Pictures from the QCD Frontier

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C. Royon, and M. Schmitt (conveners)

On behalf of QCD and Strong Interactions Topical Groups:

- EF05: Precision QCD
- EF06: Hadronic structure and forward QCD
- EF07: Heavy Ions

Joint EF05-06-07 report on QCD to be released soon!

Detailed discussions of

- Current and future hadron collider facilities
- Perturbative calculations and QCD tests (α_s, $m_b^{\overline{\mathrm{MS}}}$,…)
- Parton distribution functions (PDFs) and fragmentation functions (FFs)
- Predicting hadron structure in lattice QCD
- Forward scattering and saturation
- Jet substructure
- Photon-photon scattering
- Ultraperipheral collisions
- QCD with heavy ions
- Cross cutting aspects

Based on 19 Snowmass'2021 White Papers

- The Forward Physics Facility: Sites, Experiments, and Physics Potential [1]
- The Forward Physics Facility at the High-Luminosity LHC [2]
- Opportunities for precision QCD physics in hadronization at Belle II – a Snowmass whitepaper [3]
- The Future Circular Collider: a Summary for the US 2021 Snowmass Process [4]
- The International Linear Collider [5]
- Physics with the Phase-2 ATLAS and CMS Detectors [6]
- Event Generators for High-Energy Physics Experiments [7]
- Jets and Jet Substructure at Future Colliders [8]
- The strong coupling constant: State of the art and the decade ahead [9]
- Some aspects of the impact of the Electron Ion Collider on particle physics at the Energy Frontier [10]
- Lattice QCD Calculations of Parton Physics [11]
- Prompt electron and tau neutrinos and antineutrinos in the forward region at the LHC [12]
- `xFitter`: An Open Source QCD Analysis Framework [13]
- The Potential of a TeV-Scale Muon-Ion Collider [14]
- Forward Physics, BFKL, Saturation Physics and Diffraction [15]
- Proton structure at the precision frontier [16]
- Impact of lattice $s(x) - \bar{s}(x)$ data in the CTEQ-TEA global analysis [17]
- Opportunities for new physics searches with heavy ions at collider [18]
- Heavy Neutral Lepton Searches at the Electron-Ion Collider [19]
- Electron Ion Collider for High Energy Physics [10, 20]

QCD draws strong interest in numerous discussions at the Snowmass CSS…

1. … as the only QFT that can be experimentally studied in perturbative and nonperturbative phases
2. … as the key theory in HEP phenomenology now and in the future
3. … it is rich both in data and in ideas!

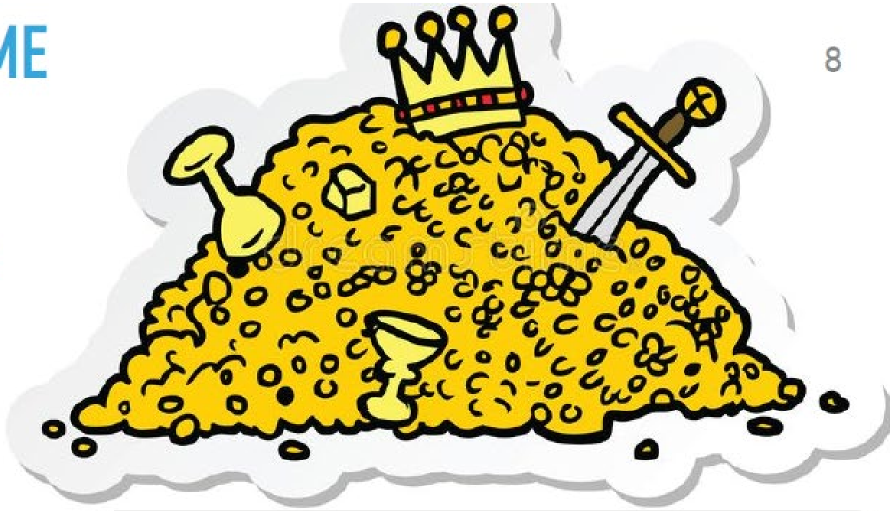
Higgs physics relies on QCD

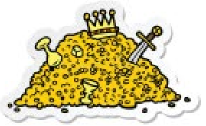
THE LHC – THINGS TO COME

8

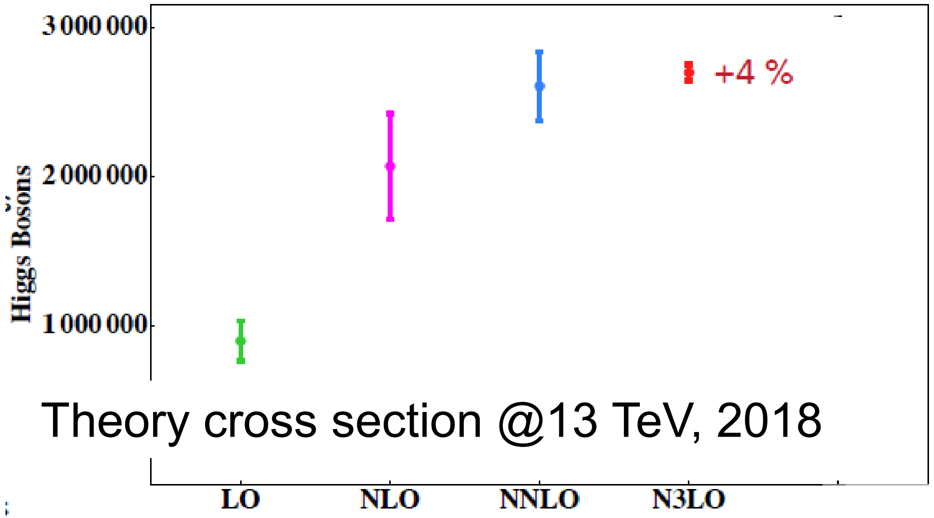
- **We are still in the early stages of LHC physics!**

Today: up to 139 fb^-1

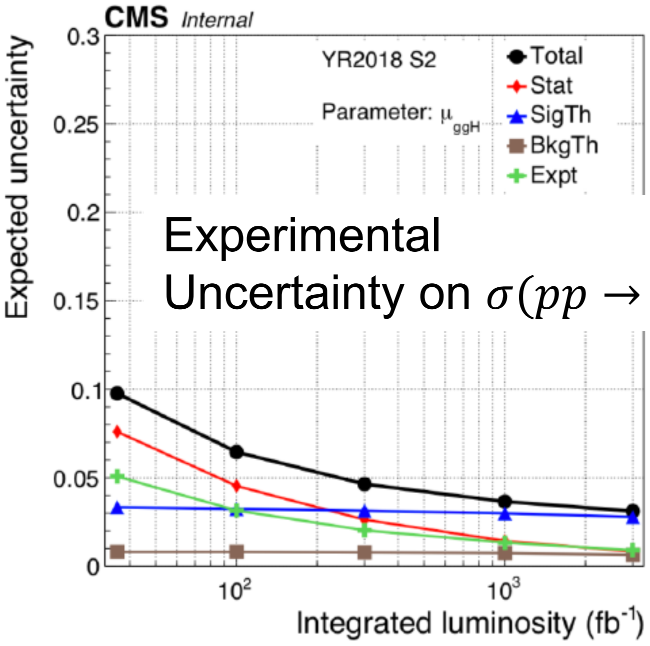




HL-LHC: 20 x current data

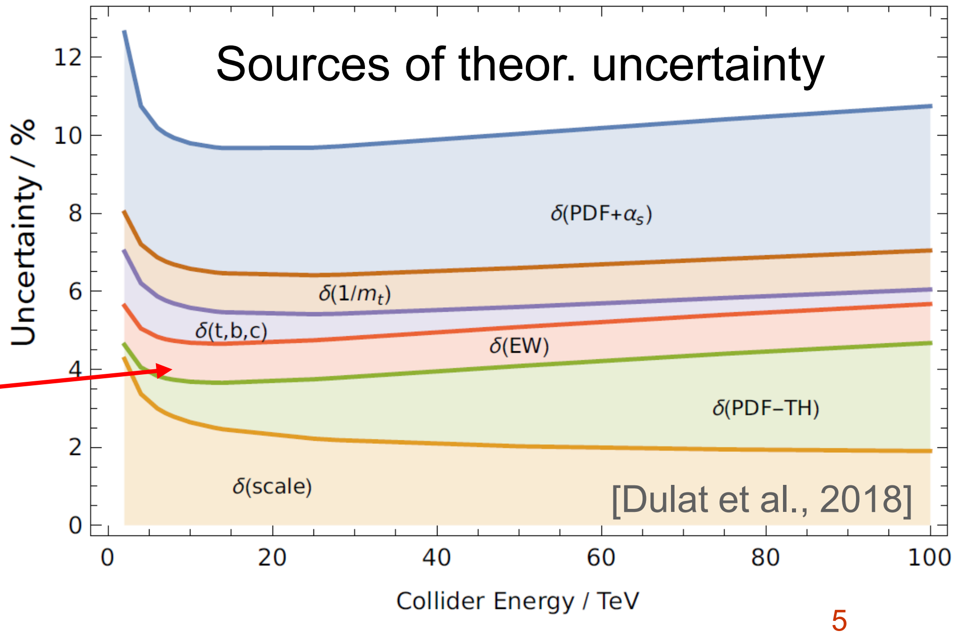


Theory cross section @13 TeV, 2018



Experimental Uncertainty on $\sigma(pp \to H)$

Experimental, perturbative, and nonpert. sources



Sources of theor. uncertainty

[Dulat et al., 2018]

