KKMC-hh for Precision EW Phenomenology at the LHC

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KKMC-hh is a collaboration with S. Jadach, B.F.L. Ward and Z. Wąs.

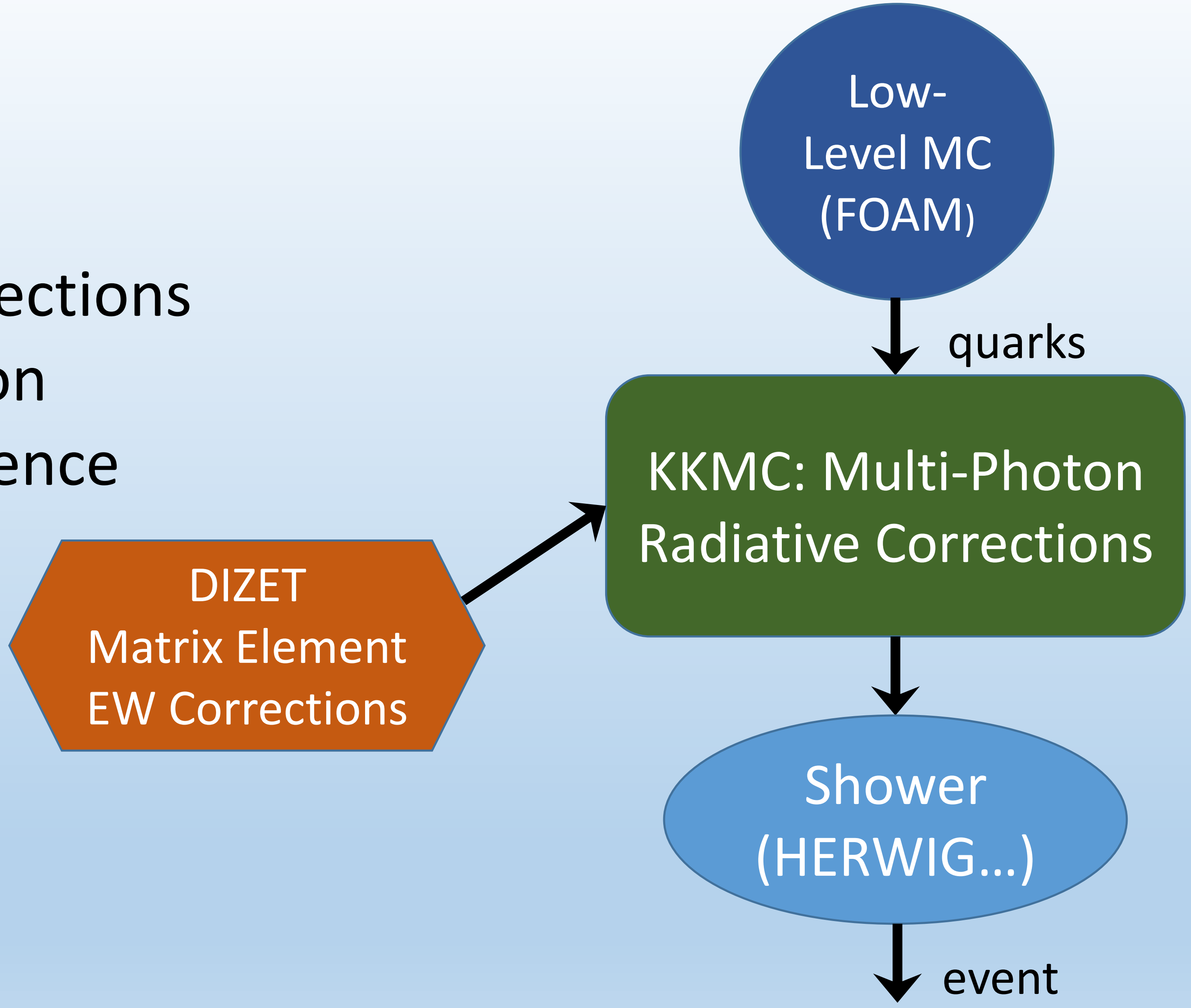
Computational resources provided by IFJ-PAN, Kraków.

KKMC-hh for Precision EW Phenomenology

- KKMC was developed for precision Z boson phenomenology in e^+e^- collisions, including exponentiated multi-photon effects:
$$e^+e^- \to Z/\gamma^* \to f\bar{f} + n\gamma$$
including exact $O(\alpha), O(\alpha^2 L)$ ISR, FSR, and IFI photonic corrections.
- $O(\alpha)$EW corrections were included via an independent DIZET6.21 module.
- Collision energies up to 1TeV are supported, with a LEP2 precision tag of 0.2%
- Version 4.22 of KKMC also included support for parton-level collisions with quark initial states.
- KKMC currently has two development branches: KKMC-ee for FCC-ee and KKMC-hh for hadron collisions. This talk will focus on the hadronic branch, which has been used in W mass studies, and is presently being used in A_{FB} studies relevant to measuring the EW mixing angle.

Outline

- Low Level MC (Foam)
- Photonic Radiative Corrections
  - Initial State Radiation
  - Initial-Final Interference
- DIZET and updates
- Parton Shower



Low-Level MC (Foam)

- An adaptive MC, Foam by S. Jadach, underlies the low-level event generation. It generates momentum fractions x_1, x_2 for the quarks and a photon radiation factor v, together with the flavor index i of the colliding quark – four variables for a general collision.
- Without ISR, the hard collision occurs at $s_X = x_1 x_2 s$, where $s = 4E_P^2$ for the protons.
- With ISR, the hard collision scale is reduced to $(1-v)s_X$.
- TheCrude MC integral has the (slightly simplified) form

$$\sigma_{\mathrm{Cr}} = \int_0^1 dx_1 \int_0^1 dx_2 \sum_{i=1}^{N_q} \mathrm{PDF}_i(s_X, x_1)\mathrm{PDF}_{\bar{\imath}}(s_X, x_2) \int_0^1 \frac{dv}{v} \gamma_i v^{\gamma_i} \sigma_{i\,\mathrm{Cr}}\big((1-v)s_X\big)$$

where $\gamma_i = \frac{2\alpha}{\pi} \, Q_i^2\big(\ln\big(s/m_i^2\big) - 1\big)$ and $\sigma_{i\,\mathrm{Cr}}$ is a crude partonic Born CS without EW corrections.

- The Foam grid is set up during an initial exploratory phase, creating a crude MC distribution that includes the PDF factors and a crude YFS form-factor for ISR photon radiation.

KKMC Photonic Radiative Corrections

KKMC has two modes of soft-photon exponentiation.

- EEX, "Exclusive Exponentiation", is YFS-style resummation at the cross-section level.
- CEEX, "Coherent Exclusive Exponentiation", is an amplitude-level version of YFS resummation introduced for better control over initial-final interference: Exponentiated IFI enters naturally when an amplitude with exponentiated ISR and FSR is squared.

KKMC-hh calculates a set of EEX and CEEX weights with various levels of exact hard-photon residuals: $O(\alpha^0), O(\alpha^1), O(\alpha^2 L)$ in CEEX mode, and adding $O(\alpha^3 L^3)$ in EEX mode.

IFI is included only in the CEEX weights. The default "best" cross section is CEEX $O(\alpha^2 L)$.

Photonic Corrections: FSR, ISR, IFI

Photonic corrections can be separated into three classes in a gauge-invariant manner:

- ISR – Initial State Radiation (from the quarks)
- FSR – Final State Radiation (from the final leptons)
- IFI – Initial-Final Interference

Final state photonic corrections are already readily available in the widely used PHOTOS package, which shares an author (Z. Wąs) and approach with KKMC.

Several other programs can calculate ISR and IFI. Other programs presently participating in LHC EW Precision studies for the LHC include:

- POWHEG-EW: F. Piccinini, M. Chiesa, et al.
- MCSANC: A Arbuzov, D. Bardin, S. Bondarenko, L. Kalinovskaya, et al.
- HORACE: C.M. Carloni Calame, G. Montagna, O. Nicrosini, A. Vicini
- ZGRAD2: U.Baur, O.Brein, W.Hollik, C.Schappacher, D. Wackeroth

Different Approaches to ISR

Traditionally, ISR has been assumed to be factorized into the PDFs and not requiring much attention.

ISR is suppressed relative to FSR due to the small quark charges – especially for d, s, b.

At the per-mil level, which is important in precision EW measurements, ISR cannot be neglected.

Parton Distribution Functions incorporating QED effects are increasingly available: eg. NNPDF3.1-LuxQED, CT14QED (and the original – MRST2004 QED)

Unlike QCD ISR, QED ISR is directly observable (unconfined) and perturbatively calculable in the soft limit. KKMC-hh includes and ab-initio calculation of exponentiated photon radiation from the initial quarks.

KKMC-hh is unique in this regard: the other programs listed factorize quark ISR into the PDFs, thus requiring a QED-corrected PDF set for precision EW calculations. KKMC-hh must use a PDF in which photonic effects are absent to within the claimed precision of the PDF.

