# New Results from KKMC-hh with Dizet 6.45


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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.

# Outline

- Overview of KKMC-hh Program Structure
- Comparisons of CS Angular Distributions for Dizet 6.45 relative to Dizet 6.21
  - ISR and IFI effects on $A_{FB},\ A_4$
- Comments on the relation between KKMC-hh ISR corrections and QED-corrected PDFs (NNPDF3.1-LuxQED here)
- Overview of KKMC-hh developments in progress

Appendices: Dizet input parameters and form factor comparisons between Dizet 6.21 and 6.45, References

# KKMC-hh for Precision EW Phenomenology

- KKMC was developed for precision $Z$ boson phenomenology in $e^+e^-$ collisions, including exponentiated multi-photon effects:

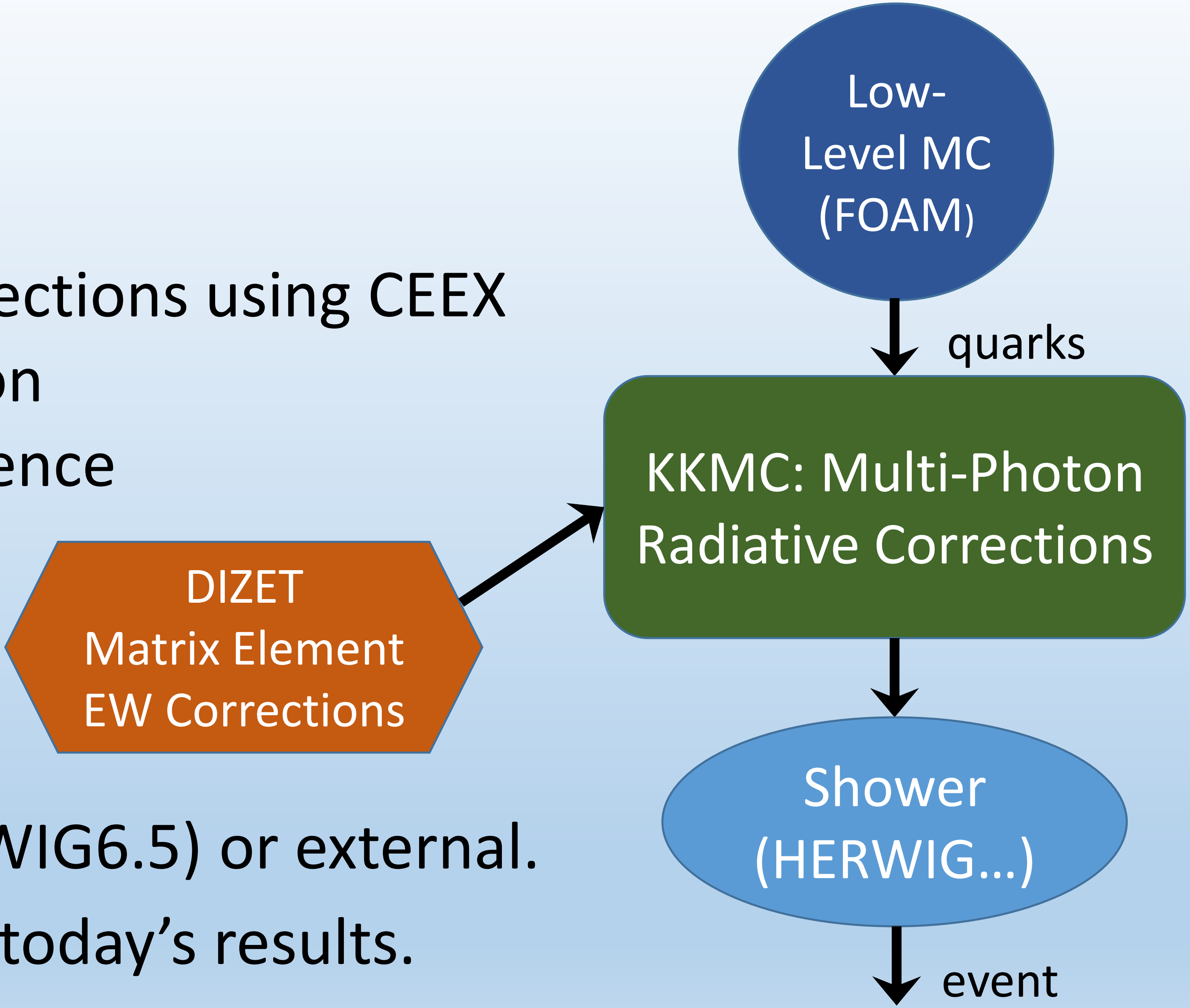
$$e^+e^- \to Z/\gamma^* \to f\bar{f} + n\gamma$$

including exact $\mathrm{O}(\alpha), O(\alpha^2 L)$ ISR, FSR, and IFI photonic corrections.

- $O(\alpha)$EW corrections were included via tables made using DIZET6.45.
- 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 using CEEX
    - Initial State Radiation
    - Initial-Final Interference
- DIZET gives corrections to hard matrix element
- Parton Shower can be internal (presently HERWIG6.5) or external. (Parton Shower is off in today's results.



# 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

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

where $\gamma_i = \frac{2\alpha}{\pi}\, Q_i^2\big(\ln\big(s_X/m_i^2\big) - 1\big)$ 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 $O(\alpha^2 L)$.

# KKMC-hh with Dizet 6.45

- The EW corrections in KKMC-hh have been upgraded to Dizet 6.45. We will present some comparisons between Dizet 6.21 and 6.45 and plots made with the new binning.
- Results have been analyzed from a 9 billion event run presented here.
- The $A_4$ definition used here is $\frac{8}{3} A_{FB}$ calculated in the full phase space. Plots with the definition $\mathrm{A}_4 = \frac{1}{4}\langle\cos\theta\rangle$ could be made if desired. Here, $\theta$ is taken to be the CS angle in the rest frame of the final muons.
- I have included an appendix with comparisons of Dizet 6.21 and 6.45 form factors.

# Results Presented in the Following Slides

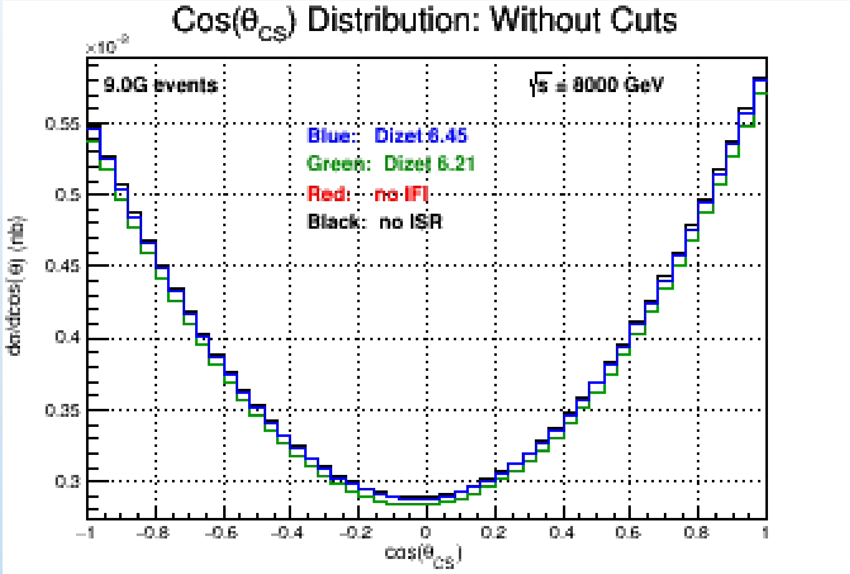
- All results are for muon pair final states with proton $\sqrt{s} = 8000\ \mathrm{GeV}$.
- Our tabulated results all include a dilepton mass cut in all cases:
$$60\ \mathrm{GeV} < M_{ll} < 150\ \mathrm{GeV}.$$
- The following table shows only $A_4$ calculated from $A_{FB}$ in the full phase space without fermion cuts.
- We also calculated $A_{FB}$ with lepton cuts $P_T > 25\ \mathrm{GeV}, |\eta| < 2.5$ on both muons but did not include this in the tables.
- All results use NNPDF3.1 NLO and include FSR corrections.
- After the table, we will show 9G event distributions for $A_{FB}$ and $A_4$ with 1 GeV binning for the full range 60 GeV < $M_{ll}$ < 150 GeV.

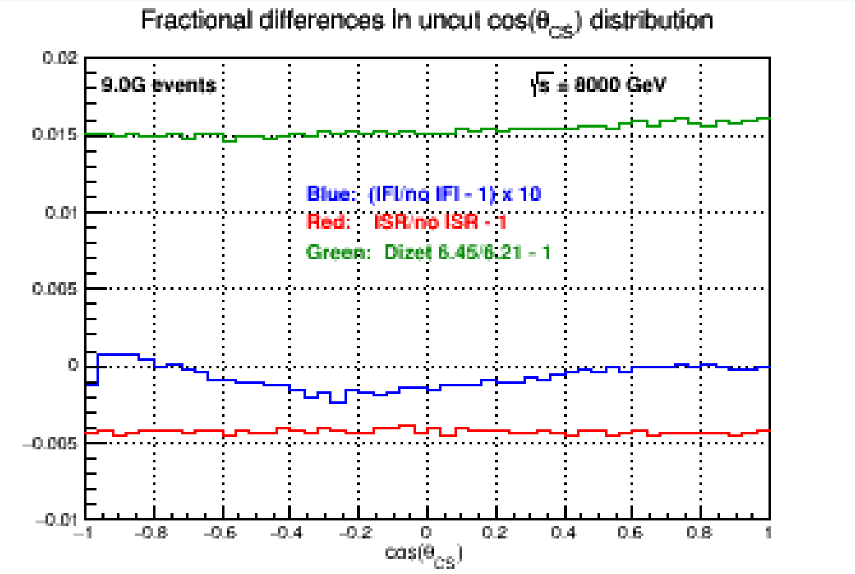
# Comparisons of $A_4$ for Dizet 6.21 and 6.45

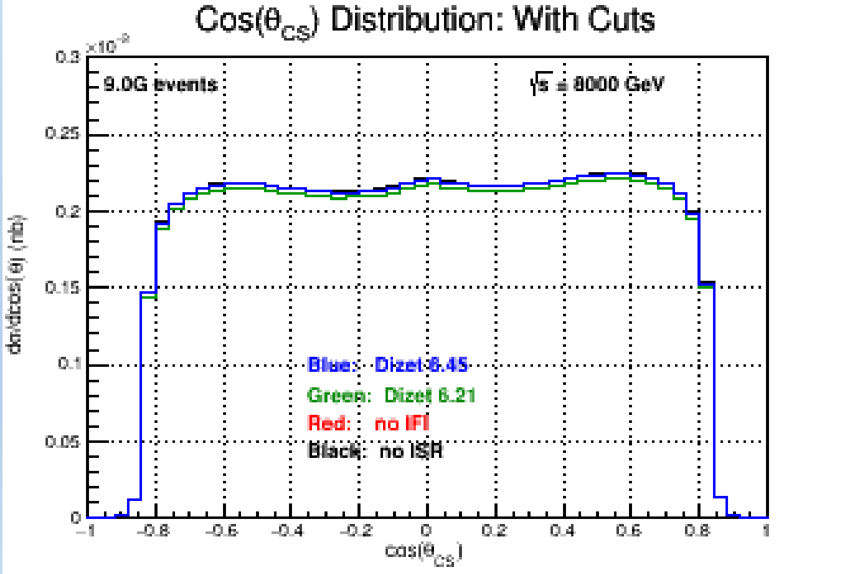
$A_4 = \frac{8}{3} A_{FB}$ is calculated in the full phases space with complete (KKMC best) photonic corrections.
$\Delta$ISR is the difference in $A_4$ with ISR on minus ISR off, with IFI off in both cases. $\Delta$IFI is the difference in $A_4$ with IFI on minus IFI off. The numbers are based on a sample of 9G – 10G muon events.

