QCD systematics for high-Q EW/Higgs measurements at FCC-hh

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[unless stated otherwise: results taken from MLM et al., arXiv:1606.09408-1607.01831]
$\textit{FCC: a wide kinematic coverage}$

- **Boosted Higgs**
  - Solid: $gg \rightarrow H$
  - Dashes: $ttH$
  - Short dash: VBF
  - Dotdash: WH

- **Top**
  - $\sigma(M_W > M_{\text{min}})$ (pb)
  - $|\eta_1 - \eta_d| < 2$

- **DY**
  - $\sigma(p_T(W) > p_T_{\text{min}})$ (pb)

- **Jets**
  - $|\eta_m| < 2.5$

- **VBS**
  - $N(M_{WW} > M_{WW}^\text{min})$ [events]

$\bullet$ FCC-hh: thorough investigation at high-Q
$\bullet$ $Q \sim 10$ TeV will be explored
QCD at high-\(Q\)

1. In general, high-\(Q\) region very clean w.r.t. QCD
   - \(\Lambda_{\text{QCD}}/Q \ll 1\) → robust first principle calculations
   - \(\alpha_s(Q) \ll 1\) → good perturbative convergence
   - Can [to some extent] afford to to go away from region contaminated by soft/physics → robust computational frameworks

2. Very different (theory) systematics w.r.t. physics EW scale
   - Very large \(Q\): measurable rate, but not large statistics → ubiquitous sub-percent precision not required
   - Still, sizeable source of uncertainties. To some extent, different from uncertainty at the EW scale
   - In the following: some illustrative examples (not a comprehensive review)
**Input parameters: PDFs**

**FCC PDFs: generic**
- A major problem for precision physics at FCC-hh: small-\(x\) PDFs
- Can systematically affect physics at the EW scale

**FCC PDFs: large Q**
- This issue is not there at very large \(Q\) (central production…)
- Intermediate \(Q \sim \text{TeV region}@\text{FCC}_{100} \leftrightarrow \text{EW region}@\text{LHC}_{14}\). Not affected by small-\(x\) physics

*One caveat: \(N^3\text{LO}\) evolution and small-\(x\). Should be clarified soon [this year?]*
Main issue: large-\(x\) PDFs

- By FCC: "collider-only" sets, minimal contamination from higher twist, nuclear effects...
- Resummation effects: should be subdominant →
- At large Q: mostly "experimental" issue, i.e. data to contain large-\(x\) region

![PDF Luminosity Ratio](image)

- Still good control in the multi-TeV region
- Loss of information at large \(x\), \(M > 10\text{-}20\) TeV
Main issue: large-\(x\) PDFs

- Photon PDF: progress w.r.t. FCC report (ingenuity still plays a major role)

rule-of-thumb:
10 TeV@FCC100
\sim
1 TeV@LHC14

\[ \text{[Manohar et al. (2017)]} \]
Large-\(x\) from collider data

- It is now established that collider data (top, jet, \(V\ldots\)) can significantly reduce large-\(x\) uncertainties
- HL-LHC: factor 2 or more in the TeV region
- Although no comprehensive dedicated FCC-study: reasonable to assume the same in the multi-TeV region
Higher precision for standard candles?

Extracting PDFs from collider data may benefit from higher theoretical prediction $\rightarrow N^3\text{LO}$ for standard candles?

- $N^3\text{LO}$ evolution almost available ($\rightarrow \text{small-}x$ issues?)
- $N^3\text{LO}$ for color singlets within reach (see C. Duhr’s talk)
- $N^3\text{LO}$ for tops, jets: serious theoretical challenges
  - Very difficult technical calculations
  - Conceptual issues, may require going beyond “standard” approaches to perturbative QCD
    - $\bar{t}t@N^3\text{LO}: \delta\sigma \neq R+V, \text{non-analytic } |\alpha_s| \text{ terms}$ [see M. Beneke, Ruiz-Fermenia 1606.02434, Melnikov, Vainshtein, Voloshin 1402.5690]
    - Jets: factorisation violation [see e.g. Catani, de Florian, Rodrigo 1112.4405]

Crucial also for “low-Q” EW physics
PDFs from collider: the usual issue

• Large-\(x\) PDFs constrained by high-\(Q\) data → "Q1: how can you be sure that you are not fitting new physics away into the PDFs?"