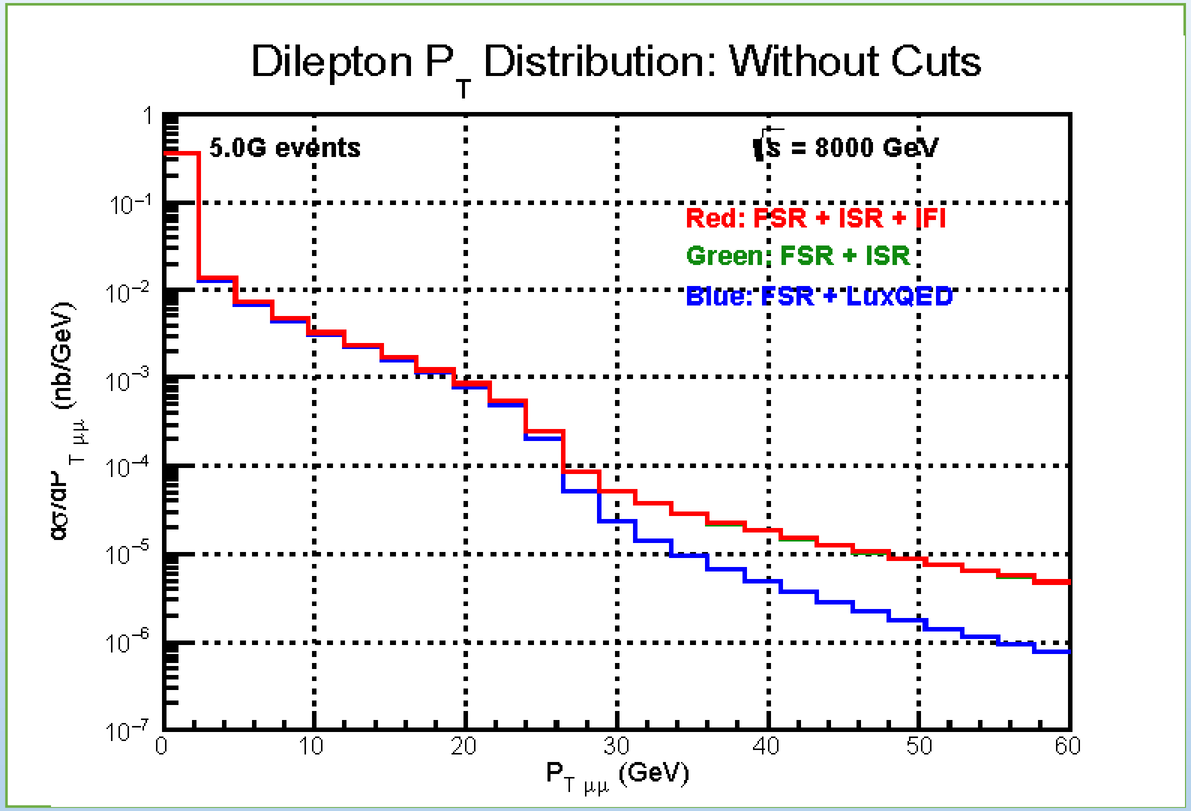
Different Approaches to ISR

The presence of the quark mass m_i in the logarithm $\ln(s_X/m_i^2)$ governing ISR introduces a fractional per-mille dependence on the value of m_i.

We do not share the philosophy adopted by the other programs that the quark masses are "unphysical" or "regulators" to be avoided, but consider them to be **physical parameters** with an observable effect on QED radiation that needs to be taken into account for precision results.

In particular, keeping the full ISR in the program permits the full effect of ISR on transverse momentum to be seen.

The results should be compatible for observables inclusive in the transverse momentum.



8000 GeV collisions, $60 < M_{ll} < 150$ GeV
NNPDF3.1 NLO, NNPDF3.1NLO + LuxQED.
5×10^9 muon events, no lepton cuts.

Comparison of M_{ll} Distributions

We show 3 comparisons for 10^9 muon events generated at an 8000 GeV CM energy.

- **No ISR:** No photonic corrections, NNPDF3.1NLO (no QED)
- **LuxQED PDF:** NNPDF3.1NLO LuxQED PDF, with photonic corrections off in KKMC.
- **KKMC-hh ISR:** ISR (only) on in KKMC.

The only cut is $60 < M_{ll} < 120$ GeV.

	No ISR	LuxQED PDF	KKMC-hh ISR
Cross Section (pb)	972.84(2)	966.80(2)	967.08(5)
Average M_{ll} value (GeV)	90.5111(2)	90.5105(2)	90.5108(2)

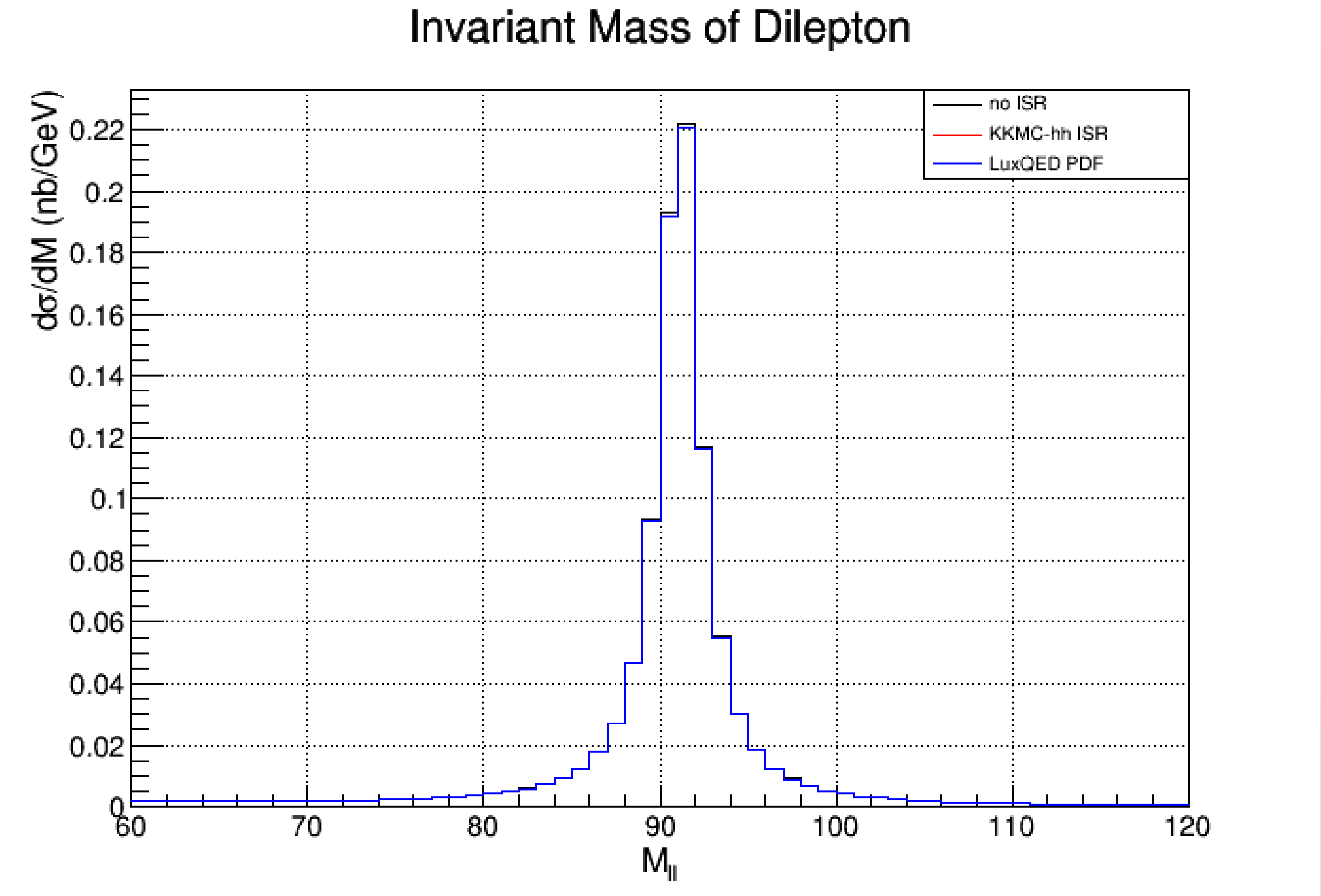
Results from work with Matthew Dittrich @ The Citadel.

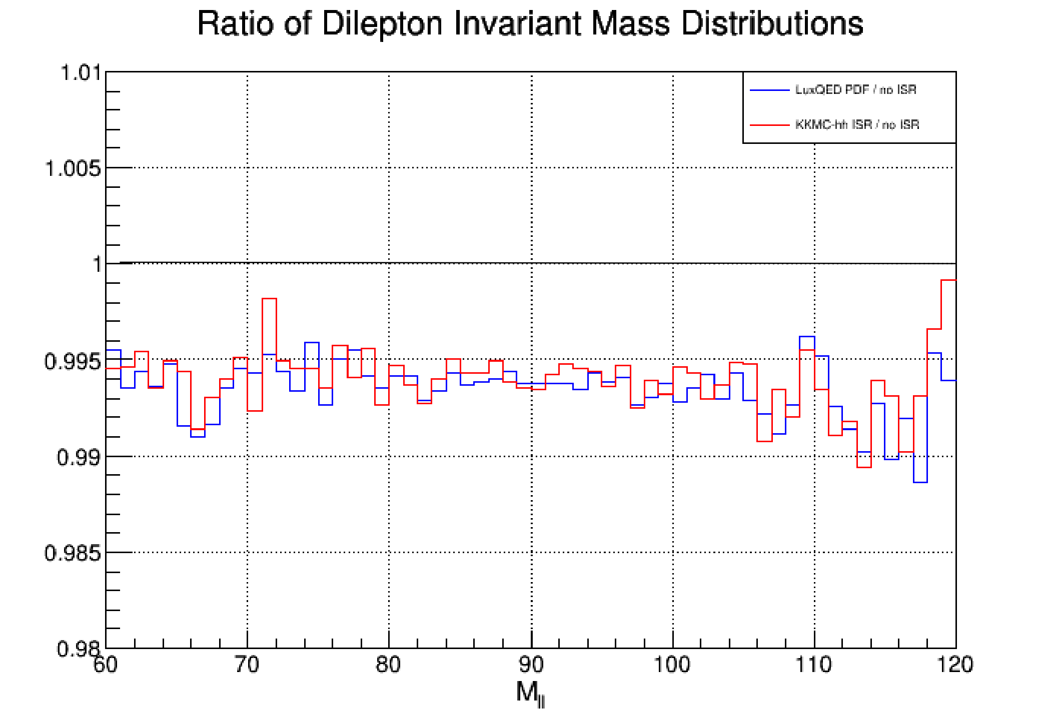
ISR reduces the cross section by 0.6%: $-0.621(3)\%$ (LuxQED), $-0.592(5)\%$ (KKMC-hh).

