Energy Frontier Topical Group 5 (EF05)
Precision QCD

Conveners: Michael Begel, Stefan Hoeche, Michael Schmitt

General scope: Physics with jets and jet substructure, higher-order calculations and their impact on precision QCD physics, measurements of the strong coupling constant and its running, measurements of quark masses, PDF fits and PDF-sensitive measurements, W/Z(+jets) boson production, MC event generators, ...

Many overlaps with EF01, 03, 04, 06, 07 and TF and CompF topical groups

Website: https://snowmass21.org/energy/qcd

Indico category: https://indico.fnal.gov/category/1139/

Outline

- Introductory overview
- α_S
- Event shapes and energy correlations
- Jet substructure
- Fragmentation functions
- HL-LHC: ATLAS/CMS
- HL-LHC: Forward physics
- Summary

Quantum Chromo Dynamics

- Firmly established as theory of strong interactions with simple Lagrangian:

$$\mathcal{L} = \sum_q \bar{\psi}_{q,a}(i\gamma^\mu \partial_\mu \delta_{ab} - g_s \gamma^\mu t^C_{ab} \mathcal{A}^C_\mu - m_q \delta_{ab})\psi_{q,b} - \frac{1}{4} F^A_{\mu\nu} F^{A\,\mu\nu}$$

$$F^A_{\mu\nu} = \partial_\mu \mathcal{A}^A_\nu - \partial_\nu \mathcal{A}^A_\mu - g_s\, f_{ABC} \mathcal{A}^B_\mu \mathcal{A}^C_\nu$$

- Rich phenomenology
  - hadronic input to SM tests and BSM searches
- Many successful predictions
  - precision QCD is an analysis tool: e.g. studies of Higgs & top quarks
  - accuracy limited by both PDFs and perturbative expansion
- Quantitative understanding often challenging
  - α_S least well known coupling in SM
  - impact of non-perturbative effects on precision observables and modeling by MC simulations
  - what calculations & measurements needed to improve our understanding?

QCD is not the driving force for many future experiments, but it is crucial for understanding them!

Focus questions

1. **What is the ultimate precision for α_s and how do we achieve it?**
   LHC, future pp/e+e-/DIS (ep and eA), particle decays (τ, hadrons), lattice
2. **What theoretical developments are needed to support precision measurements of Higgs and top quark production and properties?**
   including electroweak corrections, threshold effects, non-perturbative, ...
3. **Evaluation and interplay of uncertainties from theory and experiment**
   fixed-order/resummation scales, non-perturbative effects, etc.
4. **Can we better quantify non-perturbative uncertainties?**
   cross-cutting effort between experiments, MC community & lattice QCD
5. **How to include more higher-order QCD in MC event generators?**
   Fixed-order and parton shower development (incl EW emissions, color flow, multi-parton interactions, rescattering, scale choices, …)
6. **[Together with EF06] What is the future of PDF determination?**
   From the LHC, DIS, theoretical developments (NNLO, photon, pion, ...)

EF05 Contributions Summary

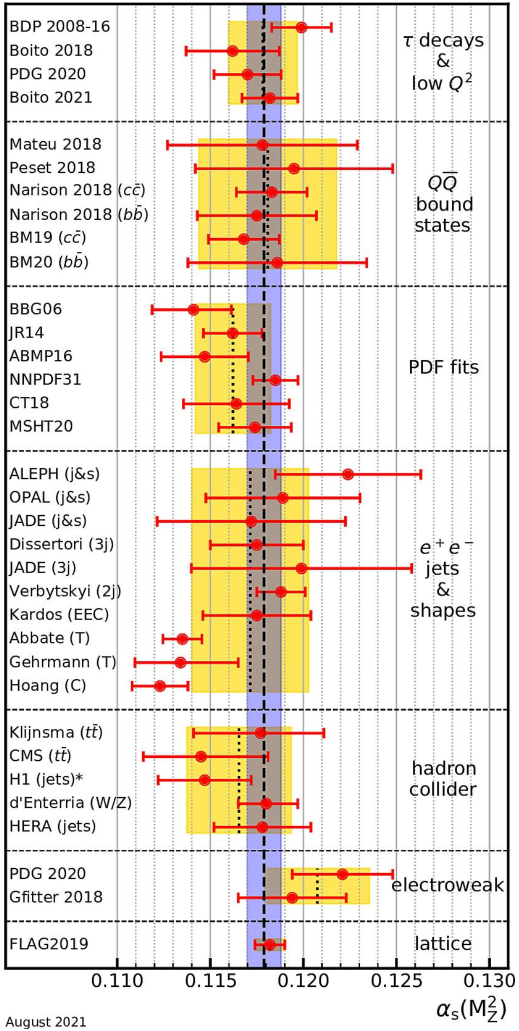
Thank you all, for submitting many interesting white papers!

This overview contains only a small selection of topics
For a more comprehensive list, see the backup slides
and the original white papers on arXiv

Thanks to the authors for providing slides!
All mistakes and misinterpretations are ours…

Summary of α_s determinations

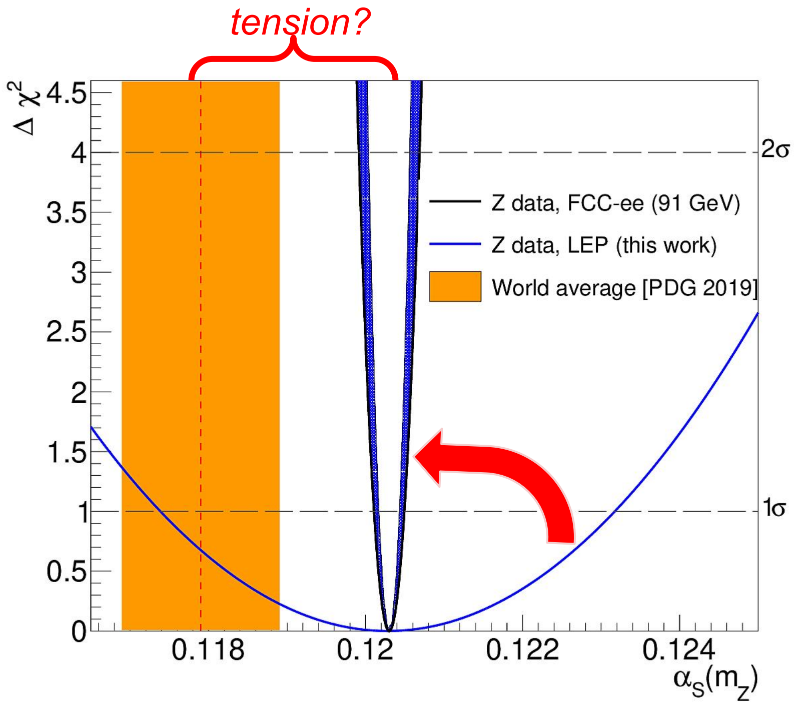
Method	Relative $\alpha_S(m_Z^2)$ uncertainty Current theory & exp. uncertainties sources	 Near (long-term) future theory & experimental progress
(1) Lattice	0.7% Finite lattice spacing & stats. $N^{2,3}$LO pQCD truncation	$\approx$ 0.3% (0.1%) Reduced latt. spacing. Add more observables Add $N^{3,4}$LO, active charm (QED effects) Higher renorm. scale via step-scaling to more observ.
(2) τ decays	1.6% N^3LO CIPT vs. FOPT diffs. Limited τ spectral data	$<$ 1.% Add N^4LO terms. Solve CIPT–FOPT diffs. Improved τ spectral functions at Belle II
(3) $Q\overline{Q}$ bound states	3.3% $N^{2,3}$LO pQCD truncation $m_{c,b}$ uncertainties	$\approx$ 1.5% Add $N^{3,4}$LO & more $(c\bar{c})$, $(b\bar{b})$ bound states Combined $m_{c,b} + \alpha_S$ fits
(4) DIS & PDF fits	1.7% $N^{2,(3)}$LO PDF (SF) fits Span of PDF-based results	$\approx$ 1% (0.2%) N^3LO fits. Add new SF fits: $F_2^{p,d}$, g_i (EIC) Better corr. matrices. More PDF data (LHeC/FCC-eh)
(5) e^+e^- jets & evt shapes	2.6% NNLO+$N^{(1,2,3)}$LL truncation Different NP analytical & PS corrs. Limited datasets w/ old detectors	$\approx$ 1.5% ($<$ 1%) Add $N^{2,3}$LO+N^3LL, power corrections Improved NP corrs. via: NNLL PS, grooming New improved data at B factories (FCC-ee)
(6) Electroweak fits	2.3% N^3LO truncation Small LEP+SLD datasets	($\approx$ 0.1%) N^4LO, reduced param. uncerts. ($m_{W,Z}$, α, CKM) Add W boson. Tera-Z, Oku-W datasets (FCC-ee)
(7) Hadron colliders	2.4% NNLO(+NNLL) truncation, PDF uncerts. Limited data sets ($t\bar{t}$, W, Z, e-p jets)	$\approx$ 1.5% N^3LO+NNLL (for color-singlets), improved PDFs Add more datasets: Z p_T, p-p jets, σ_i/σ_j ratios,...
World average	0.8%	$\approx$ 0.4% (0.1%)



arXiv:2203.08271

α_s at LEP and projections for FCC-ee

- All LEP values clustered around 0.1200
- 10^{12} hadronic Z's at FCC-ee with O(10 keV) accurate energy calibration
  → will provide factor 10 improved precision
  - uncertainties 0.1% level, about 3x smaller than current theory uncertainties
  - theory uncertainties expected to decrease ~factor 4

