Role of IR-Improvement in LHC/FCC Physics

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OUTLINE

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- Review of Parton Shower Implementation of Exact Amplitude-Based Resummation Theory
- Interplay of IR-Improved DGLAP-CS Theory and NLO Shower/ME Precision: Comparison with LHC Data on W + n jets
- Expectations for FCC Discovery Physics
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Introduction

- 1988 ICHEP-Munich Conference Dinner:
  F. Berends and I considered, 'How Accurate Can Exponentiation Really Be?'
- Limitation or Enhancement of Precision for a Given Level of Exactness: LO, NLO, NNLO, ... ?
- 'Two' Realizations:
  Jackson-Scharre(JS) vs YFS
- JS $\rightarrow$ 'limit to precision'
- YFS $\rightarrow$ 'no limit to precision'
- See 1989 CERN Yellow Book article: Frits was almost convinced, but not completely!

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Introduction

- The analogous discussion continues today with added dimensions:
- Hard Cut-off for IR: Pythia8, Herwig7,... vs Resummed Integrability: Herwiri1.031
- ISR radiation from quarks: QED PDF's with massless quarks vs Exact Feynman Diagrams with short-distance quark masses and non-QED PDF's
- ...

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Introduction

- To Wit, ATLAS-CMS BEH Boson Discovery $\Leftrightarrow$ Era of Precision QCD: Precision Tags $\lesssim$ 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)

Introduction

- From ATLAS, CMS, D0 and CDF data $\rightarrow$ 'improved precision relative to unimproved Herwig6.5', $|\eta_\ell|$ in central region; similar story in the forward region with LHCb – $2.0 < |\eta_\ell < 4.5$, **MPLA31(2016)1650063**
- IRI-semi-analytical paradigm, **MPLA31(2016)1650126** $\Rightarrow$ (future) : IRI-FEWZ, IRI-NNLOjet,...
- We extend to the LHC $W + njets$ and FCC discovery areas and a new IRI-QCD - CEEX EW Exact $\mathcal{O}(\alpha^2 L)$ Interplay

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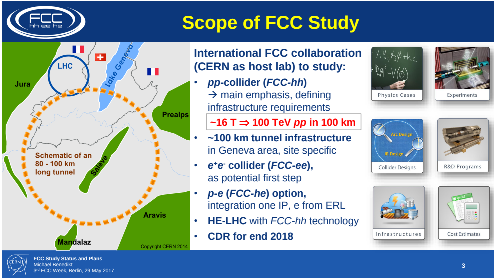
Introduction

- 50 YEARS of $SU_{2L} \times U_1$, S. Weinberg, PRL**19** (1967) 1264; 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) $\Rightarrow$



Must Keep Historical Perspective

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

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.

Here,

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

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: $\tilde{\bar{\beta}}_{n,m} \to \hat{\tilde{\bar{\beta}}}_{n,m}$

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Connection to MC@NLO

- Basic Formula:

$$d\sigma = \sum_{i,j} \int dx_1 dx_2 F_i(x_1) F_j(x_2) d\hat{\sigma}_{\rm res}(x_1 x_2 s), \tag{4}$$

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

- $$\Delta_{MC}(p_T) = e^{[-\int d\Phi_R \frac{R_{MC}(\Phi_B,\Phi_R)}{B} \theta(k_T(\Phi_B,\Phi_R) - p_T)]},$$

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Connection to MC@NLO

- $\Rightarrow$

$$\frac{1}{2}\hat{\tilde{\bar{\beta}}}_{0,0} = \bar{B} + (\bar{B}/\Delta_{MC}(0))\int (R_{MC}/B)\Delta_{MC}(k_T)d\Phi_R$$
$$\frac{1}{2}\hat{\tilde{\bar{\beta}}}_{1,0} = R - R_{MC} - B\tilde{S}_{QCD} \quad (6)$$

where

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

.

- Similar formulas hold for POWHEG and KRKNLO (BFLW, to appear).