The average M_{ll} shifts slightly in each case: $\Delta\langle M_{ll}\rangle = -0.6 \pm 0.3$ MeV (LuxQED),

$\Delta\langle M_{ll}\rangle = -0.3 \pm 0.3$ MeV (KKMC-hh).

Invariant Mass Distributions for Final Muons

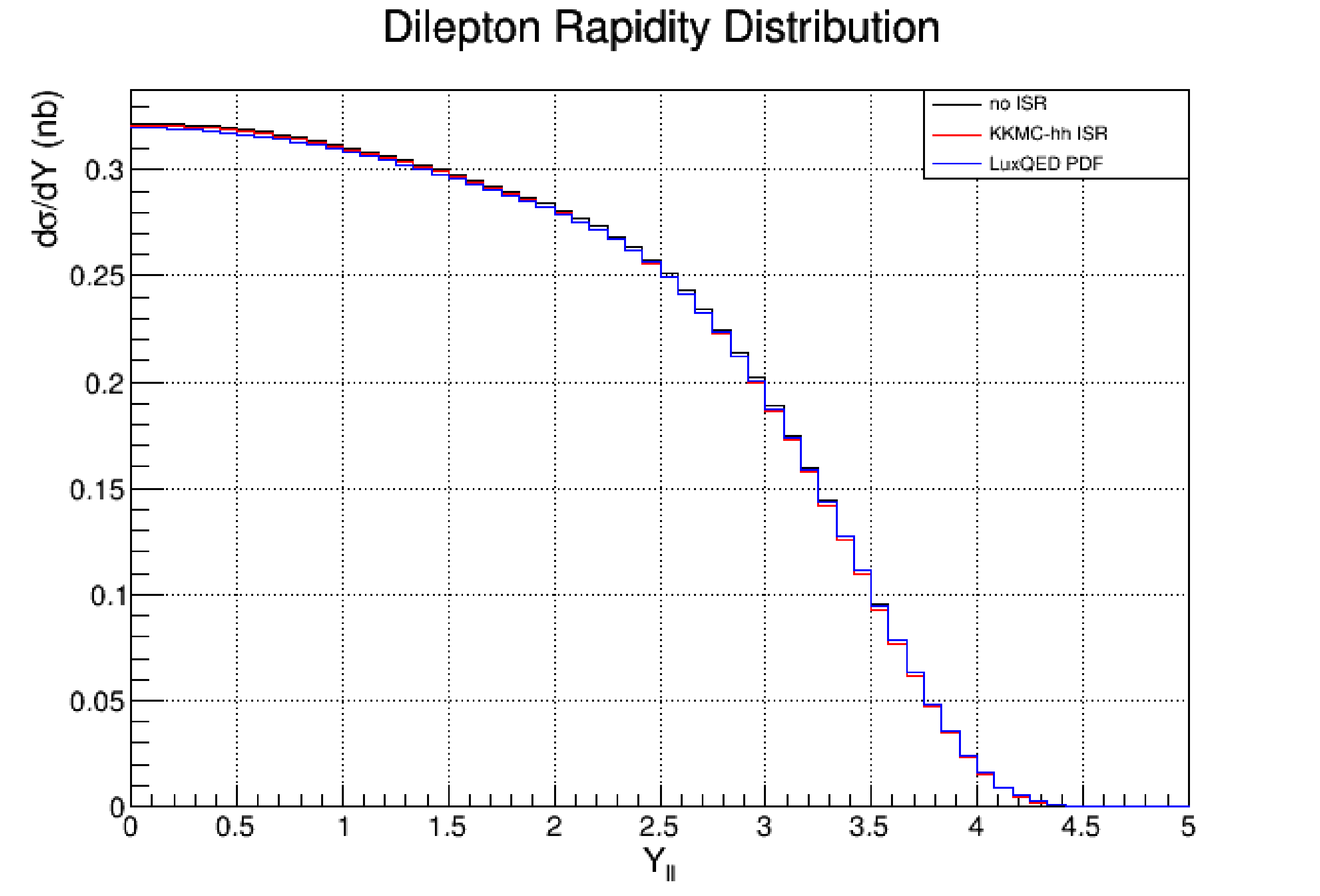


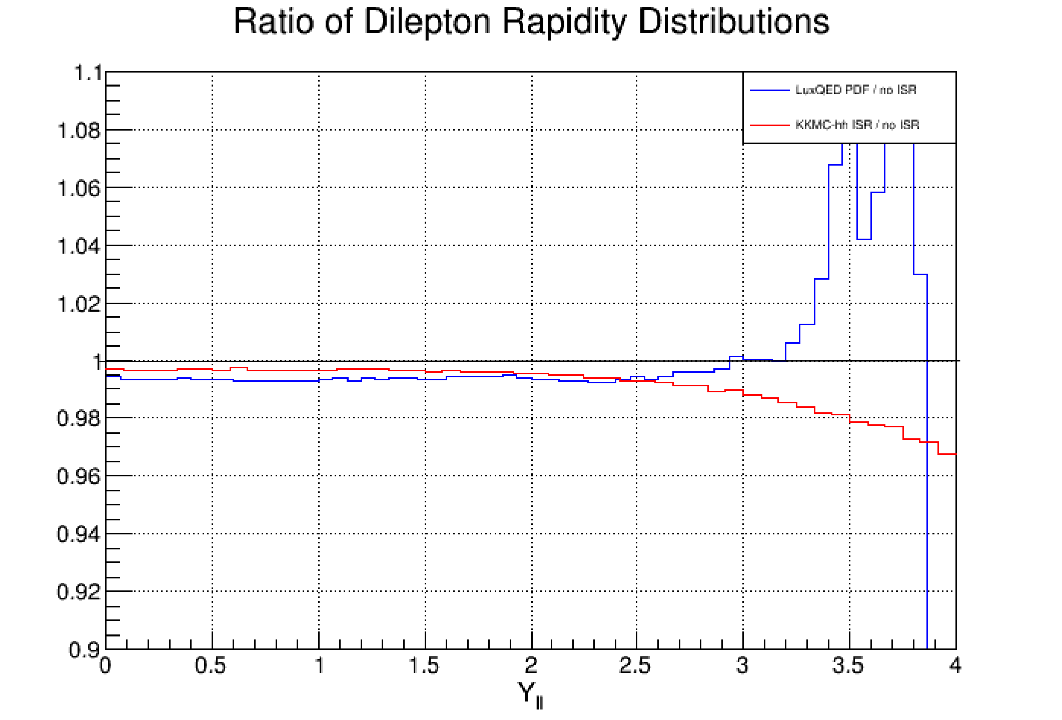


There is a small downward shift in the distributions in each case.

Graphs from work by Matthew Dittrich @ The Citadel.

Rapidity Distributions for Final Muons





Graphs from work by Matthew Dittrich @ The Citadel.

There is again a small downward shift in the distributions in each case for $Y_{ll} < 3$. The behaviors differ for large rapidity.

Initial-Final Interference

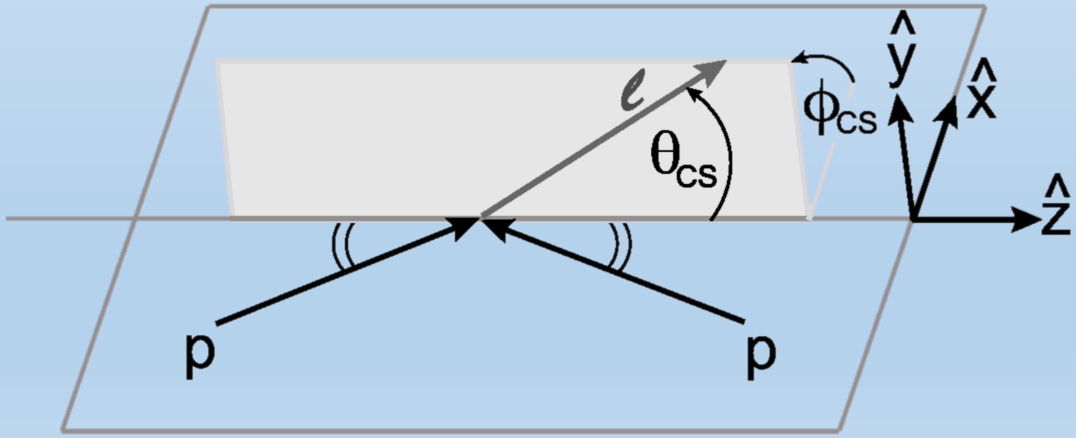
Initial-Final interference (IFI) can have an important influence on measurements of forward-backward asymmetry, since it has a strong angular dependence.