Electroweak precision physics relies on QCD

For instance, W boson mass measurements at the Tevatron and LHC

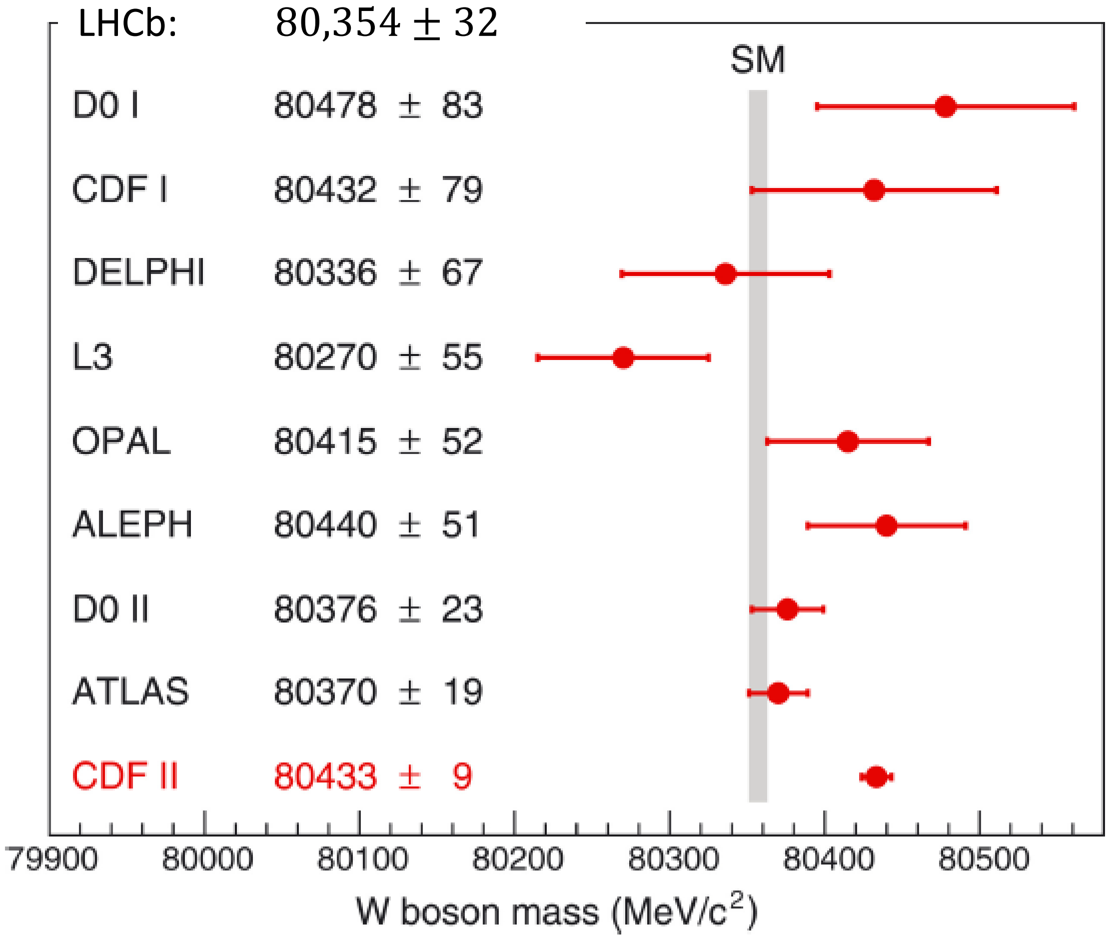


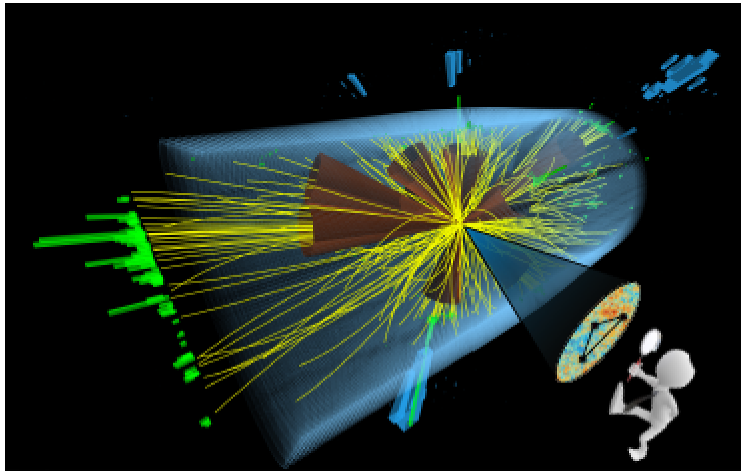
Figure reproduced from CDF-II measurement (Science 376, 170).

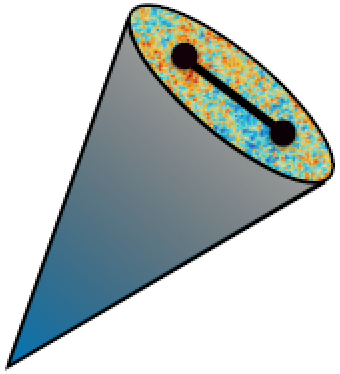
See J. Isaacson, TF06+07, for discussion of QCD+EW theory issues

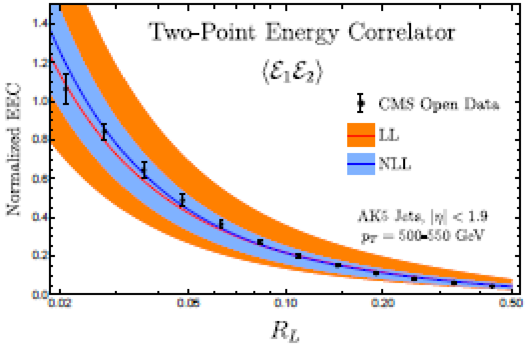
Toward jet substructure as a precision science

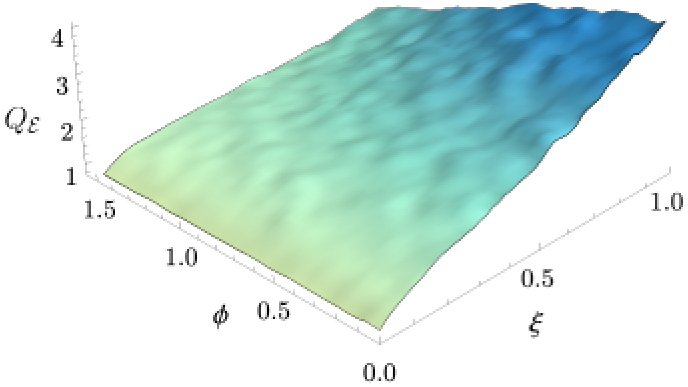
QCD dynamics at various energy scales is imprinted in angular distributions of particle energy flows.

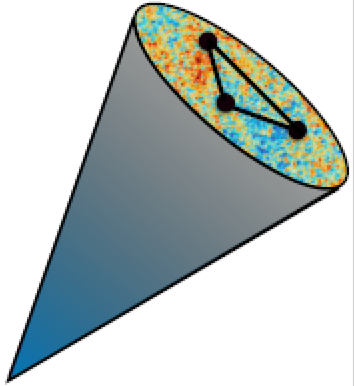
Developments in formal QCD and AI/ML open avenues to learn about this dynamics directly from recorded collider events











Forward QCD

New forward QCD experiments: LHCb, Forward Physics Facility, forward diffractive scattering, central exclusive production, LHC as a photon-photon collider

(TMD) factorization formalisms and evolution at small x

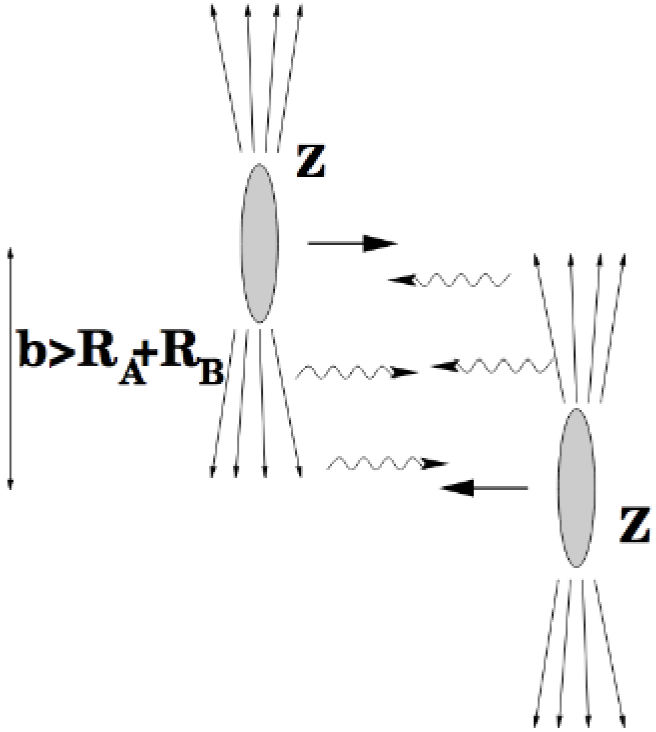
Best observables to look for small-x factorization (BFKL) and parton saturation

Incisive measurements and predictive models for diffractive scattering

Saturation in the nuclear medium (ALICE, EIC, …)

QCD dynamics at very large x (intrinsic charm)

Precision of Monte-Carlo programs for forward particle production



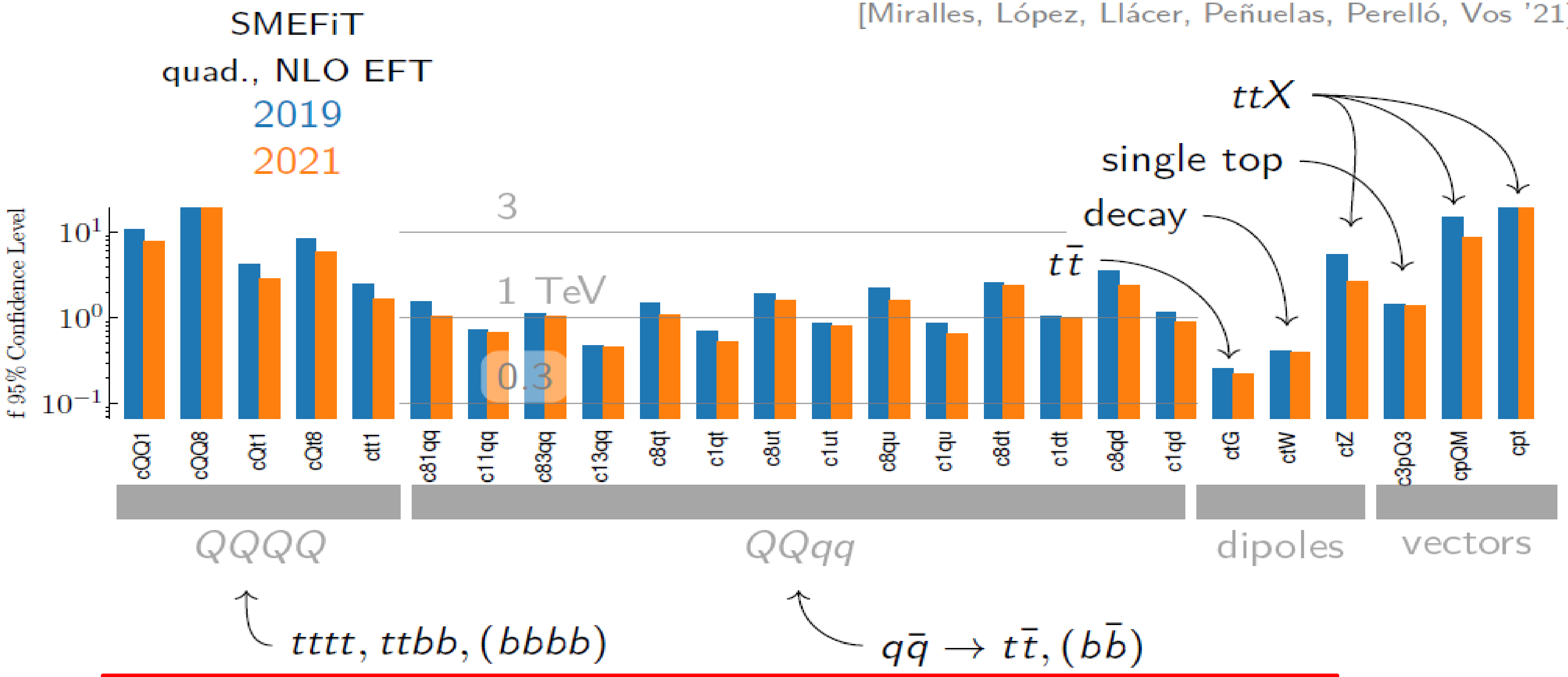
Prospects to probe small−x dynamics at intermediate virtualities in ultraperipheral pp, pA, AA collisions

M. Strikman, EF QCD

QCD controls accuracy of SMEFT analyses

Status at pp

[Brivio, Bruggisser, Maltoni, Moutafis, Plehn, Vryonidou, Westhoff, Zhang '19]
[Ellis, Madigan, Mimasu, Sanz, You '20]
[Ethier, Magni, Maltoni, Mantani, Nocera, Rojo, Slade, Vryonidou, Zhang '21]
[Miralles, López, Llácer, Peñuelas, Perelló, Vos '21]



- four-fermion limited by high-q^2 PDF and gg contamination
  … often forgotten but great BSM potential !
- ttZ, $tt\gamma$, tth limited by rare and complicated ttX

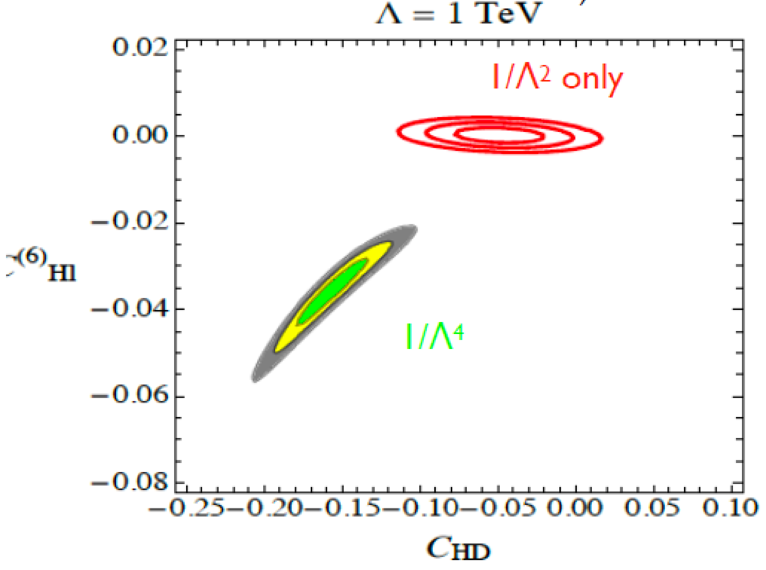
Higher-dim operators and QCD effects modify SMEFT exclusion limits

F. Petriello, TF07

- Extending fits to data to include $1/\Lambda^4$ dimension-6 squared effects can have a significant impact on the constraints.

