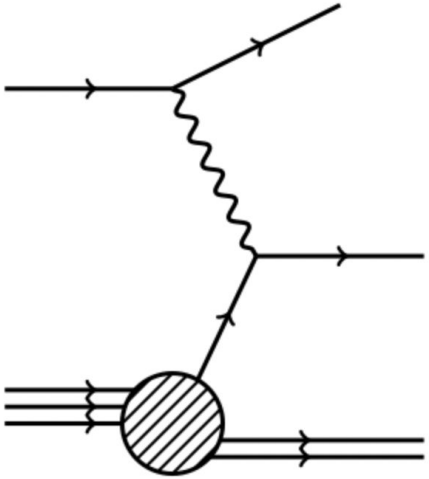


WG1 summary

F. Giuli, A. Kusina, E. Nocera

XXXI International Workshop on Deep Inelastic Scattering (DIS2024)

Grenoble, 12 April 2024

WG1: structure functions and parton densitites

Structure functions and parton densities are tools to
study the fundamental properties of proton and nuclear (collinear) structure
probe the standard model and search for New Physics

These goals are pursued by optimising models to the data,
which rely on factorisation of physical observables

Key ingredients are <u>Methodology, Theory, and Data</u>

- Basic idea is simple: $\text{Data} = \text{PDF} \otimes \sigma_H$ but many ingredients enter! Three key areas:

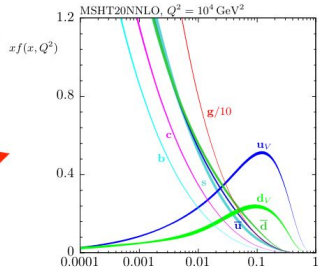
measure fit predict

Methodology

- PDF parameterisation, uncertainty prescription…

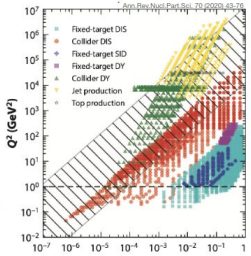
Theory

- High precision: NNLO QCD + NLO EW the standard



Data

- From fixed target, to HERA DIS and collider. LHC data increasingly important.



- Aim: high precison theory + wide range of data → **precise** + **accurate** PDFs
- Alternative/complementary route: input from lattice.

See talk by H-W Lin

Lattice QCD as an alternative/complementary way (see talk by H.-W. Lin)

The η_c distribution amplitude from lattice QCD

Teseo San José

Lattice QCD extraction of the η_c meson's t-dependent parton distribution function

Jose Manuel Morgado Chávez

Methodology

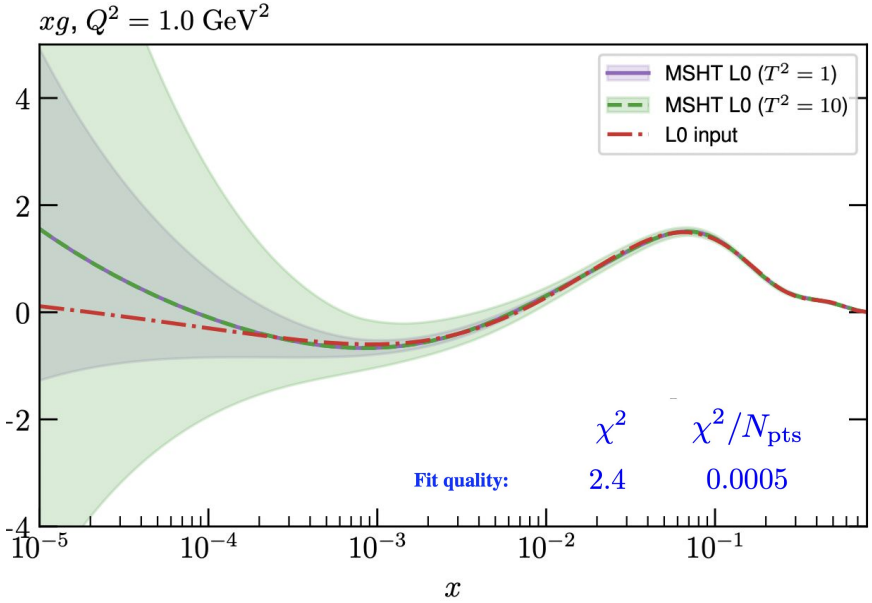
- New tests of current methodologies
  - Closure tests of MSHT (L. Harland-Lang)
  - MC sampling vs Bayesian methods (M. Constantini)
  - Systematic uncertainties in PDF fits (M. Reader)
- New methodologies
  - Gaussian processes (T. Giani)
  - MC Markov Chains (P. Risse, N. Derakhshanian)
- Computing packages
  - PartonDensities.jl (A. Caldwell)

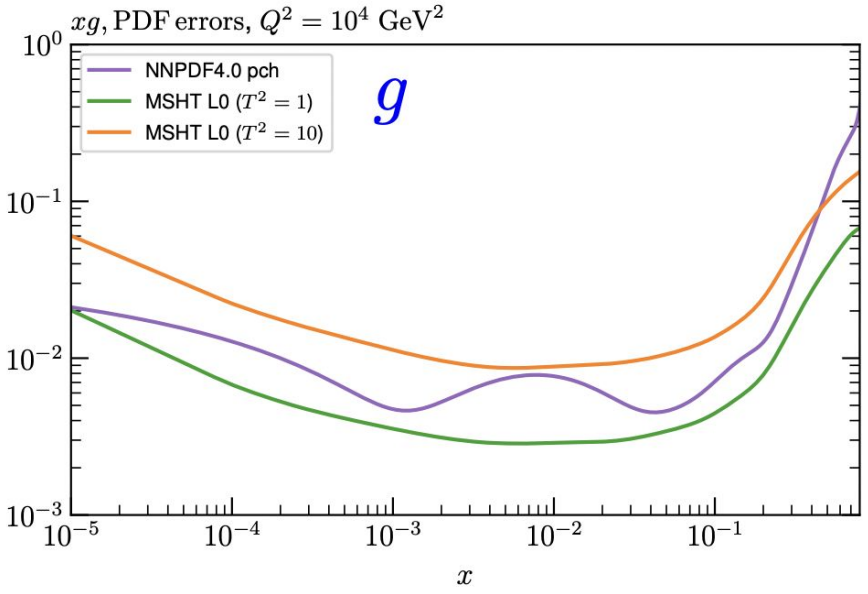
Closure tests of MSHT

- MSHT performed closure test L0
- MSHT not limited by parametrisation inflexibility
- MSHT uncertainties ($T^2 = 1$) similar to NNPDF ones

Lucian Harland-Lang

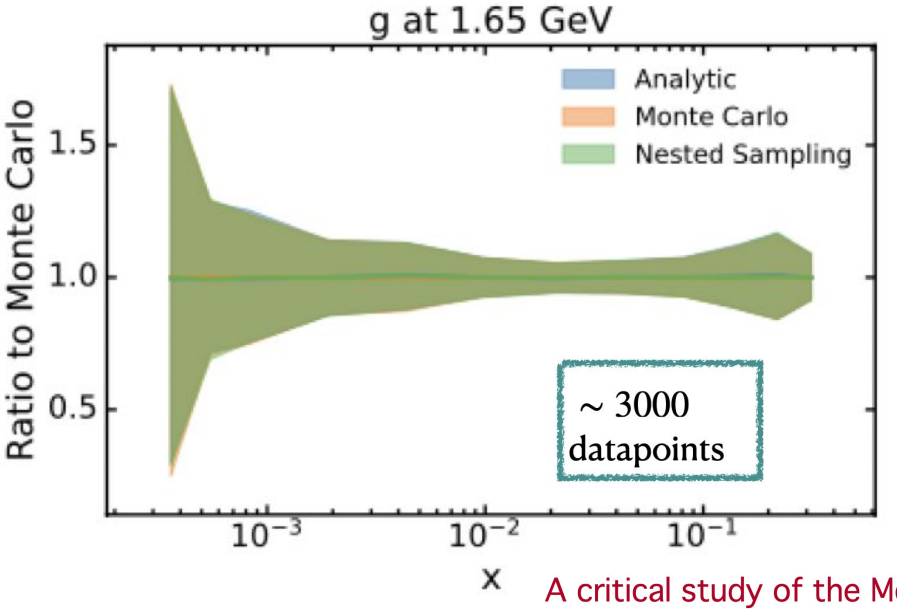
MSHT fit: Closure Test and Comparison of Approaches

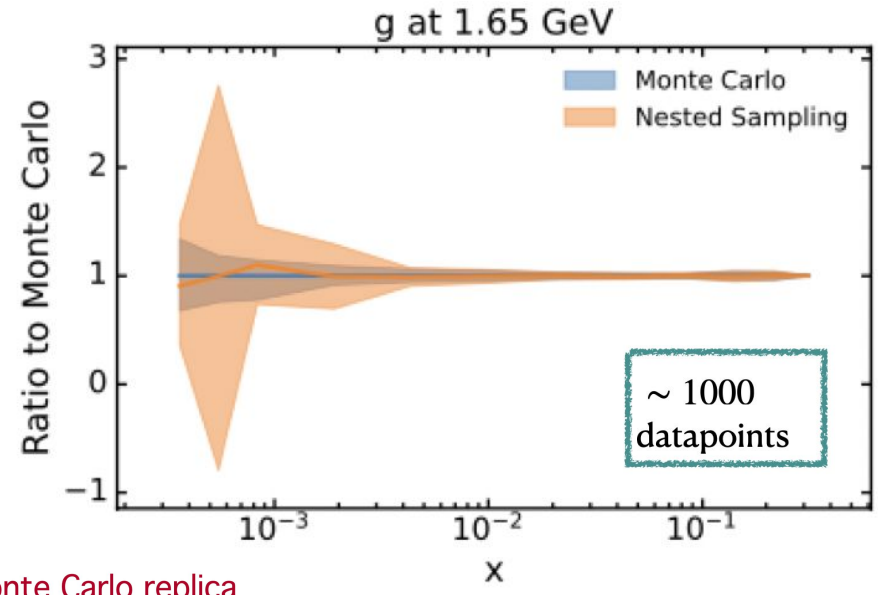




Monte Carlo and Nested Sampling

- Mathematical formulation of the Monte Carlo replica method
- Compare Monte Carlo replica approach against nested sampling
- Applications to phenomenologically relevant scenarios: SMEFT