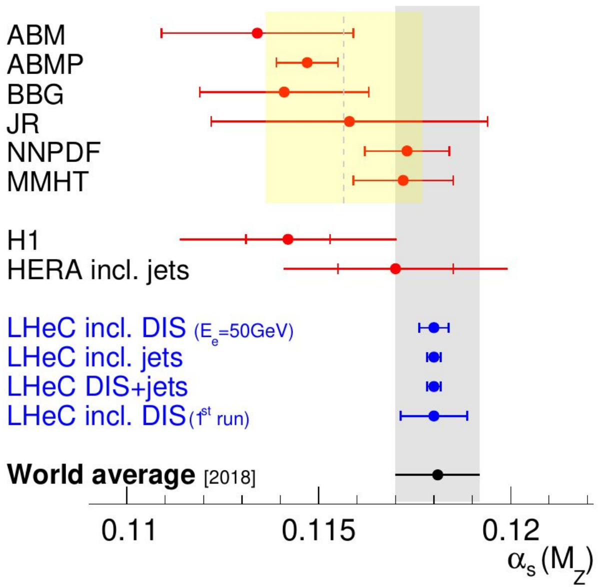


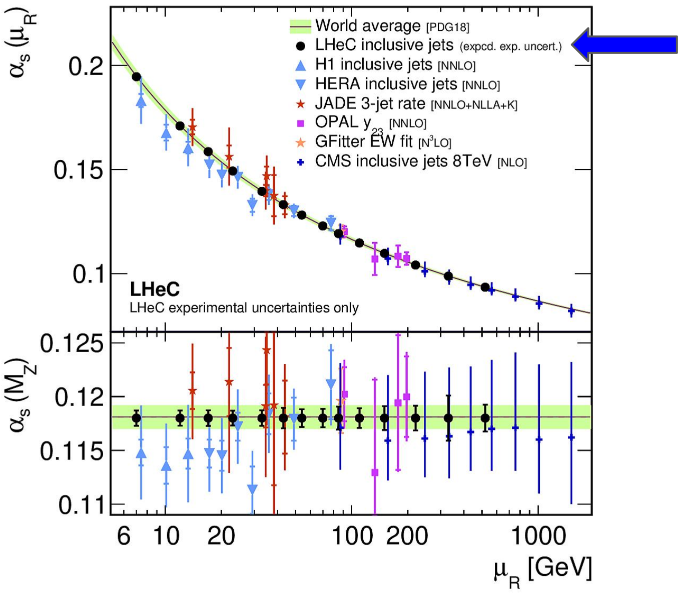
Observable	$\alpha_S(m_Z^2)$	uncertainties		
		exp.	param.	theor.
Γ_Z^{tot}	0.1192 ± 0.0047	± 0.0046	± 0.0005	± 0.000
R_Z	0.1207 ± 0.0041	± 0.0041	± 0.0001	± 0.000
σ_Z^{had}	0.1206 ± 0.0068	± 0.0067	± 0.0004	± 0.001
All above combined	0.1203 ± 0.0029	± 0.0029	± 0.0002	± 0.000
Global SM fit	0.1202 ± 0.0028	± 0.0028	± 0.0002	± 0.0008
All combined (FCC-ee)	0.12030 ± 0.00026	± 0.00013	± 0.00005	± 0.00022
Global SM fit (FCC-ee)	0.12020 ± 0.00026	± 0.00013	± 0.00005	± 0.00022

[arXiv:2203.08271](https://arxiv.org/abs/2203.08271)

α_s at LHeC

- LHeC at 1.3 TeV cms energy with excellent acceptance and high luminosity
- Will provide opportunity to determine α_s from inclusive DIS alone
- Running can be tested to very high scales

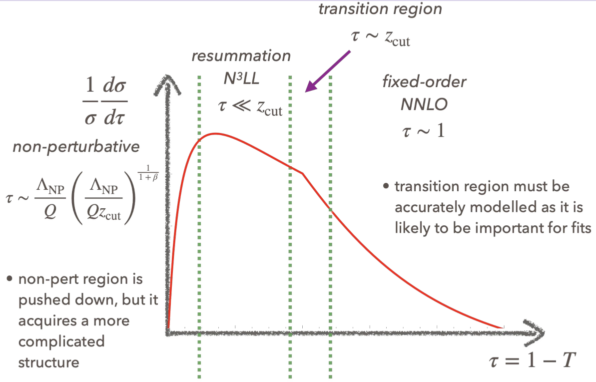


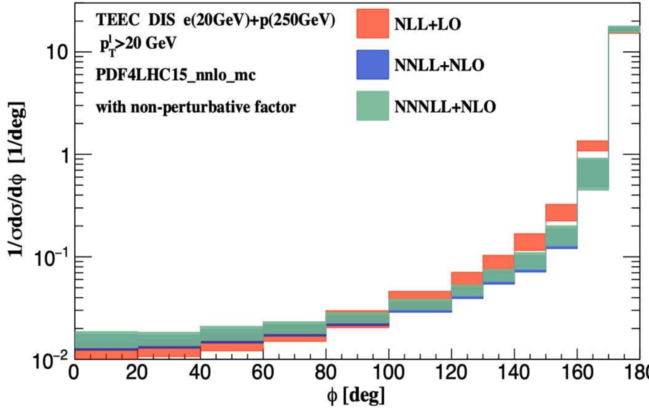


[arXiv:2203.08271](https://arxiv.org/abs/2203.08271)

α_s from event shapes and EEC

- Event shapes offer relatively clean probes of pQCD, but retain sensitivity to non-perturbative physics
  - advances in jet physics provide ways to mitigate non-perturbative corrections
  - grooming algorithms allow us to extend perturbative range of event shapes and related observables
- Energy-energy correlators (EEC) provide precision probes of perturbative and non-perturbative aspects of QCD dynamics
  - used to extract the strong coupling constant and to constrain TMD distribution functions
  - closely related energy-correlation shape variables used to tag boosted objects





arXiv:2203.08271 | arXiv:2203.07113

Jets and jet substructure

- **Science driver**: Jet substructure emerged as a key tool during the LHC era and it will have a central role in any future collider experiment
- Valuable tool:
  - for understanding the origin of jets for SM and BSM analyses
  - as a direct probe of QCD phenomena
- Broad connection with rest of Snowmass:
  - strongly aligned with the Precision Quantum Chromodynamics (QCD) EF05] and Beyond the SM (BSM) Physics [EF08, EF09, EF10] topical groups of the Energy Frontier
  - connections to other efforts in QCD and strong interactions (Hadronic Structure [EF06], Heavy Ions [EF07], 3rd generation quarks [EF03]) as well as in EW Physics
  - intimately connected with efforts in the Theory Frontier (e.g. EFT, Collider phenomenology) and Instrumentation Frontier (e.g. Solid State Detectors, Trigger, Calorimetry), Computational Frontier (e.g. Algorithms, Theory, Machine Learning, User Analysis, Quantum Computing)

arXiv:2203.07462

Jets and jet substructure

- Many interesting jet substructure signatures
  - from jets originating from SM particles (q,g,W,Z,t,H) to background mitigation from pileup and other experimental effects
  - novel signatures such as displaced ("dark") jets, photon jets, and delayed jets
- Theoretical advances and improvements in MC modeling of QCD radiation have been essential in the past decades of jet substructure development
  - further improvements include tuning of simulations, improved accuracy of calculations, and applications of machine learning and artificial intelligence to our theoretical understanding
  - continued advances in new observables and machine learning benefits greatly from theory and experiment exchange of ideas and collaboration

arXiv:2203.07462

Jets and jet substructure

- Future collider environments and challenges for jet substructure:
  - **electron-positron**: requires very high precision understand of QCD to maximize relatively cleaner environments; less emphasis on high-momentum boosted objects
  - **muon collider**: higher possible collider energies on par with LHC; experimental environment in beam backgrounds require novel noise removal techniques similar to pileup mitigation techniques at hadron colliders
  - **high-energy hadron collider**: requires more granular detectors at larger boosts; higher expected pileup means advances in timing detectors and algorithmic development
- Key role in any future collider → breeding ground for innovation
  - many examples given in white paper
  - support for this interdisciplinary work has been key, e.g. theory and experiment, detector design and physics, computer scientists and physicists