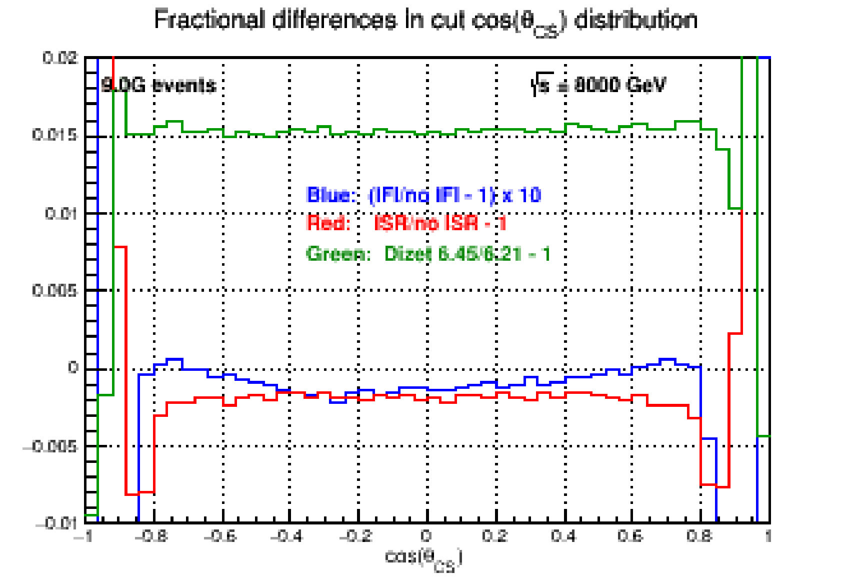
| | DIZET | $60 < M_{ll} < 81$ | $81 < M_{ll} < 101$ | $101 < M_{ll} < 150$ | $60 < M_{ll} < 120$ | $89 < M_{ll} < 93$ |
|---|---|---|---|---|---|---|
| $A_4$ (best) | 6.45 | $-0.28892(8)$ | $0.07785(3)$ | $0.5836(1)$ | $0.05606(3)$ | $0.08329(2)$ |
| | 6.21 | $-0.28892(8)$ | $0.07697(3)$ | $0.5828(1)$ | 0.05522(3) | $0.08246(5)$ |
| Difference | | $\pm 1.1 \times 10^{-4}$ | $(8.8 \pm 0.5) \times 10^{-4}$ | $(7.8 \pm 1.4) \times 10^{-4}$ | $(8.4 \pm 04) \times 10^{-4}$ | $(8.4 \pm 0.6) \times 10^{-4}$ |
| Δ ISR | 6.45 | $(0.2 \pm 1.1) \times 10^{-4}$ | $-(4.9 \pm 4.6\,) \times 10^{-5}$ | $-(0.8 \pm 0.2) \times 10^{-3}$ | $-(6.8 \pm 4.2) \times 10^{-5}$ | $-(1.0 \pm 0.6) \times 10^{-4}$ |
| | 6.21 | $(0.2 \pm 1.1) \times 10^{-4}$ | $(3.6 \pm 3.9) \times 10^{-5}$ | $-(1.1 \pm 0.1) \times 10^{-3}$ | $(2.6 \pm 3.4) \times 10^{-5}$ | $(8.5 \pm 6.0) \times 10^{-5}$ |
| Δ IFI | 6.45 | $(3.4 \pm 0.9) \times 10^{-4}$ | $(\,3.1 \pm 0.2) \times 10^{-4}$ | $-(6.19 \pm 0.08) \times 10^{-3}$ | $(1.3 \pm 0.4) \times 10^{-4}$ | $(2.0 \pm 0.3) \times 10^{-4}$ |
| | 6.21 | $(3.4 \pm 0.9) \times 10^{-4}$ | $(3.1 \pm 0.2) \times 10^{-4}$ | $-(6.18 \pm 0.06) \times 10^{-3}$ | $(1.3 \pm 0.3) \times 10^{-4}$ | $(1.8 \pm 0.4) \times 10^{-4}$ |

# Comparison of CS angle distributions



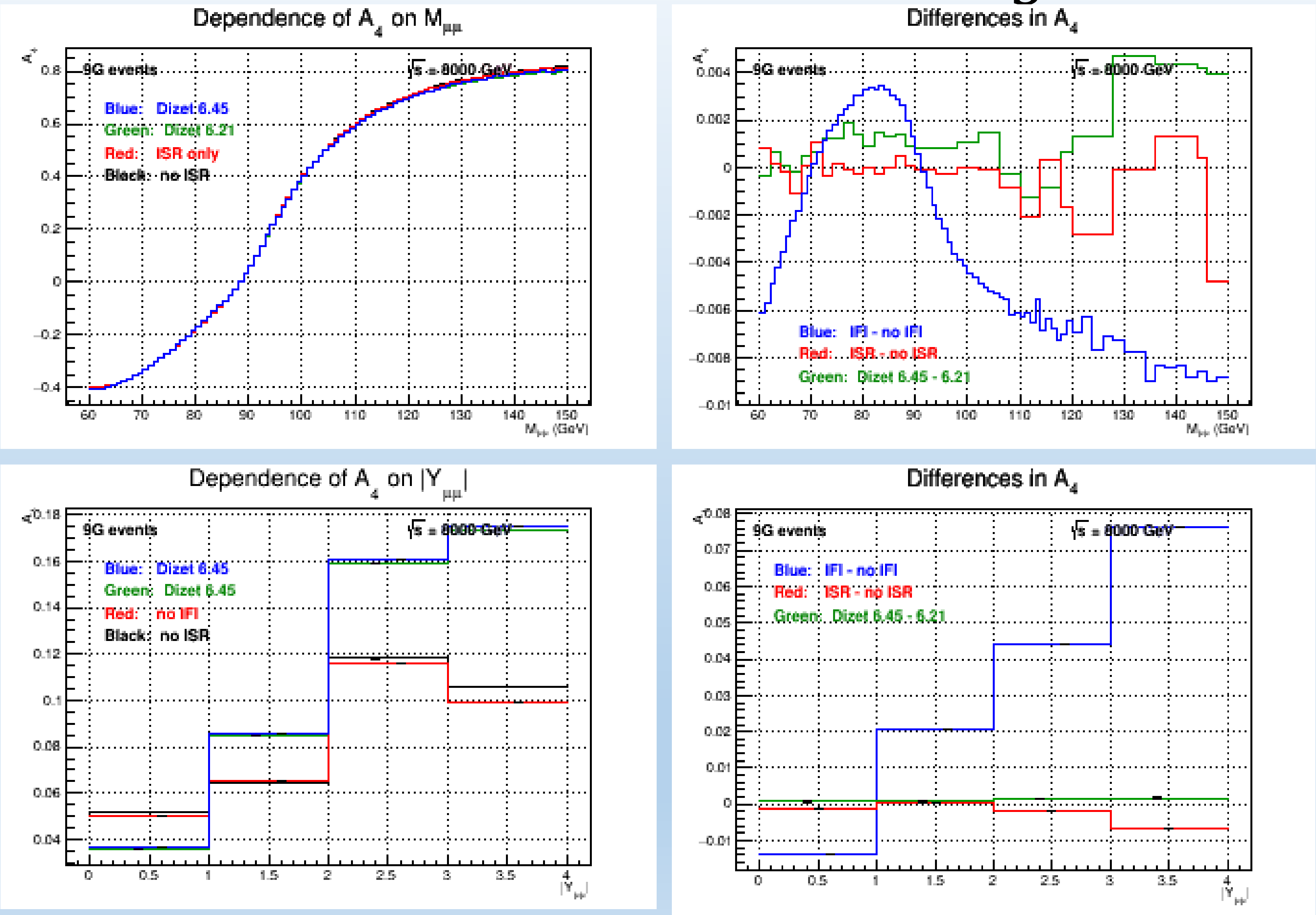

**Without Lepton Cuts (used for $A_4$)**

The IFI contributions are magnified by 10.

The Dizet shift and ISR contributions are very flat.

**With Lepton Cuts (used for $A_{\mathrm{FB}}$)**

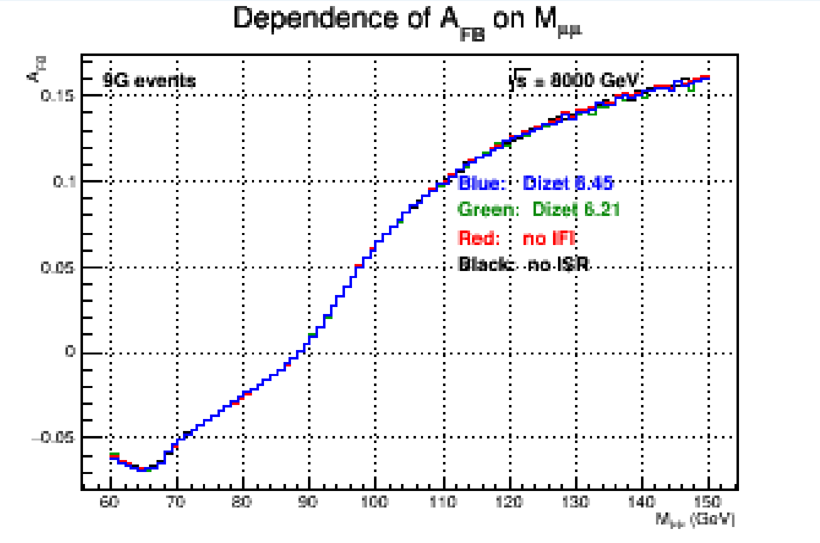
# ISR and contributions to $A_4$ ($\frac{8}{3}A_{\mathrm{FB}}$, no lepton cuts)