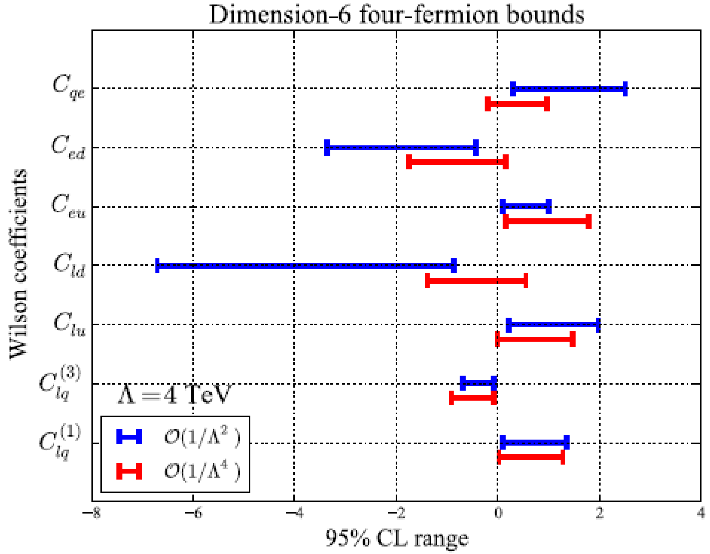
Fitting SMEFT coefficients and PDFs together can modify the constraints, too

fit to EW precision data (Zff vertex corrections)

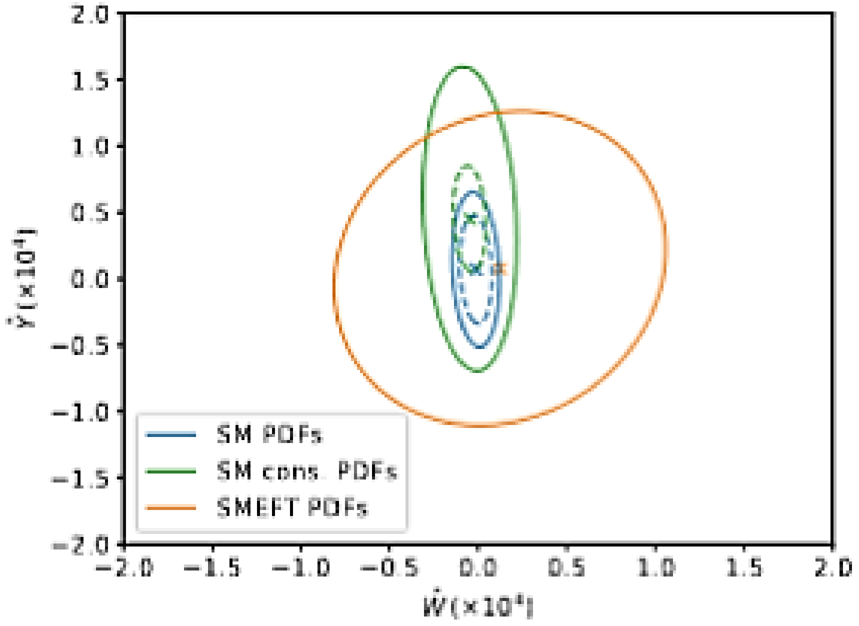


Corbett, Helset, Martin, Trott 2102.02819 21

fit to ATLAS DY data (four-fermion operators)



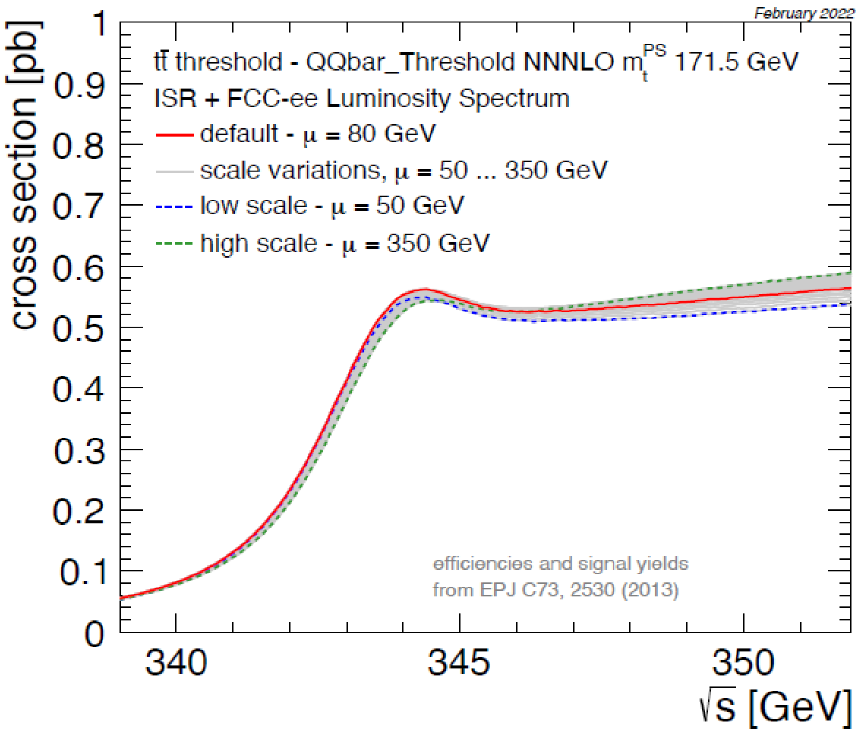
Boughezal, Mereghetti, FP 2106.05337



A. Greljo et al., arXiv:2104.02723

F. Simon, EF03

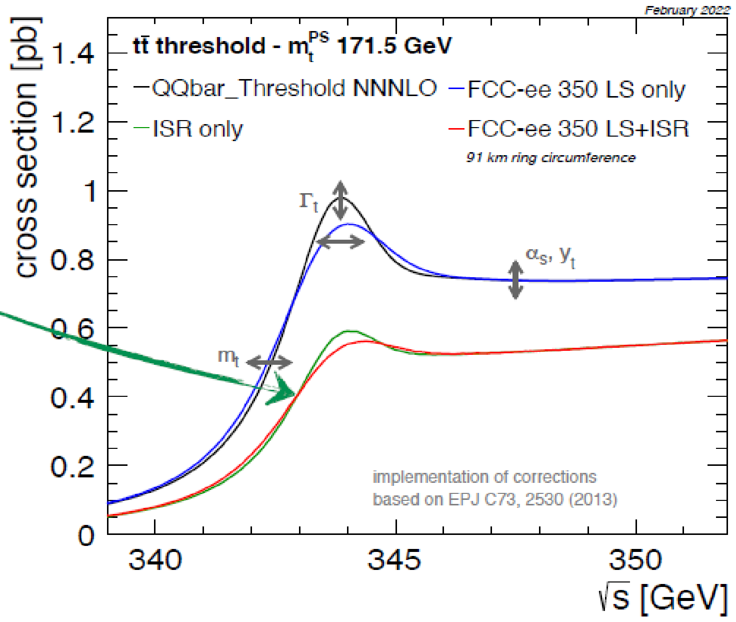
QCD theory = the key factor in $t\bar{t}$ threshold scans at FCC-ee



- QCD scale uncertainties highly relevant.
- Also need to calculate other effects, such as ISR, to the required precision!

the step from black to green

[only approximate in current experimental studies]



δm_t^{PS} [MeV]	ILC	CLIC	FCC-ee
$\mathcal{L}[\mathrm{fb}^{-1}]$	200	100 [200]	200
Statistical uncertainty	10	20 [13]	9
Theoretical uncertainty (QCD)		40 – 45	
Parametric uncertainty α_s	26	26	3.2
Parametric uncertainty y_t (HL-LHC)		5	
Non-resonant contributions		< 40	
Experimental systematic uncertainty	15 – 30		11 – 20
Total uncertainty		40 – 75	

Multi-loop revolution in perturbative QCD drives critical advancements in many areas

NNLO QCD + NLO EW predictions are now a standard for many LHC processes

N3LO is becoming available and will be in [high] demand in the HL-LHC era

2022 Les Houches wish list for PQCD calculations for hadron colliders

TABLE IV. Summary of the LesHouches precision wishlist for hadron colliders [545]. HTL stands for calculations in heavy top limit, VBF* stands for structure function approximation.

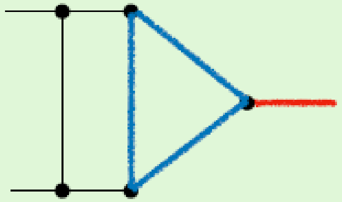
process	known	desired
$pp \to H$	$\mathrm{N^3LO_{HTL}}$, $\mathrm{NNLO^{(t)}_{QCD}}$, $\mathrm{N^{(1,1)}LO^{(HTL)}_{QCD\otimes EW}}$	$\mathrm{N^4LO_{HTL}}$ (incl.), $\mathrm{NNLO^{(b,c)}_{QCD}}$
$pp \to H+j$	$\mathrm{NNLO_{HTL}}$, $\mathrm{NLO_{QCD}}$, $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$	$\mathrm{NNLO_{HTL}} \otimes \mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to H+2j$	$\mathrm{NLO_{HTL}} \otimes \mathrm{LO_{QCD}}$ $\mathrm{N^3LO^{(VBF^*)}_{QCD}}$ (incl.), $\mathrm{NNLO^{(VBF^*)}_{QCD}}$, $\mathrm{NLO^{(VBF)}_{EW}}$	$\mathrm{NNLO_{HTL}} \otimes \mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$, $\mathrm{NNLO^{(VBF)}_{QCD}}$
$pp \to H+3j$	$\mathrm{NLO_{HTL}}$, $\mathrm{NLO^{(VBF)}_{QCD}}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to VH$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$, $\mathrm{NLO^{(t,b)}_{gg\to HZ}}$	
$pp \to VH+j$	$\mathrm{NNLO_{QCD}}$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to HH$	$\mathrm{N^3LO_{HTL}} \otimes \mathrm{NLO_{QCD}}$	$\mathrm{NLO_{EW}}$
$pp \to HHH$	$\mathrm{NNLO_{HTL}}$	
$pp \to H+t\bar{t}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$, $\mathrm{NNLO_{QCD}}$ (off-diag.)	$\mathrm{NNLO_{QCD}}$
$pp \to H+t/\bar{t}$	$\mathrm{NLO_{QCD}}$	$\mathrm{NNLO_{QCD}}$, $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to V$	$\mathrm{N^3LO_{QCD}}$, $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$, $\mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}} + \mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$, $\mathrm{N^2LO_{EW}}$
$pp \to VV'$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$, $+\mathrm{NLO_{QCD}}$ (gg)	$\mathrm{NLO_{QCD}}$ (gg,massive loops)
$pp \to V+j$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$	hadronic decays
$pp \to V+2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$, $\mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$
$pp \to V+b\bar{b}$	$\mathrm{NLO_{QCD}}$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to VV'+1j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$
$pp \to VV'+2j$	$\mathrm{NLO_{QCD}}$ (QCD), $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW)	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to W^+W^+ + 2j$	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to W^+W^- + 2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	
$pp \to W^+Z + 2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	
$pp \to ZZ + 2j$	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to VV'V''$	$\mathrm{NLO_{QCD}}$, $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to W^{\pm}W^+W^-$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to \gamma\gamma$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}}$
$pp \to \gamma + j$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}}$
$pp \to \gamma\gamma + j$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$, $+\mathrm{NLO_{QCD}}$ (gg channel)	
$pp \to \gamma\gamma\gamma$	$\mathrm{NNLO_{QCD}}$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to 2$ jets	$\mathrm{NNLO_{QCD}}$, $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to 3$ jets	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to t\bar{t}$	$\mathrm{NNLO_{QCD}}$ (w/ decays)+ $\mathrm{NLO_{EW}}$ (w/o decays) $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays, off-shell) $\mathrm{NNLO_{QCD}}$	$\mathrm{N^3LO_{QCD}}$
$pp \to t\bar{t}+j$	$\mathrm{NLO_{QCD}}$ (w/ decays, off-shell) $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)
$pp \to t\bar{t}+2j$	$\mathrm{NLO_{QCD}}$ (w/o decays)	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)
$pp \to t\bar{t}+Z$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/o decays) $\mathrm{NLO_{QCD}}$ (w/ decays, off-shell)	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)
$pp \to t\bar{t}+W$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays, off-shell)	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)
$pp \to t/\bar{t}$	$\mathrm{NNLO_{QCD}}$*(w/ decays) $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)
$pp \to tZj$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/o decays)