arXiv:2203.07462

Fragmentation functions and hadronization

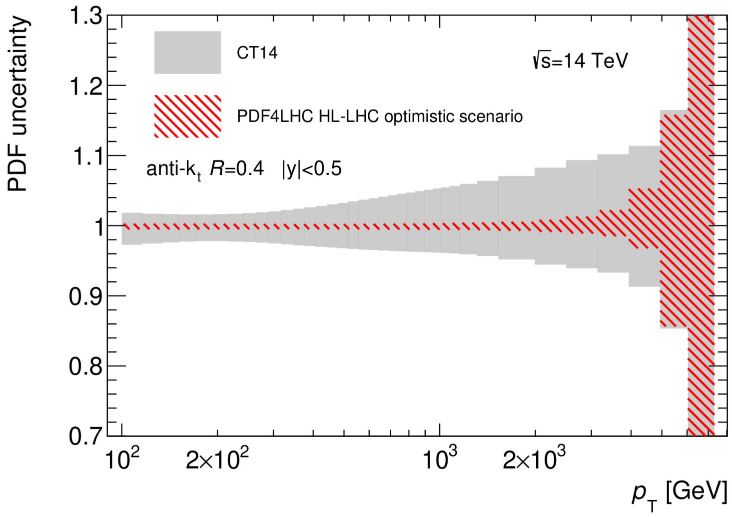
- Unique access to non-perturbative aspects of QCD
  - similar in nature to PDFs, but not (yet) amenable to lattice calculations
  - MC event generators need tuning → important for discovery physics, jet substructure, EIC …
  - correlations (flavor, spin, kinematics) essential for advancement at LHC and EIC
- Belle II can provide unique and crucial data
  - di-hadron fragmentation functions
  - leading hadron correlations —- akin to dijet differential cross sections
  - MC tuning based mainly on LEP data. Belle II data at lower sqrt(s) provides "lever arm" for checking extrapolation across wide energy ranges
- Integrated approach with theorists is very important
  - new theoretical developments provide the basis for e.g. leading hadron correlations
  - dynamical generation of mass (partons become hadrons) — behavior wrt formation time

to be submitted

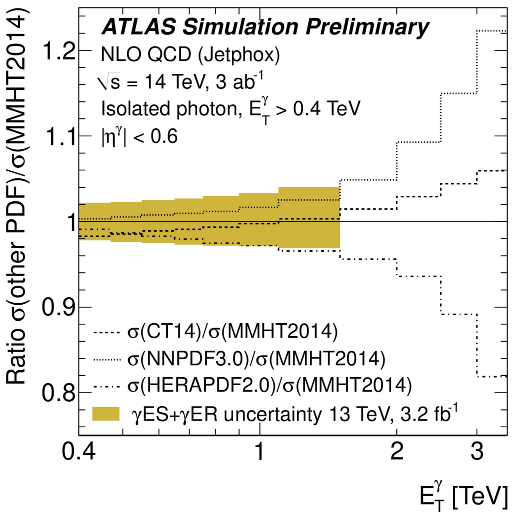
ATLAS / CMS at the HL-LHC

- HL-LHC will continue to produce amazing precision measurements that inform our understanding of QCD for decades to come
  - QCD not driving force for many future experiments, but it is crucial for understanding them!

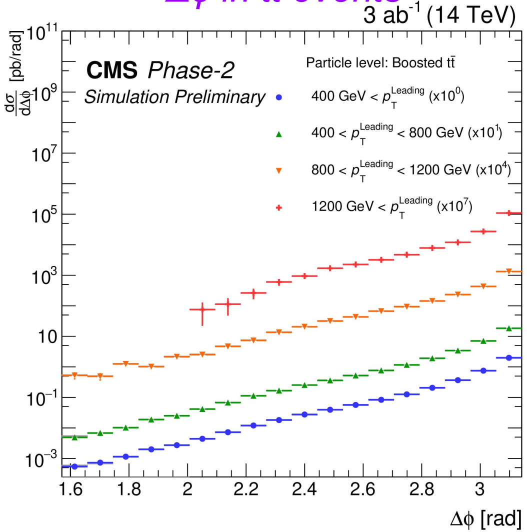
inclusive jet



direct photon



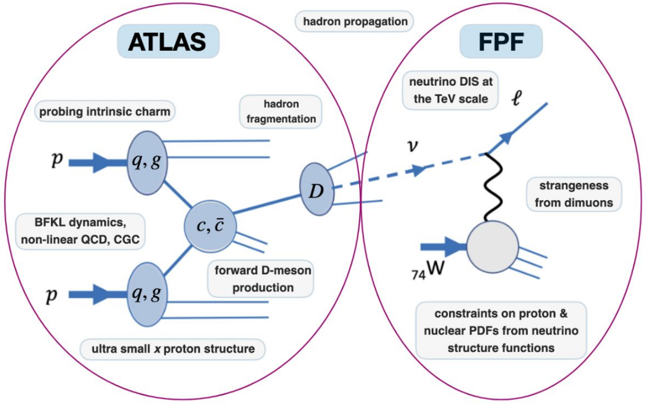
Δϕ in $t\bar{t}$ events

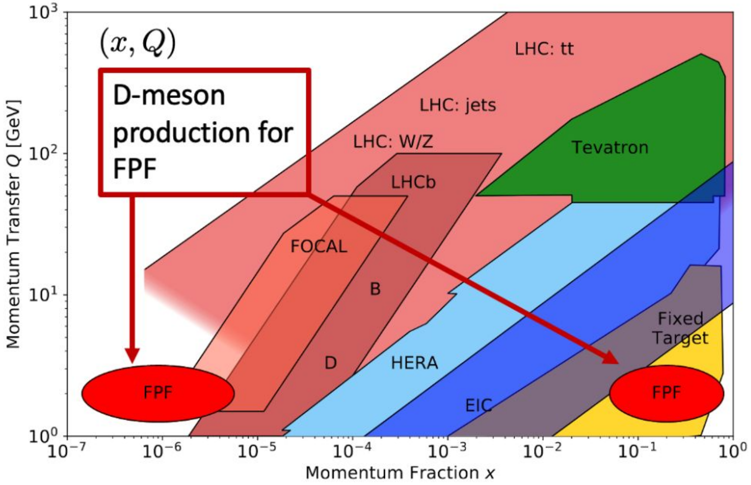


ATLAS/CMS

Forward Physics Facility at the HL-LHC

- Proposed underground facility ~620 m from ATLAS interaction point
- High energy neutrino fluxes for DIS
  - approx. 10^6 neutrino interactions with energies up to a few TeV
  - new regions of phase space in forward hadron production probing both large-x and small-x
  - nuclear structure functions, PDF
- Complementary to EIC
  - neutrino vs charged lepton DIS

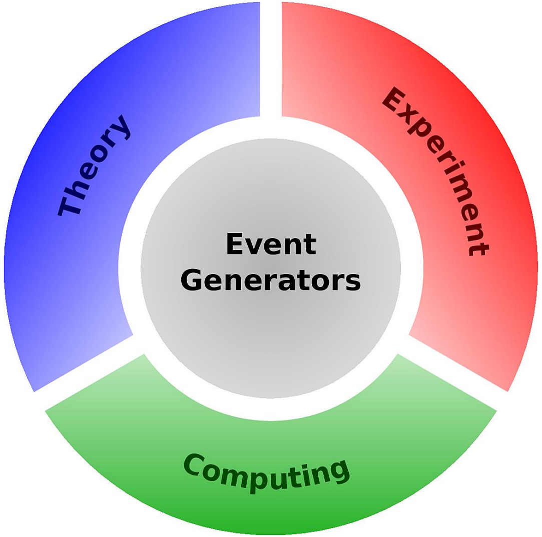




[arXiv:2109.10905]()

Theoretical and modeling advances

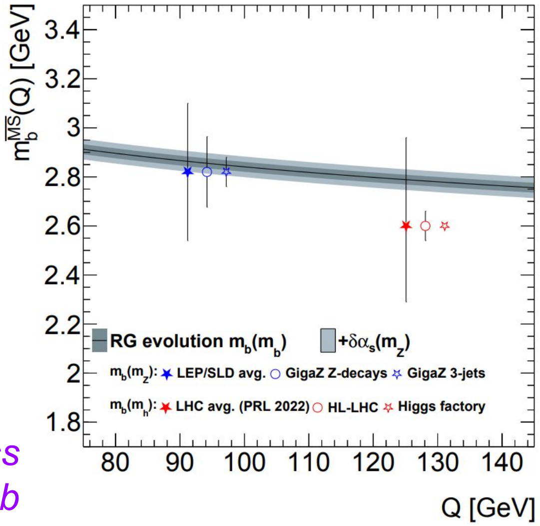
- Advances in QCD rely heavily on improvements in theoretical calculations
  - significant activity in Theory Frontier
  - several topics require interplay between theory and experiment, e.g., α_S, jet substructure, PDFs
- No experimental advances without further developments in MC generators
  - improvements in generation efficiency → 'Big Data' event production needed for colliders
  - inclusion of higher-order calculations



[arXiv:2109.10905](https://arxiv.org/abs/2109.10905) [arXiv:2203.11110](https://arxiv.org/abs/2203.11110)

Summary

- QCD is an active and vibrant area of physics with significant recent progress in both theoretical approaches and experimental measurements
    - higher-order calculations compared against precise data
    - innovative techniques taking advantage of the latest tools and technology (e.g., lattice, simulations, machine learning)
- Much remains to be learned from HL-LHC and EIC
    - important and unique results will continue to come out
    - these results will inform our understanding for decades
- QCD will not drive choice of next accelerator
    - but it will impact its utility and detector requirements



running of b-quark mass extracted from H→bb

Thanks for all the great inputs!

