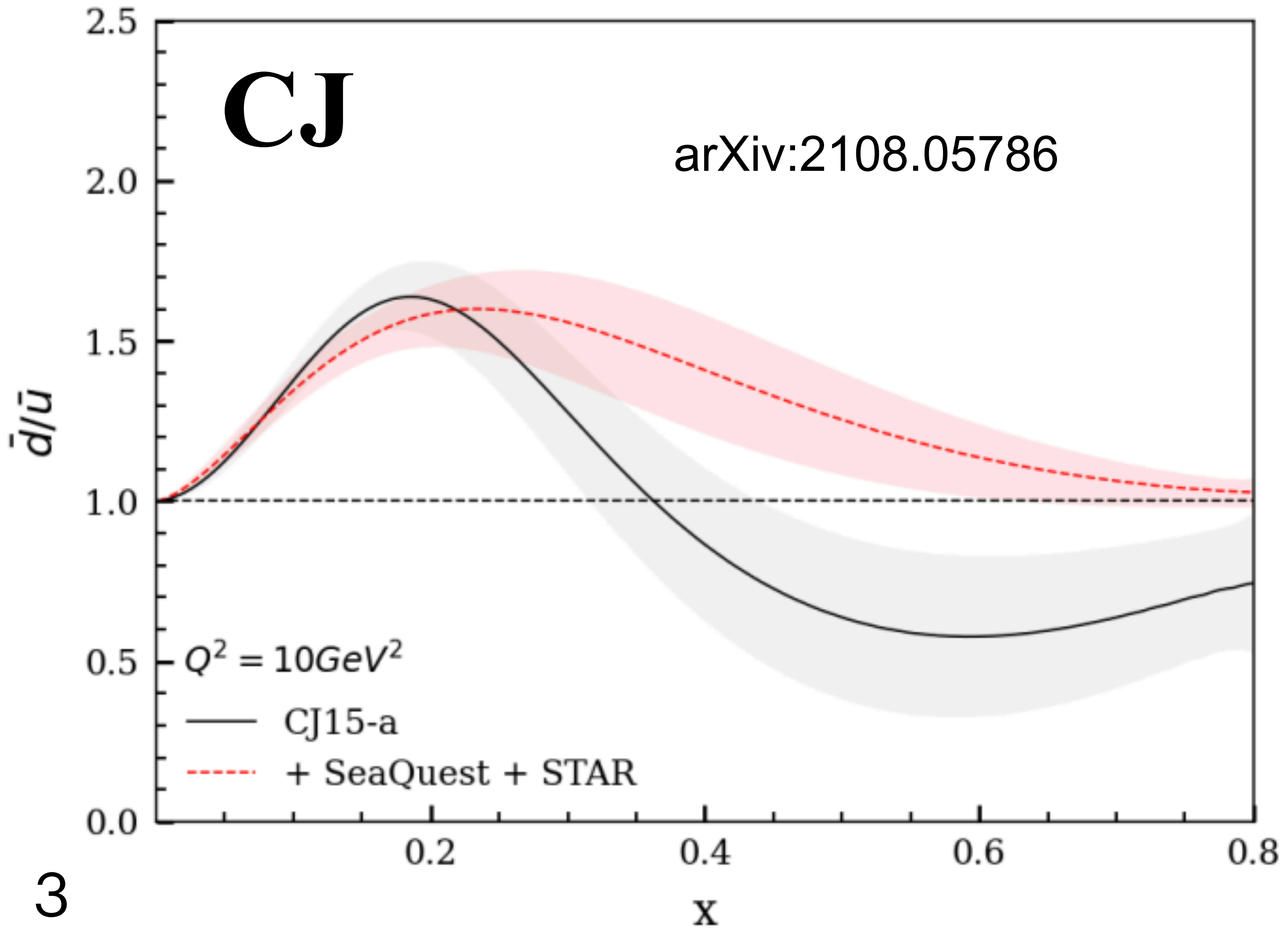
- 4 sessions
- 2 joint sessions with QCD
- 29 talks (26 here)
- Topics:
    - collinear PDFs in proton and nuclei
    - hadronization and FFs
    - Transverse Momentum Dependent distributions
    - Generalised Parton Densities

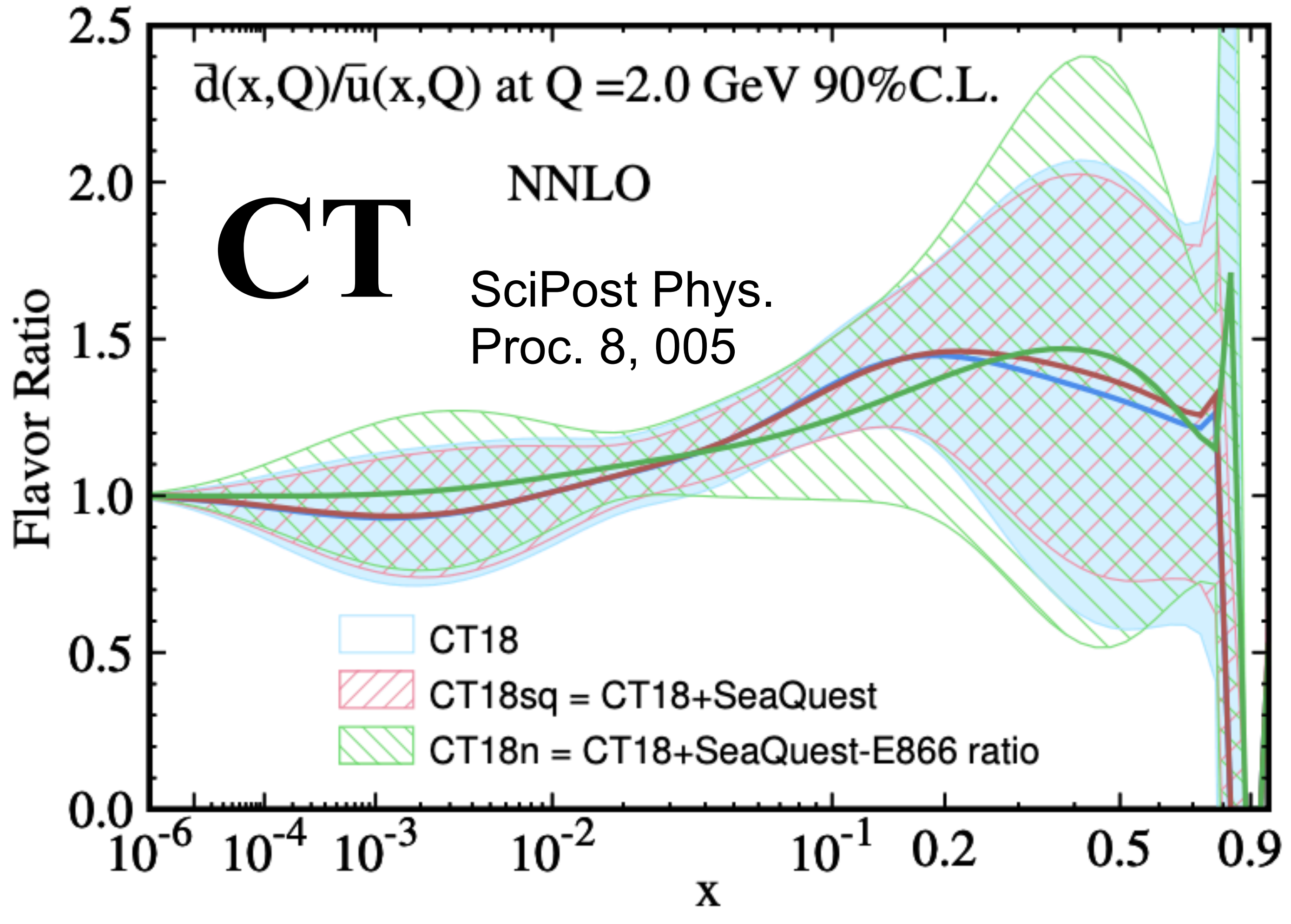



**A. Metz (Tuesday)**

# 1-dimensional unpolarised proton PDFs



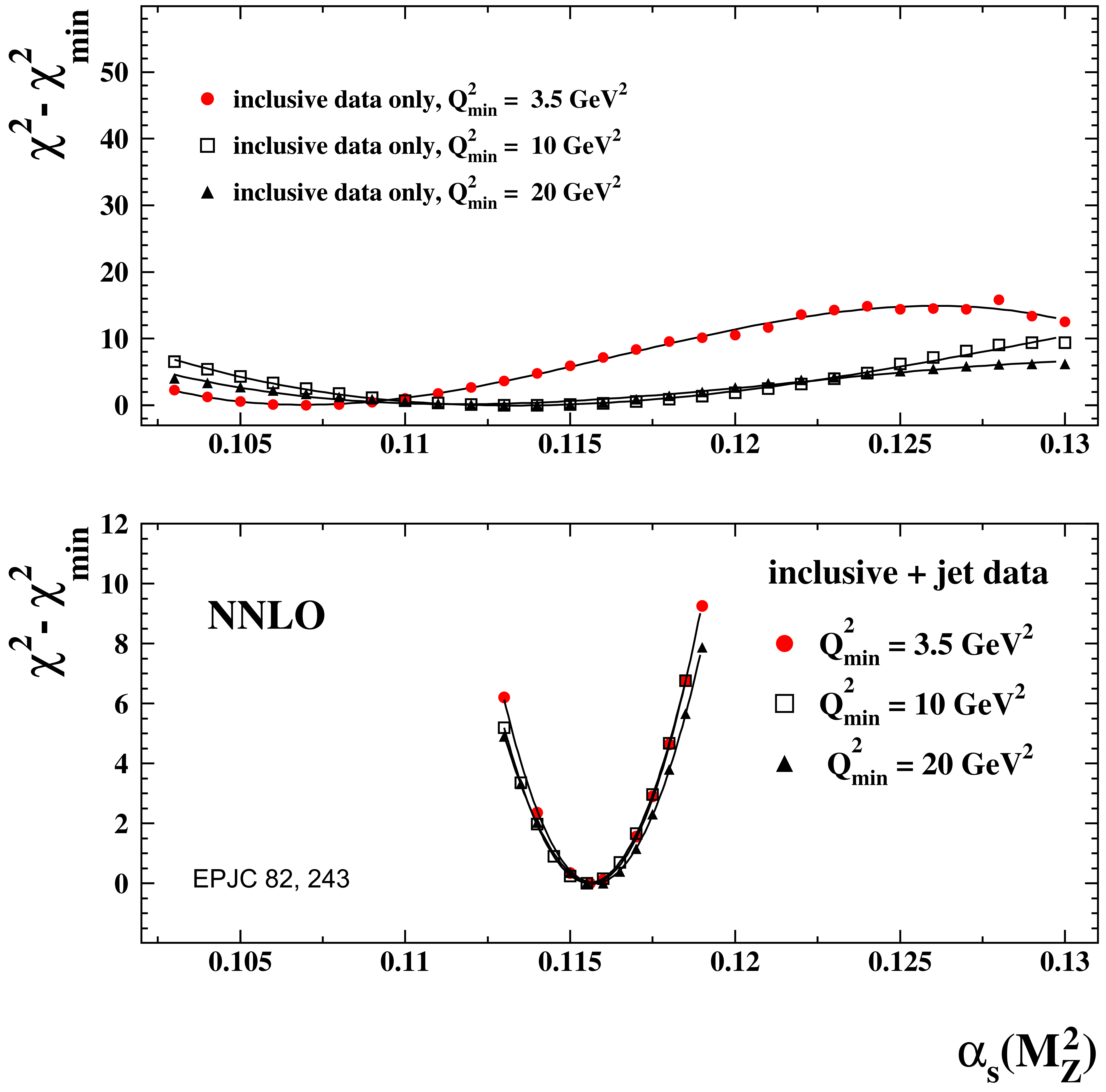




- Increase in central value at x > 0.2 (JAM and CJ).
- Reduction of the uncertainties (JAM and CT).
- Impact of LHC jet data on NNPDF: significant (up to 10%) of the charm PDF and moderate (up to 5%) for the sea quarks.

**C. Cocuzza (Tuesday)**

# 1-dimensional unpolarised proton PDFs

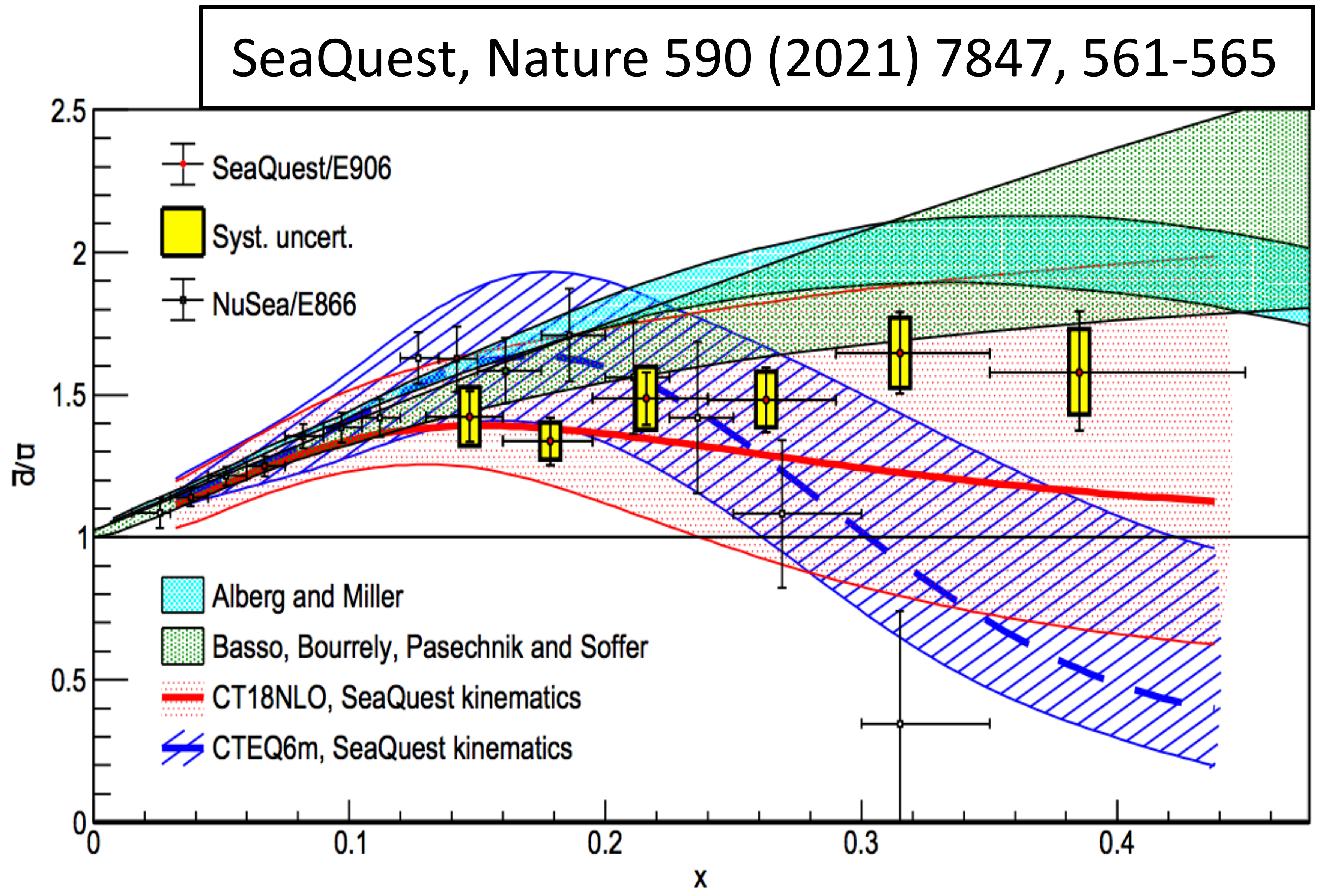


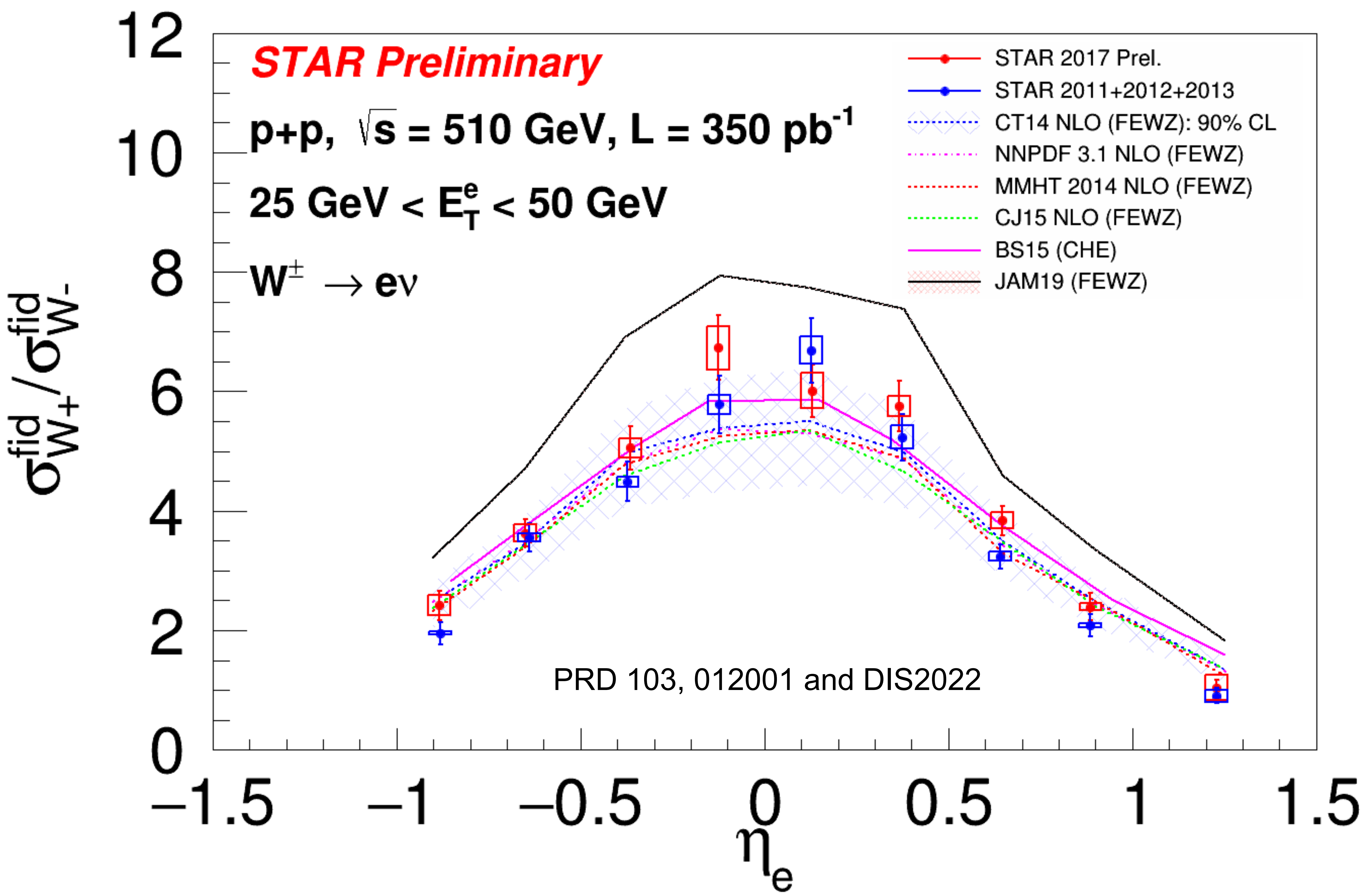

- H1 and ZEUS inclusive DIS data are not very sensitive to $\alpha_s$.
- But the jet data do. And they are fully consistent with inclusive DIS:
  - HERAPDF2.0: $\chi^2$/d.o.f. $= 1.205$
  - HERAPDF2.0Jets: $\chi^2$/d.o.f. $= 1.197$