• The standard answer: consistency checks, closure tests etc…

• Here situation slightly worse: very little info from other sources (self-consistency not as powerful)

• Crucial to over-constrain, use rapidity/asymmetries etc.

• Recently: first quantitative investigations of Q1

\[ g(x,Q)/g(x,Q)_{[SM]} \]

• NNPDF team: fit EFT and PDFs at the same time, study statistical indicators…

• Very relevant for PDFs vs BSM issue, a lot to be explored
Another strategy: PDFs from lattice

- Recent progress in obtaining PDFs from lattice
- In a nutshell: find $\sigma$ such that
  \begin{itemize}
  \item $a)$ it obeys a factorisation theorem
  \item $b)$ it can be computed on the lattice $\rightarrow \text{``lattice experimental data'', on a par with experimental data}$
  \end{itemize}

$$\sigma = \hat{\sigma} \otimes f$$

Figure 5.5. $S_2$ vs. $S_5$: $S_2$ results are more conservative than the $S_5$ ones, showing also a small shift of the replica 0 towards the light-cone PDFs. Overall, $S_2$ results are compatible with NNPDF3.1

Figure 5.6. $S_3$ vs. $S_6$: $S_3$ results are extremely conservative, while those for $S_6$ do not show a qualitative difference with respect to $S_4$ and $S_5$.

[Cichy, Del Debbio, Giani (2019)]

Lattice proof-of-concept vs NNPDF
Parton distributions and lattice QCD calculations: a community white paper

Huey-Wen Lin1,2, Emanuele R. Nocera3,4, Fred Olness5, Kostas Orginos6,7, Juan Rojo8,9 (editors), Alberto Accardi10,11, Constantia Alexandrou11,12, Alessandro Bacchetta13, Giuseppe Bozzi13, Jiunn-Wei Chen14, Sara Collins15, Amanda Cooper-Sarkar16, Martha Constantinou17, Luigi Del Debbio18, Michael Engelhardt18, Jeremy Green19, Rajan Gupta20, Lucian A. Harland-Lang21,22, Tomomi Ishikawa22, Aleksander Kusina24, Keh-Fei Liu25, Simonetta Liuti26,27, Christopher Monahan28, Pavel Nadolsky9, Jian-Wei Qiu1, Ingo Schienbein18, Gerrit Schierholz29, Robert S. Thorne30, Werner Vogelsang31, Hartmut Wittig31, C.-P. Yuan3, and James Zanotti12

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For high-Q processes: HOW EASY IS TO CONTROL THE $X\rightarrow 1$ REGION ON THE LATTICE (resonances…)?

Does not need to happen tomorrow…

Parton Distributions and Lattice Calculations in the LHC era
(PDFLattice 2017)
High-Q: the top/EW content of the proton

Very high-Q: top/EW bosons generated by SM collinear evolution → modified QCD evolution [Bauer & Webber (2018-19)]

- SM is chiral: L/R difference
- L PDFs: 5-10% correction at 10 TeV
- Sizeable $W_1$ content of the proton
- Isospin restoration
- Higher log: small → robust

**Ready for thorough phenomenological studies**
High-Q: the top/EW content of the proton

Large-Q top-induced processes: resum $\ln(Q^2/m_t^2)$

- Order-of-magnitude estimate: $m_b/m_H \sim 4.5 \text{ TeV}/m_t$
- Top becomes effectively massless at very high-scales → matching is crucial
- Investigating matching/"massive" PDFs: interesting non-trivial problem in QFT…
### Parameters: $\alpha_s$

**Current status [PDG2019]**

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<td>hadronic decays, global fits $\rightarrow$ potential to reach 0.15%. QCD-robust, but some model dependence</td>
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<td>$e^+e^-$, event shapes/jet rates $\rightarrow$ good potential, but remember the LEP lesson</td>
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| Must understand better underlying theory (NP corrections, formally subleading terms…)