KKMC-hh (CEEX mode) includes IFI contributions matched to complete $O(\alpha^2 L)$ QED and $O(\alpha)$ EW corrections and including resummation of $\ln(\Gamma_Z/M_Z)$ near the Z resonance.

The LHC EW Precision Working Group has been investigating the effect of IFI on the angular distributions used to extract a precision measurement of $\sin^2\theta_W$.

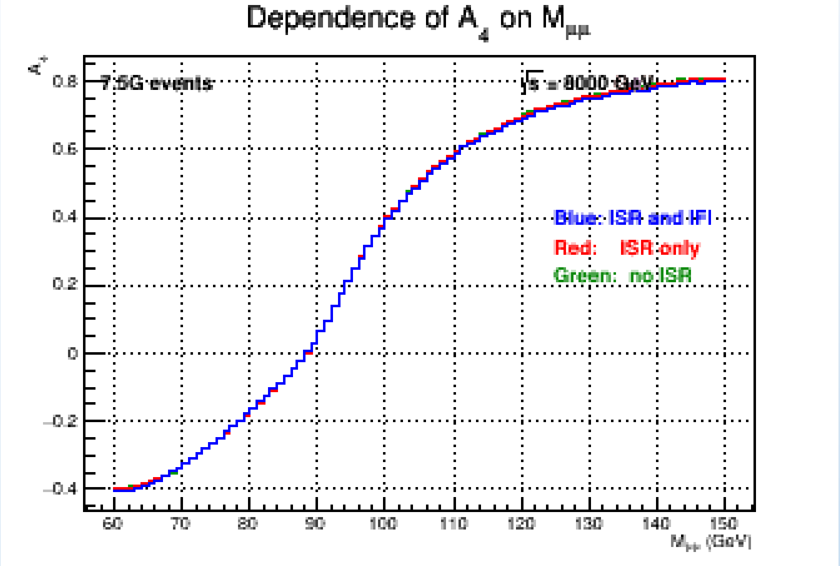
Specifically, we have been studying A_{FB} and $A_4 = 4\langle\cos\theta_{\mathrm{CS}}\rangle$, where θ_{CS} is the Collins-Soper angle in the rest-frame of the final lepton pair:

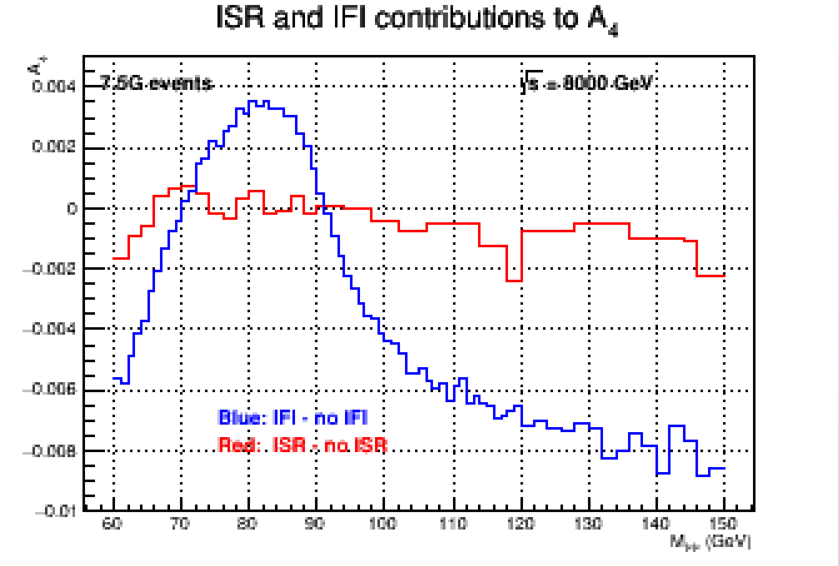
$$\cos\theta_{CS} = \mathrm{sgn}(P_{ll}^z)\frac{p_l^+ p_{\bar{l}}^- - p_l^- p_{\bar{l}}^+}{\sqrt{P_{ll}^2 P_{ll}^+ P_{ll}^-}}$$

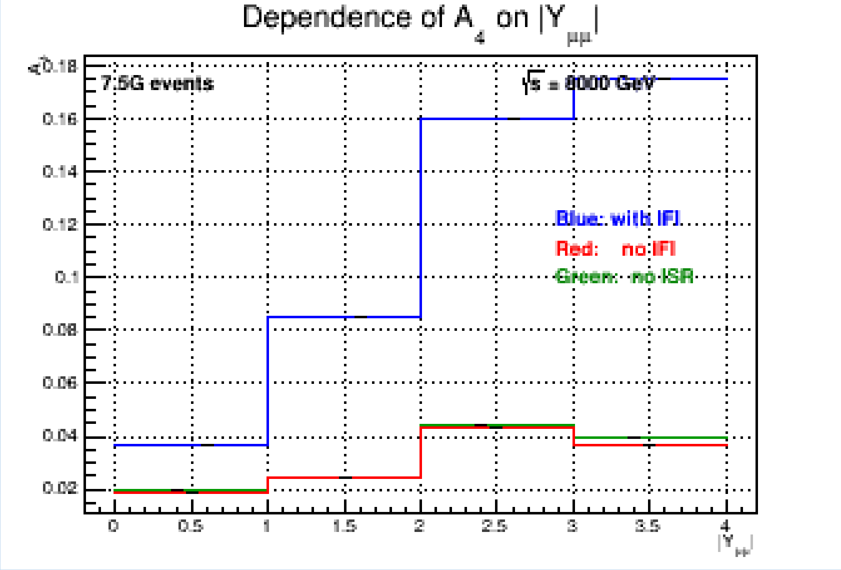


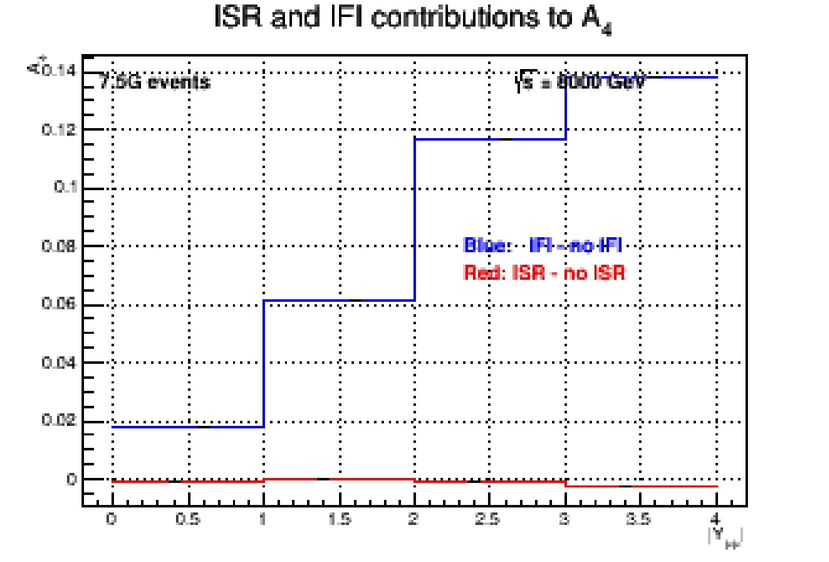
for $P_{ll} = p_l + p_{\bar{l}}$ and $p^\pm = p^0 \pm p^z$.

ISR and IFI contributions to A_4









The ISR and IFI contributions to A_4 are shown here, with A_4 defined to be $\frac{8}{3}A_{FB}$ in the full phase space,

$60 < M_{ll} < 150$ GeV

ISR is relatively flat and close to zero near the Z mass, but IFI has significant structure.

Dizet EW Corrections

Dizet provides a set of form factors that can be used in an improved Born approximation for the hard process, starting with a crude Born amplitude*

$$\mathcal{M}_{\mathrm{Born}} = \frac{1}{s}(\bar{u}\gamma^{\mu}v)_i\big(\bar{v}\gamma_{\mu}u\big)_f\{q_i q_f + v_i v_f \chi_Z(s)\}$$
$$+\frac{\chi_z(s)}{s}\Big\{(\bar{u}\gamma^{\mu}v)_i\big(\bar{v}\gamma_{\mu}\gamma^5 u\big)_f v_i a_f \chi_Z(s) + (\bar{u}\gamma^{\mu}\gamma^5 v)_i\big(\bar{v}\gamma_{\mu}u\big)_f a_i v_f$$

with

$$\chi_z(s) = \frac{G_\mu M_Z^2 \Delta^2}{8\pi\alpha(0)\sqrt{2}} \frac{s}{s - M_Z^2 + i\Gamma_Z M_Z} \quad , \qquad \Delta = 4\sin\theta_w \cos\theta_W \quad ,$$

$$v_{i,f} = \frac{1}{\Delta}\left(2T_3^{i,f} - 4q_{i,f}\sin^2\theta_W\right) \quad , \qquad a_{i,f} = \frac{2T_3^{i,f}}{\Delta} \quad .$$