$$\alpha_s(M_Z^2) = 0.1156 \pm 0.0011 \text{ (exp)}$$

**B. Surrow (Tuesday)**

# 1-dimensional unpolarised proton PDFs

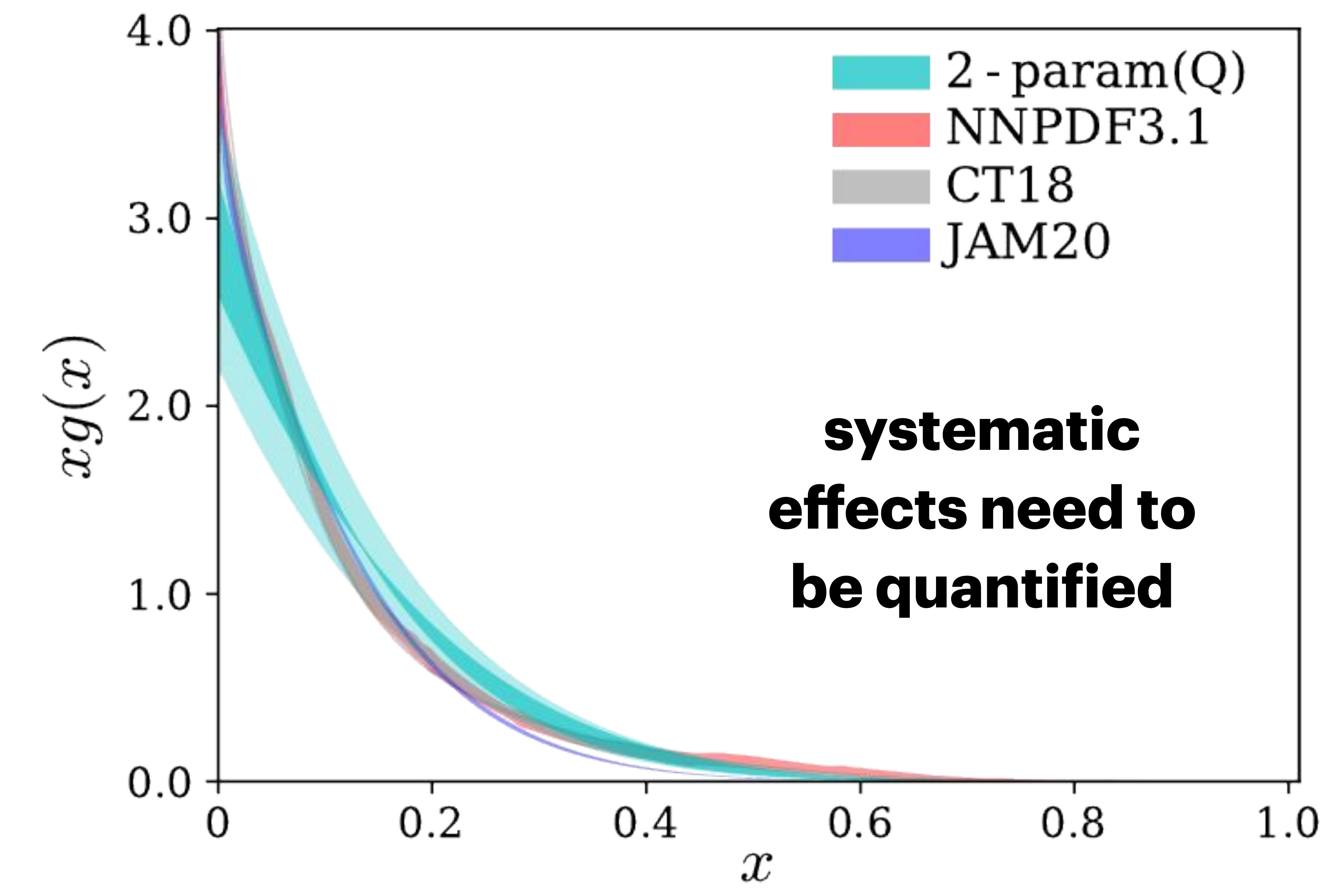


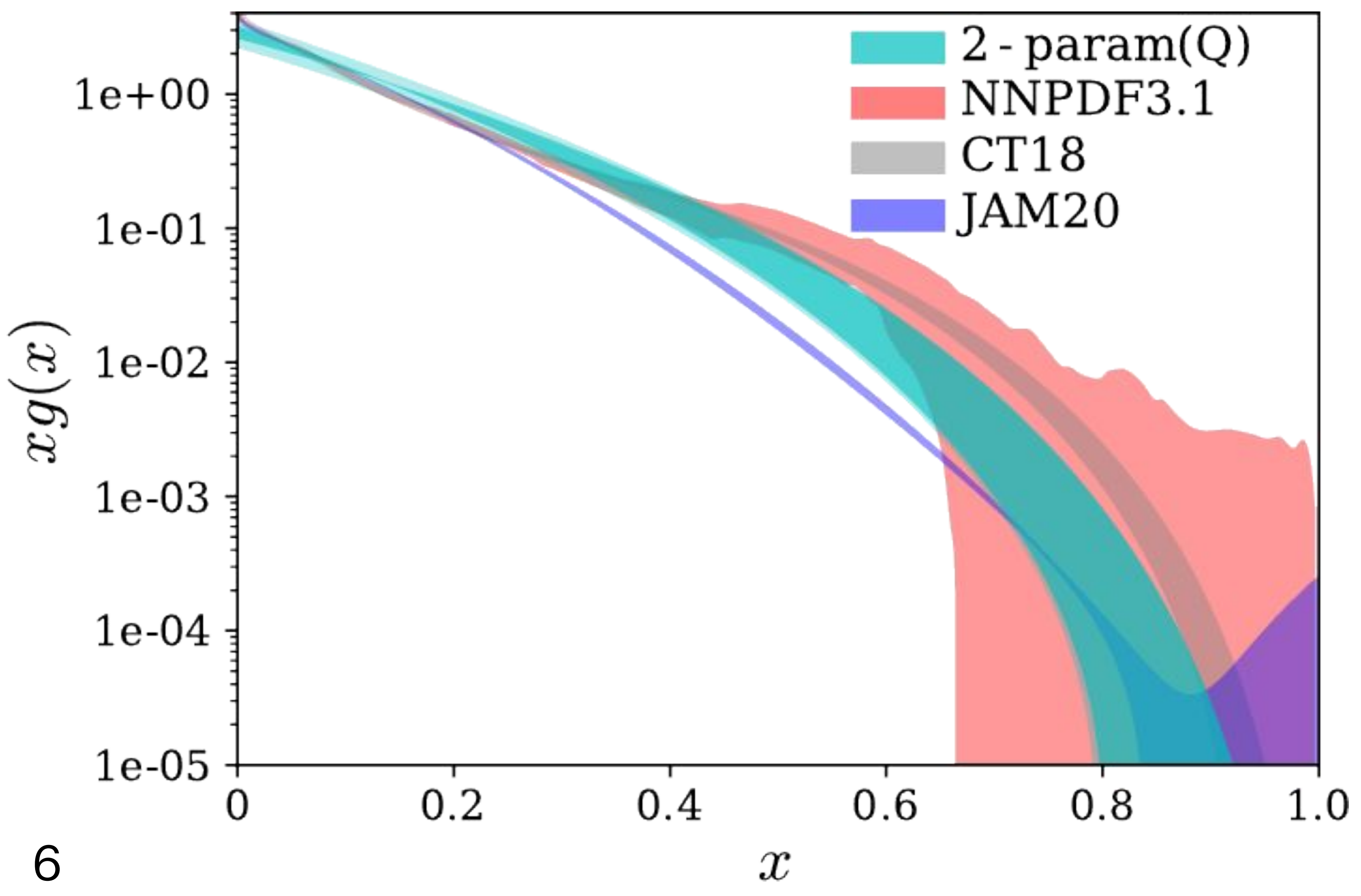




- Inconsistencies between DY NuSea and SeaQuest data at x > 0.2.
- STAR probes the region 0.06 < x < 0.4 at $Q^2 = M_W^2$
- Jet cross-section are sensitive to the gluon density at 0.01 < x < 0.5

**J. Nam (Tuesday)**

# 1-dimensional unpolarised proton PDFs



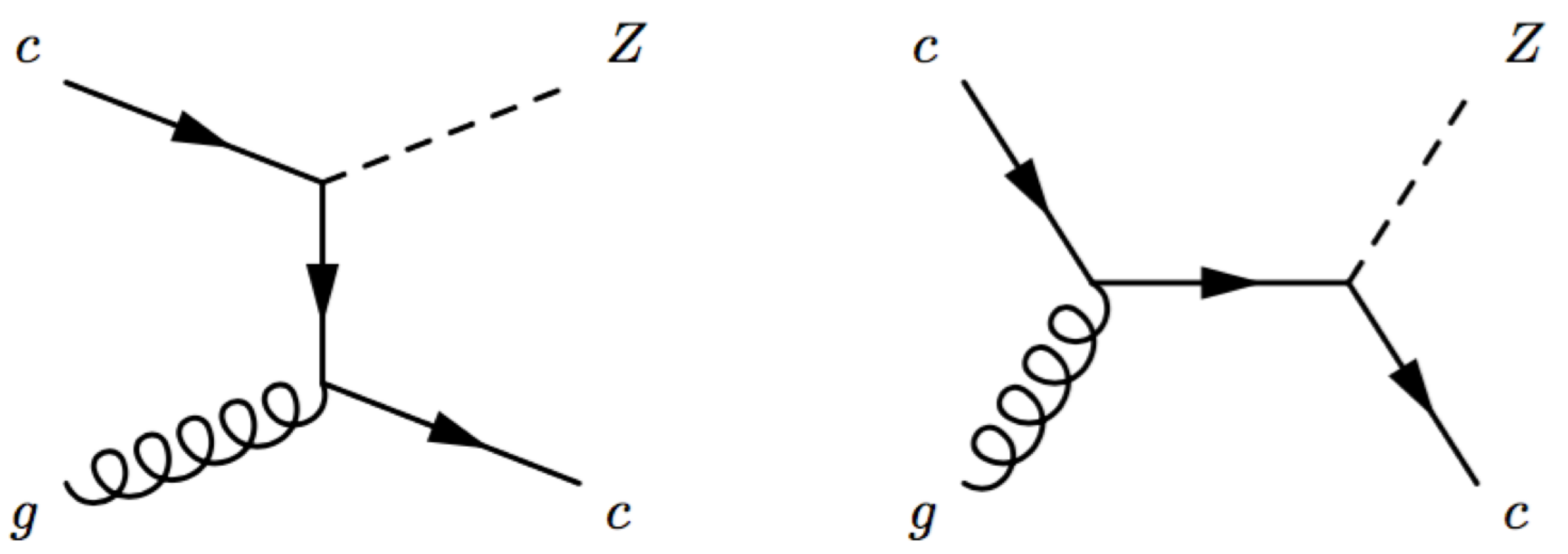




- Lattice calculations of the gluonic structure of hadrons are very challenging.
- Results from pseudo-PDF methodology are consistent with phenomenological extractions.
- Current calculations with controlled statistical uncertainties provide improvements due to the lack of experimental data.

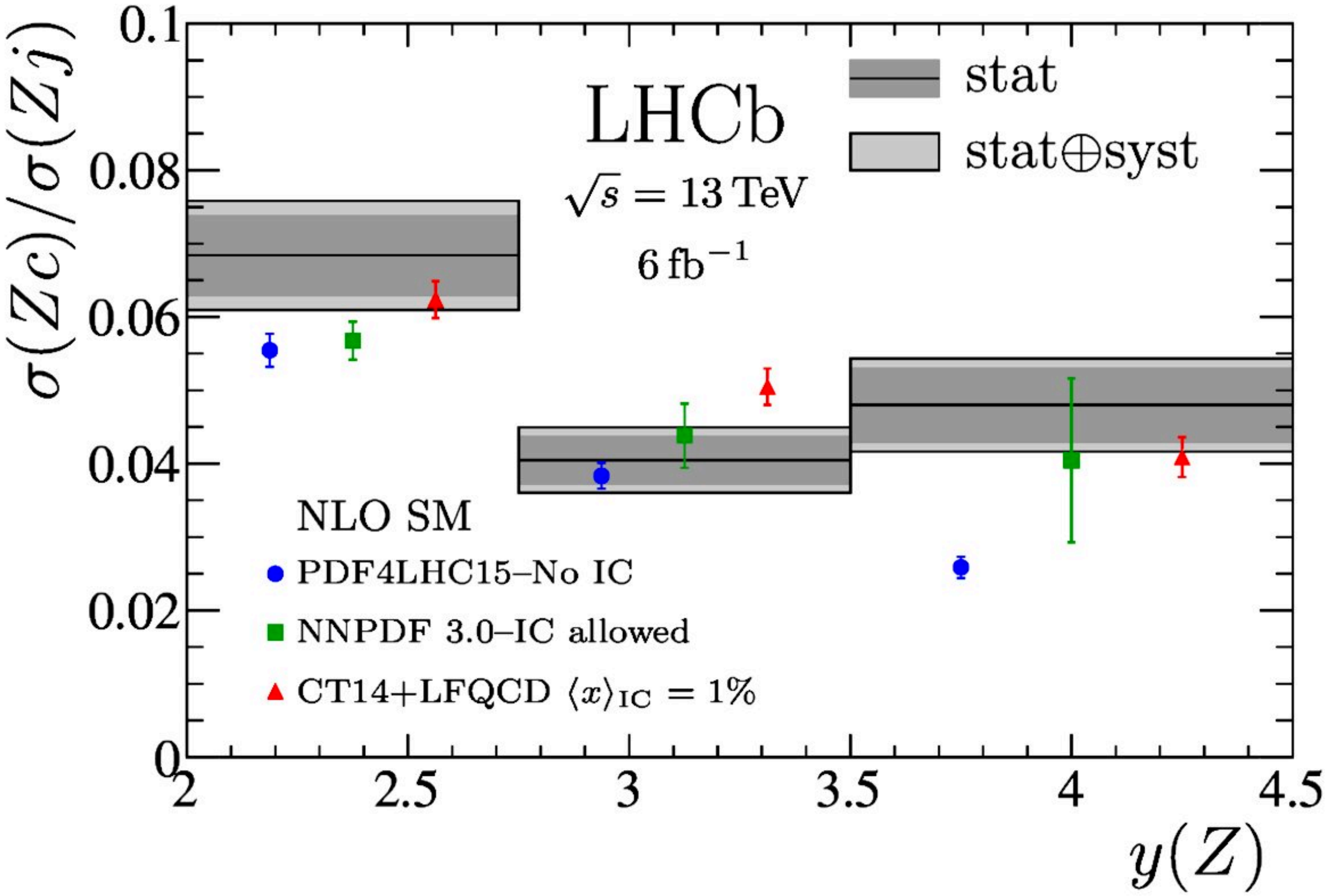
**C. Monahan (Saturday)**

# 1-dimensional unpolarised proton PDFs

- LHCb is shedding light on the question of intrinsic heavy flavour in the proton:



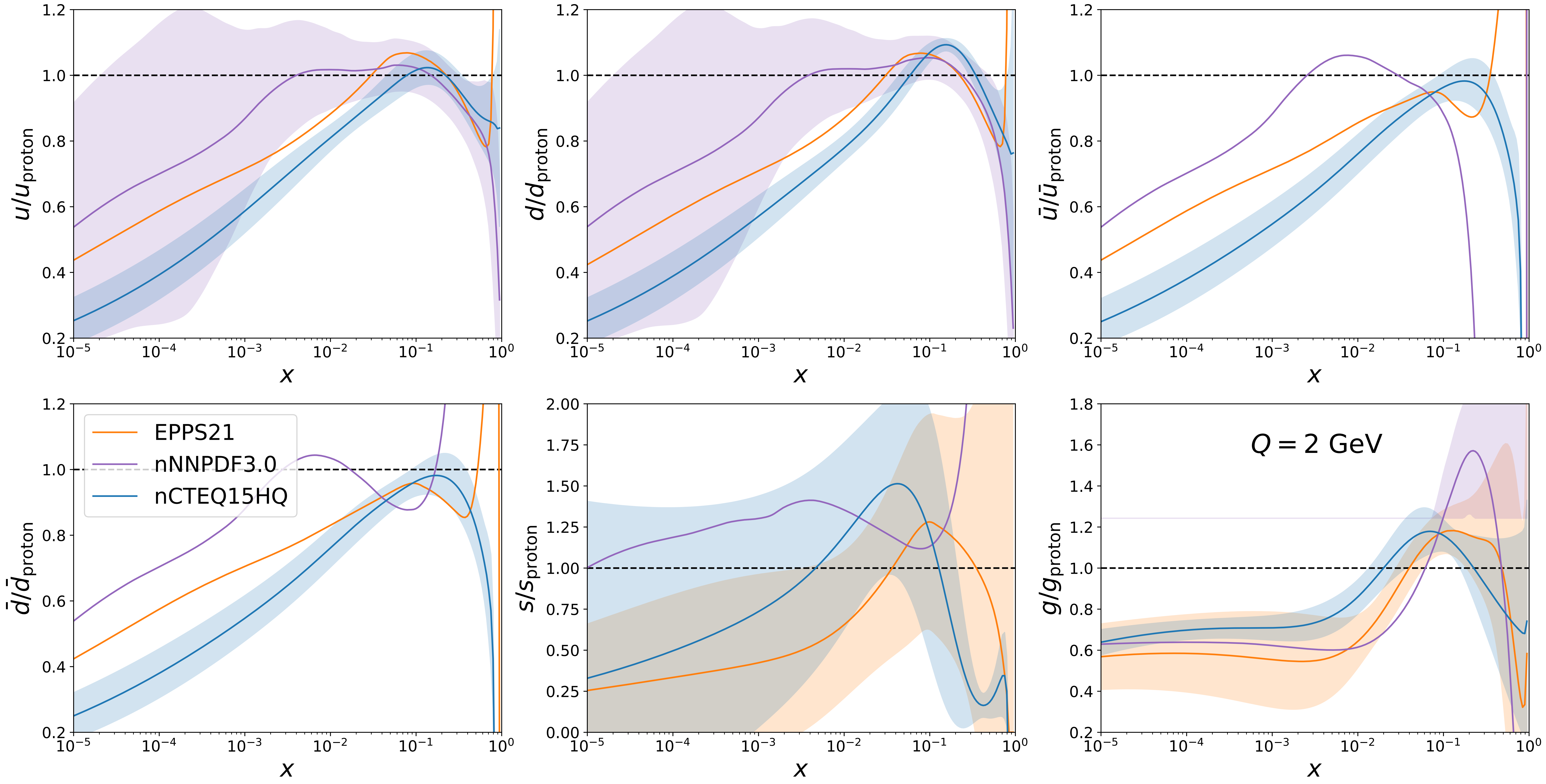

Leading order $Zc$ production via
gc → $Zc$ scattering at LHCb




Phys. Rev. Lett. **128** (2022) 082001

S. Lee (Friday)

# 1-dimensional unpolarised nuclear PDFs




- nPDF sets agree within uncertainties.
- Higher precision, broader kinematic coverage and more observables needed to improve the extractions.

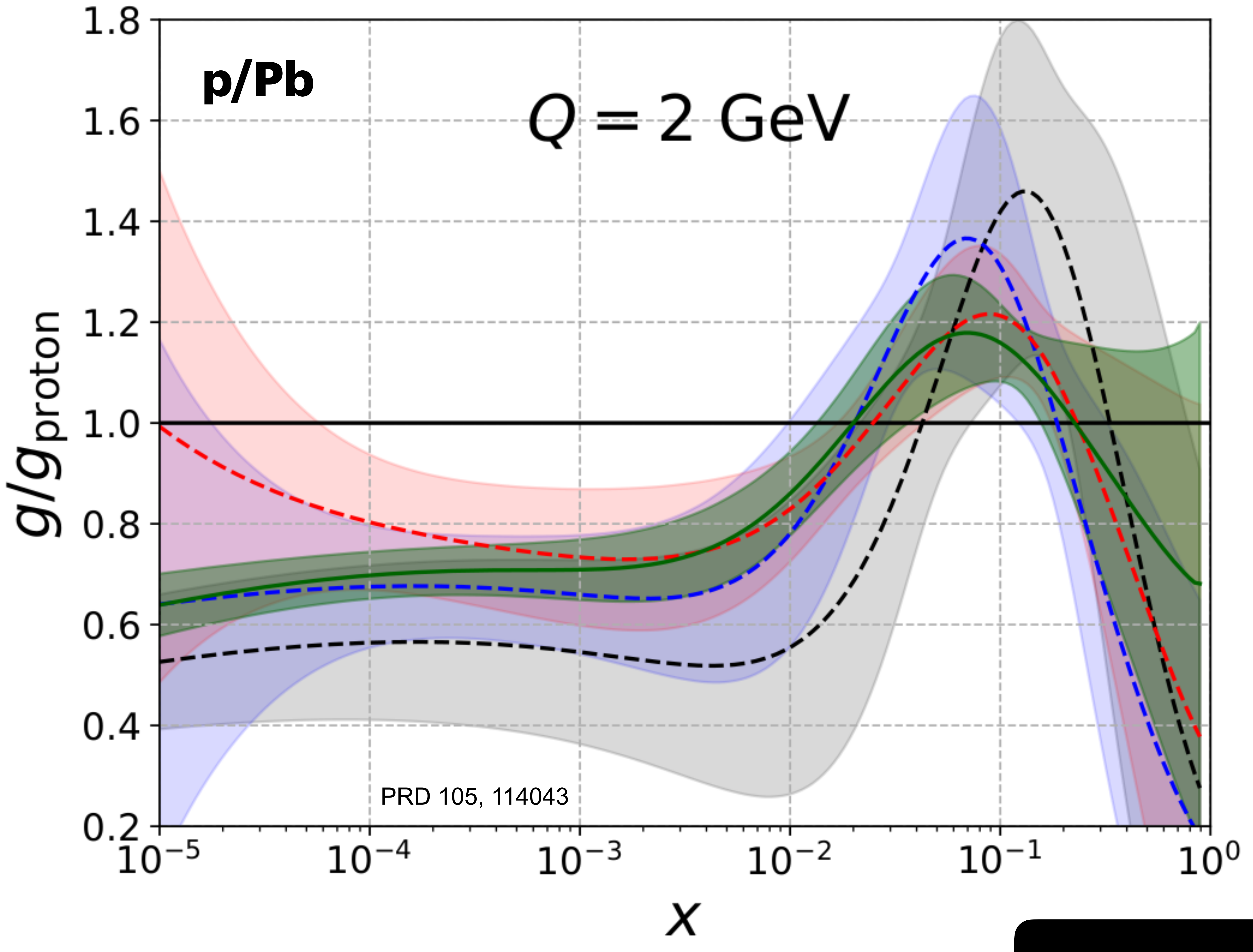
| | | $N_{\text{data}}$ | $N_{\text{params}}$ | Observables |
|---|---|---|---|---|
| PRD 105, 114043 | nCTEQ15HQ | 1488 | 19 | DIS, DY, SIH, WZ, D, Quarkonia |
| EPJC 82, 413 | EPPS21 | 2077 | 24 | ($\nu$)DIS, DY, SIH, WZ, dijet, $D$ |
| EPJC 82, 507 | nNNPDF3.0 | 2151 | 256 | ($\nu$)DIS, DY, WZ, dijet, $\gamma$, $D$ |