**Prospects**

- Hadron collider observables / PDF fits $\rightarrow$ very high accuracy, but same problems as PDF fits (low $Q$ contamination, theory uncertainties, correlations with PDFs)

- Lattice very robust. Most robust determination $\rightarrow$ new approach. Assuming computer improvements $\rightarrow$ 0.3%, promising
For instance, the full content of the Minimal Supersymmetric Standard Model (1 adjoint Weyl particles in the spectrum thus contribute to ourselves to asymptotically free theories. Asymptotic freedom is lost for representations respectively, and the modification in the running of can be written for a single Weyl fermion, and (Dirac) fermions, and where representations of the color gauge group. The running of is the number of quark flavours (i.e., , , ) and is modified by a new fermion of mass 500 GeV in various cases of , , , counting . In view of our initial motivation we do not restrict to energies below the masses of the new states. In Fig. 1, we also show how the running decrease by 3.9 (7.4)%, and can flip and asymptotic freedom of .

The purpose of this paper is to argue that hadron colliders, such as the LHC, can be used to measure running EW couplings. In order to measure running EW couplings, we can compare the process should be under good theoretical control, with minimal uncertainties. At the process should have a large cross section to produce events with high momentum-transfer, where the amplitude probes the values of EW couplings at high energy. A transfer, where the amplitude probes the values of EW couplings at high energy. A

Large Q coverage: test running Coupling $\to$ NP in the loops

- Require very good theoretical (and exp) control
- High-mass DY: theoretical uncertainty (see C. Durh's talk), QCD-EW interplay
- $\alpha_s$ in the TeV regime: $R_{3/2}$, higher order corrections (see comment at slide 8)
- Understanding jet dynamics
Jet dynamics

FCC-hh: possible to study jet dynamics through the whole $p_T$ spectrum

- Large-Q: non-standard fragmentation (EW, top, Higgs…) → see e.g. [Bauer & Webber (2018), Tweedie et al (2017-18)]

- Examples:

- flavour creation

- flavour excitation

- gluon splitting

- other

- Would require better pheno understanding, better generators, better calculations…
Intrinsic uncertainties: theory calculations

FCC integral project technical schedule

- Project preparation & administrative processes
- Permis-sions
- Funding strategy
- Funding and in-kind contribution agreements
- Geological investigations, infrastructure detailed design and tendering preparation
- Tunnel, site and technical infrastructure construction
- FCC-ee accelerator R&D and technical design
- FCC-ee detector technical design
- FCC-ee detector construction, installation, commissioning
- Superconducting wire and magnet R&D
- SC wire and 16 T magnet R&D, model magnets, prototypes, preseries
- 16 T dipole magnet series production
- FCC-hh detector R&D, technical design
- FCC-hh detector construction, installation, commissioning
- FCC-hh accelerator construction, installation, commissioning
- FCC-hh accelerator R&D and technical design
- FCC-hh accelerator construction, CE & infrastructure adaptations FCC-hh
- Update Permissions
- Permissions
- 15 years operation
- ~ 25 years operation

FCC Status
Michael Benedikt
CERN, 13 January 2020
Intrinsic uncertainties: theory calculations
**Intrinsic uncertainties: theory calculations**

**FCC integral project technical schedule**

- Natural to expect enormous progress before FCC-hh
  - Most likely, the "issues" I will mention will be considered triviality in the FCC era
  - Still, interesting to see what is needed to get there...

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**G. Salam**
Case study 1: Higgs $p_t$ in $ggF$

- Prototype of loop induced process (so I won’t consider other channels, even if dominant)
- Status today, large-$Q$: NLO, with approximated analytical/exact numerical two-loop amplitude

![Graph showing the transverse momentum distribution of the Higgs boson at the LHC with $p_T = 13$ TeV computed in ref. [6]. The upper panel shows absolute predictions at LO and NLO in the full SM and in the infinite top-mass approximation (EFT). The lower panel shows respective NLO/LO correction factors. The bands indicate theoretical errors of the full SM result due to scale variation.]