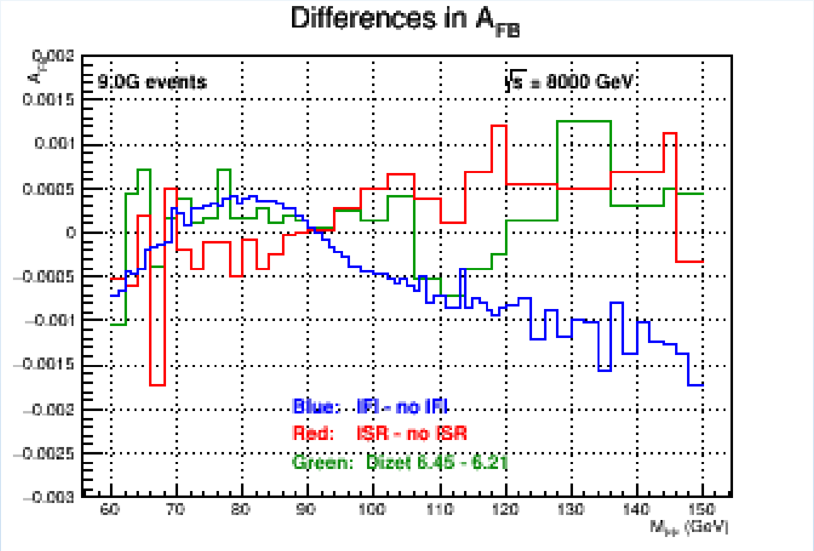


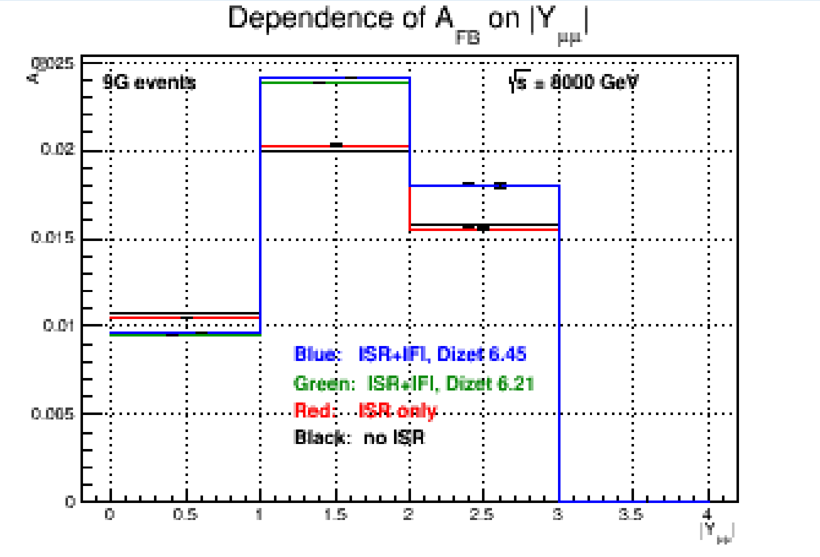

The IFI contribution has a clear structure, but the ISR contribution is near zero and flat up to statistical fluctuations. The Dizet shift is about a per-mil upward, with fluctuations.

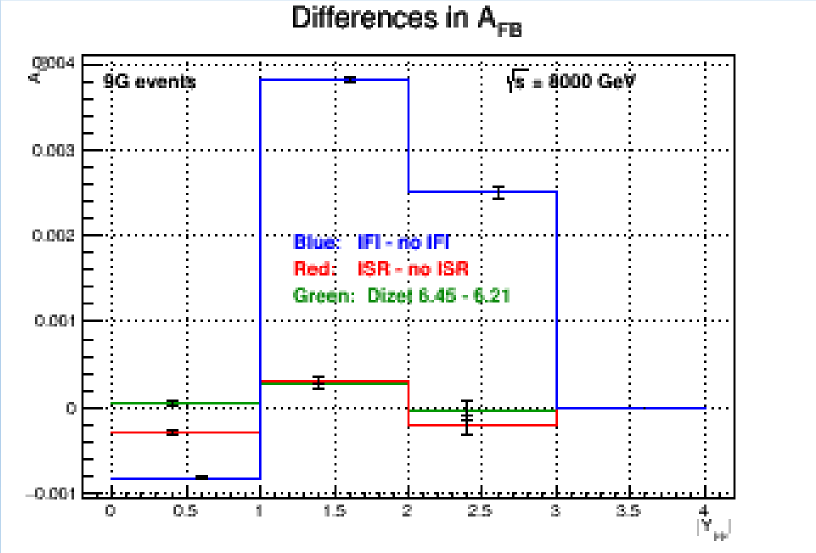
When binned in Y, the ISR contribution and Dizet shift are much smaller than IFI.

# ISR and IFI contributions to $A_{\mathrm{FB}}$ (with lepton cuts)



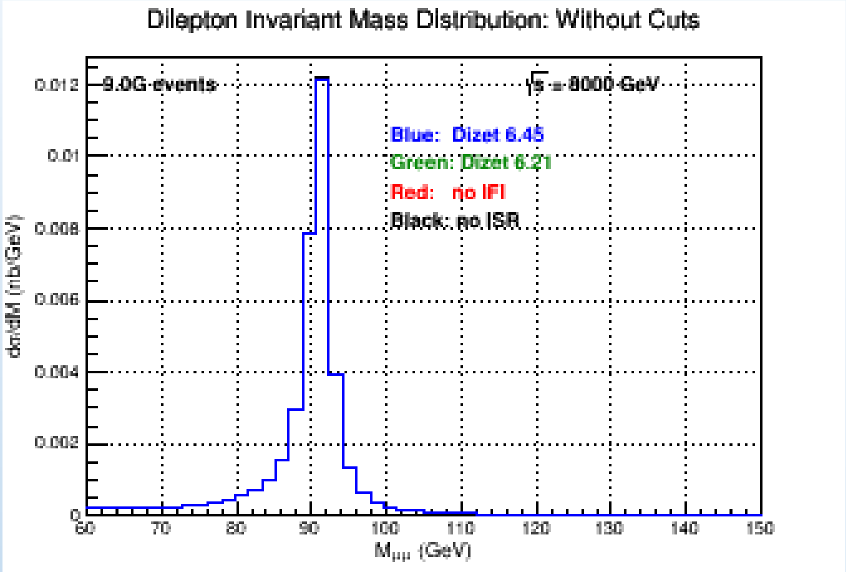



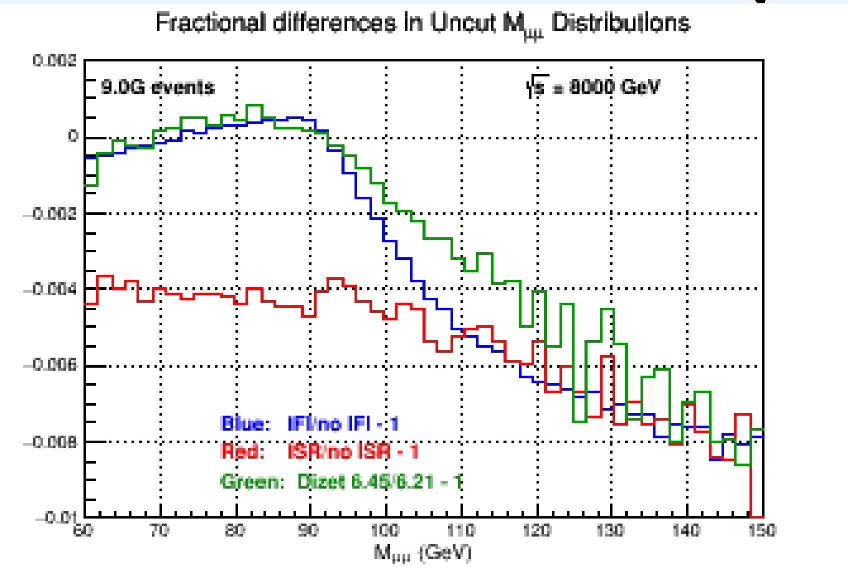



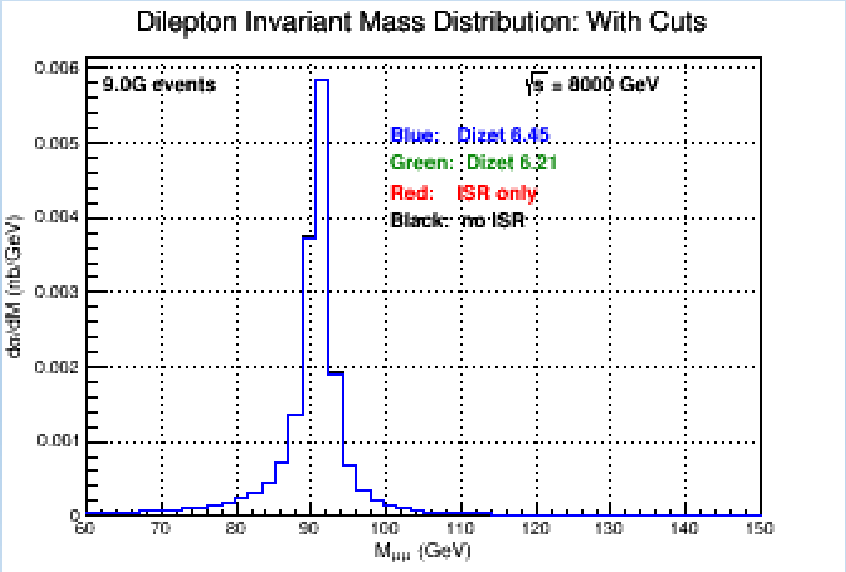

These plots show $A_{FB}$ calculated with the lepton cuts. When binned in $M_{ll}$, all three shifts, IFI, ISR, and the change in DIZET are typically below 1 per-mil.

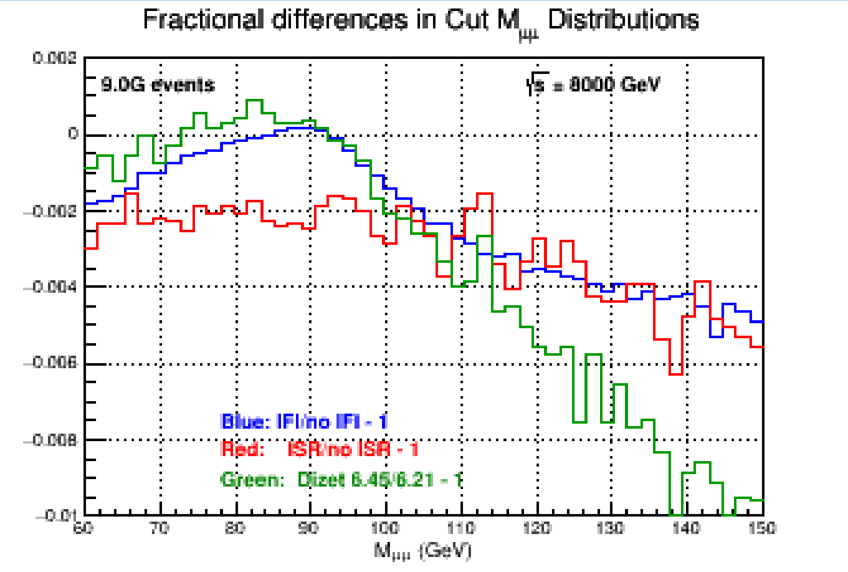
When binned in $Y_{ll}$, the IFI shift is again the largest, with the others being a fraction of a per-mil.

