New Developments in Exact Amplitude-Based Resummation in Precision Theory vs Experiments

B.F.L. Ward

Baylor University, Waco, TX, USA

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in collaboration with A. Mukhopadhyay

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Inroduction

- 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 $\rightarrow$ 'limit to precision'
- YFS $\rightarrow$ 'no limit to precision'
- See 1989 CERN Yellow Book article: Frits was almost convinced, but not completely!
- Today, the analogous discussion continues

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, **1504.00892**:IR-Improved Pythia8 (LO Shower MC), MG5_aMC@NLO/IRI-Pythia8 (NLO Shower/ME Matched MC)
- From ATLAS, CMS, D0 and CDF data $\rightarrow$ 'improved precision relative to unimproved Herwig6.5', $|\eta_\ell|$ in central region
- Today, we extend the analysis to the more forward LHCb data: $2.0 < |\eta_\ell < 4.5$ and present a new paradigm for the next step.

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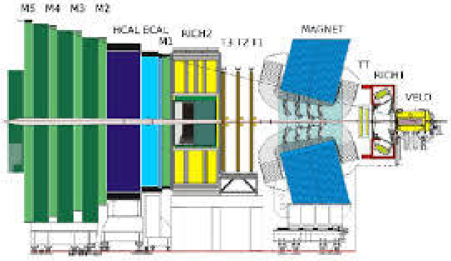
Introduction



The LHCb Detector.

Review of Parton Shower Implementation of Exact Amplitude-Based Resummation Theory

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

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,

$$\mathrm{SUM_{IR}(QCED)} = 2\alpha_s \Re B^{nls}_{QCED} + 2\alpha_s \tilde{B}^{nls}_{QCED}$$

$$D_{\mathrm{QCED}} = \int \frac{d^3k}{k^0}\left(e^{-iky} - \theta(K_{max} - k^0)\right)\tilde{S}^{nls}_{QCED} \qquad (2)$$

where K_{max} is “dummy” and

$$B^{nls}_{QCED} \equiv B^{nls}_{QCD} + \frac{\alpha}{\alpha_s} B^{nls}_{QED},$$

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

$$\tilde{S}^{nls}_{QCED} \equiv \tilde{S}^{nls}_{QCD} + \tilde{S}^{nls}_{QED}. \qquad (3)$$

“nls”$\equiv$ DGLAP-CS synthesization.

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

Connection to MC@NLO

- Basic Formula:

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

-

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

-

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

Connection to MC@NLO

- $\Rightarrow$

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

where

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

.

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

Important Observations

- Hard gluon residuals and NLO corrections relationship
  $\Rightarrow$ Study of $\Delta\sigma_{\rm th}$ requires study of latter's precision.
- Divergence in NLO corrections(+-functions) $\Rightarrow$ What does such mean?
- To proceed, we look at Drell-Yan for LHCb data to probe another regime of phase space compared to ATLAS and CMS.

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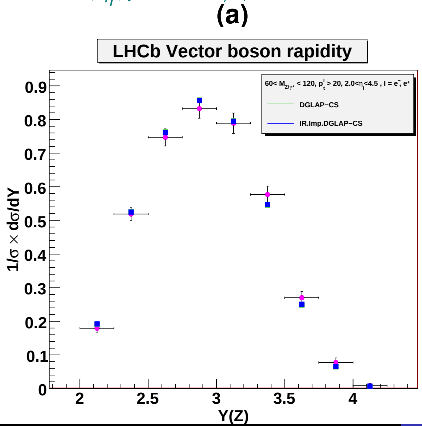
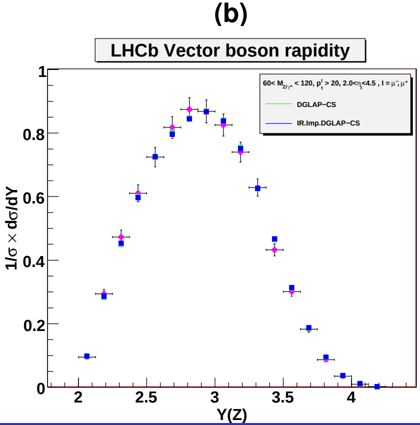
Interplay of IR-Improved DGLAP-CS Theory and NLO Shower/ME Precision: Comparison with LHCb Data