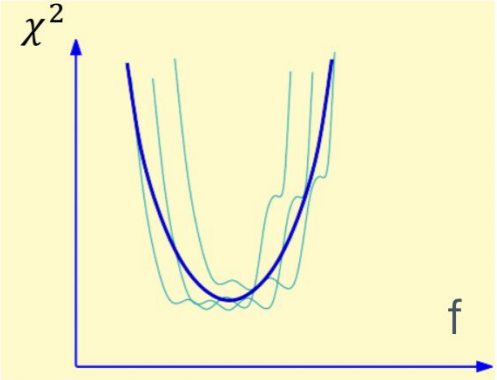


Epistemic and data uncertainties

Fantômas4QCD:
pion PDFs with epistemic uncertainties

Aurore Courtoy

- Quantify epistemic PDF uncertainties with Fantômas4QCD
- Inflate the aleatory uncertainties $T^2 = 1$ with the uncertainty due to PDF parametrization



A study of systematic uncertainties within the MSHT PDF Framework

Matt Reader

- Experimental systematic uncertainties hard to quantify…
- … and correlations are even harder!
- Incorporate errors on errors into the calculation of a χ^2 leads to non-Gaussian distributions

$$\chi^2 \equiv -2LnL = \sum_{i=1}^{N} \left(\frac{m_i - d_i - \sigma_{u_i} t_{u_i} - \sum_j \beta_{ij} t'_j}{\sigma_i} \right)^2$$

$$+(\nu+1) \sum_{i=1}^{N} Ln\left(1 + \frac{t_{u_i}^2}{\nu}\right) + (\nu+1) \sum_{j=1}^{M} Ln\left(1 + \frac{t'^2_j}{\nu}\right)$$

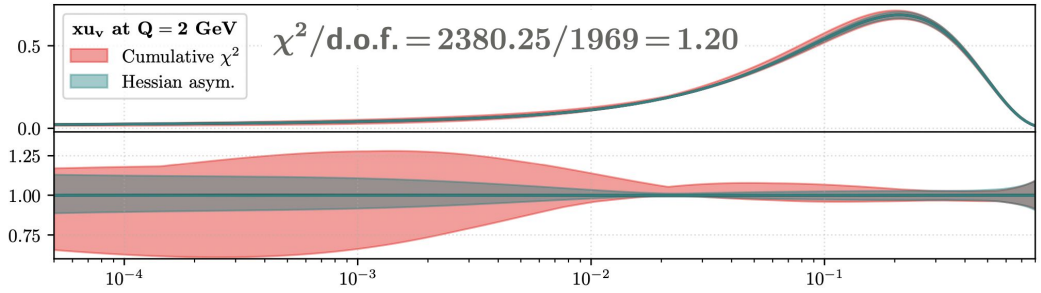
Markov Chain Monte Carlo

Markov chain Monte Carlo determination of Proton PDF uncertainties at NNLO

Peter Risse

- Proposals: Adaptive Metropolis Hastings
- 36 independent chains with 479.000 samples each
  - burn-in phase: 140.000 samples
  - **Total:** 17 million samples
- removing autocorrelation and burn-in:

Total: 4068 uncorrelated samples



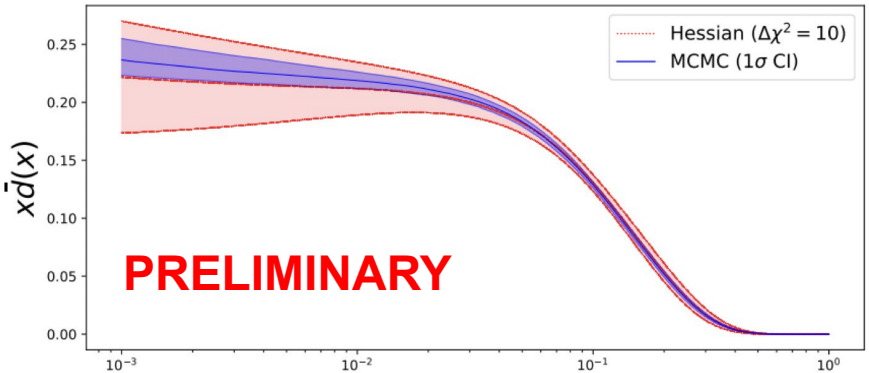
Estimating nPDF Uncertainties via Markov Chain Monte Carlo Methods

Nasim Derakhshanian

$$p(\theta \mid \text{data}) = \frac{p(\text{data} \mid \theta) \cdot p(\theta)}{p(\text{data})}$$

Posterior · Likelihood · Prior · Normalization

- MCMC applied to nuclear PDF
- Promising preliminary results



Software and Gaussian processes

PartonDensity.jl

A Novel Bayesian PDF Fitting Code

Allen Caldwell

- Based on BAT.jl, a modern Bayesian Analysis Toolkit written in Julia
- General likelihood allowing for forward modeling approach to analysis
- Standard output in useful format

Sampling result

- Total number of samples: 180725
- Total weight of samples: 999996
- Effective sample size: between 1915 and 4848

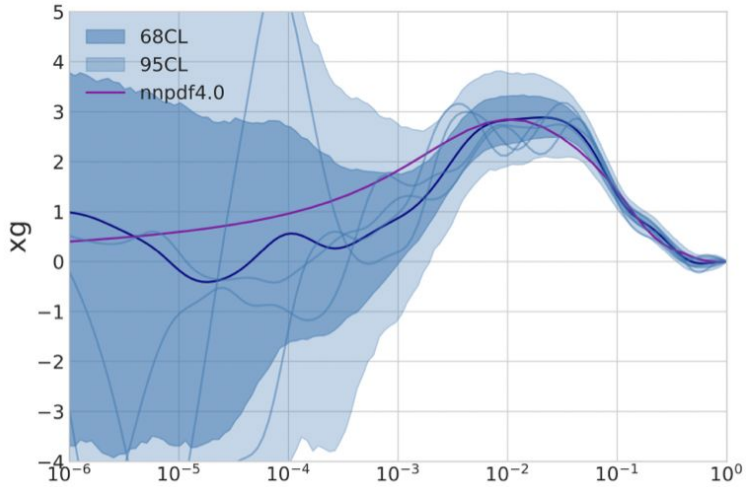
Marginals

Parameter	Mean	Std. dev.	Gobal mode	Marg. mode	Cred. interval	Histogram	
Δ_1	0.221272	0.0104517	0.214535	0.22175	0.212531..0.233155	0.172[	[0.254
Δ_2	0.135998	0.0296684	0.130628	0.1335	0.10425..0.164686	0.04[	[0.257
Δ_3	0.235809	0.0402725	0.212643	0.237	0.192969..0.274181	0.089[	[0.422
Δ_4	0.236329	0.0395947	0.280566	0.235	0.194414..0.274314	0.0995[	[0.394
Δ_5	0.0858189	0.0219218	0.110866	0.0895	0.0652377..0.108161	0.00805[	[0.203
Δ_6	0.0325197	0.0197449	0.014177	0.0225	0.00771978..0.0417355	0.000394[	[0.196
Δ_7	0.0196916	0.0159925	0.00706804	0.0065	0.00141507..0.0245333	2.05e-06[	[0.155
Δ_8	0.0259069	0.0180721	0.0295166	0.0115	0.0021522..0.0332662	3.37e-05[	[0.143
Δ_9	0.00665518	0.00952574	3.88412e-13	0.0005	3.88412e-13..0.00658574	3.88e-13[	[0.116
Ku	3.80003	0.199465	3.54776	3.775	3.59911..3.98004	3.02[	[4.78
Kd	3.50409	0.483632	3.77008	3.47	2.99302..3.96772	2[	[5
Kq	6.5525	1.27579	4.48005	6.375	5.1867..7.80312	3.01[	[10
λ_{g_1}	0.489073	0.28815	0.545423	0.0975	multiple	7.05e-06[	[1
λ_{g_2}	-0.506723	0.250449	-0.785071	-0.1975	-0.646814..-0.100004	-1[	[-0.1

Bayesian inference and gaussian processes for PDF determination

Tommaso Giani

- Non-parametric regression model
- Based on Gaussian process
- MCMC to determine hyper-parameters



Theory

- TMD Parton Branching method (S. Taheri Monfared)
- DIS without PDFs (M. Tevio)
- Analytical solution of DGLAP (A. Simonelli)
- PDFs with quantum computing (H. Xing)
- Heavy quarks in hadronic processes (M. Guzzi)
- N3LO
  - N3LO splitting functions (G. Falcioni)
  - 4-loop splitting functions (T. Yang)
- Impact of N3LO on modern PDFs
  - NNPDF (J. Rojo)
  - MSHT (R. Thorne)
  - N3LO benchmarking (R. Thorne)

Evolution of PDFs; PDFs by quantum computing

Evolution of structure functions at NLO without PDFs

Mirja Tevio

Analytic Solutions of the DGLAP Evolution and Theoretical Uncertainties

Andrea Simonelli

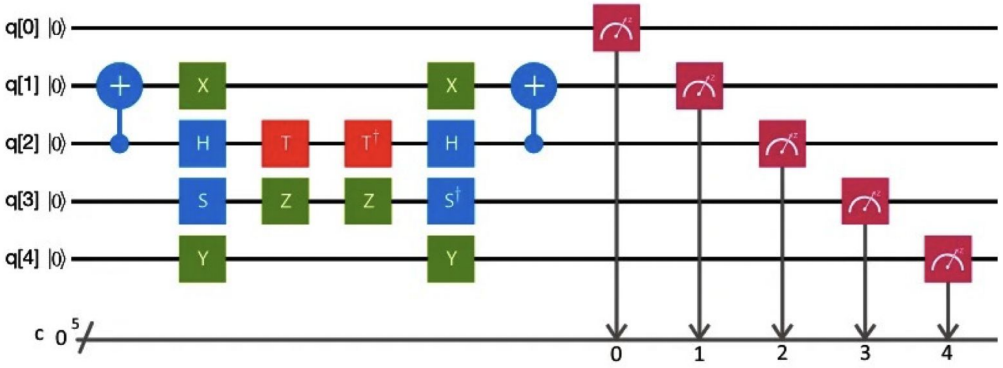
Recent Progress in TMD Parton Densities and Corresponding Parton Showers

Sara Taheri Monfared

Partonic collinear structure by quantum computing

Hongxi Xing

- First attempt for direct computing of “PDFs” using quantum computing
- Proof of concept study using toy model 1+1D, no gauge field