Backup Slides

Some Relevant Submitted Contributions for EF05

- Forward Physics
  - The Forward Physics Facility at the High-Luminosity LHC
  - The Forward Physics Facility: Sites, Experiments, and Physics Potential
  - White Paper on Forward Physics, BFKL, Saturation Physics and Diffraction
- Event Generators for High-Energy Physics Experiments
- Some aspects of impact of the Electron Ion Collider on particle physics at the Energy Frontier
- Proton structure at the precision frontier
- The Future Circular Collider: a Summary for the US 2021 Snowmass Process
- Strategies for Beam-Induced Background Reduction at Muon Colliders
- Physics with the Phase-2 ATLAS and CMS Detectors
- Jets and Jet Substructure at Future Colliders
- The strong coupling constant: State of the art and the decade ahead

Future e-p colliders – LHeC

D. Britzger for the LHeC study group
J.Phys.G 48 (2021) 110501 [arXiv:2007.14491]

e-p colliders are perfect QCD laboratory
HERA → EIC → LHeC → FCC-eh

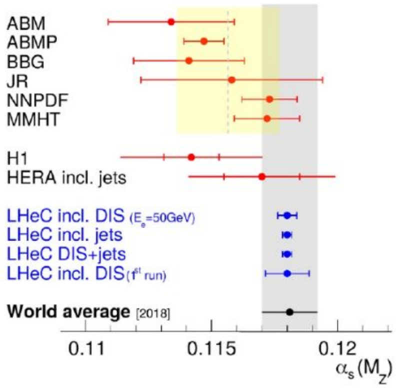
Measurements in e-p collisions provide many opportunities for precision determinations of α_s

- Inclusive measurements (F_2-scaling, F_L,...)
- Jets in neutral-current DIS
- Photoproduction
- Event shapes
- Groomed event shapes
- Jet substructure
- Multi-jet observables and jet-ratios
- Heavy quark production
- ...

→ QCD measurements at all scales at a time

Challenging for theory to reach similar uncertainties than future e-p data

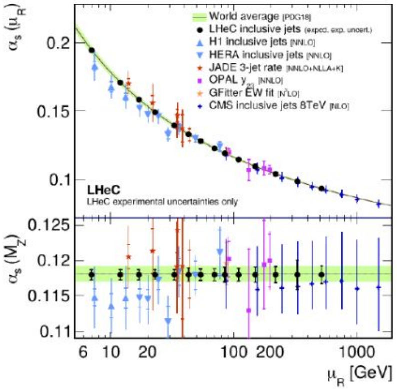
Inclusive DIS cross sections at the LHeC exhibit high sensitivity to α_s



PDF+α_s fit with LHeC inclusive DIS data

$$\boxed{\delta\alpha_S(m_Z^2) = \pm 0.00022\,(\text{exp+PDF})}$$

Jet cross sections in DIS at the LHeC have direct sensitivity to α_s at LO



Test running in range 3 < μ < 500 GeV with permille uncertainties (exp. only)

$$\boxed{\delta\alpha_S(m_Z^2) = \pm 0.00013\,(\text{exp}) \;\; \pm 0.00010\,(\text{PDF})}$$

- Measurements of DIS with new high-energy facilities (EIC first and, in the longer term LHeC/FCC-eh) will allow determining PDFs + α_S over a large phase space covering LHC kinematics. This would resolve PDF-α_S ambiguities in hadron-collider analyses, and provide new precision $\alpha_S(m_Z^2)$ determinations. A direct extraction of α_S and studies of its energy evolution will also benefit from high-precision PDFs over a large kinematic range.

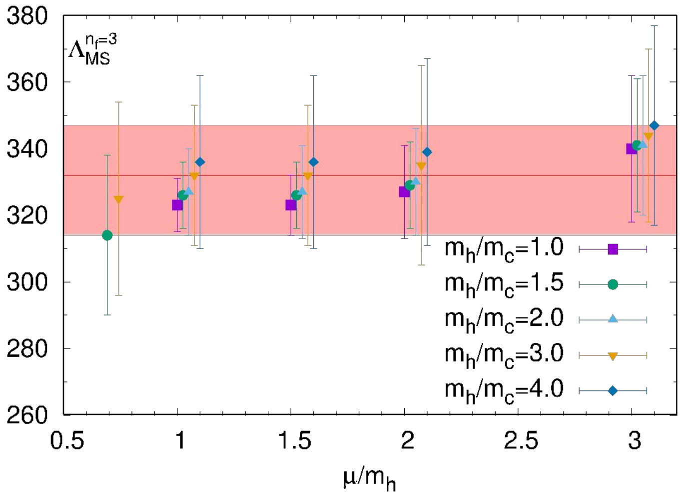
[α_s white paper (arXiv:2203.08271)]

α_s from lattice QCD: Quarkonium correlators

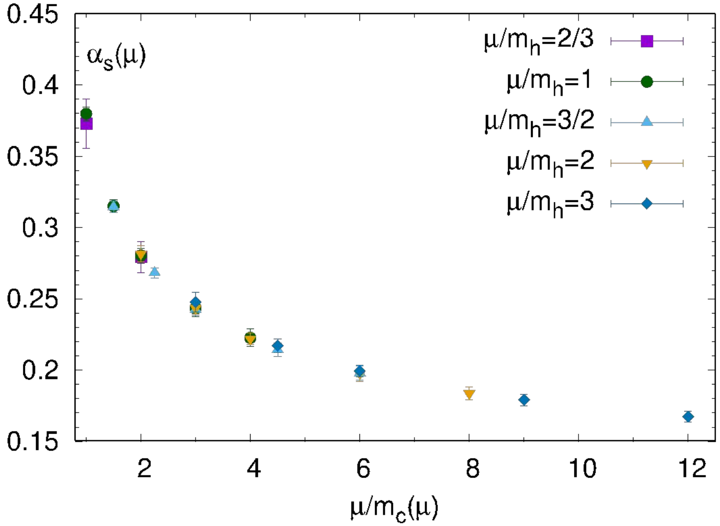
3-flavor lattice calculations with HISQ action are available at several heavy quark masses enabling to test perturbative errors and non-perturbative effects as well as the continuum extrapolation:

$$m_h = m_c,\ 1.5m_c,\ 2m_c,\ 3m_c,\ 4m_c,\ m_t$$

$$\Lambda^{n_f=3}_{\overline{MS}} = 332 \pm 17 \pm 2\ (scale)\ \mathrm{MeV}$$



$$\alpha_s^{n_f=5}(\mu = M_Z) = 0.1177(12)$$

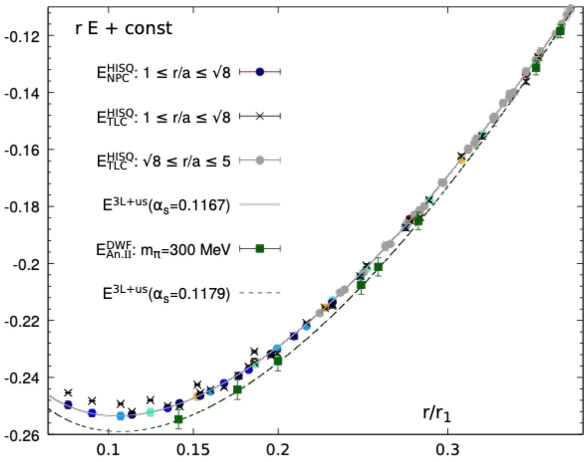


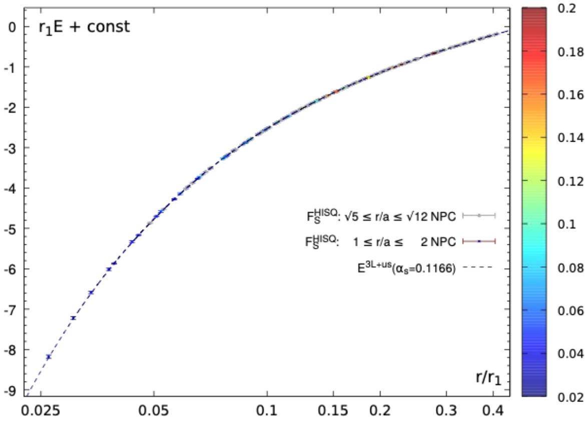
P. Petreczky, J.H. Weber, Eur. Phys. J. C 82 (2022) 1, 64

Consistent with the previous calculations by HPQCD collaboration. The reliability of the calculations can be improved by considering additional heavy quark masses.

