Overview of IR-Improvement in Precision LHC/FCC Physics[a]

S.A. Yost[1], Y. Liu, B. Shakerin, B.F.L. Ward[2]

[1] Department of Physics, The Citadel, Charleston, South Carolina, USA

[2] Department of Physics, Baylor University, Waco, Texas, USA and RISC, Johannes Kepler University, Linz, Austria

[a] Work supported in part by a grant from the Citadel Foundation.

Introduction

- WHAT IS RESUMMATION(IR,UV,CL)?
  - FAMILIAR SUMMATION: $\frac{1}{1-x} = \sum_{n=0}^{\infty} x^n$
  - RESUMMATION:

$$\sum_{n=0}^{\infty} C_n \alpha_s^n \begin{cases} = F_{\rm RES}(\alpha_s) \sum_{n=0}^{\infty} B_n \alpha_s^n, & \text{EXACT} \\ \cong G_{\rm RES}(\alpha_s) \sum_{n=0}^{N} B'_n \alpha_s^n, & \text{APROX.} \end{cases}$$

2

Introduction

- A LITTLE HISTORY: 1988 ICHEP-Munich Conference Dinner, ONE YEAR BEFORE LEP DATA TAKING THAT LED, BY PRECISION PHYSICS, TO THE 't HOOFT-VELTMAN (1999) EW AND GROSS-WILCZEK-POLITZER (2004) QCD NOBEL PRIZES IN PHYSICS:
  F. Berends and BFLW considered, 'How Accurate Can Exponentiation (RESUMMATION) Really Be?'
- Would It Limit or Enhance Precision for a Given Level of Exactness: LO, NLO, NNLO, ... ?

Introduction

- 'Two' Realizations in Literature:
  Jackson-Scharre(JS)(APPROX) vs YFS (EXACT)
- 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 to new paradigms: precision LHC/FCC physics and quantum gravity: we treat the former here.

4

Introduction

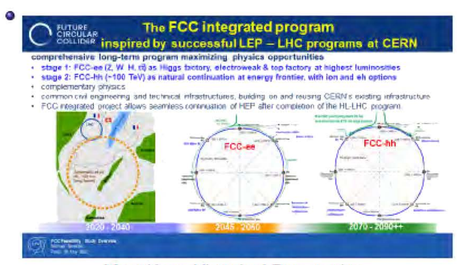
- 50 YEARS of $SU_{2L} \times U_1$,S. Weinberg, PRL19 (1967) 1264[g]; 45 YEARS of QCD, D.J. Gross and F. Wilczek, *ibid.*30 (1973) 1343,H.D. Politzer, *ibid.*30 (1973) 1346 (*SM@50*, B. Lynn *et al.*, Case Western, June, 2018) ⇒

Must Keep Historical Perspective

[g] S.L. Glashow, NP 22(1961) 579; A. Salam, in 8th Nobel Sym, 1968, p.367.

5

Introduction



Must Keep Historical Perspective

Must keep historical perspective.

6

Review of Exact Amplitude-Based Resummation Theory

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

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

QCD ⊗ QED *EXACT* Resummation Theory

Here,

$$\begin{aligned} {\rm SUM_{IR}(QCED)} &= 2\alpha_s \Re B^{nls}_{QCED} + 2\alpha_s \tilde{B}^{nls}_{QCED} \\ D_{\rm QCED} &= \int \frac{d^3k}{k^0} \left(e^{-iky} - \theta(K_{max} - k^0)\right) \tilde{S}^{nls}_{QCED} \end{aligned} \quad (2)$$

where K_{max} is "dummy" and

$$\begin{aligned} B^{nls}_{QCED} &\equiv B^{nls}_{QCD} + \frac{\alpha}{\alpha_s} B^{nls}_{QED}, \\ \tilde{B}^{nls}_{QCED} &\equiv \tilde{B}^{nls}_{QCD} + \frac{\alpha}{\alpha_s} \tilde{B}^{nls}_{QED}, \\ \tilde{S}^{nls}_{QCED} &\equiv \tilde{S}^{nls}_{QCD} + \tilde{S}^{nls}_{QED}. \end{aligned} \quad (3)$$

"nls"≡ DGLAP-CS synthesization.