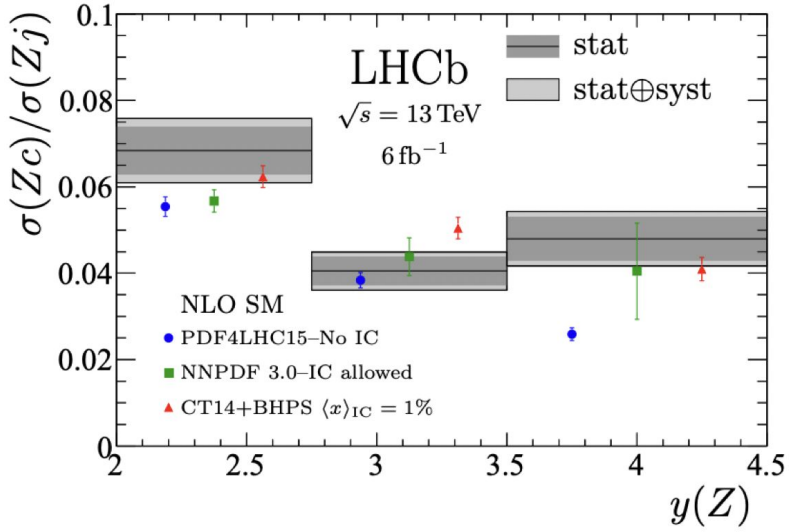


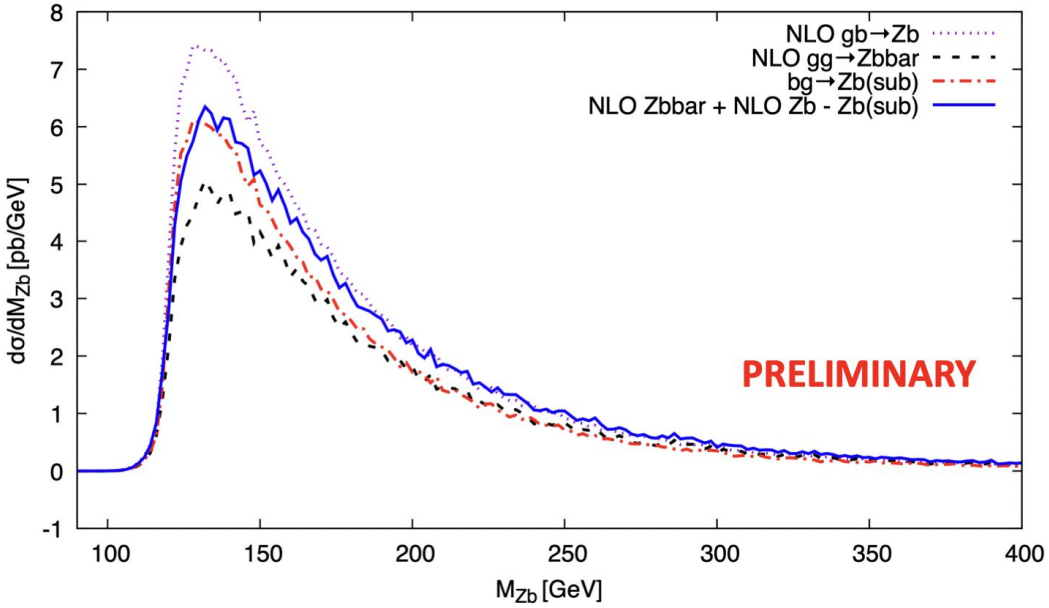
- Each gate is the result of time evolution

$$U(t)\,|\psi\rangle = e^{-it(H_0+H_1+\ldots)}\,|\psi\rangle$$

Heavy quarks in hadronic processes

- Heavy Quark production measurements at the LHC (e.g. Z+c, Z+b)
- S-ACOT-MPS: Towards accounting for HQ mass effects





A GMVFN scheme for Z boson associated with a heavy quark production at hadron colliders

Marco Guzzi

Splitting functions at N^{3}LO and beyond

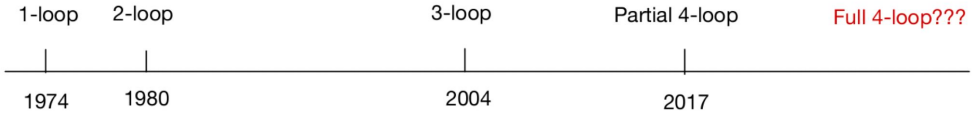
Recent progress in the calculation of the N3LO splitting functions

Giulio Falcioni

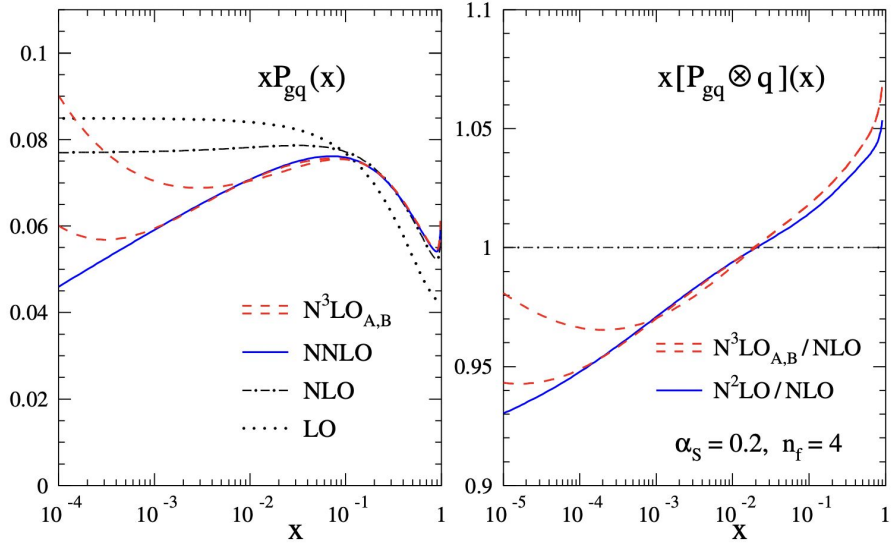
Towards four-loop splitting functions in QCD

Tong-Zhi Yang

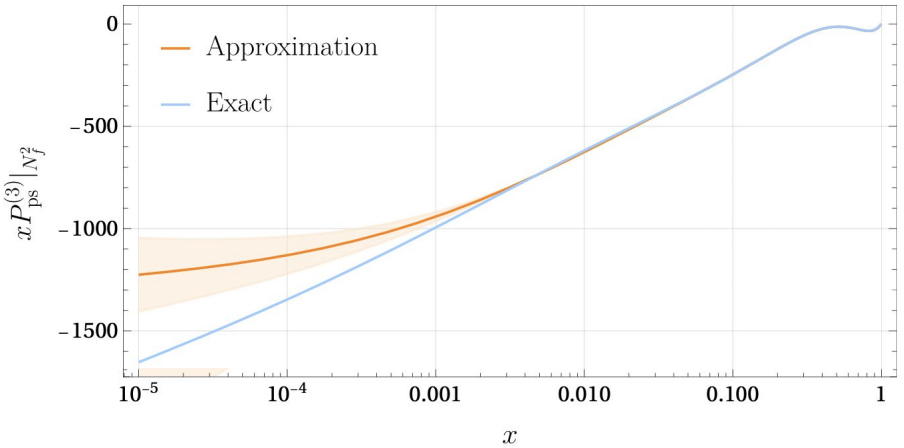
Timeline:



P_{gq} moments computed up to N = 20



- New framework to infer splitting functions
- Proof of concept: get exact results for pure singlet anomalous dimensions



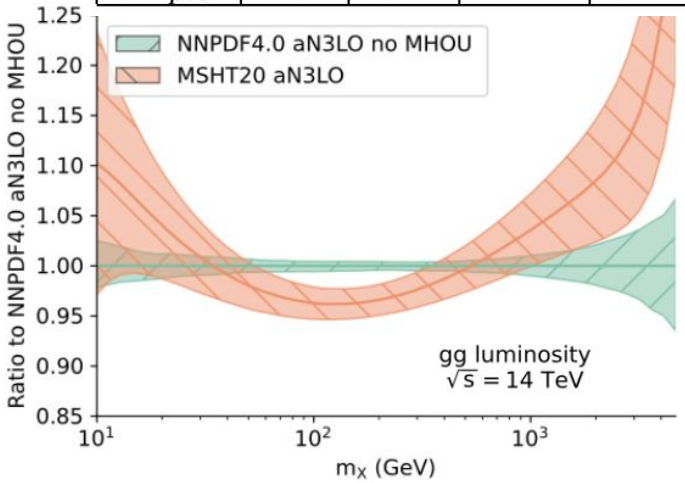
PDFs at aN^{3}LO

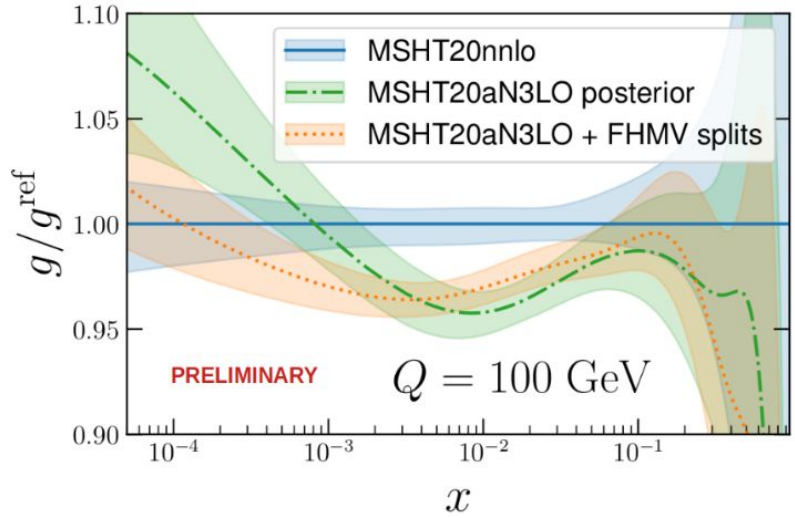
MSHT PDF updates
Robert Thorne

NNPDF progress and the path to N^{3}LO PDFs
Juan Rojo

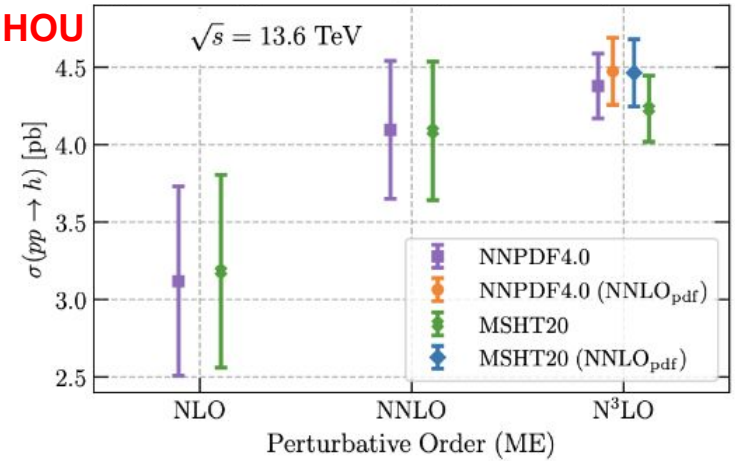
Approximate N^{3}LO PDF Benchmarking
Robert Thorne