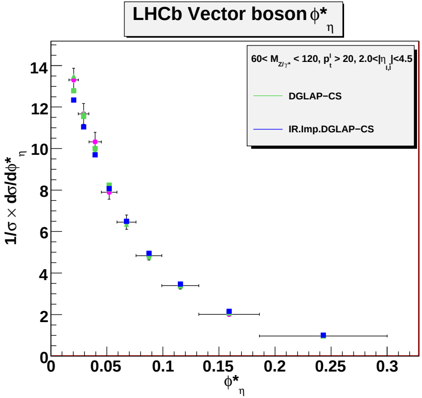
- How do LHCb Data Compare to IR-Improved and Unimproved NLO ME Matched Parton Shower MC's?
- Y, ϕ^*_η, p_T for Z/γ^* in turn





- Results similar to previous FNAL, CMS and ATLAS comparisons.
- The χ^2/d.o.f:
  0.746, 0.814, 0.836 for the respective predictions from MC@NLO/HERWIRI1.031, MC@NLO/HERWIG6.5(PTRMS $=$ 0) and MC@NLO/HERWIG6.5(PTRMS $=$ 2.2 GeV/c) for the e^+e^- data;
  0.773, 0.555, 0.537 for the respective predictions for the $\mu^+\mu^-$ data. All three calculations give acceptable values of χ^2/d.o.f.

- $\phi^*_\eta = \tan(\phi_{acop}/2)\sqrt{1-\tanh^2(\Delta\eta/2)}$, where $\Delta\eta = \eta^- - \eta^+$ when η^- and η^+ and $\phi_{acop} = \pi - \Delta\phi$ when $\Delta\phi = \phi_1 - \phi_2$.



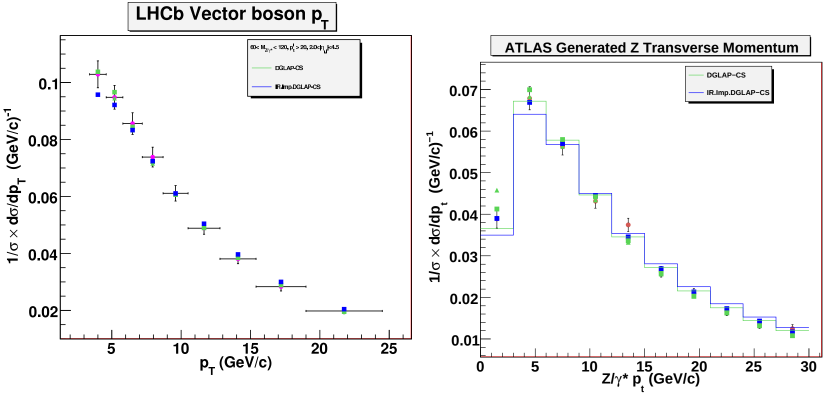
Interplay of IR-Improved DGLAP-CS Theory $\cdots$: Comparison with LHCb Data

- The respective χ^2/d.o.f. are 1.2, 0.23, 0.35 for the MC@NLO/ERWIRI1.031, MC@NLO/HERWIG6.5(PTRMS $=$ 0), MC@NLO/HERWIG6.5(PTRMS $=$ 2.2 GeV/c) simulations.
- All three simulations give acceptable fits to the data, with the curious result that the MC@NLO/HERWIG6.5 (PTRMS $=$ 0) gives a very mildly better fit than does MC@NLO/HERWIG6.5(PTRMS $=$ 2.2 GeV/c) – caution: we cannot now take $|\Delta\chi^2/\text{d.o.f.}| \simeq 0.1$ as significant.
- Recall the difference between the ϕ^*_η variable and the p_T of the Z/γ^* as well as the difference between the forward and more central observations – in arXiv:1305.0023 a good p_T-fit for the central region with HERWIG6.5 is not possible with PTRMS $=$ 0.