NLO: out of reach of “standard” analytic techniques (see C. Duhr’s talk)
Case study 1: Higgs $p_t$ in $ggF$

Lessons learned:

• No full analytic control $\rightarrow$ numerical approach [Jones, Kerner, Luisoni (2018)]. Issue: large logs, numerical stability in the TeV region

• Clever use of hierarchies $\rightarrow$ approximate analytic result [Kudashkin, Melnikov, Tancredi, Wever (2017-18)]. Issue: how to do this systematically?

Recent developments:

• Analytic result as a patch of different series expansion [Frellesvig, Hidding, Maestri, Moriello, Salvatori (2017-18)]. Issue: how does this generalise to multi-scale processes?

• “AN ANALYTIC RESULT IS A RESULT THAT CAN GIVE A NUMBER” E. Remiddi

Open questions:

• Large non-Sudakov (double) logarithms, not well understood [Penin, Melnikov, Liu (2017-2019)]. Crucial to obtain analytic insight from analytic results.
Case study 1: Higgs $p_t$ in ggF

The (likely) biggest uncertainty: top mass scheme

Guidance: bottom effects at LHC14

Same feature appearing in other processes, e.g. HH [Baglio et al (2019)]
Case study 1: Higgs $p_t$ in ggF

The (likely) biggest uncertainty: top mass scheme

• Genuine perturbative correction, little way out → compute higher orders

• Higher orders: highly non-trivial (we can barely do NLO)

• NNLO = fully differential N$^3$LO, with full top mass dependence
  • $2 \rightarrow 2$ @ 3 loops, internal masses. Beyond GPLs, two-variable problem → well beyond current analytic techniques
  • $2 \rightarrow 3$ @ 2 loops, internal masses. Same as above, probably even more complicated?

• Numerical approaches: large logs, stability, many variables…

It will keep us busy for a while, don’t hold your breath…
Case study 2: mixed QCD-EW in the tails

- High-Q: electroweak Sudakov (double) logs $\rightarrow$ enhanced EW corrections
- First approximation: trivial interplay with QCD (fully factorized)
- We may want to go beyond this approximation. Currently: major source of theoretical uncertainty for high $p_T V$ production (DM searches...)
- Tools are becoming available: thorough study of QCDxEW corrections for standard candles within reach (quantify Sudakov...)
Case study 2: mixed QCD-EW in the tails

Giant QCD K-factors and EW corrections: pTV1

- NLO QCD/LO=2-5! ("giant K-factor" [Rubin, Salam, Sapeta, '10])
- at large pTV1:V phase-space is dominated by V+jet (w/ soft V radiation)
  \[ \frac{d\sigma^{V(V)}_j}{d\sigma^{LO}_{VV}} \propto \alpha_s \log^2 \left( \frac{Q^2}{M_W^2} \right) \approx 3 \quad \text{at} \quad Q = 1 \text{ TeV} \]
- NNLO / NLO QCD moderate and NNLO uncert. 5-10%
- NLO EW/LO=-(40-50)%
- Very large difference \( d\sigma_{NLO QCD+EW} \) vs. \( d\sigma_{NLO QCD\times EW} \)
- Problems:
  1. In additive combination dominant Vj topology does not receive any EW corrections
  2. In multiplicative combination EW correction forVV is applied to Vj hard process
- Pragmatic solution: take average as nominal and spread as uncertainty
- Rigorous solution: merge VVj incl. EW corrections with VV retaining NNLO QCD + EW

• First results appearing → thorough phenomenological studies are starting
• Problems are being identified → input for FCC-hh discussion
Conclusions

• FCC-hh offers a unique opportunity to study the multi-TeV region

• Despite high-Q being “clean” w.r.t. QCD, several sources of non-trivial theoretical uncertainty

• High-Q: uncertainties different from EW region $\rightarrow$ different problems, different techniques

• In some cases, way forward is clear. In other not so much (as of now…)

• I presented SOME EXAMPLES of potentially important issue to be addressed. Choice due to time constraints and personal ignorance

• In general: highly non-trivial theoretical problems, that would most likely require developing further our understanding of QFT and collider phenomenology $\rightarrow$ interesting times ahead!
Thank you very much!