	LO	NLO	NNLO	aN^{3}LO
$\chi^2_{N_{pts}}$	2.57	1.33	1.17	1.14





ggH + MHOU



Data

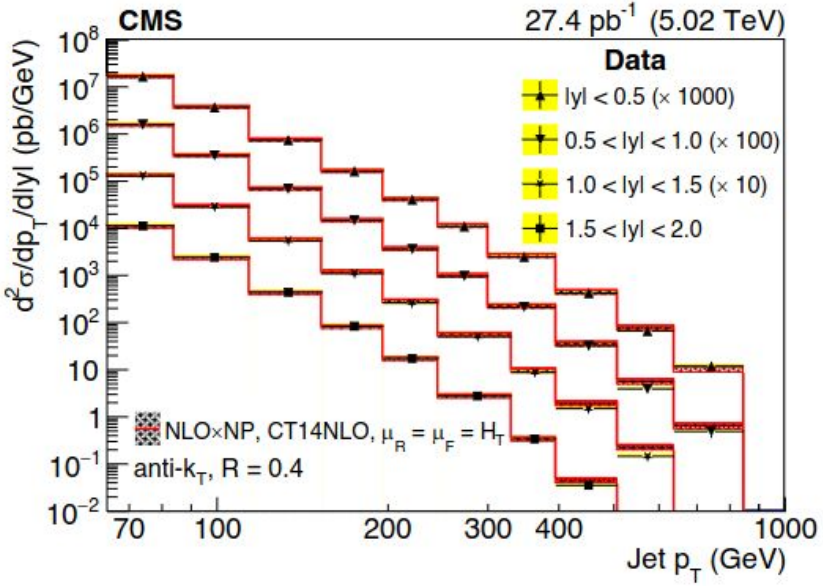
- CMS (D. Savoiu)
- JLAB (W. Henry)
- Neutrinos (J. Atkinson, O. Durhan)
- COMPASS (M. Stolarski)
- Final state fragmentations (J. Gao)

New CMS and JLab measurements

CMS jet measurements and constraints on PDFs and α_s

Daniel Savoiu

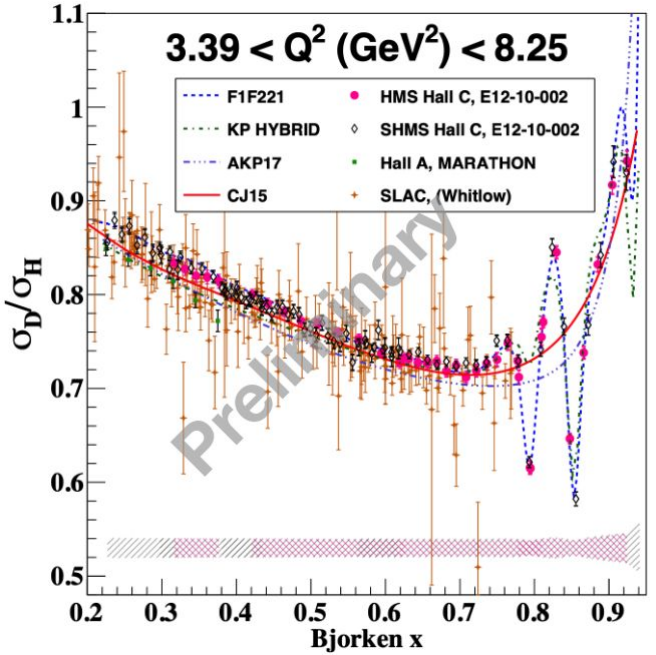
New CMS jet measurement useful to determine the strong coupling and PDFs



Precision Measurements of the Deuterium to Hydrogen F_2 Structure Function Ratio at Large x

William Henry

New Hall C measurement of F_2^d/F_2^p, useful to determine the d/u ratio

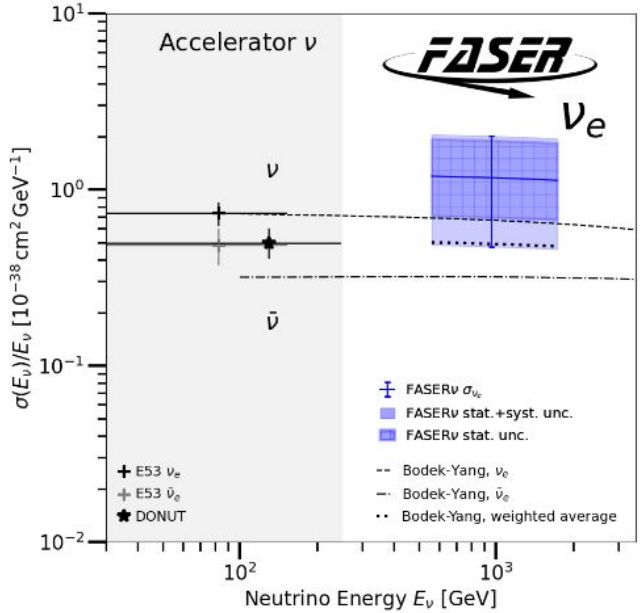


New Faser and SND@LHC measurements

Neutrinos at the LHC – Results from FASER

Jeremy Atkinson

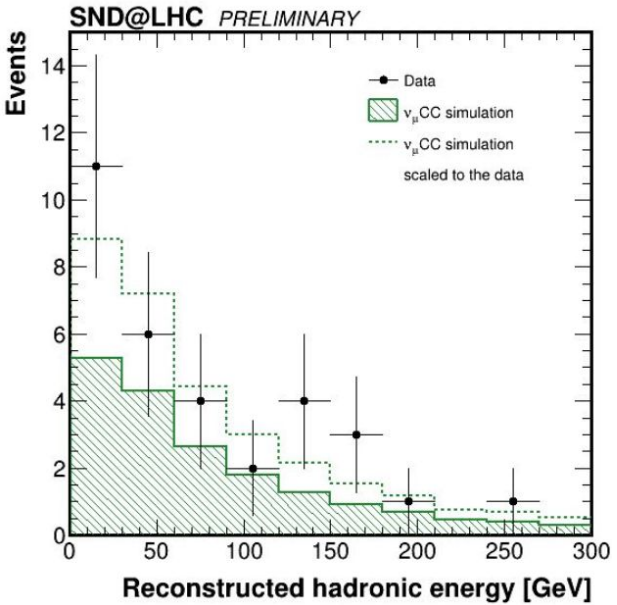
First observation of ν_e produced at the LHC



First results from the SND@LHC experiment

Onur Durhan

32 ν_μ CC interactions have been observed together with 2023 data

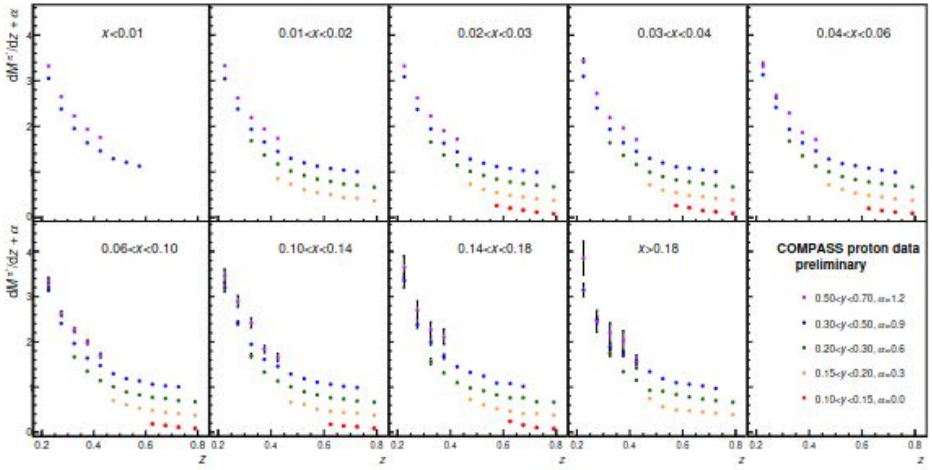


New COMPASS measurement and fragmentation

COMPASS Results
on Pion, Kaon and Unidentified Hadrons Multiplicities
from SIDIS on Proton Target

M. Stolarski

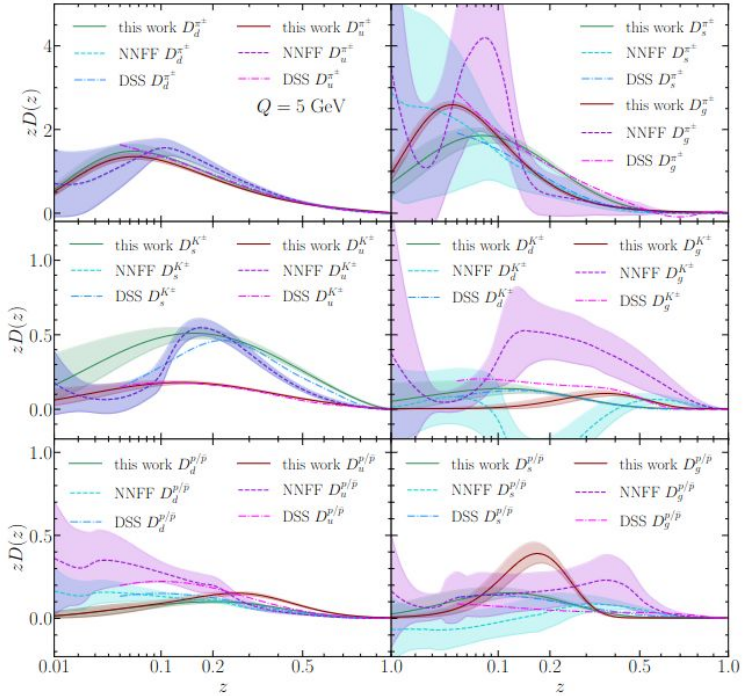
Multiplicities for pions, kaons and hadrons
useful to determine Fragmentation Functions



Simultaneous Determination of Fragmentation Functions and Test on Momentum Sum Rule

Jun Gao

Global analysis of pion, kaon and
proton Fragmentation Functions



Impact of new data on PDFs

- NNPDF (J. Cruz-Martinez, T. Sharma)
- CTEQ (P. Nadolsky)
- MSHT (R. Thorne)
- ABMP (O. Zenaiev)
- CJ (S. Li)

Impact of new data in NNPDF4.0

Phenomenological implications of modern PDF determinations

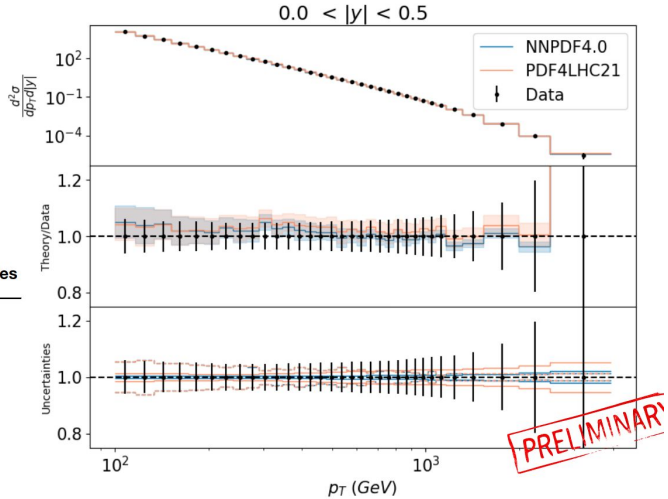
Juan M. Cruz Martínez

Generalisation power on unseen data of NNPDF4.0 and PDF4LHC21 similar despite smaller NNPDF4.0 uncertainites

Atlas 1jet

We find a score of Z = 16.87, which points to instabilities in the covariance matrix. Indeed, when we regularize with the recipe from EPJ C82 (2022) 956 the χ^2 looks a bit better.