**P. Duwentäster (Friday)**

# 1-dimensional unpolarised nuclear PDFs

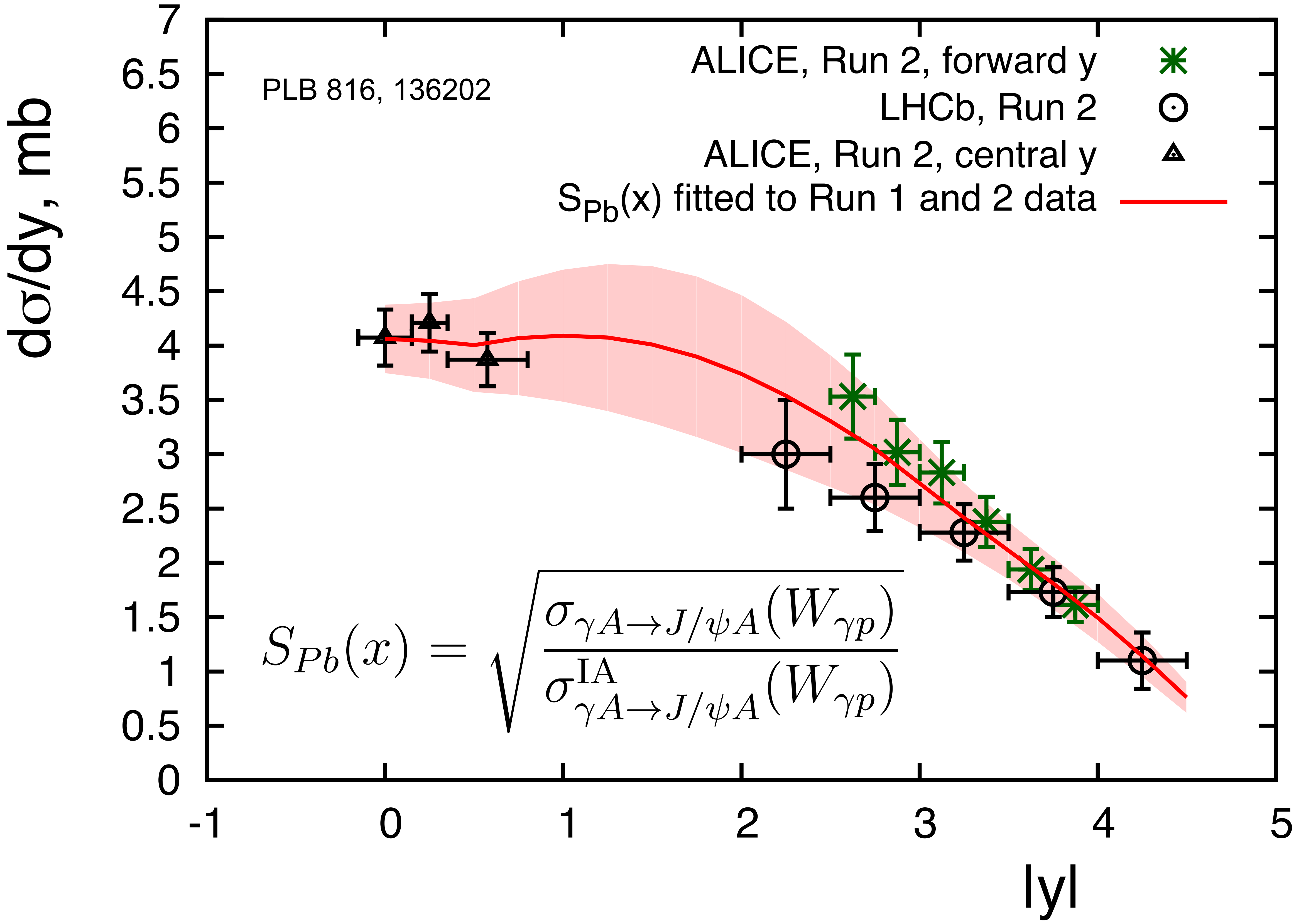
- **black** = nCTEQ15
- **blue** = nCTEQ15WZ
- **red** = nCTEQWZ+SIH
- **green** = nCTEQ15HQ

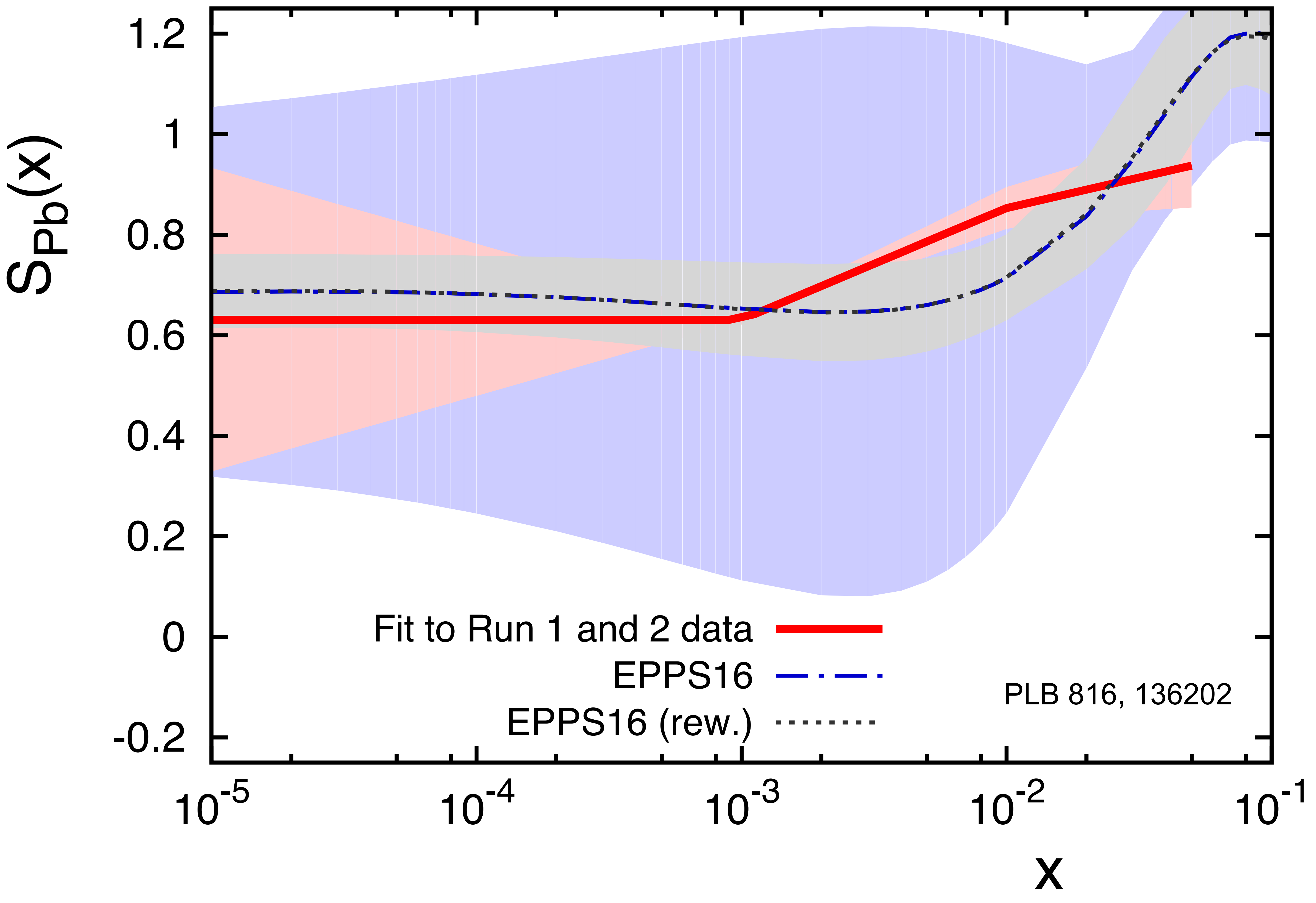
  including light and heavy meson production data.




**P. Risse (Friday)**

# 1-dimensional unpolarised nuclear PDFs



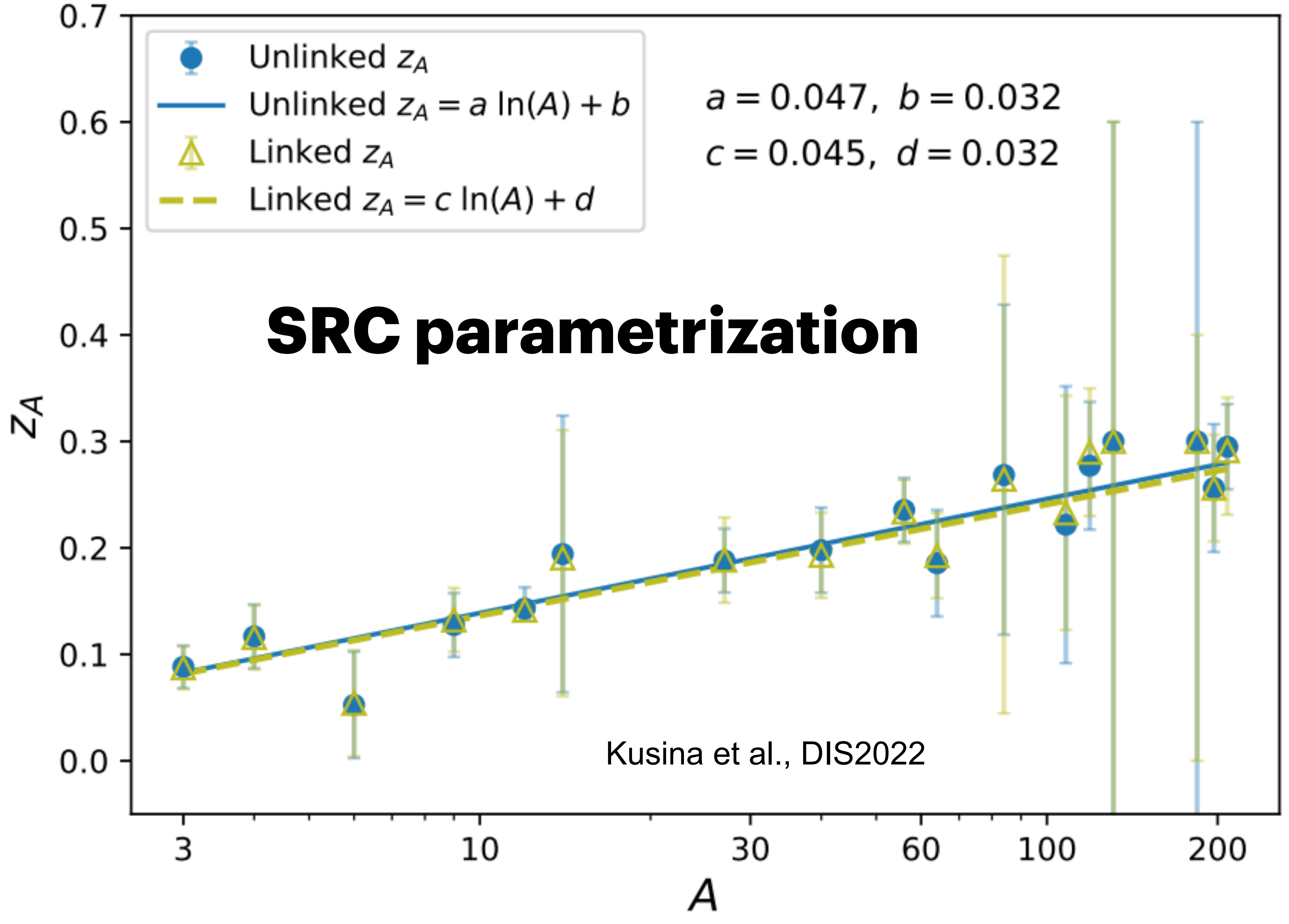




- Analysis of coherent J/ψ photoproduction in Pb-Pb UPCs.
- Access to the nuclear gluon density at $10^{-5} \leq x \leq 0.04$

**S. Ragoni (Tuesday)**

# 1-dimensional unpolarised nuclear PDFs

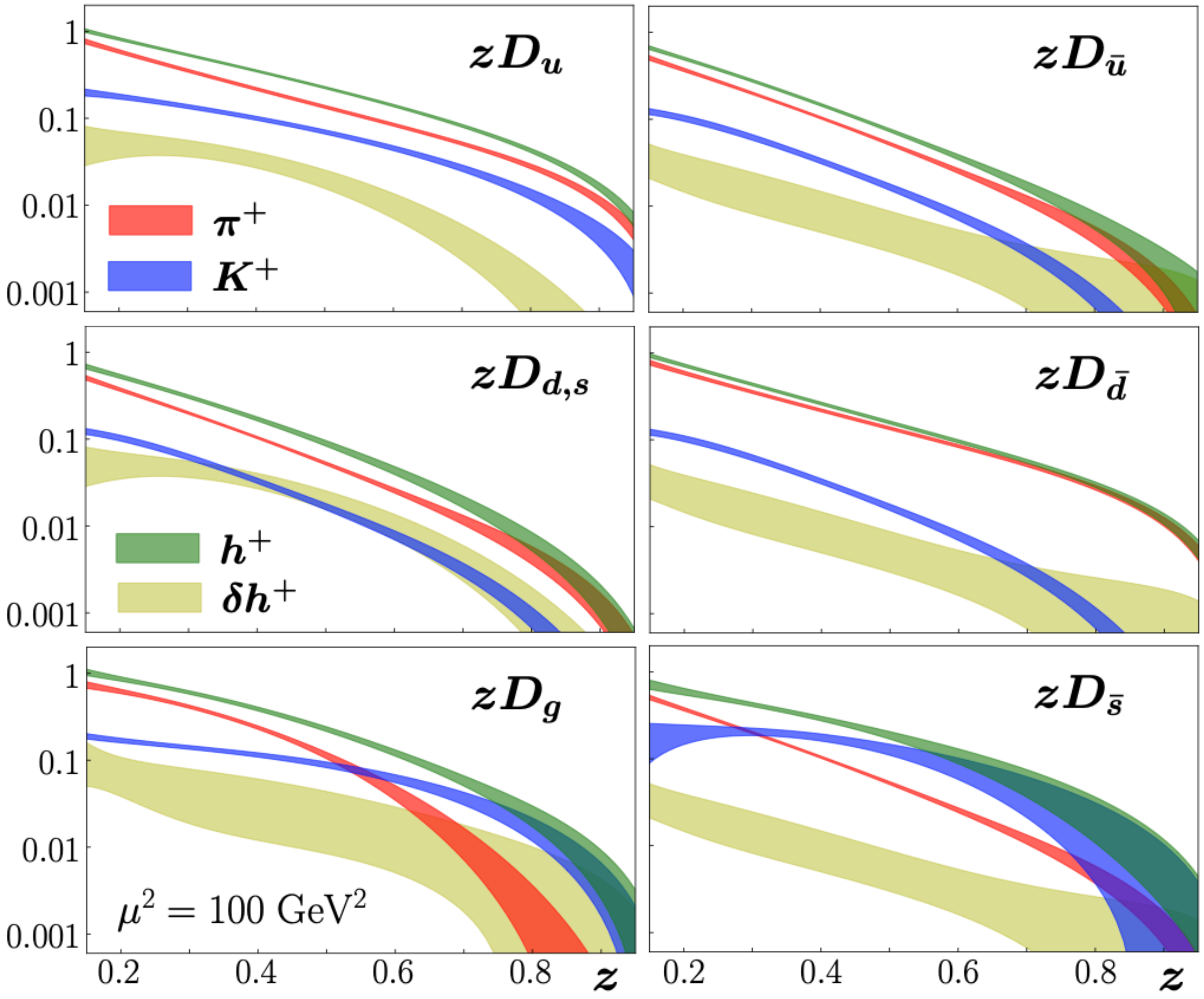
- In the NT a nucleus is a collection of protons and neutrons organised in shells (like the Bohr electron energy levels).
- 20% of the nucleons are not in shells but in short-range correlated pairs (SRC).
- SRC could be due to formation of **di-quarks** across nucleons.



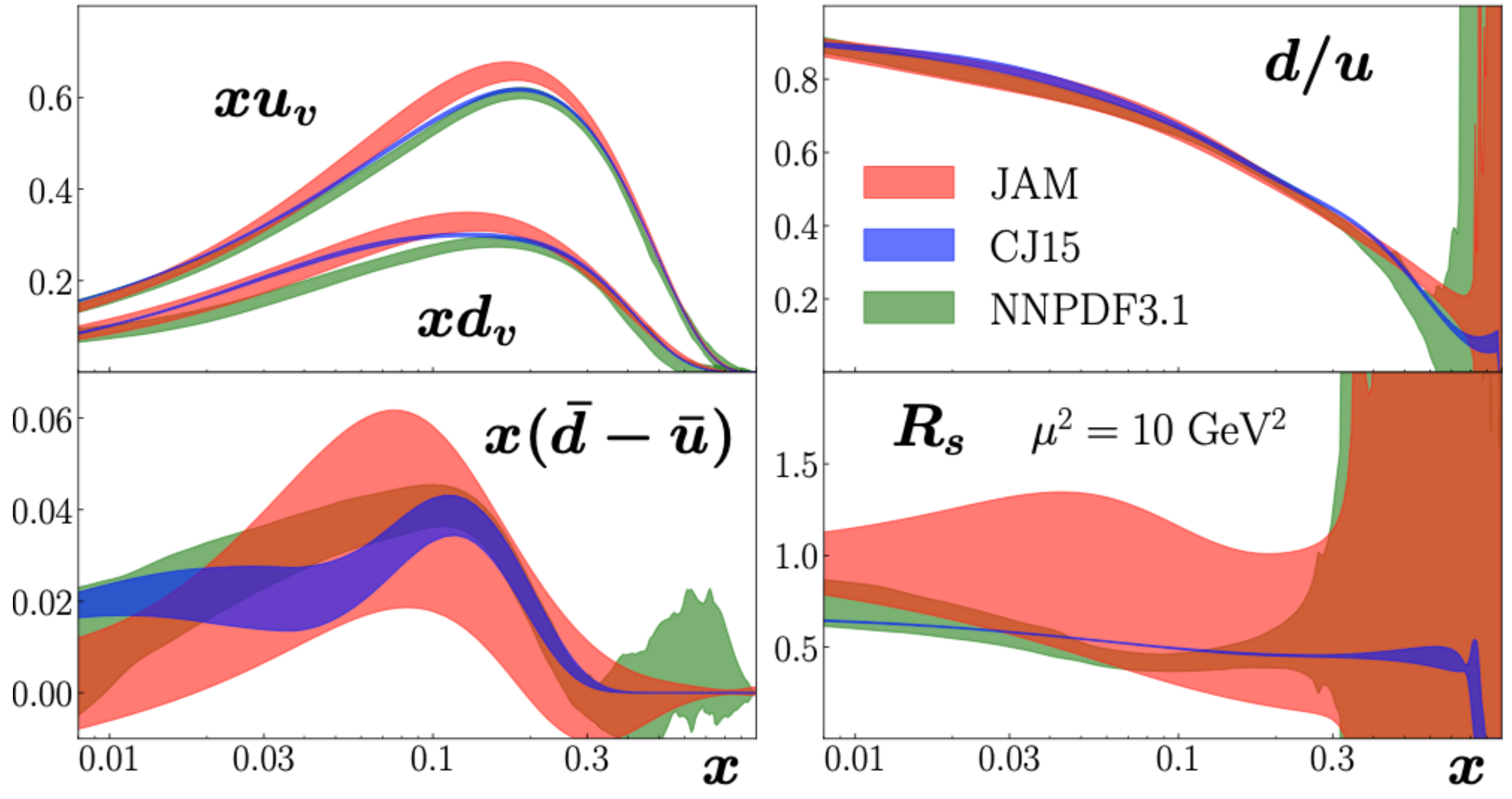

$$f_i^A(x,Q_0) = Z/A\left[(1-z_A)f_{i/p}(x,Q_0) + z_A f_{i/p}^{SRC}(x,Q_0)\right] + N/A\left[(1-n_A)f_{i/n}(x,Q_0) + n_A f_{i/n}^{SRC}(x,Q_0)\right]$$