Dizet EW Corrections

Dizet inserts factors as shown:

$$\mathcal{M}_{\text{Born}} = \frac{1}{s}(\bar{u}\gamma^{\mu}v)_i(\bar{v}\gamma_{\mu}u)_f\left\{\frac{q_i q_f}{2-\left(1+\Pi_{\gamma\gamma}(s)\right)} + v_i v_f V_{if}\chi_Z(s)\right\}$$

$$+\rho_{if}(s,t)\frac{\chi_Z(s)}{s}\left\{(\bar{u}\gamma^{\mu}v)_i(\bar{v}\gamma_{\mu}\gamma^5 u)_f v_i a_f \chi_Z(s) + (\bar{u}\gamma^{\mu}\gamma^5 v)_i(\bar{v}\gamma_{\mu}u)_f a_i v_f\right.$$

with

$$v_{i,f} = \frac{1}{\Delta}\left(2T_3^{i,f} - 4q_{i,f}K_{i,f}(s,t)\sin^2\theta_W\right) \quad , \qquad a_{i,f} = \frac{2T_3^{i,f}}{\Delta} \quad ,$$

$$V_{if} = \frac{4}{\Delta^2 v_i v_f}\left\{T_3^i T_3^f - 4\sin^2\theta_W\left(q_i K_i(s,t) + q_f K_i(s,t)\right) + 4\sin^4\theta_W\, q_i q_f K_{if}(s,t)\right\}.$$

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}	$\sin^2(\theta_\mathrm{W})$	0.22340108
M_Z	91.1876 GeV	$\sin^2(\theta_\mathrm{W})_\mathrm{eff}$	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

Shifts due to Dizet 6.21 → 6.45

The EW form-factors in Dizet changed to varying degrees: (details in appendix)

- The shift in ρ_{if} turns out to be negligible.
- The shifts in the real parts of K_i and K_f were both approximately independent of $\sqrt{s}$ and $\cos\theta$, $\sim\ -8\times 10^{-4}$.
- The shift in $\mathrm{Re}\, K_{if}$ was about twice this, $\sim -17\times 10^{-4}$, still approximately independent of $\sqrt{s}$ and $\cos\theta$
- The shift in $\Pi_{\gamma\gamma}$ was about $\sim -5\times 10^{-4}$.

In the context of KKMC-ee for FCC-ee, the EW library updates are described in: A. Arbuzov, S. Jadach, Z. Wąs, B.F.L. Ward, S.A. Yost, arXiv:2007.07964

(submitted to Computer Physics Communications). The same DIZET updates are now incorporated in KKMC-hh as well.

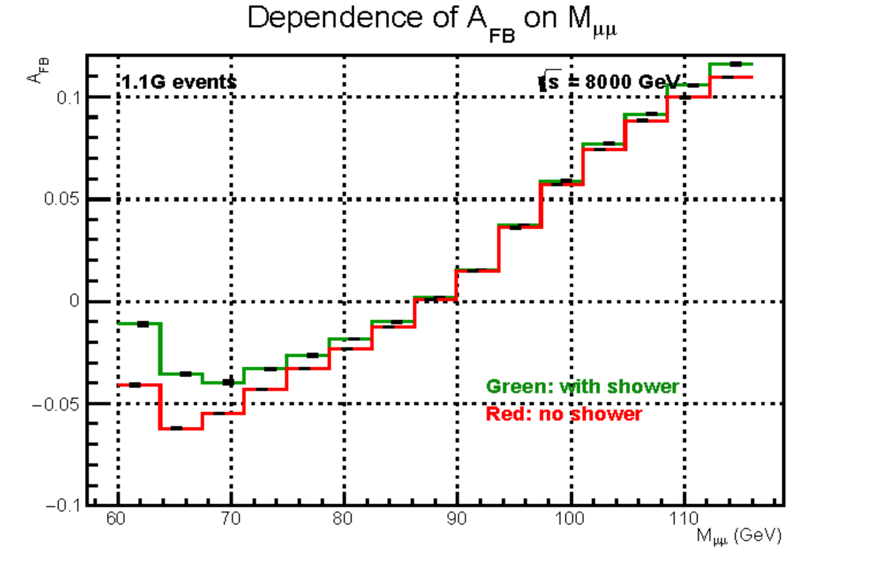
Parton Shower

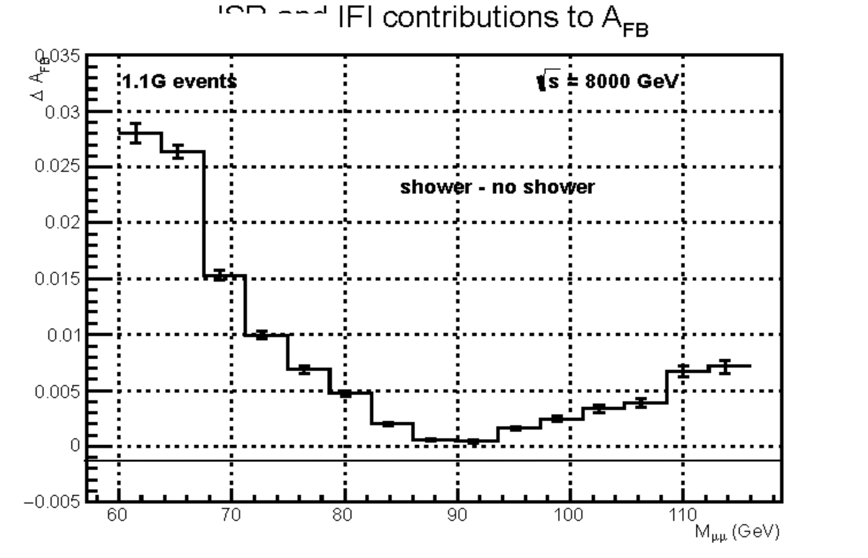
The events produced by KKMC-hh may be showered in several ways.

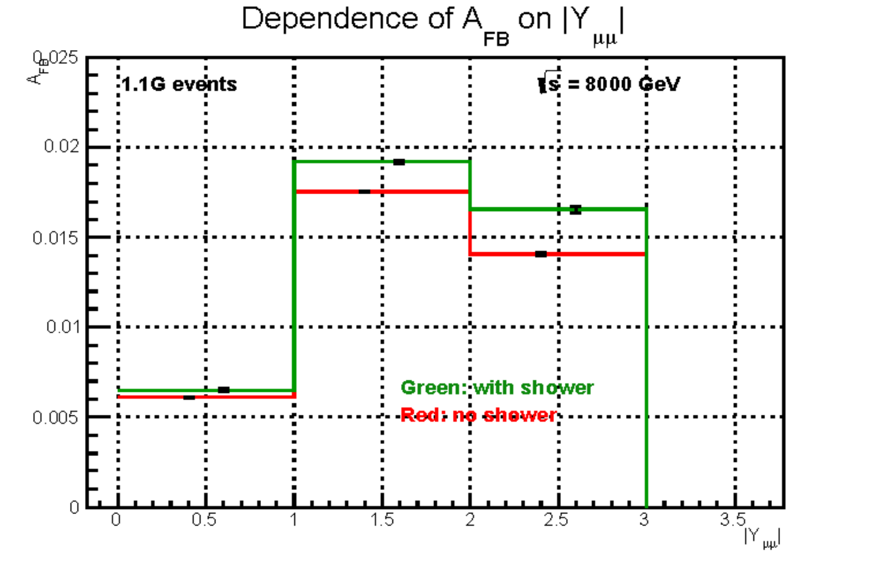
Presently, a HERWIG 6.521 shower is compiled together with KKMC-hh, and KKMC can provide an improved hard Drell Yan process over the one in HERWIG, which can then be showered as its own hard process would have been.

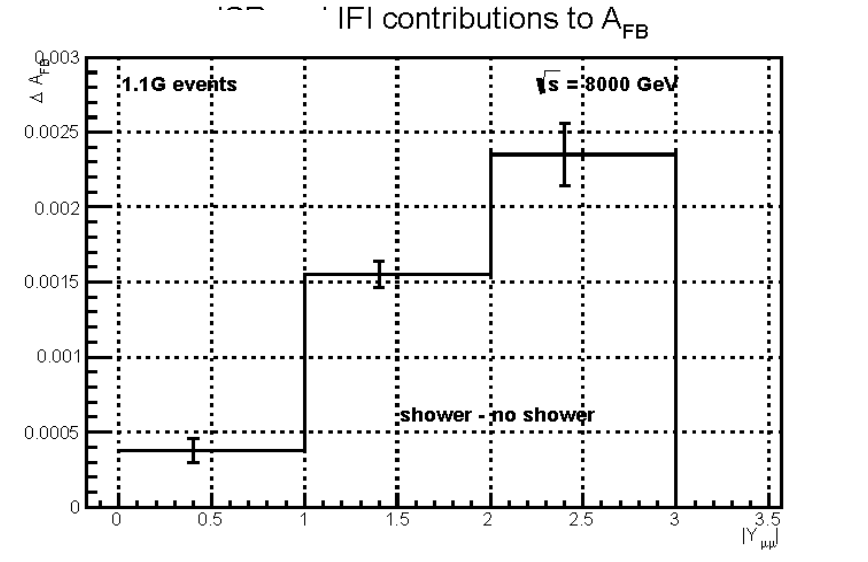
Alternatively, events may be passed via an LHA-compliant event record to an external showering program, which opens the possibility to using a variety of showers. In particular, we have recently been preparing for runs using a Herwig7 shower, and transcoding parts of KKMC-hh in C++ for deeper integration with Herwig7.