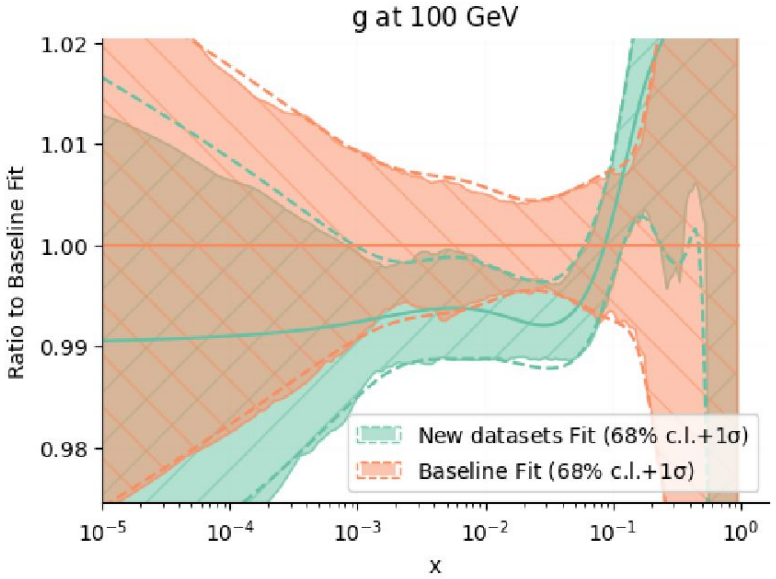
χ^2/N	Only exp. and th. unc.	All uncertainties
PDF4LHC21	1.88	1.58
NNPDF40	1.83	1.74



Impact of new data on the gluon PDF in NNPDF 4.0

Tanishq Sharma

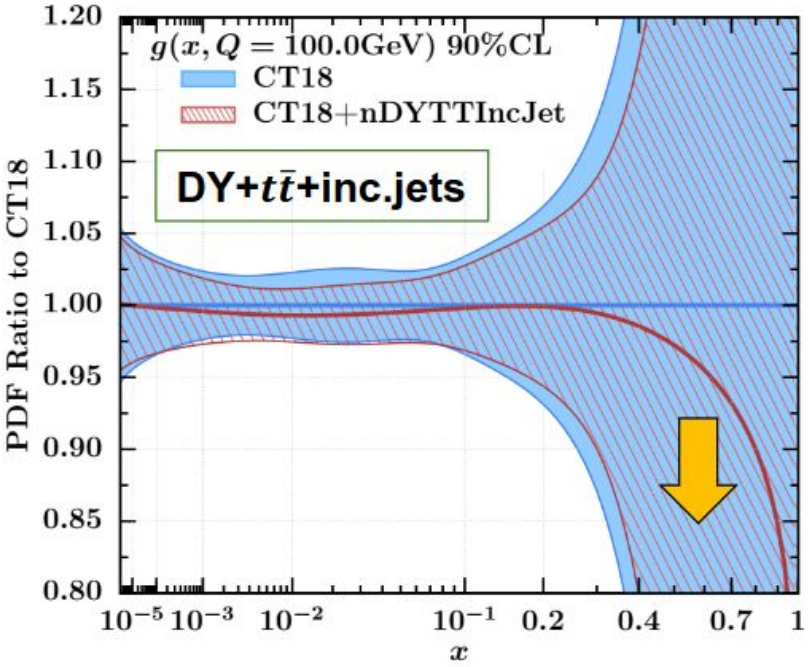
Impact of LHC ttbar, jet and dijet data (13 TeV)
Impact of HERA DIS+jet data



Impact of new data in CT18 and MSHT20

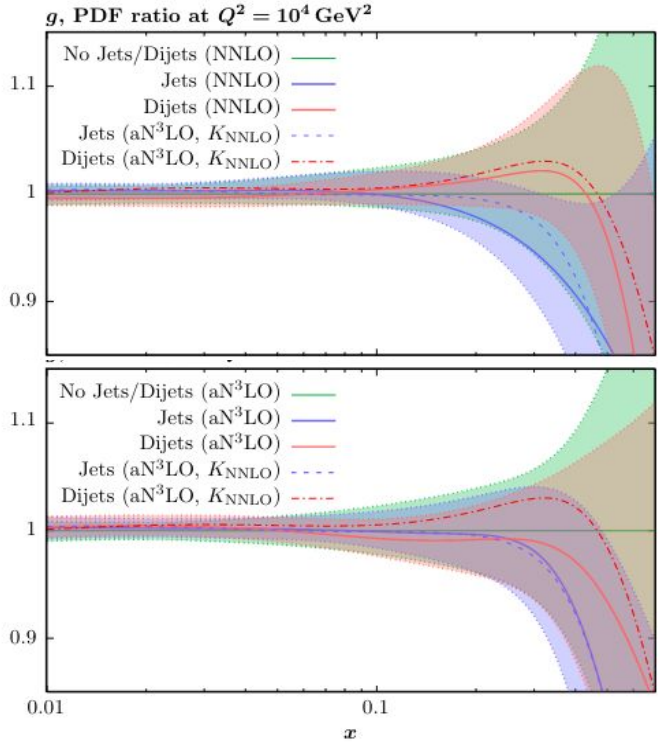
CTEQ-TEA parton distributions in a nutshell
Pavel Nadolsky

Impact of LHC DY, ttbar, and inclusive jets (8, 13 TeV) data



MSHT PDF updates
Robert Thorne

Impact of LHC single-inclusive and dijet data (8 TeV)

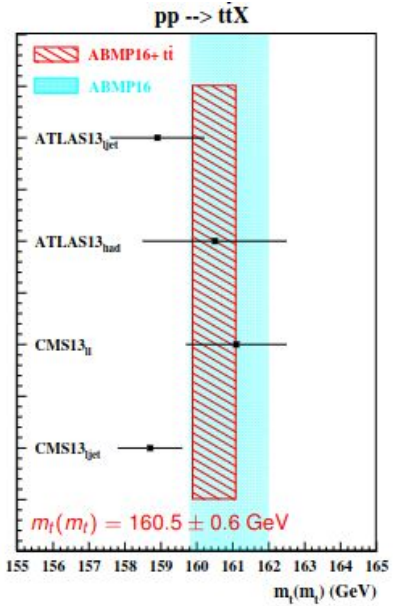


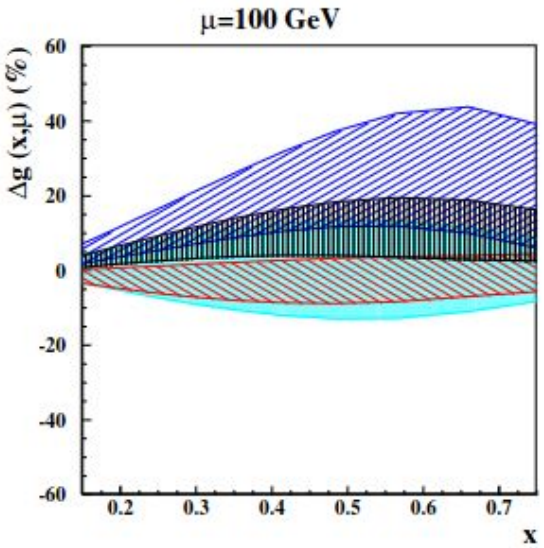
Impact of new data on ABMP16 and CJ22

LHC differential top-quark pair production cross sections in the ABMP16 PDF fit

Sasha Zenaiev

Extracted m_t^{pole} from LHC ttbar data
Assessed impact of ttbar data on the gluon PDF

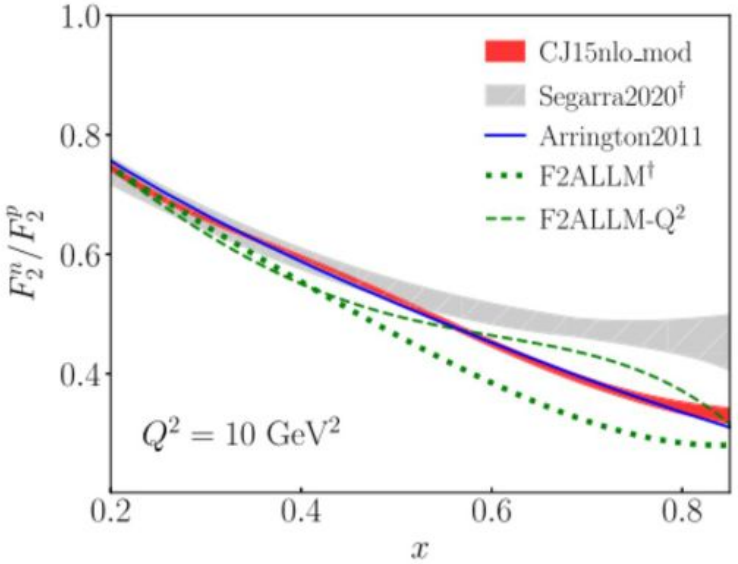




New Neutron Structure Function Extraction from Global Inclusive Proton and Deuteron Data

Shujie Li

A data-driven extraction of F_2^n from deuteron data, with knowledge of HT and nuclear effects



Nuclear PDFs

- nCTEQ (T. Ježo)
- Dimuon cross section and SIDIS (S. Yrjänheikki)
- Target mass corrections (R. Ruiz)
- Higher twist (M. Cerutti, R. Petti)
- EMC effect (C. Cotton)