# Invariant Mass Distributions for $\mu^+\mu^-$ Pair




These plots (not included previously) show the differential cross section as a function of the CM energy of the muons.

In the neighborhood of $M_Z, \sim 70-90$ GeV, the IFI and DIZET shifts are on the order of a per-mil, with the ISR contribution being a $-4$ per-mil without the lepton cuts and $-2$ per-mil with them.

# The KKMC-hh Approach 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 in many cases.

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

KKMC-hh includes and ab-initio calculation of exponentiated photon radiation from the initial quarks.

KKMC-hh must use a PDF in which photonic effects are absent to within the claimed precision of the PDF.  However, we can also turn off ISR in KKMC-hh and run tests with QED PDFs for comparison.

# The KKMC-hh Approach to ISR

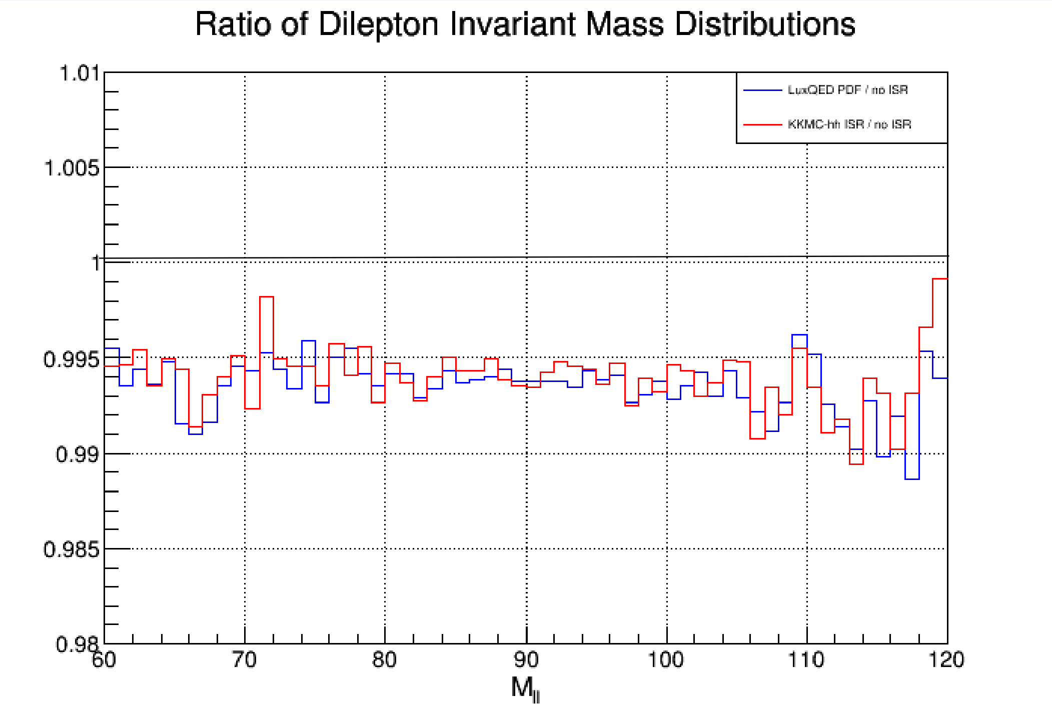
- The presence of the quark mass $m_i$ in the logarithm $\ln(sx_1x_2/m_i^2)$ governing ISR introduces dependence on the value of $m_i$ typically at the fractional per-mille level.
- We do not share the philosophy adopted by other approaches that the quark masses merely "unphysical" or "regulators" to 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.
- Keeping the full ISR in the program permits the effect of ISR on transverse momentum to be seen clearly.
- The results should be compatible for observables inclusive in the transverse momentum.

# Invariant Mass Distributions for Final Muons

Distributions can be calculated with or without ISR, or with a PDF including QED. The blue curve shows the ratio of the $\mu^+\mu^-$ invariant mass distribution calculated with KKMC-hh ISR on (no FSR) to a run with no ISR, both using standard NNPDF3.1 PDFs.

The red curve shows the ratio of a run calculated using NNPDF3.1+LuxQED to standard NNPDF3.1. For this observable, the two results are indistinguishable.

Graph from work by Matthew Dittrich @ The Citadel.



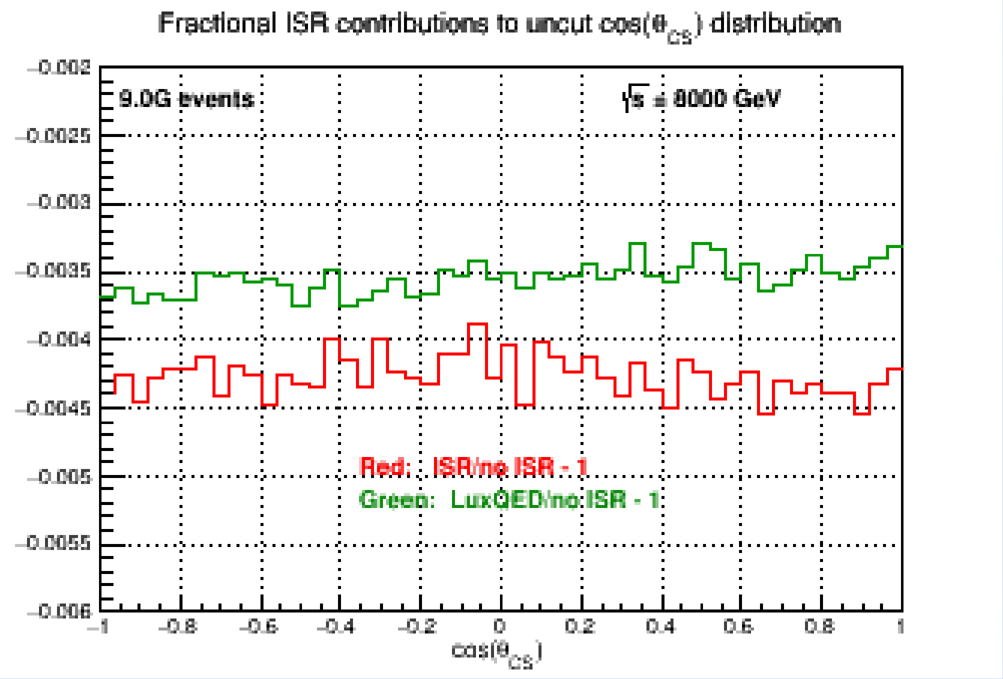

There is a small downward shift in the distributions in each case.

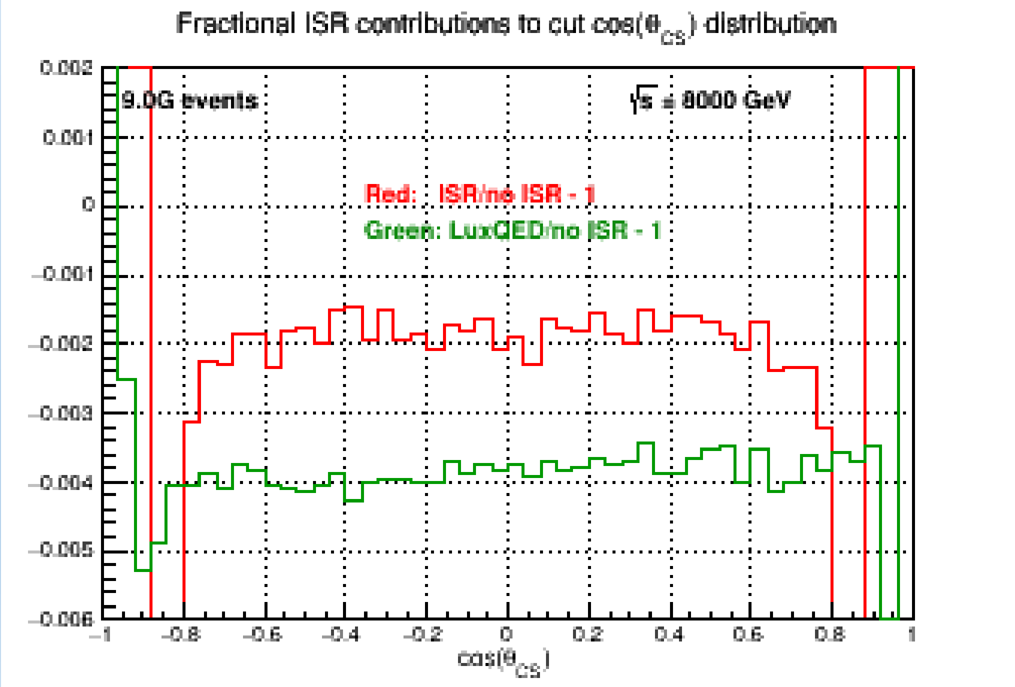
8000 GeV collisions, $60 < M_{ll} < 150$ GeV
NNPDF3.1 NLO, NNPDF3.1NLO + LuxQED.
$10^9$ muon events, no lepton cuts, no FSR.

# Comparisons of KKMC-hh ISR to LuxQED PDF

When ISR is turned off in KKMC-hh, it can be run with a QED PDF set. I have included a few comparisons here of the effect of turning on ISR in KKMC-hh to the effect of replacing NNPDF3.1 by NNPDF3.1-LuxQED in the event generation.