  $\Rightarrow$ Look next at the more forward LHCb data on p_T.

- p_T

(a) (b)



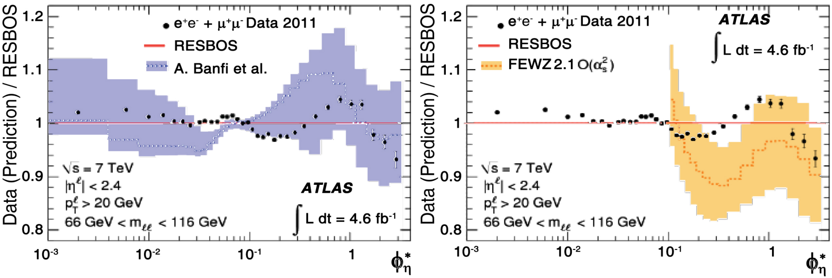
The blue(green) squares are MC@NLO/HERWIRI1.031(HERWIG6.510(PTRMS $= 2.2$GeV)), the green triangles are MC@NLO/HERWIG6.510(PTRMS $=0$)

- $\chi^2/d.o.f$
- MC@NLO/Herwig65(PTRMS=2.2GeV), MC@NLO/Herwig65(PTRMS=0), MC@NLO/Herwiri1.031(PTRMS=0) $\rightarrow$ .103,.183,.789 for (a)
- MC@NLO/Herwig65(PTRMS=2.2GeV), MC@NLO/Herwig65(PTRMS=0), MC@NLO/Herwiri1.031(PTRMS=0) $\rightarrow$ 1.37,2.23,.72 for (b)
- Proper interpretation $\Leftrightarrow$ Technical precision and physical precision under control.

In Juxtaposition, the Current Practice and LHC Data

- Consider the Drell-Yan type processes:
  $pp \rightarrow Z/\gamma^* + X \rightarrow \ell\bar{\ell} + X'$ at LHC(FCC).
- NNLO exact results are available (FEWZ,DYNNLO, etc.)
- Comparison with LHC data is shown in Fig. 1.
- Comparison with FNAL data is shown in Fig. 2.
- NOTE: The resummations in RESBOS and in the SCET in Banfi *et al.* *MATCH* on to *EXACT* fixed-orders.

Z/γ^* transverse momentum $(d\sigma/d\phi^*_\eta(\ell\ell))$

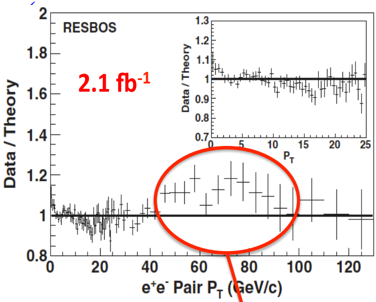


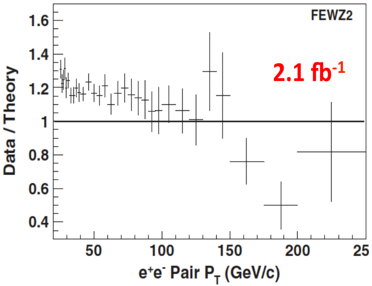
- Calculations from A. Banfi et al. (resummed QCD predictions+fixed-order pQCD) is less good than Resbos
- **Measurement precision about one order of magnitude lower than the present theoretical uncertainties**
- FEWZ predictions undershoot the data by ~10% which confirm previous CDF observation (PRD 86,052010)

Fig. 1. Comparisons of some theoretical predictions with the ATLAS Z/γ^* ϕ^*_η spectrum in single Z/γ^* production with decay to lepton pairs as given in Hassani *et al.* Banfi *et al.* is a resummed calculation of the "CSS" type – it has the same physical precision limitations as RESBOS as discussed in Ann.Phys. **350** (2014) 485.