Updates from nCTEQ

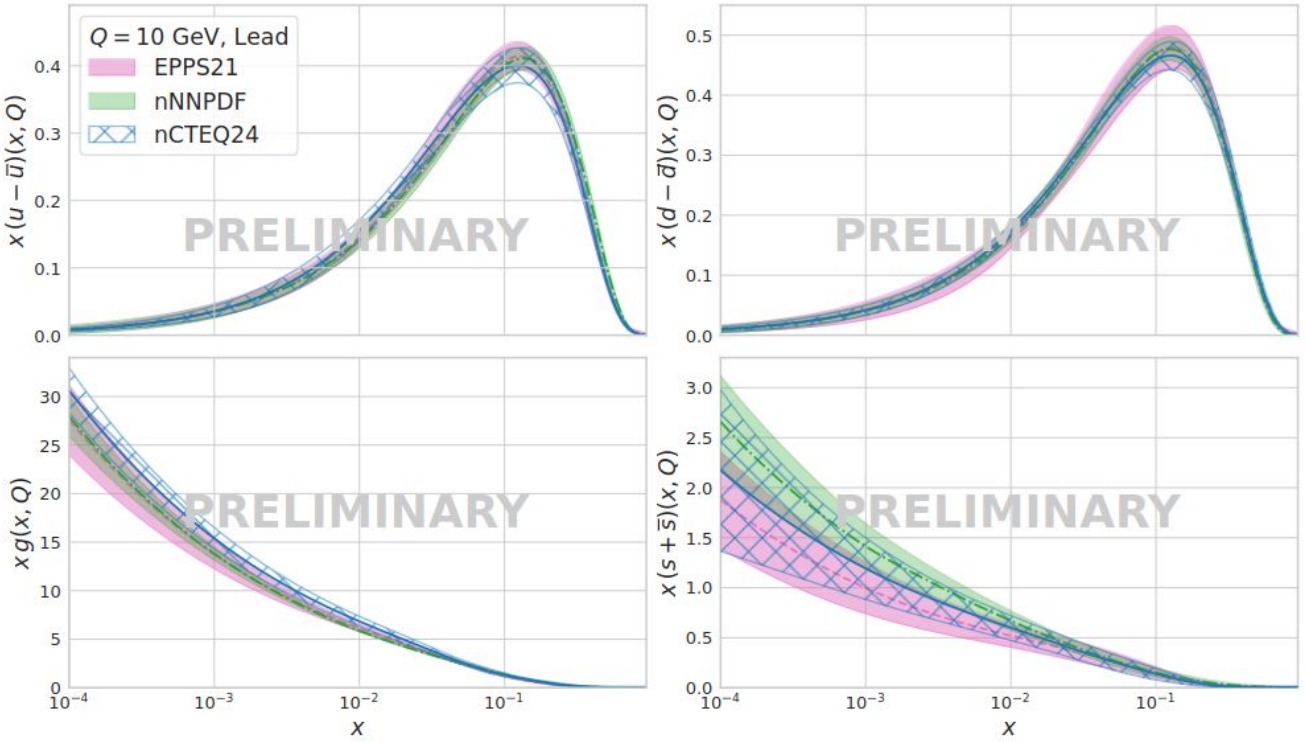
nCTEQ global analysis of nuclear PDFs

Tomáš Ježo

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

Upcoming nCTEQ global analysis:

- data: LHC: W/Z, HQ, SIH, JLAB NC DIS, DIS CC (over 3000 pts)
- theory: relaxed kinematic cuts, TMCs, deuteron corrections, HT
- methodology: parametrization, A-dep.

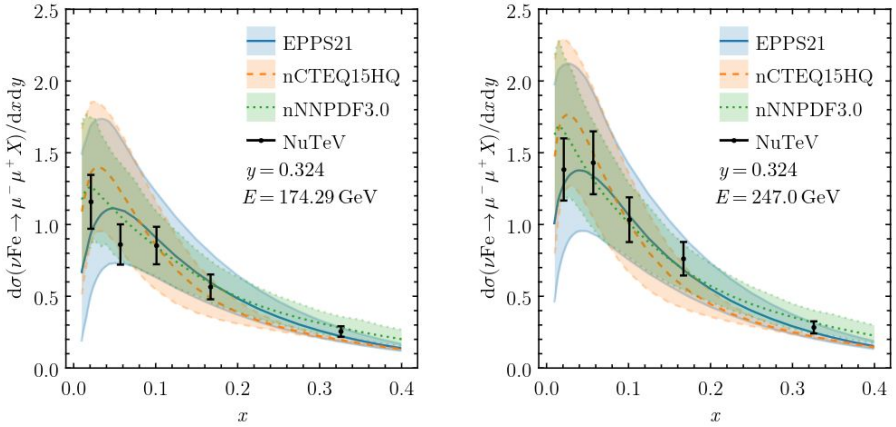


Nuclear PDFs: theoretical developments

Dimuon production in neutrino-nucleus collisions - the SIDIS approach

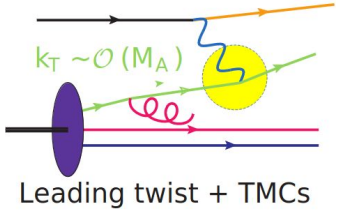
S. Yrjänheikki

- Dimuon production in neutrino-nucleus collisions important for strange PDF determination
- New calculation directly using SIDIS and a decay function
- No assumption that dimuon production is proportional to charm production
- Good data description

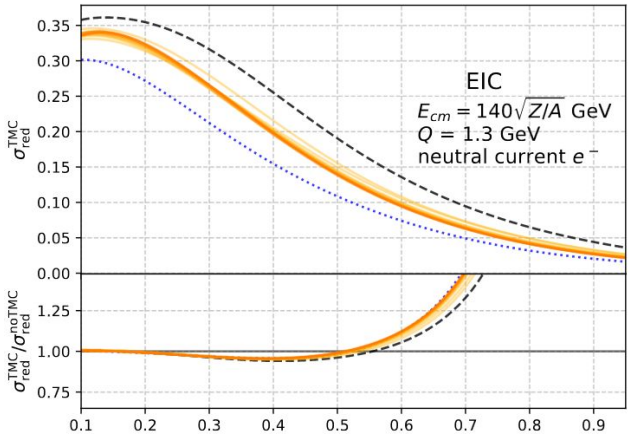


Revisiting "target mass corrections" in lepton-nucleus DIS

Richard Ruiz



- Derivation of Target Mass Corrections for **nuclei**
- Formulas known for proton hold for nuclei with simple rescaling $M_N = M_A/A$, $x_N = Ax_A$



Systematic uncertainty of off-shell corrections and higher-twist contribution in DIS at large x

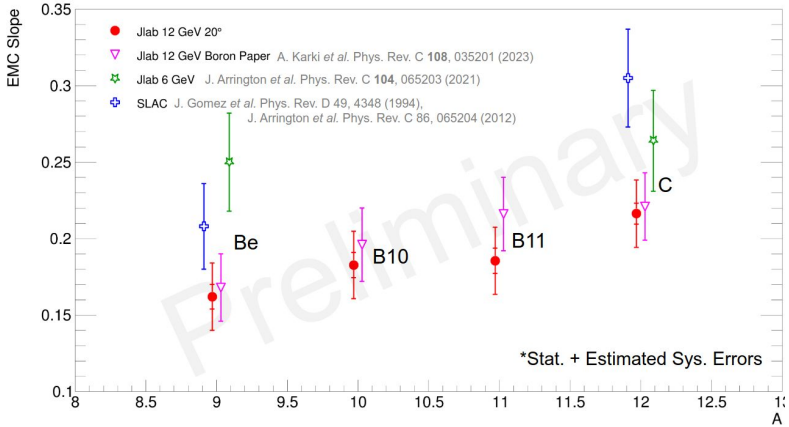
Matteo Cerutti

On the Interplay of Nuclear and Higher-Twist Corrections at Large x

R. Petti

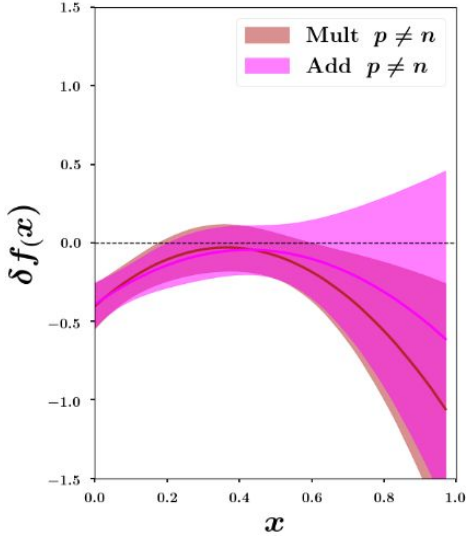
Preliminary Results from the 12 GeV EMC Effect Experiment in Hall C of Jefferson Lab

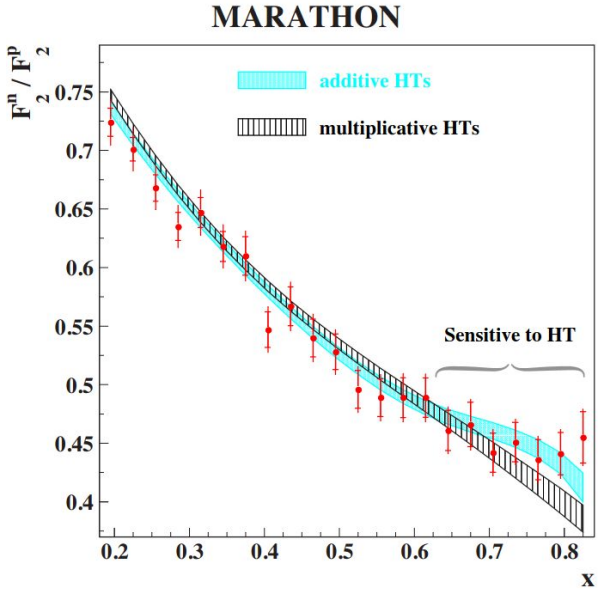
Cameron Cotton



Higher twist contributions

- Understand the behaviour of d/u PDFs in the large-x region requires nuclear corrections and HT depending on off-shell correction δf
- HT can be implemented via additive of multiplicative corrections





