WG1 summary: structure functions and parton densities

DIS 2026 - Bologna, Italy

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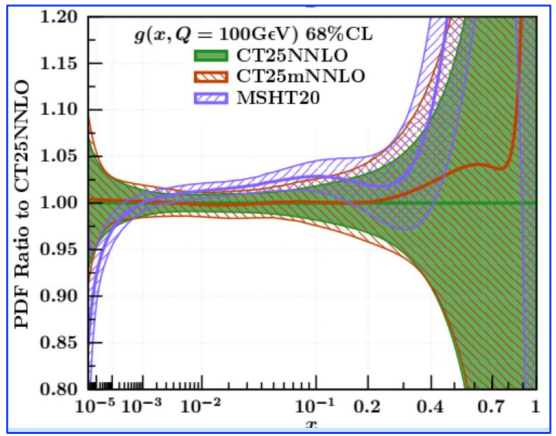
Common themes

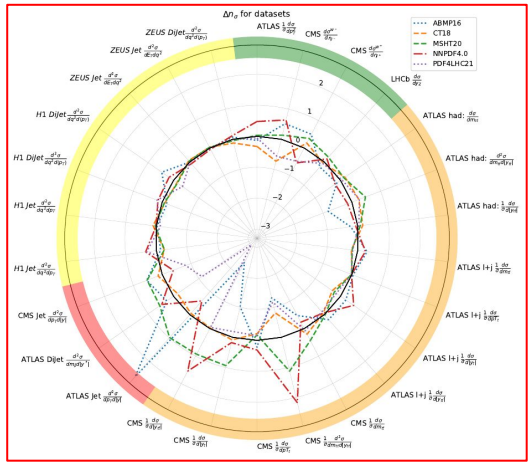
- Precision from LHC, for EIC:
  - New data spanning JLab and the LHC
  - Push theory to N^3LO
  - Uncertainty estimate more important than ever
    ⟶ Exp. & theory correlations, systematics, errors on errors, …
  - Tools & techniques:
    ⟶ Bayesian / Hessian; open numerical tools & fit packages
- Study/revisit: nuclear target dynamics, power corrections (HT/TMCs)
- Lattice PDFs: pushing the envelope
- Not only protons: meson/photon PDFs
- New observables and calculations:
  - For PDF analysis, SM parameter extraction

Global PDF updates (1)

- **P. Nadolsky, A. Courtoy**: **New CT25** (later this year)
  - 4 diverse sets
    - CT25 NNLO ⟶ well constrained regions
    - CT25m large/small-x extrapolation ⟶ BSM
    - CTT25pd
    - CT25pflat
  - CTEQ-TEA Parton Cloud repository (> 400 fits)
  - CT fitting code to be released ⟶ DragonWell

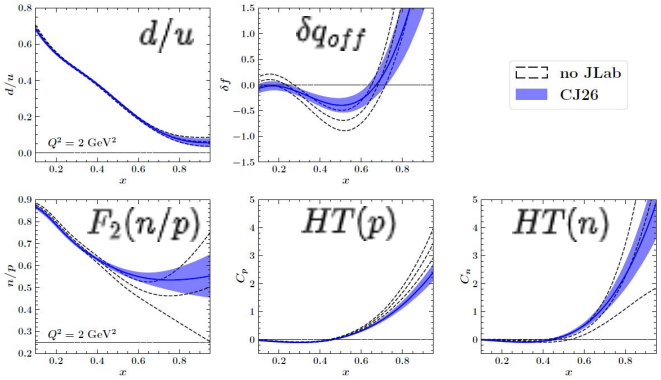


- **F. Hekhorn: new NNPDF4.1** (autumn 2026)
  - New LHC data
  - Prediction "pineline": MATRIX & NNLOJET ⟶ NNLO grids
  - Theory-related uncertainties (MHOU, EW, SM params …)
  - Check dataset consistency
  - GPU usage

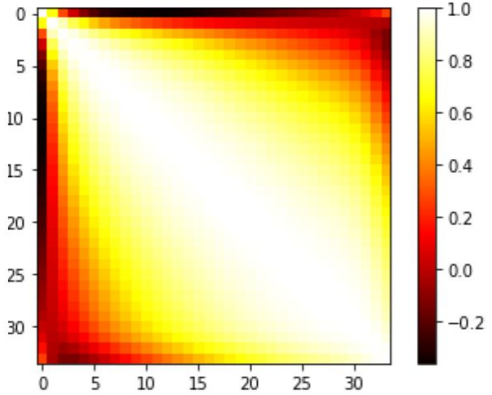


Global PDF updates (2)

- ***A. Accardi:*** **New CJ26**
  - Robust, no-LHC baseline for large-x PDFs
    ⟶ full JLab 6 and 12 GeV data for access to large x
  - Interplay of deuteron DIS & D0 W asymmetry
    ⟶ Separate HT and LT physics
    ⟶ large-x d/u & off-shell nucleon dyn. (deuteron);
  - careful HT + nuclear systematics study
  - With new JLab & EIC data to increase Q2 leverage
    ⟶ Further constrain large-x PDFs