Showered contributions to A_{FB}









As an example, the effect of the shower on A_{FB} (which is $\frac{3}{8}A_4$ in the earlier slide) is shown here.

The shower adds significant time to the run, so the statistics are lower here.

The effect of the shower on A_{FB} increases for larger rapidities Y_{ll}.

Summary/Outlook

KKMC-hh brings the high-precision of KKMC-ee to a hadronic context, where it can be used in precision EW studies at the LHC.

The ab-initio approach to ISR QED is non-traditional, but appears to be consistent with other approaches, and permits a more complete description of radiation from quarks.

KKMC-hh does not include photon-induced processes at this time, and that is probably not a high priority. Other programs can support studies of these effects (e.g. Horace, Powheg-EW).

Eventually, it is anticipated that the KRKNLO shower will be integrated with KKMC-hh, giving it NLO QCD corrections internally, and opening the way for higher-order mixed QCD/EW corrections as the demand arises.

We are also working on inverting the interface, so that events generated by a QCD shower can be fed to KKMC-hh for adding photonic and EW corrections. Some parts of this are presently in testing, but it is too early to discuss them.

Appendix 1: KKMC-hh and KKMC: References

Recent KKMC-hh papers:

- S. Jadach, B.F.L. Ward, Z. Wąs and S.A. Yost, KKMC-hh: Resummed Exact $\mathcal{O}(\alpha^2 L)$ EW Corrections in a Hadronic MC Event Generator, Phys. Rev. D94, 074006 (2016) [arXiv:1608.01260]
- Ibid., Systematic Studies of Exact $\mathcal{O}(\alpha^2 L)$ CEEX EW Corrections in a Hadronic MC for Precision Z/γ^* Physics at LHC Energies, Phys. Rev. D99, 076016 (2019) [arXiv:1707.06502]
- Ibid., IFI and ISR Effects in Z/γ^* Drell-Yan Observables using KKMC-hh, submitted to Phys. Rev. D (2020) [arXiv:2002.11692]

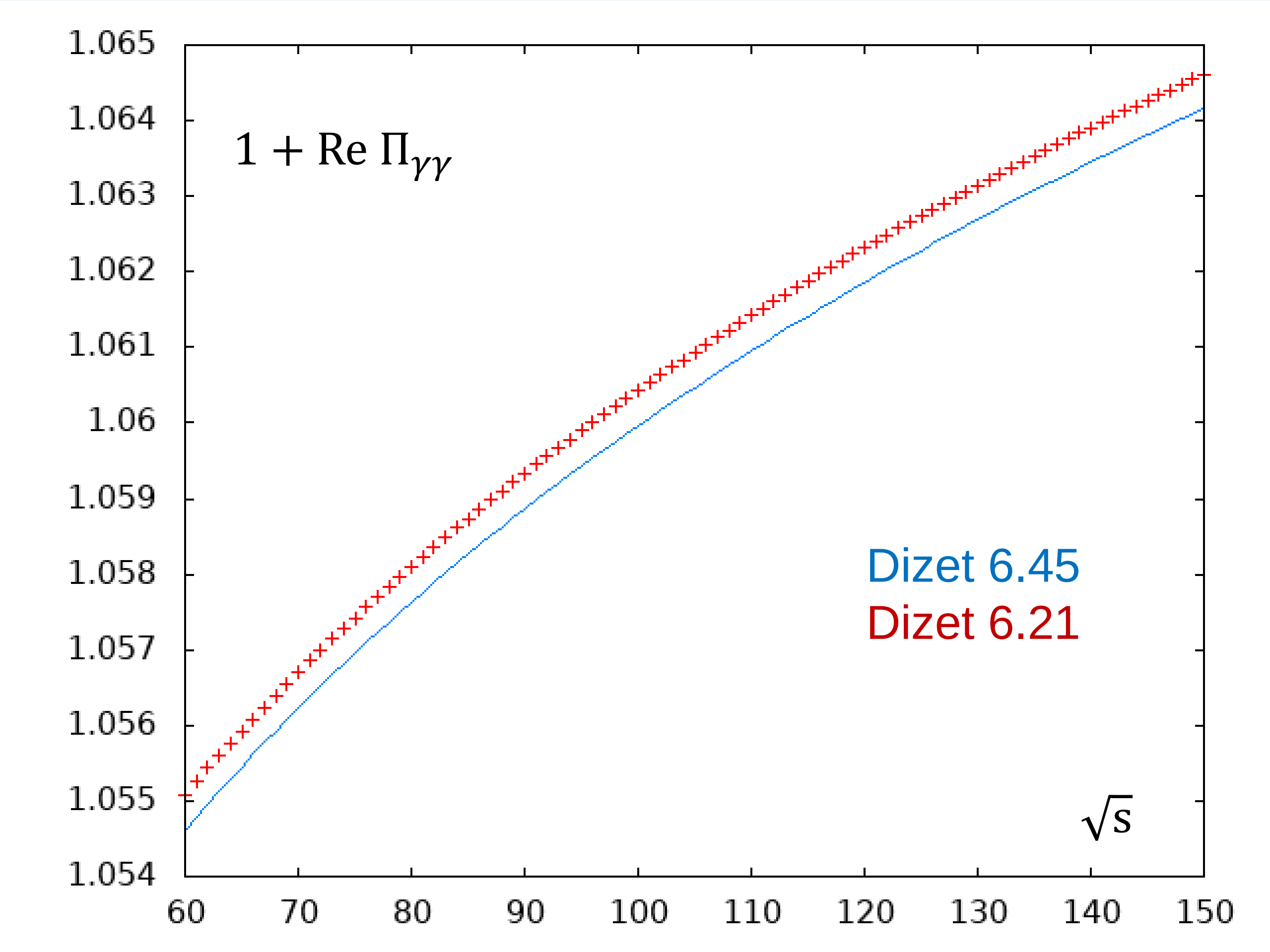
Recent KKMC-ee papers:

- S. Jadach and S. Yost, QED Interference in Charge Asymmetry near the Z resonance at Future Electron-Positron Colliders, Phys. Rev. D 100, 013002 (2019) [arXiv:1801.08611]
- A. Arbuzov, S. Jadach, Z. Wąs and S.A. Yost: The Monte Carlo Program KKMC for Lepton and Quark Pair Production at LEP/SLC Energies – Updates of Electroweak Calculations, submitted to Comp. Phys. Commun. (2020) [arXiv:2007.07964]

Original KKMC and CEEX papers:

- S. Jadach, B.F.L. Ward and Z. Wąs, Comput. Phys. Commun. 130 (2000) 260 [hep-ph/9912214]
- Ibid., Phys. Rev. D63 (2001) 113009 [hep-ph/0006359]

Appendix 2: Dizet Form Factors



This appendix includes graphs of Dizet form factors used in KKMC-hh.

$\Pi_{\gamma\gamma}$ depends only on s. It doesn't depend on the quark flavor or angle.

Dizet 6.21 is shown with red points, and Dizet 6.45 is shown with a blue line.