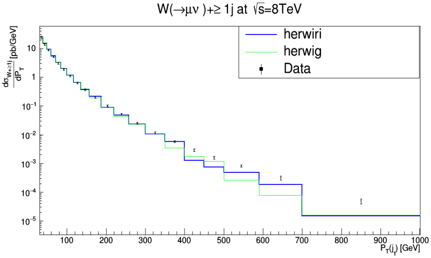
Important Observations

- Hard gluon residuals and NLO (NNLO) corrections relationship
  $\Rightarrow$ Study of $\Delta\sigma_{\rm th}$ requires study of latter's precision.
- Divergence in NLO (NNLO) corrections(+-functions) $\Rightarrow$ 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 another 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

(a)



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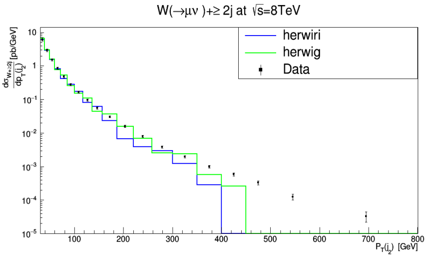


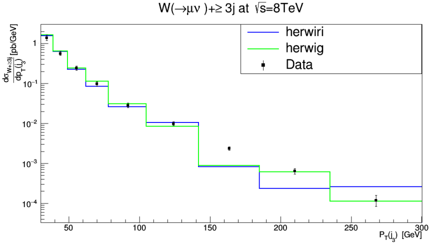
Interplay of IR-Improved DGLAP-CS Theory $\cdots$: Comparison with LHC W + n jets Data

- 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

- 3 jets 3rd leading jet p_T, H_T behave analogously:

(a)



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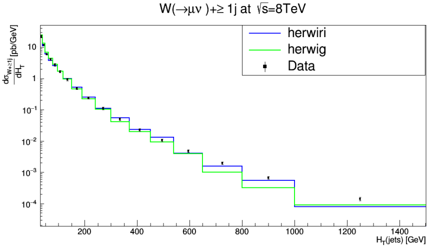

Interplay of IR-Improved DGLAP-CS Theory $\cdots$: Comparison with LHC W + n jets Data

- MC@NLO/HERWIRI1.031 is closer to data than is MC@NLO/HERWIG6.5(PTRMS $=$ 2.2 GeV/c) for lower p_T, $\mathrm{H_T}$.
- Both simulations give reasonable fits to the data at lower values of p_T, $\mathrm{H_T}$.

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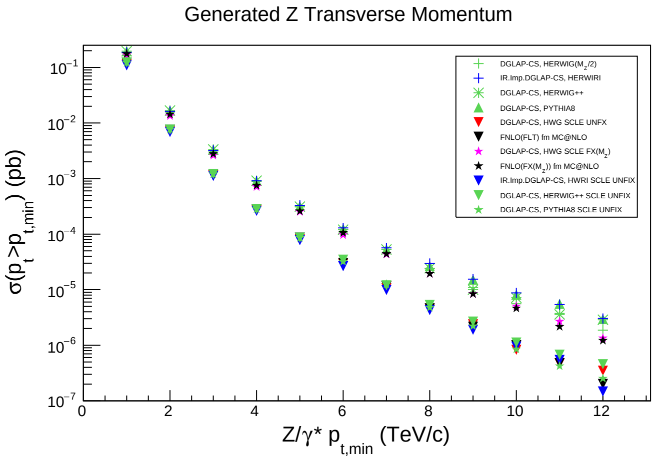
Expectations for FCC Discovery Physics

- Inclusive p_T at 100 TeV



- IR-improvement preserves discovery reach.

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

- $\mathcal{KK}$MC-hh:Exact $\mathcal{O}(\alpha^2 L)$ CEEX EW Corrections in Hadronic MC – see PRD **99** (2019) 076016(H MC = Herwig65)
- Today, we motivate/review $\mathcal{KK}$MC-hh and illustrate $\mathcal{KK}$MC-hh/Herwiri1.031, with SM input parameters as in Alioli et al., arXiv:1606.02330.