Shower/ME Matching: $\tilde{\bar{\beta}}_{n,m} \to \hat{\tilde{\beta}}_{n,m}$

8

Precision LHC Physics: New Results and New Issues

- IR-Improved DGLAP-CS Theory: Herwiri1.031
  Interfaced to MC@NLO and MG5_aMC@NLO:
  Z and W+jets Production, ...
- *KKMC-hh*: Exact $O(\alpha^2 L)$ CEEX EW Corrections Interfaced to Herwig6.5 and Herwiri1.031--new, interfaced to MG5_aMC@NLO
- In Z and W+ jets Production, IR-Improvement gives a comparable or better data fit without ad hoc parameters
- In KKMC-hh, IR-improvement allows to quantify role of ISR in precision predictions for Z production observables, as we now illustrate.

9

Precision LHC Physics: New Results and New Issues

DIZET Input/Output Parameters

DIZET6.45 uses a scheme $(\alpha(0)v_0)$ with input parameters $G_\mu, \alpha(0), M_Z$. The other EW parameters are then calculated. M_W is calculated with EW corrections. Apart from the top, quark masses are not used by DIZET. The others are parameters for generating ISR in KKMC-hh.

$1/\alpha(0)$	137.035999139	$\alpha_s(M_Z)$	0.118
$1/\alpha(M_Z)$	128.950302560	$\alpha_s(m_t)$	0.1094
G_F	1.1663787×10^{-5} GeV^{-2}	$\sin^2(\theta_W)$	0.22340108
M_Z	91.1876 GeV	$\sin^2(\theta_W)_{\rm eff}$	0.23149900
Γ_Z	2.4953785 GeV		
M_W	80.3589356 GeV	m_d	4.7 MeV
Γ_W	2.0898823 GeV	m_u	2.2 MeV
M_H	125 GeV	m_s	150 MeV
m_e	510.998928 keV	m_c	4.6 GeV
m_μ	105.658389 MeV	m_b	1.2 GeV
m_τ	1.777 GeV	m_t	173.0 GeV

Red: input
Blue: output

10

Precision LHC Physics: New Results and New Issues

Initial-Final Interference

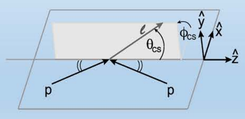
Initial-Final interference (IFI) can have an important influence on measurements of forward-backward asymmetry, since it has a strong angular dependence.

The effect of IFI on the angular distributions used to extract a precision measurement of $\sin^2\theta_W$.

We have been studying A_{FB} and $A_4 = 4\langle\cos\theta_{\rm CS}\rangle$, where θ_{CS} is the Collins-Soper angle in the rest-frame of the final lepton pair:

$$\cos\theta_{CS} = {\rm sgn}(P_{ll}^z) \frac{p_l^+ p_{\bar{l}}^- - p_l^- p_{\bar{l}}^+}{\sqrt{P_{ll}^2 P_{ll}^+ P_{ll}^-}}$$

for $P_{ll} = p_l + p_{\bar{l}}$ and $p^\pm = p^0 \pm p^z$.



11

Precision LHC Phyiscs: New Results and New Issues

Interplay of (IR-Improved) DGLAP-CS QCD Theory and Exact $\mathcal{O}(\alpha^2 L)$ CEEX EW Corrections

- Consider recent ATLAS measurement of the angular coefficients in Z-boson events at 8 TeV, arXiv: 1606.00689
- Z/γ^* data with electron and muon pairs used; EW treated as 'small'

12

Precision LHC Physics: New Results and New Issues

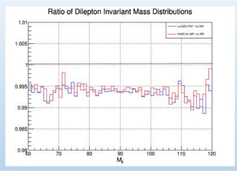
Photonic ISR: QED PDF vs KKMChh

There are presently 2 options:

1. Use a calculation that factorizes collinear QED into the PDFs, such as NNPDF3.1 NLO with LuxQED.
2. Use a complete ab-initio QED calculation including collinear contributions and physical quark masses, and a PDF that is (reasonably) free of QED effects. KKMChh follows this approach.

For NNPDF3.1, the ratio of QED to nonQED invariant mass distribution matches KKMC's ratio with ISR on vs ISR off almost exactly for M_{ll} between 60 and 120 GeV.

Graph from work by Matthew Dittrich @ The Citadel.



There is a constant 0.5% downward shift in the distributions in each case.