Z/γ^* transverse momentum $(d\sigma/dp_T)$

PRD 86,052010 (2012)





Resbos: utilizes the Collins, Soper, and Sterman (CSS) resummation formalism.

FEWZ2: QCD fixed-order perturbative calculation at $O(\alpha_s)$ (NNLO)

Resummed calculation must be matching to the fixed-order pertubative calculation

Fig. 2. Comparisons of theoretical predictions with the CDF Z/γ^* p_T spectrum in single Z/γ^* production with decay to lepton pairs as given in Yin *et al.*

Field's Analysis of Drell-Yan at NLO

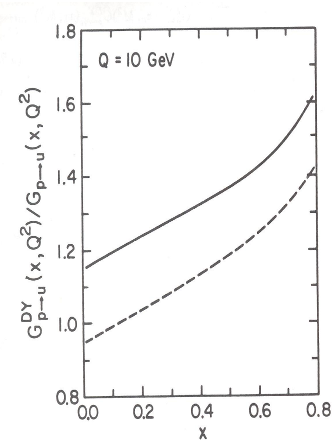


Fig. 3. Ratio of the Drell-Yan u-quark probability distribution to that from DIS as discussed in **Field,** ***Applications of Perturbative QCD*** **(Add.-Wes., Redwood City, 1989),** at $Q = 10$ GeV – solid (dashed) curve $\equiv$ to including (excluding) total xsect. in Drell-Yan.

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Field's Analysis of Drell-Yan at NLO

See eq.(5.5.30) in *Field*:

- $$\frac{G^{DY}_{p\to q}(x,Q^2)}{G_{p\to q}(x,Q^2)} \underset{x\to 1}{\to} 1+\frac{2\alpha_s(Q^2)}{3\pi}\ln^2(1-x) \tag{7}$$
- This gives ∞ at $x=1$, totally unphysical.

More Important Observations

- Divergence in (7) $\Rightarrow$ What does such mean?
  (a). Artifact of +-functions in fixed order 'exact results'
  (b). How do we tame this behavior?
  $\mathcal{EXACT}$ **AMPLITUDE-BASED RESUMMATION THEORY**
- To illustrate, we look at Drell-Yan, with just γ^* exchange for optimum pedagogics.

Taming +-Functions in Drell-Yan at NLO

Following Altarelli *et al.*, Humpert and Van Neerven, we have

$$\frac{d\sigma^{DY}}{dQ^2} = \frac{4\pi\alpha^2}{9sQ^2}\int_0^1 \frac{dx_1}{x_1}\int_0^1 \frac{dx_2}{x_2}\Big\{\Big[q^{(1)}(x_1)\bar{q}^{(2)}(x_2) + (1\leftrightarrow 2)\Big]\Big[\delta(1-z_{12})$$
$$+\alpha_s(t)\theta(1-z_{12})(\frac{1}{2\pi}P_{qq}(z_{12})(2t) + f_q^{DY}(z_{12}))\Big]$$
$$+\Big[(q^{(1)}(x_1)+\bar{q}^{(1)}(x_1))G^{(2)}(x_2) + (1\leftrightarrow 2)\Big]$$
$$\times\,[\alpha_s(t)\theta(1-z_{12})(\frac{1}{2\pi}P_{qG}(z_{12})t + f_G^{DY}(z_{12}))]\Big\} \tag{8}$$

with

$$z_{12} = \tau/(x_1 x_2),\ \tau = Q^2/s$$

Taming +-Functions in Drell-Yan at NLO

Here,

$$P_{qq}(z) = C_F\left[\frac{1+z^2}{(1-z)_+} + \frac{3}{2}\delta(1-z)\right],$$
$$P_{qG}(z) = \frac{1}{2}(z^2+(1-z)^2), \tag{9}$$

where

$t = \ln(Q^2/\mu^2)$
$\mu \equiv$ 't Hooft unity of mass.