[545] A. Huss, J. Huston, S. Jones, and M. Pellen, "Report on the standard model precision wishlist,". To appear in Les Houches 2021: Physics at TeV Colliders.

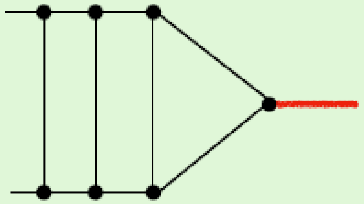
The multi-loop frontier

F. Maltoni, TF06+07

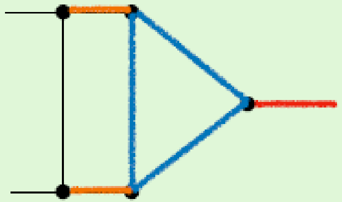
DONE



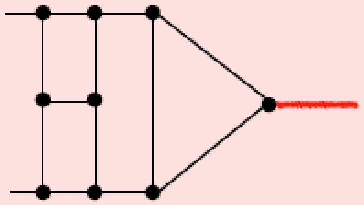
H,Z,W at $N2LO_{QCD}$



H,Z,W at N3LO



H,Z,W at $NLO2_{EWxQCD}$



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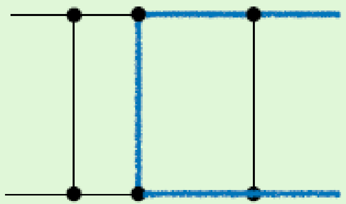
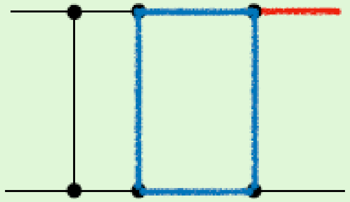
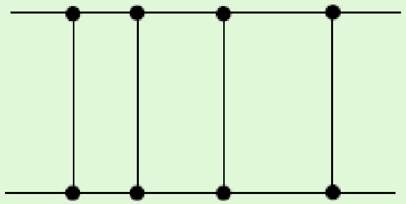


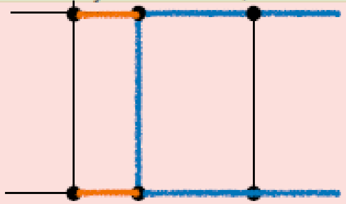
tt at $N2LO_{QCD}$



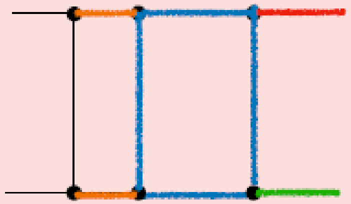
H+j at NLO_{QCD}



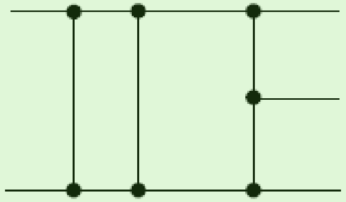
2j at $N3LO_{QCD}$



tt at $NLO2_{EWxQCD}$

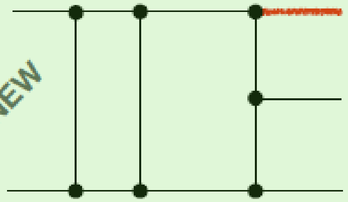


ZH at $N2LO_{EW}$

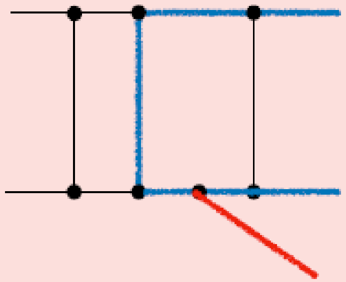


3j at $N2LO_{QCD}$

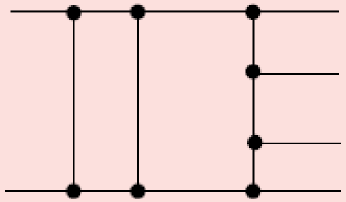
NEW



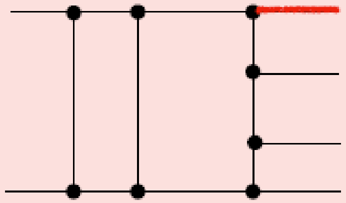
Vbb at $N2LO_{QCD}$



ttH at $N2LO_{QCD}$



4j at $N2LO_{QCD}$



V+3j at $N2LO_{QCD}$

As of 22 July 2022.
FAST MOVING FRONTIER

* The more # of loops/legs/scales (colors) the more difficult.
* Only Z,W,H 2 to 1 production known at N3LO
* EWxQCD corrections very limited
* EW N2LO still to be explored
* Need a subtraction method to turn to IR safe observables

TO DO

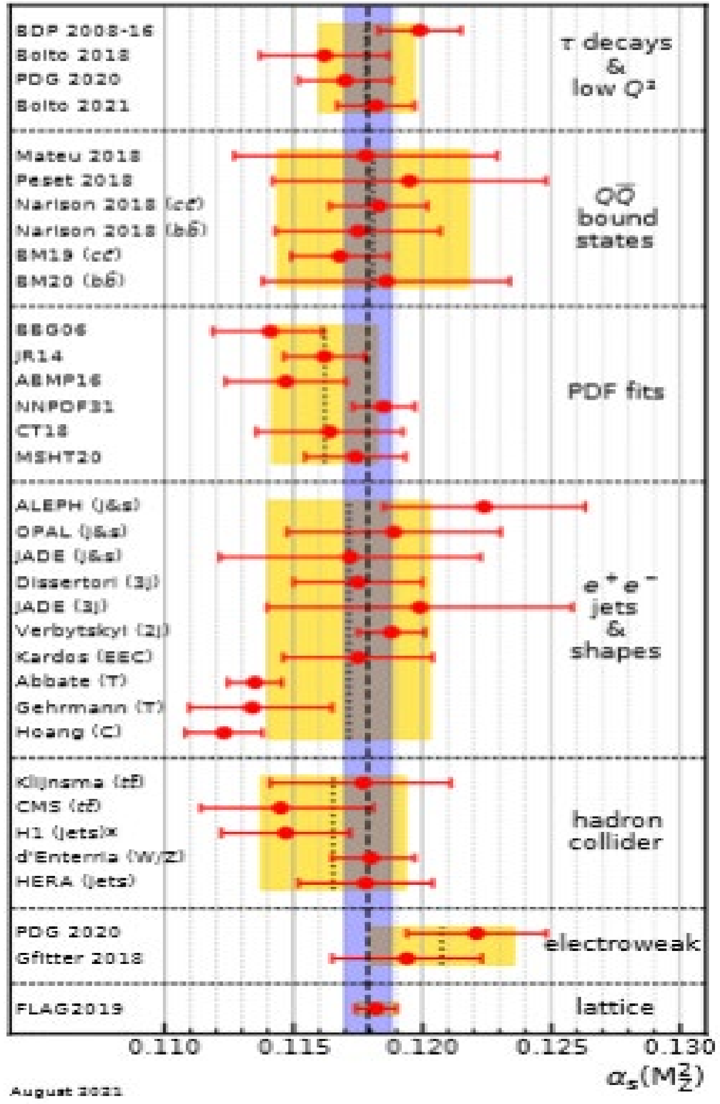
QCD coupling strength $\alpha_s(M_Z)$ is the least known coupling of the Standard Model. Even gravity is known better. Yet, α_s controls accuracy of many collider measurements.

Future measurements of the QCD coupling

individual α_s measurements can reach precision of $\sim 0.1\%$

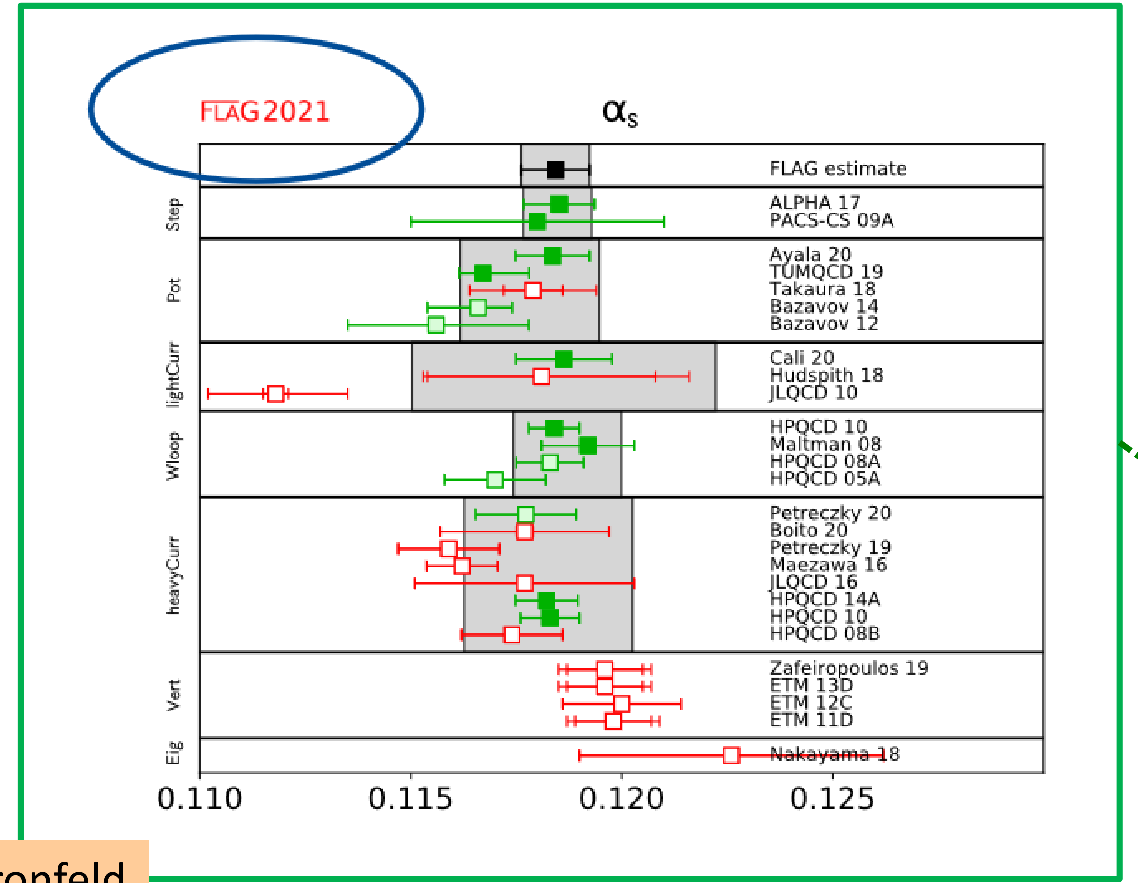
and symbols: CIPT='contour-improved perturbation theory', FOPT='fixed-order perturbation theory', NP='nonperturbative QCD', SF='structure functions', PS='Monte Carlo parton shower'.