**J. Rittenhouse West (Thursday)**
**P. Duwentäster (Friday)**

# Hadronization and FFs




- Joint PDF+FF analysis




PRD 104, 016015

**E. Moffat (Saturday)**

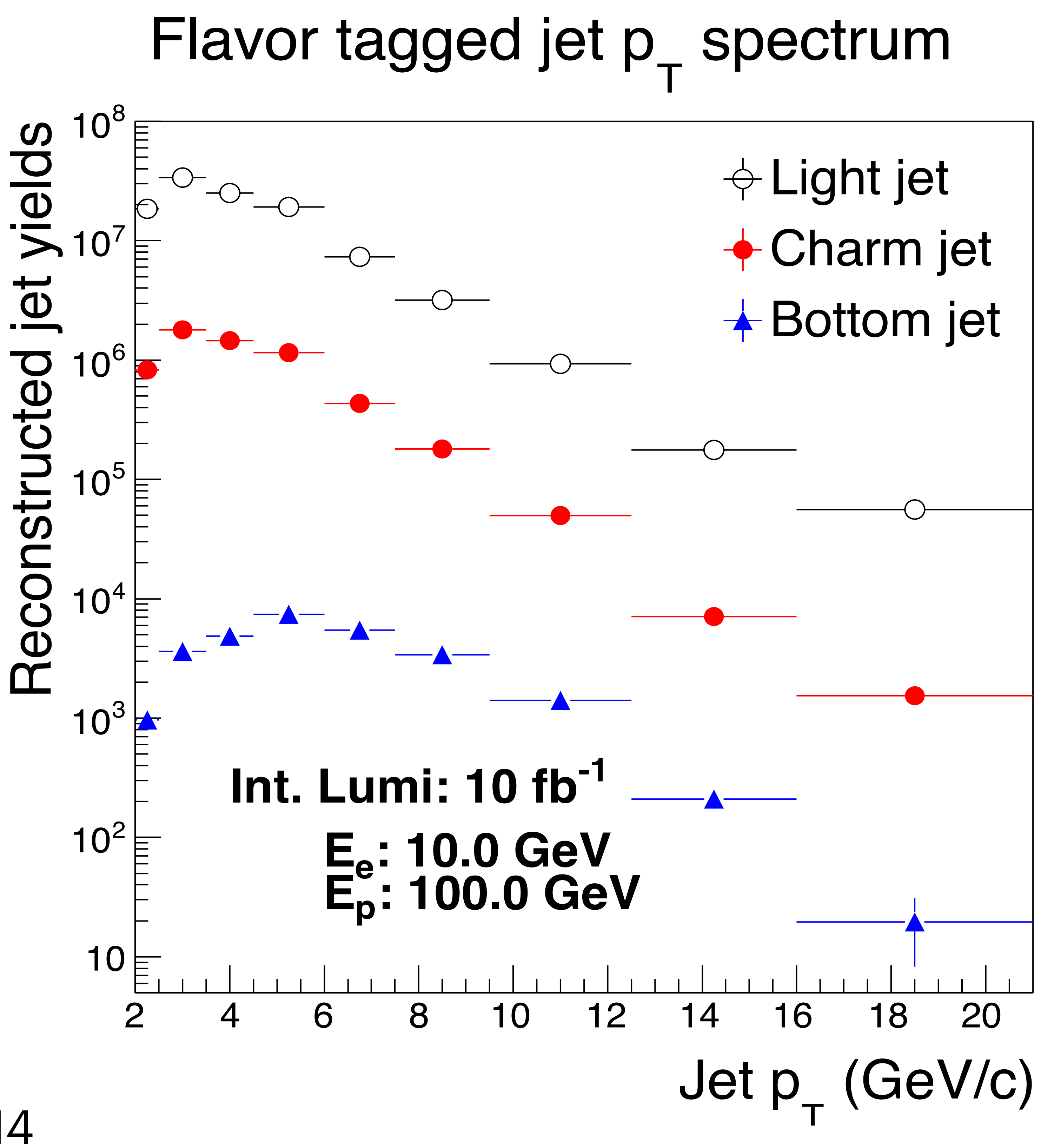
# Hadronization and FFs

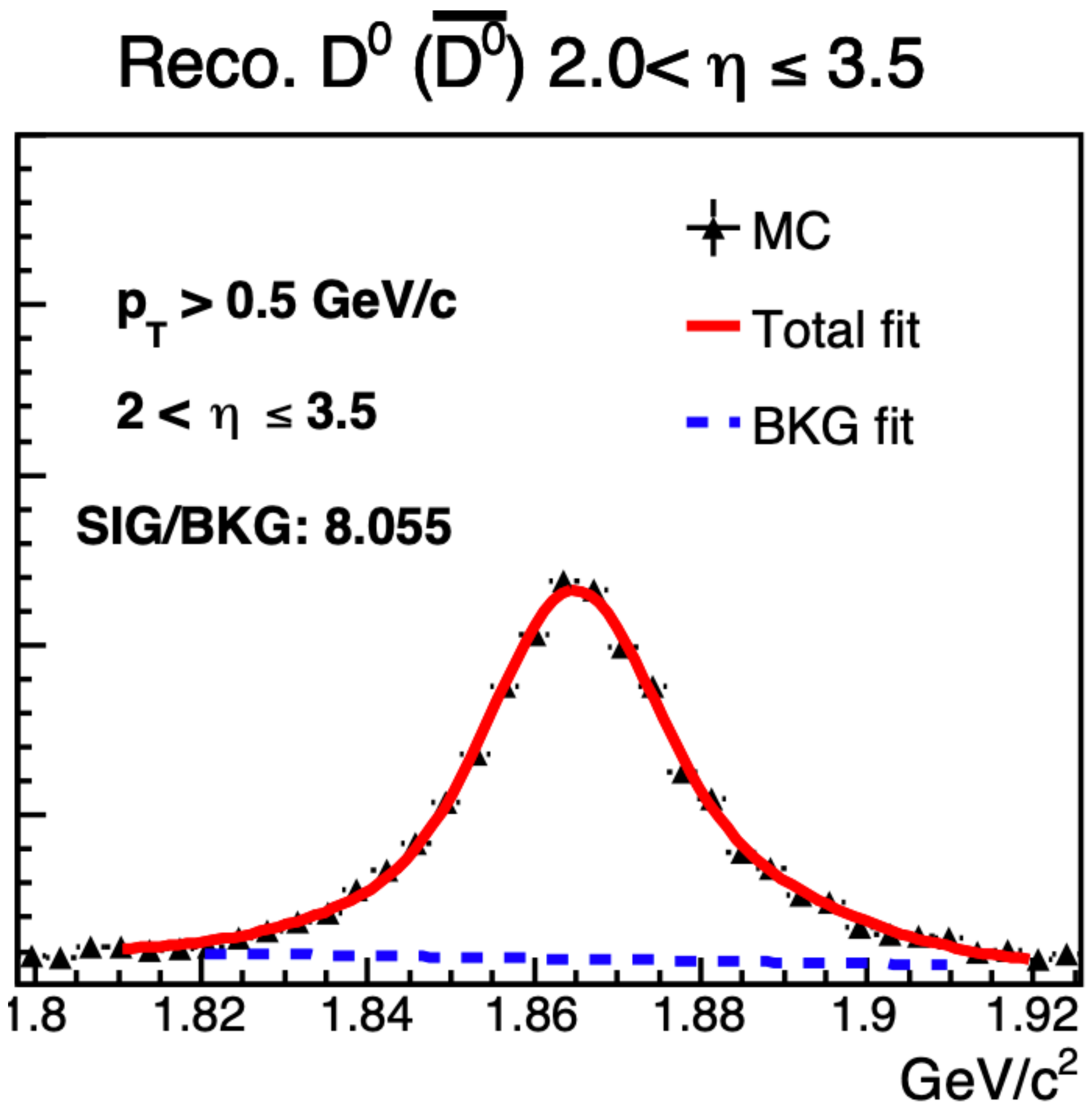
- $e^+e^-$ annihilation allow for precision studies of QCD
- Belle II will have 50×Belle luminosity (100 × BaBar) to
  - do precise measurements of FFs with complex final states
  - tune MC generators
  - probe jet calculations at low scales
  - constrain $\alpha_S$
  - test QCD calculations of event shapes
  - …
- Snowmass Whitepaper: "Opportunities for precision QCD physics in hadronization at Belle II", e-Print: 2204.02280 [hep-ex]

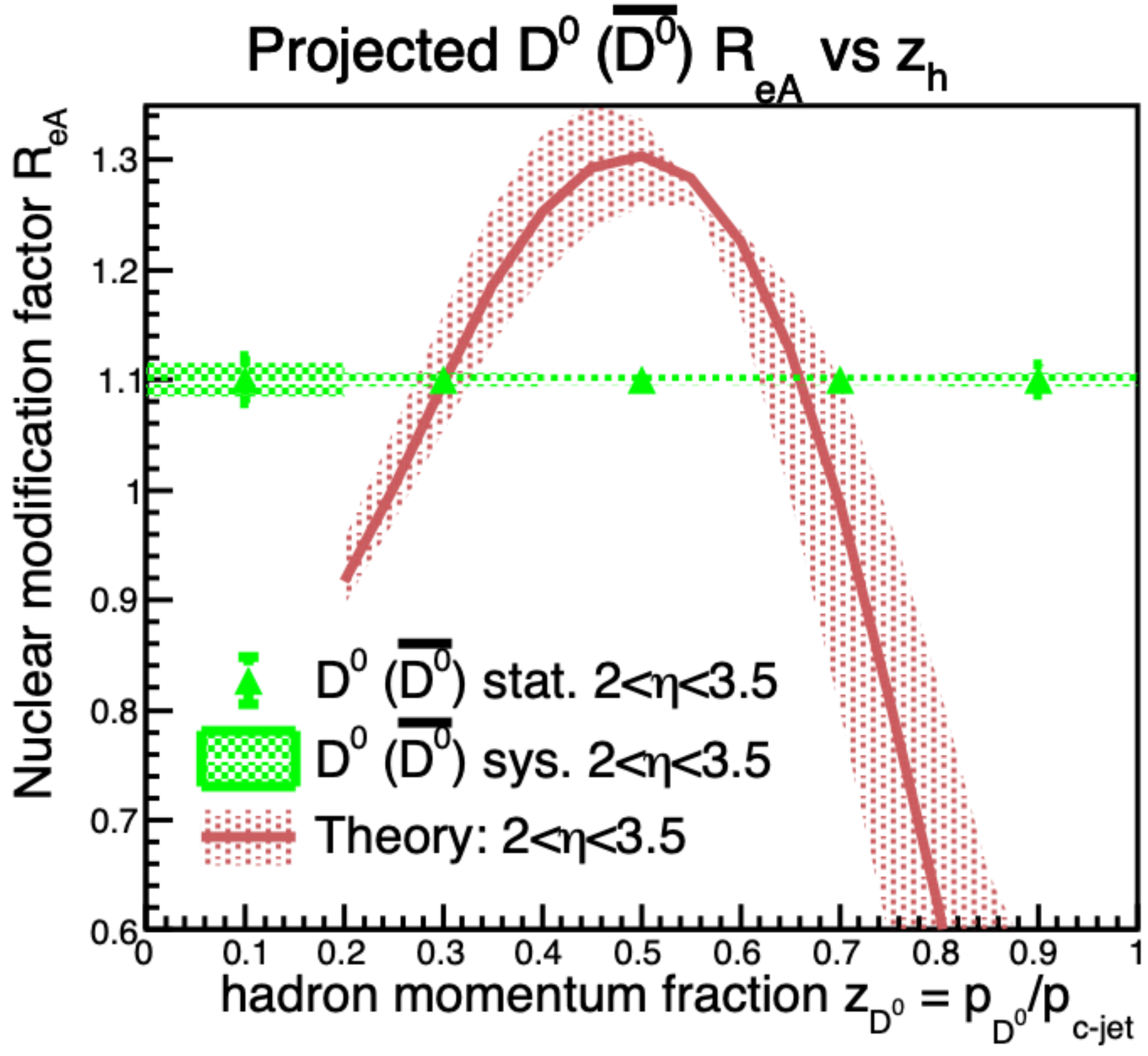
**A. Vossen (Saturday)**

# Hadronization and FFs

- The future EIC heavy flavor hadron inside jet measurements can provide great constraints on the fragmentation function in the high $z_h$ region.



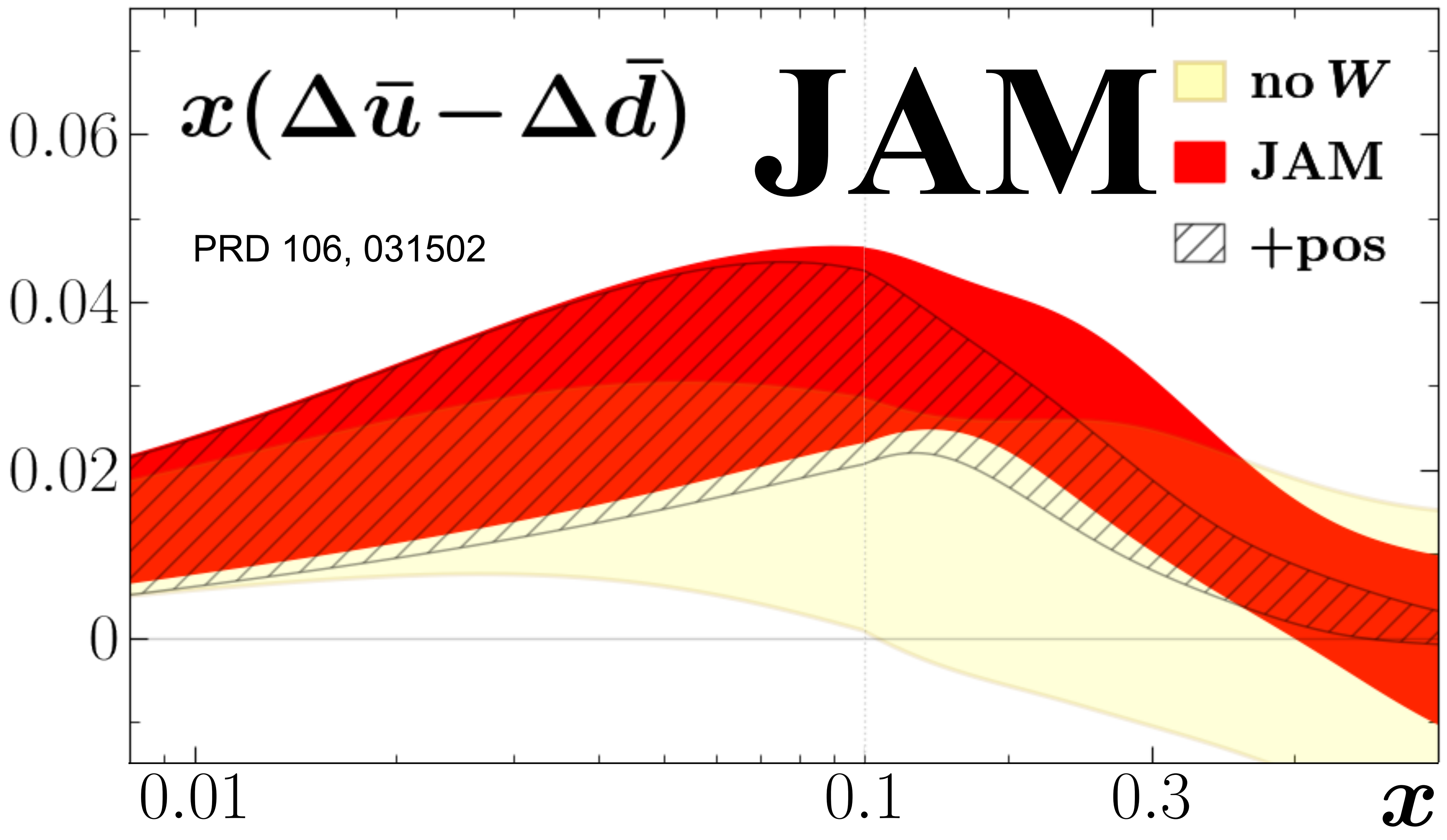




**X. Li (Tuesday)**

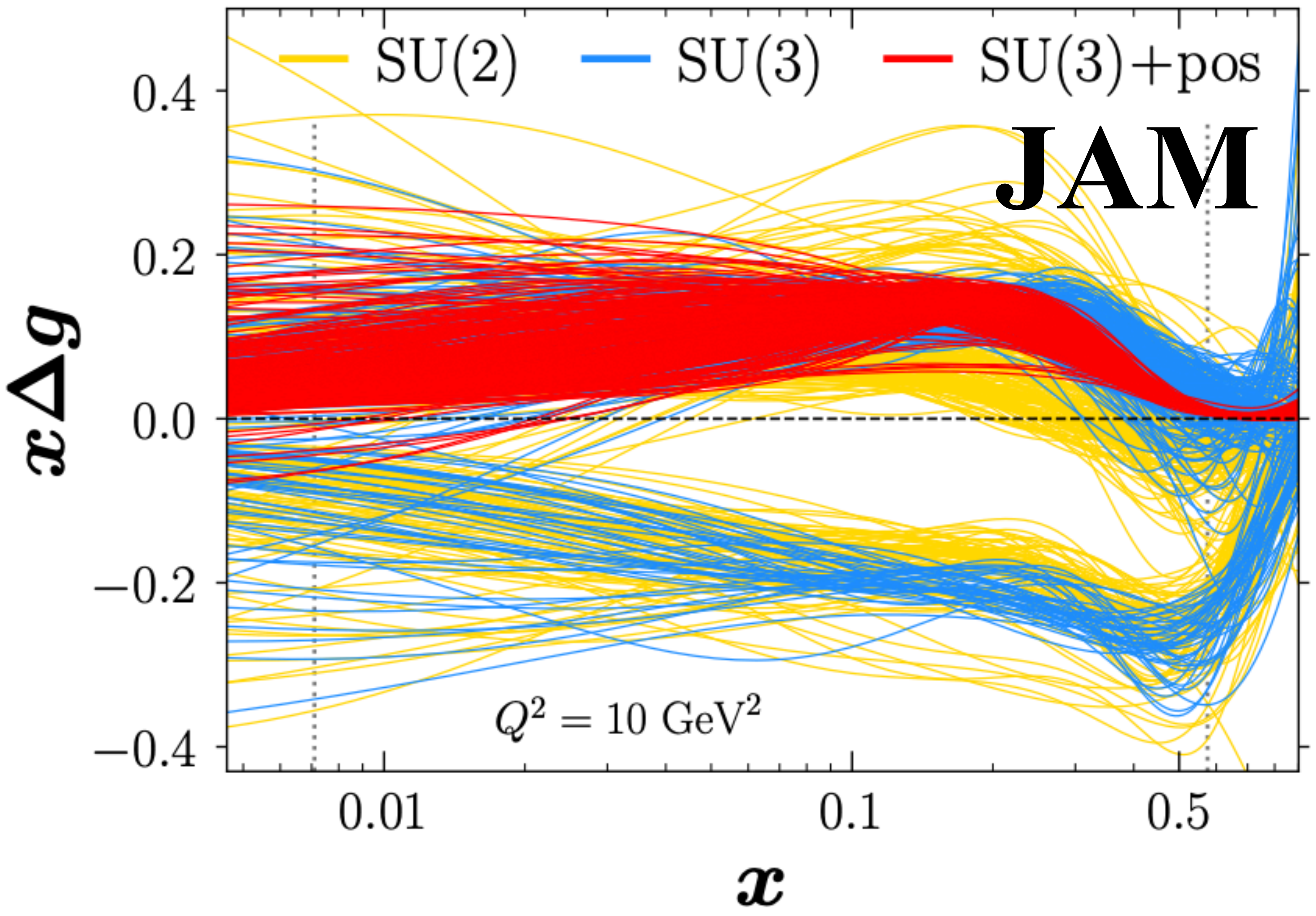
# 1-dimensional polarised PDFs

longitudinal single spin asymmetry

from W prod. at STAR.




PRD 105, 074022

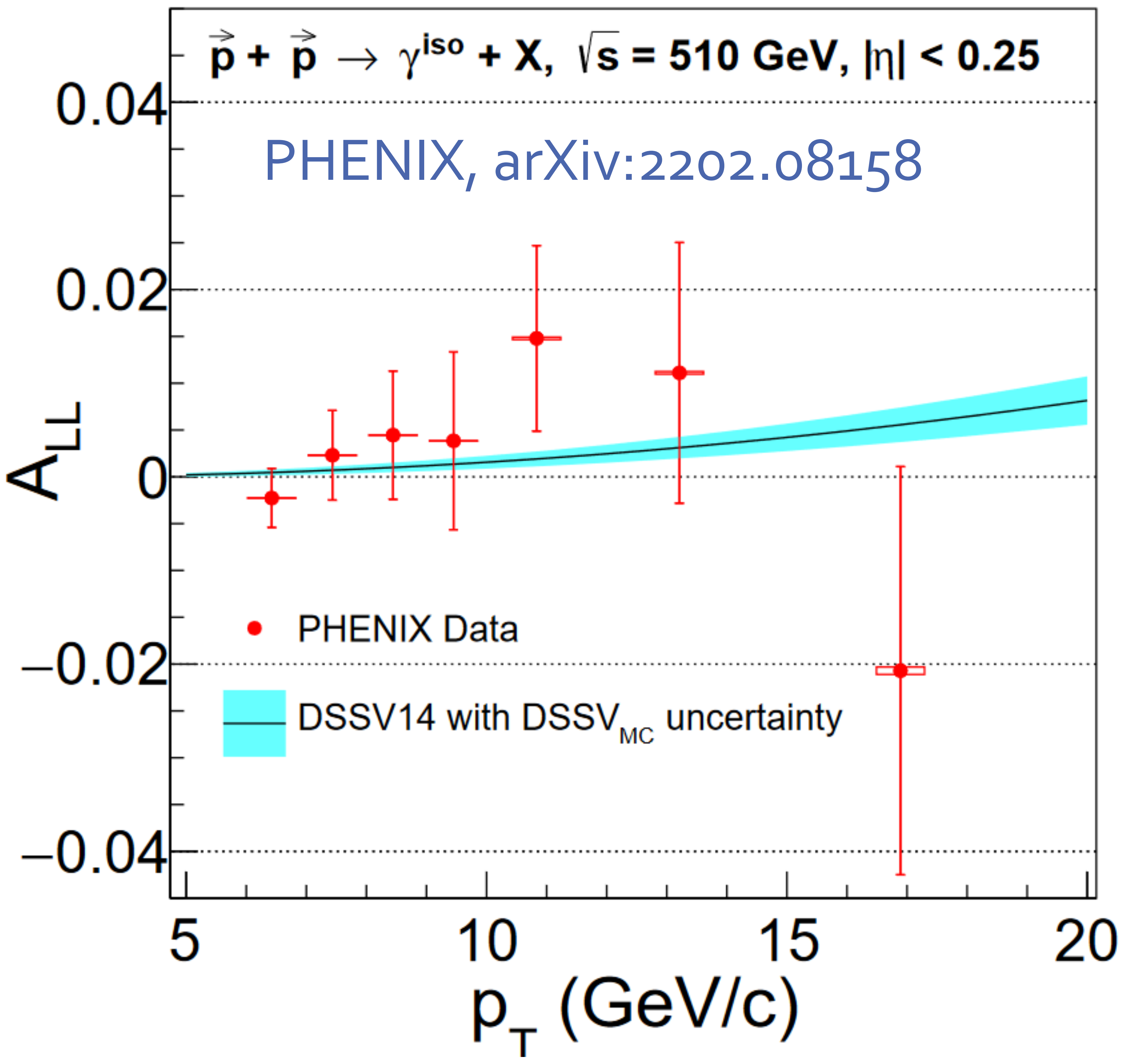



Single jet data from RHIC

+ first impact assessment of Lattice data in pol. PDF determination!