Taming +-Functions in Drell-Yan at NLO

Scheme dependent hard corrections:

$$\alpha_s f_G^{DY}(z) = \frac{\alpha_s}{2\pi}\frac{1}{2}\left[(z^2+(1-z)^2)\ln\frac{(1-z)^2}{z} - \frac{3}{2}z^2 + z + \frac{3}{2} + 2P_{qG}(z)\zeta\right]$$

$$\alpha_s f_q^{DY}(z) = C_F\frac{\alpha_s}{2\pi}\left[4(1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+ - 2\frac{1+z^2}{1-z}\ln z \right.$$
$$\left. + \left(\frac{2\pi^2}{3} - 8\right)\delta(1-z) + \frac{2}{C_F}P_{qq}(z)\zeta\right] \tag{10}$$

where
$\zeta = -\frac{1}{\epsilon} + C_E - \ln 4\pi$ for
$\epsilon = 2 - n/2$. C_E is the Euler-Mascheroni constant.
$\overline{\text{MS}}$-Scheme: Terms $\propto \zeta$ mass factorized,
$\Rightarrow$ +-functions left in hard corrections
$\Rightarrow$ divergent behavior for $z \to 1$.
How do we fix this?

Taming +-Functions in Drell-Yan at NLO

Imbed calculation of hard corrections in Master Formula (1):

$$
\begin{aligned}
\frac{d\sigma^{DY}_{res}}{dQ^2} = & \frac{4\pi\alpha^2}{9sQ^2}\int_0^1 \frac{dx_1}{x_1}\int_0^1 \frac{dx_2}{x_2}\Big\{\Big[q^{(1)}(x_1)\bar{q}^{(2)}(x_2)+(1\leftrightarrow 2)\Big]\, 2\gamma_q F_{YFS}(2\gamma_q)\\
& \times (1-z_{12})^{2\gamma_q-1}e^{\delta_q}\theta(1-z_{12})\Big[1+\gamma_q-7C_F\frac{\alpha_s}{2\pi}\\
& +(1-z_{12})(-1+\frac{1-z_{12}}{2})+2\gamma_q(-\frac{1-z_{12}}{2}-\frac{z_{12}^2}{4}\ln z_{12})\\
& +\alpha_s(t)\frac{(1-z_{12})}{2\gamma_q}f_q^{DY}(z_{12})\Big]\\
& +\Big[(q^{(1)}(x_1)+\bar{q}^{(1)}(x_1))G^{(2)}(x_2)+(1\leftrightarrow 2)\Big]\\
& \times \gamma_G F_{YFS}(\gamma_G)e^{\frac{\delta_G}{2}}[\alpha_s(t)\theta(1-z_{12})(\frac{t}{2\pi\gamma_G}(\frac{1}{2}(z_{12}^2(1-z_{12})^{\gamma_G}\\
& +(1-z_{12})^2 z_{12}{}^{\gamma_G}))+f_G^{DY'}(z_{12})/\gamma_G)]\Big\}
\end{aligned}
\tag{11}
$$

where

$$\alpha_s f_G^{DY'}(z) = \frac{\alpha_s}{2\pi}\frac{1}{2}[(z^2(1-z)^{\gamma_G} + (1-z)^2 z^{\gamma_G})\ln\frac{(1-z)^2}{z} - \frac{3}{2}z^2(1-z)^{\gamma_G} + z(1-z)^{\gamma_G} + \frac{3}{4}((1-z)^{\gamma_G} + z^{\gamma_G})], \tag{12}$$

and

$$\gamma_q = C_F\frac{\alpha_s}{\pi}t = \frac{4C_F}{\beta_0}, \qquad \delta_q = \frac{\gamma_q}{2} + \frac{\alpha_s C_F}{\pi}(\frac{\pi^2}{3} - \frac{1}{2}),$$
$$\gamma_G = C_G\frac{\alpha_s}{\pi}t = \frac{4C_G}{\beta_0}, \qquad \delta_G = \frac{\gamma_G}{2} + \frac{\alpha_s C_G}{\pi}(\frac{\pi^2}{3} - \frac{1}{2}),$$
$$F_{\mathrm{YFS}}(\gamma) = \frac{e^{-C_E\gamma}}{\Gamma(1+\gamma)}, \tag{13}$$

$\beta_0 = 11 - \frac{2}{3}n_f$ for n_f active flavors, usual.