Meson PDFs

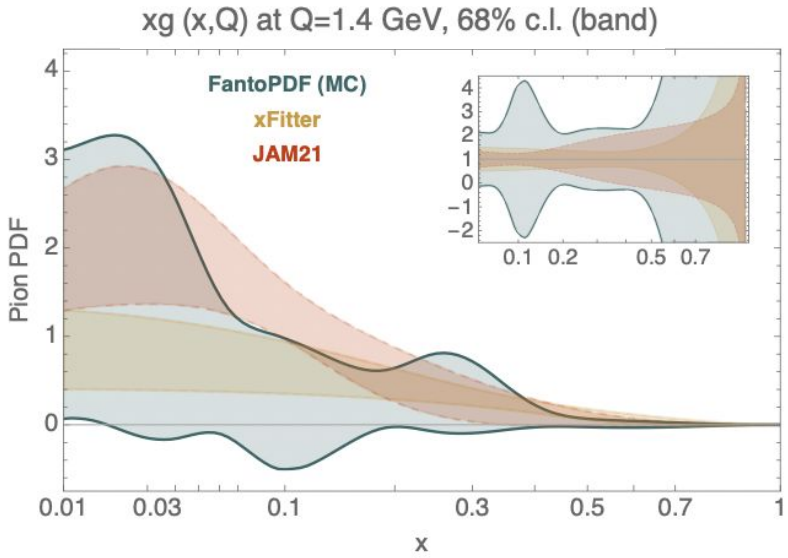
- Fantomas4QCD: pion PDF (A. Courtoy)
- Kaon PDF (J.-C. Peng)

Pion and Kaon PDFs

Fantômas4QCD:
pion PDFs with epistemic uncertainties

Aurore Courtoy

- Sea-gluon separation requires more data
- End-point behavior plays an important role

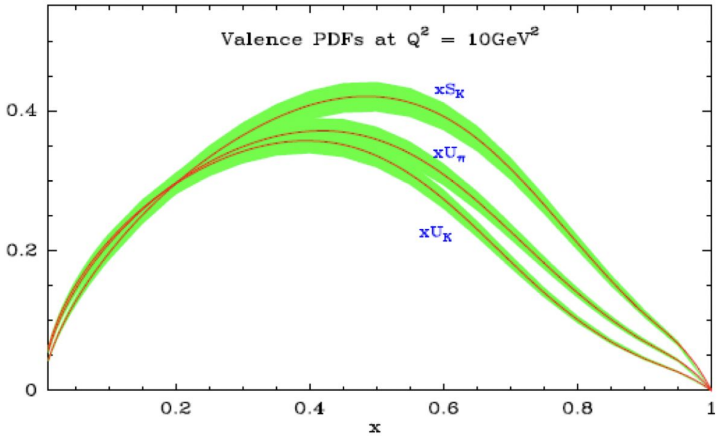


Extraction of Meson PDFs from Drell-Yan and J/ψ Production Data in the Statistical Model

Jen-Chieh Peng

Determination of meson PDFs based on statistical model with new data

Comparison between the pion and kaon valence distributions



Future facilities

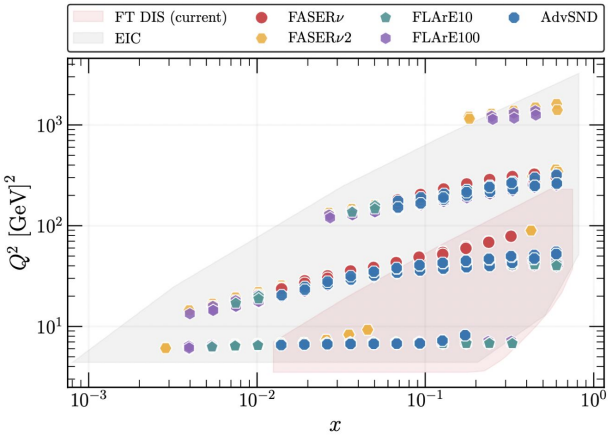
- Impact of neutrino future data on PDFs (J. Rojo)
- HL-LHC (O. Zenaiev)
- LHeC (A. Cooper-Sarkar)
- EIC on PDFs and aS (K. Wichmann)
- QED radiation (J. Qiu)

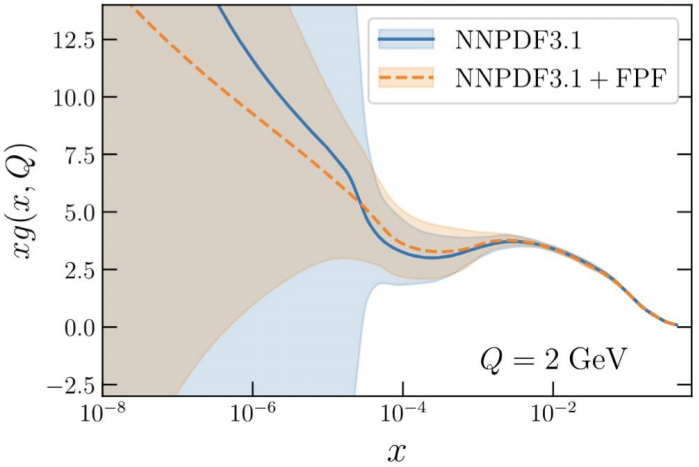
Forward Physics Facility

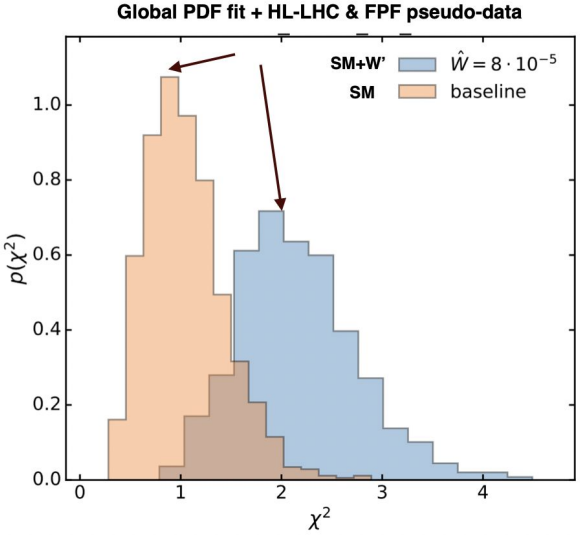
Deep-Inelastic Scattering with Collider Neutrinos

Juan Rojo

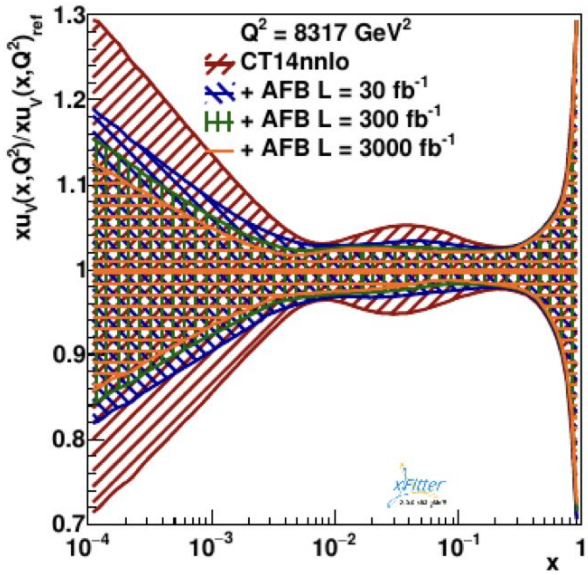
- LHC neutrinos:
  - Charged-current counterpart of the EIC to probe proton and nuclear structure
  - Probe small-x QCD (e.g. non-linear dynamics) in uncharged regions
  - Provide a laboratory validation of muon puzzle predating cosmic ray physics
  - Unique constraints for high-pT searches at LHC





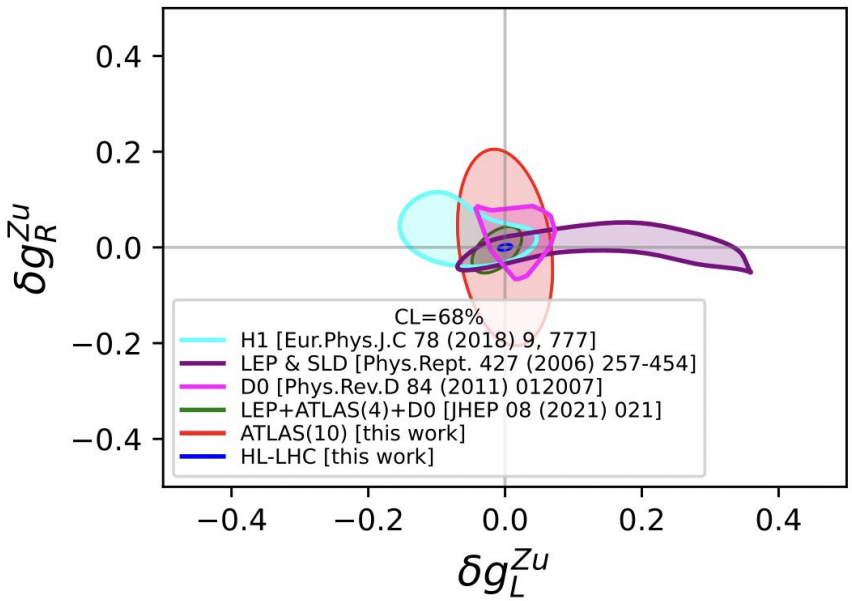


HL-LHC



xFitter Updates: Probing Z Boson Couplings with Forward-Backward Asymmetry

Sasha Zenaiev



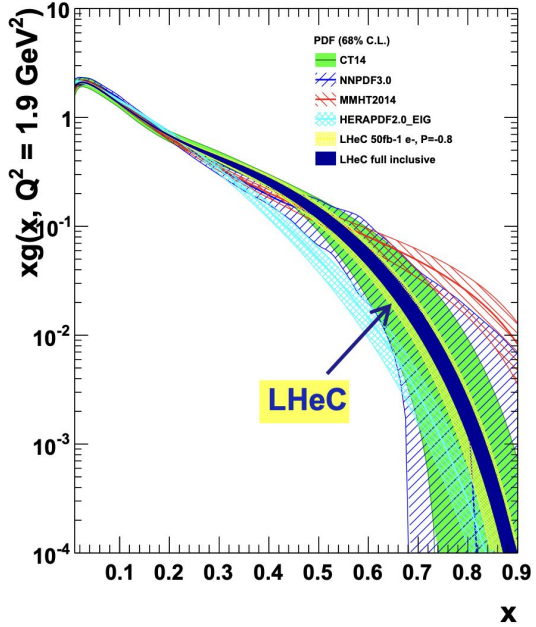
- A_{FB} as a function of m_{ll} and y_{ll} is a suitable observable which provides constraints on the PDFs and Z boson couplings
- At HL-LHC it is possible to extract these couplings with 1% level precision, which approaches the precision of LHeC and FCC-eh