Method	Relative $\alpha_s m Z$ uncertainty: Current theory & exp. uncertainties sources	Relative $\alpha_s m Z$ uncertainty: 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^{3}LO CIPT vs. FOPT diffs. Limited τ spectral data	< 1.% Add N^{4}LO terms. Solve CIPT–FOPT diffs. Improved τ spectral functions at Belle II
(3) $Q\bar{Q}$ 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^{3}LO fits. Add new SF fits: $F_2^{p,d}$, g_i (EIC) Better corr. matrices, sampling of PDF solutions. More PDF data (EIC/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^{3}LL, power corrections Improved NP corrs. via: NNLL PS, grooming New improved data at B factories (FCC-ee)
(6) Electroweak fits	2.3% N^{3}LO truncation Small LEP+SLD datasets	($\approx$ 0.1%) N^{4}LO, 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^{3}LO+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%)

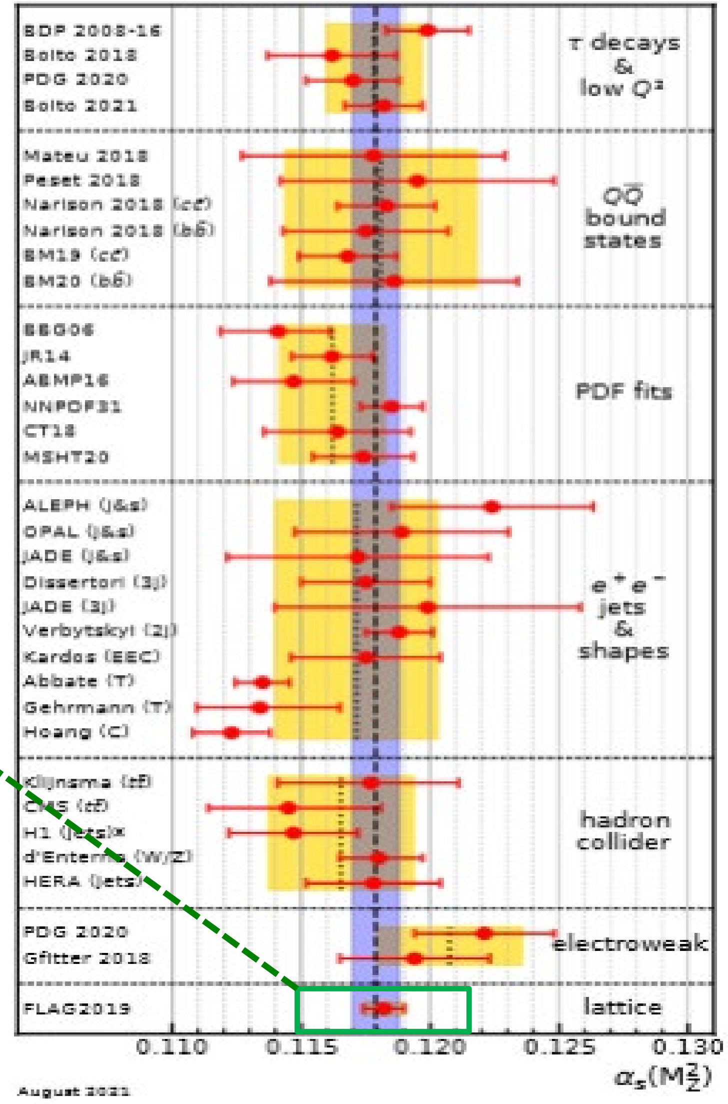


D. d'Enterria et al., EF QCD, arXiv:2203.08271

Lattice QCD & world-average α_s combination



A. Kronfeld



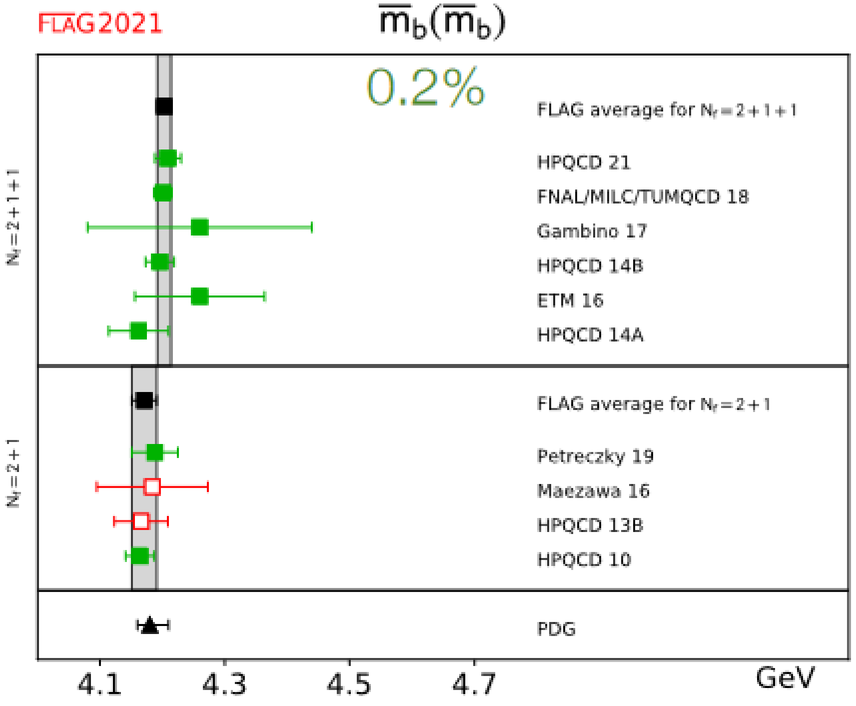
Lattice determinations of α_s in multiple channels are projected to be [far] more precise than many experiments. Several challenges with combining the eclectic α_s inputs with the current procedure.

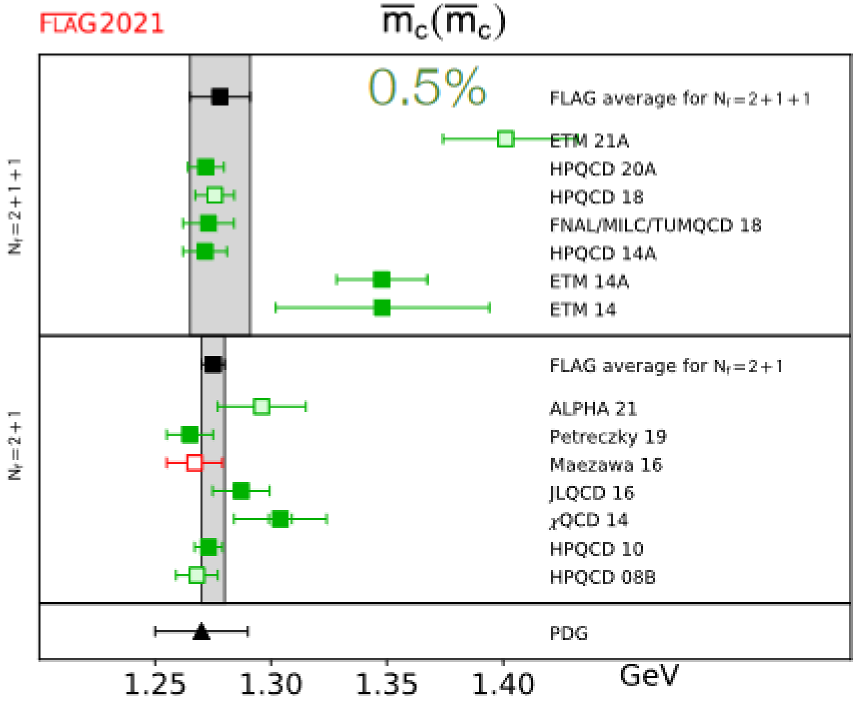
Time to rethink how the world-average α_s combination is performed?

Heavy-quark masses

A. Kronfeld

- Flavor Lattice Averaging Group (FLAG), arXiv:2111.09849.





- Green passes all quality criteria; filled enters average (open superseded).

In m_c, m_b calculations, lattice QCD already surpasses the PDG average in accuracy

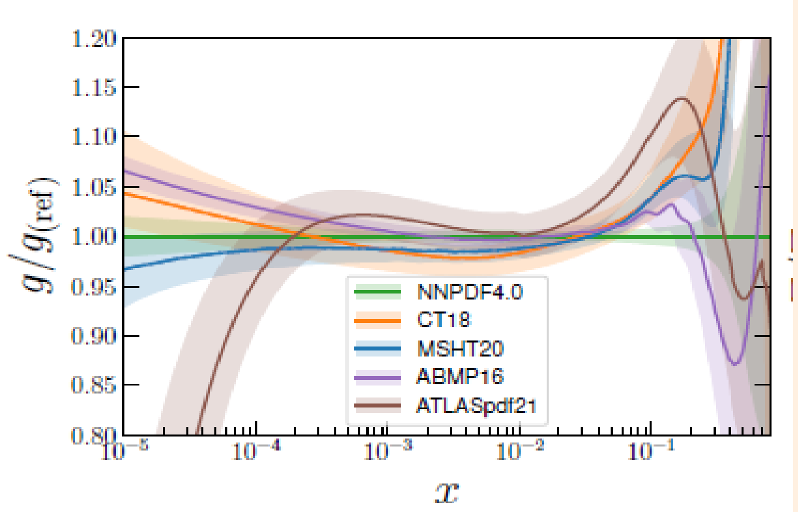
Precision **p**arton **d**istribution **f**unction**s** for (N)NNLO calculations are obtained in versatile global analyses, with lattice QCD providing increasingly valuable inputs