Taming +-Functions in Drell-Yan at NLO

Observations:

- Regime at $z_{12} \rightarrow 1$ is now under control.
- Instead of the $\ln(1-x)^2$ divergence at $x \rightarrow 1$ in (7) we now get

$$\frac{2(1-x)^{\gamma_q}\ln(1-x)}{\gamma_q} - \frac{2(1-x)^{\gamma_q}}{\gamma_q^2} \rightarrow 0$$

for $x \rightarrow 1$.

- $\Rightarrow$ Hard corrections can now be compared exclusively to LHC/FCC data.
- Stay Tuned: IR-Improved FEWZ 3.x, in progress with S. Yost

Taming +-Functions in Drell-Yan at NLO

- MC@NLO and POWHEG do not tame this divergence:

$$\begin{cases} \text{MC@NLO} & \text{- SWAPS NLO EMISSION with PS EMISSION,} \\ z \to 1 & \text{DIV IN BOTH} \\ \text{POWHEG} & \text{- KEEPS NLO EMISSION for 1st SHOWER EMISSION,} \\ z \to 1 & \text{DIV UNCHANGED THEREIN} \end{cases}$$

- Both do tame $p_T \to 0$ limit: $\Delta(p_T)$ factor in real emission

Taming +-Functions in Drell-Yan at NLO

- MadGraph5_aMC@NLO(**1403.0301**) contemplates taming this divergence:

Eqs.(2.126 -2.129) note

$$\begin{cases} \Delta = 1 + \mathcal{O}(\alpha_s),\ \Delta \to 0 \text{ IR LIMITS}, \\ \Rightarrow \text{PRECISION PRESERVED BY} \\ d\sigma_{ij}^{(\mathbb{H})} = \left(d\sigma_{ij}^{(\text{NLO,E})} - d\sigma_{ij}^{(\text{MC})} \right) \Delta, \text{ AND}, \\ d\sigma_{ij}^{(\mathbb{S})} = d\sigma_{ij}^{(\text{MC})} \Delta + \sum_{\alpha=S,C,SC} d\sigma_{ij}^{(\text{NLO},\alpha)} + d\sigma_{ij}^{(\text{NLO,E})} (1-\Delta) \end{cases}$$

- OUR IRI $\Rightarrow \Delta \propto (1-z)^{\gamma_A}, A = q, G$
- Taming $p_T \to 0$ limit by $\Delta(p_T)$ factor in real emission is separate from IR $z \to 1$ limit
- Introduce IRI in MadGraph5_aMC@NLO: IRI shower - done; IRI subtractions, in progress

A Matter of Precision

- A Fundamental Issue then Obtains: What Is the (Physical) Precision?

Usual Approach

$$\begin{cases} \text{Isolate scales: renormalization, factorization, shower, ...} \\ \text{vary by } \frac{1}{\text{f}} \text{ to f, f} \sim 2 \\ \text{independently, correlatedly, ..., ?,} \\ \text{Precison taken from attendant variation of observable} \end{cases}$$

- **BLM**:Scales should be determined by dynamics of the process.
- Shifman, Zinn-Justin,etc.: Typically, we have

$$Z = \sum_K C_K(\frac{\alpha_s}{\pi})^k k^{b-1} A^{-k} k! \tag{14}$$

$$= (-A\frac{\partial}{\partial A})^{b-1} \sum_K C_K(\frac{\alpha_s}{\pi A})^k k!, \tag{15}$$

with $C_K = \mathcal{O}(1)$, b, A process dependent.