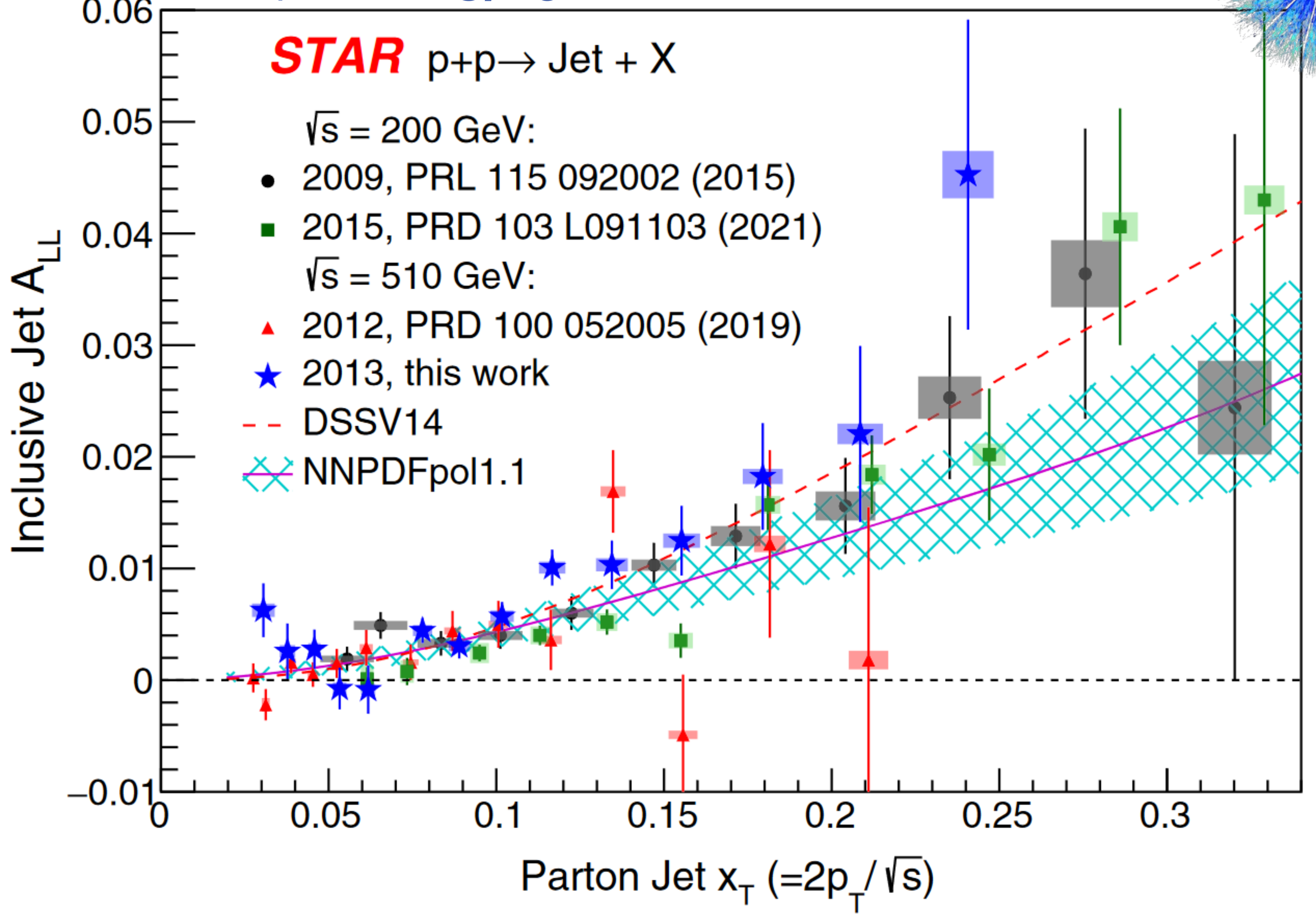
**C. Cocuzza (Tuesday)**

# 1-dimensional polarised PDFs




Direct photon double spin asymmetry for $\Delta g$ in 0.02 < x < 0.08

STAR, PRD **105,** 092011 (2022)

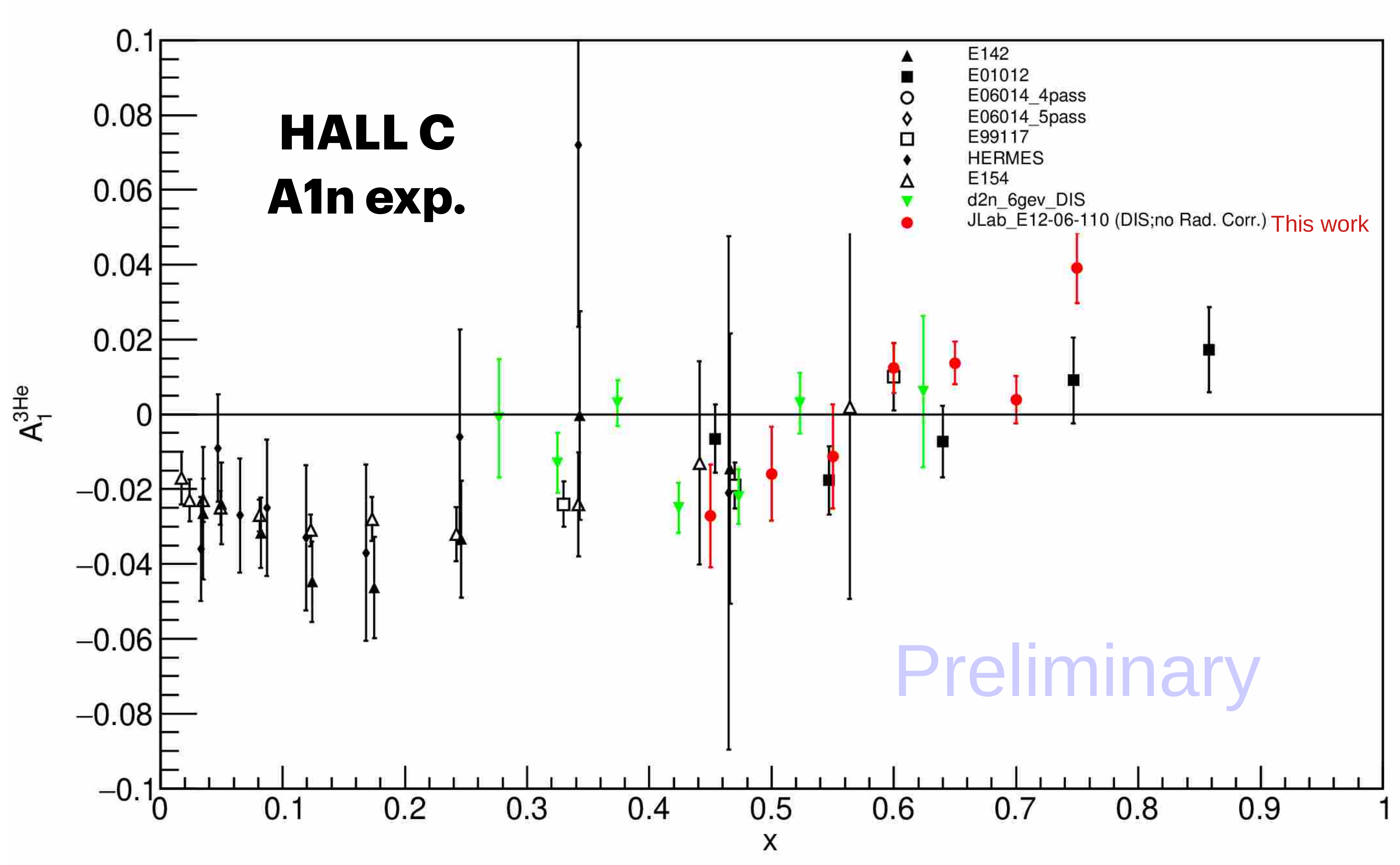



Inclusive jet double spin asymmetry.

+ di-jet data to constrain $\Delta g$ in 0.01 < x < 0.5

**S. Lee & N. Lewis (Thursday)**

# 1-dimensional polarised PDFs




- Virtual photon-nucleon asymmetry: access to neutron $g_1$ at large x.

M. Chen (Thursday)

# 1-dimensional polarised PDFs

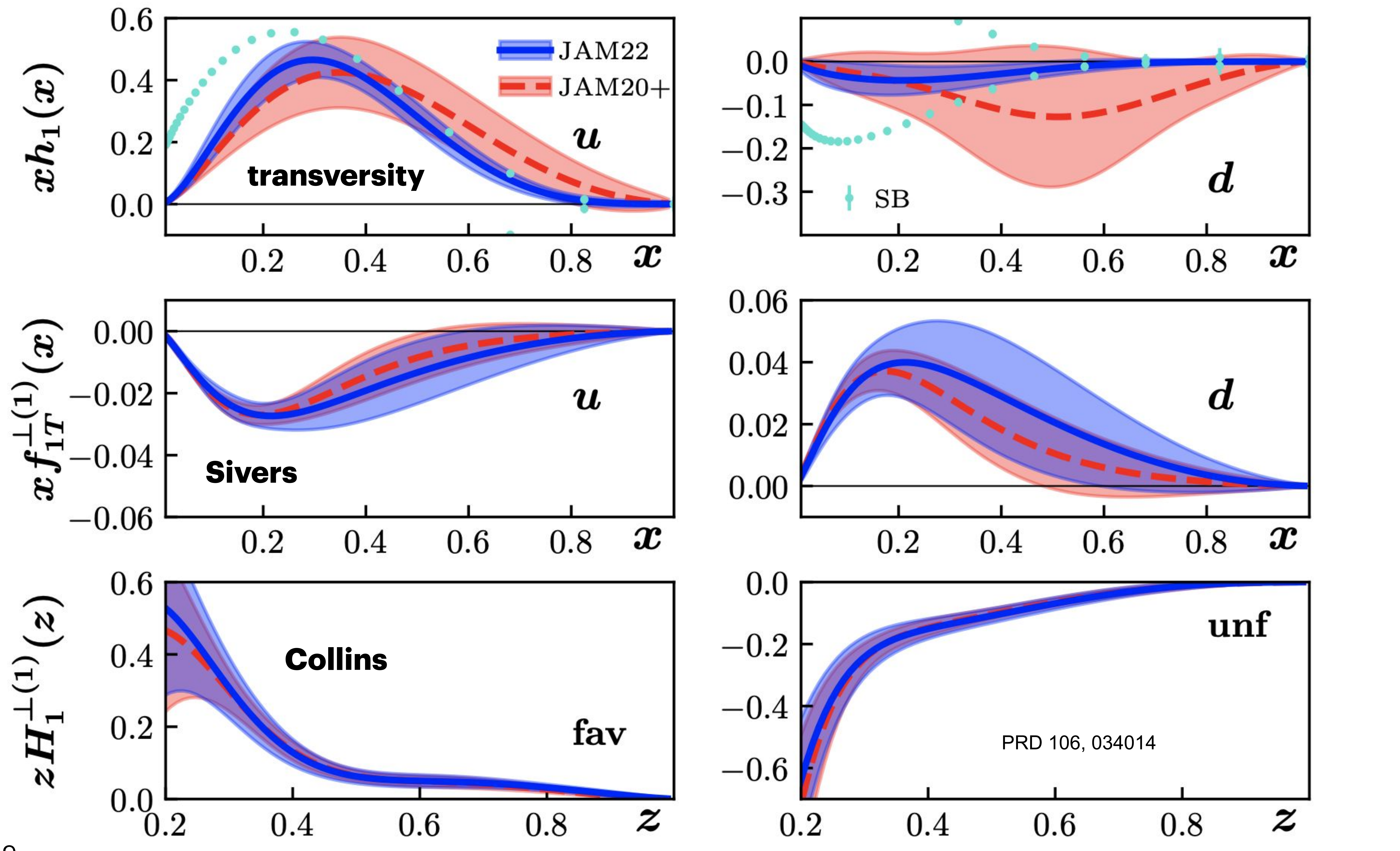
- Matrix elements calculation for composite particles with arbitrary spin use a decomposition in spin-j fields. Method calls for constraints and extra conditions.

- New approach: apply Weinberg's construction (use of $(2j + 1)$-component spinors).

  - only exact degrees of freedom
  - no need for constraints
  - direct physical interpretation
  - simple algorithm, efficient calculation of currents for any spin

F. Vera (Tuesday)

# Transverse Momentum Dependent PDFs & FFs



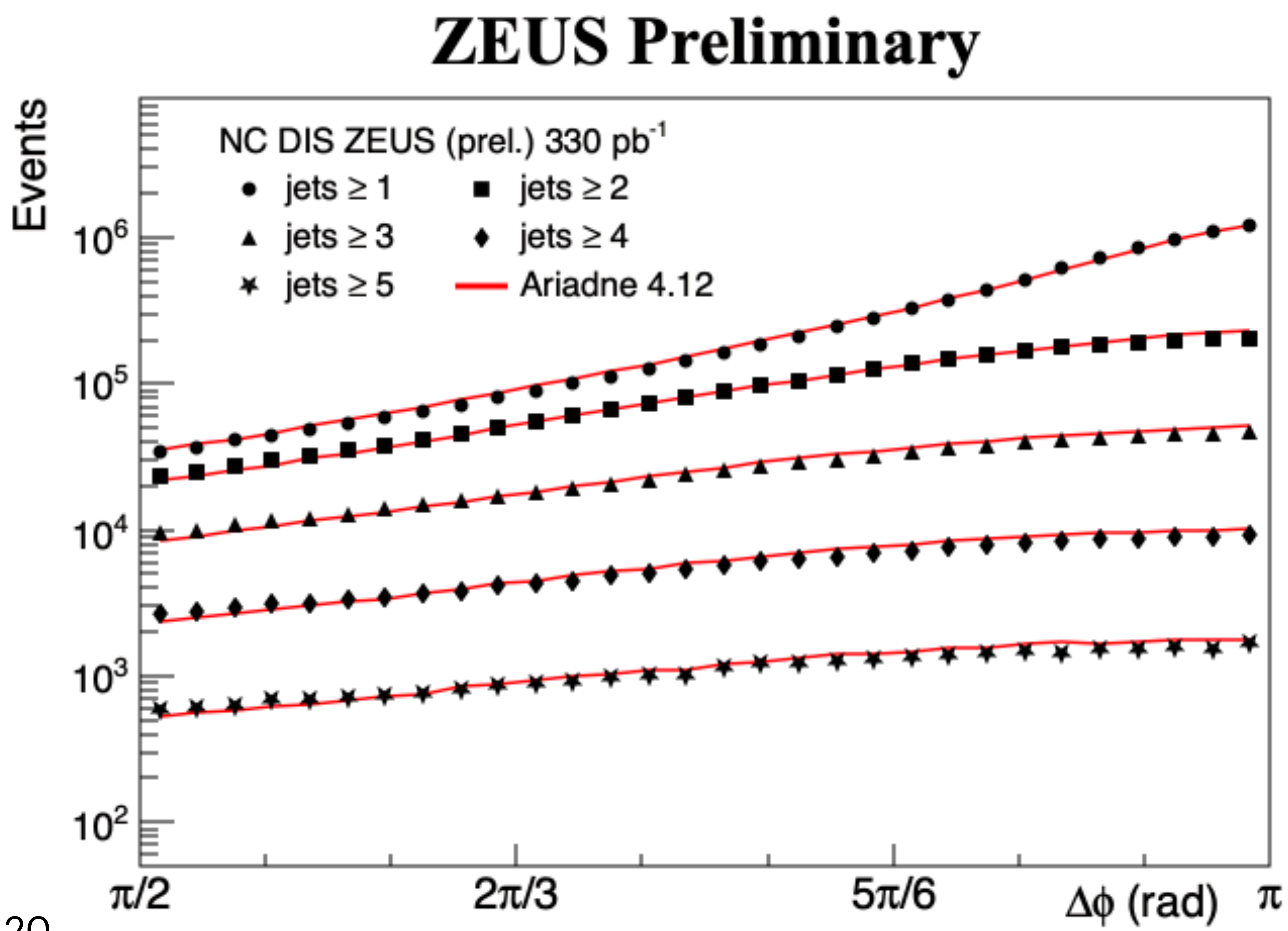

- Single spin symmetries from Drell-Yan, SIDIS, SIA, and single hadron production + **Lattice** tensor charge data.

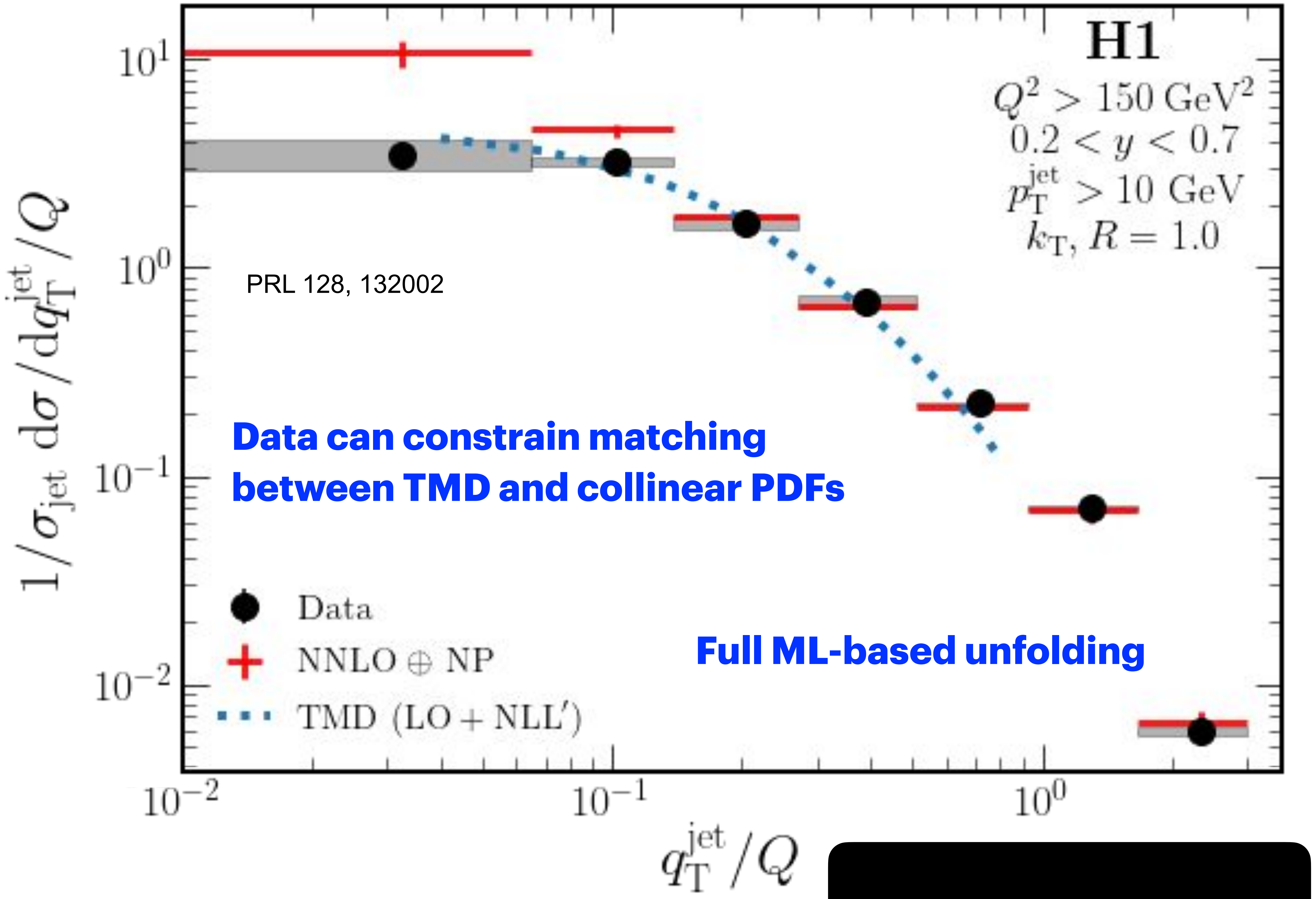
**N. Sato (Wednesday)**

# Transverse Momentum Dependent PDFs & FFs

- Azimuthal decorrelation angle between jet and lepton in DIS to study PDF TMDs.