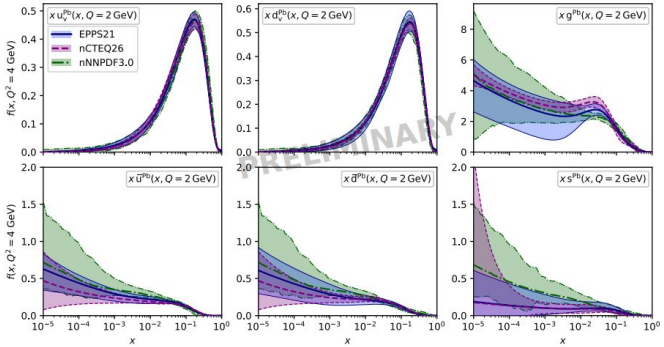


- ***R. Thorne:*** **MSHT updates**
  - Partial update with high x and dijet data
  - “errors on errors” & correlation treatment
  - Restudy higher twist & target mass effects vs. suppression cutoff
  - Suggest new, smoother “random walk” correlation model for 2-point systematics

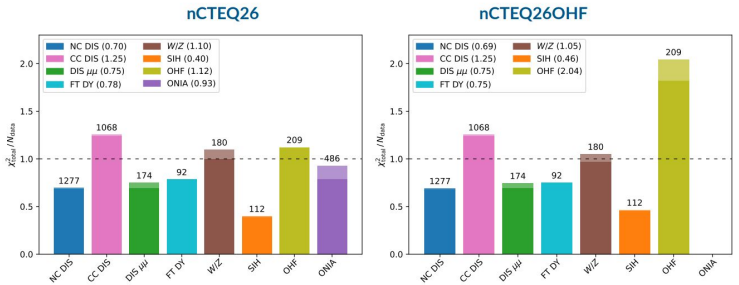


Nuclear effects

- **In proton fits (!)**
  - Microscopic modeling of nuclear dynamics
    - ⟶ CJ26, AKP Petti (fitted on- and off-shell PDFs)
  - Check model against p+p data within a global fit:
    - ⟶ d/u ⟷ D0 W-asym: **OK** **CJ15-26**
    - ⟶ db/ub ⟷ STAR W: **OK** ***B. Surrow***
    - ⟶ db/ub ⟷ LHC fwd/bwd Z-asym: **NOT?** ***W. Ma***
  - Remove heavy nuclear targets from a fit
    - ⟶ CT25pd ***Nadolsky***
    - ⟶ Hessian deweighting ***Paakkinen***



- **Nuclear PDF fits** ***T. Jezo, J. Wissmann***
  - nCTEQ26 – Wide selection of data (LHC, JLab, …)
  - nCTEQ26OHF ⟶ SACOT for open heavy flavor
    - ⟶ Remove quarkonia data
    - ⟶ ALICE and LHCb: systematic theory pT tilt
      - Worse chi^2 than nCTEQ26
      - Different factorization scale needed?



- **Warning:** L/T ratio likely to be A-dependent – ***Kumano***
  - Need new precision data to confirm: JLab E03-03-103 (2026); …

Approximate N^{3}LO PDFs

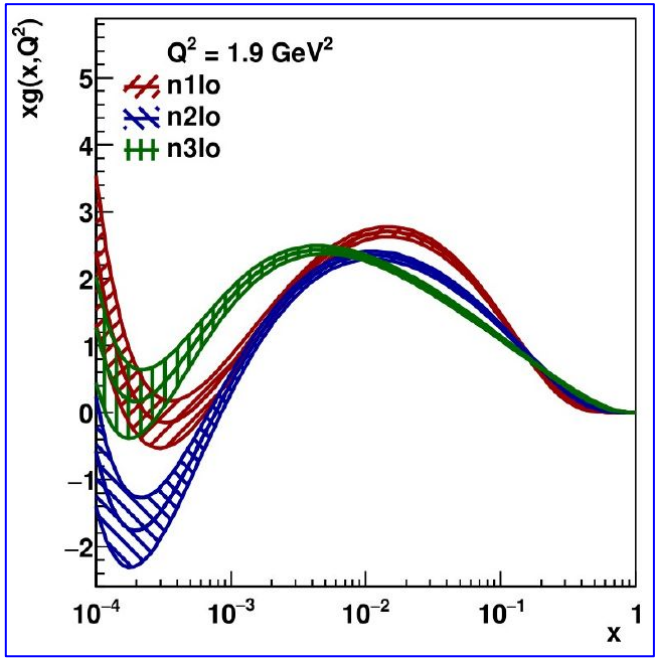
- ***F. Giuli:*** xFitter: Fits @ N^{3}LO DIS
  - Slightly improved PDF fits to DIS data; modified params compared to HERAPDF2.0
  - "Resummation scale" approach to account for MHO in RGE evolution kernels

- ***M. Guzzi:*** CT: Towards global fits @ aN^{3}LO
  - 1st step DIS@N^{3}LO → ongoing work with ACOT-χ GMVFN in partial N^{3}LO
  - CANDIAv2 evolution code @ N^{3}LO publicly available

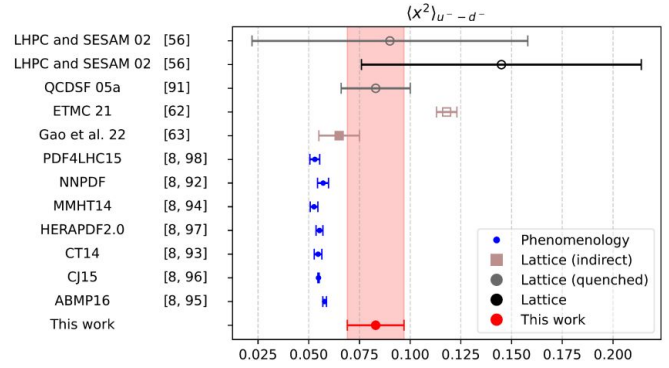
- ***T. Cridge:*** MSHT: 1st aN^{3}LO PDFs + theory nuisance parm. for uncertainty (TNP)
  - Continuously updating for new N^{3}LO ingredients
  - Improved PDF fits to data; gluon smaller by ~ 3% @ x = 0.2

- ***V. Sotnikov:***
  Serious challenge: 4-loop non-singlet splitting functions
  - Mandatory @ N^{3}LO, now fully completed!