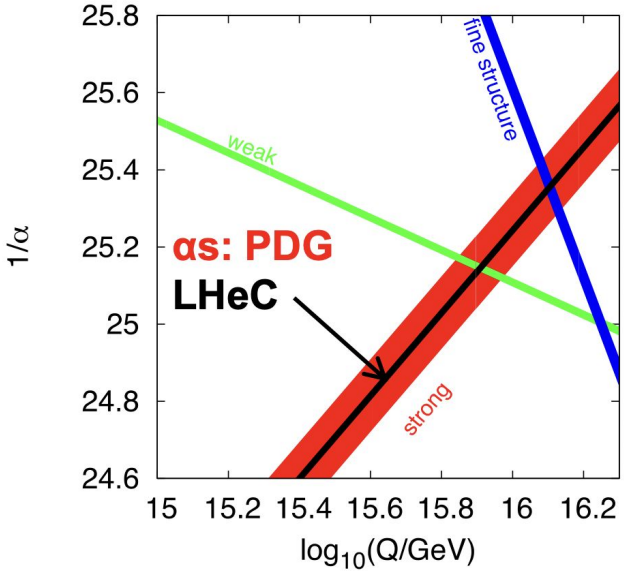
LHeC

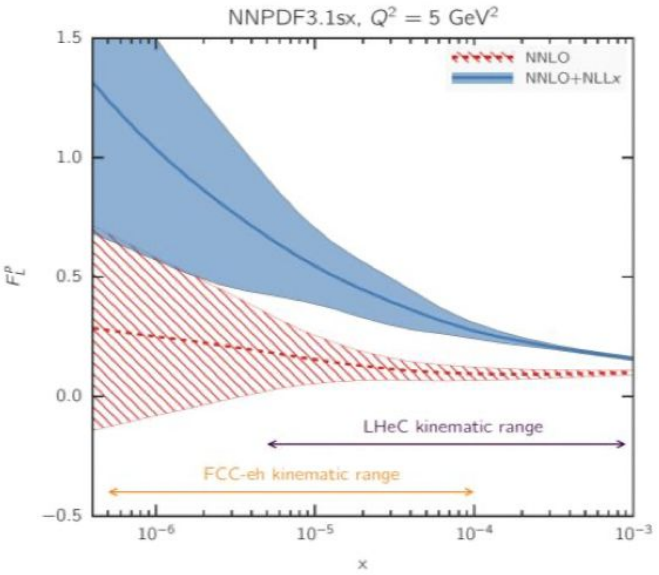
PDFs from LHeC

Amanda Cooper-Sarkar

- The LHeC offers dramatic improvements on PDFs:
  - at high-x important for direct discoveries, also brings improvement in $\alpha_S(m_Z)$
  - middling x important for SM precision measurements like m_W
  - at low-x for studying QCD beyond DGLAP (BFKL resummation and saturation)





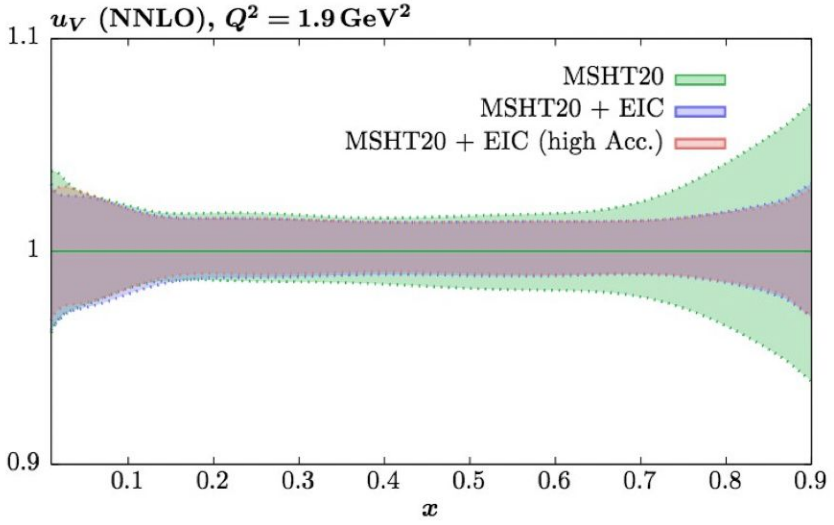


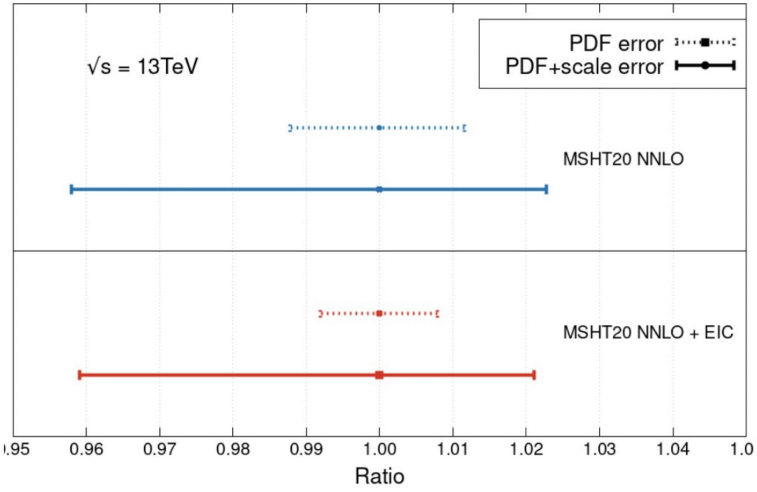
How to decrease PDF uncertainties impact of EIC

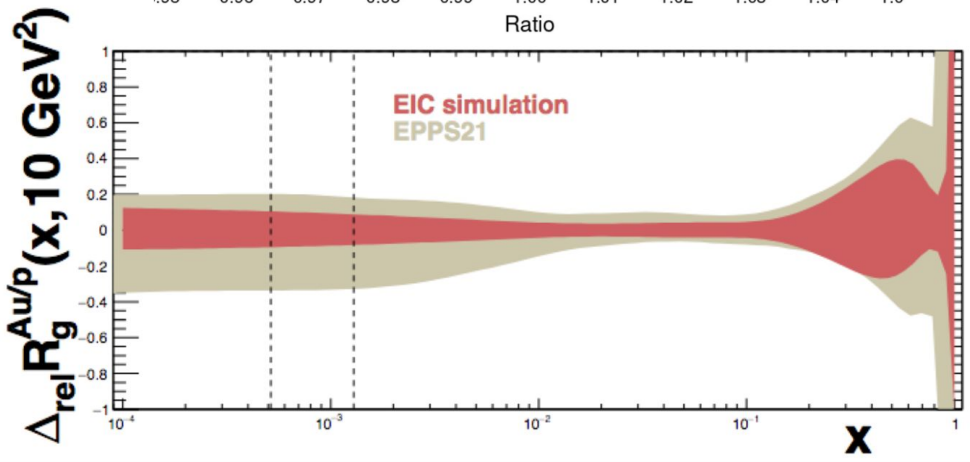
Katarzyna Wichmann

EIC: PDFs

Using EIC data will make tremendous difference in proton and nuclear PDFS, especially at high x



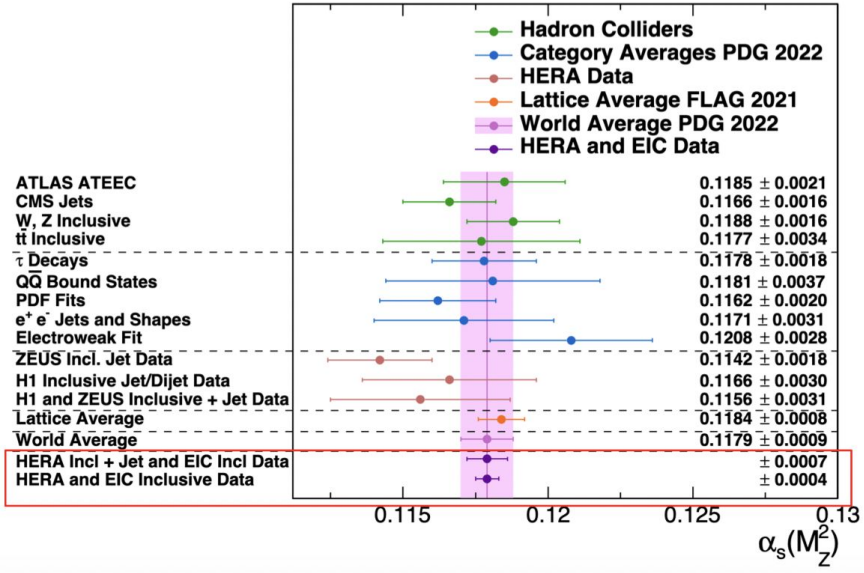




EIC: α_s and QED radiation

Extraction of the strong coupling with HERA and EIC inclusive data
Katarzyna Wichmann

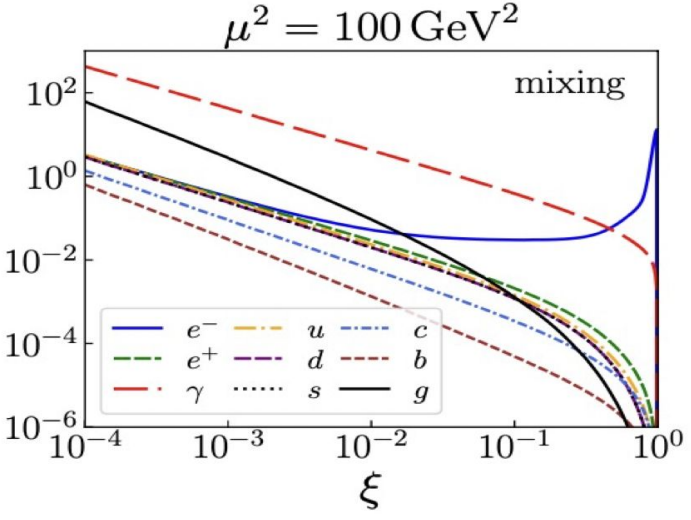
Using EIC DIS data will make tremendous difference in $\alpha_s(m_Z)$ determination



Full next-to-leading order QED contribution to lepton-hadron scattering in joint QED and QCD factorization approach

Jianwei Qiu

- Relevant for events with high momentum transfers and large phase space to shower (EIC)
- Consistent and controllable approximation to high-energy lepton-hadron scattering processes



Thanks to…

- All the speakers (47 talks in total):
  - 12 theory
  - 8 experiments
  - 16 phenomenology
  - 7 methodology
  - 4 future facilities
- The chairs (Mandy, Aurore, Katarzyna, Giovanni, Robert, Pavel, Lucian, Bill)
- The conveners of WG4 and WG6 for joint sessions (Ilkka, Giovanni, Laure and Leticia, Bill, Alessandro)
- WG1 is always a lively and productive working group
- We look forward to DIS2025

Thank you all for your attention