**probe of TMDs at low x, no FF required**

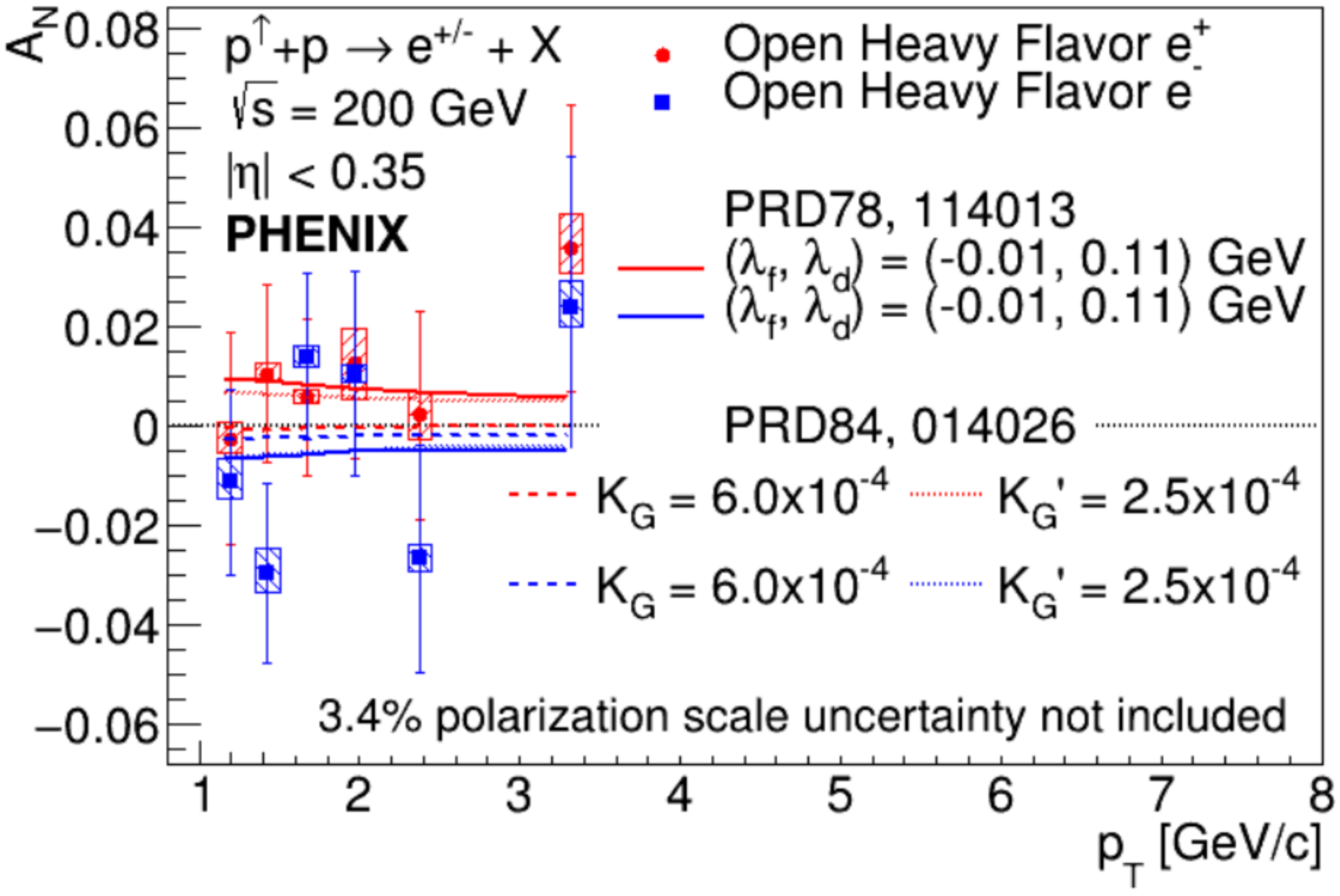


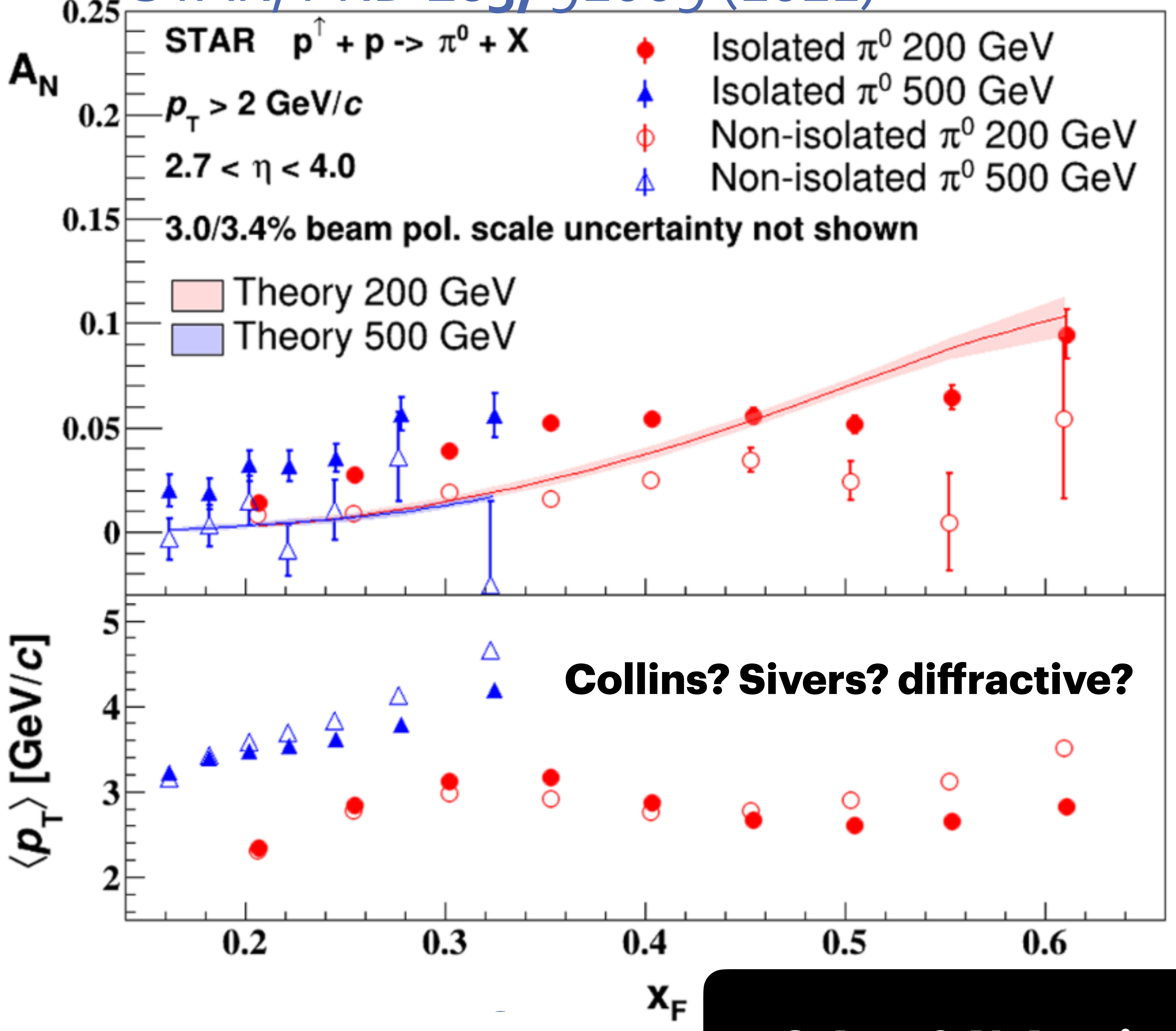

**M. Arratia (Saturday) & B. Surrow (Tuesday)**

# Transverse Momentum Dependent PDFs & FFs 🥰

PHENIX, arXiv:2204.12899



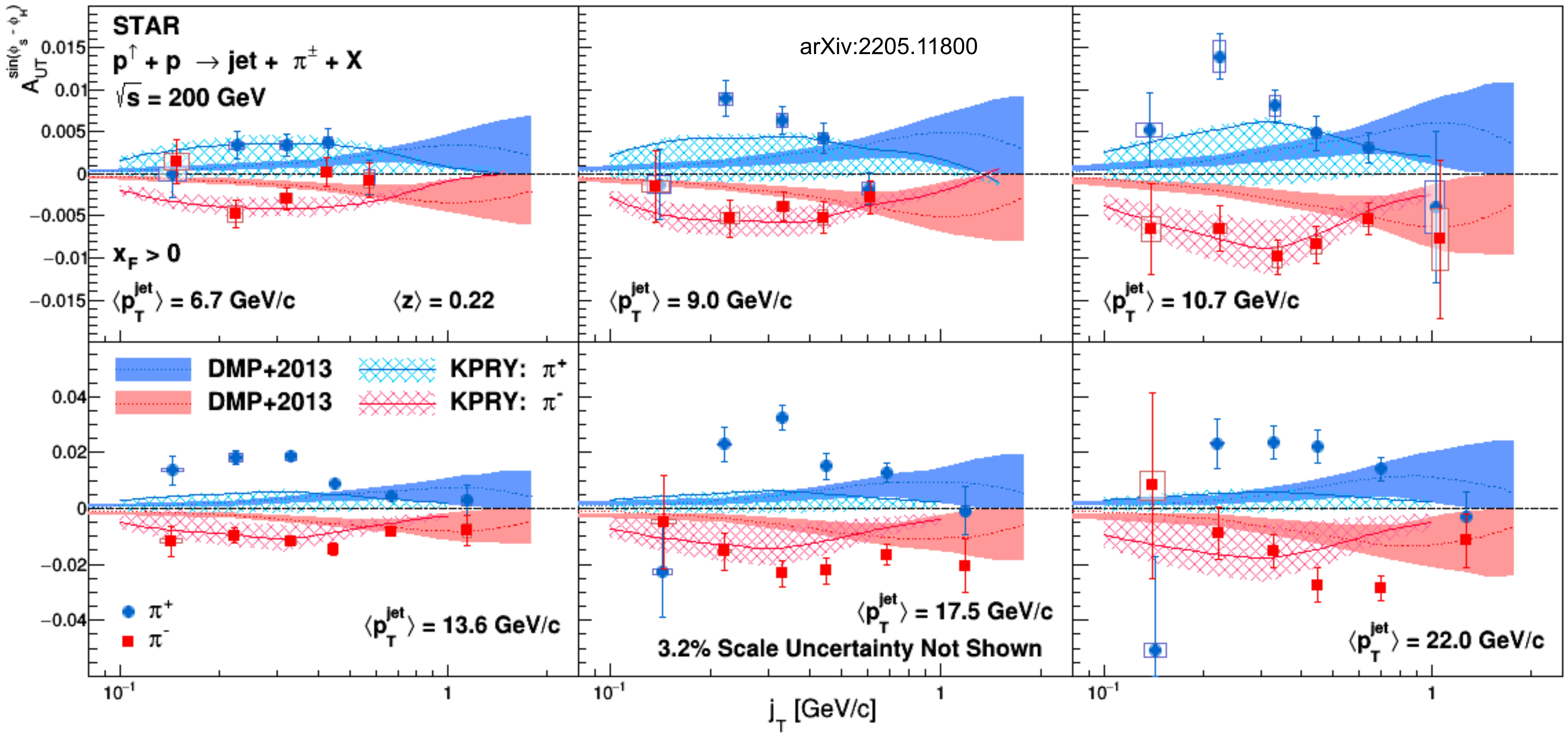

STAR, PRD **103,** 92009 (2021)




- Transverse single spin asymmetry for open HF, sensitive to gluon-spin momentum correlations.

**S. Lee & N. Lewis (Thursday)**

# Transverse Momentum Dependent PDFs & FFs 🥰




$j_T$ = $p_T$ of hadron

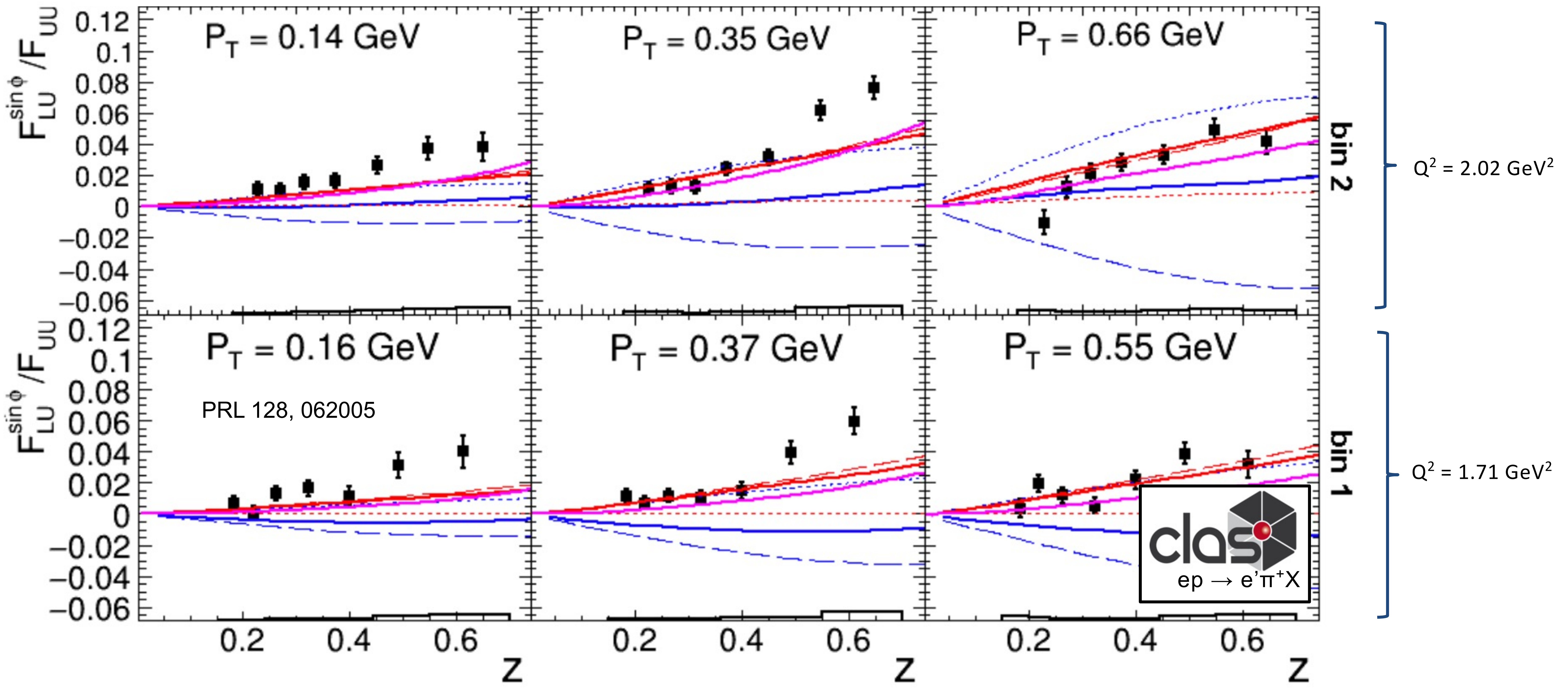
in jet w.r.t. jet axis

- STAR has the most precise measurements of Collins and di-hadron asymmetries to date.
- probe transversity and Collins FF over a wide kin. range.

**K. Adkins (Friday)**

# Transverse Momentum Dependent PDFs & FFs 🥰

- Single hadron production in SIDIS with long. polarised beam




twist-3 pdf unpolarized PDF twist-3 t-odd PDF Boer-Mulders

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left[-\frac{\hat{h}\cdot k_T}{M_h}\left(x\boxed{e}\boxed{H_1^\perp} + \frac{M_h}{M}\boxed{f_1}\frac{\boxed{\tilde{G}^\perp}}{z}\right) + \frac{\hat{h}\cdot p_T}{M}\left(x\boxed{g^\perp}\boxed{D_1} + \frac{M_h}{M}\boxed{h_1^\perp}\frac{\boxed{\tilde{E}}}{z}\right)\right]$$

Collins FF twist-3 FF unpolarized FF twist-3 FF

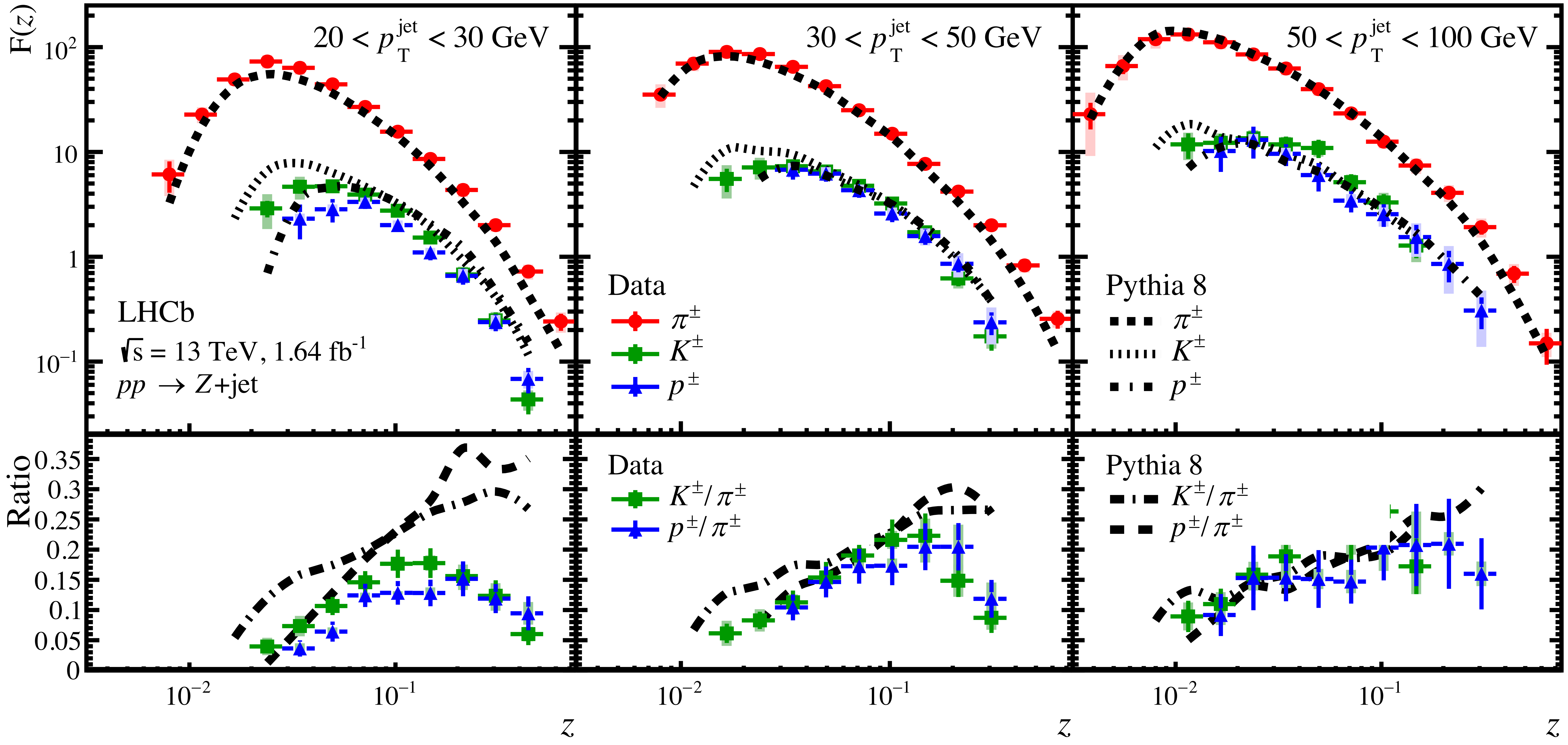
A. Bacchetta et al., *JHEP 0702*, 093 (2007).

**T. Hayward (Wednesday) & A. Vossen (Saturday)**

# Transverse Momentum Dependent PDFs & FFs 🥰

- Ratio of hadron-in-jet to jet cross-section data from Z+jet measurement at LHCb.

arxiv:2208.11691




- Multi-dimensional analysis.
- Constrains TMD FF for light quarks.
- Can help tune MCEGs.