8000 GeV collisions, $60 < M_{ll} < 150$ GeV
NNPDF3.1 NLO, NNPDF3.1NLO + LuxQED.
10^9 muon events, no lepton cuts, no FSR.

Precision LHC Physics: New Results and New Issues

- New Issues:
  Role of photon transverse degrees of freedom
  Role of quark masses:
  1. Observable parameters? YES
  2. Just unphysical (IR and CL regulators)? NO

  Input data for non-QED PDFs at Q_0~1 GeV:
  1. Is this double counting if CL singular quark mass effects are not removed?
     QFT: processes at different space-time regimes cannot double count! (Shower!)
  2. Can we get a PDF with them removed
     -- probably YES.

2

Precision LHC Physics: New Results and New Issues

- Results from KKMC-hh: arXiv:2002.11692
- We see clear evidence that the transverse degrees of freedom in the photon radiation for ISR do impact observables in single Z/γ^* production: $\cos(\theta_{CS})$, M_{ll}, A_4, A_{FB}, Y_{ll}, w/wo shower.

Illustrations: cuts - $60\ {\rm GeV} < M_{\ell\ell} < 116\ {\rm GeV}$, $P_T^{\ell\ell} < 30\ {\rm GeV}$, $P_T^\ell > 25\ {\rm GeV}$, $|\eta_\ell| < 2.5$.

Showered Numerical Results: σ, A_{FB}, A_4

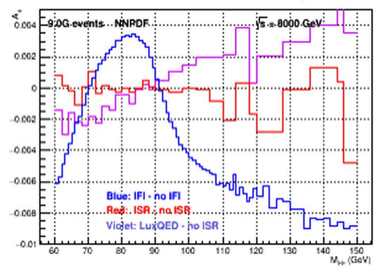
	Without Shower	With Shower	% Difference
Uncut σ(pb)	944.91(2)	938.44(4)	-0.684(7)%
Cut σ(pb)	442.33(1)	412.54(3)	-6.7307%
	without Shower	With Shower	Difference
A_{FB}	0.01132(2)	0.01211(5)	0.00109(5)
A_4	0.06102(8)	0.06052(8)	-0.00050(8)

14

Precision LHC Physics: New Results and New Issues

No cuts: NNPDF 3.1

ISR and IFI contributions to A_4



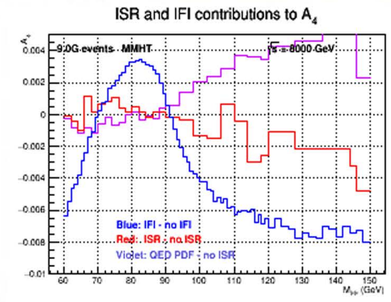
The blue curve shows the IFI correction to the asymmetry A_4
The red curve shows the much smaller ISR correction.
The purple curve shows the effect of switching from ordinary NNPDF3.1 to QED-corrected NNPDF3.1 on AFB (omitting KKMChh ISR).

15

Precision LHC Physics: New Results and New Issues

No cuts: MMHT PDFs

ISR and IFI contributions to A_4



The same curves as on the previous slide with MMHT14 PDFs instead. The IFI correction has negligible change., and the ISR shows similar patterns, but again with large errors in a small effect.

1

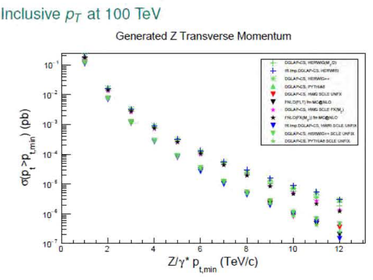
Precision FCC Physics: New Results and New Issues

- FCC <=> FCC-ee + FCC-hh
- IR-Improvement of even the FCC-hh discovery spectra is needed--see arXiv:1801.03303
- For FCC-ee, a key issue is the theoretical precision of the Luminosity. This is discussed by BFLW here.
- Today, for illustration, we address the former concern.
- We recall (IJMPA35(2020)2050197): IR-improvement for 3rd-ldg jet p_T.
- We show the corresponding new issue for FCC-hh discovery physics.

3

Expectations for FCC Discovery Physics

- Inclusive p_T at 100 TeV



- IR-improvement preserves discovery reach.

Conclusion: IR-improvement enhances LHC/FCC physics