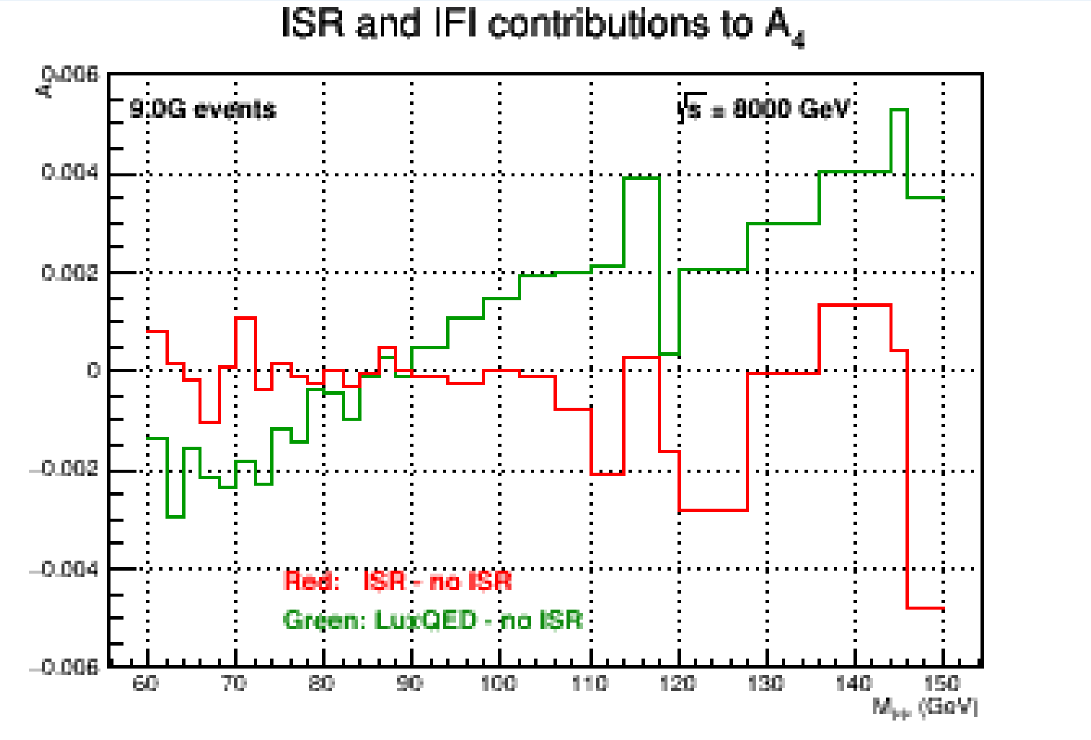
These graphs compare the fractional contribution of ISR to the uncut (left) and cut (right) $\cos\theta$ distributions calculated with KKMC ISR (red) and LuxQED (green). Agreement is best for the most inclusive calculation, and is on the order of a per-mille.

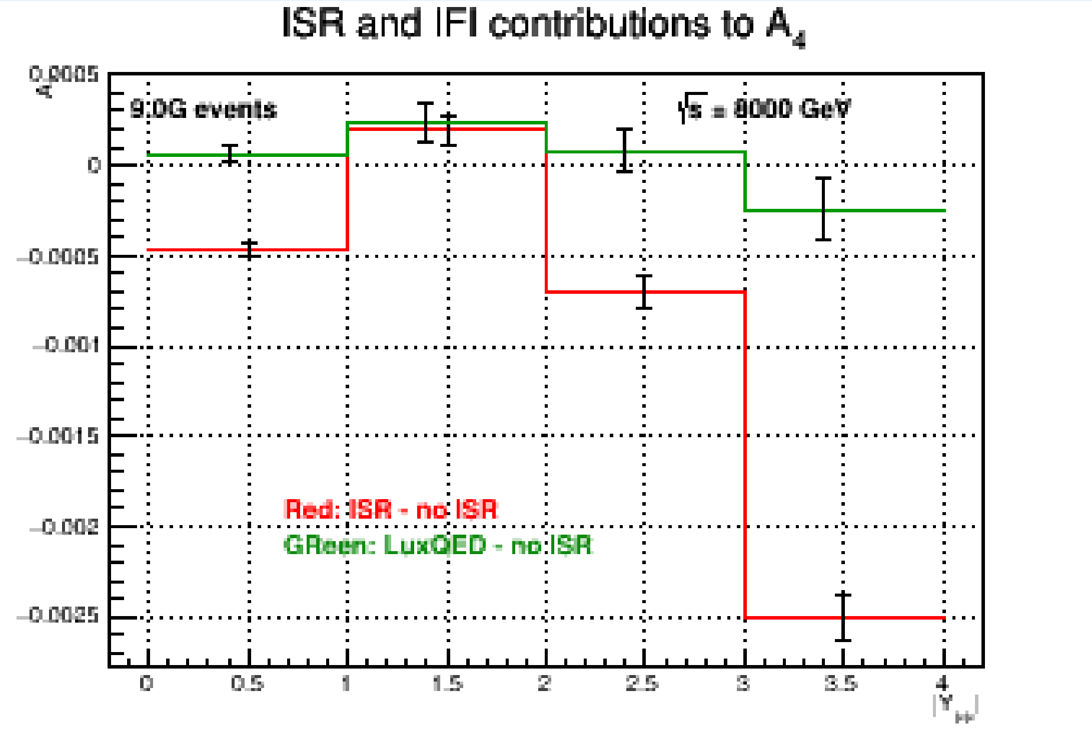


# ISR Comparisons for $A_4 = \frac{8}{3} A_{FB}$ (full phase space)

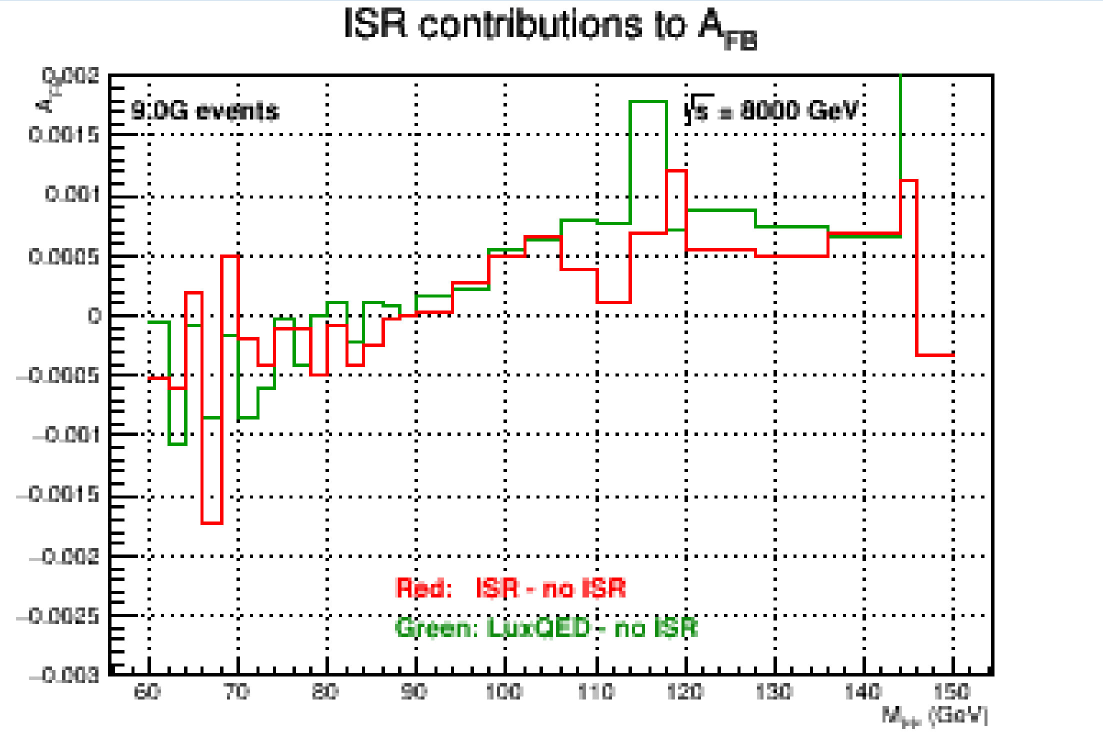
This is a similar comparison for the ISR contribution to $A_4$. The red curves were shown earlier for KKMC-hh ISR. The green curve compares the effect of turning on QED in the PDF set instead. There effects are at the per-mille level, but clearly distinct on the right.

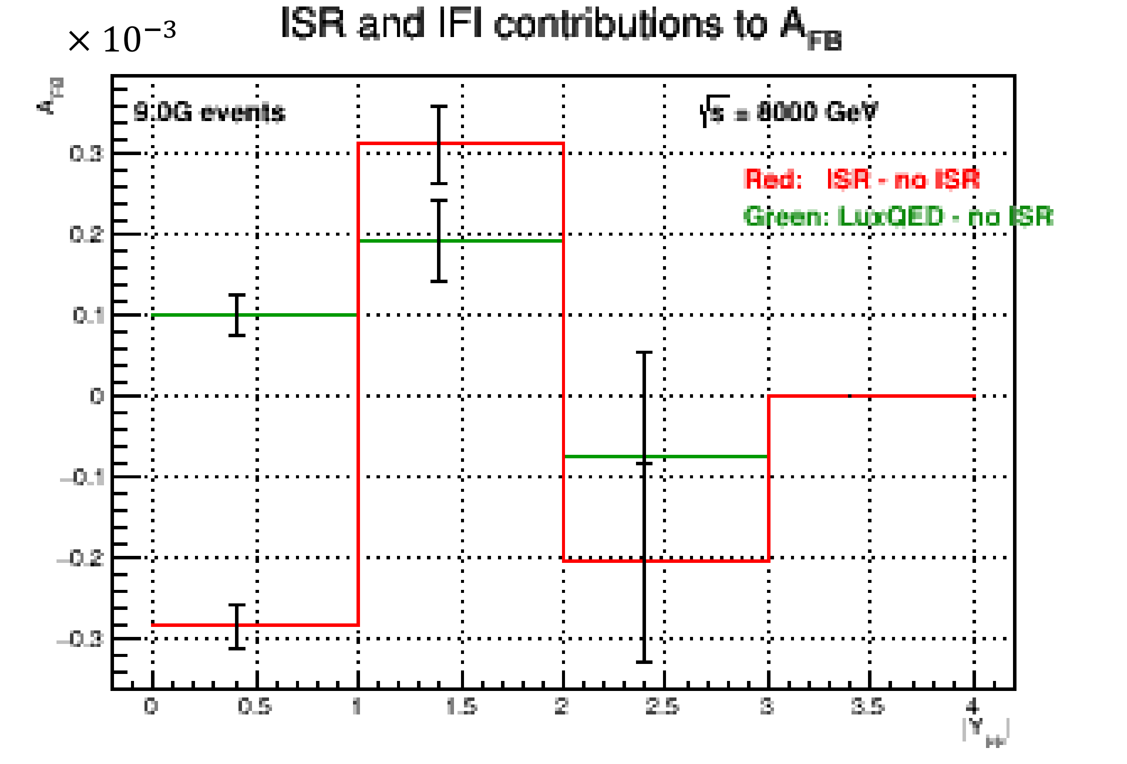


# ISR Comparisons for $A_{FB}$ with Lepton Cuts

With the lepton cuts, the KKMC-hh ISR effect is indistinguishable from turning on QED in the PDF set. The two corrections track very closely when binned in $M_{\ell\ell}$. The scale on the right is in tenths of a per-mille, so the agreement there is also within a fraction of a per-mille.



# Recent Developments

- Over the summer, KKMC-hh (and KKMC-ee) have largely been transcoded to C++.
- DIZET (FORTRAN) now generates tables outside KKMC-hh before a run. In principle, any other EW scheme could be imported this way for comparison.
- C++ transcoding is a prelude to integration with HERWIG and probably the KRKNLO parton showers.
- We can already export events to be showered externally, but we are also implementing an option to allow externally generated QCD events to be given photonic and EW corrections afterward by passing them through KKMC-hh.
- I have a student who is making a detailed study of ISR effects in KKMC-hh and comparisons to QED PDFs (NNPDF Lux-QED and CT14-QED) to better understand the relationship and quark mass effects in KKMC at the individual quark level.