(NNPDF aN^{3}LO PDFs with uncertainties since end of 2024)

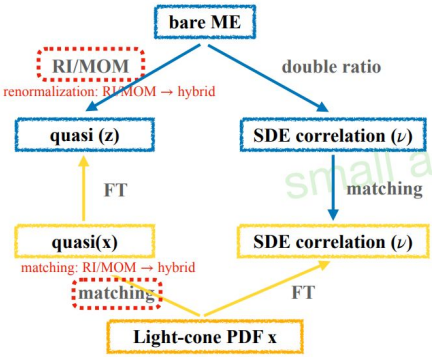


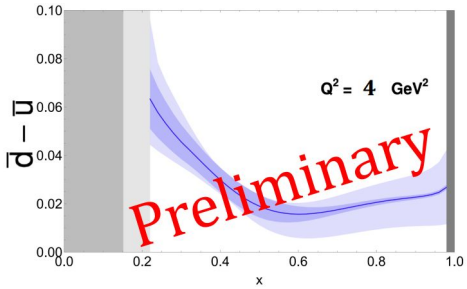
PDFs from lattice QCD



- **Mellin Moments:** 3rd moments, 4th in the works; Unpol, pol and transversity – ***Taggi***
  - Combinations of local 3-point operators to tame higher mass state contamination
  - Systematic overestimate of QCD fit results

- **x-space calculations**
  - Many methods; inverse problem
  - ***M.-H. Chu:*** Unified neural network approach to combine strengths of LaMET & SDE (medium x vs. larger and smaller x)
  - ***H.-W. Lin:*** Progress in sea quark asymmetry: it's positive!
  - Improvements needed, e.g.,
    ⟶ Hybrid RI/MOM renormalization scheme

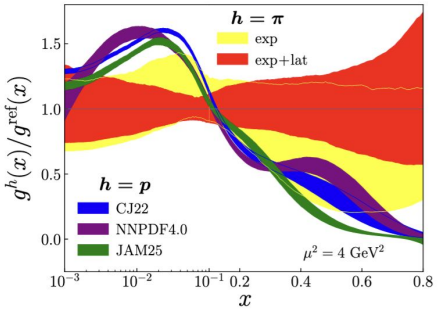


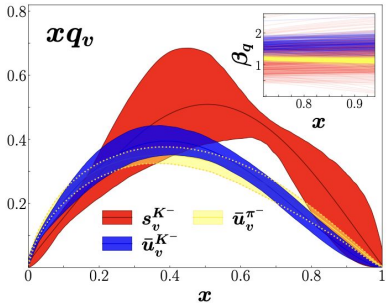


- **Combine lattice calcs with QCD fits**

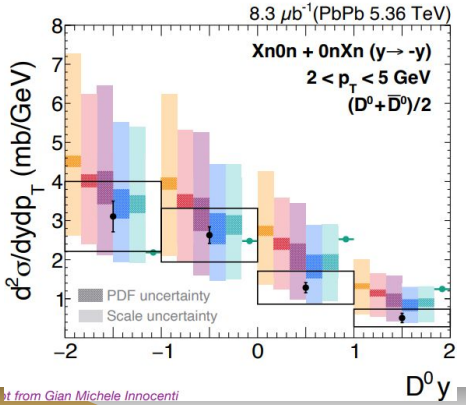
Other PDFs

- **Proton ⟶ mesons (nature of non-perturbative QCD)**
  - ***M. Sargsian*** - Mean field model of valence quarks including qq & qqq correlations; motivates peak position in proton valence, and observed large-x beta ~ 1 for pion valence
  - ***W. Melnitchouk*** - Simultaneous QCD analysis of π and K PDFs harder glue in π than p; signs of SU(3) breaking in K's valence
  - **Future experimental avenues**:
    - ⟶ Tagged DIS @ JLab
    - ⟶ ***Z. Earnshaw:*** AMBER @ CERN - pion and kaon beam DY