The change from Dizet 6.21 to 6.45 is approximately constant,

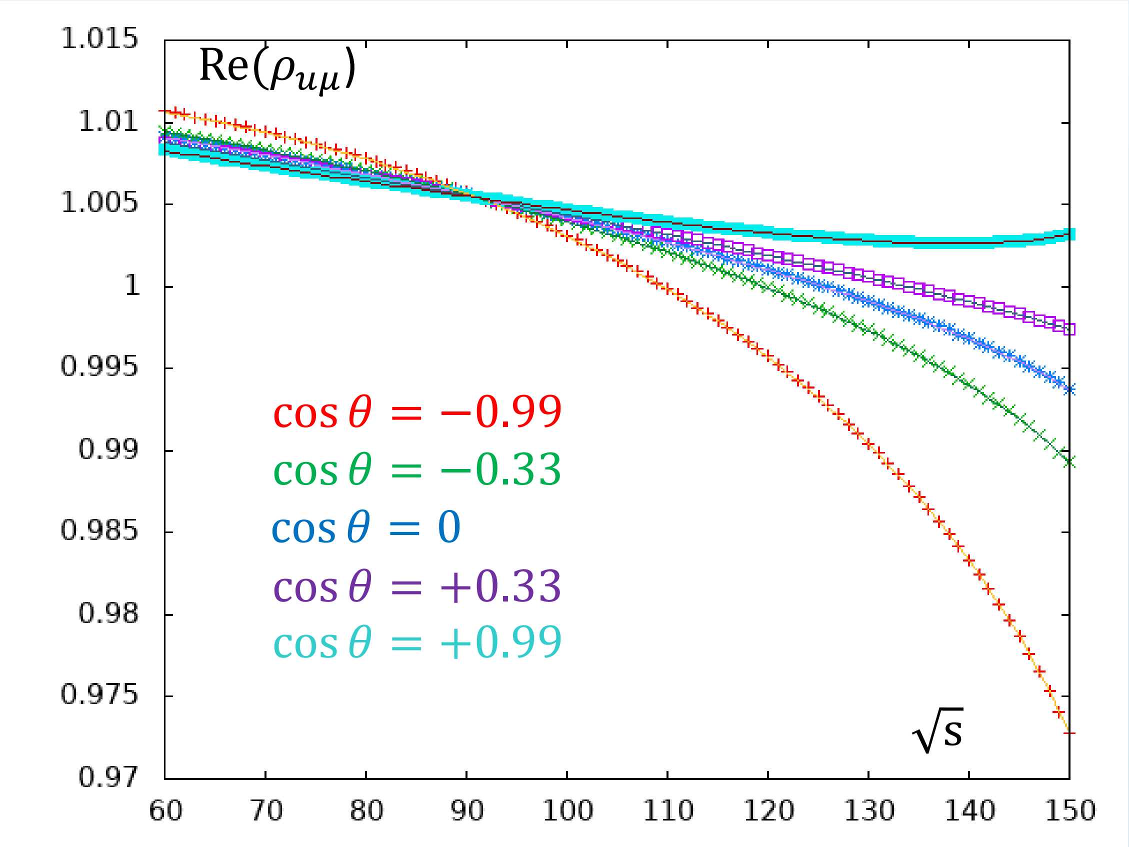
-4.75×10^{-4} at 60 GeV,

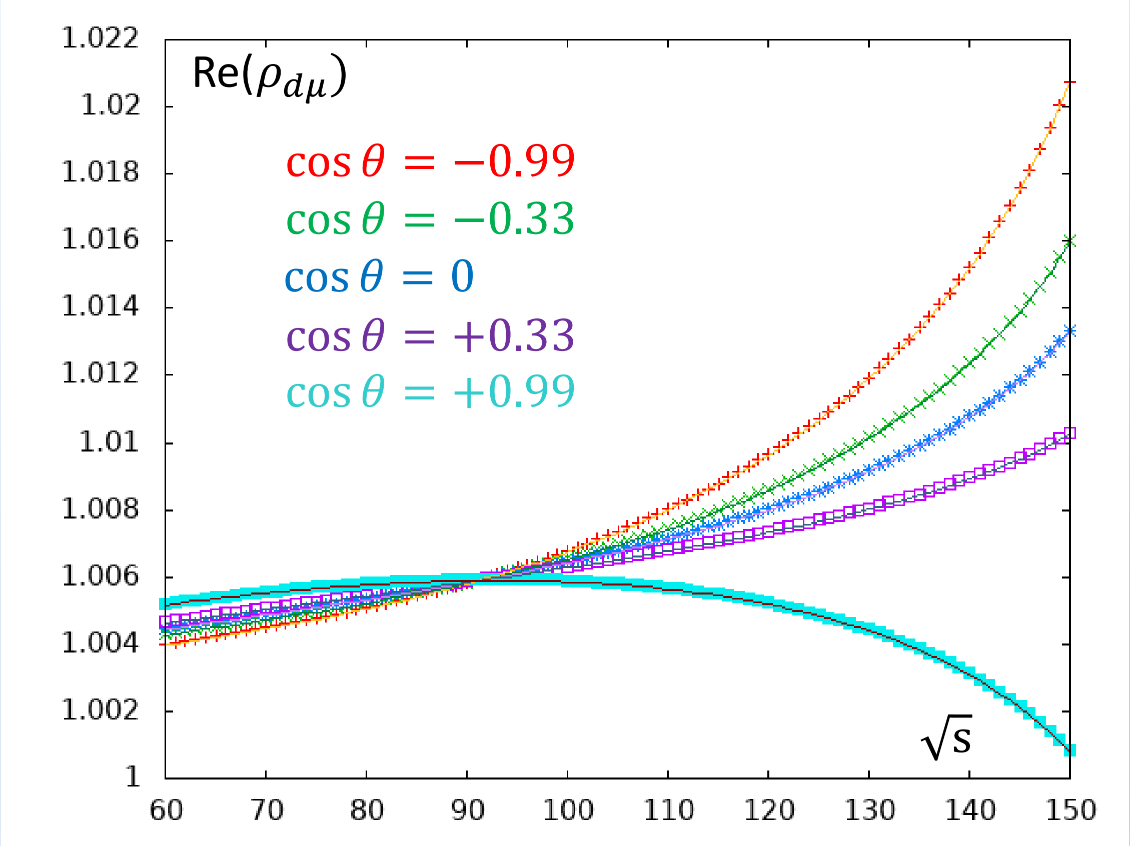
-4.57×10^{-4} at 150 GeV.

$\rho_{u\mu}$ and $\rho_{d\mu}$ for Dizet 6.21 and Dizet 6.45

The dotted lines are made using Dizet 6.21, and the solid lines are from Dizet 6.45 in all plots.

$\cos\theta$ is calculated in the quark CM frame. Only real parts are shown. There is no apparent version dependence.