**S. Lee (Friday)**

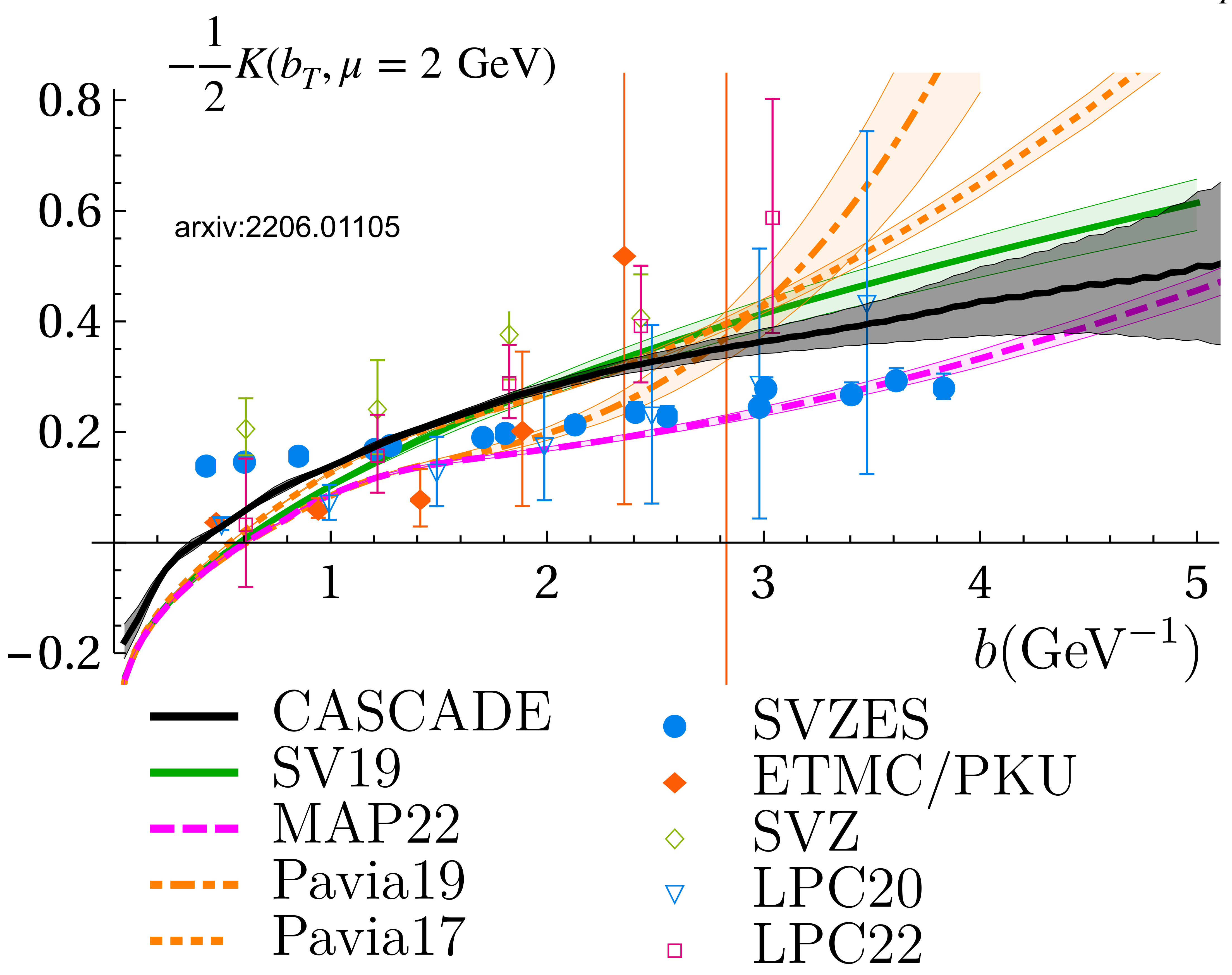
# Transverse Momentum Dependent PDFs & FFs

$$\frac{d\sigma}{dxdydz_h d^2\mathbf{P}_{hT}} \sim \int d^2\mathbf{b}_T \, e^{i\mathbf{b}_T\cdot\mathbf{P}_{hT}/z} \, f_{i/p}(x, \mathbf{b}_T, Q, Q^2) \, D_{h/i}(z_h, \mathbf{b}_T, Q, Q^2)$$

$$f_{i/p}^{\text{pert}}(x, b^*(b_T), \mu, \zeta) \left(\frac{\zeta}{Q_0^2}\right)^{g_K(b_T)/2} f_{i/p}^{\text{NP}}(x, b_T)$$

**Collins-Soper kernel (NP part)**

**intrinsic TMD**



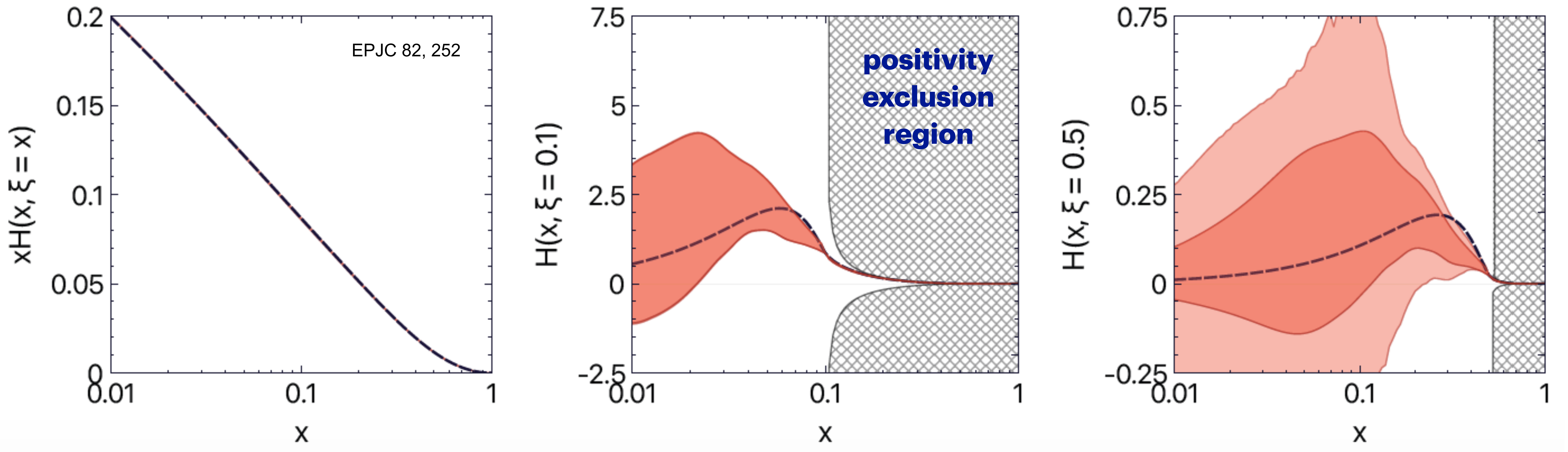

**pQCD** **Lattice QCD**

- Leading-power TMDs fully calculable in Lattice QCD.
- CS kernel determination requires more work on the systematics.
- Exploratory results with various methods show encouraging agreement.

**Y. Zhao (Friday)**

# Generalised Parton Distributions

- Joint analysis of DVCS, TCS, DVMP, DDVCS, diffractive processes, ...) using NNs:

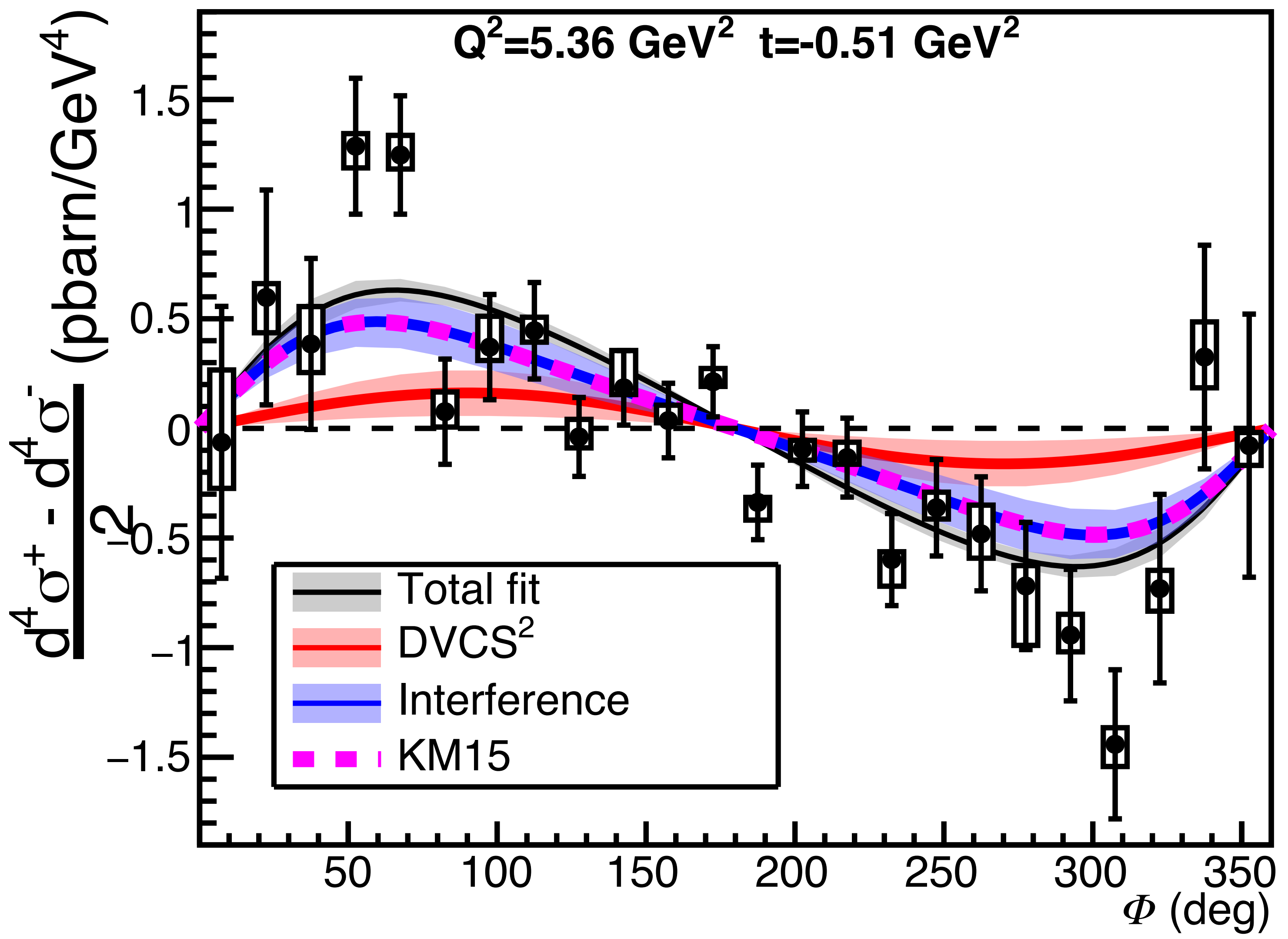


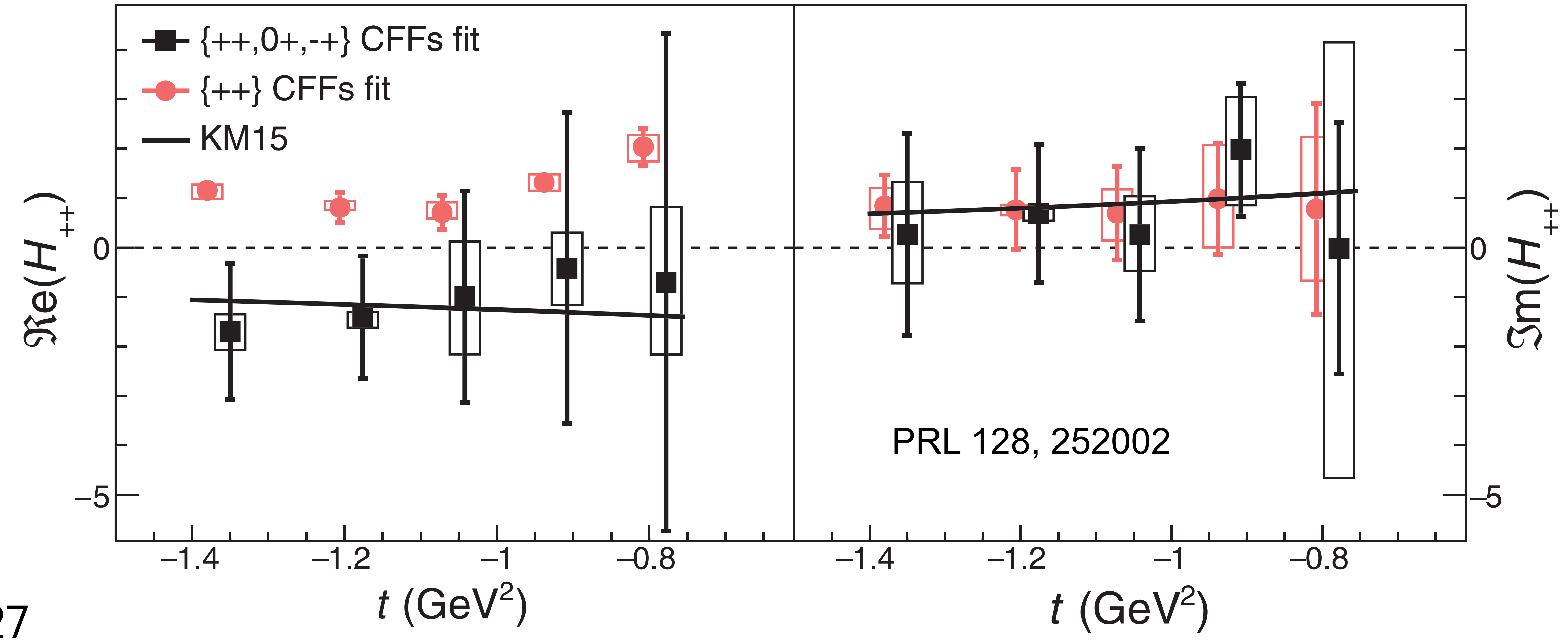

- A promising but demanding future for experimental extraction of GPDs from experiment.

**H. Dutrieux (Wednesday)**

# Generalised Parton Distributions

- High precision DVCS in Hall A.

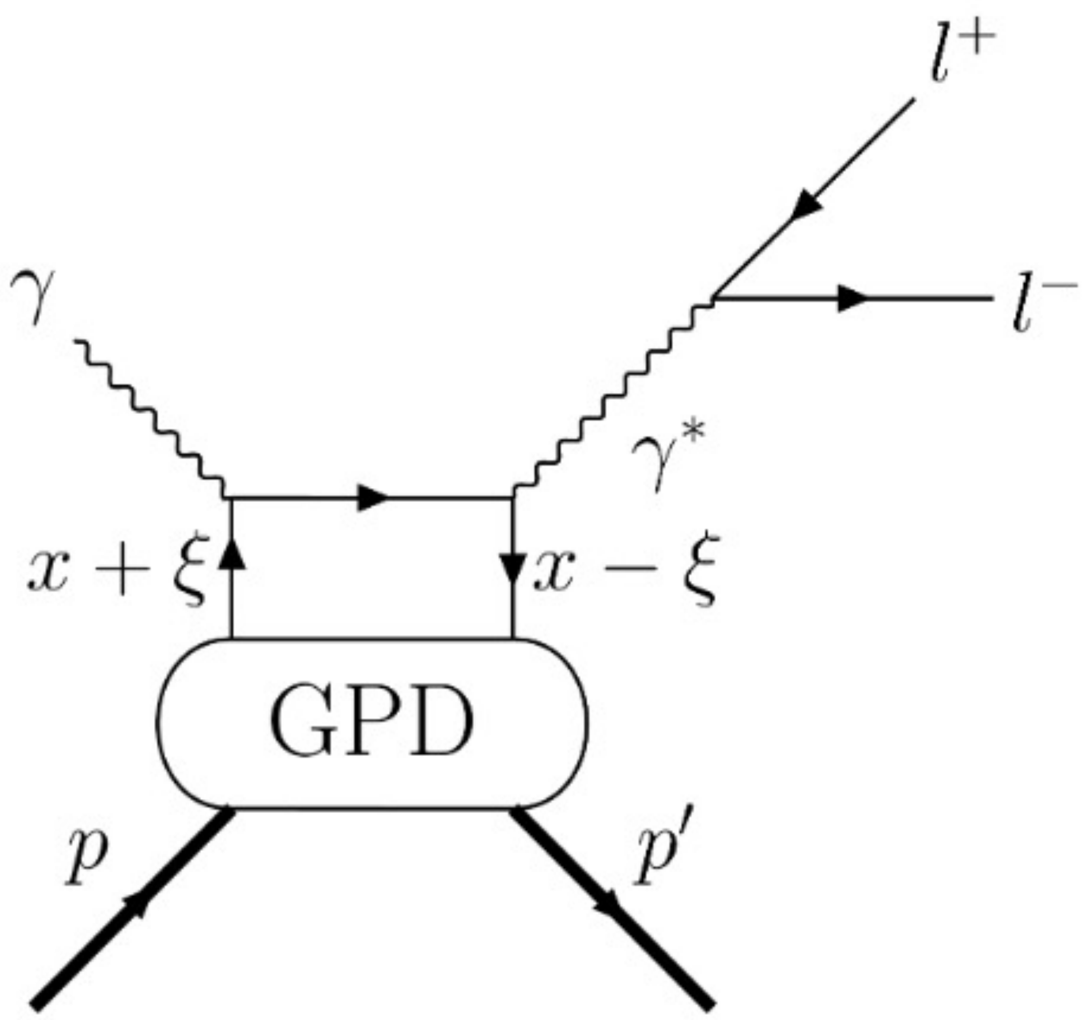


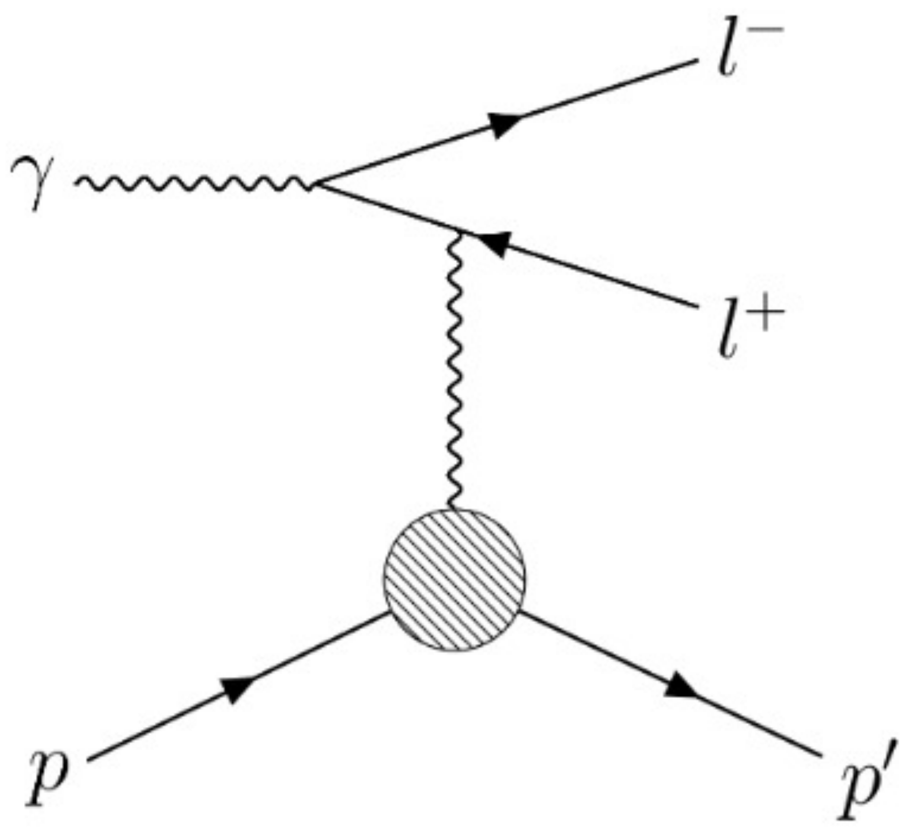




- Future multi-channel GPD sensitive measurements in Hall A & C:
  - Hall A: SoLID experiment. Large acceptance, high intensity, high resolution spectrometer.
  - Hall C Neutral Particle Spectrometer + high intensity photon beam: DVCS, TCS, DVMP.
  - positron beam?

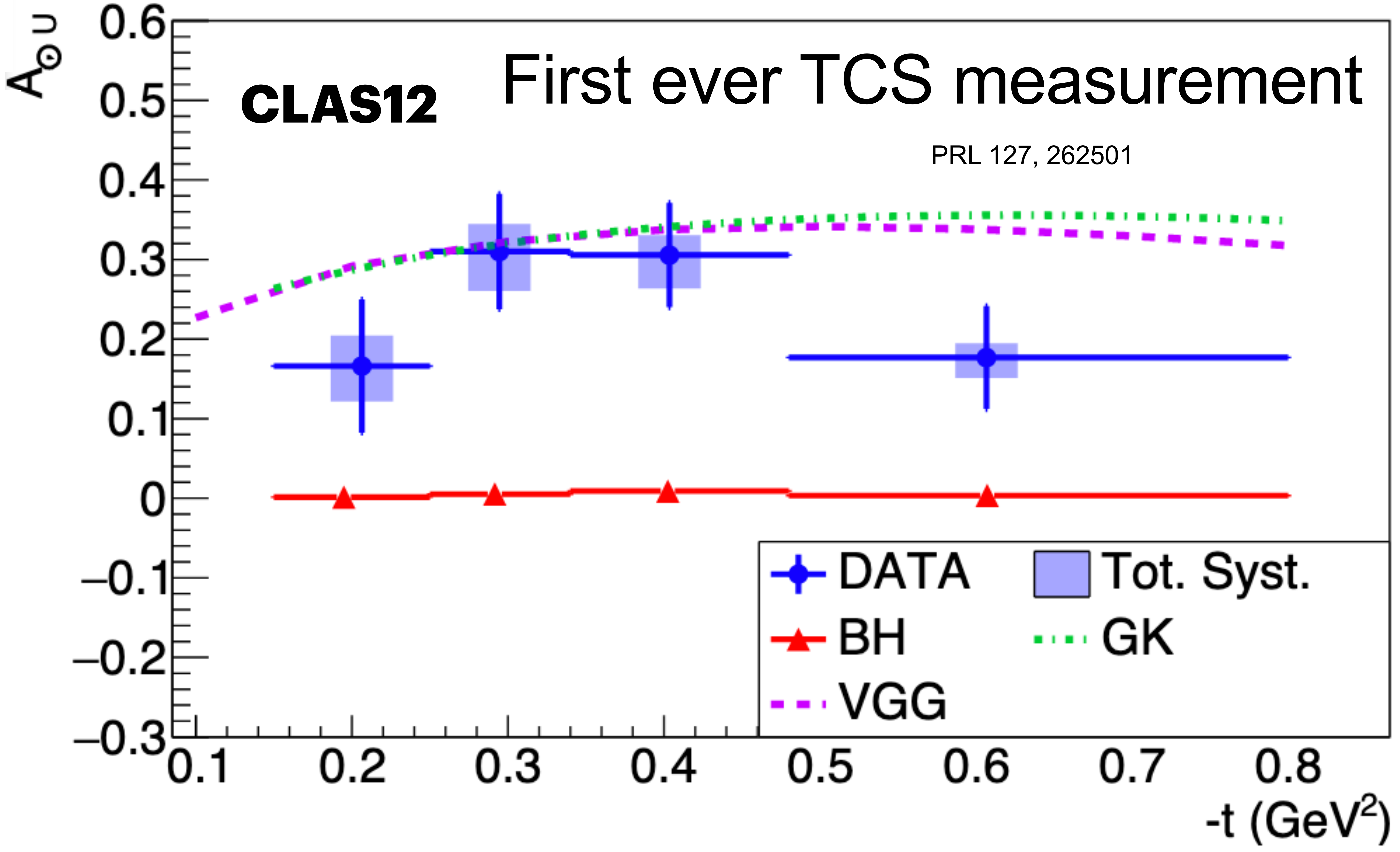
**M. Boër (Thursday)**

# Generalised Parton Distributions




- Time-like Compton Scattering (TCS): time reversal process of DVCS.
- This asymmetry is sensitive to the Im(CFF) and tests the universality of GPDs.