# Appendix: Standard Model 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 | $\alpha_s(M_Z)$ | 0.1201789 |
| $1/\alpha(M_Z)$ | 128.950302560 | $\alpha_s(m_t)$ | 0.1094 |
| $G_F$ | $1.1663787\times 10^{-5}$ GeV$^{-2}$ | $\sin^2(\theta_W)$ | 0.22340108 |
| $M_Z$ | 91.1876 GeV | $\sin^2(\theta_W)_{\mathrm{eff}}$ | 0.23149900 |
| $\Gamma_Z$ | 2.4953785 GeV | | |
| $M_W$ | 80.3589356 GeV | $m_d$ | 4.7 MeV |
| $\Gamma_W$ | 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 |
| $m_\mu$ | 105.658389 MeV | $m_b$ | 1.2 GeV |
| $m_\tau$ | 1.777 GeV | $m_t$ | 173.0 GeV |

Red: input

Blue: output

# Appendix: Dizet Form Factors

Dizet inserts factors as shown:

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

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

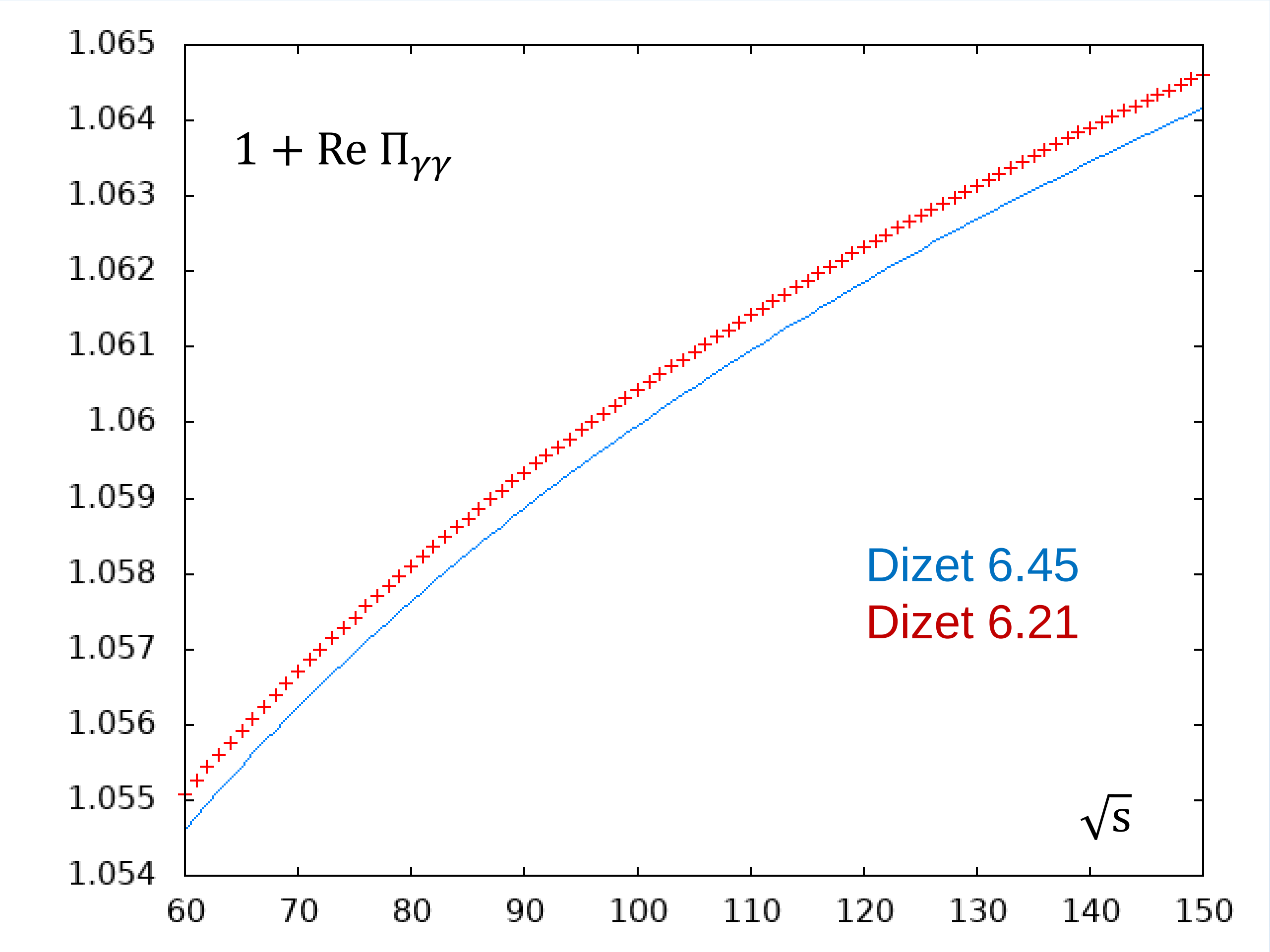
with

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

$$V_{if}=\frac{4}{\Delta^2v_iv_f}\left\{T_3^iT_3^f-4\sin^2\theta_W\left(q_iK_i(s,t)+q_fK_i(s,t)\right)+4\sin^4\theta_W\,q_iq_fK_{if}(s,t)\right\}.$$

This appendix shows comparisons of DIZET 6.21 and 6.45 form factors.

# $\Pi_{\gamma\gamma}$ for Dizet 6.21 and 6.45




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,

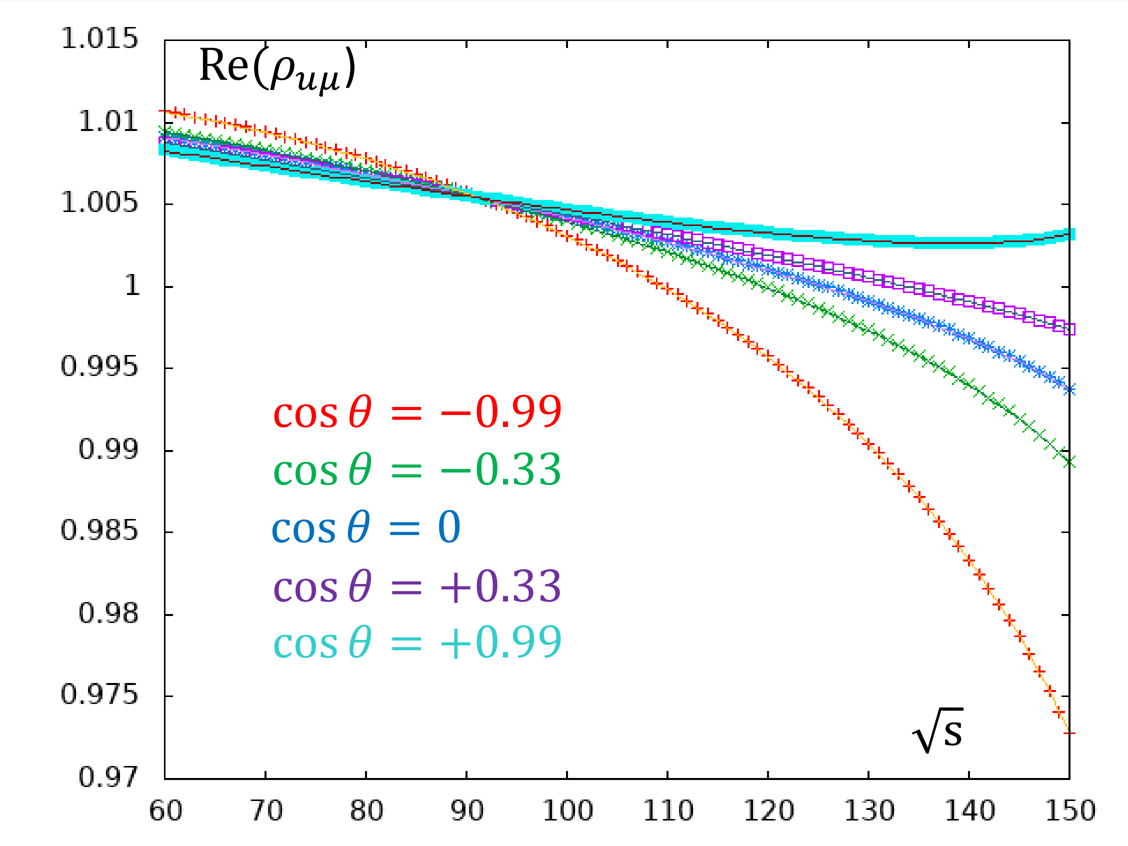
$-4.75 \times 10^{-4}$ at 60 GeV,

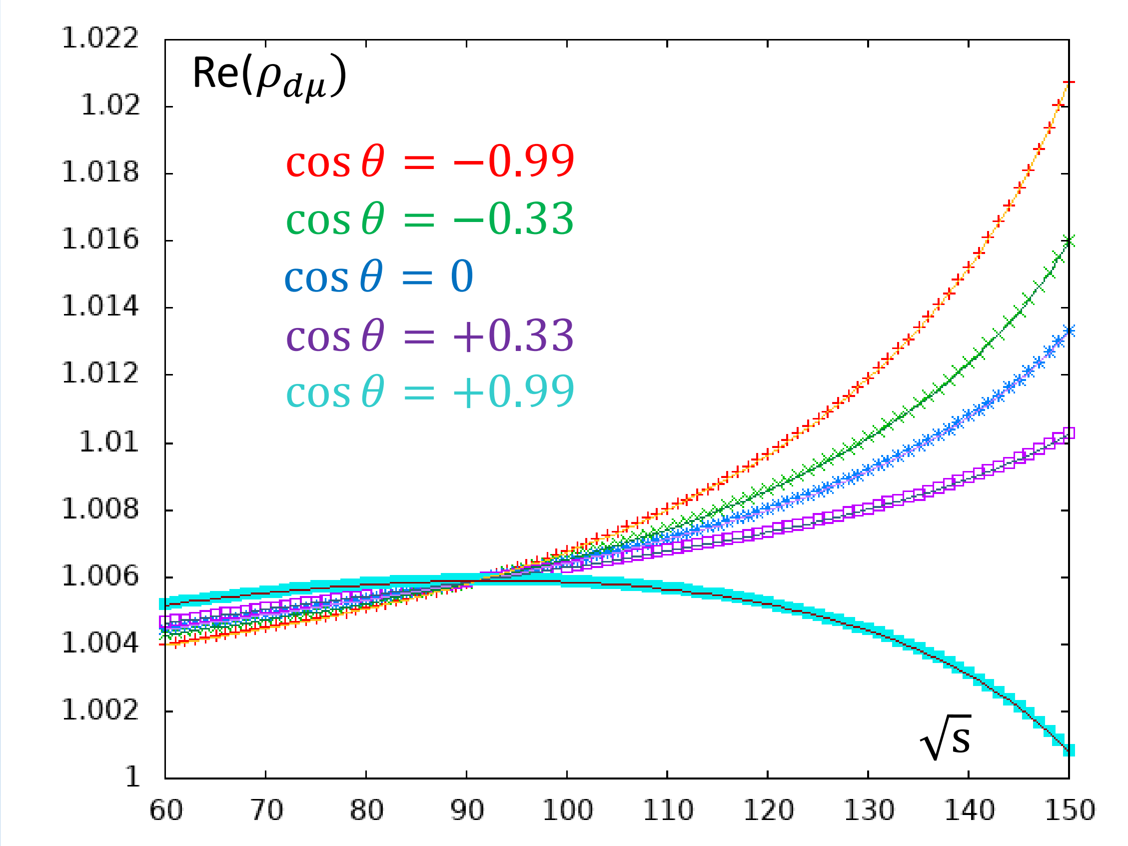
$-4.57 \times 10^{-4}$ at 150 GeV.