Introduction to KKMC-hh/KKMC

$\mathcal{KK}$ MC-hh

- $\mathcal{KK}$ MC-hh is an event-generator for Z production and decay in hadronic collisions, which grew from the e^+e^- event generator $\mathcal{KK}$ MC created by S. Jadach, B.F.L. Ward, and Z. Wąs.
- The latest version of $\mathcal{KK}$ MC supports quark initial states, and provides a natural starting point for incorporating EWK corrections to the parton-level process.
- $\mathcal{KK}$ MC-hh adds an LHAPDF interface and an interface to a shower generator, presently HERWIG6.5, but an external generator can be used.

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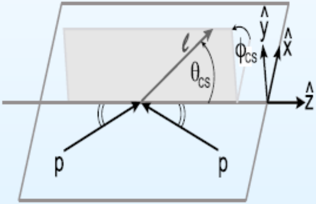
Applications in Precision LHC Physics

Angular Variables for $pp \to Z/\gamma^* \to \ell\bar{\ell}$

We will consider distributions of the angle θ_{CS} of the negative ℓ defined in the Collins-Soper frame: the CM frame of $\ell^\pm$, relative to a $\hat{z}$ axis oriented as shown relative to the proton beams.
If $P = p_\ell + p_{\bar{\ell}}$ and $p^\pm = p^0 \pm p^z$ in the lab,

$$\cos(\theta_{CS}) = \mathrm{sgn}(P^z)\frac{p_\ell^+ p_{\bar{\ell}}^- - p_\ell^- p_{\bar{\ell}}^+}{\sqrt{P^2 P^+ P^-}}$$



A_{FB}, A_4 --> $\sin^2\theta_W$

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'

ISR: QED PDFs vs KKMC-hh

QED ISR enters the angular distributions at the order of several per-mil, and cannot be neglected.

There are two options at present:

1. Use a calculation that factorizes collinear effects and absorbs them into PDFs with a PDF that includes the collinear QED. Several are available. Current studies have focused on NNPDF3.1 NLO with LuxQED.
2. Use a complete ab-initio QED calculation, including collinear contributions, with a PDF that does not contain QED effects. The result will depend parametrically on quark masses. KKMC-hh follows this approach.

The two approaches should agree for variables which are not strongly sensitive to photon P_T.

The connection between these approaches should be studied in detail. KKMC-hh can be useful in such studies. Comparisons of quark momentum distributions could help determine the most appropriate values of the light quark masses.

Results from KKMC-hh

- The following tests are based on runs generating 5.7×10^9 muon events at 8 TeV, using NNPDF3.1 NLO PDFs ($\alpha_s(M_Z) = 0.12018$). **The QCD shower is off in these results.**
- All results include a dilepton mass cut $60 \text{ GeV} < M_{ll} < 116 \text{ GeV}$.
- **Uncut** / **Without cuts** means there are no additional cuts.
- **Cuts** / **With cuts** means there is a cut $P_T > 25$ GeV, $|\eta| < 2.5$ on the individual muons.
- Levels of photonic corrections:
  1. FSR only using KKMC-hh with non-QED NNPDF3.1 NLO
  2. FSR + ISR using KKMC-hh with non-QED NNPDF3.1 NLO
  3. FSR + ISR + IFI using non-QED NNPDF3.1 NLO (KKMC-hh best result)
  4. FSR + LuxQED using KKMC-hh with NNPDF3.1 NLO + QED

All KKMC-hh photonic corrections are calculated using CEEX exponentiation with exact $\mathcal{O}(\alpha^2 L)$ residuals.

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Numerical Results

Column 1 includes FSR only, with a non-QED PDF. Column 2 has FSR with LuxQED. Column 3 has KKMC-hh ISR + FSR with a non-QED PDF. Column 5 adds KKMC-hh IFI.

	1. No ISR	2. LuxQED	3. KKMC-hh ISR	4. %(ISR – no ISR)	5. With IFI	6. %(IFI – no IFI)
Uncut σ (pb)	939.86(1)	944.04(1)	944.99(2)	0.54597(2)%	944.91(2)	−0.083(4)%
Cut σ (pb)	439.10(1)	440.93(1)	442.36(1)	0.74223(3)%	442.33(1)	−0.083(2)%

KKMC-hh shows an ISR effect of a fraction of a percent. LuxQED shows a slightly smaller effect, about 0.4% for each cross section. KKMC-hh shows an IFI effect below 0.1%.