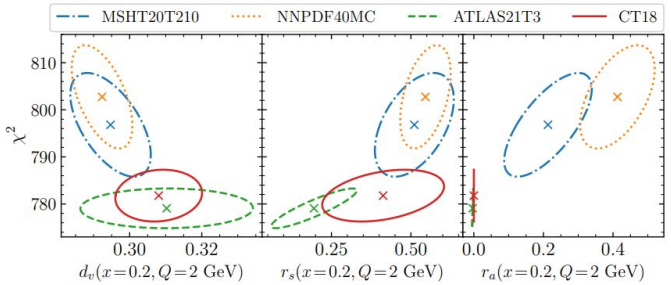
- **Photons**
  - ***M. Chithirasreemadam:*** VALO1.0:
    - ⟶ new γ PDF from global analysis of **F2γ from e+e- data**; uncertainties by MC replicas; will add HERA photoprod.
    - ⟶ relevant for UPCs@LHC and future EIC
  - ***A. Staśto:*** **open charm photoproduction in Pb+Pb UPC at LHC**
    - ⟶ GγA-FONLL + diffractive prediction for low-pt CMS D^0
    - ⟶ Nuclear gluons modifications strongest at $2<p_T<5$ GeV



t from Gian Michele Innocenti

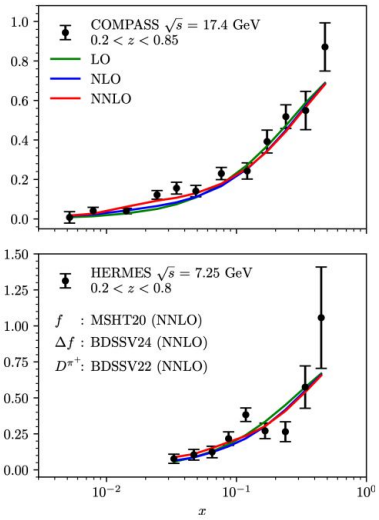
Semi-inclusive hadrons (1)

- **Fragmentation functions**
  - **New NPC23** global FFs, pions and kaons ***J. Gao***
    - ⟶ Hessian & scale uncert.; NLO & **NNLO**
    - ⟶ SIA; SIDIS, hadron-in-jet @LHC ⟶ gluons
  - **Towards NNFF2.0** ***T. Sharma***
    - ⟶ SIA only ⟶ global data sets
    - ⟶ Tool development first: time-like EKO, rehauled pineAPPL
    - ⟶ **vhf**: virtual hadron factory: NC/CC ZM-VFNS (⟶ GM-VFNS)

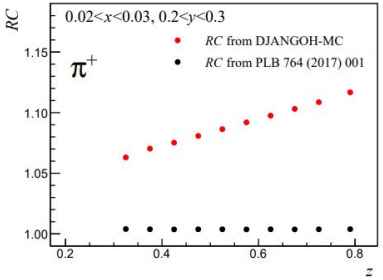


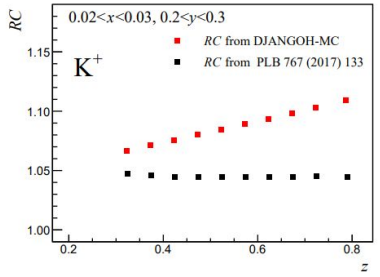
Profiling PDFs: favors small strange & small s-asym

- **Precise predictions for SIDIS**
  - Complete **NNLO** calculation; convergence ***T. Gehrmann***
    - ⟶ Flavor separation with $\nu(\bar{\nu}) + p \to l^{\pm} + h + X$ CERN data
    - ⟶ Could be revisited at EIC: $e^{\pm} p \to \nu(\bar{\nu}) + h + X$
  - Separate large-x and large-z resummation ***F. Ventola***
    - ⟶ Estimates many more HO terms; q+q channel to start



Semi-inclusive hadrons (2)

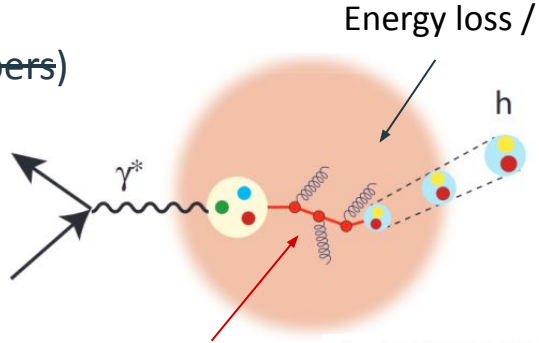




- **COMPASS pion and kaon multiplicities**

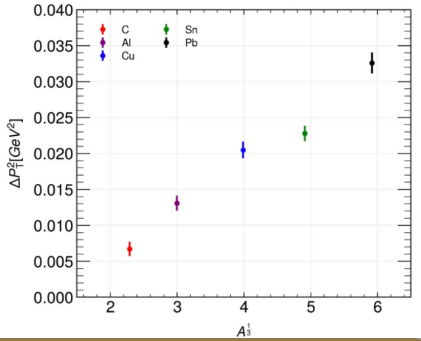
  Proton and deuteron targets ***M. Stolarski***
  - New radiative corrections (+5-10%)

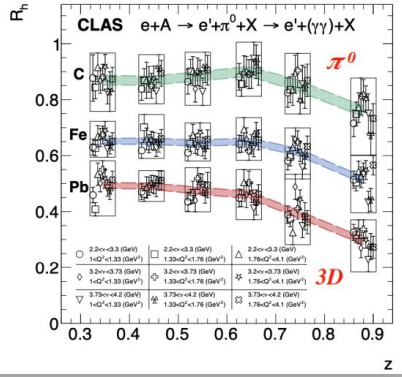
    ⟶ Different size and shape
  - Final p target; revised d target results (~~2017 papers~~)



- **JLab A/D: hadronization dynamics** ***H. Hakobyan***

  3D multiplicity ratio and pT-broadening
  - 6 GeV: new pi0, prelim. eta, omega;
  - 12 GeV: prelim pions, many targets
  - Many more flavors to come

