Recent IR-Improved Results for LHC/FCC Physics

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Introduction

1988 ICHEP-Munich Conference Dinner: F. Berends and I considered, ’How Accurate Can Exponentiation Really Be?’

Would It Limit or Enhance Precision for a Given Level of Exactness: LO, NLO, NNLO, ....  

’Two’ Realizations in Literature:  
Jackson-Scharre(JS) vs YFS

JS → ’limit to precision’  
YFS → ’no limit to precision’

See 1989 CERN Yellow Book article: Frits was almost convinced, but not completely!

Today, the analogous discussion continues with an added dimension:  
Hard Cut-off for IR vs Resummed Integrability
Introduction

To Wit, ATLAS-CMS BEH Boson Discovery ⇔ Era of Precision QCD: Precision Tags ≲ 1.0%, ’A New Challenge for Theory and Experiment’

Our Response: Exact Amplitude-Based Resummation Realized on Evt-by-Evt Basis via Shower/ME Matched MC’s – Enhanced Precision for a Given Level of Exactness: LO, NLO, NNLO, ....

Current Realizations: (a) in Herwig6.5 Environment, Herwiri1.031 (LO Shower MC), MC@NLO/Herwiri1.031 (NLO Shower/ME Matched MC); (b)Pythia8 Environment, CPC201(2016)29:IR-Improved Pythia8 (LO Shower MC), MG5_aMC@NLO/IRI-Pythia8 (NLO Shower/ME Matched MC)

From ATLAS, CMS, D0 and CDF data → ’improved precision relative to unimproved Herwig6.5’, |η_ℓ| in central region; similar story in the forward region with LHCb – 2.0 < |η_ℓ| < 4.5, MPLA31(2016)1650063

IRI-semi-analytical paradigm, MPLA31(2016)1650126 – IRI-FEWZ, IRI-NNLOjet,...

We extend to the LHC W + njets and FCC discovery
50 YEARS of $SU_{2L} \times U_1$, S. Weinberg, PRL 19(1967)1264

($SM@50$, B. Lynn et al., Case Western, June, 2018) ⇒

Must Keep Historical Perspective
$$d\bar{\sigma}_{res} = e^{\text{SUM}_{\text{IR}}(\text{QCED})} \sum_{n,m=0}^{\infty} \frac{1}{n! m!} \int \prod_{j_1=1}^{n} \frac{d^3 k_{j_1}}{k_{j_1}}$$
$$\prod_{j_2=1}^{m} \frac{d^3 k'_{j_2}}{k'_{j_2}} \int \frac{d^4 y}{(2\pi)^4} e^{iy \cdot (p_1 + q_1 - p_2 - q_2 - \sum k_{j_1} - \sum k'_{j_2}) + D_{\text{QCED}}}$$
$$\bar{\beta}_{n,m}(k_1, \ldots, k_n; k'_1, \ldots, k'_m) \frac{d^3 p_2}{p_2^0} \frac{d^3 q_2}{q_2^0},$$

where new (YFS-style) non-Abelian residuals $\bar{\beta}_{n,m}(k_1, \ldots, k_n; k'_1, \ldots, k'_m)$ have $n$ hard gluons and $m$ hard photons.
Here,

\[
\text{SUM}_{\text{IR}}(\text{QCED}) = 2\alpha_s \Re B_{\text{QCED}}^{\text{nls}} + 2\alpha_s \tilde{B}_{\text{QCED}}^{\text{nls}}
\]

\[
D_{\text{QCED}} = \int \frac{d^3 k}{k^0} \left( e^{-iky} - \theta(K_{\text{max}} - k^0) \right) \tilde{S}_{\text{QCED}}^{\text{nls}}
\]

where \(K_{\text{max}}\) is “dummy” and

\[
B_{\text{QCED}}^{\text{nls}} \equiv B_{\text{QCD}}^{\text{nls}} + \frac{\alpha}{\alpha_s} B_{\text{QED}}^{\text{nls}},
\]

\[
\tilde{B}_{\text{QCED}}^{\text{nls}} \equiv \tilde{B}_{\text{QCD}}^{\text{nls}} + \frac{\alpha}{\alpha_s} \tilde{B}_{\text{QED}}^{\text{nls}},
\]

\[
\tilde{S}_{\text{QCED}}^{\text{nls}} \equiv \tilde{S}_{\text{QCD}}^{\text{nls}} + \tilde{S}_{\text{QED}}^{\text{nls}}.
\]

“nls”\(\equiv\) DGLAP-CS synthesization.