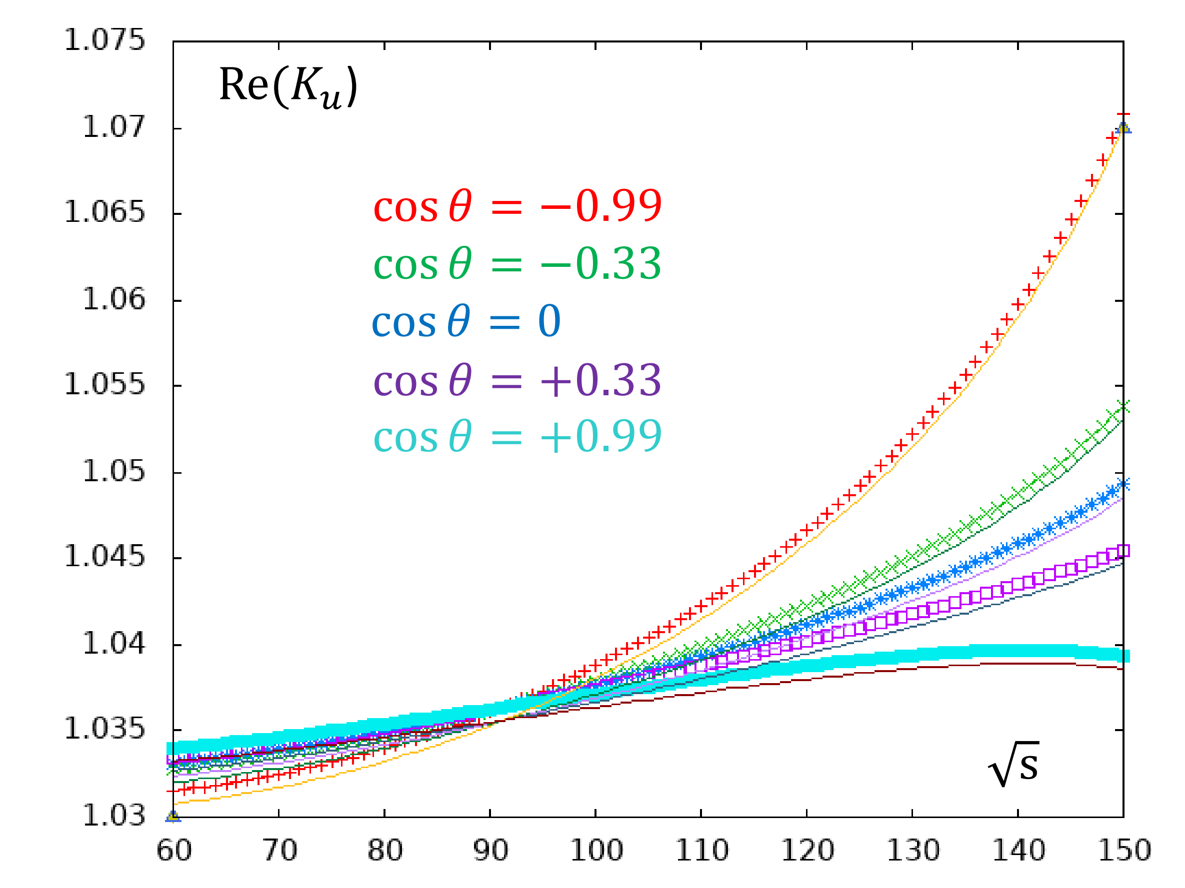


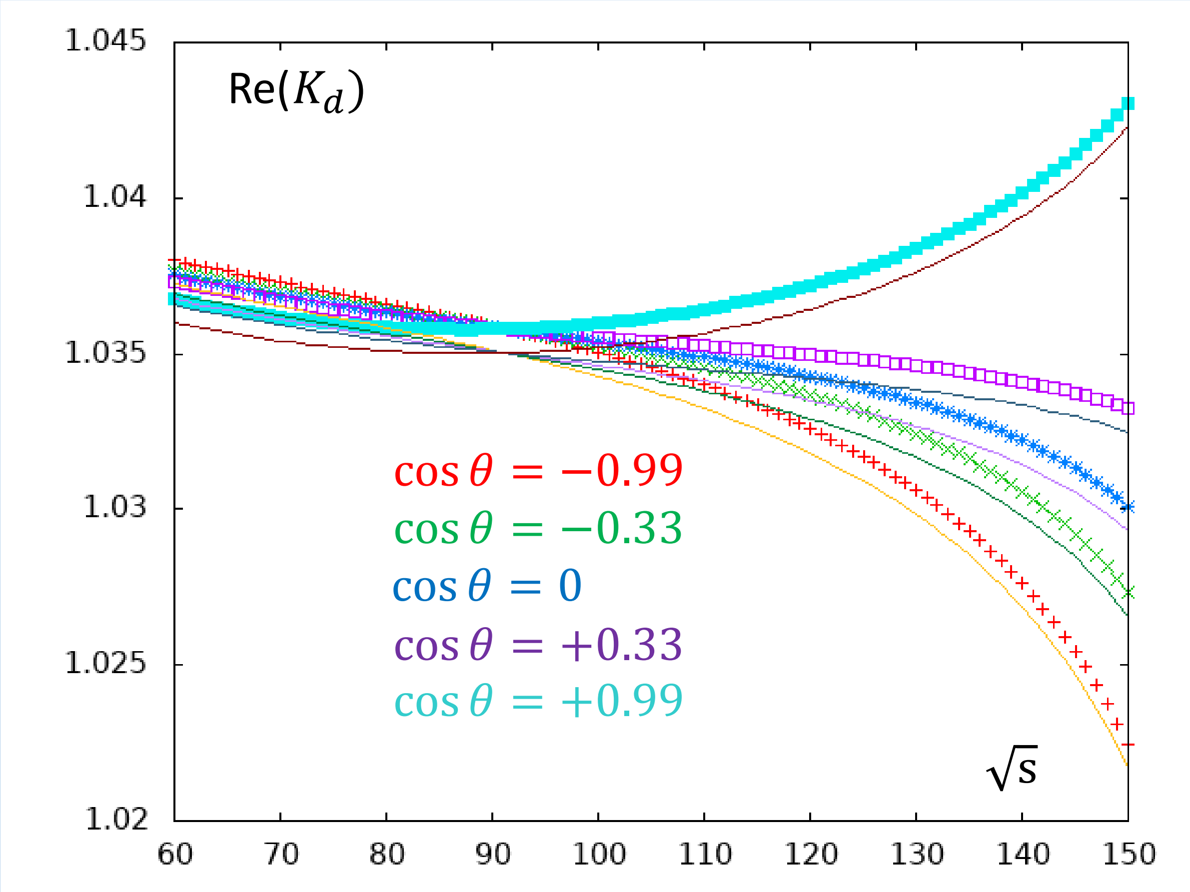
K_u and K_d for Dizet 6.21 and Dizet 6.45

The dotted lines are made using Dizet 6.21, and the solid lines are from Dizet 6.45 in all plots.

Five values of cosθ calculated in the CM frame are used. These were calculated for $u\bar{u} \to \mu_+\mu_-$, $d\bar{d} \to \mu_+\mu_-$.

There is a roughly constant shift of -8×10^{-4} from the old to new K-factors.



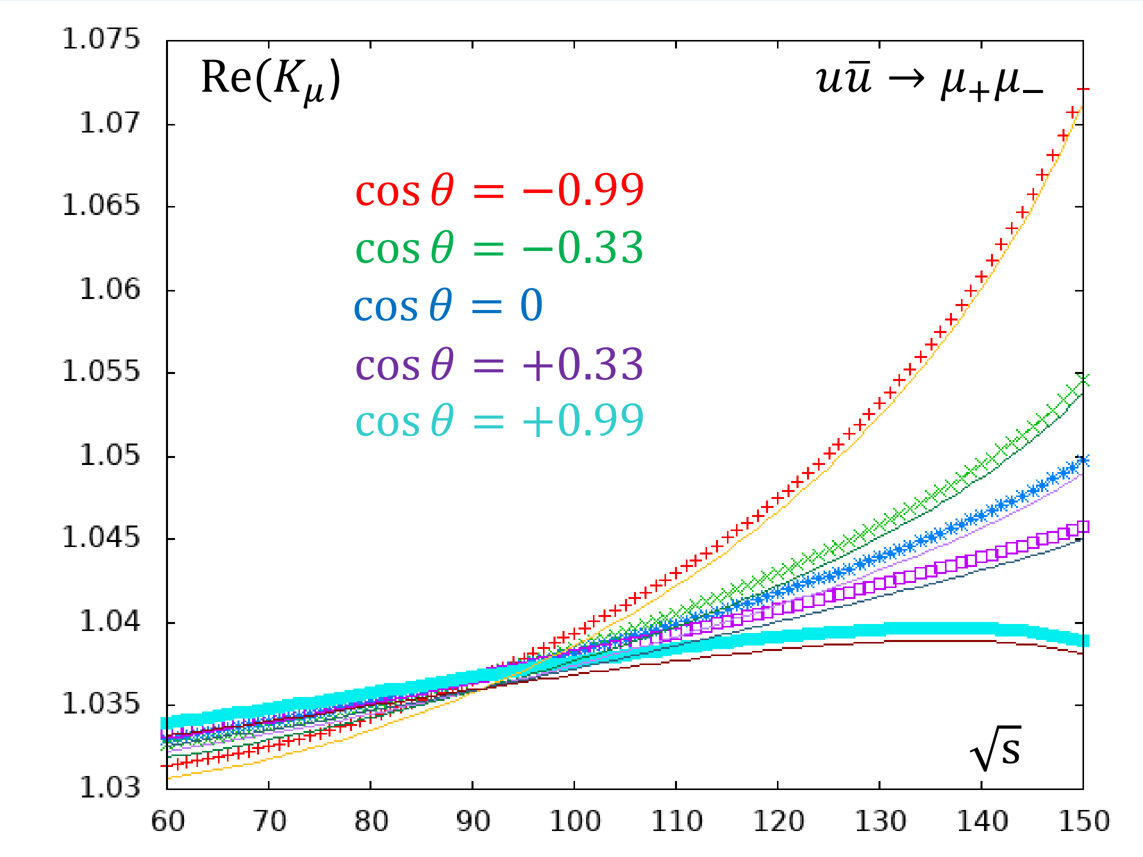


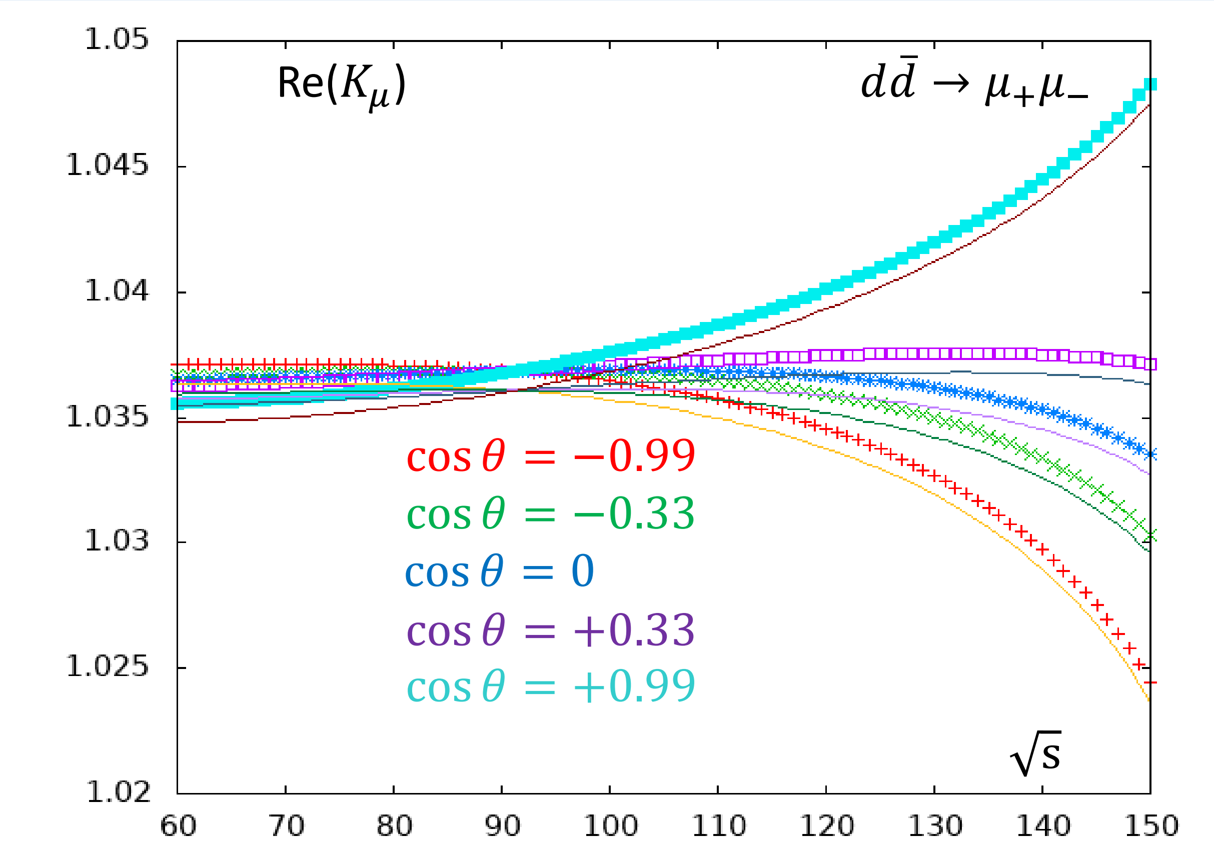
K_μ for Dizet 6.21 and Dizet 6.45

The dotted lines are made using Dizet 6.21, and the solid lines are from Dizet 6.45 in all plots.

Five values of cosθ calculated in the CM frame are used. These were calculated for $u\bar{u} \to \mu_+\mu_-$, $d\bar{d} \to \mu_+\mu_-$.

There is a roughly constant shift of -8×10^{-4} from the old to new K-factors.





$K_{u\mu}$ and $K_{d\mu}$ for Dizet 6.21 and Dizet 6.45

The dotted lines are made using Dizet 6.21, and the solid lines are from Dizet 6.45 in all plots.

Five values of cosθ calculated in the CM frame are used.

There is a roughly constant shift of -17×10^{-4} from the old to new K-factors.