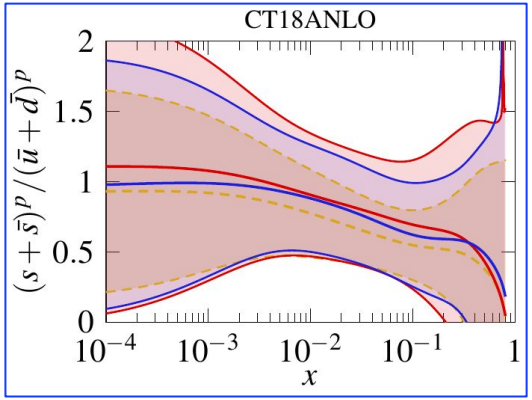




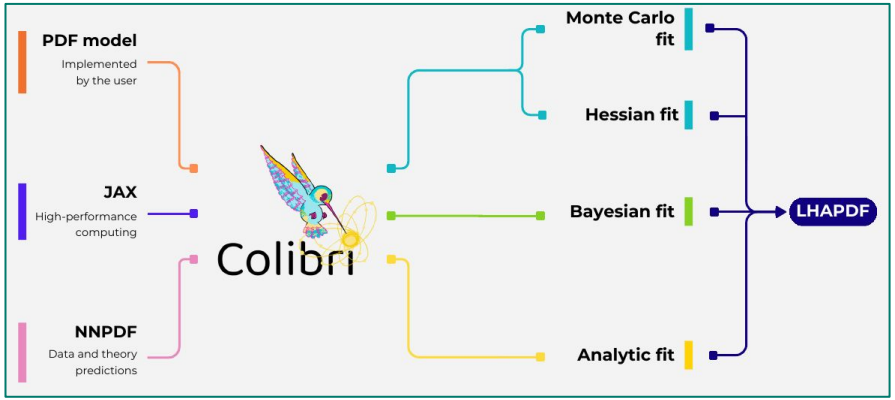
Tools & techniques (1)

- ***M. Bonvini:*** Treat correlations in MHOU in a more physics–related way, from knowledge of underlying physics or similarities in perturbative expansion
  - "Bayesianised" approach by Tackmann, more agnostic possibilities to be examined

- ***P. Paakkinen:*** Update to updating PDFs in Hessian formalism
  - Possibility to account for updated theory and/or data in fits, removal of data



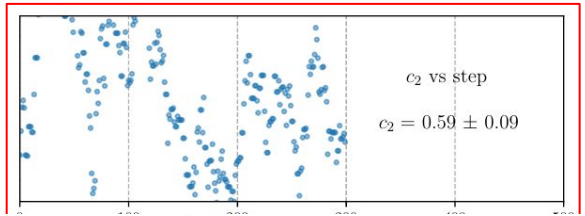
- ***V. Schütze Sànchez:*** **COLIBRI** - flexible open-source PDF-fitting framework for systematic model comparison, methodology benchmarking, and weighted PDF combinations
  - user-defined PDF parameterisations can be fitted with different inference methods, including Bayesian approaches



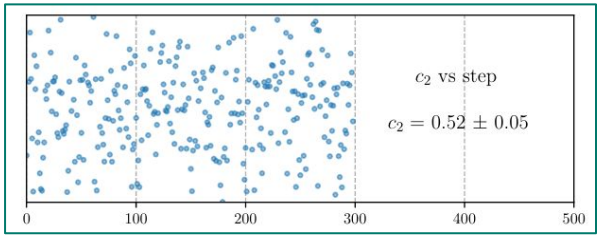
Tools & techniques (2)

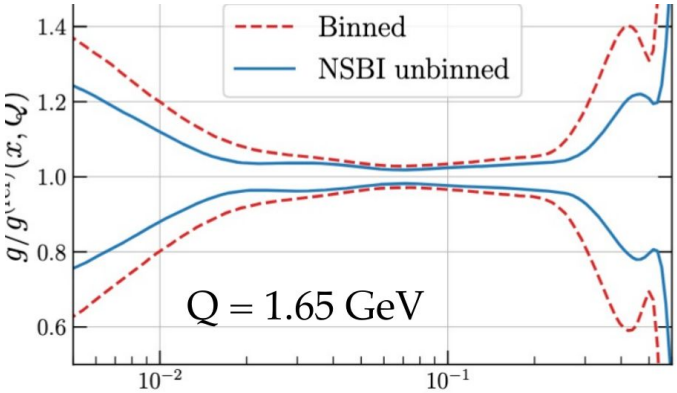
- ***A. Kusina:*** Markov Chain MC for PDF fits
  - Uses random walk Metropolis Hastings scheme, clever treatment needed to eliminate step-by-step correlations in uncertainty derivation
  - Exemplary use for p PDFs with DIS & DY data and in nuclear PDFs
  - Allows unique insight into complex likelihoods: non-Gaussianity, multiple minima; first examination of systematics from nuclear A dependence

- ***R. Schöfbeck:*** Demonstration of neural simulation-based inference for PDFs
  - Use of detector-level unbinned data → may lead to better PDF constraints e.g. from ttbar



thinning 10^4 samples to a total of 300





PDFs and SM parameter extractions (1)