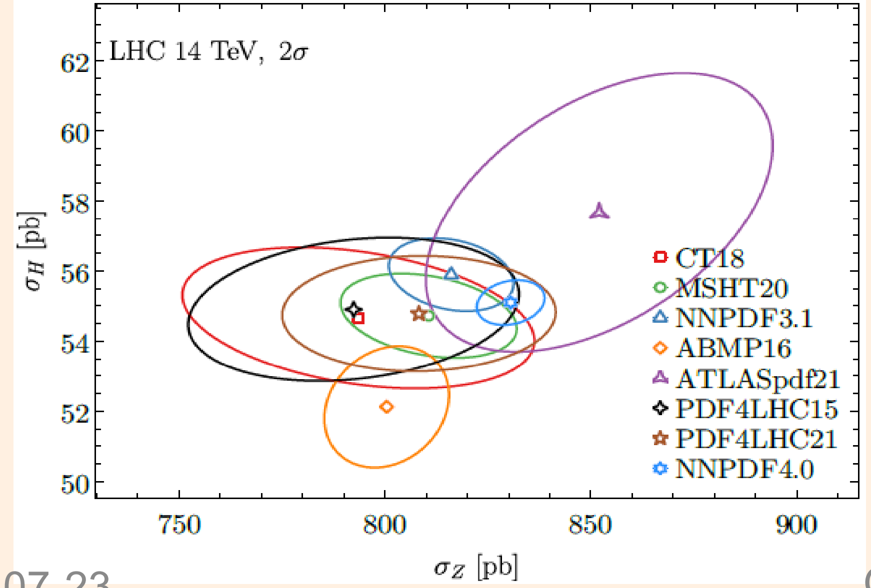
Progress in PDF analysis

K. Xie, EF QCD

The current status

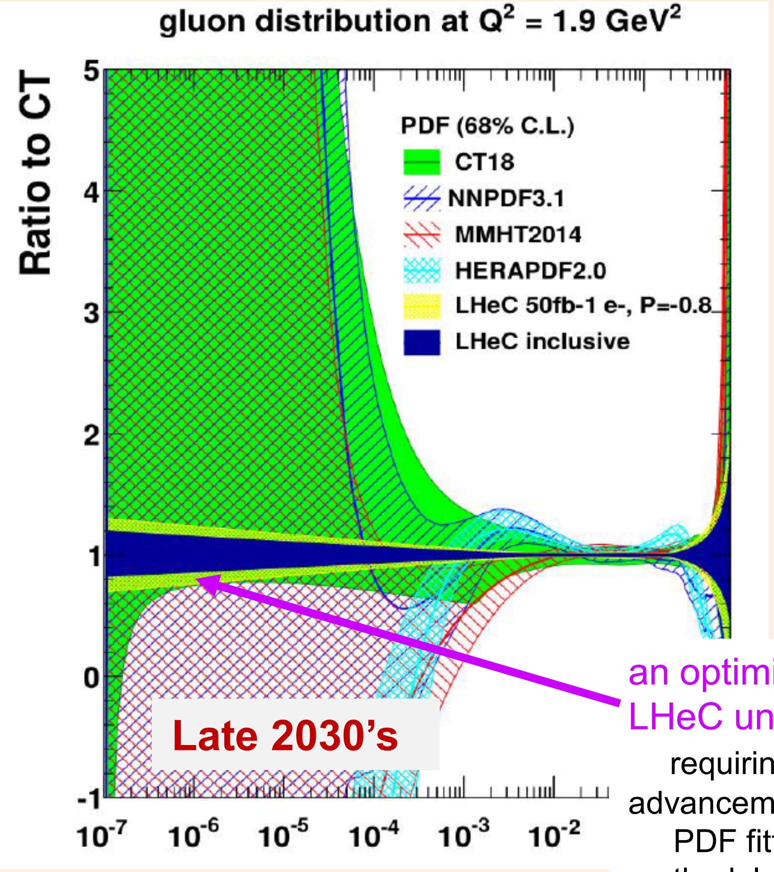
2022





S. Amoroso *et al.*, "Snowmass 2021 whitepaper: Proton structure at the precision frontier," arXiv:2203.13923 [hep-ph].

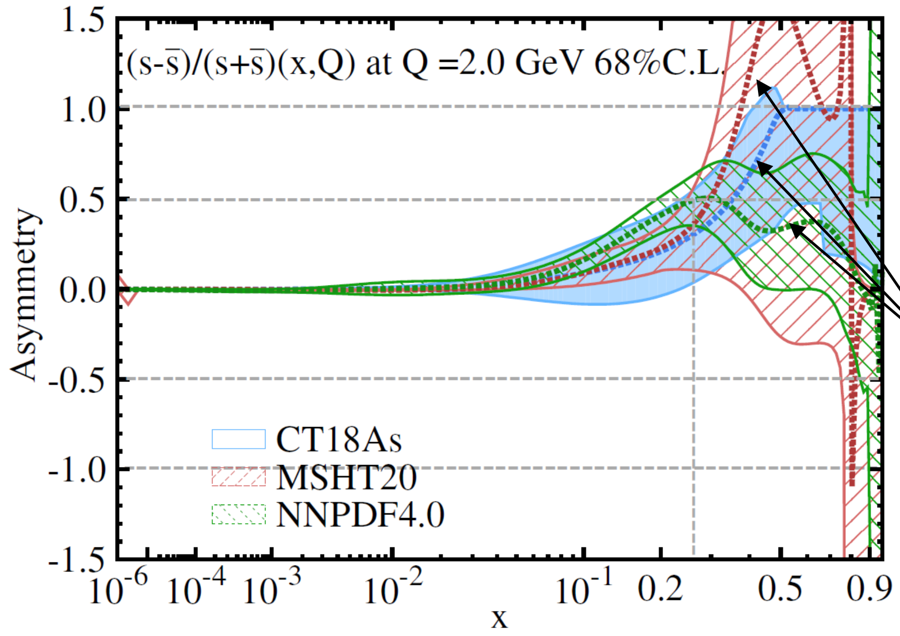
…and future prospects



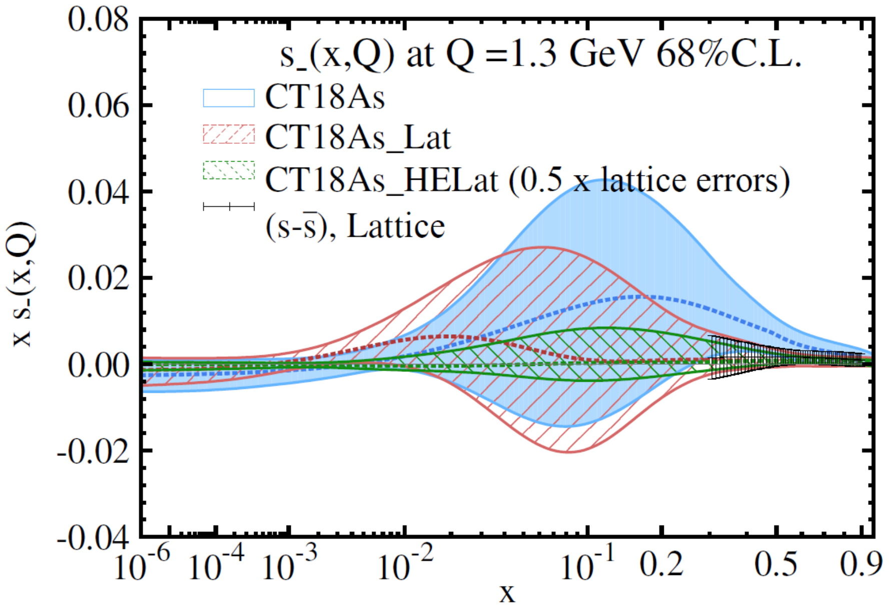
an optimistic post-LHeC uncertainty,
requiring all advancements in the PDF fitting methodology

Lattice QCD for unpolarized PDFs

- Precise pheno PDFs are used to calibrate lattice PDF calculations
- In turn, lattice QCD can constrain PDFs (subleading, polarized, meson, TMDs, GPDs,…) that are difficult to access in experiments
- Example: the strangeness asymmetry $s(x,Q) - \bar{s}(x,Q)$ at $x > 0.2$ is difficult to measure (left), but can be predicted in lattice QCD (right)



differences reflect the pulls of LHC and other experiments



T.-J. Hou et al., arXiv: 2204.07944

New DIS and forward physics experiments that run **concurrently** with, or after the HL-LHC, create a strong synergistic effect in both SM and BSM studies

Electron-Ion Collider

R. Abdul Khalek *et al.*, "Snowmass 2021 White Paper: Electron Ion Collider for High Energy Physics," in *2022 Snowmass Summer Study*. 3, 2022. arXiv:2203.13199 [hep-ph].

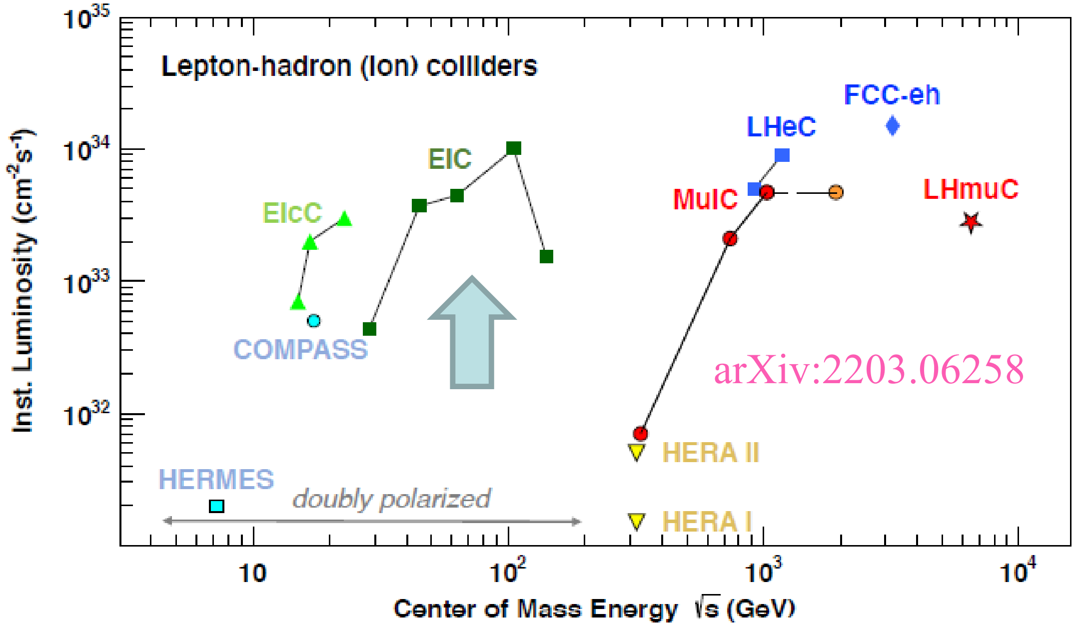
S. V. Chekanov and S. Magill, "Some aspects of impact of the Electron Ion Collider on particle physics at the Energy Frontier," in *2022 Snowmass Summer Study*. 2, 2022. arXiv:2202.11529

the only new large-scale accelerator facility planned for construction in US in the next few decades

polarized electrons with polarized beams of proton and light ions

many opportunities for QCD and beyond:

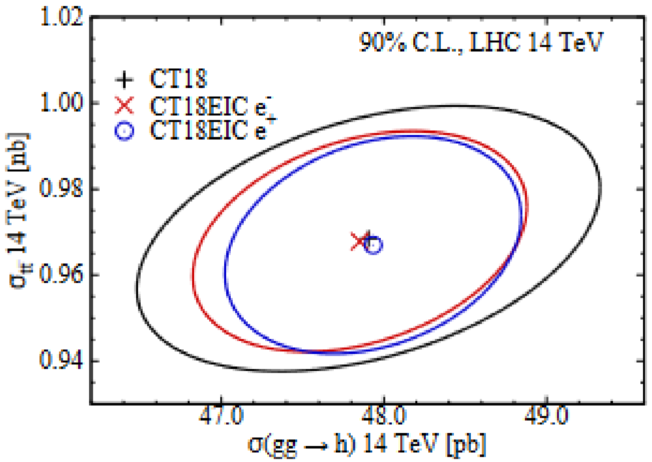
- Precision 3-dimensional tomography of hadrons and nuclei
- Physics of QCD jets
- Physics of heavy flavors
- Partonic saturation
- Electroweak and beyond standard model physics