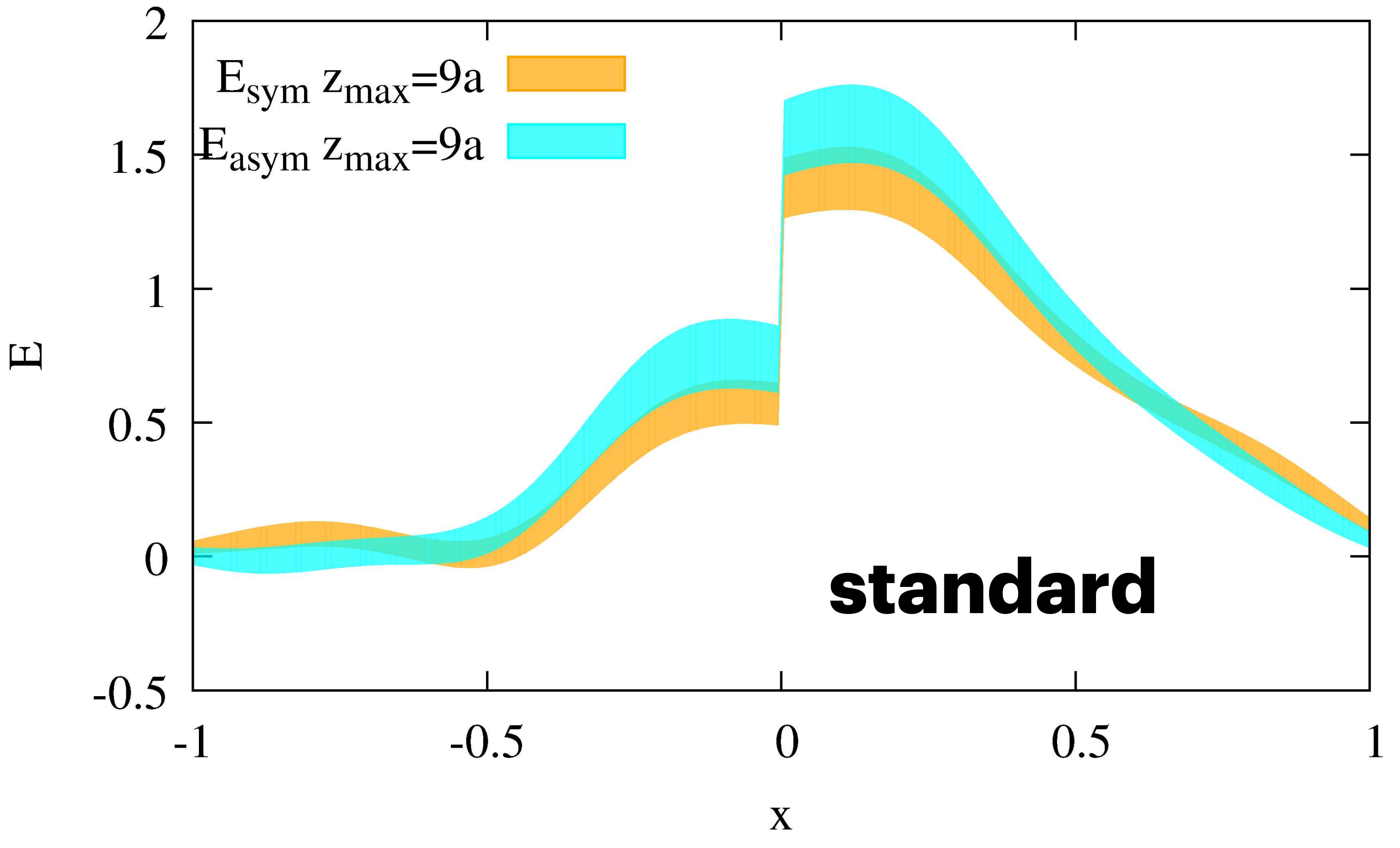


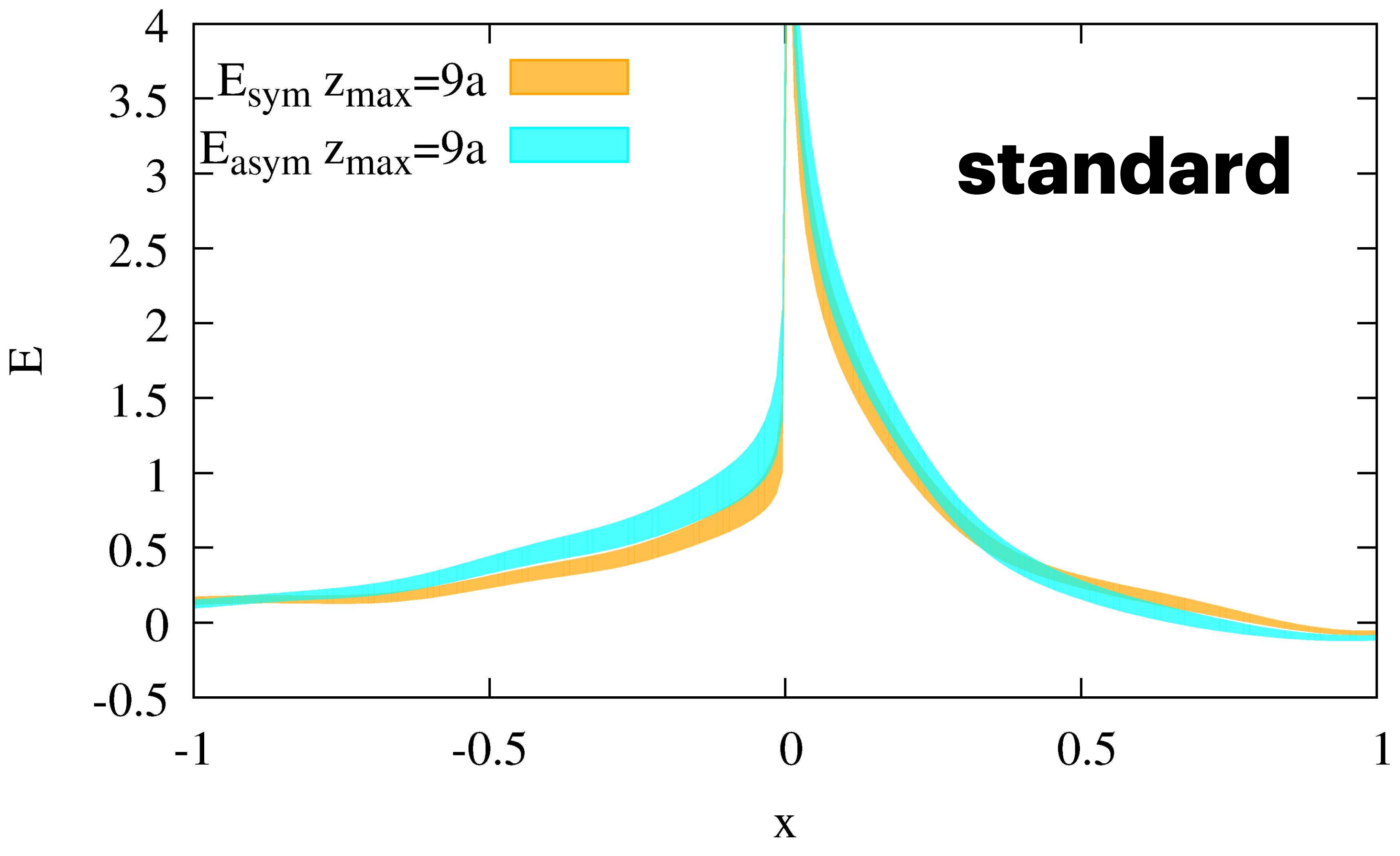

**T. Hayward (Wednesday)**

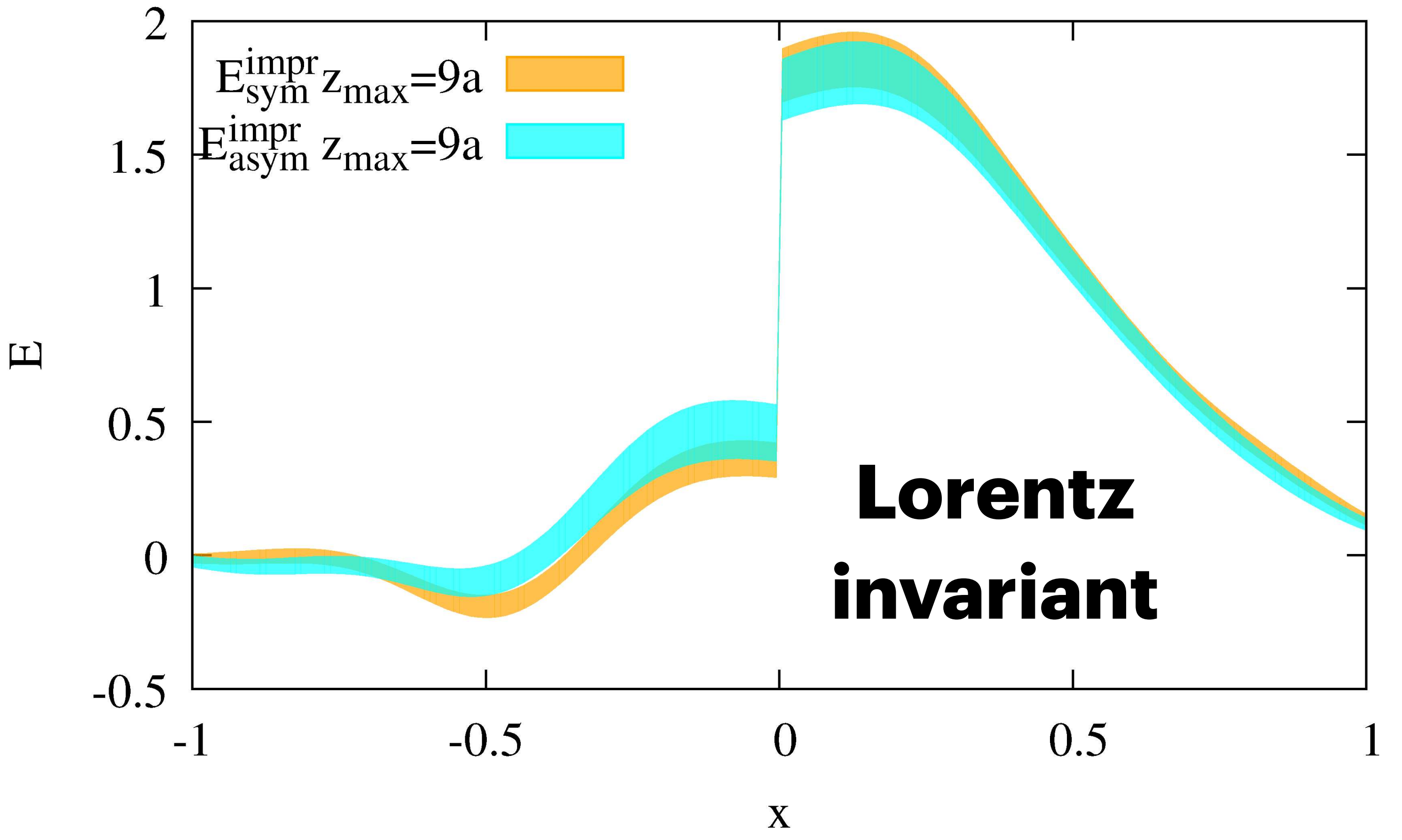
# Generalised Parton Distributions

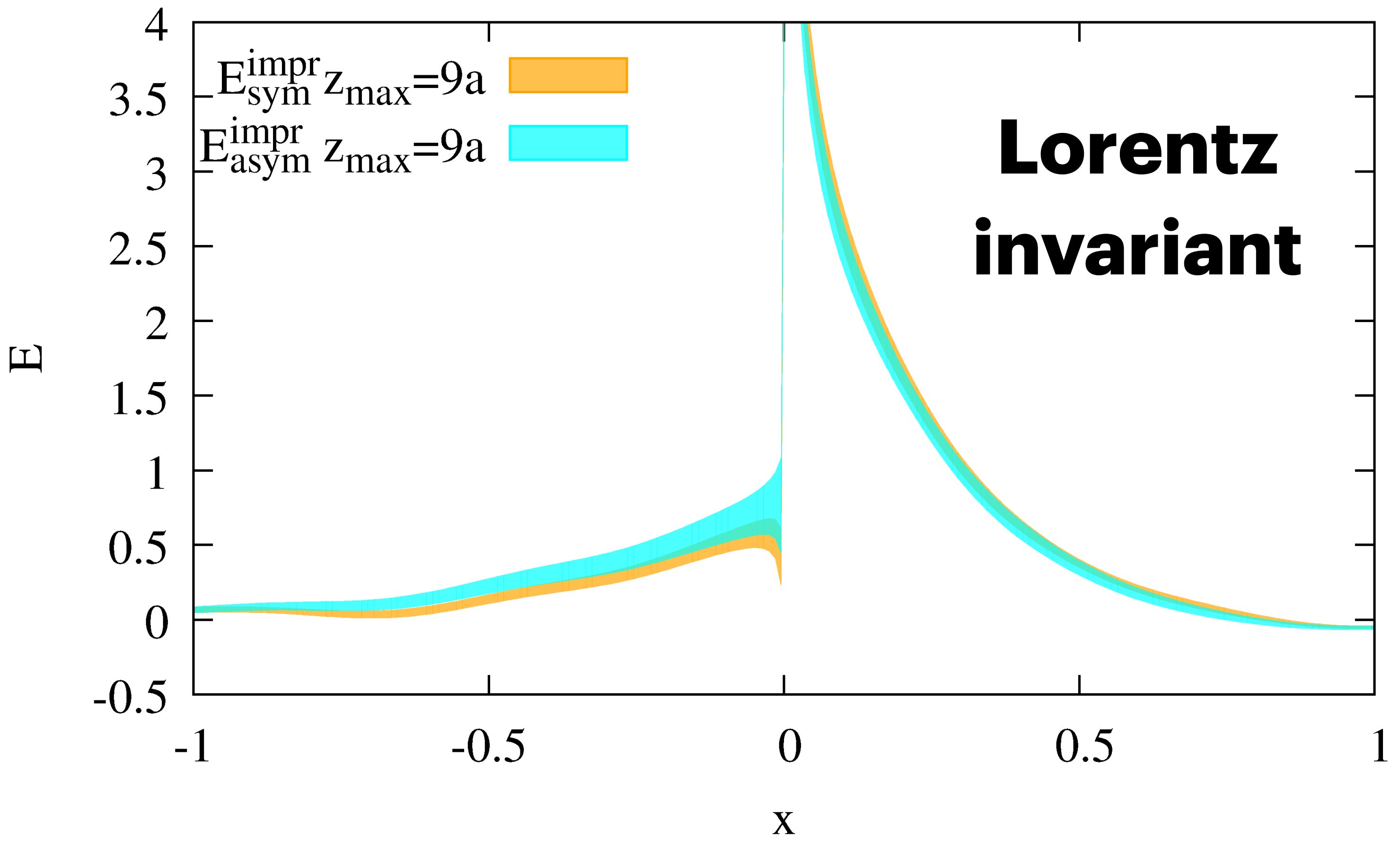
## Quasi GPDs

## Matched GPDs



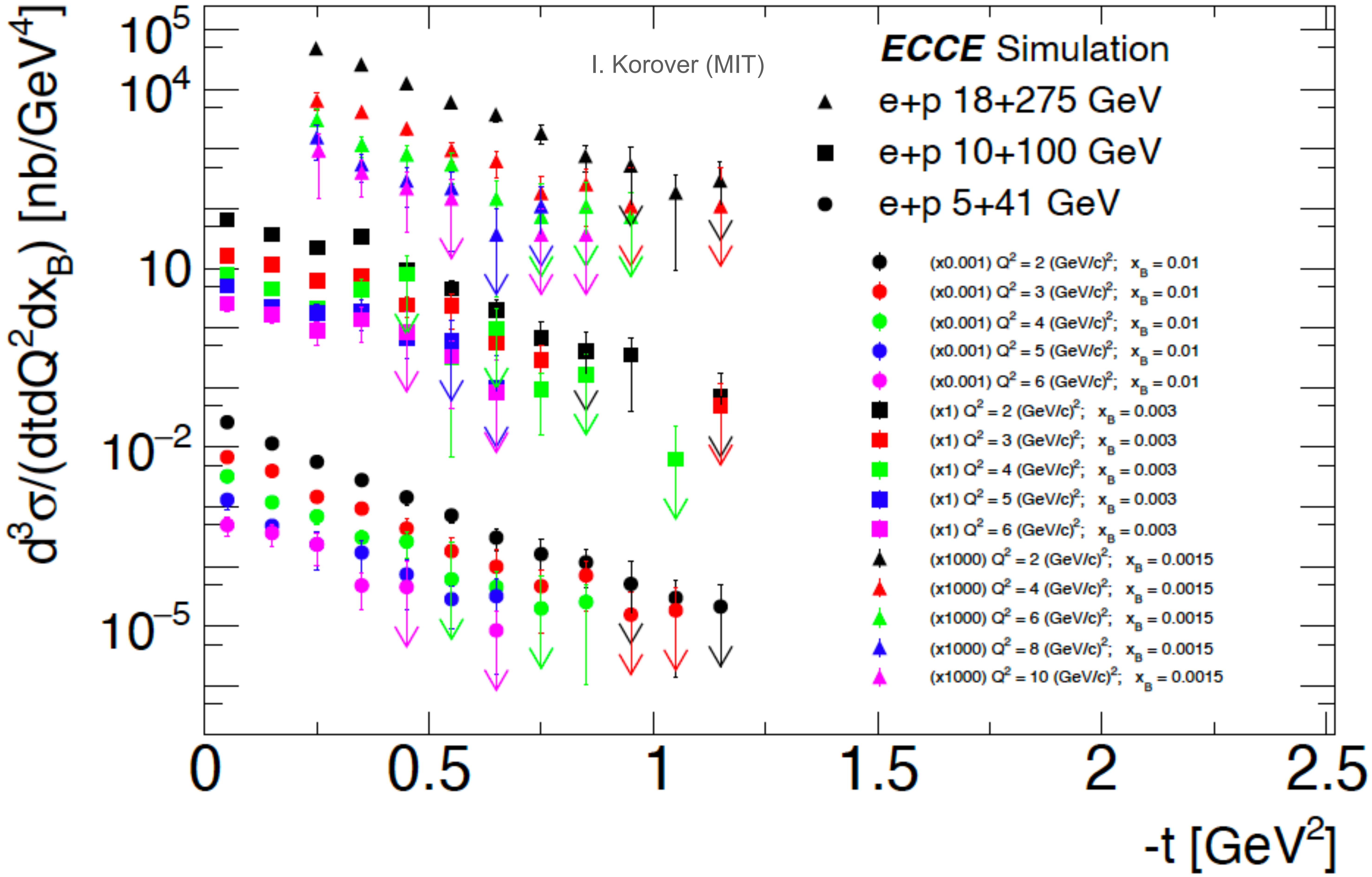




- Enormous progress in the Quasi GPD approach.
- Non-symmetric frames: more computationally-efficient.
- Frame independent achieved with Lorentz-invariant definition.
- Smaller kinematic contaminations and better signal quality.
- The new proposal is promising to obtain the GPDs for a wide range of *t* and skewness.

**K. Cichy (Wednesday)**

# Generalised Parton Distributions




**DVCS @ EIC**

- The EIC will provide reach to low-*x* (GPDs practically unconstrained).
- Statistically demanding exclusive processes will be measured.
- Hermetic detector needed for GPD extraction.

**D. Sokhan (Tuesday)**

# Thank you for your attention!

**and special thanks to all speakers that contributed with material for our summary!**

🥰