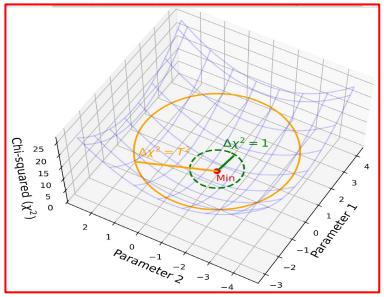
- ***T. Cridge:*** Theoretical uncertainties in α_s determinations, e.g., from Zp_T
  - Scale variation even more problematic for shape measurements ⟶ theory nuis. parm. (TNP)
  - PDF profiling must use tolerance of PDF set ⟶ $\Delta\chi^2 = T^2$

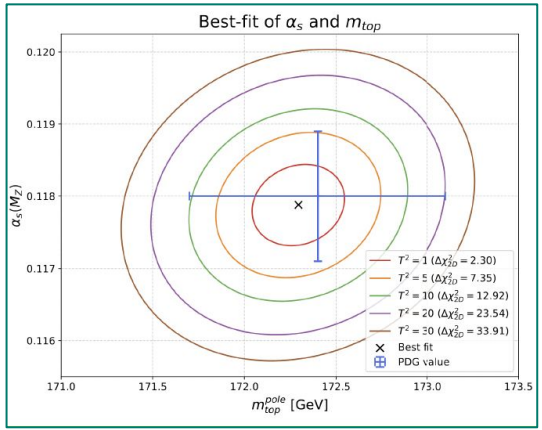
- ***T. Sharma:*** Interplay m_{top} vs α_s vs g(x) in global fit (CT)
  - PDF fits with interpolation grids at NNLO for series of m_{top} (+ series in $\alpha_s(M_Z)$ values used)

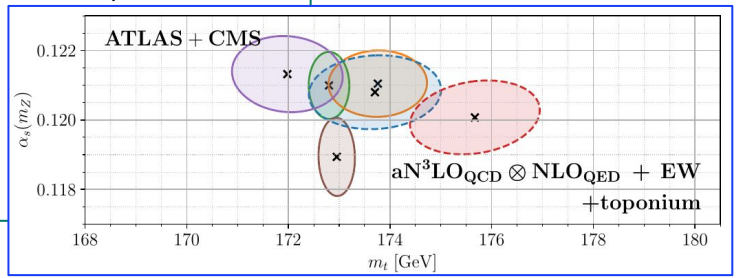
    ⟶ $m_{top} = 172.3 \pm 0.8$ GeV

- ***J. ter Hoeve:*** Interplay m_{top} vs α_s vs g(x) in global fit (NNPDF)
  - Many sets of ttbar data, often without correlations; sensitivity to data of m_{top} varies
  - Separate PDF fits for each set/observable

    ⟶ $m_{top} = 172.8 \pm 0.3$ GeV





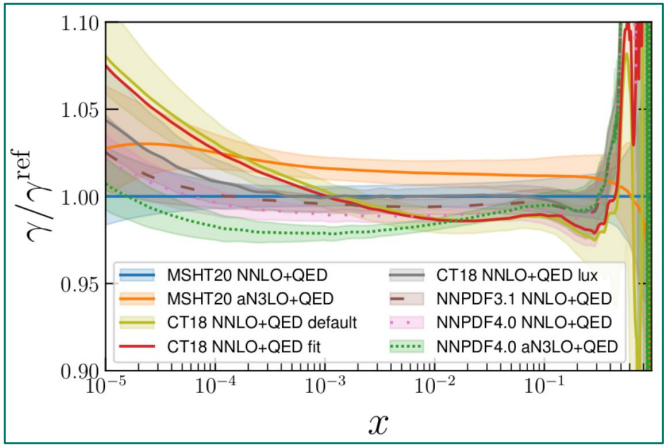


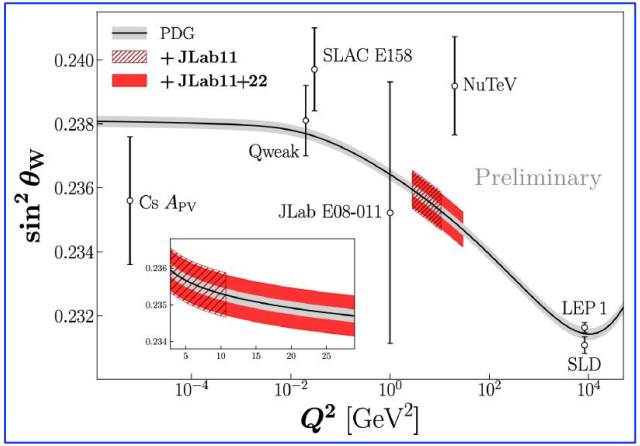
PDFs and SM parameter extractions (2)

- ***T. Cridge:*** QED effects in PDFs
  - Included in most global PDF fits (→ photon PDF)
  - Small but noticeable impact; small differences among groups largely understood

- ***R. Whitehill:*** Proposal of JAM PDF fit using parity violating asymmetry in DIS A_{PV}
  - Insights towards nucleon strangeness & $\sin^2\theta_W$ from JLAB low-Q^2 data
  - Work on QED, HT effects required