Shower/ME Matching: \(\hat{\beta}_{n,m} \rightarrow \hat{\beta}_{n,m}\)
Connection to MC@NLO

- Basic Formula:

\[ d\sigma = \sum_{i,j} \int dx_1 dx_2 F_i(x_1) F_j(x_2) d\hat{\sigma}_{\text{res}}(x_1 x_2 s), \quad (4) \]

- \[ d\sigma_{\text{MC@NLO}} = \left[ B + V + \int (R_{MC} - C) d\Phi_R \right] d\Phi_B [\Delta_{MC}(0) + \int (R_{MC}/B)\Delta_{MC}(k_T) d\Phi_R] + (R - R_{MC})\Delta_{MC}(k_T) d\Phi_B d\Phi_R \quad (5) \]

- \[ \Delta_{MC}(p_T) = e^{-\int d\Phi_R R_{MC}(\Phi_B, \Phi_R) \theta(k_T(\Phi_B, \Phi_R) - p_T)} \]
\[ \frac{1}{2} \hat{\beta}_{0,0} = \bar{B} + \left( \frac{\bar{B}}{\Delta_{MC}(0)} \right) \int \left( \frac{R_{MC}}{B} \right) \Delta_{MC}(k_T) d\Phi_R \]

\[ \frac{1}{2} \hat{\beta}_{1,0} = R - R_{MC} - B\tilde{S}_{QCD} \]

where

\[ \bar{B} = B(1 - 2\alpha_s \Re B_{QCD}) + V + \int \left( R_{MC} - C \right) d\Phi_R \]

Similar formulas hold for POWHEG (BFLW, to appear).
Important Observations

- Hard gluon residuals and NLO (NNLO) corrections relationship
  ⇒ Study of $\Delta\sigma_{th}$ requires study of latter’s precision.

- Divergence in NLO (NNLO) corrections (+-functions) ⇒ What does such mean?

- To proceed, we first look at Drell-Yan for LHC data (W+n jets) and FCC Discovery to probe another process and phase space regime.
Interplay of IR-Improved DGLAP-CS Theory and NLO Shower/ME Precision: Comparison with LHC $W + n$ jets Data

- How do LHC $W + n$ jets Data Compare to IR-Improved and Unimproved NLO ME Matched Parton Shower MC’s?
- $p_T$ for $W + njets$, $n = 1, 2, 3$ in turn
  
  ![Graphs](image-url)

(a) $W(\rightarrow \nu l) + 1j$ at $\sqrt{s}=7$ TeV

(b) $W(\rightarrow \nu l) + \geq 2j$ at $\sqrt{s}=7$ TeV
Results similar to previous FNAL, CMS and ATLAS comparisons.

MC@NLO/HERWIRI1.031 is closer to lower $p_T$ data than is MC@NLO/HERWIG6.5(PTRMS = 2.2 GeV/c).
Interplay of IR-Improved DGLAP-CS Theory · · ·: Comparison with LHC $W + n$ jets Data

- 2 jets 2nd leading jet, 3 jets leading jet behave analogously:

(a) $W(\rightarrow \nu l) + \geq 2j$ at $\sqrt{s}=7$ TeV

(b) $W(\rightarrow \nu l) + \geq 3j$ at $\sqrt{s}=7$ TeV
Interplay of IR-Improved DGLAP-CS Theory · · ·: Comparison with LHC W + n jets Data

- MC@NLO/ERWIRI1.031 is closer to data than is MC@NLO/HERWIG6.5 (PTRMS = 2.2 GeV/c) for lower $p_T$.
- Both simulations give acceptable fits to the data at lower values of $p_T$. 
In Juxtaposition, Expectations for FCC Discovery Physics

- Inclusive $p_T$ at 100 TeV

Generated Z Transverse Momentum

**IR-improvement perserves discovery reach.**

B.F.L. Ward  
RADCOR-2017, ST. GILGEN, AUSTRIA
$\mathcal{KK}$MC-hh: Exact $O(\alpha^2 L)$ CEEX EW Corrections in Hadronic MC – see talk by S. Yost tomorrow (H MC = Herwig65)

Today, we introduce $\mathcal{KK}$MC-hh/Herwiri1.031
Interplay IR-Improved DGLAP-CS QCD Theory and Exact $\mathcal{O}(\alpha^2 L)$ CEEX EW Corrections

- Consider recent ATLAS measurement of $M_W$, arXiv:1701.07240:
  $80370 \pm 7(\text{stat.}) \pm 11(\text{exp.syst.}) \pm 14(\text{mod.syst.})\text{MeV} = 80370 \pm 19$

- $Z/\gamma^*$ data used to help get mod. syst.
Interplay IR-Improved DGLAP-CS QCD Theory and Exact $O(\alpha^2 L)$ CEEX EW Corrections

Generated Z transverse momentum.

Fig. 1. Comparisons of KKMC-hh/Herwig(Herwiri) $Z/\gamma^* p_T$ spectra.
SUMMARY

- Precision Theory $\equiv$ Control both
  
  IR ($z \rightarrow 1$)
  
  and
  
  Collinear ($p_T \rightarrow 0$)
  
  emission limits

- We now have control over both for all aspects of the QCD corrections.

- Some New Physics may hang in the balance at both LHC and FCC!