α_S from lattice QCD: Static energy & force

Comparing 2+1 lattice data on the QCD static energy or the free energy at short QQbar distance with high order perturbation theory (NNNLO) in the effective field theory (pNRQCD) we get:





From the static energy:

$$\alpha_S(m_Z^2) = 0.11660^{+0.00110}_{-0.00056},$$

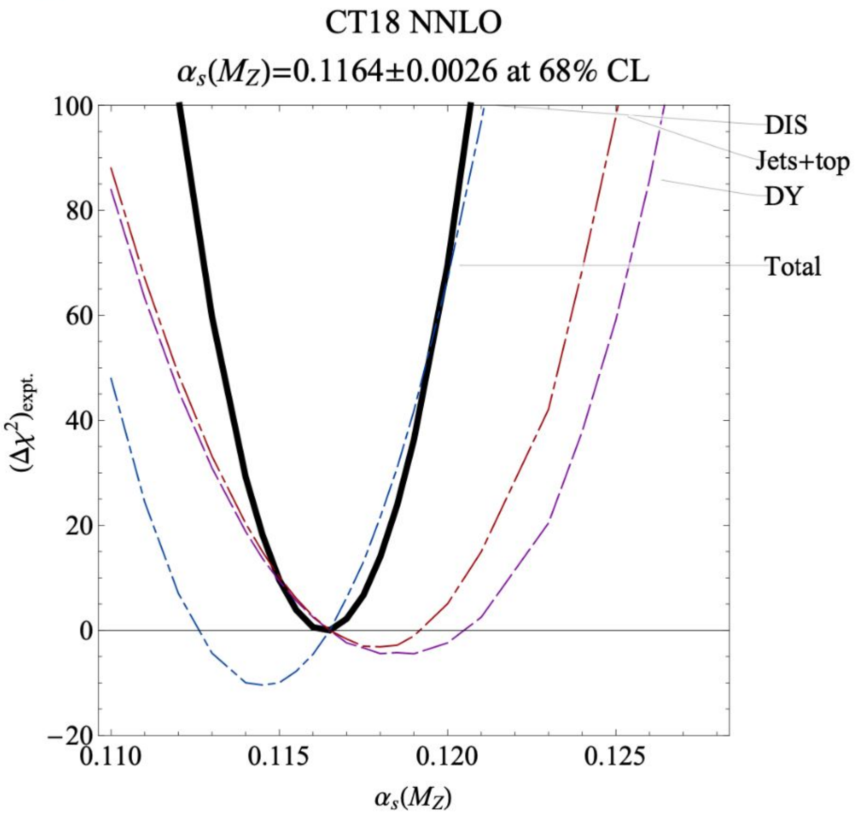
From the free energy

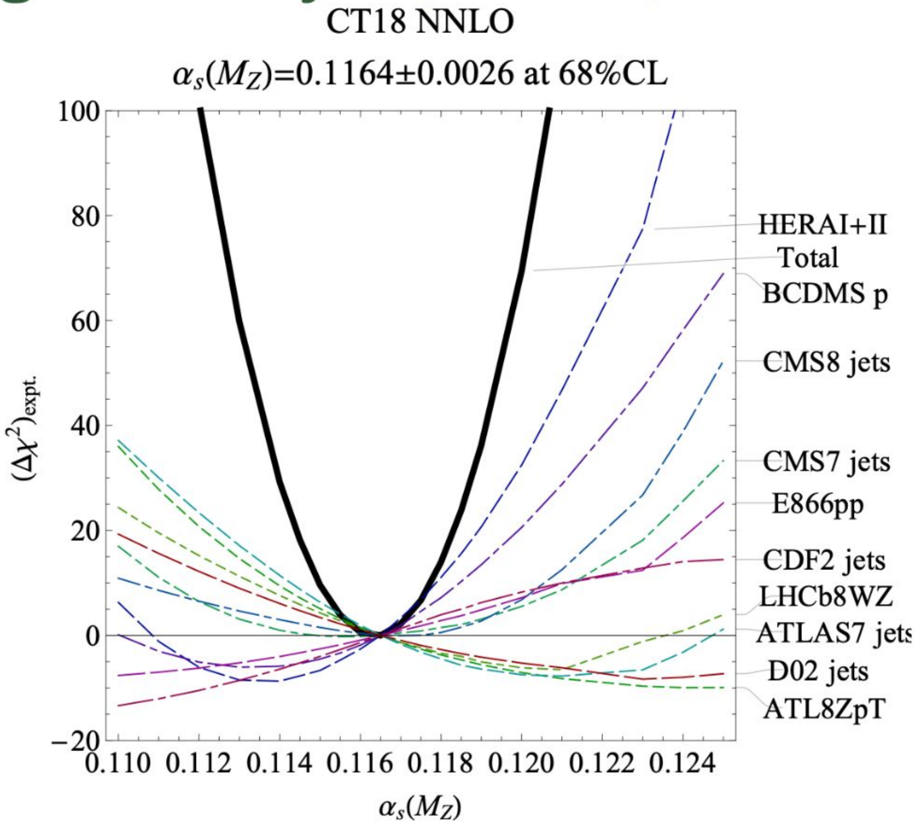
$$\alpha_S(m_Z^2) = 0.11638^{+0.00095}_{-0.00087}$$

A. Bazavov, N. Brambilla, X. Garcia, P. Petreczky, J. Soto, A. Vairo, J. Weber, PRD 100 (2019) 11, 114511

Slides by K. Xie

α_s determination in the CT18 global analysis [Hou et al., 1912.10053]



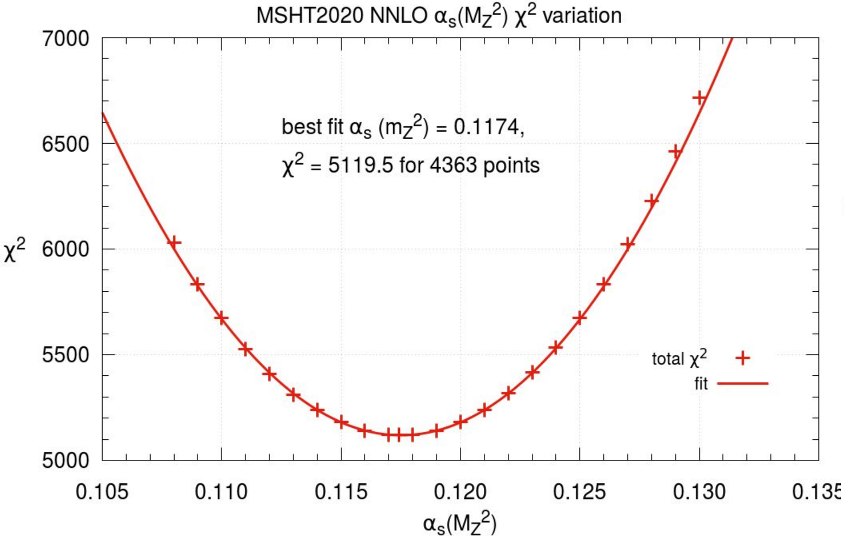


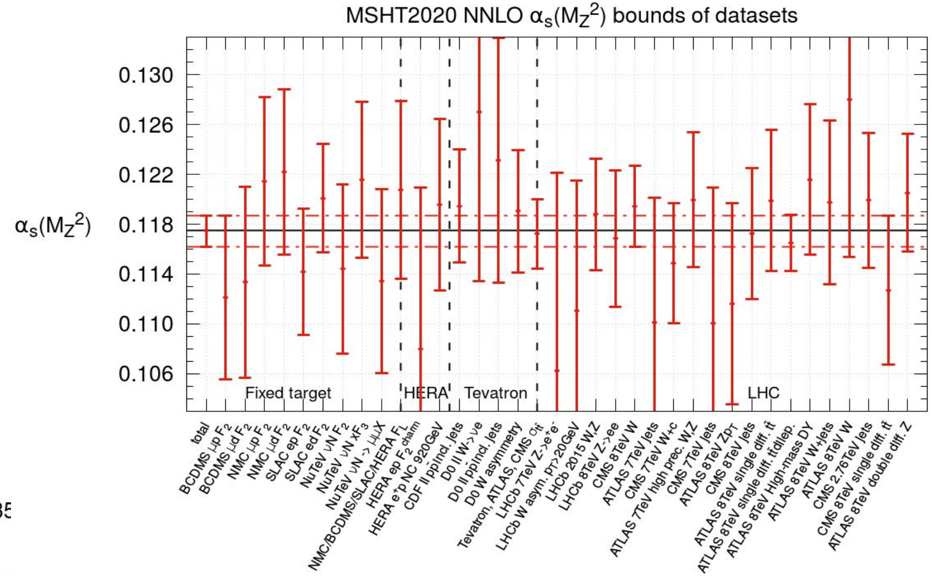
- A global fit of non-LHC experiments, as well as jet, high-p_T Z, W/Z, $t\bar{t}$ production at LHC 7/8 TeV
- CT18 uncertainty on α_s is enlarged, reflecting some tensions between experiments (seen, e.g., in χ^2 scan) and dependence on 250+ PDF parameterization forms

α_S from MSHT analyses

Thomas Cridge (University College London)

- Used MSHT20 PDFs to extract α_S (M_Z^2) best fit value, then utilised dynamical tolerance procedure to determine its uncertainty à la PDF uncertainty, including PDF correlations.





$$\alpha_{S,\mathrm{NNLO}}(M_Z^2) = 0.1174 \pm 0.0013$$

Consistent with World Average of 0.1179 ± 0.0009.

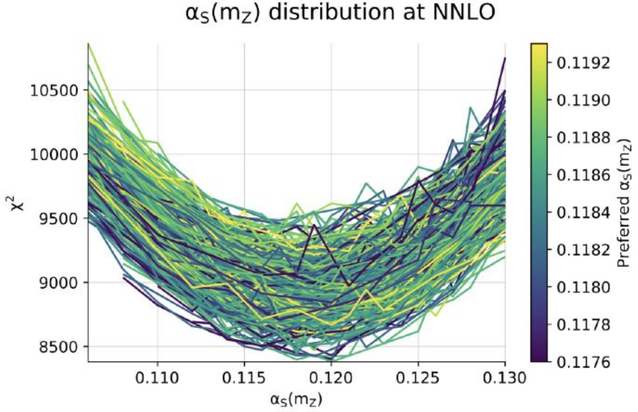
- Also examined PDF-α_S correlations, PDF+α_S uncertainties on xsecs, and heavy quark masses.
- All PDF sets publicly available on LHAPDF, including global fit $\Delta\chi^2$.