# $\rho_{u\mu}$ 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.



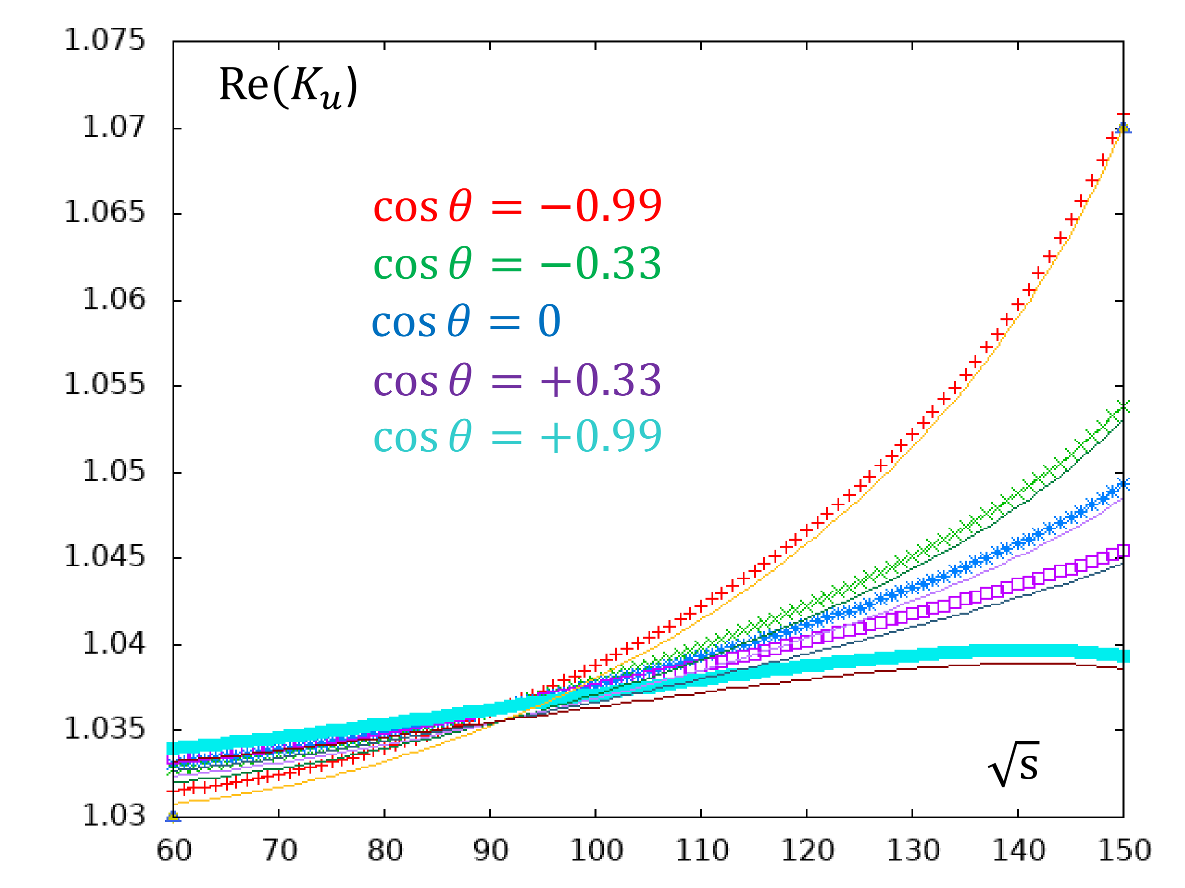



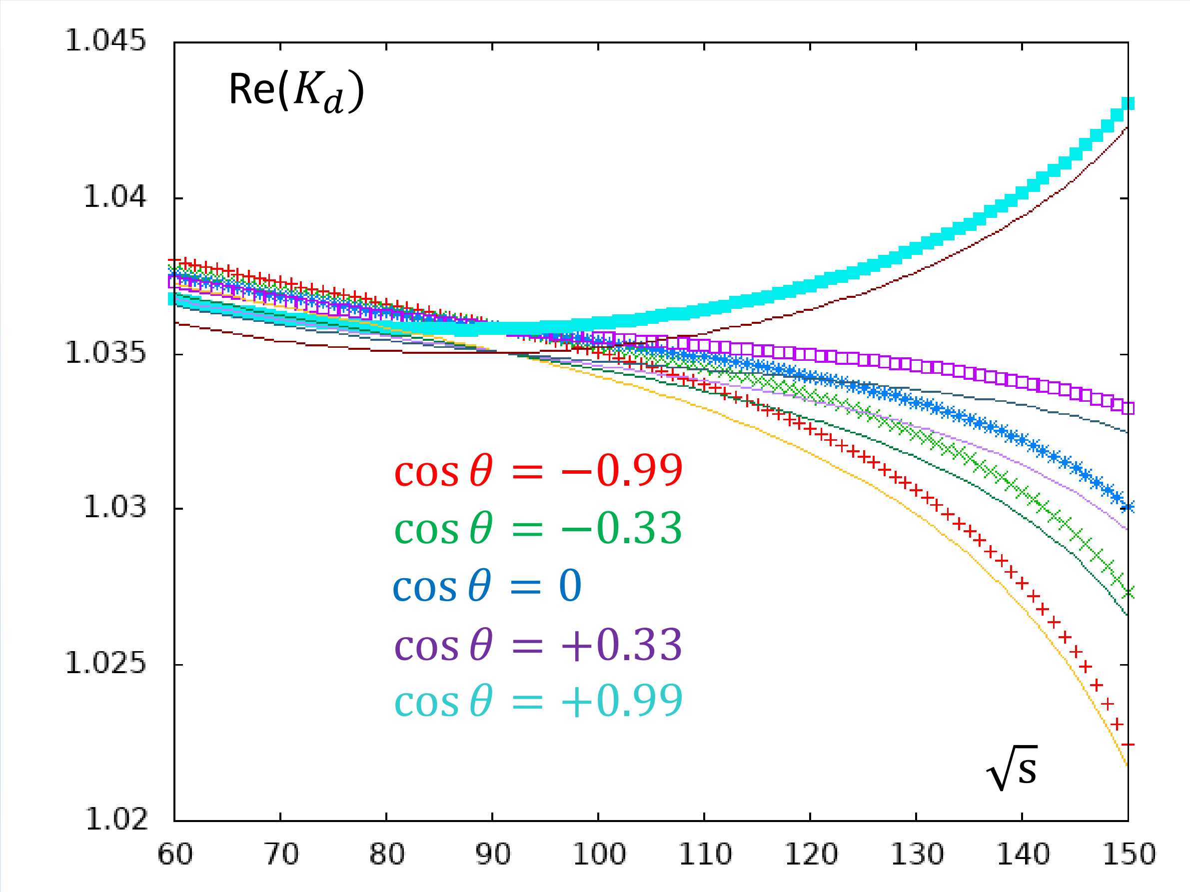
# $K_u$ and $K_d$ for Dizet 6.21 and Dizet 6.45

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

Five values of $\cos\theta$ 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 $-8 \times 10^{-4}$ from the old to new $K$-factors.