- $\Rightarrow$ MOST PROBABLY ASYMPTOTIC with
- $Z - S_N = \mathcal{O}(\alpha_s/(\pi A))^N$, Whit& Wat,4th edn.
  Error on $S_N \simeq$ a factor $\lesssim 1$ times $S_N - S_{N-1}$
  Note: Experience from LEP.
- Consider a known example:

$$R = \frac{\sigma(e^+e^- \rightarrow hadrons)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} \tag{16}$$

$$= R_{EW}\left(1 + \sum_{n=1}^{\infty} c_n \left(\frac{\alpha_s(Q^2)}{\pi}\right)^n + \text{power corr.}\right), \tag{17}$$

where the c_n are known to $n = 4$ well enough to be in the PDG2014: Chin. Phys. C**38**(2014)090001.

A Matter of Precision

- We have ($\overline{MS}$):

$$c_1 = 1,$$
$$c_2 = 1.9857 - .1152 n_f,$$
$$c_3 = -6.63694 - 1.20013 n_f - .00518 n_f^2 - 1.240\eta,$$
$$\eta = \frac{(\sum e_q)^2}{(s \sum e_q^2)},$$
$$c_4 = -156.61 + 18.775 n_f - .7974 n_f^2 + .0215 n_f^3 + (17.828 - .575 n_f)\eta,$$
$$\vdots$$

- Let us use these results to explore precision estimate methodology.

A Matter of Precision

- Toy Case
  We set $Q = 20$ GeV, $R_{EW} = 1$, $n_f = 5$
  We take QCD through $n = (1), 2$ as the predictions
  We take the ($n = 2$ term) $+$ $n = 3$ term $+$ $n = 4$ term as the missing H.O. corr.
- Two methods of estimating the physical precision
  (A) Varying the scale between $\frac{1}{2}Q$ and $2Q$
  (B) Using $f\times$ the $n = (1), 2$ contribution, $f \sim \frac{1}{2}$, as the physical precision error

A Matter of Precision

- We have also the following under $Q \to \mu_R$:
  $\bar{c}_1(\mu_R^2/Q^2) = c_1,$
  $\bar{c}_2(\mu_R^2/Q^2) = c_2 + \pi b_0 c_1 \ln(\mu_R^2/Q^2)$
  $\bar{c}_3 = c_3 + (2b_0 c_2 \pi + b_1 c_1 \pi^2) \ln(\mu_R^2/Q^2) + b_0^2 c_1 \pi^2 \ln^2(\mu_R^2/Q^2),$
  $\vdots$
- We use these results accordingly.

A Matter of Precision

- NLO$\equiv n = 1$, $\delta_{QCD} = 0.0476$
  (A):
$$\Delta(\delta_{QCD}) = \begin{cases} +.0074 \\ -.0056 \end{cases}$$
- (B):
$$\Delta(\delta_{QCD}) = \pm 0.024$$
- $$\Delta(\delta_{QCD})(HO) = 0.0014$$

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A Matter of Precision

- NNLO$\equiv n = 2,\ ,\ \delta_{QCD} = 0.0508$
  (A):

$$\Delta(\delta_{QCD}) = \begin{cases} +.00045 \\ -.0016 \end{cases}$$

- (B):

$$\Delta(\delta_{QCD}) = \pm 0.0016$$

- $$\Delta(\delta_{QCD})(HO) = -0.0018$$

- Conclusion: BLM, Zinn-Justin, Shifman,... can be observed too!

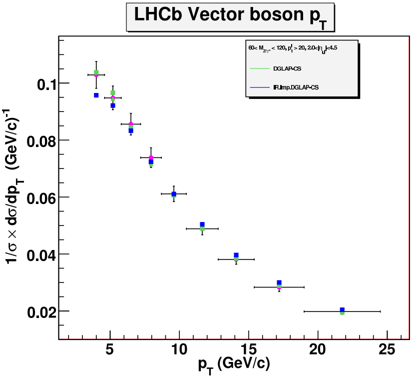
A Matter of Precision

- Methodology
- Approach (B): Physical Precision
- Semi-Analytic Baseline vs MC: Technical Precision
- Re-realization of the LEP/SLC paradigm.