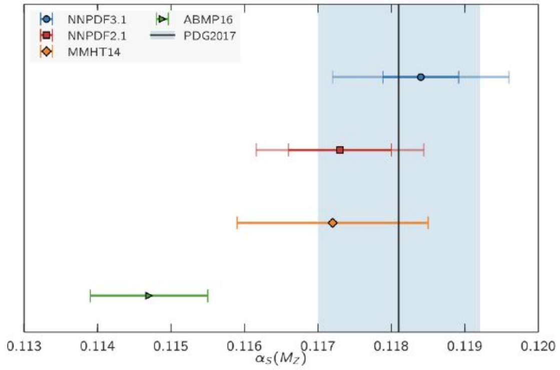
See our paper arXiv:2106.10289 for more details.

Strong coupling determination with NNPDF

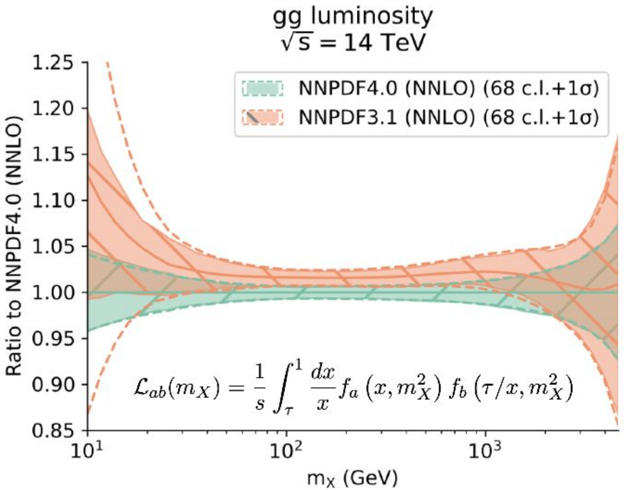
contribution to ``the strong coupling constant: State of the art and the decade ahead" (arXiv:2203.08271)

Juan Rojo (VU Amsterdam & Nikhef)





- The machine learning NNPDF methodology is suitable to be deployed for the **simultaneous determination of PDFs and (B)SM parameters**, such as the strong coupling constant or EFT Wilson coefficients
- **NNPDF4.0** benefits from enhanced precision and accuracy and hence should led to improved PDF-based extractions of $\boldsymbol{\alpha_S}$
- Complementary techniques adopted in the **NNPDF fits of $\boldsymbol{\alpha_S}$**: parabolic fits, correlated replicas, SimuNET, …
- Limiting factor is **robust estimate of MHOU**, which requires estimating the MHOUs associated to the PDFs

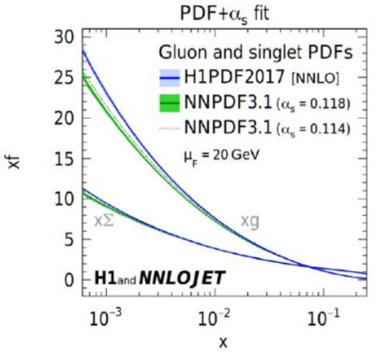


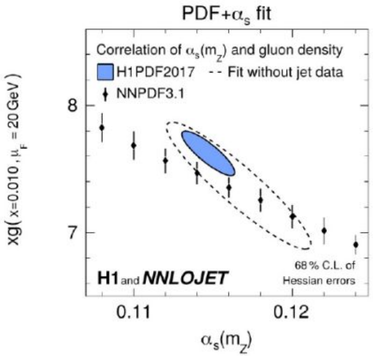
α_s from jet data in DIS

D. Britzger for the H1&NNLOJET collaborations
and for the NNLOJET+APPlfast group

α_s from normalized jet cross sections in DIS in a PDF+α_s fit together with H1's inclusive DIS data
[EPJ C77 (2017), 791]

- normalized inclusive jet and dijet data
- NNLO predictions from NNLOJET (+fastNLO)





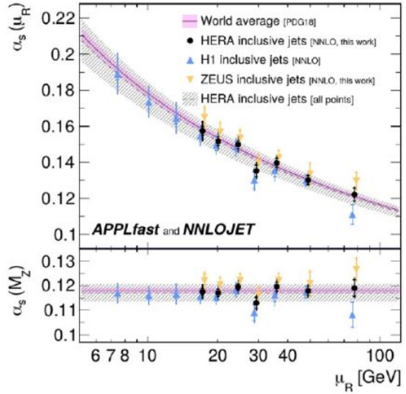
- Jet data resolve α_s and gluon correlation in the combined fit with PDFs (resulting PDF set: H1PDF2017nnlo)

$$\boxed{\alpha_S(m_Z^2) = 0.1147\,(11)_{\rm exp,had,PDF}\,(2)_{\rm mod}\,(3)_{\rm par}\,(23)_{\rm scale}}$$

Note: equivalent selection of dominant α_s-sensitive jet data than in HERAPDFjets (and equivalent NNLO predictions), but higher self-consistency: χ^2/ndf~1.0 for ndf=1516

α_s from inclusive jets by H1 and ZEUS in DIS using NNLO pQCD predictions
[EPJ C 79 (2019) 845]

- Clean theoretical and experimental observable
- Test running in range $7 < \mu < 80$GeV



$$\boxed{\alpha_S(m_Z^2) = 0.1178\,(15)_{\rm exp}\,(21)_{\rm th}}$$

α_s from dijet jet cross sections by H1 using NNLO
[EPJ C 77 (2017) 791]

$$\boxed{\alpha_S(m_Z^2) = 0.1157\,(22)_{\rm exp}\,(23)_{\rm th}}$$

α_s from inclusive and dijet jet data by H1 using NNLO
[EPJ C 77 (2017) 791]

$$\boxed{\alpha_S(m_Z^2) = 0.1166\,(19)_{\rm exp}\,(24)_{\rm th}}$$

Note: higher experimental precision can be achieved, up to $\delta\alpha_s$~±0.0009, but theory is a limiting factor

HERAPDF2.0 NNLOJets $\alpha_s(M_Z)$ determination

A M Cooper-Sarkar and behalf of H1, ZEUS and NNLOJet   Alphas-2022

- $\alpha_s(M_Z)$ determination by a simultaneous NNLO PDF and $\alpha_s(M_Z)$ fit
- To the full combined H1 and ZEUS inclusive data on NC and CC, e^+p and e^-p cross sections at various proton beam energies from HERA-I and HERA-II (1506.06042)
- And to both H1 and ZEUS inclusive jet and dijet data
- Using newly available NNLOJet predictions in the APPLFast grid formalism
- Analysis follows the well known HERAPDF formalism using a General Mass Variable Flavour Scheme (m_c and m_b and their uncertainties are set using combined H1 and ZEUS charm and beauty data) within QCDNUM framework at NNLO, including model and parametrisation variations

- Input of jet data along with inclusive data does not change the HERAPDF2.0NNLO PDFs much- but it reduces gluon PDF uncertainty
- The major effect is that it reduces the value of $\alpha_s(M_Z)$.
- The preferred value of $\alpha_s(M_Z)$ is not the PDG value 0.118, as used for HERAPDF2.0NNLO, it is lower: with $Q^2 > 3.5$ GeV^2

$$\alpha_s(M_Z)=0.1156 \pm 0.0011_{(exp)}\ {}^{+0.0001}_{-0.0002(model/param)} \pm 0.0029_{(scale)}$$

with $Q^2 > 10$ GeV^2

$$\alpha_s(M_Z)=0.1156 \pm 0.0011_{(exp)} \pm 0.0002_{(model/param)} \pm 0.0021_{(scale)}$$

Jet scale uncertainties (7-point, fully correlated) are dominant 1
Can be somewhat reduced by Q^2 cuts, best hope for the future N3LO

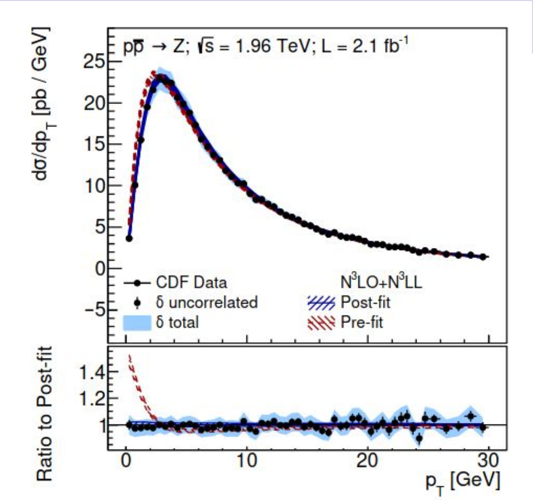
α_S from Z p_T distributions

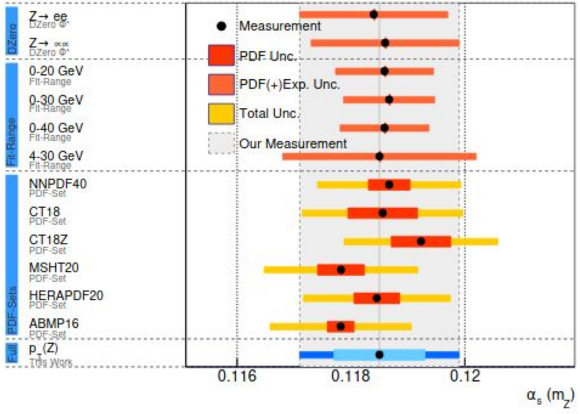
arXiv:2203.05394

Stefano Camarda (CERN)