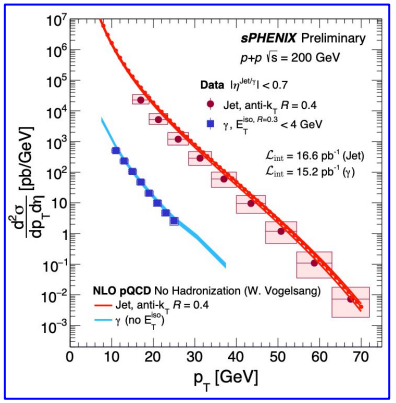
- ***A. Arbuzov:*** Theor. study of model process DY QED for fact. scale setting improvements



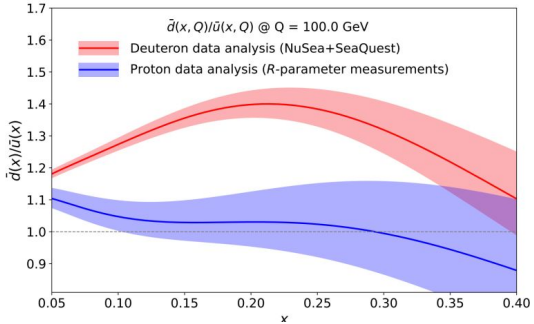


New inputs for global PDF analysis (1)

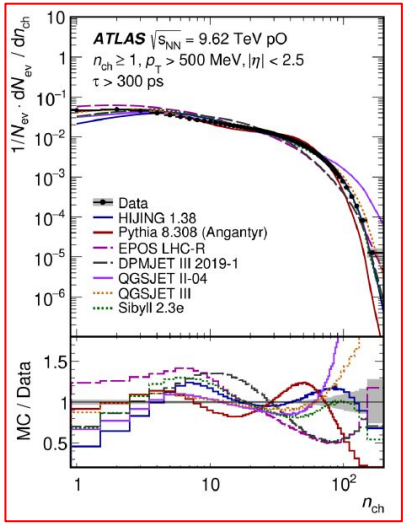
- ***Y. Go:*** sPHENIX@RHIC
  - ⅔ of all data from last 25 years new from 23-26; AuAu, pp, OO; only pp in talk
  - Good descr. @ NLO of isolated γ; less so for jets (R=0.4)



- ***W. Ma:*** **Fwd/bwd $A_{FB}(Z)$** in LHC p+p ⟶ dbar/ubar
  - Complementary to p vs. deuteron scattering
  - CMS, D0, ATLAS data
    - ⟶ Small db/ub asymmetry From p-only CT18-like fit
    - ⟶ Larger nuclear effect than expected in p/d DY?

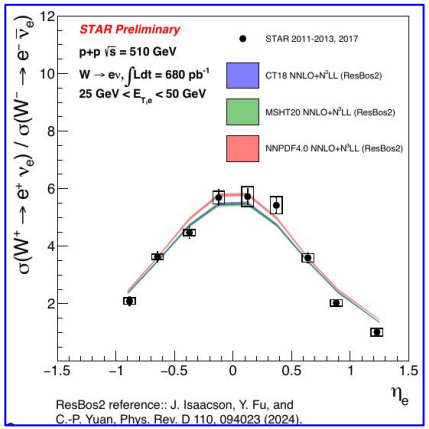


- ***Z. Hubacek:*** New ATLAS data
  - p+O: $dN_{ch}/d\eta$ input to modeling in cosmic ray Monte Carlos; all MC way off the new data ⟶ need tuning
  - W: angular coeff. well described in SM @ NNLO+NNLL
  - Dijet mass: 2 x 2D data, NNLOxEWxNP overshoots ~10% (R=0.4)



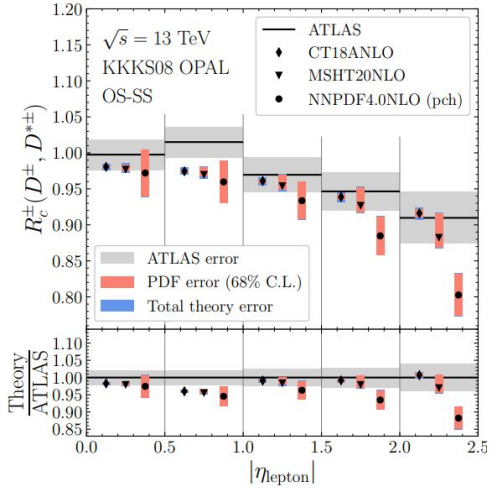
New inputs for global PDF analysis (2)

- ***B. Surrow:*** **new W boson from STAR** @ 500, 510 GeV
  - W+/W- probes dbar/ubar at x=0.1 .. 0.3;
  - 2017 almost final; 2022 in the works; tot ~ 1/fb
  - Exp. background cuts affect HO terms in σ calcs (~30% overestimate)
    - ⟶ But ratios unaffected
    - ⟶ & well described by asymmetric light sea;



- ***W. Melnitchouk:*** **JAM strange PDF**
  - W+c and SIDIS K data in global PDF+FF QCD analysis
  - SIDIS prefer smaller s, while W+c larger

- ***V. Alanko:*** Analysis of **$(W^+ + D^-)/(W^- + D^+)$** …or D*
  - Approximate ACOT-chi scheme for D production
  - Initial study prefers CT-like s=sbar