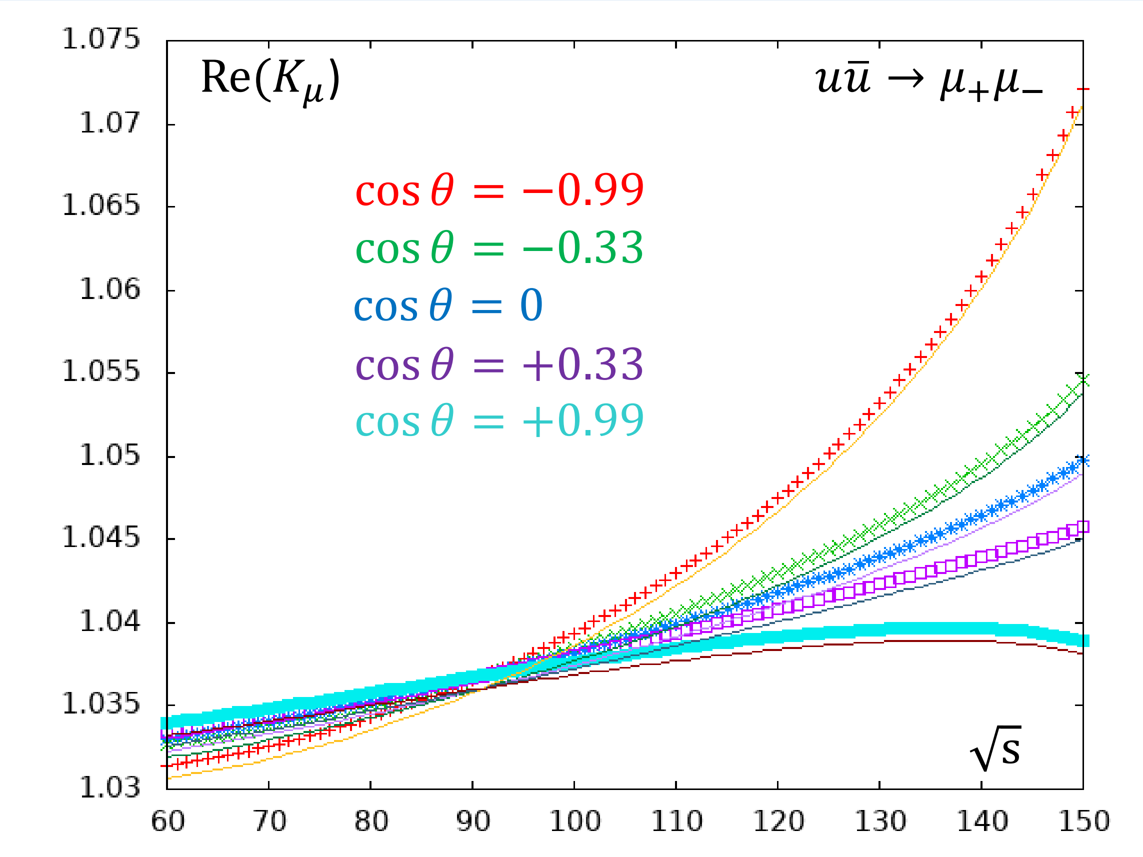



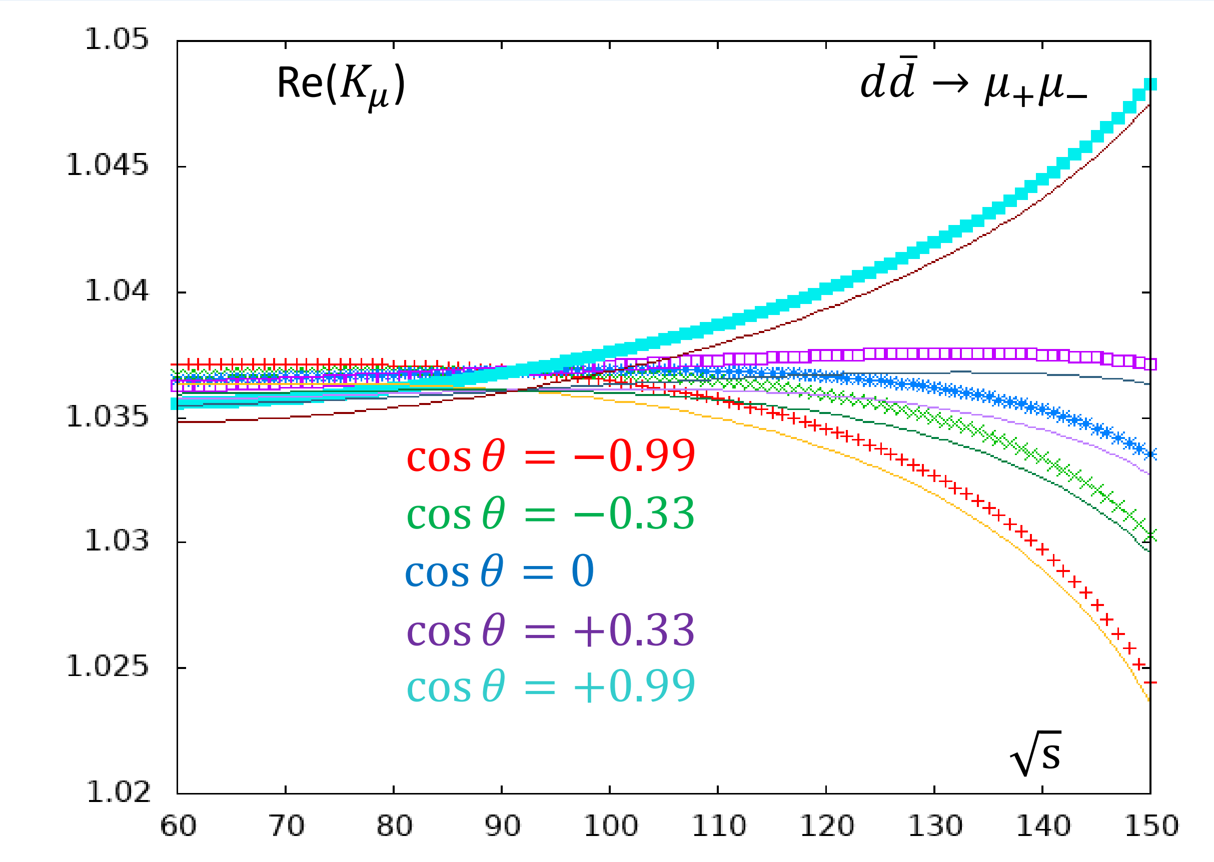
# $K_\mu$ for Dizet 6.21 and Dizet 6.45

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

Five values of $\cos\theta$ 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 $-8 \times 10^{-4}$ from the old to new $K$-factors.



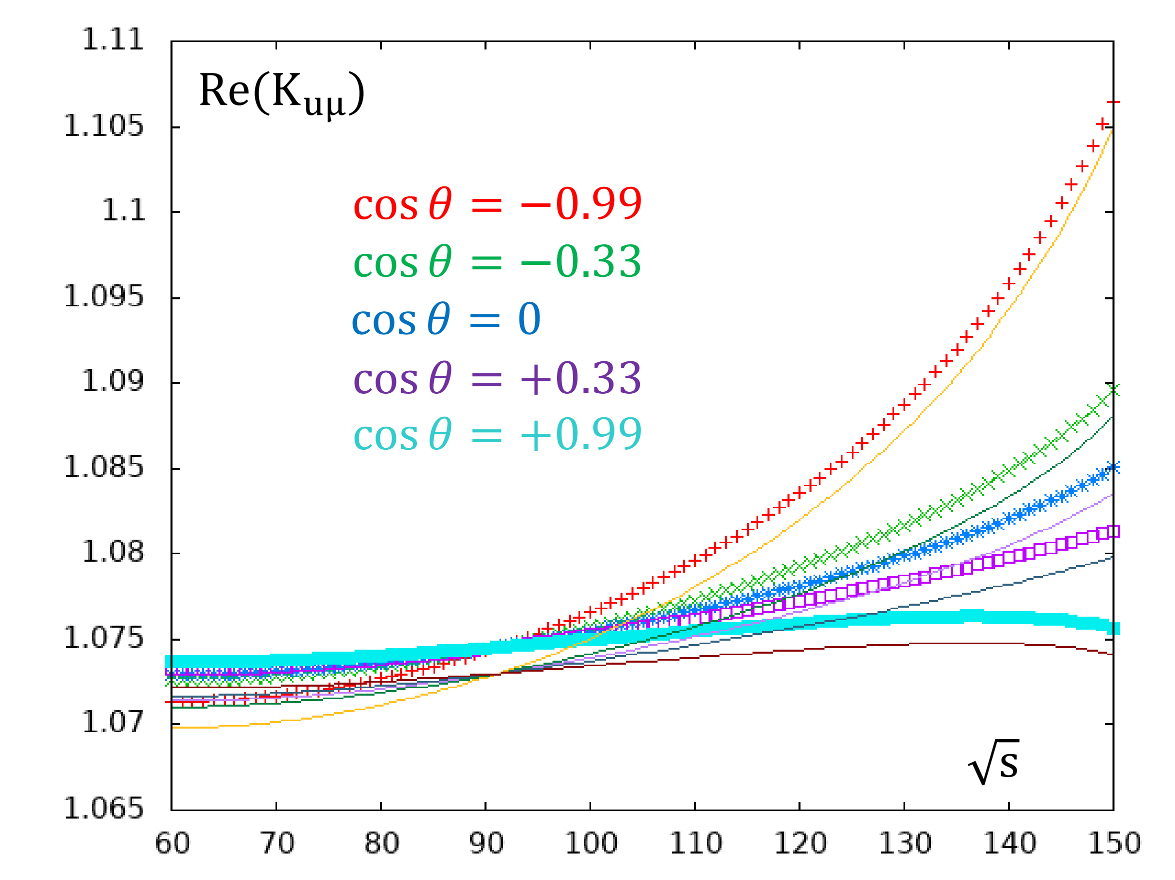



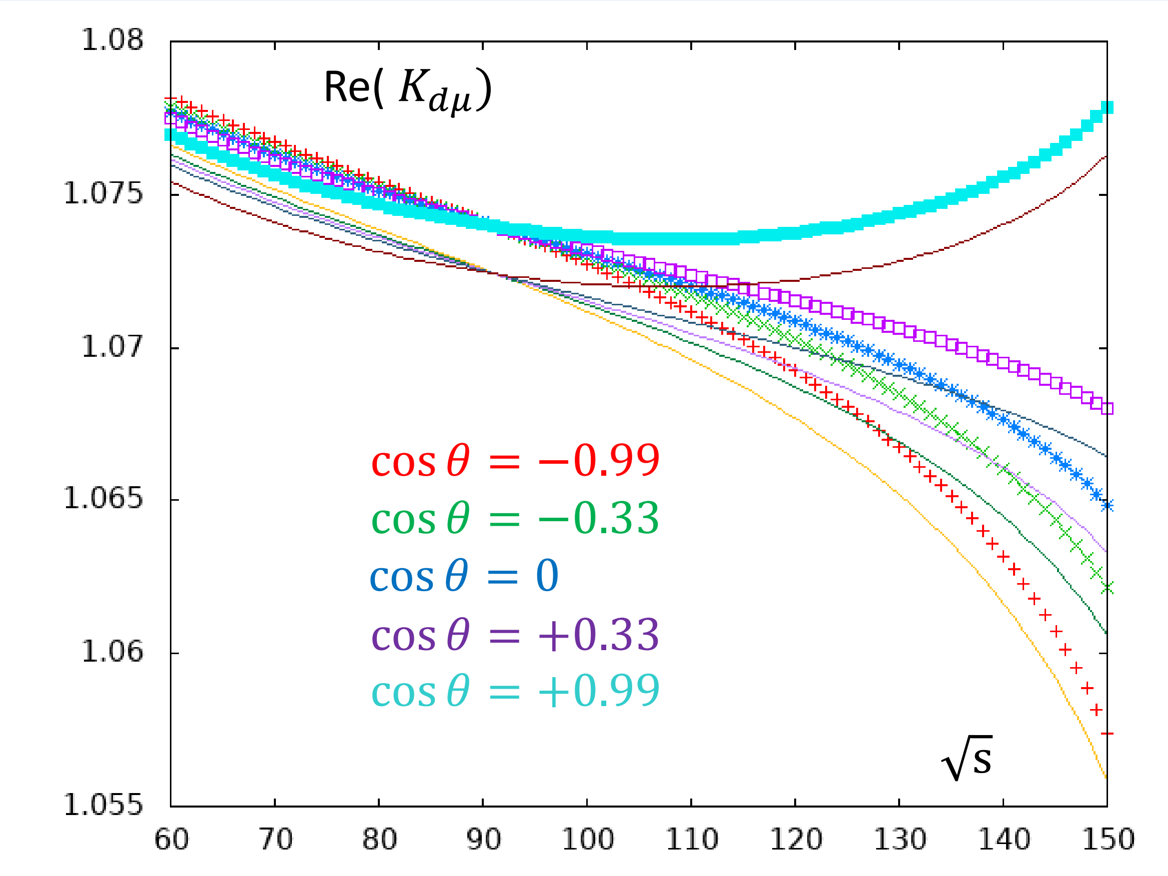
# $K_{u\mu}$ and $K_{d\mu}$ for Dizet 6.21 and Dizet 6.45

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

Five values of cos$\theta$ calculated in the CM frame are used.

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



# References on KKMC-hh and KKMC

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 $Z/\gamma^*$ Physics at LHC Energies, Phys. Rev. D99, 076016 (2019) [arXiv:1707.06502]
- Ibid., IFI and ISR Effects in $Z/\gamma^*$ 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]