- $\alpha_S(m_Z)$ from the CDF $p_T(Z)$ distribution in the Sudakov region $p_T < 30$ GeV: $\alpha_S = 0.1185 +0.0014 -0.0015$
- Conservative approach for PDF uncertainties, including envelope of 6 different PDF sets
- Observable not included in PDF fits, therefore avoiding any issue of correlation with existing PDF sets
- First N^{3}LO determination at hadron colliders
- First determination using QCD resummed theory predictions based on a semi-inclusive observable at hadron-hadron colliders

	$\delta\alpha_s(m_Z,+)$	$\delta\alpha_s(m_Z,-)$
Exp. unc.	+0.0007	–0.0007
PDF unc.	+0.0008	–0.0008
Scale var.	+0.0007	–0.0010
Theory unc.	+0.0007	–0.0004



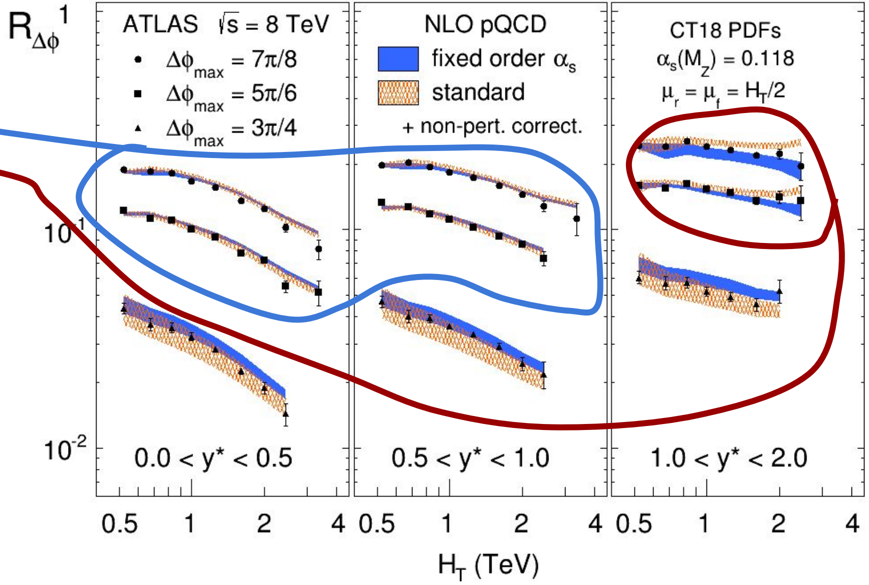


Fixed order pQCD predictions for cross section ratios R

L. Sawyer, C. Waits, M. Wobisch   arXiv:2112.01449

Standard Method: $R = \frac{\sigma_{n\,\text{fixed-order}}}{\sigma_{d\,\text{fixed-order}}}$ vs. exact fixed-order for R: $R = R_{\text{LO}} + R_{\text{NLO}} + R_{\text{NNLO}} + \cdots$

- Sometimes both agree
- But sometimes they disagree



Both methods: Equally valid representations of the fixed-order pQCD result

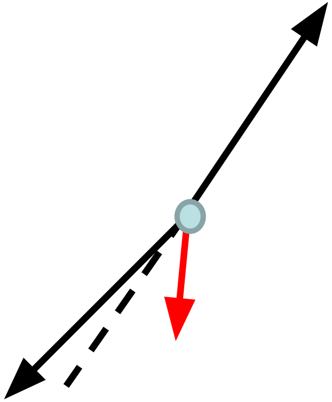
So: differences should be considered as uncertainty

- Use to get a better estimate on possible missing higher-order corrections
- Helpful for identifying robust measurable ratio-quantities for future α_s determinations

α_S from jet Xsec ratios: energy range for the RGE test and PDF sensitivity

Bogdan Malaescu (LPNHE, CNRS)

- Observables like $R_{3/2}$, $R_{\Delta\Phi}$ and (A)TEEC non-trivial due to events that are *not* back-to-back dijets: *sensitivity to α_S originates from probability of emission of extra radiation (3^{rd} jet etc.)*
- *Relevant scale for RGE test related to $p_{T,3}$ (low), not to event-level observables* (e.g. $p_T^{\text{lead. jet}}$, $p_T^{\text{(all jets)}}$, $(p_{T,1}+p_{T,2})/2$, $H_T/2$)



Observable		$\alpha_S(m_Z^2)$	Range PDF variations
R_{32}	ATLAS	$0.111 \pm 0.006\,(\text{exp})^{+0.016}_{-0.003}\,(\text{PDF, NP, scale})$	0.109 – 0.116
R_{32}	CMS	$0.1148 \pm 0.0014\,(\text{exp}) \pm 0.0018\,(\text{PDF}) \pm 0.0050\,(\text{theory})$	0.1135 – 0.1148
3-jet mass	CMS	$0.1171 \pm 0.0013\,(\text{exp}) \pm 0.0024\,(\text{PDF}) \pm 0.0008\,(\text{NP})^{+0.0069}_{-0.0040}\,(\text{scale})$	0.1143 – 0.1183
2-jets	CMS	$0.1159 \pm 0.0025\,(\text{exp, PDF, NP})$	0.1159 – 0.1183
3-jets		$0.1161 \pm 0.0021\,(\text{exp, PDF, NP})$	0.1159 – 0.1179
2- & 3-jets		$0.1161 \pm 0.0021\,(\text{exp, PDF, NP})$	0.1161 – 0.1188
R_{32}		$0.1150 \pm 0.0010\,(\text{exp}) \pm 0.0013\,(\text{PDF}) \pm 0.0015\,(\text{NP})^{+0.0050}_{-0.0000}\,(\text{scale})$	0.1139 – 0.1184
TEEC	ATLAS	$0.1162 \pm 0.0011\,(\text{exp}) \pm 0.0018\,(\text{PDF}) \pm 0.0003\,(\text{NP})^{+0.0076}_{-0.0061}\,(\text{scale})$	0.1151 – 0.1177
ATEEC		$0.1196 \pm 0.0013\,(\text{exp}) \pm 0.0017\,(\text{PDF}) \pm 0.0004\,(\text{NP})^{+0.0061}_{-0.0013}\,(\text{scale})$	0.1185 – 0.1206
$R_{\Delta\phi}$	ATLAS	$0.1127^{+0.0019}_{-0.0018}\,(\text{exp}) \pm 0.0006\,(\text{PDF})^{+0.0003}_{-0.0001}\,(\text{NP})^{+0.0052}_{-0.0019}\,(\text{scale})$	0.1127 – 0.1156

- *PDF uncertainties non-negligible for (α_S from) cross-section ratio measurements & (A)TEEC:*
  - probability of extra radiation sensitive to the type of partons in the initial state
  - both α_S & PDF sensitivities of the observables reduced for ratios: both relevant for the α_S evaluation

Constraining the Hadronic Vacuum Polarization contribution to g-2 at Belle II

- HVP is the leading theoretical uncertainty on g-2
- Discovery potential for new physics from g-2 experiment is dependent on progress on HVP
- Leading uncertainty come from measurements of e+e- →hadrons, in particular from pi+pi- channel around rho and omega resonances
- Currently large systematics and disagreement between KLOE and BaBar measurement
- Belle II measurement needed to resolve tension
- Large dataset of Belle II opens new possibilities to reduce systematics

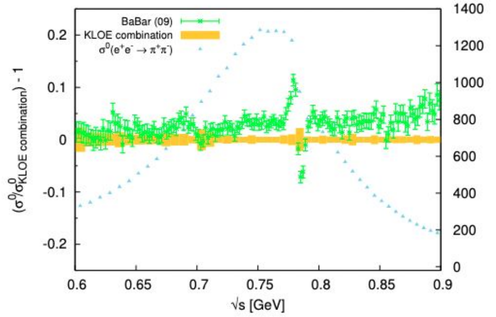
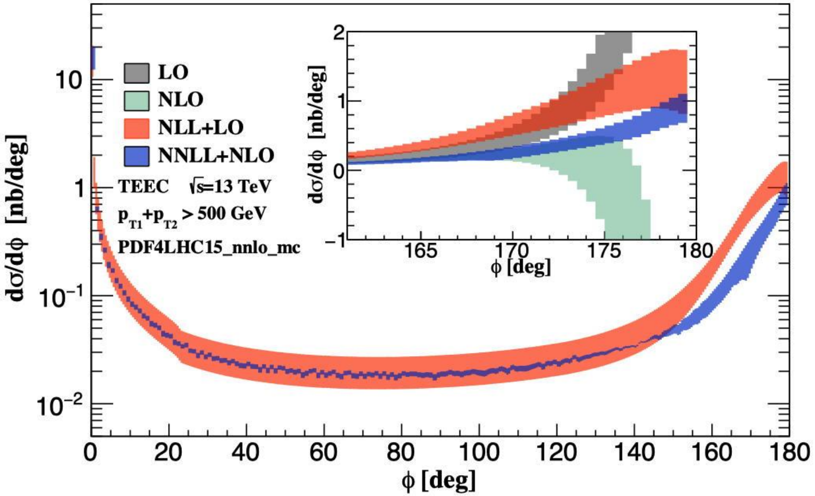