	1. No ISR	2. LuxQED	3. KKMC-hh ISR	4. ISR – no ISR	5. With IFI	6. IFI – no IFI
A_{FB}	0.01125(2)	0.01145(2)	0.01129(2)	$(3.9 \pm 2.8) \times 10^{-5}$	0.01132(2)	$(2.9 \pm 1.1) \times 10^{-5}$
A_4	0.06102(3)	0.06131(3)	0.06057(3)	$-(4.4 \pm 0.5) \times 10^{-5}$	0.06102(3)	$(4.5 \pm 0.3) \times 10^{-5}$

The ISR and IFI effects on the angular coefficients are both on the order of 10^{-5} in KKMC-hh. LuxQED gives a somewhat bigger ISR effect in this case, on the order of 10^{-4}.

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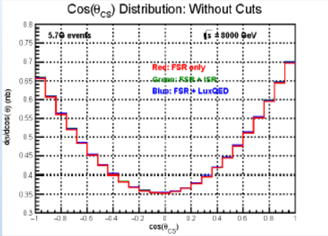
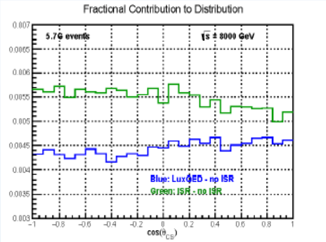
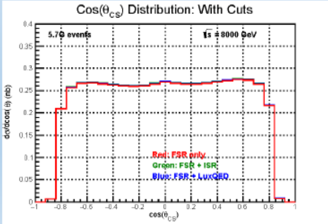
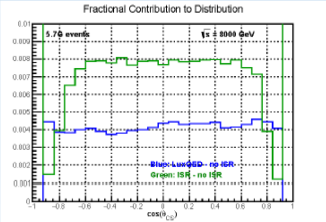
ISR contributions to CS angle distribution









Without Lepton Cuts (used for A_4)

- **LuxQED ISR** is in **blue**.
- **KKMC-hh ISR** in **green**.
- **Red** line has **FSR only** – the baseline here.

With Lepton Cuts (used for A_{FB})

- ISR enters at the per-mil level.

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

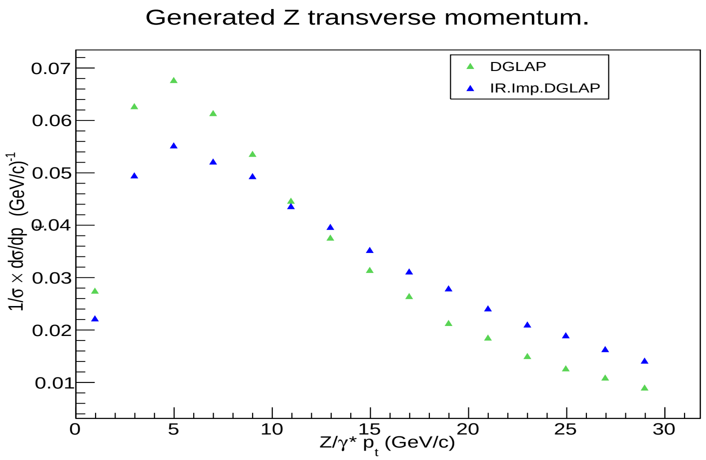


Fig. 1. Comparisons of KKMC-hh/Herwig(Herwiri) $Z/\gamma^* p_T$ spectra.

SUMMARY

- Precision Theory $\equiv$ Control both

  IR ($z \to 1$)

  and

  Collinear ($p_T \to 0$)

  emission limits

- We now have control over both for all aspects of the QCD corrections: NLO QCD for $\mathcal{KK}$MC-hh near - Liu, Siodmok & Jadach
- Some New Physics may hang in the balance at both LHC and FCC!