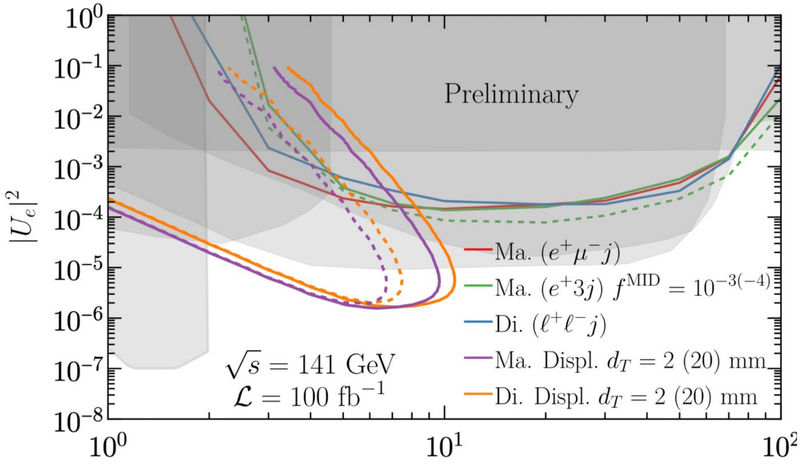
The EIC will strengthen the physics reach of the HL-LHC

Electron-Ion Collider: a wealth of HEP-focused studies

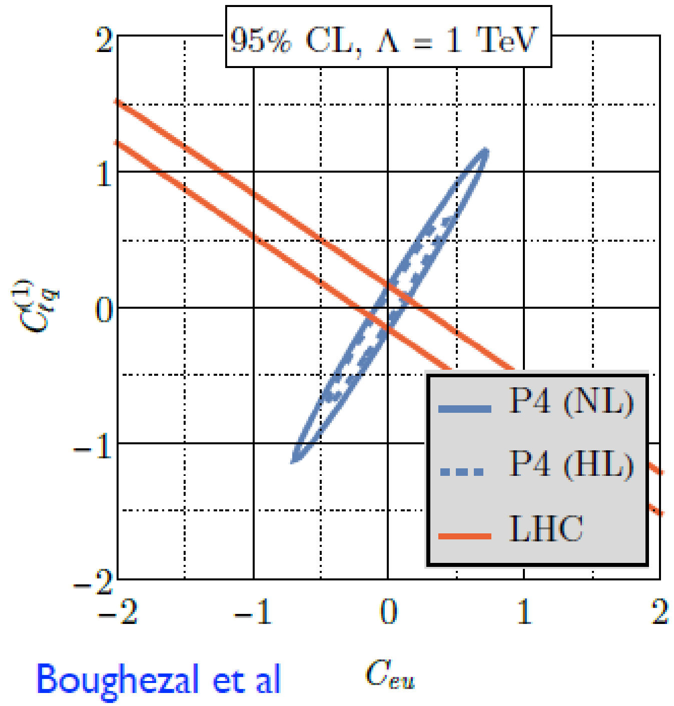
PDFs: arXiv:2103.05419



heavy neutral lepton searches arXiv: 2203.06705

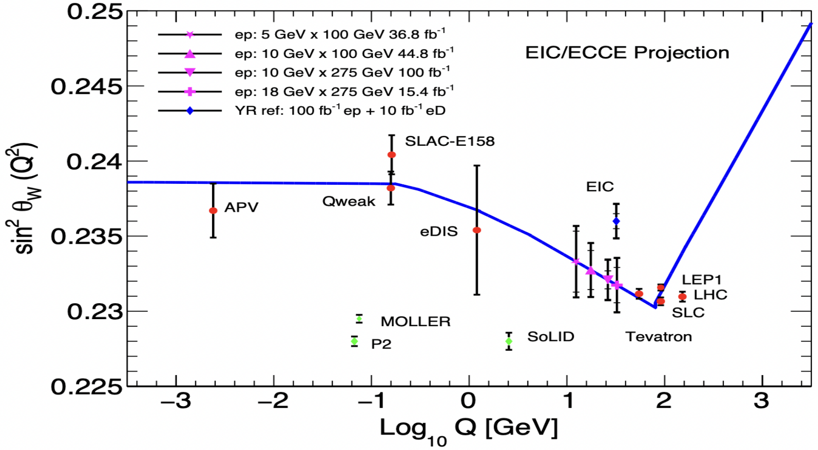


SMEFT Wilson coefficients



Boughezal et al
2004.00748, 2204.07557

weak mixing angle arXiv: 2203.13199



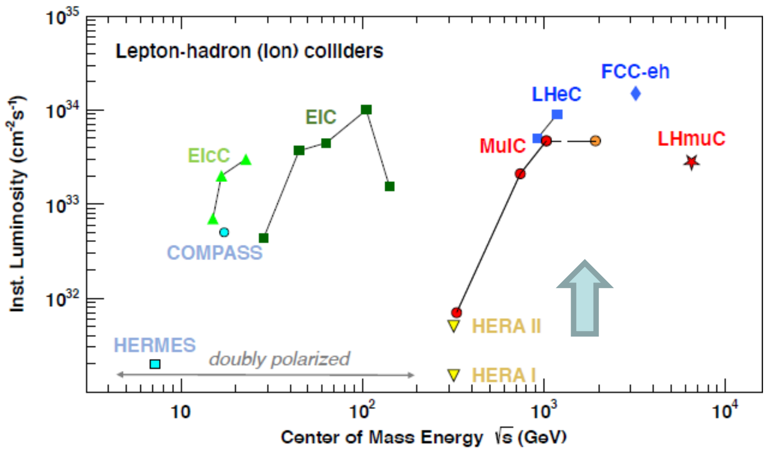
	EIC	LHC
$\lvert c_u^{XX} - c_u^{YY}\rvert$	0.37	15
$\lvert c_u^{XY}\rvert$	0.13	2.7
$\lvert c_u^{XZ}\rvert$	0.11	7.3
$\lvert c_u^{YZ}\rvert$	0.12	7.1
$\lvert a_{Su}^{(5)TXX} - a_{Su}^{(5)TYY}\rvert$	2.3	0.015
$\lvert a_{Su}^{(5)TXY}\rvert$	0.34	0.0027
$\lvert a_{Su}^{(5)TXZ}\rvert$	0.13	0.0072
$\lvert a_{Su}^{(5)TYZ}\rvert$	0.12	0.0070

Lorentz/CPT violations

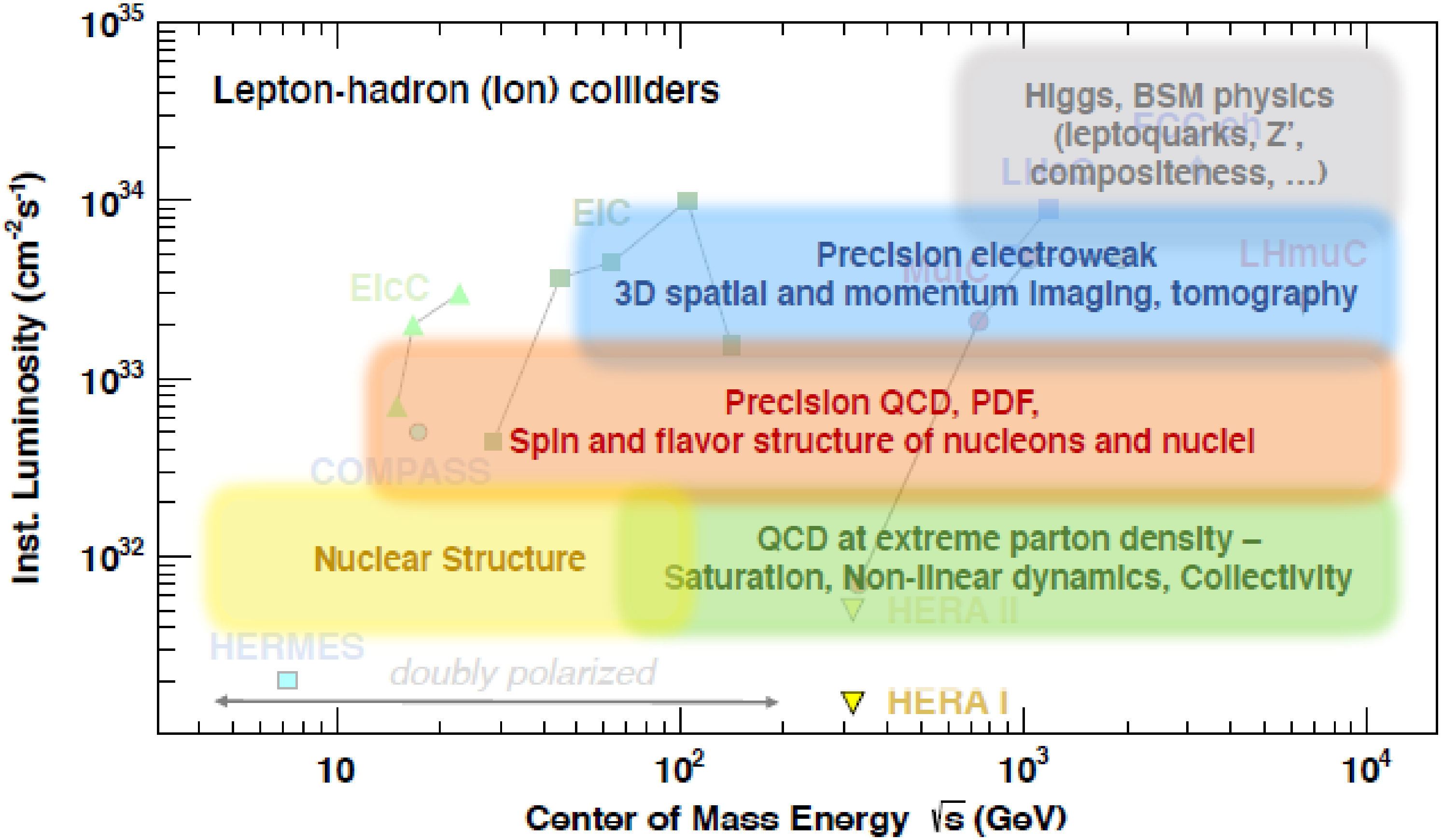
A. R. Vieira et al., 1911.04002

The Muon-Ion Collider, Large Hadron Electron Collider, FCC-eh

D. Acosta et al., "The Potential of a TeV-Scale Muon-Ion Collider," arXiv:2203.06258 [hep-ph]
LHeC, FCC-he Study Group, arXiv:1206.2913, 2007.14491



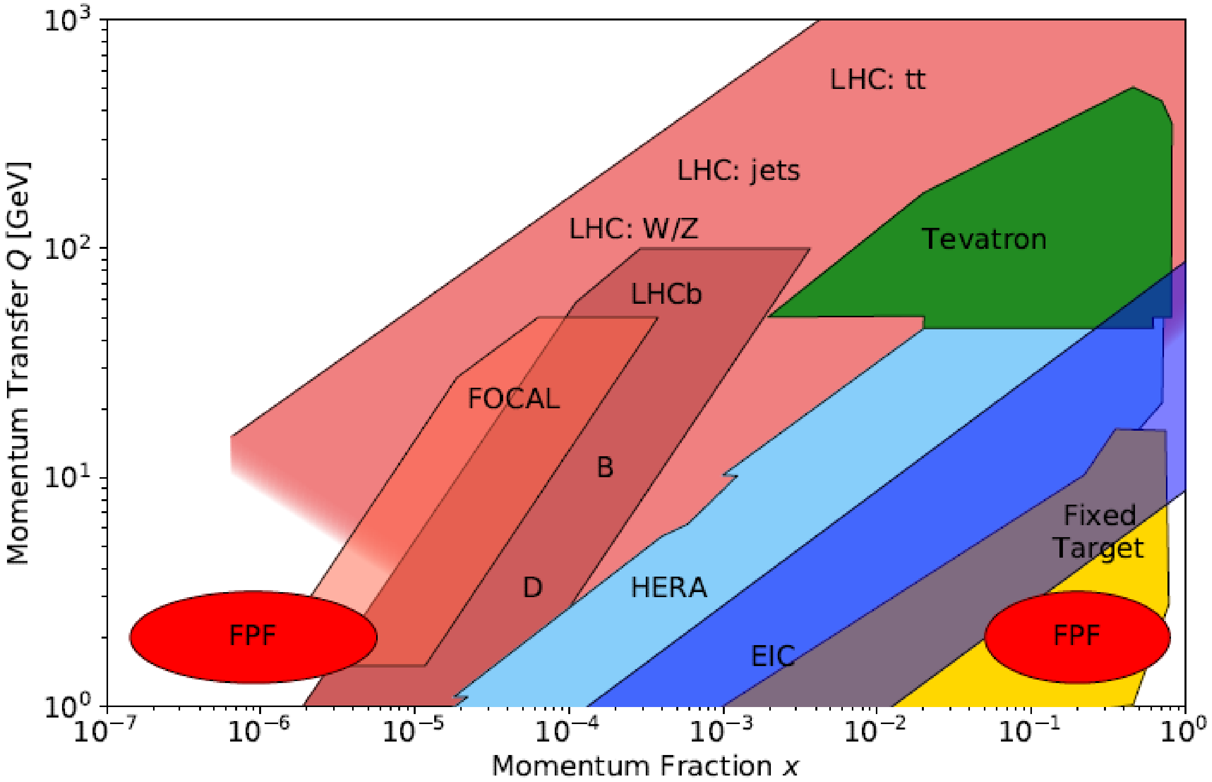
Exceptional machines for BSM discoveries, Higgs physics such as measurement of $\kappa_{H\to c\bar{c}}$, and SM tests at (sub)percent precision