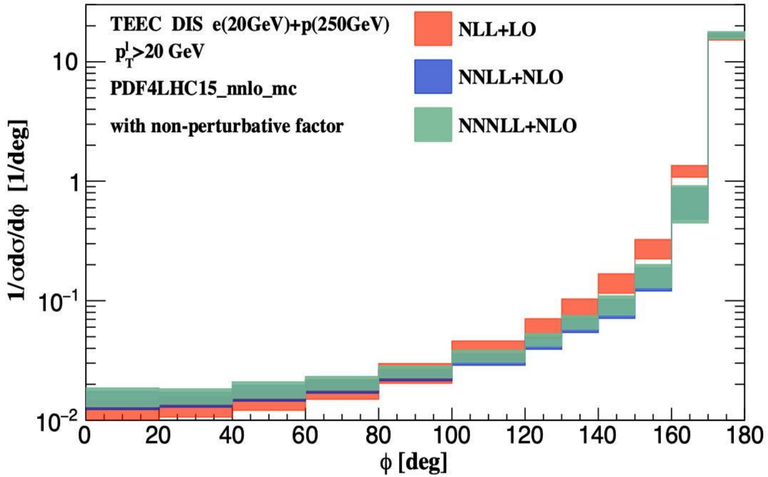
Illustration of discrepancy
Between KLOE and BaBar
From JHEP **03**,173 (2018)

Energy energy correlators

- Energy-energy correlators (EEC) are precision probes of the perturbative and non-perturbative aspects of QCD dynamics. They can be used to extract the strong coupling constant and to constrain TMD distribution functions.

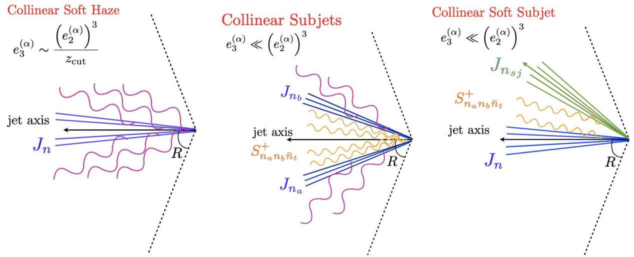


The resummed TEEC distribution matched to fixed order at both NLL+LO and NNLL+NLO at C.M energy of 13 TeV at the LHC



Predictions for the TEEC distribution at the highest lepton and proton energies at the Electron-Ion Collider at NNLL+NLO with non-perturbative corrections

- Closely related energy-correlation shape variables have also been used to tag boosted objects produced in high energy collisions.



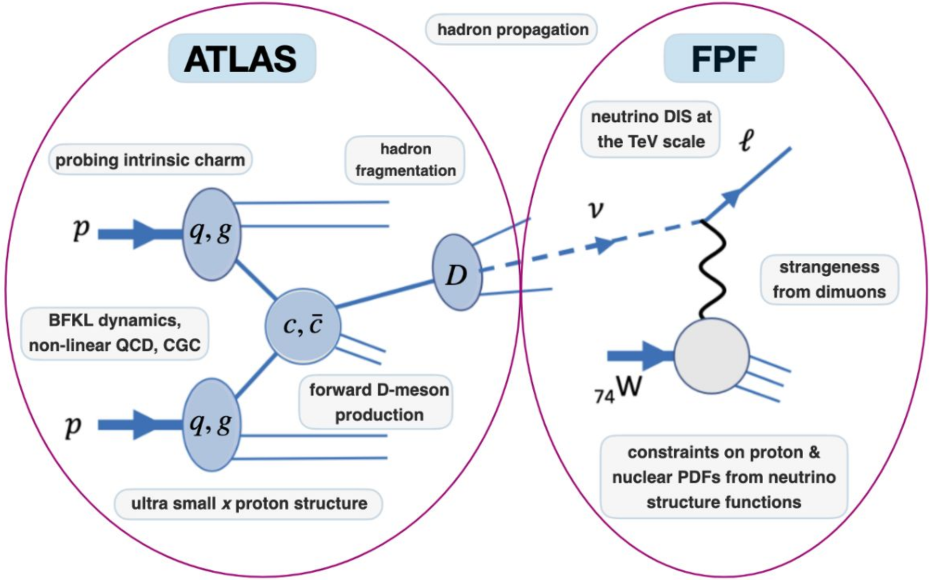
Regions of interest in the energy-energy correlations inside jets

arXiv:2203.07113

Forward Physics Facility

The Forward Physics Facility at the High-Luminosity LHC
J. L. Feng et al., arXiv:2203.05090

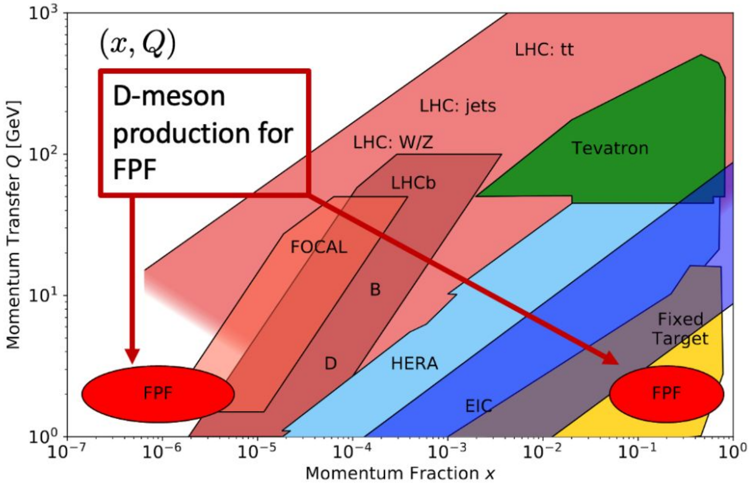
Underground facility ~620 m far forward from the ATLAS IP, shielded by concrete and rock. FPF experiments to detect $\sim 10^6$ neutrino interactions, energies up to a few TeV.

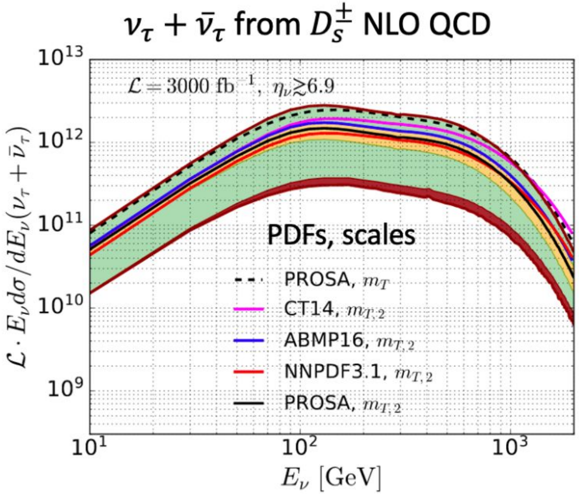


- Neutrino fluxes at high energy in forward region directly tied to charm hadron production, proton PDFs.
- Neutrino interactions in a new energy regime for nuclear structure functions and PDFs.
- Need Monte Carlo event generation of forward light and heavy hadron production, crucial for physics potential of the FPF.
- Key inputs to astroparticle physics, extensive air shower simulations.

Forward Physics Facility

- New regions of phase space in forward hadron production including charm, probing both large *x* and small *x* ($x \sim 10^{-7}$), to probe, e.g.,:
  - BFKL, non-linear dynamics
  - Transverse momentum dependent PDFs
  - Intrinsic charm





- High statistics νA charged current and neutral current measurements.
- Nuclear PDFs, strangeness.
- Broad energy for new kinematic scattering regimes including low Q.
- Neutrino DIS complementary to EIC, understanding neutrino vs charged lepton scattering.

Fragmentation Functions / Hadronization

- e+e- annihilation Belle II will probe **dynamics of hadronization**
  - Measurement full kinematic dependence of di-hadron correlations
    - Compare with factorized models and polarized string models
    - **Full kinematic** dependence needed to **reduce model dependence** and access dynamics⇒**needs Belle II luminosity**
  - Polarized final states (e.g. hyperons) to access spin-orbit correlations
  - Polarization dependence of hadronization in back-to-back correlations
  - Event shapes, Correlations of strangeness, baryon number to tune MCs
    - **Needed** (in addition to LEP) for energy lever arm⇒confidence in extrapolation to LHC
    - **Needed** for systematic studies of BSM discovery channels
  - Leading particle correlations to explore hadronization dynamics in string models
- Extraction of Fragmentation Functions of final states with additional degrees of freedom (compared to available FFs) **needed** as tools **to extract nucleon structure from EIC and JLab**
  - E.g. to disentangle twist3 effects (quark-gluon correlations) (e.g. *PRL*126 (2021) 152501)
  - To extract precision FFs
- Precision Jet Studies at Belle II energies will access an unexplored phase space
  - Explore transition from jets to hadrons →boundaries of perturbative QCD
  - Vacuum energy loss
  - Probe of TMD framework at N3LL
- Dynamical mass generation with polarized beams
  - The “QCD Higgs effect”
- More precision QCD studies
  - Energy-energy-correlations (see separate whitepaper)