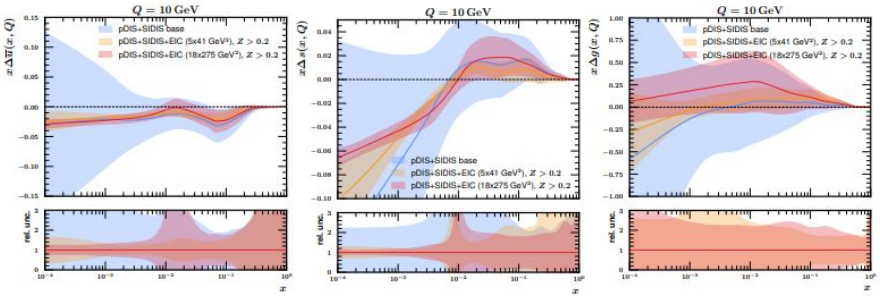


While eagerly waiting for the EIC…

- **Meaningful early science:** ***S. Maple, J. Jiménez-López***
  Possible with 1 fb^{-1} per √s
  - F_2 & F_L extraction / even F_2, F_L & F_3^{gZ}:
    ⟶ 2 energies + HERA (small y leverage)
    ⟶ 2 energies + low-E run (better precision, more F_L bins)
  - Big improvement on valence, gluon PDFs

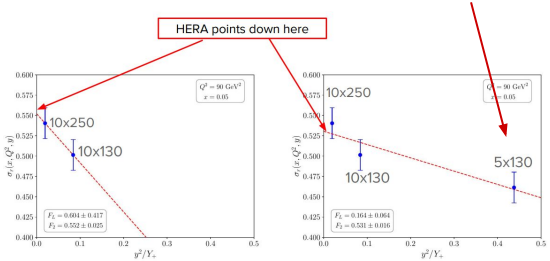
- **New for full EIC: precision α_s measurement!** ***S. Maple***

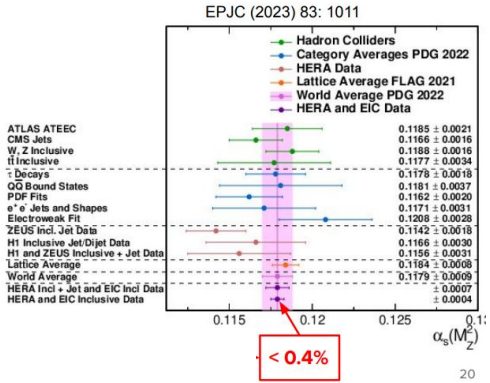
- **Precision Helicity PDFs** ***H. Khanpour***
  - New NLO global helicity PDFs – DIS + SIDIS data
  - Add EIC projections (5x41 and 18x275 GeV^2, ECCE proj.)



	Species	Energy (GeV)
YEAR 1	e+Ru or e+Cu	10 x 115
YEAR 2	e+D e+p	10 x 130
YEAR 3	e+p	10 x 130
YEAR 4	e+Au e+p	10 x 100 10 x 250
YEAR 5	e+Au e+3He	10 x 100 10 x 166

Low-E dream p+p 5x130

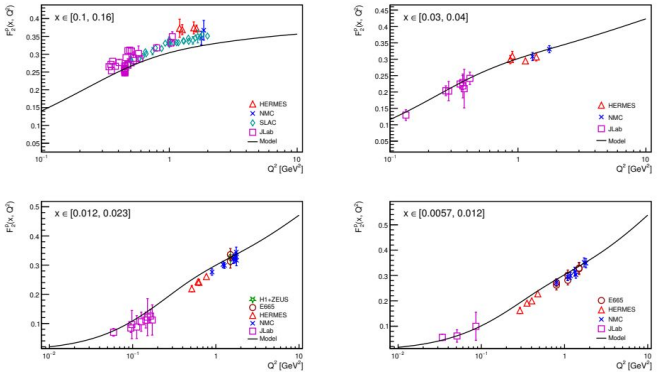




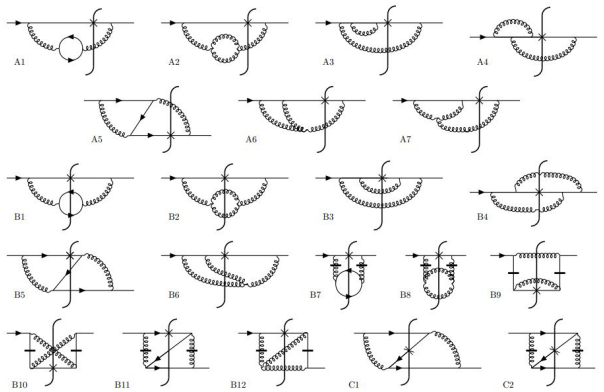
(statistical uncert. only)

While eagerly waiting for the EIC… (2)

- **Radiative corrections to match EIC precision** ***B. Badełek***
  - Need parameterisations of DIS structure functions at $\mathbf{0 < Q^2 < Q^2_{meas}}$ and $x_{meas} < x < 1$
  - Physics-based new F_2 model with nearly no parameters, reproduces world data:
    - ⟶ vector meson dominance at low Q2
    - ⟶ Partonic dynamics at high Q2



- **Precision physics at EIC with transparent partonic interpretation** ***M. Seppälä***
  - First 2-loop calculation in light-cone pert. theory
  - Work towards higher orders, automation tools like those available in normal PT



Finally...

Thank you all
for a very enjoyable WG1 session:

Speakers, Chairs, Organizers
& Attendees !!