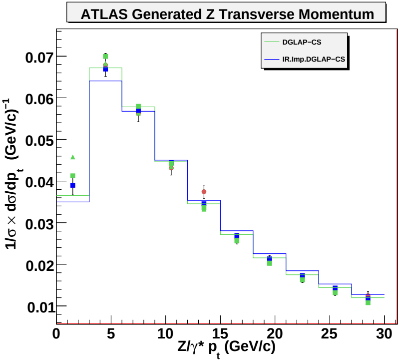
A Matter of Precision

- An Example

(a)



(b)



The blue(green) squares are MC@NLO/HERWIRI1.031(HERWIG6.510($\mathrm{PTRMS} = 2.2$GeV)), the green triangles are MC@NLO/HERWIG6.510($\mathrm{PTRMS} = 0$)

A Matter of Precision

- $\chi^2/d.o.f$
- MC@NLO/Herwig65(PTRMS=2.2GeV), MC@NLO/Herwig65(PTRMS=0), MC@NLO/Herwiri1.031(PTRMS=0) $\rightarrow$ .103,.183,.789 for (a)
- MC@NLO/Herwig65(PTRMS=2.2GeV), MC@NLO/Herwig65(PTRMS=0), MC@NLO/Herwiri1.031(PTRMS=0) $\rightarrow$ 1.37,2.23,.72 for (b)
- Proper interpretation $\Leftrightarrow$ Technical precision and physical precision under control.

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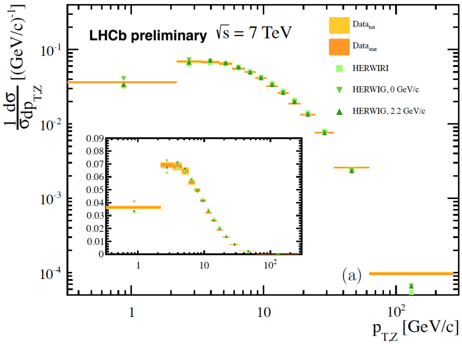
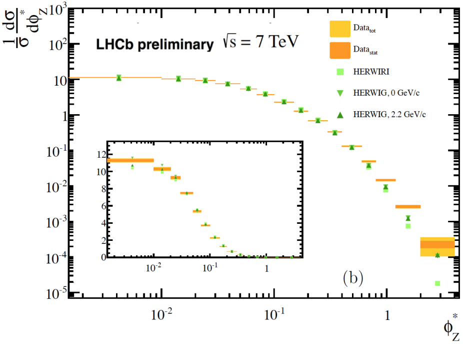
A Matter of Precision

- Recent Comparisons between LHCb Data and the Theory - 1505.07024

(a) **(b)**

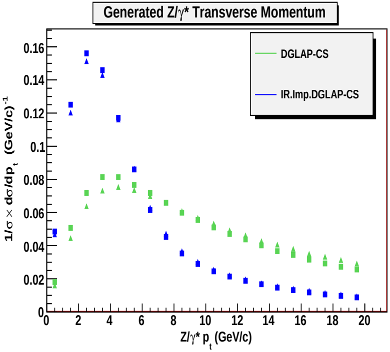




The light green squares(dark green triangles) are MC@NLO/HERWIRI1.031(HERWIG6.510(PTRMS $= 2.2$GeV)), the light green flipped triangles are MC@NLO/HERWIG6.510(PTRMS $=0$)

A Matter of Precision

- IR-Improved DGLAP-CS QCD Showers in Pythia8



Pythia8 IR-improved and unimproved p_T spectra at LHC for single Z/γ^* production, cms energies 7, 13 TeV: blue(green) squares $\Leftrightarrow$ IR-improved(unimproved) results for 7 TeV cms energy; triangles $\Leftrightarrow$ analogous results for 13 TeV cms energy. Results are untuned.

- IR-Improved Detector Effects “Soon”.

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!

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