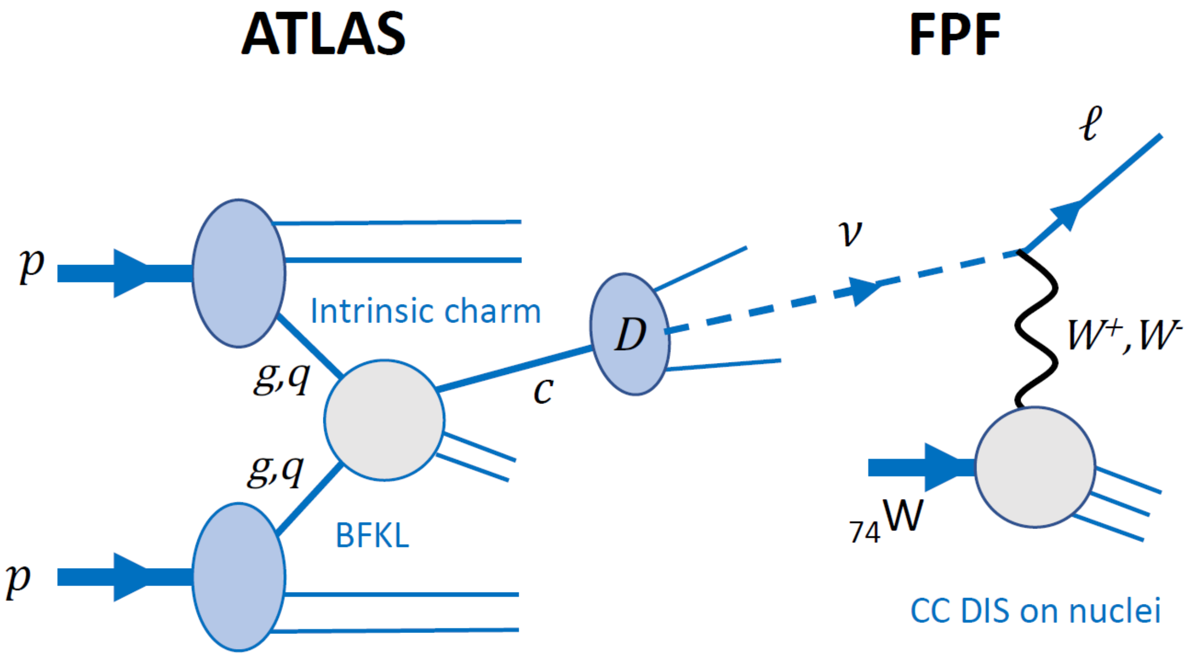


M. H. Reno, EF QCD

The Forward Physics Facility at CERN

L. A. Anchordoqui *et al.*, "The Forward Physics Facility: Sites, Experiments, and Physics Potential," arXiv:2109.10905 [hep-ph].
J. L. Feng *et al.*, "The Forward Physics Facility at the High-Luminosity LHC," arXiv:2203.05090





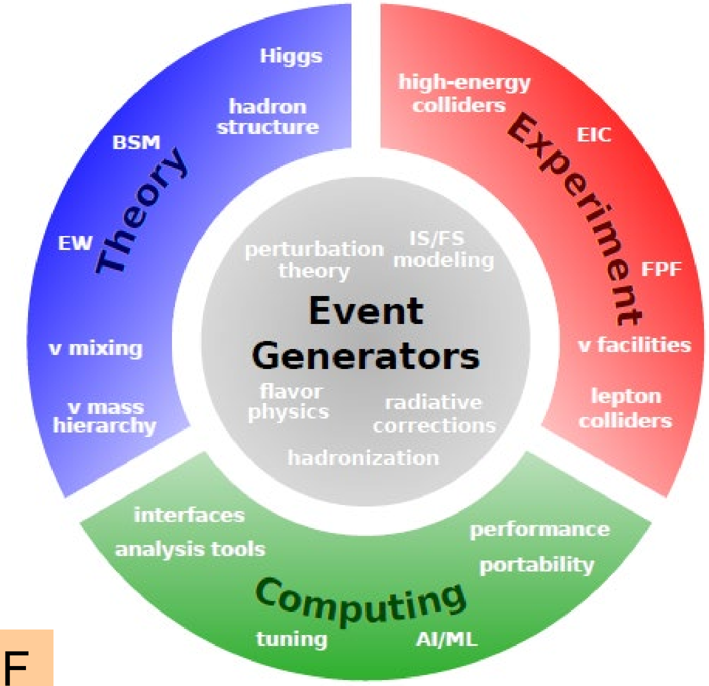
The FPF can clarify multiple aspects of QCD in the new forward region **in coordination** with the HL-LHC and EIC

Progress in QCD increasingly depends on cross-cutting research

Cross-cutting QCD

Many future successes depend on developments at the intersections of high-energy QCD and other domains

- For example, multi-functional QCD event generators play the central role in collider studies

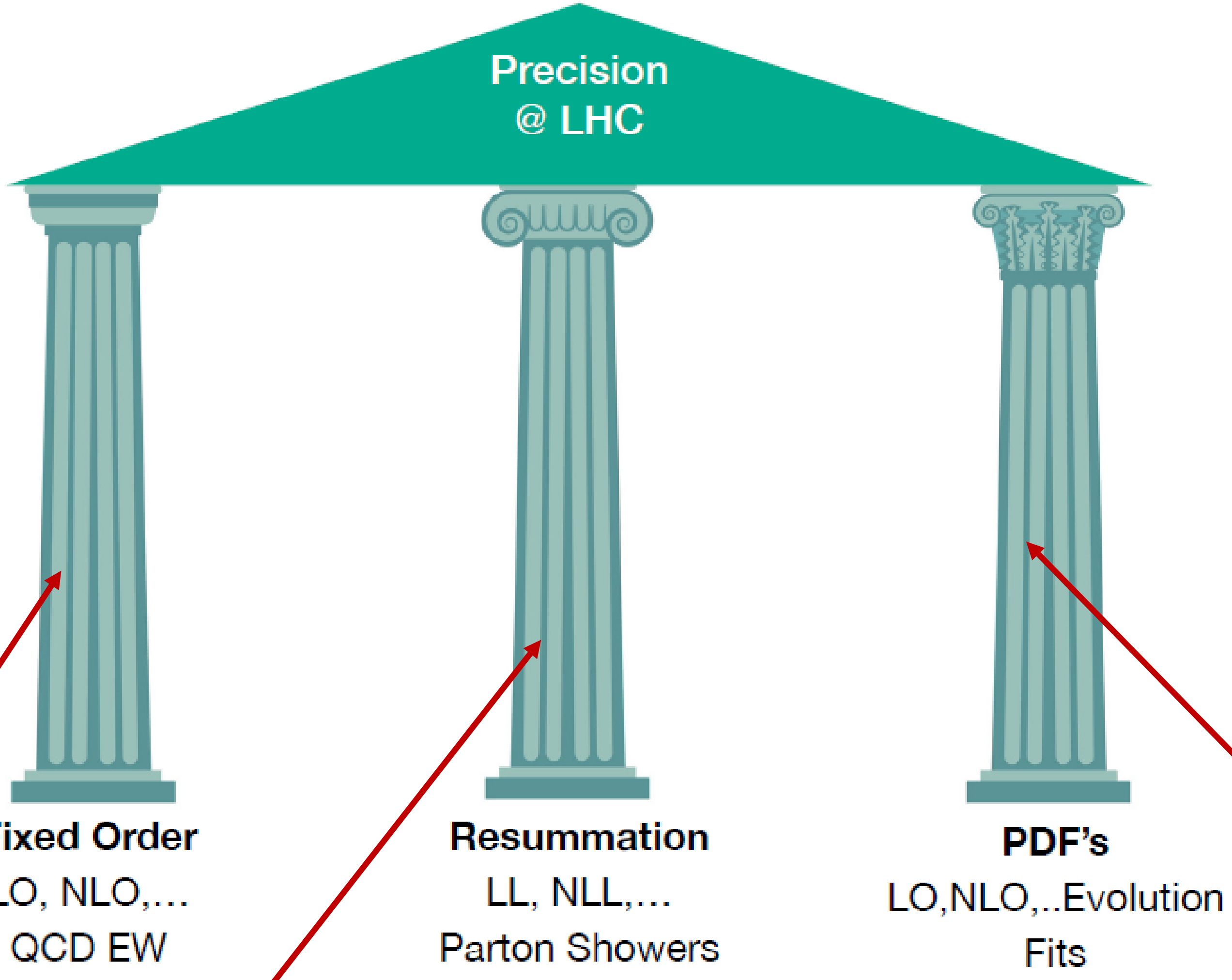


J. Isaacson, EF-TF

- Low-energy QCD facilities will elucidate nonpert. QCD aspects of resummations, jet substructure
- Consistent estimates of systematic uncertainties are indispensable for precision analyses and require experimental-theoretical collaborations

Cross-cutting goals for reaching 1% precision at the HL-LHC

F. Maltoni, TF06+07



- Very fast progress in conceptual as well as technical aspects.
- Tight and consolidated community, with high momentum.
- Considering the status of 20 years ago seems clear that NNLO will be completed and N3LO will start to become available for 2→2 (see 3-loop $q\bar{q} \to \gamma\gamma$ results)
- Mixed QCD-EW being included.

- A variety of approaches available, both analytical and numerical.
- Analytically historically matching the FO accuracy.
- NNLO+PS will be the new standard. (N3LO+PS already being explored)
- Having a NLL and beyond PS, is being explored now. To be seen.
- Not clear whether one can reach 1%.

- Complete N3LO PDF's evolution not available yet.
- PDF determination from fitting large set of data. Final quality depends on measurements.
- Error budget with many sources. MHO uncertainties yet to be included in the final assessment.
- Reaching 1% will be very challenging.
- Room for a breakthrough from lattice.

QCD at 1% accuracy

N2LO and N3LO calculations

Lots of promise in this area

QCD infrastructure for these calculations

Parton showers, fast NxLO interfaces, PDFs, ... must be comparably accurate

representative uncertainty estimates

or The Importance of Being Earnest with Systematic Errors (experiment+theory; traditional or AI/ML)

systemwide processes and standards for accuracy control

This must be a part of the precision-focused community culture

Why QCD?

- Many precision measurements - in Higgs, top, and EWK - are limited by our understanding of QCD
- Completing the HL-LHC & EIC programs - together with a Higgs factory - will provide unprecedented levels of precision in QCD impacting most areas in the Energy Frontier

Many thanks to the participants of the Seattle meeting and EF TGs for their strong interest in the topic.